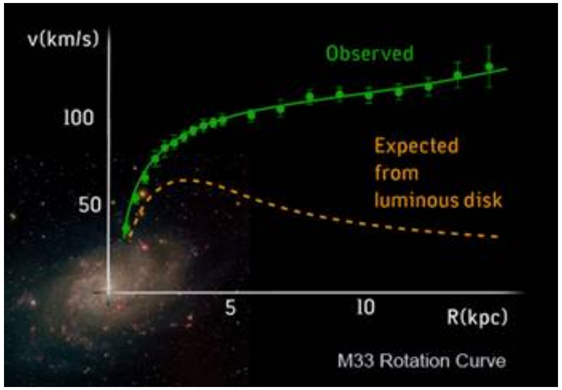
Flavor physics at hadron machines

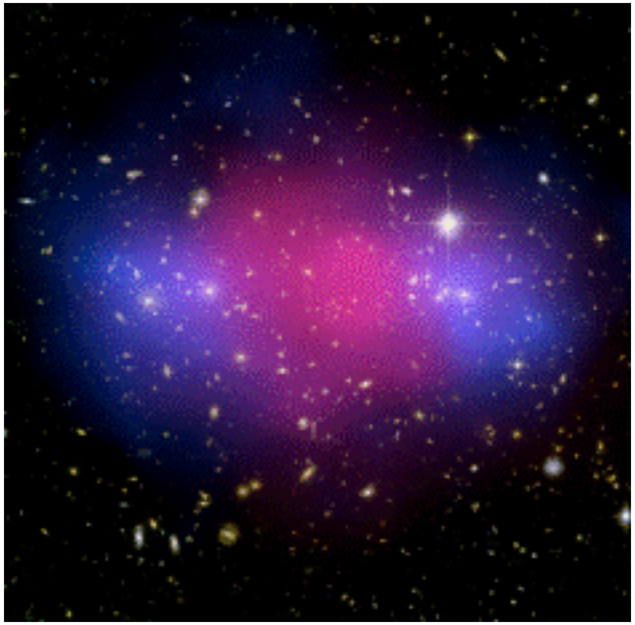
the quest for new physics through the lens of precision studies of heavy flavor decays

M. Artuso, SLAC Summer
Institute, July 11, 2013

Puzzles that motivate new physics

- Dark Matter and dark energy

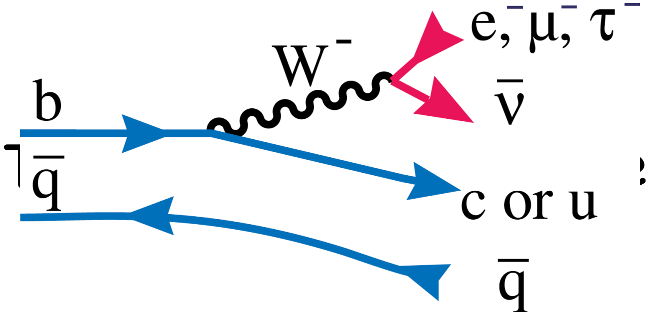


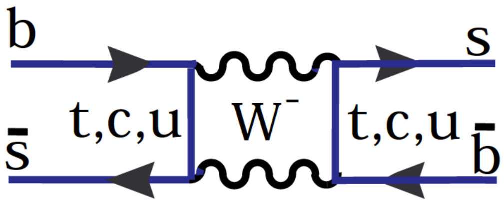


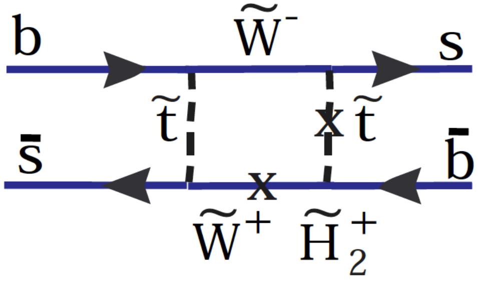
- Hierarchy Problem: We don't understand how we get from the Planck scale of Energy ~10^{19} GeV to the Electroweak Scale ~100 GeV without "fine tuning" quantum corrections
- Baryon asymmetry of the universe

Limits on New Physics

- How can new physics manifest itself in beauty decays?
- One hypothesis: assume that tree level diagrams are dominated by SM and loop diagrams could contain NP



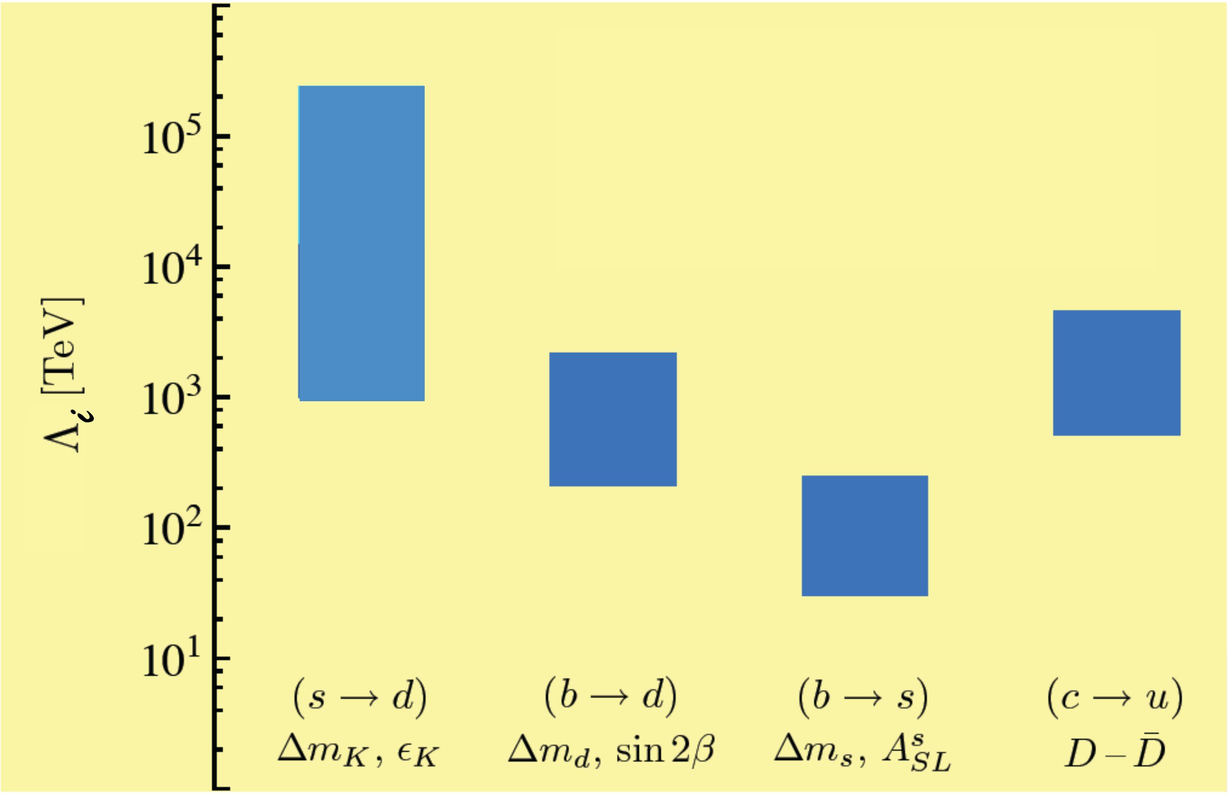




Flavor as a High Mass Probe

$$L_{\rm eff} = L_{\rm SM} + \frac{c_i}{\Lambda_i^2} O_i$$

- ☐ Already excluded ranges

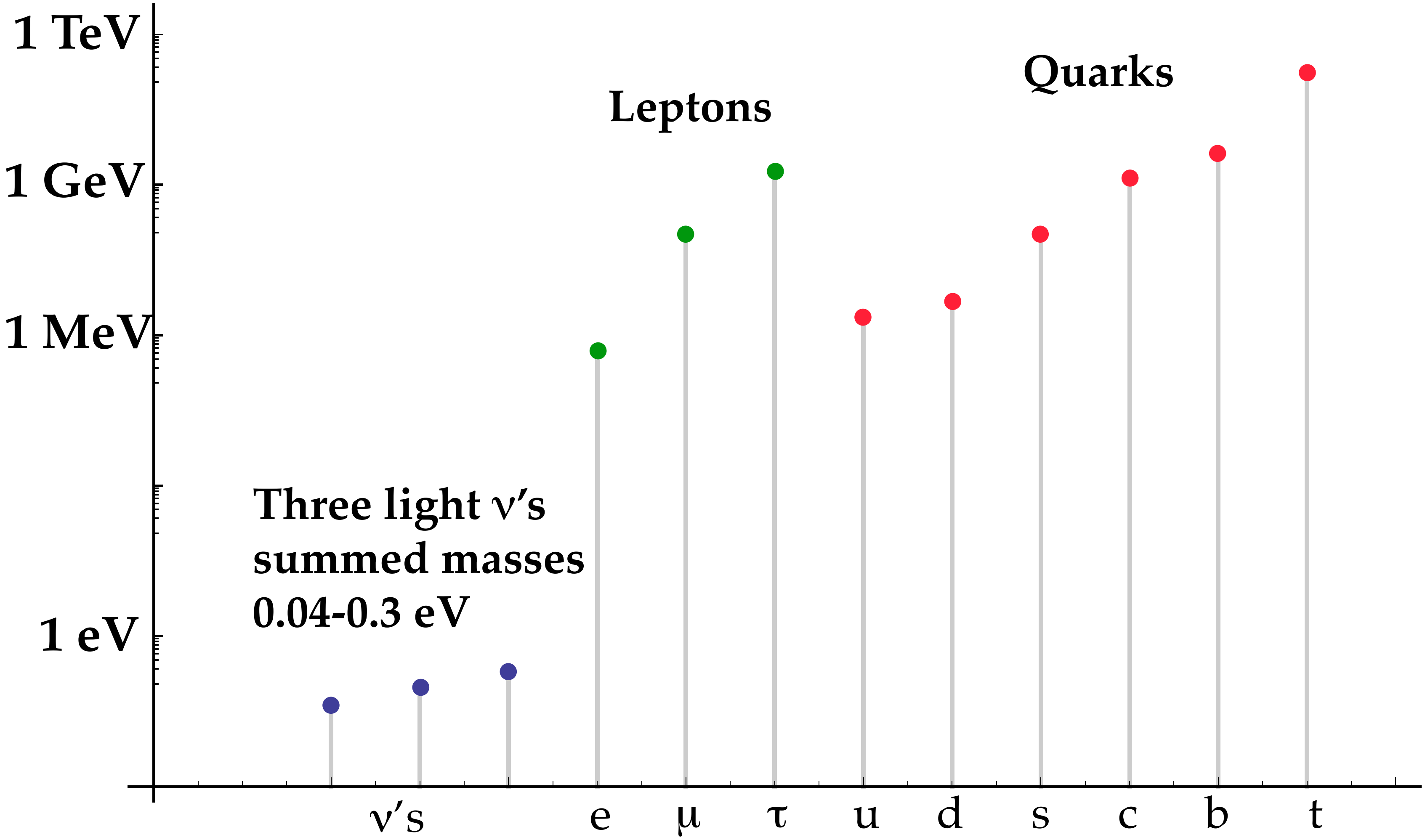


Ways out

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

Masses

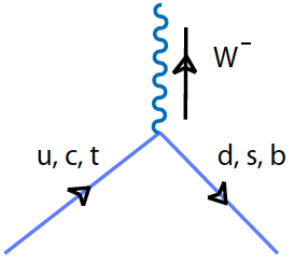


12 orders of magnitude differences not explained; t quark as heavy as Tungsten

Quark Mixing & CKM Matrix

- In SM charge -1/3 quarks (d, s, b) are mixed
- Described by CKM matrix (also ν are mixed)

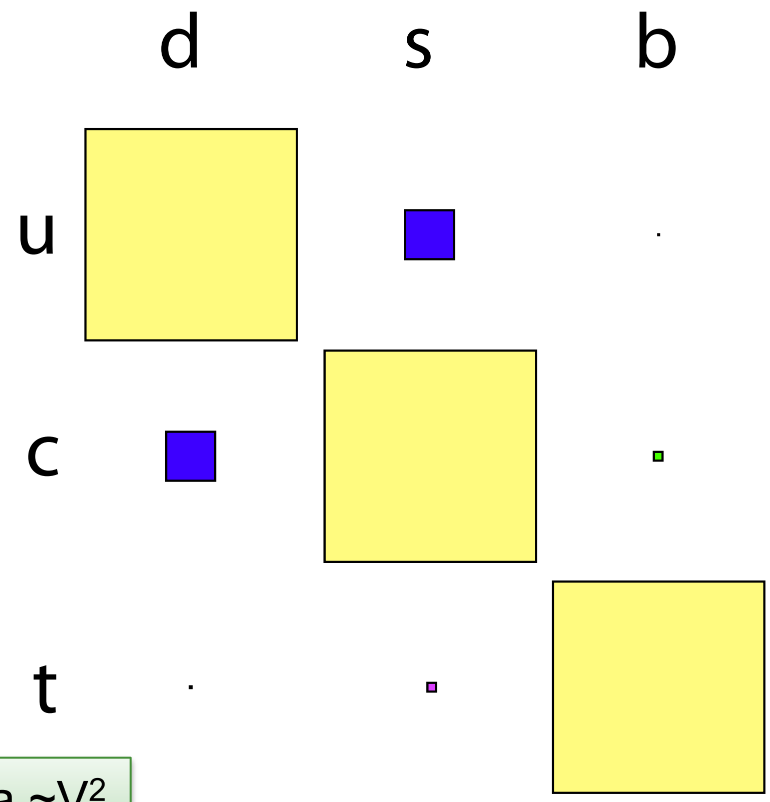
$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



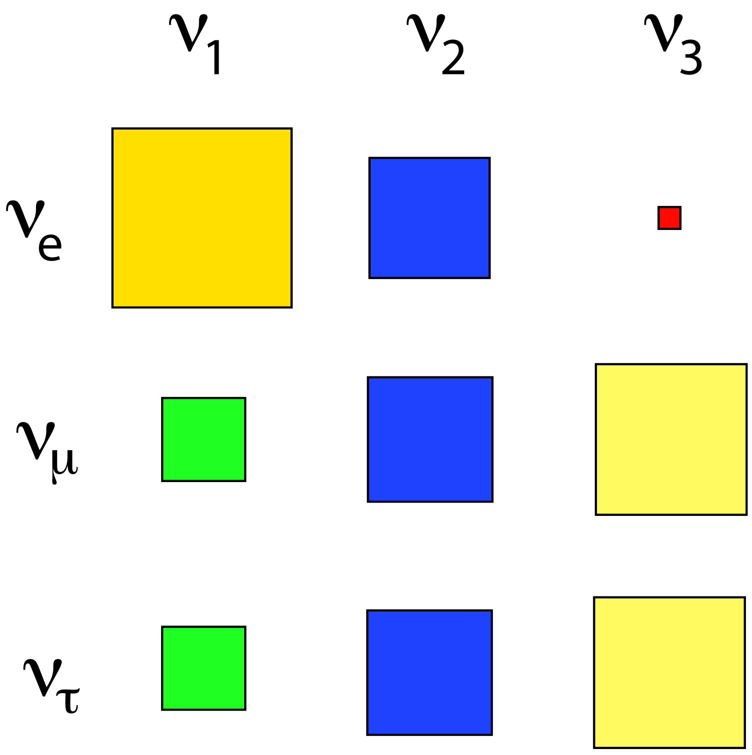
$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\left(\rho - i\eta\right) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix} + O\left(\lambda^4\right)$$

- λ=0.225, A=0.8, constraints on ρ & η
- These are fundamental constants in SM

CKM vs. PMNS



CKM



PMNS

Area ~V^2

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

Hadron colliders

Tevatron 6.9km, at surface

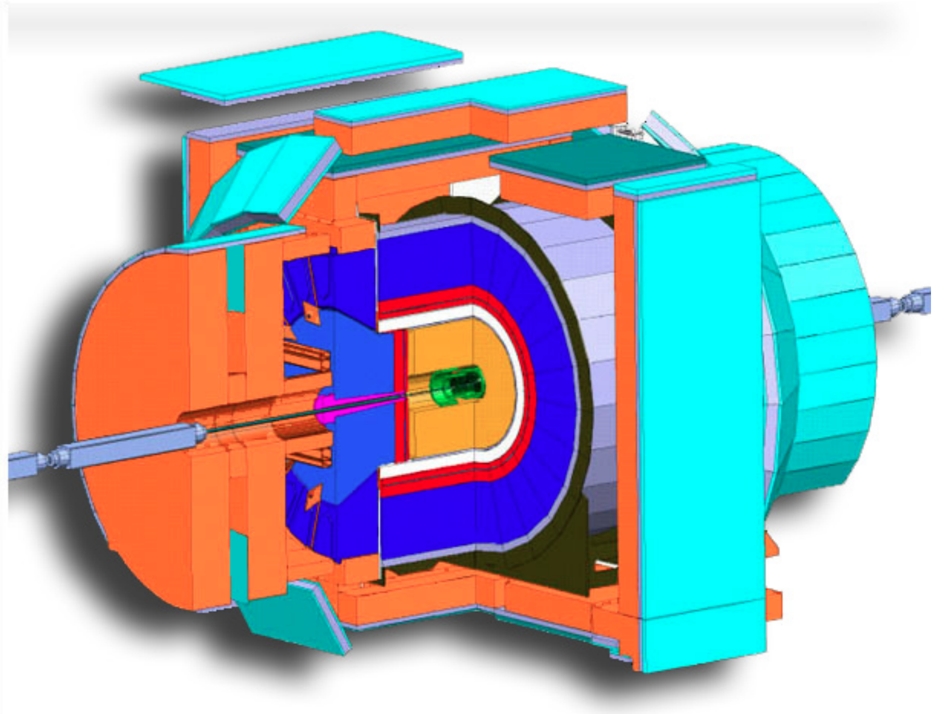
- *$p\bar{p}$ collisions at $\sqrt{s}=1.96$TeV (1.8TeV <2000)*
- *delivered 10fb^{-1} to CDF and D0*
- *data taking 1985-2011*

LHC 27km, at ~-100m

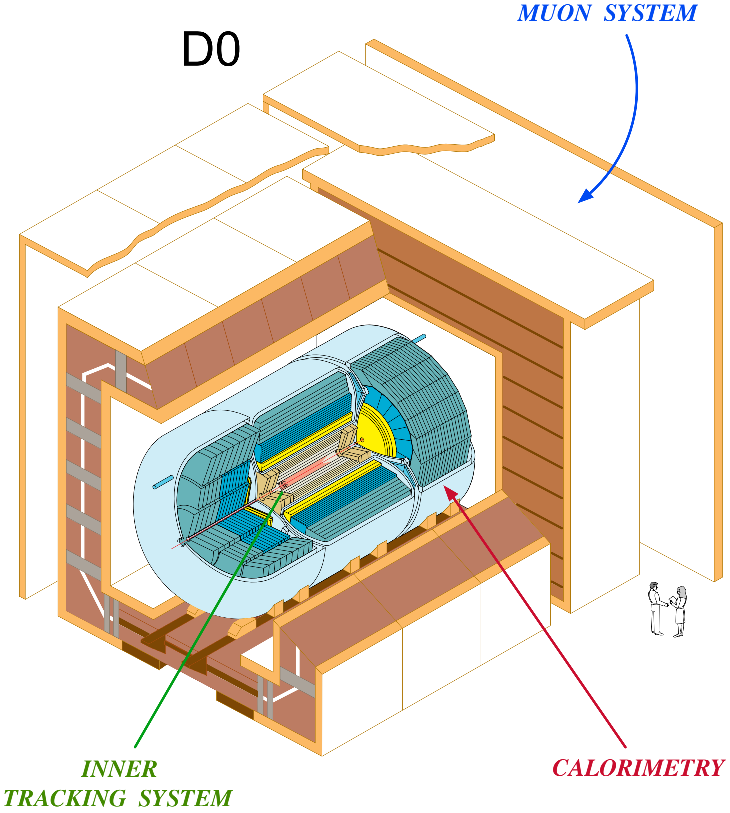
- *pp collisions at $\sqrt{s}=8$TeV in (7TeV in 2011)*
- *delivered 25 (3)fb^{-1} to ATLAS,CMS (LHCb)*
- *data taking 2010-2012*
- *resume in 2015 with $\sqrt{s}=13$TeV*

The Tevatron legacy

CDF



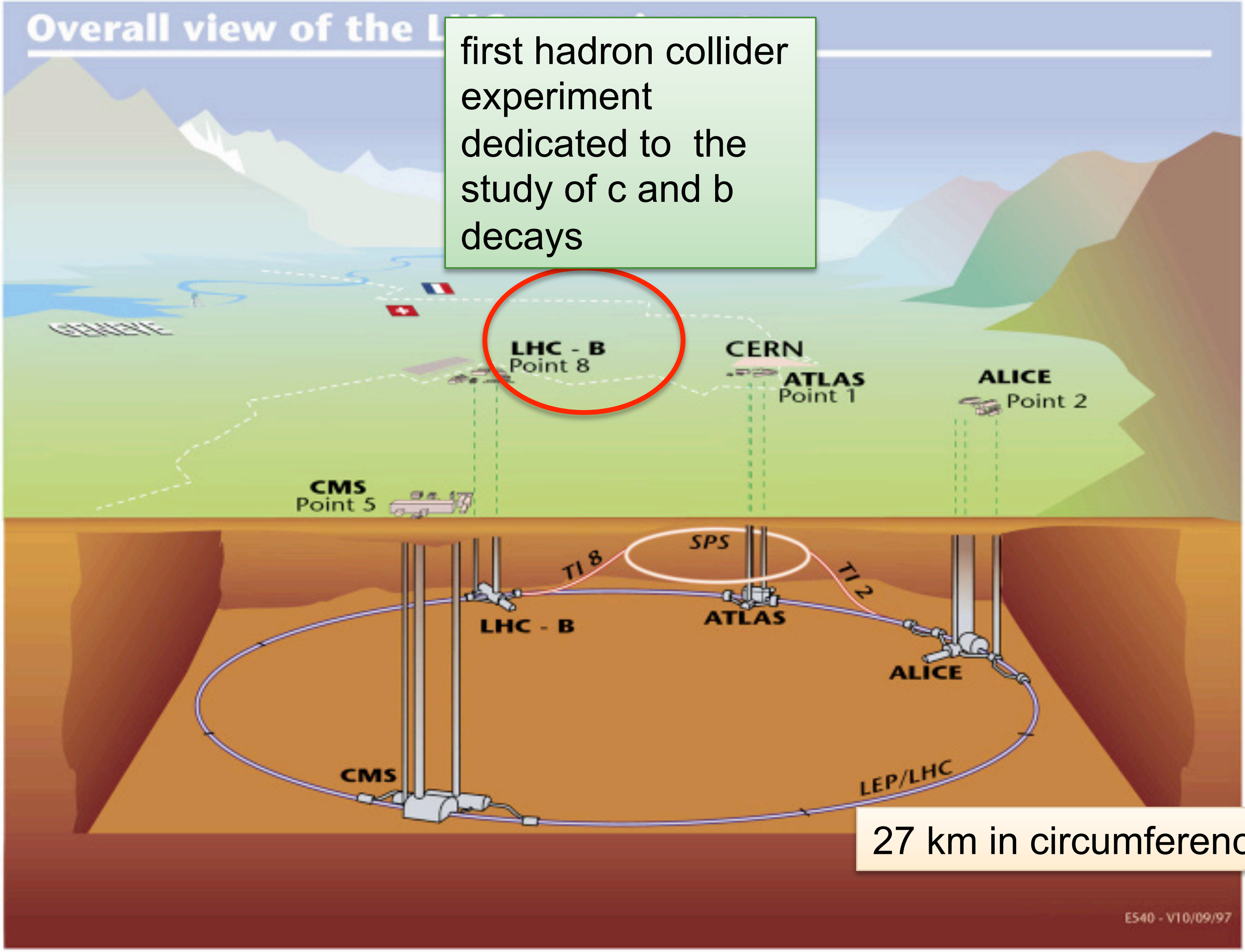
D0



Large radius solenoid
Excellent tracking
Synchronous track trigger

Large muon coverage |η|<2
Strong B field (possibility of switching polarities)
highly segmented hadron calorimeter

The LHC experiments

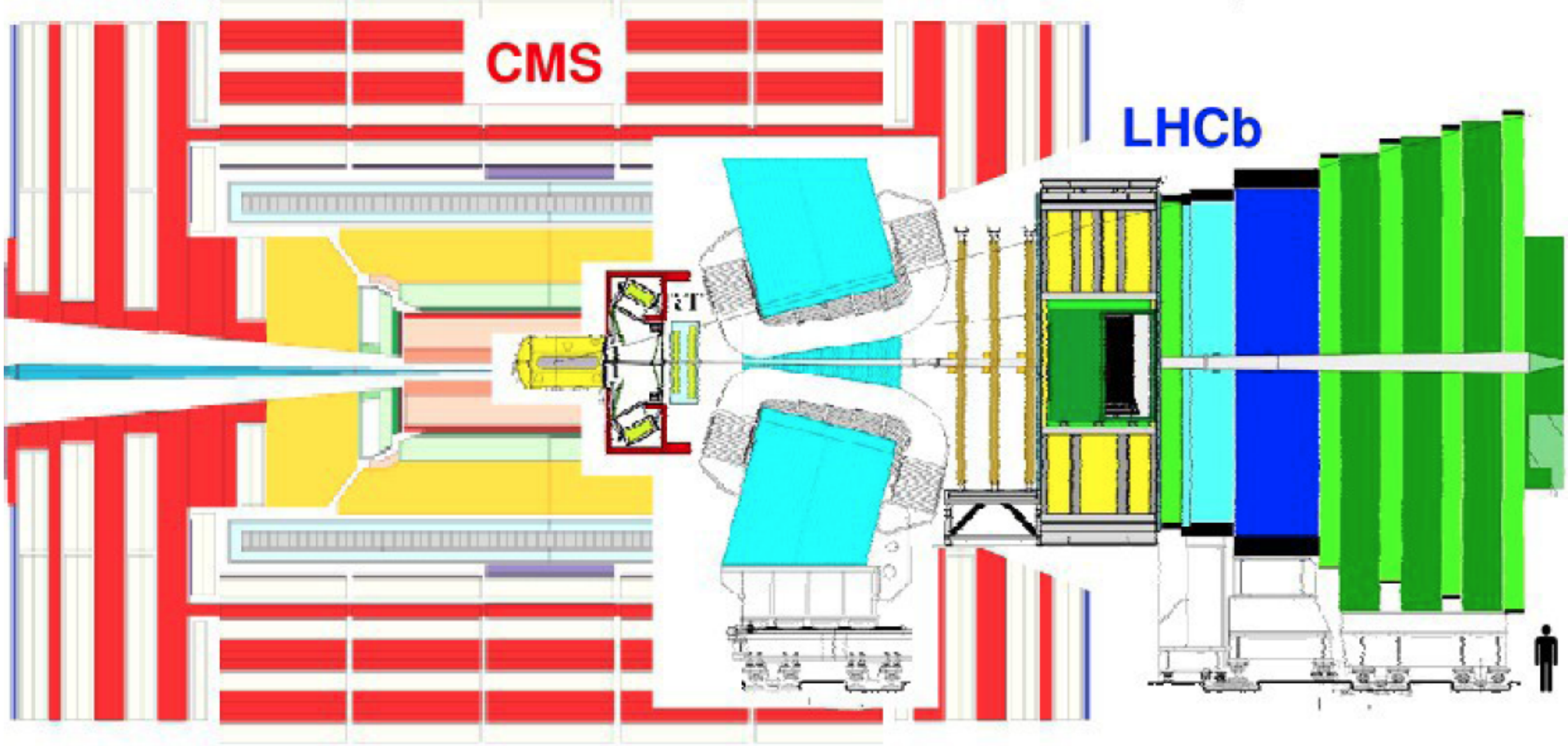


first hadron collider experiment dedicated to the study of c and b decays

27 km in circumference

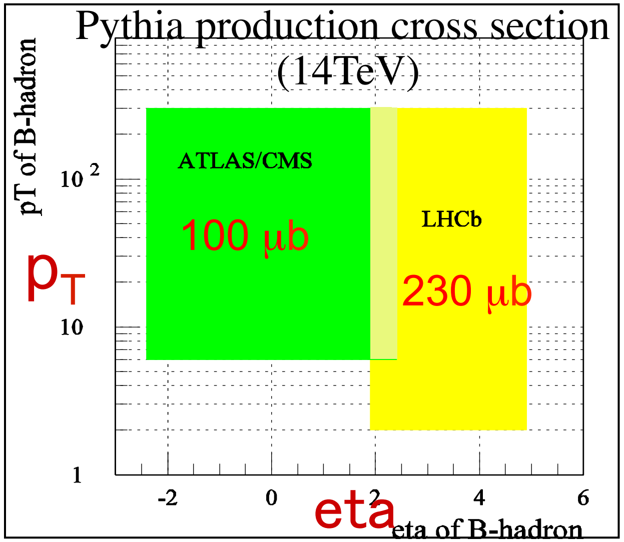
LHCb and ATLAS/CMS

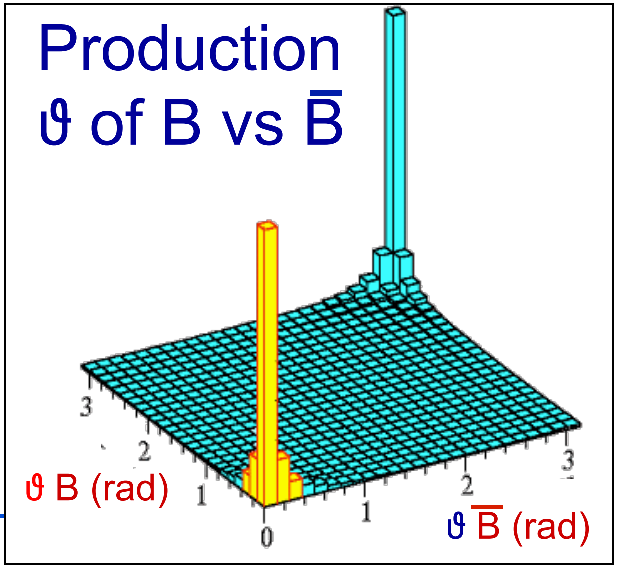
- ☐ Complementary to ATLAS & CMS
- ☐ Much less expensive



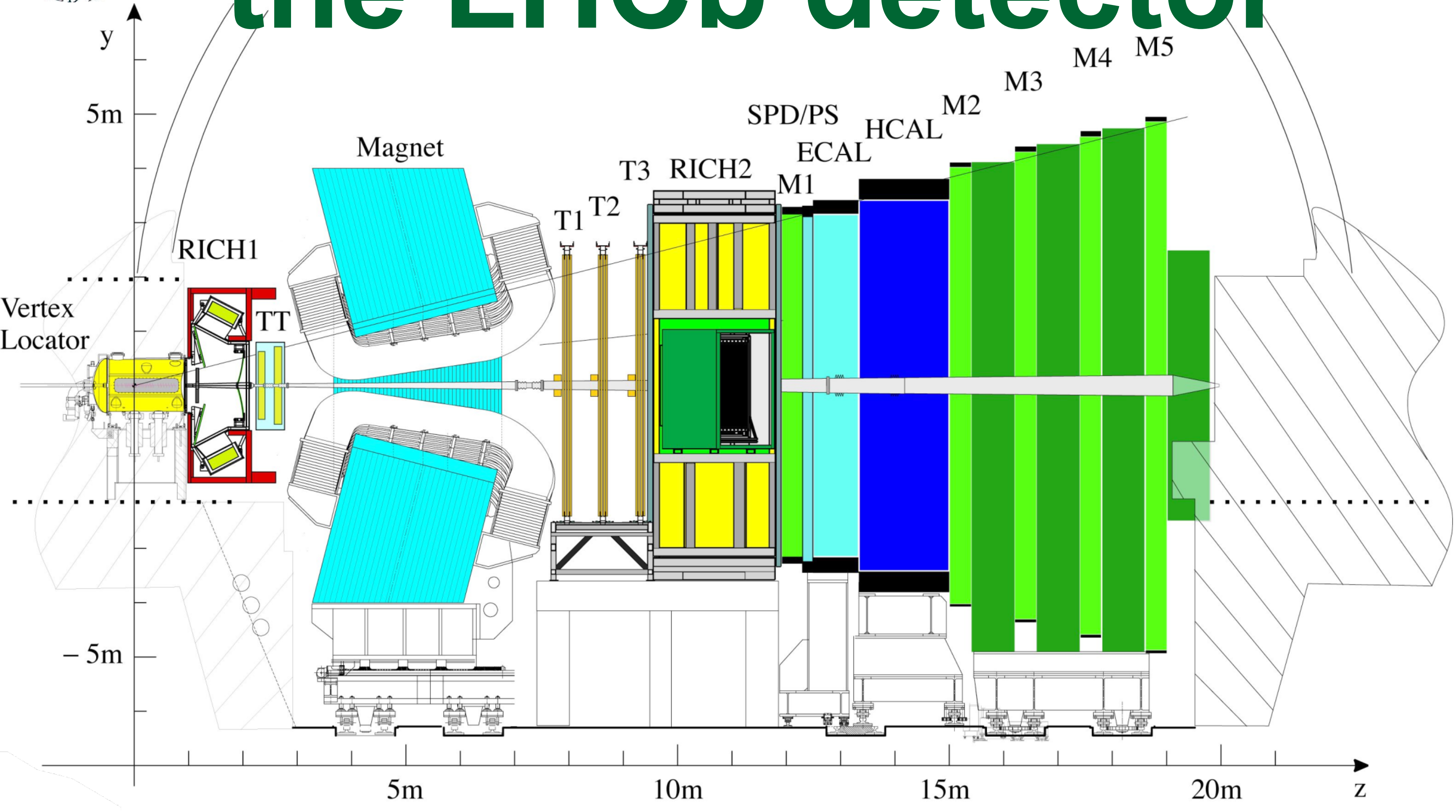
The Forward Direction at the LHC

- 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 "flavor tagging"
- LHCb uses the forward direction where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=2\times10^{32}/\text{cm}^2/\text{s}$, we get 10^{12} B hadrons in 10^7 sec

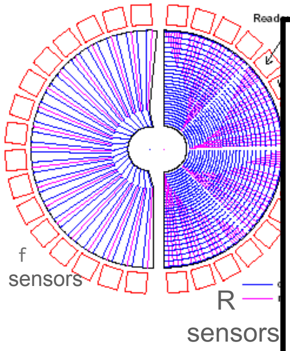




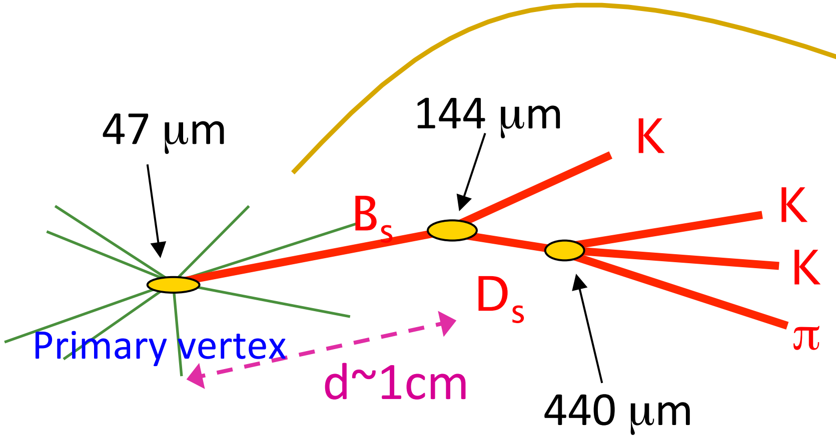
the LHCb detector

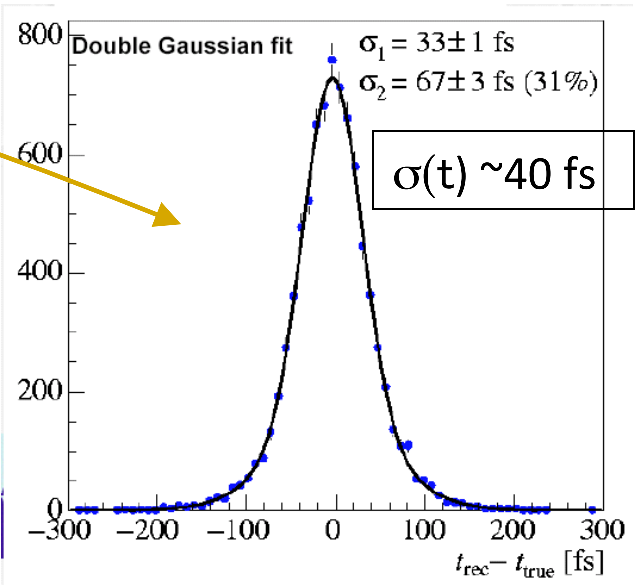


B-Vertex Measurement



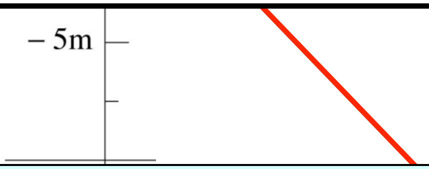
Example: $B_s \rightarrow D_s K$





σ(t) ~40 fs

Decay time resolution = 40 fs



Vertex Locator (Velo)

Silicon strip detector with

~ 5 μm hit resolution

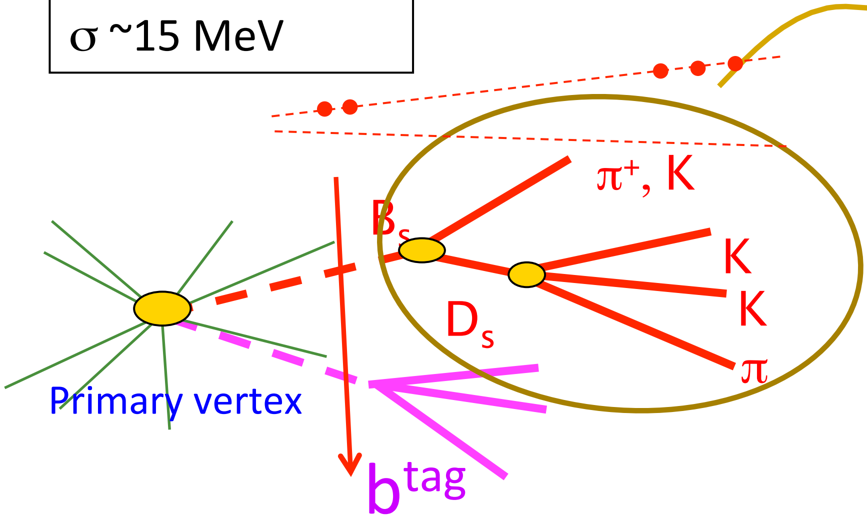
→ 30 μm IP resolution

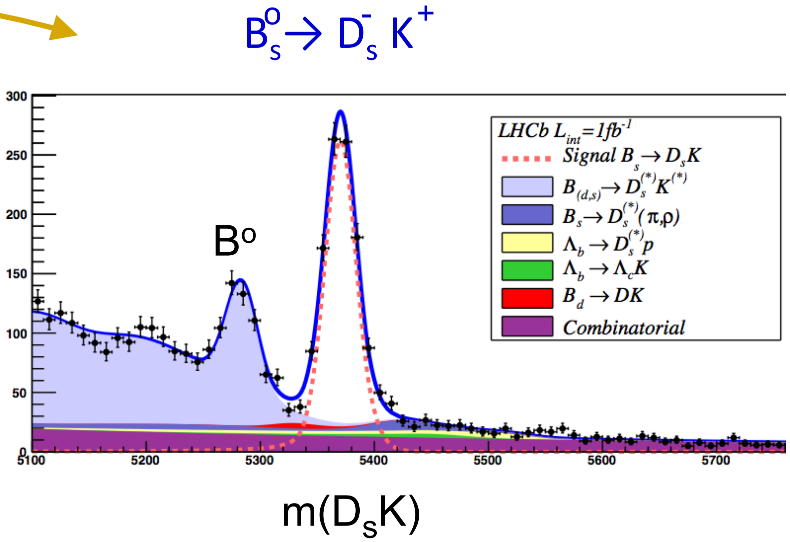
Vertexing:
- trigger on impact parameter
- measurement of decay distance (time)

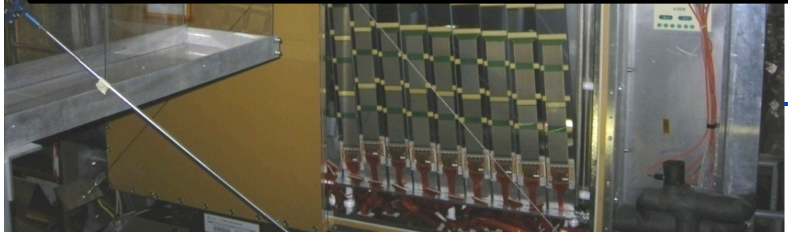
Momentum and Mass measurement

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

Mass resolution
σ ~15 MeV

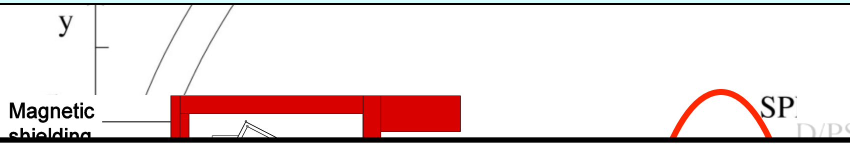






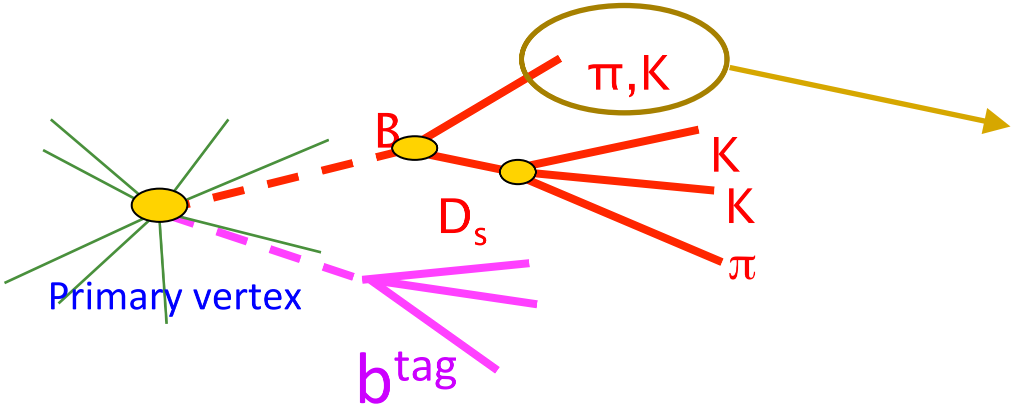
Hadron Identification

RICH: K/π identification using Cherenkov light emission angle



$B_s \rightarrow D_s K$

SS flavour tagging



K→K : 96.77 ± 0.06%

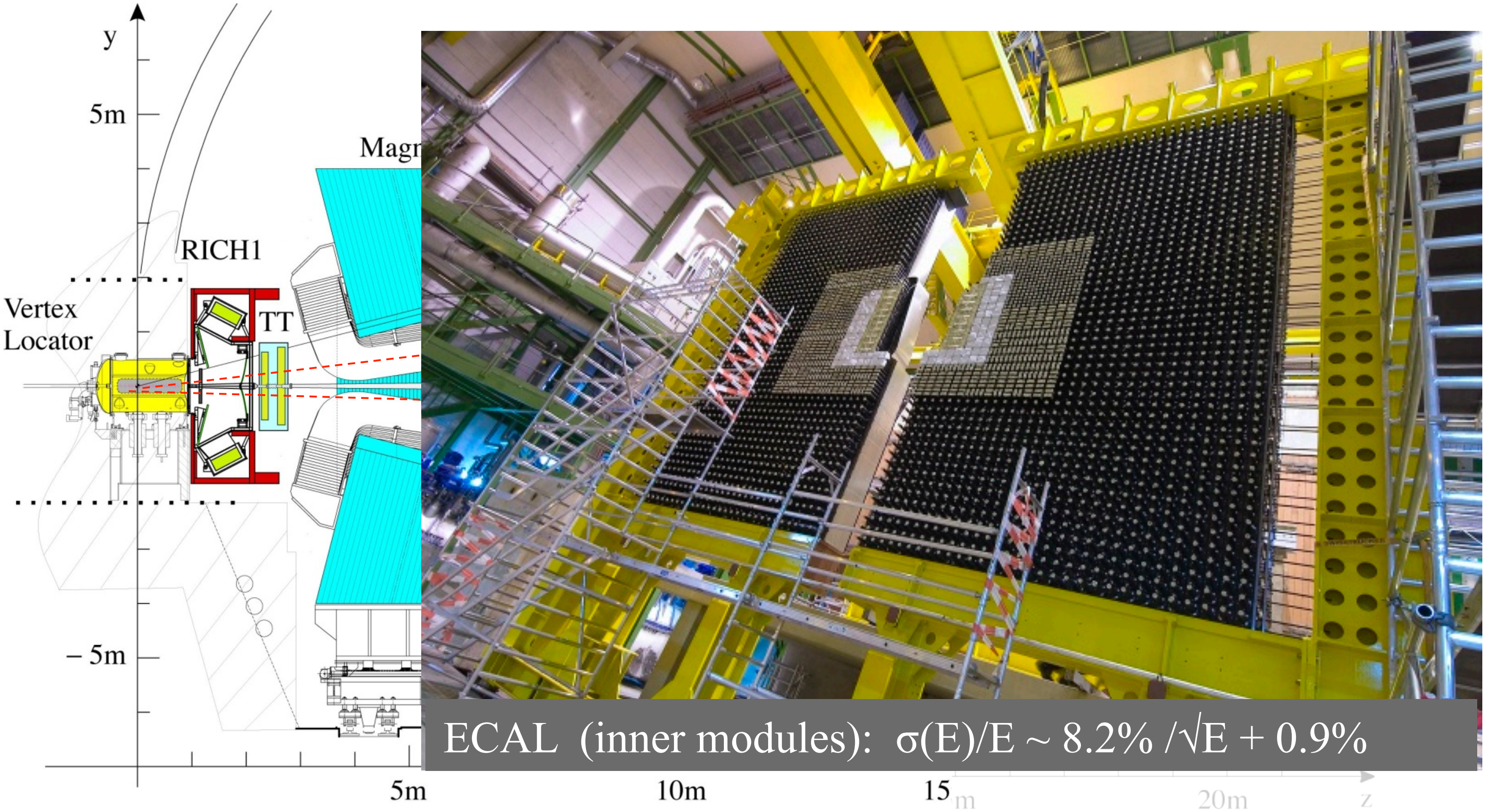
π→K : 3.94 ± 0.02%

RICH1: 5 cm aerogel n=1.03

4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m3 CF n=1.0005

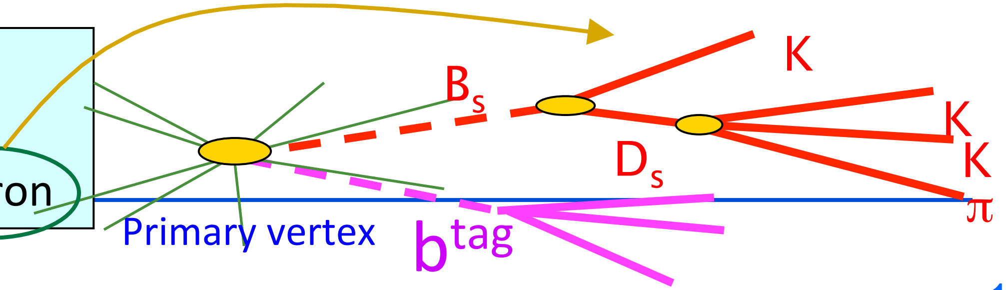
Particle identification and L0 trigger



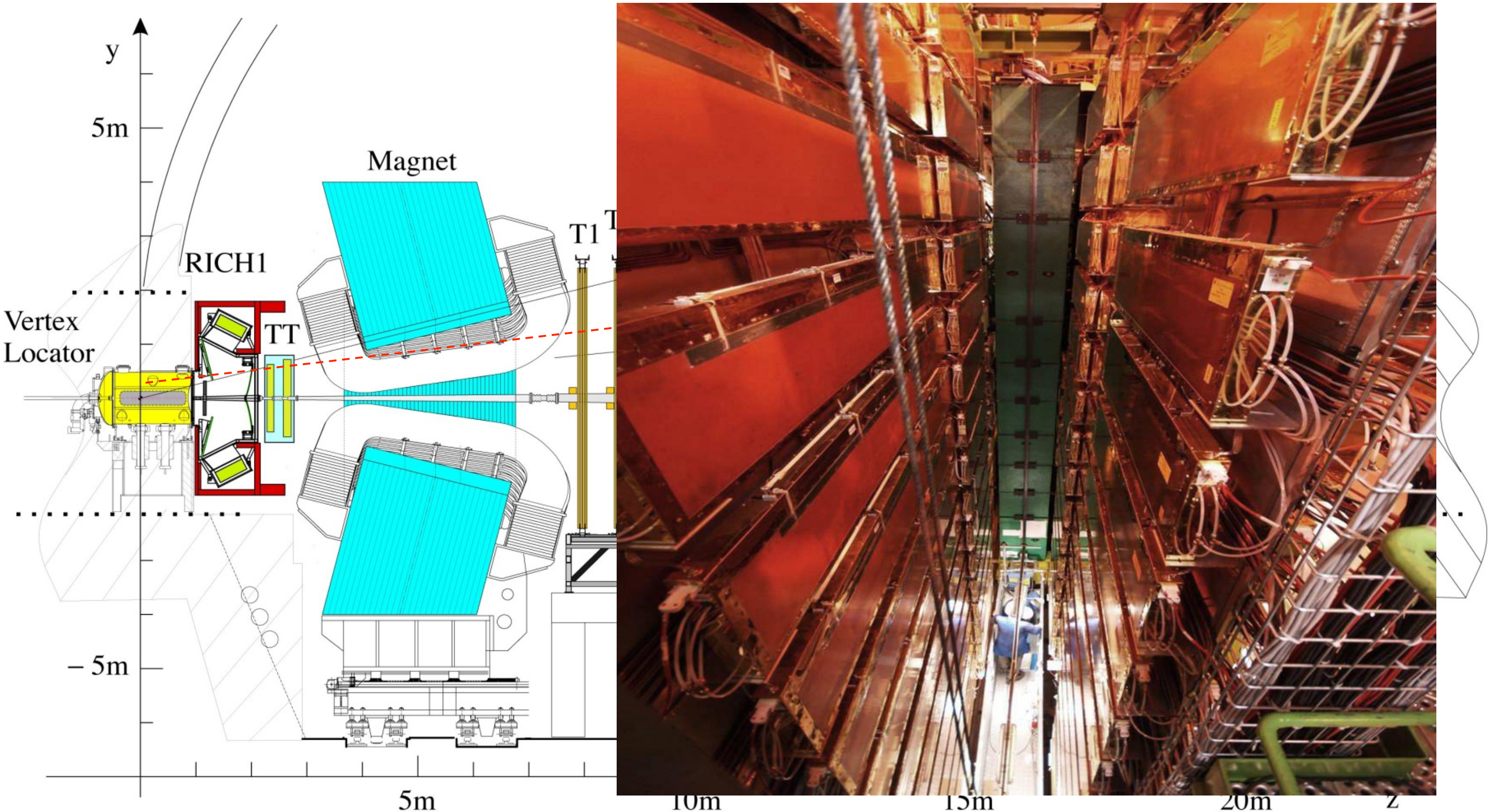
ECAL (inner modules): $\sigma(E)/E \sim 8.2\%/\sqrt{E} + 0.9\%$

Calorimeter system :

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

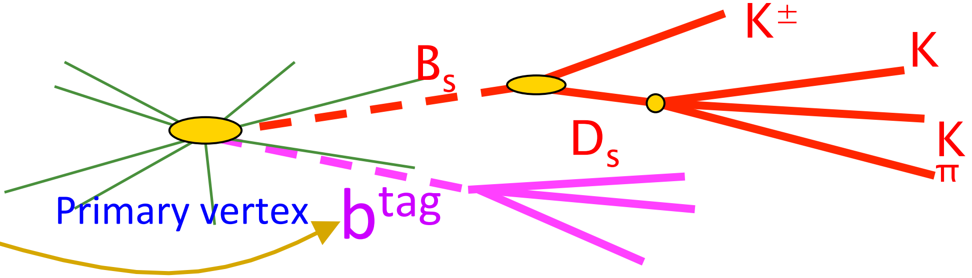


Particle identification and L0 trigger

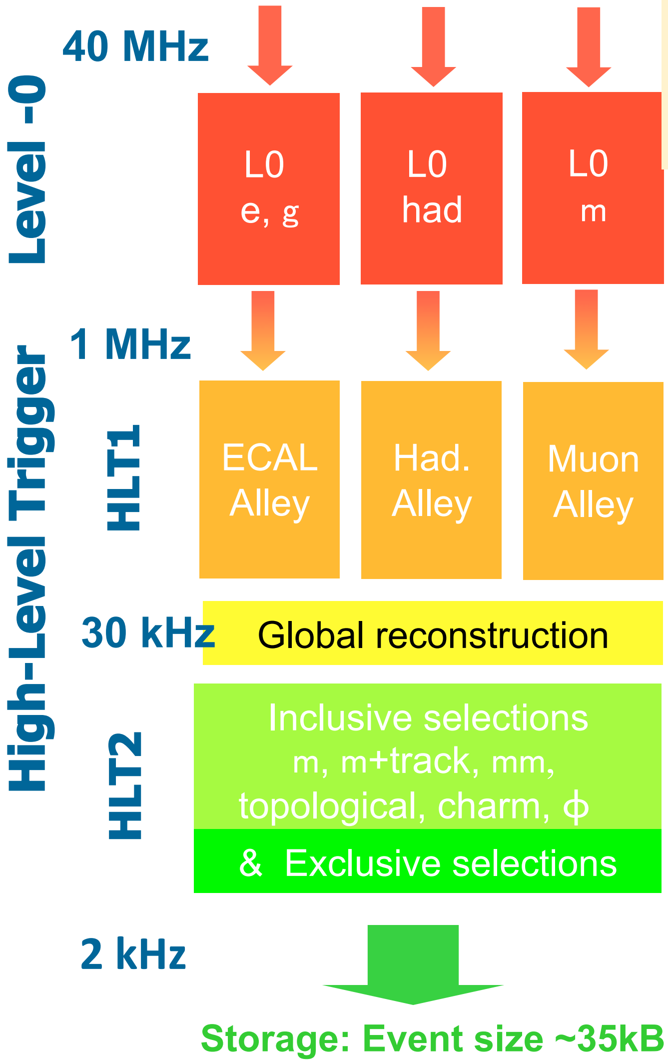


Muon system:

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



Triggering



Level -0

40 MHz

L0
e, g

L0
had

L0
m

1 MHz

High-Level Trigger

HLT1

ECAL Alley

Had. Alley

Muon Alley

30 kHz

Global reconstruction

HLT2

Inclusive selections
m, m+track, mm,
topological, charm, ϕ

& Exclusive selections

2 kHz

Storage: Event size ~35kB

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

- **Hardware level (L0)**

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

- **Software level (High Level Trigger, HLT)**

  Farm with $\mathcal{O}$(2000) multi-core processors

  HLT1: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts

  HLT2: B reconstruction + selections

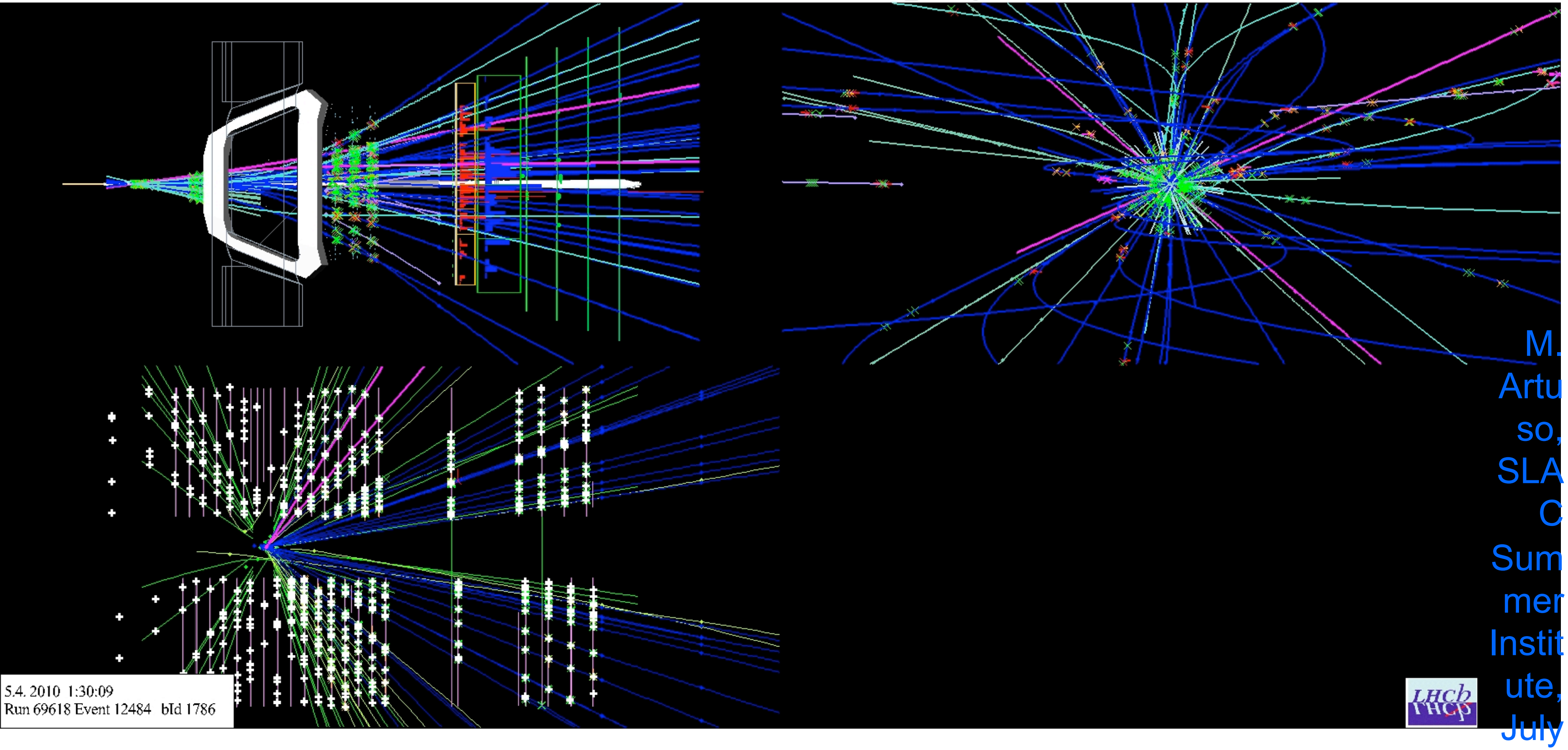
	ε(L0)	ε(HLT1)	ε(HLT2)
Electromagnetic	70 %	> ~80 %	> ~90 %
Hadronic	50 %		
Muon	90 %		

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 >90% for all systems
- Problems: Vertex resolution somewhat worse, flavor tagging somewhat poorer
- Luminosity is leveled – small changes of $\mathcal{L}$ with time, beams are brought closer together when currents decrease

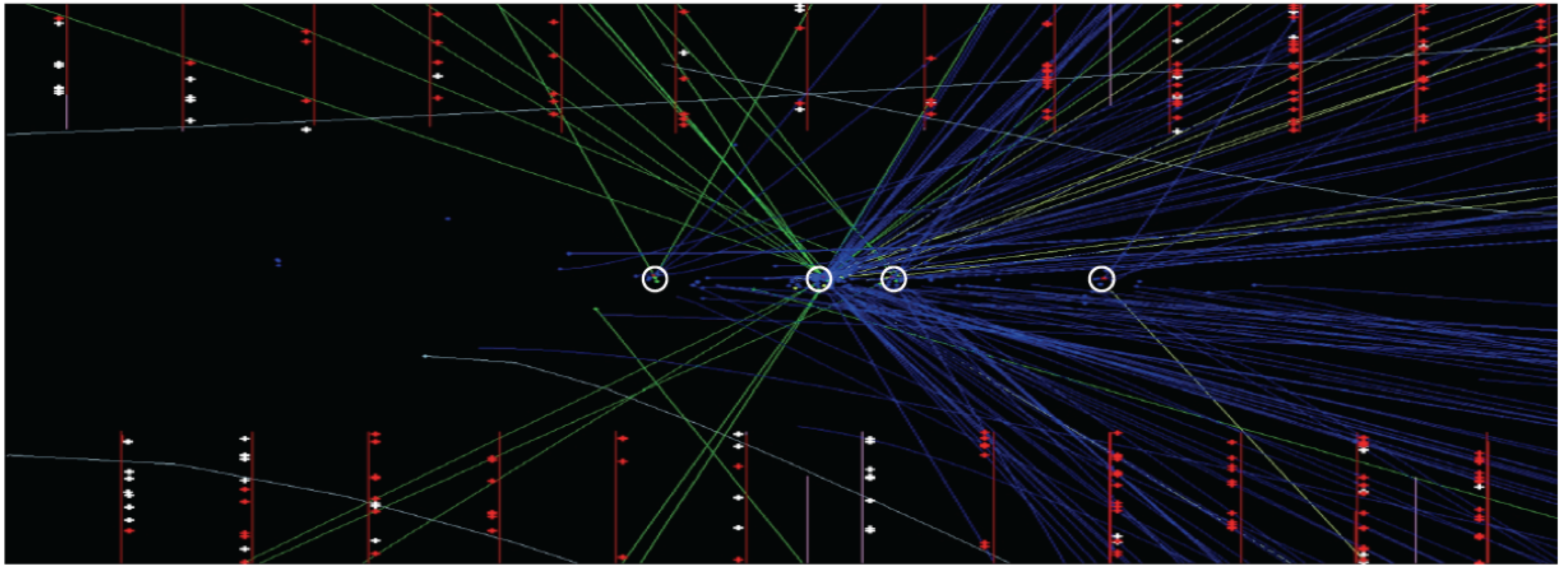
$B^{-} \rightarrow J/\psi\ K^{-}$

LHCb Event Display



Running Conditions

VELO rz view



- ☐ 20 MHz of bunch crossing (in 2012, with 50 ns bunch spacing) with an average of 2 p-p interactions per bunch crossing → this level of pileup not an issue for LHCb

towards the future: the LHCb upgrade

- New physics manifestations in flavor observables may be subtle ⇒we want a ≥ 10 increase in our data sample through:
  - Increase nominal luminosity (1-2x10^{33} cm^{-2}s^{-1})
  - Increase efficiency on beauty and charm hadronic final states trigger (≥2)

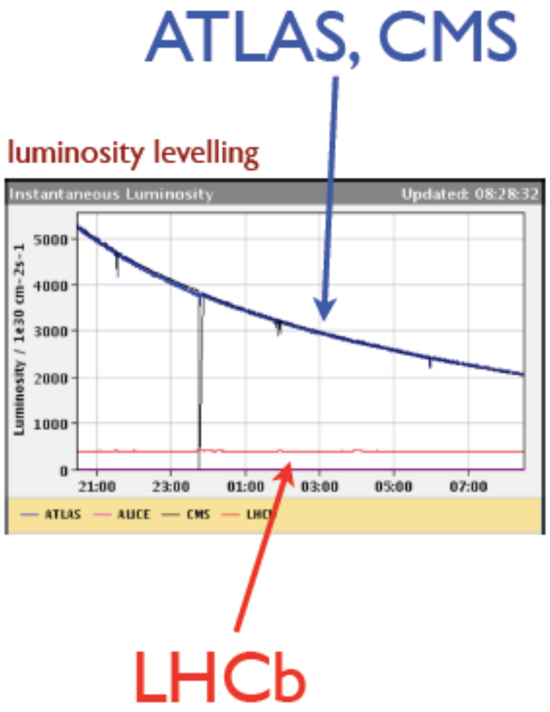
- Schedule:
  - R&D phase in progress and should end in 2014
  - Installation during long shutdown ~2018.

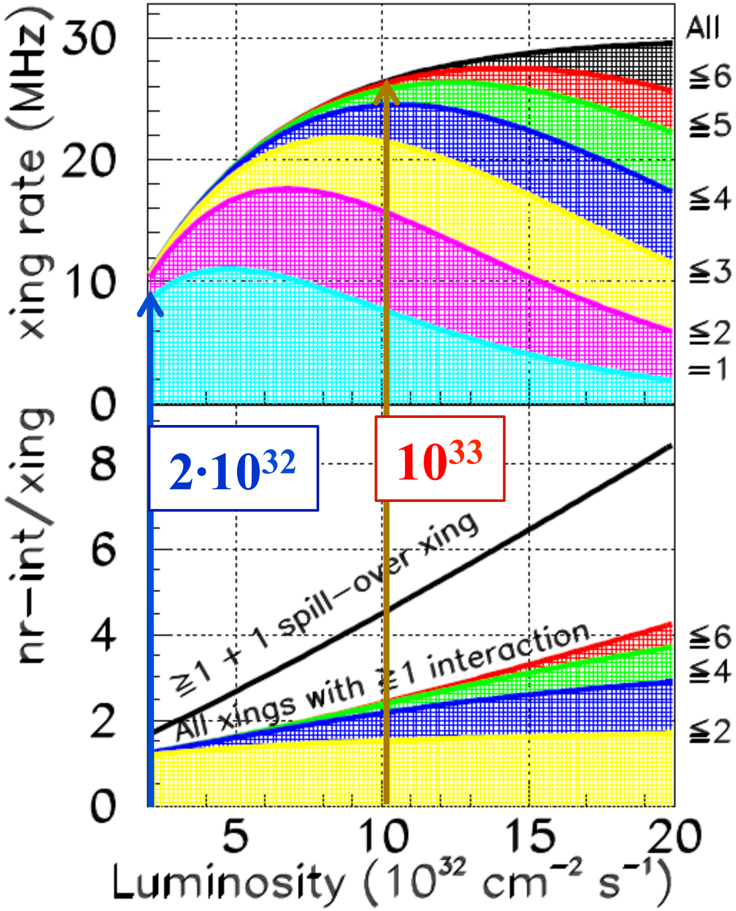
Running at $\mathcal{L} \sim 2x10^{33}$ cm^{-2} s^{-1}

- LHCb Upgrade Event Environment:
  - $\mathcal{L} \sim 2x10^{33}$ cm^{-2} s^{-1} with 40 MHZ beam crossing frequency

    ~26 MHz rate for crossings with ≥ 1 interaction

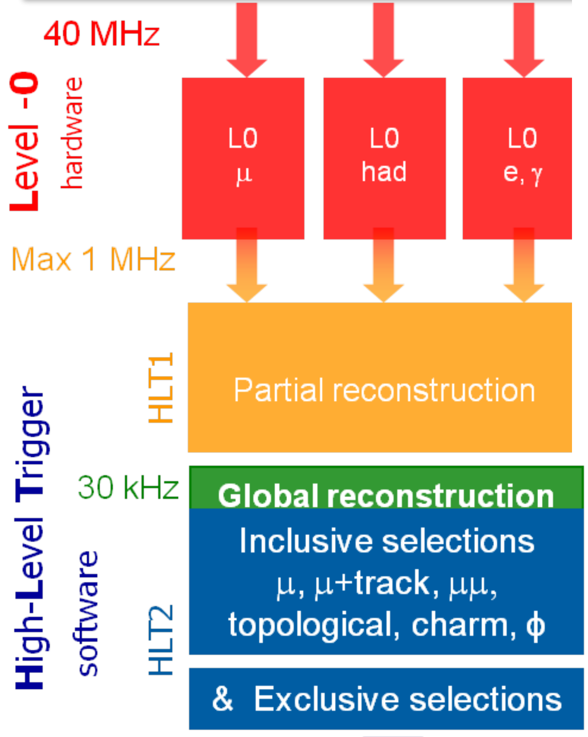
    $\mu \sim 2.3$





LHCb trigger evolution

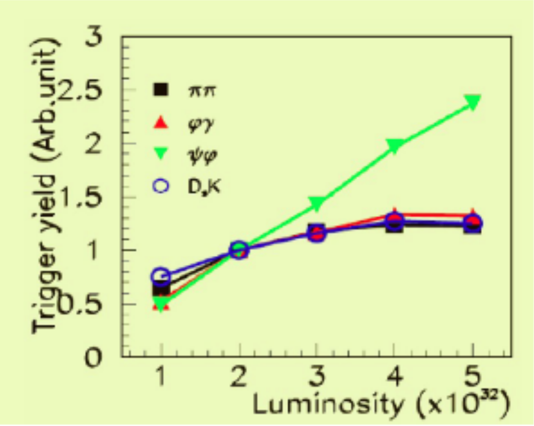
2011 First Trigger Level:
Hardware Muon/ECAL/HCAL
1.1 MHz readout



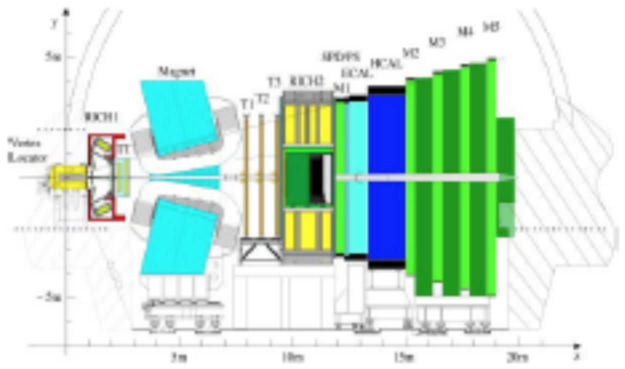
Max 3 kHz

Storage: event size ~50kB

5KHz in 2012



The hadronic channel yields saturate at high luminosity



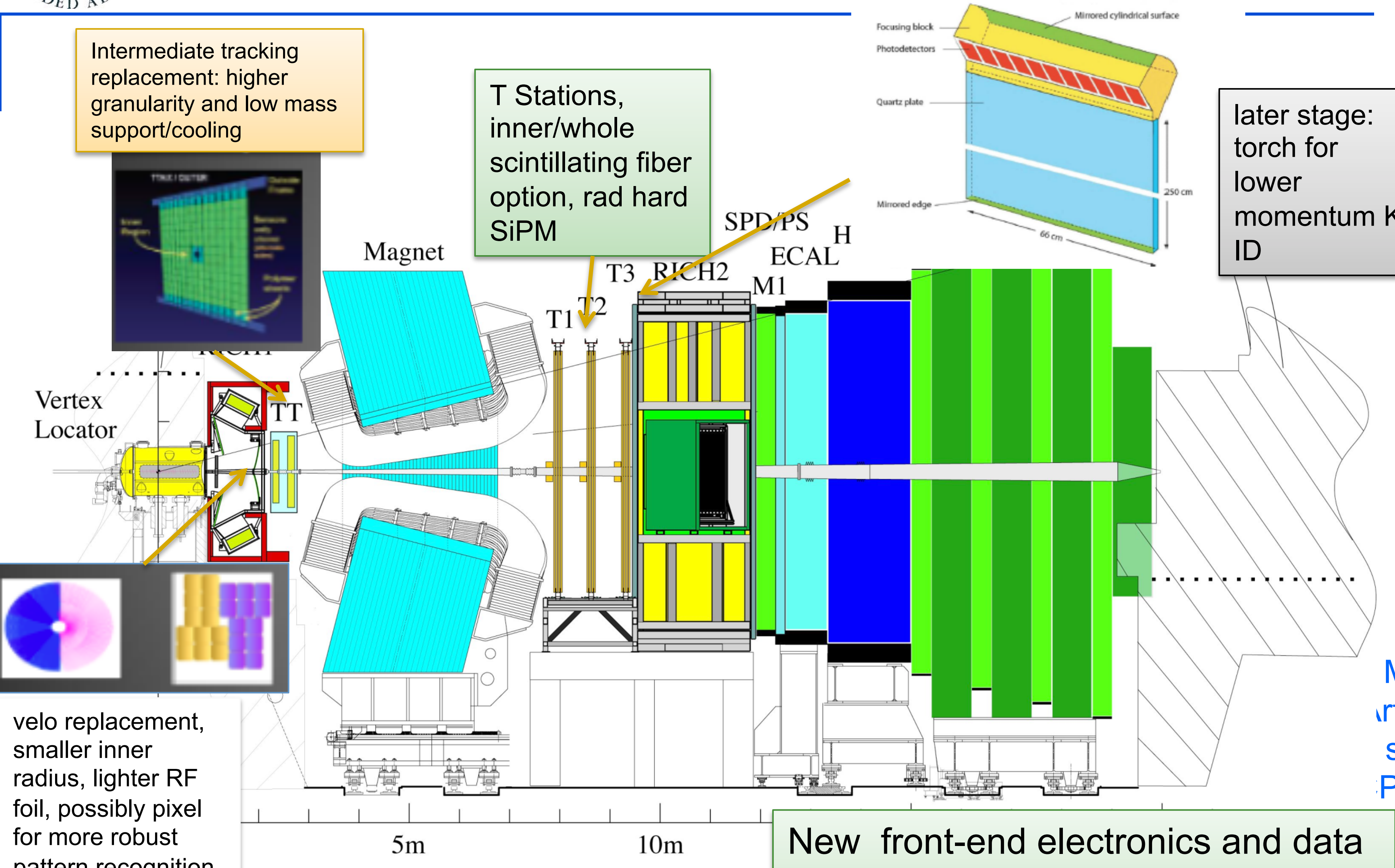
40MHz

Optional
Low Level Trigger
throttle
1-40MHz

HLT
Tracking and vertexing
Impact Parameter cuts
Inclusive/Exclusive selections

to tape
20kHz

The LHCb upgrade in a snapshot



Intermediate tracking replacement: higher granularity and low mass support/cooling

T Stations, inner/whole scintillating fiber option, rad hard SiPM

later stage: torch for lower momentum K ID

velo replacement, smaller inner radius, lighter RF foil, possibly pixel for more robust pattern recognition

New front-end electronics and data acquisition network, to push the data out at 40 MHz

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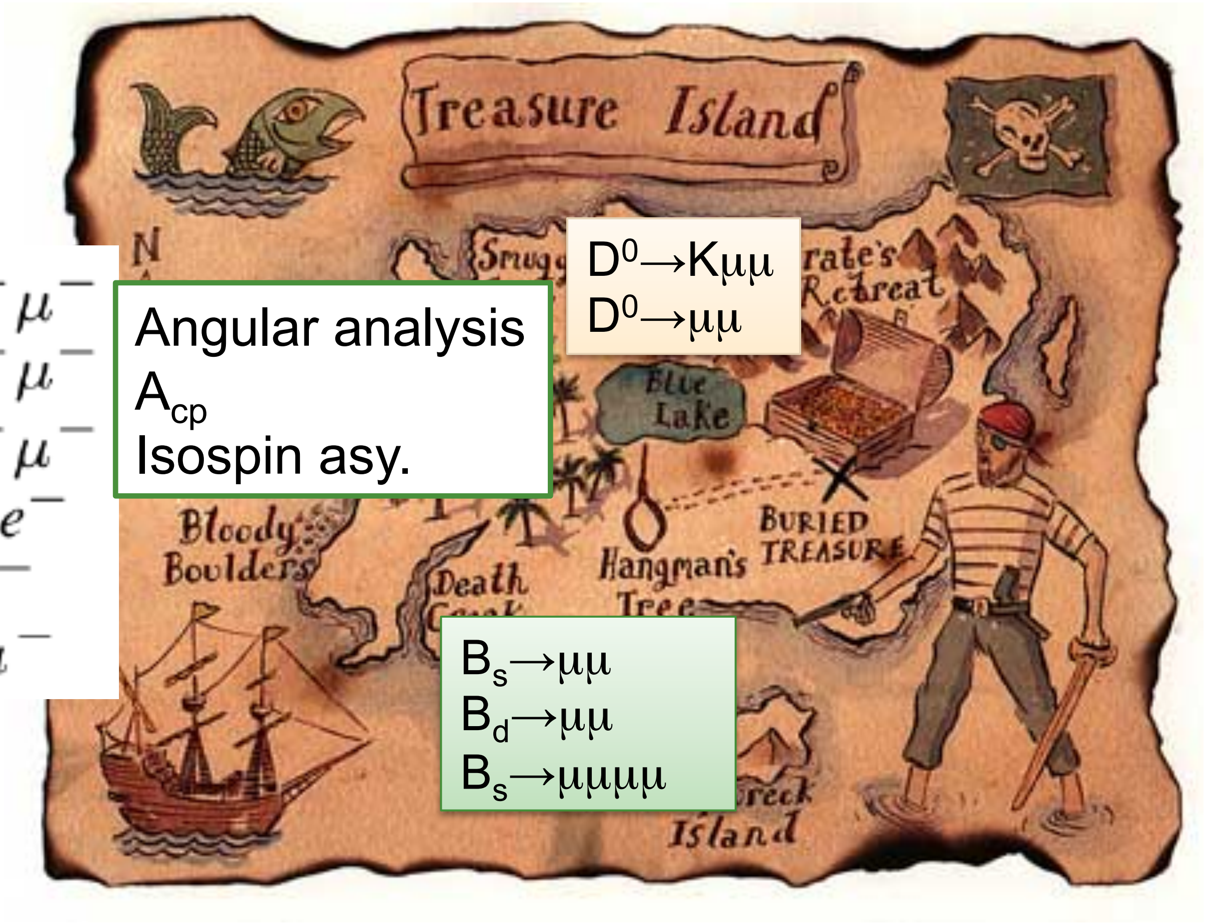
The clues from rare B decays



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

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

$B \to K^{(*)}\mu^+\mu^-$

$B^0 \to K^{*0}e^+e^-$

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

$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

Angular analysis
A_{cp}
Isospin asy.

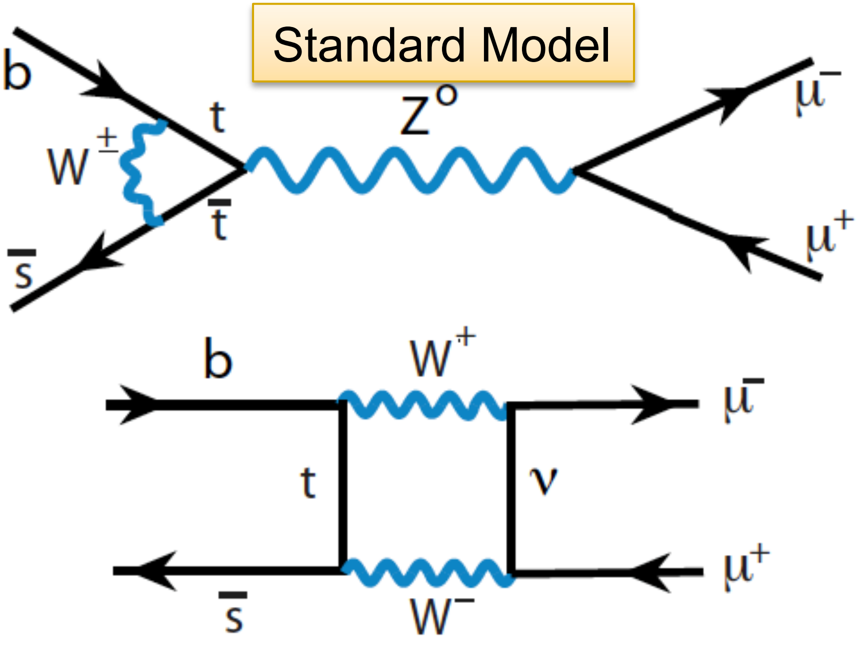
$D^0 \to K\mu\mu$
$D^0 \to \mu\mu$

$B_s \to \mu\mu$
$B_d \to \mu\mu$
$B_s \to \mu\mu\mu\mu$

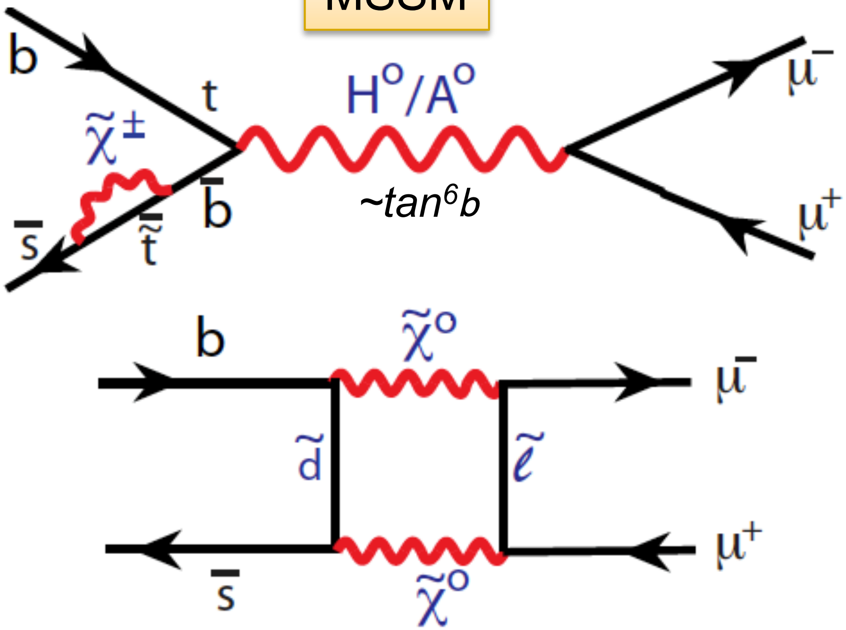
$B_s \rightarrow \mu^+\mu^-$

- SM branching ratio is $(3.2\pm0.2)\times10^{-9}$ [Buras arXiv:1012.1447], NP can make large contributions.

Standard Model

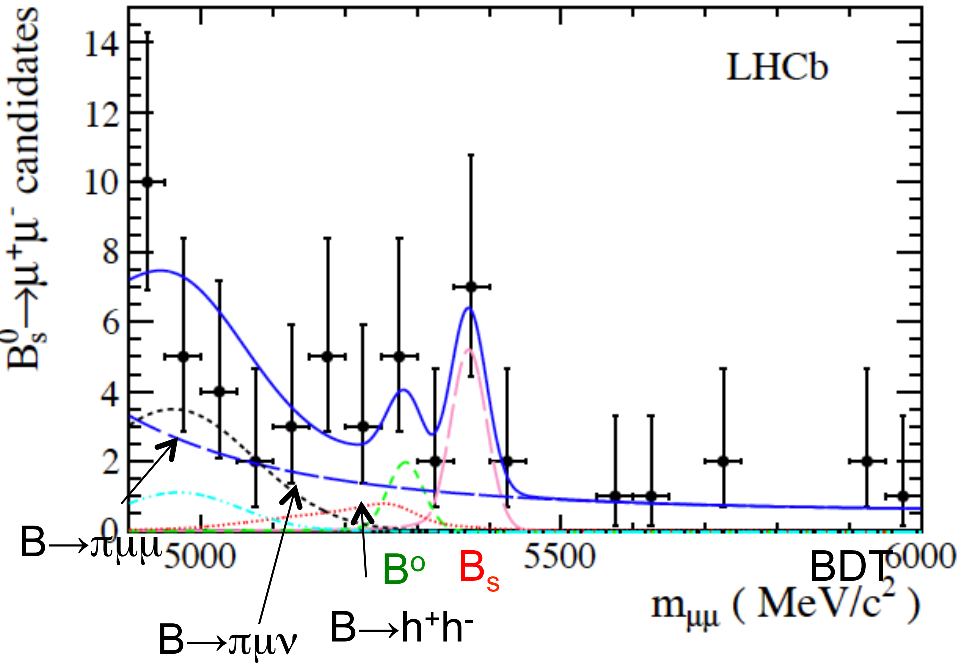


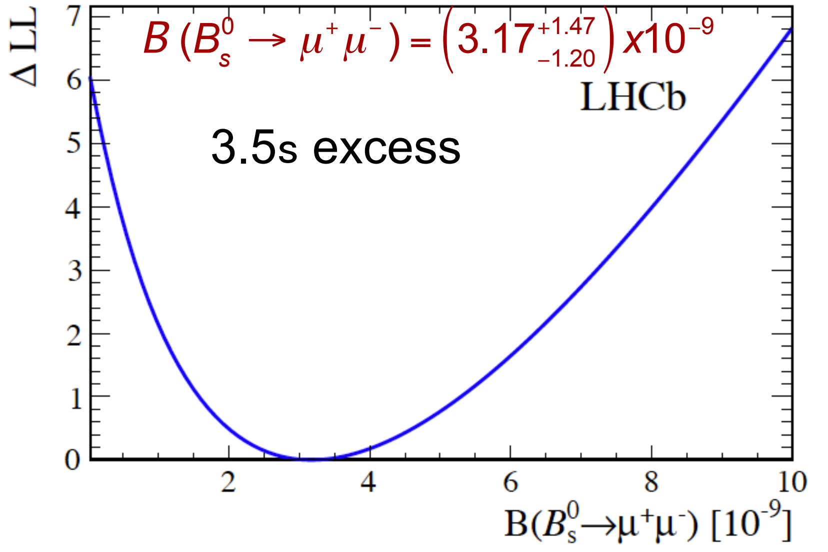
MSSM



- Many NP models possible, not just Supersymmetry

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



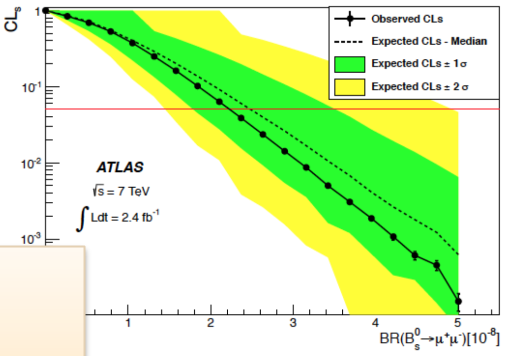


BDT

ATLAS 2011

- Set limit on BR using CLs approach
- BR($B_s \to \mu\mu$) < 2.2×10^{-8} (95% C.L.)

LHCb 1.0 fb^{-1} (2011) + 1.1 fb^{-1} (2012)



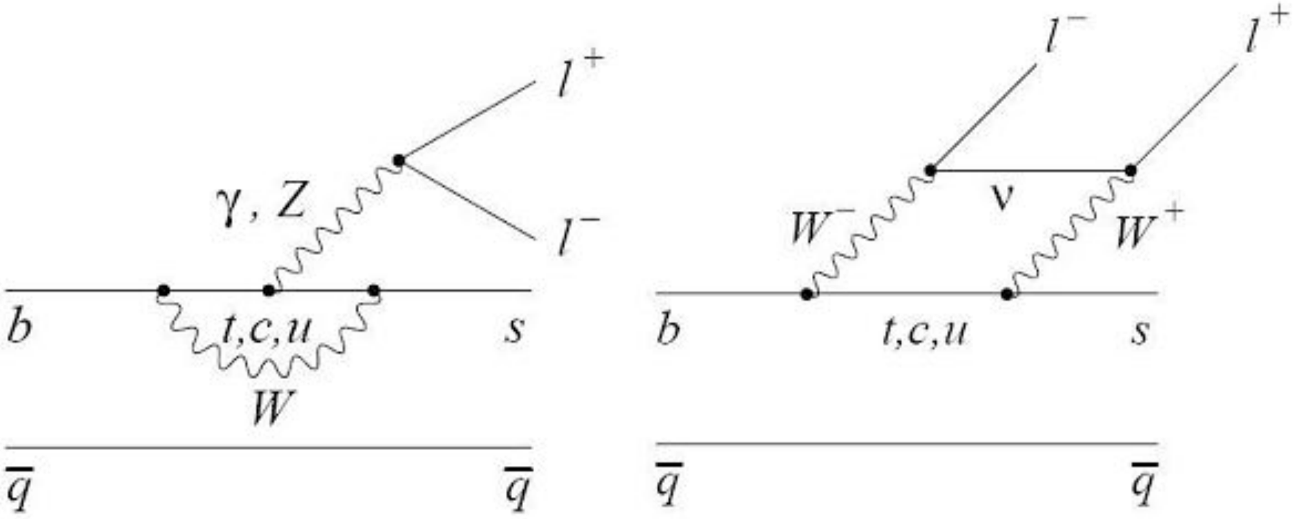
CMS 2011

upper limit (95%CL)	observed	(median) expected
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

Next challenge $B^0 \to \mu^+\mu^-$ LHCb Upgrade expected to measure ratio B^0/Bs ~35%

$B \rightarrow K^{(*)} l^+ l^-$

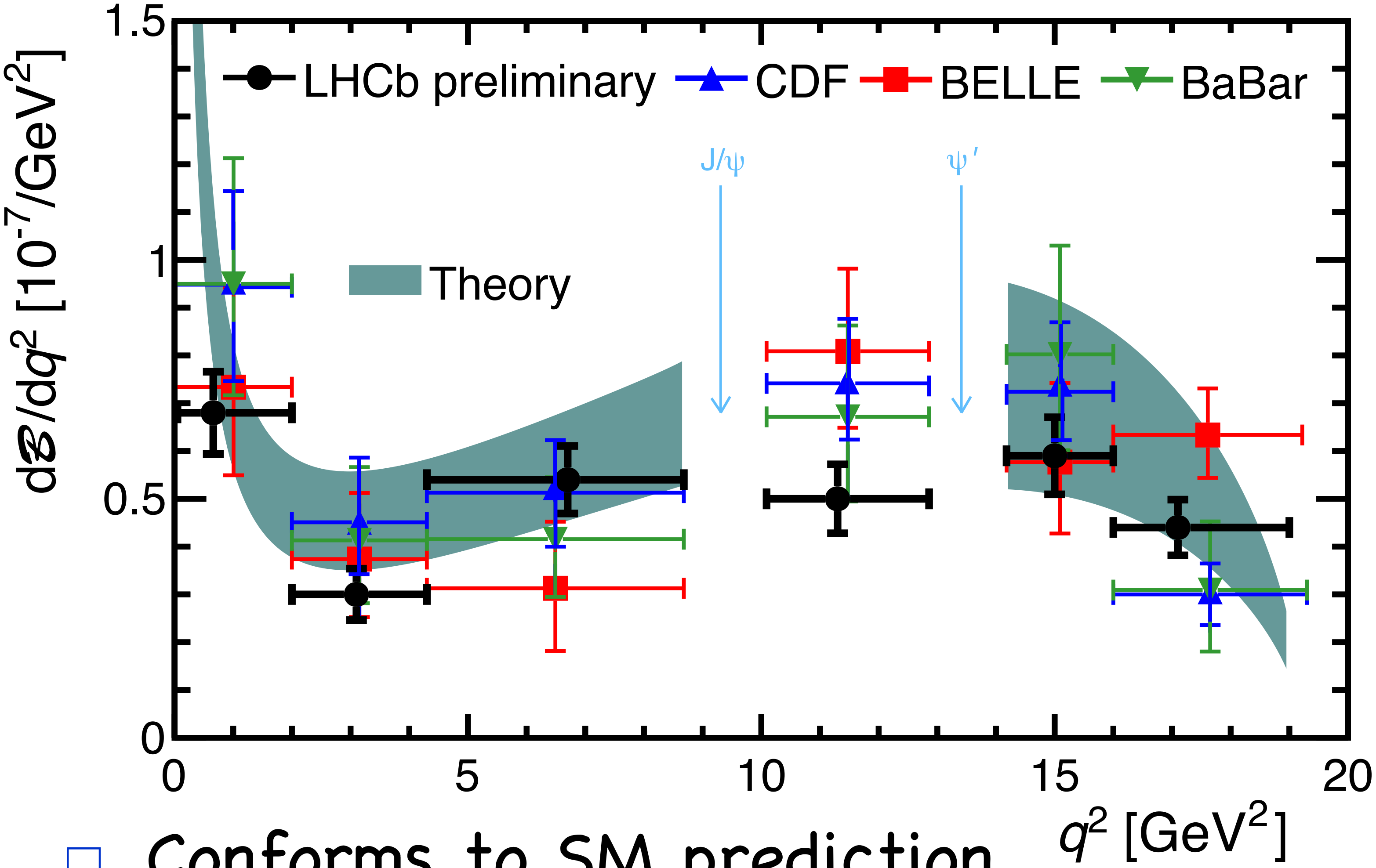
- Similar to $K^*\gamma$, but more decay paths



+ new particles in loops

- Several variables can be examined, e.g. muon forward-backward asymmetry, A_{FB} is well predicted in SM

$B^o \rightarrow K^{*o} l^+ l^-$

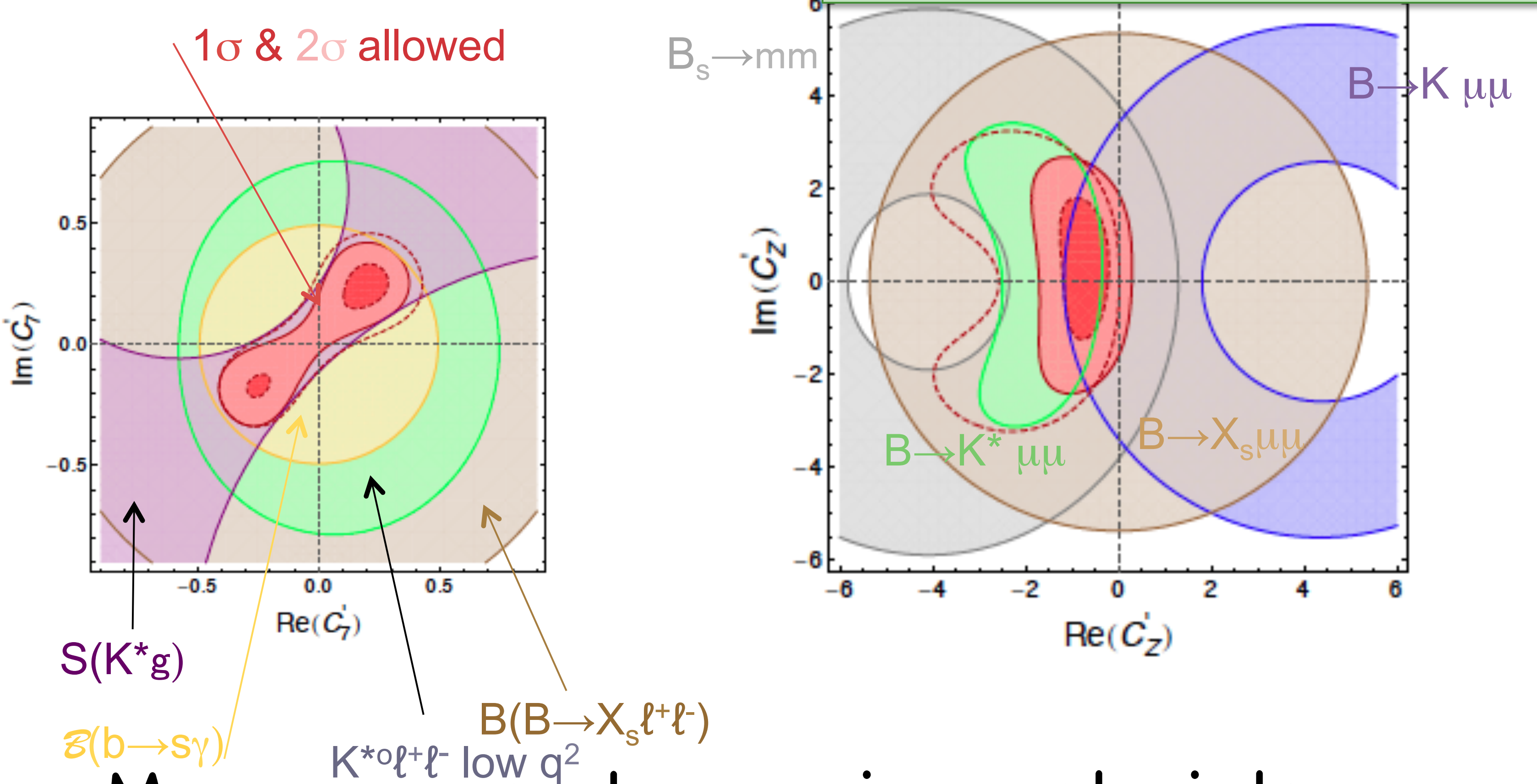


- ☐ Conforms to SM prediction

Generic constraints to new physics

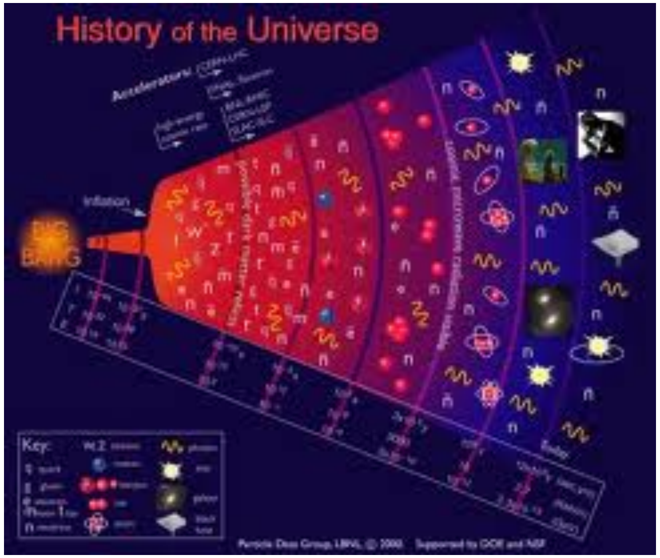
Altmannshofer and DS 1206.0273]

Wilson coefficients of local operators expected to be ~0 in SM



- ☐ Many more such generic constraints

Neutral Meson Mixing and CP Violation



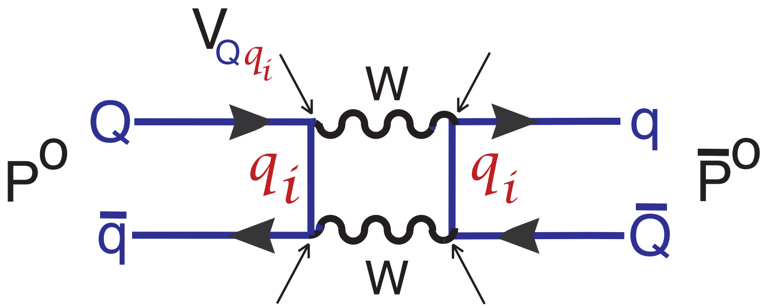

May 17, 2010

A New Clue to Explain Existence

By DENNIS OVERBYE

Neutral meson mixing

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



New particles possible in loop

Time evolution of Flavor Eigenstates

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11}^s - i\frac{\Gamma_{11}^s}{2} & M_{12}^s - i\frac{\Gamma_{12}^s}{2} \\ M_{12}^{s*} - i\frac{\Gamma_{12}^{s*}}{2} & M_{22}^s - i\frac{\Gamma_{22}^s}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

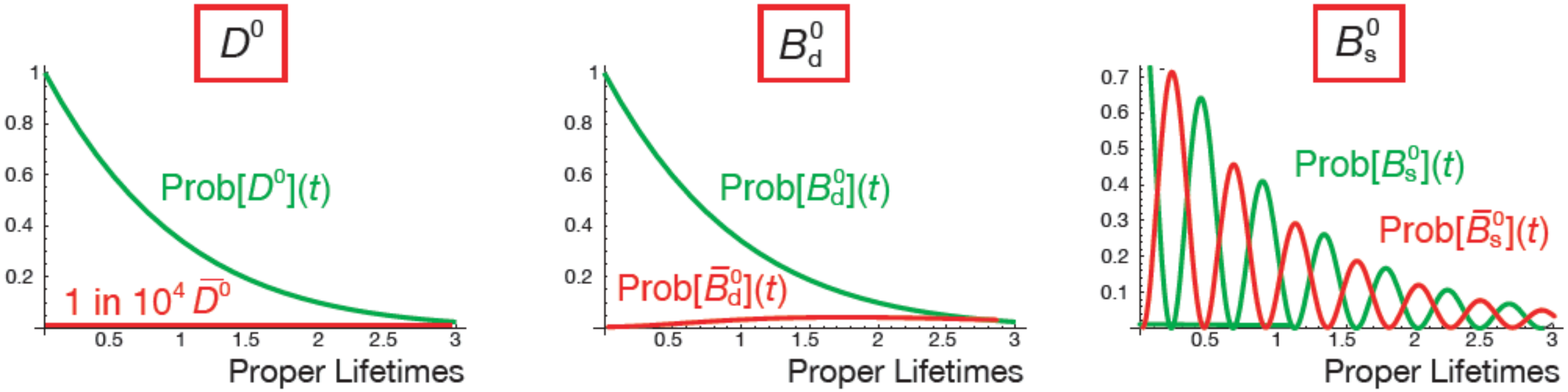
Mass eigenstates

$$\left|B_{sL}^0\right\rangle = p\left|B_s^0\right\rangle + q\left|\bar{B}_s^0\right\rangle$$

$$\left|B_{sH}^0\right\rangle = p\left|B_s^0\right\rangle - q\left|\bar{B}_s^0\right\rangle$$

Neutral Meson Mixing II

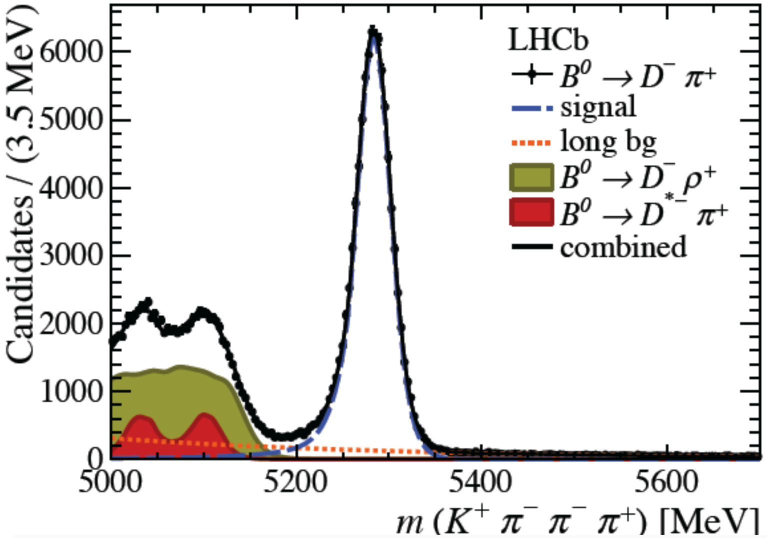
- Short distance transition rate depends on
  - mass of intermediate q_i, the heavier the better, favors s & b since t is allowed, while for c, b is the heaviest
  - CKM elements V_{ij}

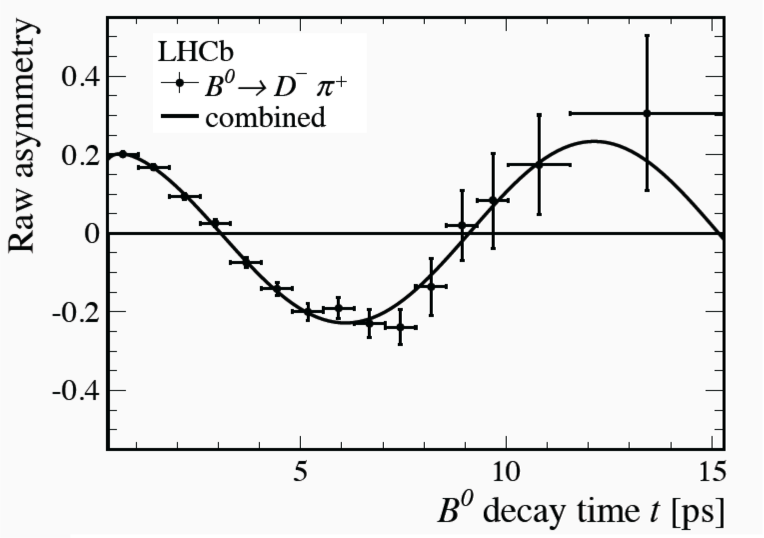


+ "long distance" for D°

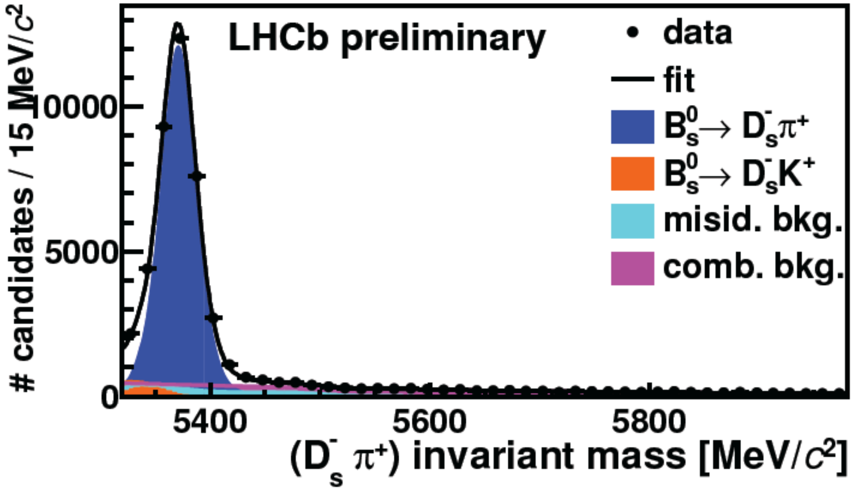
$$D^0 \Longrightarrow \pi\pi,.. \Longrightarrow \overline{D}^0$$

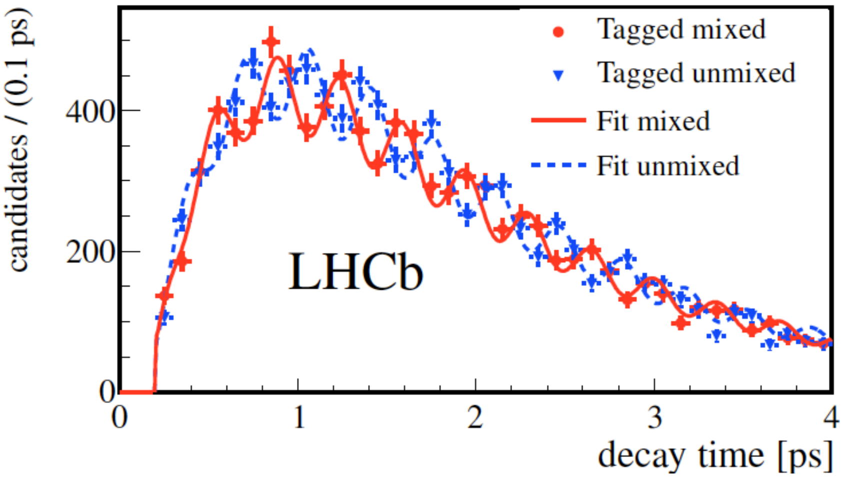
Δm





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

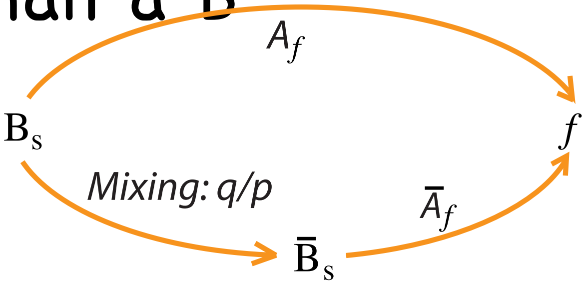




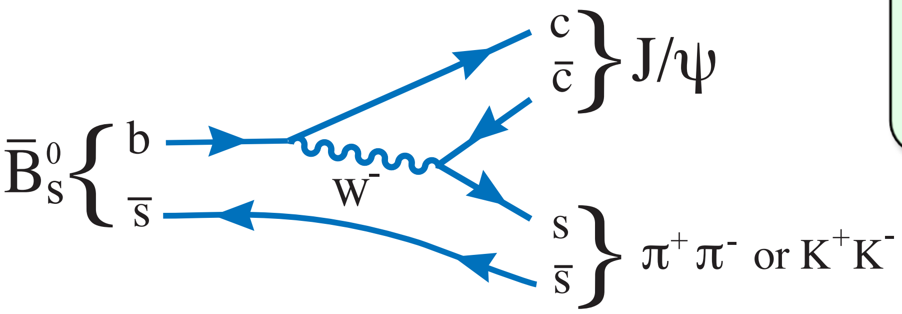
$\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$

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

- CP violation means, for example, that a B will have a different decay rate than a $\bar{B}$
- Can occur via interference between mixing & decay



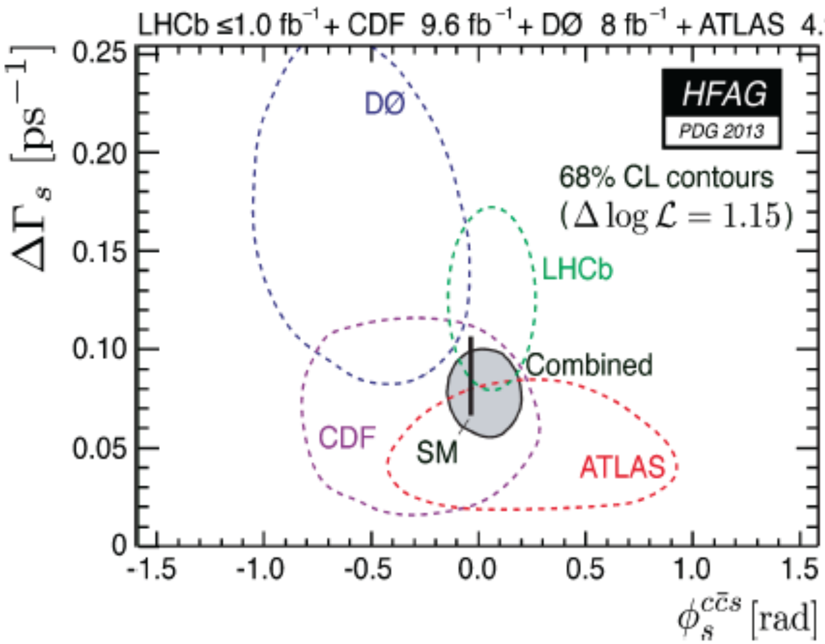
- For f =J/ψ f or J/ψ f_0



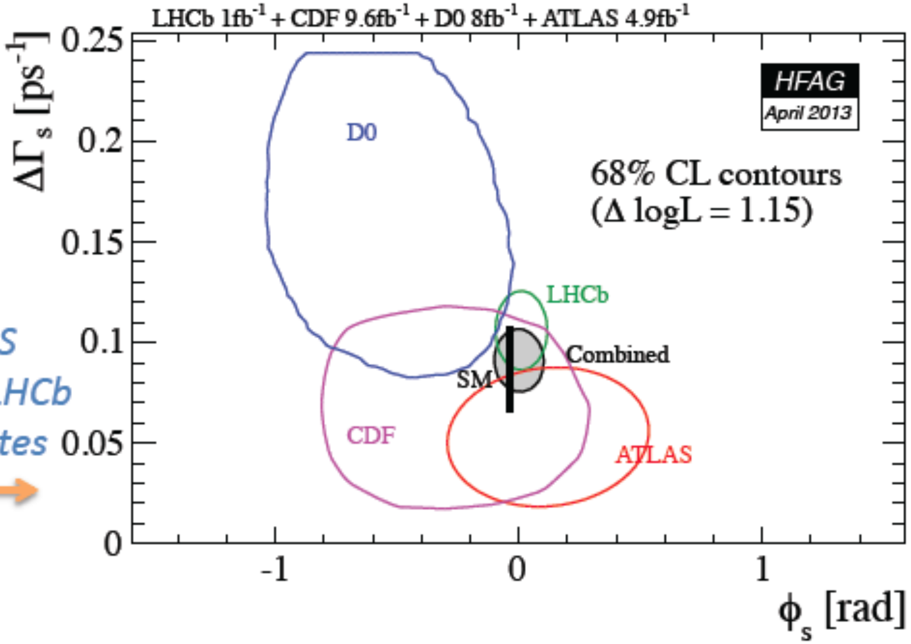
$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2^\circ$$

- Small CPV expected, good place for NP to appear

Current ϕ_s measurements



with ATLAS and LHCb updates

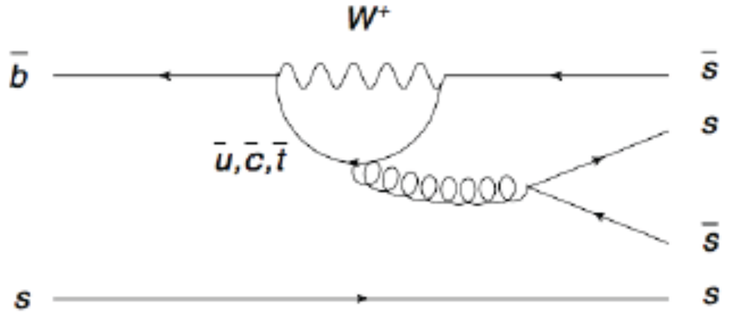


	CDF	D0	LHCb	ATLAS	CMS
Int. Lum. [fb^{-1}]	9.6	8.0	1.0	4.9	5.0
#$B_s \rightarrow J/\psi\varphi(f_0)$	11k	5.6k	27.6k (7.4k)	22.7k	14.5k
εD^2 OS (SS) [%]	1.39±0.05 (3.5±1.4)	2.48±0.22	2.29±0.22 (0.89±0.18)	1.45±0.05	-
Ref.	*PRL109(2012) 171802*	*PRD85(2012) 032006*	*PRD87(2013)112010*	*ATLAS-CONF-2013-039*	*CMS PAS BPH-11-006*

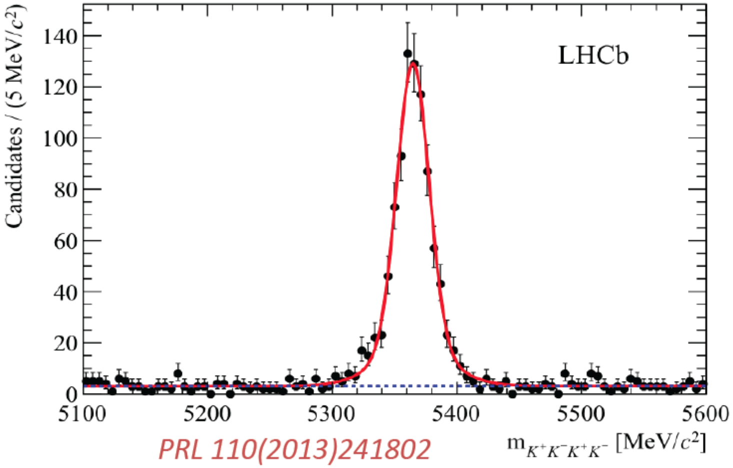
CMS: $\Delta\Gamma_s$=0.048±0.024±0.003ps^{-1}

CP violation in $B_s \to \phi\phi$

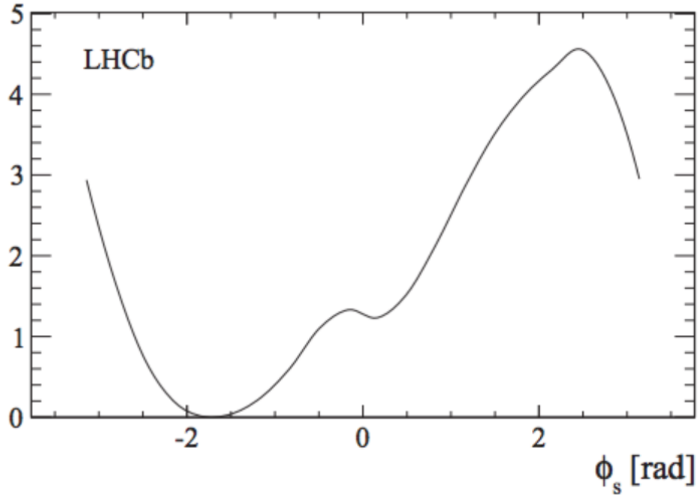
gluonic $b \to s s \bar{s}$ penguins



Not the same ϕ_s as in $J/\psi\phi$, in the Standard Model $\phi_s^{\phi\phi}$ ~0 (<0.02)
880 decays seen in 1.0 $fb^{-1} \Rightarrow \phi_s^{\phi\phi}$ in [-2.46,-0.76] at 68% CL



PRL 110(2013)241802



expected sensitivity in LHCb upgrade on $\phi_s^{\phi\phi} \sim 0.02$

Semileptonic asymmetry

- Another physical observable is the flavor specific asymmetry

$$a_s = 1 - \left|\frac{q}{p}\right|^2 = \mathrm{Im}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right) + O\left(\left(\mathrm{Im}\frac{\Gamma_{12}^s}{M_{12}^s}\right)^2\right) = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi_{12}^s$$

$$\phi_{12}^s = \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right)$$

- we can access as via flavor specific final states for example semileptonic decays

$$a_{sl}^s \equiv \frac{\Gamma(\overline{B}_s^0 \to D_s^- \mu^+ \nu) - \Gamma(B_s^0 \to D_s^+ \mu^- \overline{\nu})}{\Gamma(\overline{B}_s^0 \to D_s^- \mu^+ \nu) + \Gamma(B_s^0 \to D_s^+ \mu^- \overline{\nu})} = \frac{1-(1-a_s)^2}{1+(1-a_s)^2} \sim a_s$$

SM predictions

$$\left\{ \begin{array}{l} a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5} \\ a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4} \end{array} \right.$$

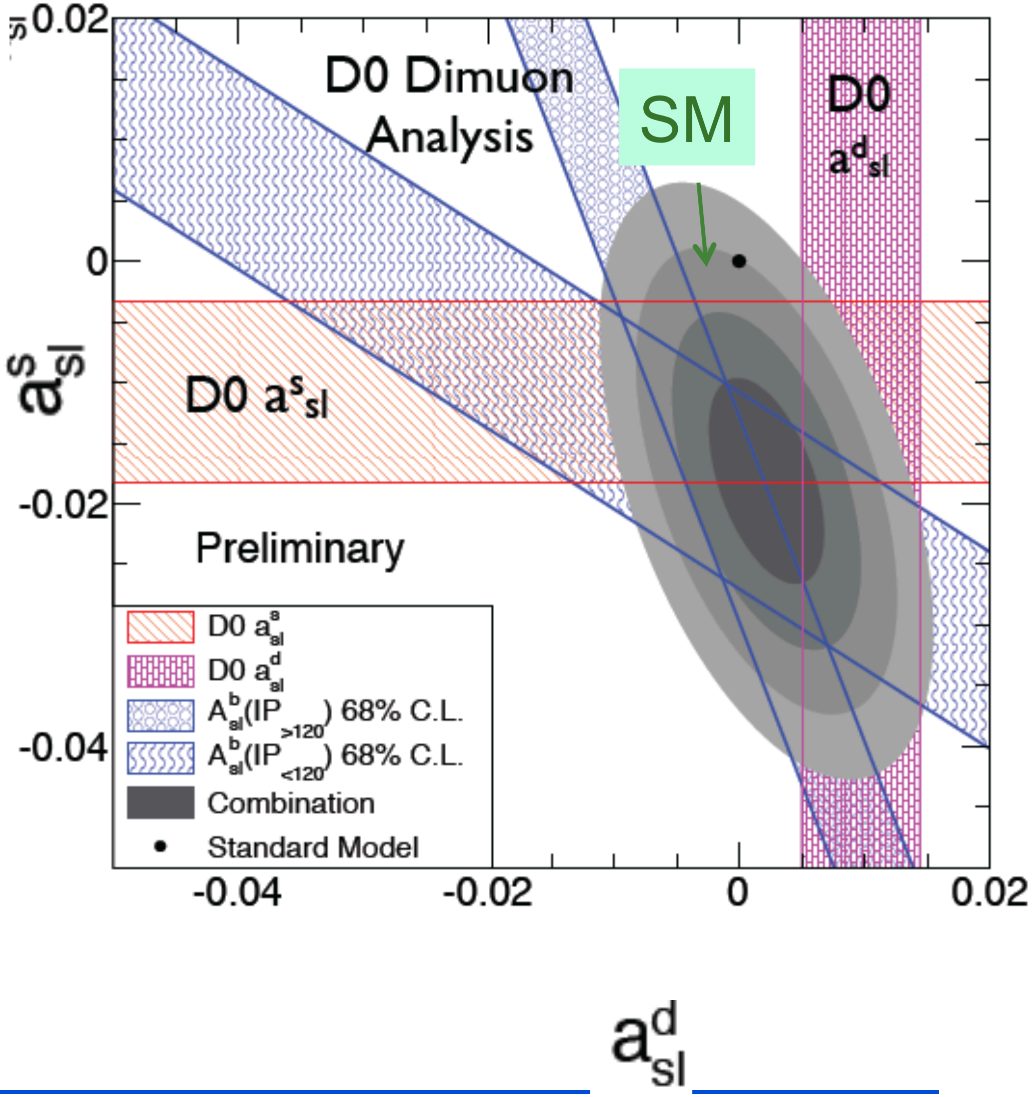
A.Lenz
arXiv:1205.1444

a_{sl} according to D0

- a^s_{sl}=(-1.12±0.76)%
- a^d_{sl}=(0.68±0.47)%
- dimuon analysis

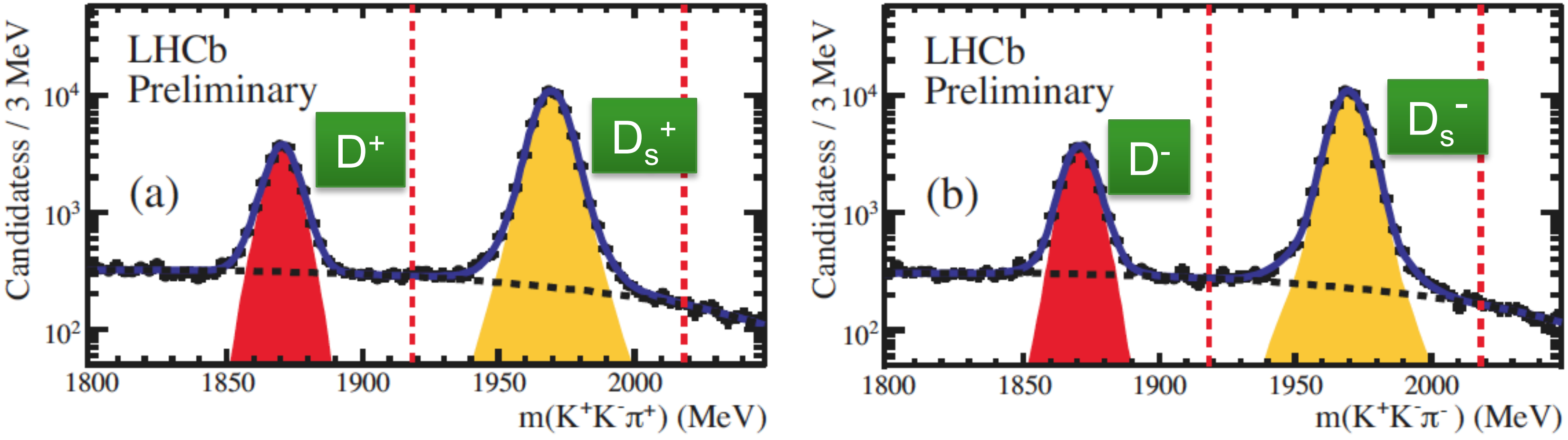
a^b_{sl}=(-0.787±0.195)%

- combination 3 sigma from SM
- arXiv:1208.5813



LHCb measurement

- ☐ Use $D_s\mu^-\nu$, $D_s \rightarrow \varphi\pi^\pm$, magnet is periodically 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

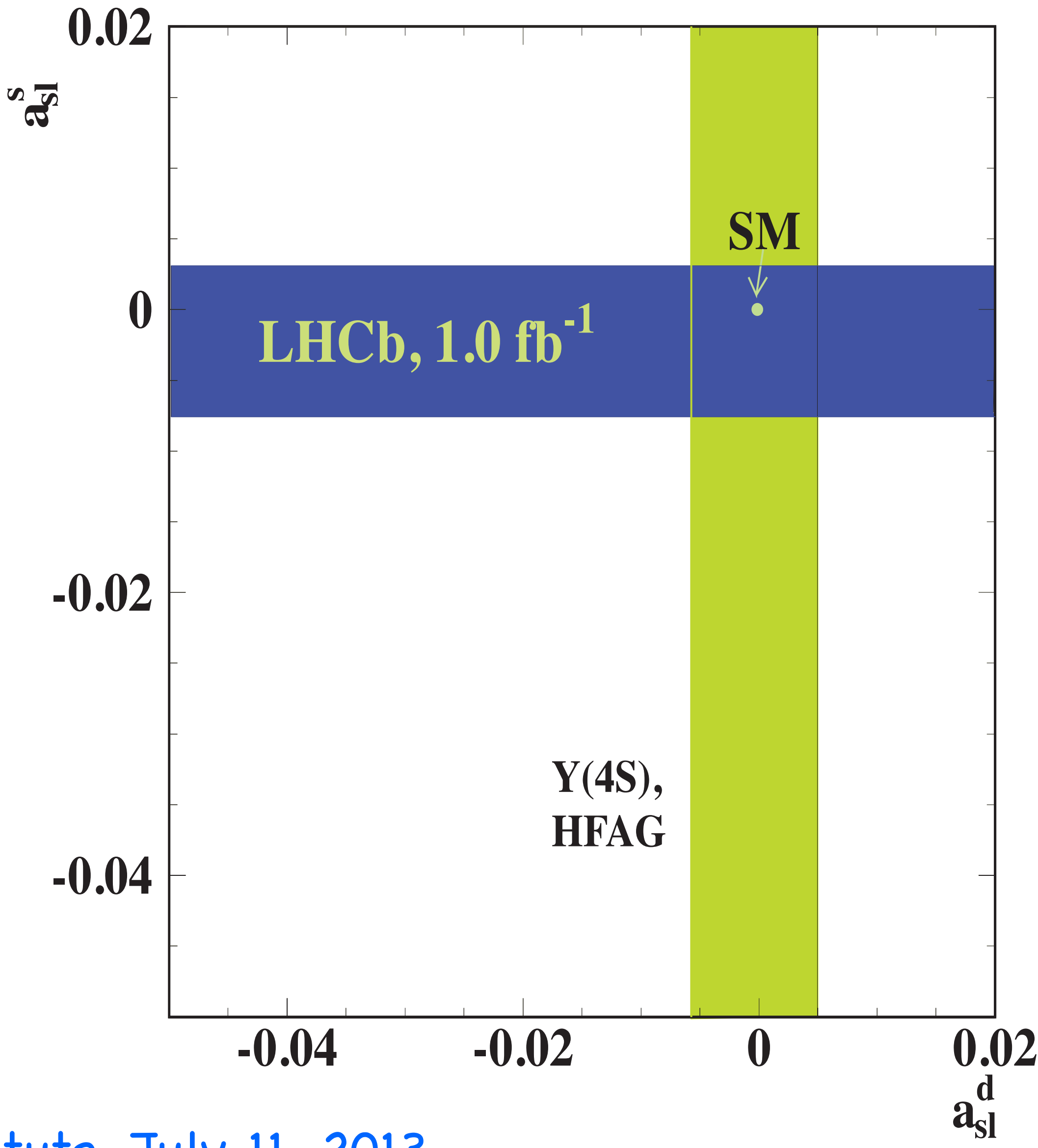
- ☐ LHCb finds

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

- ☐ B-factories

$$a_{sl}^{d} = (0.02 \pm 0.31)\%$$

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



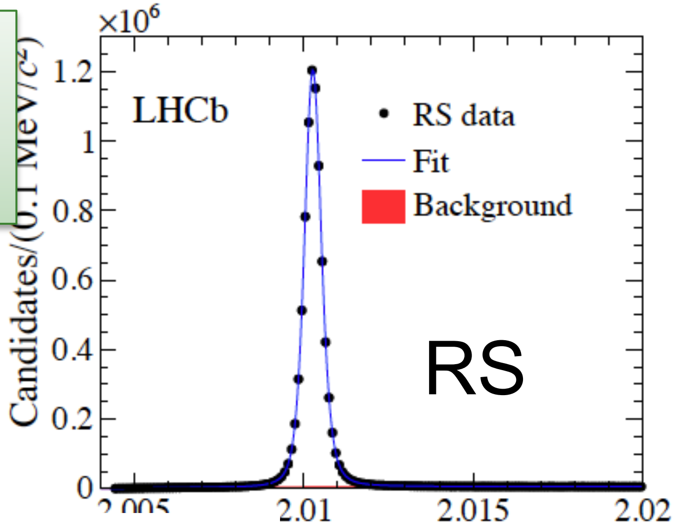
Charm Mixing

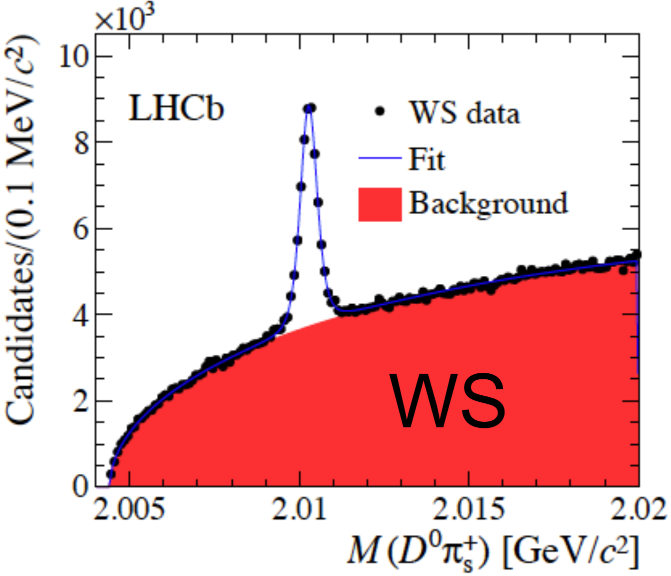
- Various experiments have seen evidence for D^o–$\overline{D}^o$ mixing, but none with significance >5s.
- $D^{*+}\to p^+D^o$ provides an initial flavor tag
- "Wrong-sign" (WS) D^o can appear via mixing or doubly-Cabbibo suppressed decay (DCS).
- DCS follows ~exp(-t/t_{D^o}).
  Define R_D=DCS/(Cabibbo favored). Mixing is parameterized as x´ & y´, functions of Dm & DG.
- Measure Wrong-sign/Right-sign, R(t)= (WS/RS)

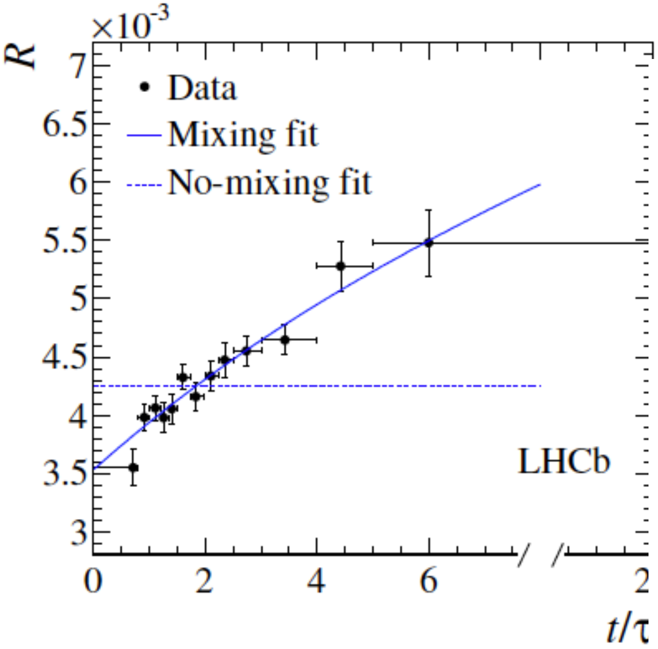
$$R(t) \approx R_D + \sqrt{R_D}\, y' \, \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

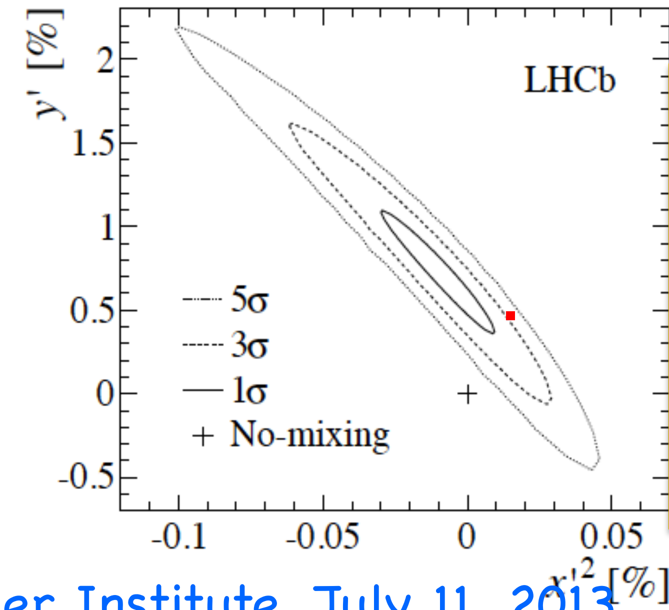
Charm mixing

$D^{*+}\to\pi^+D^o$,
$D^o\to K^-\pi^+$





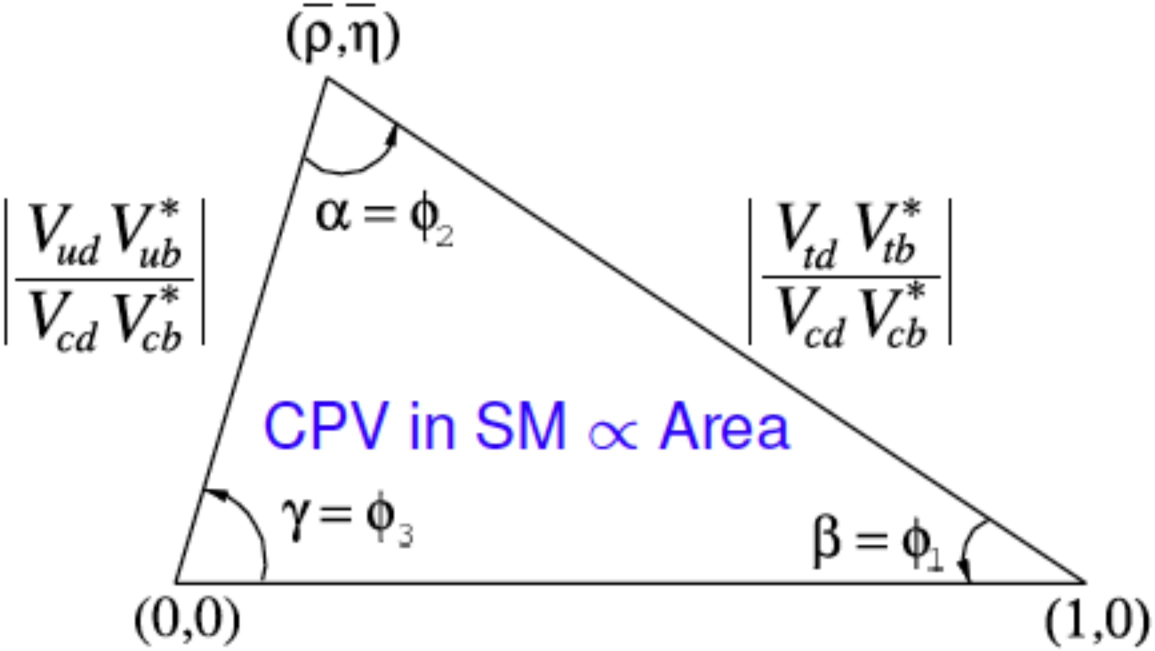




No mixing excluded at 9.1 σ, systematic errors are included

$y' = (0.72 \pm 0.24)\%$

$x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$

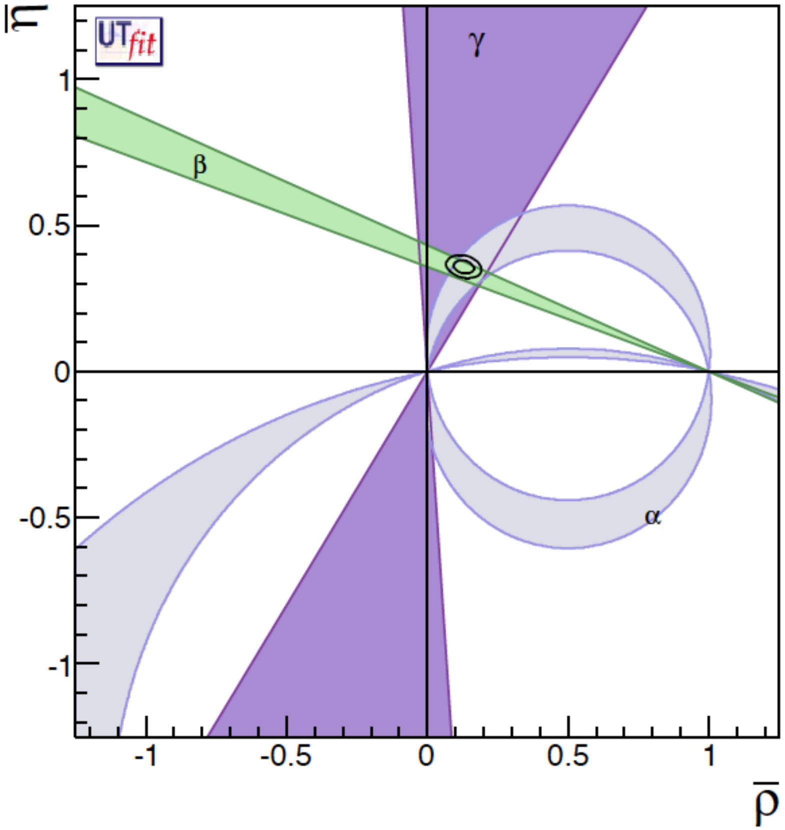


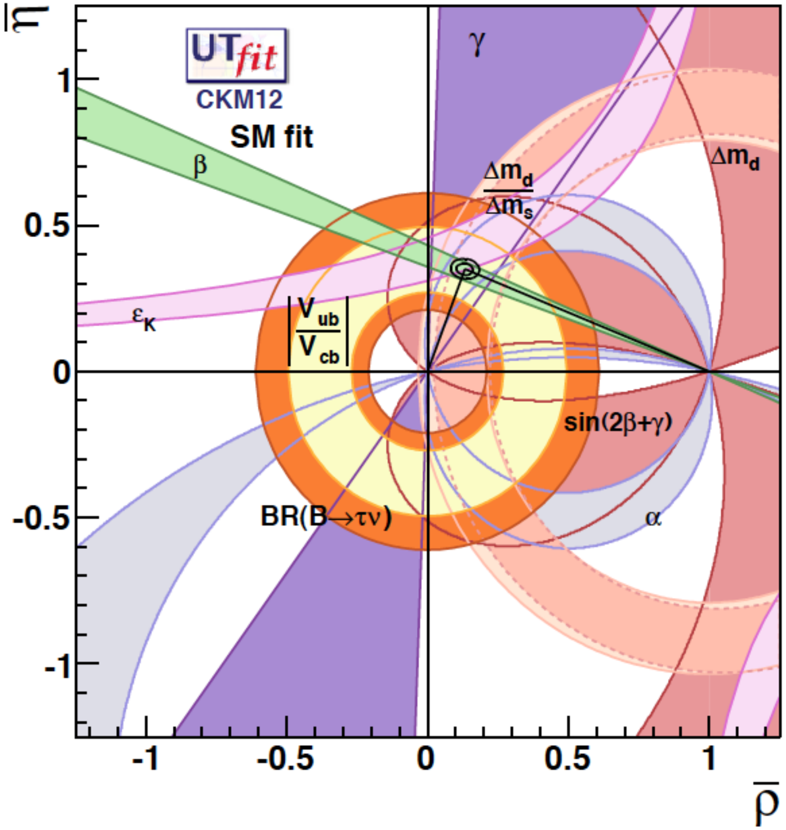
CPV in SM $\propto$ Area

CKM METROLOGY

(or the many constraints on the 6 unitarity triangles)

The unitarity triangle in a few pictures

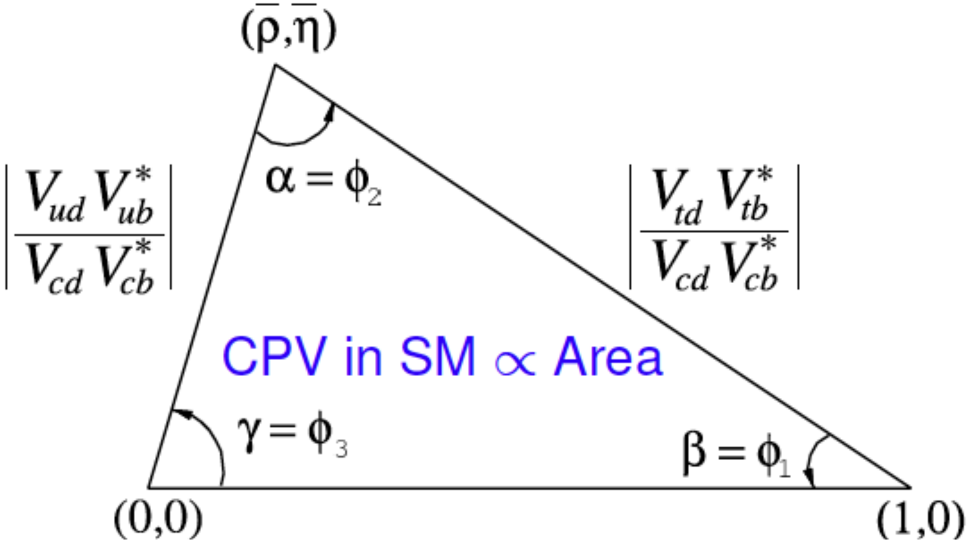




Lots of observables converge on the same apex of the unitarity triangle, but still room for surprises. Note uncertainty in γ

The angle γ

- tree level interference of $b\to c\bar{u}s$ ($B^-\to D^0K^-$) and $b\to u\bar{c}s$ ($B^-\to D^0K^-$) ⇨ extremely clean theoretically (expected precision 0.9°)
- Current LHCb combination (67±12) °
- Expected upgrade sensitivity 0.9° with this technique only ⇨ powerful consistency check on CKM picture



LHCb-CONF-2013-006, arXiv:1305:2050 subm PLB

Compare: $Belle:(69^{+17}_{-16})^{\circ}$

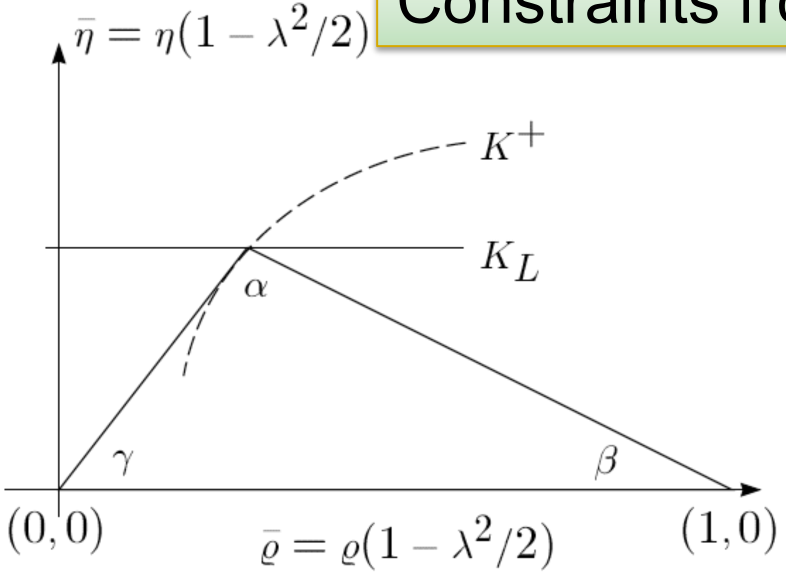
$BaBar:(68^{+15}_{-14})^{\circ}$

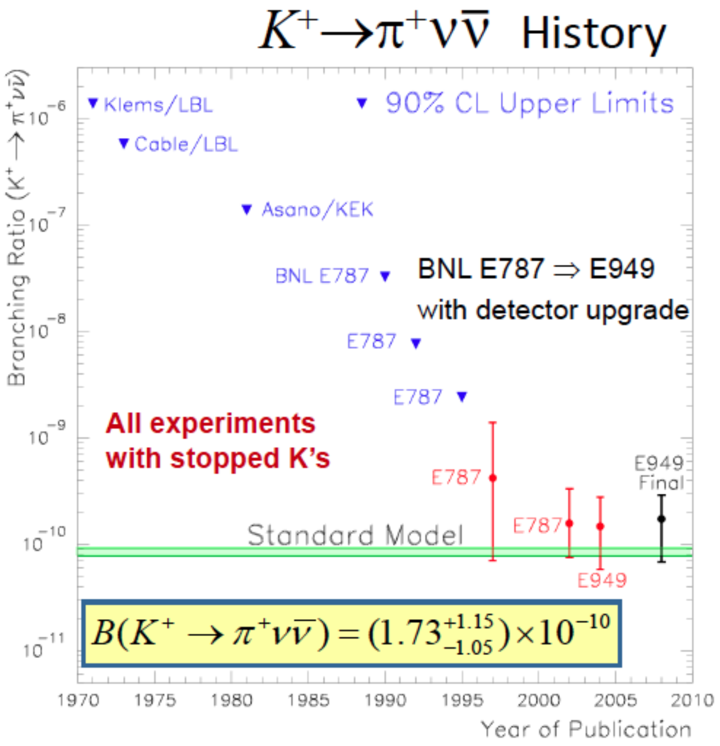
Prediction: $UTFit:(68.6\pm3.6)^{\circ}$

$CKMFitter:(68.0^{+4.1}_{-4.6})^{\circ}$

The K unitarity triangle

Constraints from K→$\pi\nu\bar{\nu}$





$$B(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

BNL E787/949 observed a total of 7 signal events.

$$B(K^+ \to \pi^+\nu\bar{\nu})_{SM} = (7.8 \pm 0.8) \times 10^{-11}$$

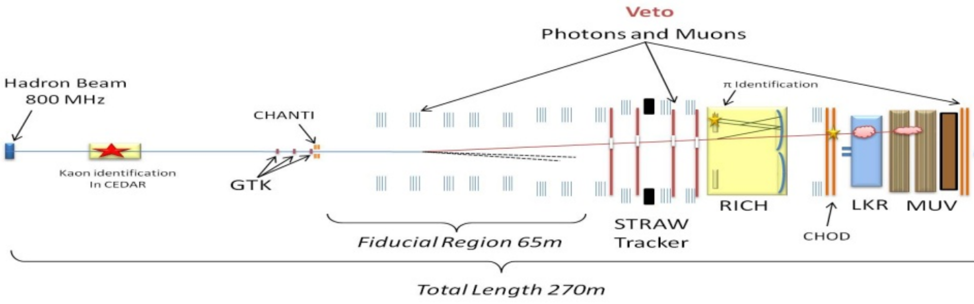
$$B(K_L^0 \to \pi^0\nu\bar{\nu})_{SM} = (2.4 \pm 0.4) \times 10^{-11}$$

largest uncertainties CKM factors ➪precision will improve by a factor of ~ 2

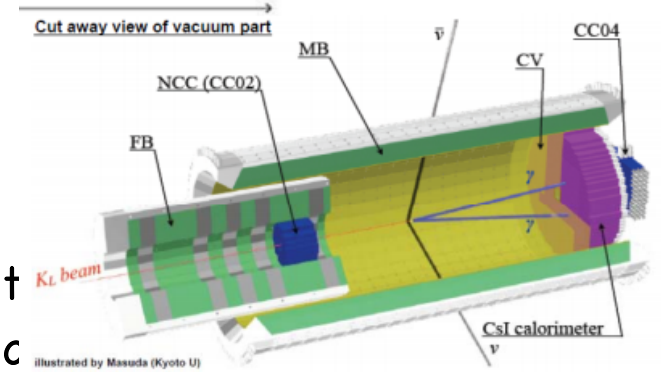
Brod, Gorbahn, and Stamou, PR D **83**, 034030(2011)

Experiments now comissioning

- CERN NA-62 ($K^+ \longrightarrow \pi \nu \bar{\nu}$)
  - Decay-in-flight experiment
    - Complementary technique to ORKA
  - Expect 10% measurement of BR
    - ~55 events per year (SM)
    - ~7 bg events per year
    - ~100 total events



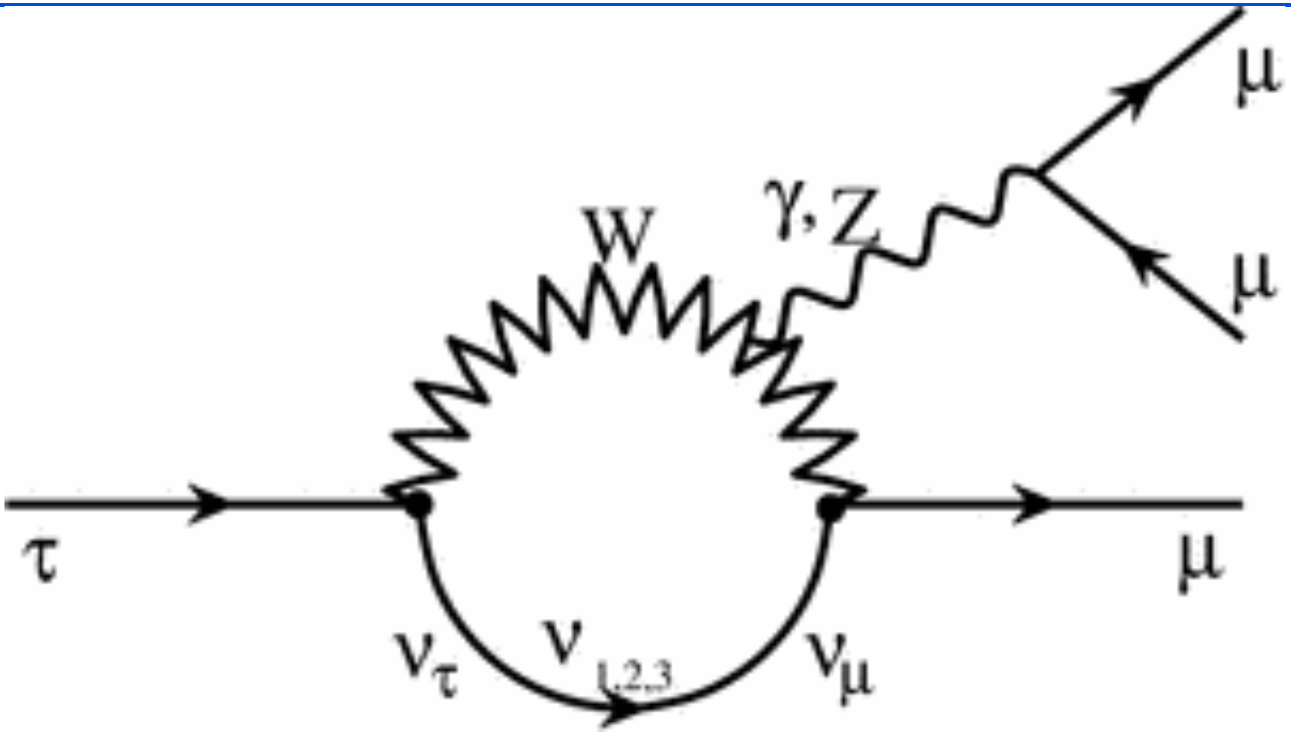
- J-PARC E14 “KOTO” ($K^0 \longrightarrow \pi \nu \bar{\nu}$)
  - Pencil beam decay-in-flight experiment
  - Improved J-PARC beam line
  - 2nd generation detector building on E391 at
  - Re-using KTeV CsI crystals to improve calc
  - Expect ~3 signal events (SM rate)



illustrated by Masuda (Kyoto U)

The next chapter: “ORKA”

- Precision measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ with ~**1000 events** using the FNAL Main Injector
- Expected BR uncertainty matches Standard Model uncertainty
- Builds on successful previous experiments
  - BNL E787/E949 3rd generation stopping K^+ experiment observed 7 events
  - Backgrounds well measured and understood, supports scaling this technique to a new high sensitivity experiment at Fermilab
  - ORKA has Stage-1 scientific approval from Fermilab, aiming for operations later this decade

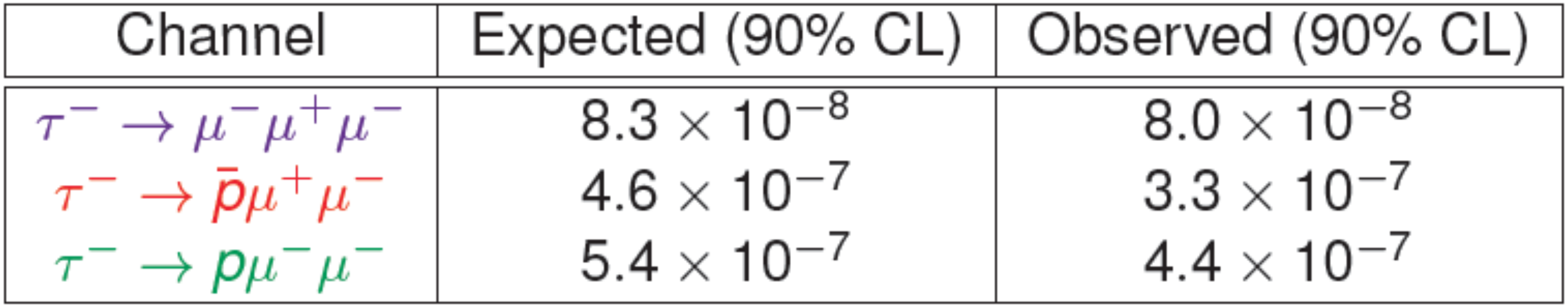


LEPTON FLAVOR VIOLATION

selected topics, no discussion of dedicated experiments on flavor violation in μ decays

Lepton flavor violation in τ decays

First lepton flavor violation (LFV) limits at a hadron collider reported by LHCb!



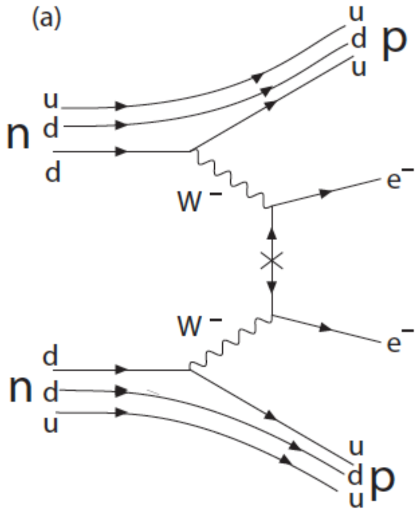
Channel	Expected (90% CL)	Observed (90% CL)
$\tau^- \to \mu^-\mu^+\mu^-$	8.3×10^{-8}	8.0×10^{-8}
$\tau^- \to \bar{p}\mu^+\mu^-$	4.6×10^{-7}	3.3×10^{-7}
$\tau^- \to p\mu^-\mu^-$	5.4×10^{-7}	4.4×10^{-7}

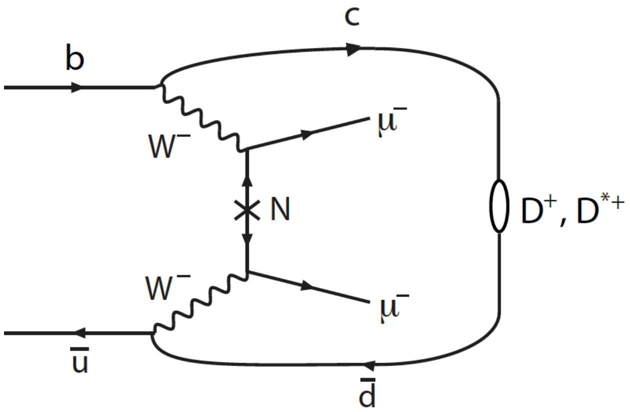
c.f. BF($\tau^- \to \mu^-\mu^+\mu^-$) $\leq 2.1 \times 10^{-8}$ at 90% CL from Belle

Projected sensitivity in the LHCb upgrade ~$2\text{x}10^{-9}$

Majorana ν's

- Several ways of looking for presence of heavy ν's (N) in heavy quark decays if they Majorana (their own anti-particles) and couple to "ordinary" ν's
- Modes analogous to ν-less nuclear β decay

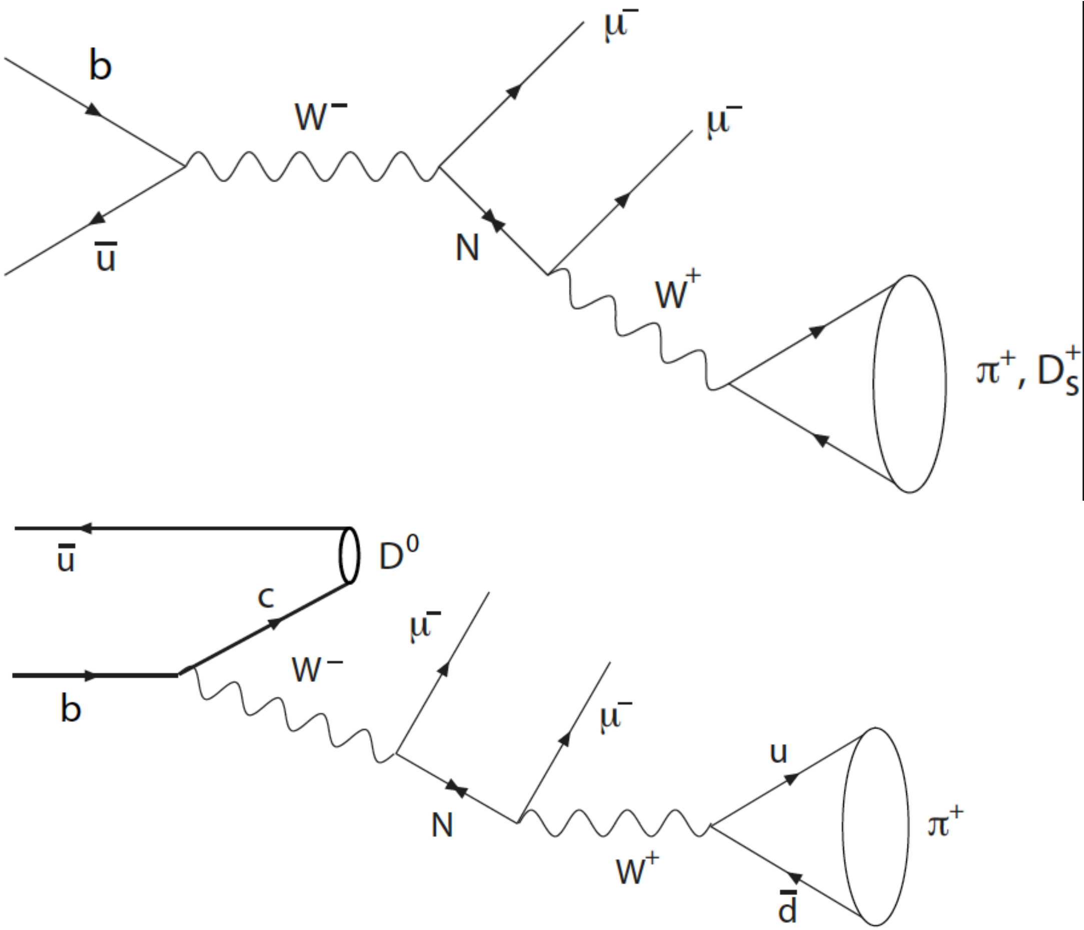




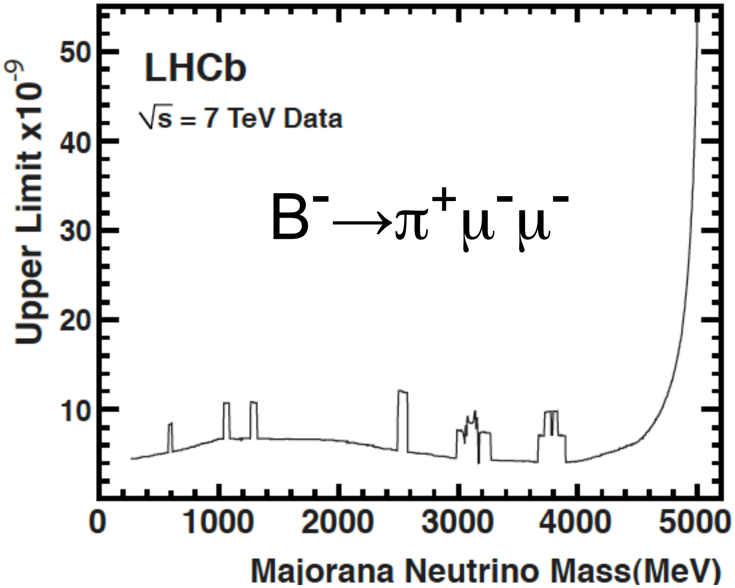
Simplest Channels:
$B^- \to D^+ l^- l'^-$ &
$B^- \to D^{*+} l^- l'^-$
l^- & l'^- can be e^-, μ^- or τ^-.

On-Shell ν

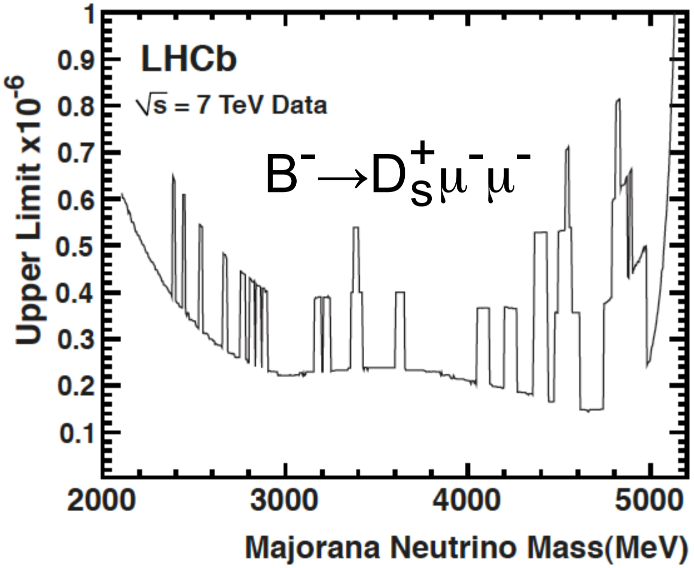
- Can also look for Majorana ν (N), where $N\rightarrow W^+\mu^-$
- Several ways
- A. Atre, T. Han, S. Pascoli, & B. Zhang [arXiv:0901.3589]
- N. Quintero, G. Lopez & Castro, [arXiv:1108.6009]

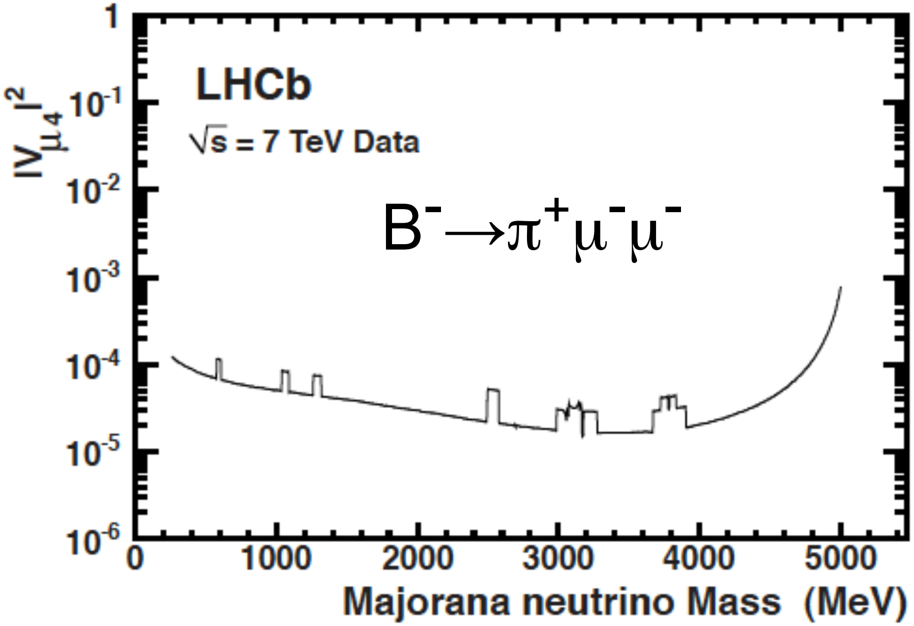


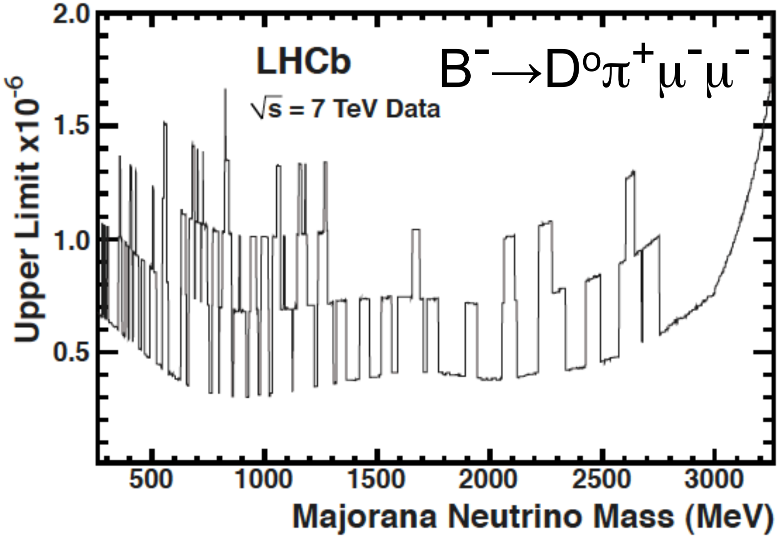
LHCb searches



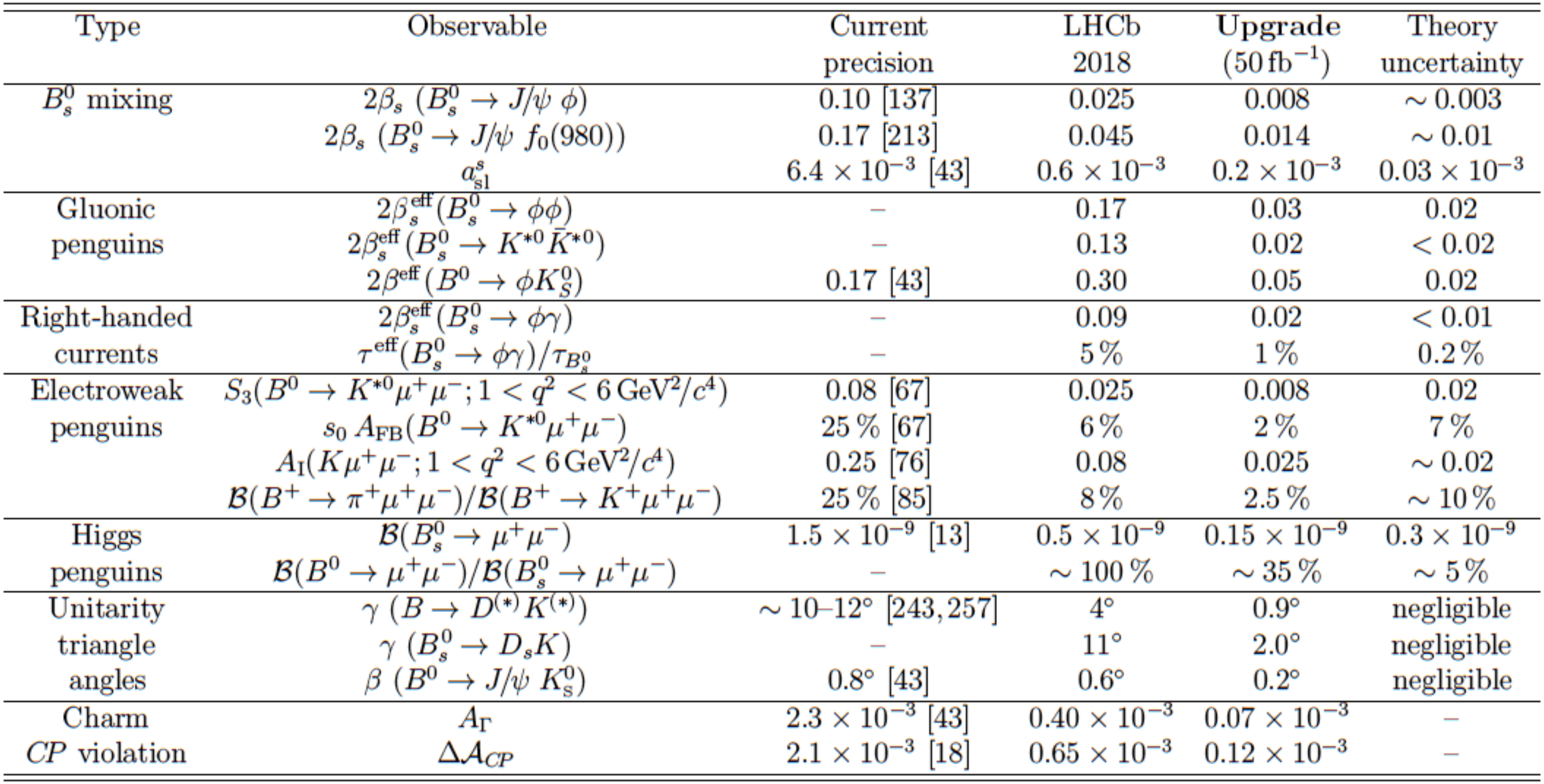
Nothing yet but only 0.41 fb^{-1} analyzed







Sensitivity of the upgraded LHCb experiment to key observables



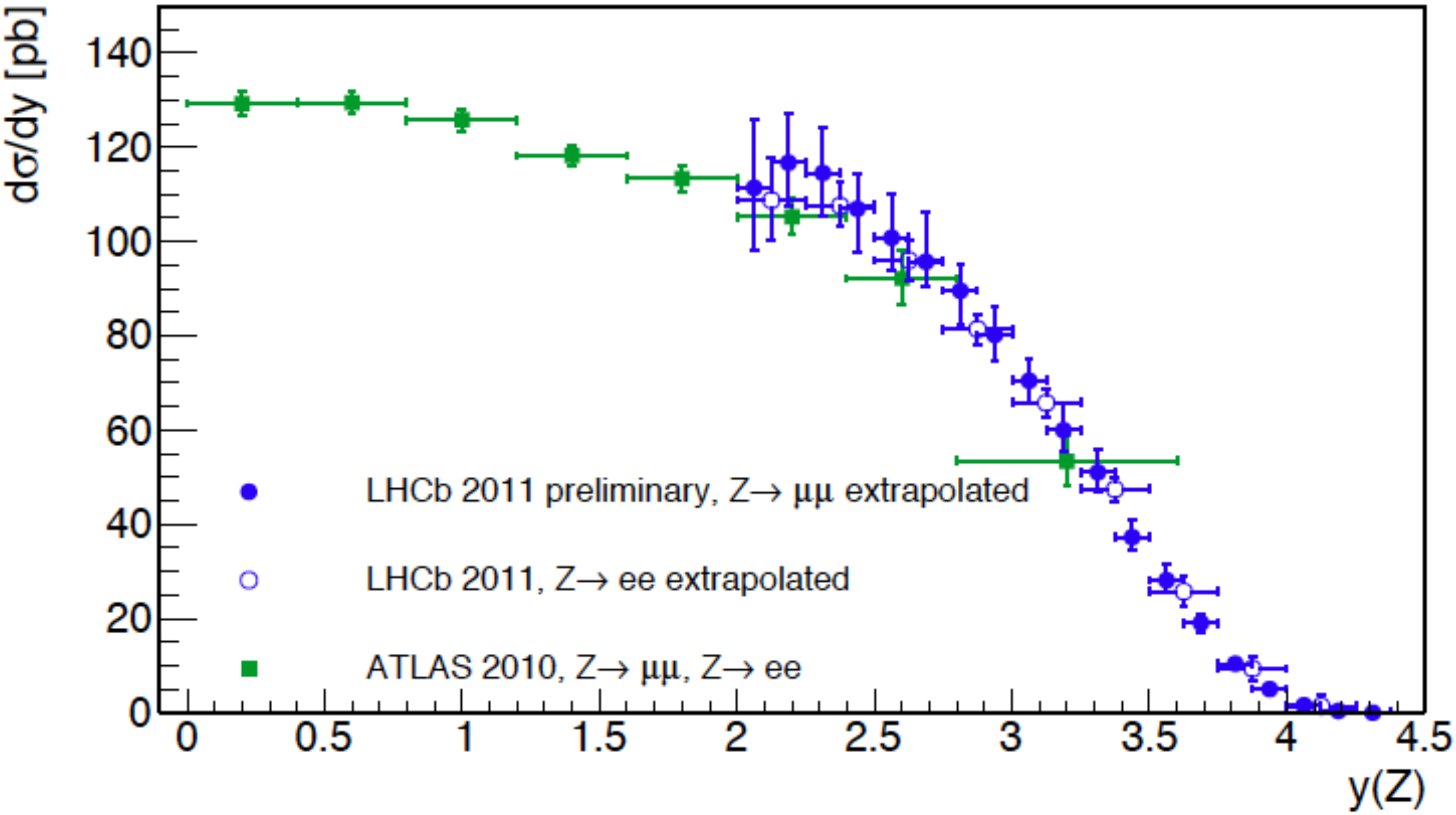
Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [137]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [213]	0.045	0.014	~ 0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [243, 257]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [43]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Implications of LHCb measurements and future prospects, LHCB-PAPER-2012-031

The two frontiers cross

- “LHCb general purpose detector in the forward direction” ⇒ some physics topics considered realm of the energy frontier can be addressed in a unique manner here
  - Search for long lived exotic particles
  - $t\bar{t}$ production
  - Electroweak physics

An illustration



Note: EW studies (Z, W production, lepton charge asymmetry) illustrate the nature of LHCb as a general purposed detector in the forward direction (LHCb data extrapolated to ATLAS acceptance in M_{ll} and p_T

Conclusions

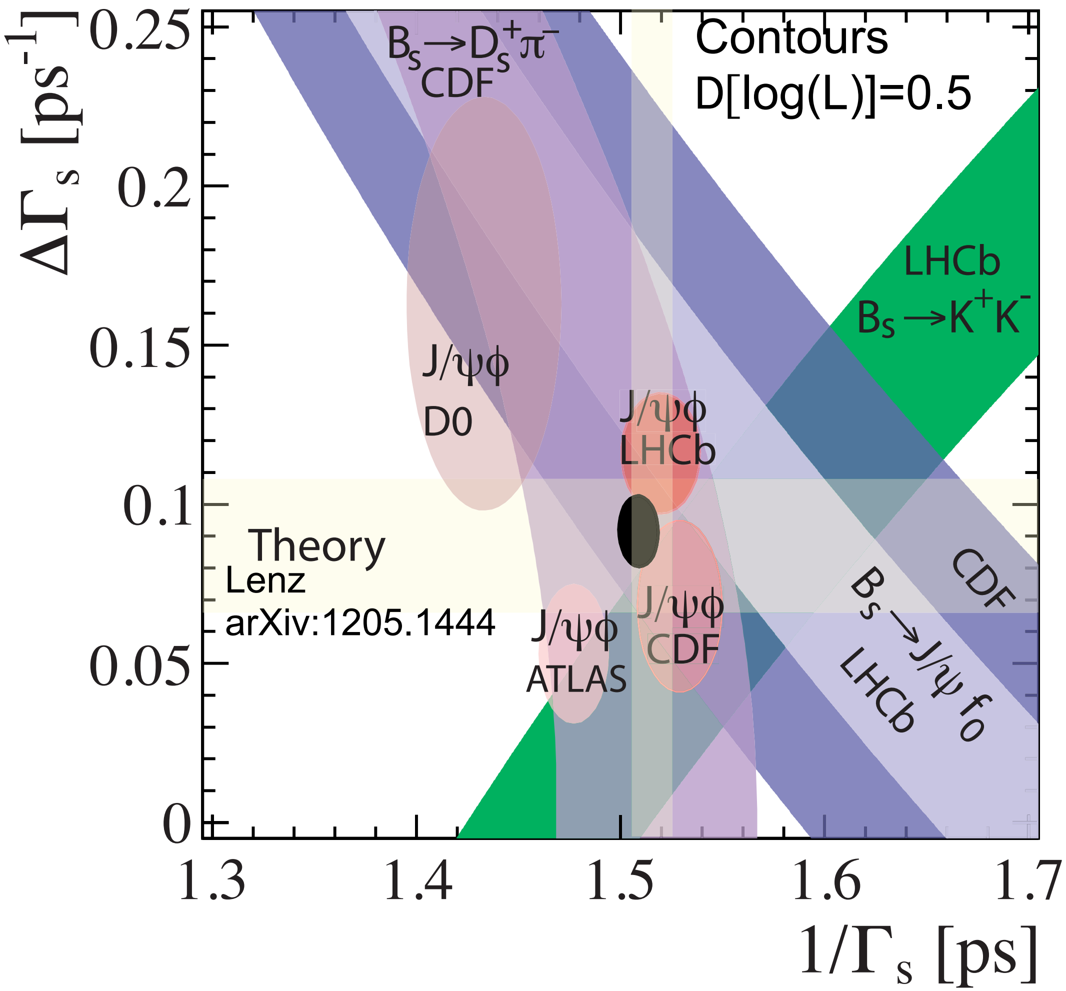
- Flavor physics provides a broad range of opportunities to uncover new physics signatures at mass scales well above 1 TeV
- LHCb is poised to pursue an upgrade strategy that can be adapted very easily to adjust to the evolving landscape of new physics scenarios
- Interesting flavor physics is being pursued also at ATLAS & CMS
- Synergistic experiments in K physics
- In the next episode of this exciting story "A complementary approach: lepton facitilities for flavor physics" presented by Tom Browder

(some random backup slides follow)

THE END

Γ_s & $\Delta\Gamma_s$

- B_s lifetime results here use only fully reconstructed decays
- K^+K^- is taken as CP even ($A_{DG}=-1$)
- Ovals show 39% cl, while bands 68% cl
- $\tau_s=1.509\pm0.010$ ps, $\Delta\Gamma_s = 0.092\pm0.011$ ps^{-1}, $y_s=\Delta\Gamma_s/2\Gamma_s=0.07\pm0.01$



only full reconstructed B_s decays used

flavor physics has an exciting future in the years to come!

Join the fun

a_{sl}

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

  at t=$\overline{0}$ M→f is zero as is $\overline{\text{M}}$→f

- Here *f* is by construction flavor specific, $\bar{f} \neq f$
- Can measure eg. $\bar{B}_s \rightarrow D_s^+ m^- n$, versus $B_s \rightarrow D_s^- m^+ n$,
- Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at m^+m^+ vs m^-m^-
- a_{sl} is expected to be very small in the SM, a_{sl}=(DG/DM) tanf$_{12}$, where tanf$_{12}$=Arg(-G$_{12}$/M$_{12}$)
- In SM (B°) a^d_{sl} =-4.1x10^{-4}, (B$_s$) a^s_{sl} =+1.9x10^{-5}

arXiv:1205.1444 [hep-ph]

The observables are many, we are still at a cross road among many paths

LHCb UPGRADE CONCEPT: FOLLOW THE OPPORTUNITIES AS THEY ARISE

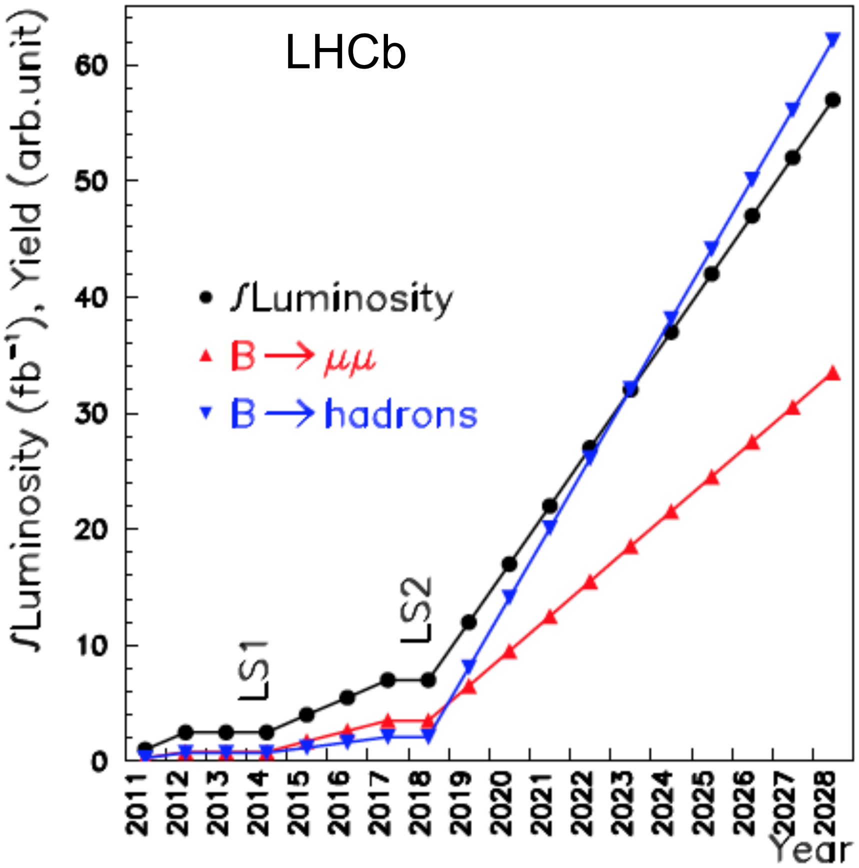
CERN/LHCC 2011-001
LHCb LoI
7 March 2011

LHCb
UPGRADE

Letter of Intent

LHCb expected performance

- LHCb has designed an upgrade path that will enable it to take advantage of a luminosity of ~10^{33}cm^{-2}s^{-1} with a flexible software trigger that can be customized to pursue exciting physics clues wherever they come from
- Pile-up and occupancy are very manageable at this luminosity (based on current data taking)
- Sensitivity scalable with CPU & analysis ingenuity (at least CPU should scale with Moore’s law!)
- Variety of new channels being considered (e.g. Bs→Kmn for Vub, B→D*tn)



G_s & DG_s

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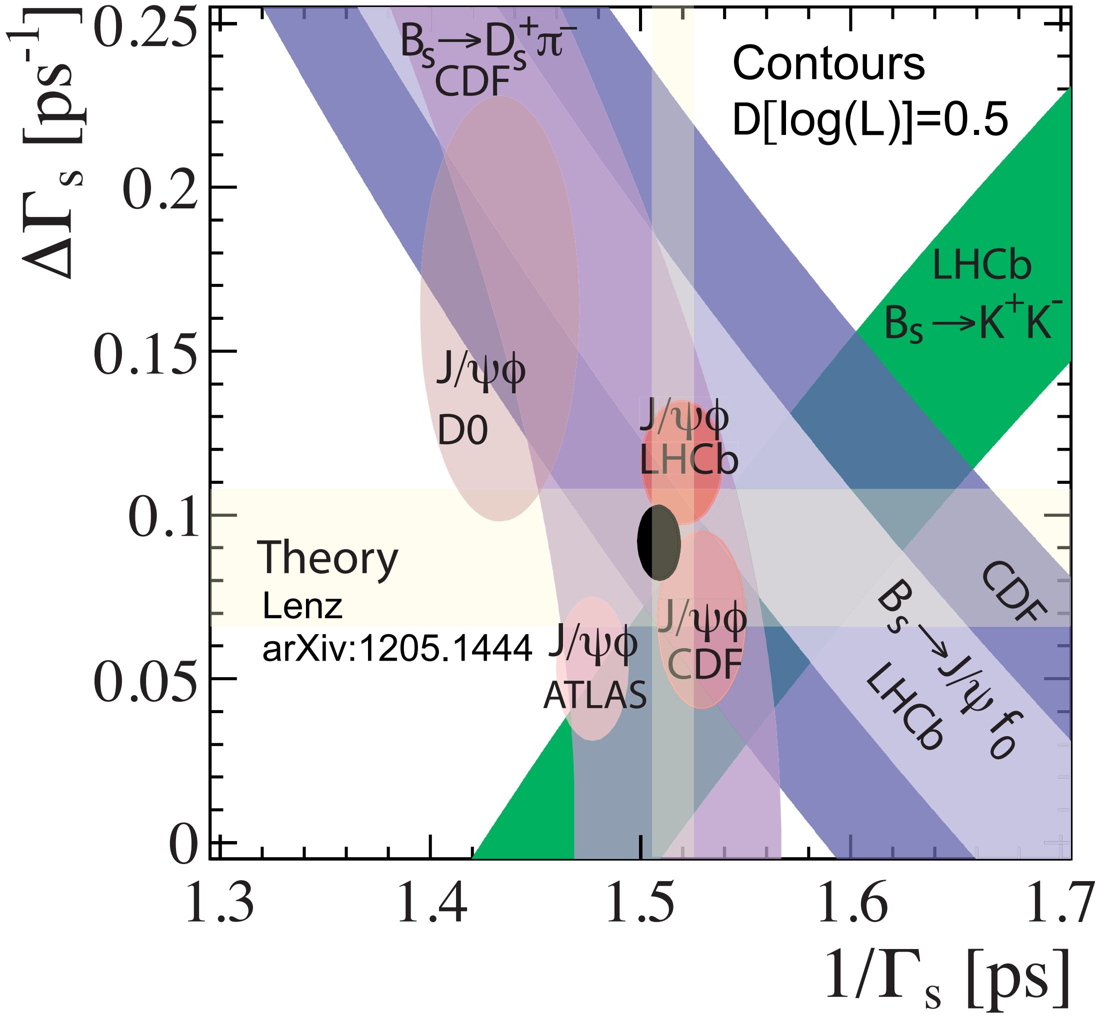

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a_{sl}

- ☐ By definition

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- ☐ In SM (B°) a^d_{sl} =-4.1x10^{-4}, (B_s) a^s_{sl} =+1.9x10^{-5}

arXiv:1205.1444 [hep-ph]

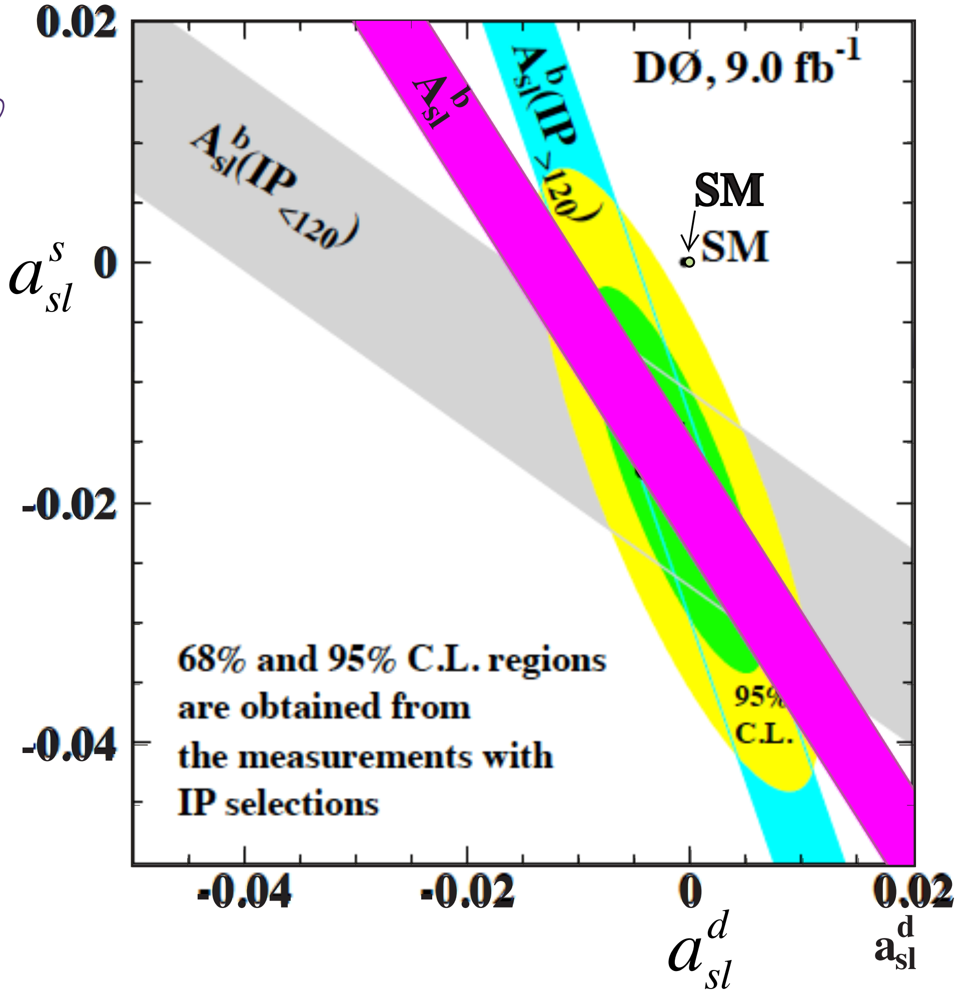
D^o a_{sl}

- Using dimuons (3.9s)

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

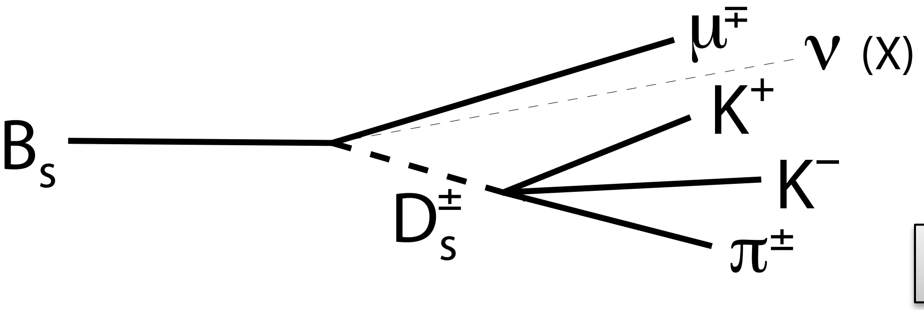
- Indication from D0 that its B_s
- Separate dimuons into B_d and B_s samples using muon impact parameter
- Find $a_{sl}^{d} = (-0.12 \pm 0.52)\%$

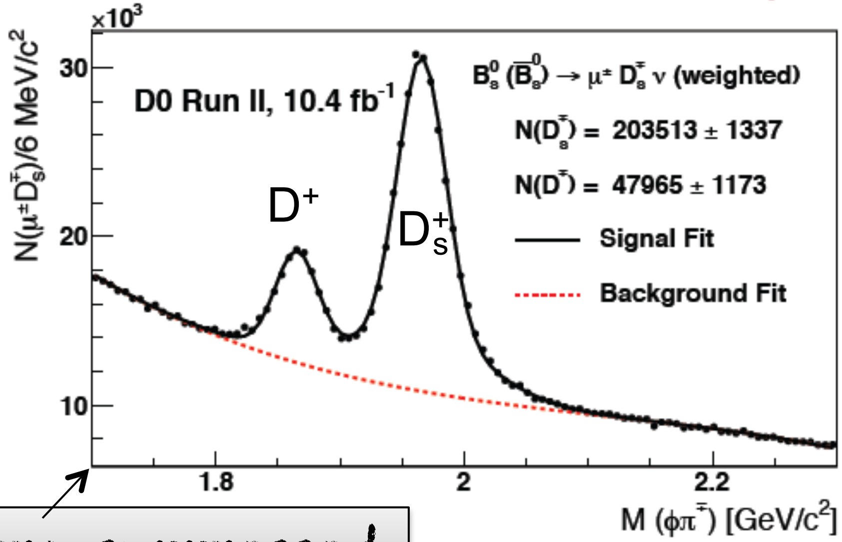
$$a_{sl}^{s} = (-1.81 \pm 1.06)\%$$



New D0 Analysis

- ☐ Measure a^s_{sl} using $D_s m^- n$ events, $D_s \rightarrow f p^\pm$
- ☐ Detect a m associate with a D_s decay



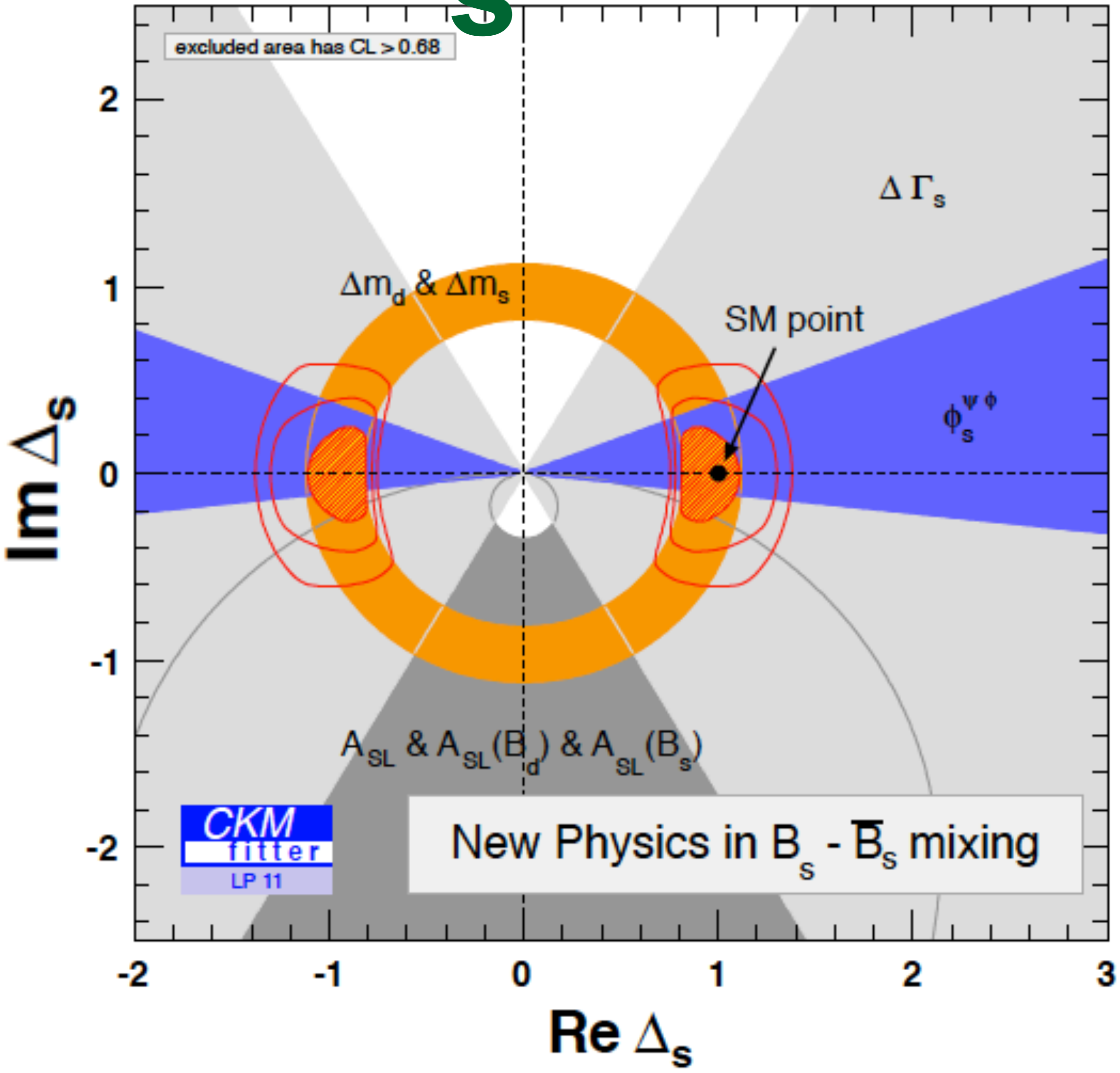


zero suppressed

- ☐ Find a^s_{sl}=(-1.08±0.72±0.17)%
- ☐ Also measure a^d_{sl} using $D^+ m^- n$, $D^+ \rightarrow K p^+ p^+$
- ☐ a^d_{sl}=(0.93±0.45±0.14)%

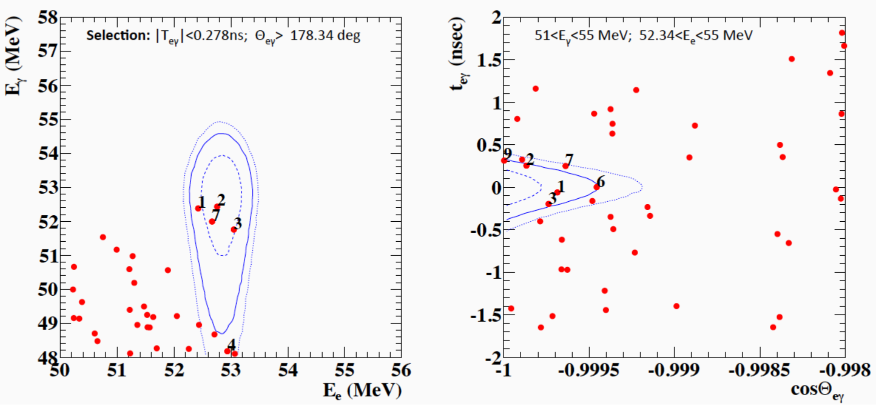
CKM B_s Fit

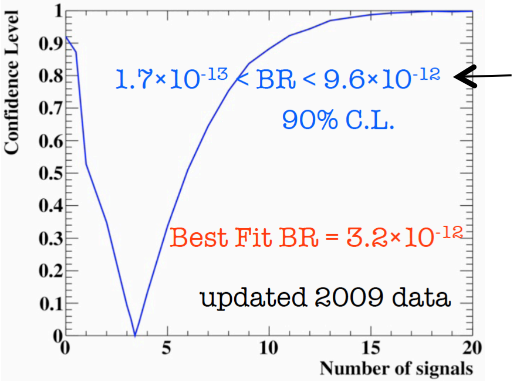
- Now even better consistency with SM than B_d
- However, much more room for NP than in B_d system due to less precise measurements



Lepton Flavor Violation

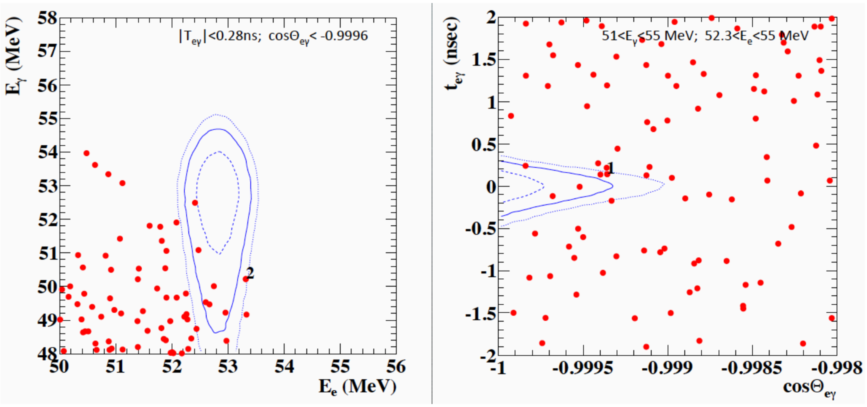
- ☐ $\mu \rightarrow e\gamma$ MEG data 2009 results (Mori EPS2011)

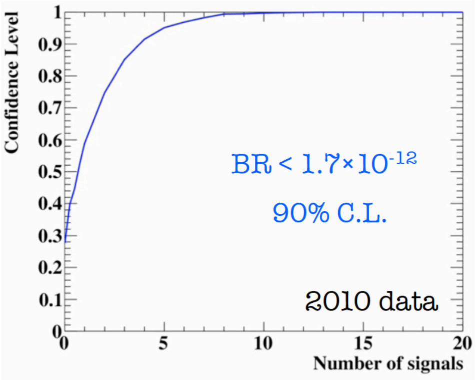




Note 2-sided limit

- ☐ Data 2010 Results





Combined $\mathcal{B}<2.4\times10^{-12}$

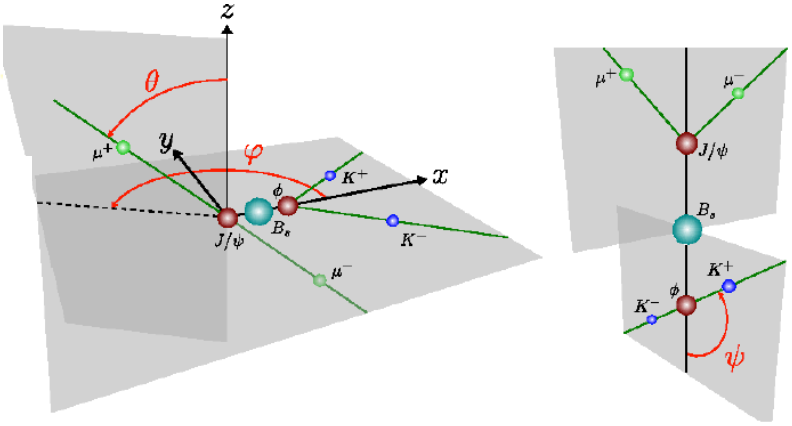
- ☐ Many limits on t→ℓhh, Lh, $\bar{L}$h, $\mu\gamma$, μh, 3μ, best limits near 10^{-8} (Belle, BaBar)

Basics For Sensitivities

- # of b's into detector acceptance
- Triggering
- Flavor tagging
- Background reduction
  - Good mass resolution
  - Good decay time resolution
  - Particle Identification

Transversity

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



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 f 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], \\
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&\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 $f=f_{cp}$

CPV in Charm

- Expect largest effects in Cabibbo Suppressed Decays. COULD REVEAL NP (see Grossman Kagan & Nir arXiv:1204.3557)
- Define: $A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$

if f is a CP eigenstate then $f = \bar{f}$

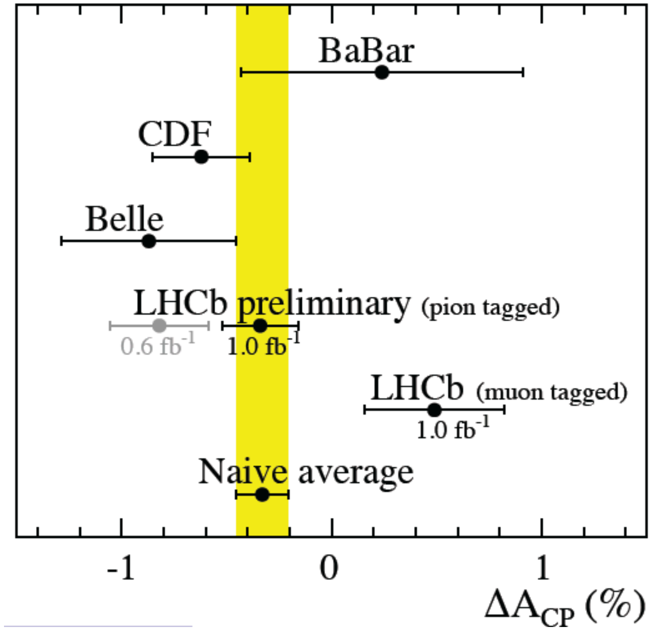
- Current data for

$$\Delta A_{CP} \equiv A_{CP}\left(K^+K^-\right) - A_{CP}\left(\pi^+\pi^-\right)$$

do not show much, though

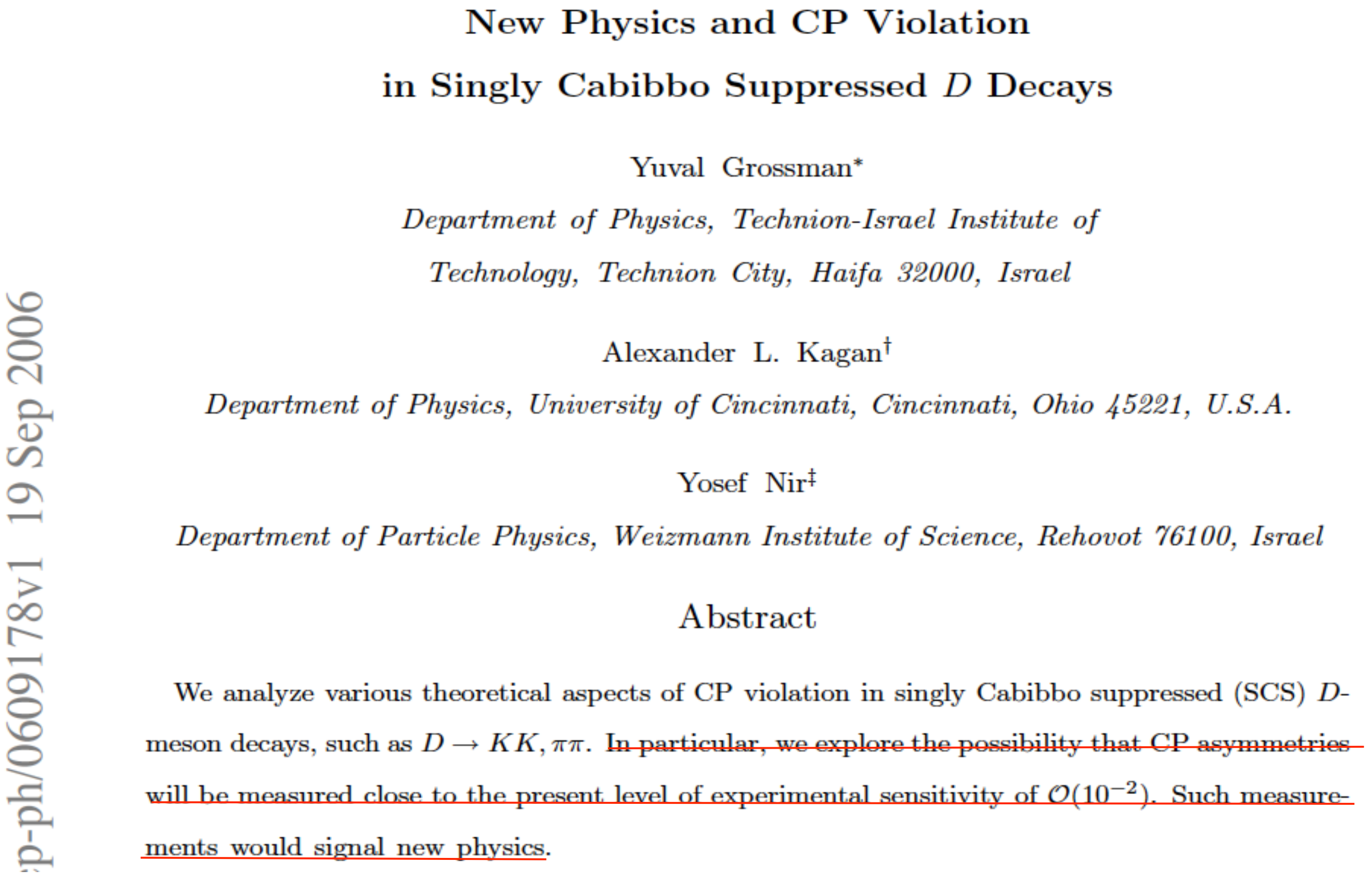
some early measurements gave a 4.5s effect.

Both SM & NP explanations are prolific



Interpretation

- Prior to result: “CPV in charm is clearly beyond the SM”



p-ph/0609178v1 19 Sep 2006

New Physics and CP Violation in Singly Cabibbo Suppressed D Decays

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Alexander L. Kagan†
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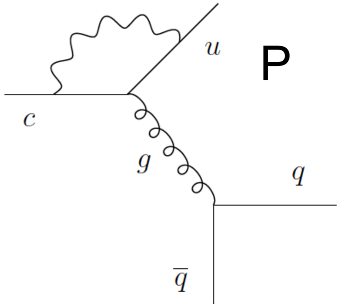
Yosef Nir‡
Department of Particle Physics, Weizmann Institute of Science, Rehovot 76100, Israel

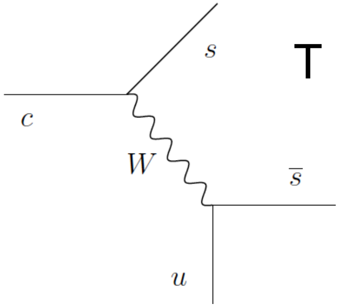
Abstract

We analyze various theoretical aspects of CP violation in singly Cabibbo suppressed (SCS) D-meson decays, such as $D \to KK, \pi\pi$. In particular, we explore the possibility that CP asymmetries will be measured close to the present level of experimental sensitivity of $\mathcal{O}(10^{-2})$. Such measurements would signal new physics.

“New think”

- Direct CP in SM caused by interference between P and T

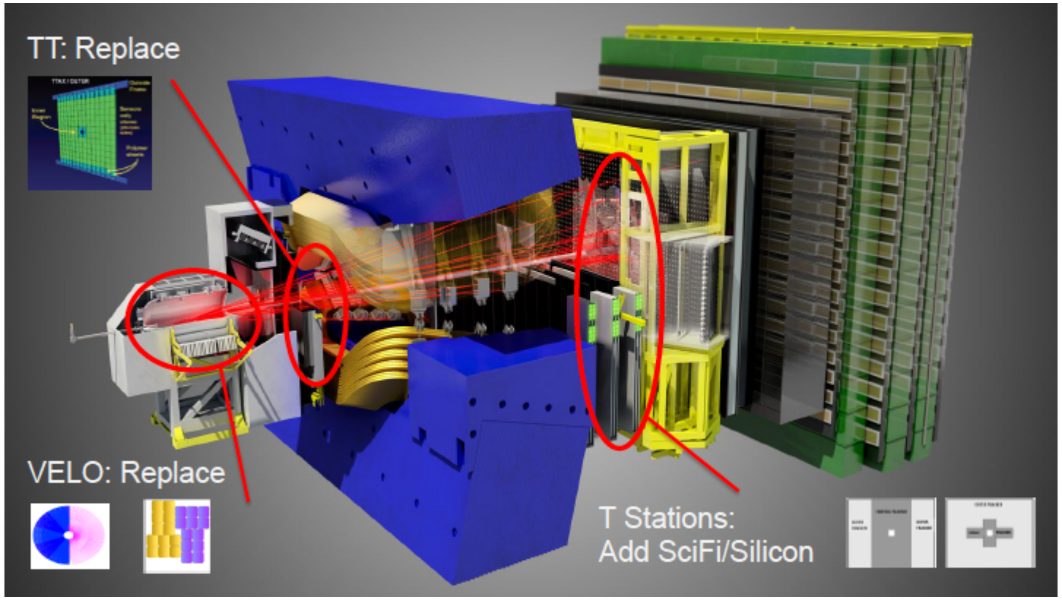




- Since $V_{us} = -V_{cd}$
  $A_{CP}(K^+K^-) = -A_{CP}(p^+p^-)$
- Still need P/T to be >3, while in B decays it is 0.15….
- But there is the DI=1/2 rule in K_L decay which is not understood, so all bets are off (Grossman, CERN seminar Jan. 12, 2012)

Tracking

- ☐ At $L=2\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$ the event topology is more complex:
  - ☐ More primary vertices
  - ☐ Increased track multiplicity
  - ☐ Bunch-to-bunch spillover
  - ☐ Detector occupancy (highly non-uniform, radial dependence)



TT: Replace

VELO: Replace

T Stations: Add SciFi/Silicon

Highlights on technological challenges:

- ☐ VELO: high radiation & data rates in the innermost section
- ☐ Super think shaped RF foil for VELO
- ☐ All tracking layers: closer to the beam line, low mass support and cooling

Rare Decays - Generic

- $$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}\ .$$
- $C_i O_i$ for SM, $C_i' O_i'$ are for NP. Operators are for $P_{R,L} = (1\pm g_5)/2$

$$O_7 = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}\,, \qquad O_8 = \frac{g m_b}{e^2} (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a}\,,$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$O_S = m_b (\bar{s} P_R b)(\bar{\ell}\ell)\,, \qquad O_P = m_b (\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)\,,$$

- $O' = O$ with $P_{R,L} \rightarrow P_{L,R}$
- Each process depends on a unique combination

Limits on $D^{(*)+}l^- l'^-$

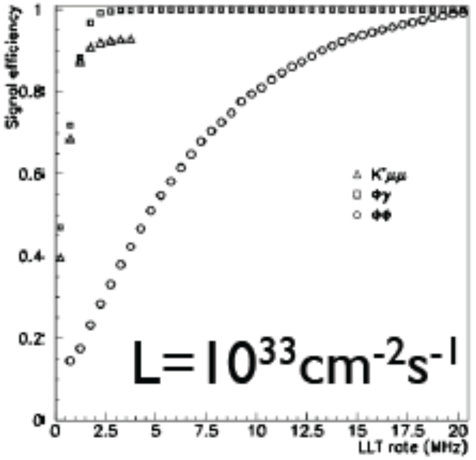
- Upper limits in e^-e^- mode not competitive with nuclear b decay
- Others unique since measure coupling of Majorana n to m^-

Mode	Exp.	u. l. x 10^{-6}
$B^-\to D^+e^-e^-$	Belle	< 2.6
$B^-\to D^+e^-m^-$	Belle	< 1.8
$B^-\to D^+m^-m^-$	Belle	< 1.0
$B^-\to D^+m^-m^-$	LHCb	< 0.69
$B^-\to D^{*+}m^-m^-$	LHCb	< 3.6

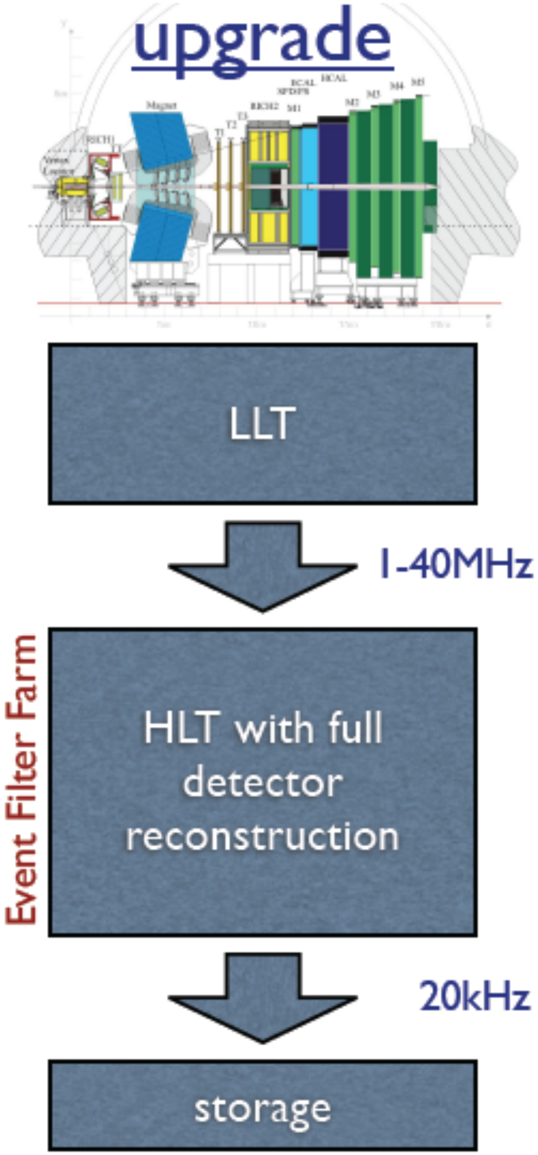
Belle [arXiv:1107.064]

Upgrade trigger information

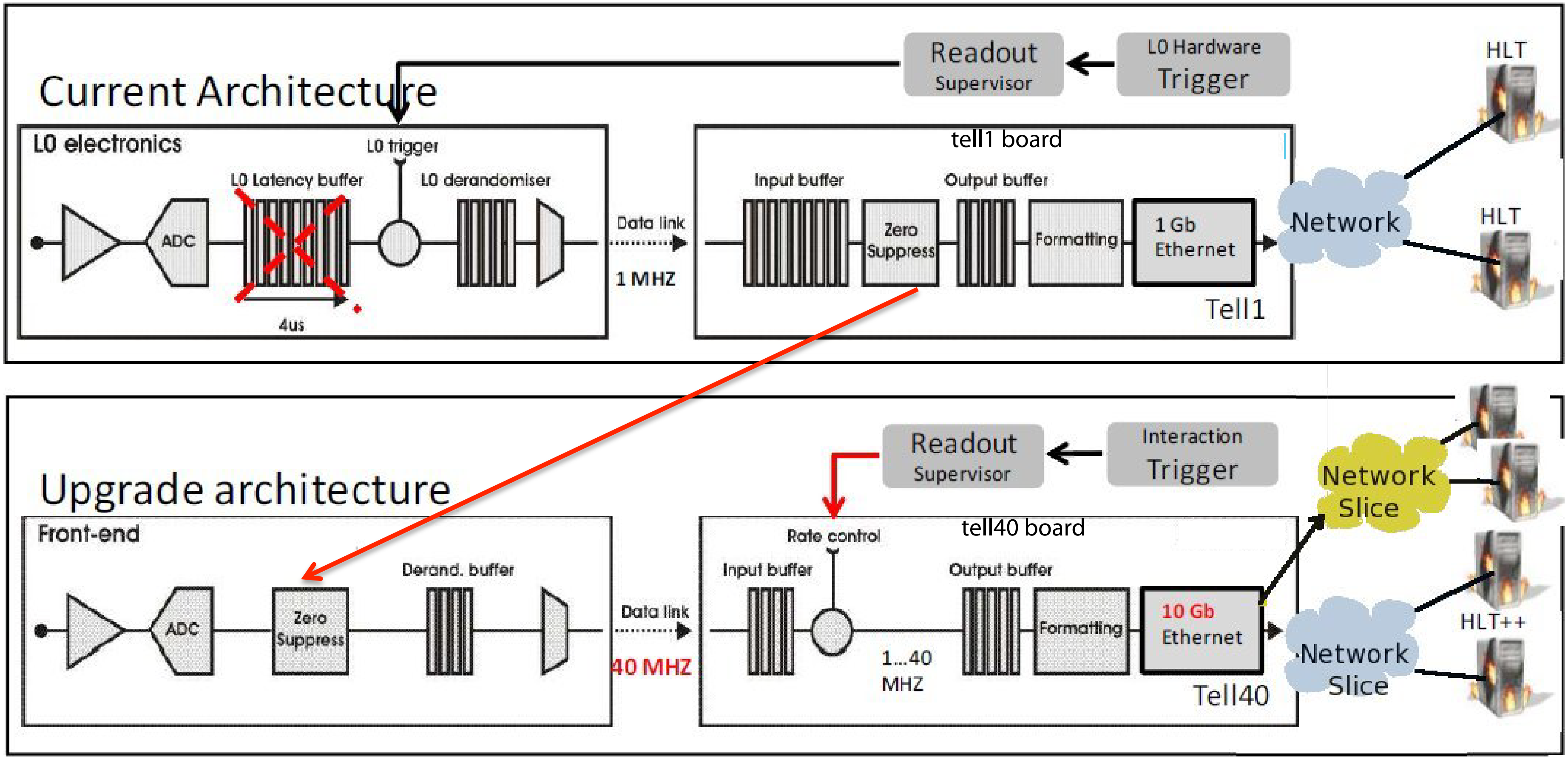
- change electronics readout to get up to 40MHz and match LHC bunch crossing
- Event Filter Farm reconstructs the event and makes trigger decisions
- Improvements of the CPU computing power are needed



EFF size	5×2011	10×2011
LLT-rate (MHz)	5.1	10.5
HLT1-rate (kHz)	270	570
HLT2-rate (kHz)	16	26
Total signal efficiency		
$B_s \to \phi\phi$	0.29	0.50
$B^0 \to K^* \mu\mu$	0.75	0.85
$B_s \to \phi\gamma$	0.43	0.53



Data acquisition strategy



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- Pile-up and occupancy are very manageable at this luminosity (based on current data taking)
- Sensitivity scalable with CPU & analysis ingenuity (at least CPU should scale with Moore’s law!)
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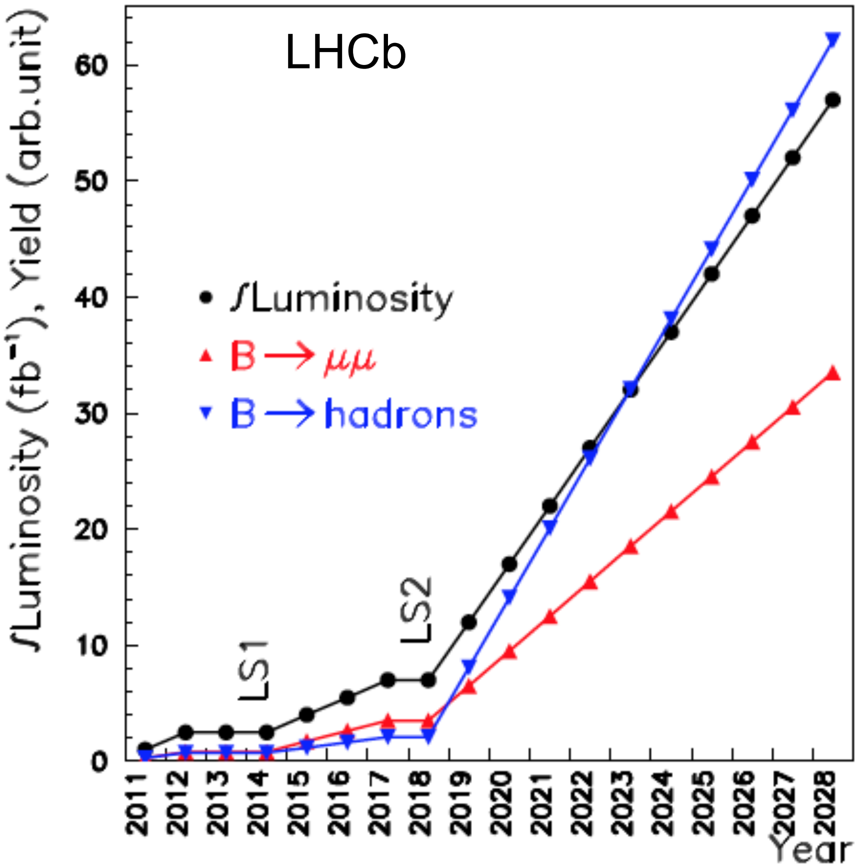
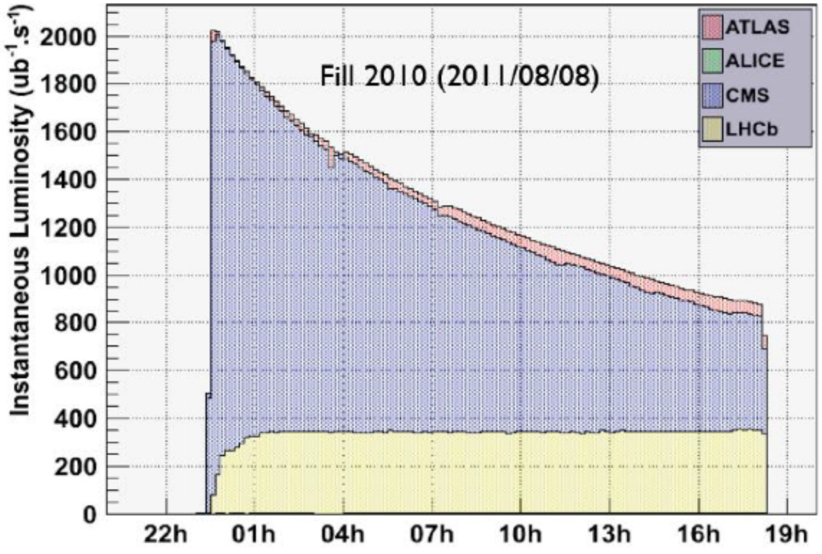
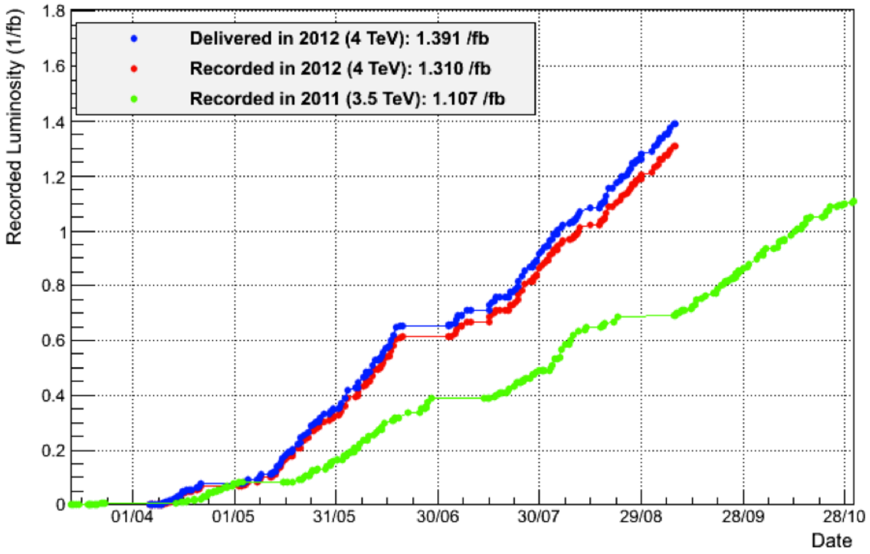


Luminosity Leveling

- Luminosity is maintained as at a constant value of ~$4 \times 10^{32}/\mathrm{cm}^2/\mathrm{s}$ by displacing beams transversely
- Integral $\mathcal{L}$ is 1/fb in 2011, expect 2.2/fb more in 2012, already have 1.8/fb recorded





Precision measurement of FCNC in the s→d system

BSM Constraints