Particle Physics Seminar
Universität Bern, May 13, 2015

LHCb – Highlights from Run I, Prospects for Run II and beyond

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Overview

- **short motivation & introduction of the LHCb experiment**
- **(small) selection of highlights from run I**
  - CKM angle γ from $B^{\pm} \rightarrow D K^{\pm}$ tree decays
  - CP violating phase ϕ_s from $B^0_s \rightarrow J/\psi\,\phi$
  - branching fraction of $B^0_s \rightarrow \mu^+\mu^-$
  - angular distributions in $B^0 \rightarrow K^{*0}\mu^+\mu^-$

  (the four items above: "core" physics programme)

  - electroweak boson production in the forward direction
- **challenges and prospects for run II**
- **the LHCb upgrade**

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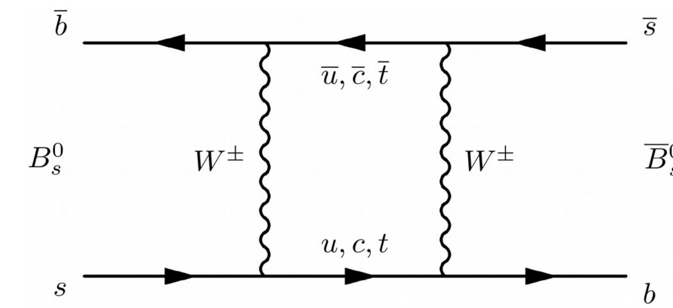
"core" physics programme

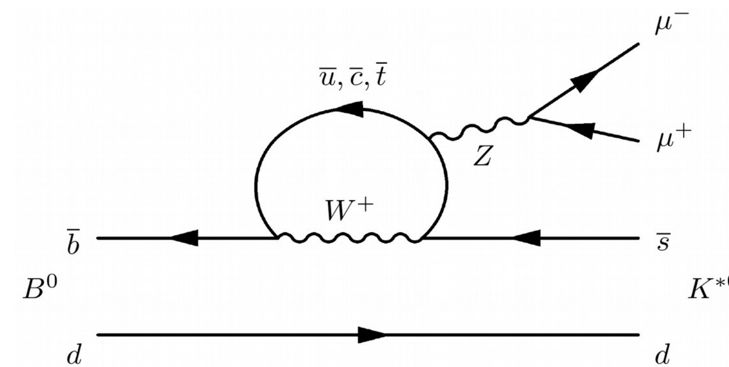
- **challenges and prospects for run II**
- **the LHCb upgrade**

Indirect Search For New Physics

- **most New Physics models predict the existence of new heavy particles**
  - **these can enter in internal loops and have sizeable effect on observables**
  - ***CP* violating phases, rare FCNC decays**



- **B^0 and B^0_s systems are an ideal hunting ground**
  - **rich phenomenology, precise SM predictions**
  - **confront predictions with precision measurements** $\Rightarrow$ LHCb

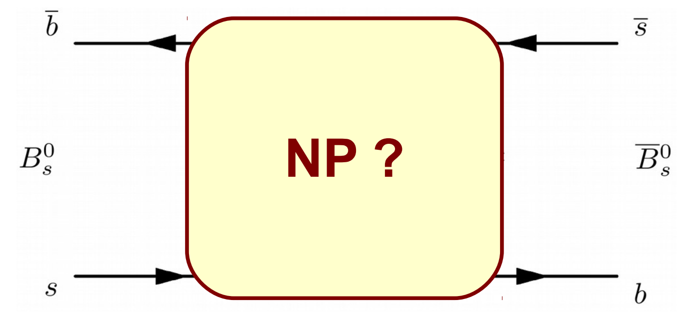


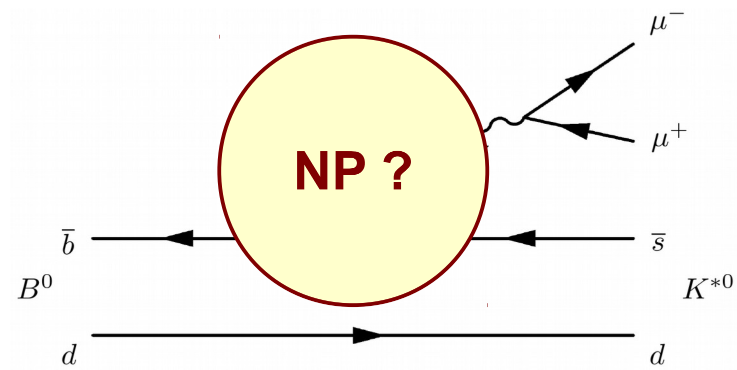
- **indirect searches for New Physics are sensitive to higher mass scales than direct searches for new particles**
- **the pattern of deviations can hint at the structure of the New Physics**

suppression of FCNC kaon decays $\rightarrow$ GIM mechanism $\rightarrow$ prediction of charm quark
CP violation in the $K^0\overline{K}^0$ system $\rightarrow$ CKM mechanism $\rightarrow$ prediction of 3rd quark doublet
electro-weak precision measurements at LEP, SLC $\rightarrow$ prediction of top quark mass

Indirect Search For New Physics

- most New Physics models predict the existence of new heavy particles
  - these can enter in internal loops and have sizeable effect on observables
  - *CP* violating phases, rare FCNC decays
- B^0 and B^0_s systems are an ideal hunting ground
  - rich phenomenology, precise SM predictions
  - confront predictions with precision measurements ⇒ LHCb





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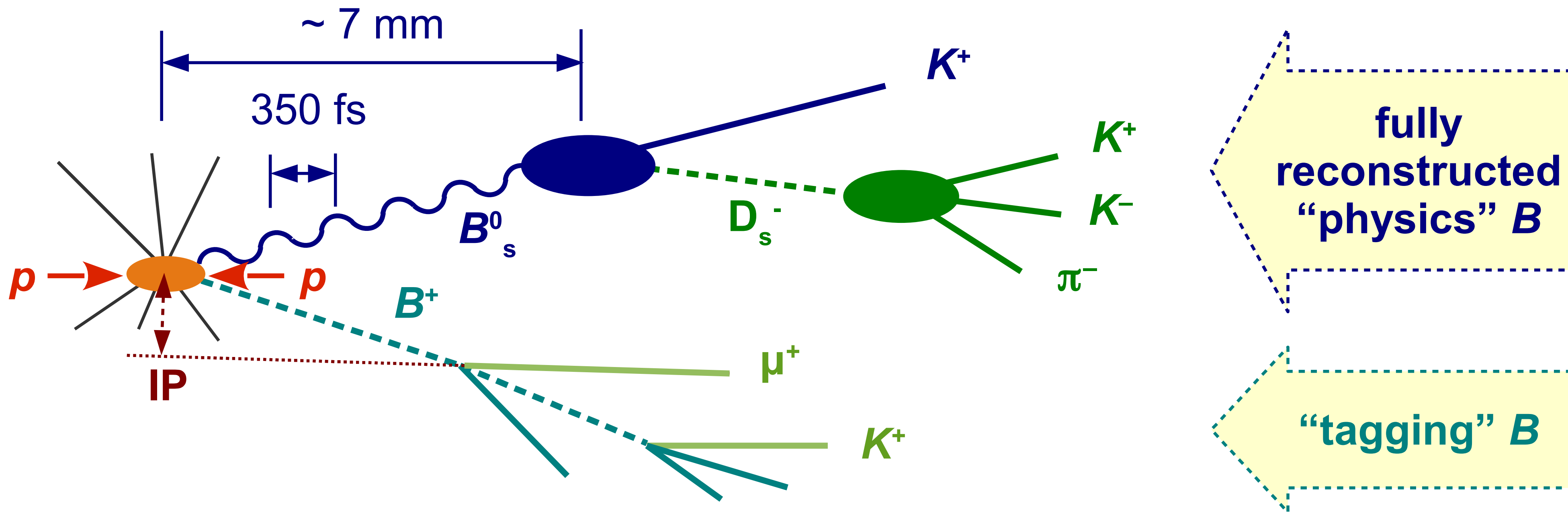
Key Requirements



- **impact parameter resolution**
  - identify secondary vertices
- **proper time resolution**
  - resolve fast B^0_s-$\overline{B}^0_s$ oscillations
- **momentum & invariant mass resolution**
  - against combinatorial backgrounds
- **large numbers of *b* hadrons (B^0, $B^\pm$, B^0_s, Λ_b)**
- ***K*/π separation**
  - against peaking backgrounds
  - flavour tagging
- **selective and efficient trigger, also for hadronic final states**

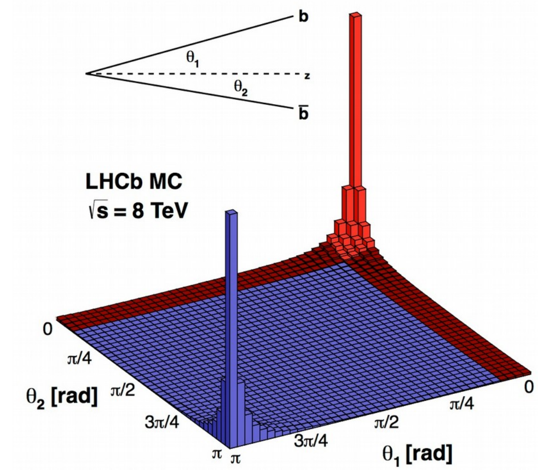
$\sigma(b\overline{b}) \approx 290\ \mu b$ @ 7 TeV
[PLB 694 (2010) 209]

Forward Acceptance

- $b\bar{b}$ **production at the LHC peaks at small polar angles:**

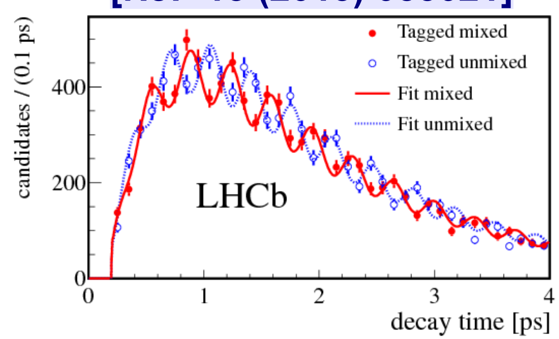
  ≈ 25 % of produced $b\bar{b}$ pairs inside LHCb acceptance

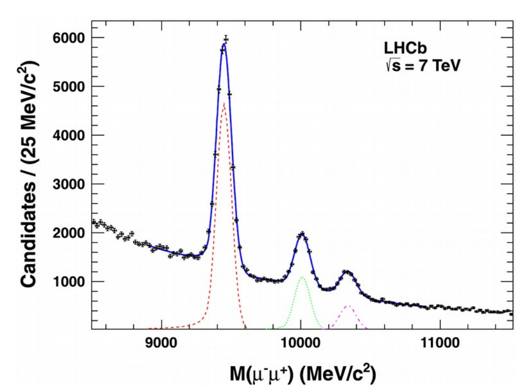
  - c.f. ≈ 40 % inside ATLAS/CMS acceptance



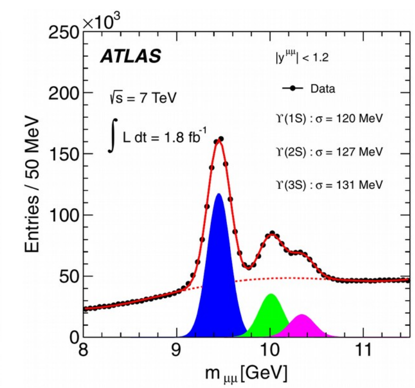
- **additional advantages:**
  - higher momentum at the same p_T → lower p_T thresholds possible
  - larger Lorentz boost of *b* hadrons → better decay time resolution
  - move dead material outside acceptance → less multiple scattering, better momentum and invariant-mass resolution
  - accessibility of detector components → installation / maintenance / repairs

[NJP 15 (2013) 053021]





[EPJ C72 (2012) 2025]



[PRD (2013) 052004]

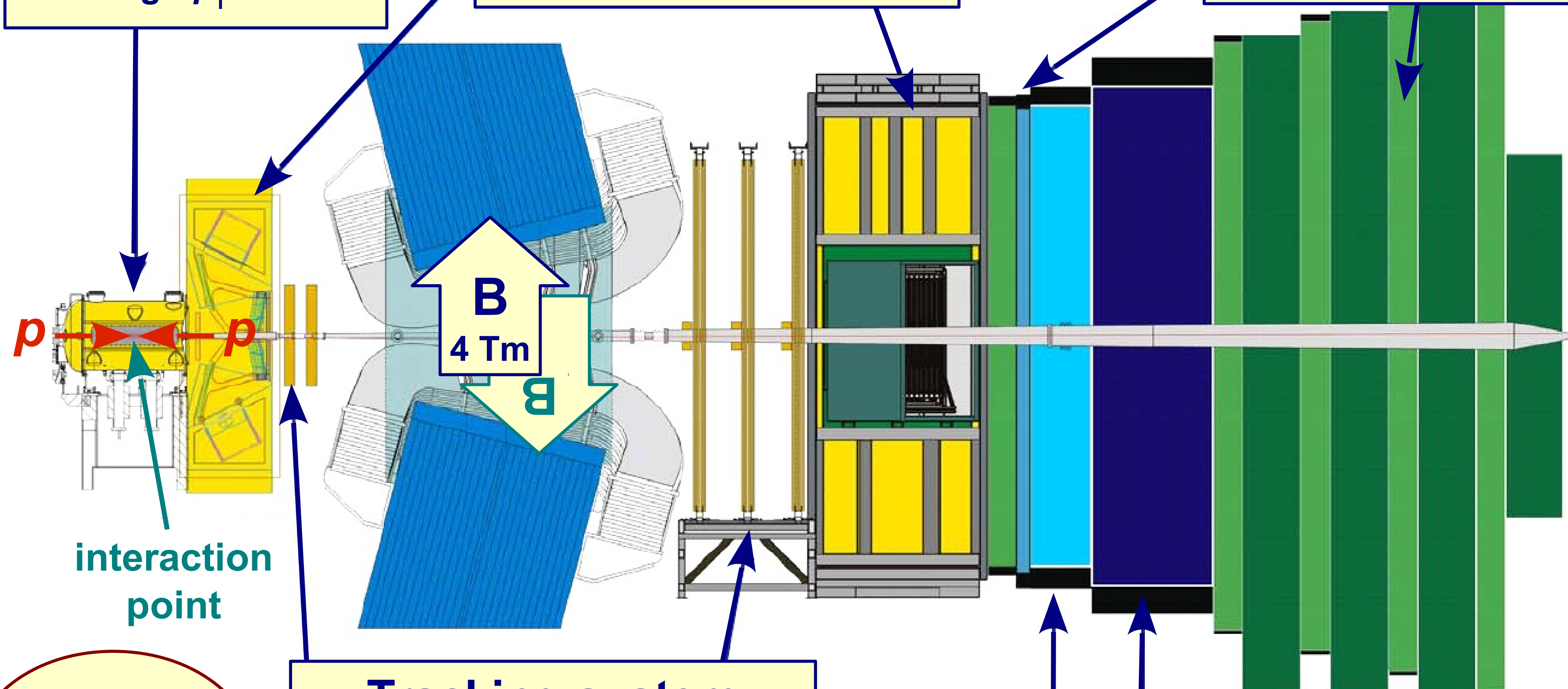
- **extra benefit: unique potential for production studies in forward direction**

LHCb Apparatus

VErtex LOcator
$\sigma_{IP} \sim 20\ \mu m$
for high-p_T tracks

RICH detectors
$\varepsilon(K \to K) \sim 95\ \%$
for 5 % $\pi \to K$ mis-id

Muon system
$\varepsilon(\mu \to \mu) \sim 97\ \%$
for 1-3 % $\mu \to \pi$ mis-id



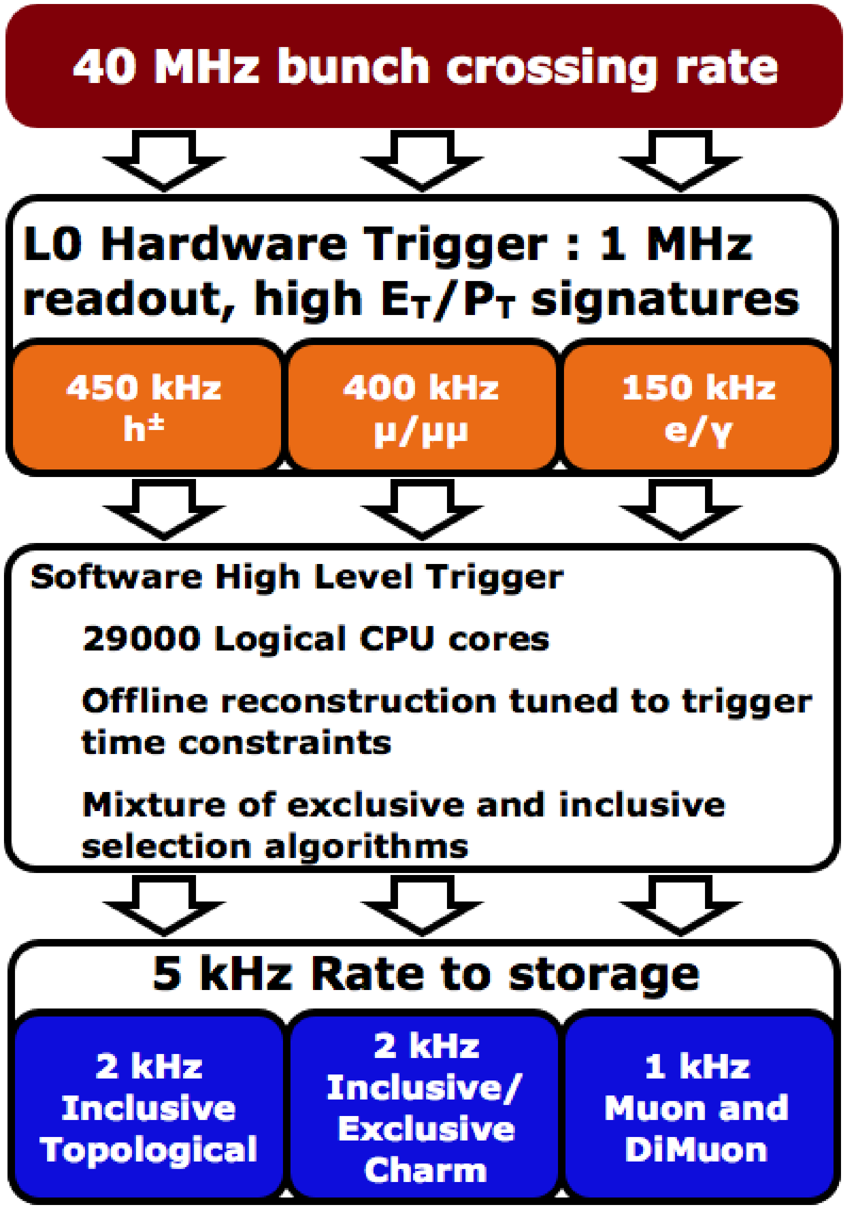
acceptance
$2 < \eta < 5$

Tracking system
$\Delta p/p = 0.4\ \%$ @ 5 GeV/c to
0.6 % @ 100 GeV/c

Calorimeters
ECAL: $\sigma_E/E \sim 1\ \% \otimes 10\ \% / \sqrt{E}$ (GeV)

[JINST 3 (2008) S08005]

LHCb Trigger



Hardware level (L0):

- maximum output rate 1 MHz
- typical thresholds

  $E_T(e/\gamma) > 2.7$ GeV

  $E_T(h) > 3.6$ GeV

  $p_T(\mu) > 1.4$ GeV

Software level (HLT):

event reconstruction similar to offline

Combined efficiency L0+HLT (2012):

~ 90 % for di-muon channels ($J/\psi\ X$)

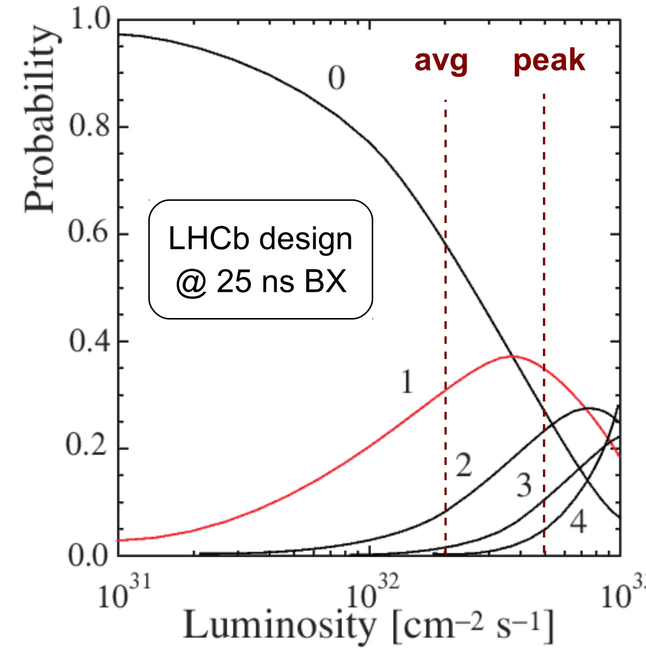
~ 30 % for multi-body hadronic final states

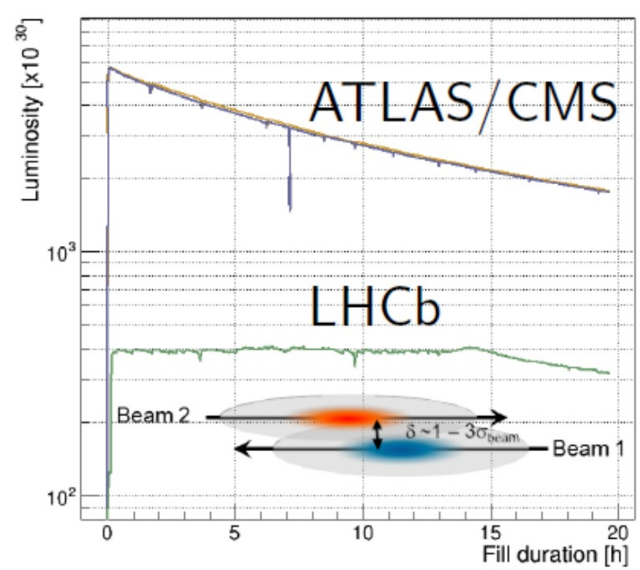
Data Taking

- **LHCb designed to operate at lower instantaneous luminosity than ATLAS/CMS**
  - avoid too high particle density in forward region
  - large number of *pp* interaction vertices can affect reconstruction of decay length, flavour tagging
- **achieved by focussing and relative displacement of the two LHC beams in the LHCb interaction point**
  - luminosity leveling: adjust displacement throughout fill → operate at constant instantaneous luminosity
  - optimal use of beams + stable operation conditions

2011:	**1 fb^{-1} *pp* at 7 TeV**
2012:	**2 fb^{-1} *pp* at 8 TeV**
2013:	**1.6 nb^{-1} *pPb* / *Pbp***

- **data taking efficiency > 93 %**





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  } "core" physics programme
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- **the LHCb upgrade**

Mapping the Unitarity Triangle

- **quark eigenstates of charged-current weak interaction ≠ mass eigenstates**

$$L_{\mathrm{cc}} = -\frac{g}{\sqrt{2}}\,\overline{u}_i\,\gamma^\mu\,(1-\gamma_5)\,V_{ij}\,d_j\,W_\mu^+ + \mathrm{h.c.}$$

- **three quark families → 3 × 3 mixing matrix**

$$V_{ij} = V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

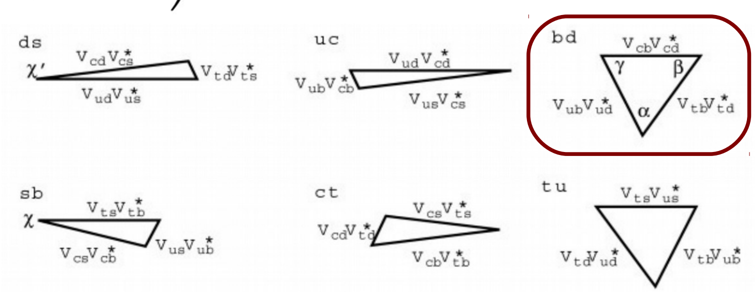
- **18 – 9 – 5 = 4 independent parameters → complex phase → *CP* violation**
  - Wolfenstein parametrization: ($\lambda = \sin\theta_c$, A, ρ, η)

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O\left(\lambda^5\right)$$

- **unitarity → six orthogonality conditions, e.g.**

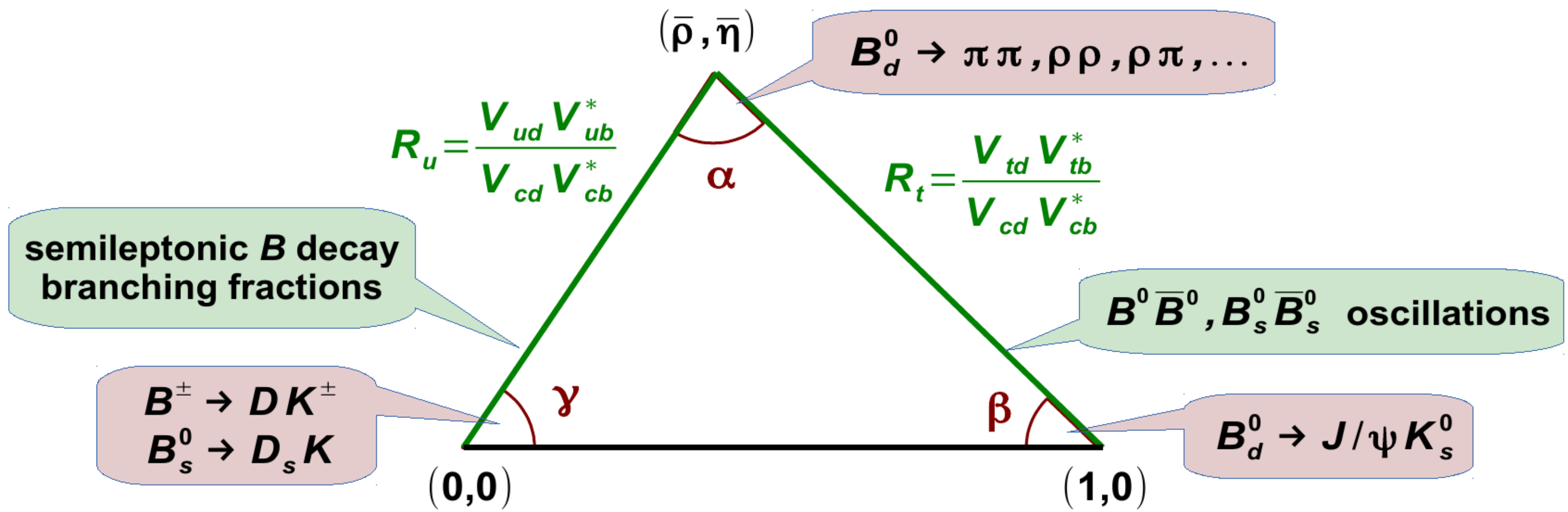
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- **visualize as triangles in the complex plane**

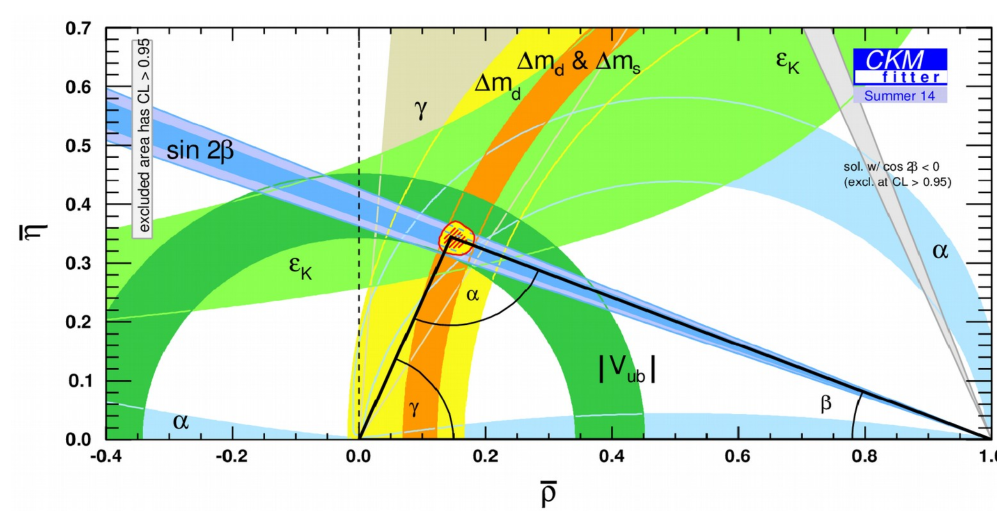


Mapping the Unitarity Triangle

- **sides and angles of Unitarity Triangle are related to measurable observables**



- sides: *CP* conserving observables
- angles: *CP* violating observables



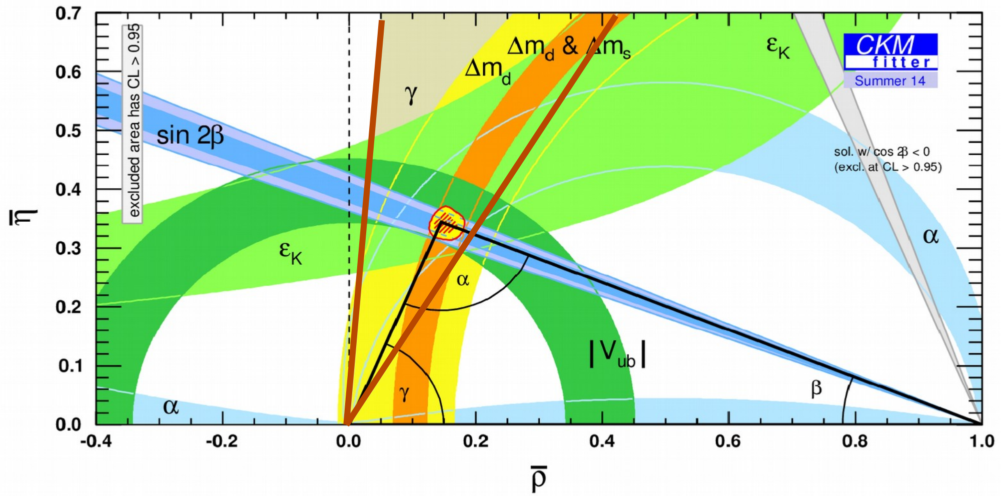
- **consistency of measurements provides test of Standard Model**
  - global fits by UTFit, CKMfitter groups

Angle γ

- **currently the least well constrained parameter of the Unitarity Triangle**
  - world average direct measurements:

$$\gamma = \left(73.2^{+6.3}_{-7.0}\right)^o \quad \text{[CKMfitter]}$$

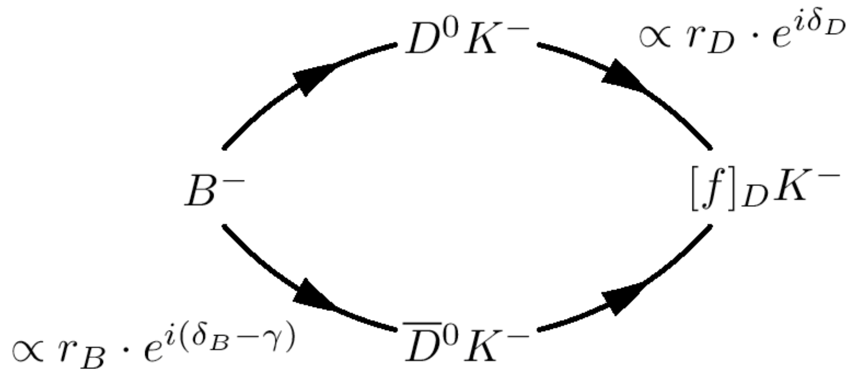
$$\gamma = \left(68.4 \pm 7.5\right)^o \quad \text{[UTfit]}$$



- **theoretically "clean" determination from tree-level decays**

$$B^\pm \rightarrow D\,K^\pm \rightarrow f_{[D]}\,K^\pm$$

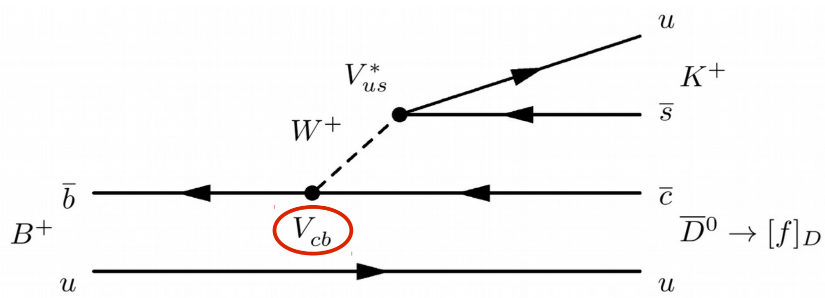
where final state $f_{[D]}$ accessible to D^0 and $\overline{D}^0$

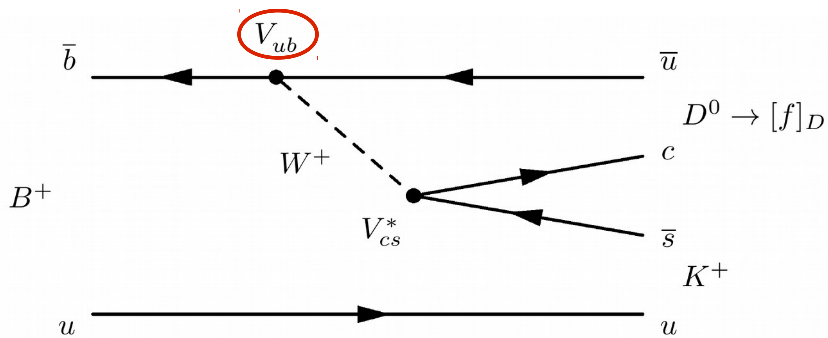


- **no loops involved → largely unaffected by possible effects from New Physics**
- **combine several final states to extract γ together with r_B and strong phase δ_B**
- **experimental challenges: small branching fractions, hadronic final states**

=> one of the key measurements for LHCb

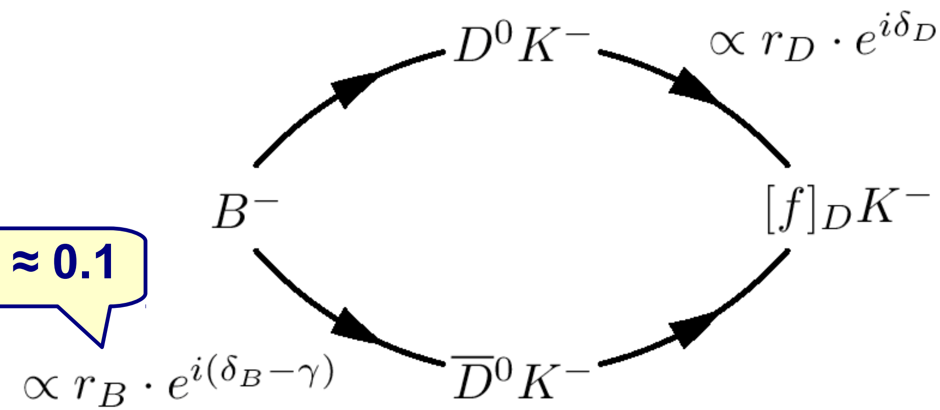
Angle γ





r_D = 1 for GLW, ≈ 0.05 for ADS

r_B ≈ 0.1



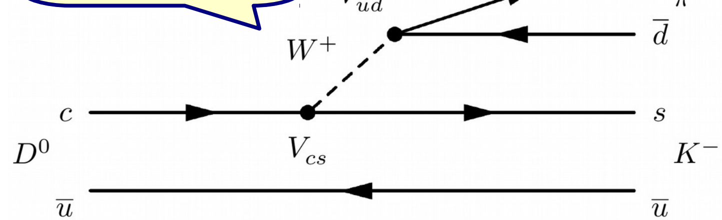
- **GLW: *CP* eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$**
  - $r_B \approx 0.1 \to$ small interference limits sensitivity to γ

[PLB 253(1991)483, PLB 265(1991)172]

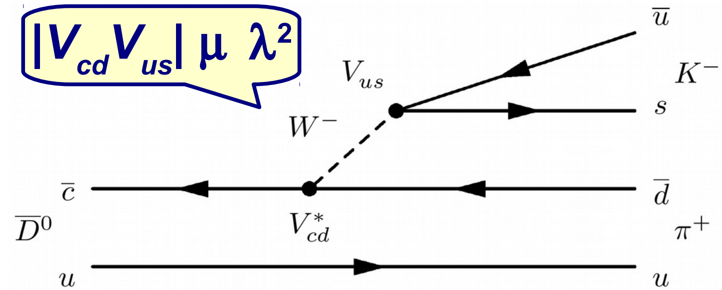
- **ADS: favoured $D^0 \to K^-\pi^+$ / suppressed $D^0 \to K^+\pi^-$**
  - small r_D compensates for $r_B \to$ larger interference
  - but very small *BF* for suppressed modes

[PRL 78 (1997) 257, PRD 63 (2001) 036005]

|$V_{cs}V_{ud}$| μ 1

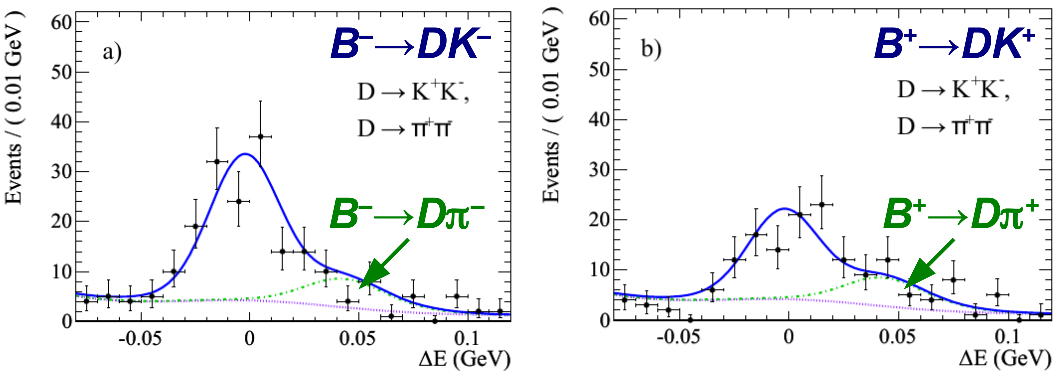


|$V_{cd}V_{us}$| μ λ^2

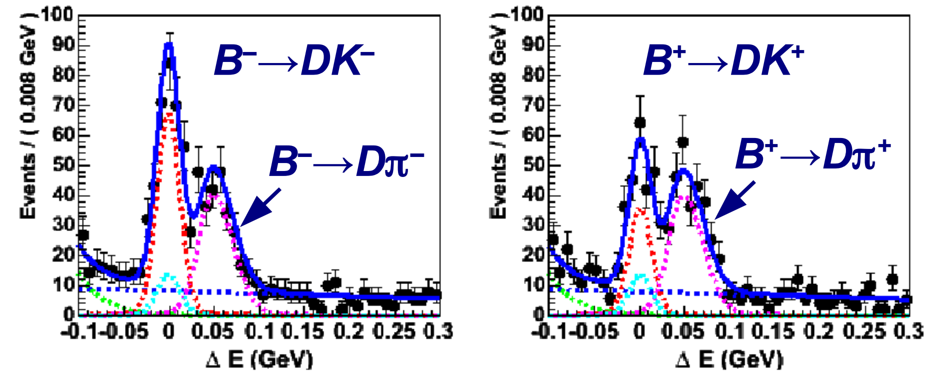


GLW modes

- **Babar / Belle measurements based on full data sets (**467M / 772M $B\bar{B}$ pairs**)**

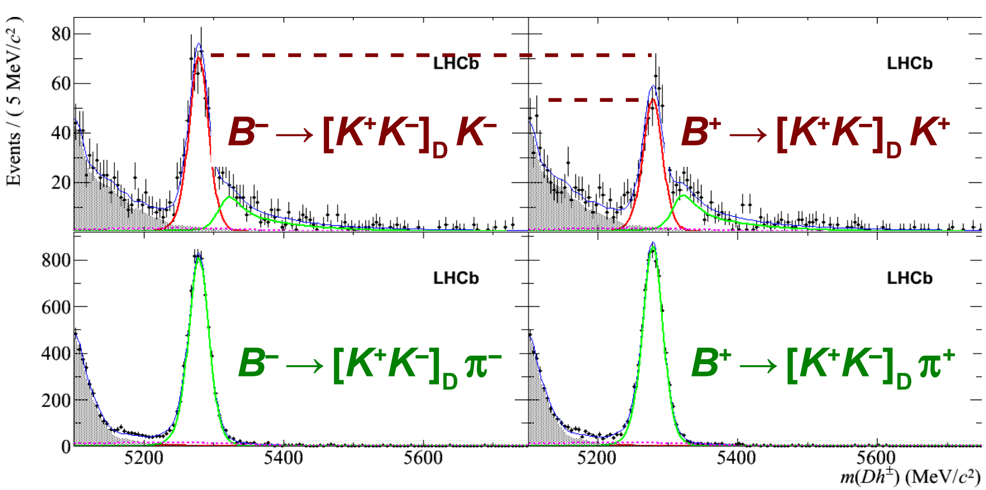


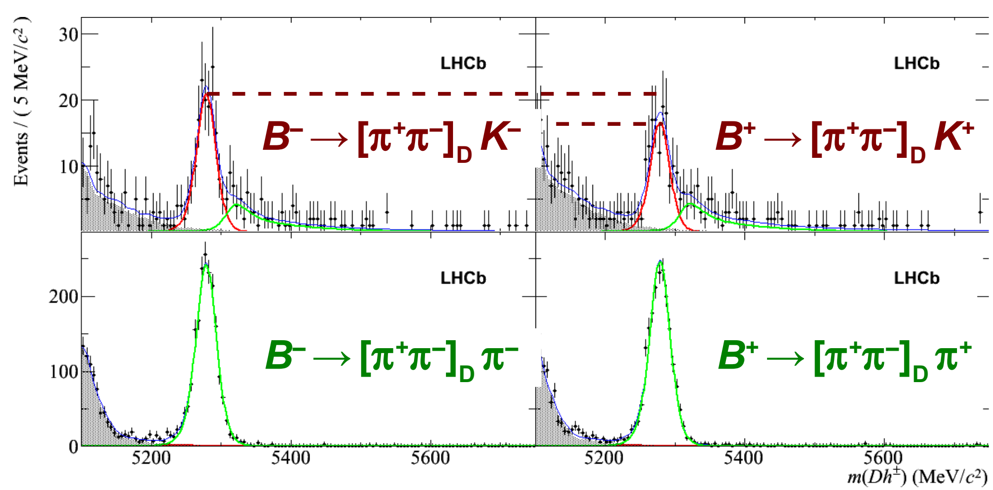
[PRD 82(2010)072004]



[arXiv:1112.1984]

- **LHCb measurement based on 2011 data (1 fb^{-1})** [PLB 713(2012)351]
  - note the excellent suppression of $B^{\pm}\to D\pi^{\pm}$ contamination in $B^{\pm}\to DK^{\pm}$ samples !





ADS modes

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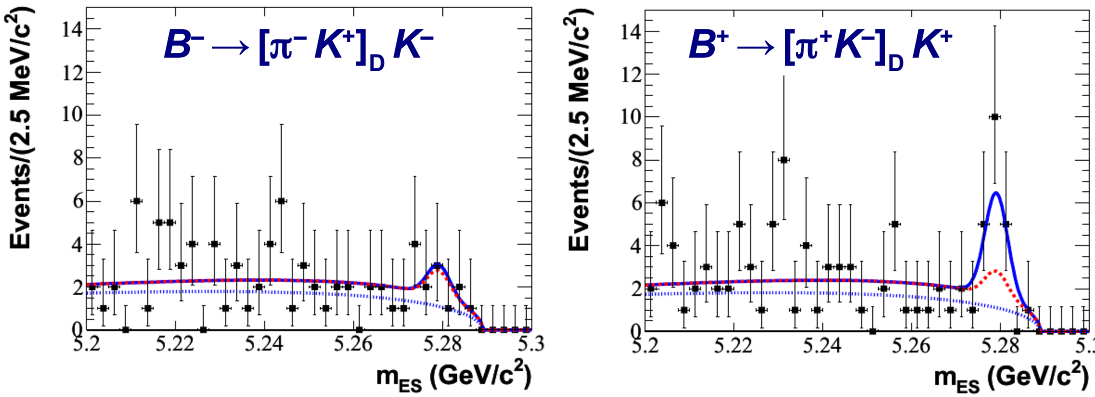
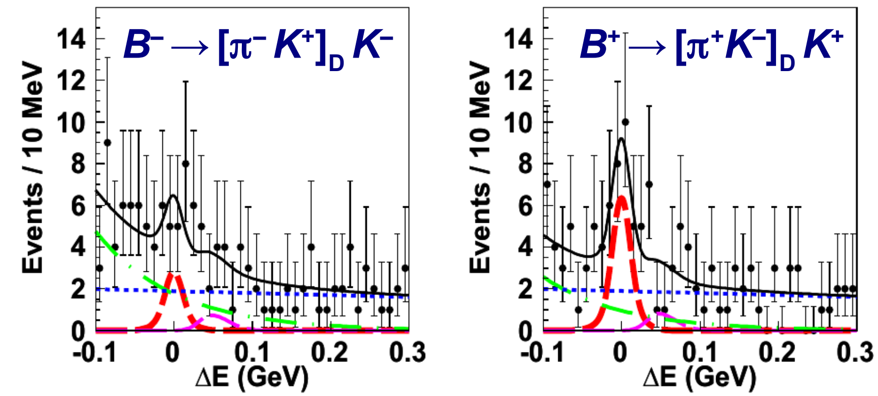
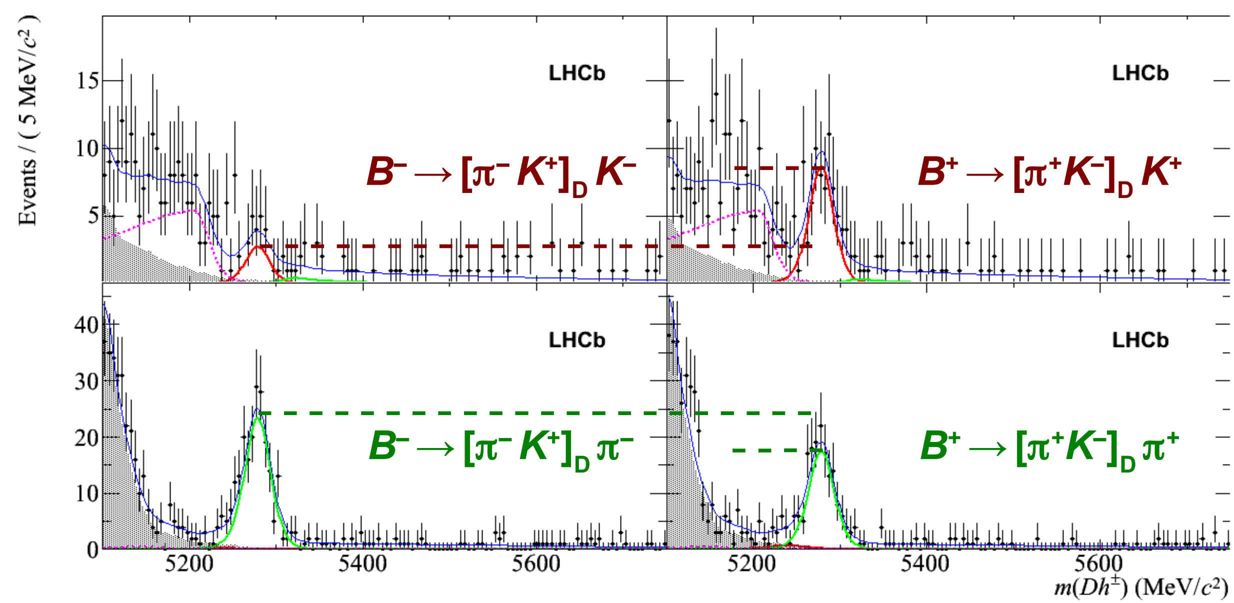


[PRD 82(2010)072006]



[PRL 106(2011)231803]

- **LHCb measurement based on 2011 data (1 fb^{-1})** [PLB 712(2012)203]
  - first observation of the doubly Cabibbo suppressed mode (10 σ significance)
  - evidence for *CP* asymmetry in $B^\pm \to DK^\pm$ (4 σ)
  - hint of an asymmetry also in $B^\pm \to D\pi^\pm$ (2.4 σ)



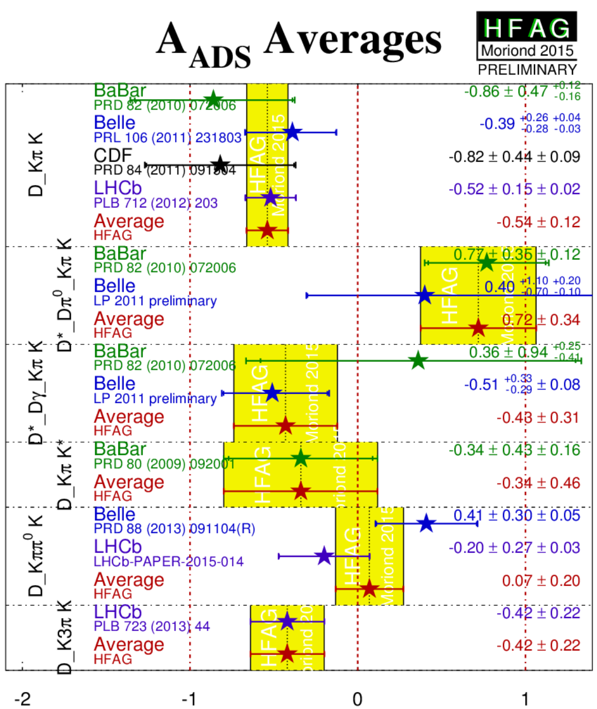
ADS modes

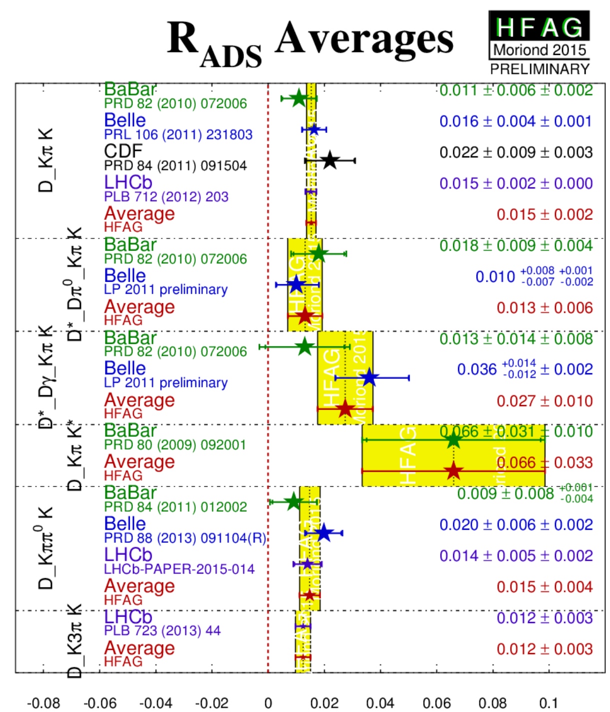
- **observables: ratios and asymmetries of time-integrated decay rates, e.g.**

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 \cdot r_B r_D \cos(\delta_B + \delta_D) \cdot \cos\gamma$$

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 \cdot r_B r_D \sin(\delta_B + \delta_D) \cdot \sin\gamma}{R_{ADS}}$$

- **similar analyses also in three- and four-body decays of *D* mesons**





$B^\pm \to [K^+\pi^-]_D K^\pm$

$B^\pm \to [K^+\pi^-\pi^0]_D K^\pm$

$B^\pm \to [K^+\pi^-\pi^+\pi^-]_D K^\pm$

Dalitz-Plot Analyses

- **study $D \to K^0_S \pi^+\pi^-$ decay amplitude as a function of the invariant masses**

$$m_+^2 \equiv m^2(K^0_S\,\pi^+) \quad \text{and} \quad m_-^2 \equiv m^2(K^0_S\,\pi^-)$$

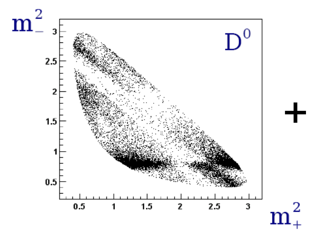
[PRD 68(2003)054018]
[PRD 70(2004)072003]

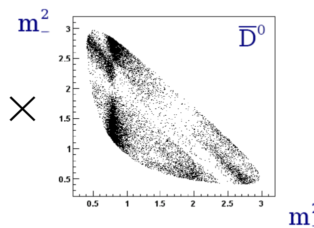
- **neglecting *CP* violation in $D^0\overline{D}^0$ mixing and decay** (known to be very small):

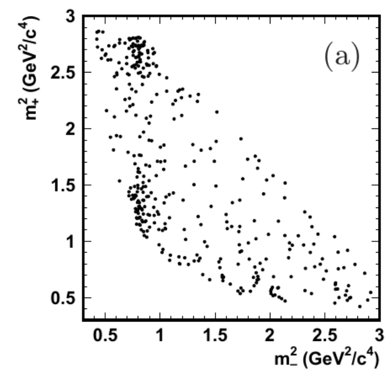
$$f_{\overline{D}^0}(m_+^2, m_-^2) = f_{D^0}(m_-^2, m_+^2)$$

- **for $B^- \to [K^0_S\pi^+\pi^-]_D K^-$**

$$\Gamma_{B^-}(m_+^2, m_-^2) \propto \left| \; f_{D^0} + r_B \cdot e^{i(\delta_B - \gamma)} \times f_{\overline{D}^0} \; \right|^2 \Rightarrow$$

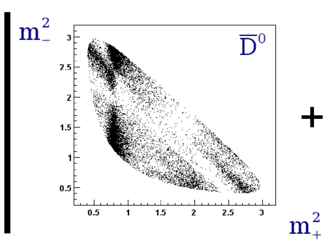


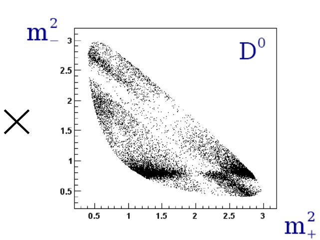


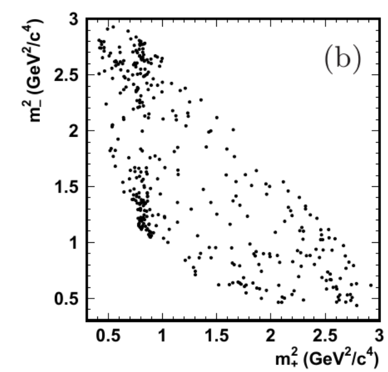


- **for $B^+ \to [K^0_S\pi^+\pi^-]_D K^+$ ($f_{D0} \leftrightarrow f_{\overline{D}0}$, $-\gamma \leftrightarrow +\gamma$)**

$$\Gamma_{B^+}(m_+^2, m_-^2) \propto \left| \; f_{\overline{D}^0} + r_B \cdot e^{i(\delta_B + \gamma)} \times f_{D^0} \; \right|^2 \Rightarrow$$





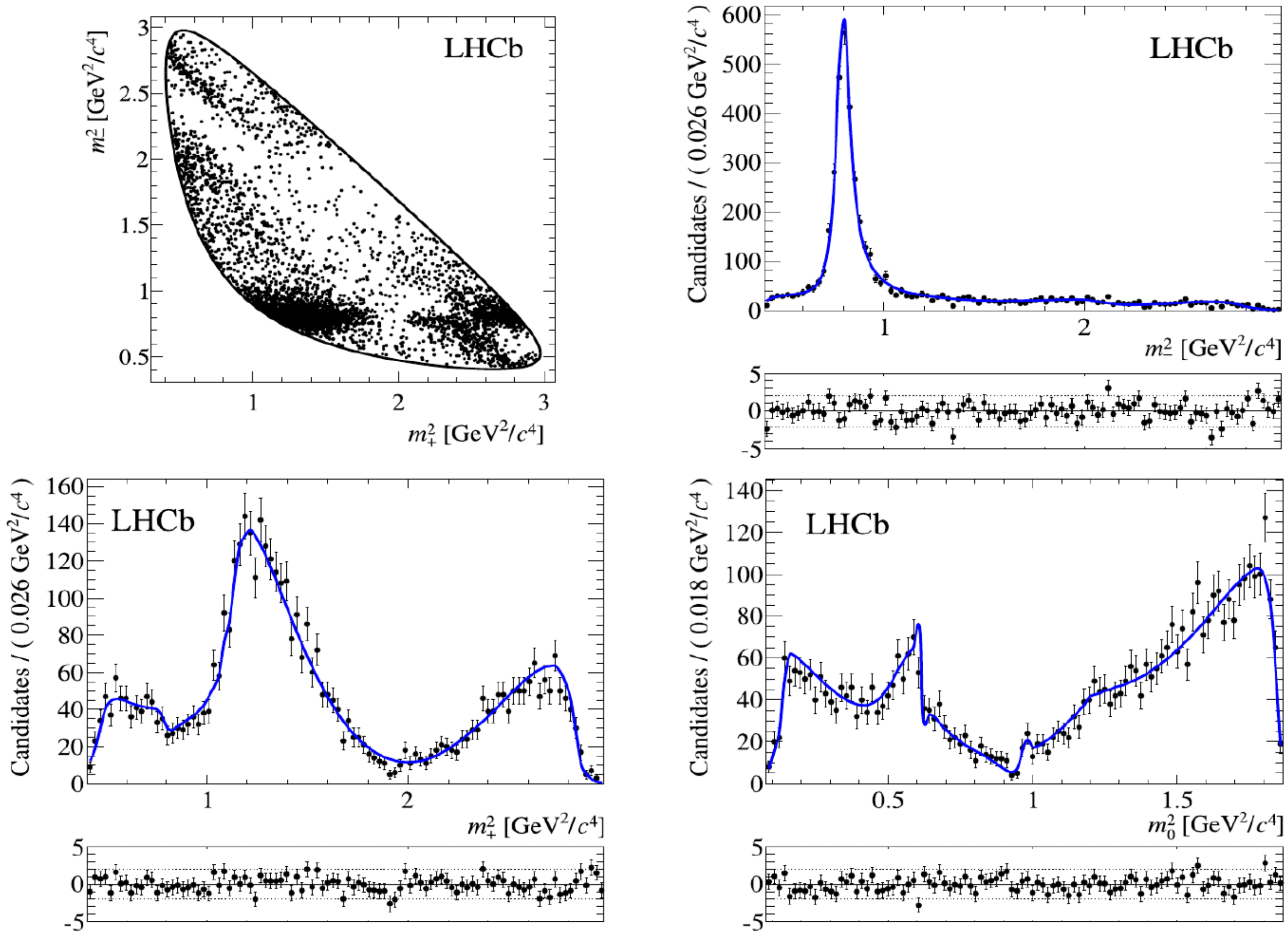


Belle, [PRD 81(2010)112002]

- **dominate precision on γ from the *B* factories**

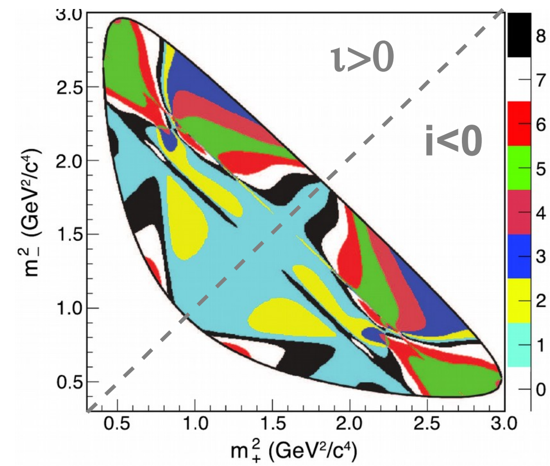
Dalitz-Plot Analyses

- **"model-dependent" analyses: describe $f_D(m_+^2, m_-^2)$ by a coherent sum of a non-resonant term and known two-body resonances ($K^*(892)^+\pi^-$, $K^0_S\,\rho(770)$, …)**
- **LHCb analysis based on 2011 data set (1 fb^{-1})** [NPB 888(2014)169]



Dalitz-Plot Analyses

- **model-independent analyses: use existing CLEO-c measurements of strong phase δ_D to divide Dalitz plot into symmetric regions $\pm i$ with ≈ constant phase difference $\Delta\delta_D = \delta_{\bar{D}0} - \delta_{D0}$**



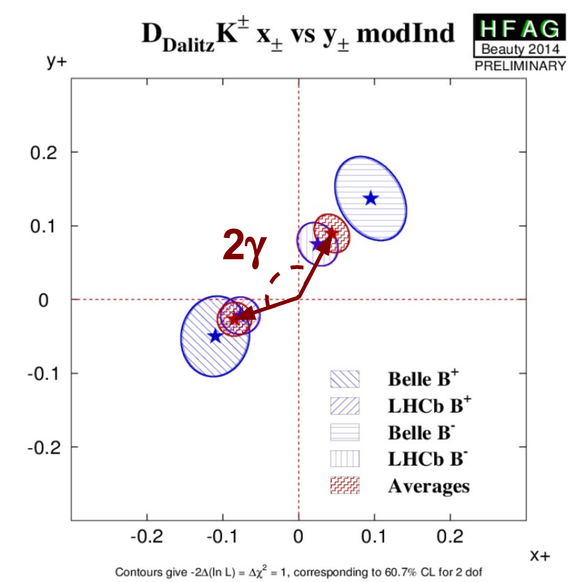
[PRD 82 (2010) 112006]

- **measure B^+ and B^- event yields in each region i**
- **normalize to measured number $K_{\pm i}$ of $D \to K^0_s\pi^+\pi^-$ events from $D^{*\pm} \to D\pi^\pm$**

$$N_i(B^\pm) = K_{\mp i} + (x_\pm^2 + y_\pm^2) \cdot K_{\pm i} + 2\sqrt{K_{+i}K_{-i}} \cdot \left\{ x_\pm \langle \cos(\Delta\delta_D) \rangle_i \mp y_\pm \langle \sin(\Delta\delta_D) \rangle_i \right\}$$

$$x_\pm = r_B \cdot \cos(\delta_B \pm \gamma)$$

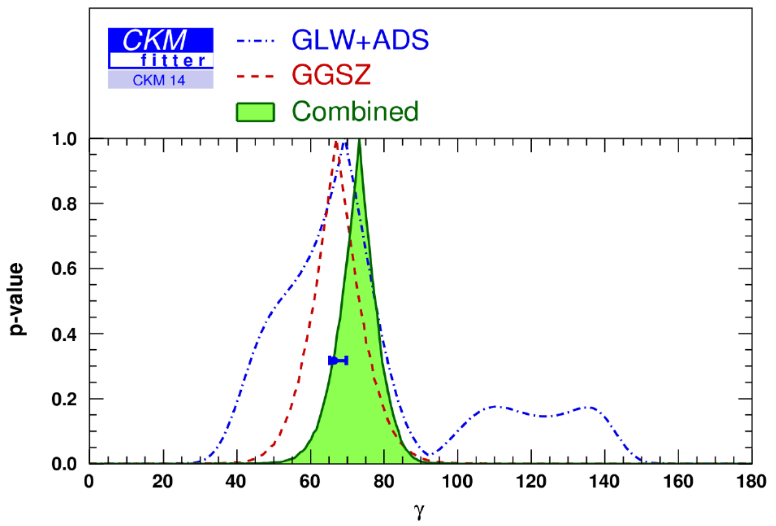
$$y_\pm = r_B \cdot \sin(\delta_B \pm \gamma)$$

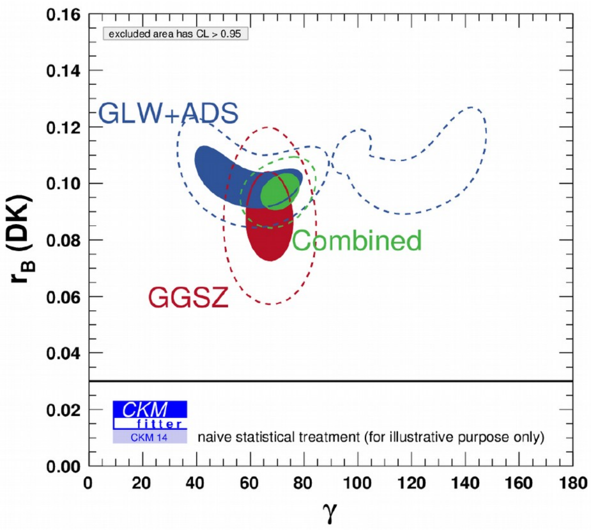


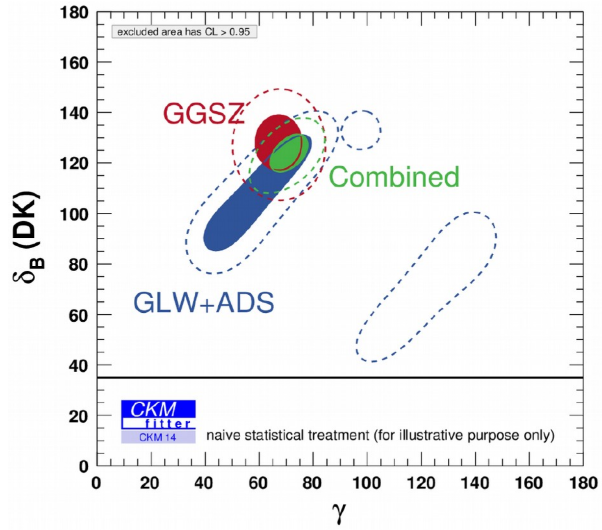
- **Belle measurement based on their full data set**
- **LHCb measurement based on run-I data set** (3 fb^{-1})

[PRD 85 (2012) 112014] [JHEP 1410 (2014) 97]

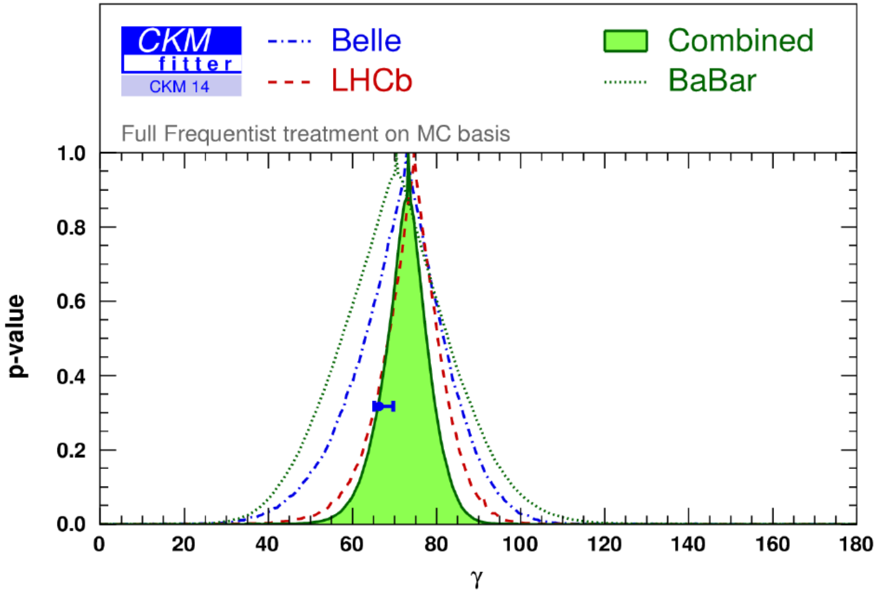
γ Combinations







- **good agreement between the different approaches**
- **good agreement between the different experiments**
- **most precise results now from LHCb**



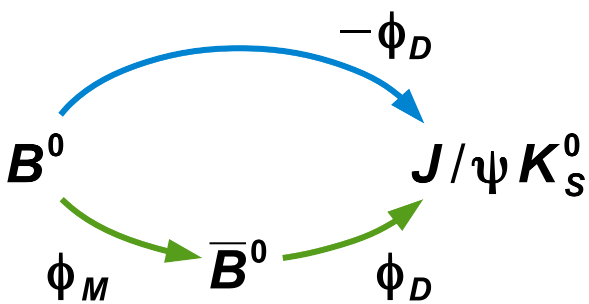
Overview

- **short motivation & introduction of the LHCb experiment**
- **(small) selection of highlights from run I**
  - CKM angle γ from $B^{\pm} \to D K^{\pm}$ tree decays
  - CP violating phase ϕ_s from $B^0_s \to J/\psi\, \phi$
  - branching fraction of $B^0_s \to \mu^+ \mu^-$
  - angular distributions in $B^0 \to K^{*0} \mu^+ \mu^-$
  - electroweak boson production in the forward direction

  (the first four items: "core" physics programme)
- **challenges and prospects for run II**
- **the LHCb upgrade**

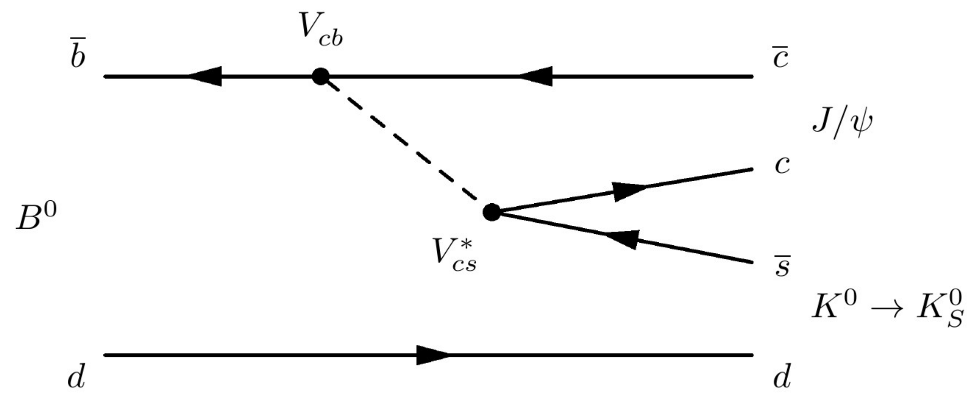
sin 2β

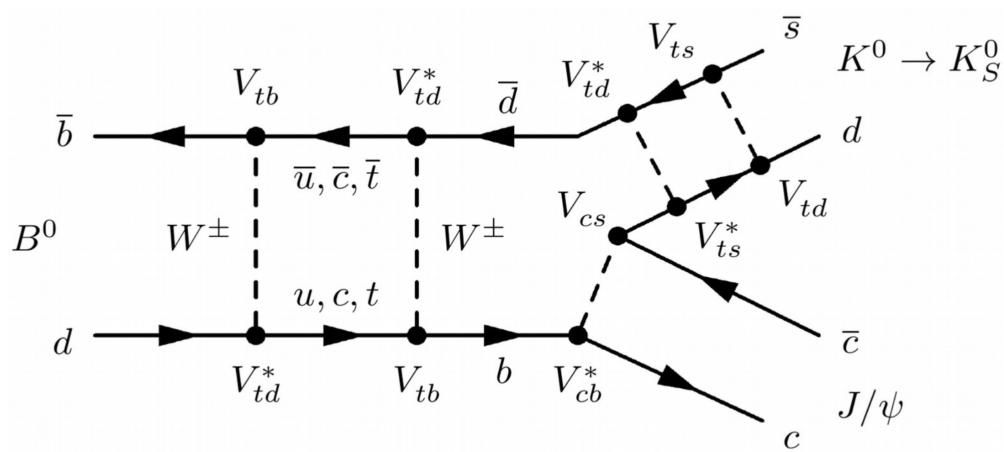
- "golden" decay mode $B^0 \to J/\psi\, K^0_S$
- time–dependent *CP* asymmetry due to "interference of mixing and decay"



$$a_{CP}(t) = \frac{\Gamma(B^0 \to J/\psi K^0_S) - \Gamma(\overline{B}^0 \to J/\psi K^0_S)}{\Gamma(B^0 \to J/\psi K^0_S) + \Gamma(\overline{B}^0 \to J/\psi K^0_S)}$$

$$= \sin(2\beta)\,\sin(\Delta m_d t)$$





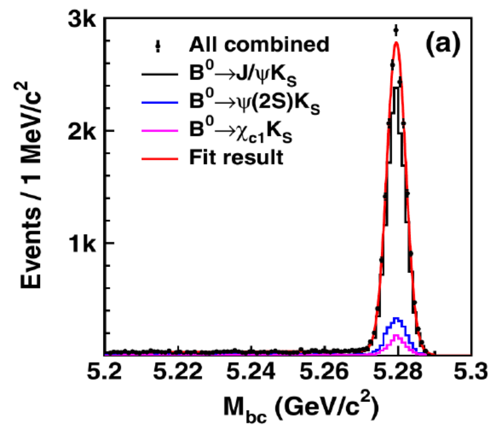
- clean event signature from $J/\psi \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$
- small theory uncertainty on extraction of sin 2β from measured asymmetry
- *the* flagship measurement of the *B* factories
- the best measured UT parameter to date

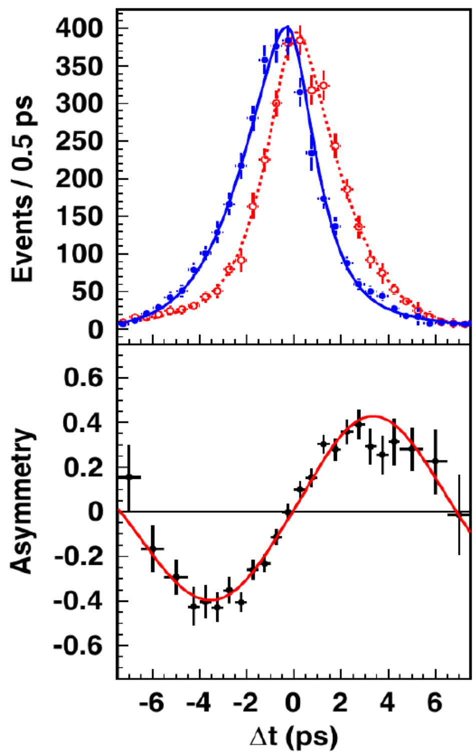
sin 2β = 0.691 ± 0.017

[HFAG, Winter 2015]

sin 2β at the *B* factories

- $e^+e^- \to \Upsilon(4s) \to B\bar{B}$ produces $B^0\bar{B}^0$ pairs in a quantum-entangled state → oscillate in phase until one decays
- measure *CP*-violating asymmetry as a function of the decay-time difference
  - average decay-time resolution 1.56 ps, about 12 % of $B^0\bar{B}^0$ oscillation period





- imply initial flavour of signal *B* meson from decay of the second *B* meson
  - tagging efficiency: ε_{tag}
  - wrong-tag fraction ω_{tag}

tagging power: $Q_{tag} = \varepsilon_{tag} \times (1 - 2\,\omega_{tag})^2 \approx 30\ \%$

$$a_{\rm meas}(\Delta t) = (1 - 2\,\omega_{\rm tag}) \cdot \sin(2\beta) \cdot \int \sin(\Delta m_d\,\Delta t') \cdot R(\Delta t - \Delta t')\, d\Delta t'$$

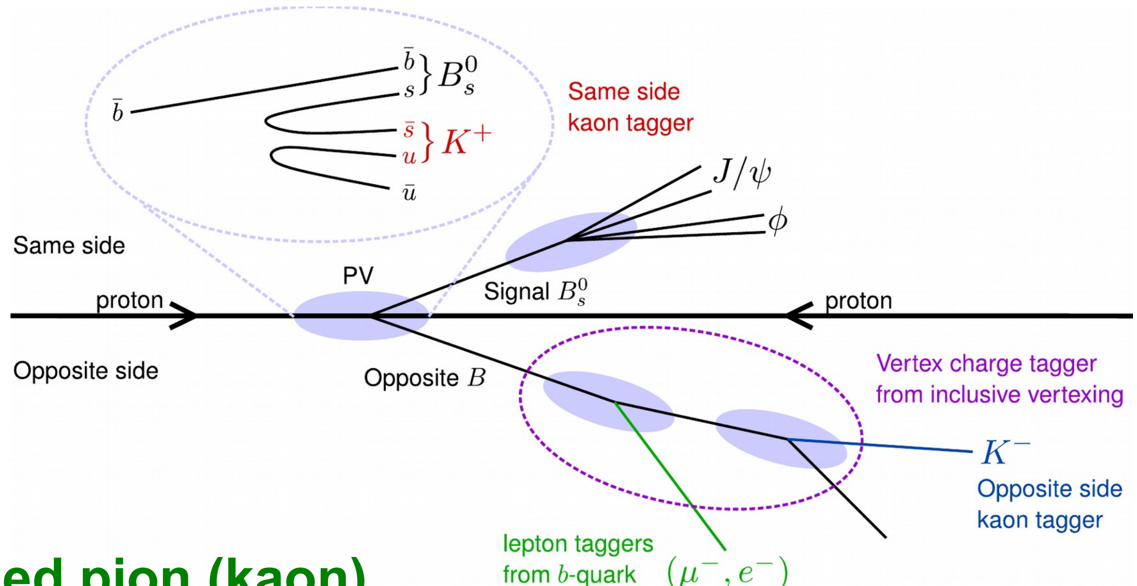
decay–time | flavour tagging dilution | $B^0\bar{B}^0$ oscillation frequency | decay–time resolution

Flavour Tagging at LHCb

- ***pp* collisions produce $b\bar{b}$ quark pairs in an uncorrelated state**
  - each hadronizes independently into any type of *b* or $\bar{b}$ hadron

    B^0 (40 %), B^+ (40 %), B^0_s (10 %), B^+_c (few %), Λ^0_b (10 %)

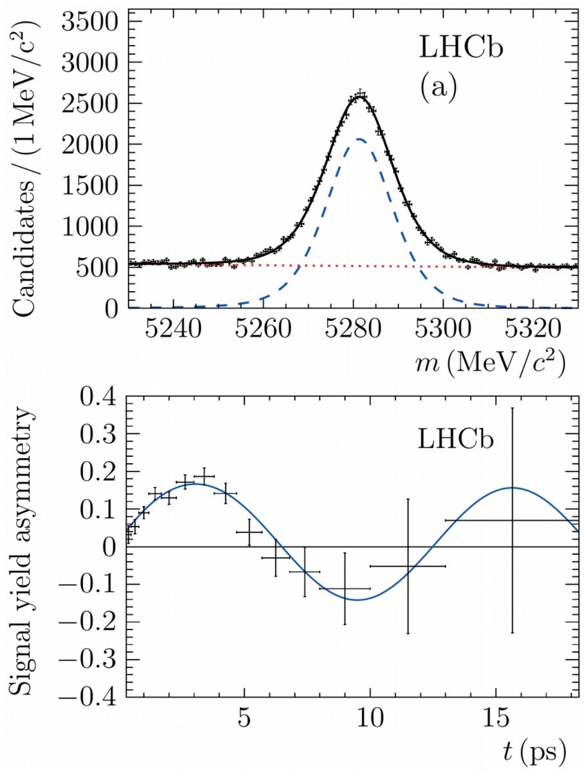
- **opposite-side flavour tagging: imply initial flavour of signal *B* meson from decay products of the second *b* hadron**
  - charged lepton from $b \rightarrow c\,\ell^- \bar{\nu}_\ell$
  - charged kaon from $b \rightarrow c \rightarrow s$
  - inclusive vertex charge

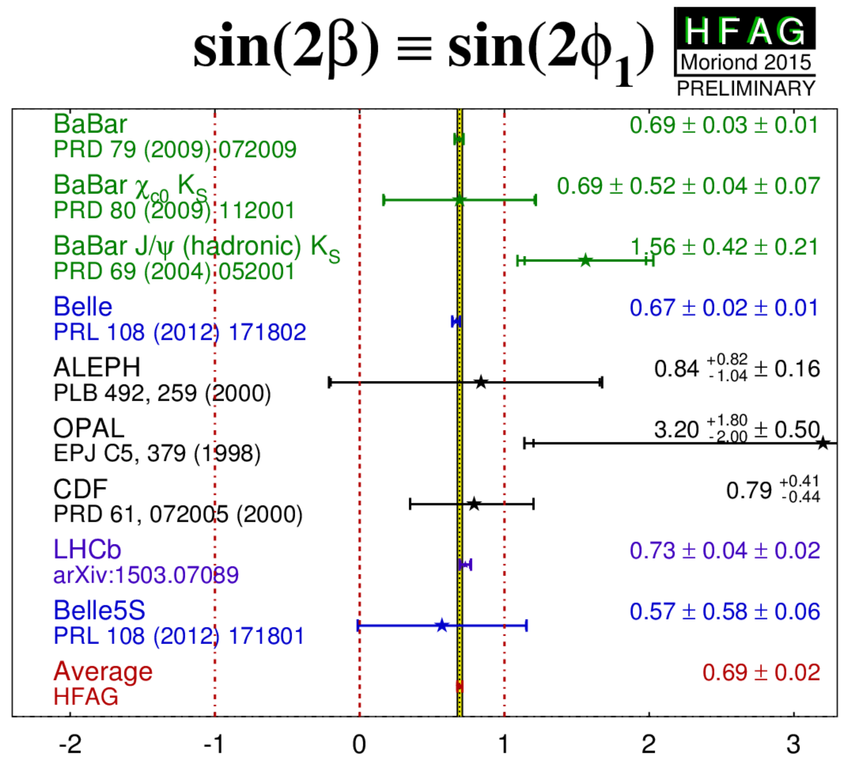


- **same-side tagging: look for charged pion (kaon) close in phase space to the signal B^0 (B^0_s) meson**
  - from $\bar{b} \rightarrow B$ hadronization chain or from $B^{+**} \rightarrow B^0\pi^+$ decays
- **combined tagging power ≈ 3 %** (c.f. 30 % at *B* factories)
  - wrong tags due to underlying event; oscillation of opposite-side B^0 or B^0_s

sin 2β at LHCb

- **Moriond 2015: LHCb measurement based on run-I data set (3 fb^{-1})**





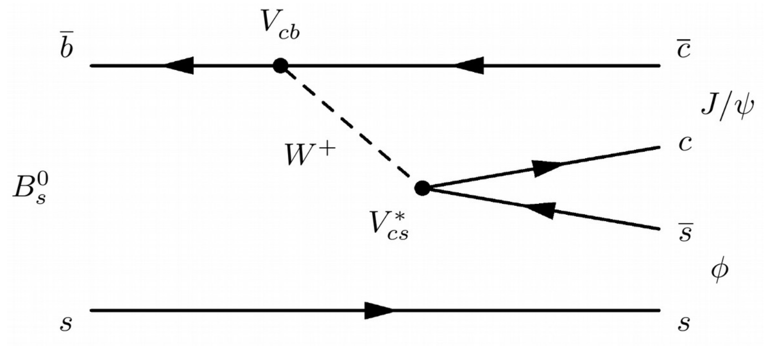
sin 2β = 0.731 ± 0.035 (stat) ± 0.020 (syst)

[arXiv:1503.07089]

- **systematic uncertainty dominated by effects related to flavour tagging**

CP violating phase ϕ_s

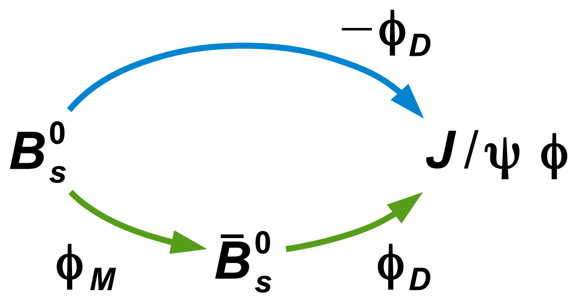
- "golden" decay mode $B^0_s \to J/\psi\ \phi$



- time-dependent *CP* asymmetry from interference between mixing and decay

$$\phi_s = \phi_M - 2\phi_D$$

- predicted to be very small in Standard Model

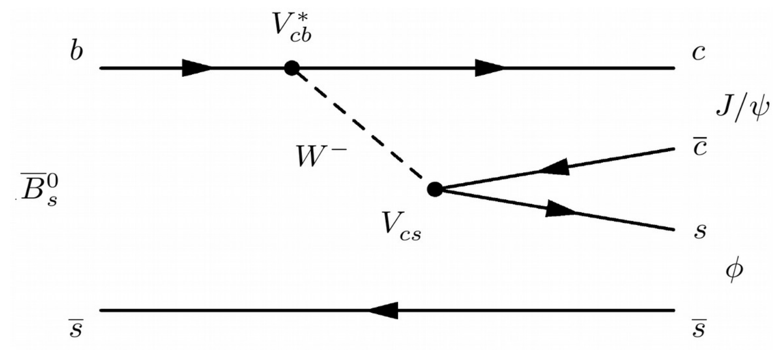


ϕ_s = 0.0364 ± 0.0016 rad [CKMfitter]

- sensitive to New Physics contributions in B^0_s–$\bar{B}^0_s$ mixing
- need to resolve fast B^0_s–$\bar{B}^0_s$ oscillations → excellent decay-time resolution
- significant decay-width difference $\Delta\Gamma_s$ between the mass eigenstates
  - need to measure simultaneously with ϕ_s
- $J/\psi\ \phi$ can have relative angular momentum L = 0,1 or 2 → not a *CP* eigenstate
  - time-dependent angular analysis to disentangle even and odd *CP* contributions

CP violating phase ϕ_s

- **"golden" decay mode $B^0_s \to J/\psi\ \phi$**



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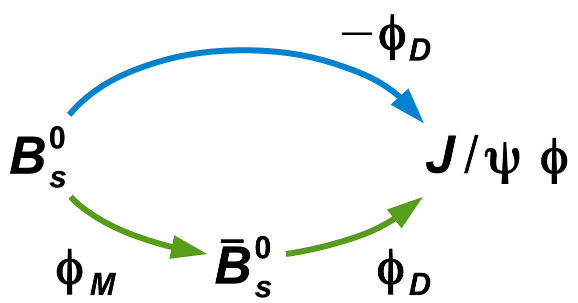
$$\phi_s = 0.0364 \pm 0.0016 \text{ rad}$$

[CKMfitter]



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  - need to measure simultaneously with ϕ_s
- **$J/\psi\ \phi$ can have relative angular momentum L = 0,1 or 2 $\to$ not a CP eigenstate**
  - time-dependent angular analysis to disentangle even and odd CP contributions

CP violating phase ϕ_s

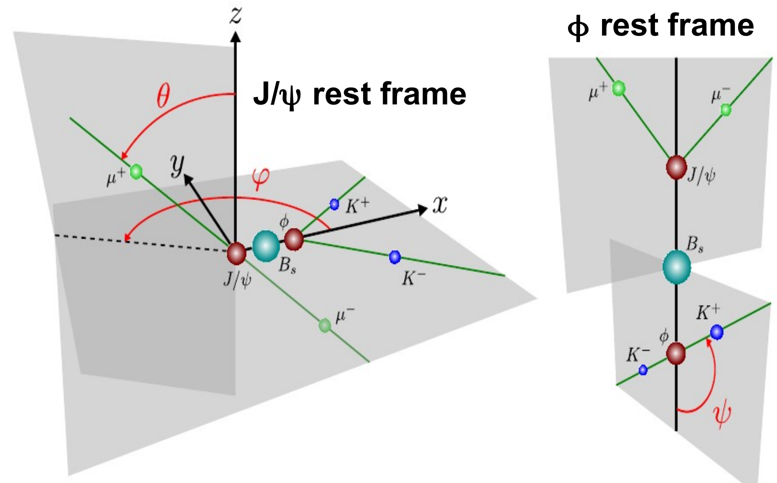
- **fit decay rates as a function of the decay time and three decay angles of final-state particles**
- **transversity amplitudes and *S*-wave amplitude**

$A_0 = |A_0| \cdot e^{i\delta_0}$: longitudinal polarization

$A_\parallel = |A_\parallel| \cdot e^{i\delta_\parallel}$: transverse parallel polarization

$A_\perp = |A_\perp| \cdot e^{i\delta_\perp}$: transverse orthogonal polarization

$A_S = |A_S| \cdot e^{i\delta_S}$: non-resonant $B_s^0 \to J/\psi K^+ K^-$



$$\Omega \equiv \left(\theta=\theta_\mu, \psi=\theta_K, \varphi=\phi_h\right)$$

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi\,\phi)}{\mathrm{d}t\;\mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

$$h_k(t) = N_k e^{-Gt}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

k	$f_k(\theta_\mu,\theta_K,\phi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\,(1-\sin^2\theta_\mu\cos^2\phi_h)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\,(1-\sin^2\theta_\mu\sin^2\phi_h)$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\phi_h$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\phi_h$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\sin\phi_h$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_s(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\cos\phi_h$	$\lvert A_s(0)A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\sin\phi_h$	$\lvert A_s(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$	$\lvert A_s(0)A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

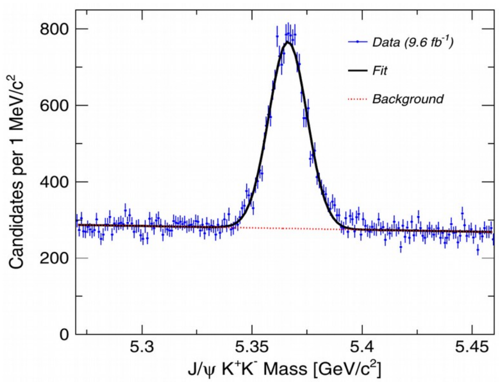
$S = \sin\phi_s$

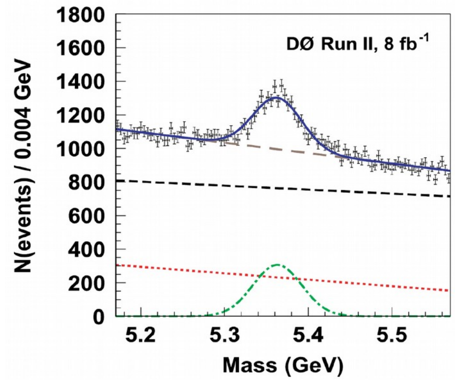
$C = \cos\phi_s$

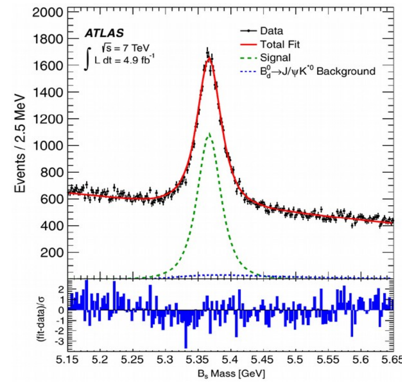
$D = 1 - C - S$

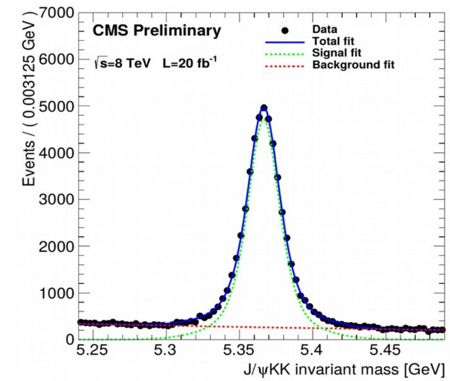
CP violating phase ϕ_s

- **measurements by CDF, D0, ATLAS, CMS**



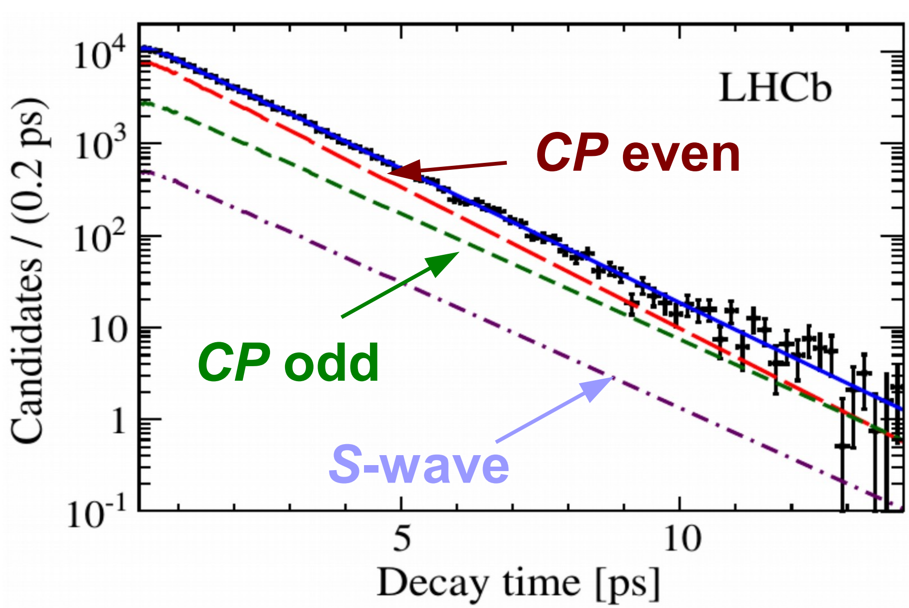


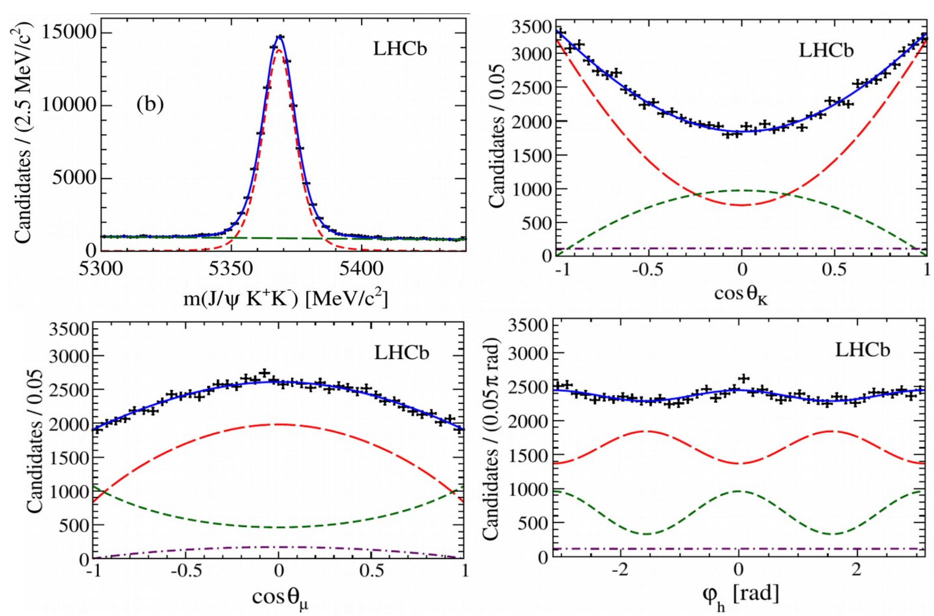




[PRL 109(2012)171802] [PRD 85(2012)032006]

- **LHCb measurement based on run-I data set** (3 fb^{-1}) [PRL 114(2015)041801]

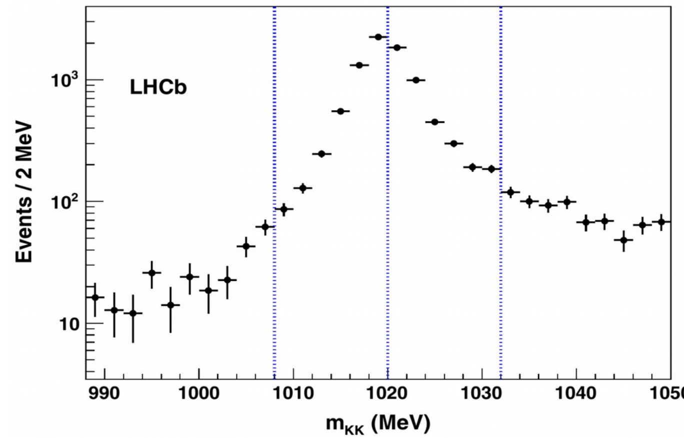




CP violating phase ϕ_s

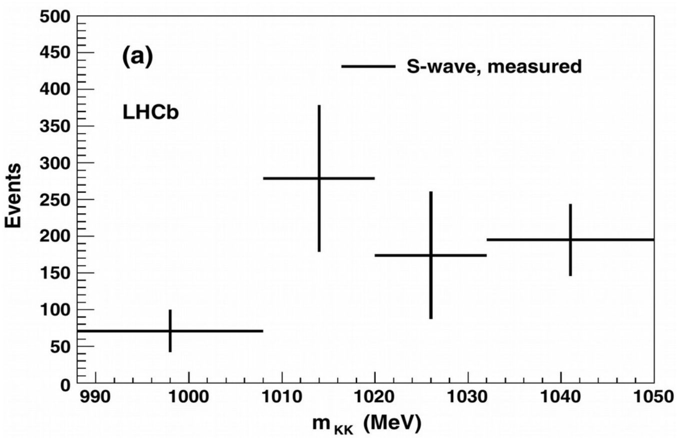
- **two ambiguous solutions for ϕ_s, $\Delta\Gamma_s$: fit function is symmetric under simultaneous transformation**

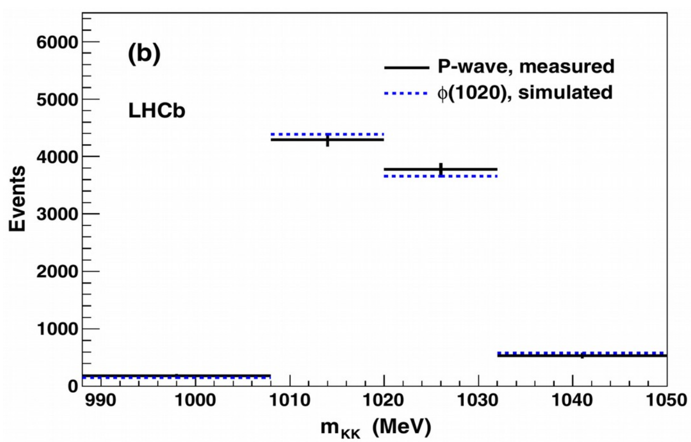
$$\left(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_S\right) \leftrightarrow \left(\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_S\right)$$

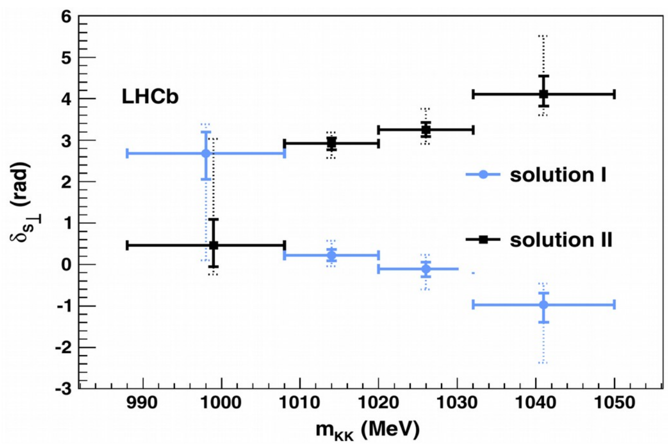


[PRL 108(2012)241801]

- **resolve this ambiguity by looking at evolution of strong phases as a function of K^+K^- invariant mass**
  - *P*-wave amplitudes: resonance at ϕ mass → expect positive phase shift
  - *S*-wave amplitude: non-resonant around ϕ mass → expect no phase shift
- **expect negative trend for $\delta_{S\perp} = \delta_S - \delta_\perp$ → observed for** $\left(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_S\right)$







CP violating phase ϕ_s

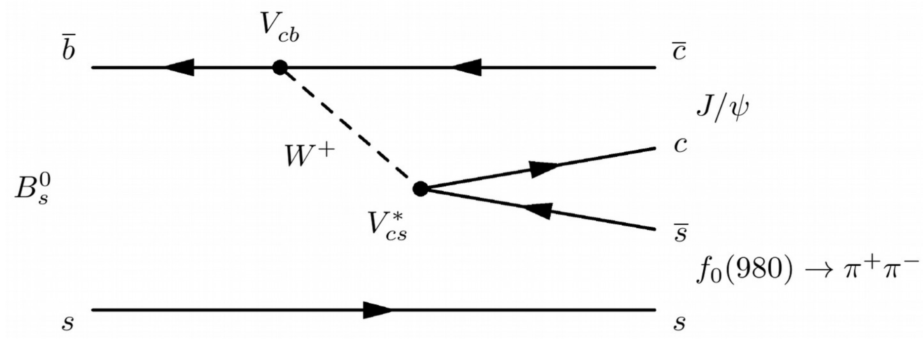
- **LHCb measurement also in $B^0_s \to J/\psi\ \pi^+\pi^-$**
  - (almost pure) *CP* eigenstate → no need for angular analysis
  - but lower branching fraction
- **combined LHCb result**

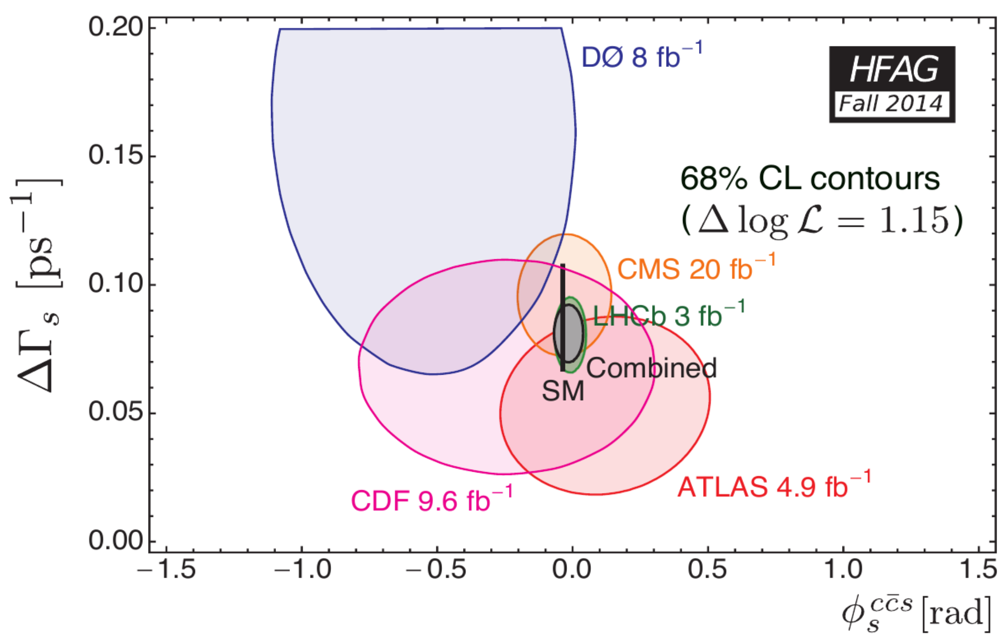
ϕ_s = –0.010 ± 0.039 rad

`[PRL 114(2015)041801]`

most precise measurement to date

- **all measurements in good agreement with Standard Model prediction**





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  - electroweak boson production in the forward direction

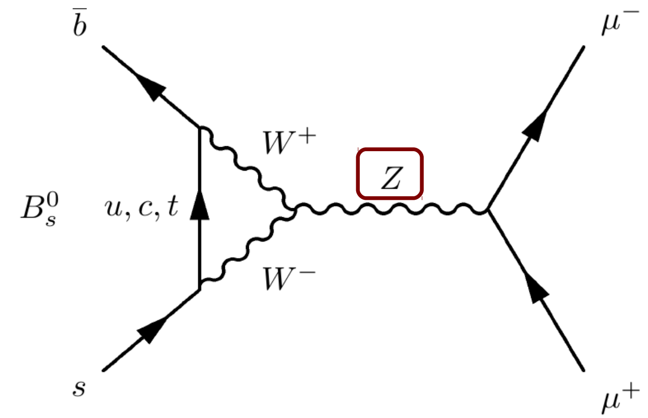
  } "core" physics programme
- **challenges and prospects for run II**
- **the LHCb upgrade**

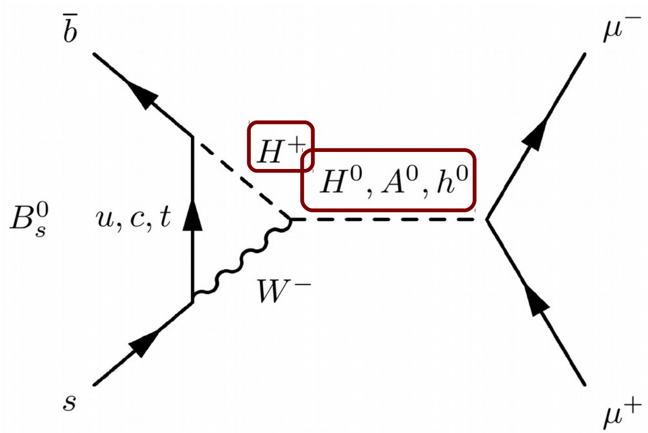
$B^0_{(s)} \rightarrow \mu^+\mu^-$

- **Flavour-Changing Neutral-Current $b \rightarrow s(d)$ transition**
  - can only proceed through loop diagrams
  - in addition helicity suppressed in Standard Model
- **branching fractions predicted to be very small**

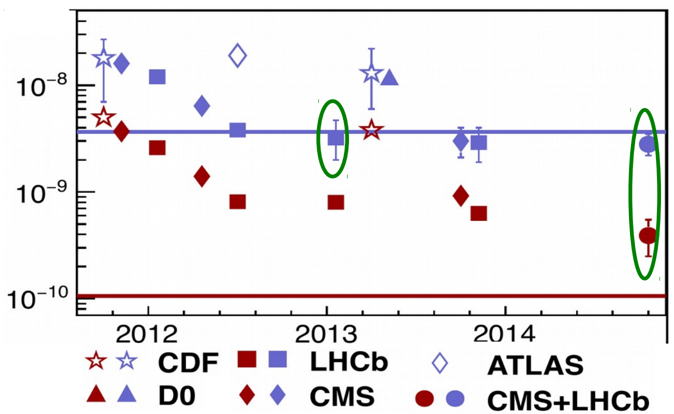
$$BF\,(B^0_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$BF\,(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[PRL 112(2014)101801]



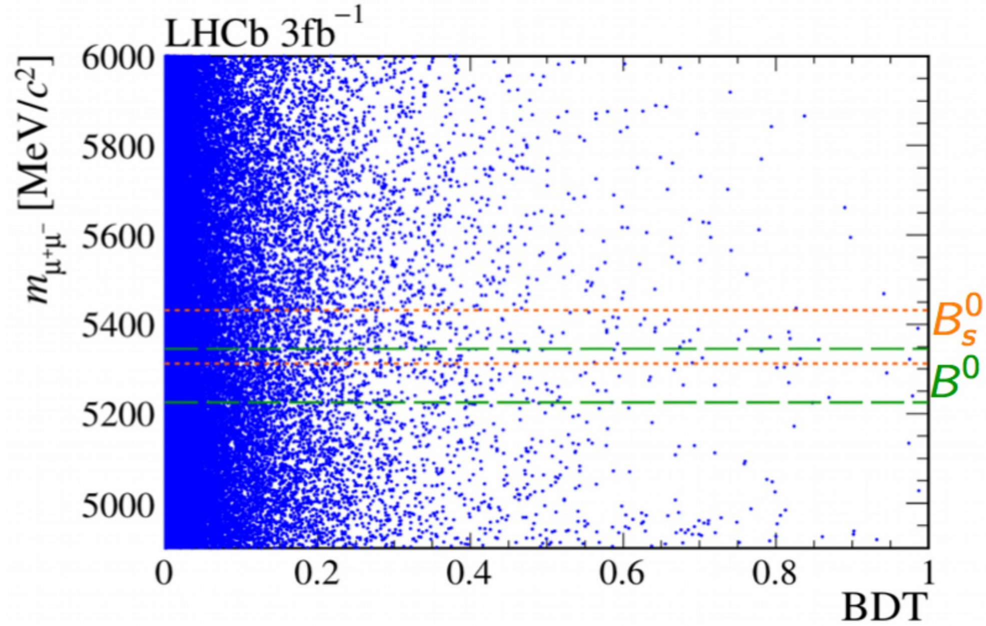


- **sensitive to possible New Physics**
  - in particular models with extended Higgs sector and large values of tan β
- **recent searches at CDF, D0, ATLAS, CMS, LHCb**
  - first $B^0_s \rightarrow \mu^+\mu^-$ evidence from LHCb analysis of 2 fb^{-1}
  - first $B^0_s \rightarrow \mu^+\mu^-$ observation, $B^0 \rightarrow \mu^+\mu^-$ evidence from combined LHCb/CMS analysis of full run-I data sets

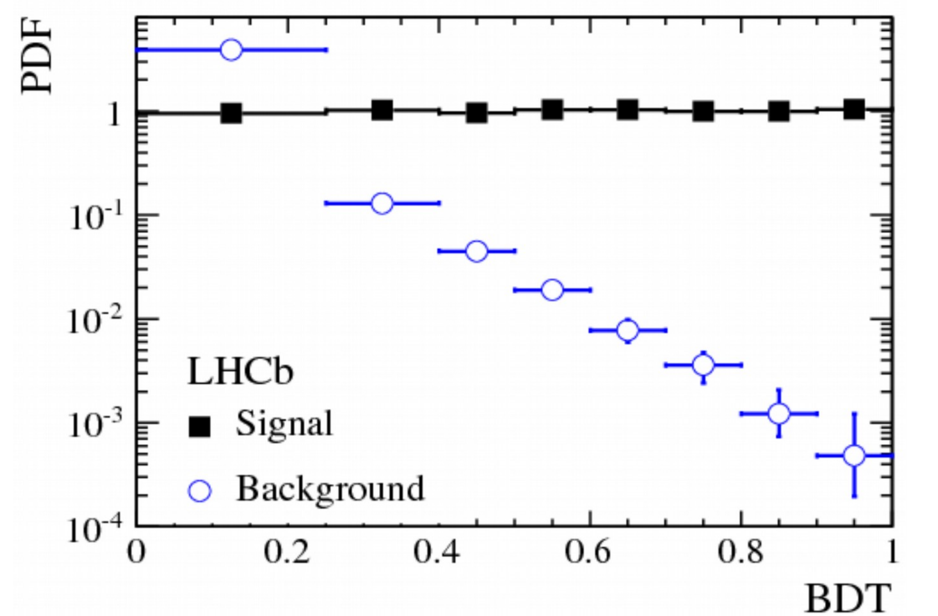


$B^0_{(s)} \rightarrow \mu^+\mu^-$

- **apply loose selection cuts to remove obvious background**
- **classify remaining candidates according to**
  - invariant mass of the $\mu^+\mu^-$ pair
  - multivariate classifier (BDT) combining information related to event topology

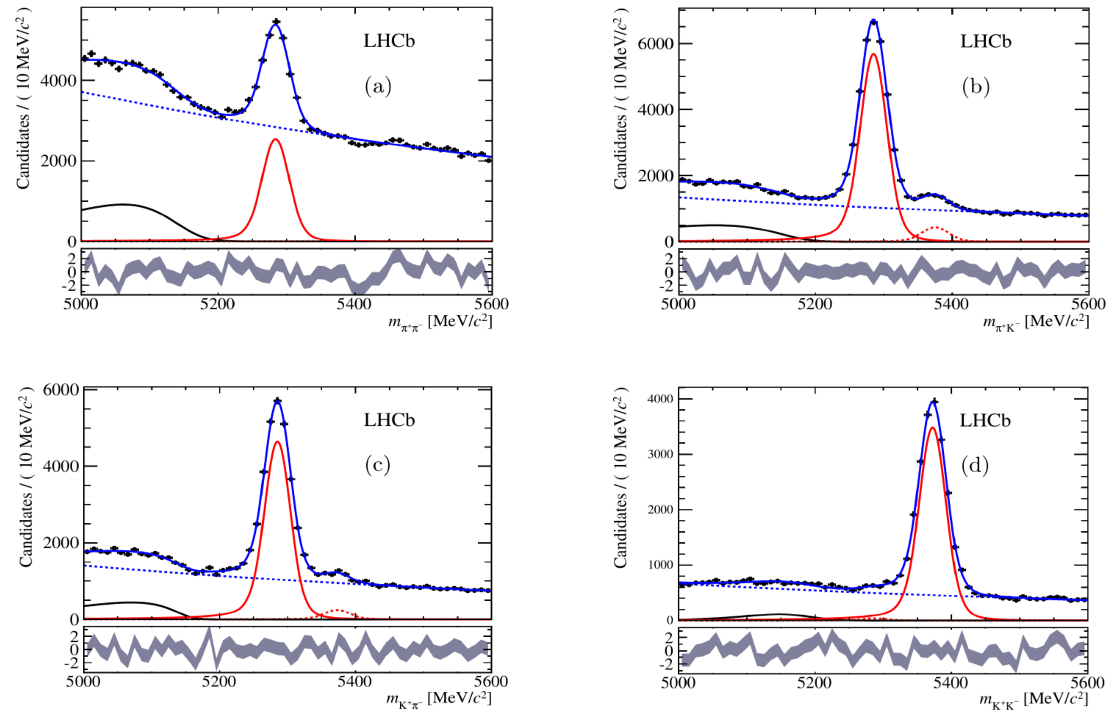


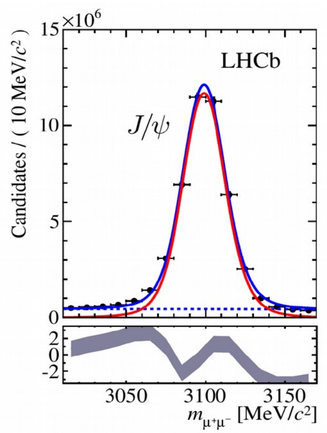
- **BDT trained on simulated events, calibrated on collision data using**
  - charmless hadronic two-body B decays $B^0_{(s)} \rightarrow \pi^+\pi^-, \pi^+K^-, \pi^-K^+, K^+K^-$ as proxy for signal
  - side-bands in invariant-mass distribution as proxy for background

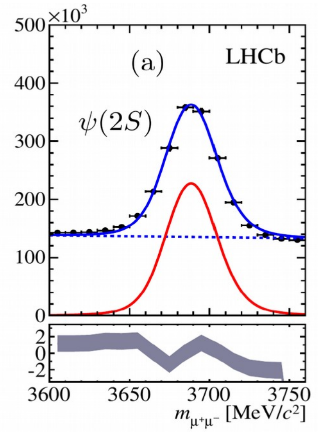


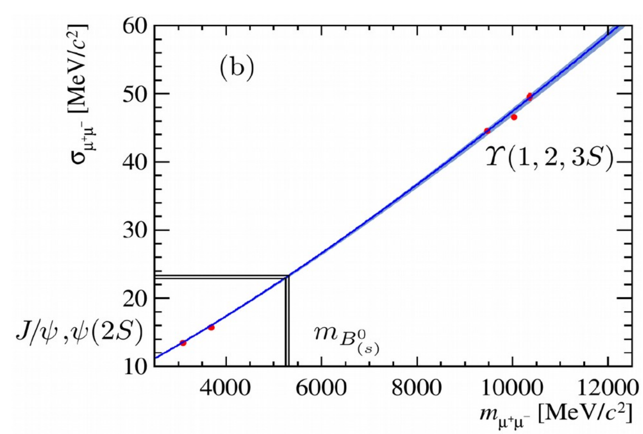
$B^0_{(s)} \to \mu^+\mu^-$

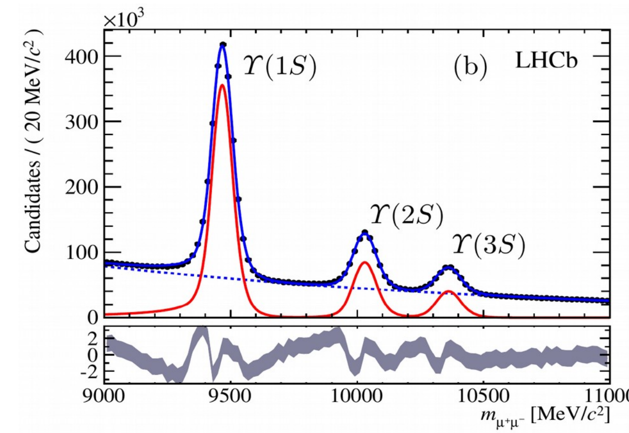
- **determine parameters of expected $B^0_{(s)} \to \mu^+\mu^-$ invariant-mass distribution from collision data**
  - expected mean from charmless hadronic two-body decays
  - expected width from charmless hadronic two-body decays and from interpolation between ψ(ns) and ϒ(ns) resonances









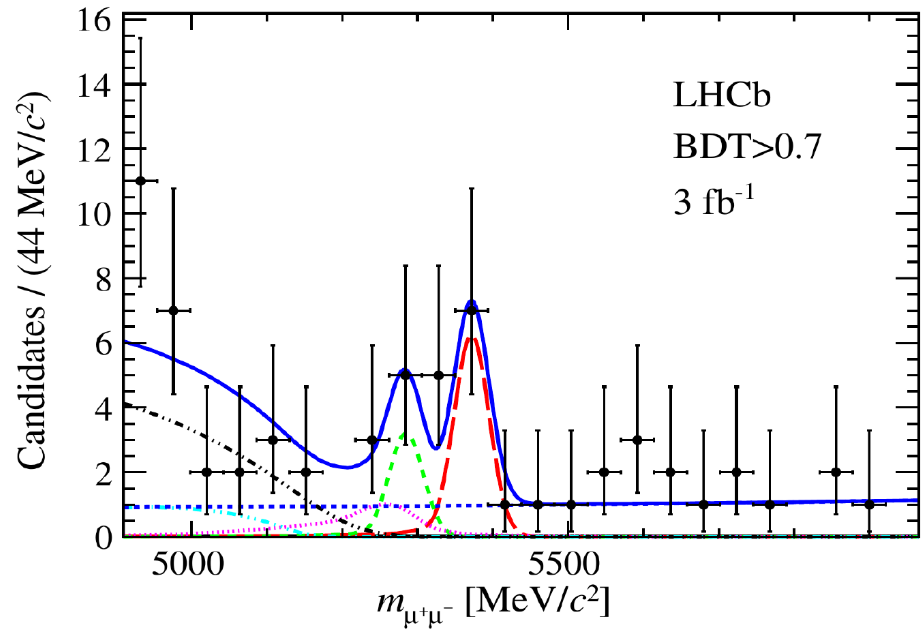


[PhD thesis C. Elsasser, Universität Zürich]

$B^0_{(s)} \to \mu^+\mu^-$

- **fit model considered background components from**
  - combinatorial background
  - charmless hadronic two-body decays
  - $B \to \pi\mu^+\mu^-$, $B^0 \to \pi^-\mu^+\nu_\mu$, $B^0_s \to K^-\mu^+\nu_\mu$
- **determine branching fraction relative to**

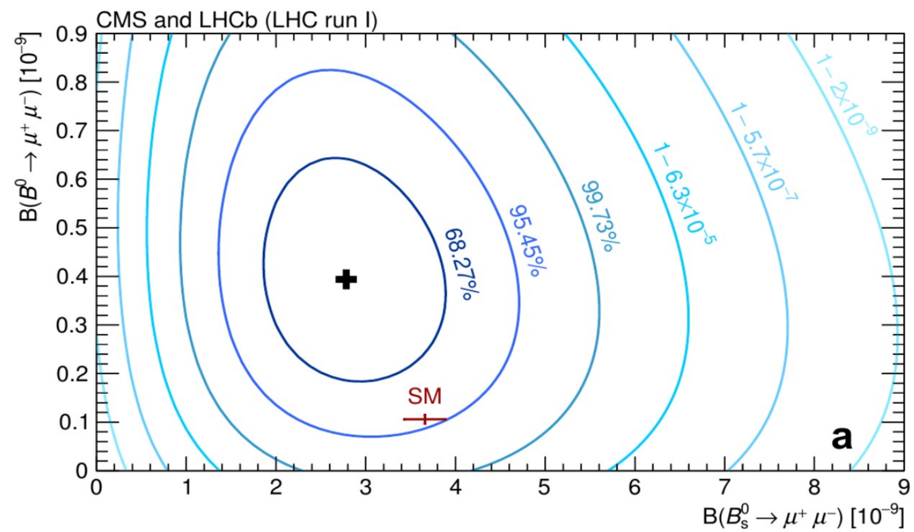
  $B^0 \to K^+\pi^-$ **and** $B^\pm \to J/\psi\, K^\pm$



- **combination with CMS measurement**

$$BF\,(B^0_s \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$
$$BF\,(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

[arXiv:1411.4413]



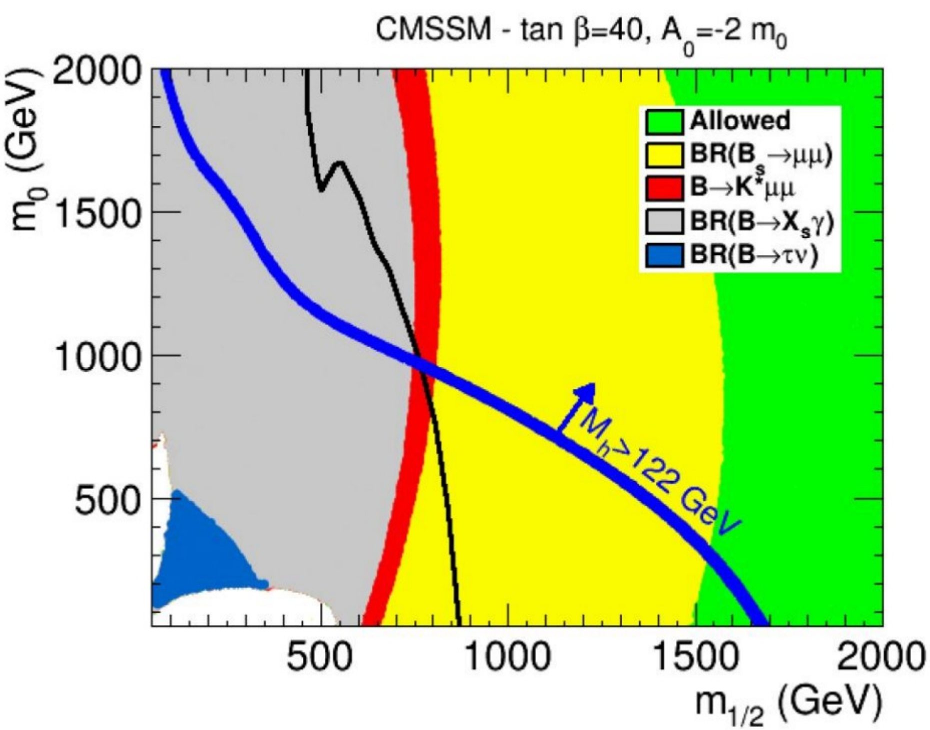
- **$B^0_s \to \mu^+\mu^-$ agrees with Standard Model**
- **$B^0 \to \mu^+\mu^-$ 2.2 σ above Standard Model**

Dear Author,

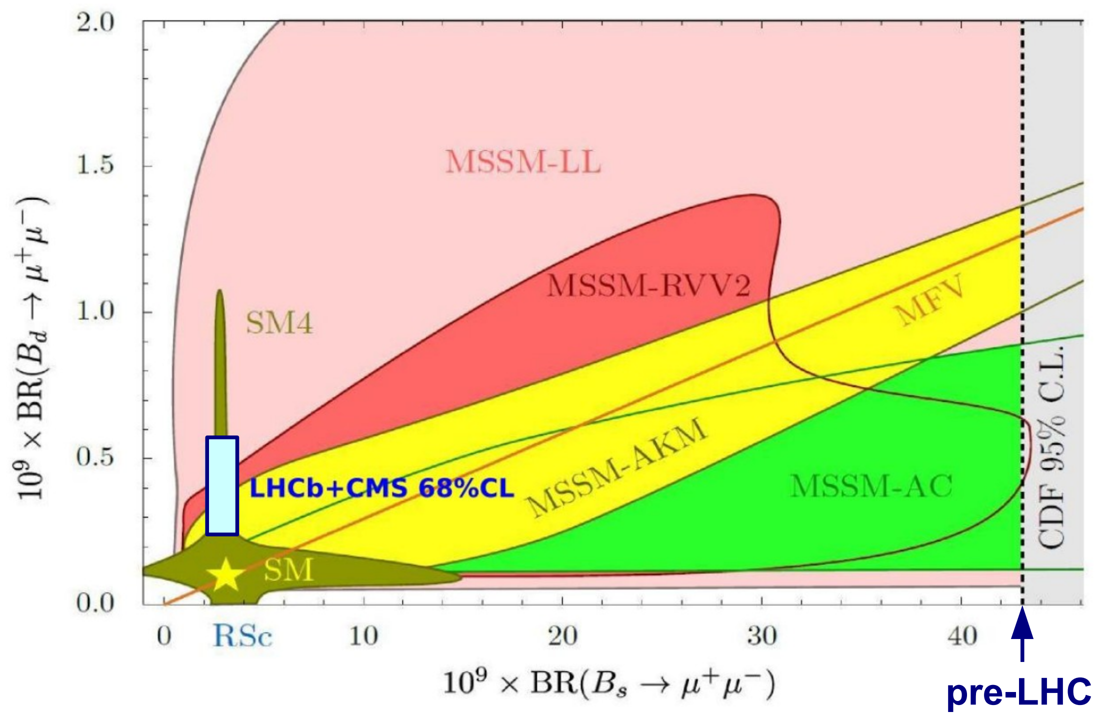
We are pleased to inform you that your paper entitled 'Observation of the rare Bs->mu+mu- decay from the combined analysis of CMS and LHCb data' has been featured in this week's press release for /Nature/. A copy of the press release entry about your paper, which has already been distributed to the media, is included below for your interest and to assist you if you receive any enquiries from journalists.

You may redistribute this press release to your coauthors and press officers of your and your coauthors' institutions and funders, but you must ensure that they are aware that the content of the press release and paper is embargoed until 1800 London time / 1300 US Eastern Time on 13 May 2015, and that distribution beyond these recipients must wait until after that time. You and your coauthors are free to discuss your work with the media before then, but we ask you to ensure that /Nature's/ embargo conditions are understood in each case, and to remind journalists to specify /Nature/ as the source of their information in any material they produce as a result of receiving the press release.

- strong constraints on models of New Physics, in particular with large tan β



[EPJ C74(2014)2927]



modified from [NC C035N1(2012)249]

- next goal: precise measurement of the ratio of branching fractions

$$BF(B^0 \to \mu^+\mu^-) / BF(B^0_s \to \mu^+\mu^-)$$

- test of minimal flavour violation

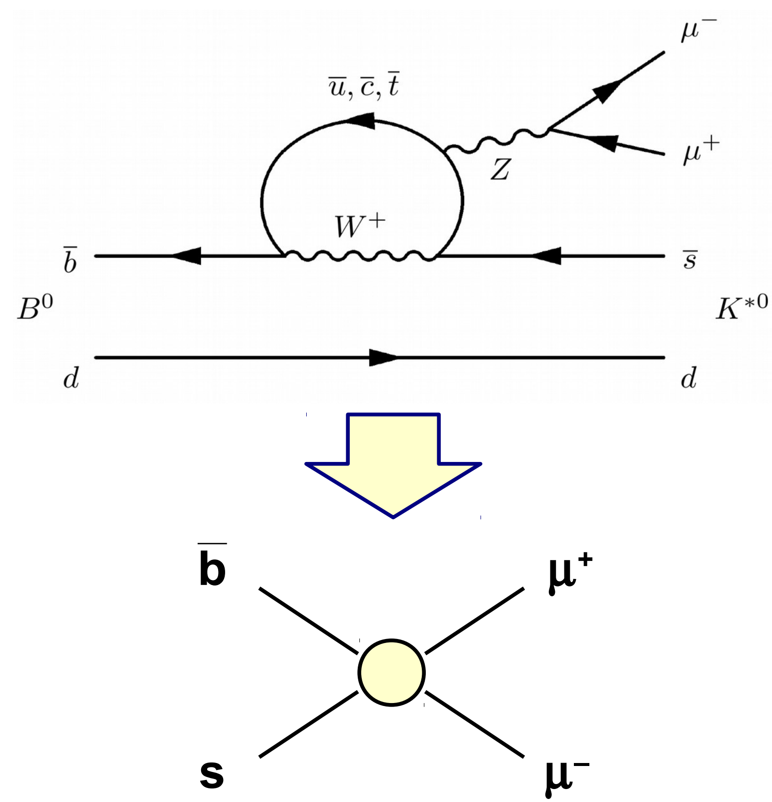
Overview

- **short motivation & introduction of the LHCb experiment**
- **(small) selection of highlights from run I**
  - CKM angle γ from $B^{\pm} \rightarrow D K^{\pm}$ tree decays
  - CP violating phase ϕ_s from $B^0_s \rightarrow J/\psi \phi$
  - branching fraction of $B^0_s \rightarrow \mu^+ \mu^-$
  - angular distributions in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - electroweak boson production in the forward direction
- **challenges and prospects for run II**
- **the LHCb upgrade**

"core" physics programme (the first four sub-items)

Angular Observables in $B^0 \to K^{*0} \mu^+ \mu^-$

- **another Flavour-Changing Neutral Current decay mediated by loop diagrams**
  - physics beyond Standard Model can affect angular distributions of final-state particles



- **theoretical treatment: effective Hamiltonian**

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

  - operators O_i: non-perturbative long-distance effects
  - Wilson coefficients C_i: perturbative short-distance effects

} factorization scale μ

- **$B^0 \to K^{*0} \mu^+ \mu^-$ dominated by O_9 µ $(\bar{b}s)_{V\text{-}A}(\mu^+\mu^-)_V$ and O_{10} µ $(\bar{b}s)_{V\text{-}A}(\mu^+\mu^-)_A$**
- **physics beyond Standard Model can affect the values of Wilson coefficients (C_9 , C_{10}) or add contributions from other operators (e.g. $O_9{}'$)**

Angular Observables in $B^0 \to K^{*0} \mu^+ \mu^-$

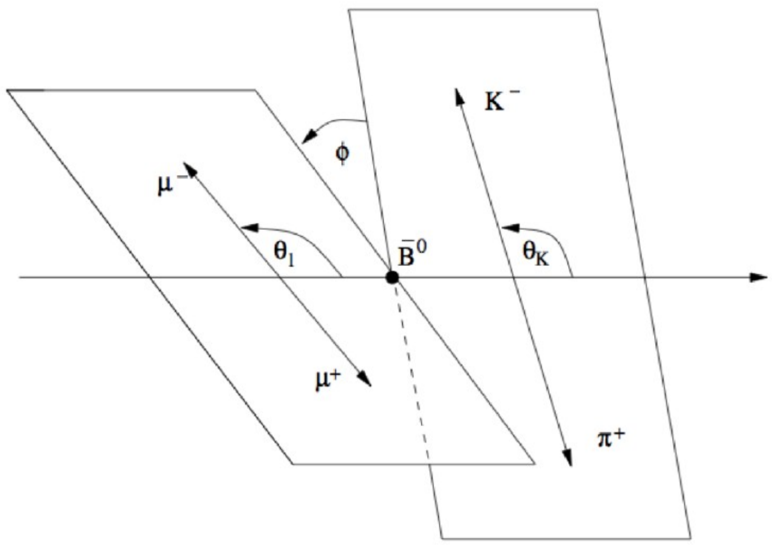
- **four final-state particles → three decay angles (θ_K, θ_ℓ, ϕ)**
- **angular distribution fully described by eight independent observables**

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- **$F_L(q^2)$ and $S_j(q^2)$ are functions of the underlying Wilson coefficients**
- **but uncertainties from hadronic form factors**
- **define combinations of F_L and S_j in which form factors cancel to leading order, e.g.**

$$P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[JHEP 1305(2013)137]

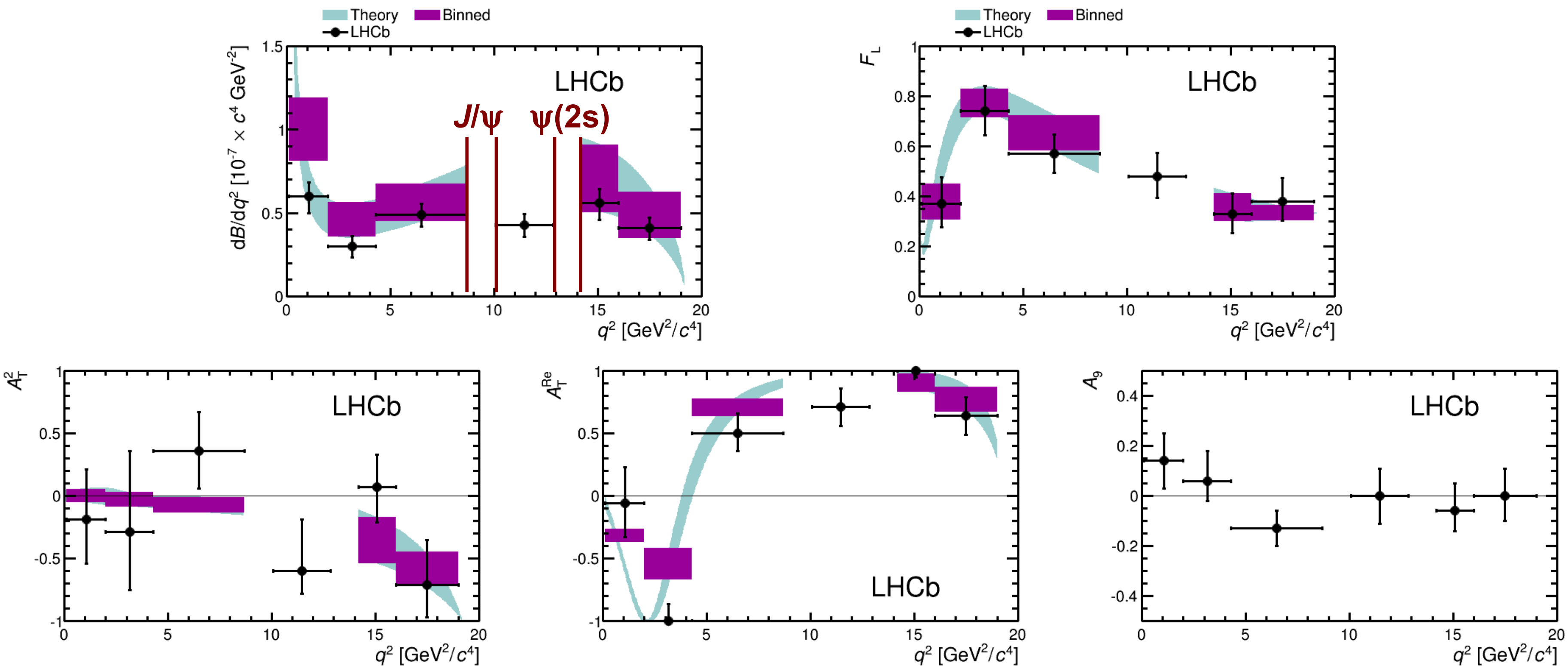


$B^0 \to K^{*0} \mu^+ \mu^-$ at LHCb – round I

- **first LHCb measurement based on 2011 data set** (1 fb^{-1})
- **statistics not sufficient for full 8-dim fit → apply "folding technique" exploiting symmetries of sin and cos functions to extract subsets of the observables**

e.g. substitute $\phi \to \phi + \pi$ for $\phi < 0$ $\Rightarrow$ terms containing S_4, S_5, S_7, S_8 cancel

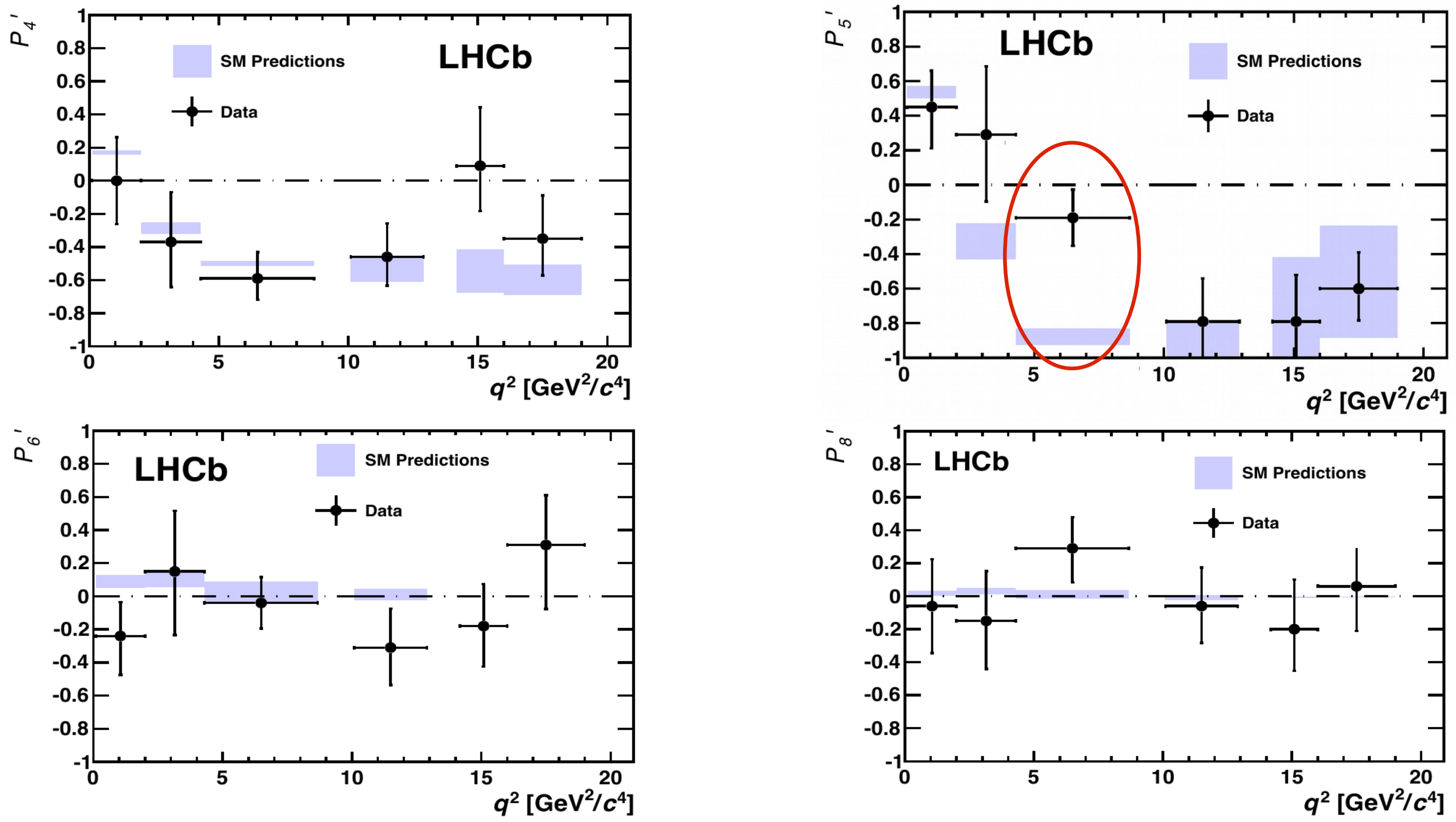
- **results in good agreement with Standard Model predictions**



[JHEP 1308(2013)131], **Standard Model prediction from** [JHEP 07(2011)067]

$B^0 \to K^{*0} \mu^+ \mu^-$ at LHCb – round II

- **second LHCb measurement, also based on 2011 data set** (1 fb^{-1})
- **apply different angular foldings to extract the remaining four observables**
- **observe large discrepancy** (3.7 σ) **in one bin of the observable P_5'**
  - probability for observing deviation ≥ 3.7 σ in one out of 24 analysed bins is 0.5 %

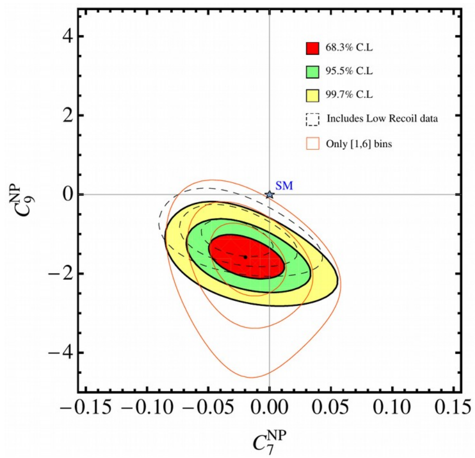


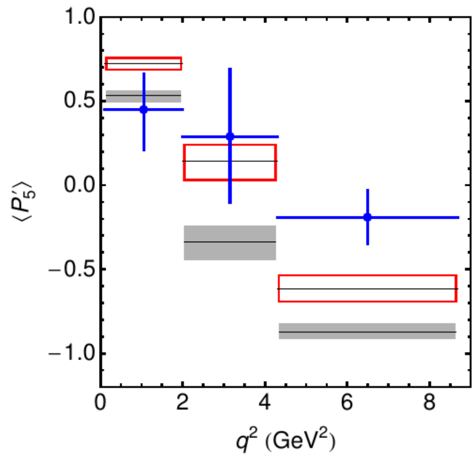
[PhD thesis M. De Cian, Universitaet Zuerich]

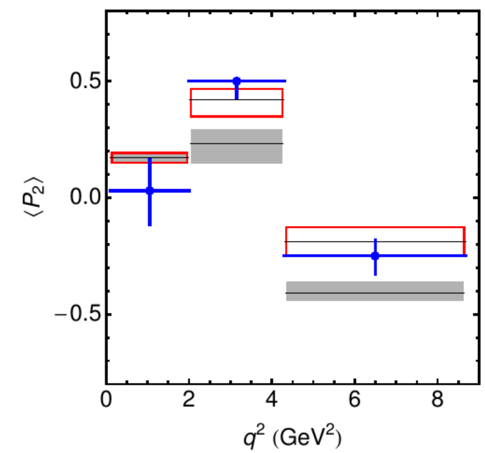
[PRL 111(2013)191801] , **Standard Model prediction from** [JHEP 05(2013)137]

$B^0 \to K^{*0} \mu^+ \mu^-$ – what theorists say

- **possible sign for New Physics contribution in Wilson coefficient C_9 ?**
  - yields slight improvement also in other observables (e.g. P_2)



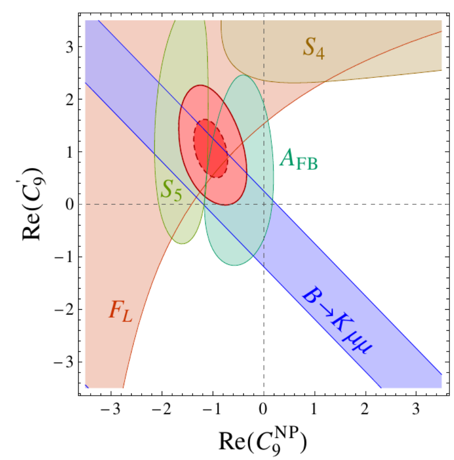




[PRD 88(2013)074002]

- **combined fits to LHCb results and measurements from other experiments also seem to hint at possible New Physics contribution in C_9 and C_9' or C_{10}'**
  - explicit interpretations in terms of a Z' (mass > 7 TeV)

[PRD 84(2011)115006] [JHEP 11(2014)121] [PRD 89(2014)095033]



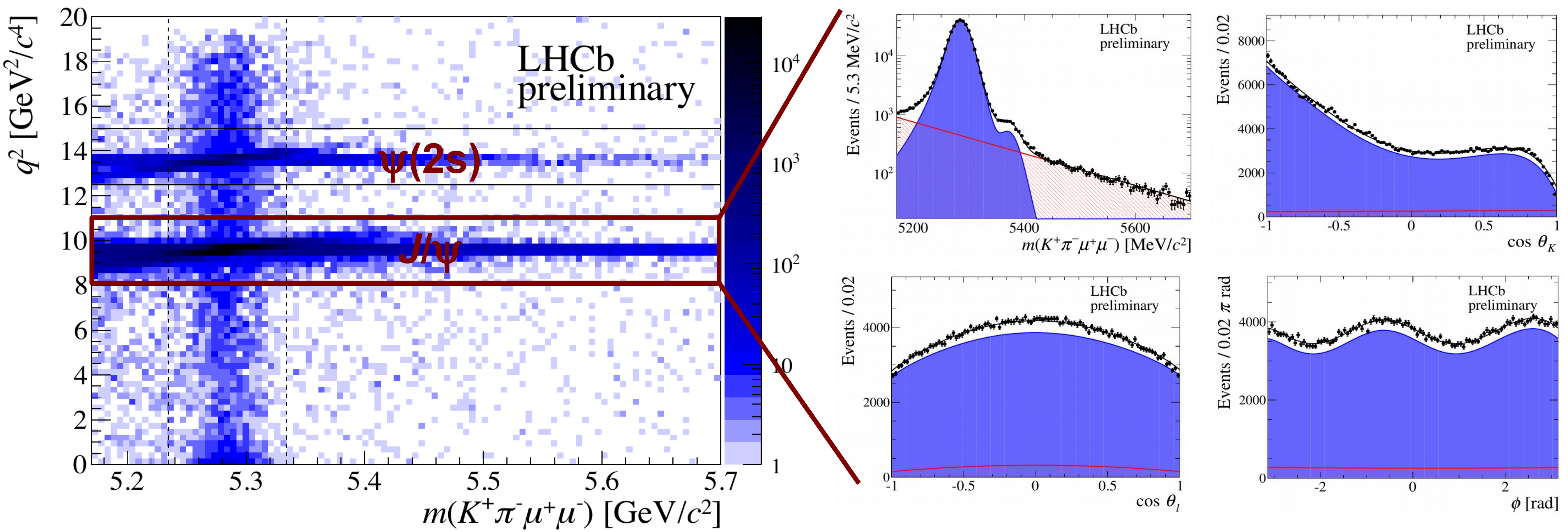
[EPJ C73(2013)2646]

- **or larger uncertainties due to QCD effects than assumed?**
  - e.g. Standard Model predictions neglect virtual $c\bar{c}$ loops

[arXiv:1406.0566]

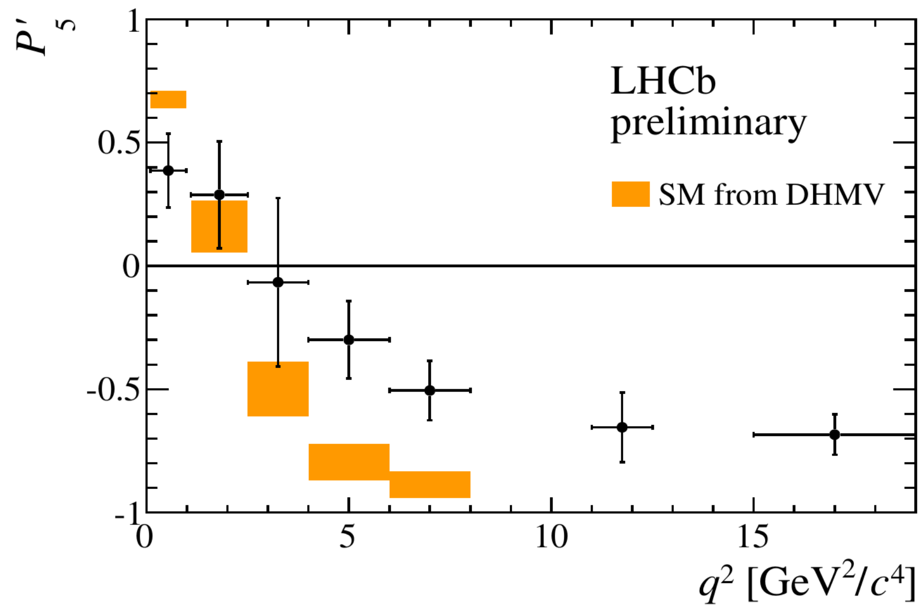
$B^0 \to K^{*0} \mu^+ \mu^-$ at LHCb – round III

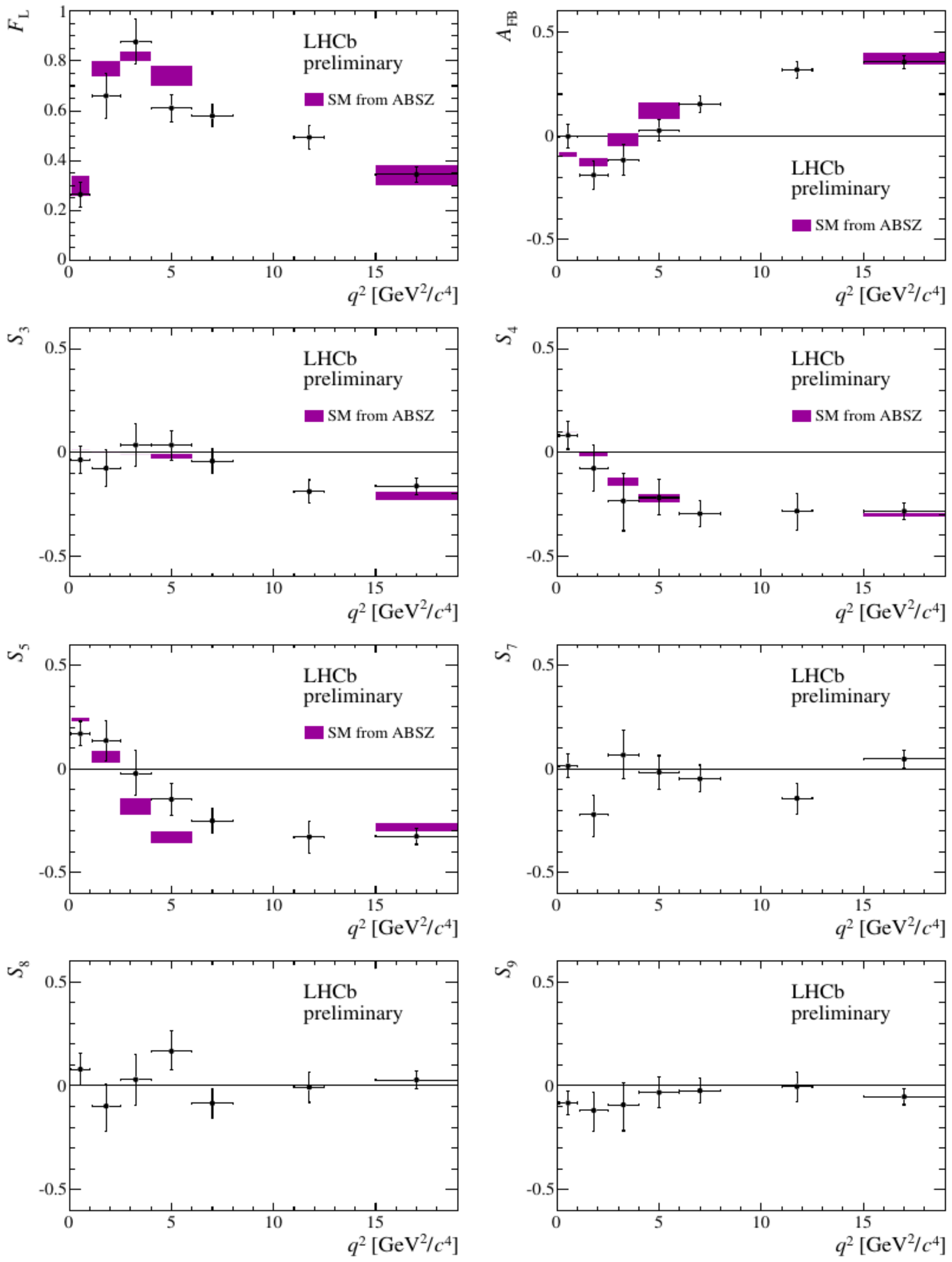
- **Moriond 2015: update using full run-I data set** (3 fb^{-1}) [LHCb-CONF-2015-002]
- **finer q^2 binning, simultaneous fit in all eight angular observables**
  - obtain full correlation matrix between observables (correlations found to be small)
- **include additional terms for non-resonant $K\pi$ S-wave**
- **as in previous analyses, use high-statistics control sample of $B^0 \to J/\psi K^{*0}$ to verify analysis procedure, in particular angular acceptance correction**



$B^0 \to K^{*0} \mu^+ \mu^-$ at LHCb – round III

- **new results consistent with the earlier LHCb measurements**
  - in particular, discrepancy from Standard Model in P_5' is confirmed
  - significance again 3.7 σ





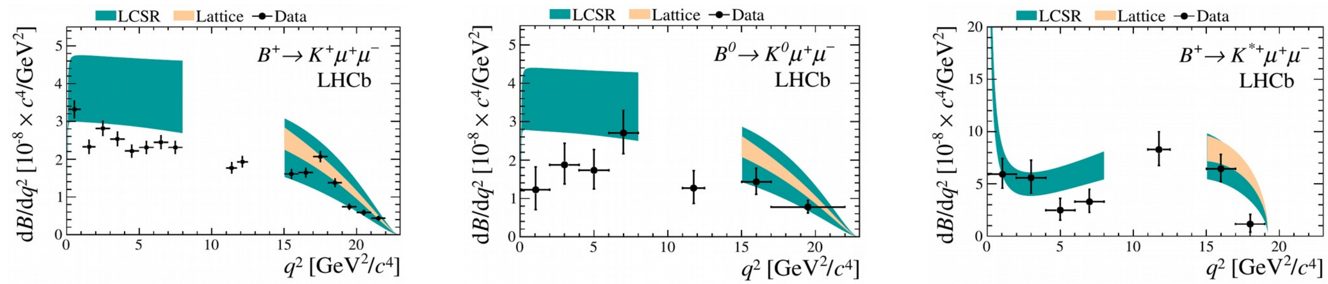
- **publication in preparation …**

$B^0 \to K^{*0} \mu^+ \mu^-$ – related results

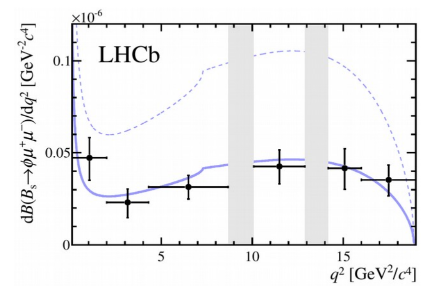
- **measurements of differential branching fractions**
  - $B^+ \to K^+ \mu^+ \mu^-$
  - $B^0 \to K^0_S \mu^+ \mu^-$
  - $B^+ \to K^{*+} \mu^+ \mu^-$

  (3 fb^{-1})

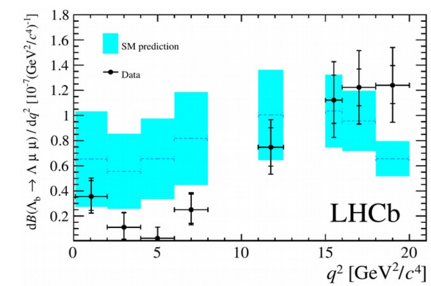
  - $\Lambda_b \to \Lambda \mu^+ \mu^-$ (3 fb^{-1})
  - $B^0_s \to \phi \mu^+ \mu^-$ (1 fb^{-1})



[JHEP 1406(2014)133]



[JHEP 1307(2013)084]



[arXiv:1503.07138]

- **tend to be lower than Standard Model**
  - but theory uncertainties not negligible

- **measurement of $R_K \equiv BF(B^+ \to K^+ \mu^+ \mu^-) / BF(B^+ \to K^+ e^+ e^-)$** [JHEP 0712(2007)040]

$$R_K = 0.745 \,^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}$$

(3 fb^{-1}, $1 < q^2 < 6$)

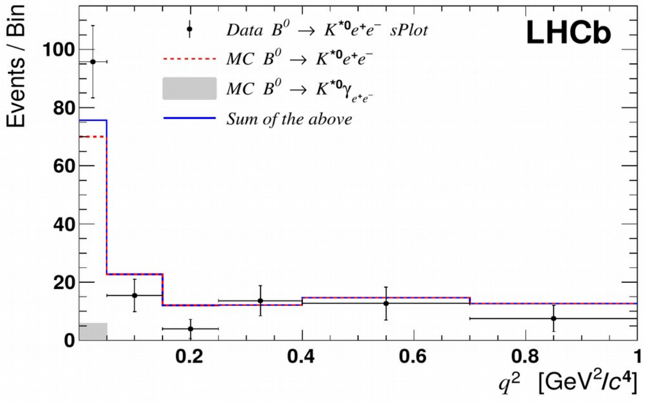
- **Standard Model prediction: $R_K = 1.0003 \pm 0.0001$** [PRL 113(2014)151601]

- **2.6 σ deviation $\to$ violation of lepton universality ???**

$B^0 \to K^{*0} \mu^+ \mu^-$ – related results

[JHEP 1504(2015)064]

- **angular analysis in $B^0 \to K^{*0} e^+ e^-$ (3 fb^{-1})**
  - $m_e < m_\mu \to$ can go to lower q^2 than in $K^{*0} \mu^+ \mu^-$
  - higher sensitivity to operator O_7 via $B^0 \to K^{*0} [e^+e^-]_\gamma$
  - but lower yields than in $K^{*0} \mu^+ \mu^-$
- **measure four of the angular observables at low q^2**
  - results agree with Standard Model predictions



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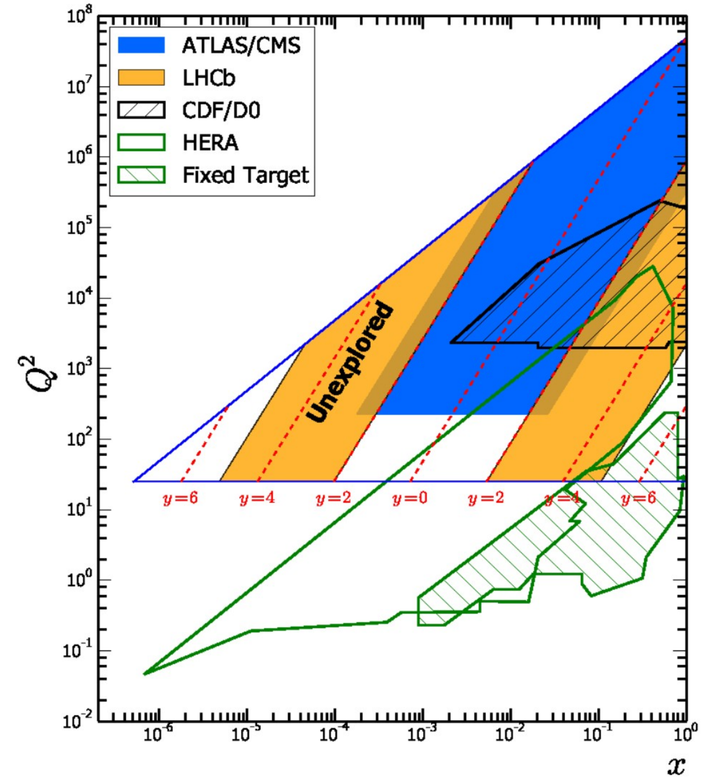
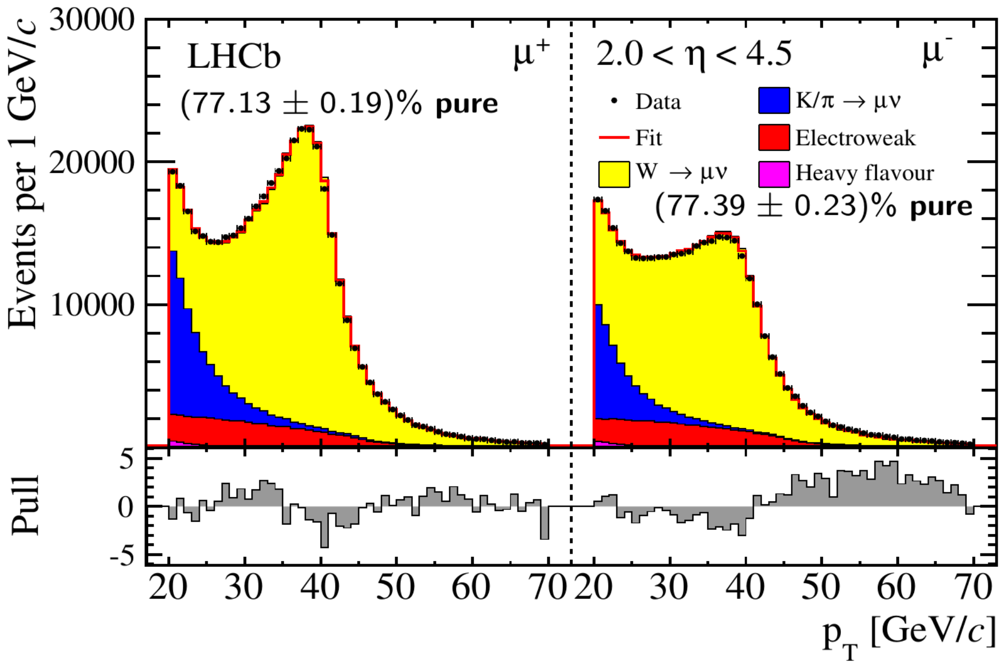
Z and *W* production in *pp* collisions

- **LHCb acceptance**

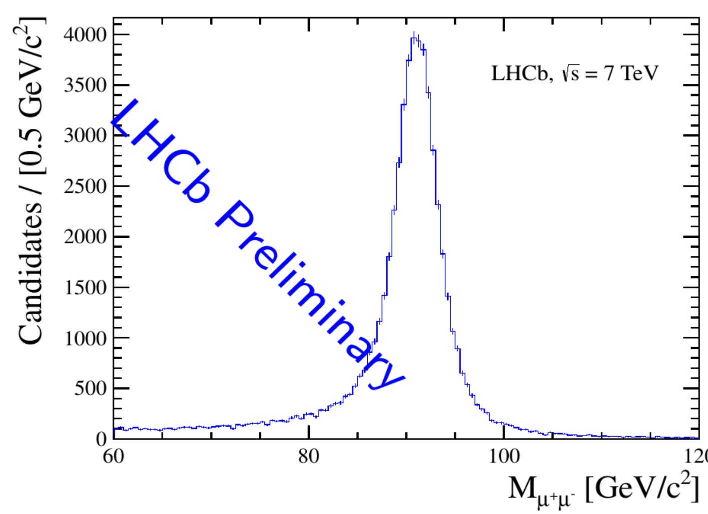
$2 < \eta < 4.5$

- **complementary to other experiments**
- **unexplored region in q^2, Bjorken-x**
- **potential to derive interesting constraints on parton density functions of the proton**



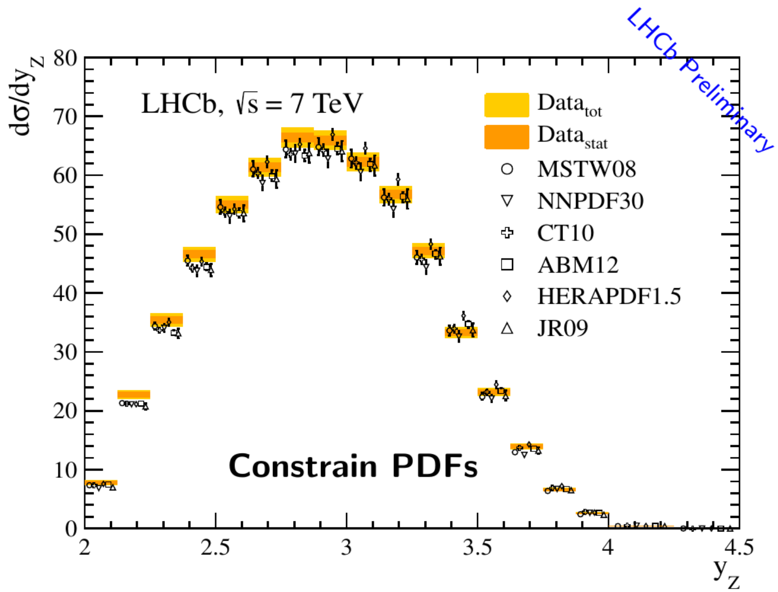


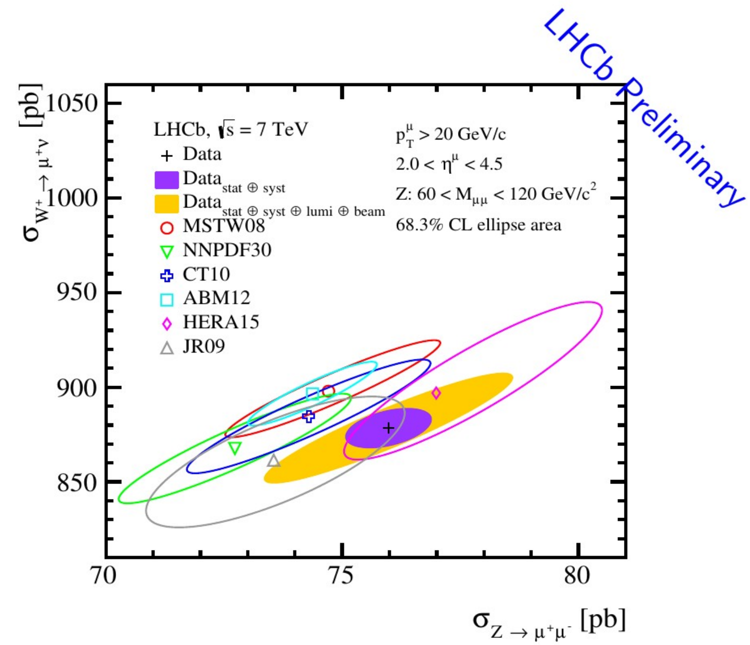
[JHEP 1412 (2014) 079]



[LHCb-PAPER-2015-001]

Electroweak Boson Production

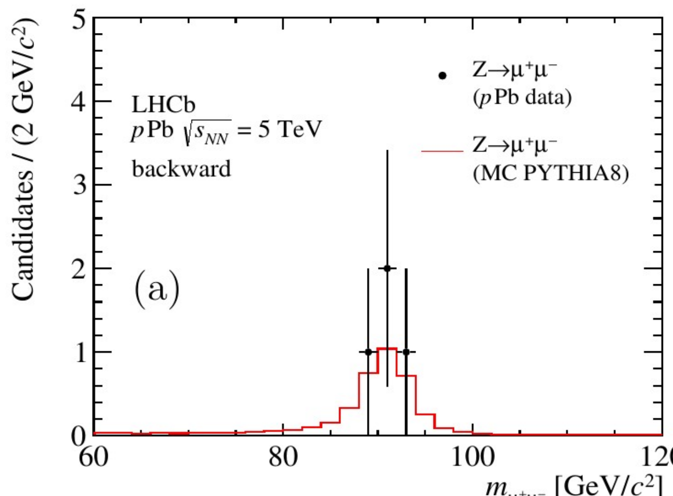


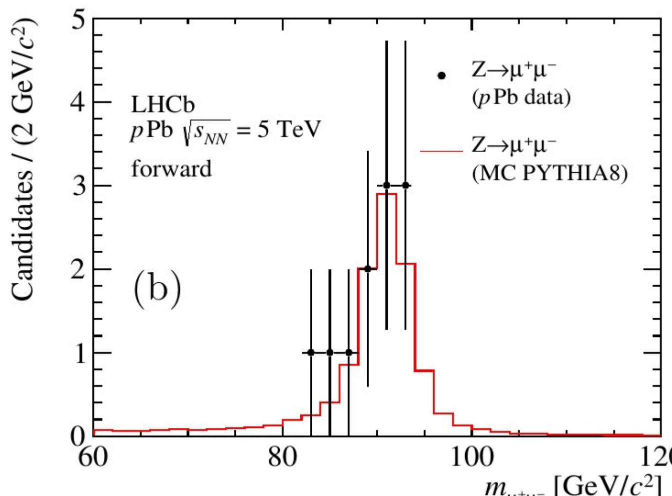


[LHCb-PAPER-2015-001]

- **also: *Z* + jet, *Z* + *b*-jet**
- **also: *Z* production in *p-Pb* and *Pb-p***

[JHEP 1409(2014)030]





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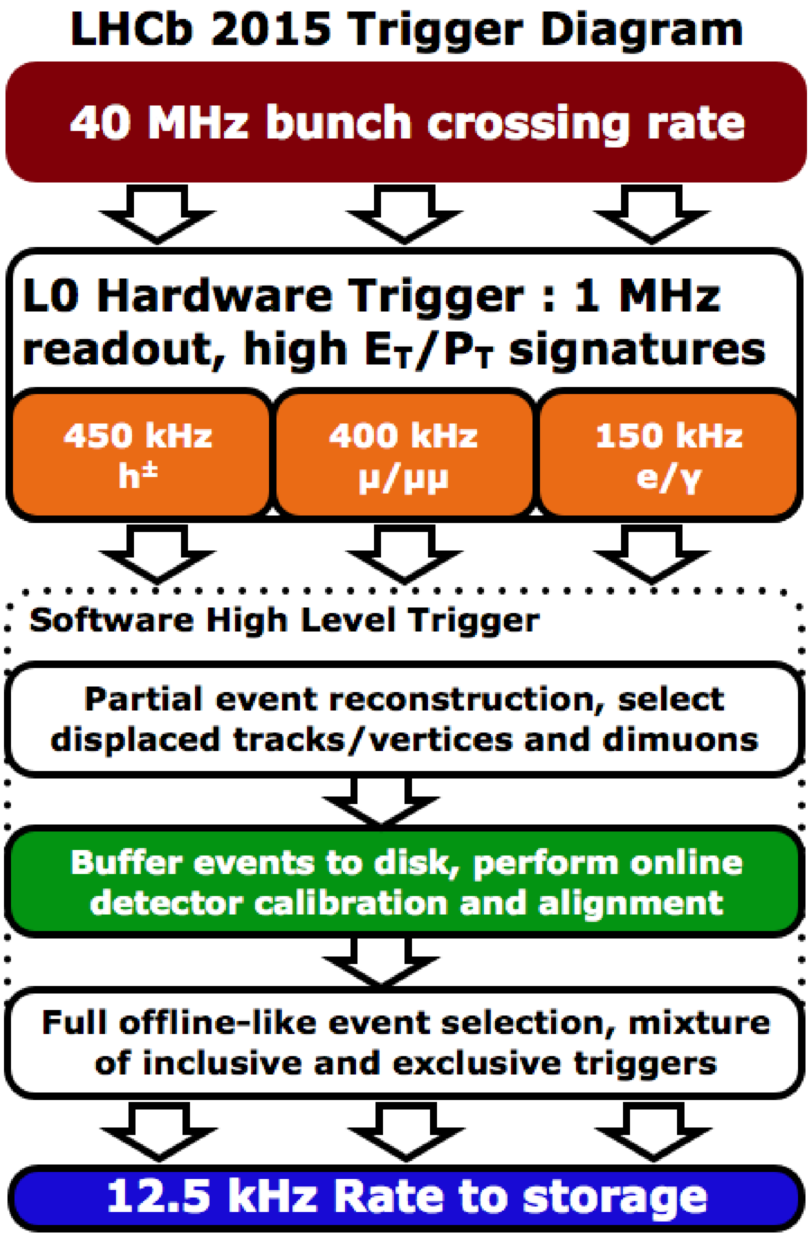
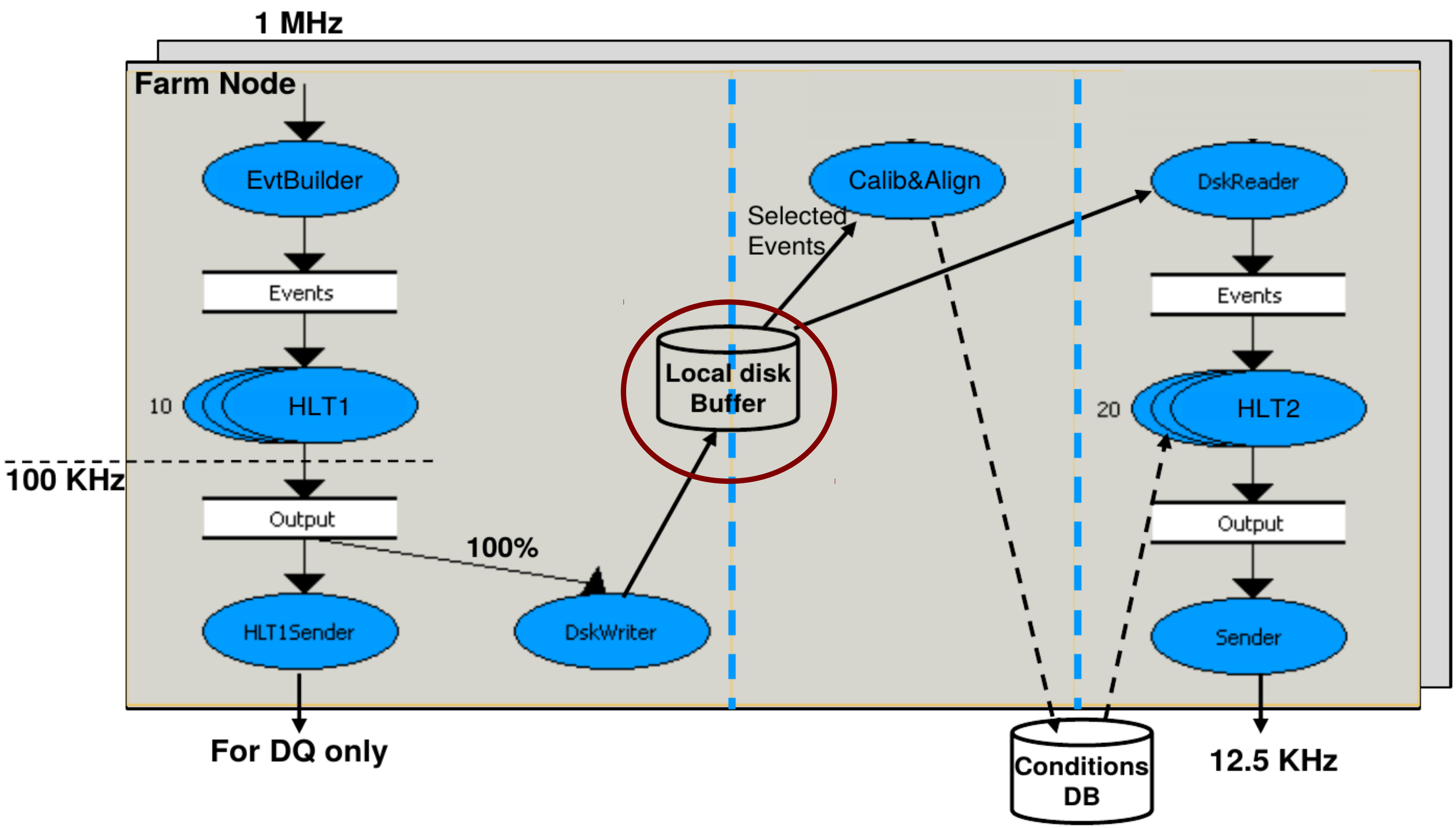
- the LHCb upgrade

Run II: "Split HLT"

- no major hardware changes in LS1
- but new trigger concept: "split HLT"
  - run only first stage of software trigger (HLT1) synchronous with collisions
  - store all accepted events on local disks
  - use a subset of these data to perform quasi-online calibration and alignment
  - apply full event reconstruction and second-level software trigger algorithms (HLT2) using updated constants
  - allows to use the same calibration/alignment constants in HLT2 as in offline reconstruction
  - allows to employ RICH particle identification information in HLT2 algorithms
- additional advantage: use resources of the HLT computer farm also when no collisions



Run II: "Split HLT"



- **local disk buffer: 12 PB** (12×10^{15} byte)**, about half of which can be used**
- **average event size 70 kB**
- **HLT accept rate 100 kHz**

- can buffer 10^6 sec worth of data
- assuming LHC efficiency of 30 %, this corresponds to data from ≈ 38 days of operation !

Run II: New Challenges

- **changing operating conditions for run II may require re-adjustment of some detector operation parameters**
- **collision energy 8 TeV → 13 TeV**
  - expect higher particle densities per collision
- **bunch spacing 50 ns → 25 ns**
  - need less "pile-up" (average number of *pp* collisions per bunch crossing) to achieve the same luminosity
  - but more "spill-over" (signal remainders from interactions in the previous bunch crossing) in some detectors
- **to be tested as soon as we get collisions at 13 TeV / 25 ns**
- **biggest challenge (in my view):**
  - **(re-)train shift crews and detector experts after > 2 year break**
  - **many important people on temporary contracts, have left or moved on**

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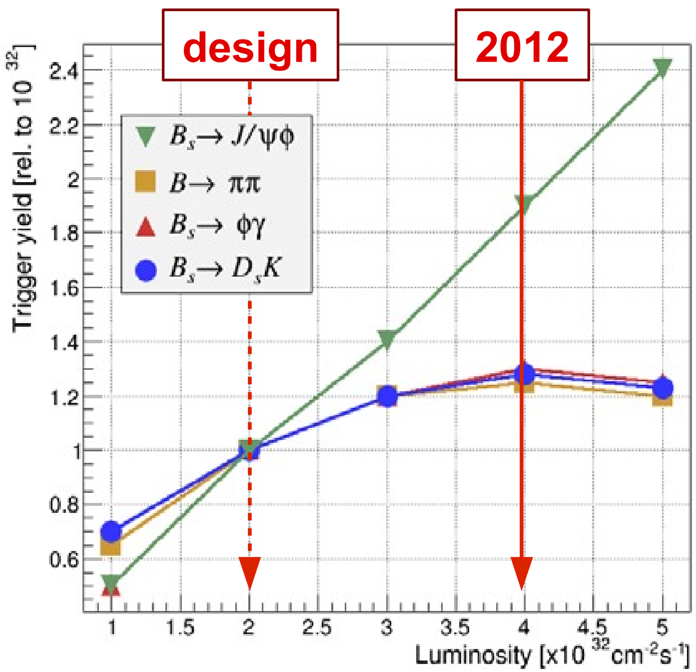
Motivation

- **current precision of measurements in the flavour sector still leaves ample room for sub-dominant contributions from New Physics**
- **almost all LHCb results are completely dominated by statistical uncertainties**
  - leading systematic uncertainties will in many cases also decrease with increasing statistics
- **assuming a total of 8 fb^{-1} by the end of run 2, it will then take another ≈ 15 years at current rate to quadruple statistics and halve uncertainties**
- **LHCb upgrade for LS 2:**
  - **operate at up to 5× higher luminosity**
  - **increase trigger efficiencies for hadronic final states, read out full detector at LHC bunch-crossing frequency**

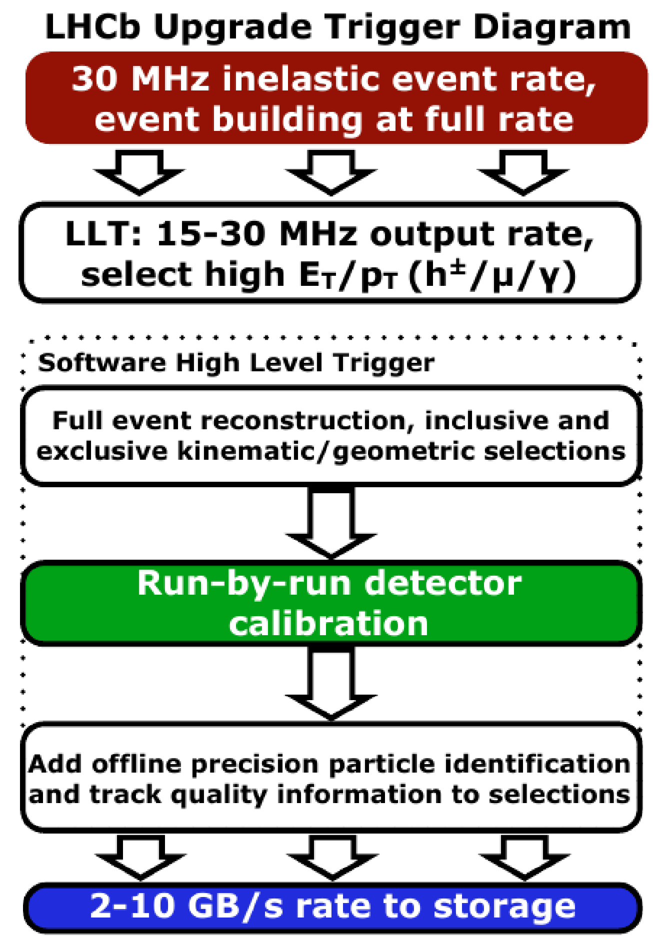
2010	**run 1**	**0.037 fb^{-1} @ 7 TeV**
2011		**1 fb^{-1} @ 7 TeV**
2012		**2 fb^{-1} @ 8 TeV**
2013	**LS 1**	minor maintenance work
2014		
2015	**run 2**	**5 fb^{-1} @ 13 TeV**
2016		
2017		
2018	**LS 2**	**LHCb upgrade**
2019		
2020	**run 3**	**15 fb^{-1} @ 14 TeV** with increased trigger efficiency
2021		
2022		
2023	**LS 3**	**?**
2024		
2025		
2026 ++	**run 4**	**5 fb^{-1} / y @ 14 TeV**

Trigger Upgrade

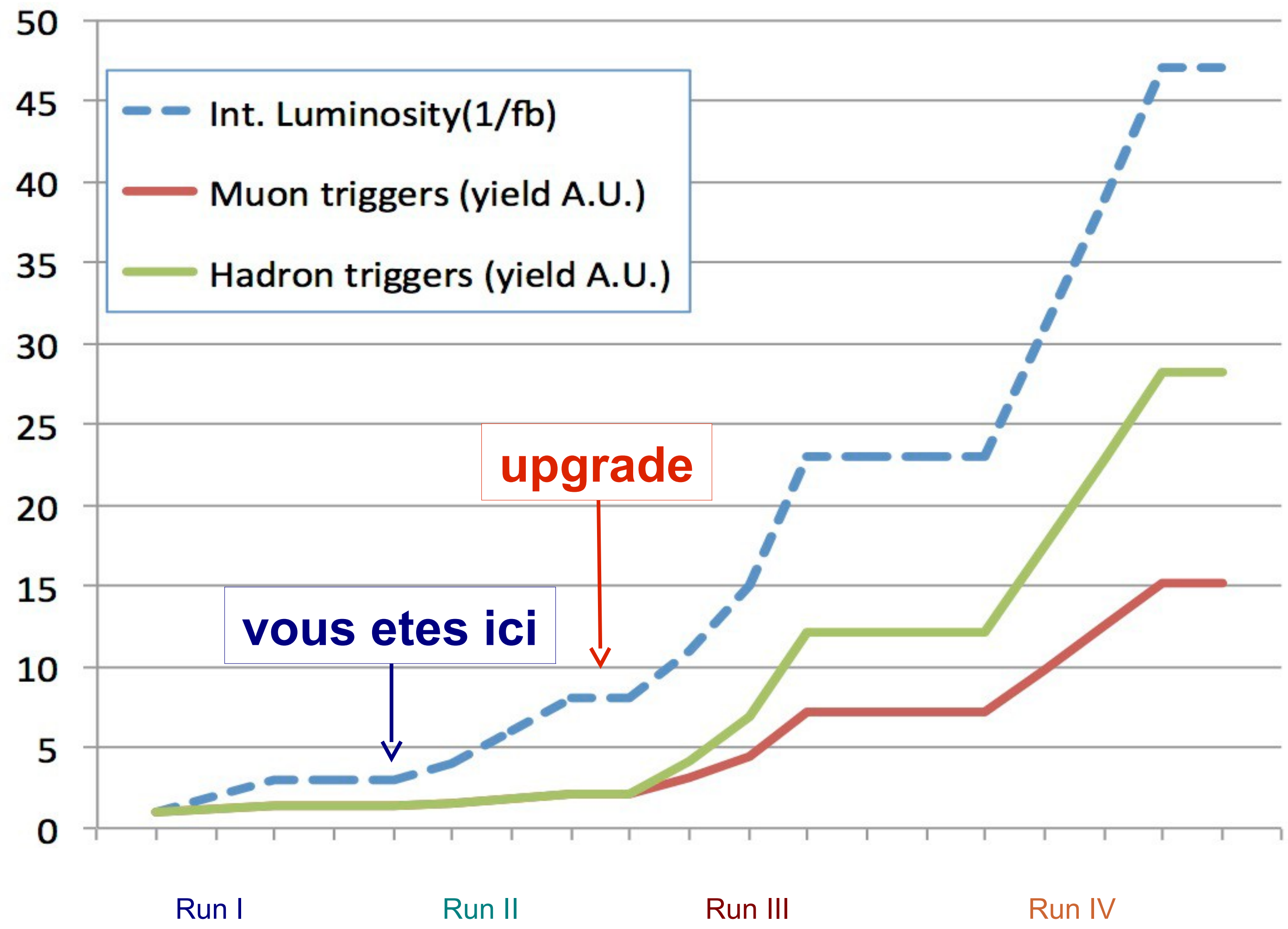
- to collect 5 fb^{-1} / year: operate at up to 5 × higher instantaneous luminosity
- final states with muons: event yields scale linearly with luminosity
- fully hadronic final states: in current trigger scheme have to increase p_T thresholds to stay within 1 MHz limit of L0 trigger → no further gain in yield



readout full detector at 40 MHz
full software trigger with 20 kHz output rate



Estimated Yields



expected increase in yearly rate (compared to 2011)**:**

× 10 for channels involving final-state muons

× 20 for channels to fully hadronic final states

Physics

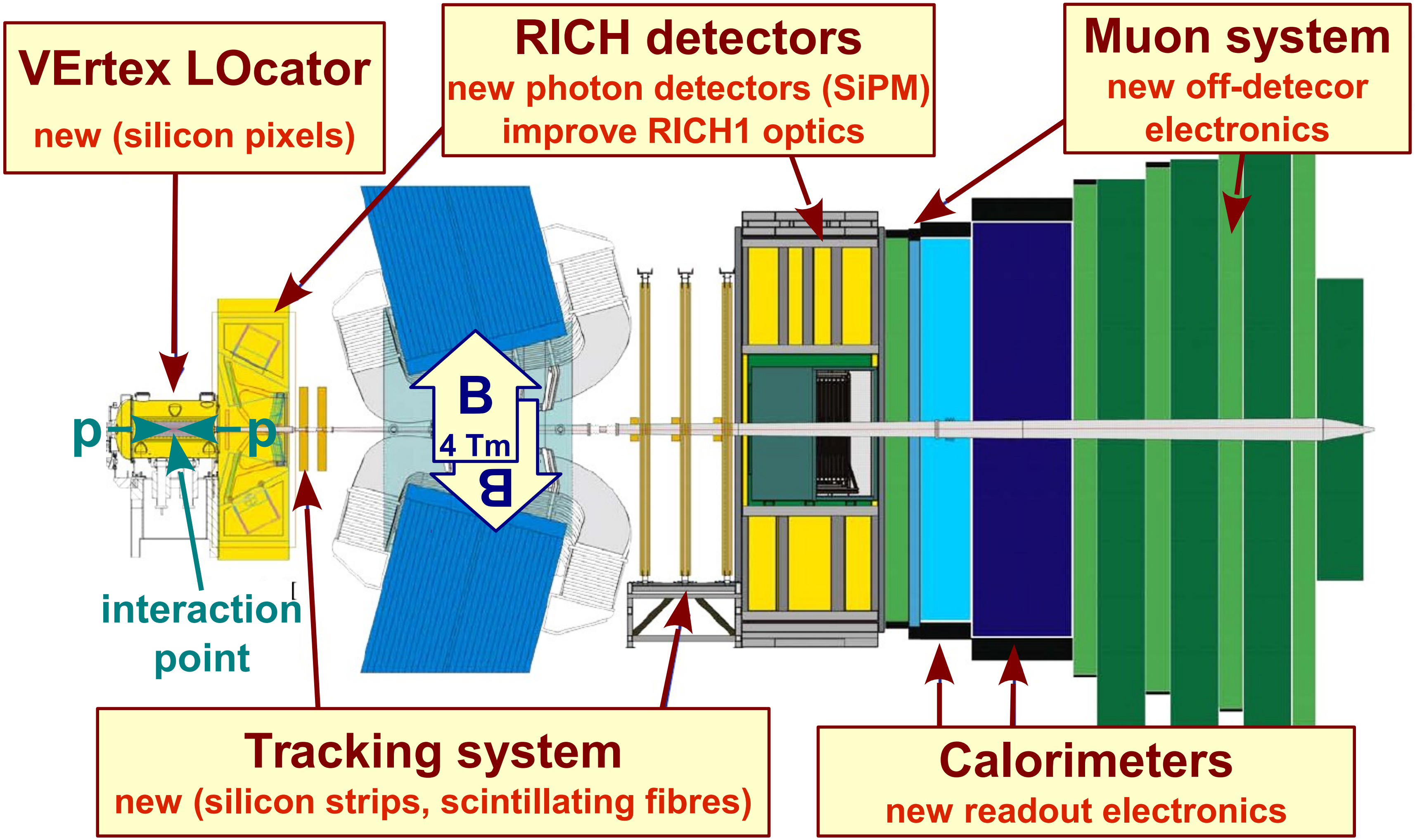
- with 50 fb^{-1}, approach theory uncertainties in key observables, e.g.:

	LHCb up to LS2		LHCb upgrade		Theory
	Run 1	Run 2	Run 3	Run 4	Theory uncertainty
Integrated lumi	$3\ fb^{-1}$	$8\ fb^{-1}$	$23\ fb^{-1}$	$46\ fb^{-1}$	
$\frac{Br(B_d \to \mu\mu)}{Br(B_s \to \mu\mu)}$	-	110 %	60%	40%	5%
$q_0^2 A_{FB}(B_d \to K^{*0}\mu\mu)$	10%	5%	2.8%	1.9%	7%
$\phi_s(B_s \to J/\psi\phi, B_s \to J/\psi\pi\pi)$	0.05	0.025	0.013	0.009	0.003
$\phi_s(B_s \to \phi\phi)$	0.18	0.12	0.04	0.026	0.02
γ	7°	4°	1.7°	1.1°	negl.
$A_\Gamma(D^0 \to KK)$	$3.4\ 10^{-4}$	$2.2\ 10^{-4}$	$0.9\ 10^{-4}$	$0.5\ 10^{-4}$	-

[M.H.Schune at "Heavy Flavour in the HL-LHC Era", Aix les Bains, 2013]

- also: reinforce LHCb as a general purpose forward detector for
  - electroweak boson production, lepton flavour violation, exotic searches, …

Detector Upgrade

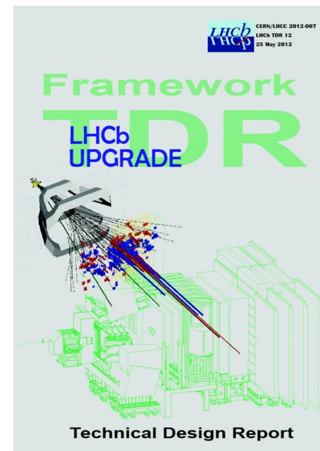


- **40 MHz readout → replace sub-systems with embedded front-end electronics**
- **5 × higher luminosity → adapt detector technology where needed to maintain excellent performance**

- upgrade effort is in full swing, all TDRs approved
- time line is tight as always, but confident to be ready for LS 2

[CERN-LHCC-2011-001]

⇒



[CERN-LHCC-2012-007]

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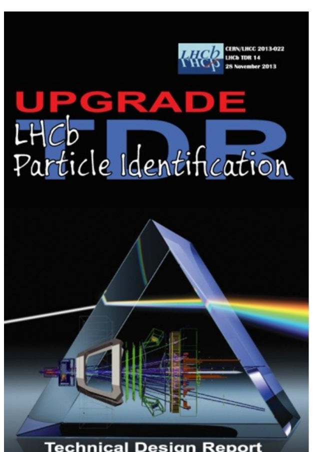
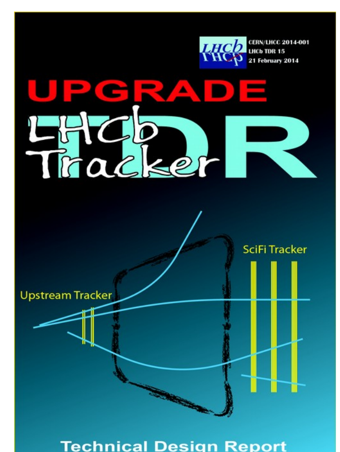


[CERN-LHCC-2013-001]

+

[CERN-LHCC-2013-021]

+



[CERN-LHCC-2014-001]

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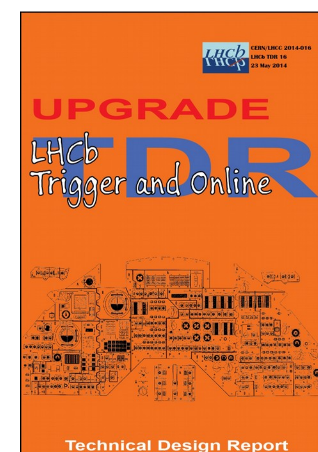
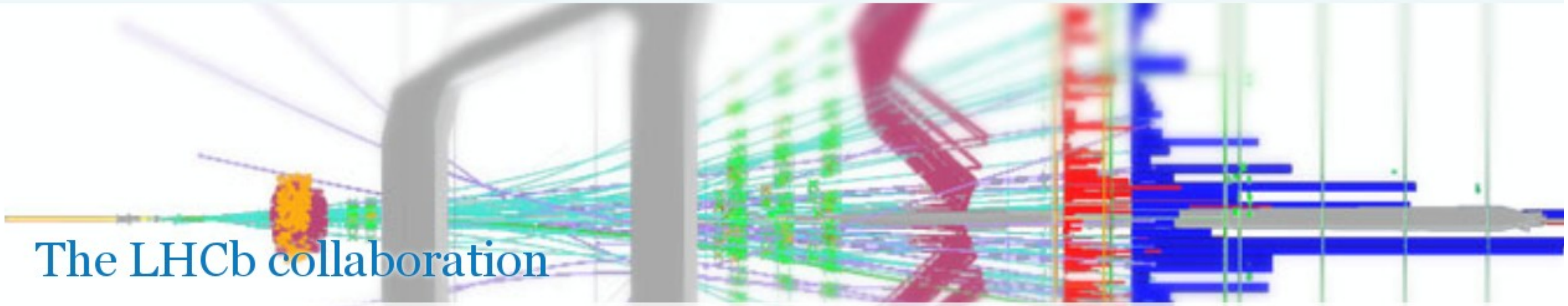


[CERN-LHCC-2014-016]



- LHCb Public Documents
- LHCb public site
- LHC pages
- Event display

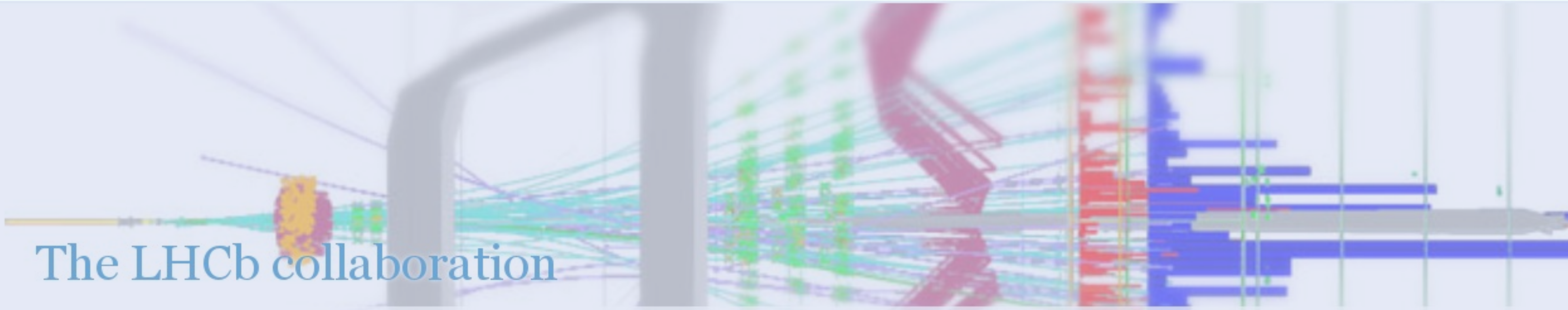
LHCB GROUPS

- QEE - QCD, Electroweak & Exotica
- B&Q - B hadrons & Quarkonia
- Charm - Charm physics
- RD - Rare decays
- B2CC - B decays to charmonia
- B2OC - B decays to open charm
- BNoC - Charmless B decays
- SLB - Semileptonic B decays
- FT - Flavour tagging
- Lumi - Luminosity

LHCb Papers

N°	Title	Journal	Code	Submit Date	Lead Group
256	Search for the decay $B^0_s\to\overline{D}^0f_0(980)$ Search for the decay $B_s^0 \to \overline{D}^{0} f_{0}(980)$	()	arXiv:1505.01654	08 May 2015	
255	Dalitz plot analysis of $B^0 \to \overline{D}^0 \pi^+\pi^-$ decays	()	arXiv:1505.01710	08 May 2015	
254	Identification of beauty and charm quark jets at LHCb	()	LHCB-PAPER-2015-016	30 Apr 2015	
253	Quantum numbers of the $X(3872)$ state and orbital angular momentum in its $\rho^0 J/\psi$ decays	()	LHCB-PAPER-2015-015	23 Apr 2015	

LHCb



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THANK YOU

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