Rare Decays at LHCb

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On behalf of the LHCb collaboration

XX Cracow EPIPHANY Conference, January 2014

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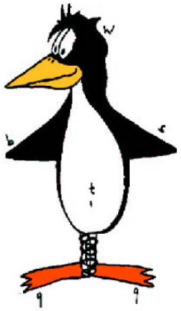
- **$B \to K^*\mu\mu$,** Phys. Rev. Lett. **08** (2013) 117, **[arXiv:1308.1707]** **($1fb^{-1}$)**
- **$B^+\to K^+\mu\mu$,** Phys. Rev. Lett. **111** (2013) 151801, **[arXiv:1308.1340]** **($1fb^{-1}$)**
- **$\psi(4160)$,** Phys. Rev. Lett. **111** (2013) 112003, **[arXiv:1307.7595]** **($3fb^{-1}$)**
- **$B_{s/d}\to\mu\mu$,** Phys. Rev. Lett. **111** (2013) 101805, **[arXiv:1307.5024]** **($3fb^{-1}$)**
- **$B_{s/d}\to\mu e$,** Phys.Rev. Lett. **111** (2013) 141801, **[arXiv:1307.4889]** **($1fb^{-1}$)**
- **$\Lambda_b\to\Lambda\mu\mu$,** Phys. Lett. **B725** (2013) 25, **[arXiv:1306.2577]** **($1fb^{-1}$)**
- **$D\to\mu\mu$,** Phys. Lett. **B725** (2013) 15, **[arXiv:1305.5059]** **($0.9fb^{-1}$)**
- **$B_s\to\phi\mu\mu$,** JHEP **1307** (2013) 084, **[arXiv:1305.2168]** **($1fb^{-1}$)**
- **$B \to K^*\mu\mu$,** JHEP **1308** (2013) 131, **[arXiv:1304.6325]** **($1fb^{-1}$)**
- **$\tau\to 3\mu$, $\tau\to p\mu\mu$,** Phys. Lett. **B724** (2013), **[arXiv:1304.4518]** **($1fb^{-1}$)**
- **$B \to K^*ee$,** JHEP **05** (2013) 159, **[arXiv:1304.3035]** **($1fb^{-1}$)**
- **$B\to 4\mu$,** Phys. Rev. Lett. **110** (2013) 211801, **[arXiv:1303.1092]** **($1fb^{-1}$)**
- **$B\to K^*\mu\mu$,** Phys. Rev. Lett. **110** (2013) 031801, **[arXiv:1210.4492]** **($1fb^{-1}$)**
- **$B^+\to\pi^+\mu\mu$,** JHEP **12** (2012) 125, **[arXiv:1210.2645]** **($1fb^{-1}$)**
- **$K_s\to\mu\mu$,** JHEP **01** (2013) 090, **[arXiv:1209.4029]** **($1fb^{-1}$)**
- **$B\to K^{(*)}\mu\mu$,** JHEP **07** (2012) 133, **[arXiv:1205.3422]** **($1fb^{-1}$)**
- **$B\to K^*\gamma/B_s\to\phi\gamma$,** Nucl. Phys. **B 867** (2012) 118, **[arXiv:1209.0313]** **($1fb^{-1}$)**
- **$B^+\to X\mu^-\mu^-$,** Phys. Rev. **D 85** (2012) 112004, **[arXiv:1201.5600]** **($0.41fb^{-1}$)**

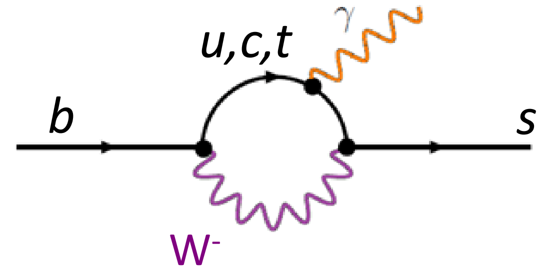
Outline

- Rare B decays
- The LHCb experiment
- Leptonic decays: $B_{s/d} \rightarrow \mu^+\mu^-$
- Lepton Flavour Violation: $B_{s/d} \rightarrow e^+\mu^-$
- Semi(di)leptonic decays: $B_d \rightarrow K^{*0}\mu^+\mu^-$
- Radiative decays: $B^+ \rightarrow K^+\pi^-\pi^+\gamma$
- Conclusions

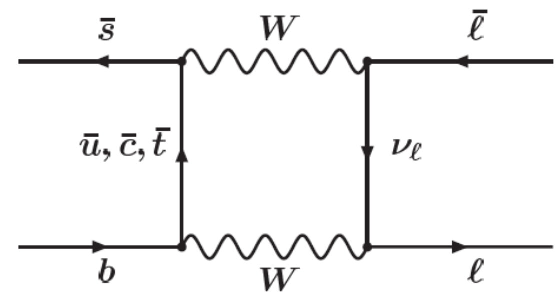
Rare B decays



- $b \to s$ transitions are **Flavor Changing Neutral Currents (FCNCs)**, forbidden in the Standard Model (SM) at tree level
$\to$ they go through loops (*penguin and box diagrams*)

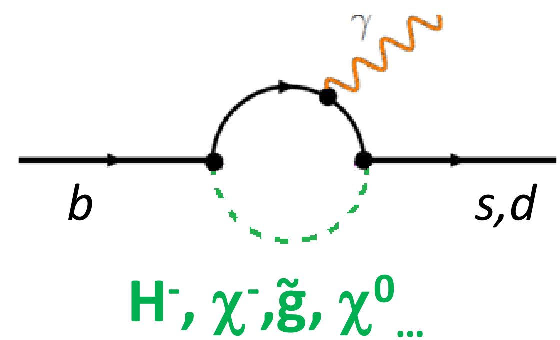


- ***Leptonic***, ***semileptonic*** and ***radiative b→s*** decays are of particular interest since the SM rates (and other observables) can be calculated with high precision using effective theories (in terms of the Wilson coefficients)

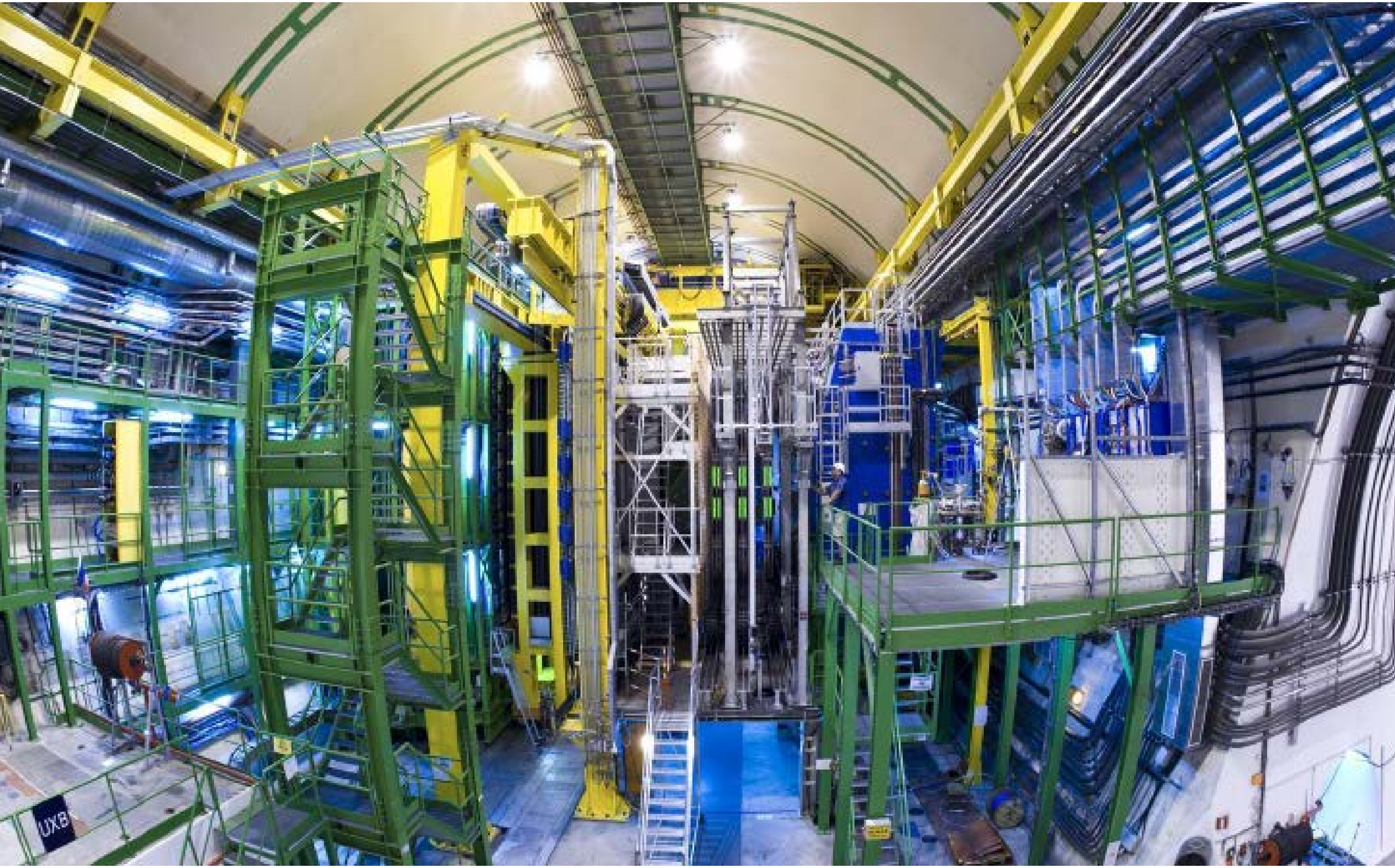


- Rare (and very rare) processes: $BR_{SM} \sim 10^{-5} - 10^{-10}$, but experimentally accessible by flavour experiments (**B- factories & LHCb**)
$\to$ Experimental signature: high P_T leptons/photons

- Excellent probe for physics beyond the SM
$\to$ sensitivity to **new heavy particles** in the loops

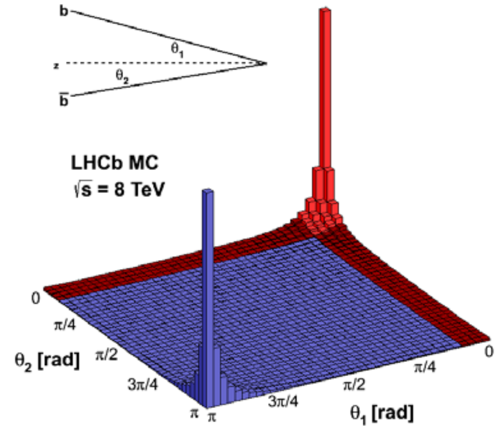


The LHCb experiment



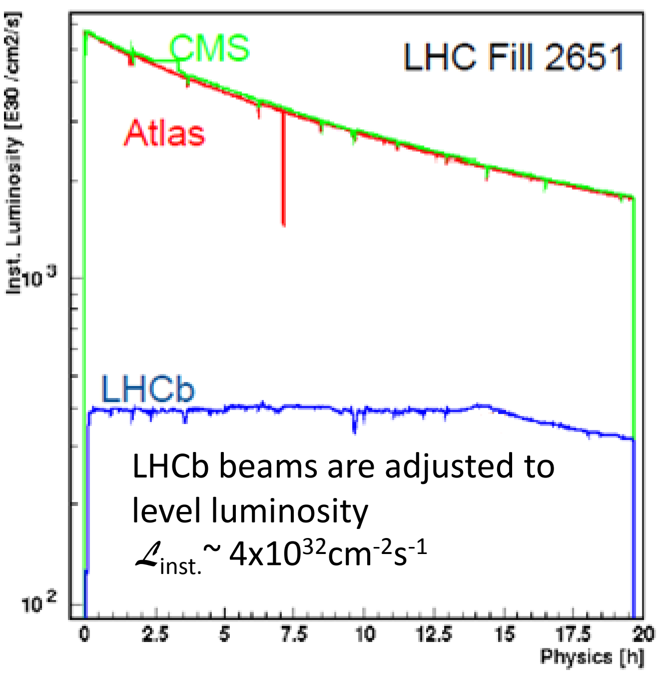
The LHCb experiment

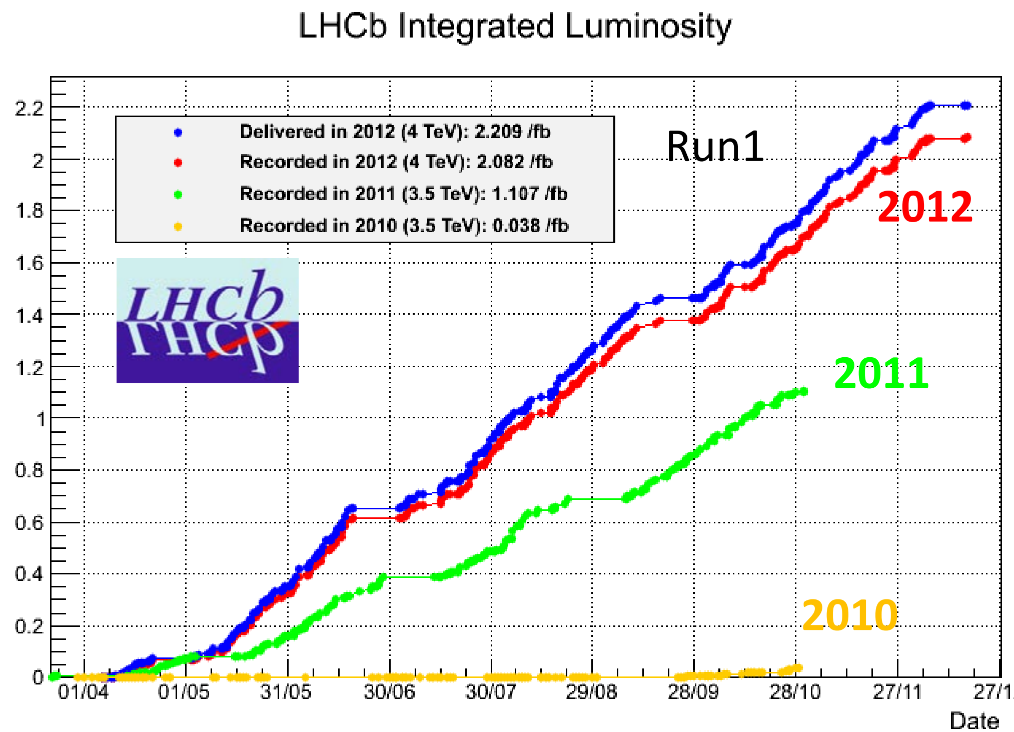
- LHC: Large $b\bar{b}$ cross section in pp colisions (gluon fusion) (~250 μb – 500 μb @ $\sqrt{s}$=7 – 14 TeV):



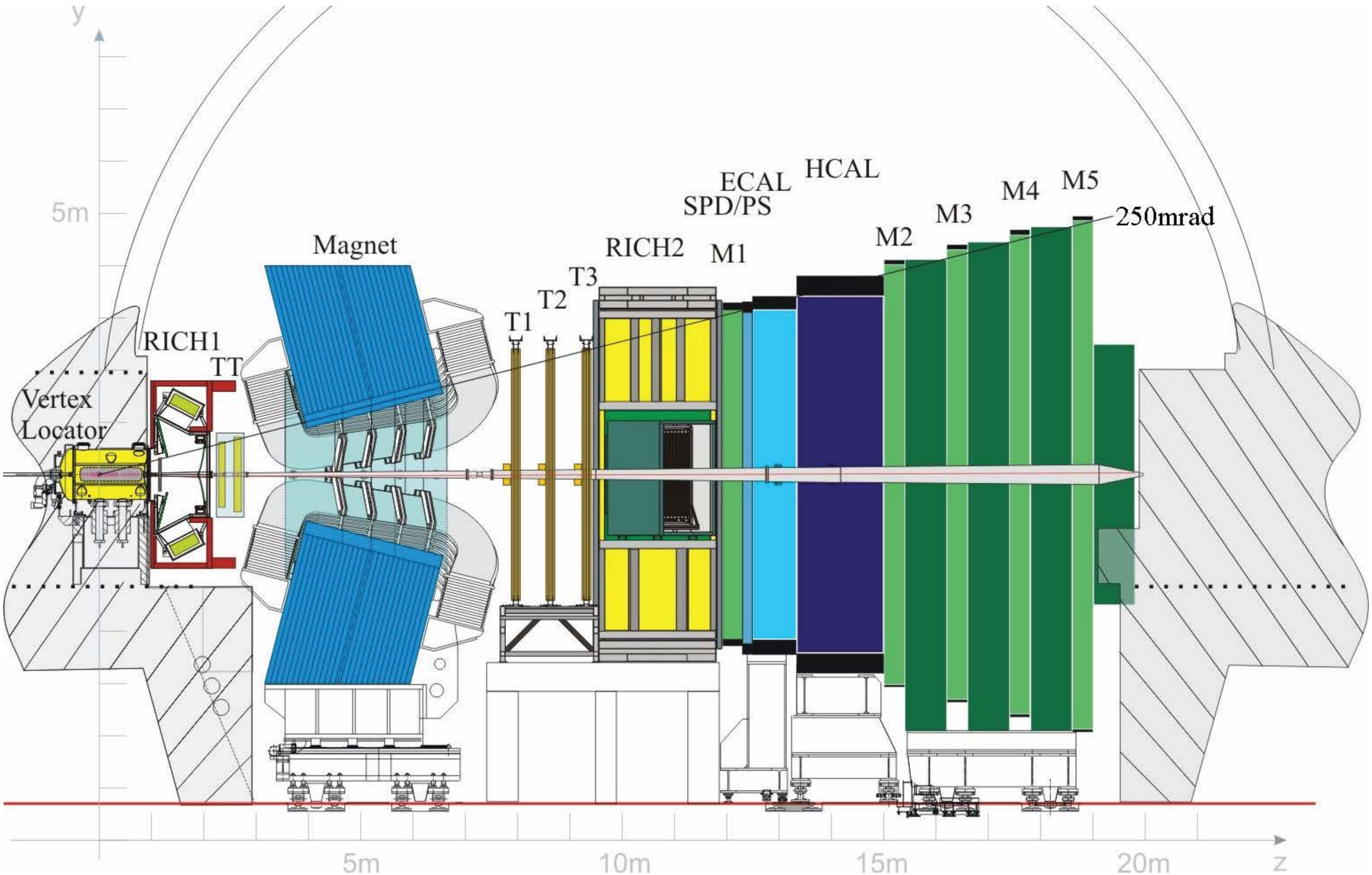
- LHCb: single-arm forward spectrometer (2 < η < 5): ~ 4% of the solid angle, ~30% of the *b* hadron production

- Very good performance: **3 fb^{-1}** accumulated in Run1



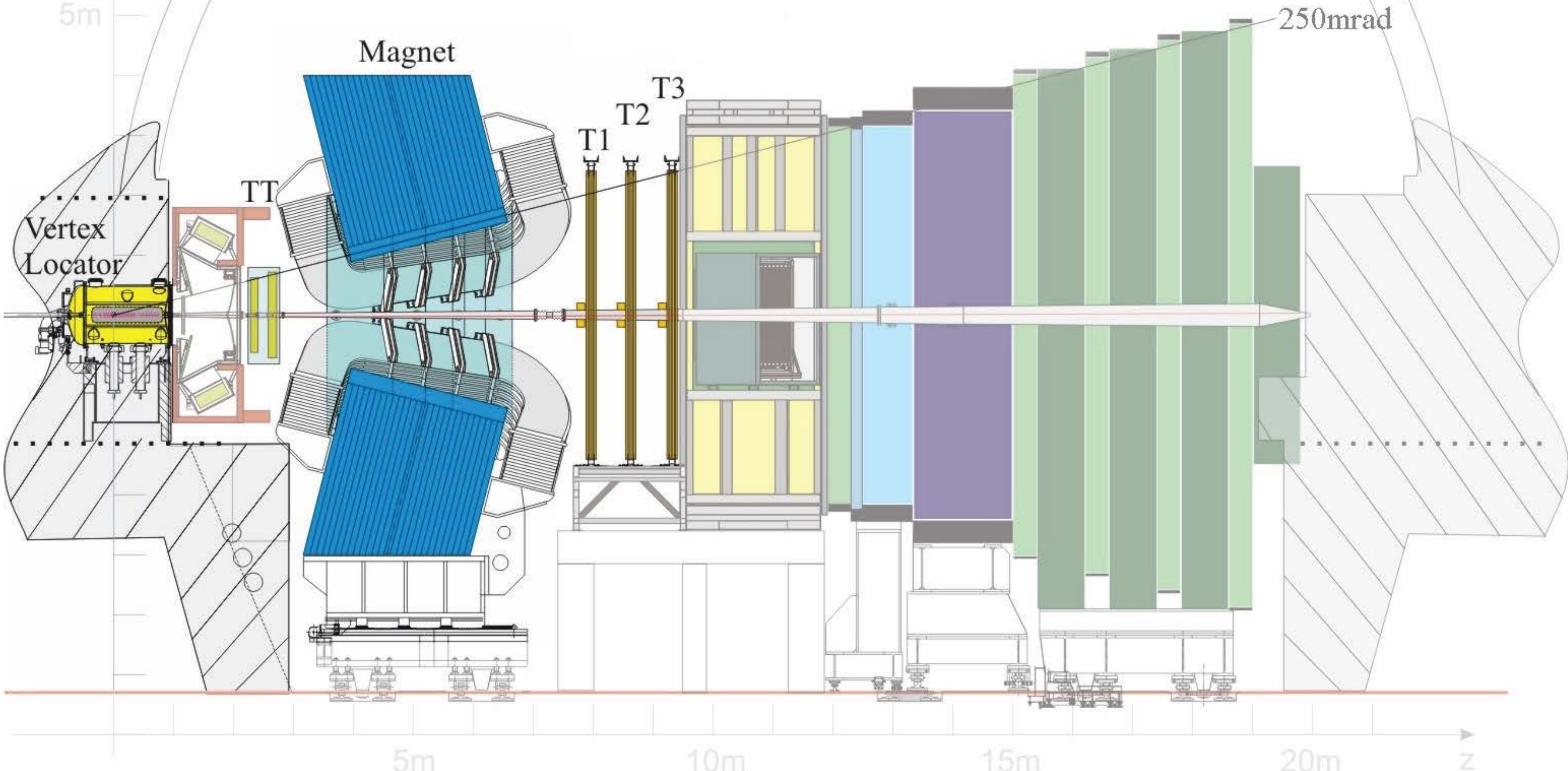


The LHCb experiment



The LHCb experiment

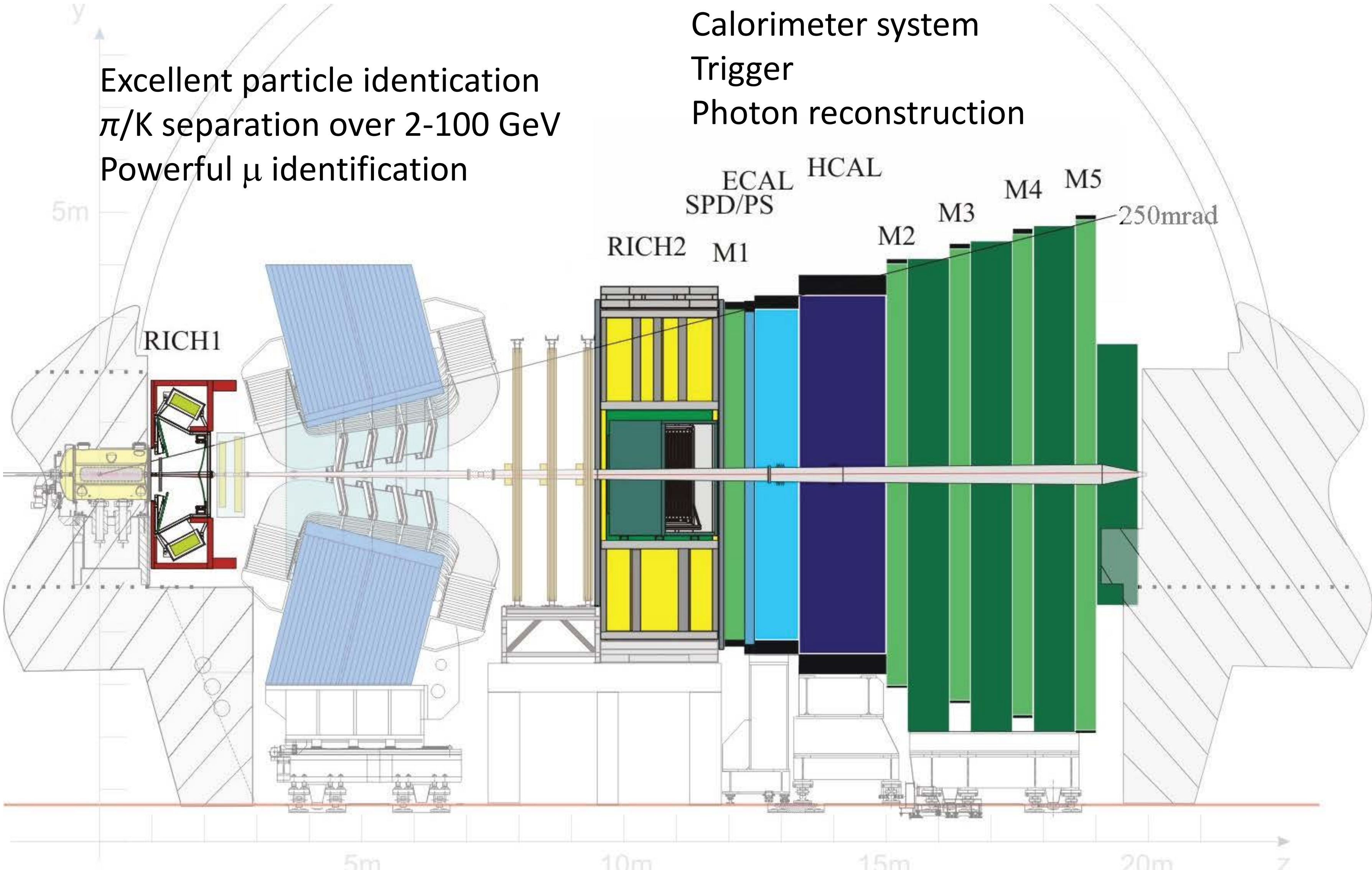
Precise tracking
Good mass and Impact Parameter (IP) resolution
Good vertex resolution



The LHCb experiment

Excellent particle identication
π/K separation over 2-100 GeV
Powerful μ identification

Calorimeter system
Trigger
Photon reconstruction

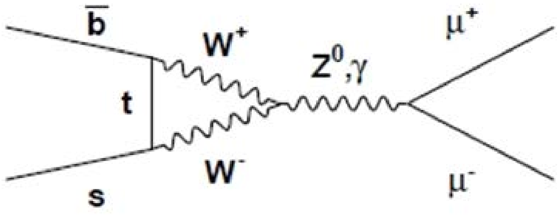


Leptonic decays: $B_{s/d}\to\mu^+\mu^-$

- FCNC + helicity supressed → **Very Rare decay**:

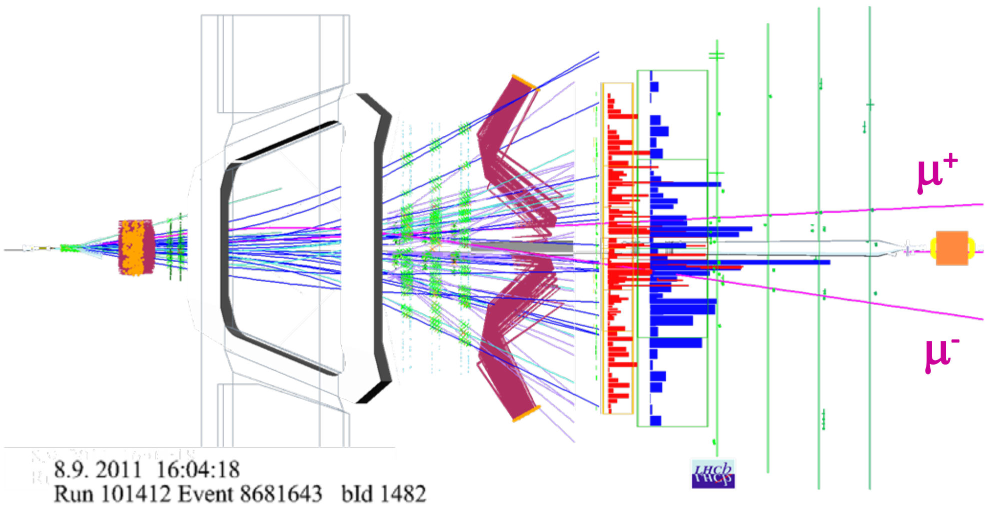
Standard Model prediction:

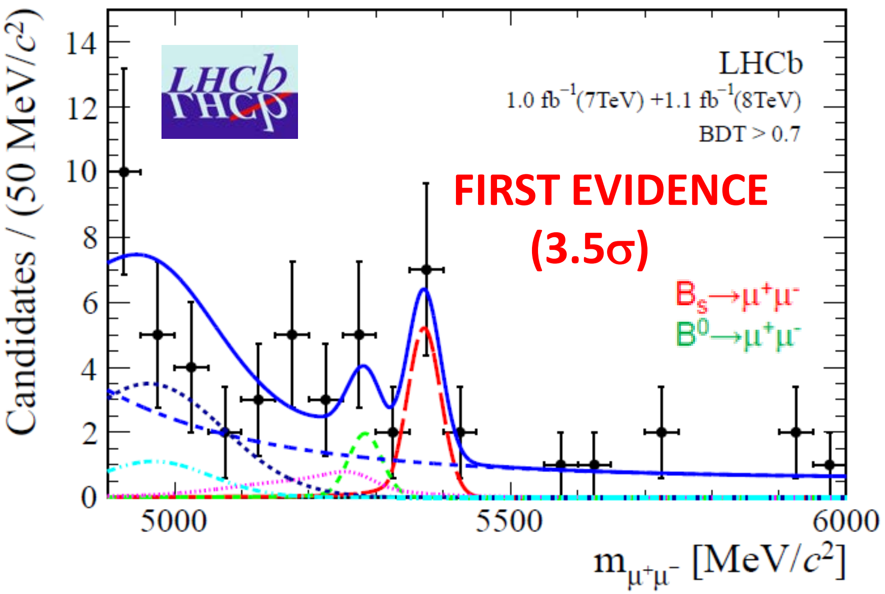
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.35 \pm 0.28) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$



- First evidence by LHCb in 2012 **[LHCb, PRL110 (2013)021801]** **($2fb^{-1}$)**

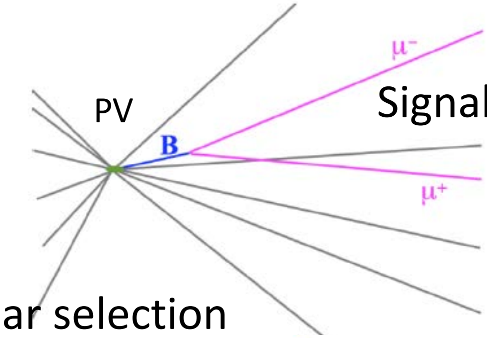
→ Now updated with **$3fb^{-1}$**





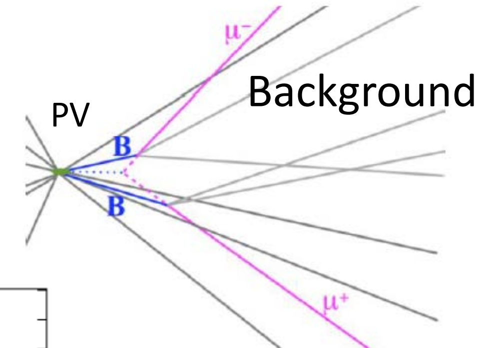
Leptonic decays: $B_{s/d} \to \mu^+\mu^-$

[LHCb, PRL 111 (2013) 101805] (3fb^{-1})

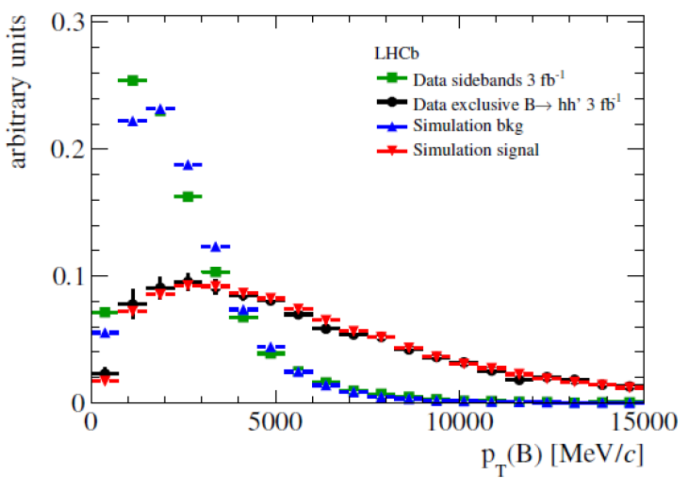


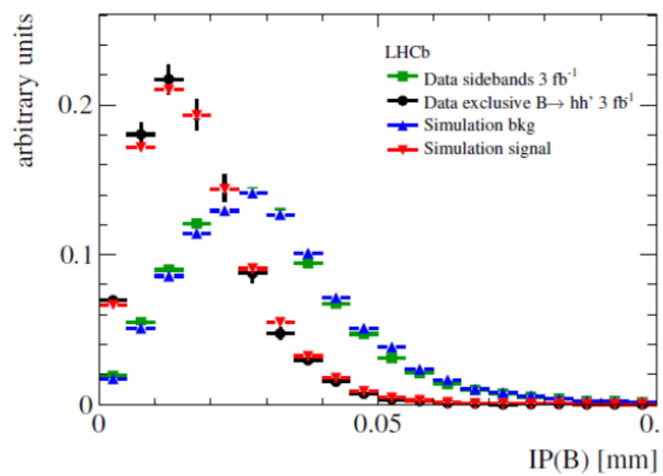
➜ Reconstruct opposite charged muons making a good vertex and separated from the PV, with $m_{\mu\mu}$ in the range [4.9-6] GeV/c^2

➜ Data control channels and normalization using the **$B^+ \to J/\Psi\, K^+$** ($J/\Psi \to \mu^+\mu^-$) and **$B_d \to K\pi$ ($\pi\pi$, KK)** decays with similar selection



➜ Signal and background discrimination based on the invariant mass and Boosted Decision Tree (**BDT**), using kinematic and topological properties (trained with **MC signal** and **$b\bar{b} \to \mu\mu X$** background)

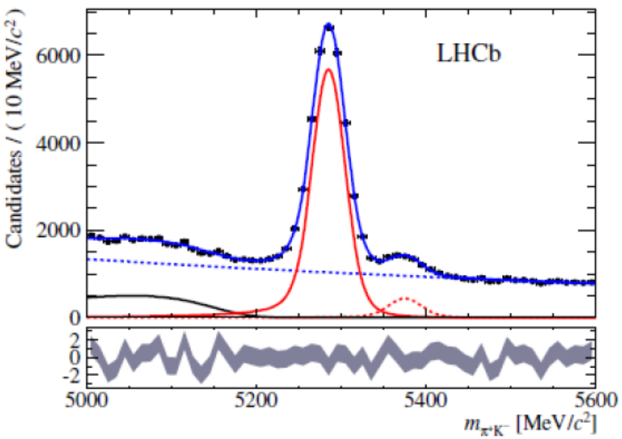


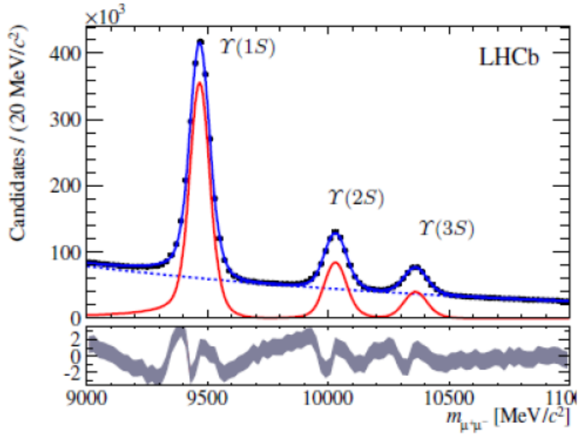


➜ Blind analysis: don't look the data in $m(B_{d/s})\pm 60$ MeV/c^2 until the end of the analysis

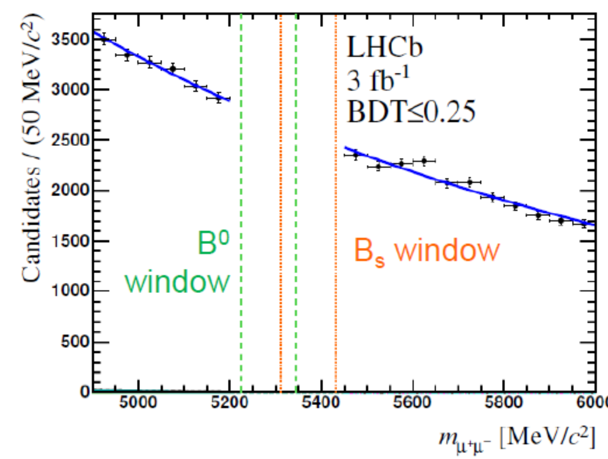
Leptonic decays: $B_{s/d} \to \mu^+\mu^-$

- Signal shape derived from $B_{d/s} \to K\pi$ data and di-muon resonances (same topology as the signal):

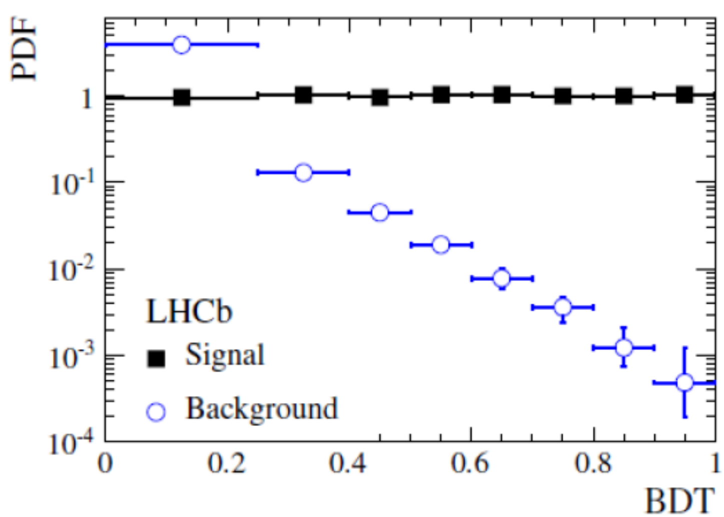


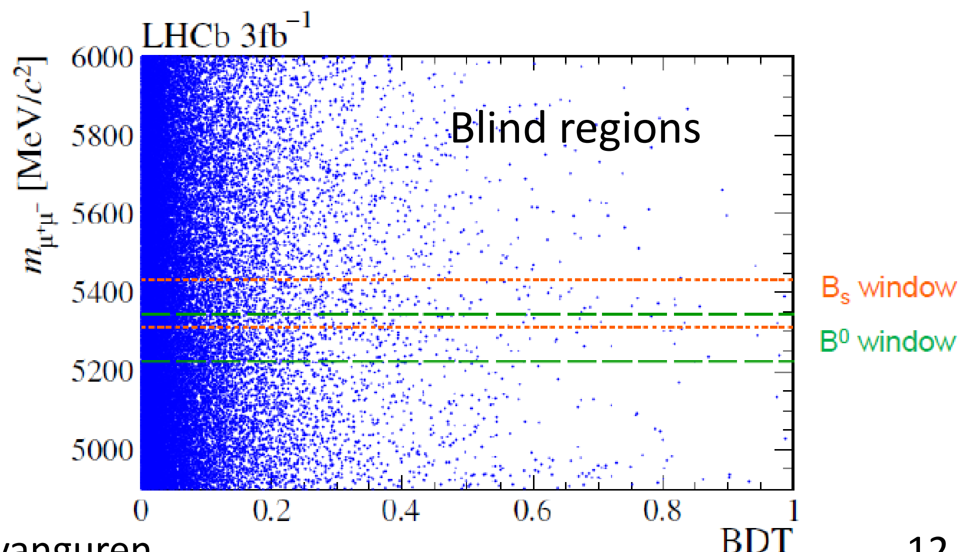


- Background from dimuon mass sidebands:



→ BDT output (defined to be flat for signal and peaked at 0 for background):

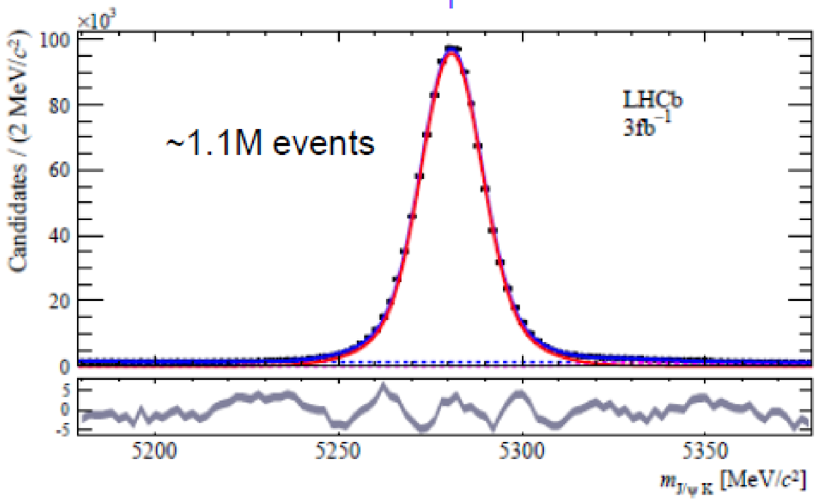




Leptonic decays: $B_{s/d} \to \mu^+\mu^-$

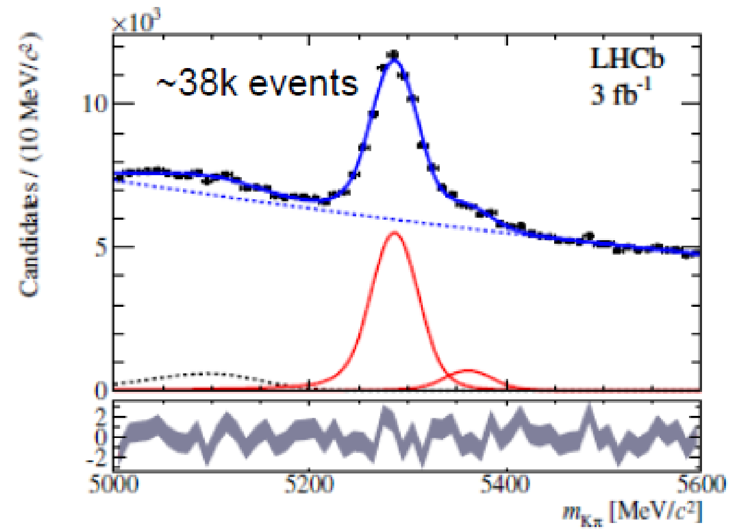
- Two different normalization channels used:

$B^+ \to J/\psi K^+$



Similar trigger, one additional track

$B_d \to K\pi$



Same topology, different trigger

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{\mathcal{B}_{\rm norm}\, \epsilon_{\rm norm}\, f_{\rm norm}}{N_{\rm norm}\, \epsilon_{\rm sig}\, f_{d(s)}} \times N_{B^0_{(s)} \to \mu^+\mu^-}$$

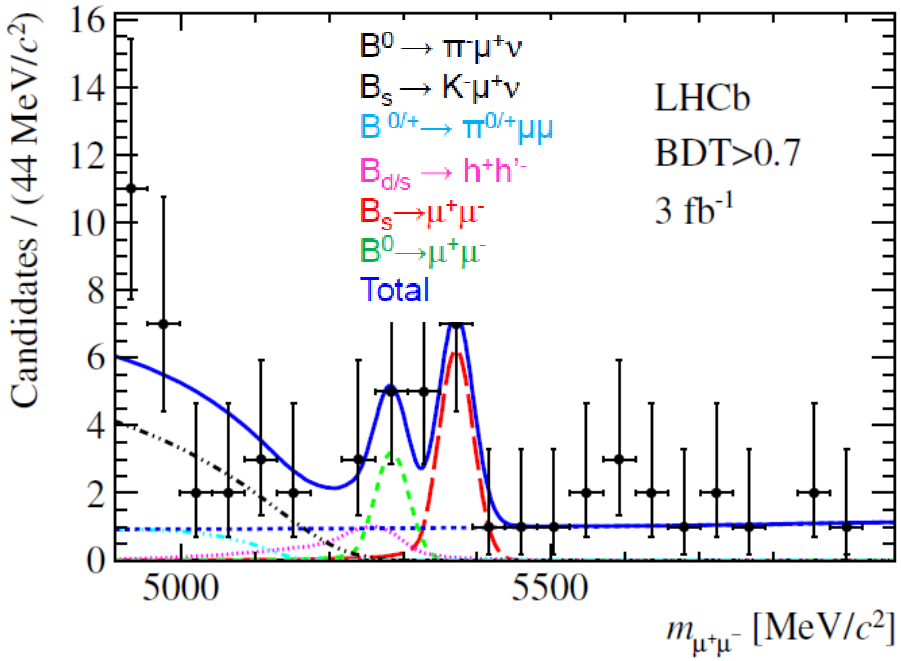
ε_{sig} and $\varepsilon_{norm} = \varepsilon_{trigger} \times \varepsilon_{selection} \times \varepsilon_{reconstruction}$

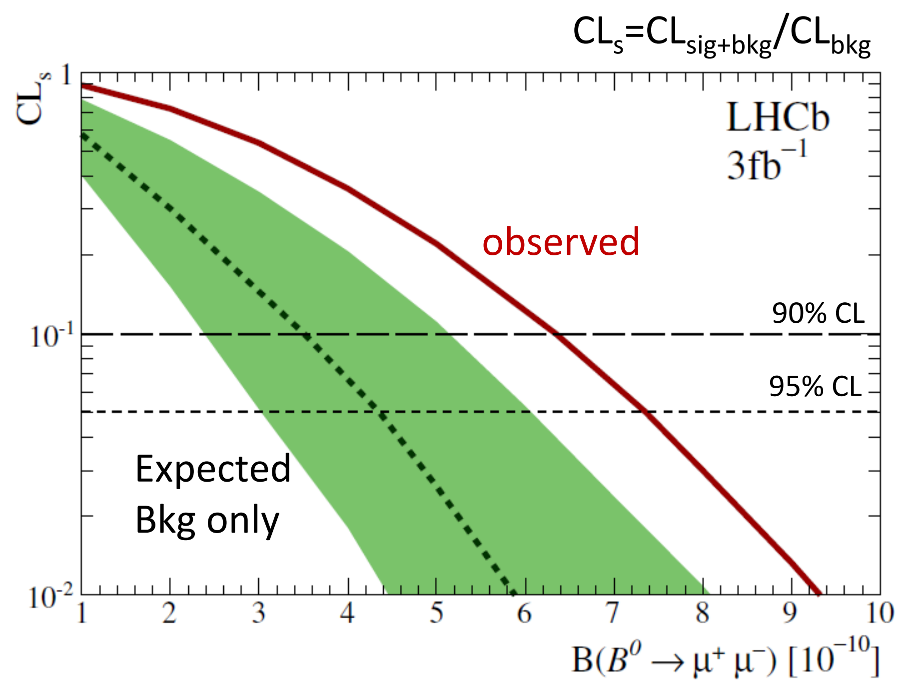
f_{norm} and $f_{d(s)}$ = production fractions @ LHCb **[LHCb-CONF-2013-011]**

→ **The 2 normalization channels give compatible results**

Leptonic decays: $B_{s/d} \to \mu^+\mu^-$

- Results:





$$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

Significance: 4.0 σ

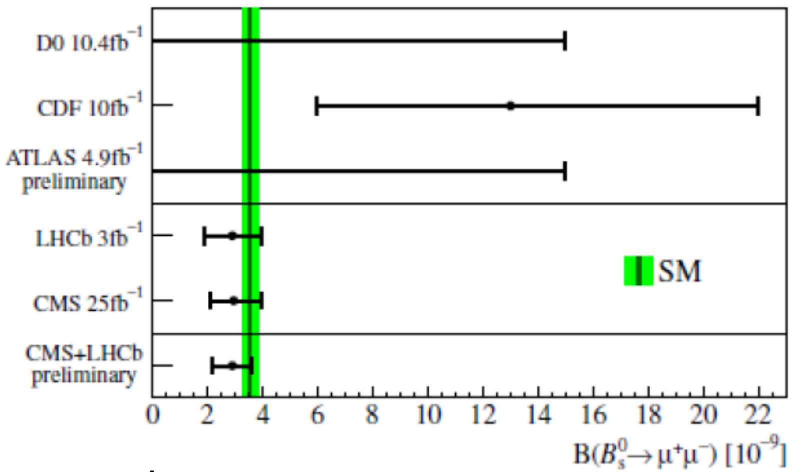
$$BR(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$$

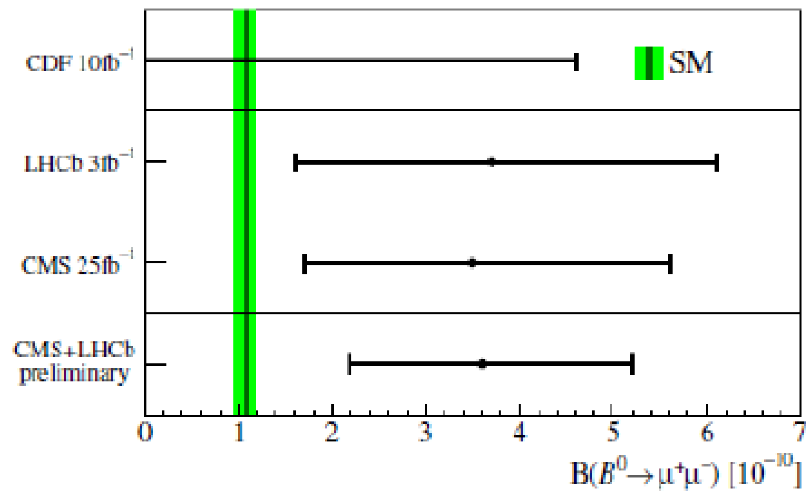
Significance: 2.0 σ

→ $\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ **@ 95% C.L:**

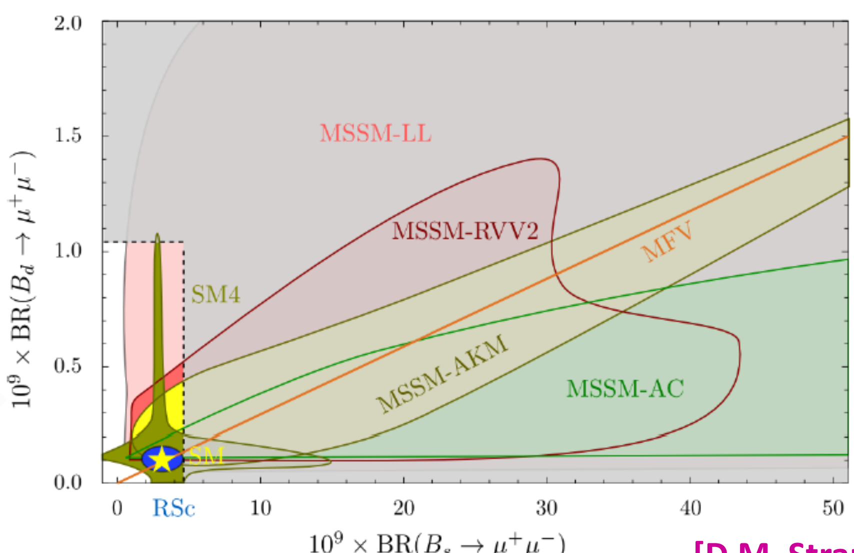
Leptonic decays: $B_{s/d} \rightarrow \mu^+\mu^-$

- Combination witch CMS: **[CMS PAS BPH-13-007]**





- New Physics constraints:

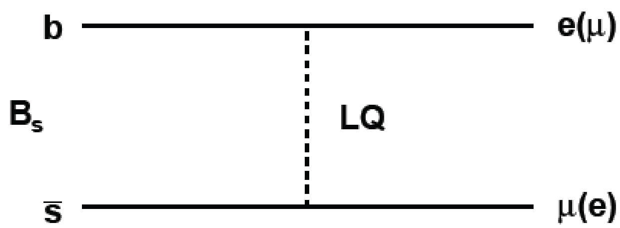


[D.M. Straub, arXiv:1205.6094]

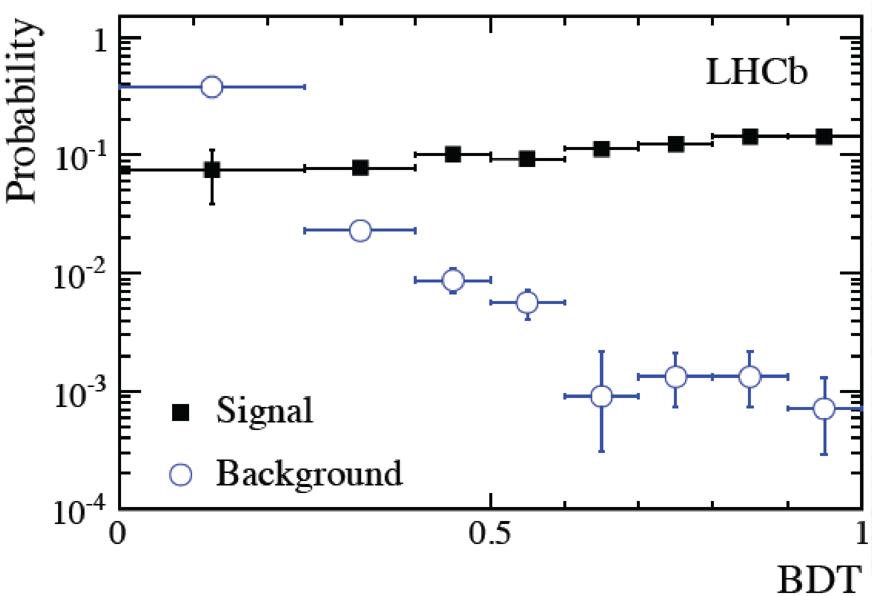
Lepton Flavour Violation: $B_{s/d} \to e^+\mu^-$

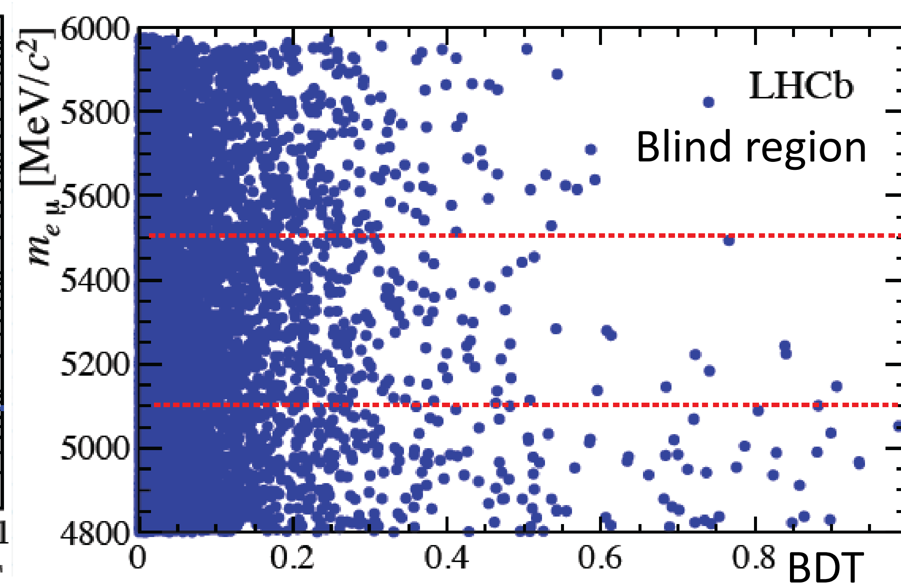
[LHCb, PRL 111 (2013) 141801] ($1 fb^{-1}$)

- Forbidden in the Standard Model
- Constrain New Physics models: Pati-Salam -LeptoQuarks (LQ)- model, 2HDM (Type III) …



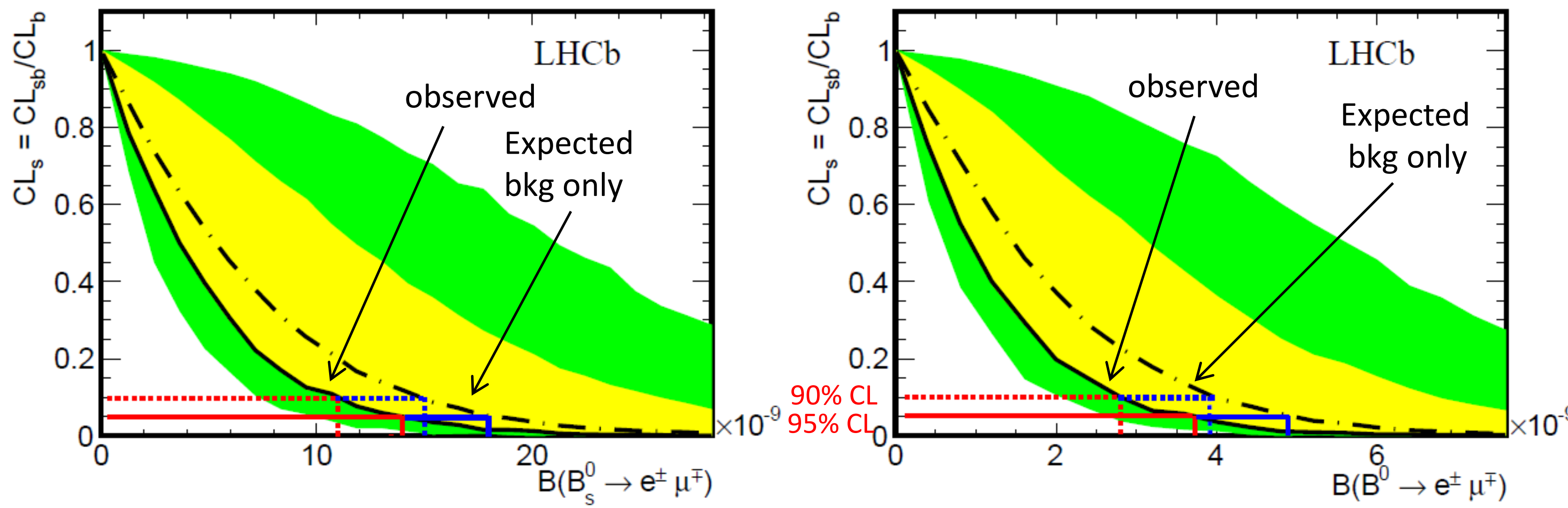
- Similar analysis method to $B_{s/d} \to \mu^+\mu^-$: normalization and control channels $B_{s/d} \to K\pi$ (KK, $\pi\pi$)





Lepton Flavour Violation: $B_{s/d} \to e^+\mu^-$

- Results:



$$\mathcal{B}(B_s^0 \to e^\pm \mu^\mp) < 1.1\,(1.4) \times 10^{-8}$$ **@ 90% (95%) C.L.**

$$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 2.8\,(3.7) \times 10^{-9}$$ **@ 90% (95%) C.L.**

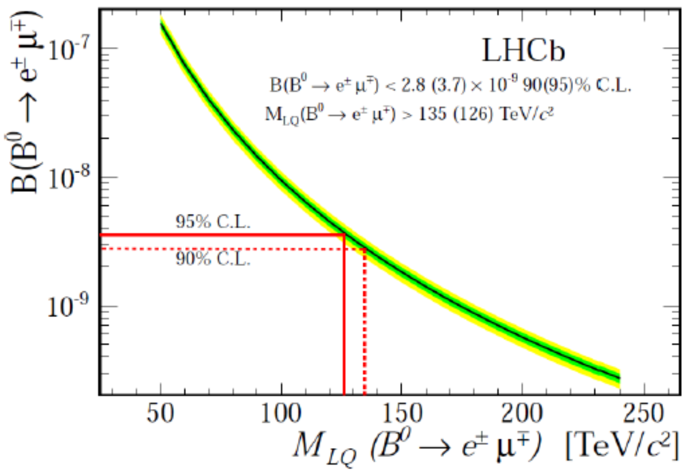
→ **Largely improves (~ /20) CDF limits [PRL102(2009)201801]**

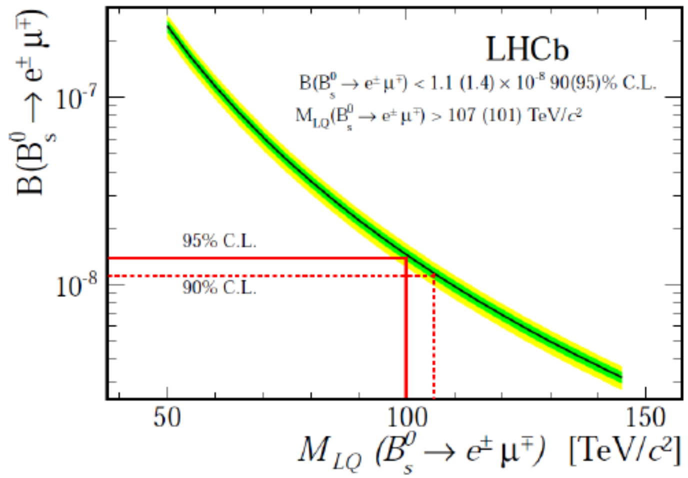
Lepton Flavour Violation: $B_{s/d} \to e^+ \mu^-$

- New Physics constraints: Pati-Salam Model (coupling different generations)

$$M_{\rm LQ}(B_s^0 \to e^\pm \mu^\mp) > 107\,(101)\ {\rm TeV}/c^2$$
$$M_{\rm LQ}(B^0 \to e^\pm \mu^\mp) > 135\,(126)\ {\rm TeV}/c^2$$

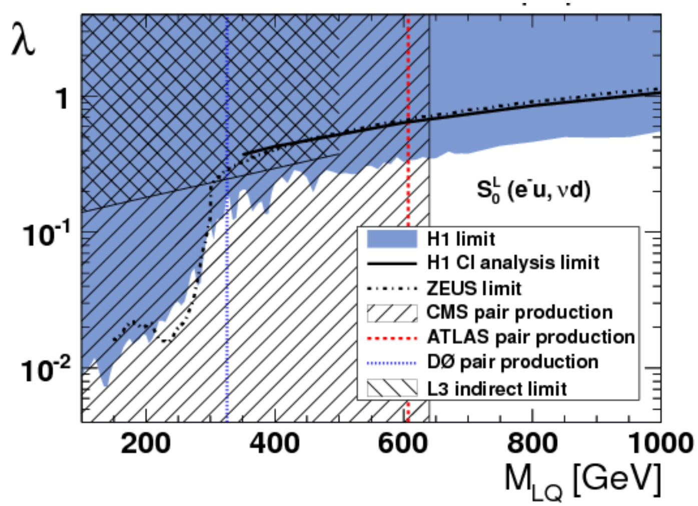
[Pati and A. Salam PRD10(1974)275].





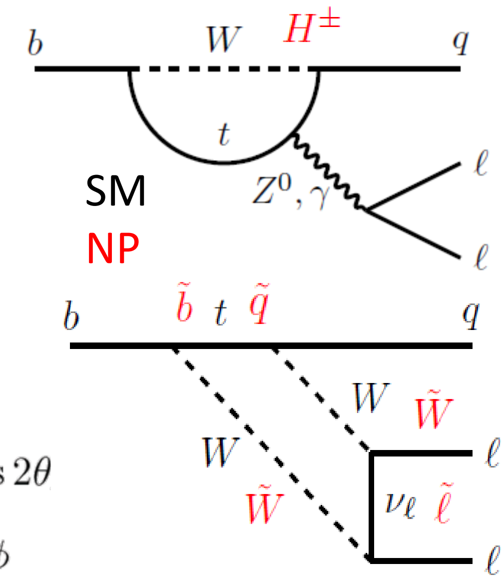
- Direct searches at LEP/TeVatron/DESY/LHC (first generation) **[PDG'13]**

(not directly comparable)



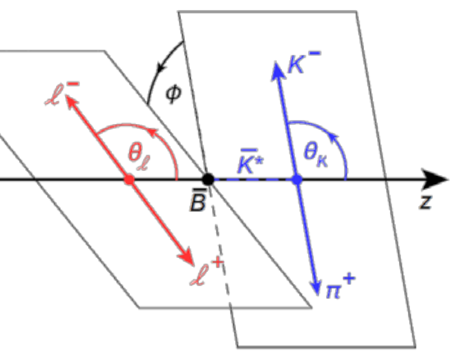
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- New Physics amplitudes can modify branching fractions, angular observables, CP and isospin asymmetries …



- The differential decay width depends on three angles θ_ℓ, θ_K, ϕ and $\mathbf{q^2=m_{\mu\mu}^2}$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_K\,d\phi\,dq^2} =$$



$$\frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K - F_L\cos^2\theta_K\cos 2\theta$$
$$+ \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell$$
$$+ S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- F_L and S_i are observables which are functions of the Wilson coefficients (sensitive to NP) and form factors (long distance effects, non-perturbative methods)

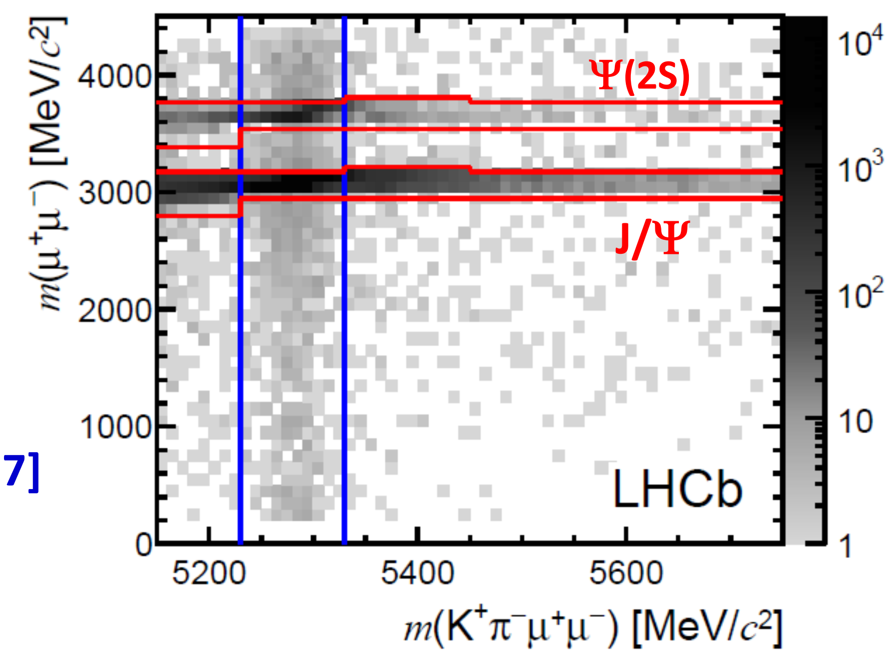
- A new set of observables, $\mathbf{P'_{i=4,5,6,8}} = \mathbf{S_{i=4,5,7,8}/\sqrt{F_L(1-F_L)}}$ can be defined, being less sensitive to the hadronic form-factors uncertainties

[S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 05 (2013) 137]

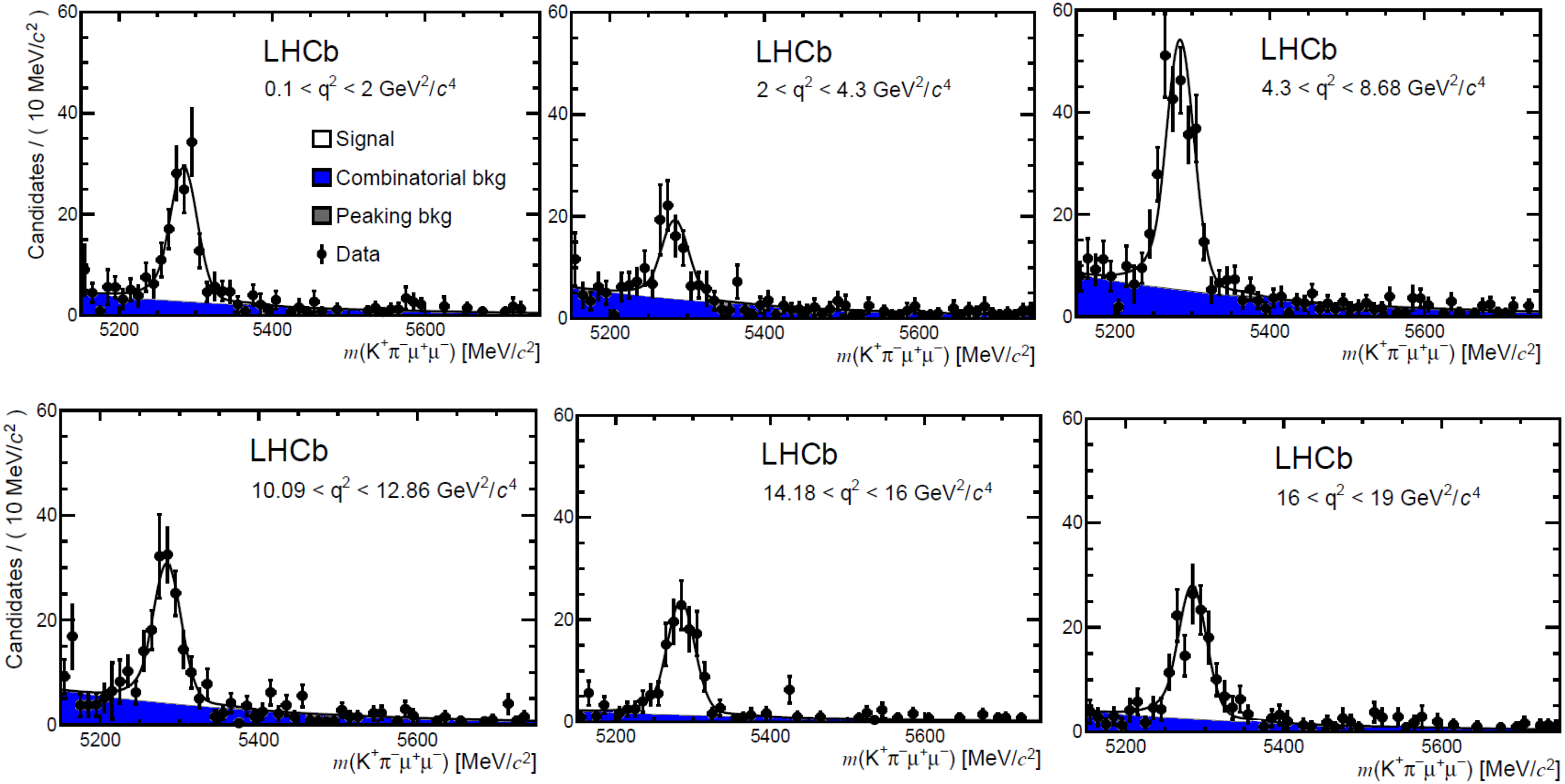
Semi(di)leptonic Decays: $B_d \to K^* \mu^+ \mu^-$

- Select at least one high P_T muon (> 1.5GeV/c) and one hadron displaced from PV
- Candidates are retained in the $K^*(\to K^+\pi^-)$ invariant mass range
- Signal selected with a BDT using kinematic, topological and PID info; trained with resonant $B \to J/\psi K^*$ data (signal) and data from sidebands (background), and keeping flat the angular acceptance
- $B \to J/\psi K^*$ data as control channel for Data/MC efficiencies
- $\Psi(2S)$ and J/Ψ resonance regions vetoed
- Analysis performed in six bins of q^2 and in the region $1<q^2<6$ GeV^2

[JHEP 1308 (2013) 131]
[LHCb, PRL08 (2013) 117]
($1fb^{-1}$)

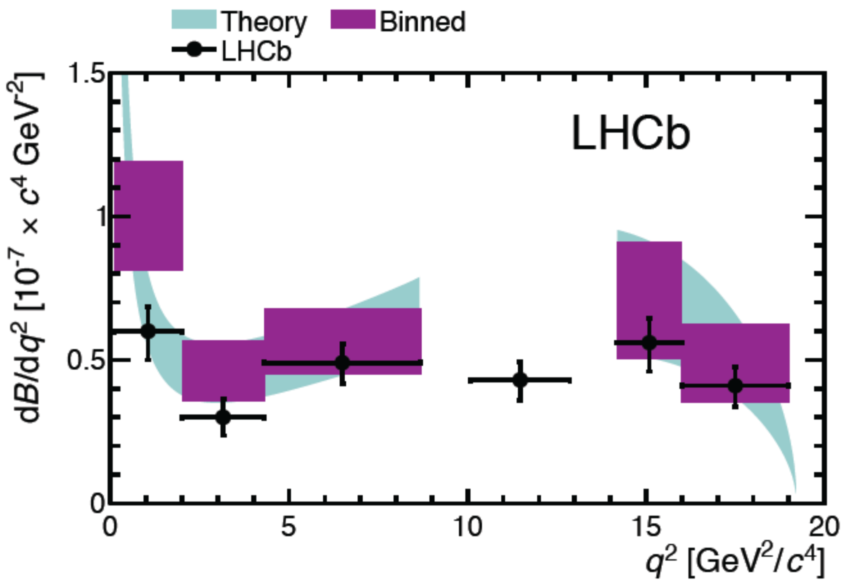


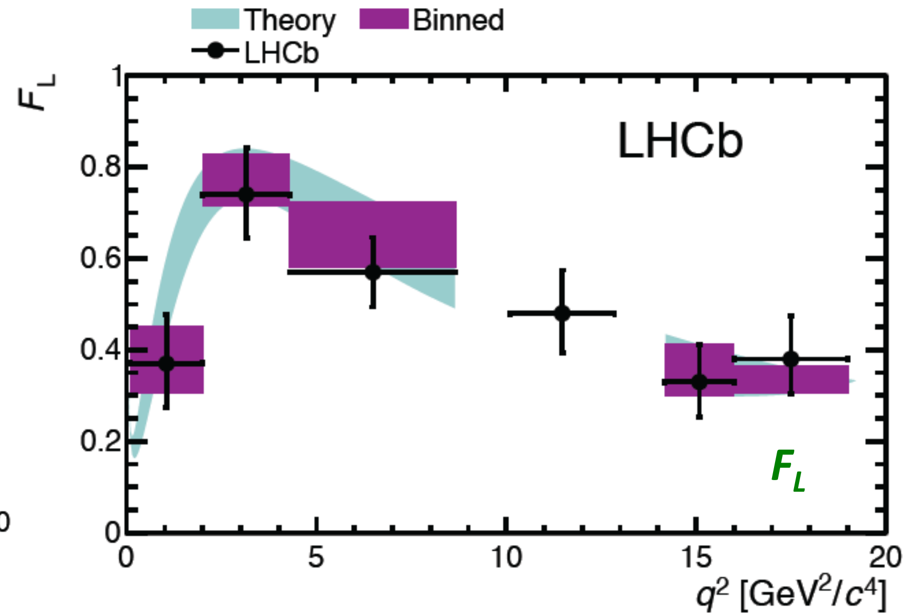
Semi(di)leptonic Decays: $B_d \to K^* \mu^+ \mu^-$

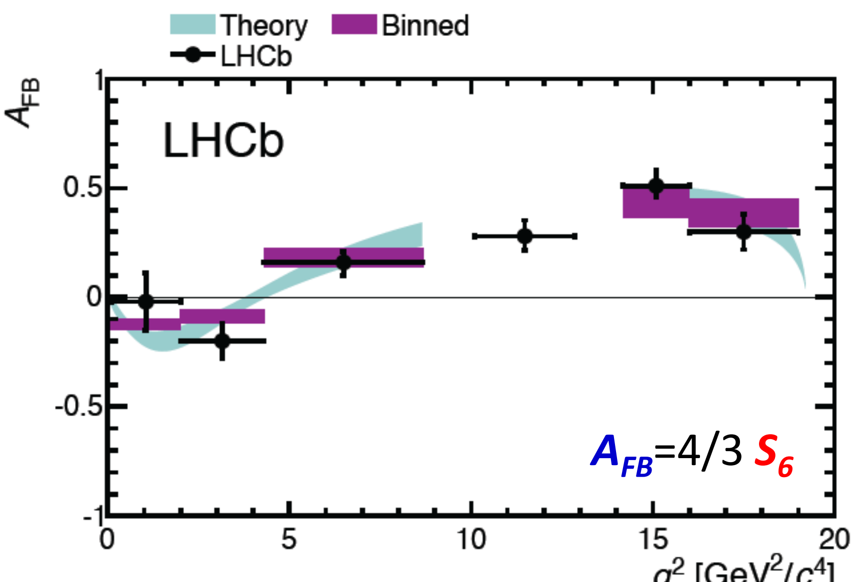


➜ peaking backgrounds reduced to a negligible level

Semi(di)leptonic Decays: $B_d \to K^* \mu^+ \mu^-$





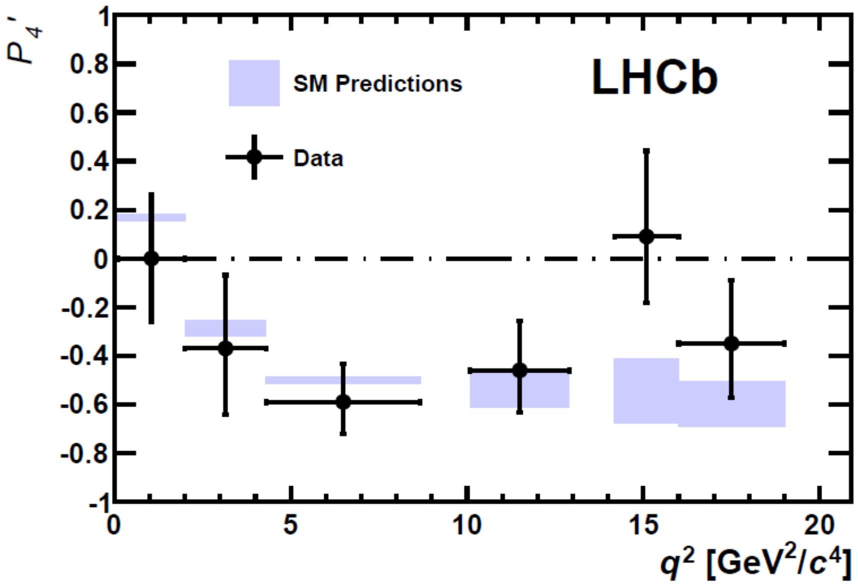


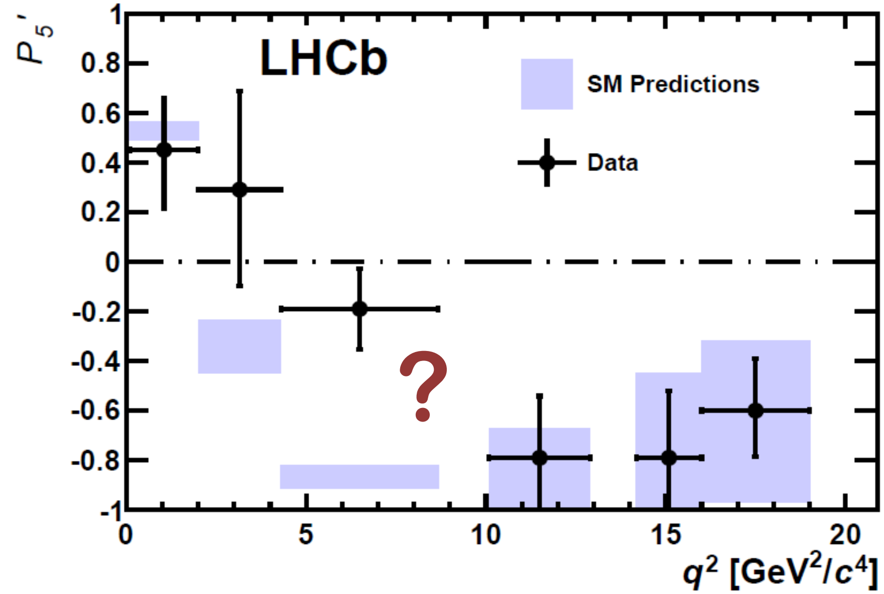
In the SM, A_{FB} changes sign as function of q^2. The zero crossing-point is free of hadronic uncertainties:

→ First measurement of the zero-crossing point in A_{FB}: $\mathbf{q_0^2 = 4.9 \pm 0.9}$ **GeV²/c⁴**

Semi(di)leptonic Decays: $B_d \to K^* \mu^+ \mu^-$

- In terms of the new observables **P'_i**:





▶ Agreement with the SM for **P'_4, P'_6, P'_8**

▶ Local discrepancy of **3.7σ** is observed in the interval $4.30 < q^2 < 8.68$ GeV^2/c^4 for **P'_5**

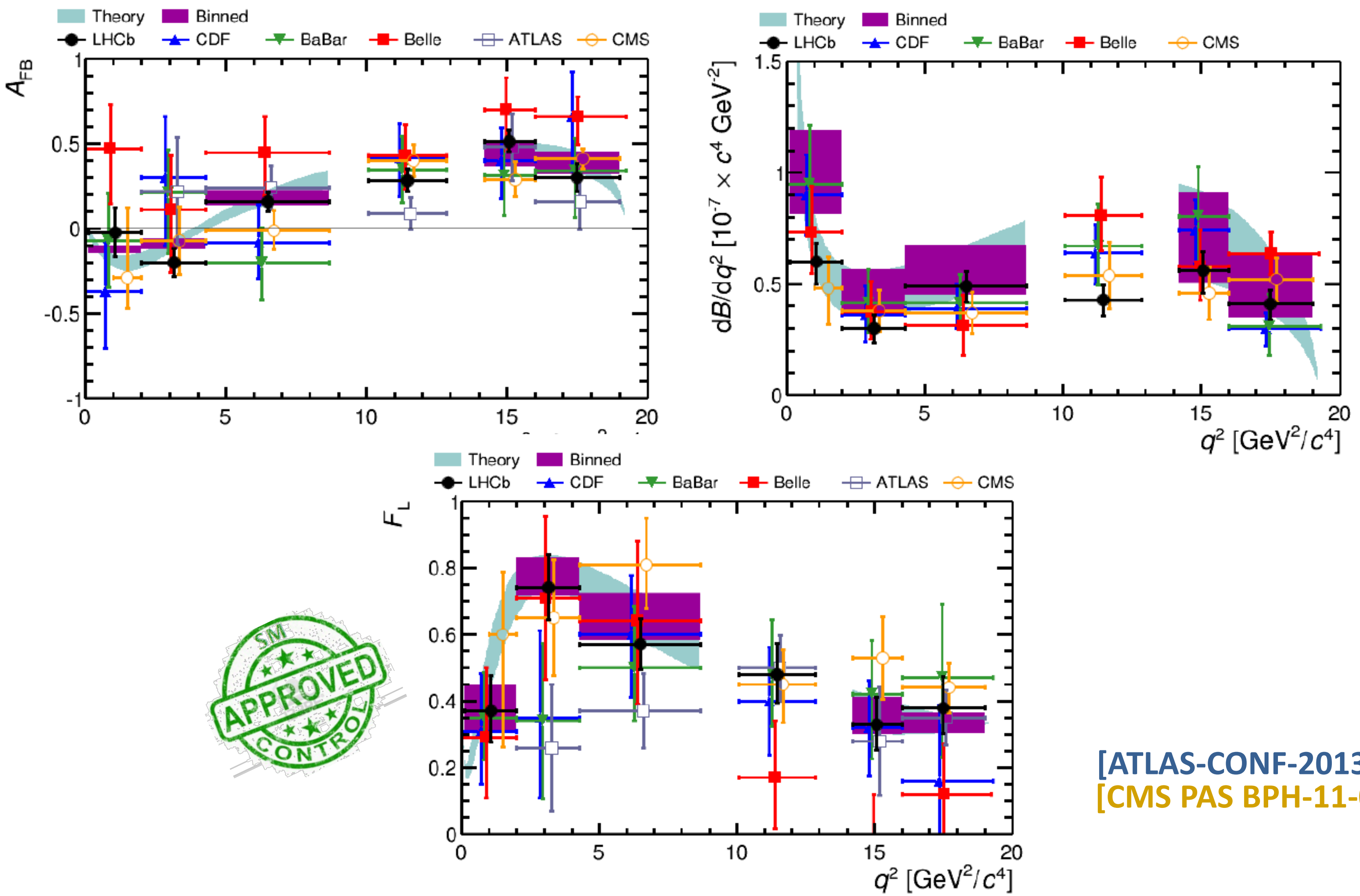
▶ Integrating over the region $1.0 < q^2 < 6.0$ GeV^2/c^4, the observed discrepancy is **2.5σ**

→ C_9 Wilson coefficient ? **(update with 3fb^{-1} in progress)**

[S. Descotes-Genon, J. Matias, J.Virto, arXiv:1311.3876]

Semi(di)leptonic Decays: $B_d \to K^* \mu^+ \mu^-$

- Comparison with other experiments:



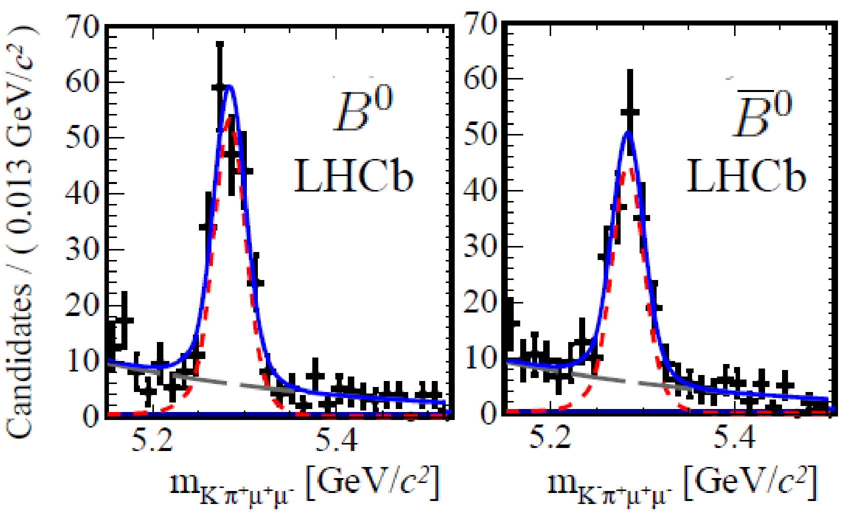
[ATLAS-CONF-2013-038]
[CMS PAS BPH-11-009]

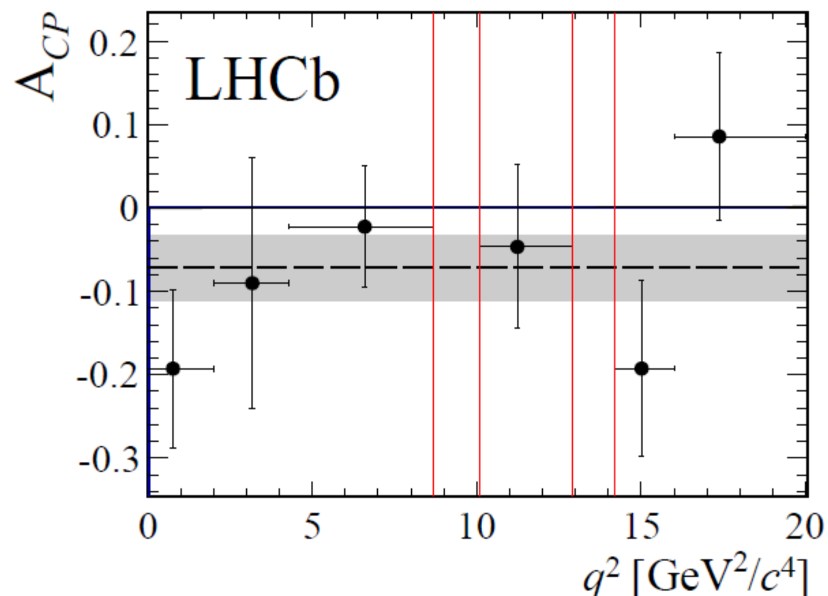
Semi(di)leptonic Decays: $B_d \to K^* \mu^+ \mu^-$

- Other (non angular) observables: **[LHCb, PRL. 110 (2013)031801]** **(1fb^{-1})**

CP asymmetry:

$$\mathcal{A}_{\rm CP} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$$





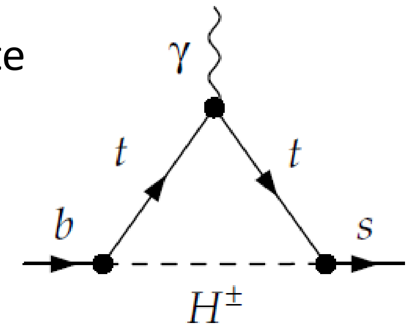
Corrected for production/detection asymmetry using $B \to J/\psi K^*$ data →

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040 \pm 0.005$$

Radiative Decays: $B^+ \to K^+\pi^-\pi^+\gamma$

- Radiative ***b→s*** decays are also FCNC, with a photon in the final state

- Branching fractions and CP asymmetries can be largely affected by New Physics contributions



- In the SM, the **photon** from *b* decays is predominantly **left handed**, with small corrections of order m_s/m_b ~2%

→The photon polarization is then sensitive to the spin structure of the New Physics
→ It is largely affected in New Physics Models (particularly in Left-Right Symmetric Models)

The **photon polarization parameter λ_γ**

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

expected to be -1 ($\bar{B}$) or +1 (B) with corrections of $(m_s/m_b)^2$
(C_R, C_L right and left amplitudes)

Can be extracted by studying the three body decay of a K_J (J^P) resonant state in **$B \to K_{res}$** γ radiative decays

[Kou et al, PRD83 (2011) 094007; Gronau et al, PRL88 (2002) 051802]

Radiative Decays: $B^+ \to K^+\pi^-\pi^+\gamma$

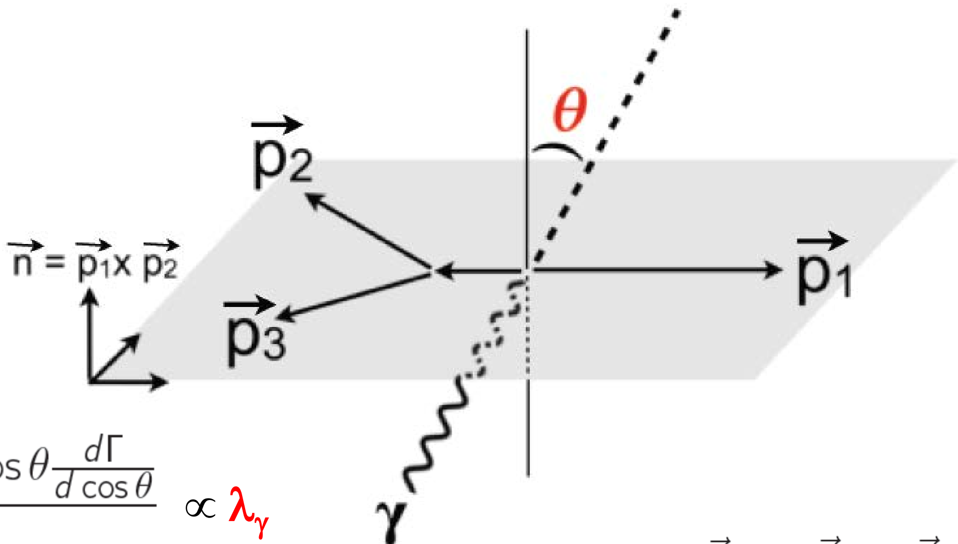
- For a radiative $B \to K_{res}\gamma$, with the K_{res} a three body decay $K_{res} \to P_1P_2P_3$

$$\frac{d\Gamma(\overline{B} \to \overline{K}_{res}\gamma \to P_1P_2P_3\gamma)}{ds\, ds_{13}\, ds_{23}\, d\cos\theta}$$

with $s_{ij}=(p_i+p_j)^2$; $s=(p_1+p_2+p_3)^2$

is the sum of the helicity amplitudes

The **Up-down asymmetry A_{UD}**



$$\mathcal{A}_{up-down} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} \propto \lambda_\gamma$$

$$\cos\theta \equiv -\frac{\vec{p}_\gamma}{|\vec{p}_\gamma|} \cdot \frac{\vec{p}_1 \times \vec{p}_2}{|\vec{p}_1 \times \vec{p}_2|}$$

Allows to extract the photon polarization information

$\rightarrow$ Need to count the number of events with photon emitted above/below the $\vec{p}_1\vec{p}_2$-plane and subtract them.

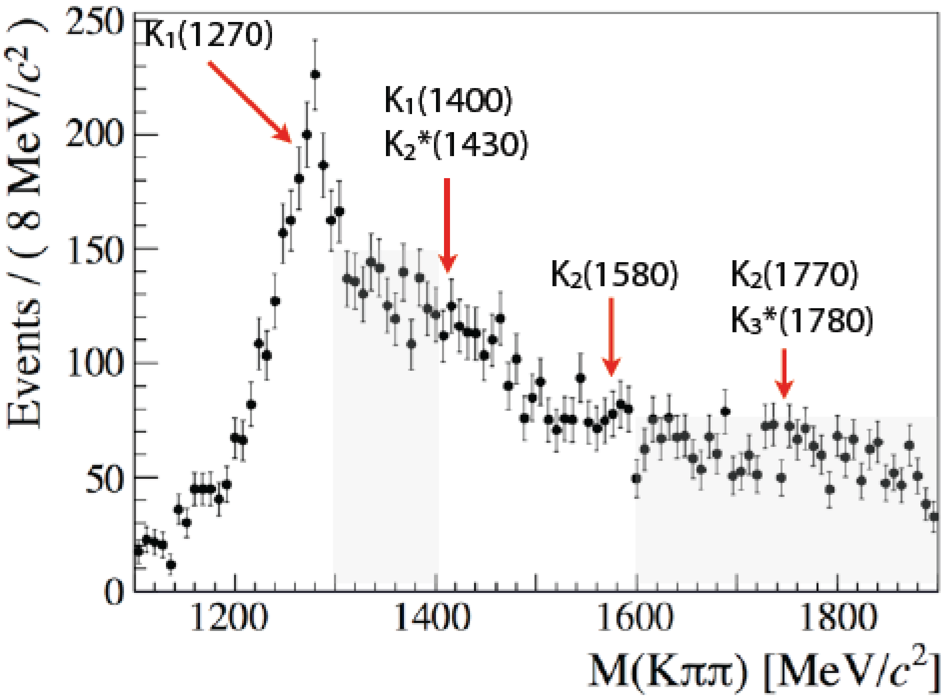
- There are two known $K_1(1^+)$ states, decaying into $K\pi\pi$ final state via $K^*\pi$ and ρK modes: the $K_1(1270)$ and $K_1(1400)$ resonances, from where the λ_γ can be measured.

Radiative Decays: $B^+ \to K^+\pi^-\pi^+\gamma$

[LHCb-CONF -2013-009] **($2 fb^{-1}$)**

- Reconstruct a kaon resonance from three charged tracks: two pions of opposite sign and a kaon, plus a **high E_T photon.**

Individual resonances cannot be resolved without angular analysis, then:



Background substracted Kππ spectrum showing the expected resonant contributions

- Use the full mass range to measure **A_{CP}**

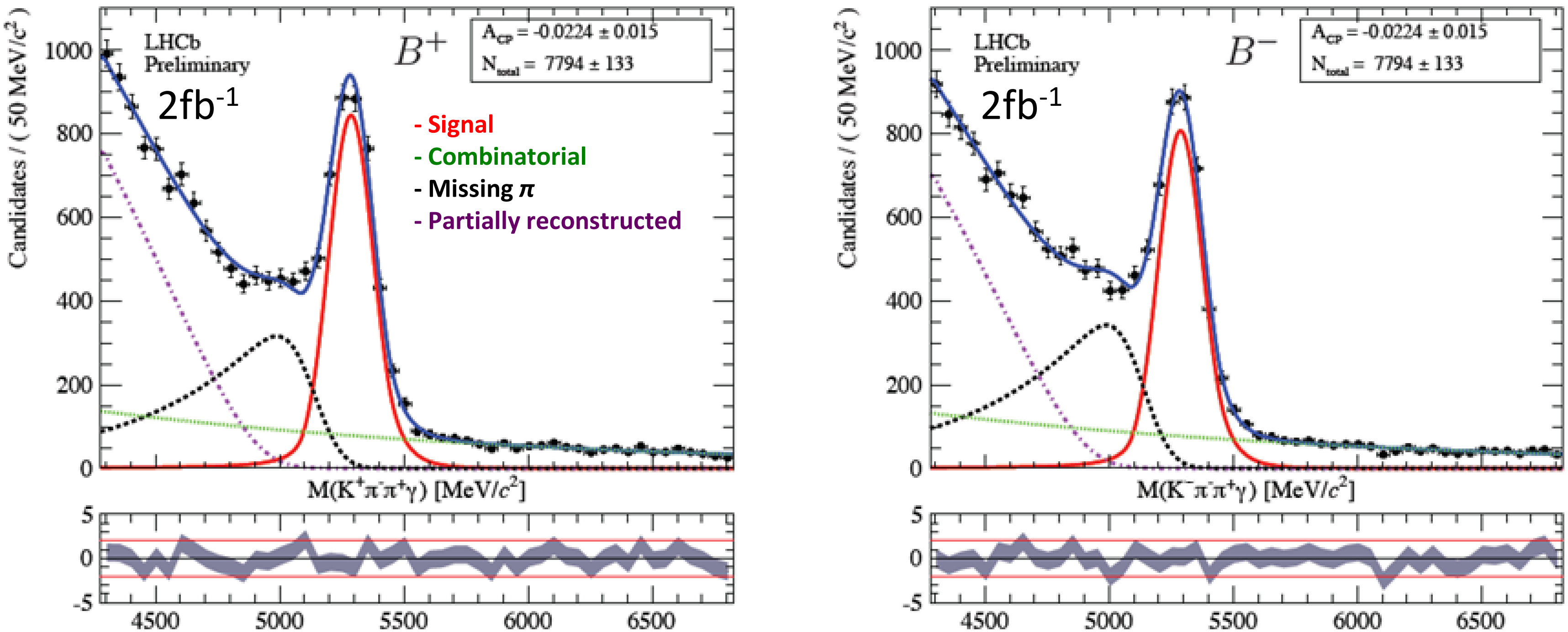
$$\mathcal{A}_{CP} = \frac{N(K^-\pi^+\pi^-\gamma) - N(K^+\pi^-\pi^+\gamma)}{N(K^-\pi^+\pi^-\gamma) + N(K^+\pi^-\pi^+\gamma)}$$

- Avoid the interference mass regions to measure **A_{UD}**

$$\mathcal{A}_{UD} = \frac{N(K\pi\pi\gamma)_{\cos\theta>0} - (K\pi\pi\gamma)_{\cos\theta<0}}{N(K\pi\pi\gamma)_{\cos\theta>0} + (K\pi\pi\gamma)_{\cos\theta<0}}$$

(since there are effects from several contributions, results are difficult to interprete in terms of photon polarization)

Radiative Decays: $B^+ \to K^+\pi^-\pi^+\gamma$



$$\mathcal{A}_{CP}^{\rm raw} = -0.022 \pm 0.015$$

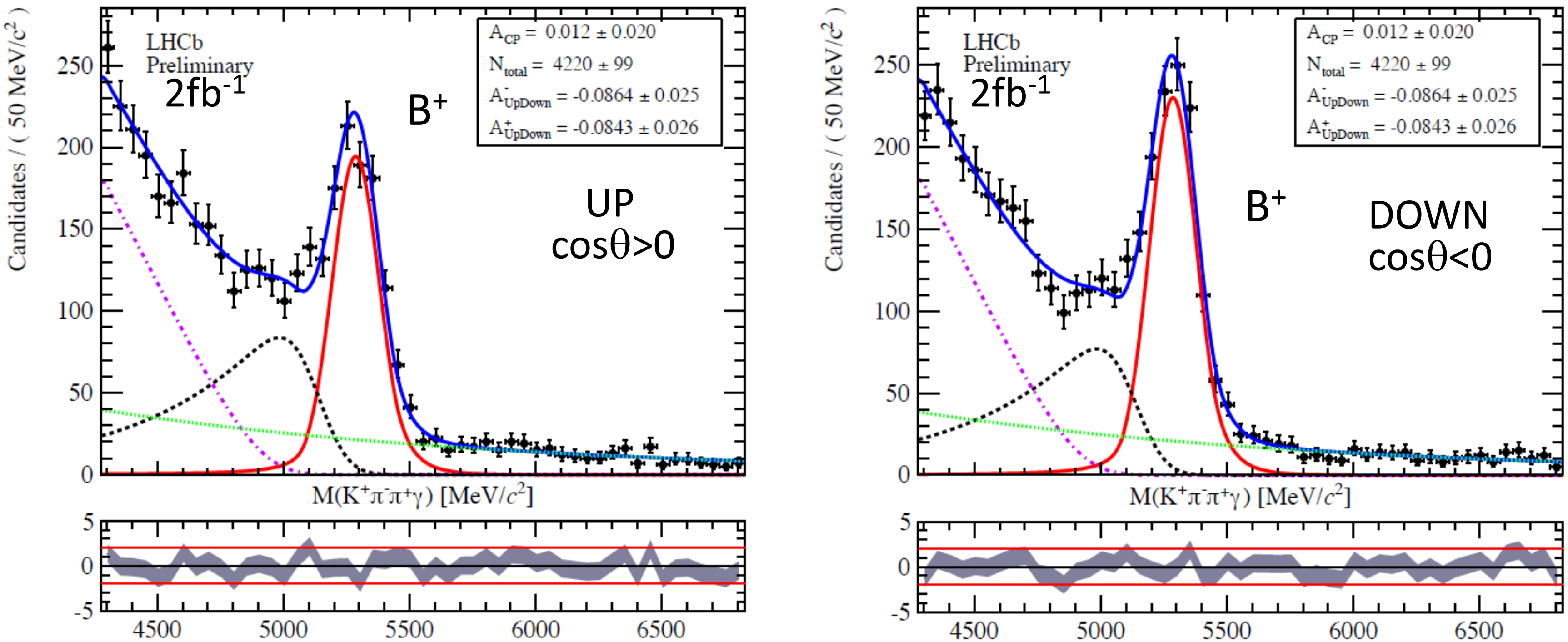
Corrections to raw A_{CP}:

$\mathcal{A}_{\rm D}$ and $\mathcal{A}_{\rm P}$	0.013 ± 0.008
$\Delta\mathcal{A}_{CP}^{\rm raw}$	0.002 ± 0.001
Fit model	0.000 ± 0.002

$$\mathcal{A}_{CP} = -0.007 \pm 0.015\ (\rm stat) \pm 0.008\ (\rm syst)$$

SM APPROVED CONTROL

Radiative Decays: $B^+ \to K^+\pi^-\pi^+\gamma$



Contributions to the A_{ud} uncertainties very small (~1-3‰)

$$\mathcal{A}_{\text{ud}}^{+} = -0.084 \pm 0.026\,(\text{stat})\,^{+0.004}_{-0.003}\,(\text{syst})$$

$$\mathcal{A}_{\text{ud}}^{-} = -0.086 \pm 0.025\,(\text{stat}) \pm 0.002\,(\text{syst})$$

$$\mathcal{A}_{\text{ud}} = -0.085 \pm 0.019\,(\text{stat}) \pm 0.003\,(\text{syst})$$

→ **Proportional to photon polarization (first evidence at 4.6σ)**

Conclusions:

- LHCb has performed very well in Run1: **$3fb^{-1}$**
- Rare B decays are probes for Physics Beyond SM
- Many new measurements on Rare Decays at LHCb:

  $\rightarrow$ **B**, charm, tau sectors

  $\rightarrow$ **Leptonic, Semi(di)leptonic, Radiative decays**

  Only a few have been covered here!

- Few discrepancy with SM predictions to be followed
- Completing the analyses with the full statistics

Thank you!