Flavour physics, status and prospects

Vladimir V. Gligorov

CERN-EP Seminar, June 17th 2014

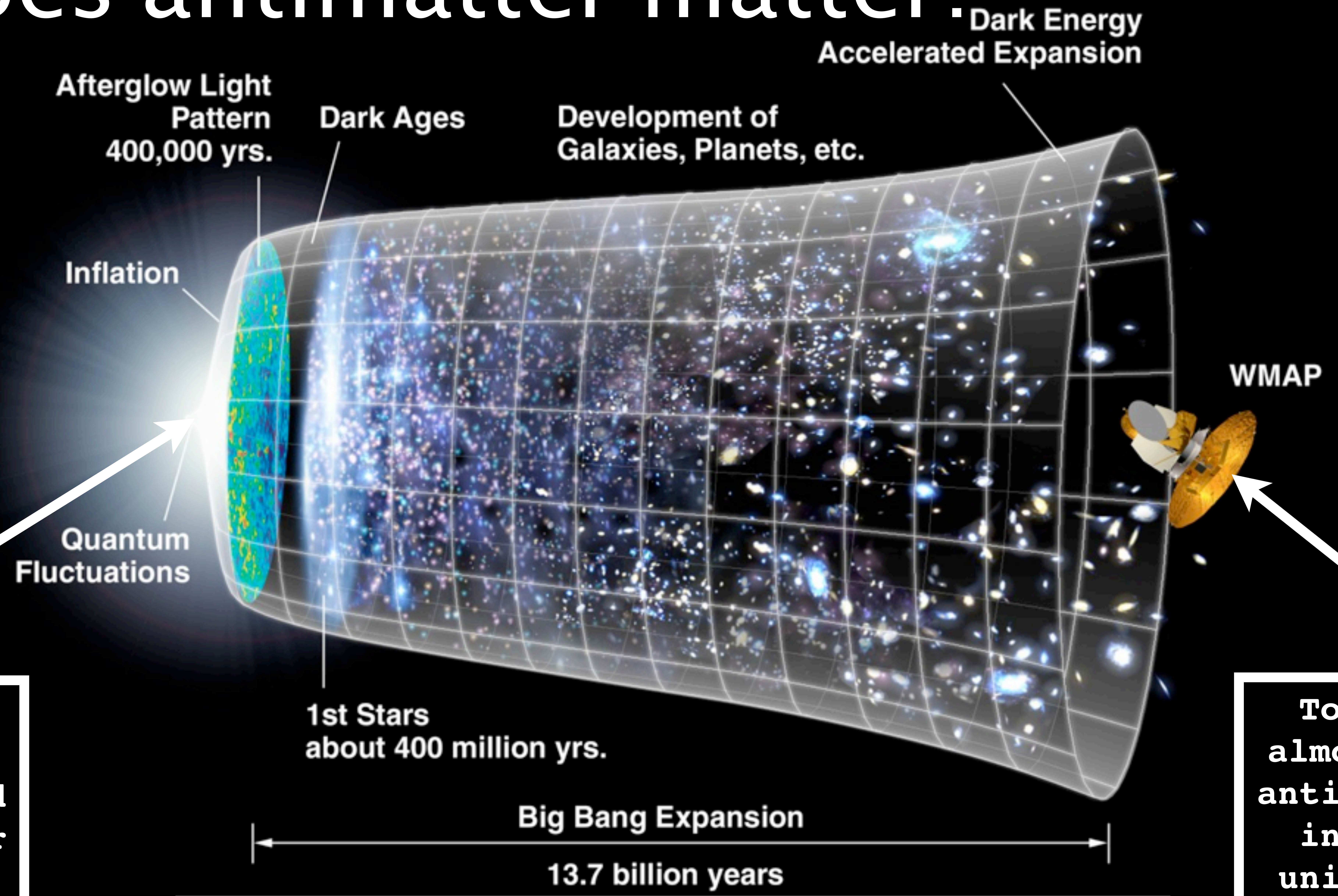
Quark mixing in the Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\mathbf{V_{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \sum_{n=4}^{N} O(\lambda^n)$$

Imaginary component gives rise to matter-antimatter asymmetry (CP violation)

Why does antimatter matter?



Equal amount of matter and antimatter created

Today: almost no antimatter in the universe

So where did all the antimatter go?

Other reasons exist

Hierachy, naturaleness, etc.

Inconsistency between SM picture of CPV and Big Bang comes directly from the quark masses and cannot be explained away though.

Assume Big Bang picture is correct, there must be sources of CPV outside the SM!

Potential NP is constrained by flavour

Hierachy, naturaleness, etc.

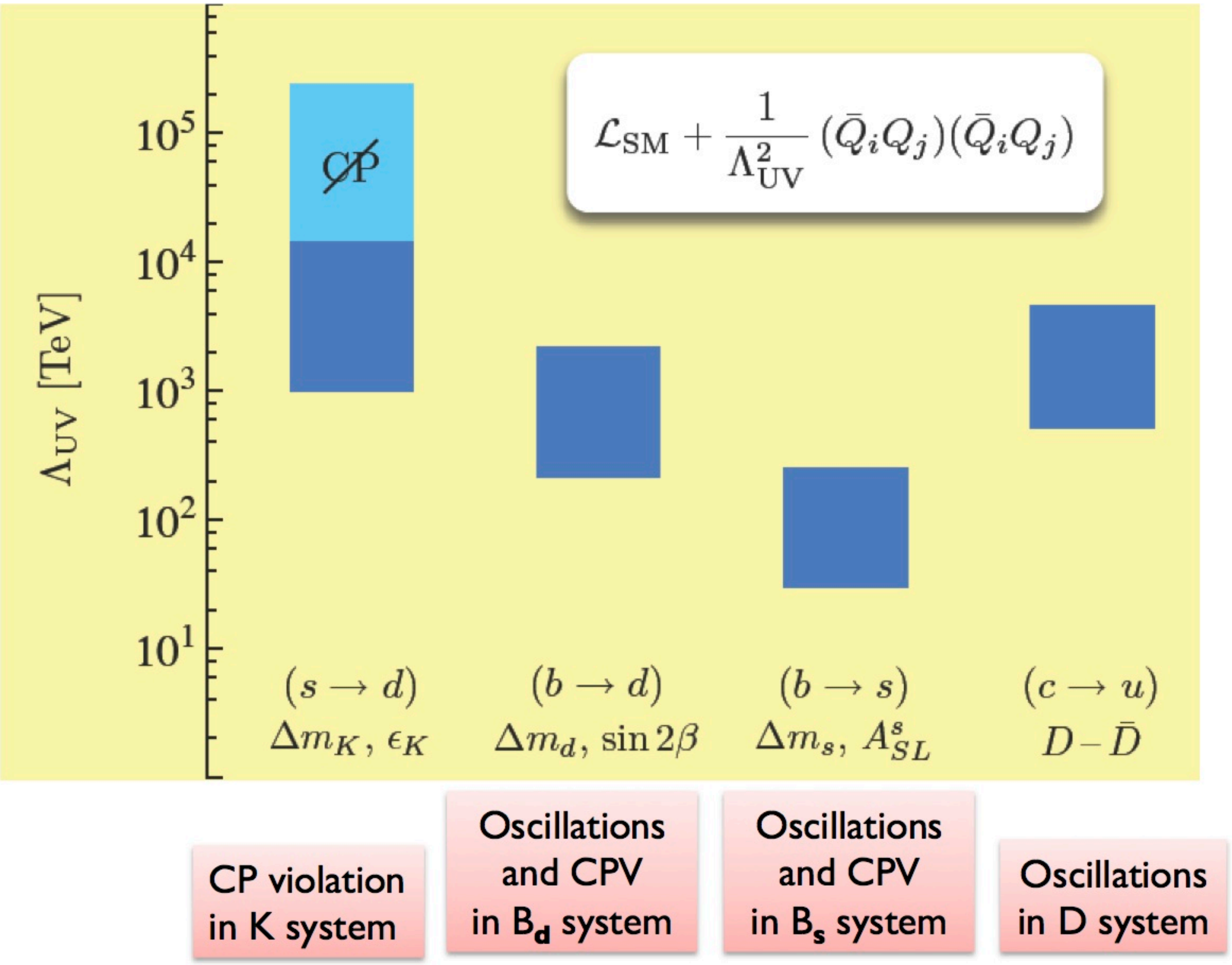
Inconsistency between SM picture of CPV and Big Bang comes directly from the quark masses and cannot be explained away though.

Assume Big Bang picture is correct, there must be sources of CPV outside the SM!

For the purposes of this talk, "flavour physics" really means "quark flavour physics", with apologies to neutrinos, lepton flavour violation, etc.

Specifically measurements which tell us about the matter-antimatter discrepancy.

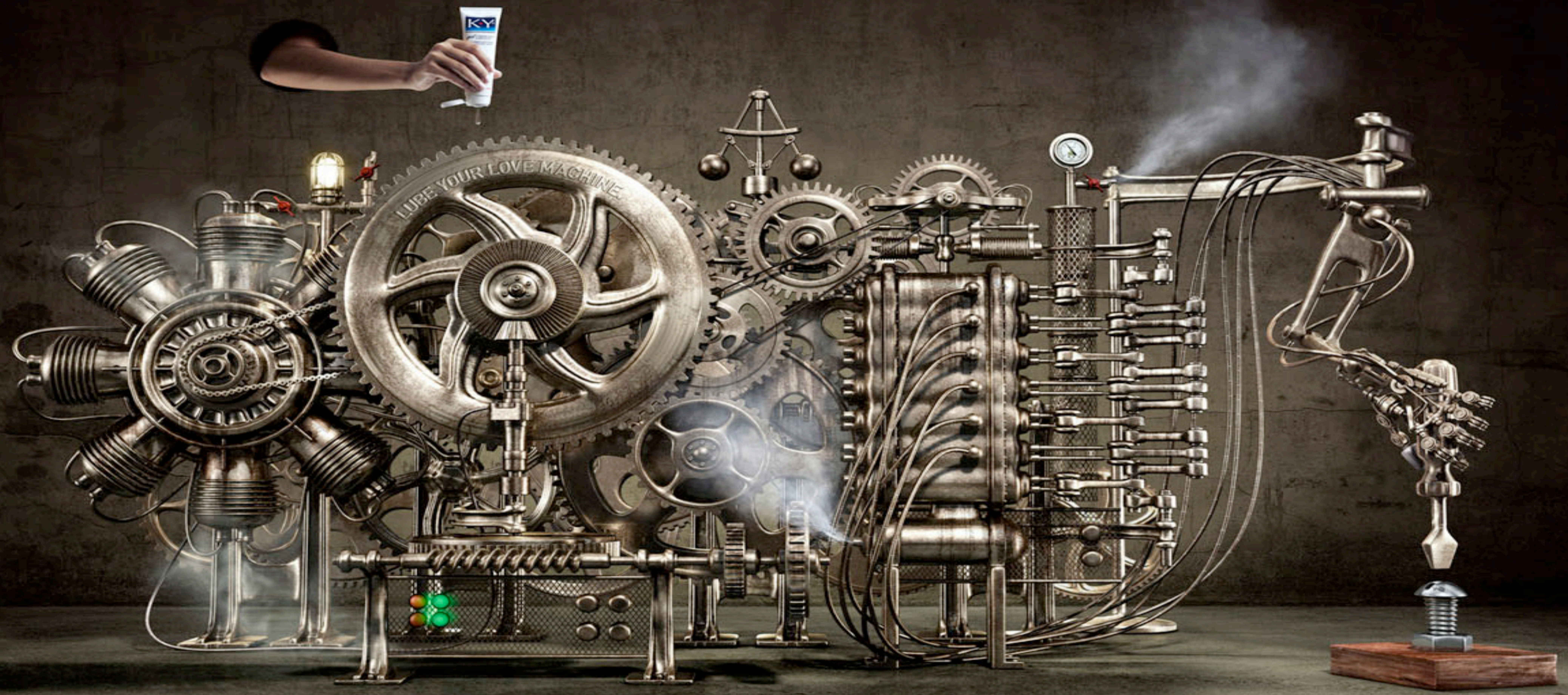
Existing flavour measurements constrain generic New Physics at the TeV scale, competitive with direct searches.

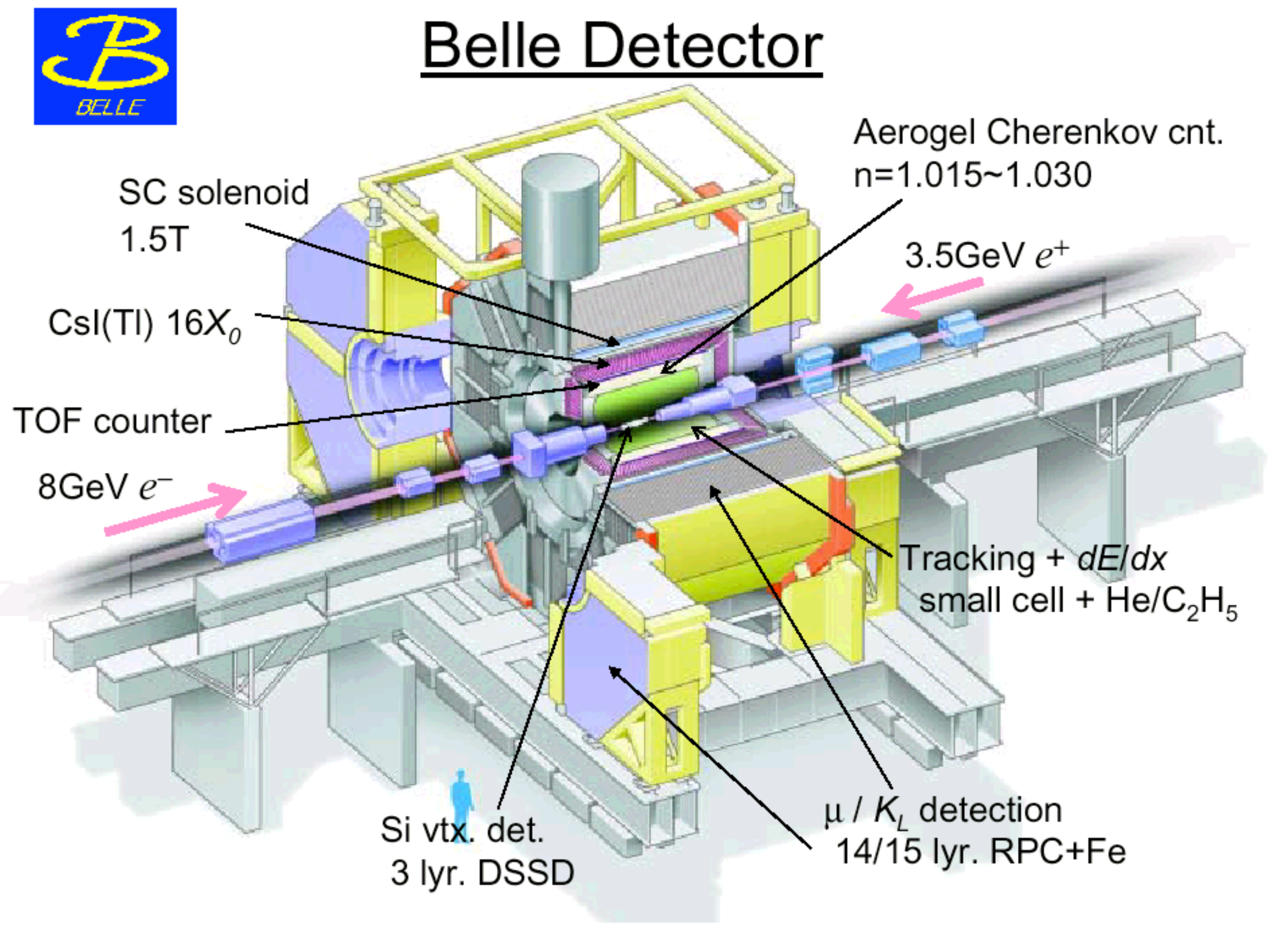


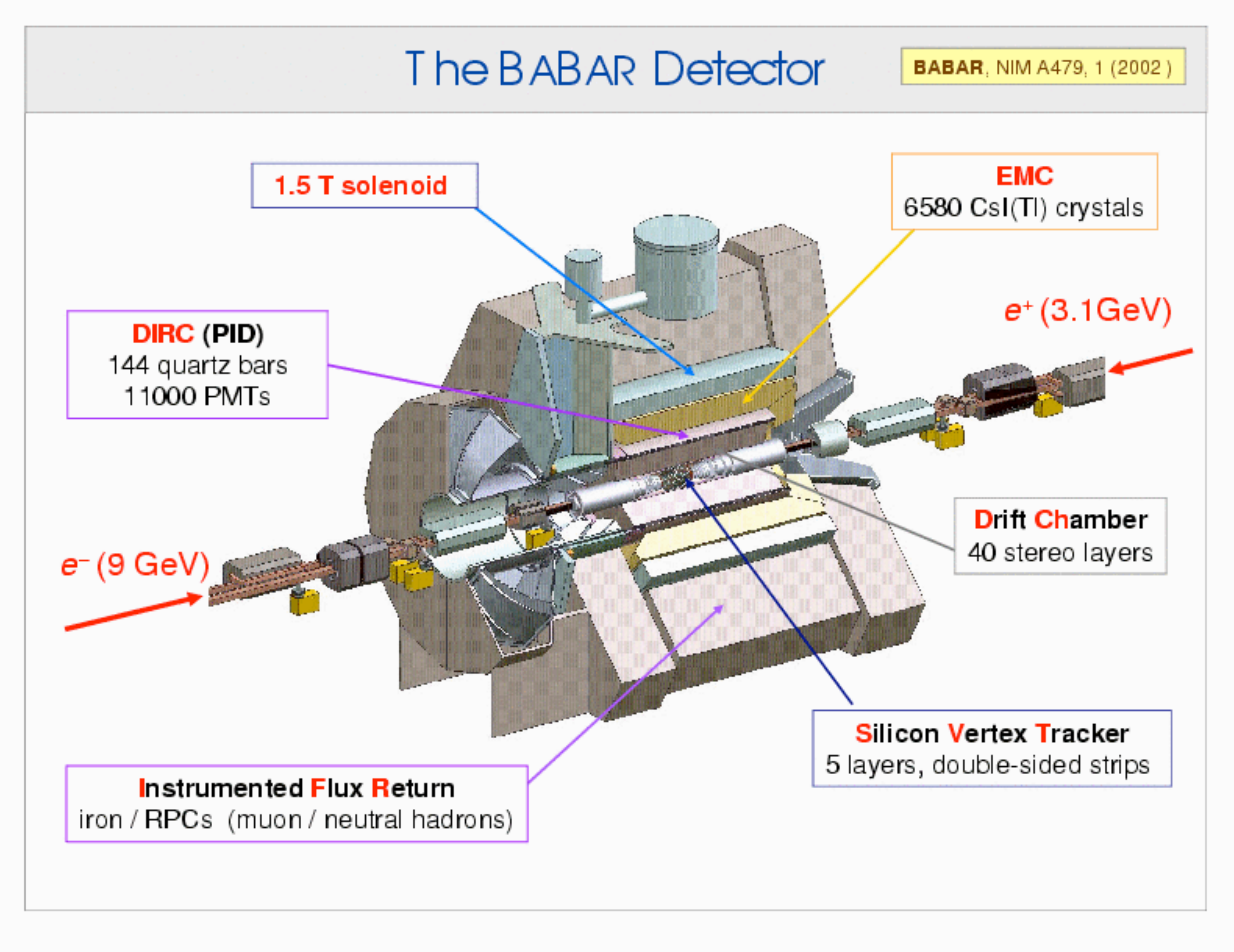
(Fig. Neubert, EPS-HEP'11)

Isidori, Nir, Perez, Ann. Rev. Nucl. Part. Sci. 60 (2010) 355 [arXiv:1002.0900],
Isidori, arXiv:1302.0661

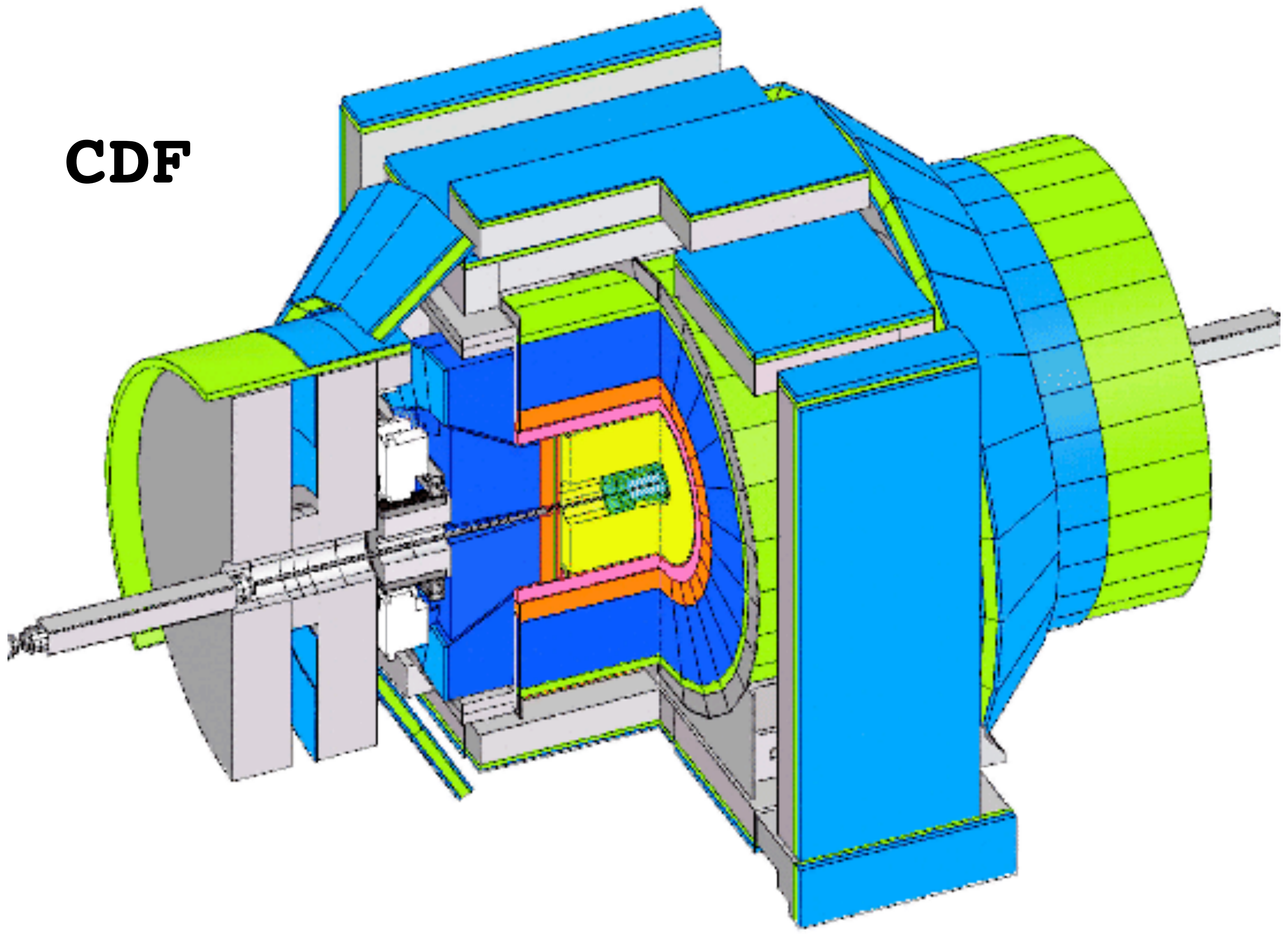
Tools of our trade

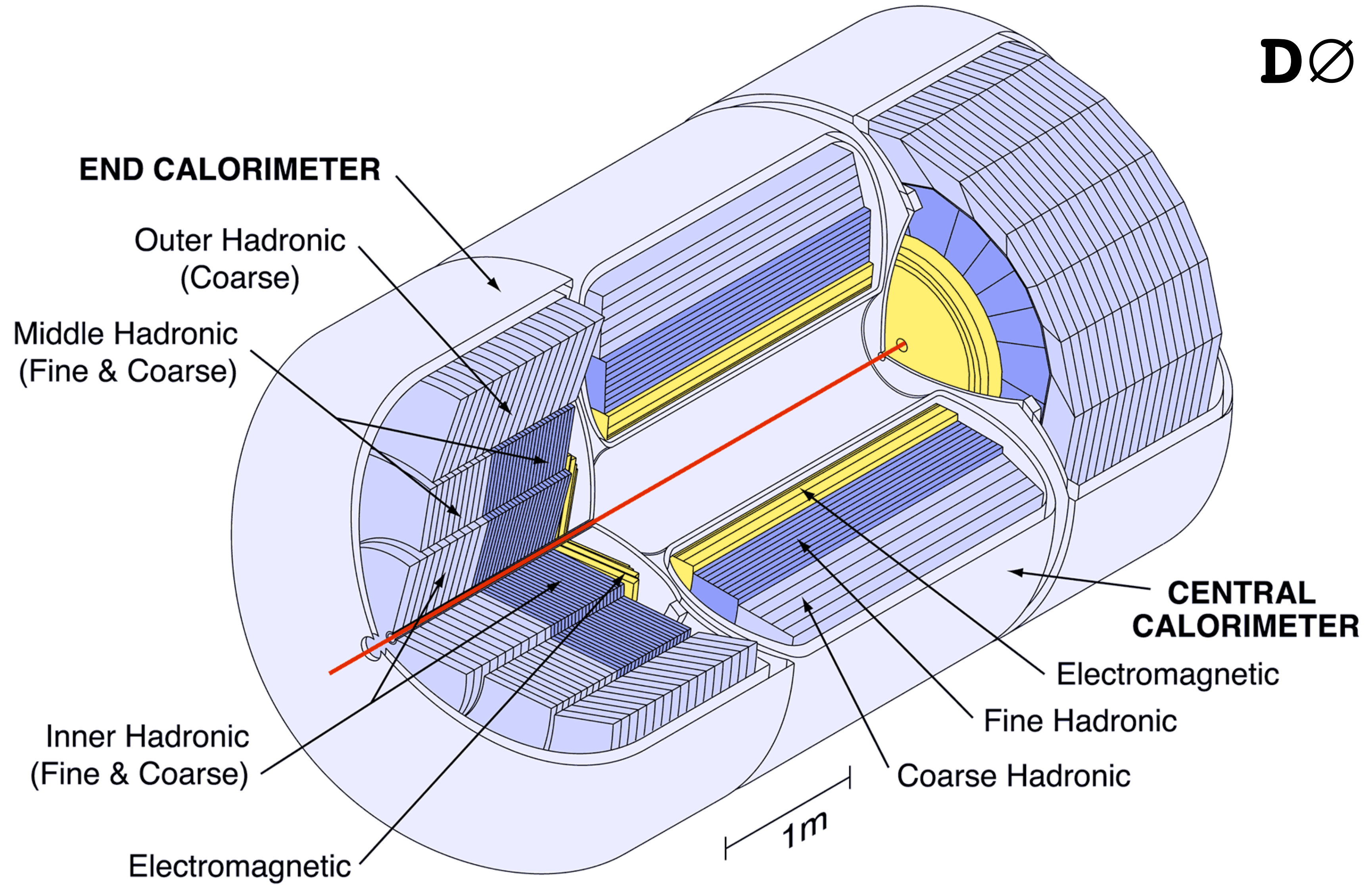


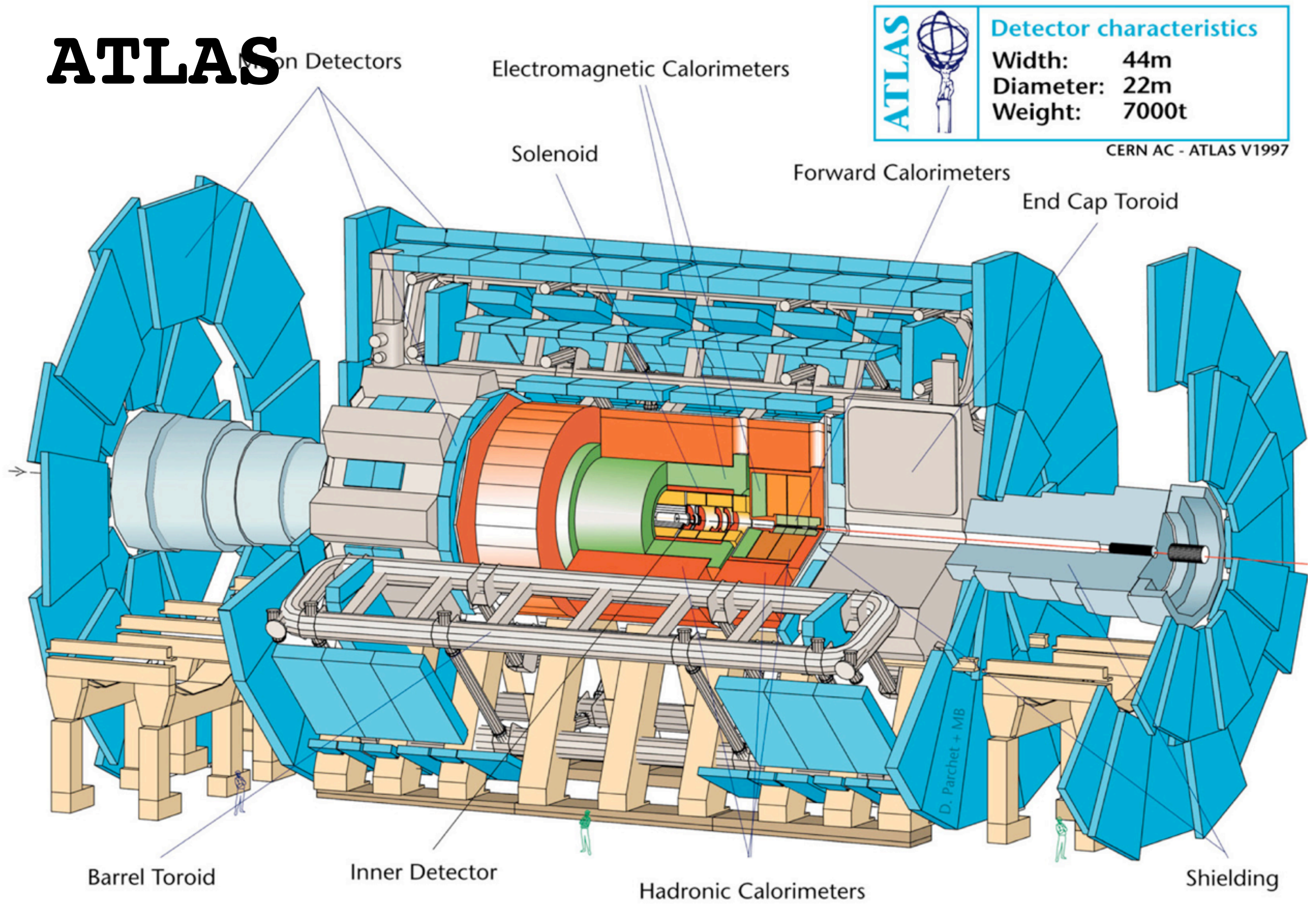


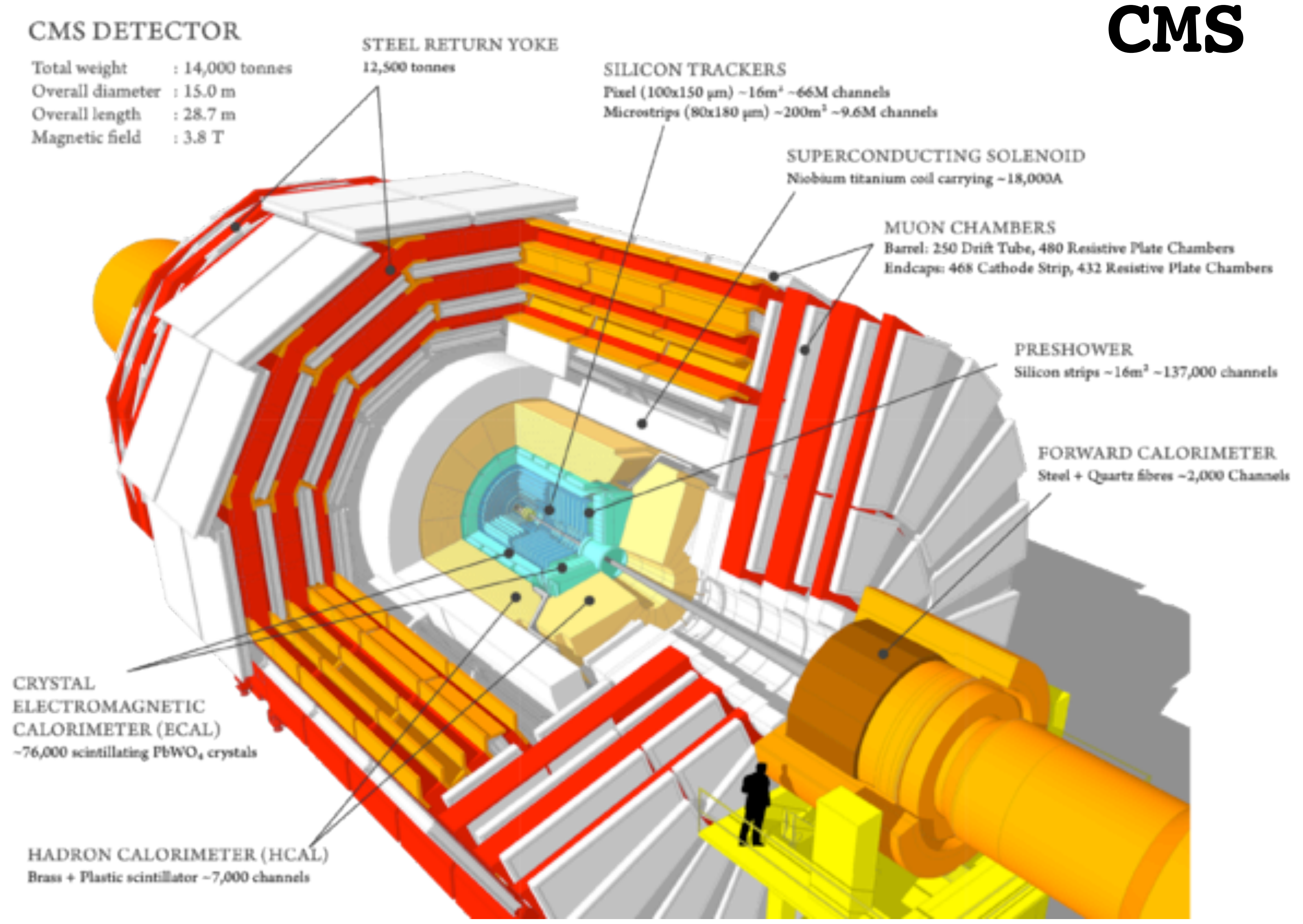


B-factories : hermetic detectors, low background, mainly access $B^{0,+}$ and charm
Belle is being upgraded, Belle II aims to collect 50x the Belle dataset

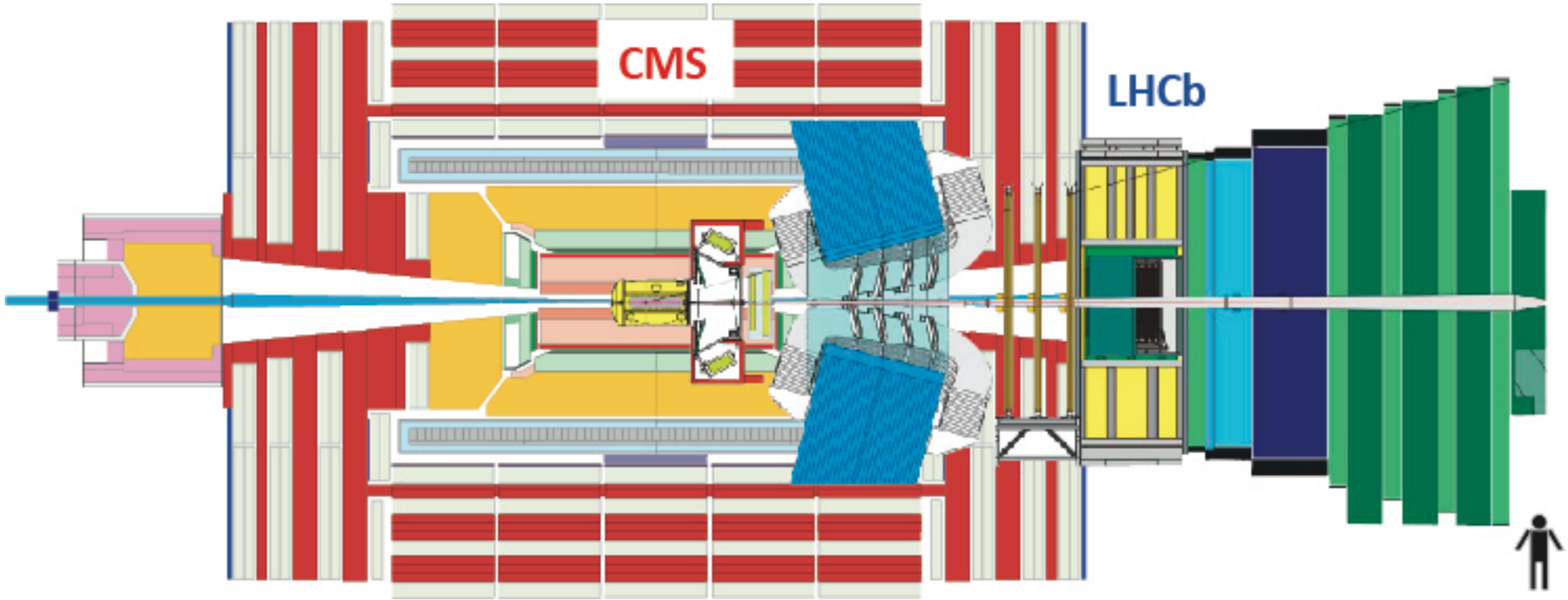






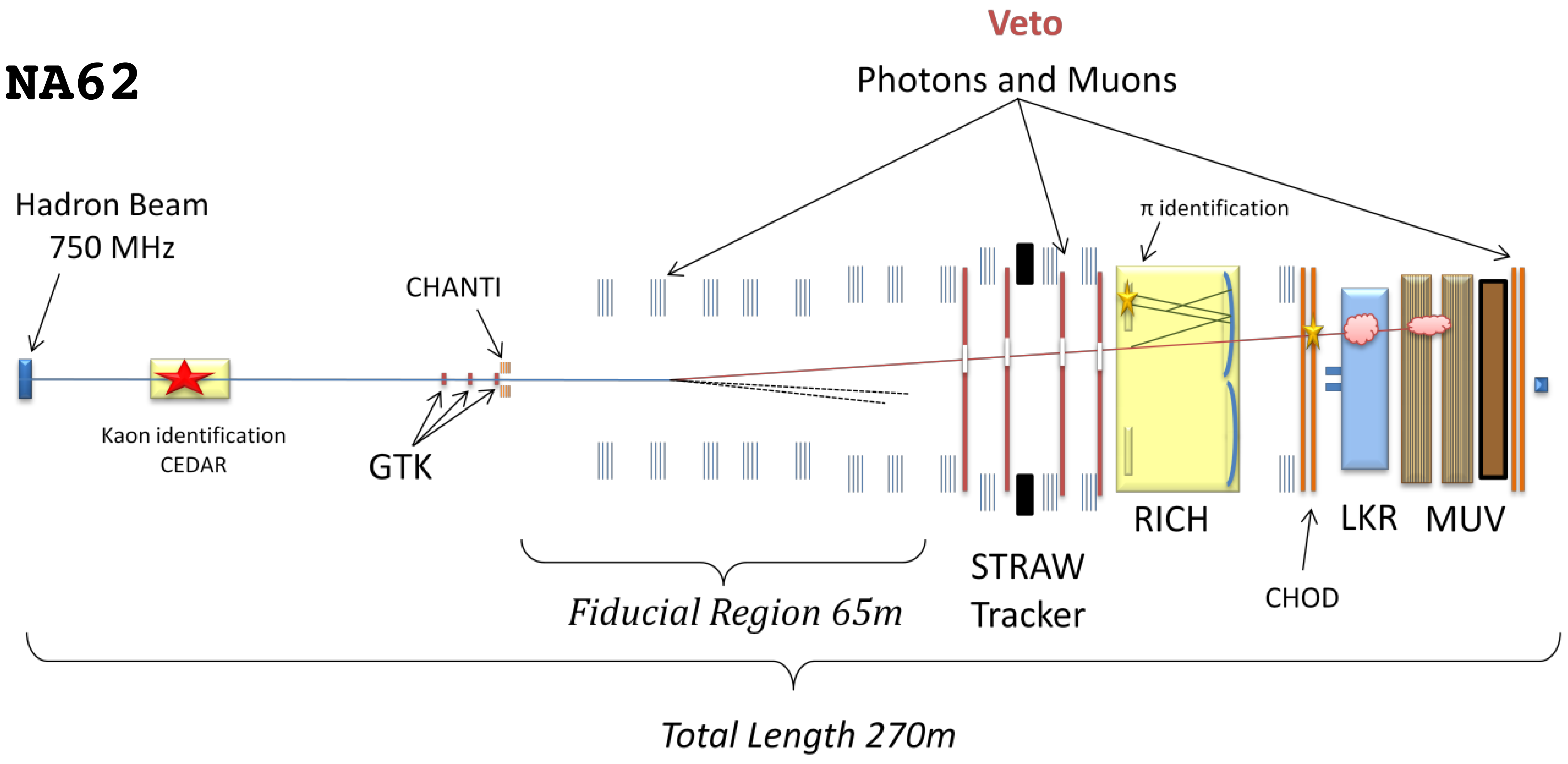


CDF/D0/ATLAS/CMS : hermetic detectors but hadronic environment, much higher backgrounds

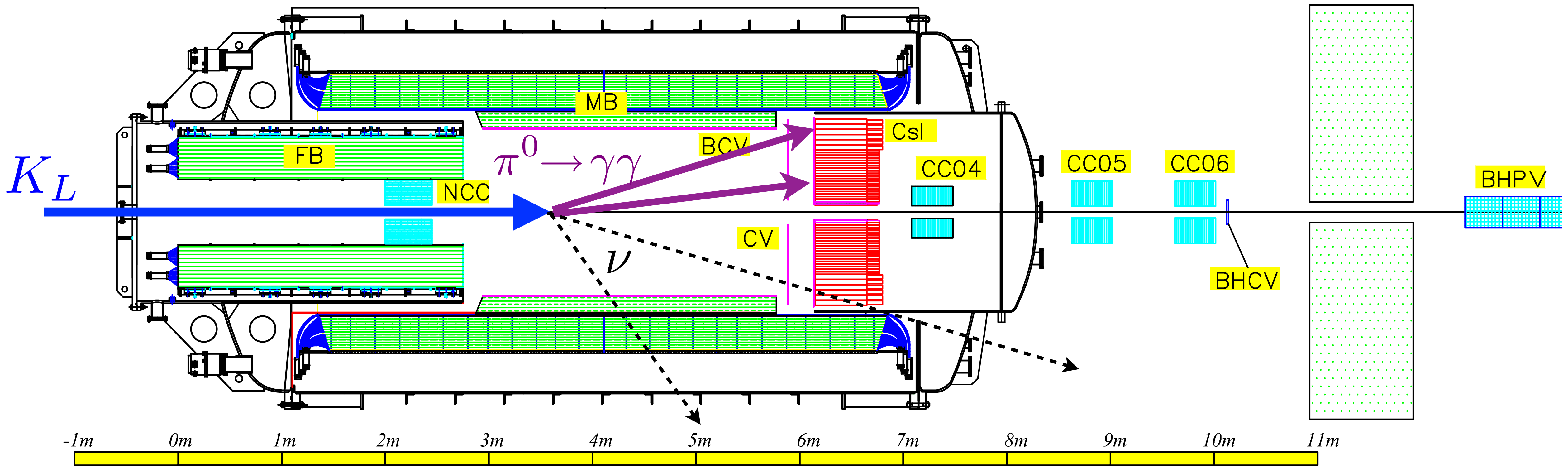


LHCb : forward spectrometer for flavour physics at LHC

NA62



KOTO

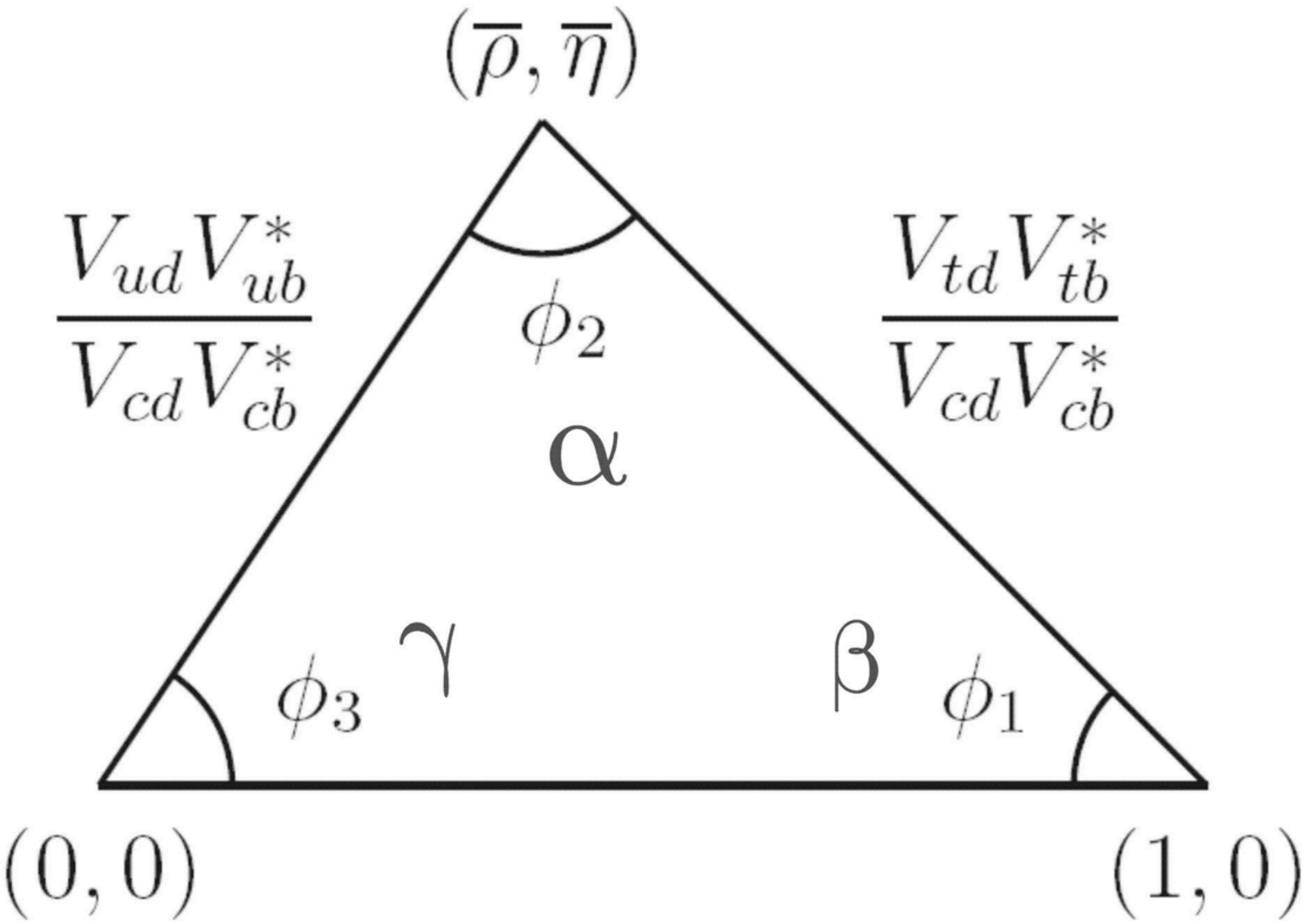


NA62/KOTO: forward spectrometers for rare kaon decays

1. Flavour physics today
2. Flavour physics in 2030
3. How do we get there?


Here & Now

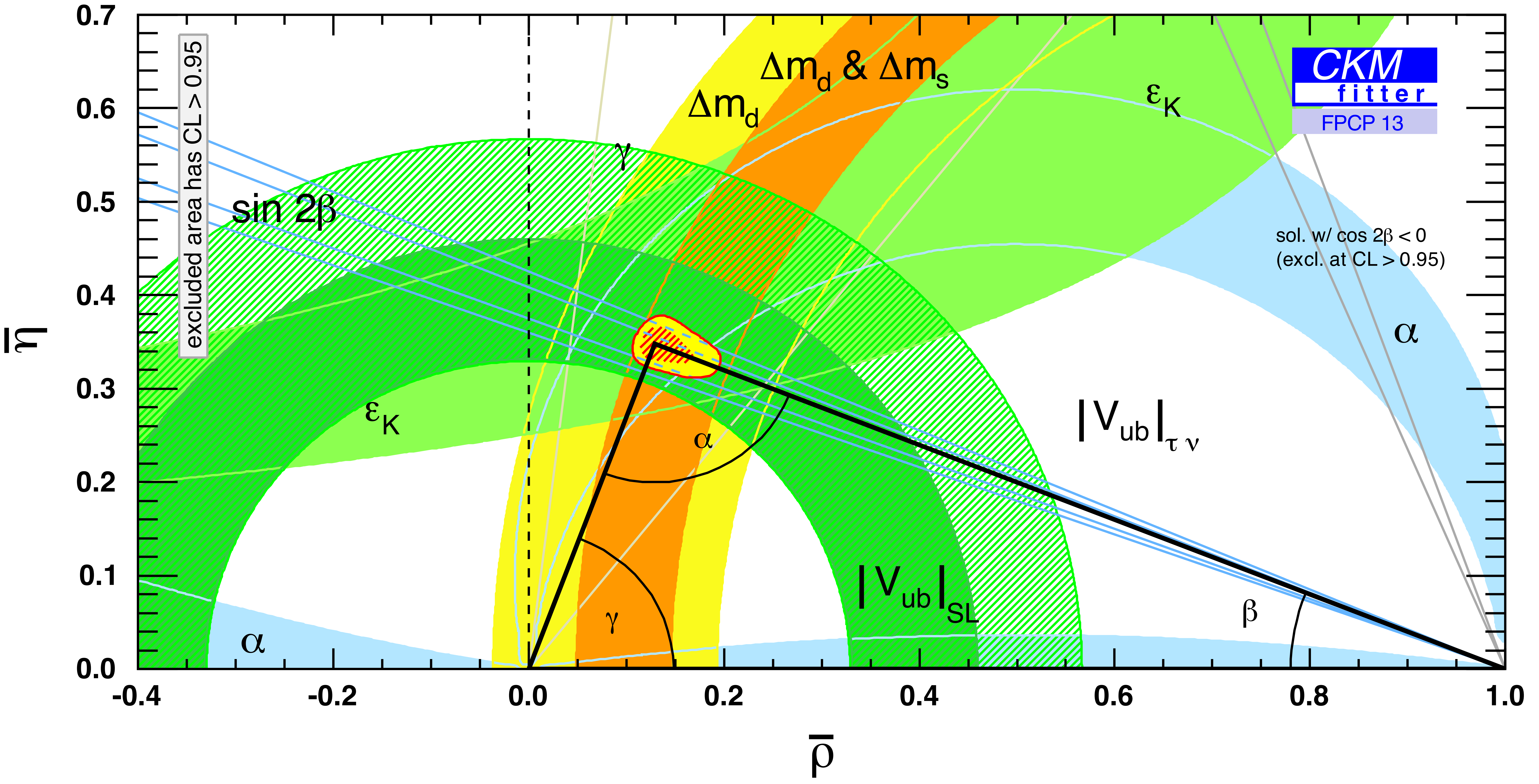
The unitarity triangle



Unitary matrix => 6 triangles in imaginary plane, one experimentally convenient

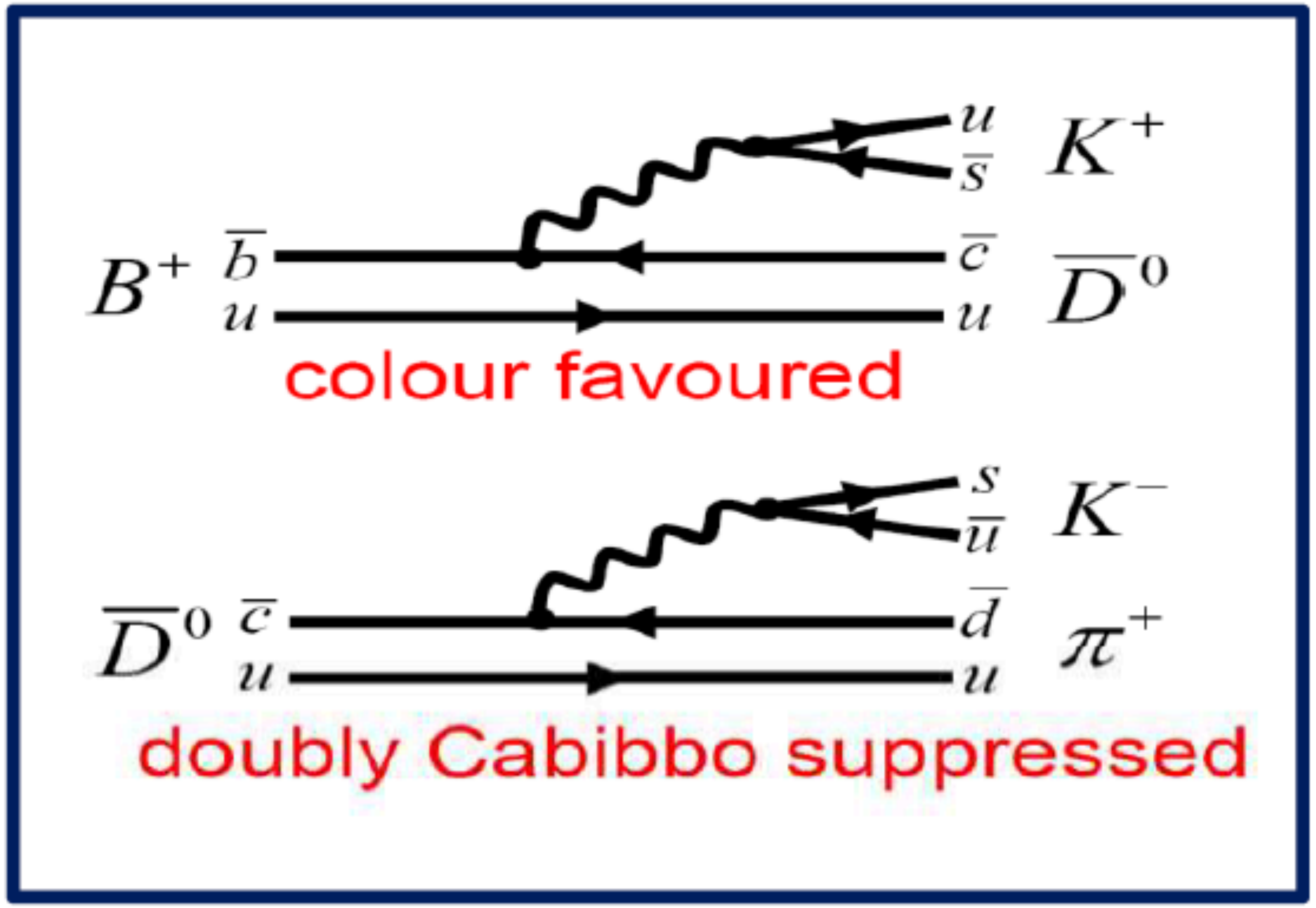
The apex of the triangle

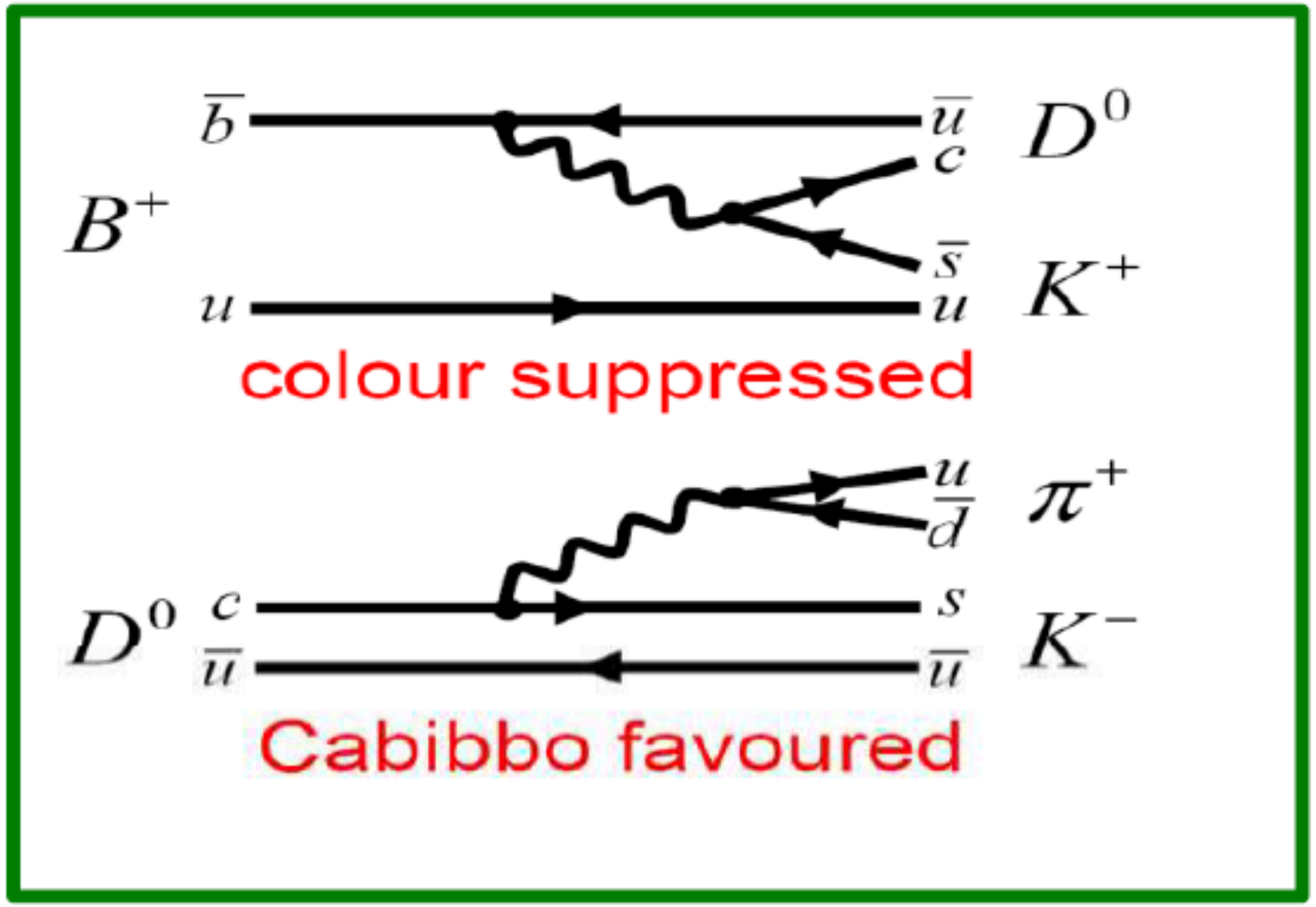
http://ckmfitter.in2p3.fr
Similar plots with Bayesian treatment available at www.utfit.org



Overconstraining the apex tests the consistency of the SM picture of CP Violation

How do we measure γ?





Interfering V_{ub} and V_{cb} decays to the same final state

What scales does γ probe?

$$|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$$

Probe	Λ_{NP} for (N)MFV NP	Λ_{NP} for gen. FV NP	$B\overline{B}$ pairs
γ from $B \to DK^{1)}$	$\Lambda \sim \mathcal{O}(10^2 \text{ TeV})$	$\Lambda \sim \mathcal{O}(10^3 \text{ TeV})$	$\sim 10^{18}$
$B \to \tau\nu^{2)}$	$\Lambda \sim \mathcal{O}(\text{ TeV})$	$\Lambda \sim \mathcal{O}(30 \text{ TeV})$	$\sim 10^{13}$
$b \to ss\overline{d}^{3)}$	$\Lambda \sim \mathcal{O}(\text{ TeV})$	$\Lambda \sim \mathcal{O}(10^3 \text{ TeV})$	$\sim 10^{13}$
β from $B \to J/\psi K_S^{4)}$	$\Lambda \sim \mathcal{O}(50 \text{ TeV})$	$\Lambda \sim \mathcal{O}(200 \text{ TeV})$	$\sim 10^{12}$
$K - \overline{K}$ mixing$^{5)}$	$\Lambda > 0.4$ TeV (6 TeV)	$\Lambda > 10^{3(4)}$ TeV	now

Zupan&Brod
http://arxiv.org/pdf/1308.5663.pdf

A decade of overachievement…

CDF ADS

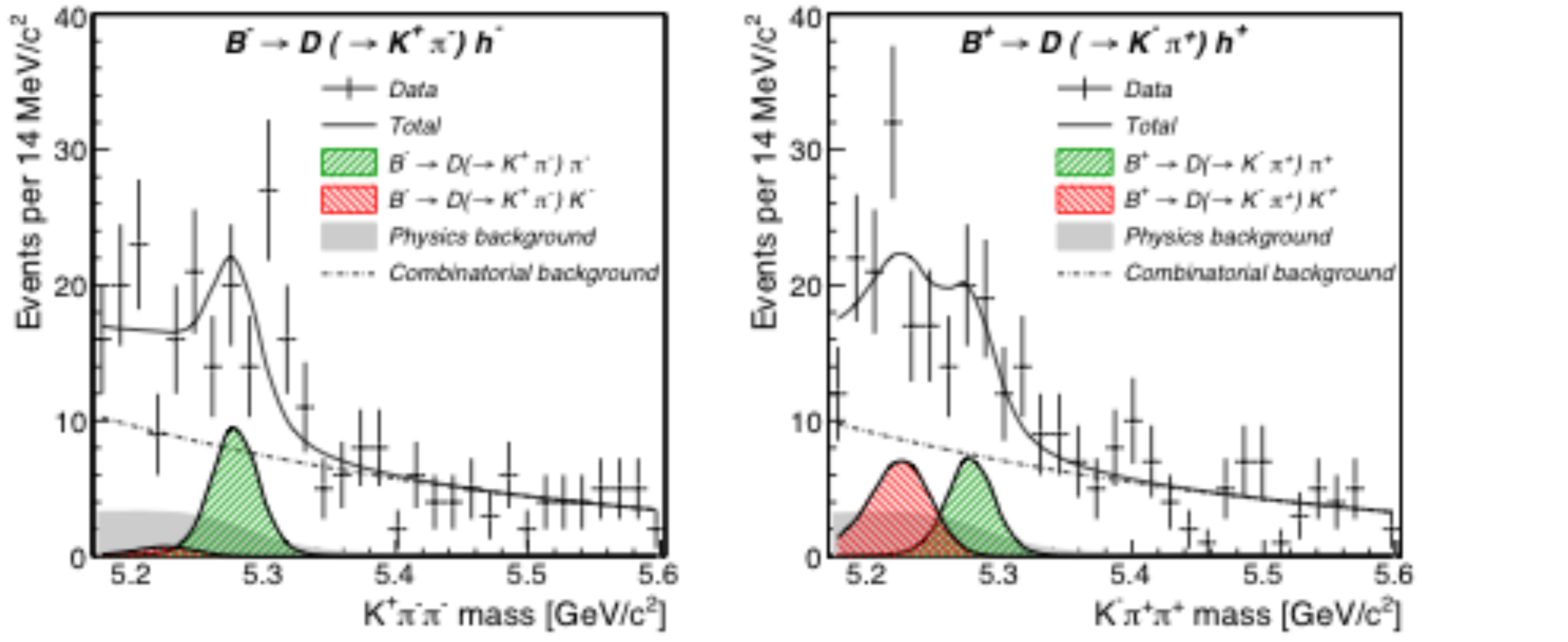


FIG. 1: Invariant mass distributions of $B^\pm \to Dh^\pm$ for the suppressed mode (bottom meson on the left and antibottom on the right). The pion mass is assigned to the charged track from the B candidate decay vertex. The projections of the common likelihood fit (see text) are overlaid.

BELLE ADS

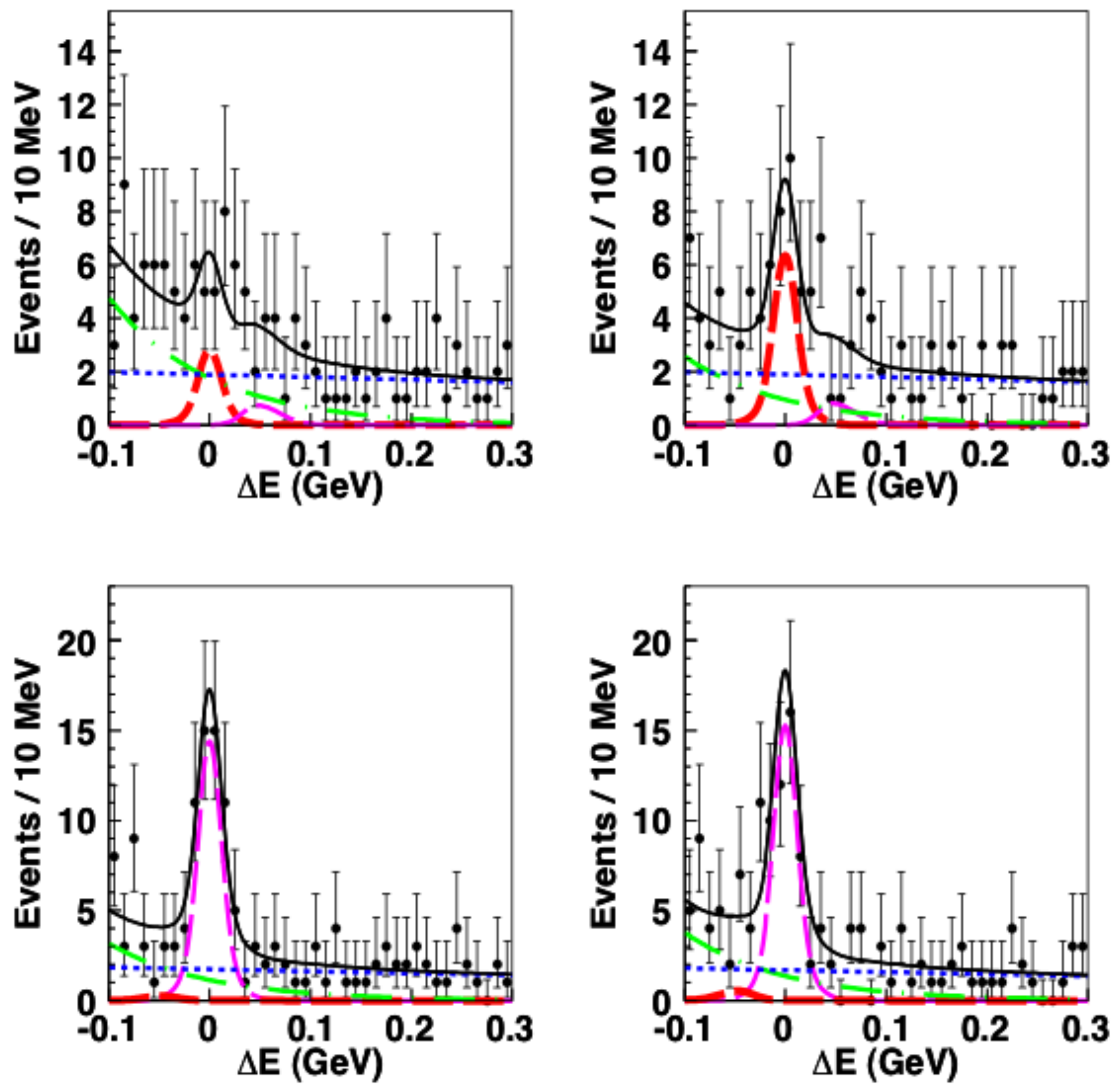


FIG. 2: ΔE distributions ($NB > 0.9$) for $[K^+\pi^-]_D K^-$ (left upper), $[K^-\pi^+]_D K^+$ (right upper), $[K^+\pi^-]_D \pi^-$ (left lower), and $[K^-\pi^+]_D \pi^+$ (right lower). The curves show the same components as in Fig. 1.

BABAR ADS

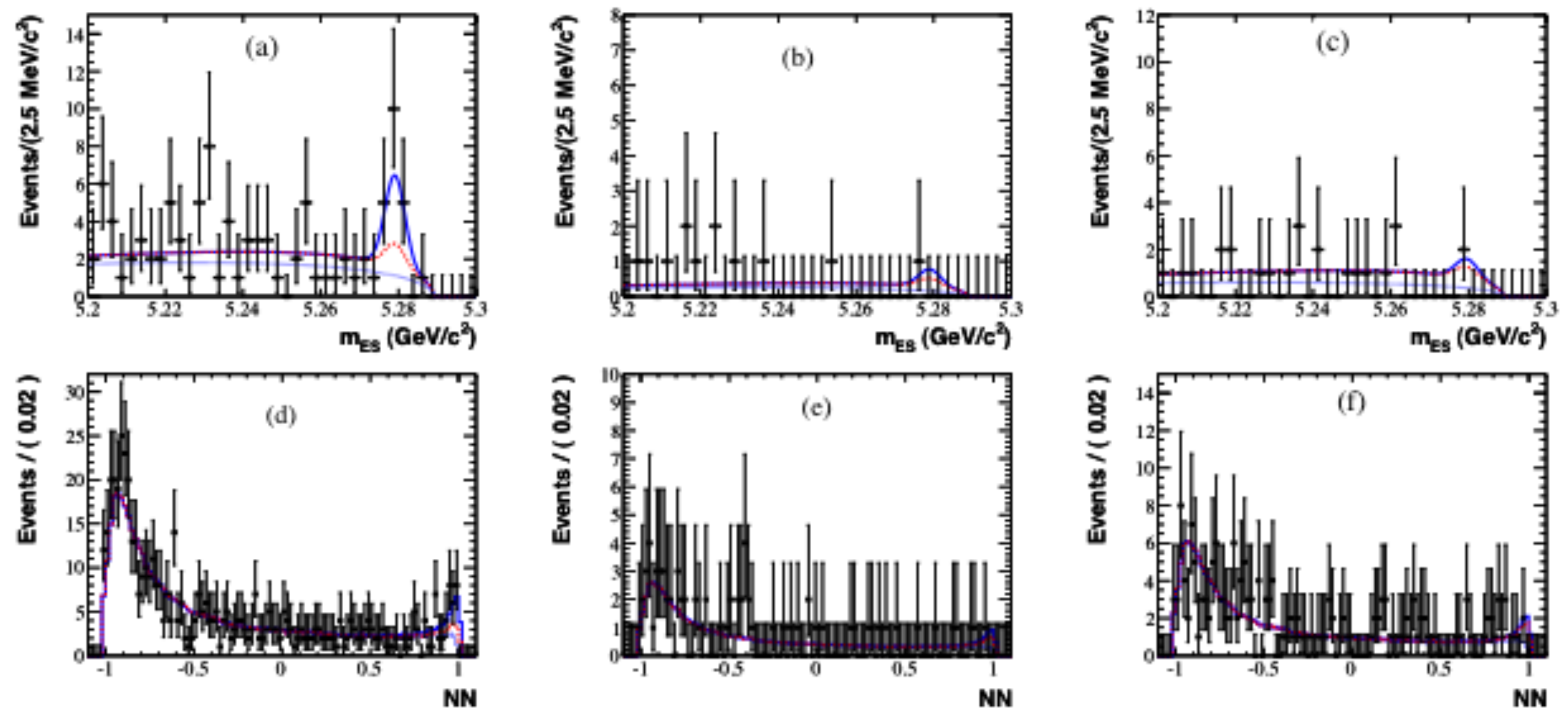


FIG. 8: (color online). Projections on m_{ES} (a, b, c) and NN (d, e, f) of the fit results for DK^+ (a, d), $D^*_{D\pi^0}K^+$ (b, e) and $D^*_{D\gamma}K^+$ (c, f) WS decays, for samples enriched in signal with the requirements $NN > 0.94$ (m_{ES} projections) or $5.2725 < m_{ES} < 5.2875$ GeV/c^2 (NN projections). The points with error bars are data. The curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and $q\bar{q}$ background only (dotted).

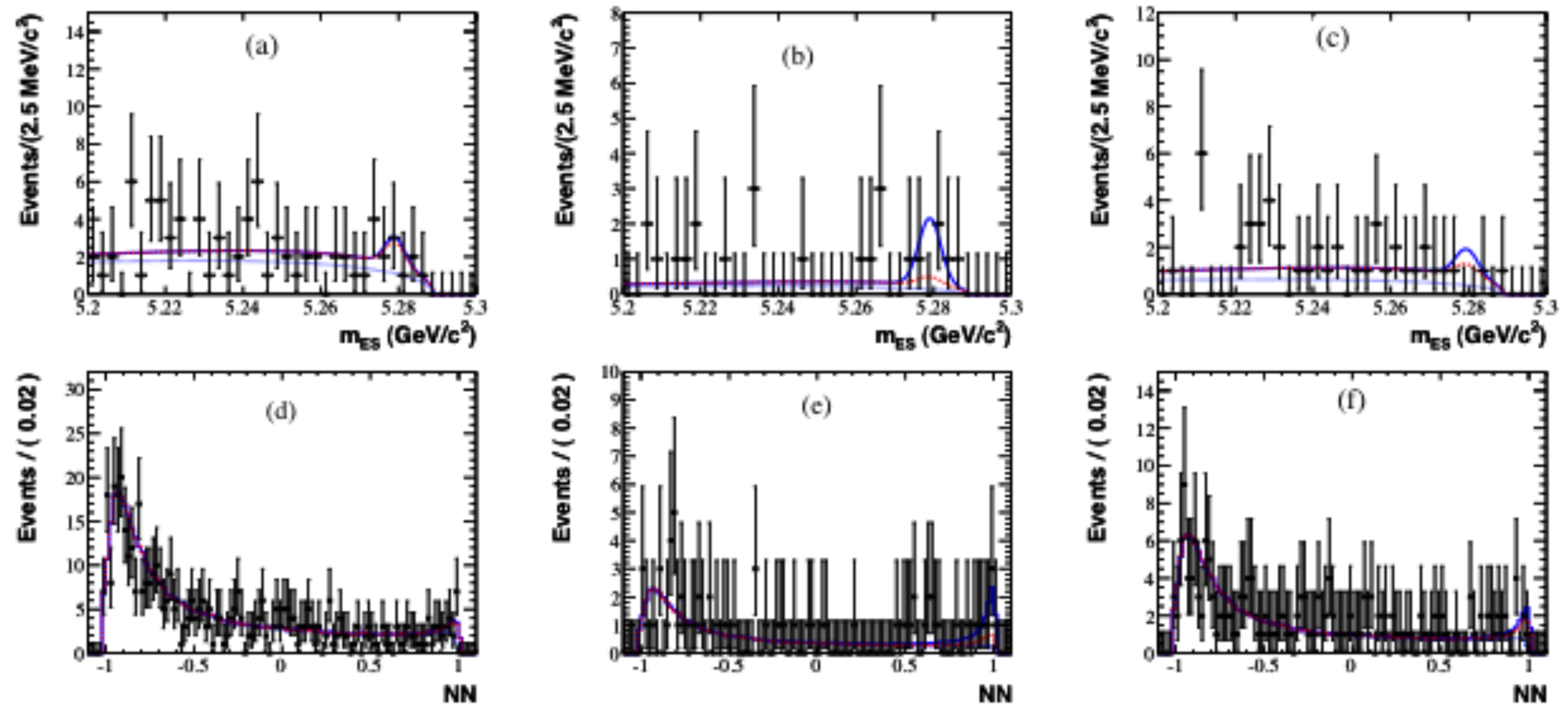


FIG. 9: (color online). Projections on m_{ES} (a, b, c) and NN (d, e, f) of the fit results for DK^- (a, d), $D^*_{D\pi^0}K^-$ (b, e) and $D^*_{D\gamma}K^-$ (c, f) WS decays, for samples enriched in signal with the requirements $NN > 0.94$ (m_{ES} projections) or $5.2725 < m_{ES} < 5.2875$ GeV/c^2 (NN projections). The points with error bars are data. The curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and $q\bar{q}$ background only (dotted).

References, left to right :

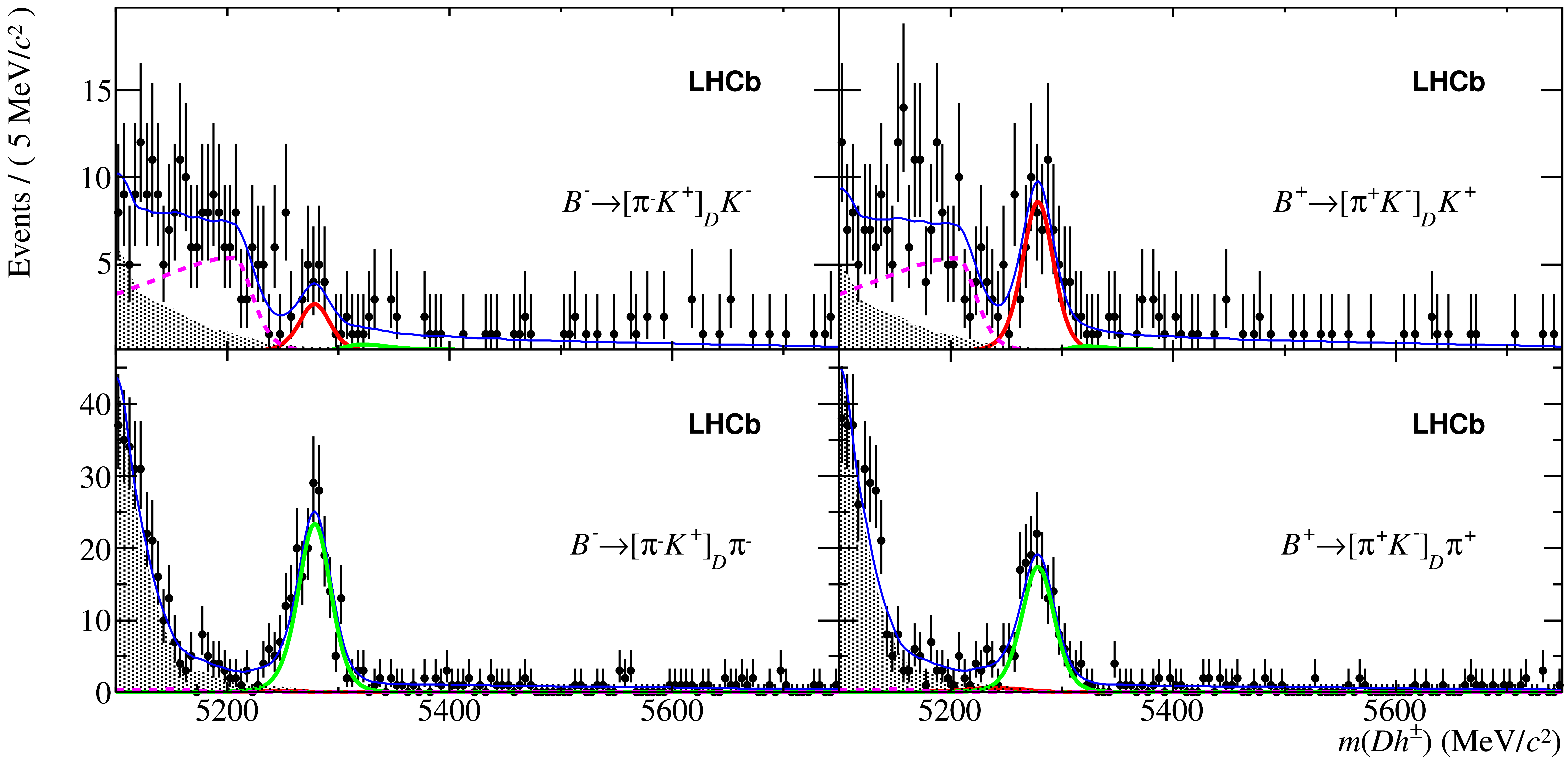
http://arxiv.org/pdf/1103.5951v2.pdf

http://arxiv.org/pdf/1006.4241v1.pdf

http://arxiv.org/pdf/1108.5765v2.pdf

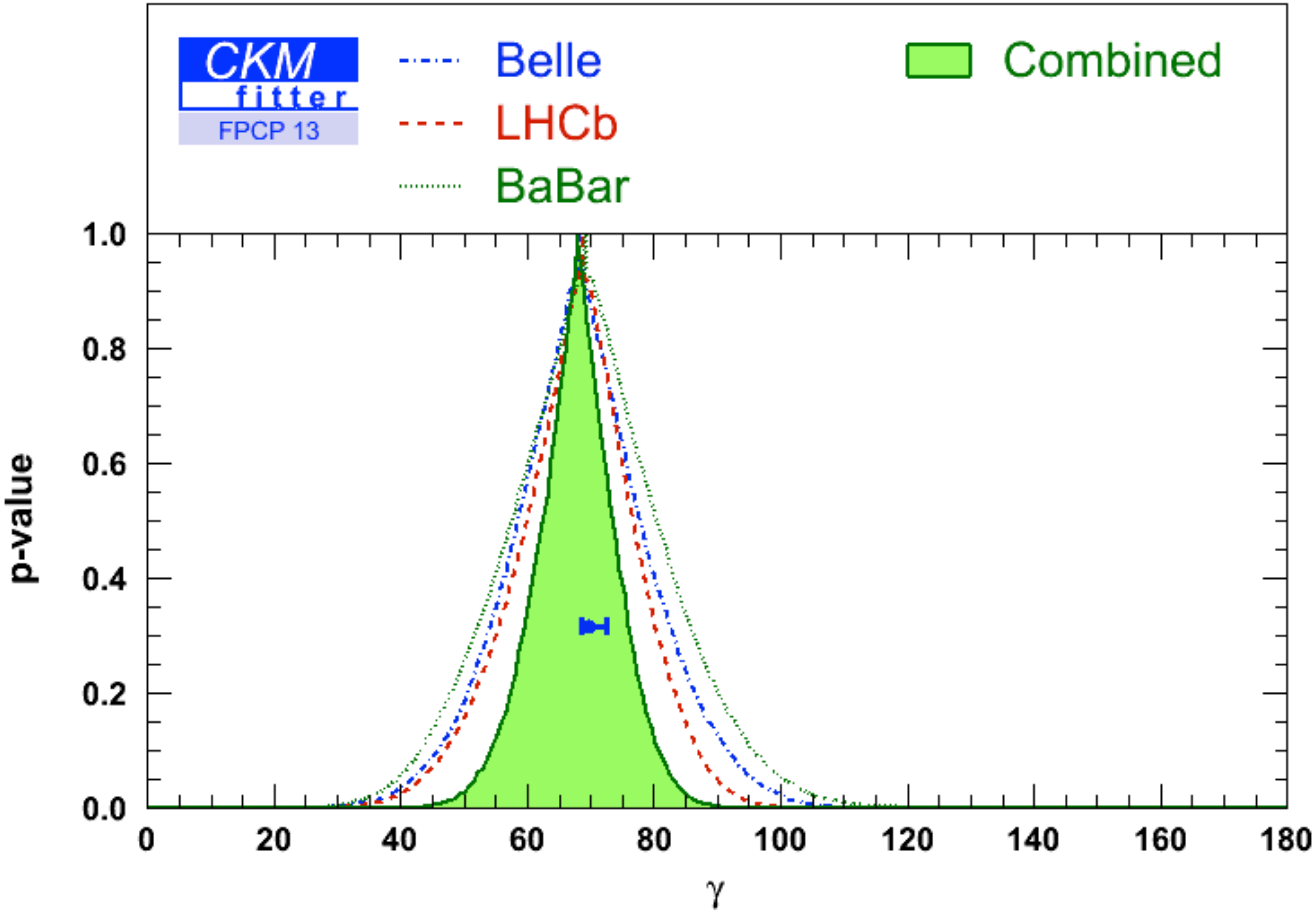
… and γ in the LHC era

The "ADS" B→DK decay mode, total branching fraction O(10^{-7})



LHCb-PAPER-2012-001

LHCb and the B-factories combined



LHCb-CONF-2013-006

sin(2β), α

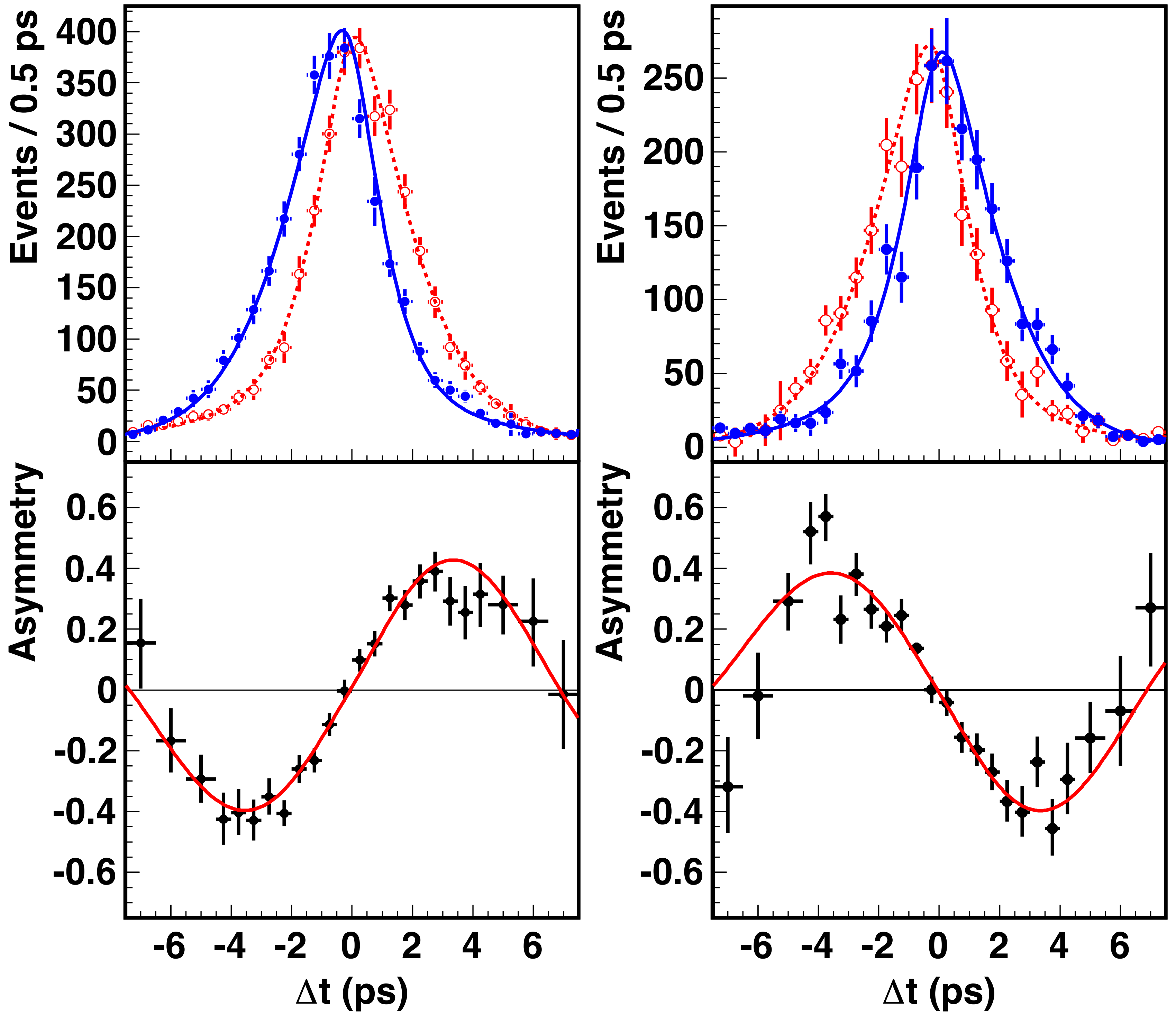
References, left to right :

http://arxiv.org/pdf/1201.4643v2.pdf

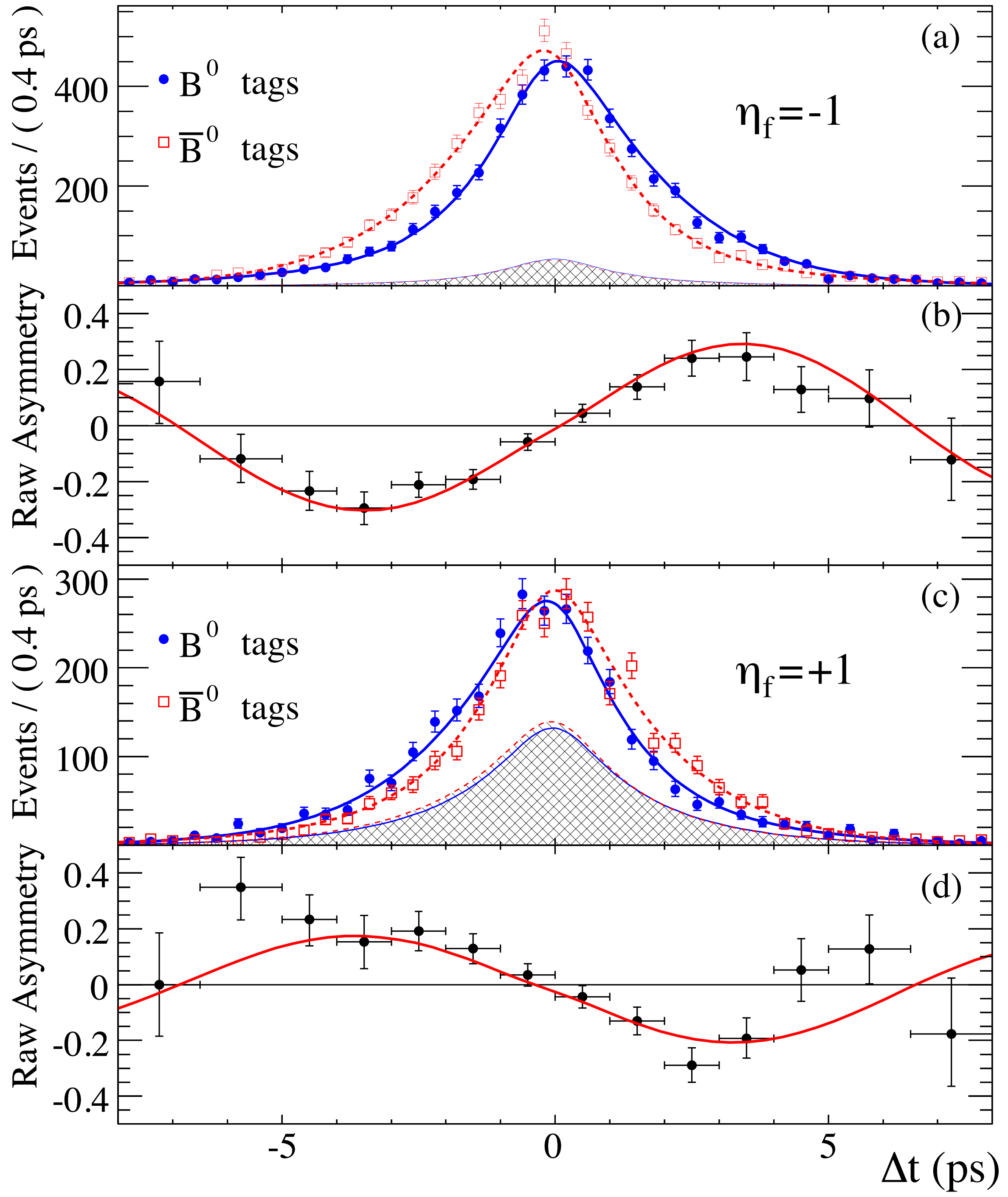
http://arxiv.org/pdf/0902.1708v2.pdf

http://arxiv.org/pdf/0901.3522v4.pdf

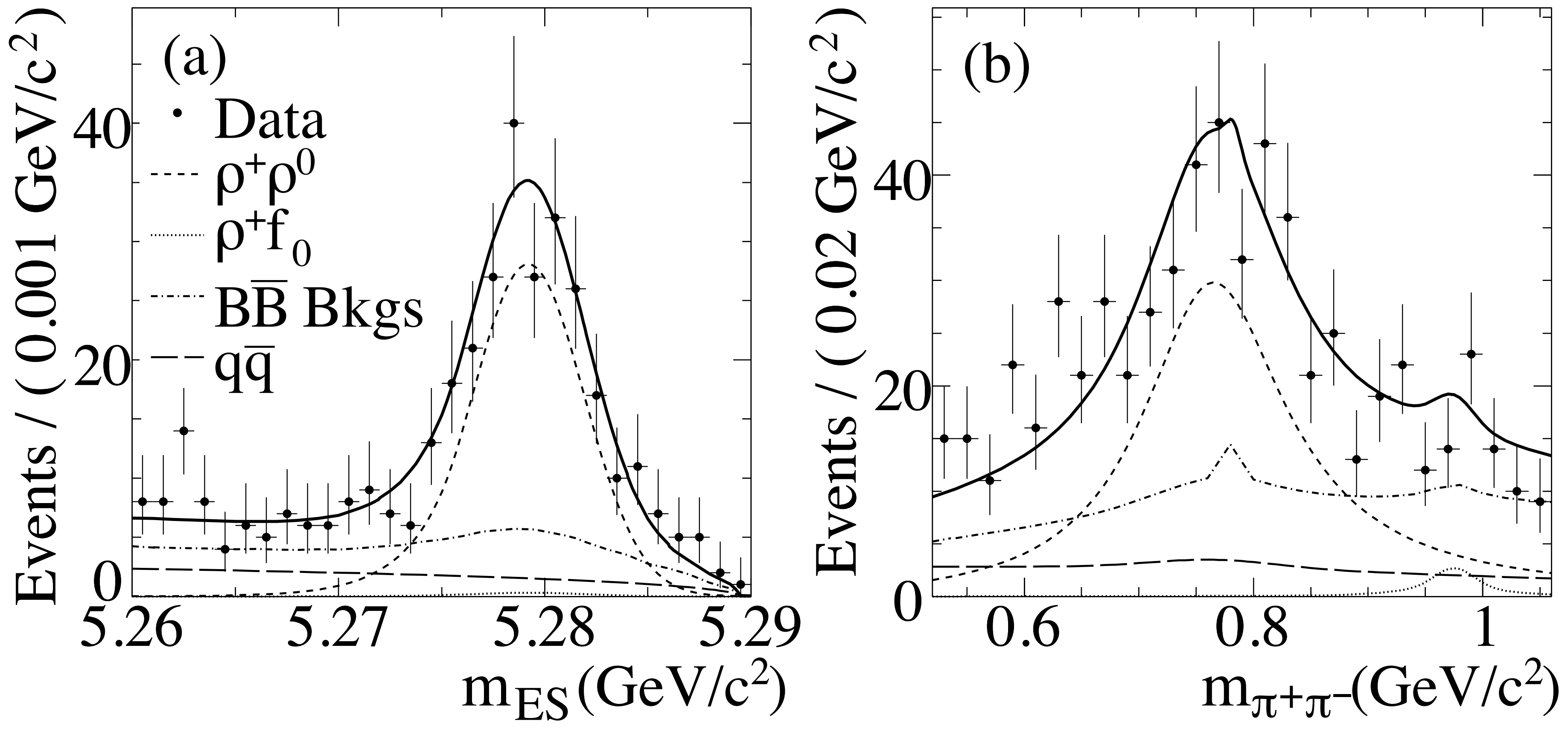
BELLE sin(2β)



BABAR sin(2β)



BABAR α



sin(2β) = 0.682 ± 0.019 (PDG)

Unlike measurements of γ, all measurements of β or α have some "penguin pollution".
At present compatible with α+β+γ=π => "consistency check" key for the HL era!

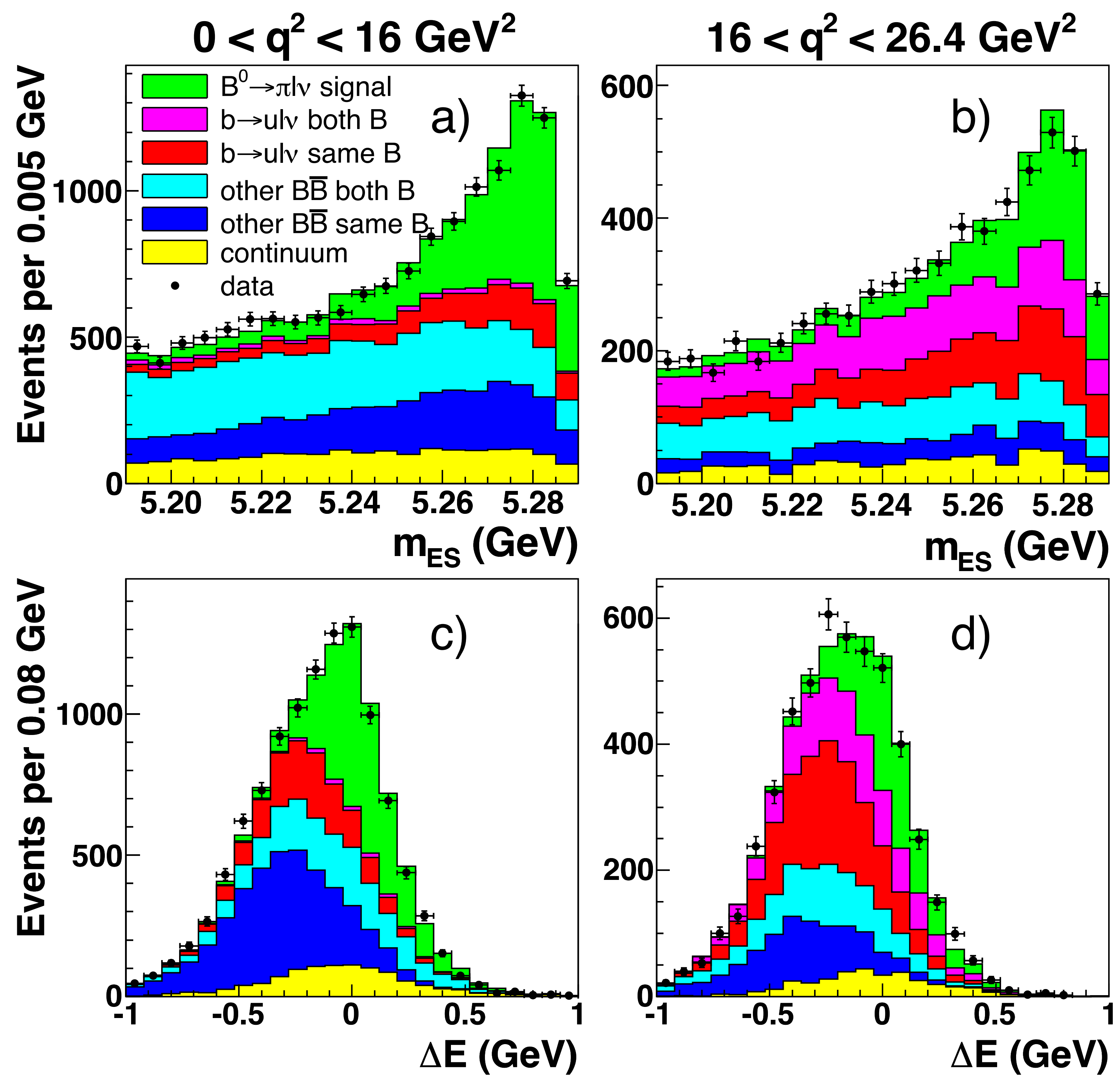
V_{ub} : inclusive, exclusive

References, left to right :

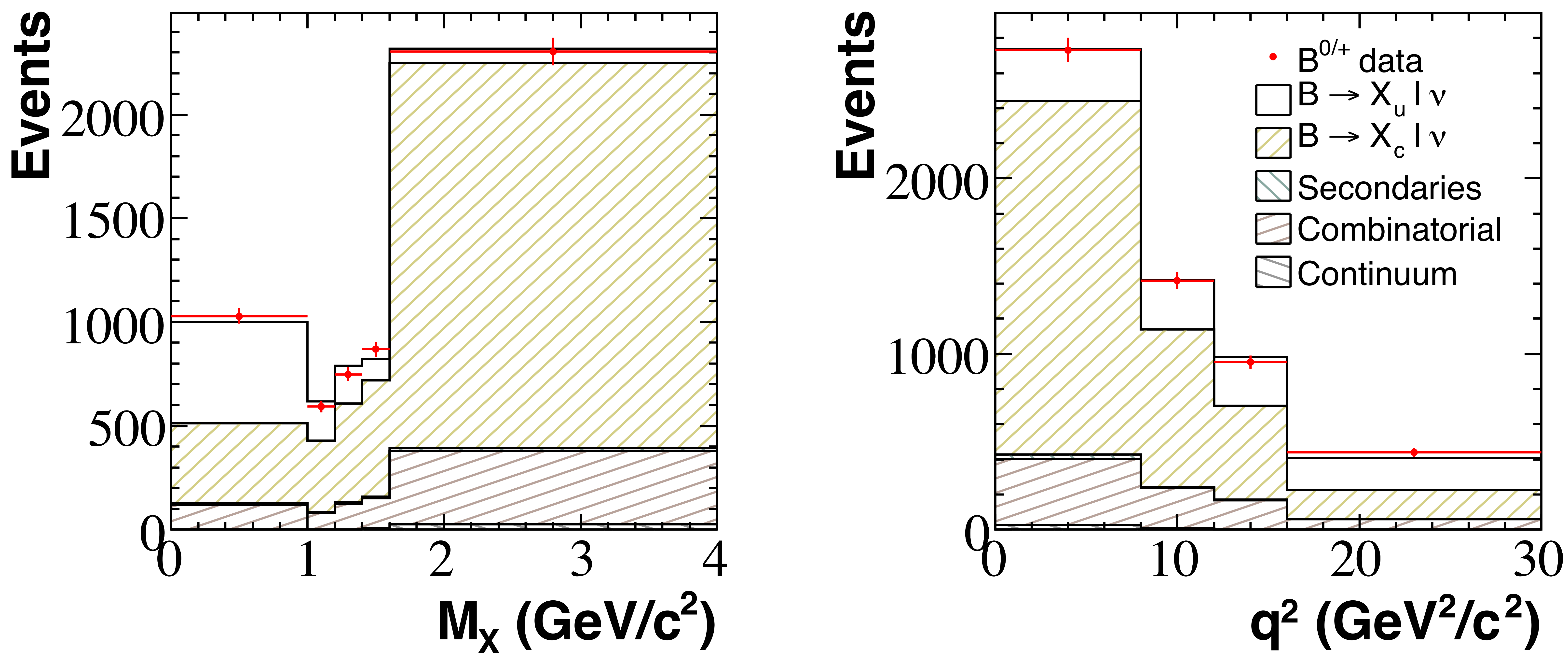
http://arxiv.org/pdf/1208.1253v2.pdf

http://arxiv.org/pdf/0907.0379v2.pdf

BABAR Exclusive



BELLE Inclusive



$$|V_{ub}| = (4.41 \pm 0.15 \,^{+\,0.15}_{-\,0.17}) \times 10^{-3} \quad \text{(inclusive)},$$

$$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \quad \text{(exclusive)}.$$

Exclusive : needs lattice input for form factors

Inclusive : large backgrounds, HQE uncertainties

V_{ub} : B→τν

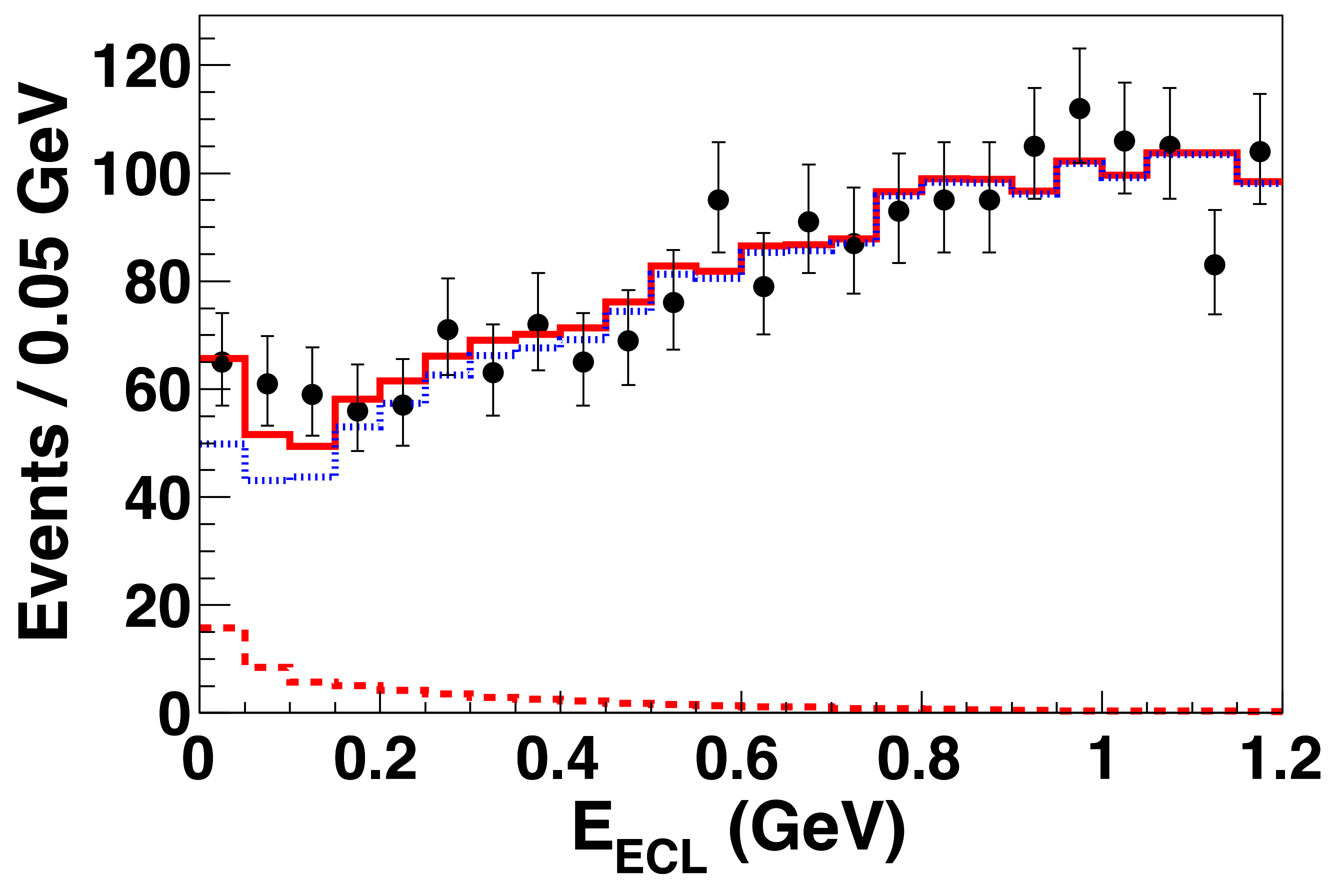
References, left to right :

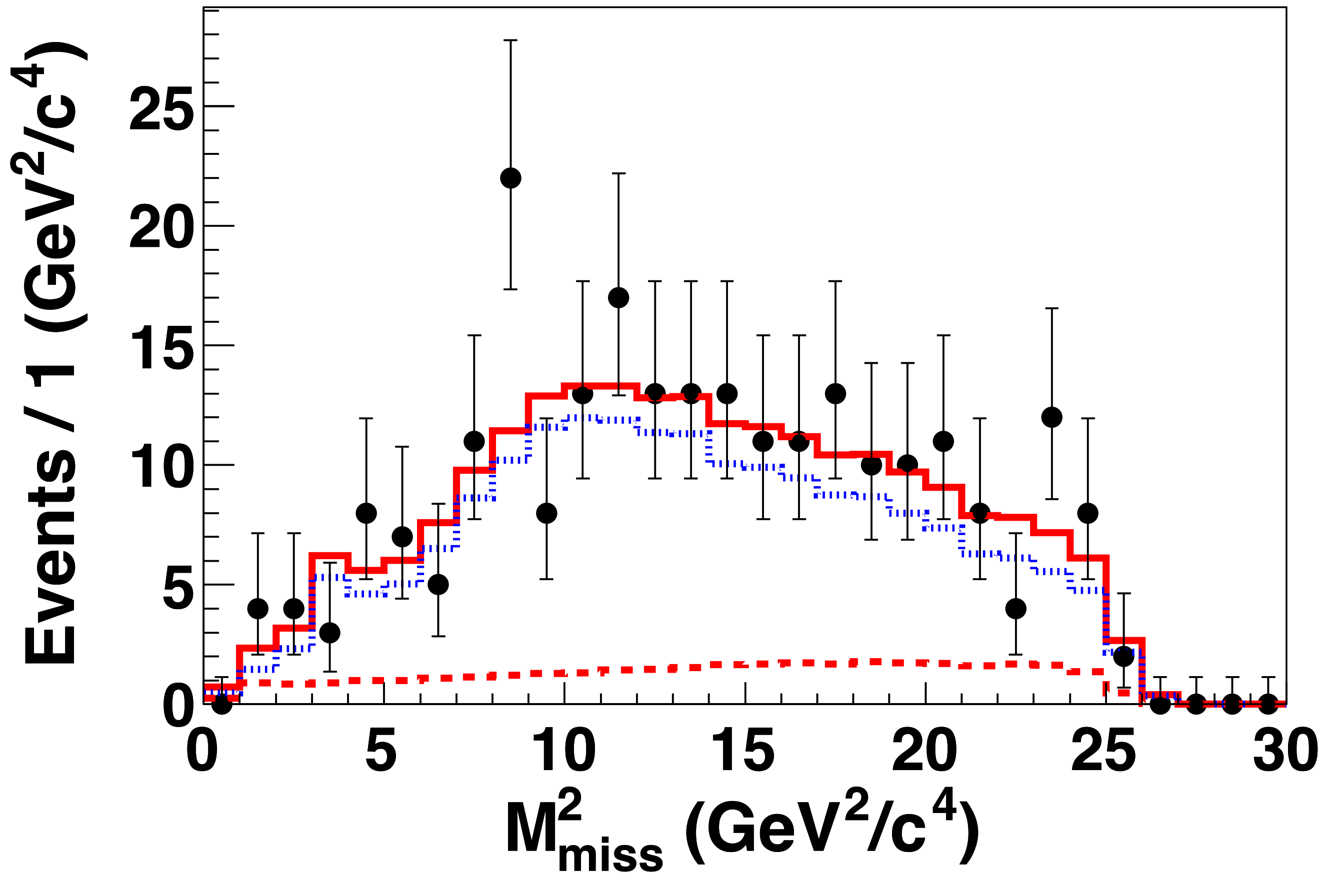
http://arxiv.org/pdf/1208.4678v3.pdf

http://arxiv.org/pdf/1207.0698v1.pdf

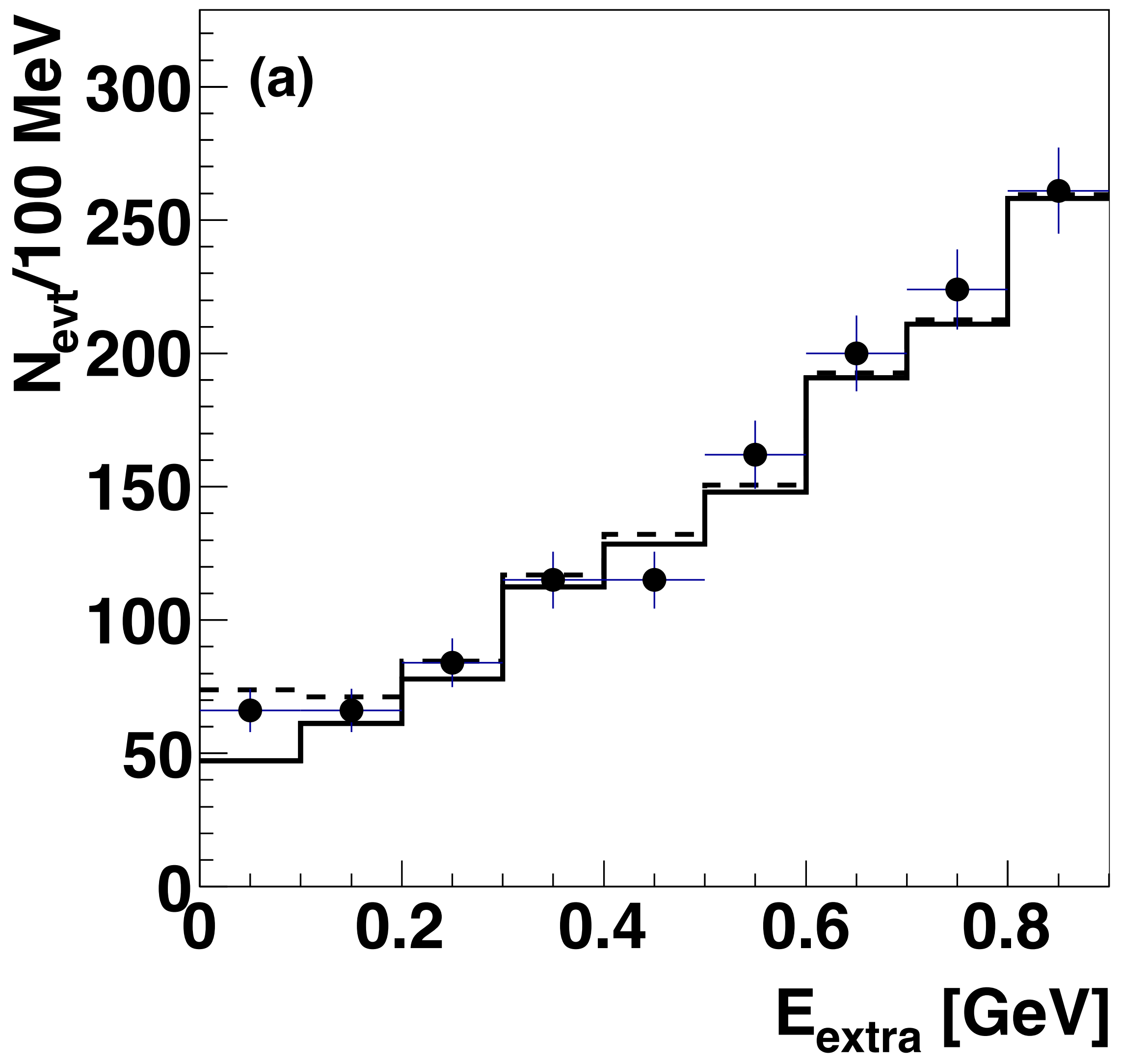
http://ckmfitter.in2p3.fr

BELLE HAD TAG

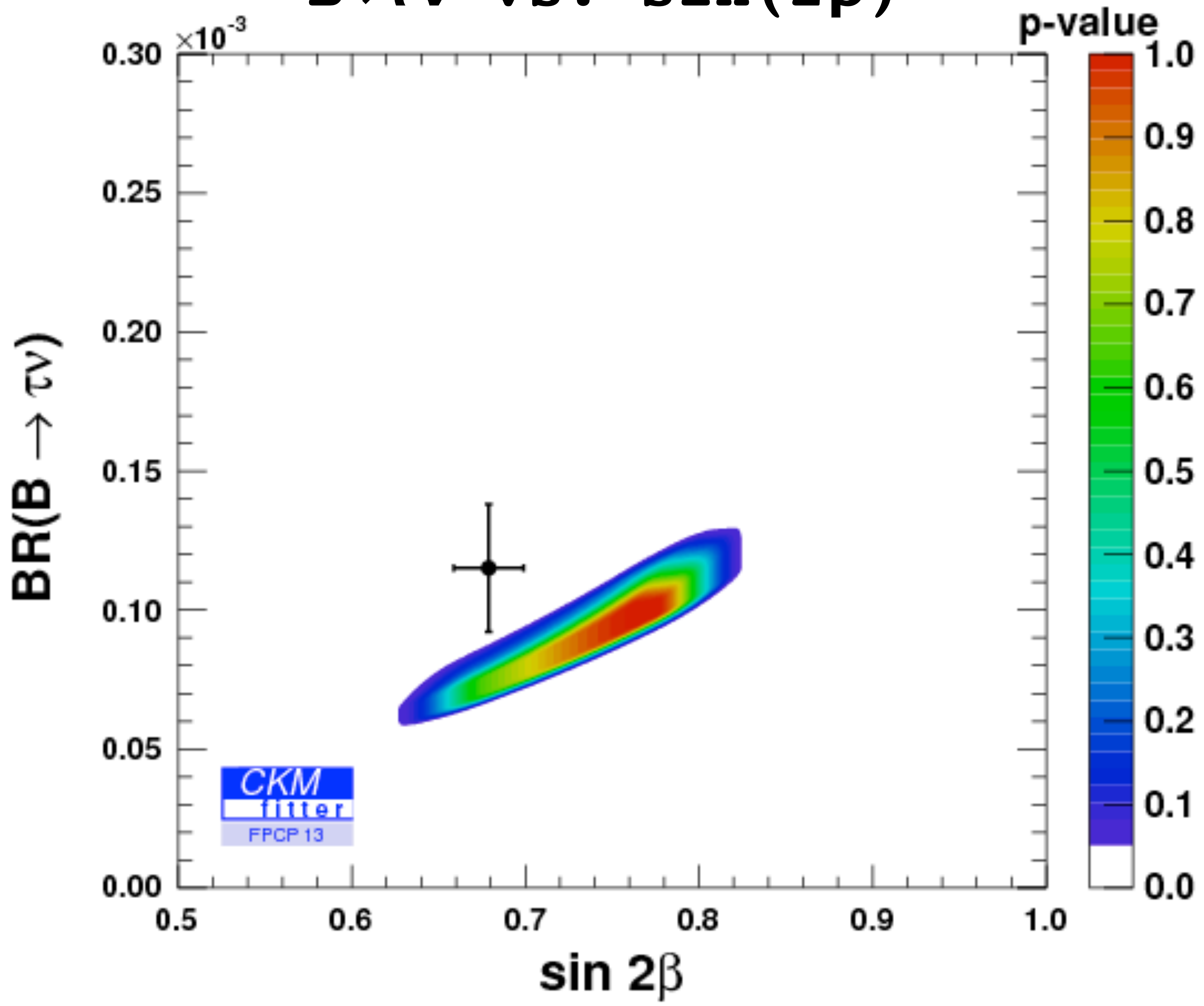




BABAR HAD TAG



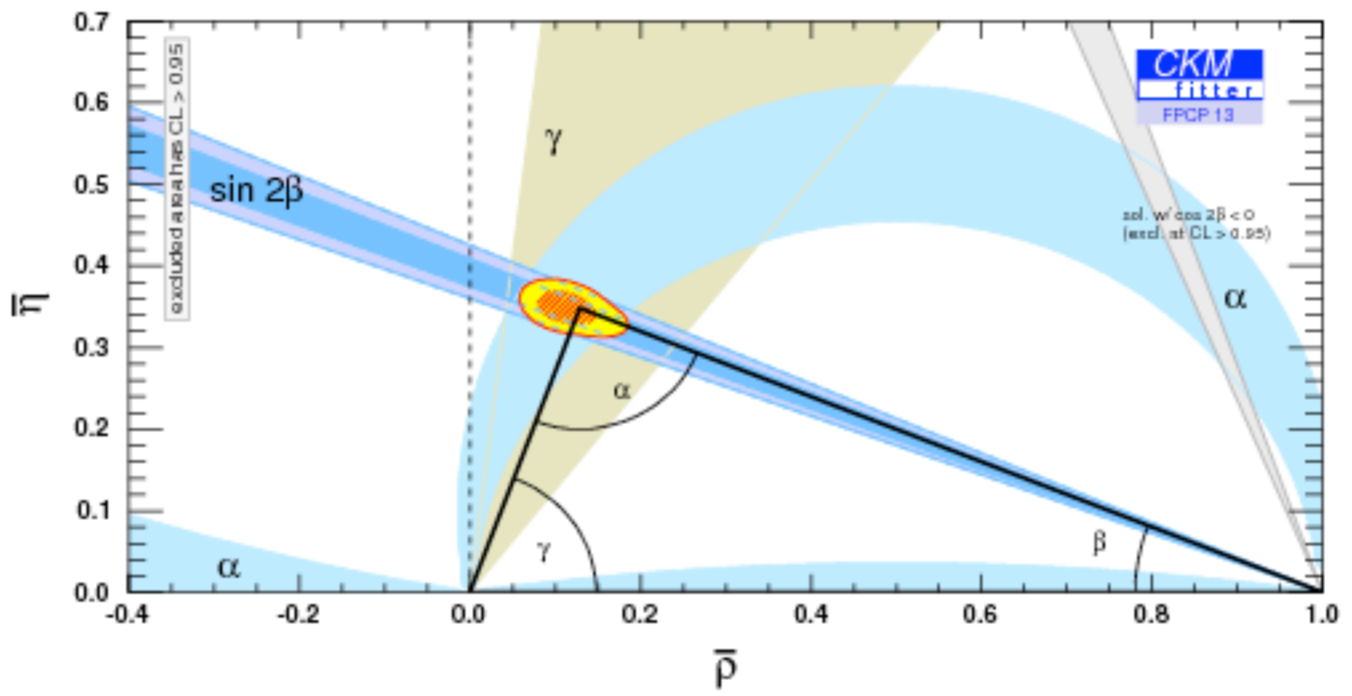
B→τν vs. sin(2β)

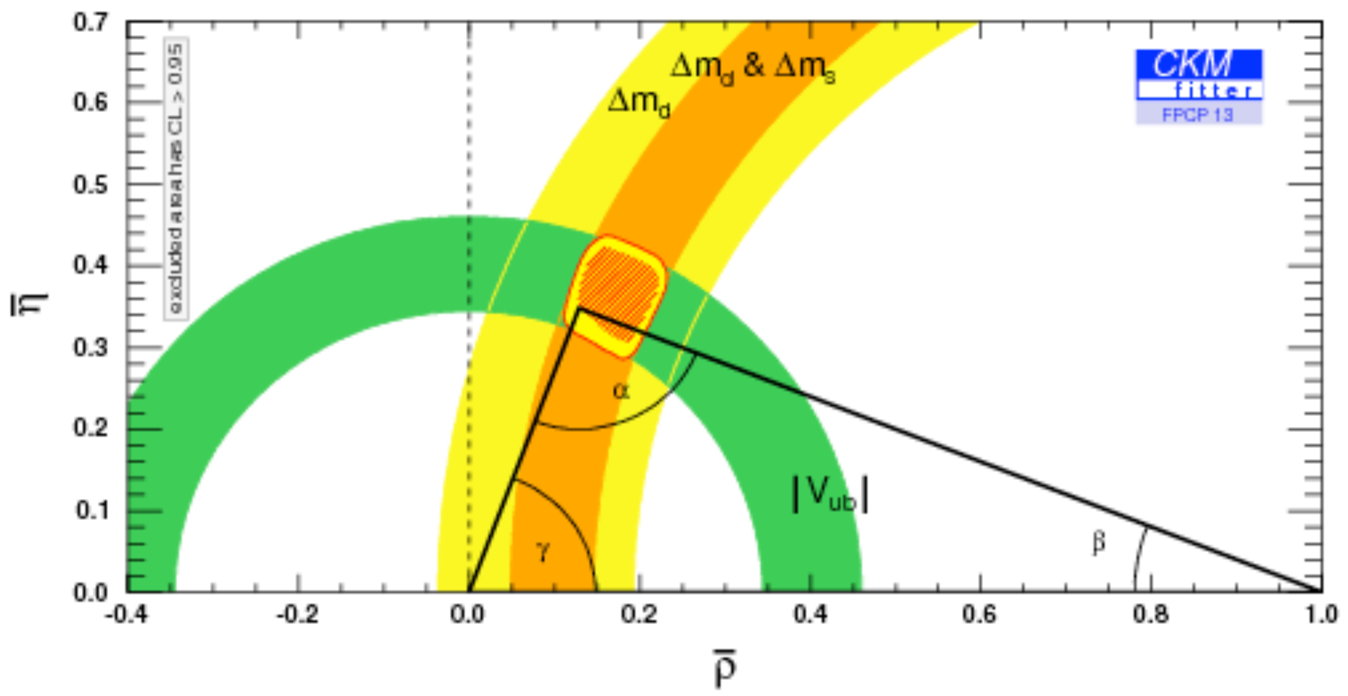


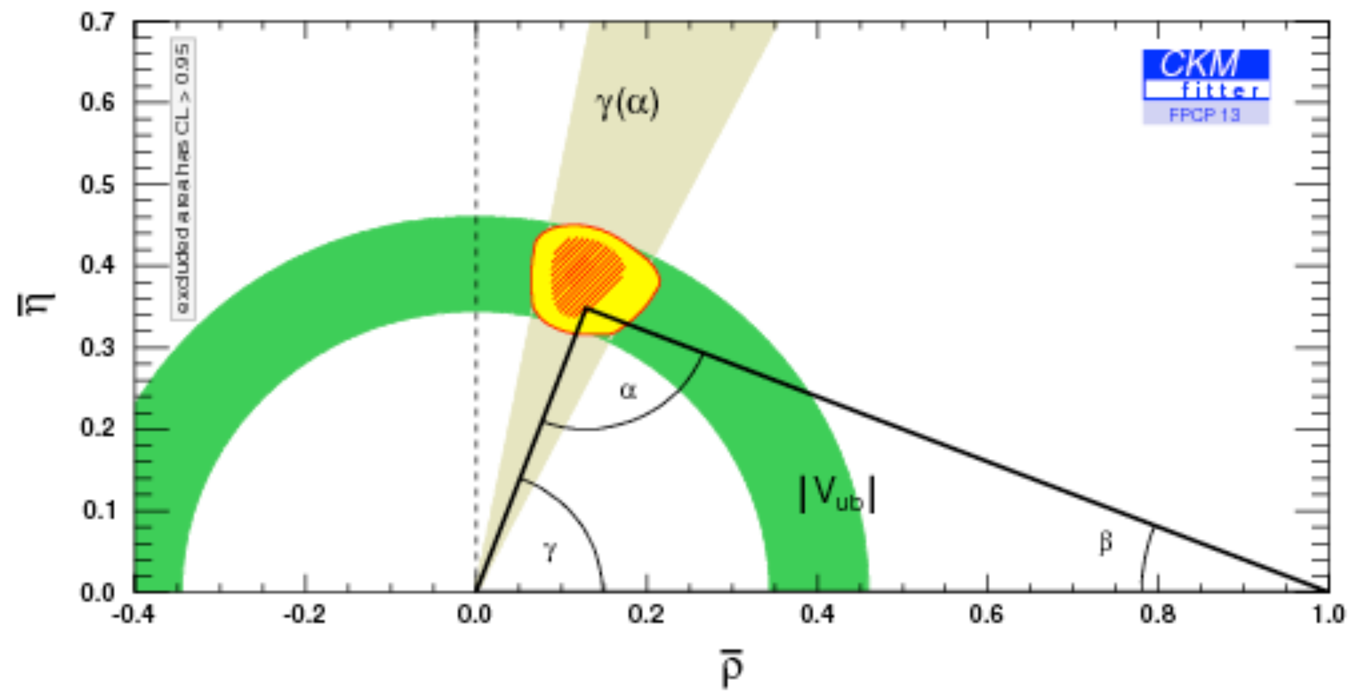
One of the more famous historical tensions, but now in pretty good agreement. Belle II upgrade will improve precision by an order of magnitude however!

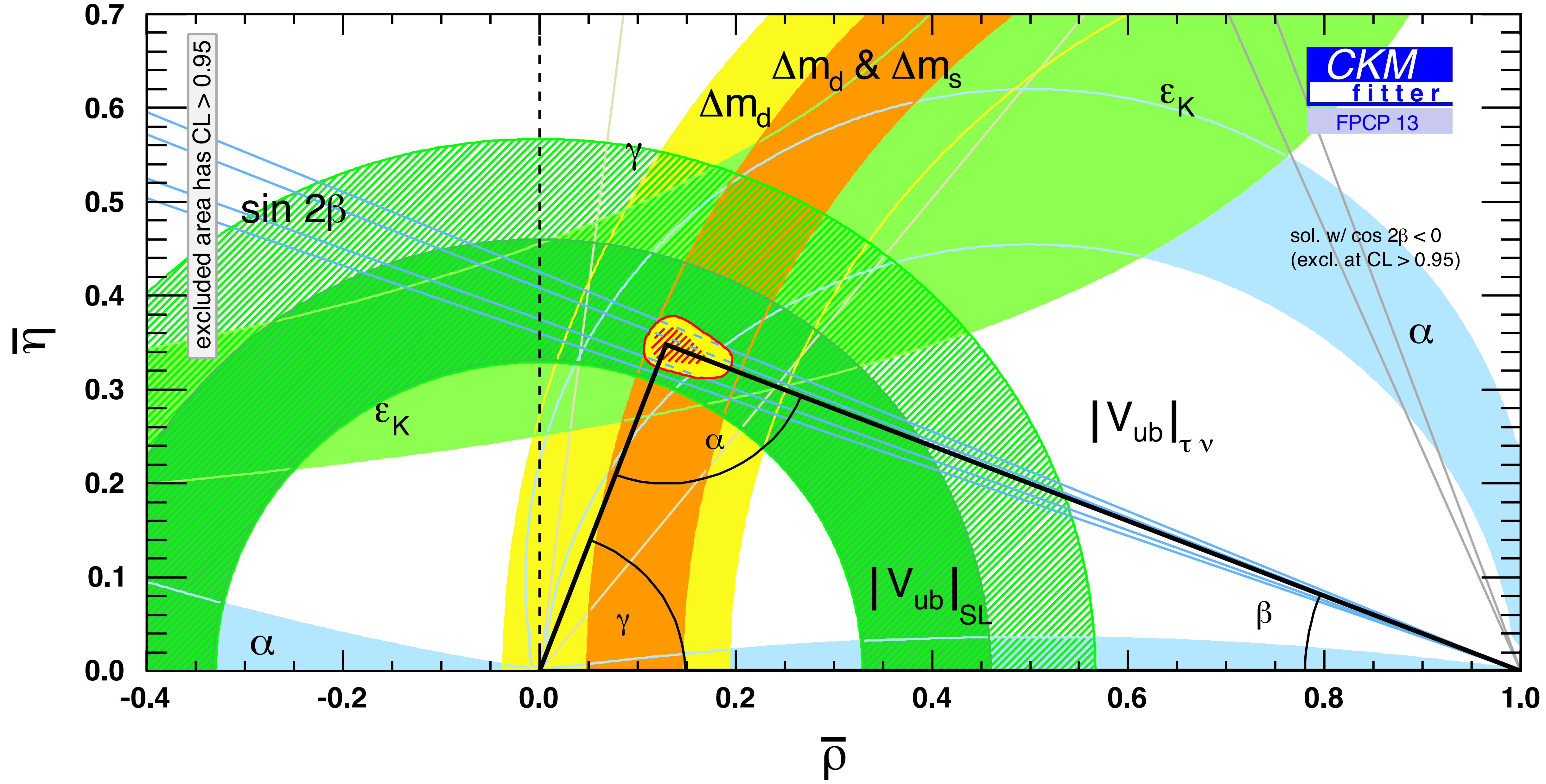
Back to the apex

http://ckmfitter.in2p3.fr
Similar plots with Bayesian treatment available at www.utfit.org





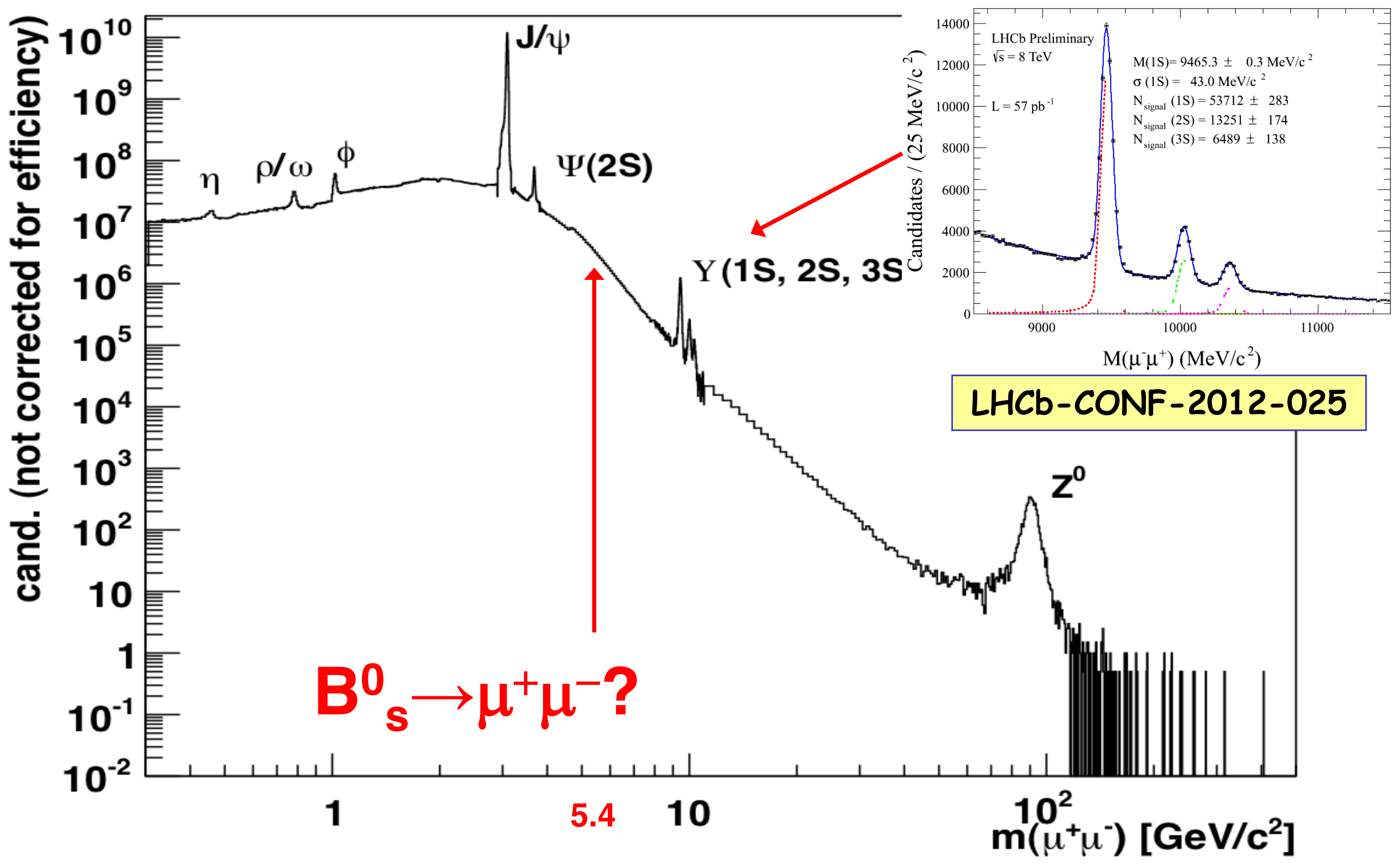


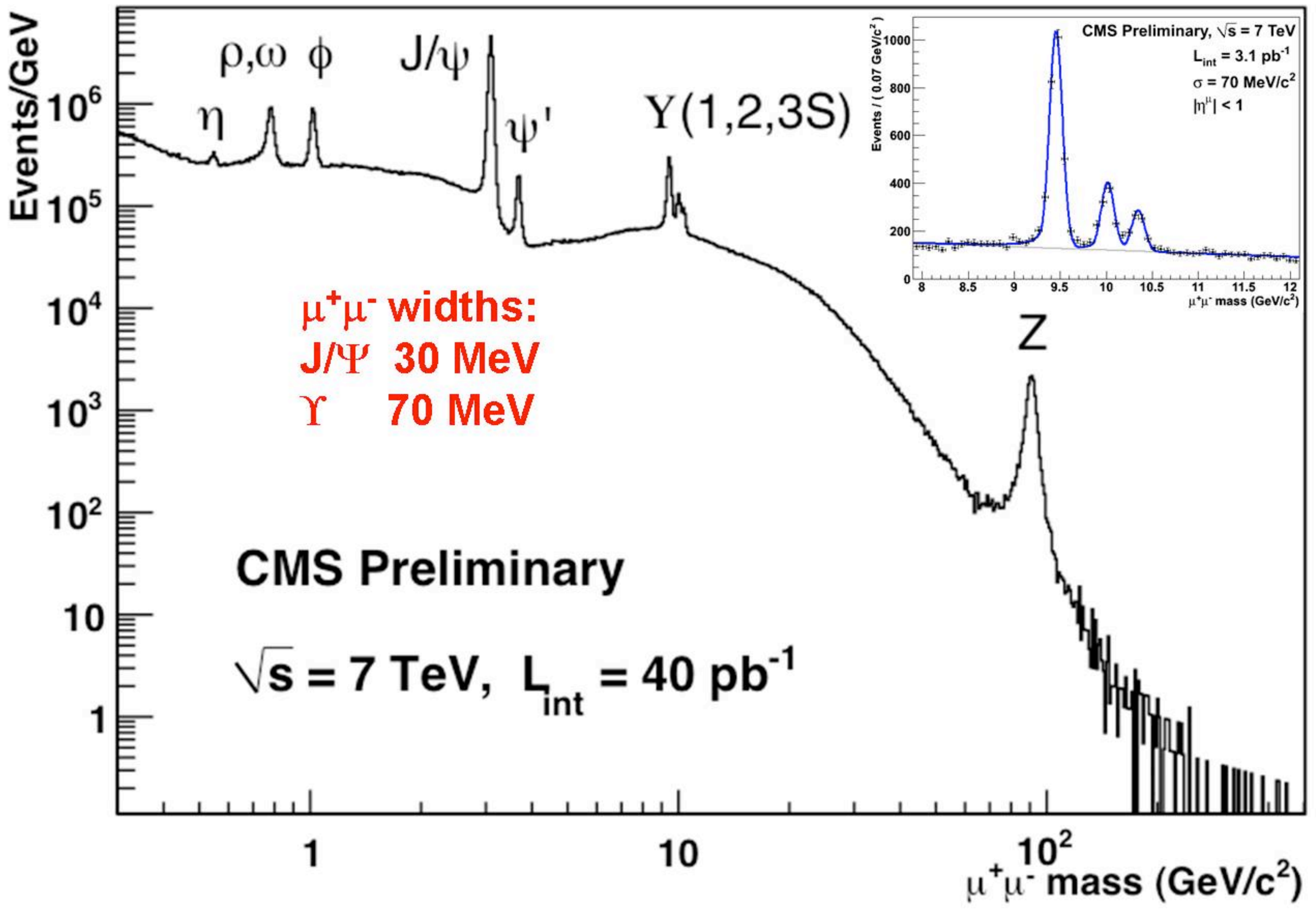


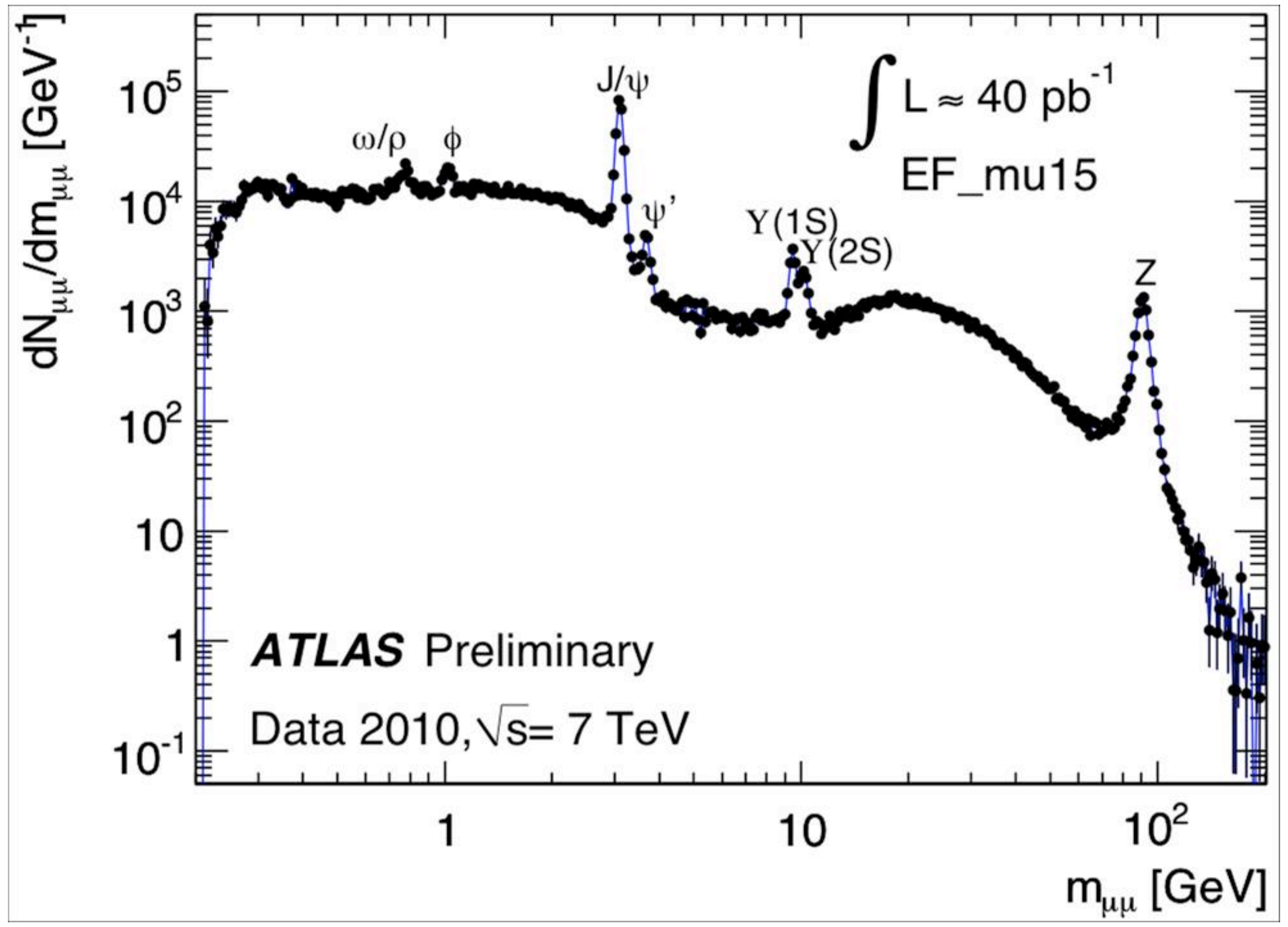
Continue to improve precision on all measurements to overconstrain the apex.
Progress in theory/lattice calculations critical to exploit experimental data.

The Dimuon Trinity

We all love dimuons







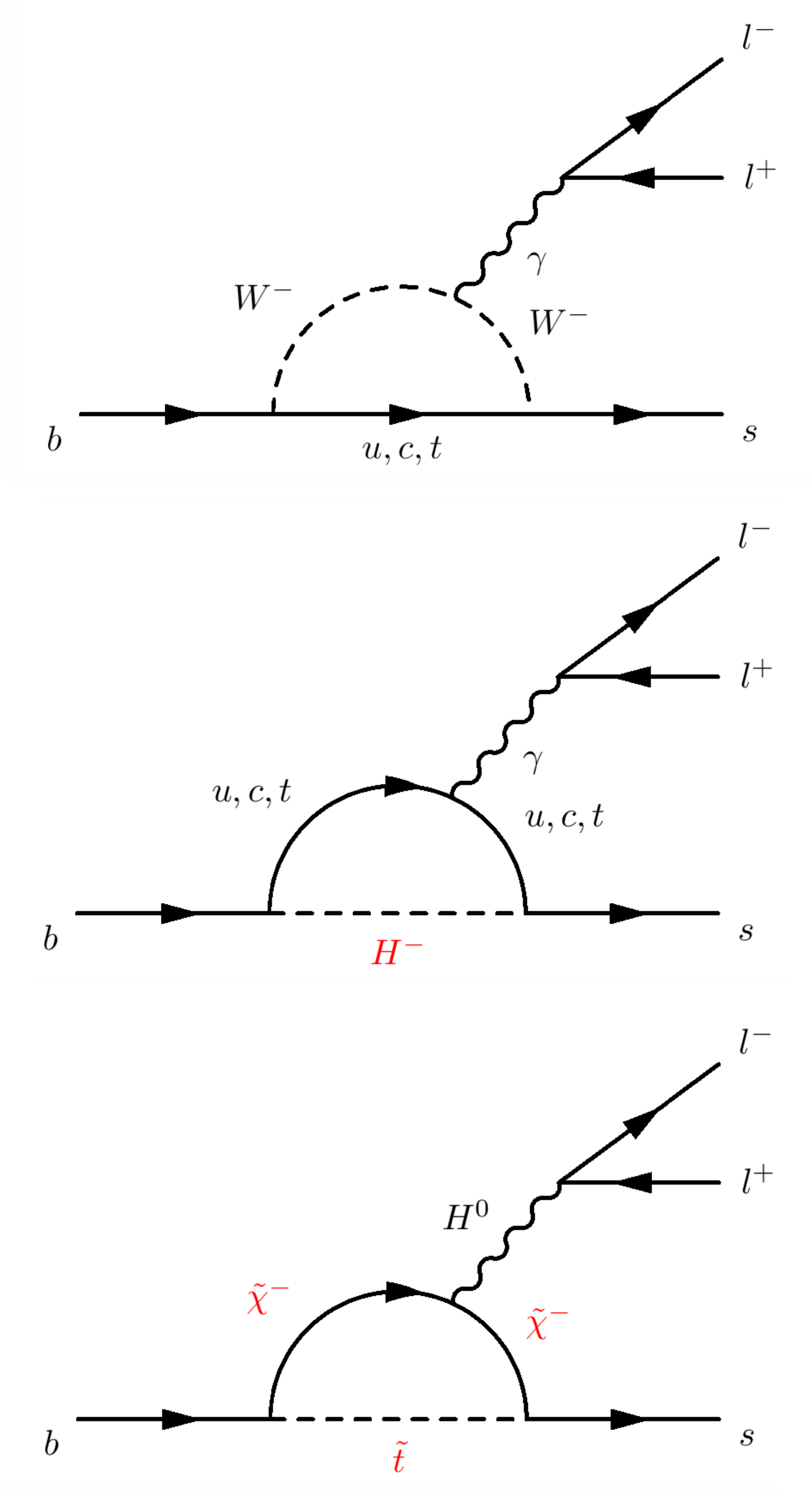
References, left to right :

LHCb-CONF-2012-025

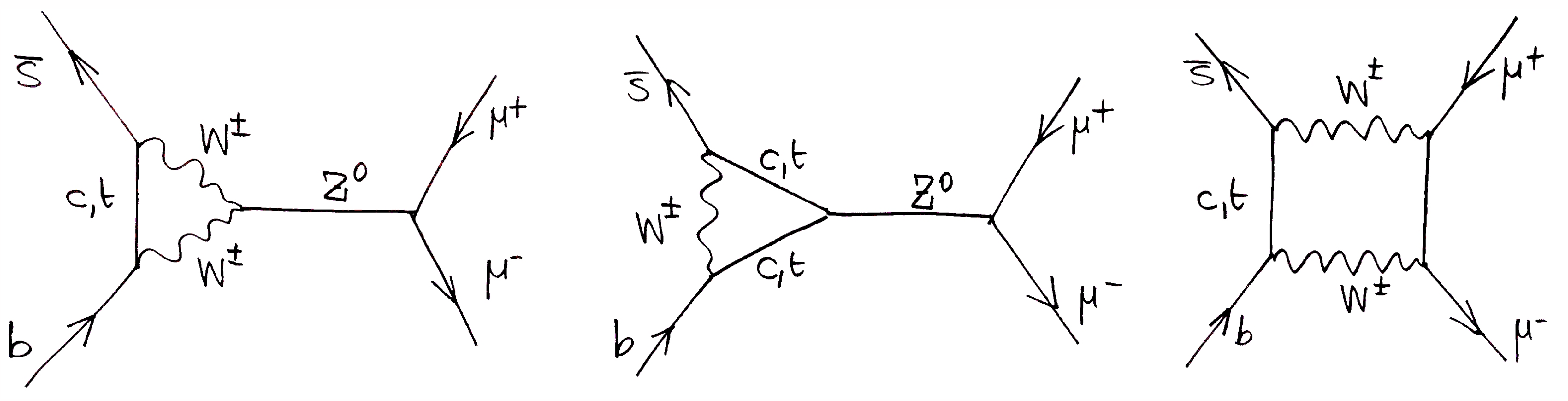
http://cms.web.cern.ch

http://www.atlas.ch

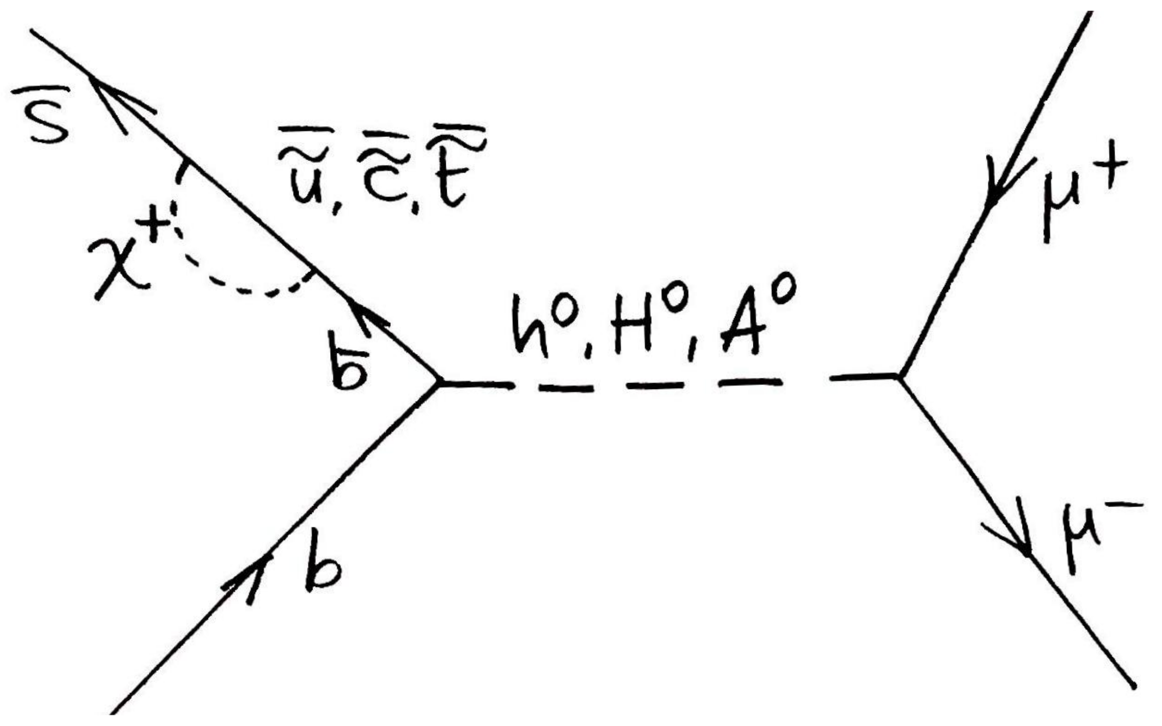
And we all love loop diagrams



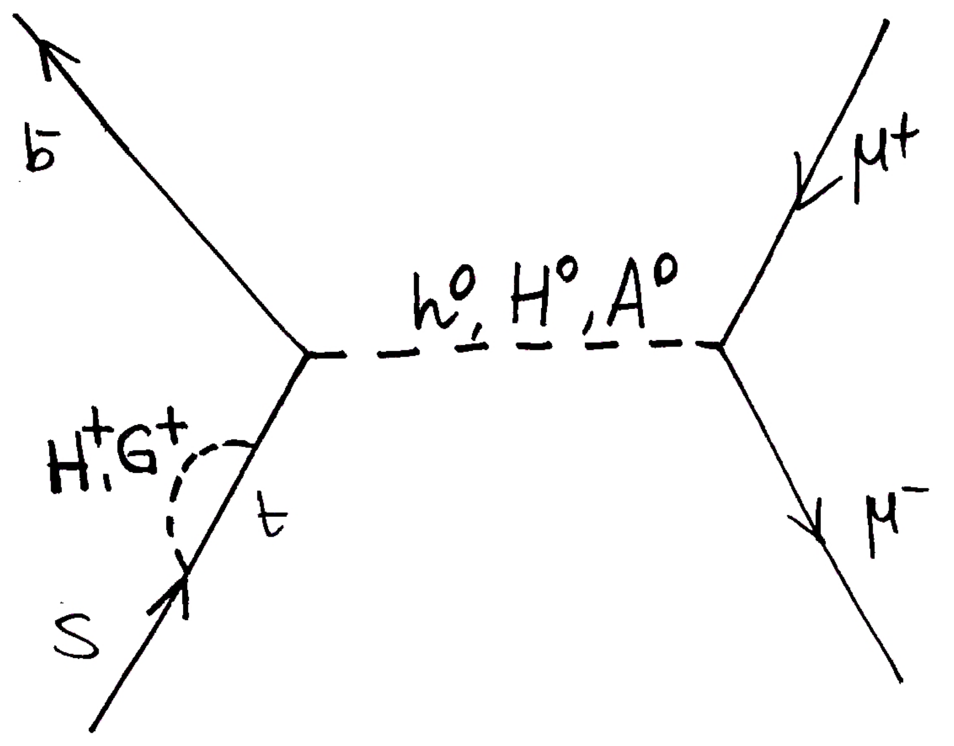
SM



MSSM



2HDM-II

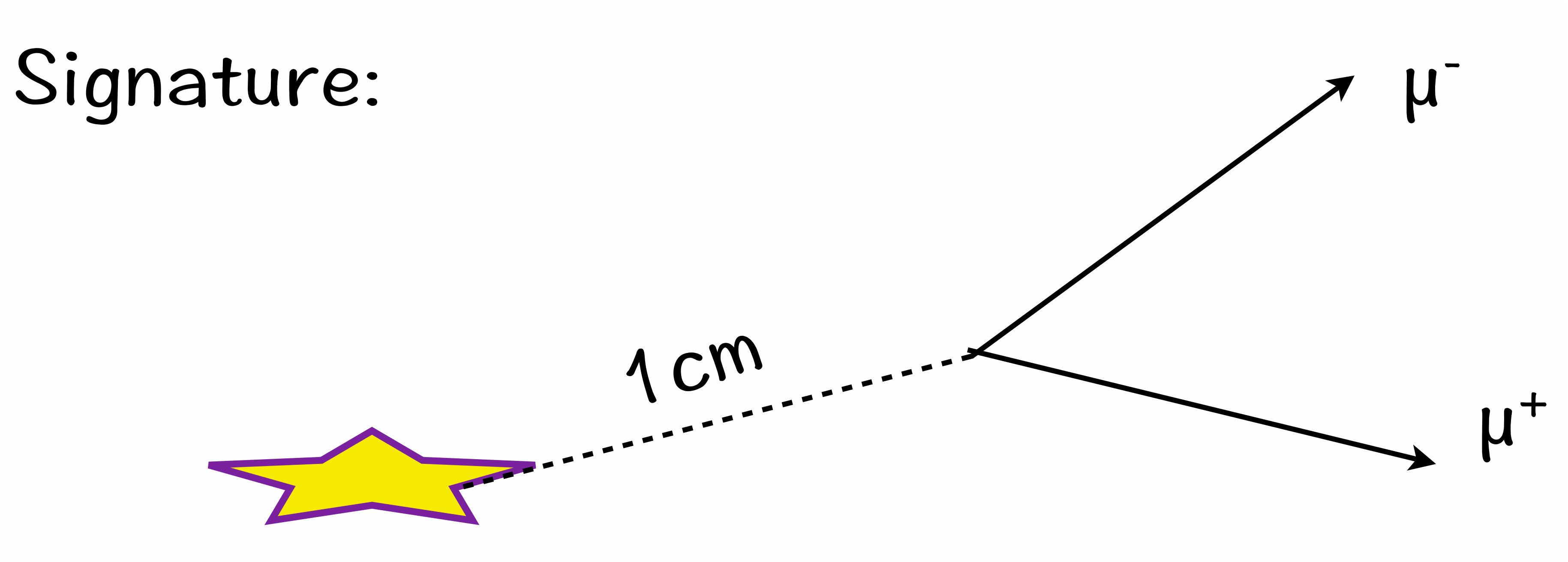


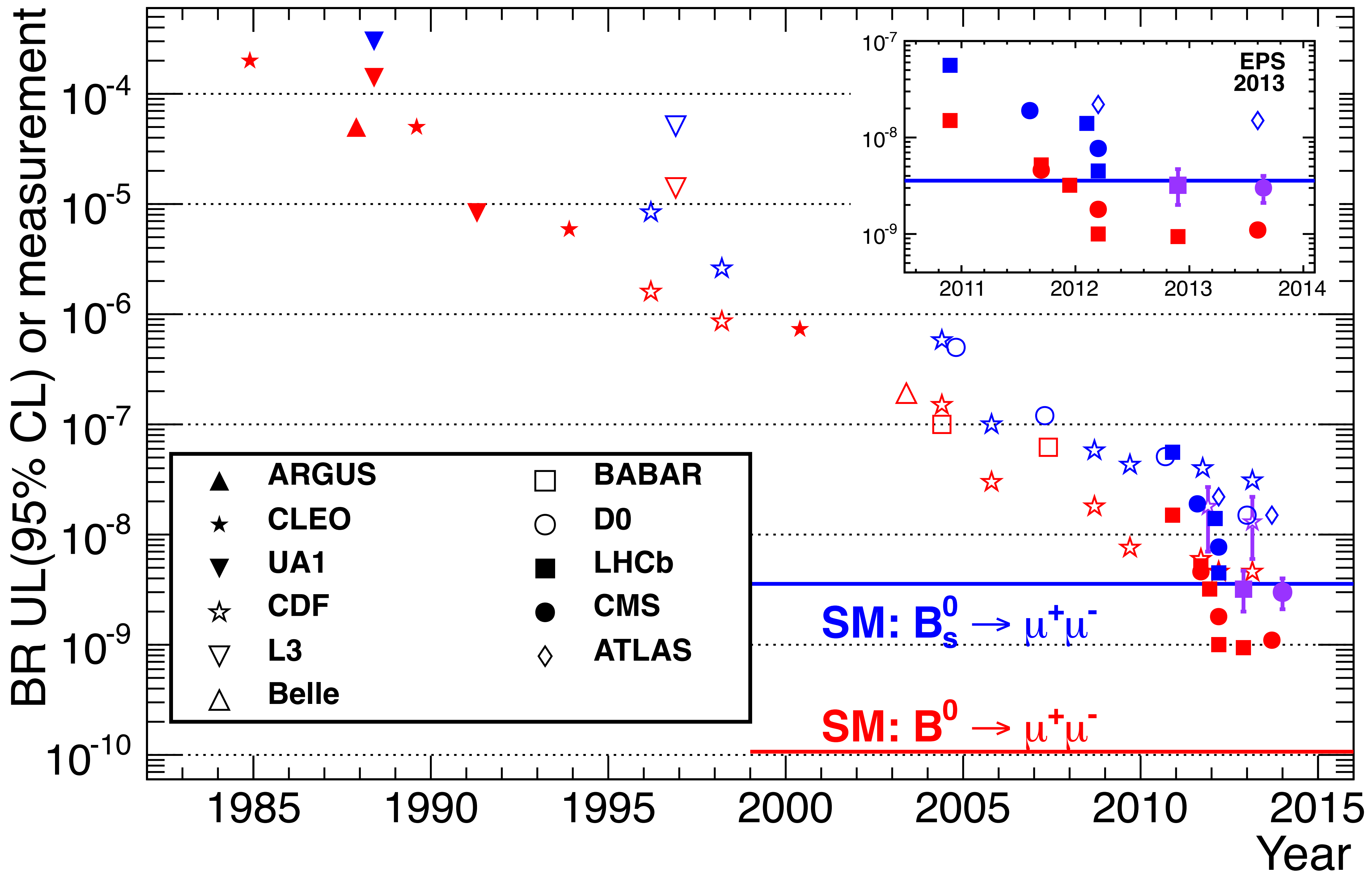
B→μμ, the ne plus ultra of dimuons

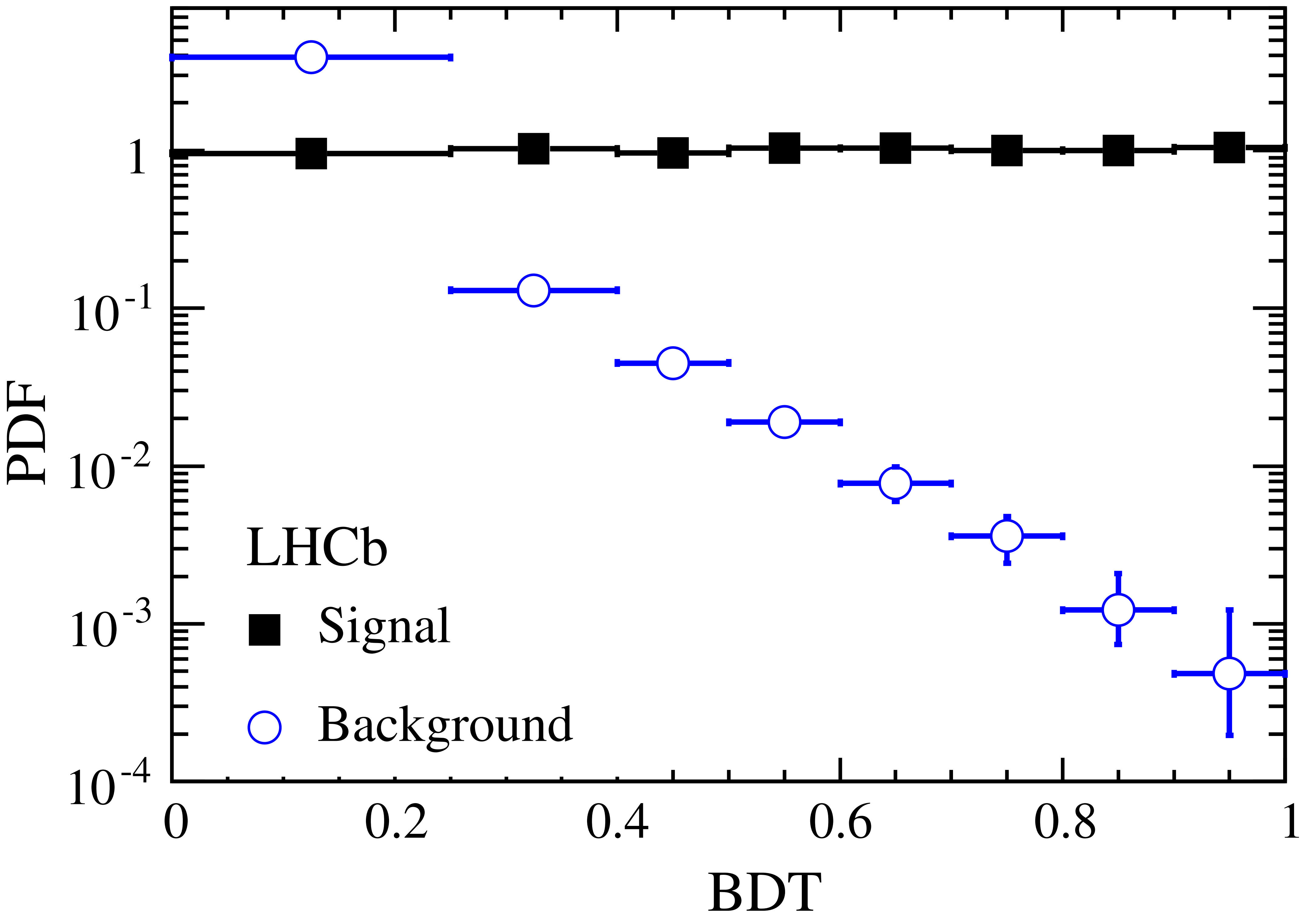
Precise SM predictions due to decay diagrams

- $Br(B_d\text{->}\mu\mu) = (1.1 \pm 0.2)\ 10^{-10}$
- $Br(B_s\text{->}\mu\mu) = (3.5 \pm 0.2)\ 10^{-9}$

Buras et al, EPJ C72 (2012) 2172; see also PRL109 (2012) 041801

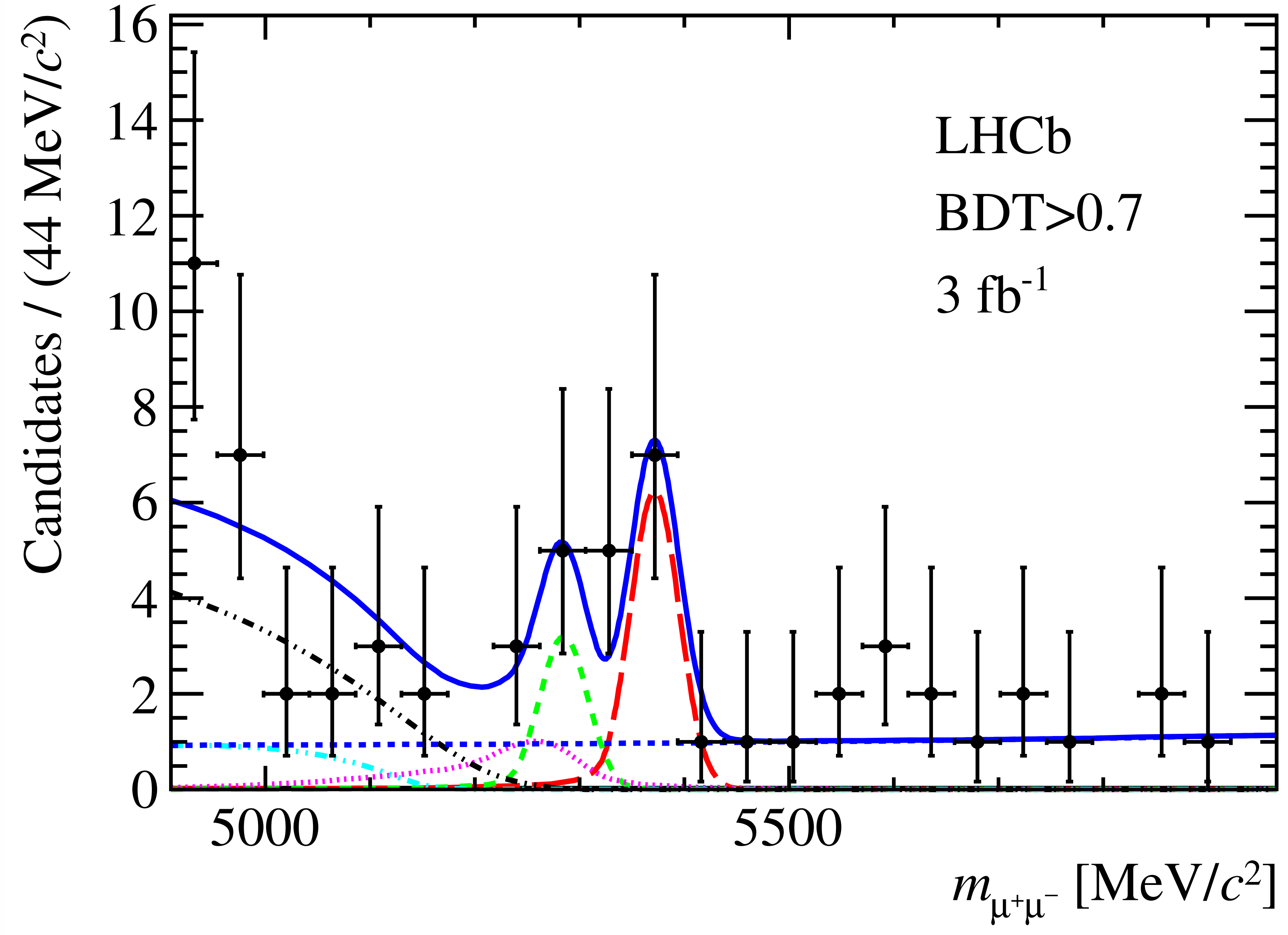






The LHCb and CMS signals

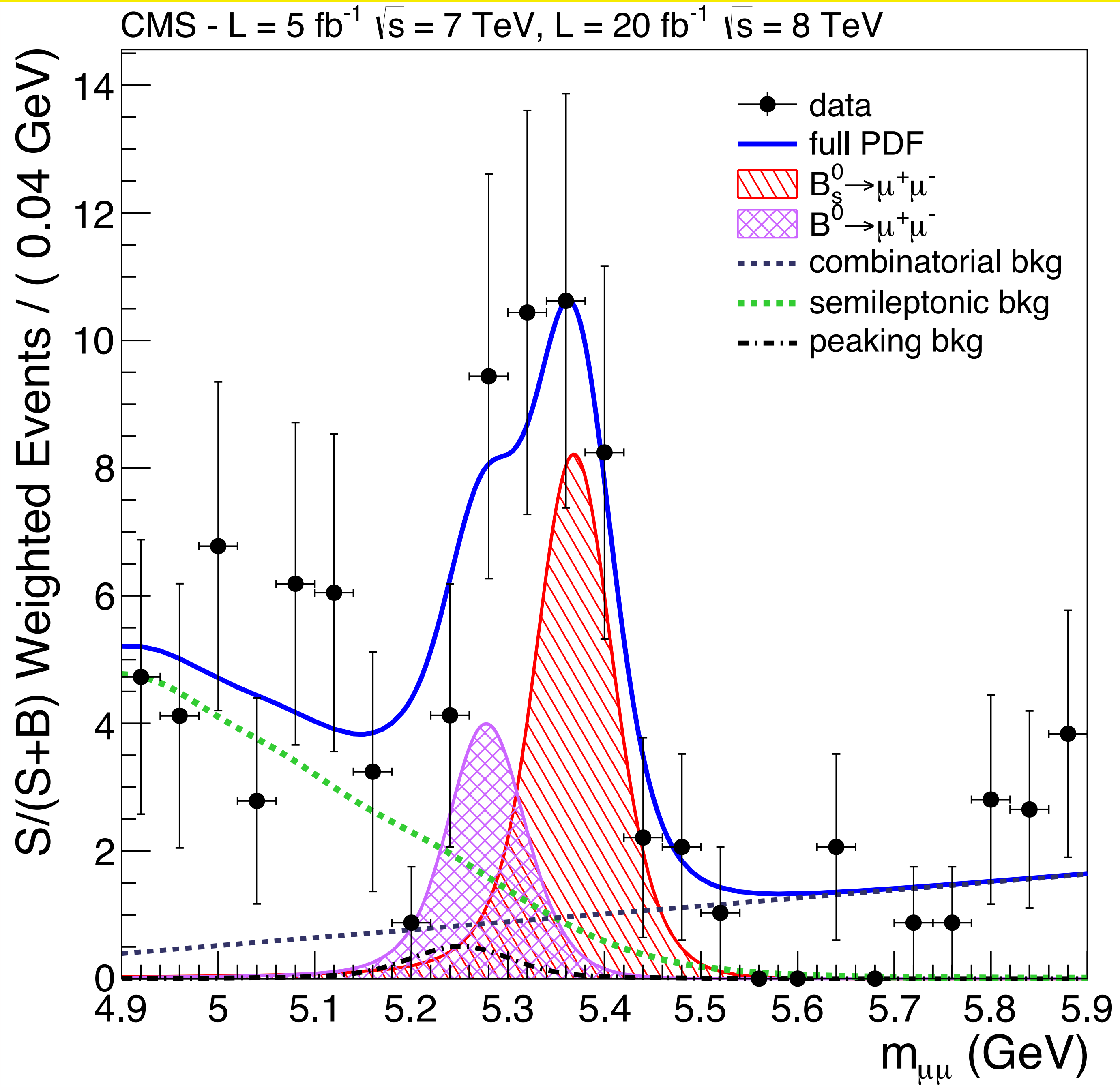
LHCb: arXiv:1307.5024, PRL.111.101805 (2013)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.9\,^{+1.1}_{-1.0}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.7\,^{+2.4}_{-2.1}\right) \times 10^{-10}$$

--> 4.0σ

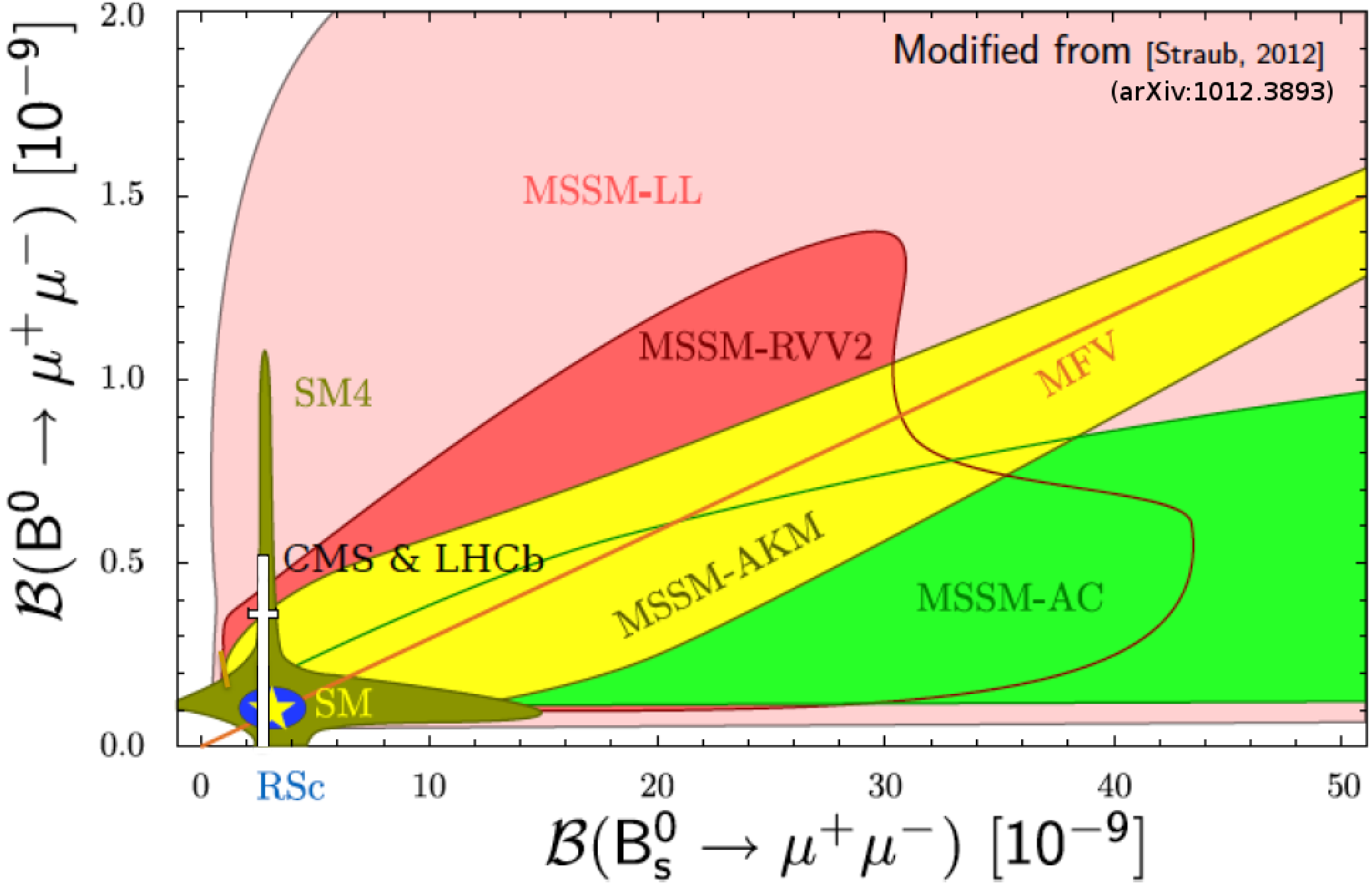
CMS: arXiv:1307.5025, PRL. 111.101804 (2013)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0\,^{+1.0}_{-0.9}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.5\,^{+2.1}_{-1.8}\right) \times 10^{-10}$$

--> 4.3σ

$B^0/B^0_s \to \mu\mu$, the golden ratio

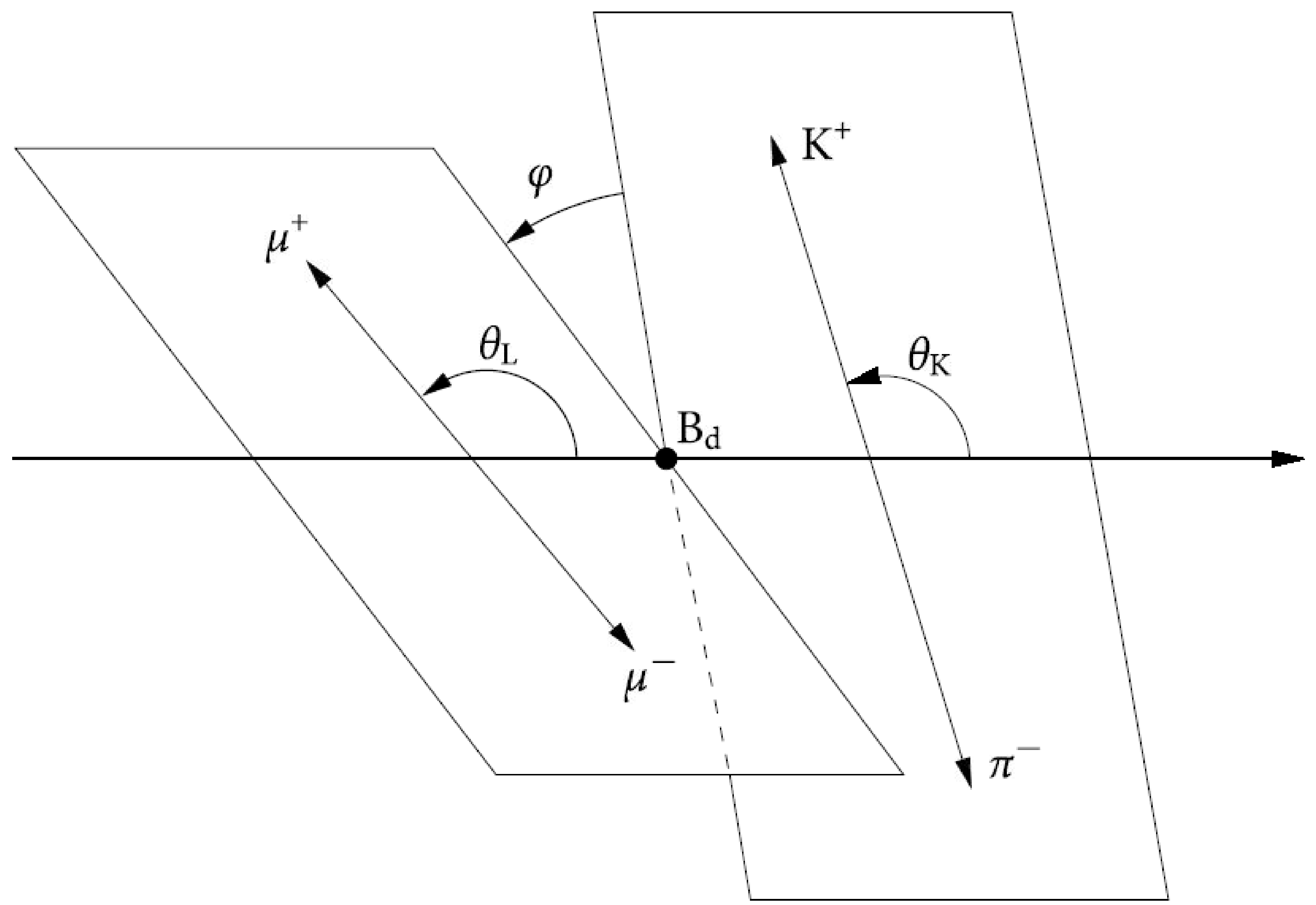


$B \to X_s \mu\mu$, the gift that keeps on giving

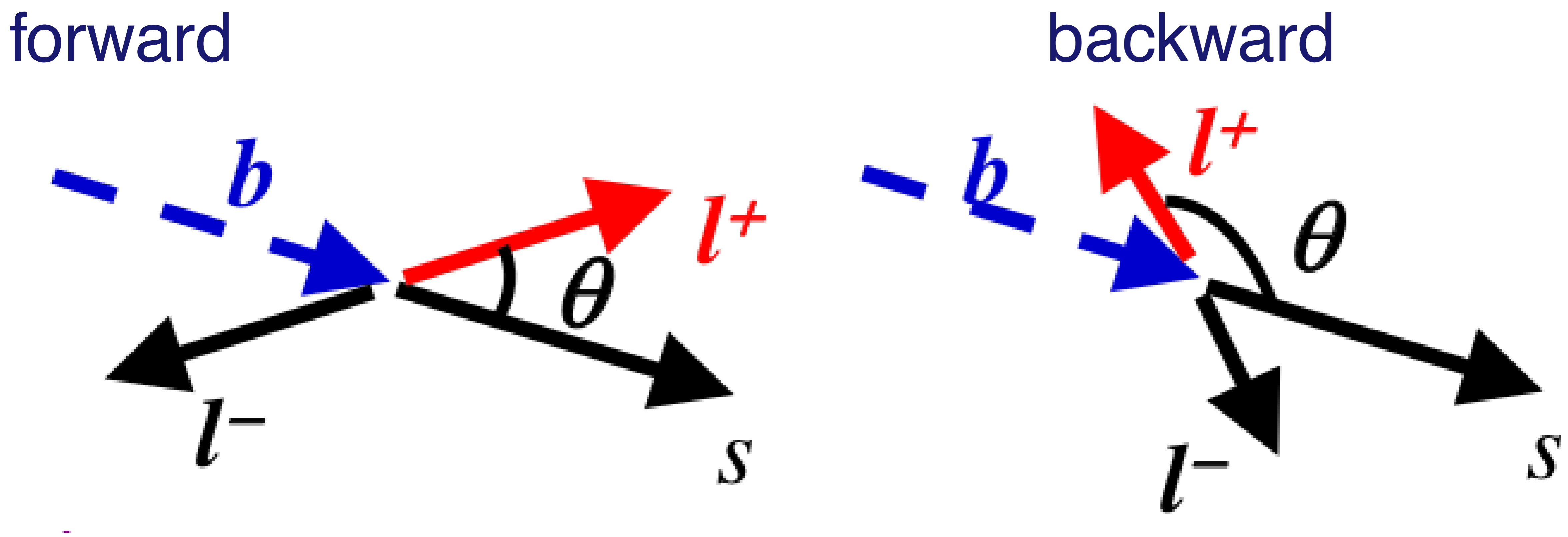
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\theta_l \mathrm{d}\theta_K \mathrm{d}\varphi \mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\varphi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_l\cos\varphi + S_5\sin 2\theta_K\sin\theta_l\cos\varphi$$
$$+ S_6^s\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\varphi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_l\sin\varphi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\varphi\Big]$$

Altmannshofer et al, JHEP 01 (2009) 019

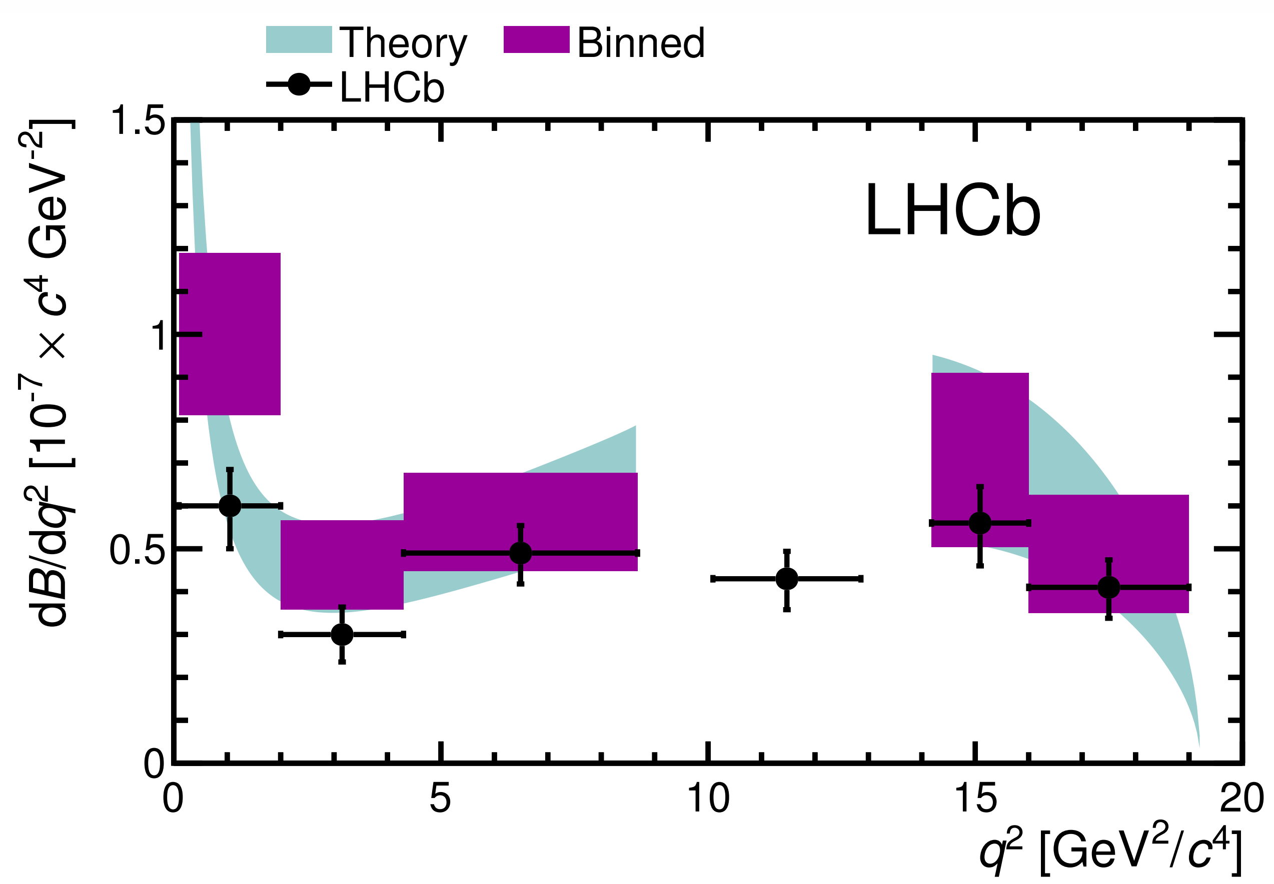
q^2 = dimuon invariant mass^2

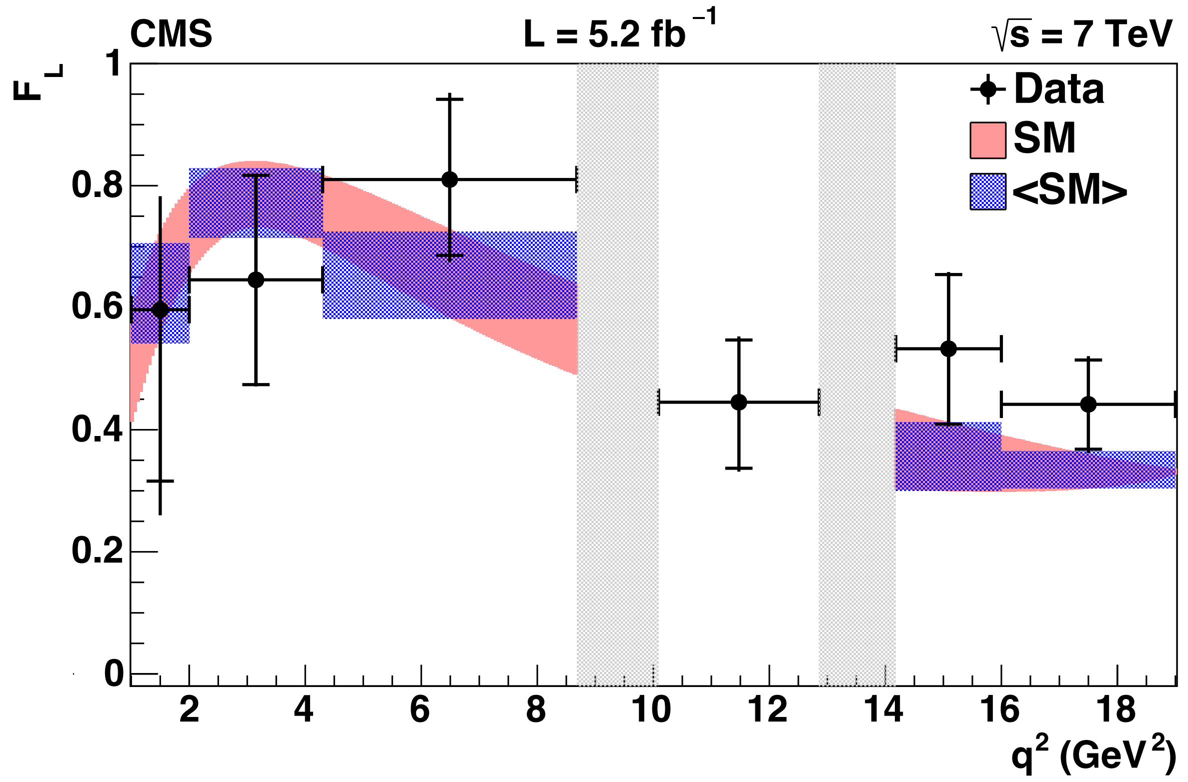


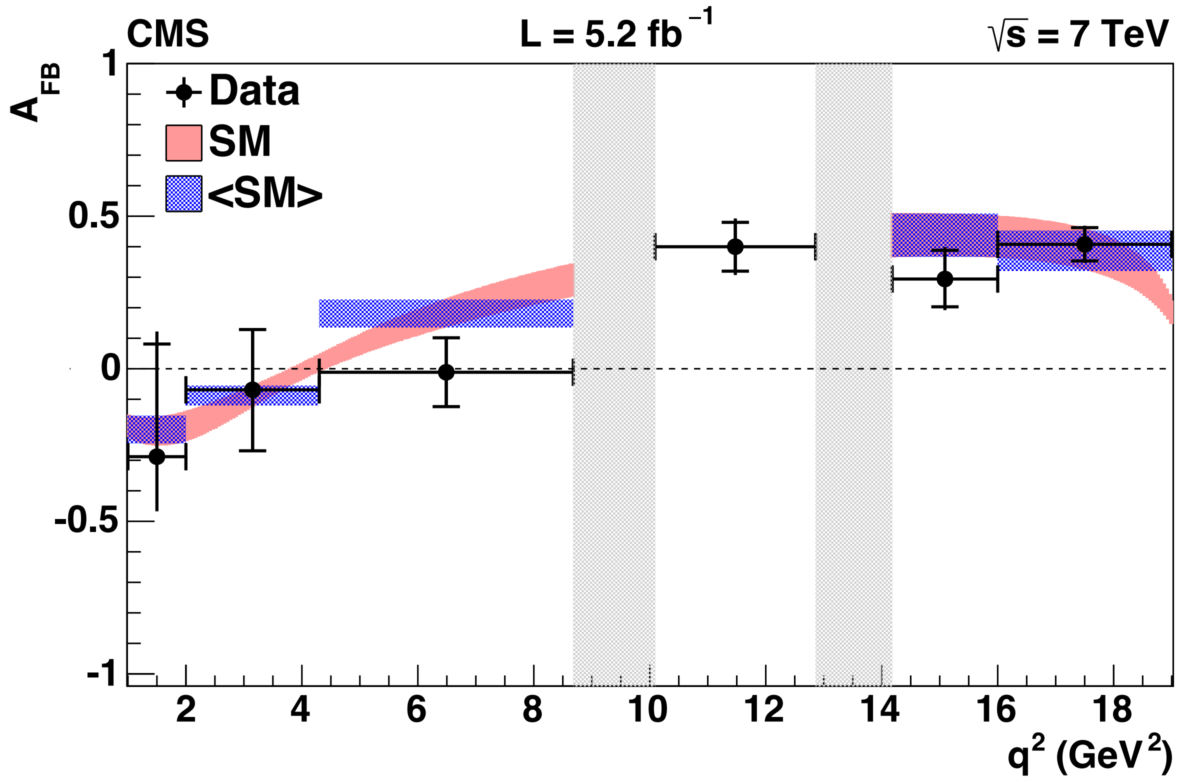
Example observables : forward backward asymmetry (sensitive to S_6), K^{*0} longitudinal polarization...

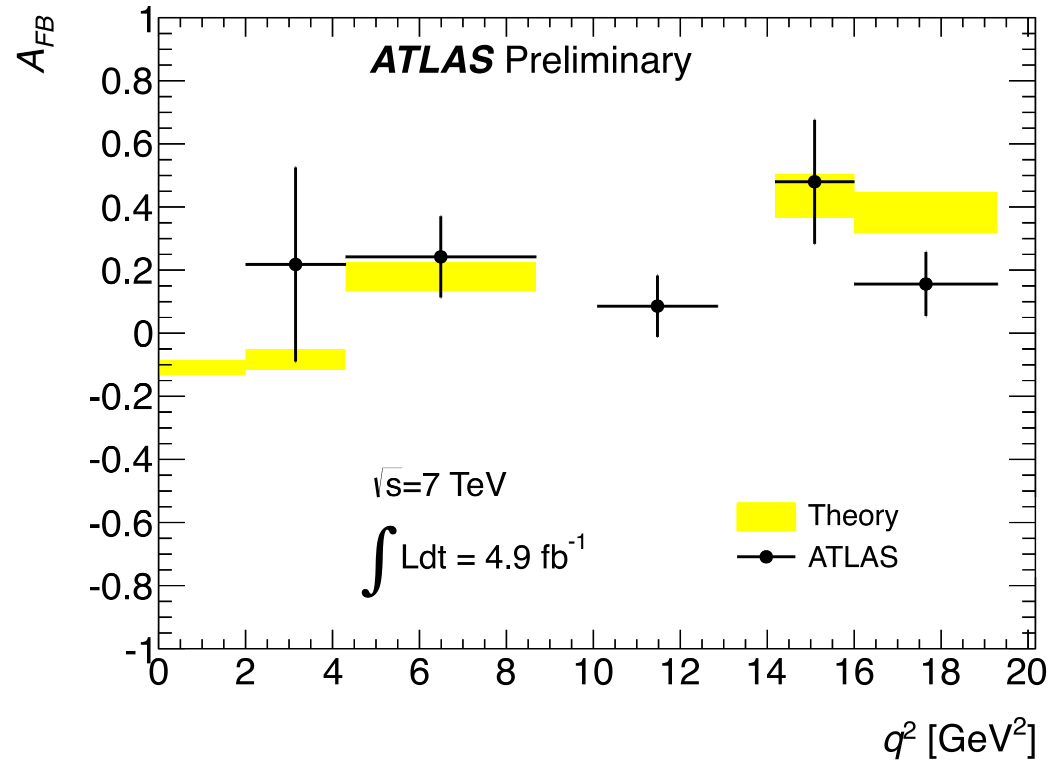


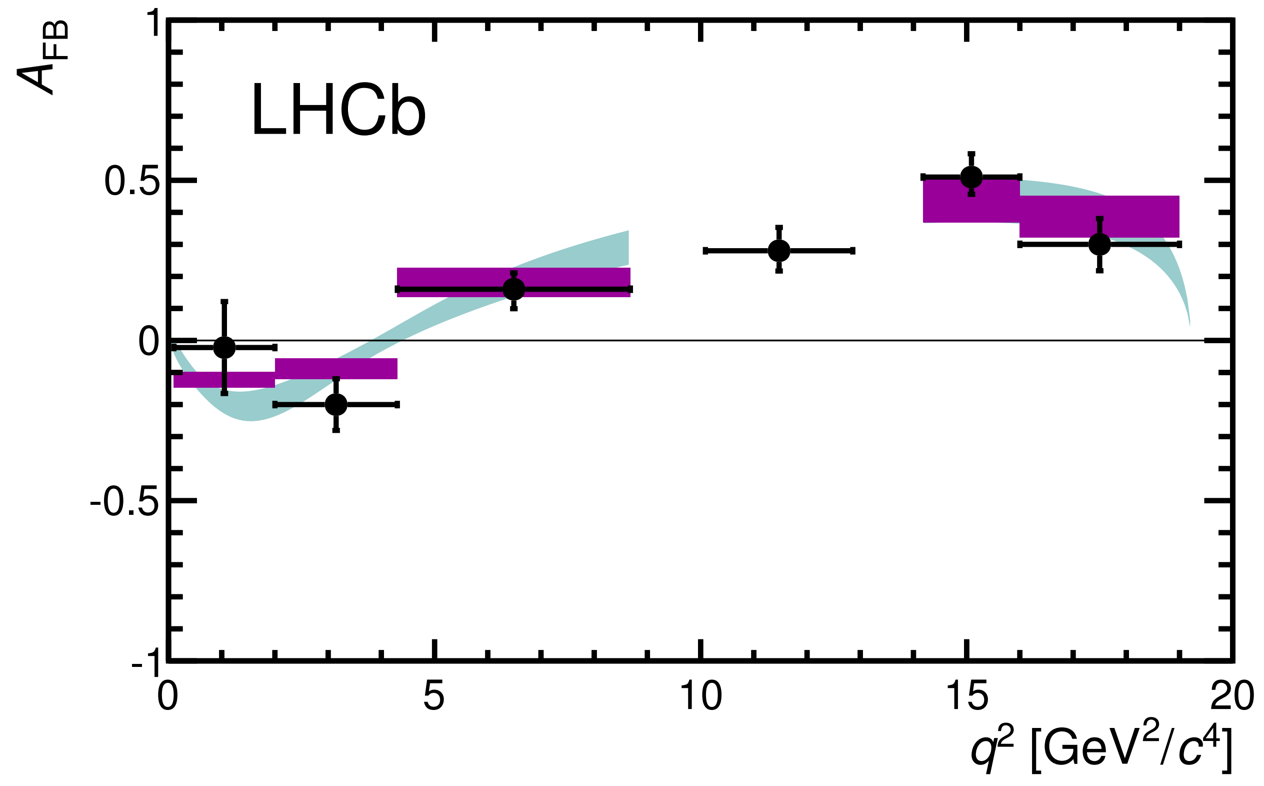
So many observables, so little time

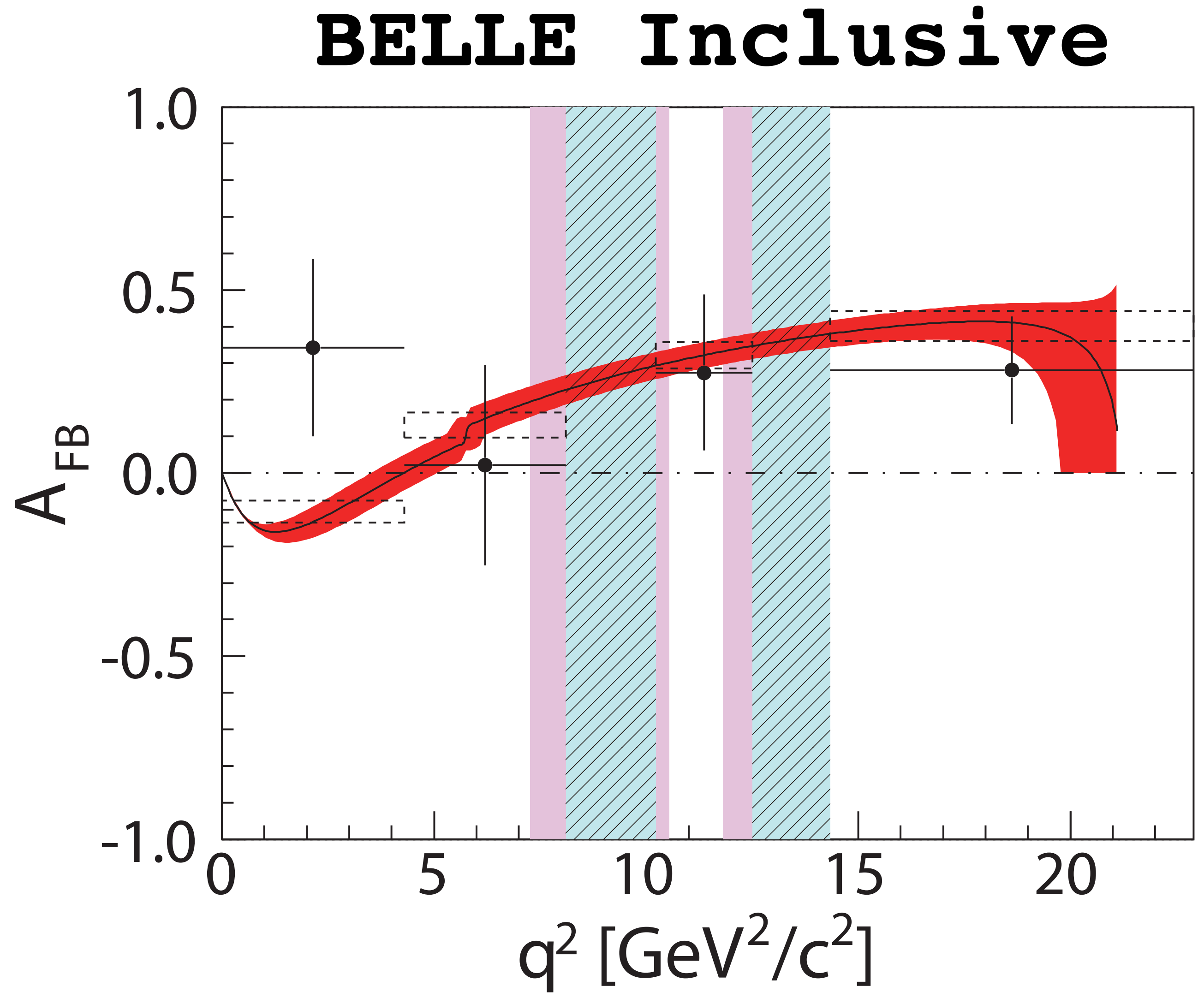


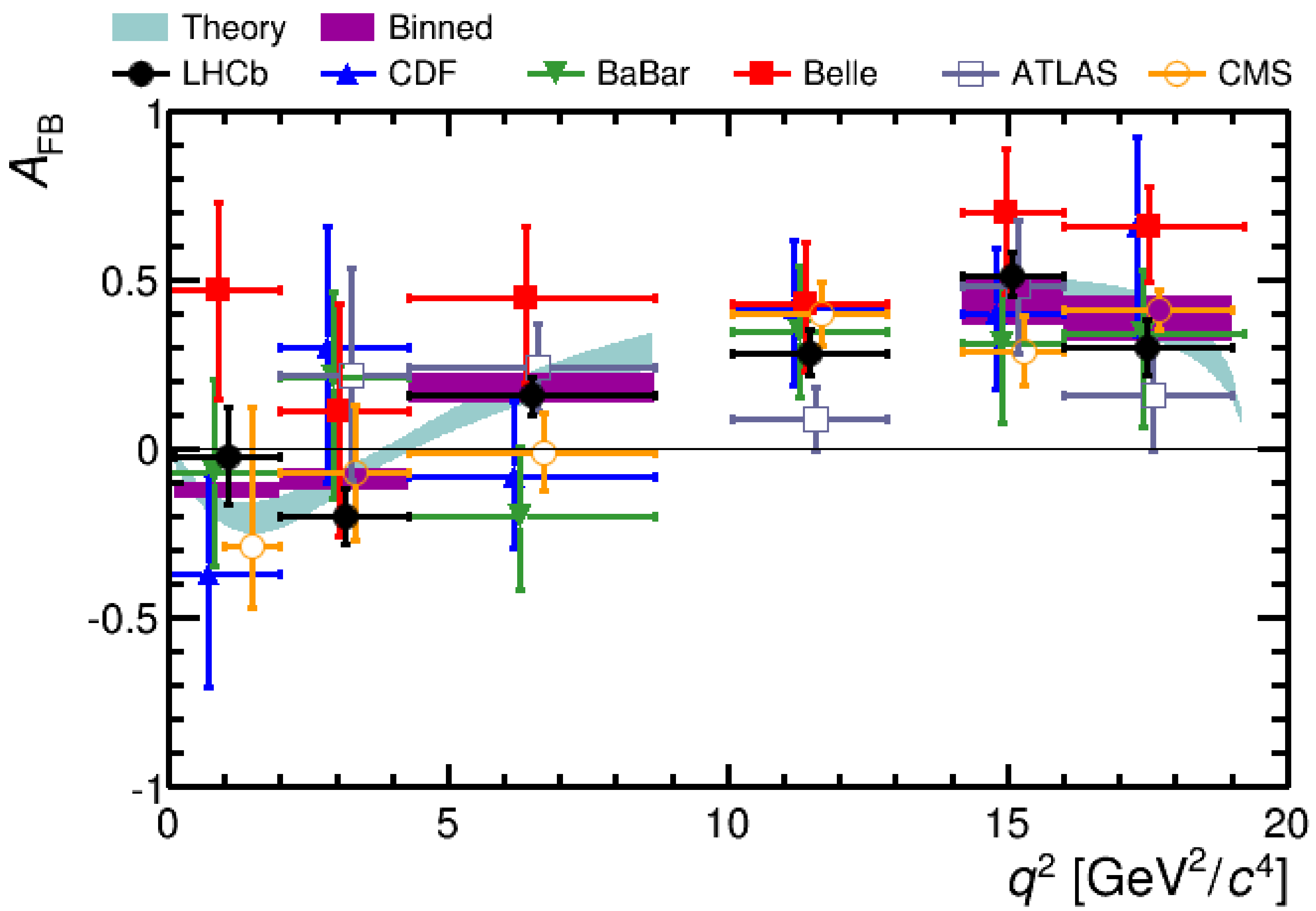








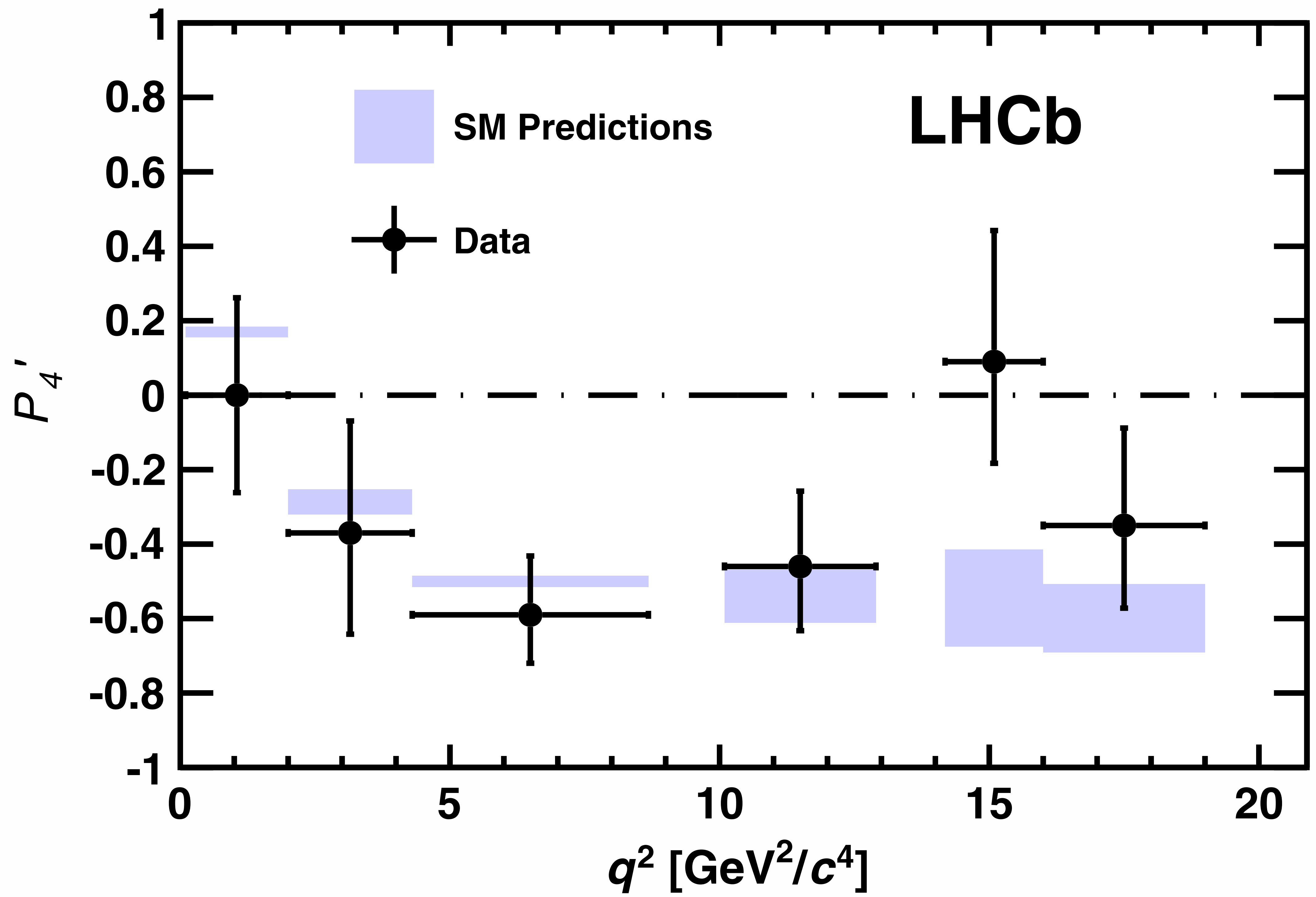


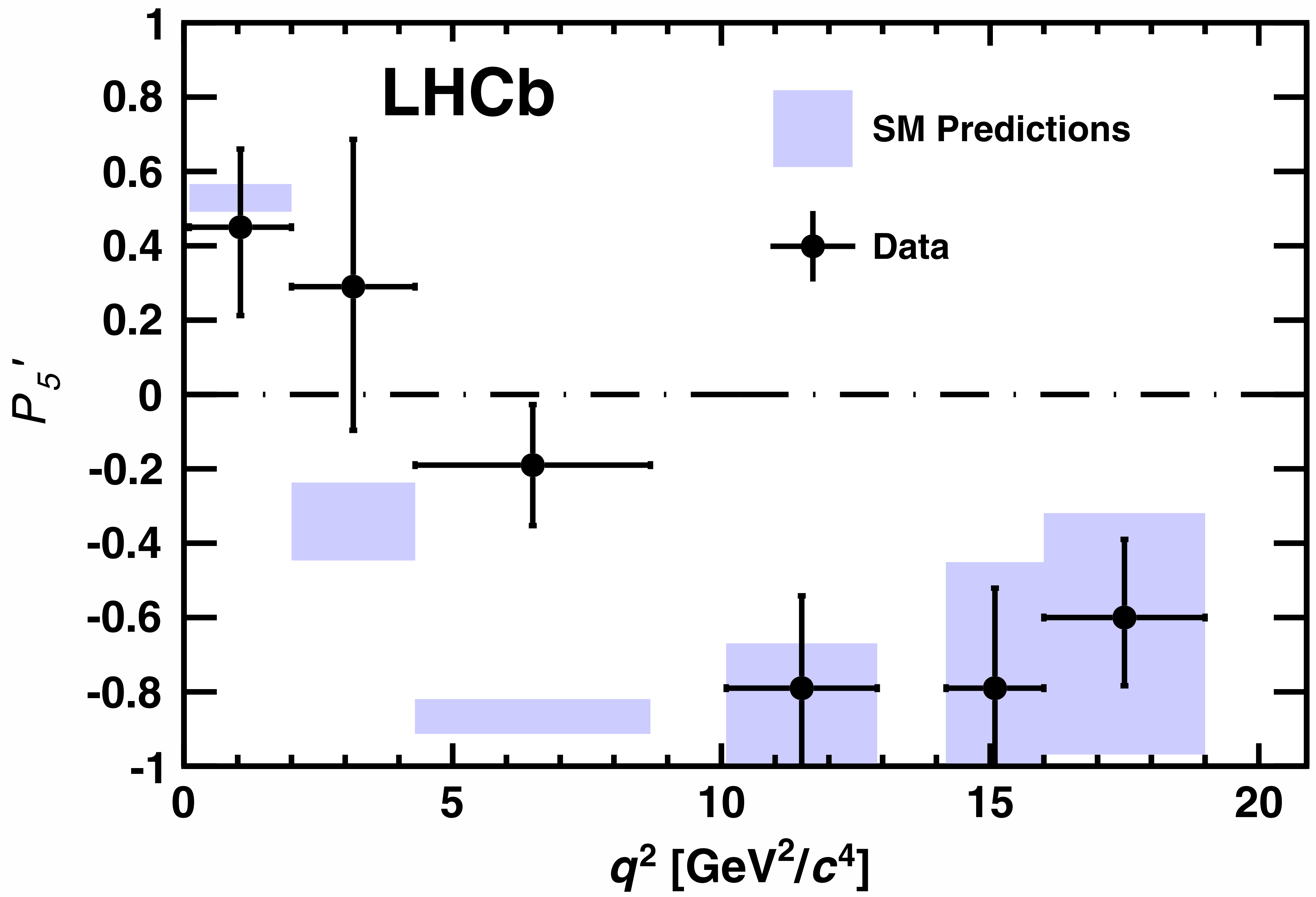


LHCb : JHEP 08 (2013) 131
CMS : 1308.3409v2
ATLAS : ATLAS-CONF-2013-038
BELLE : 1402.7134v1

We also love tensions

JHEP 08 (2013) 131
PRL 111 (2013) 191801

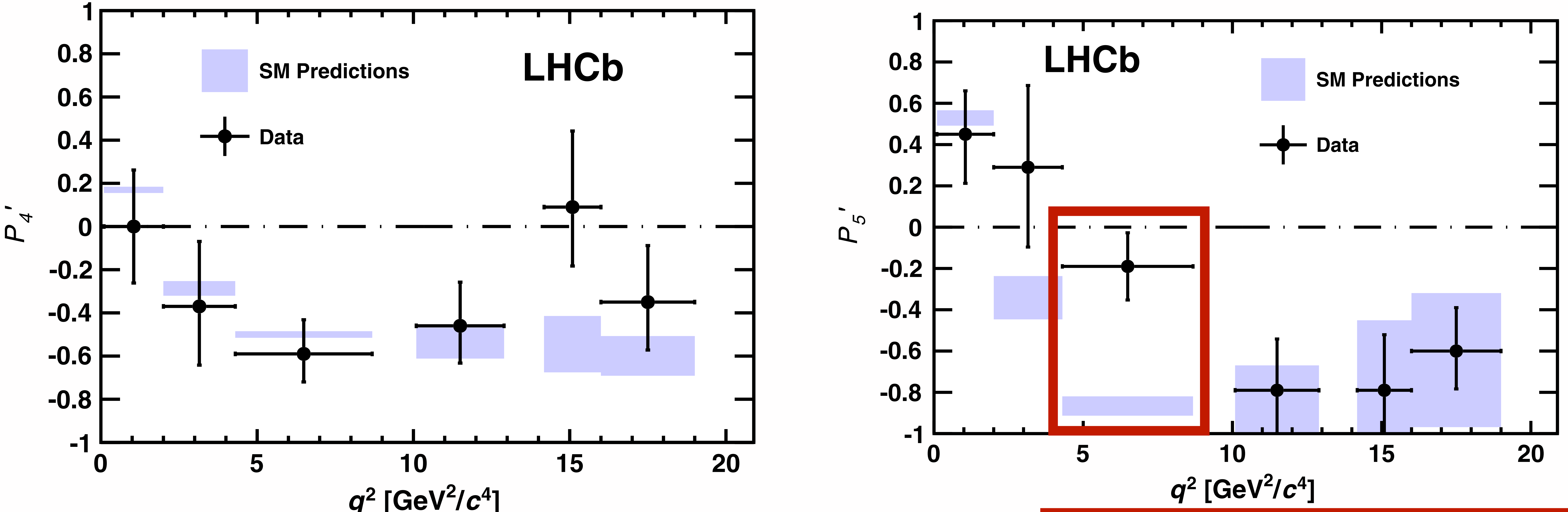




- at low q^2, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)

We also love tensions

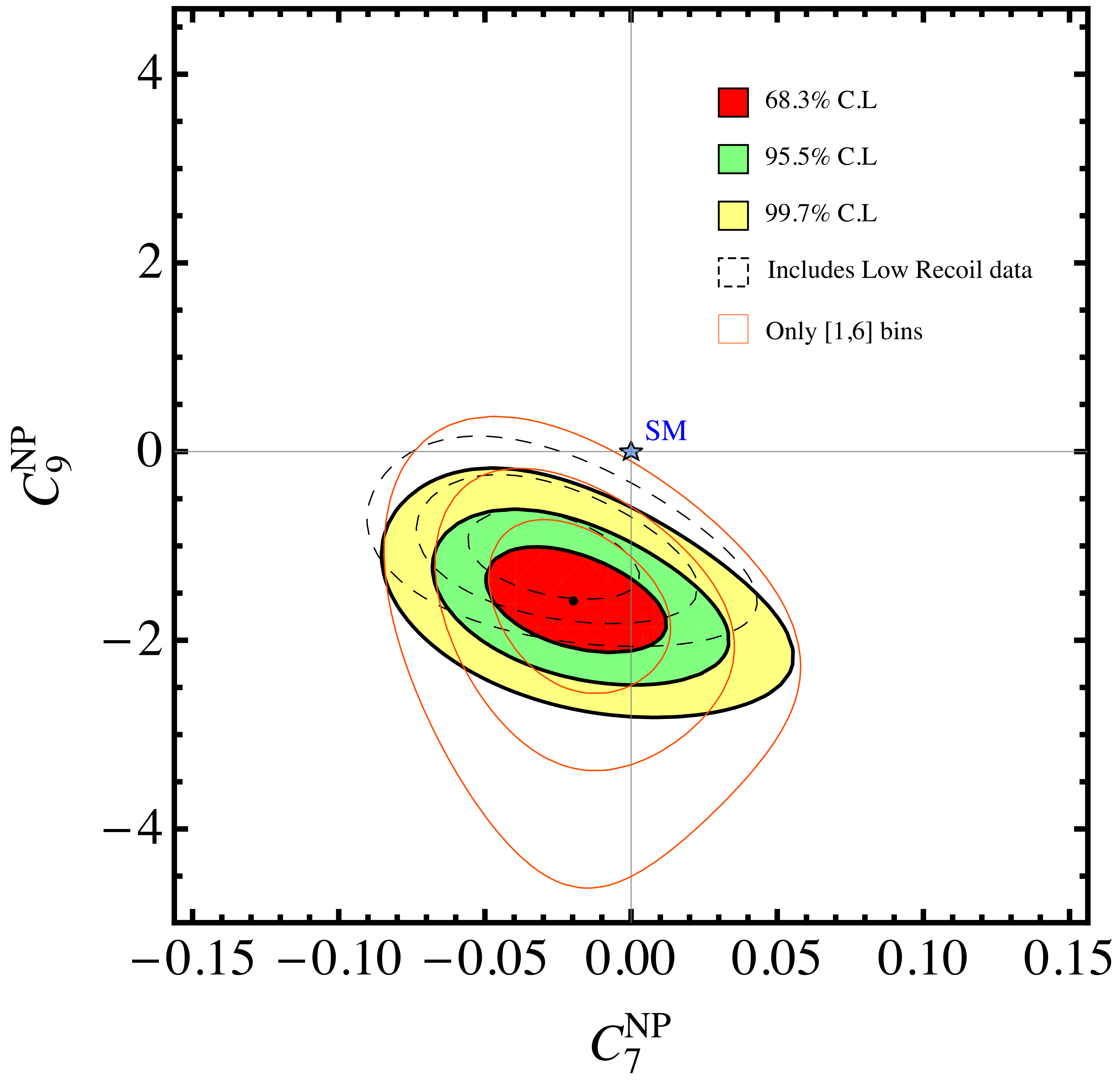
JHEP 08 (2013) 131
PRL 111 (2013) 191801



2.8σ global significance : 3 fb^{-1} result coming soon!

- at low q^2, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)

But the tension has to be consistent



Fit the $K^*\mu\mu$ "anomaly" together with

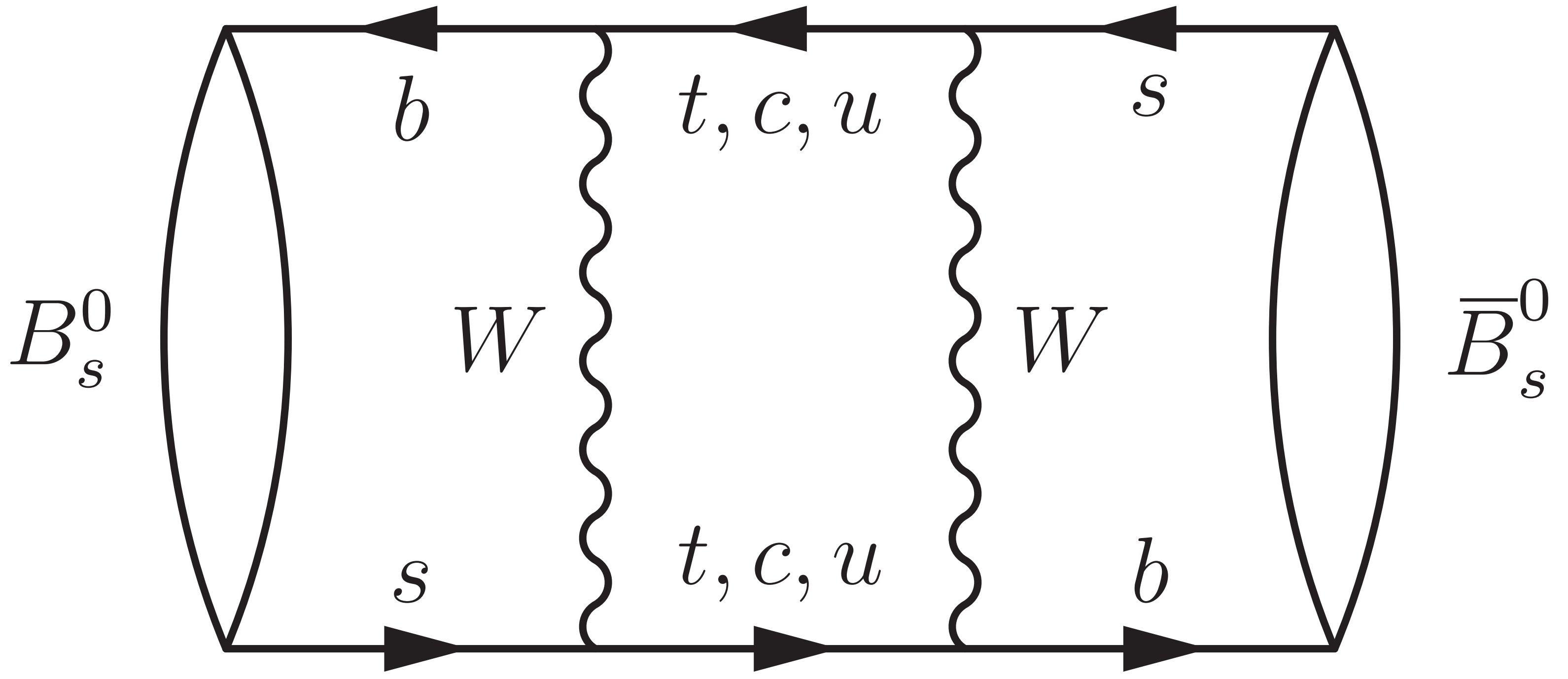
- **$B \to \mu\mu$**
- **$B \to X_s\gamma$, $K^*\gamma$**
- **$B \to X_s\mu\mu$ inclusive**

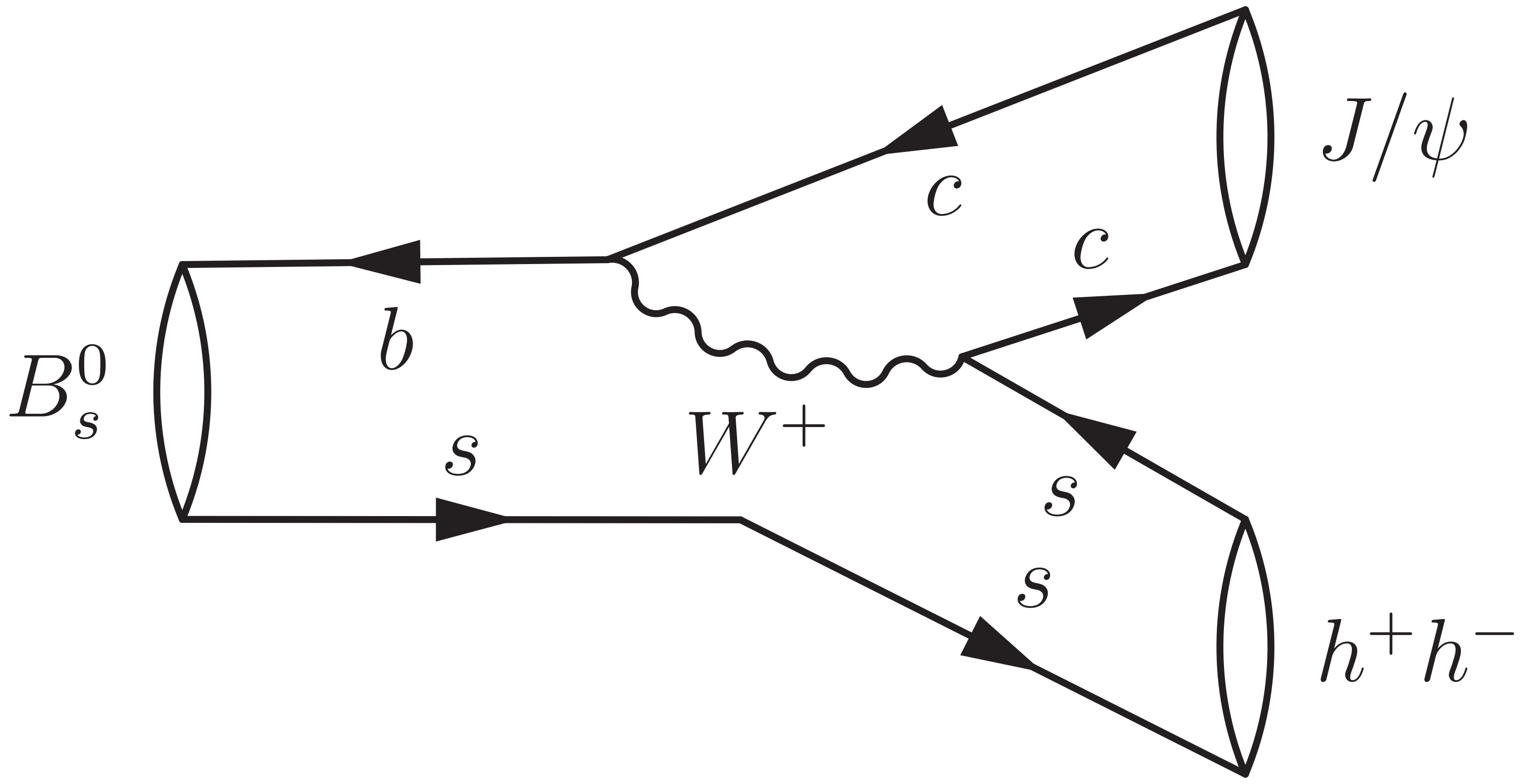
and interpret in terms of NP contributions to the Wilson coefficients

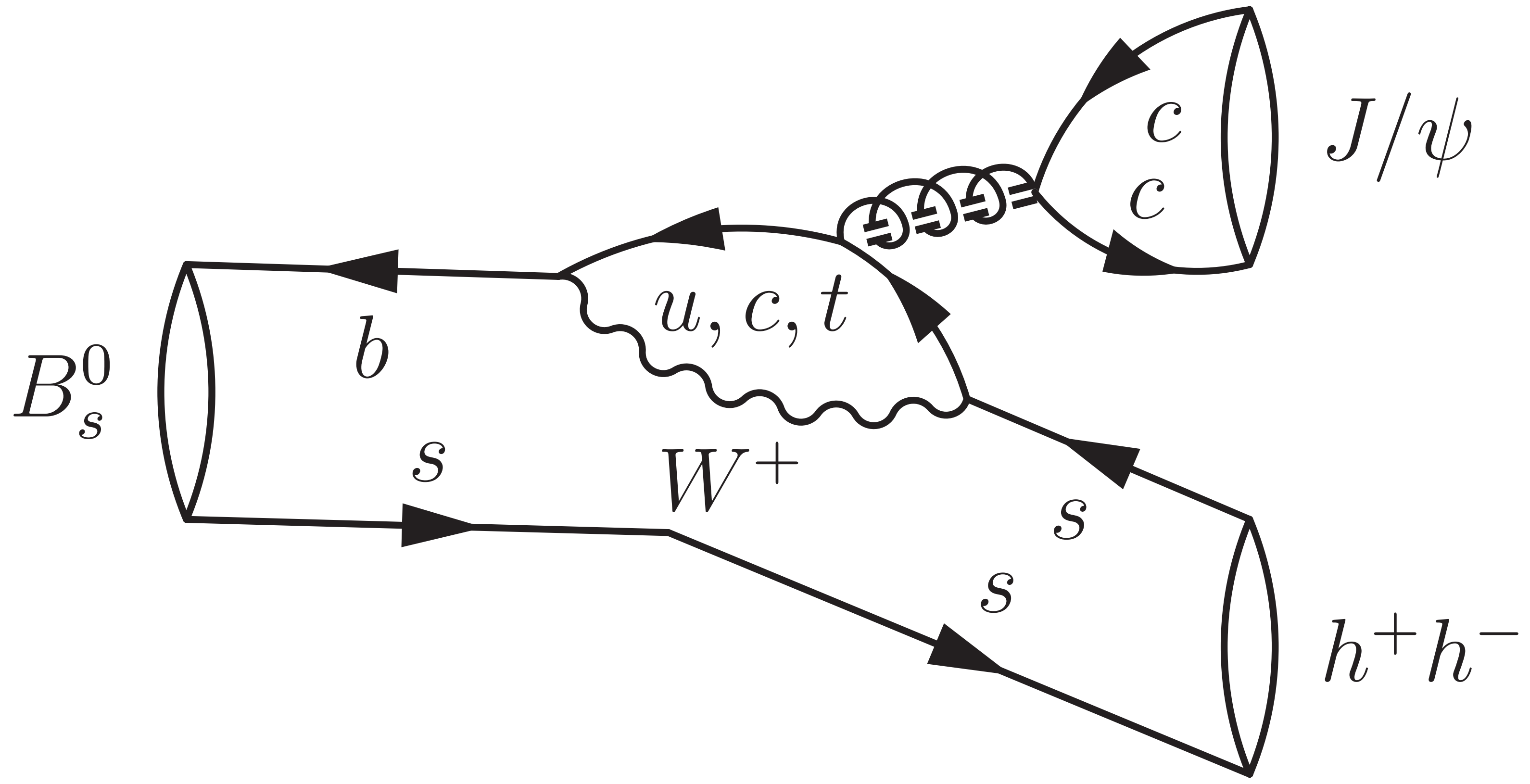
Whatever you think of this specific fit, the approach is clearly correct => we are looking for a consistent pattern of deviations!

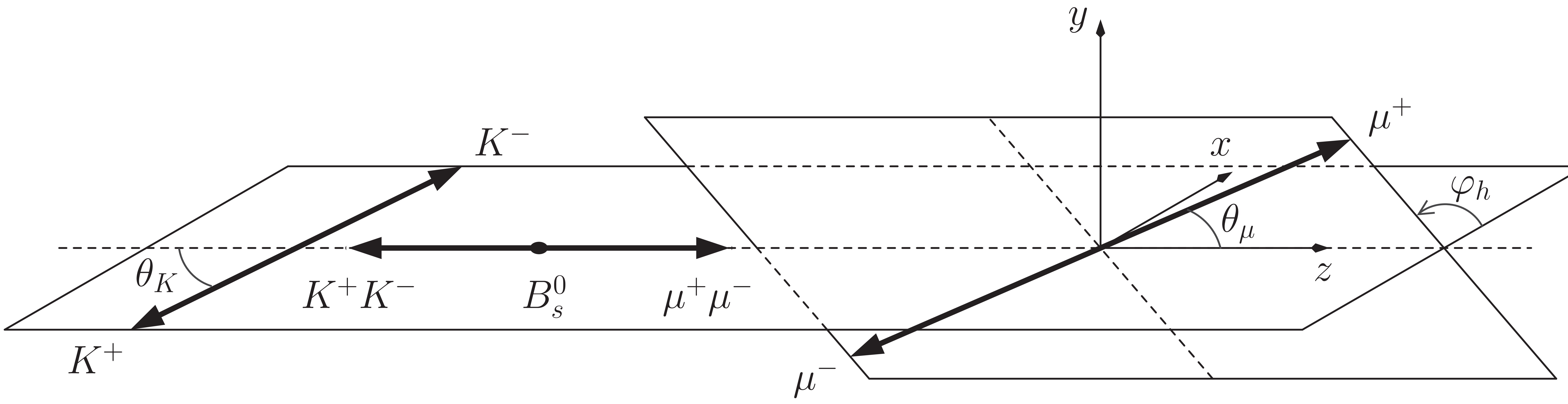
[Descotes-Genon et al., http://arxiv.org/abs/1307.5683](http://arxiv.org/abs/1307.5683)

$B_s \to J/\psi\pi\pi$ and $B_s \to J/\psi KK$







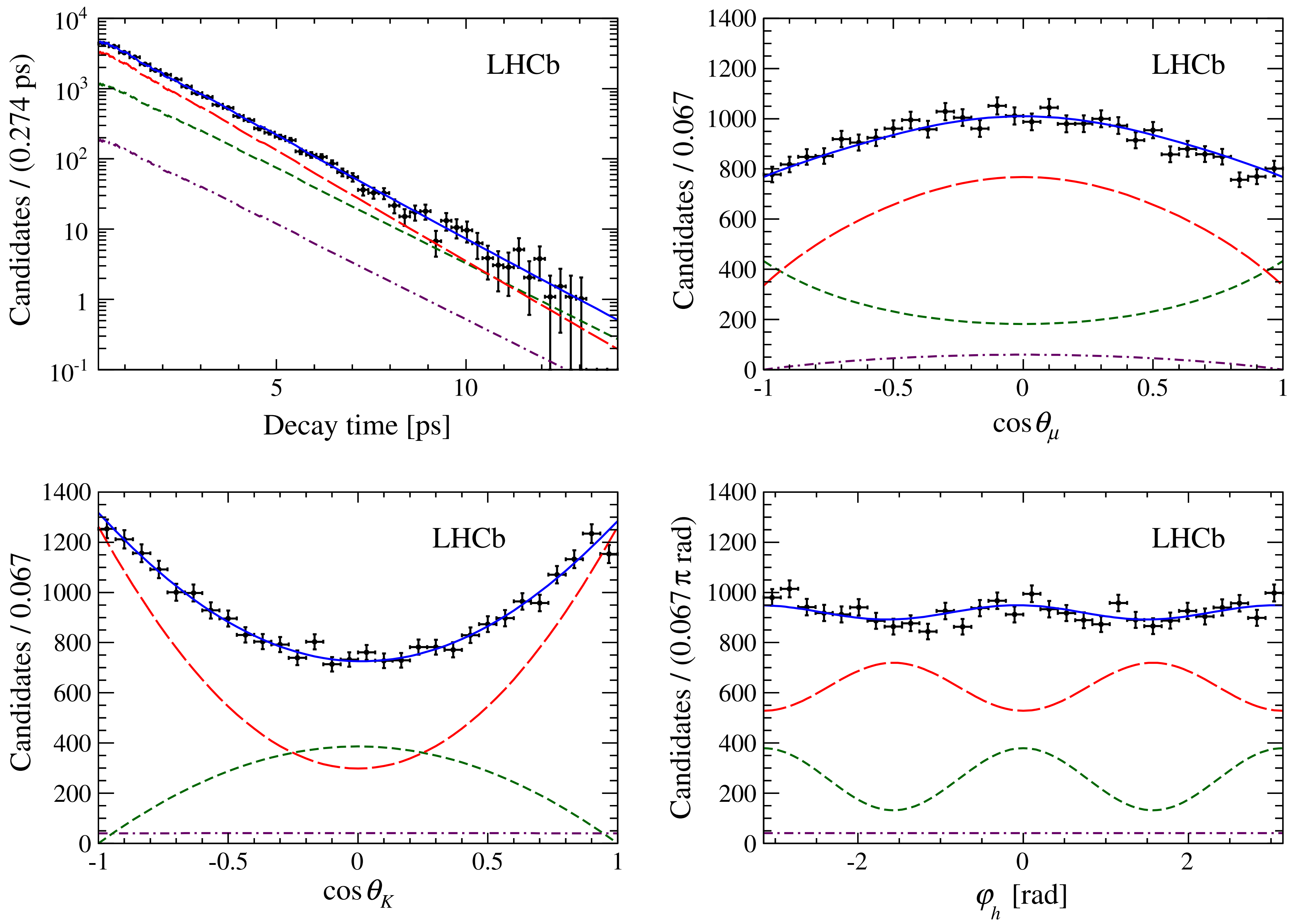


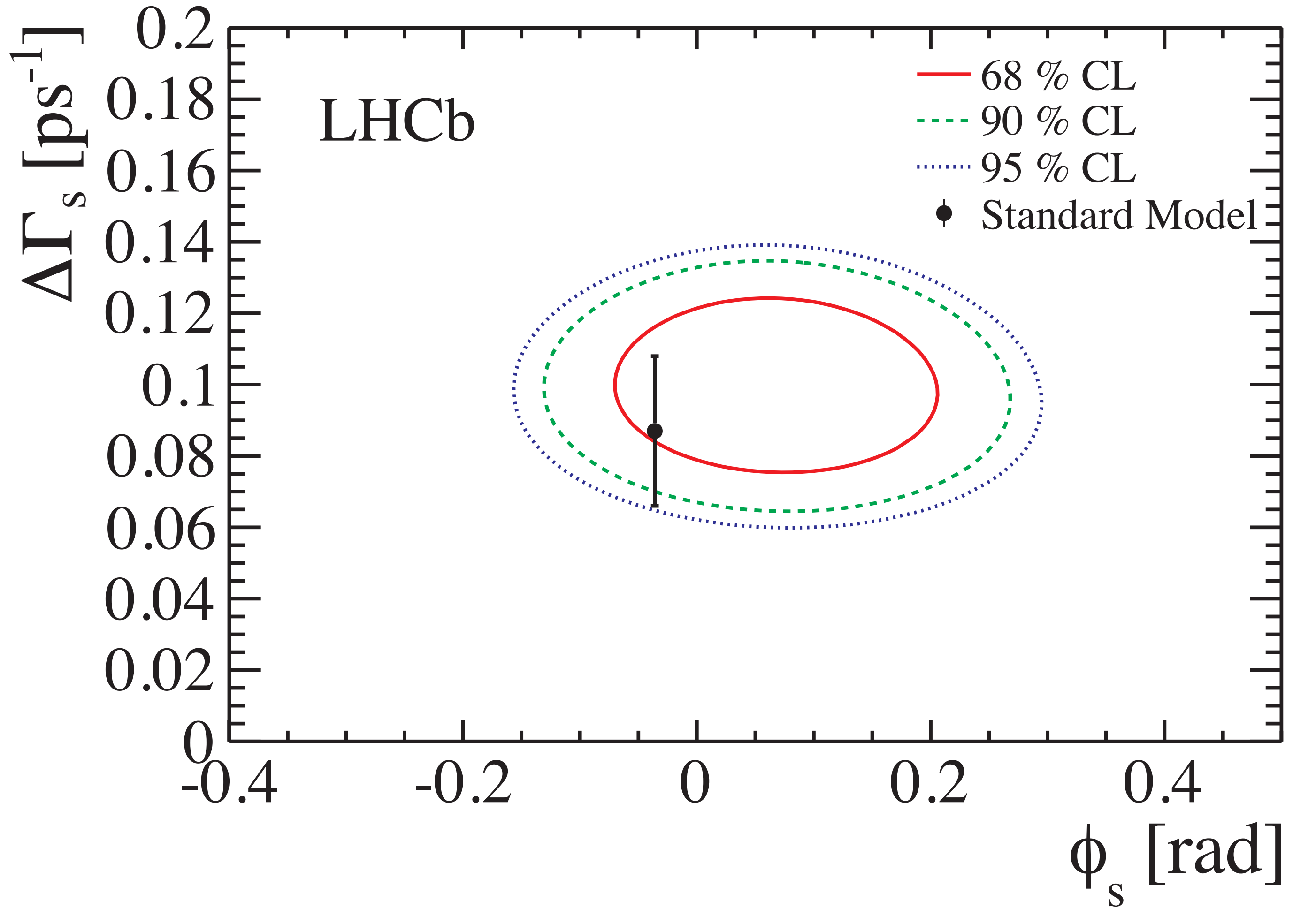
CPV in interference of decay and mixing

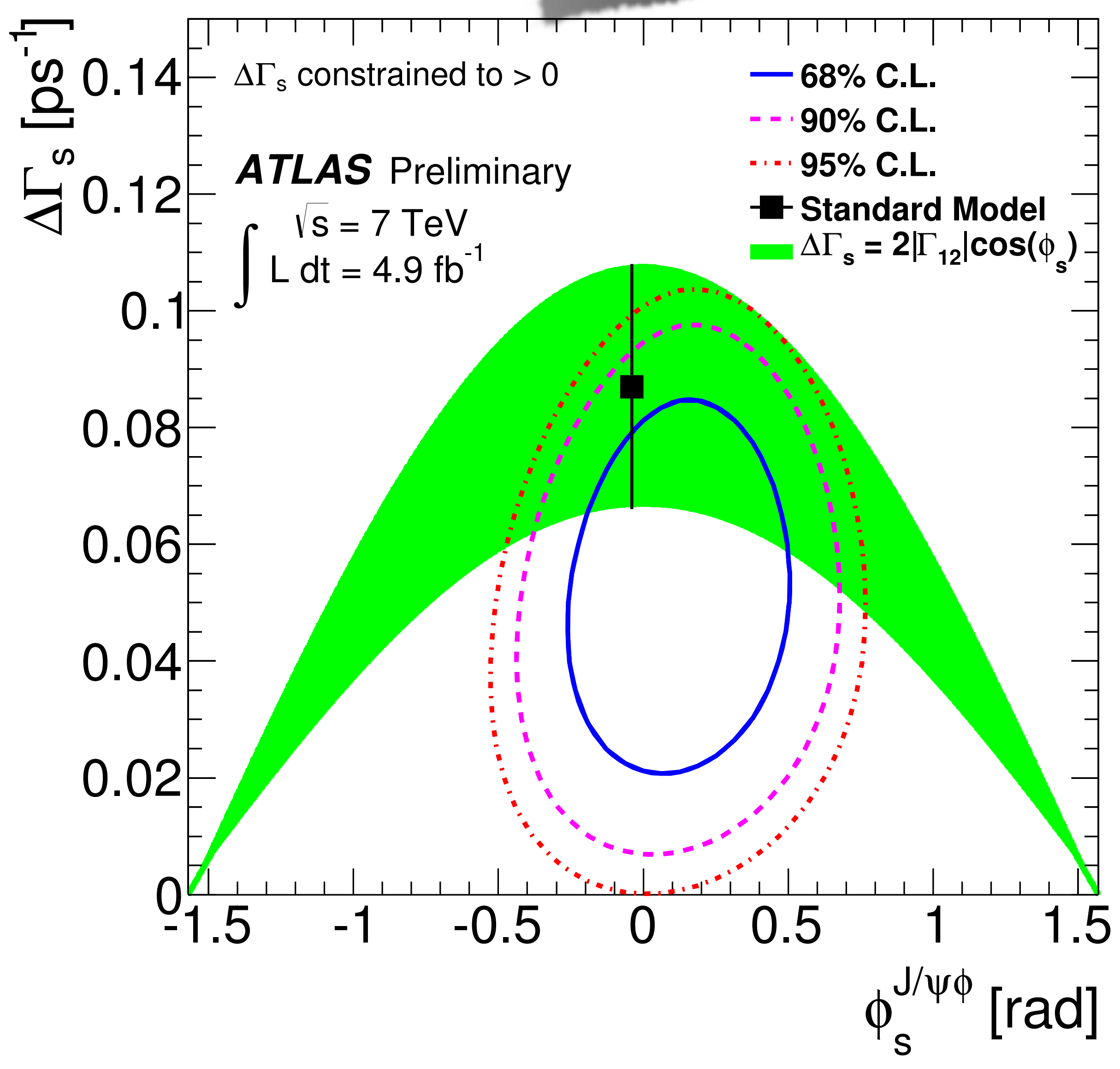
Everyone gets in on the act…

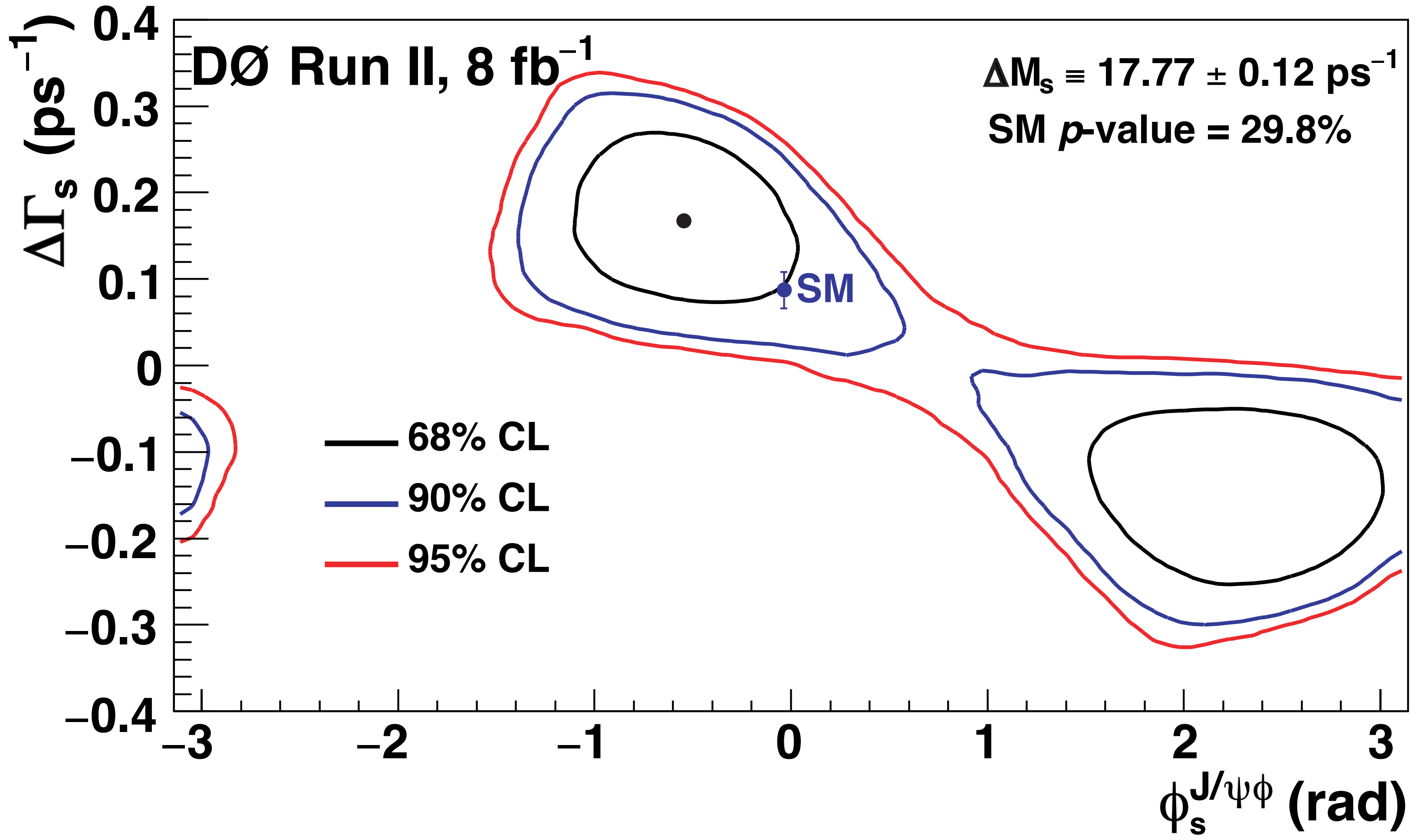
LHCb : PRD 87, 112010 (2013)
CMS : PAS-BPH-11-006
ATLAS : ATLAS-CONF-2013-039
CDF : 1208.2967v2
D0 : 1109.3166v2

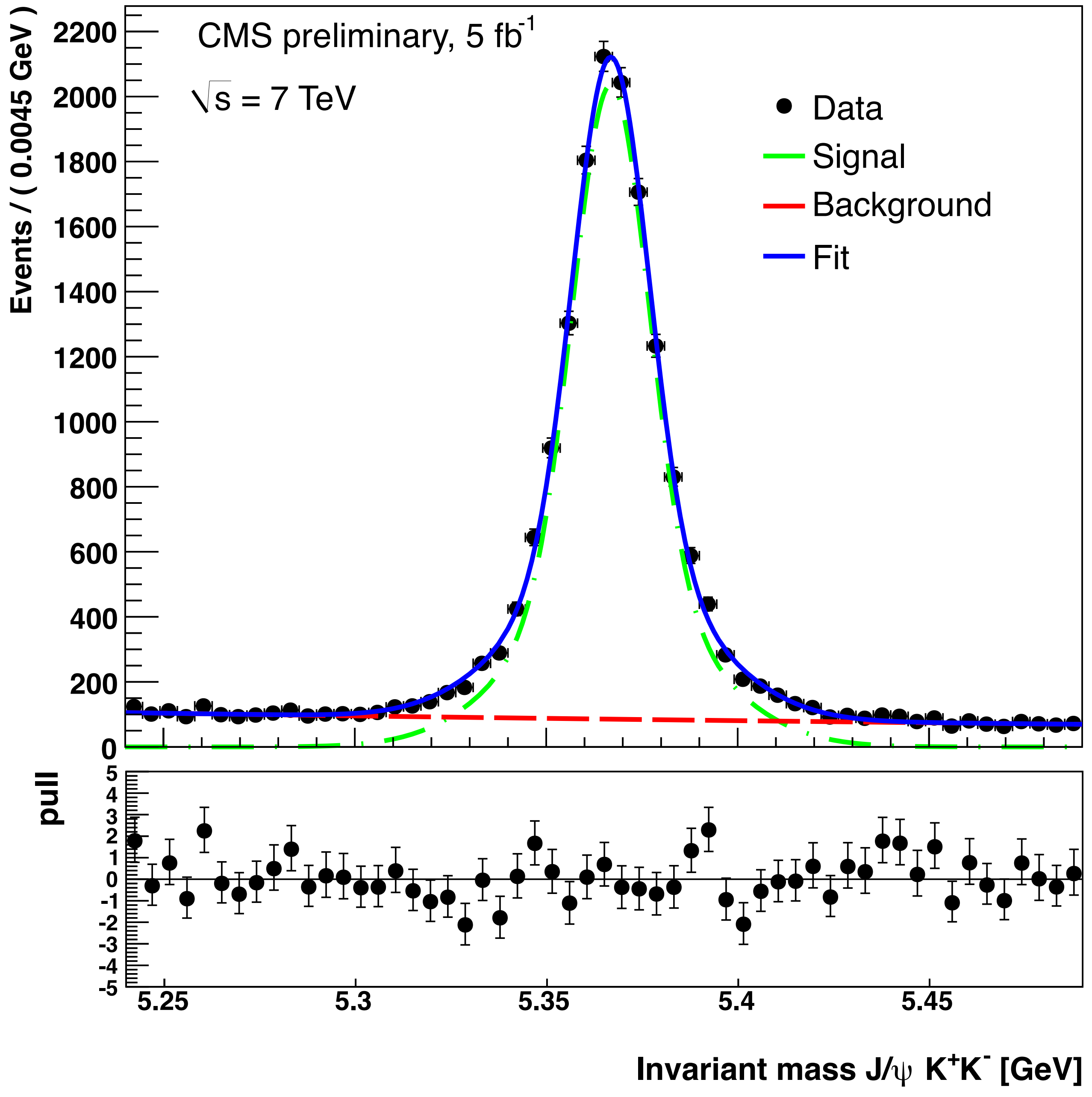
▶ CP-even ▶ CP-odd ▶ S-wave

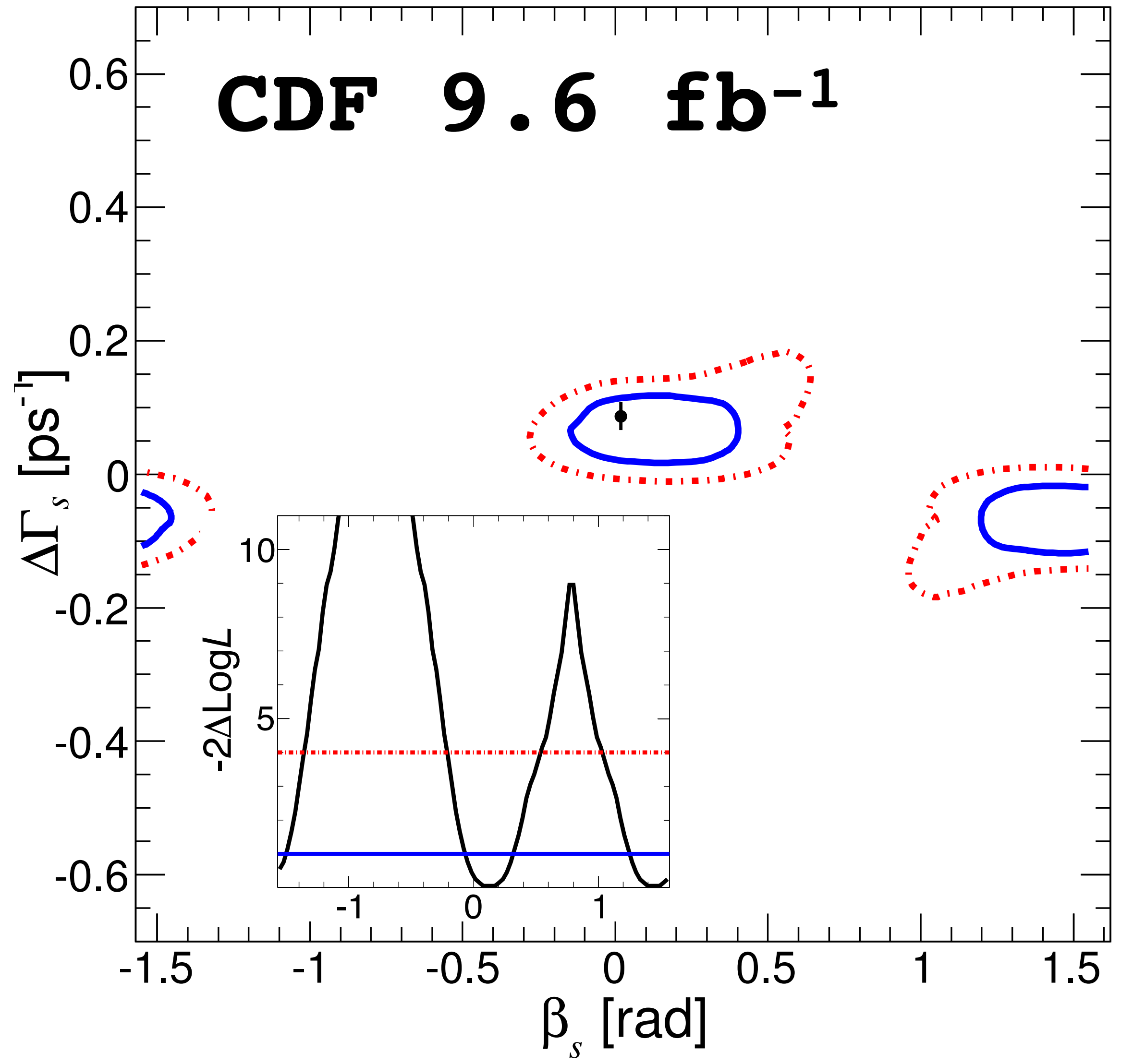




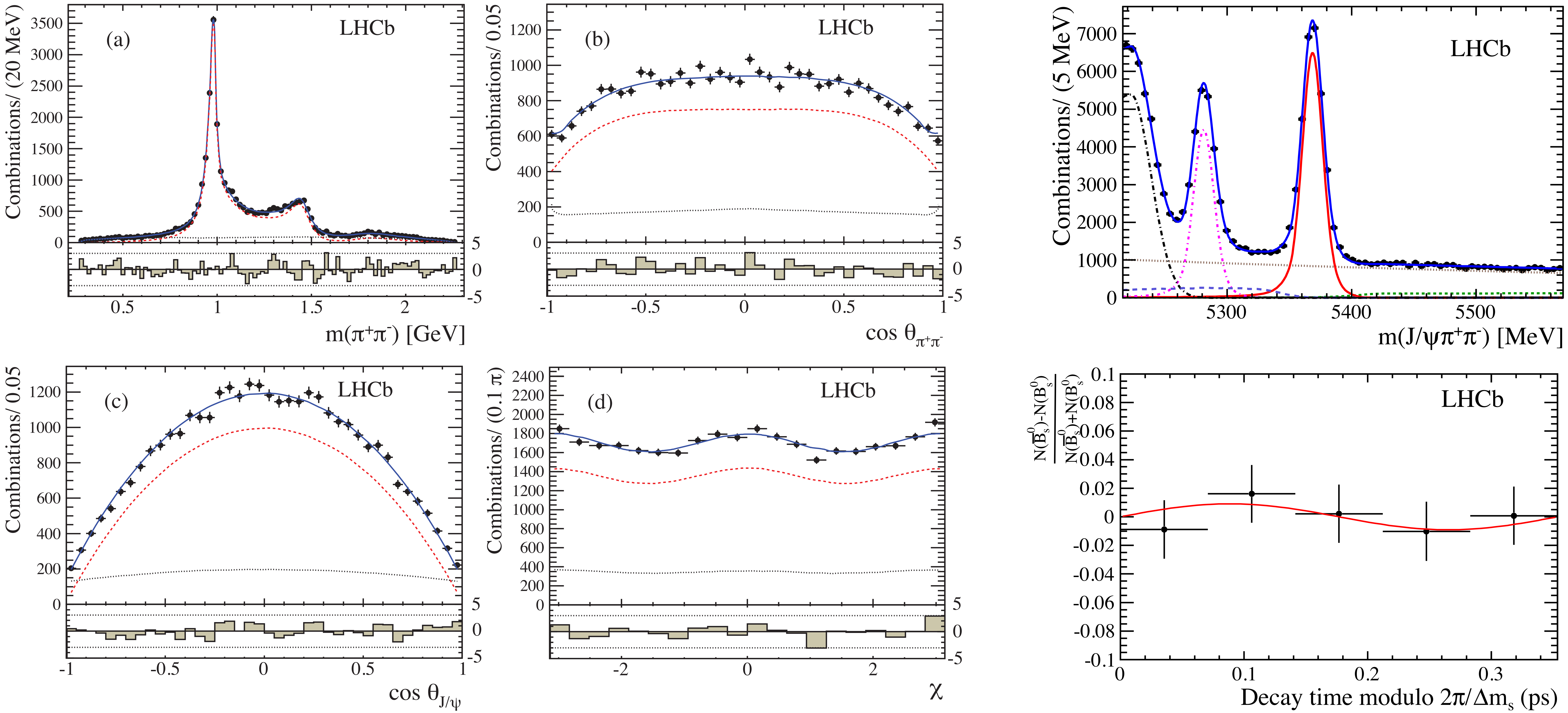








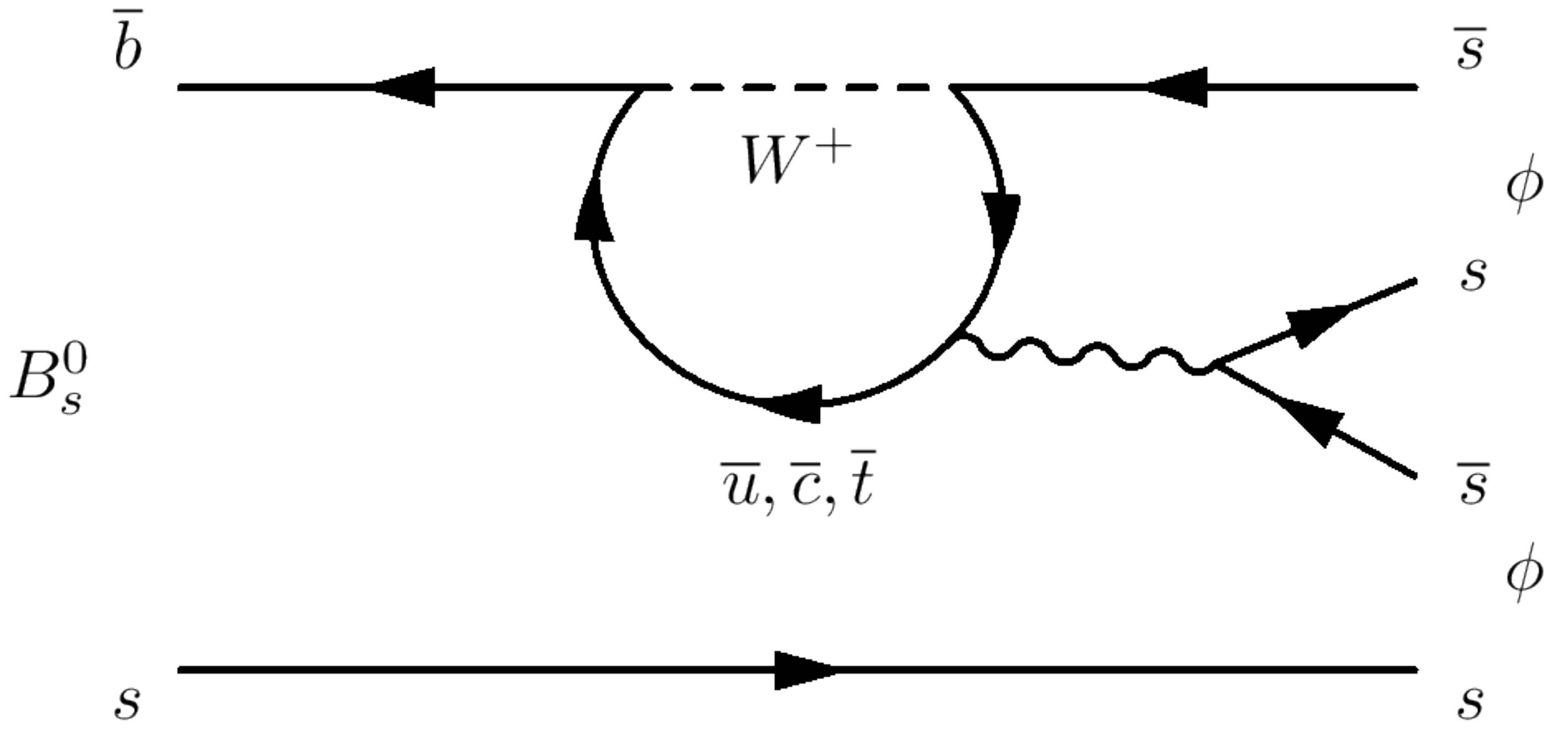
3 fb^{-1} $B_s \to J/\psi\pi\pi$, hot off the press

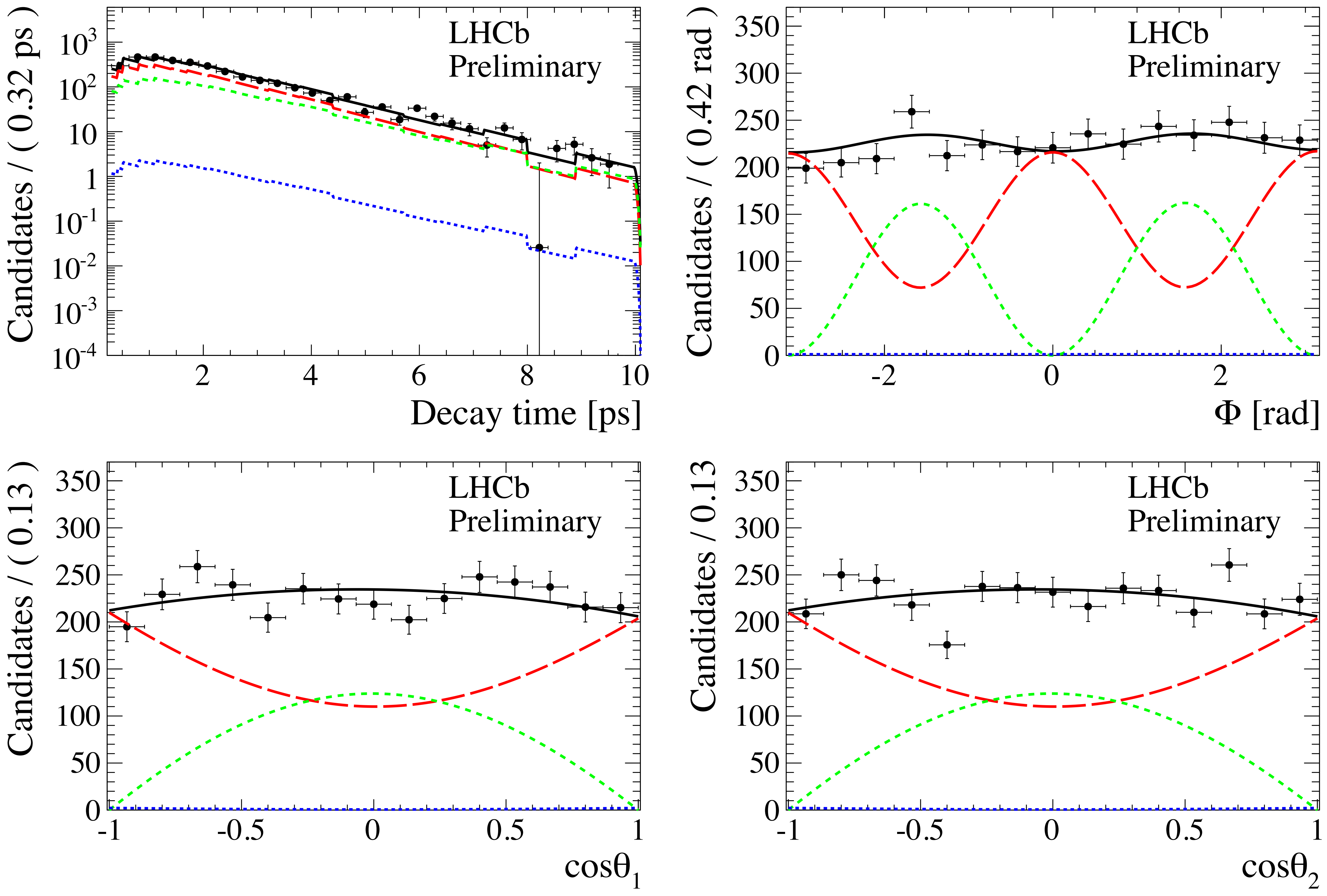


$$\phi_s = 70 \pm 68 \pm 8 \text{ mrad}, \ |\lambda| = 0.89 \pm 0.05 \pm 0.01.$$

http://arxiv.org/pdf/1405.4140.pdf

3 fb^{-1} $B_s \rightarrow \varphi\varphi$, hot off the press





Interference of decay and mixing means predicted CPV in SM is ~0

Hence an excellent null test

Also experimentally "golden", as it is almost background free => like an honorary dimuon!

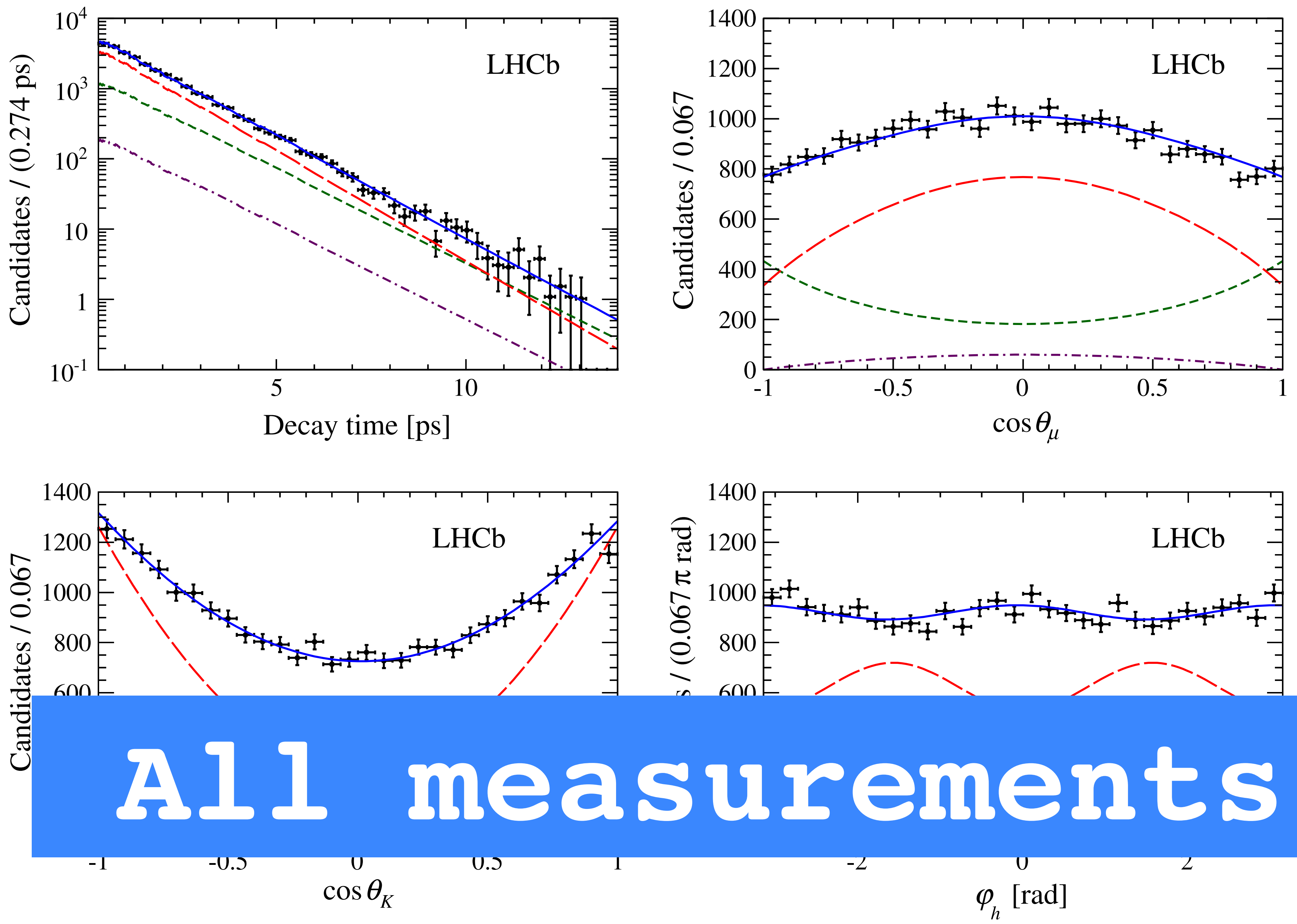
$$\phi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst}),$$
$$\lambda = 1.04 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst}).$$

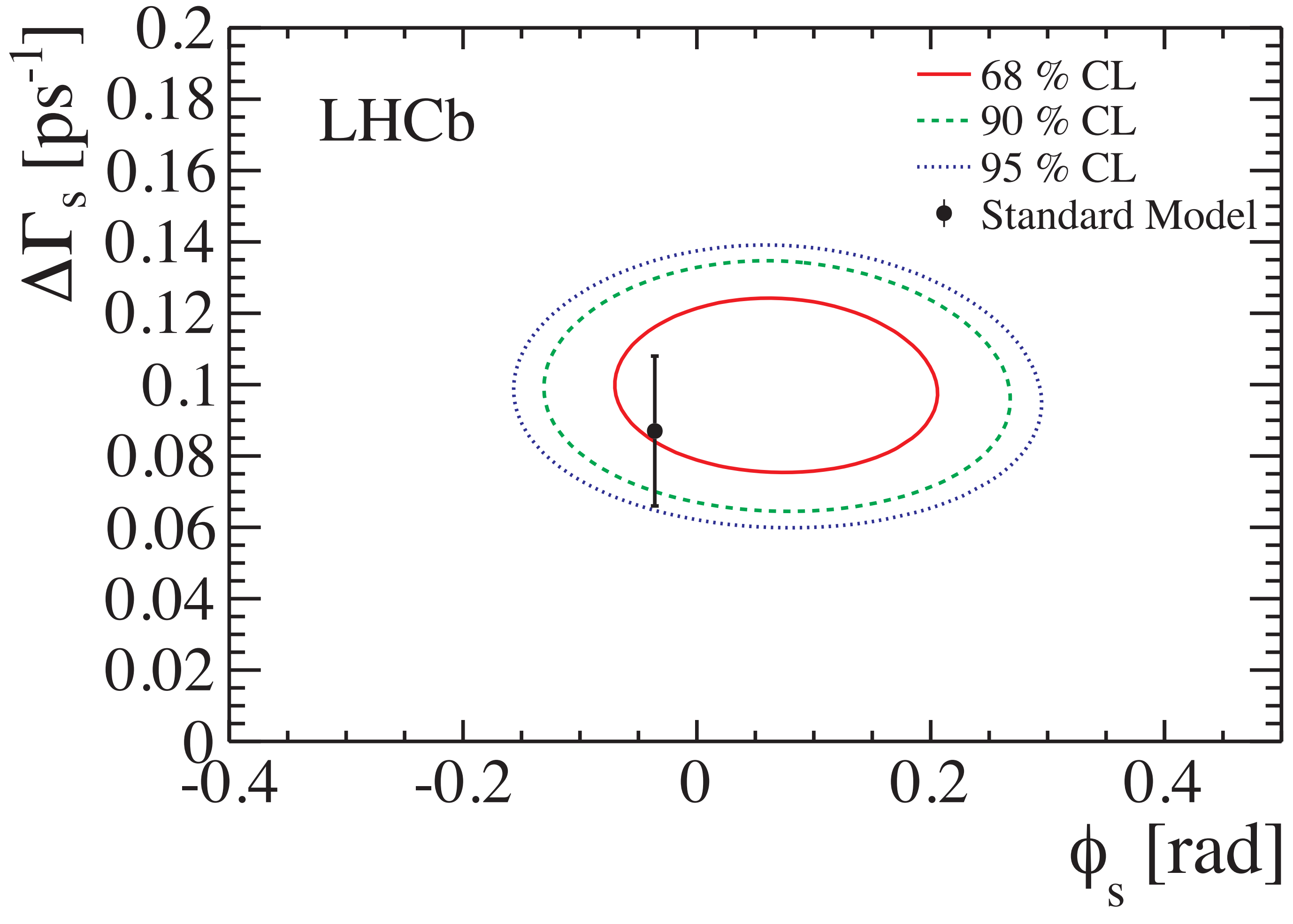
LHCb-PAPER-2014-026

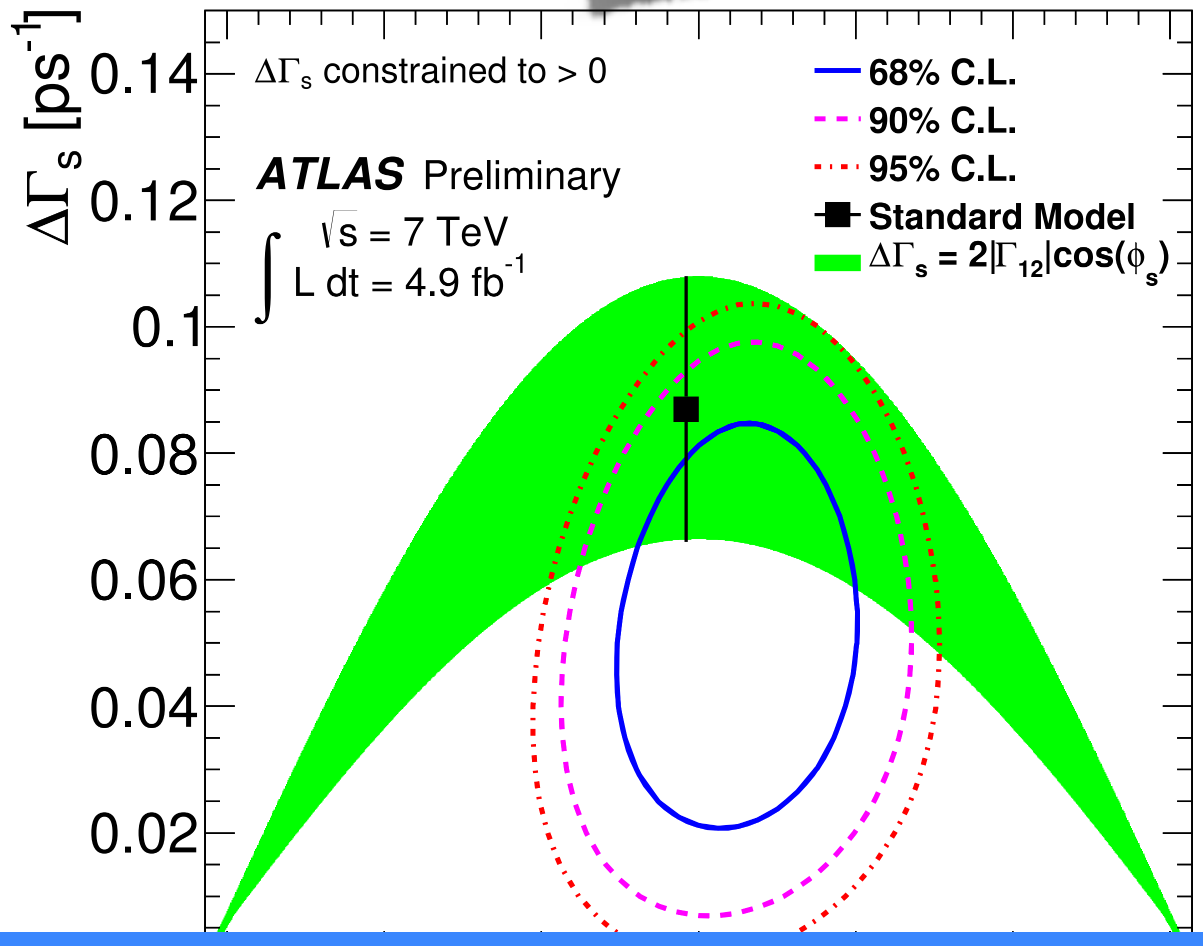
Summary of φ_s status

LHCb : PRD 87, 112010 (2013)
CMS : PAS-BPH-11-006
ATLAS : ATLAS-CONF-2013-039
CDF : 1208.2967v2
D0 : 1109.3166v2

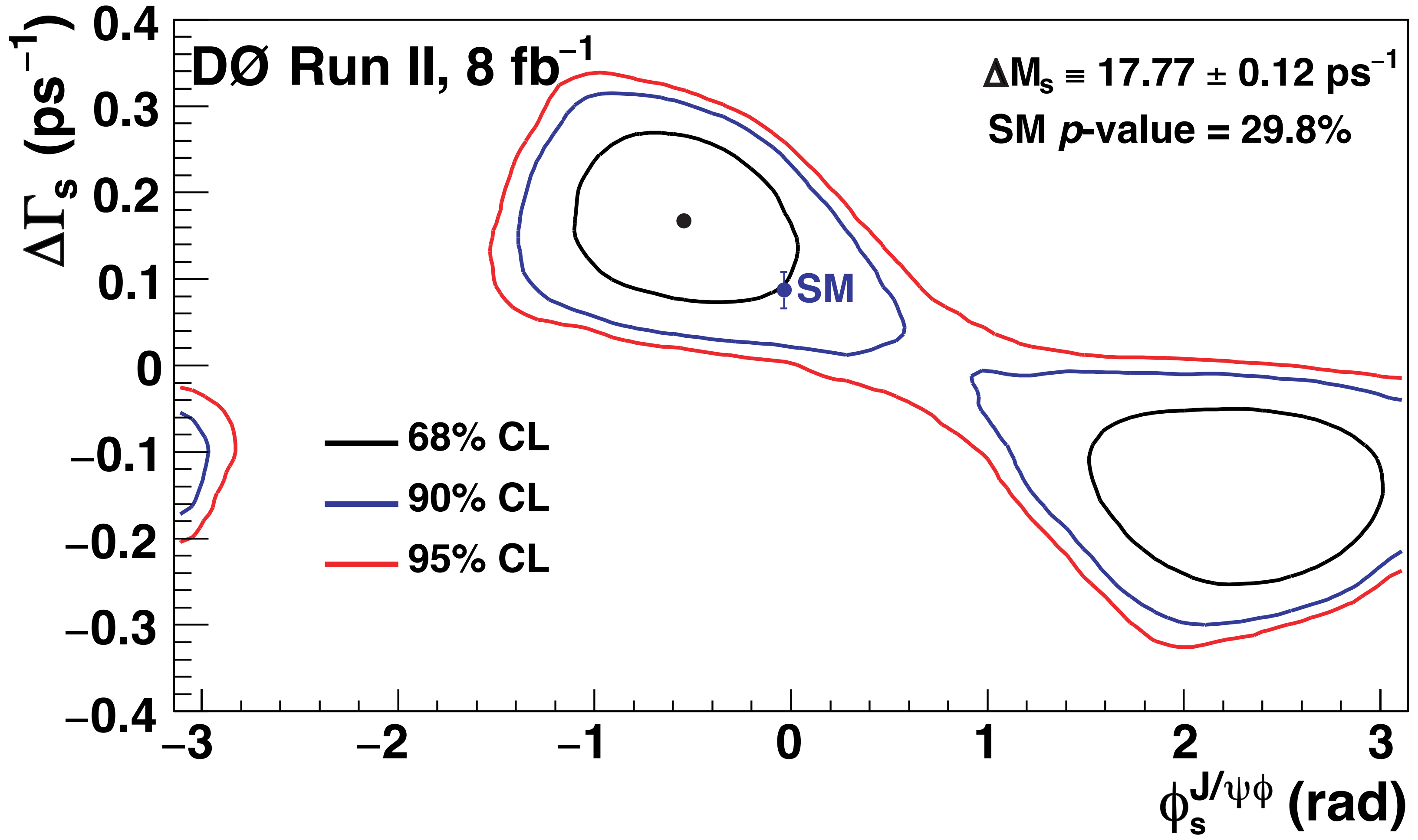
▶ CP-even ▶ CP-odd ▶ S-wave

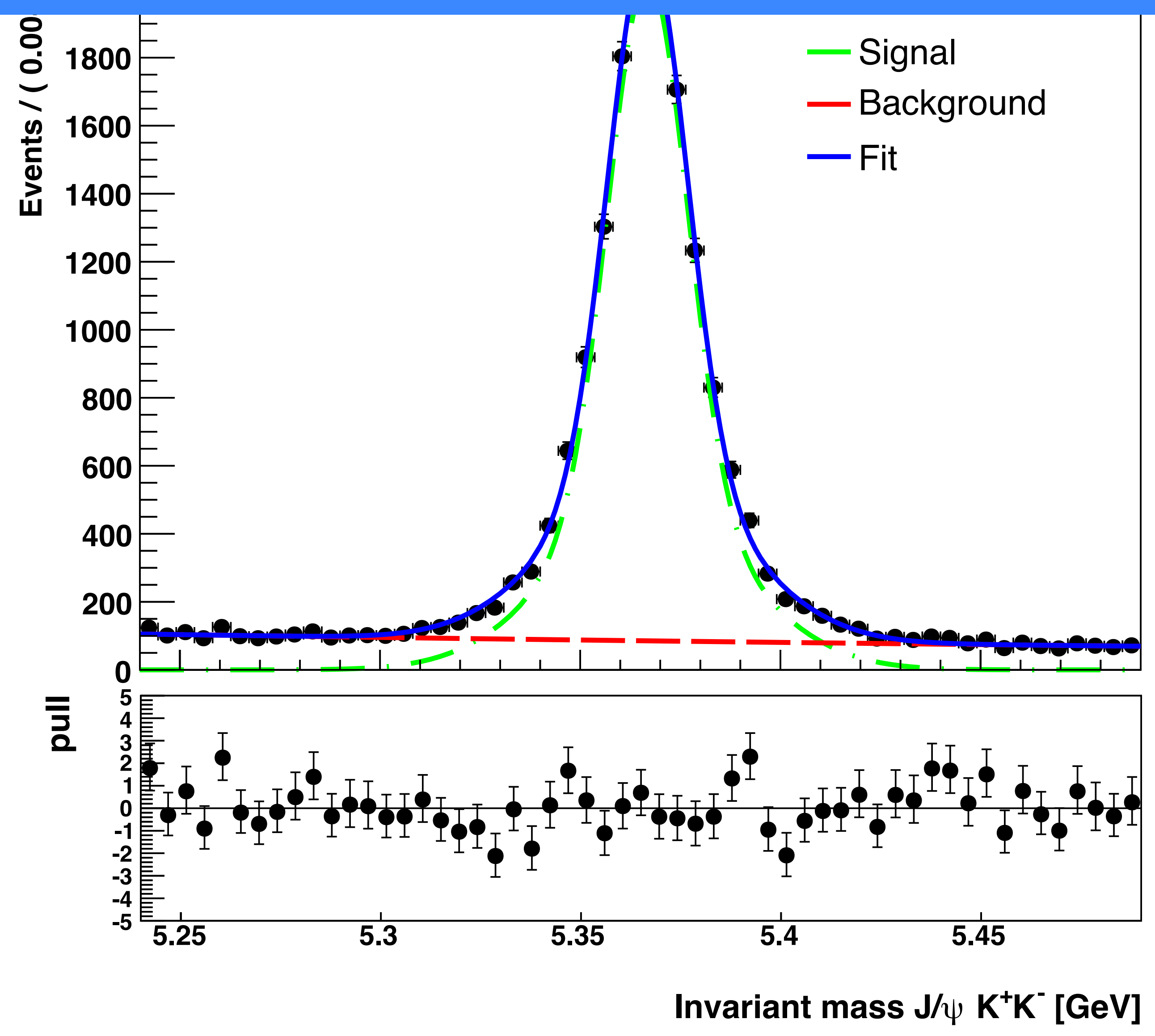


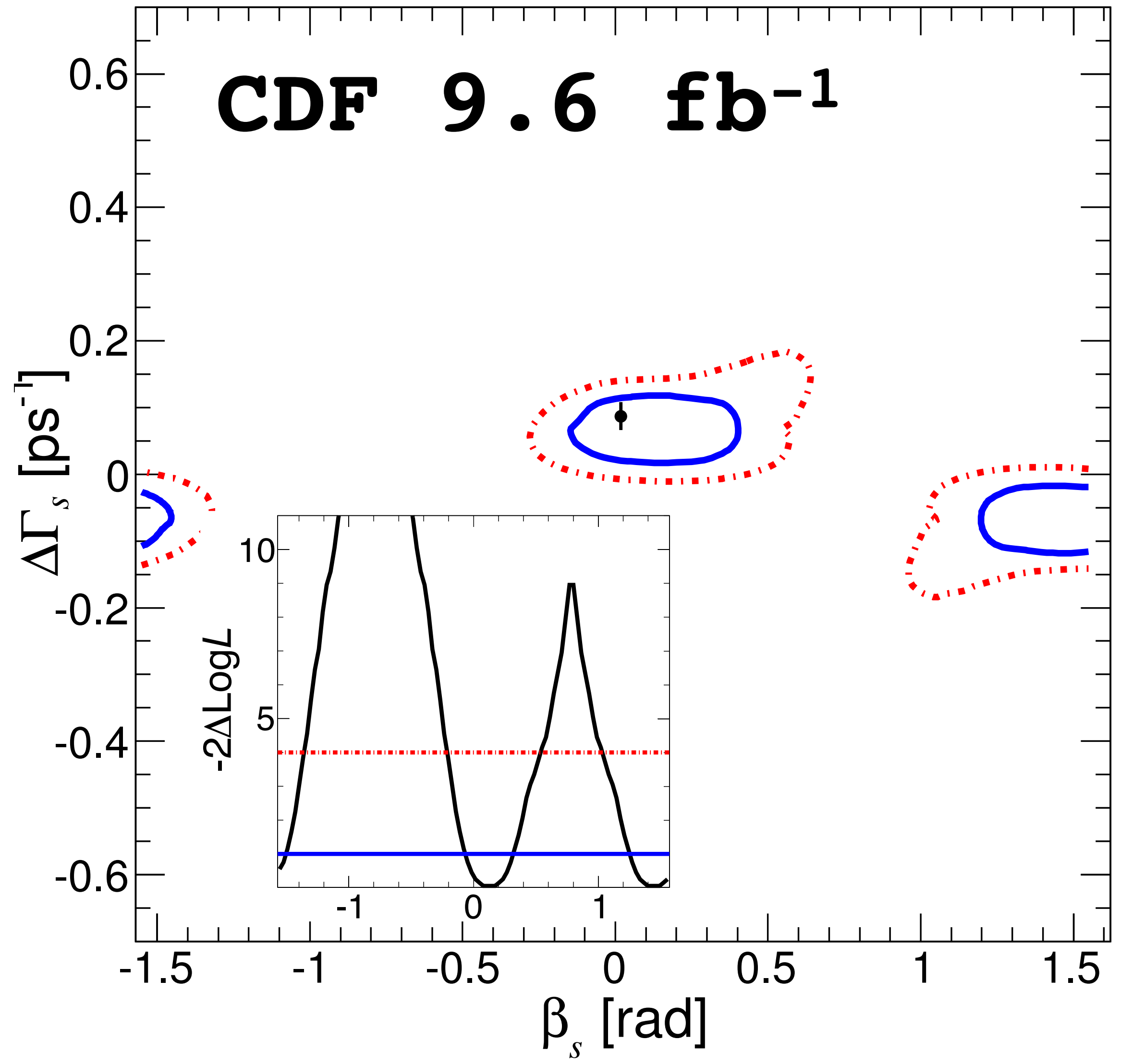




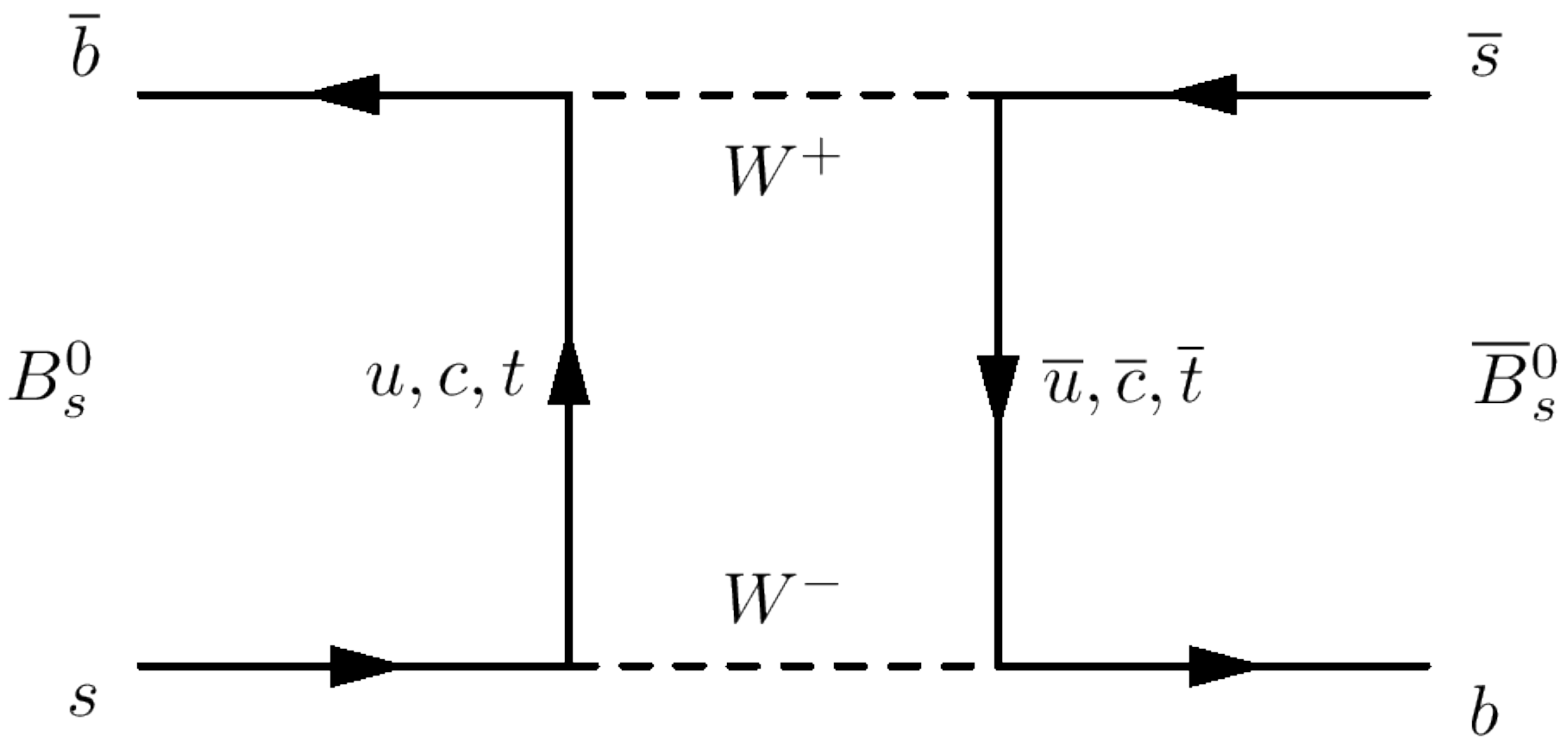
All measurements happily agree with the SM

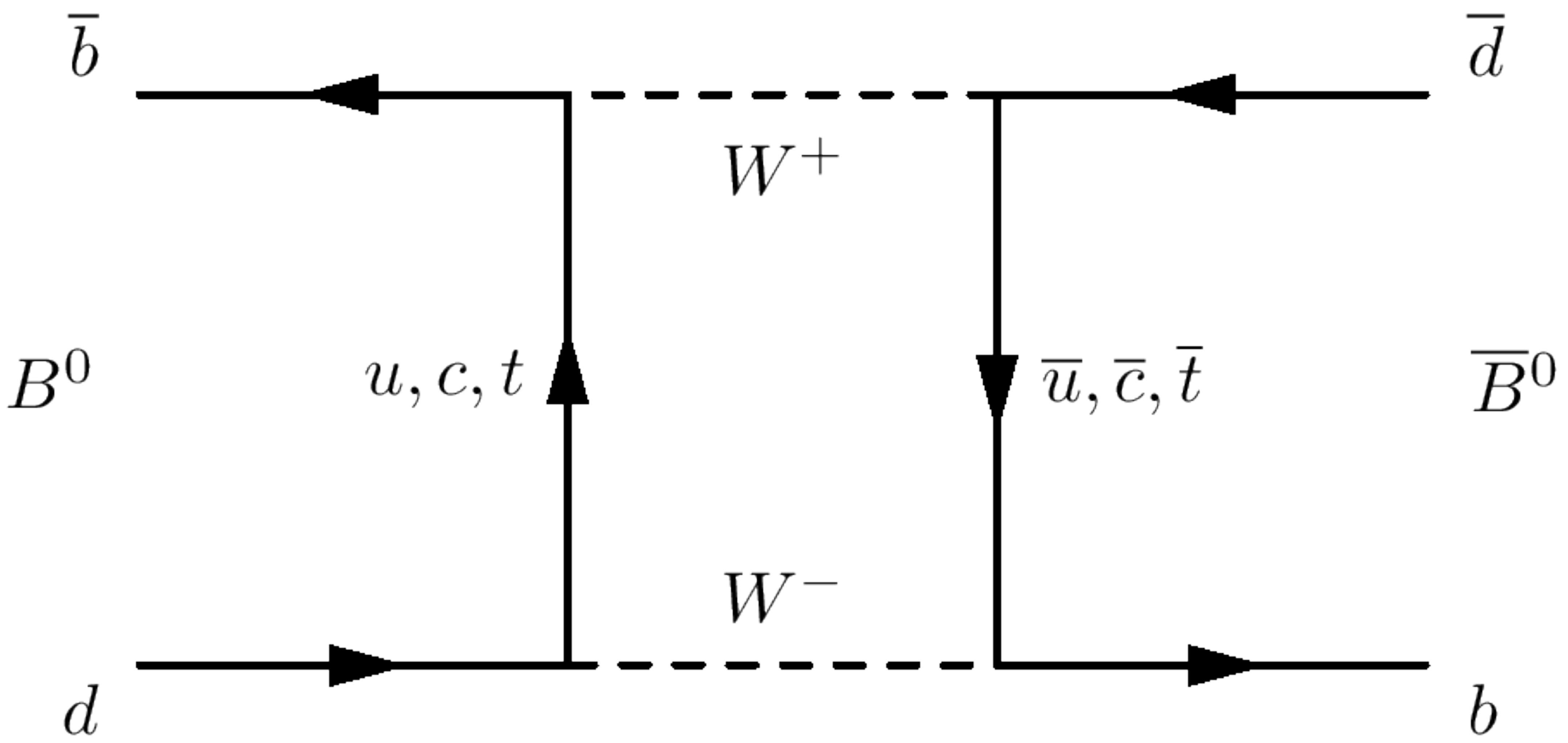






Another way of looking at mixing





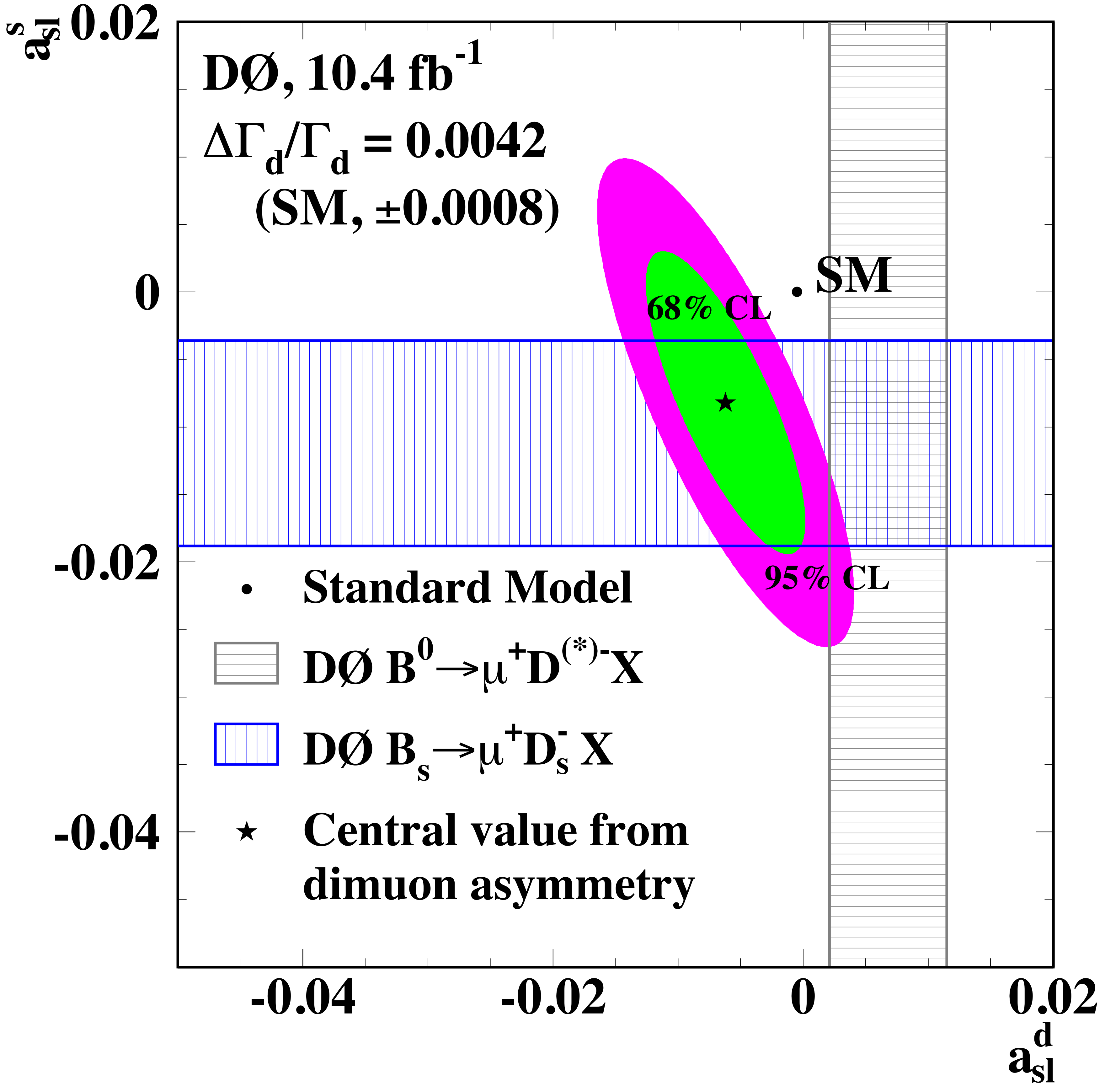
CPV in mixing essentially 0 in SM

=> Measure using B→DμX decays

=> Another excellent null test

The A_{SL} anomaly…

http://arxiv.org/pdf/1310.0447v1.pdf



D0 results 3.6σ away from the Standard Model...

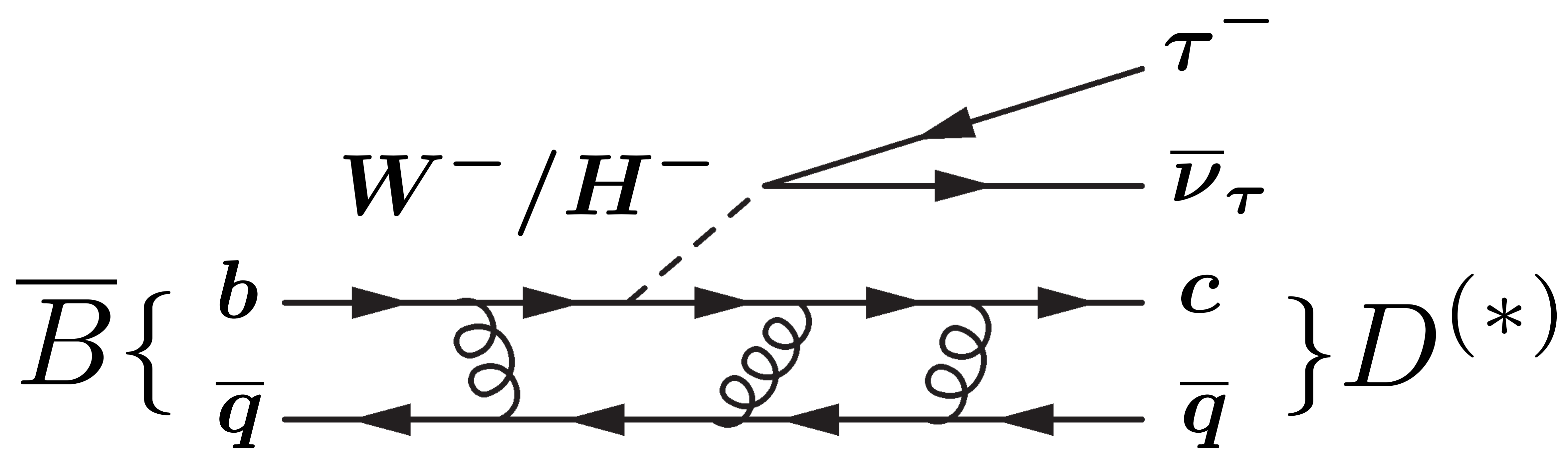
…or the Standard Model?

http://arxiv.org/pdf/1310.0447v1.pdf

…but global agreement with Standard Model at 1.5σ

Taus are leptons too

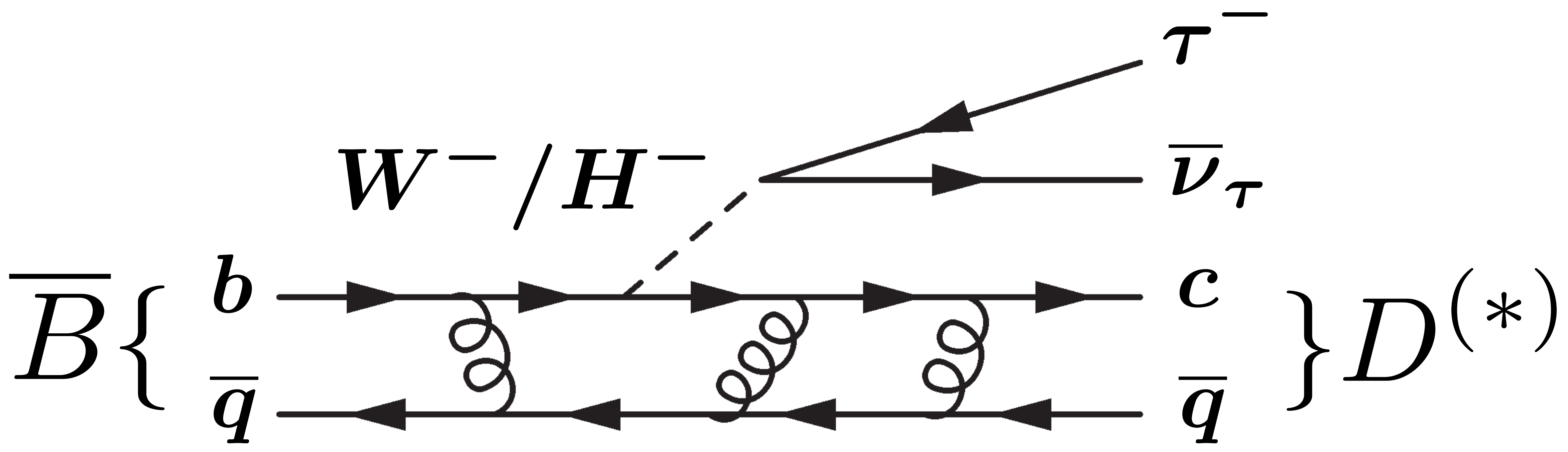
http://arxiv.org/pdf/1303.0571v1.pdf

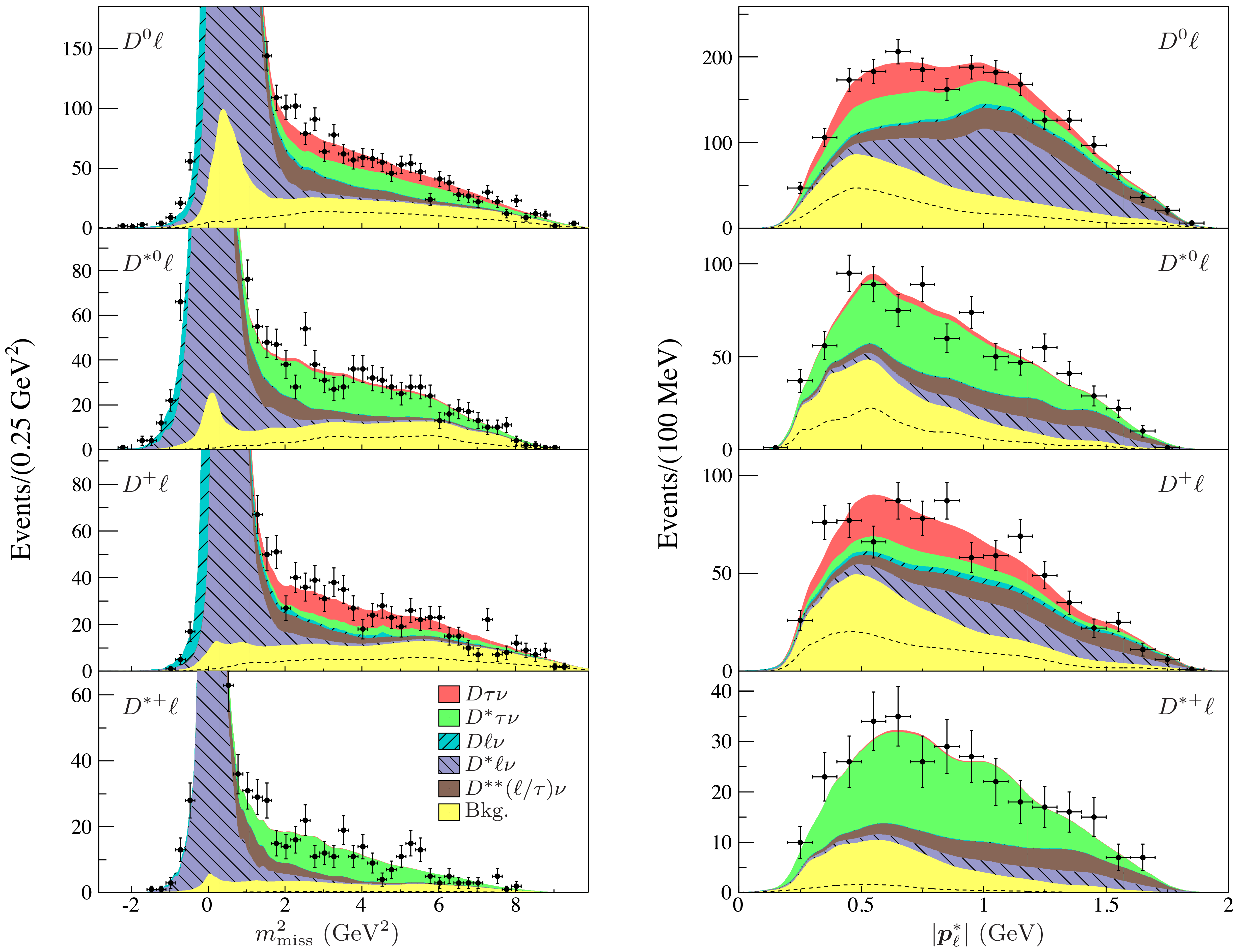


Charged Higgs contributions affect $D\tau\nu$ and $D^*\tau\nu$ differently

Taus are leptons too

http://arxiv.org/pdf/1303.0571v1.pdf

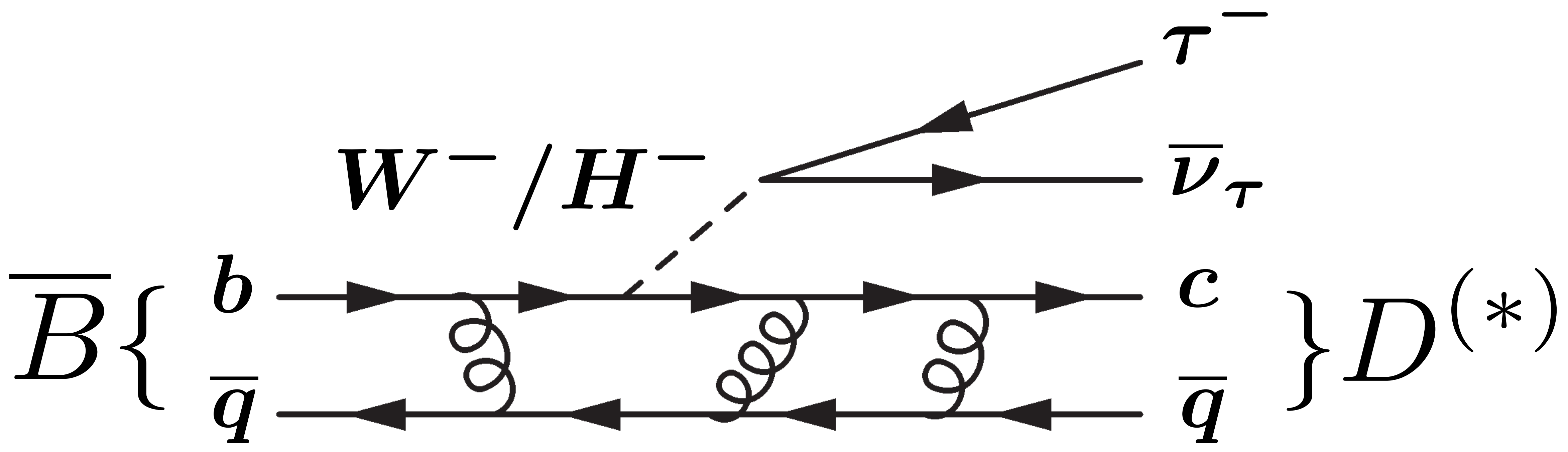


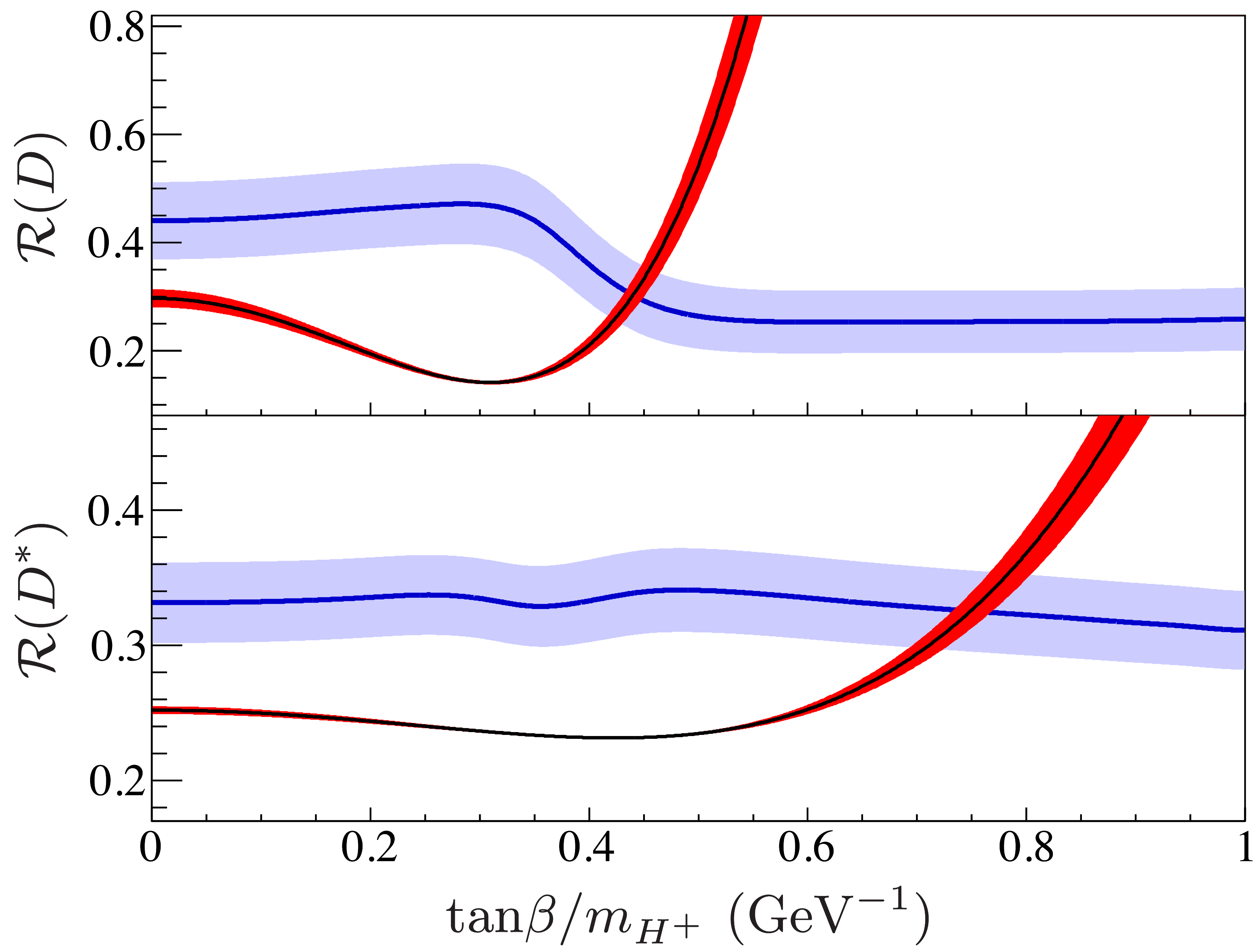


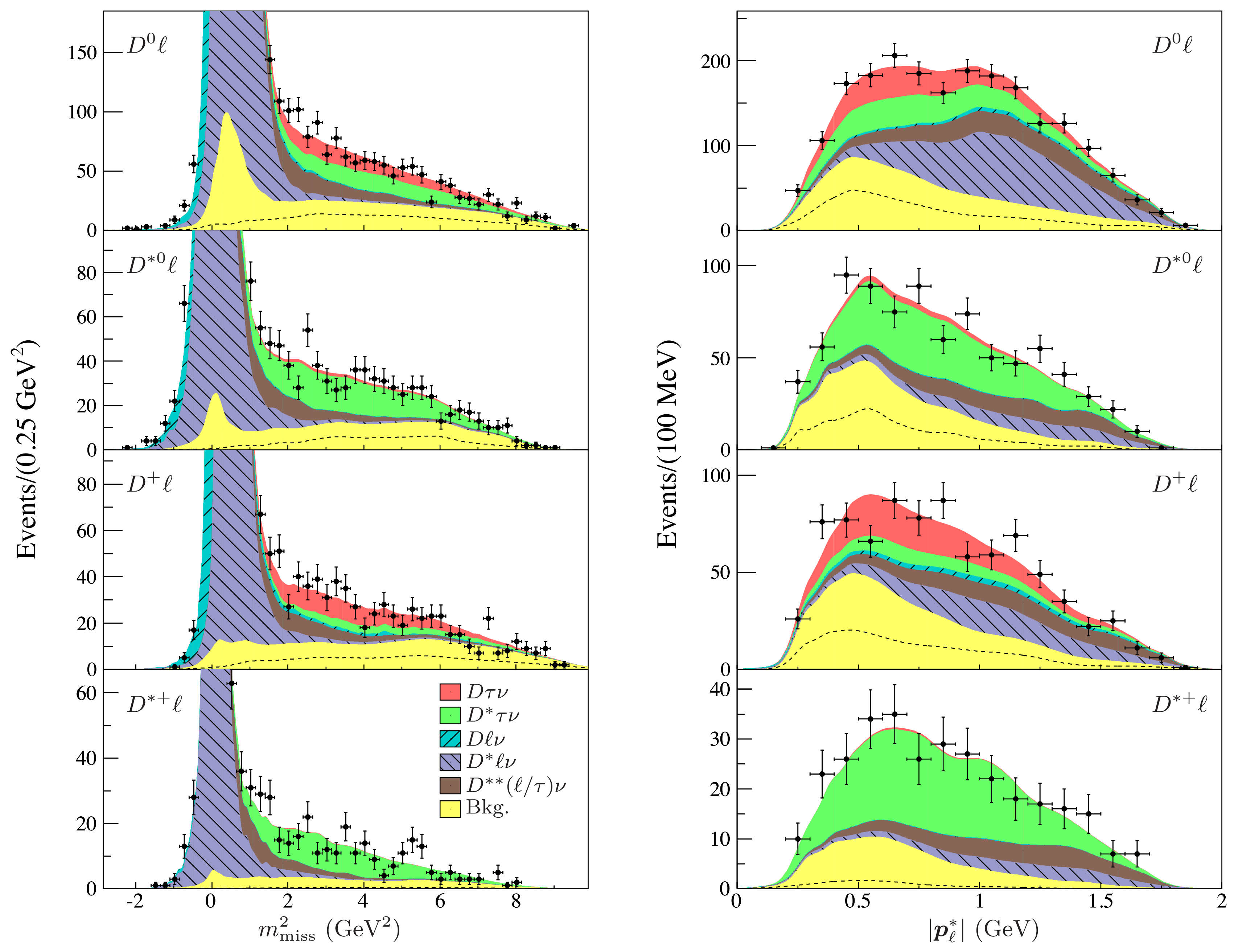
Challenging analysis, significant backgrounds even at B-factories

Taus are leptons too

http://arxiv.org/pdf/1303.0571v1.pdf







Measurement	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
Belle 2007 [13]	—	$0.44 \pm 0.08 \pm 0.08$
BABAR 2008 [14]	$0.42 \pm 0.12 \pm 0.05$	$0.30 \pm 0.06 \pm 0.02$
Belle 2009 [15]	$0.59 \pm 0.14 \pm 0.08$	$0.47 \pm 0.08 \pm 0.06$
Belle 2010 [16]	$0.34 \pm 0.10 \pm 0.06$	$0.43 \pm 0.06 \pm 0.06$

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042,$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018,$$

Results 3.4σ away from SM but also exclude type II 2HDM

The up sector

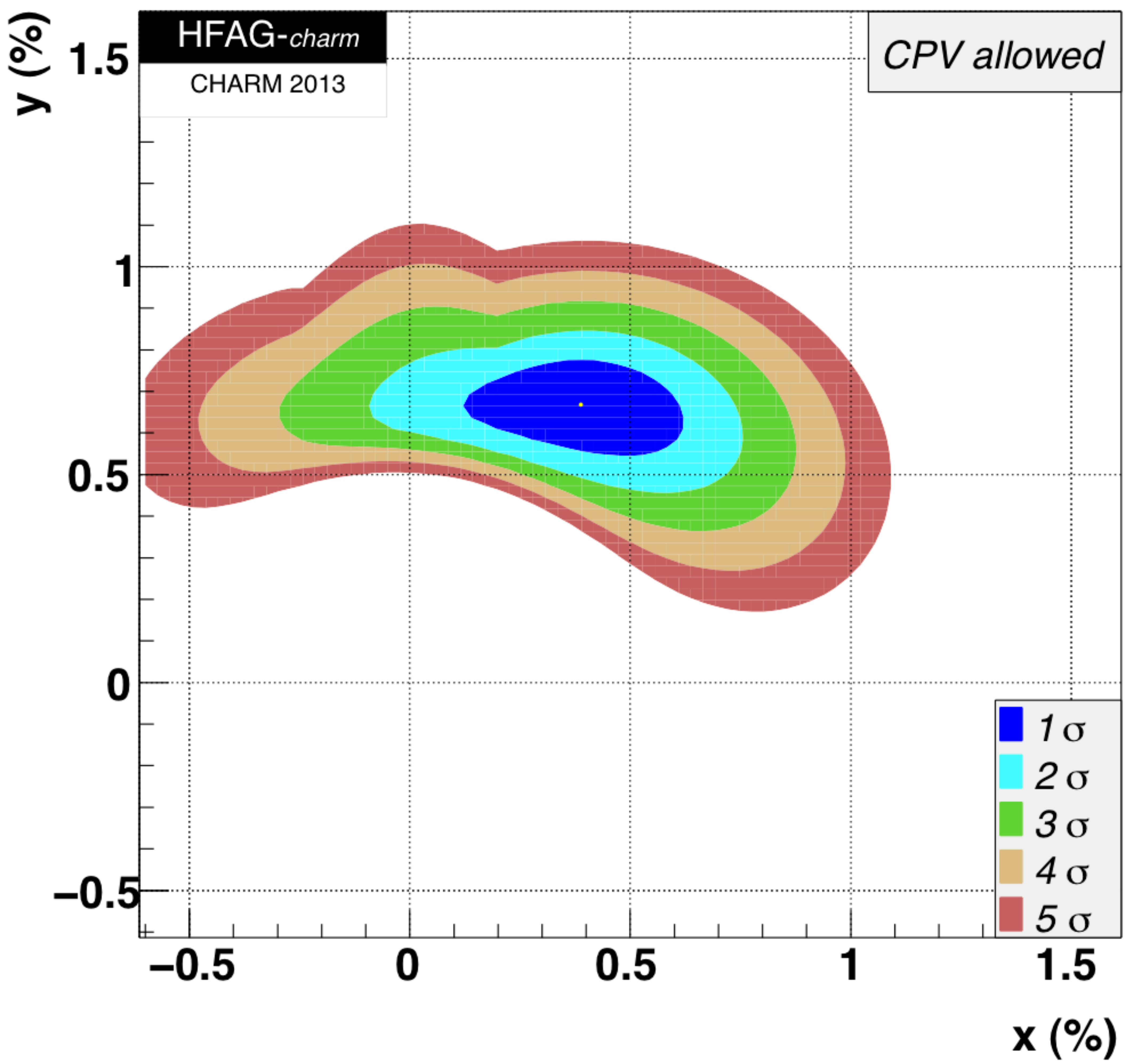
Setting the scene

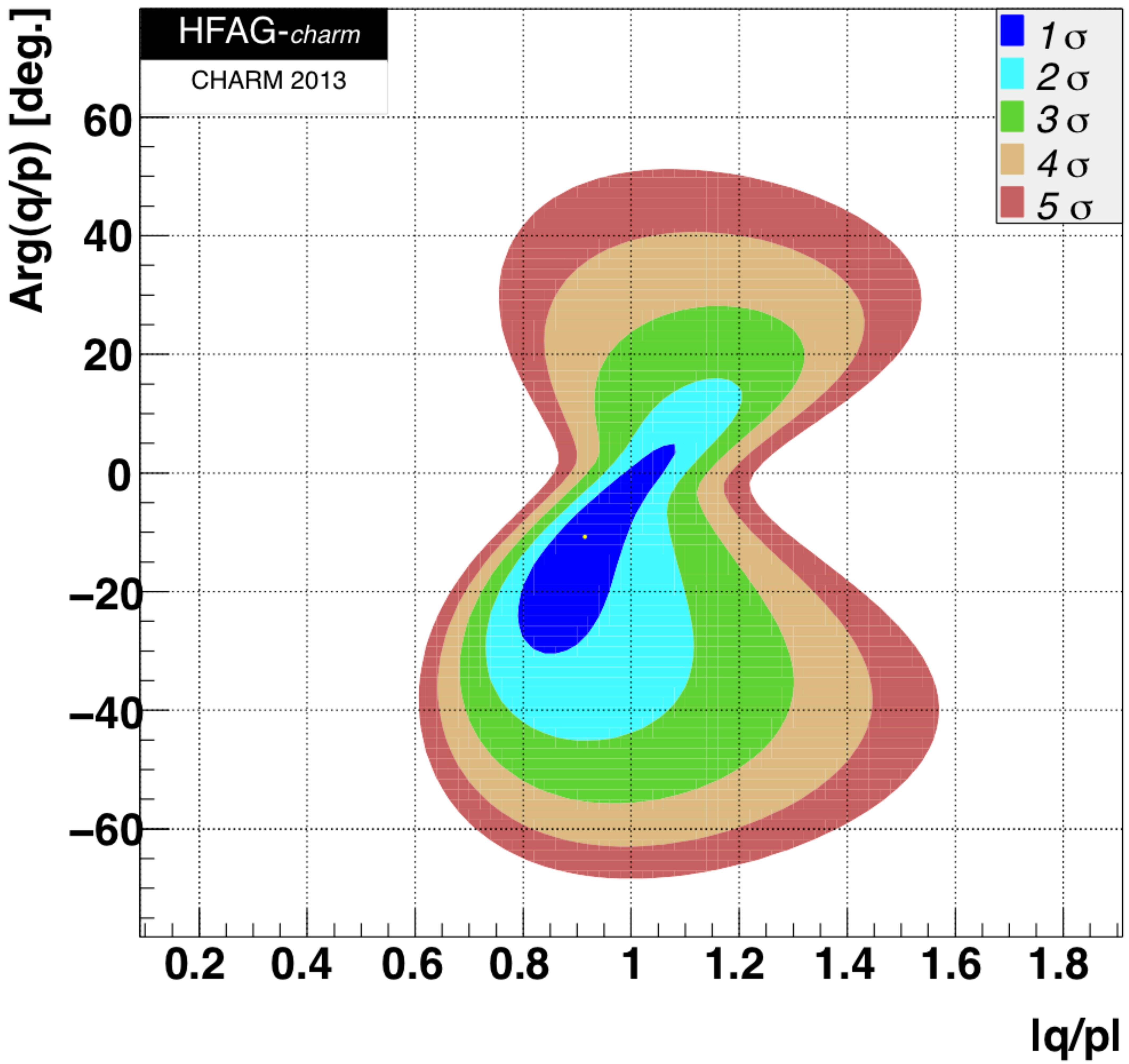
$$\mathbf{V_{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \sum_{n=4}^{N} O(\lambda^n)$$

First two gen. matrix real, so charm CPV highly suppressed in SM

Top mass >> mass of other quarks, NP preferentially couples to top

Overall picture of charm mixing/CPV

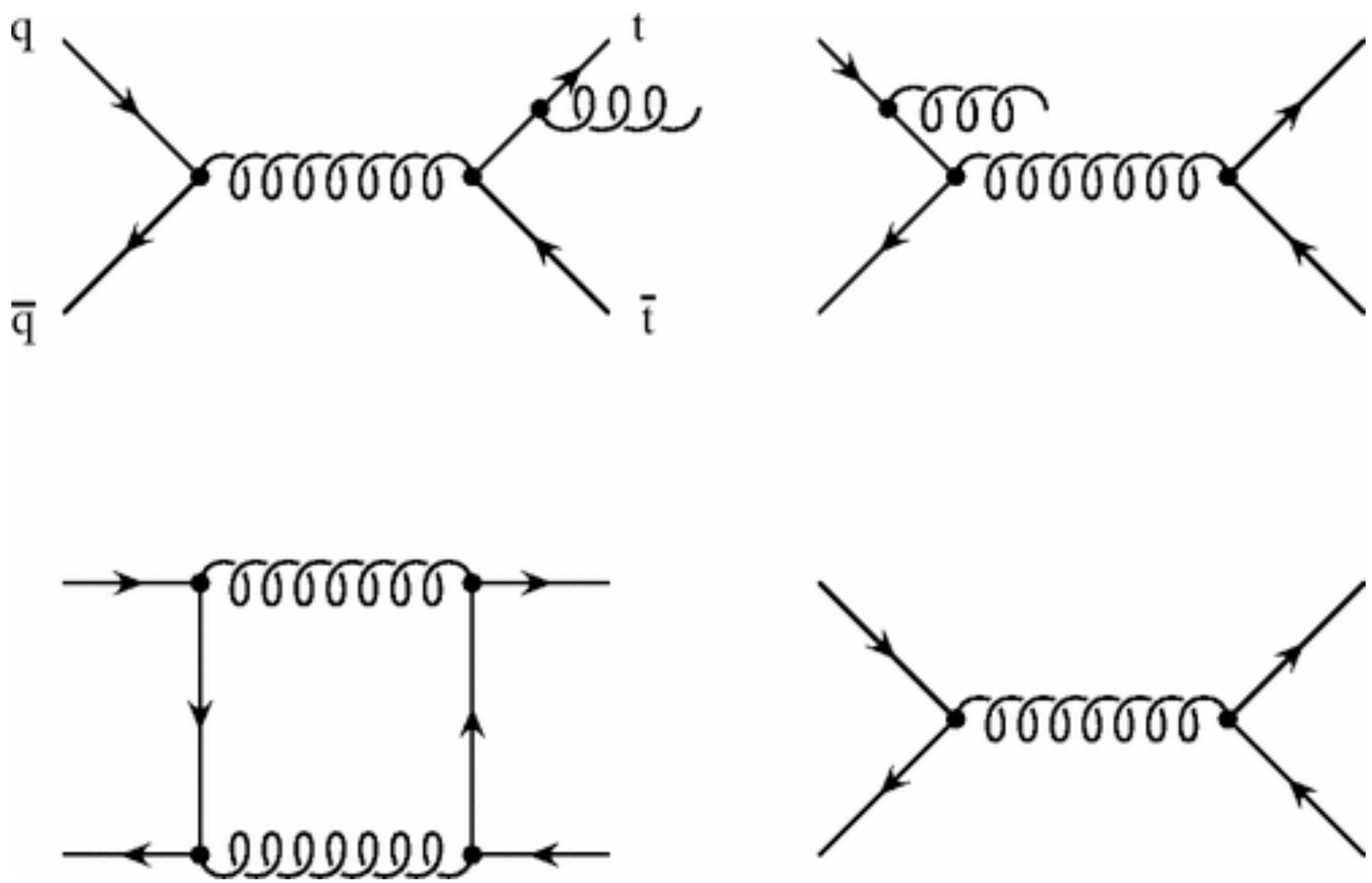


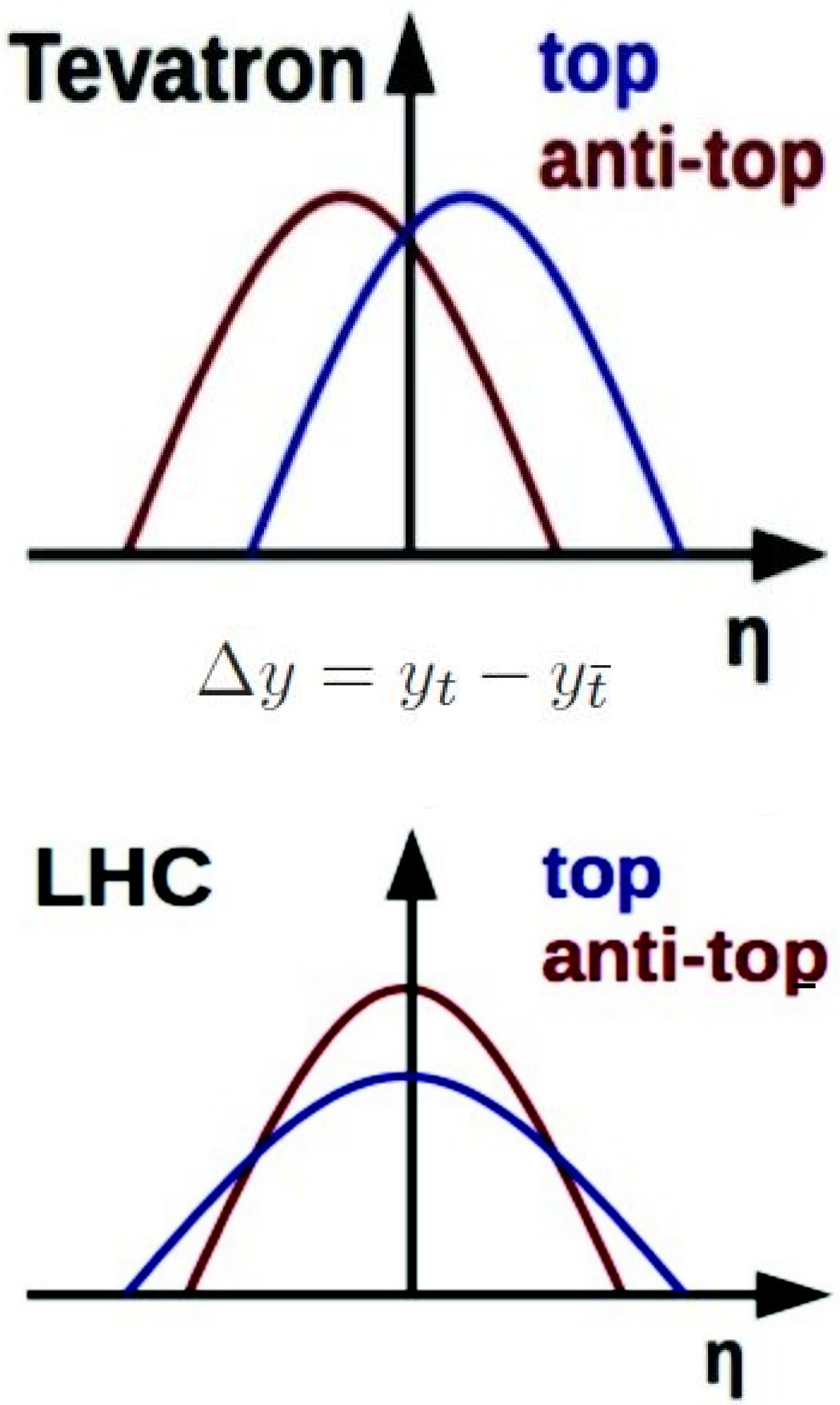


Constrains generic NP at ~10^3–10^4 TeV

Top FB asymmetry

A. Jung, LHCP 2014





Both CDF and D0 measure FB-asymmetries above SM, D0 does not see enchancement at high m_{tt}

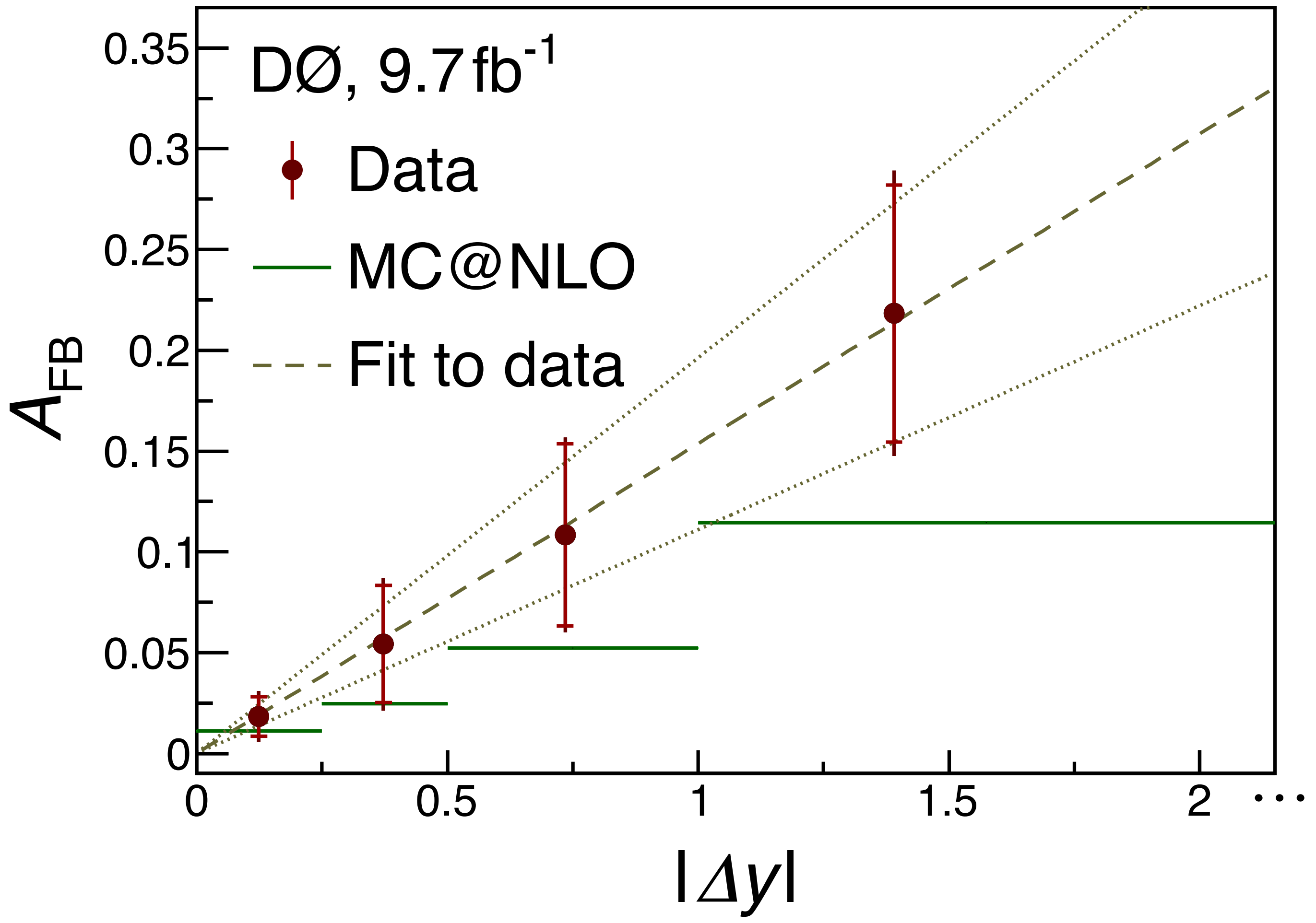
Cannot measure same quantity at LHC but related measurements compatible with SM

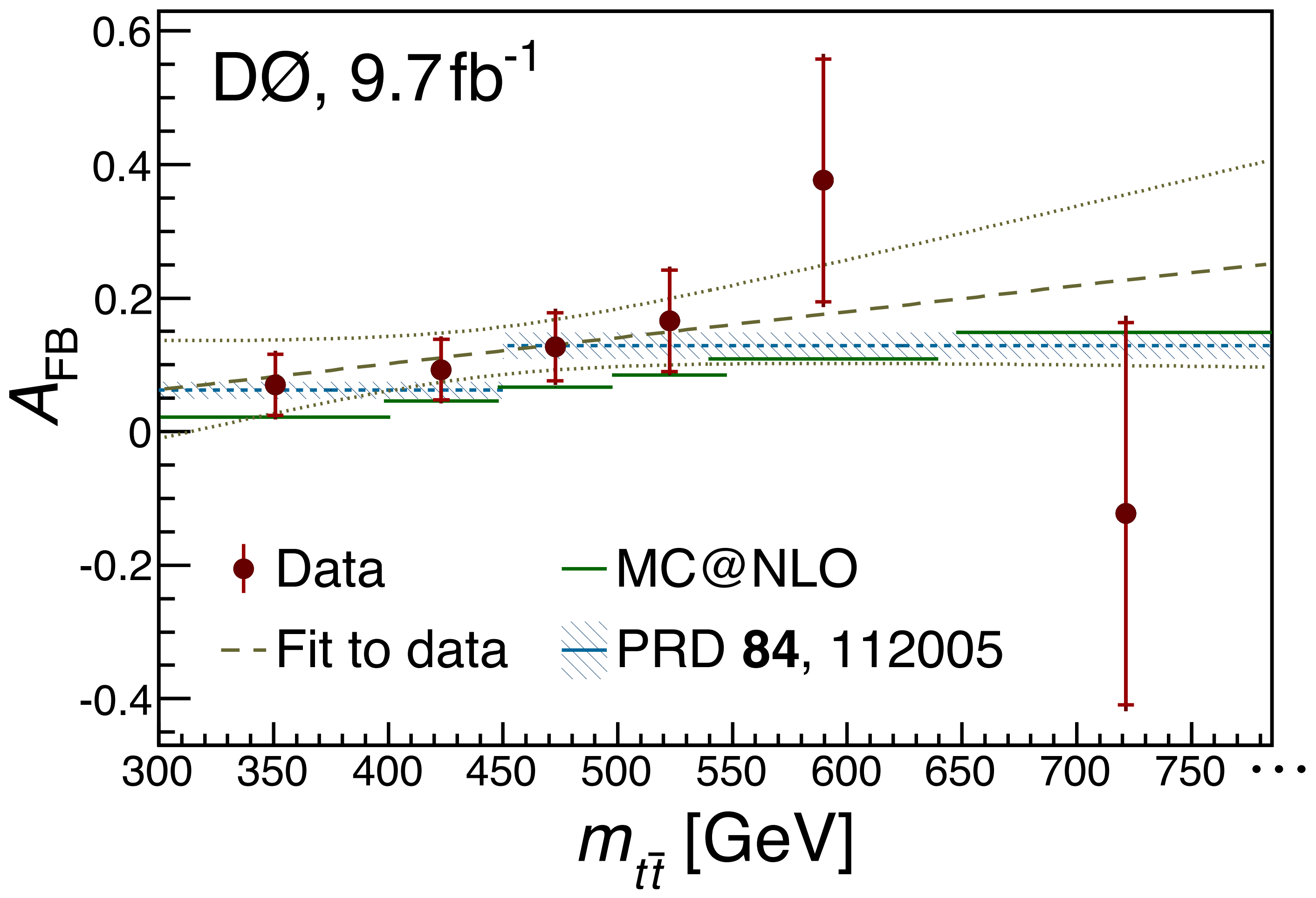
Top FB asymmetry

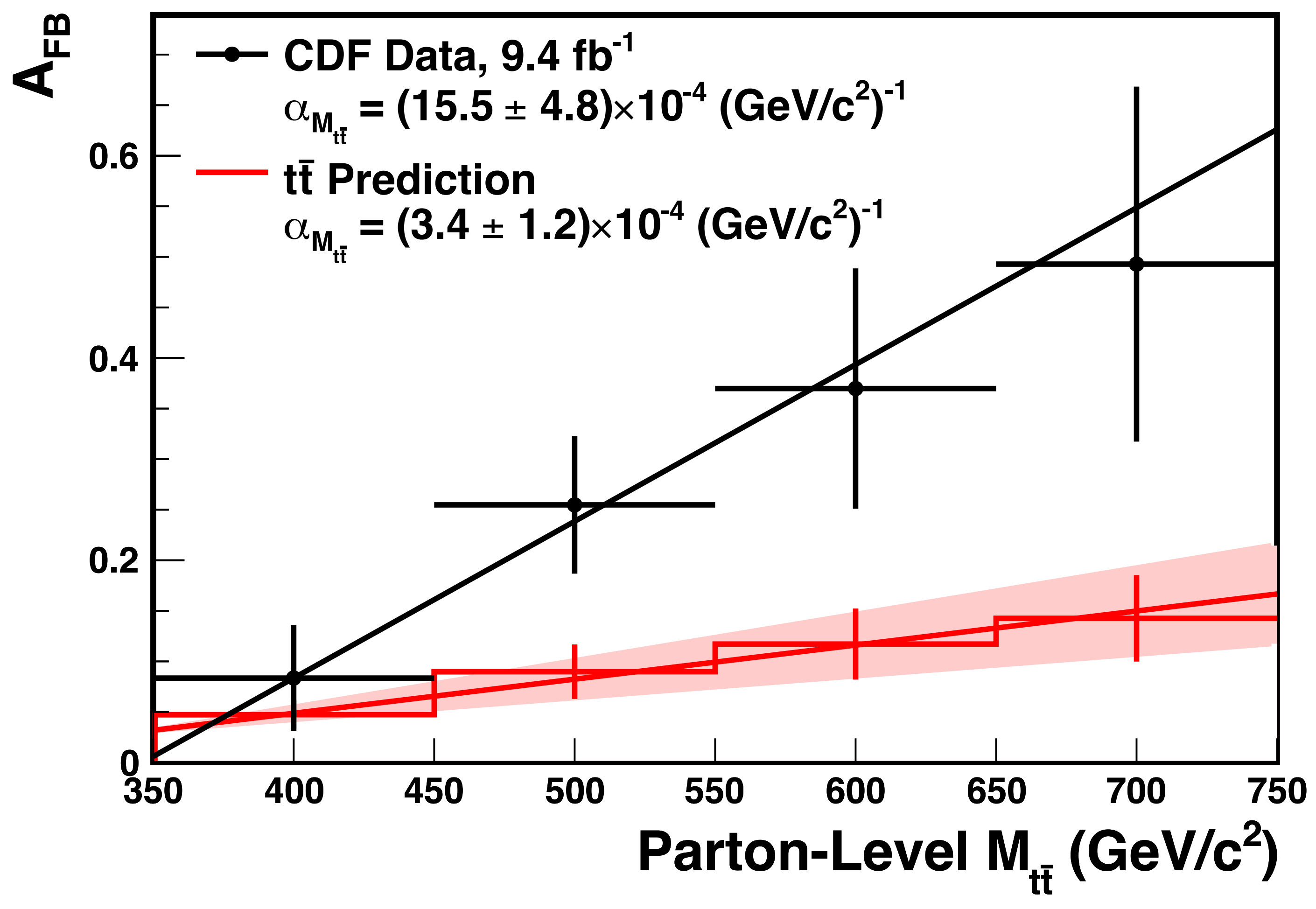
Left to right :

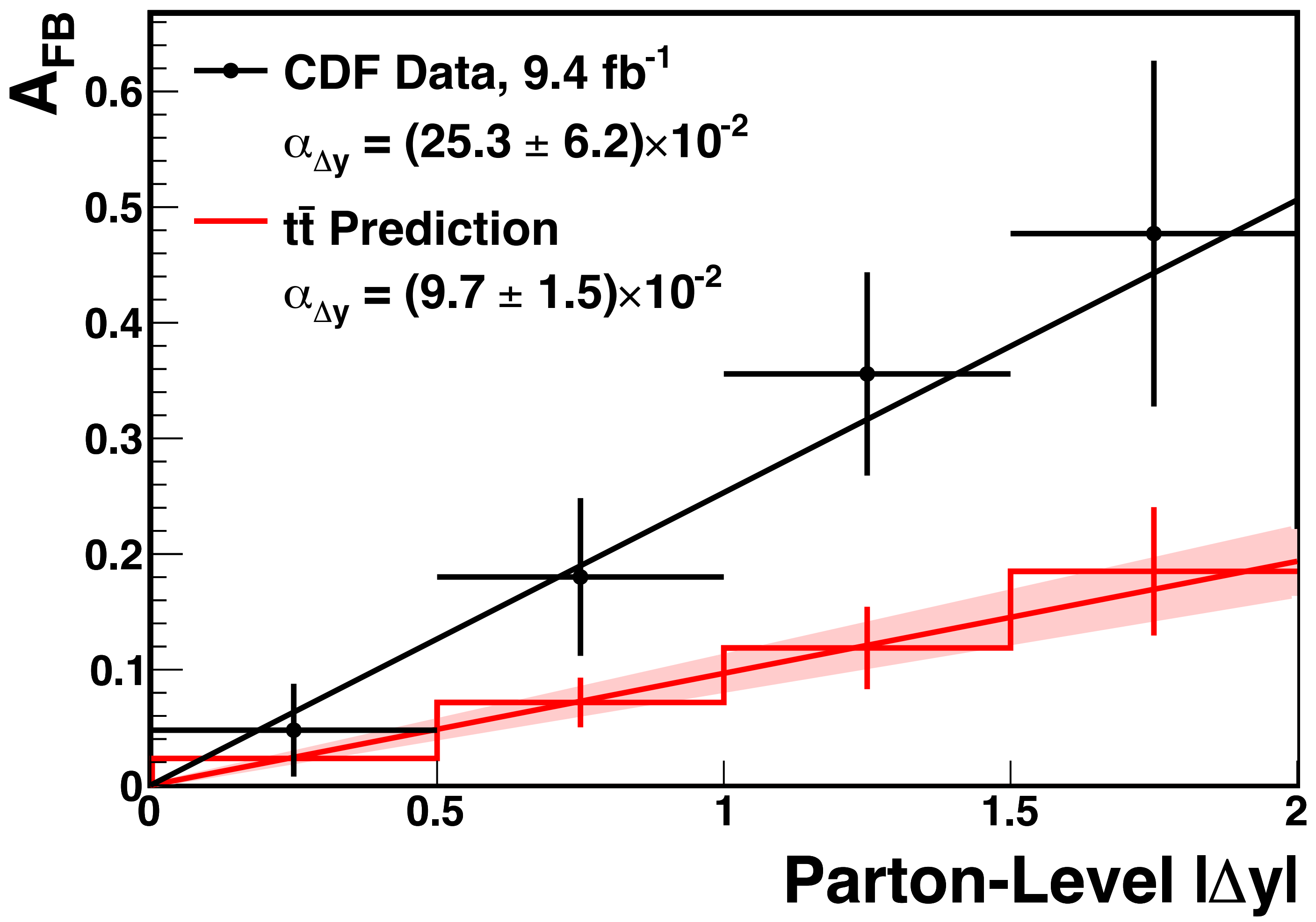
http://arxiv.org/pdf/1405.0421v1.pdf

http://arxiv.org/pdf/1211.1003v3.pdf





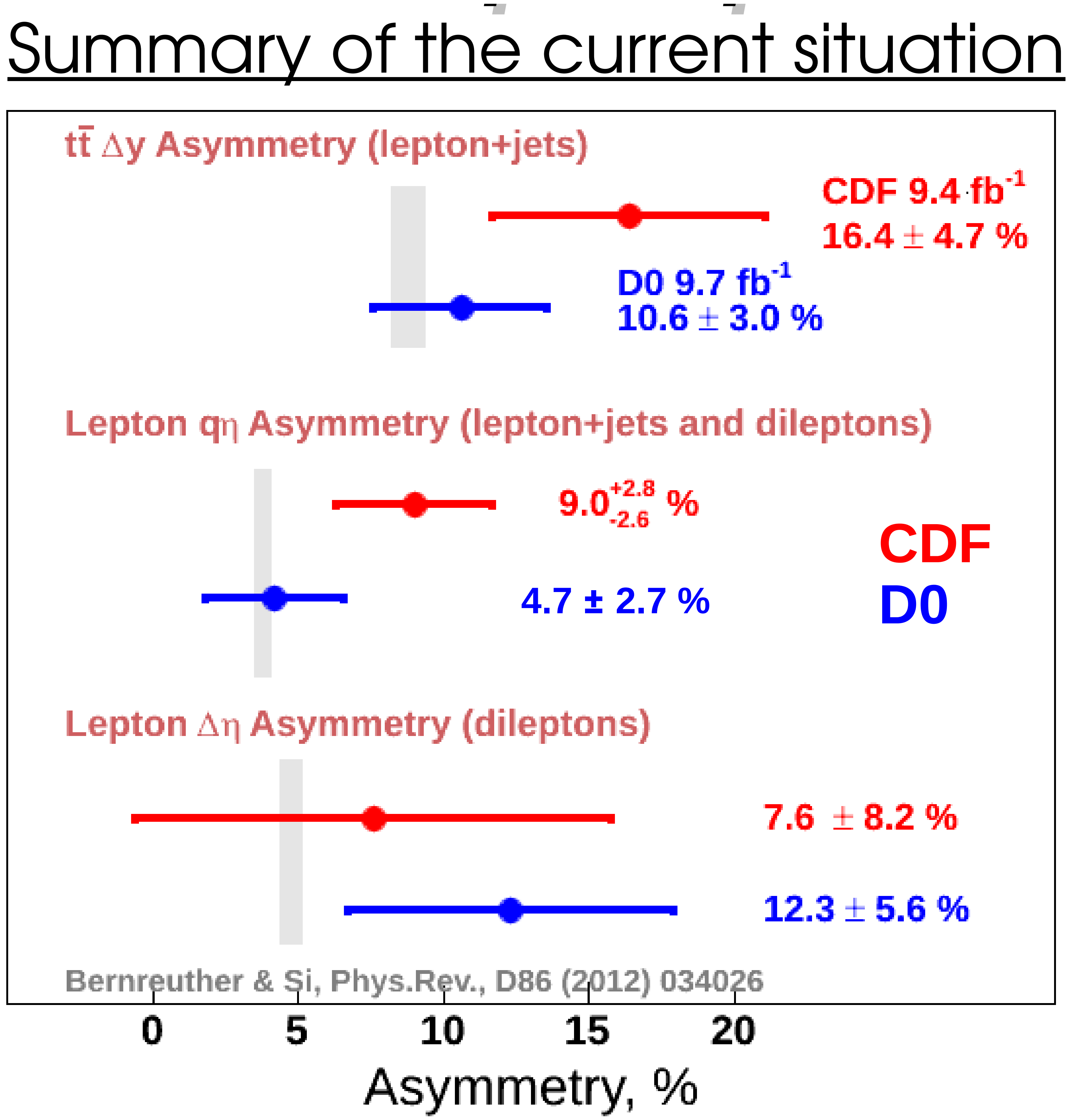


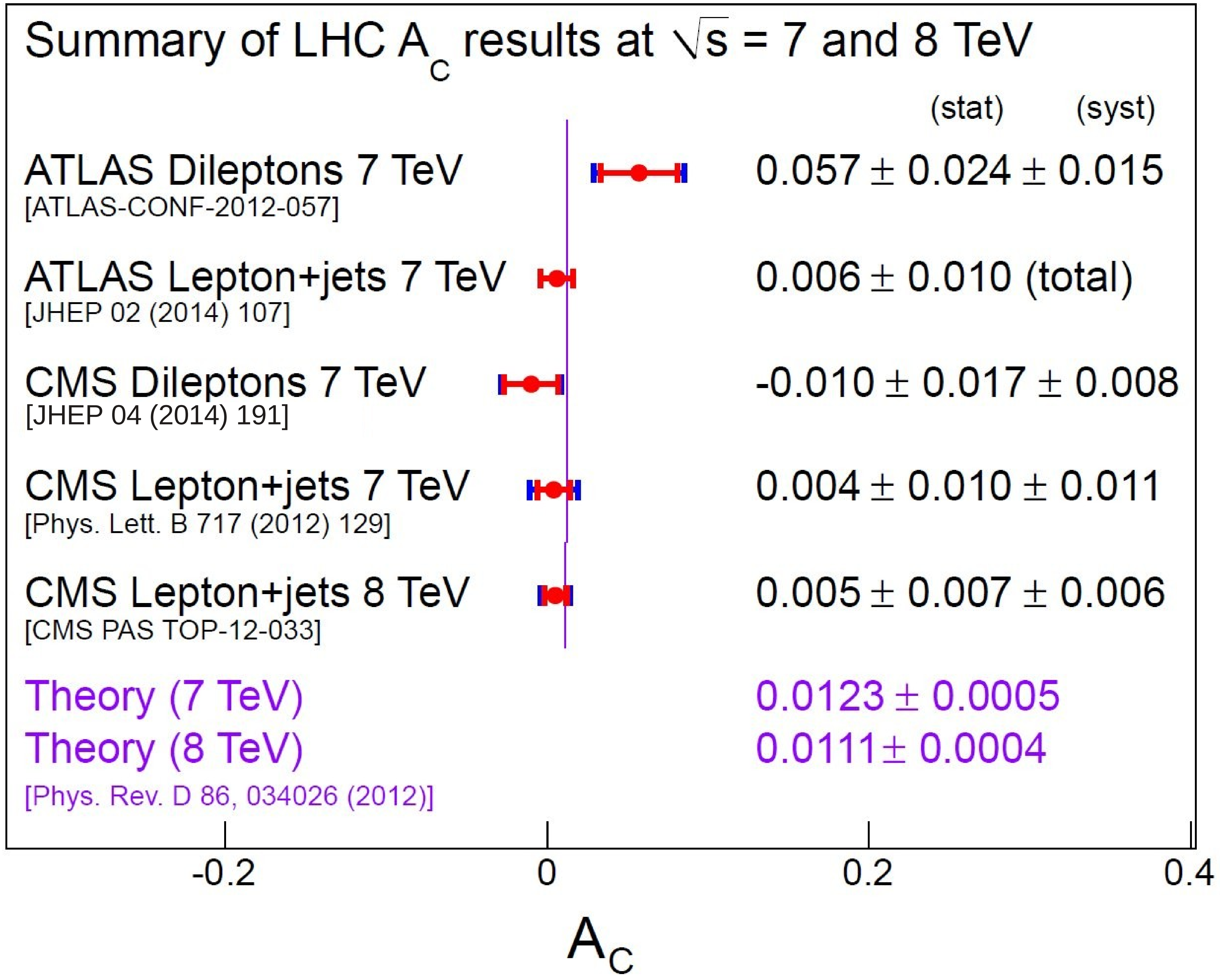


Tension with SM greater for measurements of top quark asymmetry than lepton asymmetry

Top FB asymmetry

A. Jung, LHCP 2014



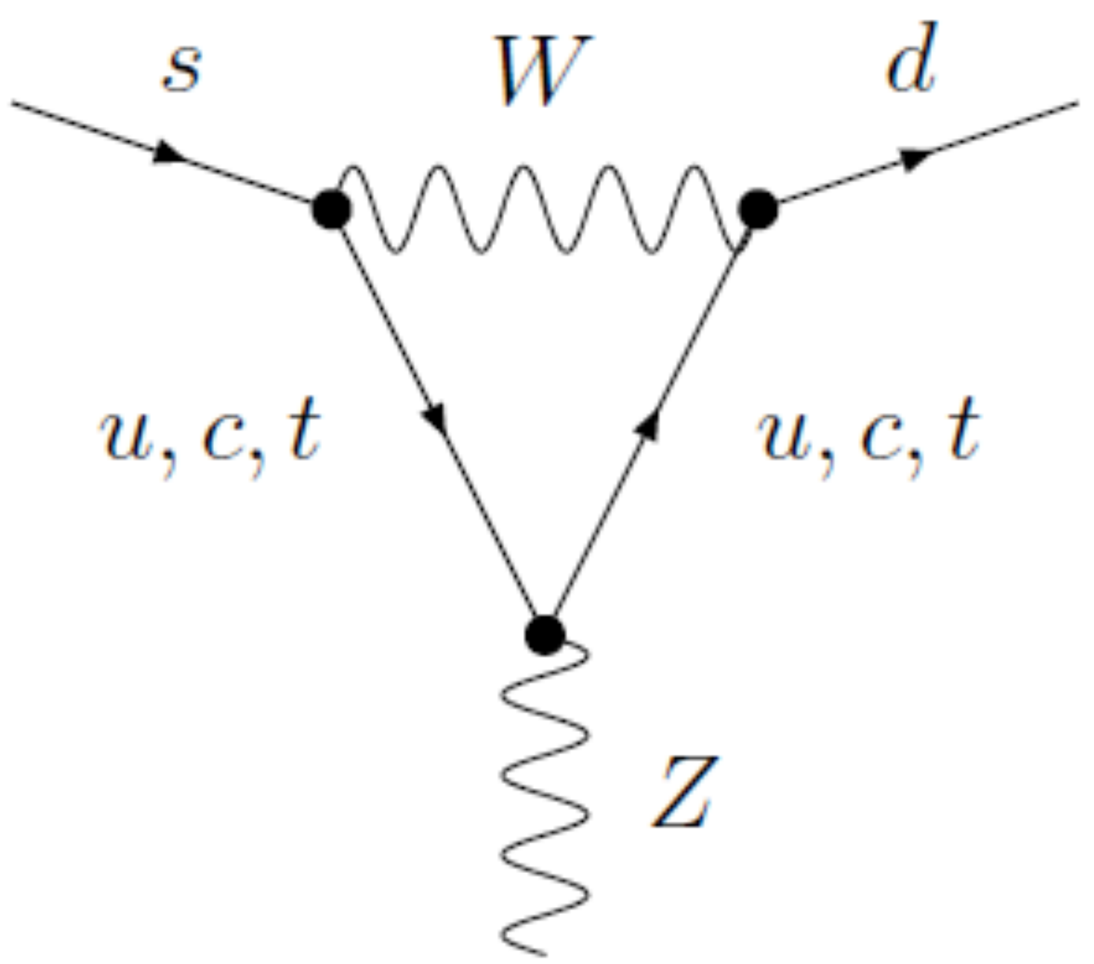


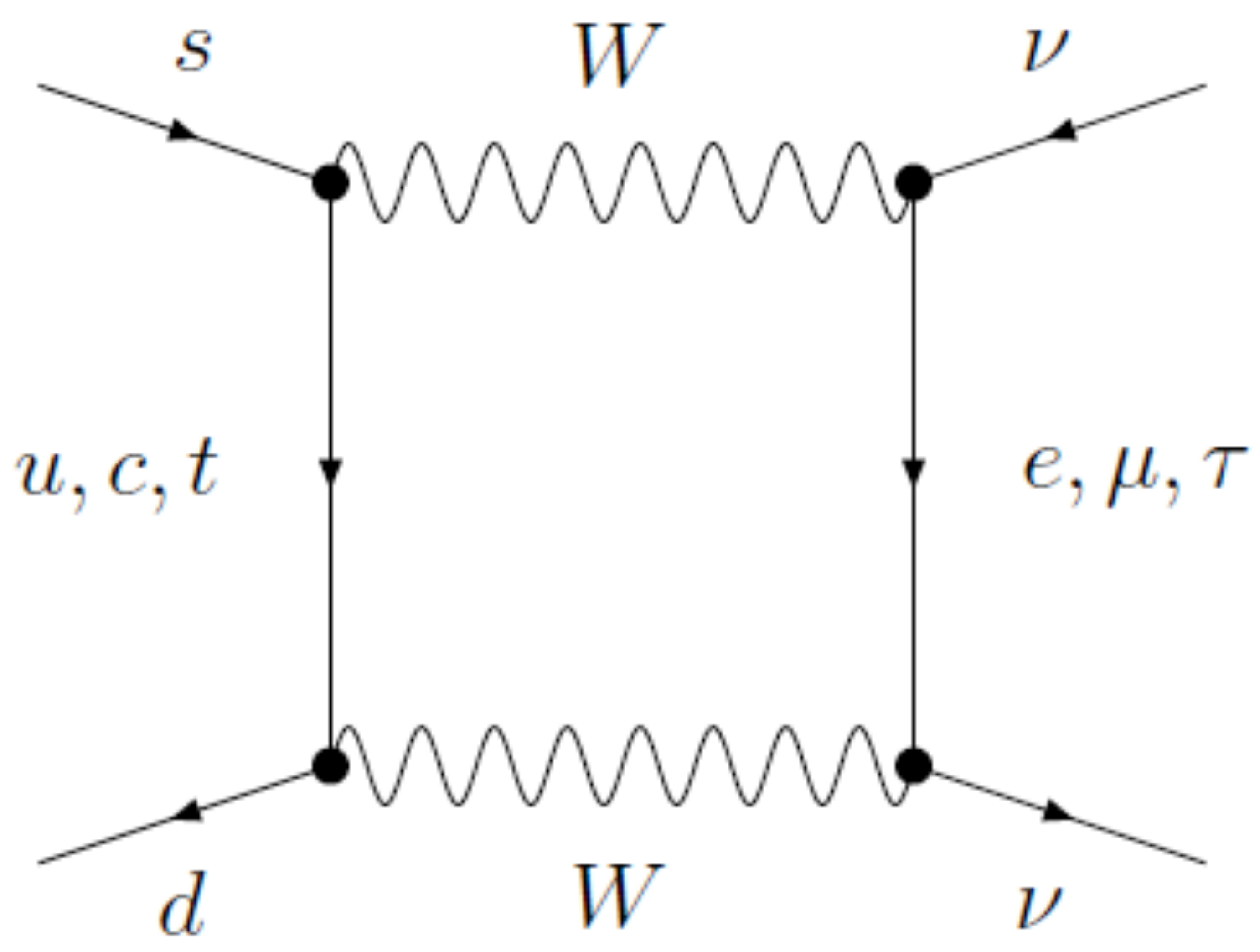
In broad agreement with SM, need NNLO QCD predictions to help resolve differences.

The strange sector

The physics of NA62

NA62 Technical design report



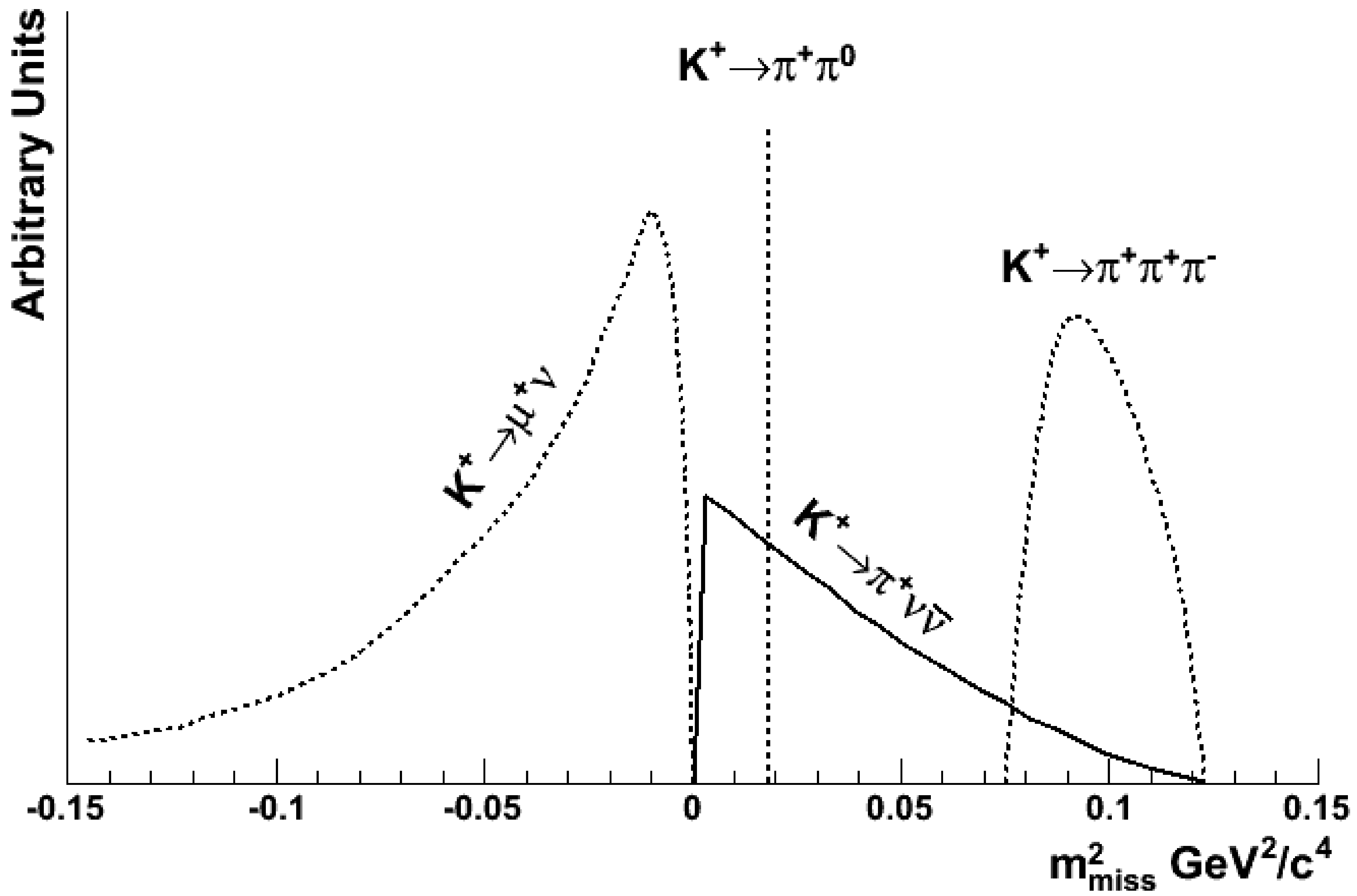


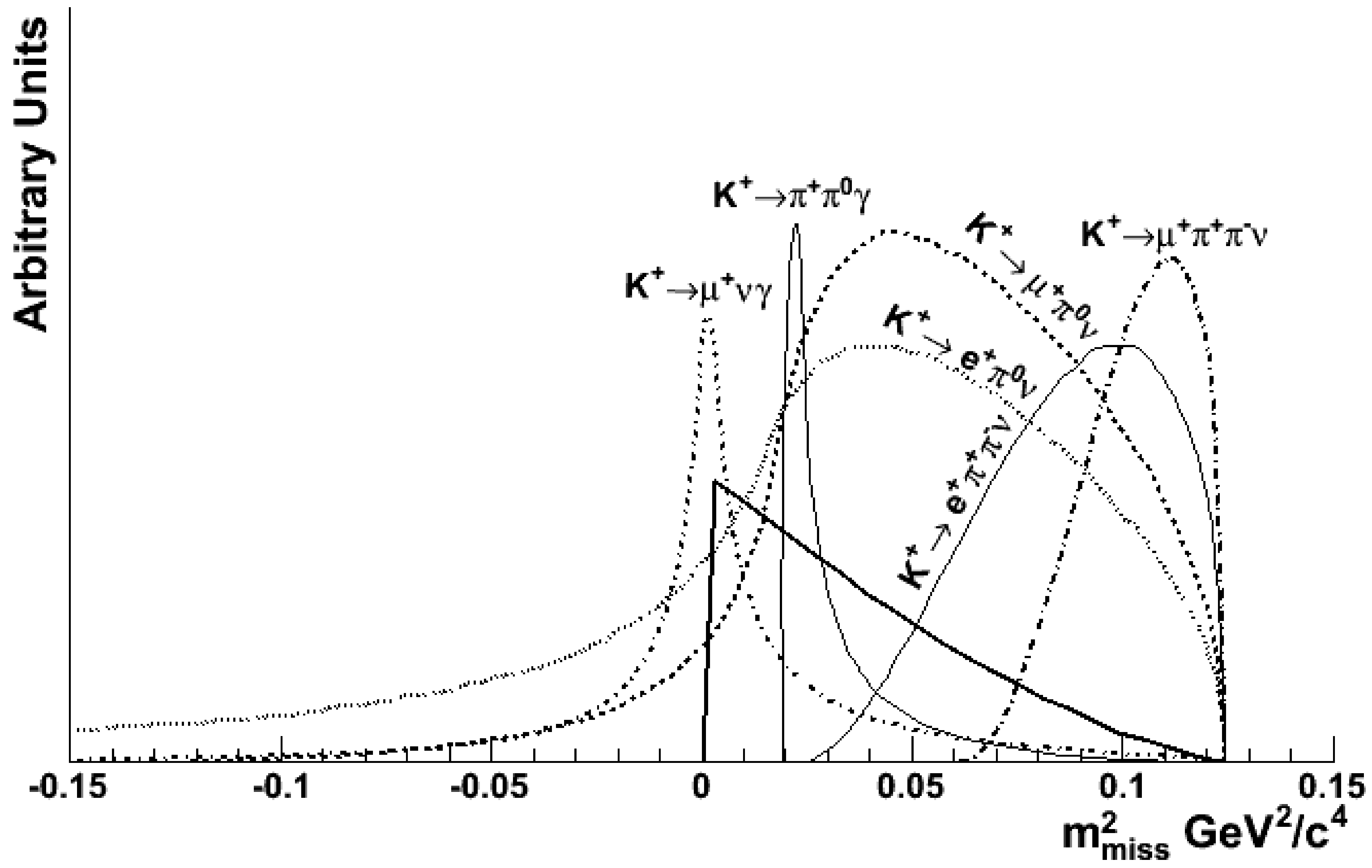
Rare decay, $(8.5 \pm 0.7)*10^{-11}$ in SM

Aim to measure with 10% experimental precision by collecting ~100 signal events

The physics of NA62

NA62 Technical design report

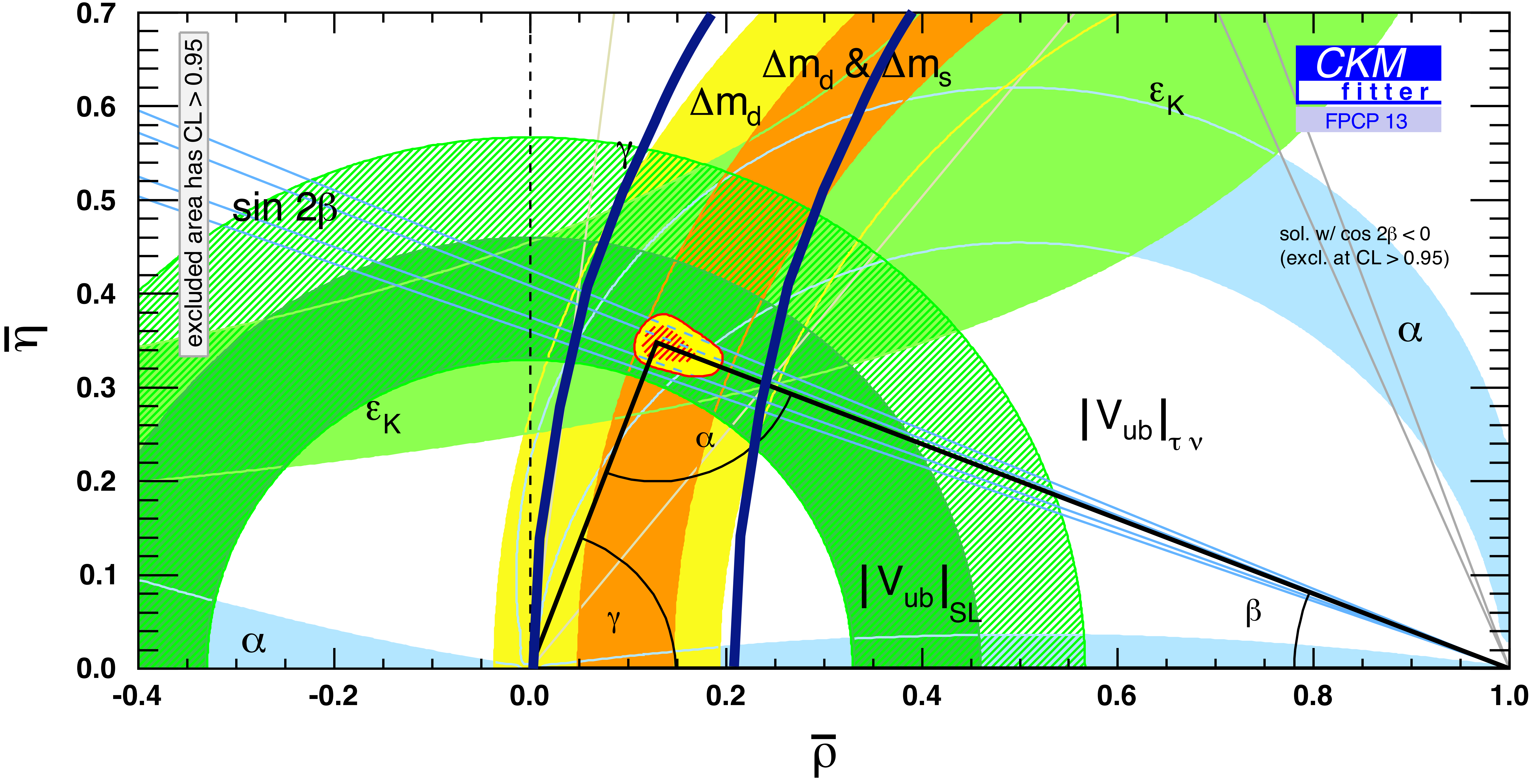




Require O(0.01%) pion-muon discrimination, O(100ps) time-stamping in the trackers, excellent vetoes for neutral particles

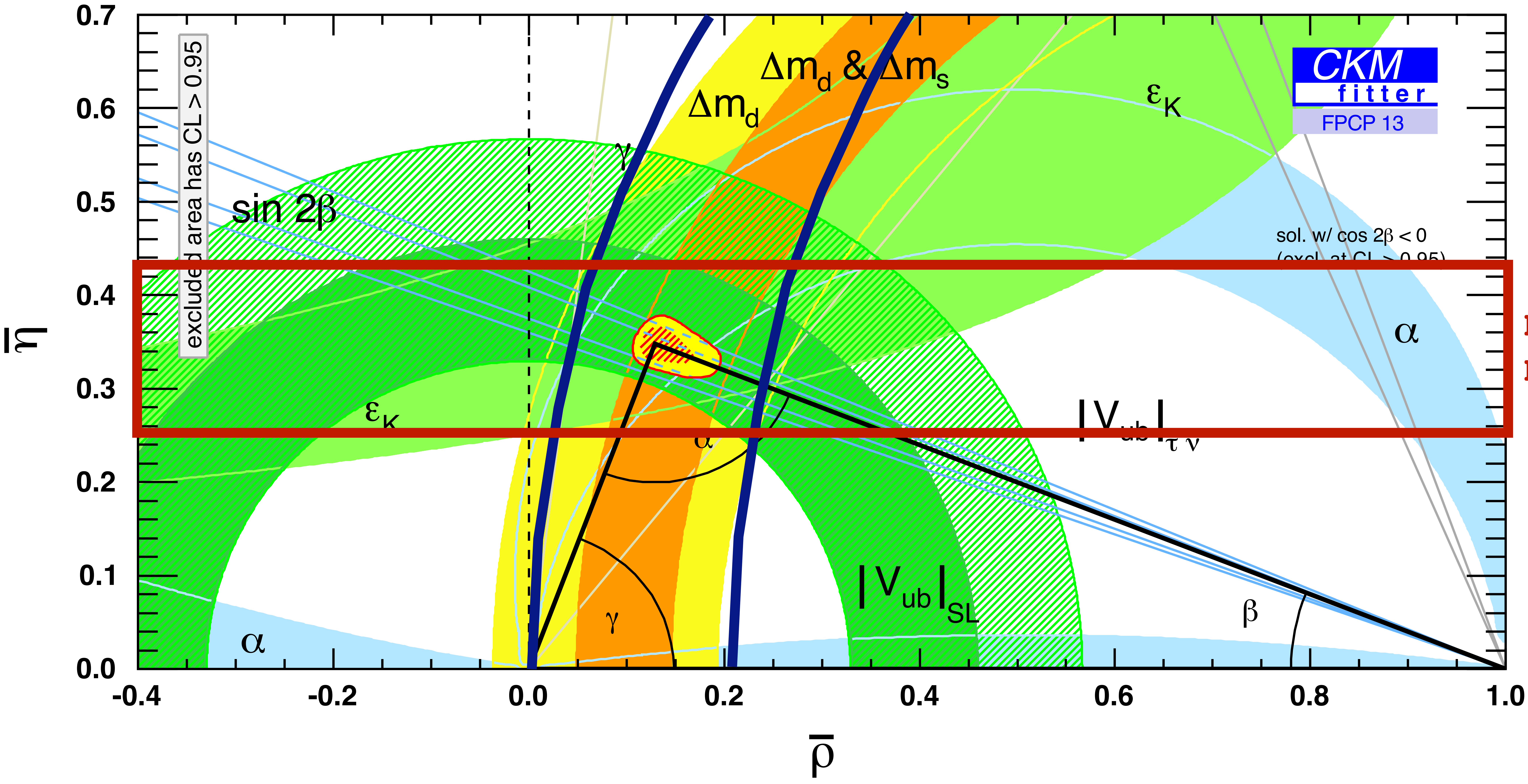
Constraint on the UT

NA62 Technical design report



Fantasizing about the future

NA62 Technical design report



$K^0 \to \pi^0 \nu\nu$, KOTO (?)

Basically gives an independent measure of sin(2β)!


The Future Is Now!

Latest crystal ball projections

	LHC era			HL-LHC era	
	Run 1 (2010–12)	Run 2 (2015–17)	Run 3 (2019–21)	Run 4 (2024–26)	Run 5+ (2028–30+)
ATLAS & CMS	$25\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$	$\longrightarrow$	$3000\,\mathrm{fb}^{-1}$
LHCb	$3\,\mathrm{fb}^{-1}$	$8\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$46\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$
Belle II	—	$0.5\,\mathrm{ab}^{-1}$	$25\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$	—

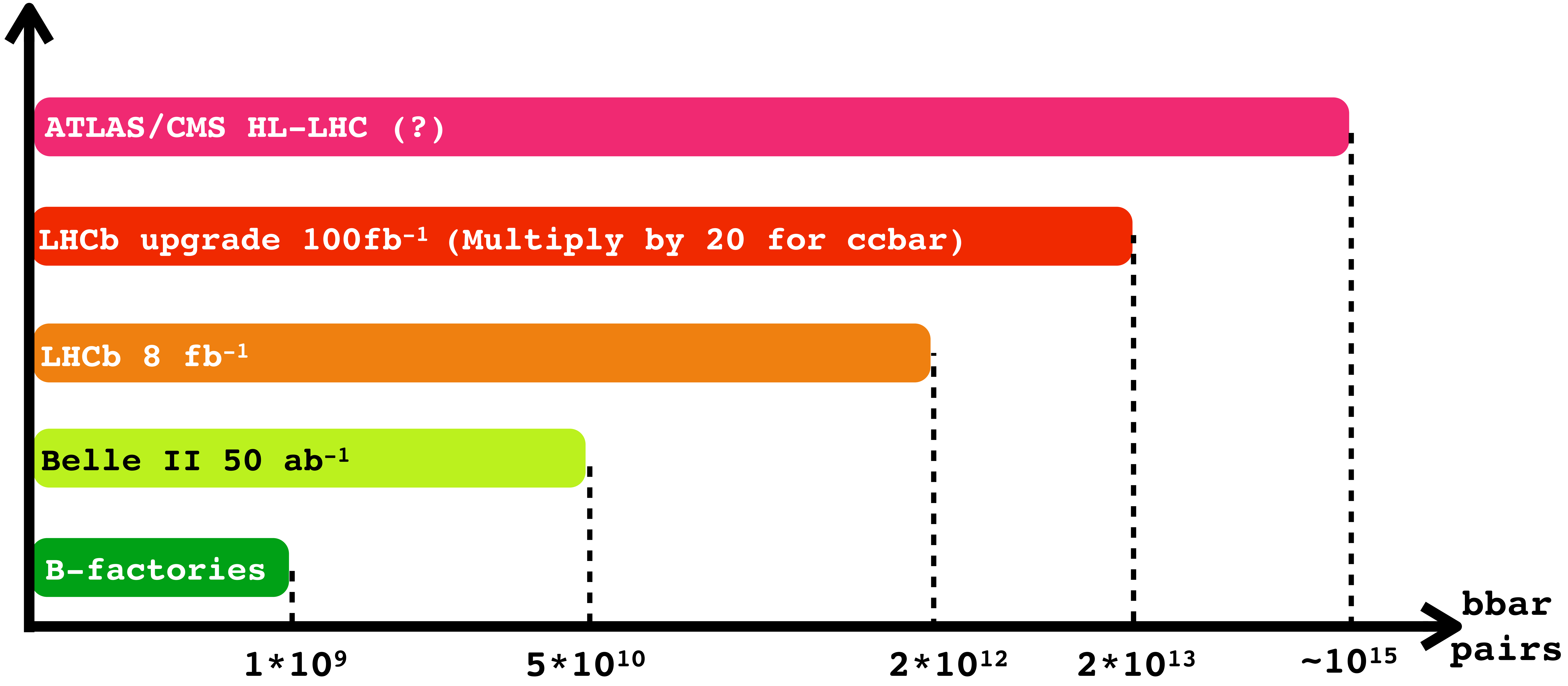
+NA62, 10% on BR($K^+\to\pi^+\nu\nu$) roughly by end of Run II

+TLEP collecting $2{*}10^{11}$ $Z\to b\bar{b}$ by 20XX?

+KOTO observes $K^0\to\pi^0\nu\nu$ by the end of Run II?

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

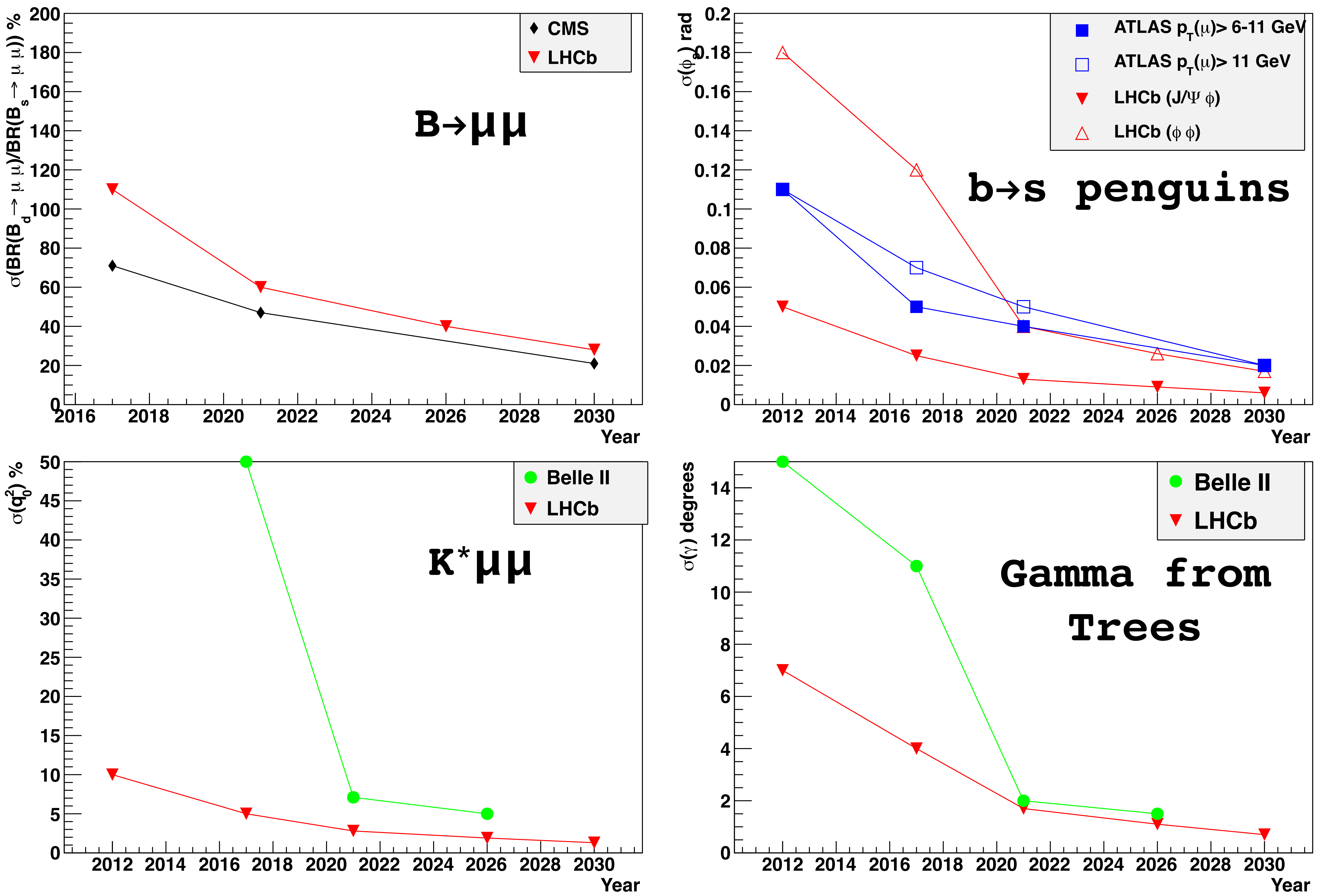
Some example signal rates



B-factories/Belle II should be scaled by ~10 compared to LHCb to account for efficiencies, hermetic detectors, and a cleaner environment.

Effective size of ATLAS/CMS sample depends on their trigger evolution.

A few key observables



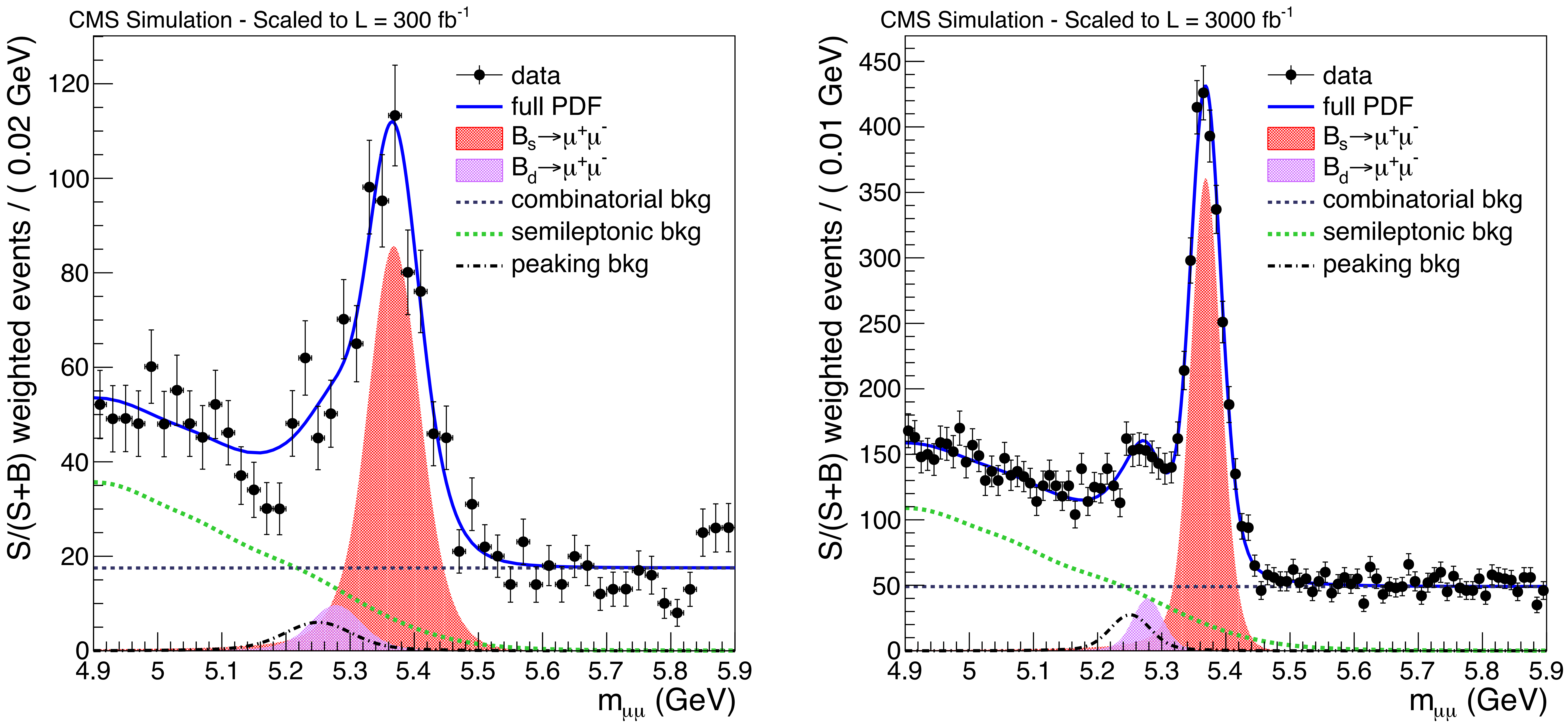
https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

Personal aside on complementarity

	LHCb upgrade	Belle II	ATLAS/CMS
Rare B decays	*****	***	****
B_s mixing	*****		**
B_d mixing	**	*****	
Incl. processes ($X_s\gamma$, X_sll, etc.)		*****	
b-baryon and B_c physics	*****		**
Charm, charged final states	*****	**	?
Charm, neutral final states	**	*****	
LFV ($\tau\to\mu\gamma,\mu\mu\mu$)	**	*****	?

Publicity plots are made with observables which are by definition common to all experiments, therefore they hide the complementarity of the programme.

Personal aside on CMS

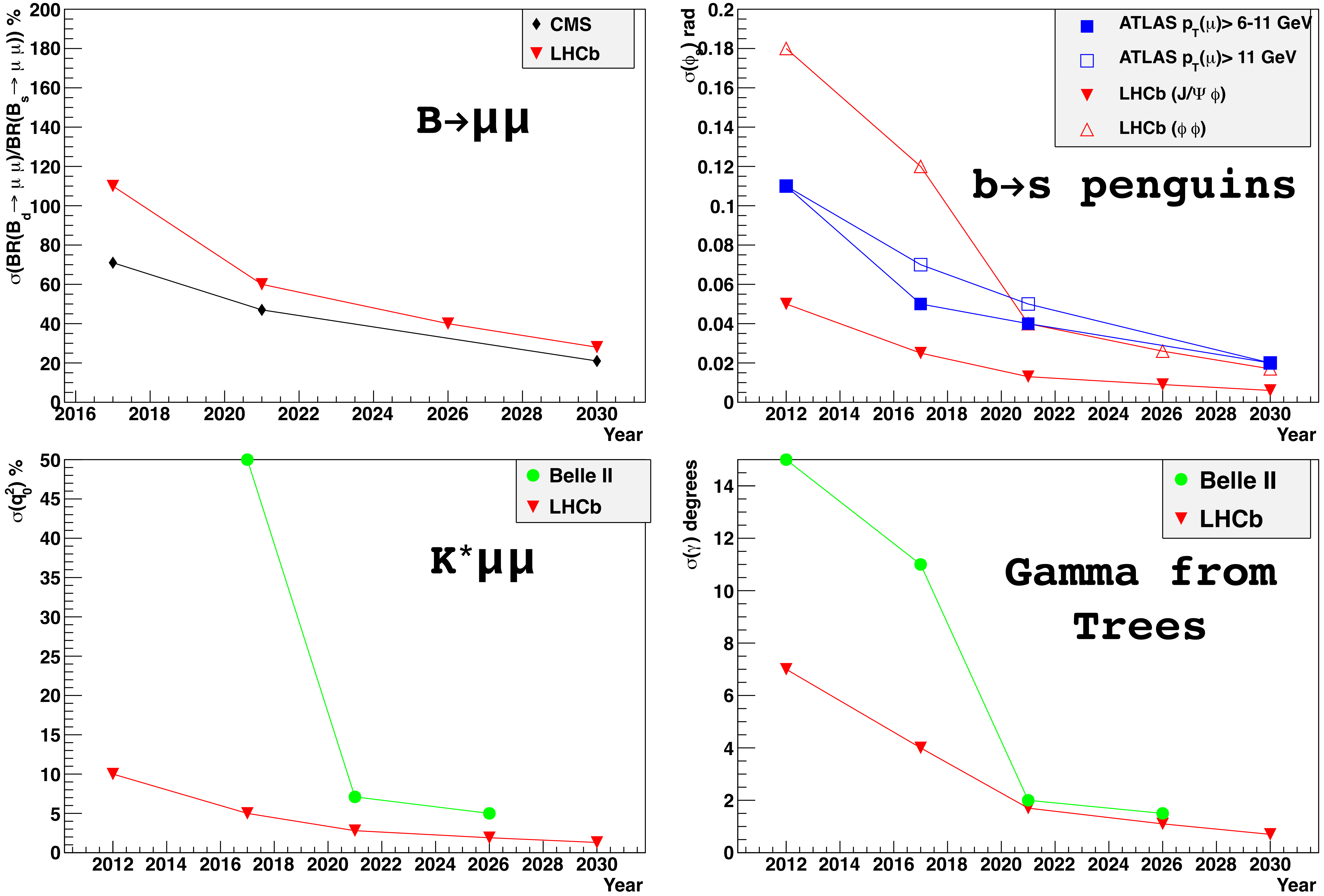


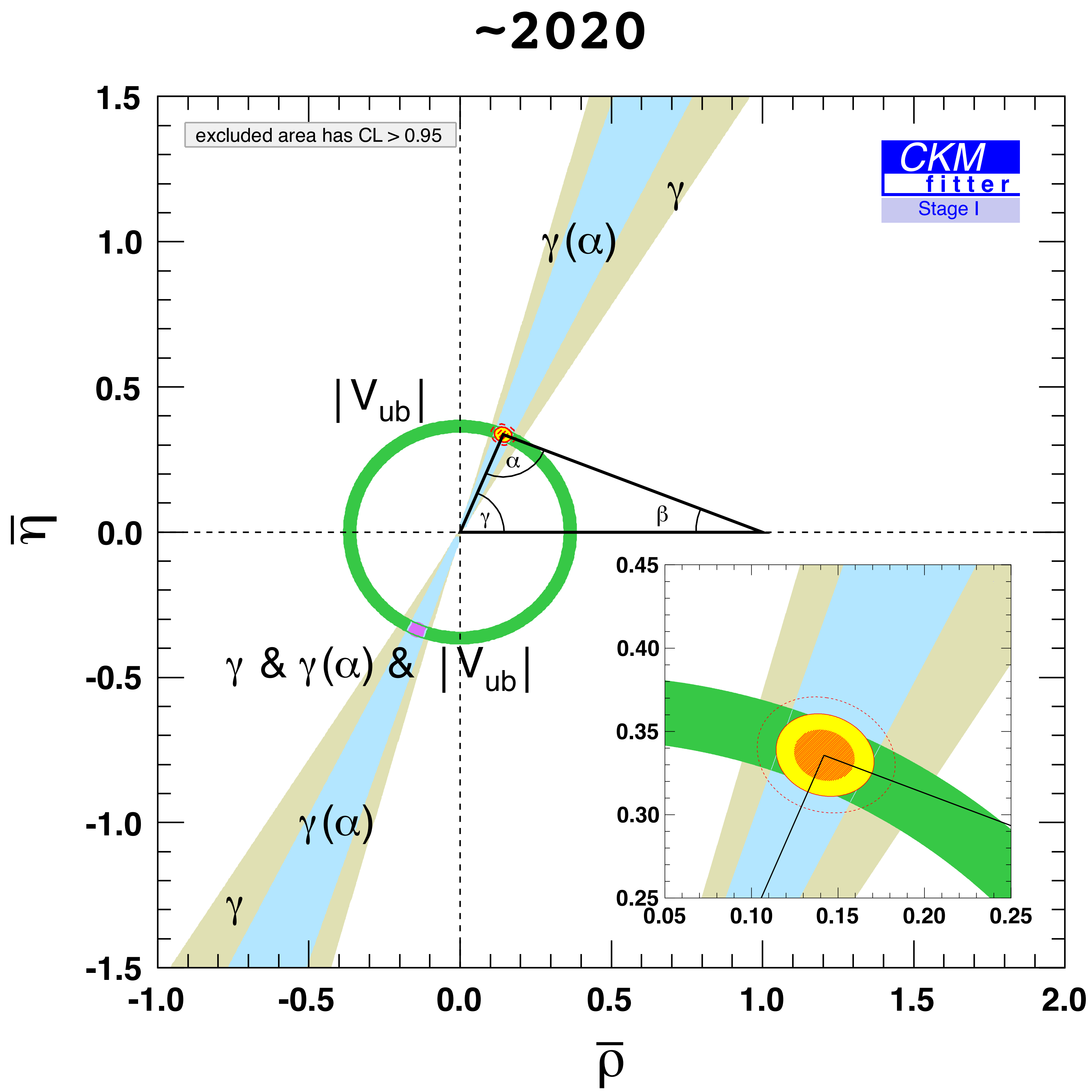
If the CMS tracker performs like this in the HL-LHC era, and you read 1 MHz into your HLT, CMS will be a heck of a flavour factory not only for $B_s \to \mu\mu$.

Even imagining that the B-physics hardware trigger was a pure prescale, which it won't be, CMS would have the same effective luminosity as LHCb.

Are there plans for charm physics with the CMS upgrade? If not, why not?

The impact on the UT, 2020

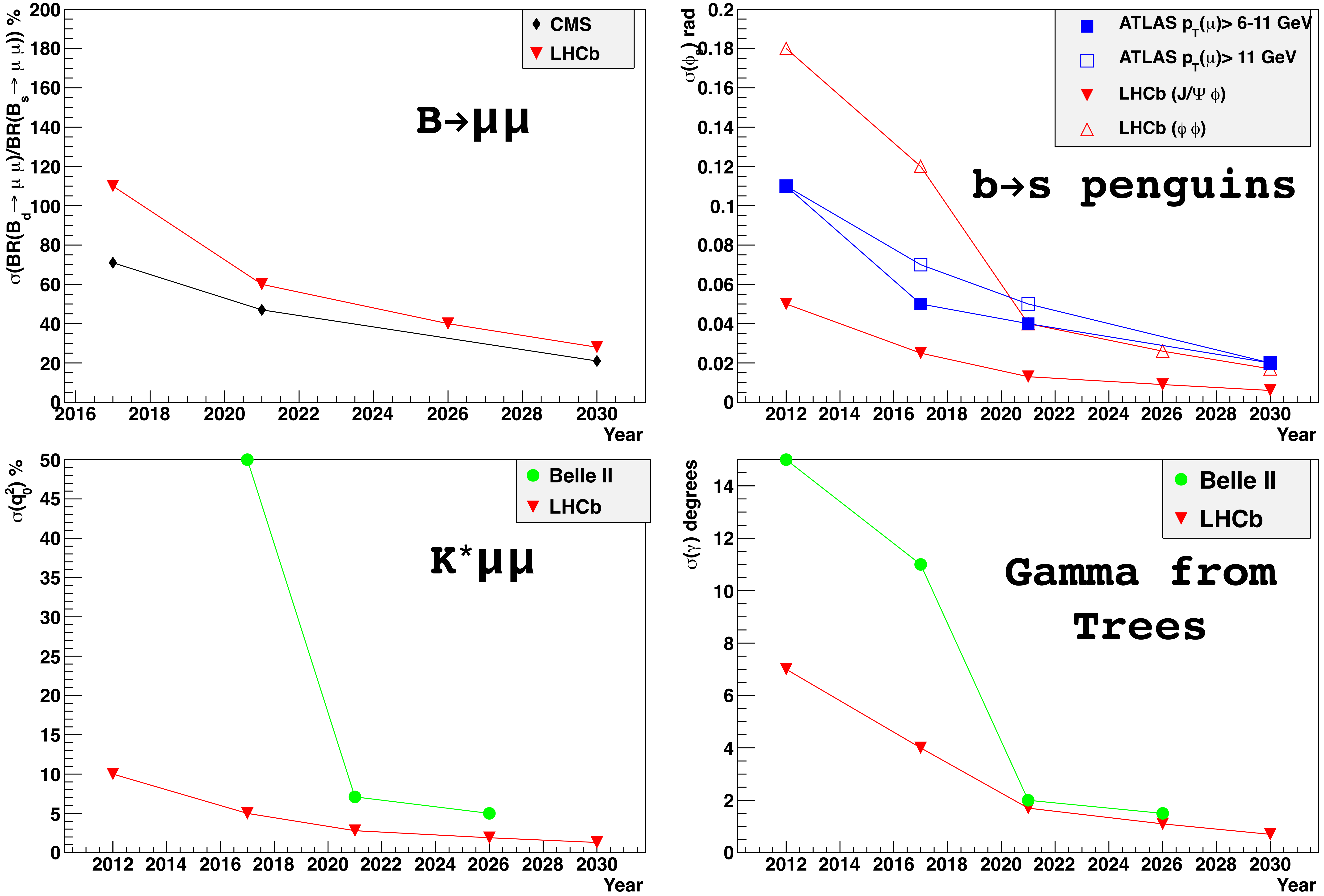


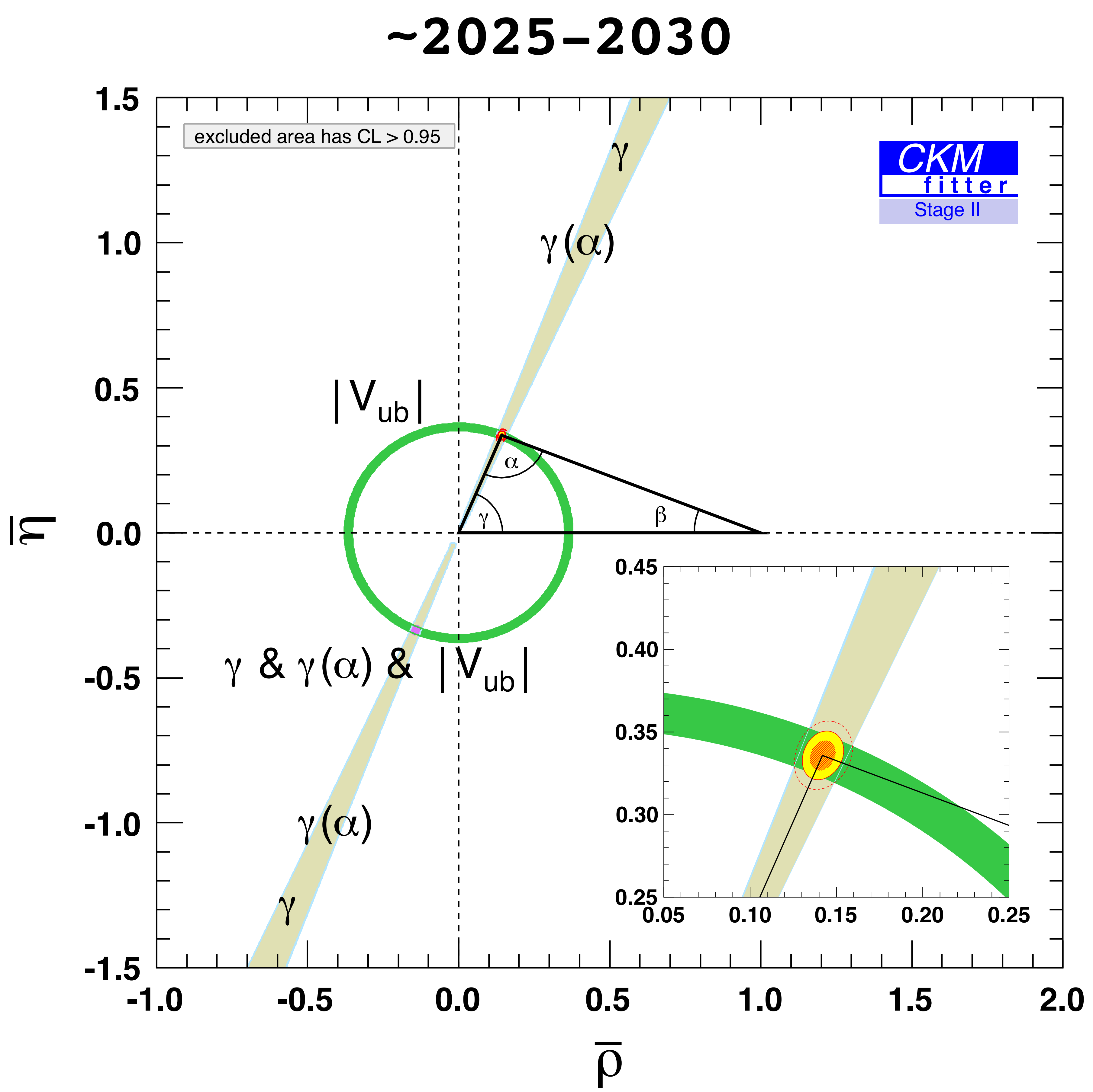


https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

J. Charles et al. http://arxiv.org/abs/1309.2293

The impact on the UT, 2030

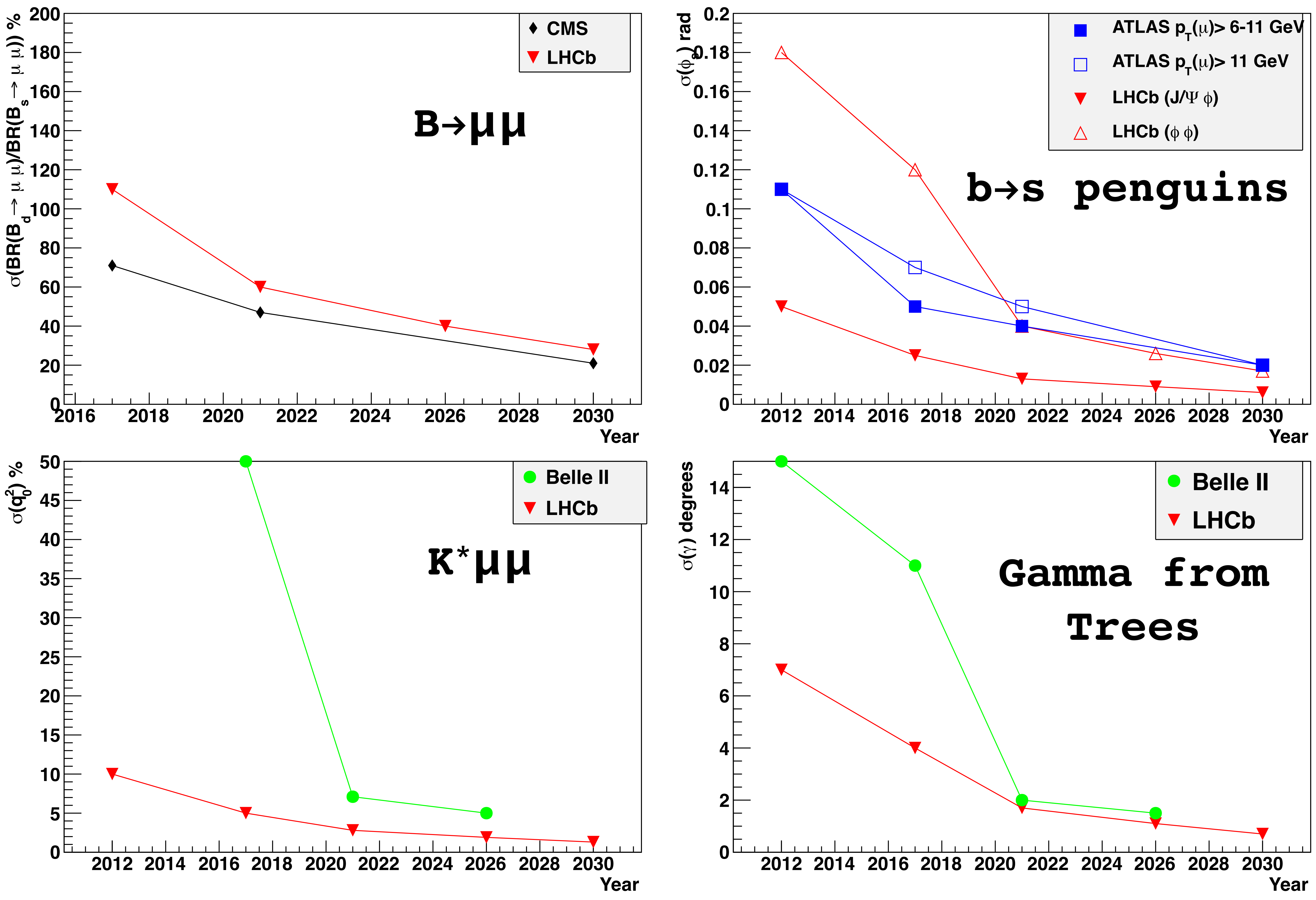


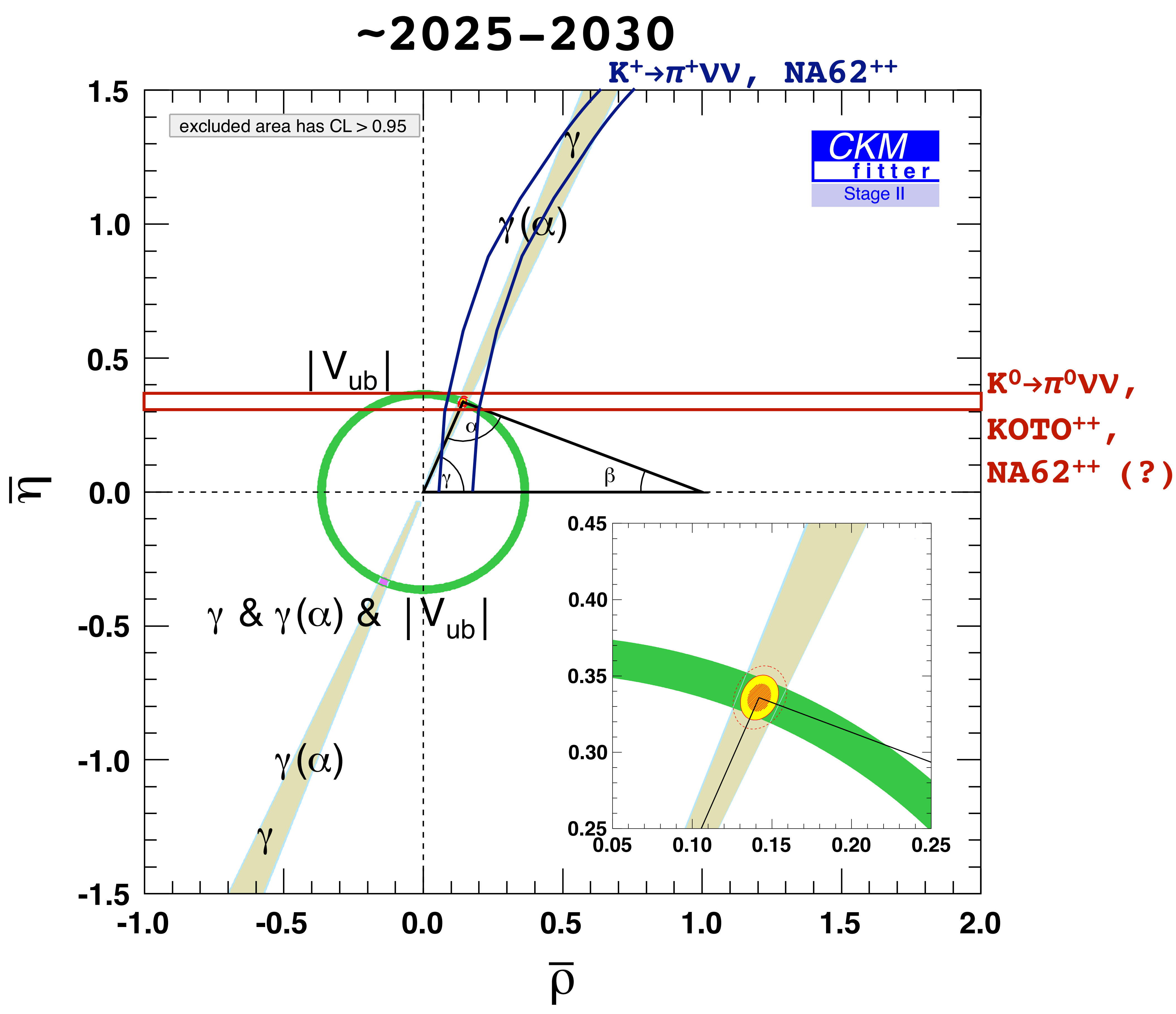


https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

J. Charles et al. http://arxiv.org/abs/1309.2293

Let's add a bit of wishful thinking



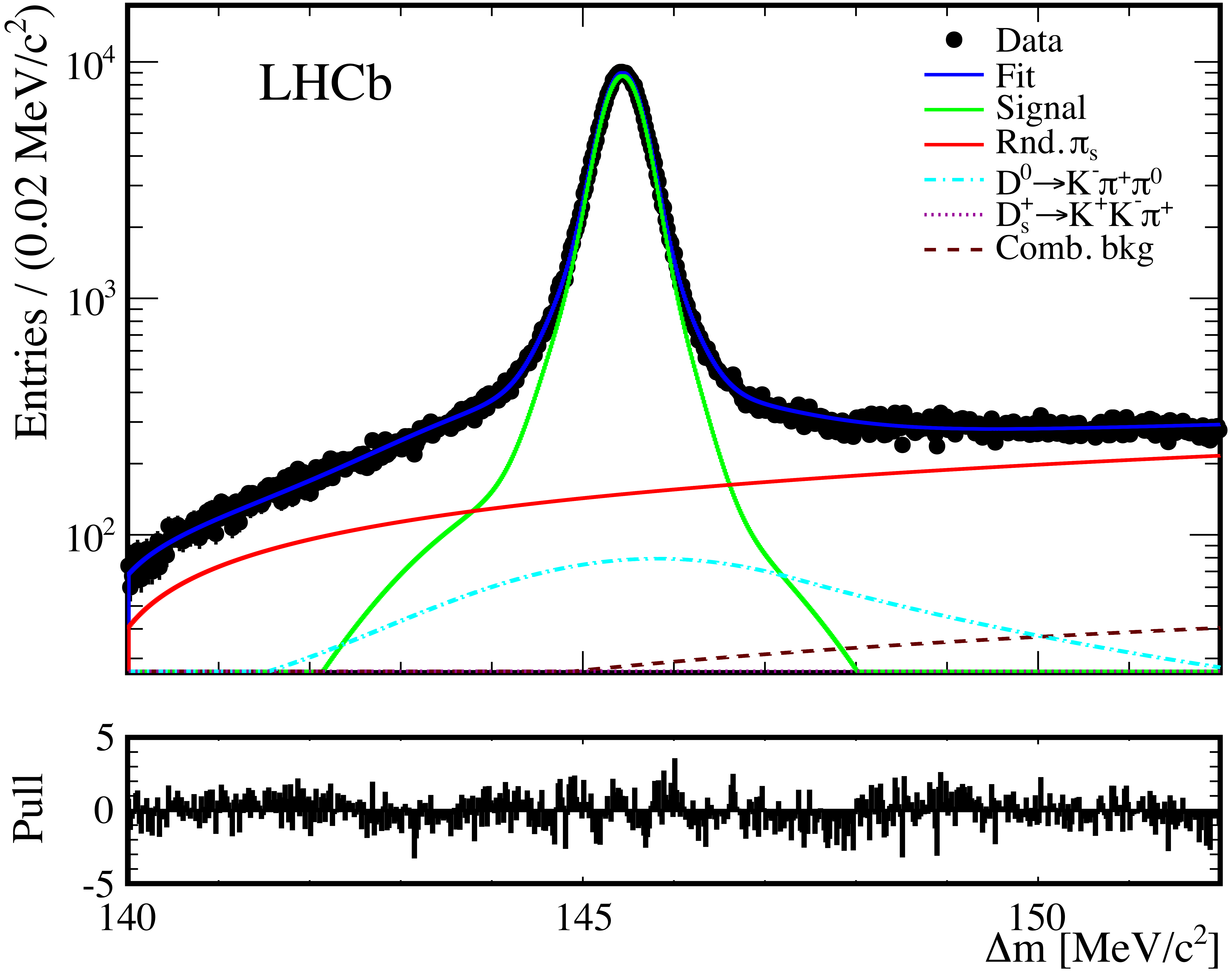


https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

J. Charles et al. http://arxiv.org/abs/1309.2293

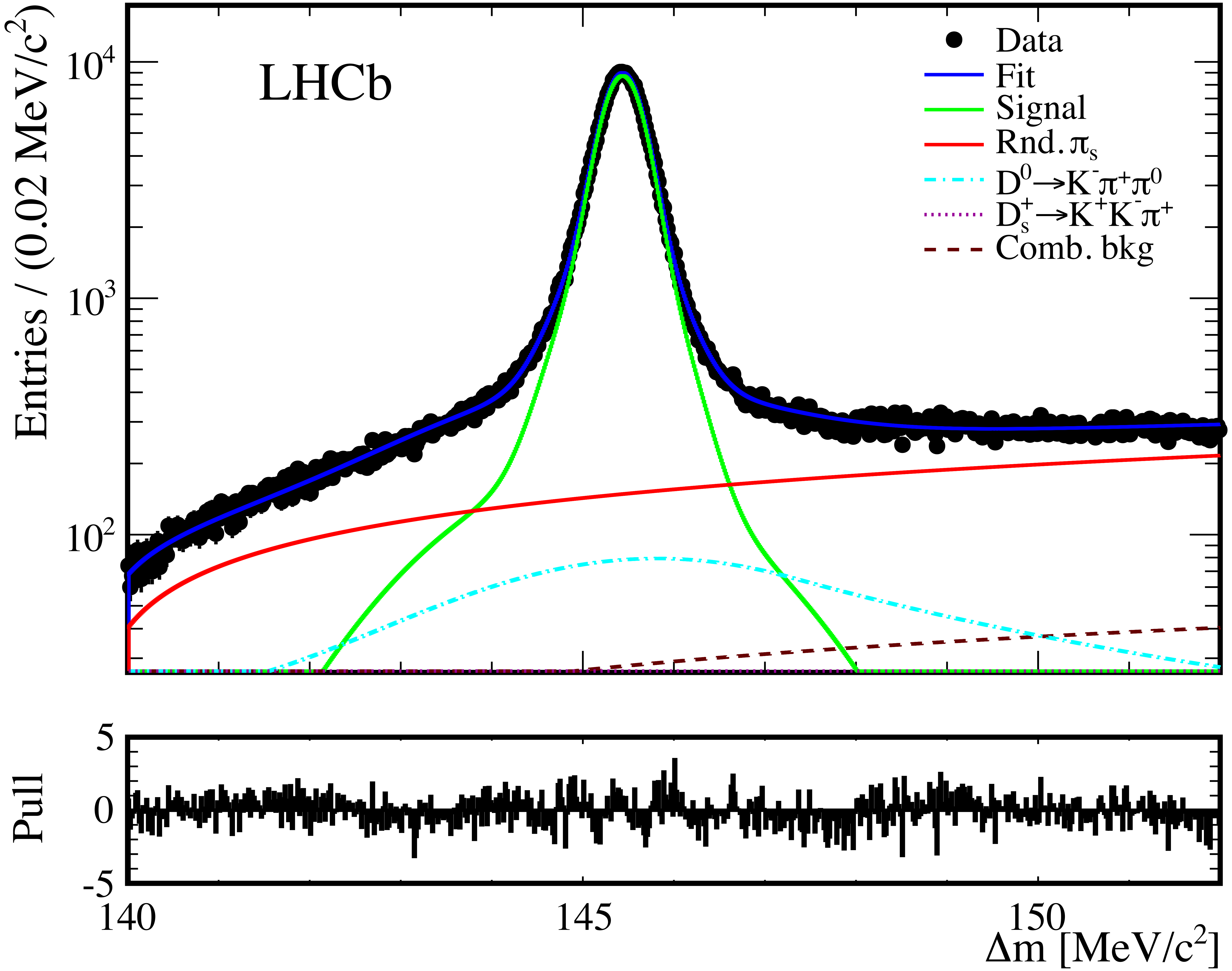
Let's talk about practicalities

Charm, a window into the future…



http://arxiv-web3.library.cornell.edu/abs/1310.7201

...of computing



>10^9 signal events

imagine performing toy studies to evaluate fit biases!

Must take advantage of future computing architecture

Code parallelization key

Also critical to enable progress in lattice QCD

Where charm goes, there beauty will follow soon enough.

http://arxiv-web3.library.cornell.edu/abs/1310.7201

I want to talk about something else though :

Real-time data analysis

Why do we need triggers at the LHC?

Input data rate of the LHCb experiment = 1.5 TB/second

NB : ATLAS/CMS about a bit more than one order of magnitude above LHCb

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→

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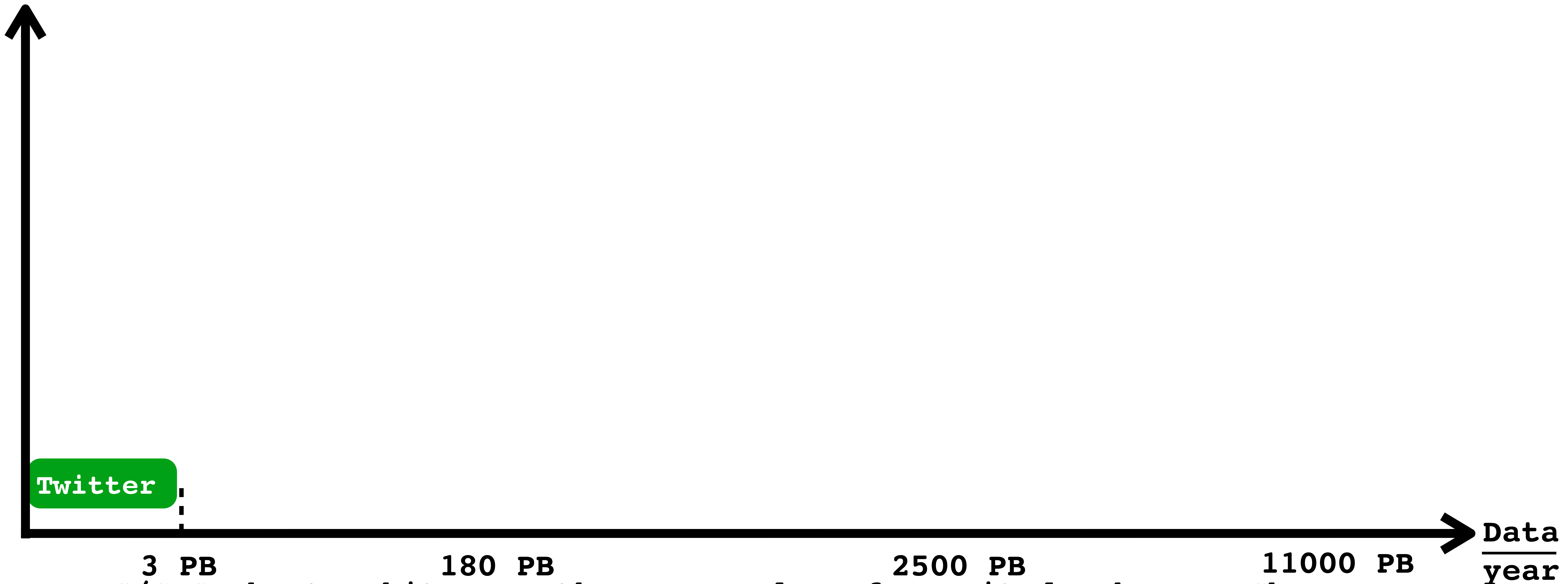

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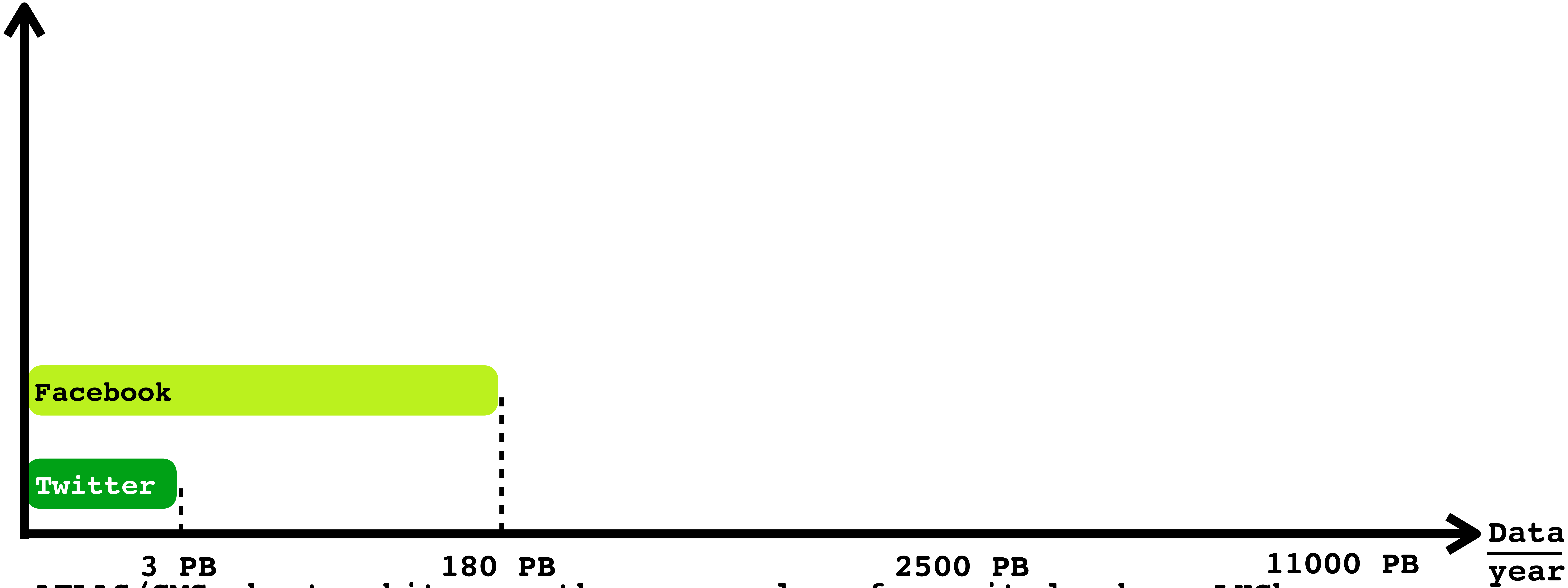

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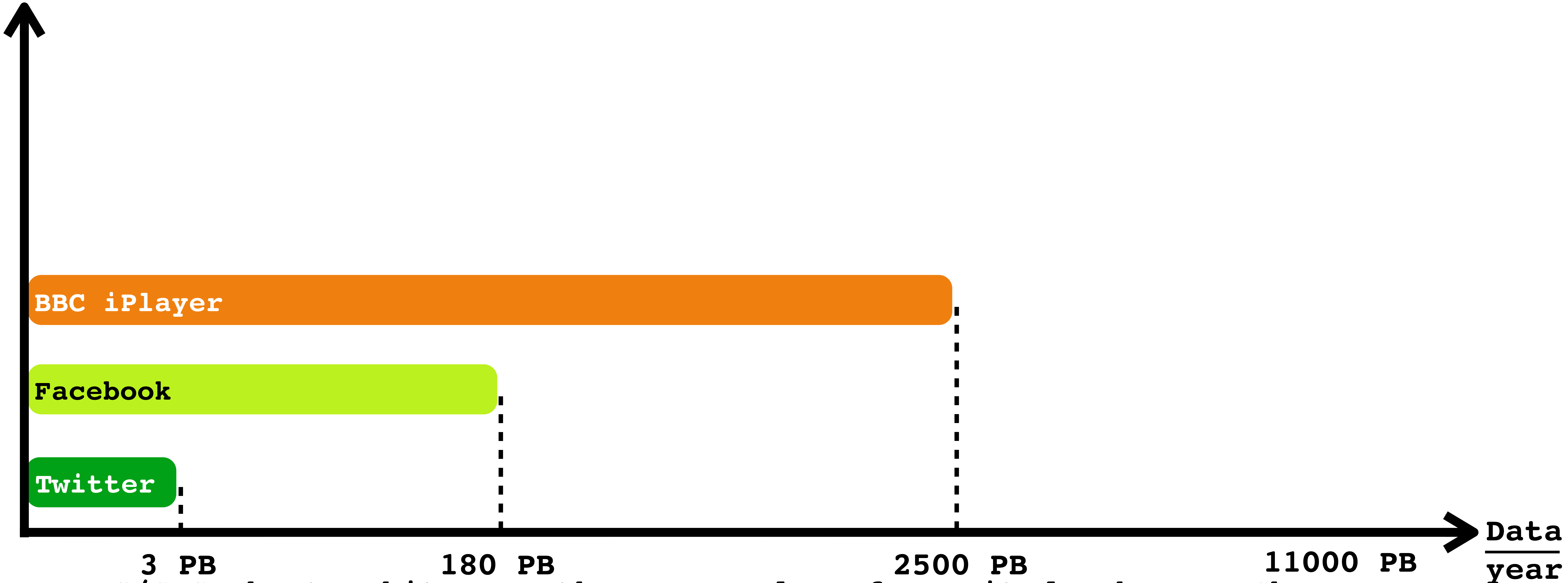

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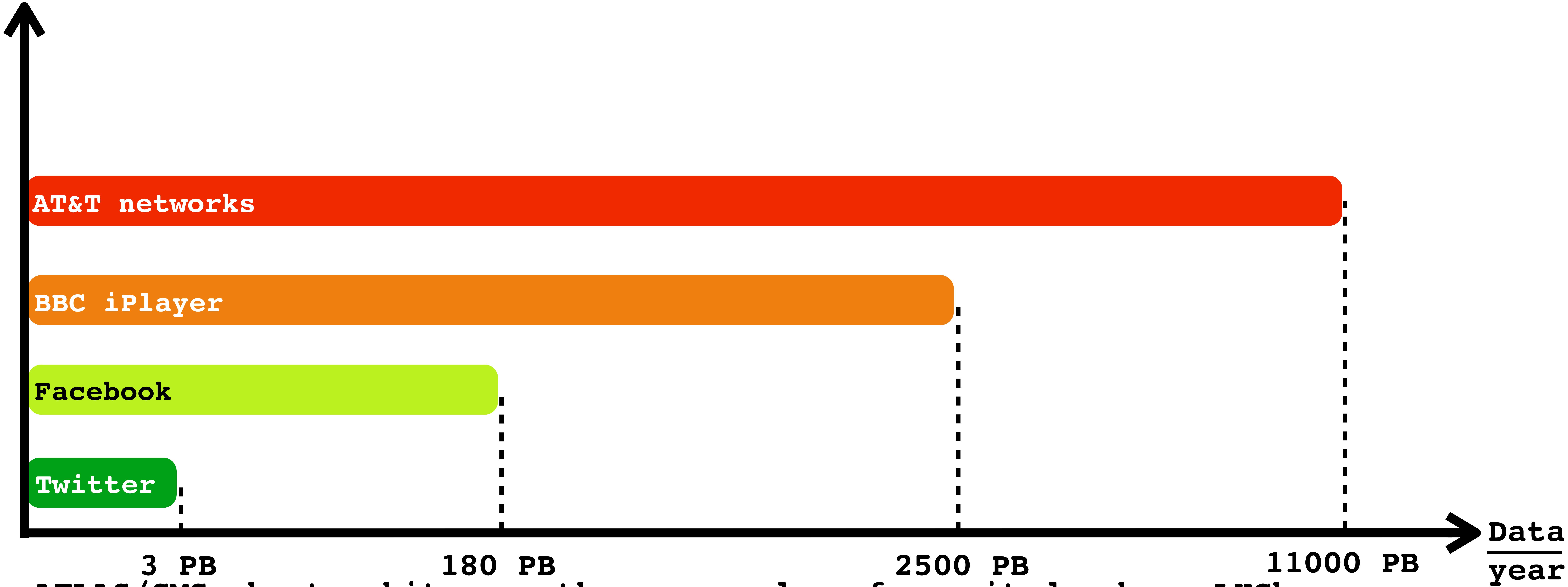

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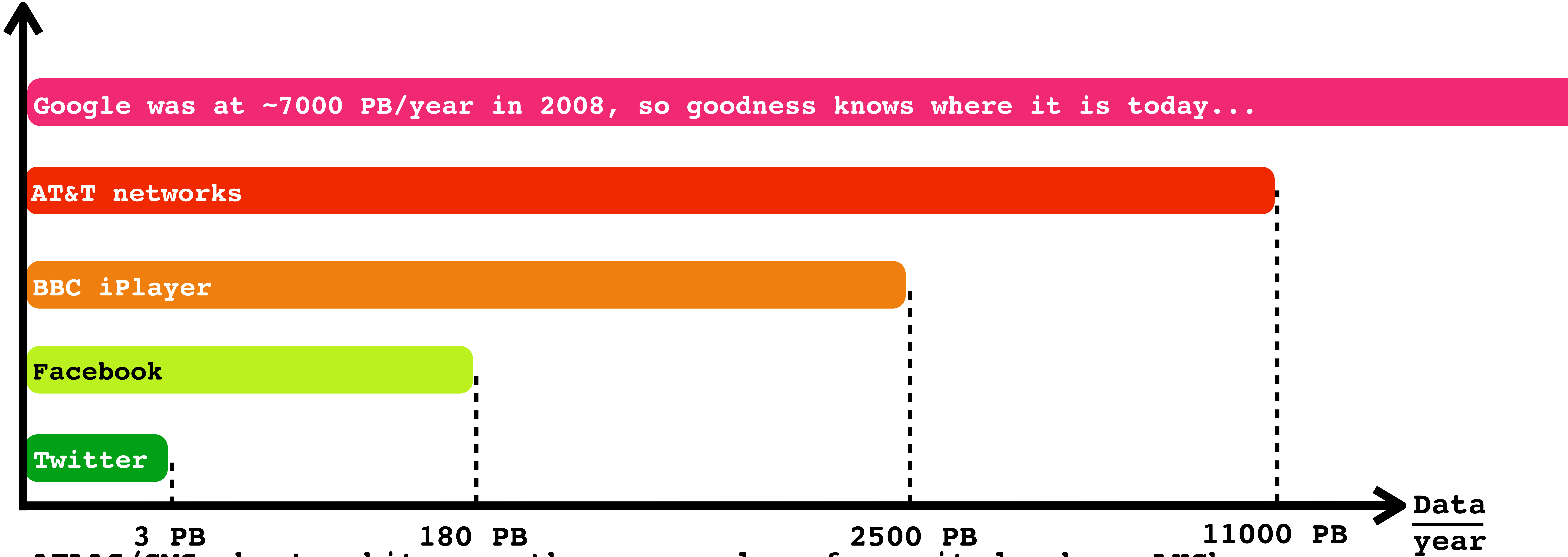

NB : ATLAS/CMS about a bit more than one order of magnitude above LHCb

It is mostly about the money

```
Facebook ~= 180 PB/year
```

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Facebook spending on data
~= 600 M$/year (circa 2011)
```

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Scaled cost of triggerless storage of LHCb ~= 50 B$/year

Total LHC budget ~= 10 B$

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Facebook ~= 180 PB/year

Facebook spending on data
~= 600 M$/year (circa 2011)

Scaled cost of triggerless storage of LHCb ~= 50 B$/year

Total LHC budget ~= 10 B$

Real time event selection

==

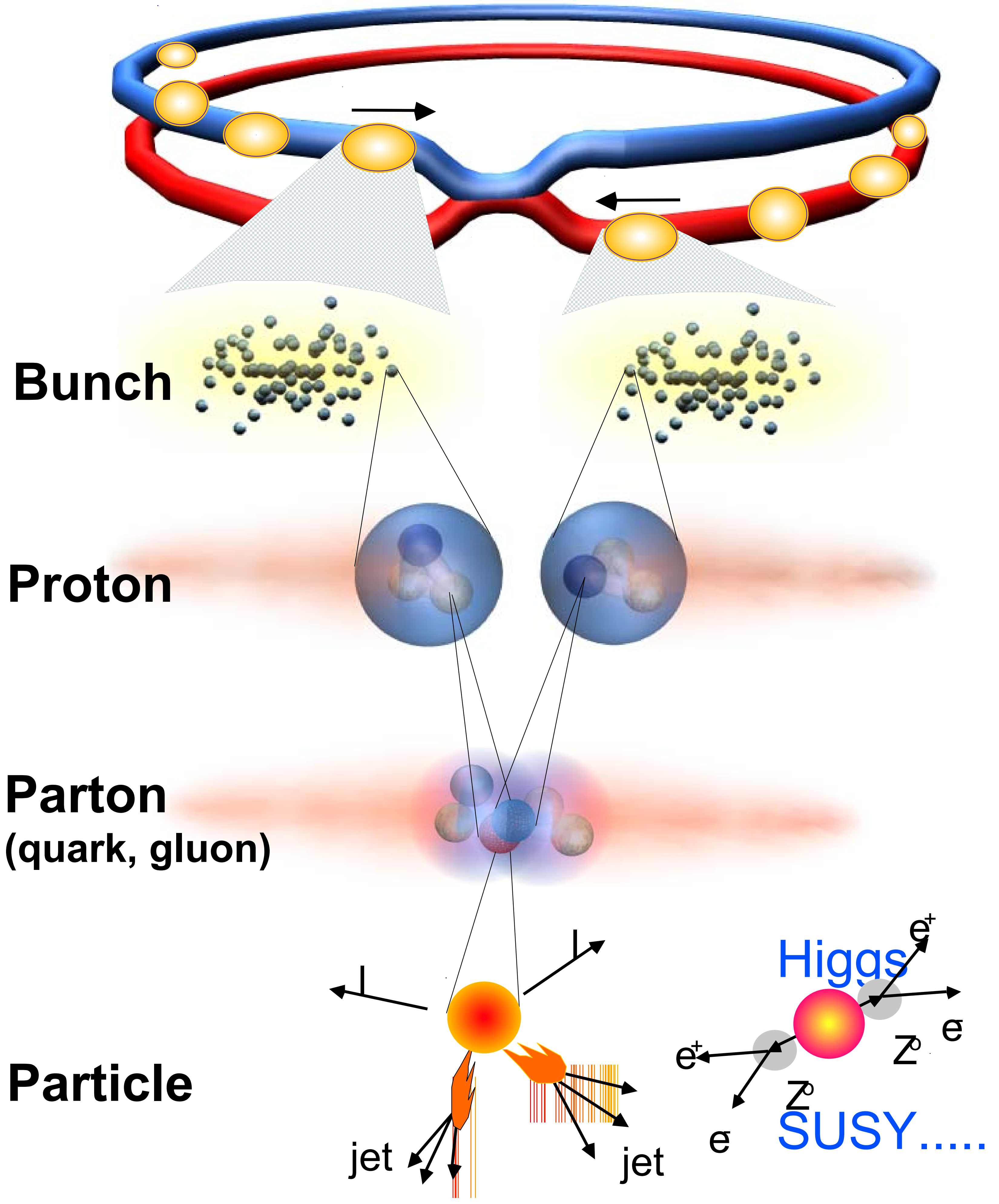
Money

Nota bene **: Even assuming infinite resources, transferring 1.5 TB/second from the detectors to storage is not easy... although we are getting to the point where it is possible (more on this later)**

Nota bene 2 **: Processing data is way cheaper than storing it**

The traditional view of triggers

Collisions at the LHC: summary



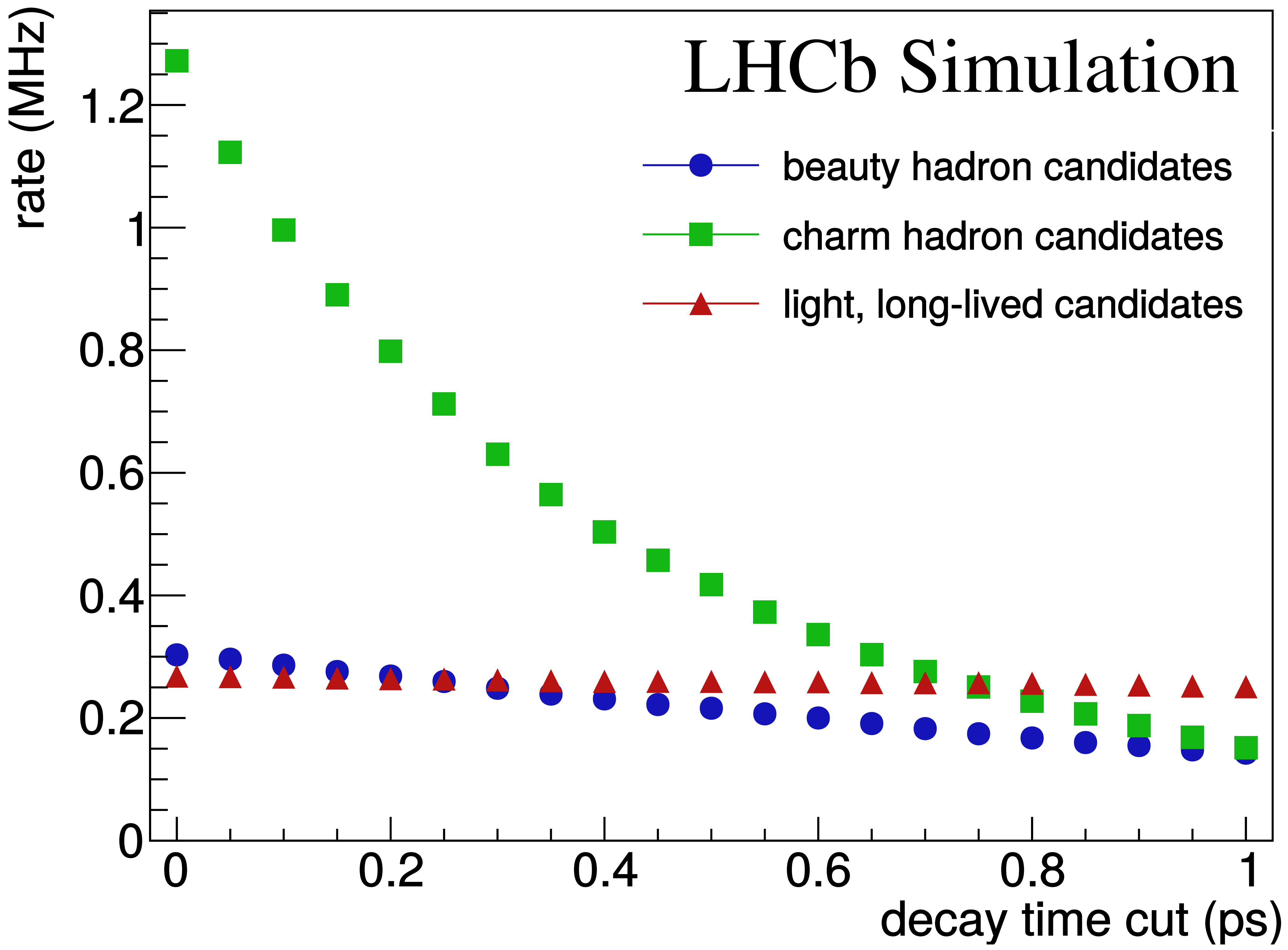
Proton - Proton	2804 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	$10^{34}cm^{-2}s^{-1}$
Crossing rate	40 MHz
Collision rate ≈	10^{7}-10^{9}

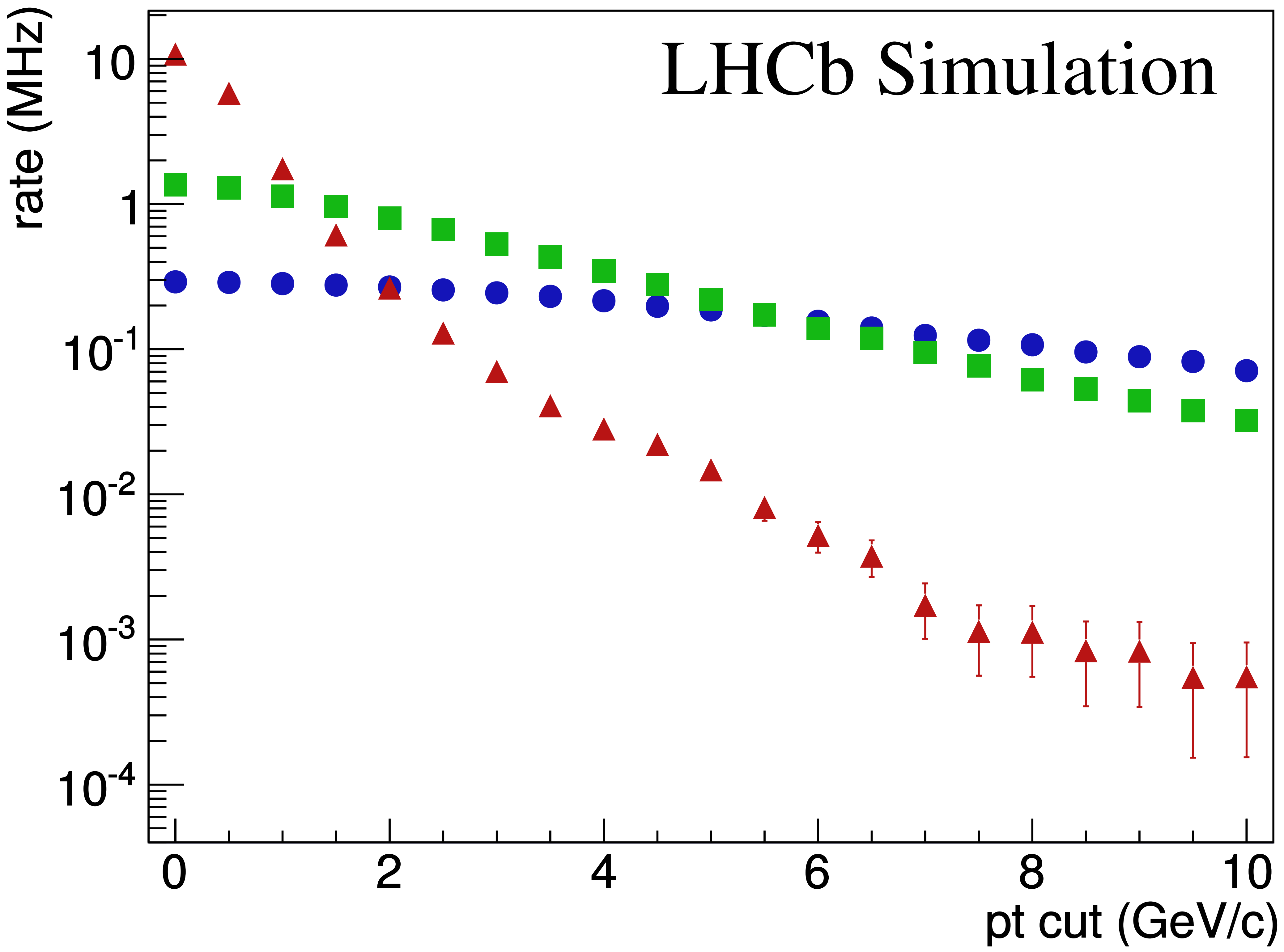
New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

Triggers today

Enter the MHz signal era





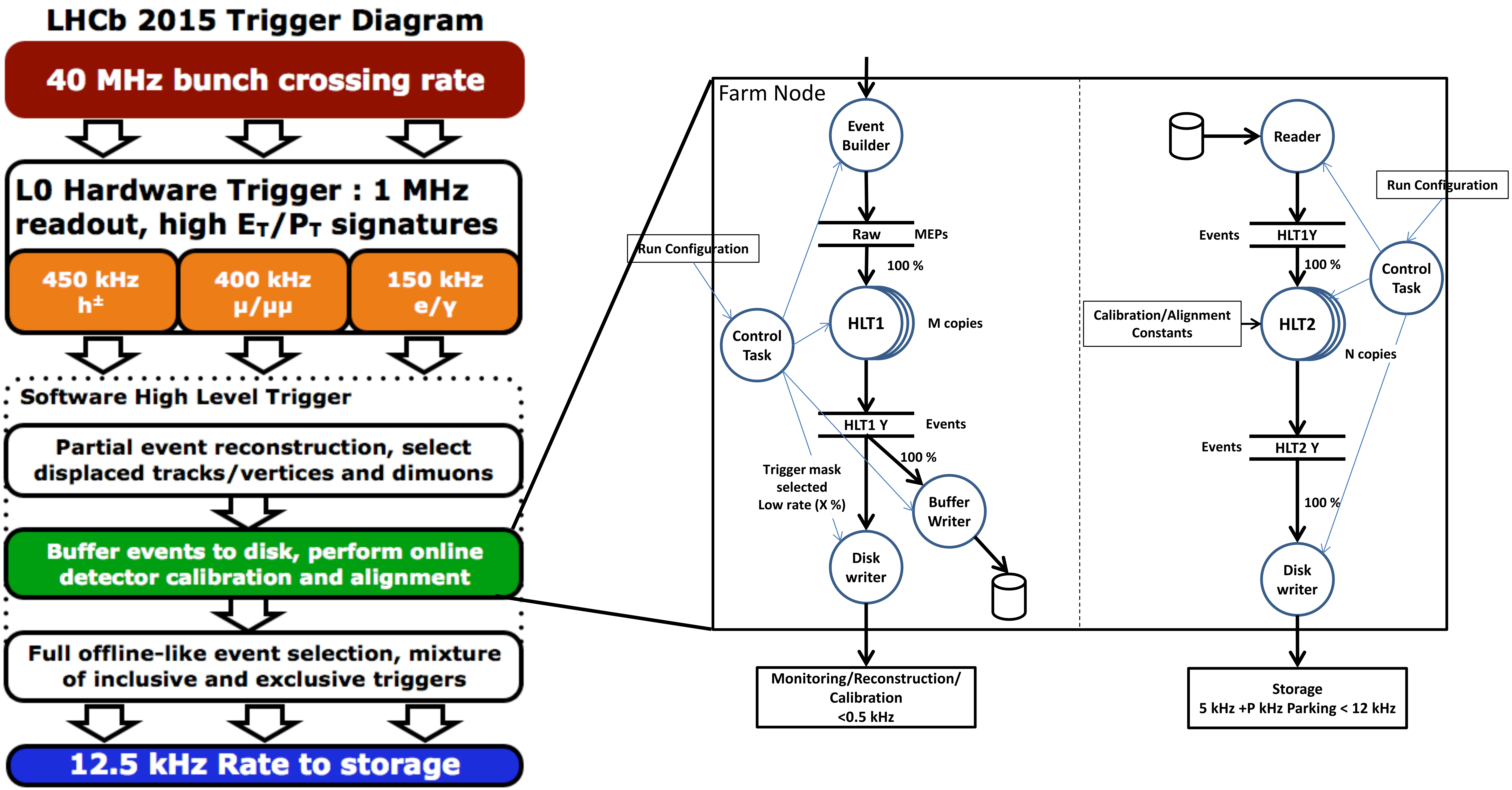
In the HL-LHC era triggers will discriminate between different signal classes!

Fitzpatrick&Gligorov http://cds.cern.ch/record/1670985?ln=en

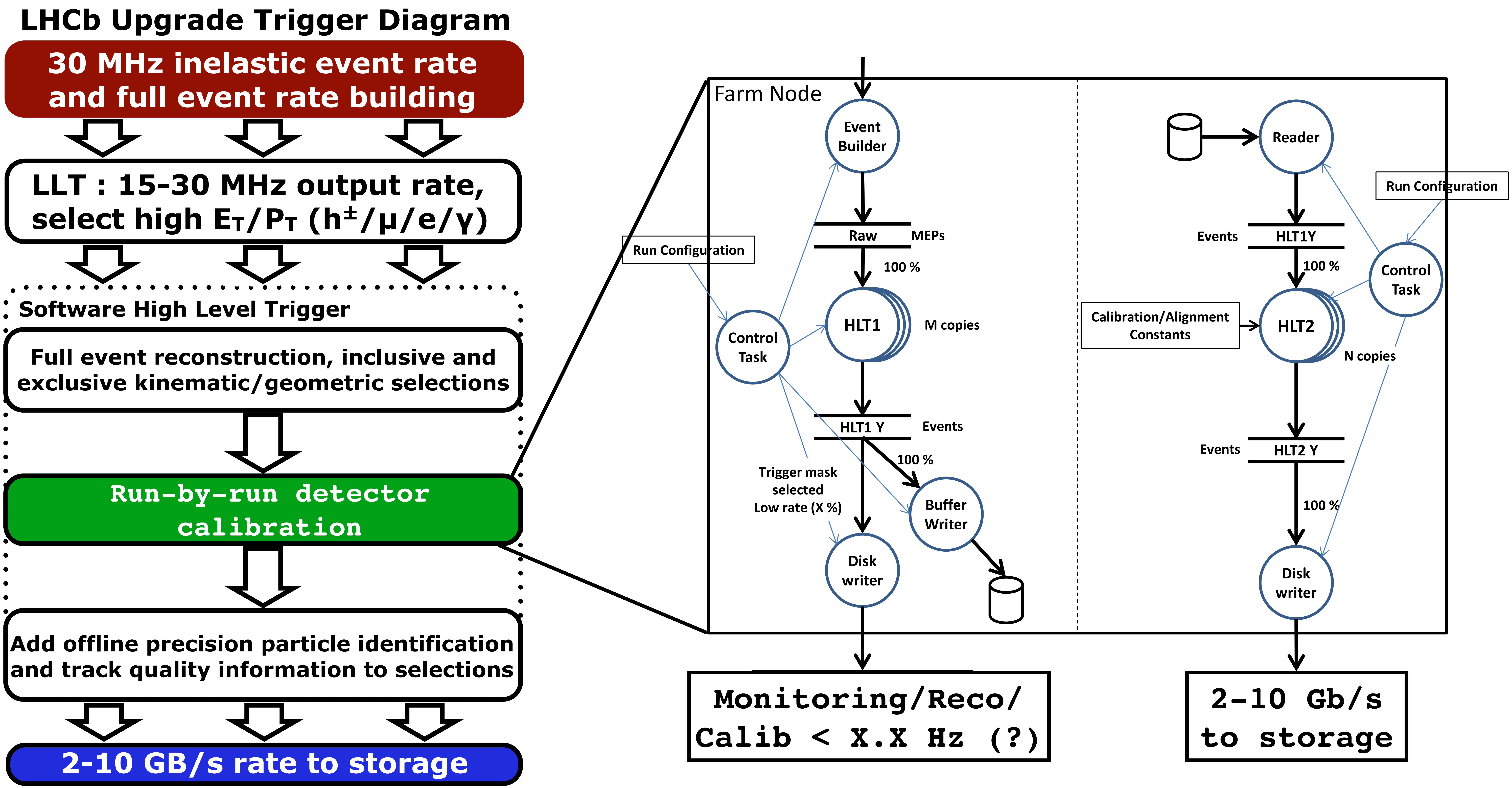
Triggers today

Triggers in the future

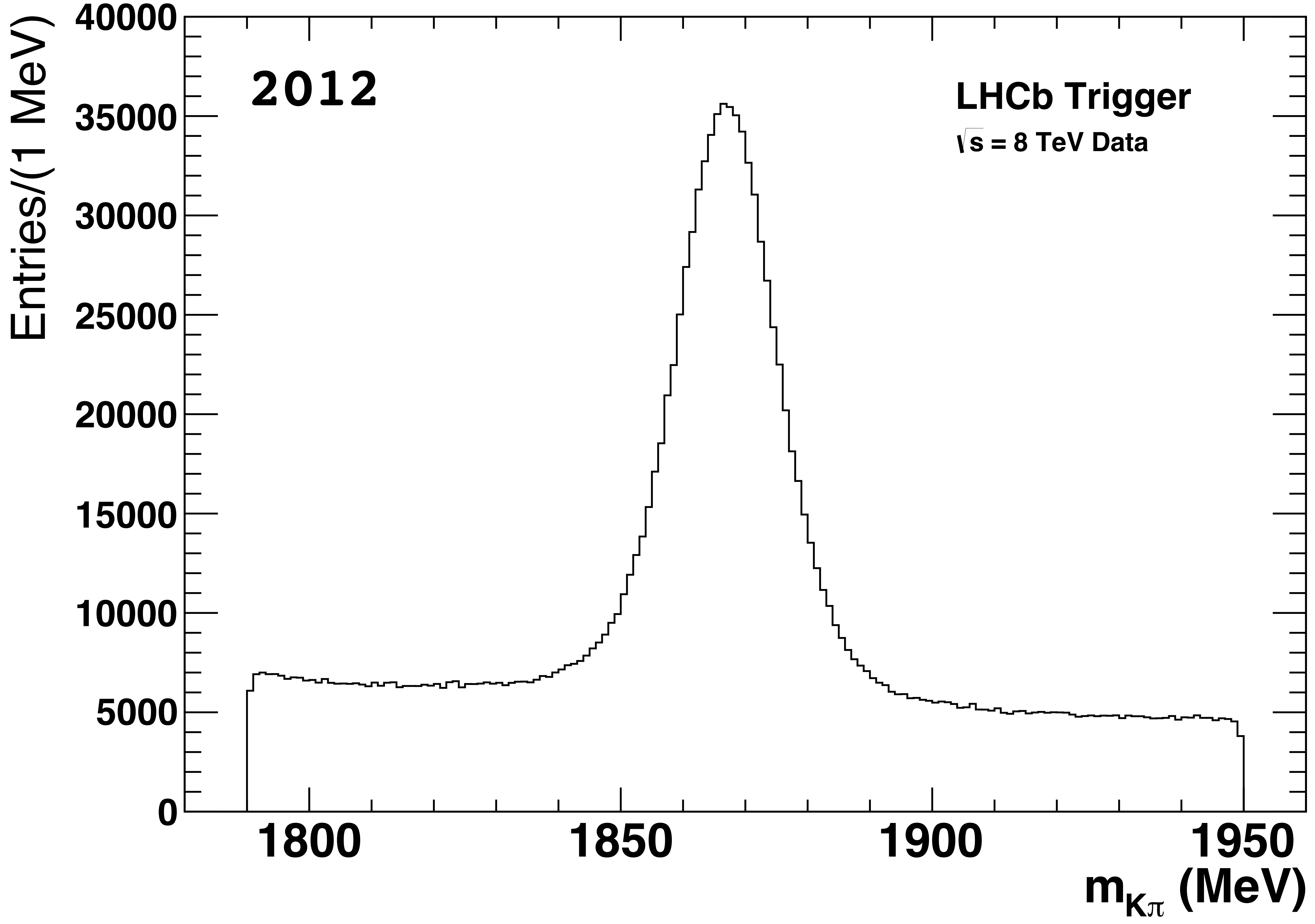
More precision ⇒ real time analysis



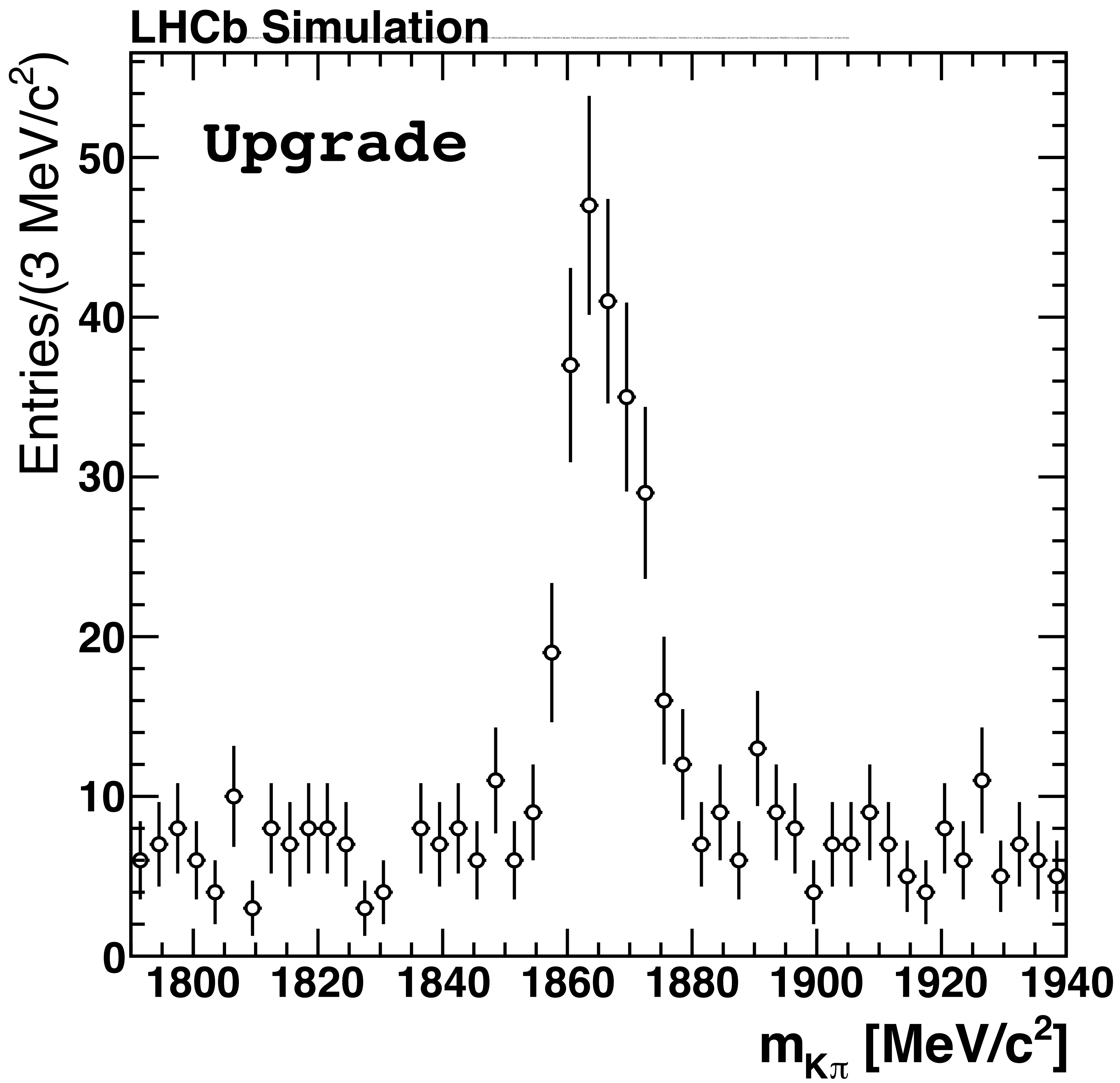
And so on into the upgrade era



Charm signal purity from LHCb trigger



HLT2 $D^0 \to K^- \pi^+$



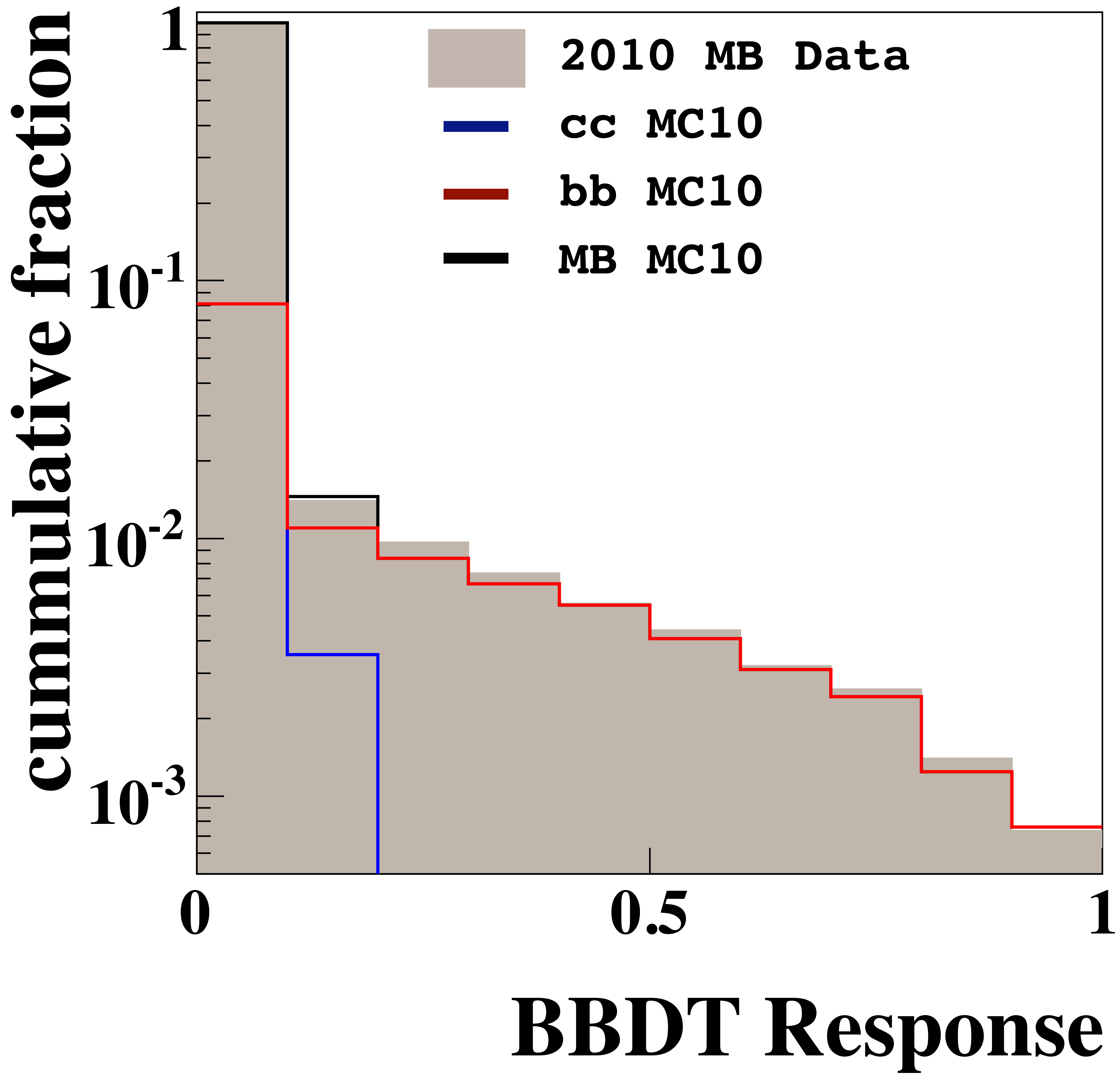
Remember we said charm today == beauty tomorrow.
I hope you are getting scared about systematics.

Real time MVA is challenging

In the future the trigger/DAQ systems will perform almost all the event reconstruction, detector calibration, and signal selection.

We need multivariate trigger algorithms which are safe for real-time use and robust against detector inefficiencies.

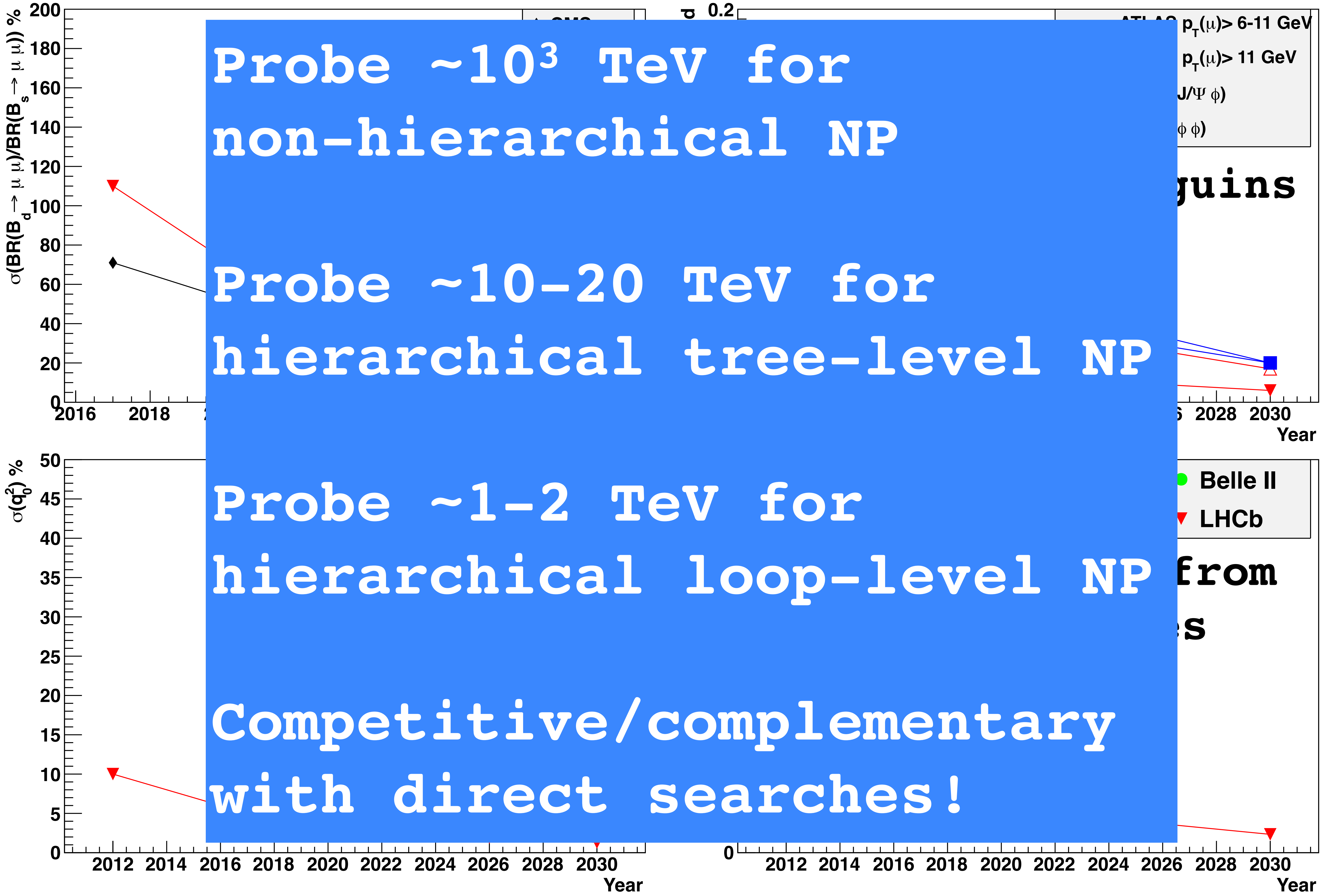
Have made a start on this at LHCb, but a lot of R&D still needed!



See also LHCb-PUB-2011-002,003,016
http://arxiv.org/abs/1310.8544
http://arxiv.org/abs/1211.3055

Gligorov&Williams http://arxiv.org/abs/1210.6861

The rewards are great, however



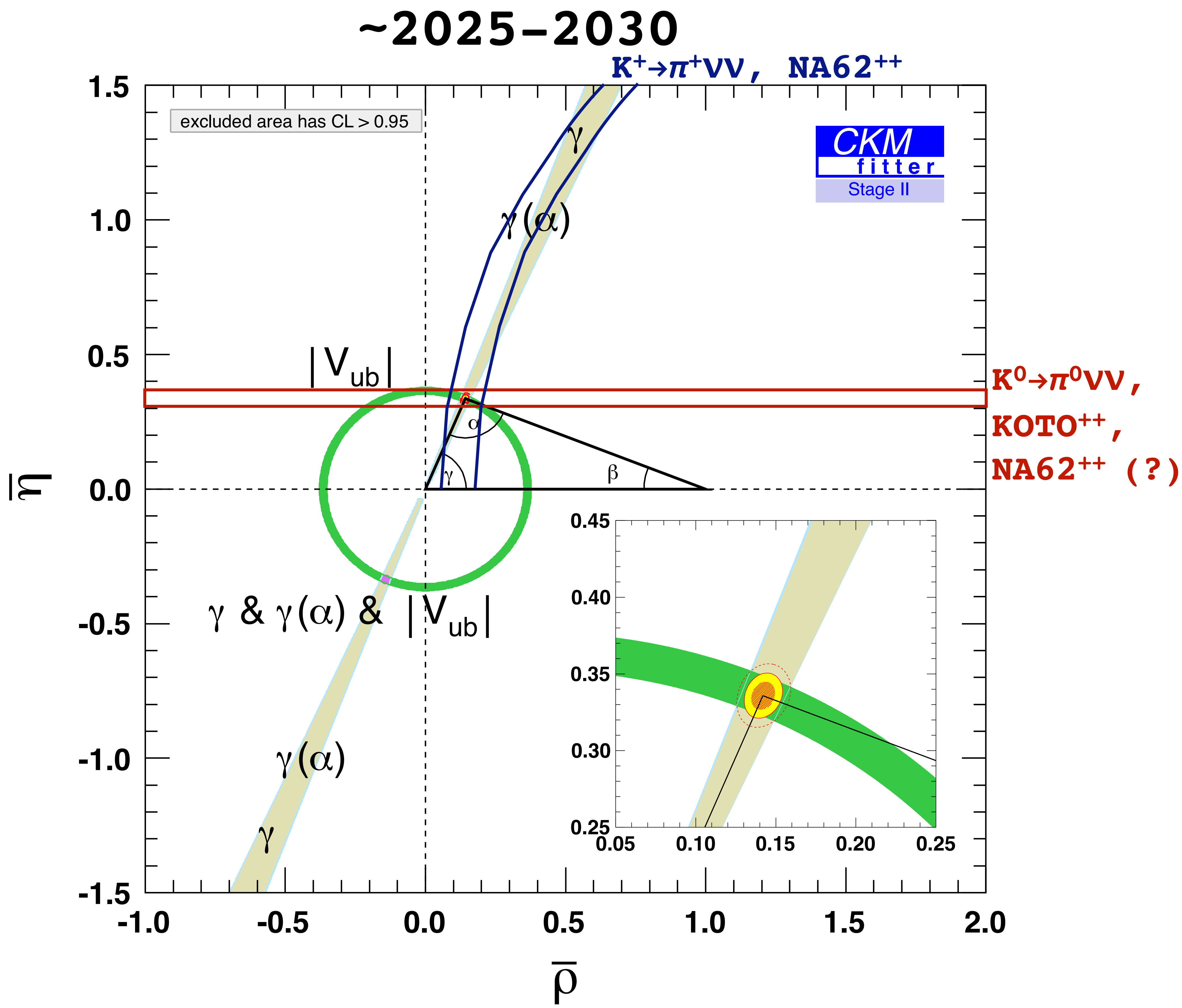
Probe ~10^3 TeV for non-hierarchical NP

Probe ~10-20 TeV for hierarchical tree-level NP

Probe ~1-2 TeV for hierarchical loop-level NP

Competitive/complementary with direct searches!

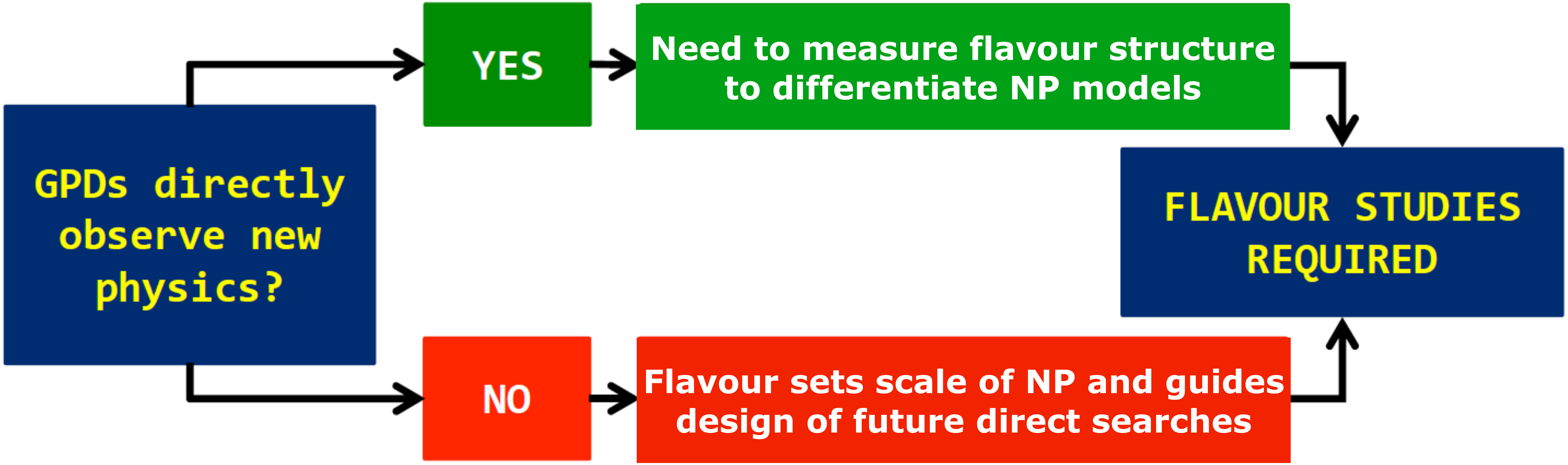
~2025-2030



https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

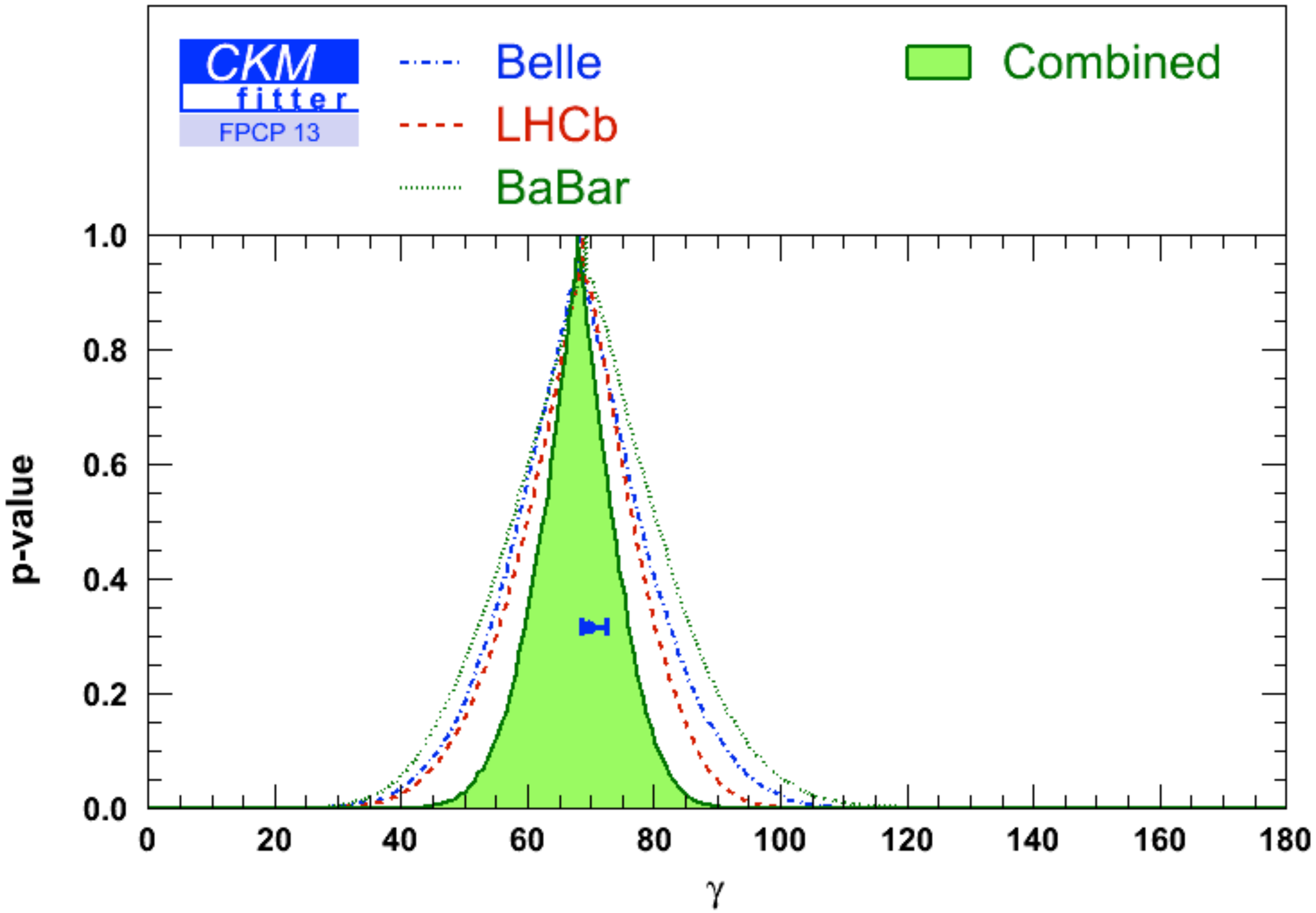
J. Charles et al. http://arxiv.org/abs/1309.2293

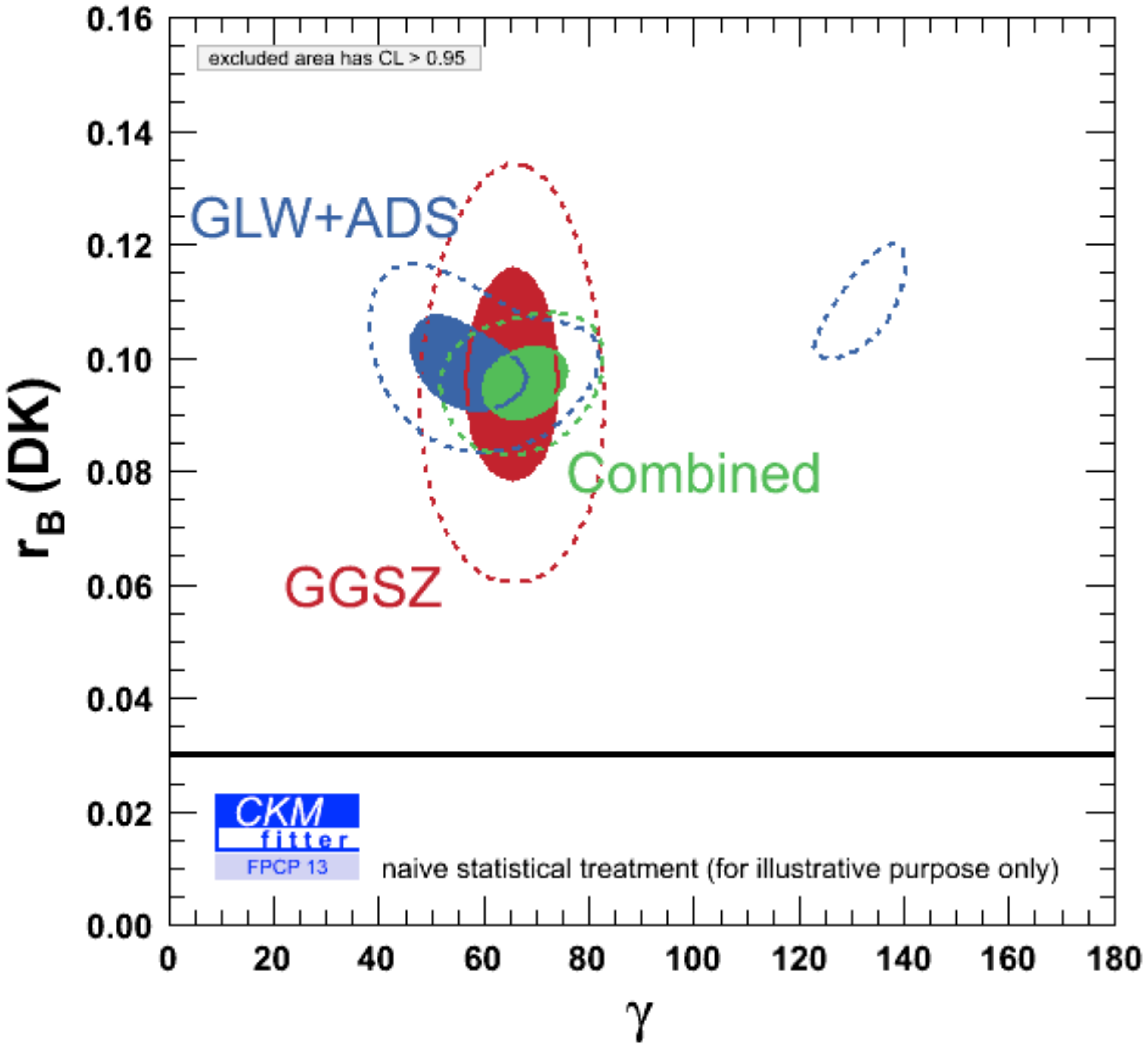
Ceterum censeo, flavour importante est



Backups

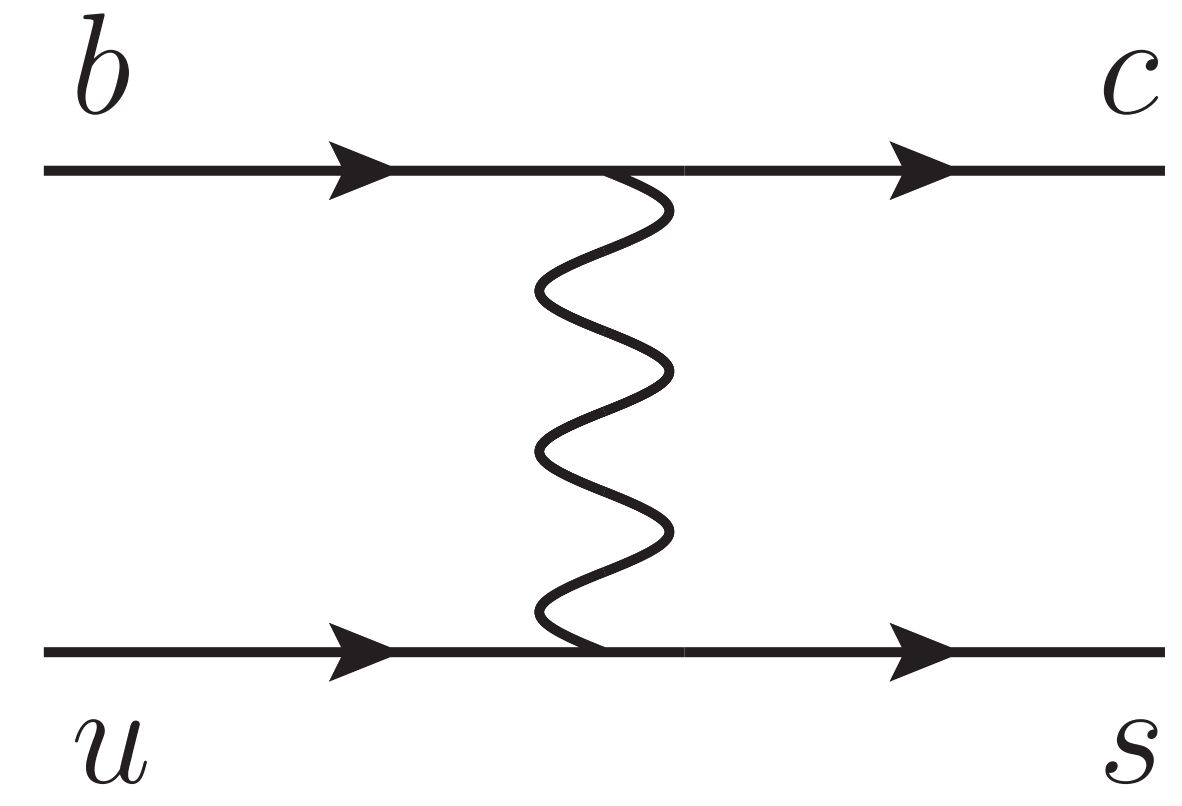
LHCb and the B-factories combined

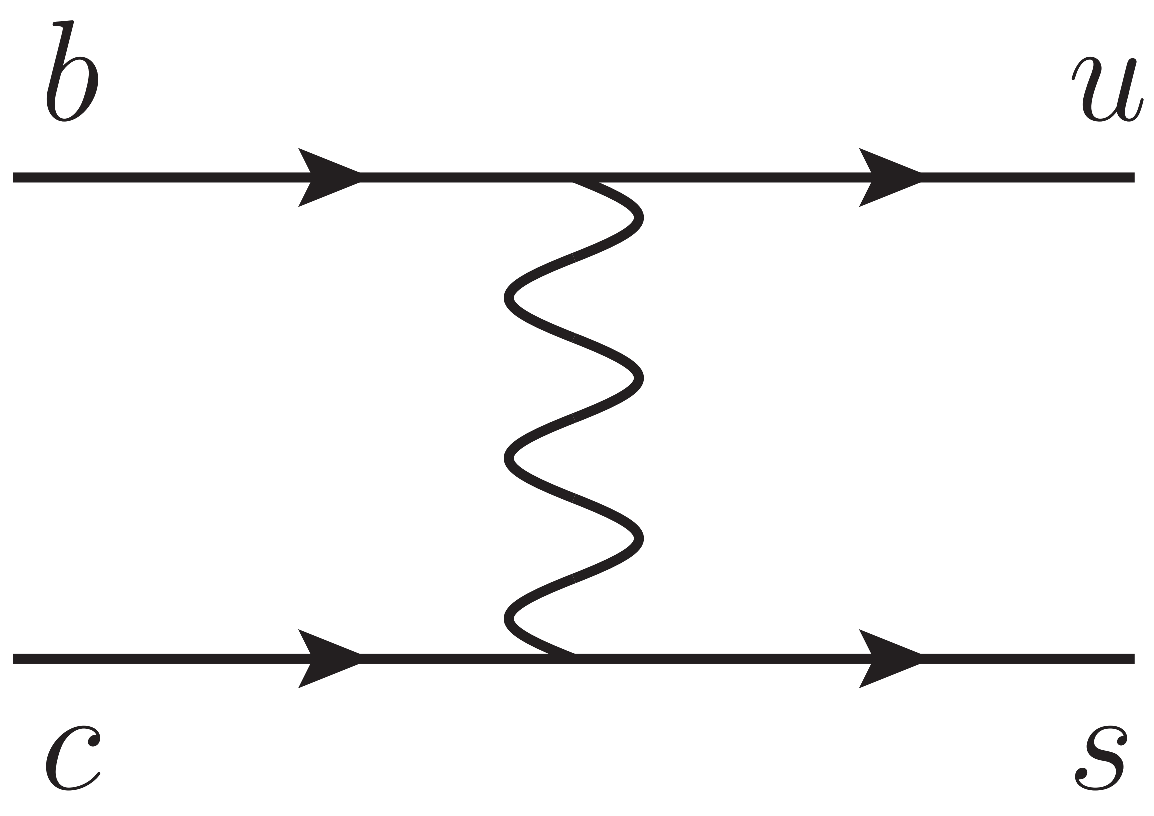


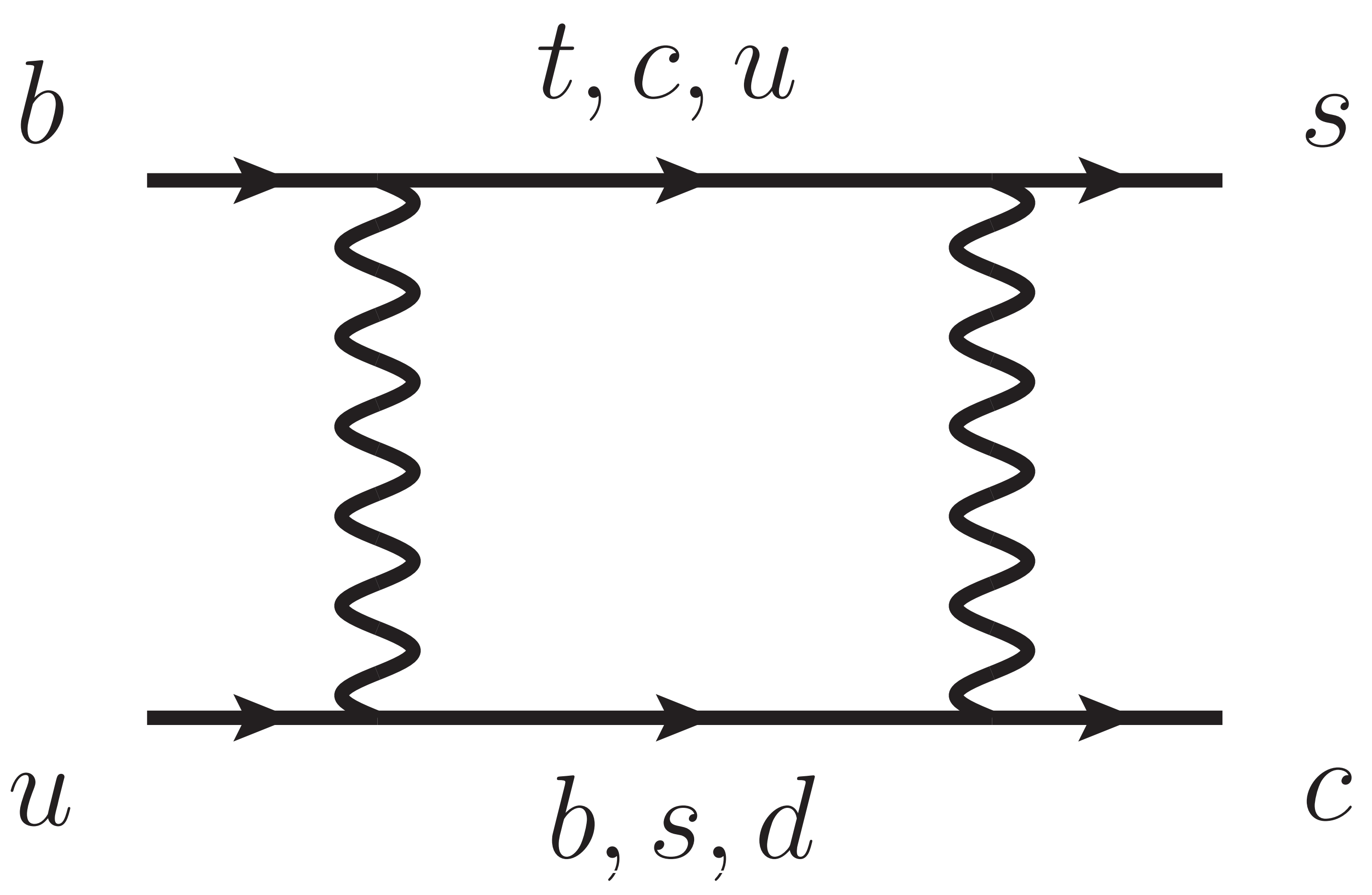


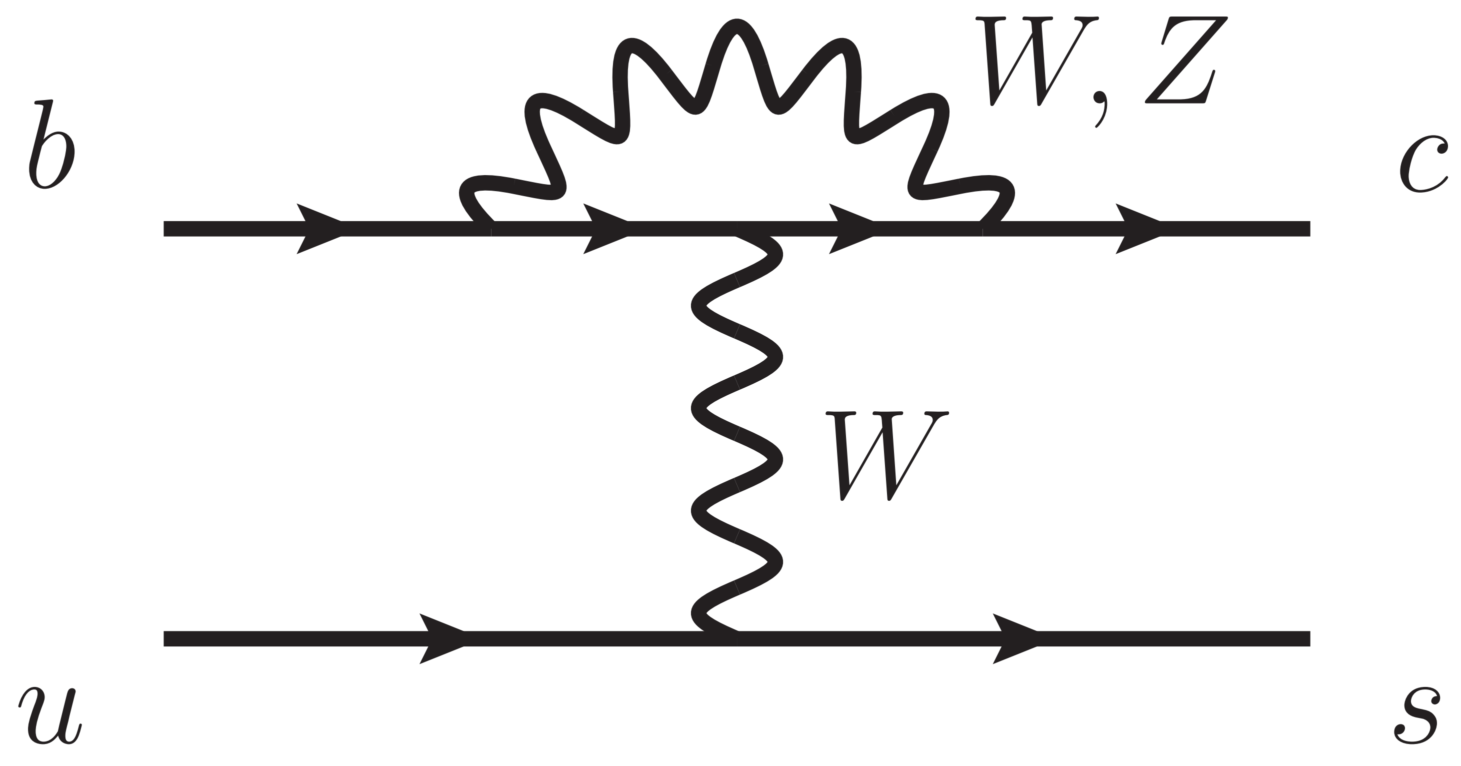
LHCb-CONF-2013-006

Ultimate theory error on γ



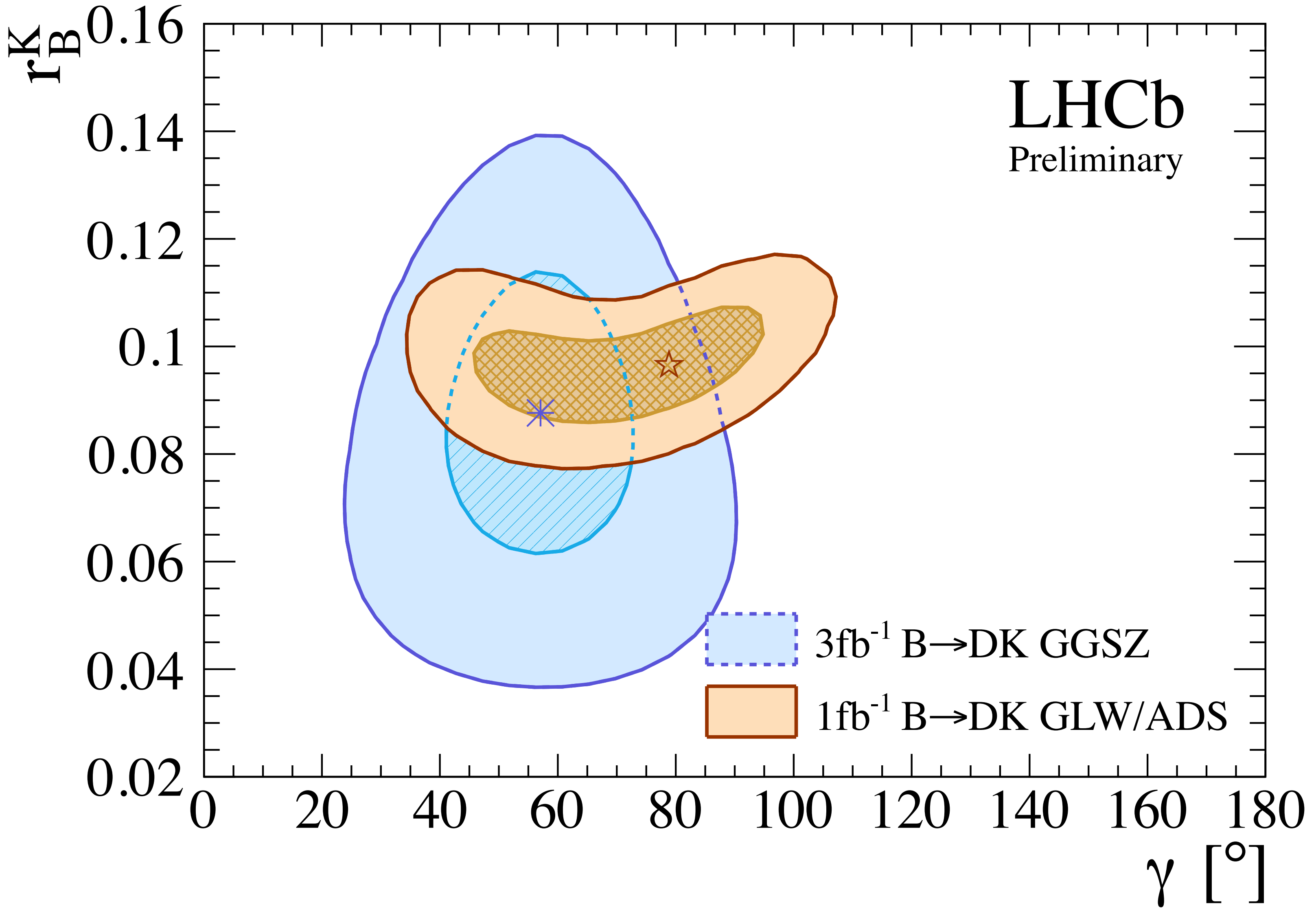




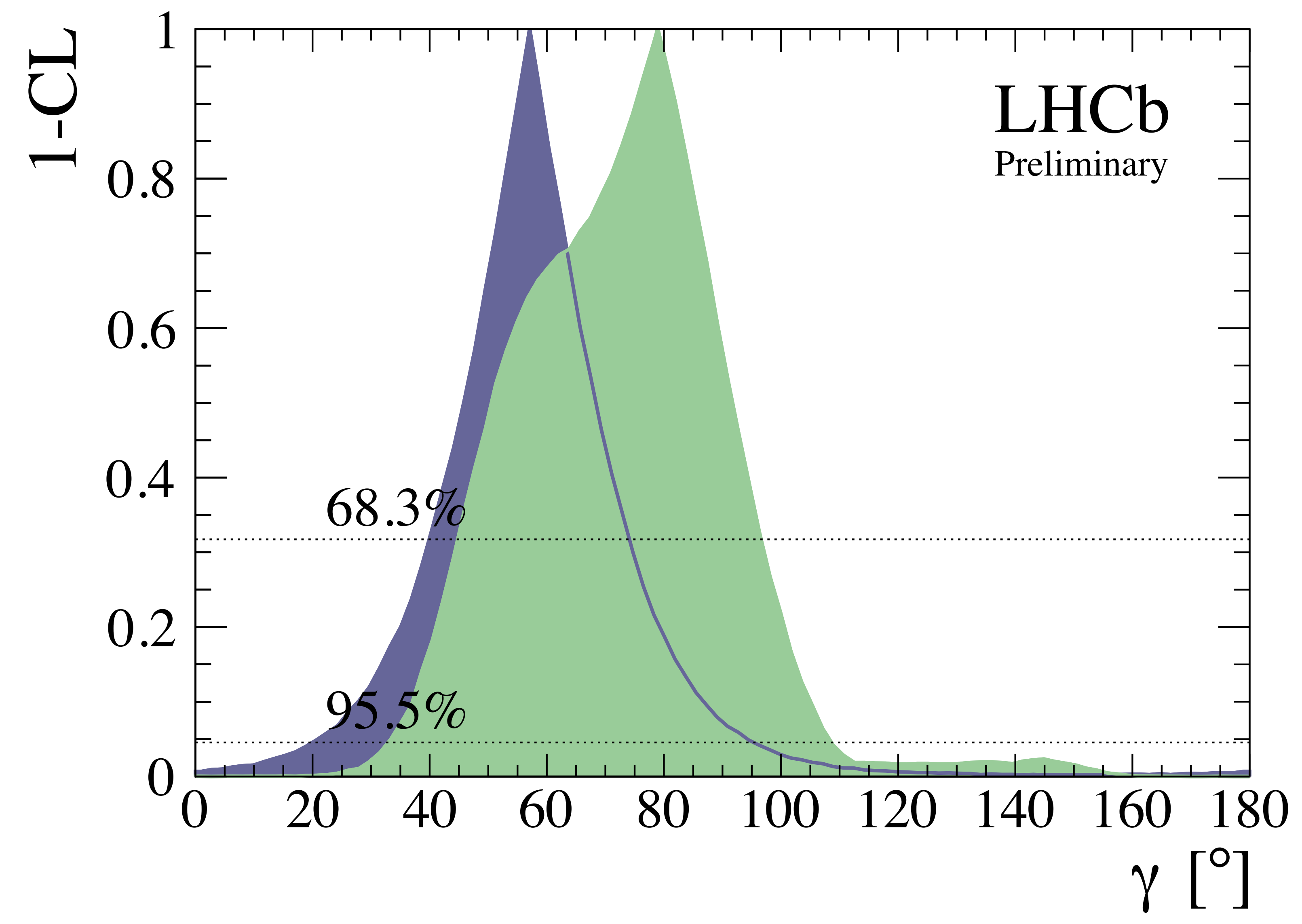


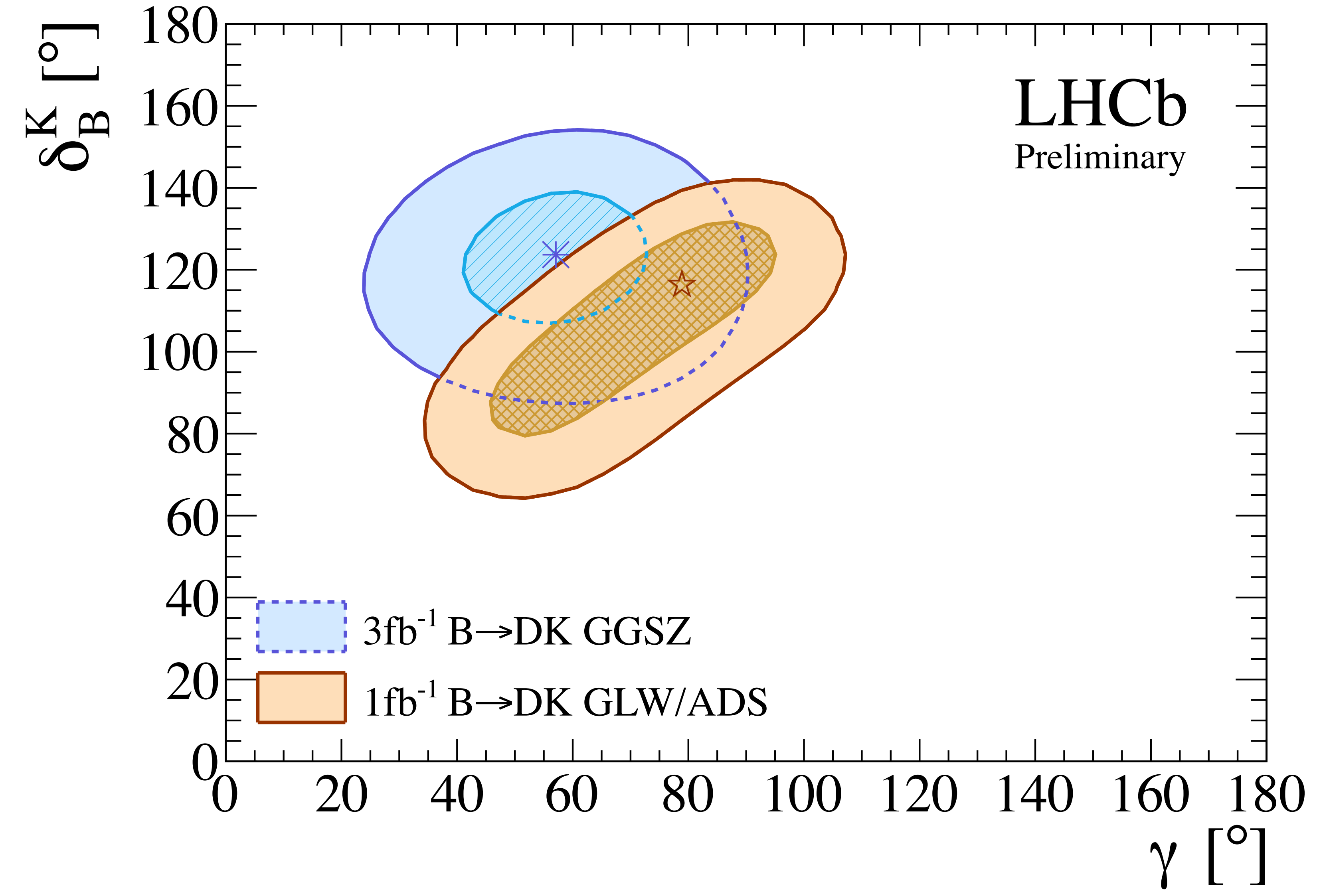
Zupan&Brod
http://arxiv.org/pdf/1308.5663.pdf

Combining the individual measurements



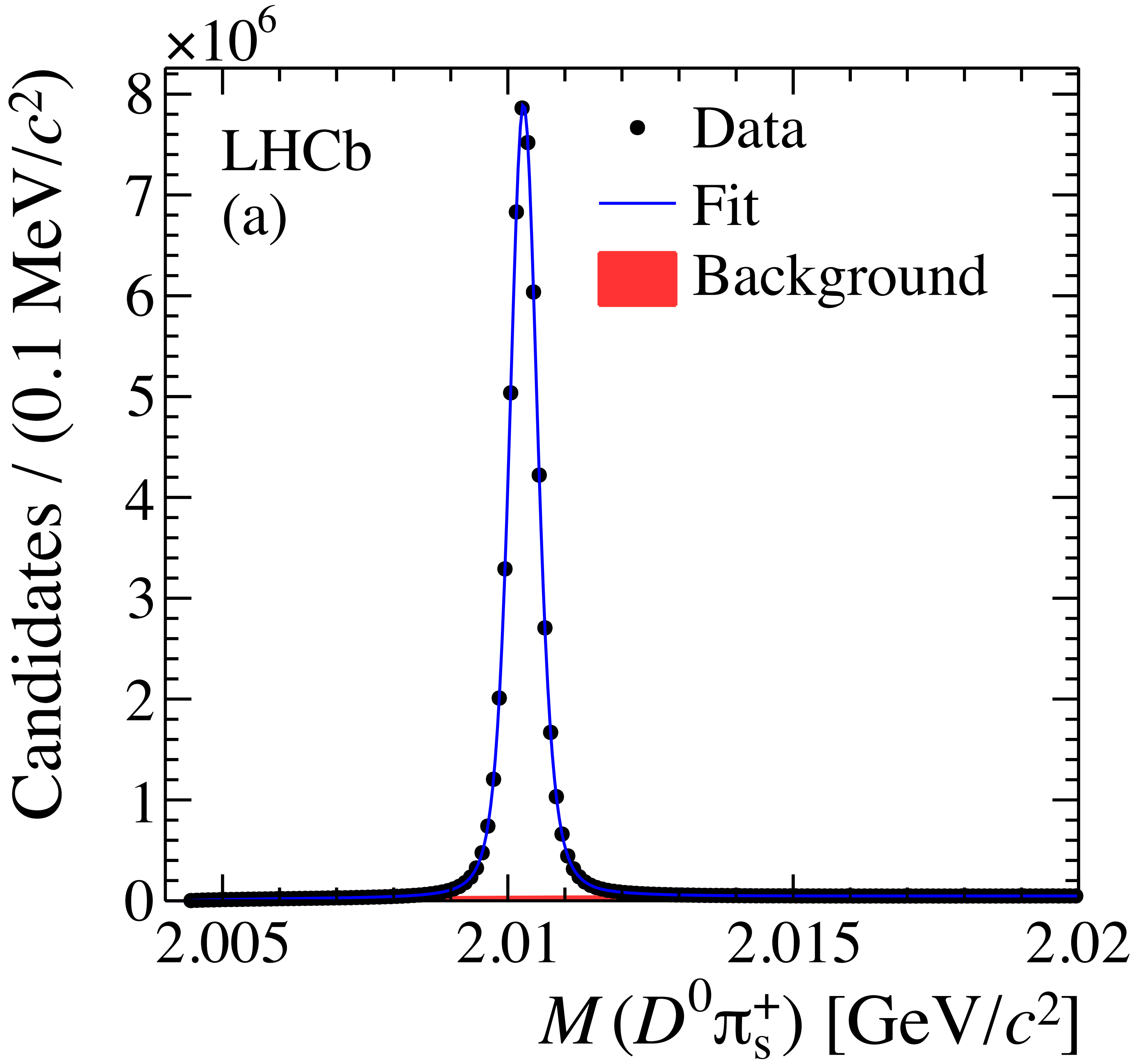
- ADS/GLW 1 fb^{-1} analysis
- GGSZ 3 fb^{-1} analysis

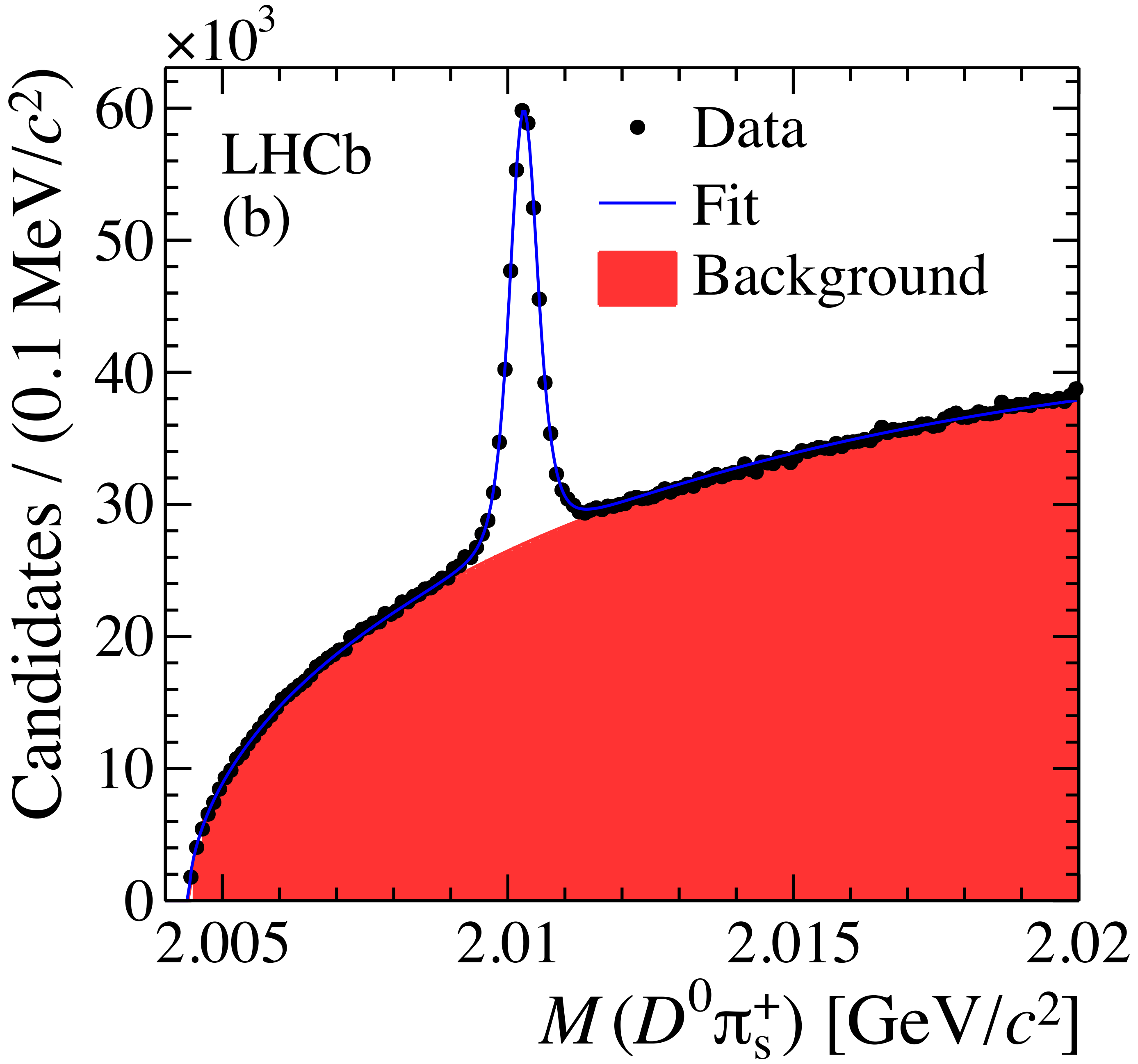




LHCb-CONF-2013-006

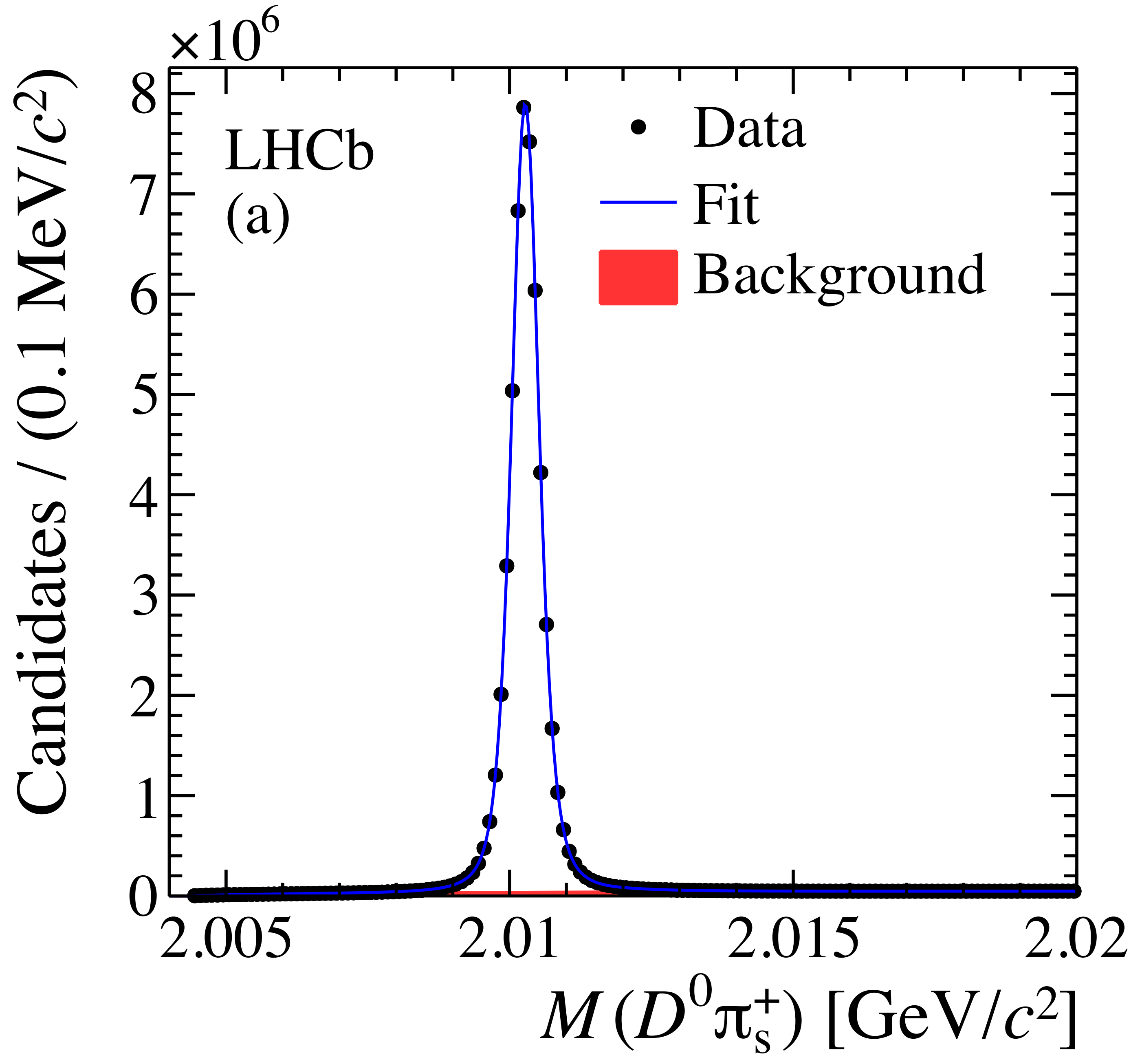
D^0 mixing and CPV

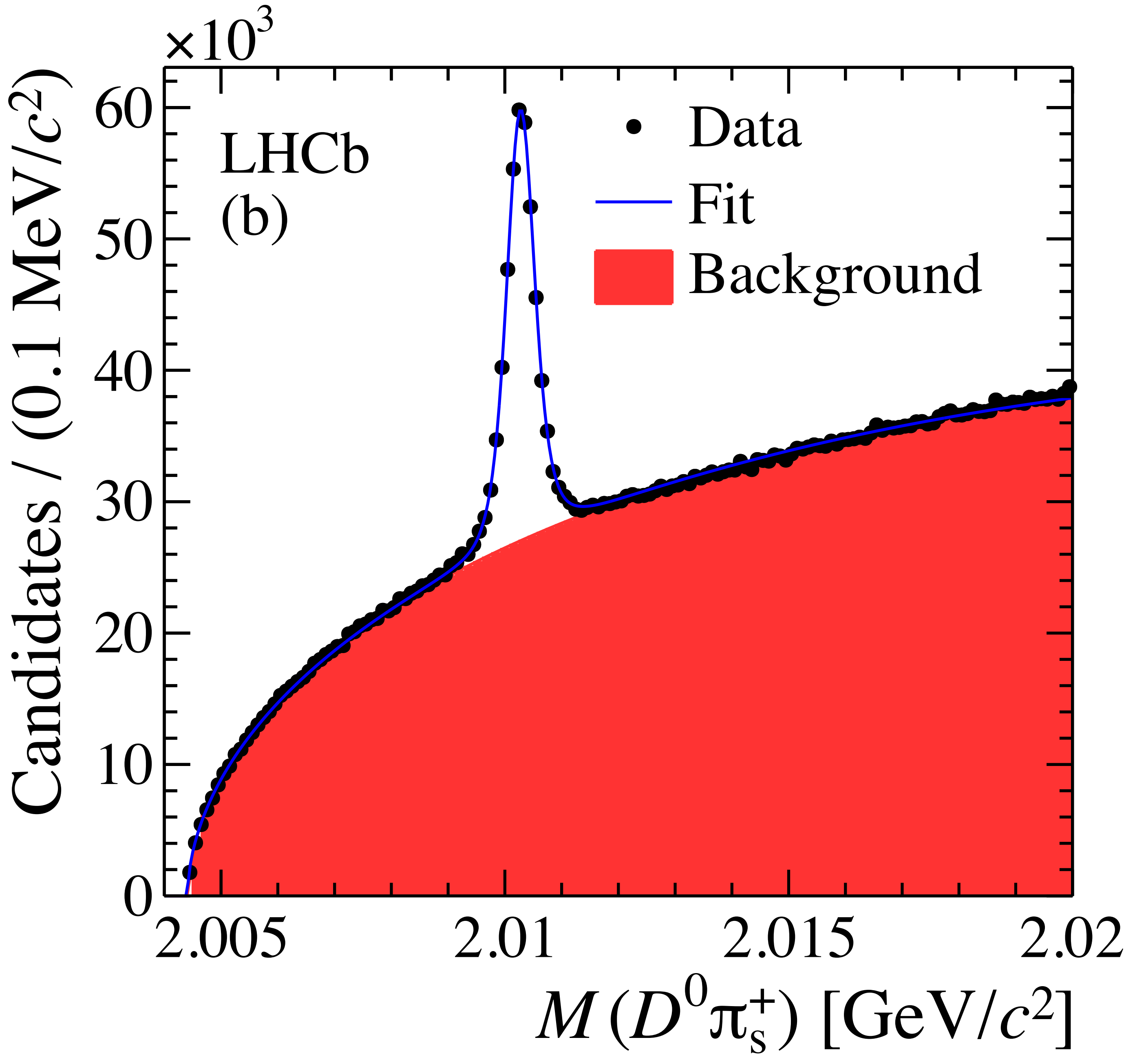


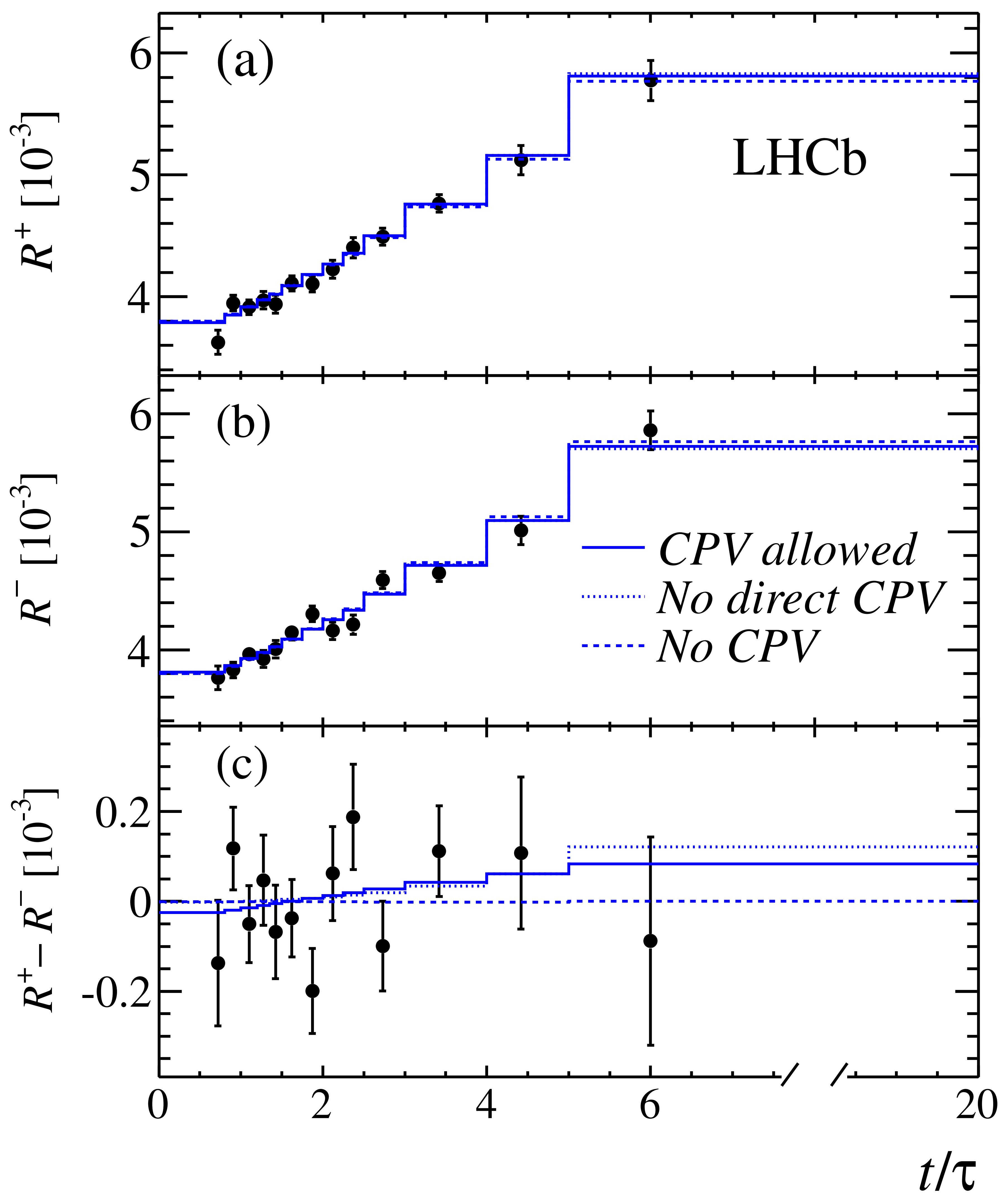


PRL 110 (2013) 101802
PRL 111 (2013) 251801

D^0 mixing and CPV







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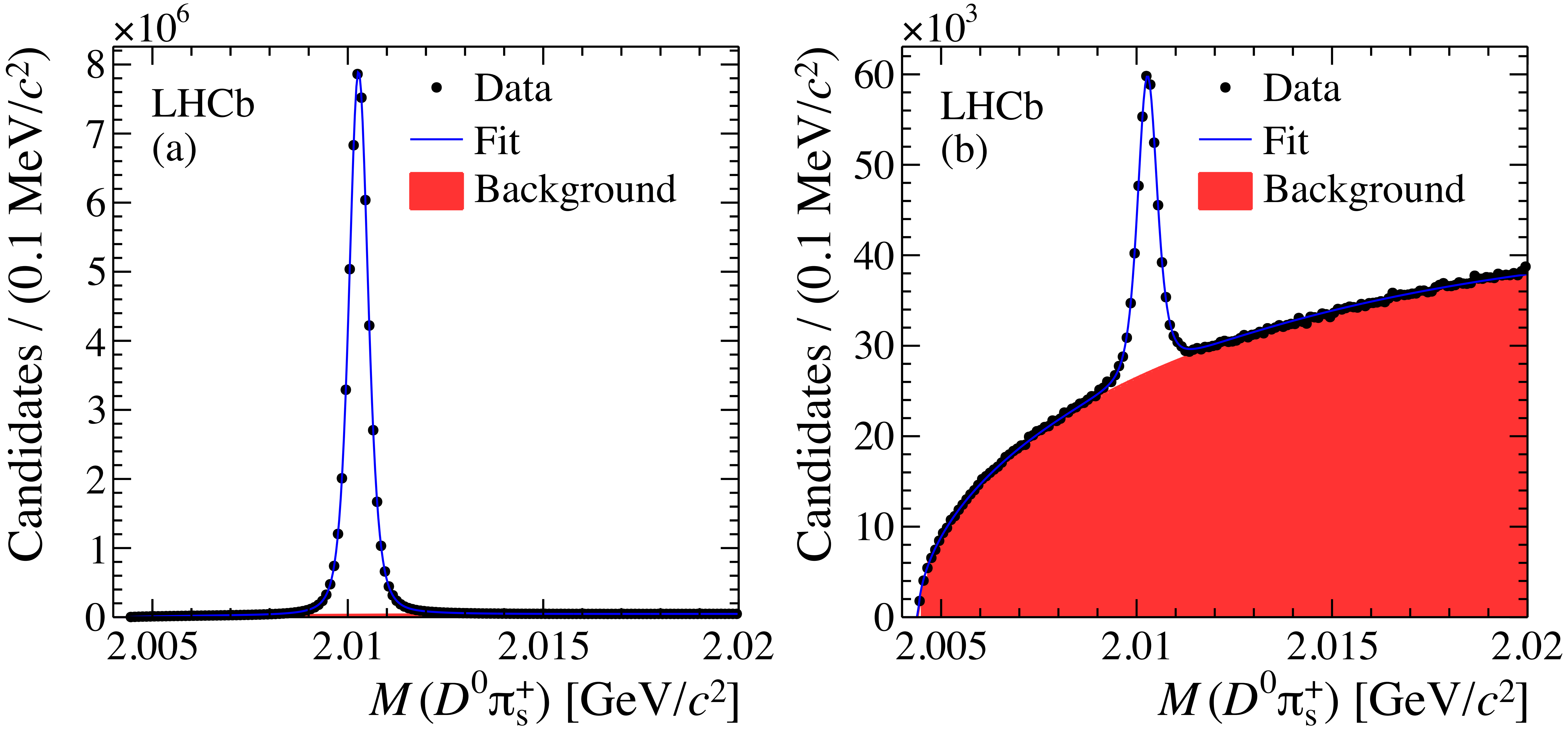
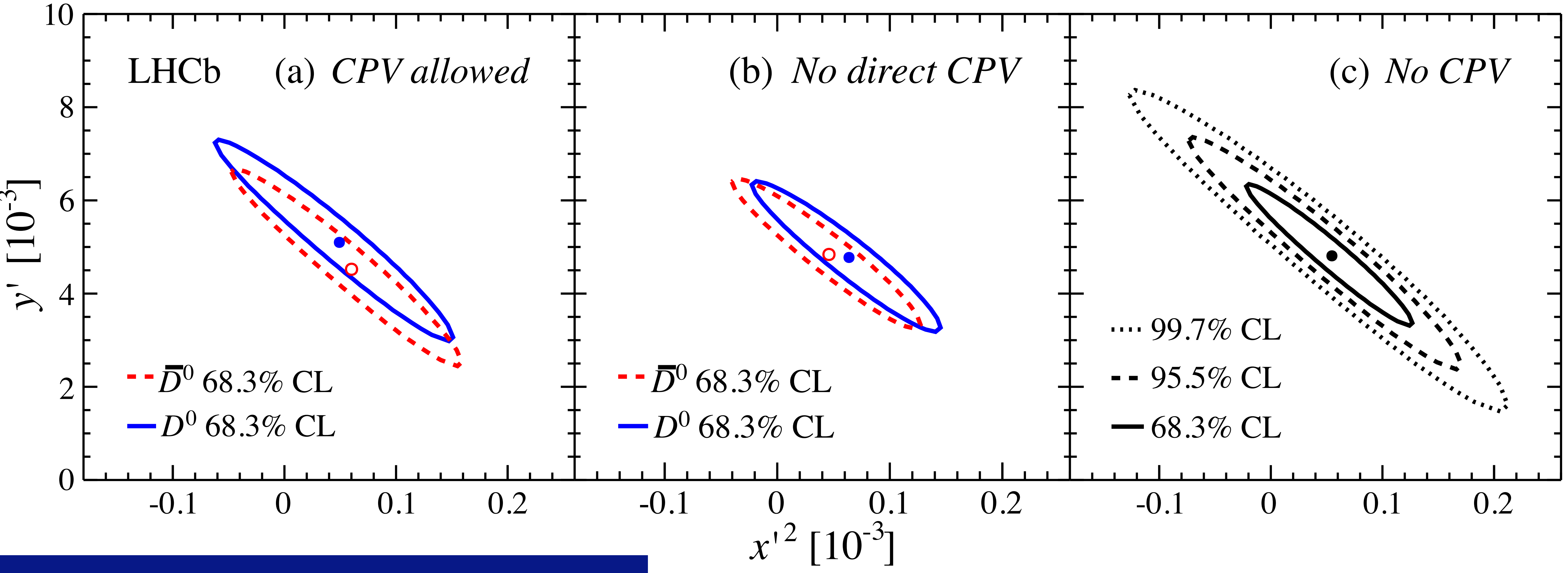
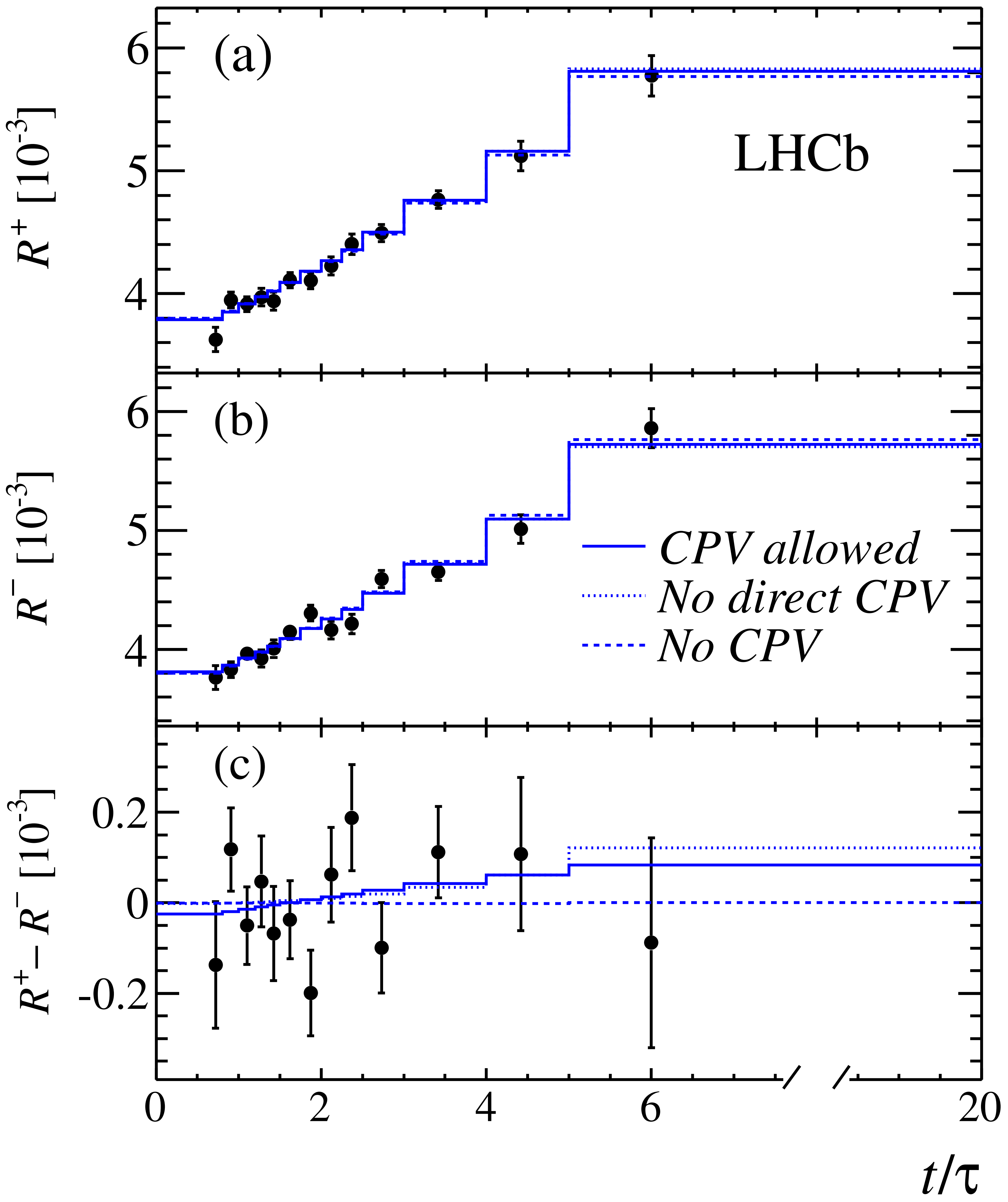




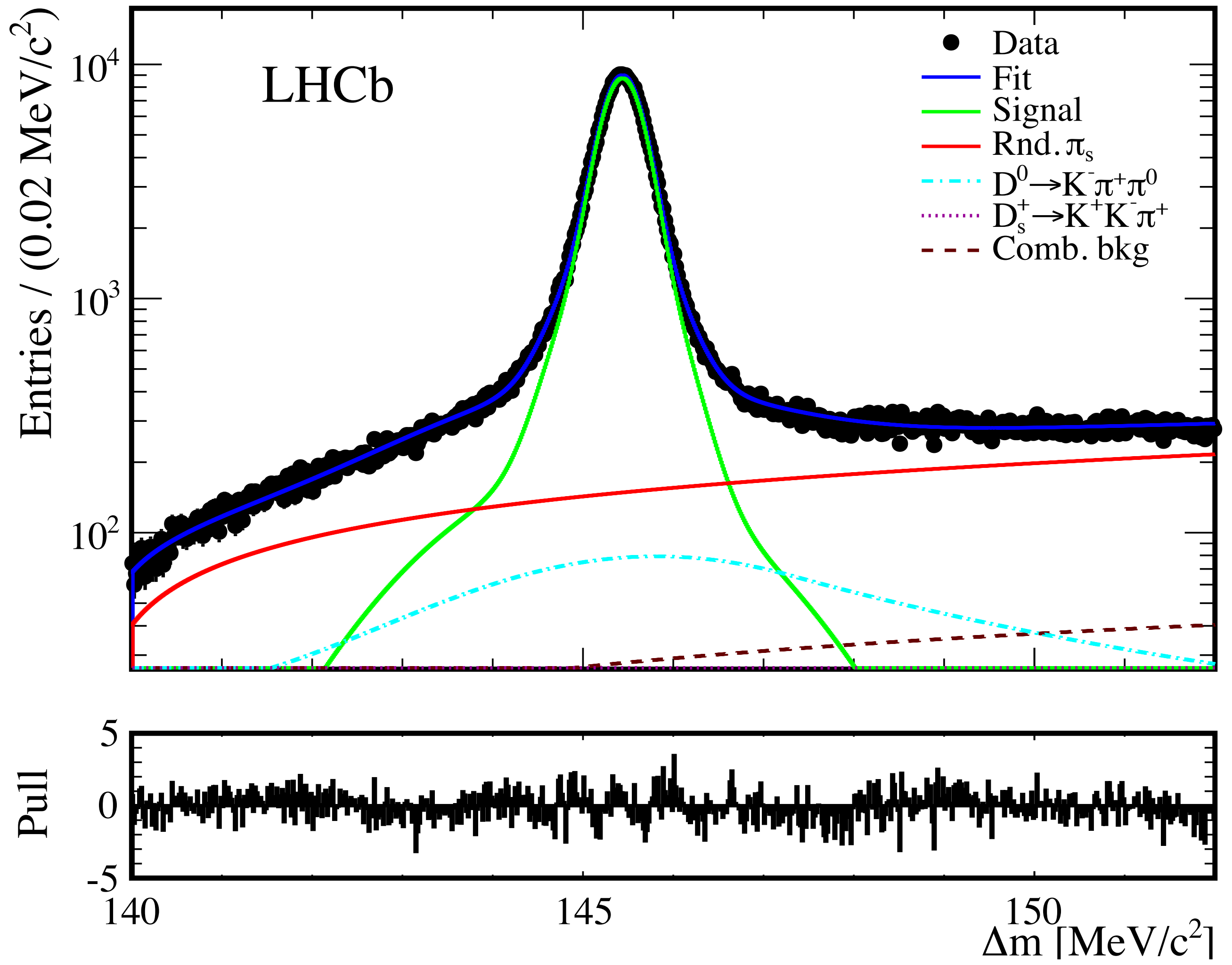


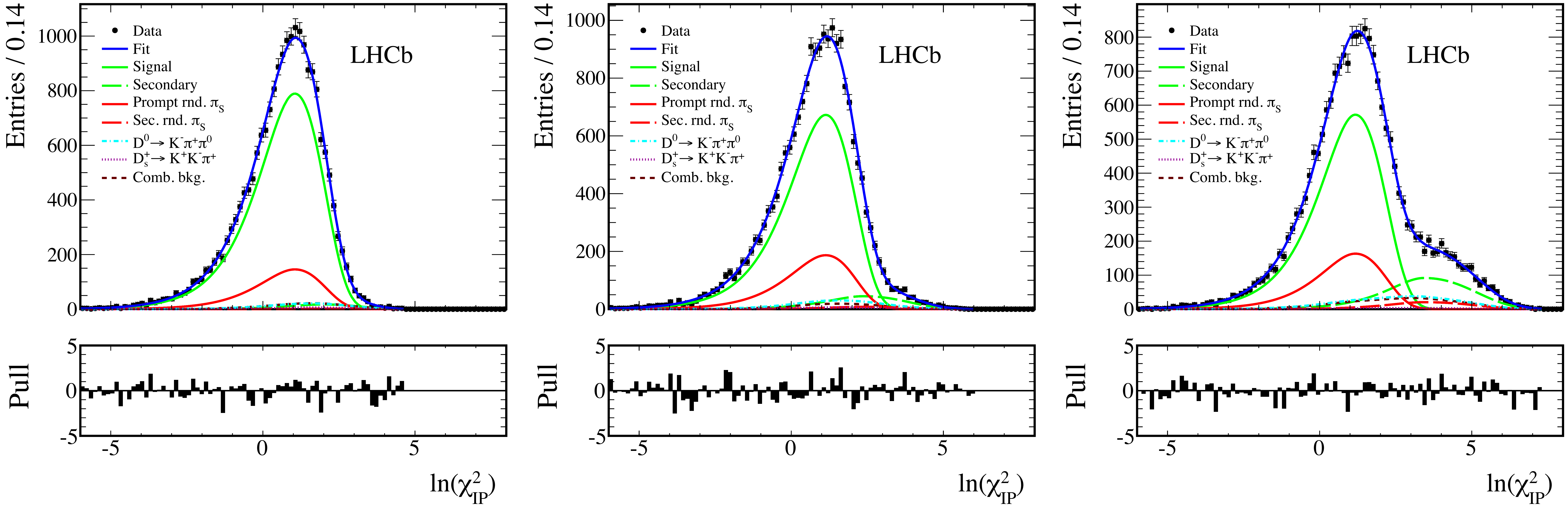
PRL 110 (2013) 101802

PRL 111 (2013) 251801

Indirect CPV, A_Γ

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}} \approx \eta_{CP}\left(\frac{A_m + A_d}{2} y\cos\phi - x\sin\phi\right)$$





http://arxiv-web3.library.cornell.edu/abs/1310.7201

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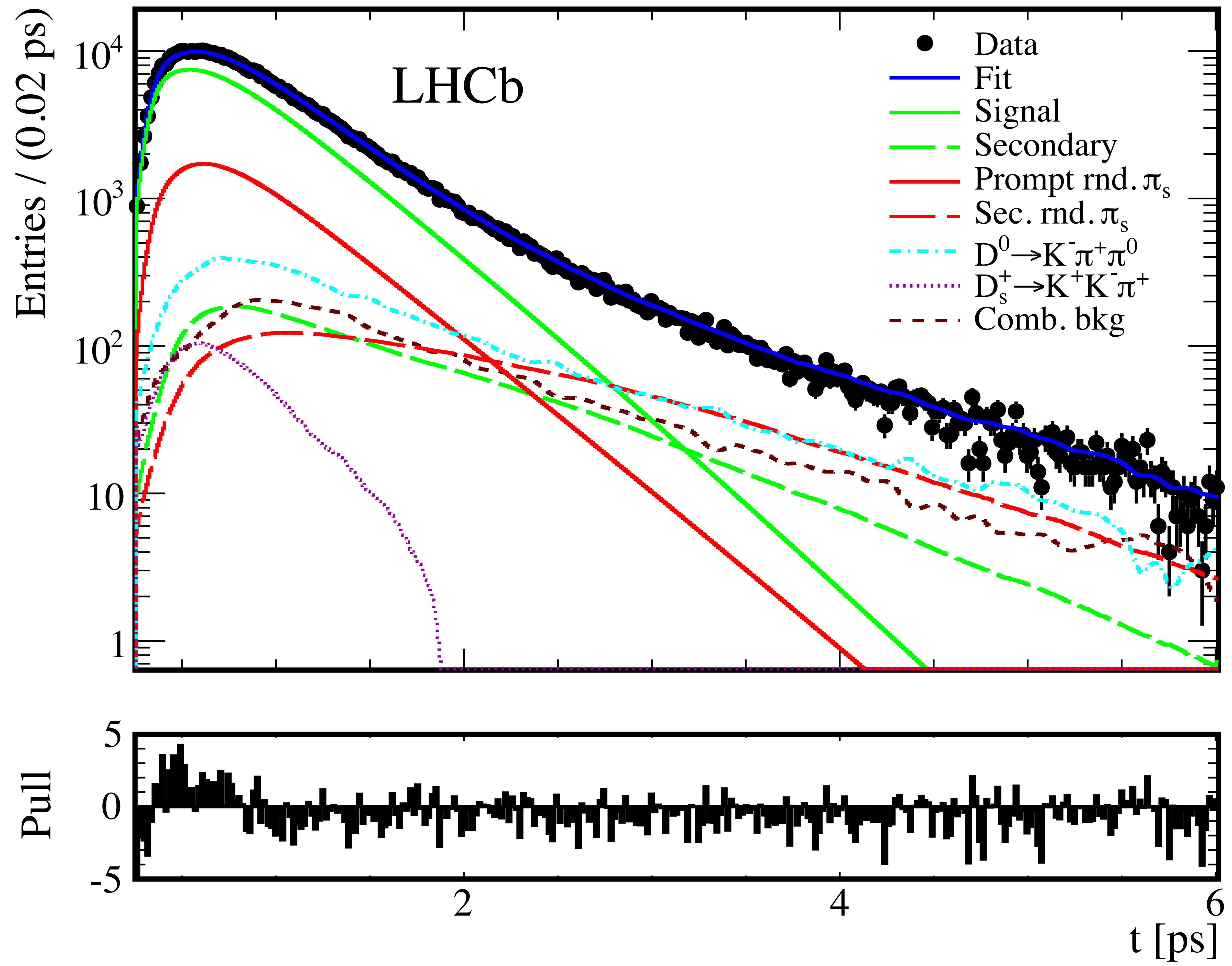
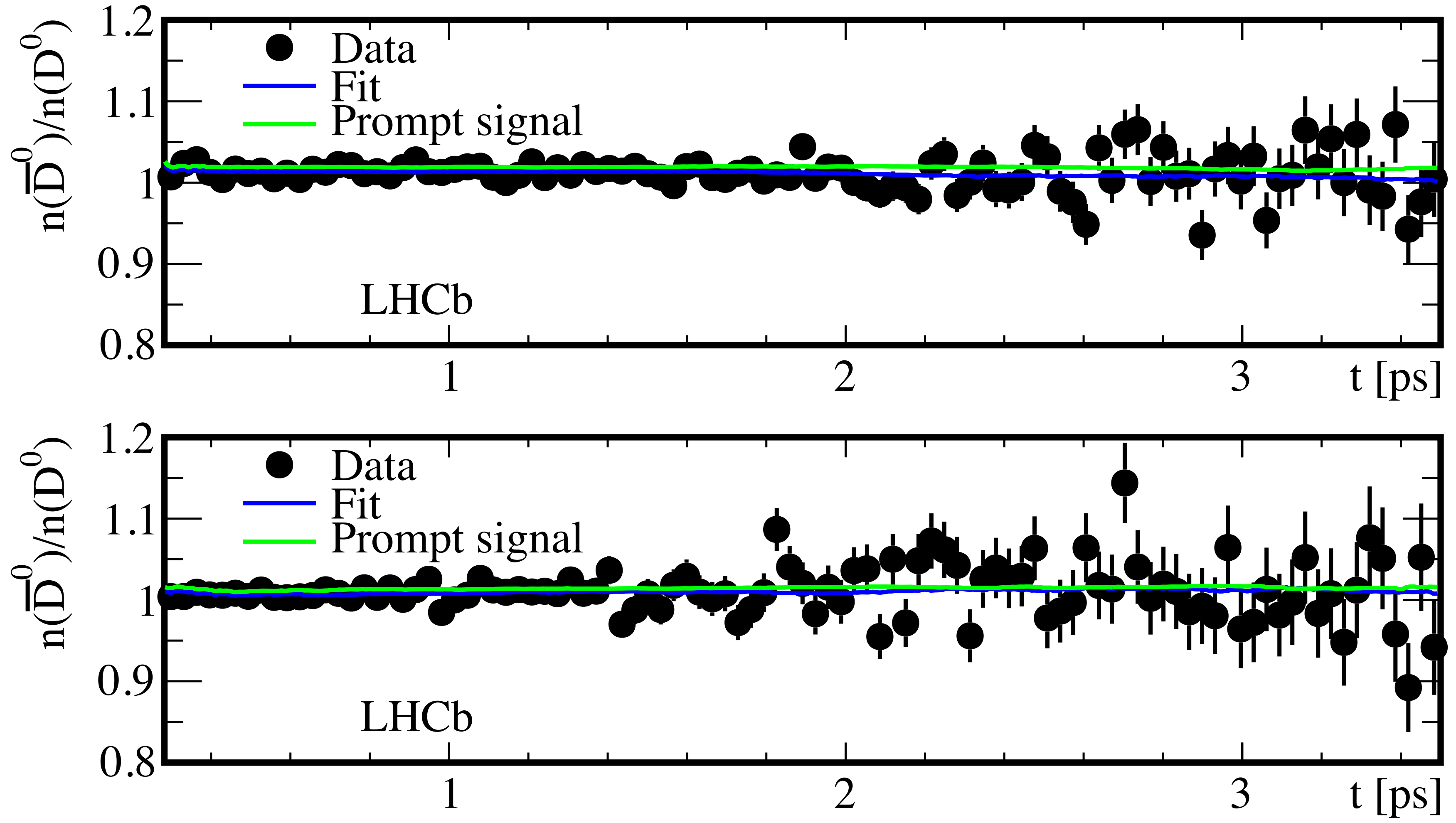
A_Γ(KK) = (-0.35 ± 0.62 ± 0.12)•10^{-3}

A_Γ($\pi\pi$) = (0.33 ± 1.06 ± 0.14)•10^{-3}

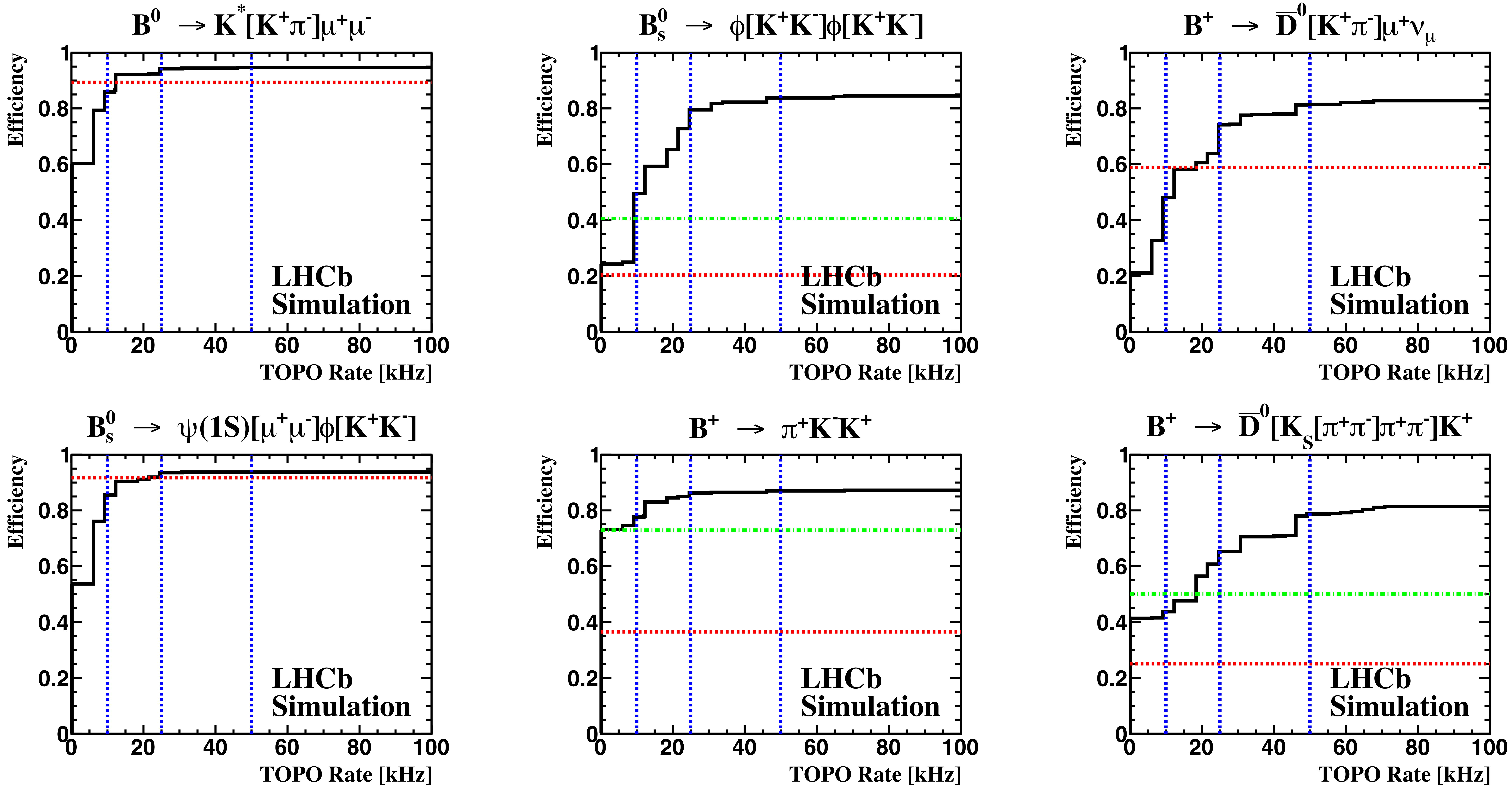




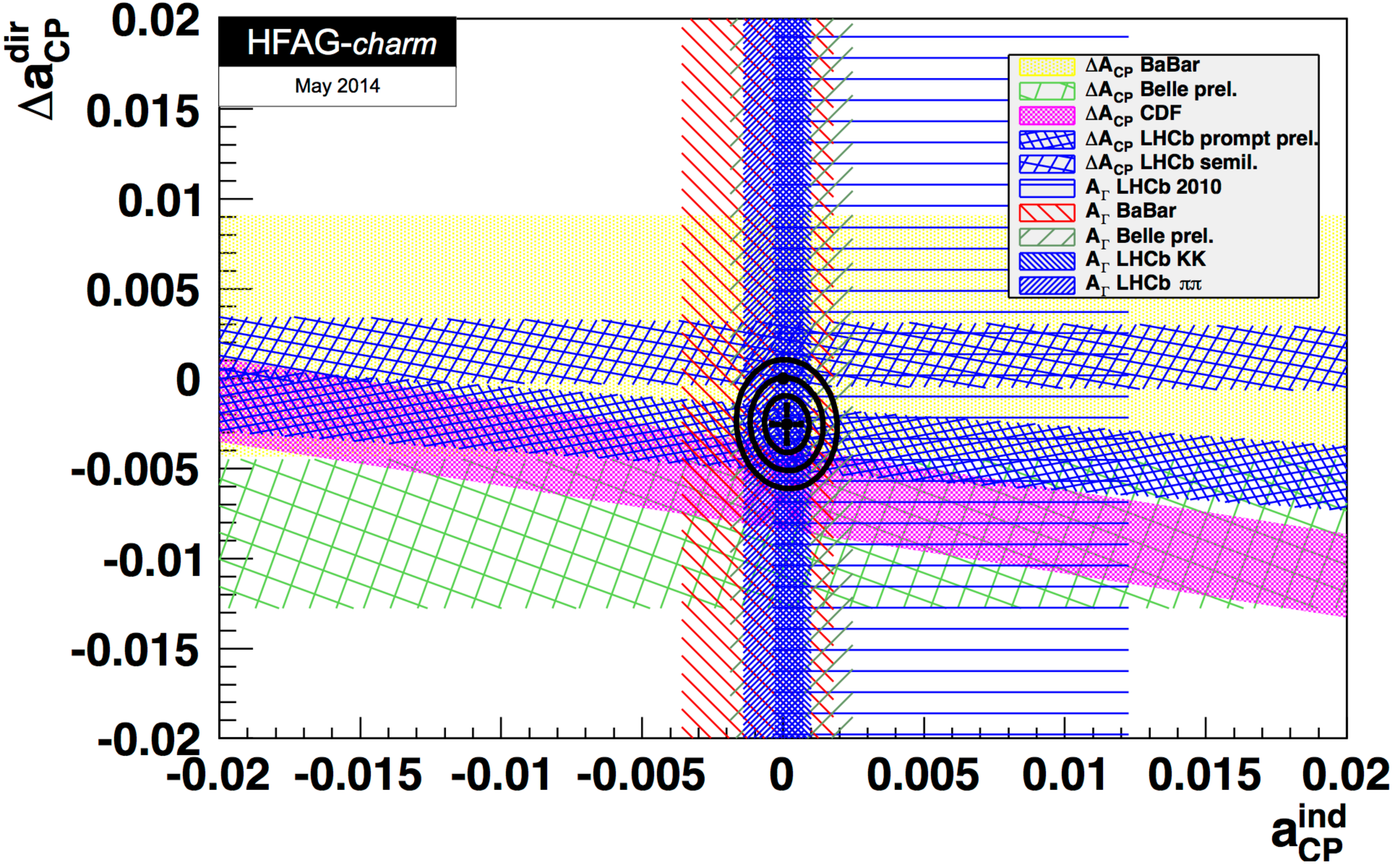
Source	$A_\Gamma^{\rm unb}(KK)$	$A_\Gamma^{\rm bin}(KK)$	$A_\Gamma^{\rm unb}(\pi\pi)$	$A_\Gamma^{\rm bin}(\pi\pi)$
Partially reconstructed backgrounds	±0.02	±0.09	±0.00	±0.00
Charm from b decays	±0.07	±0.55	±0.07	±0.53
Other backgrounds	±0.02	±0.40	±0.04	±0.57
Acceptance function	±0.09	—	±0.11	—
Magnet polarity	—	±0.58	—	±0.82
Total syst. uncertainty	±0.12	±0.89	±0.14	±1.13

http://arxiv-web3.library.cornell.edu/abs/1310.7201

Inclusive B trigger performance



Including direct CPV into the picture

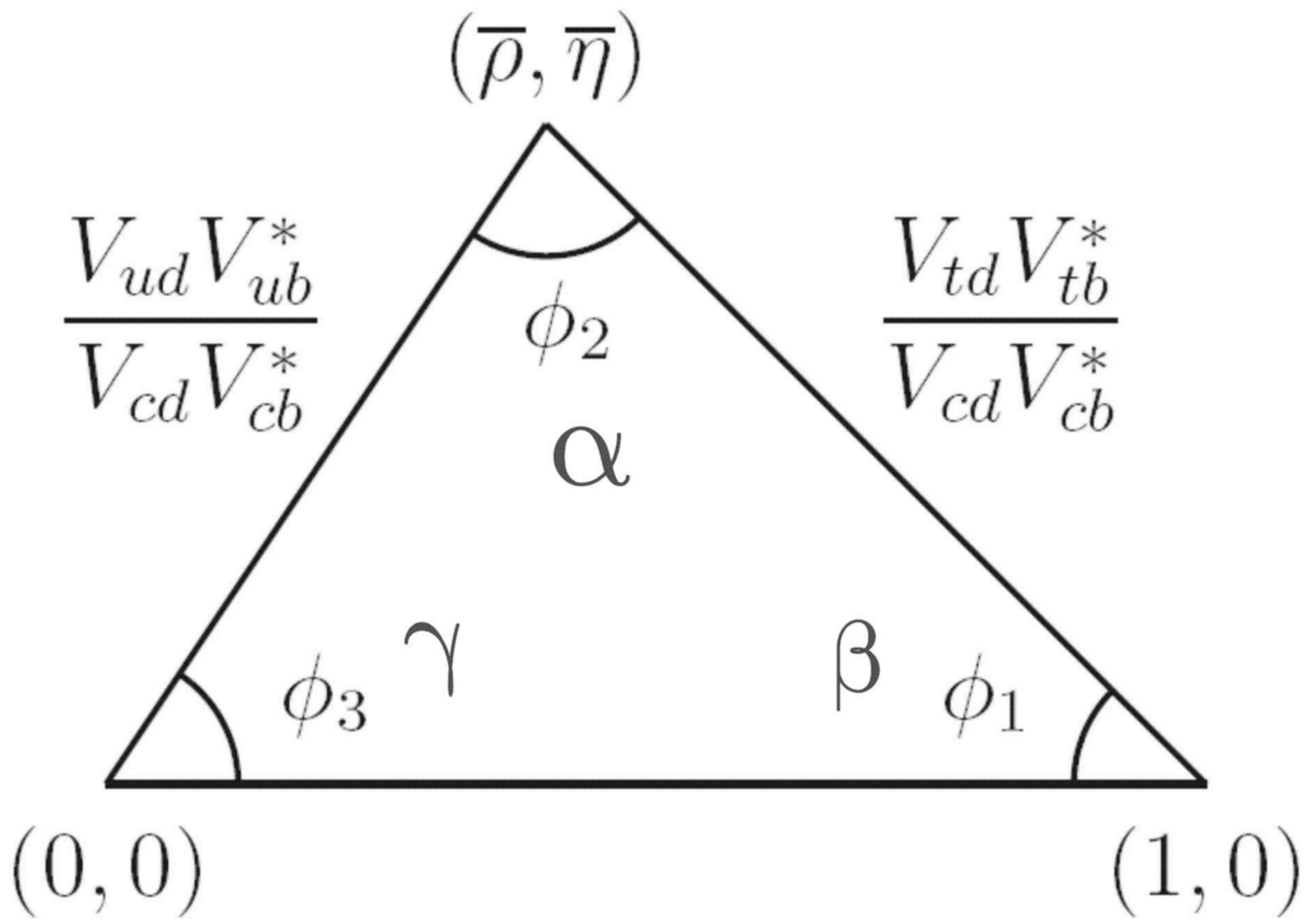


The CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

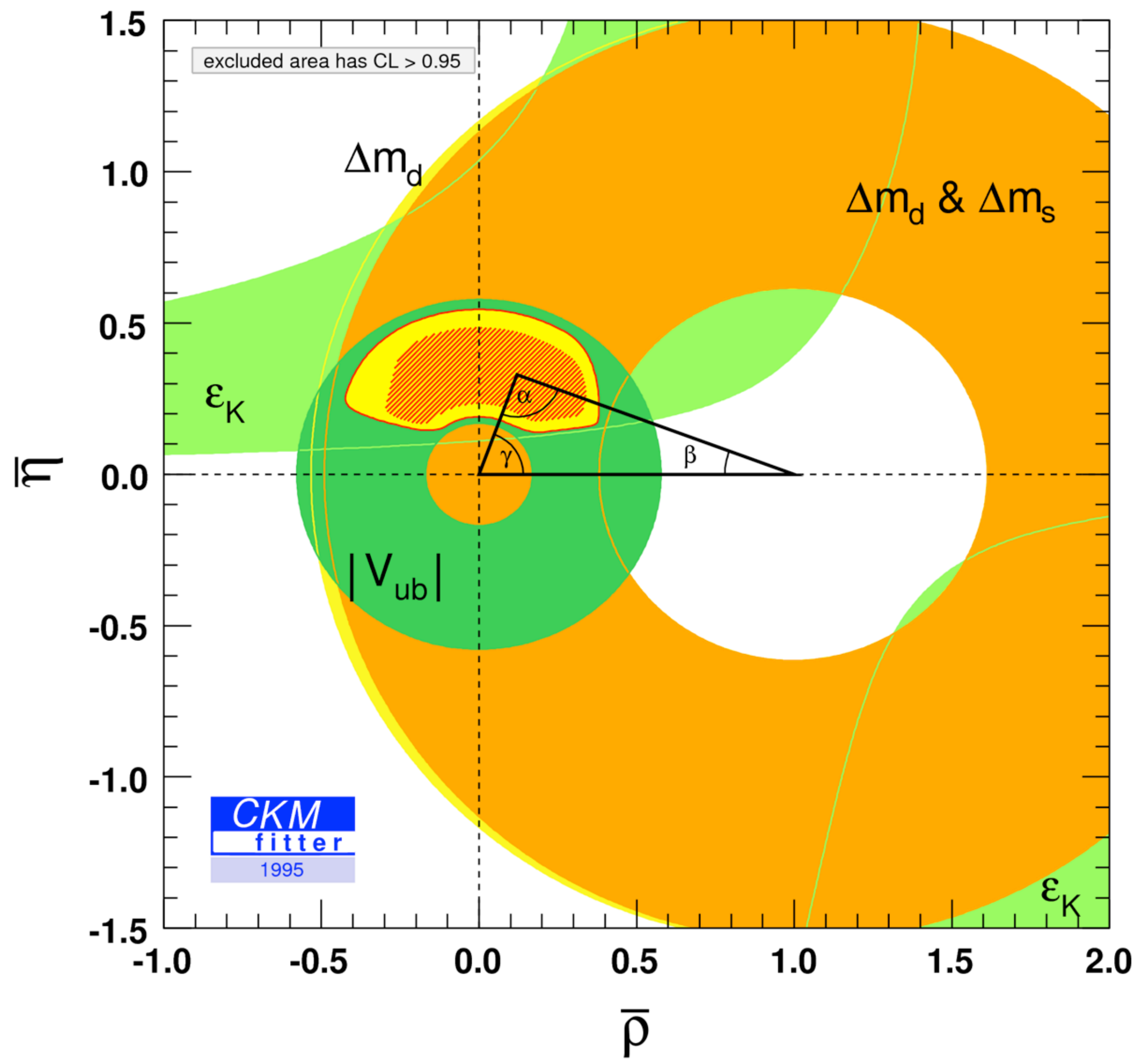
$$\mathbf{V_{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \sum_{n=4}^{N} O(\lambda^n)$$

As a triangle



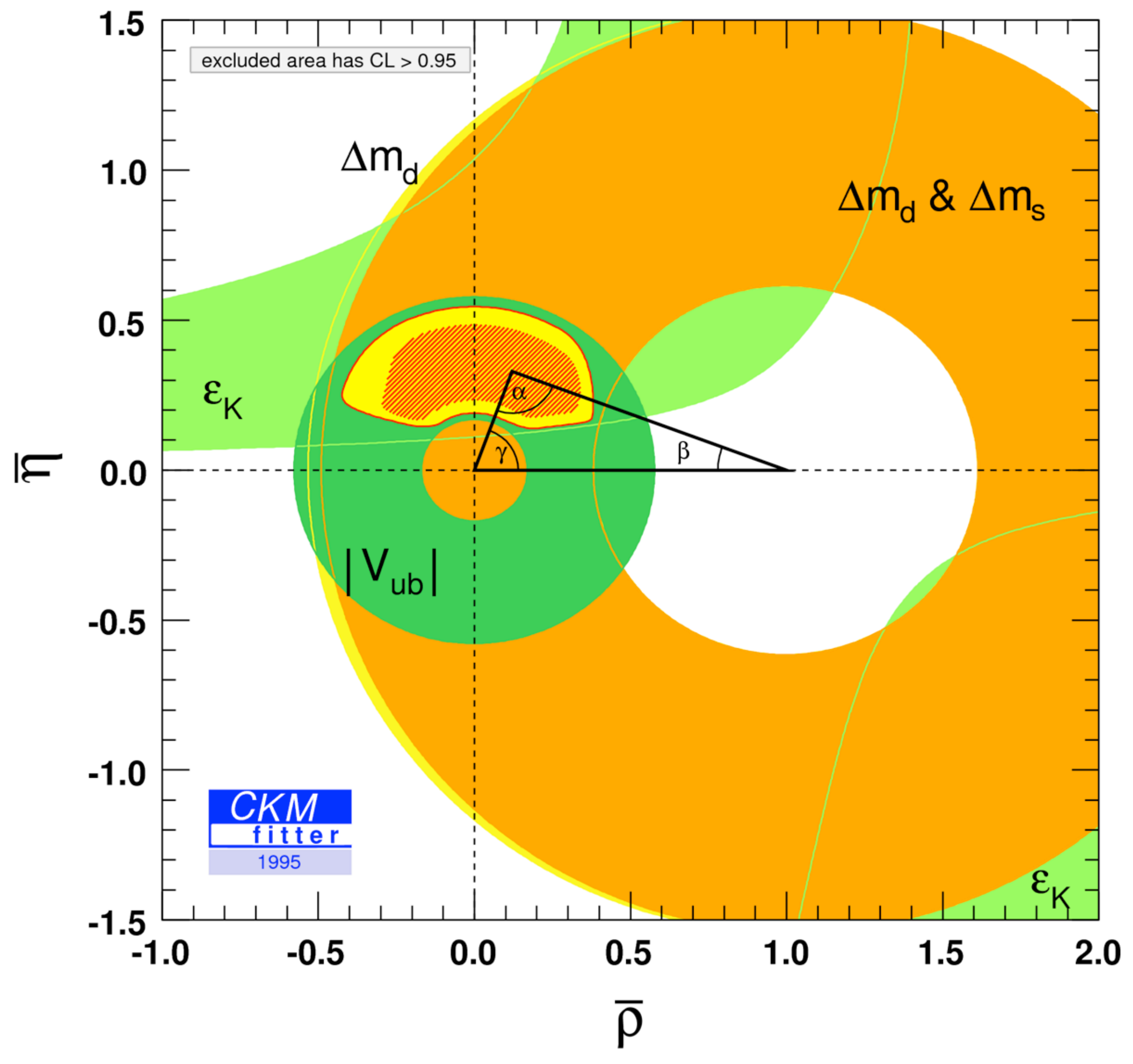
Experimental status through the years

1995



Experimental status through the years

1995



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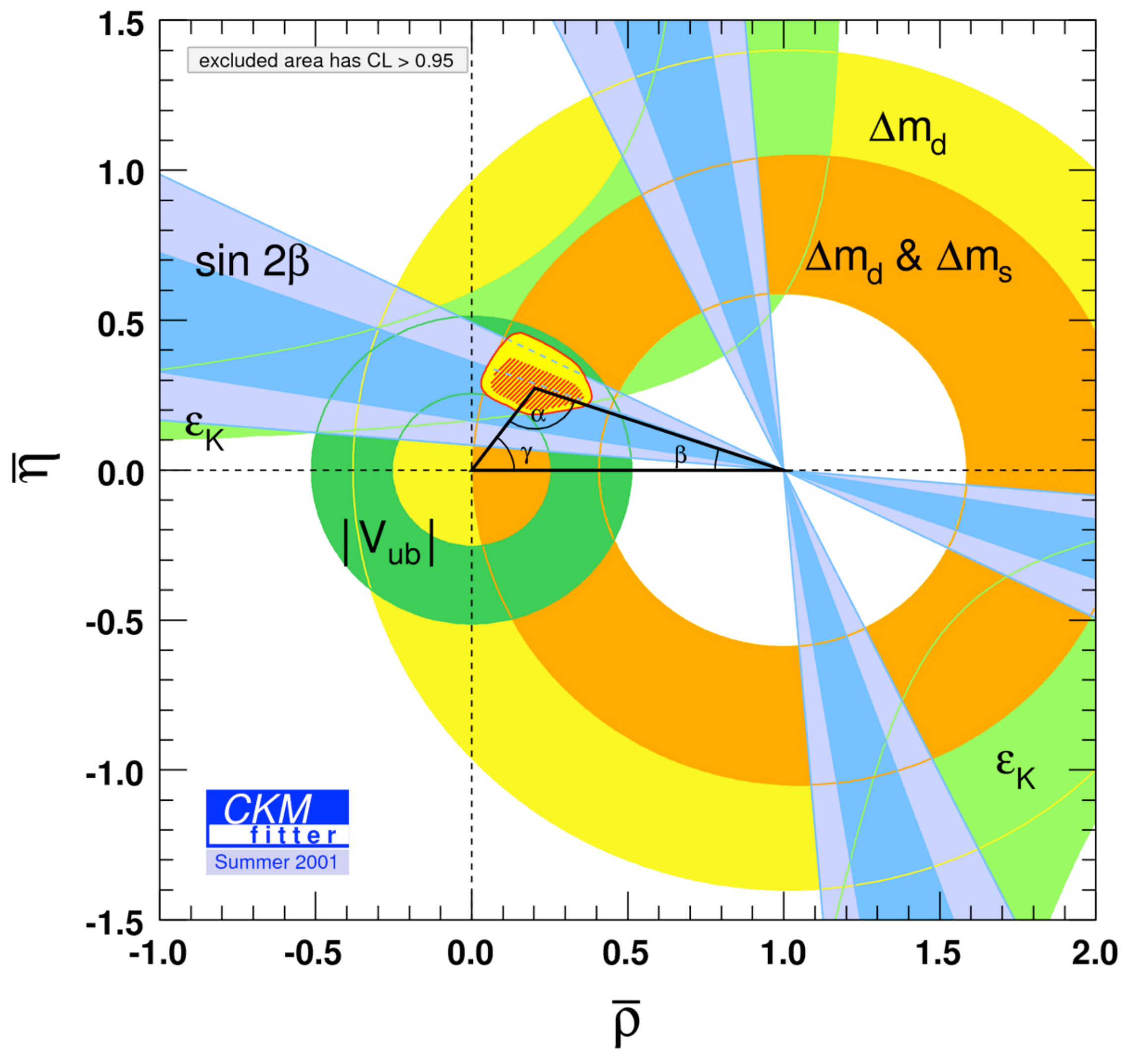
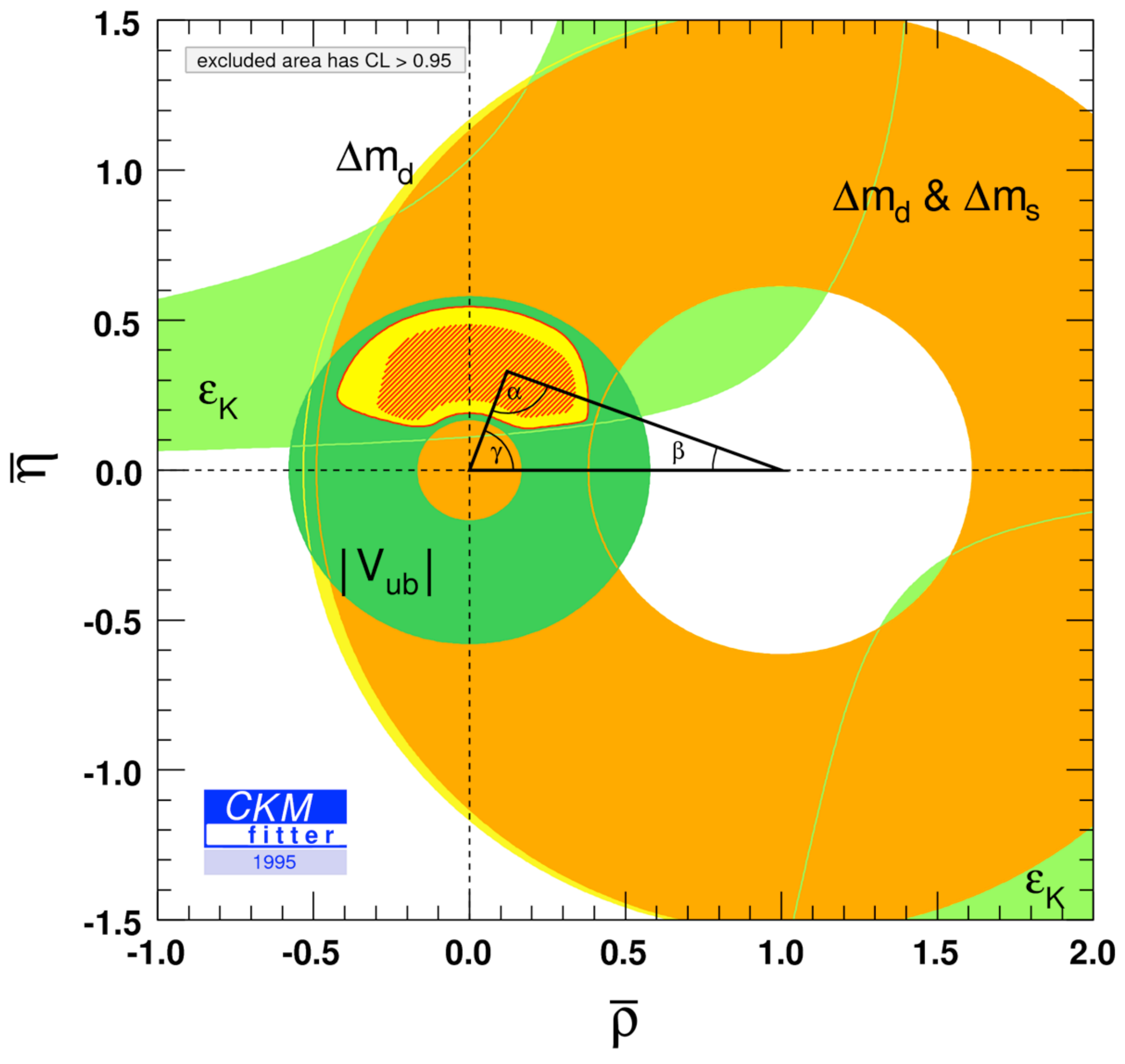


Experimental status through the years

1995



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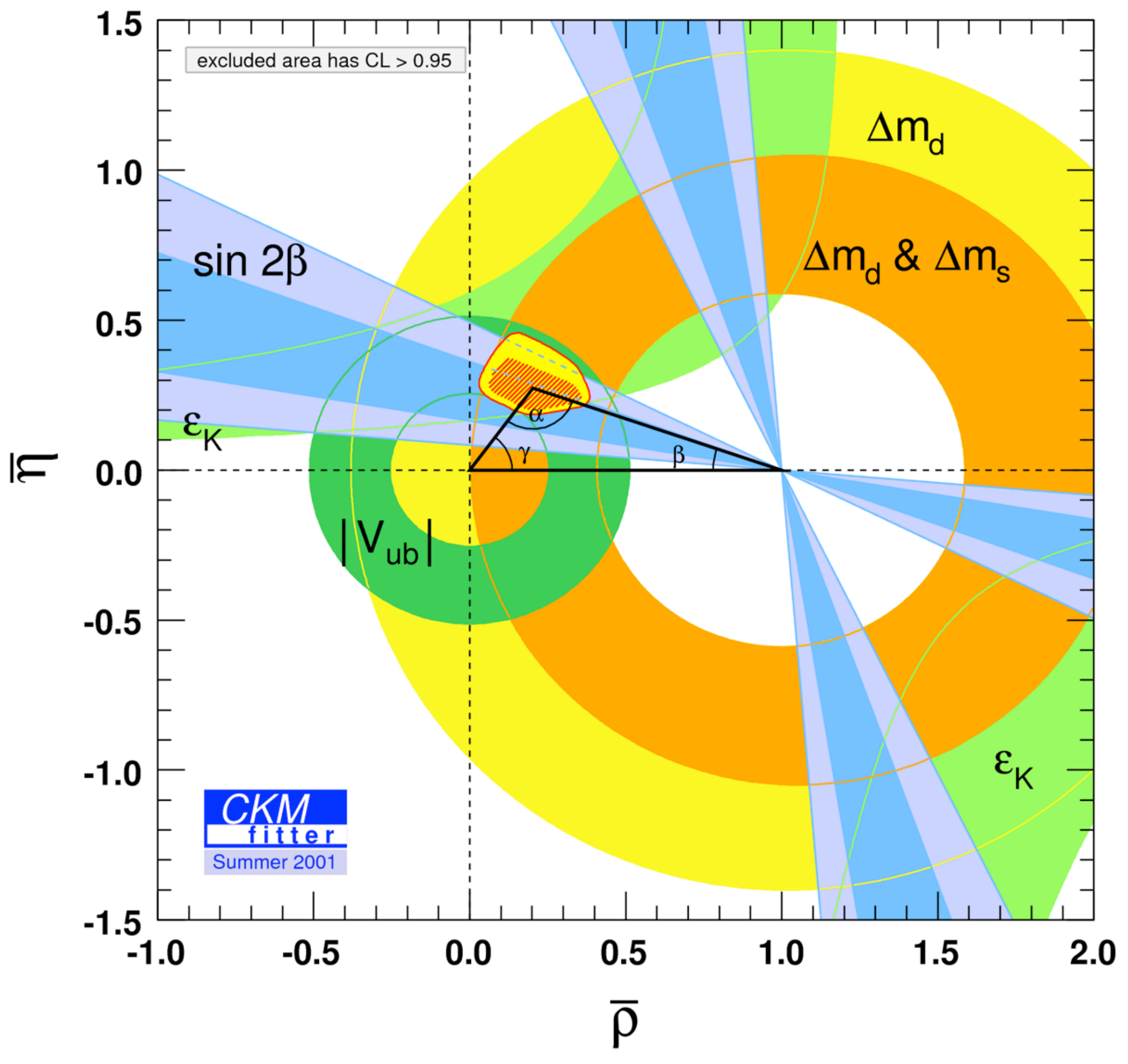

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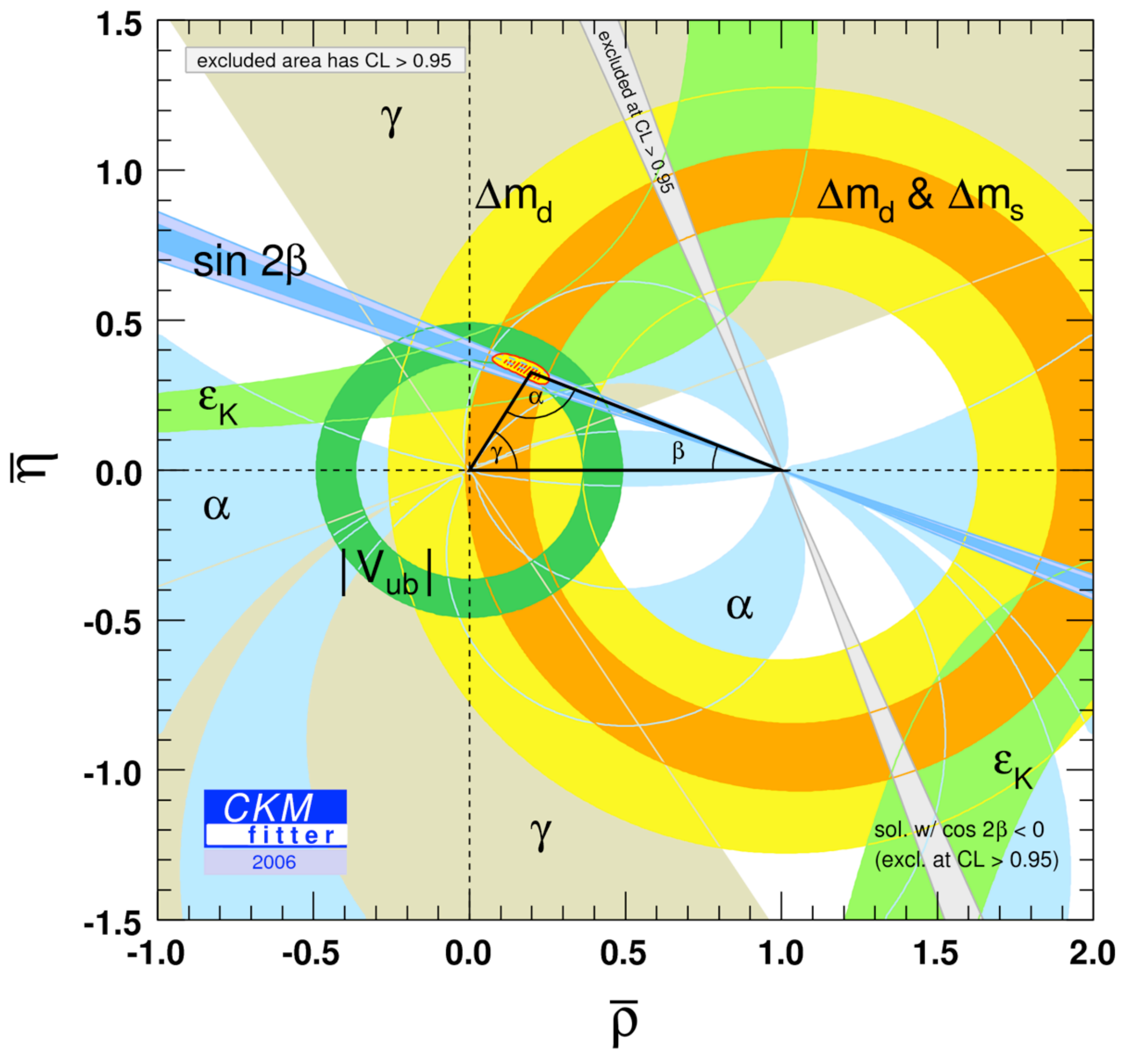
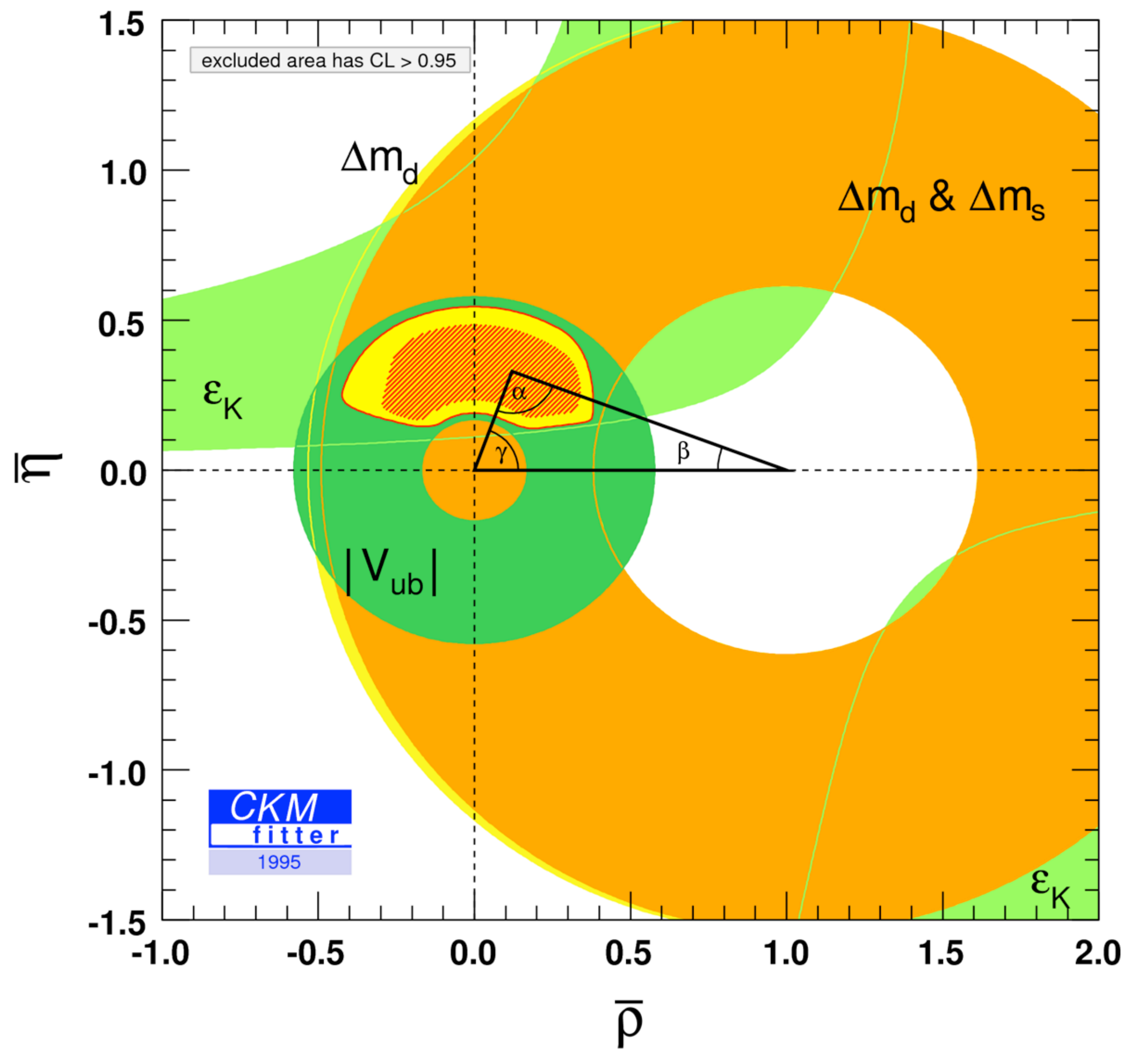


Experimental status through the years

1995



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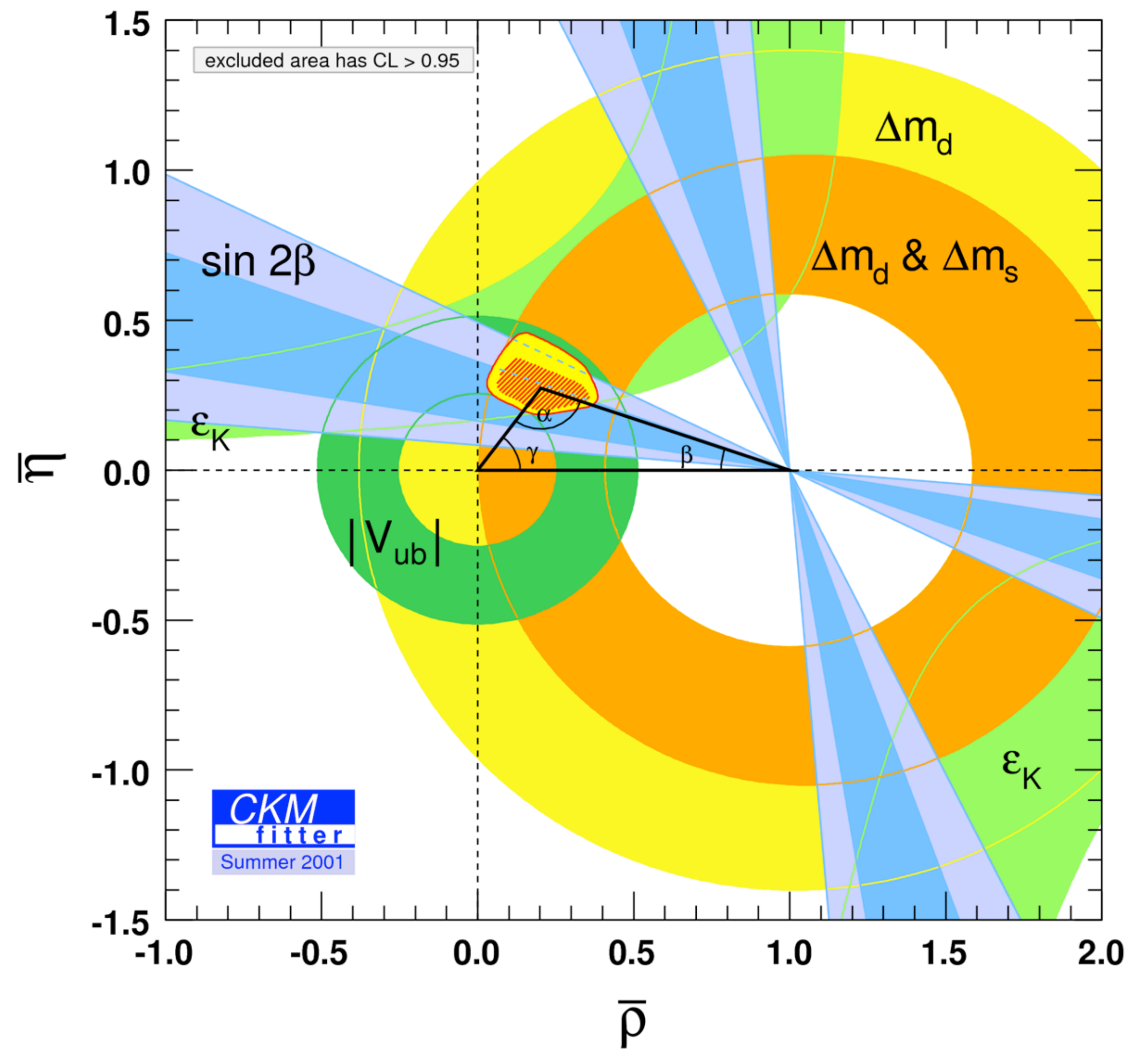

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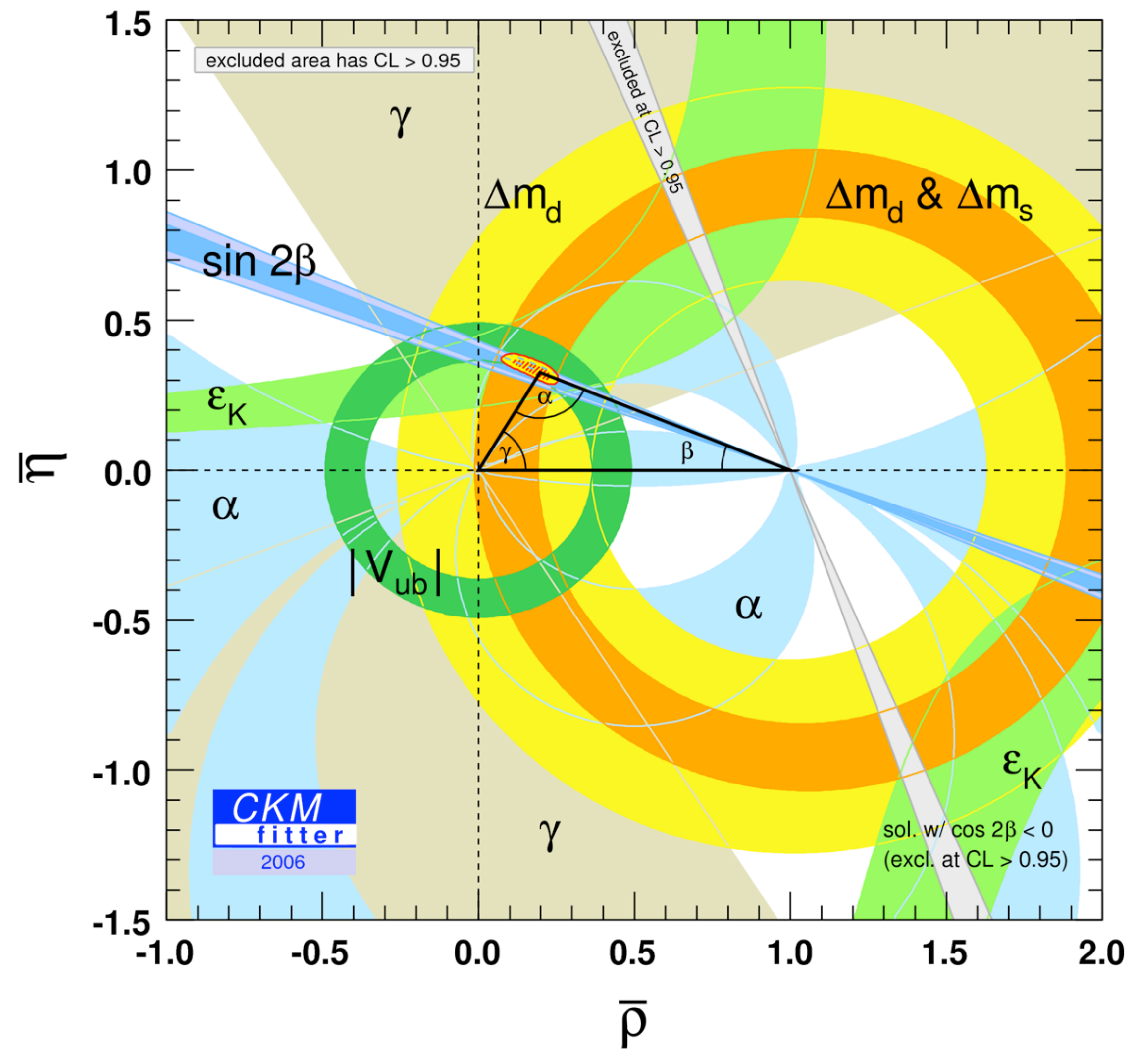
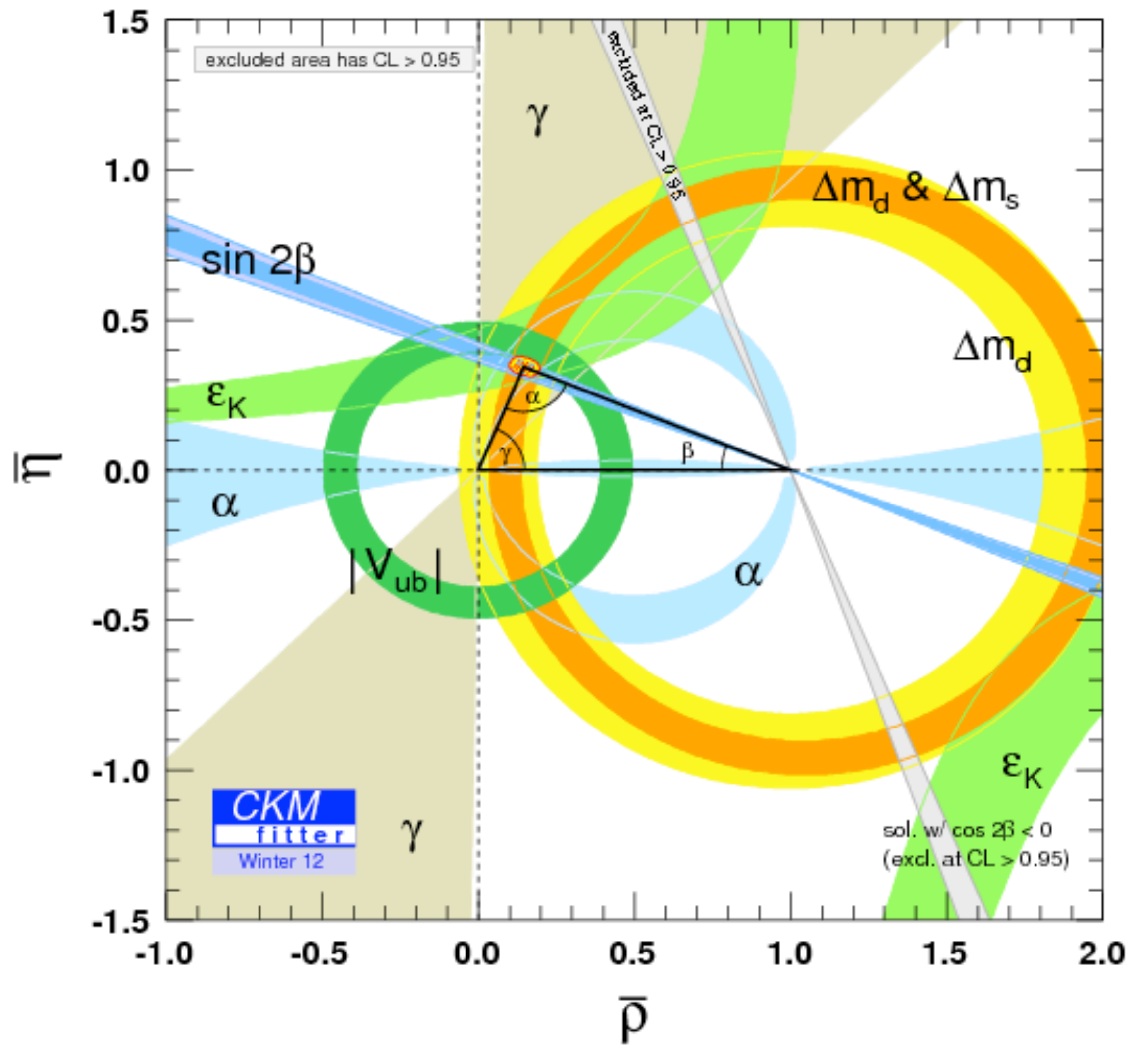
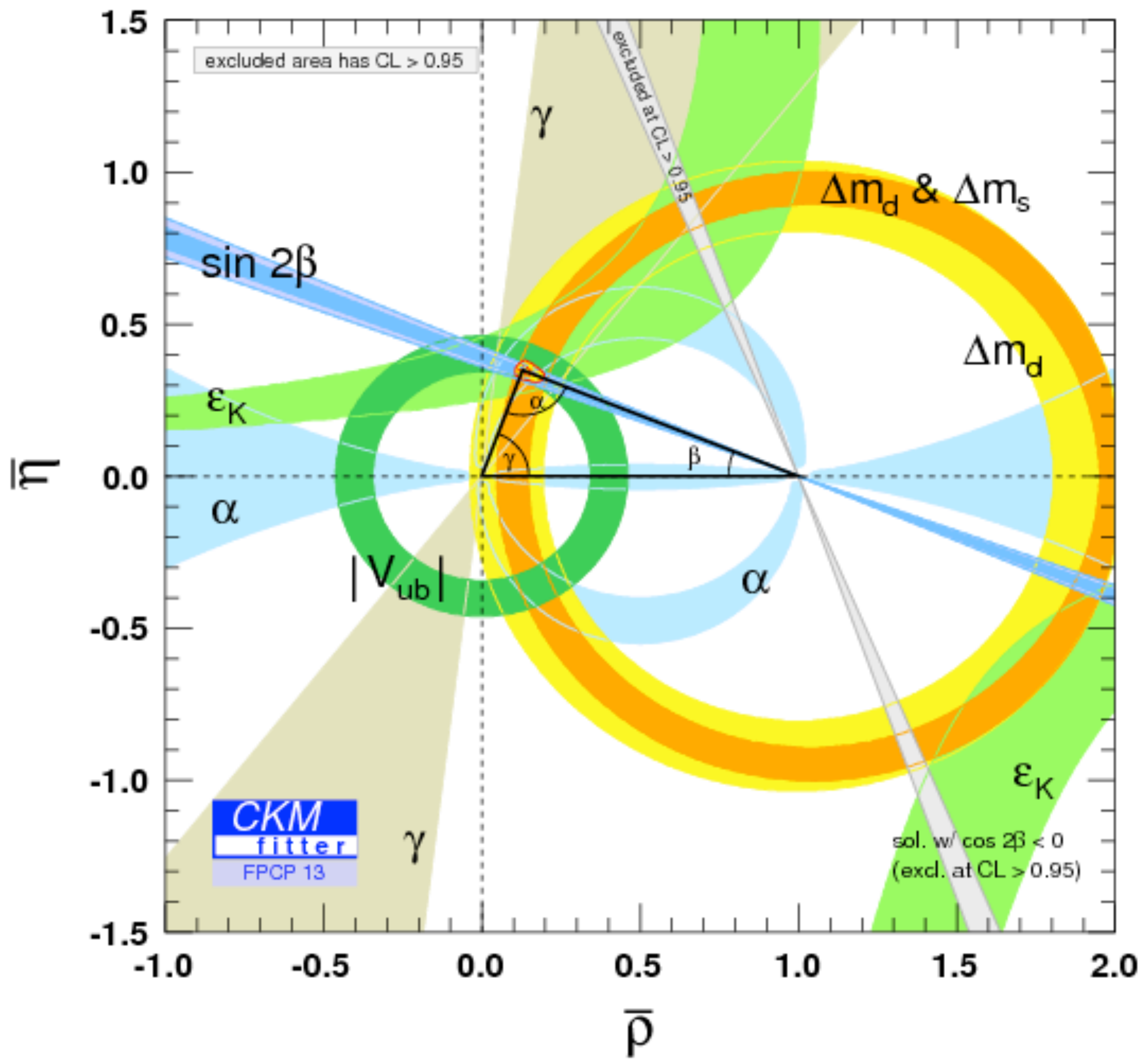


2012

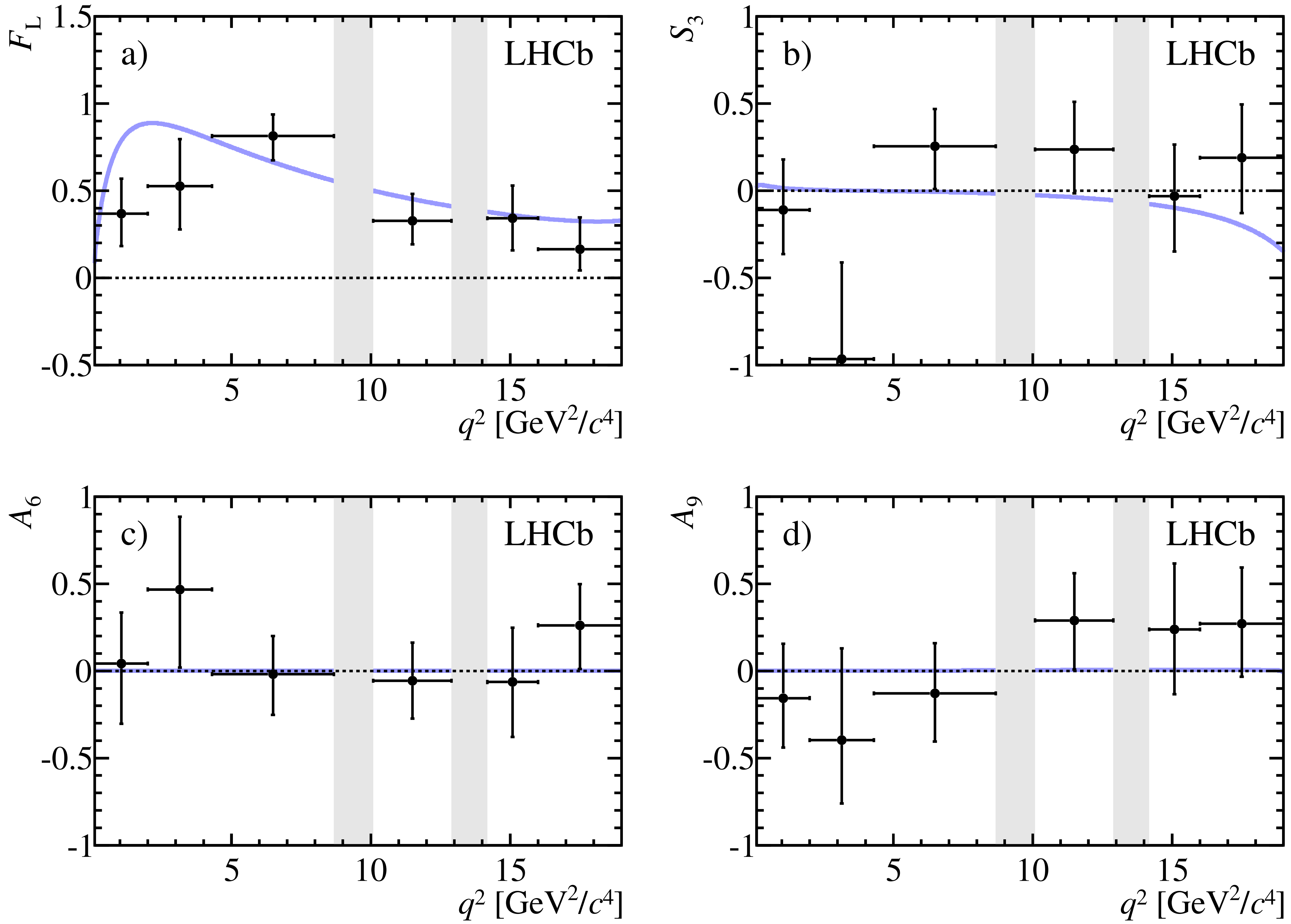


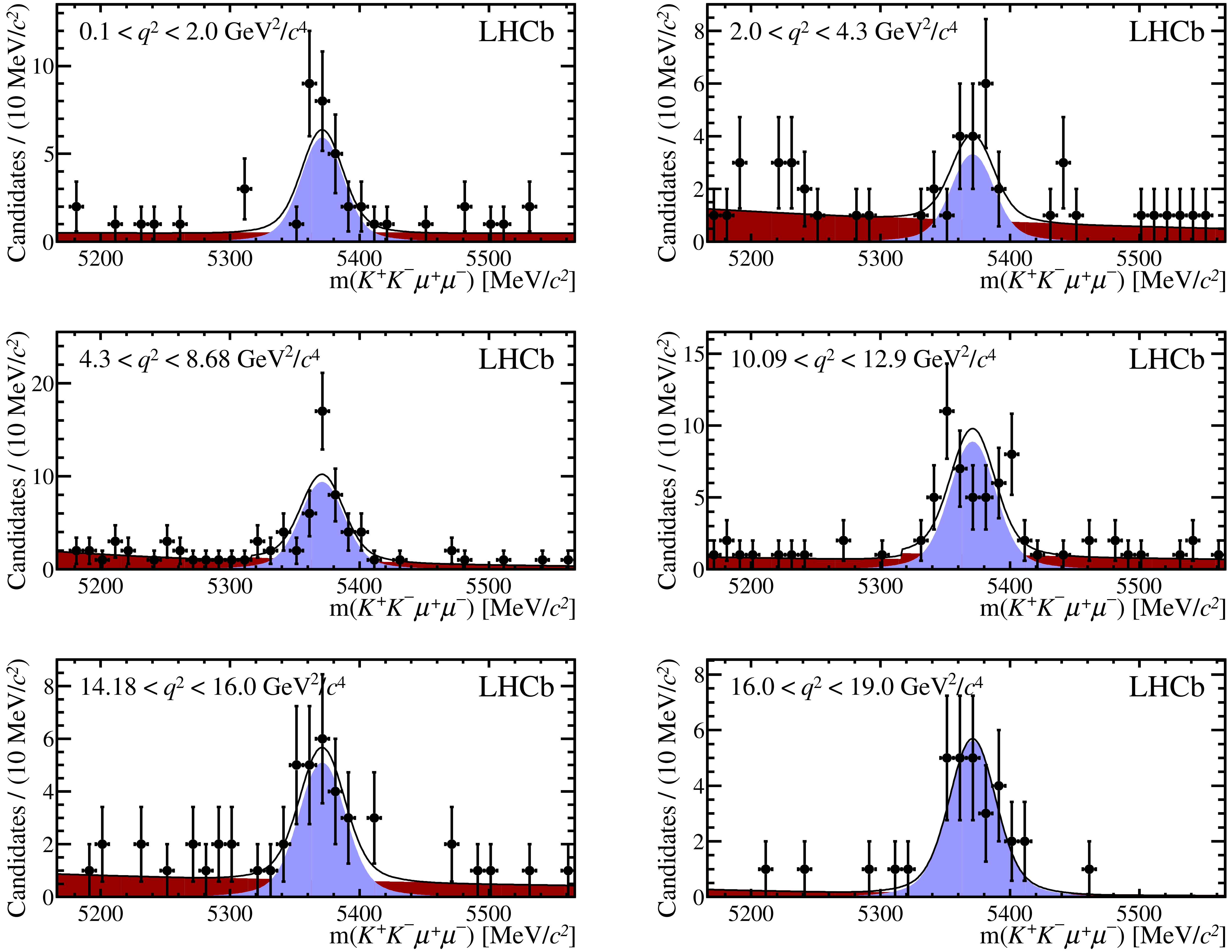
The CKM triangle “state of the art”…



$B \to X_s \mu\mu$, the B_s sector

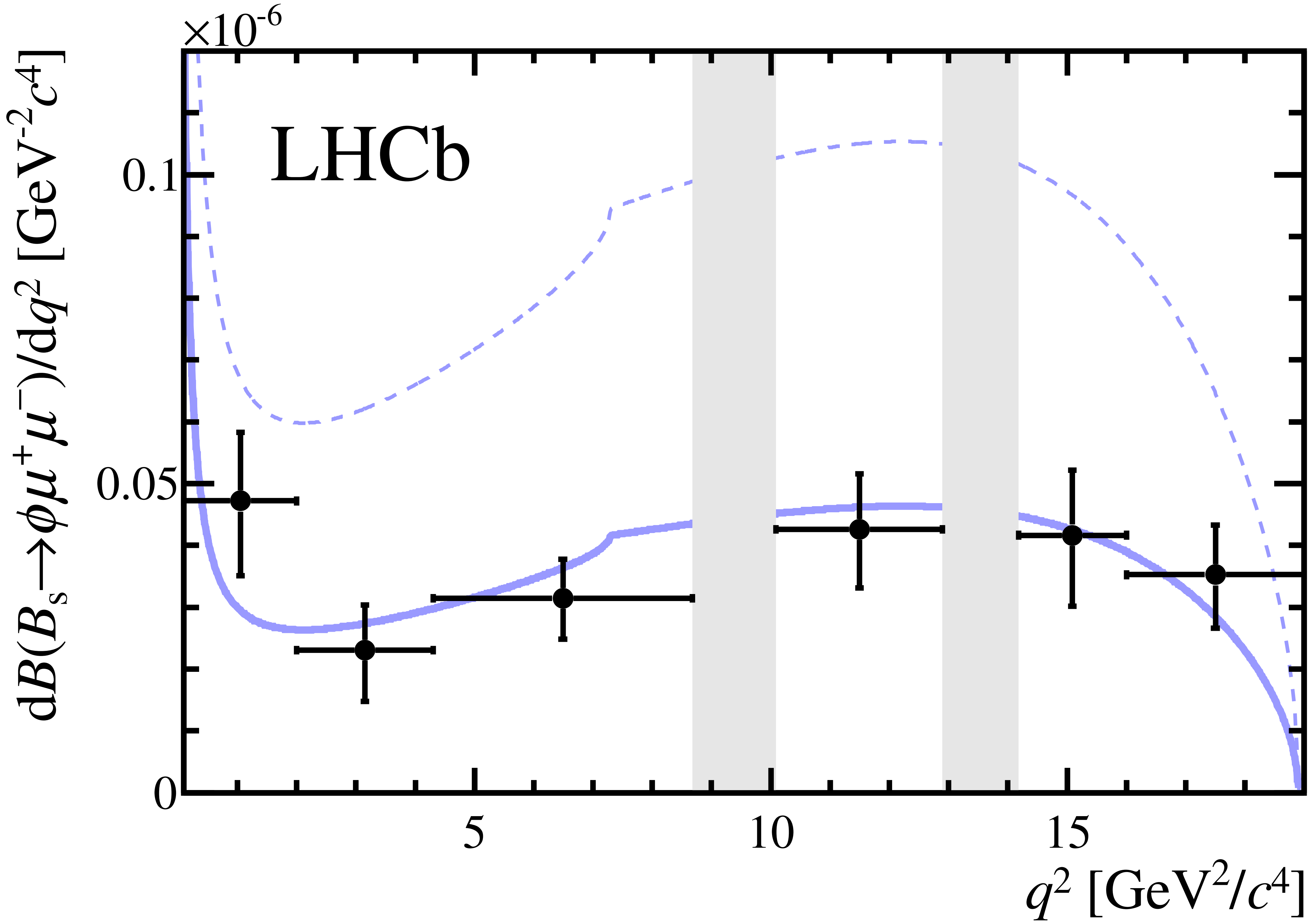
JHEP 07 (2012) 084

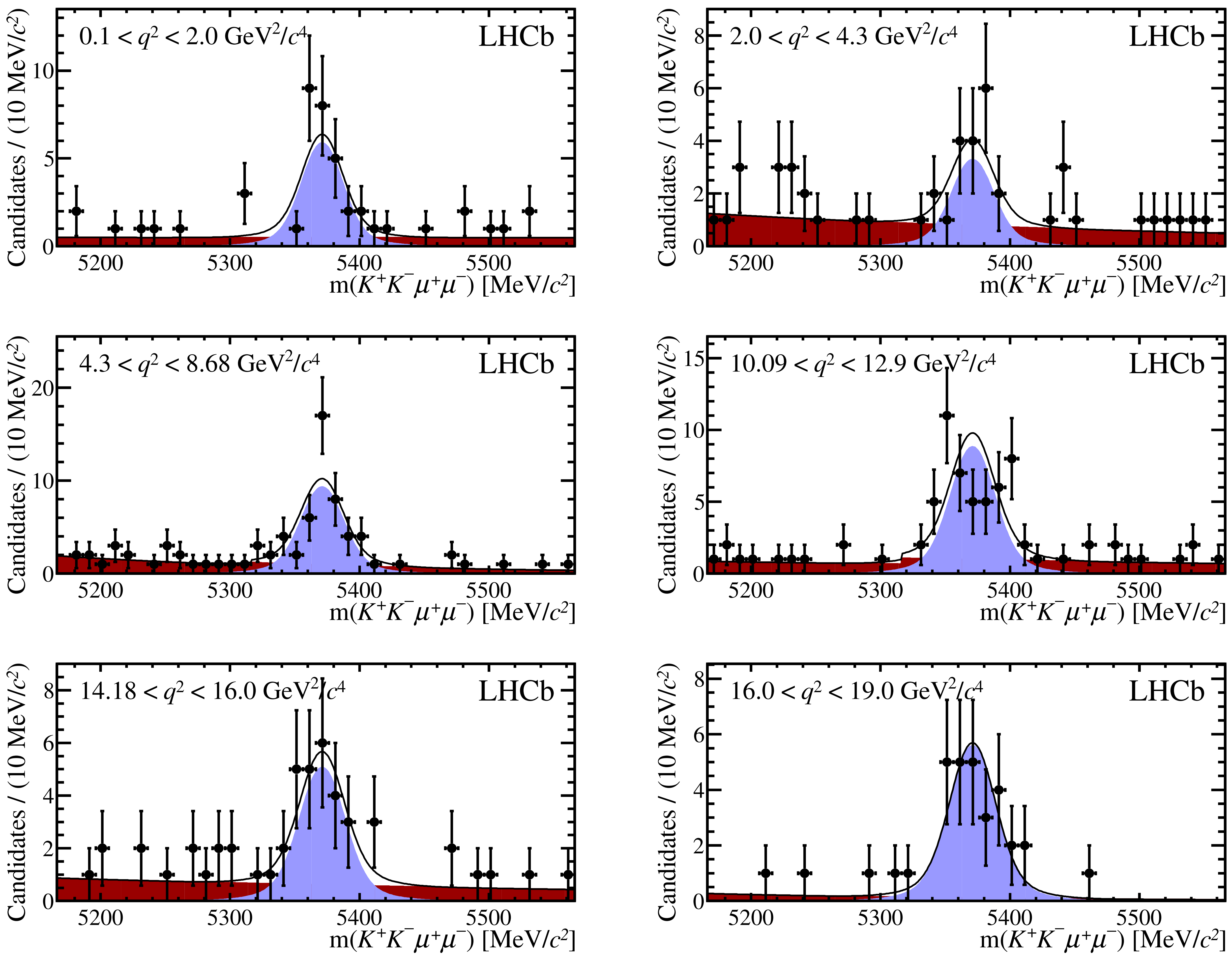




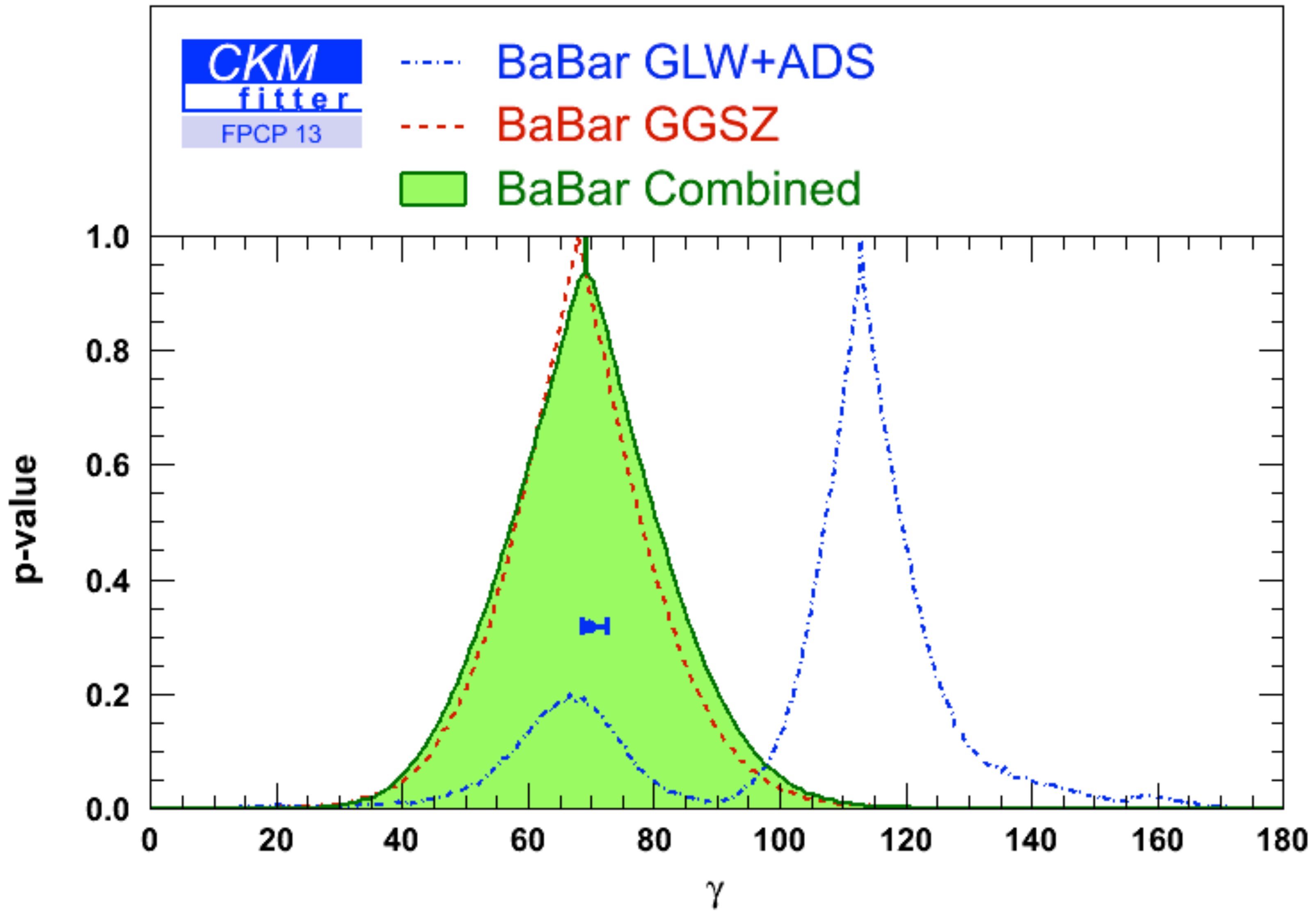
$B \to X_s \mu\mu$, the B_s sector

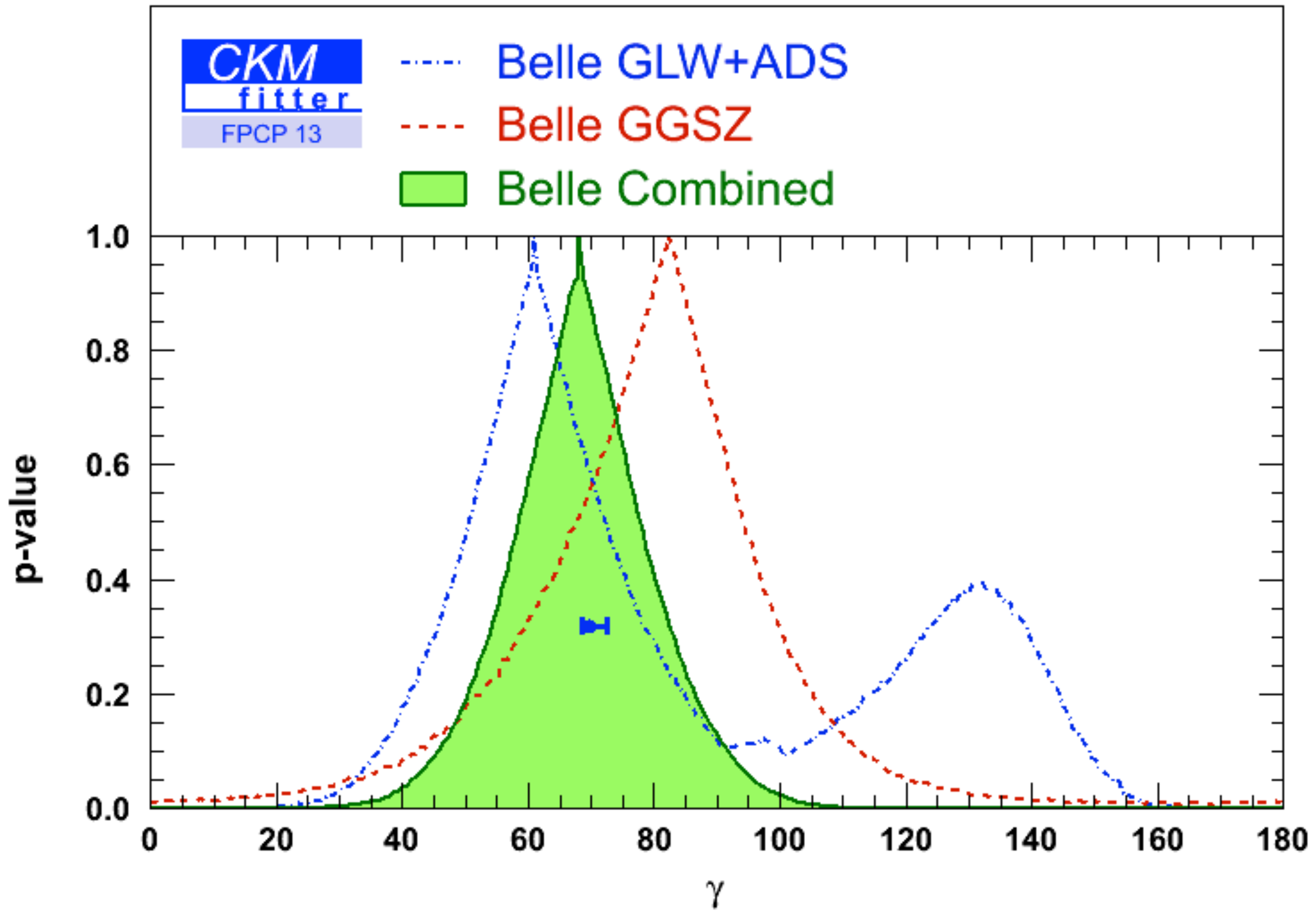
JHEP 07 (2012) 084

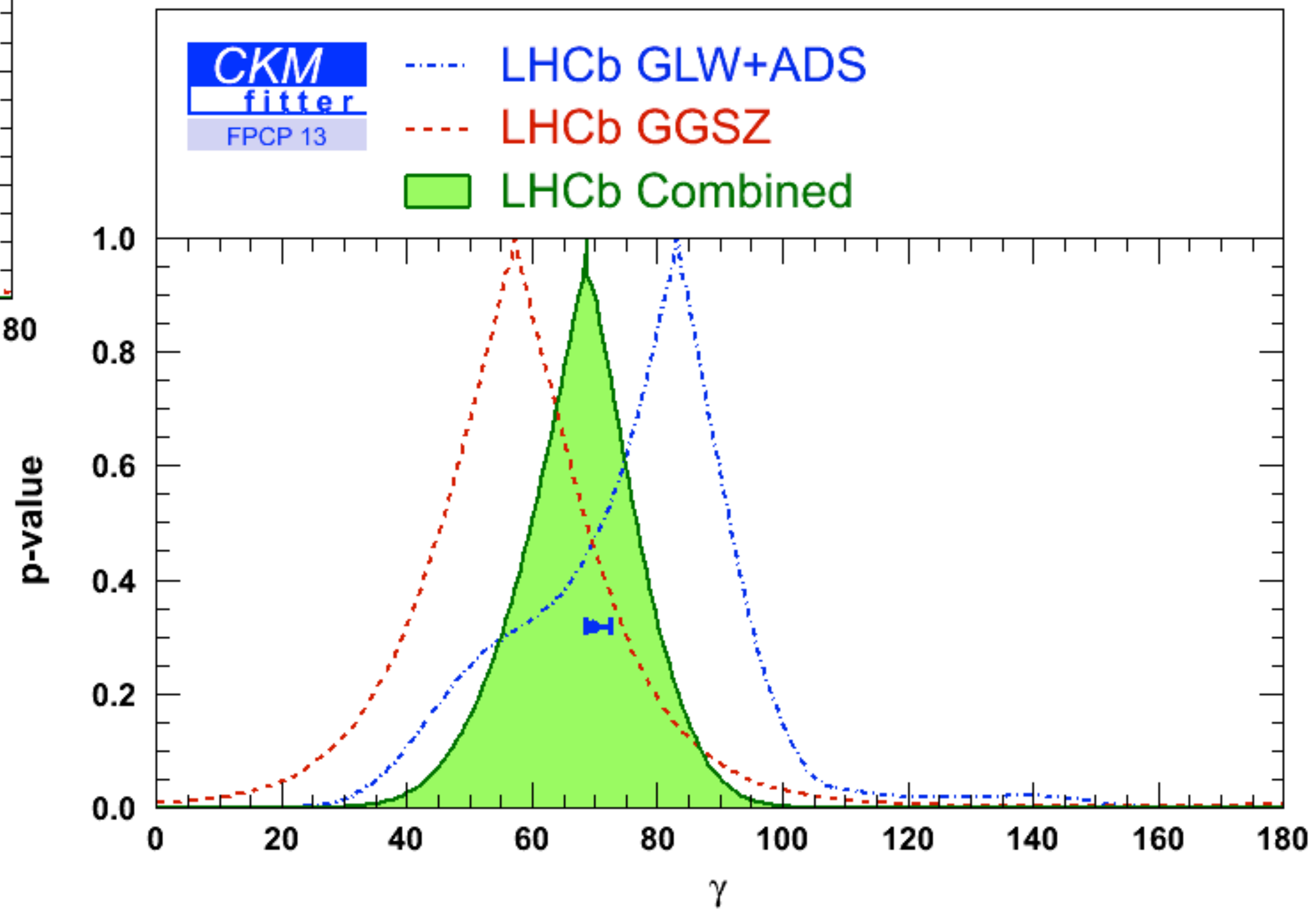




The many faces of γ

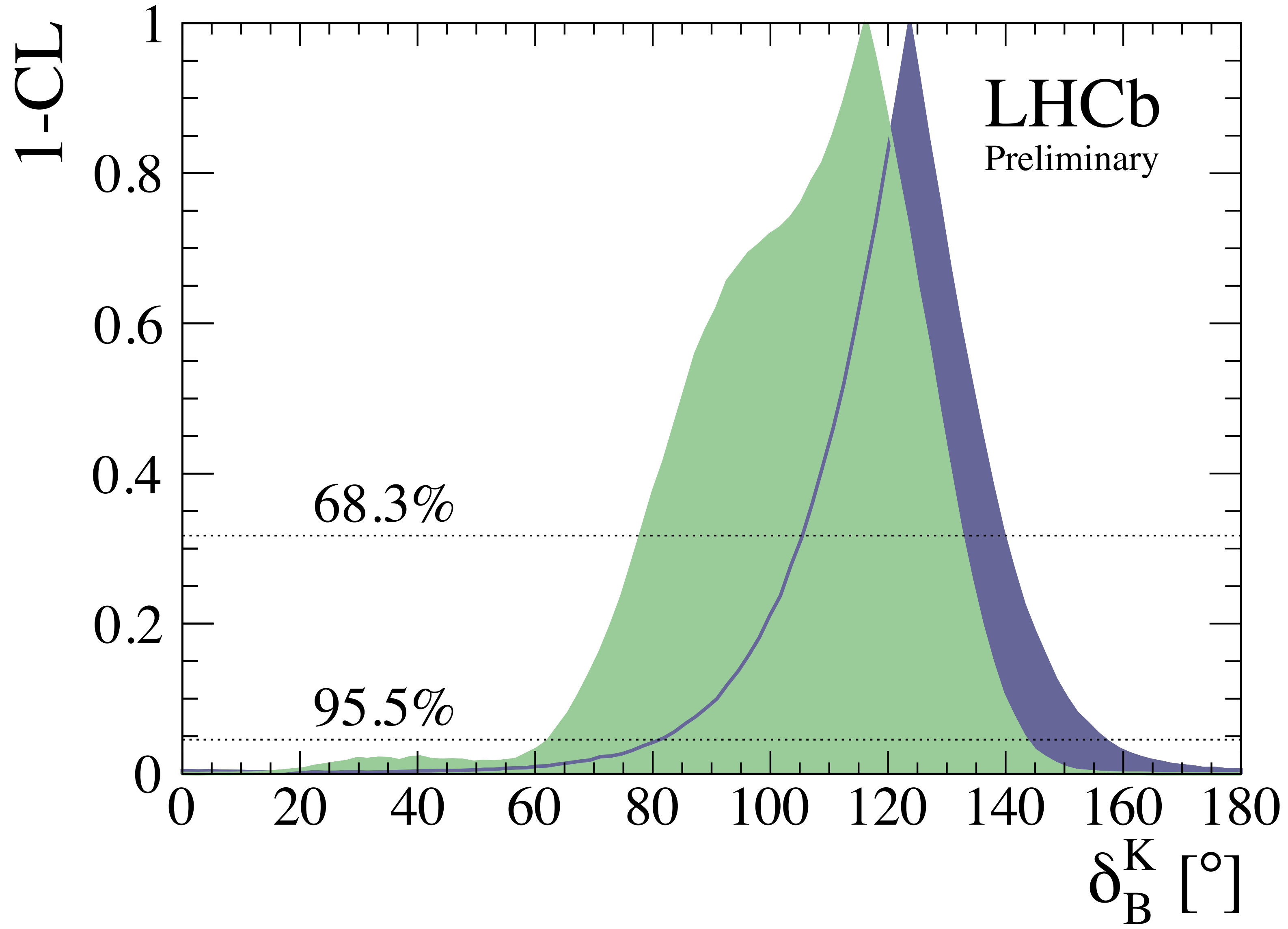


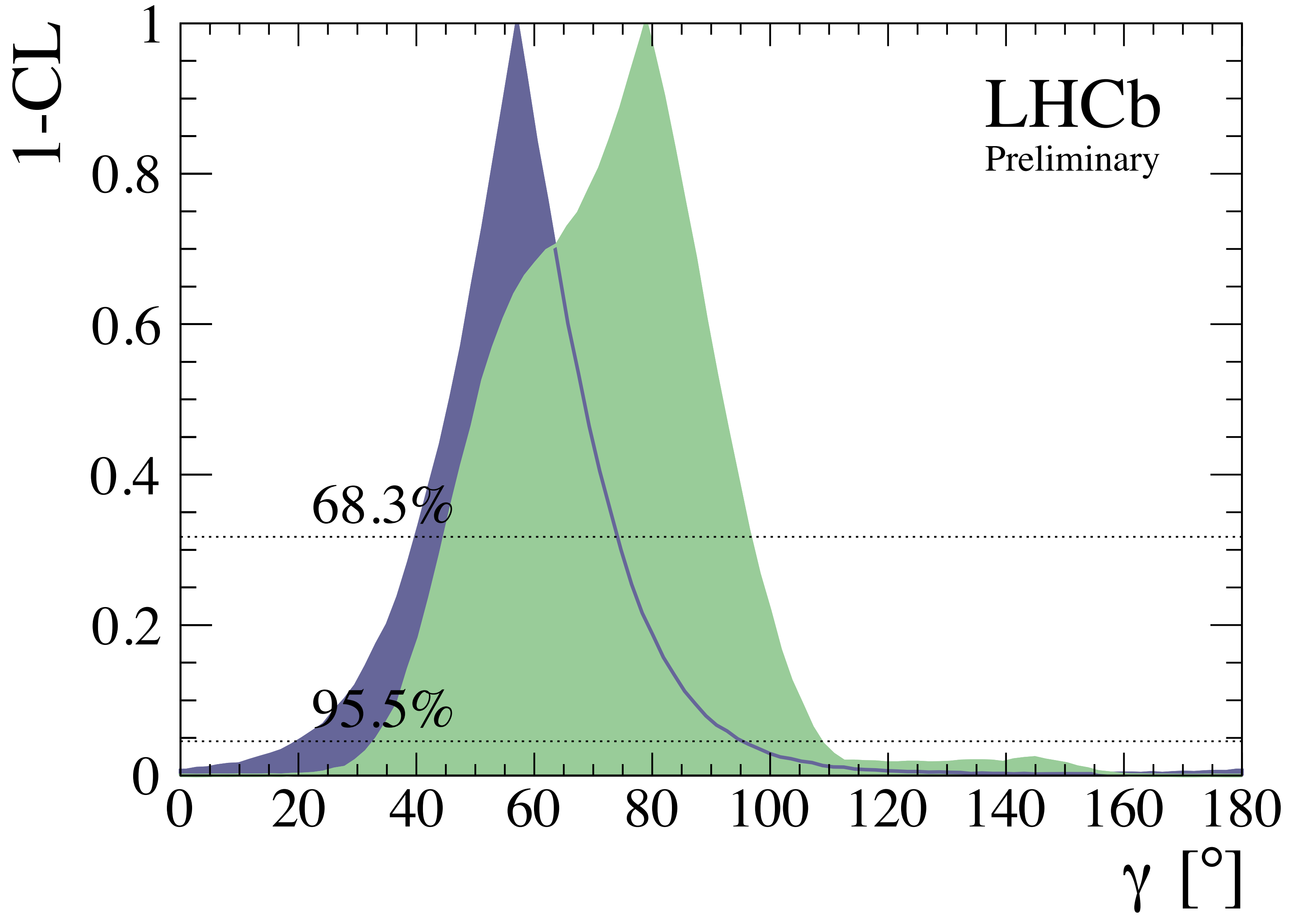




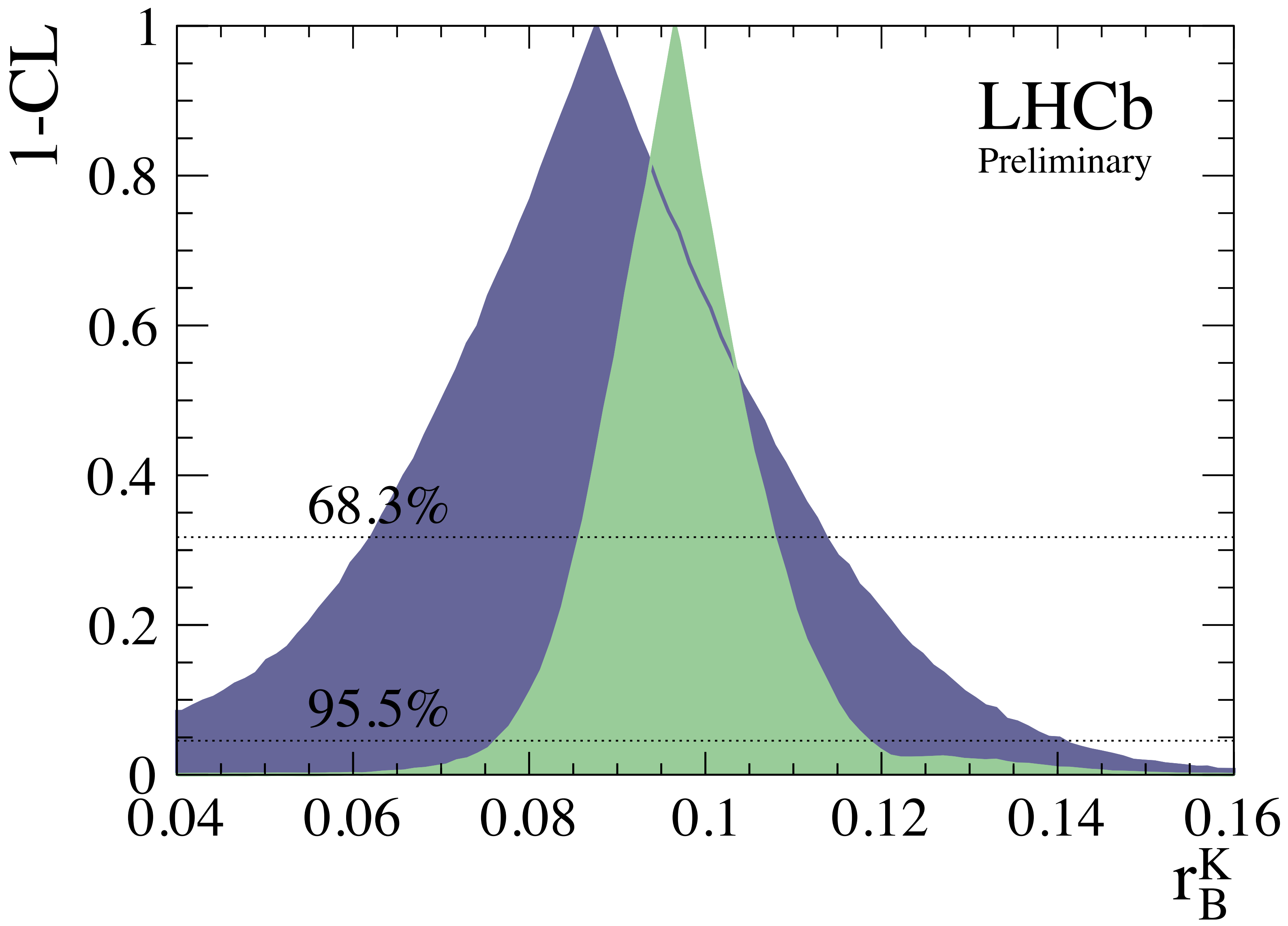
The number of ways in which it is being measured is growing...

Combining the individual measurements



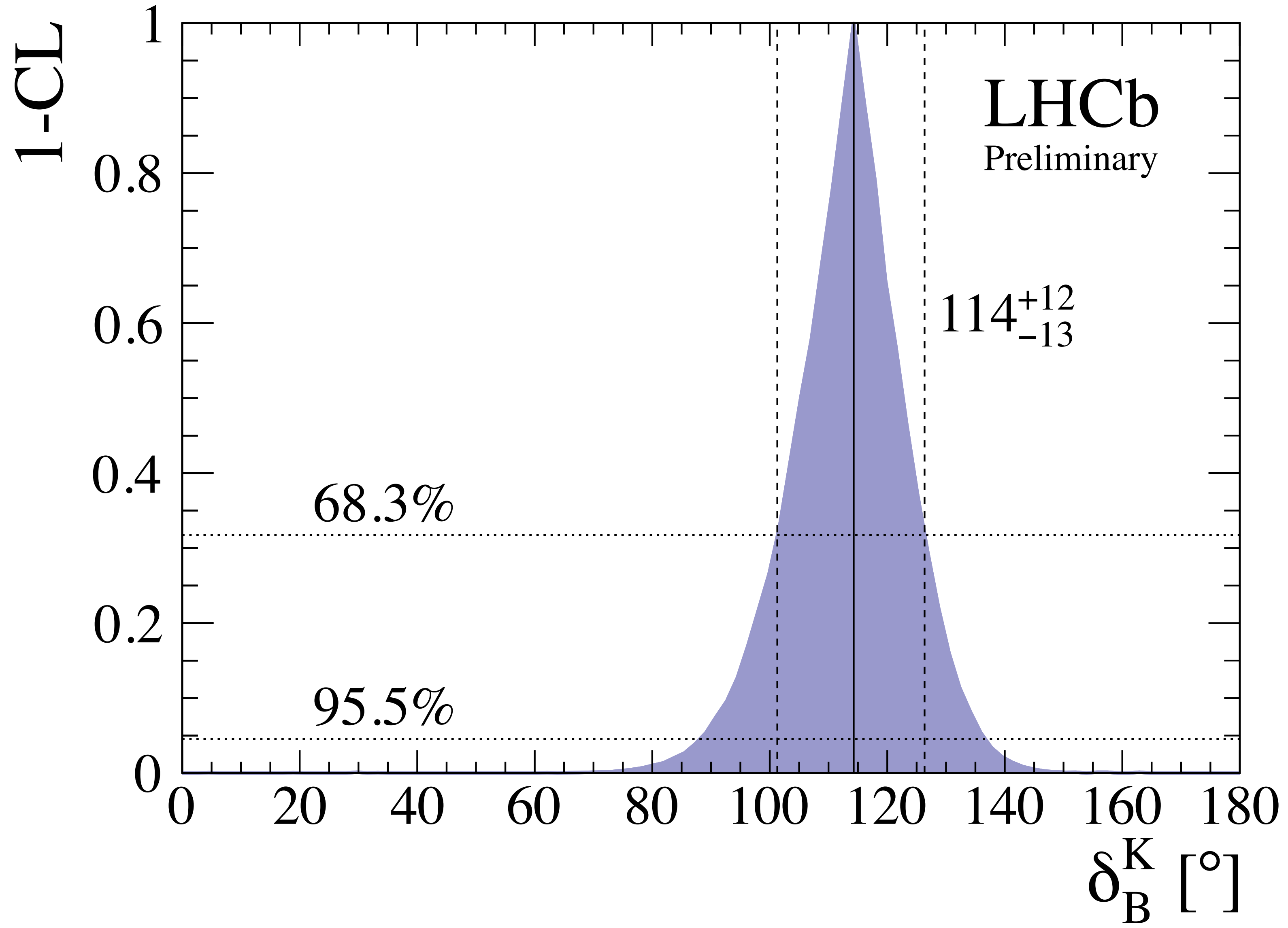


- **ADS/GLW 1 fb^{-1} analysis**
- **GGSZ 3 fb^{-1} analysis**

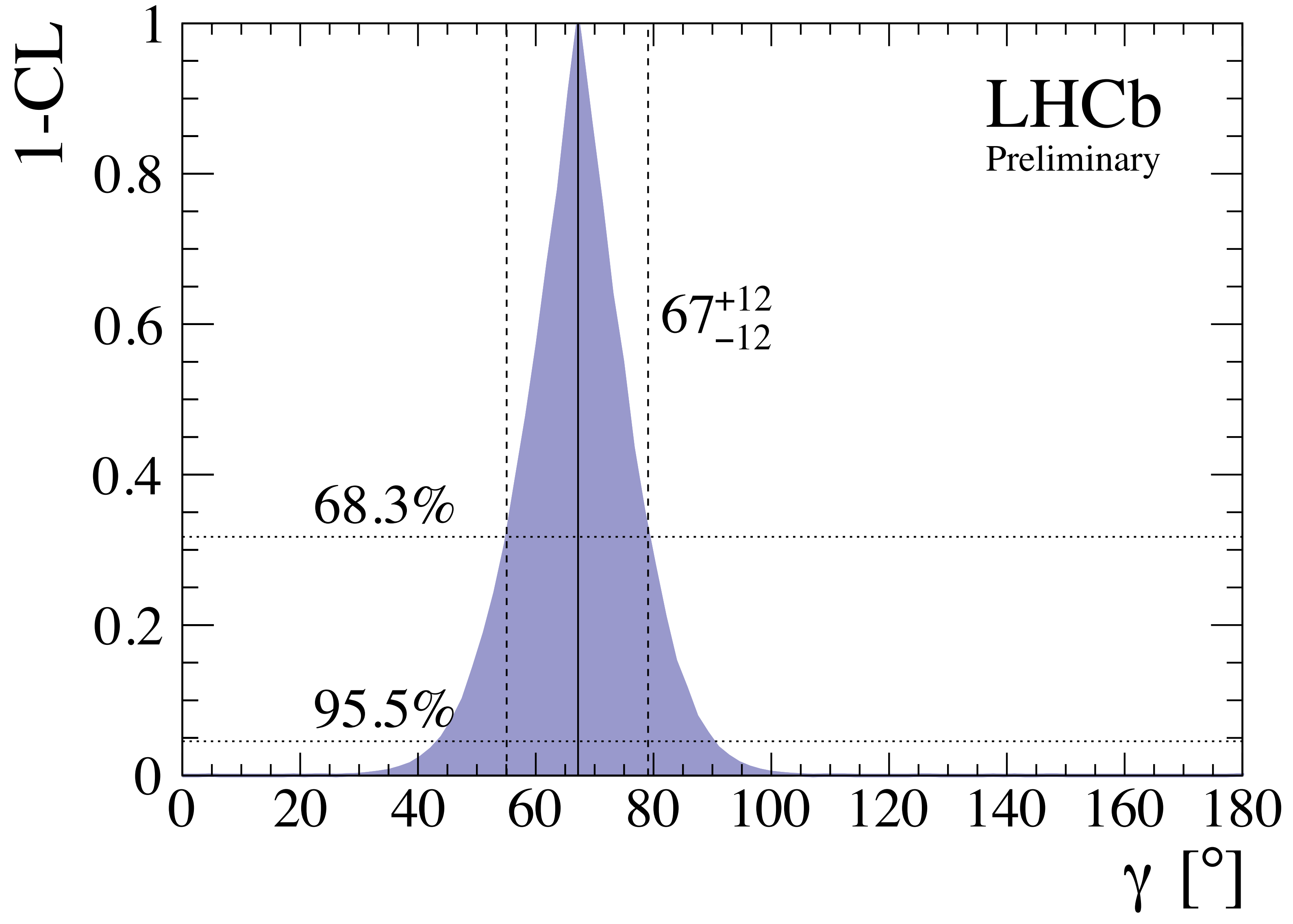


LHCb-CONF-2013-006

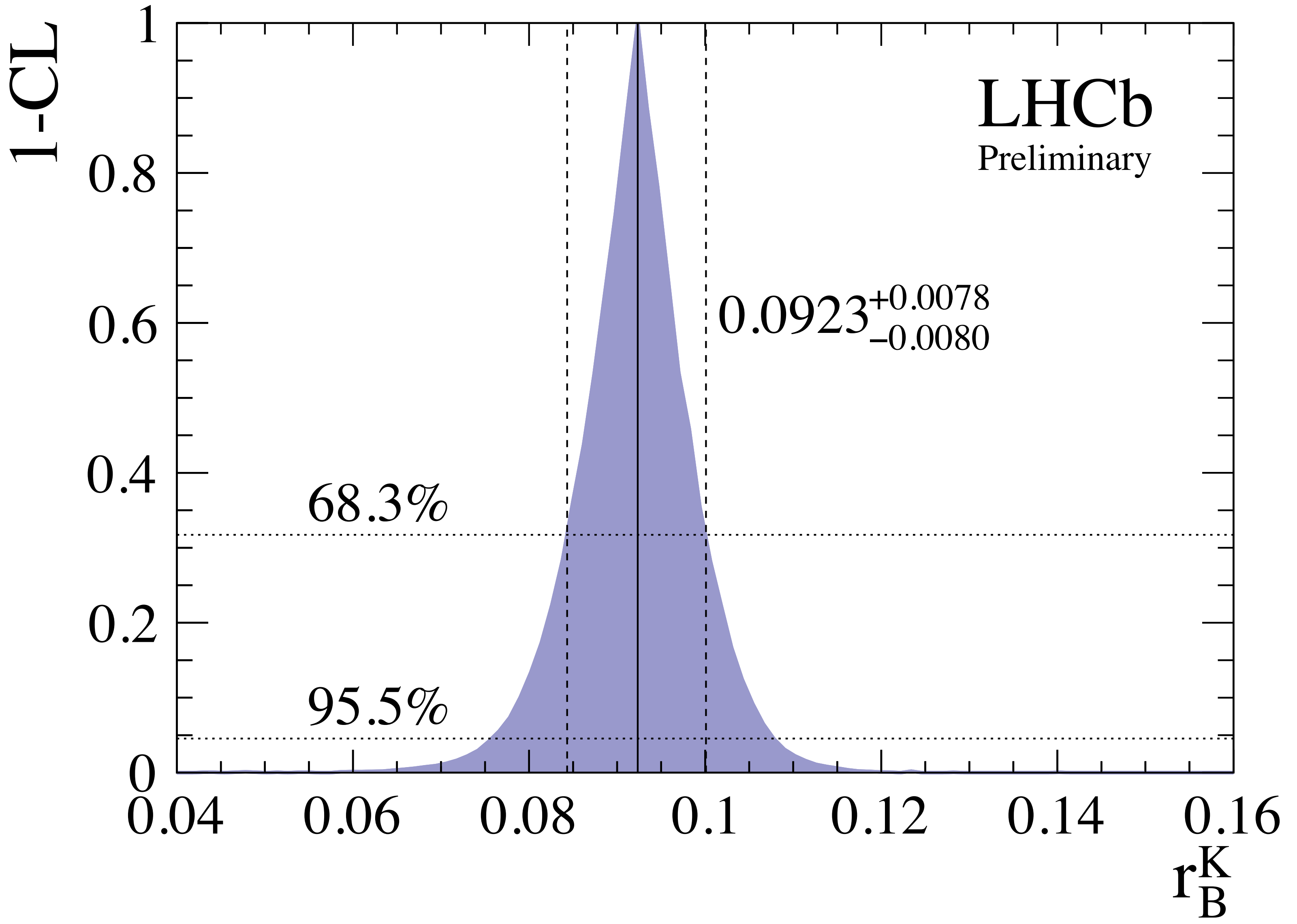
Combining the individual measurements



- Combined 3 fb^{-1} analysis



$\gamma = (67 \pm 12)°$



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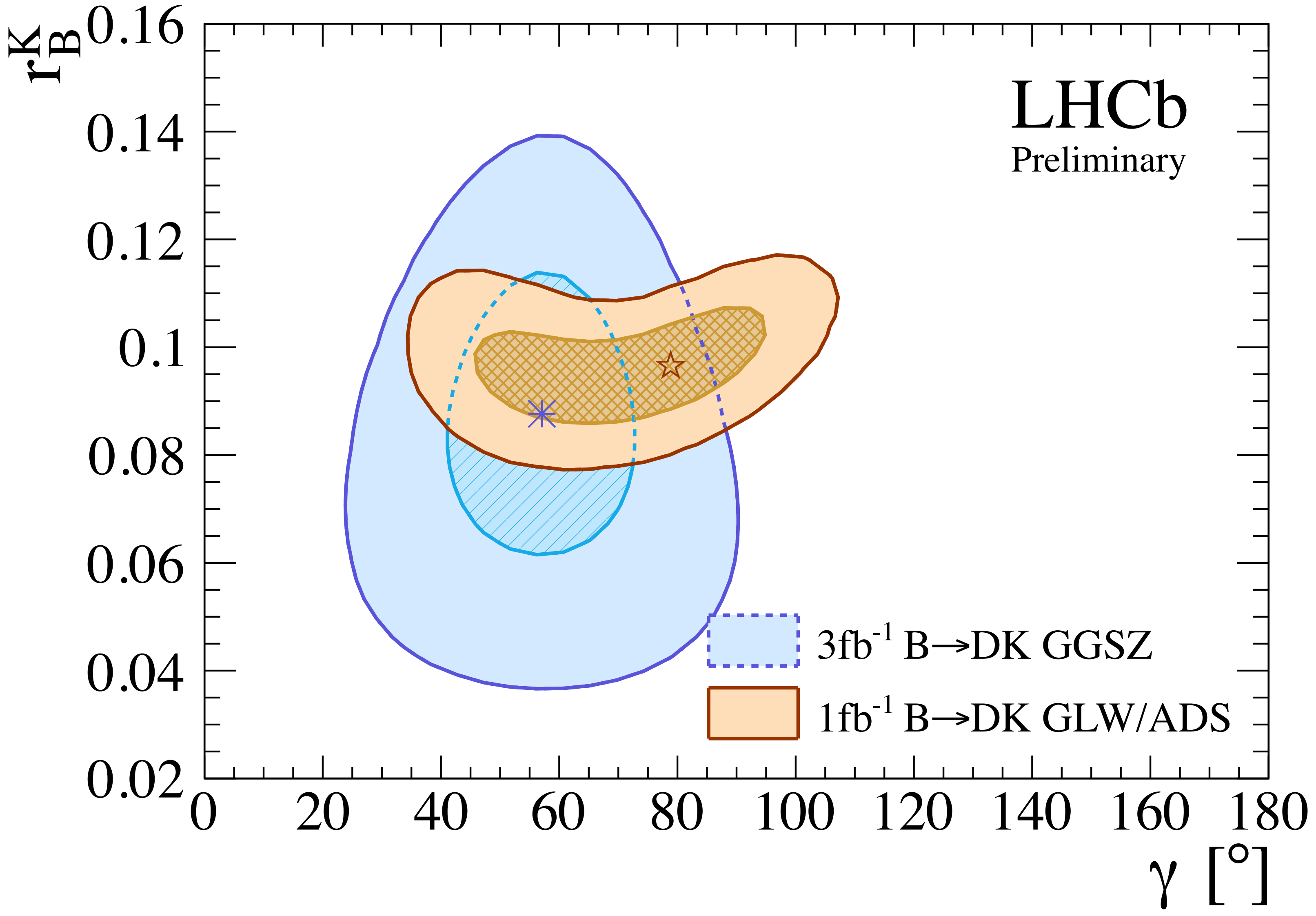
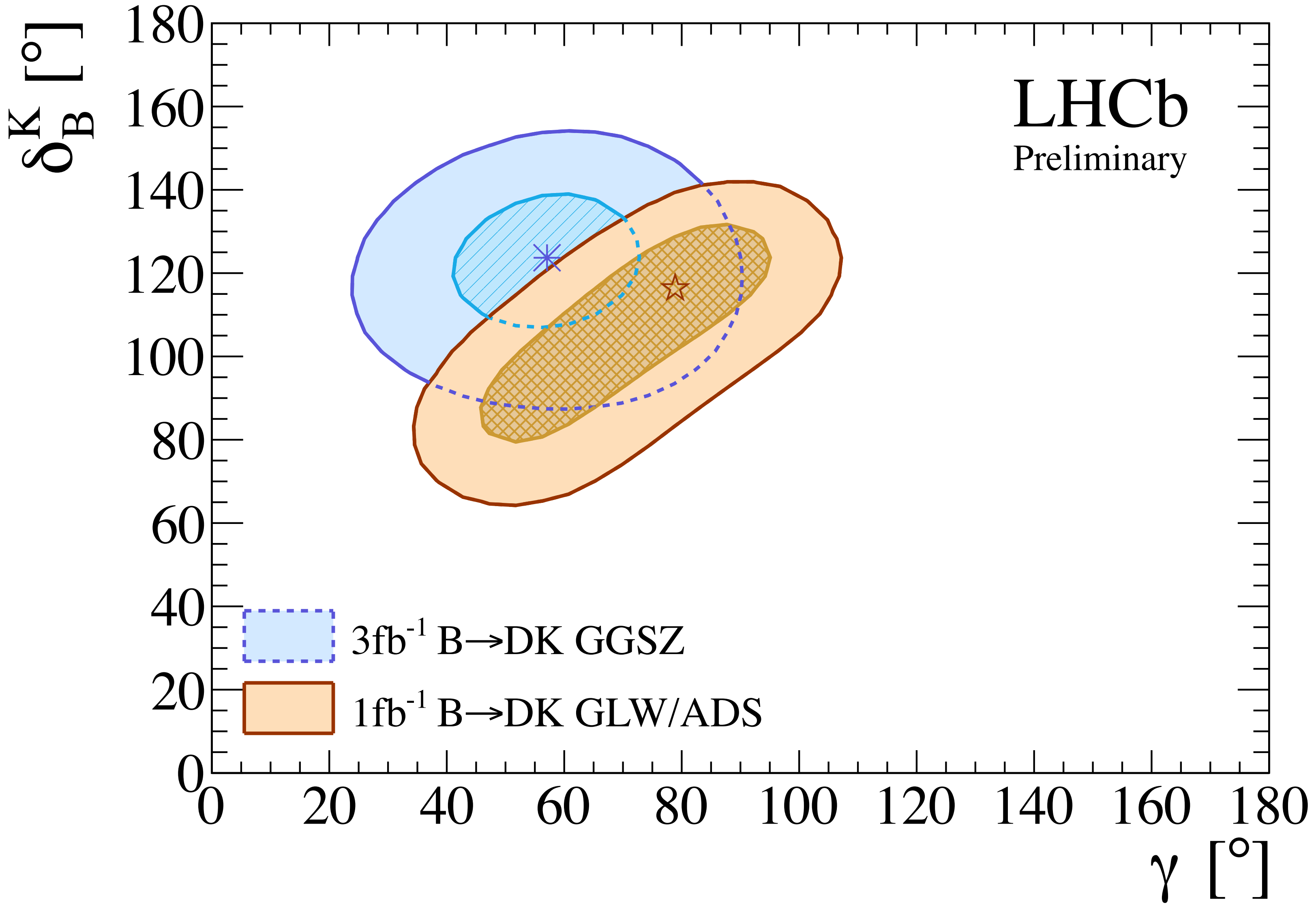
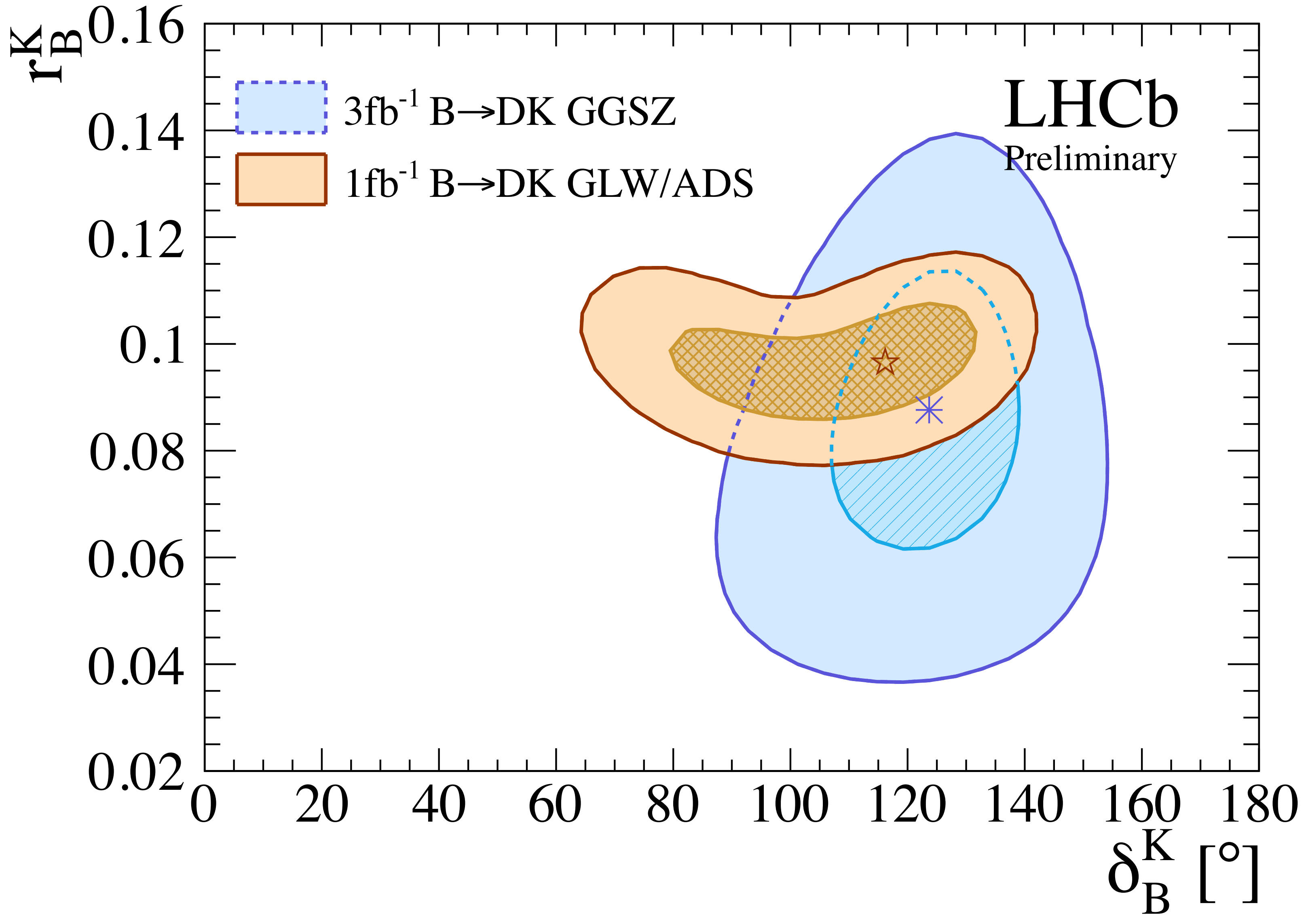
What about the 2D likelihoods?



3fb^{-1} B→DK GGSZ

1fb^{-1} B→DK GLW/ADS





LHCb-CONF-2013-006

The future

			LHC era		HL-LHC era	
		Run 1	Run 2	Run 3	Run 4	Run 5+
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$	CMS	$> 100\%$	71%	47%	...	21%
	LHCb	220%	110%	60%	40%	28%
$\phi_s(B_s^0 \to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	...	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B_s^0 \to \phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle II	—	11°	2°	1.5°	—
$A_\Gamma(D^0 \to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle II	—	18×10^{-4}	$4–6 \times 10^{-4}$	$3–5 \times 10^{-4}$	—
$q_0^2\ A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle II	—	50%	7%	5%	—
$t \to qZ$	ATLAS	...	...	23×10^{-5}	...	$4.1–7.2 \times 10^{-5}$
	CMS	100×10^{-5}	...	27×10^{-5}	...	10×10^{-5}
$t \to q\gamma$	ATLAS	...	...	7.8×10^{-5}	...	$1.3–2.5 \times 10^{-5}$

https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour

The future, LHCb

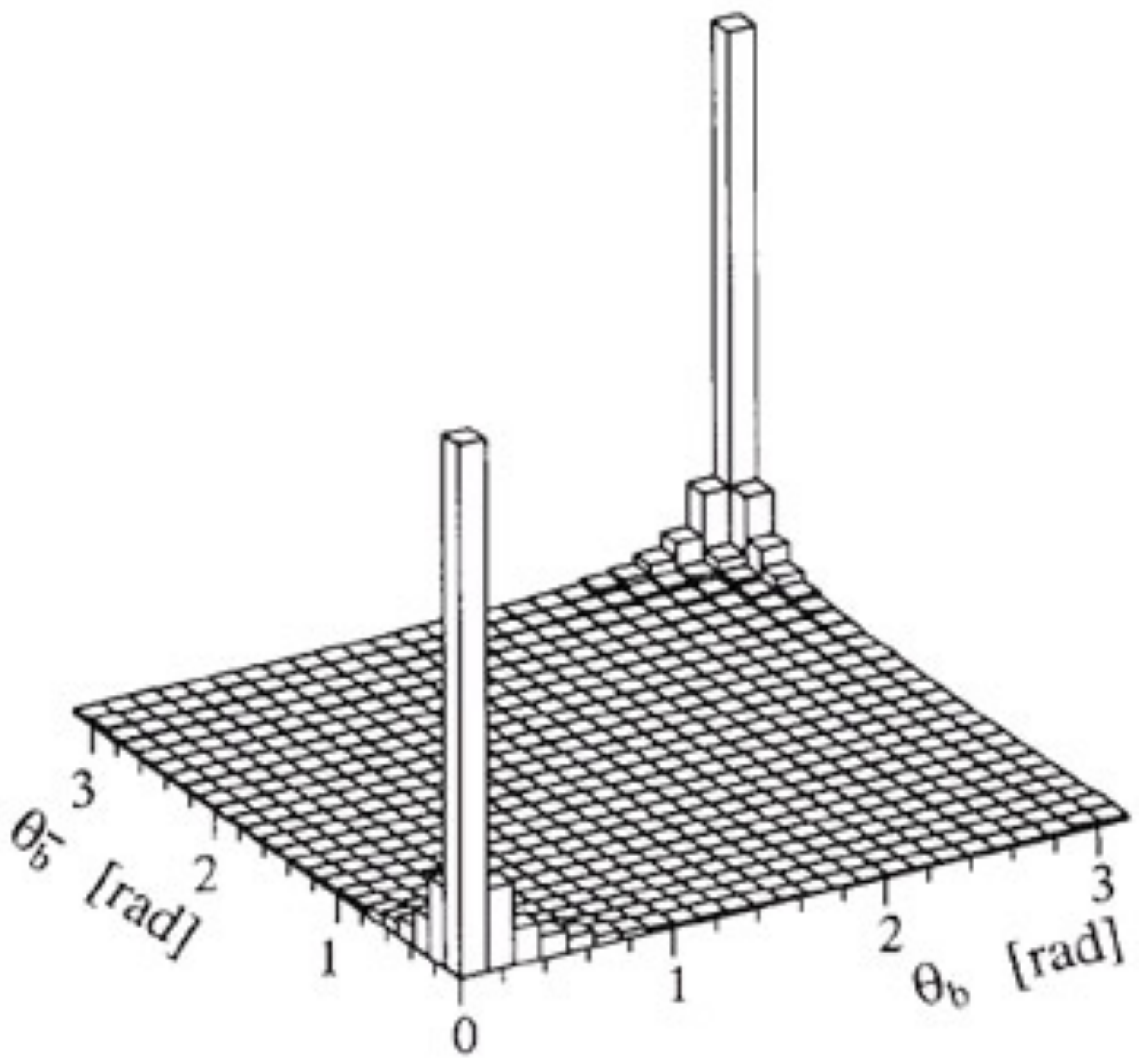
Table 3: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity i given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Ru 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potentia sources of systematic uncertainty are discussed in the text.

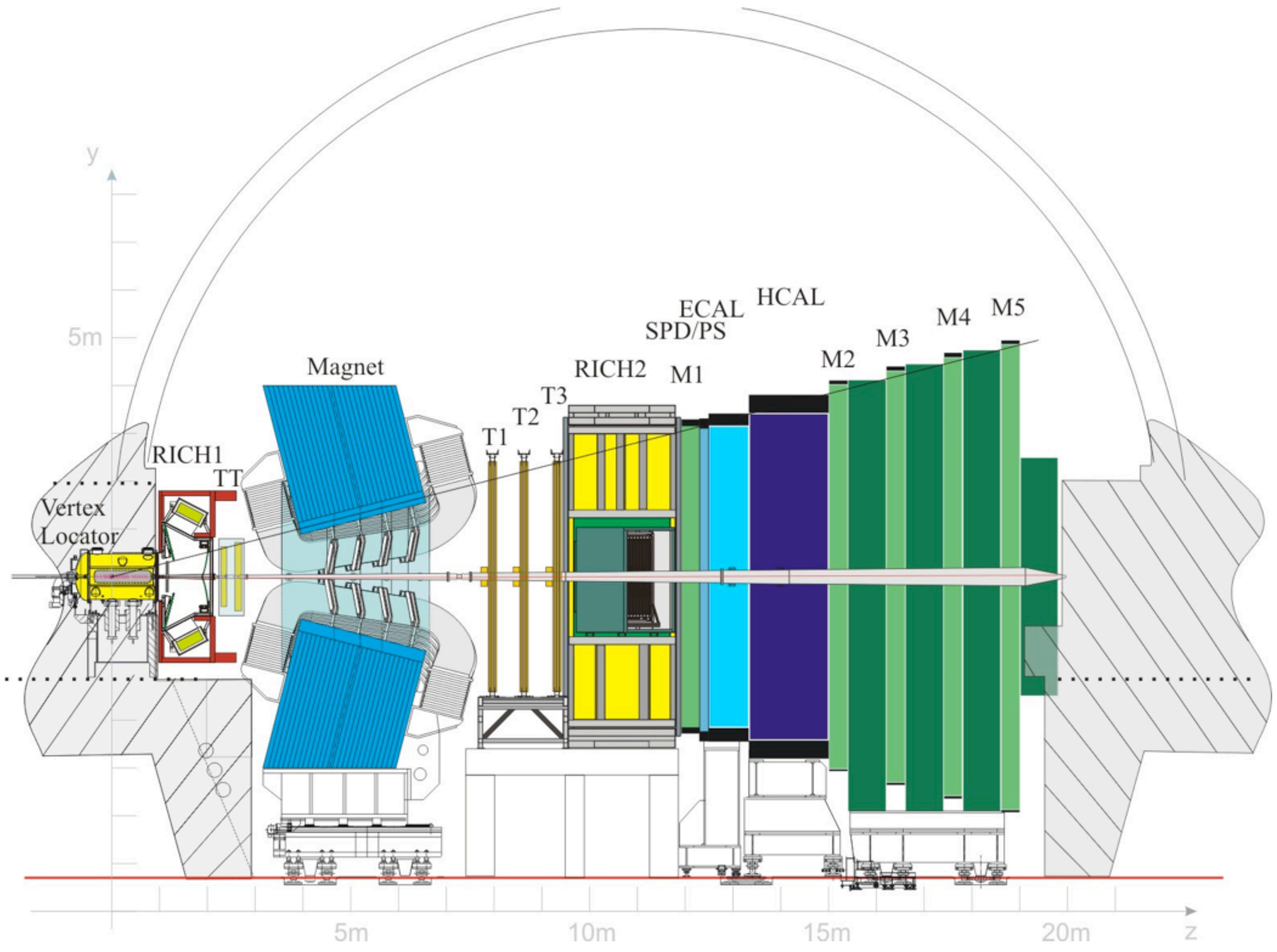
Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\mathrm{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

The future, Belle II

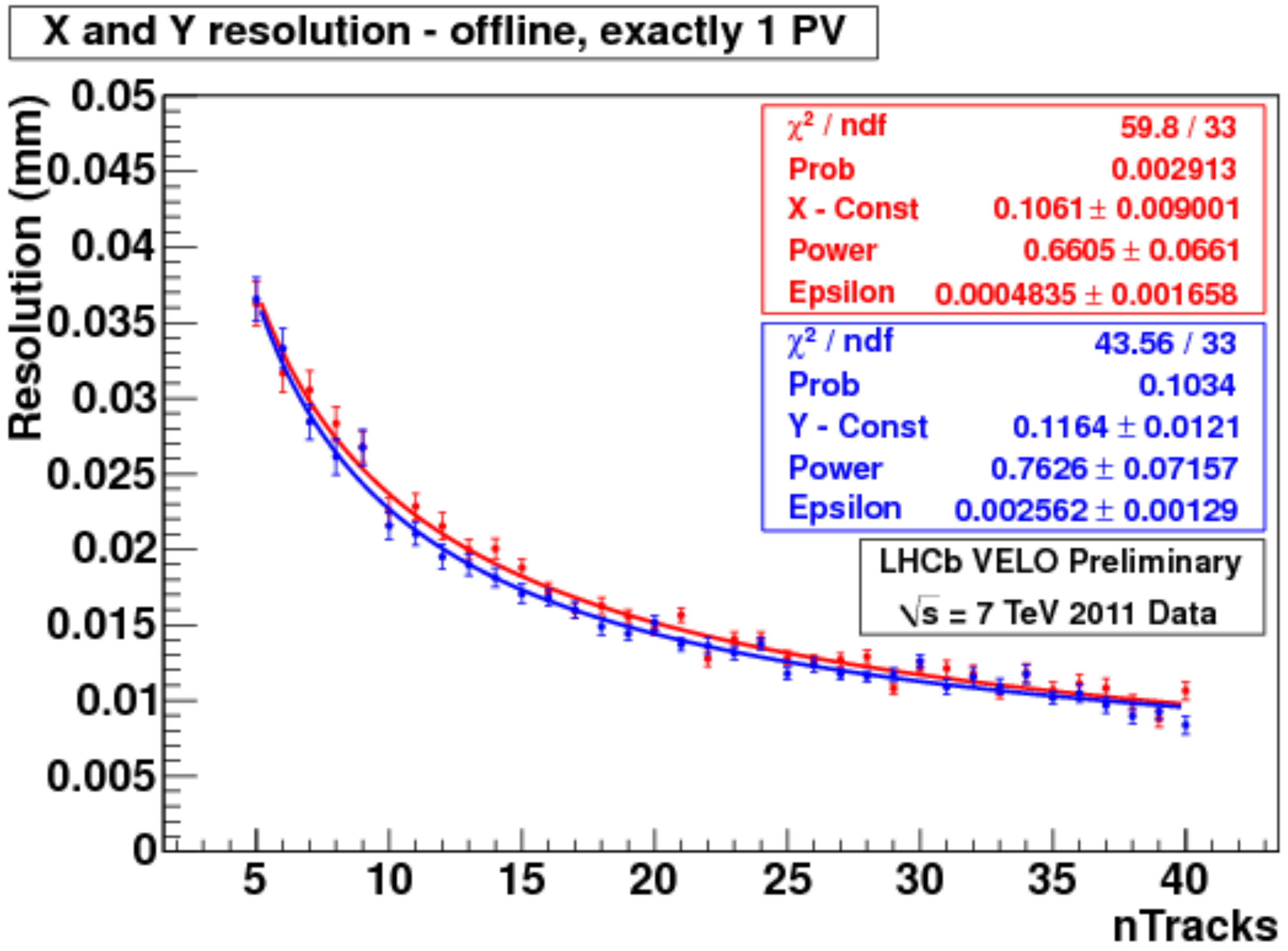
Observable	Belle 2006 ($\sim$0.5 ab^{-1})	SuperKEKB (5 ab^{-1})	SuperKEKB (50 ab^{-1})
Hadronic $b \to s$ transitions			
$\Delta\mathcal{S}_{\phi K^0}$	0.22	0.073	0.029
$\Delta\mathcal{S}_{\eta' K^0}$	0.11	0.038	0.020
$\Delta\mathcal{S}_{K_S^0 K_S^0 K_S^0}$	0.33	0.105	0.037
$\Delta\mathcal{A}_{\pi^0 K_S^0}$	0.15	0.072	0.042
$\mathcal{A}_{\phi\phi K^+}$	0.17	0.05	0.014
$\phi_1^{eff}(\phi K_S)$ Dalitz		3.3°	1.5°
Radiative/electroweak $b \to s$ transitions			
$\mathcal{S}_{K_S^0 \pi^0 \gamma}$	0.32	0.10	0.03
$\mathcal{B}(B \to X_s \gamma)$	13%	7%	6%
$A_{CP}(B \to X_s \gamma)$	0.058	0.01	0.005
C_9 from $\overline{A}_{\rm FB}(B \to K^* \ell^+ \ell^-)$	-	11%	4%
C_{10} from $\overline{A}_{\rm FB}(B \to K^* \ell^+ \ell^-)$	-	13%	4%
C_7/C_9 from $\overline{A}_{\rm FB}(B \to K^* \ell^+ \ell^-)$	-		5%
R_K		0.07	0.02
$\mathcal{B}(B^+ \to K^+ \nu\nu)$	$^{\dagger\dagger} < 3\ \mathcal{B}_{\rm SM}$		30%
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	$^{\dagger\dagger} < 40\ \mathcal{B}_{\rm SM}$		35%
Leptonic/semileptonic B decays			
$\mathcal{B}(B^+ \to \tau^+ \nu)$	3.5σ	10%	3%
$\mathcal{B}(B^+ \to \mu^+ \nu)$	$^{\dagger\dagger} < 2.4\mathcal{B}_{\rm SM}$	4.3 ab^{-1} for 5σ discovery	
$\mathcal{B}(B^+ \to D \tau \nu)$	-	8%	3%
$\mathcal{B}(B^0 \to D \tau \nu)$	-	30%	10%
LFV in τ decays (U.L. at 90% C.L.)			
$\mathcal{B}(\tau \to \mu\gamma)$ [10^{-9}]	45	10	5
$\mathcal{B}(\tau \to \mu\eta)$ [10^{-9}]	65	5	2
$\mathcal{B}(\tau \to \mu\mu\mu)$ [10^{-9}]	21	3	1
Unitarity triangle parameters			
$\sin 2\phi_1$	0.026	0.016	0.012
ϕ_2 ($\pi\pi$)	11°	10°	3°
ϕ_2 ($\rho\pi$)	$68° < \phi_2 < 95°$	3°	1.5°
ϕ_2 ($\rho\rho$)	$62° < \phi_2 < 107°$	3°	1.5°
ϕ_2 (combined)		2°	$\lesssim 1°$
ϕ_3 ($D^{(*)}K^{(*)}$) (Dalitz mod. ind.)	20°	7°	2°
ϕ_3 ($DK^{(*)}$) (ADS+GLW)	-	16°	5°
ϕ_3 ($D^{(*)}\pi$)	-	18°	6°
ϕ_3 (combined)		6°	1.5°
$\|V_{ub}\|$ (inclusive)	6%	5%	3%
$\|V_{ub}\|$ (exclusive)	15%	12% (LQCD)	5% (LQCD)
††† [illegible]	[illegible]		[illegible]

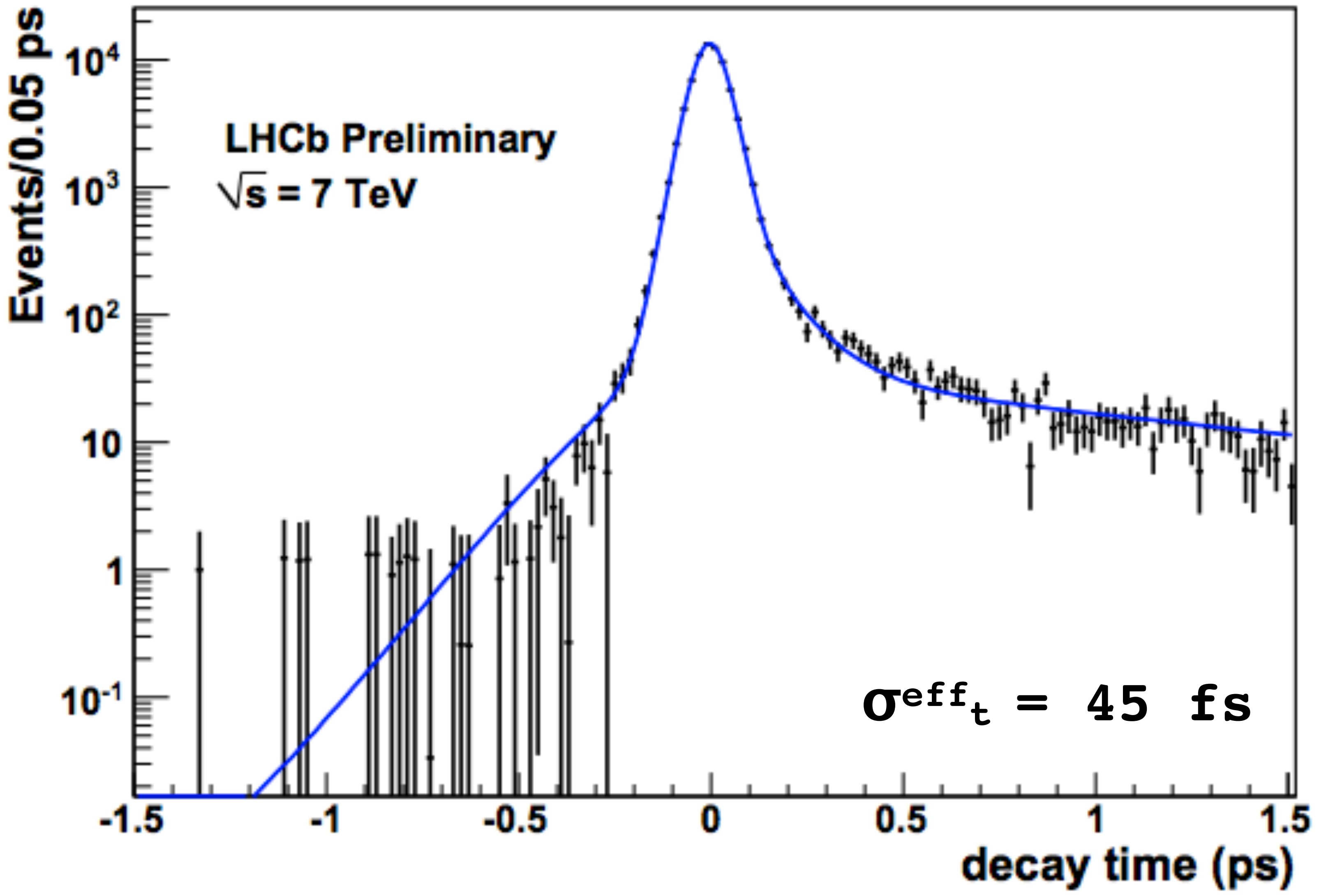
A forward spectrometer for the LHC

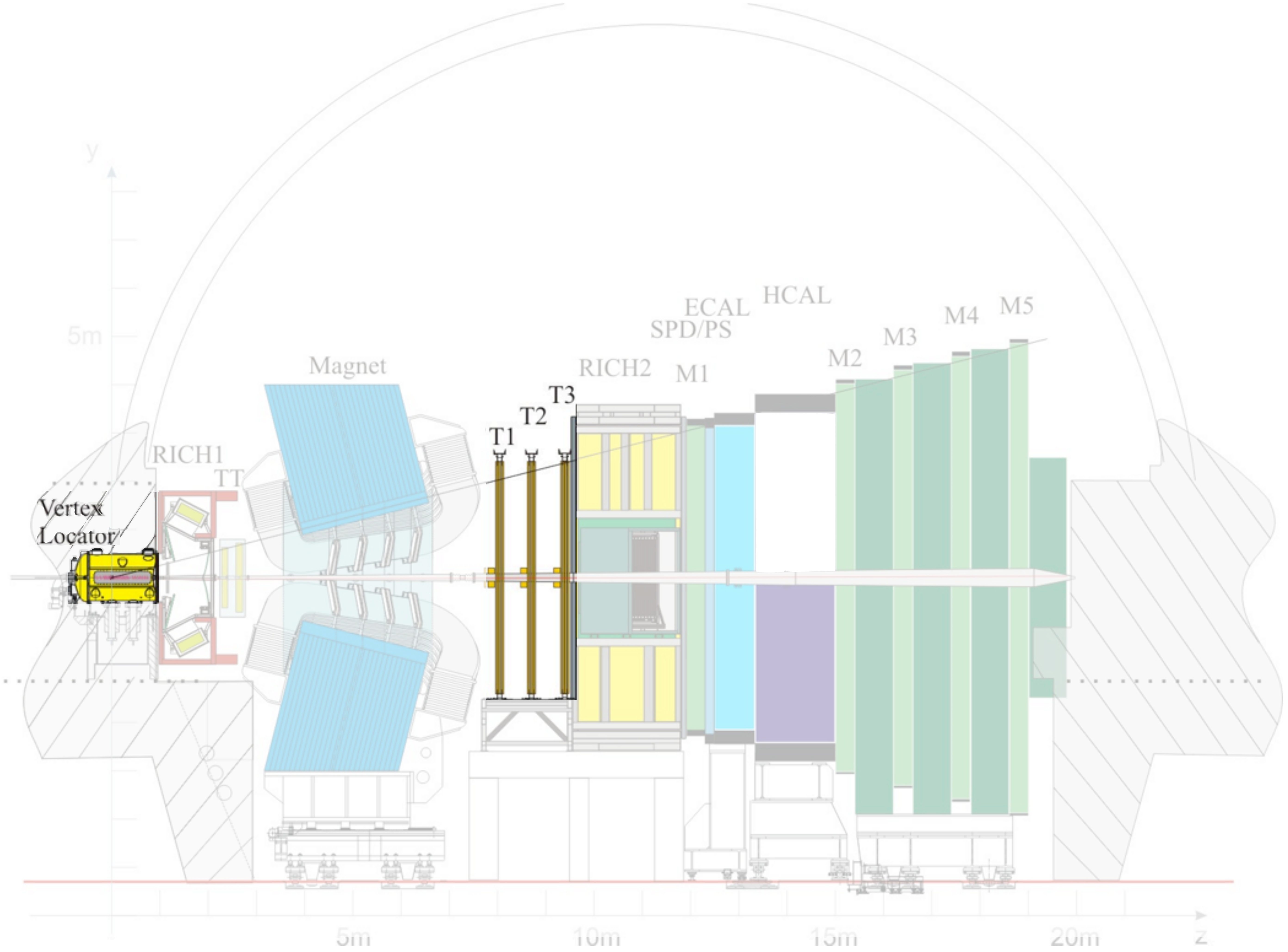




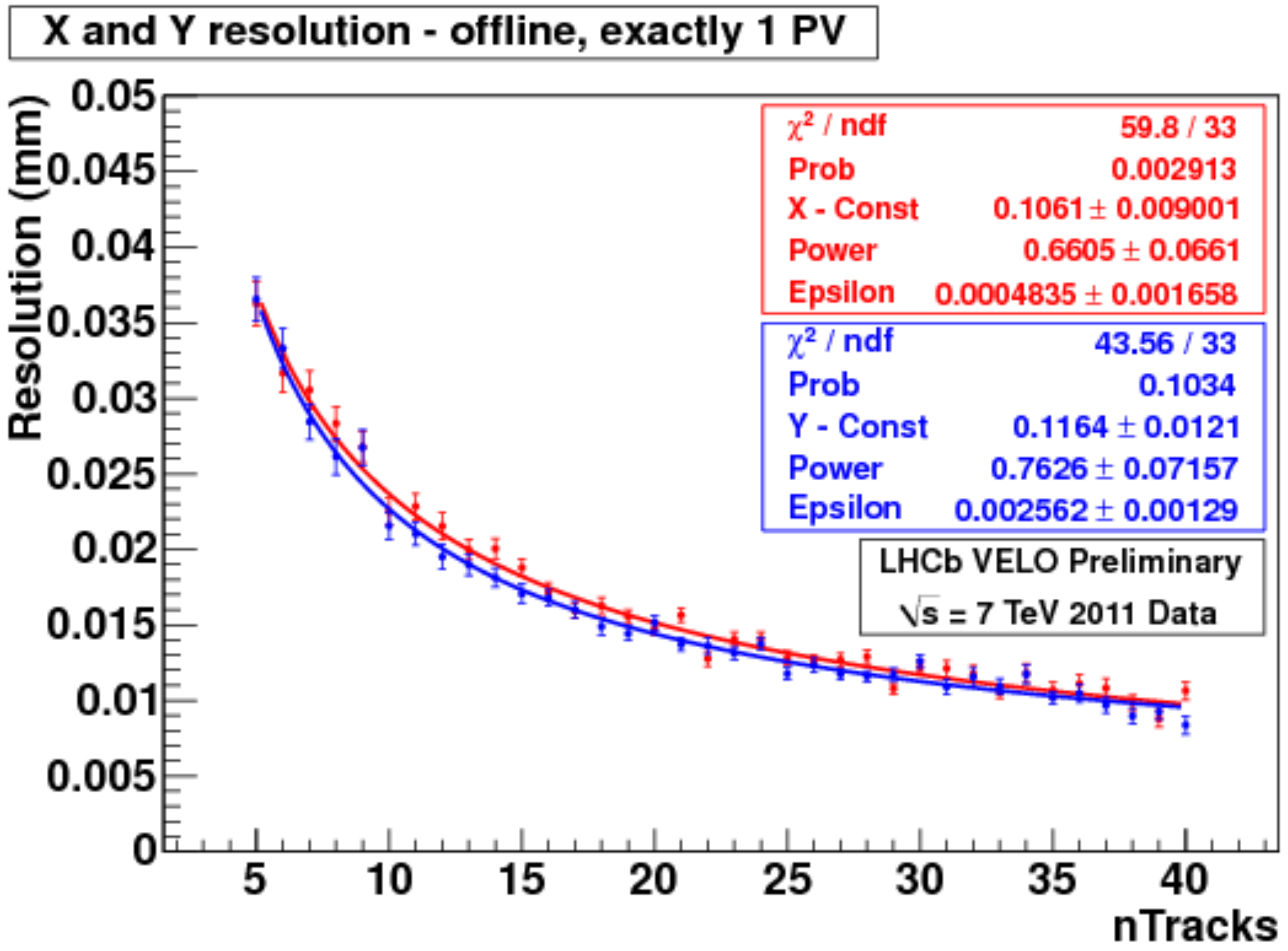
with excellent tracking resolution

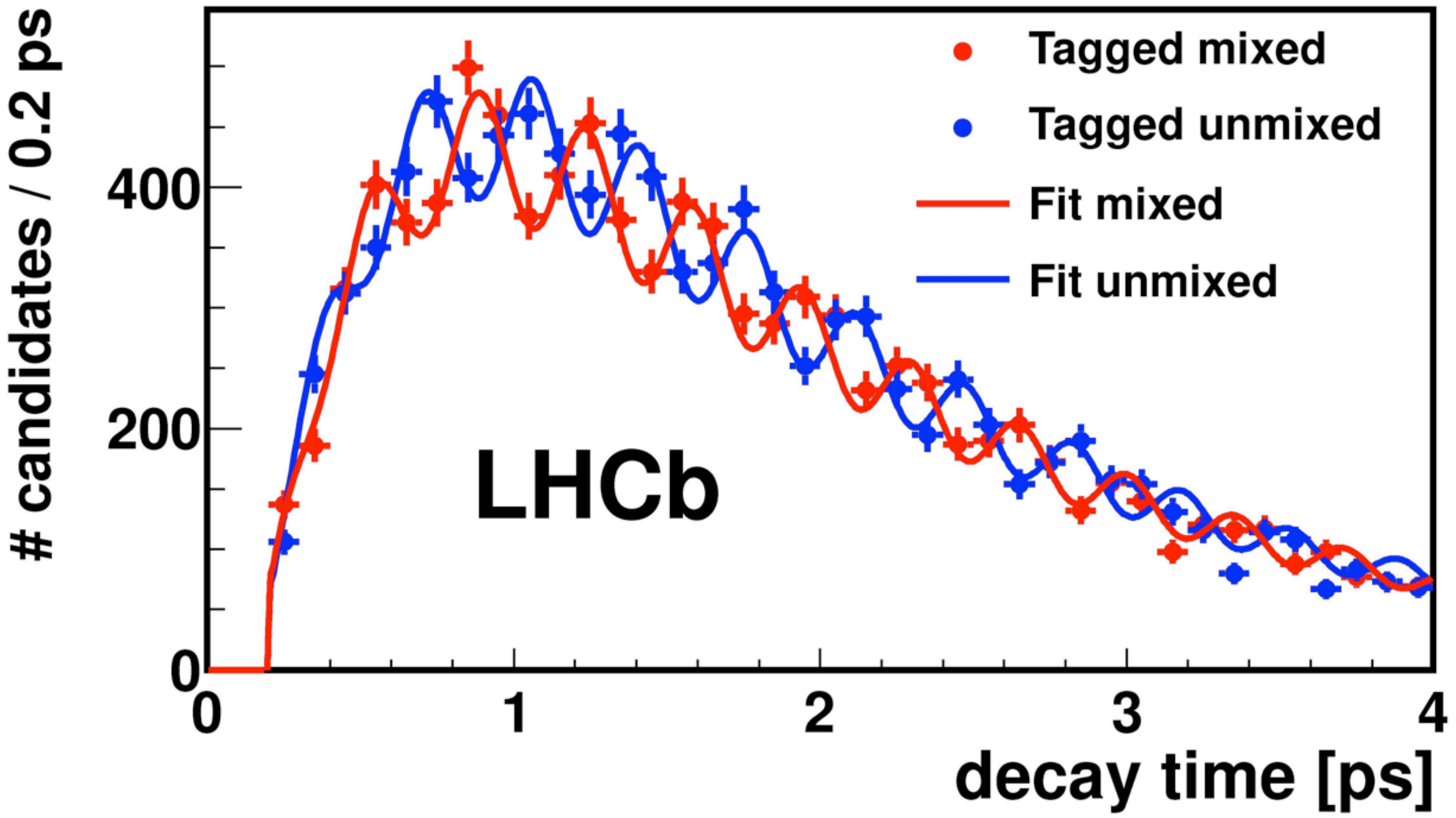


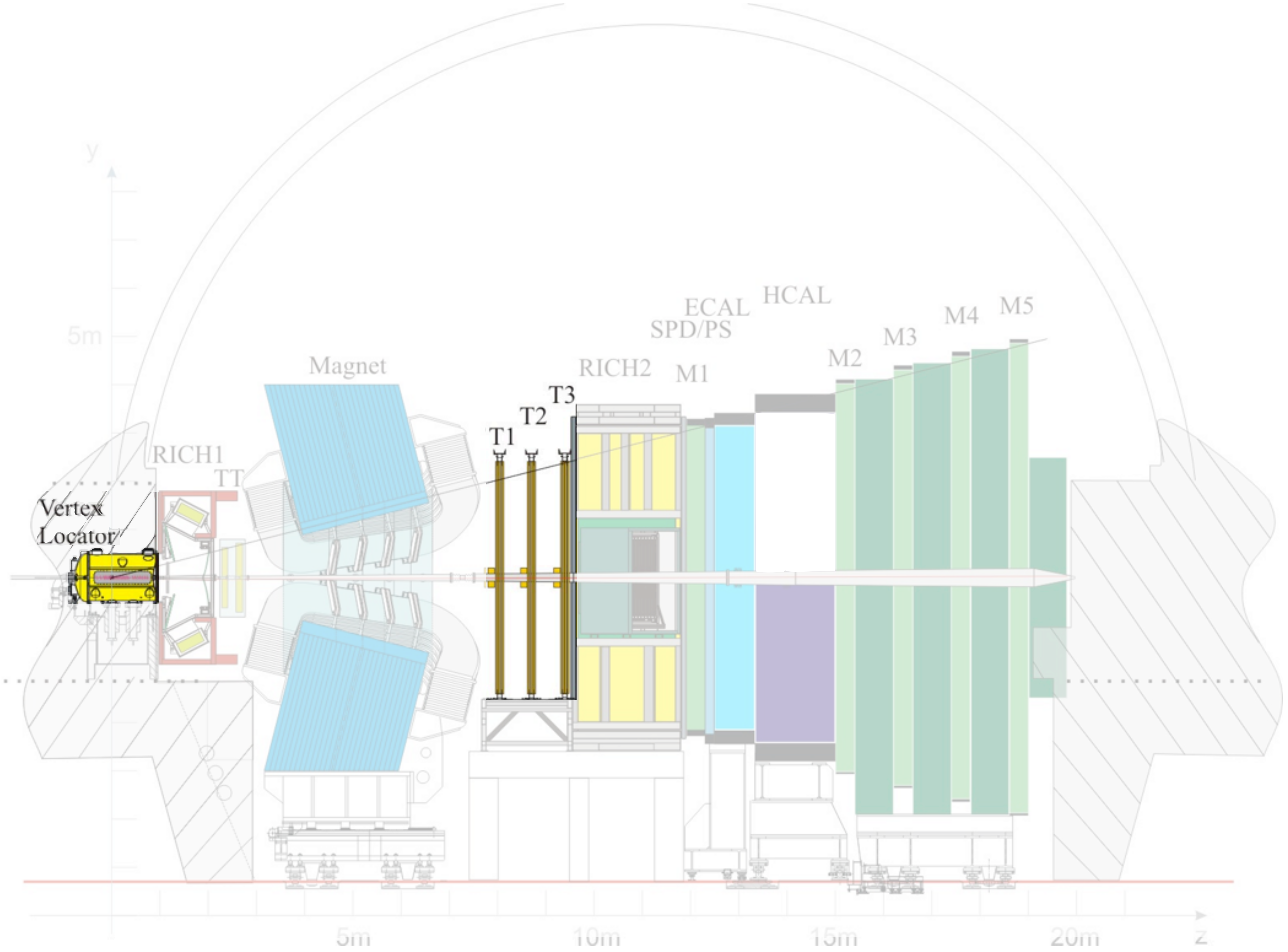




with excellent tracking resolution

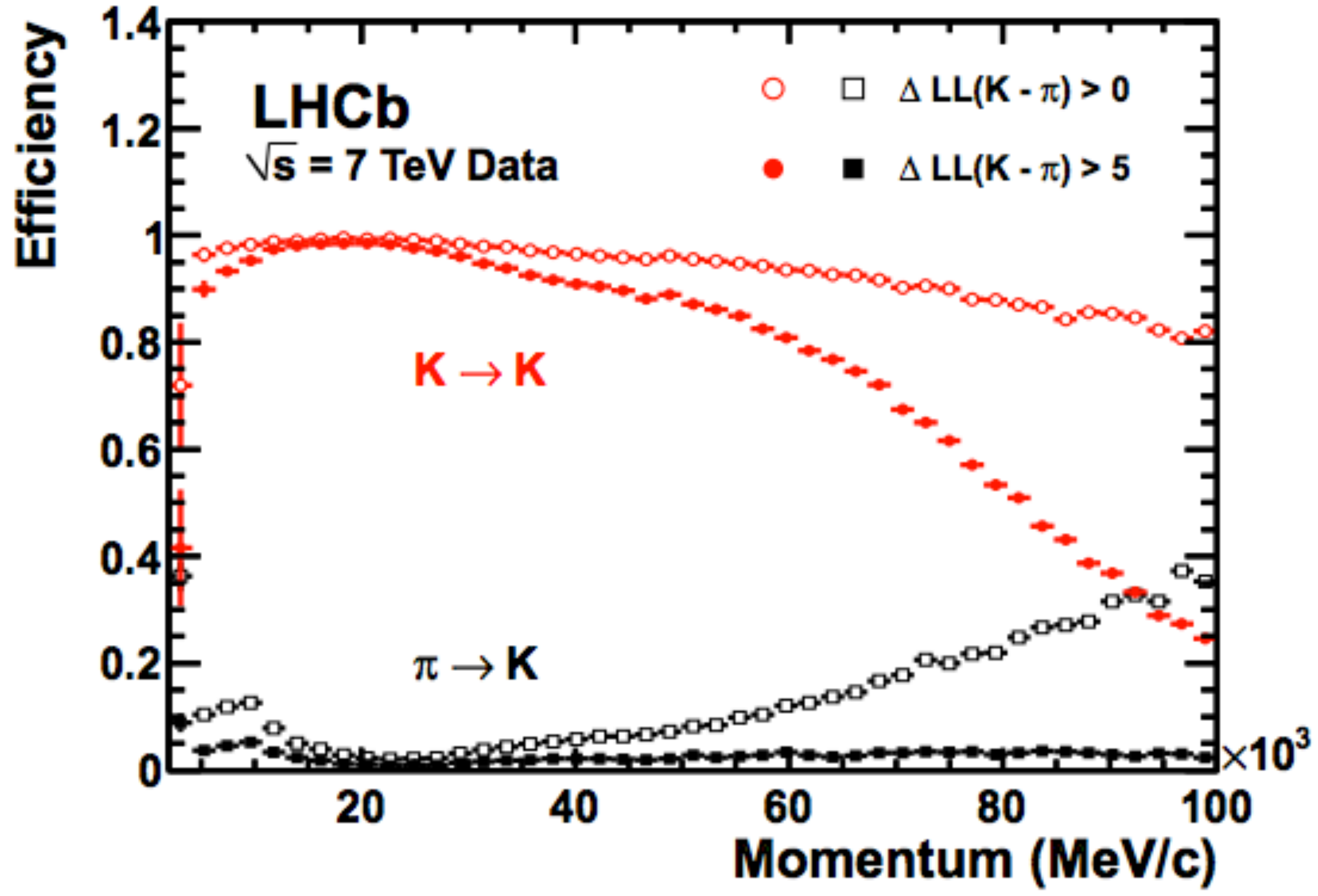


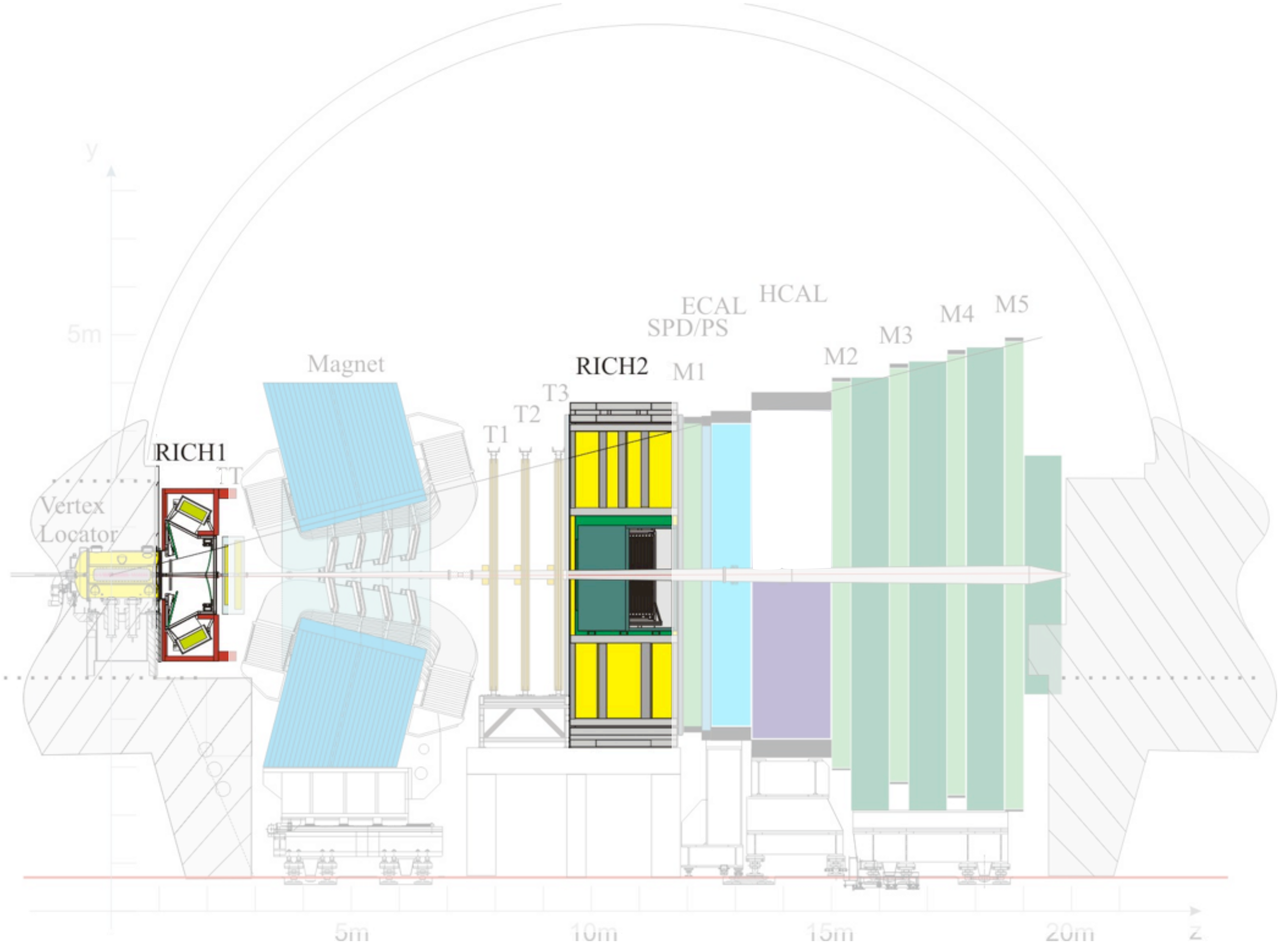




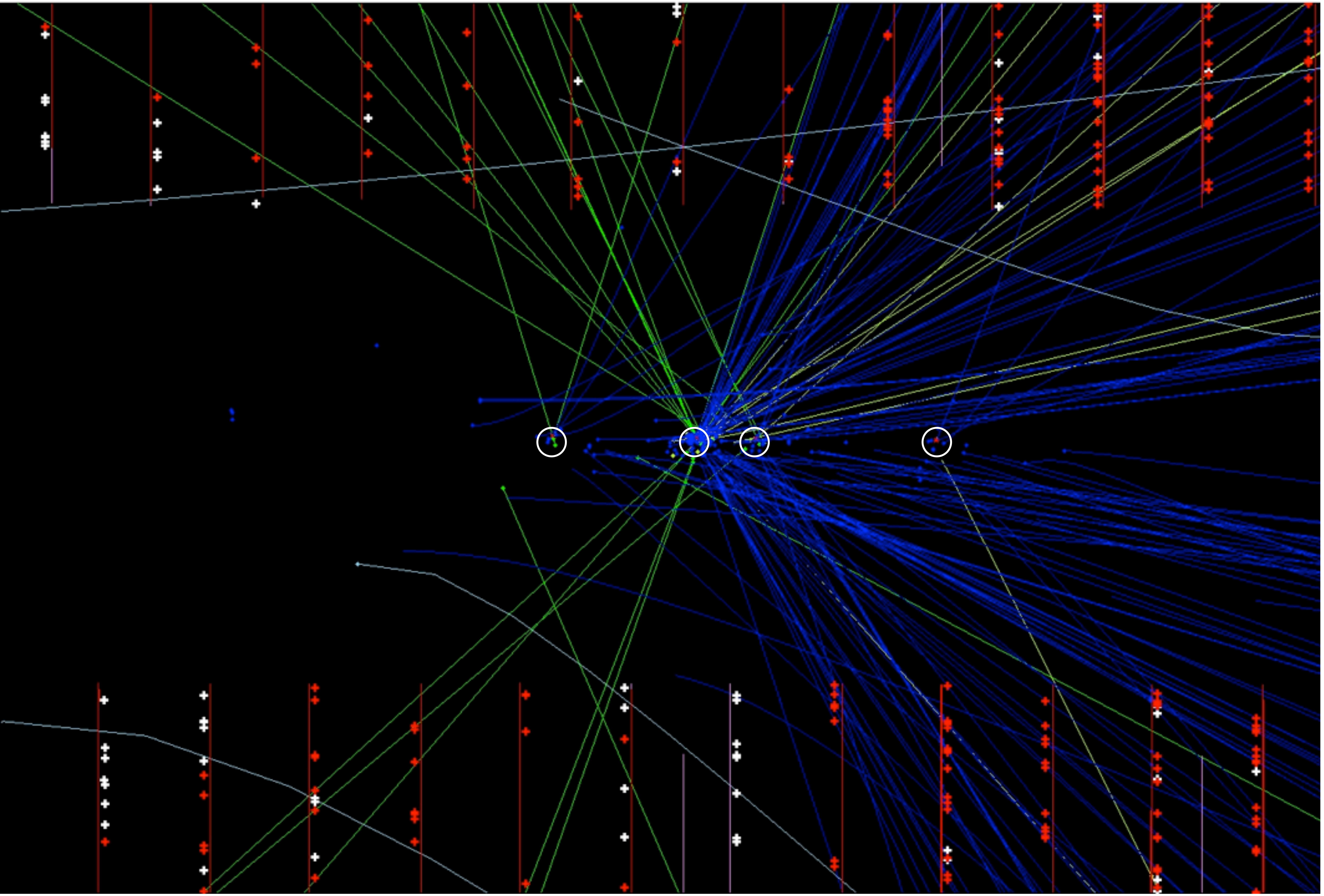
LHCb's is uniquely able to make high precision time-dependent B_s sector measurements

and charged hadron separation





The LHC environment



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz	400 kHz	150 kHz
$h^{\pm}$	$\mu/\mu\mu$	e/γ

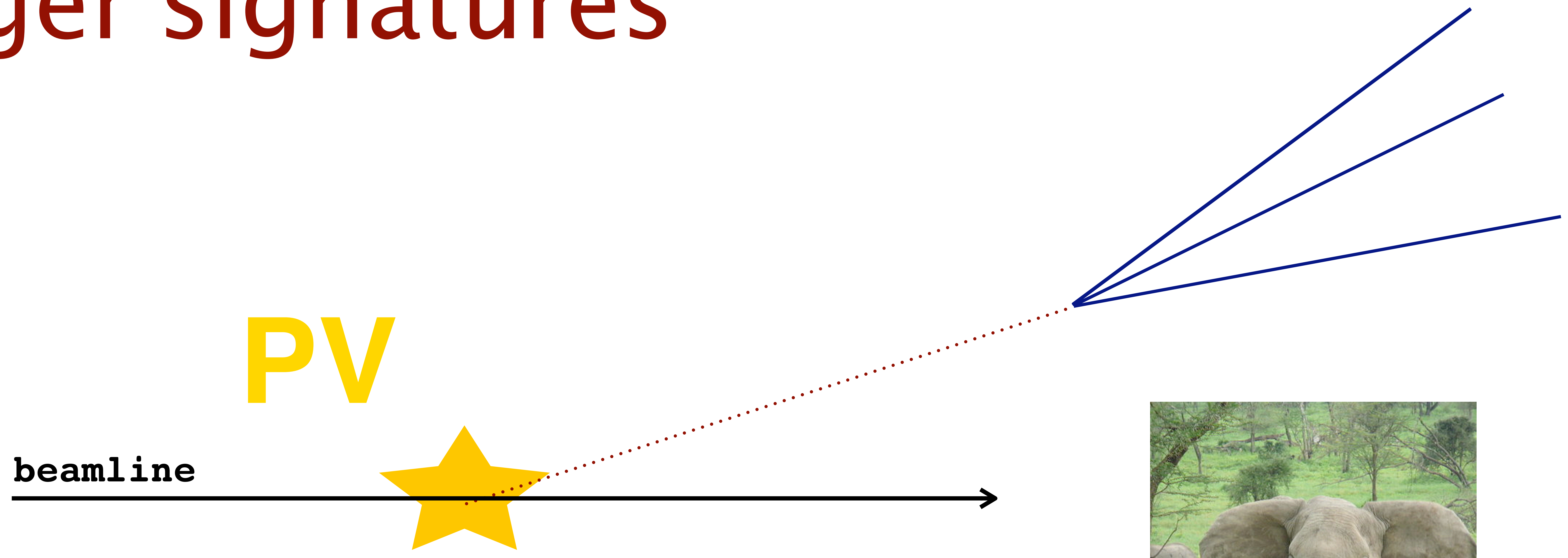
Defer 20% to disk

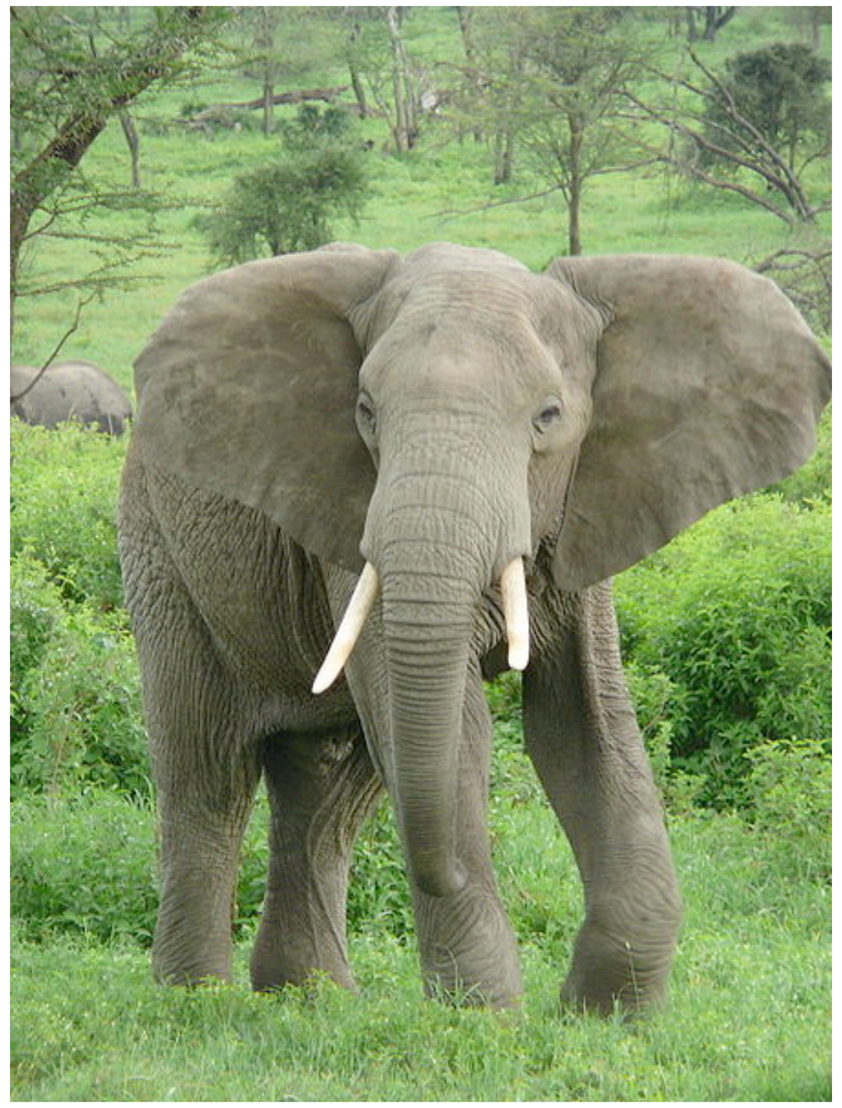
Software High Level Trigger

- **29000 Logical CPU cores**
- **Offline reconstruction tuned to trigger time constraints**
- **Mixture of exclusive and inclusive selection algorithms**

5 kHz Rate to storage

Trigger signatures





B meson signatures :

- **Large child transverse momentum**
- **Large child impact parameter or vertex displacement**
- **DiMuon candidate**

“A B is the elephant of the particle zoo: it is very heavy and lives a long time” -- T. Schietinger

Real time event selection

1.

Information gathering
("reconstruction") stage

Real time event selection

1\.

Information gathering
("reconstruction") stage

⇛

Real time event selection

1. Information gathering (“reconstruction”) stage ⇒ 

⇓

2. Event selection stage

Real time event selection

1. Information gathering ("reconstruction") stage ⇒

⇓

2. Event selection stage ⇒ Selected | Rejected

Real time event selection

1. **Information gathering ("reconstruction") stage** ⇒ 

⇓

2. **Event selection stage** ⇒ Selected | Rejected

⇓

3. **Next reconstruction stage** ⇒  

⇓

Displaced track trigger

1.

Full reconstruction of tracks in vertex locator

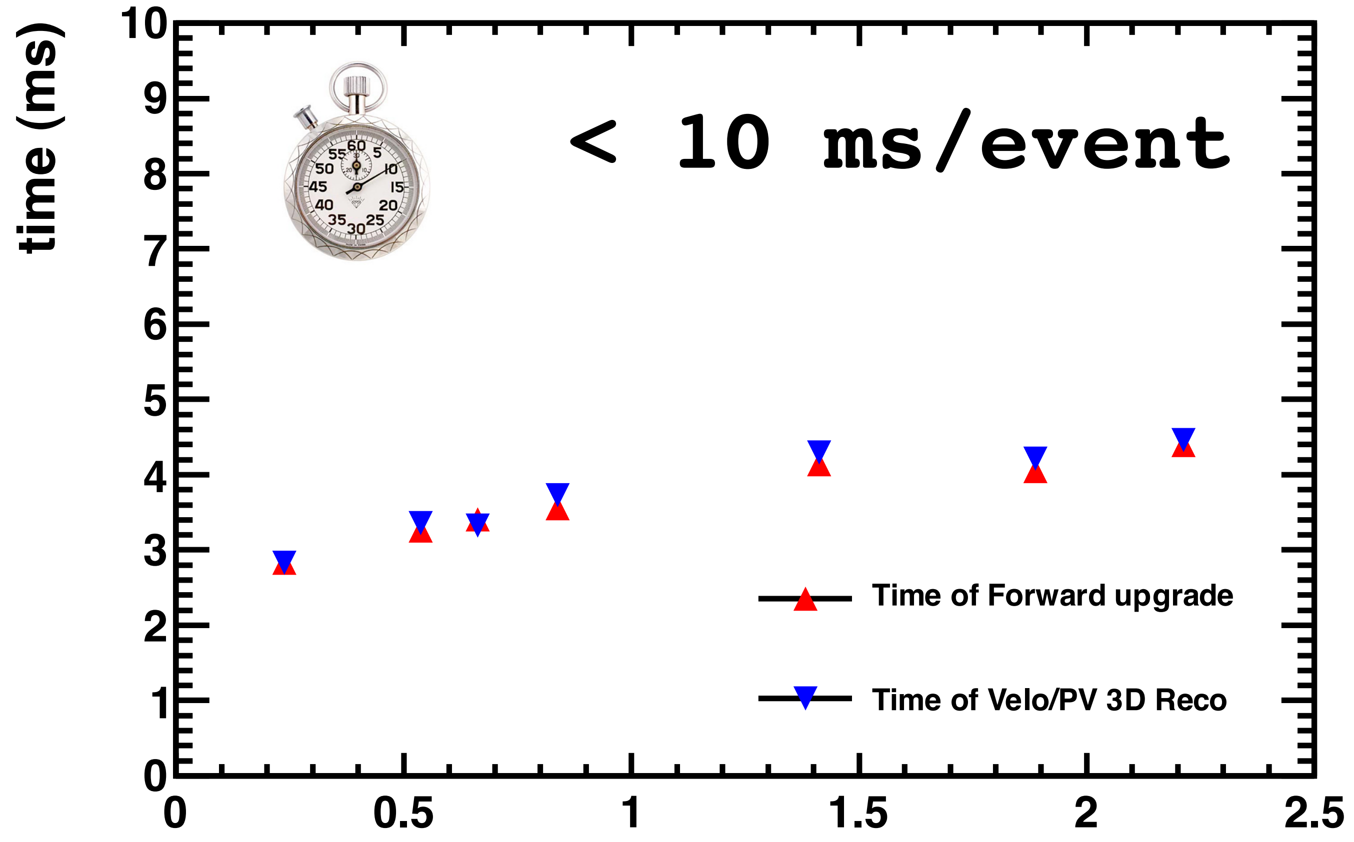
⇓

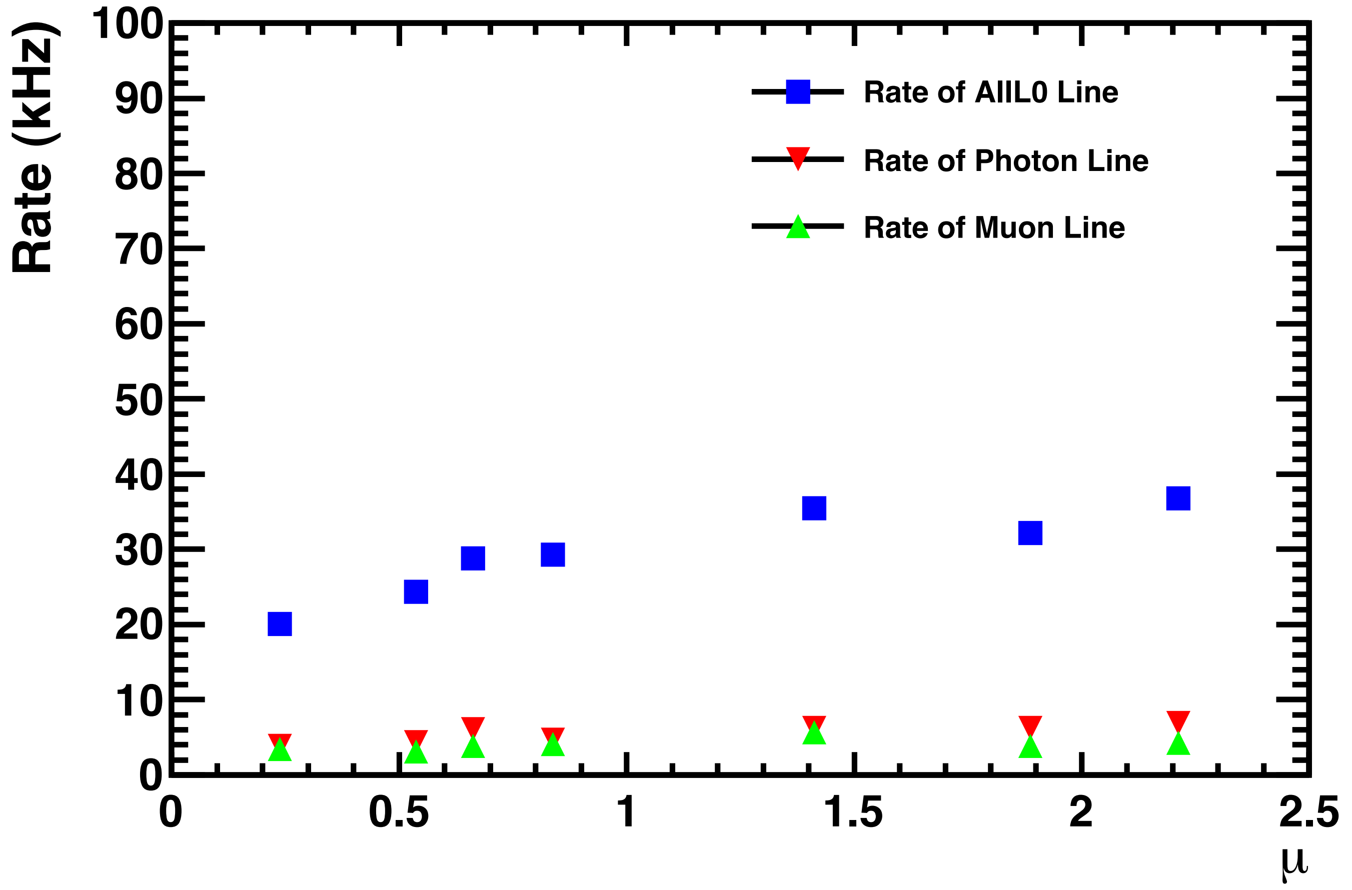
Select displaced tracks

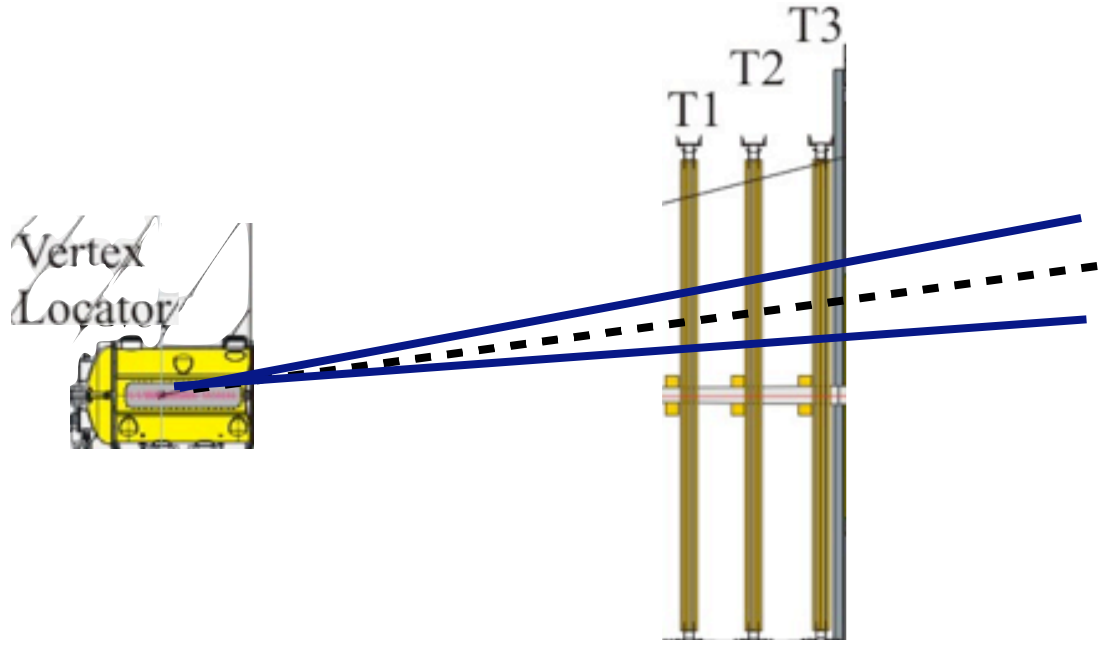
⇓

2.

Reconstruction of displaced tracks in regions of interest

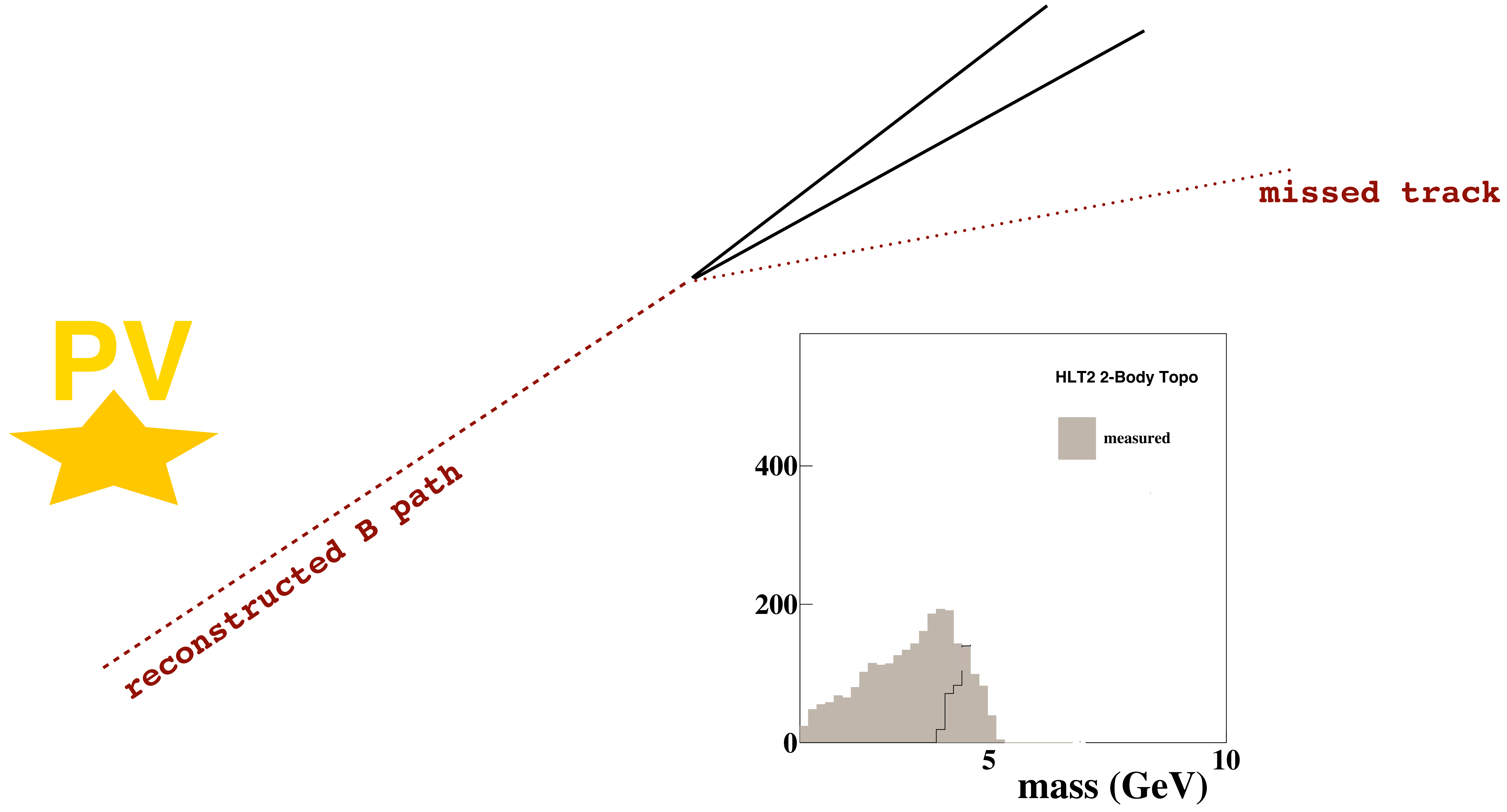




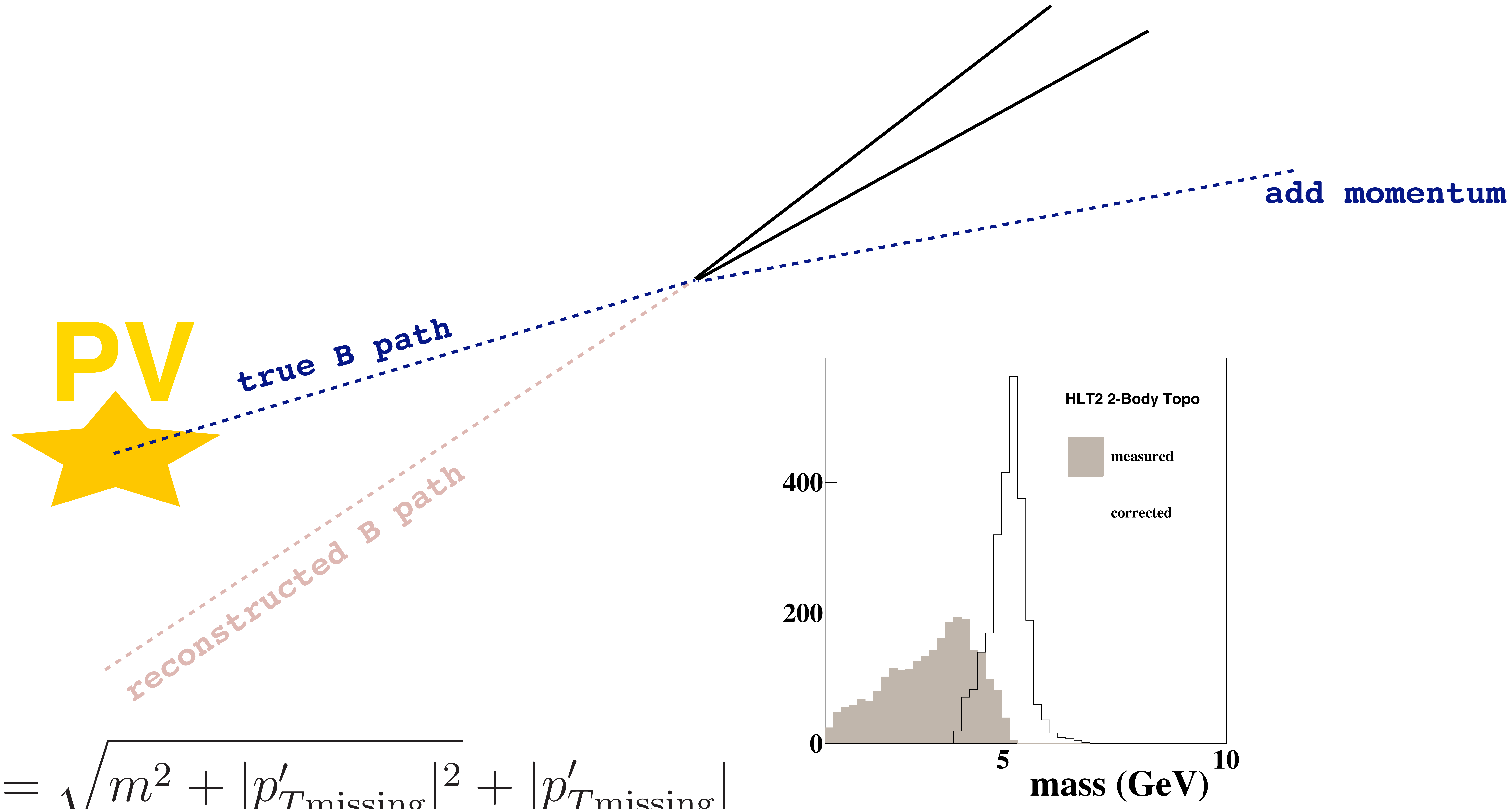


Region of interest defined by assumed track P&P_T

A topological decision tree trigger



A topological decision tree trigger



$$m_{\mathrm{corrected}} = \sqrt{m^2 + |p'_{T\mathrm{missing}}|^2} + |p'_{T\mathrm{missing}}|$$

What has this enabled LHCb to produce?

GLW/ADS in $B \to DK, D\pi$ with $D \to hh$

ADS in $B \to DK, D\pi$ with $D \to hhhh$

GGSZ in $B \to DK$ with $D \to K_S hh$

GLW in $B \to DK^{0*}$

GLW in $B \to Dhhh$

Frequentist γ combination

Time dependent CPV in $B_S \to D_S K$

What has this enabled LHCb to produce?

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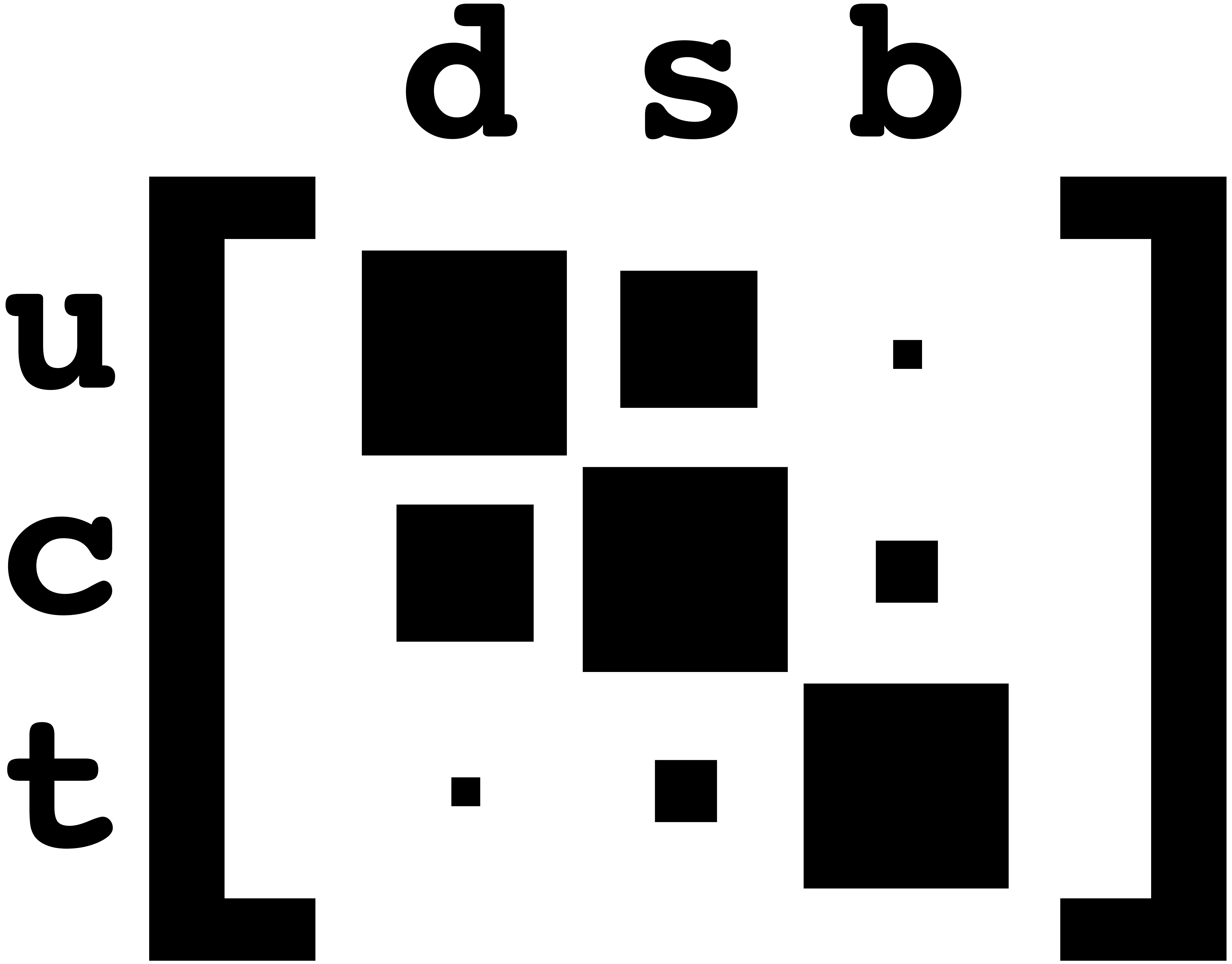
GLW in $B \to Dhhh$

Frequentist γ combination

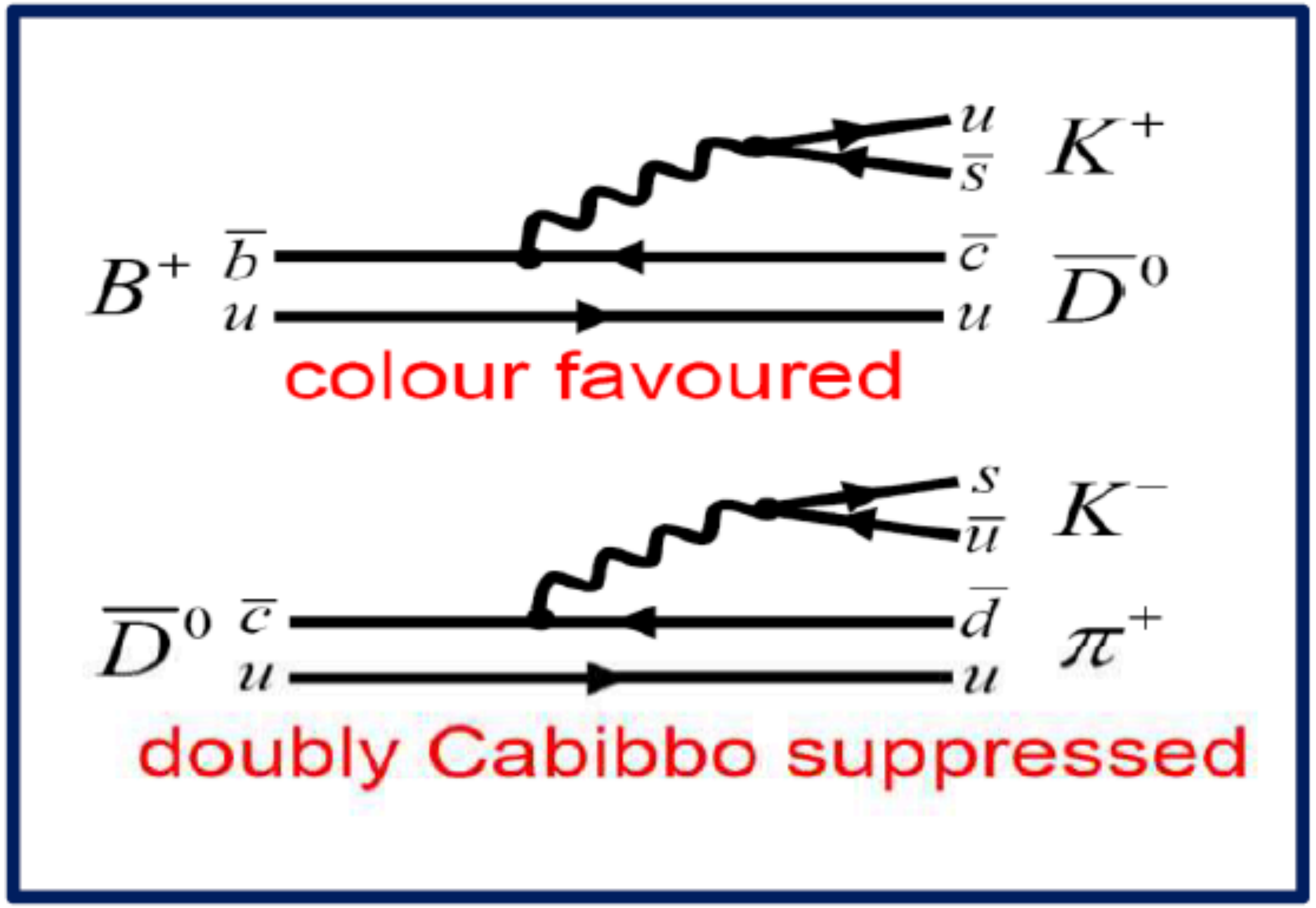
Time dependent CPV in $B_S \to D_S K$

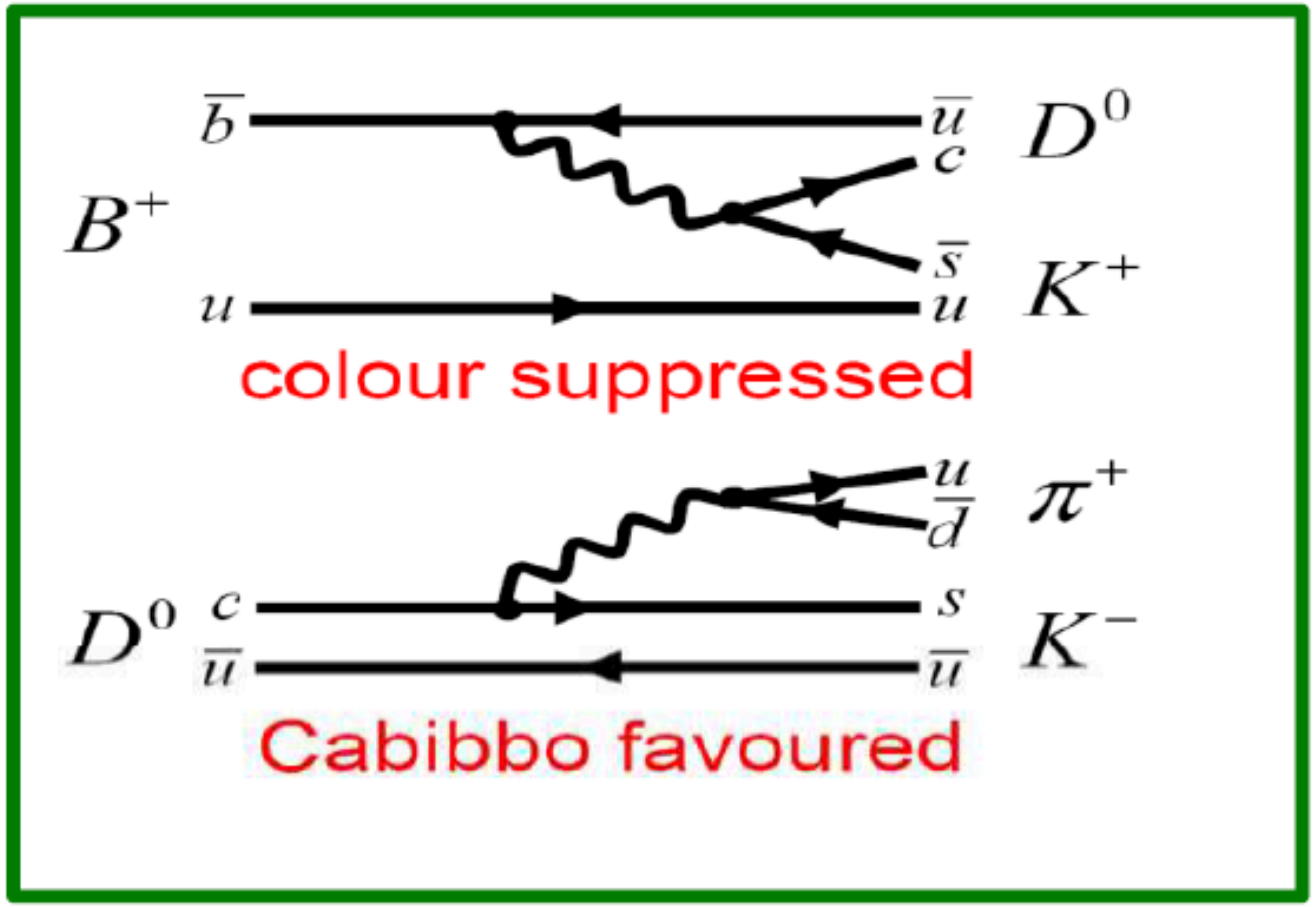
Aside on the CKM matrix structure



Bigger box == stronger coupling
(not to scale)

Observables ⇔ physics parameters





Observables ⇔ physics parameters

$$
\begin{aligned}
R_{K/\pi}^{K\pi} &= R\,\frac{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma} \\
R_{K/\pi}^{KK} = R_{K/\pi}^{\pi\pi} &= R\,\frac{1+{r_B}^2+2r_B\cos\delta_B\cos\gamma}{1+{r_B^\pi}^2+2r_B^\pi\cos\delta_B^\pi\cos\gamma} \\
A^{Fav} &= \frac{2r_B r_D\sin(\delta_B-\delta_D)\sin\gamma}{1+(r_B r_D)^2+r_B r_D\cos(\delta_B-\delta_D)\cos\gamma} \\
A_\pi^{Fav} &= \frac{2r_B^\pi r_D\sin(\delta_B^\pi-\delta_D)\sin\gamma}{1+(r_B^\pi r_D)^2+r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma} \\
A^{KK} = A^{\pi\pi} &= \frac{2r_B\sin\delta_B\sin\gamma}{1+{r_B}^2+r_B\cos\delta_B\cos\gamma} \\
A_\pi^{KK} = A_\pi^{\pi\pi} &= \frac{2r_B^\pi\sin\delta_B^\pi\sin\gamma}{1+{r_B^\pi}^2+r_B^\pi\cos\delta_B^\pi\cos\gamma} \\
R^{ADS} &= \frac{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma} \\
A^{ADS} &= \frac{2r_B r_D\sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma} \\
R_\pi^{ADS} &= \frac{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma} \\
A_\pi^{ADS} &= \frac{2r_B^\pi r_D\sin(\delta_B^\pi+\delta_D)\sin\gamma}{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}
\end{aligned}
$$

Observables ⇔ physics parameters

r_B, δ_B are the amplitude ratio and relative strong phase of the interfering B decays

$$
\begin{aligned}
R^{K\pi}_{K/\pi} &= R\,\frac{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}\\
R^{KK}_{K/\pi}=R^{\pi\pi}_{K/\pi} &= R\,\frac{1+{r_B}^2+2r_B\cos\delta_B\cos\gamma}{1+{r_B^\pi}^2+2r_B^\pi\cos\delta_B^\pi\cos\gamma}\\
A^{Fav} &= \frac{2r_B r_D\sin(\delta_B-\delta_D)\sin\gamma}{1+(r_B r_D)^2+r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}\\
A^{Fav}_\pi &= \frac{2r_B^\pi r_D\sin(\delta_B^\pi-\delta_D)\sin\gamma}{1+(r_B^\pi r_D)^2+r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}\\
A^{KK}=A^{\pi\pi} &= \frac{2r_B\sin\delta_B\sin\gamma}{1+{r_B}^2+r_B\cos\delta_B\cos\gamma}\\
A^{KK}_\pi=A^{\pi\pi}_\pi &= \frac{2r_B^\pi\sin\delta_B^\pi\sin\gamma}{1+{r_B^\pi}^2+r_B^\pi\cos\delta_B^\pi\cos\gamma}\\
R^{ADS} &= \frac{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}\\
A^{ADS} &= \frac{2r_B r_D\sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}\\
R^{ADS}_\pi &= \frac{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}\\
A^{ADS}_\pi &= \frac{2r_B^\pi r_D\sin(\delta_B^\pi+\delta_D)\sin\gamma}{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}
\end{aligned}
$$

Observables ⇔ physics parameters

r_B, δ_B are the amplitude ratio and relative strong phase of the interfering B decays

r_D, δ_D are hadronic parameters describing the $D^0 \to K\pi(\pi K)$ decays

- **r_D is the amplitude ratio of the CF to DCS D^0 decays**

- **δ_D is the relative strong phase between the CF and DCS decays**

Both are taken from CLEO measurements

$$
\begin{aligned}
R^{K\pi}_{K/\pi} &= R\,\frac{1+(r_Br_D)^2+2r_Br_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}\\
R^{KK}_{K/\pi} = R^{\pi\pi}_{K/\pi} &= R\,\frac{1+{r_B}^2+2r_B\cos\delta_B\cos\gamma}{1+{r_B^\pi}^2+2r_B^\pi\cos\delta_B^\pi\cos\gamma}\\
A^{Fav} &= \frac{2r_Br_D\sin(\delta_B-\delta_D)\sin\gamma}{1+(r_Br_D)^2+r_Br_D\cos(\delta_B-\delta_D)\cos\gamma}\\
A^{Fav}_{\pi} &= \frac{2r_B^\pi r_D\sin(\delta_B^\pi-\delta_D)\sin\gamma}{1+(r_B^\pi r_D)^2+r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}\\
A^{KK} = A^{\pi\pi} &= \frac{2r_B\sin\delta_B\sin\gamma}{1+{r_B}^2+r_B\cos\delta_B\cos\gamma}\\
A^{KK}_{\pi} = A^{\pi\pi}_{\pi} &= \frac{2r_B^\pi\sin\delta_B^\pi\sin\gamma}{1+{r_B^\pi}^2+r_B^\pi\cos\delta_B^\pi\cos\gamma}\\
R^{ADS} &= \frac{{r_B}^2+{r_D}^2+2r_Br_D\cos(\delta_B+\delta_D)\cos\gamma}{1+(r_Br_D)^2+2r_Br_D\cos(\delta_B-\delta_D)\cos\gamma}\\
A^{ADS} &= \frac{2r_Br_D\sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2+{r_D}^2+2r_Br_D\cos(\delta_B+\delta_D)\cos\gamma}\\
R^{ADS}_{\pi} &= \frac{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}\\
A^{ADS}_{\pi} &= \frac{2r_B^\pi r_D\sin(\delta_B^\pi+\delta_D)\sin\gamma}{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}
\end{aligned}
$$

Observables ⇔ physics parameters

r_B, δ_B are the amplitude ratio and relative strong phase of the interfering B decays

r_D, δ_D are hadronic parameters describing the $D^0 \to K\pi(\pi K)$ decays

- r_D is the amplitude ratio of the CF to DCS D^0 decays

- δ_D is the relative strong phase between the CF and DCS decays

Both are taken from CLEO measurements

Notice that ADS asymmetries are enhanced by the absence of a "1 +" term in the denominator compared to the GLW ones

$$R^{K\pi}_{K/\pi} = R\,\frac{1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}{1 + (r_B^\pi r_D)^2 + 2 r_B^\pi r_D \cos(\delta_B^\pi - \delta_D)\cos\gamma}$$

$$R^{KK}_{K/\pi} = R^{\pi\pi}_{K/\pi} = R\,\frac{1 + {r_B}^2 + 2 r_B \cos\delta_B \cos\gamma}{1 + {r_B^\pi}^2 + 2 r_B^\pi \cos\delta_B^\pi \cos\gamma}$$

$$A^{Fav} = \frac{2 r_B r_D \sin(\delta_B - \delta_D)\sin\gamma}{1 + (r_B r_D)^2 + r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}$$

$$A^{Fav}_\pi = \frac{2 r_B^\pi r_D \sin(\delta_B^\pi - \delta_D)\sin\gamma}{1 + (r_B^\pi r_D)^2 + r_B^\pi r_D \cos(\delta_B^\pi - \delta_D)\cos\gamma}$$

$$\boxed{A^{KK} = A^{\pi\pi} = \frac{2 r_B \sin\delta_B \sin\gamma}{1 + {r_B}^2 + r_B \cos\delta_B \cos\gamma}}$$

$$A^{KK}_\pi = A^{\pi\pi}_\pi = \frac{2 r_B^\pi \sin\delta_B^\pi \sin\gamma}{1 + {r_B^\pi}^2 + r_B^\pi \cos\delta_B^\pi \cos\gamma}$$

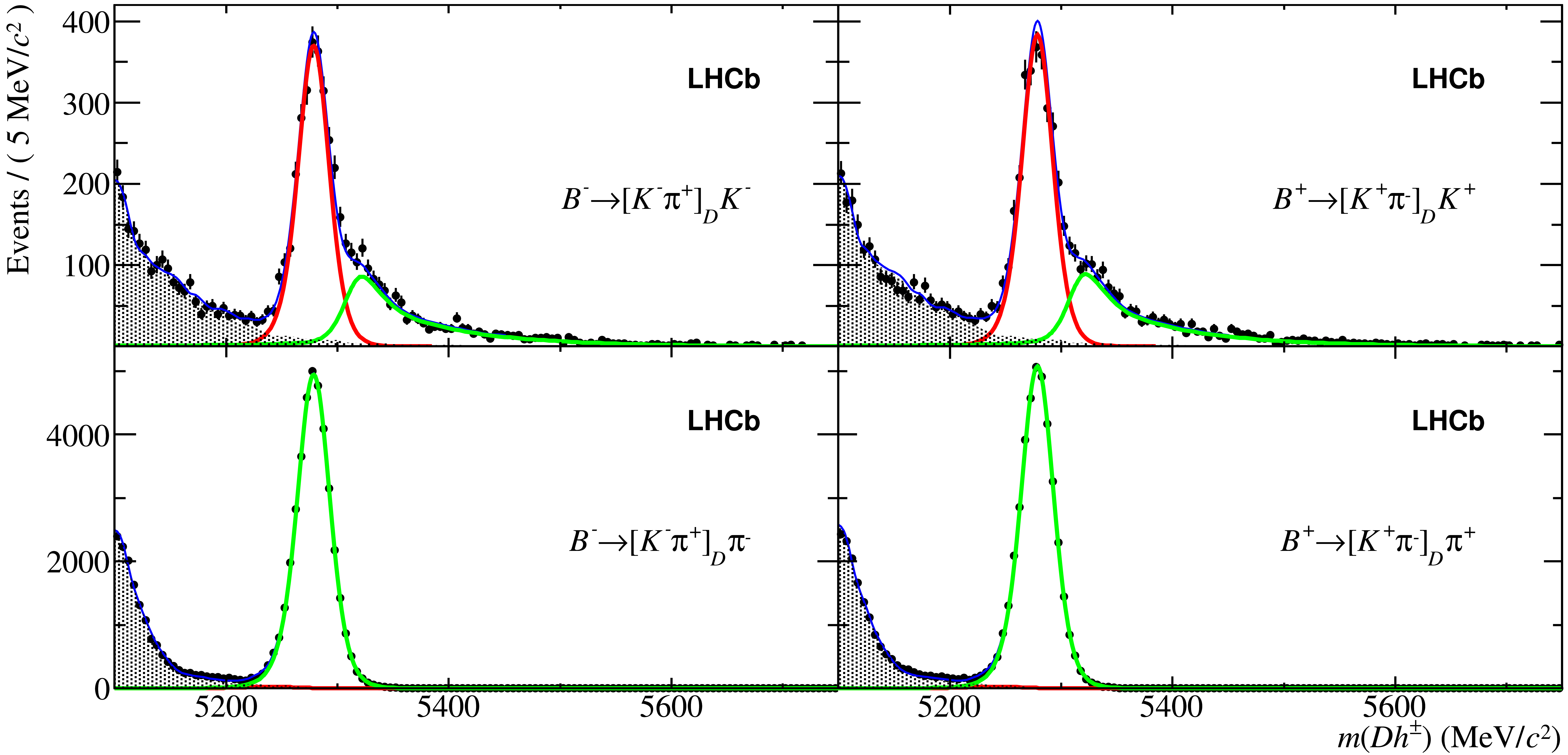
$$R^{ADS} = \frac{{r_B}^2 + {r_D}^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}$$

$$\boxed{A^{ADS} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{{r_B}^2 + {r_D}^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}}$$

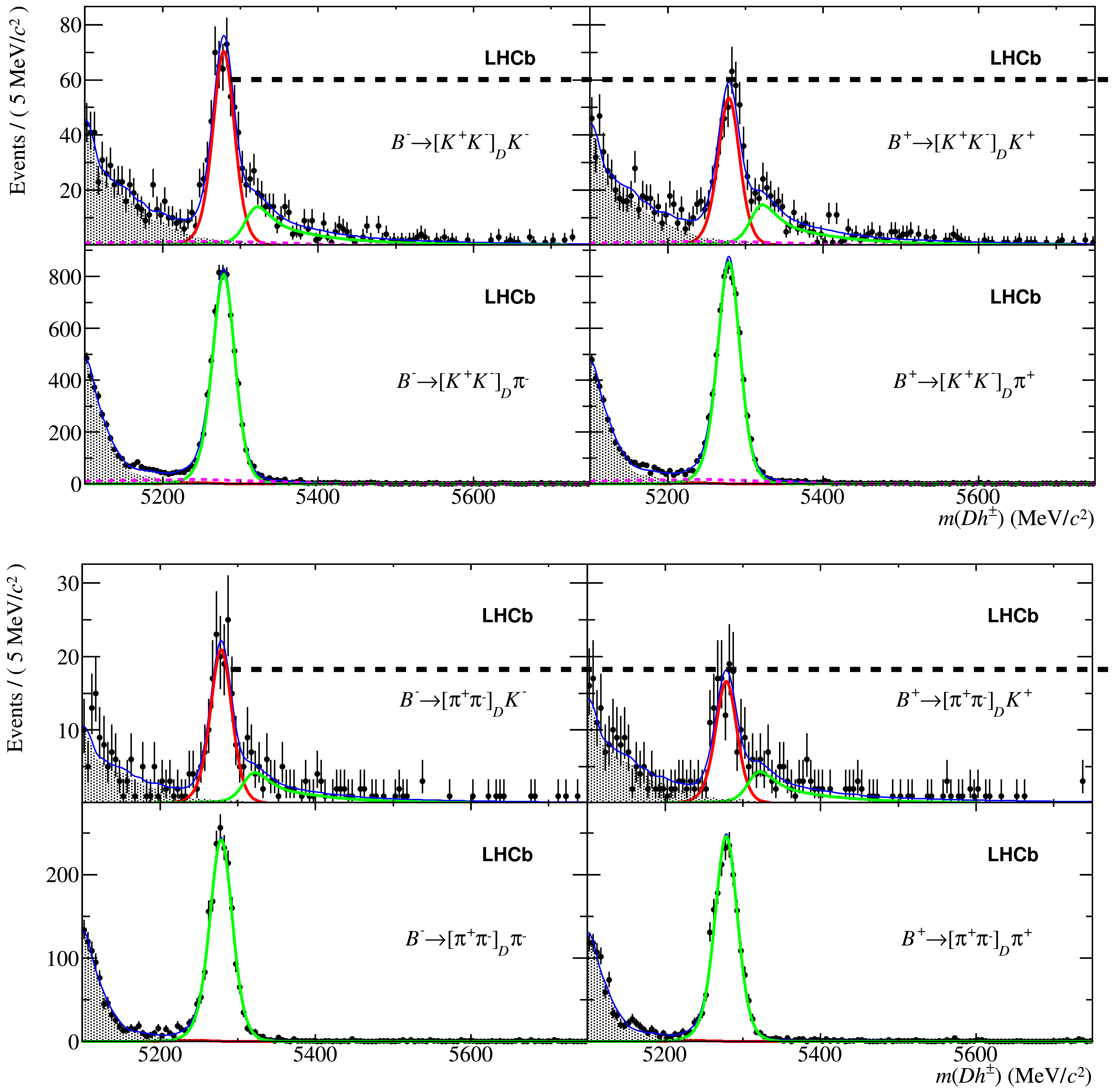
$$R^{ADS}_\pi = \frac{{r_B^\pi}^2 + {r_D}^2 + 2 r_B^\pi r_D \cos(\delta_B^\pi + \delta_D)\cos\gamma}{1 + (r_B^\pi r_D)^2 + 2 r_B^\pi r_D \cos(\delta_B^\pi - \delta_D)\cos\gamma}$$

$$A^{ADS}_\pi = \frac{2 r_B^\pi r_D \sin(\delta_B^\pi + \delta_D)\sin\gamma}{{r_B^\pi}^2 + {r_D}^2 + 2 r_B^\pi r_D \cos(\delta_B^\pi + \delta_D)\cos\gamma}$$

The Cabbibo-favoured signals



The singly Cabbibo-Suppressed signals



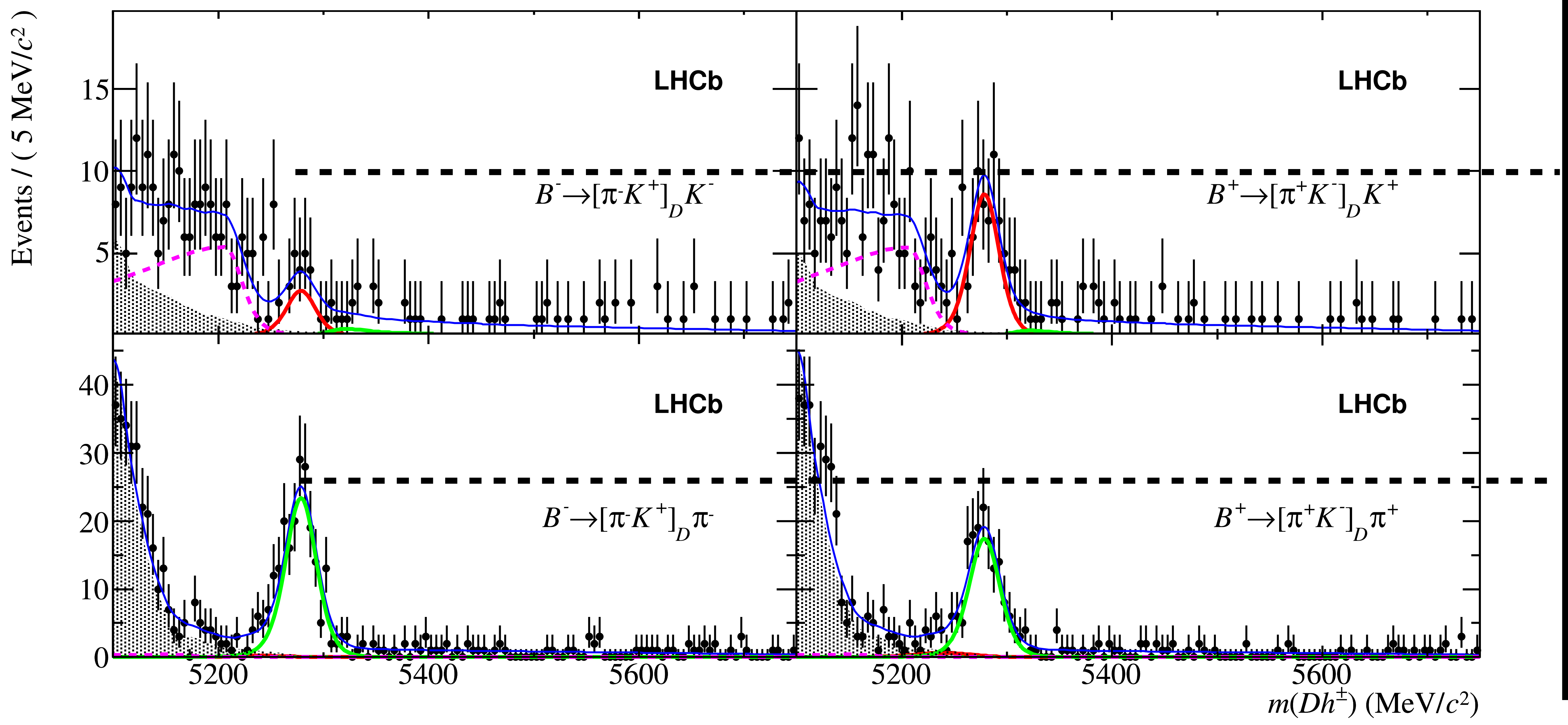
KK and ππ show similar-sized CP asymmetries, in the same direction

$$A_{CP+} = < A_K^{KK}, A_K^{\pi\pi} > \quad = \quad 0.145 \pm 0.032 \pm 0.010$$

Branching fraction ratios consistent with CF D⁰ decay mode

$$R_{CP+} = \frac{< R_{K/\pi}^{KK}, R_{K/\pi}^{\pi\pi} >}{R_{K/\pi}^{Kpi}} \quad = \quad 1.007 \pm 0.038 \pm 0.012$$

The ADS signals



The Kaon mode shows a large CP asymmetery

$$A_{ADS(K)} = \frac{R_K^- - R_K^+}{R_K^- + R_K^+} = -0.520 \pm 0.150 \pm 0.021$$

And there is also a hint of something in the pion mode!

$$A_{ADS(\pi)} = \frac{R_\pi^- - R_\pi^+}{R_\pi^- + R_\pi^+} = 0.1426 \pm 0.0621 \pm 0.0110$$

ADS modes established at >5σ significance

Combining all two body modes, direct CPV is observed at 5.8σ significance

LHCb-PAPER-2012-001

What has this enabled us to produce?

GLW/ADS in $B \to DK, D\pi$ with $D \to hh$

ADS in $B \to DK, D\pi$ with $D \to hhhh$

GGSZ in $B \to DK$ with $D \to K_S hh$

GLW in $B \to DK^{0*}$

GLW in $B \to Dhhh$

Frequentist γ combination

Time dependent CPV in $B_S \to D_S K$

Observables ⇔ physics parameters

$$\Gamma(B^\pm \to D(K^\pm\pi^\mp\pi^+\pi^-)K^\pm) \propto 1 + (r_B r_D^{K3\pi})^2 + 2\boxed{R_{K3\pi}} r_B r_D^{K3\pi} \cos(\delta_B - \delta_D^{K3\pi} \pm \gamma),$$

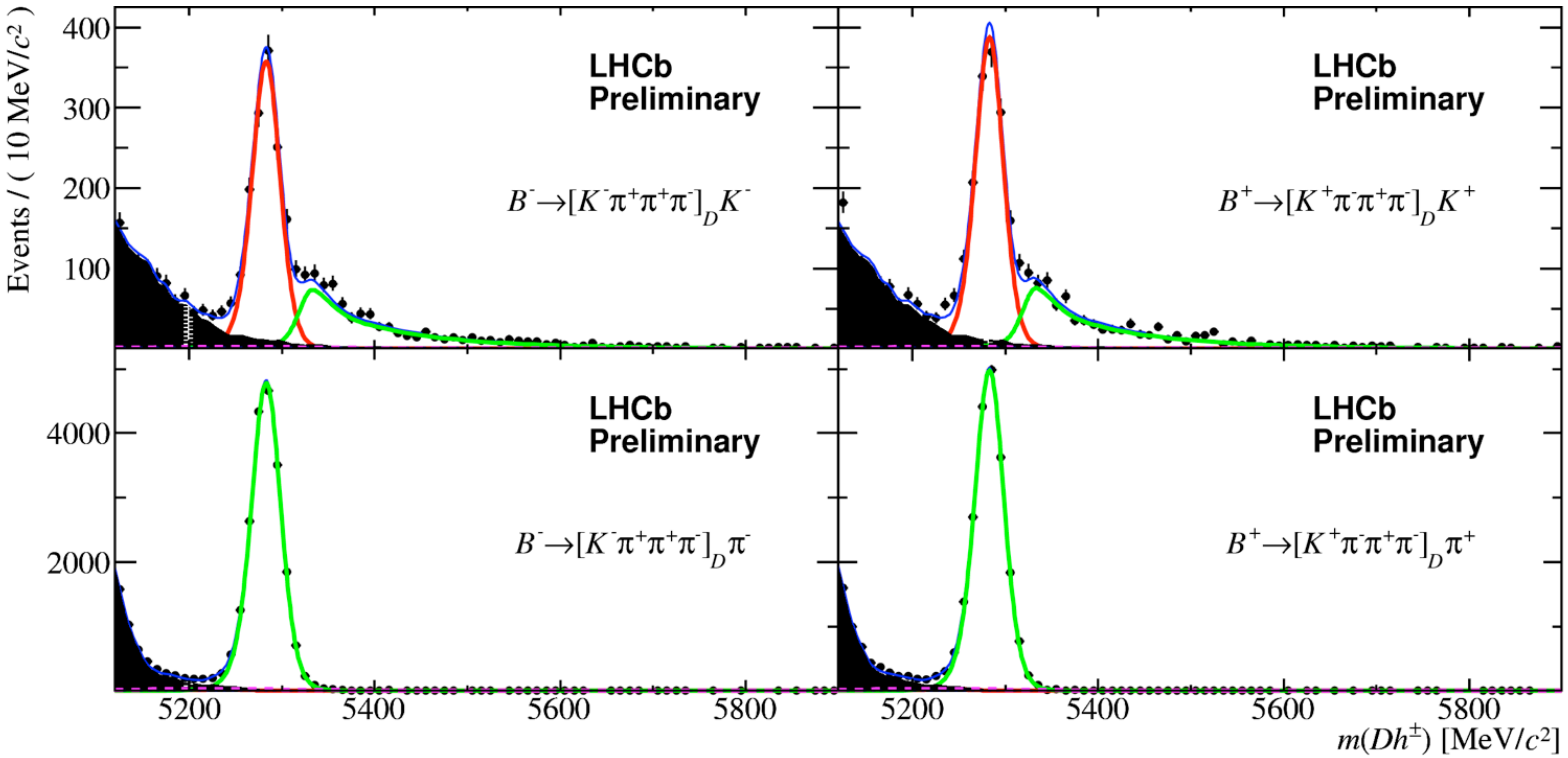
$$\Gamma(B^\pm \to D(K^\mp\pi^\pm\pi^+\pi^-)K^\pm) \propto r_B^2 + (r_D^{K3\pi})^2 + 2\boxed{R_{K3\pi}} r_B r_D^{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} \pm \gamma),$$

Same formalism as for the two-body case, except for the coherence factor $R_{K3\pi}$. This is necessary because the D^0 decay is a sum of amplitudes varying across the Dalitz plot; when we perform an analysis integrating over these amplitudes, we lose sensitivity from the way in which they interfere.

$R_{K3\pi}$ has been measured at CLEO and is small (~0.33) which indicates that these modes have a smaller sensitivity to γ when treated in this integrated manner than the two-body modes. However, they can still provide a good constraint on r_B.

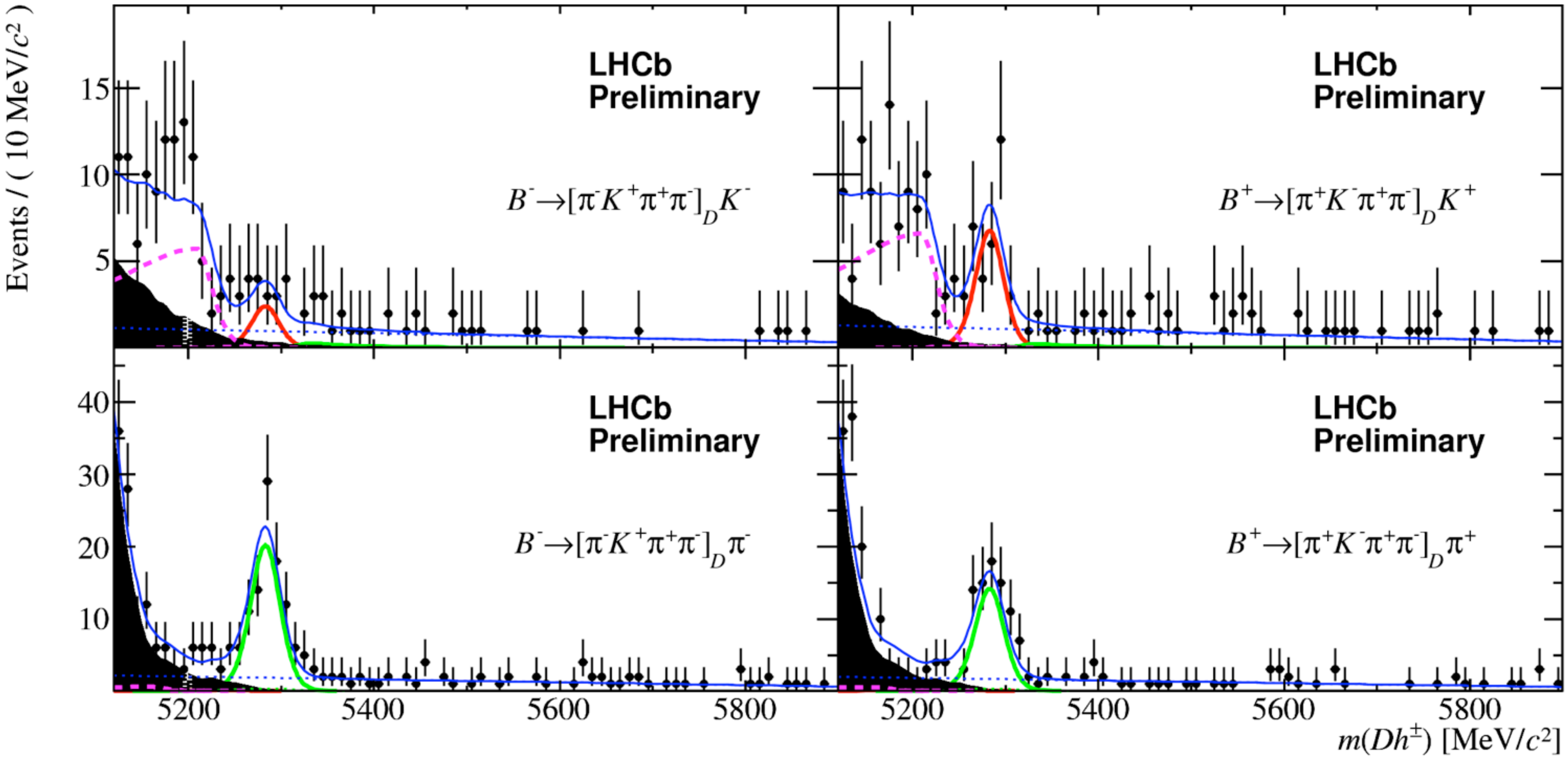
LHCb-PAPER-2012-055

The Cabbibo-favoured signals



LHCb-PAPER-2012-055

The ADS signals



LHCb-PAPER-2012-055

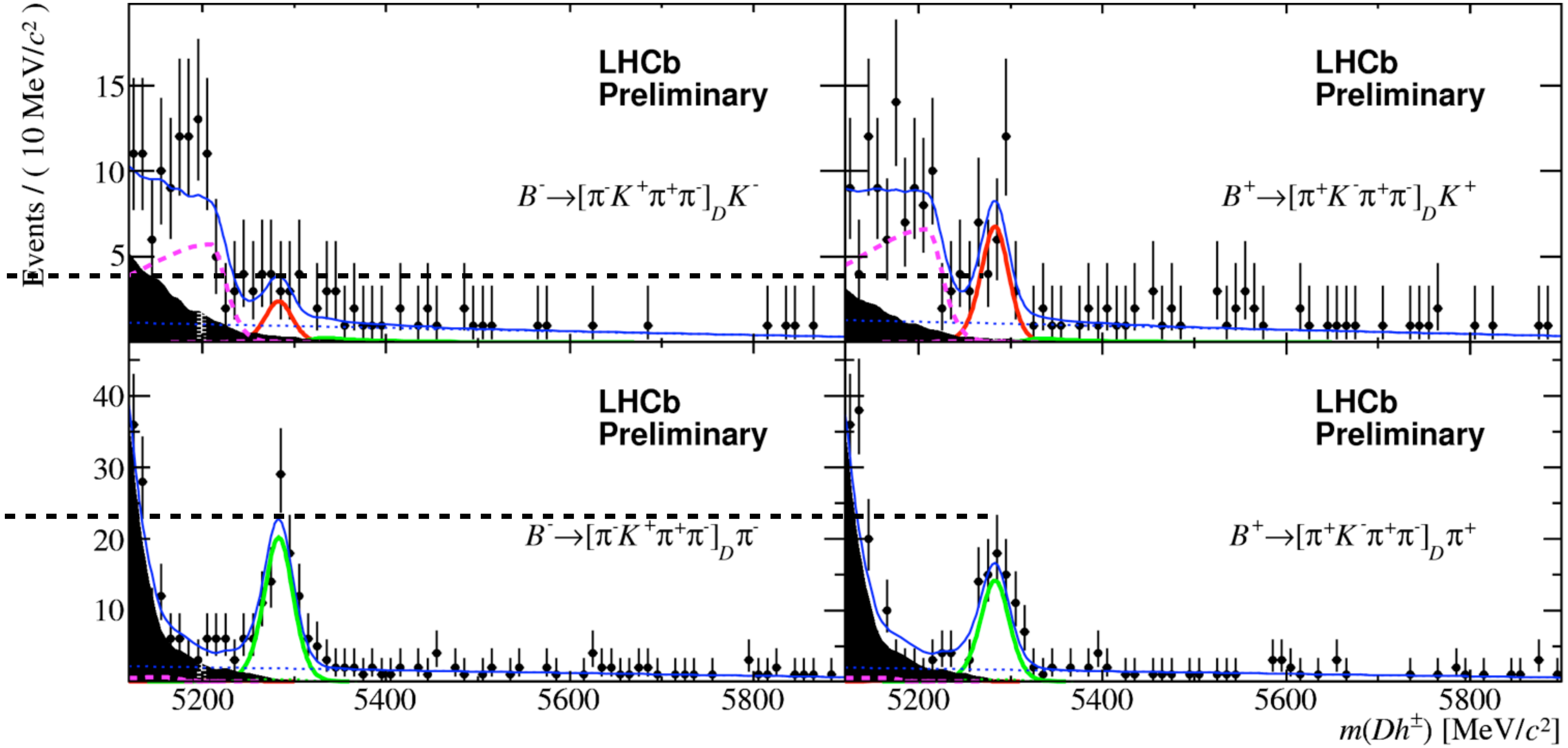
The ADS signals

Once again, indications of CP asymmetries in both the Kaon and the Pion modes

And again, going in the same direction as for the two-body modes.

$$A^{K3\pi}_{\mathrm{ADS}(K)} = (R_K^{K3\pi,-} - R_K^{K3\pi,+})/(R_K^{K3\pi,-} + R_K^{K3\pi,+}) = -0.42 \pm 0.22$$

$$A^{K3\pi}_{\mathrm{ADS}(\pi)} = (R_\pi^{K3\pi,-} - R_\pi^{K3\pi,+})/(R_\pi^{K3\pi,-} + R_\pi^{K3\pi,+}) = +0.13 \pm 0.10,$$



ADS modes established at >5σ significance!

LHCb-PAPER-2012-055

What has this enabled LHCb to produce?

GLW/ADS in B→DK,Dπ with D→hh

ADS in B→DK,Dπ with D→hhhh

GGSZ in B→DK with D→K$_S$hh

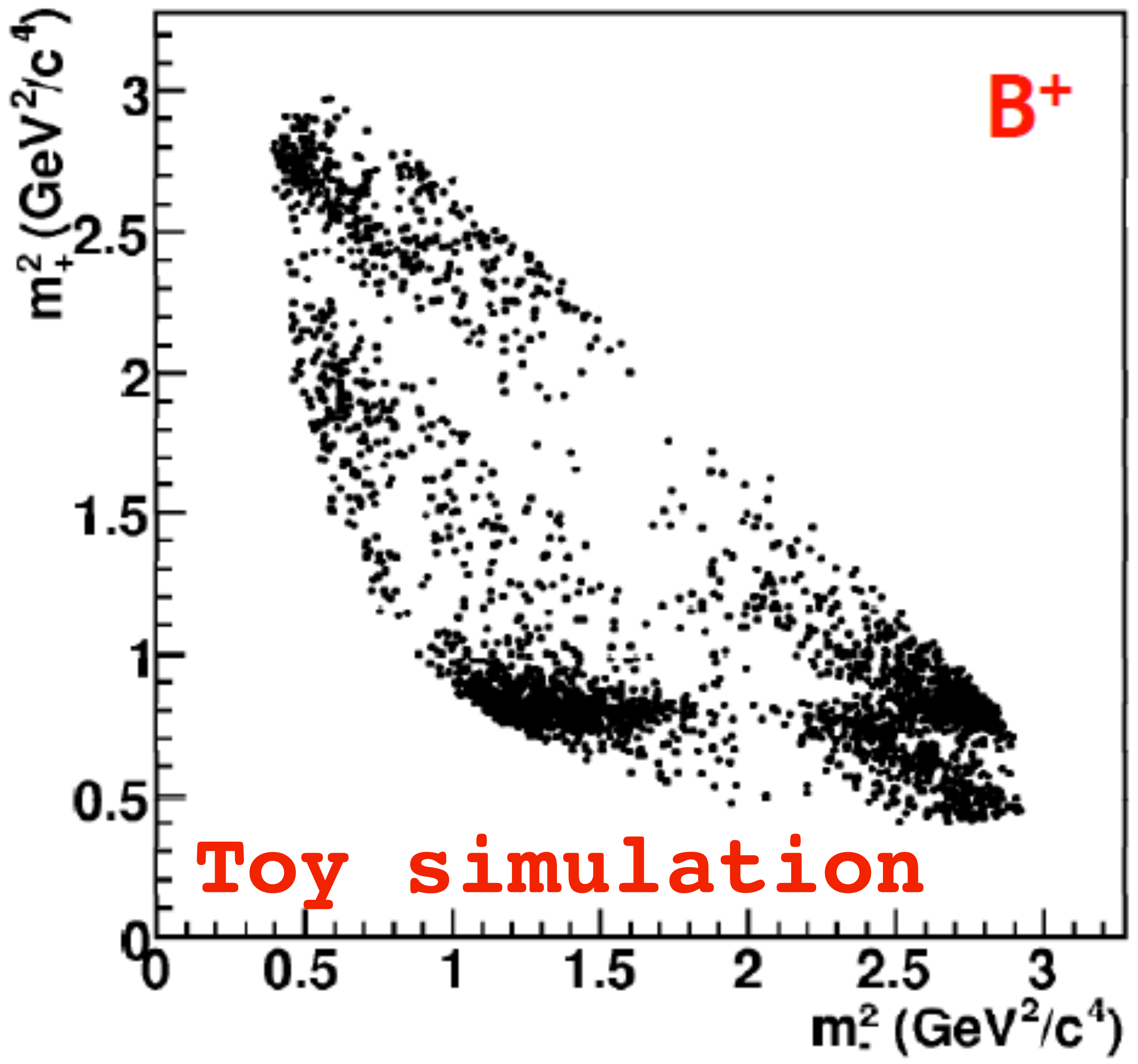
GLW in B→DK^{0*}

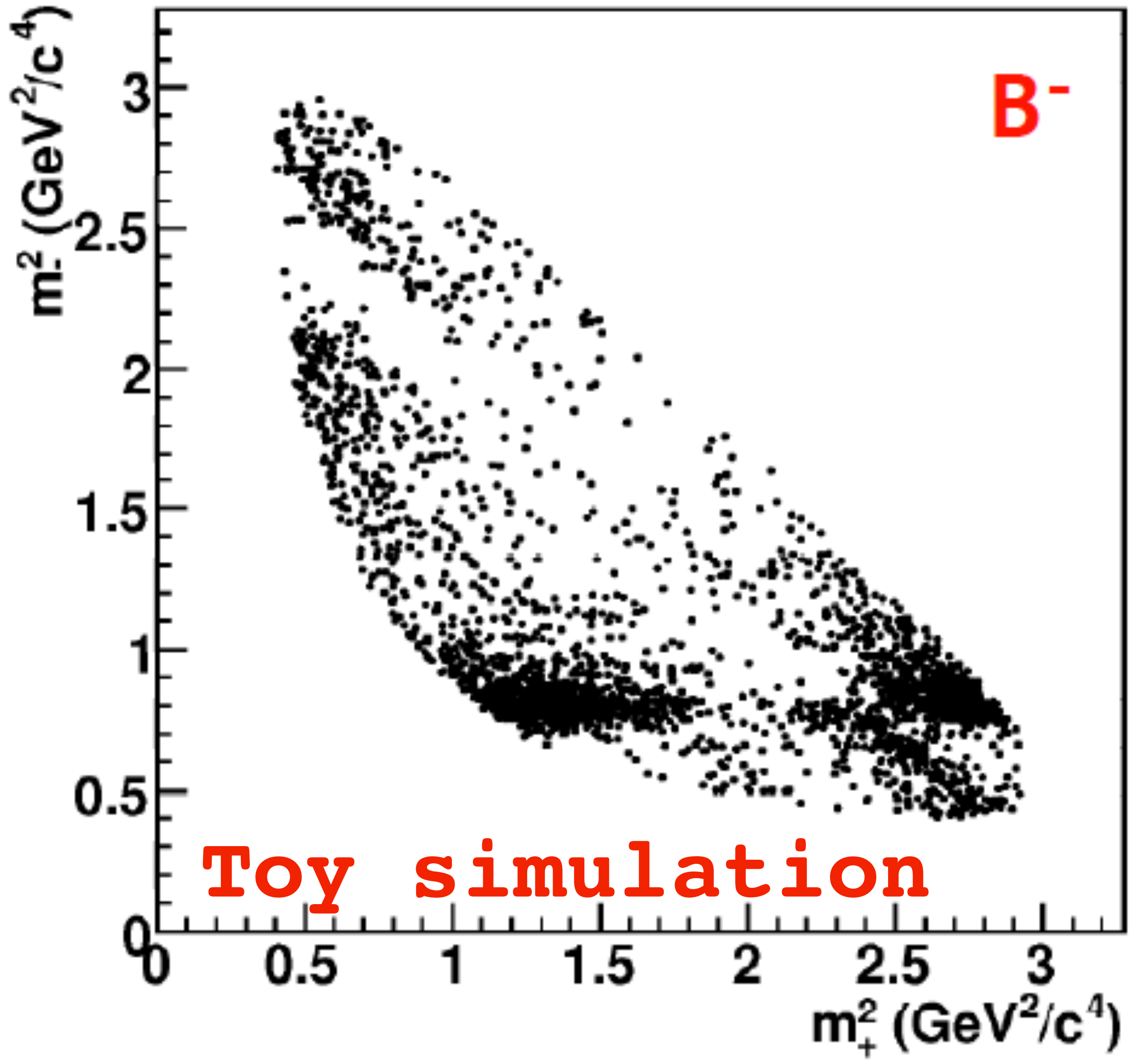
GLW in B→Dhhh

Frequentist γ combination

Time dependent CPV in B$_S$→D$_S$K

Observables ⇔ physics parameters



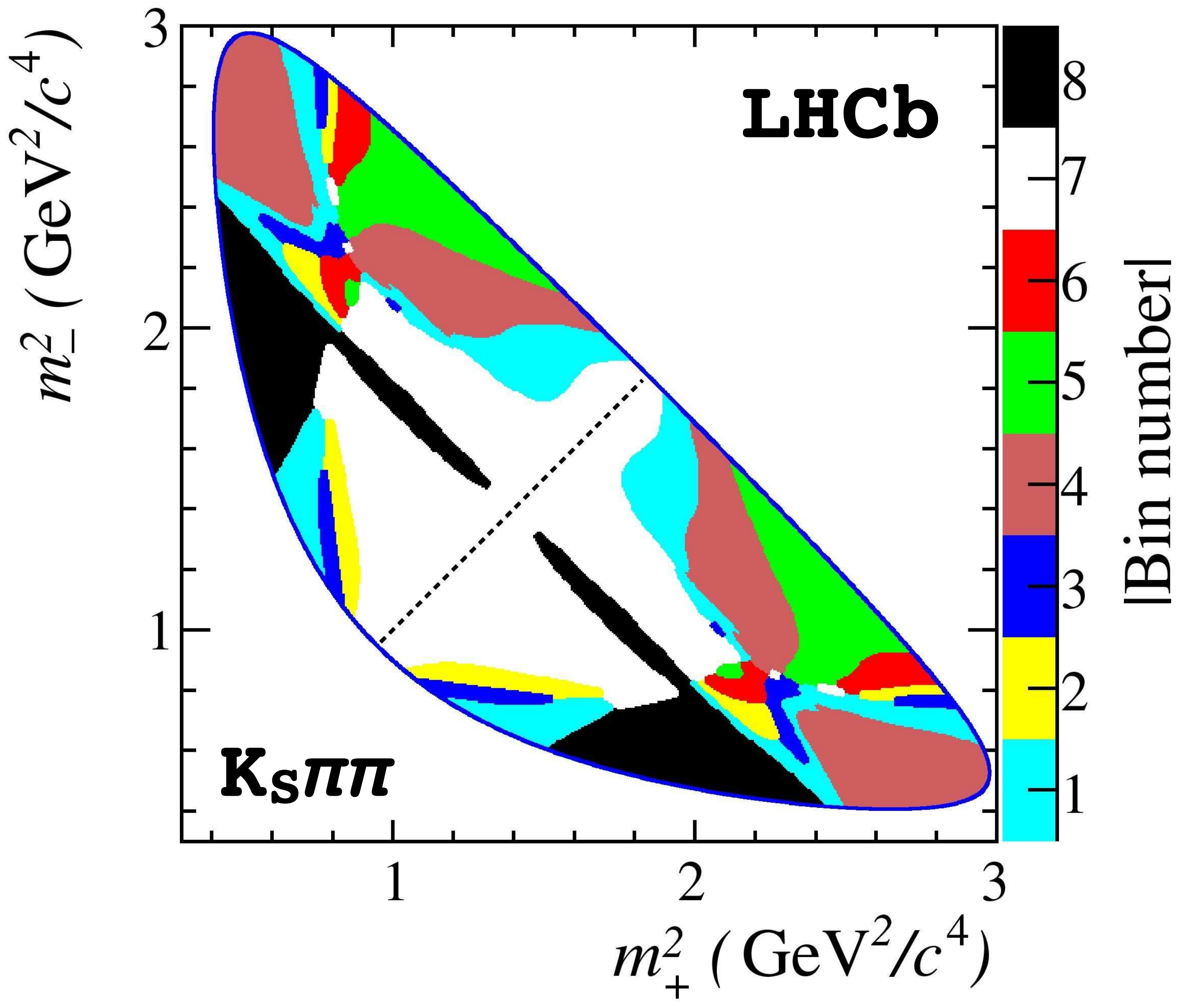


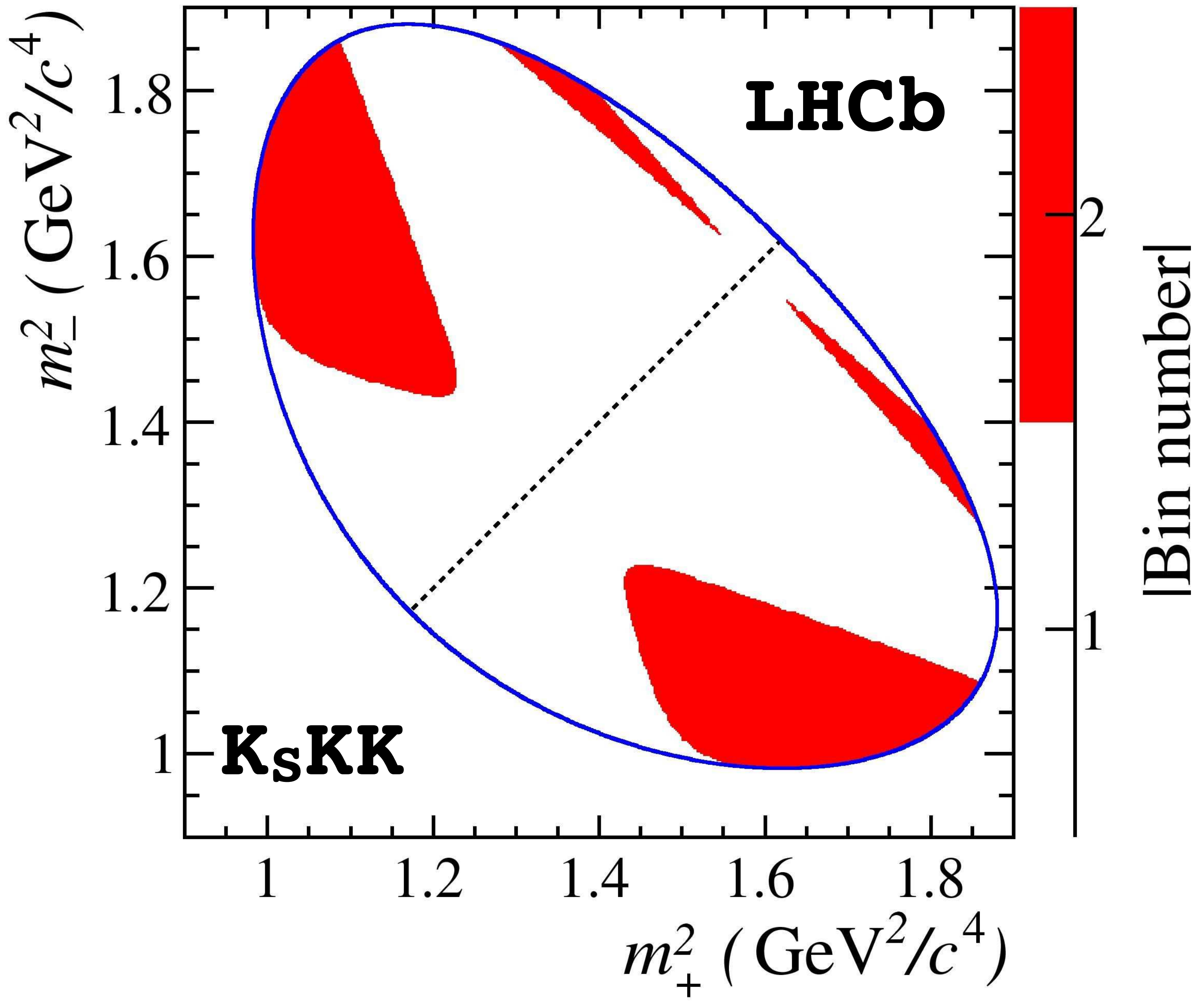
Here the decay chain is $B \to D^0 K$, with $D^0 \to K_S \pi\pi / K_S KK$

The D^0 decays proceed through many interfering amplitudes, some of which are Cabbibo-favoured, some singly Cabbibo-suppressed, and some doubly Cabbibo-suppressed

You are effectively doing a simultaneous ADS/GLW analysis, as long as you understand how the amplitudes and their phases vary across the Dalitz plot.

Observables ⇔ physics parameters





Here the decay chain is $B \to D^0K$, with $D^0 \to K_S\pi\pi/K_SKK$

The D^0 decays proceed through many interfering amplitudes, some of which are Cabbibo-favoured, some singly Cabbibo-suppressed, and some doubly Cabbibo-suppressed

You are effectively doing a simultaneous ADS/GLW analysis, as long as you understand how the amplitudes and their phases vary across the Dalitz plot.

"Model-independent" : Bin the Dalitz plot and fit for yield of B^+ and B^- in each bin of the Dalitz plot, plugging in the strong phase in each bin from a CLEO measurement.

$$N_{+i}^{+} = n_{B^+}[K_{-i} + (x_+^2 + y_+^2)K_{+i} + 2\sqrt{K_{+i}K_{-i}}(x_+c_{+i} - y_+s_{+i})]$$

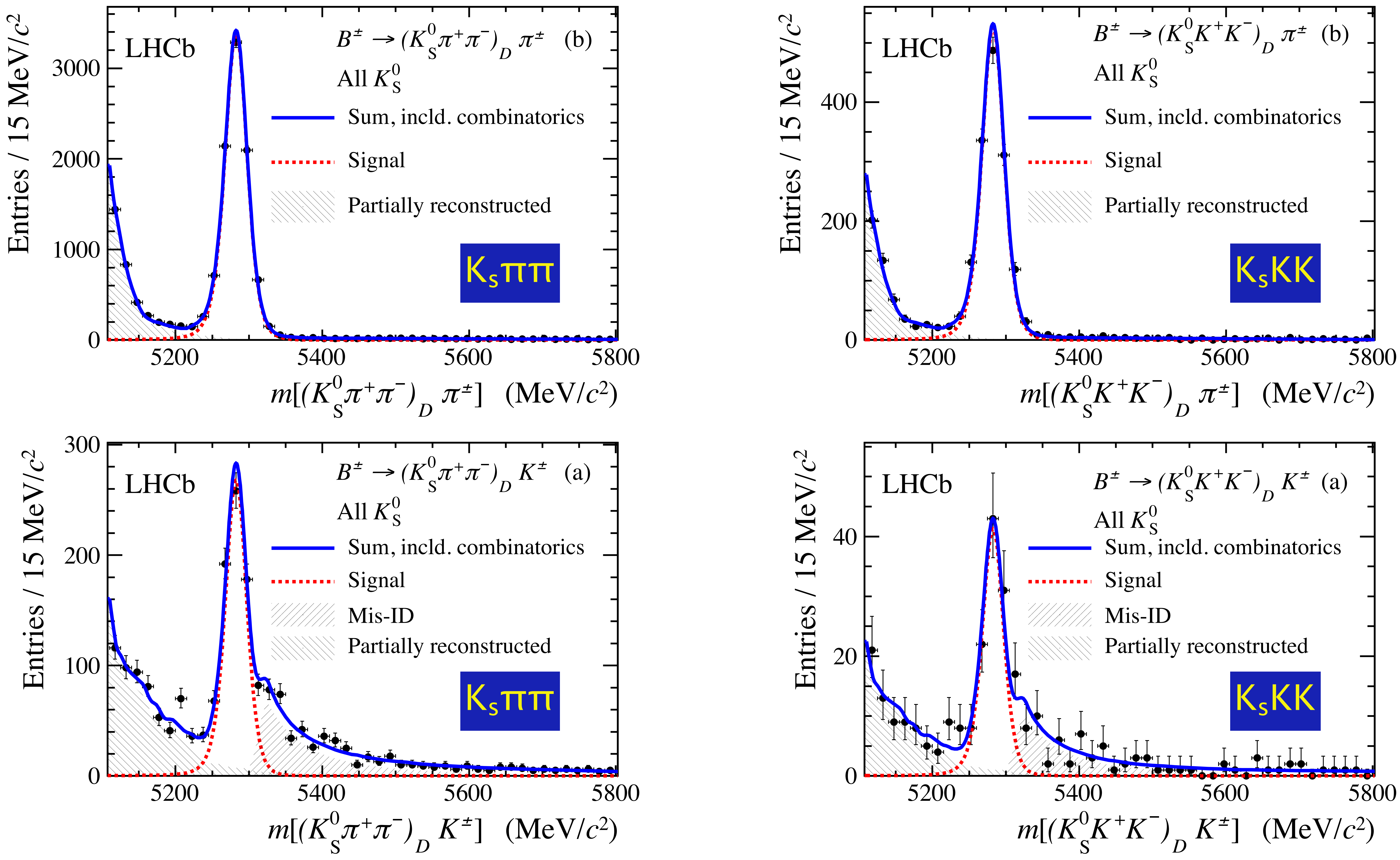
$$x_\pm = r_B\cos(\delta_B \pm \gamma), y_\pm = r_B\sin(\delta_B \pm \gamma)$$

c_i, s_i are the CLEO inputs

K_i are the yields of tagged D^0 decays in each bin

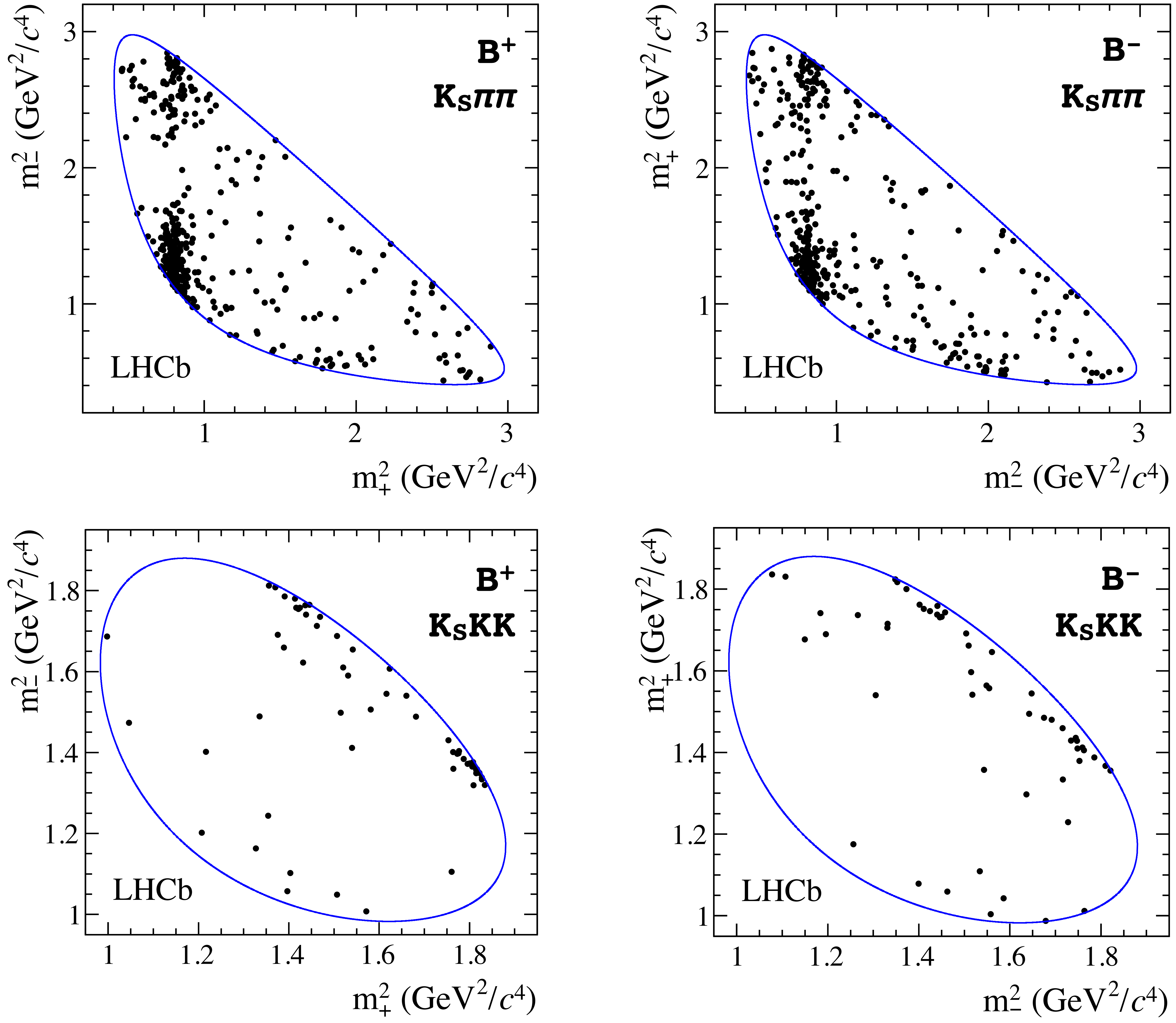
LHCb-PAPER-2012-027

$K_S\pi\pi$ and K_SKK signals for 1 fb^{-1}



LHCb-PAPER-2012-027

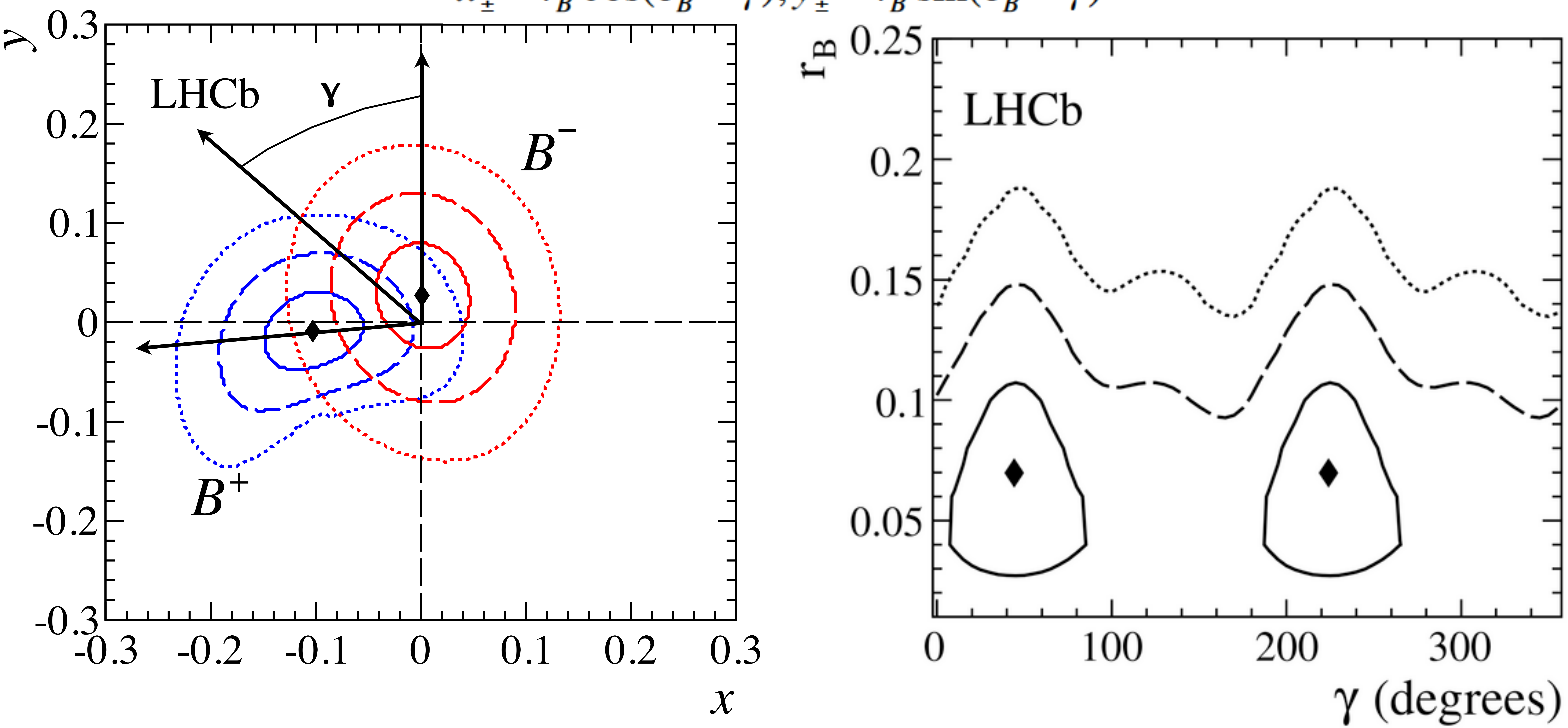
Dalitz distributions for 1 fb^{-1}



LHCb-PAPER-2012-027

$x^{\pm}, y^{\pm}$ for 1 fb^{-1}

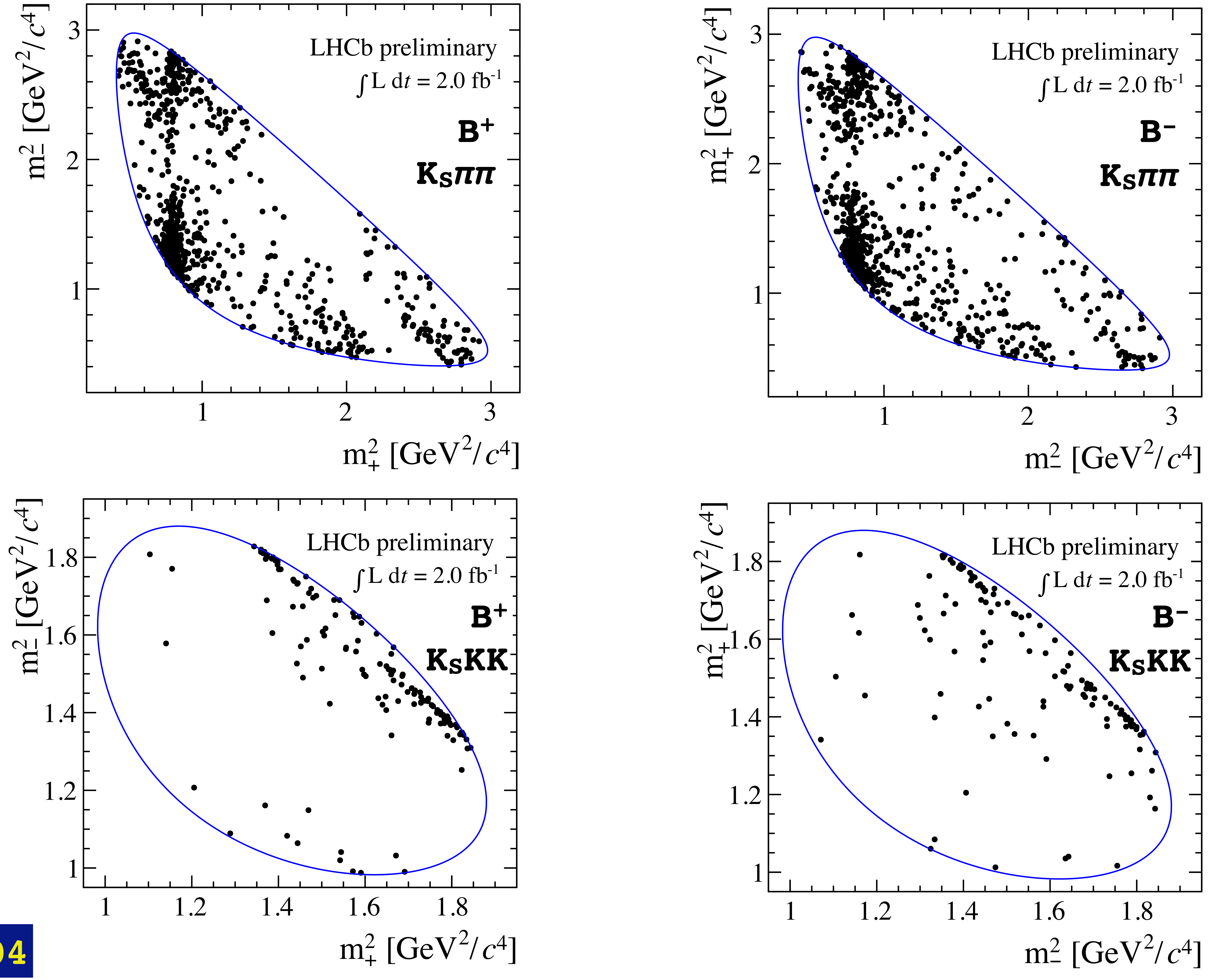
$$x_{\pm} = r_B \cos(\delta_B \pm \gamma), y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$



Largest systematic arises from the assumption of no CPV in the control mode Dπ
Little stand-alone sensitivity due to "unlucky" fluctuation of r_B

LHCb-PAPER-2012-027

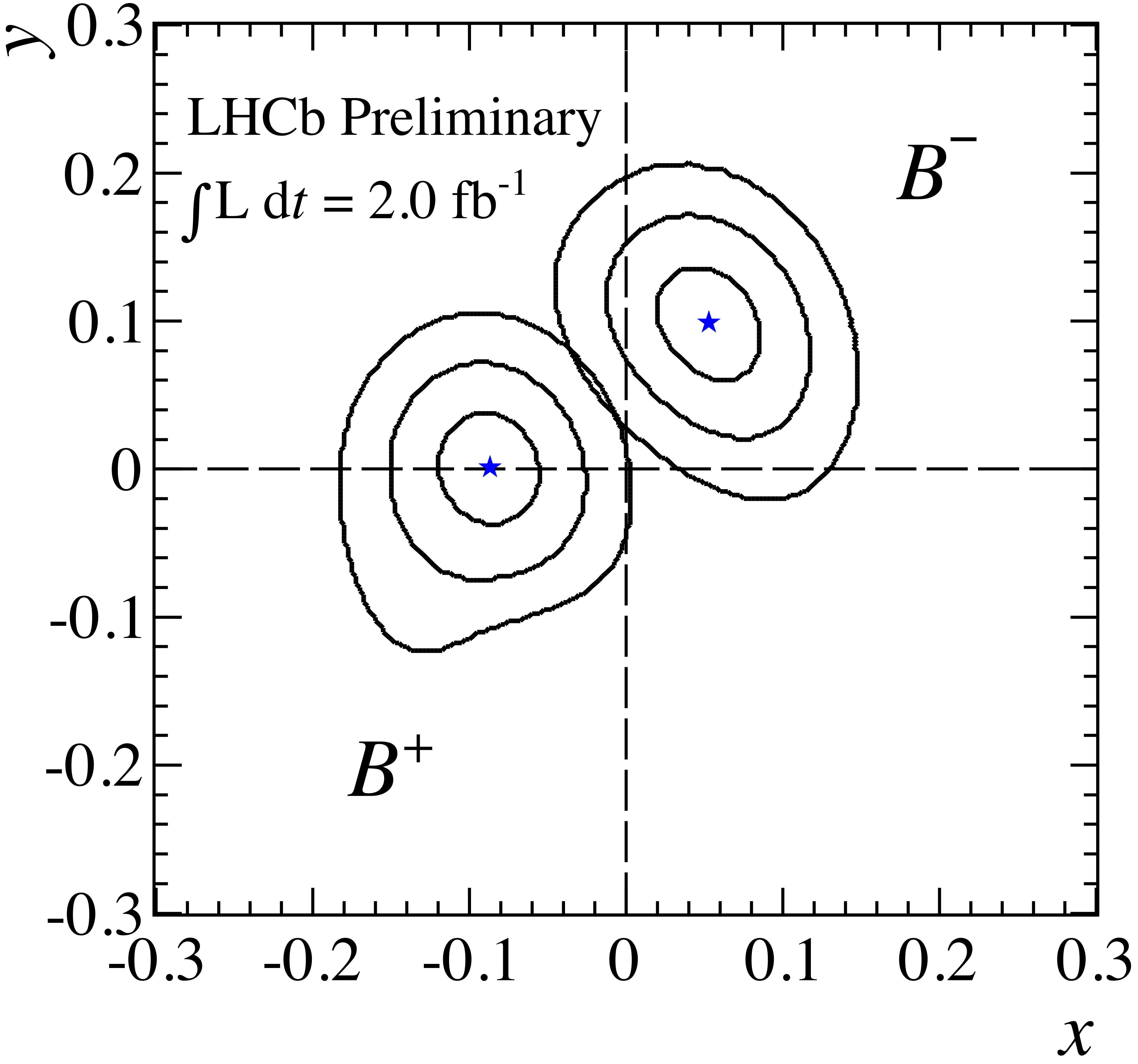
Dalitz distributions for 2 fb^{-1}

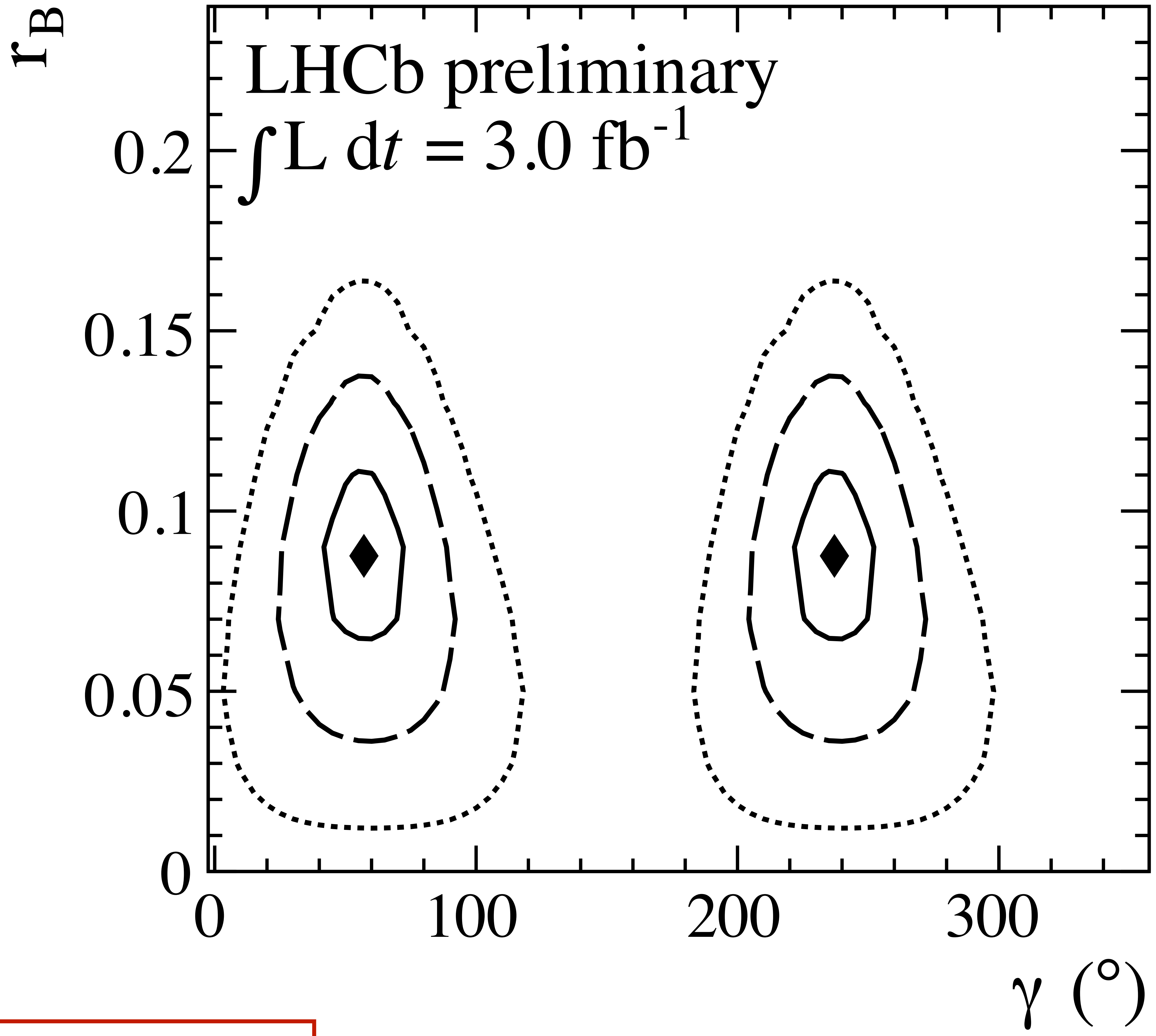


LHCb-CONF-2013-004

$x^{\pm}, y^{\pm}$ for 2 fb^{-1}

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma), y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

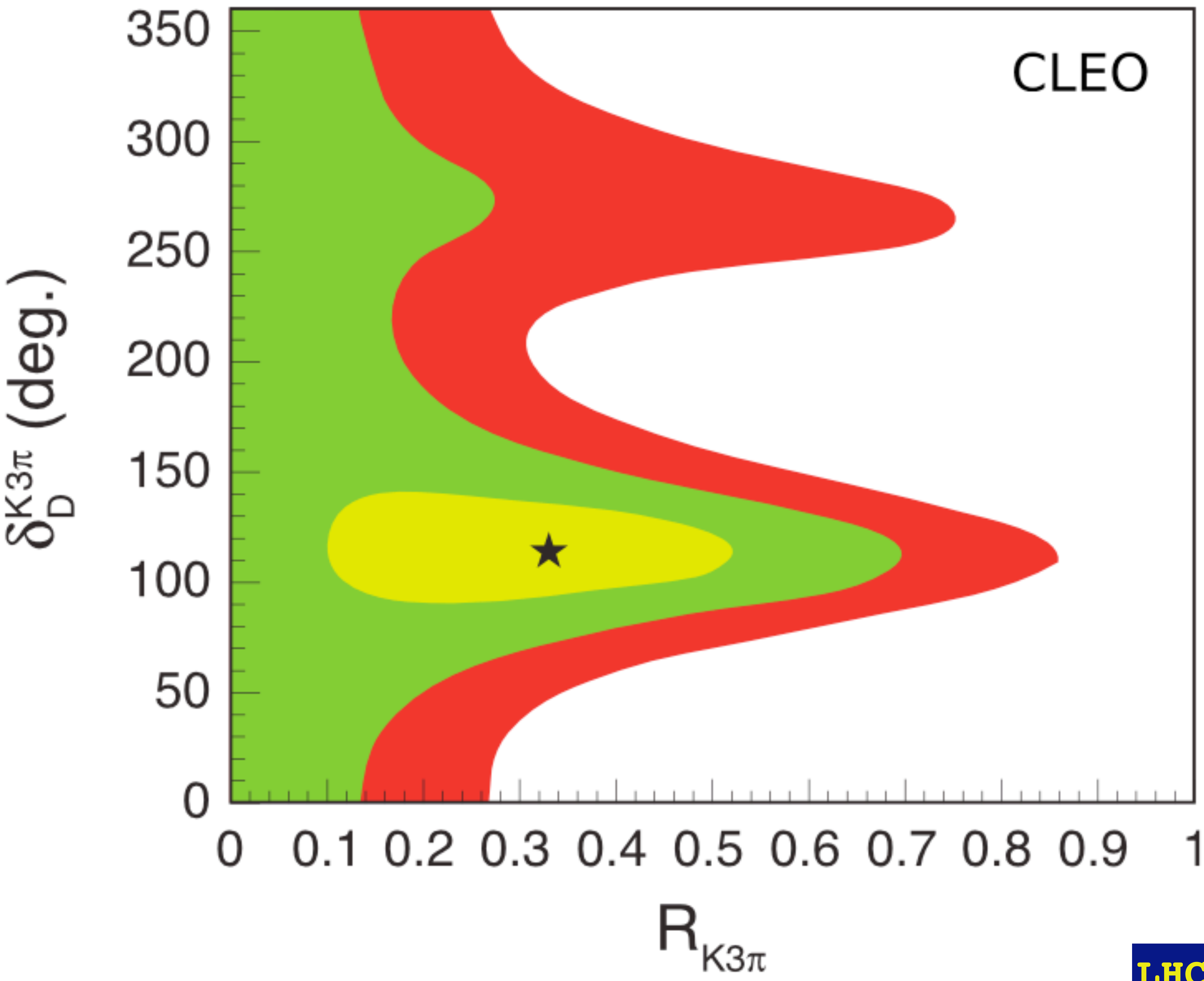




$\gamma = (57 \pm 16)°$

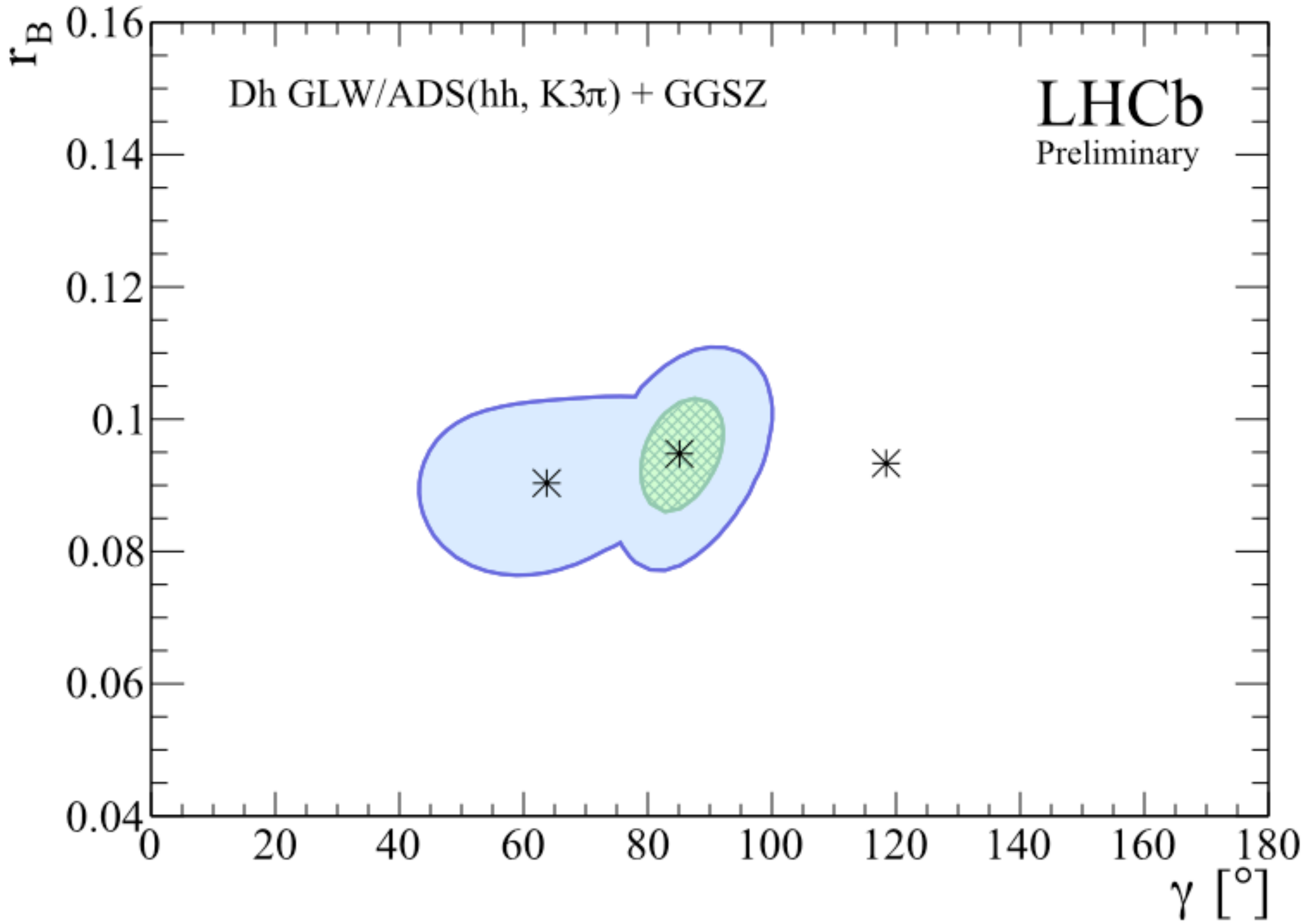
LHCb-CONF-2013-004

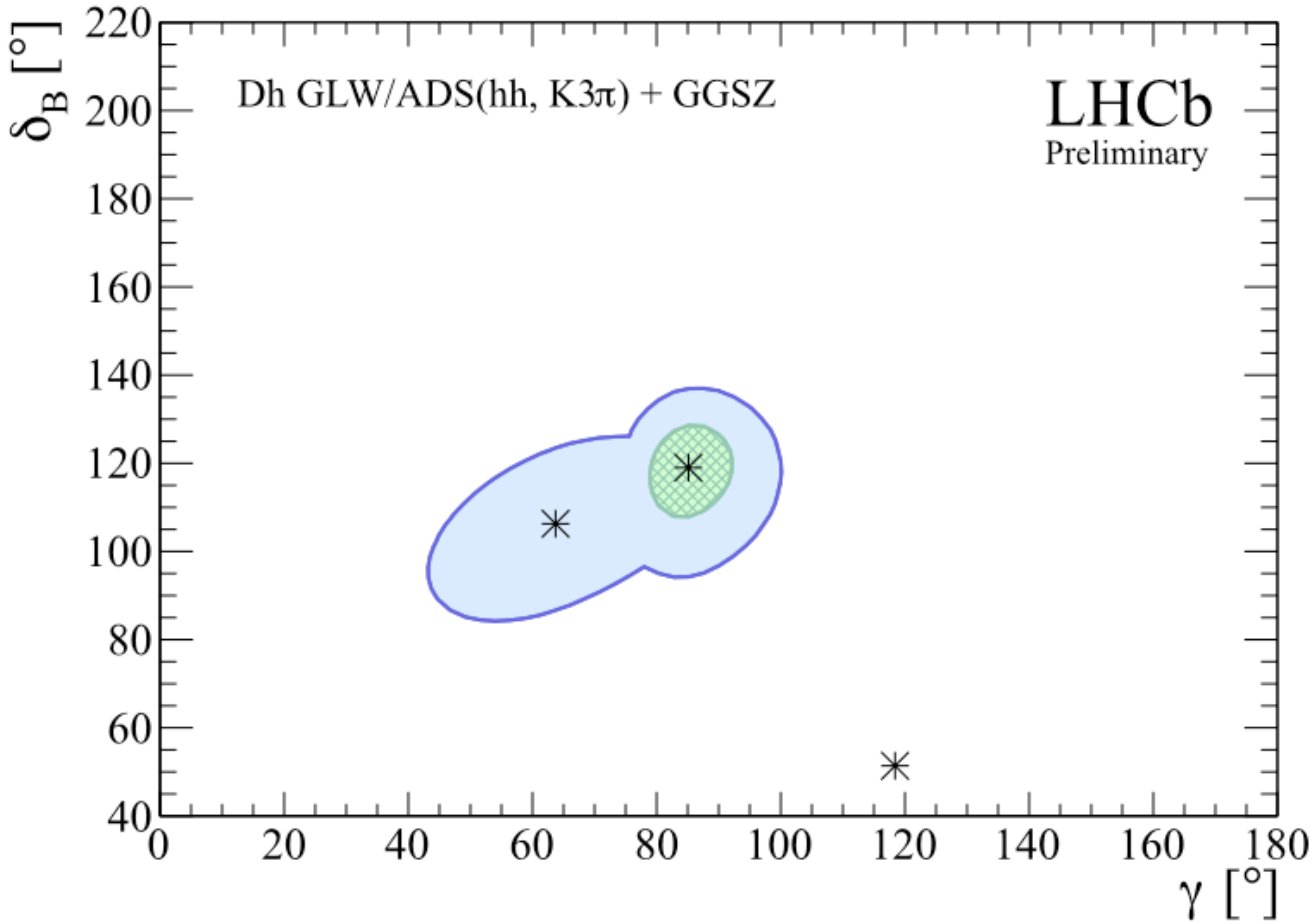
CLEO inputs



LHCb-CONF-2012-032

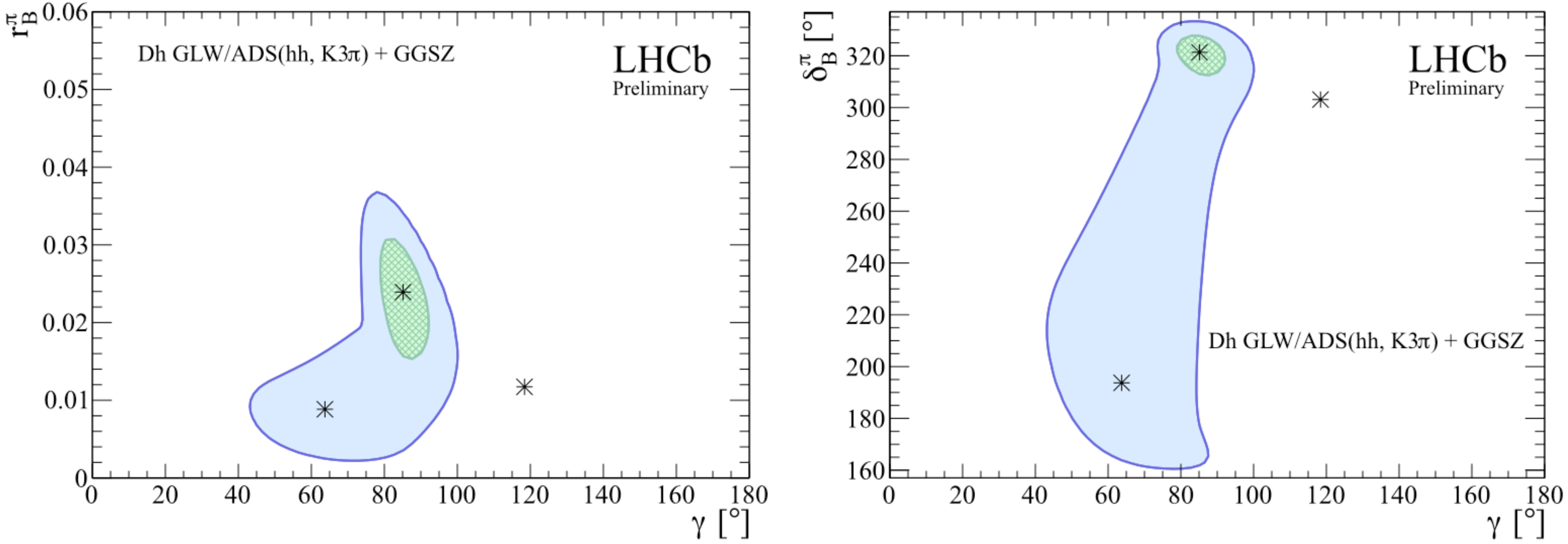
GLW/ADS 2D plots



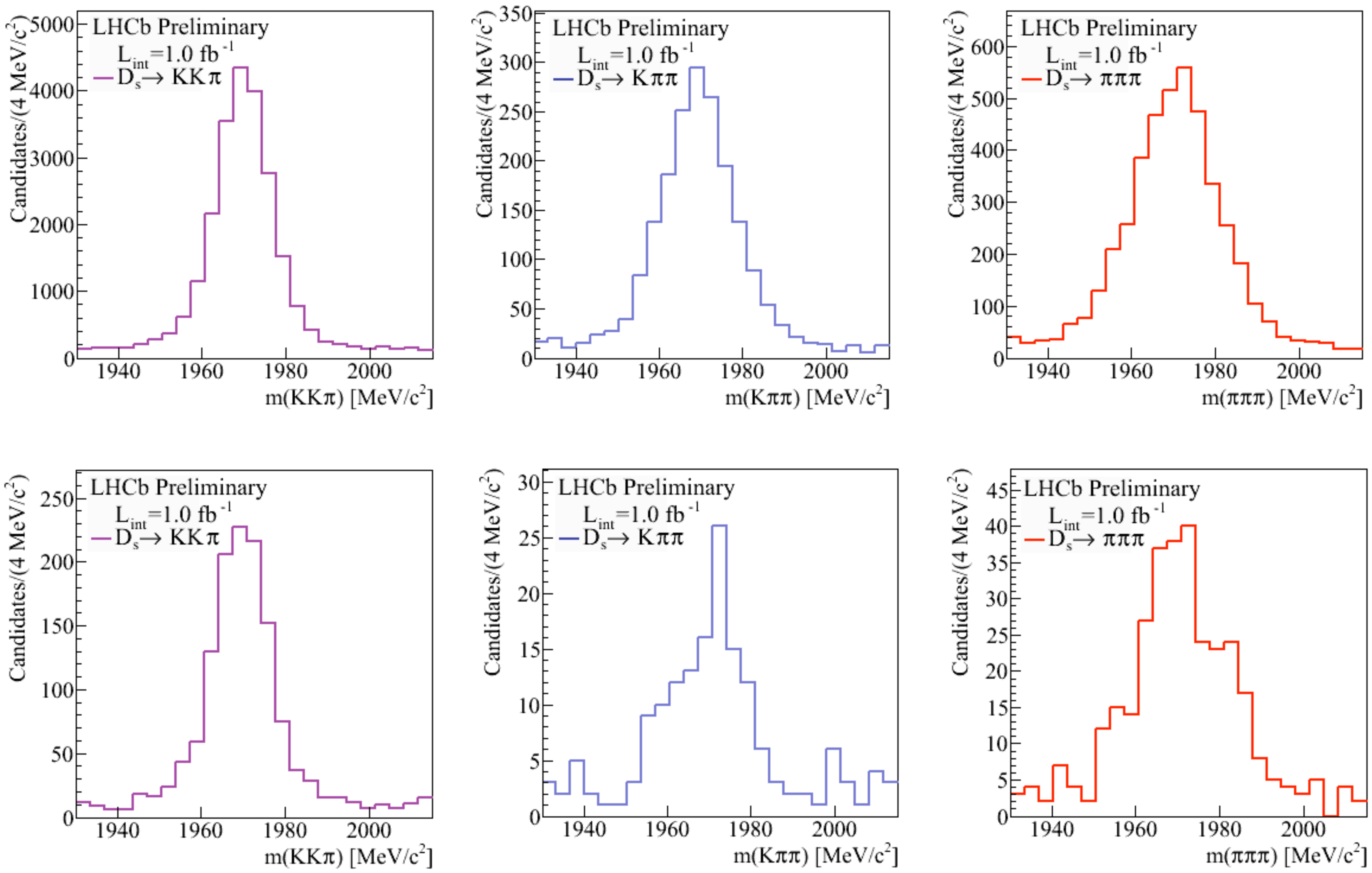


LHCb-CONF-2012-032

GLW/ADS 2D plots

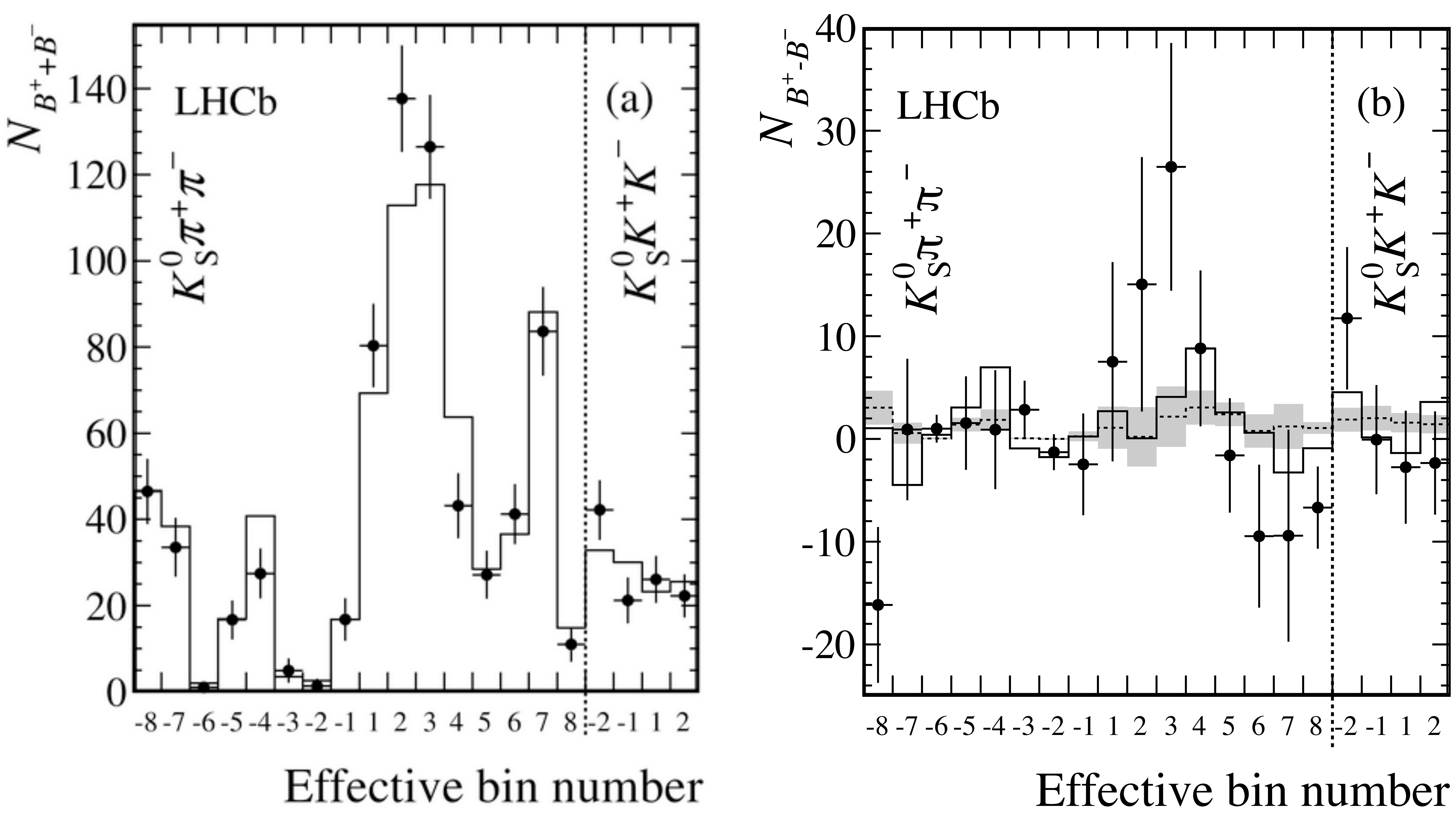


$D_S K$ charm signals

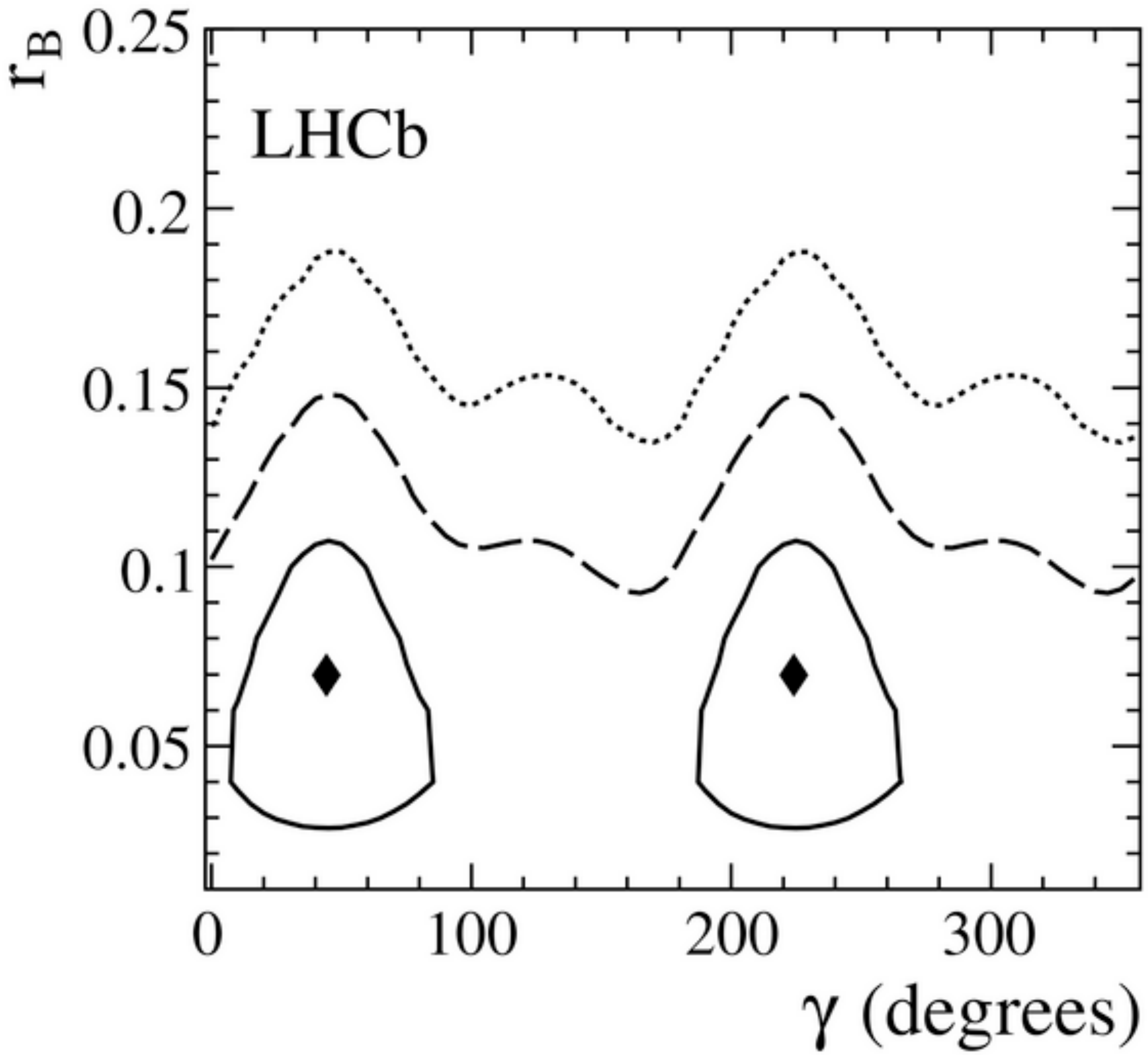


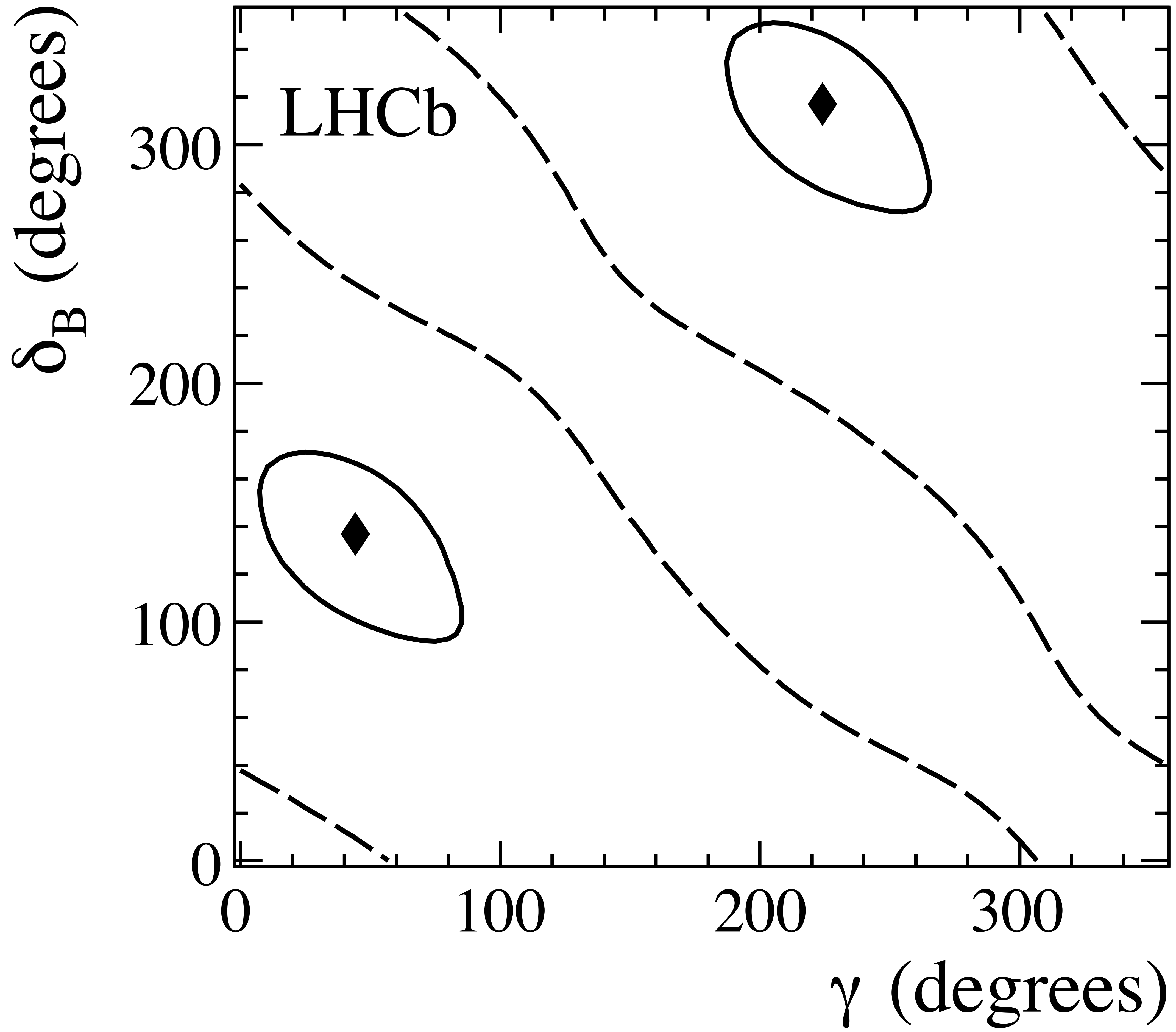
LHCb-CONF-2012-029

GGSZ asymmetries per bin $1fb^{-1}$



GGSZ only extractions 1fb^{-1}





LHCb-PAPER-2012-027

GLW/ADS full results

$$R^{K\pi}_{K/\pi} = 0.0774 \pm 0.0012 \pm 0.0018$$
$$R^{KK}_{K/\pi} = 0.0773 \pm 0.0030 \pm 0.0018$$
$$R^{\pi\pi}_{K/\pi} = 0.0803 \pm 0.0056 \pm 0.0017$$
$$A^{K\pi}_{\pi} = -0.0001 \pm 0.0036 \pm 0.0095$$
$$A^{K\pi}_{K} = 0.0044 \pm 0.0144 \pm 0.0174$$
$$A^{KK}_{K} = 0.148 \pm 0.037 \pm 0.010$$
$$A^{\pi\pi}_{K} = 0.135 \pm 0.066 \pm 0.010$$
$$A^{KK}_{\pi} = -0.020 \pm 0.009 \pm 0.012$$
$$A^{\pi\pi}_{\pi} = -0.001 \pm 0.017 \pm 0.010$$
$$R^{-}_{K} = 0.0073 \pm 0.0023 \pm 0.0004$$
$$R^{+}_{K} = 0.0232 \pm 0.0034 \pm 0.0007$$
$$R^{-}_{\pi} = 0.00469 \pm 0.00038 \pm 0.00008$$
$$R^{+}_{\pi} = 0.00352 \pm 0.00033 \pm 0.00007.$$

Table 2: Systematic uncertainties on the observables. PID refers to the fixed efficiency of the $\mathrm{DLL}_{K\pi}$ cut on the bachelor track. PDFs refers to the variations of the fixed shapes in the fit. "Sim" refers to the use of simulation to estimate relative efficiencies of the signal modes which includes the branching fraction estimates of the Λ_b^0 background. $A_{\text{instr.}}$ quantifies the uncertainty on the production, interaction and detection asymmetries.

$\times 10^{-3}$	PID	PDFs	Sim	$A_{\text{instr.}}$	Total
$R^{K\pi}_{K/\pi}$	1.4	0.9	0.8	0	1.8
$R^{KK}_{K/\pi}$	1.3	0.8	0.9	0	1.8
$R^{\pi\pi}_{K/\pi}$	1.3	0.6	0.8	0	1.7
$A^{K\pi}_{\pi}$	0	1.0	0	9.4	9.5
$A^{K\pi}_{K}$	0.2	4.1	0	16.9	17.4
A^{KK}_{K}	1.6	1.3	0.5	9.5	9.7
$A^{\pi\pi}_{K}$	1.9	2.3	0	9.0	9.5
A^{KK}_{π}	0.1	6.6	0	9.5	11.6
$A^{\pi\pi}_{\pi}$	0.1	0.4	0	9.9	9.9
R^{-}_{K}	0.2	0.4	0	0.1	0.4
R^{+}_{K}	0.4	0.5	0	0.1	0.7
R^{-}_{π}	0.01	0.03	0	0.07	0.08
R^{+}_{π}	0.01	0.03	0	0.07	0.07

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GLW/ADS 4h full results

Table 2: Systematic uncertainties on the observables. PID refers to the fixed efficiency for the bachelor $\mathrm{DLL}_{K\pi}$ requirement which is determined using the $D^{*\pm}$ calibration sample. PDFs refers to the variations of the fixed shapes in the fit. Sim refers to the use of simulation to estimate relative efficiencies of the signal modes. $A_{\mathrm{instr.}}$ quantifies the uncertainty on the production, interaction and detection asymmetries.

$\times 10^{-3}$	PID	PDFs	Sim	$A_{\mathrm{instr.}}$	Total
$R_{K/\pi}^{K3\pi}$	1.7	1.2	1.5	0.0	2.6
$A_{\pi}^{K3\pi}$	0.2	1.3	0.1	9.9	10.0
$A_{K}^{K3\pi}$	0.6	4.4	0.3	17.1	17.7
$R_{K}^{K3\pi,-}$	0.4	0.7	0.1	0.1	0.8
$R_{K}^{K3\pi,+}$	0.4	0.9	0.2	0.1	1.0
$R_{\pi}^{K3\pi,-}$	0.02	0.09	0.01	0.06	0.11
$R_{\pi}^{K3\pi,+}$	0.04	0.08	0.02	0.06	0.11

$$R_{K/\pi}^{K3\pi} = 0.0771 \pm 0.0017 \pm 0.0026$$

$$A_{K}^{K3\pi} = -0.029 \pm 0.020 \pm 0.018$$

$$A_{\pi}^{K3\pi} = -0.006 \pm 0.005 \pm 0.010$$

$$R_{K}^{K3\pi,-} = 0.0072 \,{}^{+0.0036}_{-0.0032} \pm 0.0008$$

$$R_{K}^{K3\pi,+} = 0.0175 \,{}^{+0.0043}_{-0.0039} \pm 0.0010$$

$$R_{\pi}^{K3\pi,-} = 0.00417 \,{}^{+0.00054}_{-0.00050} \pm 0.00011$$

$$R_{\pi}^{K3\pi,+} = 0.00321 \,{}^{+0.00048}_{-0.00045} \pm 0.00011$$

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GGSZ full results 1fb^{-1}

Table 3: Results for $x_\pm$ and $y_\pm$ from the fits to the data in the case when both $D \to K^0_S\pi^+\pi^-$ and $D \to K^0_S K^+ K^-$ are considered and when only the $D \to K^0_S\pi^+\pi^-$ final state is included. The first, second, and third uncertainties are the statistical, the experimental systematic, and the error associated with the precision of the strong-phase parameters, respectively. The correlation coefficients are calculated including all sources of uncertainty (the values in parentheses correspond to the case where only the statistical uncertainties are considered).

Parameter	All data	$D \to K^0_S\pi^+\pi^-$ alone
x_- $[\times 10^{-2}]$	$0.0 \pm 4.3 \pm 1.5 \pm 0.6$	$1.6 \pm 4.8 \pm 1.4 \pm 0.8$
y_- $[\times 10^{-2}]$	$2.7 \pm 5.2 \pm 0.8 \pm 2.3$	$1.4 \pm 5.4 \pm 0.8 \pm 2.4$
corr(x_-, y_-)	-0.10 (-0.11)	-0.12 (-0.12)
x_+ $[\times 10^{-2}]$	$-10.3 \pm 4.5 \pm 1.8 \pm 1.4$	$-8.6 \pm 5.4 \pm 1.7 \pm 1.6$
y_+ $[\times 10^{-2}]$	$-0.9 \pm 3.7 \pm 0.8 \pm 3.0$	$-0.3 \pm 3.7 \pm 0.9 \pm 2.7$
corr(x_+, y_+)	0.22 (0.17)	0.20 (0.17)

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