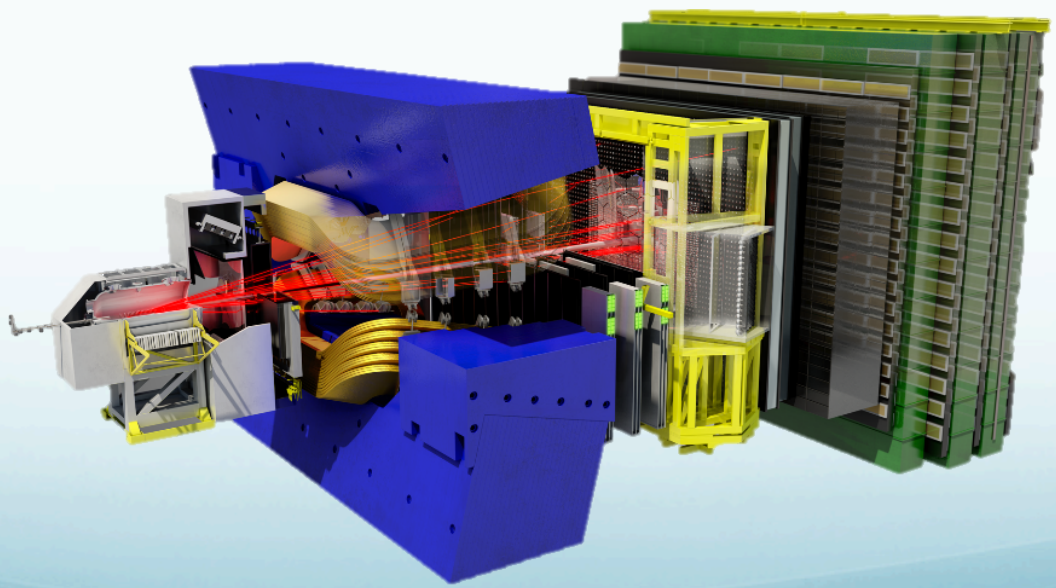
Recent hot results & semileptonic *b* hadron decays

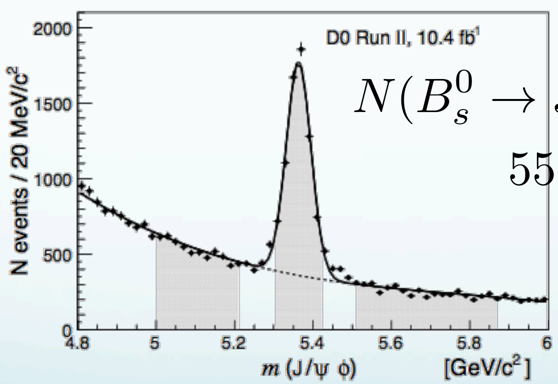
Jeroen van Tilburg
On behalf of the LHCb collaboration



Hot result: new tetraquark from D0?

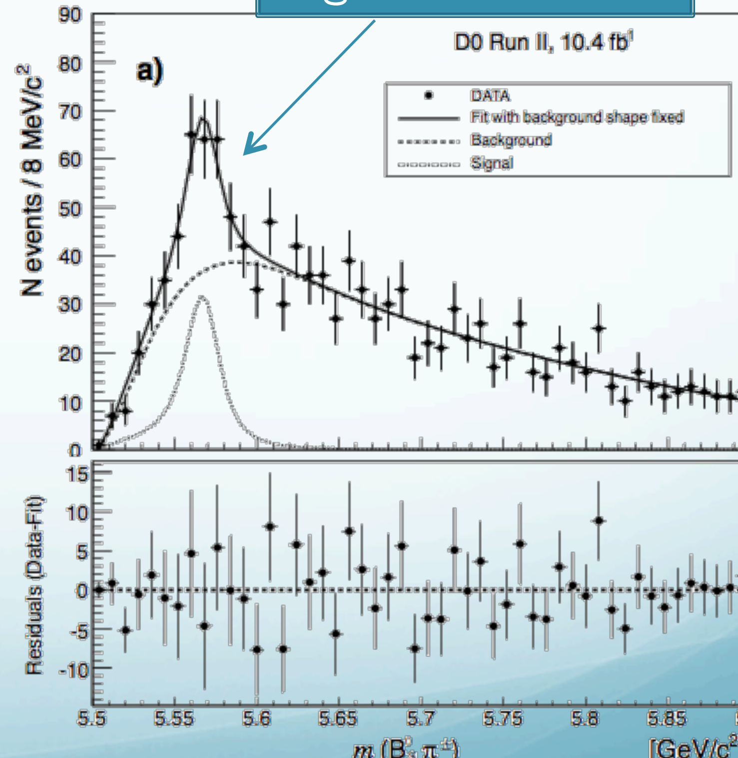
D0 collaboration: [arXiv:1602.07588]

- D0 announced new state on 24 Feb: $X(5568) \to B_s \pi^{\pm}$
- Fraction B_s from $X(5568)$: $(8.6 \pm 1.9 \pm 1.4)\%$
- $m = 5567.8 \pm 2.9\,(\text{stat})\,^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$
  $\Gamma = 21.9 \pm 6.4\,(\text{stat})\,^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$



$N(B_s^0 \to J/\psi\phi) = 5582 \pm 100$

Significance: 5.1σ



- Many citations:

arXiv:1603.02915, arXiv:1603.02708, arXiv:1603.02498, arXiv:1603.02249, arXiv:1603.01471, arXiv:1603.01131, arXiv:1603.00708, arXiv:1603.00290, arXiv:1602.08916, arXiv:1602.08711, arXiv:1602.09041, arXiv:1602.08806, arXiv:1602.08642, arXiv:1602.08421, and counting

D0: Observation of a new $B_s^0 \pi^{\pm}$ state

Invitation to:

CDF, LHCb, CMS, ATLAS

Go find those tetraquarks!

Thank you!

Peter

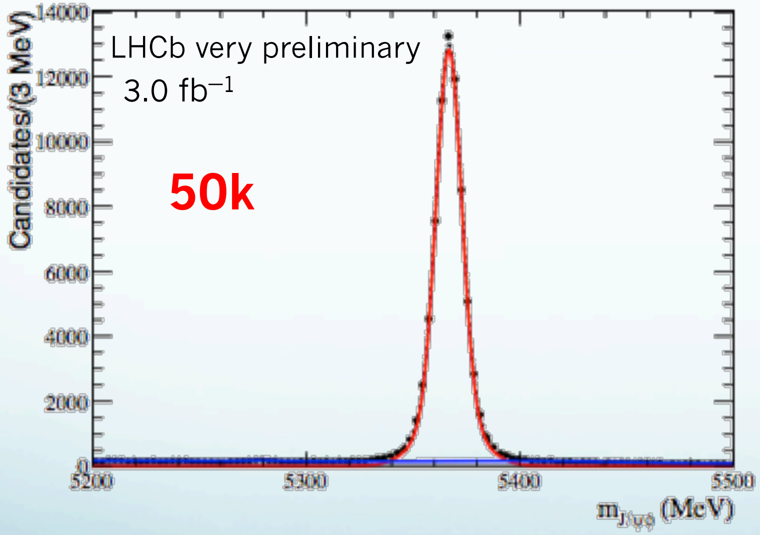
Recent Tevatron Results on Heavy Flavors - Peter H. Garbincius - La Thuile - March 2016 22

Hot result: new tetraquark from LHCb?

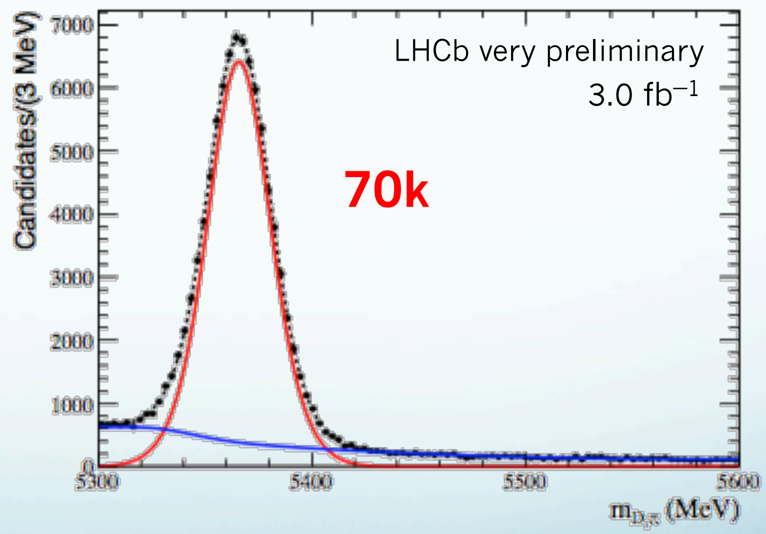
[LHCb-CONF-2016-004]
in preparation

- Very preliminary.
- Large B_s samples:

$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(KK)$



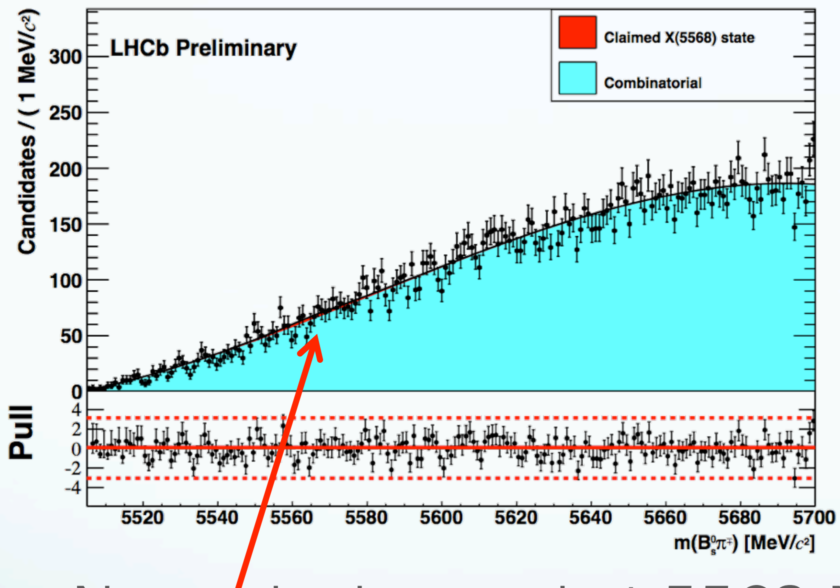
$B_s^0 \to D_s^-(KK\pi)\pi^+$



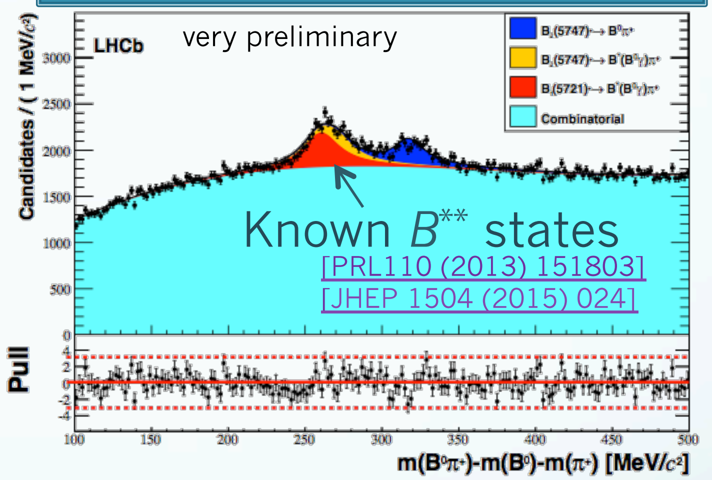
Hot result: new tetraquark from LHCb?

[LHCb-CONF-2016-004]
in preparation

- Add pion:



Cross-check with $B^0\pi$ spectrum

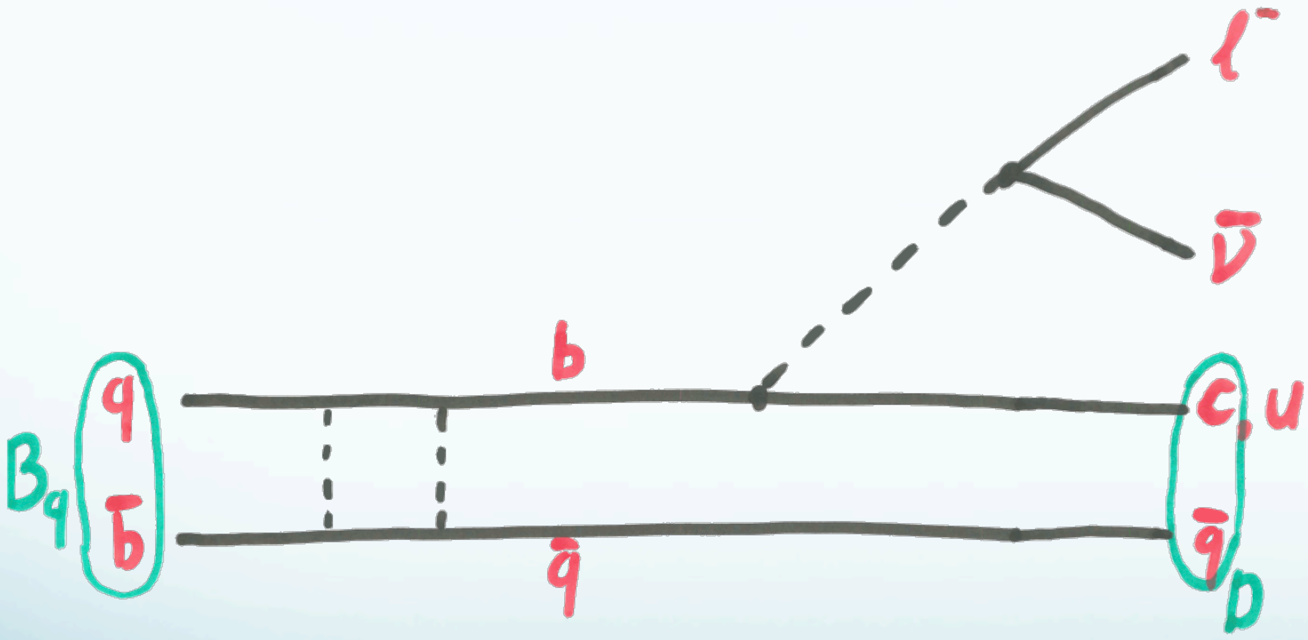


- No peak observed at 5568 MeV. Cannot confirm D0 peak.
  - UL cross section ratio ~1%

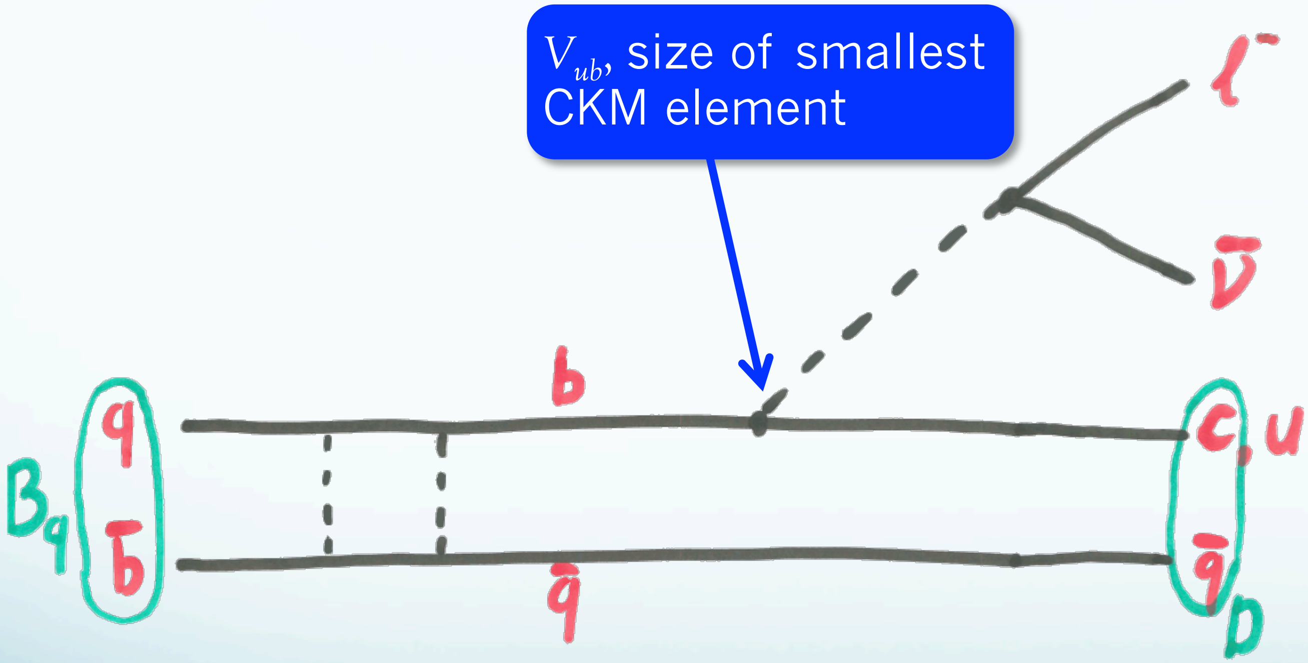
$$\rho_X^{\text{LHCb}} \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0\pi)}{\sigma(pp \to B_s^0 + \text{anything})}$$

- More details in Moriond QCD

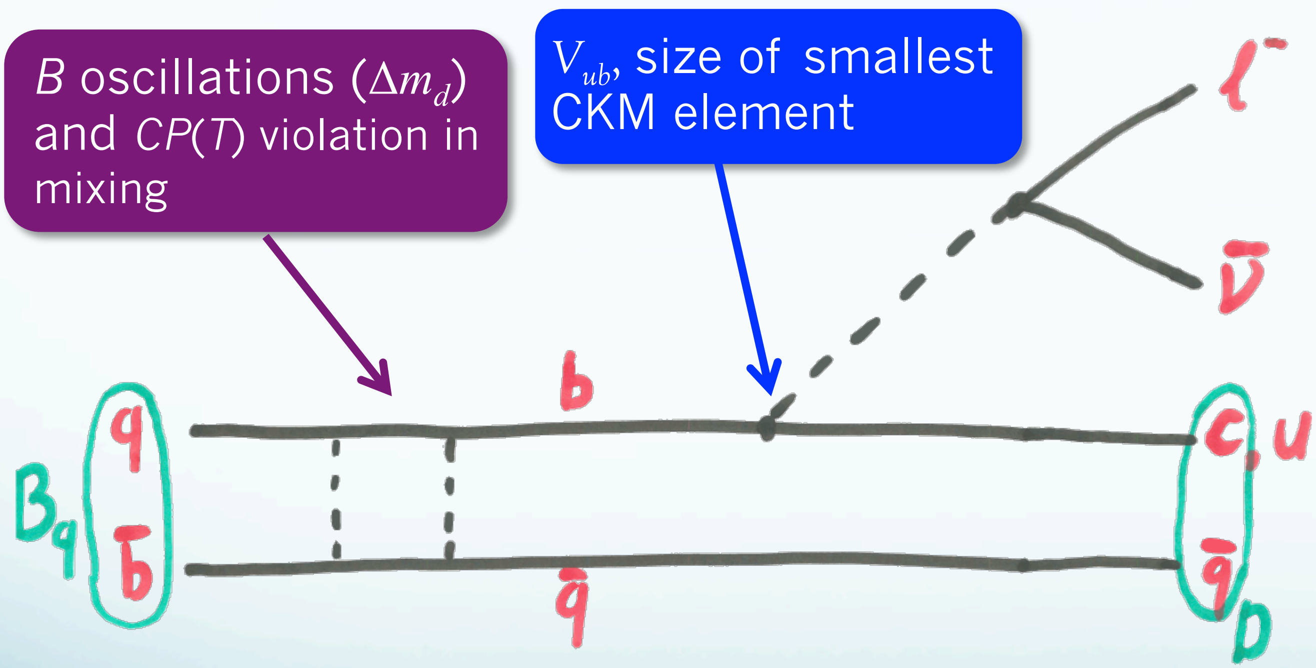
Physics of semileptonic *B* decays



Physics of semileptonic *B* decays



Physics of semileptonic *B* decays



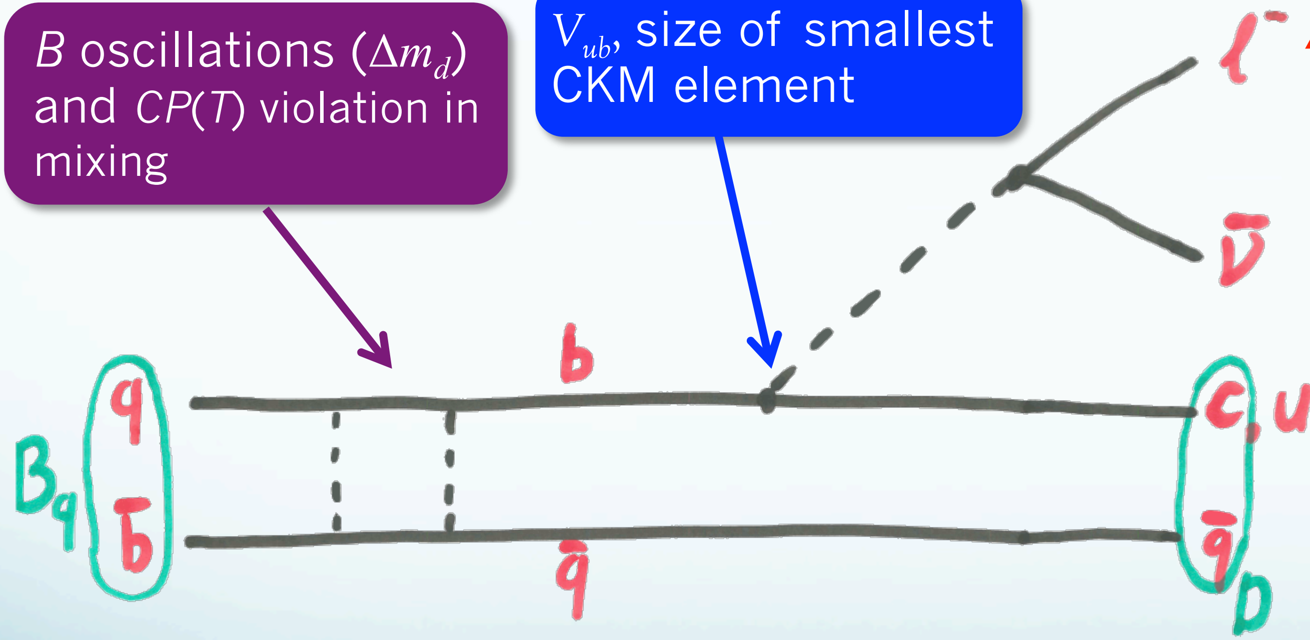
Physics of semileptonic *B* decays

B oscillations (Δm_d) and *CP*(*T*) violation in mixing

V_{ub}, size of smallest CKM element

Are all leptons equal? $\tau = e, \mu$?

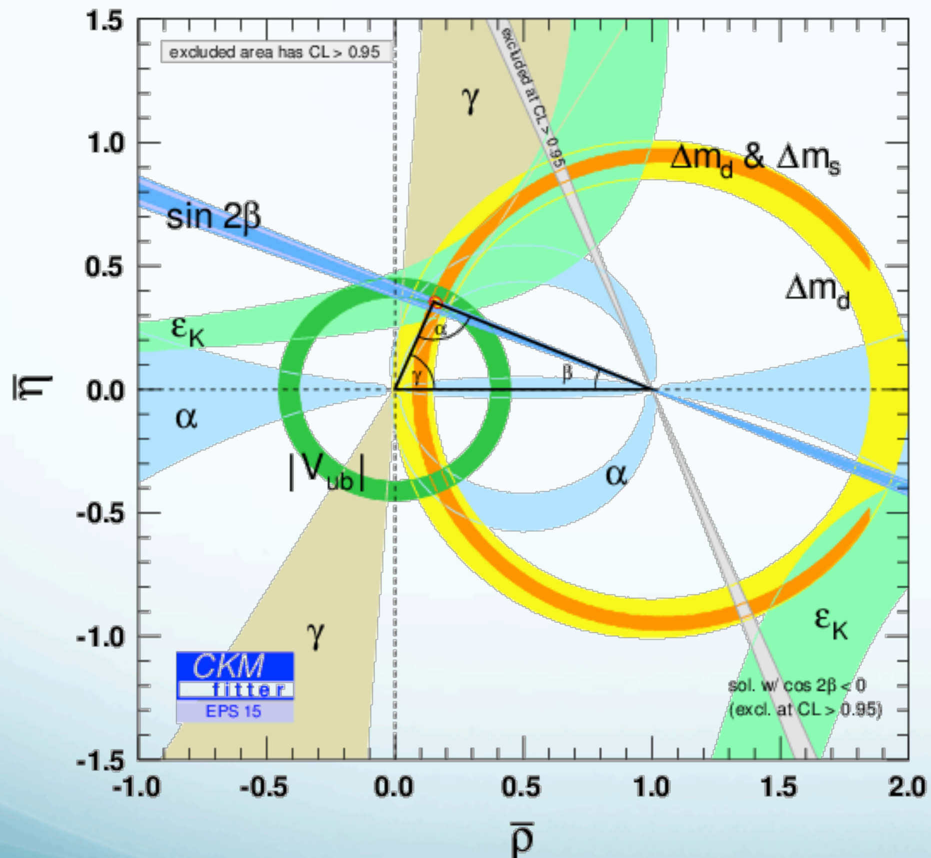
See talks this morning by Johannes Albrecht and Pablo Goldenzweig



$|V_{ub}|$
the smallest CKM element

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

Ultimate test of CKM unitarity



$|V_{ub}|$ VS $\sin 2\beta$

Disagreement of $|V_{ub}|$ methods:

$$|V_{ub}|(\text{incl.}) = (4.41 \pm 0.22) \times 10^{-3} \ \ \text{PDG}$$

$$|V_{ub}|(\text{excl.}) = (3.72 \pm 0.16) \times 10^{-3} \ \ \text{FNAL/MILC}$$

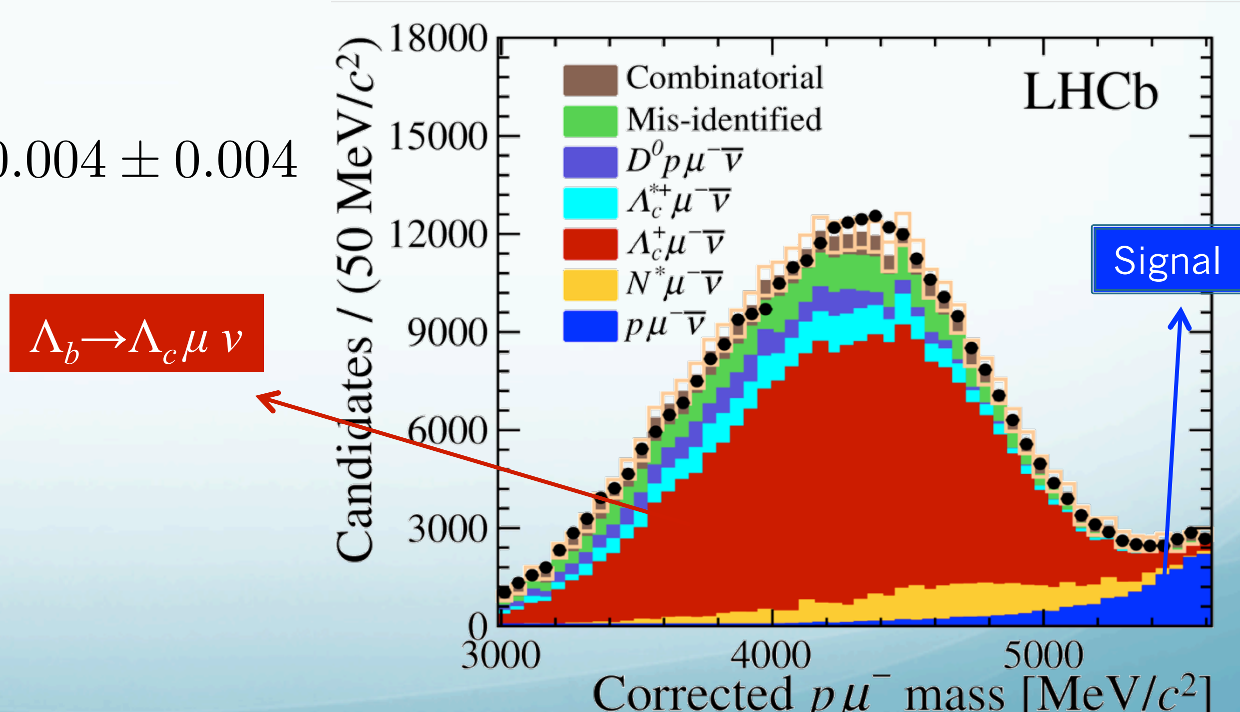
[PRD 92 (2015) 014024]

LHCb's $|V_{ub}|$ with $\Lambda_b \to p\mu\nu$

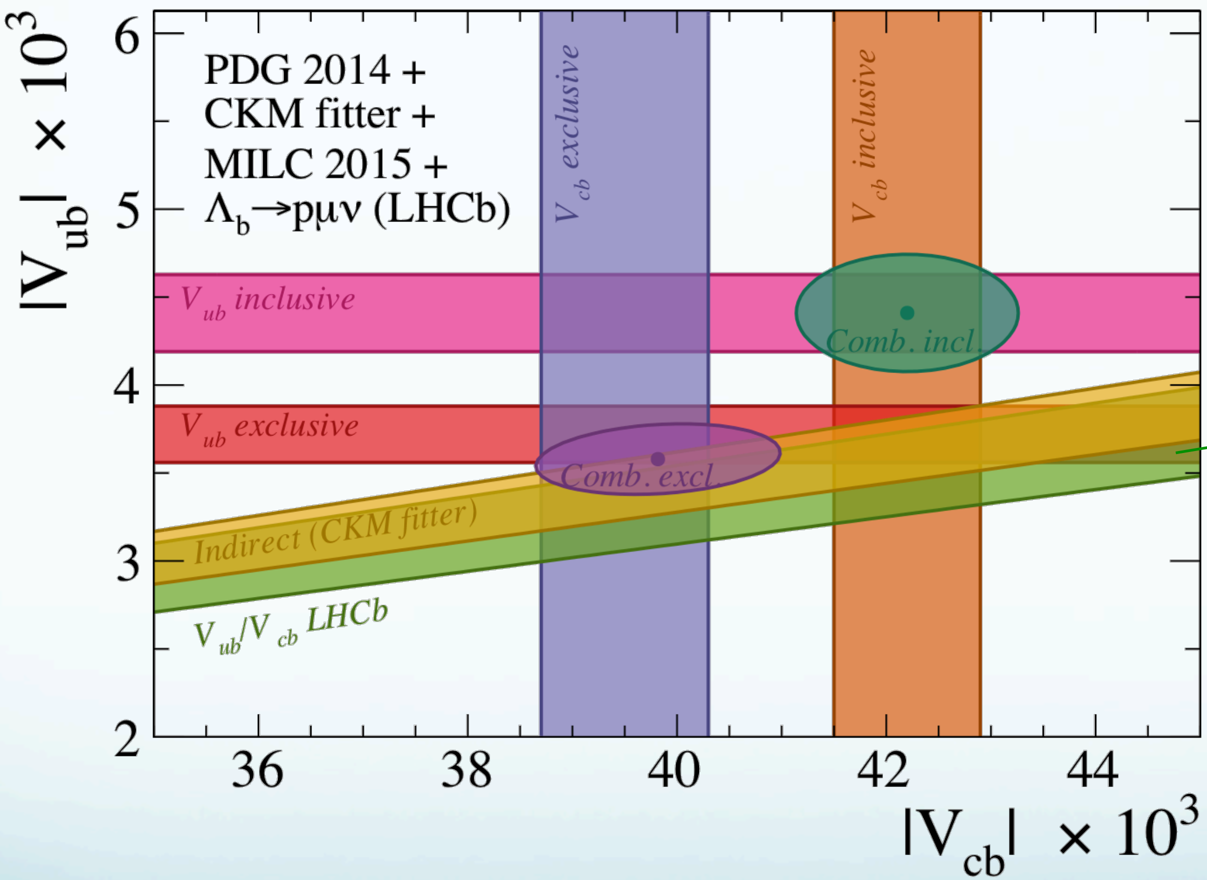
[Nature Physics 10 (2015) 1038]

- Large backgrounds for $B \to \pi \mu \nu$
- ~20% of b-hadrons are Λ_b baryons
- Accurate lattice prediction on $\Lambda_b \to p$ form factors
  - Uncertainty ~5% [PRD 92 (2015) 034503 (2015)]
- Result:

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$



$V_{ub} - V_{cb}$ plane



LHCb result

B_d oscillations

New result

Precision measurement of Δm_d

[LHCb-PAPER-2015-031], 3 fb^{-1}

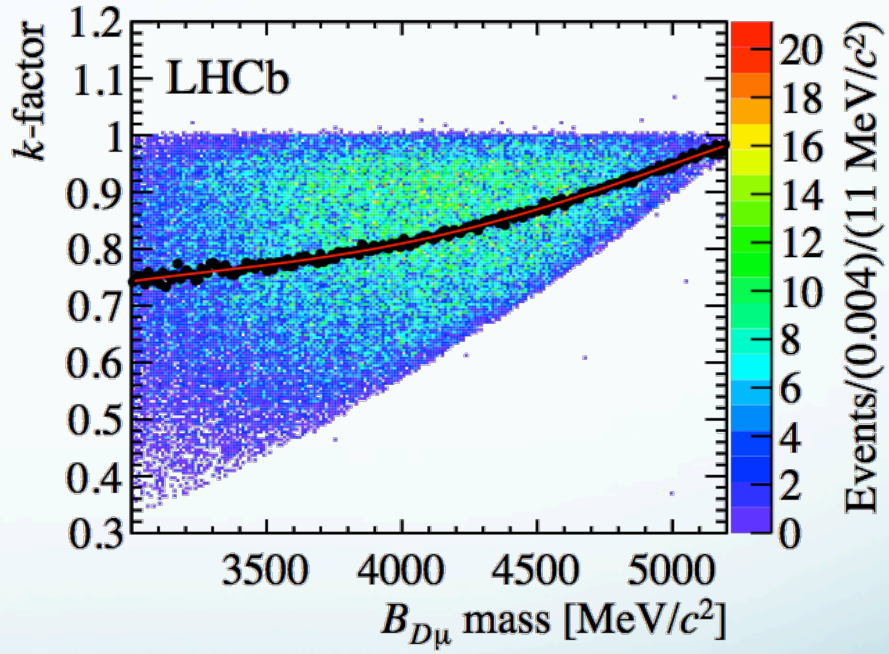
- Time-dependent analysis of flavour-tagged semileptonic decays

$$B^0 \to D^{(*)-}\mu^+\nu_\mu X$$

- Decay time reconstructed with *k*-factor method

$$t_{corr} = \frac{L_B \; M_{B^0}{}_{PDG}}{p^{rec}_{D\mu}} \times k(m_{D\mu})$$

$k(m_{D\mu})$: $p^{rec}_{D\mu}/p^{true}$



- Background from charged *B* decays suppressed by MVA exploiting kinematic and isolation criteria

New result

Precision measurement of Δm_d

[LHCb-PAPER-2015-031], 3 fb^{-1}

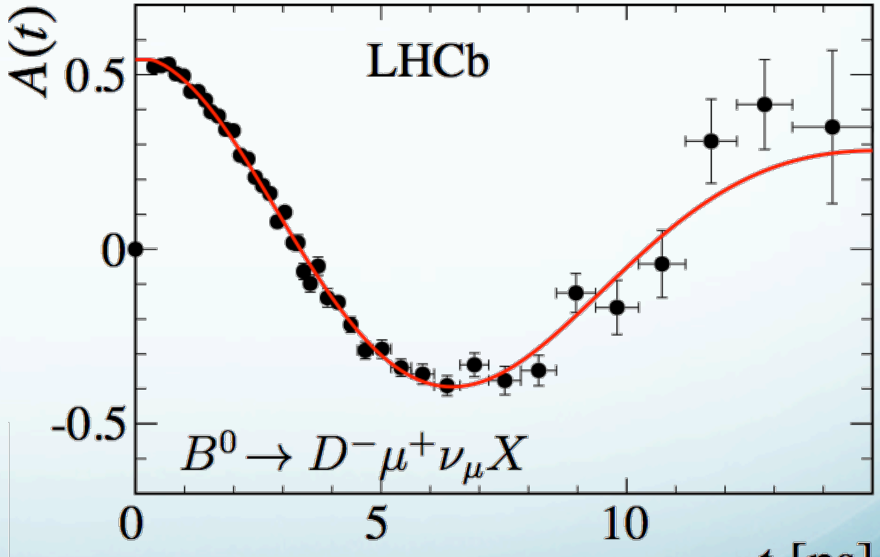
$$\Delta m_d = (505.0 \pm 2.1(\text{stat}) \pm 1.0(\text{syst}))\,\text{ns}^{-1}$$

- Most precise single measurement!
- World average (without this measurement)

  $$\Delta m_d = (510 \pm 3)\,\text{ns}^{-1}$$

- Recent lattice improvements [arXiv:1602.03560] allow stronger constraints on CKM Unitarity Triangle

$$A(t) = \frac{N^{\text{unmix}}(t) - N^{\text{mix}}(t)}{N^{\text{unmix}}(t) + N^{\text{mix}}(t)} = \cos(\Delta m_d t)$$



2012 data, best tagging category

CP violation in *B* mixing

CP violation in *B* mixing

- Different mixing probability for $B \to \overline{B}$ and $\overline{B} \to B$

$$a_{sl} = \frac{N(B \to \overline{B}) - N(\overline{B} \to B)}{N(B \to \overline{B}) + N(\overline{B} \to B)}$$

  - So far, only observed in neutral kaon system ($\varepsilon_K \approx 0.2\%$)

- SM predictions for *B* systems effectively zero

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

Lenz, Nierste [arXiv:1102.4274]

Measurement of a_{sl}

Untagged asymmetry:

$$A(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} = A_D + \frac{a_{\mathrm{sl}}}{2} + \left(A_P - \frac{a_{\mathrm{sl}}}{2}\right)\cos(\Delta m t)$$

Measurement of a_{sl}

Untagged asymmetry:

$$A(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} = A_D + \frac{a_{\mathrm{sl}}}{2} + \left(A_P - \frac{a_{\mathrm{sl}}}{2}\right)\cos(\Delta m t)$$

Detection asymmetry A_D:
- Muons, kaons, pions.
- Large calibration samples.

Production asymmetry A_P:
- For B_s , Δm_s large → time-integrated analysis.
- For B_d , Δm_d small → time-dependent analysis to disentangle a_{sl} and A_P.

Measurement of $a_{\rm sl}$

Untagged asymmetry:

$$A(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} = A_D + \frac{a_{\rm sl}}{2} + \left(A_P - \frac{a_{\rm sl}}{2}\right)\cos(\Delta m t)$$

Detection asymmetry A_D:
- Muons, kaons, pions.
- Large calibration samples.

Production asymmetry A_P:
- For B_s , Δm_s large → time-integrated analysis.
- For B_d , Δm_d small → time-dependent analysis to disentangle a_{sl} and A_P.

$$B_s^0 \to D_s^-(\to K^+K^-\pi^-)\mu^+\nu$$

$$a_{\rm sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

[PLB 728 (2014) 607] 1.0 fb^{-1}

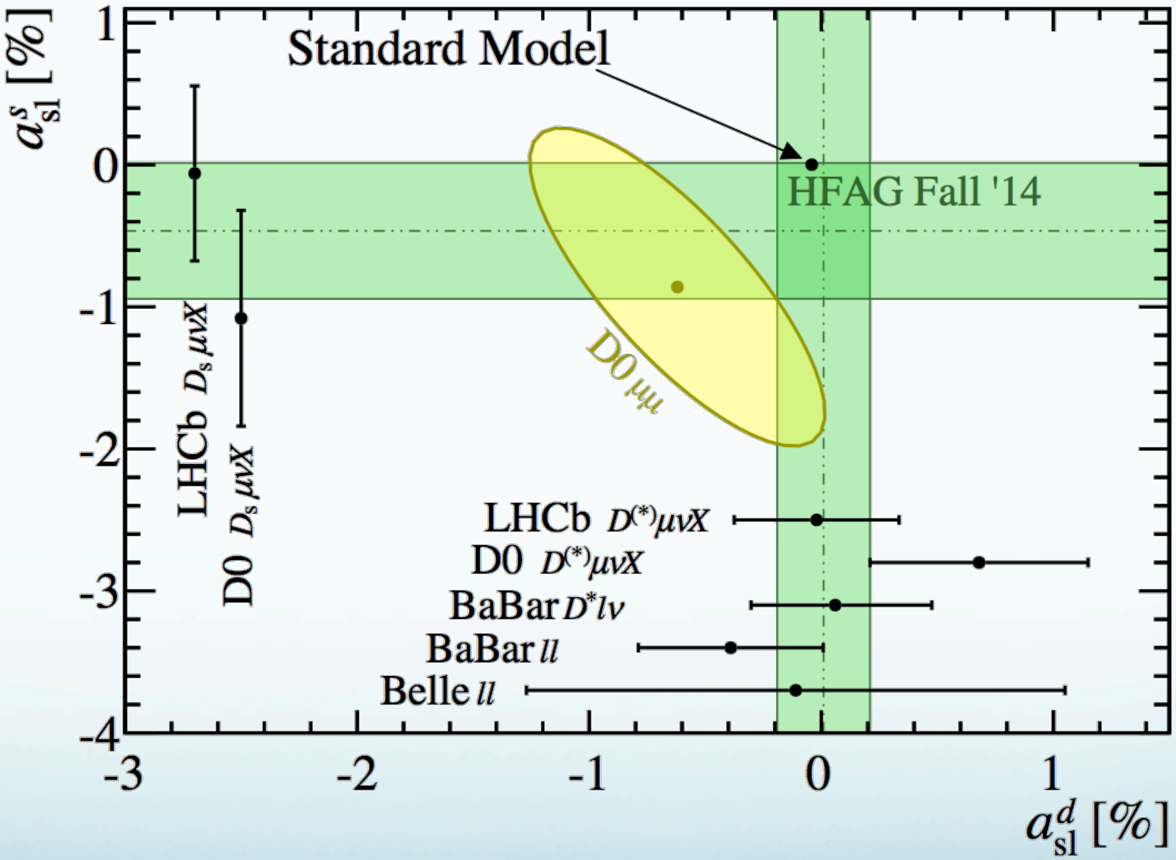
$$B^0 \to D^-(\to K^+\pi^-\pi^-)\mu^+\nu$$

$$a_{\rm sl}^d = (-0.02 \pm 0.19 \pm 0.30)\%$$

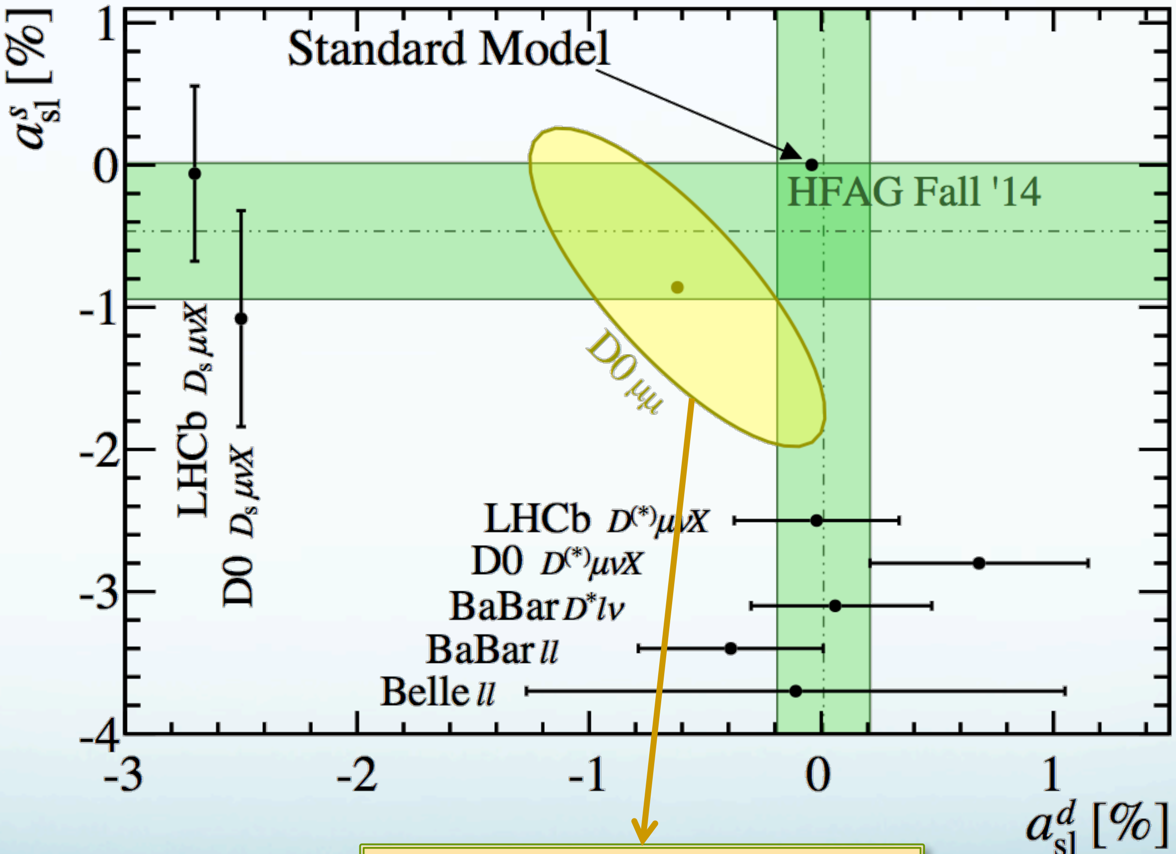
[PRL 114 (2015) 041601] 3.0 fb^{-1}

→ Systematic dominated by detection asymmetries

Current a_{sl} status



Current a_{sl} status

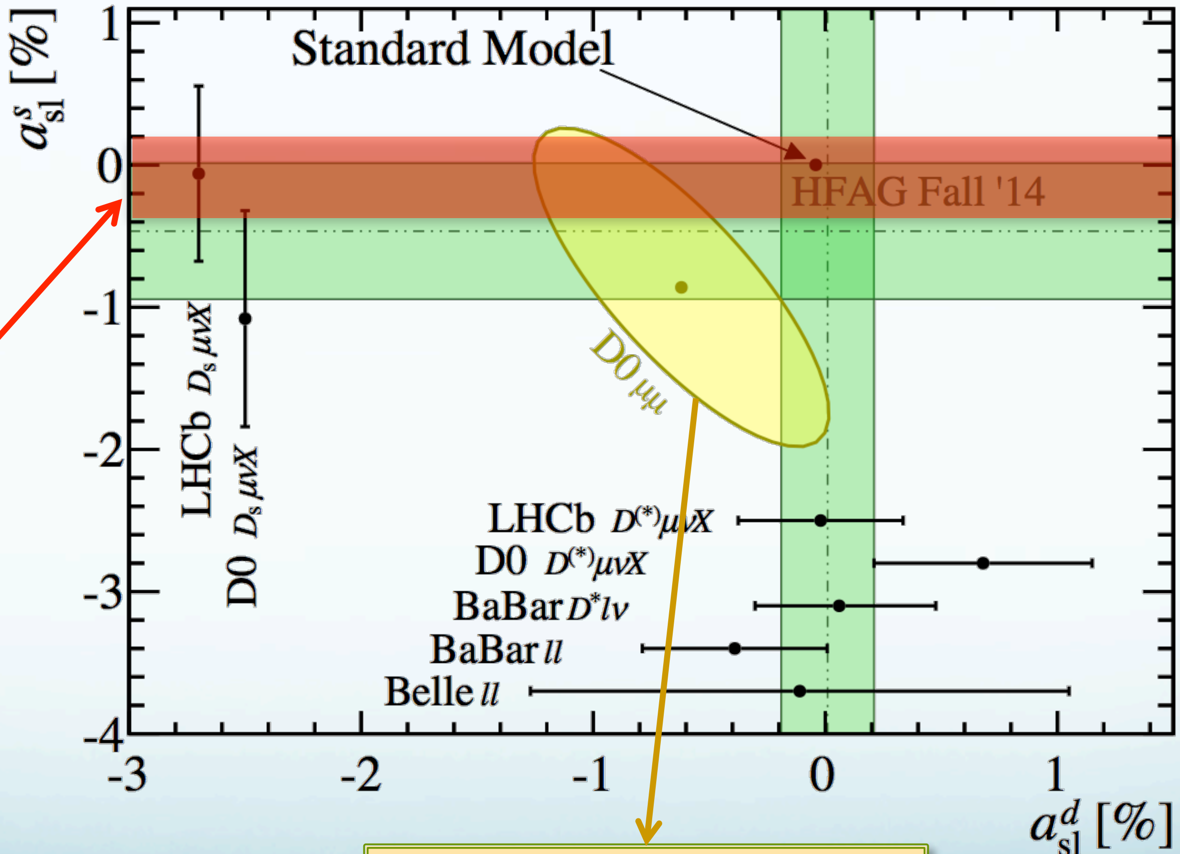


D0 measured non-zero CPV in di-muon analysis (3.6σ)

D0 [PRD89 (2014) 012002]

Current a_{sl} status

Expected sensitivity with full data set



D0 measured non-zero CPV in di-muon analysis (3.6σ)

D0 [PRD89 (2014) 012002]

CPT violation in *B* mixing

CPT violation

- *CPT* symmetry implies equal mass & lifetime B^0 and $\bar{B}^0$ mesons

$$z = \frac{\delta m - i\delta\Gamma/2}{\Delta m - i\Delta\Gamma/2}$$

- Mass eigenstates:

$$|B_L^0\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle$$
$$|B_H^0\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle$$

  - *CP* violation: $|q/p| \neq 1$
  - *CPT* violation: $z \neq 0$

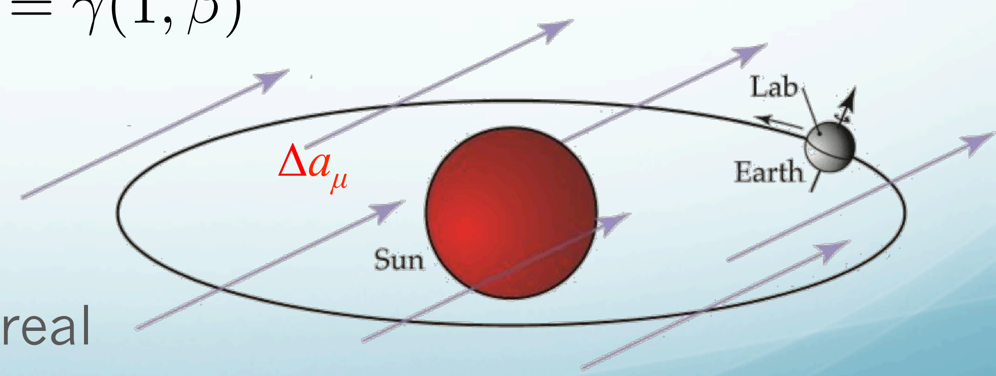
CPT and Lorentz symmetry

- *CPT* violation implies Lorentz invariance breaking.
  [Greenberg, PRL 89 (2002)]
- SME: EFT framework with *CPT*- & Lorentz-violating terms.
  [Kostelecky, PRD55 (1997) 6760]
- Experimental opportunity: measure SME parameters.

$$z = \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$$

SME coefficient for neutral mesons

- z depends on four-velocity $\beta^\mu = \gamma(1, \vec{\beta})$
  - i.e. on momentum and on direction in space
- Δa_μ is real 4-vector vacuum expectation value → z mostly real



Sidereal dependence

$$z = \frac{\beta^{\mu} \Delta a_{\mu}}{\Delta m - i\Delta\Gamma/2} \quad \rightarrow$$

$$\mathcal{R}e(z) = \frac{\gamma}{\Delta m}\left[\Delta a_0 + \cos(\chi)\Delta a_Z + \sin(\chi)\left[\Delta a_Y \sin(\Omega\hat{t}) + \Delta a_X \cos(\Omega\hat{t})\right]\right]$$

Sidereal dependence

$$z = \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2} \quad \rightarrow$$

$$\mathcal{R}e(z) = \frac{\gamma}{\Delta m}\left[\Delta a_0 + \cos(\chi)\Delta a_Z + \sin(\chi)\left[\Delta a_Y \sin(\Omega\hat{t}) + \Delta a_X \cos(\Omega\hat{t})\right]\right]$$

High sensitivity from small Δm and B meson boost.
$\langle\gamma\beta\rangle \approx 20$

Angle of B meson with Earth rotational axis. B mesons mostly along beam: $\cos(\chi)\approx-0.38$

Sidereal frequency

Sidereal dependence

$$z = \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2} \quad \rightarrow$$

$$\mathcal{R}e(z) = \frac{\gamma}{\Delta m}\Big[\Delta a_0 + \cos(\chi)\Delta a_Z + \sin(\chi)\big[\Delta a_Y \sin(\Omega\hat{t}) + \Delta a_X \cos(\Omega\hat{t})\big]\Big]$$

High sensitivity from small Δm and B meson boost.
$\langle\gamma\beta\rangle \approx 20$

Angle of B meson with Earth rotational axis. B mesons mostly along beam: $\cos(\chi) \approx -0.38$

Sidereal frequency

Hadronic decay modes give larger sensitivity than semileptonic

$$B^0 \rightarrow J/\psi\, K_S^0$$

$$B_s^0 \rightarrow J/\psi\, K^+ K^-$$

Sidereal dependence

[LHCb-PAPER-2016-005]

New result (preliminary)

$$z = \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2} \quad \rightarrow$$

$$\mathcal{R}e(z) = \frac{\gamma}{\Delta m}\left[\Delta a_0 + \cos(\chi)\Delta a_Z + \sin(\chi)\left[\Delta a_Y \sin(\Omega\hat{t}) + \Delta a_X \cos(\Omega\hat{t})\right]\right]$$

High sensitivity from small Δm and B meson boost. $\langle\gamma\beta\rangle \approx 20$

Angle of B meson with Earth rotational axis. B mesons mostly along beam: cos(χ)≈–0.38

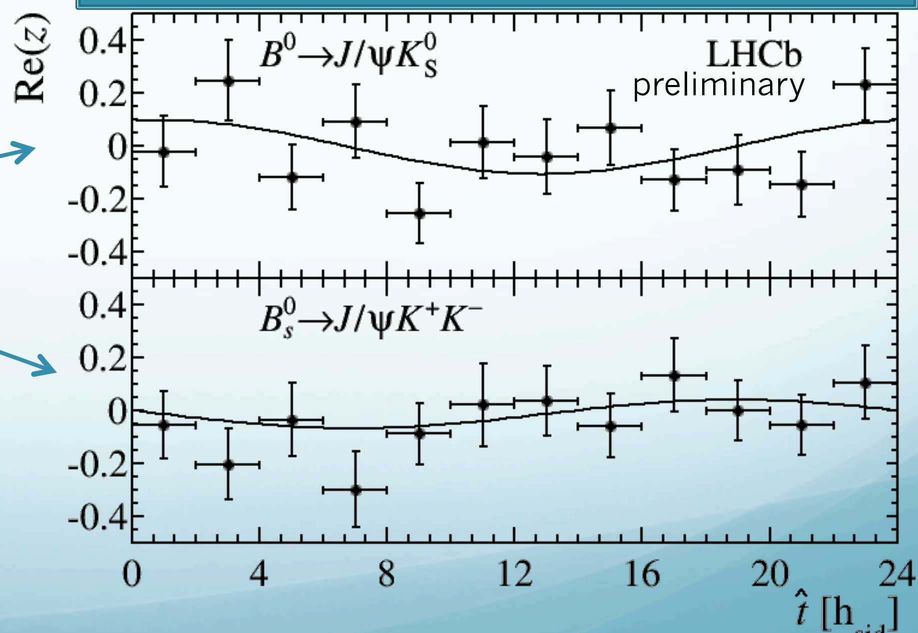
Sidereal frequency

Hadronic decay modes give larger sensitivity than semileptonic

$$B^0 \rightarrow J/\psi\, K^0_S$$

$$B^0_s \rightarrow J/\psi\, K^+K^-$$

Re(z) as function of sidereal phase



Results

[LHCb-PAPER-2016-005]

New result (preliminary)

- B_d system (SME):

$$\Delta a_0^{B^0} - 0.38\Delta a_Z^{B^0} = (-0.10 \pm 0.82\,(\text{stat}) \pm 0.54\,(\text{syst})) \times 10^{-15}\,\text{GeV}$$
$$0.38\Delta a_0^{B^0} + \Delta a_Z^{B^0} = (-0.20 \pm 0.22\,(\text{stat}) \pm 0.04\,(\text{syst})) \times 10^{-13}\,\text{GeV}$$
$$\Delta a_X^{B^0} = (+1.97 \pm 1.30\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-15}\,\text{GeV}$$
$$\Delta a_Y^{B^0} = (+0.44 \pm 1.26\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-15}\,\text{GeV}$$

O(10^3) more precise than BaBar result [PRL 100 (2008) 131802]

- B_s system (SME):

$$\Delta a_0^{B_s^0} - 0.38\Delta a_Z^{B_s^0} = (-0.89 \pm 1.41\,(\text{stat}) \pm 0.36\,(\text{syst})) \times 10^{-14}\,\text{GeV}$$
$$0.38\Delta a_0^{B_s^0} + \Delta a_Z^{B_s^0} = (-0.47 \pm 0.39\,(\text{stat}) \pm 0.08\,(\text{syst})) \times 10^{-12}\,\text{GeV}$$
$$\Delta a_X^{B_s^0} = (+1.01 \pm 2.08\,(\text{stat}) \pm 0.71\,(\text{syst})) \times 10^{-14}\,\text{GeV}$$
$$\Delta a_Y^{B_s^0} = (-3.83 \pm 2.09\,(\text{stat}) \pm 0.71\,(\text{syst})) \times 10^{-14}\,\text{GeV}$$

O(10) more precise than recent D0 result [PRL 115 (2015) 161601]

- B_s system: (no assumption on Lorentz breaking)

$$\mathcal{R}e(z^{B_s^0}) = -0.022 \pm 0.033\,(\text{stat}) \pm 0.003\,(\text{syst})$$
$$\mathcal{I}m(z^{B_s^0}) = 0.004 \pm 0.011\,(\text{stat}) \pm 0.002\,(\text{syst})$$

First measurement of z in B_s system

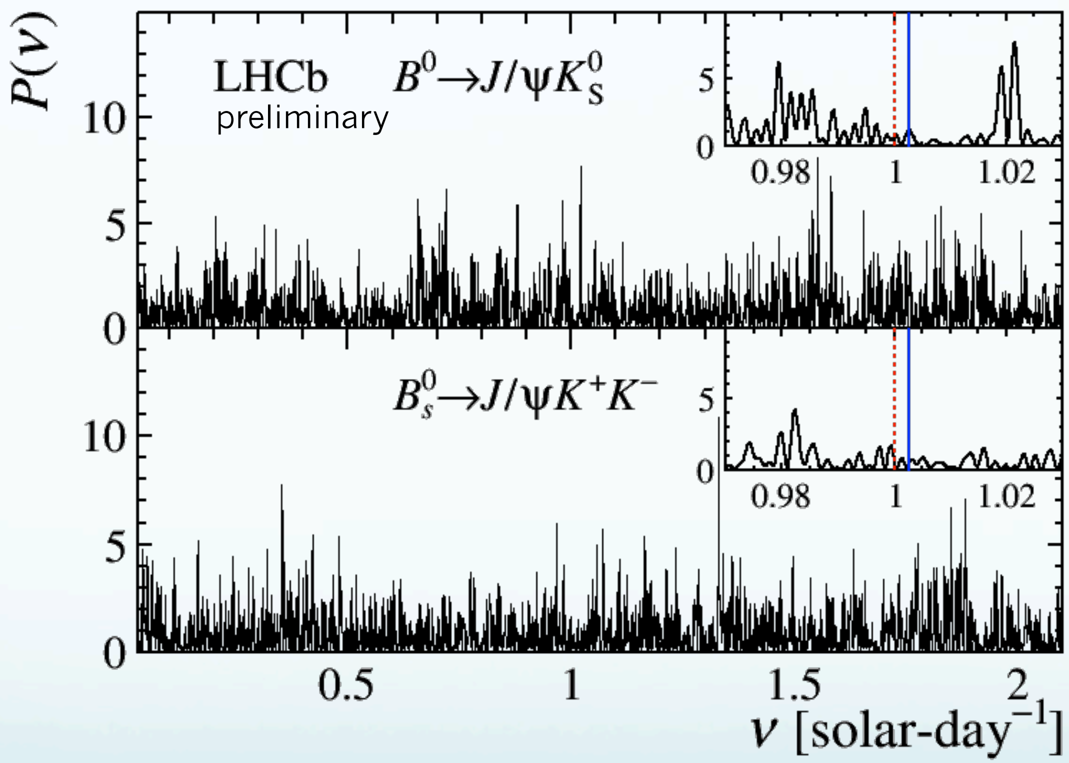
Consistent with *CPT* and Lorentz symmetry

Periodogram test

[LHCb-PAPER-2016-005]

New result (preliminary)

Scan large frequency range (not only sidereal):



→ No significant peaks found at *p*-values of 0.57 and 0.06

Conclusions

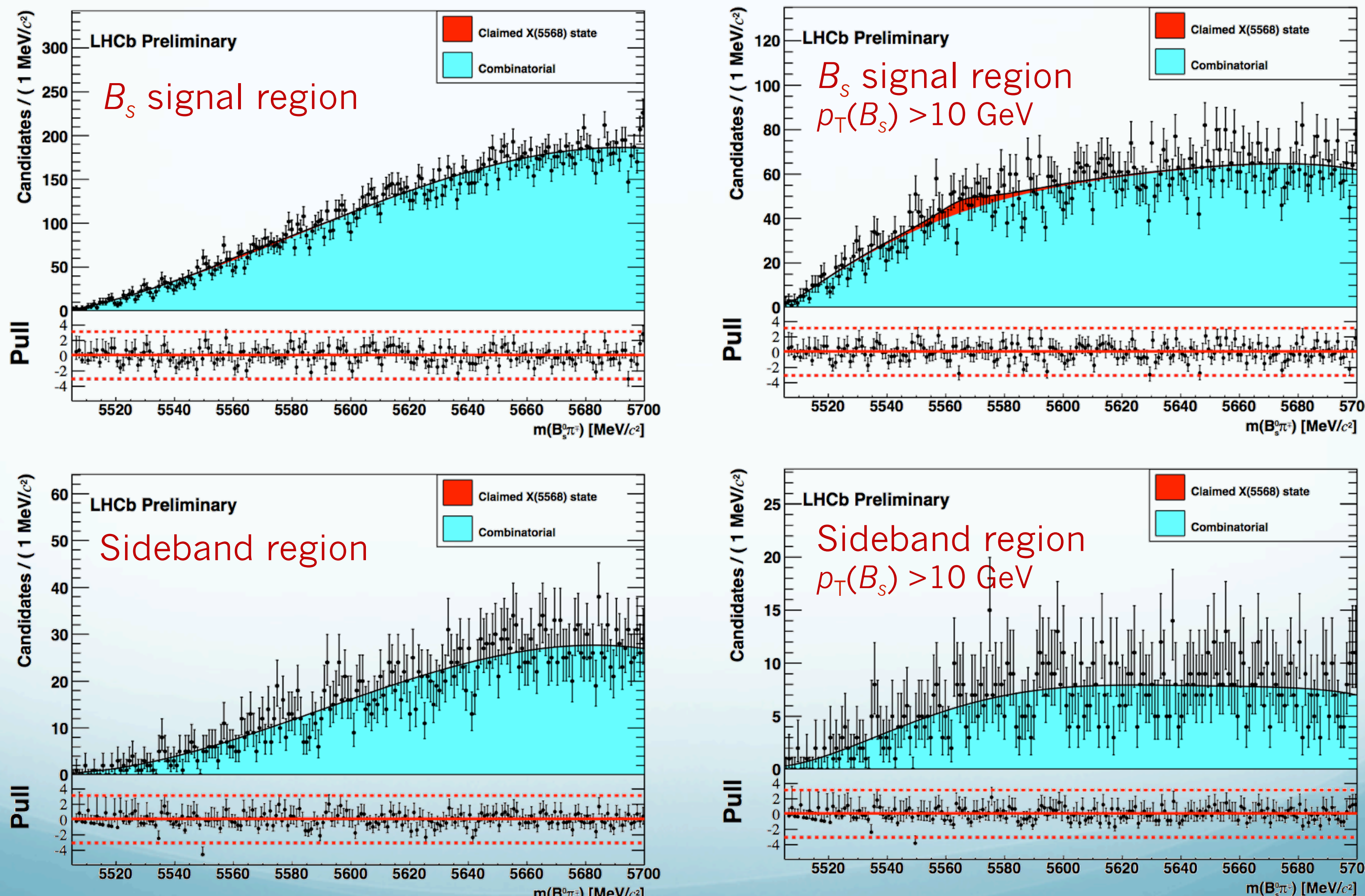
- No confirmation of X(5568) (LHCb-CONF-2016-004 preliminary)
- Semileptonic decays challenging, but interesting results:
  - B_d oscillations, CP violation, $|V_{ub}/V_{cb}|$.

    [LHCb-PAPER-2015-031] [PLB 728 (2014) 607] [PRL 114 (2015) 041601] [NP 10 (2015) 1038]
- New results on *CPT* & Lorentz violation
  - Improved limits SME parameters in B_d system [LHCb-PAPER-2016-005]
  - First measurements in B_s system (Δa_μ and z)

Backup

More $B_s\pi$ spectra

[LHCb-CONF-2016-004]
in preparation



Systematic uncertainties

[LHCb-PAPER-2016-005]

New result (preliminary)

B^0 mixing Source	$\Delta a_{\parallel}$	$\Delta a_{\perp}$ [$\times 10^{-15}$ GeV]	$\Delta a_{X,Y}$
Mass correlation	–	–	0.04
Wrong PV assignment	–	1	–
Production asymmetry	0.28	1	0.05
External input C_f, S_f	0.46	4	0.28
Decay width difference	0.07	–	–
Neutral kaon asymmetry	–	1	–
Quadratic sum	0.54	4	0.29

Largest contribution: Fixed C_f & S_f due to correlation with z. External input not affected by LIV, due to low boost. Only works for SME approach.

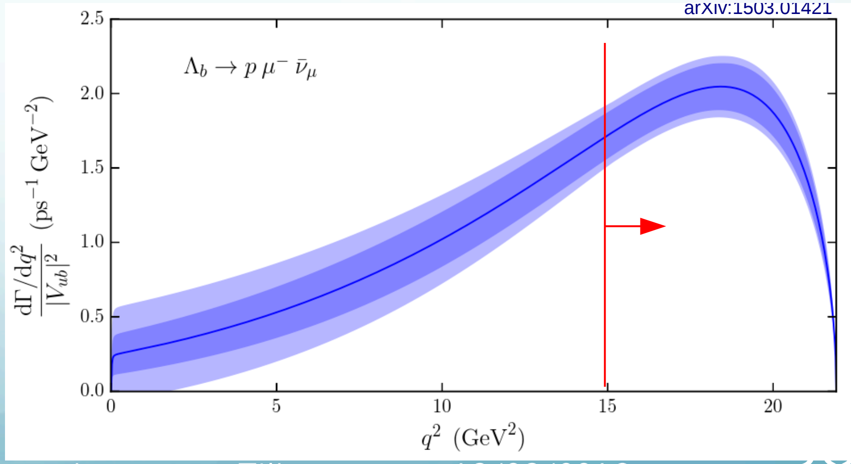
B_s^0 mixing Source	$\Delta a_{\parallel}$	$\Delta a_{\perp}$ [$\times 10^{-14}$ GeV]	$\Delta a_{X,Y}$	$\mathcal{R}e(z)$	$\mathcal{I}m(z)$
Mass correlation	0.10	3	0.24	0.001	0.002
Peaking background	0.14	3	0.15	0.003	–
Decay time acceptance	0.30	7	0.65	–	0.001
Angular acceptance	–	–	–	0.002	0.001
Quadratic sum	0.36	8	0.71	0.003	0.002

Small → No systematic effects expected with sidereal and boost dependence.

LHCb's $|V_{ub}|$ with $\Lambda_b \to p\mu\nu$

[Nature Physics 10 (2015) 1038]

- Backgrounds too large for inclusive decays and for exclusive $B \to \pi\mu\nu$
- ~20% of b-hadrons are Λ_b baryons
- Use BF($\Lambda_c \to pK\pi$) for normalisation: 5% uncertainty
  - Belle measurement [PRL 113 (2014) 04002]
- Accurate lattice prediction on $\Lambda_b \to p$ form factors:
  - Uncertainty ~5%
  - [Phys. Rev. D 92, 034503 (2015)]
- Analysis strategy:
  - Normalization & main background $\Lambda_b \to \Lambda_c \mu\nu$
  - Corrected mass from flight direction (+uncertainty)

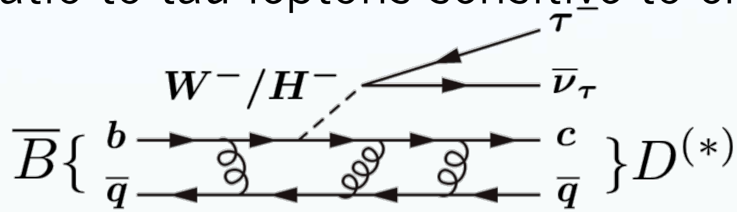


Are all leptons equal?

Semitauonic branching ratio

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

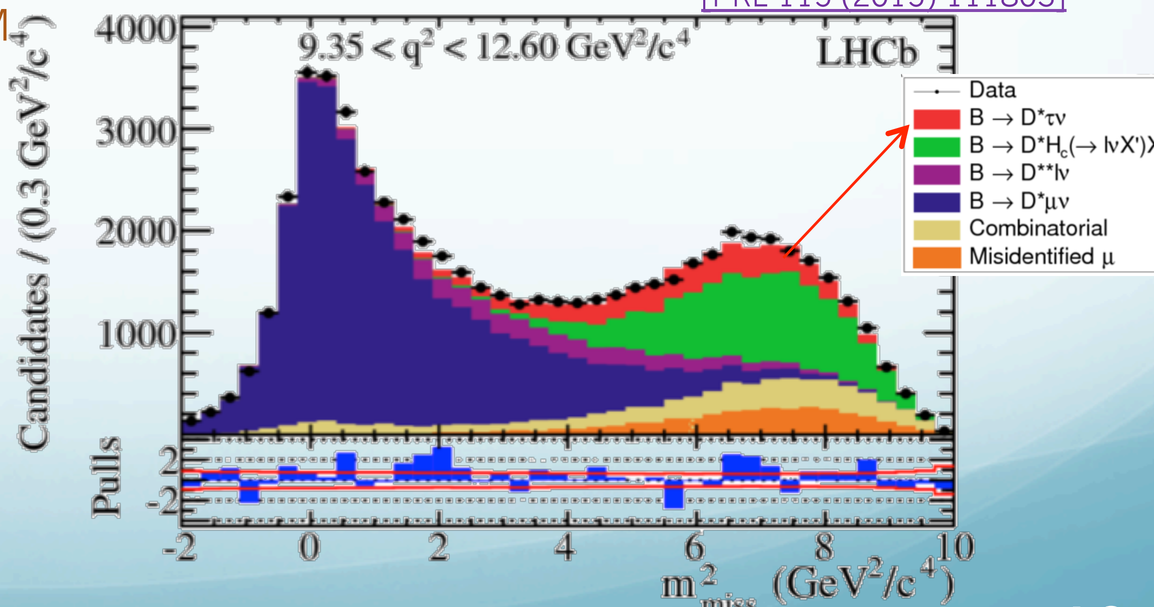
- Branching ratio to tau leptons sensitive to charged Higgs



- Large, anomalous BR in $B \to D^{(*)}\tau\nu$ at BaBar.
  - 3.2σ tension with SM.

- LHCb:
  - Start with cleaner D^* and $\tau\to\mu\nu\nu$ mode.
  - Fit to m^2_{miss} and E_μ in q^2 bins.

[PRL 115 (2015) 111803]



BR of $B \to D^* \tau \nu$ at LHCb

- LHCb measurement confirms BaBar result.

$$\mathcal{R}(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$$ [PRL 115 (2015) 111803]

- Increases tension with SM

Difference with SM 3.9 σ (HFAG)