Review of recent LHCb results

A.Hicheur
(Universidade Federal do Rio de Janeiro)
LISHEP 2015, Manaus, Amazonas
02-08/08/2015

laboratório de partículas elementares
Universidade Federal do Rio de Janeiro

Outline

- LHCb experiment
- Physics program
- Selected results
- Run II news and further prospects
- Summary

LHCb detector

Forward single-arm spectrometer with warm magnet (possibility to inverse polarity)

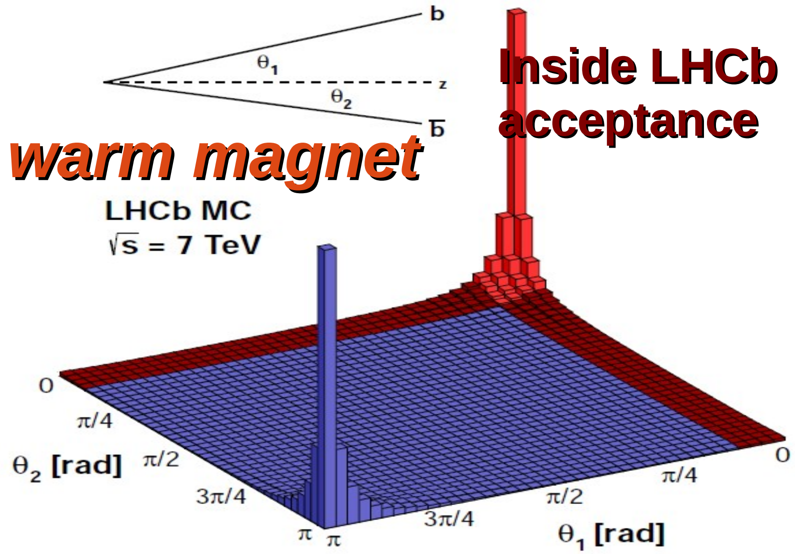
Optimize for b and c hadron studies

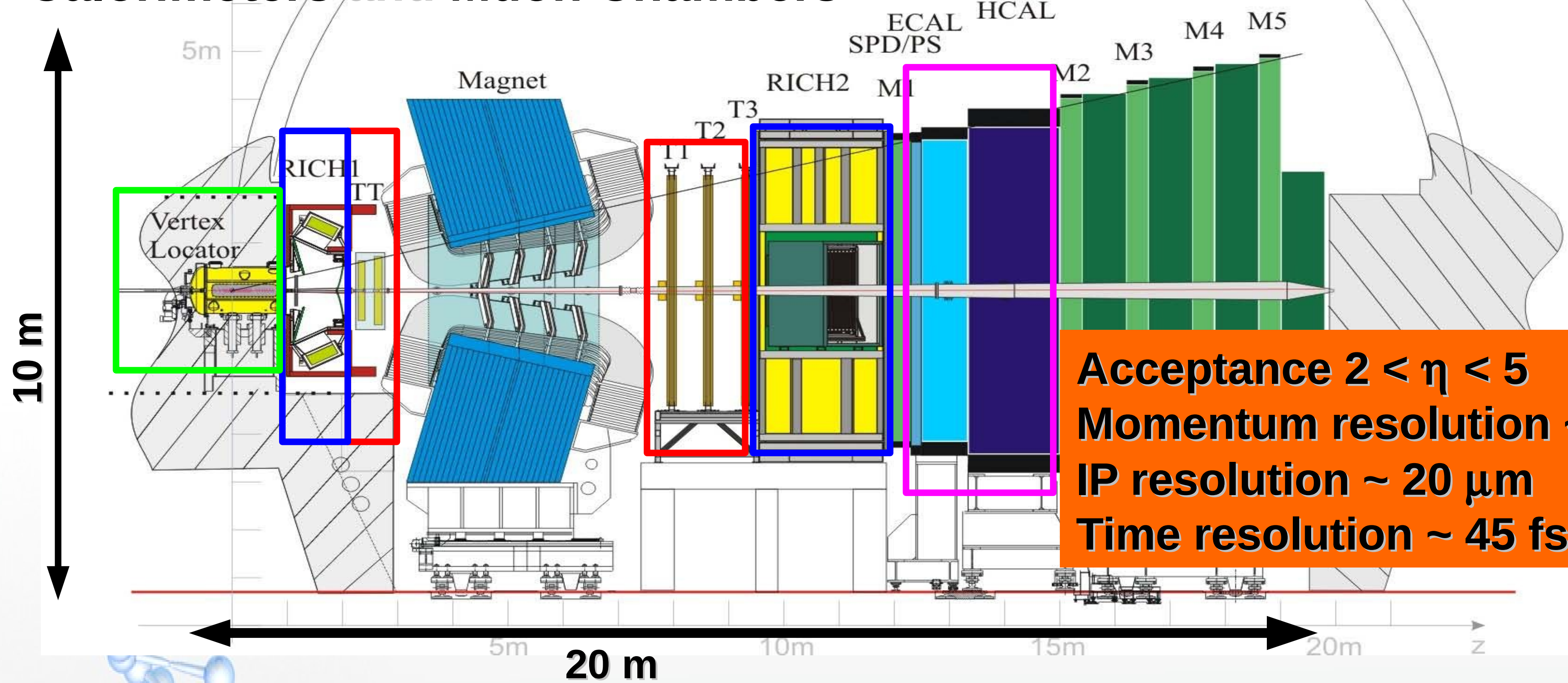
Vertexing

Tracking stations

Particle ID Ring Imaging Cherenkov

Calorimeters and Muon Chambers





Acceptance $2 < \eta < 5$

Momentum resolution ~ 0.5%

IP resolution ~ 20 μm

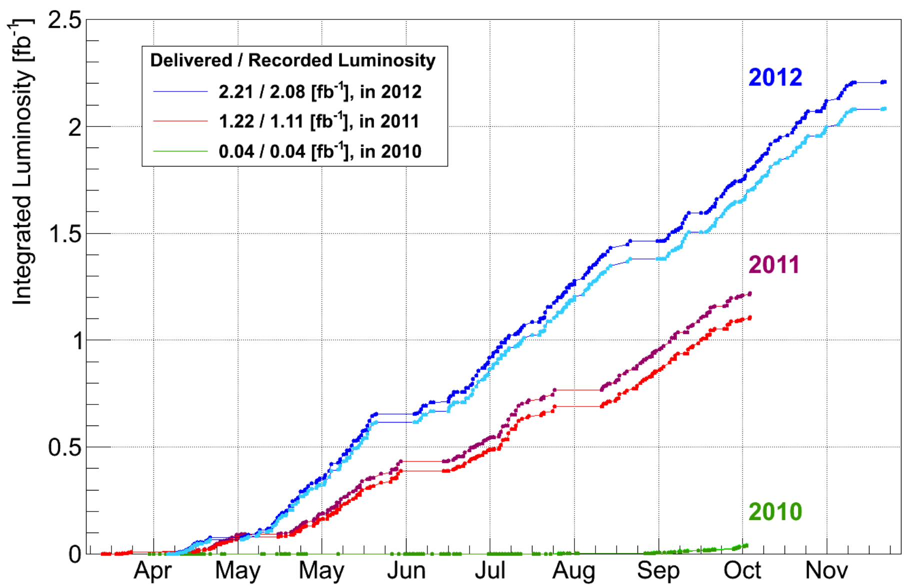
Time resolution ~ 45 fs

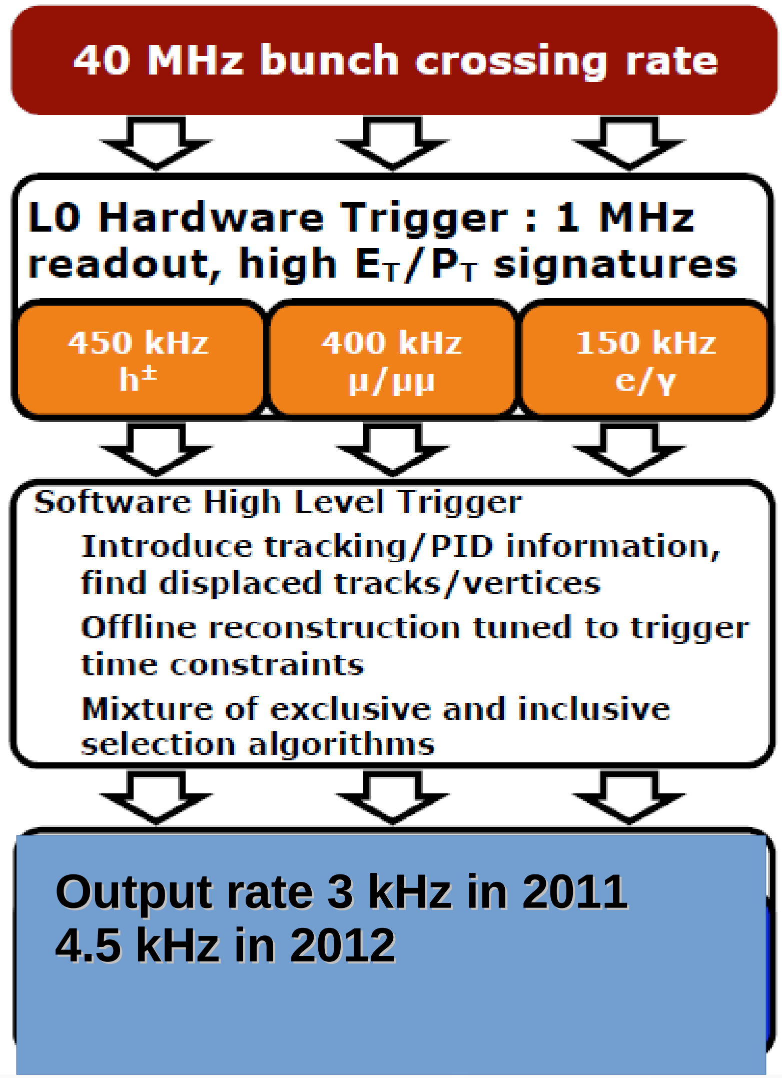
LHCb data for Run I (2011+2012)

10^{11} protons per bunch colliding at 7 (2011) and 8 (2012) TeV

Luminosity at IP8 (LHCb): 2-4 x 10^{32} cm^{-2} s^{-1}
About 1500 charged particles produced at each pp collision

$\sigma(b\bar{b})$ ~ 75 μb @ 7 TeV* in LHCb acceptance
~ 40% B+, 40% B0, ~ 10% Bs
Remaining b baryons, Bc, etc...





* *J. High Energy Phys.08 (2013) 117*

Physics program

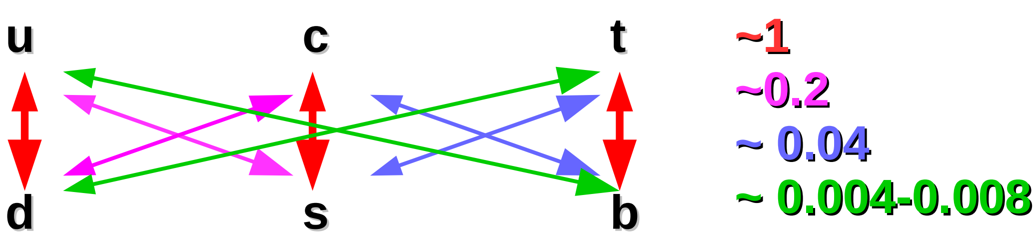
- Rare decays, BSM and exotics
  - see J. Serrano (Fri 07/08) and X. Cid Vidal (Wed 05/08) for details
- CP violation
  - See B. Souza de Paula (Fri 07/08) for details
- Heavy flavours and spectroscopy
- Forward physics: QCD, EW and BSM in the forward region
  - See M. Rangel (later this afternoon) for details
  - See X. Cid Vidal (Wed 05/08) for direct searches on forward Higgs and BSM particles

Selected results

- Rare $b \to s \ell^+ \ell^-$
  - New $B \to \pi\mu\mu$ results on $b \to d \ell^+ \ell^-$ imminently shown at DPF2015 meeting
- Semileptonics: $\Lambda_b \to p \mu \nu$, $B \to D^{(*)} \tau \nu$
- Top physics: first top measurement
- Spectroscopy: multiquark bound states
- Unitarity triangle: γ angle

CKM picture in brief

Weak interaction couples quarks through elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix
Weak eigenstates are different from mass eigenstates = CKM matrix is not diagonal and may relate quarks of different generation



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

Clear hierarchy in the couplings: the further from diagonal, the weaker

Unitarity imposes relations, among which $\sum_k V_{ik} V^*_{jk} = 0$

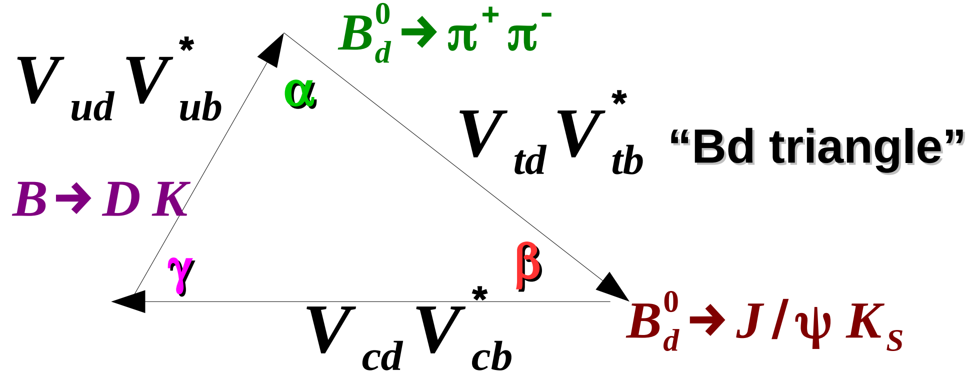
Elements forming sides (and angles) of 3 independent "unitarity" triangles, of which only a couple are of interest for heavy-flavour decays

CKM and unitarity triangles

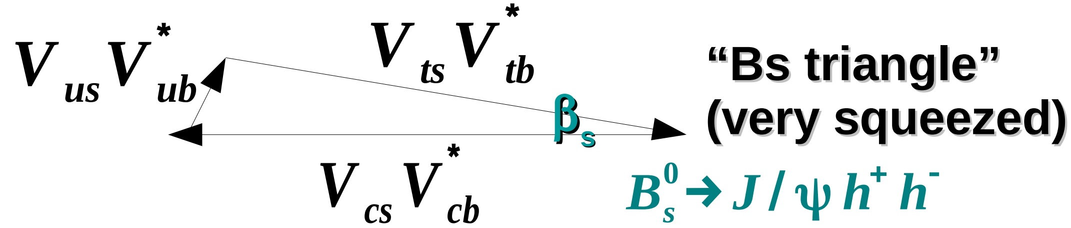
Most interesting relation:

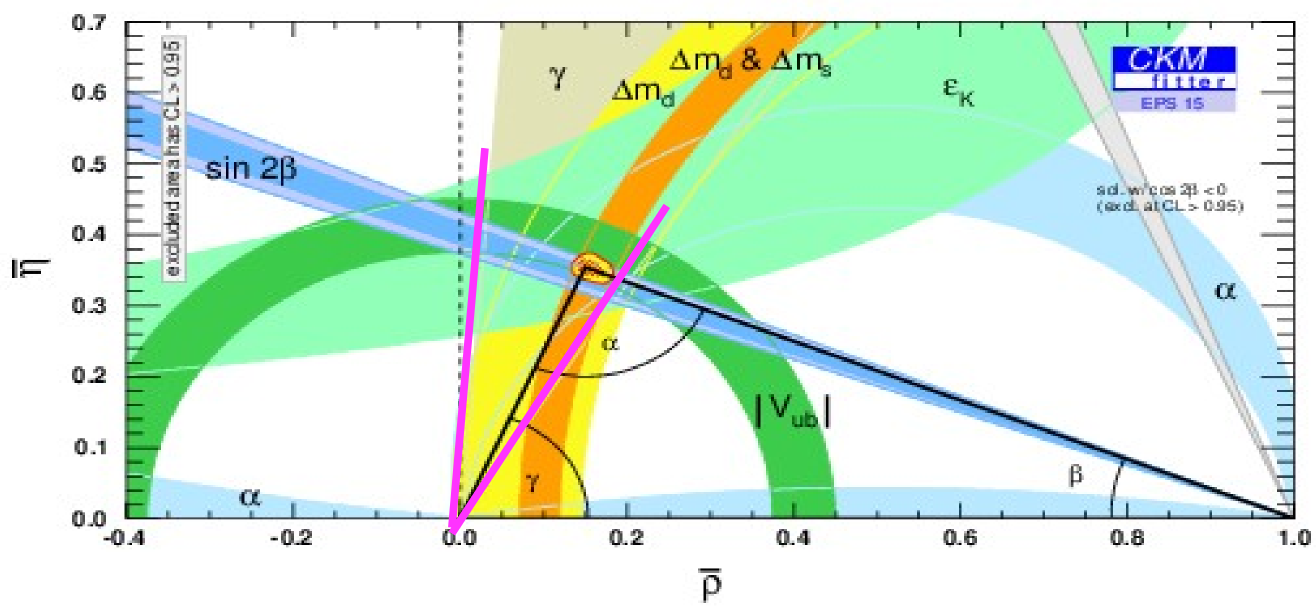
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

Sides usually measured in semileptonic decays and oscillation frequency, angles in CP asymmetries

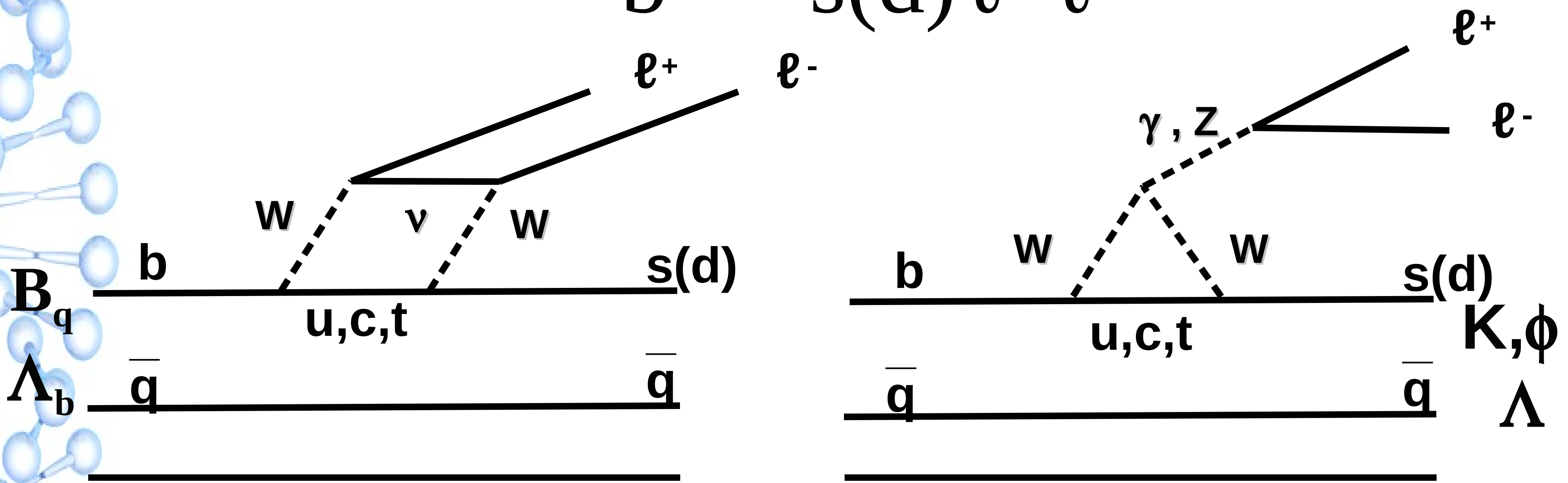


$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0$$





$b \to s(d)\ell^+\ell^-$



New physics can intervene in the loops/boxes

Can be probed through the analysis of the dynamics of the decays

Or testing, e.g., lepton universality $b \to s\, e^+e^- / b \to s\mu^+\mu^-$

Dynamics for $B^0 \rightarrow K^{*0}\mu^+\mu^-$, $B_s \rightarrow \phi\mu^+\mu^-$

$$\frac{1}{d\Gamma/dq^2}\frac{d^3\Gamma}{d\cos\theta_l\, d\cos\theta_K\, d\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\Phi + A_5\sin 2\theta_K\sin\theta_l\cos\Phi + A_6\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\Phi + A_8\sin 2\theta_K\sin 2\theta_l\sin\Phi + A_9\sin^2\theta_K\sin^2\theta_l\sin 2\Phi\Big].$$

$q^2 = \mu^+\mu^-$ invariant mass squared

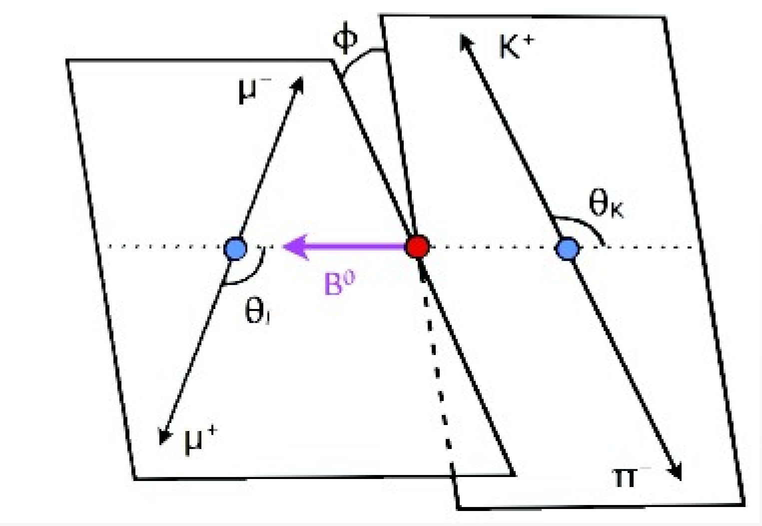
Formula slightly different between K* (self-tagging) and ϕ

F_L: fraction of longitudinal polarization of K*/ϕ

$A_6 \sim A_{FB}$ = forward-backward asymmetry of the dimuon system

$A_5 = S_5$ in the case of K*

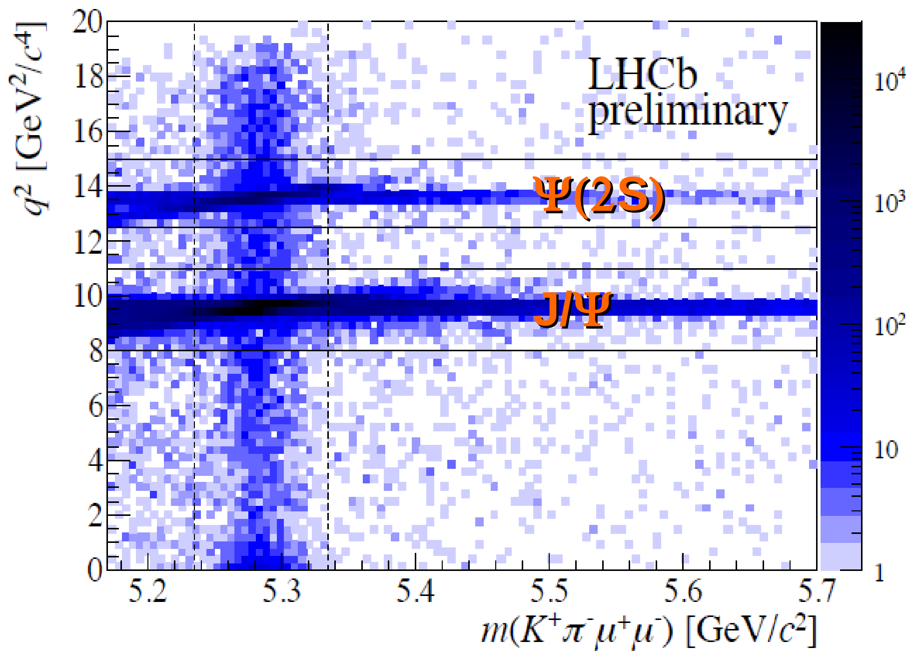
They depend on B →K*/ϕ form factors and Wilson Coefficients of the OPE



$B \rightarrow X \mu^+\mu^-$ events distribution

LHCb-CONF-2015-002

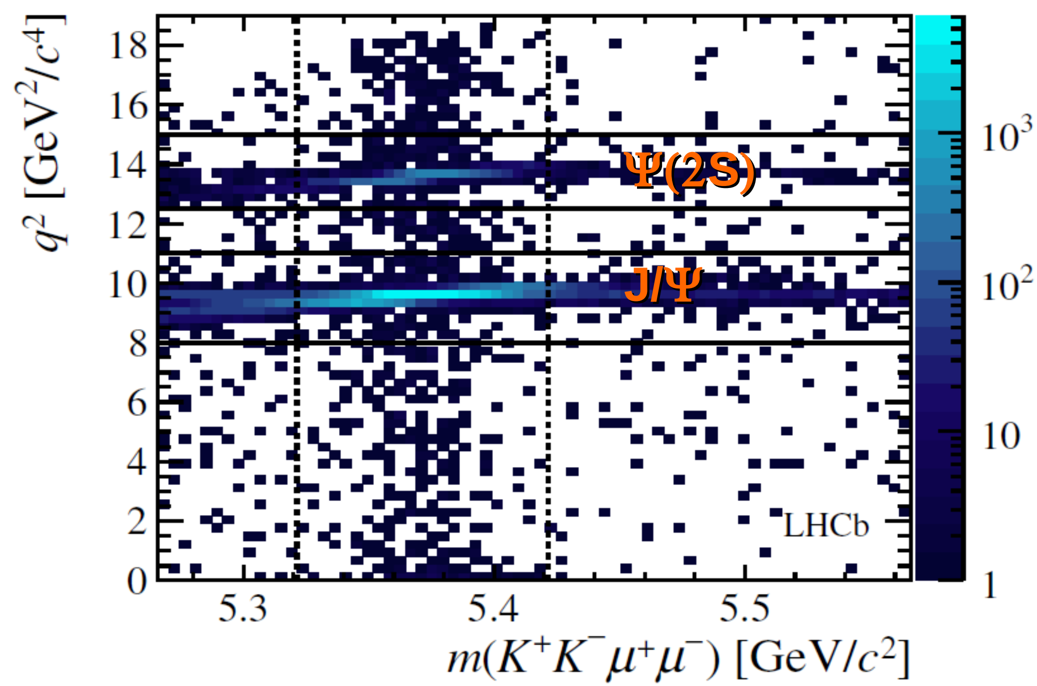
$B^0 \rightarrow K^{*0}\mu^+\mu^-$



Signal yield excluding charmonia: 2.4 k evts

LHCb-PAPER-2015-023

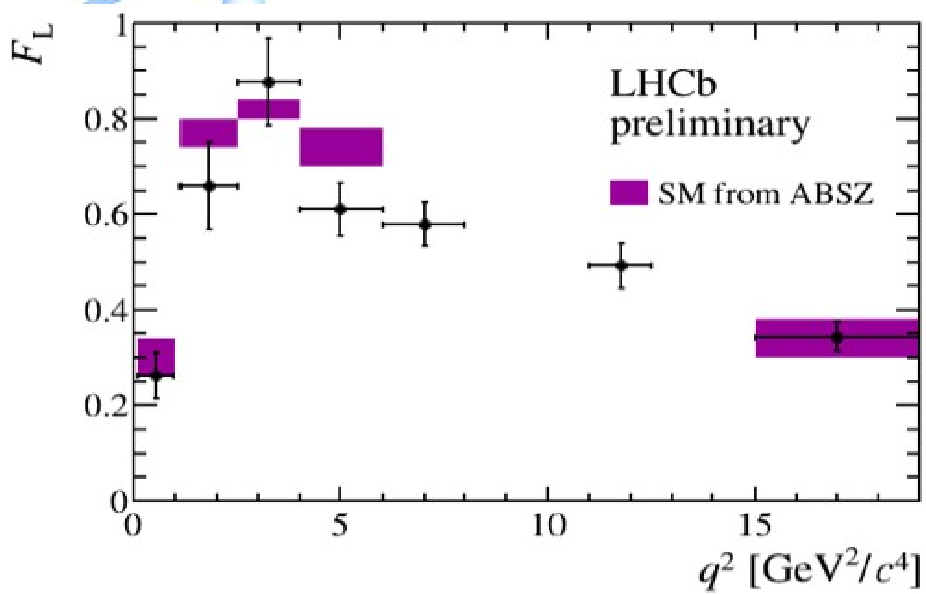
$B_s \rightarrow \phi\mu^+\mu^-$

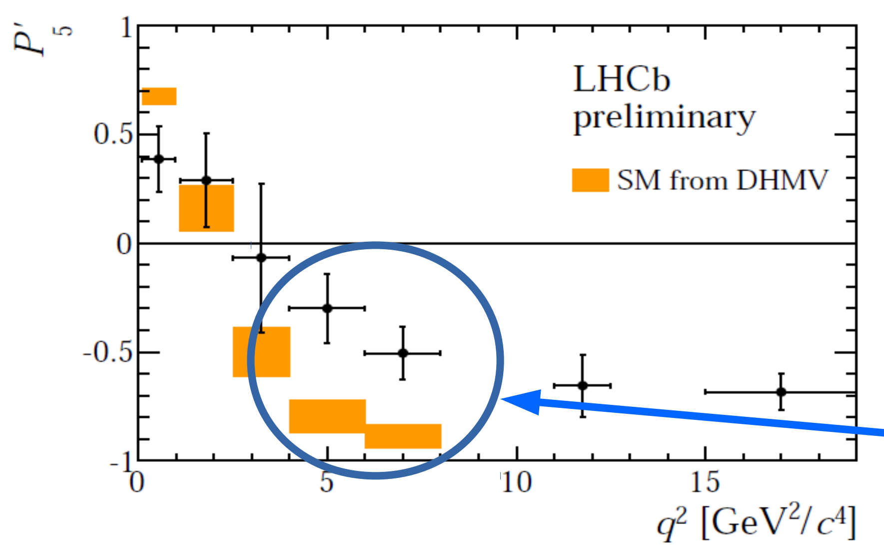


Signal Yield excluding charmonia: ~400 evts

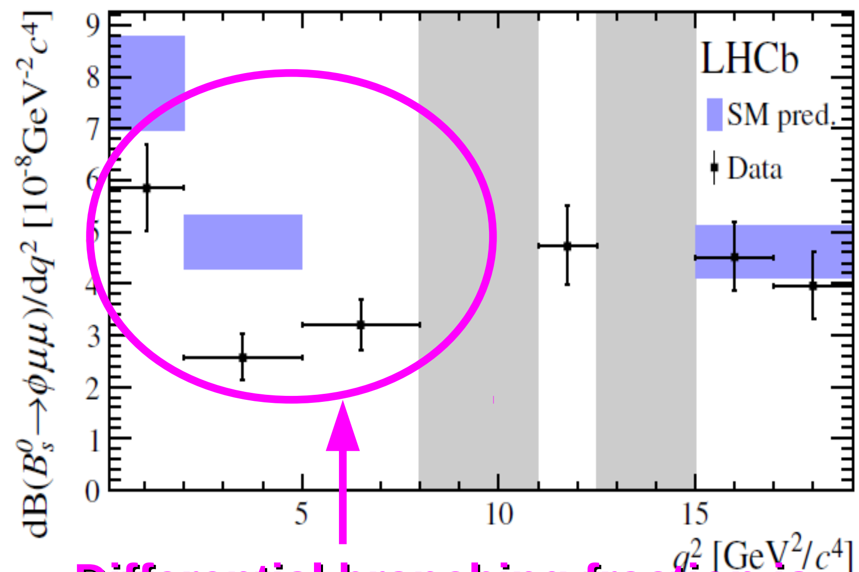
B → X $\mu^+\mu^-$ results

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





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



Differential branching fraction is 3.5σ below SM prediction in the lower q half, no discrepancy for the angular variables with this statistics

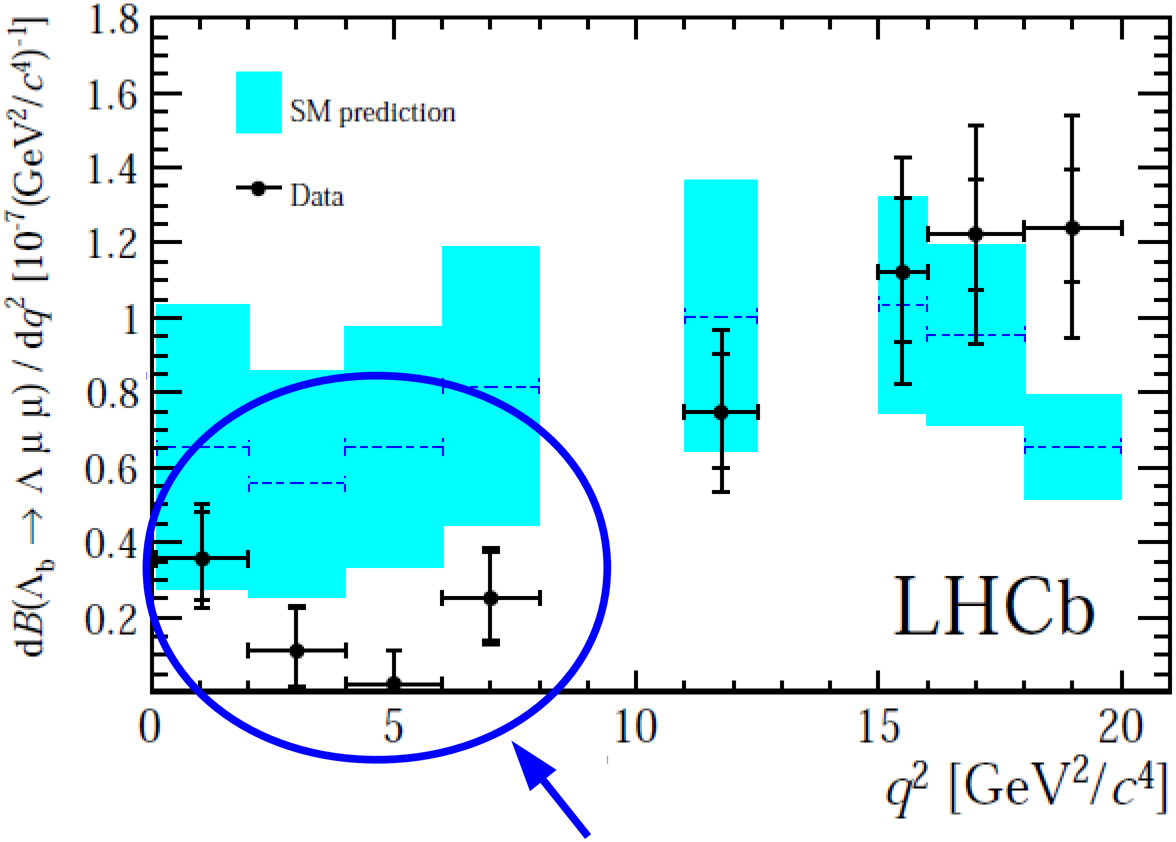
$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Form-factor independent

3.7σ combined difference with SM

$\Lambda_b \to \Lambda \mu^+\mu^-$

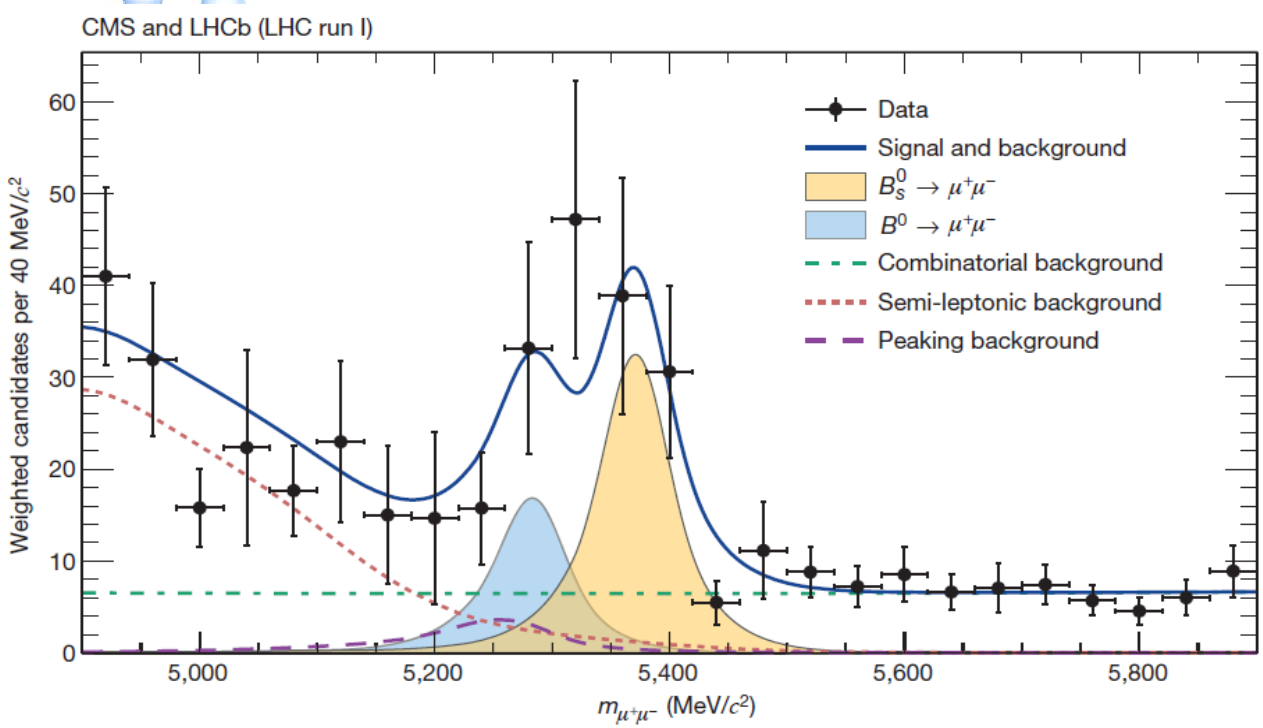
LHCb-PAPER-2015-009, arXiv:1503.07138

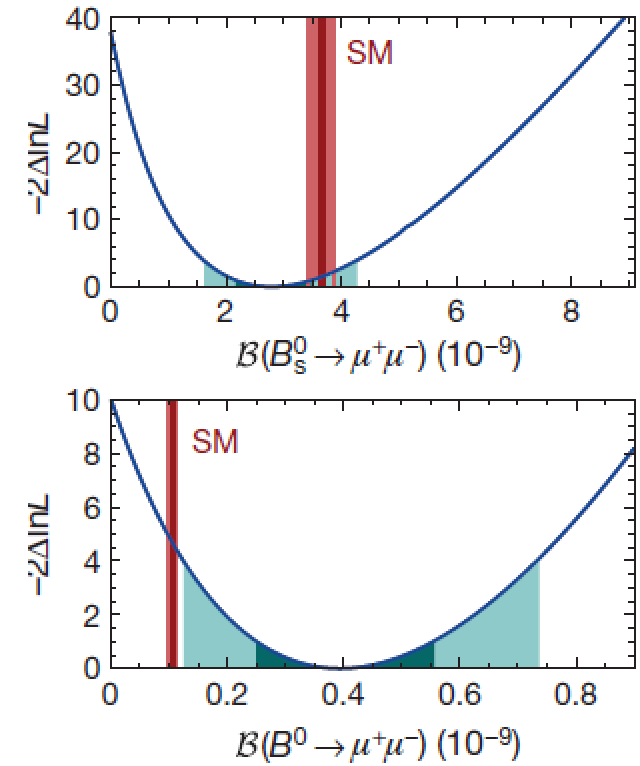


Similar as in $B_s \to \phi\mu^+\mu^-$!

$B_{s,d} \rightarrow \mu\mu$

Nature 522, 68-72 (04 June 2015)





No significant deviation from SM yet (ratio of Bd/Bs is still 2,1σ within SM)

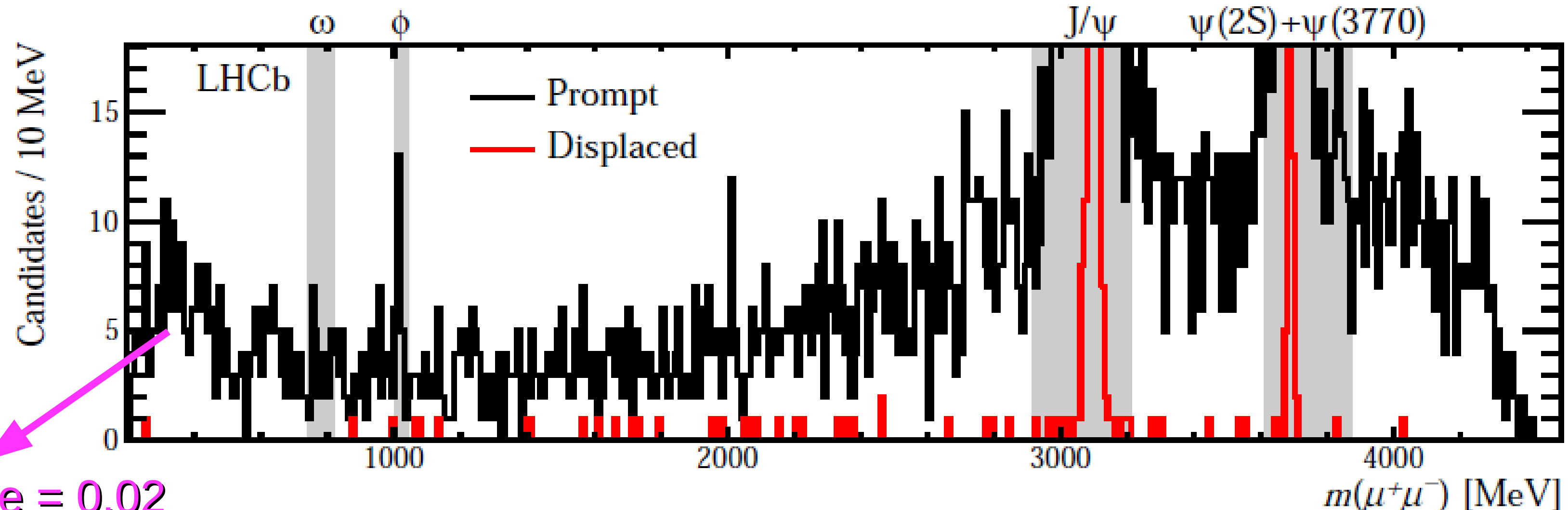
Hidden sector bosons $B^0 \rightarrow K^*\chi(\rightarrow\mu^+\mu^-)$

LHCb-PAPER-2015-036 in preparation

Theoretical models predicting new particle to couple to SM particle through mixing with Z, H, γ, ν

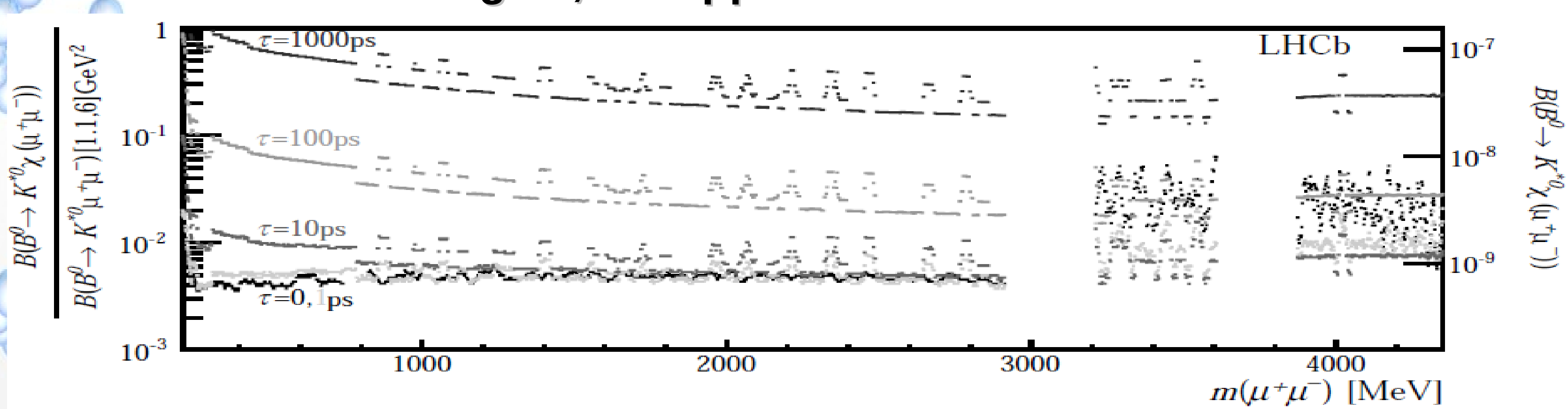
Short (axion-like PRD81(2010)034001, DM mediator PLB727(2013)) vs long (inflaton JHEP1005(2010)010) lifetime predictions

Typical mass < O(1 GeV) and lifetime coverage up to 10^{-8} s

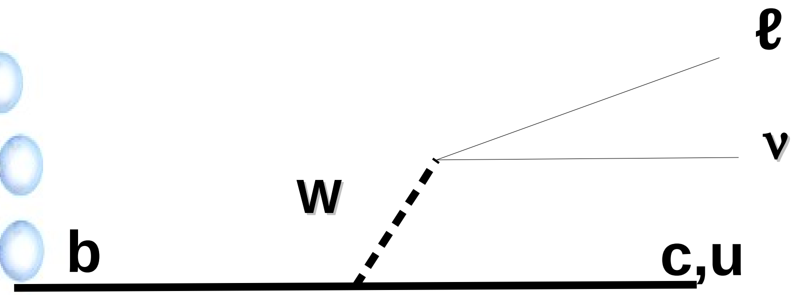


p-value = 0,02

No hint of signal, set upper limit vs lifetime and mass:

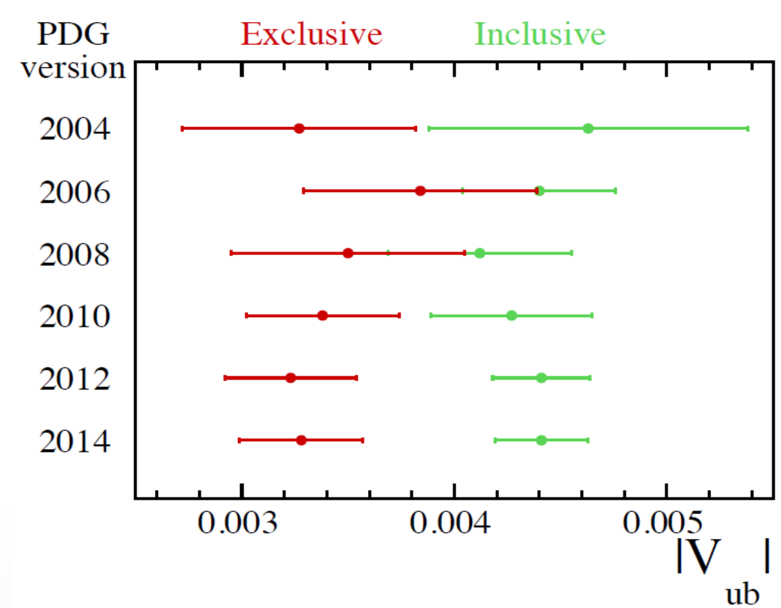


Semileptonics



Theoretically well-understood in the SM
Decays to light leptons well-measured by B factories
a) Not as good for τ lepton
b) Good way to extract V_{qb} CKM element

a) Any new (charged) intermediate boson/mediator would couples preferentially to τ: LHCb studied $B^0 \to D^{*+} \tau \nu$ / $B^0 \to D^{*+} \mu \nu$
(LHCb-PAPER-2015-025, arXiv:1506.08614)



b) Use of $b \to u \mu \nu$ to improve $|V_{ub}|$ (relative uncertainty still ~ 12-13%) + solve the tension between measurements from exclusive $B \to \pi \mu \nu$ and inclusive $B \to X_u \mu \nu$:

Use of $\Lambda_b \to p \mu \nu$ (LHCb-PAPER-2015-013, arXiv:1504.01568)

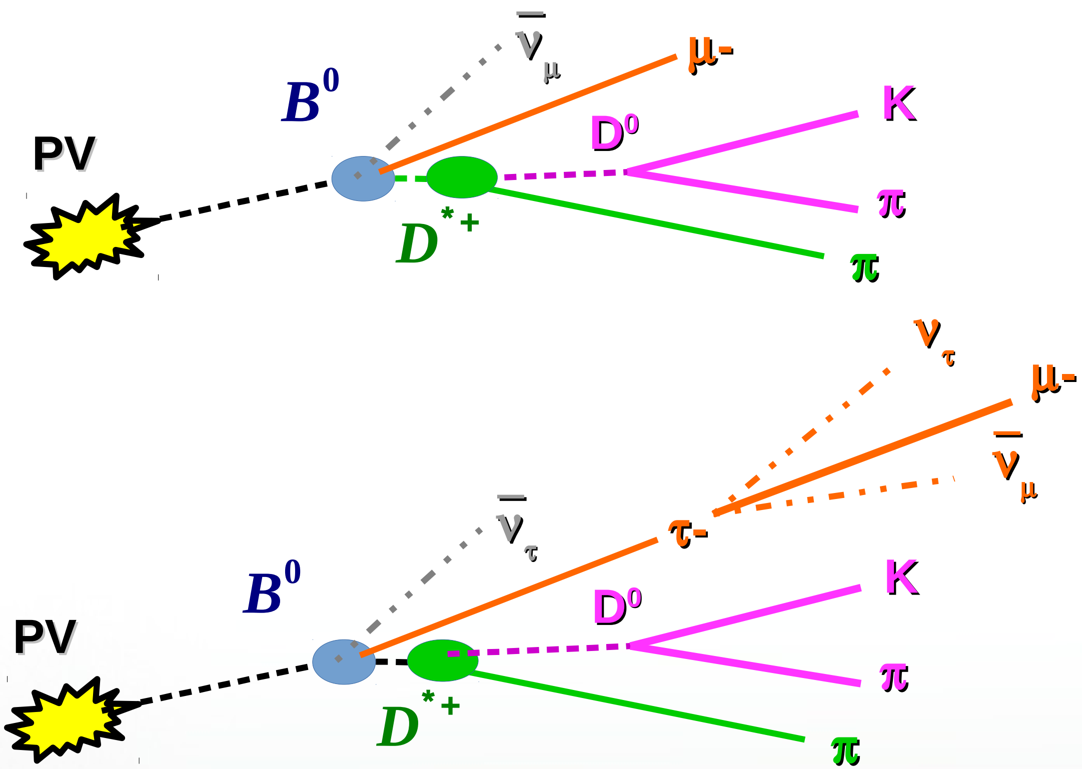
$\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$

Measure: $$R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)}$$

Using τ decay:

$$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$$

= 0.252 in SM (PRD 85094025 (2012)), with very good precision



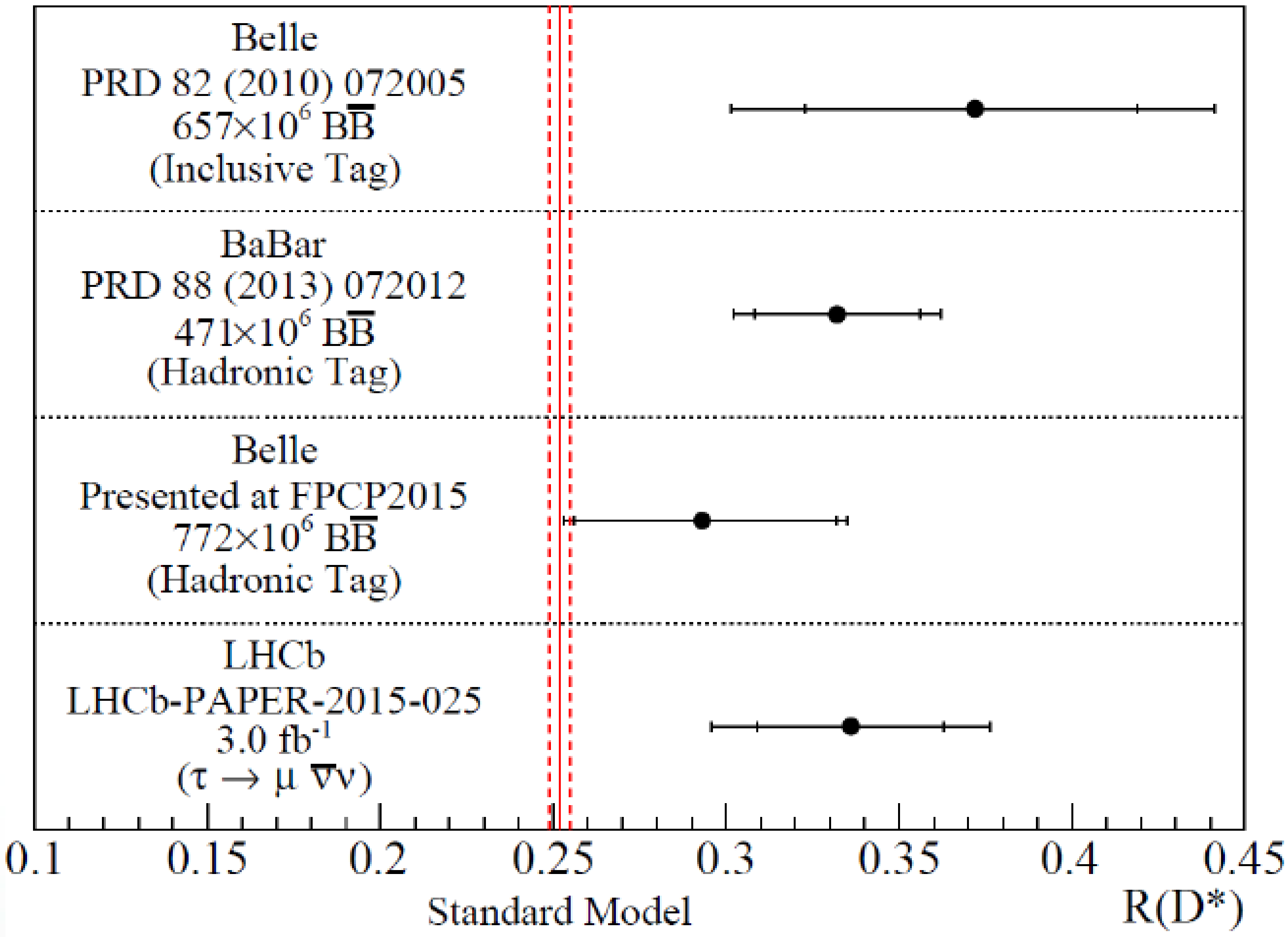
Very specific topologies + use of missing mass, muon energy and momentum transfer q

LHCb-PAPER-2015-025, arXiv:1506.08614

R(D*) result

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

Follows historical trend, above SM prediction by ~ 2.1σ



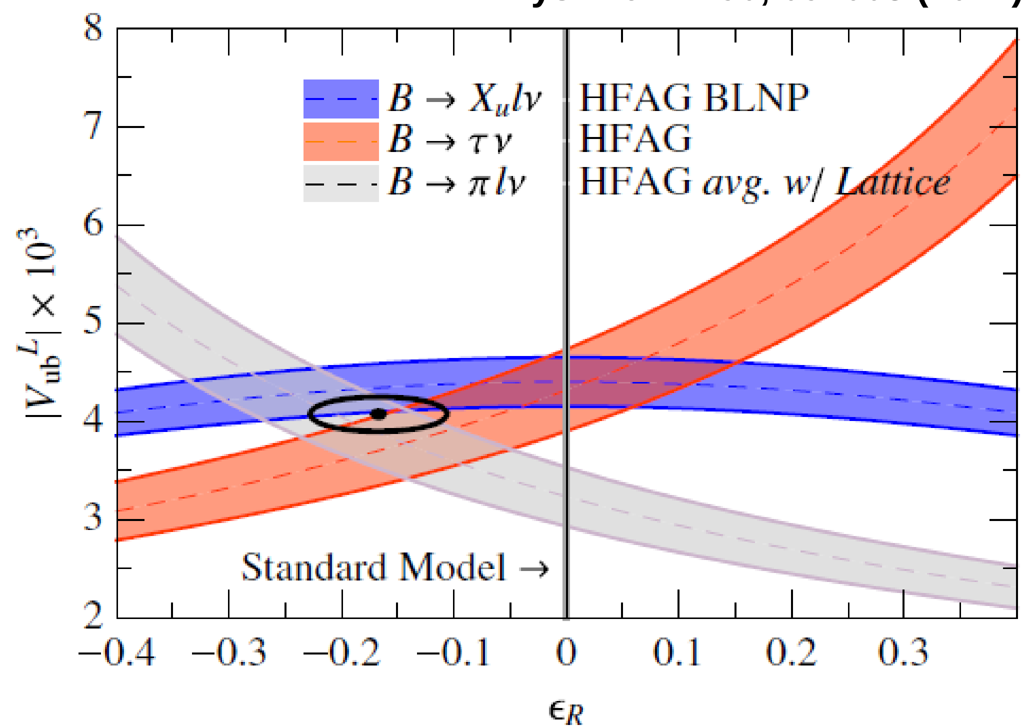
LHCb-PAPER-2015-013, arXiv:1504.01568

Nature Physics (2015) doi:10.1038/nphys3415

$\Lambda_b \rightarrow p\,\mu^- \bar{\nu}_\mu$

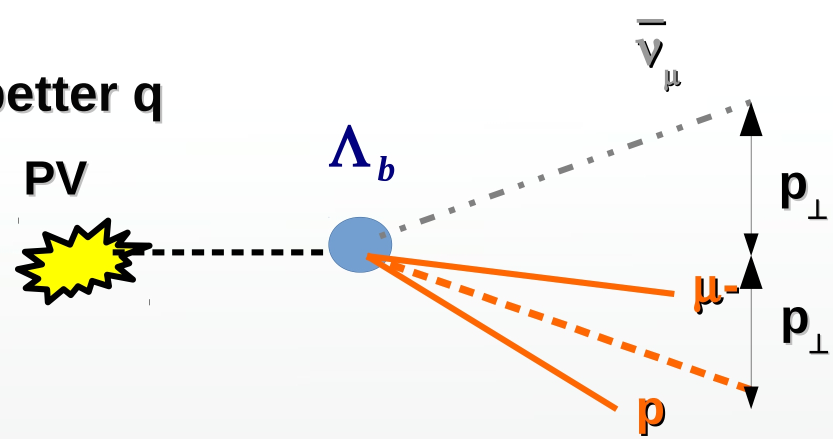
Phys. Rev. D 90, 094003 (2014)

- **Help clarify the debate on $|V_{ub}|$ and the tension between inclusive and exclusive measurements**
  - Fit the ε_R dependence on additional left-handed V+A current →



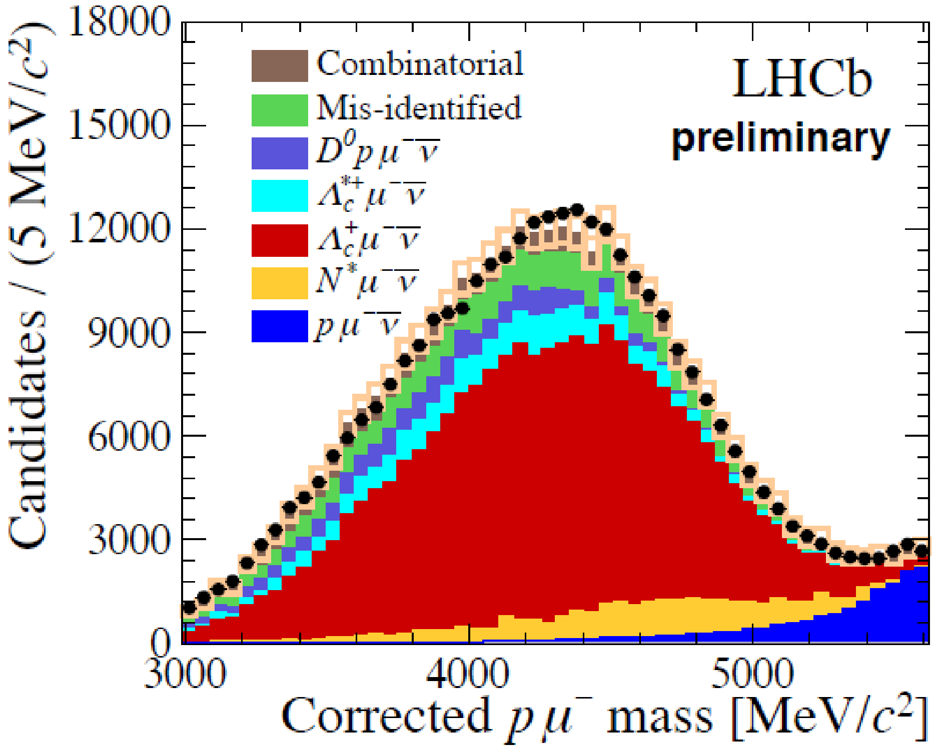
- **Experimentally:**
  - use $\Lambda_b \rightarrow \Lambda_c\,\mu^- \bar{\nu}_\mu$ as a normalization channel to minimize systematics
    - Derive $|V_{ub}|/|V_{cb}|$
  - Momentum transfer q and corrected mass as analysis variables
  - Fit corrected mass at high q^2 (better q determination)

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

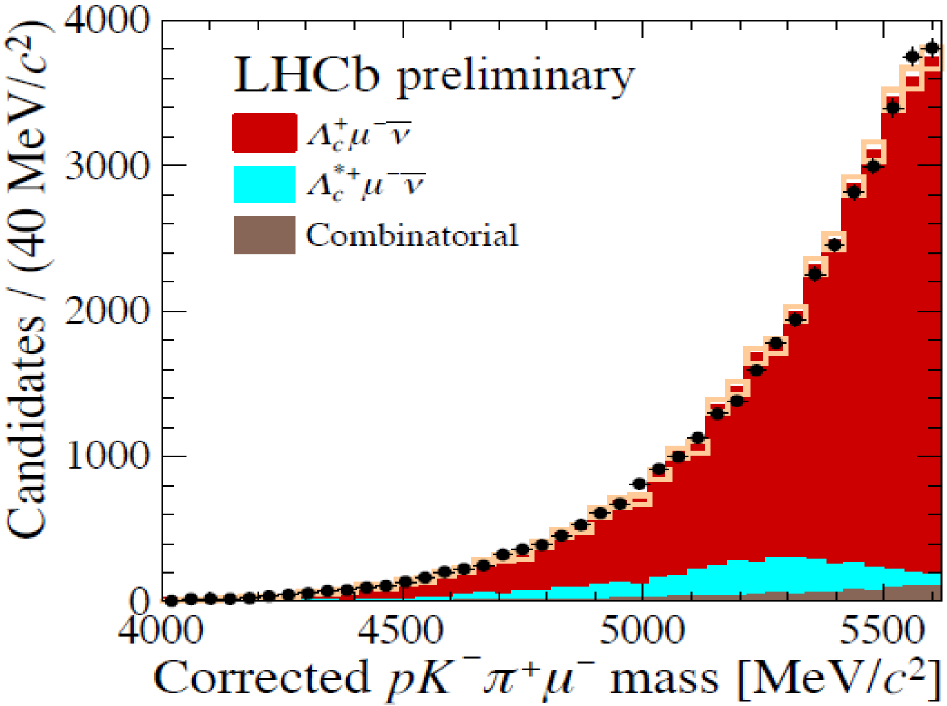


$\Lambda_b \rightarrow p\,\mu^- \bar{\nu}_\mu$ fits

Signal



Normalization channel $\Lambda_b \rightarrow \Lambda_c\,\mu^- \bar{\nu}_\mu$



First observation with the yield $N(\Lambda_b \rightarrow p\,\mu^- \bar{\nu}_\mu) = 17687 \pm 733$

Yield ratio is then corrected for efficiency ratio to derive CKM elements

$\Lambda_b \to p\,\mu^- \bar{\nu}_\mu$ - V_{ub}

Using result from lattice QCD calculations arXiv:1503.01421:

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\int_{15\,\mathrm{GeV}^2}^{q^2_{\max}} \frac{d\Gamma(\Lambda_b \to p\,\mu^- \bar{\nu}_\mu)}{dq^2} dq^2}{\int_{7\,\mathrm{GeV}^2}^{q^2_{\max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\,\mu^- \bar{\nu}_\mu)}{dq^2} dq^2} (0.68 \pm 0.07)$$

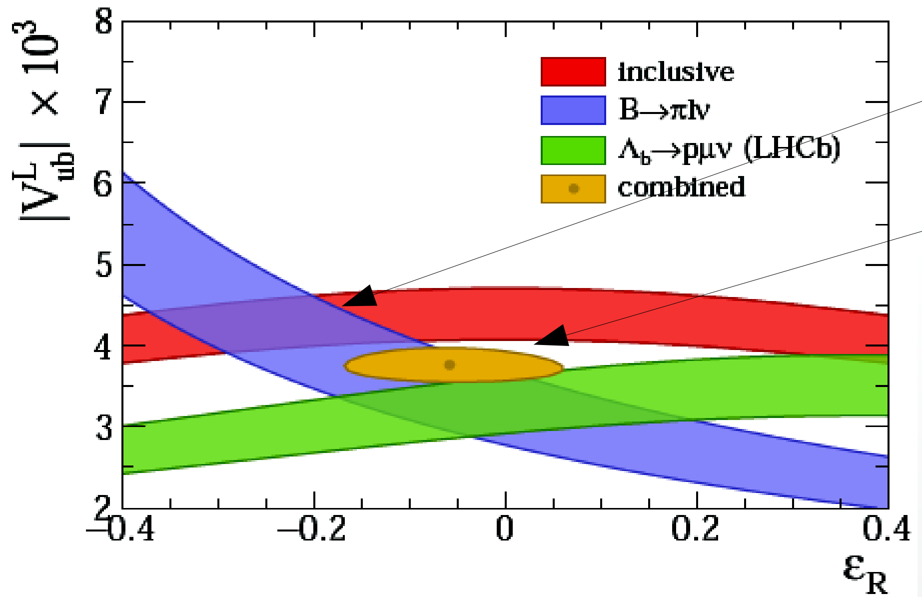
One gets:

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\mathrm{expt}) \pm 0.004(\mathrm{lattice})$$

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

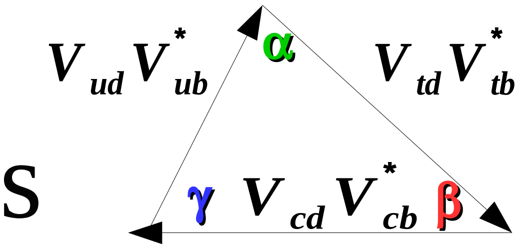
I) inclusive/exclusive mismatch confirmed

II) Fit to the fraction of right-handed current:
$p\mu\nu$ has different dependency from $\pi\mu\nu$ due to proton spin. LHCb measurement does not support significant right-handed current

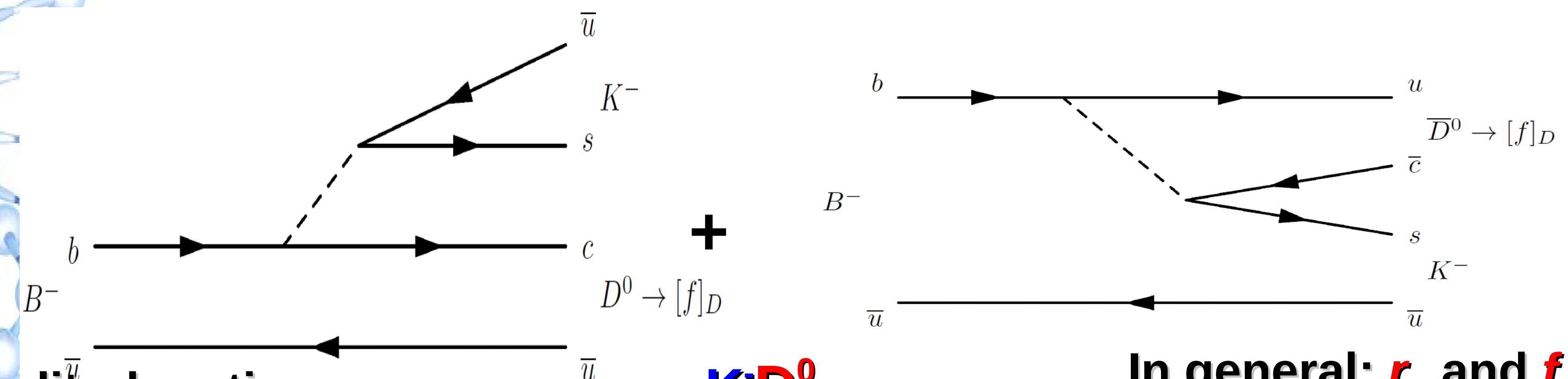


$$\gamma = arg\left(\frac{-V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$$

γ angle from trees

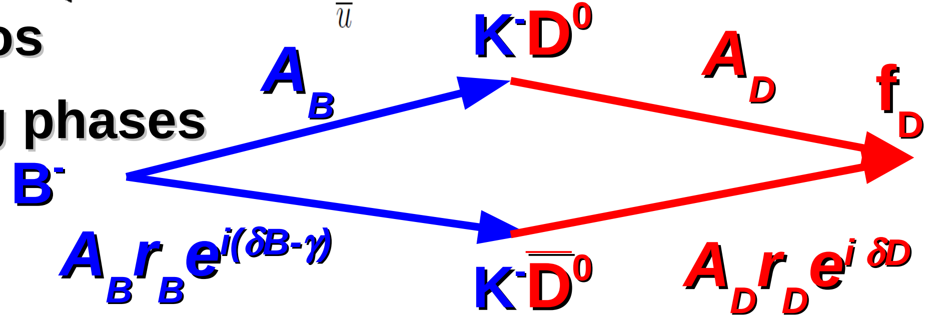


- Use interfering amplitudes in tree-level B→DK(*)(h,hh) decays



r_i: amplitude ratios

δ_i: relative strong phases



<u>In general</u>: r_D and f_D used as external inputs (e.g. from CLEO-c data)

- Fits use ratios of allowed/suppressed BF + asymmetries
- For multibody D decays, dilution factor due to δ_D variation across phase space
- Compare to γ from loop diagrams: mismatch? BSM particles in the loop?
- Numerous LHCb analyses already published or on-going, several new channels adding up more information
  - We will see two recent examples of such novelties

Recently added decays modes for γ

$B^- \to D K^-$ with $D \to h^+h^-\pi^0$ and $D \to K^+\pi^-\pi^0$

Recent determination of CP-even contents **F** of $D \to h^+h^-\pi^0$ - CLEO-c, PLB740 (2015) 1

$[h^+h^-\pi^0]K$ to $[h^+h^-\pi^0]\pi$ ratio and $[h^+h^-\pi^0]K$ CP asymmetries used to extract observables:

$$R(h^+h^-\pi^0) = 1 + (r_B)^2 + (2F(h^+h^-\pi^0) - 1)\, 2 r_B \cos\delta_B \cos\gamma$$

$$A_{CP}(h^+h^-\pi^0) = (2F(h^+h^-\pi^0) - 1)\, 2 r_B \sin\delta_B \sin\gamma / R(h^+h^-\pi^0)$$

$B^- \to D K^-\pi\pi$ with $D \to h^+h^-, h'^+h^-$

Generalization of techniques from $\mathbf{B^- \to D K^-}$ to $\mathbf{B^- \to D X_s}$ **states**

κ : dilution factor

$$\Gamma(B^- \to [h^-h^+]_D X_s^-) \propto 1 + r_B^2 + 2\kappa r_B \cos(\delta_B - \gamma)$$

$$\Gamma(B^+ \to [h^-h^+]_D X_s^+) \propto 1 + r_B^2 + 2\kappa r_B \cos(\delta_B + \gamma)$$

$$\Gamma(B^- \to [K^+\pi^-]_D X_s^-) \propto r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D - \gamma)$$

$$\Gamma(B^+ \to [K^-\pi^+]_D X_s^+) \propto r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D + \gamma)$$

$$\Gamma(B^- \to [K^-\pi^+]_D X_s^-) \propto 1 + (r_B r_D)^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D - \gamma)$$

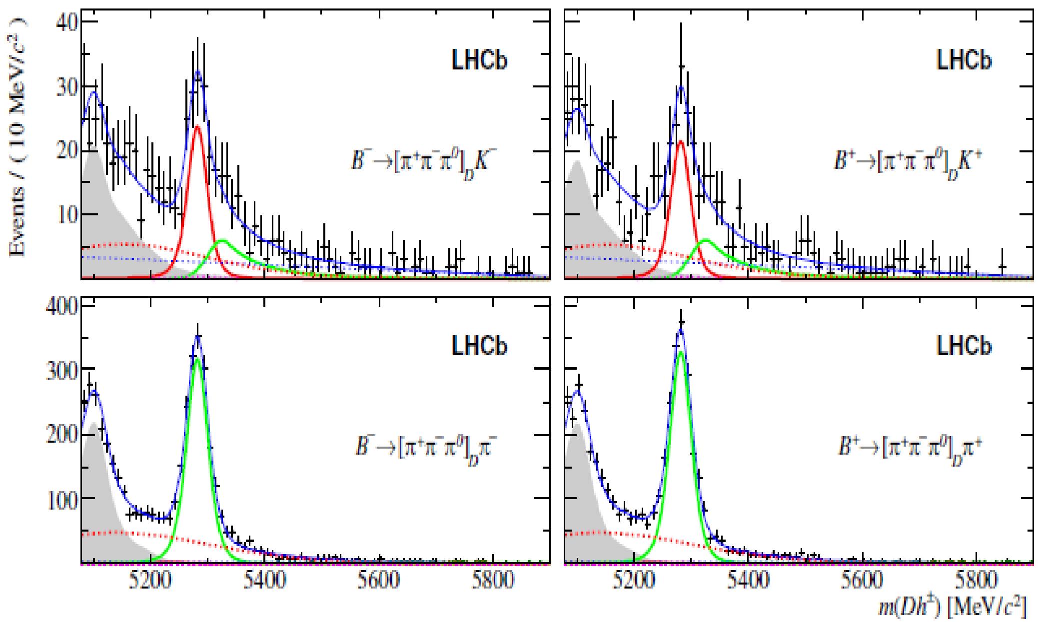
$$\Gamma(B^+ \to [K^+\pi^-]_D X_s^+) \propto 1 + (r_B r_D)^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D + \gamma)$$

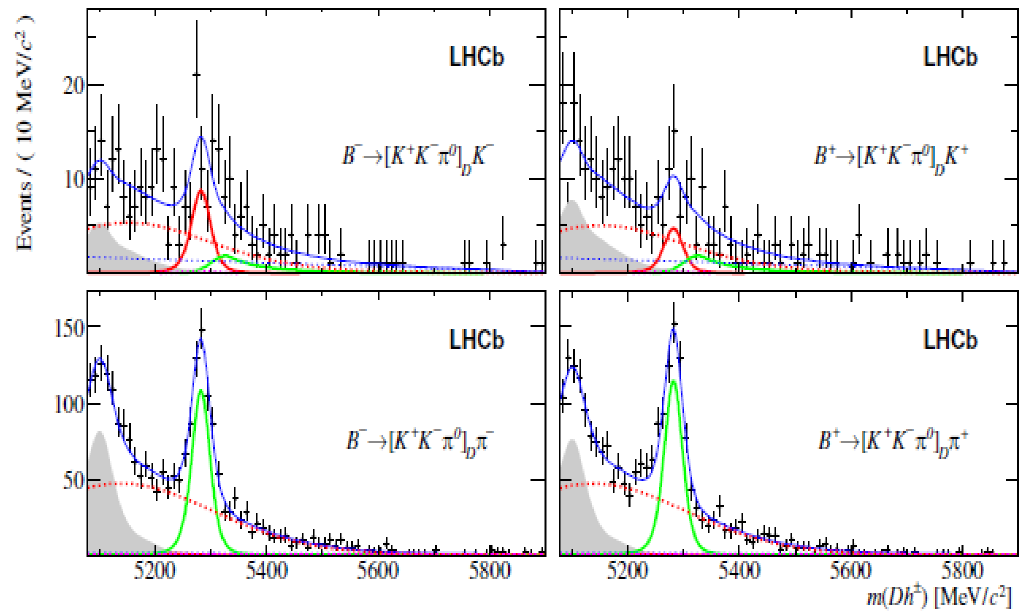
$B^- \to D K^-$ with $D \to h^+h^-\pi^0$ and $D \to K^+\pi^-\pi^0$

arXiv:1504.05442, PRD 91, 112014 (2015)

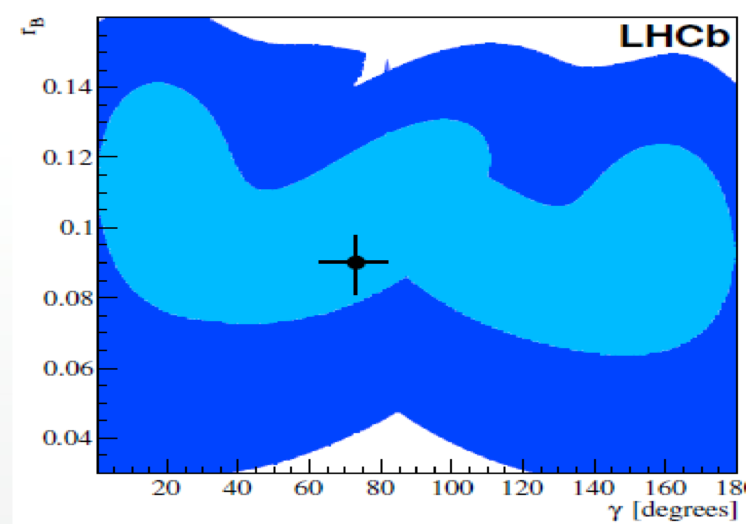
$D \to \pi^+\pi^-\pi^0$

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





From CLEO-c $D\overline{D}$ data:
small dilution in $D \to K^+\pi^-\pi^0$
High fraction of CP-even in $D \to h^+h^-\pi^0$
Make them very adequate for γ measurement, particularly $D \to h^+h^-\pi^0$
Final fit improves measurements obtained by B-factories



$B^- \to D K^- \pi\pi$ with $D \to h^+h^-, h'^+h^-$

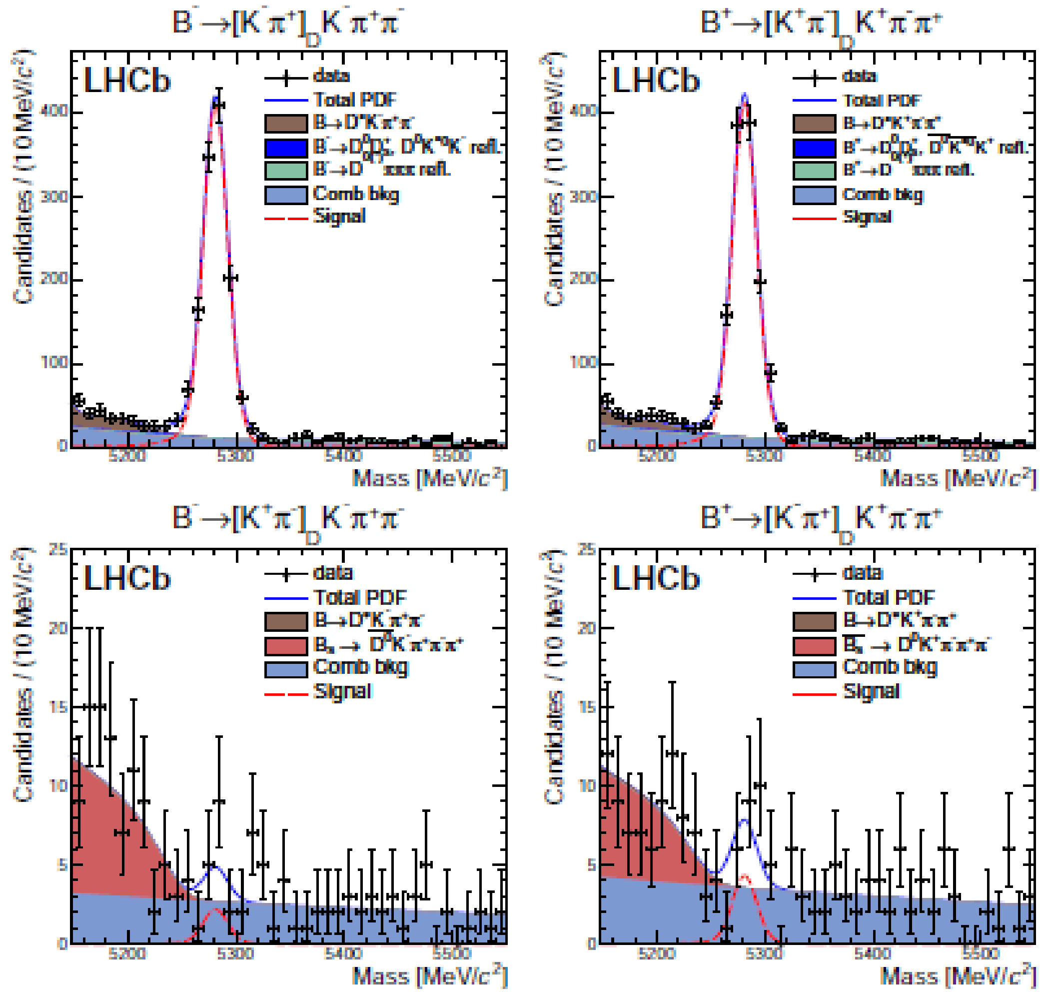
LHCb-PAPER-2015-020, arXiv:1505.07044

B+/B- invariant mass for the case $D \to K\pi$
favored $K^-\pi^+$ vs suppressed $K^+\pi^-$

Global fit for all $D \to h^+h^-$ modes gives:

$$\gamma = (74^{+20}_{-18})^\circ$$

Which agrees with the global average published in LHCb-CONF-2014-004

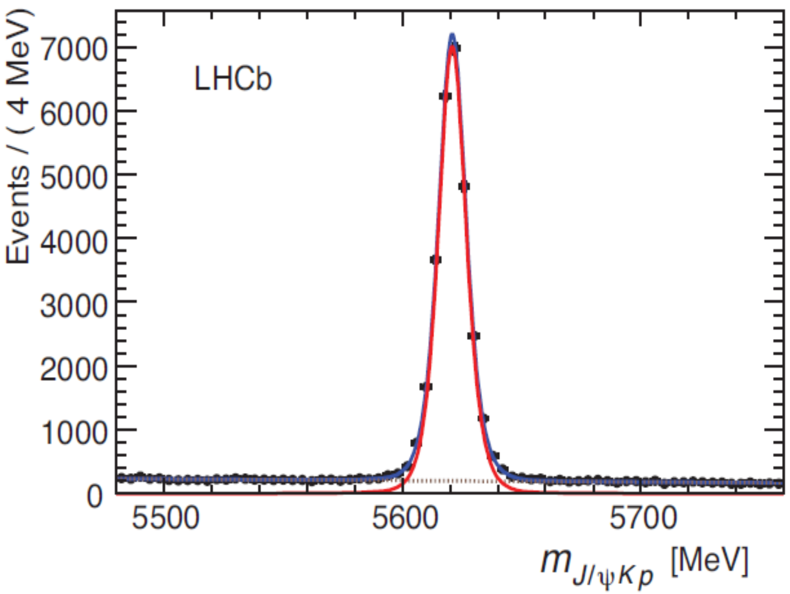


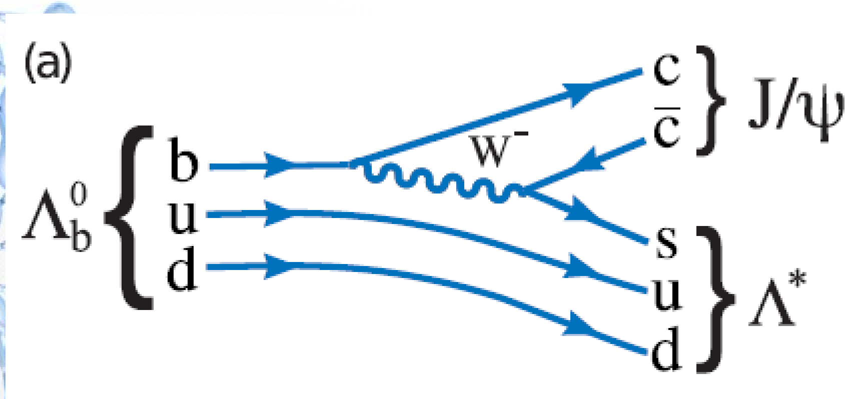
LHCb-PAPER-2015-029, arXiv:1507.03414

J/Ψ p pentaquark resonances in $\Lambda_b \to J/\Psi K^- p$

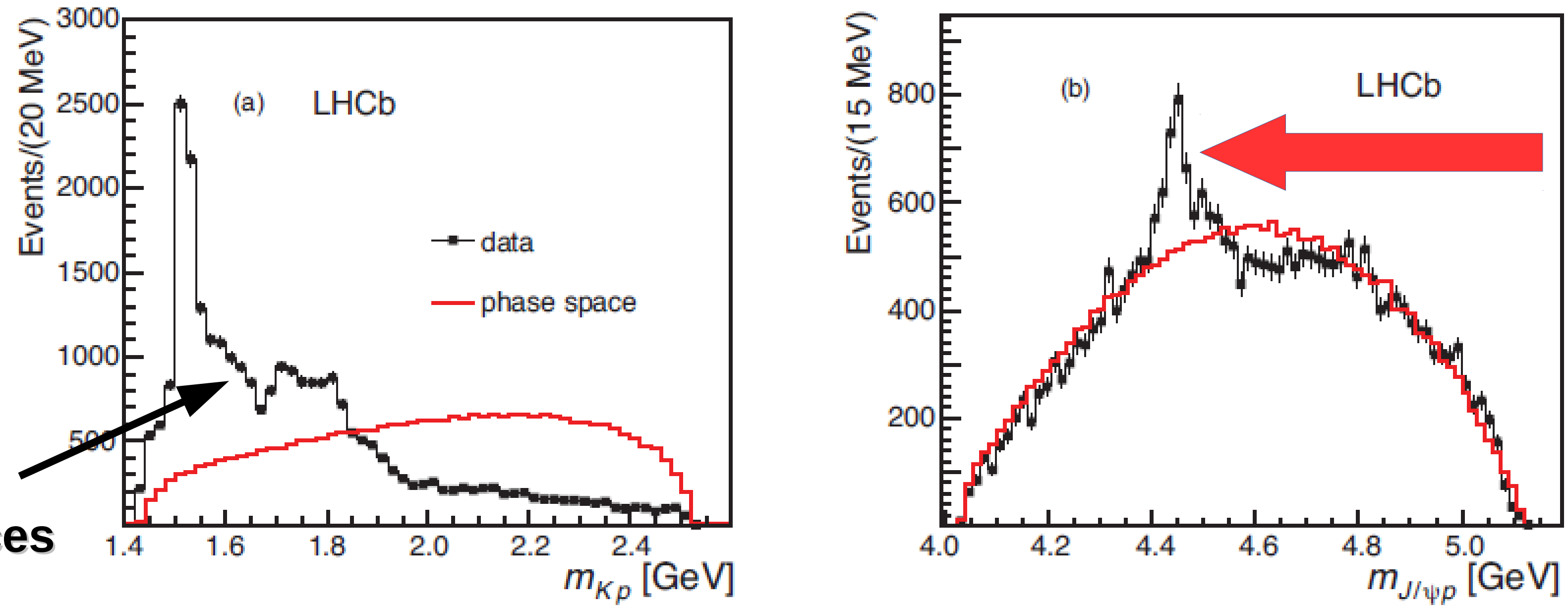
- Hypothesis of hadrons with more than three quarks raised 50 years ago (Gell-Mann, Phys. Lett. 8 (1964) 214 + later works of Jaffe, Strottman and Lipkin)
- A lot of past claims of pentaquark ended up not convincing (Eur. Phys. J.H37(2012) 1)
- One strong tetraquark candidate: $Z(4430)^+$ observed in $\bar{B}^0 \to \Psi' K^- \pi^+$ decays (Belle, then LHCb)
- A priori $\Lambda_b \to J/\Psi(\mu\mu) K^- p$ are expected to proceed dominantly through $\Lambda_b \to J/\Psi(\mu\mu) \Lambda^*$

$\Lambda_b \to J/\Psi K^- p$ signal in data





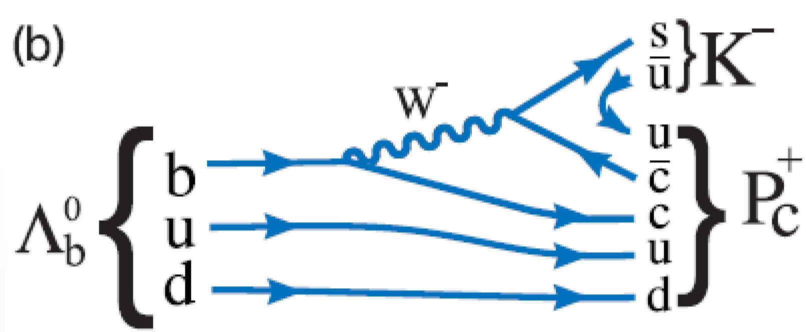
Looking at invariant masses in $\Lambda_b \rightarrow J/\Psi K^- p$



Λ and Σ resonances

!!!!

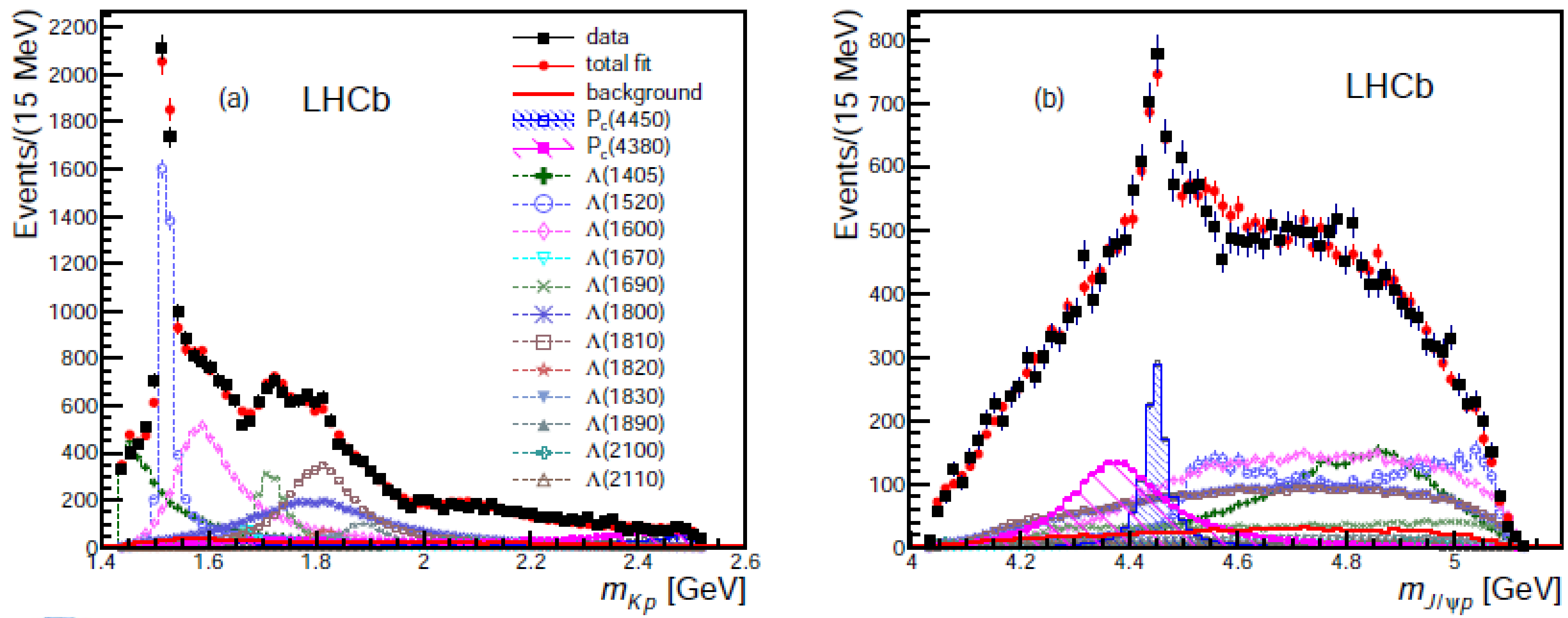
J/Ψ p resonances should have a minimal quark content of $c\bar{c}uud$, i.e. charmonium pentaquark, labelled as P_c^+



Full amplitude analysis performed to check that these are not reflections from Λ*

Amplitudes in $\Lambda_b \rightarrow J/\Psi\ K^- p$

Full fit includes 2 invariant masses and 5 decay angles!



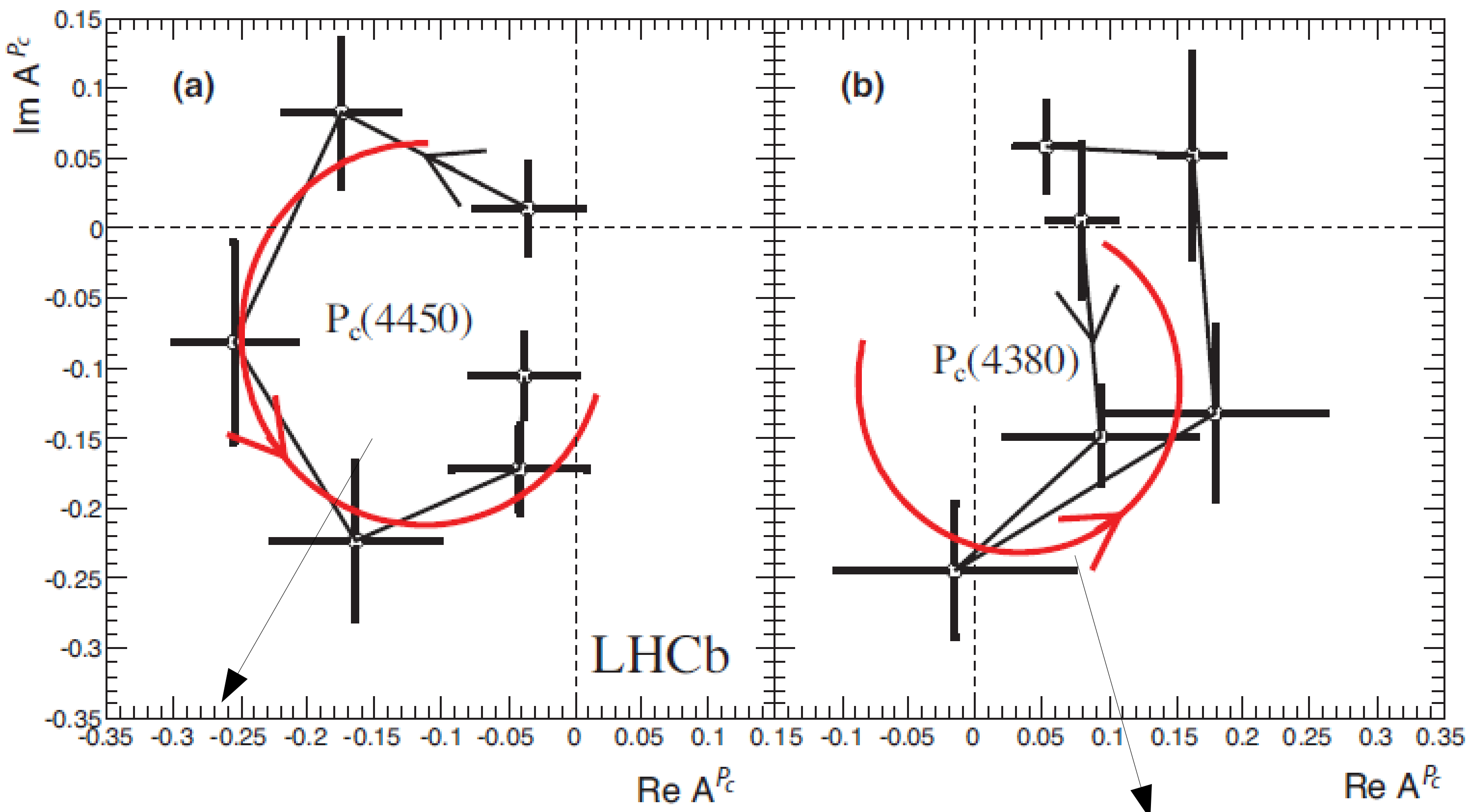
Minimal content for correct convergence/quality found to be 14 Λ^* states + 2 P_c^+ resonances, $P_c^+(4380)$ and $P_c^+(4450)$

Masses: 4380 ± 8 ± 29 MeV and 4449.8 ± 1.7 ± 2.5 MeV

Widths: 205 ± 18 ± 86 MeV and 39 ± 5 ± 19 MeV

Spin-parity: best fit gives (3/2-, 5/2+) but (3/2+, 5/2-) and (5/2+, 3/2-) also acceptable solutions

P_c^+ argand diagrams

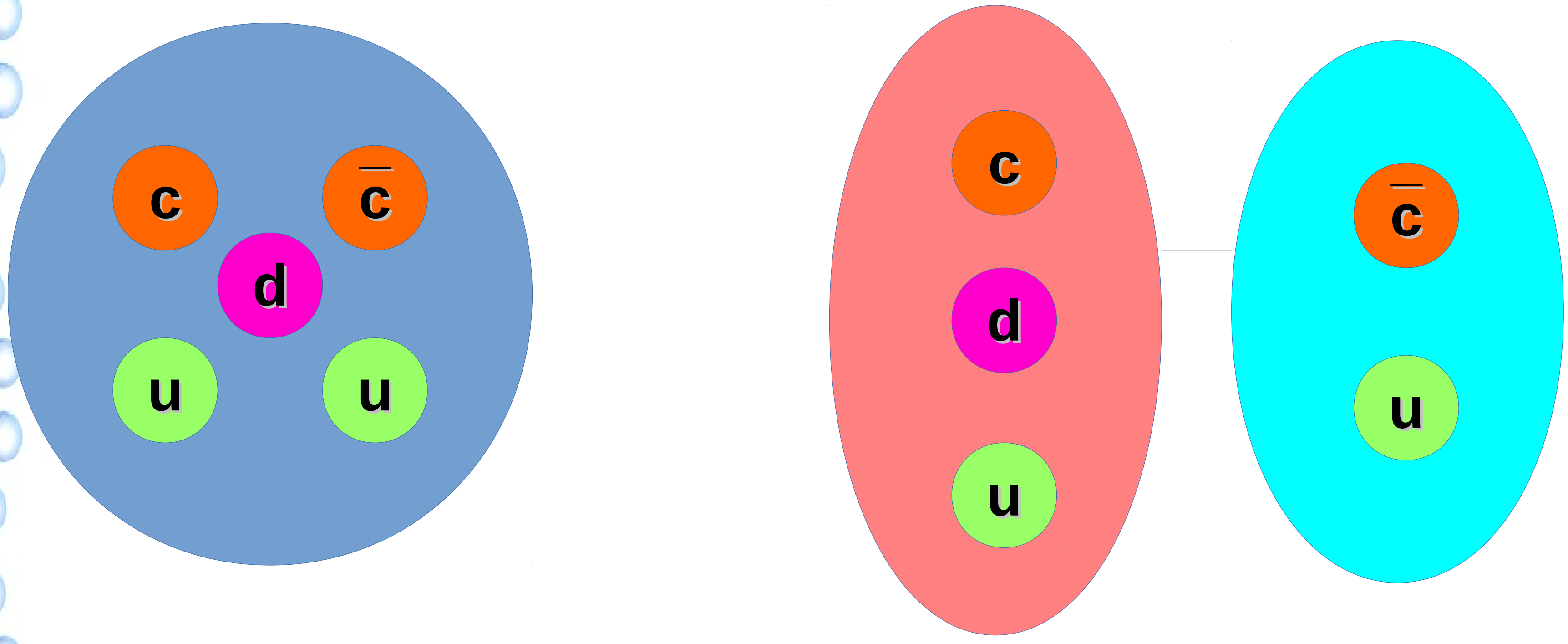


Very conclusive!

Because of wider state, amplitude is more sensitive to the details of modeling of Λ*

Although many tests have been performed to insure the robustness of the results, further work is being performed

P_c^+ detailed structure?



Tight bounds? Molecular?

arXiv:1404.1903, PRL 112, 222002 (2014)

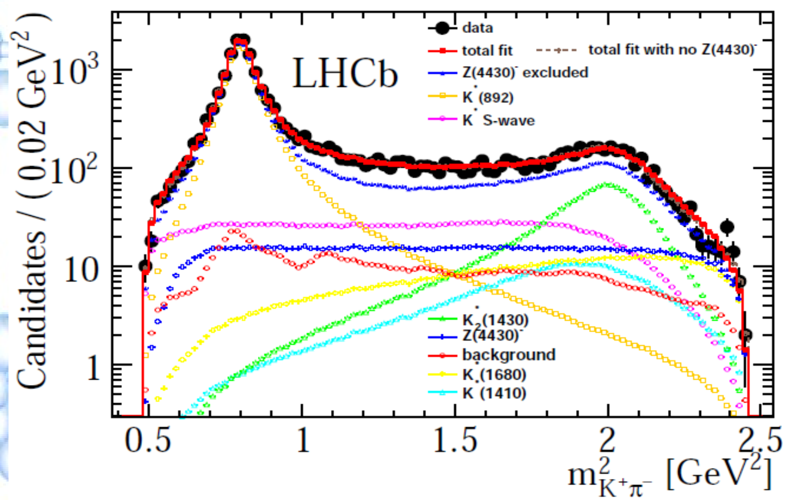
+ supplementary work being done in LHCb-PAPER-2015-038 (in preparation)

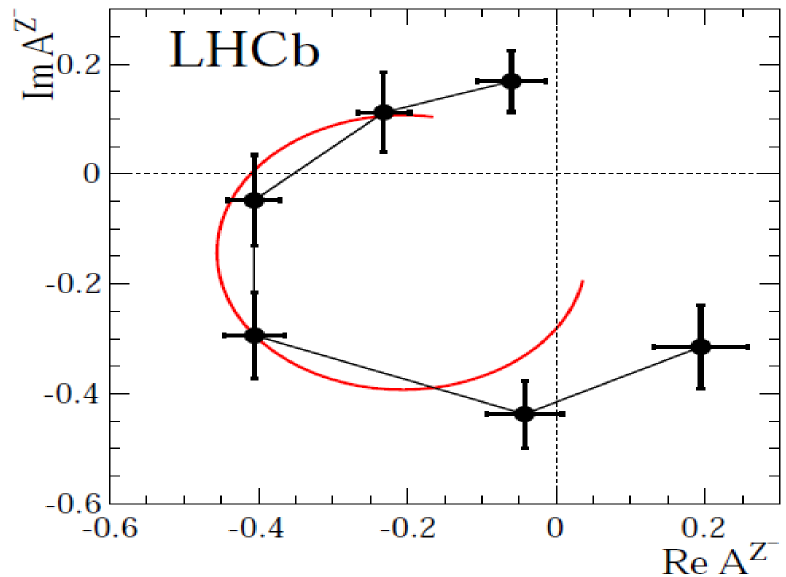
Tetraquark $Z(4430)^-$ in $B^0 \rightarrow \Psi' \pi^- K^+$

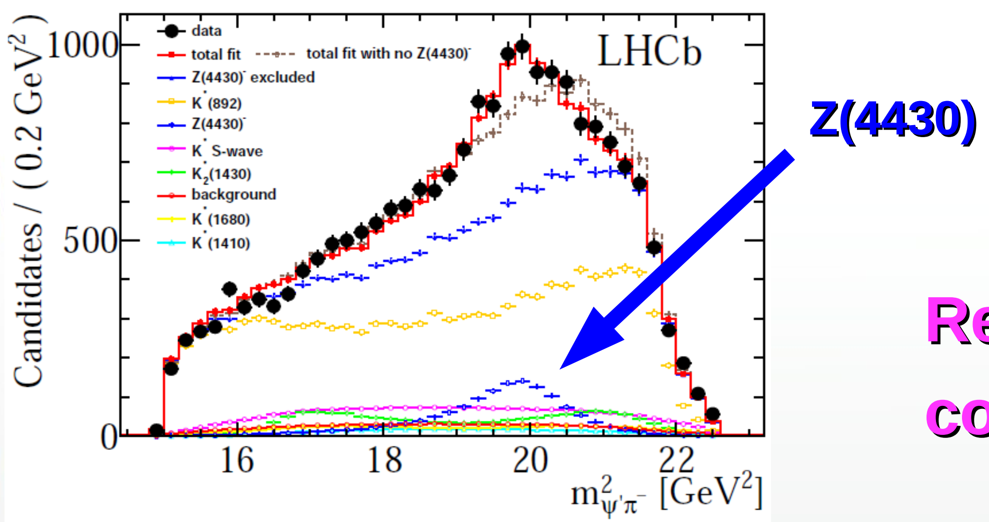
Already observed by Belle, resonant character was not established

4D amplitude analysis converge to $J^P = 1^+$

LHCb uses a sample of 25k signal events (vs 2k for B-factories)







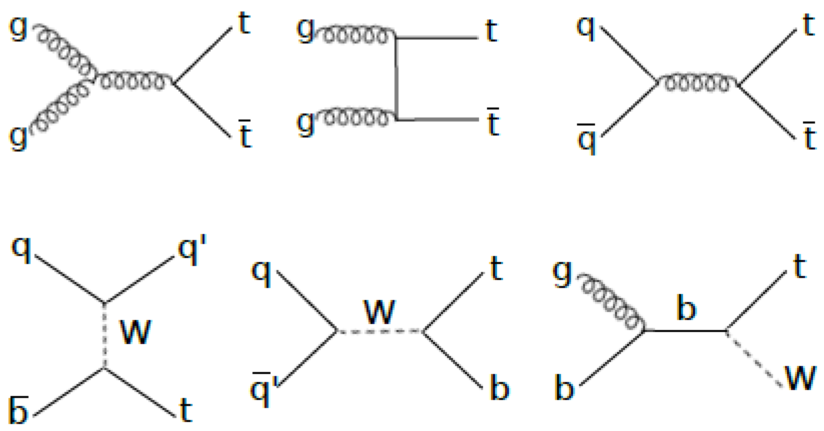
Mass: $4475 \pm 7\ ^{+15}_{-25}$ MeV

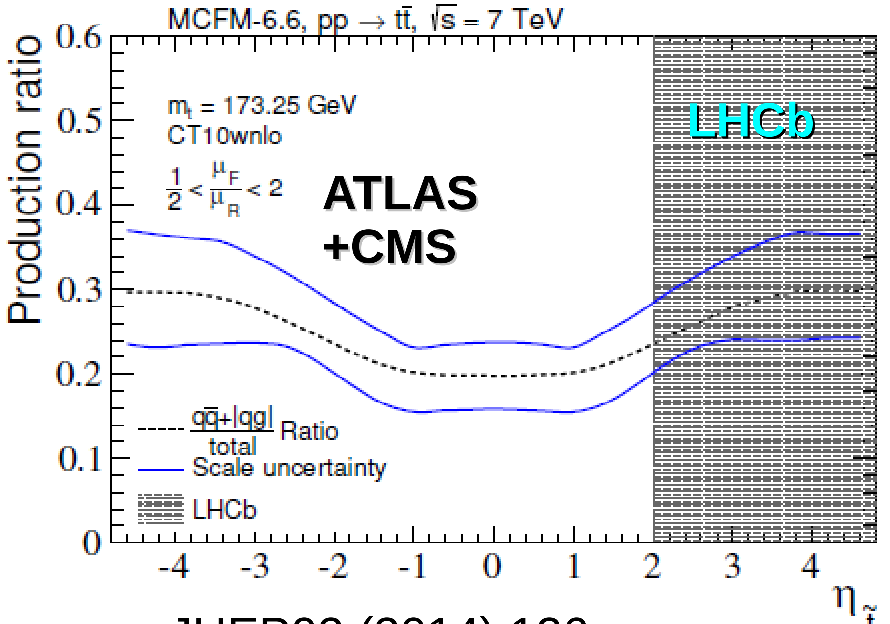
Width: $172 \pm 13\ ^{+37}_{-34}$ MeV

Remark: both P_c and Z contain charmonium

Top quark

- $t\bar{t}$ and single top physics extensively explored by ATLAS and CMS in the central region
- LHCb will complete the knowledge at high pseudorapidities



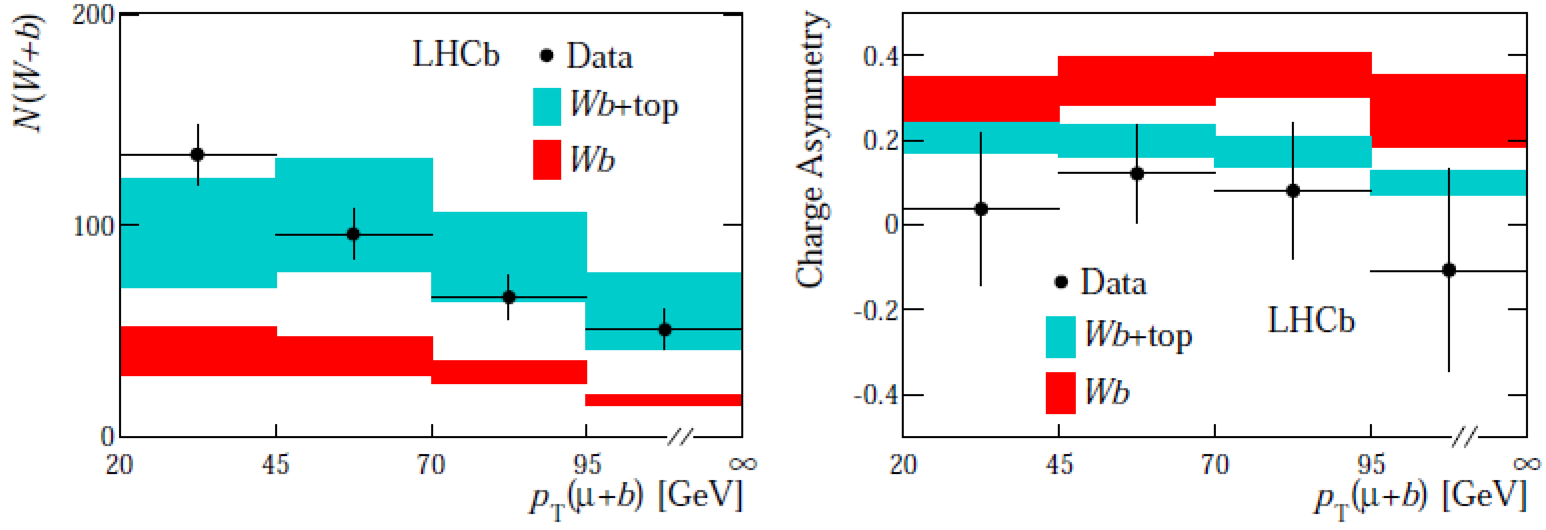


JHEP02 (2014) 126

Top in LHCb (LHCb-PAPER-2015-022)

arXiv:1506.00903

- **Searched for in W(lept) + b-jet events**
  - **Use W + j-jet events as normalization**
  - **MVA discrimination to discard light + c jets**
- **Compare W+b yield and asymmetry with expectations with and without top**



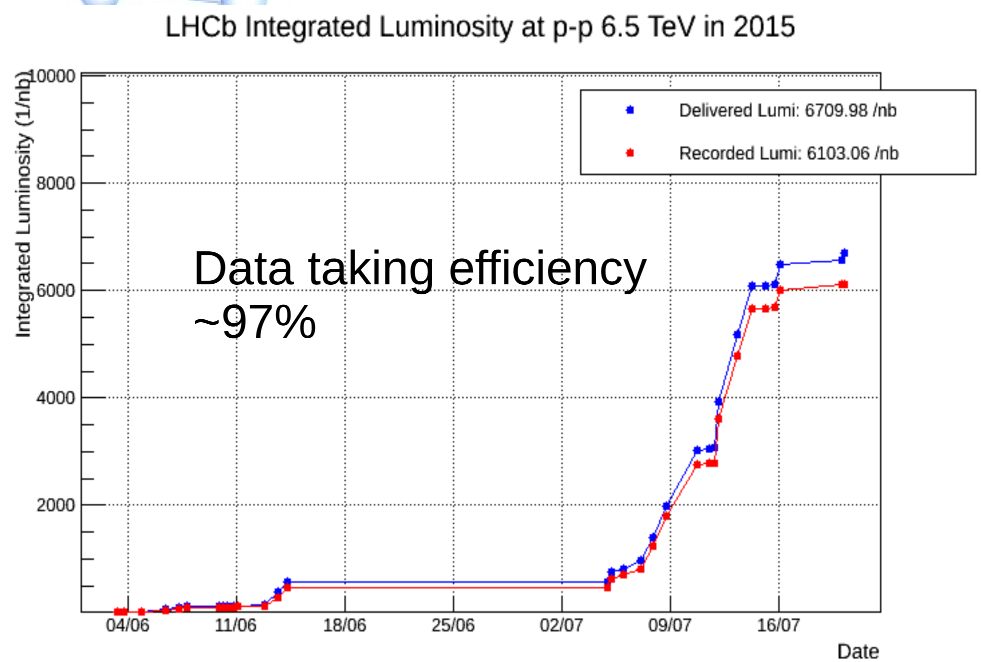
5.4σ (first) observation of top production in the forward region

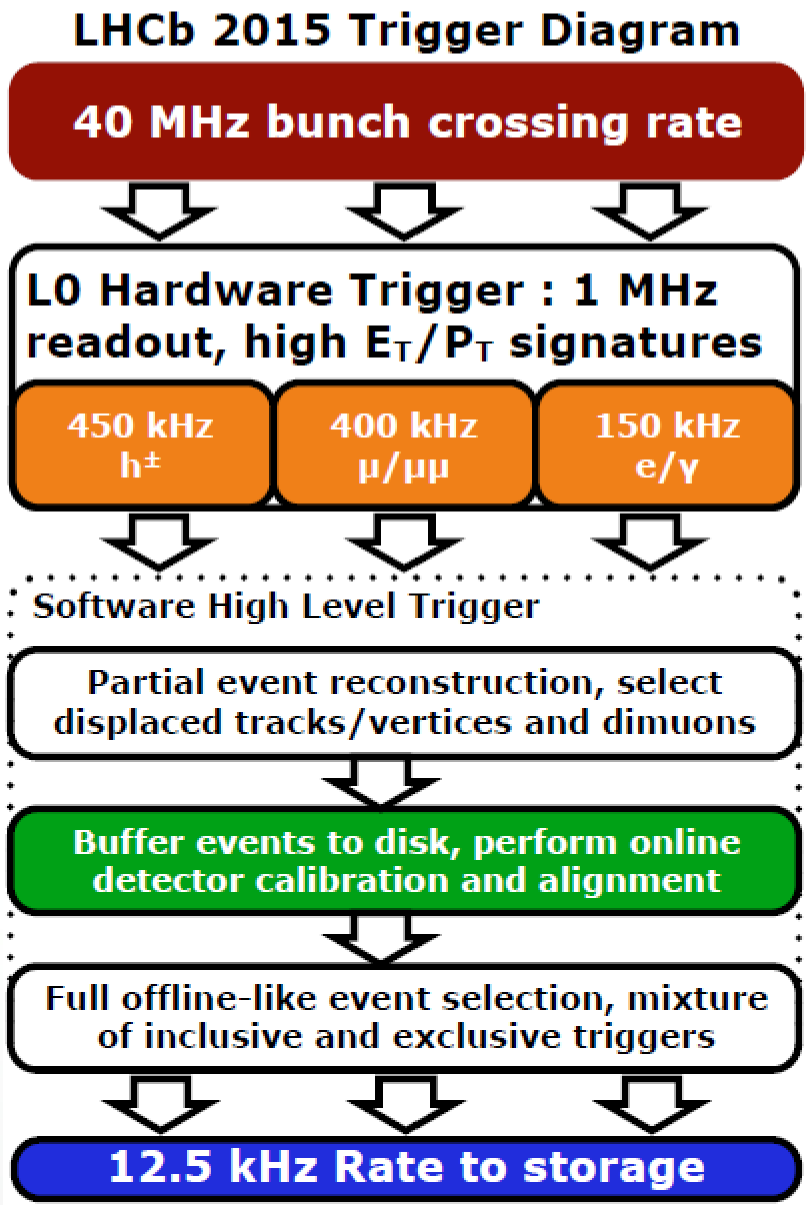
$$\sigma(\text{top})[7\,\text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 38\,(\text{syst})\,\text{fb}$$

$$\sigma(\text{top})[8\,\text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 46\,(\text{syst})\,\text{fb}$$

Current data taking (Run II)

Run II has begun!
Higher CM energy + small bunch spacing (25 ns) = data rate ⇑
Finished 50 ns bunch spacing run



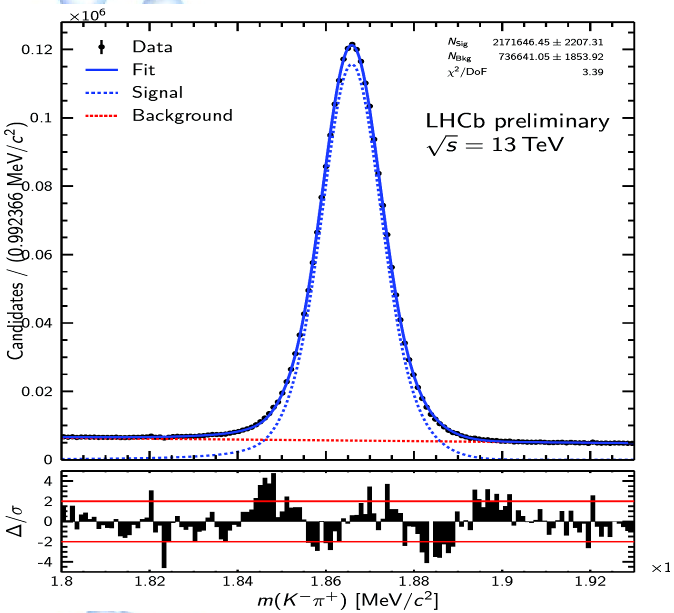


About ~ 6 pb^{-1} @ 13 TeV already taken,
25 ns data taking will start soon

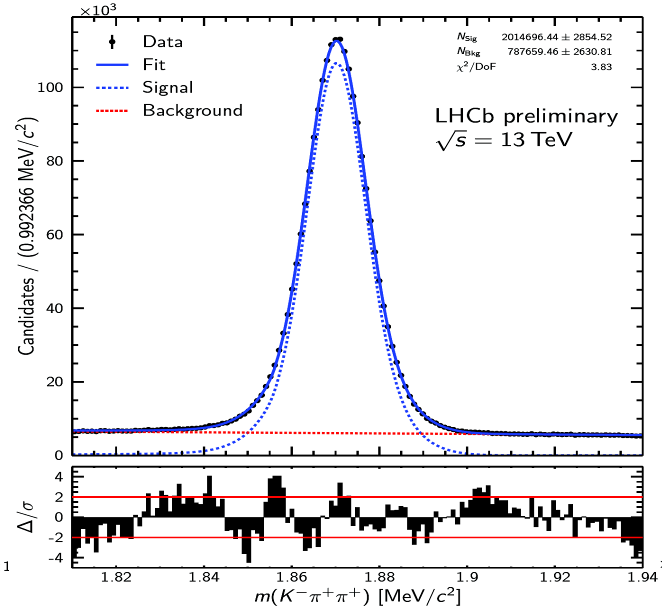
New trigger flow: calibrations performed between High Level Triggers 1 and 2

Early signals from first Run II data

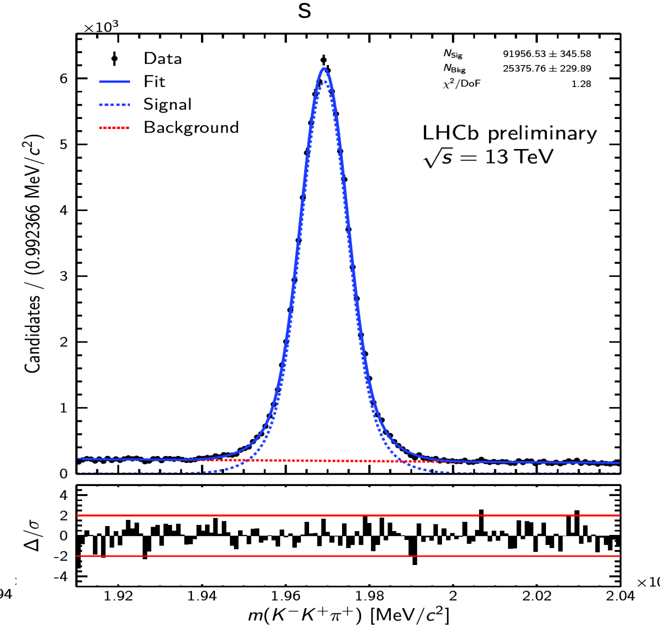
$D^0 \rightarrow K\pi$



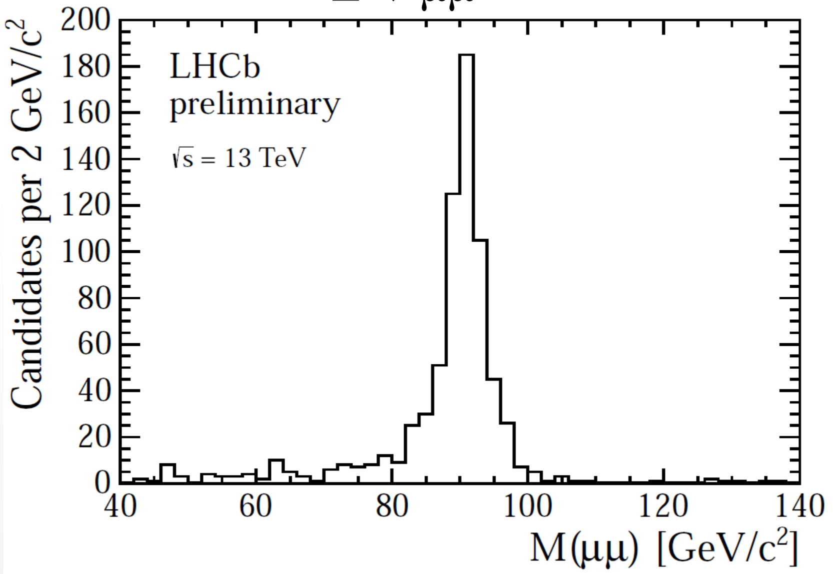
$D^+ \rightarrow K\pi\pi$



$D_s \rightarrow KK\pi$



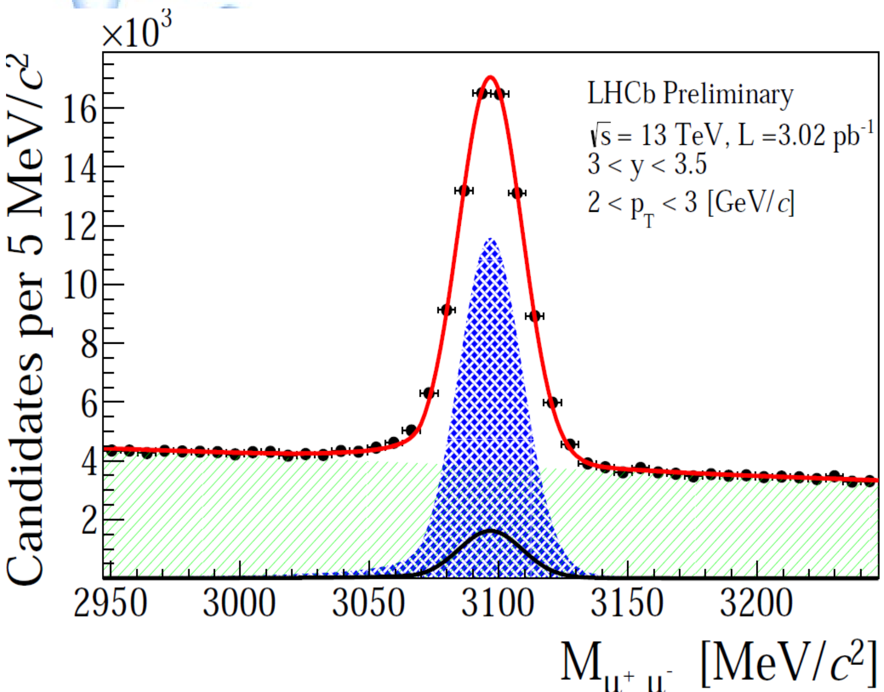
$Z \rightarrow \mu\mu$

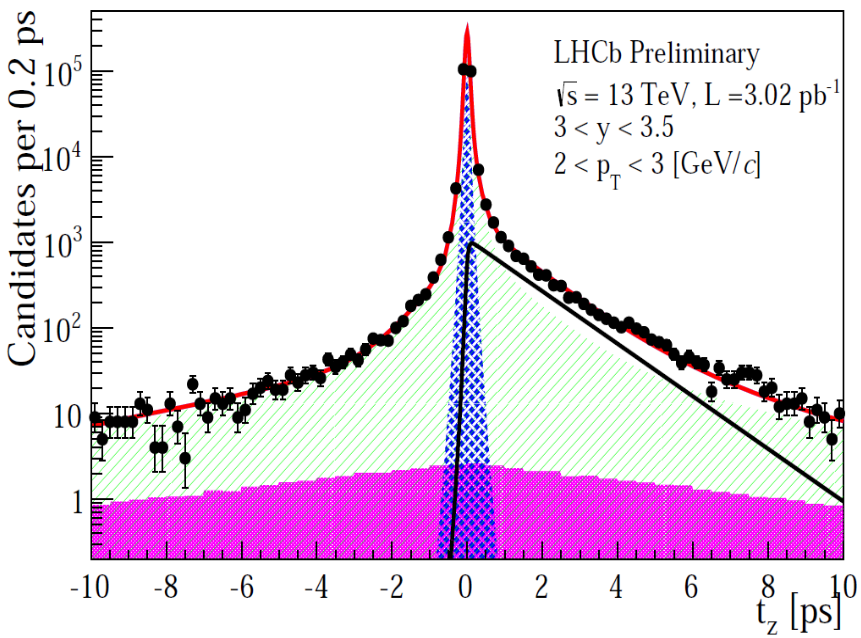


Early measurements from first Run II data

LHCb-PAPER-2015-037

J/Ψ cross-sections @ √s = 13 TeV
Measured prompt + component from b decays





J/Ψ from b, prompt J/Ψ, background, wrong PV association (tails)

$$\sigma(\text{prompt } J/\psi) = 15.35 \pm 0.03\,(\text{stat}) \pm 0.85\,(\text{syst})\ \mu\text{b}$$
$$\sigma(J/\psi \text{ from } b) = 2.36 \pm 0.01\,(\text{stat}) \pm 0.13\,(\text{syst})\ \mu\text{b}.$$

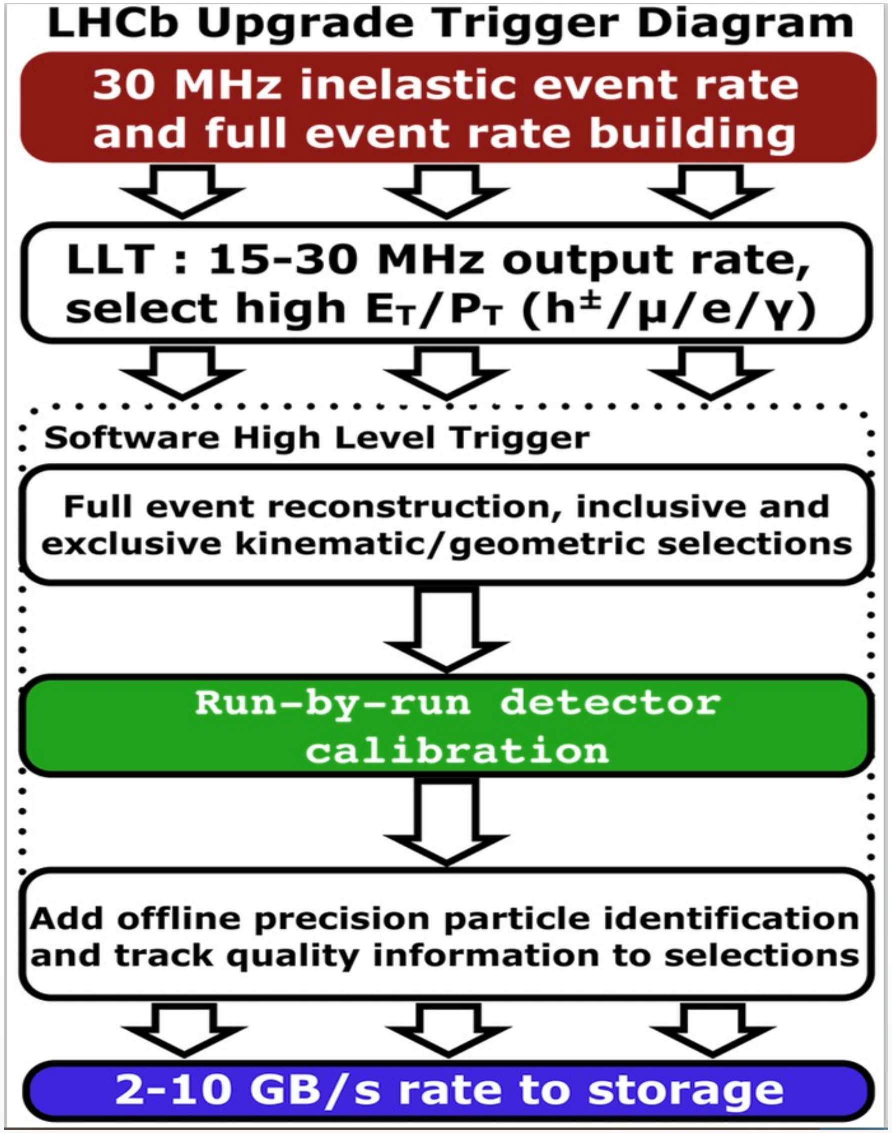
In LHCb acceptance

Using acceptance rescaling from Pythia + b→J/ΨX BF from PDG:

$$\sigma(pp \to b\bar{b}X) = 518 \pm 2\,(\text{stat}) \pm 53\,(\text{syst})\ \mu\text{b}$$

Upgrade
(see A.Schopper Wed 05/08)

- Planned during LS2 (2019-2020)
  - Prepare for acquisition of 50 fb^{-1}
- Detectors:
  - full upgrade of the tracking system
  - new RICH (Particle ID) detectors
  - Calorimeters and muon system: new electronics, more shielding, etc...
- Triggering: full software trigger
  - This removes the limitation of the L0 Hardware trigger (1 MHz)



Summary

- A big variety of results released in all aspects of the physics program
  - Pushing the SM further in the corners and hunt for intervention of NP: e.g., persisting discrepancies in some observables of rare decays
  - New quark bound states
  - Direct searches are now ramping up as part of forward physics studies
- Very promising first Run II data taking: the detector is running Ok, fast and efficient data acquisition and analysis with the new streaming model
  - First paper draft ready almost immediately after data taking
  - Very exciting prospects ahead for the coming 25 ns running
- Preparation for upgrade is well advanced and most of the R&D phases are now achieved

Backup

γ from B → DK, different techniques

- f_D = CP eigenstates, $D^0 \to K^+K^-$, $\pi^+\pi^-$, $K_s\pi^0$
  - Gronau, London, Wyler (GLW) 1991
- f_D = flavour states: $D^0 \to K^+\pi^-$, $K^-\pi^+$
  - Atwood, Dunietz, Soni (ADS) 1997
- f_D = multibody final states (variation of δ_D over phase space)
  - $K_sh^+h^-$ Giri, Grossman, Soffer, Zupan 2003; Poluektov 2004 (GGSZ-P)
  - $K^\pm\pi^{-/+}\pi^+\pi^-$, multibody ADS
  - $K_sK^\pm\pi^{-/+}$, GLS
- Some variants involving neutrals, B^0 and Bs

Observables: charge asymmetries and BF ratios of suppressed/favoured D decays (applies for self-tagging decays)

γ from trees

Case of $D^0 \to K^- \pi^+$ (Cabibbo Allowed), $D^0 \to K^+ \pi^-$ (double Cabibbo Suppressed)

$$R_h^{\pm} = \frac{\Gamma\left(B^{\pm} \to D_{DCS} h^{\pm}\right)}{\Gamma\left(B^{\pm} \to D_{CA} h^{\pm}\right)} = \frac{r_B^2 + r_D^2 + 2 r_B r_D \cos\left(\delta_B + \delta_D \pm \gamma\right)}{1 + \left(r_B r_D\right)^2 + 2 r_B r_D \cos\left(\delta_B - \delta_D \pm \gamma\right)}$$

For multibody decays, must take into account the interference term between the two amplitudes in the D meson phase space, using a coherence factor κ_D

PRD68 (2003) 033003, arXiv:hep-ph/0304085

$$2 r_B r_D \cos\left(\delta_B + \delta_D \pm \gamma\right) \to 2 r_B r_D \kappa_D \cos\left(\delta_B + \delta_D \pm \gamma\right)$$