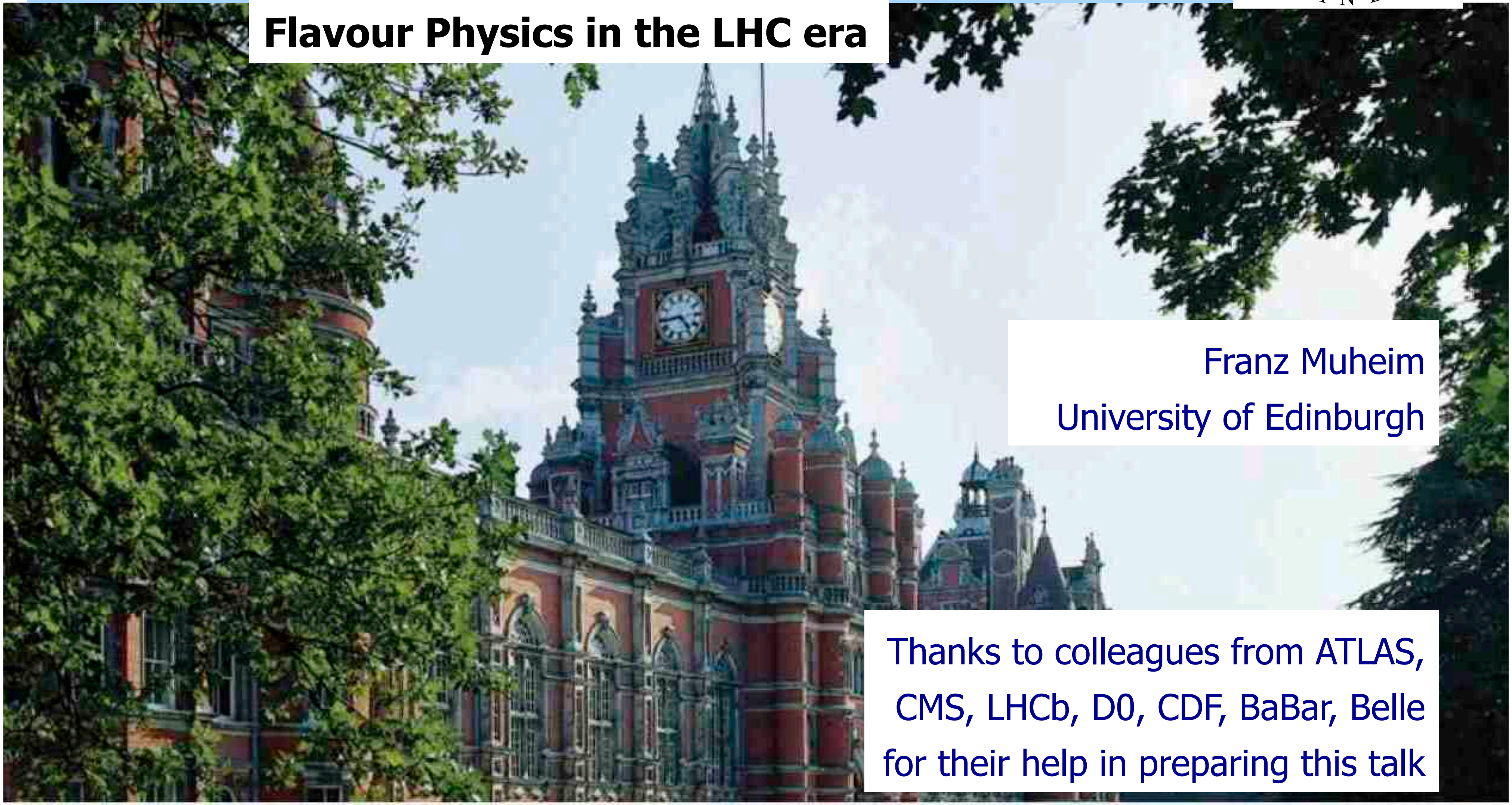
Status of Quark Flavor Physics



Flavour Physics in the LHC era

Franz Muheim
University of Edinburgh

Thanks to colleagues from ATLAS, CMS, LHCb, D0, CDF, BaBar, Belle for their help in preparing this talk

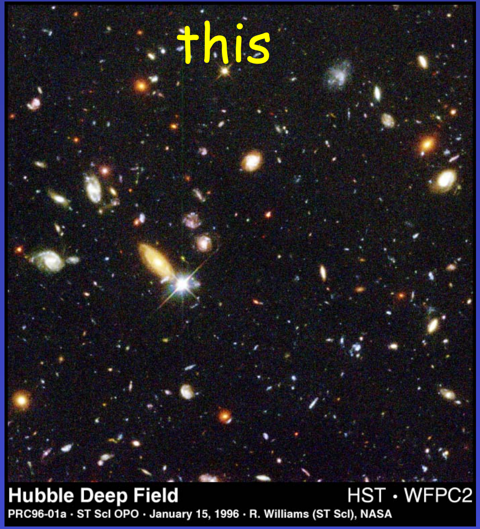
Outline

- **Motivation**
  - Matter-Antimatter asymmetry, Dark Matter
  - Probing New Physics in CP violation and rare decays
- **LHCb experiment**
- **Flavour Physics Results – Selected Highlights**
  - Rare decays
  - CP Violation (~~CP~~)
  - Lifetimes
  - Charm physics
  - CKM angle gamma
  - Spectroscopy
- **Future plans**
  - LHCb upgrade and Belle/SuperKEKB
- **Conclusions**

Major Open Questions

Flavour physics is searching for answers to these questions

- **What is the universe made of?**
  - only 4% of observed universe is made of known matter
    96% is not understood
- **Why is there so much matter and almost no antimatter?**
  - only one in a billion particles are antimatter
  - Protons & antiprotons annihilated within 1 ms after Big Bang
- Why does the Universe look like



and not

like that???

CP Violation

- **CP Violation is necessary for matter-antimatter asymmetry**
- **CKM mechanism**
  - predicts $\cancel{CP}$ for 3 generations of quarks
  - Cabibbo-Kobayashi-Maskawa quark mixing matrix

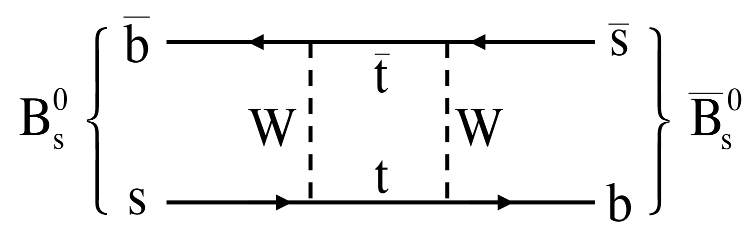
$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-\boxed{i\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-\boxed{i\eta}) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

  - $\cancel{CP}$ discovered in Kaons in 1964 and in B-mesons in 2001
  - CKM mechanism implies $n_p/n_\gamma \sim 10^{-18}$ 9 orders of magnitudes too low
- **Additional sources of $\cancel{CP}$ are required**
  - Quark sector? Flavour experiments – LHCb, (Super) B-factory
  - Leptogenesis? Neutrinos

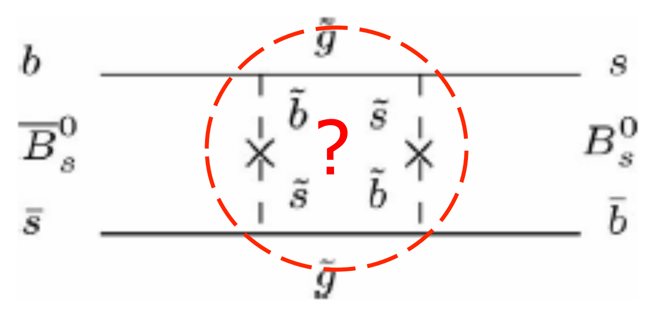
New Physics in Flavour

- **Flavour explores new physics (NP) beyond the energy frontier**
  - Sensitive to NP appearing as virtual particles in loop processes
  - Observable deviations from SM expectations in flavour physics
  - CP violation ($\cancel{CP}$)

Standard Model



New Physics ?

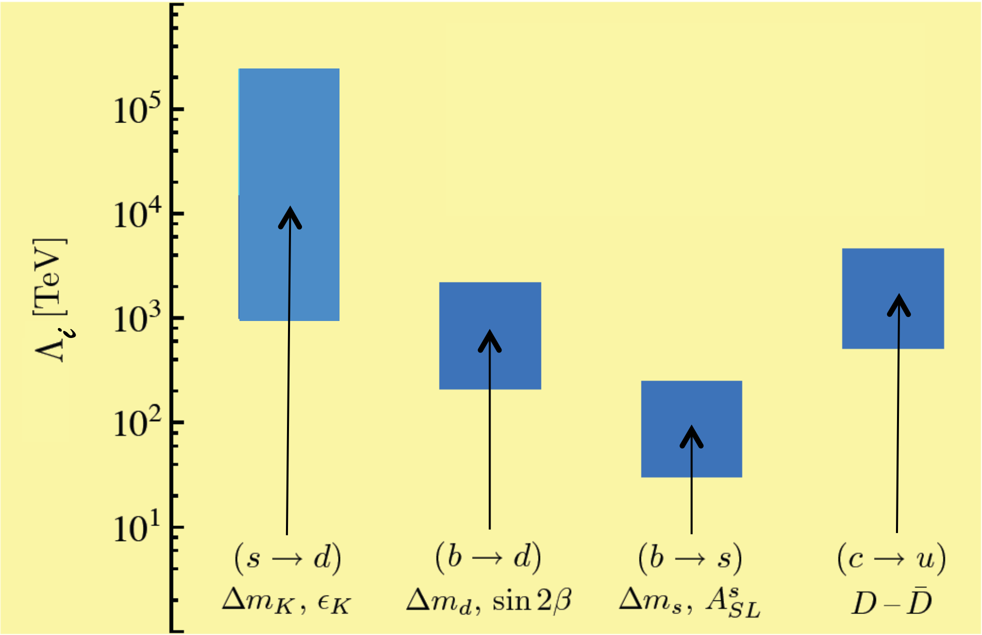


B_s-$\overline{B}_s$ oscillations

New Physics Flavour Problem

- Add new physics to SM Lagrangian
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$
- Flavour transitions
  - probe high mass scales
  - parameterised in terms of operators, couplings and mass scales
- NP flavour problem
  - If couplings c_i ~1 NP should have been seen
  - particles have large masses » 1 TeV or couplings are small c_i « 1 & same as in SM

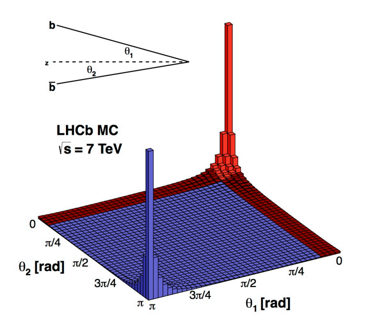
New physics ruled out from Λ_i=0 to somewhere in the blue boxes

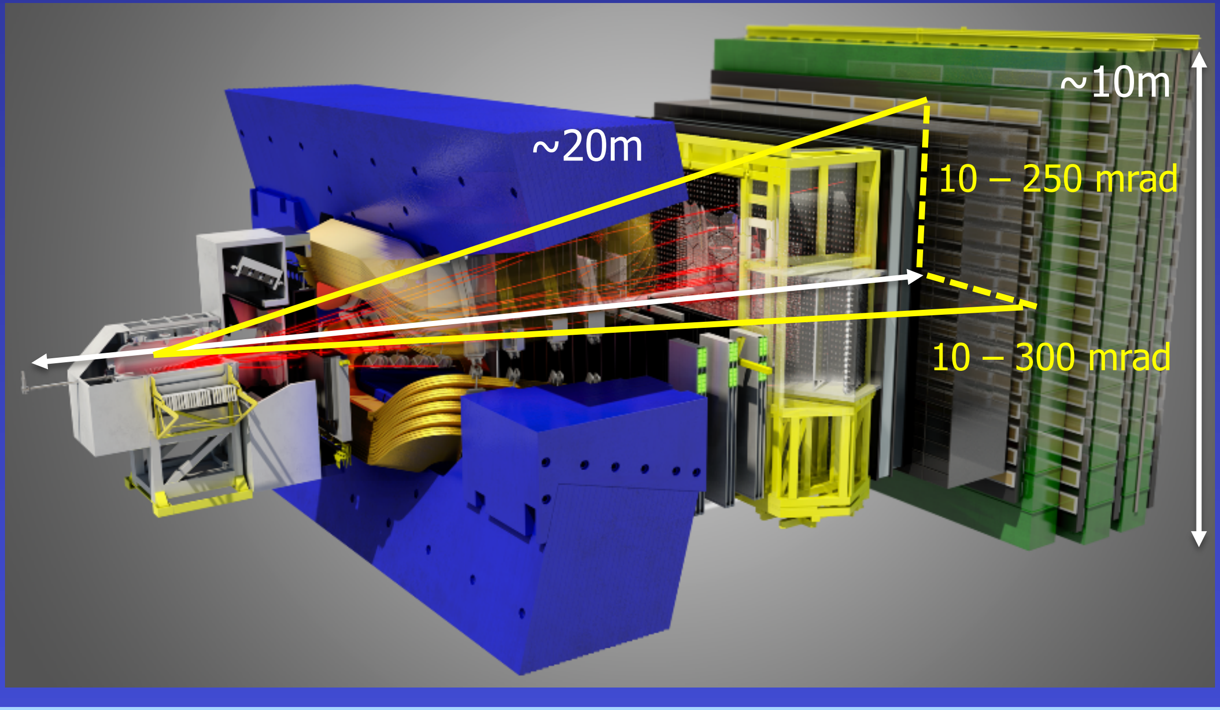


See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

LHCb Experiment

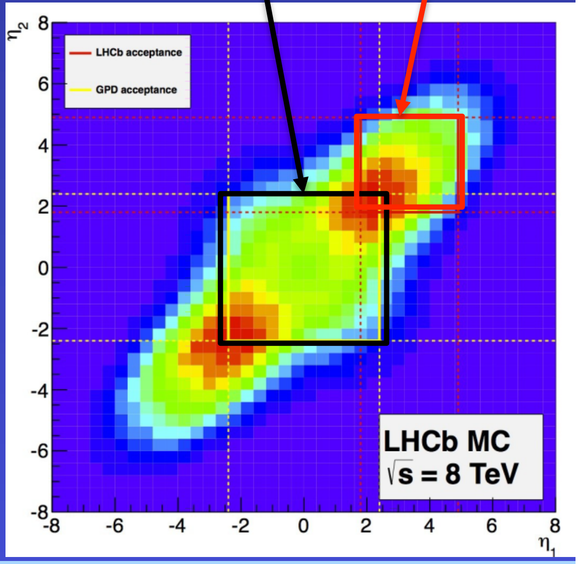
- **LHC is a flavour factory**
  - beauty quark cross section $\sigma_{bb} \sim 300\ \mu b$
  - Very large charm cross section $\sigma_{cc} \sim 20\ \sigma_{bb} \sim 6\ mb$
- **LHCb**
  - dedicated experiment for heavy flavour physics





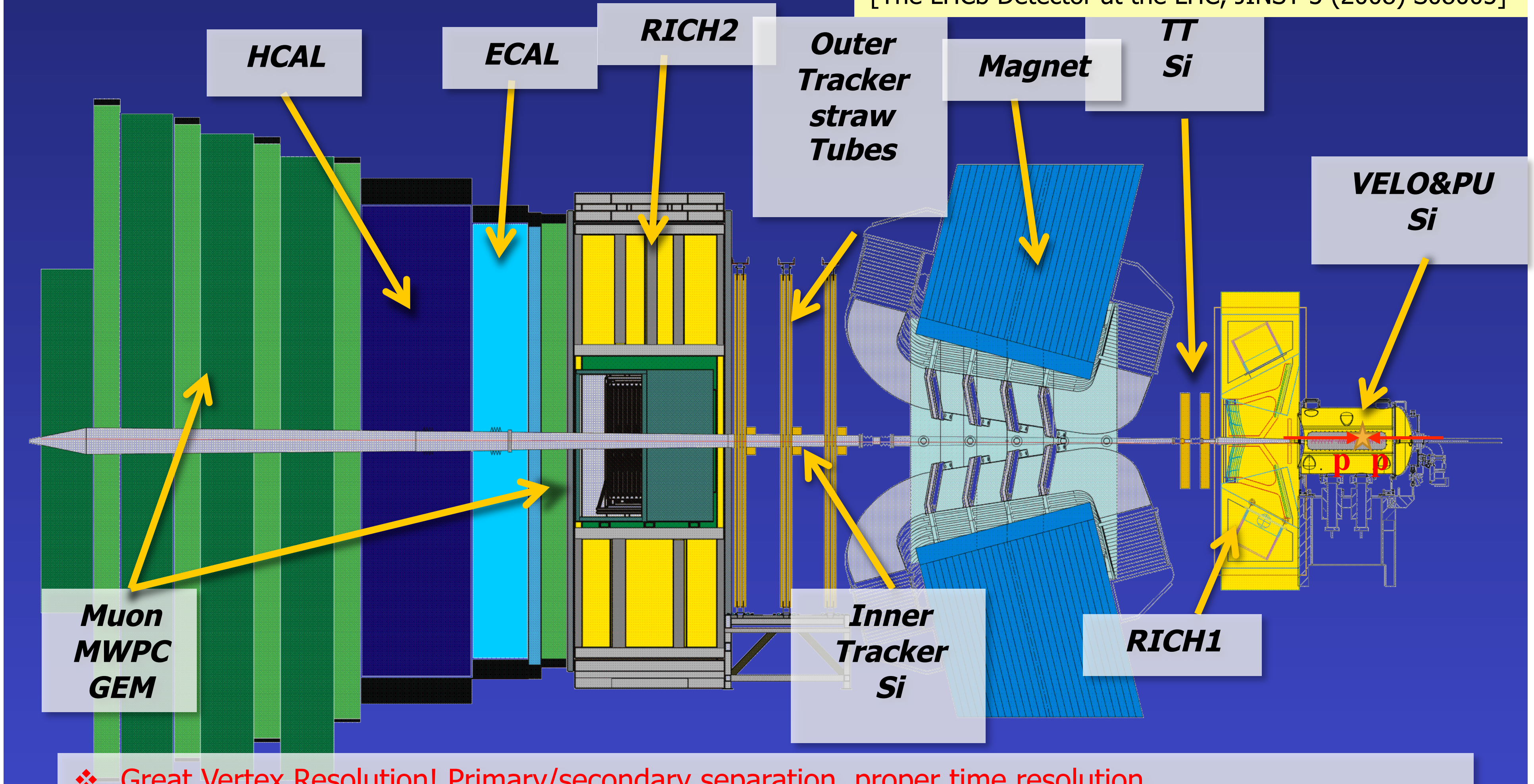
ATLAS & CMS region $|\eta| < 2.5$

LHCb region $2 < \eta < 5$



The LHCb Detector

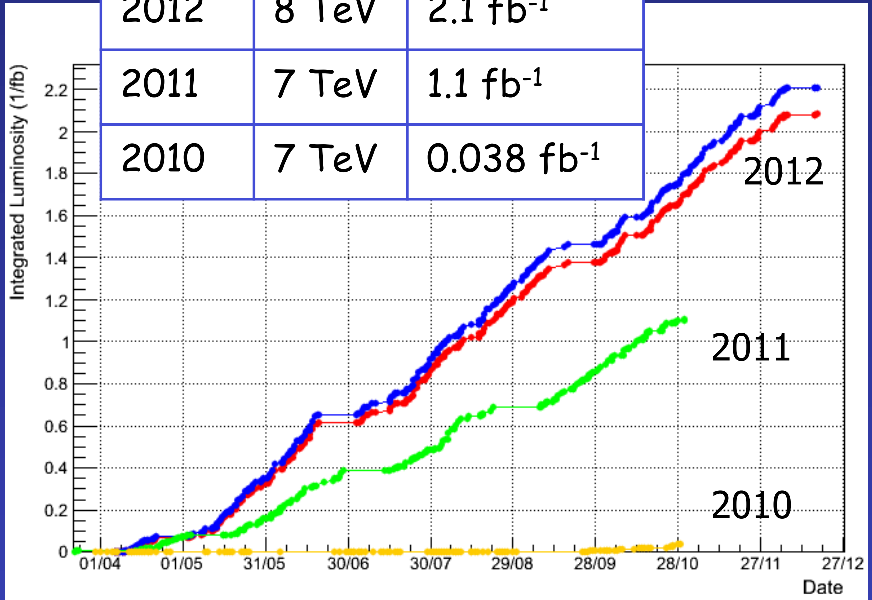
[The LHCb Detector at the LHC, JINST 3 (2008) S08005]



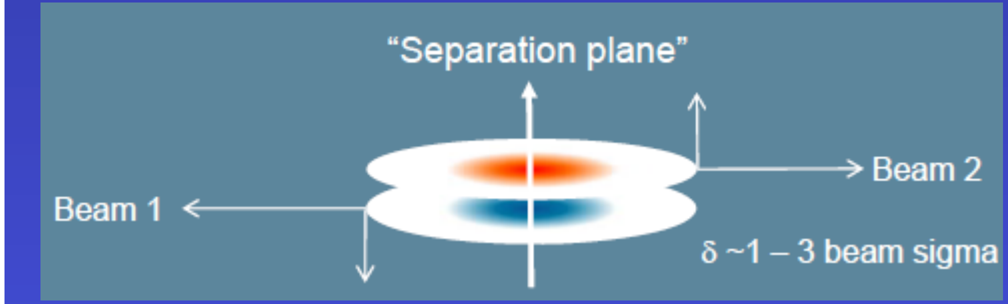
- Great Vertex Resolution! Primary/secondary separation, proper time resolution.
- Excellent momentum and mass resolution.
- Outstanding PID (K-π) and μ reconstruction.
- Dedicated Trigger system for beauty and charmed hadrons

LHCb Performance

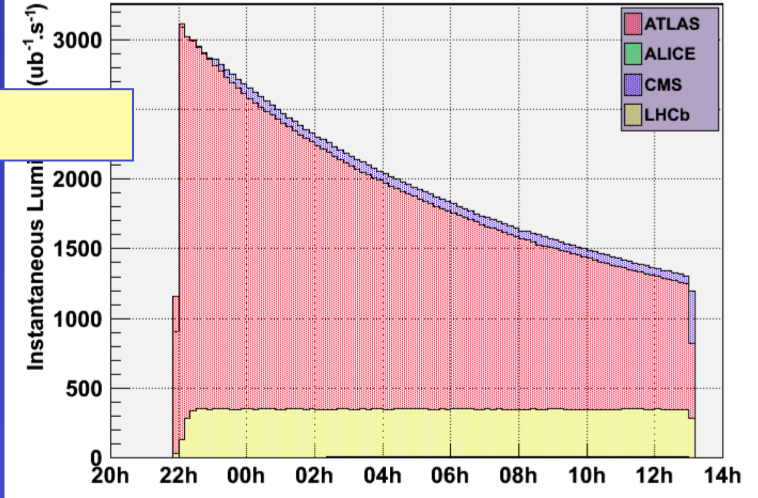
2012	8 TeV	2.1 fb^{-1}
2011	7 TeV	1.1 fb^{-1}
2010	7 TeV	0.038 fb^{-1}



- **Very successful 2010/11/12 run**
  - LHCb operated at luminosities up to $L = 4 \times 10^{32}\ cm^{-2}\ s^{-1}$ 2x design luminosity
  - Average # of visible interactions/ crossing $\mu = 1.4$ (nominal 0.4)
  - Integrated $\int Ldt \sim 3\ fb^{-1}$ on tape
  - 91% data taking efficiency, 99% of channels operational
  - ~ 5 kHz of physics data to tape

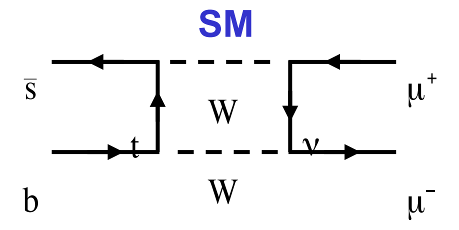


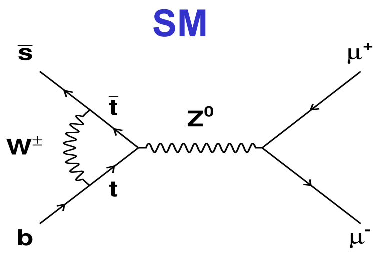
Luminosity levelling

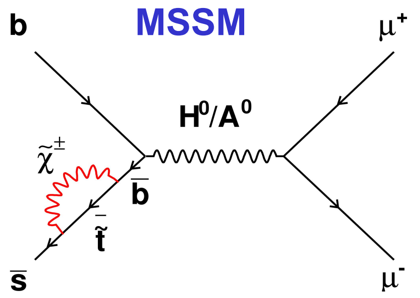


Rare Decays

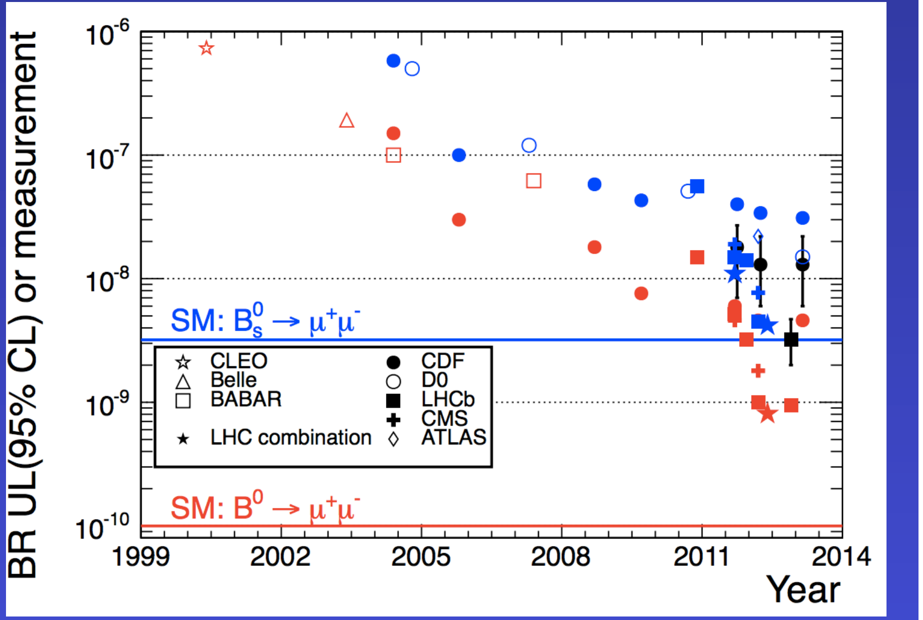
Very rare decay $B_s \rightarrow \mu+\mu-$





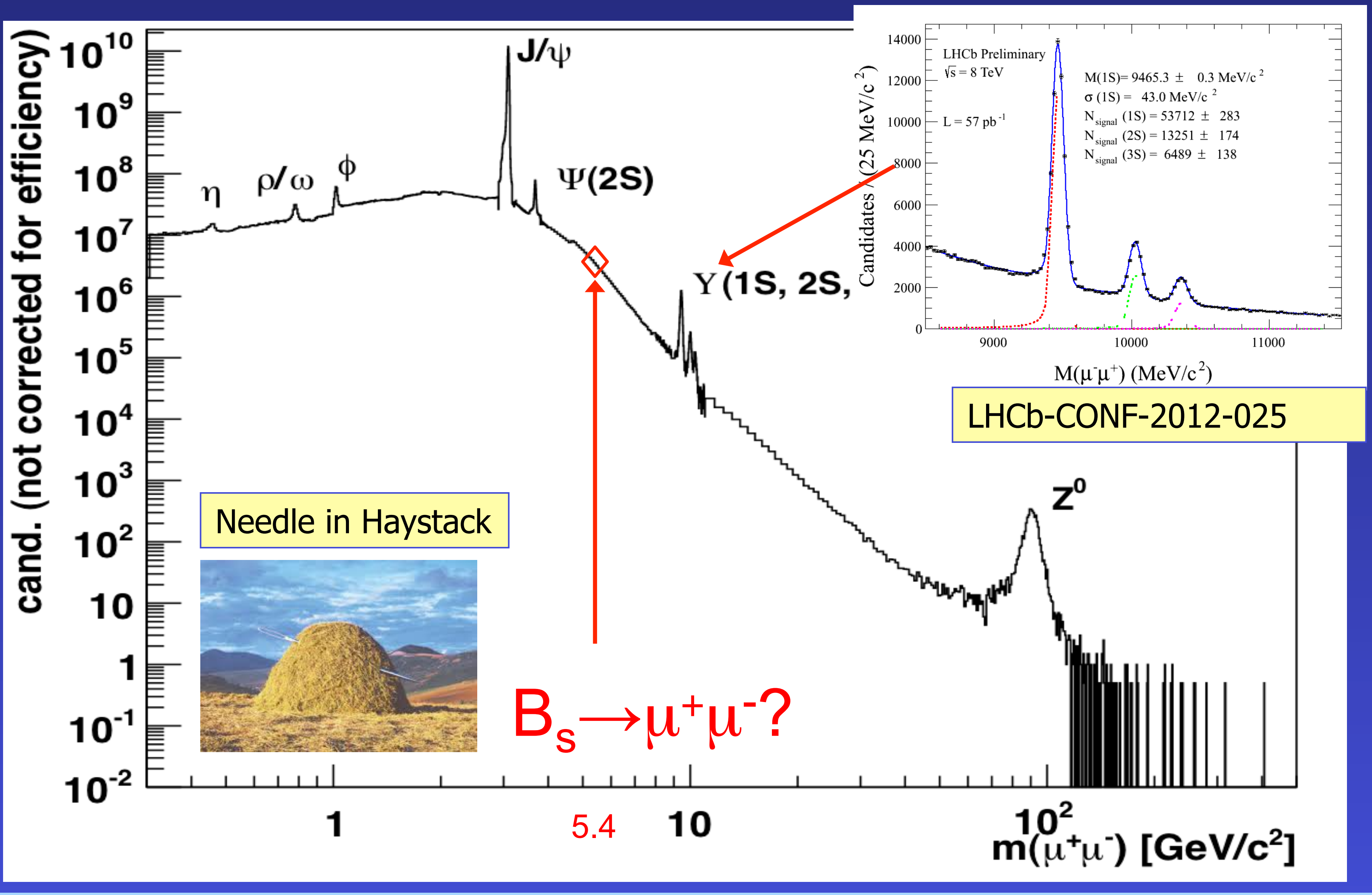


- **Decay highly suppressed in SM**
  - CKM and helicity suppressed
  - Predicted branching ratio
  - BR $(B_s \rightarrow \mu+\mu-) = (3.5 \pm 0.2) \times 10^{-9}$
  - BR $(B^0 \rightarrow \mu+\mu-) = (1.1 \pm 0.2) \times 10^{-10}$



- **Very sensitive to new physics**
  - Strongly enhanced in MSSM models
  - Rate ∝ $\tan^6\beta/M_H$

LHCb $\mu^+\mu^-$ mass spectrum



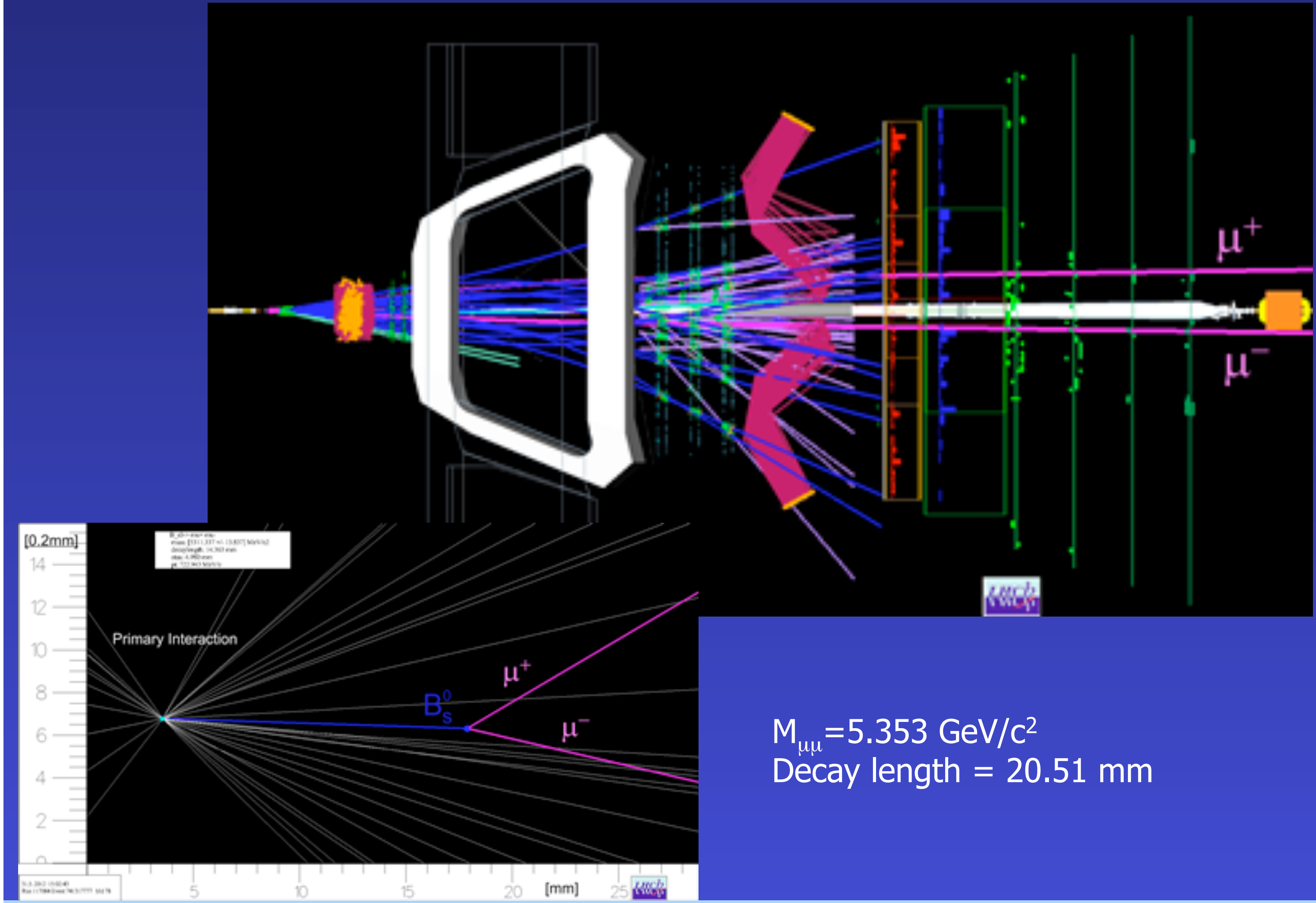
LHCb-CONF-2012-025

Needle in Haystack

5.4

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

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



$M_{\mu\mu}$=5.353 GeV/c^2
Decay length = 20.51 mm

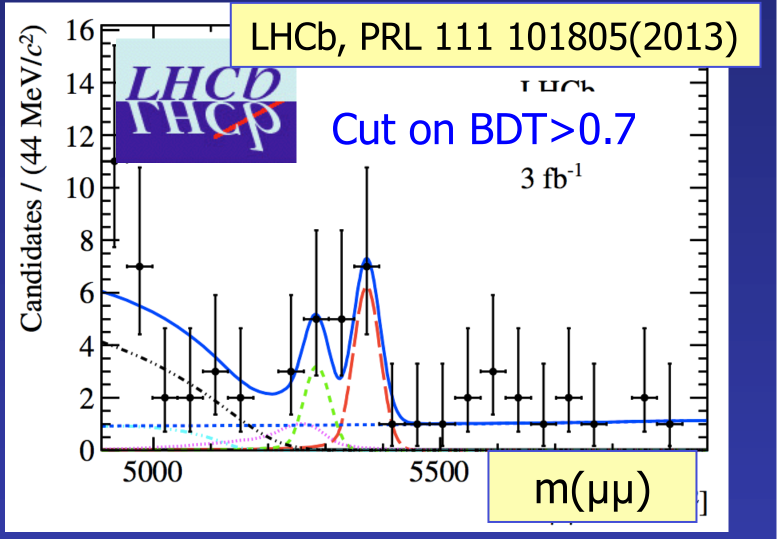
Discovery of $B_s \rightarrow \mu^+\mu^-$

- **Observation of $B_s \rightarrow \mu^+\mu^-$**
  - 2012 LHCb: 3.5σ evidence
  - 2013 CMS & LHCb observation > 5σ combined
- **LHCb Observation**
  - 1.0 fb^{-1} 2011 (7 TeV) & 2.0 fb^{-1} 2012 (8 TeV) data
  - Selection based on BDT combining vertex and geometrical information

$BR(B_s^0 \rightarrow \mu^+\mu^-) = 2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)\cdot 10^{-9}$	4.0σ
$BR(B^0 \rightarrow \mu^+\mu^-) = 3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)\cdot 10^{-10}$	2.0σ

- **CMS Observation**

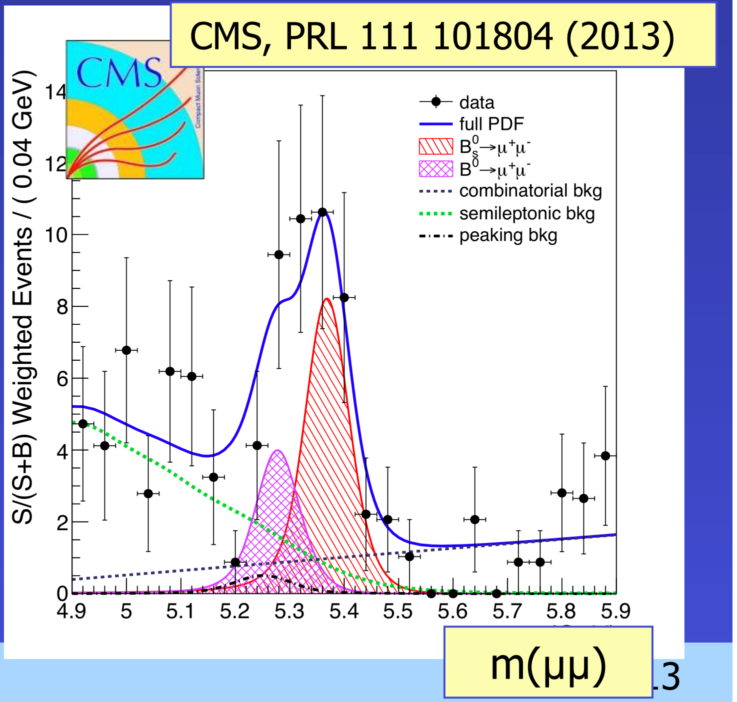
$BR(B_s^0 \rightarrow \mu^+\mu^-) = 3.0^{+1.1}_{-0.9}\cdot 10^{-9}$	4.3σ
$BR(B^0 \rightarrow \mu^+\mu^-) = 3.5^{+2.1}_{-1.8}\cdot 10^{-10}$	2.0σ



LHCb, PRL 111 101805(2013)

Cut on BDT>0.7

m(μμ)



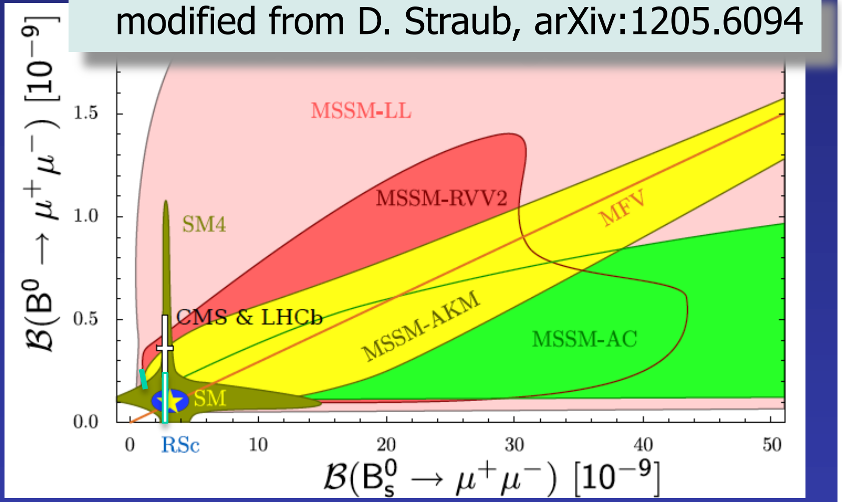
CMS, PRL 111 101804 (2013)

m(μμ)

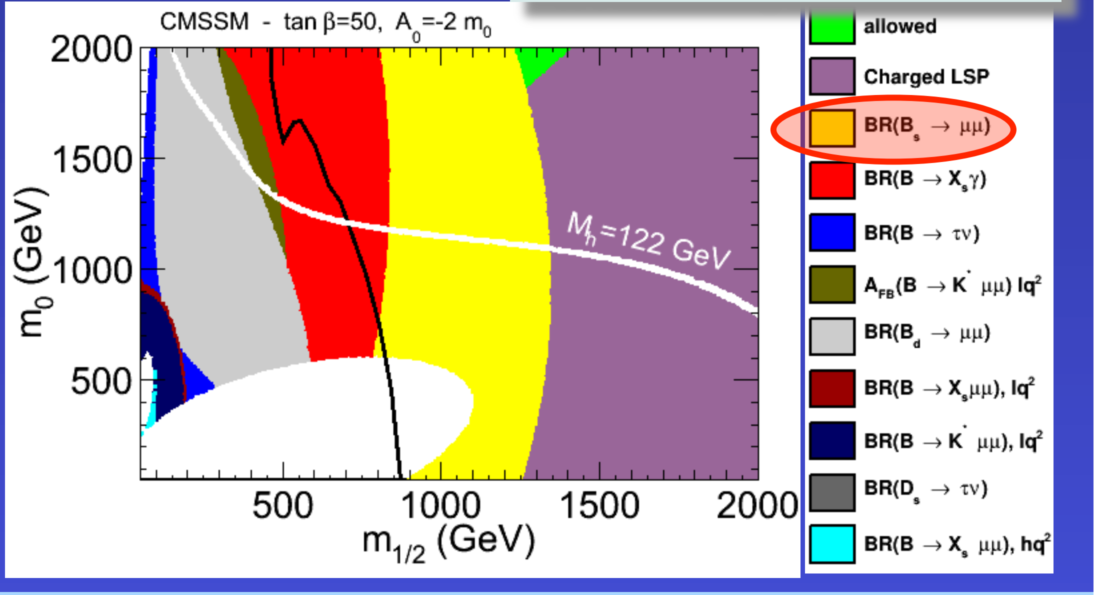
Constraints from $B_s \to \mu^+\mu^-$

- **CMSSM**
  - Constrained Minimal Supersymmetry
- **Exclusion ranges**
  - at large tanβ flavour physics excludes full parameter space

modified from D. Straub, arXiv:1205.6094

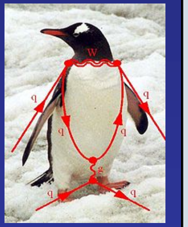


F. Mahmoudi, arXiv:1310.2556

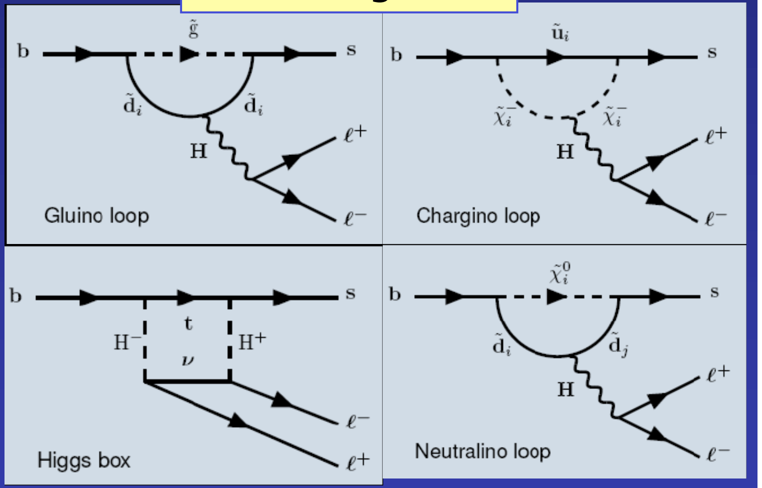


EW Penguin Decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$

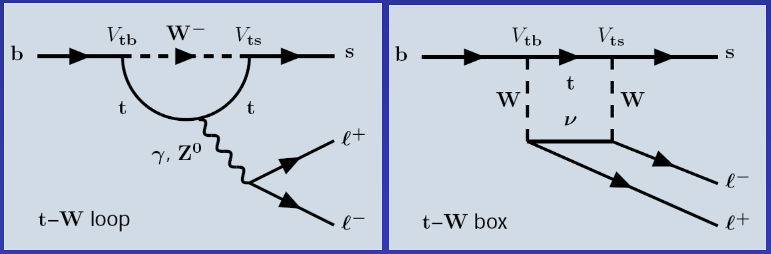
- **Flavour Changing Neutral Currents**
  - Suppressed in SM
  - Sensitive to new Physics



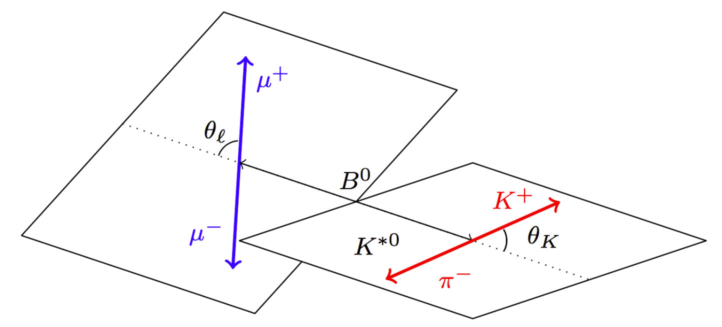
SUSY diagrams



SM diagrams

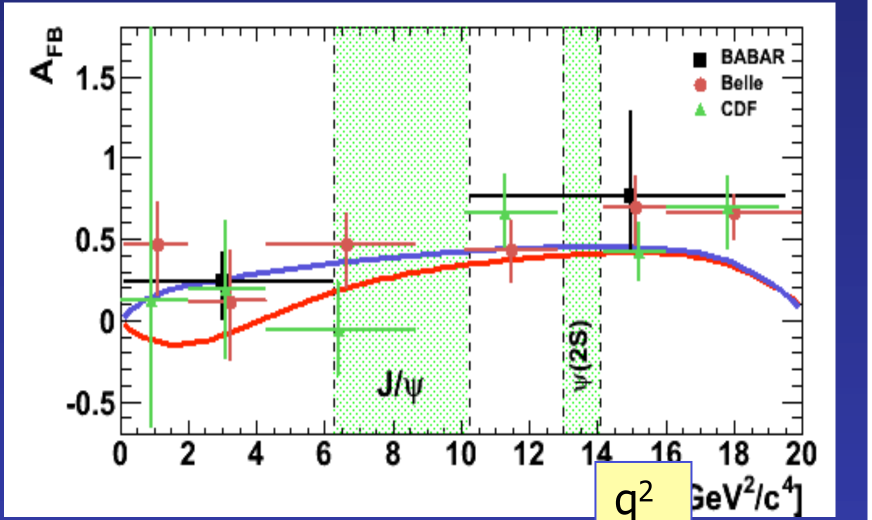


  - BR = (1.22+0.38-0.32) x 10^{-6}
  - Measured by BaBar and Belle
- **Parameterisation**
  - q^2 = $m^2(\mu\mu)$ invariant mass
  - Forward Backward Asymmetry A_{FB}
  - K^{*0} longitudinal polarisation fraction F_L



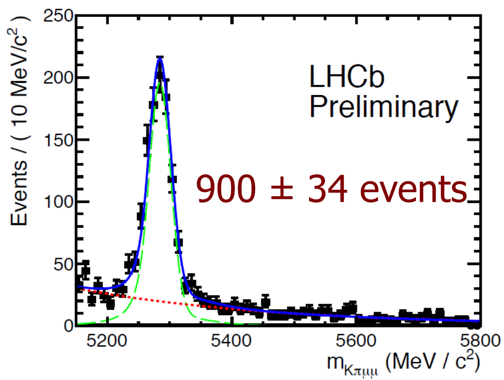
Angular Analysis in $B^0 \rightarrow K^{*0}\mu^+\mu^-$

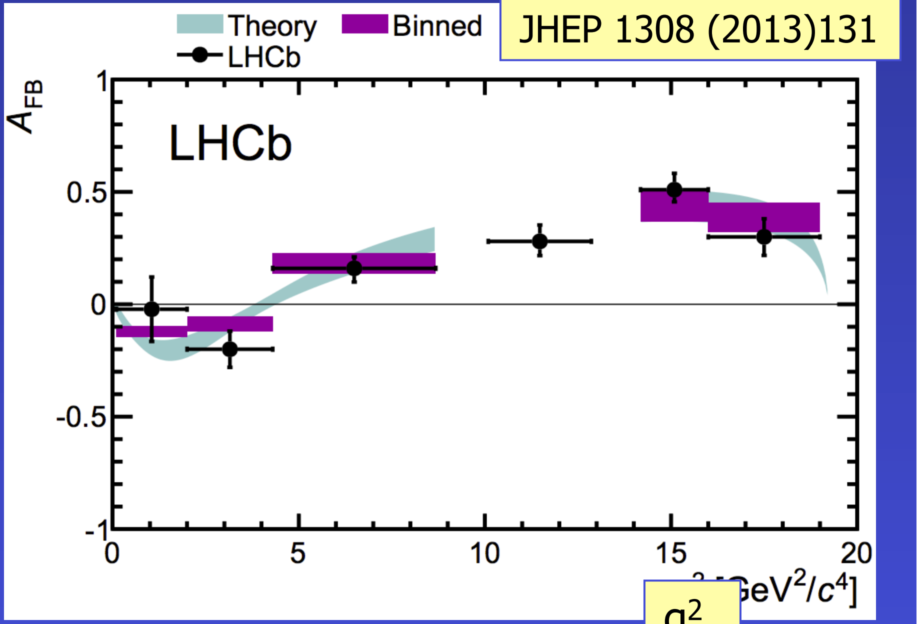
- **Forward Backward Asymmetry**
  - In SM A_{FB} changes sign at $q^2(A_{FB}=0) = 4.36^{+0.33}_{-0.31}$ GeV^2
  - Previous results Babar, Belle, CDF hint at discrepancy with SM



q^2

- **LHCb measurement**



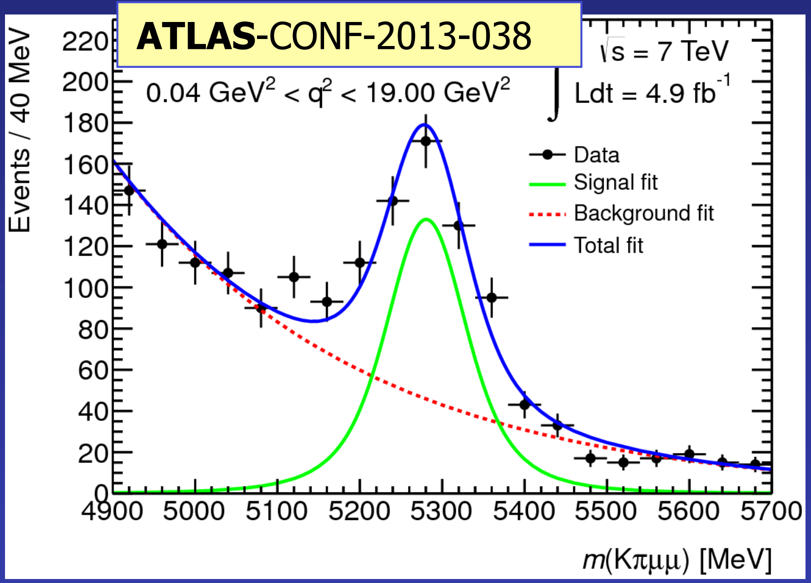


JHEP 1308 (2013)131

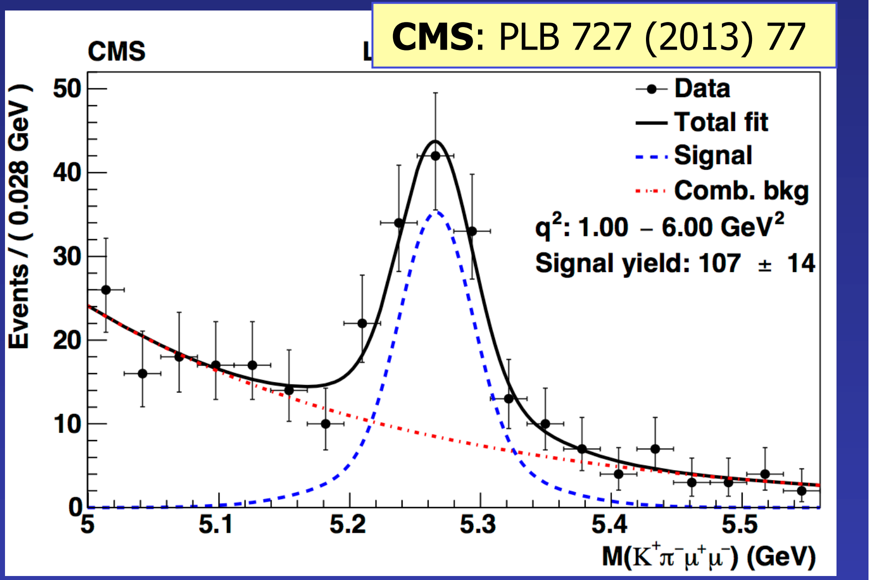
q^2

  - A_{FB} zero crossing point $q^2(A_{FB}=0) = 4.9 \pm 0.9$ GeV^2/c^4
  - consistent with SM

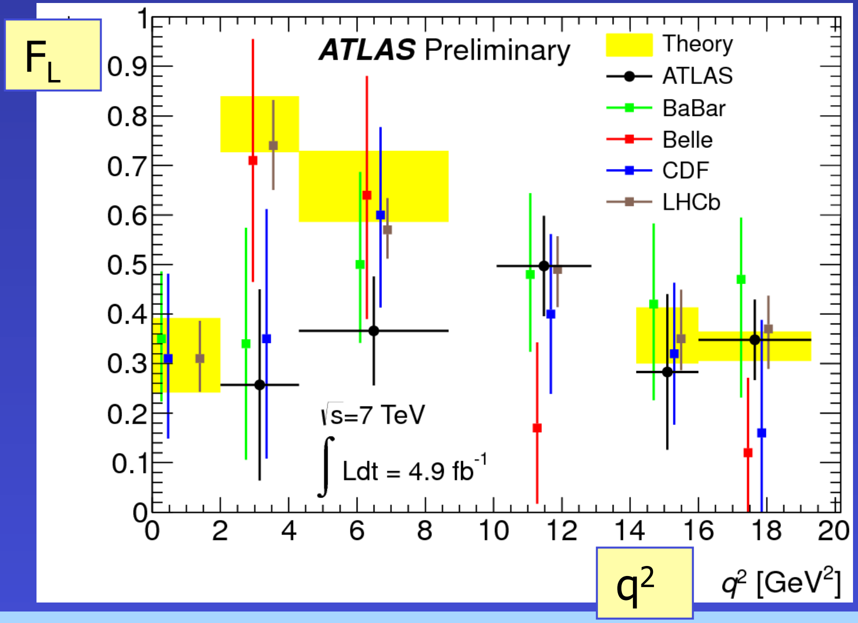
Angular Analysis in $B^0 \to K^{*0}\mu^+\mu^-$



ATLAS-CONF-2013-038

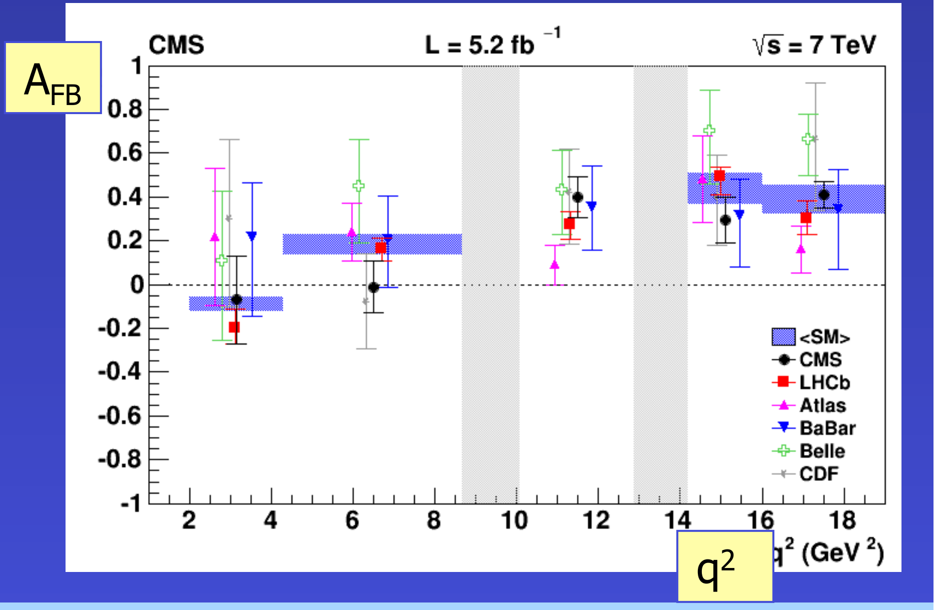


CMS: PLB 727 (2013) 77



F_L

q^2



A_{FB}

q^2

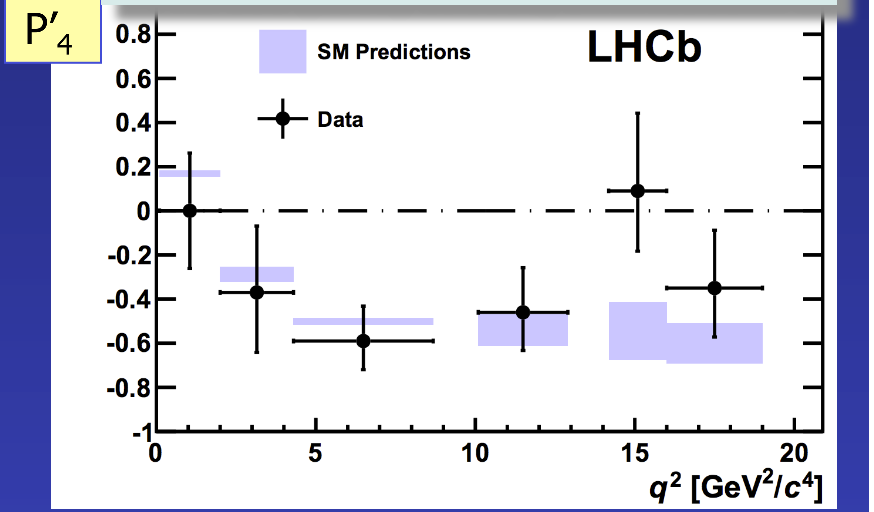
Angular Analysis in $B^0 \to K^{*0}\mu^+\mu^-$

- **New observable basis**
  - form factor independent

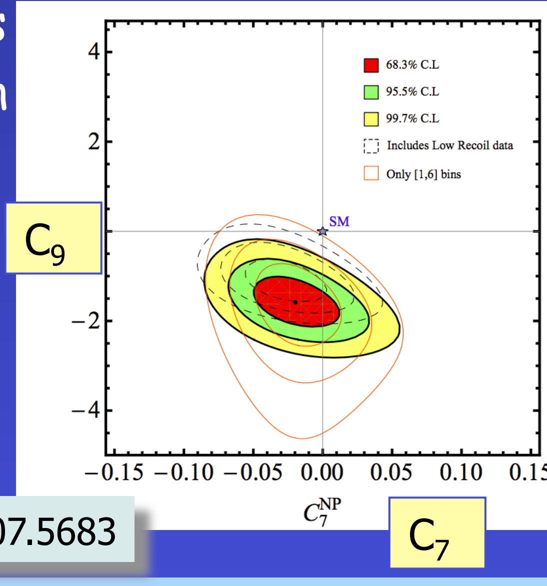
$$P'_{i=4,5,6,8} = \frac{S_{i=4,5,6,8}}{\sqrt{F_L(1-F_L)}}$$

- **LHCb result**
  - P_5' has 3.7 σ discrepancy to SM in one q^2 bin, 0.5% probability
  - New Physics contribution to Wilson coeff. C_9 or QCD?

Descotes et al, arXiv:1303.5794
PRL 111 (2013) 191801, arXiv:1308.1707



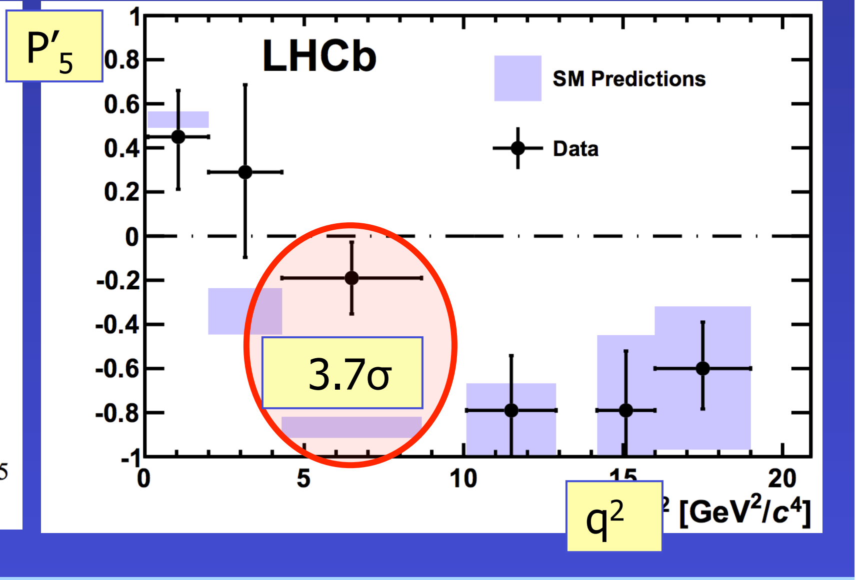
P'_4



C_9

C_7

Descotes et al, arXiv:1307.5683



P'_5

3.7σ

q^2

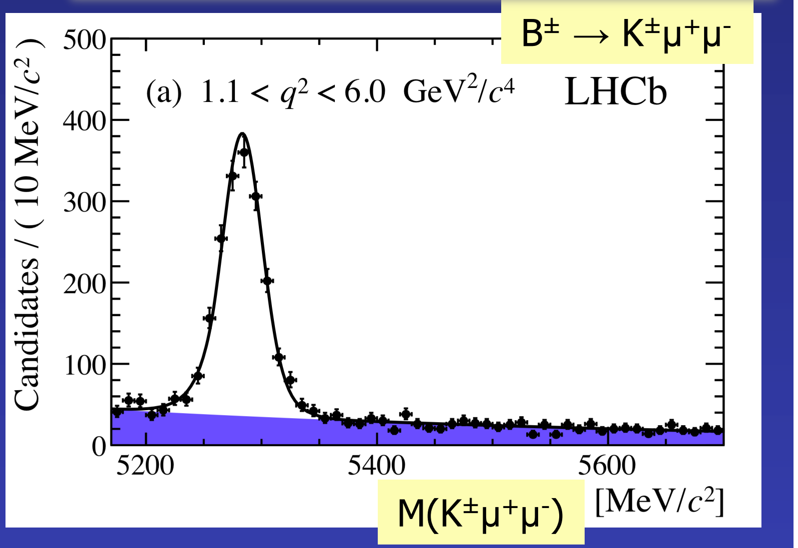
Angular Analysis in $B \rightarrow K\mu^+\mu^-$

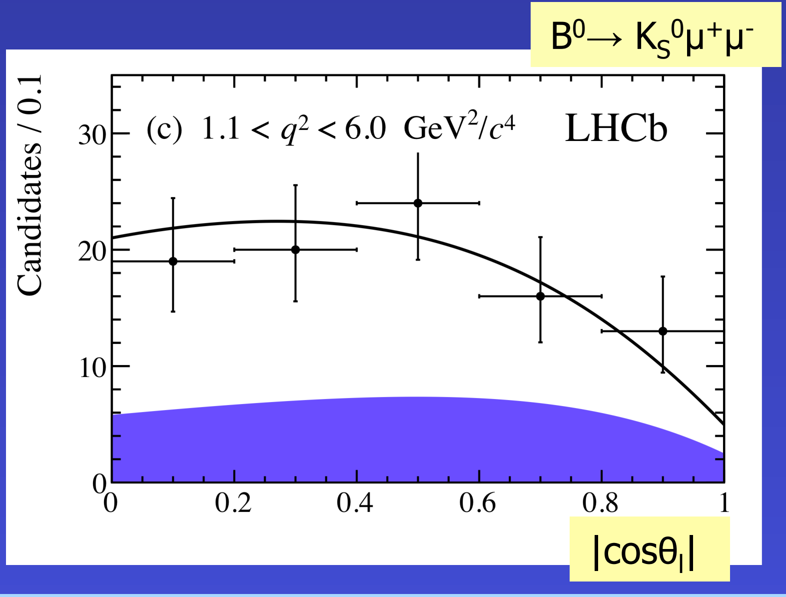
LHCb-PAPER-2014-007, arXiv:1403.8045

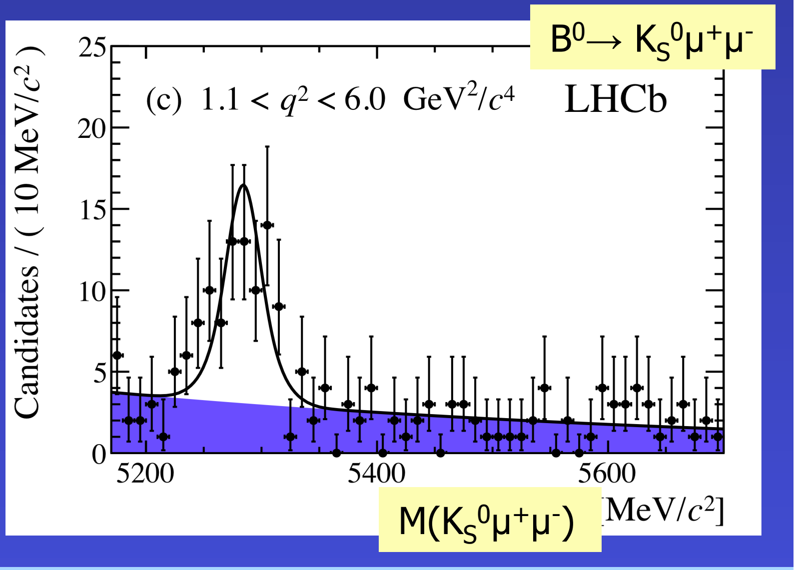
- Differential rates
  - for $B^\pm \rightarrow K^\pm\mu^+\mu^-$

$$\frac{d\Gamma}{\Gamma\cdot d\cos\theta_l} = \frac{3}{4}\left(1-F_H\right)\left(1-\cos^2\theta_l\right)+\frac{1}{2}F_H + A_{FB}\cos\theta_l$$

  - Forward Backward Asymmetry A_{FB} and constant term F_H
  - $B^0 \rightarrow K_S{}^0\mu^+\mu^-$ not sensitive to A_{FB}



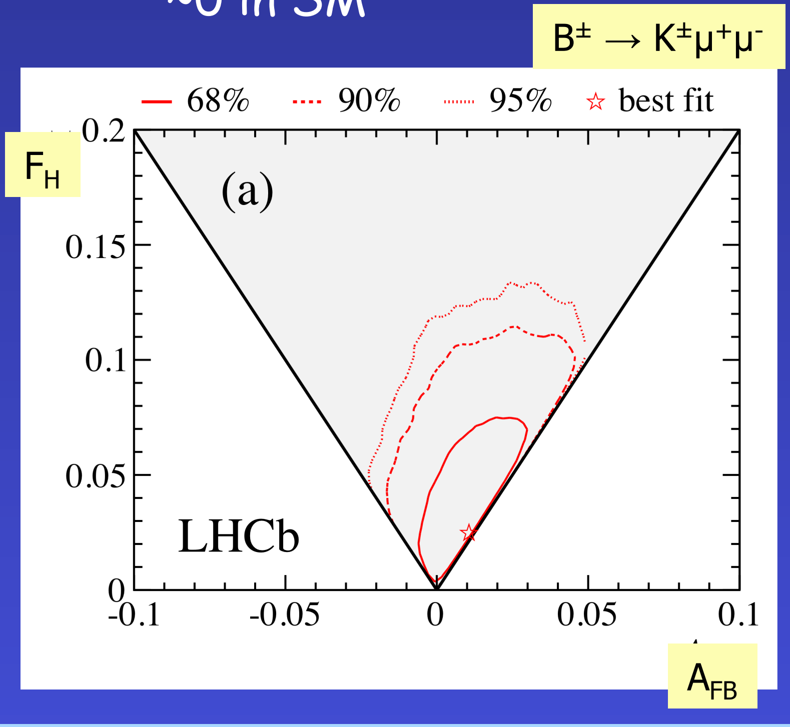




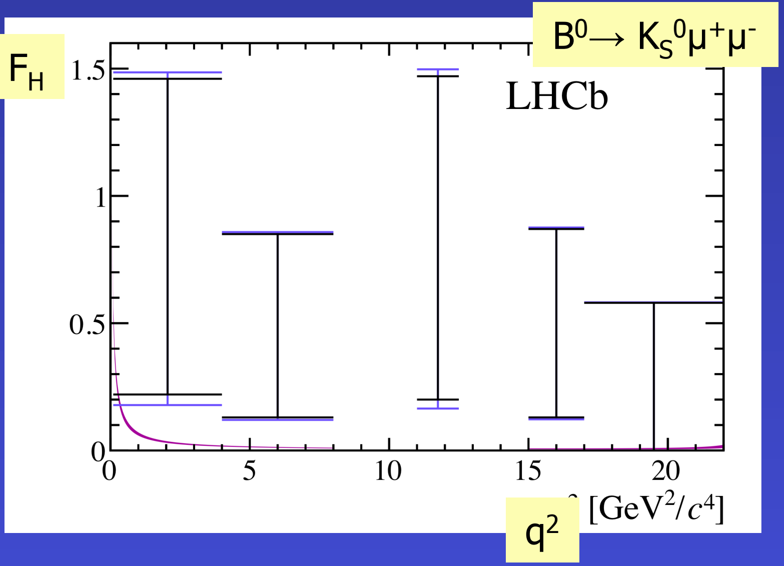
Angular Analysis in B → $K\mu^+\mu^-$

- **$B^\pm \rightarrow K^\pm\mu^+\mu^-$**
  - Measure A_{FB} and F_H
- **$B^0 \rightarrow K_S^0\mu^+\mu^-$**
  - Measure F_H
  - A_{FB} and F_H expected to be ~0 in SM

- **Results**
  - Consistent with SM in all q^2 bins
  - No evidence for new (pseudo)-scalar or tensor contributions

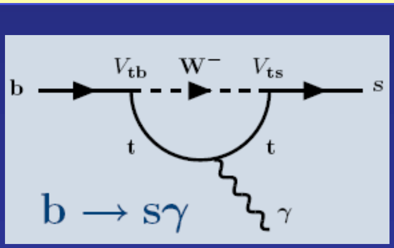


LHCb-PAPER-2014-007, arXiv:1403.8045

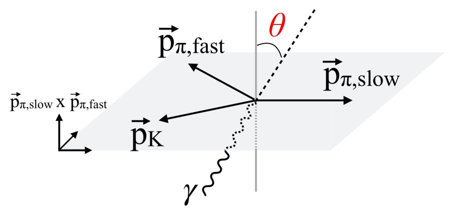


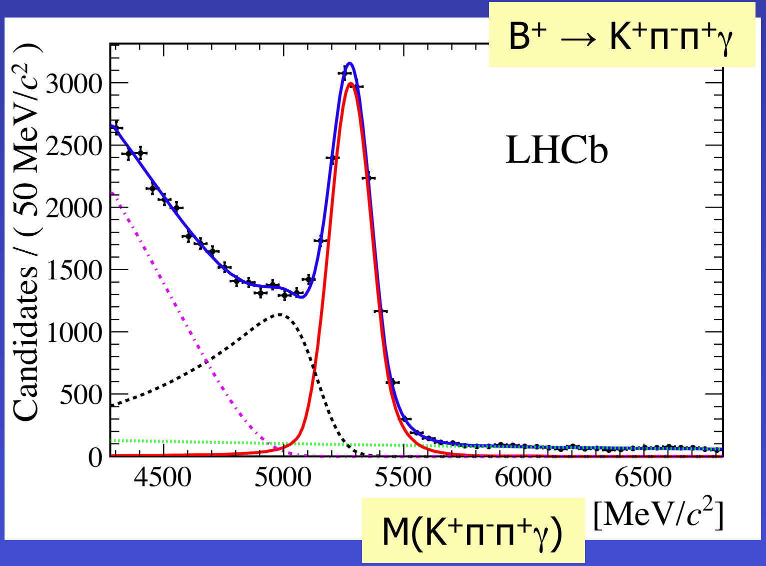
Radiative Penguin Decays

LHCb-PAPER-2014-001

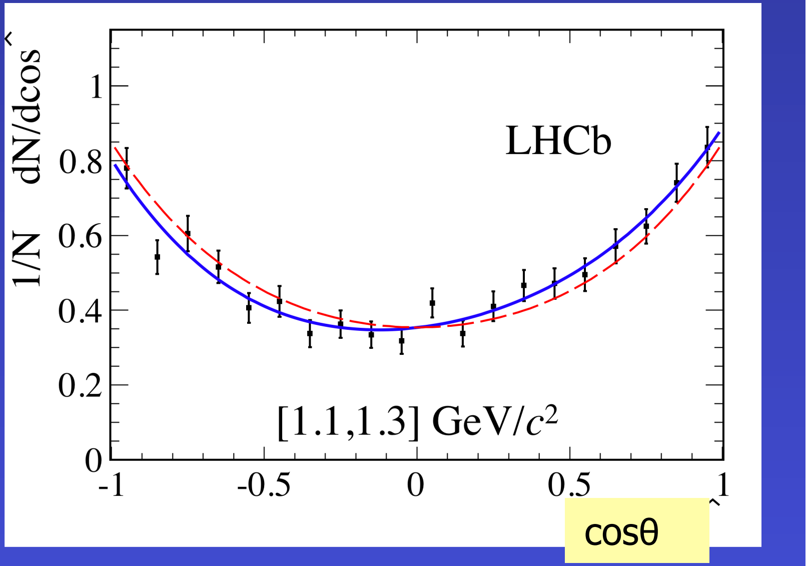


- $B^+ \to K^+\pi^-\pi^+\gamma$
  - observed at the B-factories
  - LHCb: first measurement of photon polarisation in $b \to s\gamma$ transition
  - measure up-down asymmetry in angle θ between γ and $\pi^-\pi^+$ plane
  - A_{ud} non-zero at 5.2σ



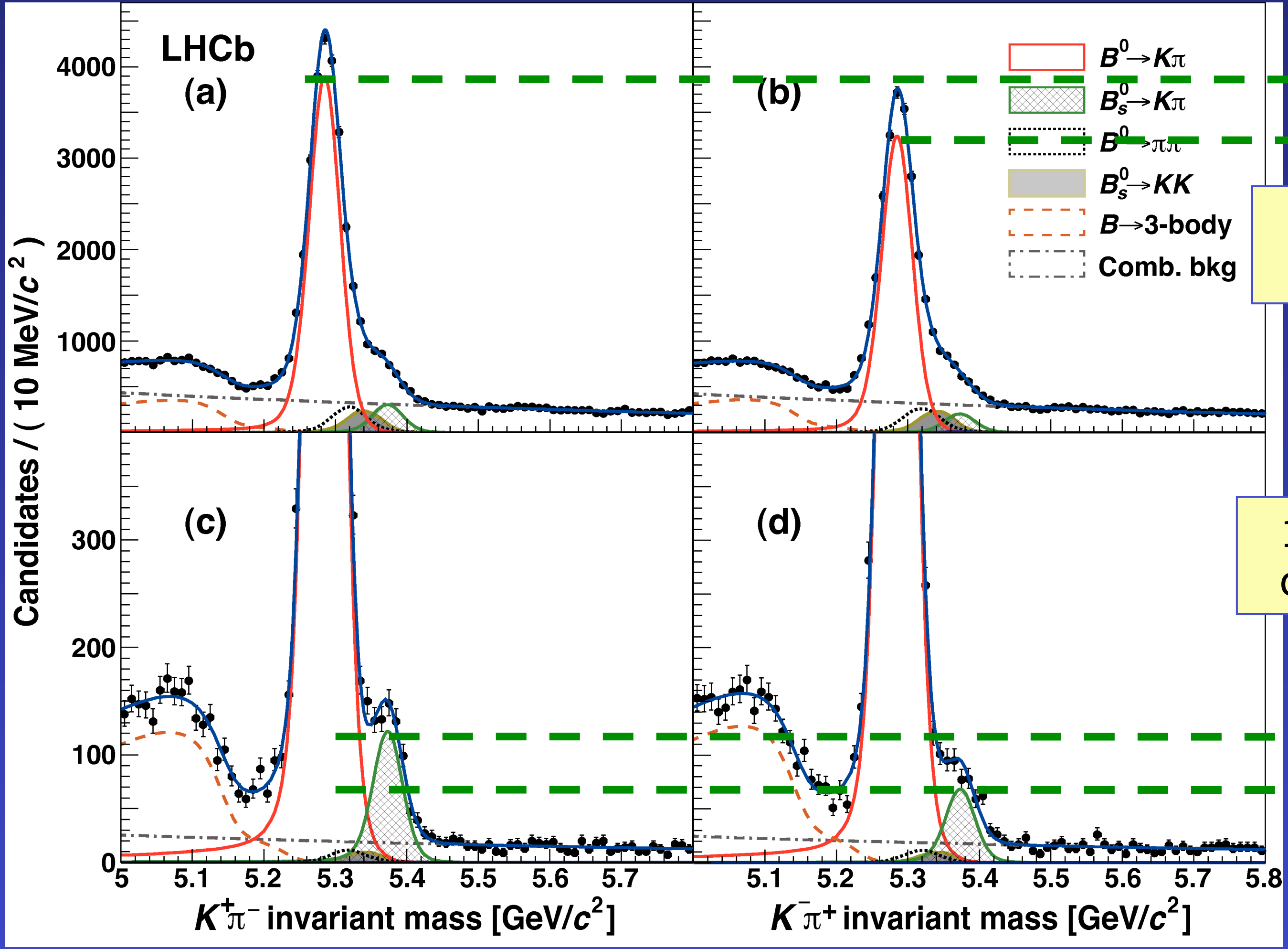

$B^+ \to K^+\pi^-\pi^+\gamma$

$M(K^+\pi^-\pi^+\gamma)$


cosθ

CP Violation and Mixing

Large direct CPV in $B_{(s)} \to K^+\pi^-$



10.5σ

41,000 $B_d \to K^+\pi^-$ candidates

1065±65 $B_s \to K^-\pi^+$ candidates

6.5σ

$$A_{CP}\left(B^0 \to K^+\pi^-\right) = -0.080 \pm 0.007 \pm 0.003$$

$$A_{CP}\left(B_s^0 \to K^-\pi^+\right) = +0.27 \pm 0.04 \pm 0.01$$

First observation of CP violation in B_s mesons

PRL 110 (2013) 221601

CP Violation in Mixing

Lenz, Nierste, 2012

$$a_{sl}^{d} = (-4.1 \pm 0.6) \cdot 10^{-4}$$
$$a_{sl}^{s} = (+1.9 \pm 0.3) \cdot 10^{-5}$$

- **Semileptonic Asymmetry**
  - measures $\cancel{CP}$ in mixing
  - very small in SM

$$a_{sl} = 1 - \left|\frac{q}{p}\right|^2 = \frac{|\Gamma_{12}|}{|M_{12}|} \sin\phi_{12}$$

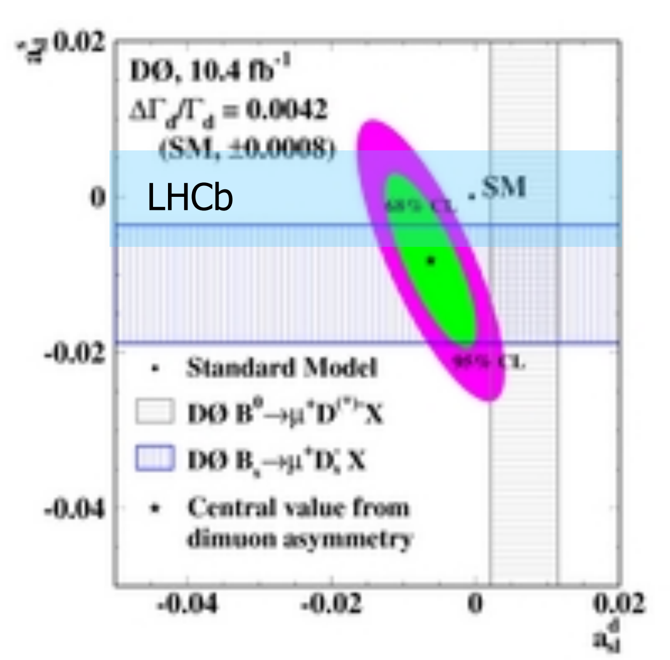
- **D0 at Tevatron**
  - evidence for a_{sl} >> SM prediction
  - updated measurement
  - fit for a_{sl}^{s}, a_{sl}^{d} and $\Delta\Gamma_d$
  - differs from SM at 3.0σ
- **a_{sl} at LHCb**
  - Time-integrated asymmetry in $B_s \rightarrow D_s^- \mu^+ \nu$

$$A = \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)} = \frac{a_{sl}^s}{2} + \left(a_p - \frac{a_{sl}^s}{2}\right) \frac{\int \exp(-\Gamma_s t) \cos(\Delta m_s t) \varepsilon(t) dt}{\int \exp(-\Gamma_s t) \cos(\Delta \Gamma_s / 2 \cdot t) \varepsilon(t) dt}$$

  - $a_{sl} = (-0.06 \pm 0.50 \pm 0.36)\%$
  - does not confirm nor exclude D0 result

LHCb-PAPER-2013-033

D0: Phys. Rev. D 89, 012002 (2014)



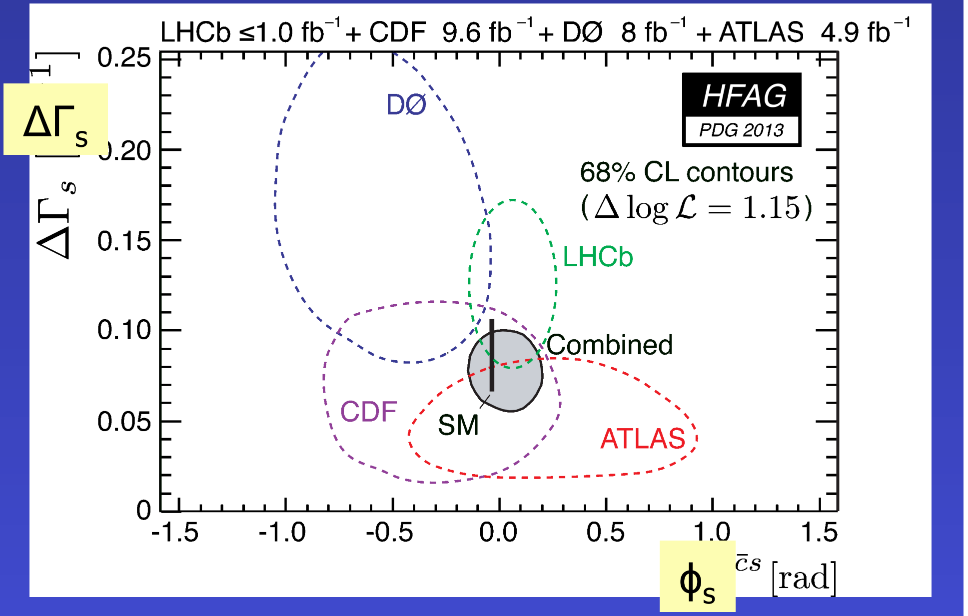
CP Violation in $B_s \rightarrow J/\psi\phi$

1 fb^{-1}, PRD87, 112010 (2013)
PLB 707(2012) 497

- LHCb CP violating weak phase ϕ_s
  - $\phi_s = 0.007 \pm 0.009 \pm 0.001$ using $B_s \rightarrow J/\psi\phi$
  - additional mode $B_s \rightarrow J/\psi f_0$
    $\phi_s = 0.014 \pm 0.17 \pm 0.02$
- Combination of $B_s \rightarrow J/\psi\phi$ and $B_s \rightarrow J/\psi f_0$

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

  - consistent with SM prediction



- ATLAS

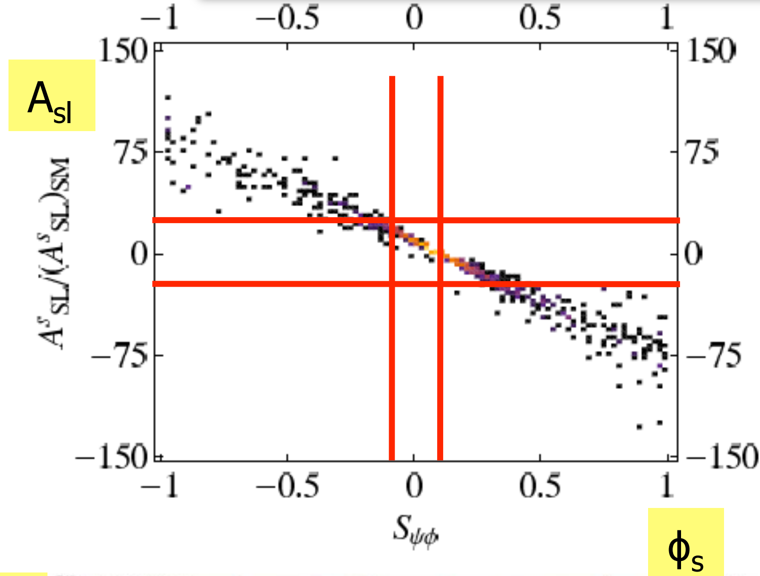
ATLAS-CONF-2013-039

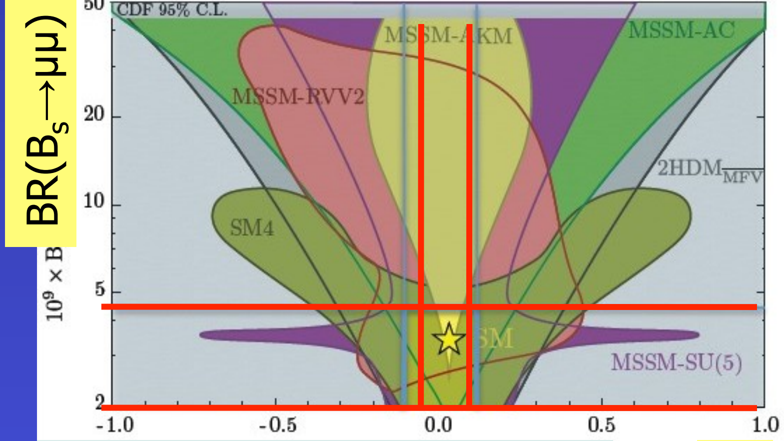
$$\phi_s = 0.12 \pm 0.25 \pm 0.11$$
$$\Delta\Gamma_s = 0.053 \pm 0.021 \pm 0.009 \text{ ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007 \pm 0.003 \text{ ps}^{-1}$$

CP Violation in $B_s \to J/\psi\phi$

- **Implications**
  - from ϕ_s and A_{sl} allowed range
  - ϕ_s and $BR(B_s \to \mu\mu)$ severely restrict NP parameter space
  - model independent $M_{12} = M_{12}^{SM}\ \Delta_s$

M. Blanke et al., arXiv0809.1073

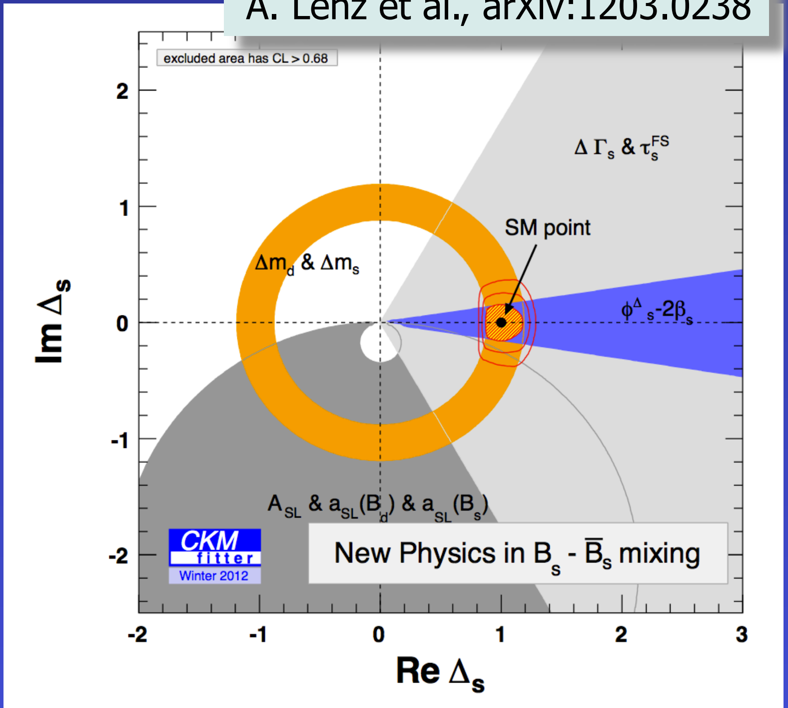




D.M. Straub, arXiv:1107.0266

ϕ_s

A. Lenz et al., arXiv:1203.0238



Charm Physics

Charm Mixing and CP Violation

- **Status of charm mixing before LHCb**
  - Standard model expectation is very small (< 1%)
  - Charm mixing has been measured by BaBar, Belle & CDF, but no 5σ observation in a single experiment
- **Charm mixing**
  - Measures time-dependent ratio of D^0 decays to Wrong Sign versus Right Sign
  - Tagging of initial D^0 flavour with sign of charge of slow pion from $D^{*+} \rightarrow D^o \pi^+_s$ and $D^{*-} \rightarrow D^o \pi^-_s$

$$R(t) = \frac{N(D^0 \rightarrow K^+ \pi^-)}{N(D^0 \rightarrow K^- \pi^+)}$$

- **Effective lifetime asymmetry**
  - non-zero if indirect CP violation in mixing
  - talk by Mark Smith

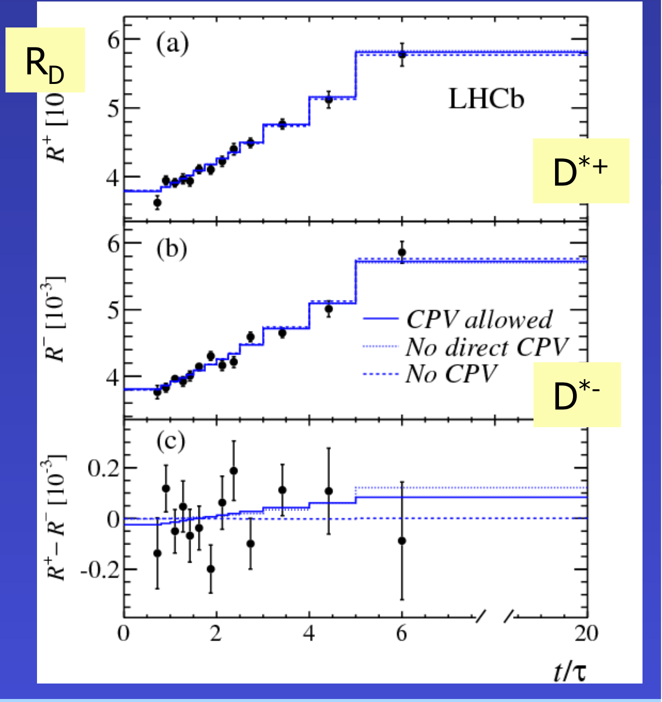
Mixing and CPV in $D^0 \rightarrow K^-\pi^+$

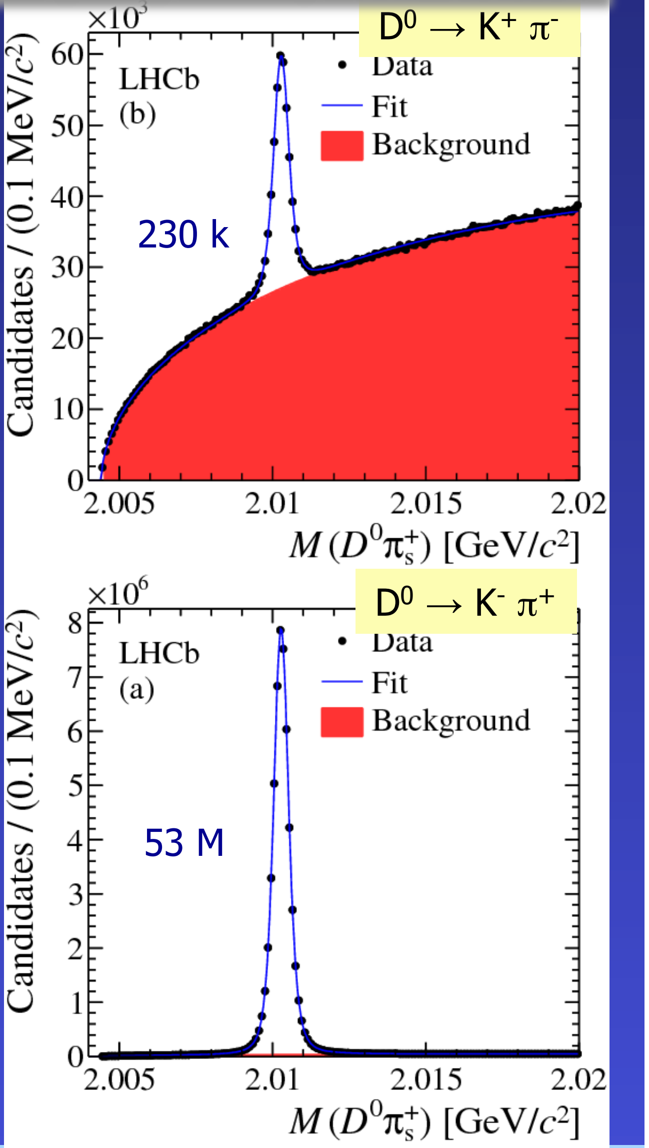
PRL 111 (2013) 251801, arXiv.1309.6534

- **Ratio R_D**

$$R_D = \frac{BR(DCS)}{BR(CF)} = (3.568 \pm 0.066)\cdot 10^{-3}$$

- **D^0-D^0 Mixing**
  - best measurement of mixing parameters
  - No mixing hypothesis is excluded
- **CP violation**
  - no evidence



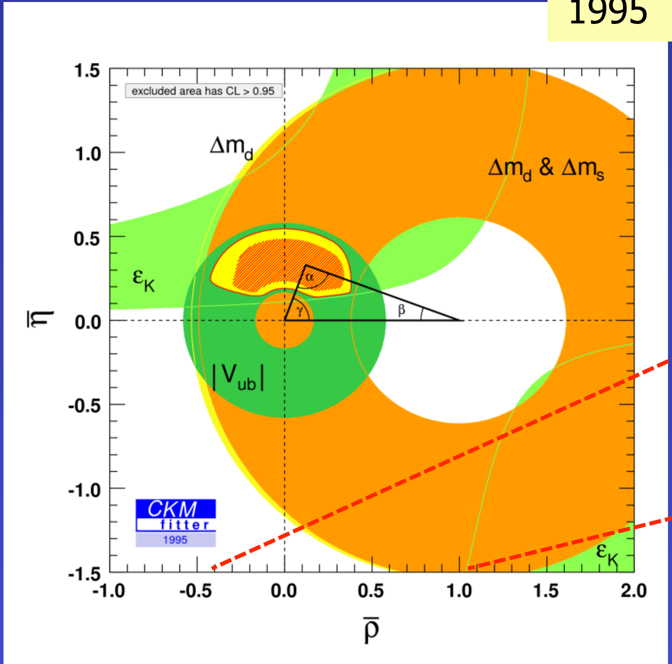


CKM angle γ

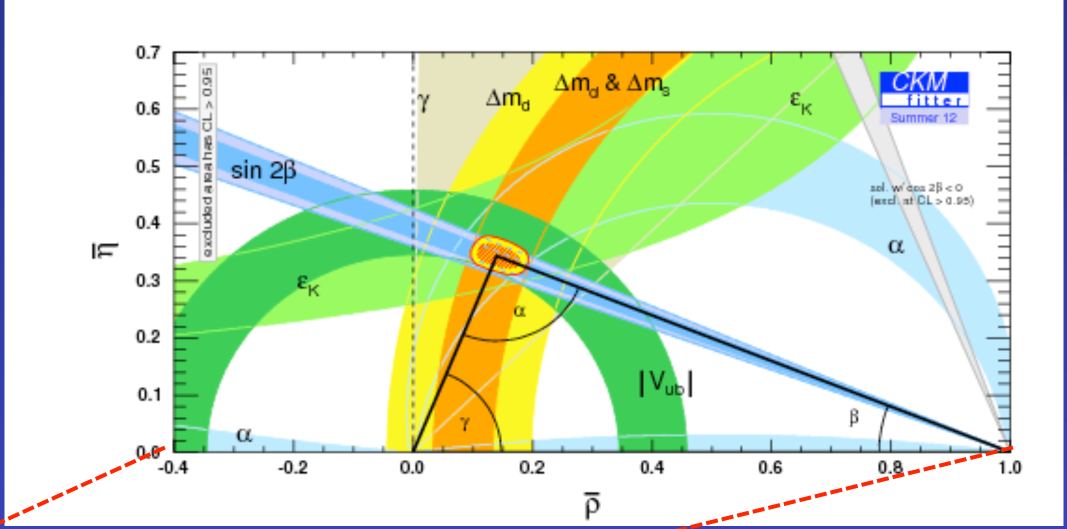
Unitarity triangle

- **Amazing progress since 1995**
  - well done B factories !
- **CKM angle γ**
  - Not yet well constrained

1995



2012



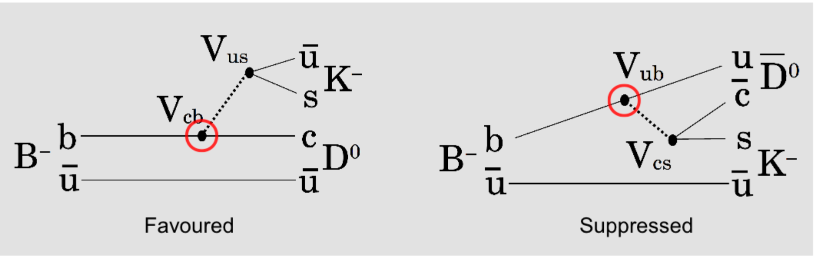
From Babar + Belle

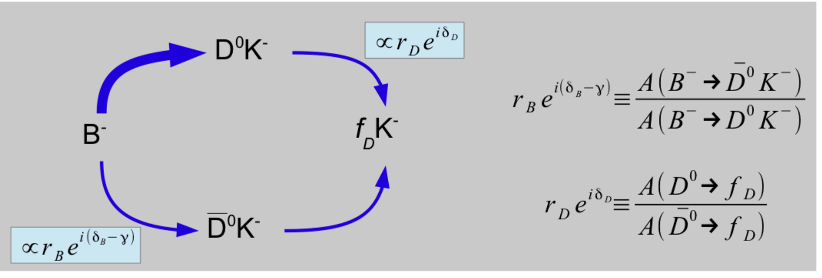
$$\gamma = \arg\left(\frac{-V_{ud}\,V_{ub}^*}{V_{cd}\,V_{cb}^*}\right)$$

CKM fitter	66±12°
UTFit	72±9°

CKM angle γ with $B^\pm \to DK^\pm$ and $D\pi^\pm$

- **Sensitivity to γ**
  - from interference between b→c and b→u transitions at tree level
  - D final state accessible to D^0 and $\bar{D}^0$
  - several methods: ADS, GLW, GGSZ
- **New LHCb measurement**
  - First ADS analysis to use singly-Cabibbo suppressed D decay



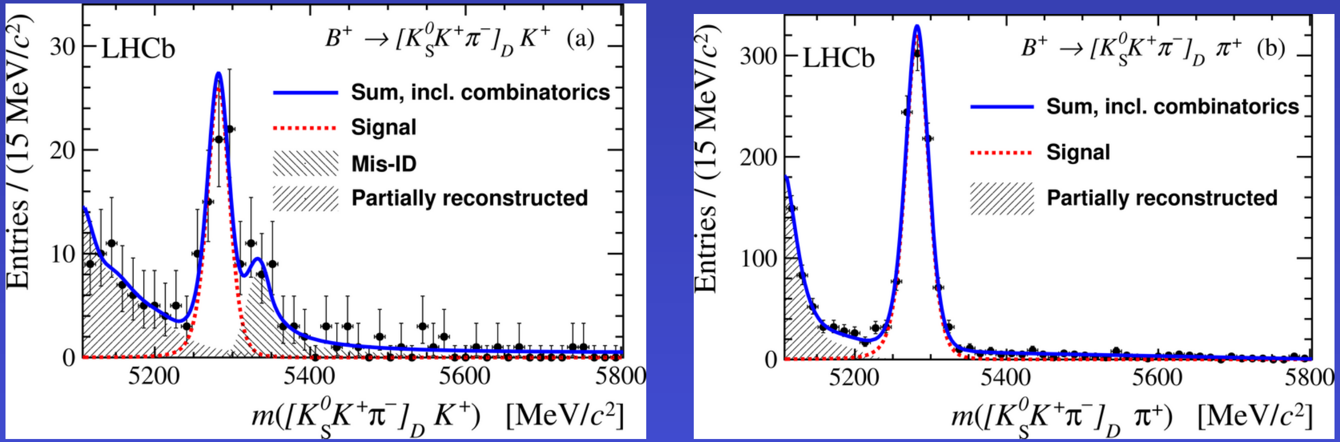


$$r_B e^{i(\delta_B-\gamma)} \equiv \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}$$

$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\bar{D}^0 \to f_D)}$$

LHCb-PAPER-2013-068, arXiv:1402.2982

$B^+ \to DK^+$, $D\pi^+$
$D \to K_S K\pi$

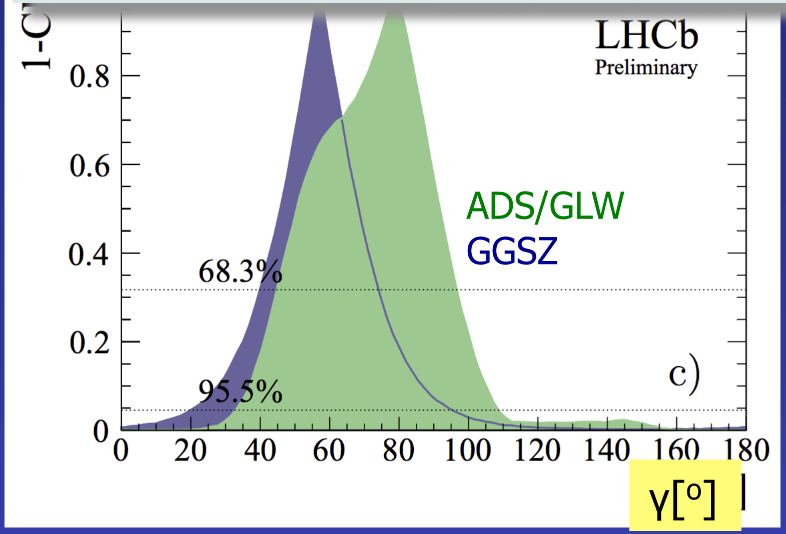


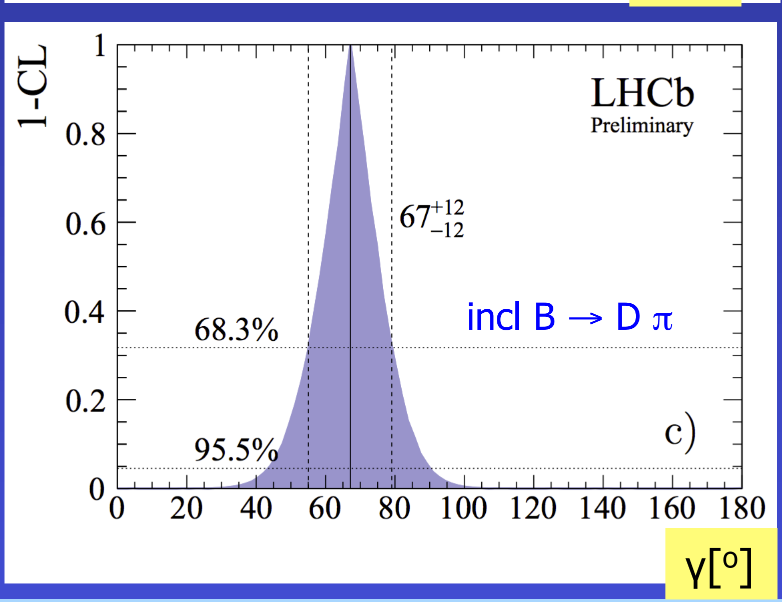
CKM angle γ

LHCb-PAPER-2013-020, PLB 726 (2013) 151
LHCb-CONF-2013-006

- **LHCb combination**
  - 2011/12 data
  - using B→Dh (h=K,π), 1 fb^{-1} with D→hh, $K_s$hh, K3π, 3 fb^{-1}
- **LHCb Results**
  - γ = 67 ± 12°
  - Best single measurement
  - Precision competitive with γ averages from B factories
    Babar: γ = 69 ± 17°
    Belle: γ = 68 ± 15°
  - 3x more data available (ADS/GLW)

talks by Donal Hill, Nazim Hussein

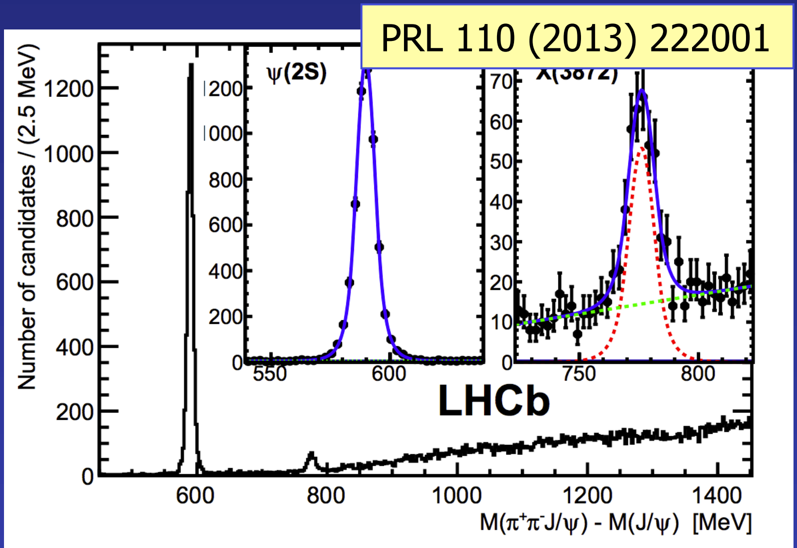


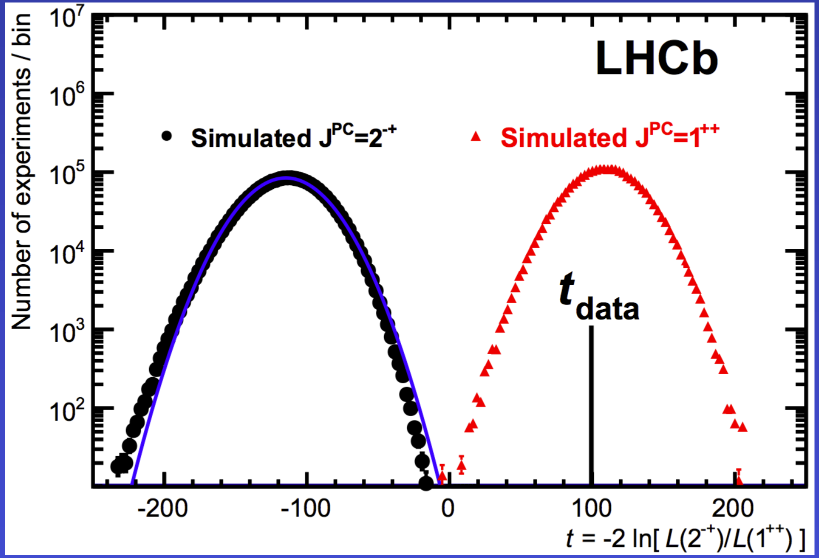


Spectroscopy

Spectroscopy

- **Exotic X(3872) state**
  - is it tetra-quark, c anti-c DD* molecule, …
  - CDF previously ruled out all J^{PC} except 1^{++} and 2^{-+}
- **New measurements**
  - LHCb 313 events in decay $B \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$
  - angular analysis establishes $J^{PC} = 1^{++}$
  - Belle sees no evidence for $B \to X(3872)K^+$, $X(3872) \to \chi_{c1}\pi^+\pi^-$


PRL 110 (2013) 222001



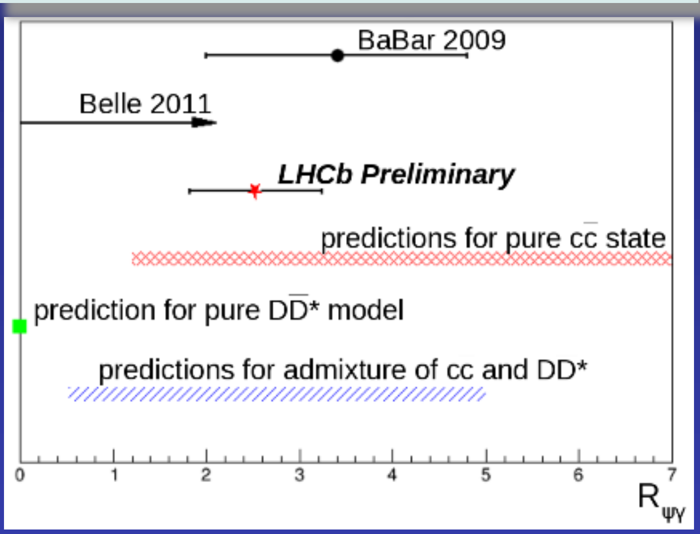
Spectroscopy

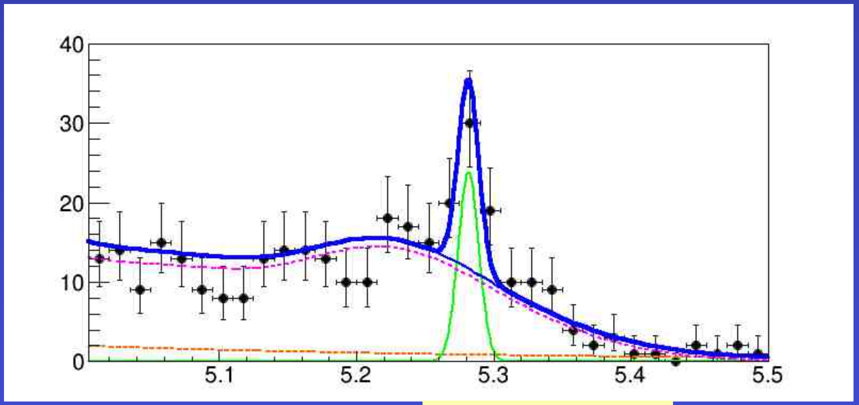
LHCb-PAPER-2014-008, arXiv:1404.0275

- **X(3872) radiative decays**
  - branching ratio sensitive to interpretation: tetra-quark, c anti-c, DD* molecule and mixtures

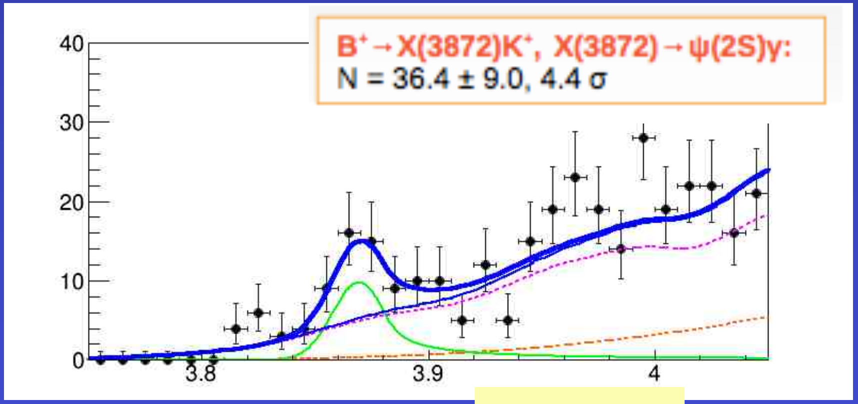
$$R = \frac{BR(X(3872) \to \psi(2S)\gamma)}{BR(X(3872) \to J/\psi\gamma)}$$

  - Babar evidence & Belle upper limit
- **LHCb measurement**
  - R = 2.46±0.64±0.29±0.06
  - does not support a pure DD* molecule interpretation





M(ψ(2S)γK⁺)



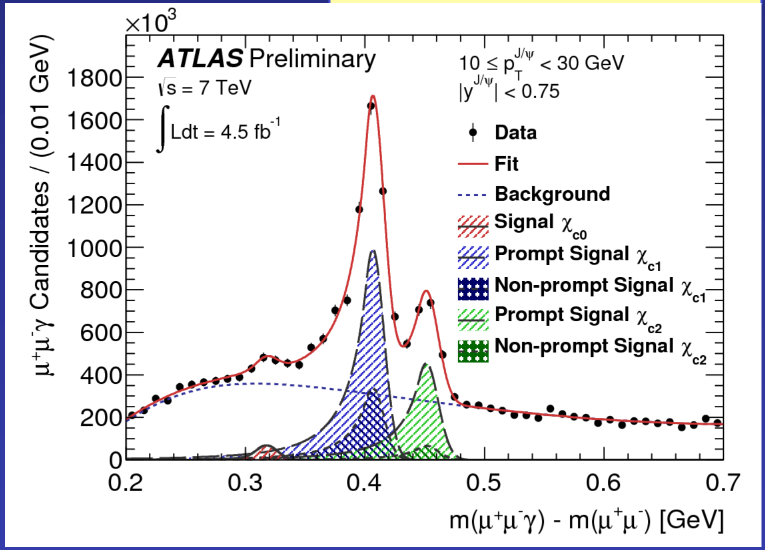
B⁺→X(3872)K⁺, X(3872)→ψ(2S)γ:
N = 36.4 ± 9.0, 4.4 σ

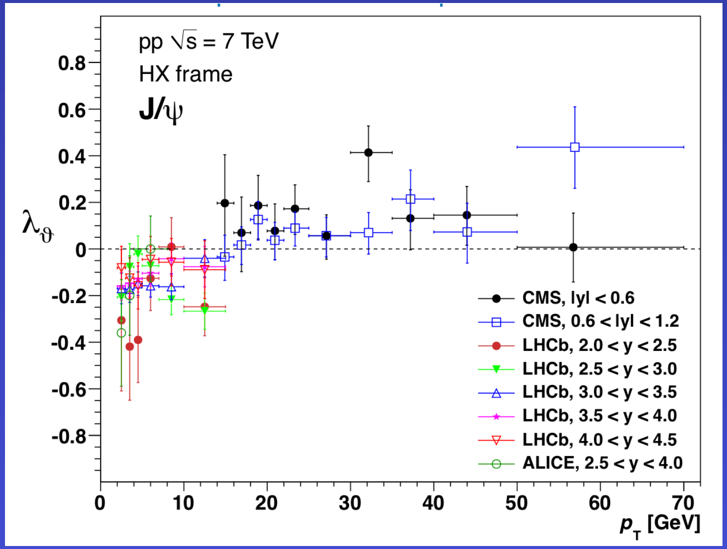
M(ψ(2S)γ)

Spectroscopy

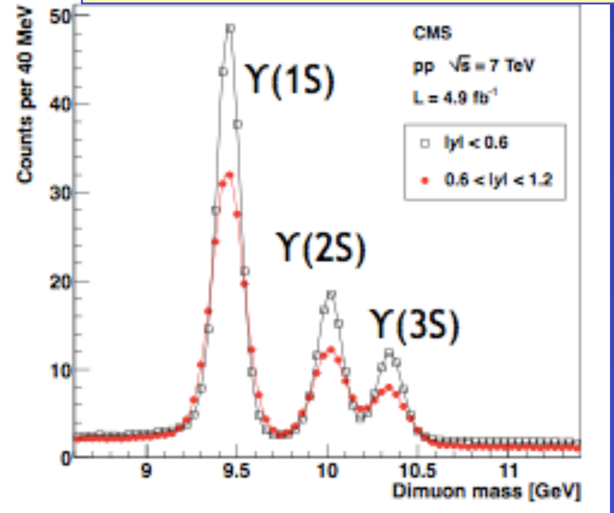
- **Quarkonia**
  - χ_{c1} and χ_{c1} production cross section
  - new ATLAS result
  - χ_{b1} and χ_{b1} production cross section
  - new CMS result
  - LHCb results
- **J/ψ and Υ polarization**

ATLAS-CONF-2013-095





CMS PRL 110, 081802 (2013)



What is the $Z(4430)^-$?

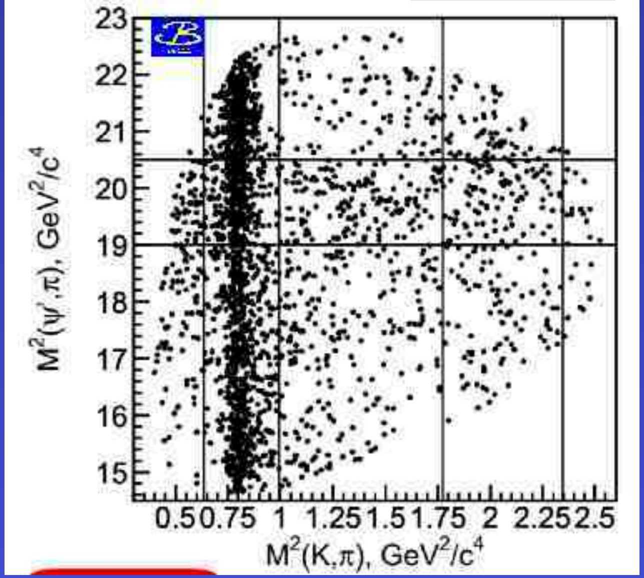
- **Status**
  - $Z(4430)^- \to \psi(2S)\pi^-$ observed by Belle in $B^0 \to \psi(2S) K^+\pi^-$ decays
  - not seen by BaBar
  - charged state, not described by quark model
  - quark content $c\bar{c}u\bar{d}$?

PRD88 (2013) 074026

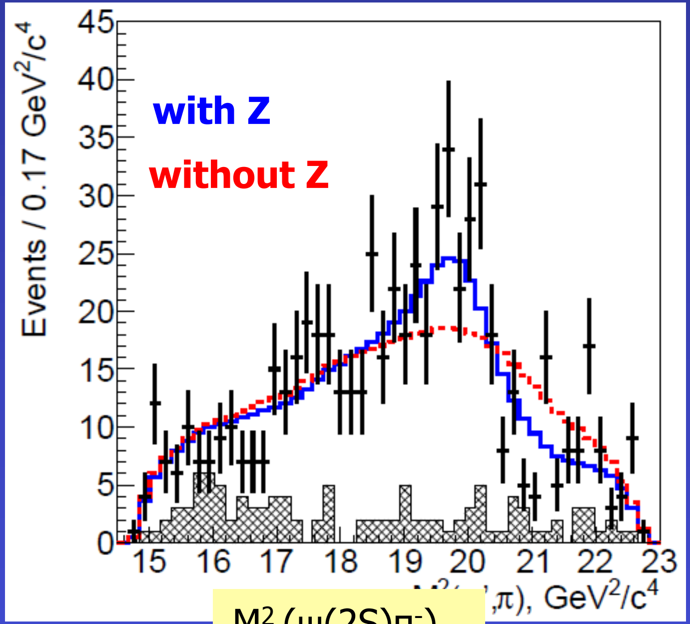
PRD79 (2009) 112001

K*(892)

K$_2$(1430)



K* veto region

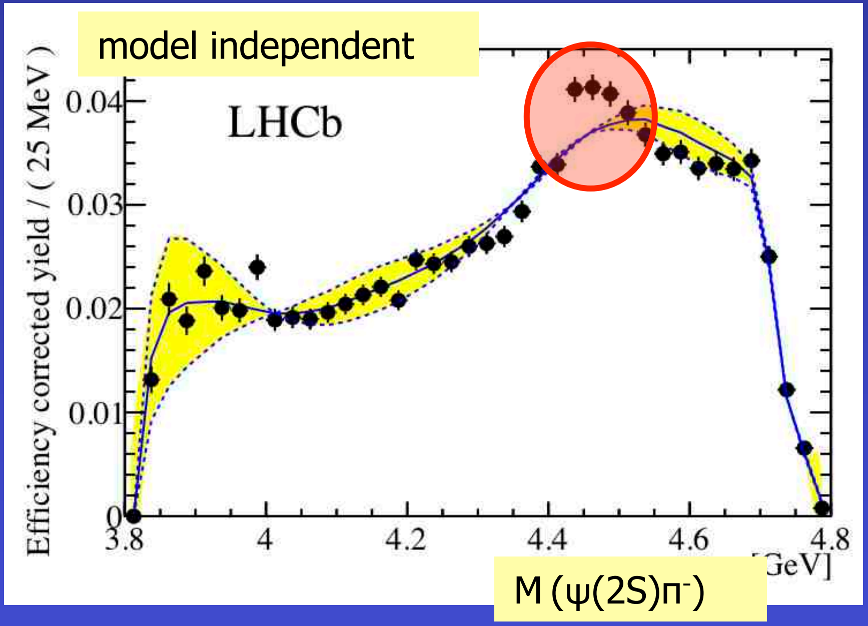


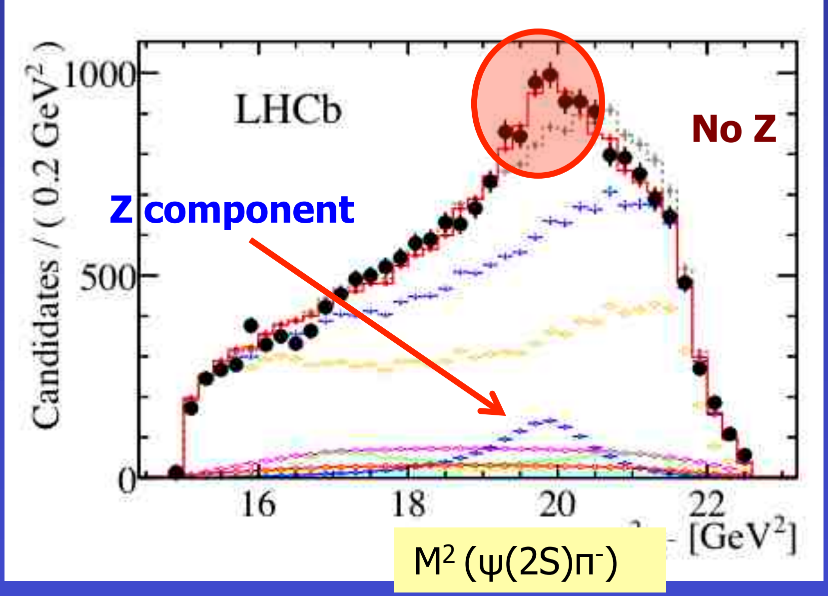
M^2 ($\psi(2S)\pi^-$)

What is the Z(4430)$^-$?

- **Hot off the press!**
  - LHCb result submitted 4 hours ago
  - "Observation of the resonant character of the Z(4430)$^-$ state"
- **Measurement based on 4-dim amplitude fit**
  - highly significant Z(4430)$^-$ state is required
  - spin-parity is unambiguosly 1^+

LHCb-PAPER-2014-014, arXiv:1404.1903





Flavour physics is much more

- **Results from LHCb, ATLAS, CMS, D0, CDF, Babar, Belle**
  - Rare decays
  - CP Violation and lifetimes
  - Charm mixing and CP violation
  - CKM angle gamma
  - Spectroscopy
- **No time to present results on**
  - Lepton flavour violation
    - tau decays, majorana searches in B decays
  - Electorweak physics
    - W, Z and H forward production
  - More Production and Spectroscopy, …
    - Exotic Zb resonance
    - B_c meson, beauty baryons
    - fragmentation fractions
    - Central Eclusive production
- **Lots of flavour physics papers, mainly from LHCb**

talks by Sam Cunliffe, Simon Wright

talks by Sam Hall, Haofei Luo

talk by Rafael S. Coutinho

talk by Daniel Craig

talk by Adrien Pritchard

talk by Jon Harrison

talks by John Beddow,
Michael Kiss,
James McCarthy

talk by Scott Stevenson

Future Plans

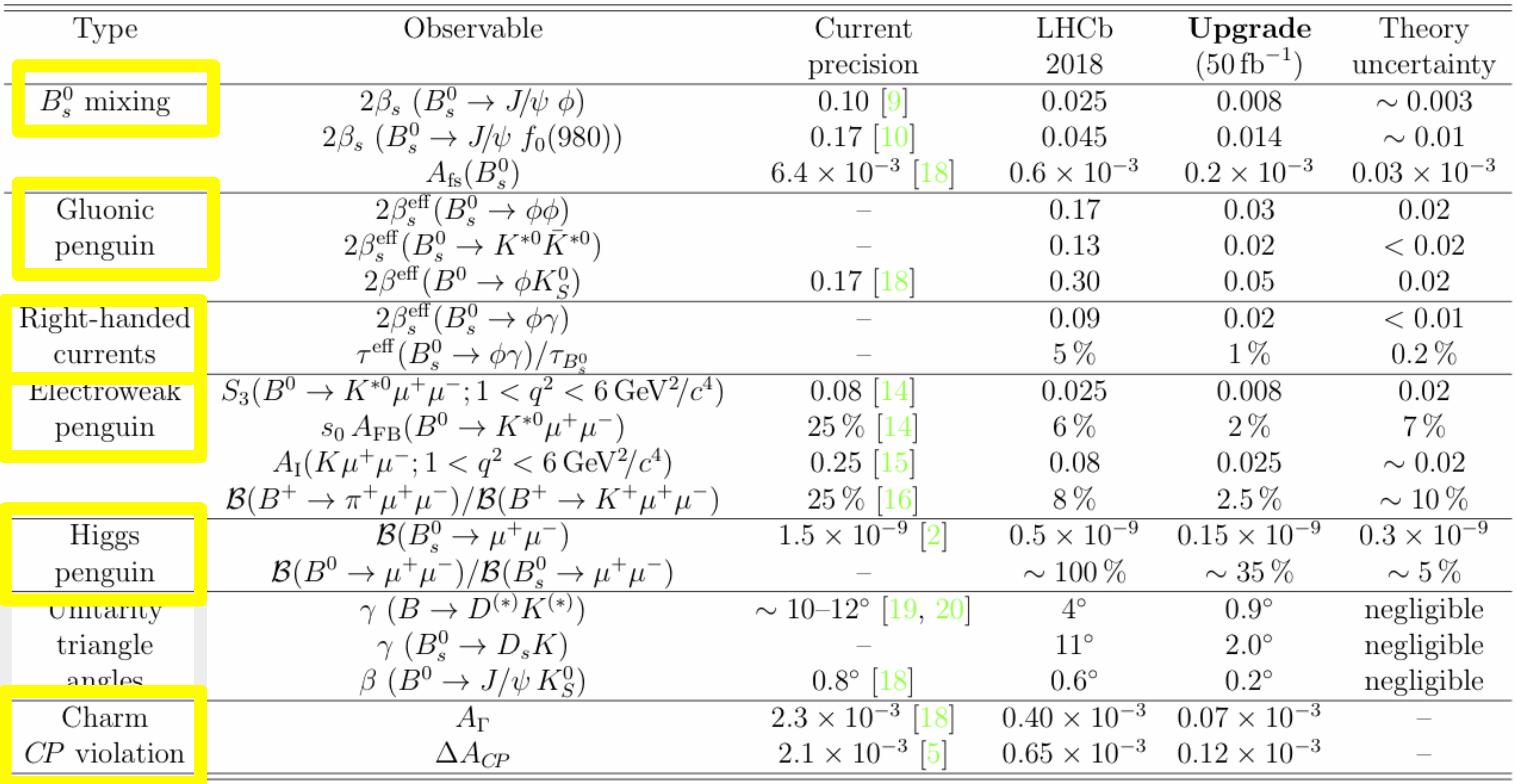
LHCb Upgrade

- **LHCb and B-factories hugely successful**
  - Large New Physics ruled out in many flavour physics observables
  - LHC run 2, LHCb will collect 7 to 8 fb^{-1}
  - production cross section σ_{bb} and σ_{cc} doubles, $\sqrt{s}$: 7/8→13/14 TeV
- **LHCb upgrade rationale**
  - Large increase in statistics required to investigate small NP deviations
  - Key element is 40 MHz Readout of all sub-detectors
  - Full Software Trigger increases trigger efficiency at least x2 in hadronic channels
- **Upgraded LHCb detector**
  - to be installed in Long Shutdown 2018/19

talk by Thomas Bird

- **LHCb Upgrade is General Purpose Experiment in Forward region**
  - Beauty, Charm, LFV, Electroweak, QCD, Exotica
  - Probe/measure New Physics at the percentage level

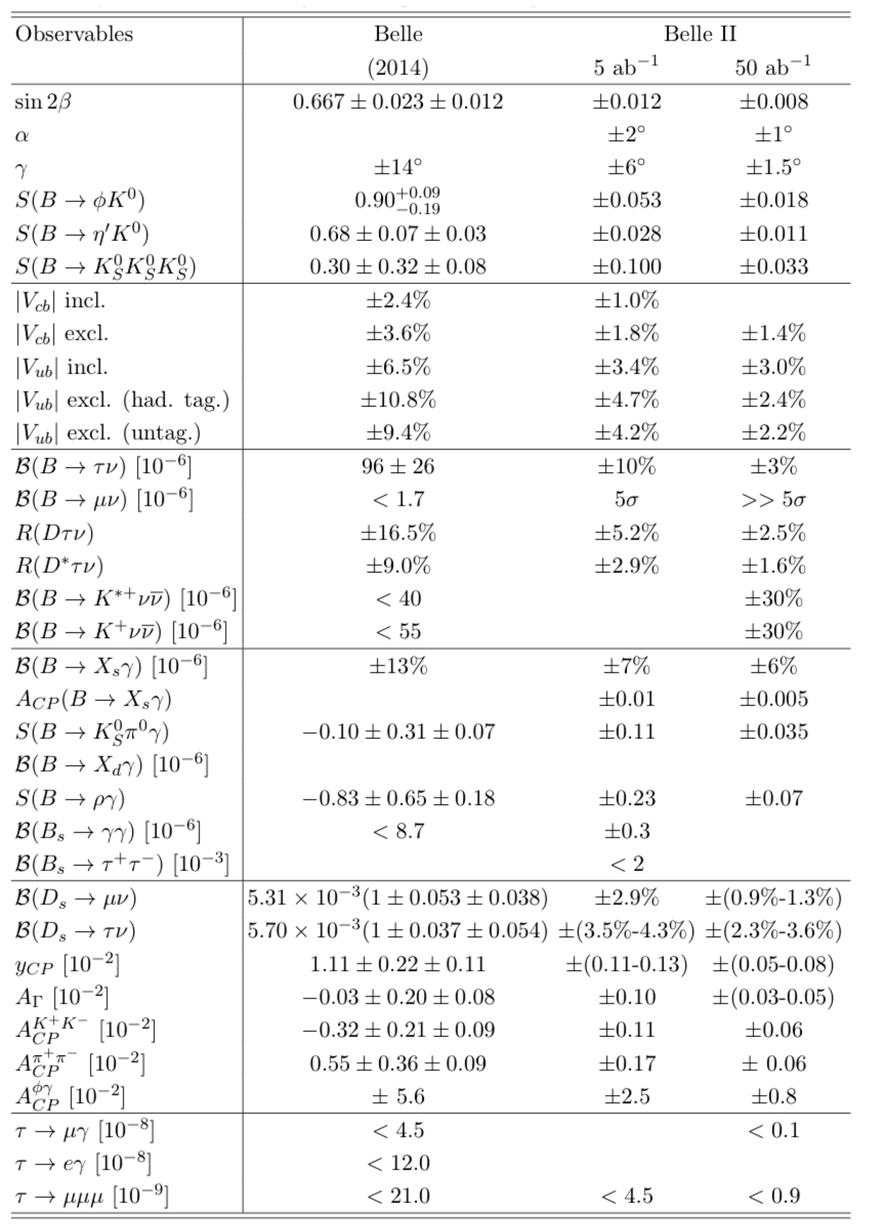
LHCb Upgrade Physics Reach



Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	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	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Belle-II@SuperKEKB Physics Reach

- SuperKEKB Belle-II
  - 2015 collider commissioning
  - 2016 detector commissioning
- Physics reach
  - golden modes
  - silver modes complementary with LHCb



Observables	Belle	Belle II	
	(2014)	5 ab^{-1}	50 ab^{-1}
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008
α		$\pm 2°$	$\pm 1°$
γ	$\pm 14°$	$\pm 6°$	$\pm 1.5°$
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033
$\|V_{cb}\|$ incl.	$\pm 2.4\%$	$\pm 1.0\%$	
$\|V_{cb}\|$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$
$\|V_{ub}\|$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$
$\|V_{ub}\|$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$
$\|V_{ub}\|$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	96 ± 26	$\pm 10\%$	$\pm 3\%$
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	5σ	$>> 5\sigma$
$R(D\tau\nu)$	$\pm 16.5\%$	$\pm 5.2\%$	$\pm 2.5\%$
$R(D^*\tau\nu)$	$\pm 9.0\%$	$\pm 2.9\%$	$\pm 1.6\%$
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ $[10^{-6}]$	< 40		$\pm 30\%$
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ $[10^{-6}]$	< 55		$\pm 30\%$
$\mathcal{B}(B \to X_s\gamma)$ $[10^{-6}]$	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005
$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035
$\mathcal{B}(B \to X_d\gamma)$ $[10^{-6}]$			
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7	± 0.3	
$\mathcal{B}(B_s \to \tau^+\tau^-)$ $[10^{-3}]$		< 2	
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%\text{-}1.3\%)$
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%\text{-}4.3\%)$	$\pm(2.3\%\text{-}3.6\%)$
y_{CP} $[10^{-2}]$	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11\text{-}0.13)$	$\pm(0.05\text{-}0.08)$
A_Γ $[10^{-2}]$	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03\text{-}0.05)$
$A_{CP}^{K^+K^-}$ $[10^{-2}]$	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06
$A_{CP}^{\pi^+\pi^-}$ $[10^{-2}]$	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm\ 0.06$
$A_{CP}^{\phi\gamma}$ $[10^{-2}]$	$\pm\ 5.6$	± 2.5	± 0.8
$\tau \to \mu\gamma$ $[10^{-8}]$	< 4.5		< 0.1
$\tau \to e\gamma$ $[10^{-8}]$	< 12.0		
$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 4.5	< 0.9

CKM angle γ

sin2β^{eff}

Neutrino modes

b->sγ inclusive

charm

Lepton flavour violation

Conclusions

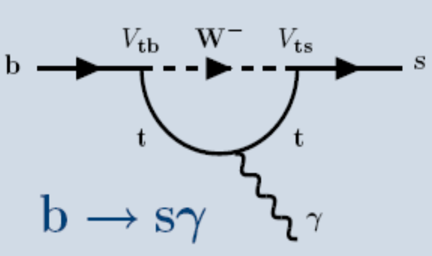
- **Flavour physics has entered successfully into LHC era**
  - LHC and detectors (ATLAS, CMS and LHCb) work extremely well
  - dedicated LHCb experiment: 179 papers and counting
  - B-factories and Tevatron still contributing
- **Many new and important results**
  - Weak phase ϕ_s and decay width difference $\Delta\Gamma_s$ in B_s decays
  - CKM angle γ competitive with B factories
  - Observation for $B_s \rightarrow \mu^+\mu^-$
  - Strong constraints on new physics
- ***All consistent with SM – few hints for new physics?***
  - Angular analysis (P_5') of $B^0 \rightarrow K^{*0} \mu^+\mu^-$, need more data
- **LHC run 2 will start in 2015**
  - Production cross section σ_{bb} and σ_{cc} doubles, $\sqrt{s}$: 7/8→13/14 TeV
- **LHCb upgrade and Belle/SuperKEKB**
  - Probe/measure New Physics at the percentage level

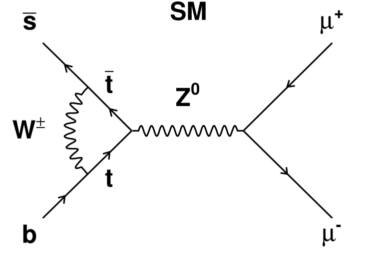
Backup

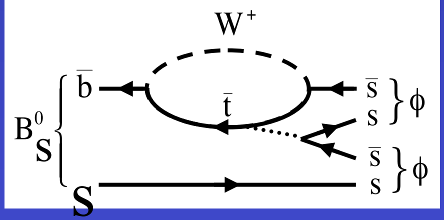
New Physics in Flavour

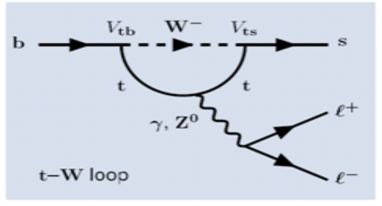
- **Flavour explores new physics (NP) beyond the energy frontier**
  - Sensitive to NP appearing as virtual particles in loop processes
  - Observable deviations from SM expectations in flavour physics
  - Rare decays, e.g. Flavour Changing Neutral Current Interactions

Standard Model

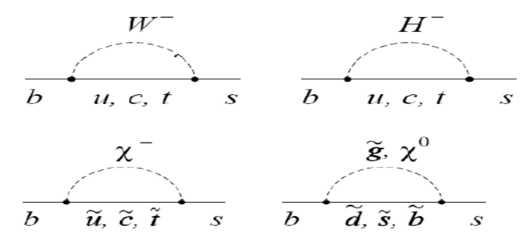


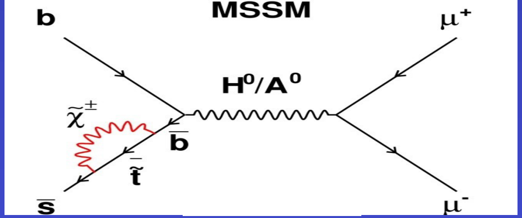


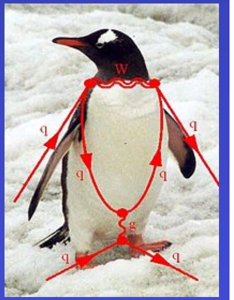




New Physics ?



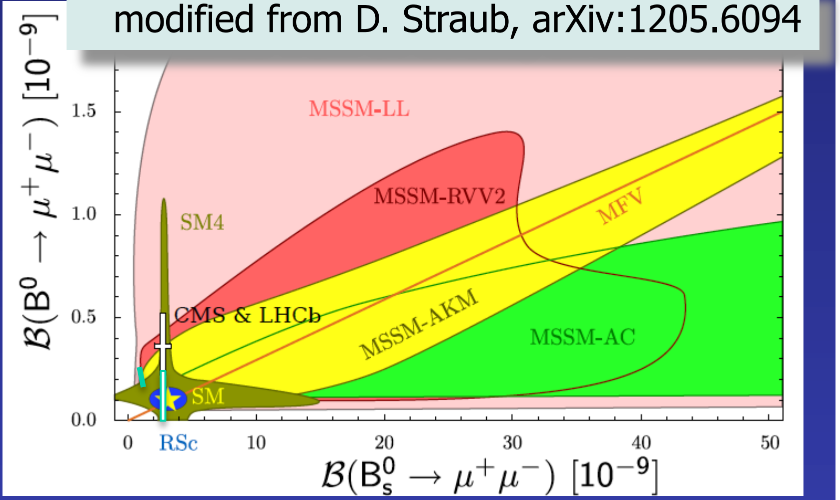


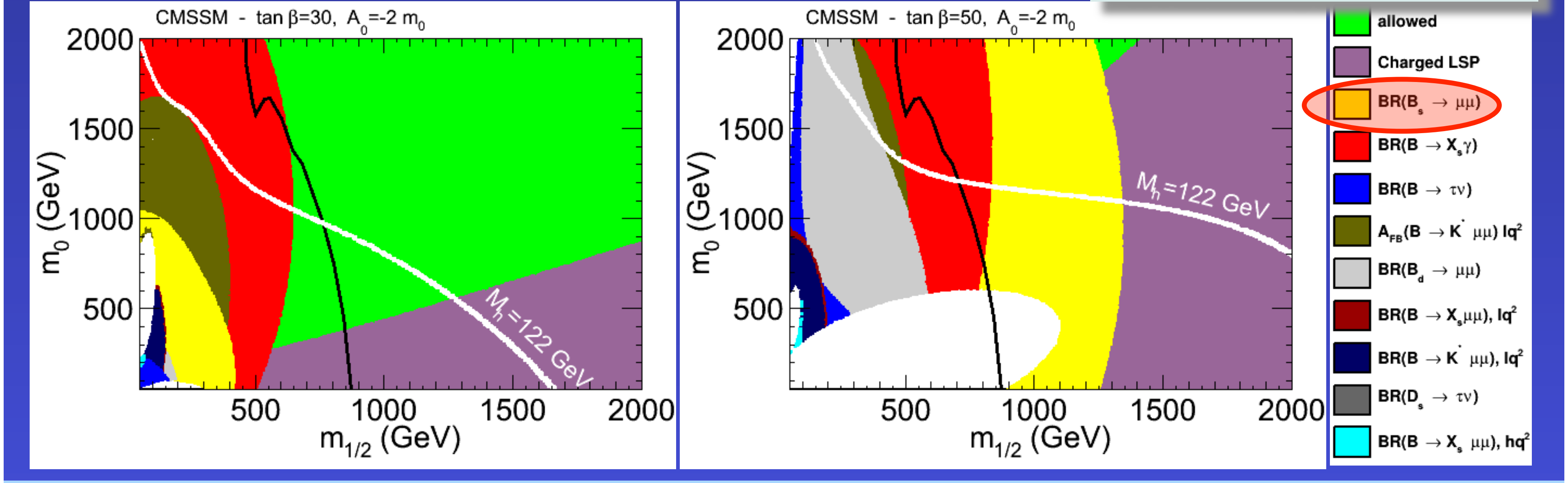


b → s penguin transitions

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

- **CMSSM**
  - Constrained Minimal Supersymmetry
- **Exclusion ranges**
  - at large tanβ flavour physics excludes full parameter space
  - at tanβ ~ 30 flavour physics and direct searches complementary


modified from D. Straub, arXiv:1205.6094


F. Mahmoudi, arXiv:1310.2556

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

- **Isospin asymmetry**

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

  - A_I predicted to be very small in SM
- **LHCb results 2011 data: 1 fb^{-1}**

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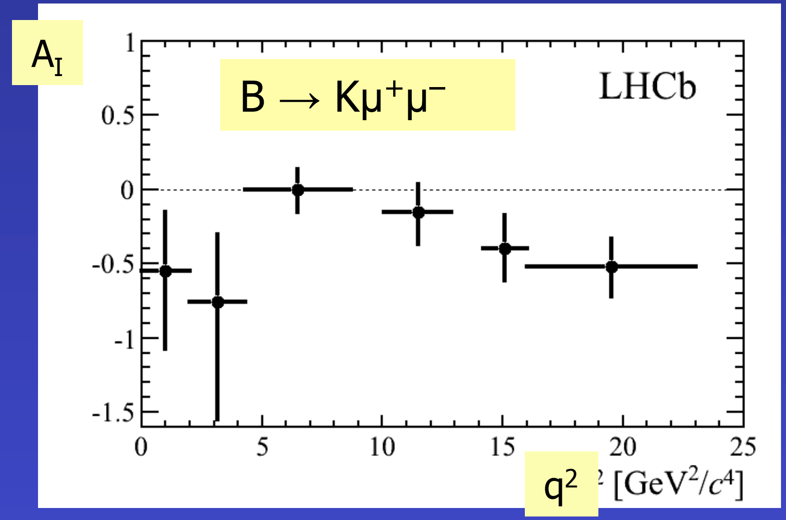
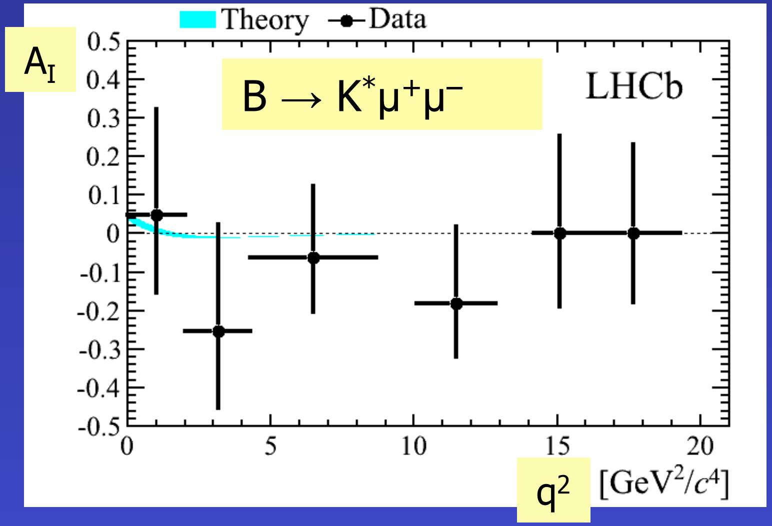




- $A_I(B \to K\mu^+\mu^-)$ significant deviation 4.4 σ from zero

$A_I(B \to K^* \mu^+\mu^-)$ consistent with zero

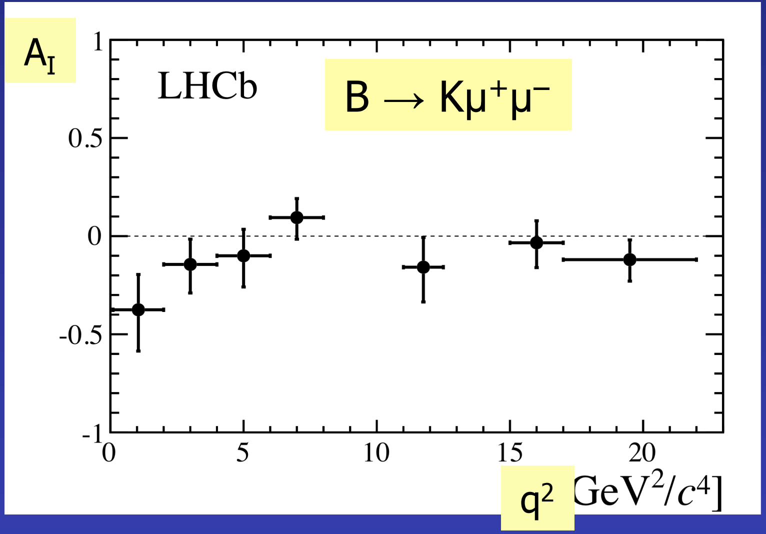
Isospin asymmetry: $B \to K^{(*)}\mu^+\mu^-$

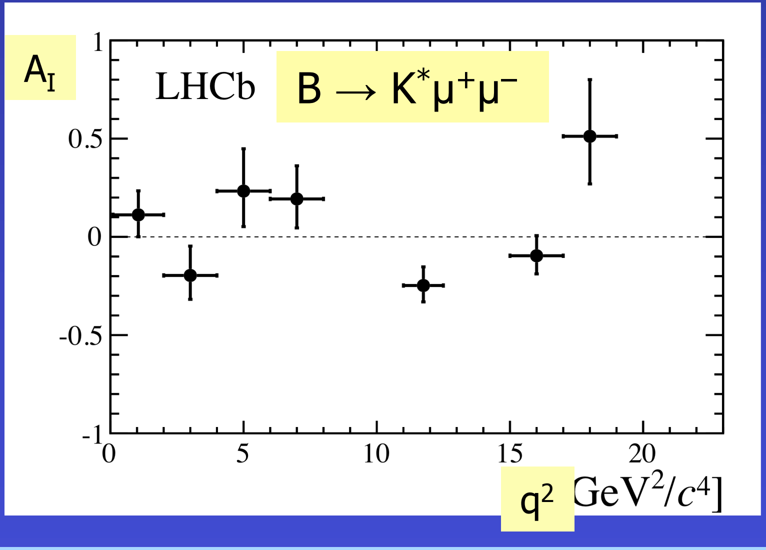
LHCb-PAPER-2014-006, arXiv:1403.8044

- **LHCb 2011/12 data: 3 fb^{-1}**
  - Extract A_I measuring four modes
    - $B^\pm \to K^\pm\mu^+\mu^-$, $B^0 \to K_S^0\mu^+\mu^-$
    - $B^\pm \to K^{*\pm} (\to K_S^0\pi^\pm)\ \mu^+\mu^-$
    - $B^0 \to K^{*0} (\to K^+\pi^-)\ \mu^+\mu^-$
  - Fit $K^{(*)}\mu^+\mu^-$ mass in q^2 bins

- **Results**
  - Estimate p-value for A_I differing from zero assuming constant A_I
  - $p = 11\%$ (1.5σ) for A_I in $B \to K\mu^+\mu^-$
  - A_I result consistent with SM

talks by Sam Cunliffe, Simon Wright

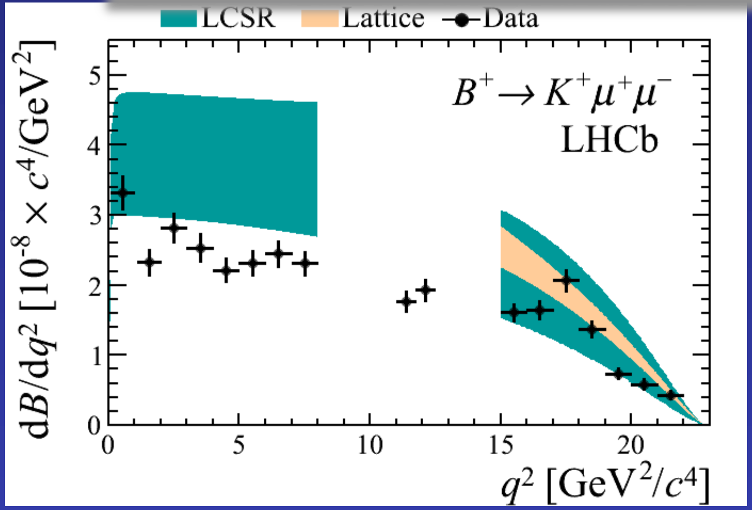


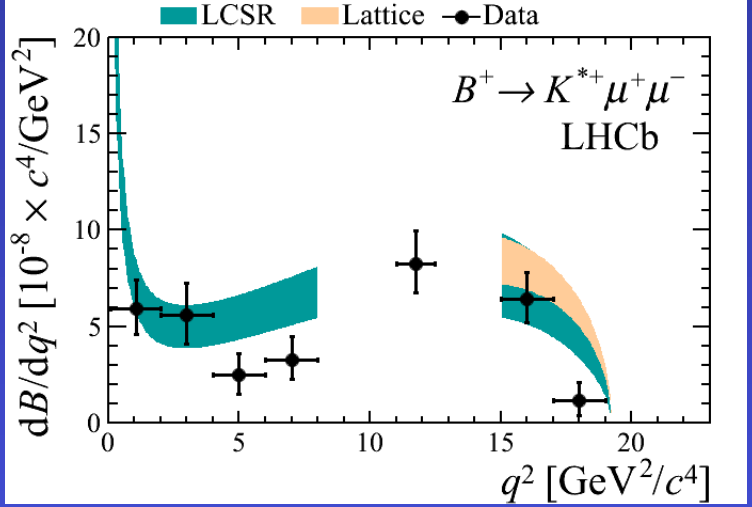


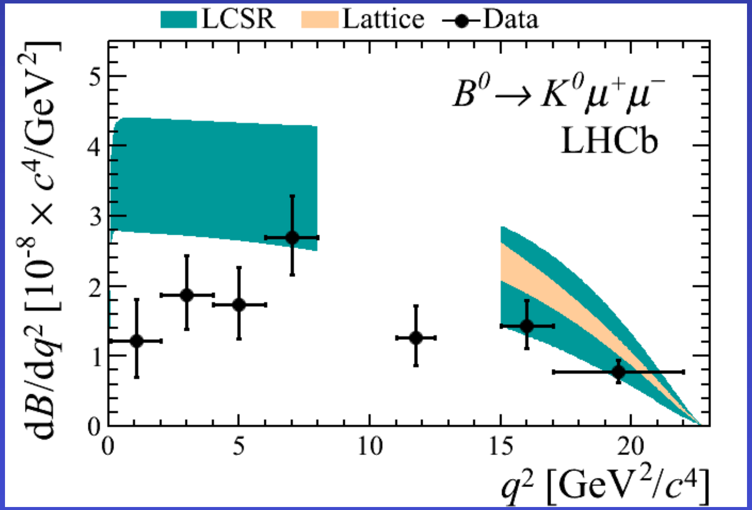
Differential Branching Ratios

LHCb-PAPER-2014-006, arXiv:1403.8044

- **LHCb 2011/12 data: 3 fb^{-1}**
  - Measurements compared to predictions from Lattice QCD and Light Cone Sum Rules
- **Results**
  - Consistent with SM, but data tend to lie below predictions







Large direct CPV in B±→K±h-h+

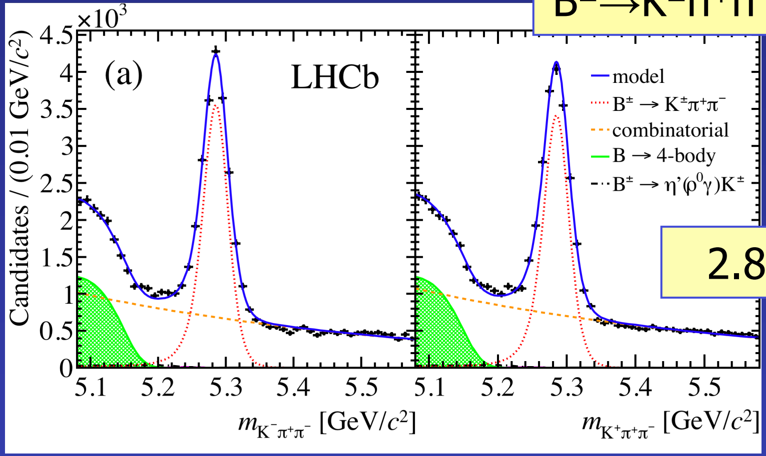
Evidence for direct CP in B±→K±h-h+ decays

$$A_{CP}\left(B^{\pm}\to K^{\pm}\pi^{+}\pi^{-}\right)=0.032\pm0.008\pm0.004\pm0.007$$

$$A_{CP}\left(B^{\pm}\to K^{\pm}K^{+}K^{-}\right)=-0.043\pm0.009\pm0.003\pm0.007$$

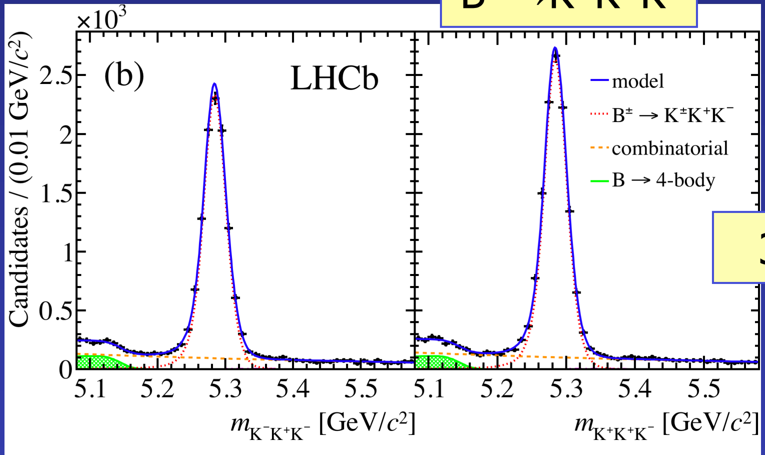
LHCb-PAPER-2013-027

B±→K±π+π-

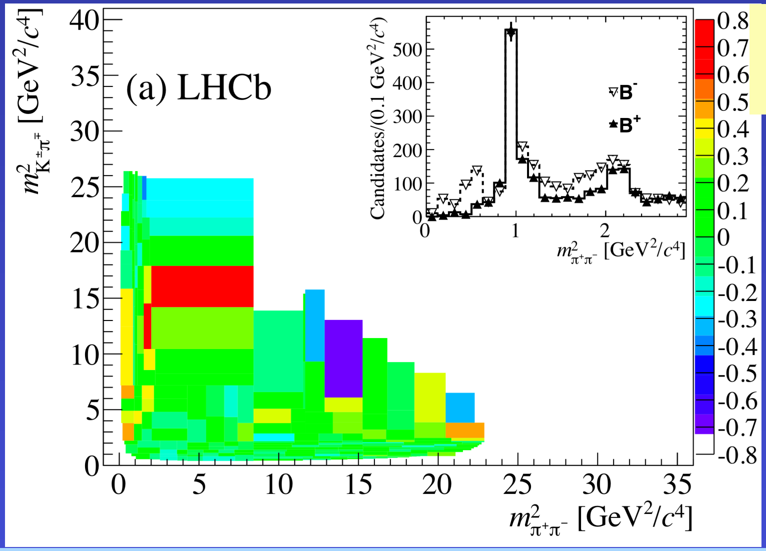


2.8σ

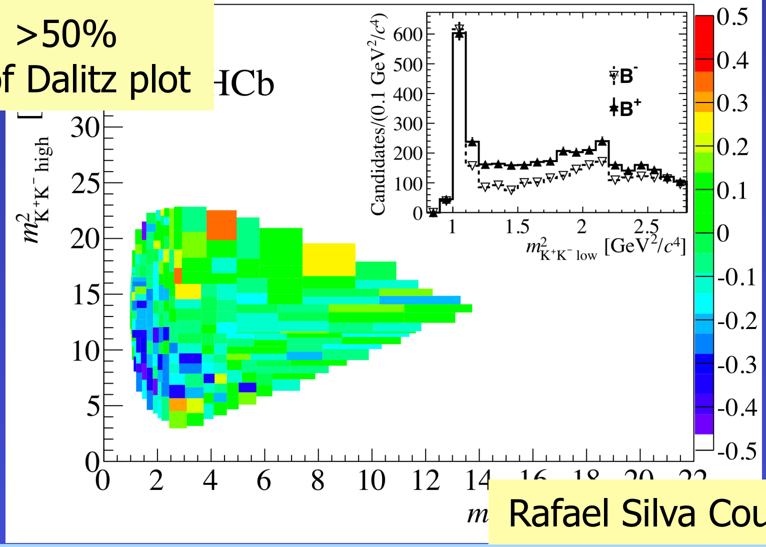
B±→K±K+K-



3.7σ



CP violation >50%
in regions of Dalitz plot



Rafael Silva Coutinho

CP Violation in Mixing

- **Semileptonic Asymmetry**
  - measures ~~CP~~ in mixing
  - very small in SM

$$a_{sl} = 1 - \left|\frac{q}{p}\right|^2 = \frac{|\Gamma_{12}|}{|M_{12}|}\sin\phi_{12}$$

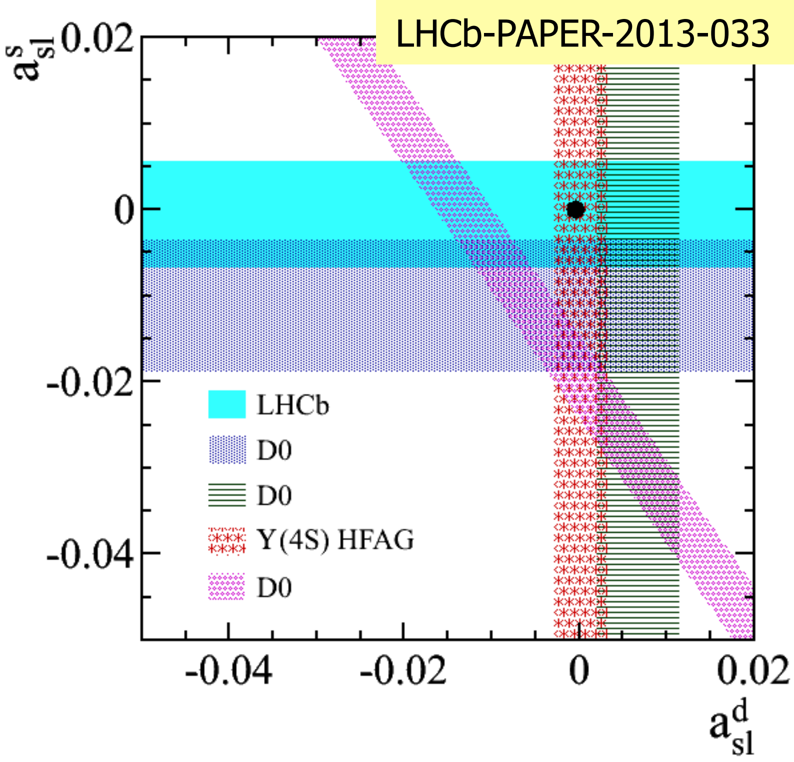
Lenz, Nierste, 2012

$$a_{sl}^d = (-4.1 \pm 0.6)\cdot 10^{-4}$$
$$a_{sl}^s = (+1.9 \pm 0.3)\cdot 10^{-5}$$

- **D0 at Tevatron evidence**
  - a_{sl} >> SM prediction at 3.0σ

- **a_{sl} at LHCb**
  - Time-integrated asymmetry in $B_s \to D_s^- \mu^+ \nu$

$$A = \frac{\Gamma(D_s^-\mu^+) - \Gamma(D_s^+\mu^-)}{\Gamma(D_s^-\mu^+) + \Gamma(D_s^+\mu^-)} = \frac{a_{sl}^s}{2} + \left(a_p - \frac{a_{sl}^s}{2}\right)\frac{\int \exp(-\Gamma_s t)\cos(\Delta m_s t)\varepsilon(t)dt}{\int \exp(-\Gamma_s t)\cos(\Delta\Gamma_s/2\cdot t)\varepsilon(t)dt}$$



LHCb-PAPER-2013-033

  - a_{sl} = (-0.06 ± 0.50 ± 0.36)%
  - does not confirm nor exclude D0 result

CP Violation in Mixing

- **Semileptonic Asymmetry**
  - measures $\cancel{CP}$ in mixing
  - very small in SM

$$a_{sl} = 1 - \left|\frac{q}{p}\right|^2 = \frac{|\Gamma_{12}|}{|M_{12}|}\sin\phi_{12}$$

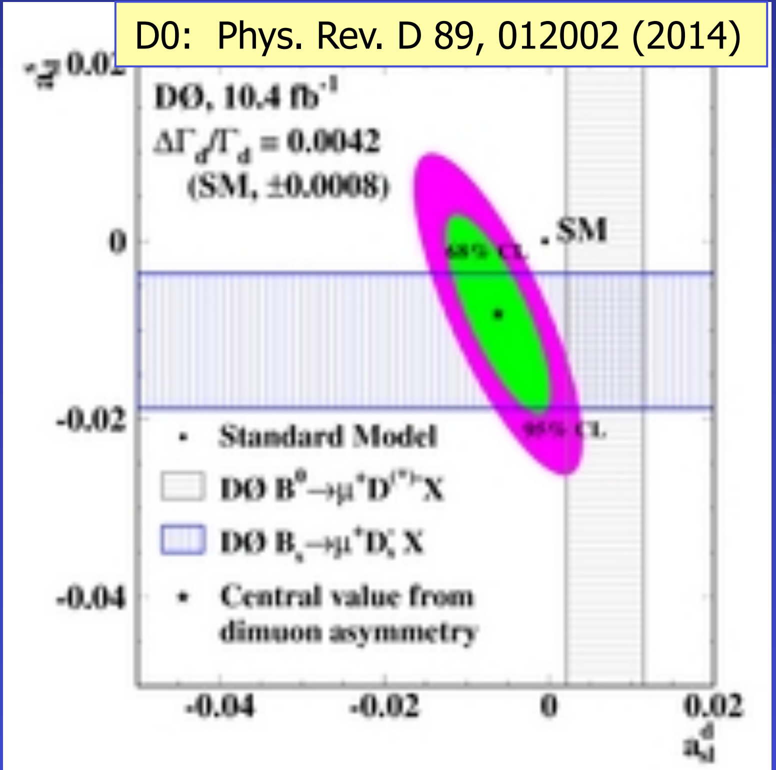
Lenz, Nierste, 2012

$$a_{sl}^d = (-4.1 \pm 0.6)\cdot 10^{-4}$$
$$a_{sl}^s = (+1.9 \pm 0.3)\cdot 10^{-5}$$

- **D0 final result**
  - fit for a_{sl}^s, a_{sl}^d and $\Delta\Gamma_d$

$$\begin{aligned} a_{\text{sl}}^d &= (-0.62 \pm 0.43) \times 10^{-2}, && (96) \\ a_{\text{sl}}^s &= (-0.82 \pm 0.99) \times 10^{-2}, && (97) \\ \frac{\Delta\Gamma_d}{\Gamma_d} &= (+0.50 \pm 1.38) \times 10^{-2}, && (98) \end{aligned}$$

  - differs from SM prediction at 3.0σ



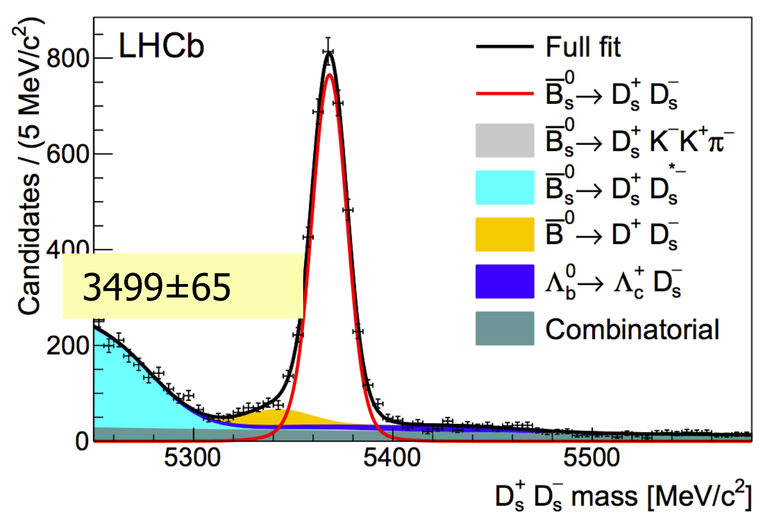
D0: Phys. Rev. D 89, 012002 (2014)

Lifetimes

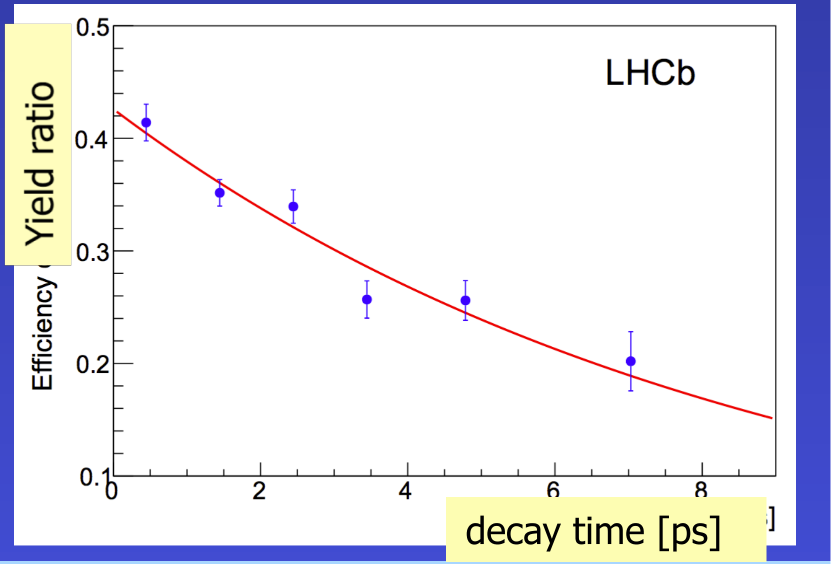
$B_s \rightarrow D_s^+ D_s^-$ Lifetime

LHCb: arXiv.1312.1217

- **How to measure B_s decay widths Γ_L and Γ_H ?**
  - use decays to CP even and odd final states
  - in limit of small CP violation $\phi_s \approx 0$
  - $\tau_{eff}\ (B_s \rightarrow D_s^+\ D_s^-) \approx\ 1/\Gamma_L$



- **LHCb method**
  - measure directly lifetime ratio in $B_s \rightarrow D_s^+\ D_s^-$ and $B^- \rightarrow D^0\ D_s^-$ decays



- **Result**
  - $$\tau_{\text{eff}}\left(B_s^0 \rightarrow D_s^+ D_s^-\right) = 1.379 \pm 0.026 \pm 0.017 \text{ ps}$$ $$\Gamma_L = 0.725 \pm 0.014 \pm 0.009 \text{ ps}^{-1}$$
  - Most precise Γ_L measurement

Λ_b Lifetime

- **Heavy Quark Expansion (HQE)**
  - predicts Λ_b Lifetime

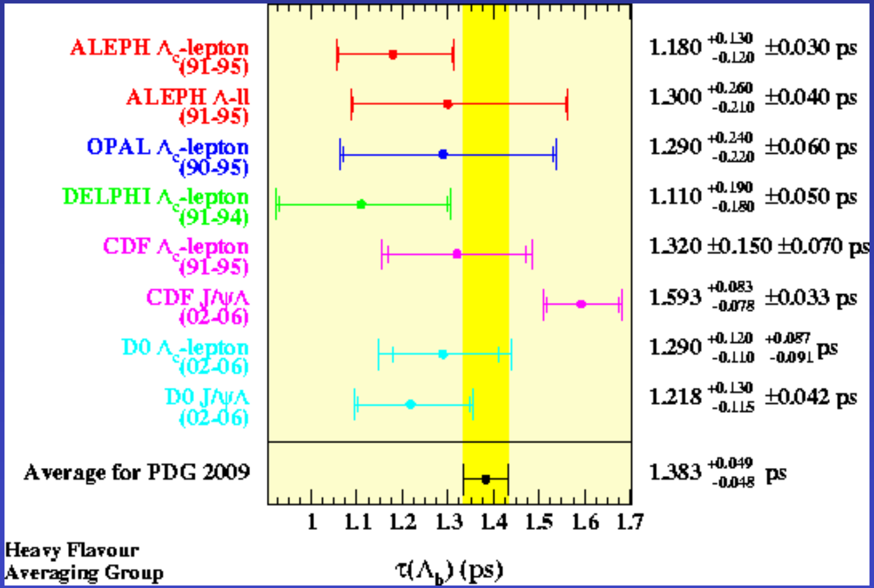
$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.98 \pm O\left(\frac{1}{m_b^3}\right)$$

- **LEP and Tevatron measure shorter Λ_b Lifetime**
  - LEP average (2003)

$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.798 \pm 0.052$$

  - PDG average in 2009

$$\tau_{\Lambda_b^0} = 1.383^{+0.049}_{-0.048}\ \text{ps}$$



- **LHCb**
  - measures directly ratio of Λ_b to B^0 lifetime
  - use similar final states
  - $\Lambda_b \rightarrow J/\psi Kp$ (previously unobserved) and $B^0 \rightarrow J/\psi K\pi$

Λ_b Lifetime

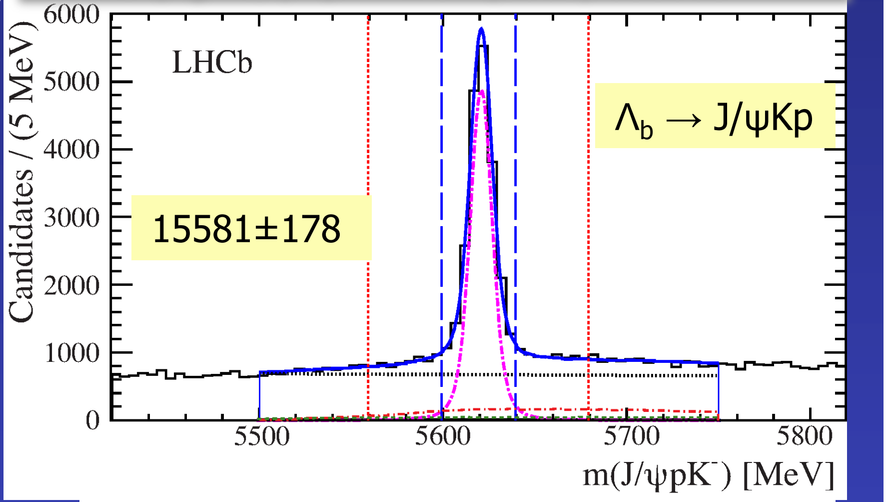
LHCb ($\Lambda_b \to J/\psi\Lambda$): arXiv.1402.2554
LHCb ($\Lambda_b \to J/\psi Kp$): PRD87 (2013) 112010
CMS ($\Lambda_b \to J/\psi\Lambda$): arXiv:1304.7495
ATLAS ($\Lambda_b \to J/\psi\Lambda$): PRD87 (2013) 032002

- **Results**
  - LHCb $\tau(\Lambda_b \to J/\psi Kp)/\tau(B^0 \to J/\psi K\pi)$

$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.976 \pm 0.012 \pm 0.006$$

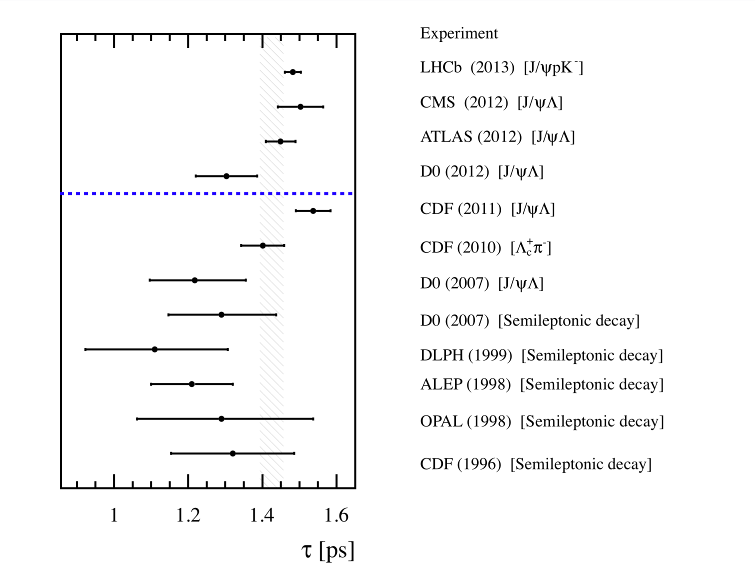
$$\tau_{\Lambda_b^0} = 1.482 \pm 0.018 \pm 0.012\ \text{ps}$$

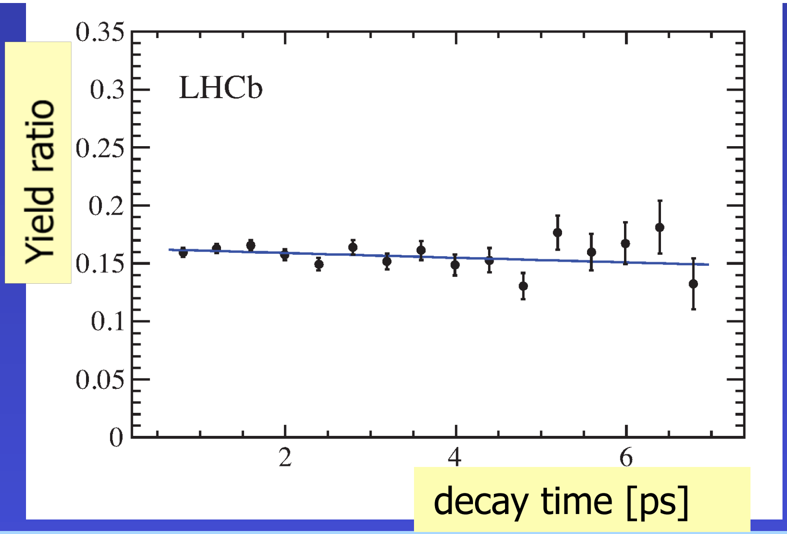
  - consistent with $\Lambda_b \to J/\psi\Lambda$ results
  - ATLAS, CMS, LHCb, D0, CDF



$\Lambda_b \to J/\psi Kp$

15581±178

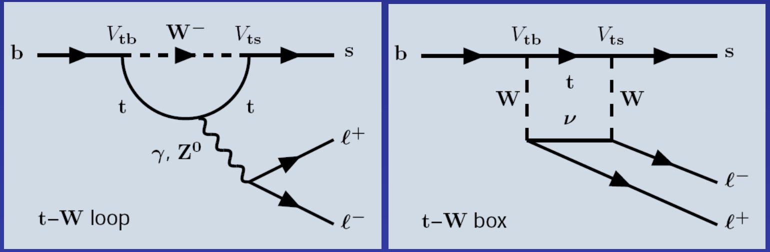




EW Penguin Decay $B^0 \to K^{*0}\mu^+\mu^-$

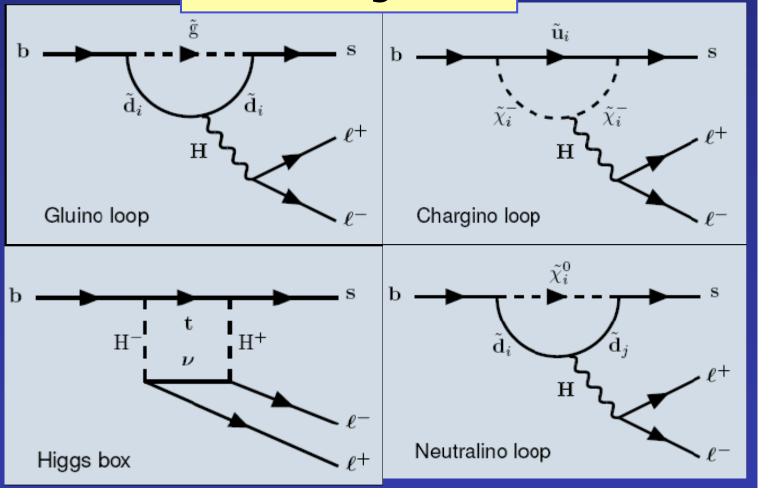
- Flavour Changing Neutral Currents
  - Suppressed in SM
  - Sensitive to new Physics

SM diagrams

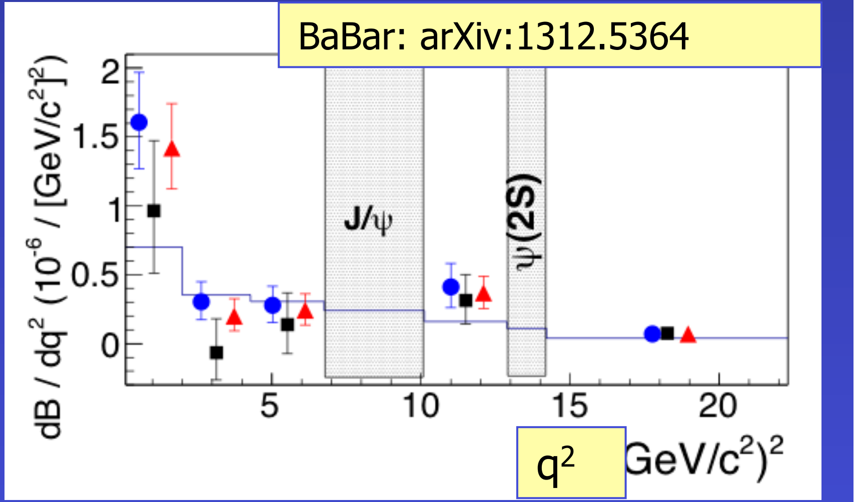


  - BR = (1.22+0.38-0.32) x 10^{-6}
  - Measured by BaBar and Belle

SUSY diagrams



- New BaBar measurement
  - Differential dB/dq^2
  - Sum over exclusive modes
  - $B \to X_s l^+ l^-$ where l = μ or e



BaBar: arXiv:1312.5364

q^2

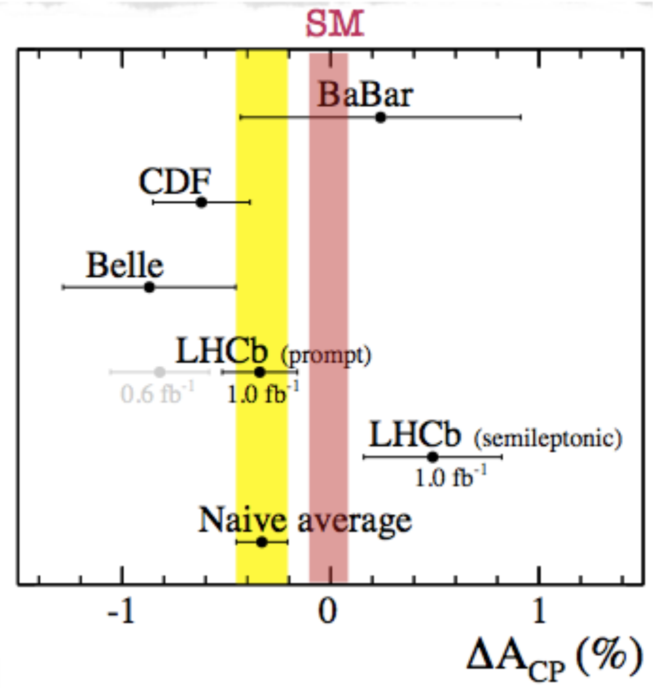
CP Violation in Charm

PRL 108 (2012) 111602
PLB 723 (2013) 33

- **Direct CP violation in charm**
  - Predicted to be ≤ 10^{-3} in SM
  - Long distance effects
  - difficult to estimate
  - A_{raw} (f) depends on production and detection asymmetries
  - measure $\Delta A_{CP} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$

$$A_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

- **Measurement**
  - LHCb and CDF: Charge of $\pi^\pm_s$ from $D^{*+} \to D^0 \pi^+_s$, $D^{*-} \to D^0 \pi^-_s$ tags the D flavour
  - LHCb: Charge of $\mu^\pm$ from $B \to D^0 \mu^\pm X$ tags the D flavour
- **Results**
  - inconclusive, need more data
  - LHCb analyses on full run 1 data underway



The End