中国科学院大学

University of Chinese Academy of Sciences

CP violation and rare decays at LHCb

Jibo HE (UCAS), for the LHCb collaboration

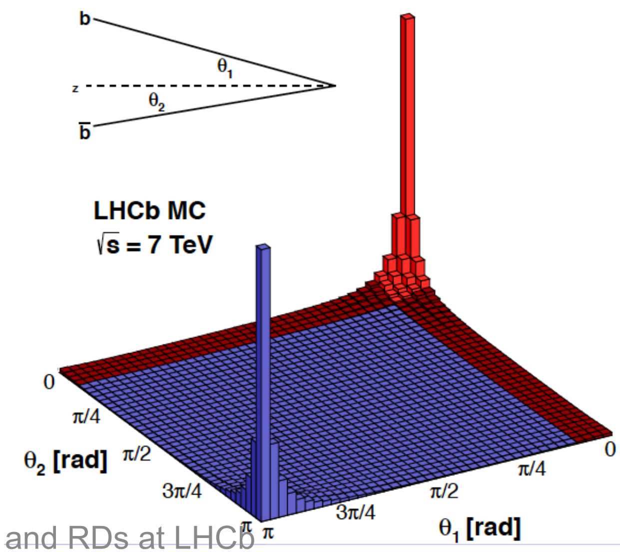
Presented at CLHCP 2016 @ PKU

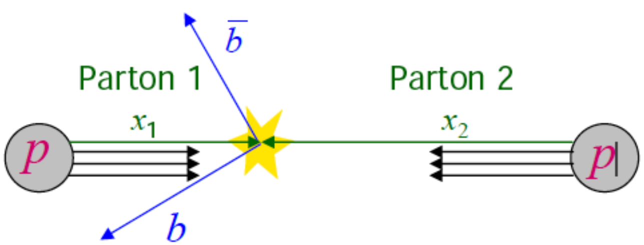
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb **c.f. 1nb @*Y(4S)***

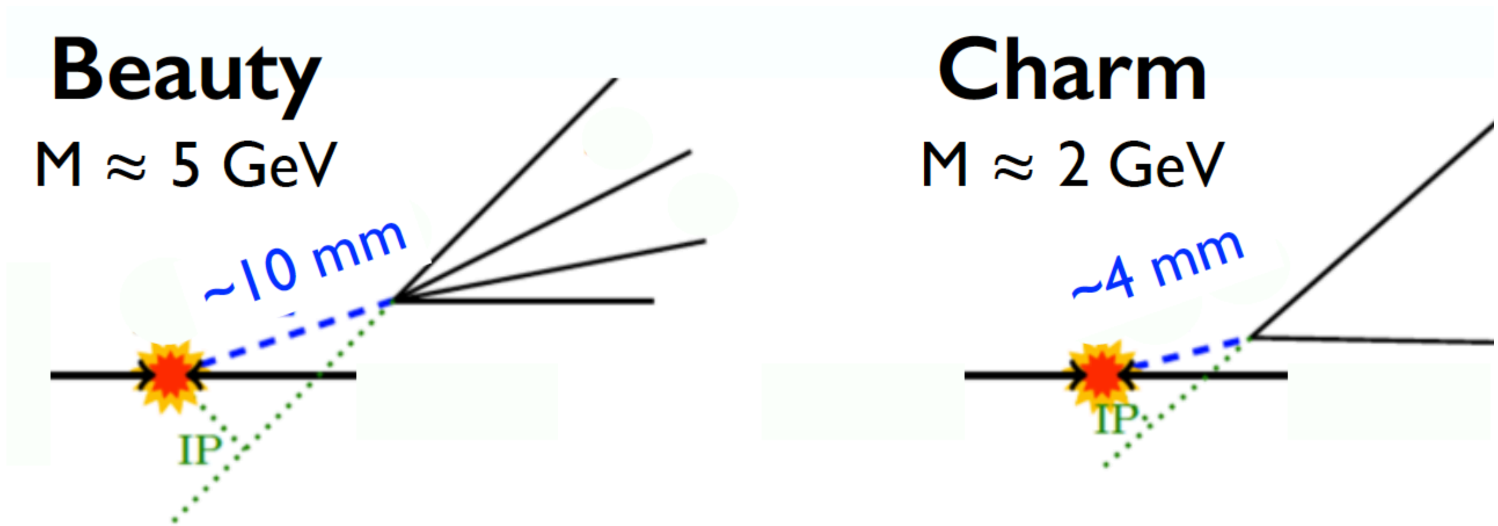
Flavor factory!

- Predominantly in forward/backward cones





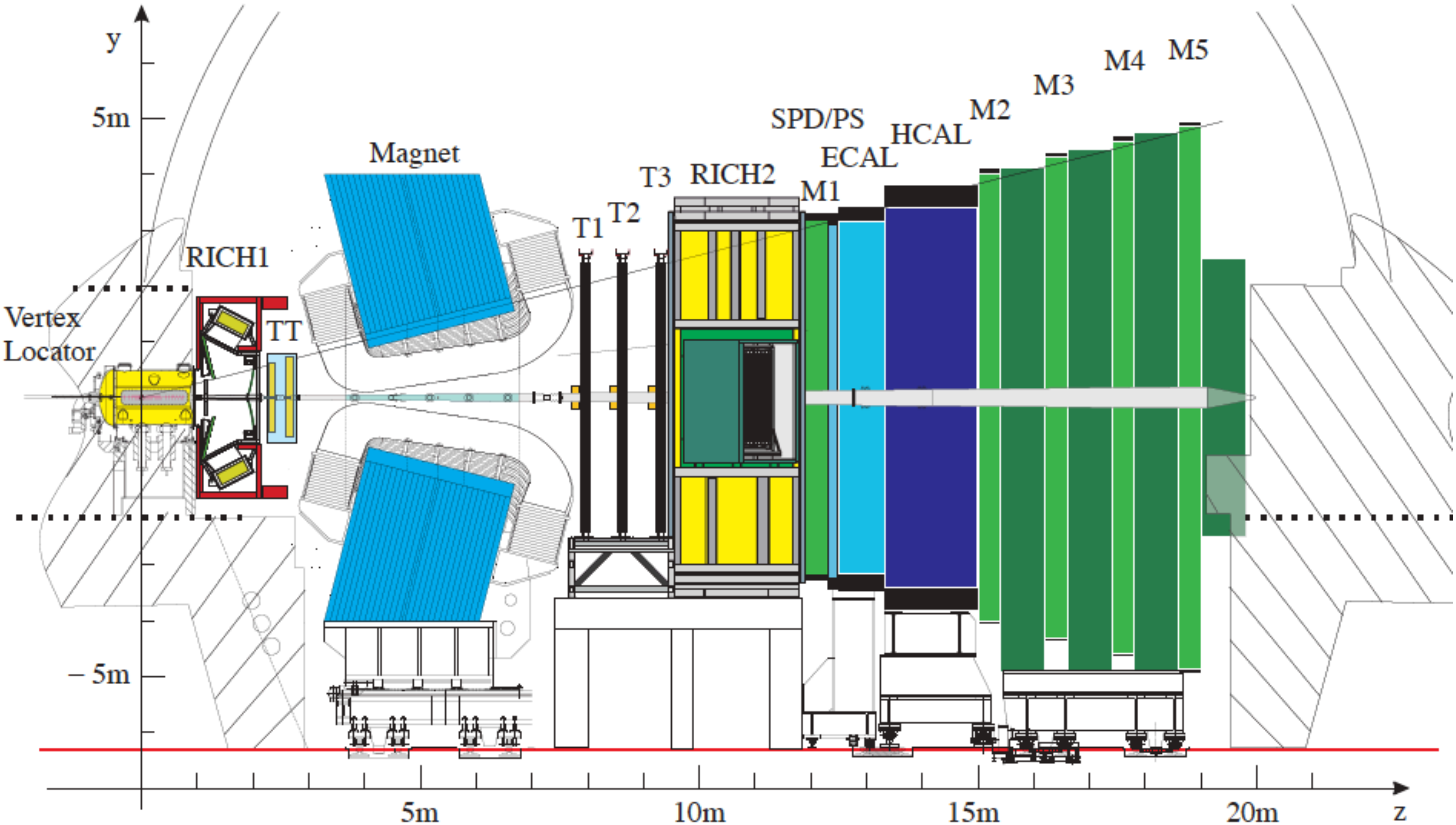
Beauty/charm signature



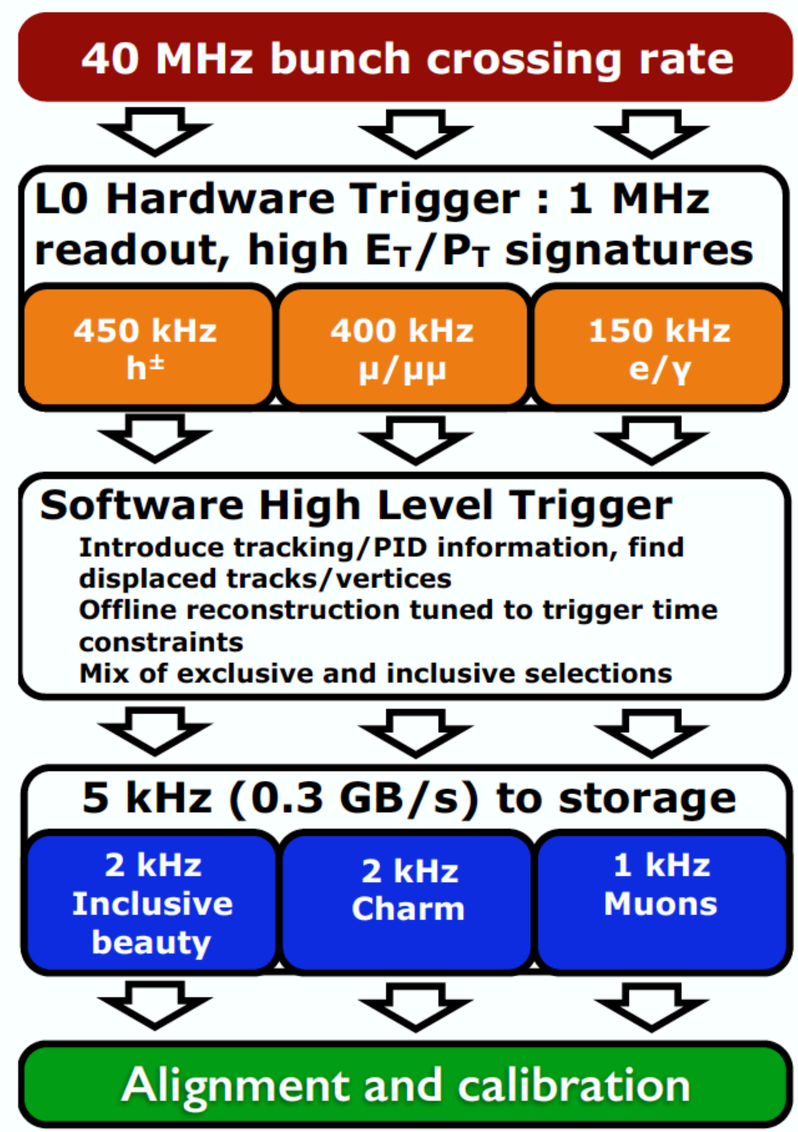
- Compared to minibias (background)
  - Relatively high mass → high p_T
  - Relatively long lifetime → large IP
- Requires excellent vertexing, tracking, PID

The LHCb experiment

- Dedicated to precision study of *b/c*-hadrons



The LHCb data flow: Run-I



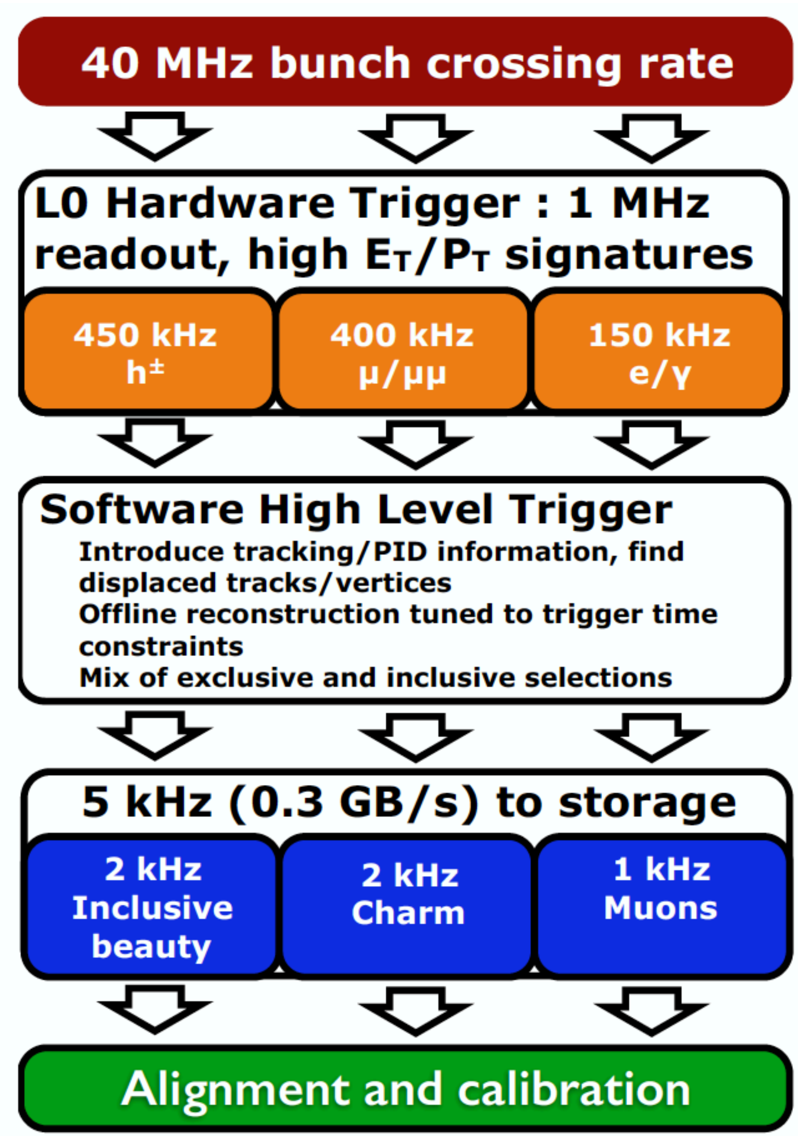
- Level-0, Hardware
  - Fully synchronous at 40 MHz
  - Selection of high p_T particles
    - ★ $p_T(\mu) >\sim 1.5$ GeV/c, $p_T(\mu_1) \times p_T(\mu_2) >\sim (1.5\,\mathrm{GeV}/c)^2$
    - ★ $E_T(h, e, \gamma) > 2.5 - 4$ GeV
- High Level Trigger (HLT), Software
  - Stage 1, tracking info, IP cuts
  - Stage 2, full reconstruction + selections

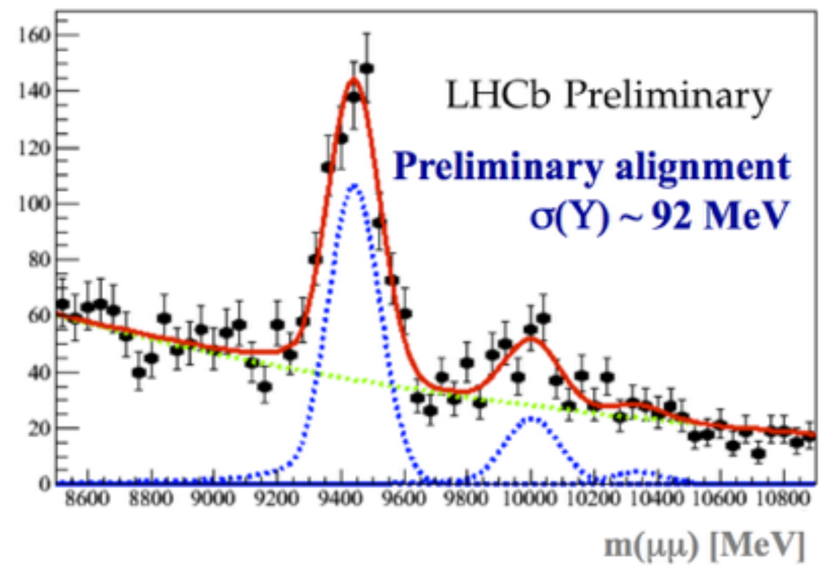
  $\sim$50 kB/event $\Rightarrow$ 0.25GB/s, $\sim$ 2 PB/year
- Offline data flow

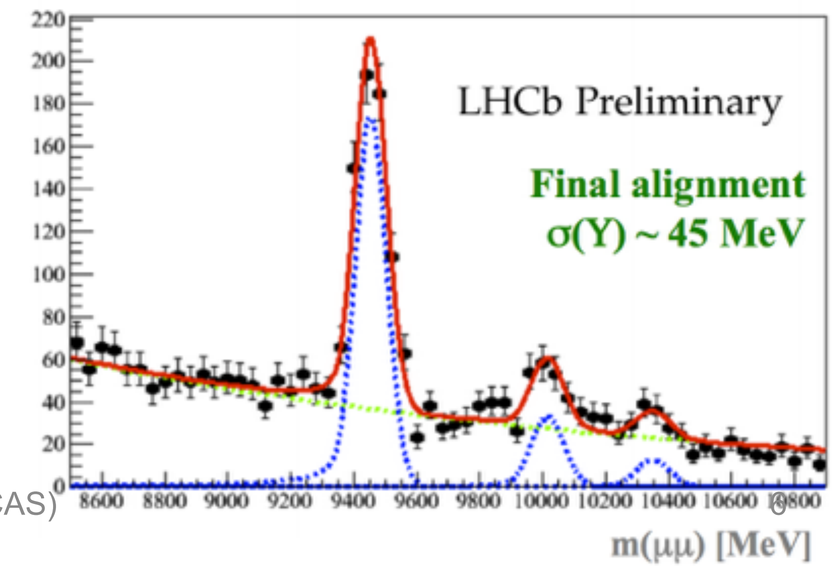
  Raw data $\xrightarrow{\text{Rec}}$ $\boxed{\text{Stripping}}$ $\xrightarrow{10\%}$ (μ)DST

  Stripping, also as HLT3, Pre-selections of all decay channels under study

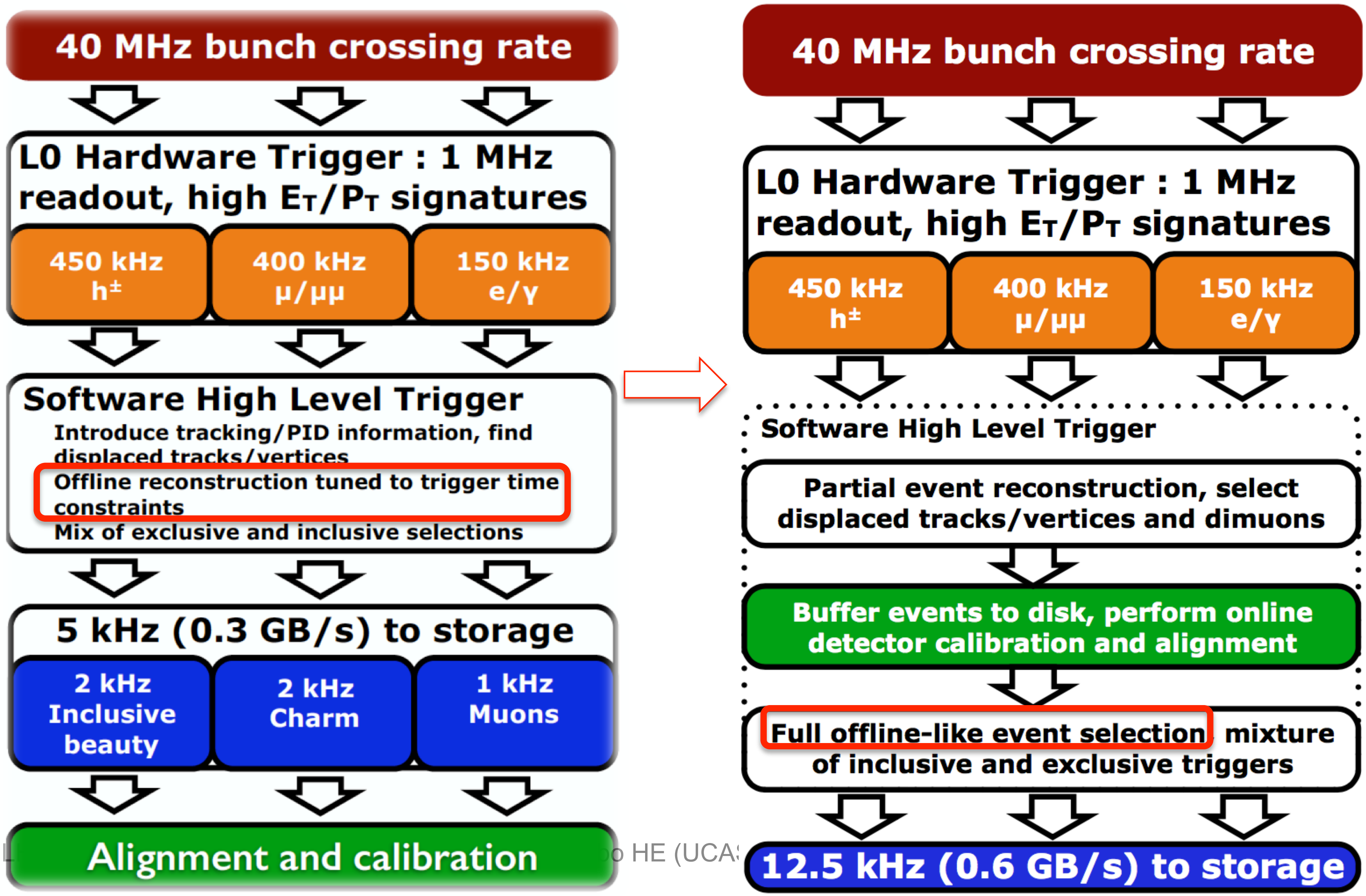
The LHCb data flow: Run-I



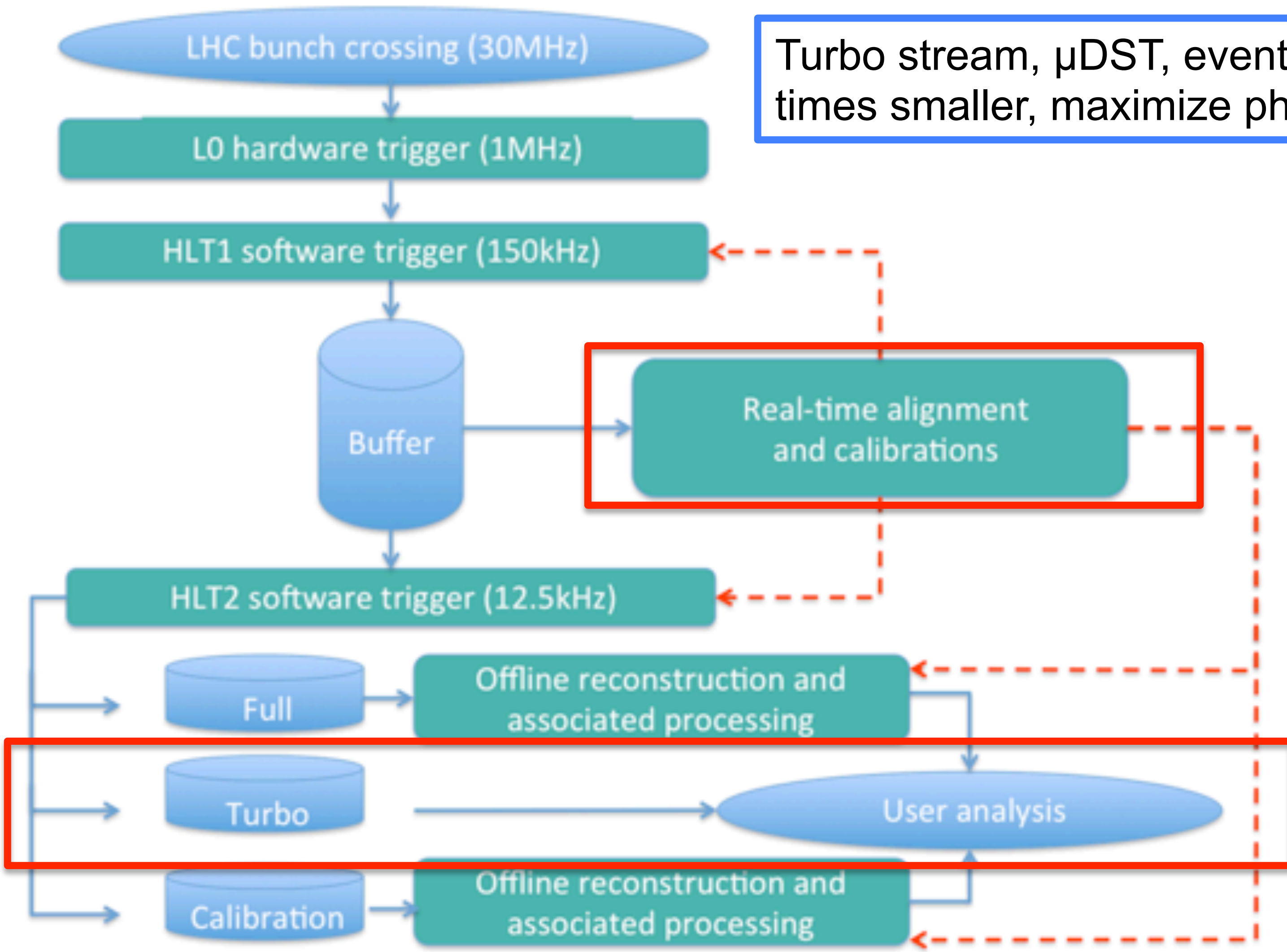




Run-I to Run-II



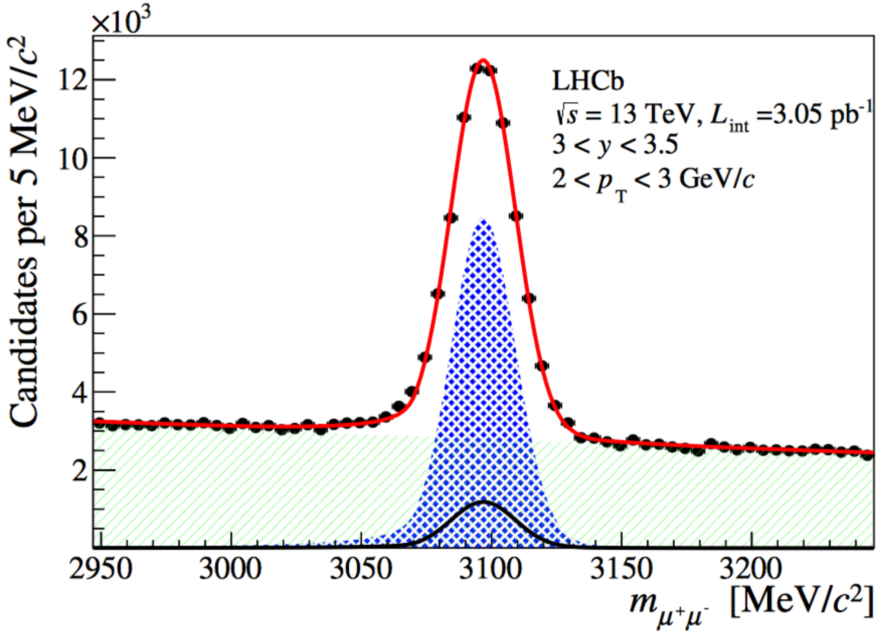
The turbo stream

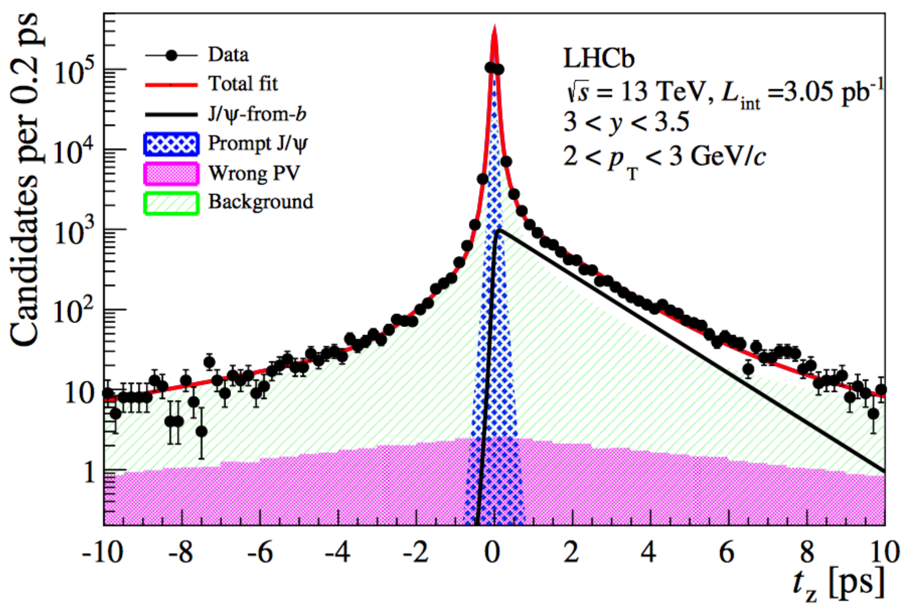


Turbo stream, μDST, event size 10 times smaller, maximize physics output!

Real-time analysis

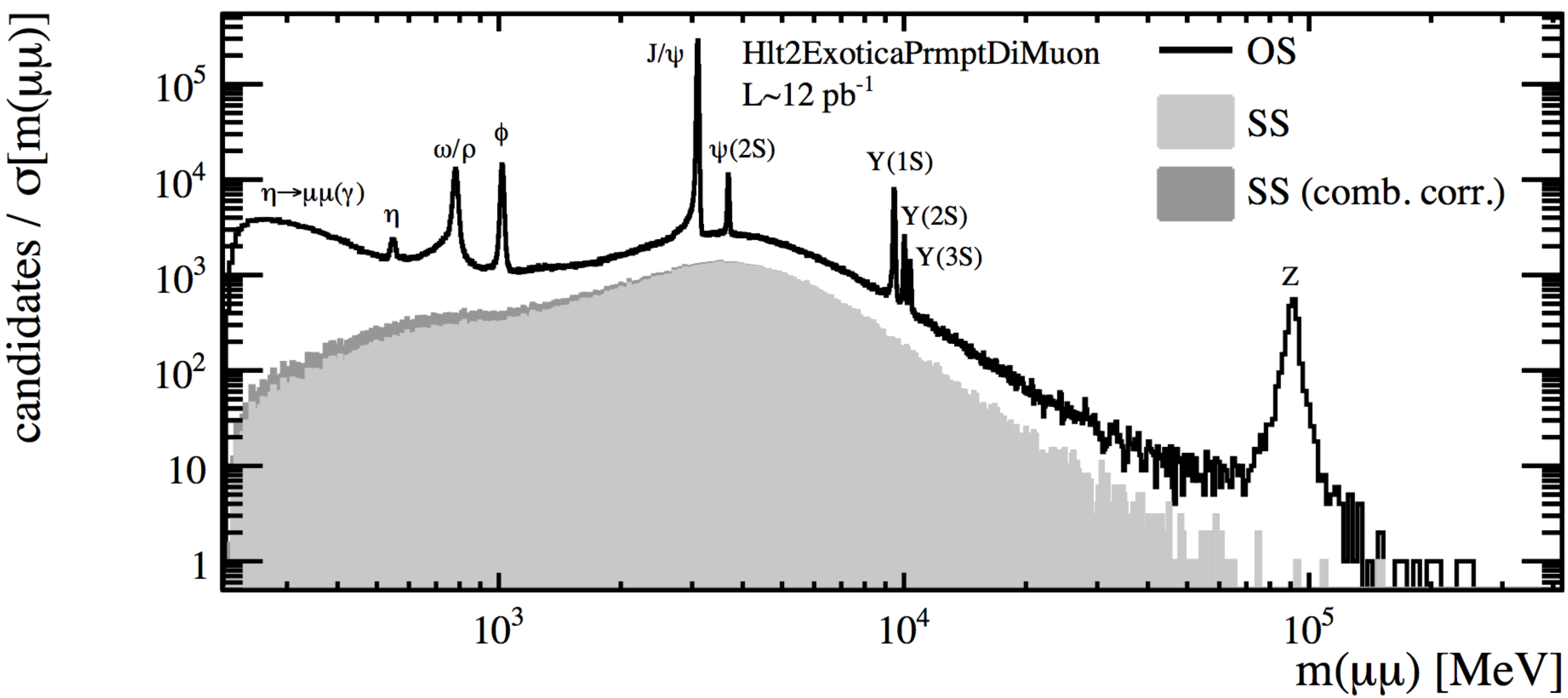
- *J/ψ* production @13 TeV presented only one week after the data was taken



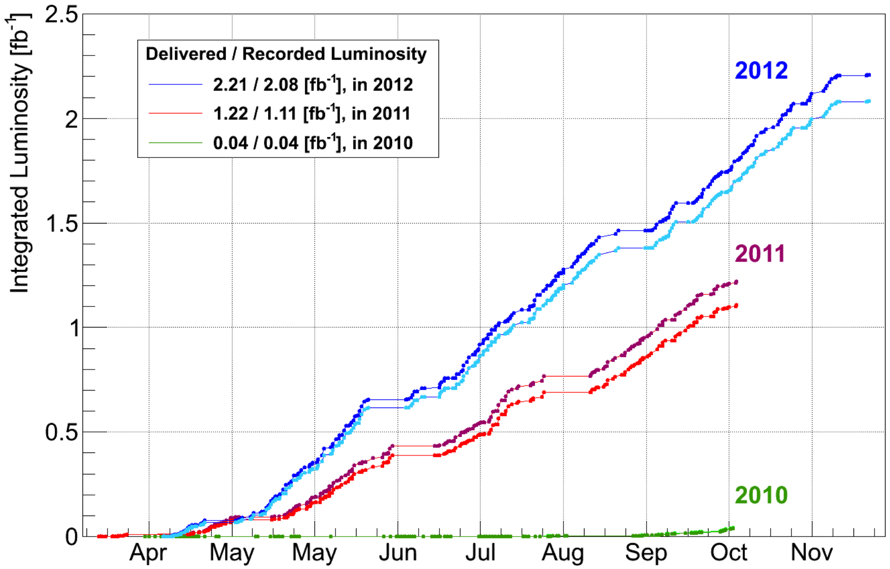


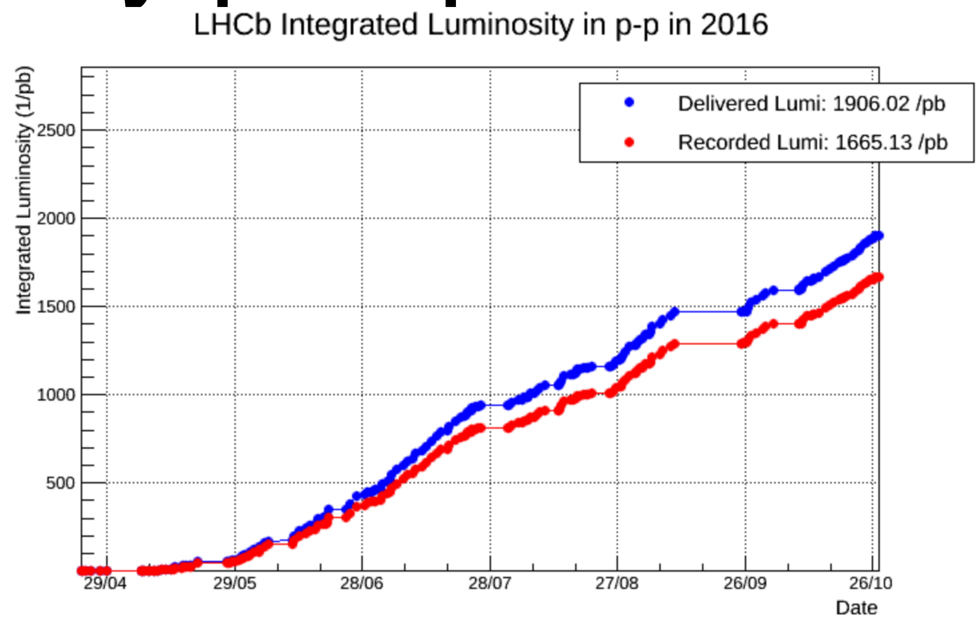
Bonus: full dimuon spectrum

- Useful for studies of, e.g., dark photon



LHCb luminosity prospects

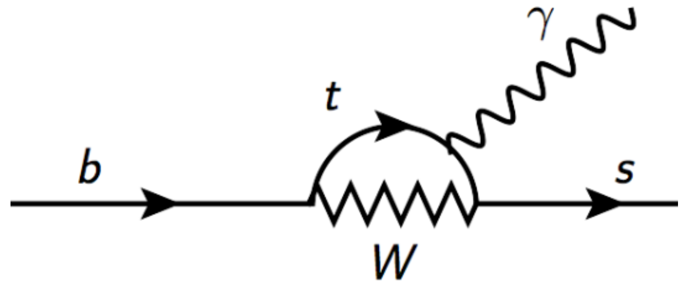




LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

Phase-1 Upgrade!! **Phase-1b Upgrade!?** **Phase-2 Upgrade??**

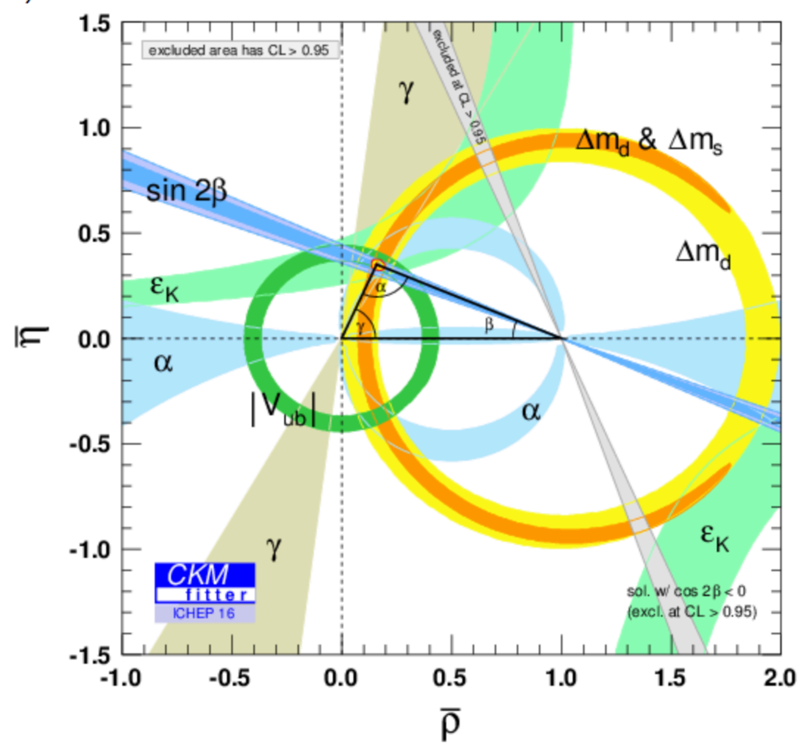
Indirect searches for New Physics



- FCNC

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i=1\ldots10,S,P} (C_i O_i + C_i' O_i') + \text{h.c.}$$

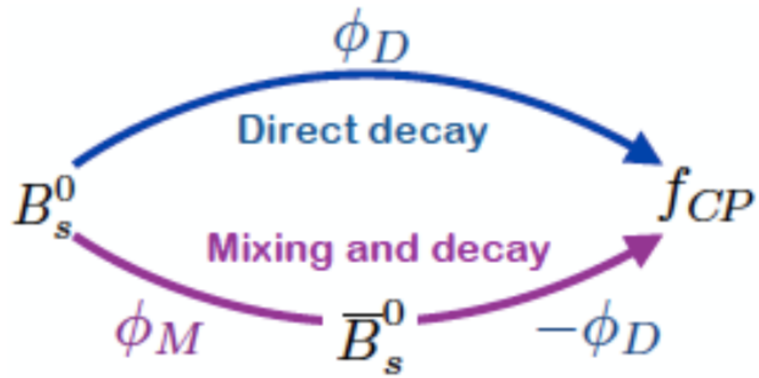
  - NP modify C_i,
  - NP introduce new O_i
- CKM
  - Over-constrain CKM



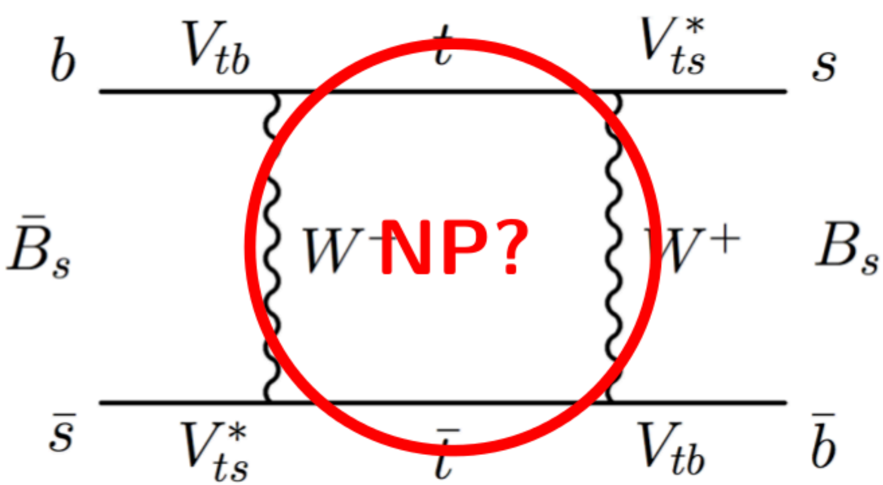
CP violation

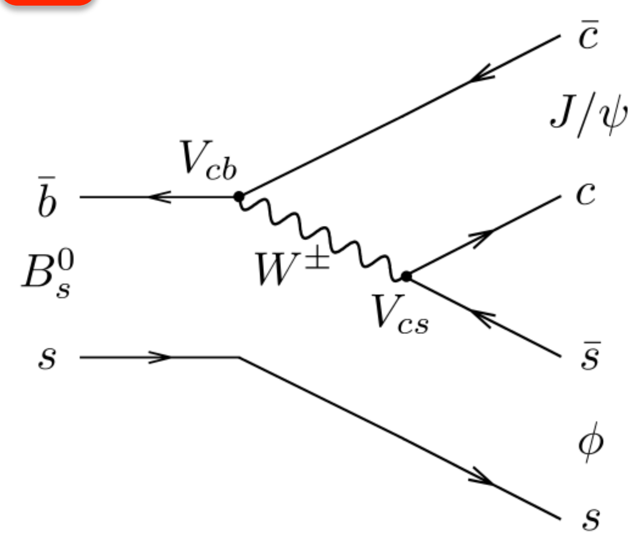
CPV in $B_s \rightarrow J/\psi h^+ h^-$

- $\phi_s = \phi_M - 2\phi_d$, small in SM, sensitive to New Physics
- Small penguin pollution



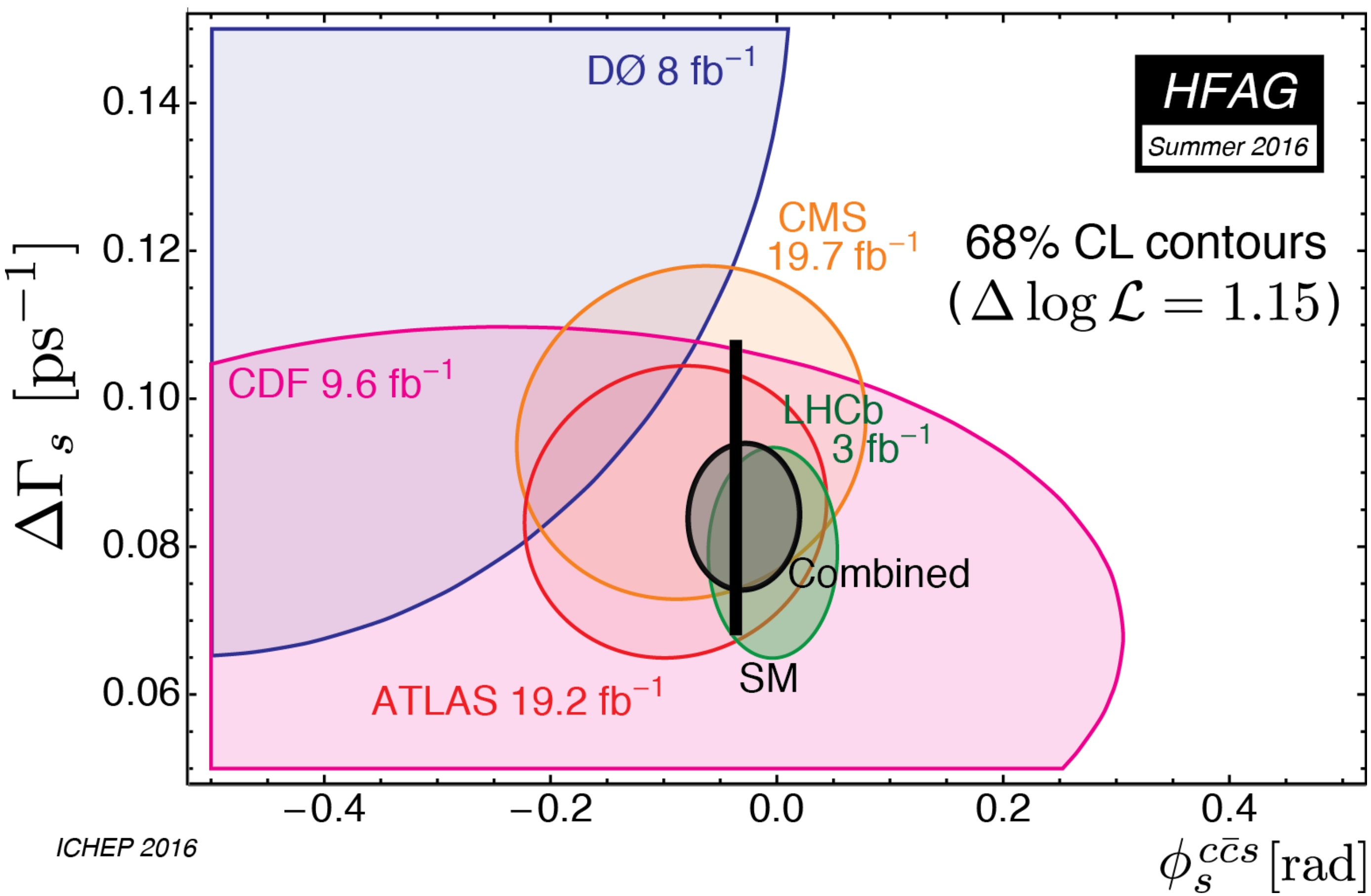
$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}, \text{ with } \phi_s^{\rm SM} = -2\beta_s + \boxed{\delta P} = (-0.0376^{+0.0008}_{-0.0007})\text{rad} + \delta P$$





Latest results on ϕ_s

- As experimental precision improves, important to control penguin contribution

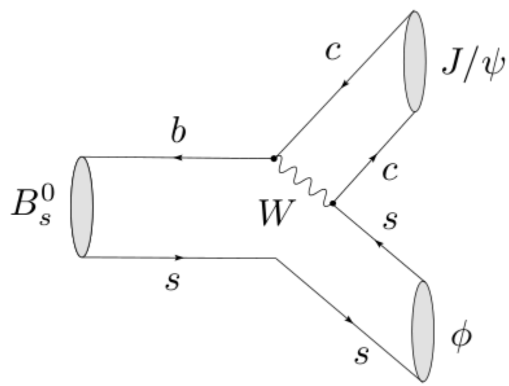


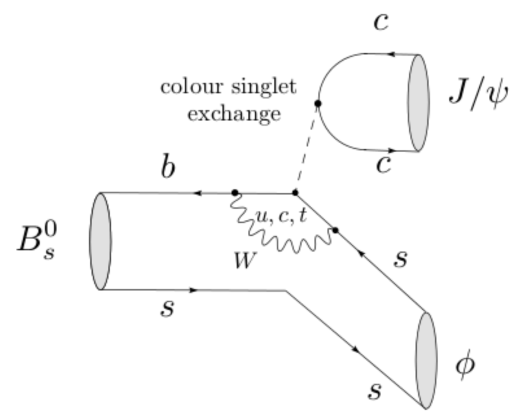
ATLAS, JHEP 08 (2016) 147
CMS, PLB 757 (2016) 97
LHCb, PRL 114 (2015) 041801,
PLB736 (2014) 186, arXiv: 1608.08455
PRL 113 (2014) 211801

Penguin pollution

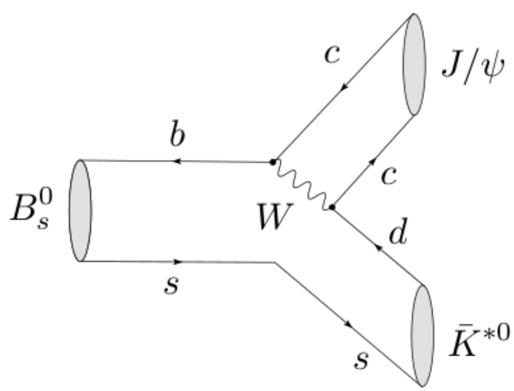
- Small but hard to quantify from theory
- Using SU(3) partner, *s*→*d*

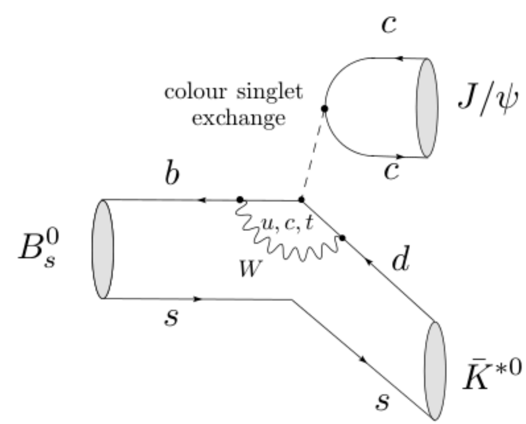
$b \to c\bar{c}s$





$b \to c\bar{c}d$

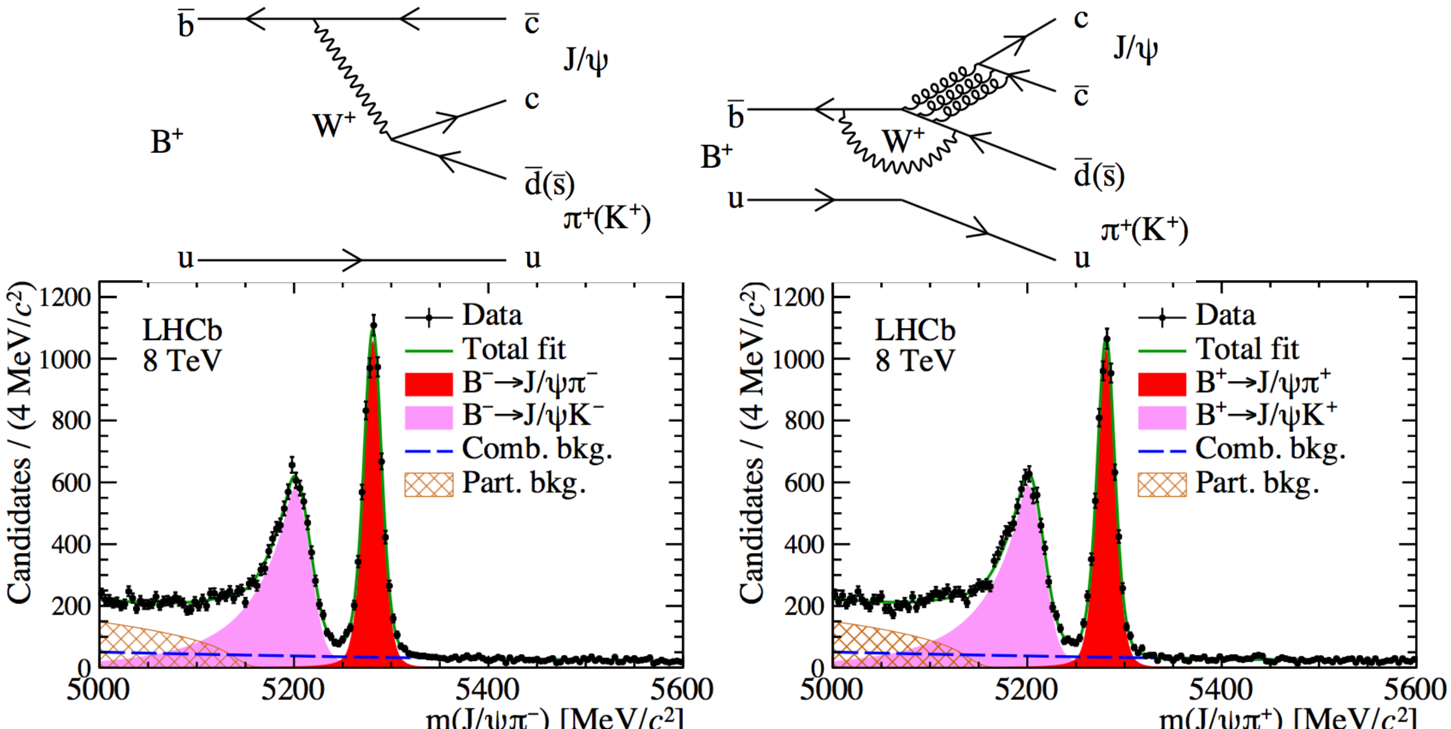




CPV in $B^+ \rightarrow J/\psi\pi^+$

LHCb-PAPER-2016-051

- Similarly, $B^+ \rightarrow J/\psi\pi^+$ useful to estimate penguin contribution to sin2β

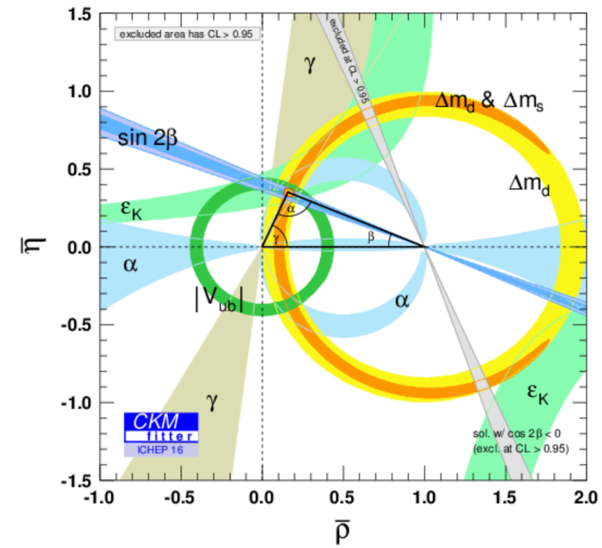


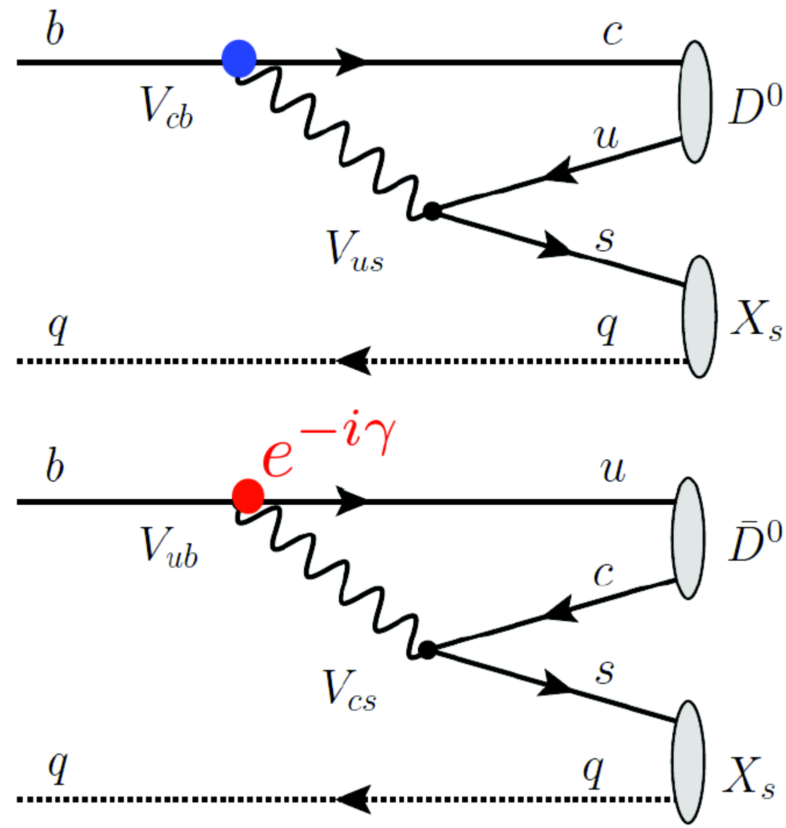
- Most precise estimate

$$\boxed{\mathcal{A}^{CP}(B^+ \to J/\psi\,\pi^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}}$$

CKM-γ

- Least well-measured angle
- Interference between $b \to u$ and $b \to c$ transitions
  - $q=u$, $X_s=K^+, K^{*+}$
  - $q=d$, $X_s=K^{*0}$
- GLW/ADS
  - $D^0, \bar{D}^0 \to \pi^+\pi^-$ or K^+K^- (GLW)
  - $D^0, \bar{D}^0 \to K^+\pi^-$ (ADS)
- CP observations => γ

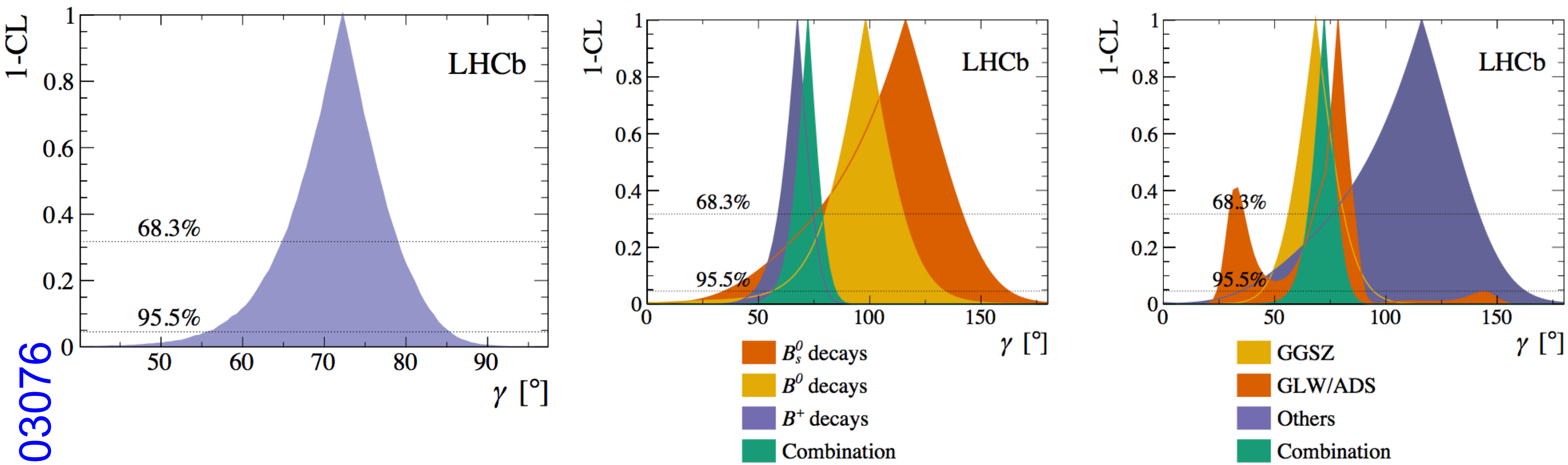




CKM-γ combination at LHCb

- Most accurate determination of CKM-γ

$$\gamma = (72.2^{+6.8}_{-7.3})^{\circ}$$

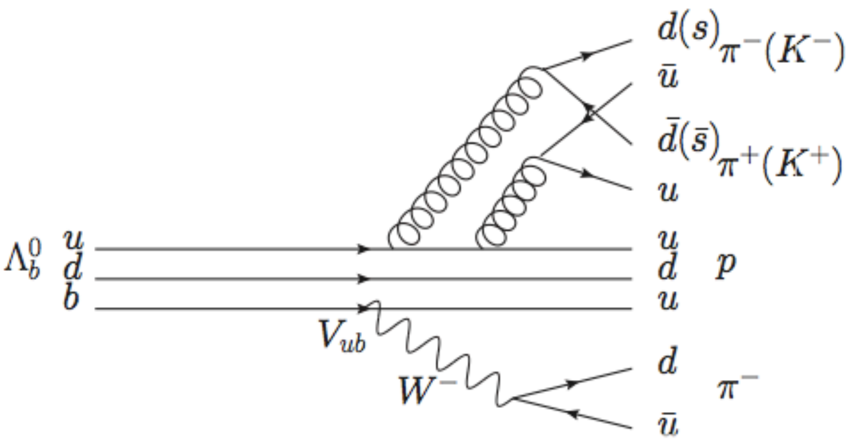


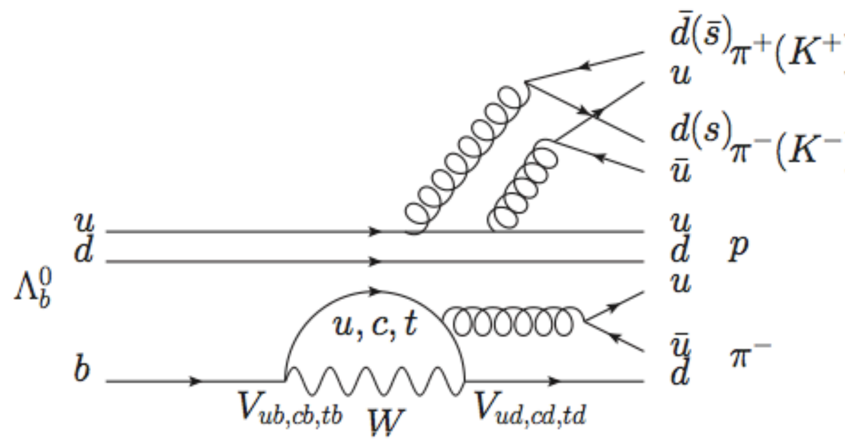
arXiv:1611.03076

- Current one syst. ~2° from CLEO strong phase measurements, BES-III can help

$\Lambda_b \rightarrow p\pi^- h^+ h^-$

- CPV not-yet observed in baryon sector
- A_{cp}~20% expected in charmless Λ_b decays in SM [Y. K. Hsiao et al., PRD 91 (2015) 116007]
- $\Lambda_b \rightarrow p\pi^- h^+ h^-$: tree & loop comparable

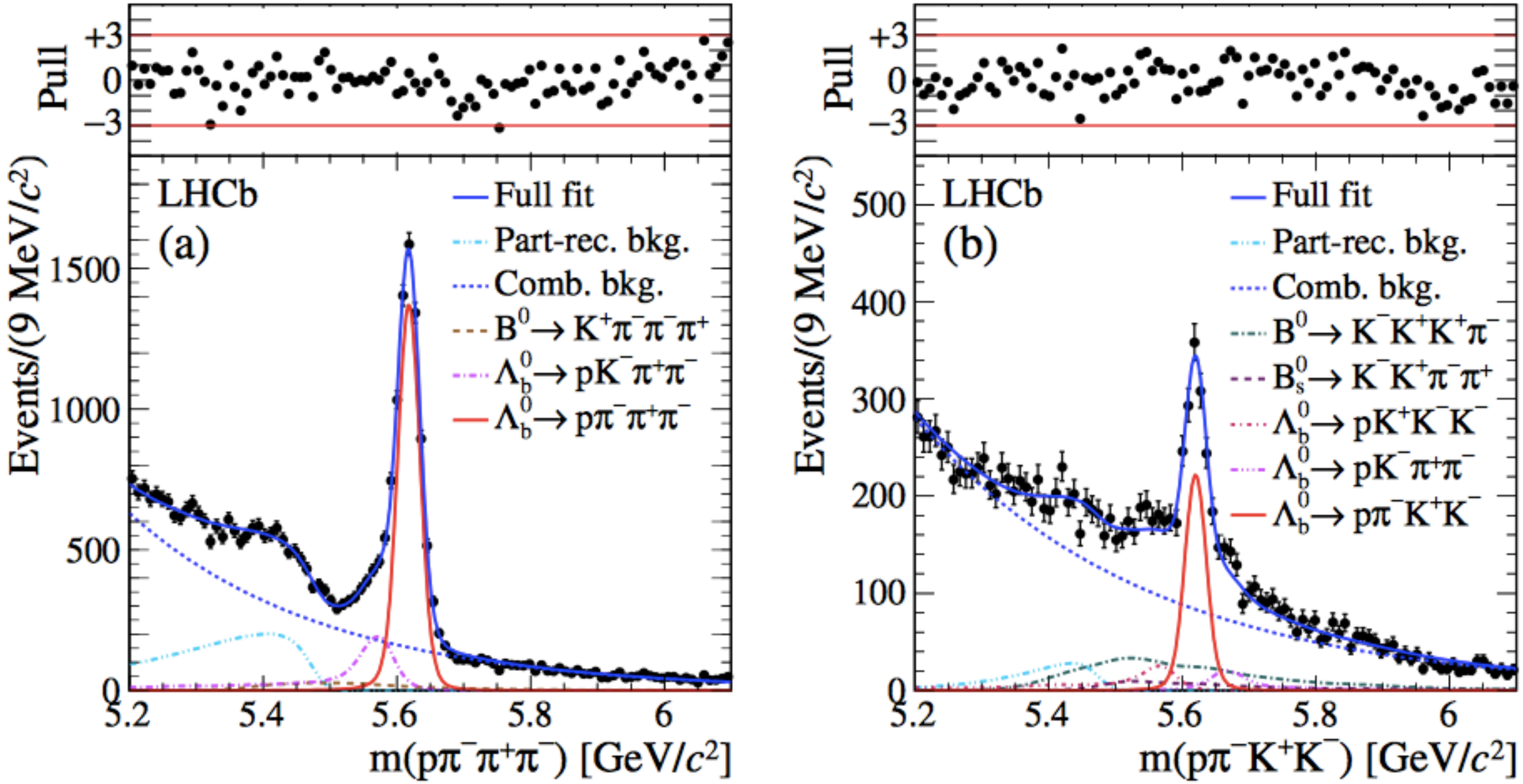




Tree $\propto |V_{ub}| \sim \lambda^3$

Penguin $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$

$\Lambda_b \to p\pi^- h^+ h^-$: signal yields



arXiv:1609.05216

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

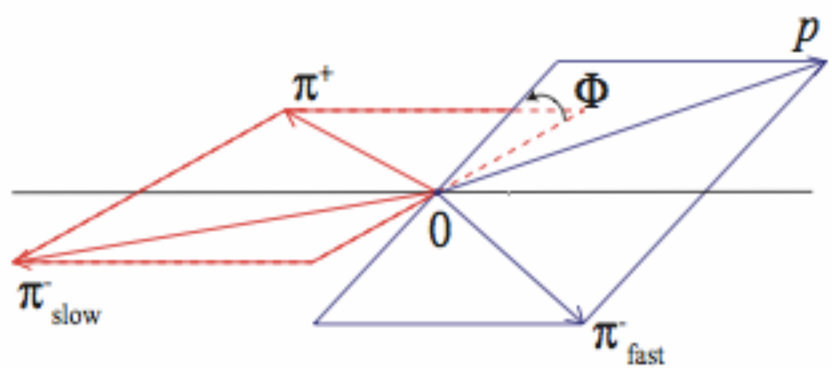
$$N_{\Lambda_b^0 \to p\pi^- K^+ K^-} = 1030 \pm 56(\text{stat})$$

Triple product asymmetry

- Search for CPV using TPA

Triple products in the Λ_b rest frame:

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



[M.Gronau, J. L. Rosner, arXiv: 1506.01346]

$\hat{T}$-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:

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

P-violating observable:

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

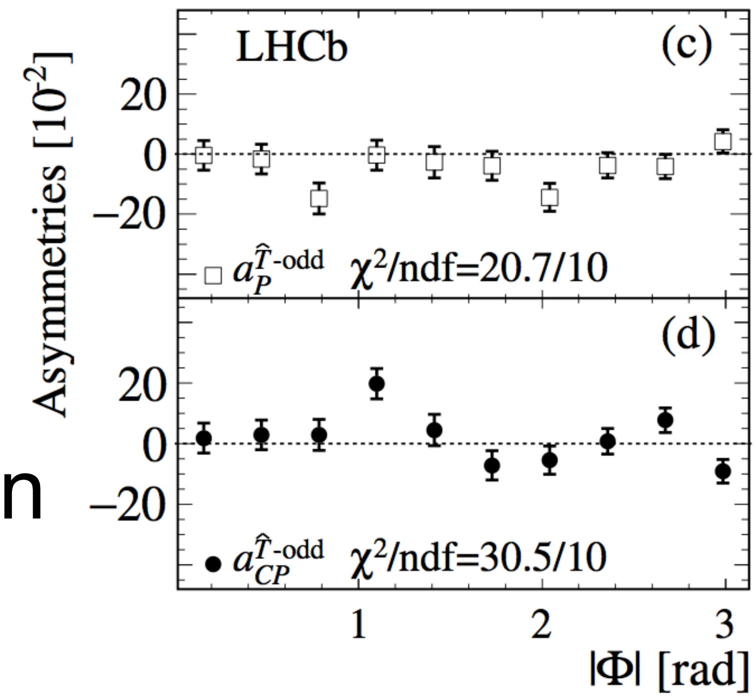
CPV in baryon decays

- Measurements integrated over phase space

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

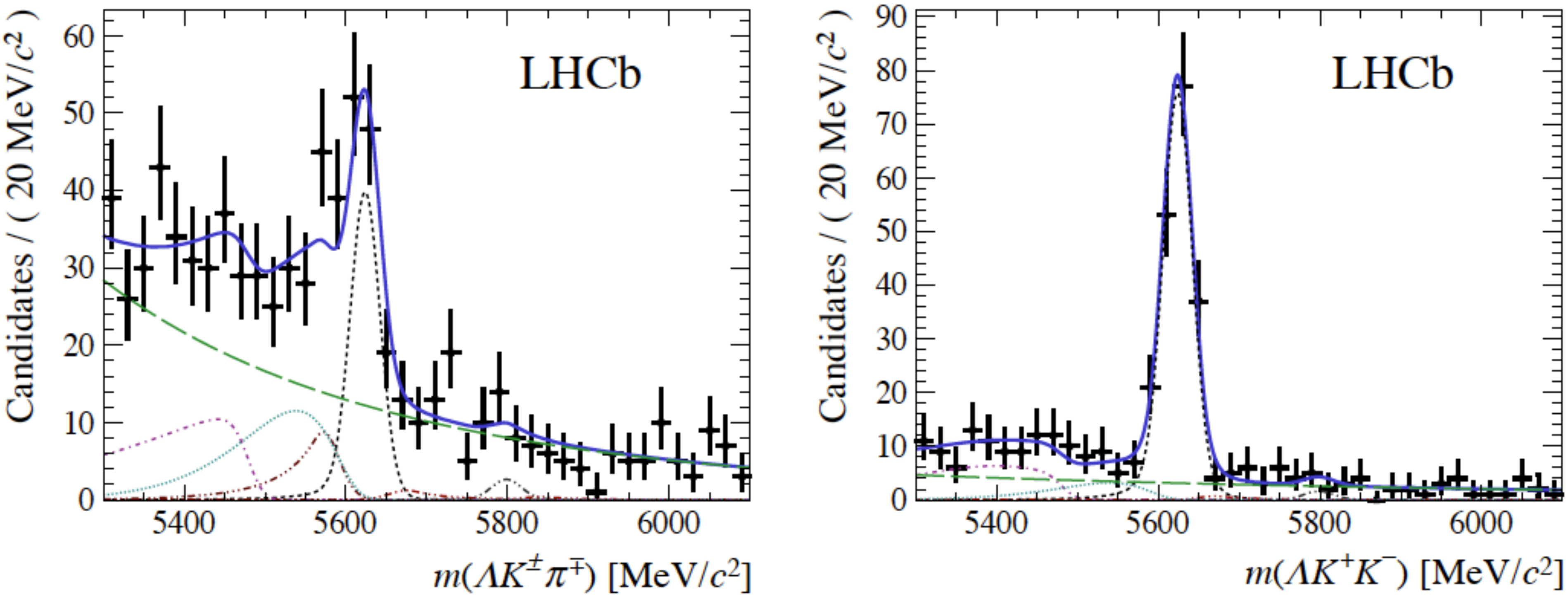
arXiv:1609.05216

- Local measurements
  - 3.3σ localized CPV in $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$
  - Compatible with SM
- First evidence of CPV in baryon decays



CPV in other Λ_b decays

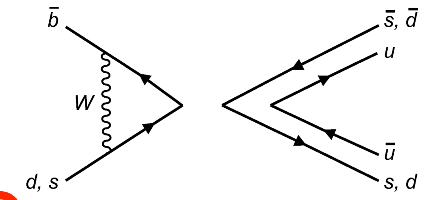
- First observation of $\Lambda_b^0 \to \Lambda K^+\pi^-$ and $\Lambda_b^0 \to \Lambda K^+K^-$



$$\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = -0.53 \pm 0.23 \pm 0.11$$
$$\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = -0.28 \pm 0.10 \pm 0.07$$

Observation of $B^0 \rightarrow K^+K^-$

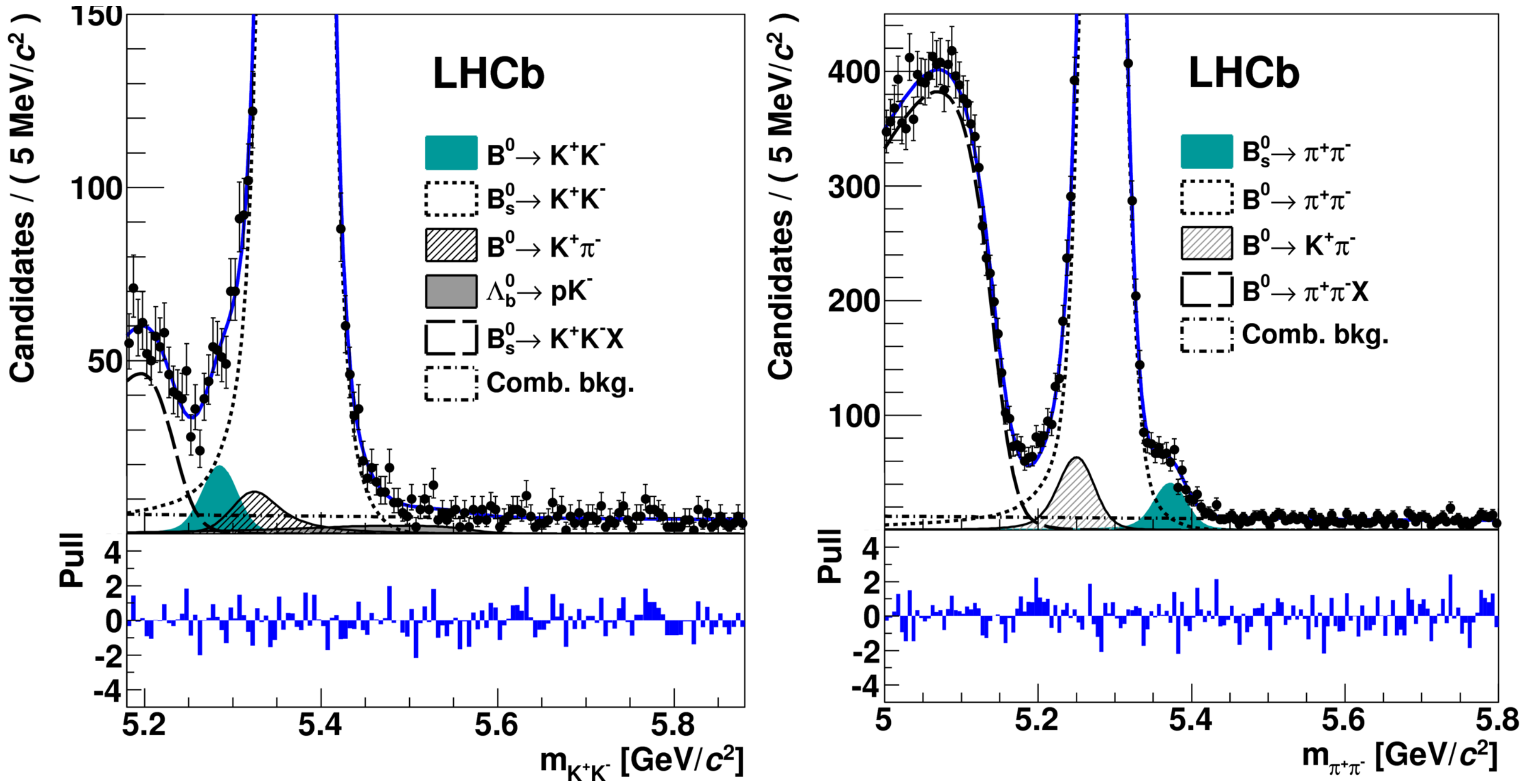
- $B^0 \rightarrow K^+K^-$, weak annihilation
  - QCD dynamics, CKM-γ



$$\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times \boxed{10^{-8}}$$

$$\mathcal{B}(B^0_s \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

arXiv:1610.08288



Semi-leptonic asymmetries

- $a_{\rm sl}$ quantifies CPV in mixing, using flavor specific decays, e.g., $B_s^0 \to D_s^- \mu^+ \nu$

$$\begin{tikzcd} B^0 \arrow[rr] & & f \\ \overline{B^0} \arrow[rr, "/" marking] \arrow[dr, bend right] & & f \\ & B^0 \arrow[ur, bend right] & \end{tikzcd}$$

$$a_{\rm sl} = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})}$$

- Expected to be small in SM

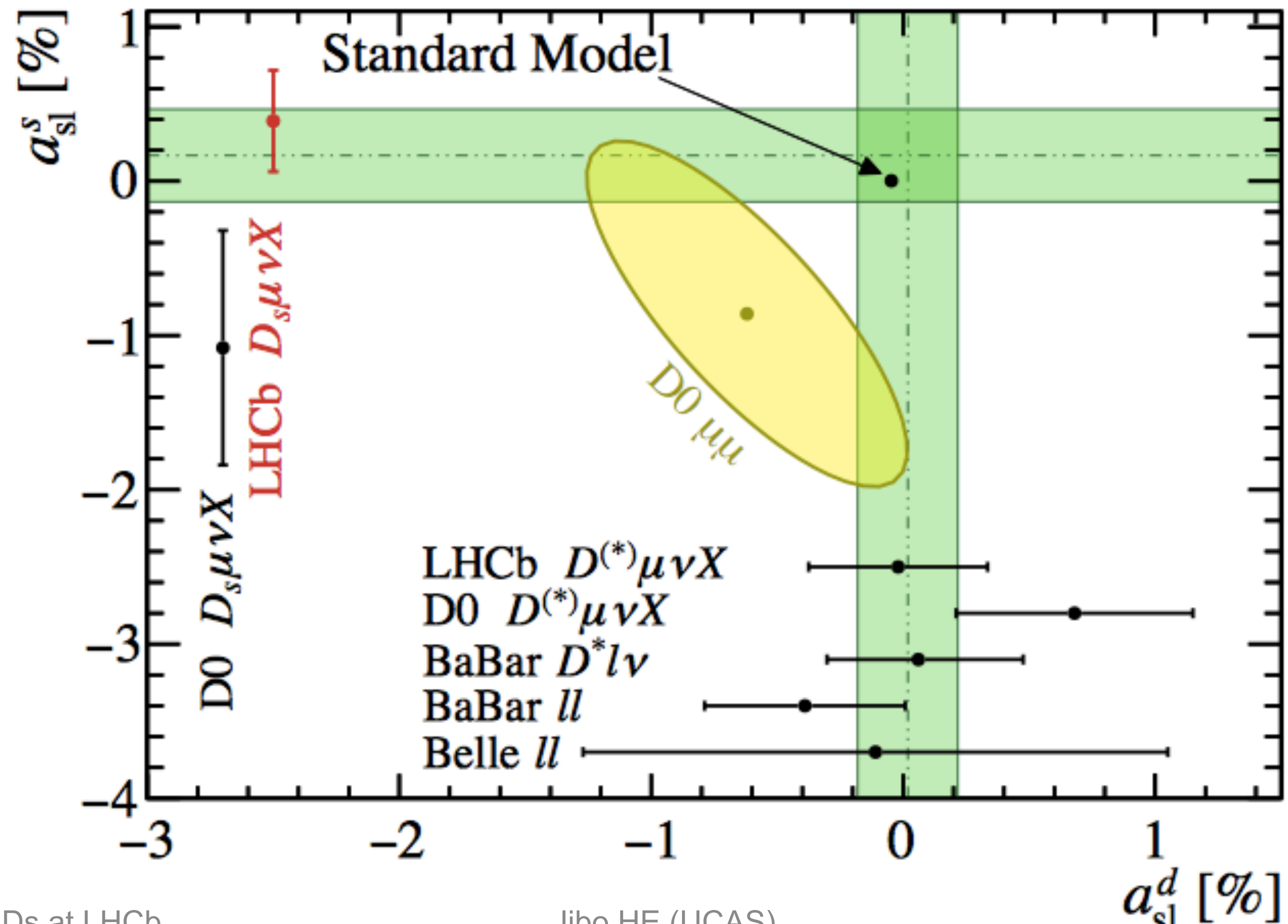
$$a_{\rm sl}^d = (-4.7 \pm 0.6) \times 10^{-4}$$
$$a_{\rm sl}^s = (2.22 \pm 0.27) \times 10^{-5}$$

[A. Lenz, U. Nierste JHEP 06 (2007) 072]
[M. Artuso, et al., arXiv: 1511.09466]

LHCb results on a_{sl}

- Some tension with D0 results

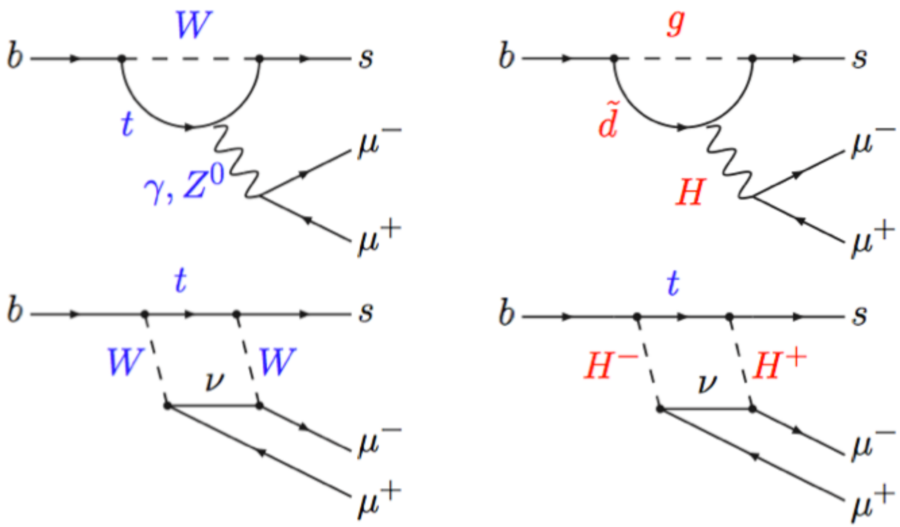
PRL 117 (2016) 061803

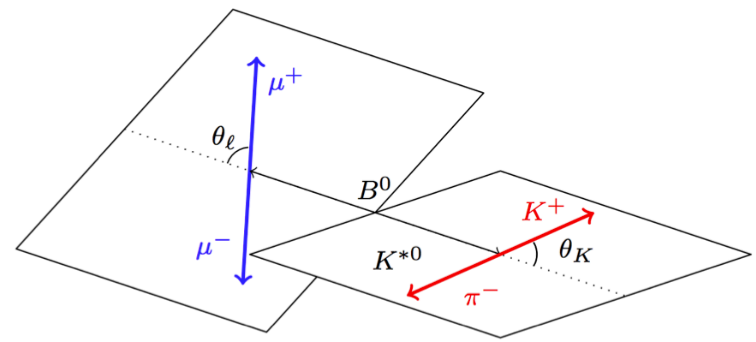


Rare decays

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

- FCNC process, rates and angular distributions sensitive to NP



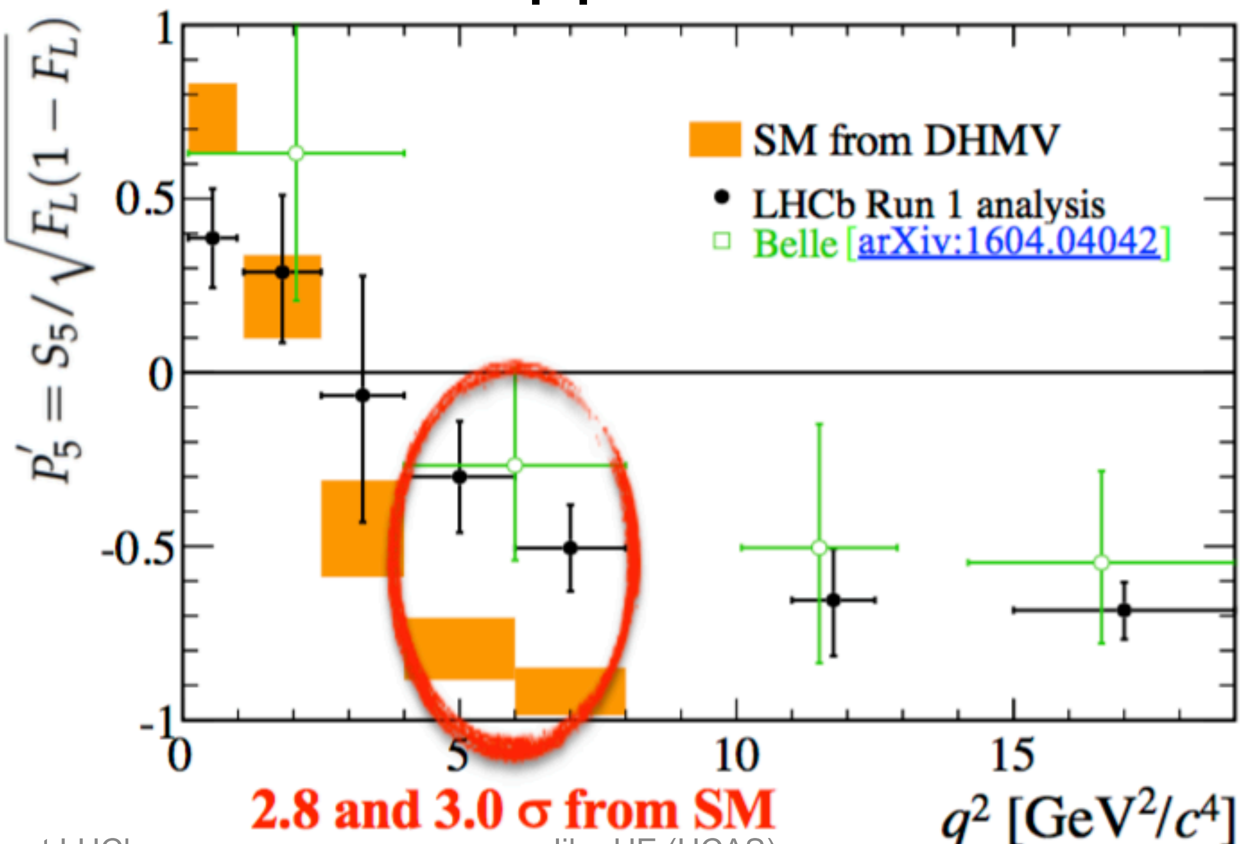


$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\
&- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
&+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\
&+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\
&+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]
\end{aligned}
$$

$B^0 \rightarrow K^{*0}\mu^+\mu^-$: P_5'

- Updated with 3 fb^{-1}, anomaly still there
- Belle's results supports deviation from SM

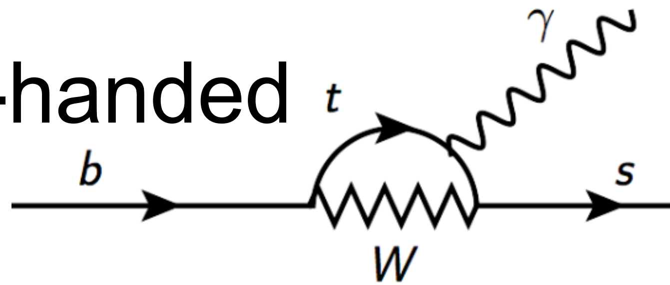
JHEP 02 (2016) 104



2.8 and 3.0 σ from SM

Photon polarization in $B_s \rightarrow \phi\gamma$

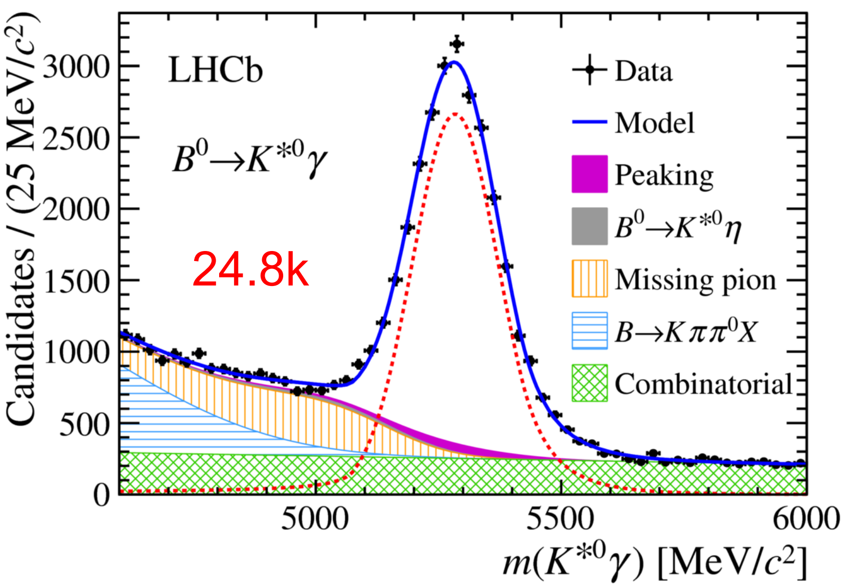
- Photons in $b \rightarrow s\gamma$ mainly left-handed
- Time-dependent signal rate

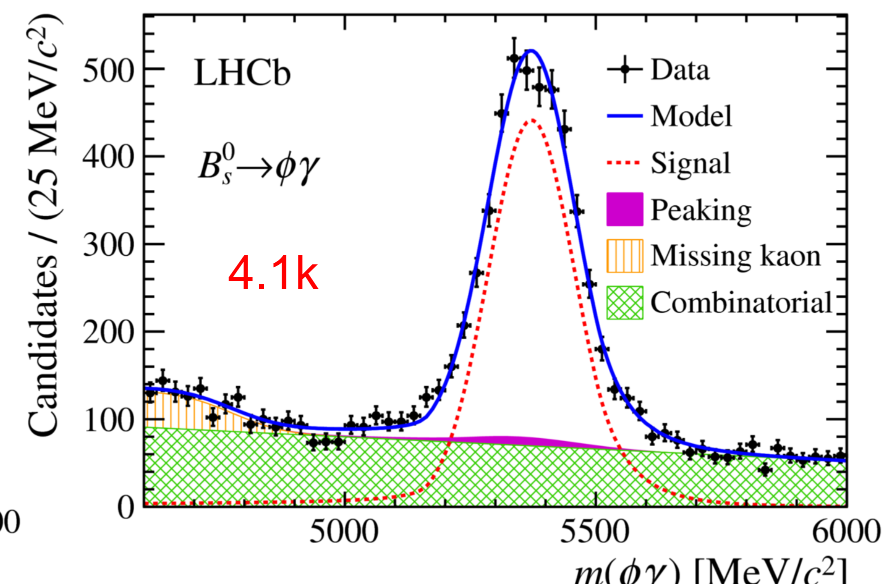


$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2)\}$$

with $\mathcal{A}^{\Delta} \propto 2\frac{\gamma_R}{\gamma_L}$. $\mathcal{A}^{\Delta}_{SM} = 0.05 \pm 0.03$

arXiv:1609.02032



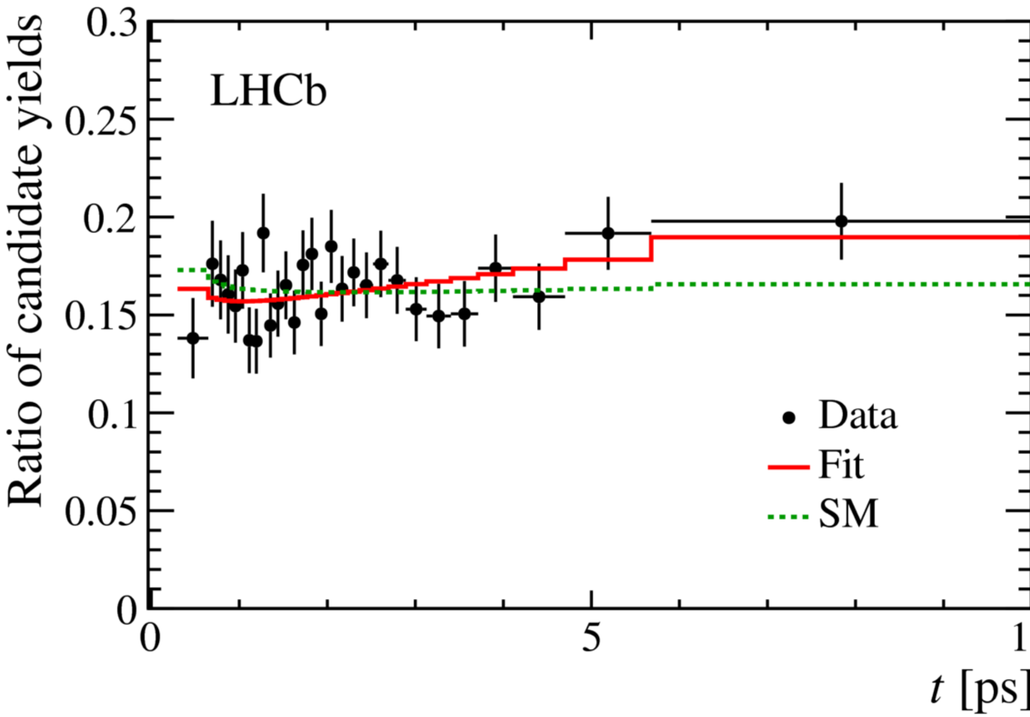


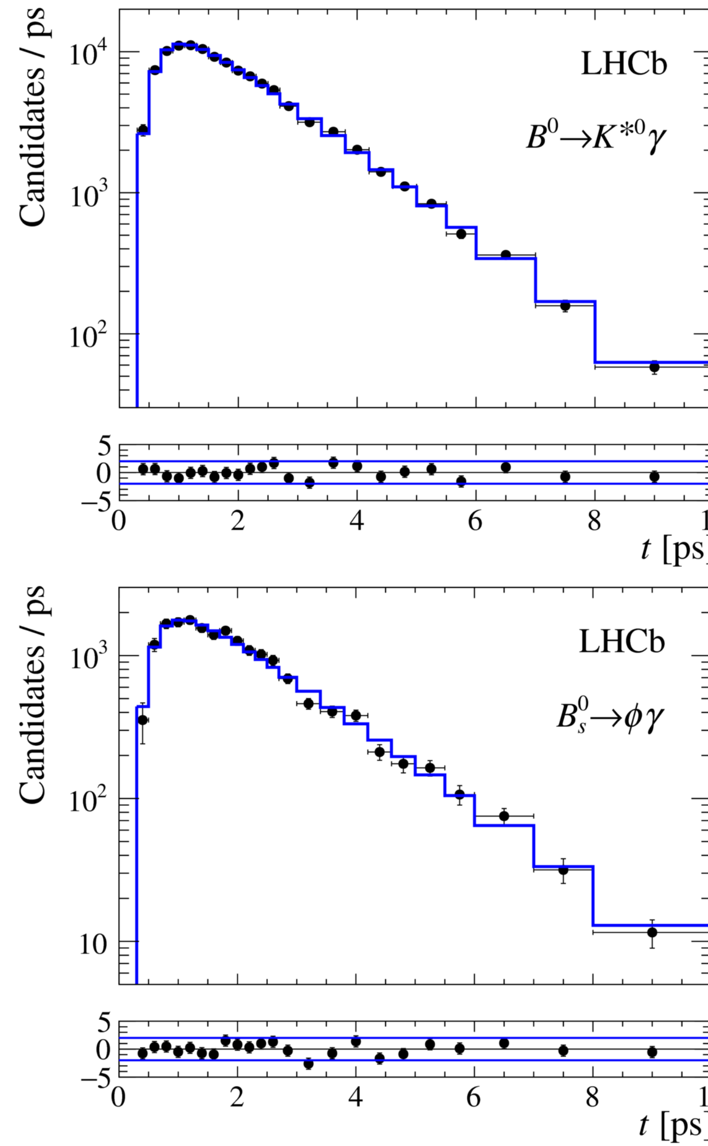
Photon polarization in $B_s \rightarrow \phi\gamma$

- Ratio between B^0/B_s as t
- Compatible with SM in 2σ

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

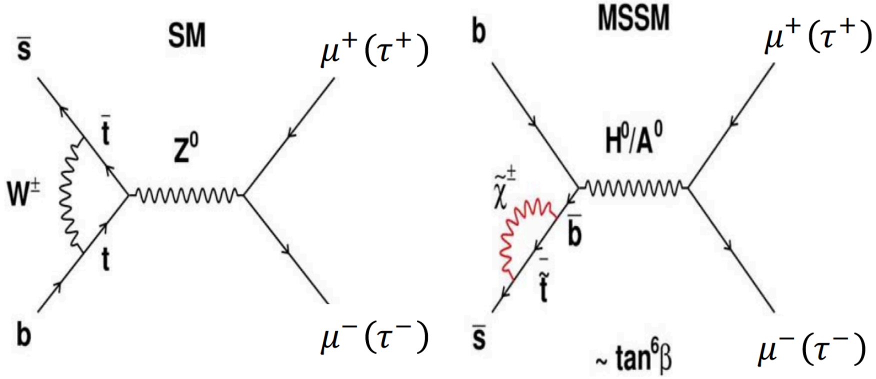
arXiv:1609.02032

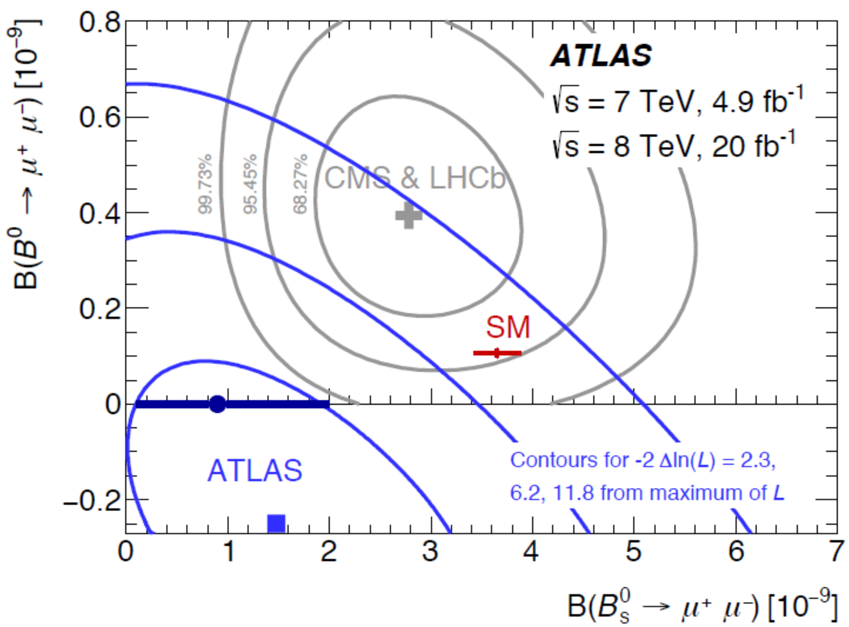


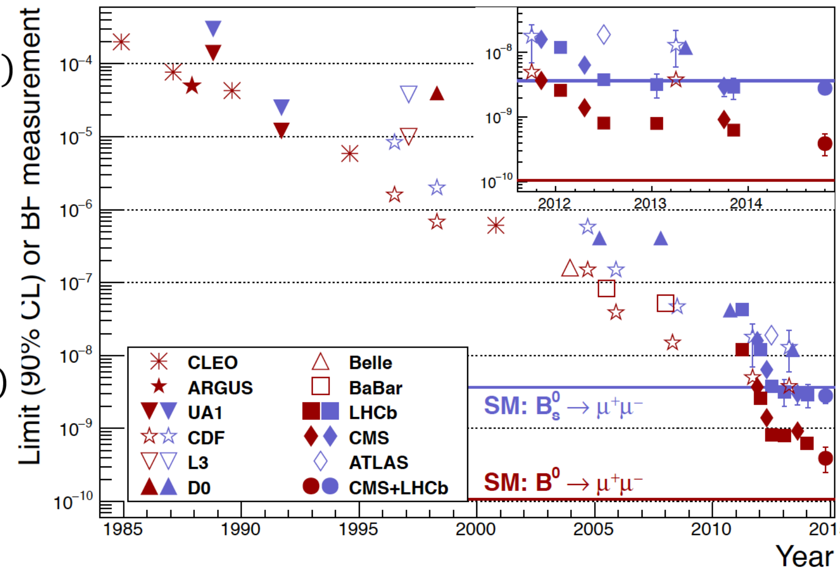


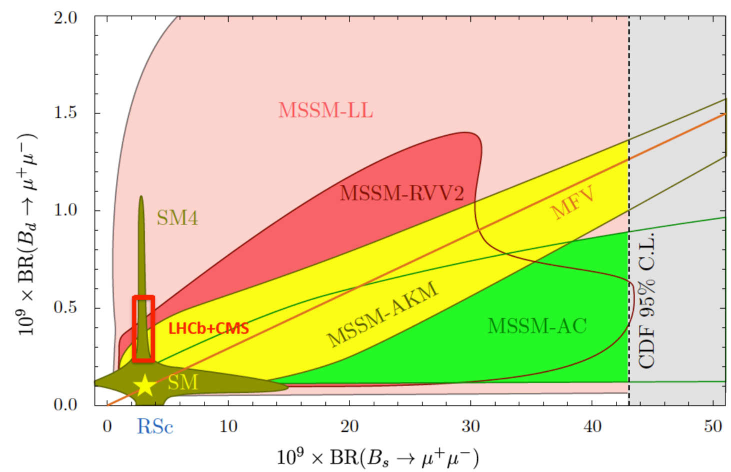
$B_{(s)} \to \mu^+\mu^-$

- $B_{(s)} \to l^+l^-$ attracts continuous efforts









$B_{(s)} \rightarrow \tau^+\tau^-$

- $B_{(s)} \rightarrow \tau^+\tau^-$ not helicity suppressed in SM, predicted *BR* ~200 higher than $B_{(s)} \rightarrow \mu^+\mu^-$

$$
\begin{aligned}
\mathcal{B}(B_s^0 \to \tau^+\tau^-)_{SM} &= (7.73 \pm 0.49) \times 10^{-7} \\
\mathcal{B}(B^0 \to \tau^+\tau^-)_{SM} &= (2.22 \pm 0.19) \times 10^{-8}
\end{aligned}
$$

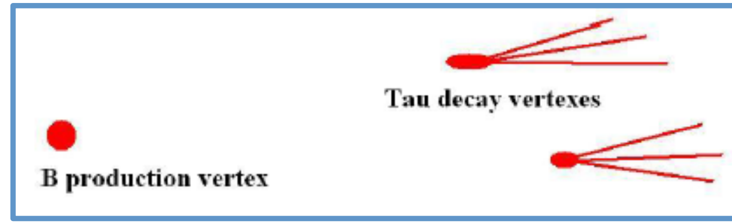
- $\mathcal{B}(B_{(s)} \rightarrow \tau^+\tau^-)$ enhanced in NP scenarios, current best limit from Babar

$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3}$ @ 90% C.L.

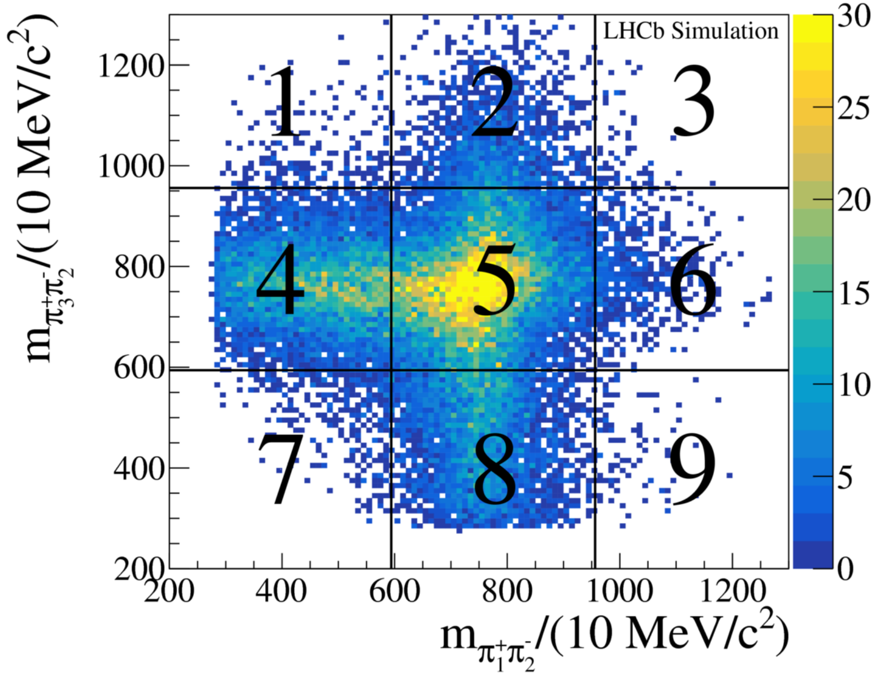
[Babar, PRL 96 (2006) 241802]

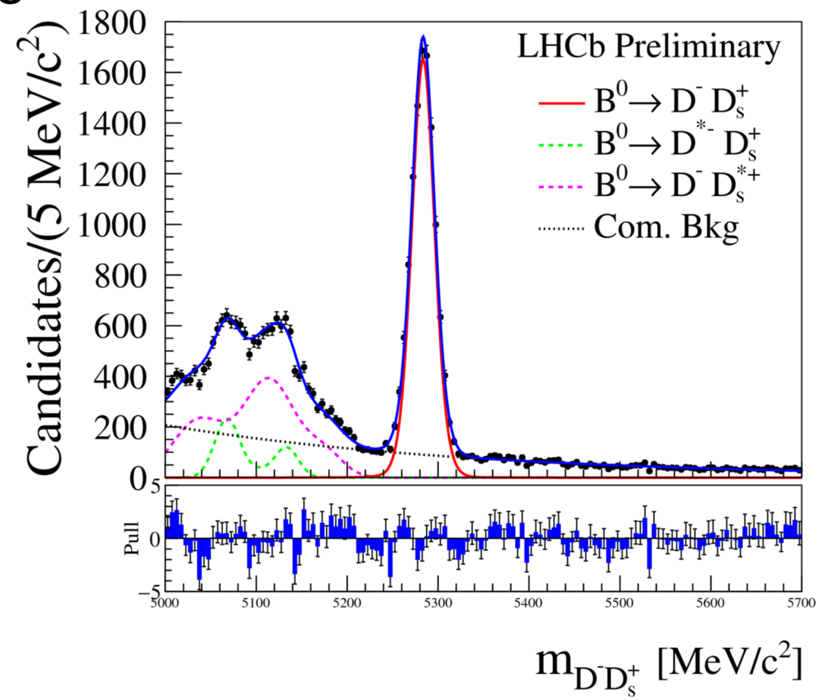
$B_{(s)} \to \tau^+\tau^-$

- Using $\tau \to 3\pi\nu$ (a_1) mode
- Normalized to $B \to D^+D_s$



LHCb-CONF-2016-011



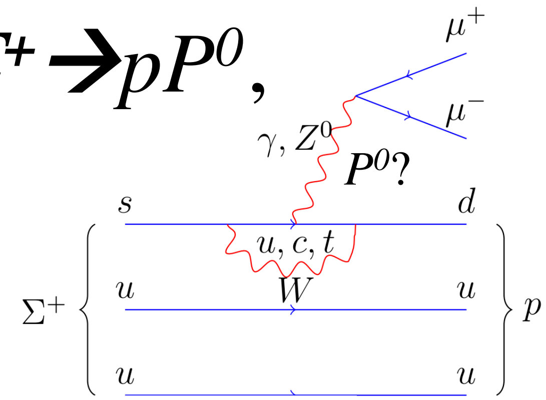


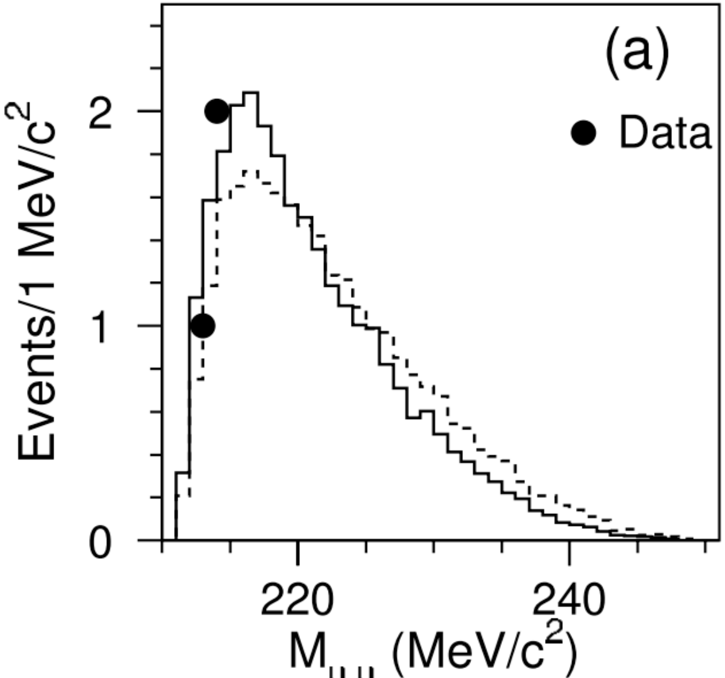
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 2.4(3.0) \times 10^{-3} \text{ @ 90 (95)\% C.L.}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.0(1.3) \times 10^{-3} \text{ @ 90 (95)\% C.L.}$$

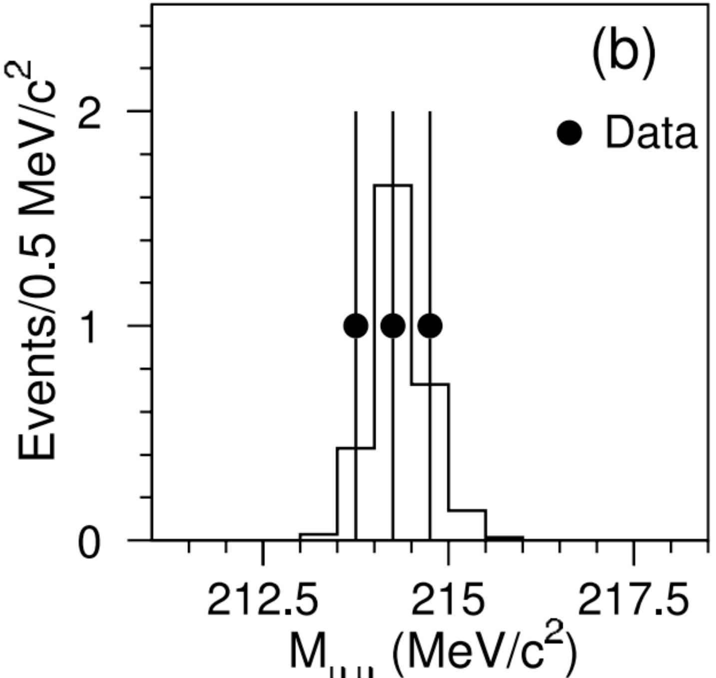
$\Sigma^+ \rightarrow p\mu^+\mu^-$

- Hint of intermediate particle, $\Sigma^+ \rightarrow pP^0$, $X^0 \rightarrow \mu^+\mu^-$, mass 214.3 MeV

  [HyperCP, PRL 94 (2005) 021801]



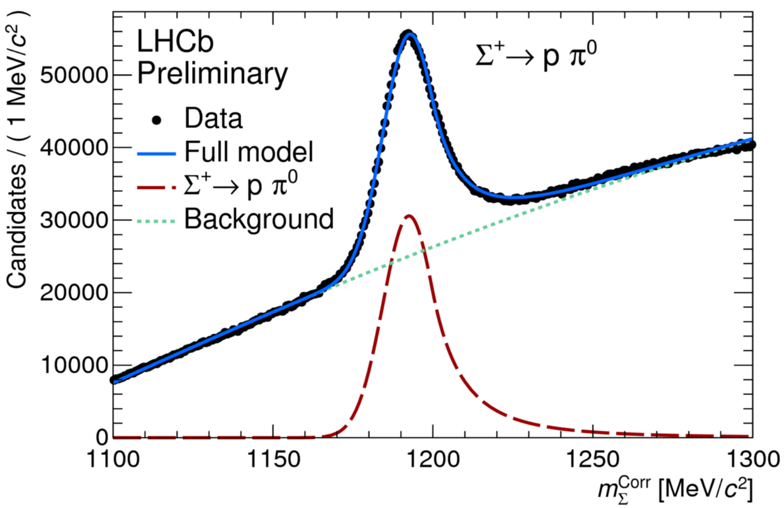


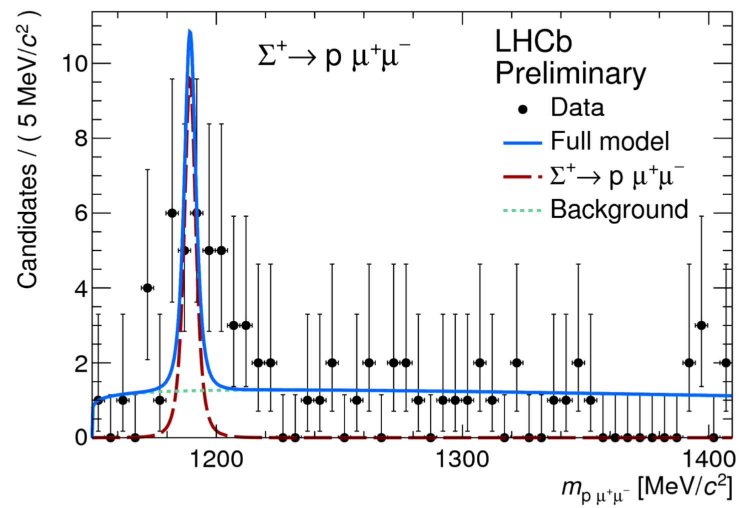


$\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb

- Studied with Run-I data
- $\Sigma^+ \rightarrow p\mu^+\mu^-$ signal of $12.9^{+5.1}_{-4.2}$ seen, 4.0σ

LHCb-CONF-2016-013

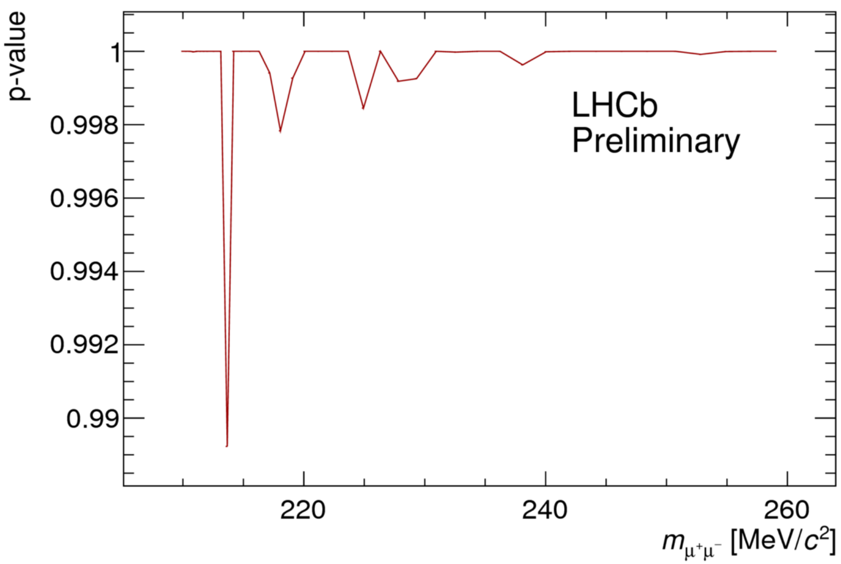


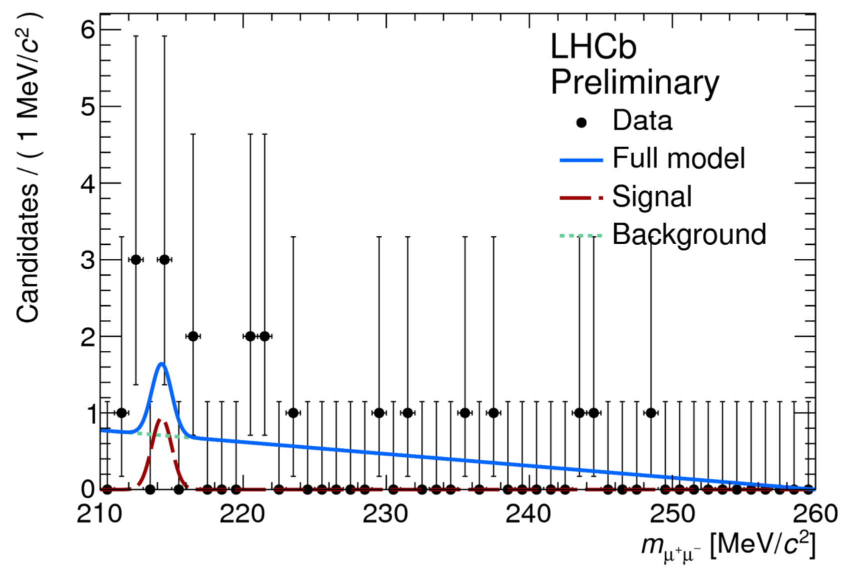


$P^0 \rightarrow \mu^+\mu^-$?

- Scan for P^0 in the $m(\mu^+\mu^-)$ within Σ^+ signal region, no sign of narrow peak

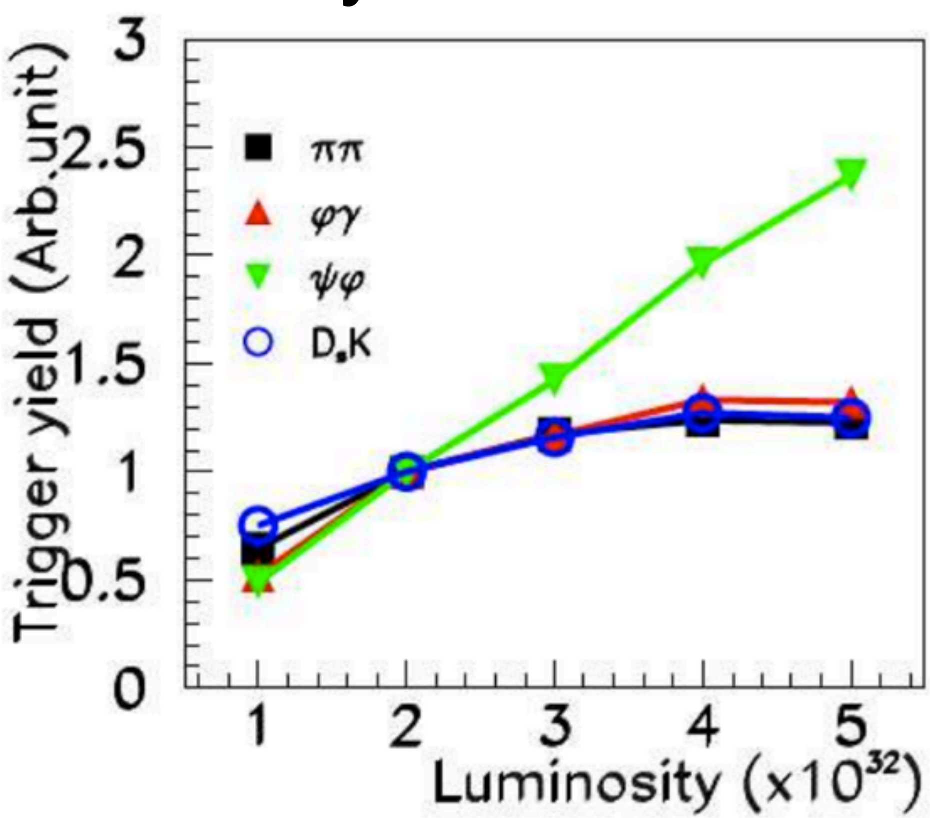
LHCb-CONF-2016-013

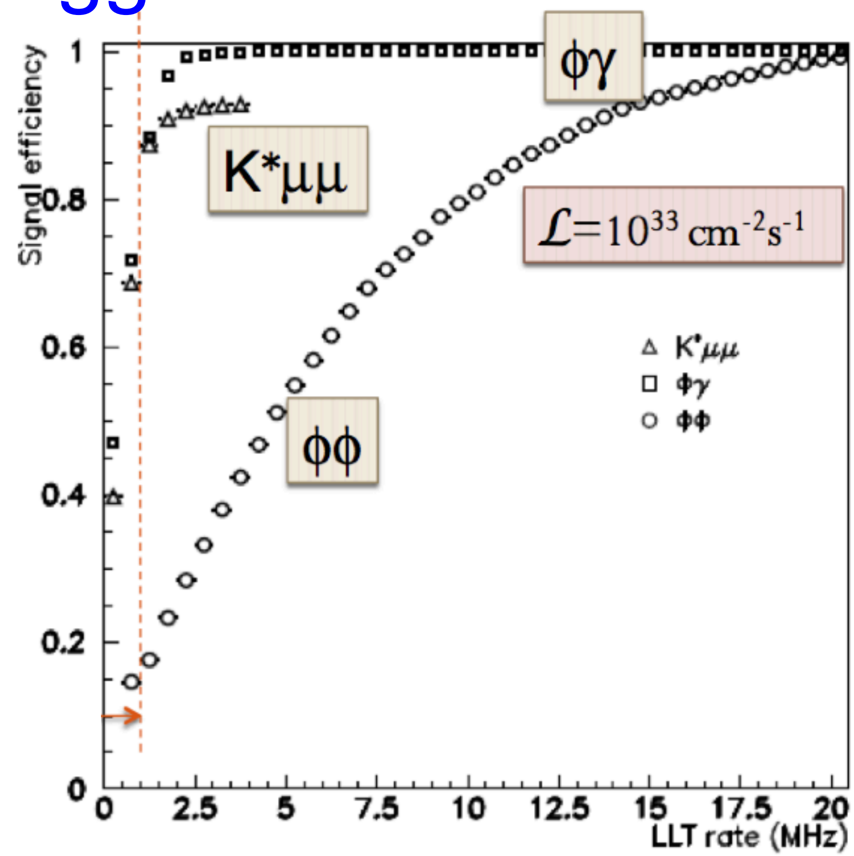




The LHCb upgrade

- Lumi, from $4 \times 10^{32} cm^{-2}s^{-1}$ to $20 \times 10^{32} cm^{-2}s^{-1}$
- Increase trigger efficiency of hadronic decays ➔ hardware trigger removed





Projections after the upgrade

See X. Yuan's talk this afternoon

EPJC 73 (2013) 2373

Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.17 [219]	0.045	0.014	$\sim$0.01
	a_{sl}^s	6.4×10^{-3} [44]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\overline{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [44]	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 penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [68]	0.025	0.008	0.02
	$s_0 A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [77]	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	2.5 %	$\sim$10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	$\sim$10–12° [252, 266]	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Summary

- The LHC(b) is a flavor factory
- LHCb performed world-leading CPV and RD measurements, with Run-I data
  - ϕ_s, CKM-γ, CPV in baryon, a_{sl}
  - P_5', photon polarization, $B_s \rightarrow \tau^+\tau^-$
- Analysis with Run-II ongoing, stay tuned
- LHCb upgrade under its way