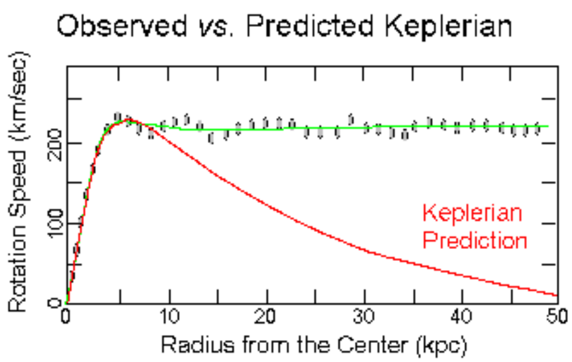
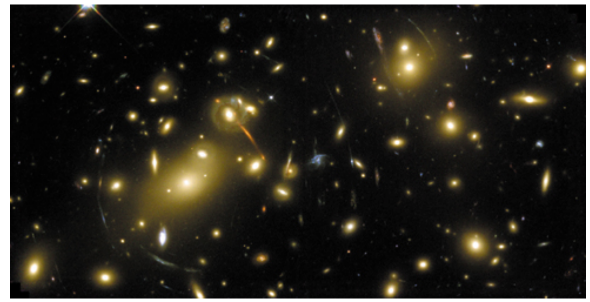
S. Stone
May 2, 2014

How technological innovations could influence the physics potential of b physics at hadron colliders

Reasons for Physics Beyond the Standard Model

- Dark Matter





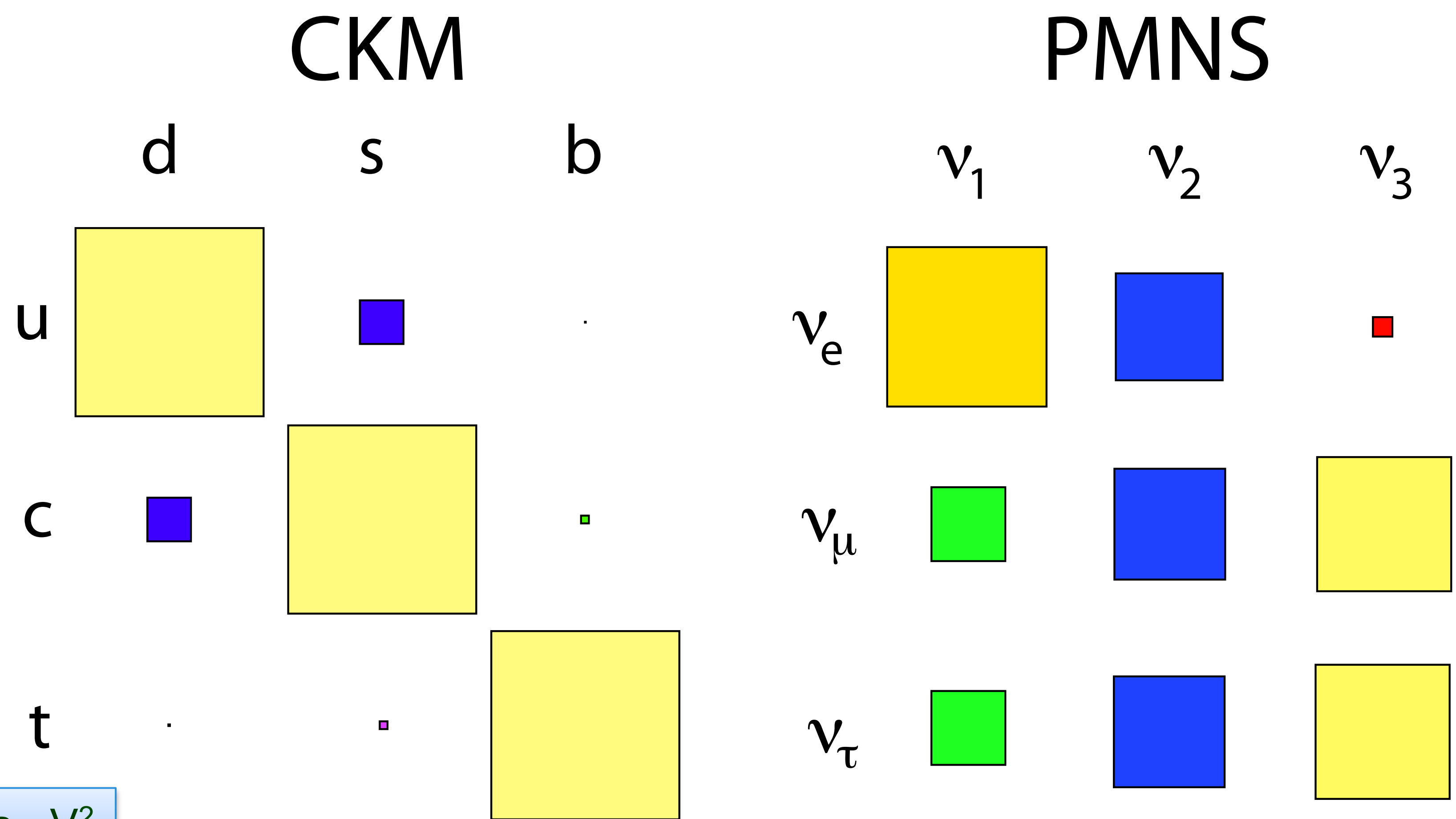
Gravitational lensing

- Dark Energy: Cosmological constant
- Hierarchy Problem: Divergent quantum corrections to go from Electroweak scale ~100 GeV to Planck scale of Energy $\sim 10^{19}$ GeV without "fine tuning" quantum corrections
- *All of the above may only be related to Gravity*

Other reasons for NP

- Flavor problem: Why 3 replications of quarks & leptons?
- Baryogenesis: The amount of CP Violation observed thus far in the quark sector is too small: $(n_B-n_{\bar{B}})/n_\gamma$ =~10^{-20} but ~6×10^{-10} is needed. Thus New Physics must exist to generate needed CP Violation
- To explain the values of CKM couplings, V_{ij}, (both neutrino & quark)
- To explain the masses of fundamental objects. Are they related to the V_{ij}'s?

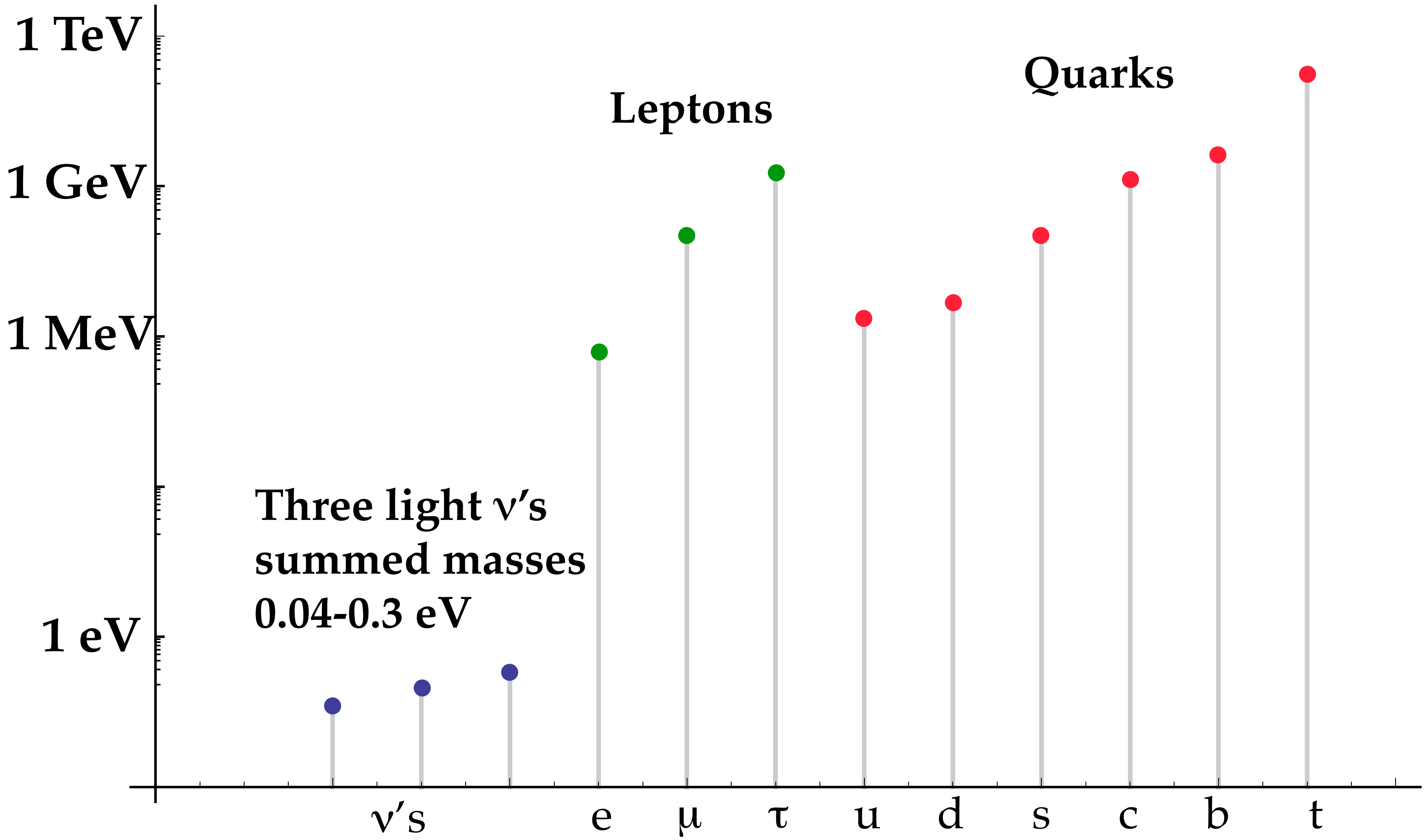
CKM vs. PMNS



Area ~V^2

Why these values? Are the two related? Are they related to masses?

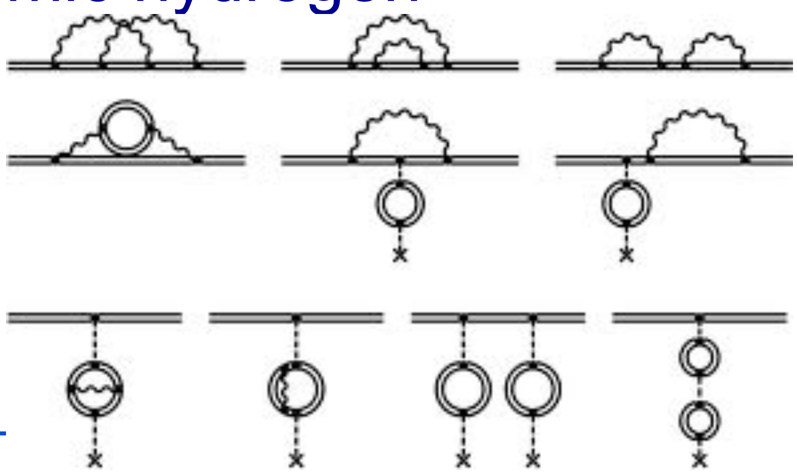
Masses



12 orders of magnitude differences not explained; t quark as heavy as Tungsten

Seeking New Physics

- Flavor Physics as a tool for NP discovery
  - While measurements of CKM elements (fundamental constants) are fun, the main purpose of HFP is to find and/or define the properties of physics beyond the SM
  - FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops is the Lamb shift in atomic hydrogen
  - A small difference in energy between $2S_{1/2}$ & $2P_{1/2}$ that should be of equal energy at lowest order



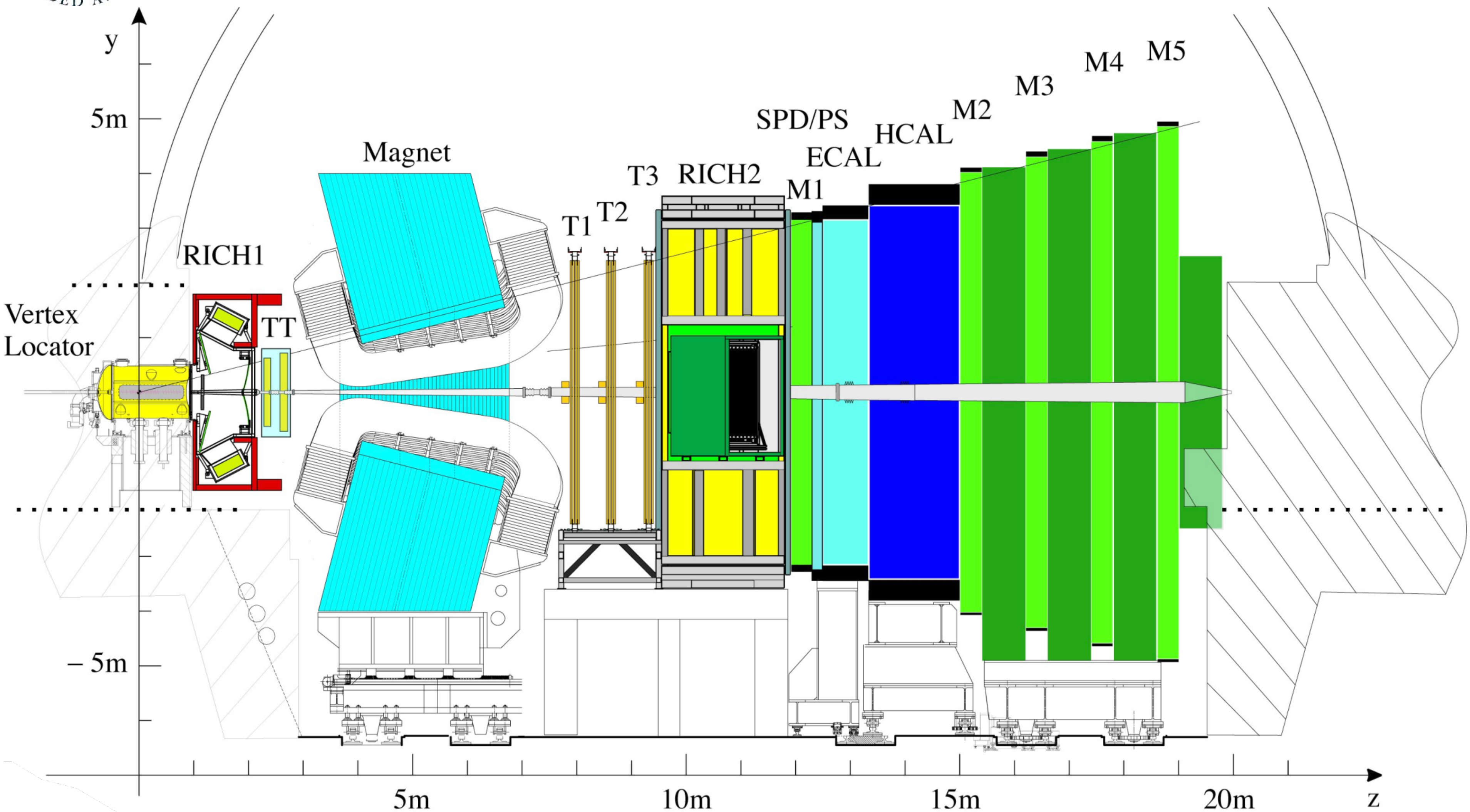
TPC impact on flavor physics

- At PEP many interesting measurements, a few:
  - First evidence for the F* meson (now D_s*) only 1 year after CLEO found the F
  - τ^- lepton studies, including branching fractions
  - Inclusive particle production in e^+e^- collisions, possible because of particle ID provided
  - Test of models for quark and gluon fragmentation
  - Total hadronic cross-section in 2γ collisions
  - $f_1(1285)$ formation in photon photon fusion reactions $\Rightarrow f_1(1285)$ is spin-1. Still an interesting state

Flavor experiments at hadron colliders

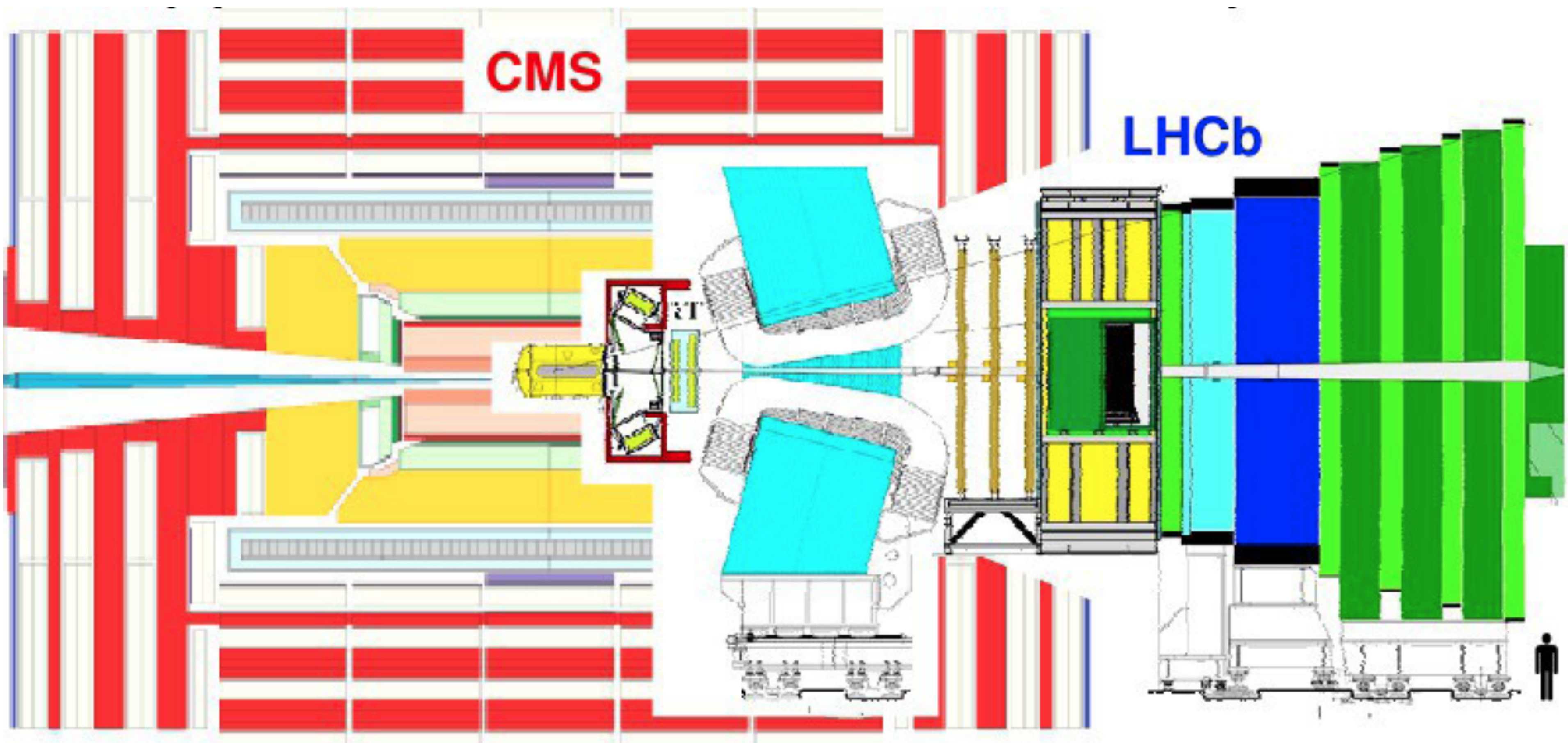
- In the past: CDF & D0 (not designed for flavor)
- Now & foreseeable future: LHCb & some from CMS & ATLAS, both also not designed for flavor, but have capabilities especially on final states containing $\mu^+\mu^-$ & have 10x the LHCb $\int \mathcal{L}$
- Triggering on b & c decays is a key issue
  - LHCb is >90% for muon final states & ~50% for pure hadronic decays
  - CMS & ATLAS only use dimuons & are less efficient
- Backgrounds: at e^+e^- have only $B\overline{B}$, σ_B/σ_{tot}~1/4, hadron colliders rely on detached b decay vertex

The LHCb Detector



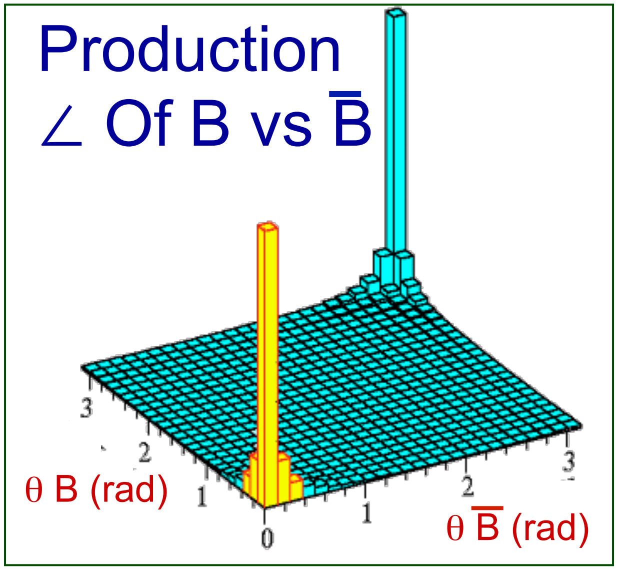
Detector Geometry

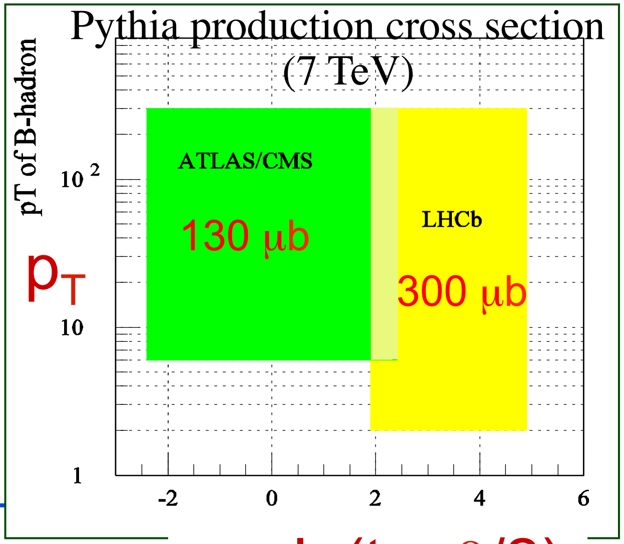
- Complementary to ATLAS & CMS
- Much less expensive



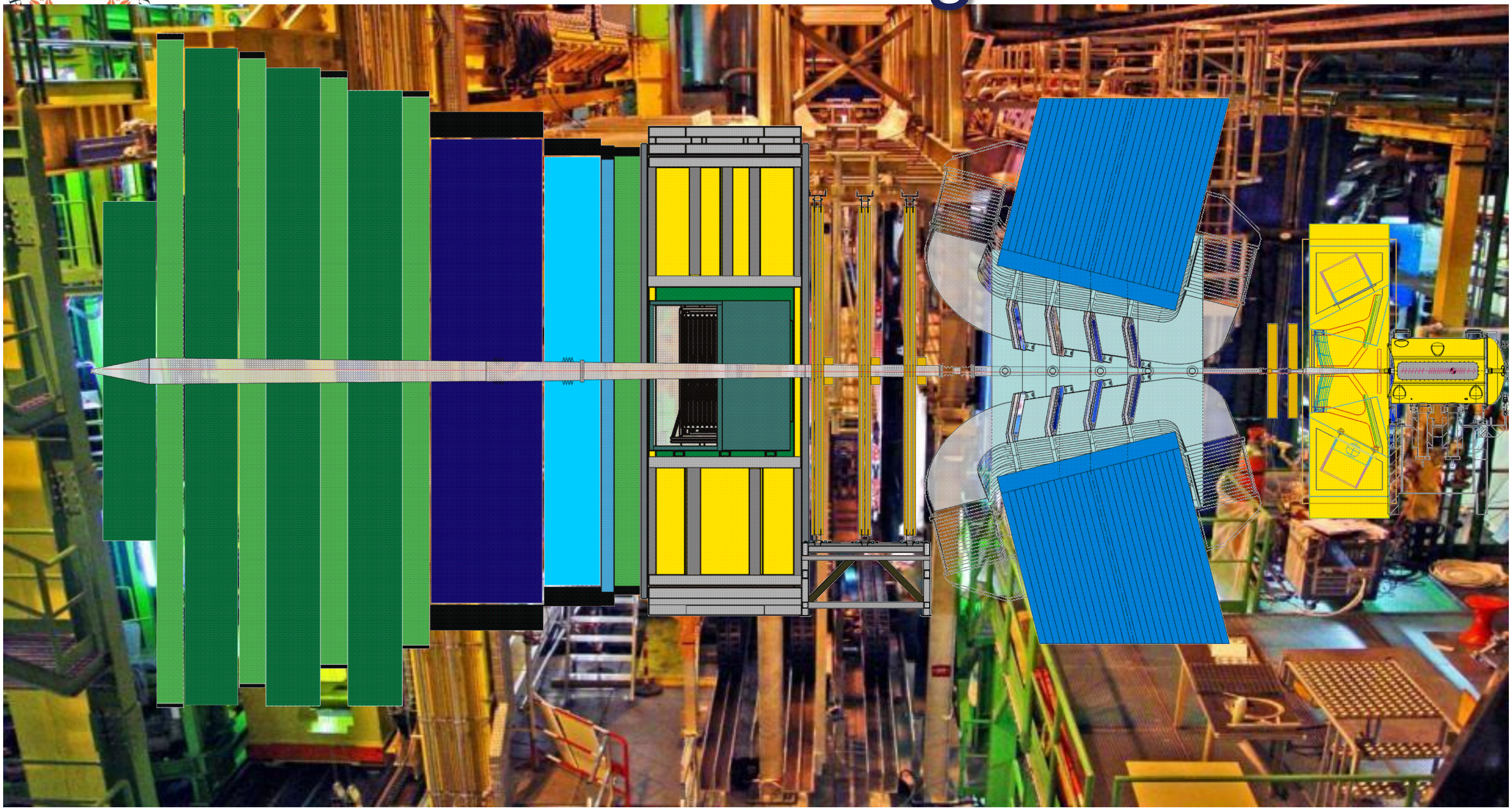
The Forward Direction at the LHC

- The primary pp collision produces a pair of $b\bar{b}$ quarks. They then form hadrons. In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for knowing if a neutral B meson started out as a B^0 or $\bar{B}^0$, determined by "flavor tagging"
- At $\mathcal{L}$=2x10^{32}/cm^2-s, we get ~6x10^{11} B hadrons in 10^7 sec in detector



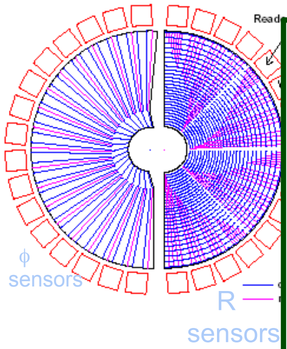


Detector Workings

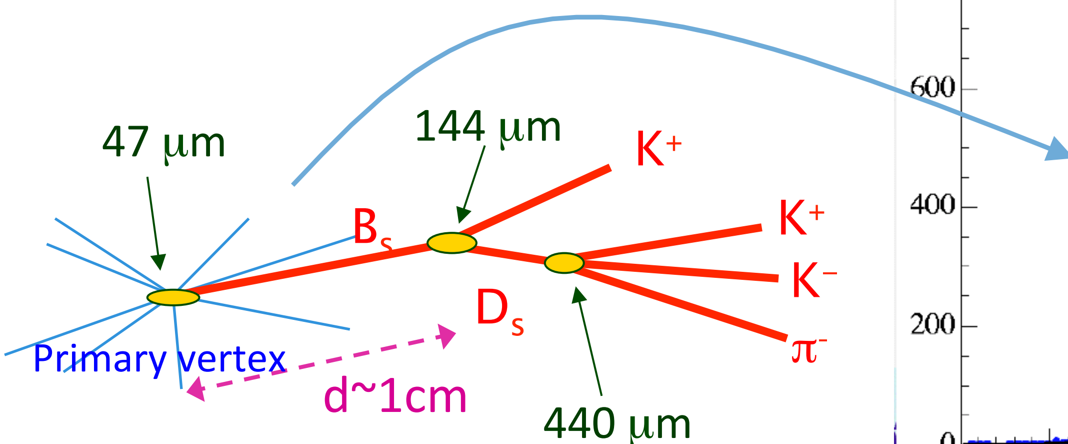


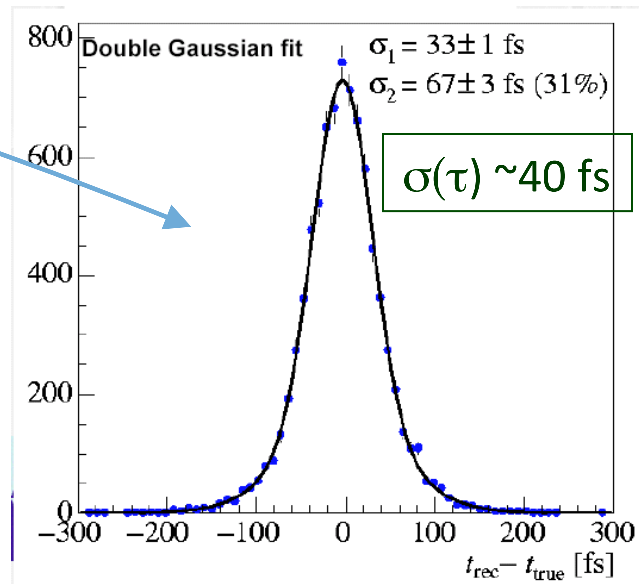
LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

B-Vertex Measurement



Example: $B_s \rightarrow D_s K$





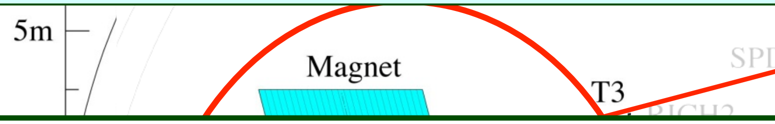
Decay time resolution = 40 fs

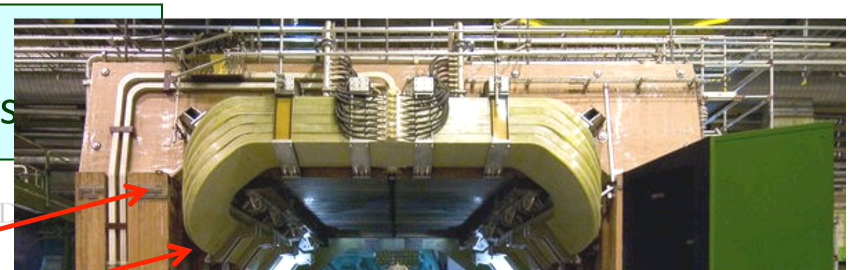
Vertex Locator (Velo)
Silicon strip detector with
~ 5 μm hit resolution
→ 30 μm IP resolution

Vertexing:
- trigger on impact parameter
- measurement of decay distance & decay time=d/v=md/p

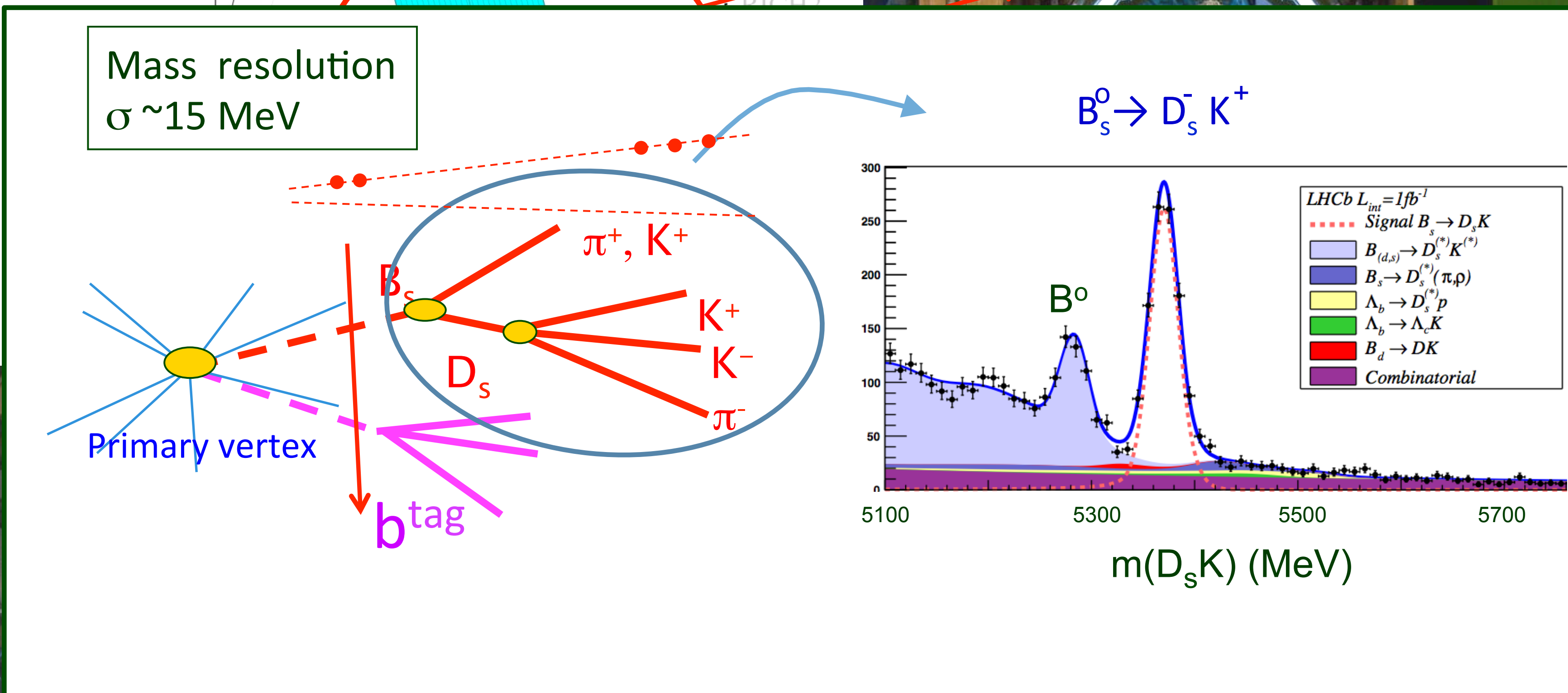
Momentum and Mass measurement

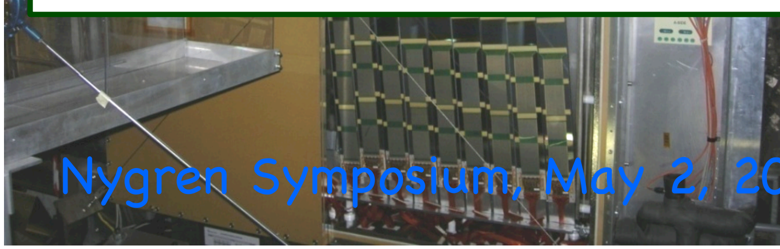
Momentum meas. + direction (VELO):
Mass resolution for background suppres





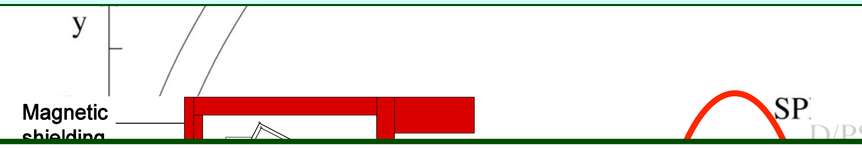
Mass resolution
σ ~15 MeV





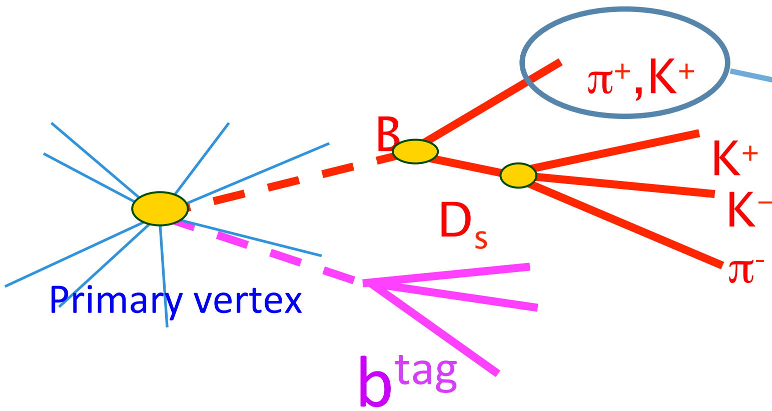
Hadron Identification

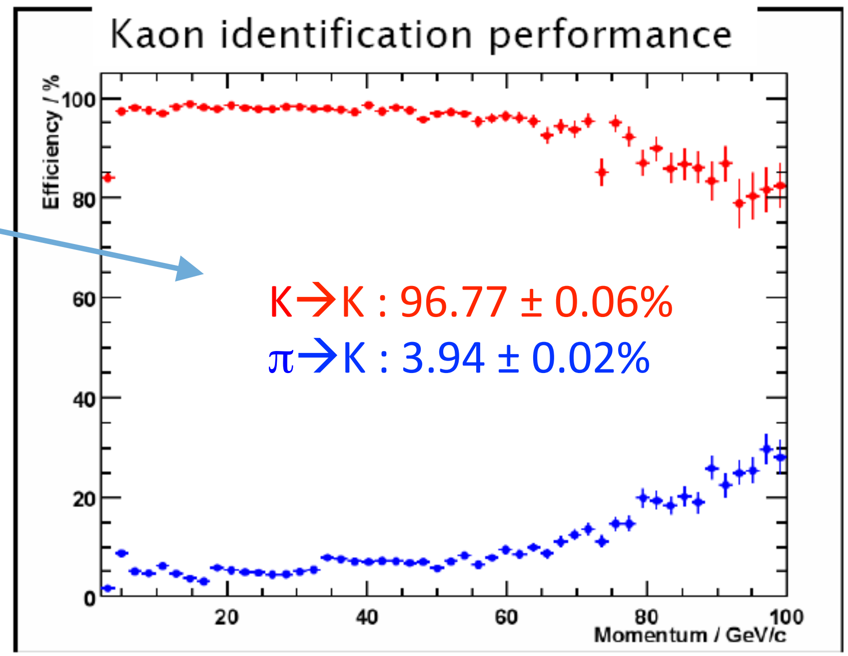
RICH: K/π identification using Cherenkov light emission angle



$B_s \to D_s K$

SS flavour tagging



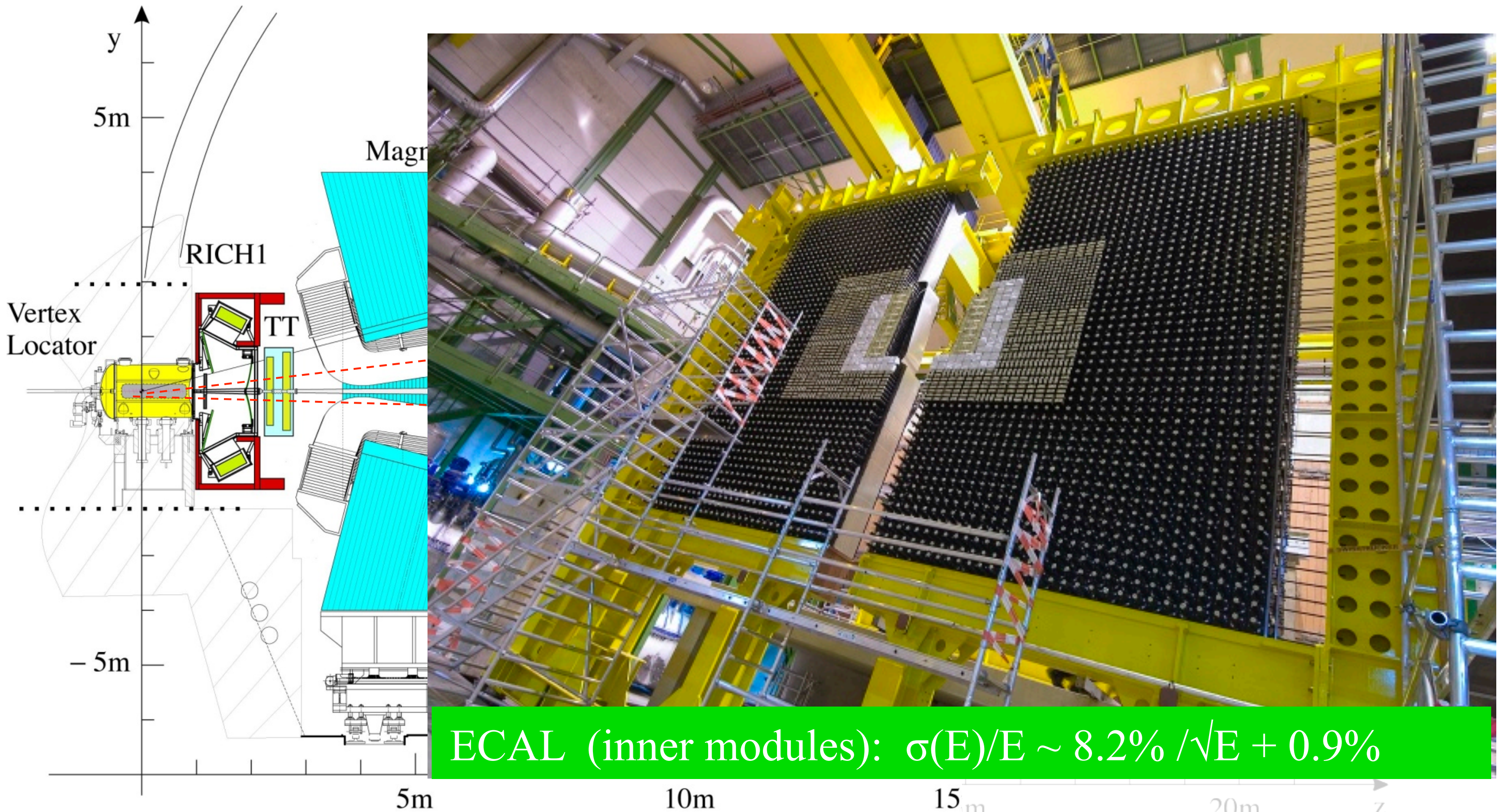


RICH1: 5 cm aerogel n=1.03

4 m^3 C_4F_{10} n=1.0014

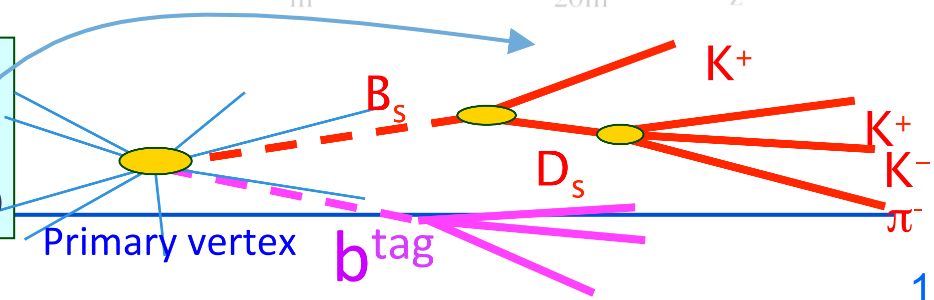
RICH2: 100 m3 CF_4 n=1.0005

Calorimetry and L0 trigger

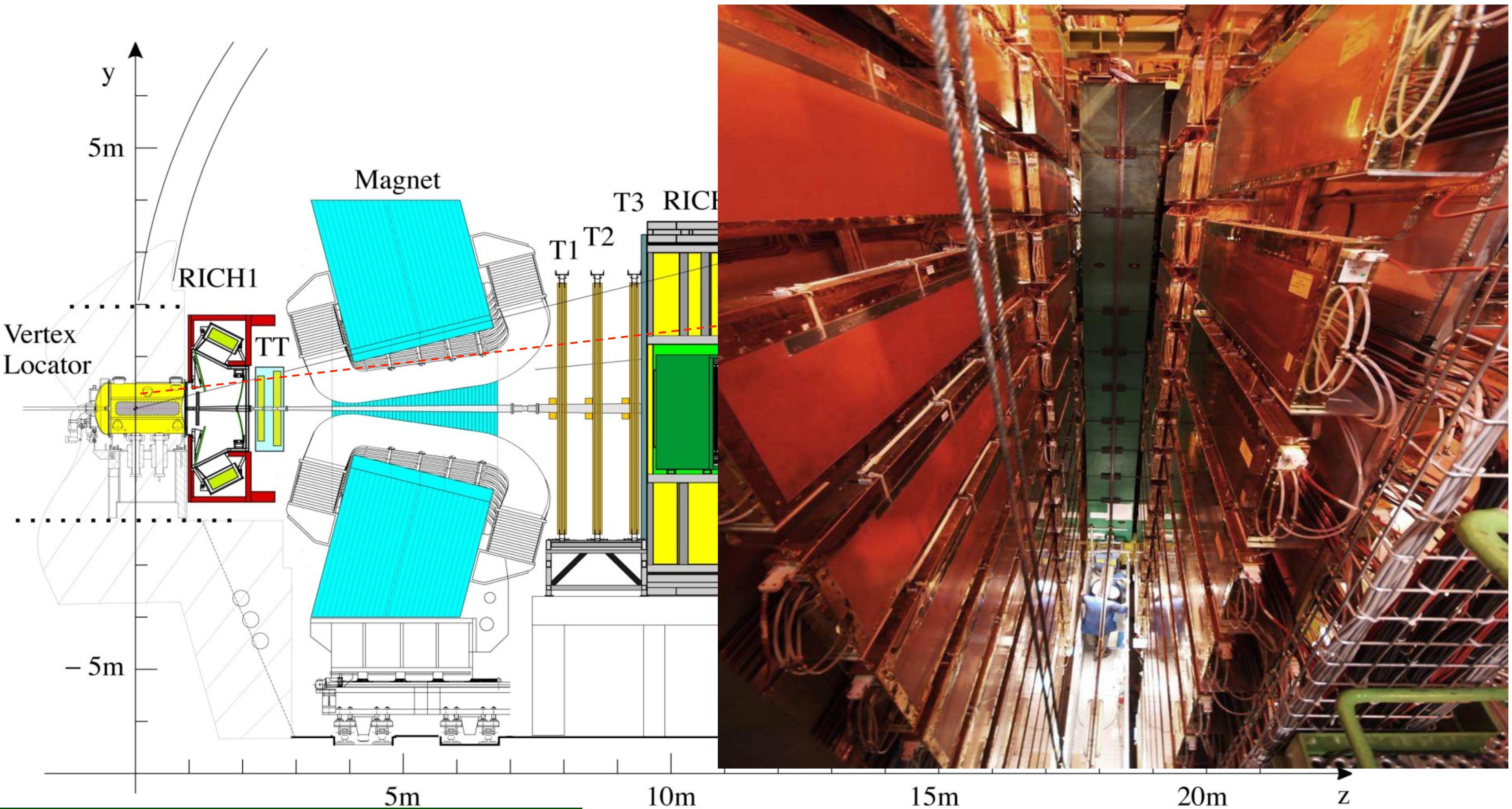


Calorimeter system :

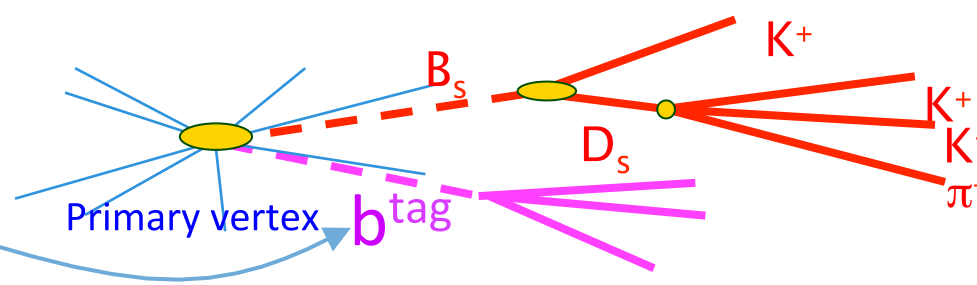
- Identify electrons, hadrons, π^0 ,γ
- Level 0 trigger: high E_T electron and hadron



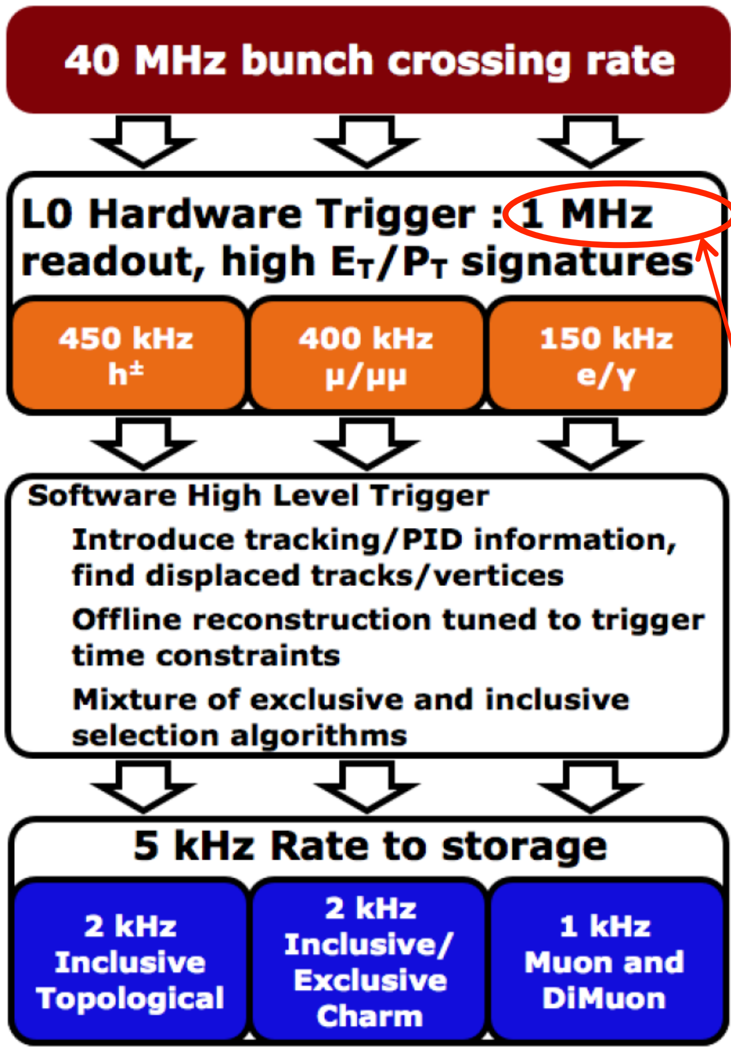
Muon identification and L0 trigger



Muon system:
- Level 0 trigger: High P_t muons
- OS flavour tagging



Triggering



Trigger is crucial as $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section and B decays of interest typically have $\mathcal{B}$ranching ratios of <10^{-5}

Hardware level (L0)

Search for high-p_T μ, e, γ and hadron candidates

Software level (High Level Trigger, HLT)

Farm with $\mathcal{O}$(29000) multi-core processors)

Very flexible algorithms, writes ~5 kHz to storage

This is the bottleneck

Detector Performance

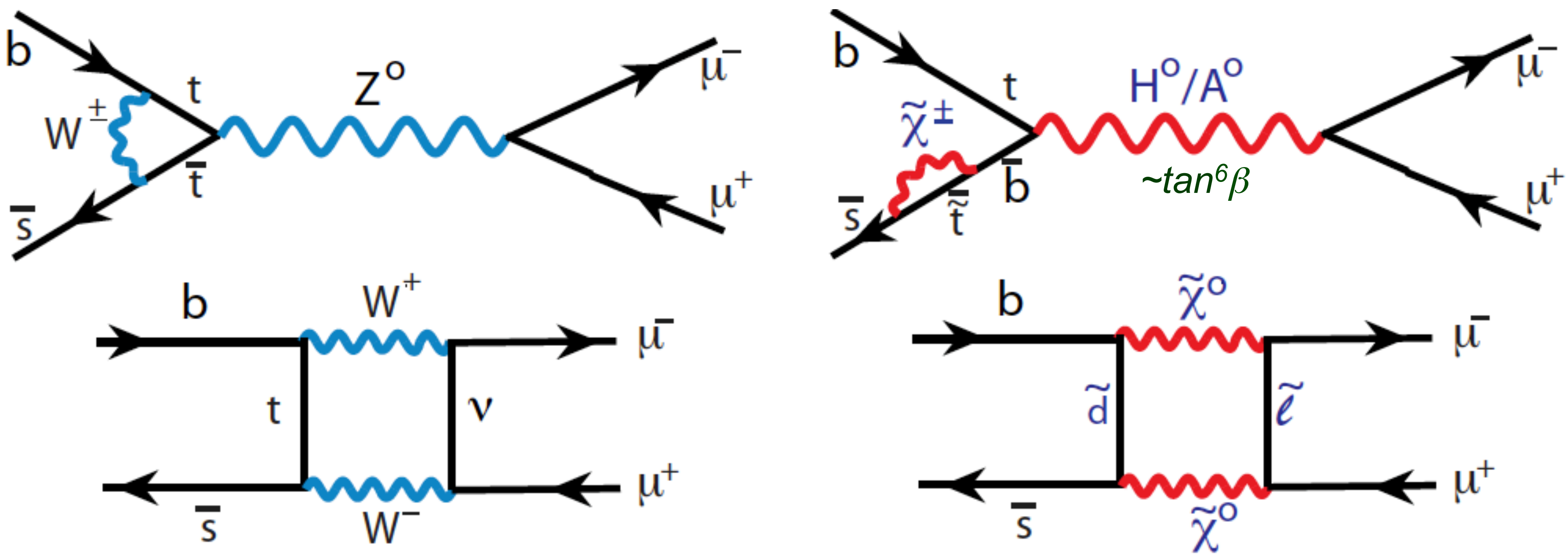
- Detector works better than expected
- Run at 4x10^{32} cm^{-2}/s instead of 2x10^{32}, with fewer bunches in the machine which is more difficult ~<1.5> interactions/crossing
- Detector efficiency >95% for all systems
- Problems: Vertex resolution slightly worse, flavor tagging somewhat poorer
- $\mathcal{L}$uminosity is leveled – small changes of $\mathcal{L}$ with time; beams are brought closer together when currents decrease

A few results

$B_s \to \mu^+\mu^-$

- SM branching ratio is $(3.65\pm0.23)\times10^{-9}$ [Bobeth et al., arXiv:1311.0903], NP can make large contributions.

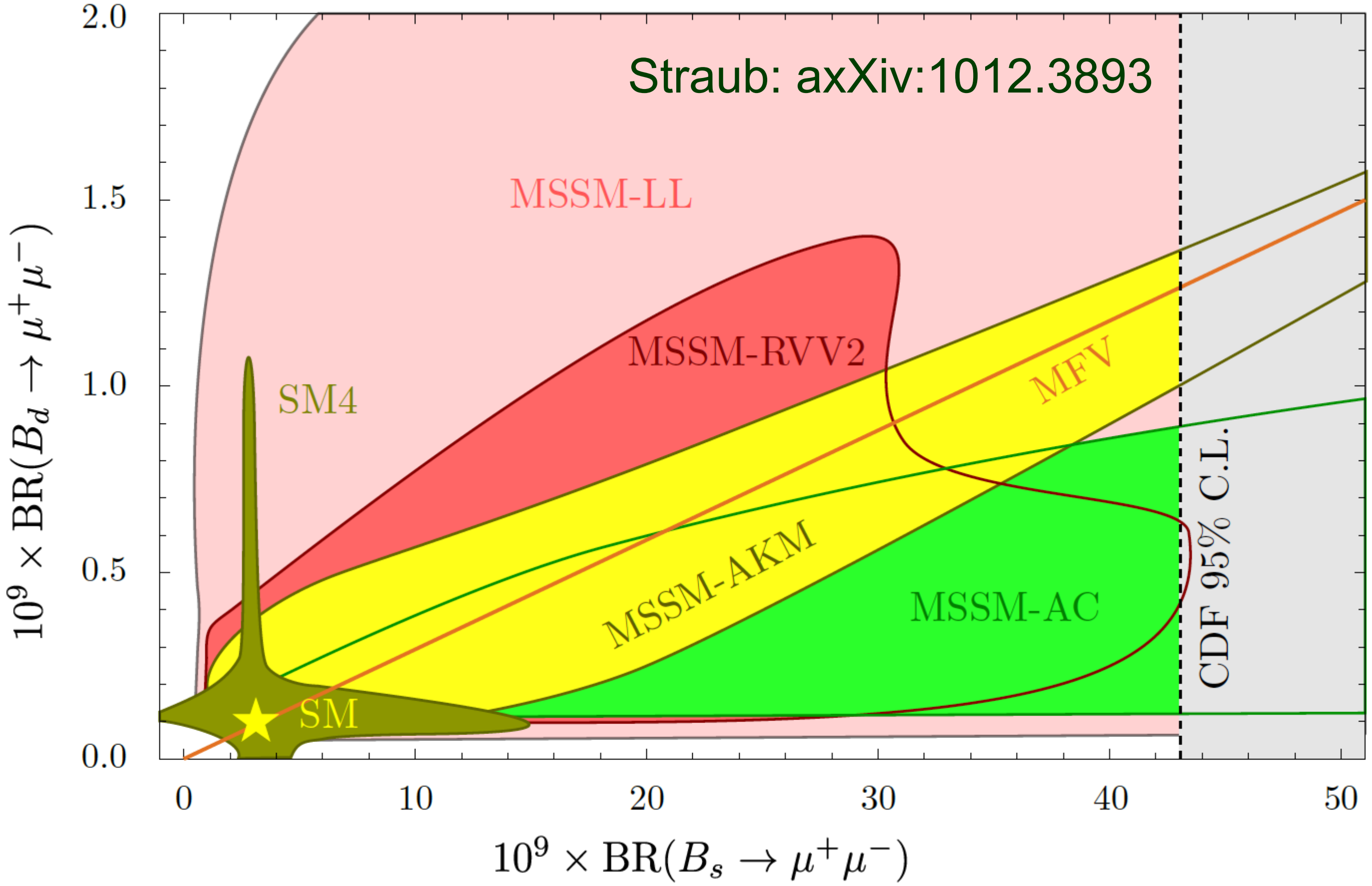
Standard Model | MSSM



- Many NP models possible, not just Super-Sym

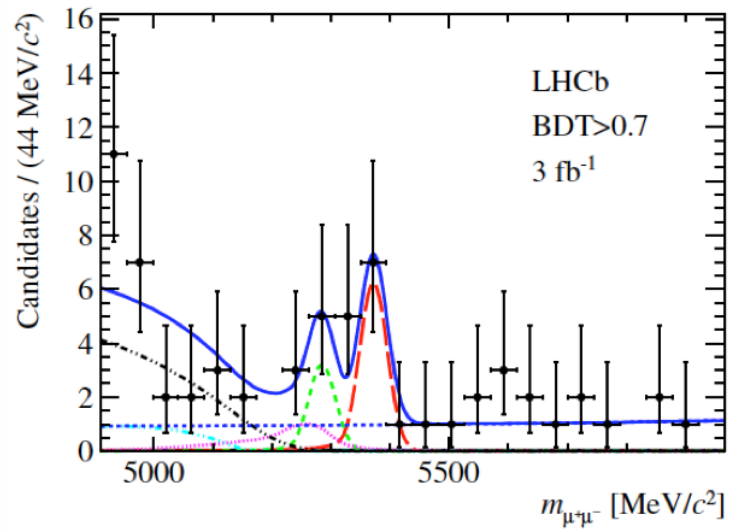
Top Down Analyses

- Here we pick models and work out their consequences in many modes. Ex. (circa 2010):



Evidence for $B_s \to \mu^+\mu^-$

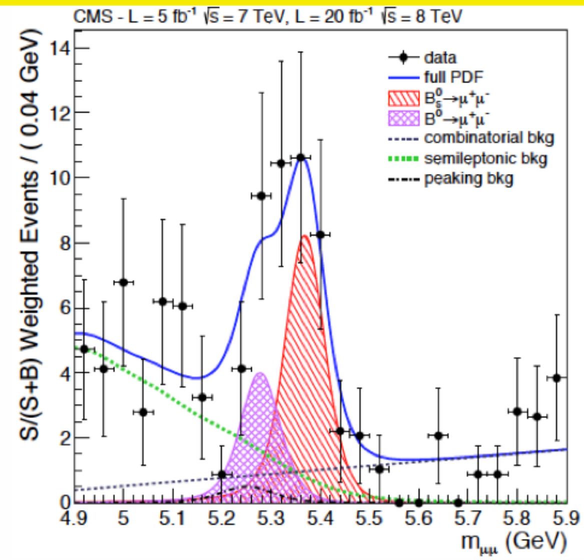
LHCb: arXiv:1307.5024, PRL.111.101805 (2013)



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

--> 4.0σ

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

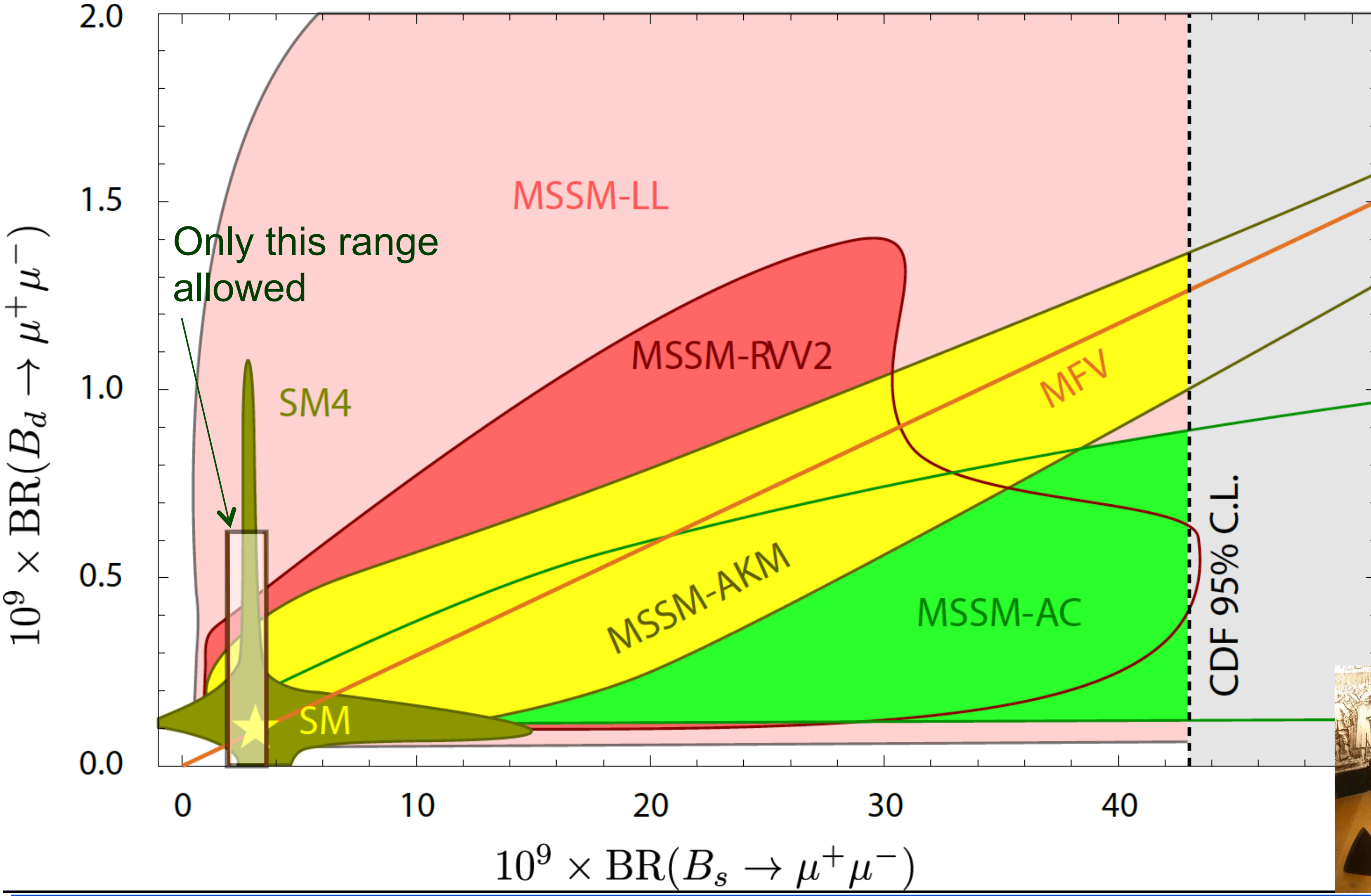


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9}) \times 10^{-9}, \quad \mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5\,^{+2.1}_{-1.8}) \times 10^{-10}$$

--> 4.3σ

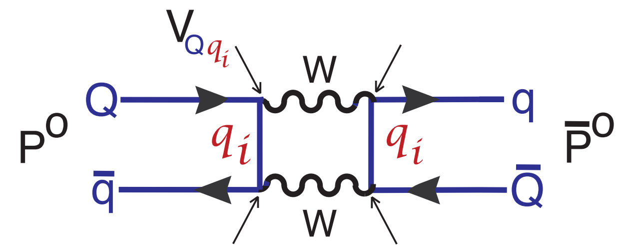
- Avg: $\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$
- Avg: $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}$ (not significant)

Implications



Neutral Meson Mixing

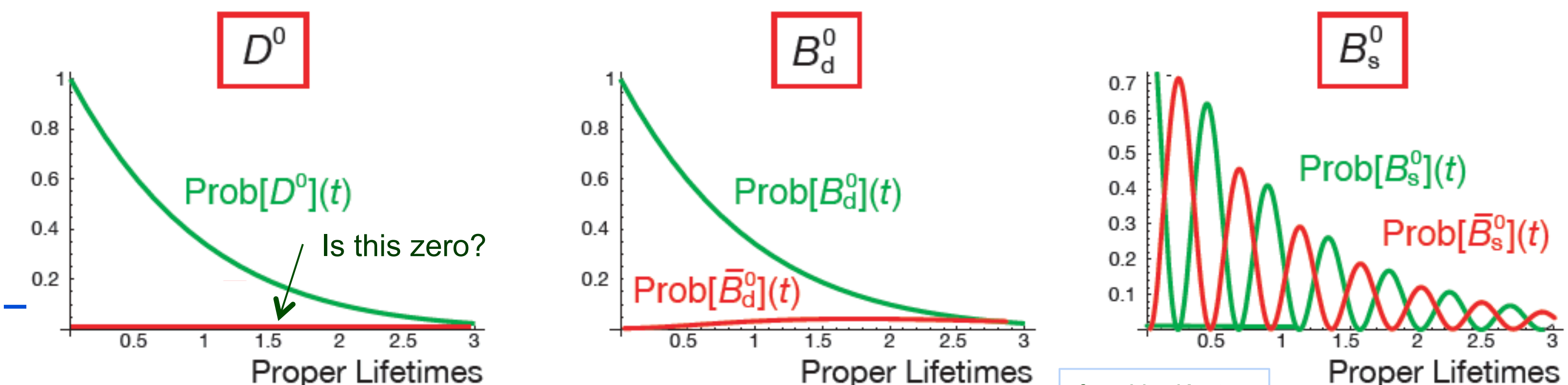
- Neutral mesons can transform into their anti-particles via 2nd order weak interactions
- Short distance transition rate depends on
  - mass of intermediate q_i, the heavier the better, favors s & b since t is allowed, while for c, b is the heaviest
  - CKM elements V_{ij}



New particles possible in loop

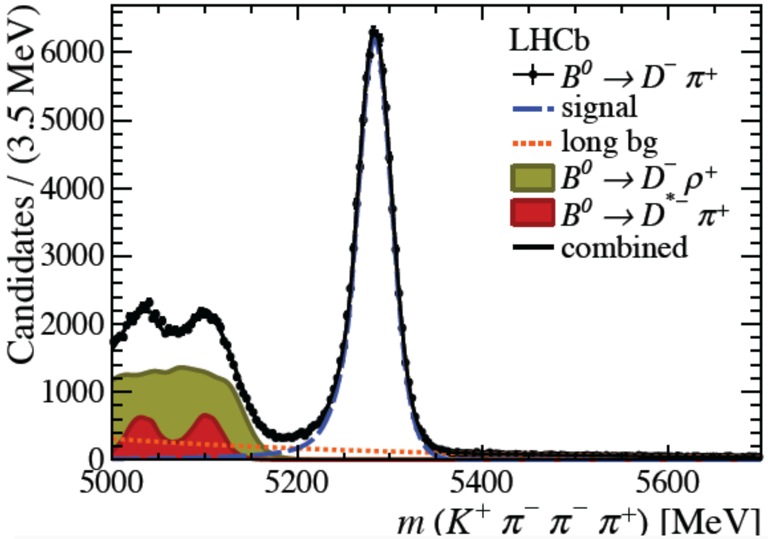
+ "long distance" for D^o

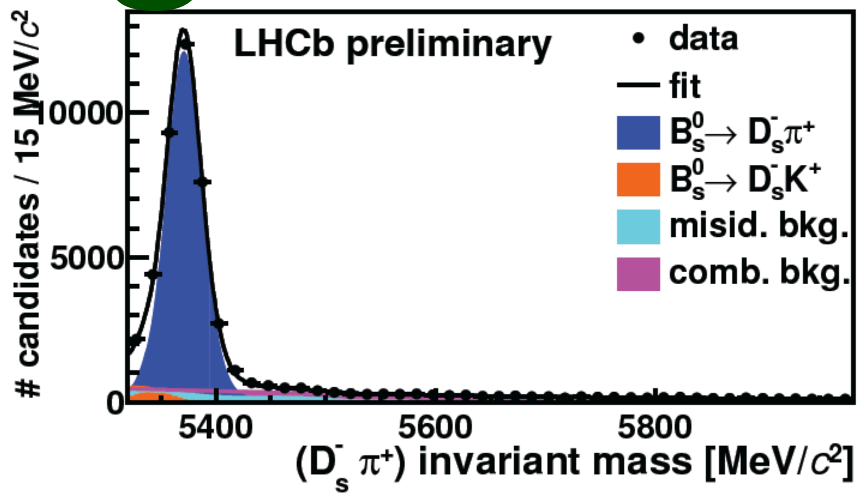
$D^o \Longrightarrow \pi\pi,.. \Longrightarrow \bar{D}^o$

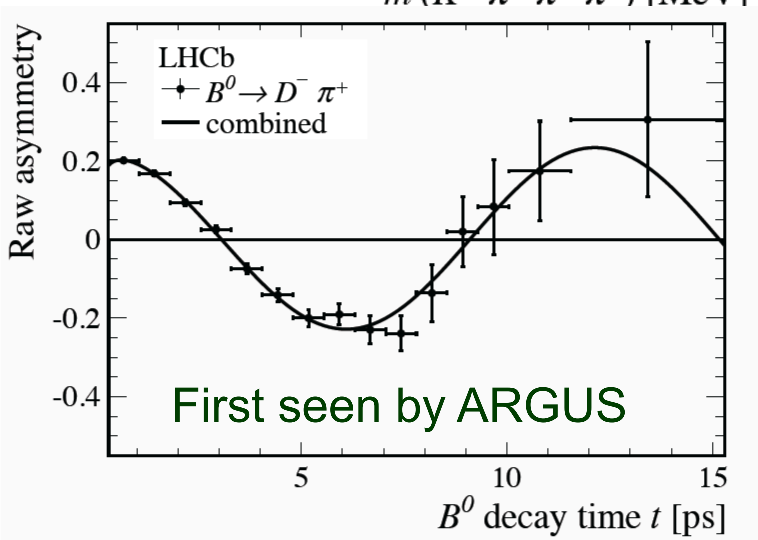


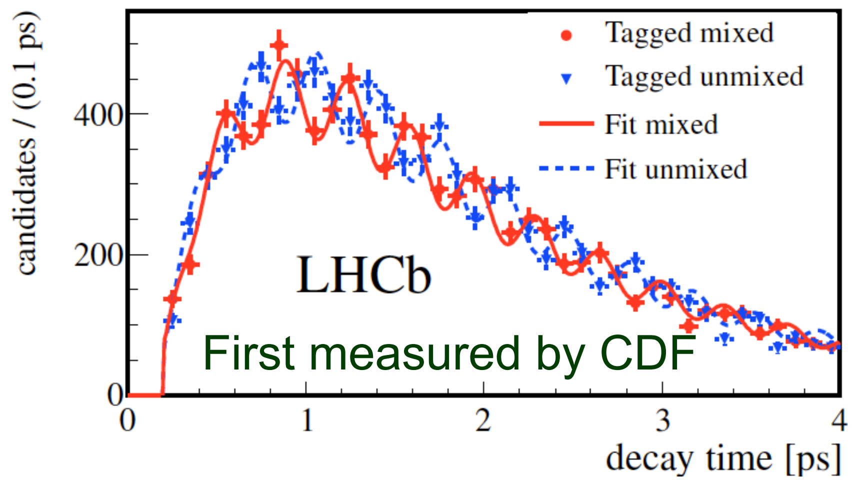
from Van Kooten

Mixing data







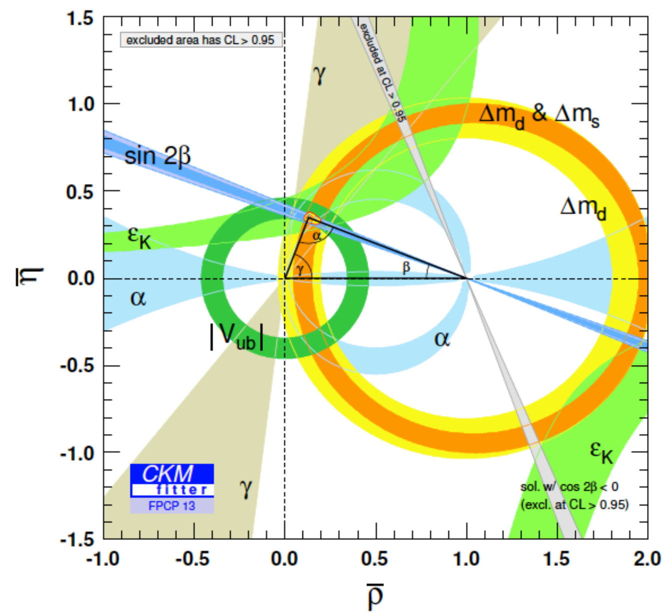


$\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$

$\Delta m_d = 0.5156 \pm 0.0051\ (\text{stat}) \pm 0.0033\ (\text{syst})\ \text{ps}^{-1}$

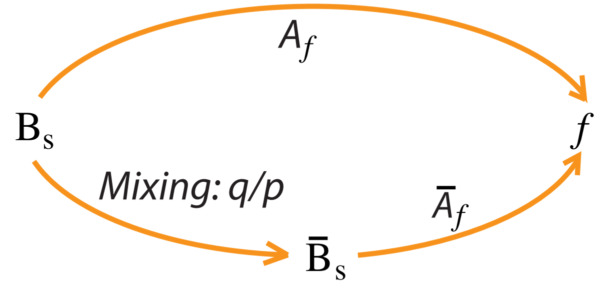
CPV measurements

- CPV measure: $a[f(t)] = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to f)}{\Gamma(\bar{M} \to f) + \Gamma(M \to f)}$
  - Angle probed depends on M, i.e. B^0, B_s, D^0…& f
  - For $B^0 \to J/\psi K_s$, measure angle β, which is not predicted
  - For $B_s \to J/\psi f_0(980)$, $J/\psi\phi$, measure angle ϕ_s predicted from Other measurements to be small in the SM = -0.036 rad

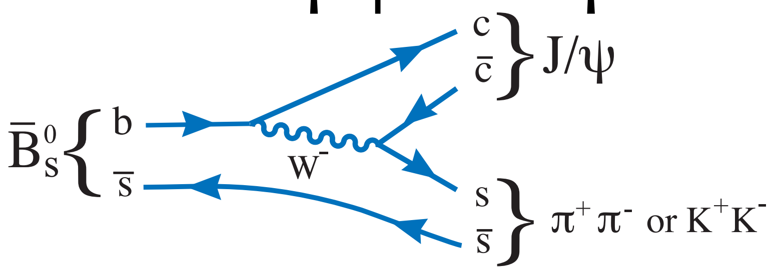


CPV in $B_s \to J/\psi\ X$

- Interference between mixing & decay



- For f =$J/\psi\ \phi$ or $J/\psi\pi^+\pi^-$

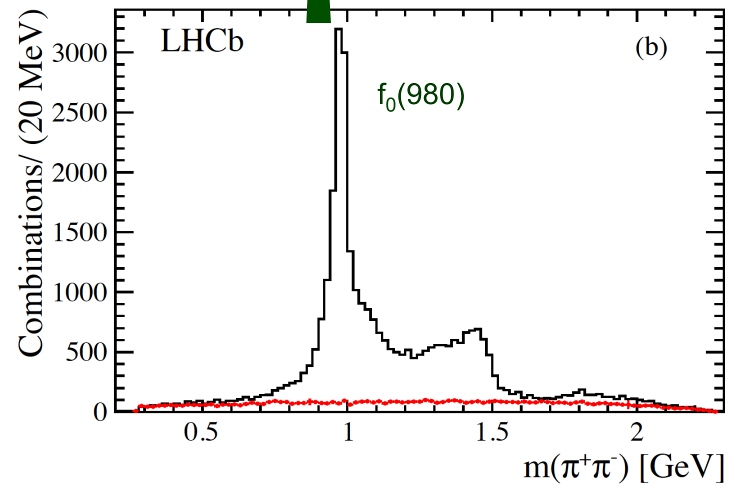


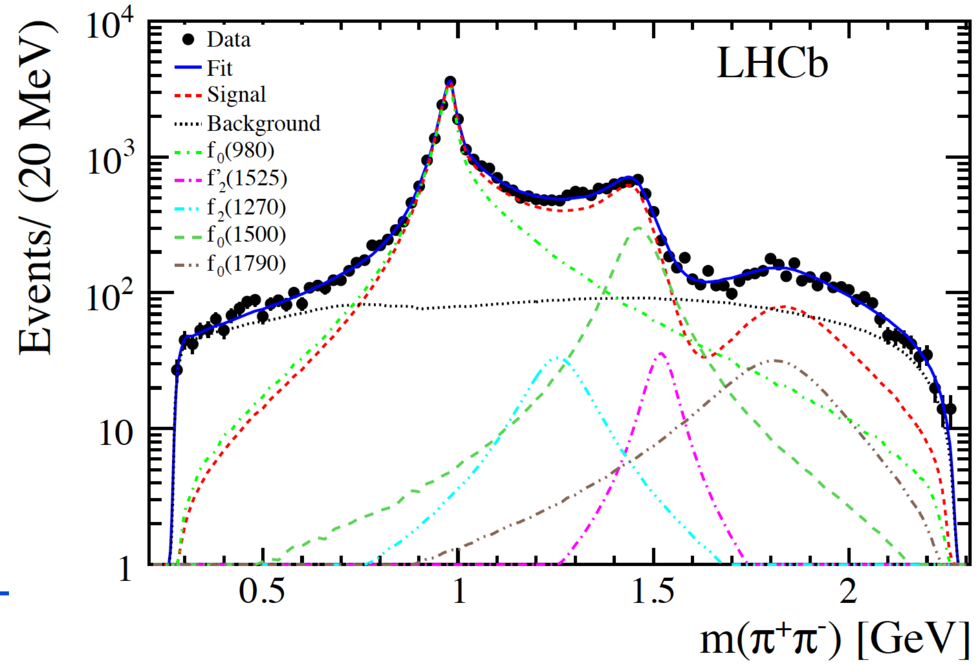
$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right) = -0.04 \text{ rad}$$

- Small CPV expected, good place for NP to appear
- $B_s \to J/\psi\phi$ is not a CP eigenstate, as it's a vector-vector final state, so must do an angular analysis to separate the CP+ and CP- components

ϕ_s from $J/\psi\pi^+\pi^-$

- Reconstructed $\pi^+\pi^-$ mass spectrum
- In region between arrows, measured to be >97.7% CP-odd @95% cl
- $a[f(t)] \sim 2\sin\phi_s \sin(\Delta M t)$
- $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$ rad





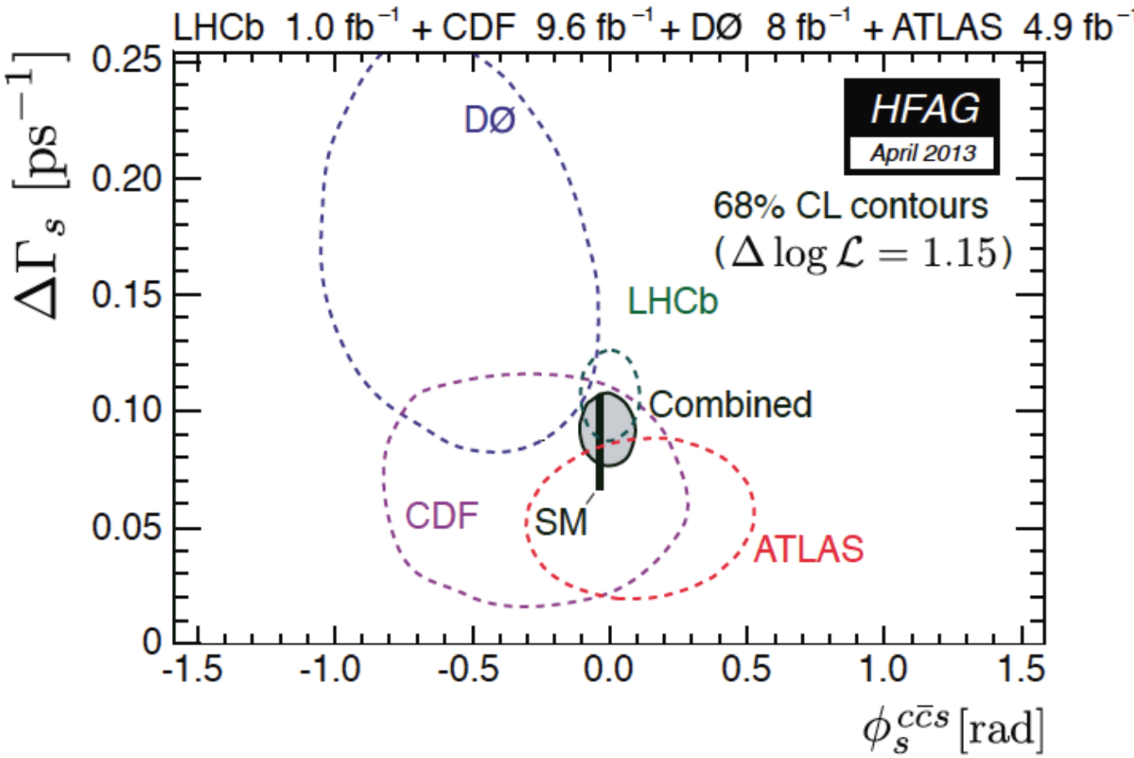
ϕ_s results from J/ψφ

LHCb values

$\Gamma = 0.6580 \pm 0.0054 \pm 0.0066$ (ps^{-1})

$\Delta\Gamma = 0.116 \pm 0.018 \pm 0.006$ (ps^{-1})

$\phi_s = 0.001 \pm 0.101 \pm 0.027$ (rad)

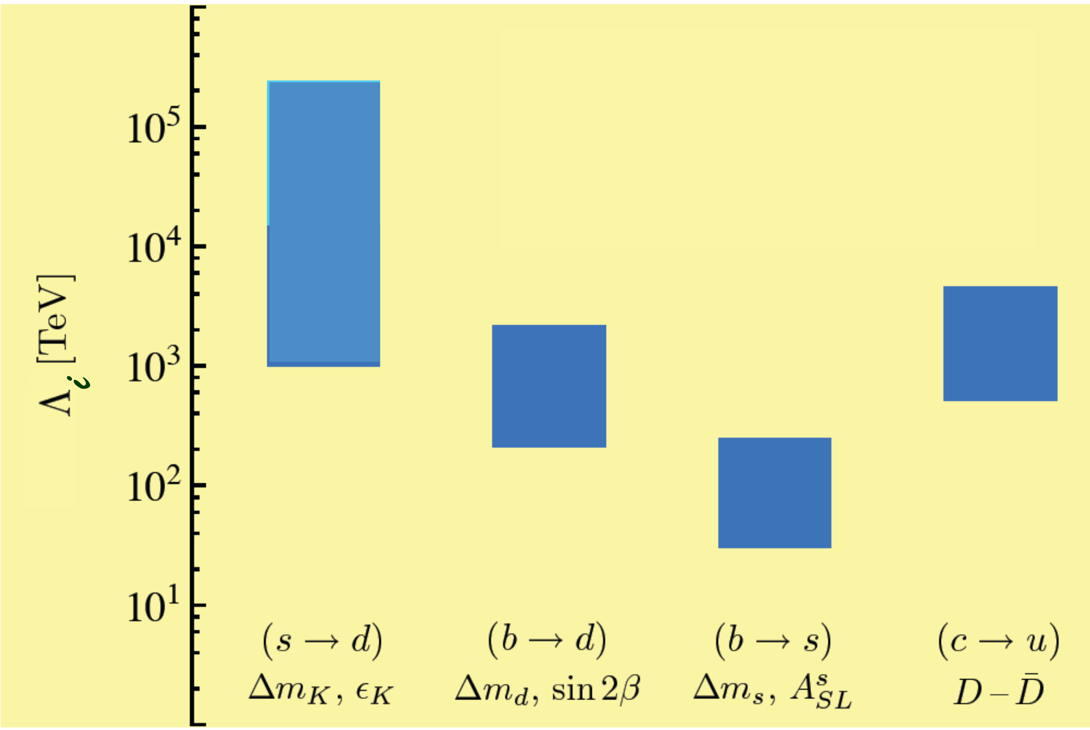


- Combining LHCb J/ψφ & J/ψπ⁺π⁻ results:

$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07 \pm 0.01 \ \text{rad} \\
\Gamma_s &= 0.661 \pm 0.004 \pm 0.006 \ \text{ps}^{-1} \\
\Delta\Gamma_s &= 0.106 \pm 0.011 \pm 0.007 \ \text{ps}^{-1}
\end{aligned}$$

Flavor as a High Mass Probe

- Already excluded ranges from box diagrams
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$, take $c_i \sim 1$



Ways out
1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

LHCb Upgrade

- Goals: run at $\mathcal{L}$ up to 2x10^{33} cm/s with double efficiency on B→hadrons (x10)
- Move to an all software trigger with higher output ~50 kHz
- Higher density tracking elements
  - New pixel VELO
  - New Si strip TT called UT (US responsibility)
  - New Outer Tracker made of scintillating fibers
  - RICH switching to MAPMT's
- Approved by LHCC

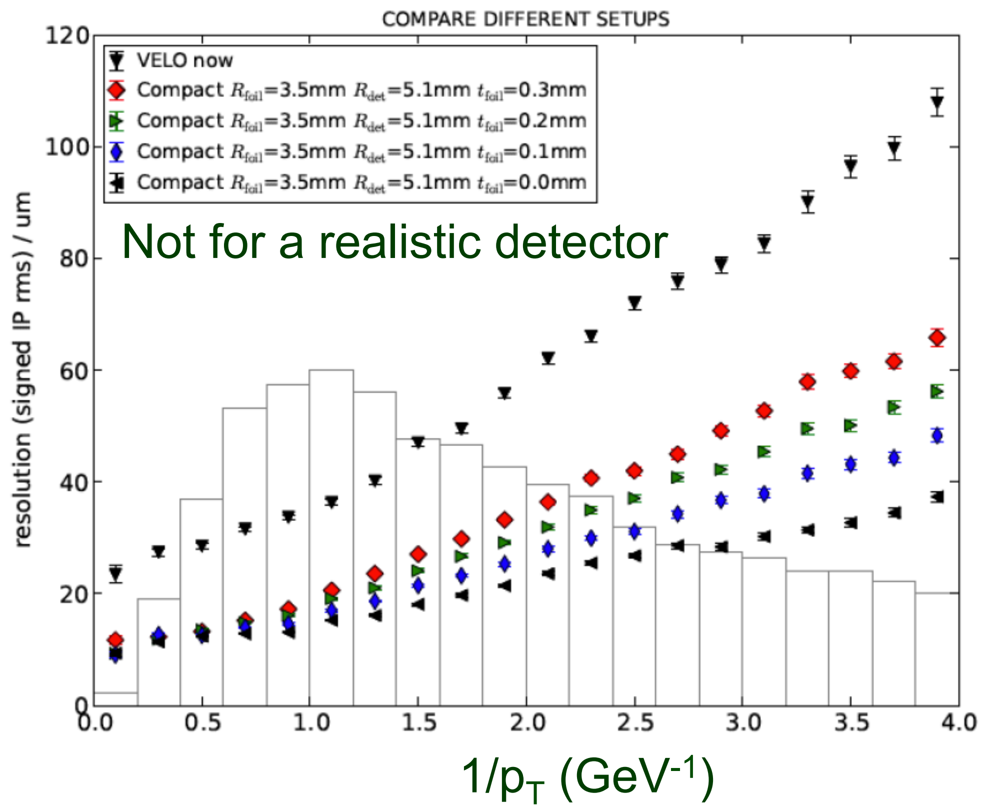
Post upgrade:
The Torch

Possible additional improvements

What follows is only my speculations

Remove 250 μm thick RF foil, separating beam vacuum from VELO vacuum & replace with wires to absorb image charge from the beam.

Would improve vertex resolution significantly



A high resolution E&M calorimeter

- LHCb could do more with an excellent E&M calorimeter
- Although final states such as $B \rightarrow K^{*}\gamma$ have been done by LHCb, the efficiencies are relatively low & the resolution relatively poor
- π^0's are more difficult
- $PbWO_4$ would be great, but it would cost as much as CMS. Note ½ of the solid angle could be covered for ¼ of the cost. Could also use Noble liquids, Argon, Xenon?

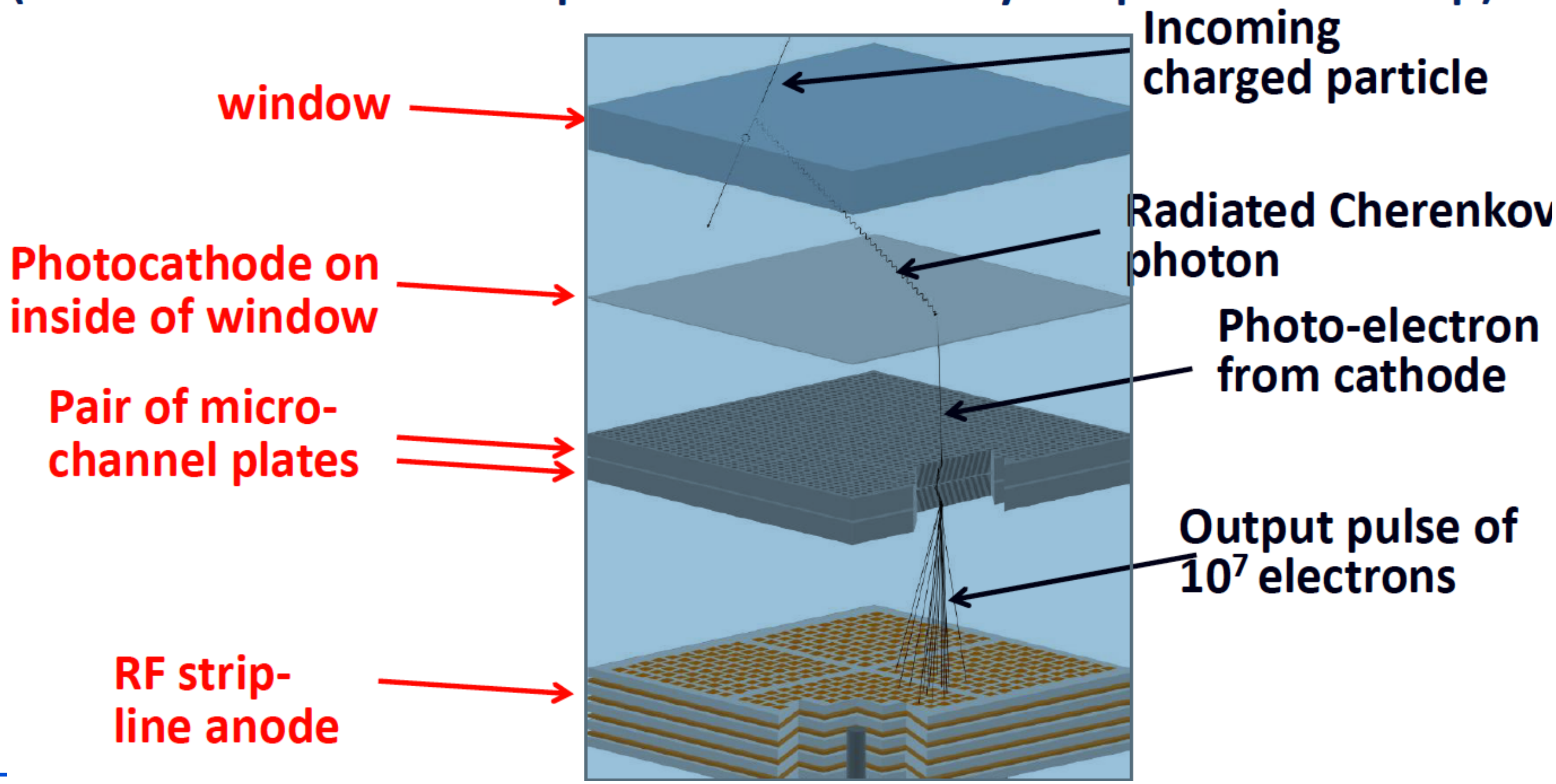
Timing photons

- H. Fritsch et al., Large area picosecond timing
  - See http://psec.uchicago.edu
- In principle, can tell origin of photon by measuring the difference of time between γ's & pions. Could be enormously useful to tell if a γ came from a particular detached B decay vertex. For 1 ps, decay length is known to 0.1 mm, where average B decay length is ~10 mm
- Also useful for low momentum charged particle ID.

How it works

Requires large-area, gain > 10^7, low noise, low-power, long life, $\sigma(t)$<10 psec, $\sigma(x)$ < 1mm, and low large-area system cost

Realized that an MCP-PMT has all these but large-area, low-cost: (since intrinsic time and space scales are set by the pore sizes- 2-20μ)



Test results

- Already achieved 5 ps timing on 8”x8” area
- With 5 ps, have 0.5 mm resolution on γ origin, already beginning to be useful to distinguish among associated primary vertices, but really would like 1 ps $\Longrightarrow$ 0.1 mm resolution good enough to tell if its from a detached B decay

Final states with a missing particle

- We often want to detect B decays with a missing neutrino, such as $B \rightarrow D^{(*)}\mu^{-}\nu$ for $|V_{cb}|$ or $\Lambda_b \rightarrow p\mu^{-}\nu$ for $|V_{ub}|$
- Also look for new scalar fields such as inflatons, Berukov & Gorbunov prediction: "Light inflaton Hunter's Guide" (arXiv:0912.0390)

$$\mathcal{B}(\overline{B} \to \chi X_s) \simeq 0.3 \frac{|V_{ts}V_{tb}^*|^2}{|V_{cb}|^2} \left(\frac{m_t}{M_W}\right)^4 \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \theta^2$$

X_s ↕ K or K*

$$\simeq 10^{-6} \cdot \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{\beta}{\beta_0}\right) \left(\frac{300\text{ MeV}}{m_\chi}\right)^2,$$

- Here we don't detect the χ

B-factories vs LHCb

- B factories can fully reconstruct the B and then measure the $\overline{B}$ decay even with a missing particle, but the efficiency is only few x 10^{-3}.
- This works because the **p** of the $\overline{B}$ is –**p** of the B. Signal appears as a peak in:

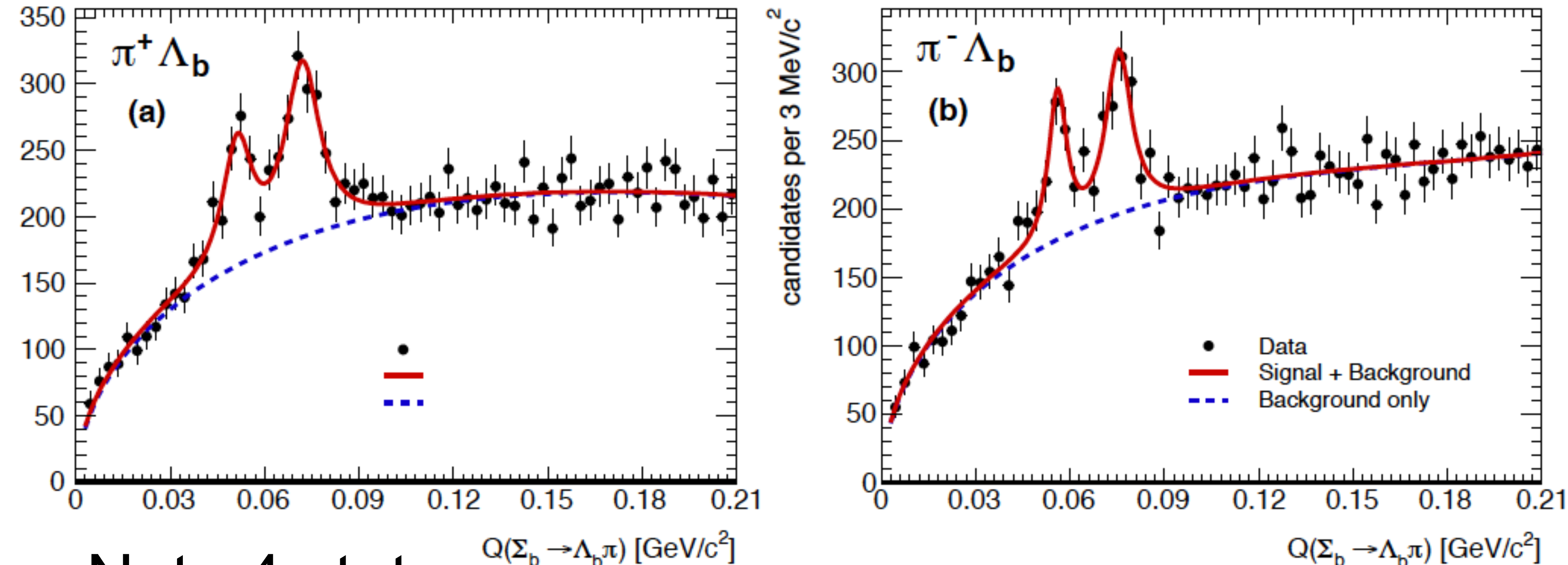
$$m_x^2 = (E_B - E_X)^2 - (\overrightarrow{p}_B - \overrightarrow{p}_X)^2$$

An alternative technique has been used, e.g., in D^0 decay: Measure the D^0 direction from production to the primary vertex, but then we are missing the $|\mathbf{p}_{D^0}|$. Get an extra constraint from $D^{*+} \rightarrow \pi^+ D^0$ decay, works because of large rate and narrow D^{*+} width, which is 0.1 MeV, so observed width depends on detector resolution

How can LHCb do this?

- $B^{**} \rightarrow \pi^+ B$, this doesn't work because B^{**}/B is ~15%, unlike D^{*+}/D ~100%, & the widths are ~25 MeV & ~130 MeV
- How about $\Sigma_b^+ \rightarrow \pi^+ \Lambda_b^0$? (See Stone & Zhang arXiv:1402.4205)
  - Should be a large rate. Expect Σ_b^+,& Σ_b^- production to be about the same size as Λ_b^0 (bud, versus buu & bdd)
  - There has even been an observation of the decay by CDF, but not a measurement of the relative rate, which appears to be quite low

CDF results: Only published measurement

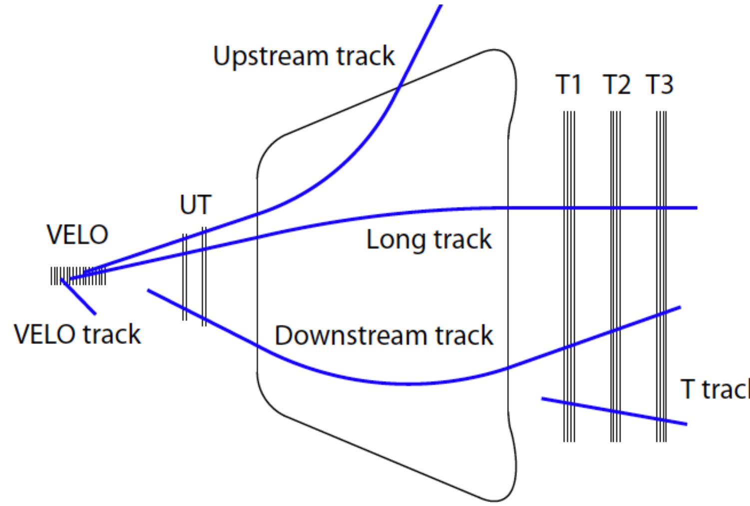


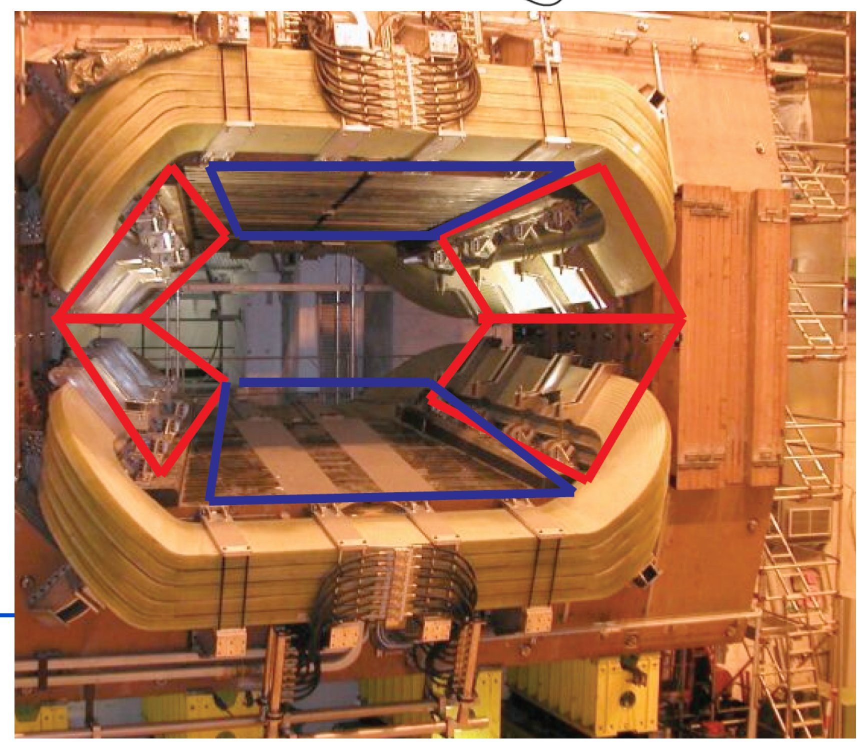
- Note 4 states
- S/B not great
- Suspect poor ε on low p tracks

State	Q value, MeV	Natural width, Γ_0, MeV	Yield
Σ_b^-	$56.2^{+0.6}_{-0.5}$	$4.9^{+3.1}_{-2.1}$	340^{+90}_{-70}
Σ_b^{*-}	75.8 ± 0.6	$7.5^{+2.2}_{-1.8}$	540^{+90}_{-80}
Σ_b^+	$52.1^{+0.9}_{-0.8}$	$9.7^{+3.8}_{-2.8}$	470^{+110}_{-90}
Σ_b^{*+}	72.8 ± 0.7	$11.5^{+2.7}_{-2.2}$	800^{+110}_{-100}

Augmenting the tracking

- A useful technique, can be improved by detecting low p tracks, only ~60 MeV Q for these decays about the same as for D*-D
- Examples of LHCb tracks
- Upstream tracks typically have Δp/p~15%, so not useful for most physics. So put detectors in the magnet





Conclusions

- Flavor physics offers unique searches for high mass New Physics
- Hadron colliders provide enormous samples of b & c decays
- Several improvements are possible that could vastly improve the prospects of finding such new phenomena
- Good luck to Dave!

The End

What is Heavy Flavor Physics ?

- Define Heavy Flavor Physics
  - Flavor Physics: Study of interactions that differ among flavors: (quark flavors are u, d, c, s, b, t)
  - Heavy: Not SM neutrino's or u or d quarks, maybe s quarks, concentrate here on b quarks (some c), t too heavy

u, d, ν's

too light

s, μ

maybe

c & b, τ; ν_M's ?

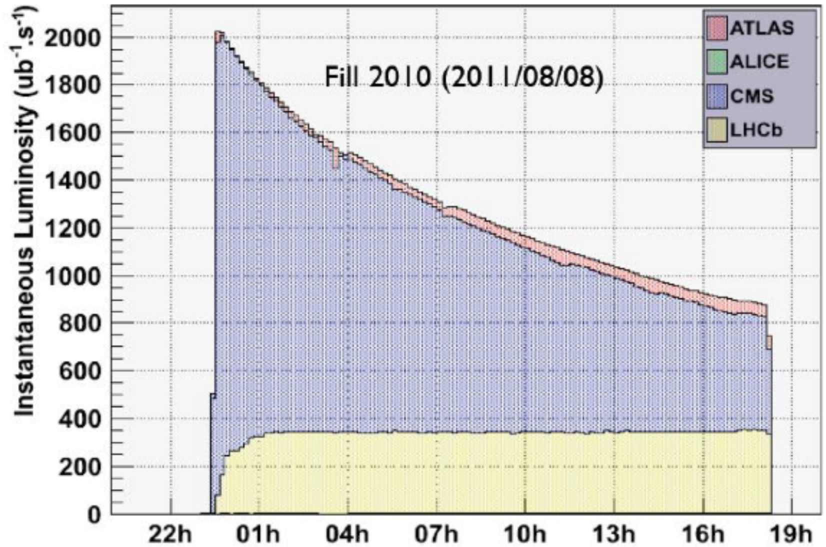
just right

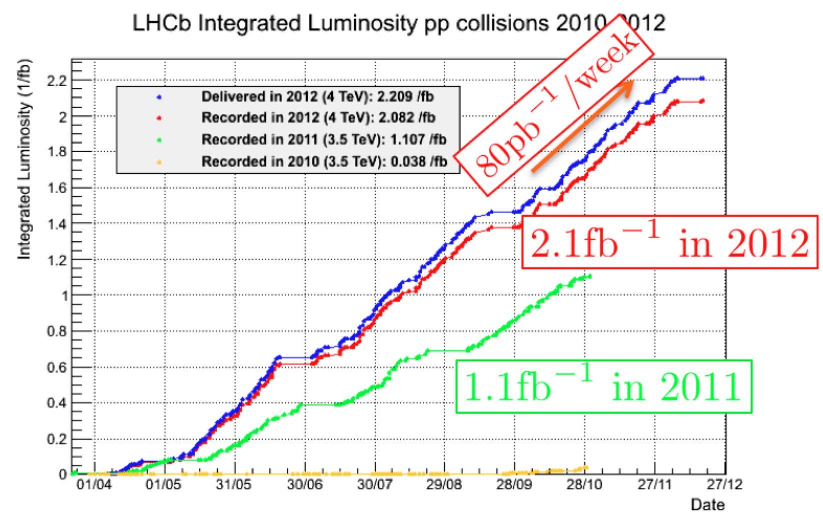
t

too heavy

$\mathcal{L}$uminosity Leveling

- $\mathcal{L}$uminosity is maintained as at a constant value of ~4x10^{32}/cm·s by displacing beams transversely
- Integral $\mathcal{L}$ is 1/fb in 2011, collected 2/fb more in 2012





a_{sl}

- By definition $$a_{sl} = \frac{\Gamma\left(\bar{M} \to f\right) - \Gamma\left(M \to \bar{f}\right)}{\Gamma\left(\bar{M} \to f\right) + \Gamma\left(M \to \bar{f}\right)}$$

  at t=0 $\overline{M} \to f$ is zero as is $M \to \overline{f}$
- Here *f* is by construction flavor specific, $f \neq \bar{f}$
- Can measure eg. $\overline{B}_s \to D_s^+ \mu^- \nu$, versus $B_s \to D_s^- \mu^+ \nu$,
- Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at $\mu^+\mu^+$ vs $\mu^-\mu^-$
- a_{sl} is expected to be very small in the SM, $a_{sl}=(\Delta\Gamma/\Delta M) \tan\phi_{12}$, where $\tan\phi_{12}=\mathrm{Arg}(-\Gamma_{12}/M_{12})$
- In SM (B^o) a^d_{sl} =-4.1x10^{-4}, (B_s) a^s_{sl} =+1.9x10^{-5}

 arXiv:1205.1444 [hep-ph]

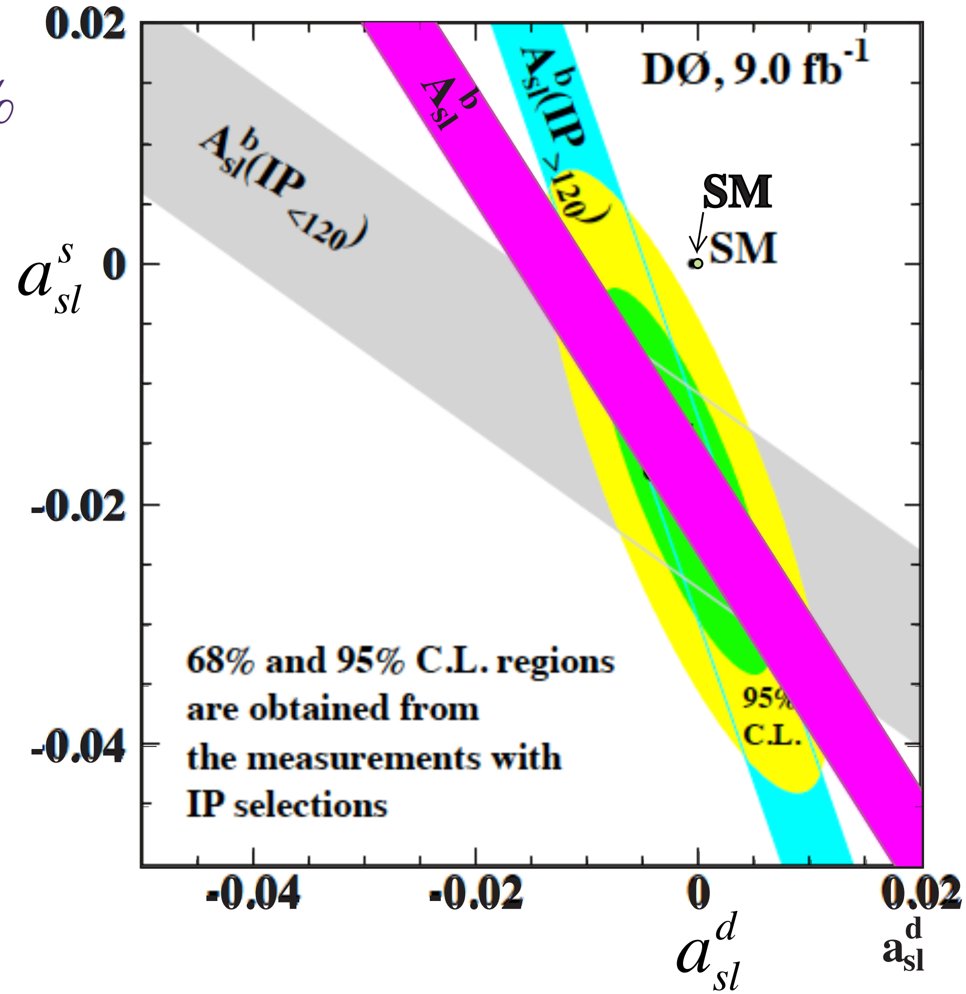
D0 a_{sl}

- Using dimuons (3.9σ)

$$A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$$

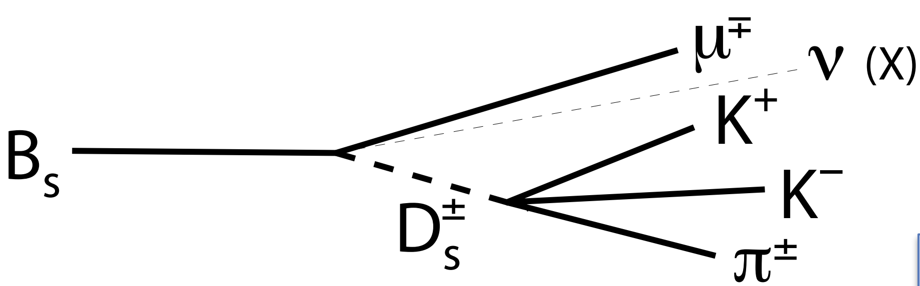
- Indication from D0 that its B_s
- Separate dimuons into B_d and B_s samples using muon impact parameter
- Find $a^d_{sl} = (-0.12 \pm 0.52)\%$

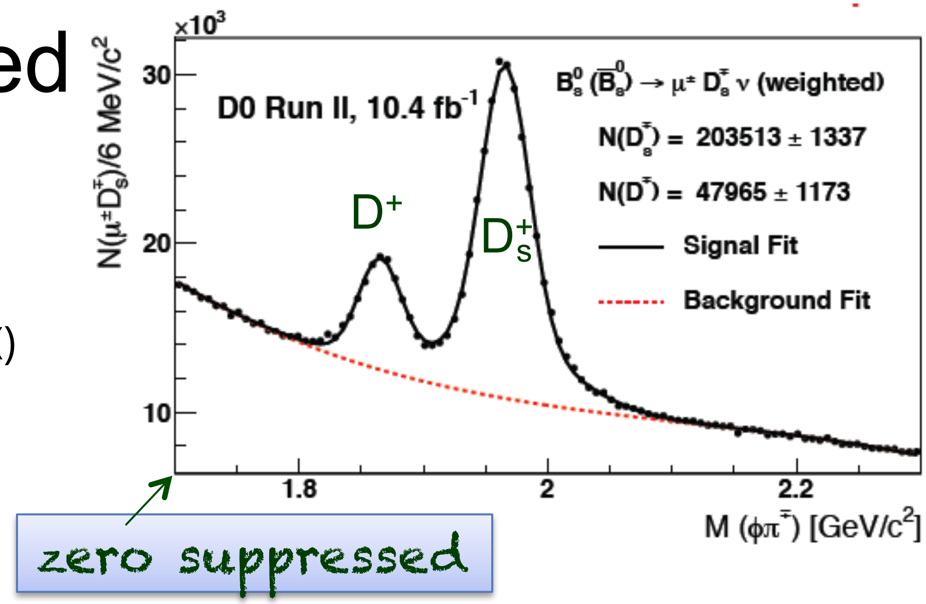
$$a^s_{sl} = (-1.81 \pm 1.06)\%$$



New D0 Analysis

- Measure a_{sl}^{s} using $D_s\mu^-\nu$ events, $D_s \rightarrow \phi\pi^{\pm}$
- Detect a μ associated with a D_s decay

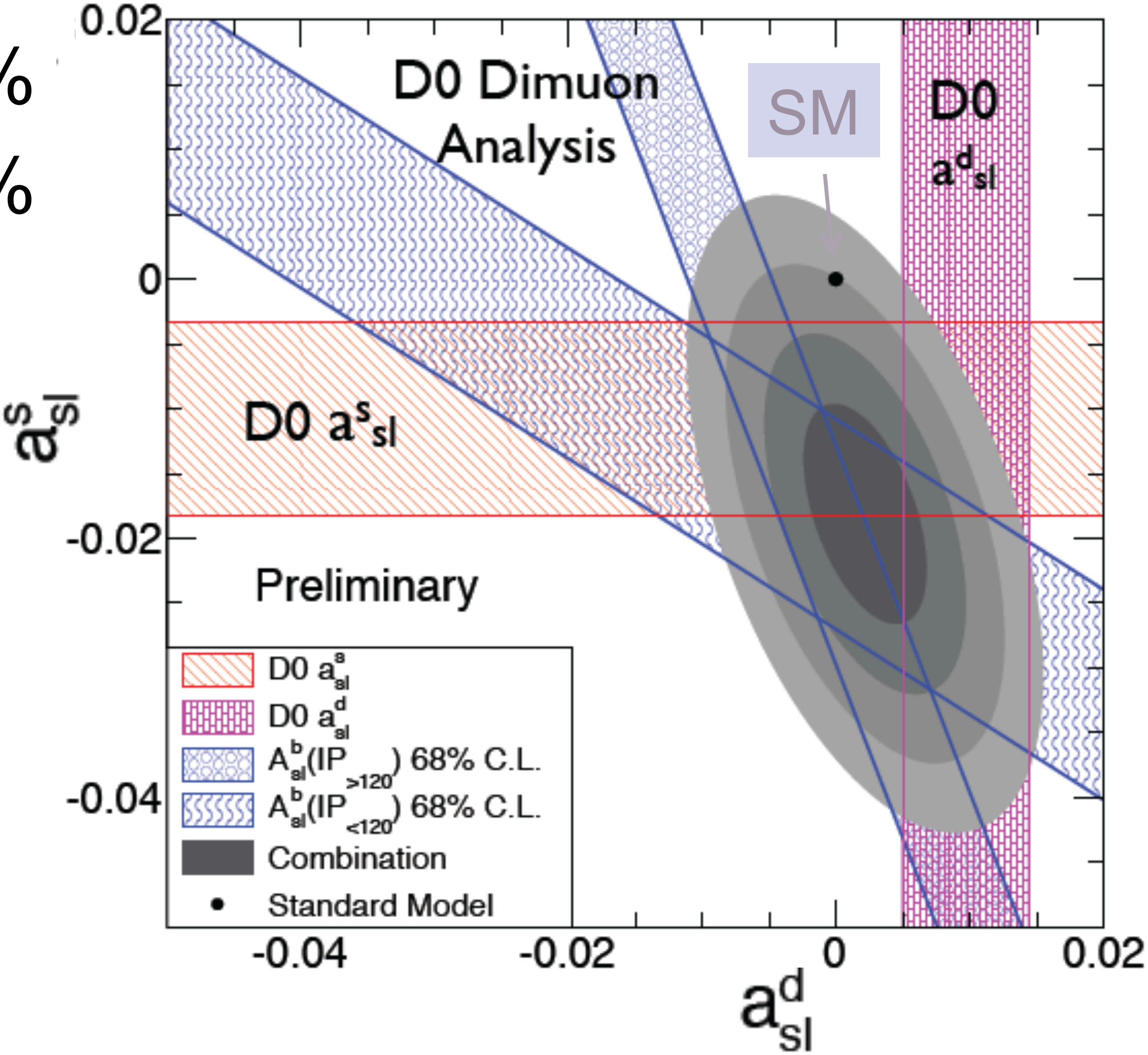




- Find a_{sl}^{s}=(-1.08±0.72±0.17)%
- Also measure a_{sl}^{d} using $D^+\mu^-\nu$, $D^+ \rightarrow K\pi^+\pi^+$
- a_{sl}^{d}=(0.93±0.45±0.14)%

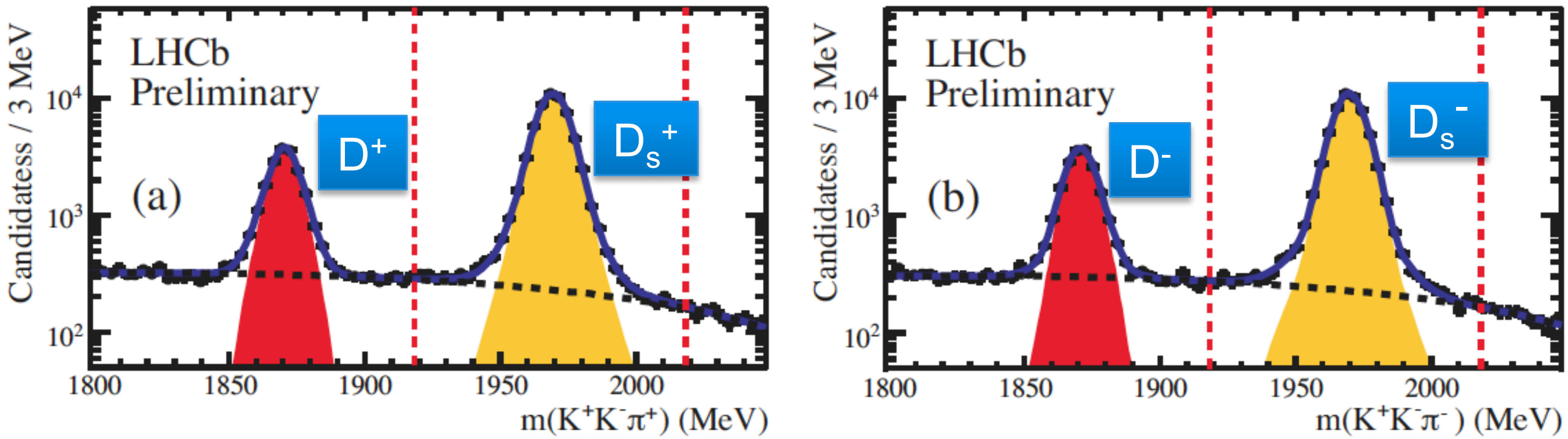
a_{sl} according to D0

- a_{sl}^{s}=(-1.81±0.56)%
- a_{sl}^{d}=(-0.22±0.30)%
- 3σ from SM
- arXiv:1208.5813



LHCb measurement

- Use $D_s\mu^-\nu$, $D_s \to \phi\pi^\pm$, magnet is periodicaly reversed. For magnet down:



- Effect of B_s production asymmetry is reduced to a negligible level by rapid mixing oscillations
- Calibration samples (J/ψ, D^{*+}) used to measure detector trigger, track & muon ID biases

a_{sl} not D0

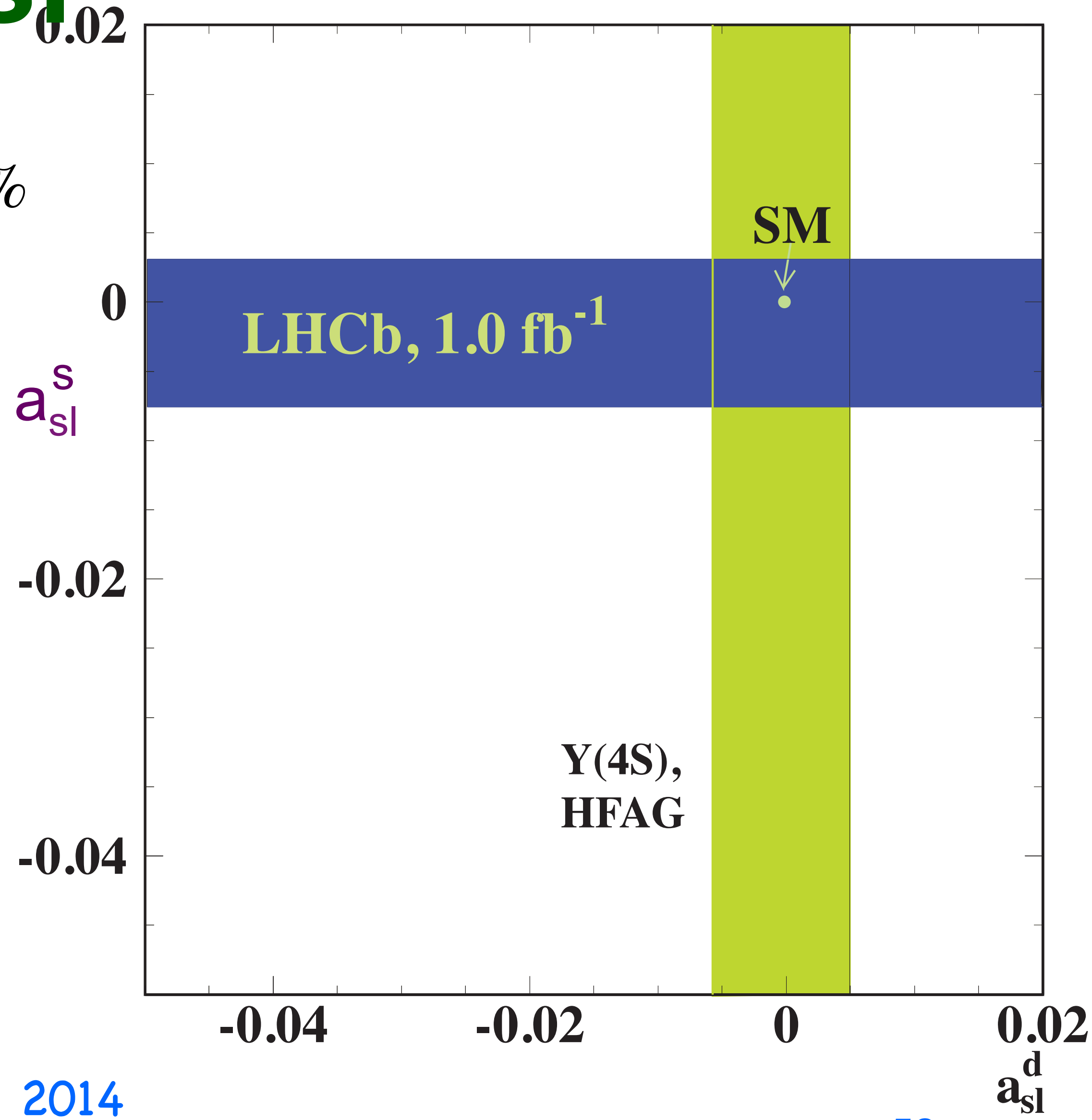
- LHCb finds

$$a_{sl}^{s} = \left(-0.24 \pm 0.54 \pm 0.33\right)\%$$

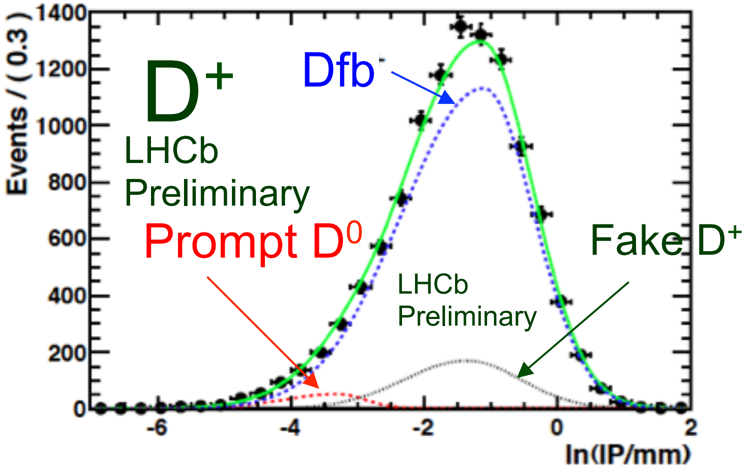
- B-factory

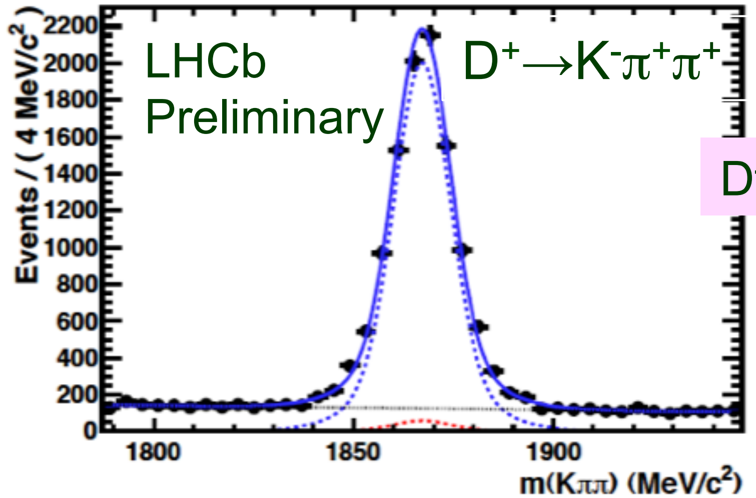
$$a_{sl}^{d} = \left(-0.05 \pm 0.56\right)\%$$

- Results consistent with SM
- Expect ϕ_s to grow as $\sin[2|\beta_s| + \arg(M_{12}^{s})]$ for finite a_{sl}.

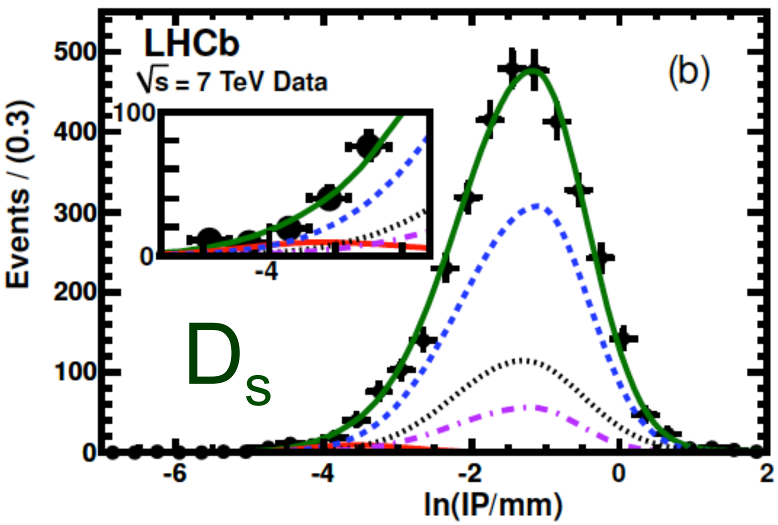


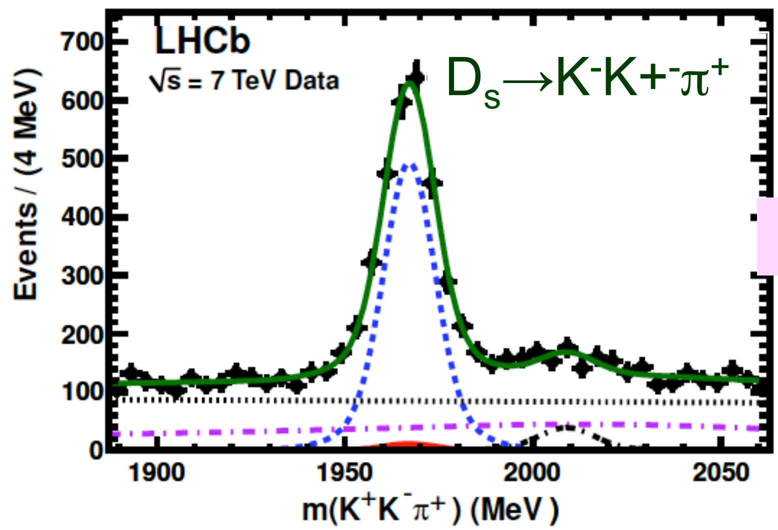
Also D^+, D_s, Λ_b





Dfb: 9406±110



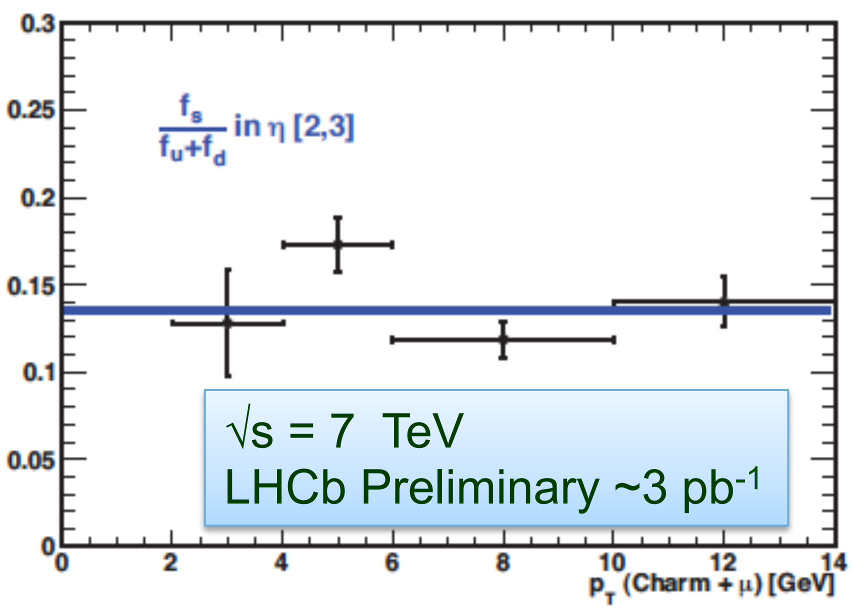


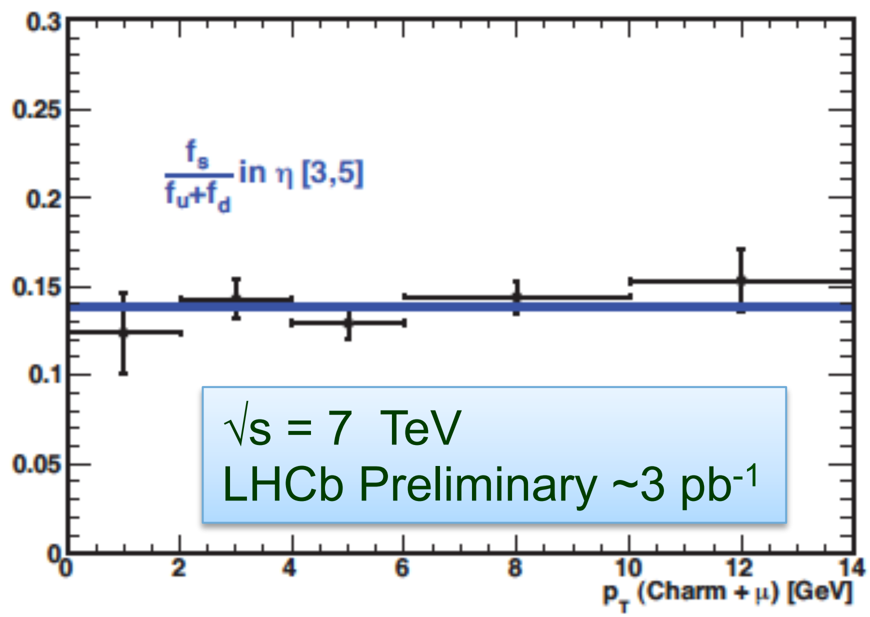
Dfb: 2446±60

Extract B_s fractions

- Crucial to set absolute scale for B_s rates, since not given by e^+e^- machines.
- Must correct for $B_s \rightarrow D^o K^+ X \mu\nu$, also $\Lambda_b \rightarrow D^o p X \mu\nu$

$$f_s / (f_u + f_d) = 0.136 \pm 0.004^{+0.012}_{-0.011}$$

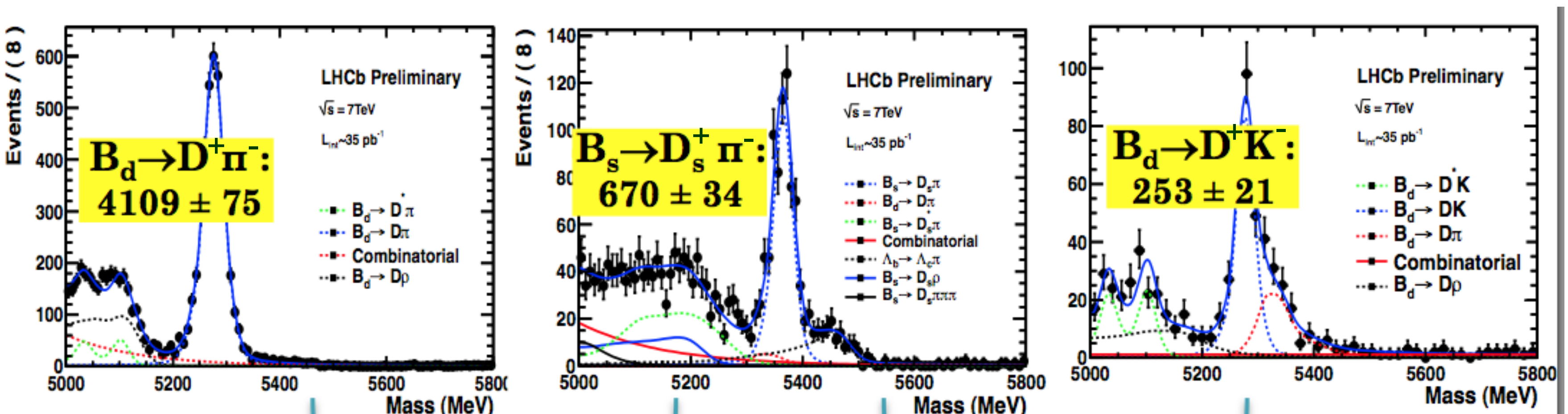




B_s fraction - hadronic

- Also can use hadronic decays + theory ~35 pb^{-1}

√s = 7 TeV
LHCb Preliminary



$$\frac{f_s}{f_d} = 0.249 \pm 0.013^{\rm stat} \pm 0.020^{\rm syst} \pm 0.025^{\rm theor}$$

$$\frac{f_s}{f_d} = 0.242 \pm 0.024^{\rm stat} \pm 0.018^{\rm syst} \pm 0.016^{\rm theor},$$

Semileptonics: $f_s / f_d = 0.272 \pm 0.008^{+0.024}_{-0.022}$

Detector Requirements - General

- Every modern heavy quark experiment needs:
  - Vertexing: to measure decay points and reduce backgrounds, especially at hadron colliders
  - Particle Identification: to eliminate insidious backgrounds from one mode to another where kinematical separation is not sufficient
  - Muon & electron identification because of the importance of semileptonic & leptonic final states including J/ψ decay
  - γ, π^o & η detection
  - Triggering, especially at hadronic colliders
  - High speed DAQ coupled to large computing for data processing
  - An accelerator capable of producing a large rate of b's

CPV Time Evolution

- Consider $$a[f(t)] = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to f)}{\Gamma(\bar{M} \to f) + \Gamma(M \to f)}$$
- Define $$A_f \equiv A(M \to f), \bar{A}_f \equiv A(\bar{M} \to f), \quad \lambda_f = \frac{p}{q}\frac{\bar{A}_f}{A_f}$$
- Only 1 A_f & $\Delta\Gamma=0$ $\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(1 - \text{Im}\,\lambda_f \sin(\Delta M t)\right)$
- Then $a[f(t)] = -\text{Im}\,\lambda_f$, & λ_f is a function of V_{ij} in SM
- For B^o, $\Delta\Gamma\approx 0$, but there can be multiple A_f

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(\frac{1-|\lambda_f|^2}{2}\cos(\Delta M t) - \text{Im}\,\lambda_f \sin(\Delta M t)\right)$$

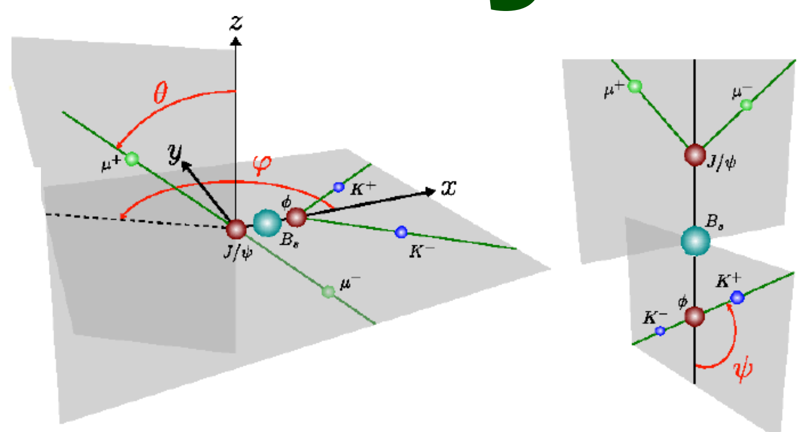
- If in addition $\Delta\Gamma\neq 0$, eg. B_s

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma t}{2} + \frac{1-|\lambda_f|^2}{2}\cos(\Delta M t) - \text{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} - \text{Im}\,\lambda_f \sin(\Delta M t)\right)$$

See Nierste
arXiv:0904.1869 [hep-ph]

Transversity

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



k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\|A_0\|^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\|A_\parallel(t)\|^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\|A_\perp(t)\|^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\|A_s(t)\|^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

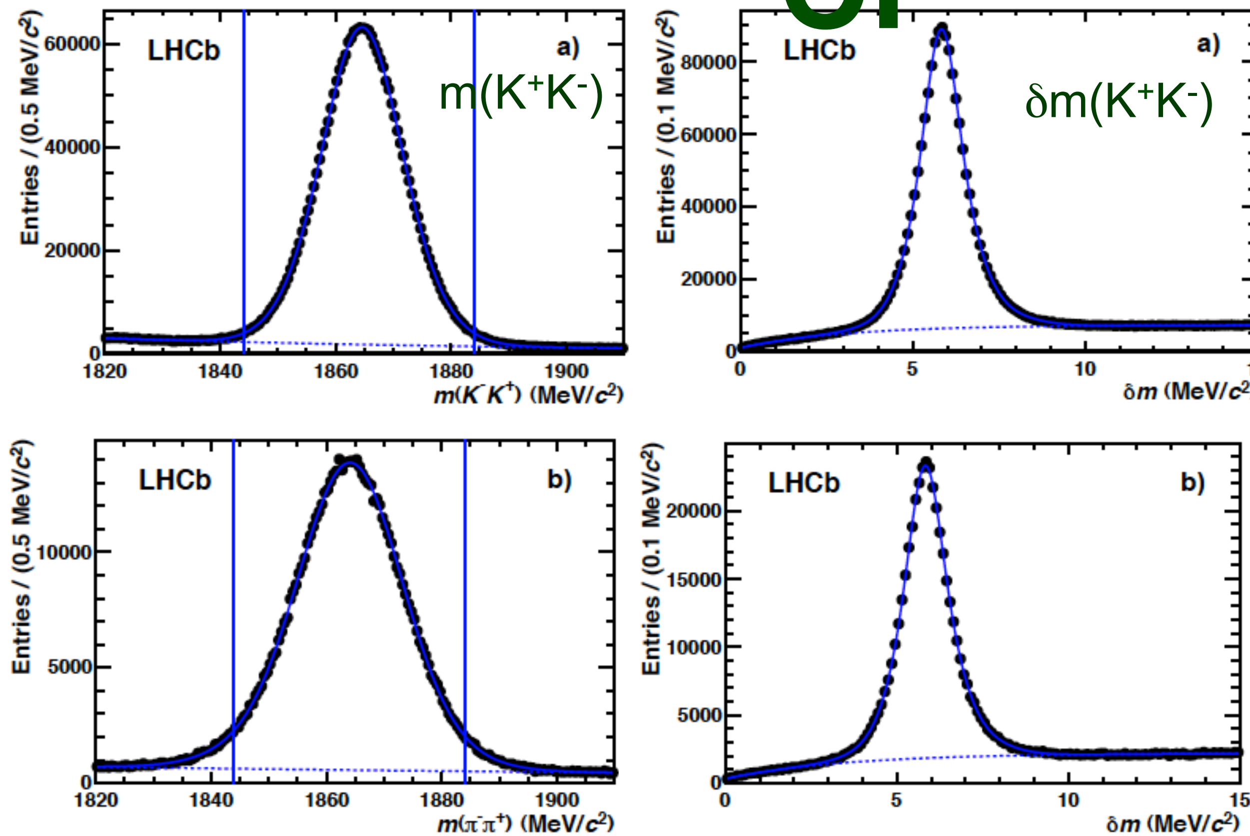
for S-wave under ϕ predicted by Stone & Zhang PRD 79, 074024 (2009)

Transversity II

$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_\parallel^*(t)\,A_\perp(t)) &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta\_\|)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)\right], \\
\Re(A_0^*(t)\,A_\parallel(t)) &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_0^*(t)\,A_\perp(t)) &= |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)\right], \\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right], \\
\Re(A_s^*(t)A_\parallel(t)) &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\ \cos\phi_s \sin(\Delta m t)\right. \\
&\quad \left. + \cos(\delta_\parallel - \delta_s)\cos(\Delta m t)\right], \\
\Im(A_s^*(t)A_\perp(t)) &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta m t)\right], \\
\Re(A_s^*(t)A_0(t)) &= |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)\right].
\end{aligned}
$$

only term for $f=f_{cp}$

LHCb ΔA_{CP}



Systematic err

Source	certain
Fiducial requirement	0.01%
Peaking background asymmetry	0.04%
Fit procedure	0.08%
Multiple candidates	0.06%
Kinematic binning	0.02%
Total	0.11%

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$$

Not definitive: only 3.5σ, but is a nice hint, adding other experiments get (-0.65±0.18)%

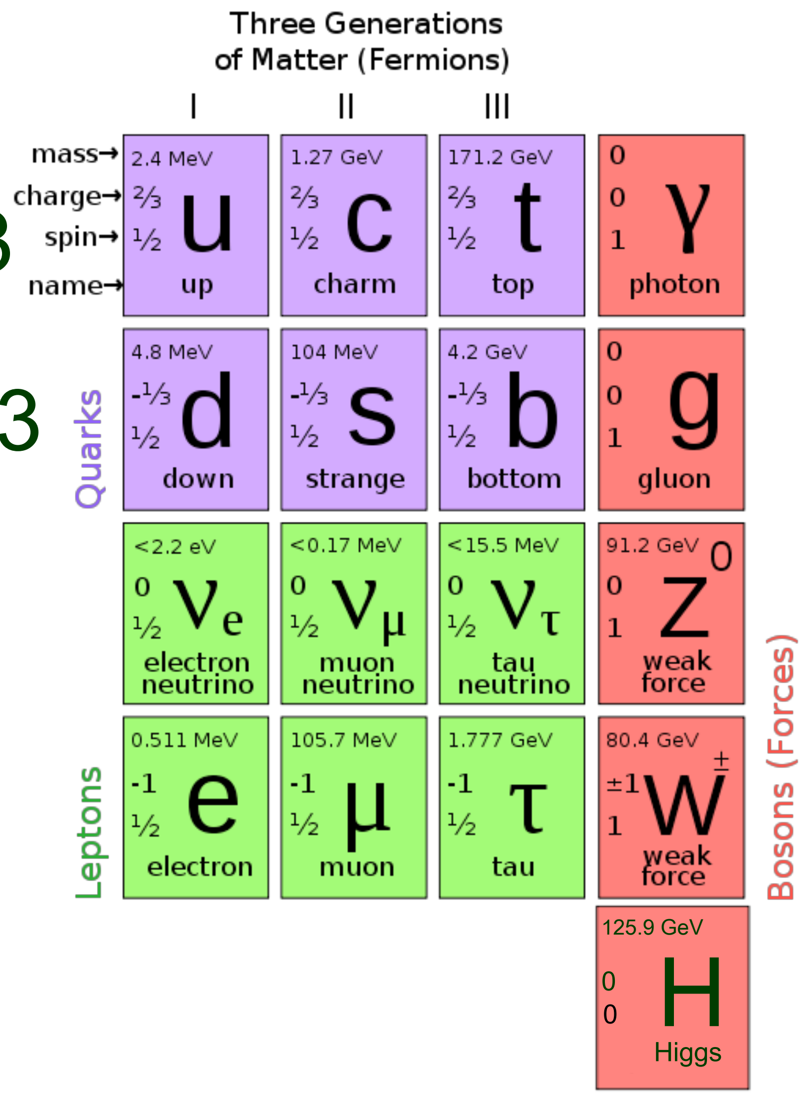
The Standard Model

charge 2/3

charge -1/3

charge 0

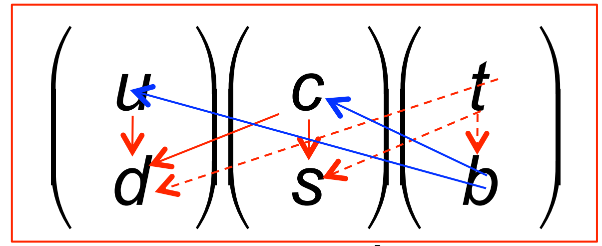
charge -1



No understanding of why 3 generations, but allows for CP violation in both quark & neutrino sectors

Quark Mixing & CKM Matrix

- All 3 generations of -1/3 quarks (d, s, b) are mixed



- Described by CKM matrix (also ν are mixed)

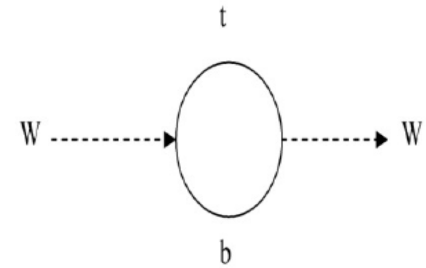
$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\left(\rho - i\eta\right) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix}$$

- Unitary 3x3 matrix can be described by 4 parameters λ=0.225, A=0.8, constraints on ρ & η
- These are fundamental constants of nature in the Standard Model

Effects on M_W from quantum loops

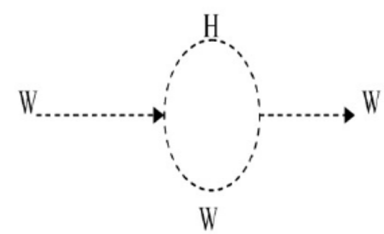
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t

$$\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$$



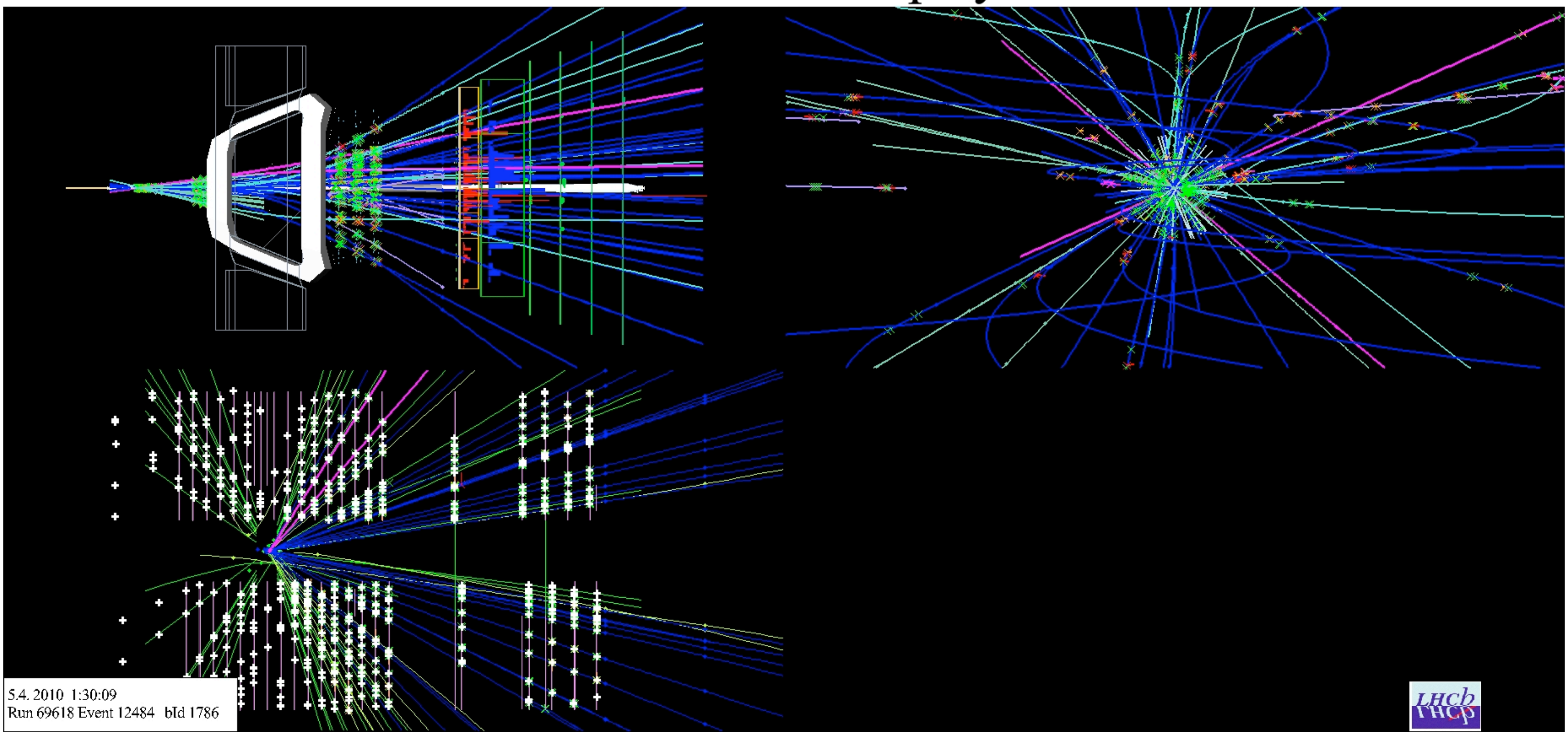
  - M_w changes due to m_H
  - Gave predictions of m_H prior to discovery

$$\frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H}$$

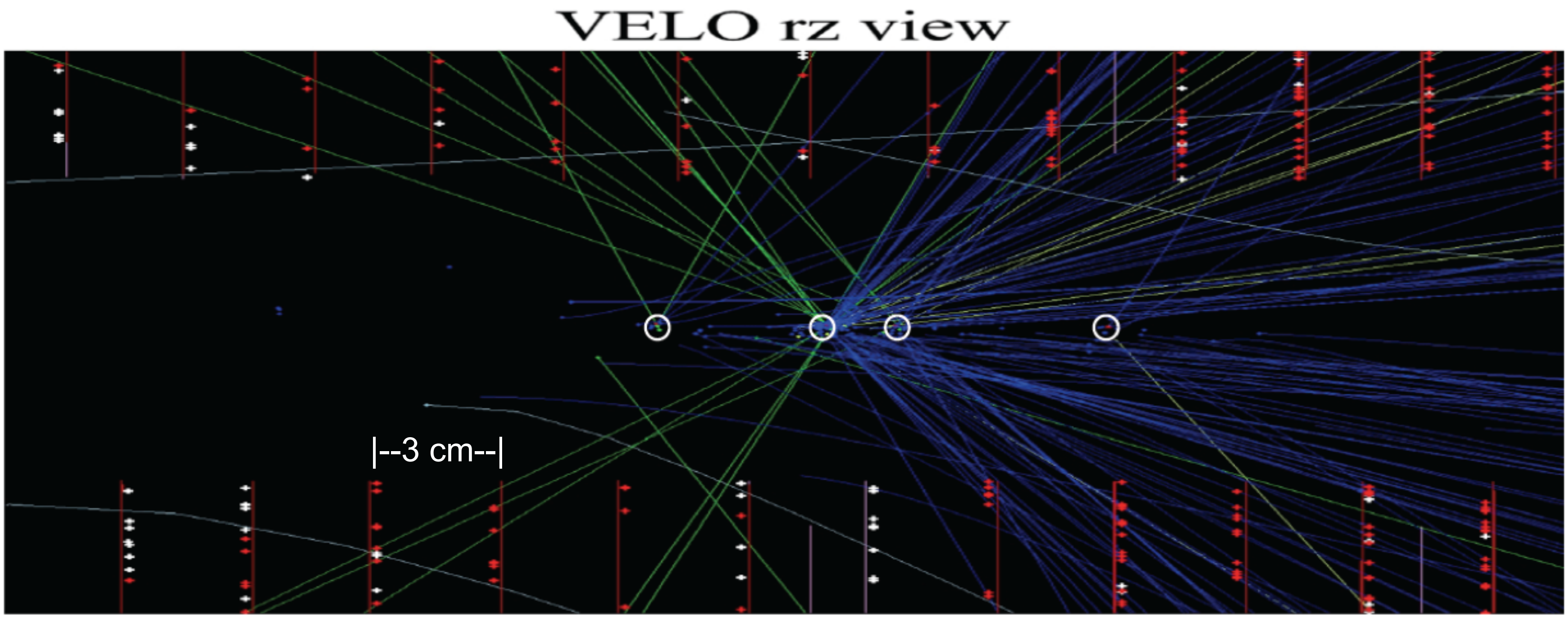


$B^- \rightarrow J/\psi\ K^-$

LHCb Event Display



Running Conditions



- 20 MHz of bunch crossing (in 2012, with 50 ns bunch spacing) with an average of 1.5 pp interactions per bunch crossing → this level of pileup not an issue for LHCb