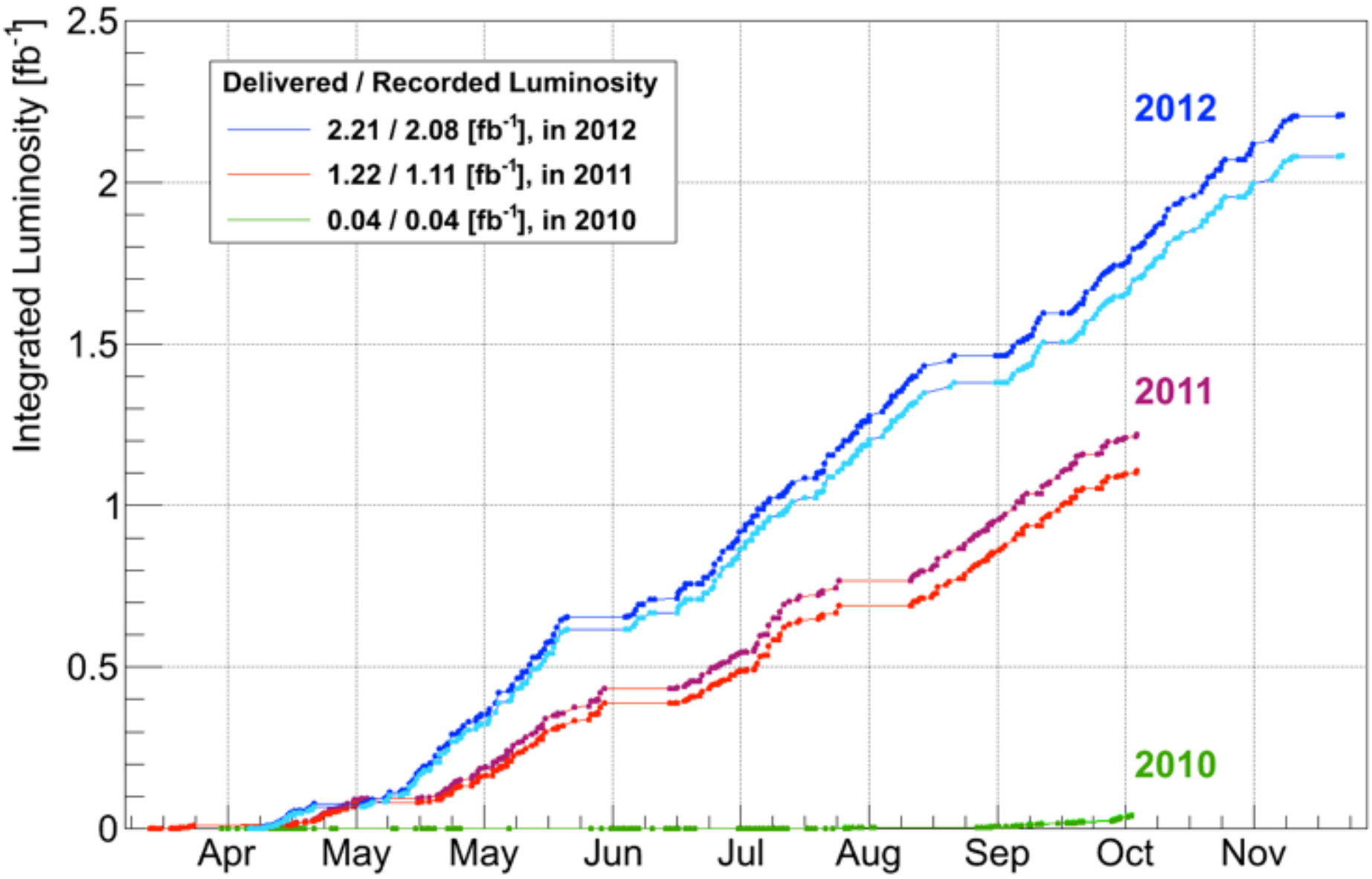
Status and recent highlights from LHCb

Matthew CHARLES (UPMC/LPNHE)

LHCb in Run 2 (and Run 1!)

Run I

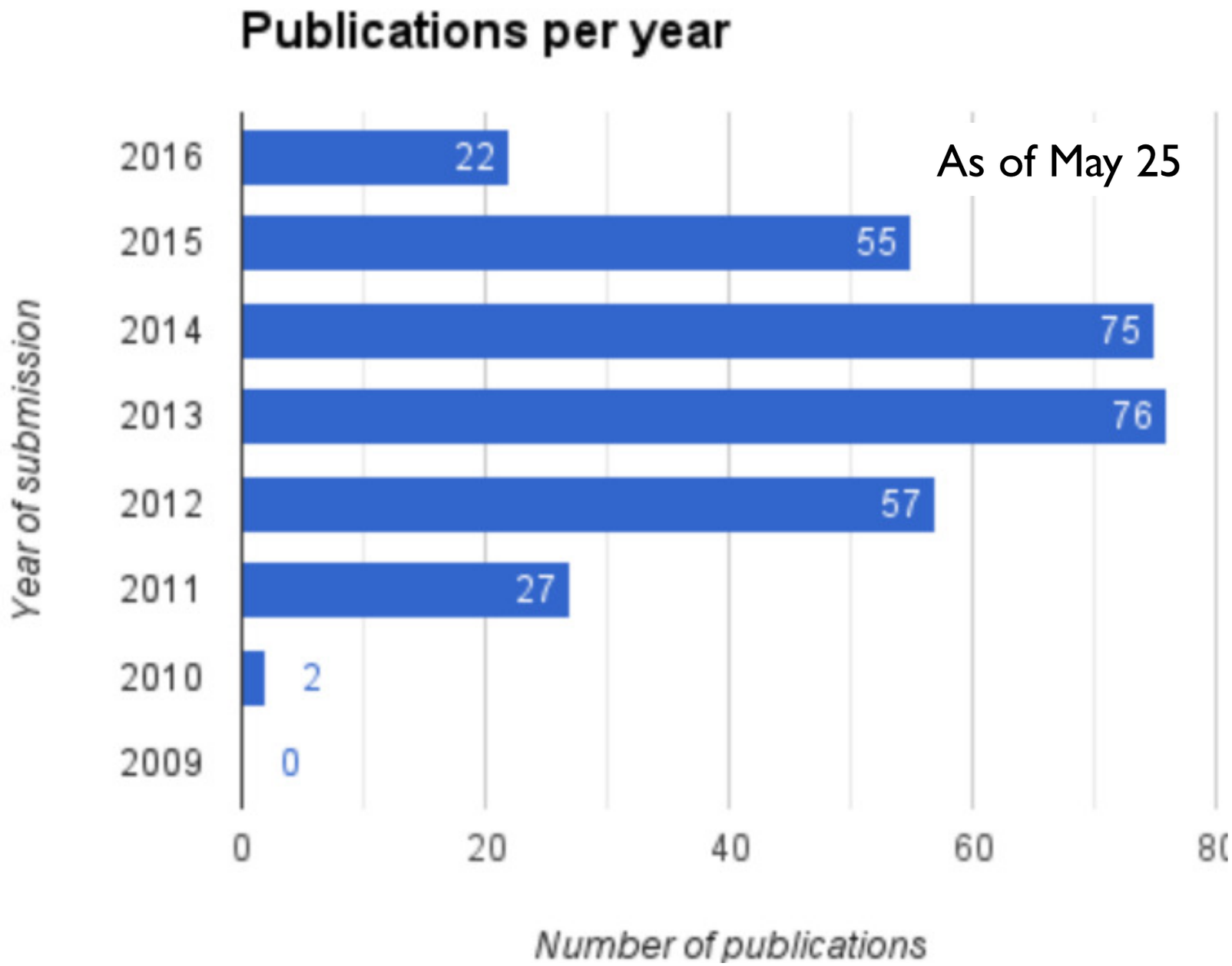


8 TeV: 2 fb^{-1}

7 TeV: 1 fb^{-1}

7 TeV: 0.04 pb^{-1}

Run I

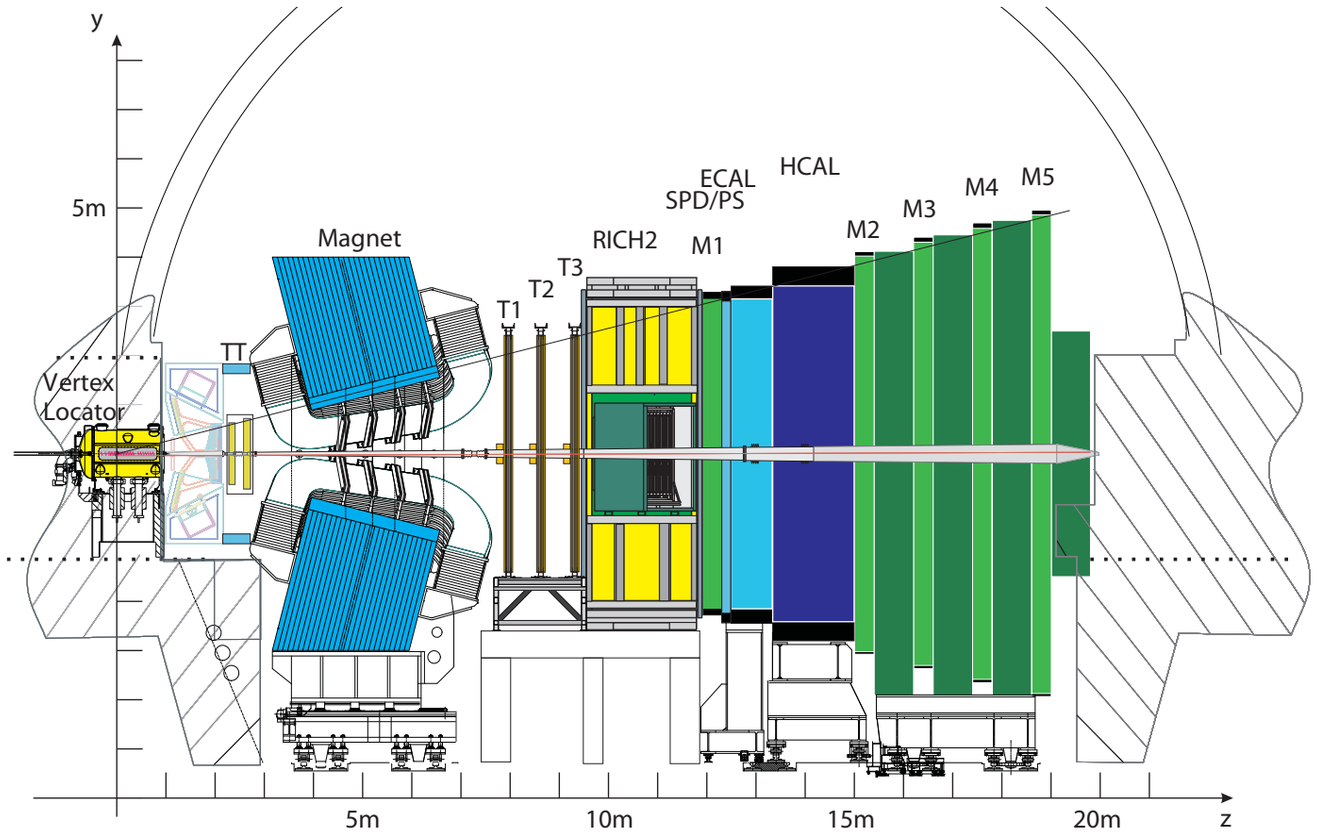


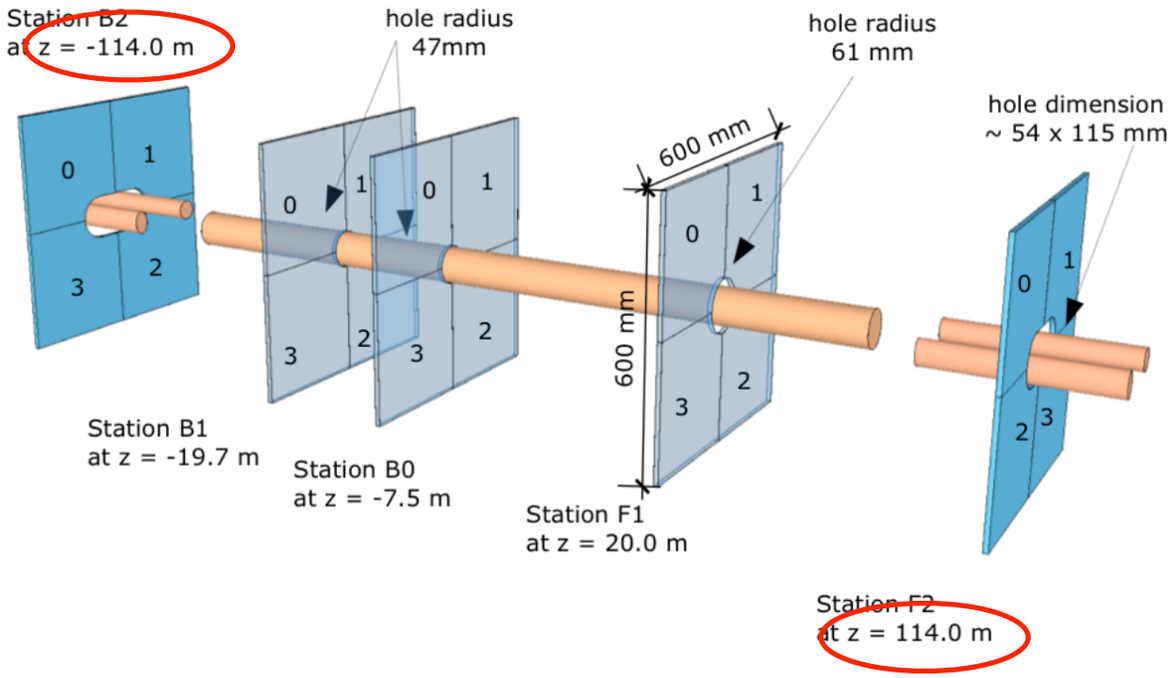
As of May 25

Full list of papers submitted/published: 315 as of June 2.

Run 2: Detector

The LHCb detector we know and love from Run 1...

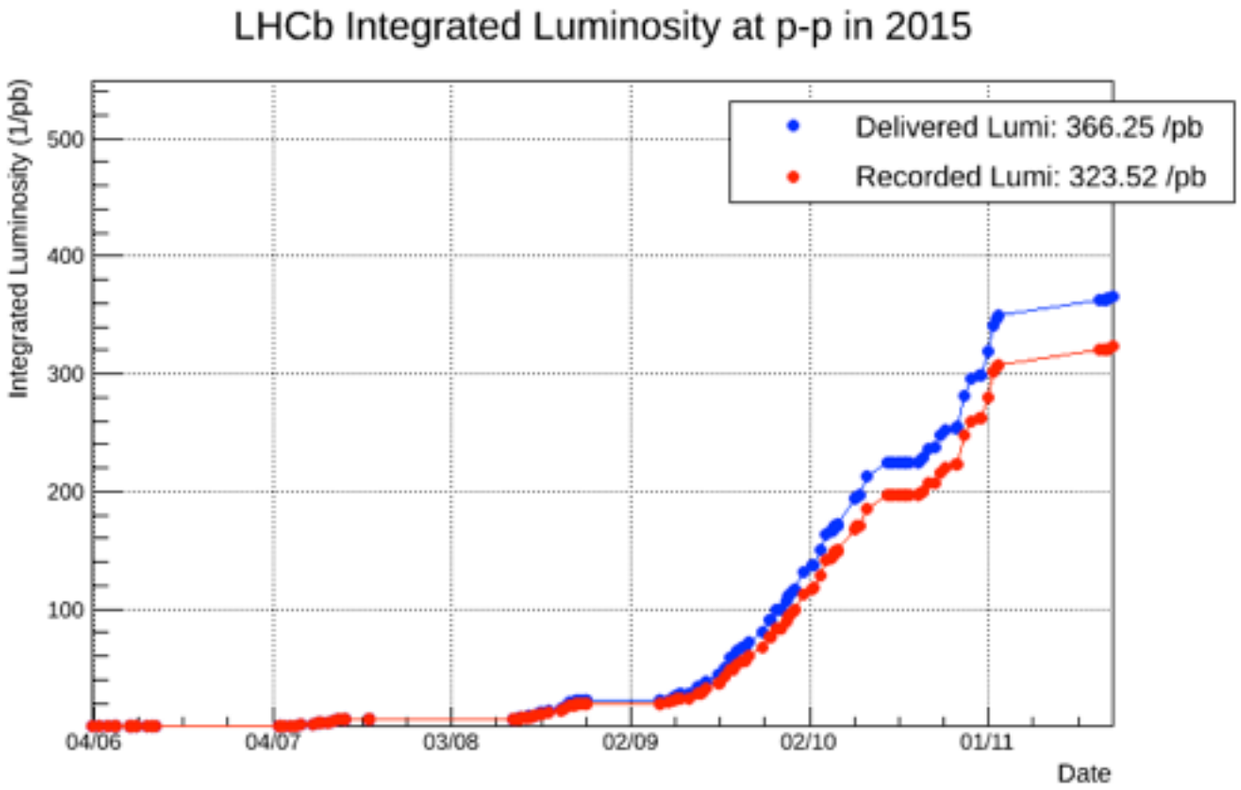


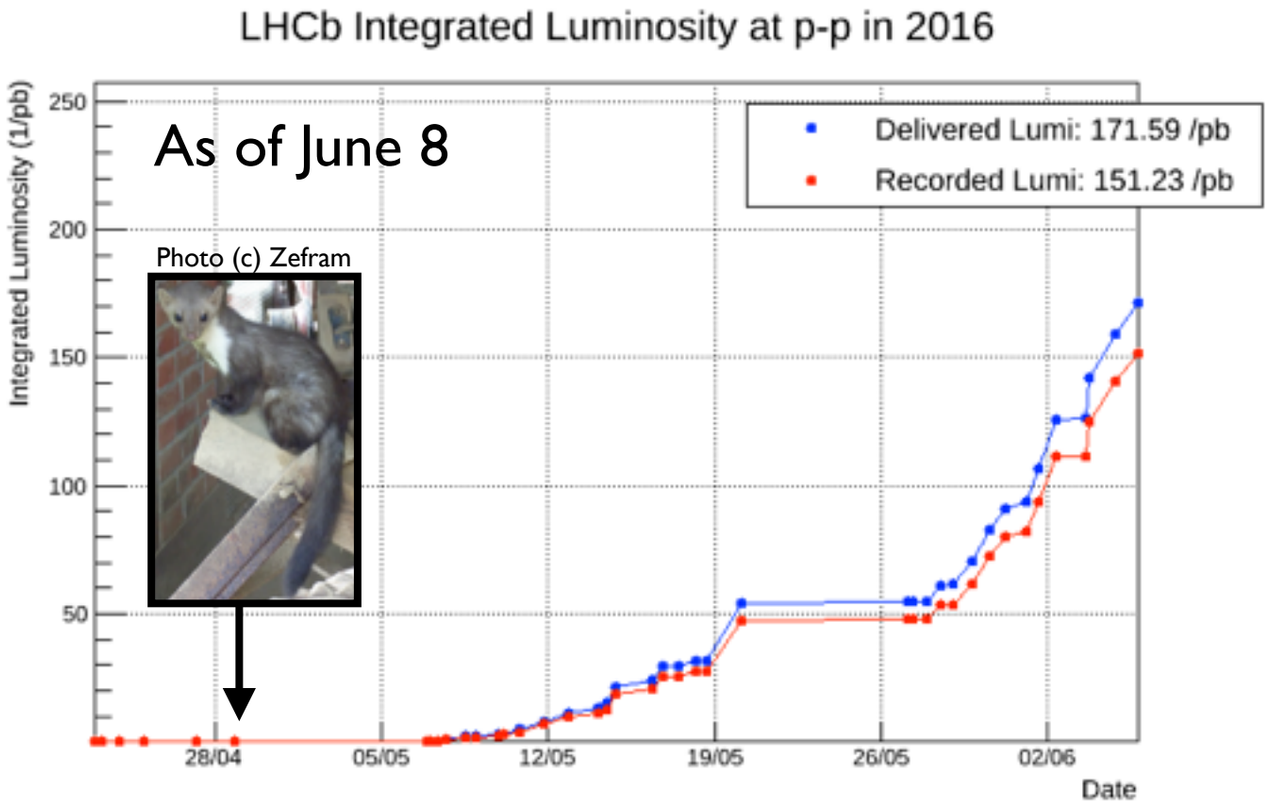


... with a new subdetector, HERSCHEL*, to instrument $5 < |\eta| < 8$ for CEP physics.

* High Rapidity Shower Counter for LHCb

Run 2: 13 TeV data





... and in addition, heavy ion physics from (p-Pb, Pb-Pb) and from SMOG (p-He, p-Ne, p-Ar, Pb-Ar, ...)

Thanks very much to our LHC colleagues for their hard work!

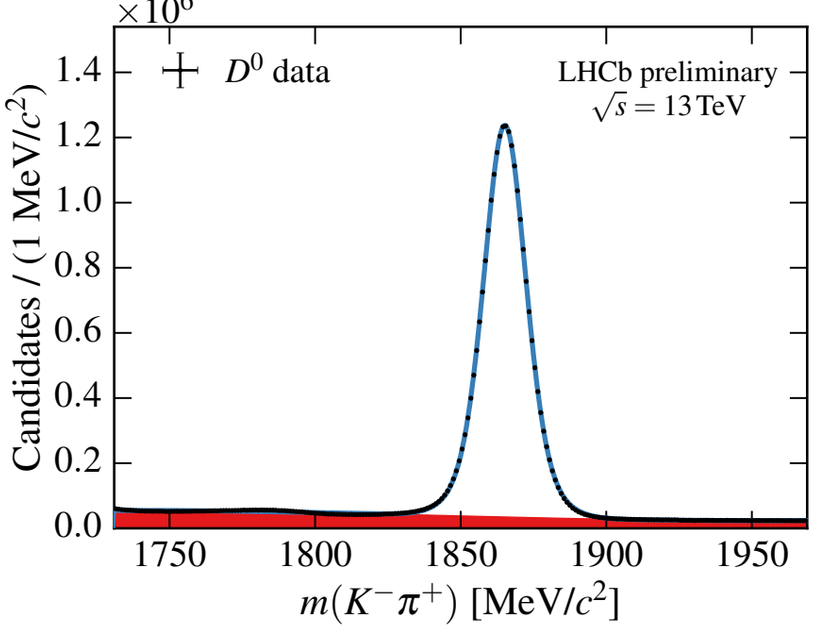
Run 2: Trigger

Two key improvements in Run 2:

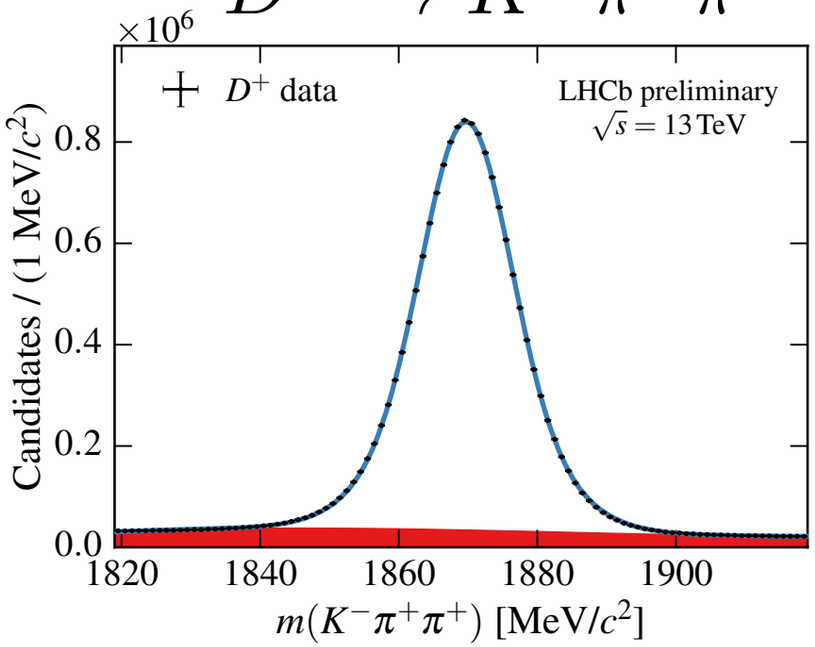
- Smarter trigger
  - Deferred trigger => more CPU time per event
  - Real-time calibration => offline-quality reco in HLT
- Higher output rate (3-5 kHz → 12.5 kHz)
  - More bandwidth (0.3 → 0.6 GB/s)
  - Smaller avg event size
  - Turbo: use online output directly for physics!

2016 Turbo++ output

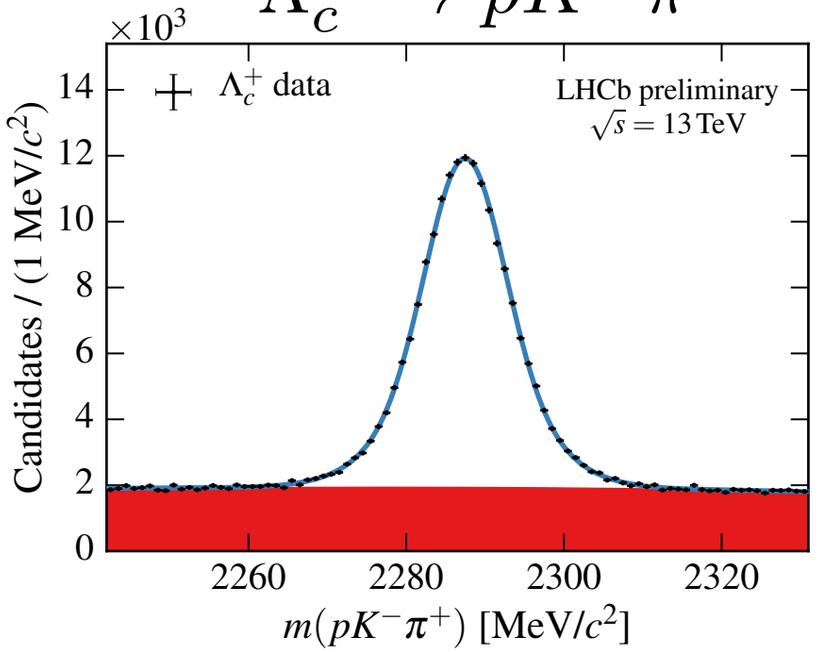
$D^0 \to K^-\pi^+$



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



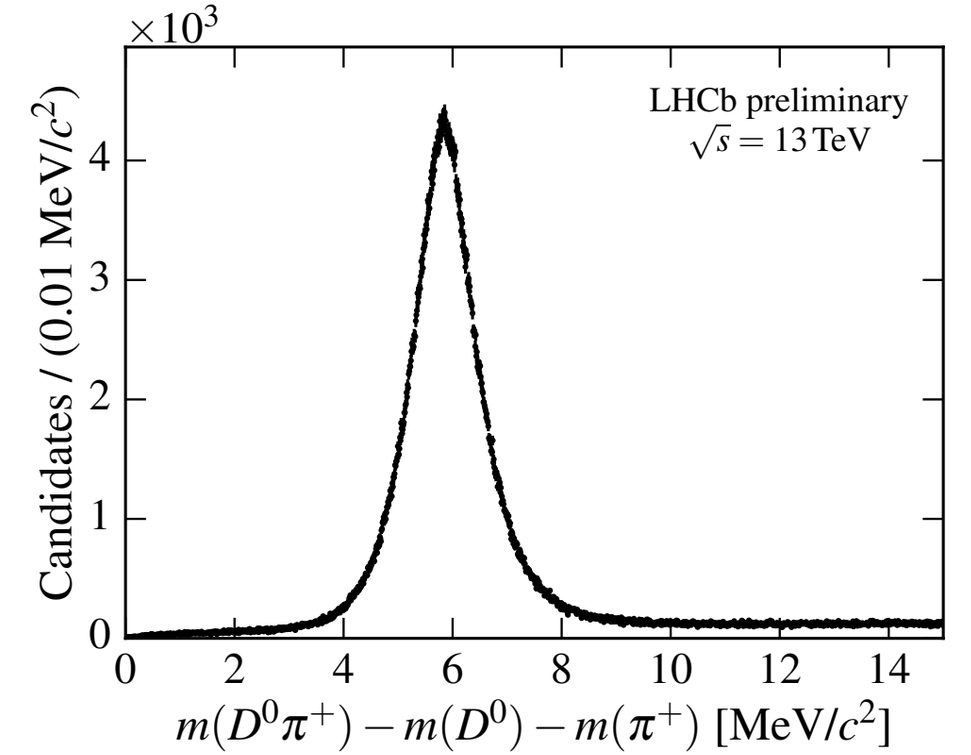
$\Lambda_c^+ \to pK^-\pi^+$



Physics-quality output, directly from the trigger.

Data: some tens of pb^{-1} from 2016.

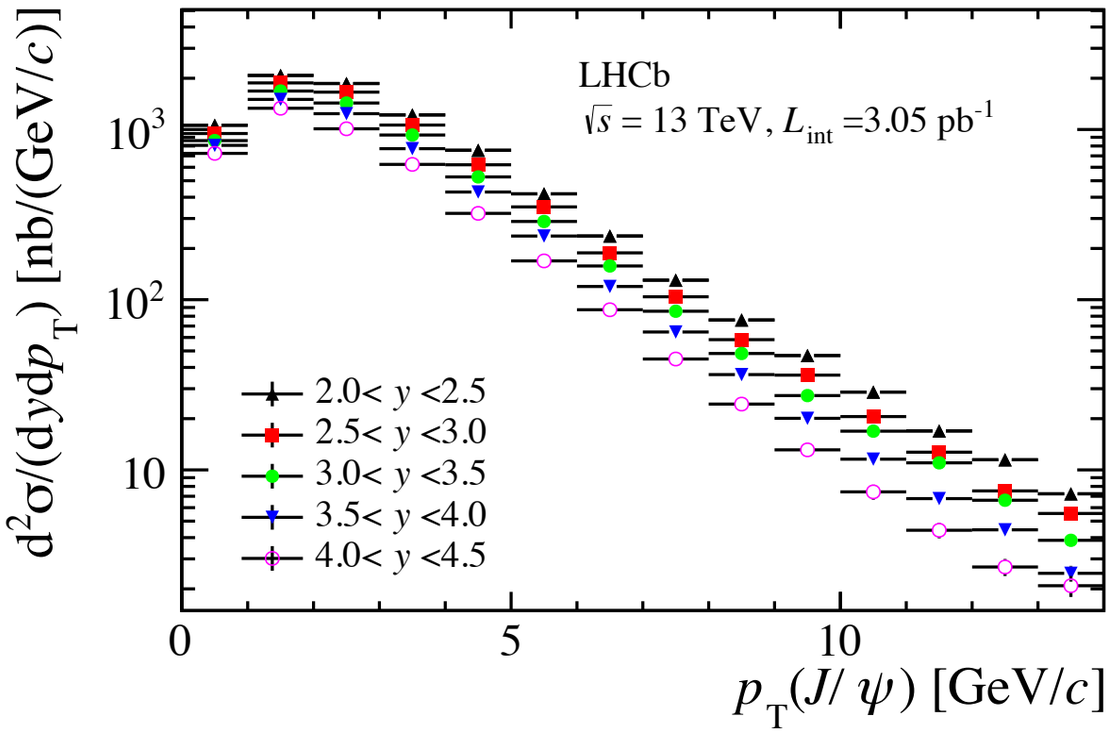
Method already used for 13 TeV papers...



$D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$

Results with 13 TeV data

Hidden charm production



$\sigma(\text{prompt } J/\psi, p_{\rm T} < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 15.30 \pm 0.03 \pm 0.86\,\mu\text{b}$

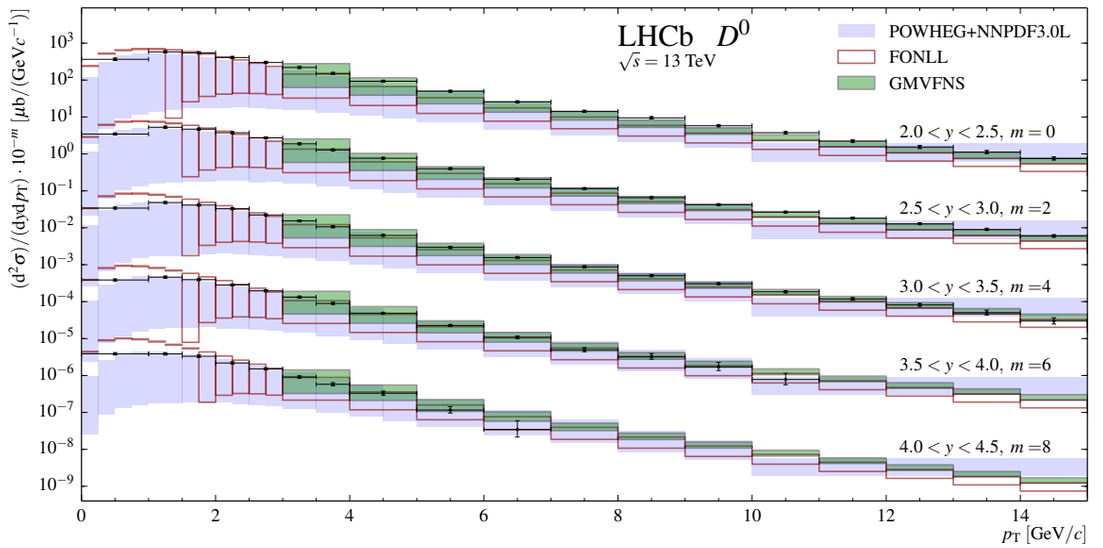
$\sigma(J/\psi\text{-from-}b, p_{\rm T} < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 2.34 \pm 0.01 \pm 0.13\,\mu\text{b}$

$$\Rightarrow \sigma(pp \to b\bar{b}X,\ 4\pi) = 515 \pm 2 \pm 53 \mu\text{b}$$

of which $99\,\mu$b in $(2.0 < y < 4.5,\ p_{\rm T} < 14\text{GeV}/c)$

JHEP 10 (2015) 172 [LHCb-PAPER-2015-037]

Open charm production



			Cross-section (μb)
D^0	$0 < p_{\rm T} < 8$ GeV/c	$2 < y < 4.5$	$3370 \pm 4 \pm 200$
D^+	$0 < p_{\rm T} < 8$ GeV/c	$2 < y < 4.5$	$1290 \pm 8 \pm 190$
D^0	$1 < p_{\rm T} < 8$ GeV/c	$2 < y < 4.5$	$2460 \pm 3 \pm 130$
D^+	$1 < p_{\rm T} < 8$ GeV/c	$2 < y < 4.5$	$1000 \pm 3 \pm 110$
D_s^+	$1 < p_{\rm T} < 8$ GeV/c	$2 < y < 4.5$	$460 \pm 13 \pm 100$
D^{*+}	$1 < p_{\rm T} < 8$ GeV/c	$2 < y < 4.5$	$880 \pm 5 \pm 140$

JHEP 03 (2016) 159 [LHCb-PAPER-2015-041]

New and exciting

CPV in mixing

CPV

Direct
(time-independent)

$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$

Indirect
(time-dependent, mixing-induced)

CPV in mixing
$\Gamma(B_s \to \bar{B}_s) \neq \Gamma(\bar{B}_s \to B_s)$

Seen only in K^0

CPV in interference between mixing and decay

e.g. sin2β

CPV in B_s mixing: $a^s_{\rm sl}$

$$a_{\rm sl} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\overline{B} \to f) + \Gamma(B \to \bar{f})} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_{12}$$

- Predicted to be small in the SM...

B_d: $a^d_{\rm sl}({\rm SM}) = (-4.7 \pm 0.6) \times 10^{-4}$

B_s: $a^s_{\rm sl}({\rm SM}) = (-2.22 \pm 0.27) \times 10^{-5}$

arXiv:1511.09466
[Artuso, Borissov, Lenz]

- ... but could be enhanced by NP.

PRD86 (2012) 033008
[Lenz et al]

- Study with $B_s \to D_s^- \mu^+ \nu_\mu X$

arXiv:1605.09768 [LHCB-PAPER-2016-013]

CPV in B_s mixing: $a^s_{\rm sl}$

- B_s mixing rate is fast (period/lifetime ~ 1/4)
- Don't need to tag individual mesons; can simply count whether more end up in the B_s or $\bar{B}_s$ pile.
  - Production asymmetry washes out => unimportant.

$$a^s_{\rm sl} = \frac{2}{1 - f_{\rm bkg}} \left(A_{\rm raw} - A_{\rm det} - f_{\rm bkg} A_{\rm bkg} \right)$$

Raw measured yield asymmetry

Detection efficiency asymmetry

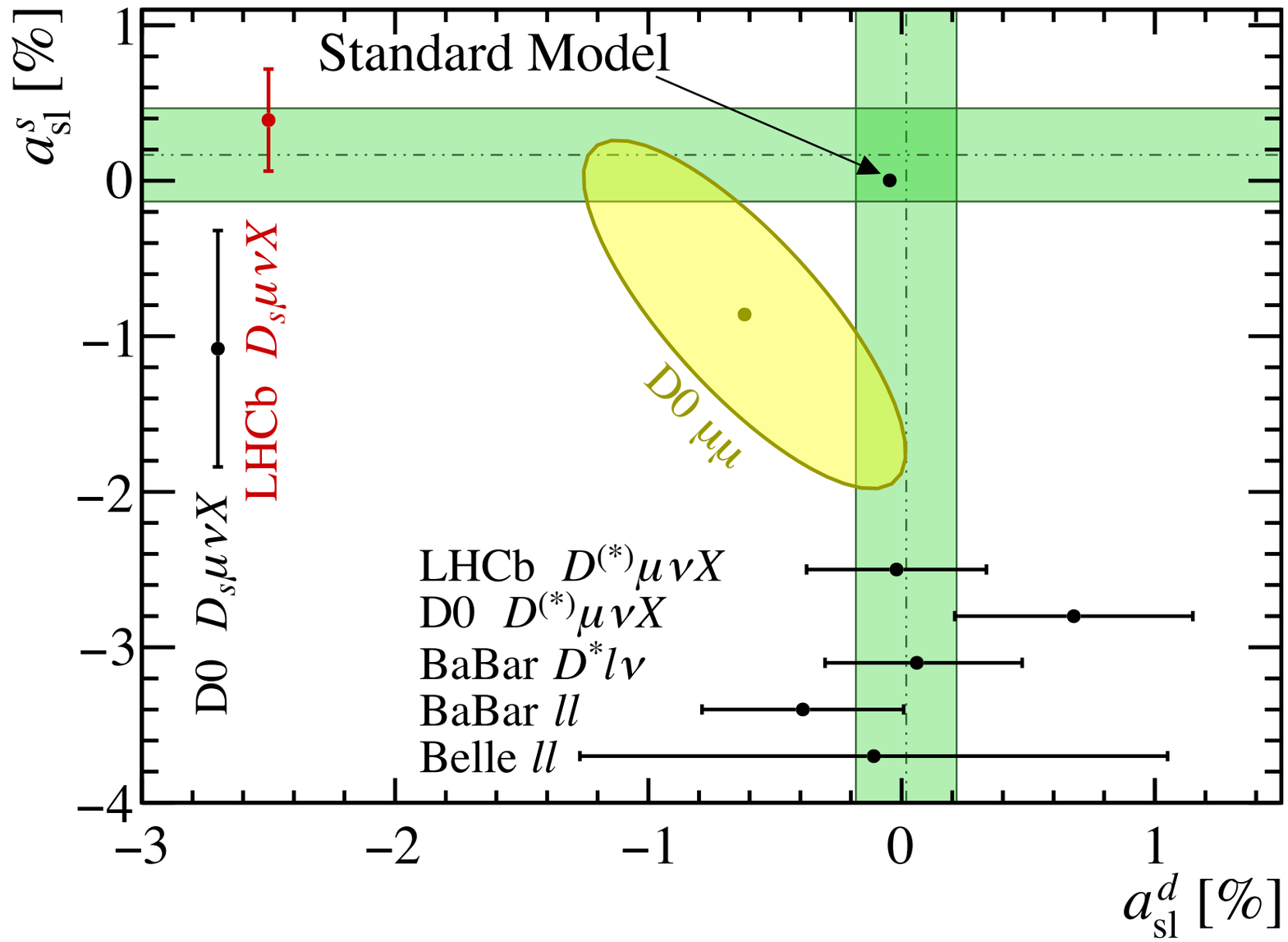
Background fraction f_{bkg} and asymmetry A_{bkg}

- Must control detector asymmetry, background.

arXiv:1605.09768 [LHCB-PAPER-2016-013]

CPV in B_s mixing: $a^s_{\rm sl}$

This measurement: $a^s_{\rm sl} = (0.39 \pm 0.26 \pm 0.20)\%$



Average of pure $a_{\rm sl}$ measurements:

$$\begin{cases} a^d_{\rm sl} = (0.02 \pm 0.20)\% \\ a^s_{\rm sl} = (0.17 \pm 0.30)\% \end{cases}$$

Sadly consistent with SM.

arXiv:1605.09768 [LHCB-PAPER-2016-013]

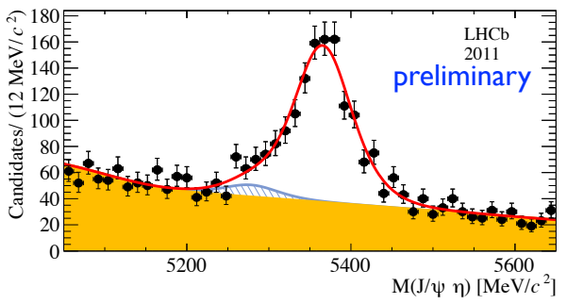
B_s mixing: lifetime ($J/\psi\,\eta$)

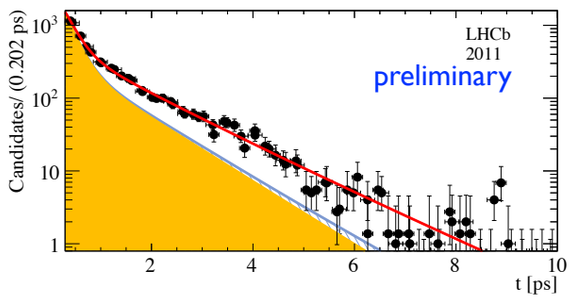
- So we know CPV in B_s mixing is small.
- Mass eigenstates (light, heavy) are almost the same as CP eigenstates (even, odd).
- Effective lifetime of $B_s \to$ CP-even final state ~ τ_L. Can compare to SM prediction: 1.43 ± 0.03 ps. arXiv:1205.1444 [Lenz]
- Golden channel: $B_s \to J/\psi\phi$ -- high stats. But CP-mixed, requires angular analysis.
- This analysis: $B_s \to J/\psi\eta$, pure CP-even
  - $J/\psi \to \mu^+\mu^-$ and $\eta \to \gamma\gamma$

LHCb-PAPER-2016-017 (preliminary)

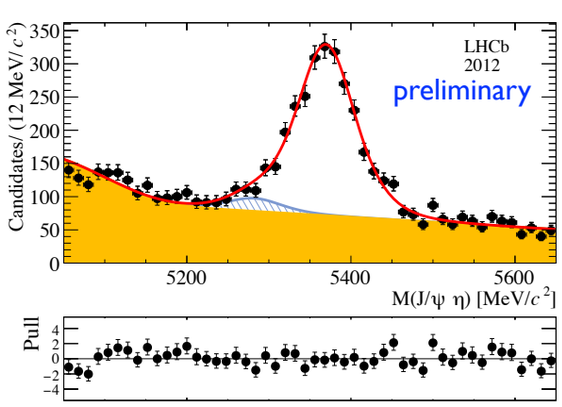
B_s mixing: lifetime ($J/\psi\,\eta$)

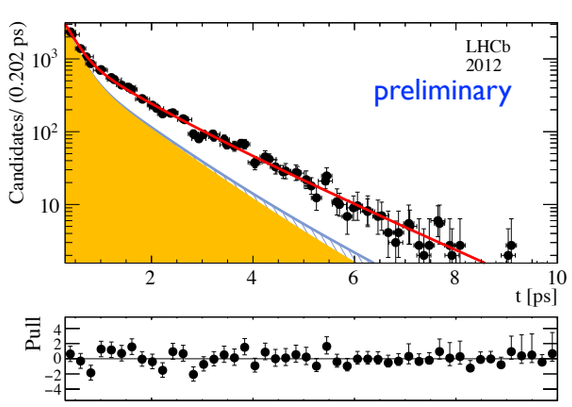
2011





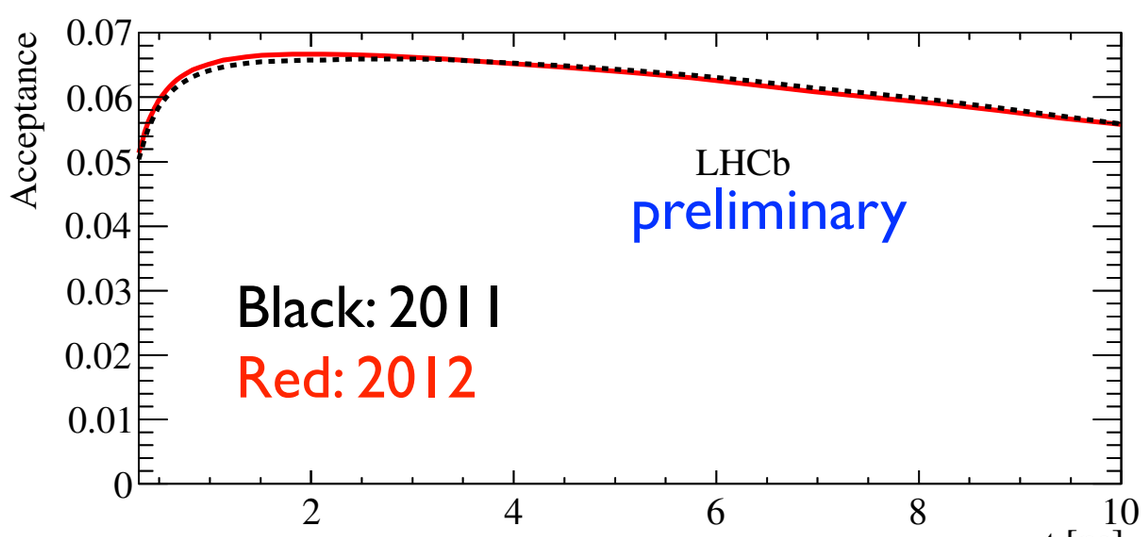
2012





Mass

Decay time



Acceptance

Put it all together, taking underlying signal as a single exponential:

$$\tau_{\rm eff} = 1.479 \pm 0.034\ ({\rm stat}) \pm 0.011\ ({\rm syst})\ {\rm ps}$$ preliminary

Sadly consistent with SM (1.43 ± 0.03 ps) arXiv:1205.1444 [Lenz]

LHCb-PAPER-2016-017 (preliminary)

Exotic hadrons

- Reminder of two key past sets of results:
  - Amplitude analysis of $B^0 \to \psi' \pi^+ K^-$, showing definitively the presence of $Z_c^+ \to \psi' \pi^+$ resonances (tetraquarks*)
  - Amplitude analysis of ($\Lambda_b \to J/\psi\, p\, K^-$), showing definitively the presence of $P_c^+ \to J/\psi\, p$ resonances (pentaquarks*)
- For each: amplitude analysis, followed by model-independent method (angular moments)
- Today: searches for similar states in new decay modes

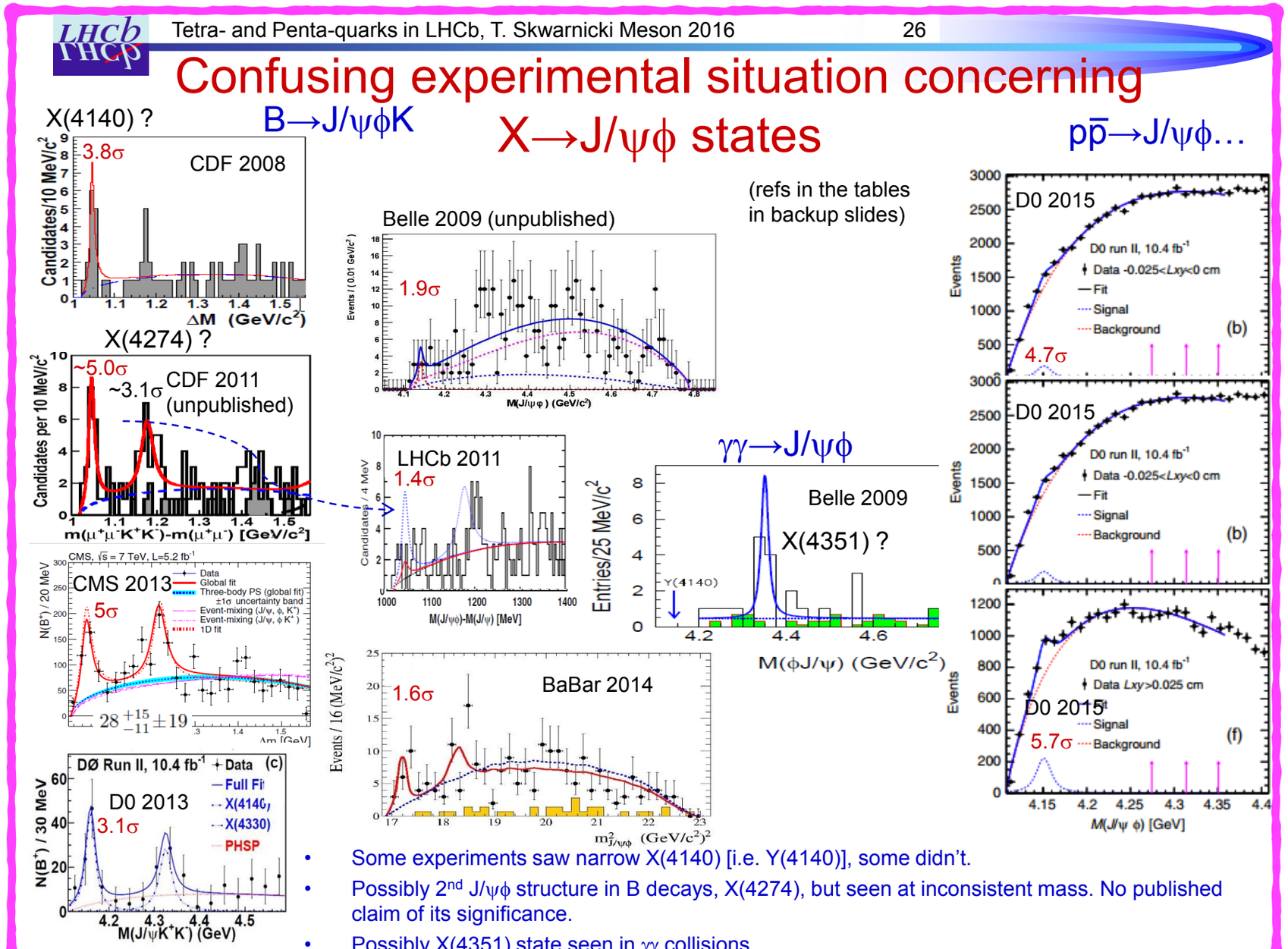
PRL 115 (2015) 072001 [LHCb-PAPER-2015-029]
PRL 112 (2014) 222002 [LHCb-PAPER-2014-014]
PRD 92 (2015) 112009 [LHCb-PAPER-2015-038]
arXiv:1604.05708 [LHCb-PAPER-2016-009]

* In the broad sense, including meson-meson/meson-baryon molecules.

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

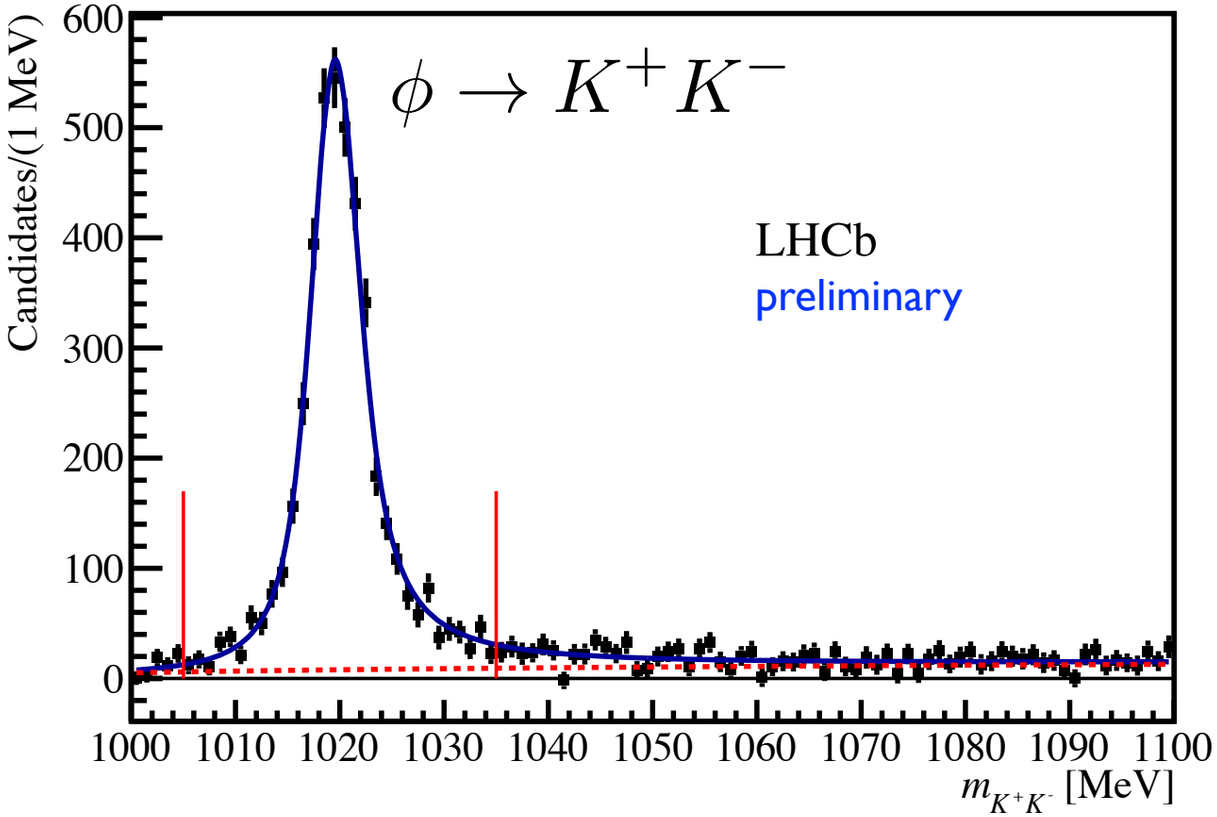
- Many prior studies of ($J/\psi\ \phi$) system.
  - Different experiments; inclusive, exclusive, ...
  - Situation unclear.

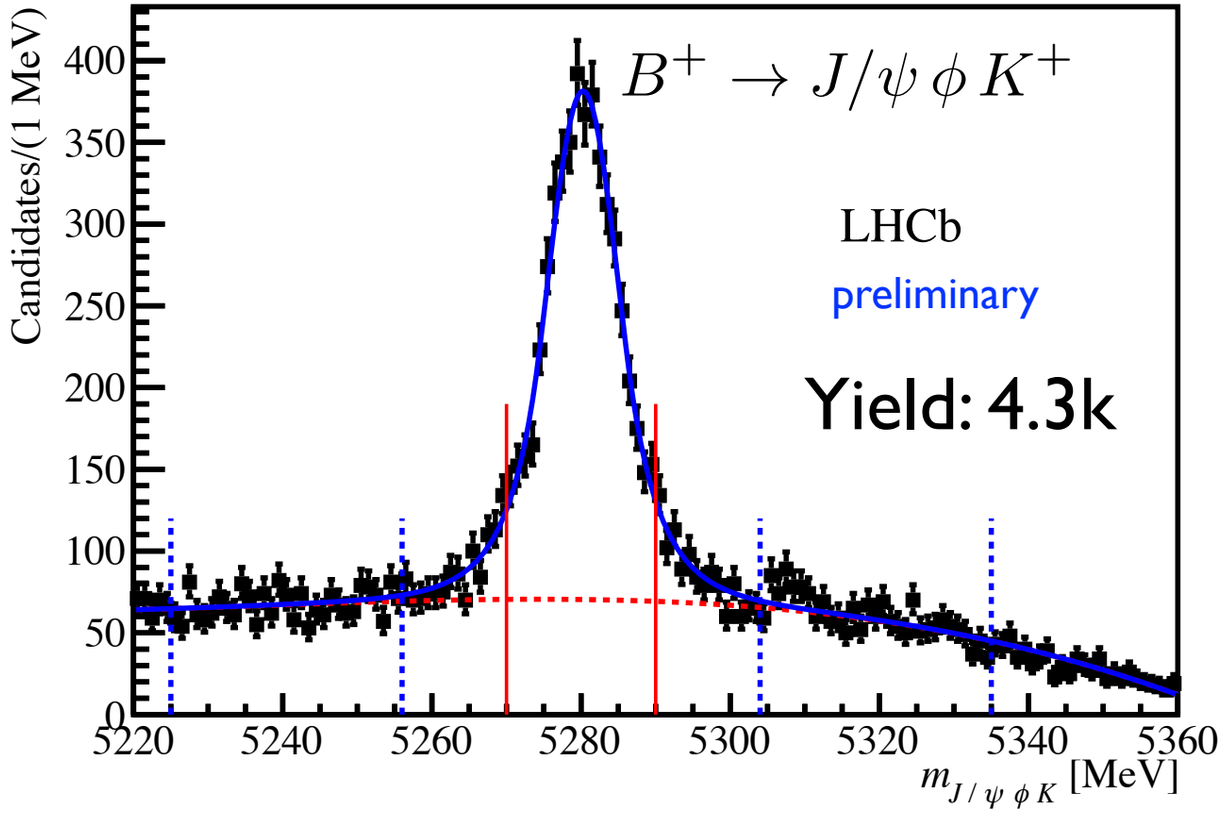
Slide by Tomasz Skwarnicki, MESON2016 (link)



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

- Many prior studies of ($J/\psi\ \phi$) system.
  - Different experiments; inclusive, exclusive, ...
  - Situation unclear.
- Today: new results with 3/fb of LHCb data.





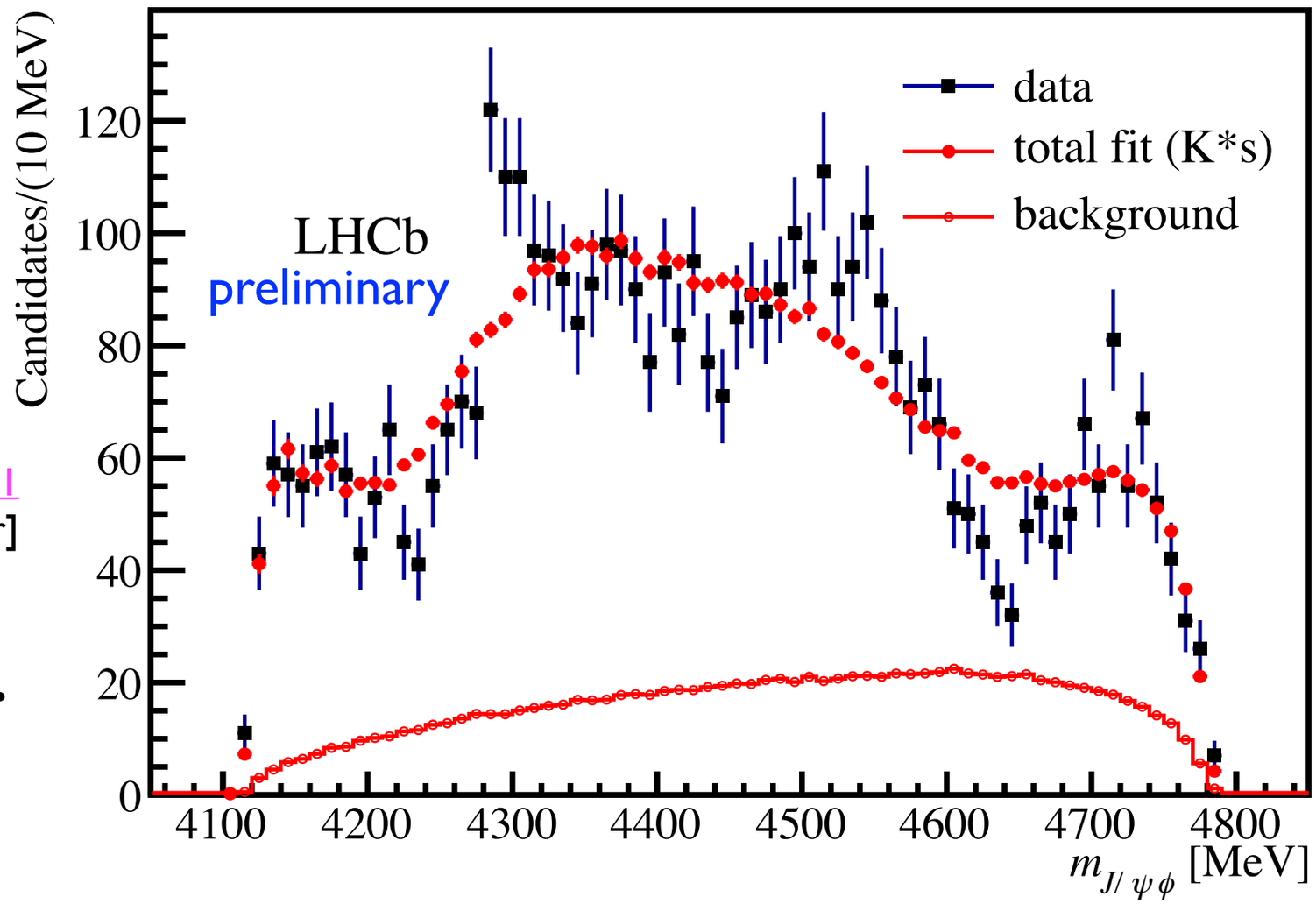
LHCb-PAPER-2016-018 & LHCb-PAPER-2016-019 (preliminary)

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

Q: Can data be described with only conventional ($K^{*+} \to \phi\, K^+$) resonances only?

A: No, based on amplitude fit with all known or expected kinematically allowed kaon resonances. ($p < 10^{-7}$)

PRD 32 (1985) 189-231
[Godfrey & Isgur]



=> Exotics must be present. What are they?

Method: add combinations of ($X \to J/\psi\, \phi$), ($Z \to J/\psi\, K^+$) resonances, refit data, see what's necessary to describe it.

LHCb-PAPER-2016-018 & LHCb-PAPER-2016-019 (preliminary)

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

Best model requires ($X \to J/\psi\, \phi$) but not ($Z \to J/\psi\, K^+$) states.

Contribution	sign. or Ref.	M_0 [MeV] (preliminary)	Γ_0 [MeV] (preliminary)	Fit results F.F. % (preliminary)	J^{PC}
All $X(1^+)$				$16 \pm 3\ ^{+\ 6}_{-\ 2}$	
$X(4140)$	8.4σ	$4146.5 \pm 4.5\ ^{+4.6}_{-2.8}$	$83 \pm 21\ ^{+21}_{-14}$	$13 \pm 3.2\ ^{+4.8}_{-2.0}$	1^{++} (5.7σ)
ave.	Table 1	4146.9 ± 2.3	17.8 ± 6.8		
$X(4274)$	6.0σ	$4273.3 \pm 8.3\ ^{+17.2}_{-\ 3.6}$	$56 \pm 11\ ^{+\ 8}_{-11}$	$7.1 \pm 2.5\ ^{+3.5}_{-2.4}$	1^{++} (5.8σ)
CDF	[27]	$4274.4\ ^{+8.4}_{-6.7} \pm 1.9$	$32\ ^{+22}_{-15} \pm 8$		
CMS	[24]	$4313.8 \pm 5.3 \pm 7.3$	$38\ ^{+30}_{-15} \pm 16$		
All $X(0^+)$				$28 \pm\ 5\ ^{+7}_{-7}$	
$\mathrm{NR}_{J/\psi\phi}$	6.4σ			$46 \pm 11\ ^{+11}_{-21}$	
$X(4500)$	6.1σ	$4506 \pm 11\ ^{+12}_{-15}$	$92 \pm 21\ ^{+21}_{-20}$	$6.6 \pm 2.4\ ^{+3.5}_{-2.3}$	0^{++} (4.0σ)
$X(4700)$	5.6σ	$4704 \pm 10\ ^{+14}_{-24}$	$120 \pm 31\ ^{+42}_{-33}$	$12 \pm\ 5\ ^{+\ 9}_{-\ 5}$	0^{++} (4.5σ)

Additional X states: significance < 2σ

Additional Z states: significance ≤ 3.1σ

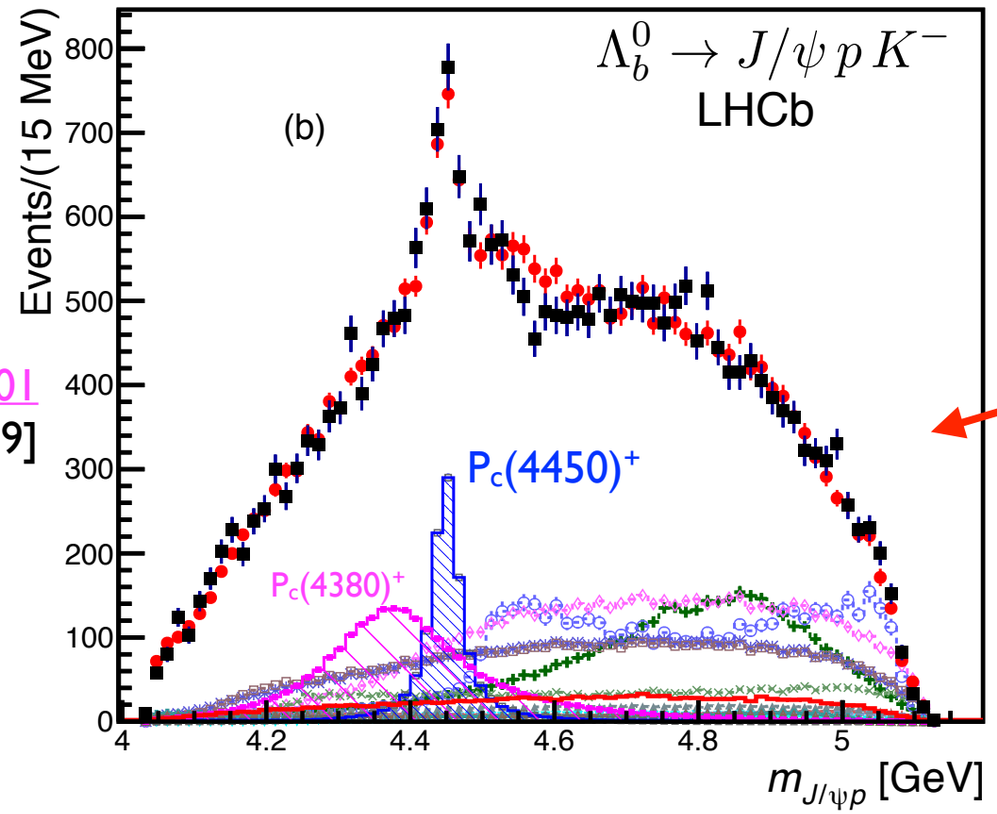
Disclaimer: absence of evidence is not evidence of absence.

LHCb-PAPER-2016-018 & LHCb-PAPER-2016-019 (preliminary)

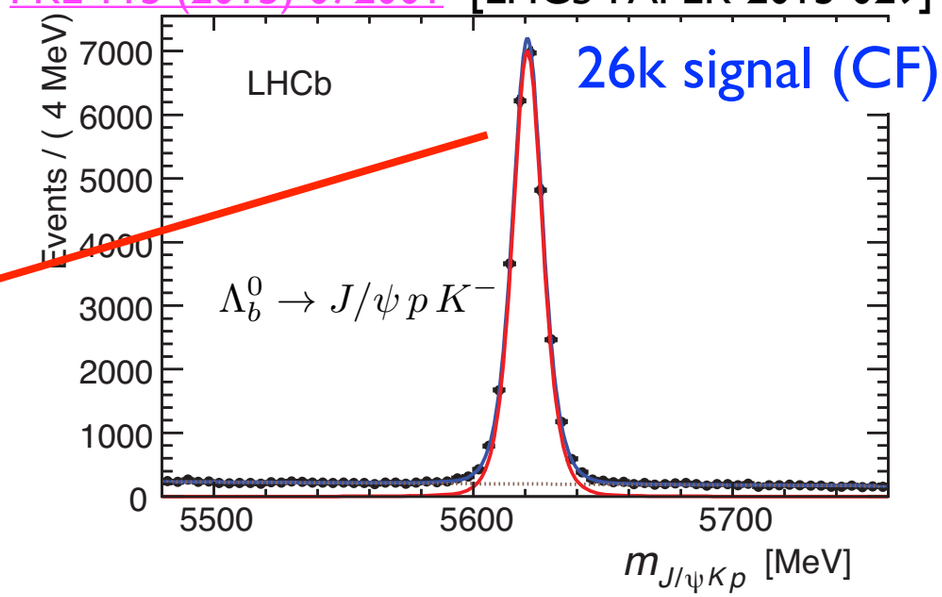
$\Lambda_b \to J/\psi\, p\, (K/\pi)^-$

- $\Lambda_b \to J/\psi\, p\, K^-$ studied previously: two $P_c^+ \to J/\psi\, p$

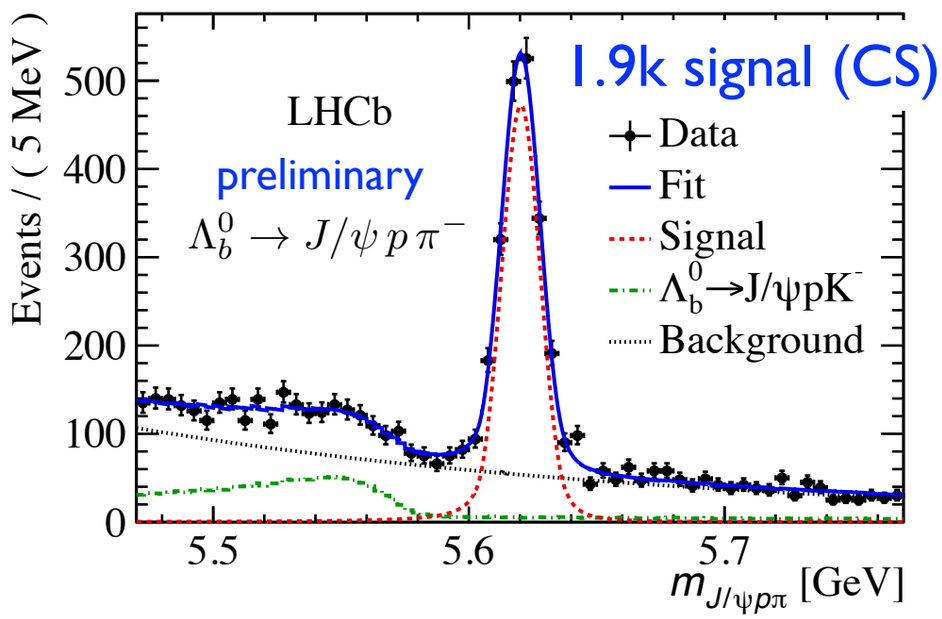
PRL 115 (2015) 072001
[LHCb-PAPER-2015-029]



PRL 115 (2015) 072001 [LHCb-PAPER-2015-029]



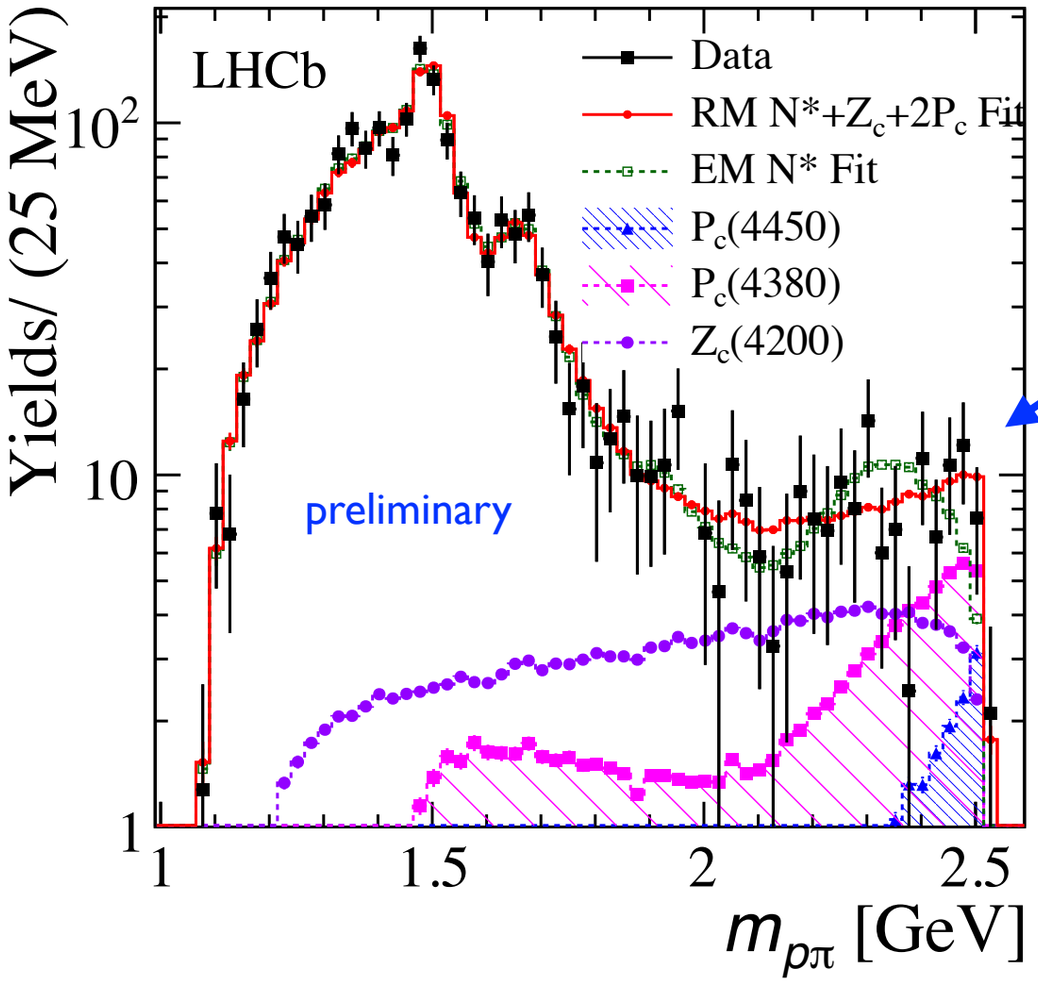
- Today: CS mode, $\Lambda_b \to J/\psi\, p\, \pi^-$
- No guarantees, but worth a look!
- Also sensitive to $Z_c^- \to J/\psi\, \pi^-$



LHCb-PAPER-2016-015 (preliminary)

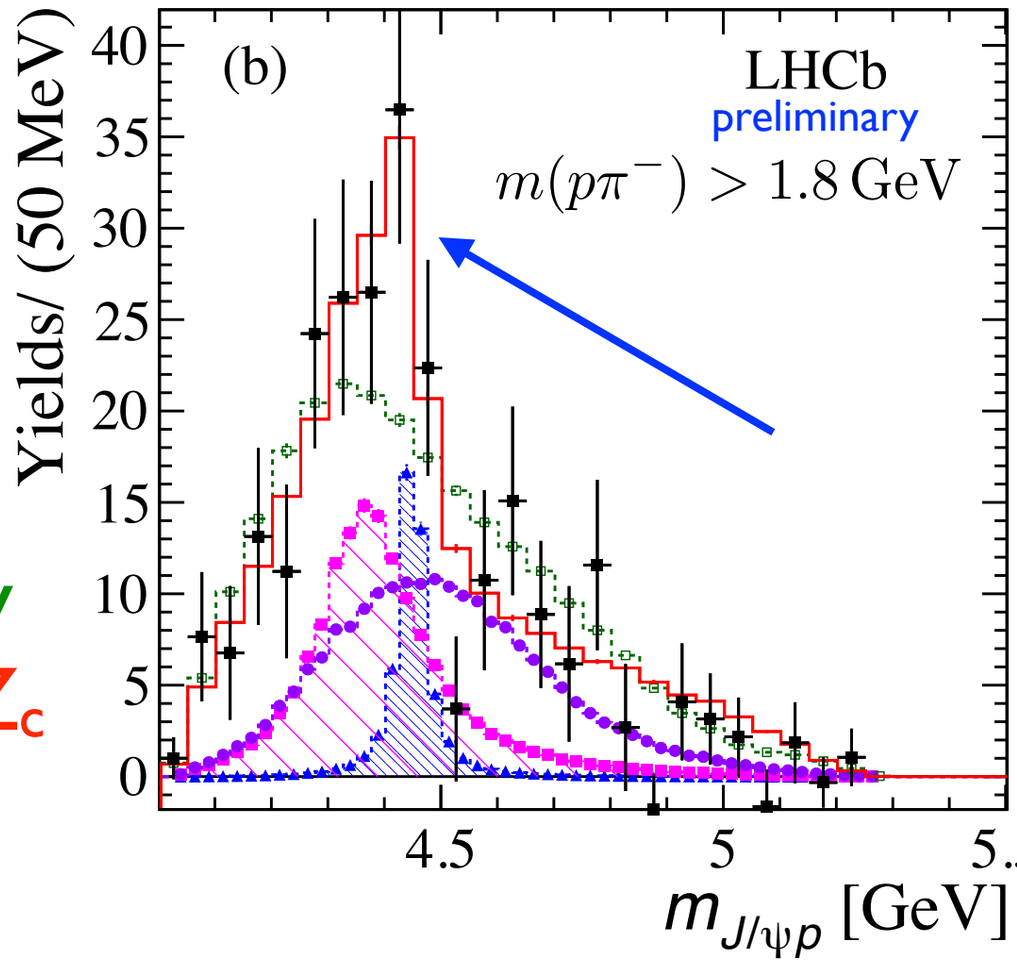
$\Lambda_b \to J/\psi\, p\, \pi^-$

- Similar approach to $B^+ \to J/\psi\, \phi\, K^+$ discussed before
  - Null hypothesis: only $N^{*-} \to p\, \pi^-$ resonances
- Limited stats => focus only on known P_c, Z_c states



N* only

N*+Pc, Zc



LHCb-PAPER-2016-015 (preliminary)

$\Lambda_b \rightarrow J/\psi\ p\ \pi^-$

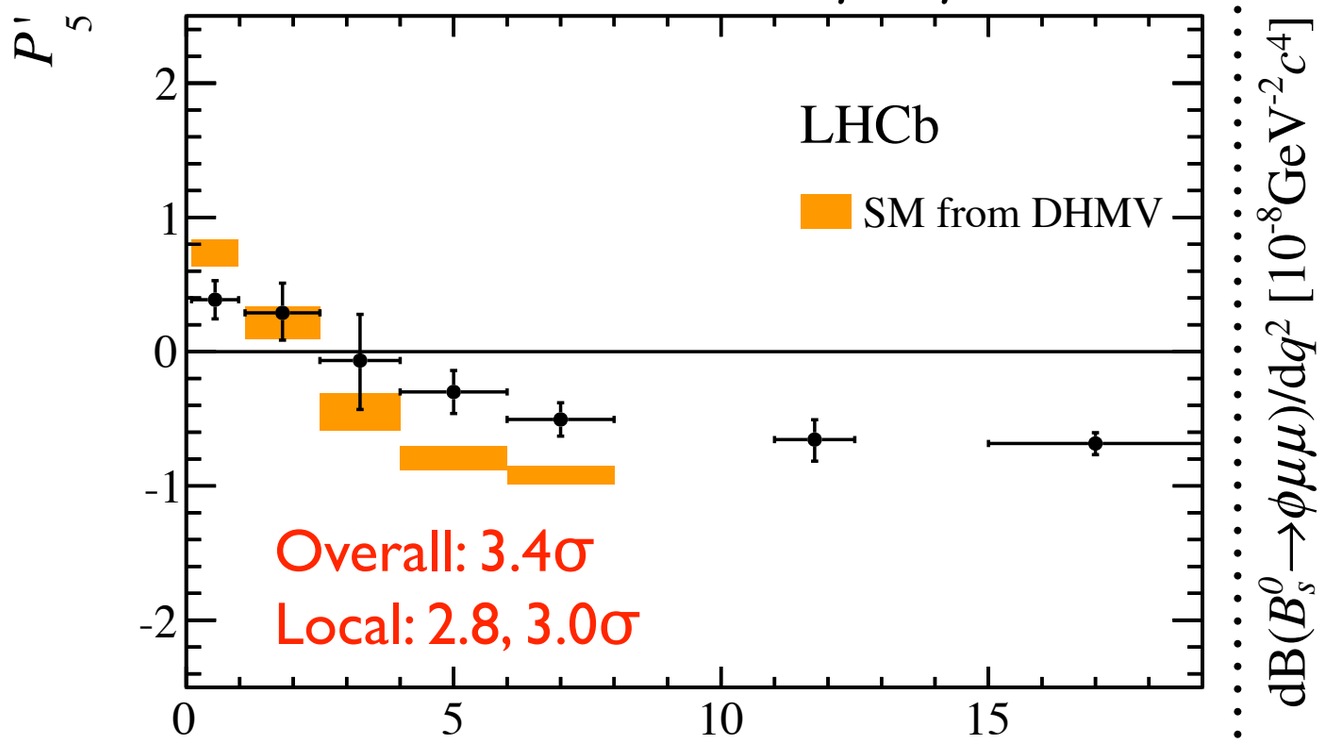
- Full model fits the data better than N^*-only model
  - Full model = $\sum N^* + P_c(4380)^+ + P_c(4450)^+ + Z_c(4200)^-$
  - "Better" = 3.1σ compared to N^*-only model
- Therefore: evidence for presence of exotic hadrons in this Λ_b decay mode too.
- But: not enough stats yet to say which ones
  - Individual contributions not significant
  - Interference makes it tricky to disentangle them
- Bottom line: consistent with ($\Lambda_b \rightarrow J/\psi\ p\ K^-$) but not an independent 5σ confirmation yet.

LHCb-PAPER-2016-015 (preliminary)

Less new, still exciting

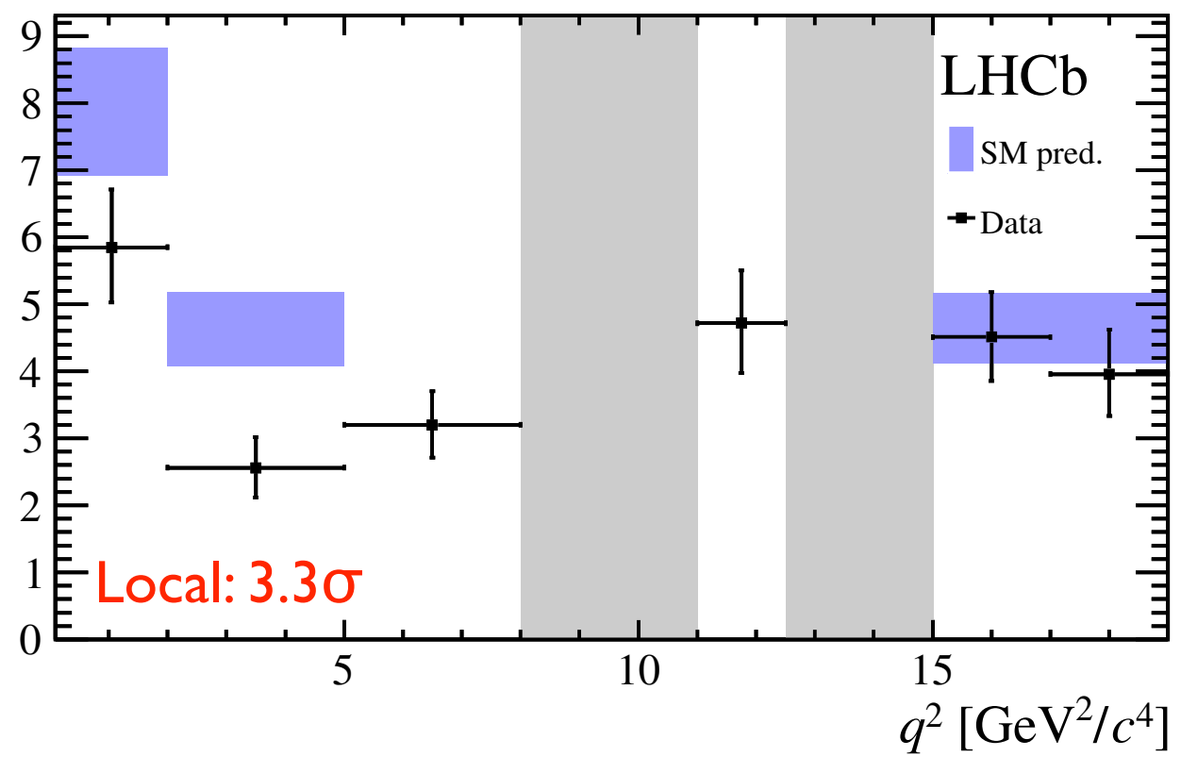
Angular analyses of rare decays

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



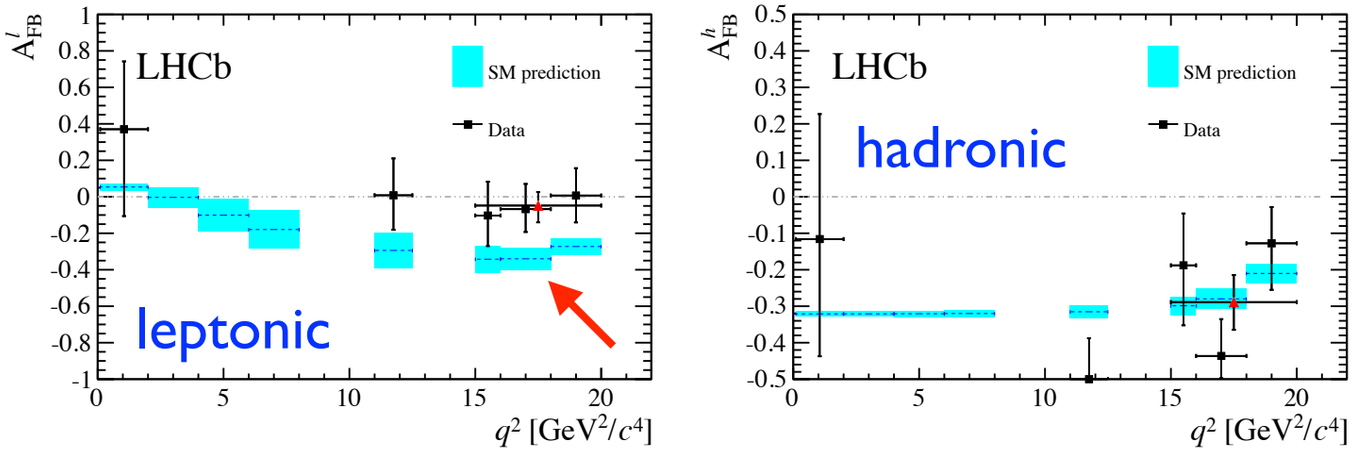
JHEP 02 (2016) 104 [LHCb-PAPER-2015-051]

$B_s^0 \to \phi\mu^+\mu^-$

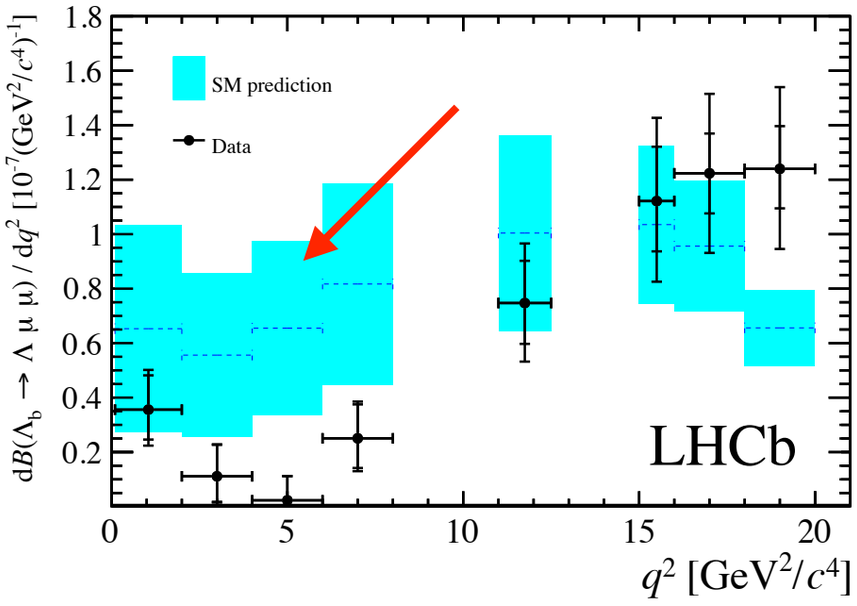


JHEP 09 (2015) 179 [LHCb-PAPER-2015-023]

$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

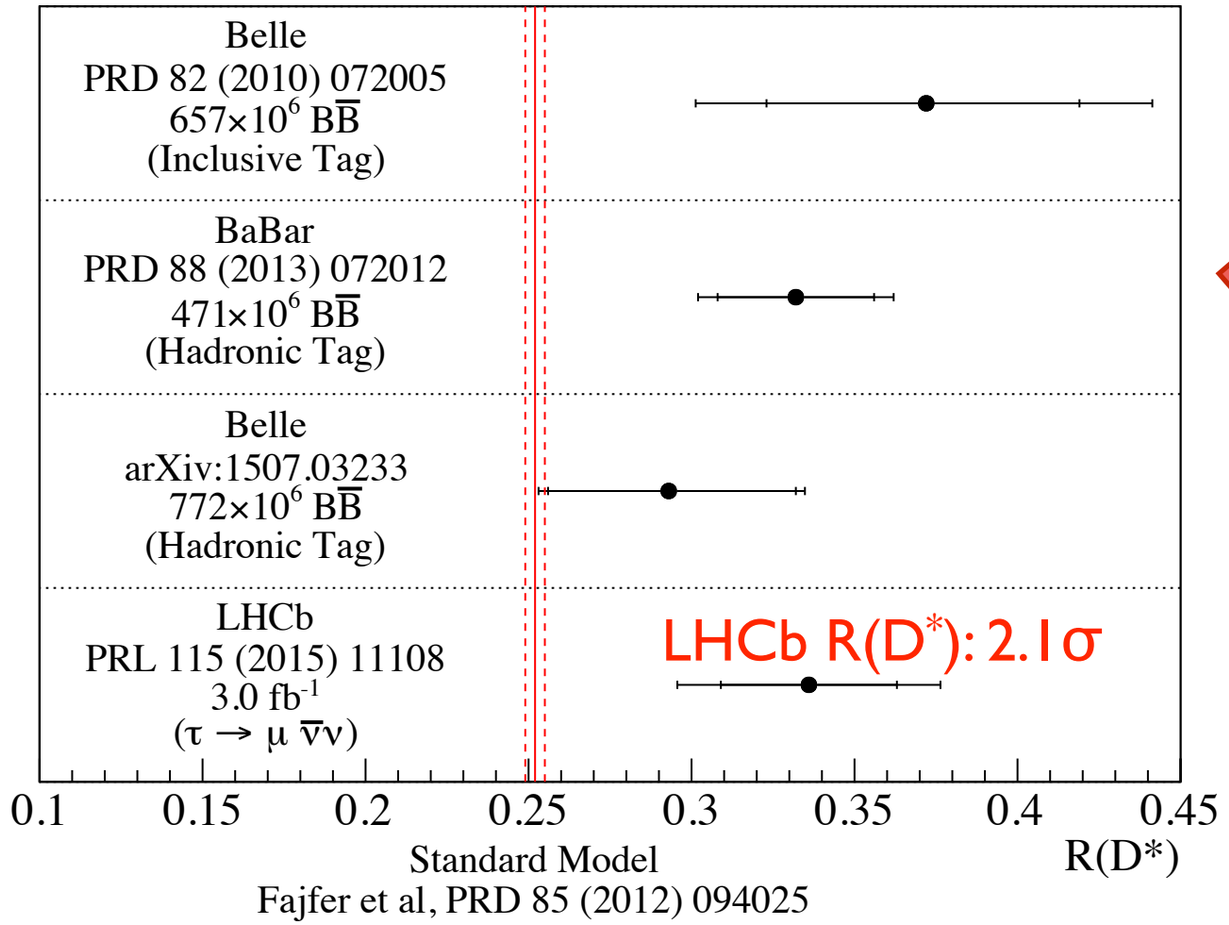


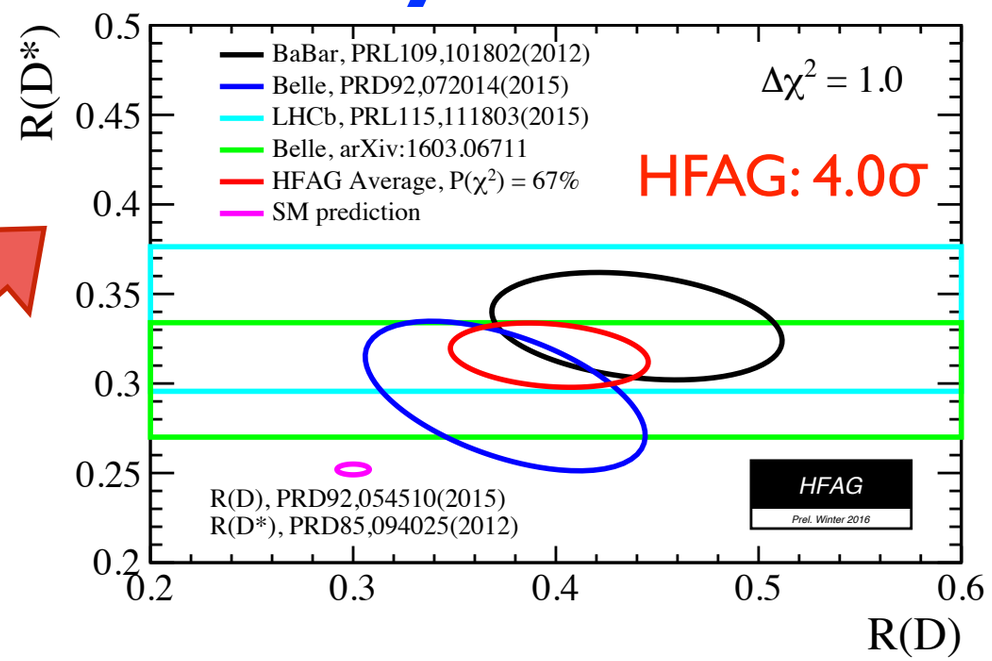
JHEP 06 (2015) 115 [LHCb-PAPER-2015-009]



Lepton universality?

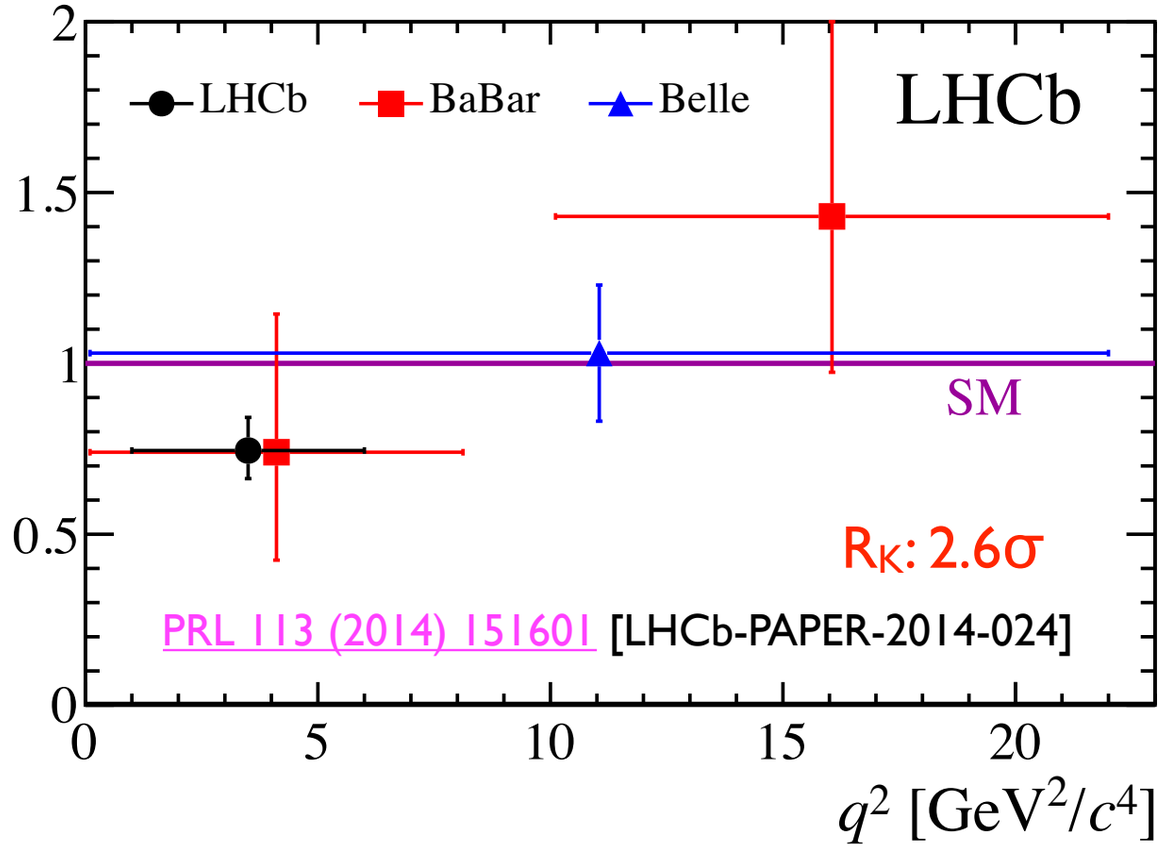
$$R(D^*) = \mathcal{B}(\overline{B^0} \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\overline{B^0} \to D^{*+}\mu^-\bar{\nu}_\mu)$$



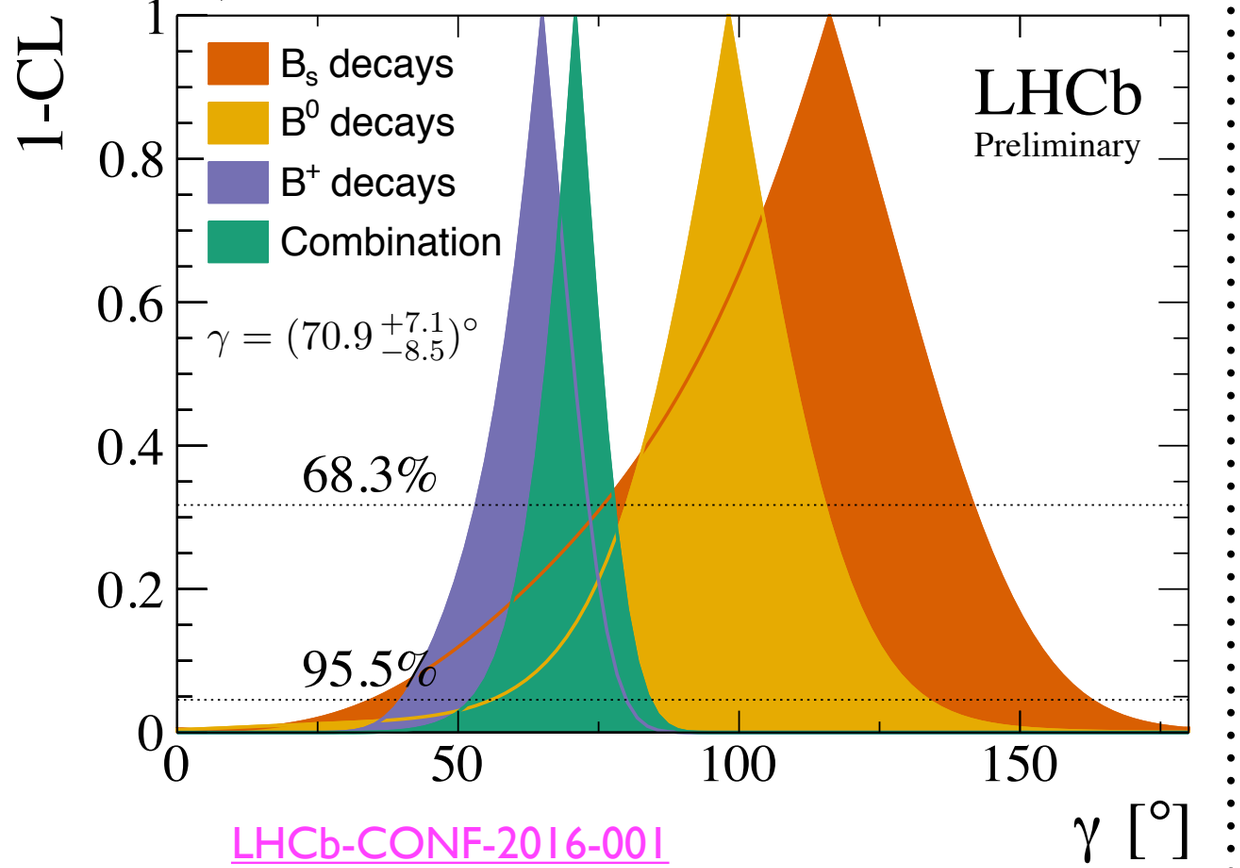


PRL 115 (2015) 111803 [LHCb-PAPER-2015-025]

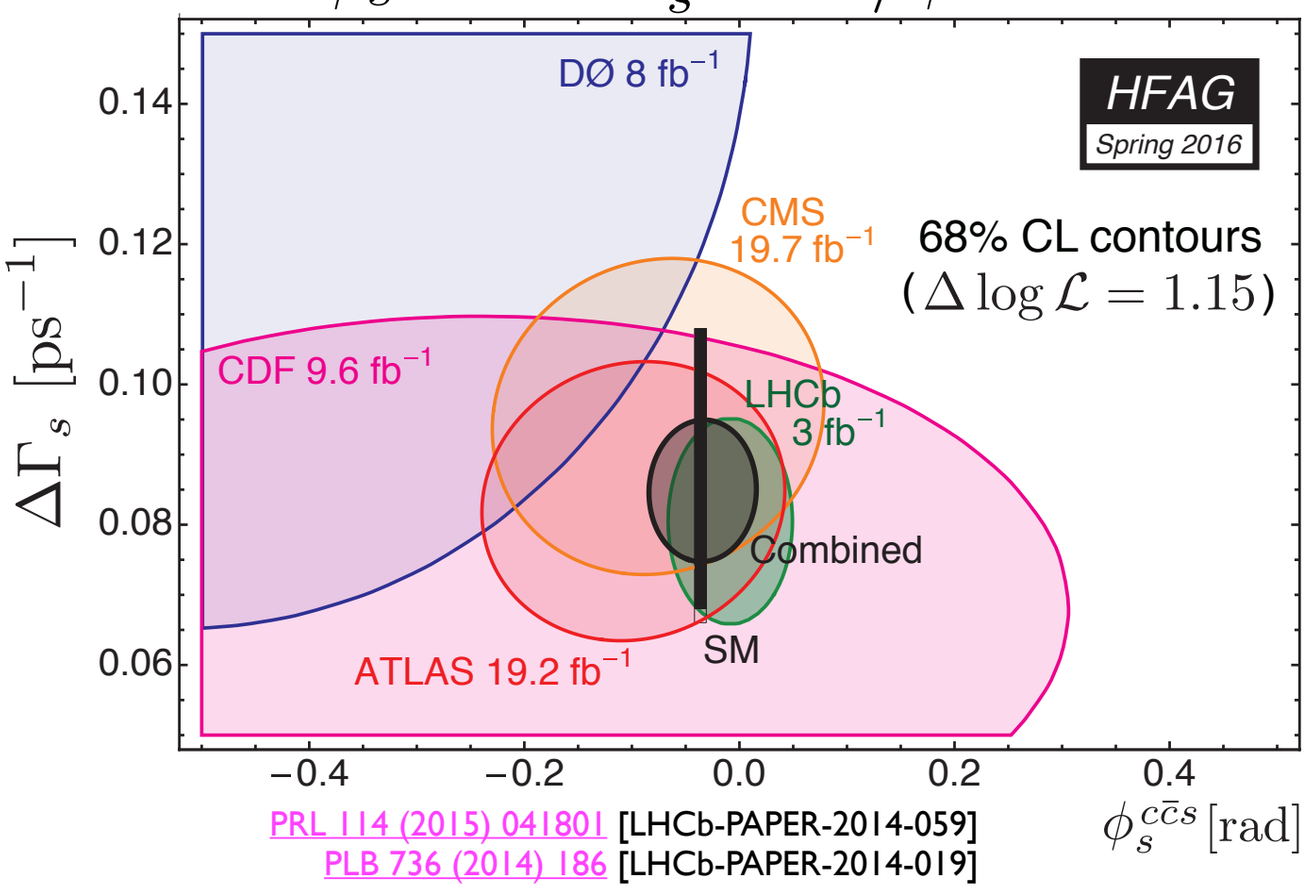
$$R_K\ (B^+ \to K^+\mu^+\mu^-/B^+ \to K^+e^+e^-)$$



CKM physics

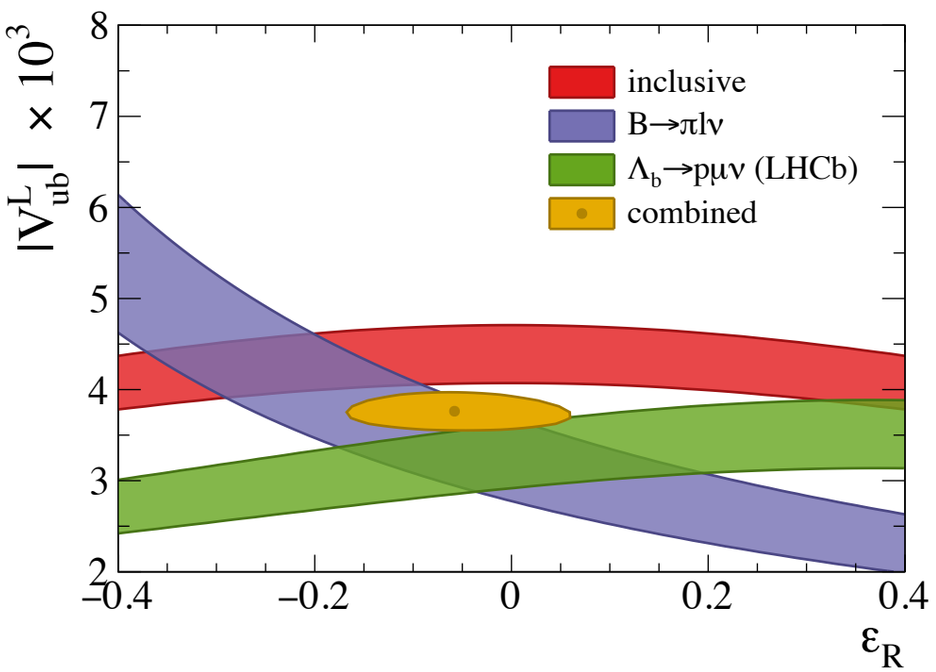


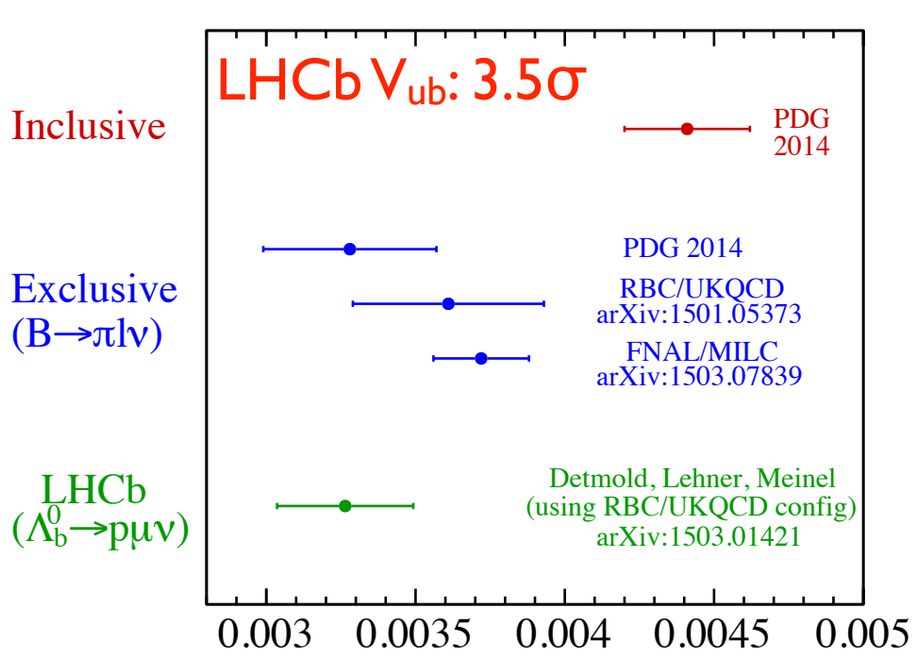
LHCb-CONF-2016-001



PRL 114 (2015) 041801 [LHCb-PAPER-2014-059]
PLB 736 (2014) 186 [LHCb-PAPER-2014-019]

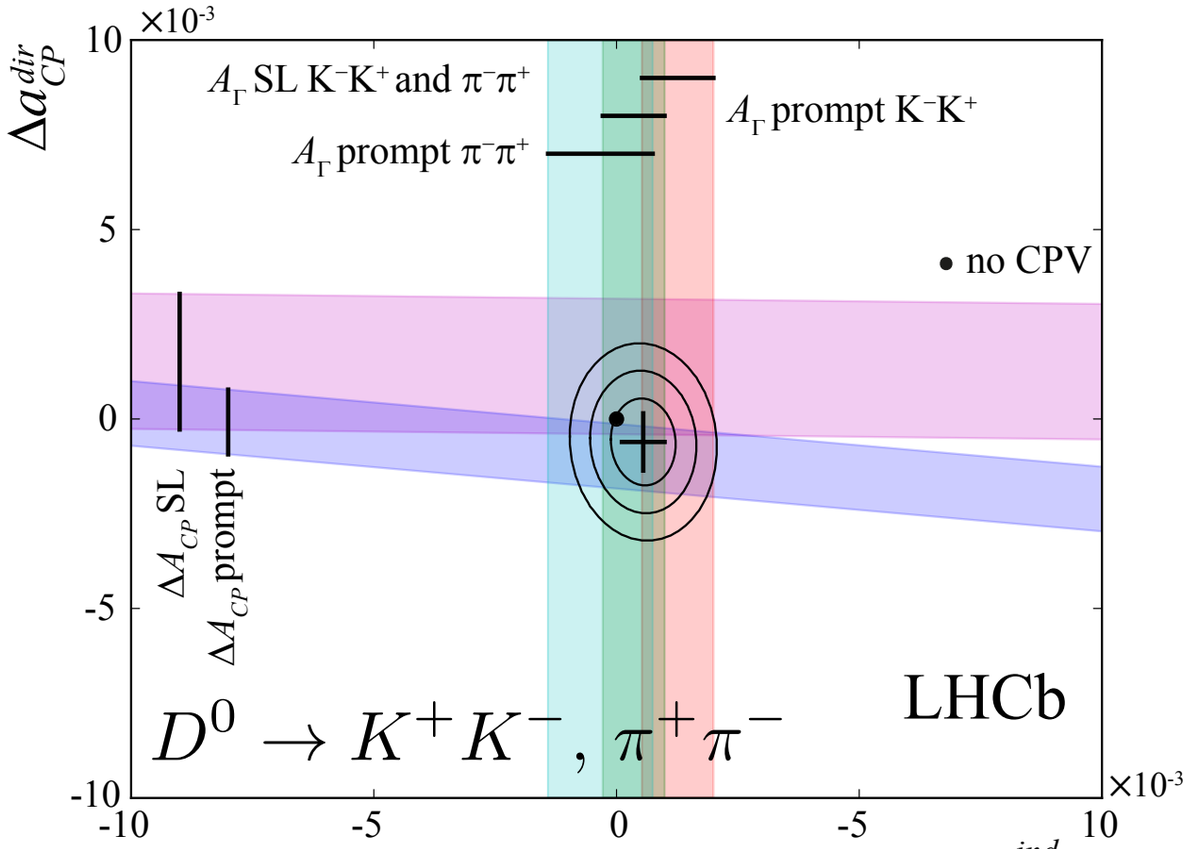
V_{ub} from $\dfrac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}$



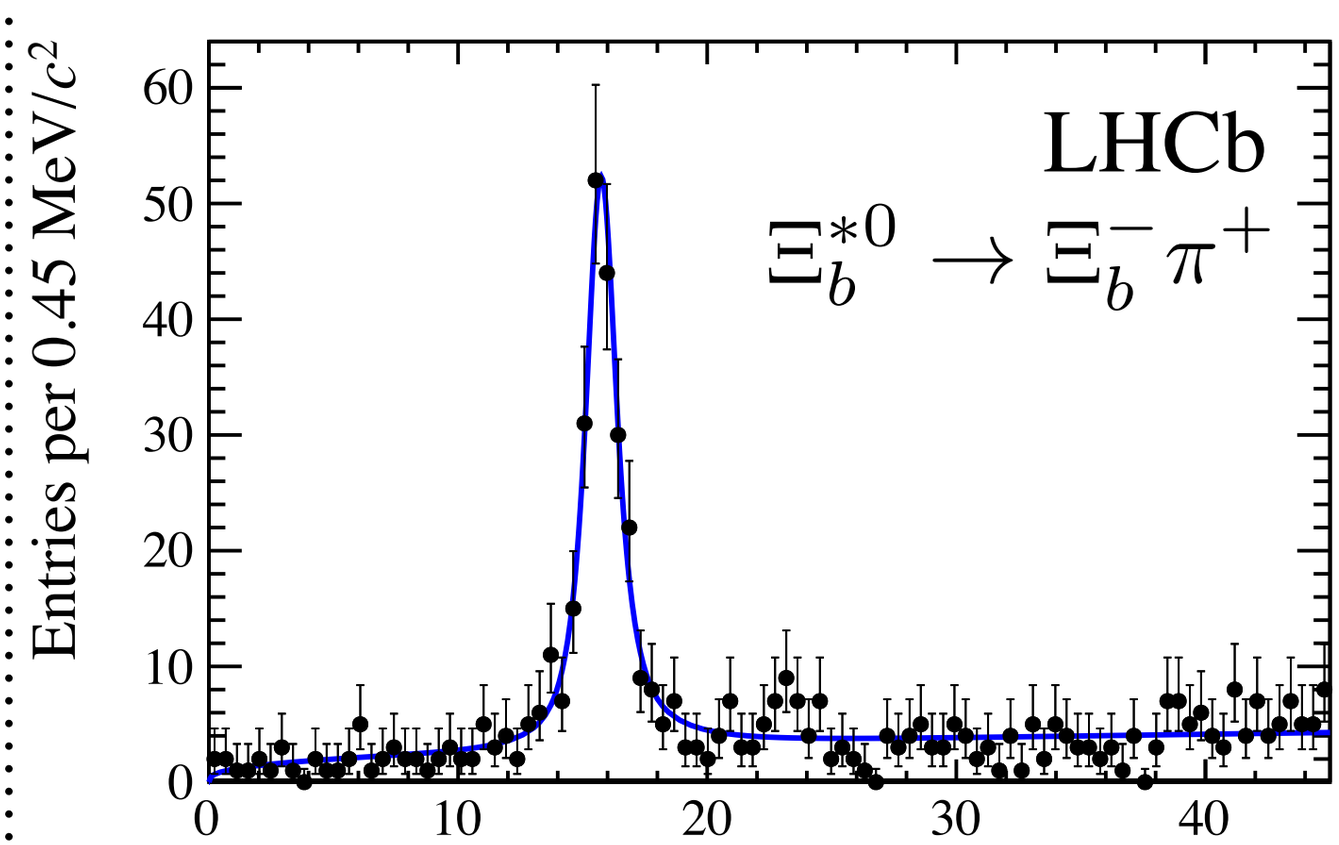


Nature Physics 10 (2015) 1038
[LHCb-PAPER-2015-013]

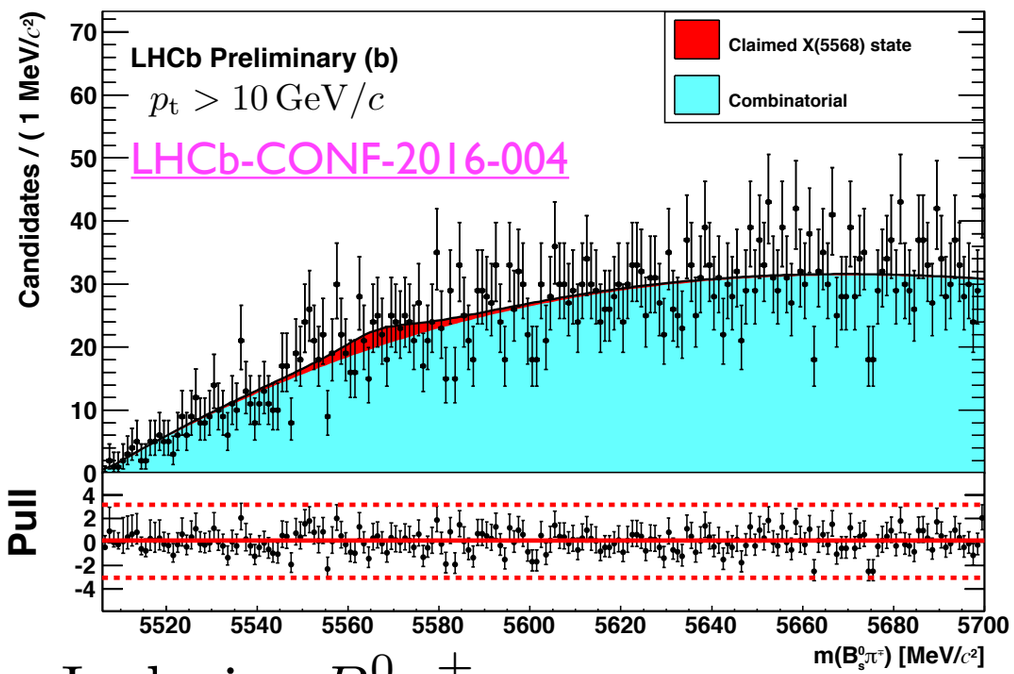
Charm, spectroscopy, ...



PRL 116 (2016) 191601 [LHCb-PAPER-2015-055]

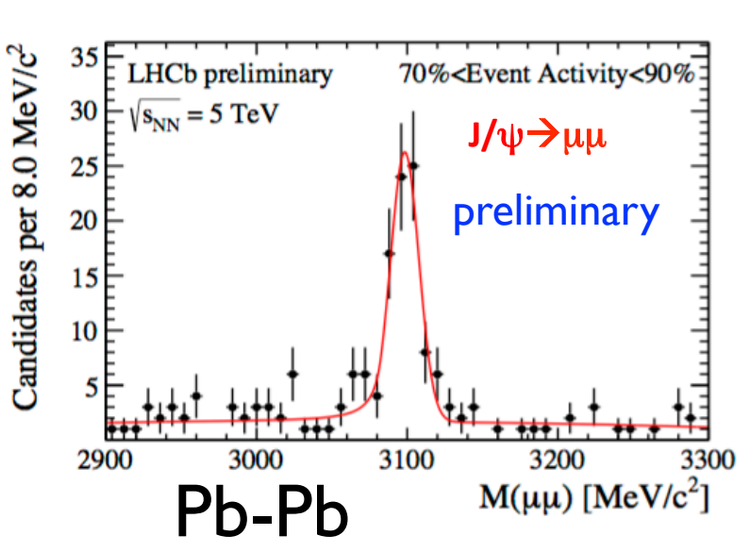


JHEP 1605 (2016) 161 [LHCb-PAPER-2016-010]

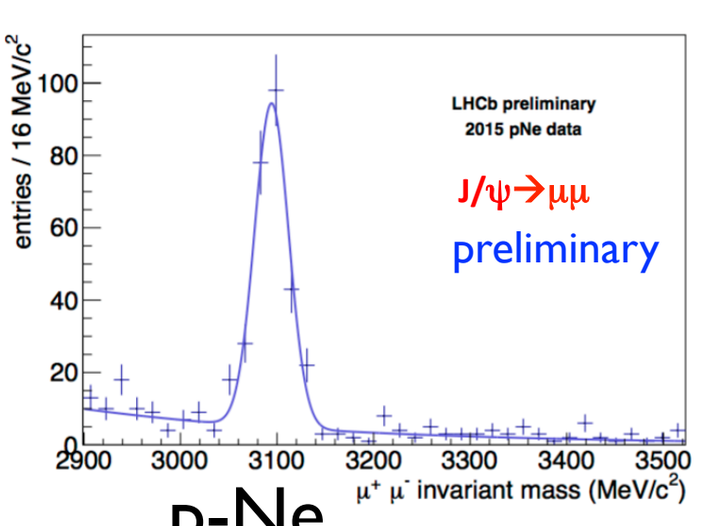


LHCb-CONF-2016-004

Inclusive $B_s^0\pi^\pm$



Pb-Pb



p-Ne (SMOG)

... and yet more

... heavy ion physics, forward electroweak, QCD, lifetimes, more charm, more spectroscopy, dark matter, more everything!

Monday, Performance: Real-time physics: novel concepts for trigger, calibration & alignment, and data processing with LHCb (Lucia Grillo)
Tuesday, QCD: QCD Results from LHCb (Giovanni Passaleva)
Tuesday, Heavy Ion: First LHCb Results from pA and PbPb collisions (Laure Marie Massacrier)
Thursday, Heavy Flavour: New results in semileptonic beauty decays with LHCb (Laurent Dufour)
Thursday, Heavy Flavour: New results in LU/LFV tests with LHCb (Jessica Prisciandaro)
Thursday, Electroweak: Vector Boson studies in LHCb (including AFB results from all experiments) (Murilo Santana Rangel)
Friday, Heavy Flavour: HF Production results at 13 TeV with LHCb (Max Neuner)
Friday, Heavy Flavour: New results in beauty and charm spectroscopy with LHCb (Roberta Cardinale)
Friday, Exotics & Dark Matter: Searches for exotic new physics with LHCb (Bartlomiej Rachwal)
Friday, Heavy Flavour: CPV in beauty decays with LHCb (Frank Meier)
Friday, Heavy Flavour: CPV in charm decays with LHCb (Denis Derkach)
Saturday, Plenary: LHCb upgrade plans & potential (Alessandro Cardini)

Monday, QCD: Impact of LHC measurements on parton density functions (Katharina Mueller)
Monday, Outreach: LHC Masterclasses. Bringing Particle Physics into the Classroom: Present and Future (Vladimir Gligorov)
Tuesday, Plenary: Vector boson (plus jets) physics in pp collisions at the LHC (Murilo Santana Rangel)
Friday, Upgrade (LHC & experiments): Flavour at HL-LHC (Giovanni Punzi)
Friday, Plenary: Heavy flavour production and spectroscopy at the LHC (Michal Kreps)
Friday, Plenary: CP violation, mixing and semileptonic decays in beauty and charm at the LHC (Matthew David Needham)
Friday, Plenary: Rare decays of flavoured mesons at the LHC (Albert Puig Navarro)
Friday, Exotics & Dark Matter: Searches for heavy neutrinos, LFV (Raja Nandakumar)

The future

Forthcoming attractions

- Very excited about Run 2. Will these hints hold up?
- Testing ideas for trigger and DAQ ahead of upgrade
- Approved upgrade: Lots and lots of work to do
  - ... so we can raise lumi and trigger efficiency
  - Complete overhaul of tracking systems
- Further ahead: preparing for success
  - Thinking about a possible far-future upgrade
- Once more unto the breach!

→ see talks by Alessandro Cardini, Giovanni Punzi

The LHCb experiment has collected large samples of heavy flavoured hadrons during Run 1, corresponding to an integrated luminosity of 3.0/fb at pp centre-of-mass energies of 7 and 8 TeV. Data-taking at a CM energy of 13 TeV has now begun. The current status of LHCb after the 2016 restart will be presented. Key results from LHCb will be summarised, with emphasis on the most recent.