

Recent results from LHCb

29th of June 2015

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on behalf of the LHCb collaboration



**The XXII International Workshop
High Energy Physics and Quantum Field Theory (QFTHEP-2015)
Samara, Russia / June 24 – July 1, 2015**

Outline

Main goal of this talk: Show how precise LHCb measurements in b- and c-sectors make constraints on fundamental parameters 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*-tagged jets.
- Summary and Outlook (what can be achieved after upgrade?)

Also check LHCb talks at LHC Seminars

- 30 Jun 2015 Brian Hamilton**, "Measurement of the semitauonic decay $B^0 \rightarrow D^* \tau \nu$ at LHCb"
soon at <https://cds.cern.ch>
- 26 May 2015 Victor Coco**, "Observation of top-quark production in the forward region with LHCb"
<https://cds.cern.ch/record/2018487?ln=en>
- 24 Mar 2015 Patrick Owen**, "First determination of V_{ub} using the exclusive decay $\Lambda_b \rightarrow p \mu \nu$ with the LHCb detector"
<https://cds.cern.ch/record/2004374?ln=en>
- 10 Feb 2015 Marco Pappagallo**, "Latest results on b-hadron spectroscopy at LHCb"
<https://cds.cern.ch/record/1988103?ln=en>
- 18 Nov 2014 Sevda Esen**, "Measurement of the B_s mixing phase at LHCb"
<https://cds.cern.ch/record/1971320?ln=en>
- 30 Sep 2014 Mika Anton Vesterinen**, "Measurement of semileptonic asymmetries at LHCb"
<https://cds.cern.ch/record/1951445?ln=en>
- 12 Aug 2014 Manuel Tobias Schiller**, "Gamma measurements in $B_s \rightarrow D_s K$ and other tree-level decays"
<https://cds.cern.ch/record/1749146?ln=en>
- 3 Jun 2014 Greig Cowan**, "Confirmation of the Z(4430)- resonance and other exotic meson results from the LHCb experiment"
<https://cds.cern.ch/record/1706201?ln=en>
- 18 Mar 2014 Albert Puig Navarro**, "Observation of photon polarization in the $b \rightarrow s \gamma$ transition at LHCb"
<https://cds.cern.ch/record/1706201?ln=en>

Introduction

Standard Model (SM)

No doubt that SM is great achievement!

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

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	$\leq 10^{-10}$
$m_u (2 \Gamma \ni B)$	$2,5^{+0,8}_{-1,0} M \ni B$
$m_d (2 \Gamma \ni B)$	$5,0^{+1,0}_{-1,5} M \ni B$
$m_s (2 \Gamma \ni B)$	$105^{+25}_{-35} M \ni B$
$m_c (m_c)$	$1,266^{+0,031}_{-0,036} \Gamma \ni B$
$m_b (m_b)$	$4,198 \pm 0,023 \Gamma \ni B$
$m_t (m_t)$	$173,10 \pm 1,35 \Gamma \ni B$
m_e	$510,998910 \pm 0,000013 \kappa \ni B$
m_μ	$105,658367 \pm 0,000004 M \ni B$
m_τ	$1,77682 \pm 0,00016 \Gamma \ni B$
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	$1,20 \pm 0,08$
$v(m_\mu)$	$246,221 \pm 0,002 \Gamma \ni B$
M_H	$115,5 - 127,0 \Gamma \ni B$

Flavour sector of SM

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

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

- dark matter
- baryon asymmetry of Universe

(CPV is needed)

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

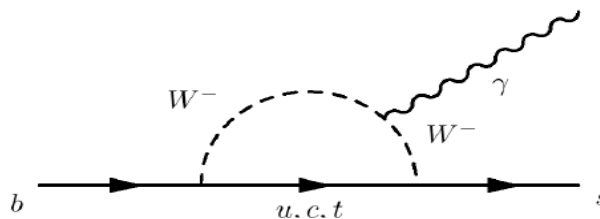
Indirect measurements at LHC

- 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



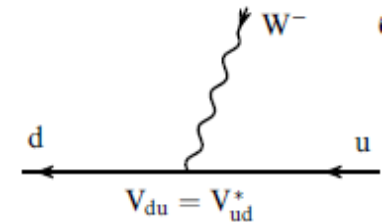
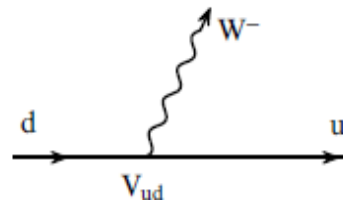
- **Many historical successful HEP examples (Kaon CPV \rightarrow KM predictions of 3rd quark generation, neutral currents \rightarrow Z-discovery, B-meson mixing \rightarrow top quark mass scale)**
- **Direct searches are restricted by LHCb kinematics conditions, but they are possible! (this talk: search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

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

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



Wolfenstein parametrization to demonstrate CKM elements hierarchy

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

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

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

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

Unitarity triangles

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0,$$

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

$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0,$$

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

$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0,$$

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0,$$

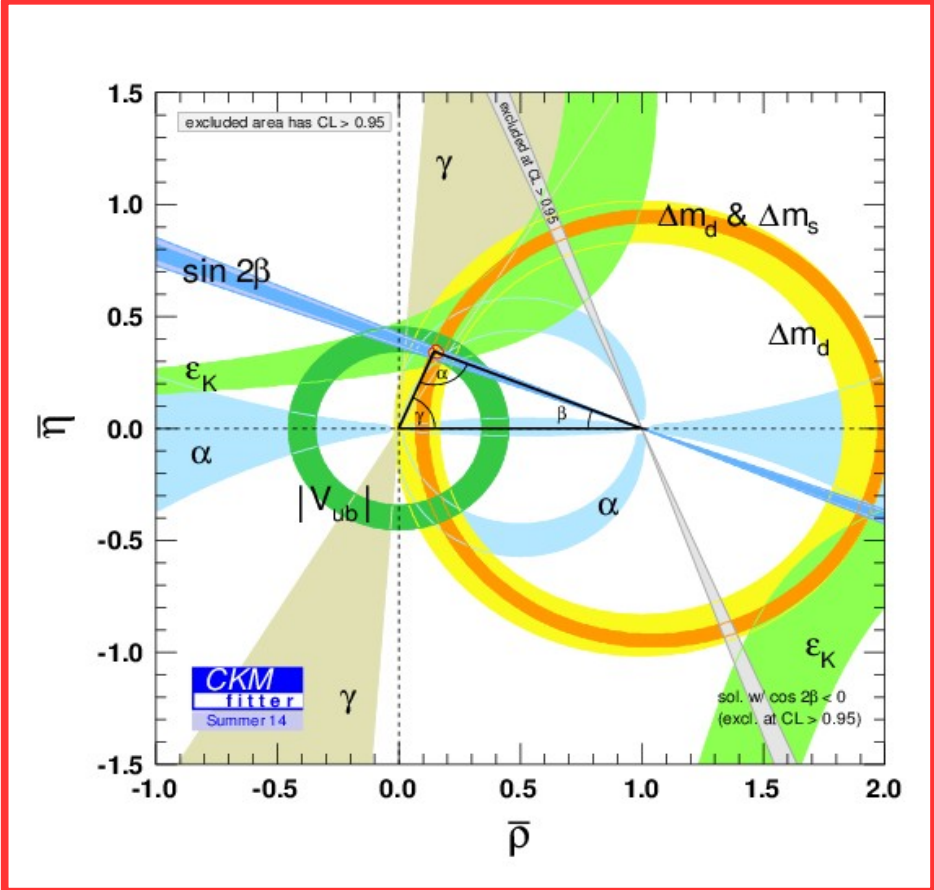
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$

$$O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$$

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

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0.$$

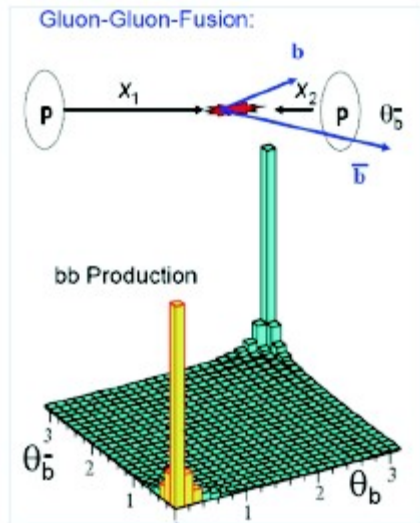
$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right), \quad \bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right)$$



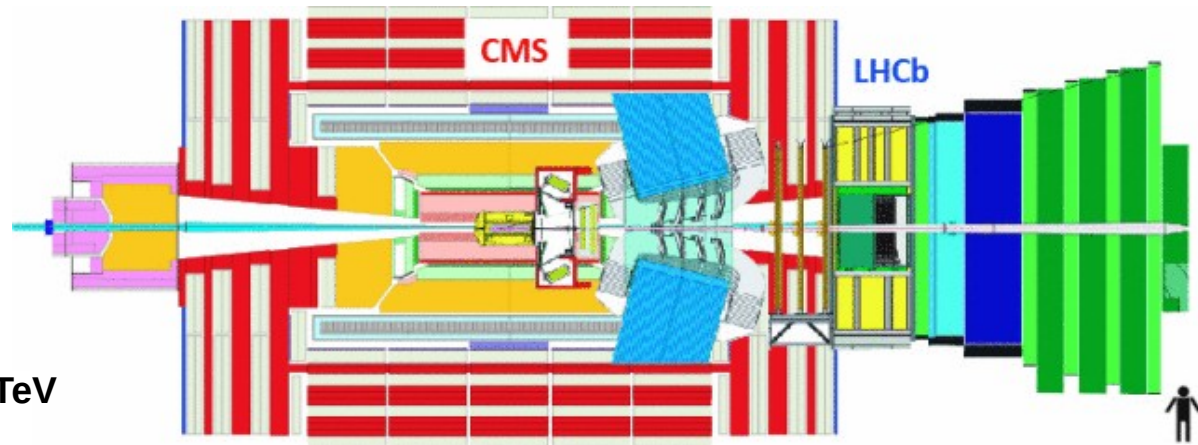
- 2 of 6 relations have all three contribution of same size
- Parameters of the triangle can be measured at the decay
- Contain experimentally known CPV source in SM.
- Can be drawn as triangle at the complex plane
- Many different experimental constraints
- In this talk will show LHCb results on $|V_{ub}|$,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

LHCb features

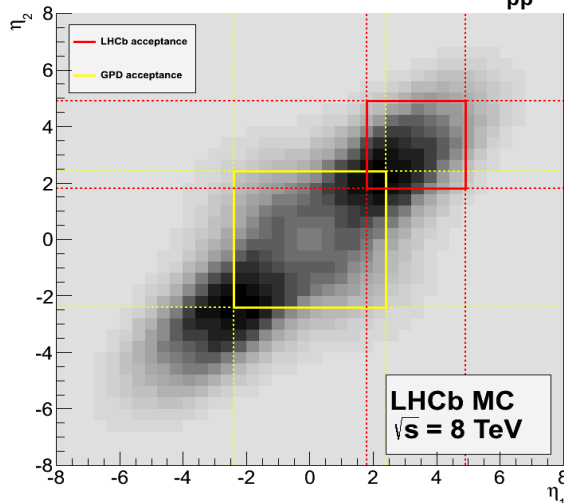
Beauty and charm production



- **LHCb: forward spectrometer** $2 < \eta < 5$
(ATLAS & CMS: $|\eta| < 2.5$)



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



- In LHCb acceptance (pp -collisions $\sqrt{s} = 7\text{TeV}$)

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

Phys.Lett.B694 (2010) 209-216

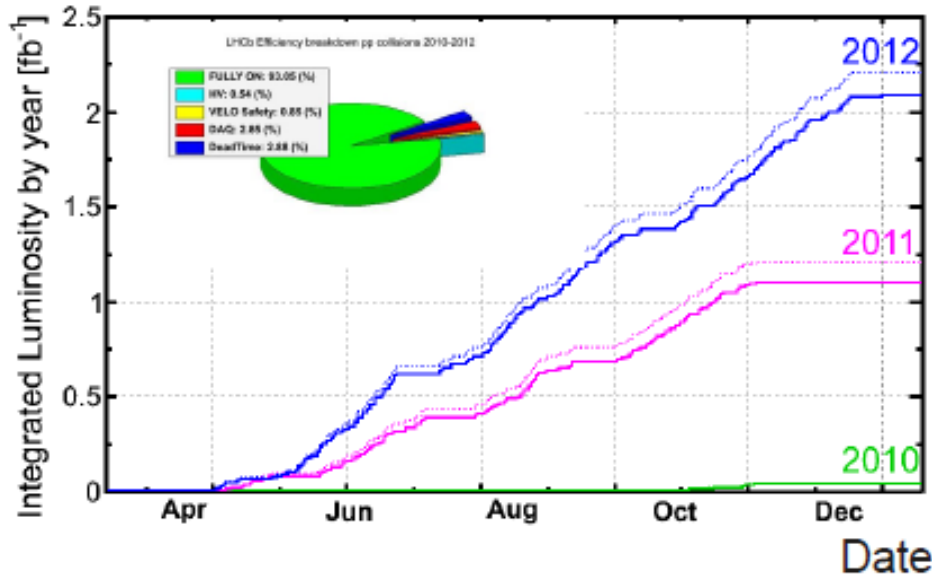
$$\sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \mu b \sim 20 \times \sigma(b\bar{b})$$

Largest charm samples in the world

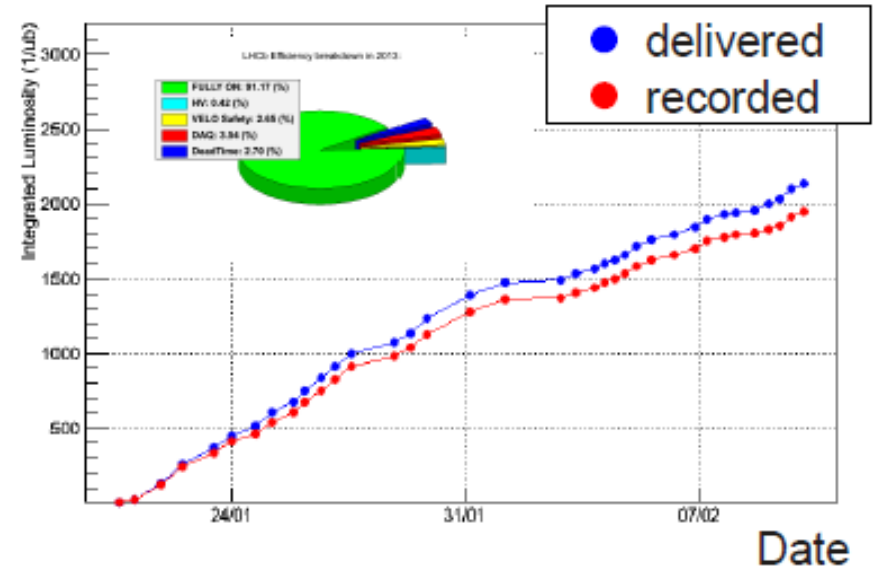
Nucl.Phys.B871 (2013) 1

Operation in 2010/12

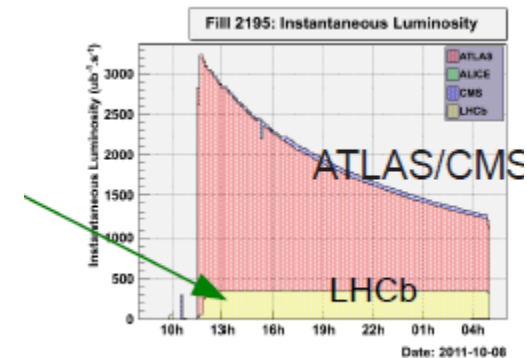
pp-collisions at $\sqrt{s} = 7 \text{ \& } 8 \text{ TeV}$ (2011-12)



pPb-collisions at $\sqrt{s_{NN}} = 5 \text{ TeV}$ in 2013

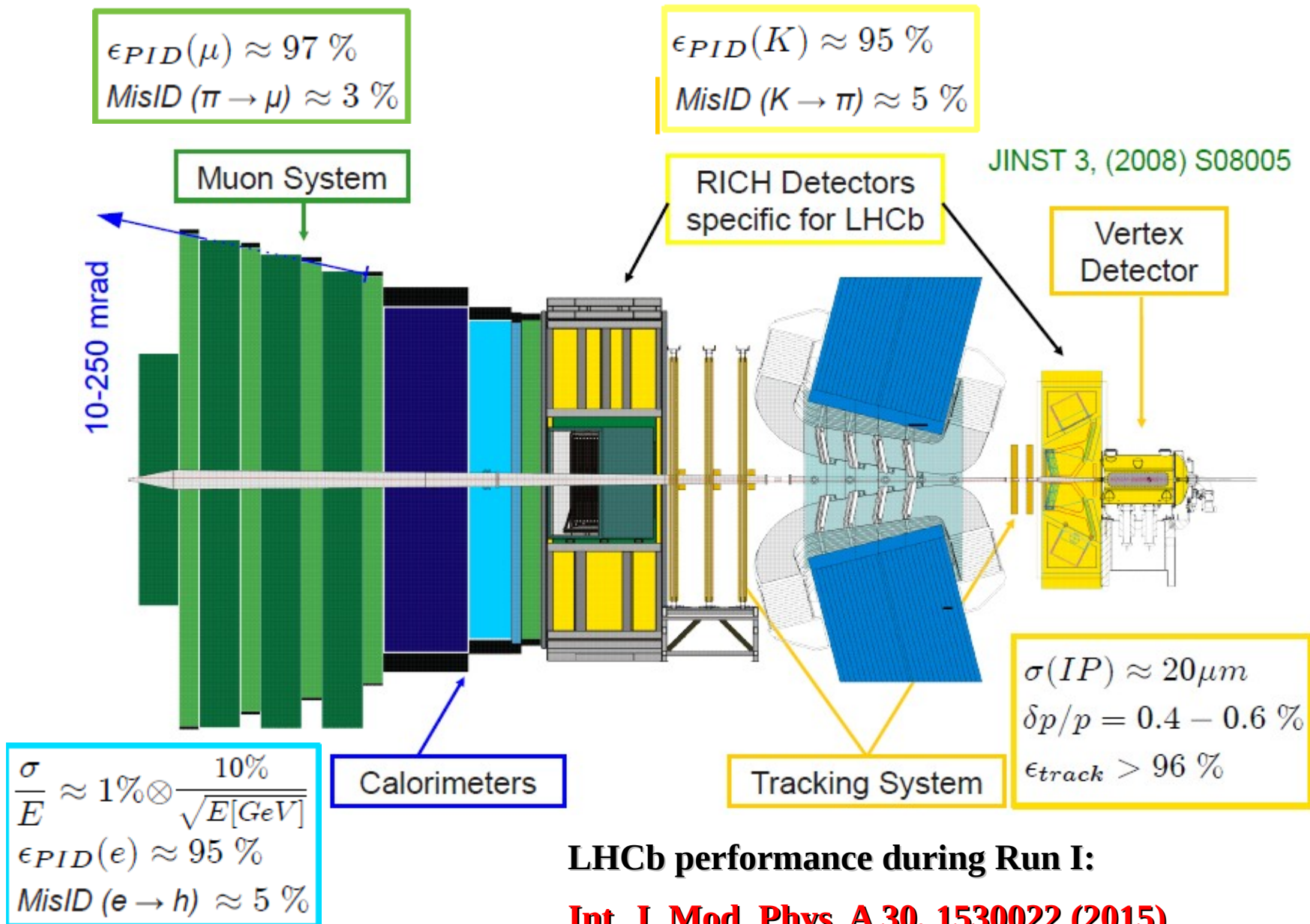


- High recording efficiency
- 50 ns between bunch crossings
(will try 25 ns this year)
- Constant luminosity of $\sim 4 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
(twice higher than design luminosity)
- **1.7 visible interaction per bunch crossing**



LHCb also has set of *pp* data at $\sqrt{s} = 2.76 \text{ TeV}$ (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, Neurobays, etc.

Optimization of selection

Using MC

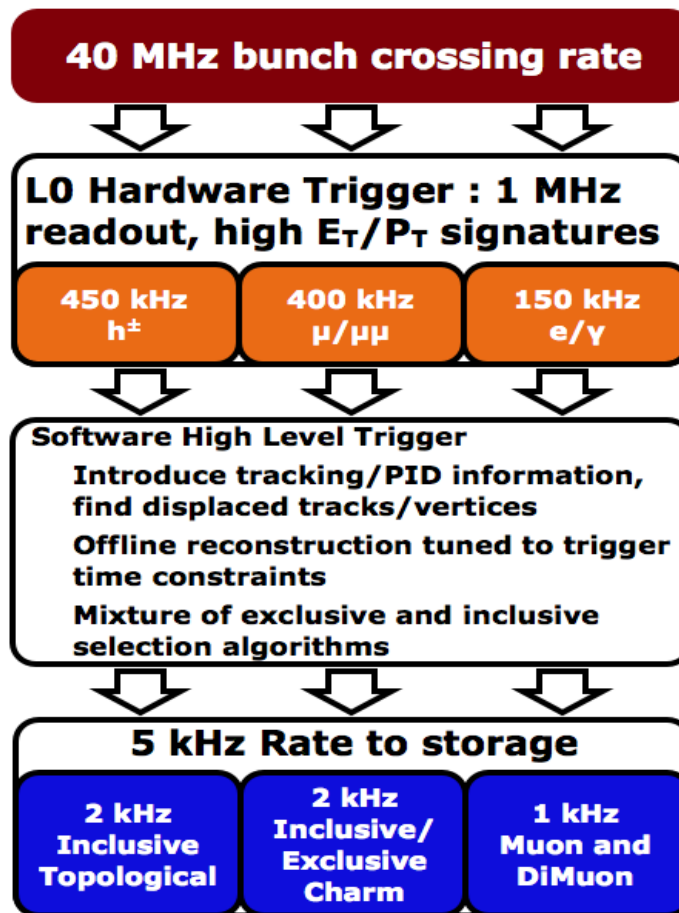
Using small sample of real data

Angular analysis++

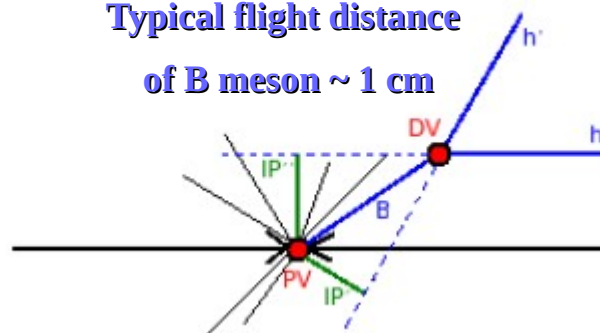
Check for systematics

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 than 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, Δm_s ; Γ_s , $\Delta\Gamma$, ϕ_s ; CKM β , γ , $|V_{ub}|$ determination

3) Mixing and CPV in the D mesons

Mixing observ., $\Delta A(\text{CP})$

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

In this talk!

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) $B_s^0 \rightarrow \phi \mu^+ \mu^-$

5) $\bar{B}^0 \rightarrow D^* \tau \bar{\nu}$

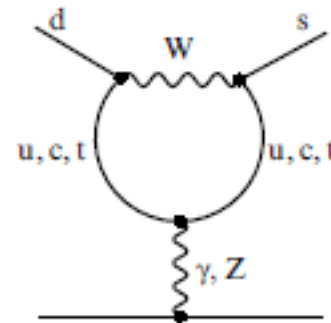
NP and flavour symmetry; Wilson's coefficients

- 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)
- \mathcal{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:

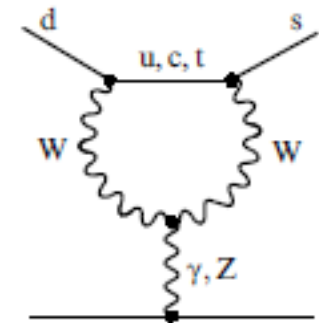
$$\frac{\text{BR}(B_s \rightarrow \mu^+ \mu^-)}{\text{BR}(B_d \rightarrow \mu^+ \mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}$$

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

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



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



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

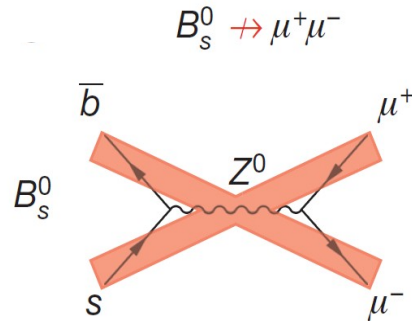
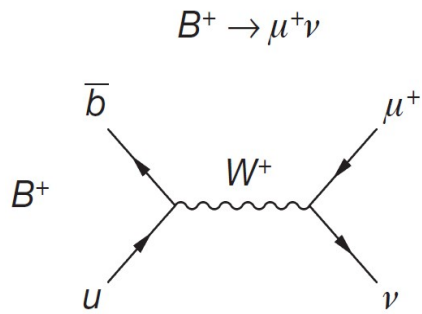
Example

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

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

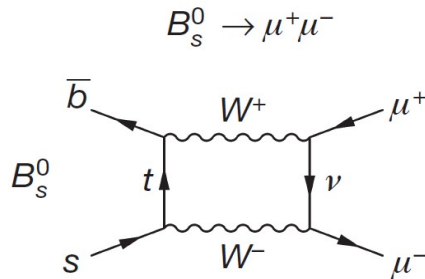
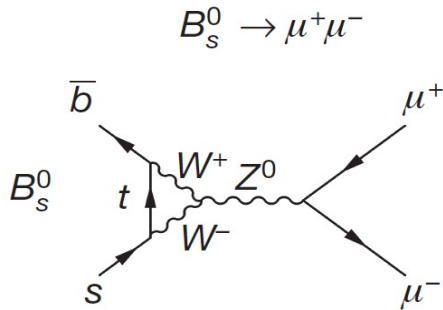
– Helicity suppressed in SM

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



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

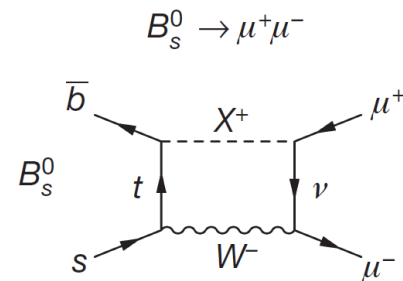
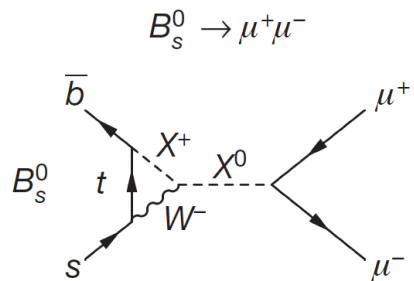
$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$



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

5% precision SM calculations!

Ratio is power discriminator as well



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

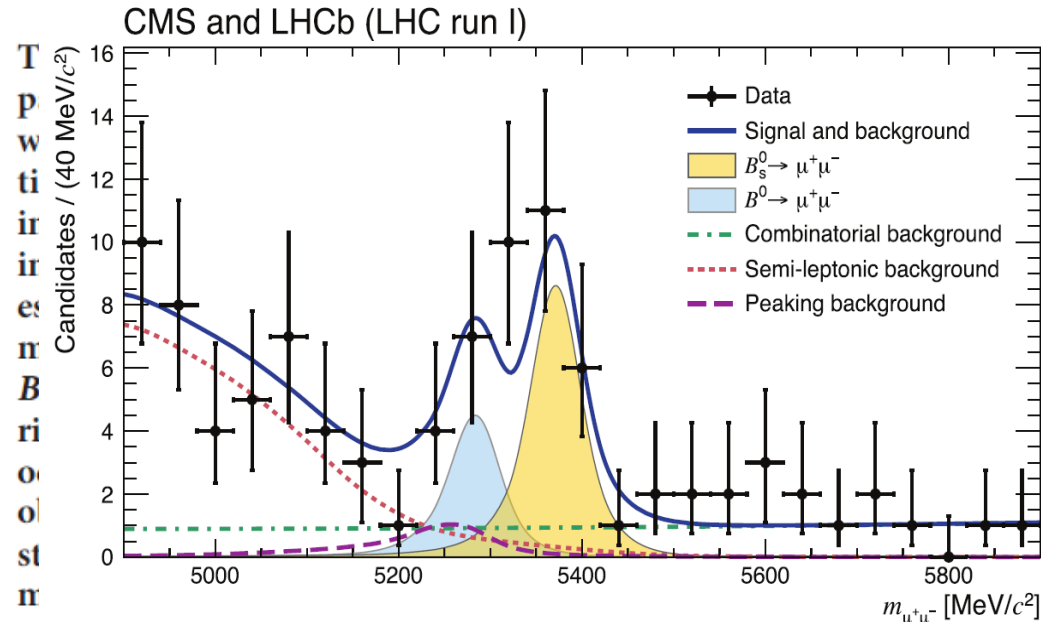
Sensitive to new scalar, pseudoscalar, axial-vector particles in loops

In MSSM:

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

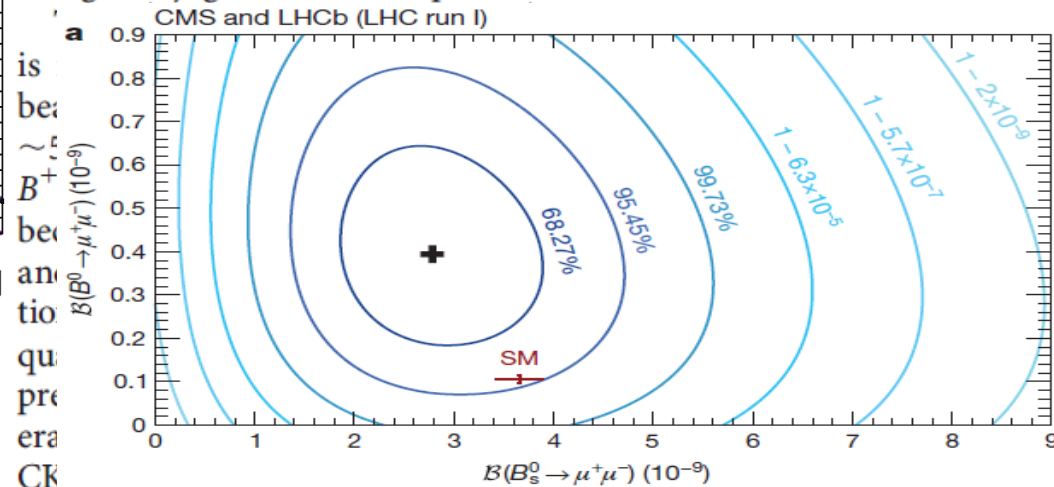
Observation of the rare $B_s^0 \rightarrow \mu^+ \mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*



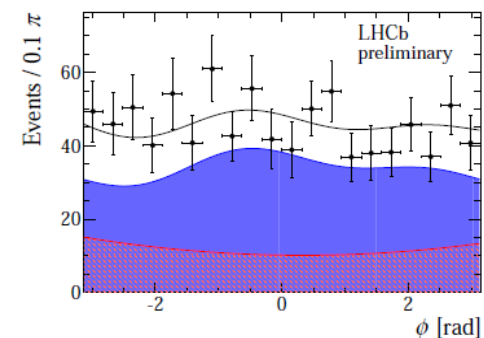
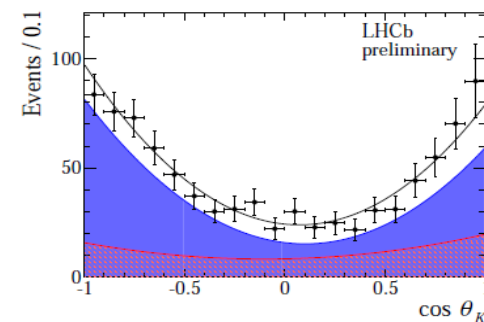
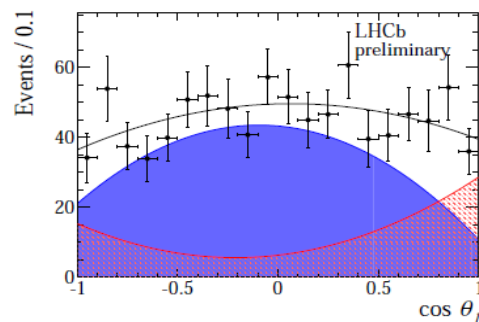
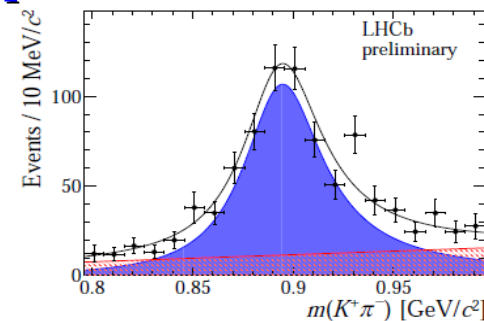
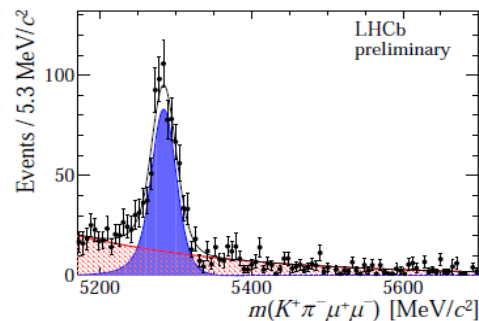
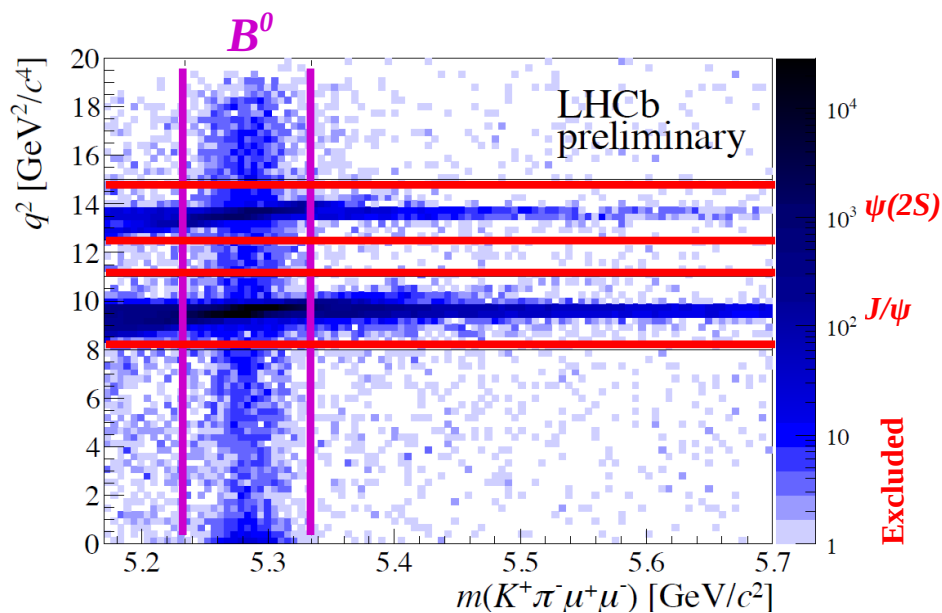
at CERN started operating, no evidence for either decay mode had been found. Upper limits on the branching fractions were an order of magnitude above the standard model predictions. The CMS (Compact Muon Solenoid) and LHCb (Large Hadron Collider beauty) collaborations have performed a joint analysis 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 $1 < q^2 < 6 \text{ GeV}^2/c^4$



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

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} \Big|_P = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ \left. + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l \right. \\ \left. - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \right. \\ \left. + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \right. \\ \left. + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \right. \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

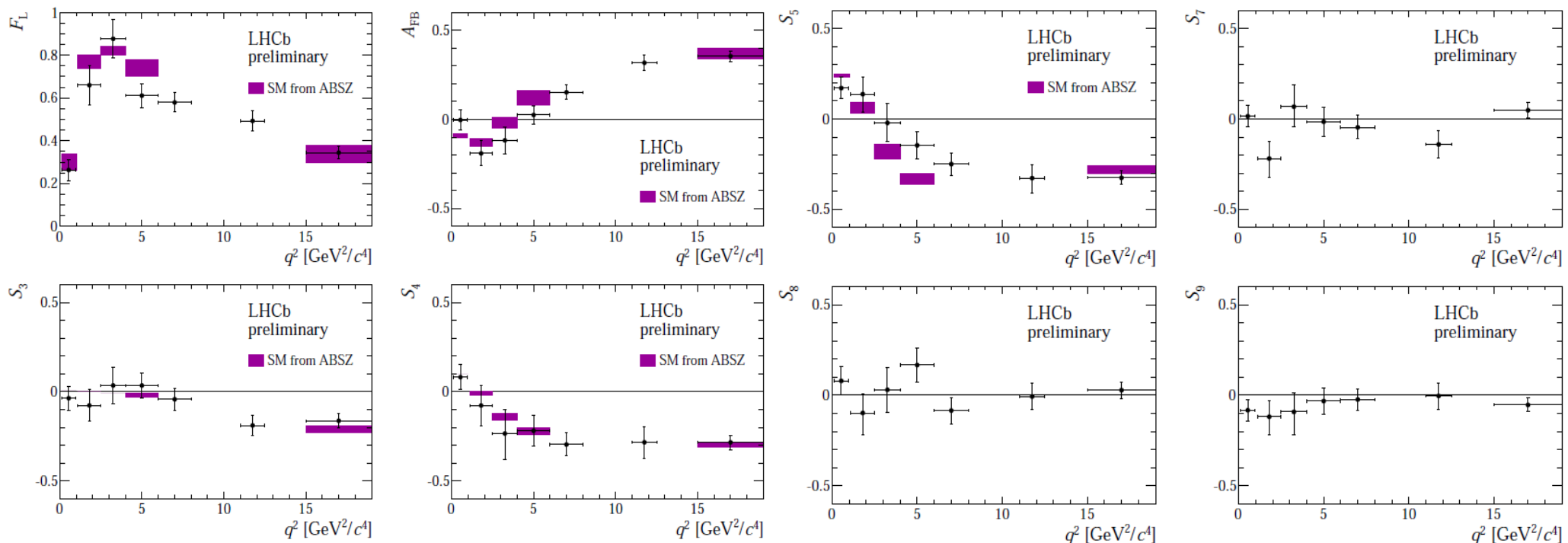
– three angles + q^2 to describe data

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

(short-distance interaction + hadronic form factors)

– Precise theoretical calculations

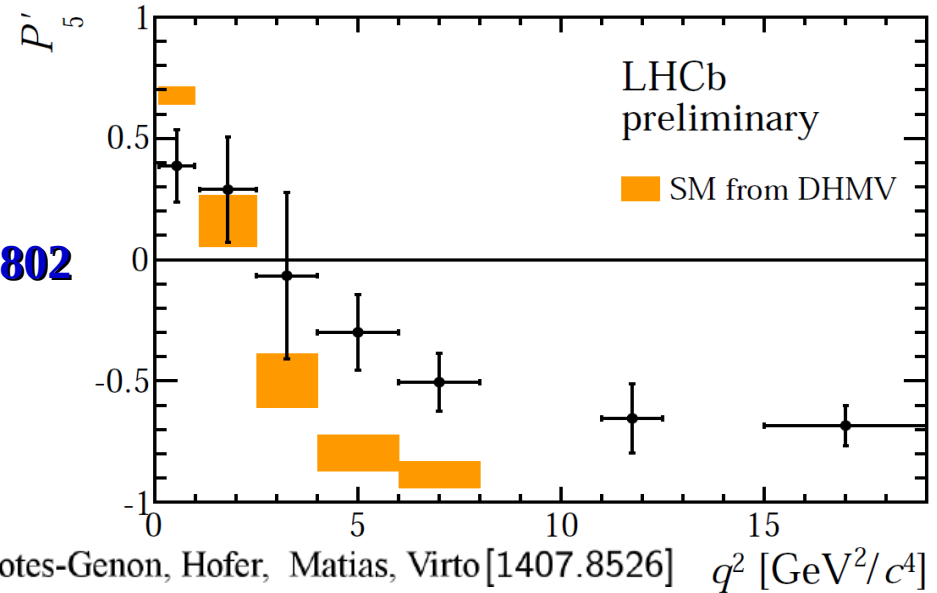
Altmannhofer, Bharucha, Straub, Zwicky [1503.05534][1411.3161]



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

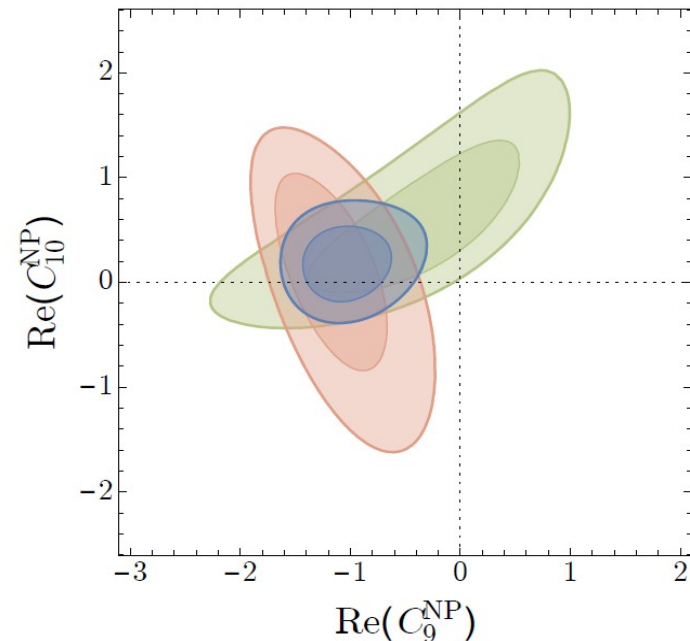
[LHCb-CONF-2015-002]

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



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

- Global fit of the available $b \rightarrow sy$ & $b \rightarrow sll$
- $C_9^{NP} = -1.5$, 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

Test of lepton flavour universality

– In Standard Model

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

– Event migration (MC)

– Bremsstrahlung

– Double ratio with $B^+ \rightarrow J/\psi K^+$ to cancel systematics

– 3/fb dataset

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

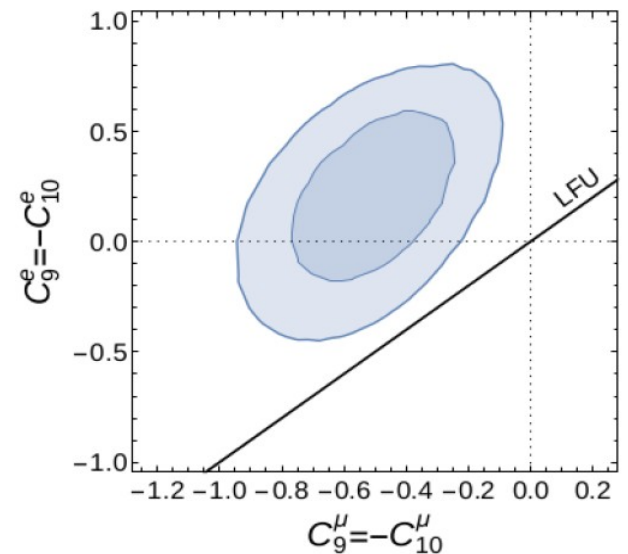
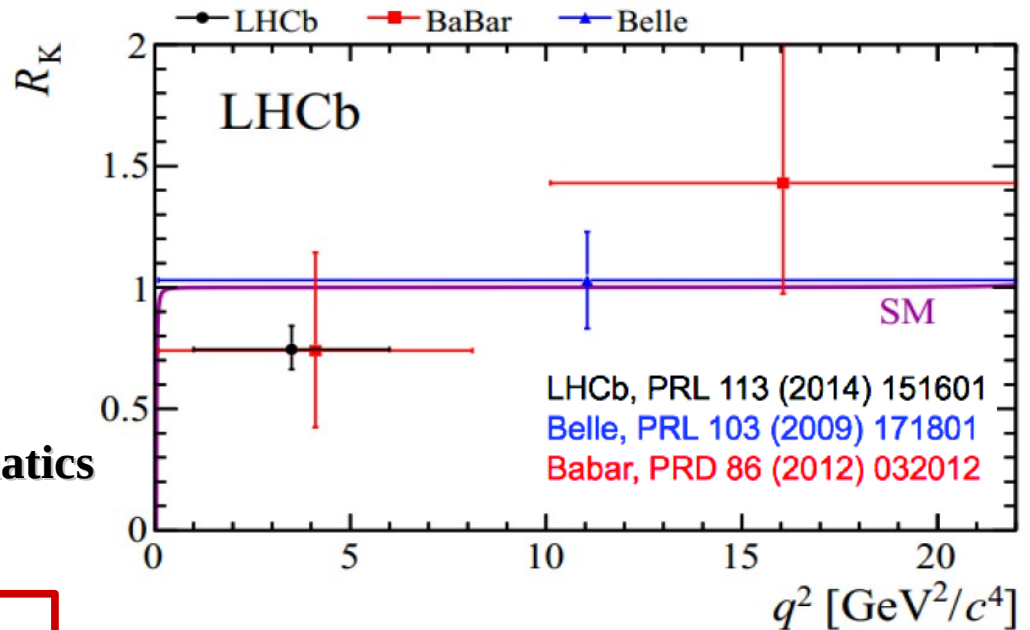
– Deviation from SM expectation at **2.9 σ** level

– QCD can't explain NON-LFU

– Non universal Z' can produce such effect

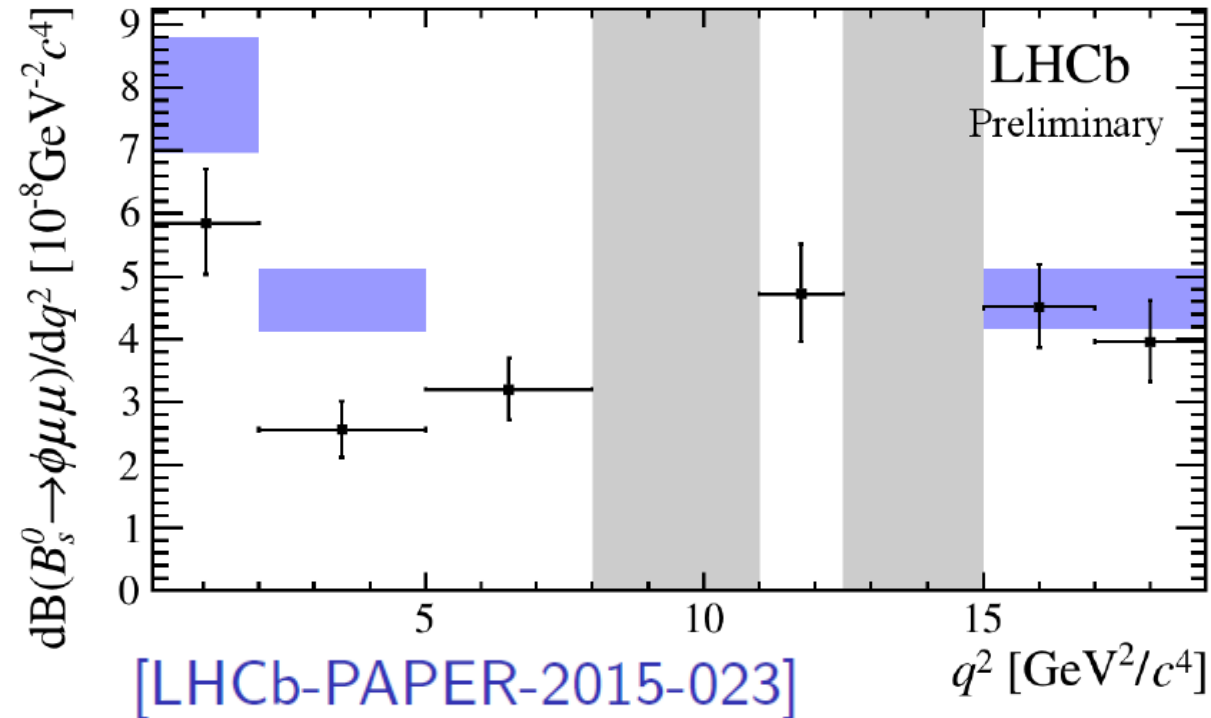
– Ghosh et al. [arXiv:1408.4097](https://arxiv.org/abs/1408.4097)

– Such explanation in agreement with P_5' anomaly



Analysis of $B_s^0 \rightarrow \phi \mu^+ \mu^-$

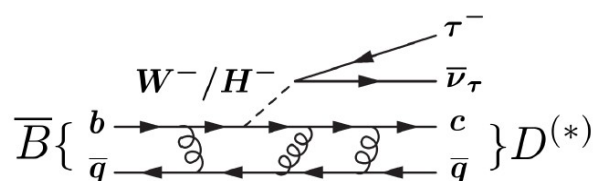
- Analysis similar to $B^0 \rightarrow K^* \mu \mu$
- No sensitivity to P'_5
- Measurement of branching fraction and angular analysis
- Theory: [arXiv:1411.3161](#), [1503.05534](#)
- New analysis confirms tension in 1fb^{-1} dataset analysis [JHEP 07 \(2013\) 084](#)
- Extrapolation to full q^2 range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



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

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

Analysis of $\bar{B}^0 \rightarrow D^* \tau \bar{u}$



– Measurement of the ratio:

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

– Theoretically clean

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

– No narrow signal structures for signal, many bkg.

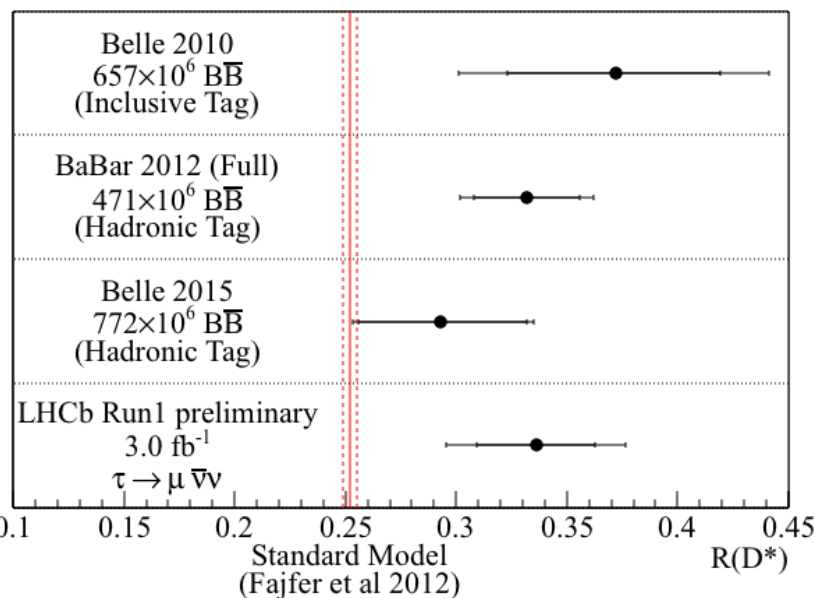
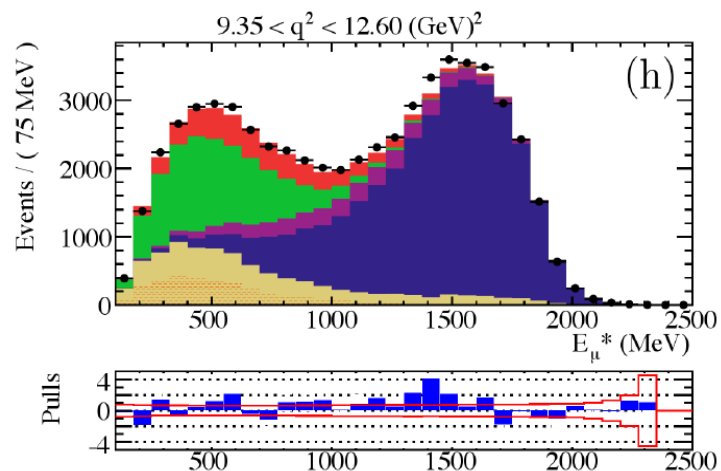
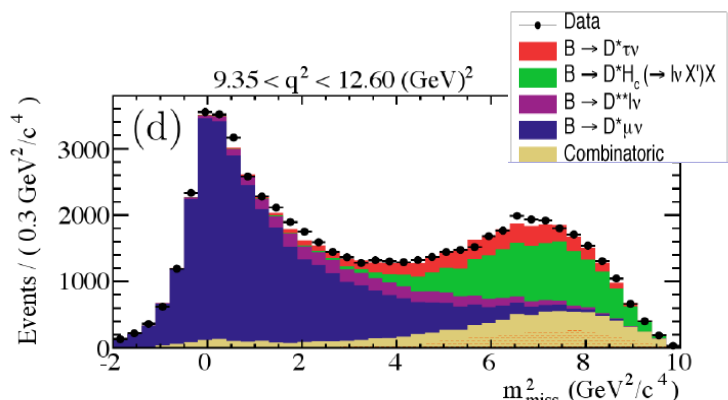
– Isolation technique against partially reco. bkg.

– 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

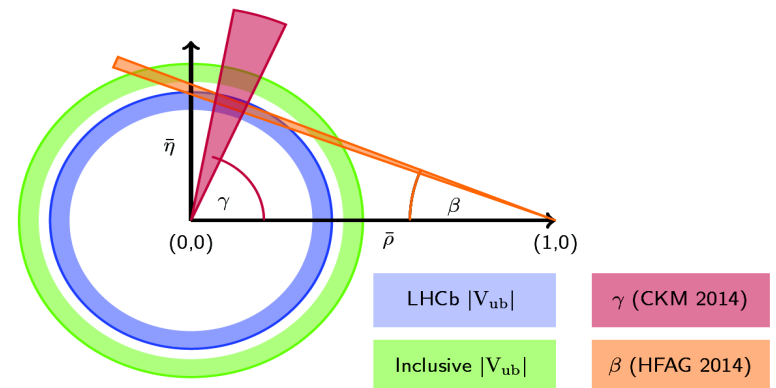


CKM studies

1) $|V_{ub}|$ determination

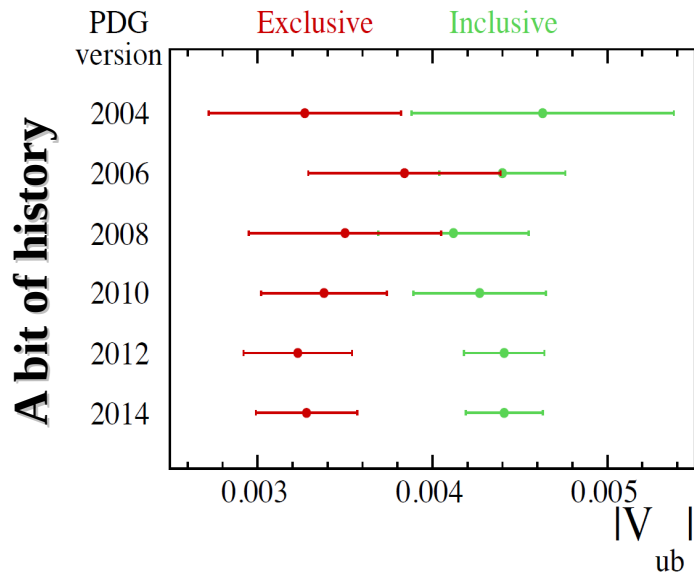
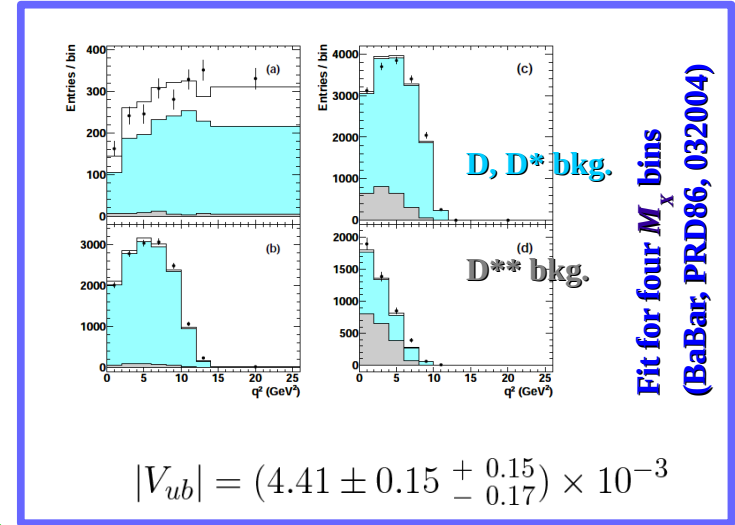
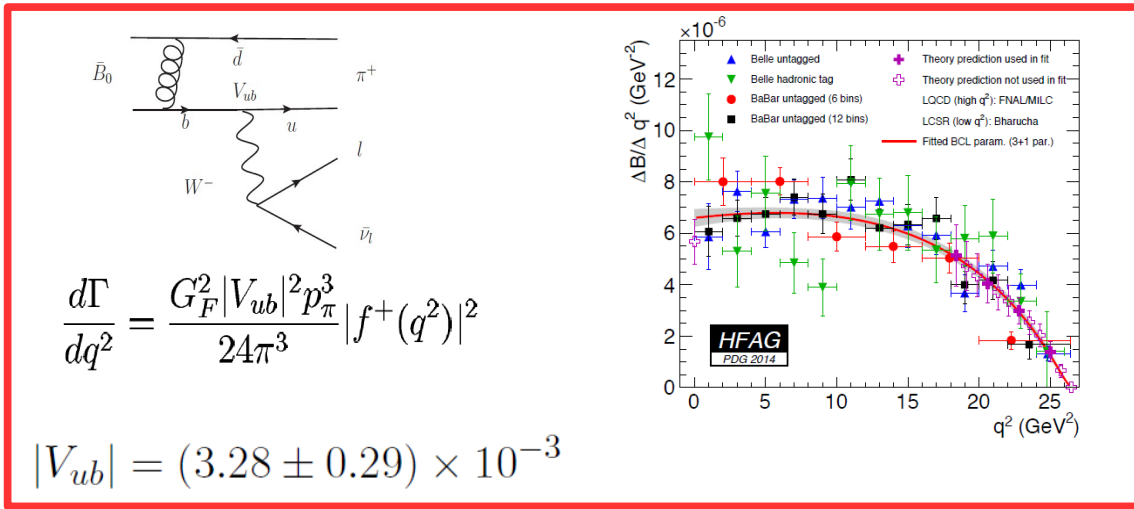
2) Measurement of $\sin(2\beta)$

+ reminder about LHCb -measurement of γ

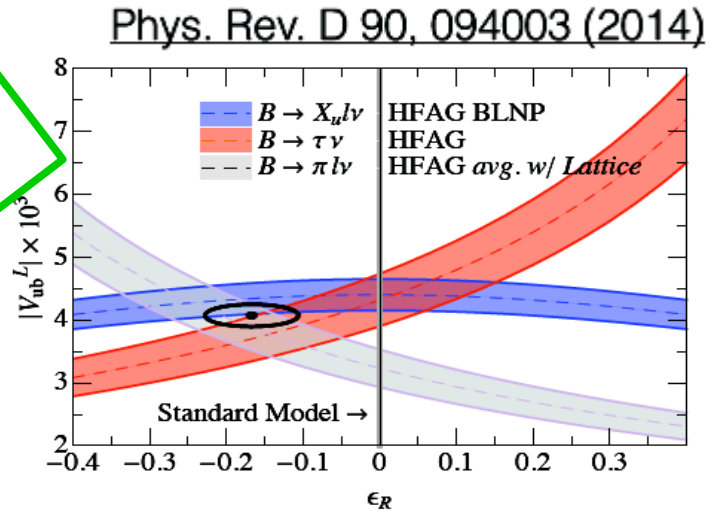


$|V_{ub}|$ measurement

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



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



$|V_{ub}|$ measurement

– LHCb measures ratio:

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

– 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

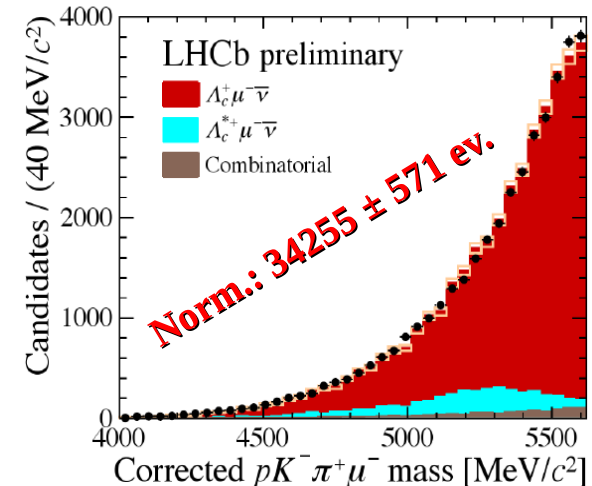
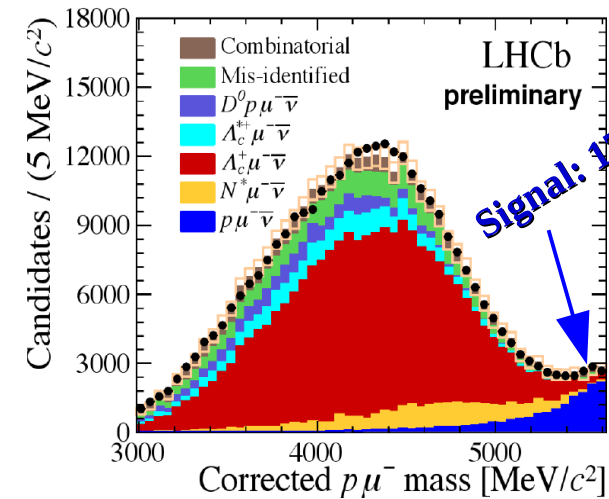
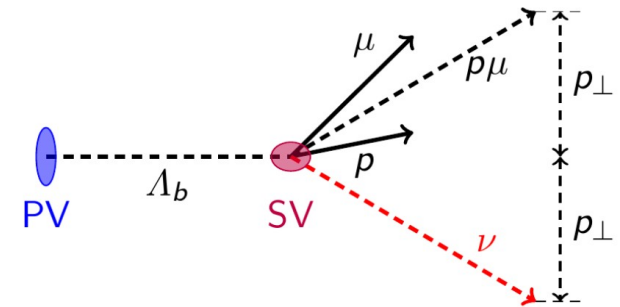
$$M_{corr} = \sqrt{p_{\perp}^2 + M_{p\mu}^2 + p_{\perp}}$$

– Two solutions for q^2 , bin migration problem

both required to be $> 15 \text{ GeV}^2/c^4$

– Isolation technique sensitive to the extra tracks close to SV for background reduction

– Main systematics from: $\Lambda_c \rightarrow pK\pi$ BF and decay model, trigger and tracking efficiency



Signal: $17687 \pm 733 \text{ ev.}$

[arxiv:1504.01568]

$|V_{ub}|$ measurement

[arxiv:1504.01568]

– Measured ratio is:

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

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

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

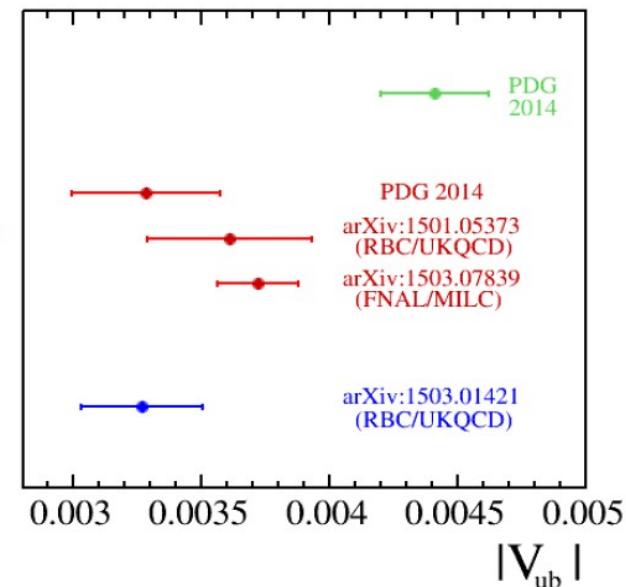
– 3.5σ tension to the inclusive measurements

– Right-handed current hypothesis is in trouble

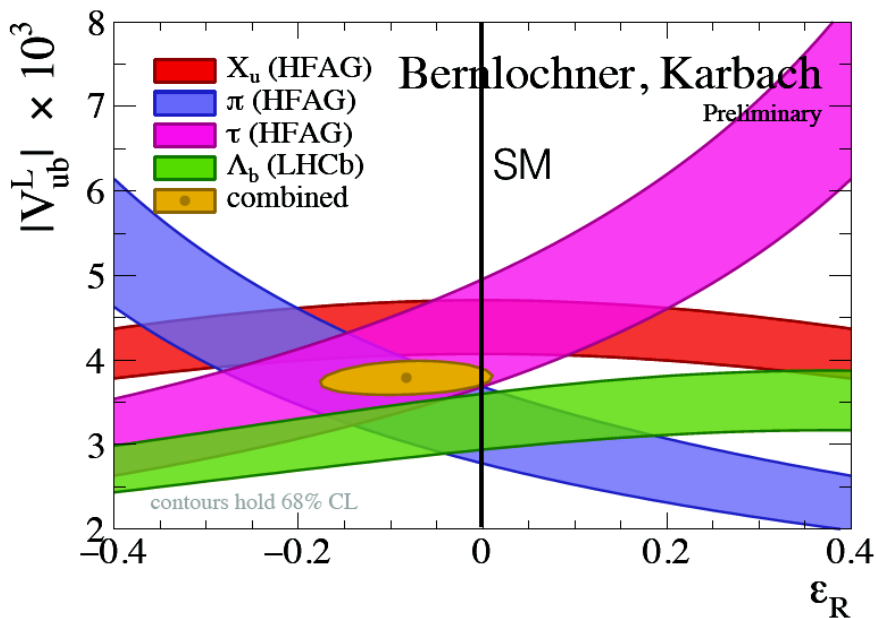
Inclusive

Exclusive
($B \rightarrow \pi l\nu$)

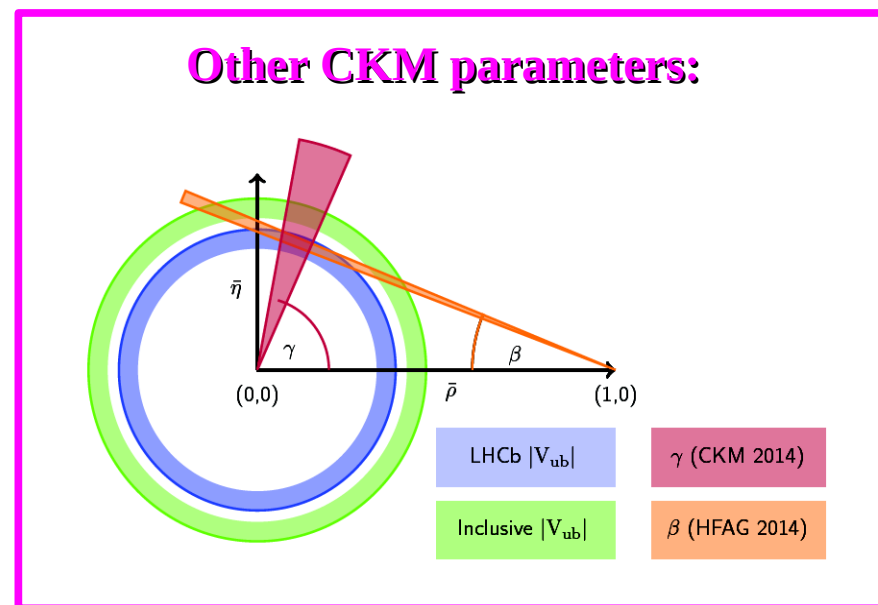
LHCb
($\Lambda_b^0 \rightarrow p\mu\nu$)



$$\chi^2/\text{ndf} = 2.8 / 1, \text{ p-value} = 9\% \rightarrow 16.0/2, 0.03\%$$

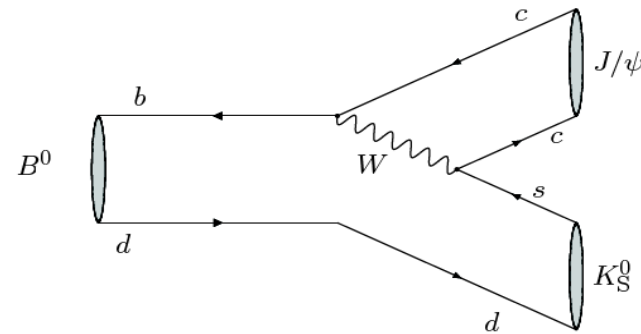


Other CKM parameters:



LHCb measurements of $\sin(2\beta)$

- $B^0 \rightarrow J/\psi K_s^0$ is tree-level dominated decay,
negligible contribution from penguins



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

$K_S^0 \rightarrow \pi^+ \pi^-$

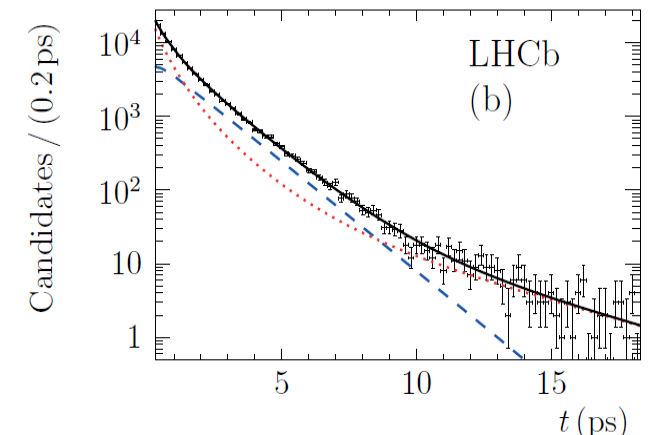
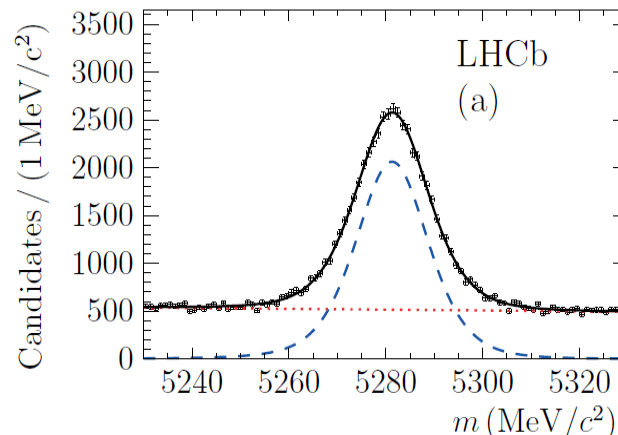
- Time dependent CP asymmetry to measure:

$$\mathcal{A}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) - \Gamma(B^0(t) \rightarrow J/\psi K_S^0)}{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) + \Gamma(B^0(t) \rightarrow J/\psi K_S^0)} = \frac{S \sin(\Delta m t) - C \cos(\Delta m t)}{\cosh(\frac{\Delta\Gamma t}{2}) + A_{\Delta\Gamma} \sinh(\frac{\Delta\Gamma t}{2})}$$

- For B^0 mesons $\Delta\Gamma \approx 0 \Rightarrow$ 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
- $41\,560 \pm 270$ signal events

[arXiv:1503.07089](https://arxiv.org/abs/1503.07089)



LHCb measurements of $\sin(2\beta)$

- [arXiv:1503.07089](https://arxiv.org/abs/1503.07089) $B^0 \rightarrow J/\psi K_s^0$
- Multidimensional PDF includes reconstructed mass, decay time, **flavour tagging**

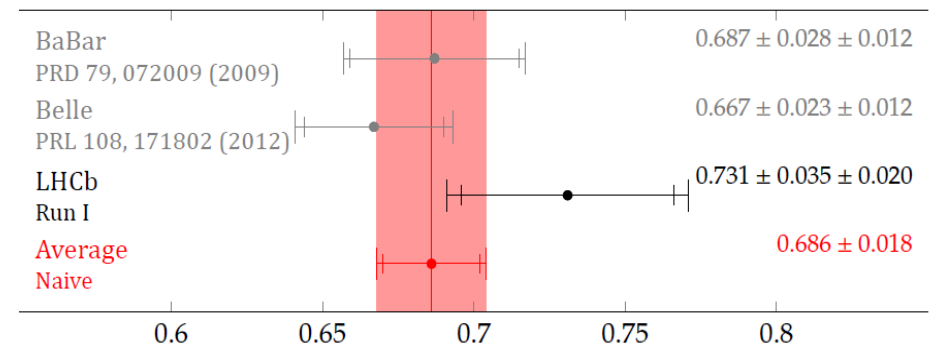
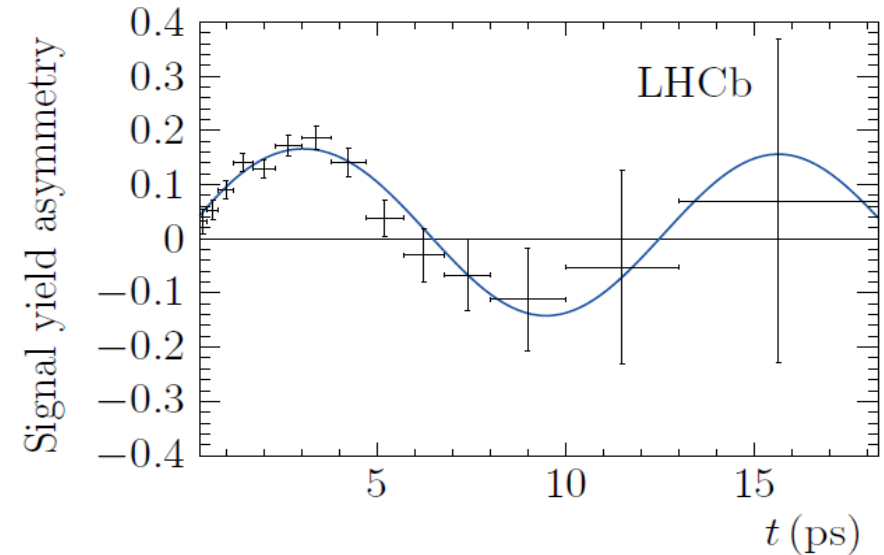
$$\epsilon_{\text{tag}} = 36.5\%, \quad \omega_{\text{miss}} = 35.6\%$$

$$S = 0.731 \pm 0.035 \text{ (stat)} \pm 0.020 \text{ (syst)},$$

$$C = -0.038 \pm 0.032 \text{ (stat)} \pm 0.005 \text{ (syst)},$$

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

- See also [arXiv:1503.07055](https://arxiv.org/abs/1503.07055) $B_s^0 \rightarrow J/\psi K_s^0$
- **Is used to constrain penguin contributions, which are enhanced for this decay since it is CKM suppressed**



$$A_{\Delta\Gamma}(B_s^0 \rightarrow J/\psi K_s^0) = 0.49 \pm_{0.65}^{0.77} \text{ (stat)} \pm 0.06 \text{ (syst)}$$

$$C_{\text{dir}}(B_s^0 \rightarrow J/\psi K_s^0) = -0.28 \pm 0.41 \text{ (stat)} \pm 0.08 \text{ (syst)}$$

$$S_{\text{mix}}(B_s^0 \rightarrow J/\psi K_s^0) = -0.08 \pm 0.40 \text{ (stat)} \pm 0.08 \text{ (syst)}$$

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)

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

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

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

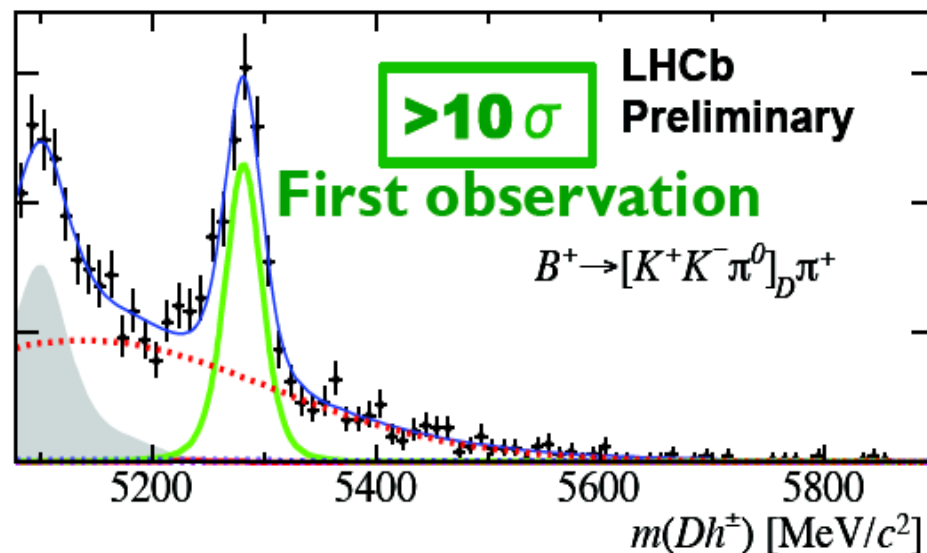
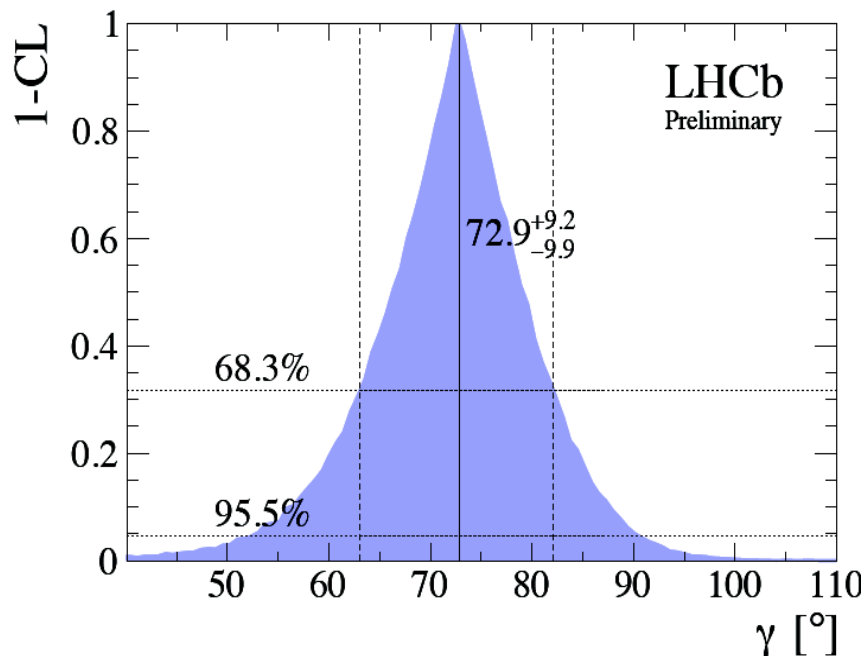
– Consistent with Belle and BaBar results

– More precise than B factories!

– Negligible theoretical uncertainty ($\sim 10^{-6}$)

– **NEW: LHCb-PAPER-2015-014** for $B^\pm \rightarrow [hhh\pi^0]_D h^\pm$

– First evidence of $B^+ \rightarrow [K^+K^-\pi^0]_D K^+$



– First observation of $B^+ \rightarrow [K^+K^-\pi^0]_D \pi^+$

Physics with *b*-tagged 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: $\chi^2_{IP} > 16$; High $p_T > 0.5$ GeV/c

– Inclusive 2-body vertexing:

$$\text{DOCA} < 0.2 \text{ mm}, \quad \chi^2_{\text{vertex}} < 10$$

$$0.4 < m_{\text{vertex}} < m_{B_0} \text{ (all particles assigned to } \pi \text{)}$$

$$\Delta R(\text{PV-SV, jet}) < 0.5$$

– Merge into n-body

$$\text{Not more than 1 track with } \Delta R(\text{trk, jet}) < 0.5$$

$$p_T > 2 \text{ GeV/c}, \quad \text{Flight-Distance-}\chi^2 > 5\sigma$$

$$(\text{PV-SV})/p < 1.5 \text{ mm/GeV}$$

– BDT(bc|udsg), BDT(b|c) $M, M_{\text{cor}}, FD_T^{\text{SV}}, \Delta R(\text{SV, jet}), N_{\text{trk}}^{\text{SV}},$

$$N_{\text{trk}}^{\text{SV}}(\Delta R < 0.5), Q_{\text{SV}}, FD-\chi^2, \sum \chi_{IP}^2$$

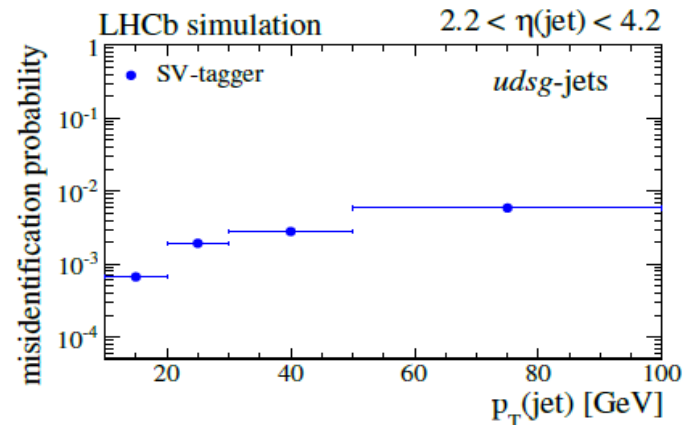
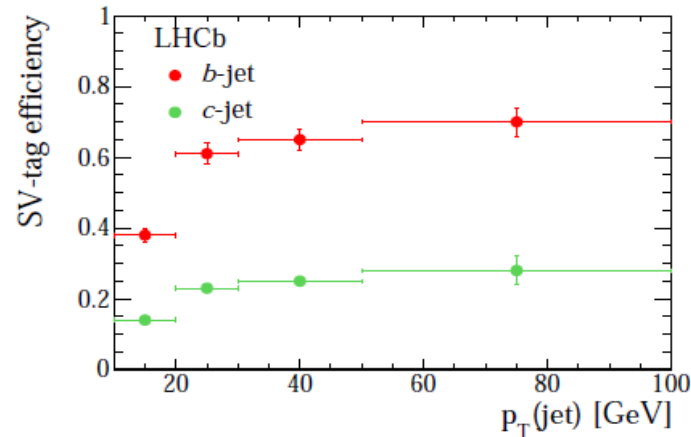
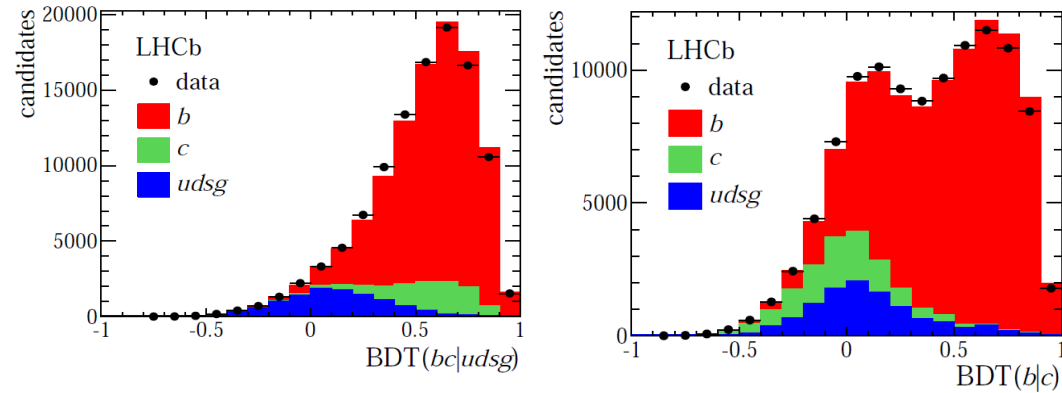
Data samples (tagging):

– Fully reconstructed b-hadron + jet

– Fully reconstructed c-hadron + jet

– $\mu(\text{b,c}) + \text{jet}$

– Prompt isolated high- p_T muon + jet



arXiv:1504.07670

W + c- / b-jet selection

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

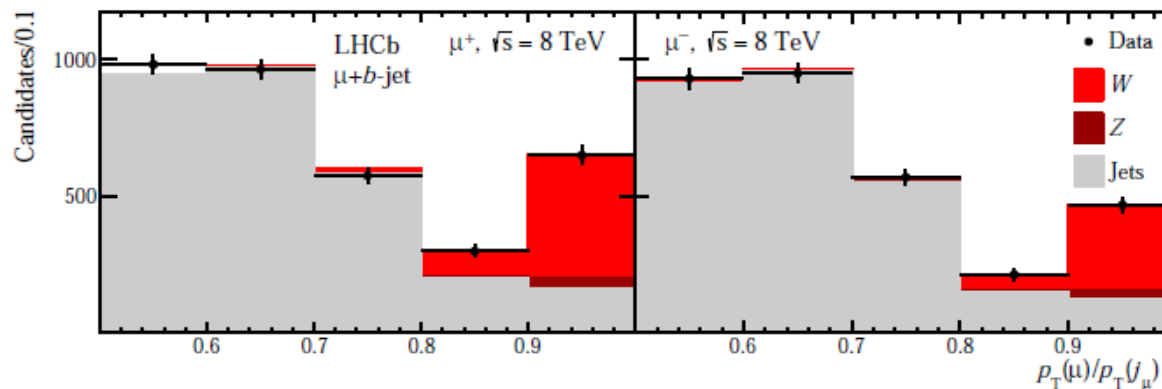
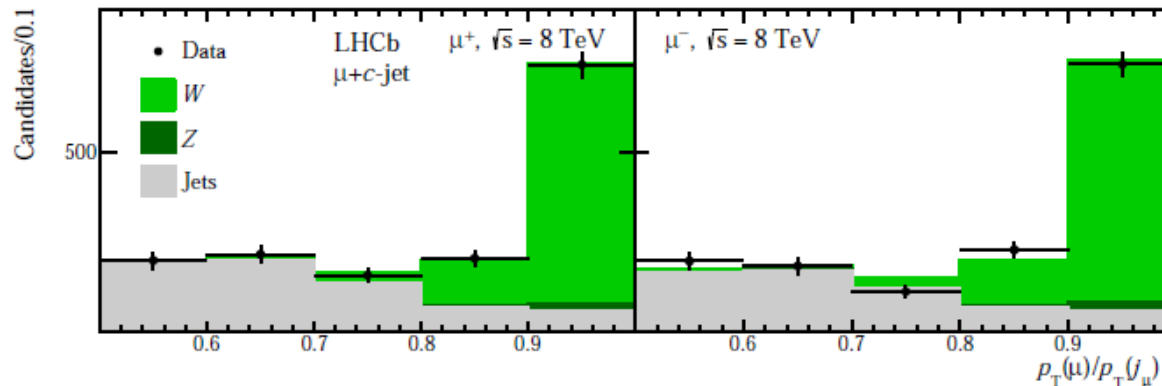
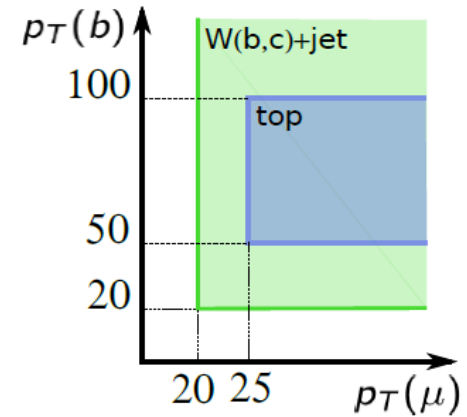
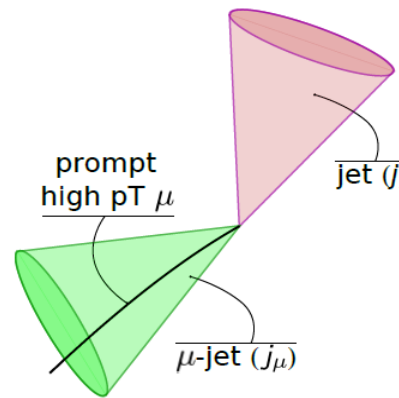
Jets tagged with the SV-tagger.

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

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

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

$$p_T(\mu + j) > 20 \text{ GeV}$$



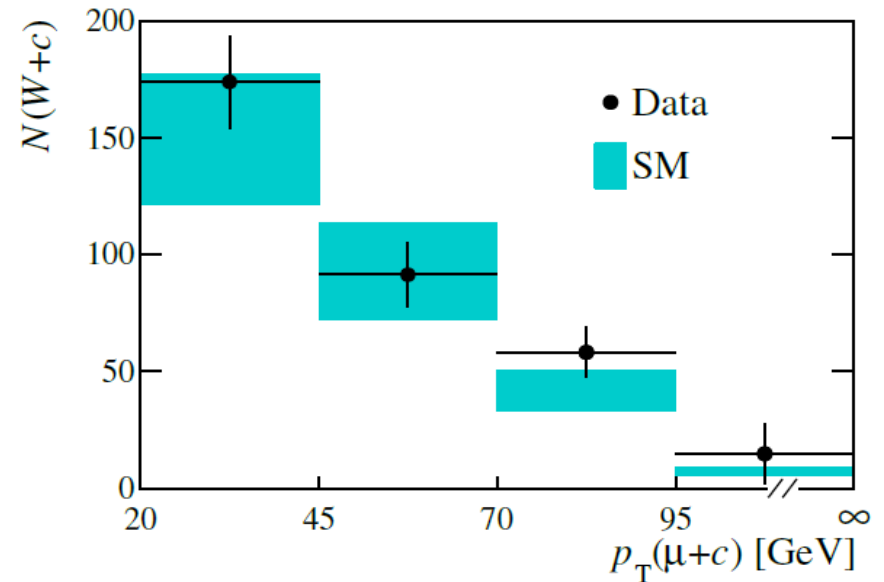
[arXiv:1505.04051](https://arxiv.org/abs/1505.04051)

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

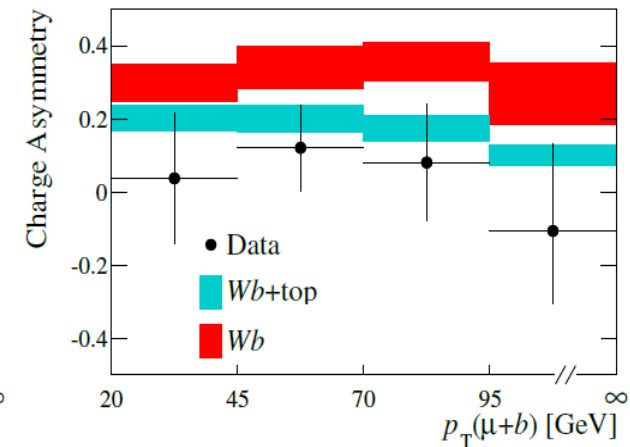
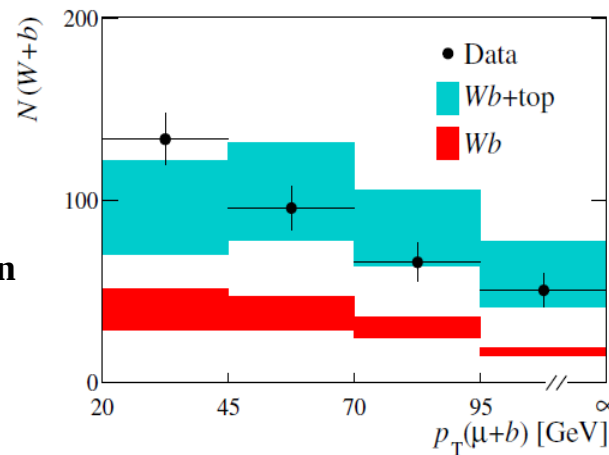
$$\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}$$



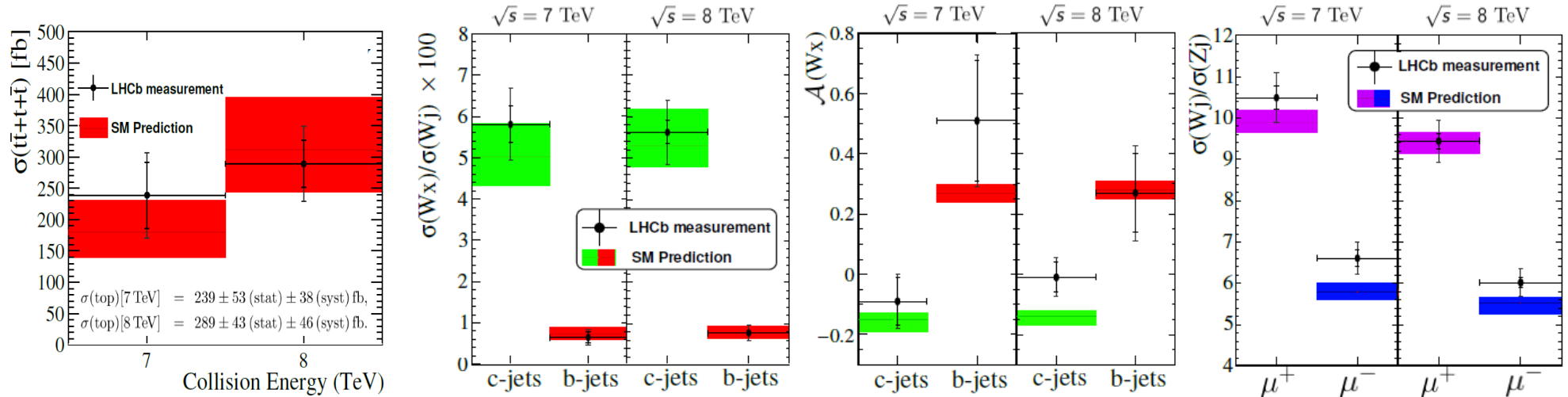
W + b-jet:

- Discrepancy between data and Wb predictions
- Good agreement with $Wb+top$ predictions
- Profile likelihood to compare $Wb+top$ and Wb
- $N(Wb)$ and $\mathcal{A}(Wb)$ -shapes fixed, yields variation
- 5.4σ observation of top production

in forward region



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



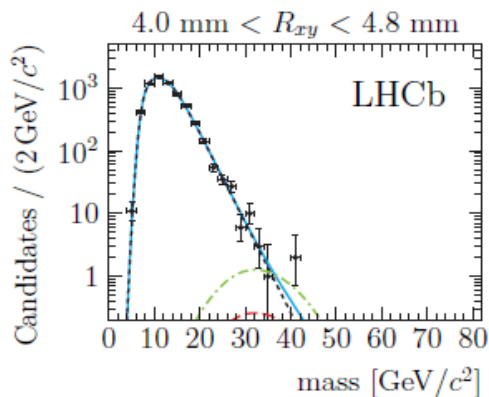
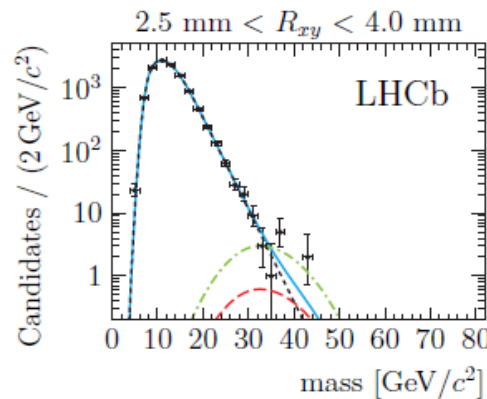
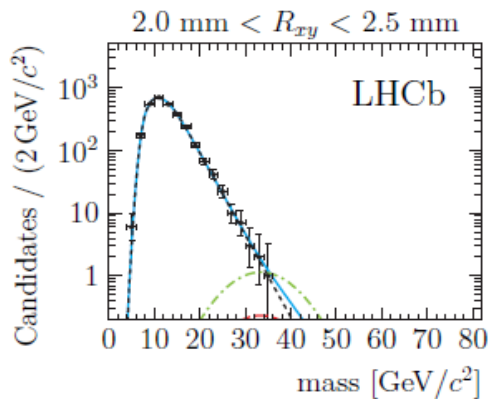
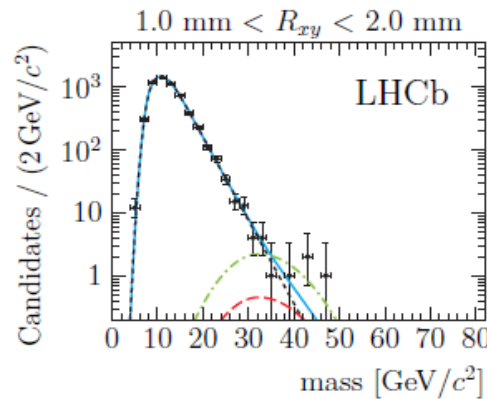
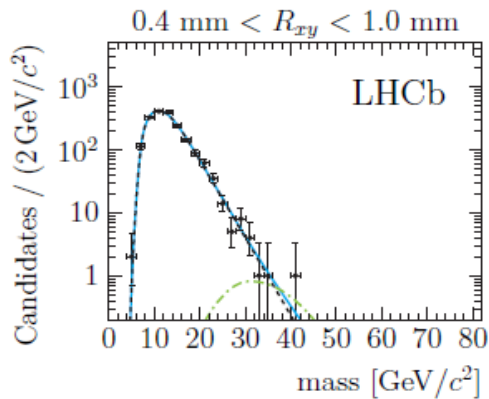
$$\frac{\sigma(Wb+top)}{\sigma(Wj)}_{7\text{ TeV}} = 1.17 \pm 0.13 \pm 0.18\% \text{ (NLO prediction = } 1.23 \pm 0.24\%)$$

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

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

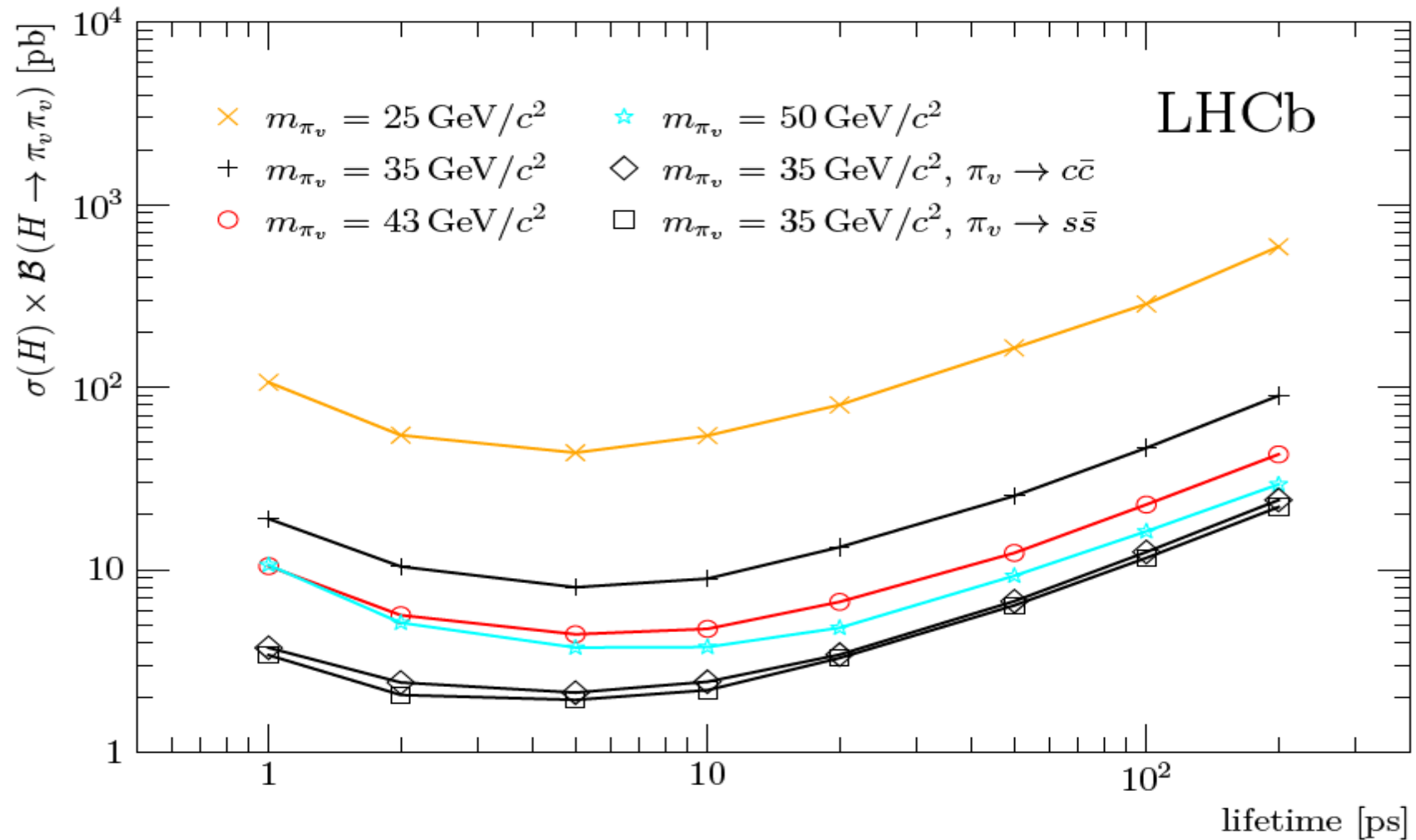


R_{xy} – distance to
interaction region
in transverse plane

- Generic search for heavy $25 < m < 50 \text{ GeV}/c^2$
long-lived $1 < t < 200 \text{ ps}$ particles using
displaced two-jet vertices
- Hidden valley $H \rightarrow \pi_{\nu} \pi_{\nu}$ as benchmark model
- $\sqrt{s} = 7 \text{ TeV}$, $L_{\text{int}} = 0.62/\text{fb}$
- Reconstruct π_{ν} 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

EPJ C 75 (2015) 152

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 $\sim 5 \text{ fb}^{-1}$ at $\sqrt{s} = 13\text{-}14 \text{ TeV}$ 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	$2\beta_s(B_s^0 \rightarrow J/\psi\phi)$	0.025	0.008	~ 0.003
	$2\beta_s(B_s^0 \rightarrow J/\psi f_0(980))$	0.045	0.014	~ 0.01
	α_{sl}^s	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \rightarrow \phi\phi)$	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})$	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)$	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)/\tau_{B_s^0}$	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.025	0.008	0.02
	$s_0 A_{\text{FB}}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$	6 %	2 %	7 %
	$A_1(K\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \rightarrow \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$	8 %	2.5 %	$\sim 10 \%$
Higgs penguins	$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	$\sim 100 \%$	$\sim 35 \%$	$\sim 5 \%$
Unitarity triangle angles	$\gamma(B \rightarrow D^{(*)}K^{(*)})$	4°	0.9°	negligible
	$\gamma(B_s^0 \rightarrow D_s K)$	11°	2.0°	negligible
	$\beta(B^0 \rightarrow J/\psi K_S^0)$	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}	–