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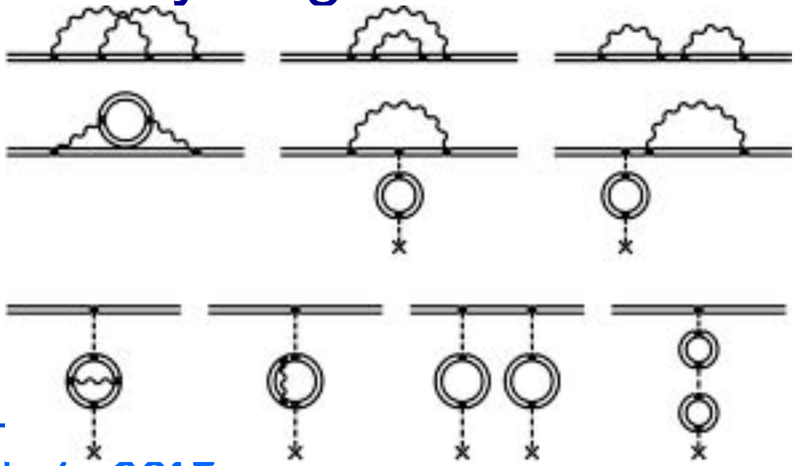
Oct. 10, 2015

New technology and b physics at LHCb

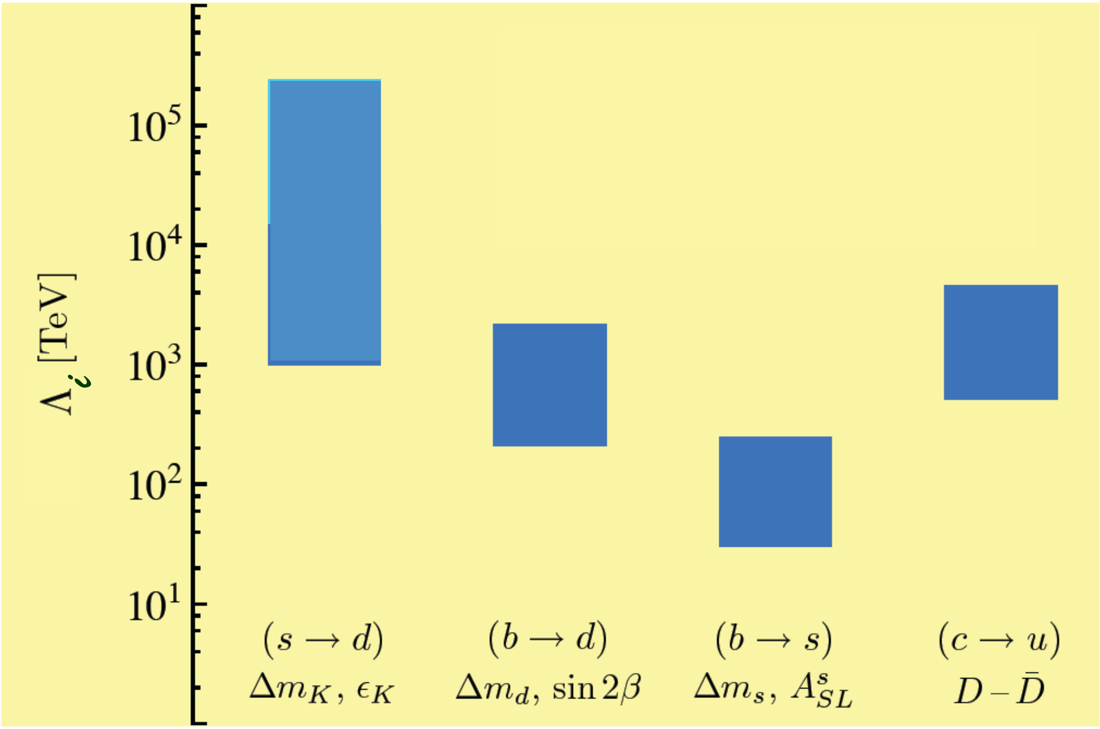
Seeking New Physics

- Flavor Physics as a tool for NP discovery
  - While measurements of CKM elements (fundamental constants) are fun, the main purpose 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



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 $c_i \sim 1$



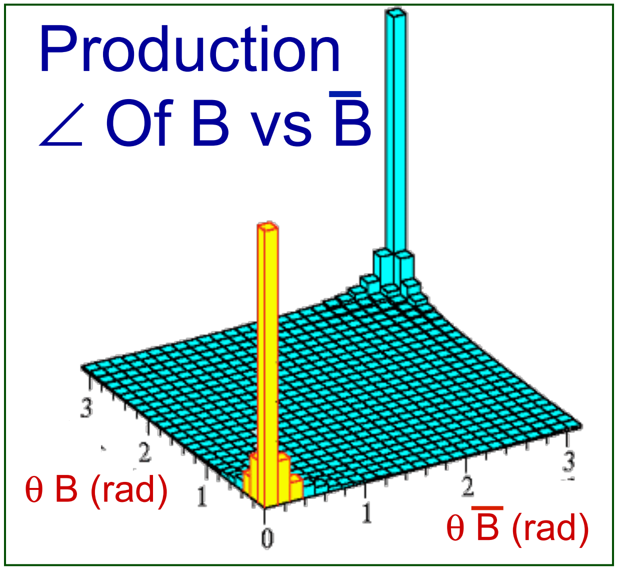
Ways out

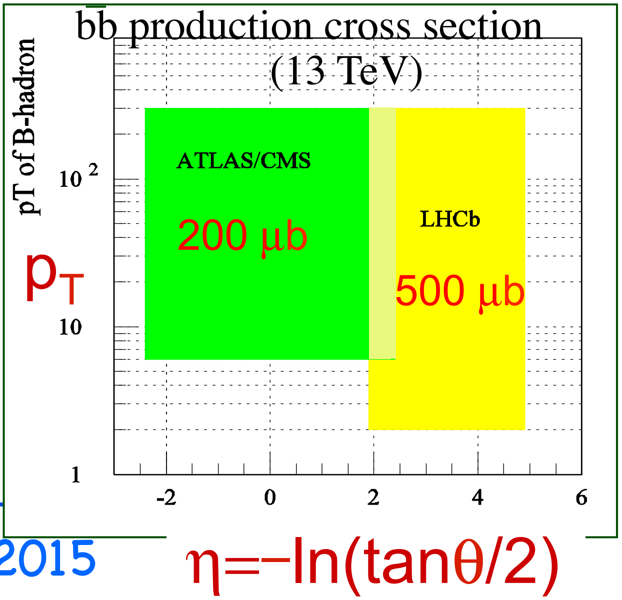
1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

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

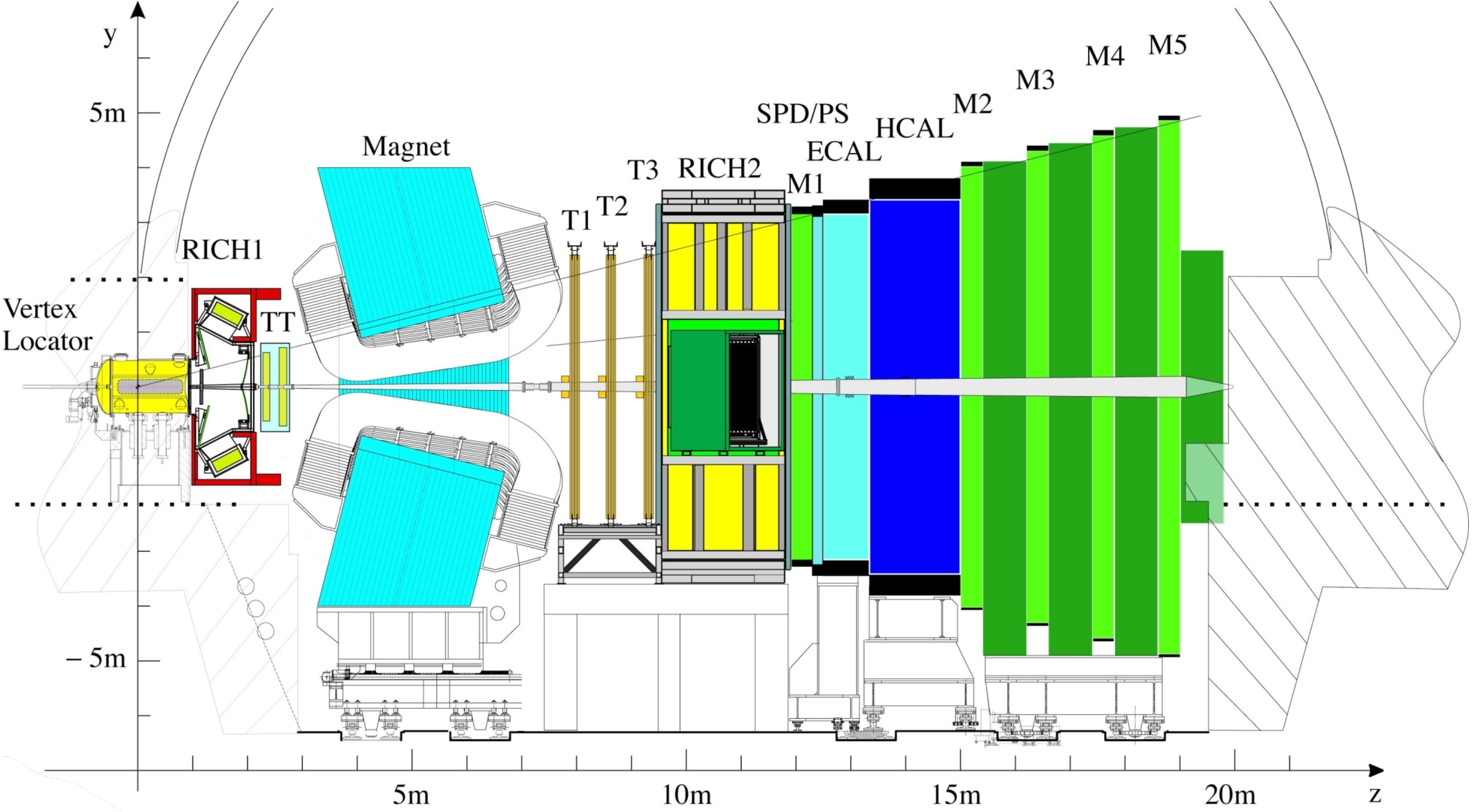
The Forward Direction at the LHC

- 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 $\mathcal{L}=4\text{x}10^{32}/\text{cm}^2\text{-s}$, we get $\sim 10^{12}$ B hadrons in 10^7 sec in detector


Production ∠ Of B vs $\bar{B}$

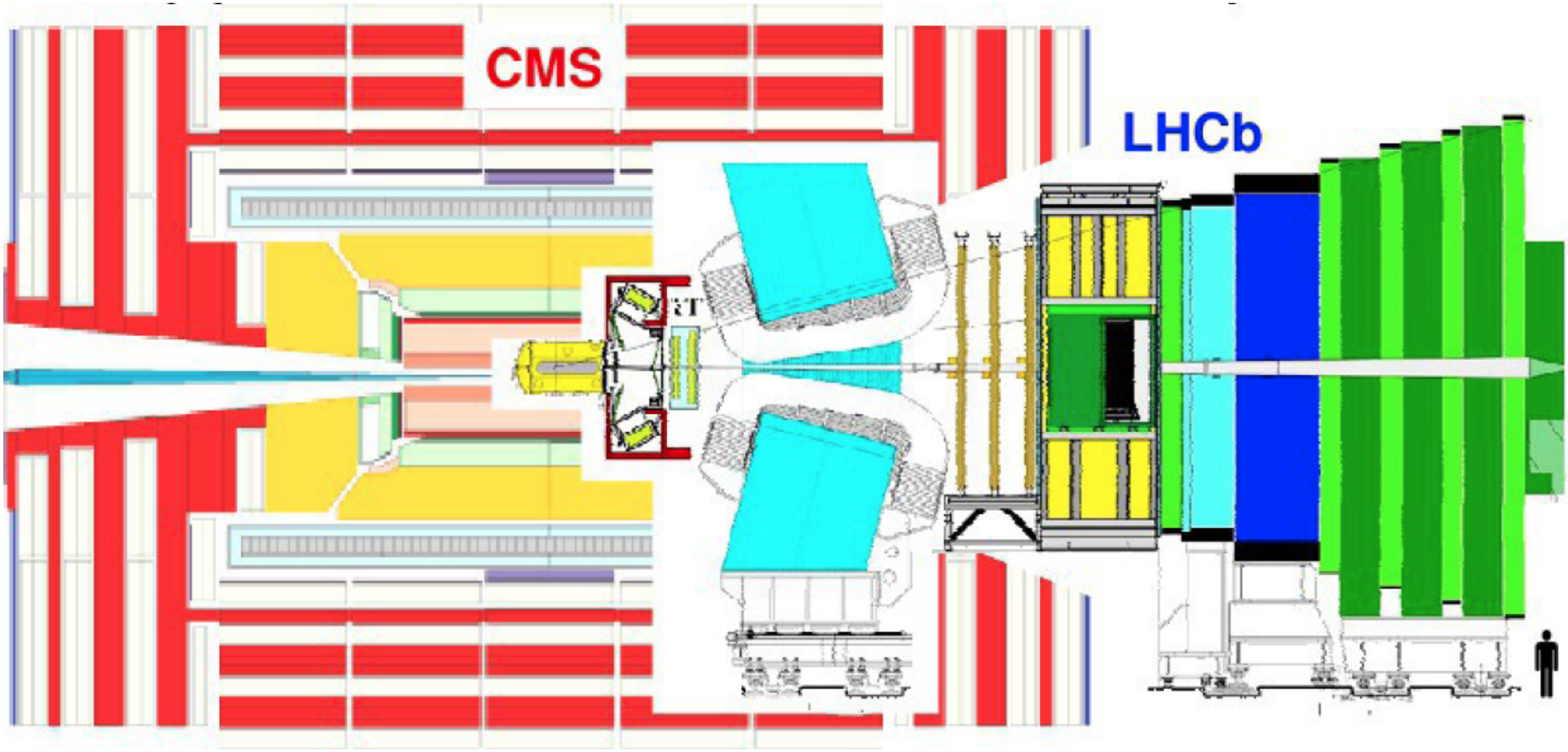


The LHCb Detector



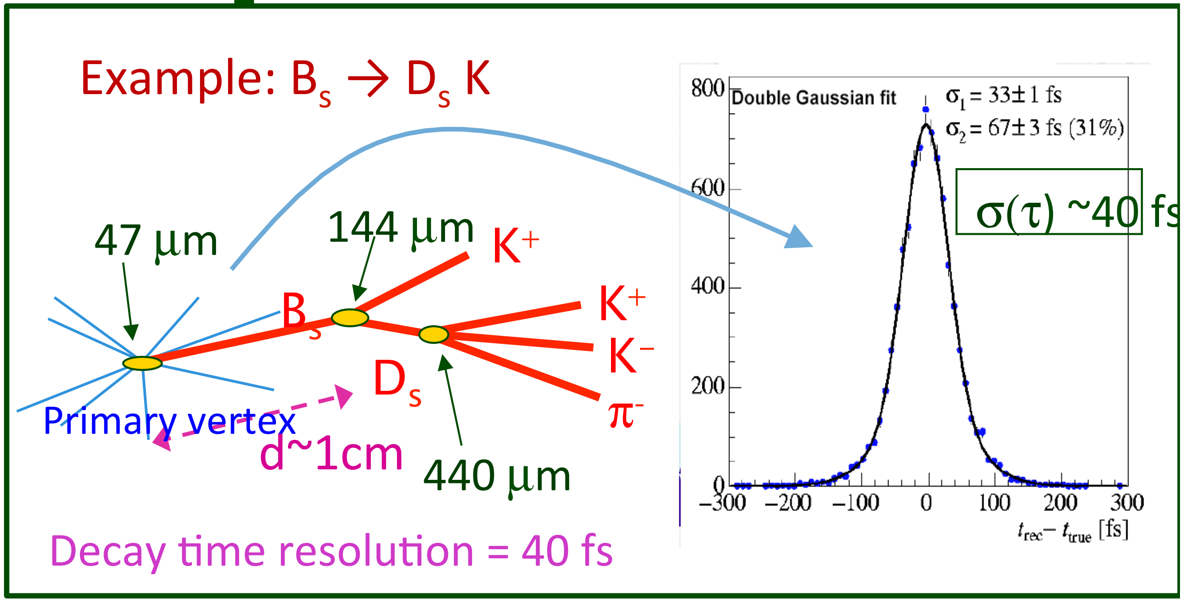
Detector Geometry

- Complementary to ATLAS & CMS
- Much less expensive



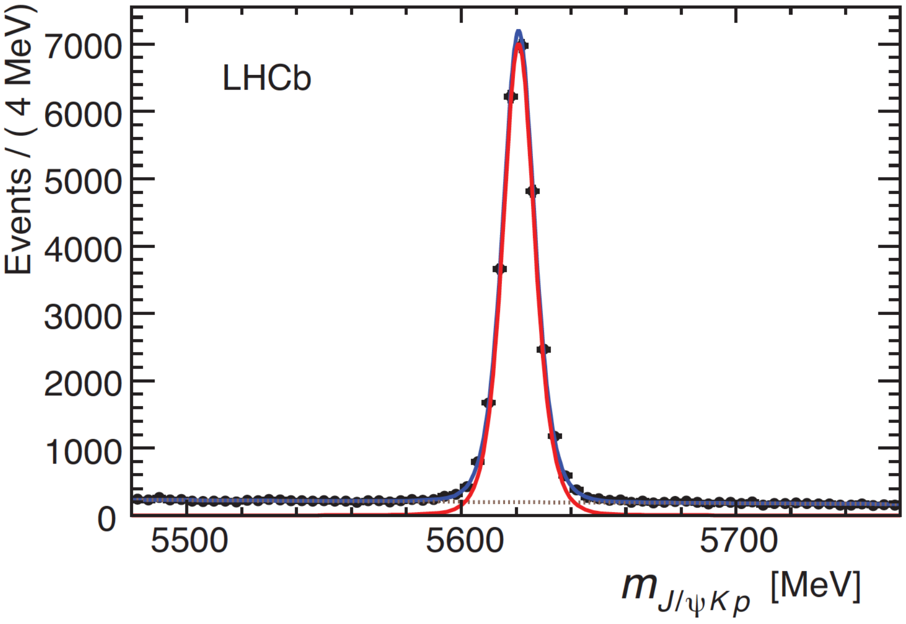
Detector performance

- Successful run 1 operation
- Typical resolutions


Example: $B_s \to D_s K$

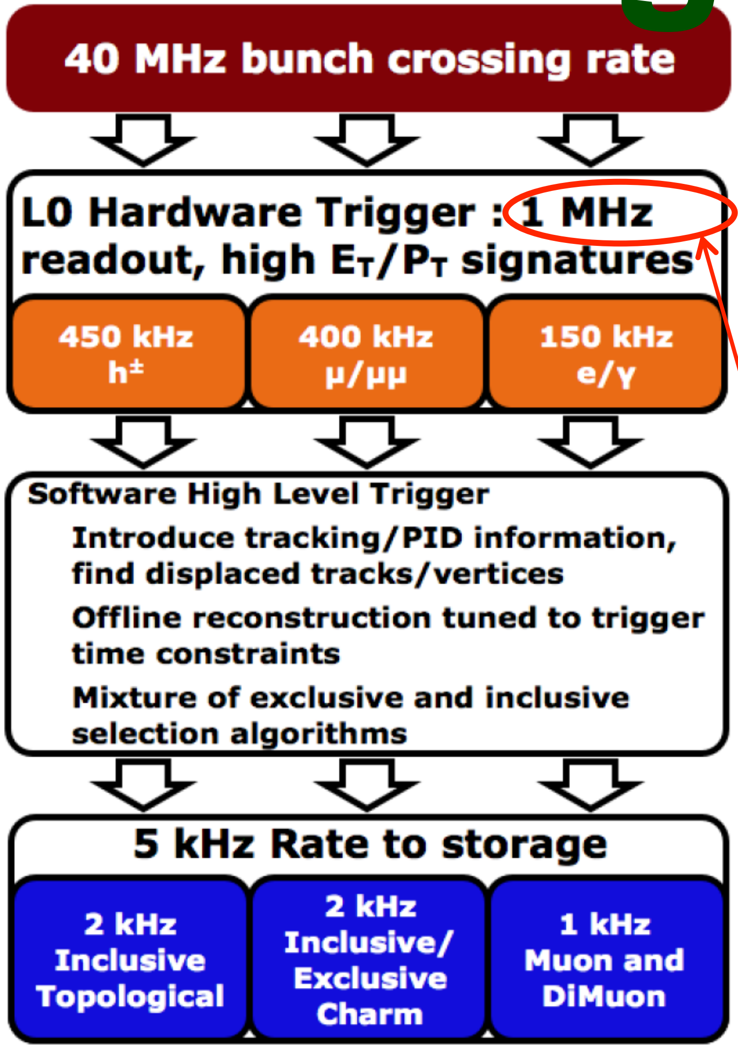
Decay time resolution = 40 fs

$$\Lambda_b^0 \to J/\psi K^- p$$



- Excellent particle
- identification

Triggering 2012



40 MHz bunch crossing rate

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

450 kHz h±	400 kHz μ/μμ	150 kHz e/γ

Software High Level Trigger

- Introduce tracking/PID information, find displaced tracks/vertices
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

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

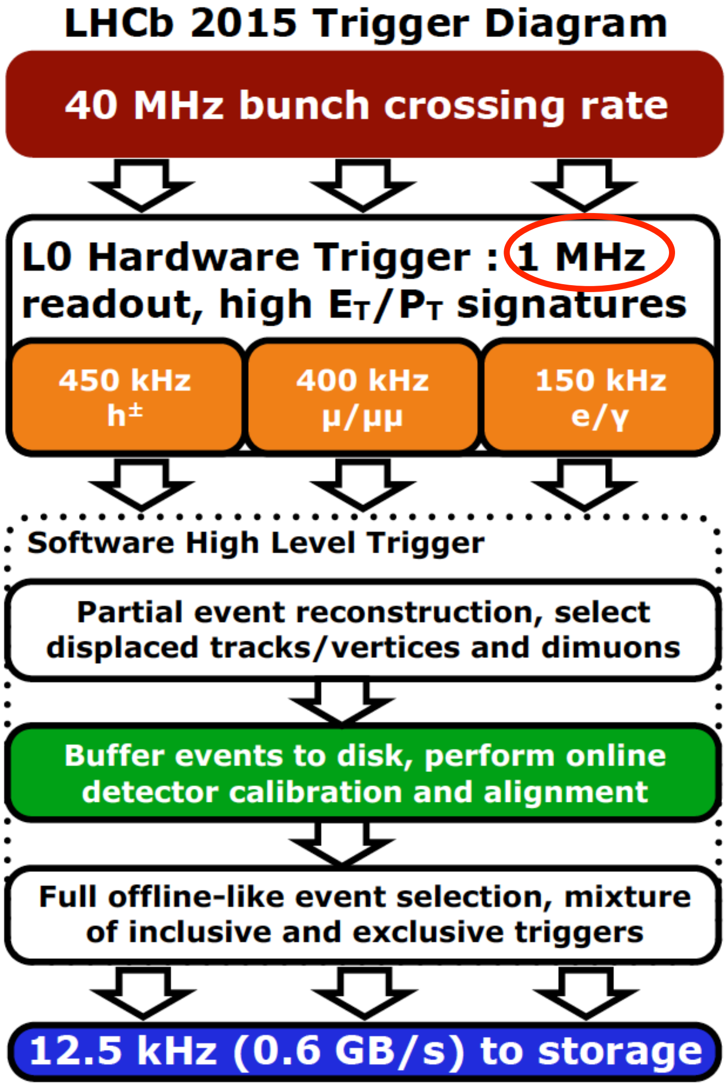
Software level (High Level Trigger, HLT)

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

Very flexible algorithms, writes ~5 kHz to storage

This is the bottleneck

Triggering 2015



- Calibration is done completely online
- Event reconstruction is done online & not repeated
- Turbo stream implemented for some analyses: only tracks & vertices that satisfy trigger
- Off to a good start

LHCb upgrade

- Triggering 2020- No 1 MHz limit, all triggers done by reading out full detector at 40 MHz & using only software to decide.
- All detector elements are being rebuilt to allow this to occur
  - New pixel vertex locator (VELO)
  - New Upstream Silcon Tracker (UT)
  - RICH HPD's replaced by PM's
  - New Ecal & Muon readouts (minor changes)
  - More trigger & online computing
- Consequences: increased ε_{trig}, more lines

Detector Performance

- Current 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

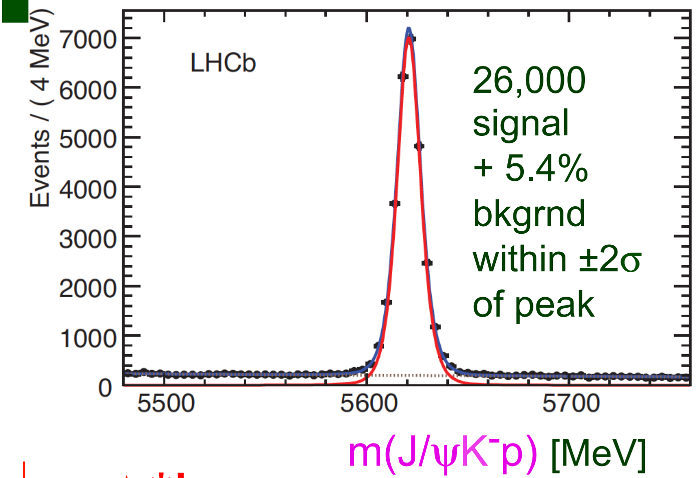
A few results

Pentaquarks

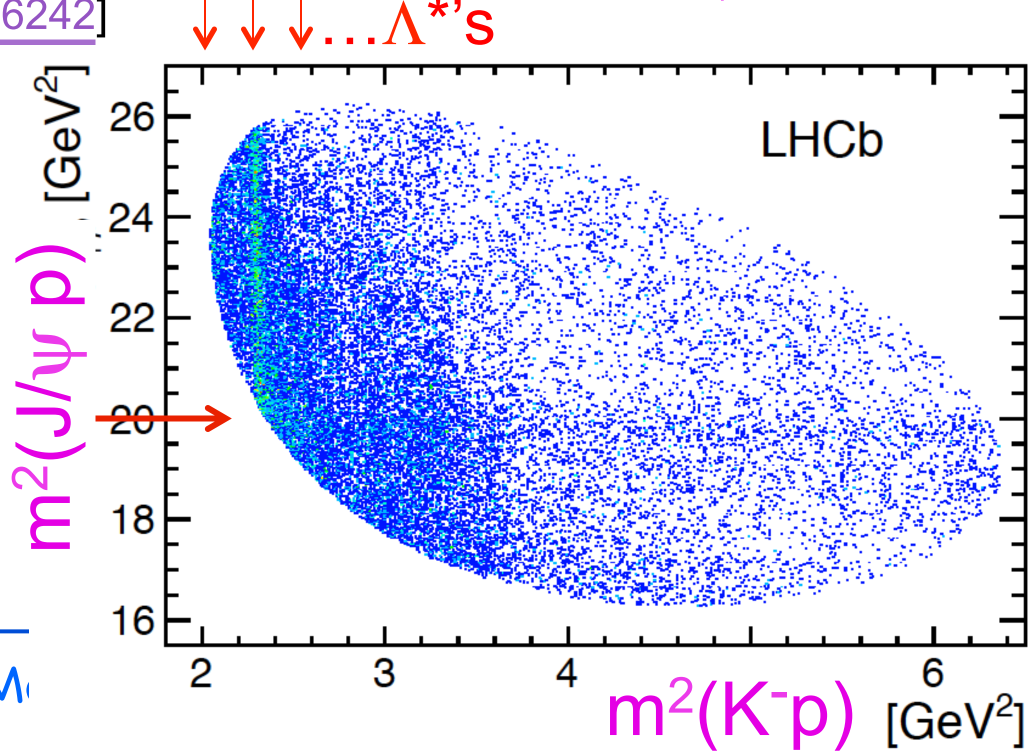
- $\Lambda_b \to J/\psi K^- p$, first looked for in LHCb as a potential background for $B^0 \to J/\psi K^+ K^-$
- Large signal found, used for Λ_b lifetime [arXiv:1402.6242]
- Dalitz plot

showed an unusual feature

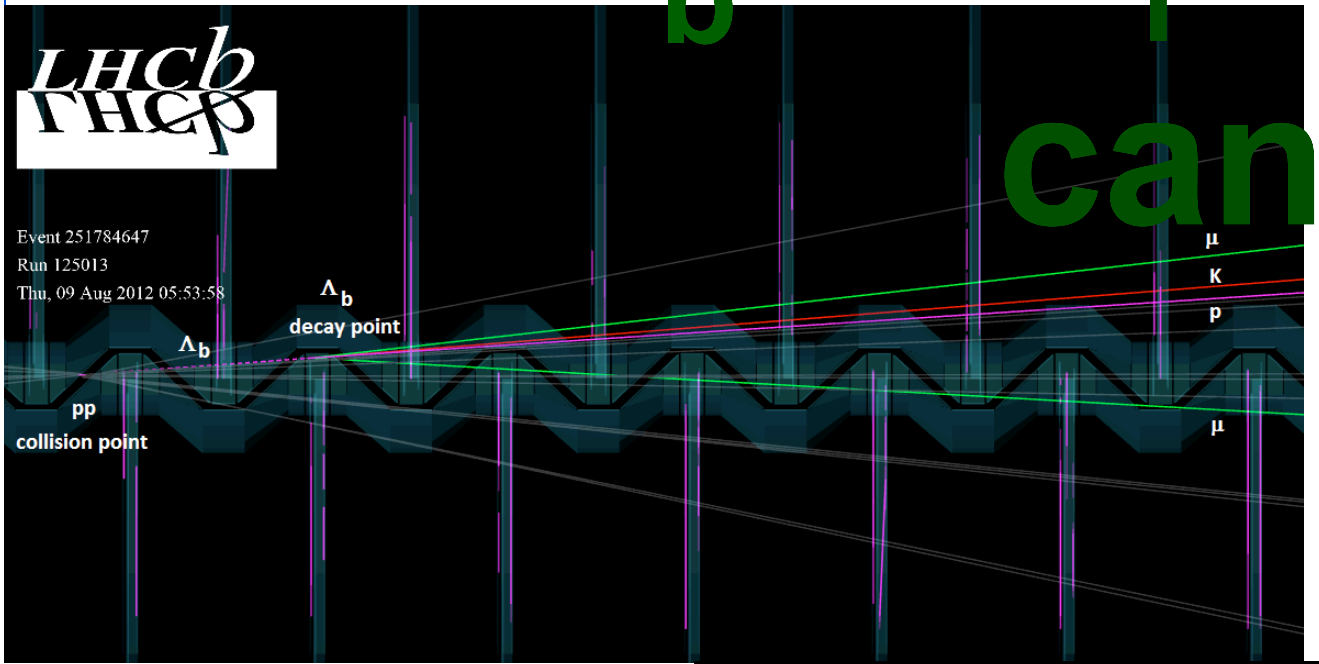
[arXiv:1507.03414]

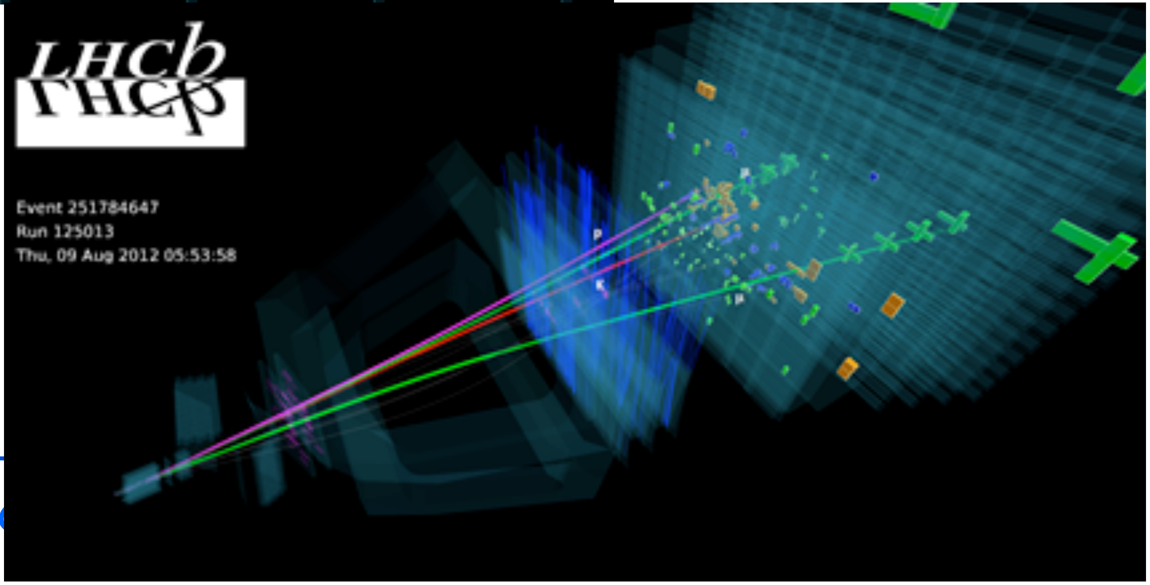


26,000 signal + 5.4% bkgrnd within ±2σ of peak

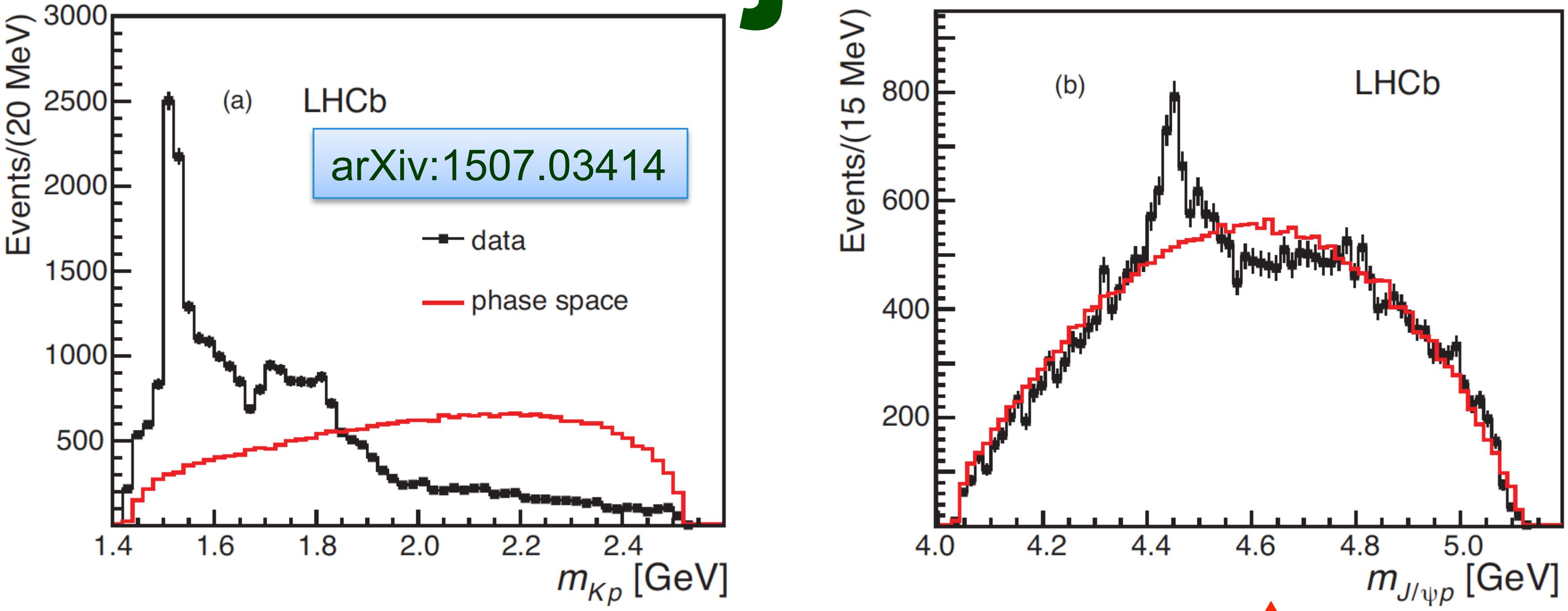


A $\Lambda_b \rightarrow J/\psi K^- p$ candidate

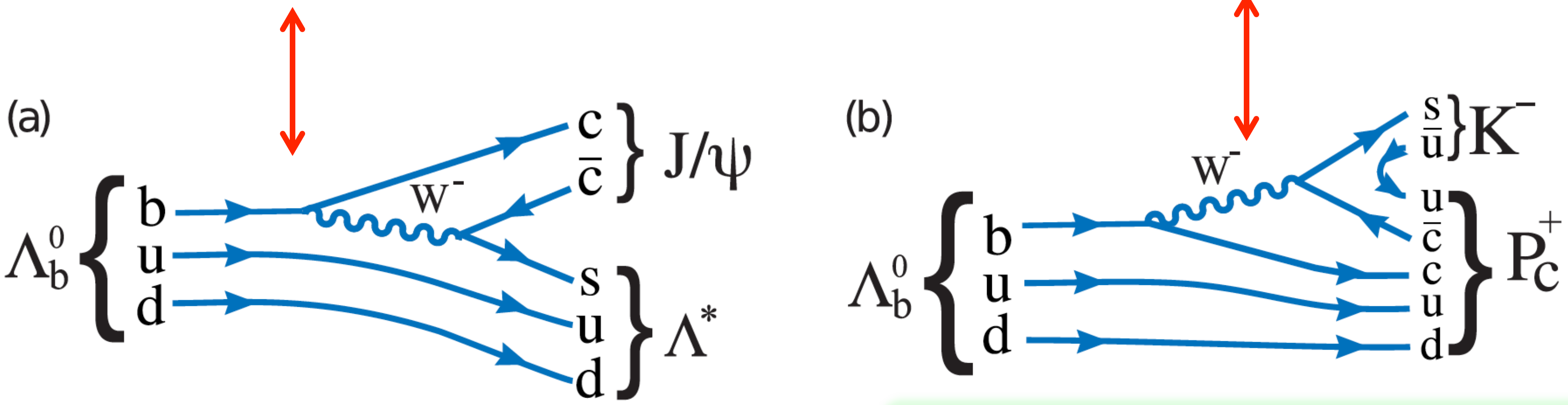




Projections



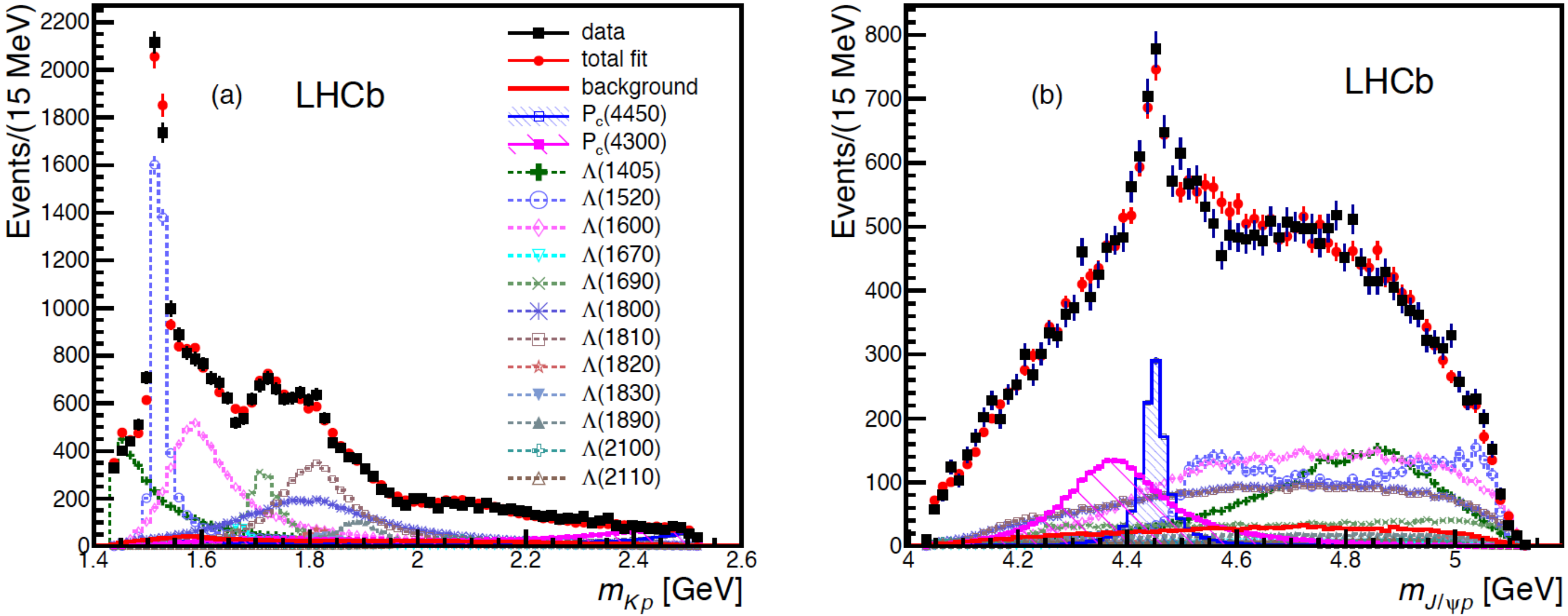
arXiv:1507.03414



Does this diagram exist?

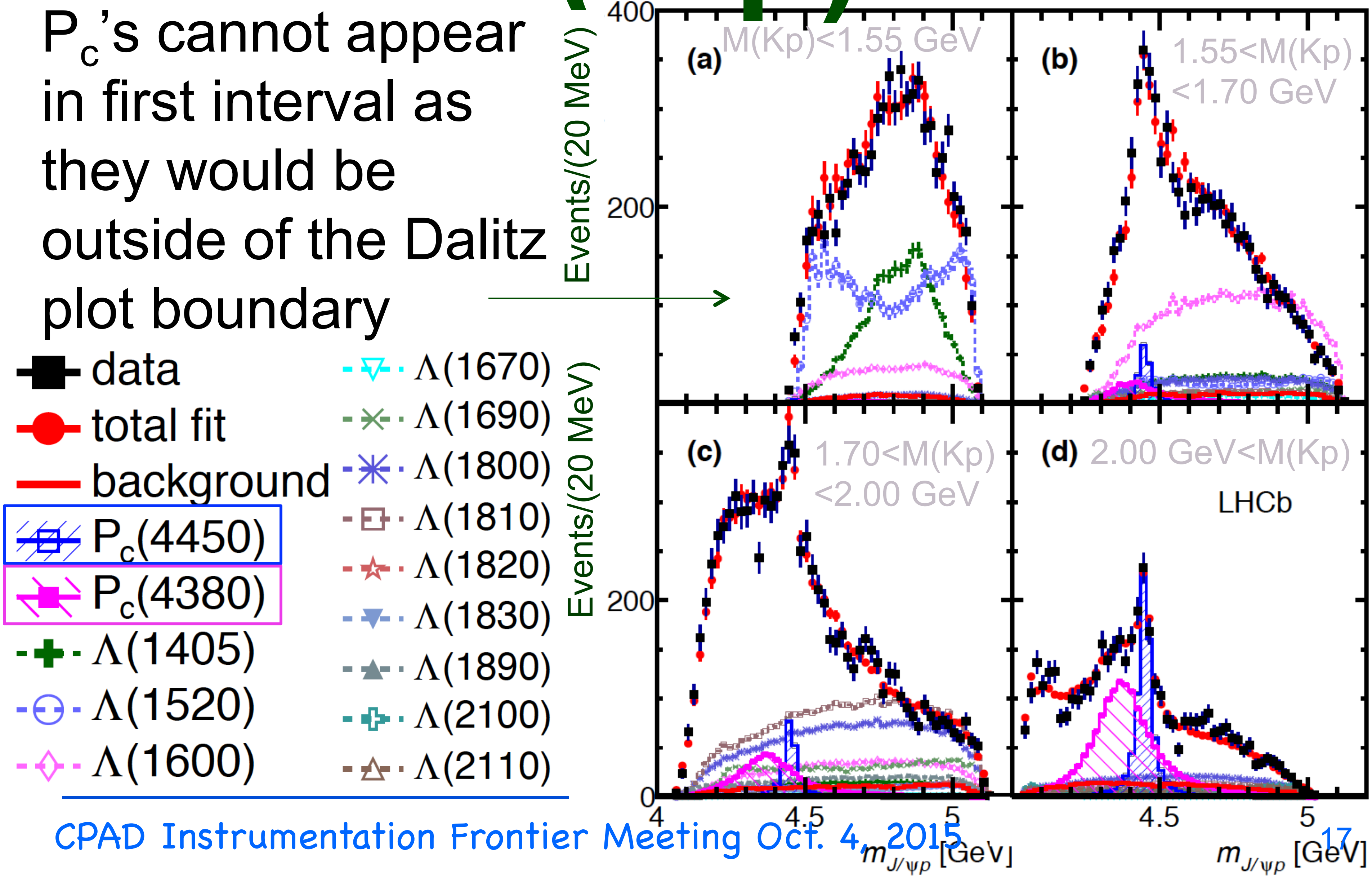
Reduced model with 2 P_c's

- Do a full amplitude fit. No solution with zero or one P_c states. Best fit has two states, masses 4380±30 MeV, & 4450±3 MeV with $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are allowed



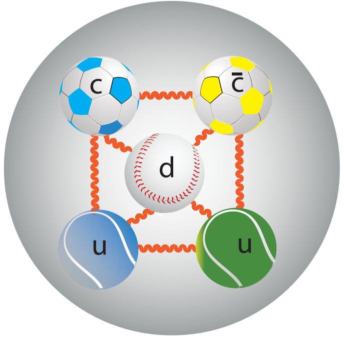
In m(K^-p) slices

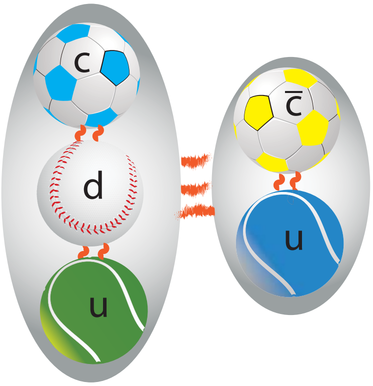
P_c's cannot appear in first interval as they would be outside of the Dalitz plot boundary



Internal binding?

- Tightly bound or Molecularly bound

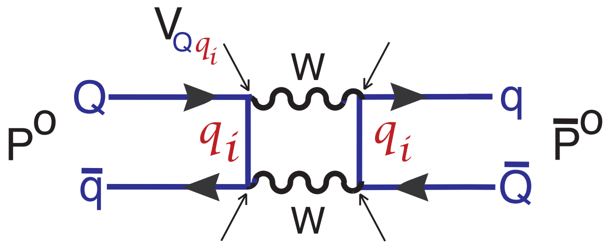




- Need to find new states & new decay modes
- Many predicted, e.g. $P_c \rightarrow \Lambda_c D^*$, $\eta_c p$ - high multiplicity final states

Neutral Meson Mixing

- Neutral mesons can transform into their anti-particles via 2nd order weak interactions

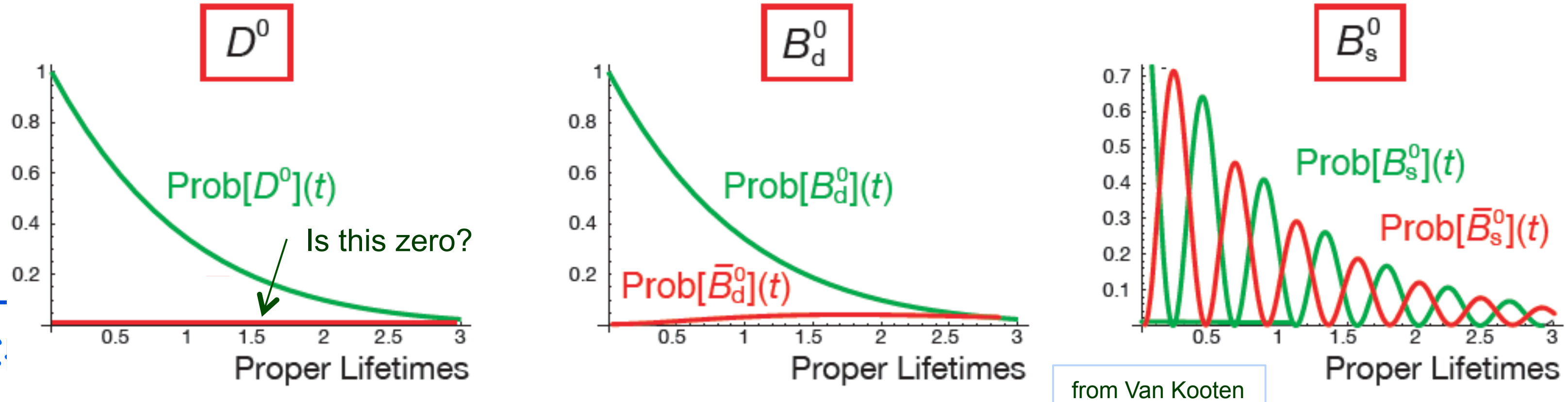


New particles possible in loop

+ “long distance” for D^o

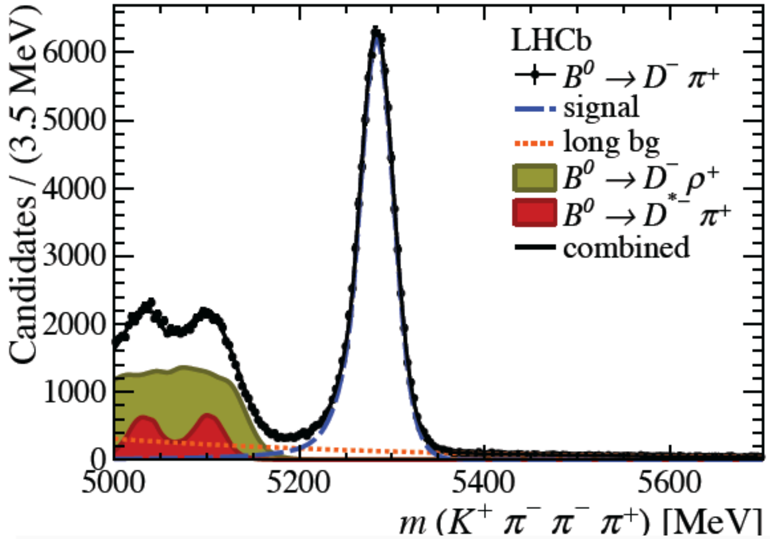
$D^0 \Longrightarrow \pi\pi,.. \Longrightarrow \bar{D}^0$

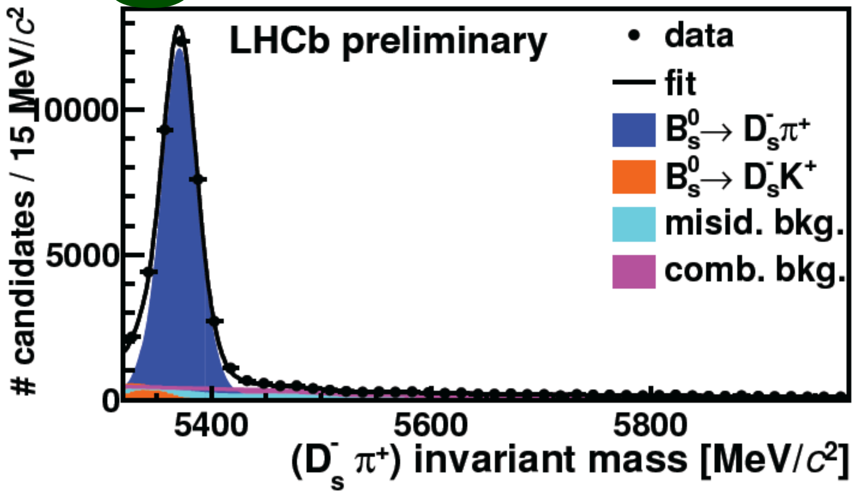
- Short distance transition rate depends on
  - mass of intermediate q_i, the heavier the better, favors s & b since t is allowed, while for c, b is the heaviest
  - CKM elements V_{ij}

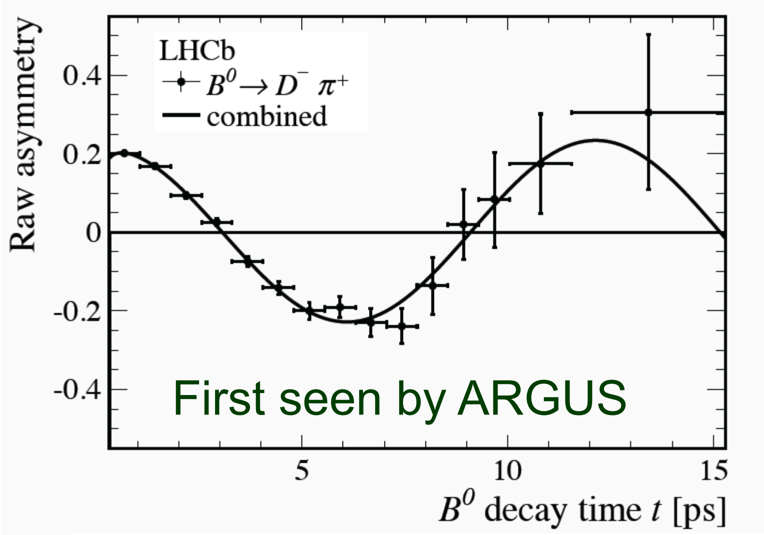


from Van Kooten

Mixing data

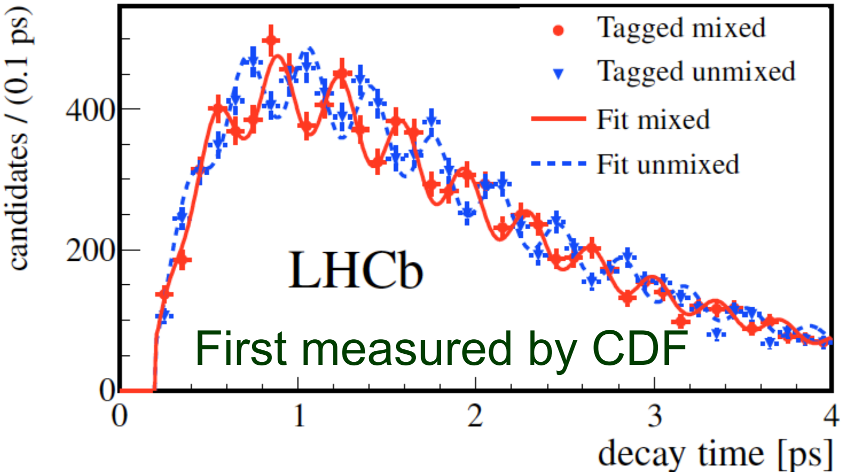






First seen by ARGUS

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

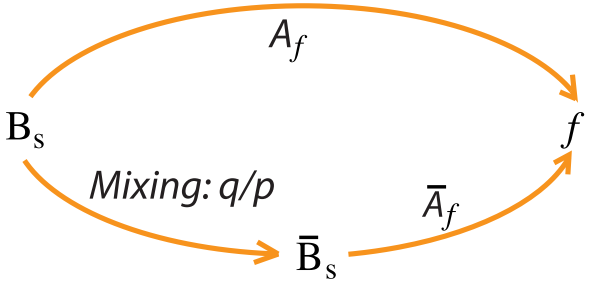


First measured by CDF

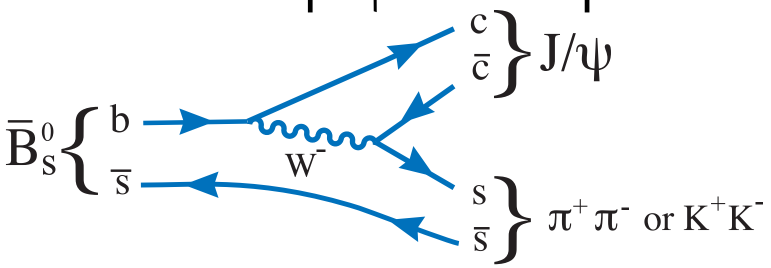
$$\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}$$

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

- Interference between mixing & decay



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



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

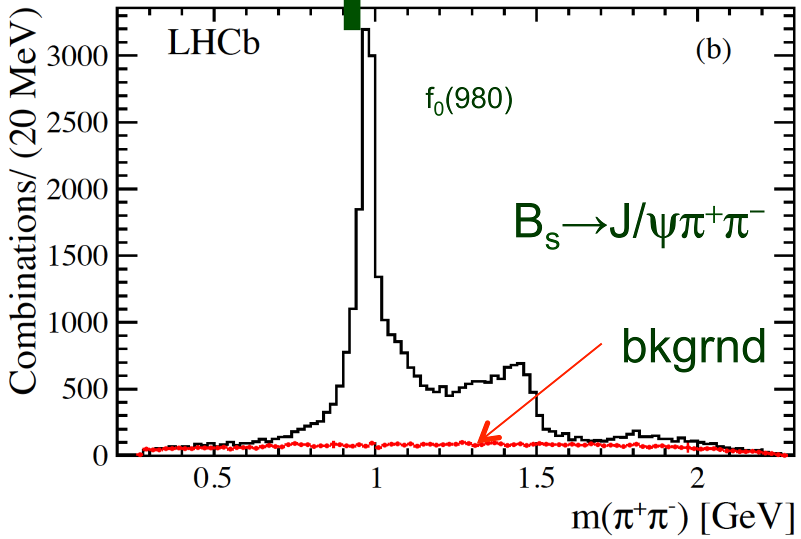
- Small CPV expected, good place for NP to appear
- $B_s \rightarrow J/\psi\phi$ is not a CP eigenstate, as it's a vector-vector final state, so must do an angular analysis to separate the CP+ and CP- components

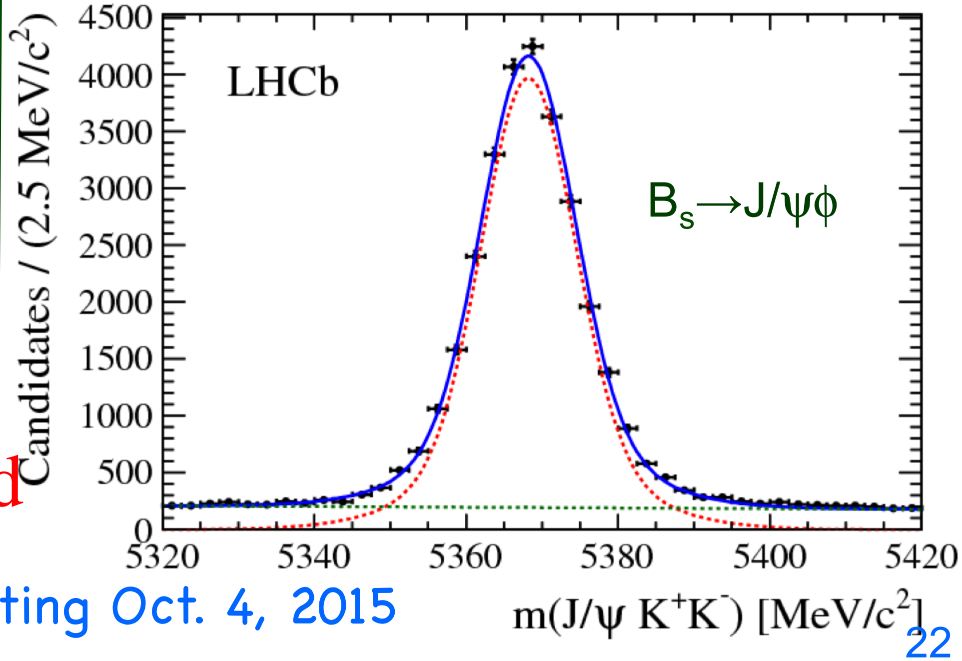
ϕ_s from $J/\psi h^+h^-$

- Reconstructed $\pi^+\pi^-$ mass spectrum
- In region between arrows, measured to be >97.7% CP-odd @95% cl
- $a[f(t)] \sim 2\sin\phi_s \sin\left(\Delta M t\right)$

  $\phi_s = 70 \pm 68 \pm 8$ mrad

- Also $\phi_s = -58 \pm 49 \pm 6$ mrad

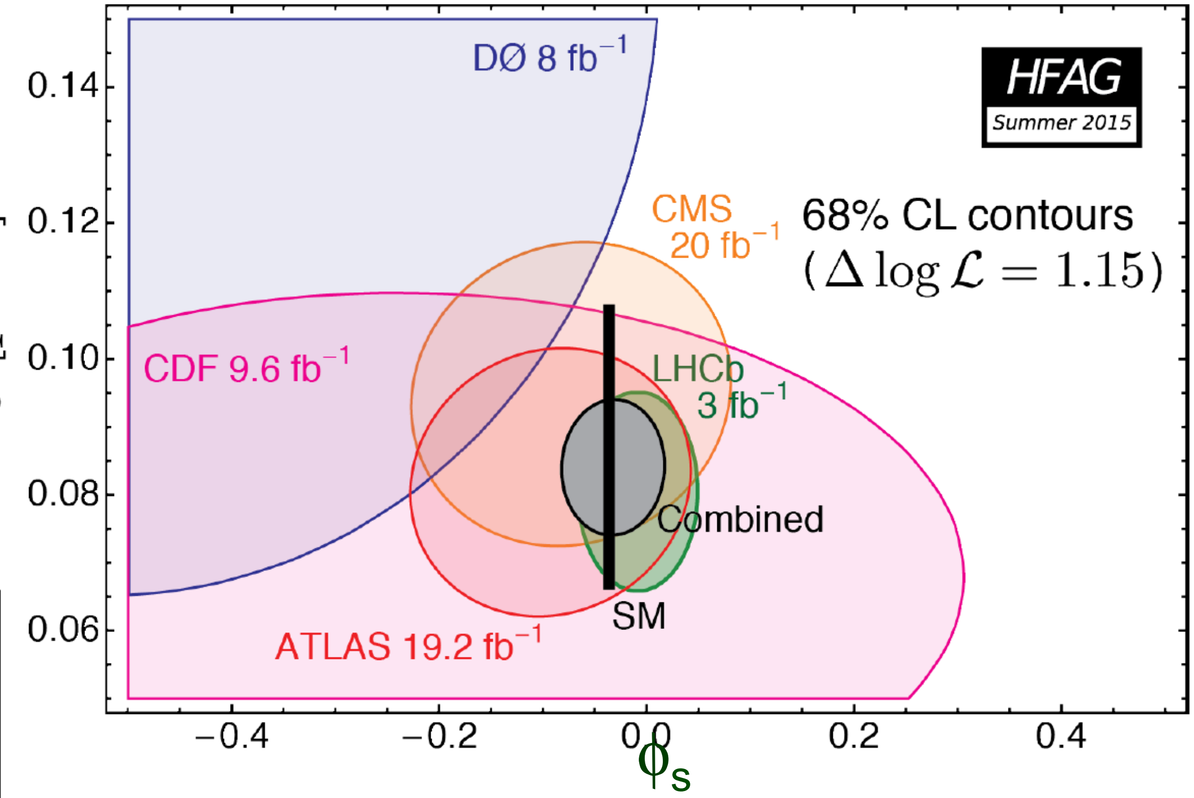


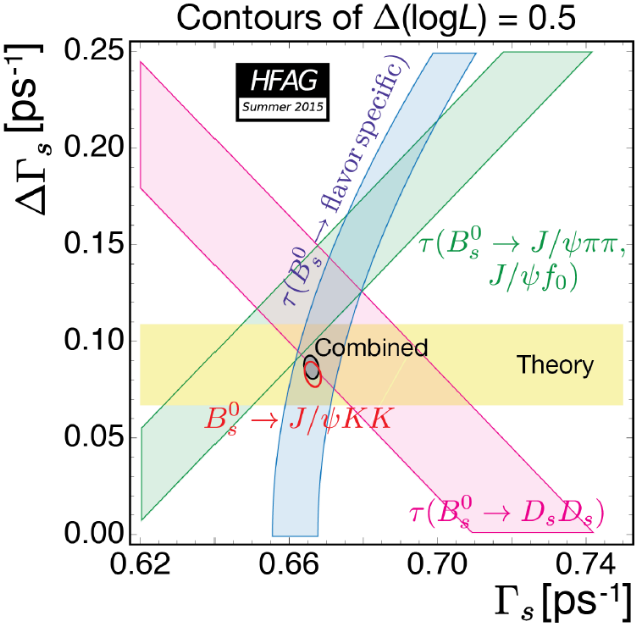


ϕ_s results

Combining $J/\psi\phi$, $J/\psi\pi^+\pi^-$, & $D_s^+D_s^-$ results:

ϕ_s=-34±33 mrad



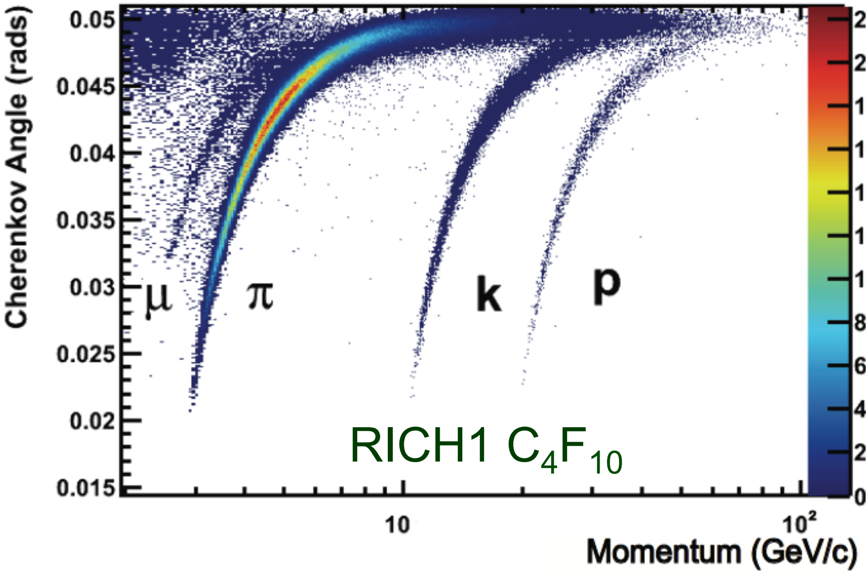


LHCb Upgrade

- Goals: run at $\mathcal{L}$ up to 2×10^{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
- This upgrade is funded

Beyond the 1st Upgrade

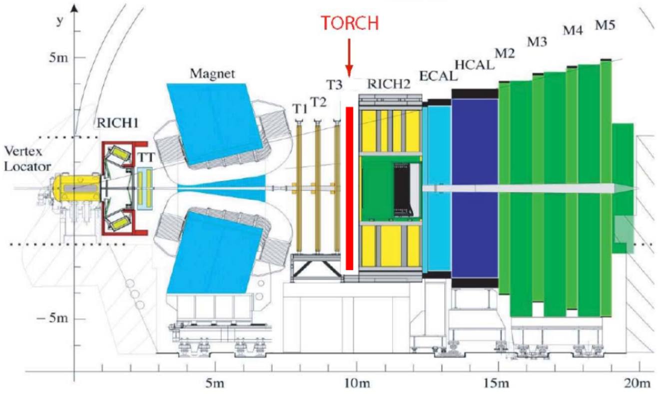
PID improvement: Torch

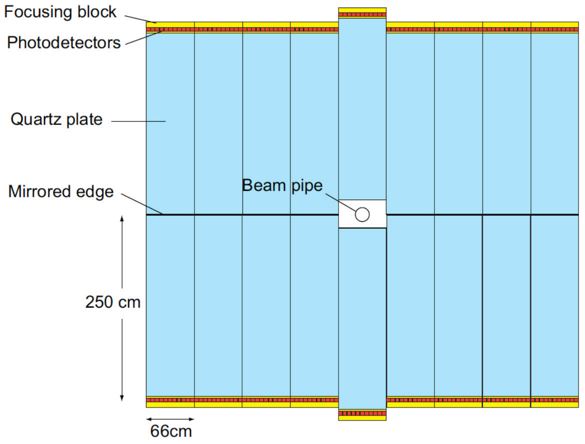


- Lower p particle ID cannot separate K/p below 10 GeV/c
- R&D being done on time-of-flight device that measures the time of arrival of particles in a quartz plate plus the time it takes the internally reflected Cherenkov light to traverse a quarks plate, by measuring its angle using MCP's.
- Promises full K detection up to 10 GeV/c

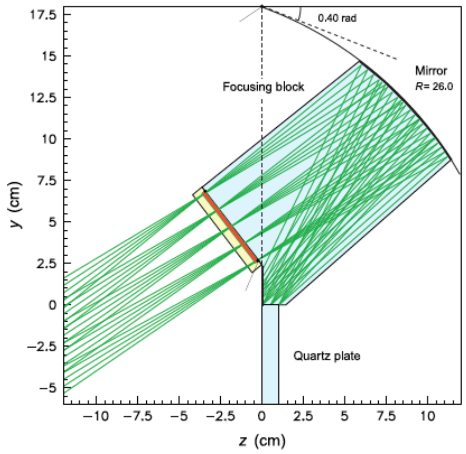
Torch details

- Location

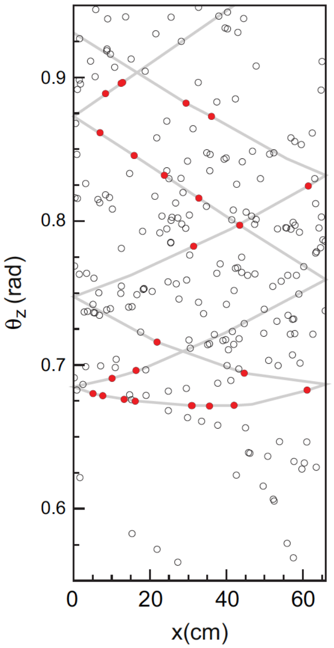




- Focusing at quartz edge



Photon Patterns, the red is the kaon of interest



- See van Dijk et al, NIM A 766 (2014) 118

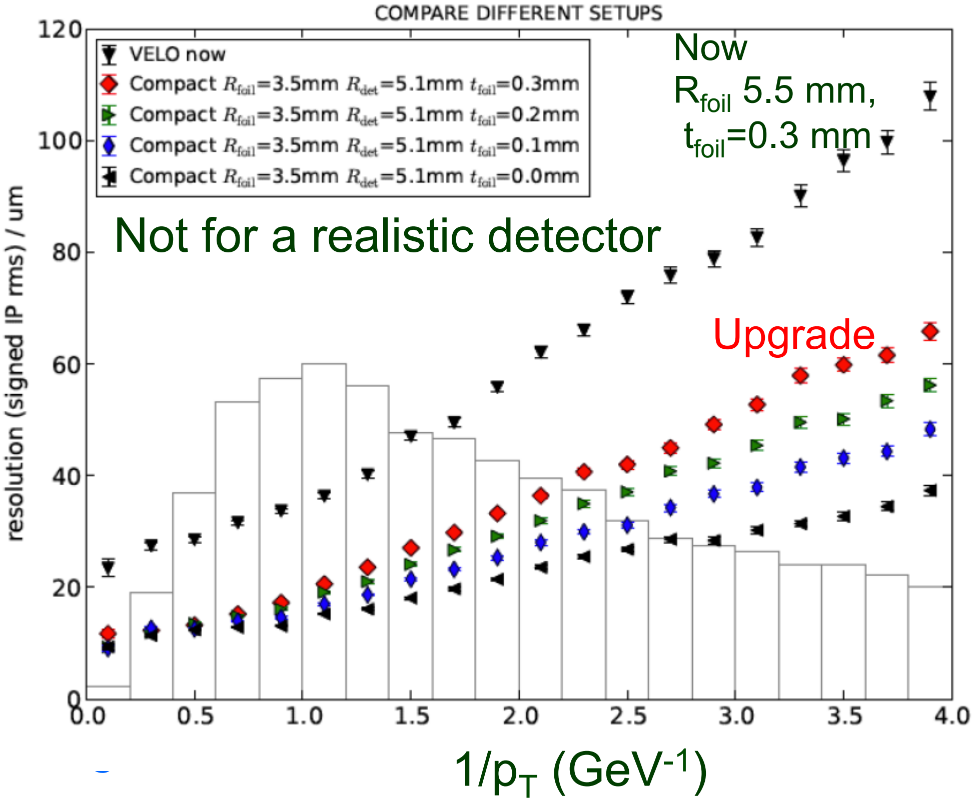
Possible additional improvements

Besides increasing luminosity which will require specific detector changes

What follows are 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.

ßWould improve vertex resolution significantly



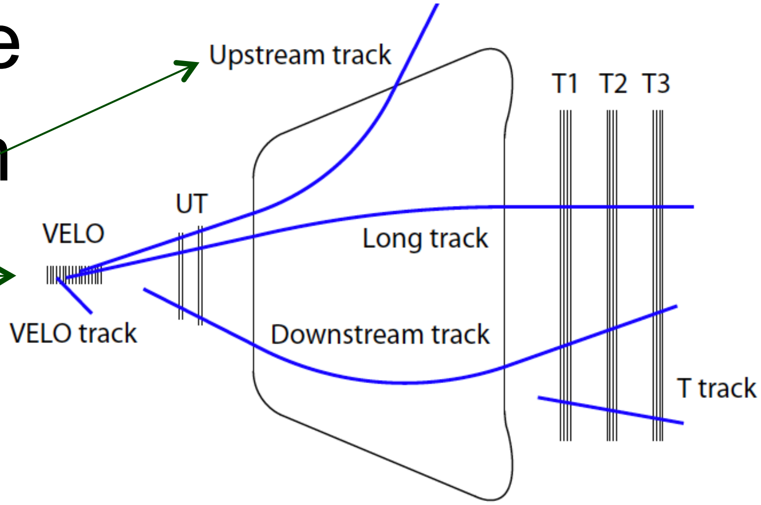
Now R_{foil} 5.5 mm, t_{foil}=0.3 mm

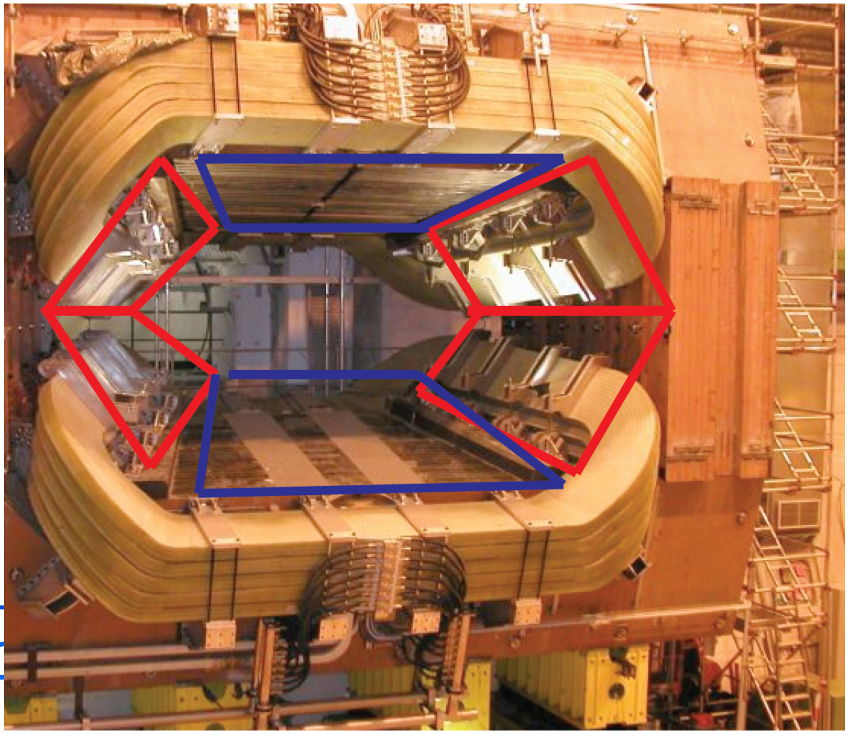
Not for a realistic detector

Upgrade

Augmenting the tracking

- Increase tracking acceptance especially for lower momentum
- Examples of LHCb tracks →
- Upstream tracks typically have $\Delta p/p \sim 15\%$, not useful for most physics. So put detectors on the inside faces, get excellent $\Delta p/p$
- Increases ε of some $b \rightarrow 6$ track final states by ~x3





A high resolution E&M calorimeter

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

Physics import

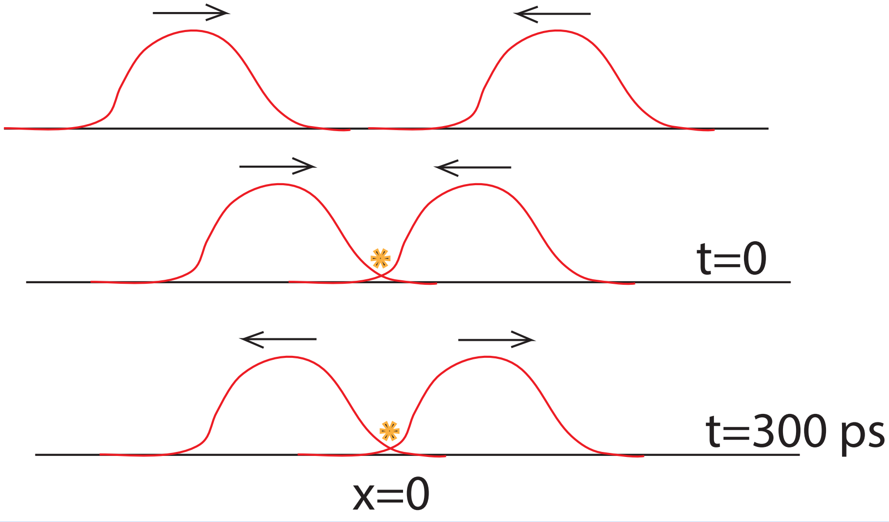
- Many physics reasons to have as good as possible γ, π^0, & η reconstruction & e^- id
  - $Ke^+e^-/K\mu^+\mu^-$, now $0.75^{+0.09}_{-0.07}\pm 0.04$, NP?
  - η_c decays mainly neutrals, $B\rightarrow K\pi^0$, etc..
- However, this will be more difficult for *higher* luminosities
- Ecal design was for ~1 int/xing, Phase I upgrade 7.5 int/xing, Phase II at least 20 int/xing & likely higher

Possible improvements to γ & e^- detection

- Better segmentation, reduces shower overlaps
- Better position resolution
- Time photons: If TOF is known to ~4 ps we can determine the parent primary pp interaction. The bunch σ_z design is 7.55 cm, corresponding to σ_t of 350 ps. Use charged tracks from each primary & measure the time difference. Very useful at ~20 int/crossing
- Better angular resolution

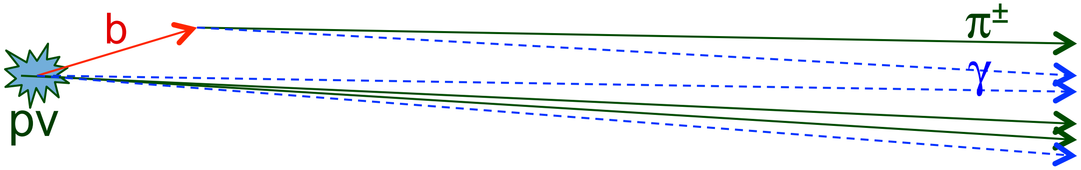
Vertexing

- LHCb beam size is σ=7.6 cm, giving an interaction region length σ=10.7 cm
- It takes about 300 ps for beams to cross each other, so there is on average 30 ps between collisions for 10 int/xing
- Time info is different than position info



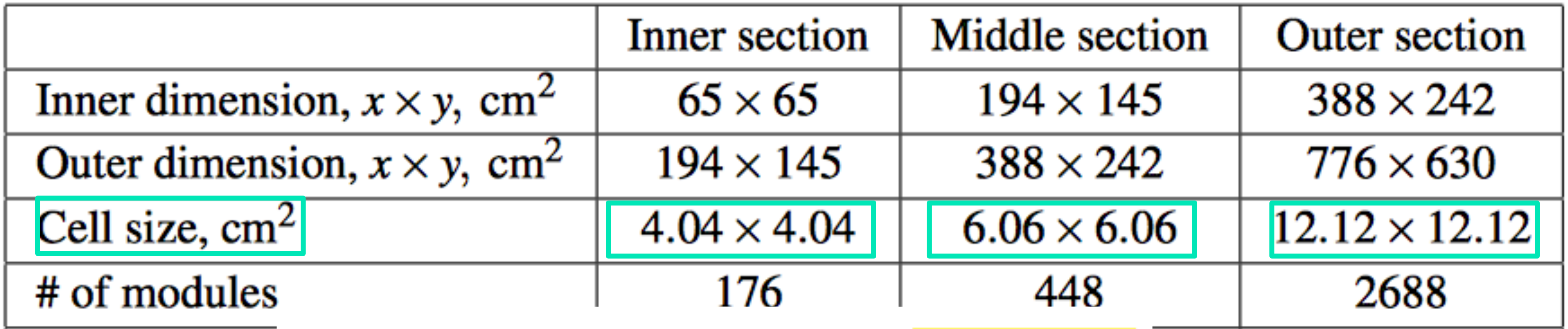
Vertexing γ's

- Having sorted the charged tracks into pv's we next address the photons
- Each pv (+b decays) has a set of γ's associated to it & only it. The time is set by the charged tracks. Since they are mostly highly relativistic they move almost in time with the γ's.
- Thus we can find out which γ's come from which pv & associated b's (but not separately)

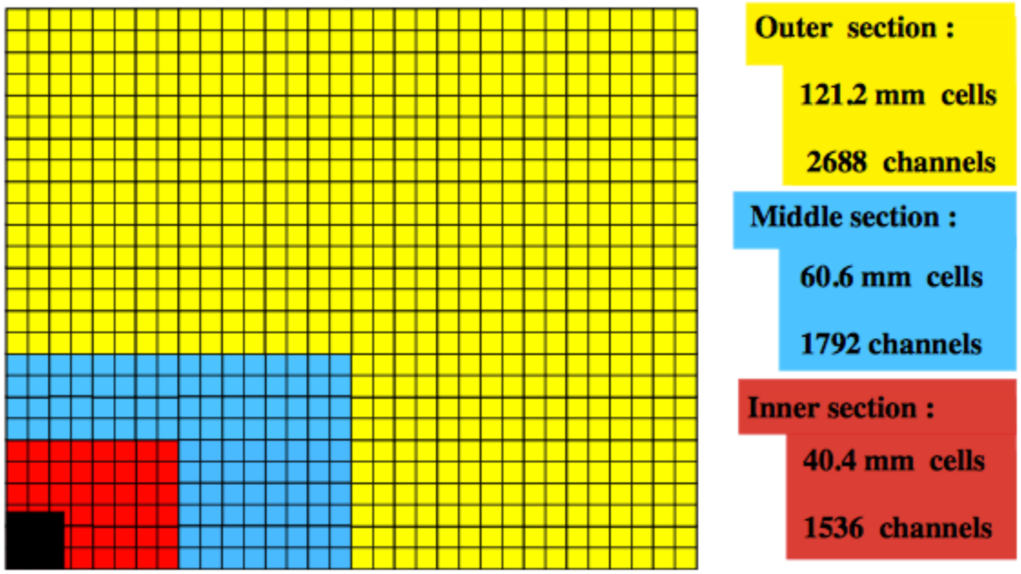


Better Segmentation

- Current ECAL



	Inner section	Middle section	Outer section
Inner dimension, $x \times y$, cm^2	65×65	194×145	388×242
Outer dimension, $x \times y$, cm^2	194×145	388×242	776×630
Cell size, cm^2	4.04×4.04	6.06×6.06	12.12×12.12
# of modules	176	448	2688



Segmentation for >20x design

- Moliere radius (r_M) contains 90% of the shower currently is 3.5 cm. Other materials with smaller r_M are $PbWO_4$ 2.2 cm, W 0.9 cm.
- Possible to obtain γ position at mm level by having "thin" W layers alternating with Si
- Example: Calice proposal SiW, the thickness of the ECAL will be around 23 radiation lengths. Around 30 layers of silicon will be used, giving an energy resolution of about $0.16 / \sqrt{E}$. There is about 2400m^2 of silicon sensors. Segmentation at 1x1 mm^2 level.

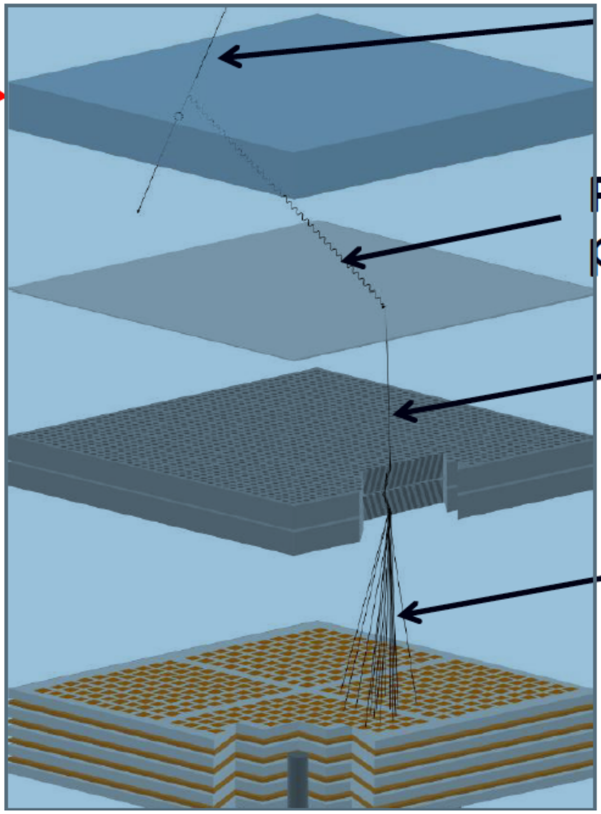
Timing

- Si readout can give timing to ~30 ps, & there are many layers
- Large area ps TOF: aim to time charged tracks or photons to 1 ps (See http://psec.uchicago.edu/)
- Have already achieved 4 ps
- Working on large area commercialization see http://dx.doi.org/10.1016/j.nima.2014.11.025

How it works

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



window

Photocathode on inside of window

Pair of micro-channel plates

RF strip-line anode

Incoming charged particle

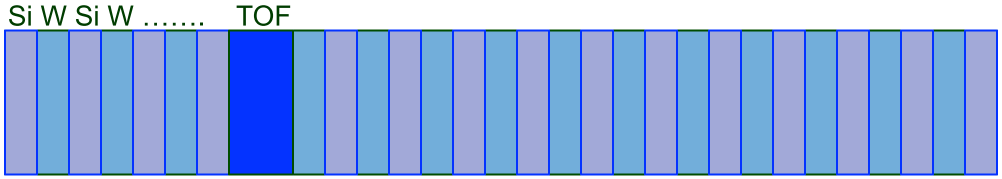
Radiated Cherenkov photon

Photo-electron from cathode

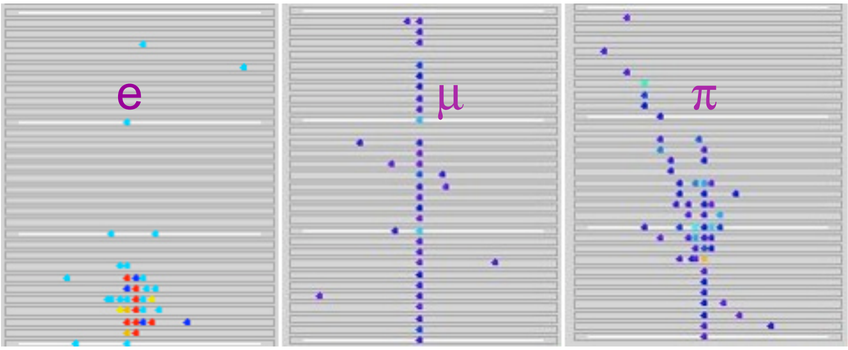
Output pulse of 10^7 electrons

π/e separation

- Consider measuring the number of tracks & Si energy deposit in many layers



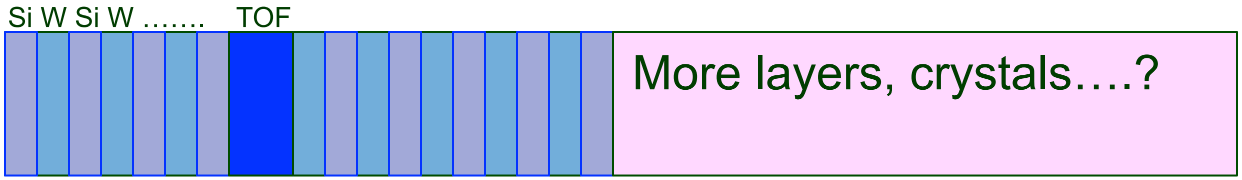
- The shower development is quite different for pions & electrons



- Limit on π/e rejection is the amount of charge exchange ($\pi^+\rightarrow\pi^0$) in the first few Si layers

Ecal summary

- It may be possible to construct an upgrade Ecal that would allow LHCb to do full reconstruction of final states with γ's and have excellent π/e rejection at phase II upgrade luminosities
- It might involve excellent segmentation, position resolution, picosecond level timing & relatively poor energy resolution



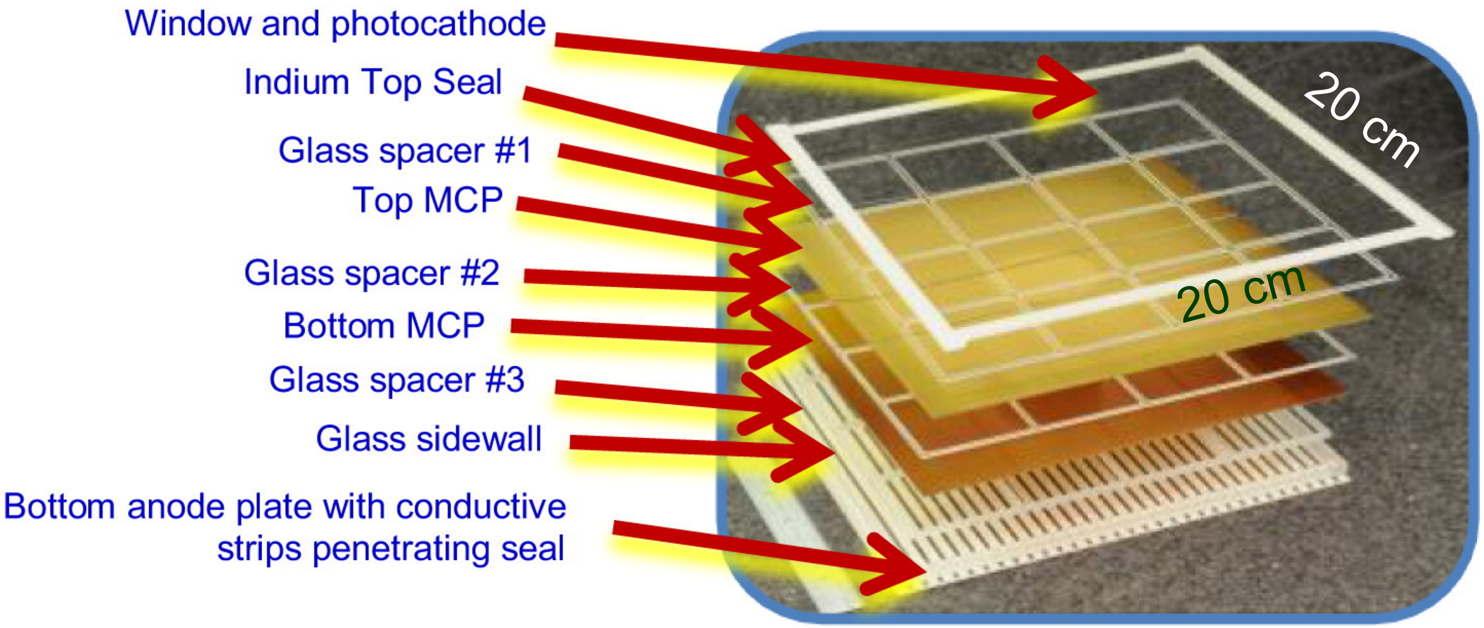
Conclusions

- Many fundamental measurements have been made by LHCb
- LHCb has a bright physics future. Run II & the Upgrade will produce many more interesting results, either find or limit NP
- Augmenting the tracking and Ecal can provide much larger acceptances & thus the potential for seminal discoveries in many channels specifically for new physics searches or exotic spectroscopy or …..

The End

Technical description

- Microchannel plate based technology



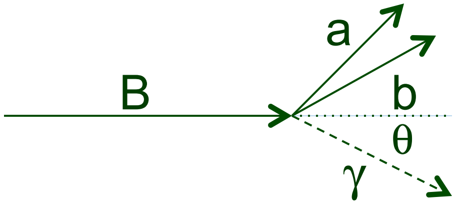
- pilot production of LAPPDs in 2015 and the delivery of commercial LAPPD tiles in 2016.

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

B decays with γ or π^0

- Suppose that we don't have any information on the γ energy, but excellent position σ. We still can detect final states with a γ or π^0.
- We take our Ecal with Si-W plus ps TOF, which gives us excellent γ position resolution & lets us consider γ's from only 1 interaction.
- Now consider B→a+b+γ, where we measure the B direction, the **p** of a & b & the γ direction.



- If we measured the B & γ energies, we would have 4 constraints of E & **p**, here we lack 2

γ or π^0 reconstruction

- Thus we have two constraints left, enough to allow us to reconstruct the state
- One primitive method is to use the B direction to calculate the p_T of the γ, then use the γ direction wrt the B to get p_L, that gives us E_γ & p_γ, so the invariant mass of the (a+b+γ) can be calculated $p_T(\gamma) = p_T(a) + p_T(b), \quad p_L(\gamma) = p_T(\gamma)\cot(\theta)$

$$m_B^2 = (E_a + E_b + E_\gamma)^2 - (\vec{p}_a + \vec{p}_b + \vec{p}_\gamma)^2, \quad E_\gamma = |\vec{p}_\gamma|$$

- Can also do π^0; although you lose a constraint you get another one from the π^0 mass
- Can do better with some Energy info

Energy resolution

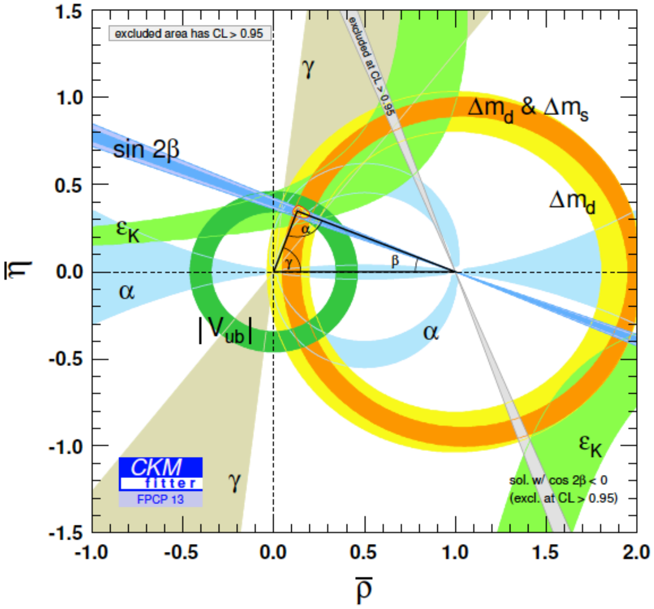
- In principle want to sample as much energy as possible

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 ⟹ 0.1 mm resolution good enough to tell if its from a detached B decay

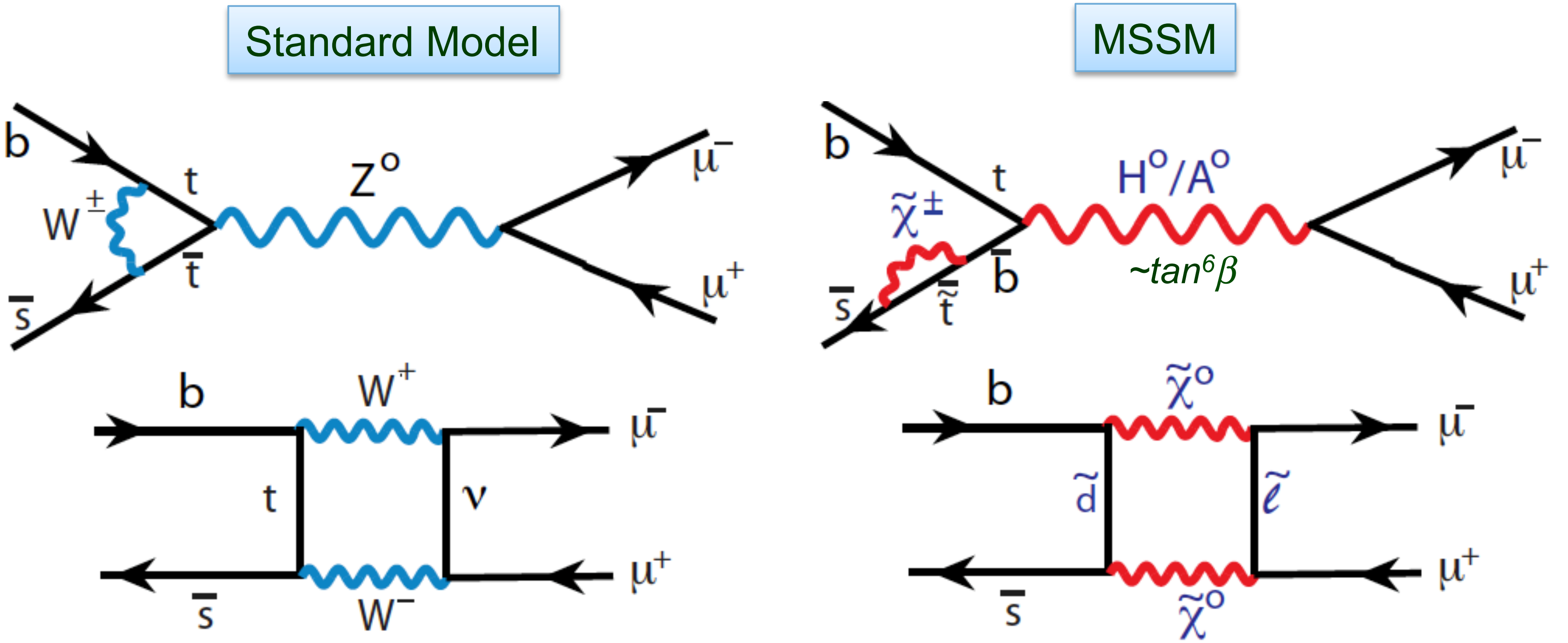
CPV measurements

- CPV measure: $a[f(t)] = \frac{\Gamma\left(\bar{M} \to f\right) - \Gamma\left(M \to f\right)}{\Gamma\left(\bar{M} \to f\right) + \Gamma\left(M \to f\right)}$
    - 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



$B_s \rightarrow \mu^+\mu^-$

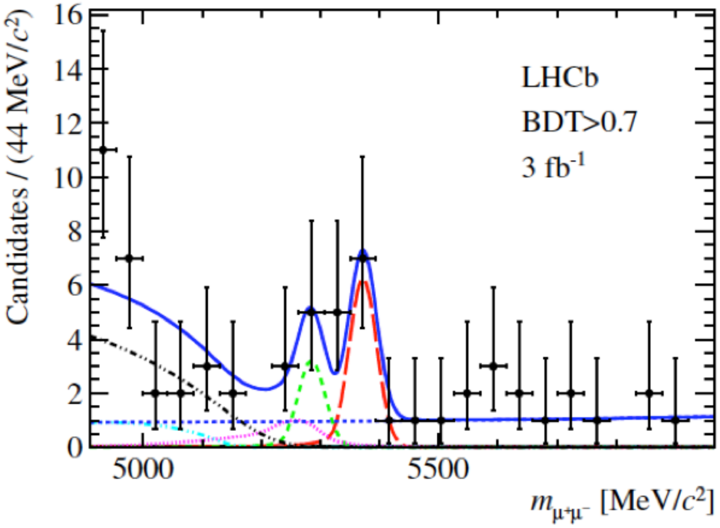
- SM branching ratio is (3.65±0.23)x10^{-9} [Bobeth et al., arXiv:1311.0903], NP can make large contributions.



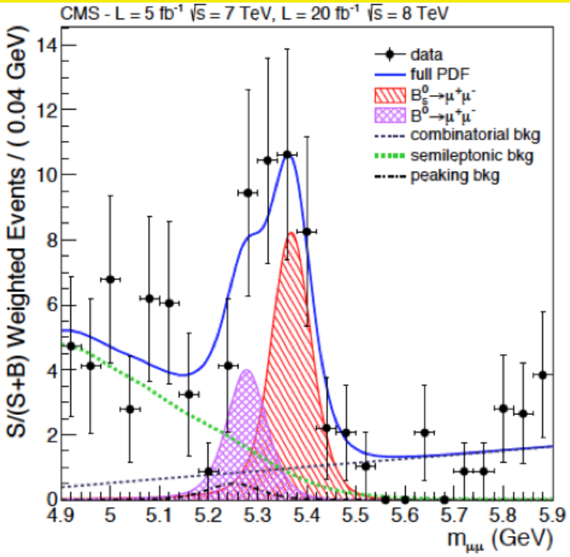
- Many NP models possible, not just Super-Sym

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

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



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



$$\boxed{\begin{aligned}\mathcal{B}(B_s^0\to\mu^+\mu^-) &= (2.9\,^{+1.1}_{-1.0})\times10^{-9},\\ \mathcal{B}(B^0\to\mu^+\mu^-) &= (3.7\,^{+2.4}_{-2.1})\times10^{-10}\end{aligned}}$$

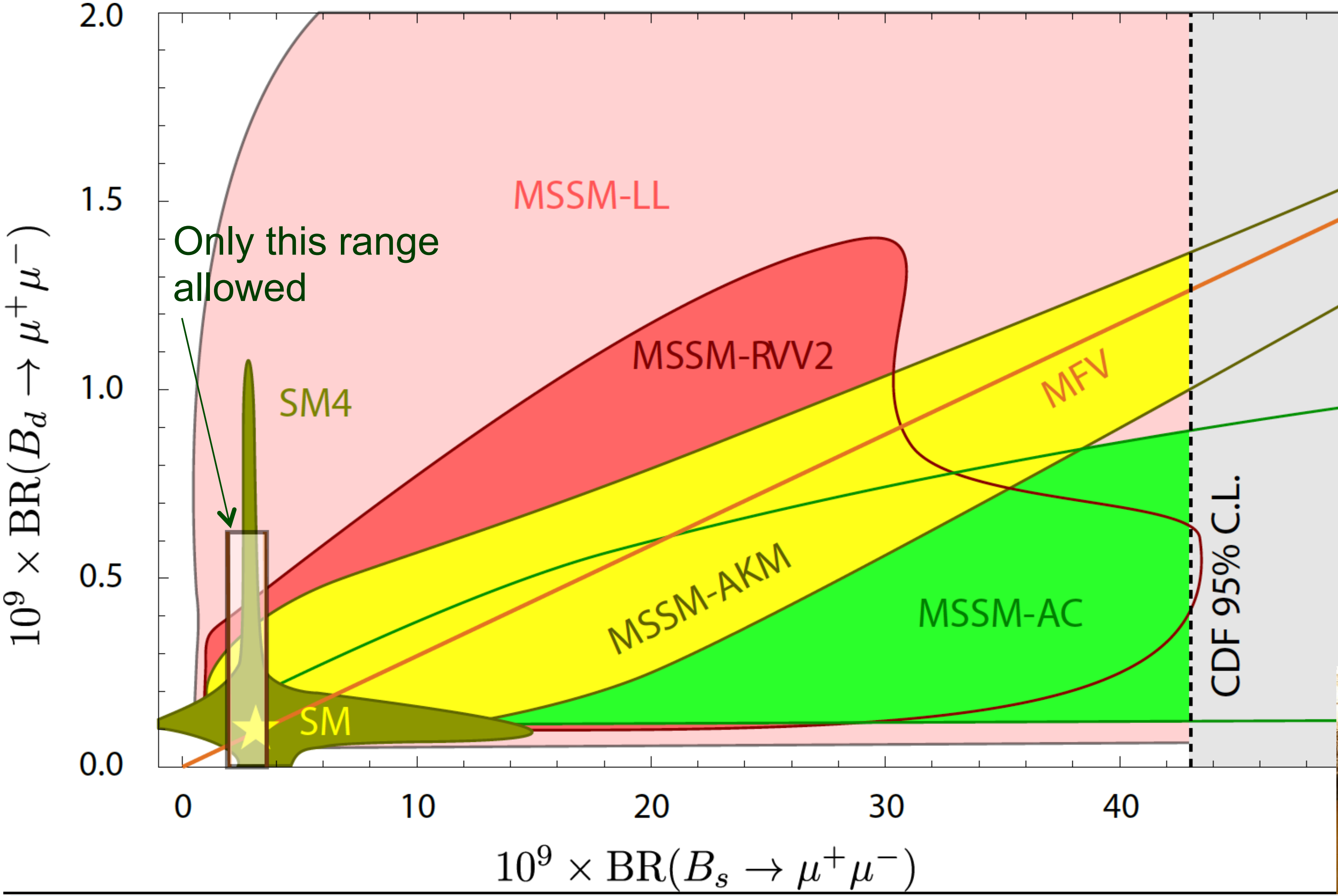
--> 4.0σ

$$\boxed{\begin{aligned}\mathcal{B}(B_s^0\to\mu^+\mu^-) &= (3.0\,^{+1.0}_{-0.9})\times10^{-9},\\ \mathcal{B}(B^0\to\mu^+\mu^-) &= (3.5\,^{+2.1}_{-1.8})\times10^{-10}\end{aligned}}$$

--> 4.3σ

- Avg: $\mathcal{B}(B_s\to\mu^+\mu^-)=(2.9\pm0.7)\times10^{-9}$
- Avg: $\mathcal{B}(B^0\to\mu^+\mu^-)=(3.6^{+1.6}_{-1.4})\times10^{-10}$ (not significant)

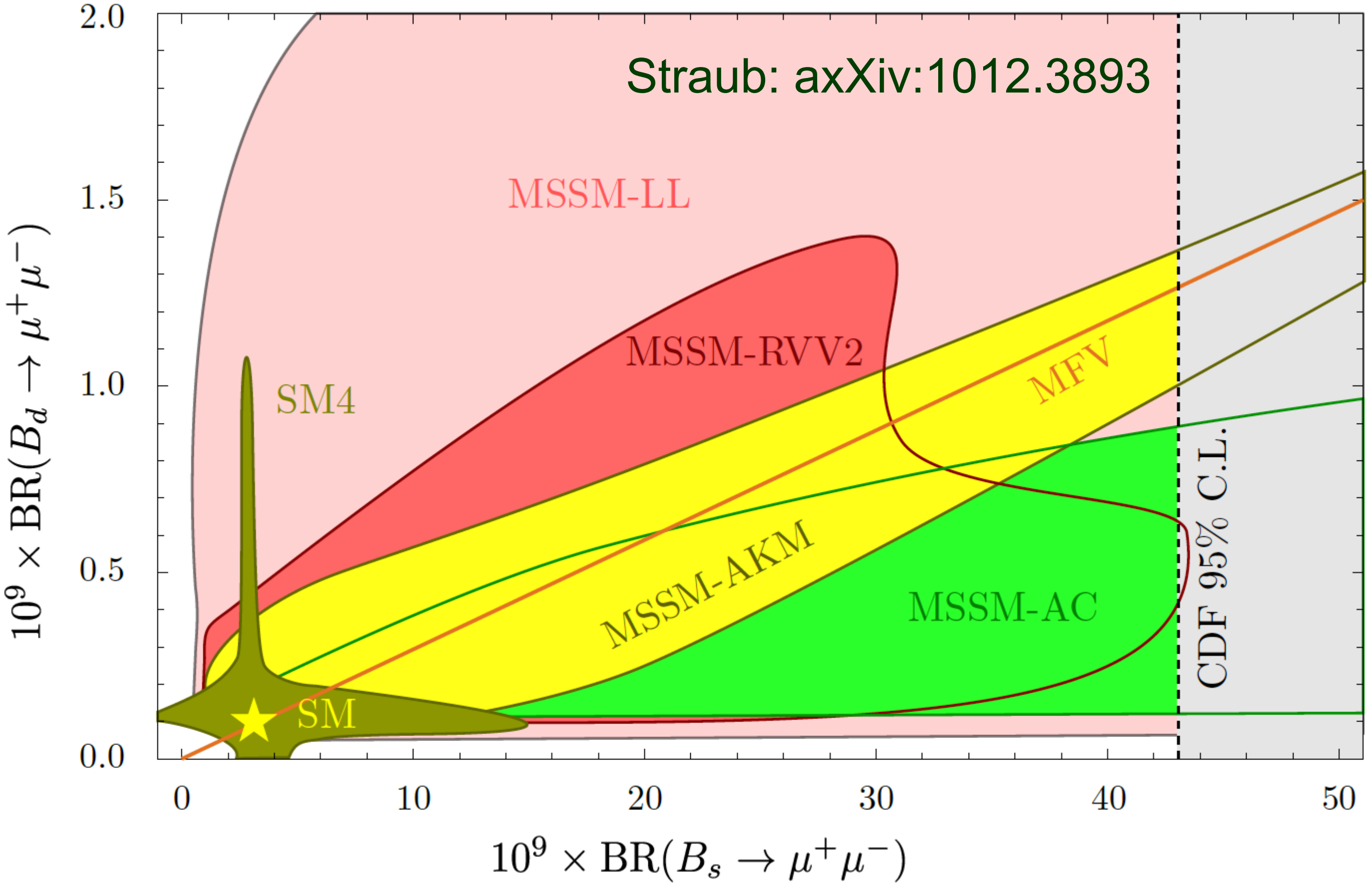
Implications



Only this range allowed

Top Down Analyses

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



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 ?

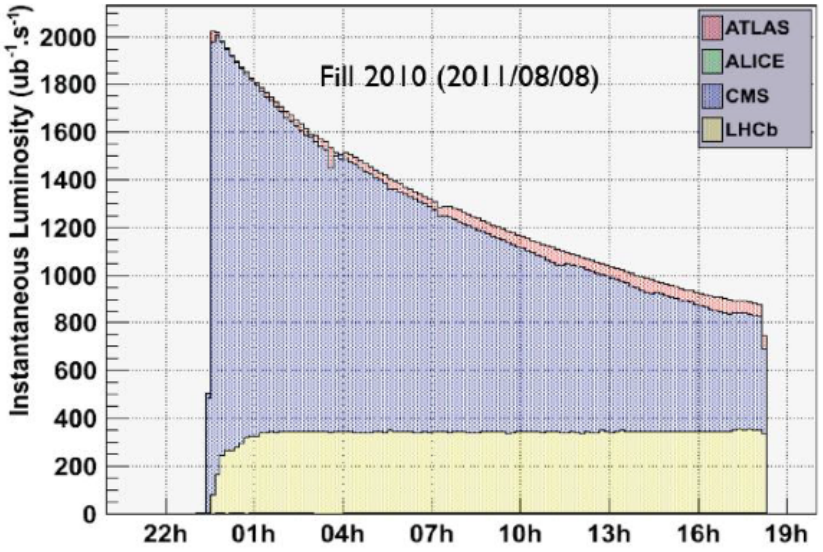
just right

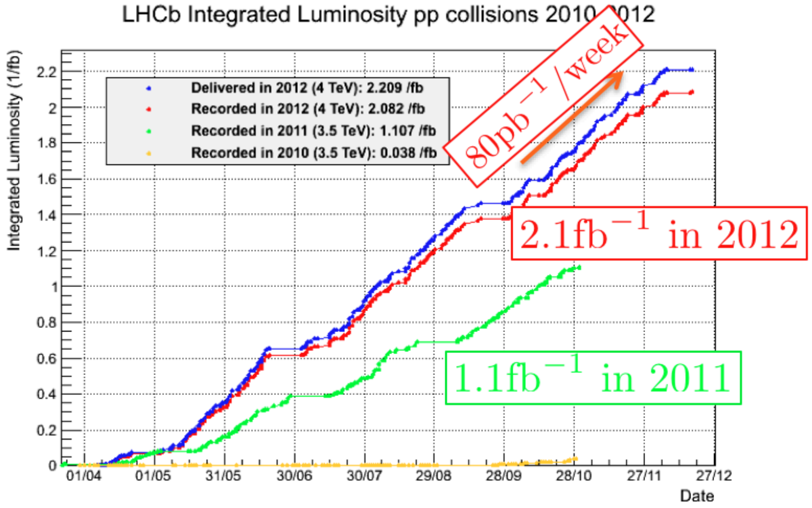
t

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 $\bar{M}\to f$ is zero as is $M\to\bar{f}$

- Here *f* is by construction flavor specific, $f\neq\bar{f}$
- Can measure eg. $\bar{B}_s\to D_s^+\mu^-\nu$, 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°) $a_{sl}^{d}=-4.1\times10^{-4}$, ($B_s$) $a_{sl}^{s}=+1.9\times10^{-5}$

arXiv:1205.1444 [hep-ph]

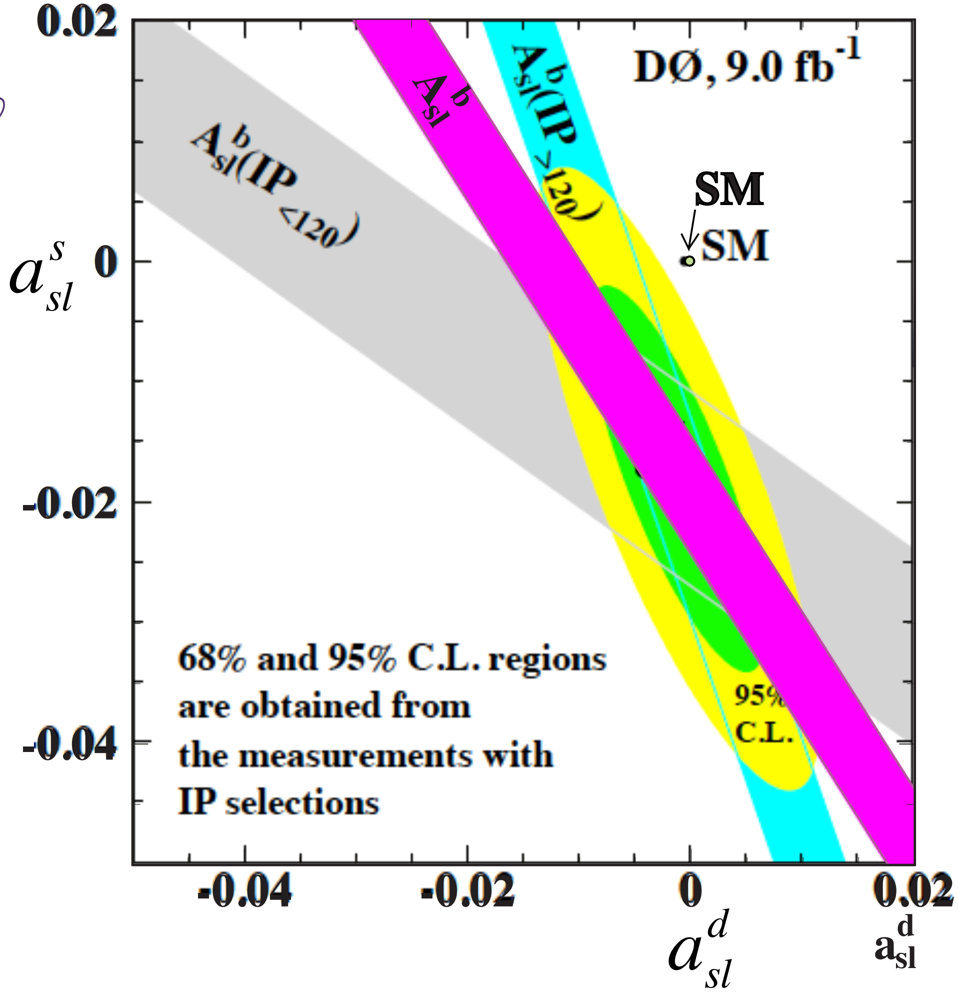
D0 a_{sl}

- Using dimuons (3.9σ)

$$A_{sl}^{b} = (-0.787 \pm 0.172 \pm 0.093)\%$$

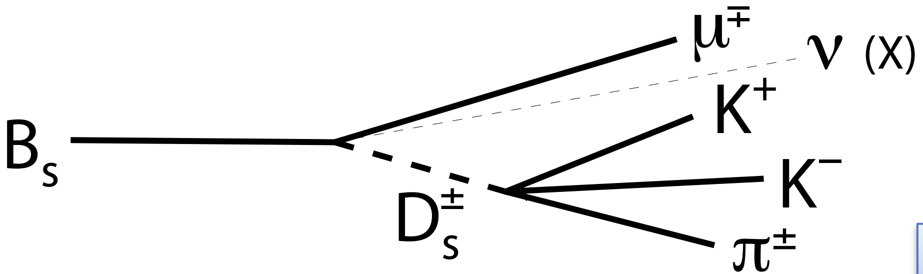
- Indication from D0 that its B_s
- Separate dimuons into B_d and B_s samples using muon impact parameter
- Find

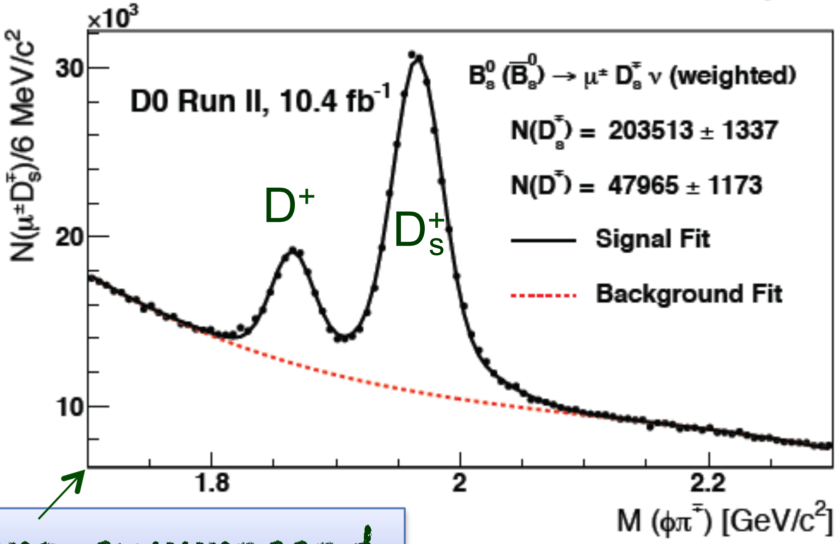
$$a_{sl}^{d} = (-0.12 \pm 0.52)\%$$
$$a_{sl}^{s} = (-1.81 \pm 1.06)\%$$



New D0 Analysis

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



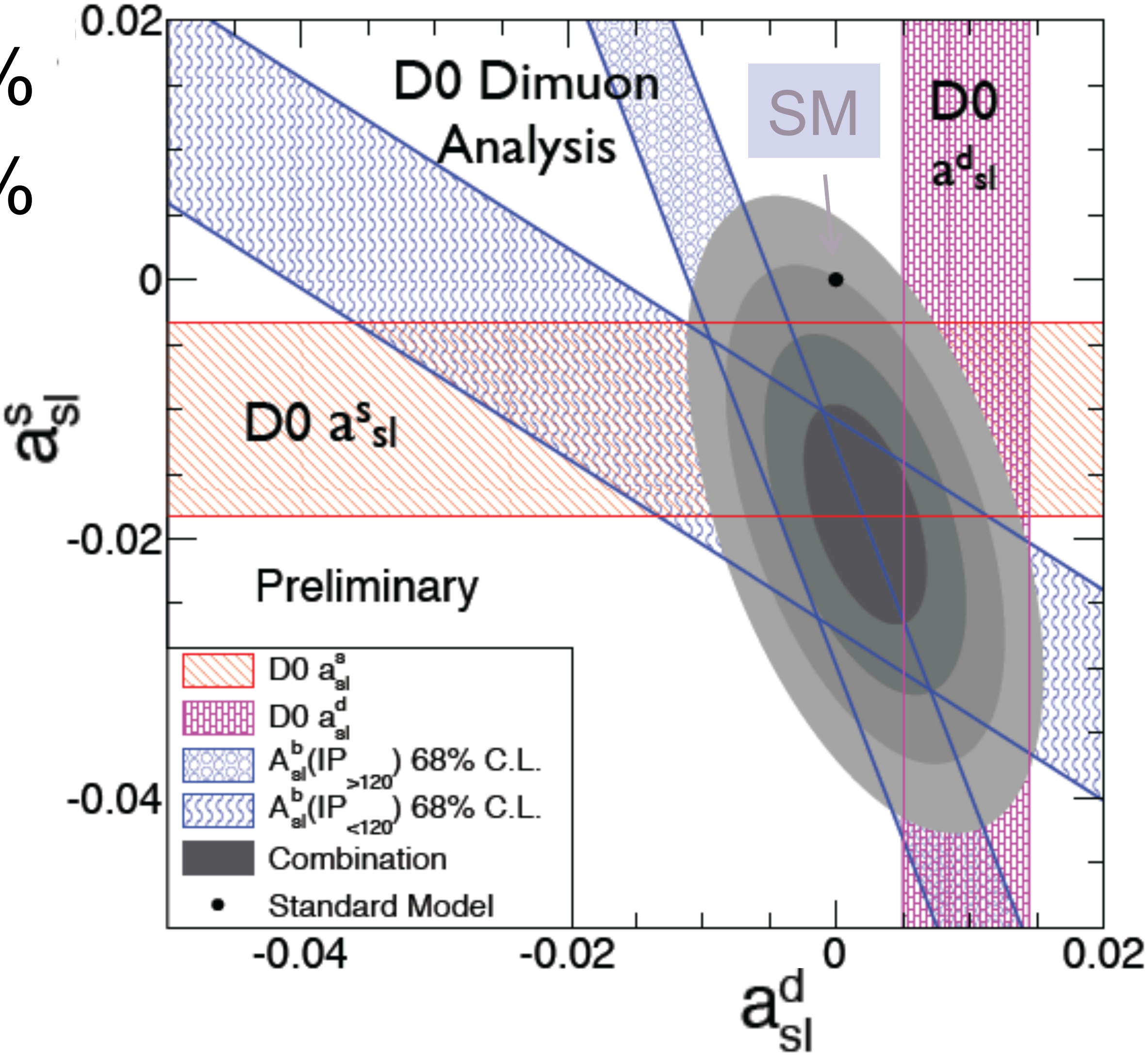


zero suppressed

- Find $a^s_{sl}=(-1.08\pm0.72\pm0.17)\%$
- Also measure a^d_{sl} using $D^+\mu^-\nu, D^+ \rightarrow K\pi^+\pi^+$
- $a^d_{sl}=(0.93\pm0.45\pm0.14)\%$

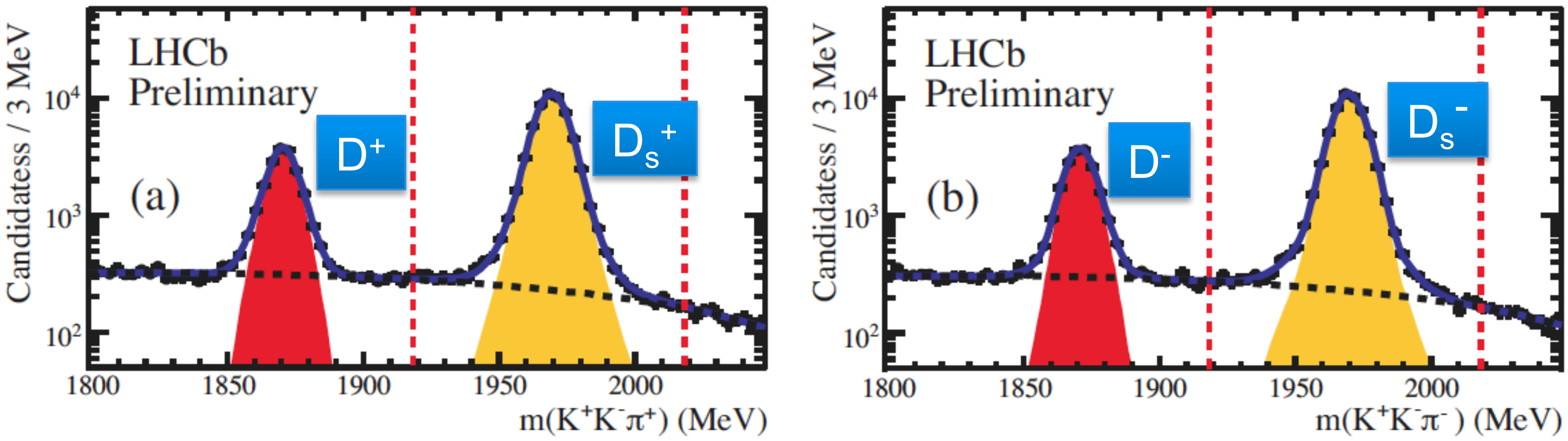
a_{sl} according to D0

- a^{s}_{sl}=(-1.81±0.56)%
- a^{d}_{sl}=(-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

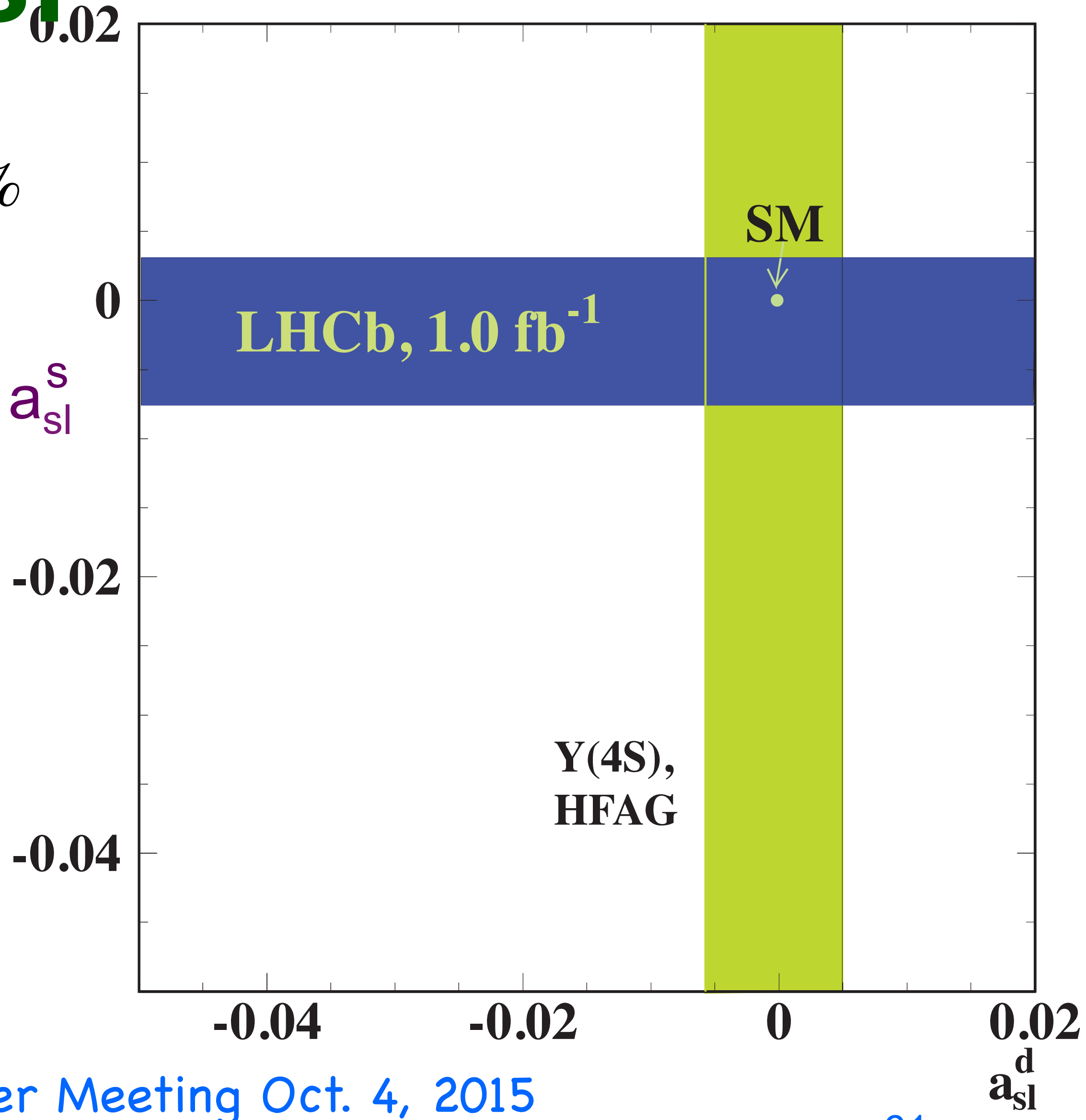
- LHCb finds

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

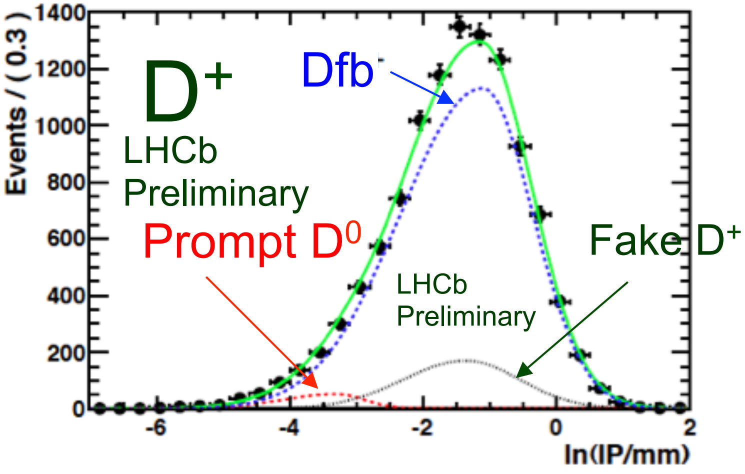
- B-factory

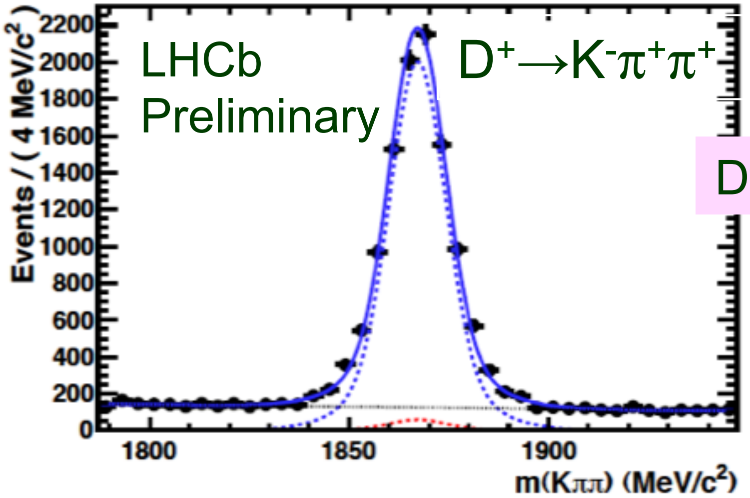
$$a^d_{sl} = \left(-0.05 \pm 0.56\right)\%$$

- Results consistent with SM
- Expect ϕ_s to grow as sin[2|β_s| +ar^{s}g(M_{12})] for finit a_{sl}.

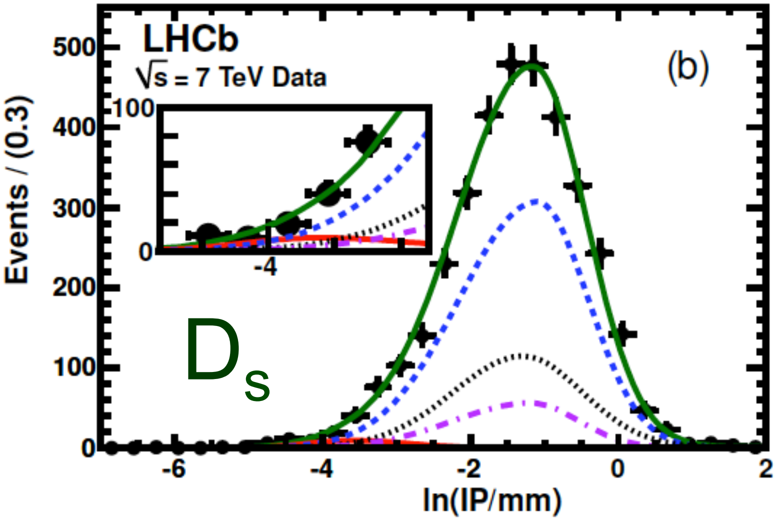


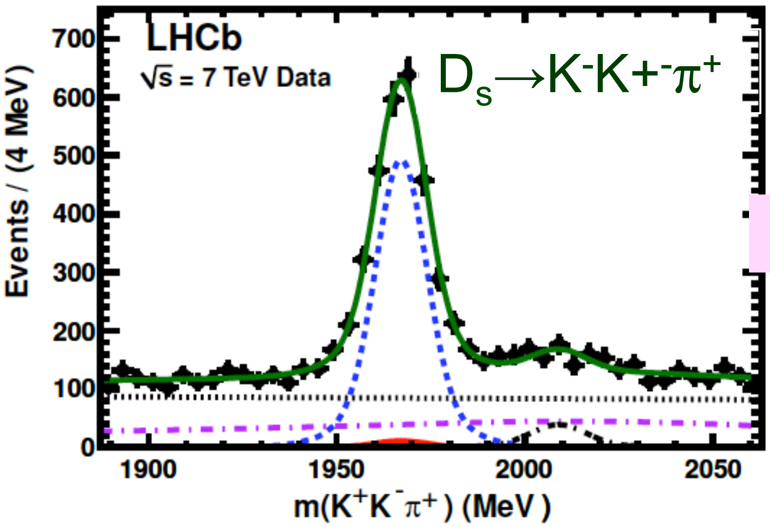
Also D^+, D_s, Λ_b





Dfb: 9406±110



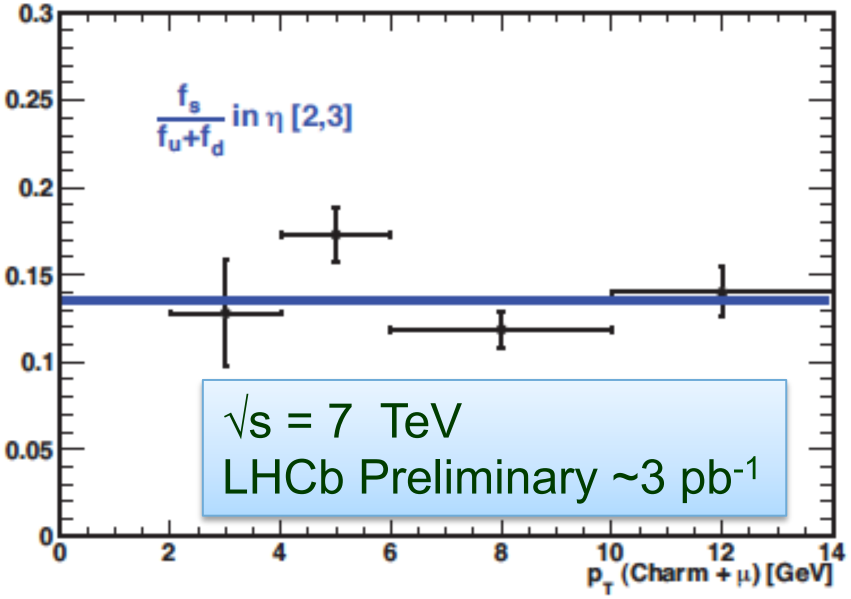


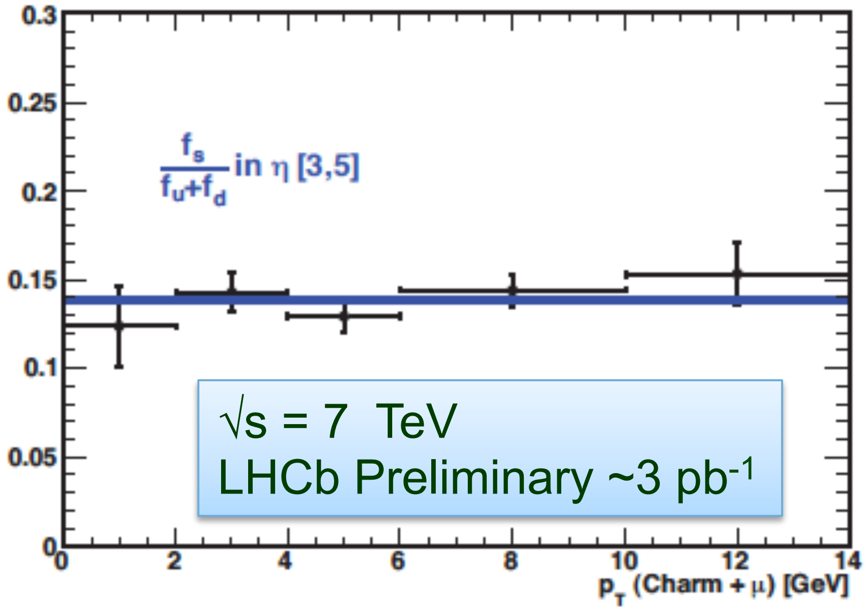
Dfb: 2446±60

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 $\Lambda_b \rightarrow D^o p X \mu \nu$

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

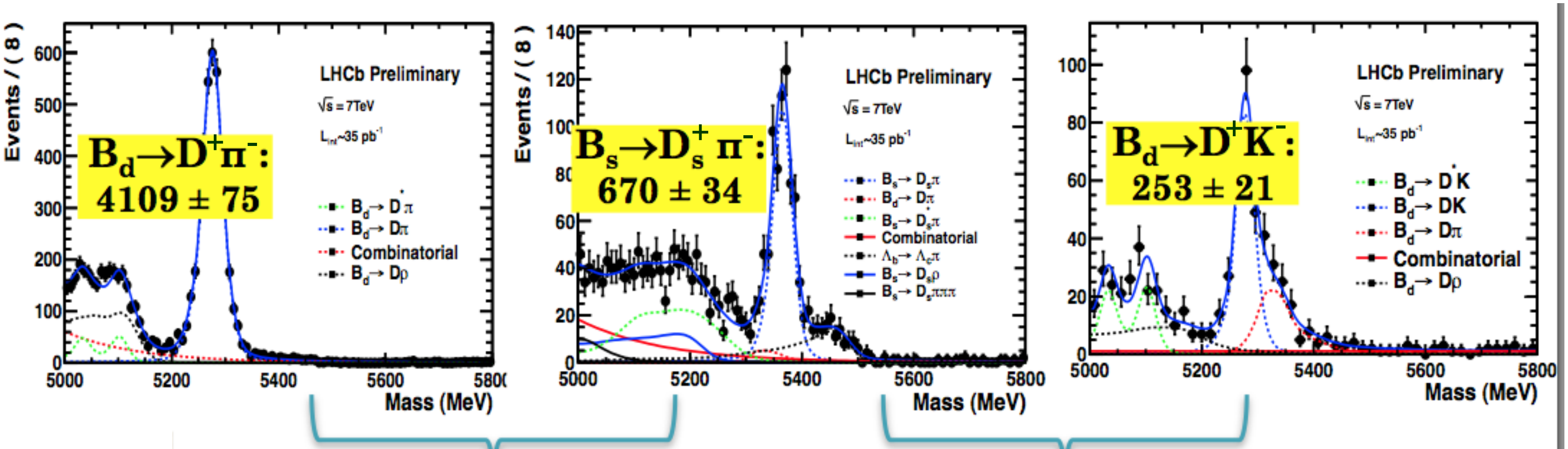




B_s fraction - hadronic

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

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

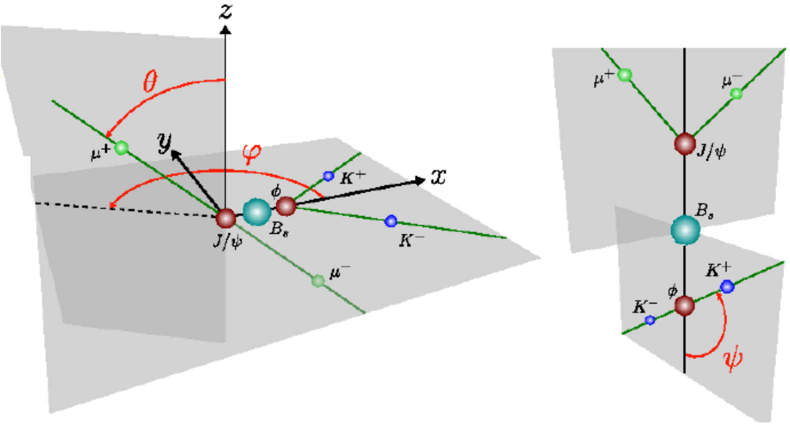
- If in addition $\Delta\Gamma\neq 0$, eg. B$_s$

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

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	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
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	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
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

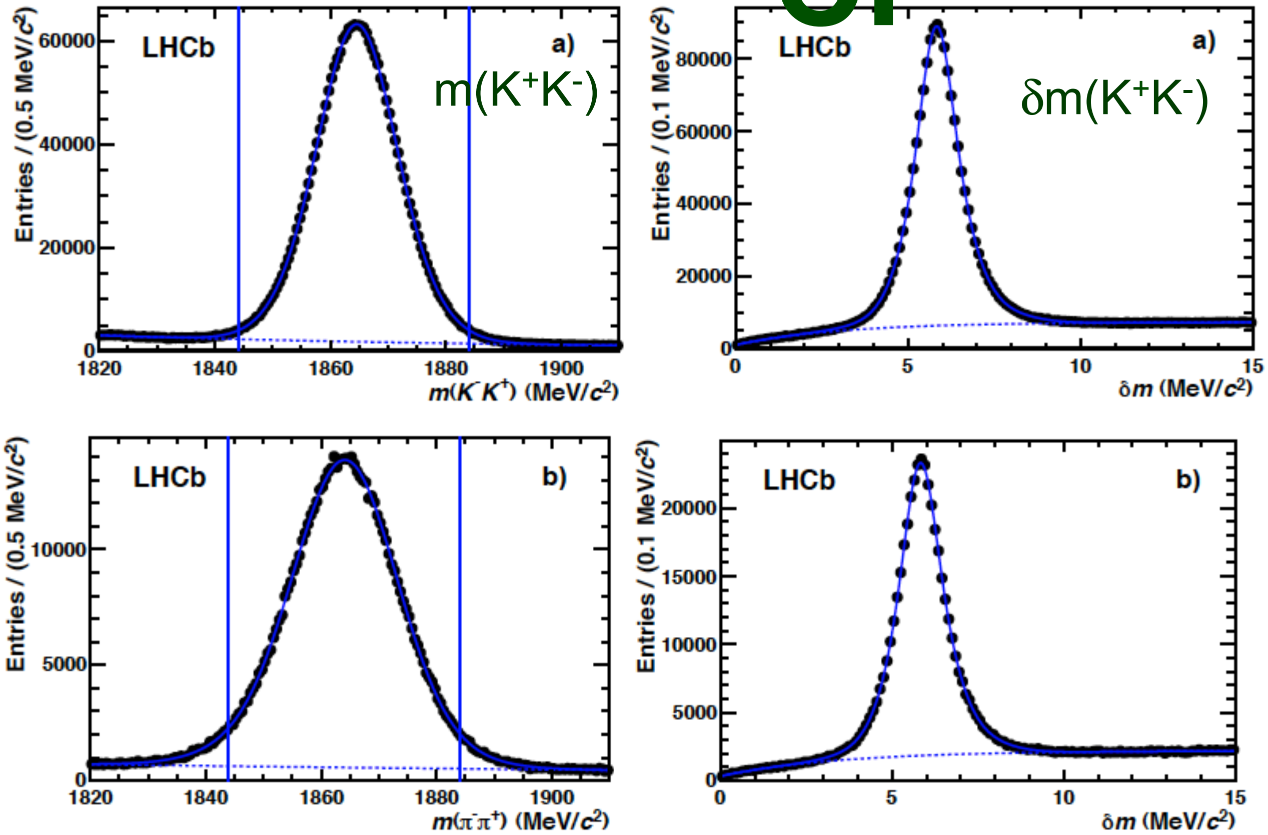
$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\|(t)|^2 &= |A_\||^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)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

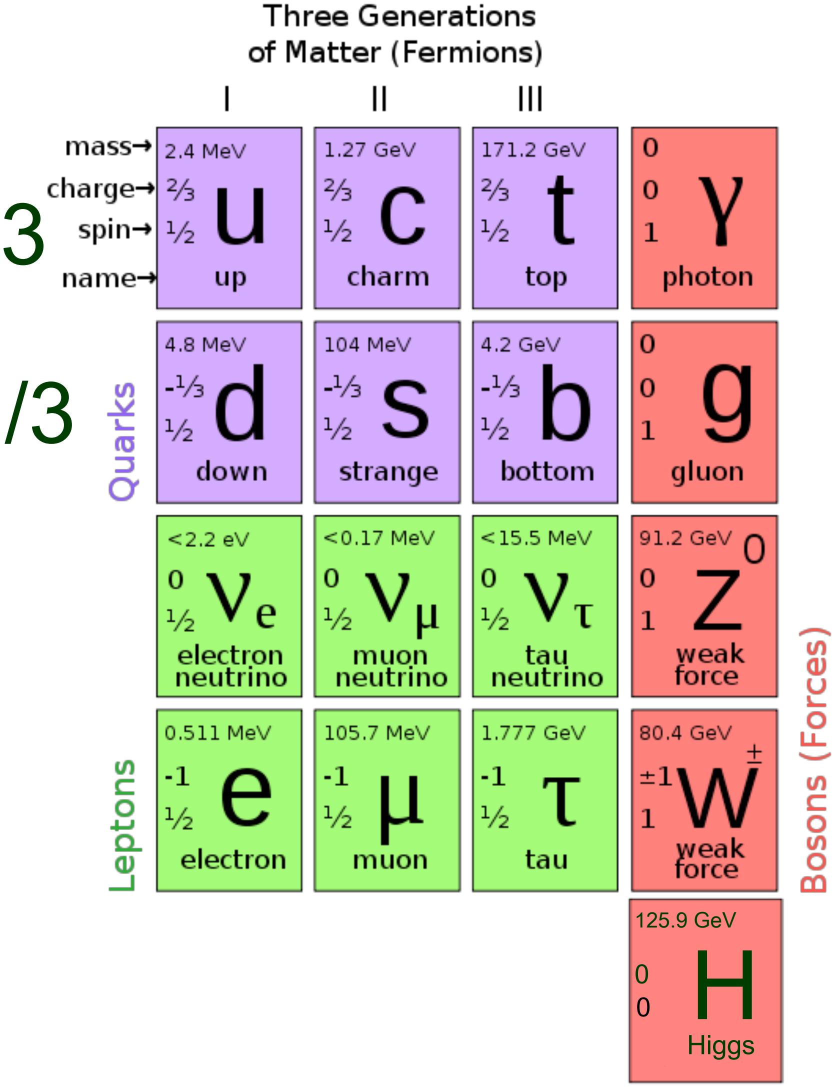
The Standard Model

charge 2/3

charge -1/3

charge 0

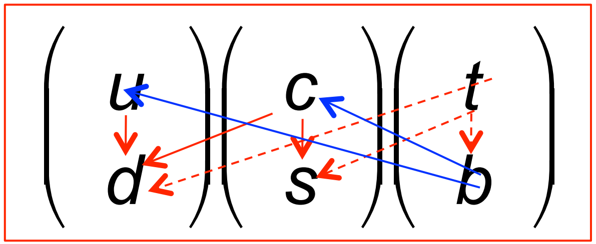
charge -1



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)

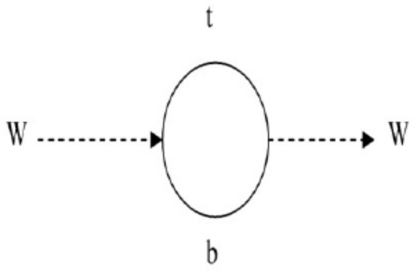
$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2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

- 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

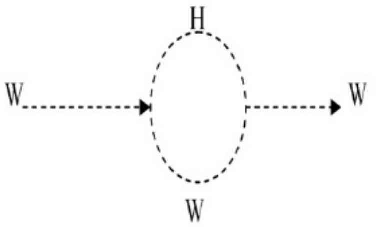
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t

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



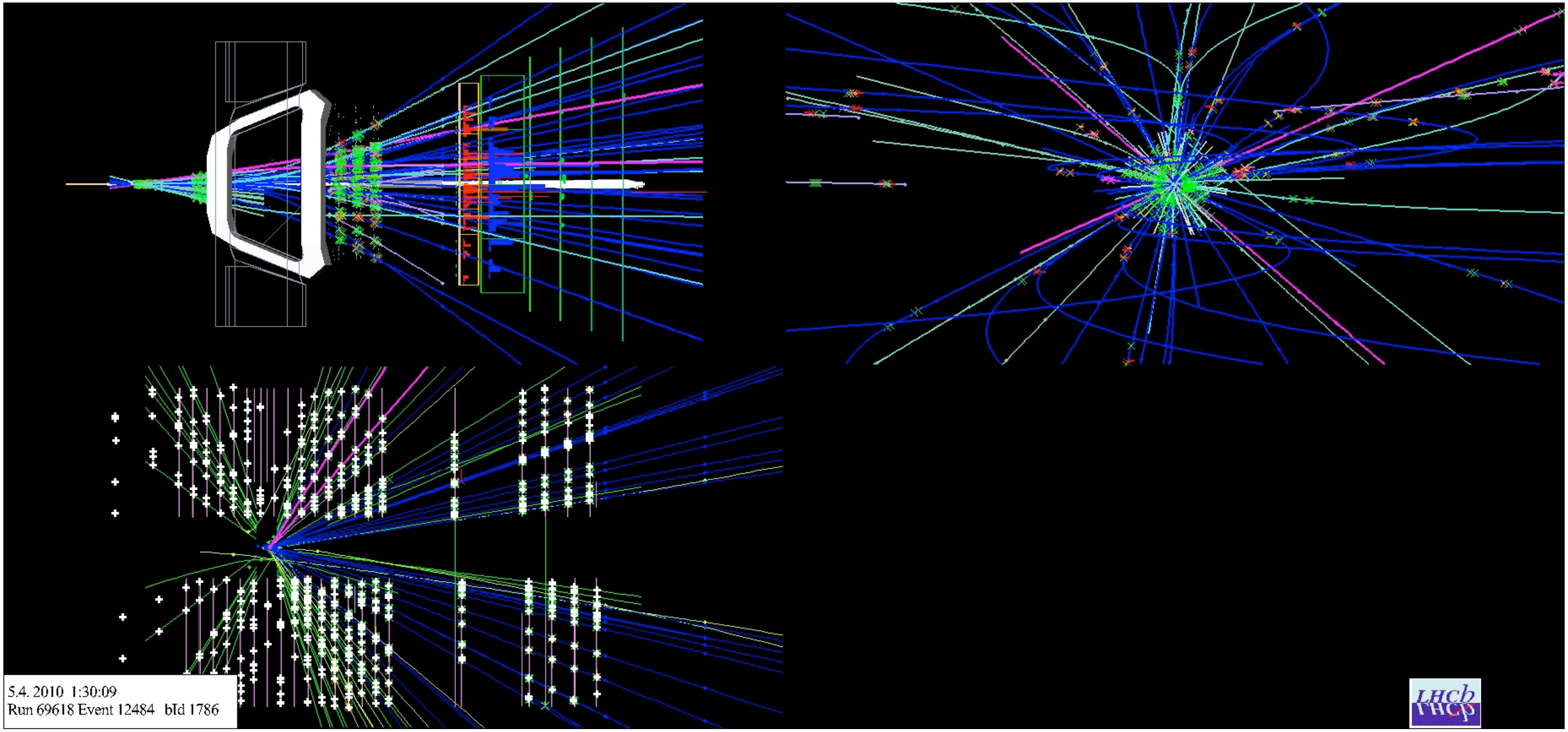
  - M_w changes due to m_H
  - Gave predictions of m_H prior to discovery

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

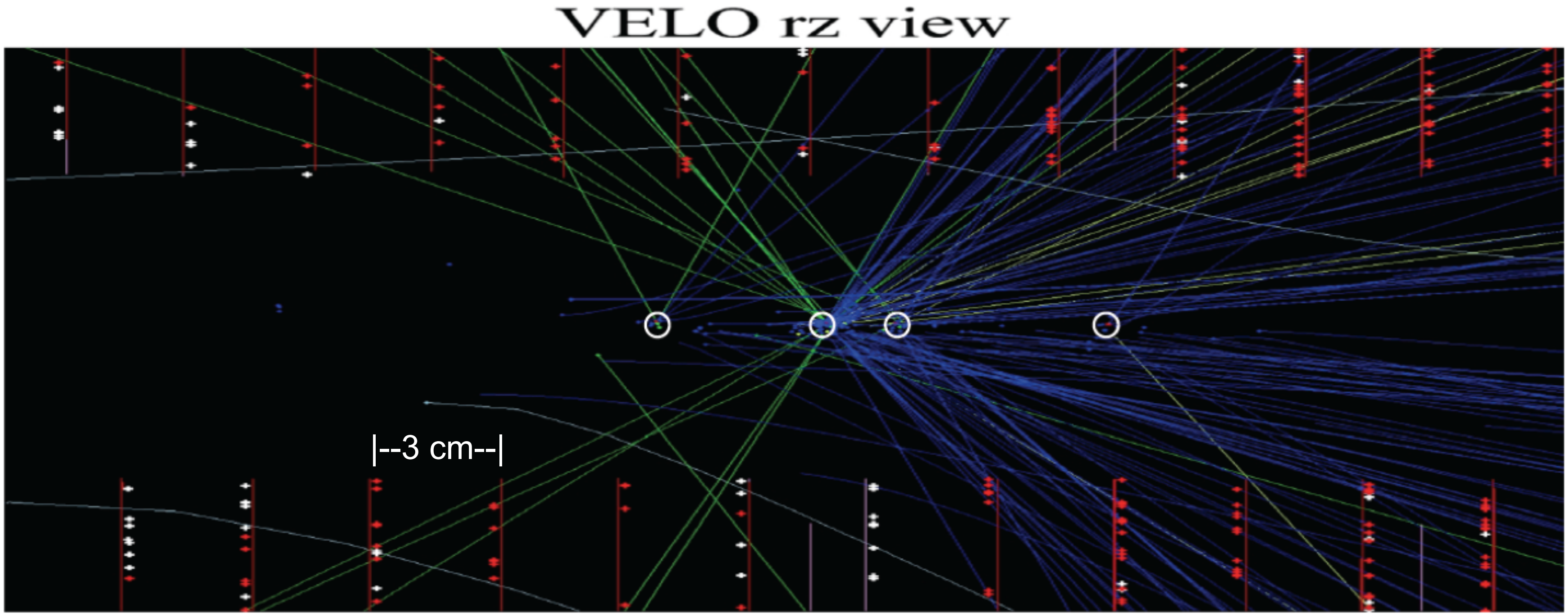


$B^- \rightarrow J/\psi\ K^-$

LHCb Event Display



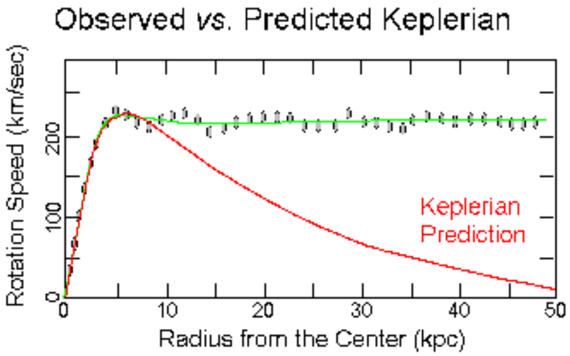
Running Conditions

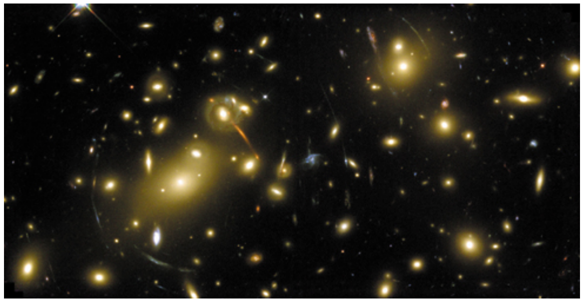

VELO rz view

- 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

Reasons for Physics Beyond the Standard Model

- Dark Matter





Gravitational lensing

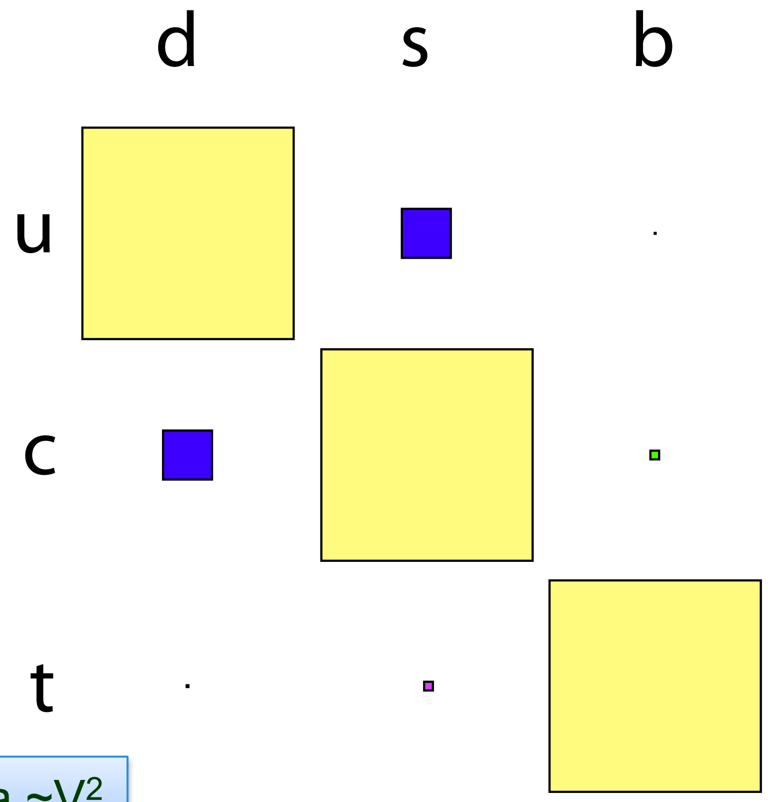
- Dark Energy: Cosmological constant
- Hierarchy Problem: Divergent quantum corrections to go from Electroweak scale ~100 GeV to Planck scale of Energy ~10^{19} GeV without “fine tuning” quantum corrections
- *All of the above may only be related to Gravity*

Other reasons for NP

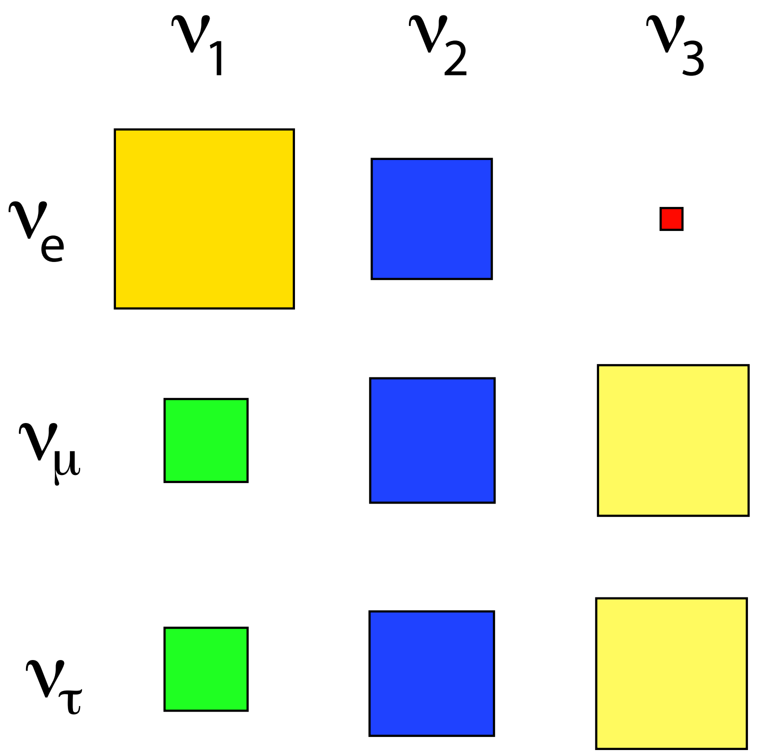
- Flavor problem: Why 3 replications of quarks & leptons?
- Baryogenesis: The amount of CP Violation observed thus far in the quark sector is too small: $(n_B-n_{\bar{B}})/n_\gamma =\sim 10^{-20}$ but $\sim 6\times 10^{-10}$ is needed. Thus New Physics must exist to generate needed CP Violation
- To 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

CKM



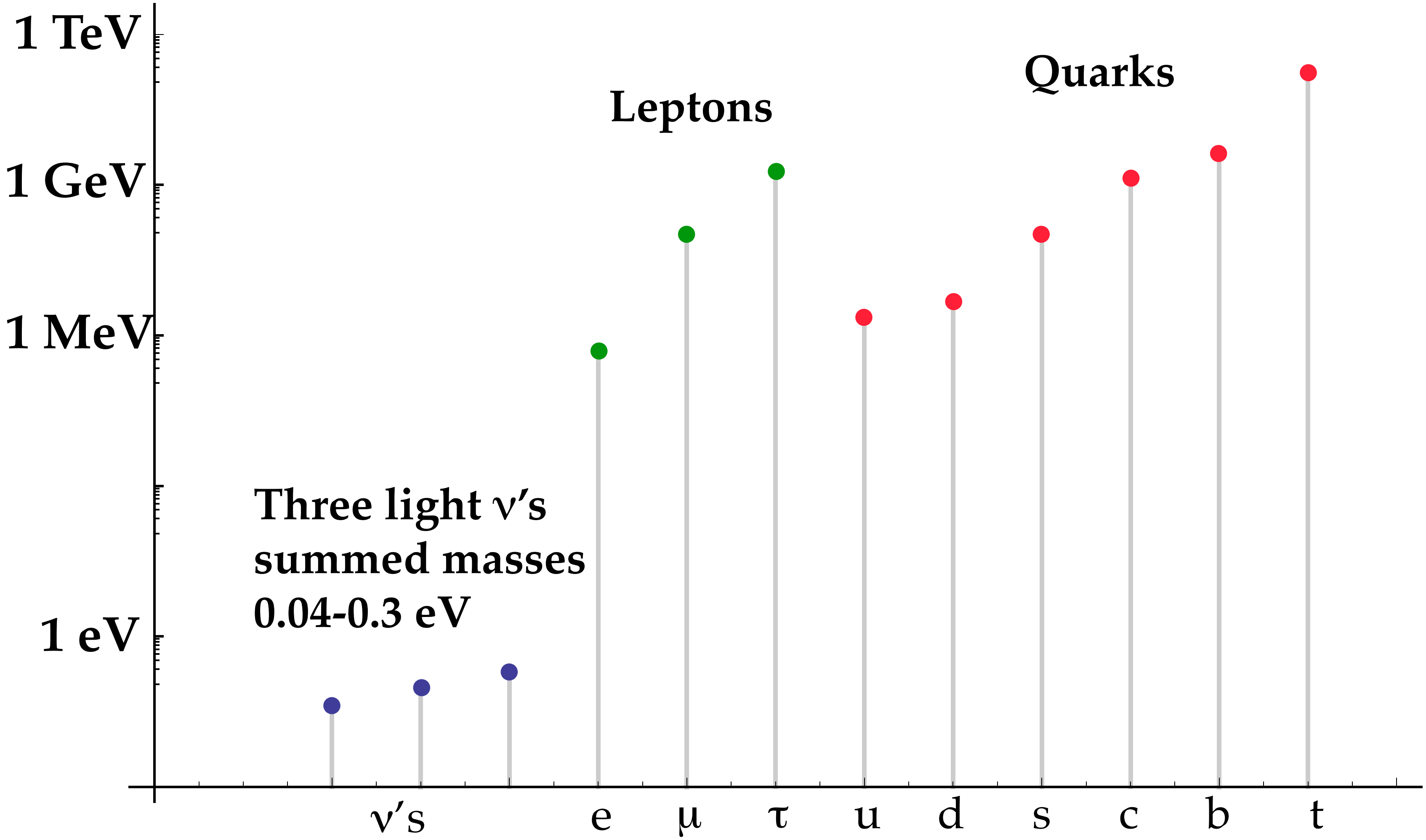
PMNS



Area ~V^2

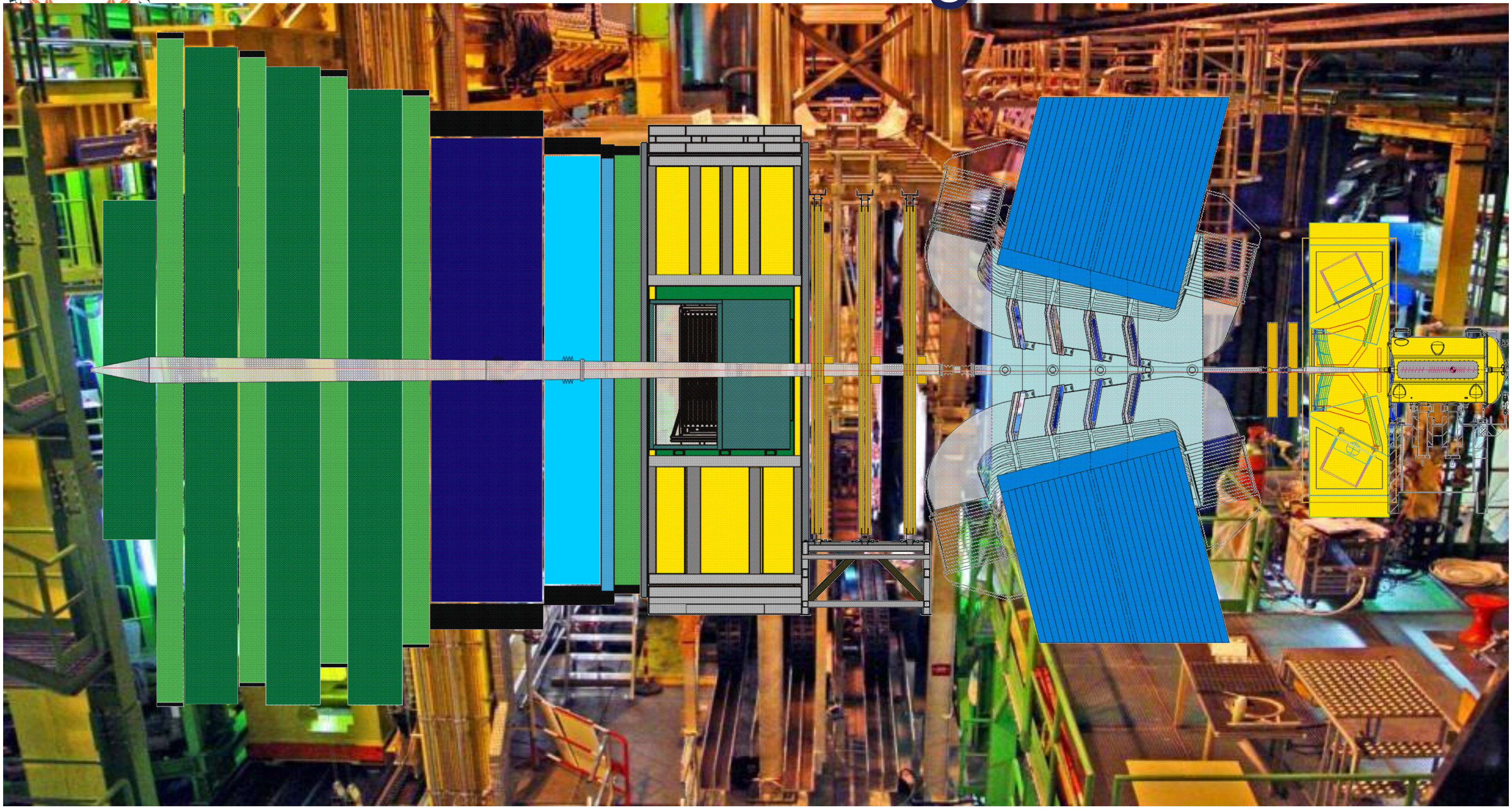
Why these values? Are the two related? Are they related to masses?

Masses



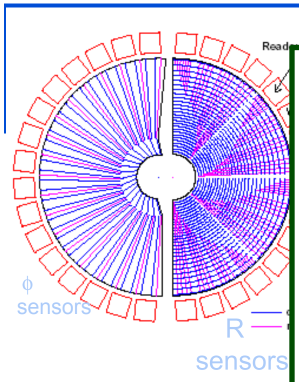
12 orders of magnitude differences not explained; t quark as heavy as Tungsten

Detector Workings

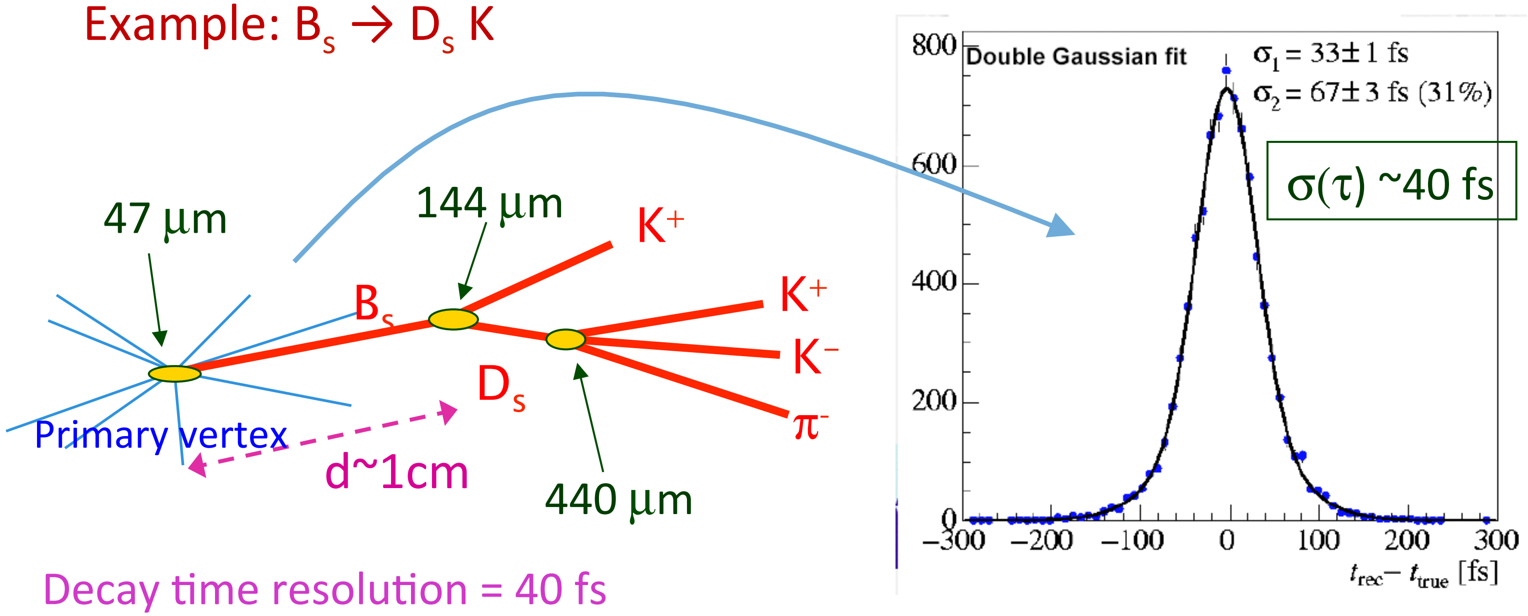


LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

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

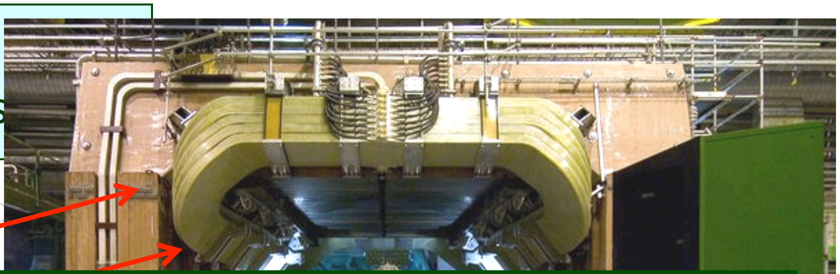
→ 30 μm IP resolution

Vertexing:

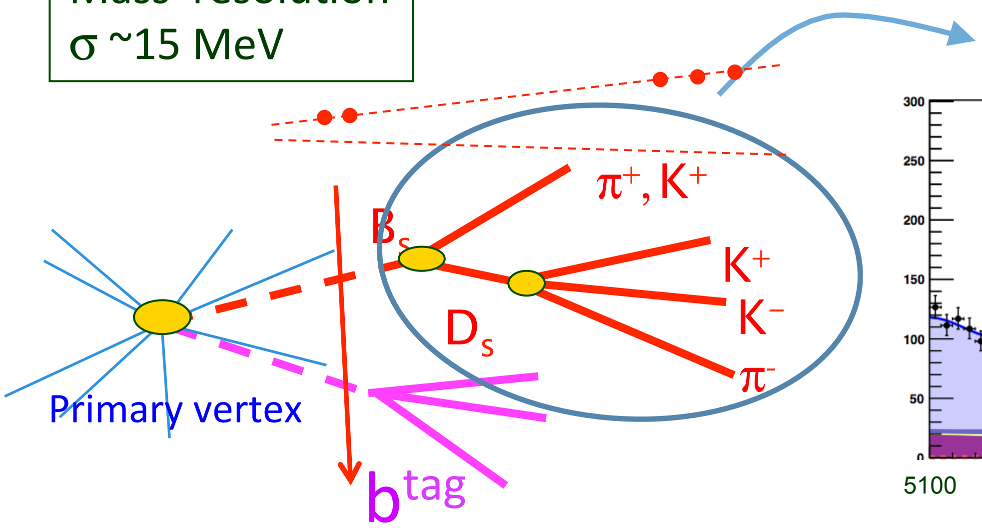
- trigger on impact parameter
- measurement of decay distance & decay time=d/v=md/p

Momentum and Mass measurement

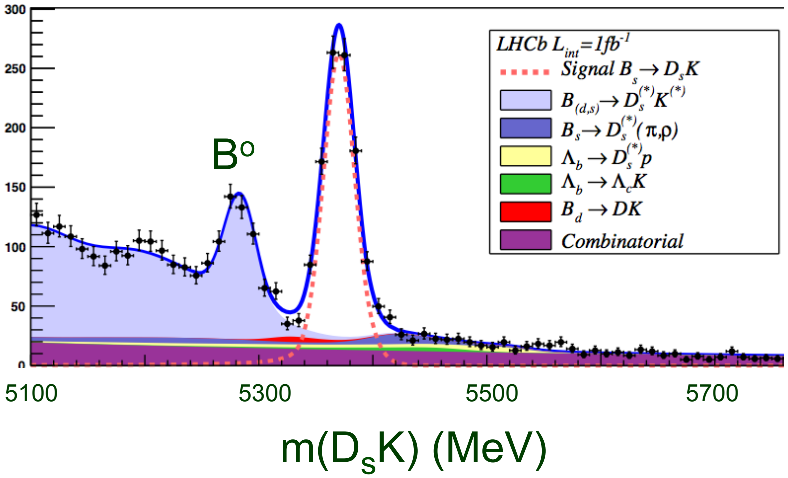
Momentum meas. + direction (VELO):
Mass resolution for background suppres



Mass resolution
σ ~15 MeV

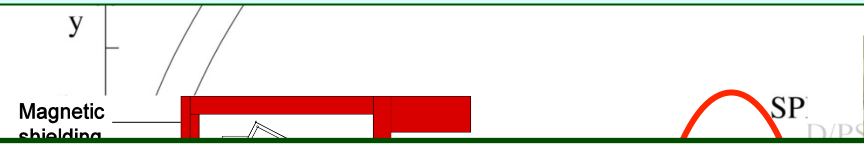


$B_s^o \to D_s^- K^+$



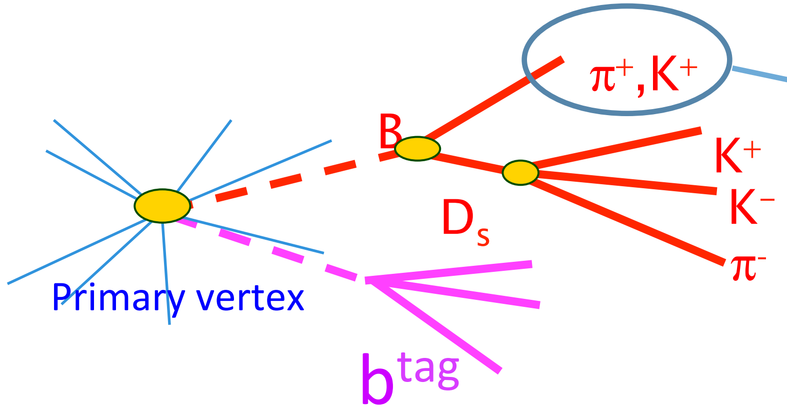
Hadron Identification

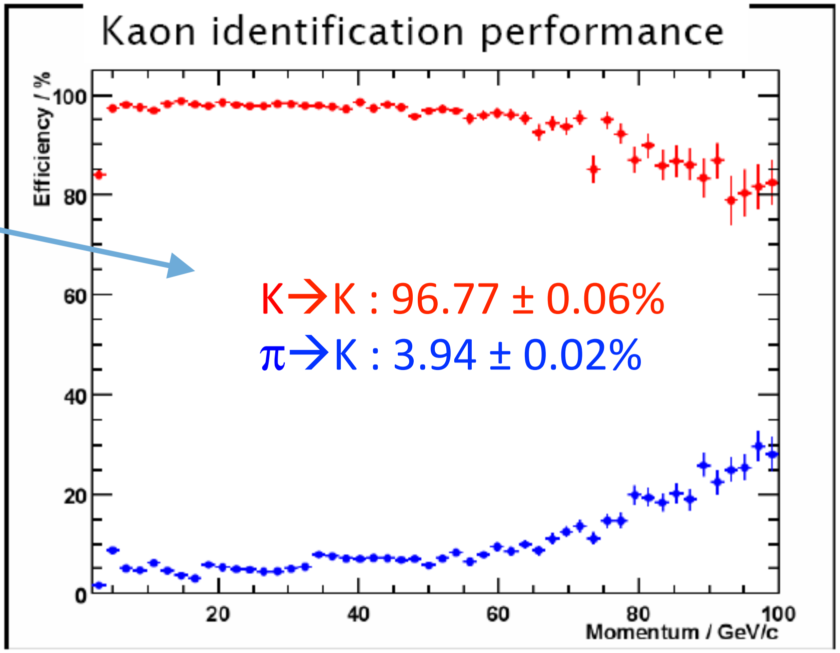
RICH: K/π identification using Cherenkov light emission angle



Bs → Ds K

SS flavour tagging





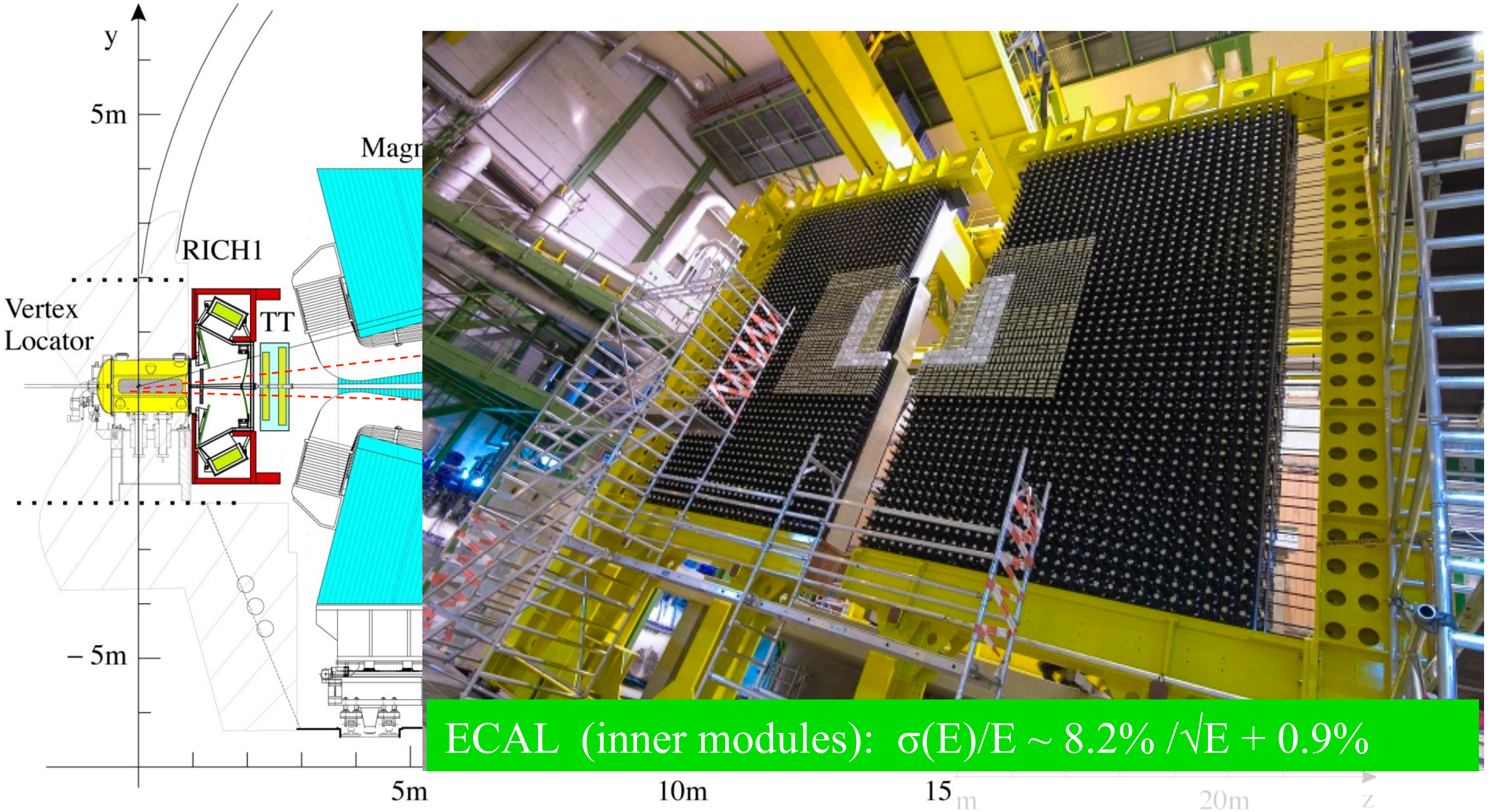
K→K : 96.77 ± 0.06%

π→K : 3.94 ± 0.02%

RICH1: 4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m3 CF_4 n=1.0005

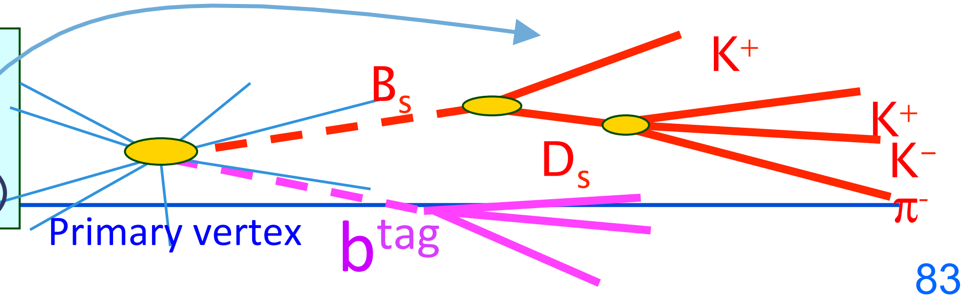
Calorimetry and L0 trigger



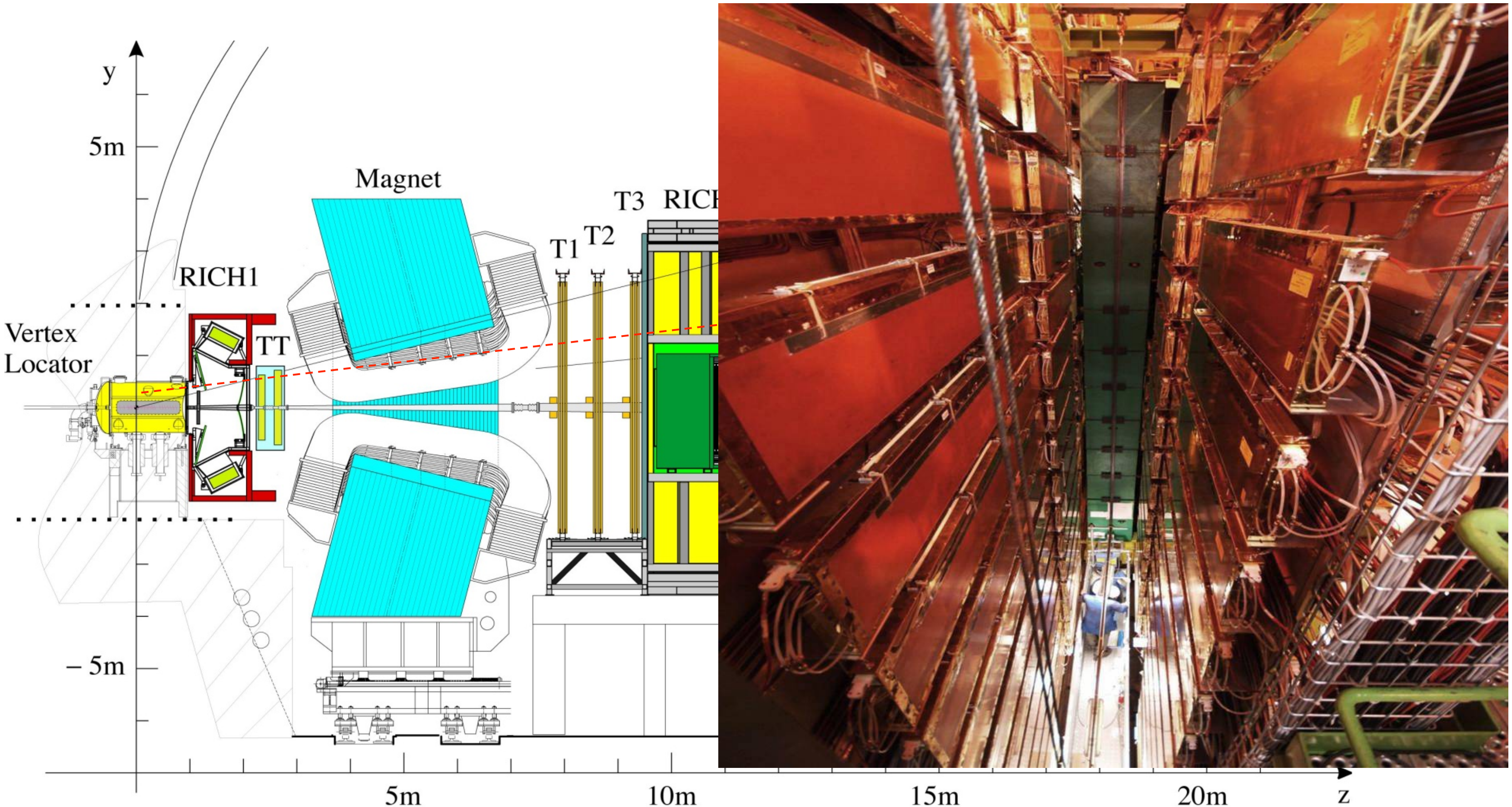
ECAL (inner modules): $\sigma(E)/E \sim 8.2\% / \sqrt{E} + 0.9\%$

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