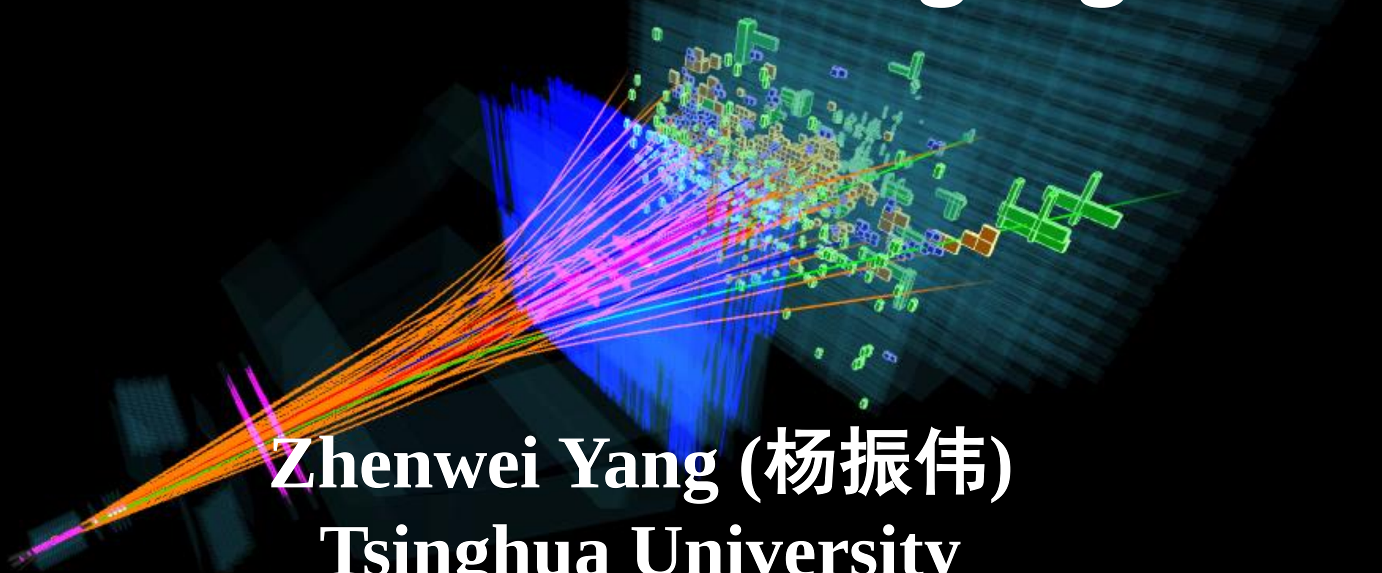
第十二届全国粒子物理学术会议
2016.08.22-26, 合肥

TSINGHUA UNIVERSITY

LHCb status report
— selected recent highlights



Zhenwei Yang (杨振伟)
Tsinghua University

on behalf of the LHCb collaboration

2016.08.22

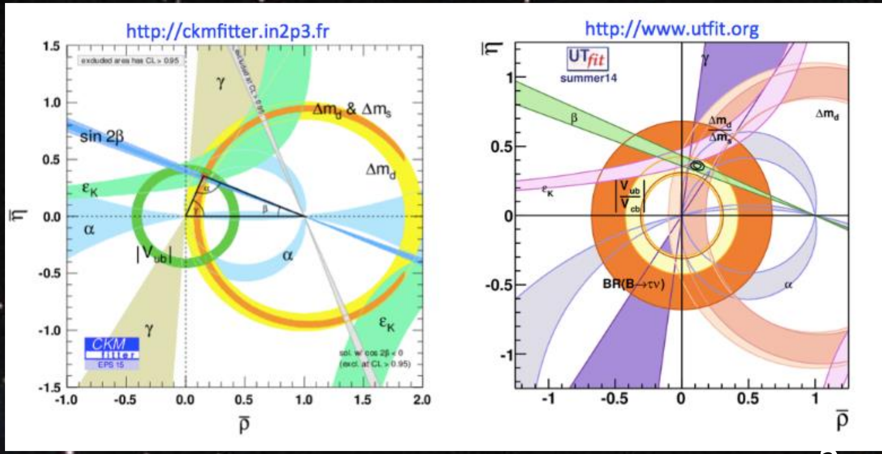
Outline

- **Introduction**
- **CPV in *b* sector**
- **Rare *B* decay & lepton universality**
- **Summary and outlook**

- Rare decays and CPV in *c* sector
  — talk by Liang SUN at 16:10, Tuesday
- Exotic hadrons
  — talk by Liming ZHANG at 14:40, Tuesday

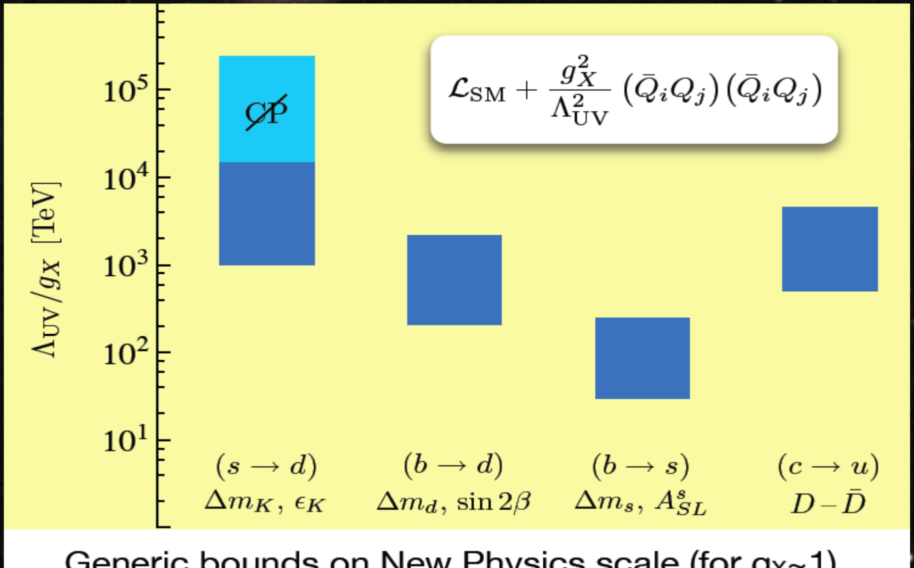
Are we satisfied with SM?

- The Standard Model (SM) works fantastically in a profound way, however, it is believed to be
  - An effective theory up to some scale
- Good reasons to believe that SM is incomplete and that New Physics (NP) beyond is needed
  - Missing dark matter candidate
  - CP violation for dynamical generation of Baryon Asymmetry in Universe (BAU) largely insufficient
  - ……
- We must search for
  - New particles & interactions
  - New sources of CPV



Opportunities in flavor sector

- Flavor as a window to NP, complementary to direct searches
  - Exploring NP scale ≫ TeV
  - Distinguishing NP models



Generic bounds on New Physics scale (for g_X~1)

- NP could have significant effects in processes where SM contribution is suppressed and well understood
  - Mixing processes
  - Rare loop decays
  - SM forbidden decays

- Decay rates
- CP asymmetries
- Angular correlations

Precision measurements are essential !!

The power of precision

- **Sensitive to "New" Physics effects off-shell**
  - When was the Z boson discovered?
    - ✓1973 from $\nu N \to \nu N$? 1983 at SPS collider?
  - c quark needed to explain $K_L^0 \to \mu^+\mu^-$ (GIM)
  - The 3rd family (b, t) to explain CP violation (Kobayashi & Maskawa)
  - ……
- **Ingredients for where to look**
  - Precise SM prediction
  - (desirable) Precise beyond-SM predictions
  - Good experimental precision

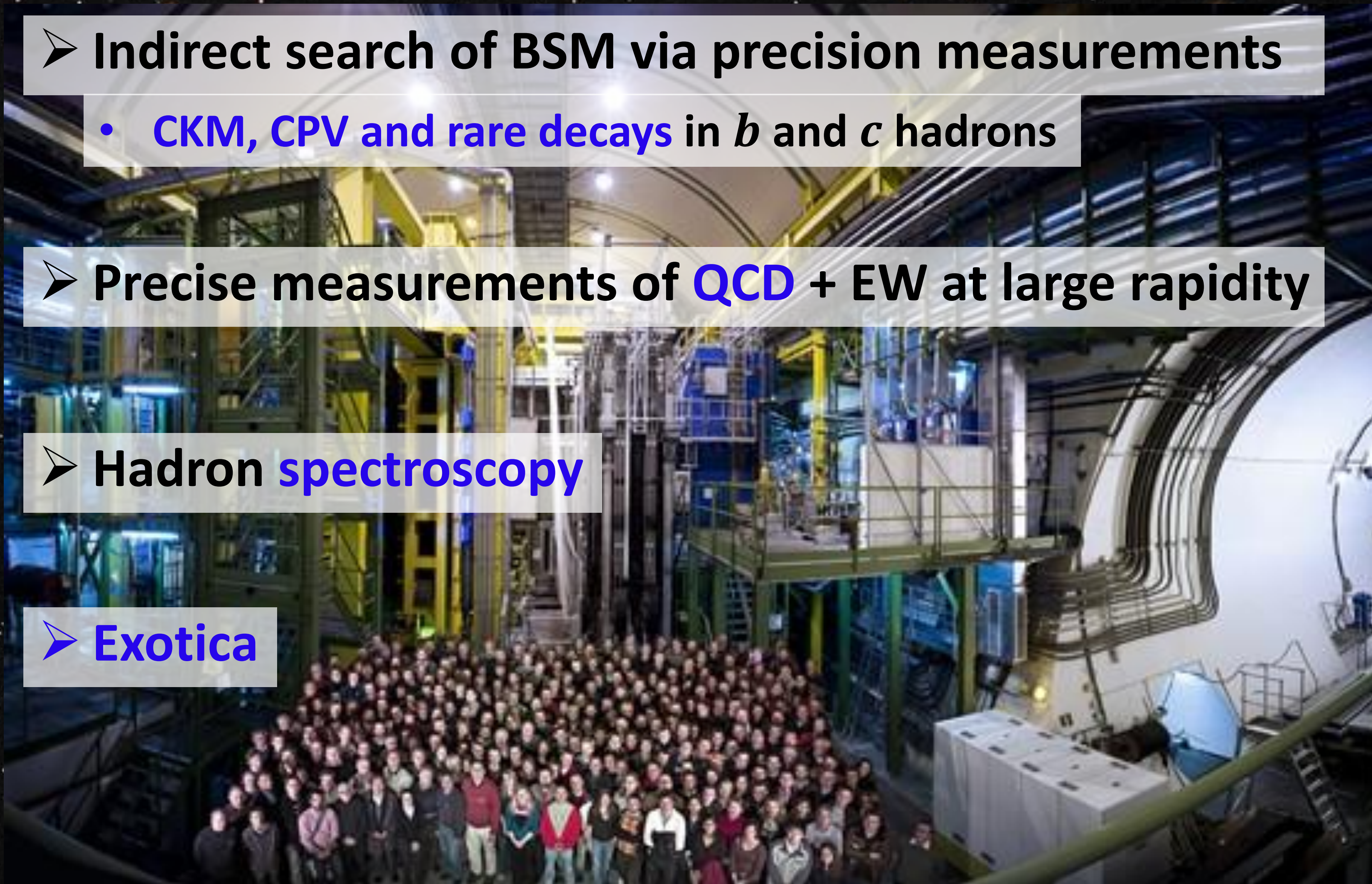
This is what the LHCb detector designed for ……

The LHCb collaboration

- 1199 members from 69 institutes in 16 countries
- 4 institutes from China
  - Tsinghua Univ.
  - CCNU
  - UCAS
  - Wuhan Univ.

Physics goals of LHCb

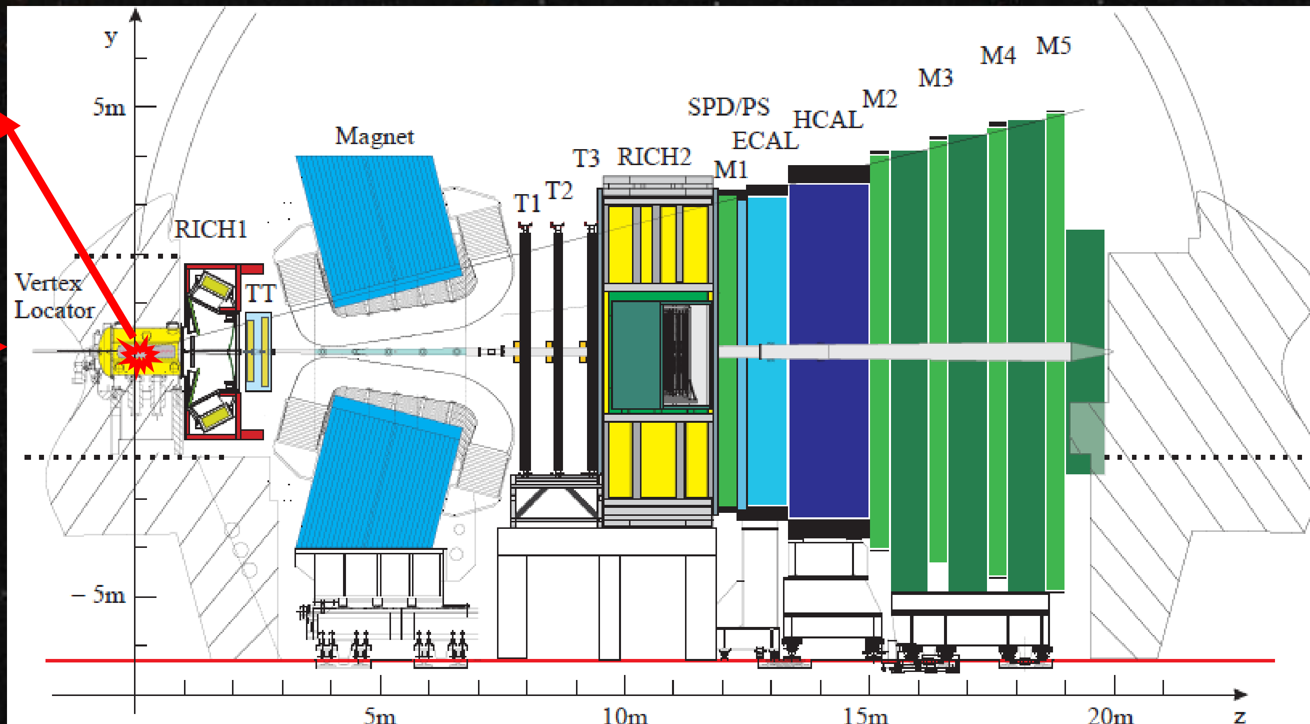
- ➢ Indirect search of BSM via precision measurements
  - CKM, CPV and rare decays in b and c hadrons
- ➢ Precise measurements of QCD + EW at large rapidity
- ➢ Hadron spectroscopy
- ➢ Exotica



The LHCb detector

Collision point

Beam



Beam

Acceptance
$2 < \eta < 5$

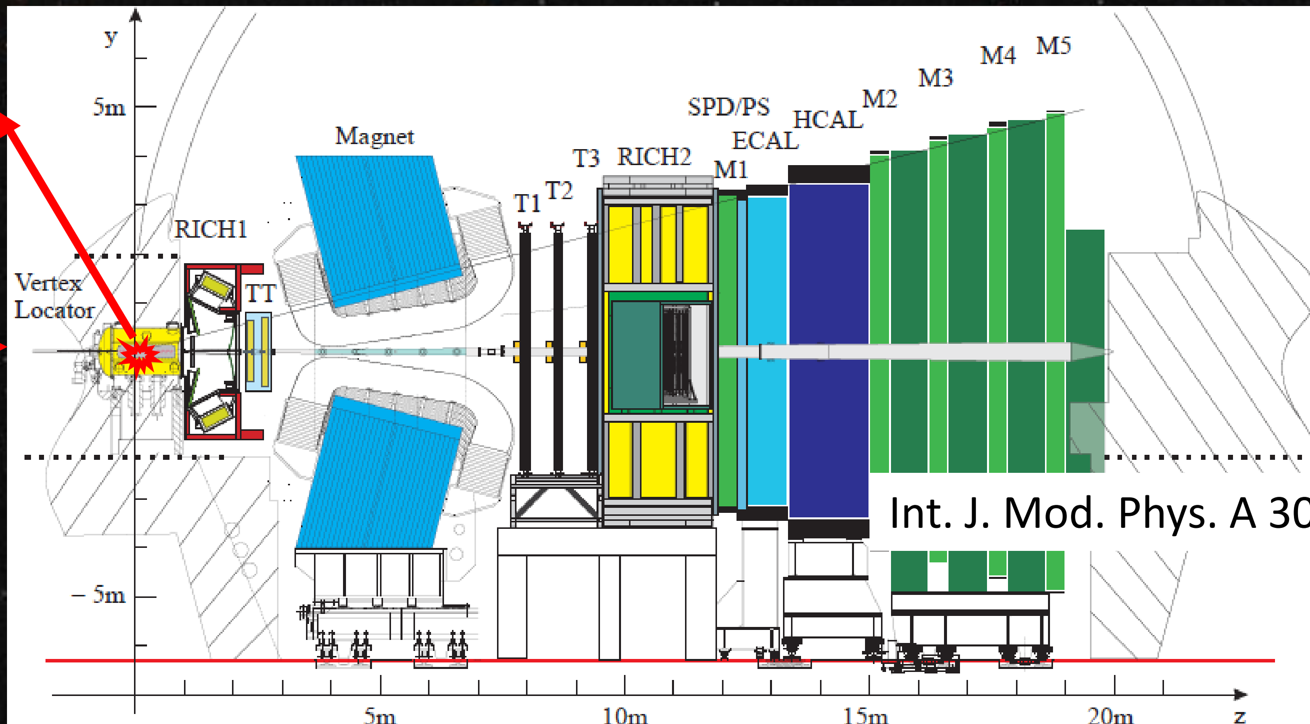
Int. J. Mod. Phys. A 30 (2015) 1530022

Impact parameter:	$\sigma_{IP} = 20\ \mu\text{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $m_{J/\psi}$)
RICH $K-\pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1-3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

The LHCb detector

Collision point

Beam



Beam

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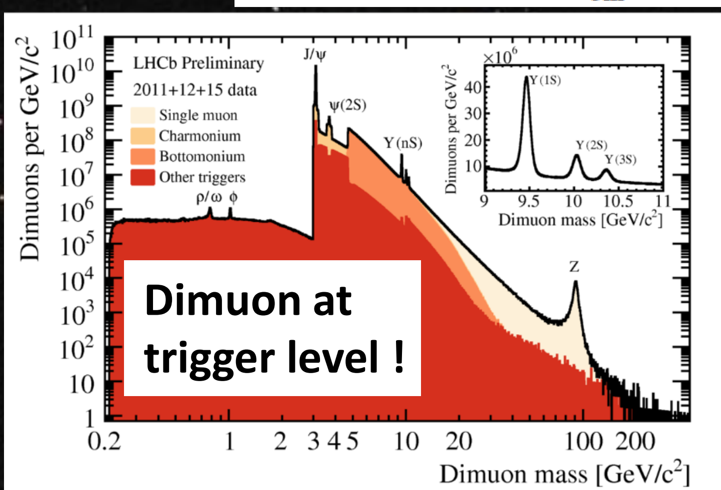


Dimuon at trigger level !

$\sigma_{IP} = 20\ \mu\text{m}$

$\sigma_\tau = 45$ fs for $B_s^0 \rightarrow$

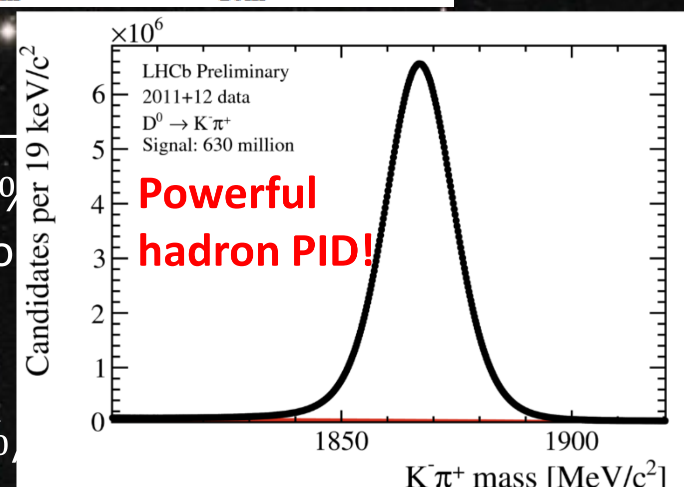
$\Delta p/p = 0.4 \sim 0.6\%$

$\sigma_m = 8\ \text{MeV}/c^2$ fo

$\epsilon(K \rightarrow K) \sim 95\%$

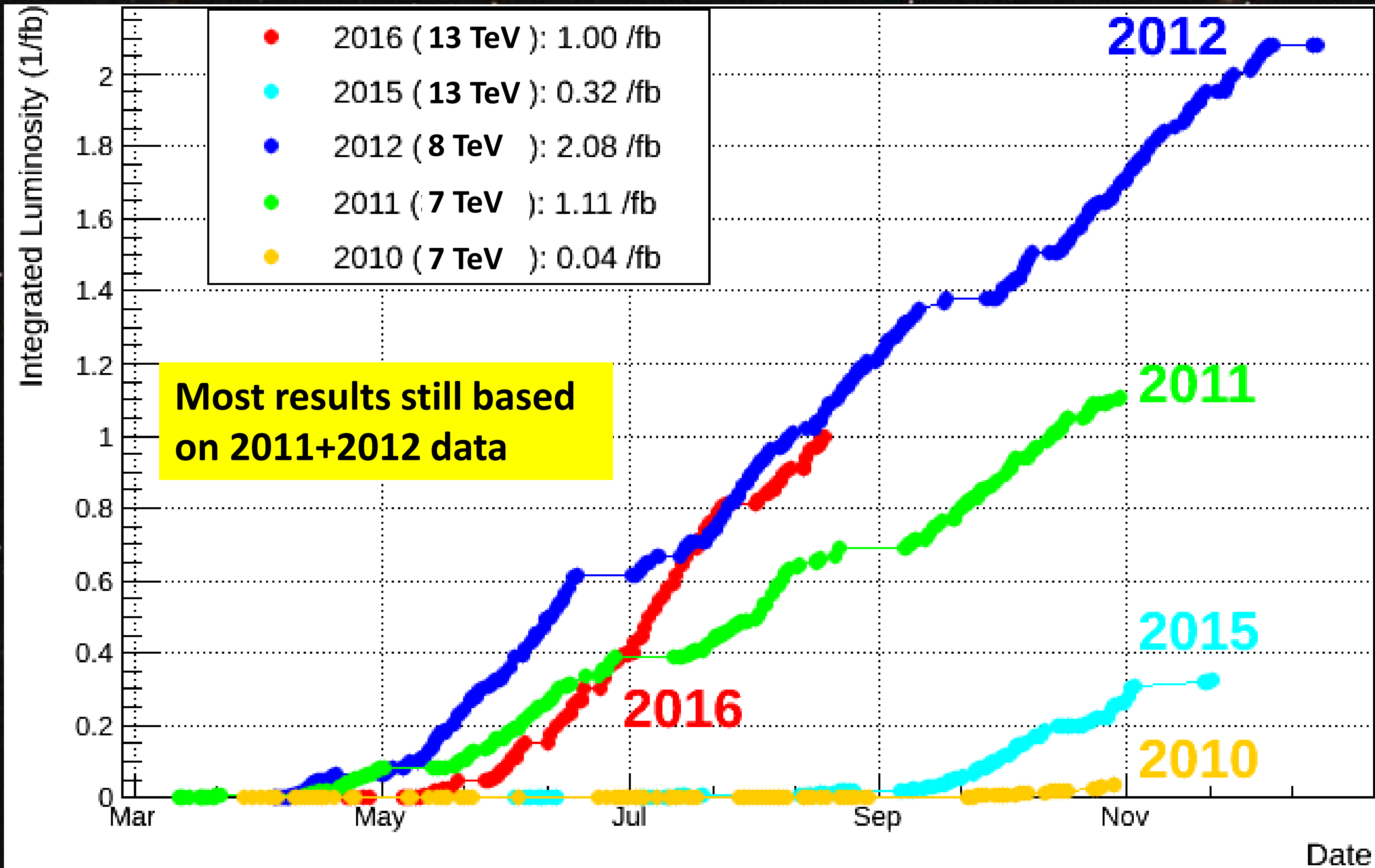
$\epsilon(\mu \rightarrow \mu) \sim 97\%$

$\Delta E/E = 1 \oplus 10\%$



Powerful hadron PID!

LHCb data taking



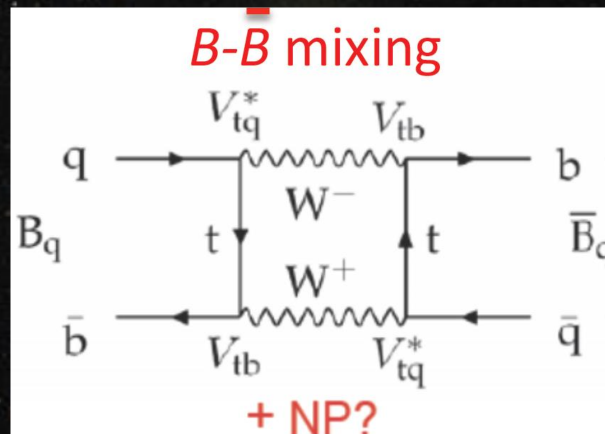
CPV in b sector

- a_{sl}^{q} in $B \to D\mu\nu X$
- $\sin 2\beta$ in $B^0 \to J/\psi K_s^0$
- ϕ_s measurements
- Evidence of CPV in $\Lambda_b^0 \to p\pi^- h^+ h^-$

Neutral B mixing

➢ **Weak states mix via box diagram: flavor oscillation**

$|B_q\rangle = |\bar{b}q\rangle$



$|\bar{B}_q\rangle = |b\bar{q}\rangle$

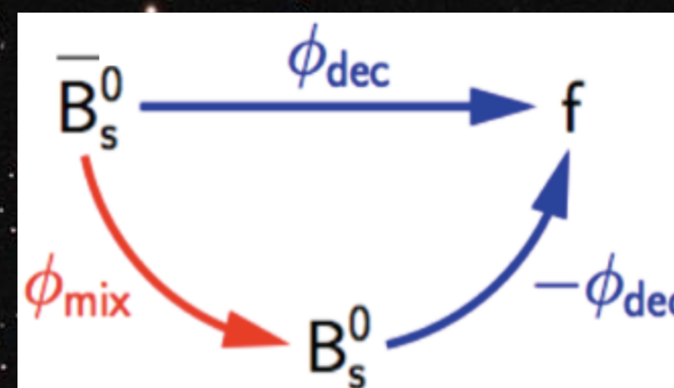
$$|B_L^q\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$$
$$|B_H^q\rangle = p|B_q\rangle - q|\bar{B}_q\rangle$$

Mass eigenstates

$\Delta m_q = m_H - m_L, \ \Delta\Gamma_q = \Gamma_L - \Gamma_H$

CPV observables

- CPV in mixing: a_{sl}^{q}
- Mixing-induced CPV: $\phi_s, \phi_d = 2\beta$



a_{sl}^{q}, ϕ_q and Δm_q are very sensitive to NP in mixing

a_{sl}^{q} results

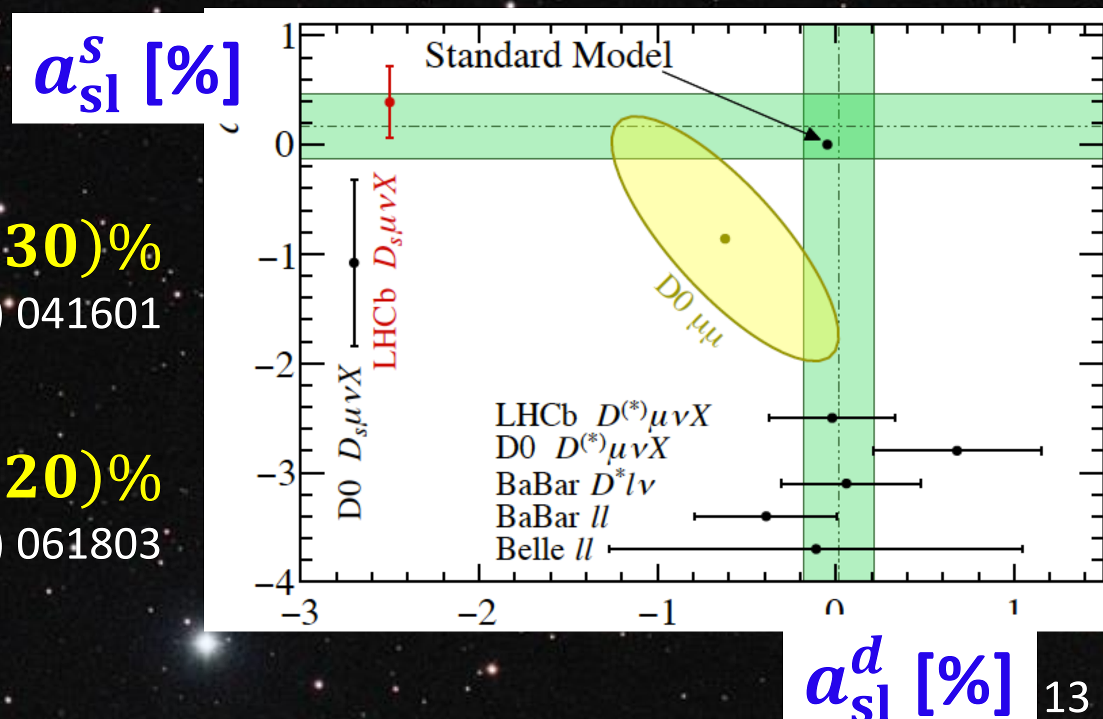
- The D0 measurement yields an anomalous **dimuon asymmetry** [PRD 89 (2014) 012002], indicating a surprising deviation from SM in the $(a_{\mathrm{sl}}^{d}, a_{\mathrm{sl}}^{s})$ plane
- LHCb measurements of a_{sl}^{d} and a_{sl}^{s} do not support the deviation

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

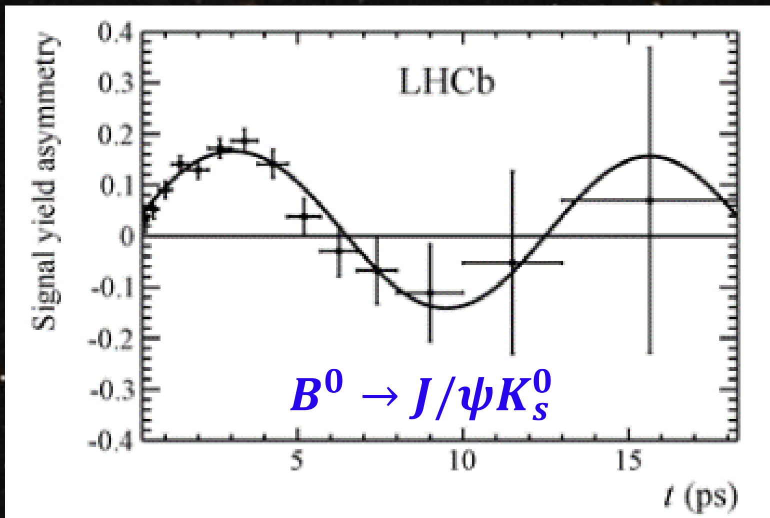
PRL 114 (2015) 041601

$$a_{\mathrm{sl}}^{s} = (-0.39 \pm 0.26 \pm 0.20)\%$$

PRL 117 (2016) 061803

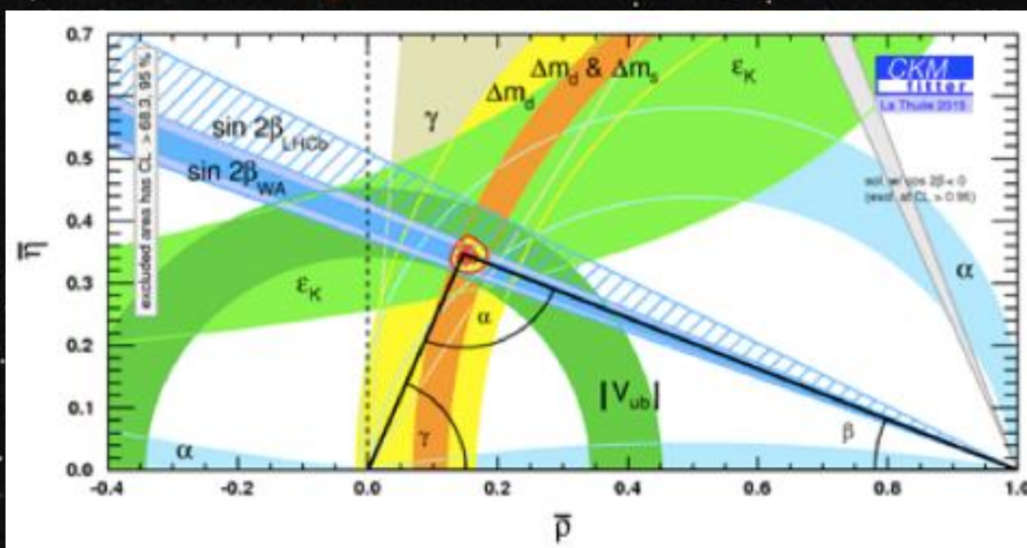


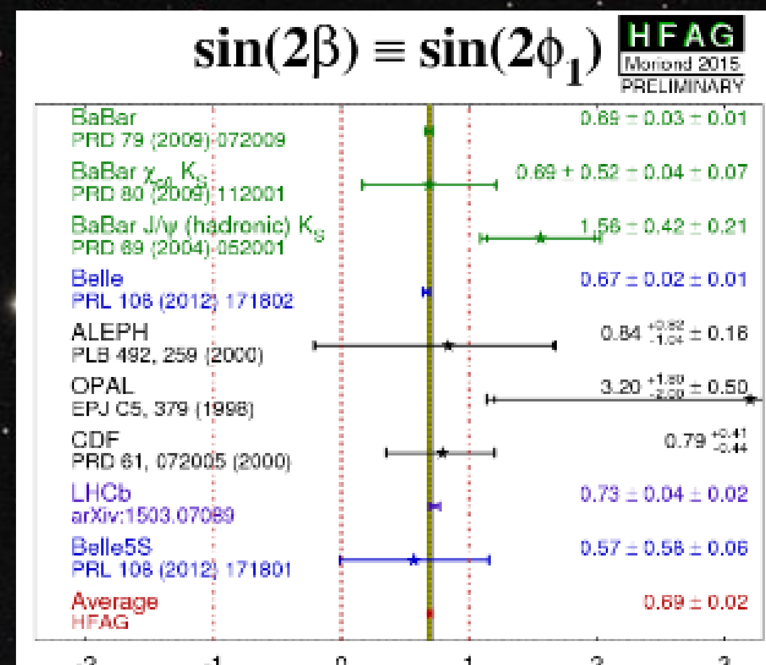
Sin2β: a milestone of modern beauty physics



- First CPV in B decays observed by BaBar and Belle in 2001 [PRL 87 (2001) 091801/2]
- $\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$

  LHCb, PRL 115 (2015) 031601
- Indirect fit in SM: $\sin 2\beta = 0.771^{+0.017}_{-0.041}$

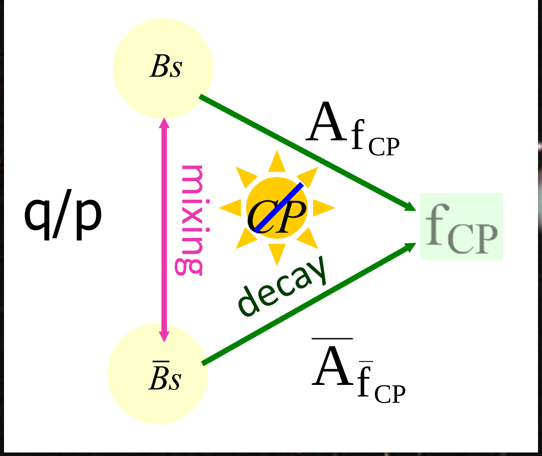


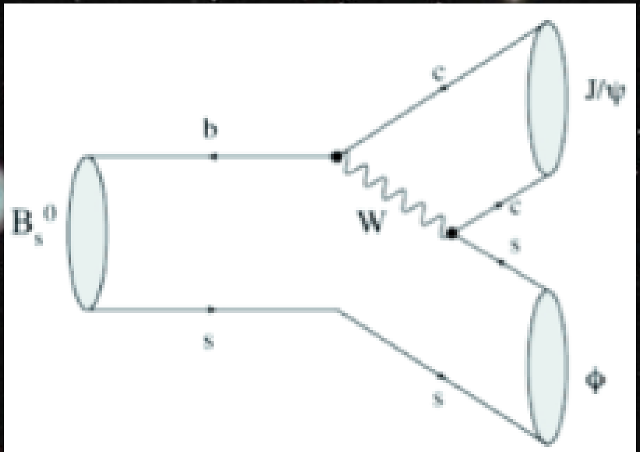


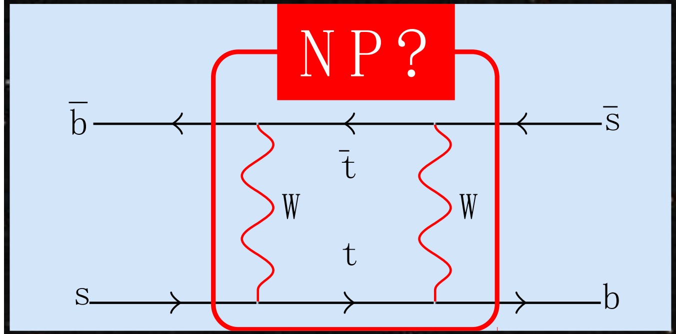
LHCb result is now competitive with B factories.

ϕ_s from $b - c\bar{c}s$ transitions

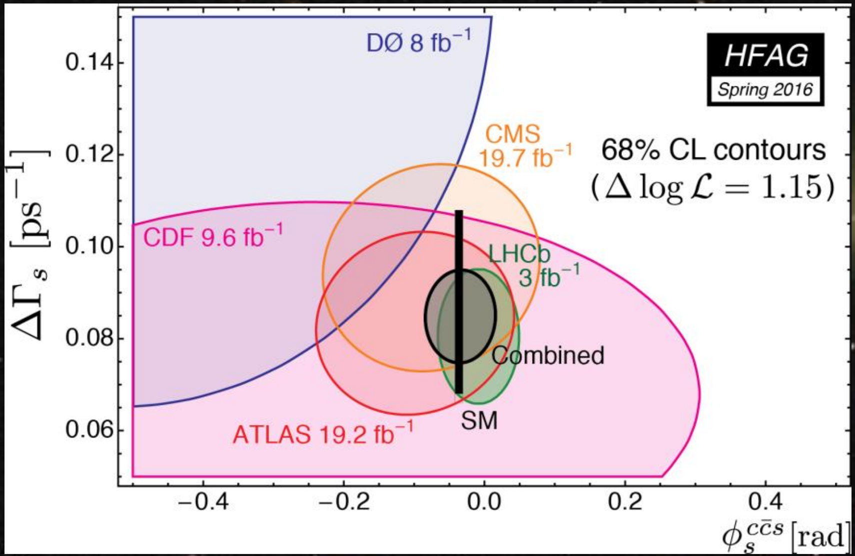
- A crucial goal of LHCb
  - 10% of b hadrons in pp collisions at the LHC are B_s^0 mesons
  - Measuring CPV in B_s^0 is the LHC(b) territory
- For $\phi_s \equiv -\arg\left(\eta_{f_{CP}} \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right)$ for $B_s^0 \to J/\psi\phi$ decays
- Precisely predicted in SM: $\phi_s^{\mathrm{SM}} = -0.038 \pm 0.001\,\mathrm{rad}$
  - Up to small corrections due to penguin pollution
- Very sensitive to NP in mixing: $\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$







ϕ_s from $B_s^0 \to J/\psi\phi, J/\psi\pi^+\pi^-$



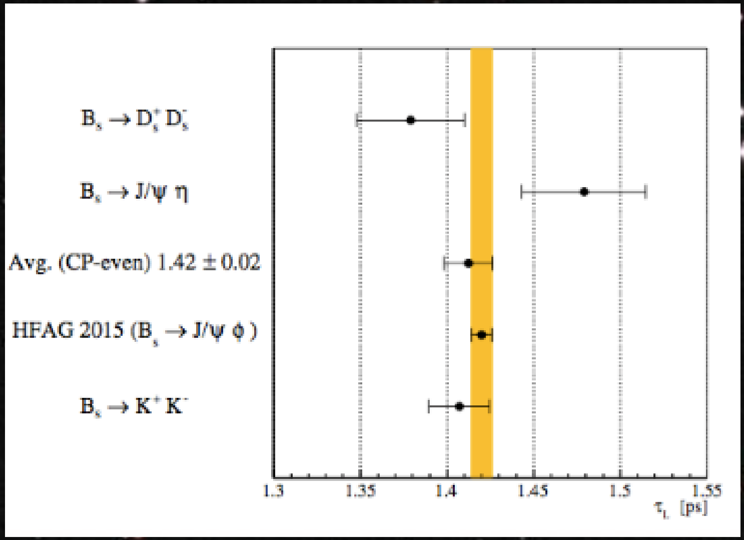
PRL 114 (2014) 041801

- $\phi_s = -0.010 \pm 0.039$ **rad**
- **Consistent with SM prediction:**
  - $\phi_s^{SM} = -0.038 \pm 0.001$ rad
- **Dominating world average**
  - $\phi_s^{HFAG} = -0.030 \pm 0.033$ rad
- **Still statistically limited**

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	[−0.60, +0.12], 68% CL	$+0.068 \pm 0.026 \pm 0.009$	Phys. Rev. Lett. **109**, 171802 (2012)
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	Phys. Rev. **D85**, 032006 (2012)
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	Phys. Rev. **D90**, 052007 (2014)
ATLAS	$J/\psi\phi$	14.3 fb^{-1}	$-0.123 \pm 0.089 \pm 0.041$	$+0.096 \pm 0.013 \pm 0.007$	arXiv:1601.03297
ATLAS	above 2 combined		$-0.098 \pm 0.084 \pm 0.040$	$+0.083 \pm 0.011 \pm 0.007$	arXiv:1601.03297
CMS	$J/\psi\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	Phys. Lett. **B757**, 97–120 (2016)
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	Phys. Lett. **B736**, 186 (2014)
LHCb	above 2 combined		-0.010 ± 0.039(tot)	—	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	Phys. Rev. Lett. **113**, 211801 (2014)
All combined			-0.033 ± 0.033	$+0.084 \pm 0.007$	

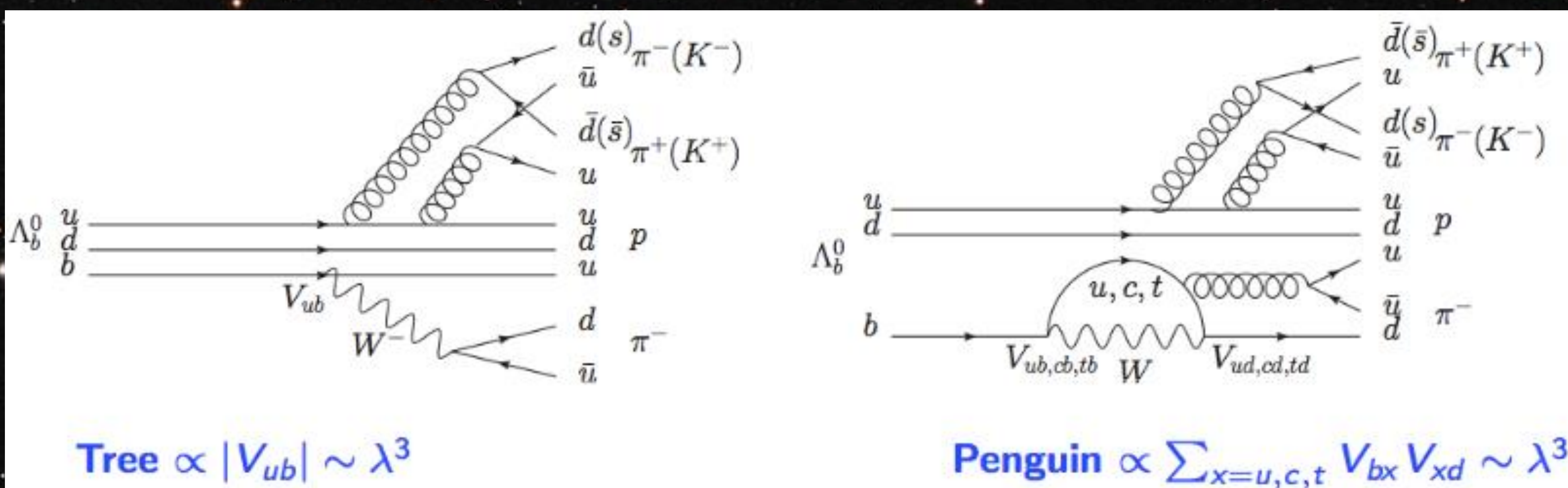
ϕ_s from more $b \to c\bar{c}s$ modes

- $B_s^0 \to D_s^+ D_s^-$: [PRL 113 (2014) 211801]
  - $\phi_s = 0.02 \pm 0.17 \pm 0.02$ rad
- $B_s^0 \to \psi(2S)\phi$: [arXiv:1608.04855]
  - $\phi_s = 0.23 \pm 0.17 \pm 0.02$ rad
- $B_s^0 \to J/\psi\eta$: CP-even mode, lifetime measured: [LHCb-PAPER-2016-017]
  - $\tau(B_s^0 \to J/\psi\eta) = 1.479 \pm 0.034 \pm 0.011$ ps
- More results is underway
  - $B_s^0 \to J/\psi K^+K^-$ above $\phi(1020)$
  - $B_s^0 \to \eta_c\phi(1020)$
  - $B_s^0 \to J/\psi\phi$ with $J/\psi \to e^+e^-$
  - ……



CPV in baryon decays: $\Lambda_b^0 \to p\pi^- h^+ h^-$

- CPV has never been observed in the decays of baryons
- A_{CP} expected in charmless decays of Λ_b^0 by SM: $\sim 20\%$
  - Y. K. Hsiao et al, PRD 91 (2015) 116007
- Contributions from tree and loop diagrams are comparable for $\Lambda_b^0 \to p\pi^- h^+ h^-$ decays



V_{ub} has large phase γ

Triple product asymmetry

- Search for CPV using **Triple Product Asymmetry (TPA)**

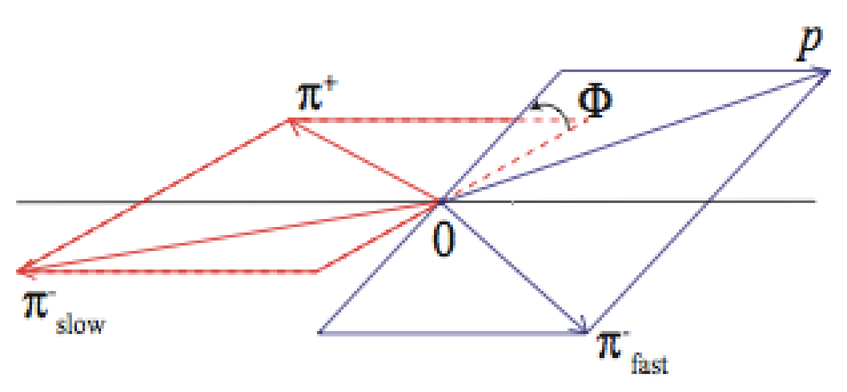
Triple products in the Λ_b rest frame:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h-} \times \vec{p}_{h+}) \propto \sin\Phi$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h+} \times \vec{p}_{h-}) \propto \sin\overline{\Phi}$$

$\hat{T}$-odd asymmetries:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}}>0) - N_{\Lambda_b^0}(C_{\hat{T}}<0)}{N_{\Lambda_b^0}(C_{\hat{T}}>0) + N_{\Lambda_b^0}(C_{\hat{T}}<0)}$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}$$



CP-violating observable:

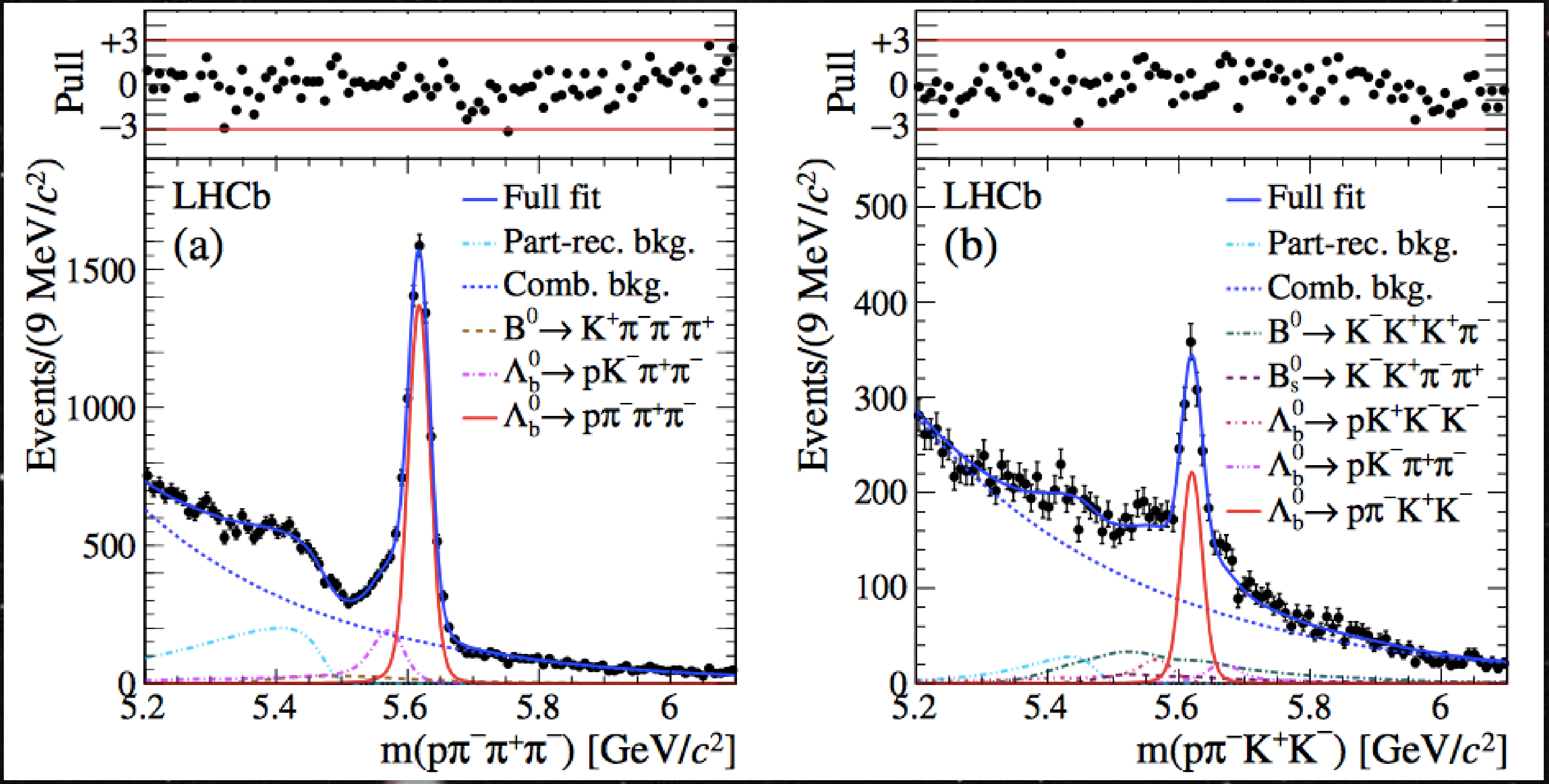
$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$

P-violating observable:

$$a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})$$

Signal yields of $\Lambda_b^0 \to p\pi^- h^+ h^-$

LHCb-PAPER-2016-030, in preparation



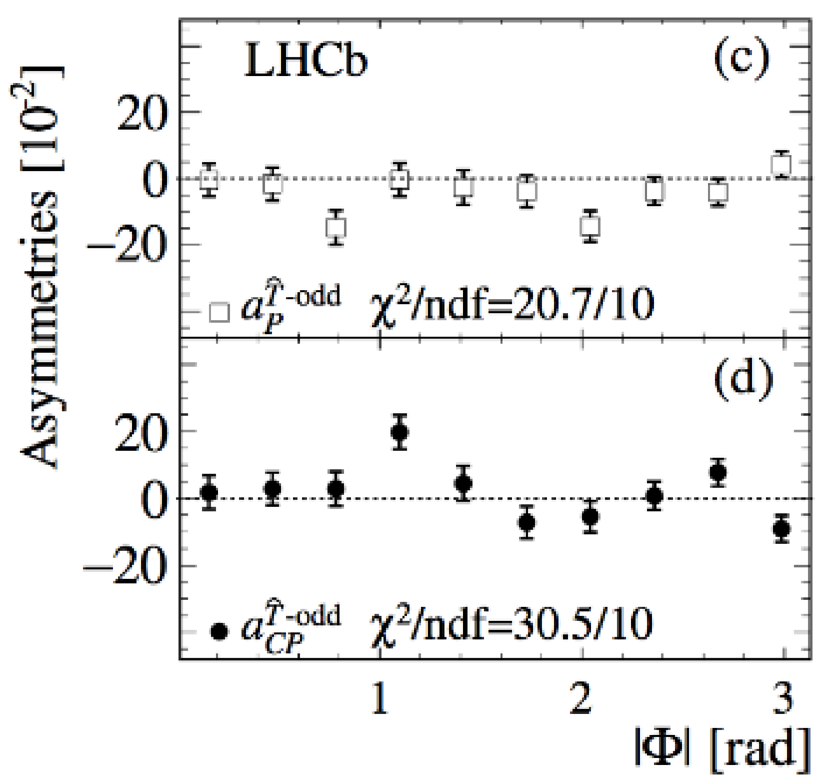
$N_{\Lambda_b^0 \to p\pi^-\pi^+\pi^-} = 6646 \pm 105(\text{stat})$ $N_{\Lambda_b^0 \to p\pi^- K^+ K^-} = 1030 \pm 56(\text{stat})$

First evidence for CPV in $\Lambda_b^0 \to p\pi^- h^+ h^-$

LHCb-PAPER-2016-030, in preparation

- No significant CPV integrated over phase space

Λ_b^0 decay	$A_{\widehat{T}}$ [%]	$\overline{A}_{\widehat{T}}$ [%]	$a_{CP}^{\widehat{T}\text{-odd}}$ ($a_P^{\widehat{T}\text{-odd}}$) [%]
$p\pi^-\pi^+\pi^-$	$-2.56 \pm 2.06 \pm 0.45$	$-4.86 \pm 2.06 \pm 0.44$	$-1.15(-3.71) \pm 1.45 \pm 0.32$
$p\pi^-K^-K^+$	$-2.68 \pm 6.76 \pm 0.85$	$-4.55 \pm 6.07 \pm 0.52$	$-0.93(-3.62) \pm 4.54 \pm 0.42$



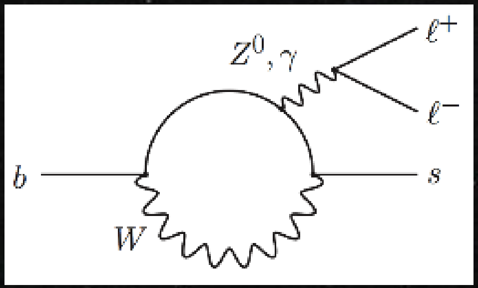
- Results in bins of $|\phi|$
  - An evidence for localized CPV at the $3.3\ \sigma$ level
  - Compatible with SM predictions

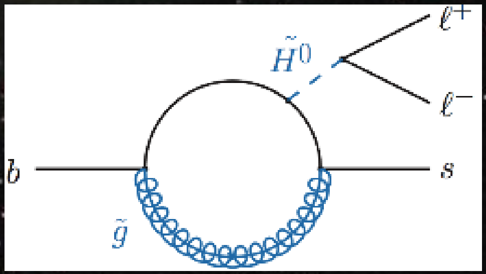
Rare B decay & lepton universality

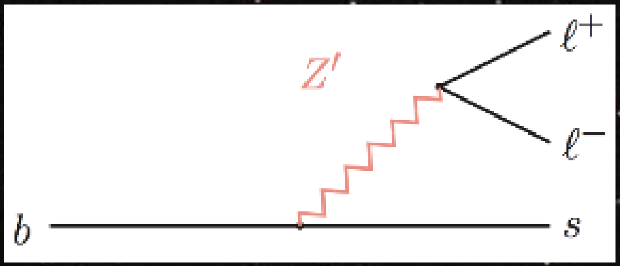
- $B^0_{s/d} \to \mu^+\mu^-$
- $B^0 \to K^+K^-$ (fully hadronic final states)
- Photon polarization in $b \to s\gamma$
- Anomaly in $B^0 \to K^{*0}\mu^+\mu^-$
- Lepton universality in $W^+ \to l^+\nu_l$
- Lepton universality in $B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$: $R(D^*)$

Motivation

- $b \to s l^+ l^-$ transitions are FCNC processes, where
  - SM contributions is suppressed, while
  - NP effects could be large







- Lepton universality (LU)
  - In SM, ratios like R_K differs from unity only due to the difference of phase space

$$R_K \equiv \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)}$$

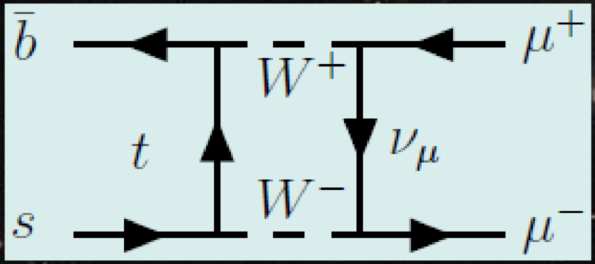
  - Additional difference would imply LU
  - $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$, $2.6\,\sigma$ discrepancy from unity

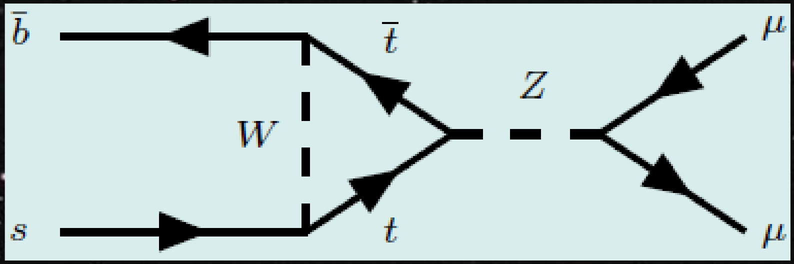
PRL 113 (2014) 151601

$B^0_{s/d} \to \mu^+\mu^-$

- Very rare (and well described) in SM, since only loop contributions exist, e.g.

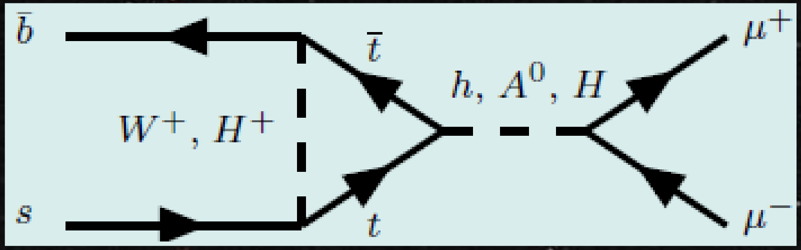
$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = (3.66 \pm 0.23) \times 10^{-9}$$



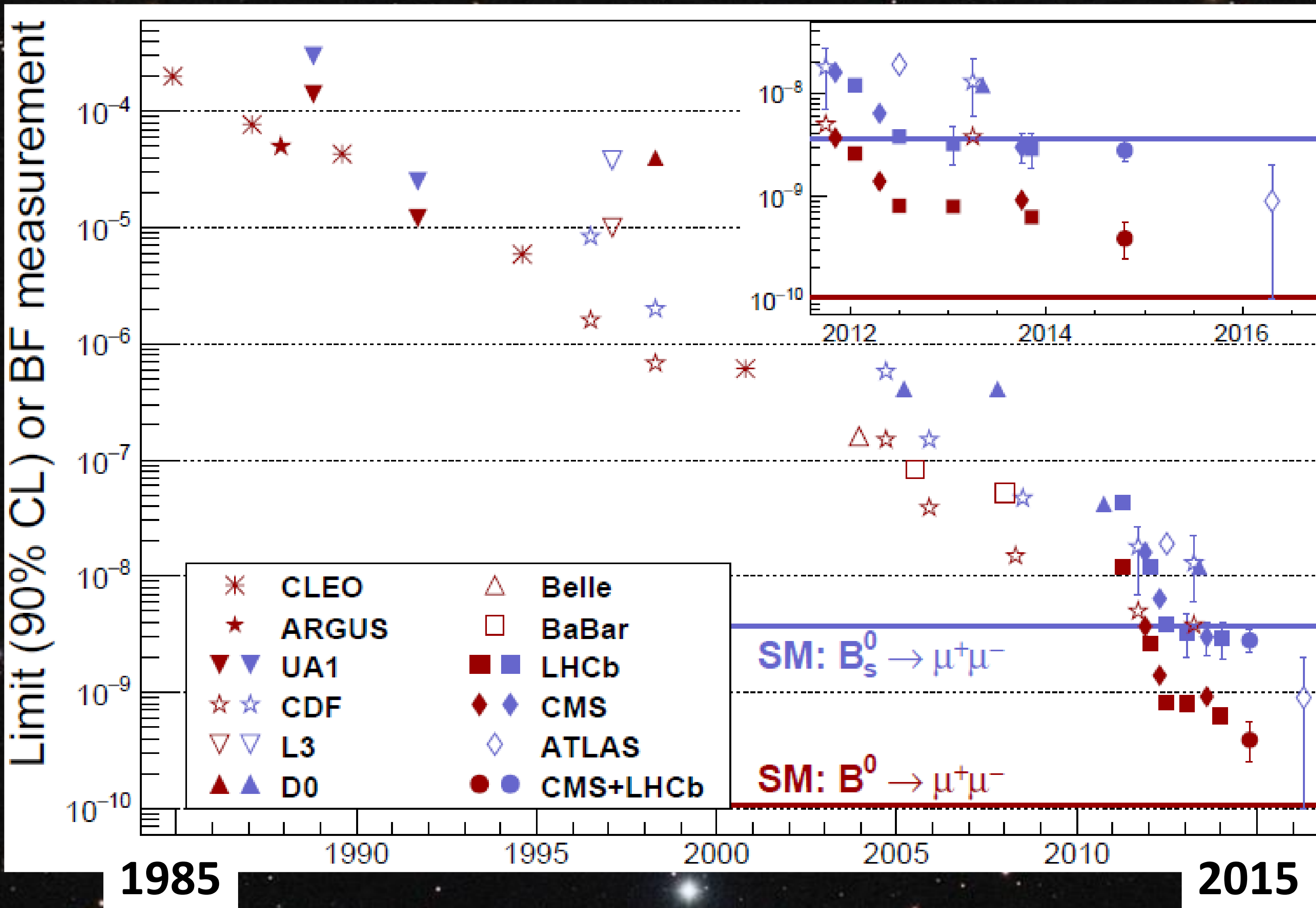


- NP, if existing, could have significant contributions through loops, e.g.

$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right)_{\mathrm{MSSM}} \propto \frac{m_b^2 m_l^2 \tan^6\beta}{m_A^4}$$



$B^0_{s/d} \to \mu^+\mu^-$ chronology



LHCb&CMS combined results

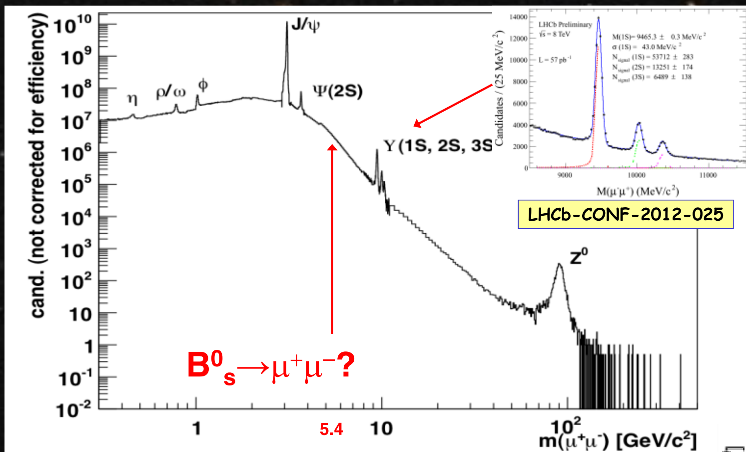
CMS&LHCb, Nature 522 (2015) 68

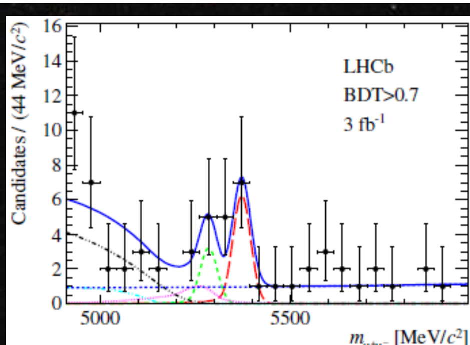
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

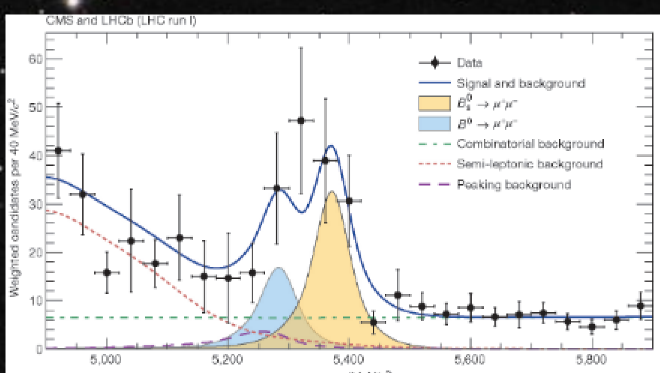
$6.2\,\sigma$, first observation

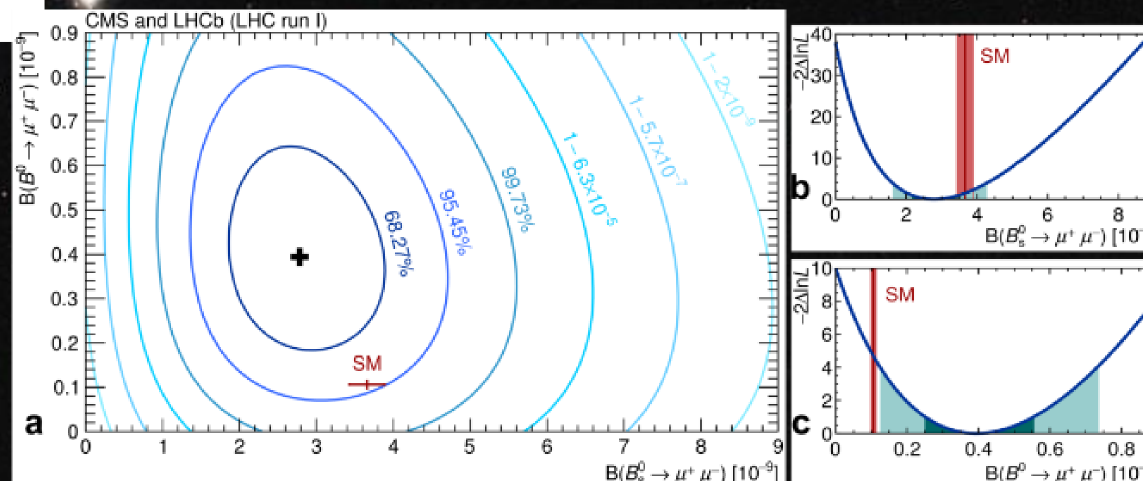
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

$3.0\,\sigma$, first evidence









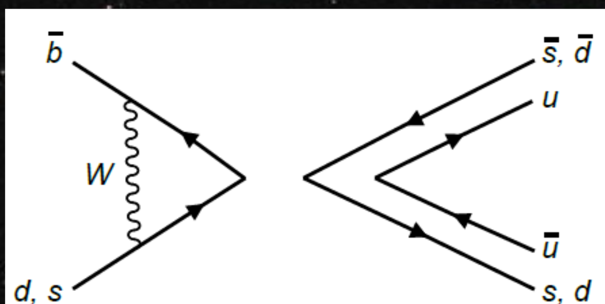
SM expectations:

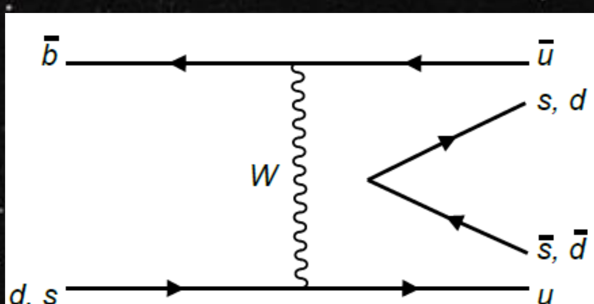
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$B^0 \to K^+K^-$ observation & $B_s^0 \to \pi^+\pi^-$

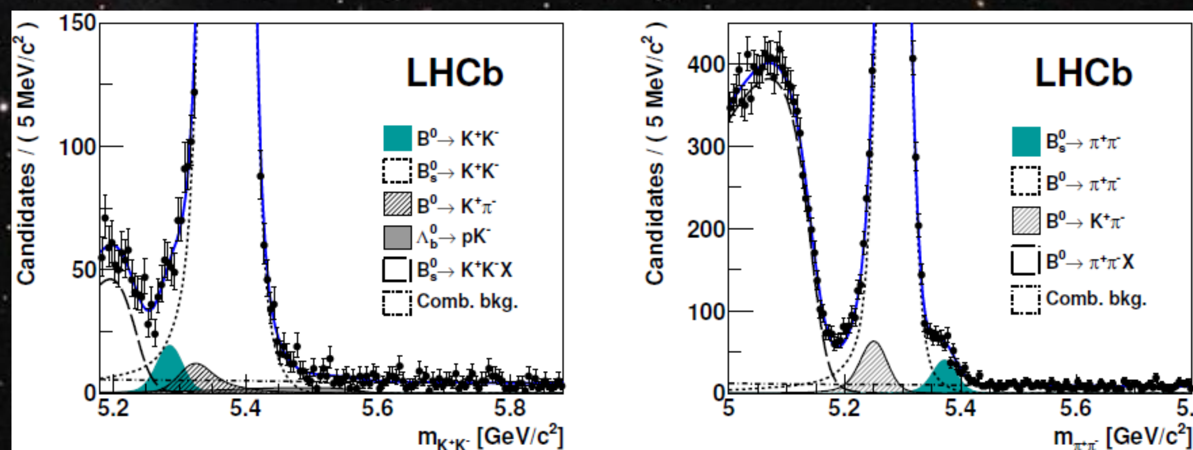
LHCb-PAPER-2016-036, in preparation

- **Highly suppressed fully hadronic final states, only penguin annihilation and W-exchange contributions**
  - Test of QCD calculations, information of penguin pollution





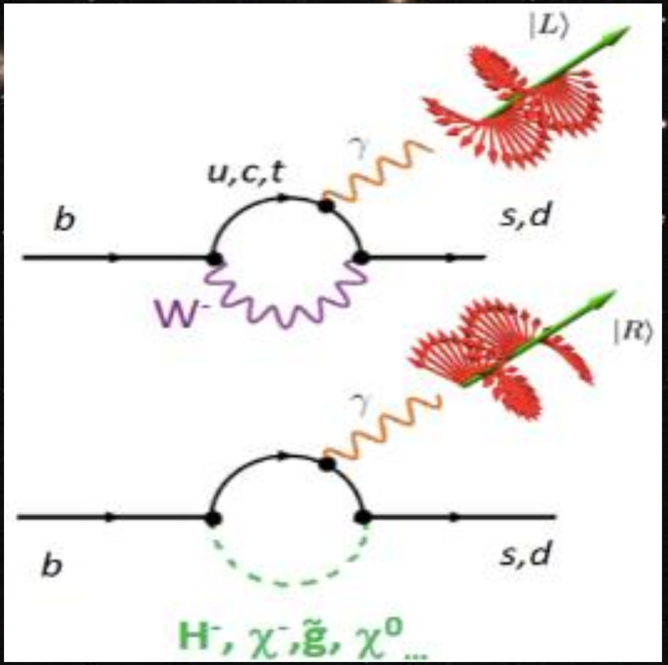
$B^0 - K^+K^-$ $\quad$ $B_s^0 - \pi^+\pi^-$



- $\mathcal{B}(B^0 \to K^+K^-) = (7.8 \pm 1.3 \pm 0.8 \pm 0.2(\mathcal{B})) \times 10^{-8}$ **(5.8 σ)**
  The rarest B decay to hadronic final state ever observed!
- $\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (6.9 \pm 0.5 \pm 0.6 \pm 0.2(\mathcal{B}) \pm 0.4(f_d/f_s)) \times 10^{-7}$

Photon polarization in $b \to s\gamma$

- The $b \to s\gamma$ transition is the mother of all penguins, where the emitted γ is predominantly **left-handed** in SM
- When **right-handed** NP particles entered the loop, the polarization of the γ would change, leading to observable effects, e.g.
  - Mixing-induced CP violation [Atwood, Gronau, Soni, PRL79 (1997) 185]
  - Decay rate of B_s^0 eigenstates [Muheim, Xie, Zwicky, PLB 664 (2008) 174]



$$P(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^\Delta \sinh(\Delta\Gamma_s t/2) + \zeta\,\mathcal{C}\cos(\Delta m_s t) - \zeta\,\mathcal{S}\sin(\Delta m_s t)\}$$

$\mathcal{C}$, $\mathcal{S}$ and $\mathcal{A}^\Delta$: functions of left- and right-handed γ polarization amplitude

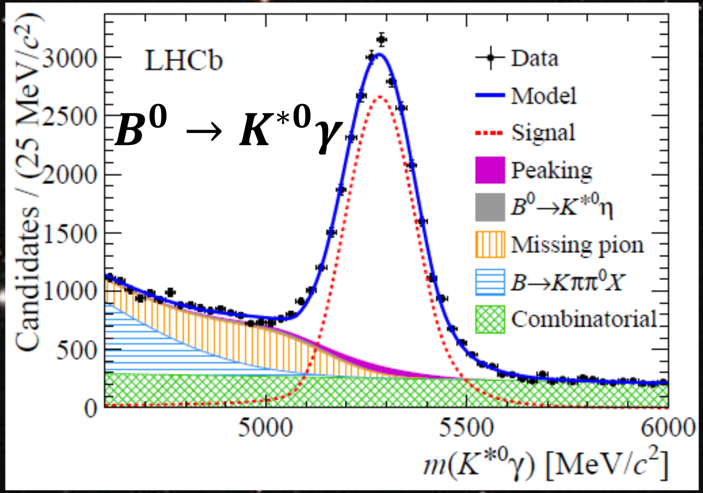
First measurement of γ polarization in $B_s^0 \to \phi\gamma$

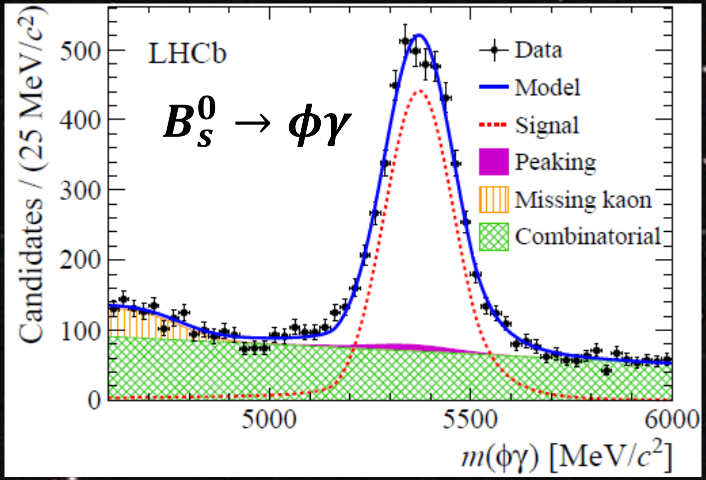
LHCb-PAPER-2016-036, in preparation

- **Polarized photons in $b \to s\gamma$ first observed at LHCb in the decay $B^+ \to K^+\pi^+\pi^-\gamma$ [LHCb, PRL112 (2014) 161801]**
- **Time-dependent decay rate measured in $B_s^0 \to \phi\gamma$**

$$\Gamma_{B_s^0\to\phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}^\Delta \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right]$$

$$\mathcal{A}^\Delta_{\mathrm{SM}} = 0.047^{+0.029}_{-0.025}$$





24800 ± 300: control mode

$N_{\mathrm{sig}} = 4100 \pm 100$

First measurement of γ polarization in $B_s^0 \to \phi\gamma$

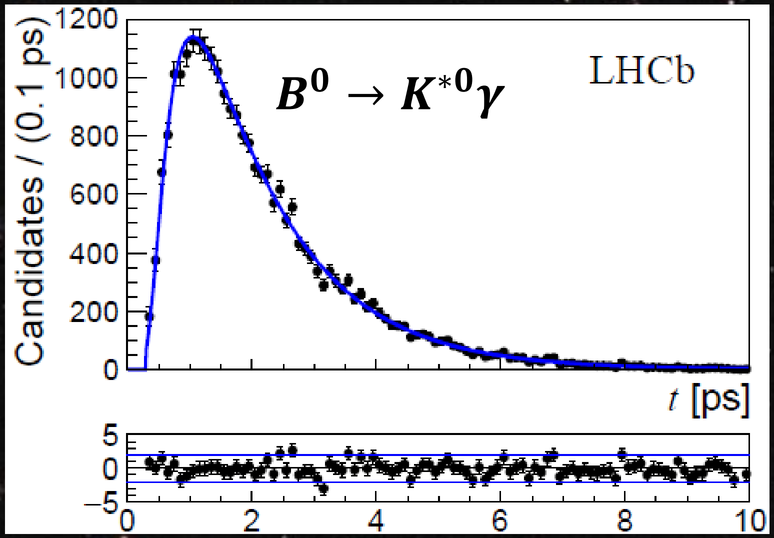
LHCb-PAPER-2016-036, in preparation

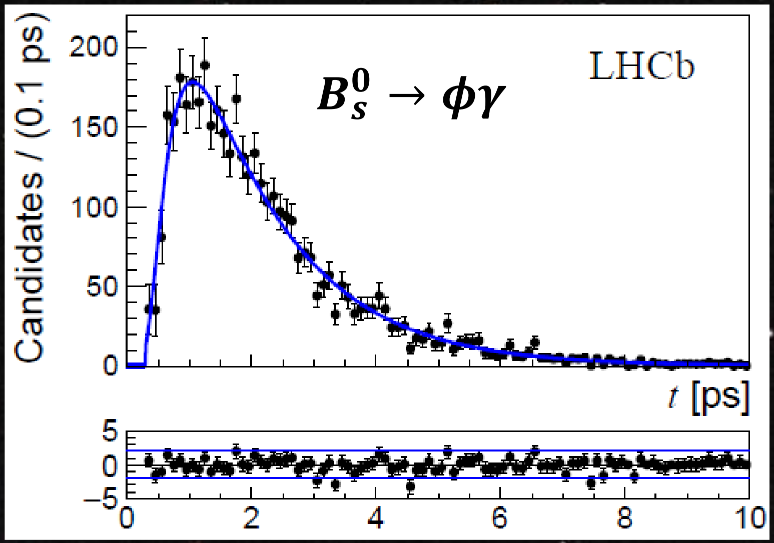
- Fit to $\Gamma_{B_s^0\to\phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right]$

$$\Rightarrow \quad \mathcal{A}^{\Delta} = -0.98^{+0.46}_{-0.52}{}^{+0.23}_{-0.20}$$

  - Other parameters fixed to the HFAG values
- Agree with the SM expectation in $2\,\sigma$

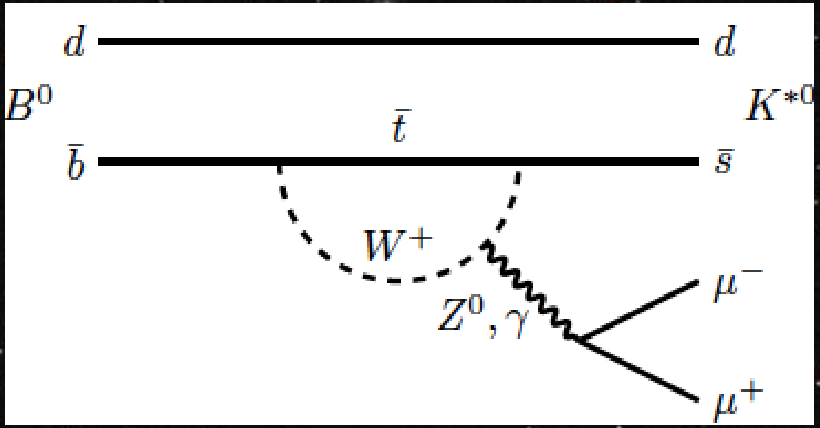
$$\mathcal{A}^{\Delta}_{\mathrm{SM}} = 0.047^{+0.029}_{-0.025}$$





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

- Angular analysis of the decay can probe potential NP contributions

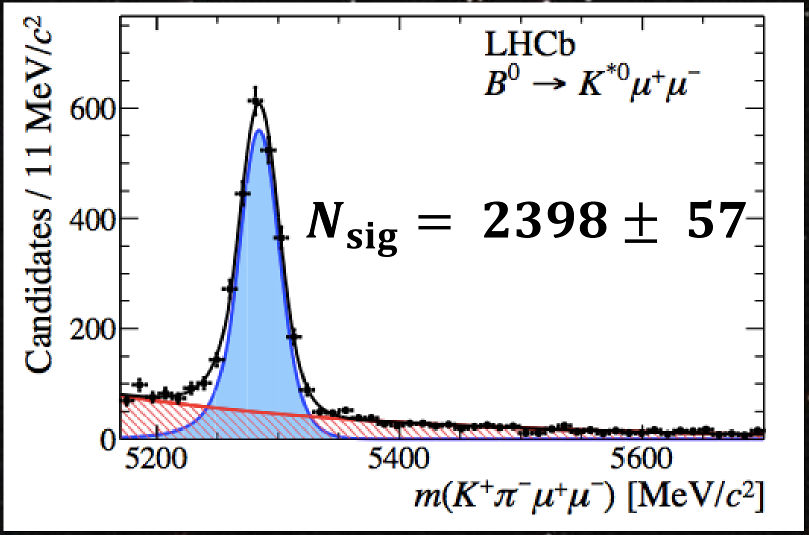


- Observables include: $A_{\mathrm{FB}}, F_L, P_i', \ldots\ldots$
- First LHCb measurement used data of 1 fb^{-1} [PRL 111 (2013) 191801]
- Recent update used full Run I data (3 fb^{-1})

JHEP 02 (2016) 104

- S-wave contribution measured
  - $F_S = 0.101 \pm 0.017 \pm 0.009$

arXiv:1606.04731



P'_5 anomoly in $B^0 \to K^{*0}\mu^+\mu^-$

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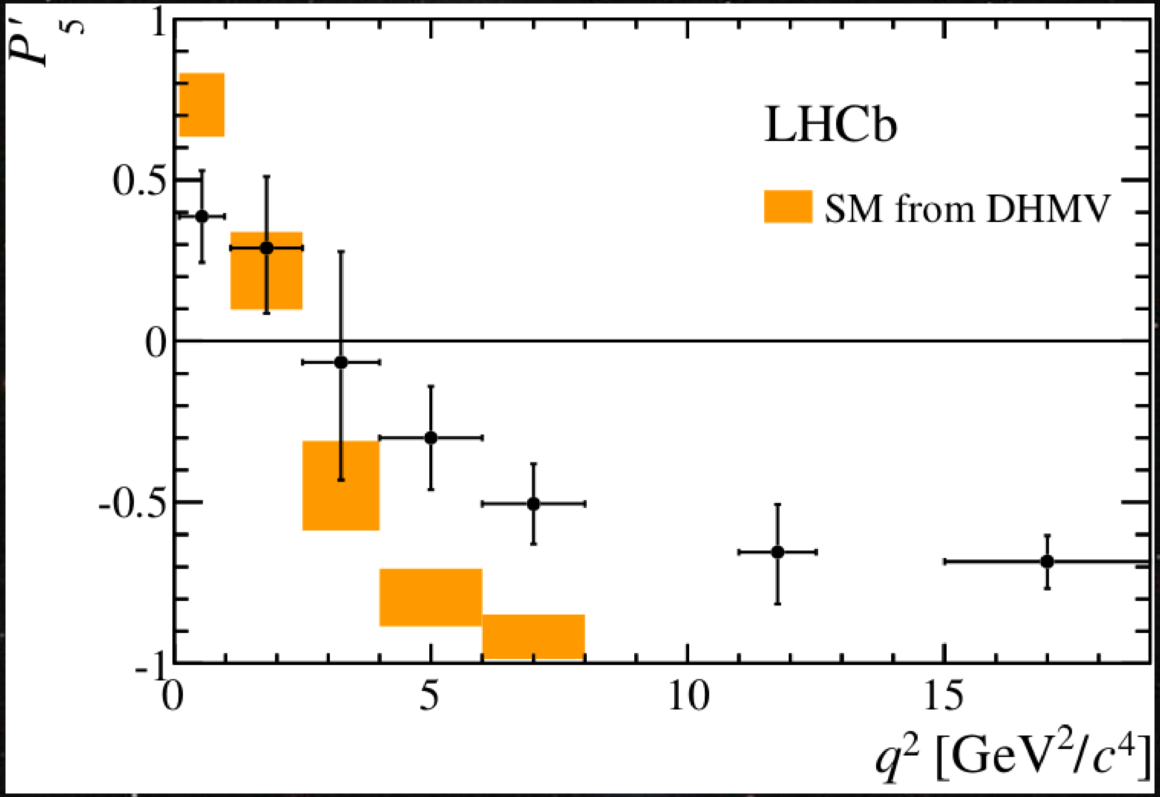
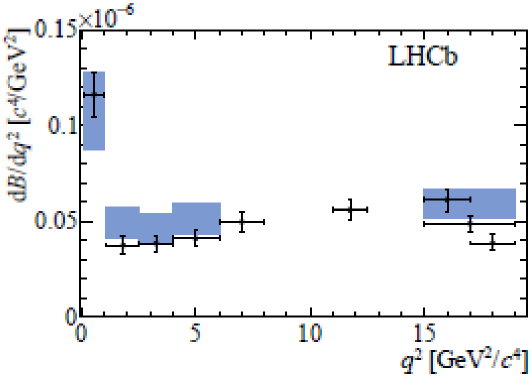
- P'_5 is theoretically clean
- The tension with SM remains, a local discrepancy at $3.4\ \sigma$

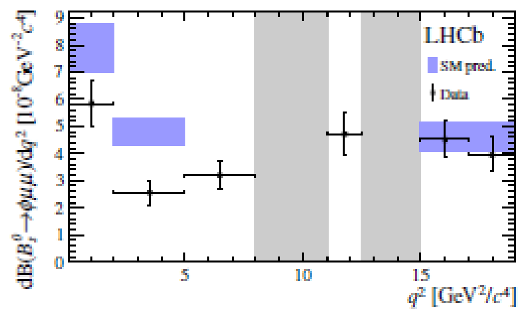


Puzzles in $b \to s\mu^+\mu^-$ branching fractions

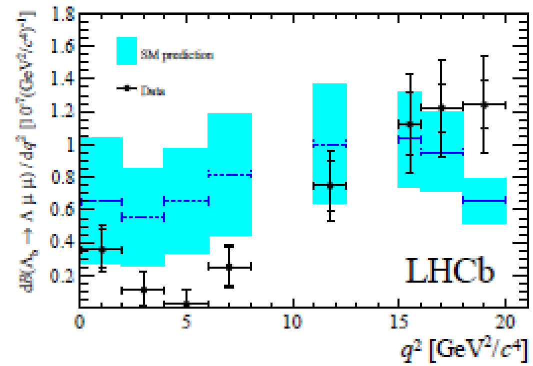
➢ **Systematically lower than SM predictions in all channels**



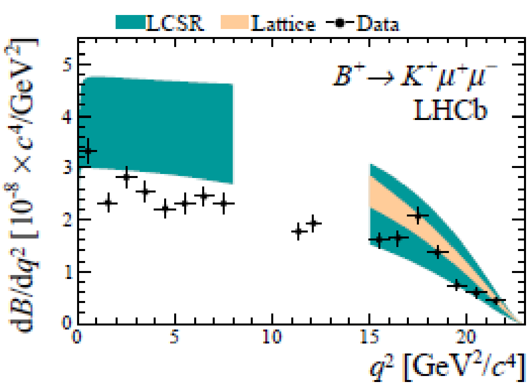
$B^0 \to K^{*0}\mu^+\mu^-$ [arXiv:1606.04731]



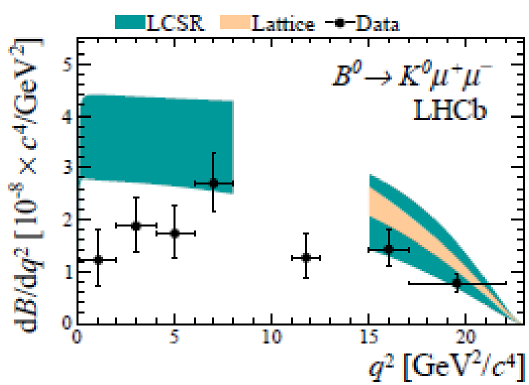
$B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



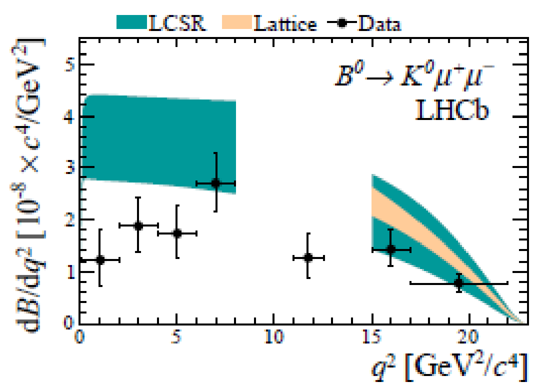
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



$B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



$B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]

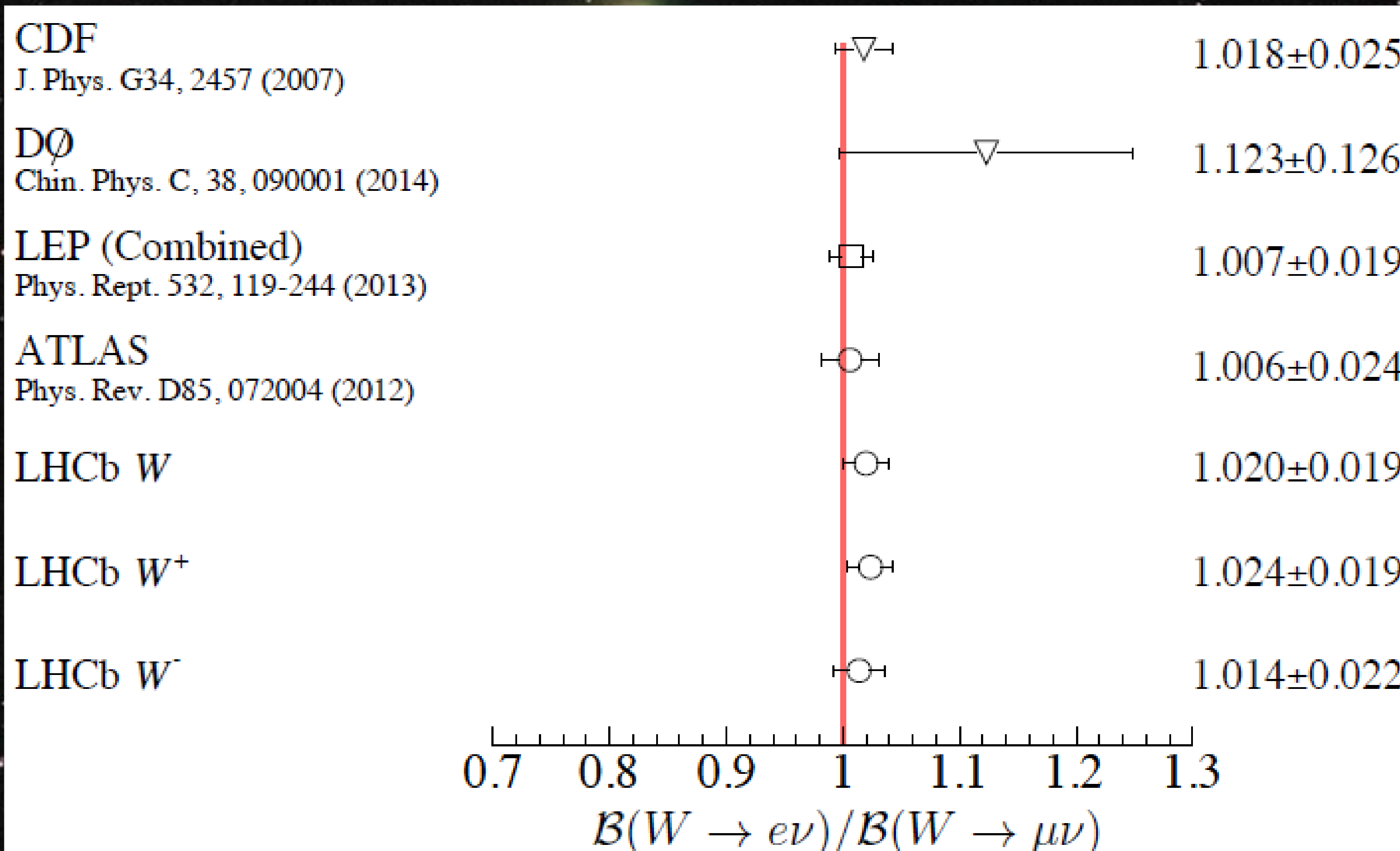


$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]

Lepton universality in $W \to l\nu$

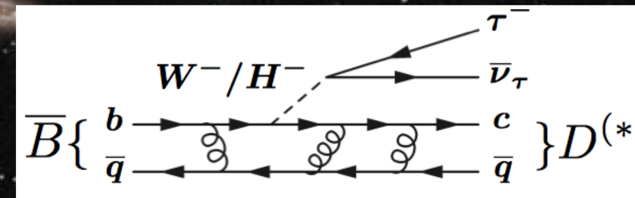
arXiv:1608.01484

➢ **Agree with the SM prediction**

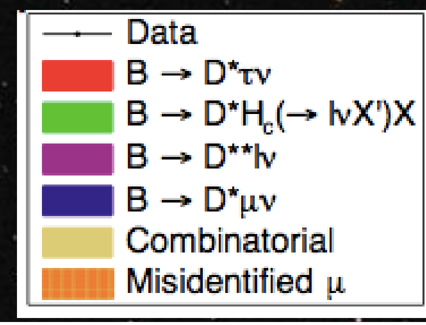


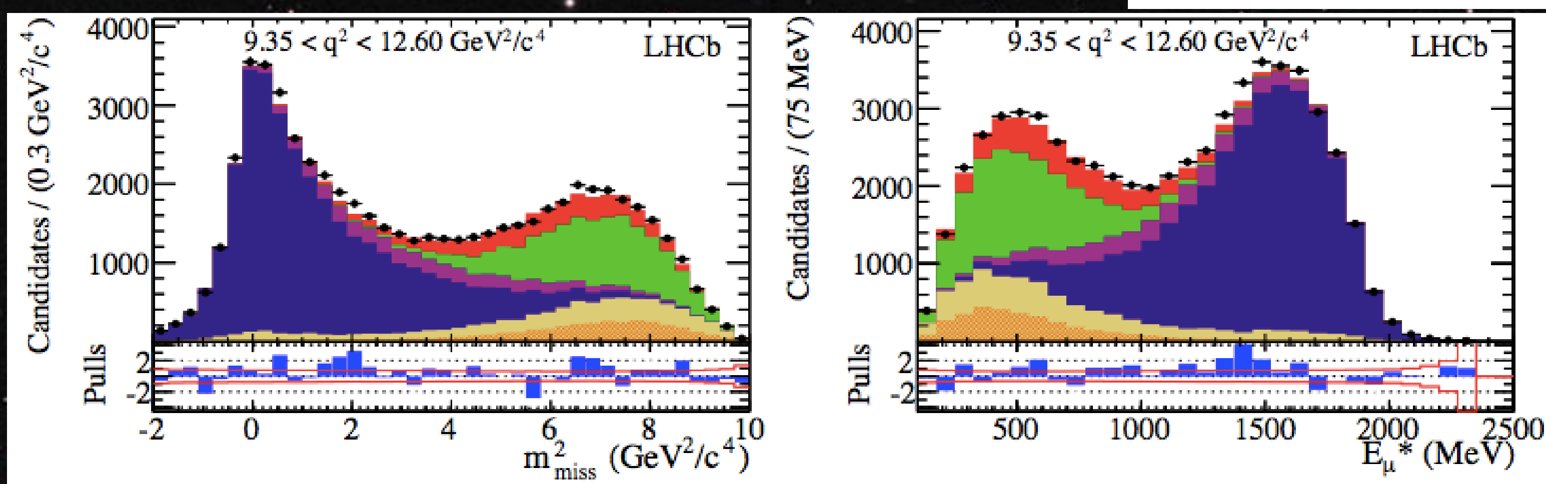
Lepton universality in $B^0 \to D^{*+}\tau^-\bar{\nu}_\tau$

PRL 115 (2015) 111803

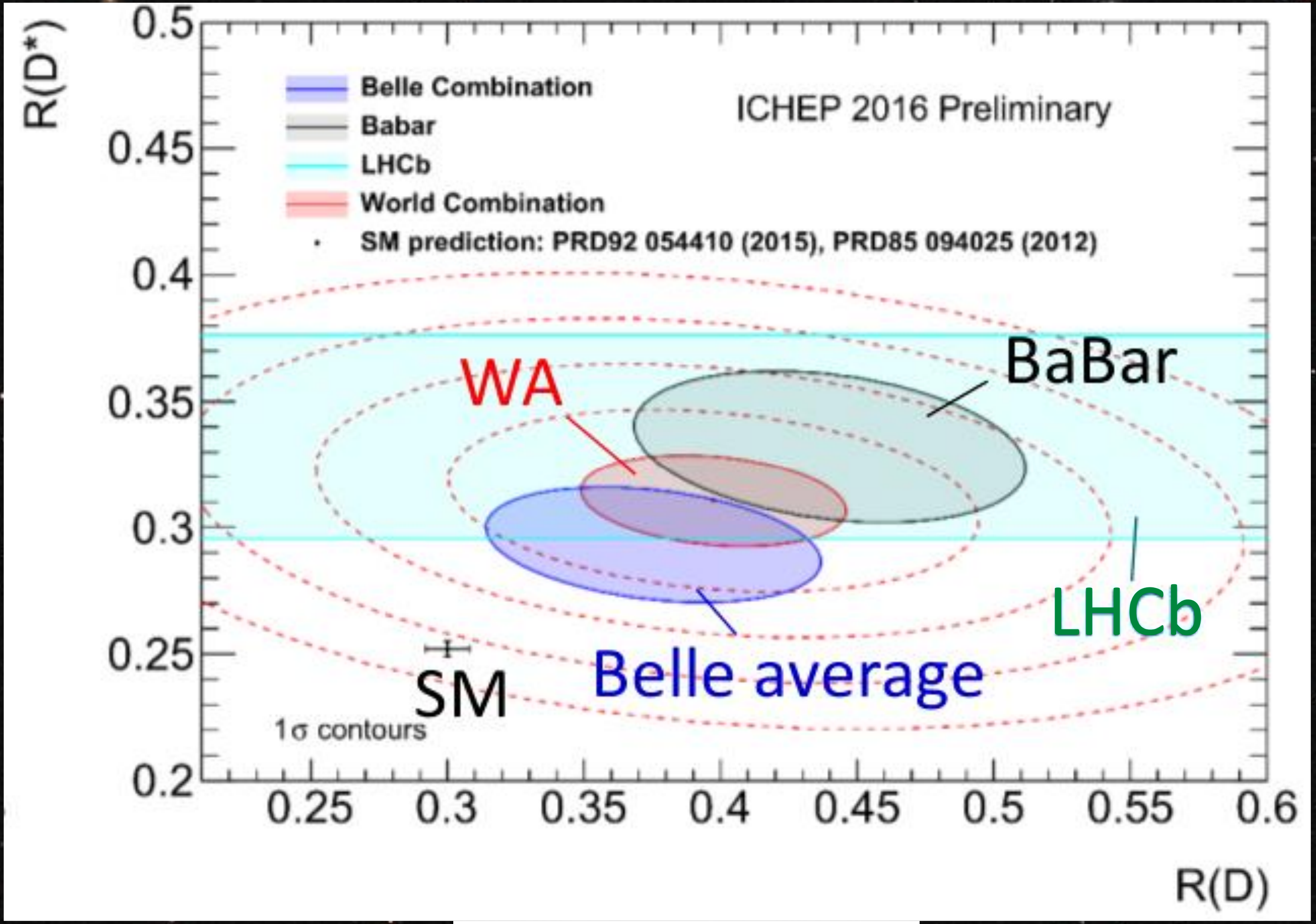


- $R(D^{(*)})$ sensitive to, e.g. charged Higgs
- With $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$, and $\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ discriminated by kinematical variables: $q^2, E^*_\mu, m^2_{\text{miss}}$
- $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
  - Above SM prediction at $2.1\,\sigma$
    - ✓ $R(D^*) = 0.252 \pm 0.003$
  - Confirmed by BaBar/Belle





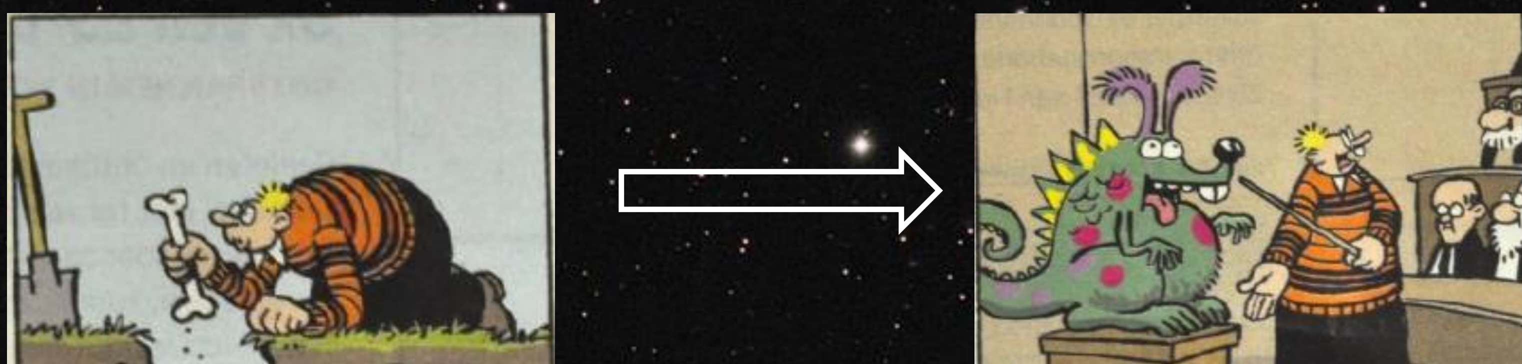
$R(D)$ and $R(D^*)$ world average



4 σ above SM

Summary

- LHCb has performed many measurements with unprecedented sensitivity in various aspects: CPV, rare decays, …… **Generally agree with SM well**
- A handful of $2-4\,\sigma$ deviations from SM observed, and further investigations needed from both theory and experimental sides



Summary

- LHCb has performed many measurements with unprecedented sensitivity in various aspects: CPV, rare decays, …… **Generally agree with SM well**
- A handful of $2-4\,\sigma$ deviations from SM observed, and further investigations needed from both theory and experimental sides

Prospects

	LHC era			HL LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
Lumi	$3\ \mathrm{fb}^{-1}$	$8\ \mathrm{fb}^{-1}$	$25\ \mathrm{fb}^{-1}$	$50\ \mathrm{fb}^{-1}$	$*300\ \mathrm{fb}^{-1}$

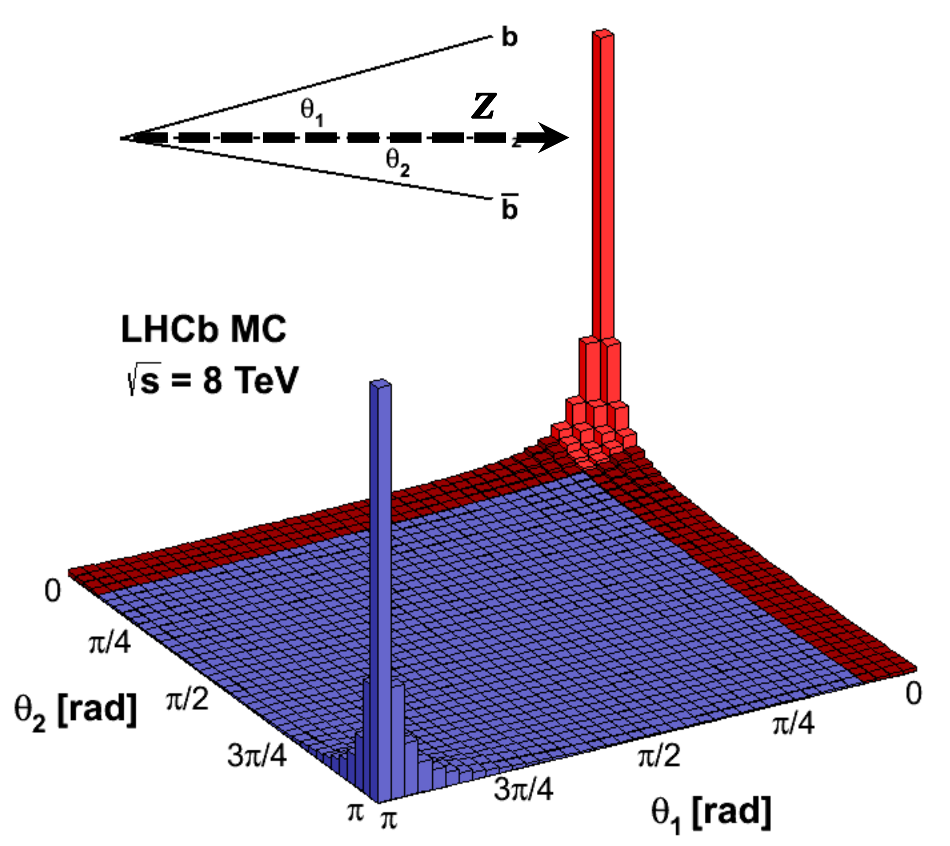
- **Run-1 data still not fully explored, and many results with Run-2 data have been coming**
- **LHCb upgrade comes already after Run-2**
  - **Instantaneous lumi will be raised by a factor of 5**
  - **Hardware triggers removed, running at 40 MHz**
- **LHCb is starting to consider a 2nd upgrade for Run-5+**
- **Flavor physics will play a key role to fully understand SM and search for NP beyond with more precision**

Thanks !

Backup slides

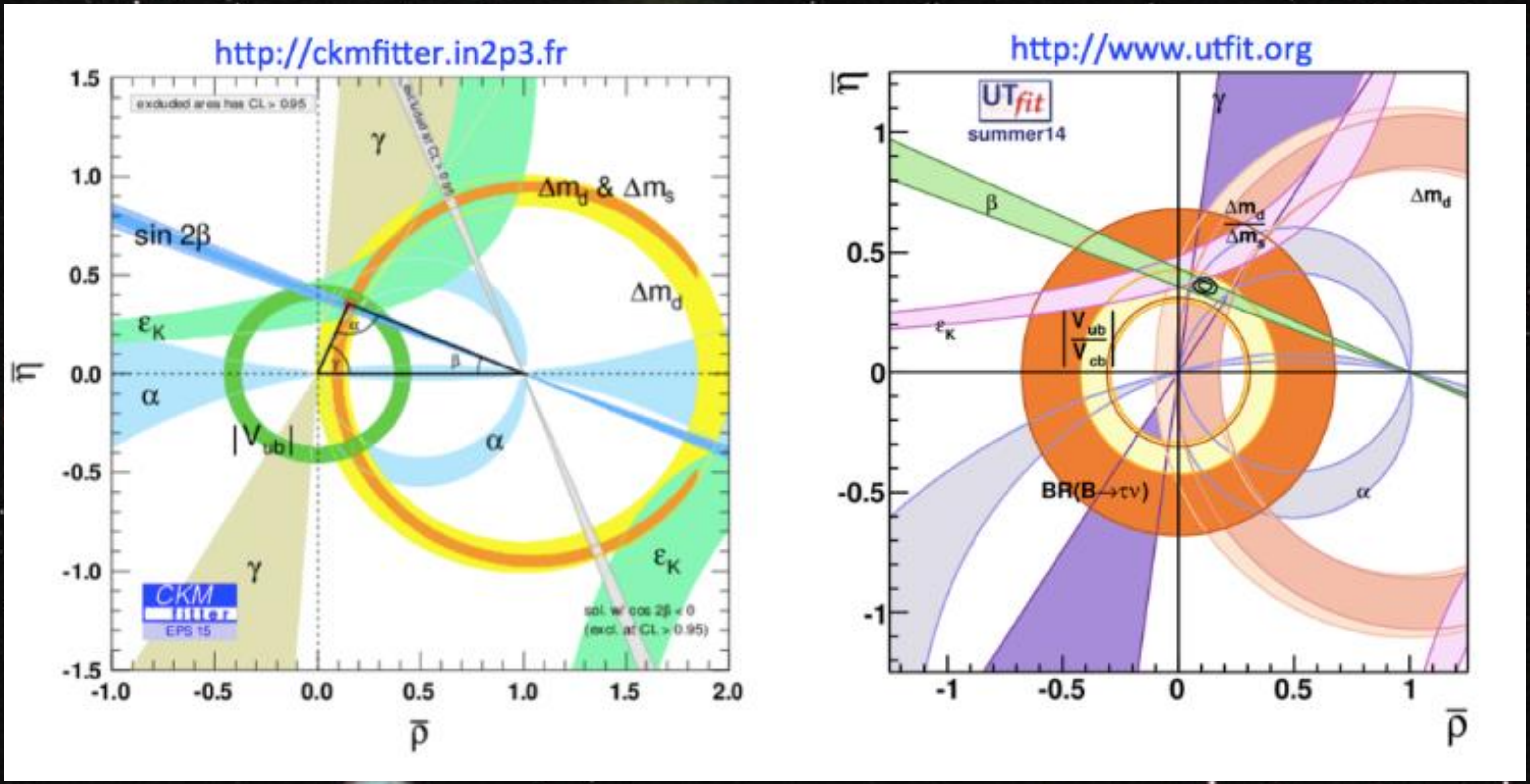
Heavy quarks at LHC

- **Large cross-sections** of heavy flavor production at high energy pp collisions
  - $\sigma_{b\bar{b}} \simeq 300 - 500\ \mu\text{b @ } 7 - 14\ \text{TeV}$
  - $\sigma_{c\bar{c}} \simeq 15\,\sigma_{b\bar{b}}$



- The (anti-)quark(s) in the $b\bar{b}$ ($c\bar{c}$) pair **highly correlated**
  - $g + g$ fusion dominates

Where we are with CKM?



Constraints on NP from $b \to s\gamma$

- $\mathcal{A}^{\Delta}(B_s^0 \to \phi\gamma)$ **shows slight preference to non-zero** $\mathrm{Re}(C_7'^{\mathrm{NP}})$ **while the global fit does not show significant tension**
  [A. Paul &D. Straub, arXiv:1608.02556]