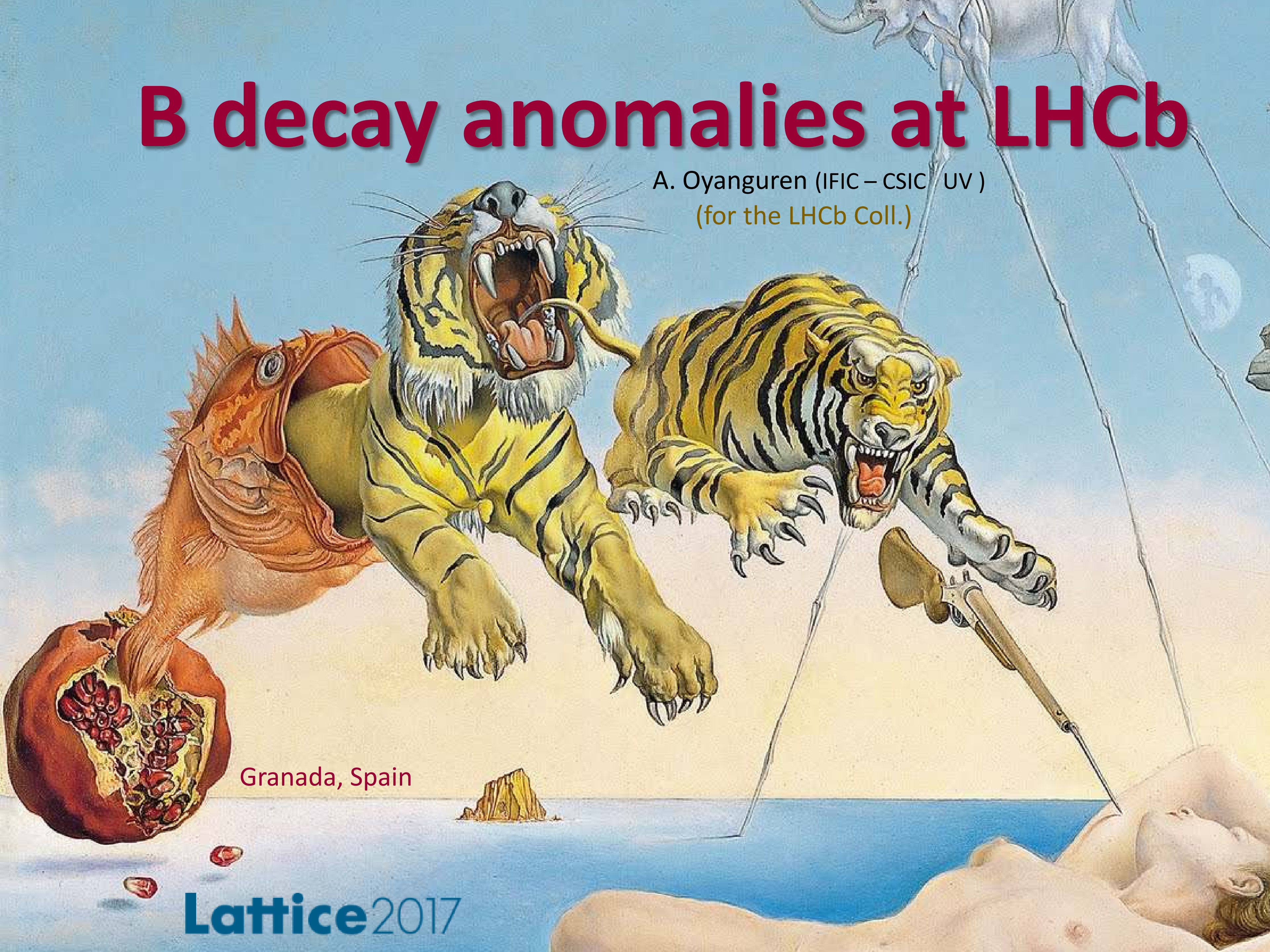


# B decay anomalies at LHCb


A. Oyanguren (IFIC – CSIC UV )
(for the LHCb Coll.)


Granada, Spain

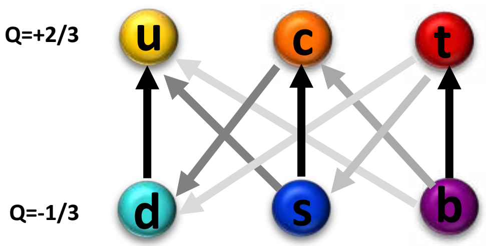
Lattice2017

# Outline

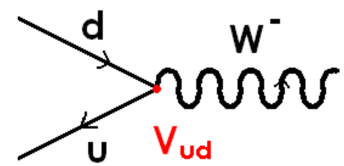
- Introduction
- The LHCb experiment
- Rare B decays
- Semileptonic B decays
- Wish list for Lattice
- Conclusions

# Introduction

- In the Standard Model of Particle Physics, transitions between different quarks are governed by the CKM mechanism:

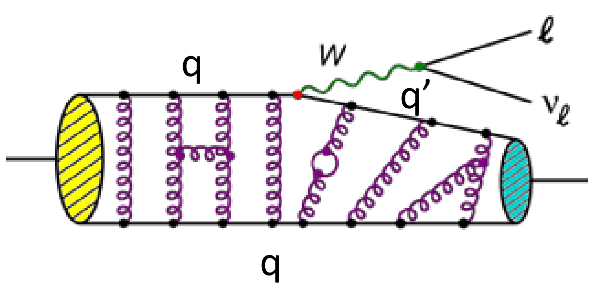



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$




- The amplitude of a hadron decay process can be described using Effective Field Theories: Operator Product Expansion (OPE)

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|Q_i(\mu)|M\rangle$$




CKM couplings

Wilson Coefficients (μ = scale)

Hadronic Matrix Elements

# Why B decays?

- The *b*-quark is the heaviest quark forming hadronic bound states (m~4.7 GeV)
- Must decay outside the 3rd family
  - $\rightarrow$ Long lifetime (~1.6 ps)
  - $\rightarrow$ Many accessible decay channels (small BR's)

Good for experimentalists!


- Type of processes:

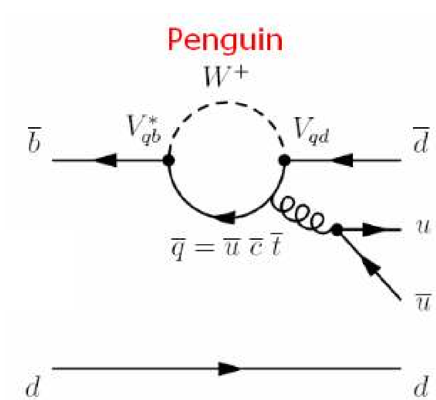

Dominant: $b \rightarrow c$ (favoured) and $b \rightarrow u$ (suppressed)


Rare: Flavour Changing Neutral Current (FCNC): $b \rightarrow s,d$

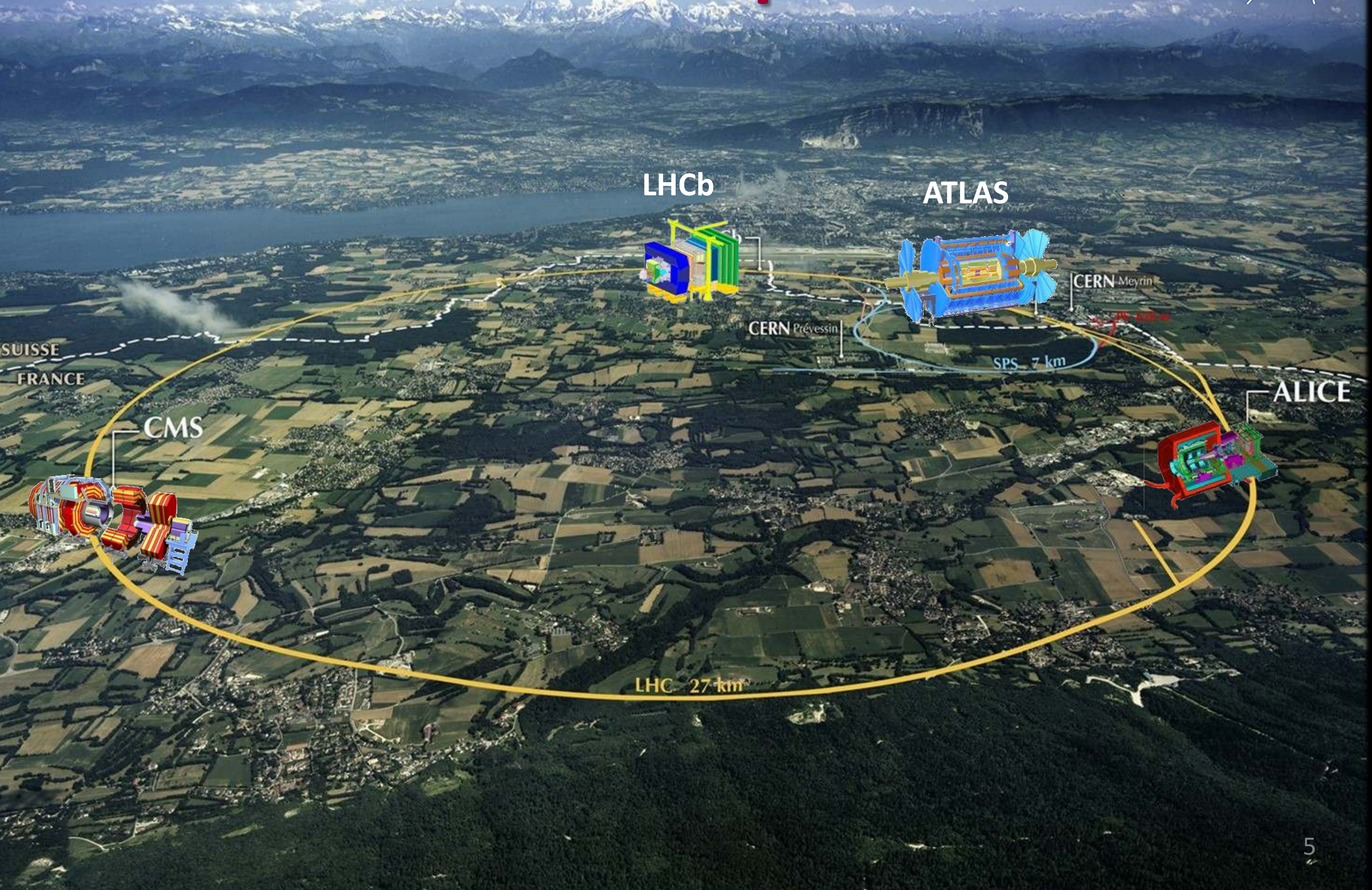

Flavour oscillations and CP violation


Good for theorists!

**Ideal place to probe New Physics effects!**



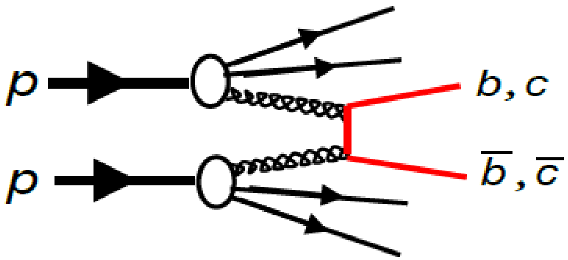
# The LHCb experiment

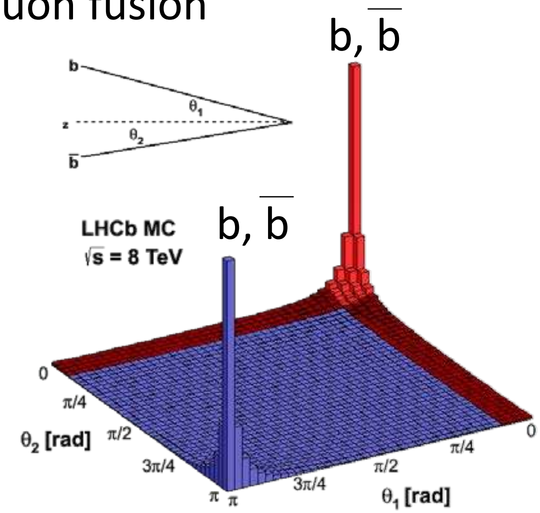


# The LHCb experiment

# The LHCb experiment

- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion
  ~ 300 μb @ √s=7 TeV
  ~ 600 μb @ √s=13 TeV
  [PRL 118 (2017) 052002]

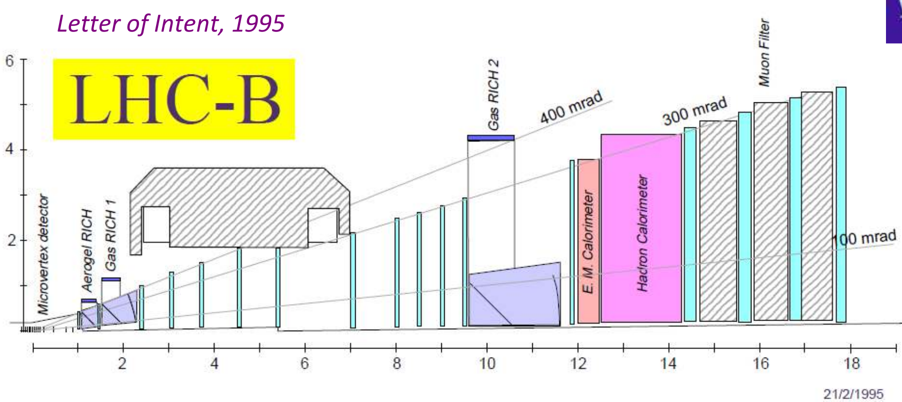


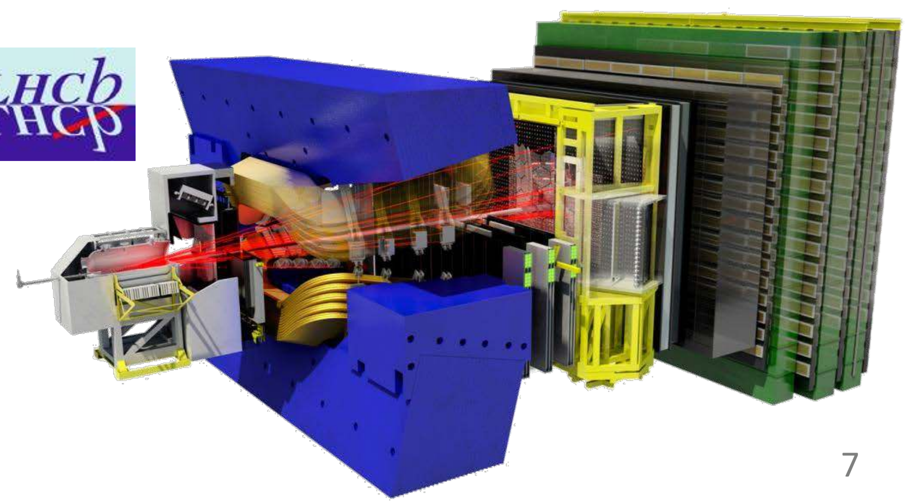




The $b$ quarks hadronize in B, $B_s$, $B^*_{(s)}$, $b$-baryons…
→ average B meson momentum ~ 80 GeV

- The LHCb idea: to build a single-arm forward spectrometer:
  ~ 4% of the solid angle (2 < η < 5),
  ~30% of the $b$ hadron production

*Letter of Intent, 1995*

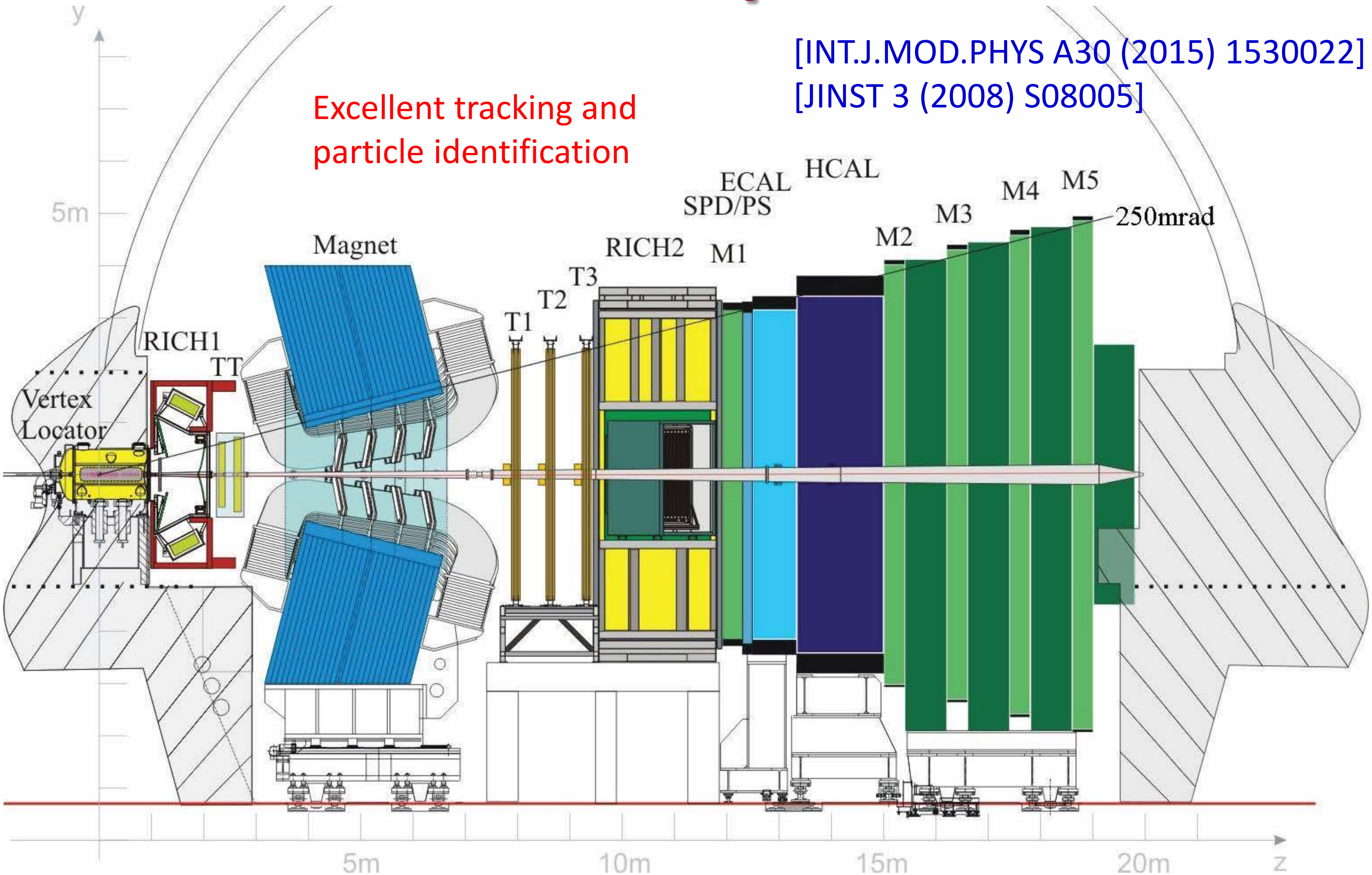


# The LHCb experiment

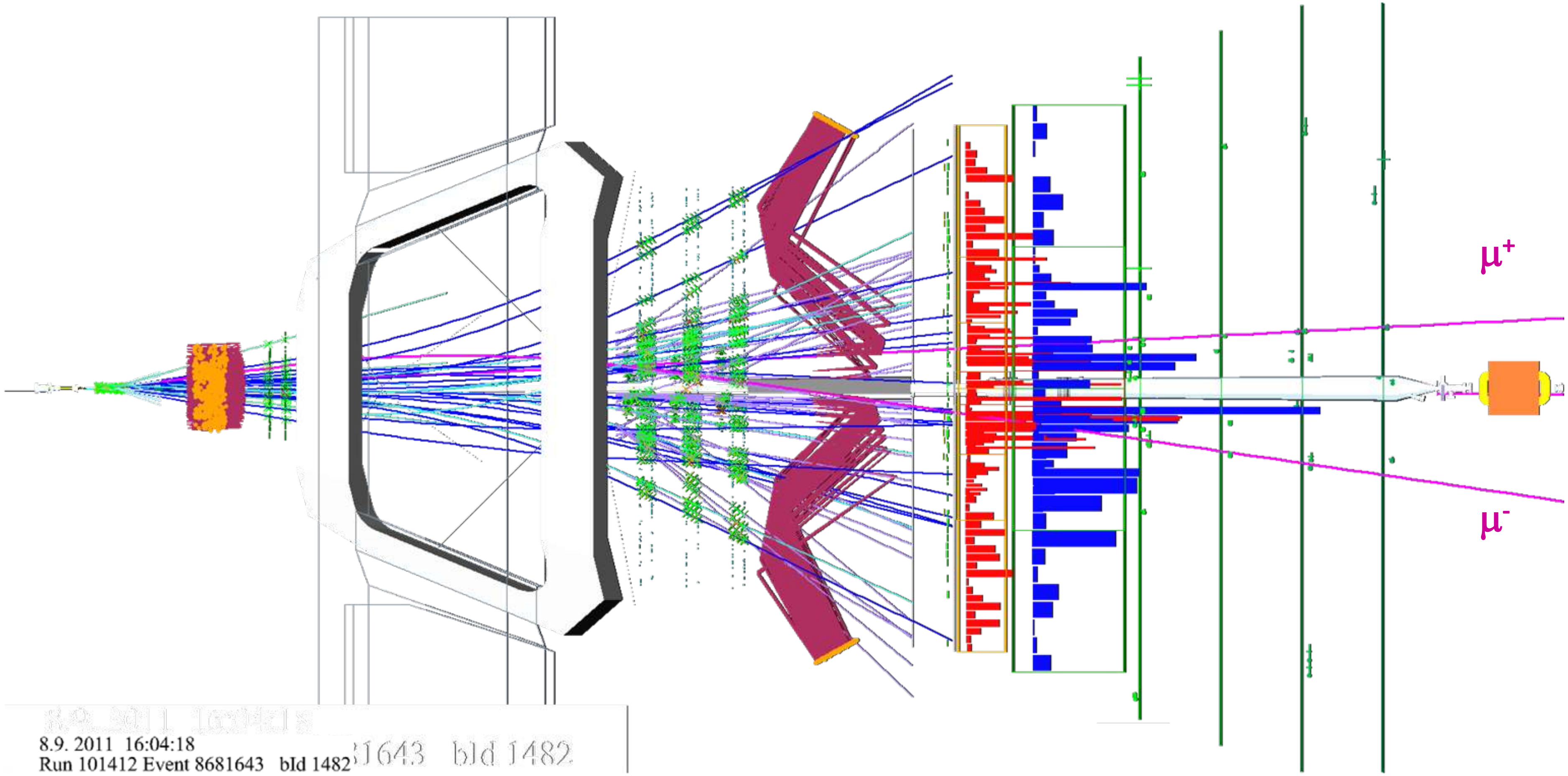
[INT.J.MOD.PHYS A30 (2015) 1530022]
[JINST 3 (2008) S08005]

Excellent tracking and
particle identification



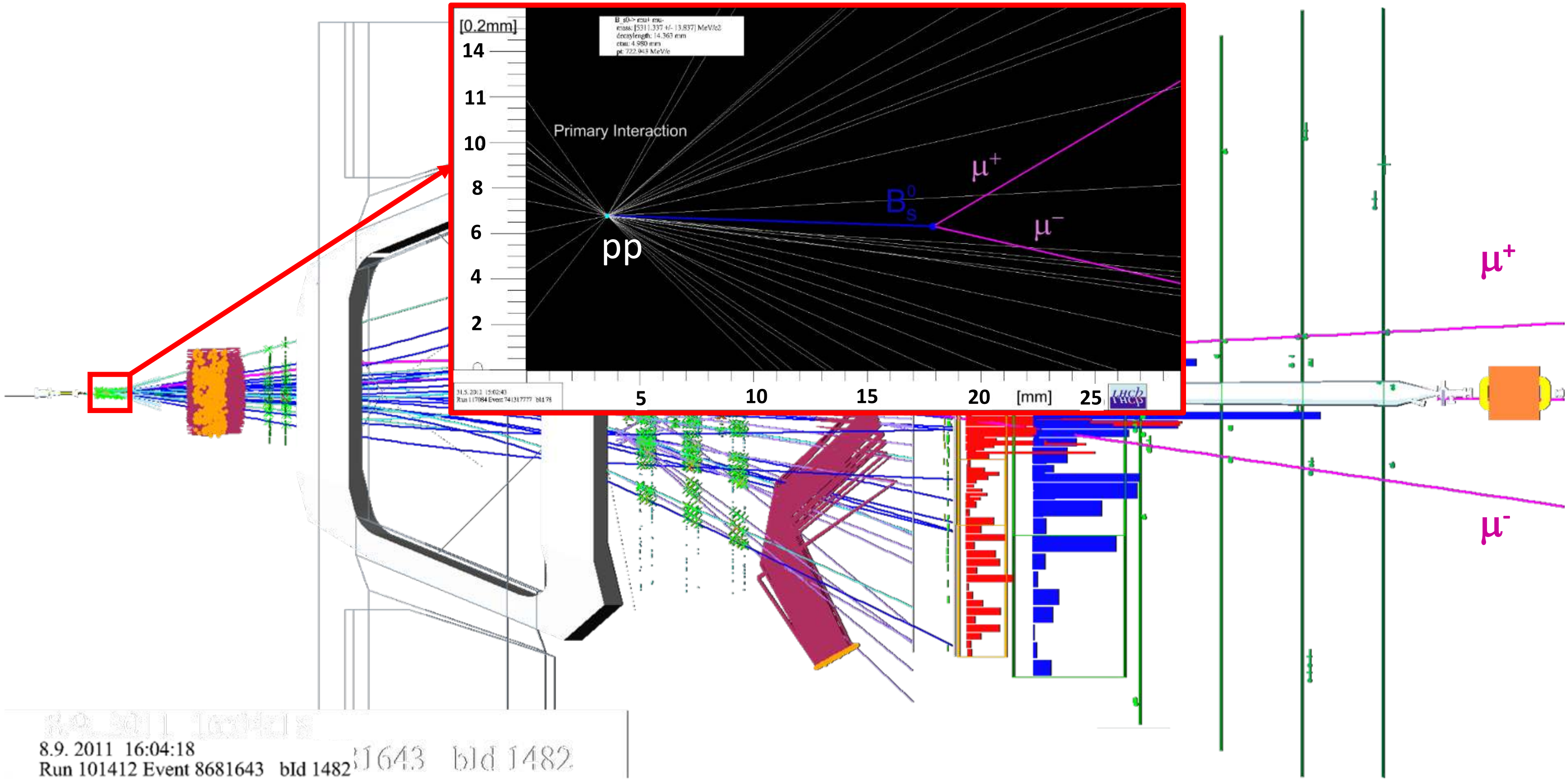
# The LHCb experiment

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



# The LHCb experiment

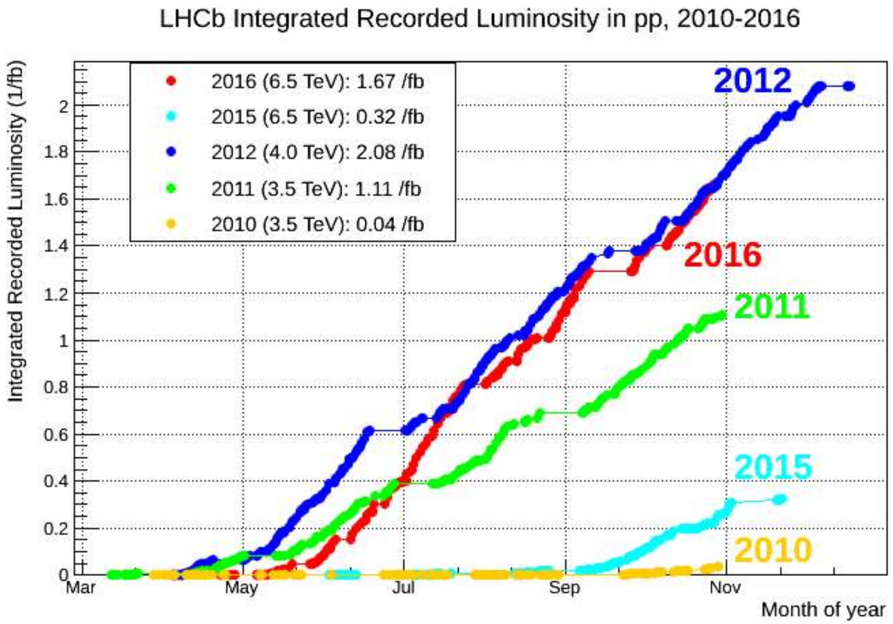
$B_s \to \mu^+\mu^-$ event

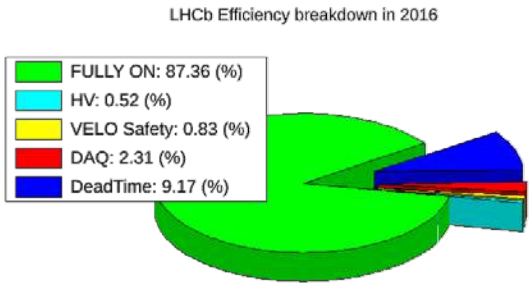



Impact Parameter (IP) resolution ~ 20 μm
Vertex resolution ~ 15μm (x,y) - 70μm(z)

# The LHCb experiment

- Very good performance: **3 fb$^{-1}$** accumulated in Run1 at 7 TeV,
  Working well for Run2 at 13TeV, expected **5 fb$^{-1}$** at the end of 2017

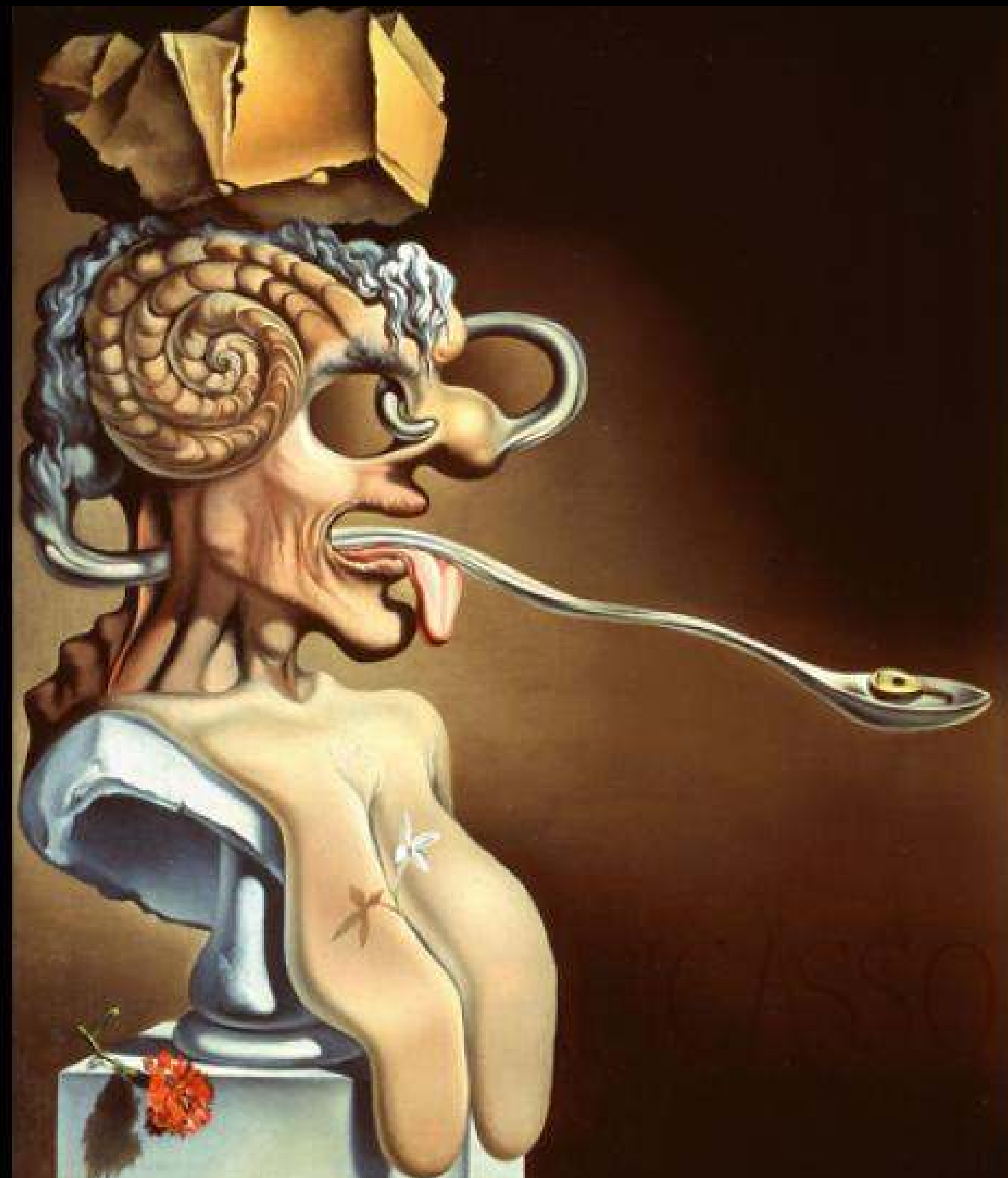



In terms of *b*-hadrons: $N=\int \mathcal{L}\sigma$

$\rightarrow$ $\sigma$ ~ 600 μb at 13TeV, x 30% (due to the acceptance) = 180 μb
$\rightarrow$ $b\bar{b}$ pairs produced in 1 fb$^{-1}$ $\rightarrow$ **~ 1.8 x 10$^{11}$**

# Rare
# B decays

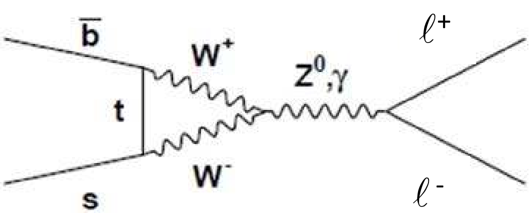


*Portrait of Picasso* (1947)

# Rare B decays

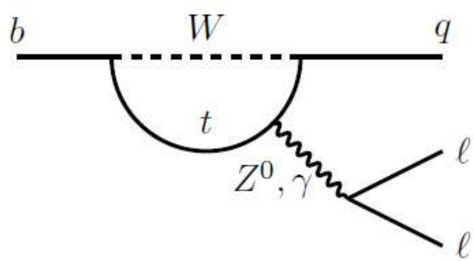
- *b → s,d* quark transitions are Flavor Changing Neutral Currents (FCNCs),
  → they only can occur through loops (*penguin and box diagrams*),
  excellent probe for physics beyond the SM

***leptonic***



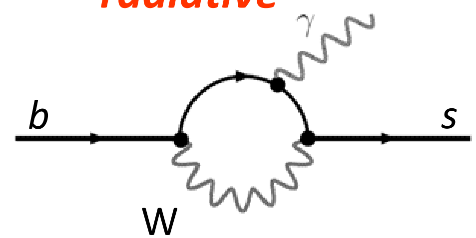

BR ~ $10^{-9}$

***semileptonic***




BR ~ $10^{-7}$

***radiative***




BR ~ $10^{-5}$

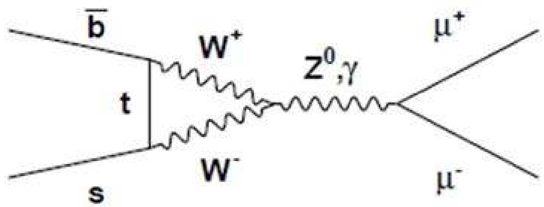
**Experimentally** → leptons/photons with high transverse momenta

**Theoretically** → observables can be calculated in terms of Wilson coefficients

Ex: $$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2 \left|2m_\mu C_{10}\right|^2$$

Hadronic uncertainties in decay constants or form factors

# Rare B decays: $B_s \to \mu^+\mu^-$




- Very rare decay:
  FCNC and helicity suppressed
  $BR_{SM} = 3.66(23) \times 10^{-9}$

- Searched for over the last 30 years, observed by LHCb and CMS
  [Nature 522 (2015) 68]

★ Updated analysis by LHCb, including Run2 data

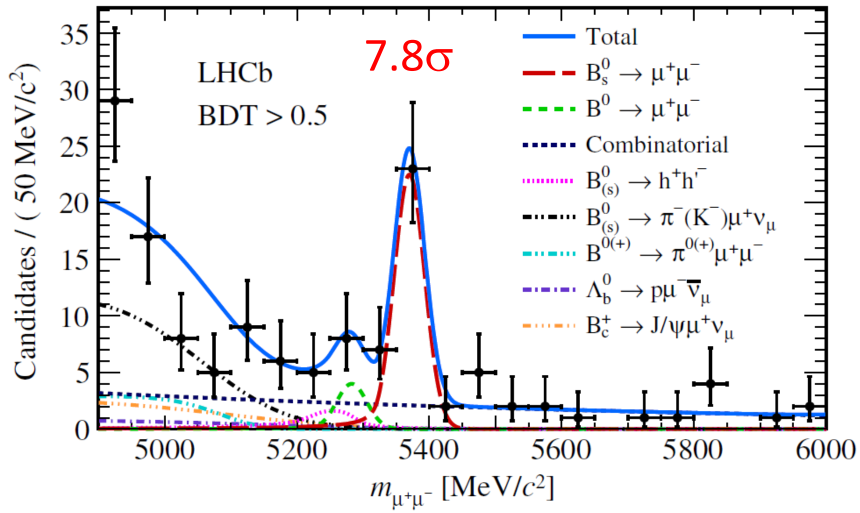
[PRL 118 (2017) 191801]

- $B_s \to \tau^+\tau^-$ also searched for at LHCb:

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\%$$

[arXiv:1703.02508 [hep-ex]]

4.4 $fb^{-1}$ [PRL 118 (2017) 191801]




$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\%$$

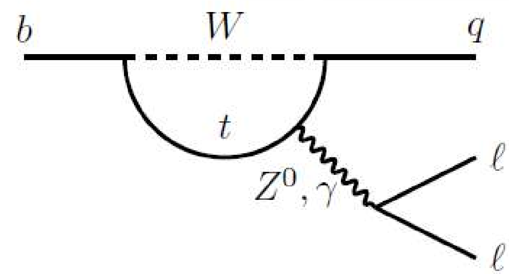
→ **In agreement with the SM**

→ Theoretical uncertainties ($f_{B(s)}$, $V_{CKM}$) well below statistical uncertainty

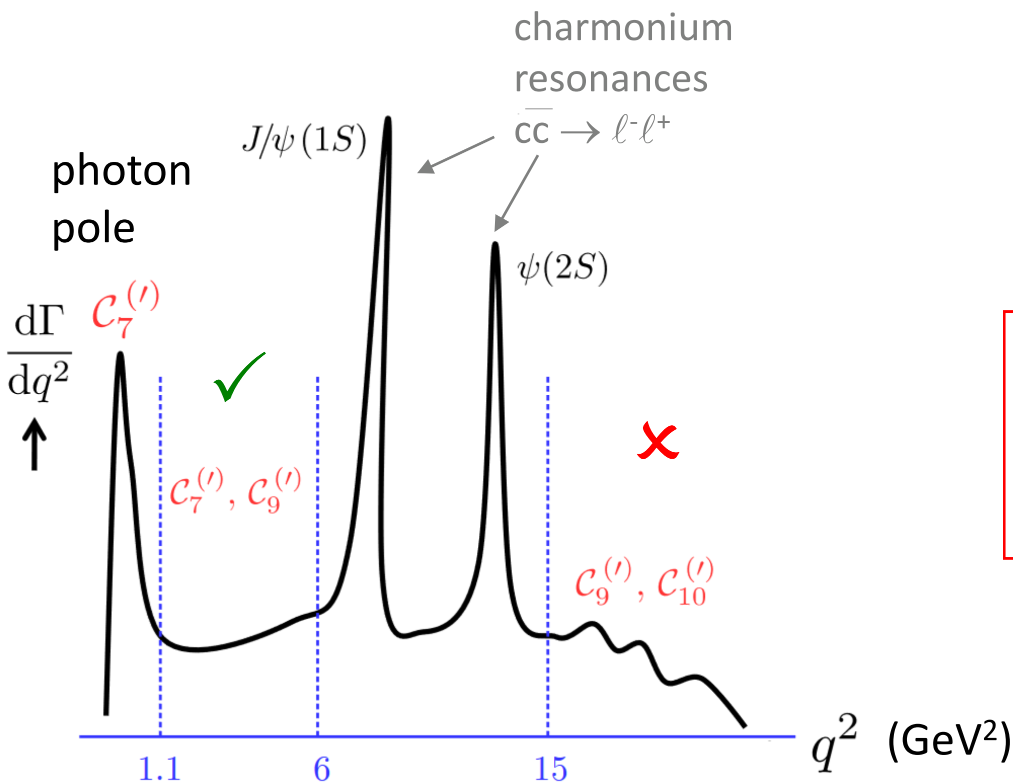
# Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

Differential branching fraction: $d\Gamma/dq^2$

Each $q^2$ region probes different processes




$q^2 = (p_{\ell^+} + p_{\ell^-})^2$





SM values ($\mu = m_b$): $C_7$ ~ - 0.33
$C_9$ ~ 4.27
$C_{10}$ ~ - 4.17

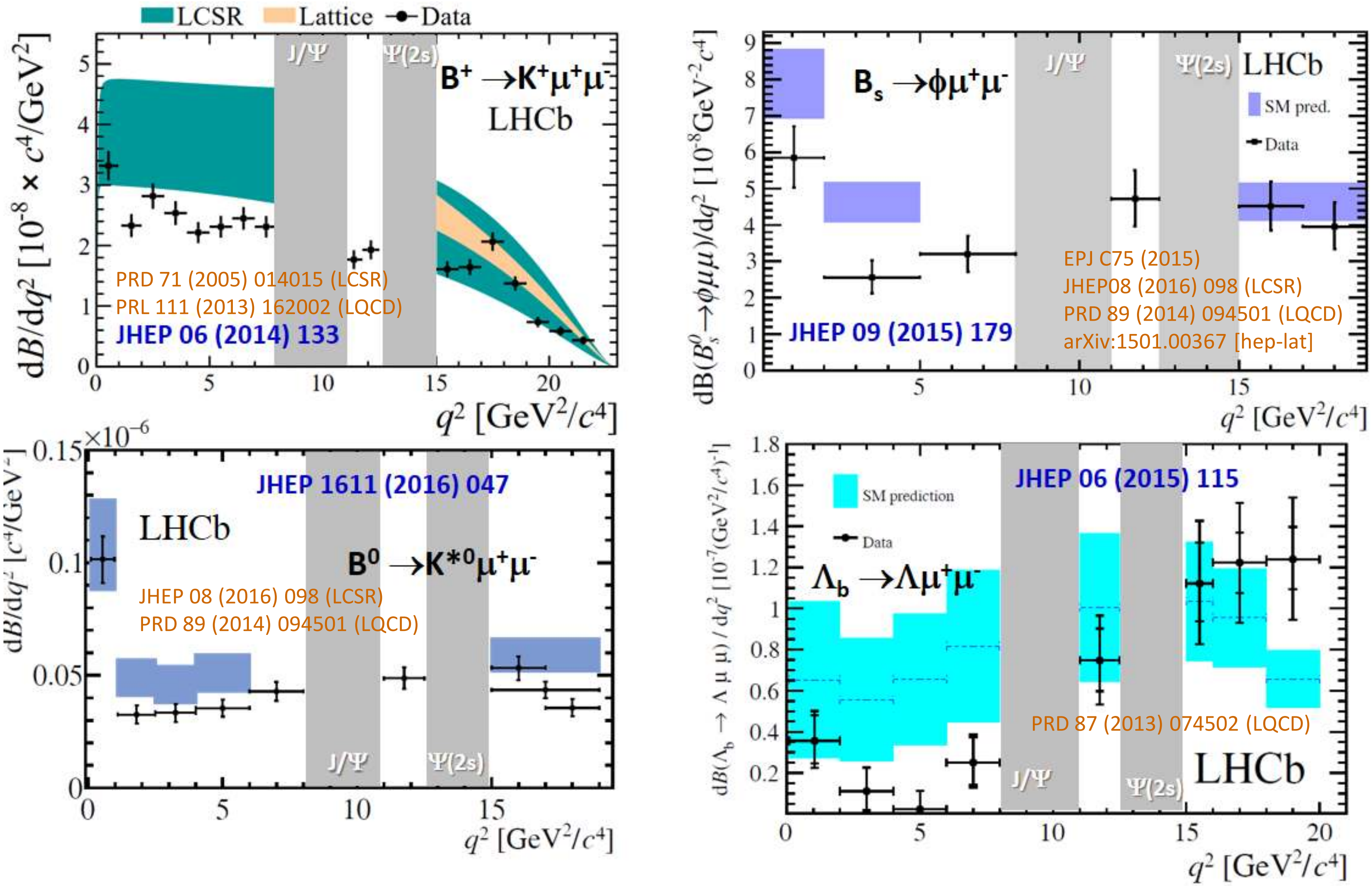
(Everything else small or negligible)

$C_i = C_i^{SM} + C_i^{NP}$

(Primed $C'_i \to$ right handed currents: suppressed in SM)

# Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

- Differential decay width as function of $q^2 = m^2_{\mu\mu}$

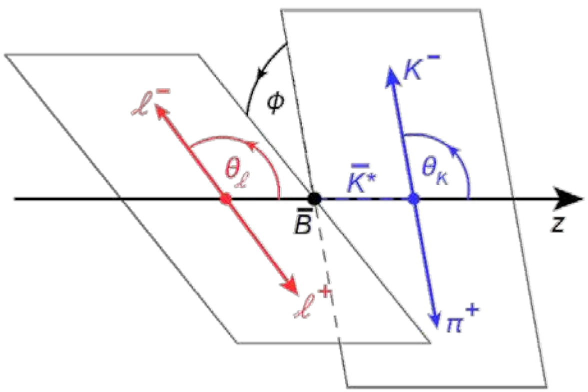



**Theory affected by hadronic uncertainties: LCSR + LQCD**

# Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

- Angular distribution in $B \to K^* \ell^- \ell^+$ : $q^2$ and three angles

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




$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

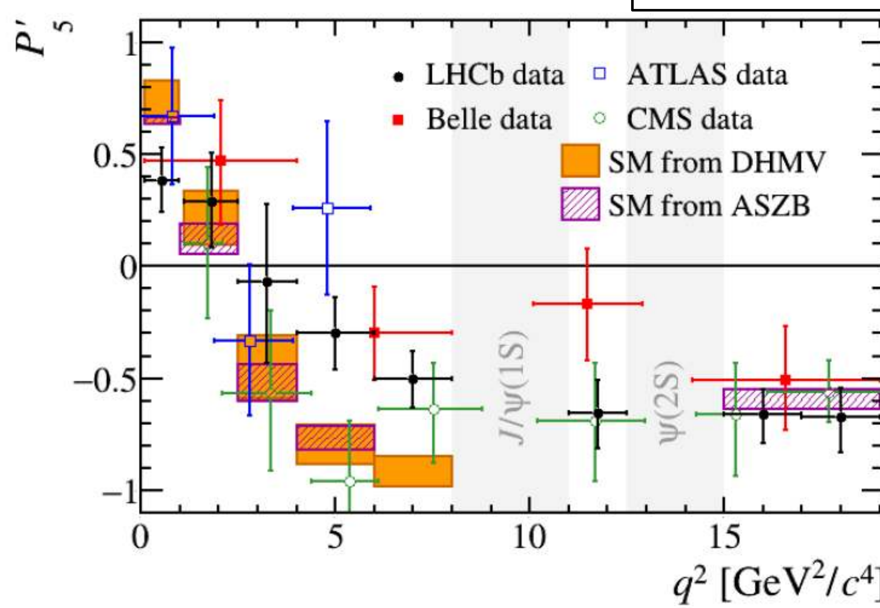
Functions of $q^2$ and Wilson coef. $\mathbf{C_i}$

**Optimized observables: cancellation of form factor dependencies: $P'_i$**

[Descotes-Genon et al, JHEP 05 (2013) 137]

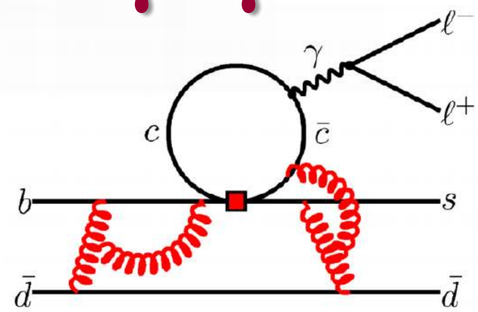
- JHEP 02 (2016) 104
- PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

→ Deviation from SM ~ **3σ**



# Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

## Understanding effects from charm:



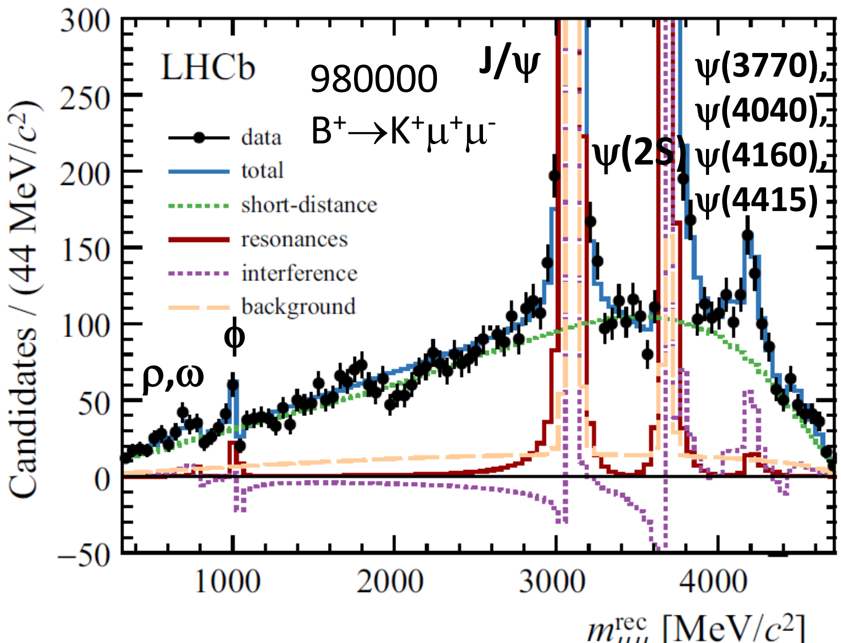

- Phase difference between short- and long-distance amplitudes in the $B^+ \to K^+\mu^+\mu^-$ decay [EPJ C(2017) 77]

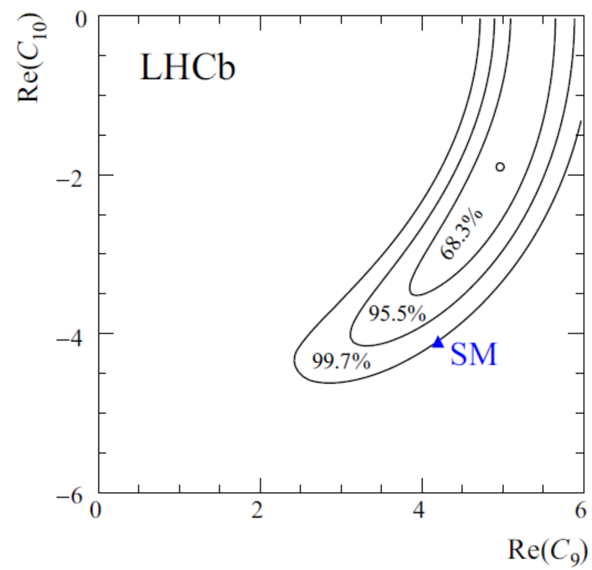
→ $d\Gamma/dm_{\mu\mu}$ is a function of form factors and $\mathbf{C_i}$

→ $\mathbf{C_i^{eff}}$ expressed as a sum of relativistic Breit-Wigner amplitudes: **magnitudes and phases extracted from data**

→ Form factors from FNAL & MILC [PRD 93(16)025026]

$$C_9^{\mathrm{eff}} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\mathrm{res}}(q^2)$$




→ **Small effect of hadronic resonances in Wilson coefficients**

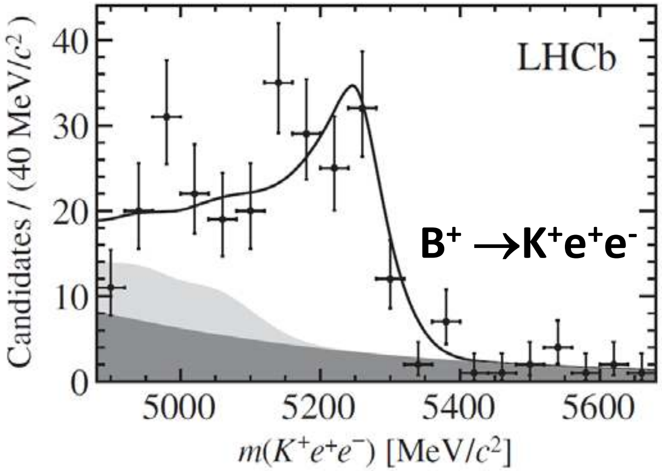
# Rare B decays: $R_K$

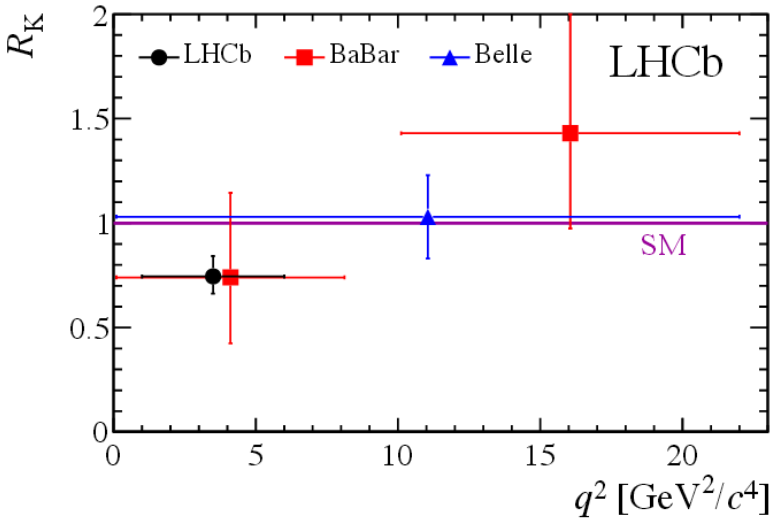
- In the SM all leptons are expected to behave in the same way:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$ = 1.000 + $O(m_\mu^2/m_b^2)$ (SM)

- Experimentally, use the $B^+ \to K^+ J/\psi(\to e^+e^-)$ and $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ to perform a double ratio

- Precise theory prediction due to cancellation of hadronic form factor uncertainties



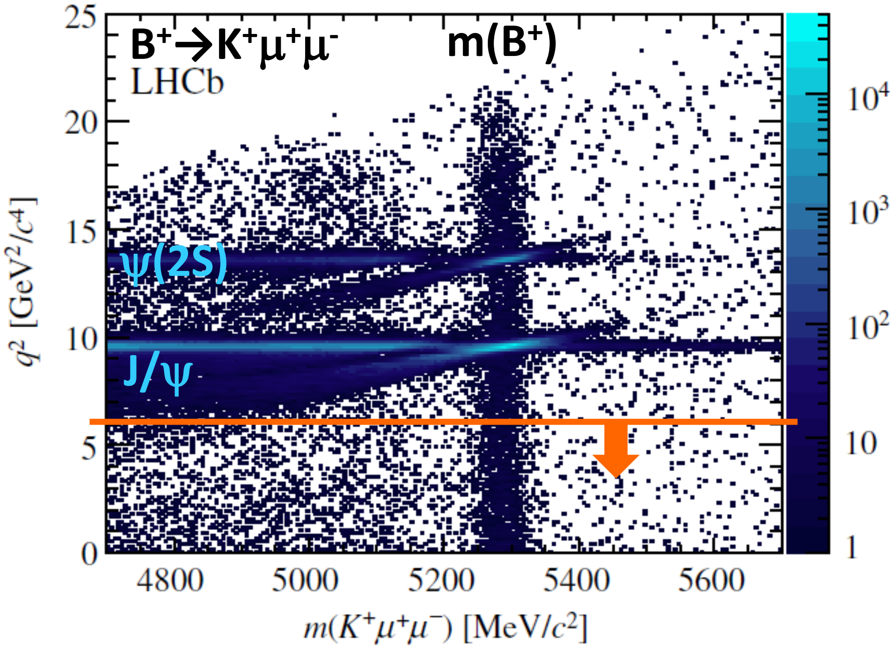

1 GeV < $q^2$ < 6 GeV [PRL 113 (2014) 151601]

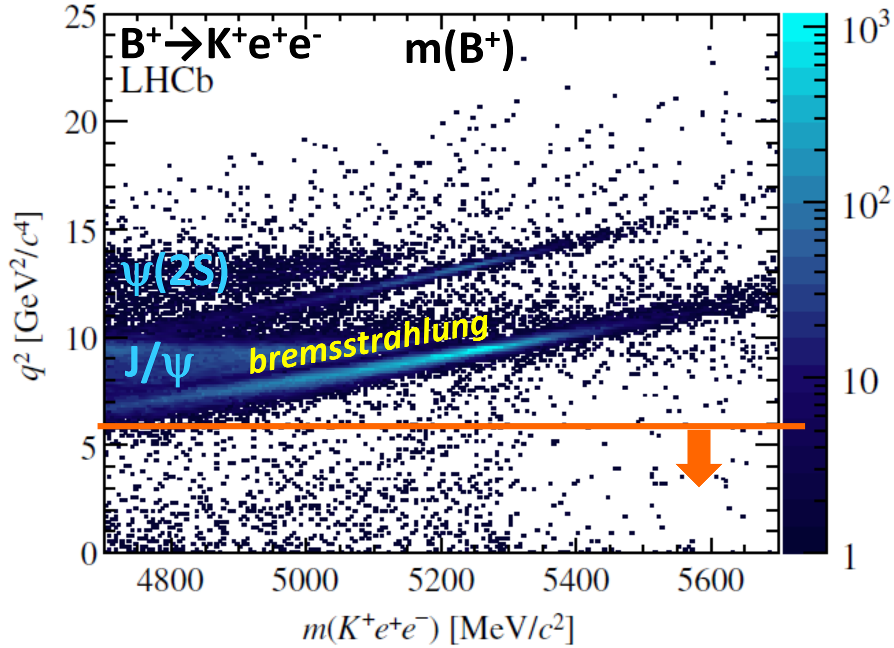
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

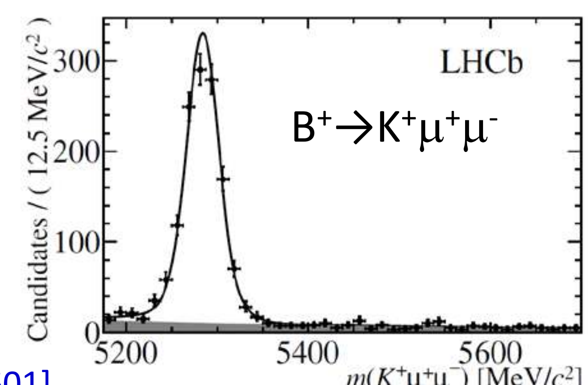
→ Consistent, but lower, than the SM at **2.6σ**

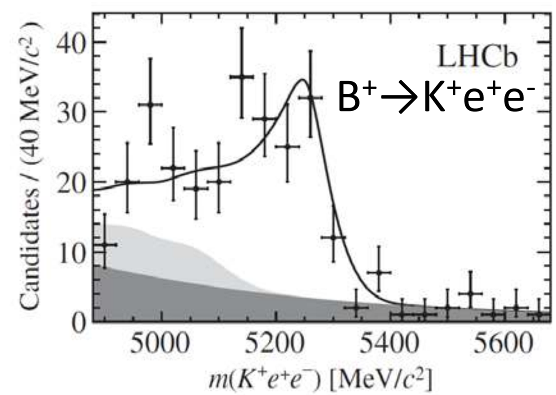
# Rare B decays: $R_K$

B mass vesus $q^2$ for $B^+ \to K^+\ell^+\ell^-$



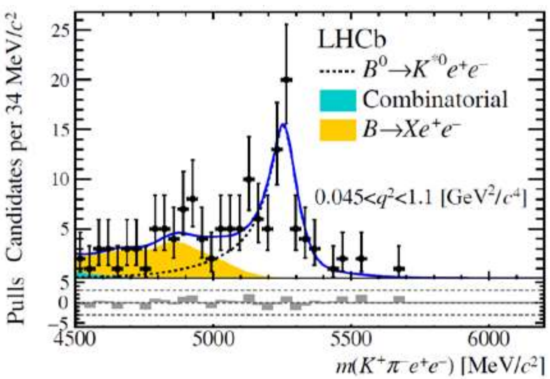

[PRL 113 (2014) 151601]

# Rare B decays: $R_{K*}$

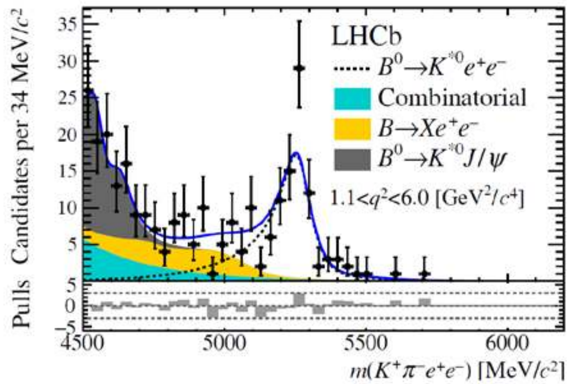
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

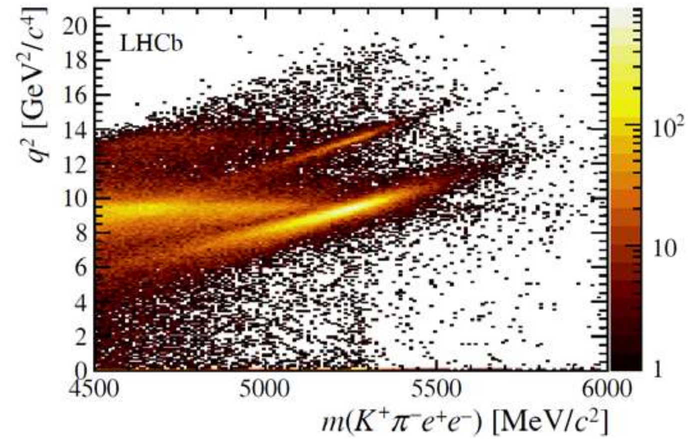
[arXiv:1705.05802 [hep-ex]]

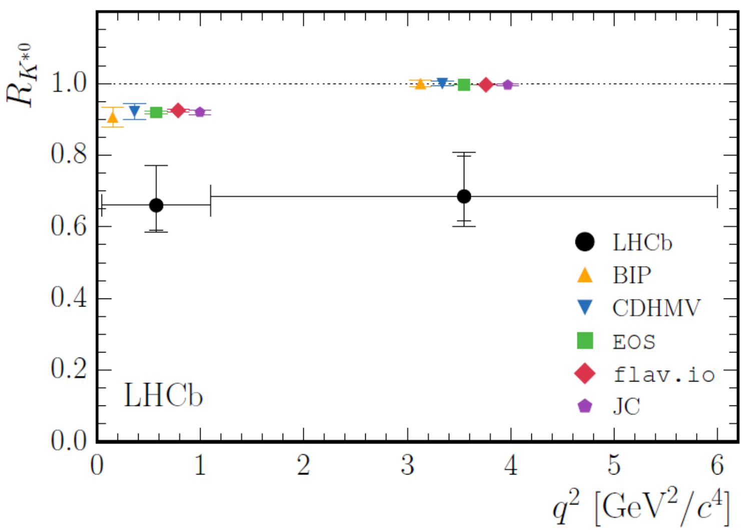
0.045 GeV < $q^2$ < 1.1 GeV




1.1 GeV < $q^2$ < 6 GeV




Low $q^2$: SM = 0.922(22)

$$R_{K^{*0}} = 0.66\ {}^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$

Central $q^2$: SM = 1.000(6)

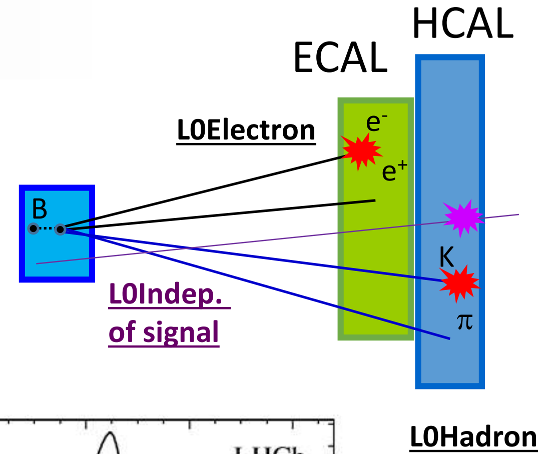
$$R_{K^{*0}} = 0.69\ {}^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

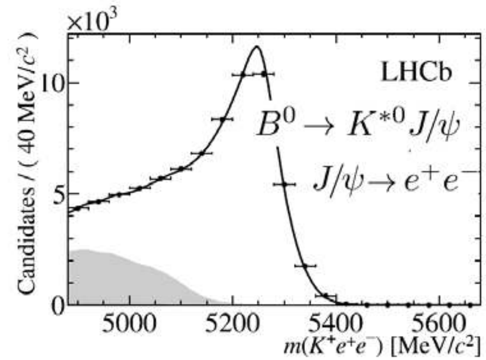
→ Consistent, but lower than the SM at **2.1-2.3σ** (low $q^2$) and **2.4-2.5σ** (central $q^2$)

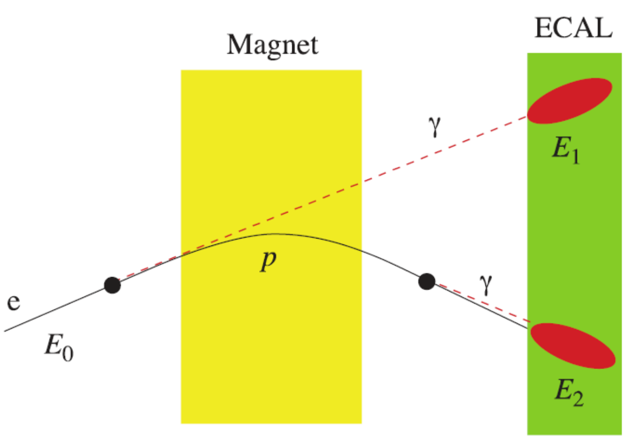
# Rare B decays: $R_{K^{(*)}}$

**<u>Quick note on experimental issues:</u>**

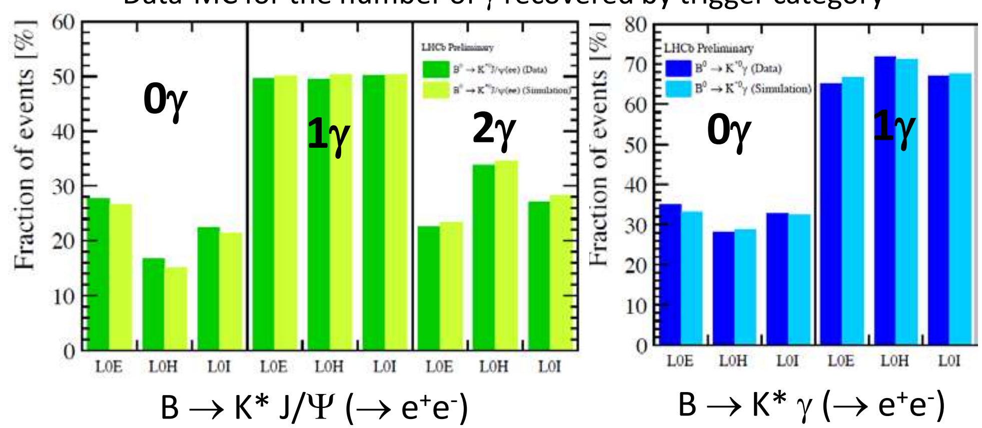
- LHCb is far better with muons than electrons
- *Trigger*, reconstruction, selection and particle identification are harder with electrons
- Mass resolution affected by *e bremsstrahlung* $\rightarrow$ need energy recovery
- Mass shape modelled according to the number of *bremsstrahlung* recovered



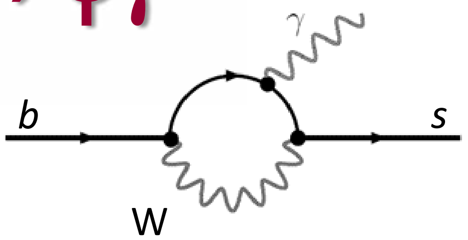




Data-MC for the number of γ recovered by trigger category



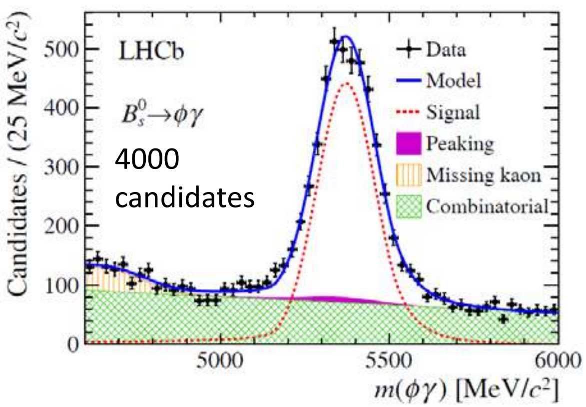
# Rare B decays: $B_s \to \phi\gamma$

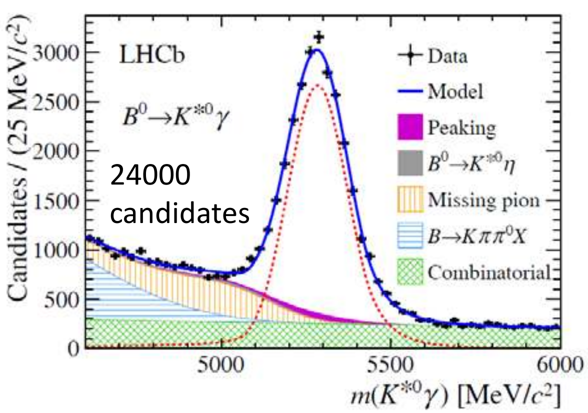



- Ratio of branching fractions: [Nuc. Phys. B 867 (2013) 1]

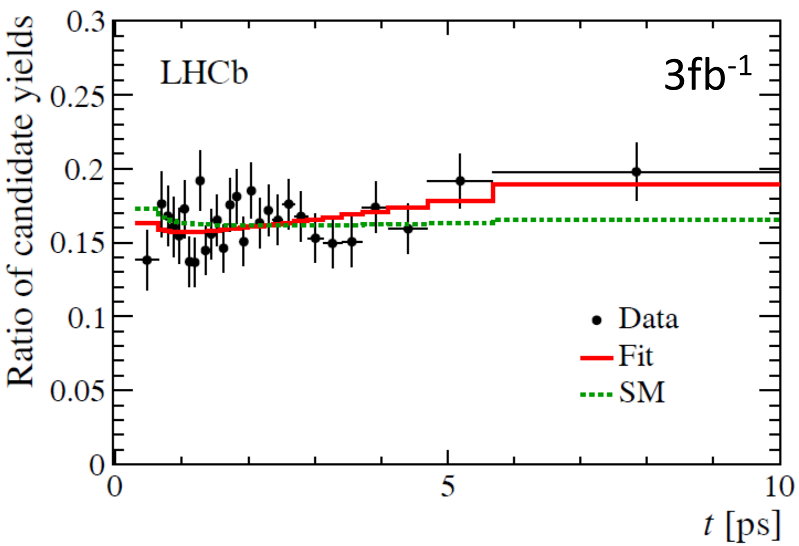
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$

- Time dependent distribution for $B_s \to \phi\gamma$ is sensitive to the photon polarization (predicted to be right-handed in the SM)




[PRL 118 (2017) 021801]

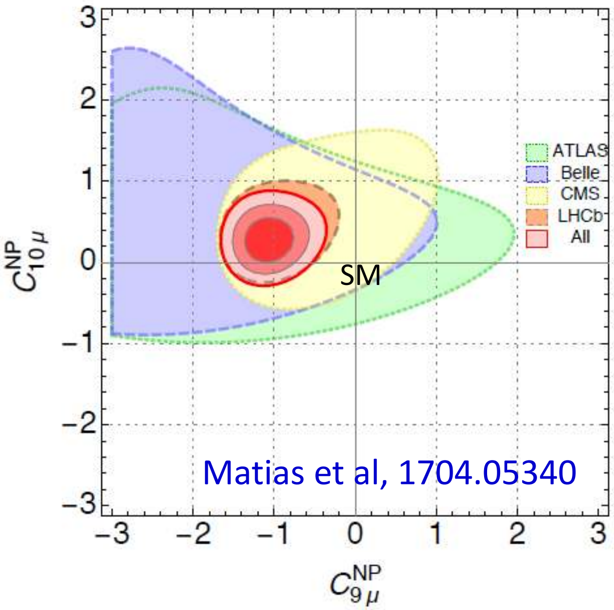


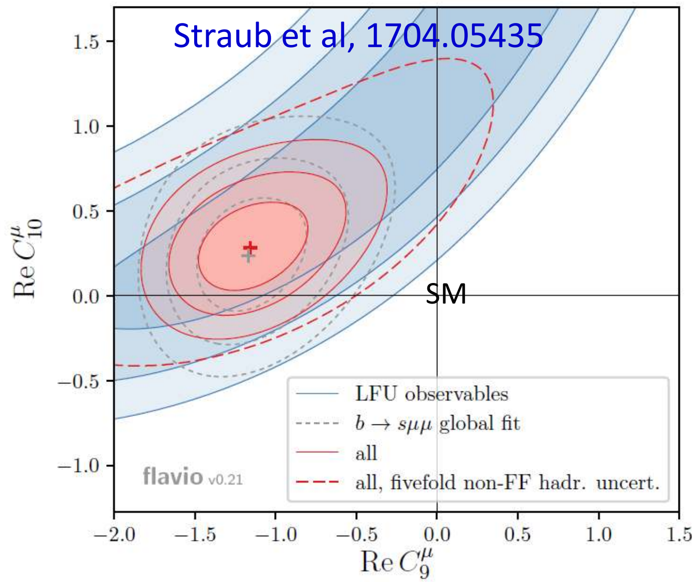

$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20} \qquad \mathcal{A}^{\Delta}_{\rm SM} = 0.047\,^{+0.029}_{-0.025}$$

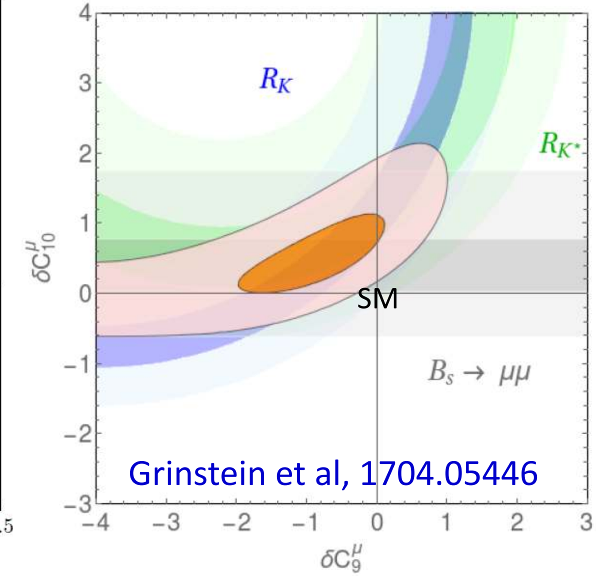
→ Compatible with the SM within **2σ**

# Rare B decays

Global fits (some cases with more than 100 observables)

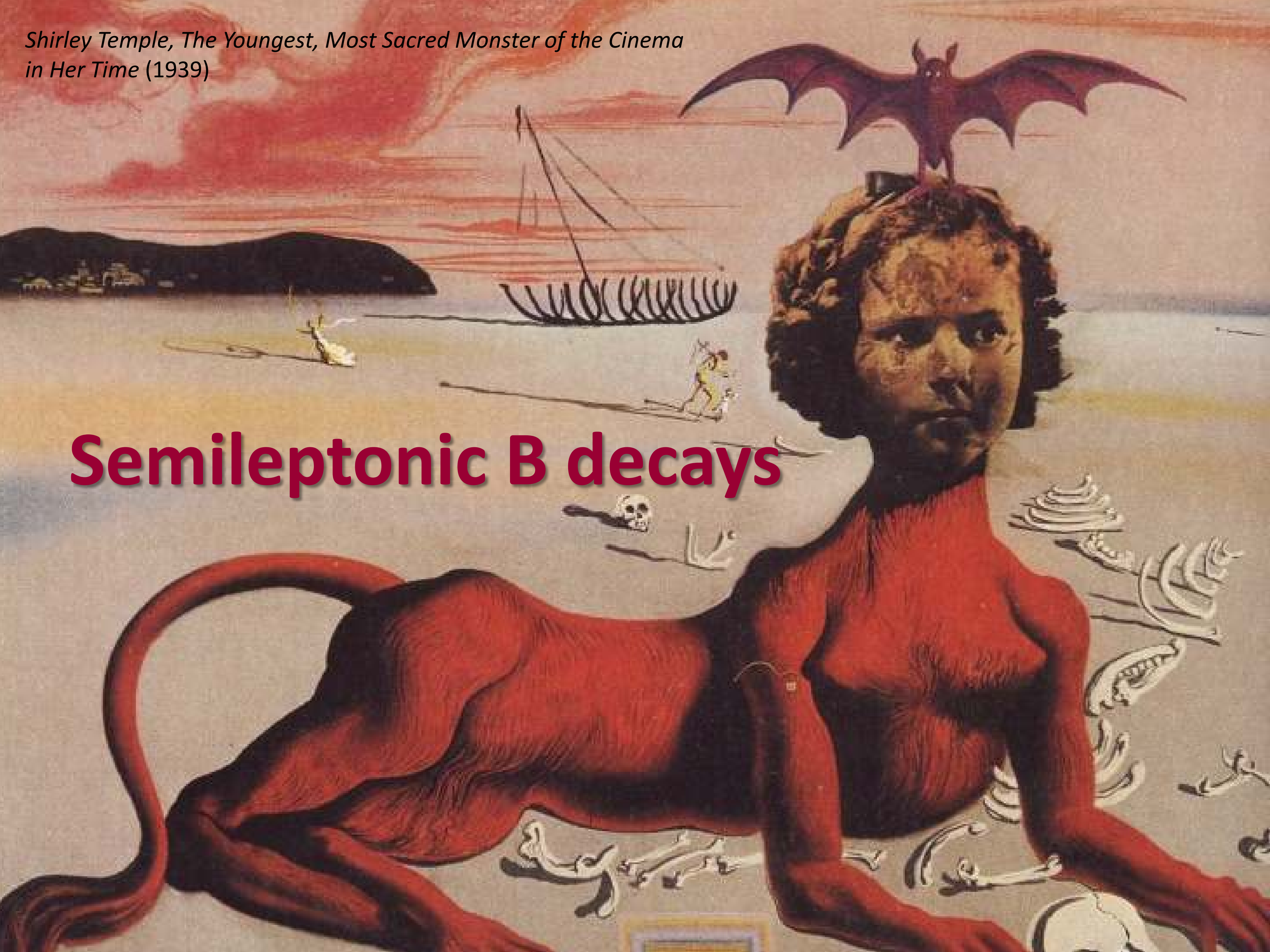



New Physics hypothesis preferred over SM by more than 4 - 5σ
Main effect on the $C_{9\mu}$ coefficient: **$4.27^{SM}$ $-1.1^{NP}$**

Triggered models with Z', leptoquarks (LQ), and composite Higgs



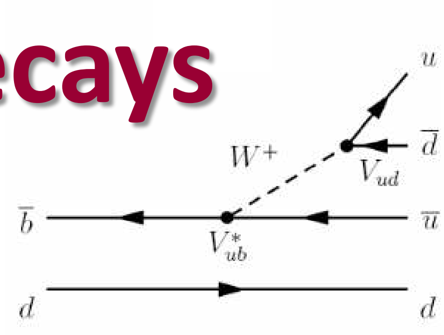
*Shirley Temple, The Youngest, Most Sacred Monster of the Cinema in Her Time* (1939)

# Semileptonic B decays

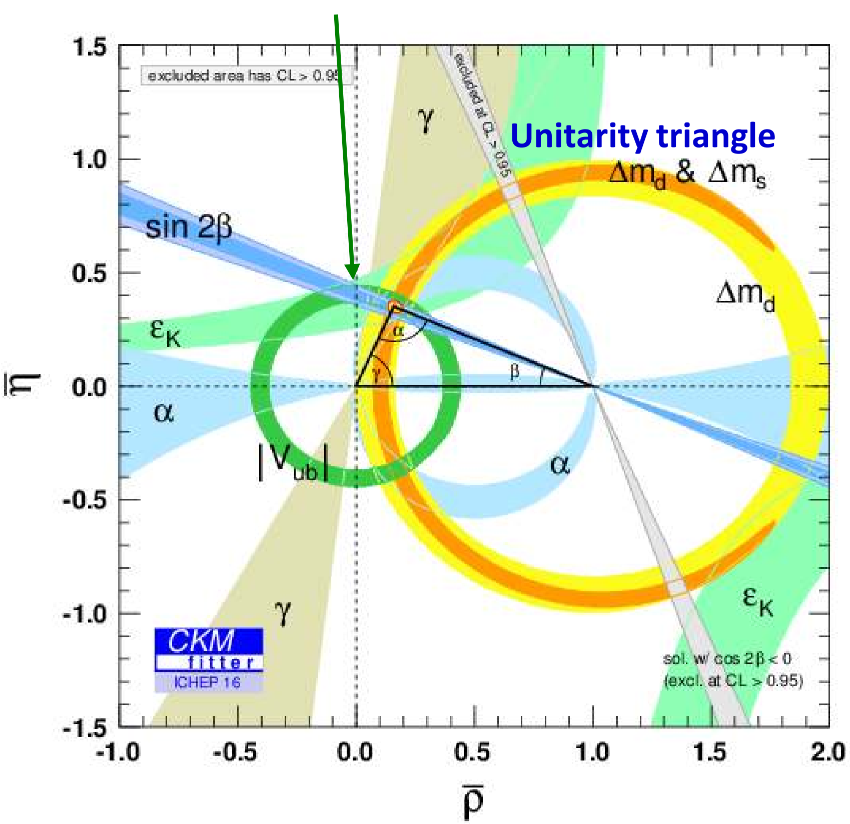
# Semileptonic B decays

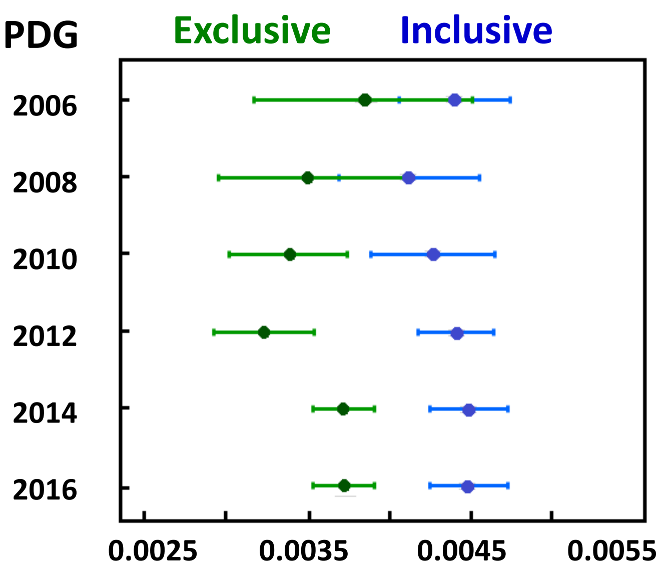
- $b \to c,u$ quark transitions proceed at tree level

  $V_{ub}$ is the smallest CKM element ~ 4‰



Key constraint in the flavour picture




Large discrepancies between $|V_{ub}|$ from different determinations ( ~3σ)

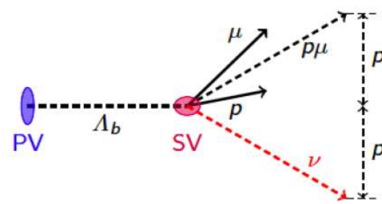
# Semileptonic B decays: $V_{cb}, V_{ub}$

- Using semileptonic decays of *b*-baryons: [Nature Physics 10 (2015) 1038]

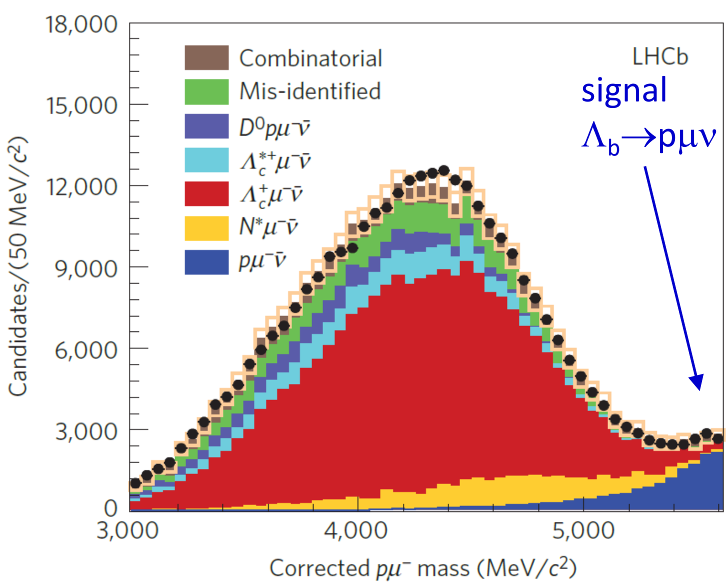
$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2}$$ x Ratio of form factors

(5% accuracy from LQCD)

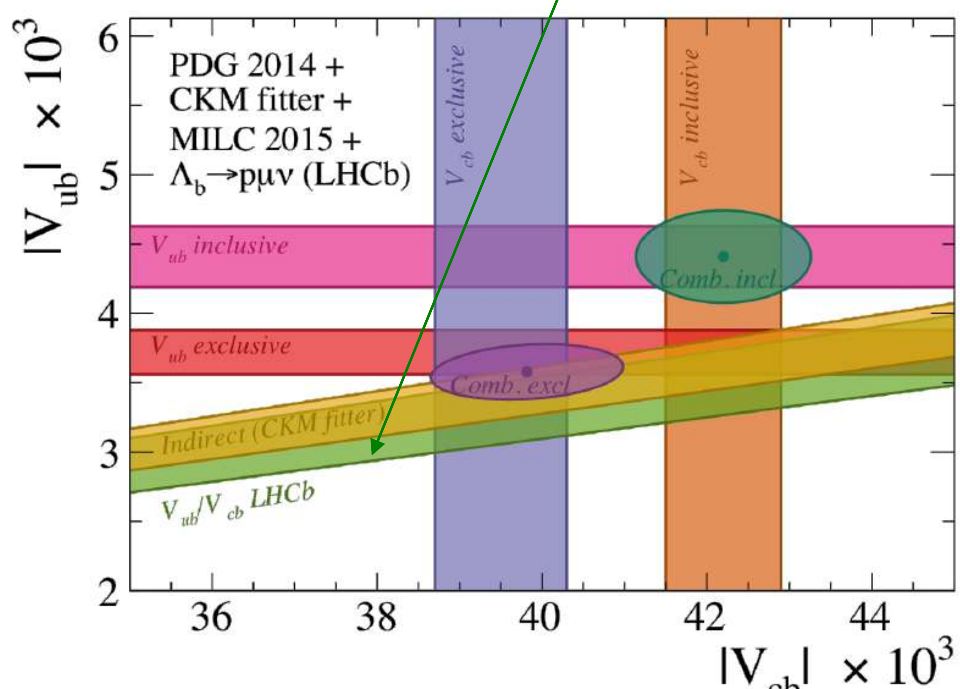
[RBC & UKQCD, PRD 92 (2015) 034503]




$$m_{\text{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$




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

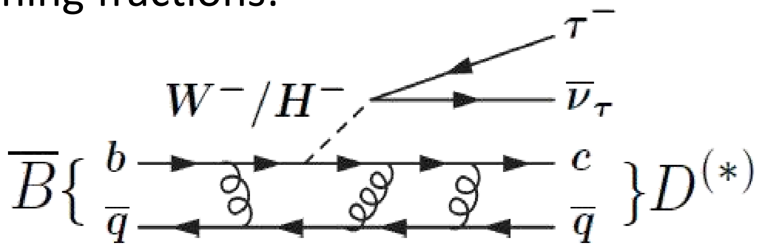


# Semileptonic B decays: $R_{D,} R_{D*}$

- Another test of lepton universality (now at tree level):

Ratio of semi-tauonic and semi-muonic branching fractions:

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$




Sensitive to charged Higgs bosons and leptoquarks

**SM predictions very precise :** ($V_{cb}$ and form factors (partially) cancel)

$R(D)_{SM}$=0.299 $\pm$ 0.003

$R(D^*)_{SM}$=0.252 $\pm$ 0.003

Based on HQET form factors:
**[H. Na *et al.*, PRD 92 (2015) 054510]**
**[Fajfer, Kamenic, Nišandižć: PRD85 (2012) 094025]**
and experimental measurements (HFLAV)
**[D.Bigi, Gambino, PRD 94 (2016) 094008]**

BaBar measured an excess of $\overline{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$ (3$\sigma$ away from SM) [PRD 88 (2013) 072012]
[Nature 546(2017)227]

LHCb has performed two analyses:

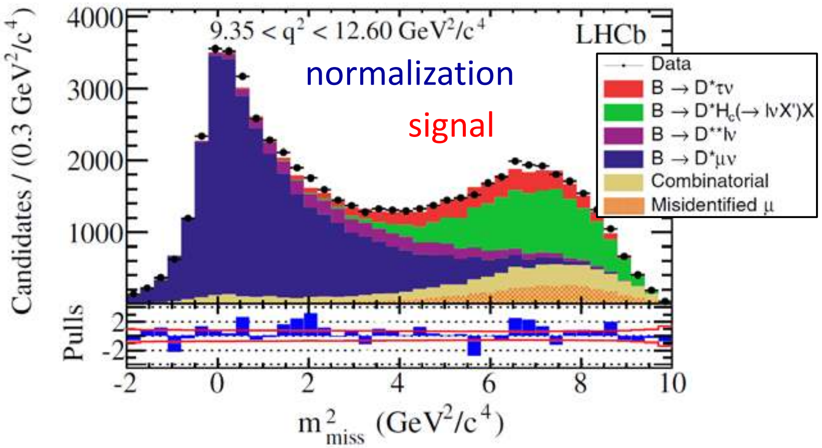
- $\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ , with $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ [PRL 115 (2015) 111803]
- $B^0 \to D^{*-}\tau^+\nu$ , with $\tau^+ \to \pi^+\pi^-\pi^+\pi^{(0)}\ \bar{\nu}_\tau$ (**NEW!**) [LHCb-PAPER-2017-17]

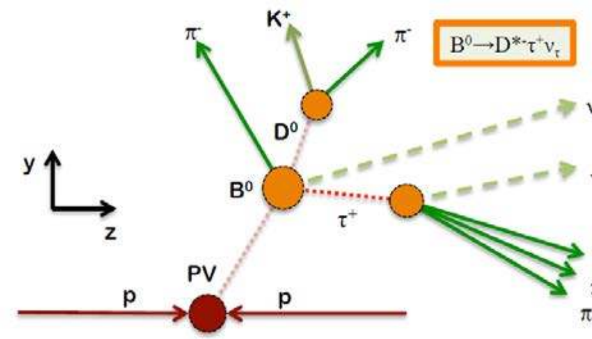
# Semileptonic B decays

- Using $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$
- Information from the missing mass squared $m_{miss}^2 = (P_B - P_{D*} - P_\mu)^2$ and muon energy in several $q^2$ bins

$$\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

[PRL 115 (2015) 111803]

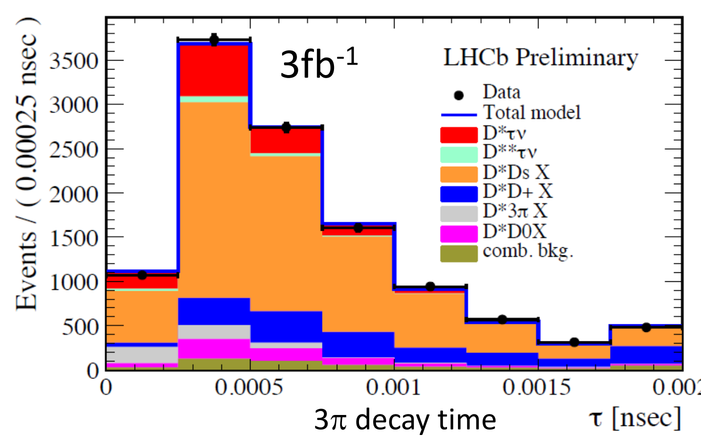



- New analysis by LHCb: using $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$
- Information from the position of the three pions
- Normalized to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

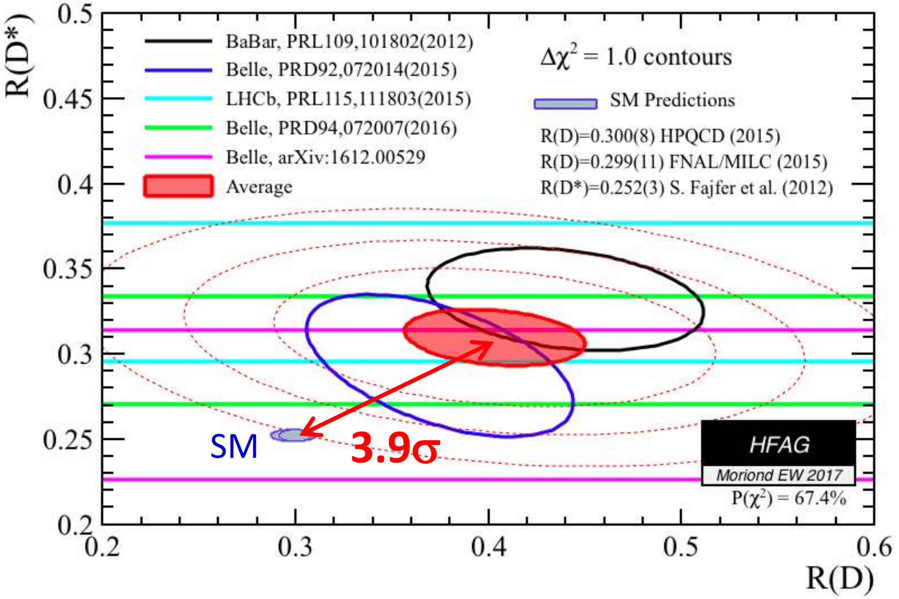
$$\mathcal{R}(D^{*-}) = 0.285 \pm 0.019 \pm 0.025 \pm 0.014$$

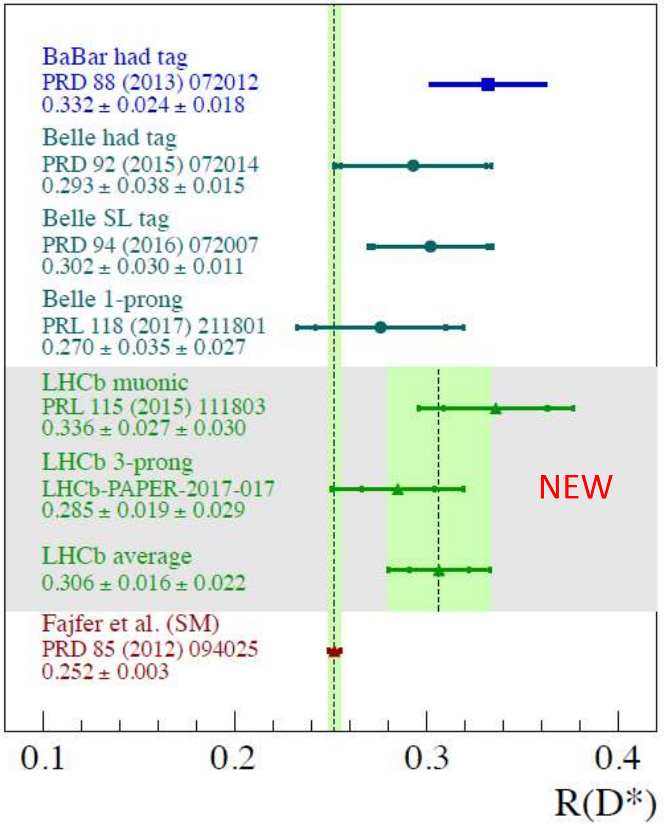
[LHCb-PAPER-2017-17]



# Semileptonic B decays

- Global picture of $R_D$ and $R_{D*}$



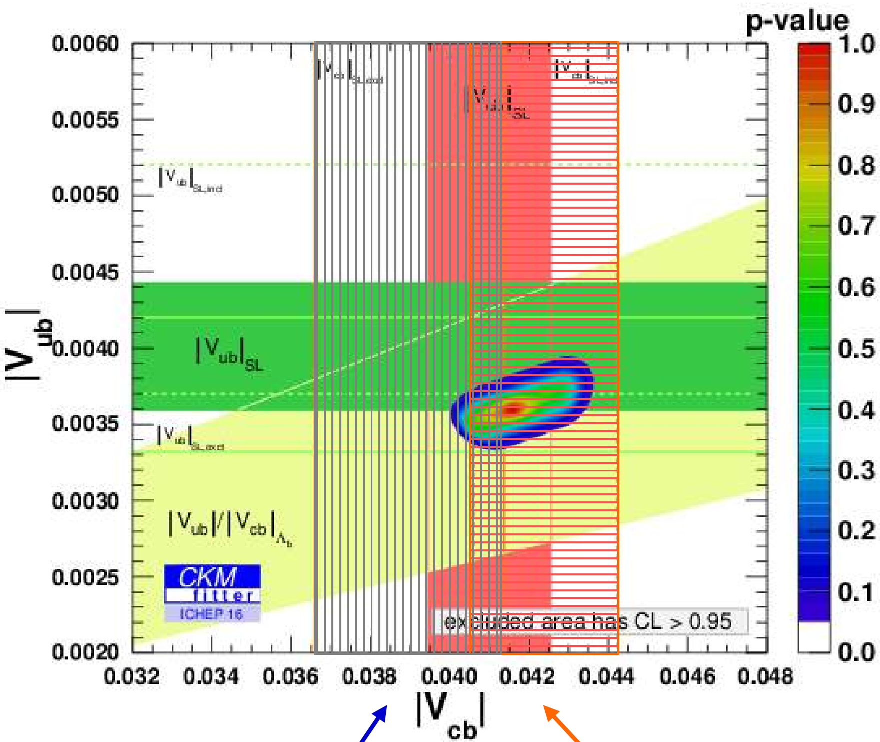

→ About 4σ deviation from SM

# Wish list for Lattice

*Galatea of the Spheres* (1952)

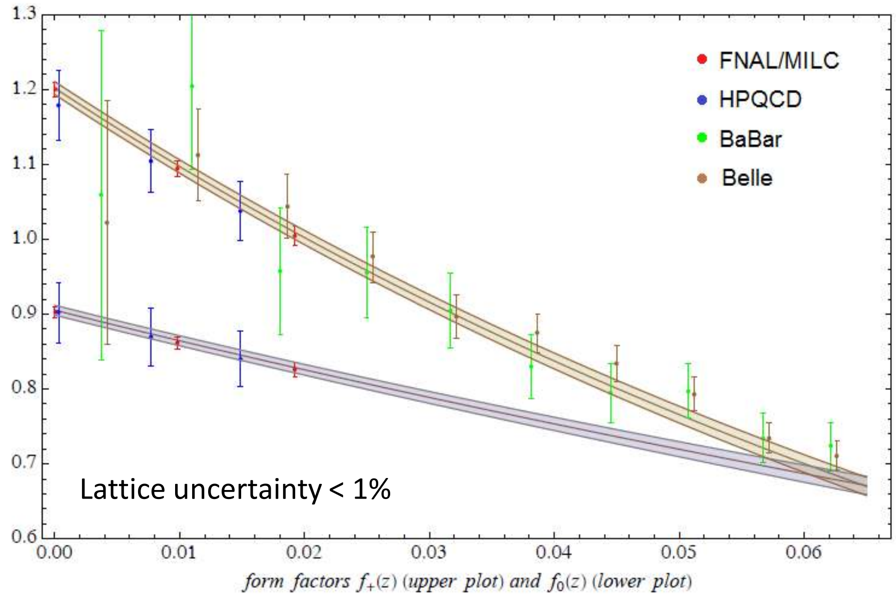
# Wish list for Lattice

- Decisive inputs to solve some long-standing puzzles:




Large difference between
$V_{cb}$ exclusive and $V_{cb}$ inclusive
from form factor parameterizatios (BGL/CLN)?

Also important for $R_{D(*)}$ calculation




Fit to Lattice + B-factories data

[D. Bigi and Gambino, PRD 94 (16) 094008,
D. Bigi, Gambino, Schacht PLB769(2017)441
Grinstein and Kobach, arXiv:1703.08170 [hep-ph]]

# Wish list for Lattice

- $B \to D^{(*)}$ form factors, affecting $V_{cb}$, $R_{D^{(*)}}$, at different $q^2$ values.

- Other form factors ($B_s$, $B_c$ and $\Lambda_b$ decays) to perform semitauonic over semileptonic rates; $\Lambda_b \to p \ell \nu$ form factors from other group.

- $V_{cb}$ and $V_{ub}$, they are inputs for BR calculation in many rare decays.

- $B_{(s)}$ decay constant, even if at present the $B_s \to \mu^+ \mu^-$ BR is limited by experimental uncertainties, it will be key in the coming years to confirm new physics scenarios.

- $B \to K^{(*)}$ form factors; effect from unstable vector resonances in form factor predictions; form factors for higher states.

- Charm contributions in $b \to s \ell \ell$ transitions, maybe above the open-charm threshold to be checked against data.

# Conclusions

- Deviations from the Standard Model in the flavour sector have been found by LHCb and other experiments:

  * **Differential branching fractions:** $B^0 \to K^{(*)0}\mu^+\mu^-$, $B^+ \to K^{(*)+}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $B^+ \to \pi^+\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$

    $\to$ Affected by hadronic uncertainties in the theory predictions

  * **Angular analyses:** $B^0 \to K^{(*)0}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $B^0 \to K^{*0}e^+e^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$

    $\to$ Observables with smaller theory uncertainties

  * **Test of Lepton Flavour Universality :** $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ ; $B \to D^{(*)}\tau\nu$

    $\to$ Hadronic uncertainties in theory predictions cancel in ratios

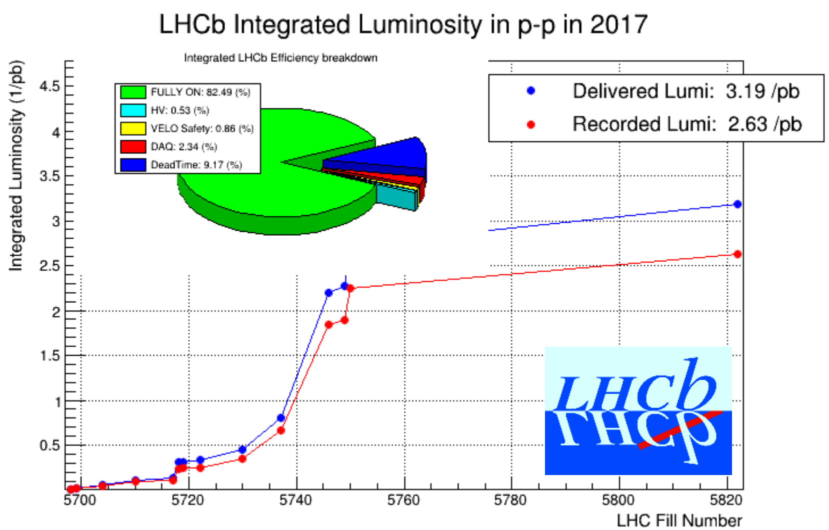
- Deviations show a consistent pattern in global fits, pointing to new physics in the Wilson coefficient $C_{9\mu}$, affecting differently to lepton families.

  $\to$ **Difficult to be explained by just experimental effects.**

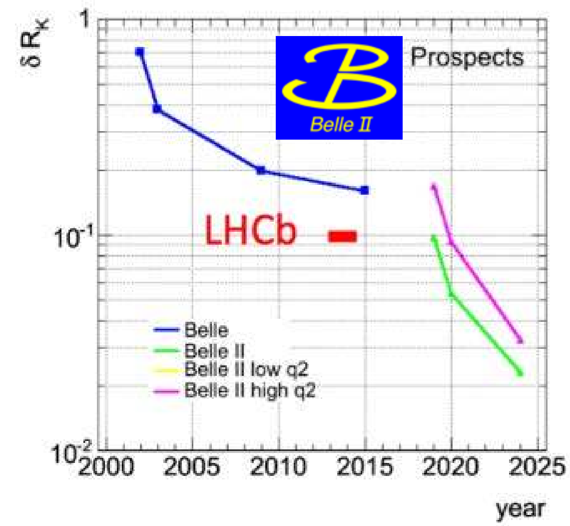
  $\to$ **Difficult to be explained by just QCD effects…**

# Conclusions

LHCb Run 2 in progress… (+ Upgrade)



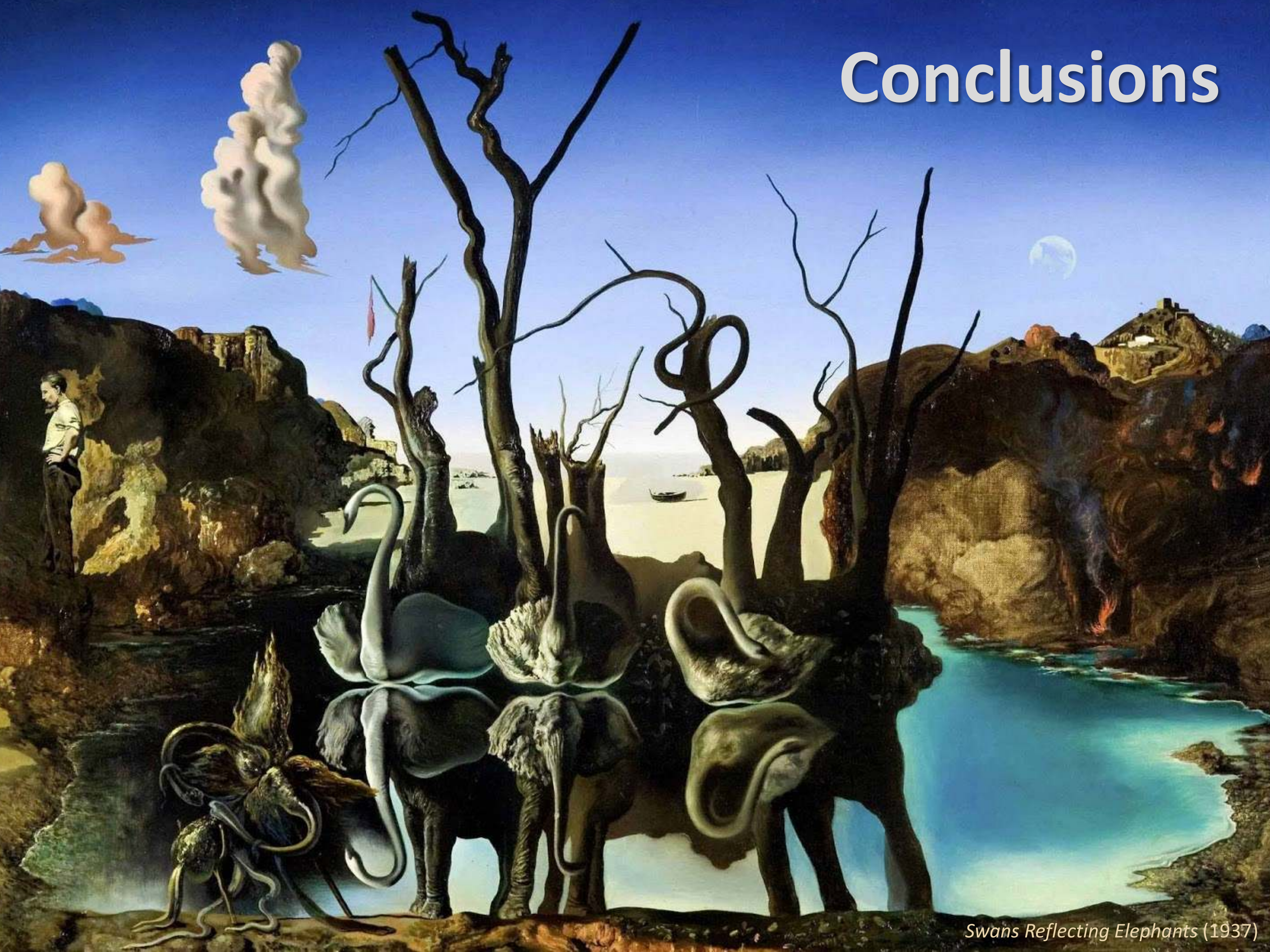

Belle II just to start …




And many new and interesting results from Lattice at this conference!

*Time is a great thickener of things…*

# Conclusions



*Swans Reflecting Elephants* (1937)


# Thanks!