Recent results from LHCb

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Outline

Main goal of this talk: **Show how precise LHCb measurements in b- and c-sectors make constraints on fundamental prameters of Standard Model (SM) and provide New Physics (NP) searches.**

- Standard Model (SM) and its difficulties
  - Cabibbo-Kobayashi-Maskawa (CKM) matrix, CP violation (CPV)
  - Why and where to find New Physics (NP)? MFV or not?
  - Power of indirect measurements
- LHCb setup (apparatus, physical program *etc.*)
- Selected results
  - Rare decays
  - Results which demonstrate tensions with SM predictions
  - Studies of the CKM parameters
  - Physics with *b*- and *c*-tagget jets.
- Summary and Outlook (what can be achieved after upgrade?)

Introduction

Standard Model (SM)

SM parameters before LHC:

$\alpha_s(M_Z)$	$0{,}114 \pm 0{,}0007$
$1/\alpha(M_Z)$	$127{,}916 \pm 0{,}015$
$\sin^2\theta_W(M_Z)$	$0{,}23108 \pm 0{,}00005$
Θ	$\lesssim 10^{-10}$
m_u (2 ГэВ)	$2{,}5^{+0{,}8}_{-1{,}0}$ МэВ
m_d (2 ГэВ)	$5{,}0^{+1{,}0}_{-1{,}5}$ МэВ
m_s (2 ГэВ)	105^{+25}_{-35} МэВ
$m_c(m_c)$	$1{,}266^{+0{,}031}_{-0{,}036}$ ГэВ
$m_b(m_b)$	$4{,}198 \pm 0{,}023$ ГэВ
$m_t(m_t)$	$173{,}10 \pm 1{,}35$ ГэВ
m_e	$510{,}998910 \pm 0{,}000013$ кэВ
m_μ	$105{,}658367 \pm 0{,}000004$ МэВ
m_τ	$1{,}77682 \pm 0{,}00016$ ГэВ
θ_{12}	$13{,}02^\circ \pm 0{,}05^\circ$
θ_{23}	$2{,}35^\circ \pm 0{,}06^\circ$
θ_{13}	$0{,}199^\circ \pm 0{,}011^\circ$
δ	$1{,}20 \pm 0{,}08$
$v(m_\mu)$	$246{,}221 \pm 0{,}002$ ГэВ
M_H	115,5– 127,0 ГэВ

Flavour sector of SM

Great success of ATLAS and CMS in determination of Higgs boson parameters.

No doubt that SM is great achievement!

(no large conflict with HEP, but some tension will be discussed in this talk)

Reasons for New Physics (NP):

1) Neutrino sector
   - mass
   - oscillations

2) Hierarchy of quark masses

3) Radiative correction to m_H
   - fine tuning
   - desert between M_{EW} and M_{GUT}

4) Astrophysics **(CPV is needed)**
   - dark matter
   - baryon asymmetry of Universe

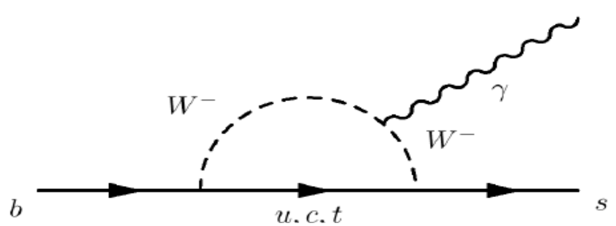
SUSY was considered as a good candidate to solve 2) &3)

Indirect measurements at LHC

- How NP related to flavour physics?
- Is NP weakly coupled to flavour sector (MFV) or at very high scale?

  Important to have a **probes beyond LHC energies** (direct observation)!
- Better to use processes which are either forbidden either highly suppressed in SM

  Flavour Changing Neutral Currents (FCNC) can be such a probe



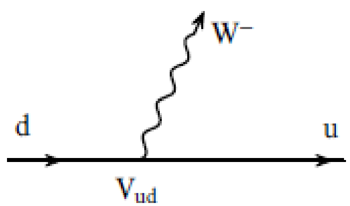
- **Many historical successful HEP examples (Kaon CPV→KM predictions of 3rd quark generation, neutral currents → Z-discovery, B-meson mixing → top quark mass scale)**
- **Direct searches are restricted by LHCb kinematics conditions, but they are possible!**
  (this talk: search for massive long-lived particles)

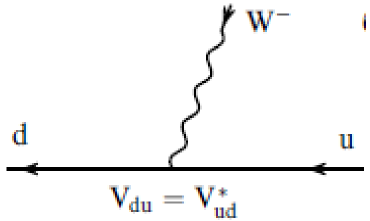
Cabibbo-Kobayashi-Maskawa

- **Flavour eigenstates do not coincide with weak eigenstates**
- **Mixing matrix V_{CKM}**
- **CP violating phase can appear if we have 3 generations of fermions**
- **Elements of the CKM matrix appear at the decay vertices**

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

$$A(d \to u) \propto i \frac{g_2}{2\sqrt{2}} \bar{u} V_{ud} \gamma_\mu (1 + \gamma_5) d \qquad A(u \to d) \propto i \frac{g_2}{2\sqrt{2}} \bar{d} V^*_{ud} \gamma_\mu (1 + \gamma_5) u$$





Wolfenstein parametrization to demonstrate CKM elements hierarchy

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4).$$

$$s_{ij} = \sin\vartheta_{ij},\ c_{ij} = \cos\vartheta_{ij} \qquad c_{13} = c_{23} = 1$$

$$s_{12} = \lambda\,, \quad s_{23} = A\lambda^2\,, \quad s_{13}\exp(-i\delta) = A\lambda^3(\rho - i\eta)$$

$$s_{12} = \lambda = 0{,}222 \pm 0{,}002\,, \quad s_{23} = O(10^{-2})\,, \quad s_{13} = O(10^{-3})$$

Unitarity triangles

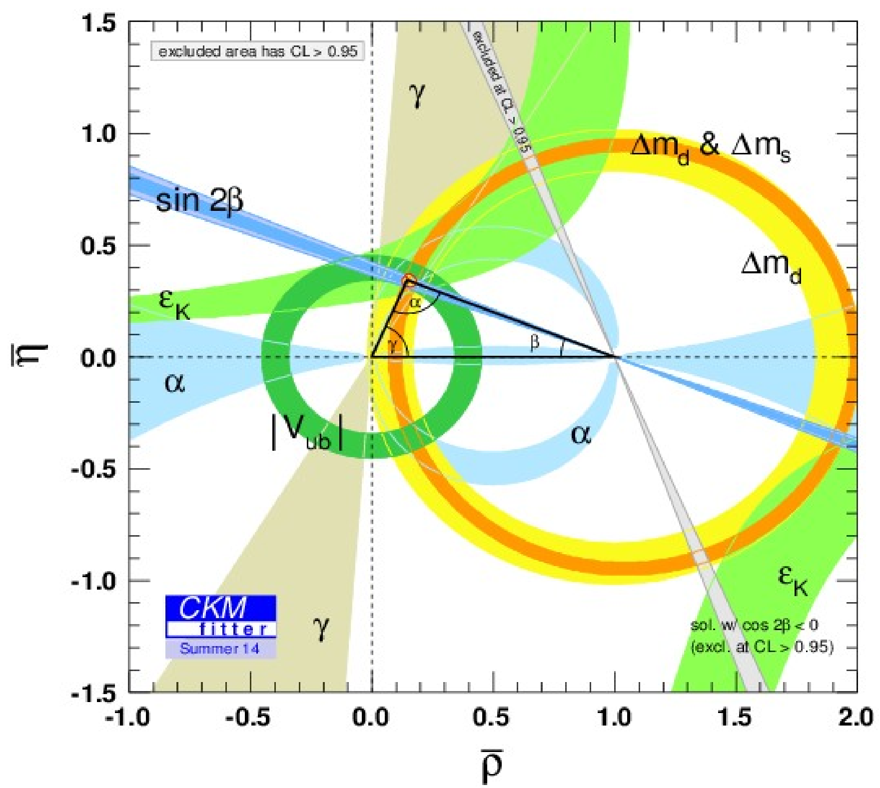
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0\,,$$
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0\,,$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0\,,$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0\,,$$
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\,,$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0\,.$$

$$O(\lambda) + O(\lambda) + O(\lambda^5) = 0$$

$$O(\lambda^2) + O(\lambda^2) + O(\lambda^4) = 0\,.$$

$$O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$$
$$A\lambda^3(1-\rho-i\eta) + (-A\lambda^3) + A\lambda^3(\rho-i\eta) = 0$$

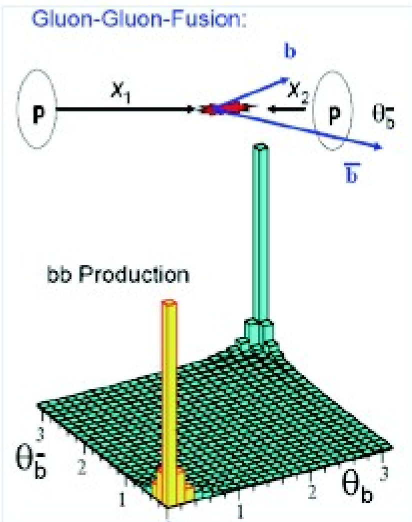
$$\bar\rho = \rho\left(1-\frac{\lambda^2}{2}\right), \quad \bar\eta = \eta\left(1-\frac{\lambda^2}{2}\right)$$



- **2 of 6 relations have all three contribution of same size**
- **Parameters of the triangle can be measured at the decay**
- **Contain experimentally known CPV source in SM.**
- **Can be drawn as triangle at the complex plane**
- **Many different experimental constraints**
- **In this talk will show LHCb results on $|V_{ub}|$, $\sin(2\beta)$, γ**
- **Other triangles are also very important**
- **Unitarity of CKM => $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$**

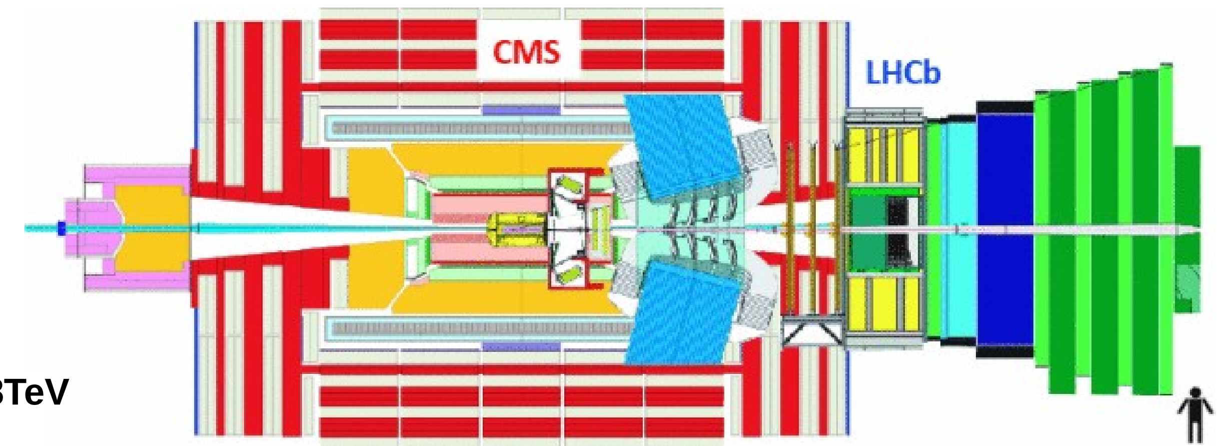
LHCb features

Beauty and charm production

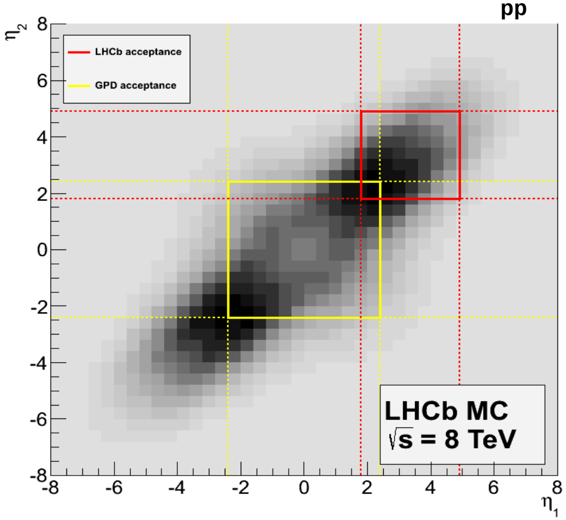


- **LHCb: forward spectrometer** $2 < \eta < 5$

  (ATLAS & CMS: $|\eta|<2.5$)



$\sqrt{s}_{pp}$ =8TeV



- In LHCb acceptance (*pp*-collisions √s = 7TeV)

$$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0\ \mu b$$

Phys.Lett.B694 (2010) 209-216

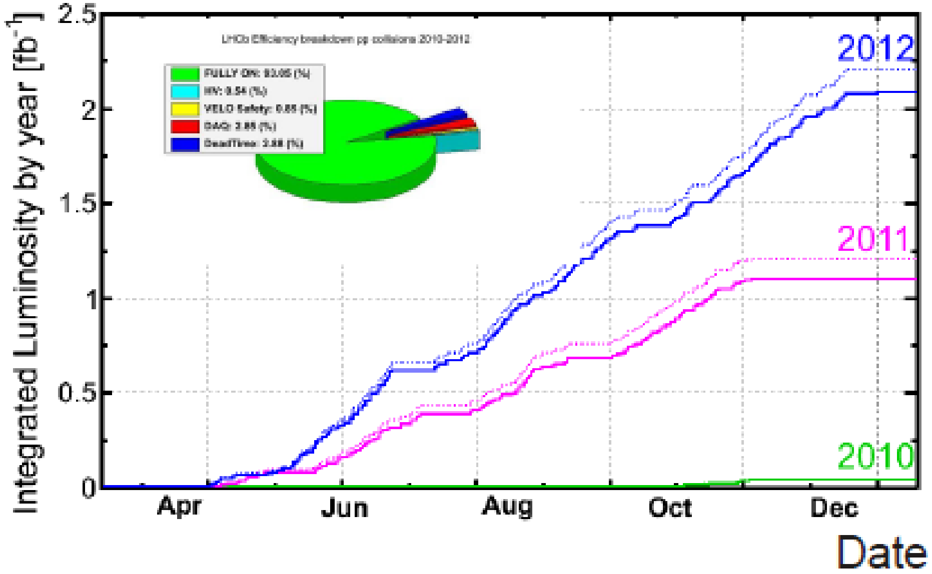
$$\sigma(c\bar{c}) = 1419 \pm 12 \pm 116\ \mu b \sim 20 \times \sigma(b\bar{b})$$

Largest charm samples in the world

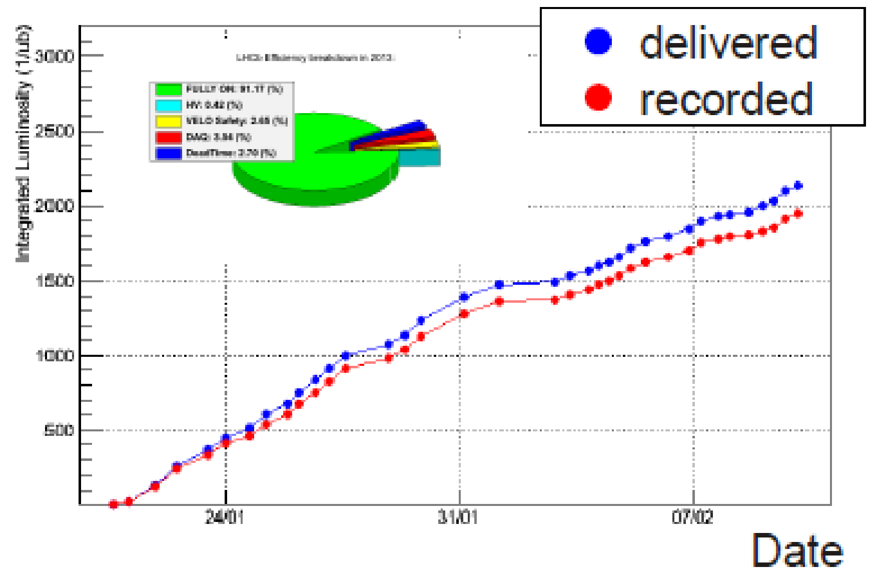
Nucl.Phys.B871 (2013) 1

Operation in 2010/12

***pp*-collisions at √s = 7 & 8 TeV (2011-12)**



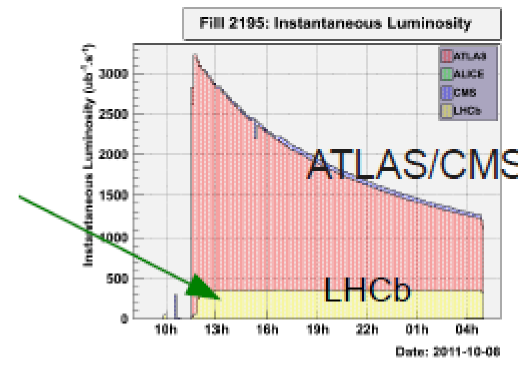
***p*Pb-collisions at √s$_{NN}$ = 5 TeV in 2013**



- **High recording efficiency**
- **50 ns between bunch crossings**

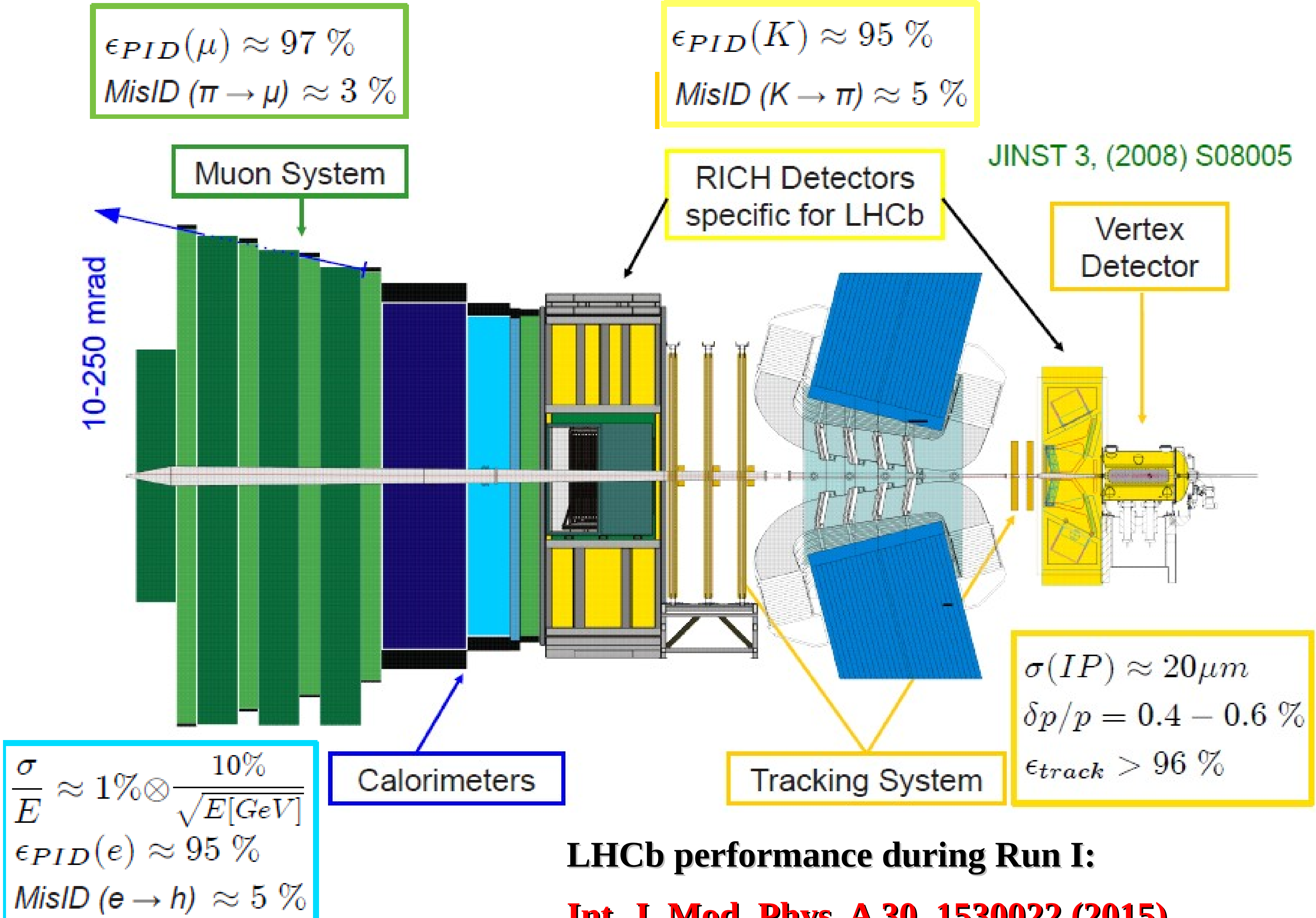
  (will try 25 ns this year)
- **Constant luminosity of ~$4 \cdot 10^{32}$ cm^{-2}s^{-1}**

  (twice higher than design luminosity)
- **1.7 visible interaction per bunch crossing**



LHCb also has set of *pp* data at √s =2.76 TeV (collected in 2011)

Experimental setup



LHCb performance during Run I:

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

LHCb data analysis

Efficient trigger (L0/HLT1/HLT2):

40MHz → 5kHz

Tagging if needed

Event selection

Kinematical and topological info
(p_T, p, IP, vertex and track quality)

PID information

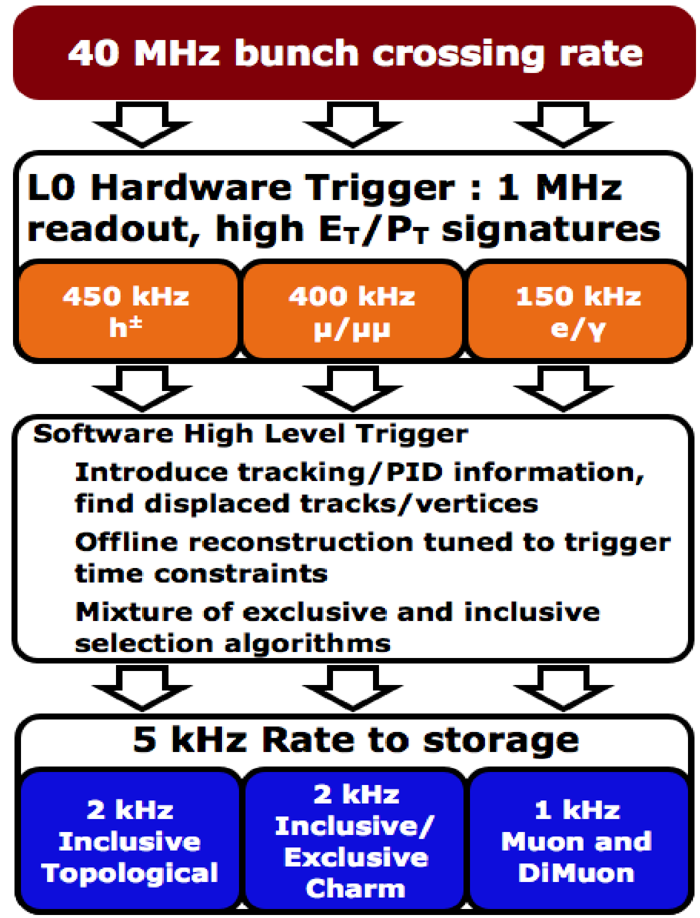
Cut based or multivariate selection
BDT, Neurobayes, *etc.*

Optimization of selection
Using MC
Using small sample of real data

Angular analysis++

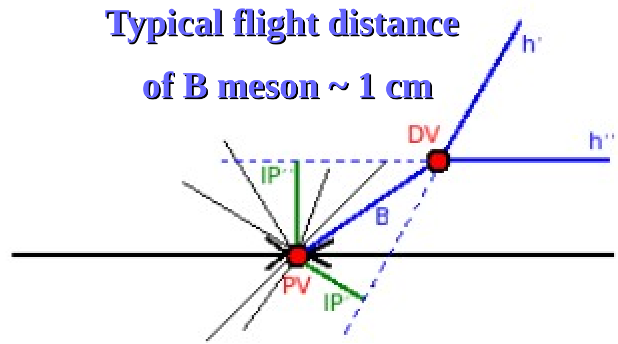
Check for systematics

And a lot of other checks!



Trigger

Typical flight distance of B meson ~ 1 cm



Selection using SV/PV separation:

PV = Primary Vertex

DV = Daughter Vertex

(secondary vertex SV)

Physics program of LHCb

GOAL: **Search for evidence of NP in CP violation and rare decays of beauty and charm hadrons.**
(Probing large mass scales *via* study of virtual quantum loops of new particles)

LHCb results are available in more that 260 papers submitted to journals and 120 conference contributions

https://cds.cern.ch/collection/LHCb%20Conference%20Contributions?ln=en
https://cds.cern.ch/collection/LHCb%20Papers?ln=en

Main direction of searches:

1) **Rare decays**
   RD with di-muons
2) **Properties of the B systems**
   CPV, Δms; Γs, ΔΓ, ϕs ; CKM β, γ, $|V_{ub}|$ determination
3) **Mixing and CPV in the D mesons**
   Mixing observ., ΔA(CP)

In this talk!

4) **Spectroscopy and production of heavy quarks + Exotics**

5) **Electroweak physics** (top quark in fd.region, W+c-/b-jet)

6) **Soft QCD physics, pA and Ap results**

Rare decays and test of lepton universality

1) $B_{s,d}^0 \rightarrow \mu^+\mu^-$

2) $B^0 \rightarrow K^*\mu^+\mu^-$

3) $B^+ \rightarrow K^+\mu^+\mu^- / B^+ \rightarrow K^+e^+e^-$

4) $B_s^0 \rightarrow \varphi\mu^+\mu^-$

5) $\overline{B}^0 \rightarrow D^*\tau\overline{\upsilon}$

NP and flavour symmetry; Wilson's coefficients

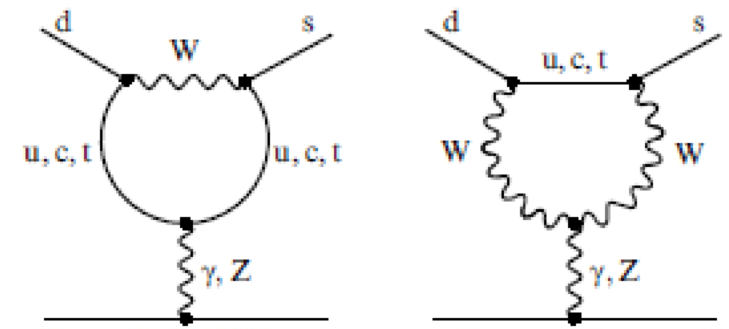
- **Progress of theory calculations allows to take into account QCD corrections needed for SM FCNC implementation to decays. (Calculation of C_i in SM as well as quite precise predictions for certain processes)**
- **H_{eff} is an effective way to test different classes of possible NPs, because C_i depend on their flavour structures.**
- **Minimal Flavour Violation (MFV) paradigm: NP has same source of FV as SM => real numbers, same CPV effects, relations like:**

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}$$

$\Delta F = 1$ operators in the SM and in MFV

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \mathrm{h.c.}$$

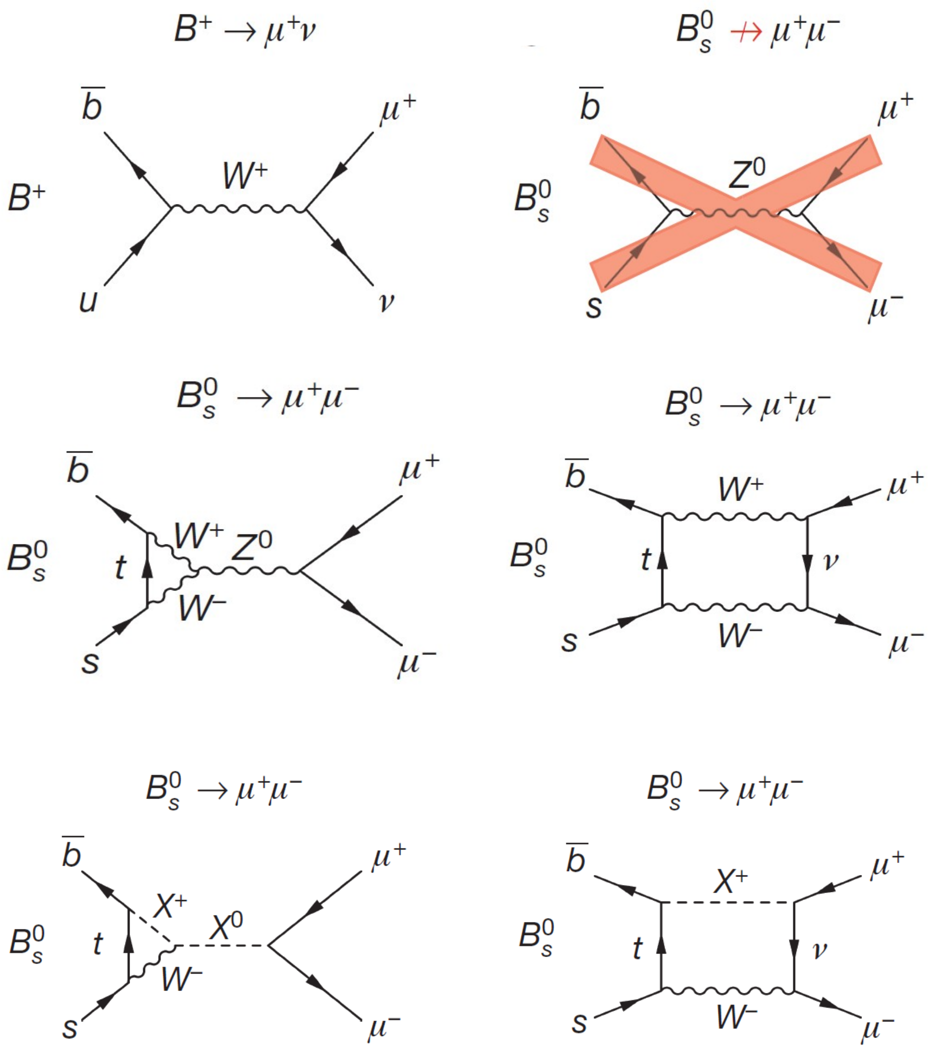
Example



$O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$ $\quad$ $O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

- **If NP contains additional FV sources of C_i become complex as well as new CPV effects might appear!**

Rare decays $B_{(s)}^{0} \to \mu^{+}\mu^{-}$



– **Helicity suppressed in SM**

– **$\Delta\Gamma_s$ correction [PRD 86, 014027]**

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

Bobeth et al. Phys. Rev. Lett 112 (2014) 101801

5% precision SM calculations!

Ratio is power discriminator as well

$$\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} / \mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = 0.0295^{+0.0028}_{-0.0025}$$

Sensitive to new scalar, pseudoscalar, axial-vector particles in loops

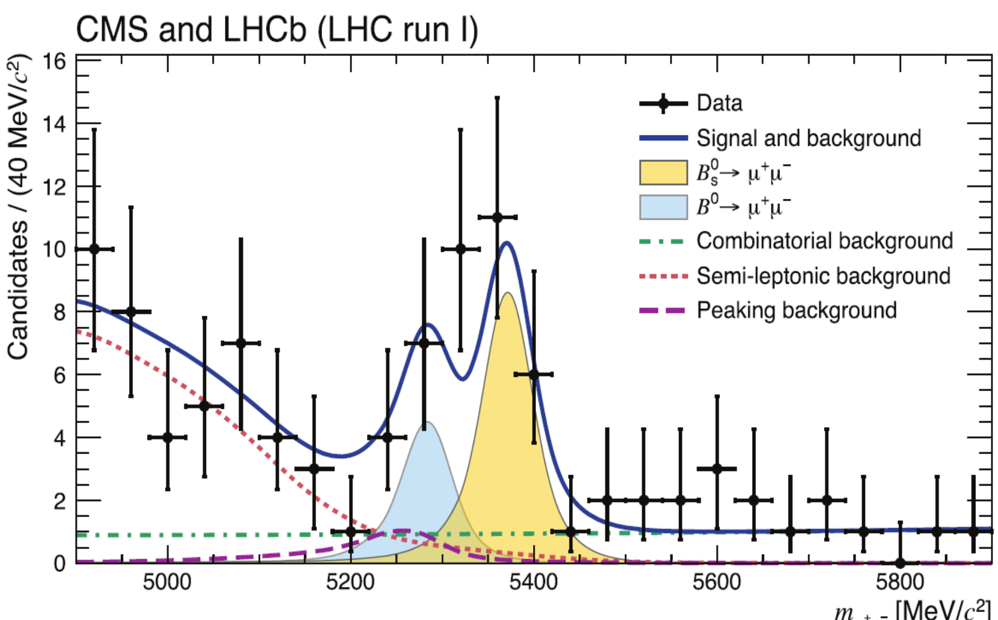
In MSSM:

$$c_{S,P}^{MSSM\,2} \propto \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$$

OPEN
doi:10.1038/nature14474

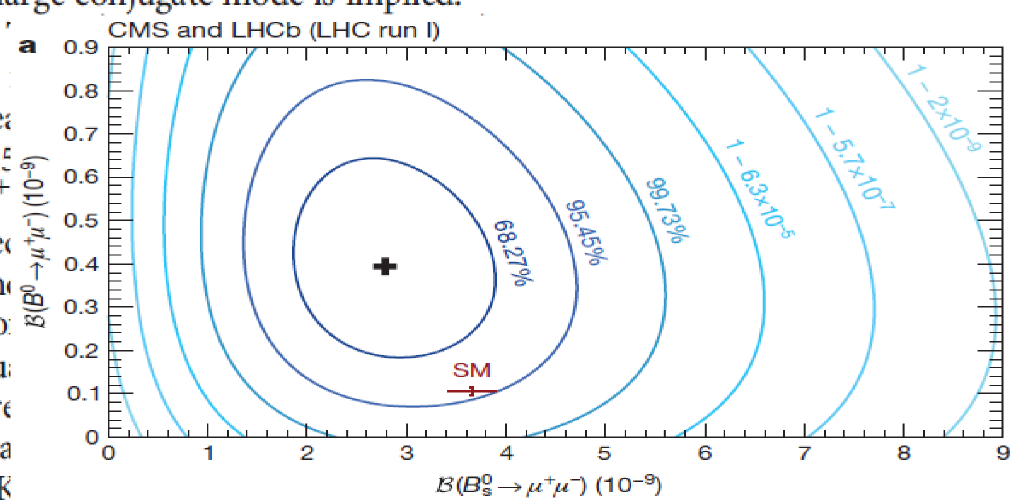
Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*

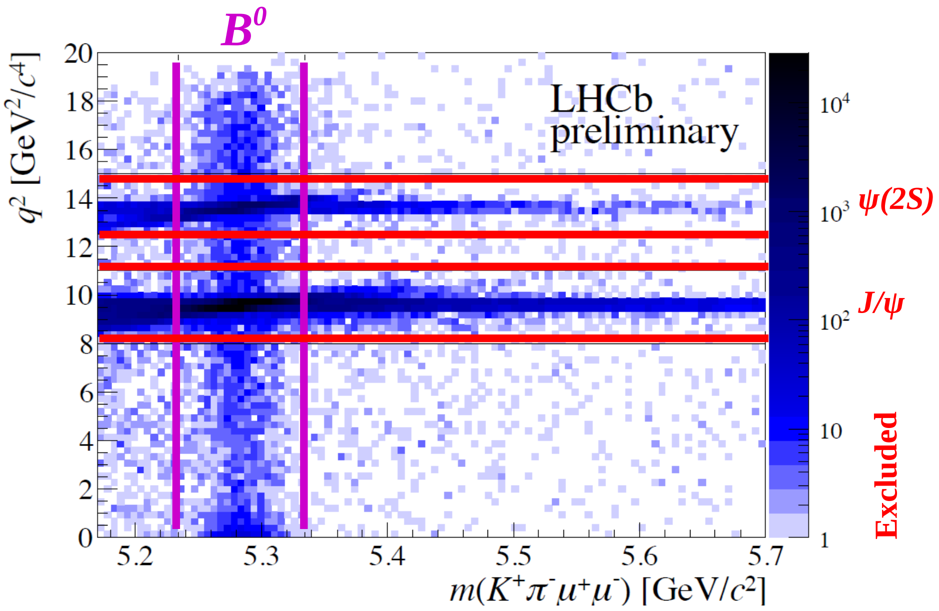


at CERN started operating, no evidence for either decay mode had been found. Upper limits on the branching fractions were an order of magnitude above the standard model predictions. The CMS (Compact Muon Solenoid) and LHCb (Large Hadron Collider beauty) collaborations have performed a joint analysis of the data from

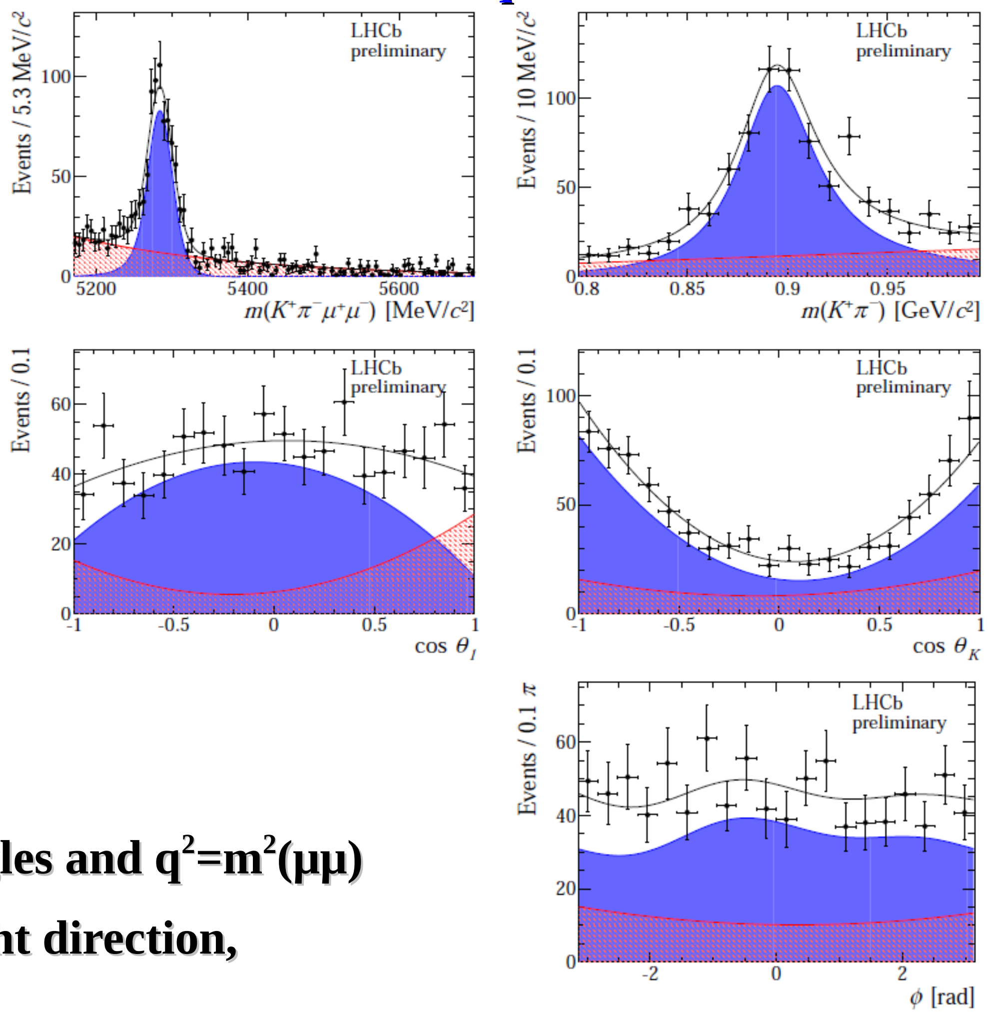
respectively. An example of the charged current is the decay of the π^+ meson, which consists of an up (u) quark of electrical charge $+2/3$ of the charge of the proton and a down (d) antiquark of charge $+1/3$. A pictorial representation of this process, known as a Feynman diagram, is shown in Fig. 1a. The u and d quarks are 'first generation' or lowest mass quarks. Whenever a decay mode is specified in this Letter, the charge conjugate mode is implied.



Analysis of $B^0 \rightarrow K^*\mu^+\mu^-$



Fit result for $1 < q^2 < 6$ GeV^2/c^4



- **Loose preselection cuts**
- **Using BDT trained on proxy $B \rightarrow K^*J/\psi$**
- **Background from upper B sideband**
- **Choice of variables to avoid biases on angles and $q^2=m^2(\mu\mu)$**
- **Final selection from BDT decay time, flight direction, trk/vtx quality, p_T, PID**

[LHCb-CONF-2015-002]

Analysis of $B^0 \to K^*\mu^+\mu^-$

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

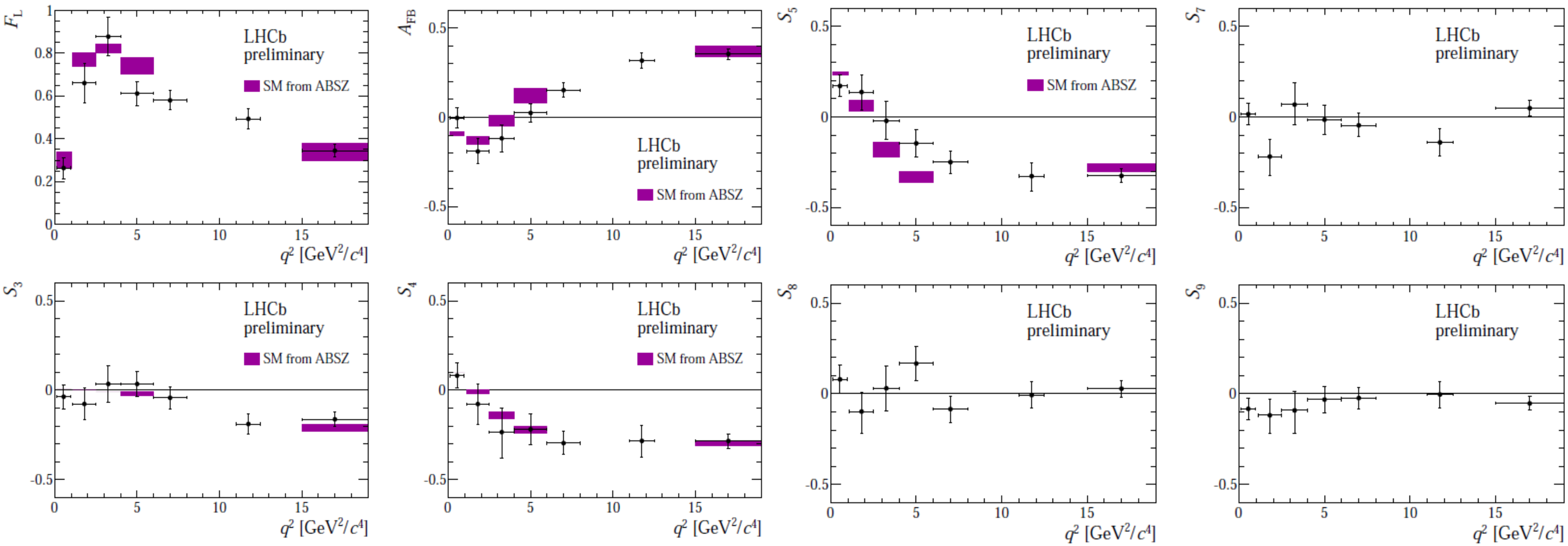
– **three angles + q^2 to describe data**

– **F_L, A_{FB} & S_i bilinear combinations of amplitudes**

(short-distance interaction + hadronic form factors)

– **Precise theoretical calculations**

Altmannhofer, Bharucha, Straub, Zwicki [1503.05534][1411.3161]

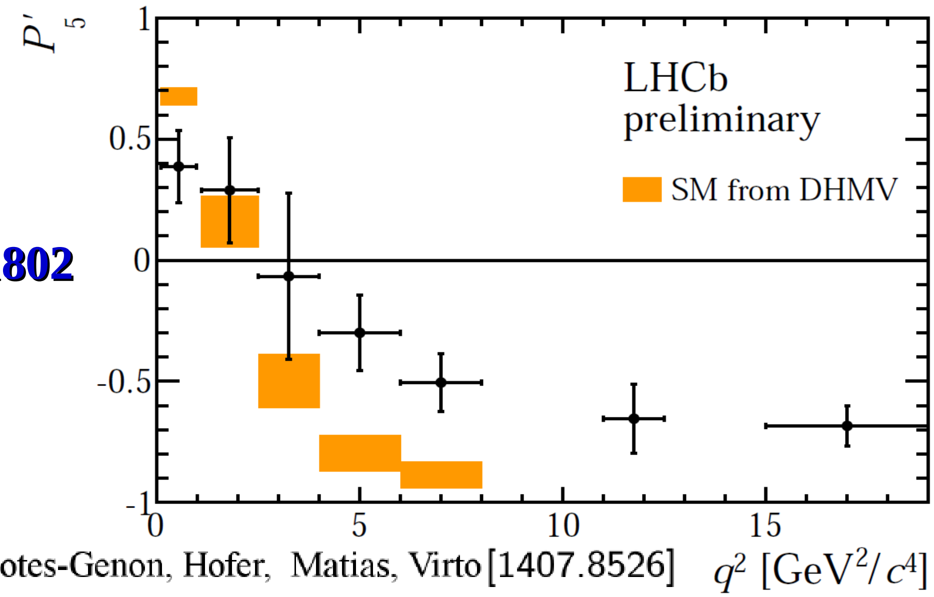


[LHCb-CONF-2015-002]

Analysis of $B^0 \to K^*\mu^+\mu^-$

[LHCb-CONF-2015-002]

- $P'_{4,5} = S_{4,5} \cdot [F_L \cdot (1-F_L)]^{-1/2}$
- **Less dependent on form factor**
- **Consistent with previous result PRL 111, 191802**
- **2.9σ deviation for [4,6] and [6,8] GeV²/c⁴ bin**
- **Naive combinations 3.7σ local significance**

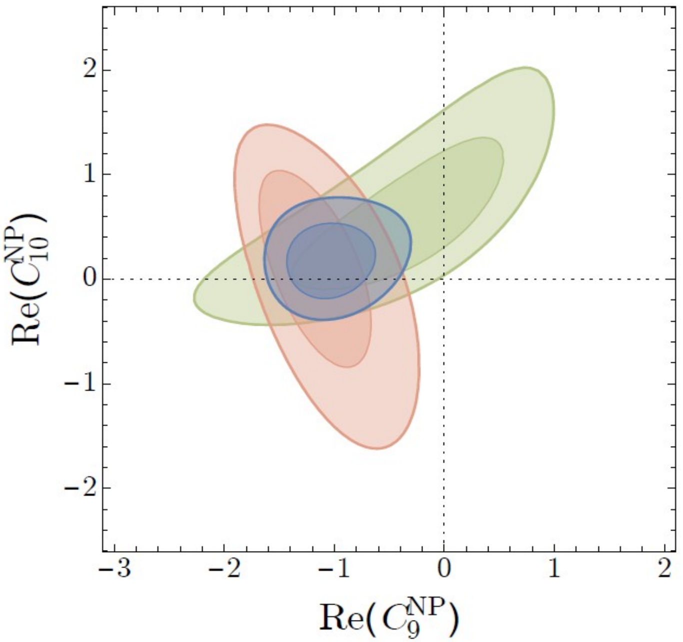


SM from Descotes-Genon, Hofer, Matias, Virto [1407.8526]

What theory can say about $B^0 \to K^*\mu^+\mu^-$?

- **Global fit of the available $b \to s\gamma$ & $b \to sll$**
- $C_9^{NP} = -1.5$, **4.5σ deviation from SM**
- **Matias, Descotes-Genon, Vitro: PRD 88, 074002**

- **Straub, Altmannshofer: EPJC 73, 2646,**
- **arXiv:1503.06199 (3fb^{-1} result is discussed)**
- **3σ discrepancy, modification of C_9 needed**
- **Possible solution – flavour changing Z'**



arXiv:1503.06199

LHCb results which are in tension with SM predictions

Test of lepton flavour universality

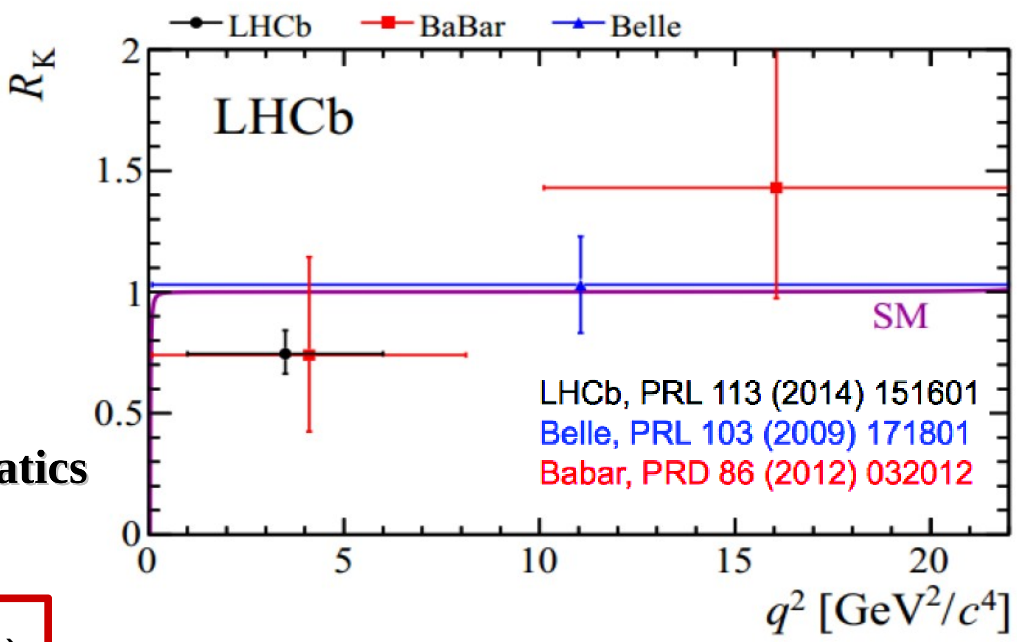
- **In Standard Model**

$$R_K = \frac{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2)\mathrm{d}q^2}{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+e^+e^-]/\mathrm{d}q^2)\mathrm{d}q^2} = 1 \pm \mathcal{O}(10^{-3})$$

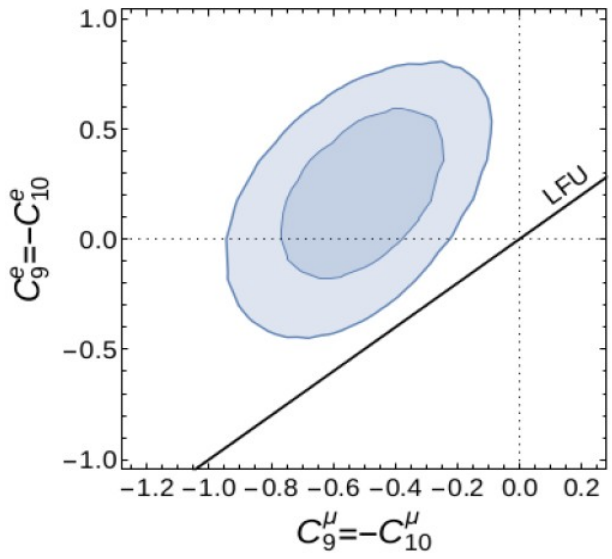
- **Event migration (MC)**
- **Bremsstrahlung**
- **Double ratio with $B^+ \to J/\psi K^+$ to cancel systematics**
- **3/fb dataset**

$$R_K = 0.745^{+0.090}_{-0.074}(stat.)^{+0.036}_{-0.036}(syst.)$$

- **Deviation from SM expectation at 2.9σ level**

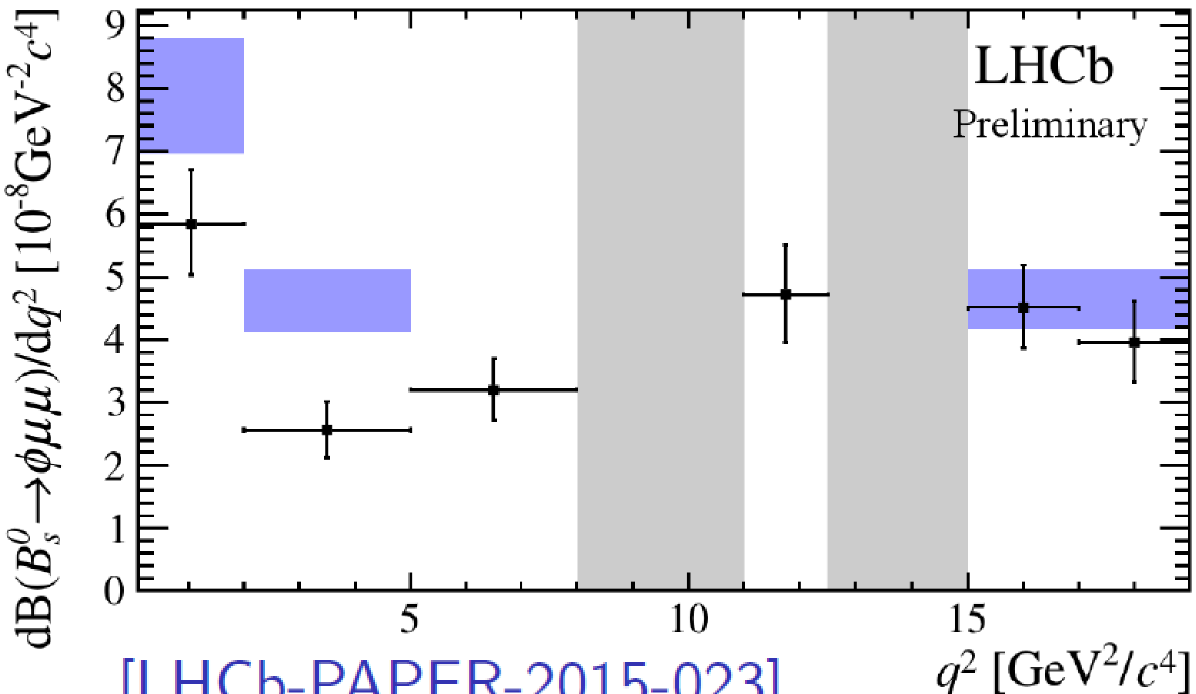


- **QCD can't explain NON-LFU**
- **Non universal Z' can produce such effect**
- **Ghosh et al. arXiv:1408.4097**
- **Such explanation in agreement with P_5' anomaly**



Analysis of $B_s^0 \to \varphi\mu^+\mu^-$

- **Analysis similar to $B^0 \to K^*\mu\mu$**
- **No sensitivity to P'_5**
- **Measurement of branching fraction and angular analysis**
- **Theory: arXiv:1411.3161, 1503.05534**
- **New analysis confirms tension in 1fb^{-1} dataset analysis JHEP 07 (2013) 084**
- **Extrapolation to full q^2 range** (using PRD 66, 034002 & PRD 71, 014029)

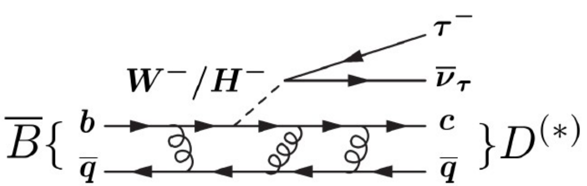


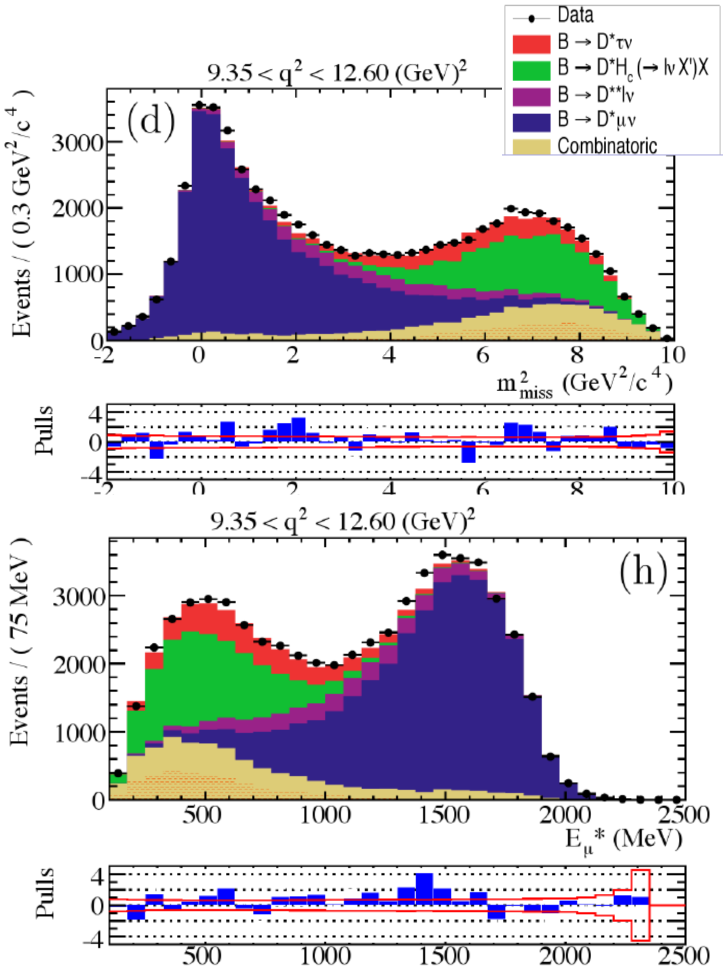
[LHCb-PAPER-2015-023]

$$\frac{\mathcal{B}(B_s^0 \to \phi\mu\mu)}{\mathcal{B}(B_s^0 \to \phi J/\psi)} = (7.40^{+0.42}_{-0.40} \pm 0.20 \pm 0.21) \times 10^{-4}$$

$$\mathcal{B}(B_s^0 \to \phi\mu\mu) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7}$$

Analysis of $\bar{B}^0 \to D^* \tau \bar{\upsilon}$





LHCB-PAPER-2015-025

– **Measurement of the ratio:**

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

– **Theoretically clean**

– **Sensitive to charged Higgs or non-MFV couplings favoring τ.**

– **No narrow signal structures for signal, many bkg.**

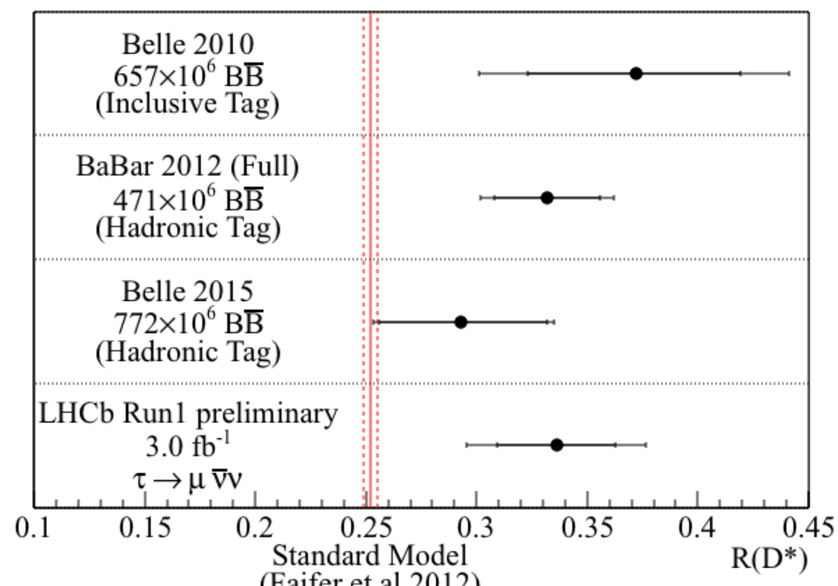
– **Isolation technique against partially reco. bkg.**

– **Shapes are taken from simulation, validated against data**

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

– **Agreement with SM at 2.1σ**

– **Main systematic comes from the size of simulated sample**

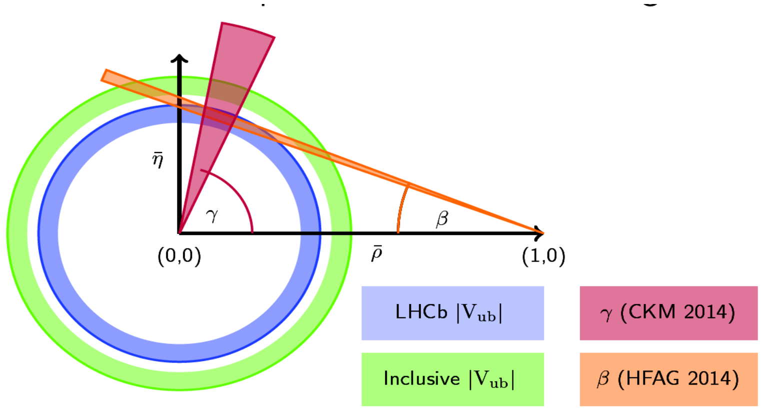


CKM studies

1) $|V_{ub}|$ determination

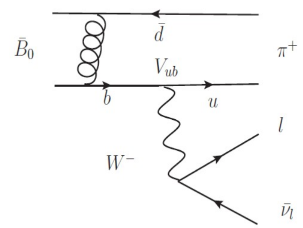
2) Measurement of sin(2β)

+ reminder about LHCb -measurement of γ

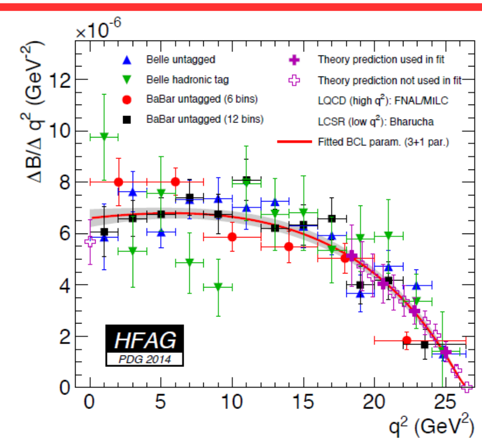


$|V_{ub}|$ measurement

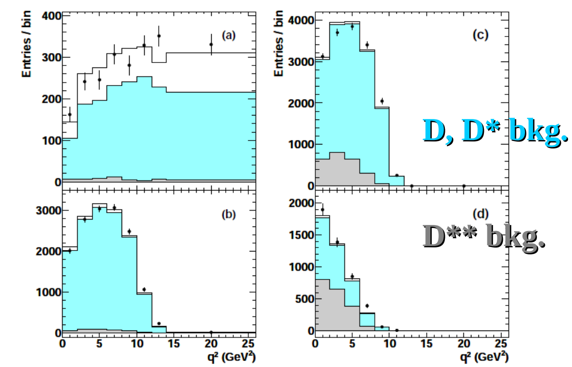
- $|V_{ub}|$ has largest fractional uncertainty among all other CKM elements
- Discrepancy between **exclusive ($B \rightarrow \pi l \upsilon$)** and **inclusive (any $b \rightarrow u l \upsilon$)** determination of $|V_{ub}|$



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2 p_\pi^3}{24\pi^3} |f^+(q^2)|^2$$

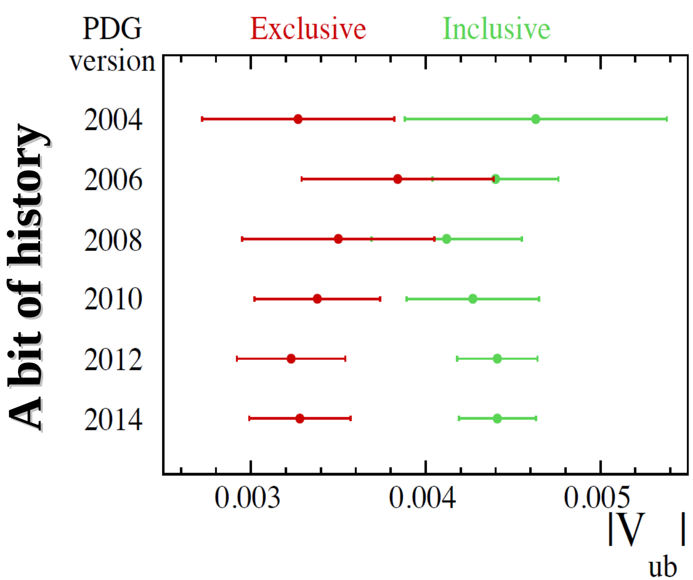


$$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$$



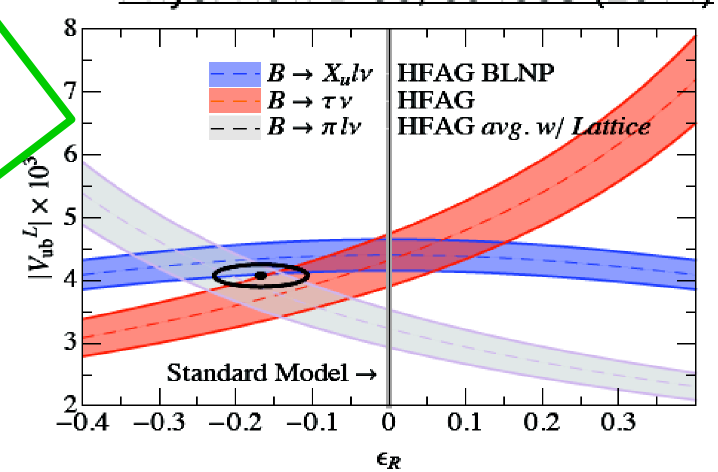
Fit for four M_X bins (BaBar, PRD86, 032004)

$$|V_{ub}| = (4.41 \pm 0.15 \, {}^{+\,0.15}_{-\,0.17}) \times 10^{-3}$$



A negative right-handed V+A current was considered as a possible puzzle solution

Phys. Rev. D 90, 094003 (2014)



$|V_{ub}|$ measurement

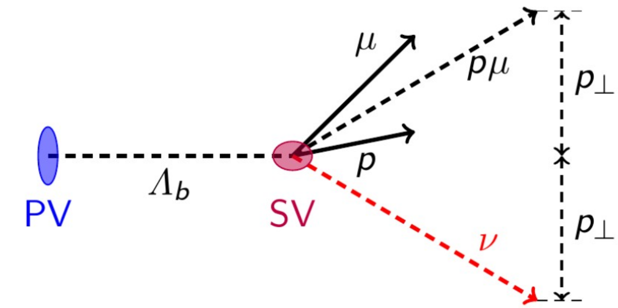
- **LHCb measures ratio:**

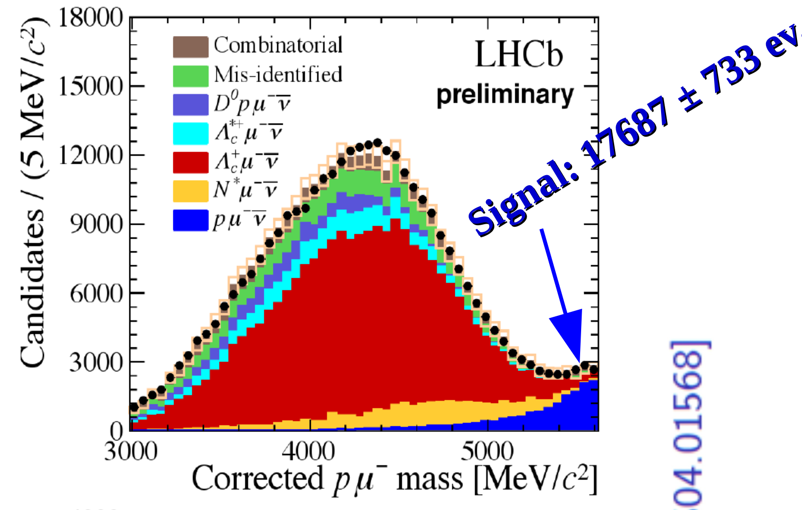
$$\mathcal{B}\left(\Lambda_b^0 \to p\mu\nu\right) / \mathcal{B}\left(\Lambda_b^0 \to \Lambda_c(\to pK\pi)\mu\nu\right)$$

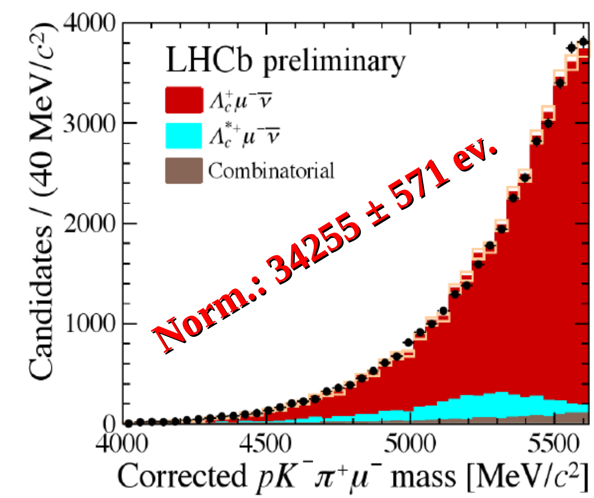
- **Sensitive to $|V_{ub}| / |V_{cb}|$**
- **Direct Lattice QCD calculation gives sufficient precision for high q^2 [arXiv:1503.01421]**
- **Corrected mass is good discriminating variable**

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

- **Two solutions for q^2, bin migration problem both required to be > 15 GeV^2/c^4**
- **Isolation technique sensitive to the extra tracks close to SV for background reduction**
- **Main systematics from: $\Lambda_c \to pK\pi$ BF and decay model, trigger and tracking efficiency**







[arxiv:1504.01568]

$|V_{ub}|$ measurement

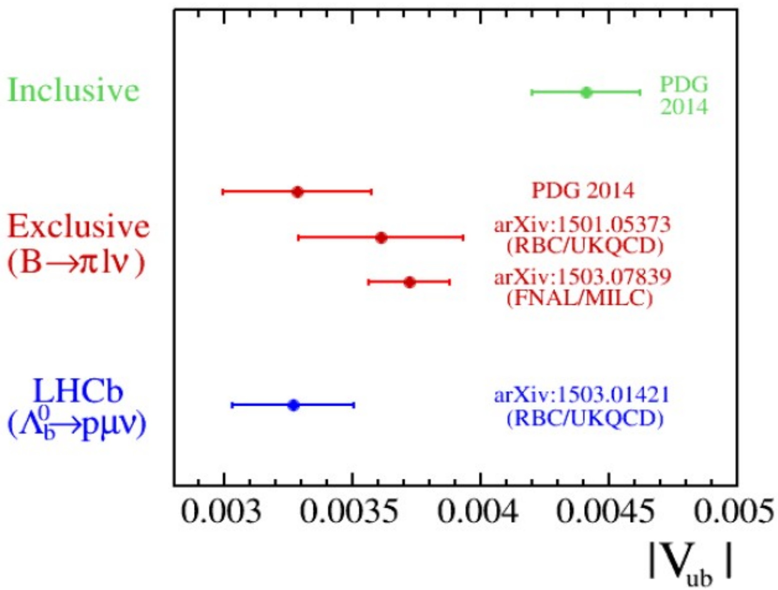
[arxiv:1504.01568]

– **Measured ratio is:**

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

– **Using exclusive measurement of the $|V_{cb}|$:**

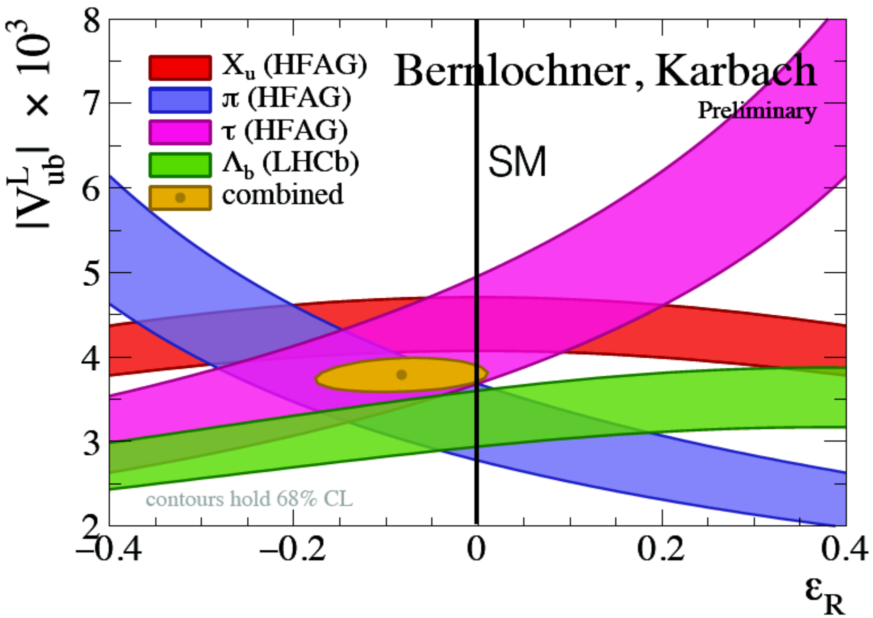
$$|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3}$$



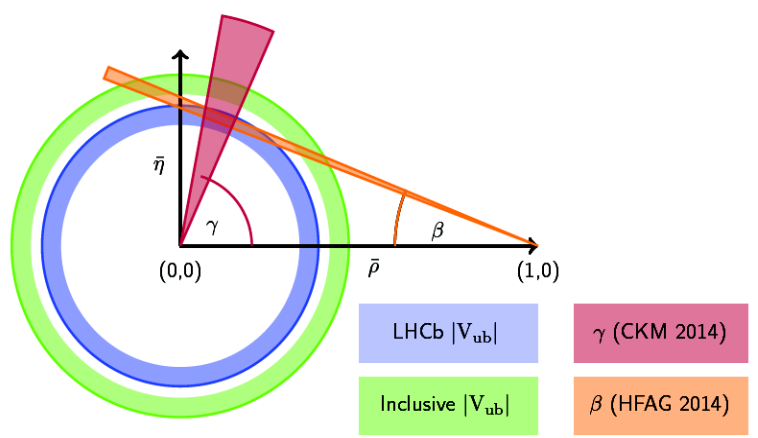
– **3.5σ tension to the inclusive measurements**

– **Right-handed current hypothesis is in trouble**

χ^2/ndf = 2.8 / 1, p-value=9% → 16.0/2 , 0.03%



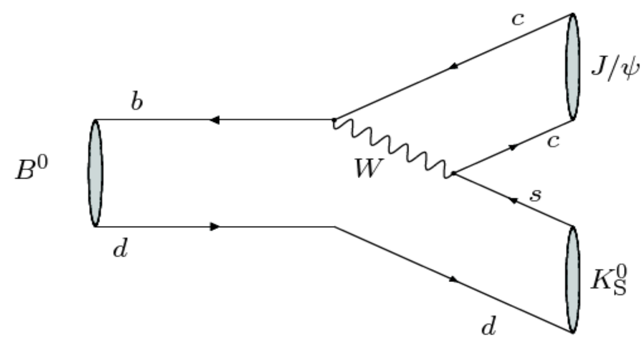
Other CKM parameters:



LHCb measurements of sin(2β)

– ***$B^0 \to J/\psi K_s^0$*** **is tree-level dominated decay,**

negligible contribution from penguins



$J/\psi \to \mu^+\mu^-$

$K^0_s \to \pi^+\pi^-$

– **Time dependent CP asymmetry to measure:**

$$\mathcal{A}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_{\rm S}) - \Gamma(B^0(t) \to J/\psi\, K^0_{\rm S})}{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_{\rm S}) + \Gamma(B^0(t) \to J/\psi\, K^0_{\rm S})} = \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\frac{\Delta\Gamma\, t}{2}) + A_{\Delta\Gamma}\sinh(\frac{\Delta\Gamma\, t}{2})}$$

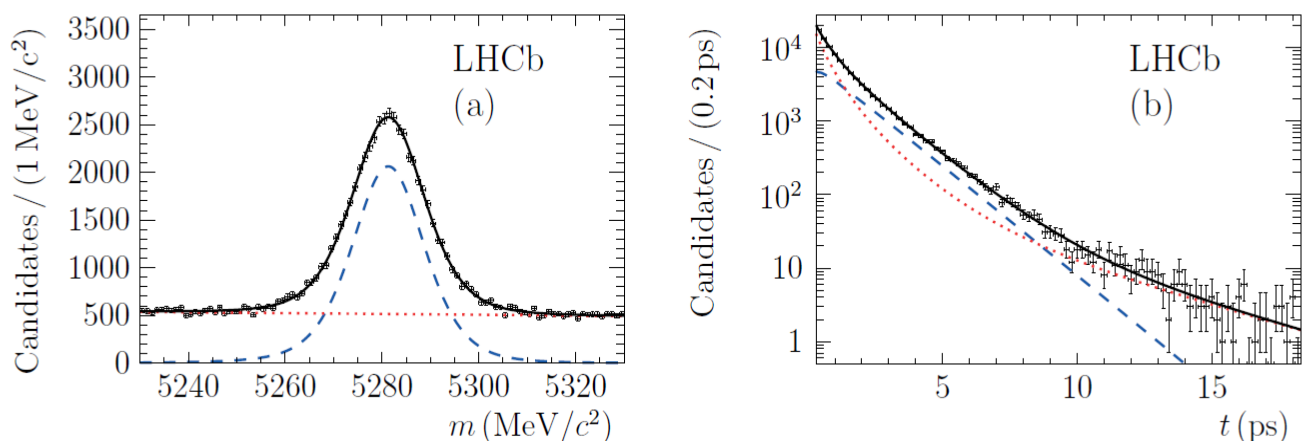
– **For *B^0* mesons $\Delta\Gamma \approx 0$ => two CP observables:**

$$\mathcal{A}(t) = S\sin(\Delta m\, t) - C\cos(\Delta m\, t)$$

– **$S \approx \sin(2\beta)$**

– **Good tagging is required**

– **41 560 ± 270 signal events**

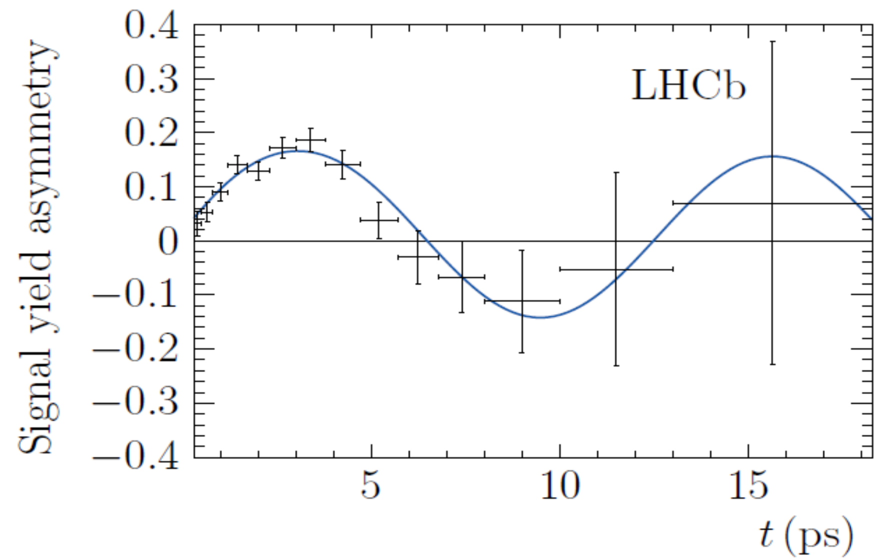


arXiv:1503.07089

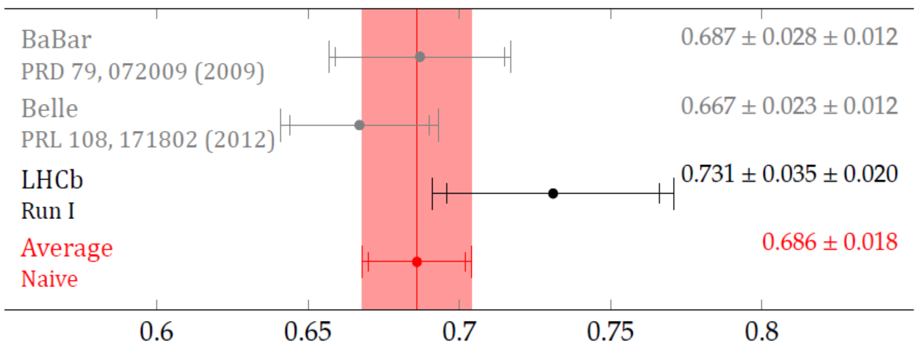
LHCb measurements of sin(2β)

- **arXiv:1503.07089** ***$B^0 \to J/\psi K_s^0$***
- **Multidimensional PDF includes reconstructed mass, decay time, flavour tagging**
  ε_{tag}=36.5%, ω_{miss} = 35.6%

$$S = 0.731 \pm 0.035\,(\mathrm{stat}) \pm 0.020\,(\mathrm{syst}),$$
$$C = -0.038 \pm 0.032\,(\mathrm{stat}) \pm 0.005\,(\mathrm{syst}),$$



- **Consistent with Belle and BaBar results**
- **Most precise time-dependent CPV measurement at hadron machine!**

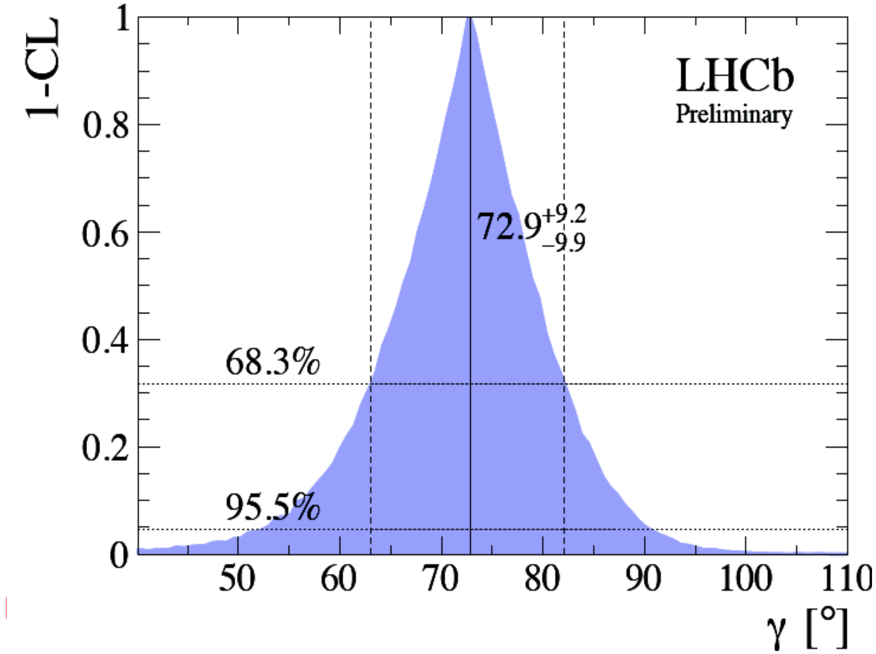


- **See also arXiv:1503.07055** ***$B_s^0 \to J/\psi K_s^0$***
- **Is used to constrain penguin contributions, which are enhanced for this decay since it is CKM suppressed**

$$\mathcal{A}_{\Delta\Gamma}\left(B_s^0 \to J/\psi\, K_S^0\right) = 0.49 \pm {}^{0.77}_{0.65}\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})$$
$$C_{\mathrm{dir}}\left(B_s^0 \to J/\psi\, K_S^0\right) = -0.28 \pm 0.41\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})$$
$$S_{\mathrm{mix}}\left(B_s^0 \to J/\psi\, K_S^0\right) = -0.08 \pm 0.40\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})$$

Don't forget about LHCb measurements of γ

- **LHCb-CONF-2014-004**
- **γ is the only UT angle that can be directly Measured at tree-level**
- **Many channels to study**
  - **Interference between D and D-bar**
  - **A lot of D final states**
- **Combined results from several analyses sensitive to γ**

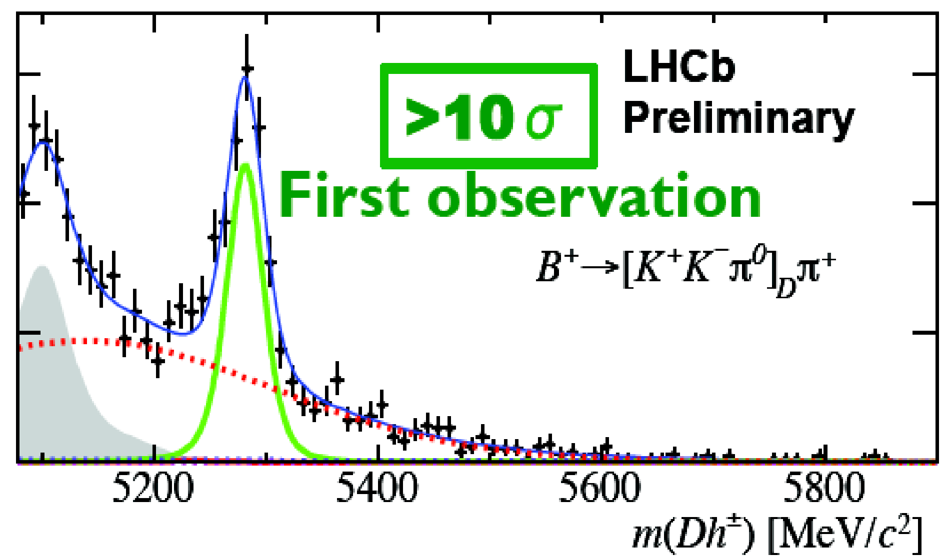


DK only (68% CL)

$$\gamma = (73^{+9}_{-10})^\circ$$

$$r_B = 0.091^{+0.008}_{-0.009}$$

$$\delta_B = (127^{+10}_{-12})^\circ$$



- **Consistent with Belle and BaBar results**
- **More precise than B factories!**
- **Negligible theoretical uncertainty (~10^{-6})**
- **NEW: LHCb-PAPER-2015-014 for $B^\pm \to [hh\pi^0]_D h^\pm$**
  - **First evidence of $B^+ \to [K^+K^-\pi^0]_D K^+$**
  - **First observation of $B^+ \to [K^+K^-\pi^0]_D\pi^+$**

Physics with *b*-tagget jets

1) Top quark production in forward region

2) Direct search for massive long-lived particles

A bit about *c*- and *b*-jets tagging.

Jet ID: anti-k_T algo with a distance parameter 0.5.

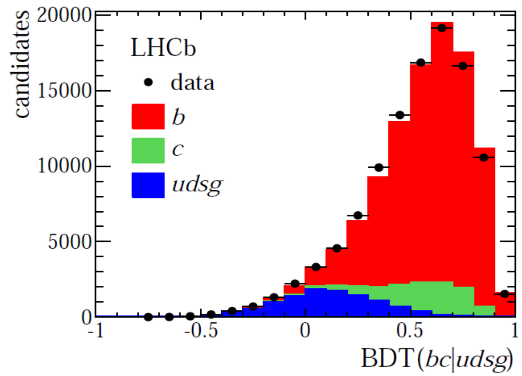
Particle flow approach → charged & neutral particle inputs.

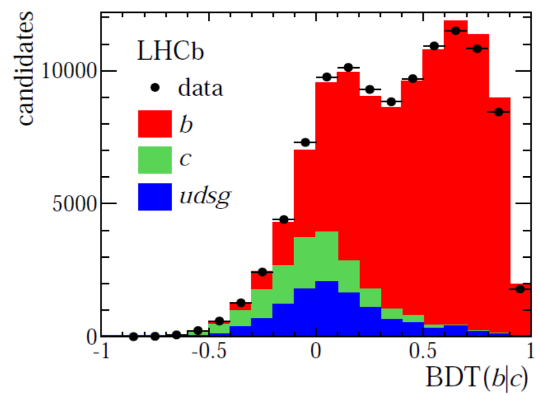
SV-tagger algorithm:

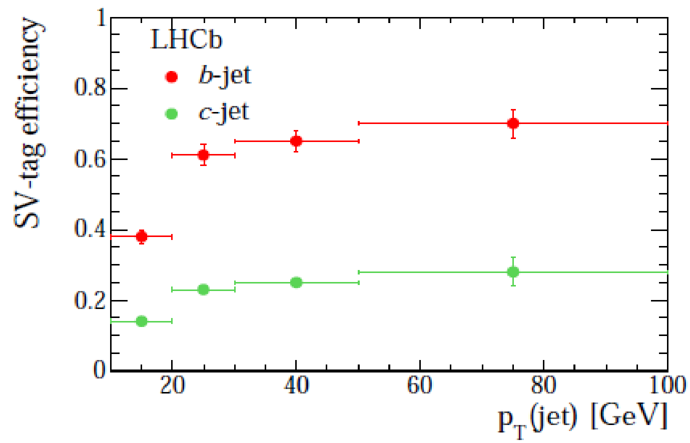
- **Displaced: χ^2_{IP}>16; High p_T > 0.5 GeV/c**
- **Inclusive 2-body vertexing:**
  - **DOCA<0.2 mm, χ^2_{vertex}<10**
  - **0.4 < m_{vertex} < m_{B0} (all particles assigned to π)**
  - **ΔR(PV-SV, jet) < 0.5**
- **Merge into n-body**
  - **Not more than 1 track with ΔR(trk,jet) < 0.5**
  - **p_T > 2 GeV/c, Flight-Distance-χ^2 > 5σ**
  - **(PV-SV)/p < 1.5 mm/GeV**
- **BDT(bc|udsg), BDT(b|c) *M, M_{cor}, FD_T^{SV}, ΔR(SV,jet), N_{trk}^{SV}, N_{trk}^{SV}(ΔR<0.5), Q_{SV}, FD-χ^2, $\sum\chi^2_{IP}$***

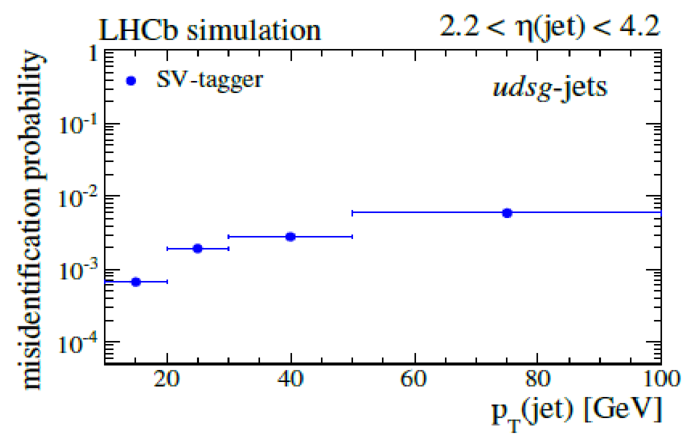
Data samples (tagging):

- **Fully reconstructed b-hadron + jet**
- **Fully reconstructed c-hadron + jet**
- **μ(b,c) + jet**
- **Prompt isolated high-p_T muon + jet**









arXiv:1504.07670

W + c- / b-jet selection

$W \to \mu\nu$ final state.

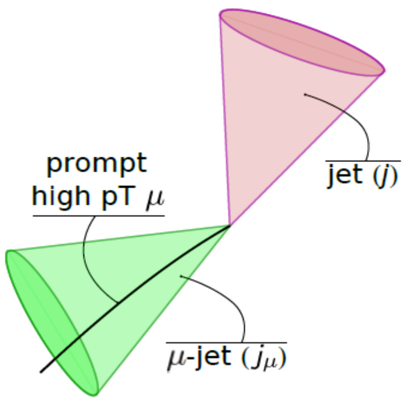
Jets tagged with the SV-tagger.

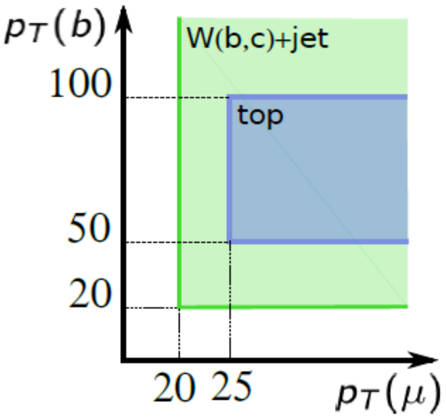
$p_T(\mu) > 20$ GeV, $2.0 < \eta_\mu < 4.5$

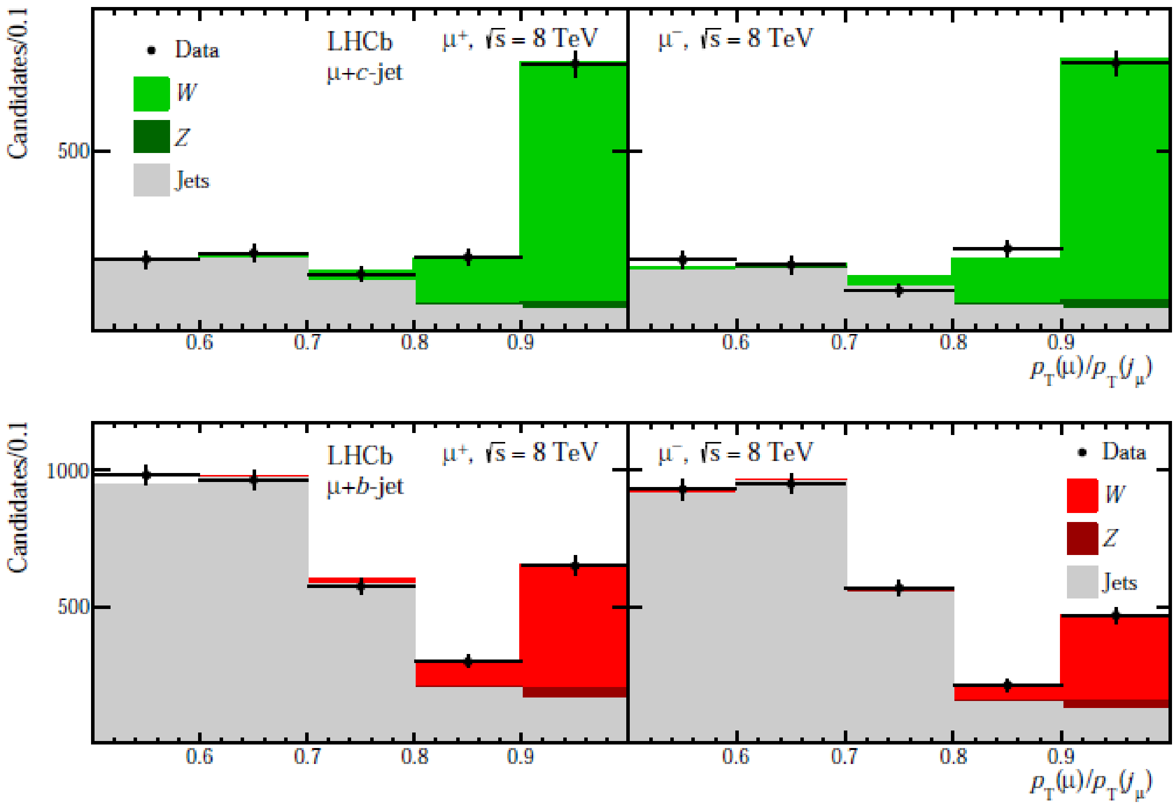
$p_T(j) > 20$ GeV, $2.2 < \eta_j < 4.2$

$\Delta R(\mu, j) > 0.5$

$p_T(\mu + j) > 20$ GeV







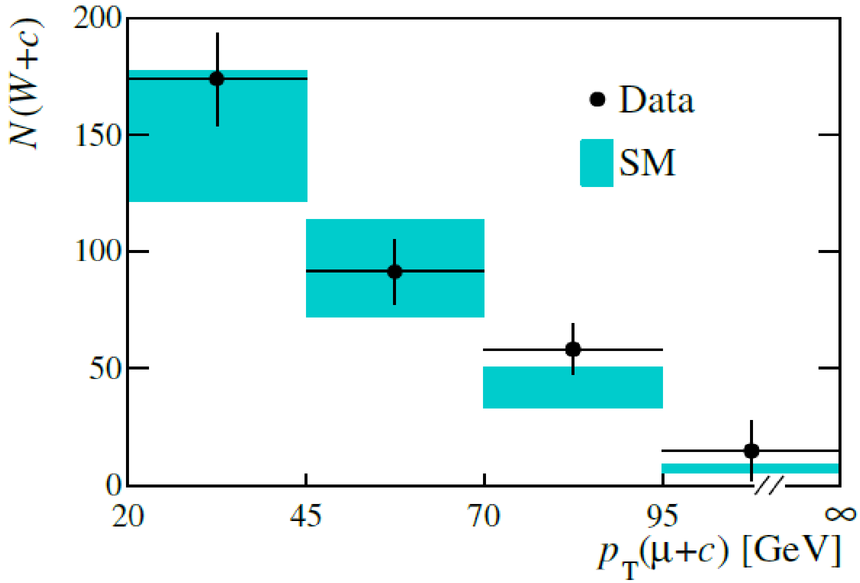
arXiv:1505.04051

Top quark observation

W + c-jet:

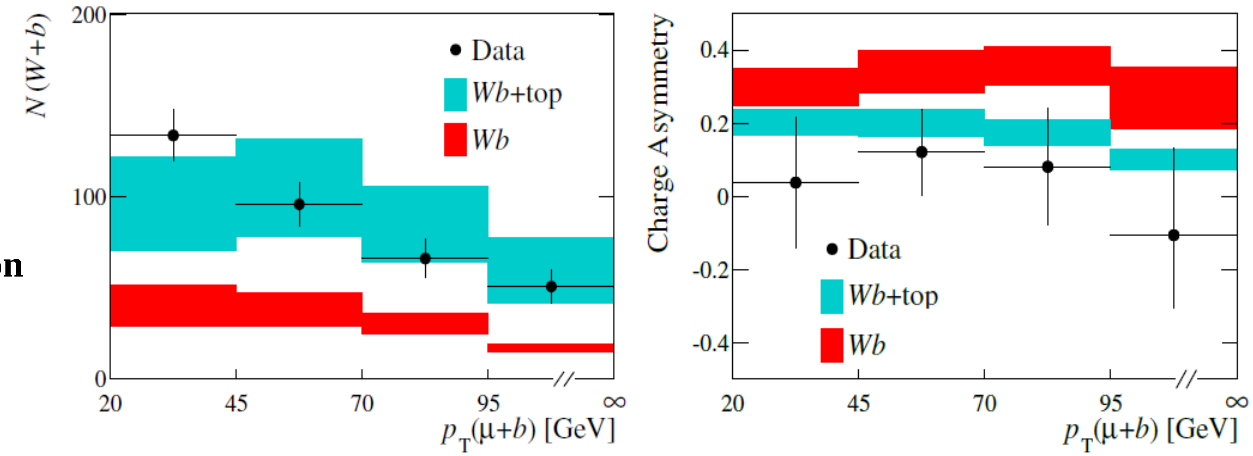
- **Free of top contribution (method validation)**
- **NLO SM prediction folded to LHCb-detector response**
- **Yields are in a good agreement with SM predictions**
- **Charge asymmetry: 2σ difference with SM prediction**

$$\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}$$



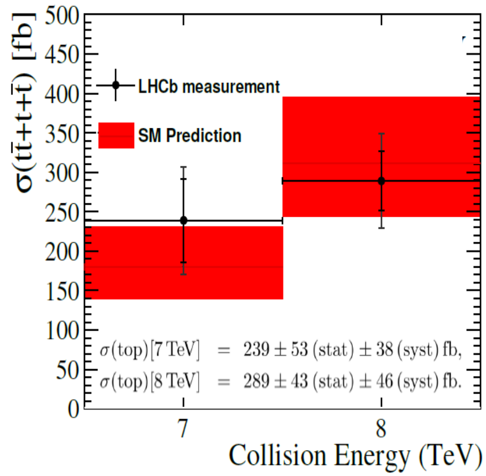
W + b-jet:

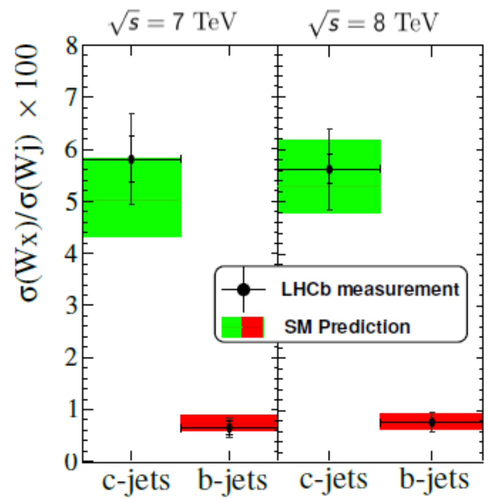
- **Discrepancy between data and *Wb* predictions**
- **Good agreement with Wb+top predictions**
- **Profile likelihood to compare Wb+top and Wb**
- **N(Wb) and A(Wb)-shapes fixed, yields variation**
- **5.4σ observation of top production in forward region**

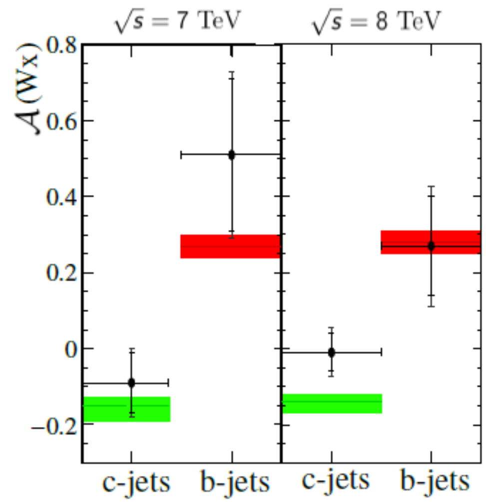


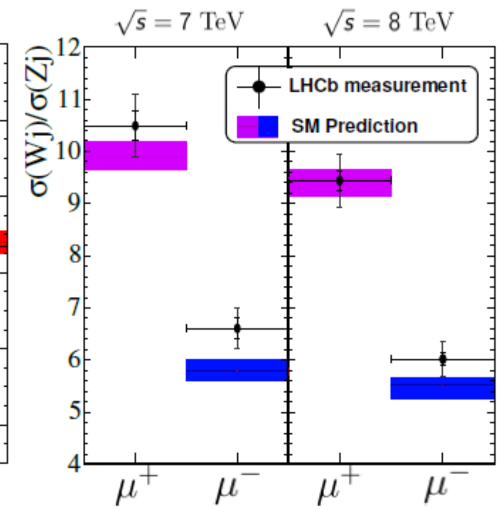
arXiv:1506.00903

Top quark & W + c- / b-jet results









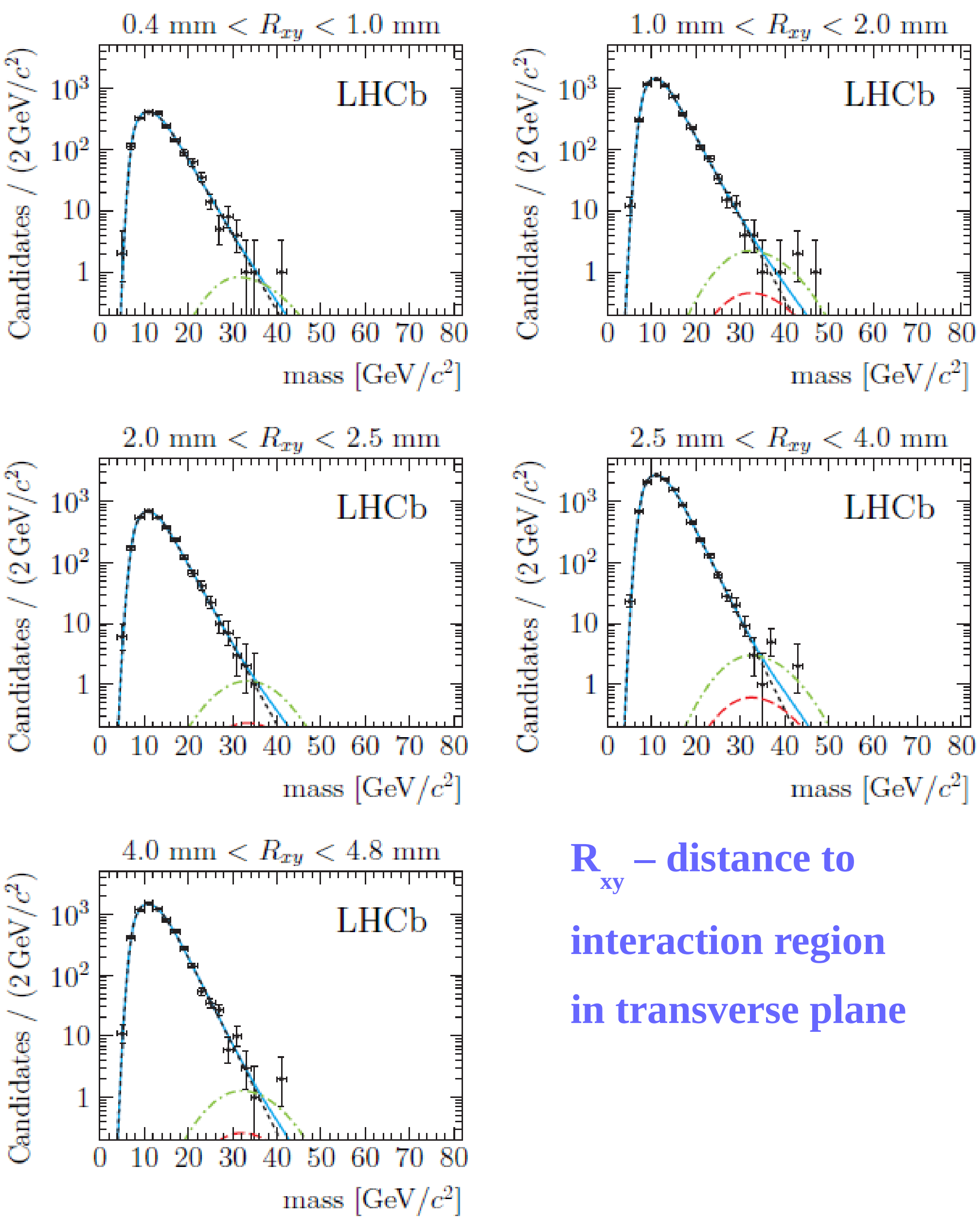
$$\left.\frac{\sigma(Wb{+}top)}{\sigma(Wj)}\right|_{7\ \mathrm{TeV}} = 1.17 \pm 0.13 \pm 0.18\%\ (\text{NLO prediction} = 1.23 \pm 0.24\%)$$

$$\left.\frac{\sigma(Wb{+}top)}{\sigma(Wj)}\right|_{8\ \mathrm{TeV}} = 1.29 \pm 0.08 \pm 0.19\%\ (\text{NLO prediction} = 1.38 \pm 0.26\%)$$

Data does not support large contribution of b-quarks in proton

- **Study of W boson production in association with beauty and charm** arXiv:1505.04051
- **Identification of beauty and charm quark jets at LHCb** arXiv:1504.07670
- **First observation of top-quark production in the forward region** arXiv:1506.00903

Direct search for long-lived particles

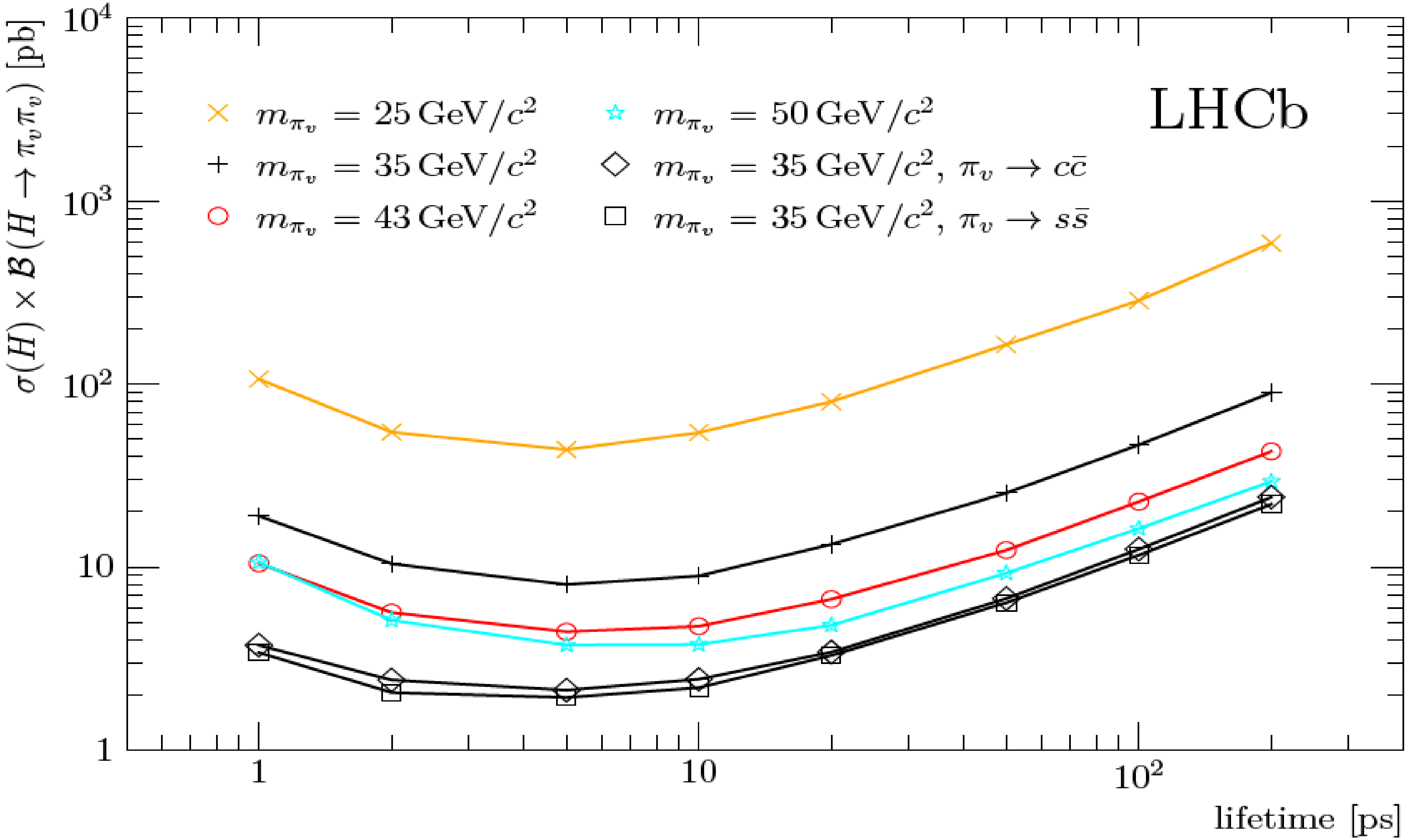


R_{xy} – distance to interaction region in transverse plane

- **Generic search for heavy 25<m<50GeV/c2 long-lived 1<t<200ps particles using displaced two-jet verteces**
- **Hidden valley $H \rightarrow \pi_\upsilon \pi_\upsilon$ as benchmark model**
- **$\sqrt{s}$ = 7 TeV, L_{int} = 0.62/fb**
- **Reconstruct π_υ with two (b-tagged) jets**
- **Fit mass in 5 bins R_{xy}**
- **No signal is observed**
- **Upper limits are better for decays into light quarks due to large multiplicity and smaller jet mass**

EPJ C 75 (2015) 152

Direct search for long-lived particles



Complementary to ATLAS & CMS

More restrictive than Tevatron

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Summary

LHCb, the forward spectrometer for precision studies in flavour physics domain

Excellent performance of the LHC and LHCb has led to a lot of physics results

- **Test of SM**
- **Search for NP**
- **Make CP violation measurements in b- and c-sectors**
- **Direct measurements as well**

World best quality of the results in charm and beauty physics!

Most measurements agree with SM predictions, but some exciting tensions exist

=> Further studies certainly needed!

Presented here measurements use mainly the 3 fb^{-1} dataset

(**several analyses still going**)

OUTLOOK:

1) Plan to have more than ~ 5 fb^{-1} at $\sqrt{s}$ = 13-14 TeV during next LHC run (2015-18)

2) **Upgrade** (next slide)

Outlook. ***Theory vs. 50 fb^{-1}***

Type	Observable	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.025	0.008	~0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.045	0.014	~0.01
	a_{sl}^s	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{eff}(B_s^0 \to \phi\phi)$	0.17	0.03	0.02
	$2\beta_s^{eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	0.13	0.02	< 0.02
	$2\beta^{eff}(B^0 \to \phi K_S^0)$	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{eff}(B_s^0 \to \phi\gamma)$	0.09	0.02	<0.01
	$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,GeV^2/c^4)$	0.025	0.008	0.02
	$s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	6 %	2 %	7 %
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,GeV^2/c^4)$	0.08	0.025	~0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	8 %	2.5 %	~10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	~100 %	~35 %	~5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	0.65×10^{-3}	0.12×10^{-3}	–

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