Heavy Quarks @ LHC

Carla Göbel

PUC-Rio

on behalf of the LHCb Collaboration

presenting results also from ATLAS and CMS

with mentions to BaBar, Belle, D0

Aug 28th - Sept 2nd 2017

Outline

Most recent/interesting/intriguing results on

- Heavy Flavour Production & Properties
- Rare decays & Lepton Universality
- Spectroscopy (including exotics)
- Highlights on CP violation

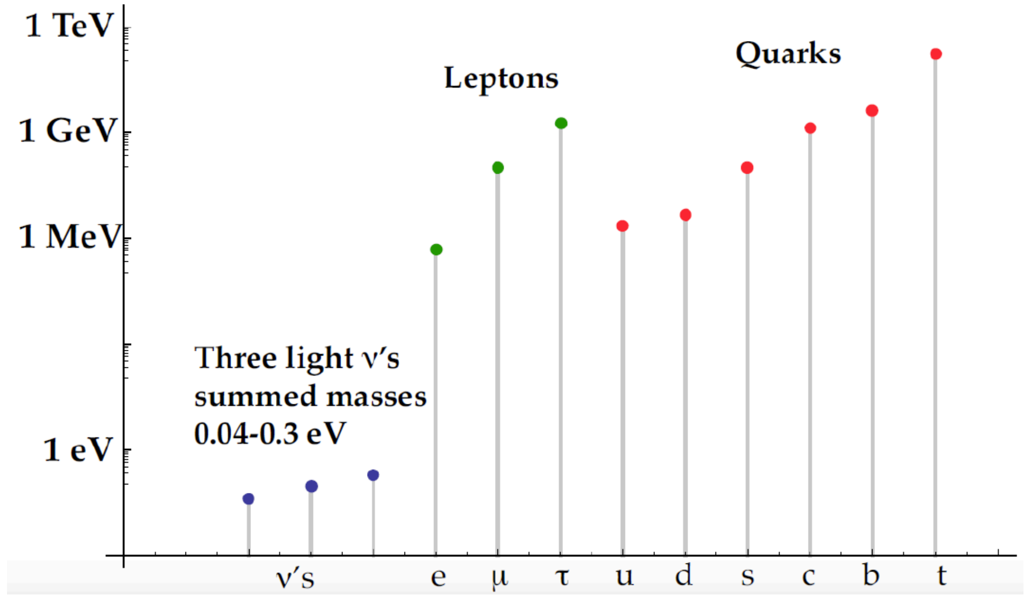
Disclamer: Impossible to cover everything !

- I won't touch on Top Physics and Heavy Ions (dedicate plenaries)
- Focus on most recent ($\lesssim$ 1y) and/or significant results from ATLAS, CMS and LHCb
- Yet, some bias may appear: sorry if your preferred topic/result is not covered

Why study flavours....

- Standard Model (SM) alive and very well for half a decade!
- Yet, it cannot be all...

  dark matter, fermion mass scales, baryon asymmetry, hierarchy problem, etc...



- **The quest for New Physics (NP) relies on complementary approaches**

Energy Frontier

direct searches for new particles and interactions

Precision Frontier

look for deviations of the SM predictions: heavy particles affects lower energy processes

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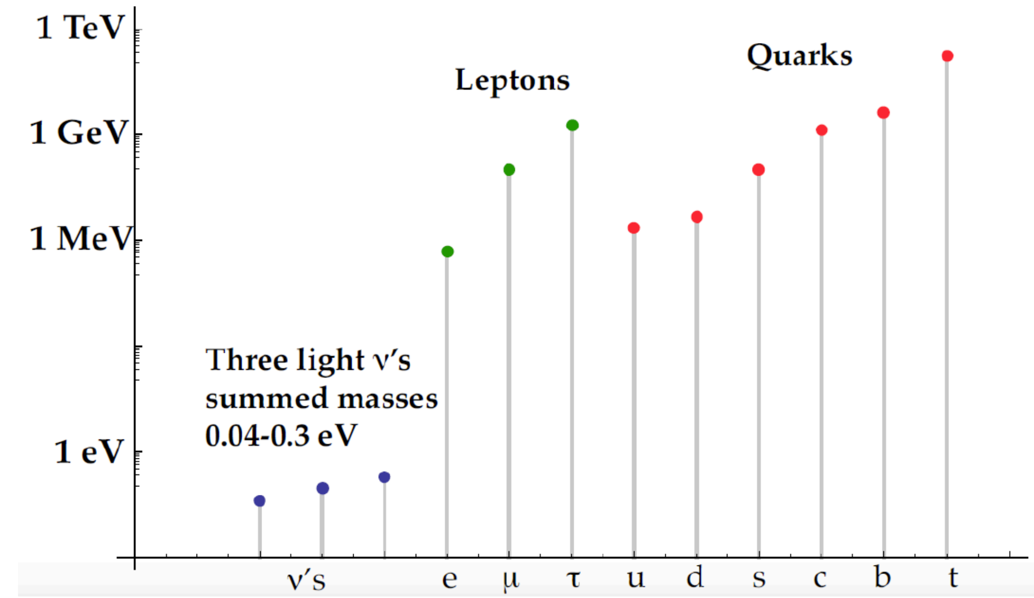

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The flavour sector in the richest and most puzzling part of the Standard Model (SM)

☞ 20 parameters: masses and mixing of the 12 fermions

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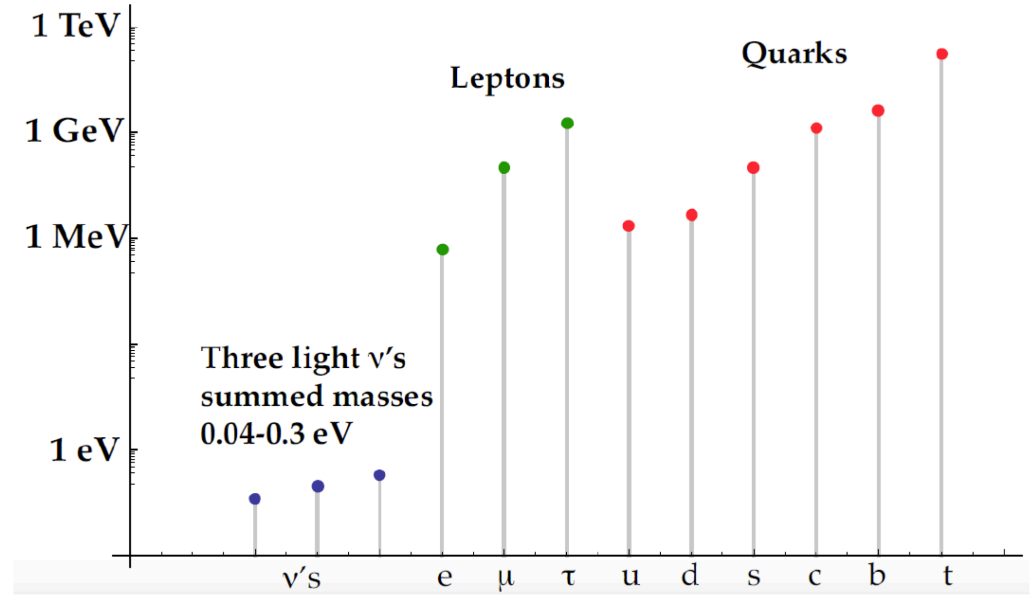

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direct searches for new particles and interactions

Precision Frontier

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The flavour sector in the richest and most puzzling part of the Standard Model (SM)

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QUARK SECTOR

a tool for:

Study QCD in different regimes

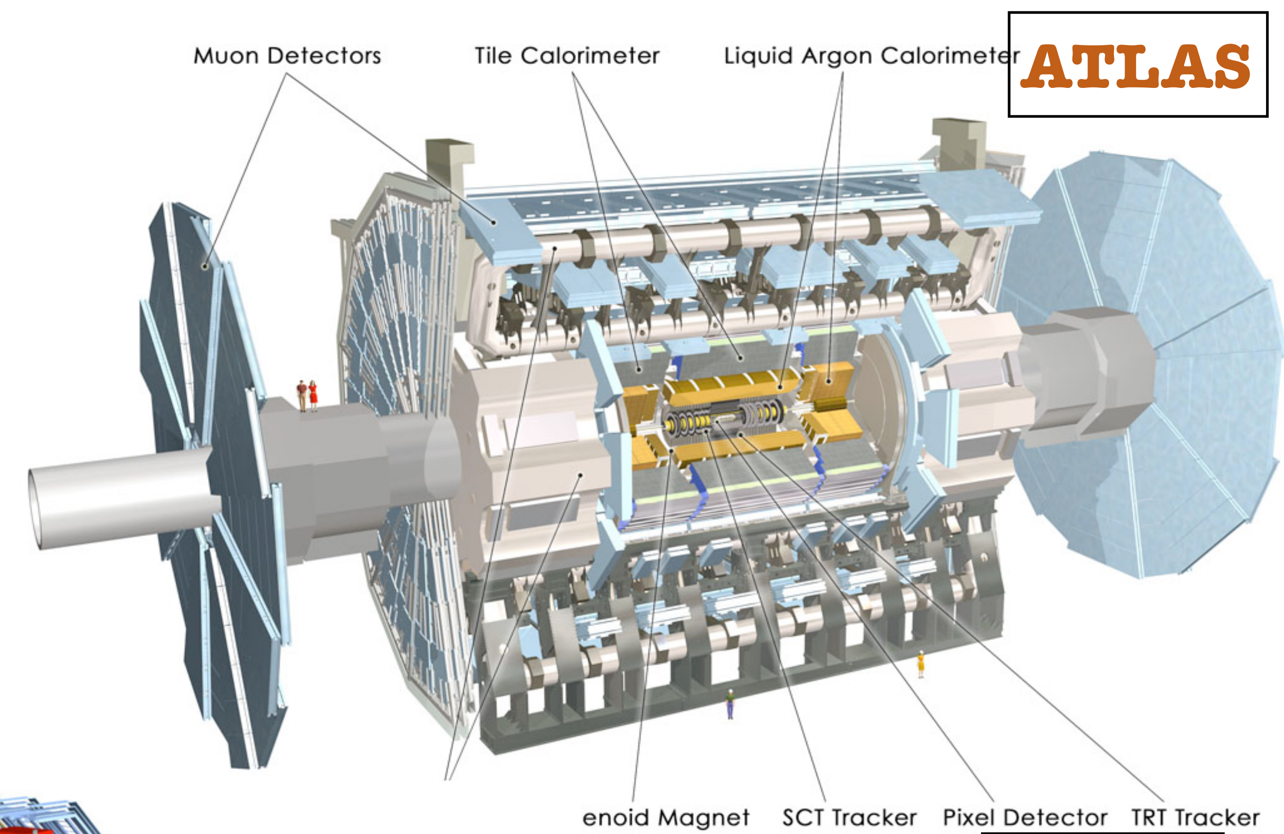
New physics searches

Understand CP violation mechanisms

Flavour Physics @ the LHC

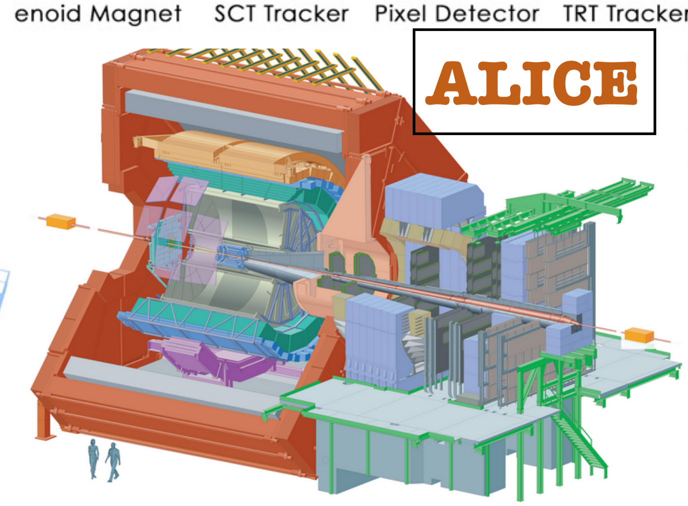
LHC is a flavour factory!

- Huge b cross section, and 20x higher for charm
- All types of b- and c-hadrons produced



- ATLAS, CMS
  - general purpose, "discovery machines"
  - efficient di-muon trigger: great capabilities in b decays to μμ
  - maximal luminosity
- ALICE
  - cleanly reconstruct heavy flavours
  - focused on quark-gluon plasma
  - contributing in heavy flavour production in pp collisions too

(L. Vermunt, Tue 29/08)



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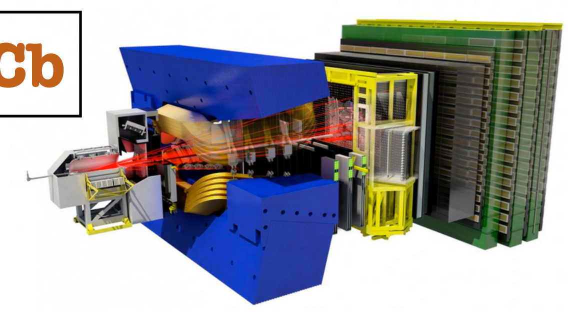
LHCb



- **LHCb is the dedicated flavour experiment**
  - forward detector (optimised geometry)
  - RICH particle ID (K/π separation)
  - excellent vertexing
  - dedicated b- and c- triggers (inclusive & exclusive)
  - operates at lower luminosity

  but lots and lots of flavour

- ATLAS, CMS
  - general purpose, “discovery machines”
  - efficient di-muon trigger: great capabilities in b decays to $\mu\mu$
  - maximal luminosity
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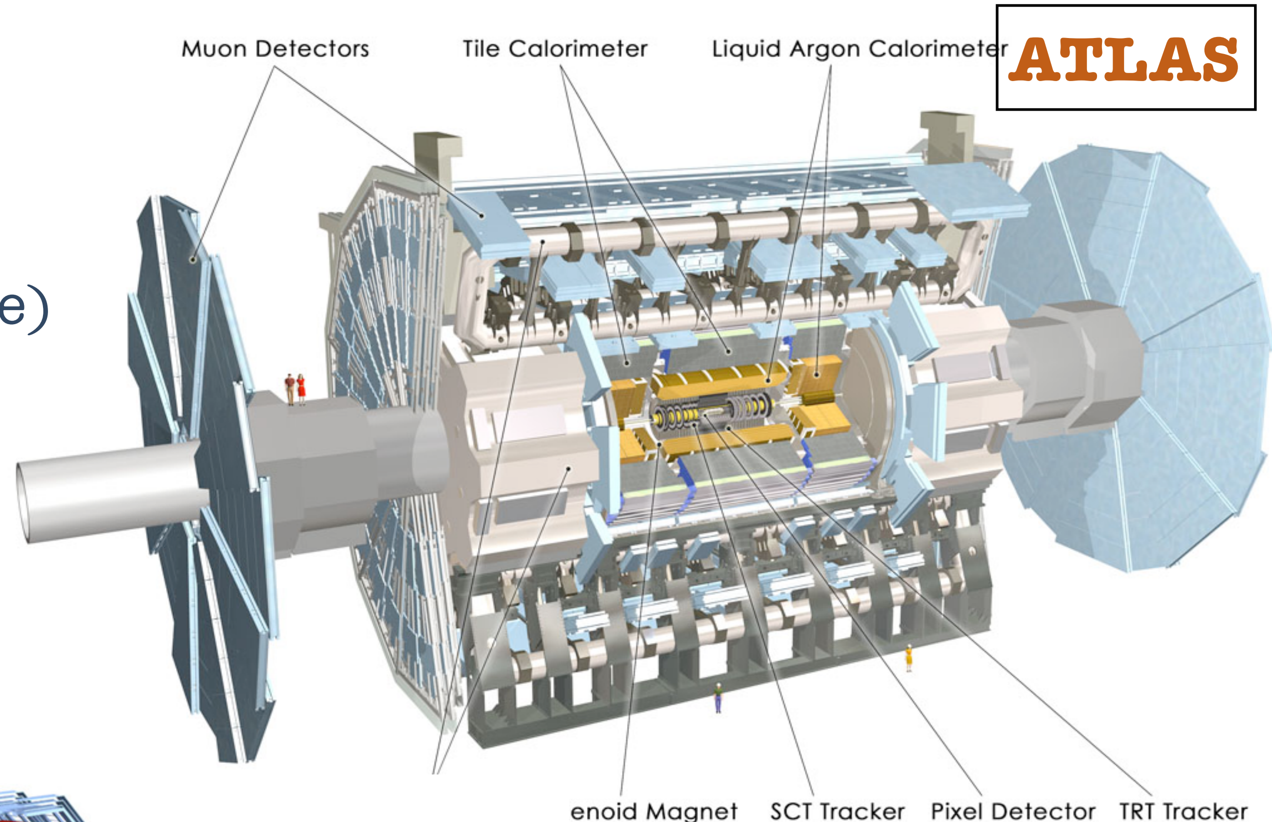
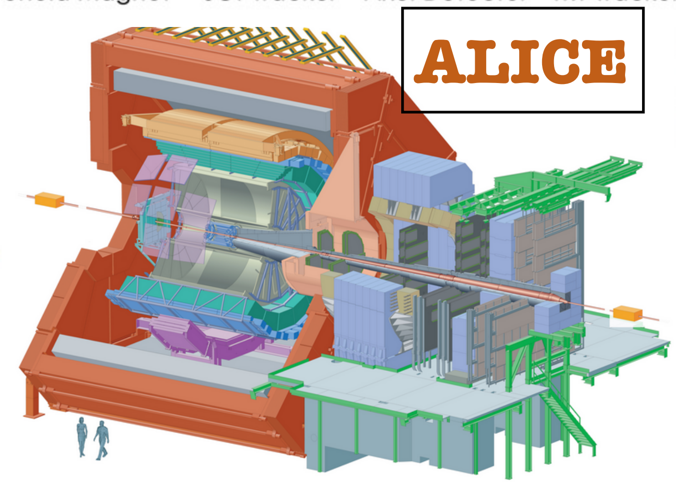
ATLAS

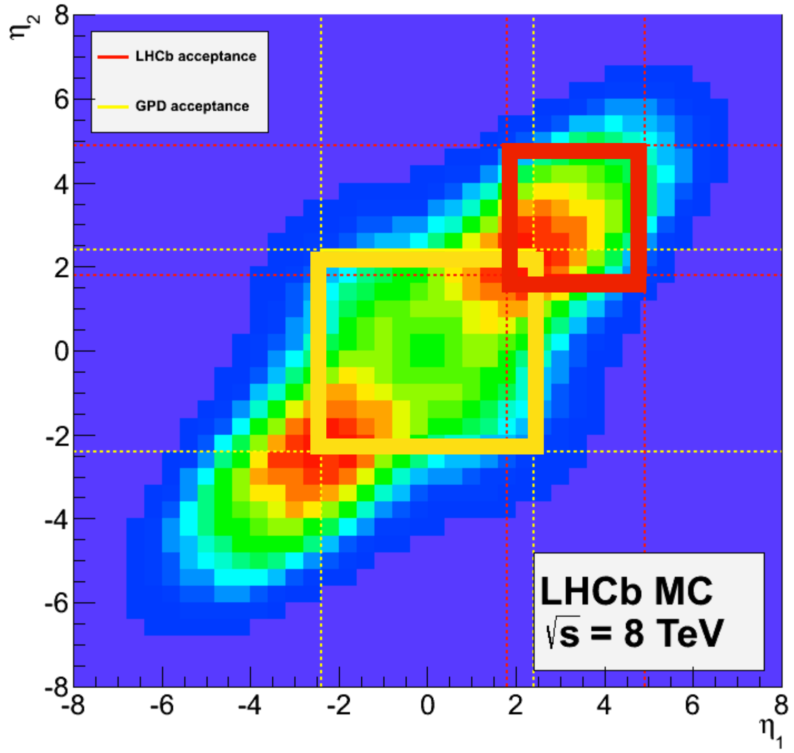


CMS

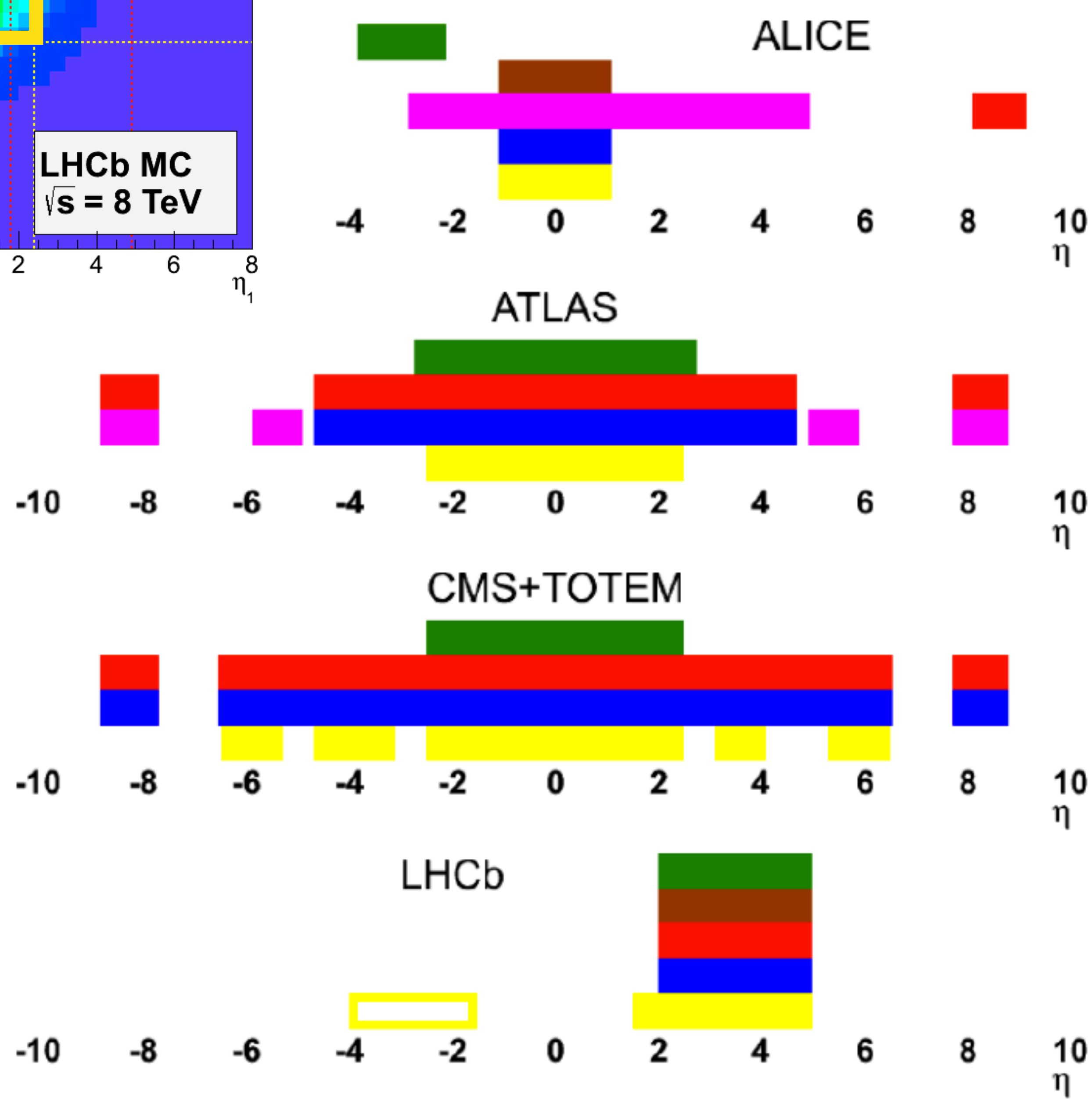
ALICE



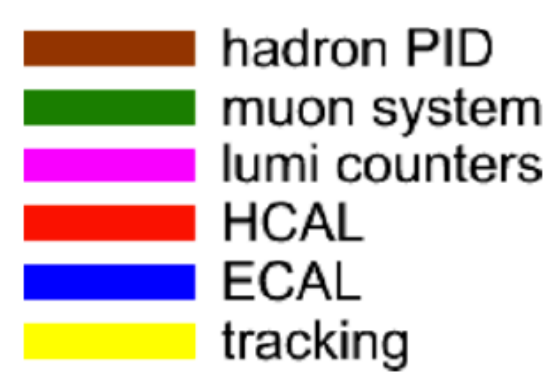
Heavy Quarks @ LHC



Different == complementary coverage



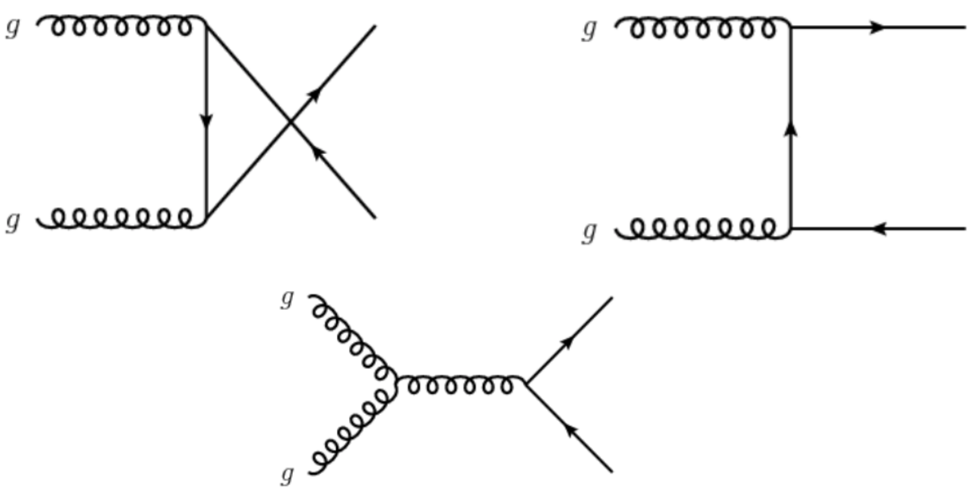
- ALICE
  - ➜ central
  - ➜ forward muon coverage
- ATLAS & CMS
  - ➜ central detectors
- LHCb
  - ➜ forward detector
  - ➜ tracking, particle-ID and calorimetry in full acceptance



Flavour Production & Properties

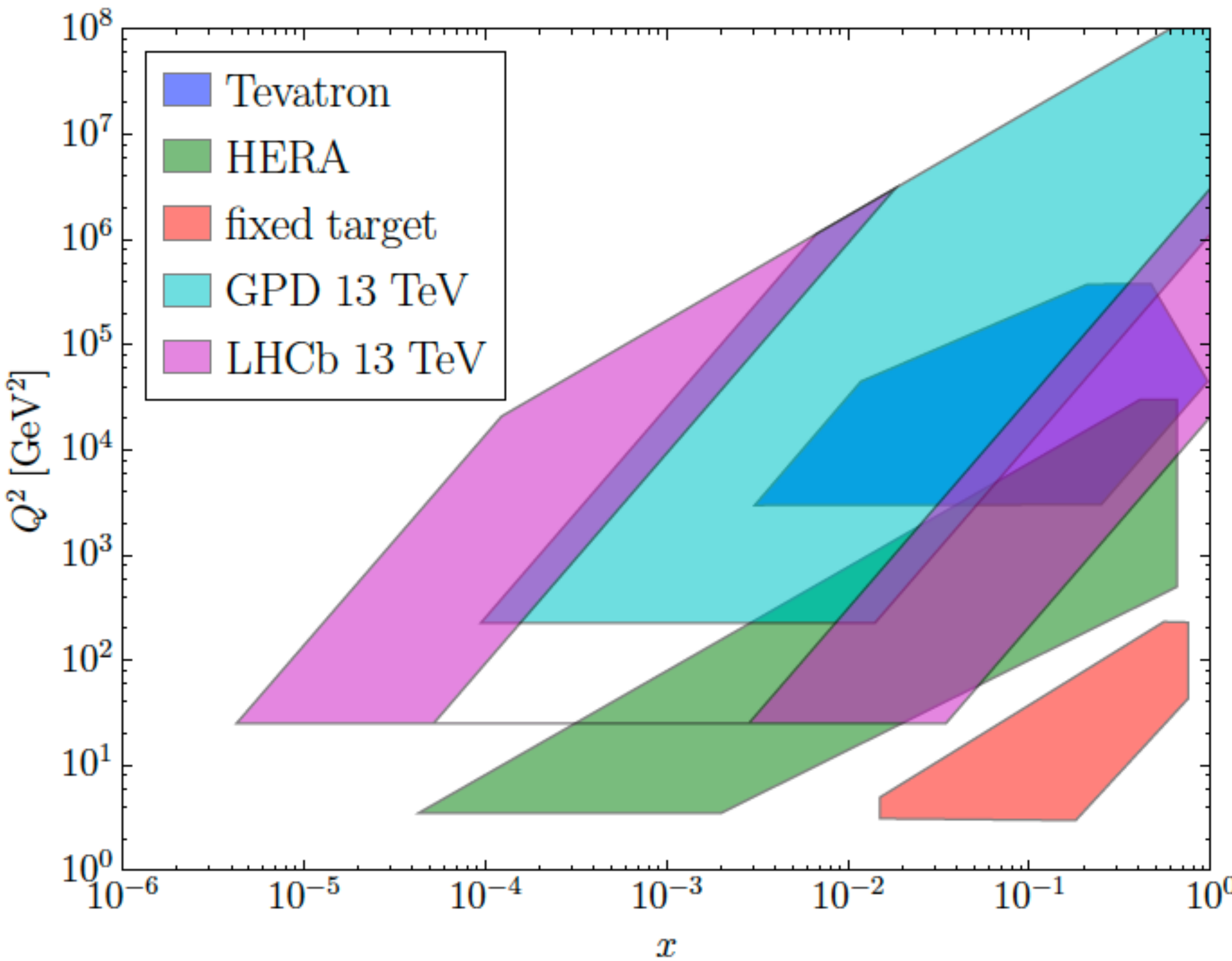
Heavy Flavour Production @ LHC

- For pp collisions at LHC energies, the main mechanism for flavour production is gluon-gluon fusion



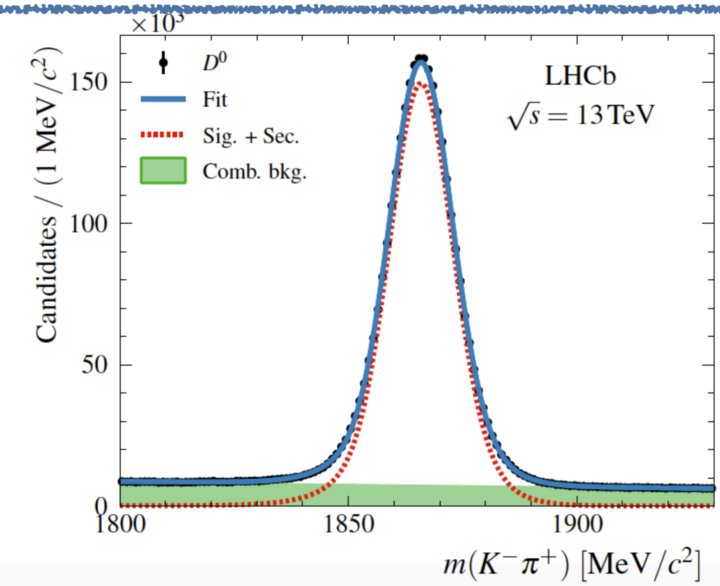
- Production measurements are fundamental for understanding of QCD

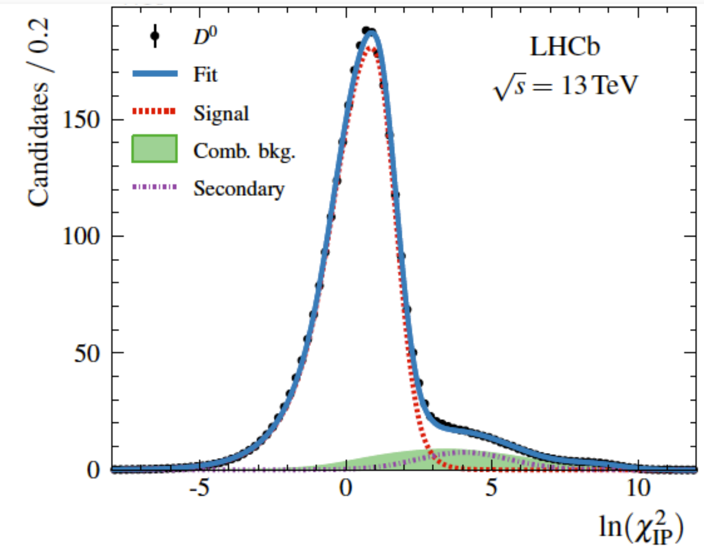
  - x-section measurements and ratios sensitive to parton density functions (PDFs)
  - probe proton structure at low-x
  - MC tuning: inputs for precise flavour physics measurements
  - NP searches: precise SM precisions are crucial



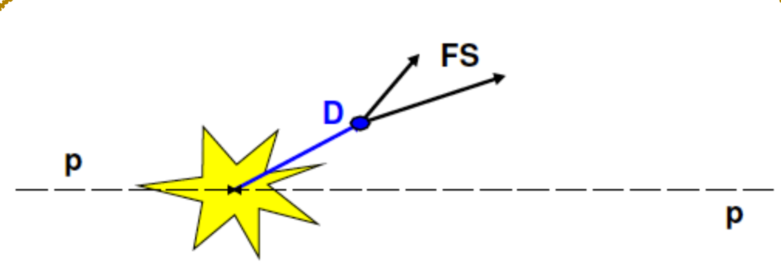
Open Charm: new @ 5 & 13 TeV (LHCb)

- D^0, D^+, D_s^+ and D^{*+} double differential cross-sections measured at three pp energies: 7, 5 & 13 TeV (new)
- in Run II: data directly from 'Turbo Trigger'
  Comput. Phys. Commun. 208, 35
- prompt and secondary production distinguished by $\log(\mathrm{IP}\ \chi^2)$ distribution

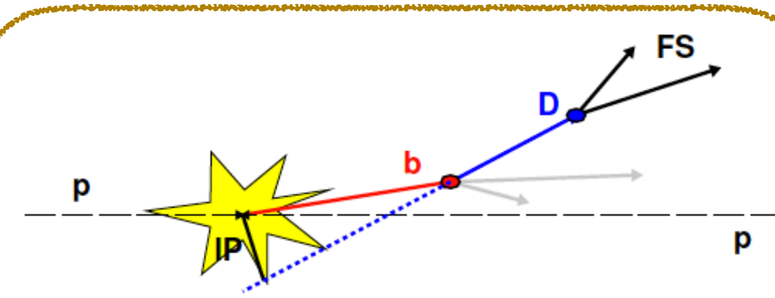




JHEP 03 (2016) 159, err. JHEP 09 (2016) 013
err. JHEP 05 (2017) 074

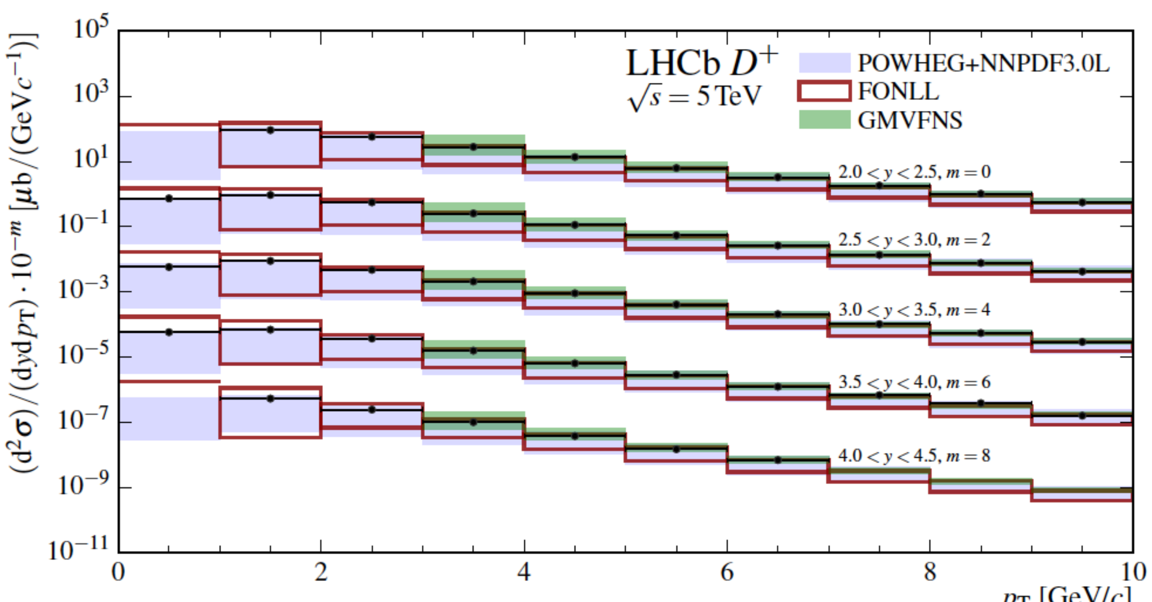


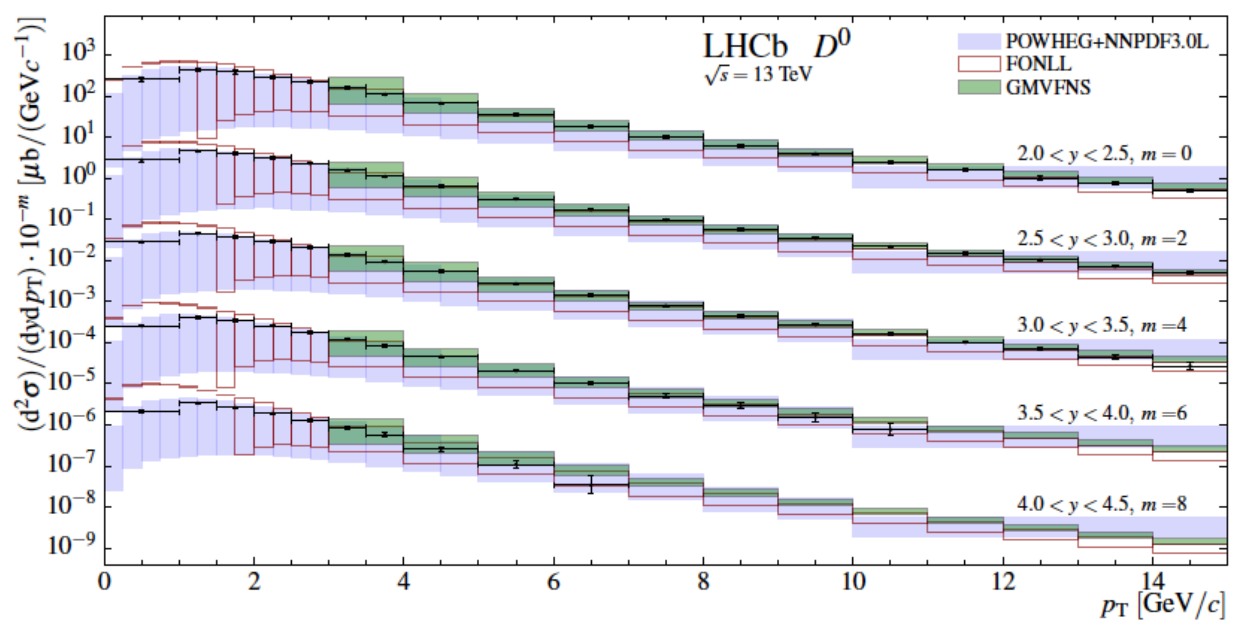
prompt production



secondary production

JHEP 06 (2017) 147





FONLL: EPJC 75 (2015) 610
POWHEG+NNPDF3.0L: JHEP 1511 (2015) 009
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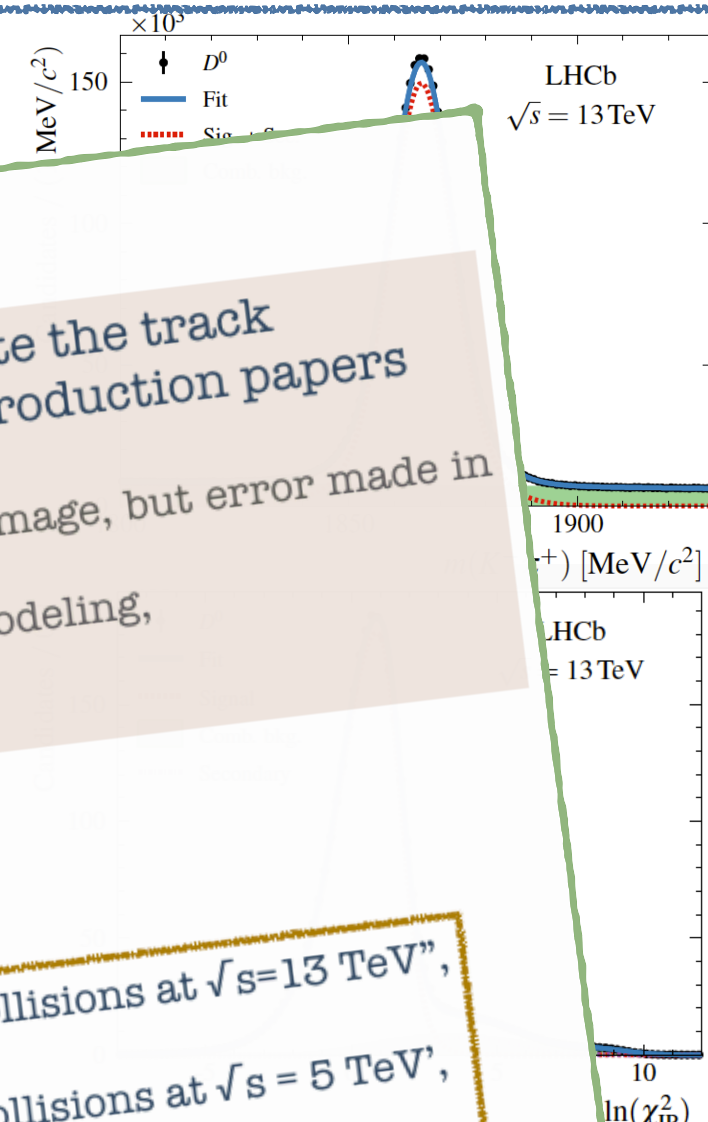


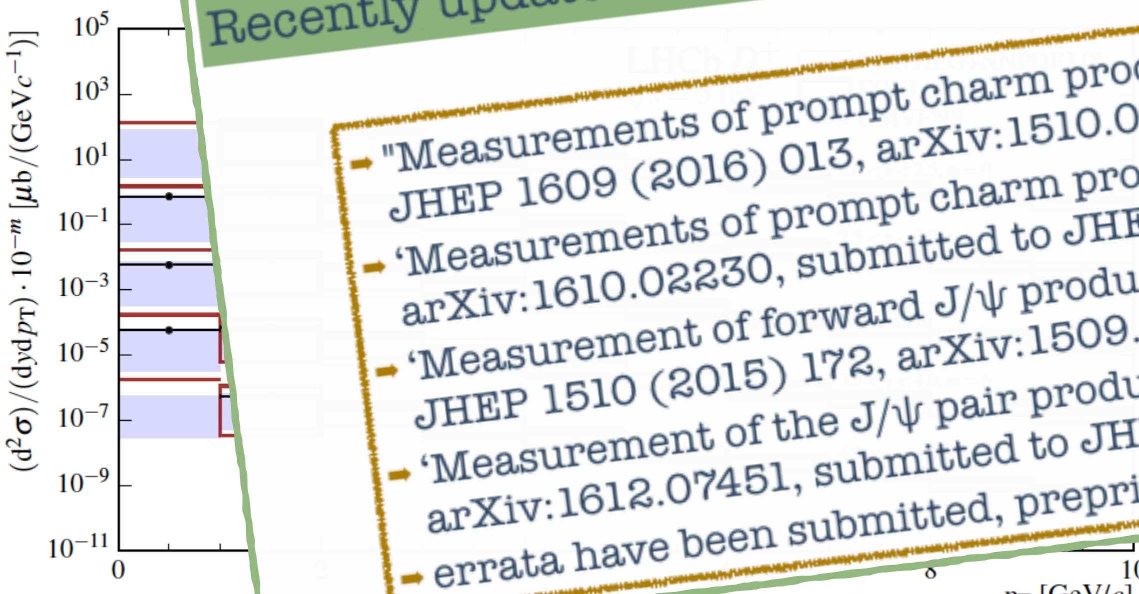
p
prompt production ... secondary production

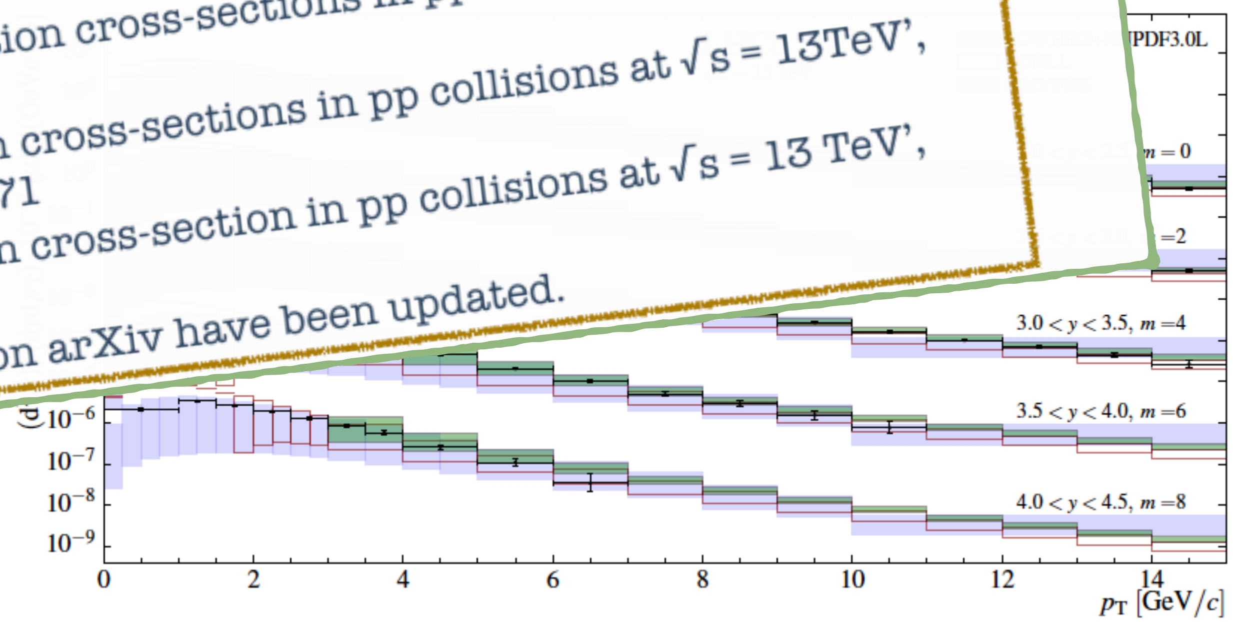
Run II erratum:

- An issue was identified in the simulated samples used to calculate the track reconstruction efficiencies, affecting a small number of Run II production papers
  - LHCb VELO simulation updated prior to Run II to account for radiation damage, but error made in the parametric correction for the effect.
  - track efficiency calibration procedure in data was unable to correct mis-modeling,
  - track reconstruction efficiency underestimated in simulation,
  - most affected: low pseudorapidity and low p_T

Recently updated measurements:

- "Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s}$=13 TeV", JHEP 1609 (2016) 013, arXiv:1510.01707
- 'Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s}$ = 5 TeV', arXiv:1610.02230, submitted to JHEP
- 'Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s}$ = 13TeV', JHEP 1510 (2015) 172, arXiv:1509.00771
- 'Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV', arXiv:1612.07451, submitted to JHEP
- errata have been submitted, preprints on arXiv have been updated.





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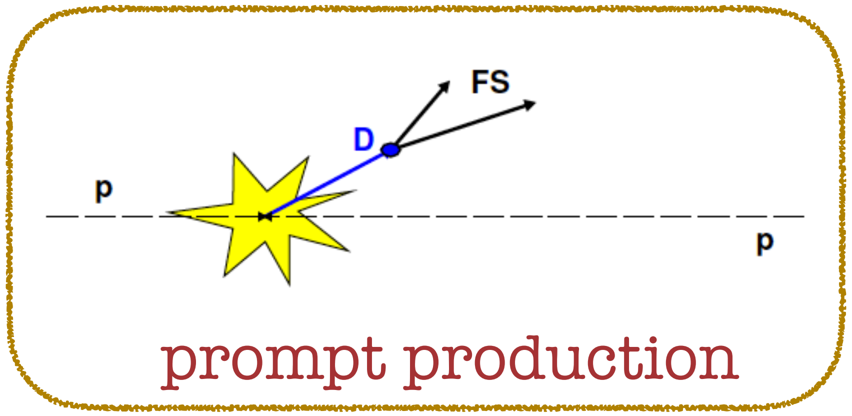

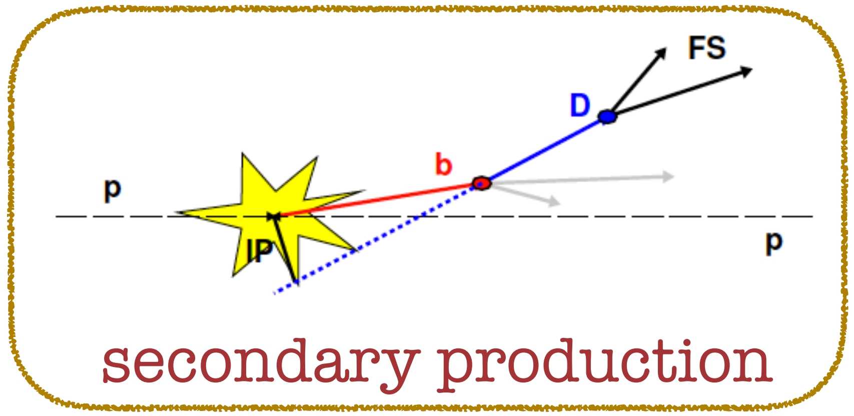

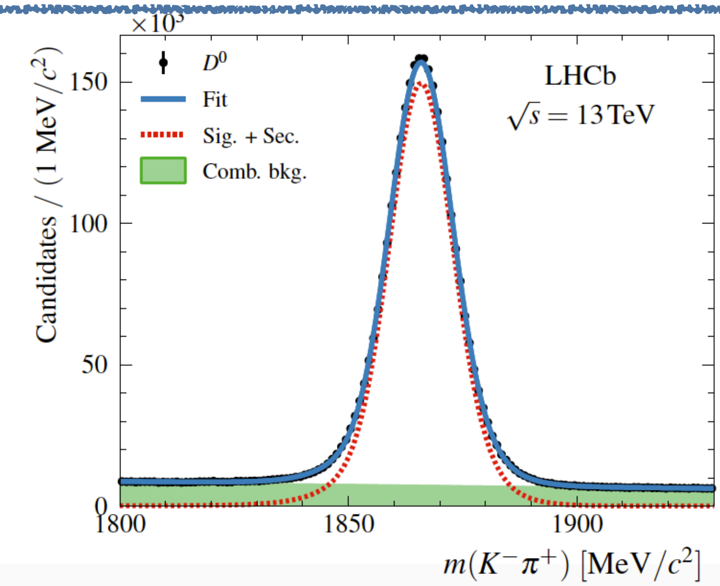

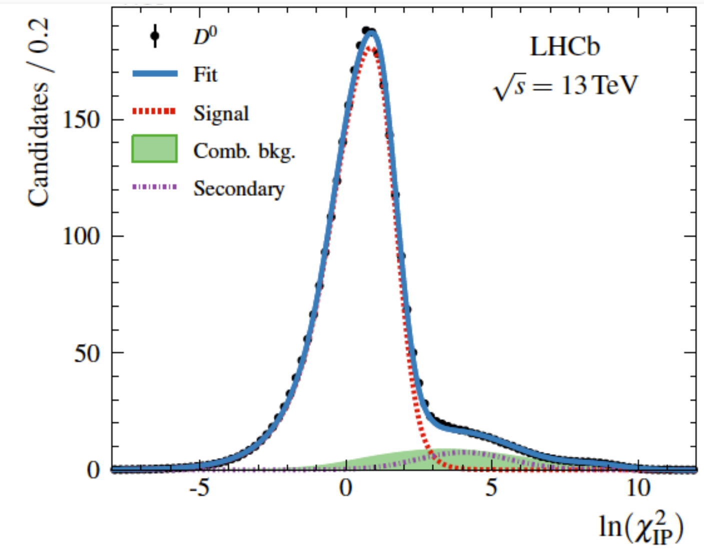

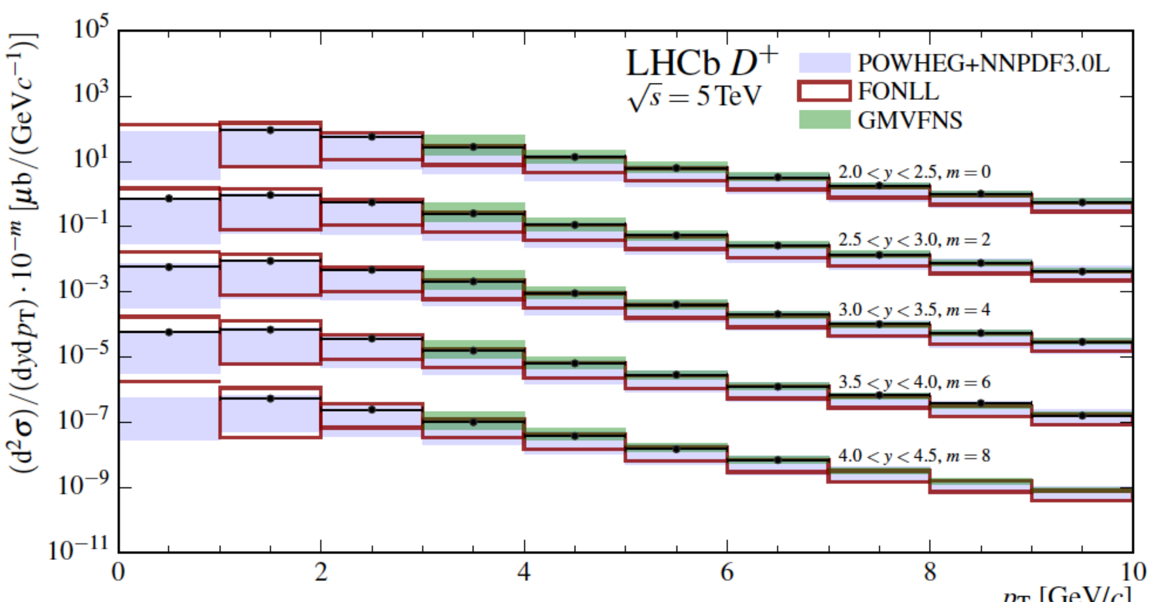

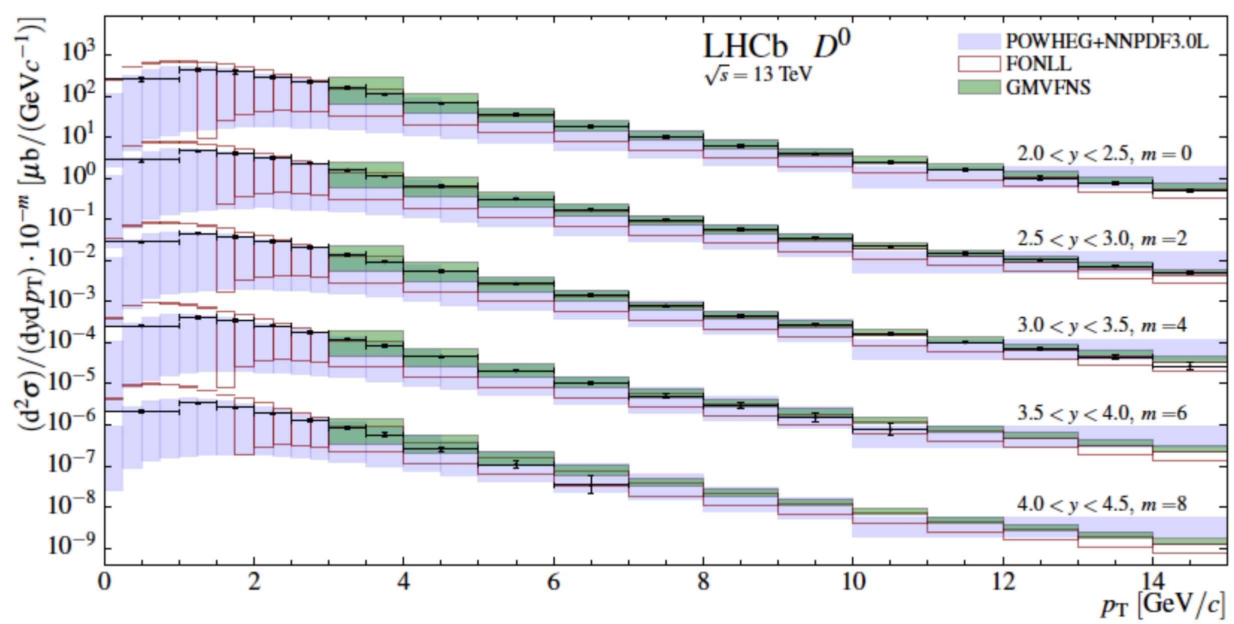

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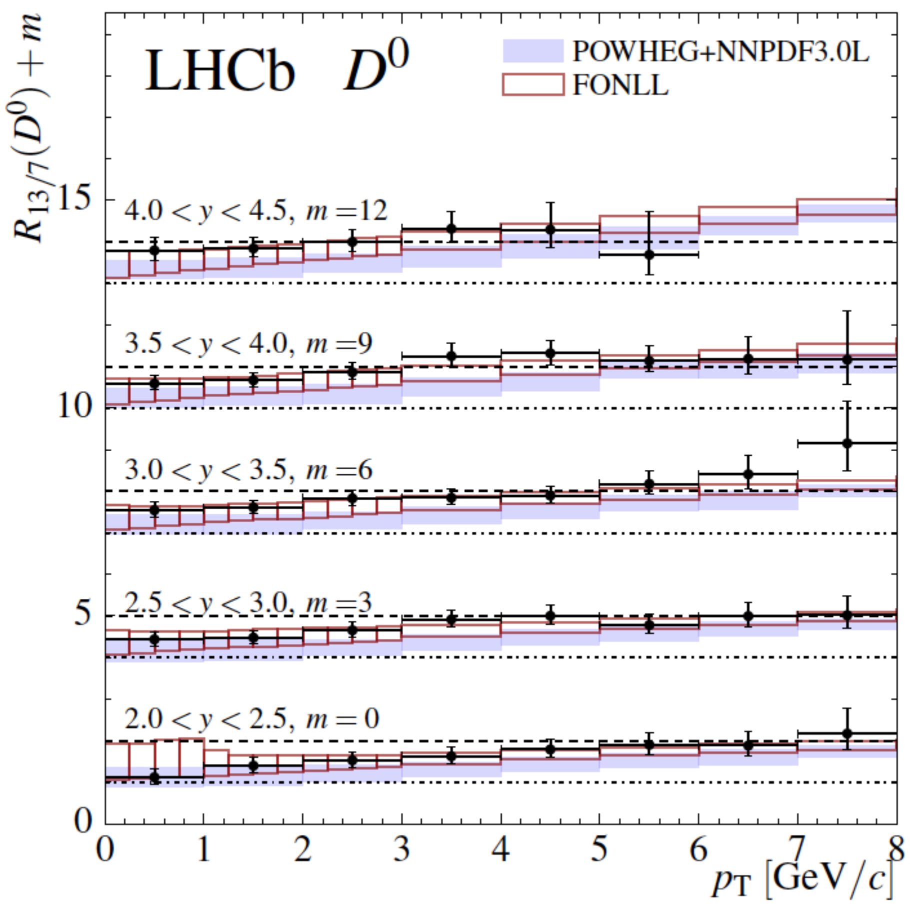
Open Charm: new @ 5 & 13 TeV (LHCb)

13 to 7 TeV ratio:



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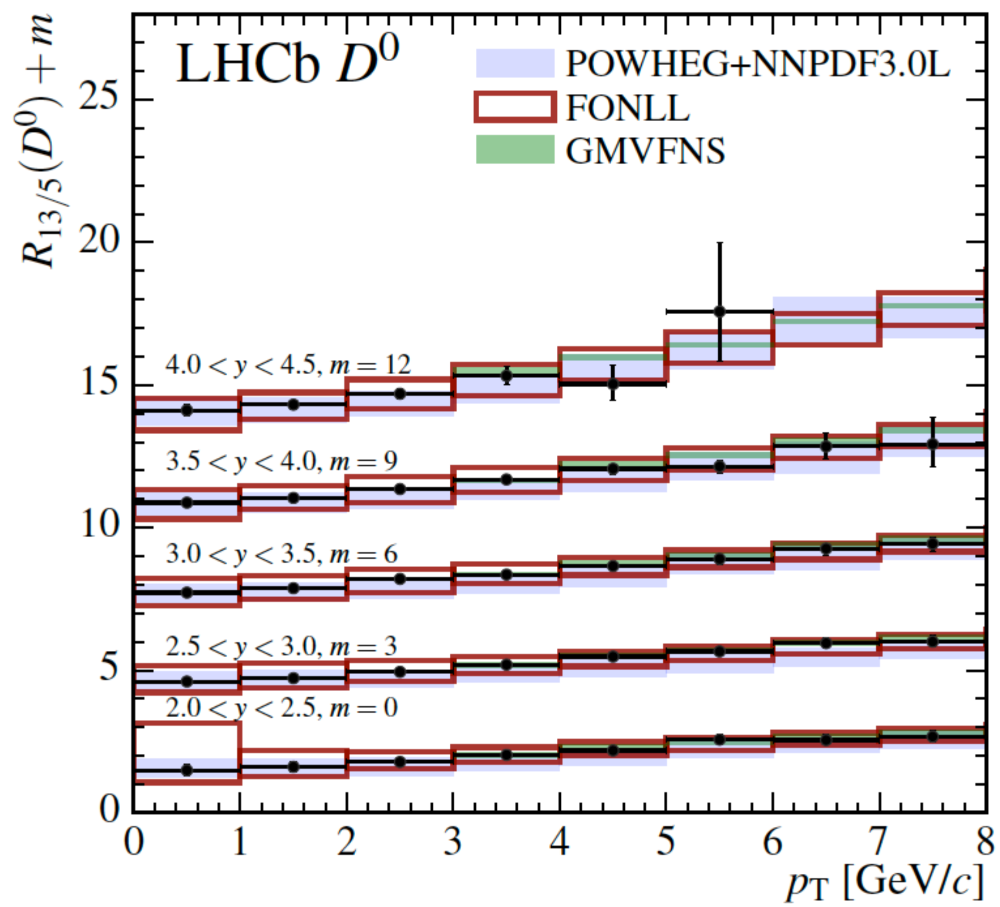

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In general (all D species, all energies):

- agreement with predictions, although large uncertainties at low p_T
- data tends to lie at upper end of predictions

- $\sqrt{s}$ = 13 TeV total c-cbar cross-section using fragmentation fractions:

$$\sigma(pp \to c\bar{c}X)_{p_T<8\,\mathrm{GeV},1.0<y<4.5} = 2369 \pm 3 \pm 152 \pm 118\ \mu\mathrm{b}$$

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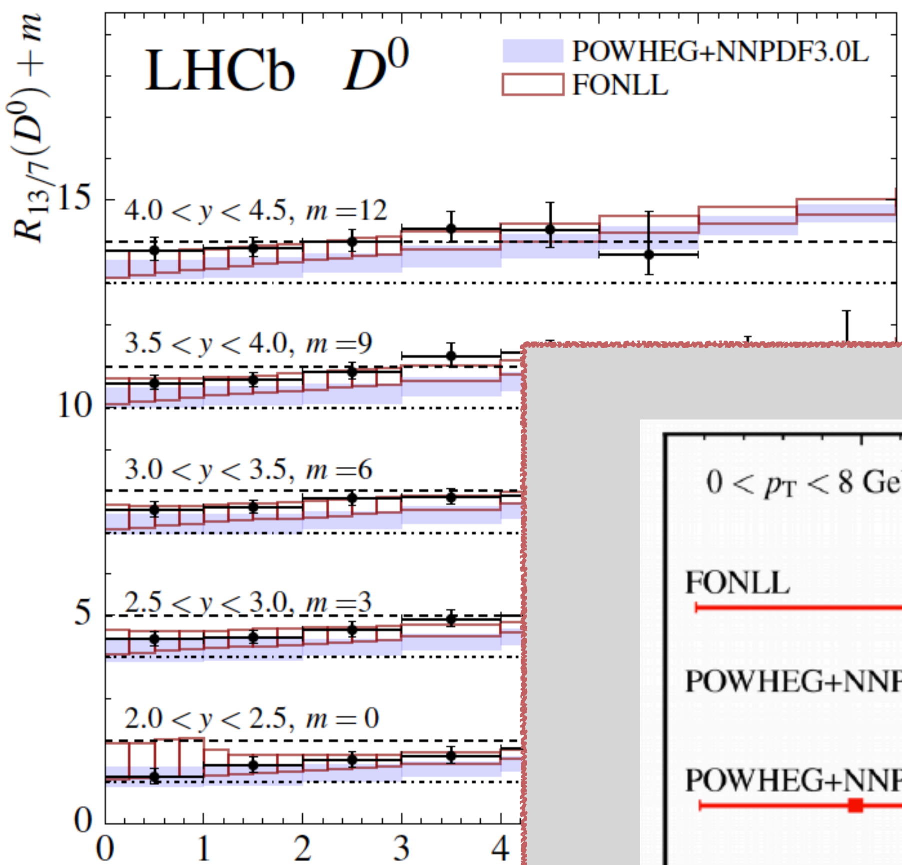
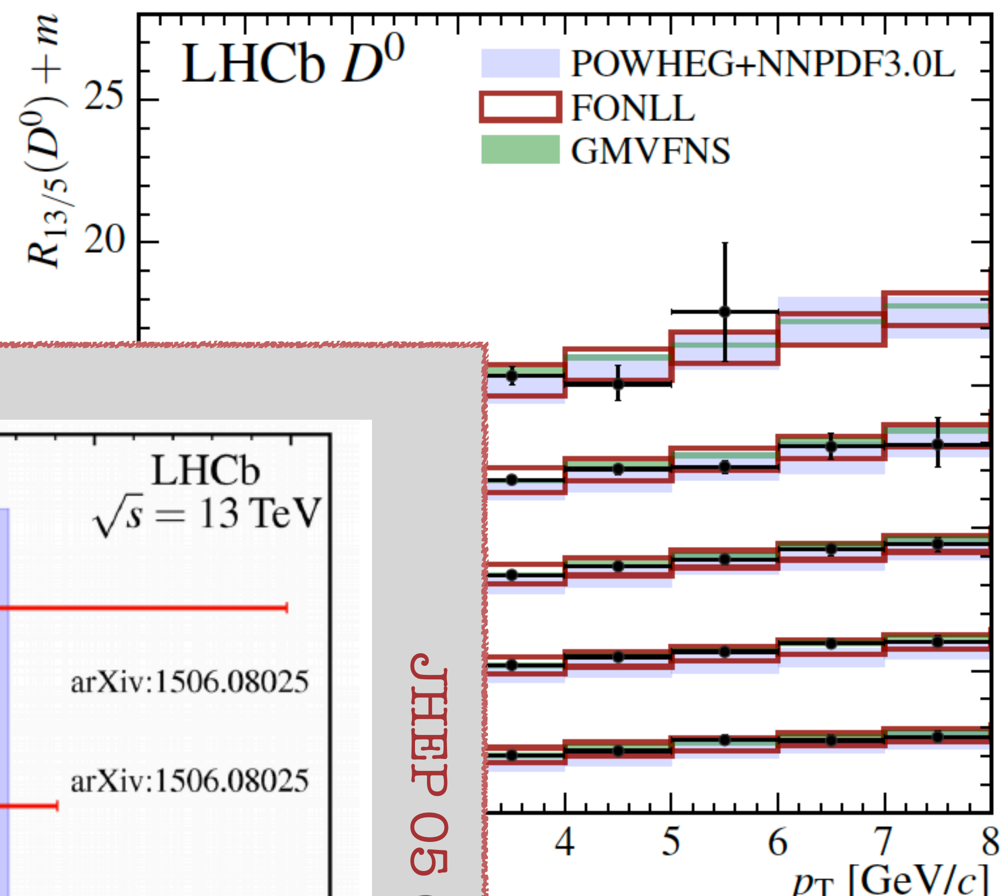


1511 (2015) 009
082

13 to 5 TeV ratio:



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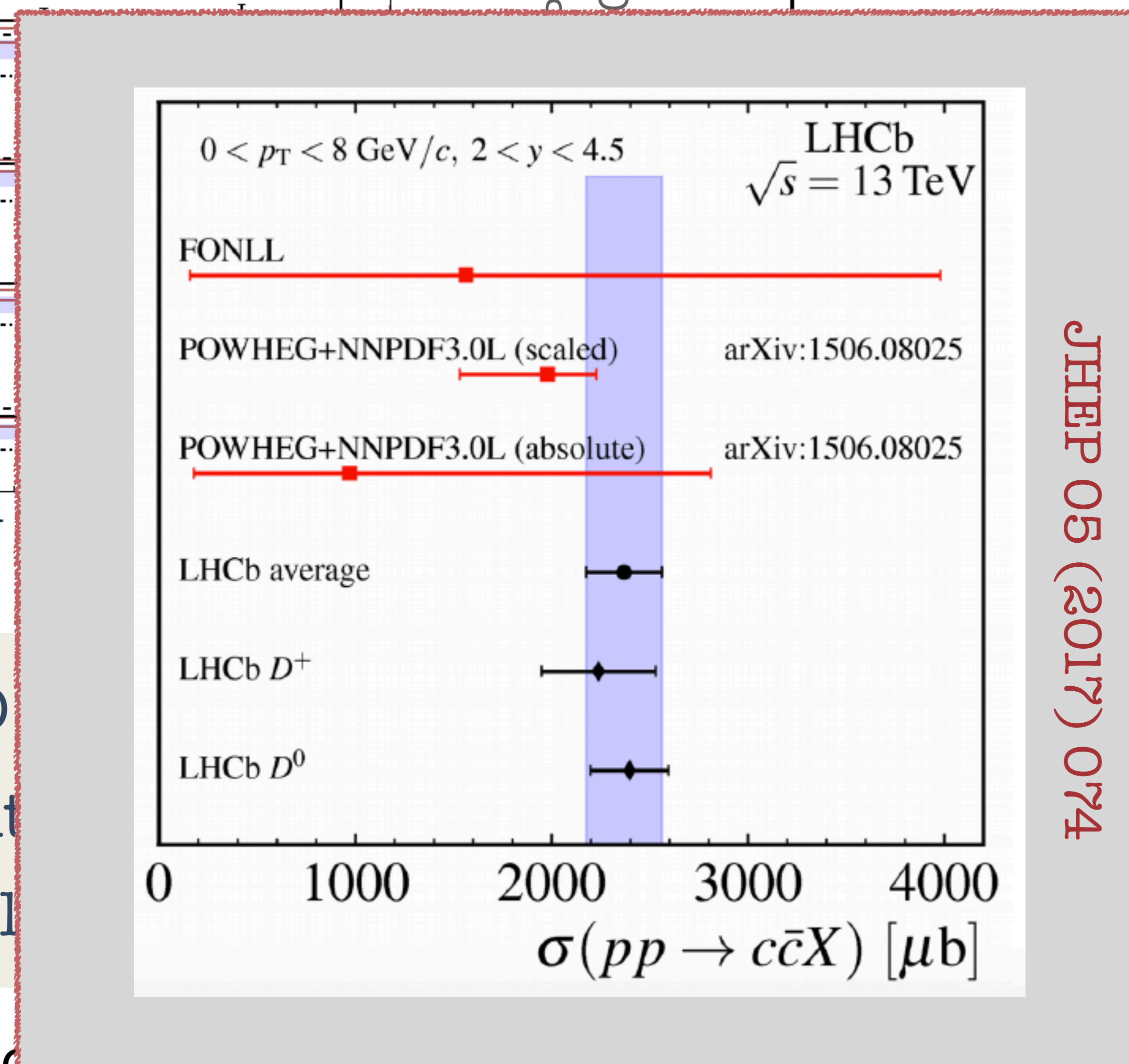

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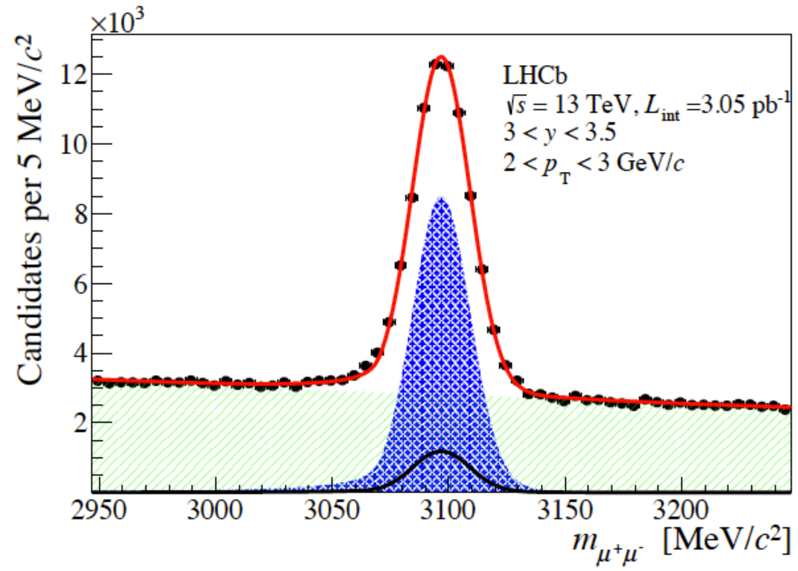
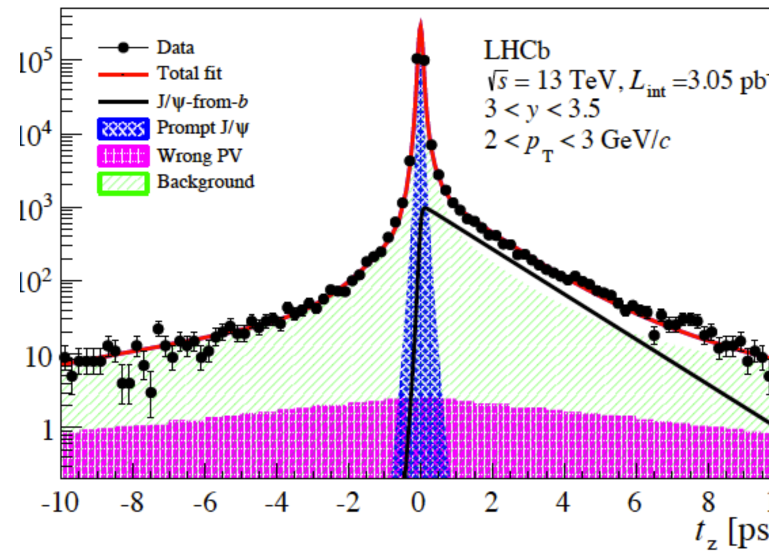
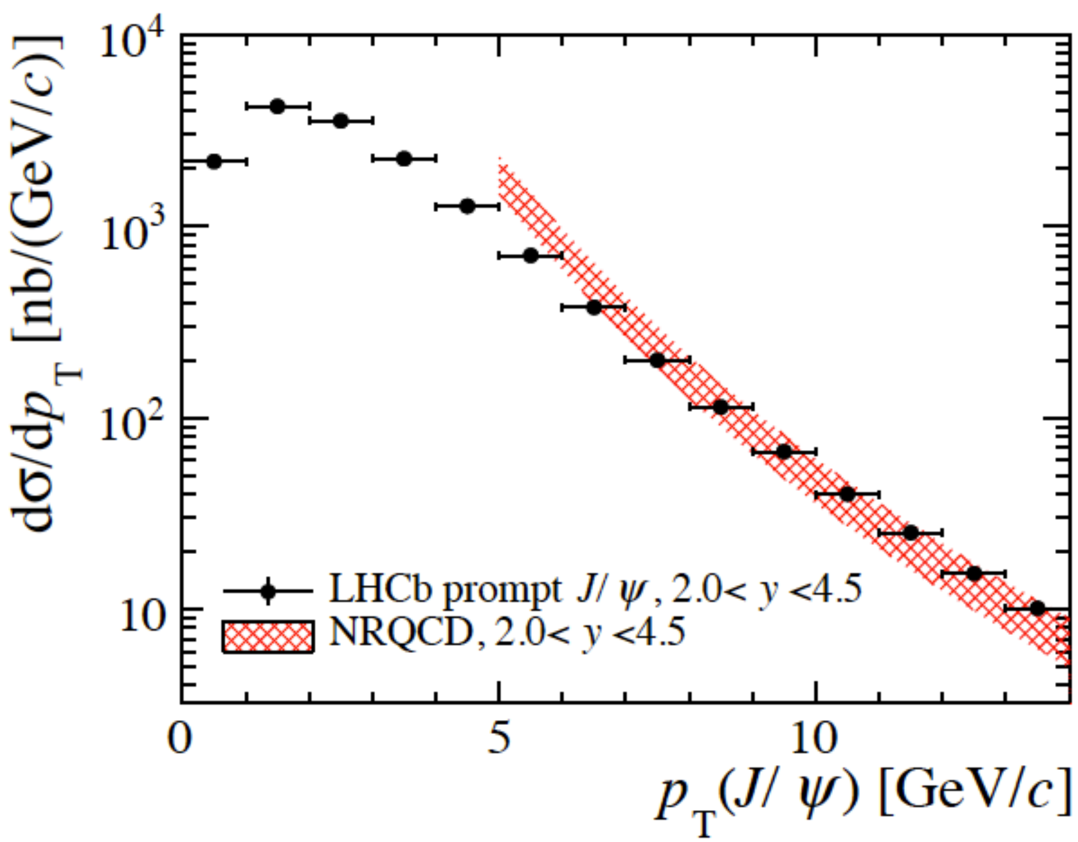
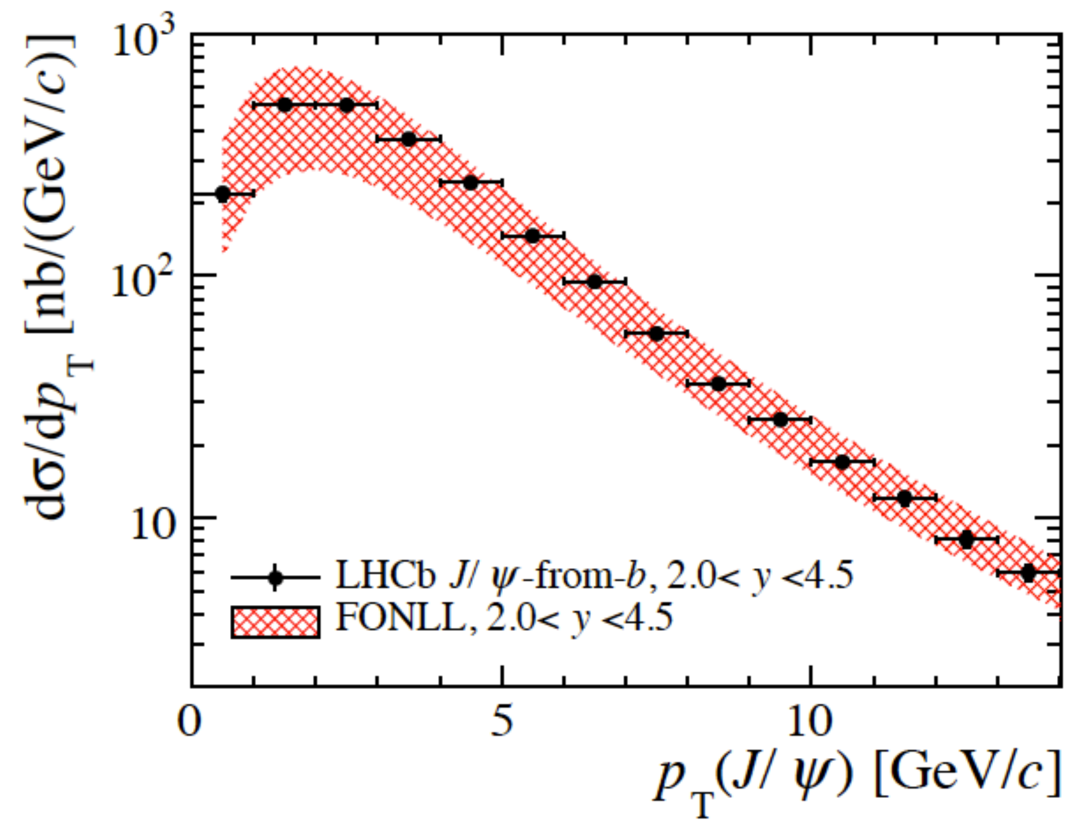
J/ψ production @ 13 TeV - LHCb

- Double differential cross-sections: $$\frac{d^2\sigma(X_c)}{dp_T\,dy}$$
- Separation of prompt from b-decays through pseudo decay time: $$t_z = \frac{(z_{J/\psi} - z_{\rm PV})M_{J/\psi}}{p_z}$$









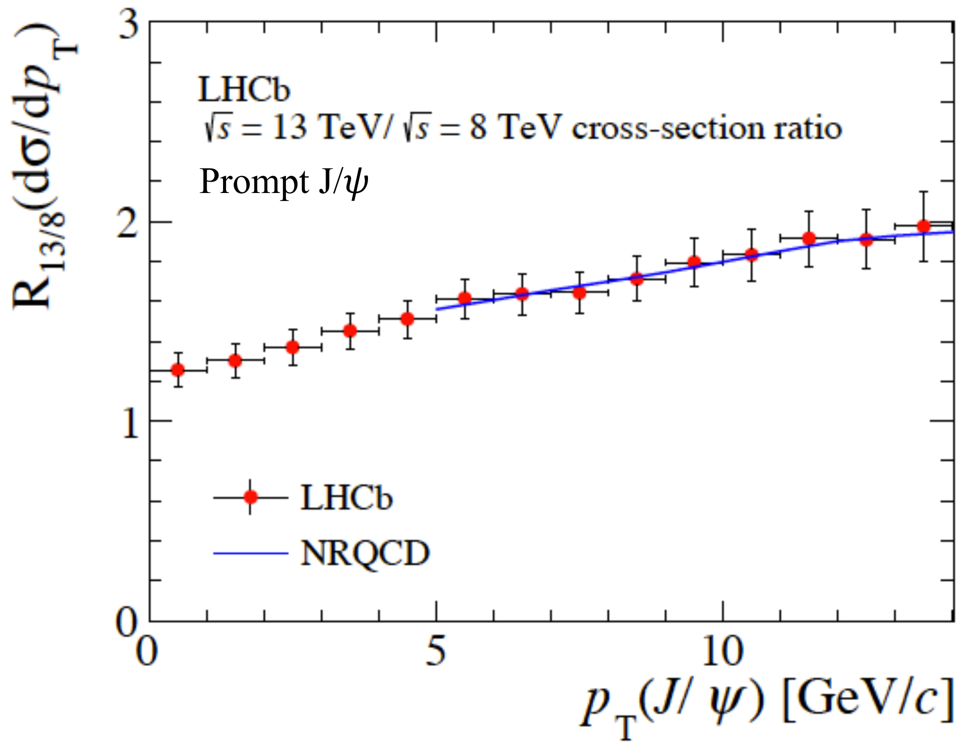
JHEP 10 (2015) 172; Erratum JHEP 1705 (2017) 063

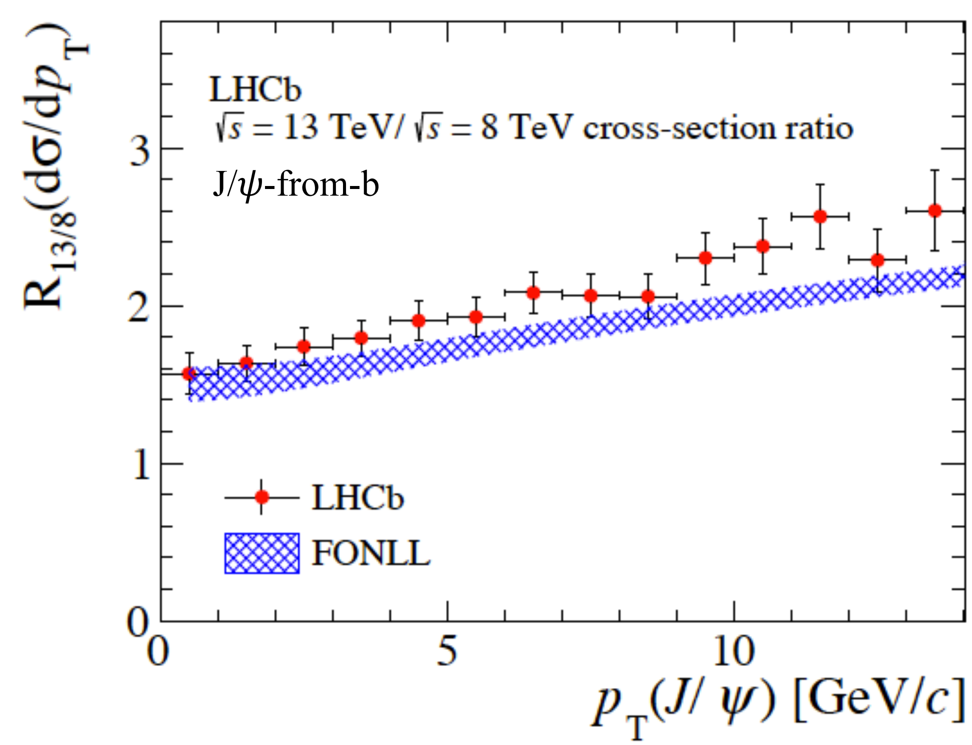
$$\sigma(\text{prompt } J/\psi, p_{\rm T} < 14\,{\rm GeV}/c, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94\,\mu{\rm b}$$
$$\sigma(J/\psi\text{-from-}b, p_{\rm T} < 14\,{\rm GeV}/c, 2.0 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14\,\mu{\rm b}$$

J/ψ production @ 13 TeV - LHCb

13 to 8 TeV ratio

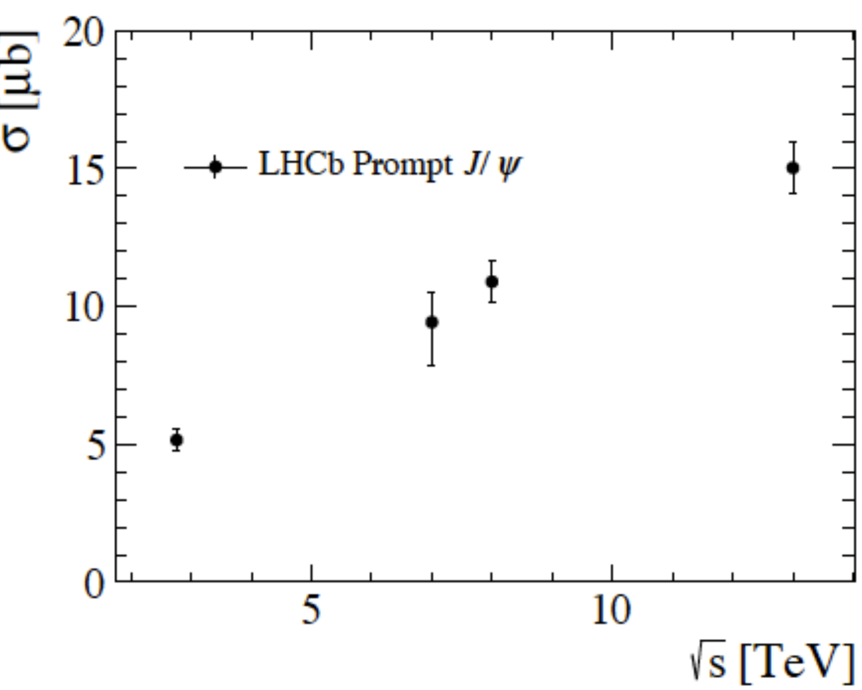
NRQCD: JHEP 05 (2015) 103
FONLL: JHEP 10 (2012) 137

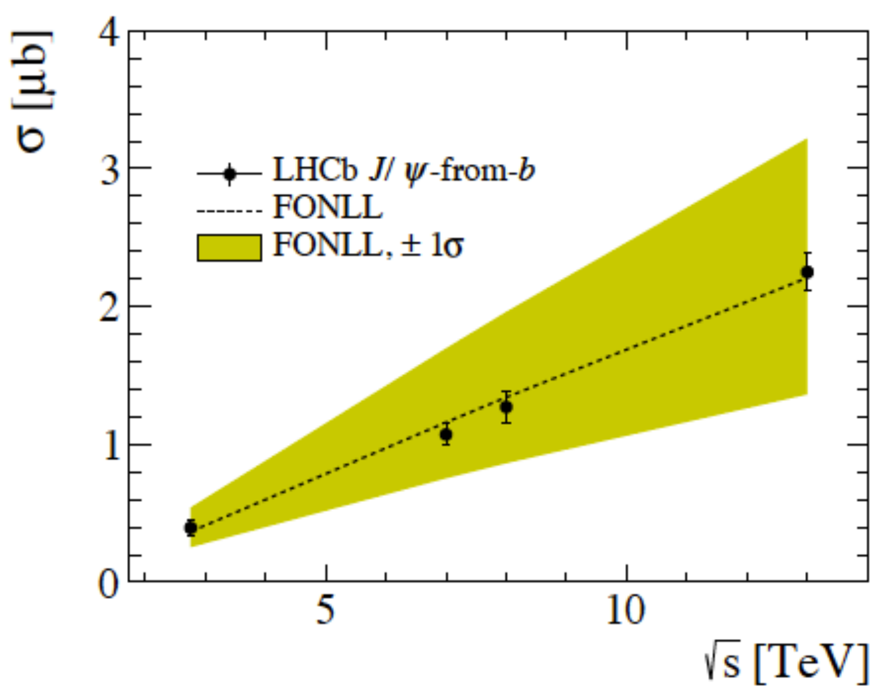




JHEP 10 (2015) 172;
Erratum JHEP 1705 (2017) 063

- NRQCD describes data well; FONLL with tendency below data



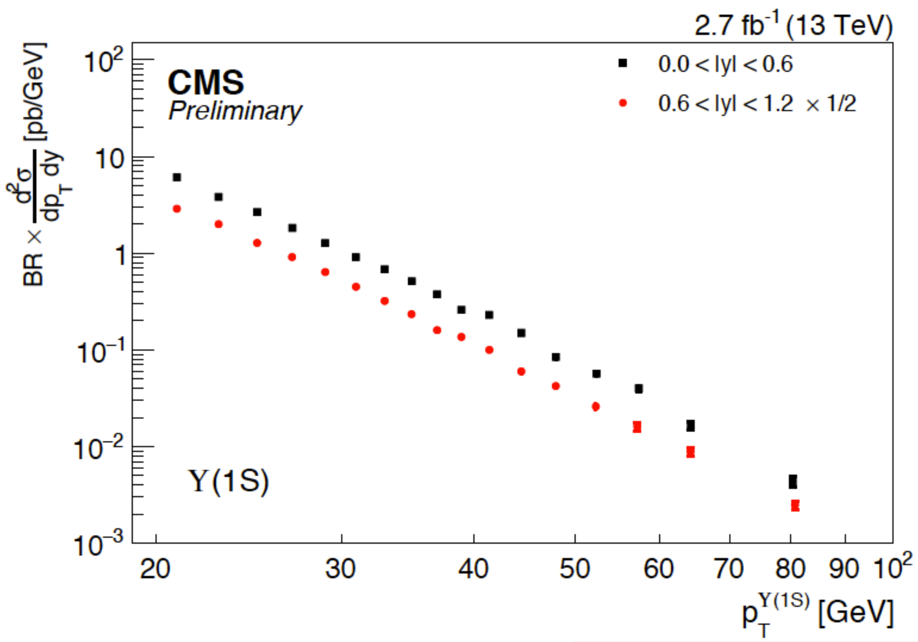


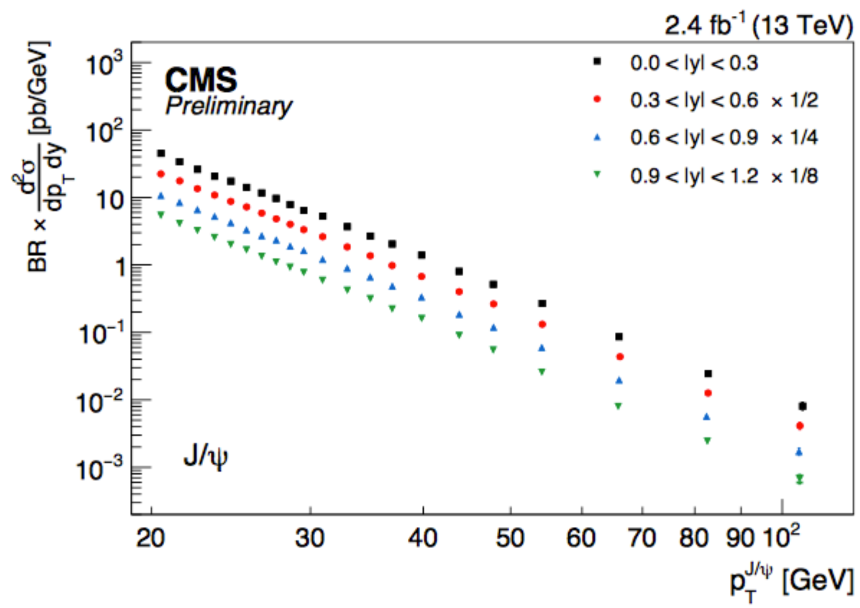
- extrapolation to total 4π bb X-sec using PYTHIA 6:

$$\sigma(pp \to b\bar{b}X)_{13\text{TeV}} = 495 \pm 2 \pm 52\mu\text{b}$$

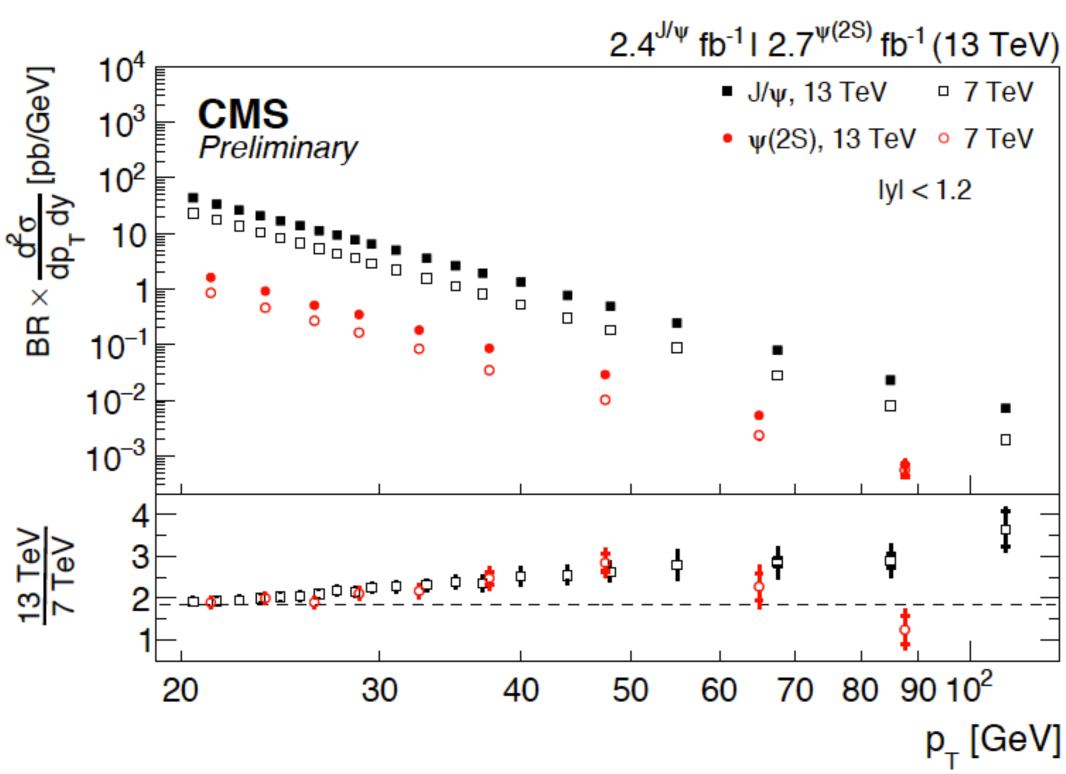
Onia production @ 13 TeV - CMS

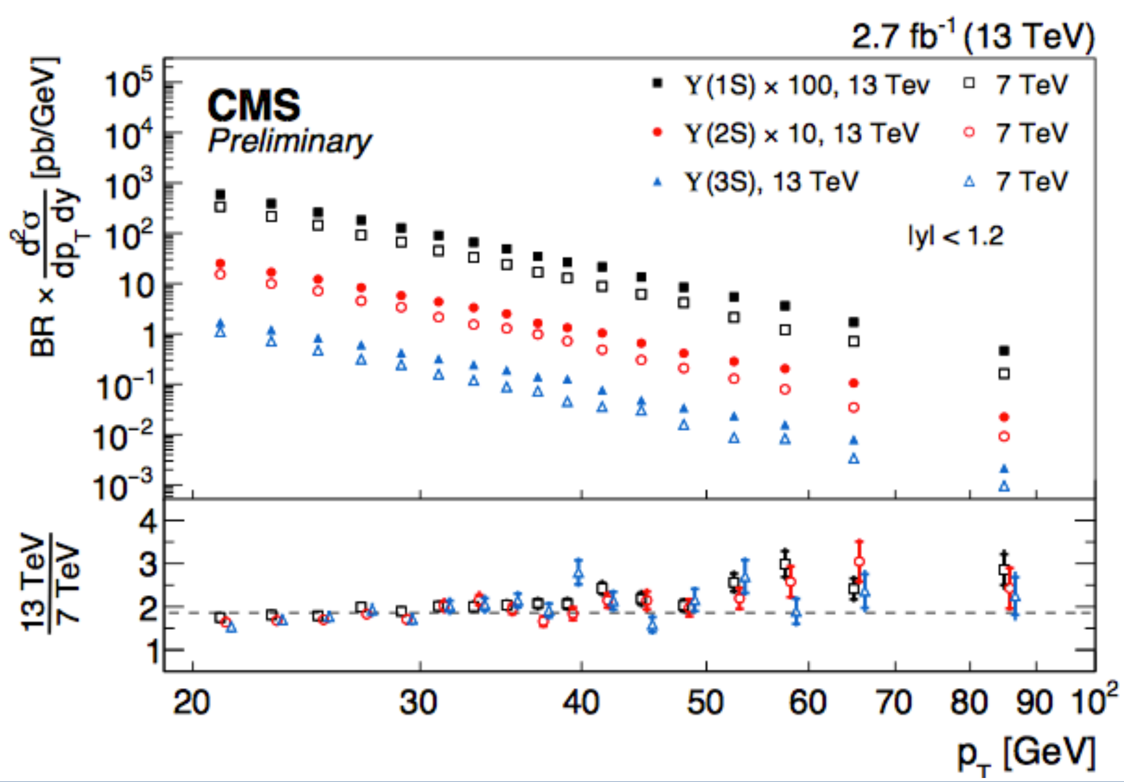
- CMS measures differential cross-sections for J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ (n=1,2,3) for $|y|<1.2$





Cross sections ratios 13/7 TeV:

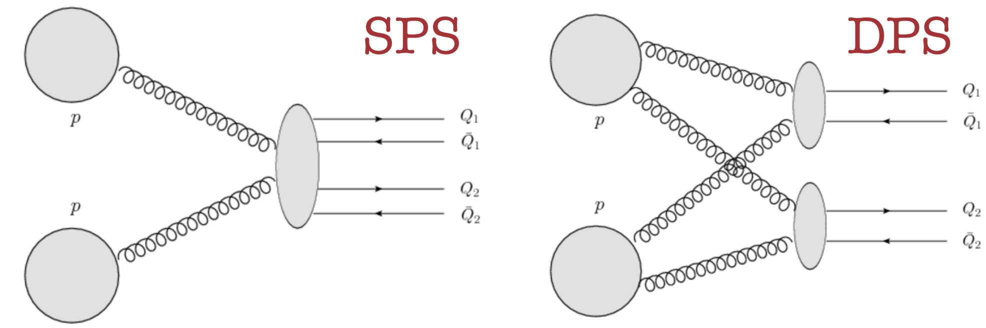




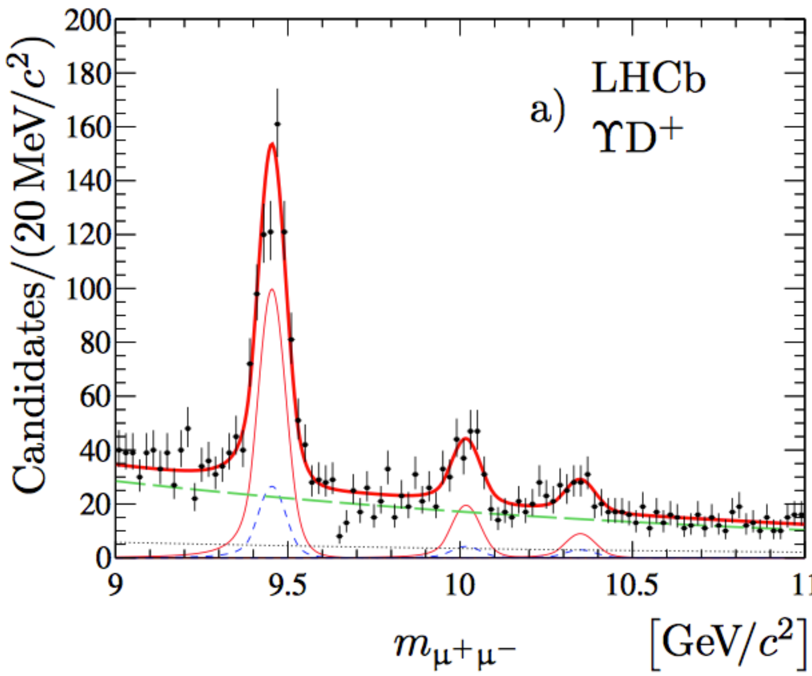
CMS PAS BPH-15-005

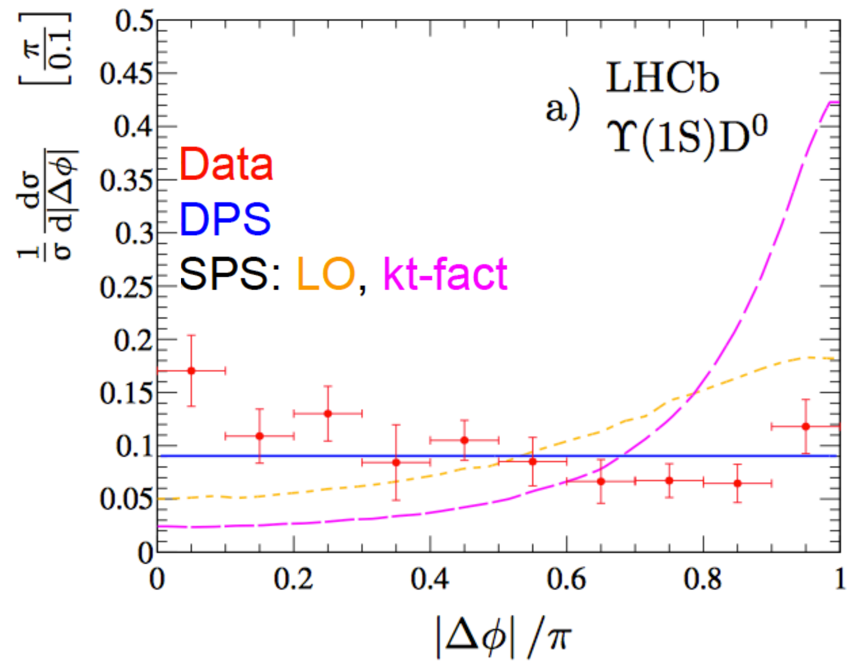
Υ and open charm @ 7 & 8 TeV - LHCb

- Υ(nS)(→ μμ) associated with D^0, D^+, D_s^+
- sensitive to mechanism: single (SPD) vs. double parton scattering (DPS)
- for DPS: $\sigma^{\Upsilon c\bar{c}} = \dfrac{\sigma^{\Upsilon} \times \sigma^{c\bar{c}}}{\sigma_{\text{eff}}}$

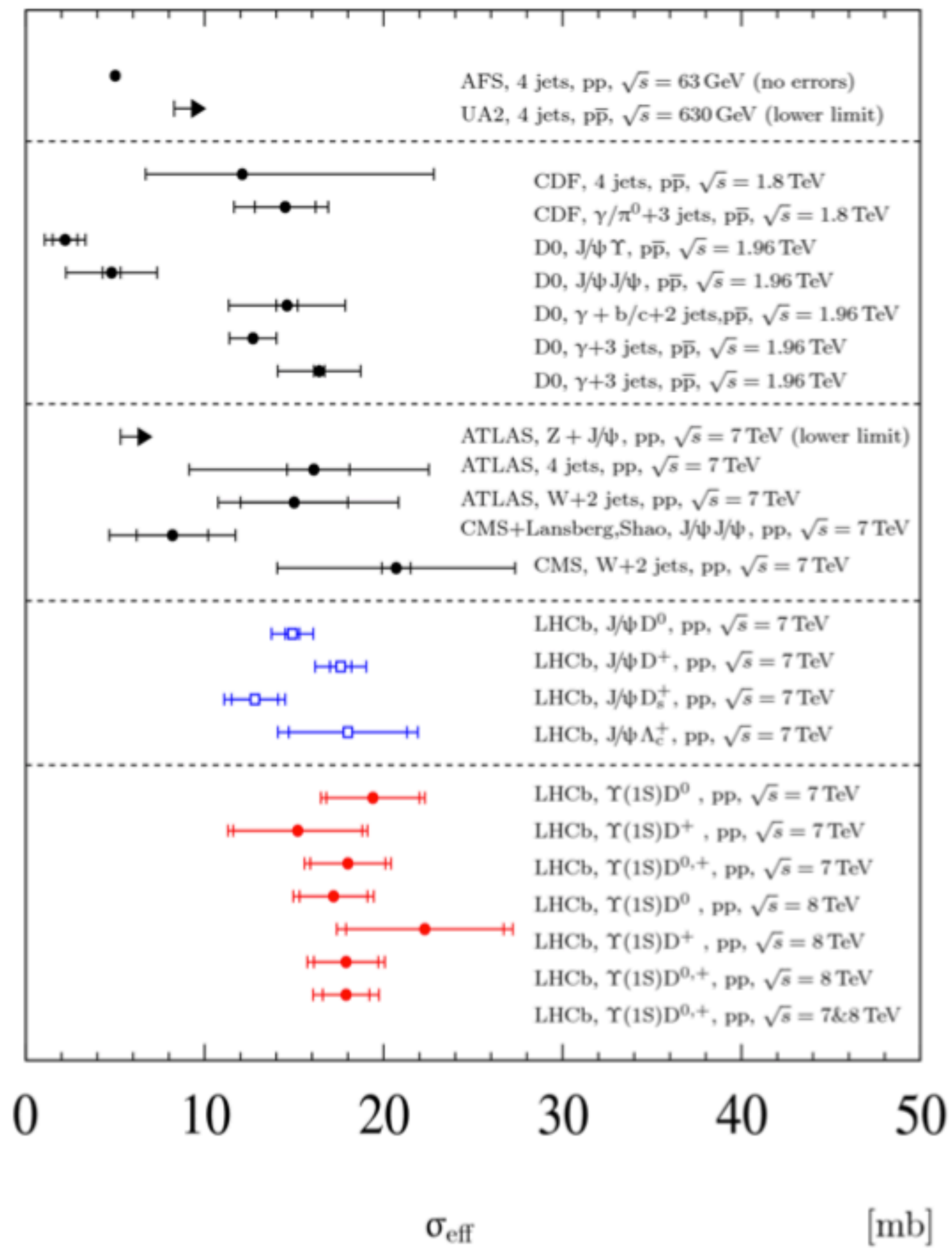


JHEP 17 (2016) 052





$$R^{\Upsilon(1S)c\bar{c}}_{\sqrt{s}=8\,\text{TeV}} = \left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\text{TeV}} = (8.0 \pm 0.9)\,\%$$



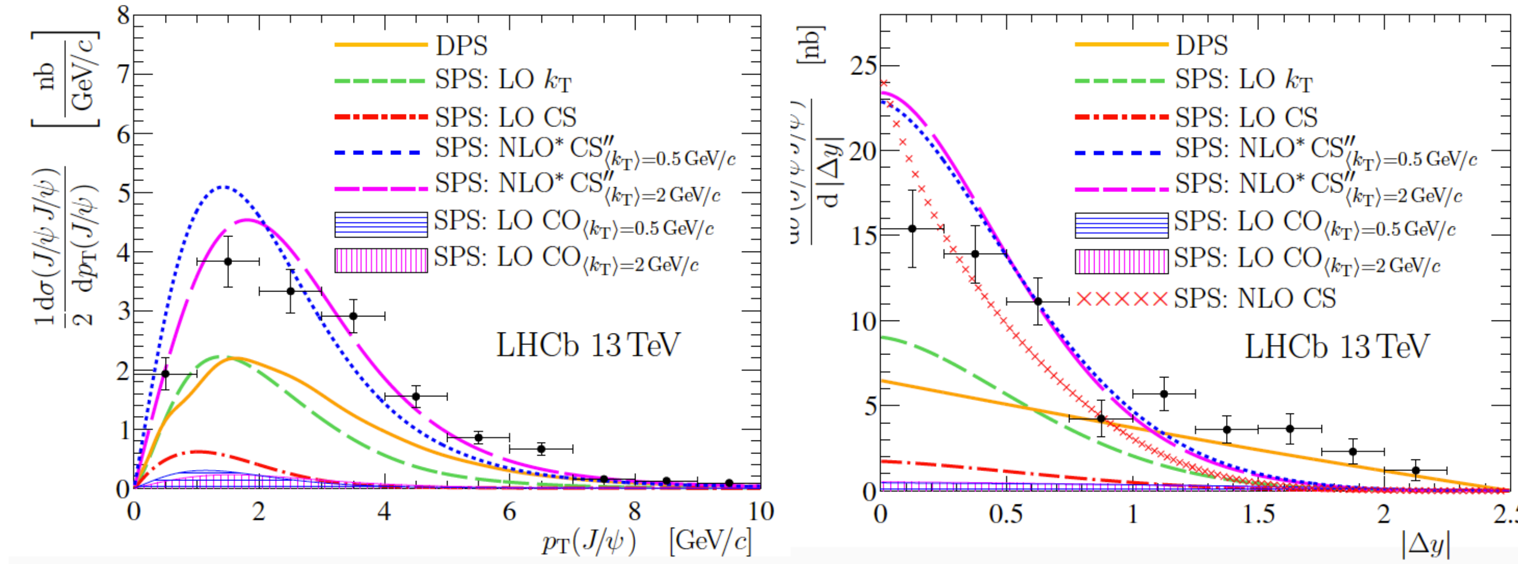
- Results indicate dominance of production via DPS

J/ψ pair production

LHCb @ 13 TeV

- $p_T < 10$ GeV, $2.0 < y < 4.5$
- Both SPS and DPS are found to contribute: fit cannot be described by only one of them

$\sigma(J/\psi\, J/\psi)_{13\,\text{TeV}} = 15.2 \pm 1.0 \pm 0.9$ nb



JHEP 06 (2017) 047

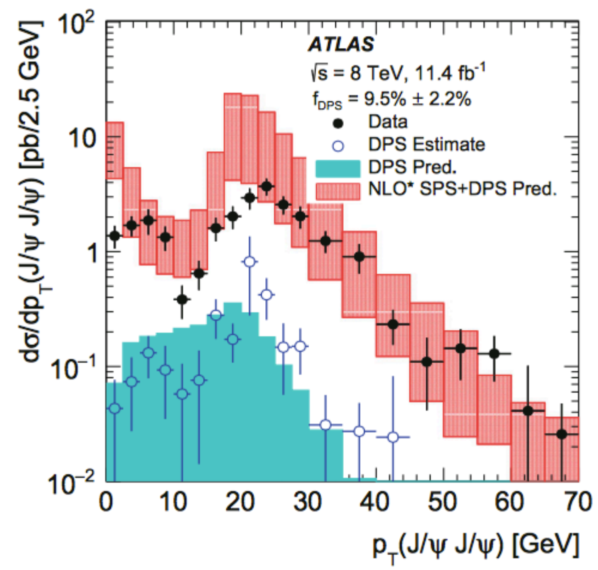
ATLAS @ 8 TeV

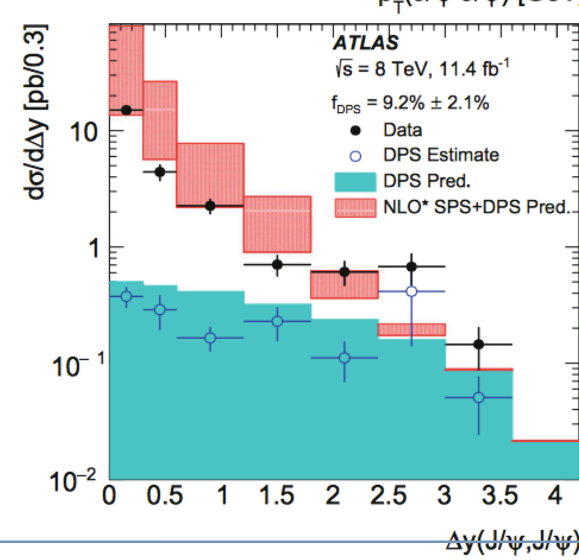
- $p_T > 8.5$ GeV, $|y| < 2.1$
- for $|y(J/\psi_2)| < 1.05$:

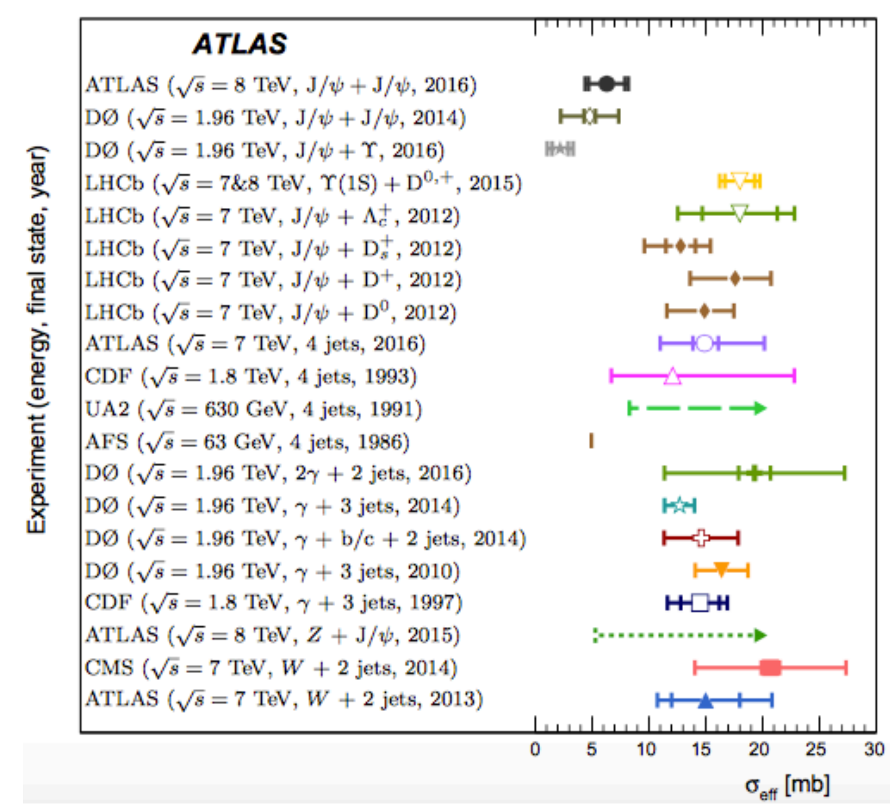
$\sigma(J/\psi\, J/\psi)_{8\,\text{TeV}} =$
$82.2 \pm 8.3_{stat} \pm 6.3_{syst} \pm 0.9_{BF} \pm 1.6_{lumi}$ pb

- for $1.05 < |y(J/\psi_2)| < 2.1$:

$\sigma(J/\psi\, J/\psi)_{8\,\text{TeV}} =$
$78.3 \pm 9.2_{stat} \pm 6.6_{syst} \pm 0.9_{BF} \pm 1.5_{lumi}$ pb







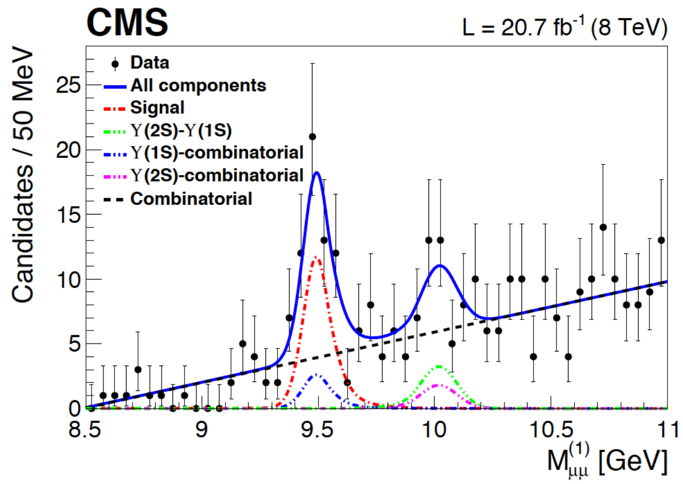
EPJC 77 (2017) 76

more pair productions

Υ(1s) pair production @ 8 TeV - CMS

JHEP 05 (2017) 013

- probe QCD at both pertubative and non-perturbative regimes
- both Υ(1s) reconstructed as a μ+μ⁻
- Fiducial X-section: $|y^{\Upsilon}| < 2.0$



$$\sigma_{\rm fid}(\Upsilon(1S)\Upsilon(1S)) = 68.8 \pm 12.7_{\rm stat} \pm 7.4_{\rm syst} \pm 2.8_{\mathcal{B}}\ {\rm pb}$$

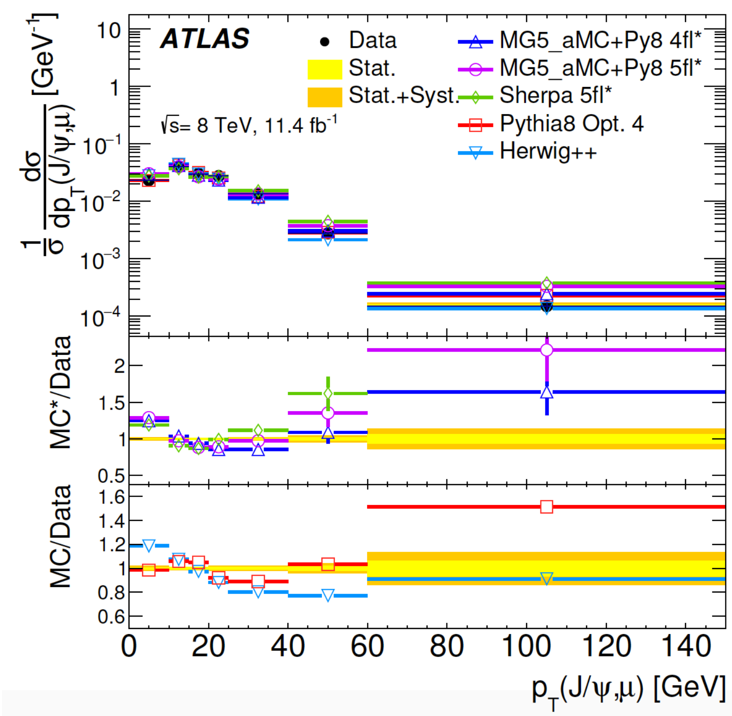
b-hadron pair @ 8 TeV - ATLAS

arXiv:1705.03374 (2017)

- b-hadron pairs investigated through
  - One b decays to J/psi(μμ) + X;
  - the other to μ + Y
  - A three μ final state

$$\sigma(B(\to J/\psi(\mu\mu) + X)B(\to \mu + X)) = 17.7 \pm 0.1_{\rm stat} \pm 2.0_{\rm syst}\ {\rm nb}$$

- results compared with predictions from many generators

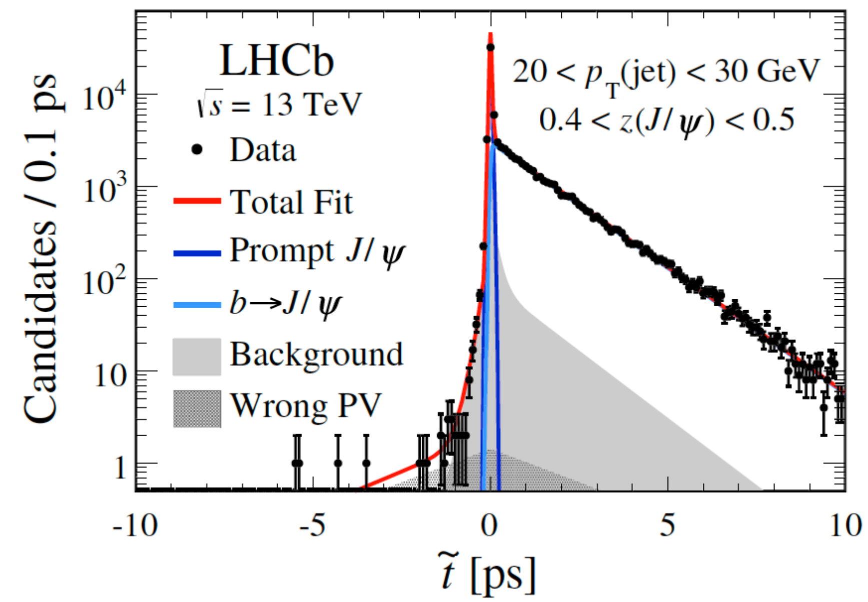


J/ψ in jets @ 13 TeV - LHCb

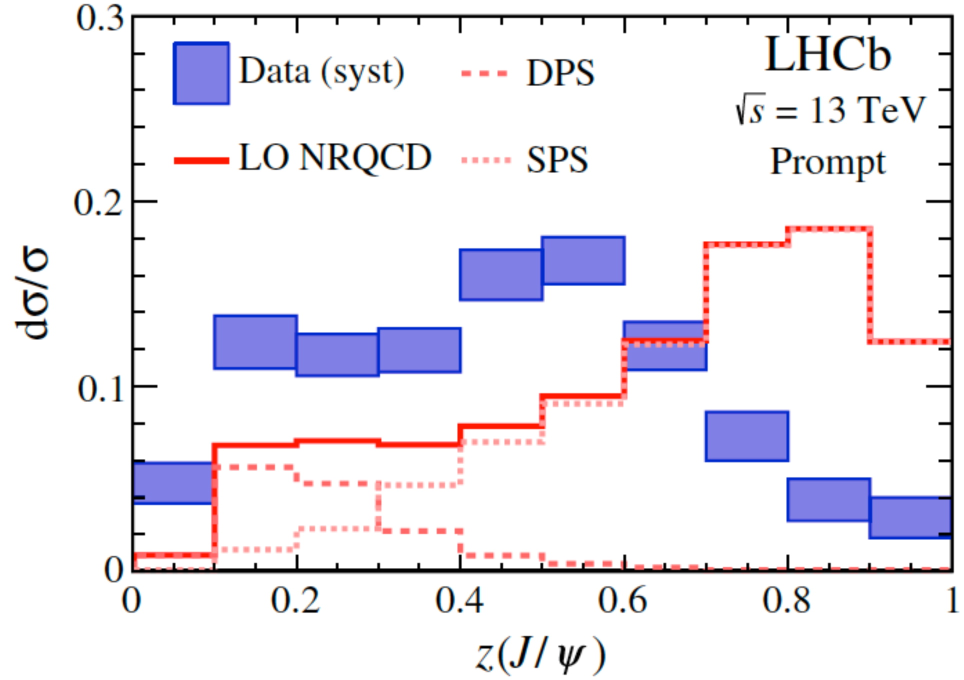
- $2.5 < \eta(\text{jet}) < 4.0$ and $p_T(\text{jet}) > 20$ GeV
- measure momentum fraction of J/ψ n the jet:

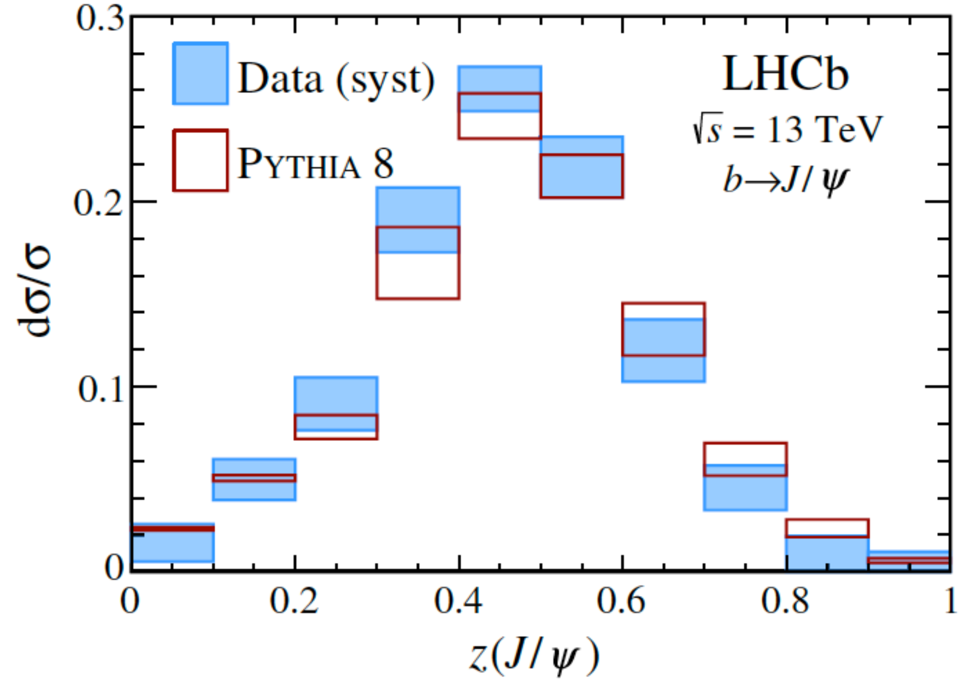
$$z = p_T(J/\psi)/p_T(\text{jet})$$

- again, J/ψ prompt and from-b separated by pseudo-decay time



PRL 118 (2017) 192001

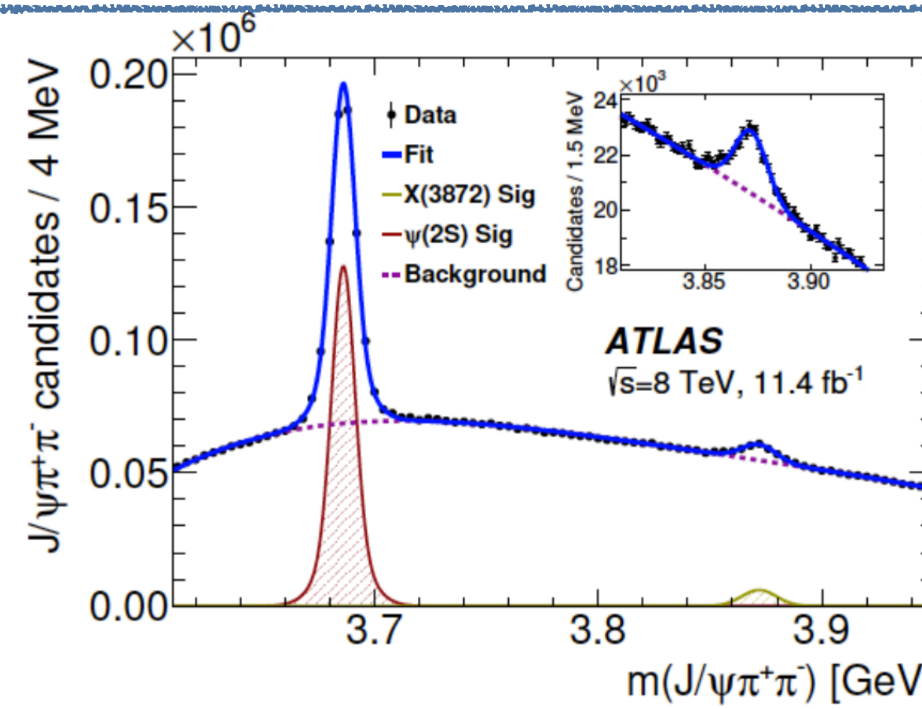




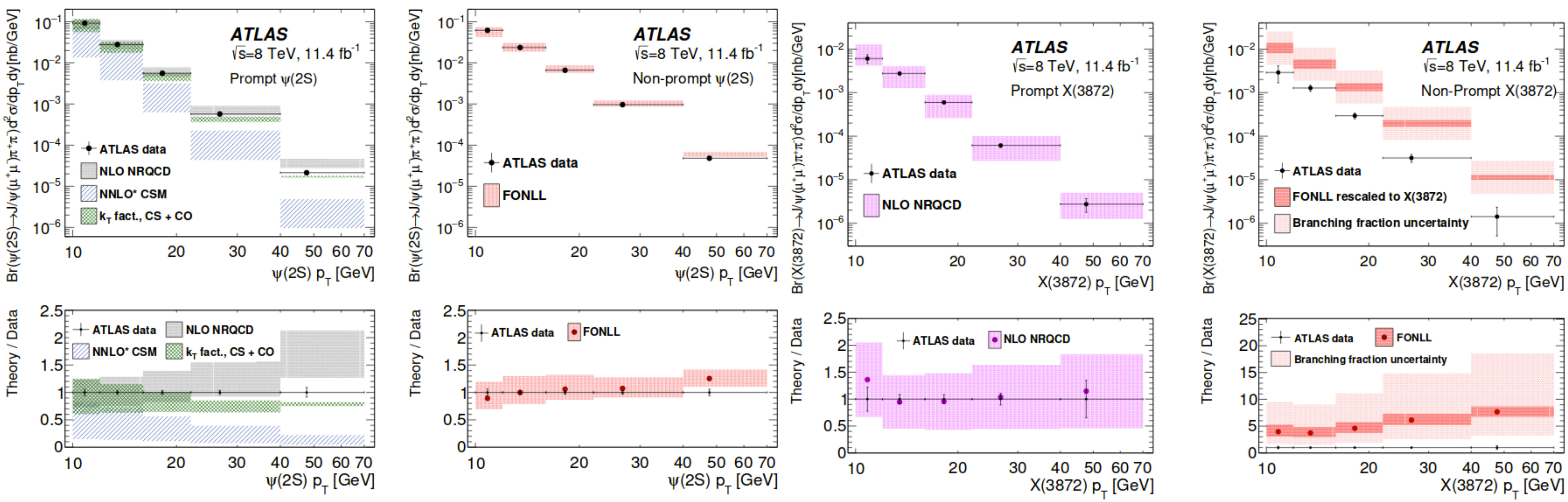
- b-hadron results consistent with PYTHIA8
- results from prompt do not agree with LO NRQCD (as implemented in PYTHIA8)
- prompt J/ψ less isolated than predicted: big contribution from parton shower

Production of X(3872) and ψ(2S) - ATLAS

- The nature of X(3872) is an open subject!
- ATLAS studies through final state $J/\psi(\mu\mu)\pi^+\pi^-$
- 11.4 fb^{-1} from 2012 data, $|y| < 0.75$, $10 < p_T < 70$ GeV
- separate prompt, short- and long-lived contributions through pseudo-decay time



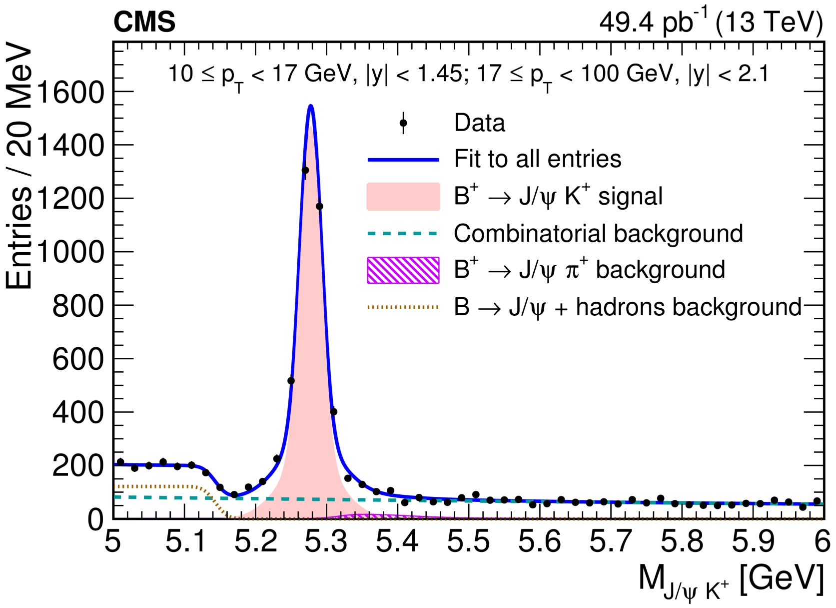
JHEP 01 (2017) 117



For X(3872):

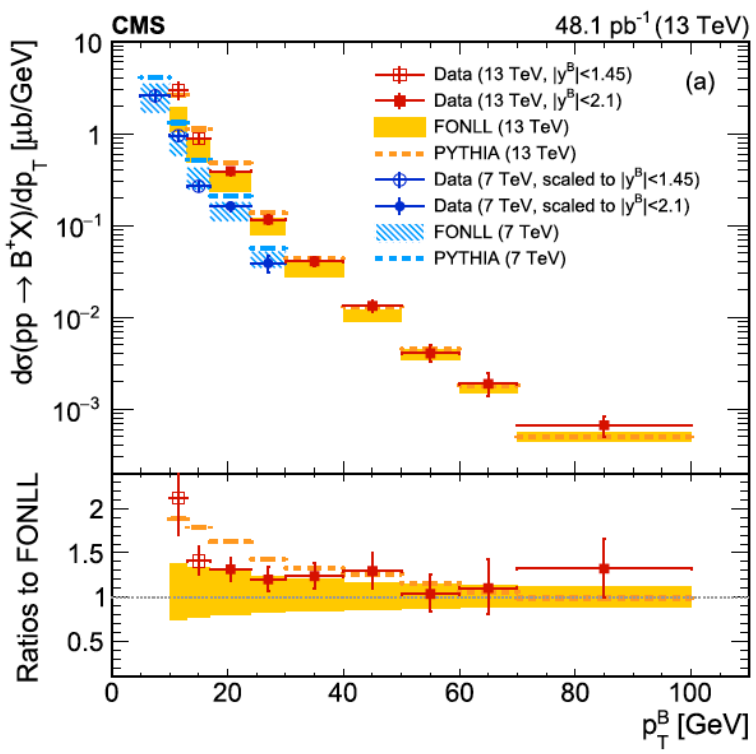
- prompt data well described by NLO NRQCD
- FONLL overestimated data for non-prompt

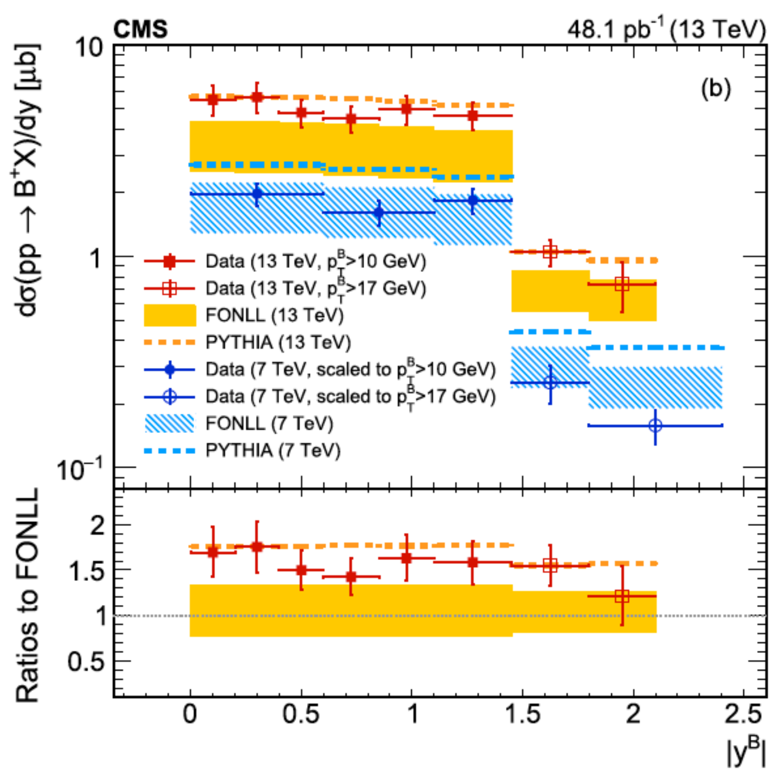
B^+ production @ 13 TeV (CMS)

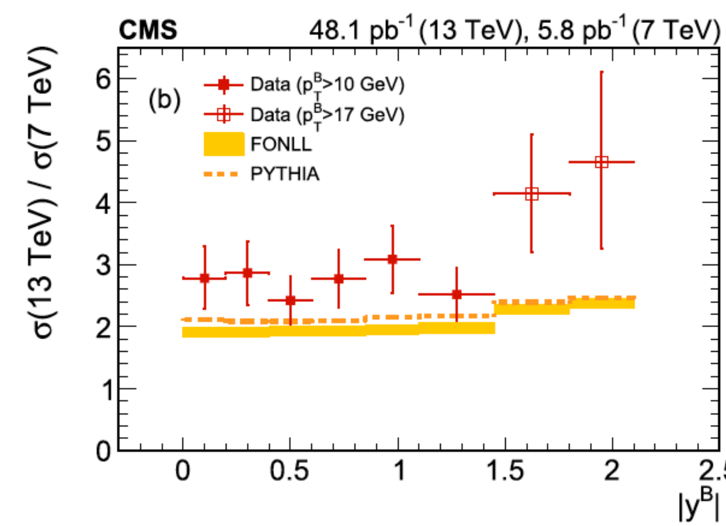


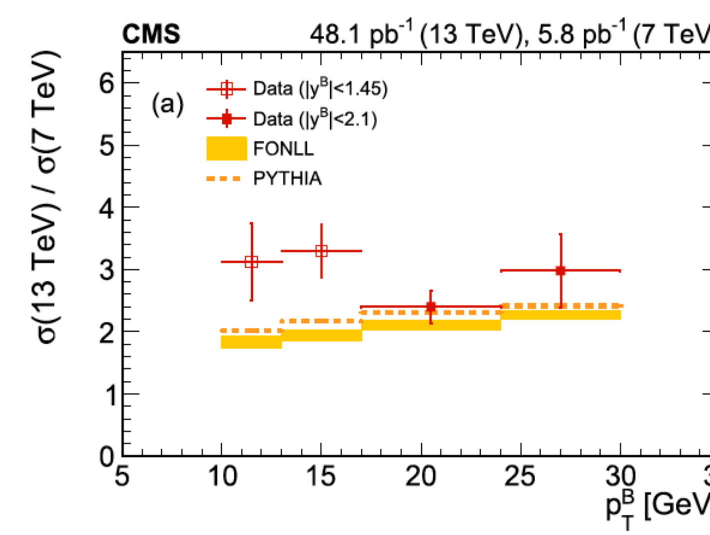
- B^+ production for: $10 < p_T{}^B < 17$ GeV, $|y^B| < 1.45$
  $17 < p_T{}^B < 100$ GeV, $|y^B| < 2.10$
- Uses $B^+ \to J/\psi(\mu^+\mu^-) K^+$
- Measured for the 1st time at 13 TeV

$$\sigma(pp \to B^+ X) = 15.3 \pm 0.4_{stat} \pm 2.1_{syst} \pm 0.4_{lumi}\ \mu b$$









- Shape and normalisation in reasonable agreement with FONLL and PYTHIA
- 13 to 7 TeV ratio tend to prefer higher values wrt predictions

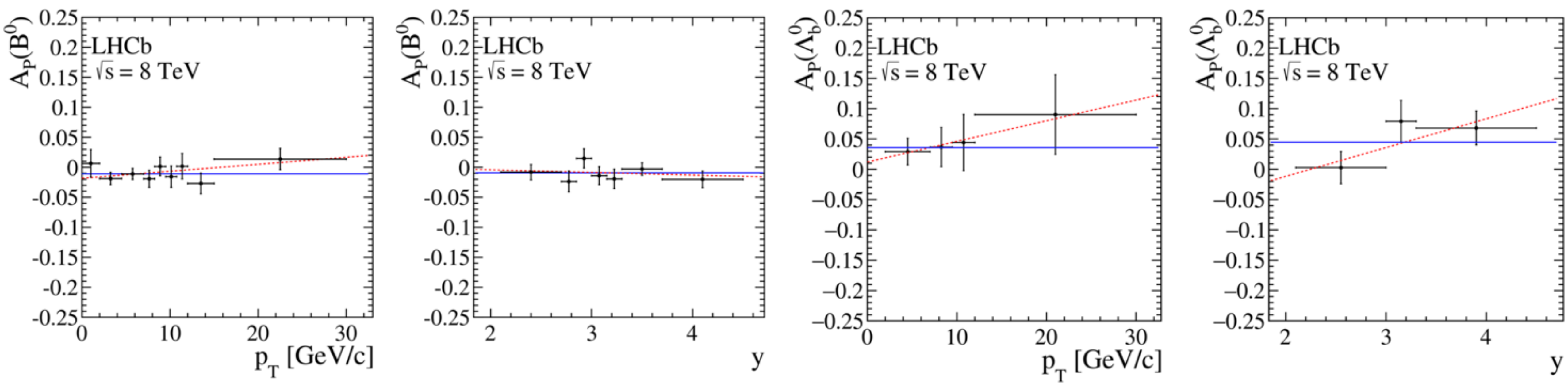
arXiv:1609.00873, PLB in press (2017)

b-hadron production asymmetries - LHCb

- in pp collisions, production asymmetries can arise due to the valence quark content of the proton

$$A_{\mathrm{P}} \equiv \frac{\sigma(\bar{X}_b) - \sigma(X_b)}{\sigma(\bar{X}_b) + \sigma(X_b)}$$

- important for understanding production mechanisms as well as input for CP violation studies
- LHCb measures production asymmetries for B^0, B^+, B_s^0 @ 7 and 8 TeV (full run I data) as a function (p_T, η) and determine Λ_b^0 as function of the others



arXiv:1703.08464

	A_{P} $\sqrt{s} = 7$ TeV	A_{P} $\sqrt{s} = 8$ TeV
B^+	$-0.0023 \pm 0.0024 \pm 0.0037$	$-0.0074 \pm 0.0015 \pm 0.0032$
B^0	$0.0044 \pm 0.0088 \pm 0.0011$	$-0.0140 \pm 0.0055 \pm 0.0010$
B_s^0	$-0.0065 \pm 0.0288 \pm 0.0059$	$0.0198 \pm 0.0190 \pm 0.0059$
Λ_b^0	$-0.0011 \pm 0.0253 \pm 0.0108$	$0.0344 \pm 0.0161 \pm 0.0076$

- all values consistent with zero within 2.5σ

$B^0 - \bar{B}^0$ width difference: $\Delta\Gamma_d$ (ATLAS)

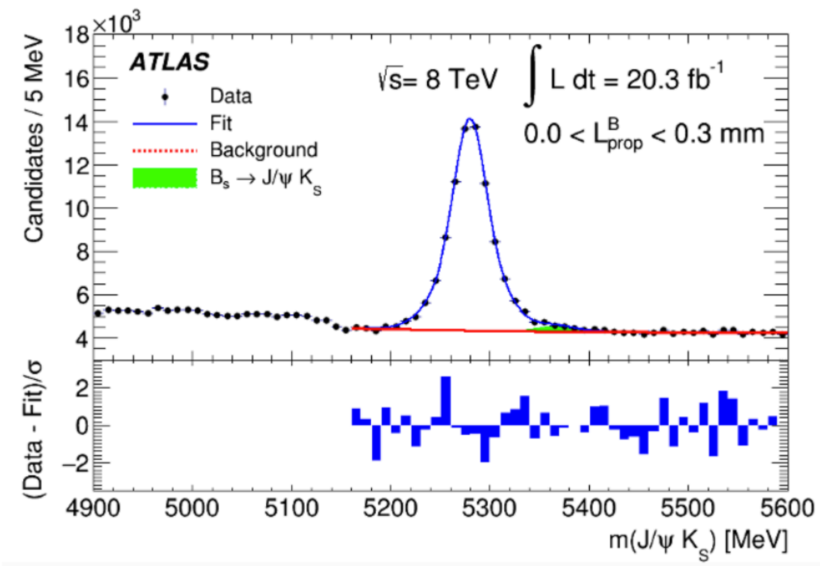
- Eigenstates H (heavy) and L (light) have different widths. Value is well predicted in the SM:

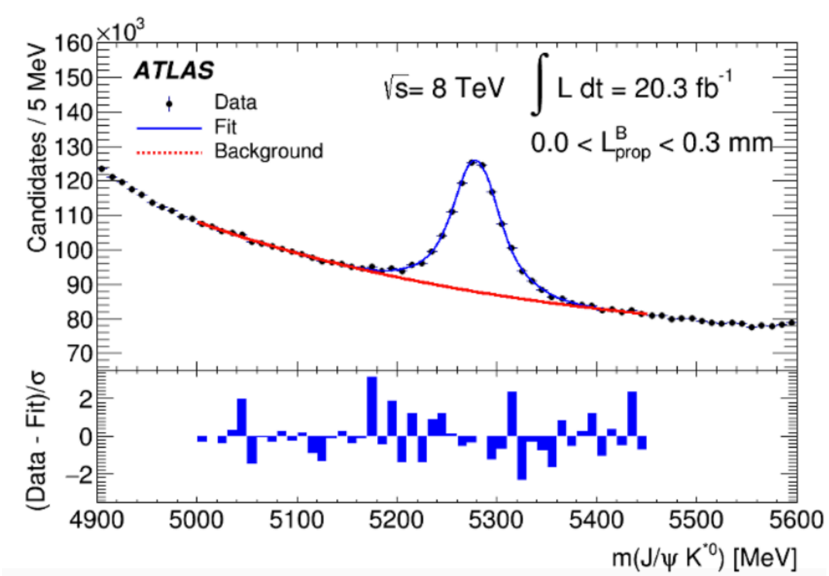
$$\Delta\Gamma_d/\Gamma_d(\mathrm{SM}) = (0.42 \pm 0.08) \times 10^{-2}$$

Lenz & Niesrte, arXiv:1102.4274

$$|B_d^H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$
$$|B_d^L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$
$$\boxed{\Delta\Gamma_d = \Gamma_d^L - \Gamma_d^H}$$

ATLAS measures $\Delta\Gamma_d$ with run I data:

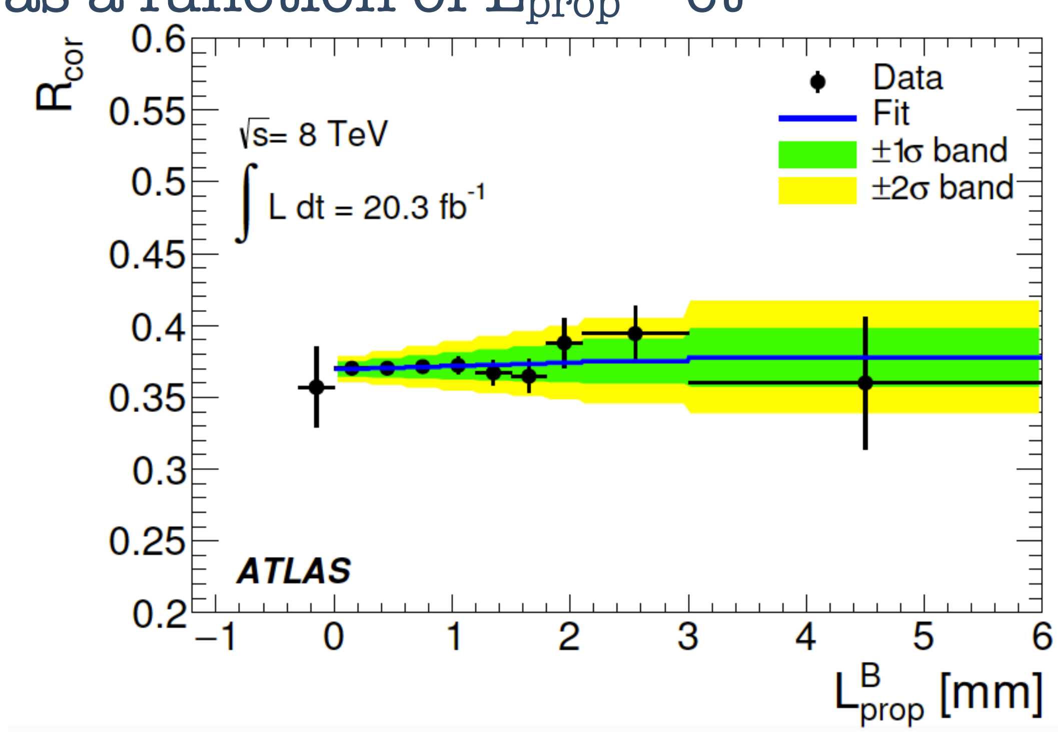




- Obtains B^0 production asymmetry

$$A_P(B^0) = (+0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$$

- Get $\Delta\Gamma_d$ by the ratio of to $J/\psi\ K_S$ and $B \to J/\psi K^*$ yields as a function of L_{prop} = ct



JHEP 06 (2016) 081

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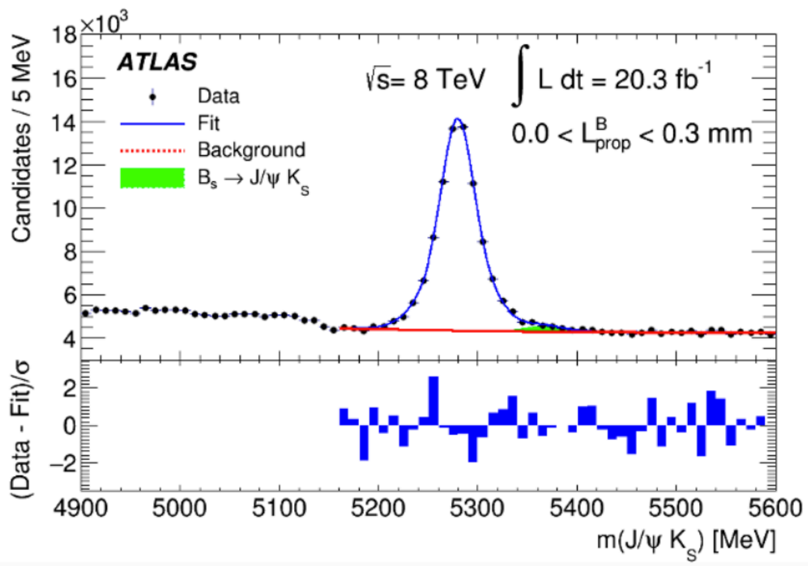

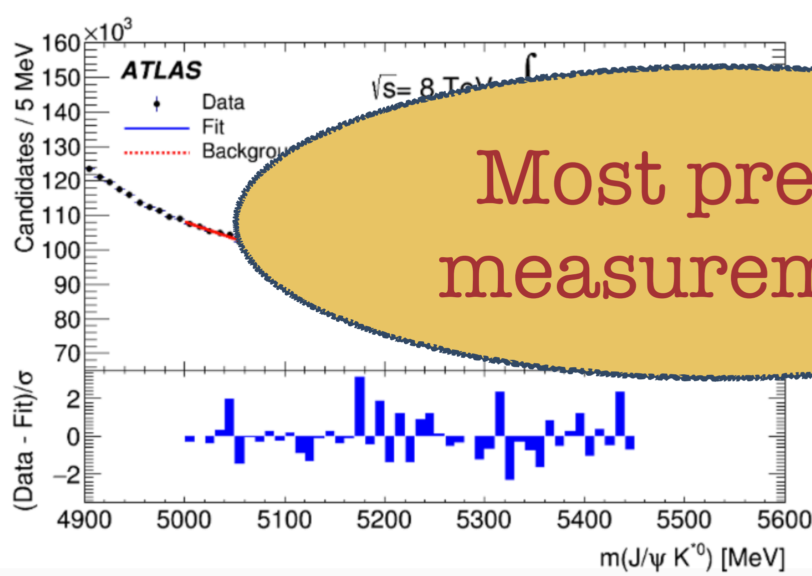

Most precise measurement!

- Obtains B^0 production asymmetry

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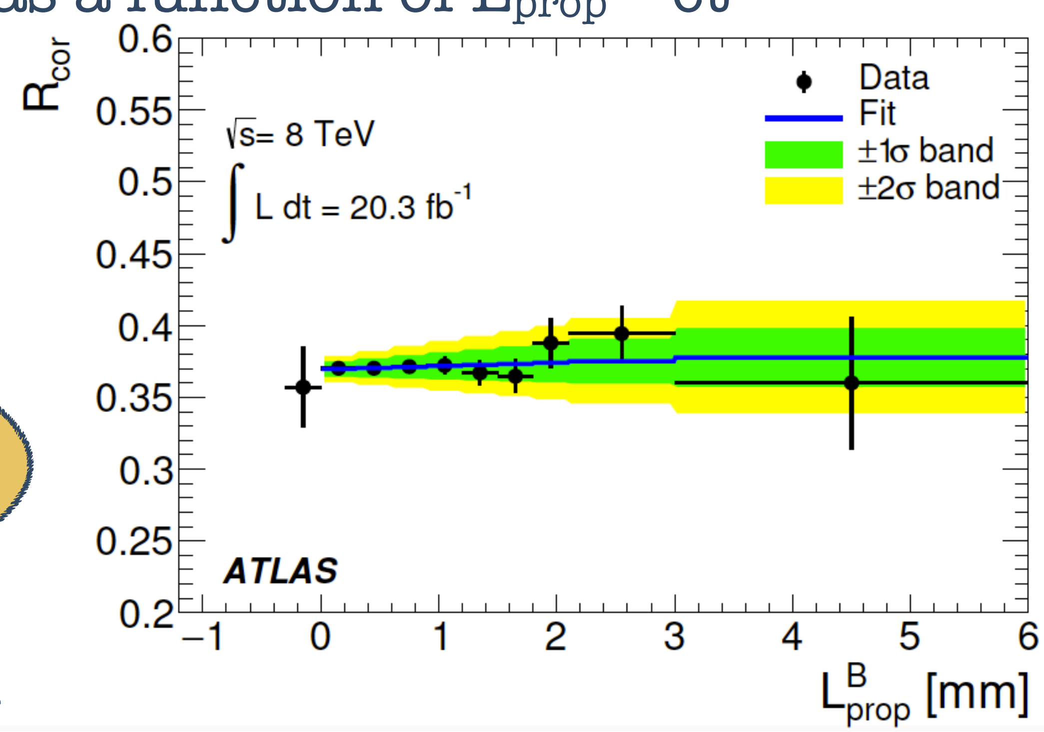

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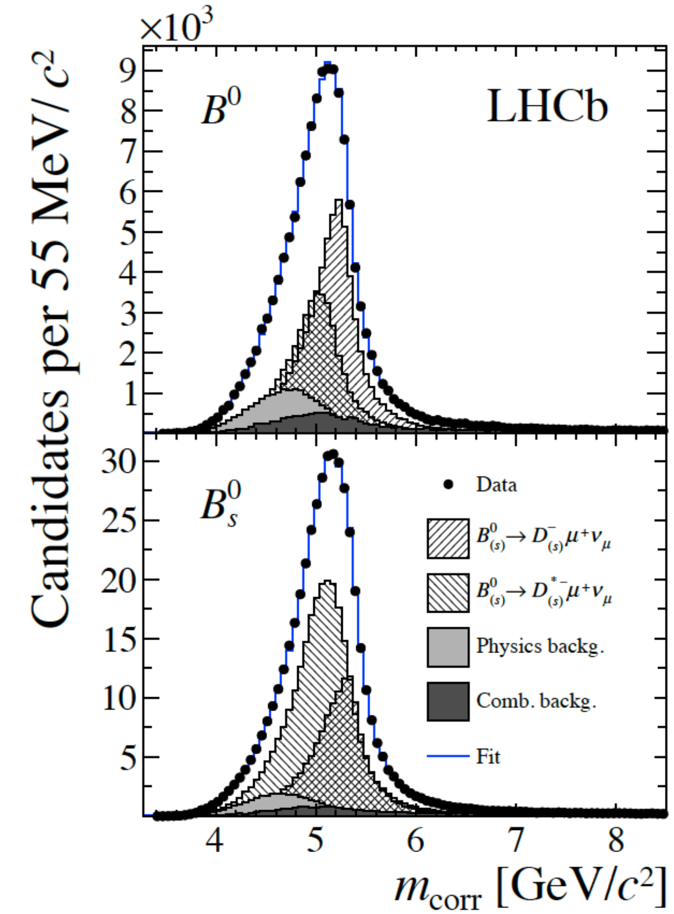
$$\Delta\Gamma_d/\Gamma_d(\mathrm{SM}) = (-0.1 \pm 1.1 \pm 0.9) \times 10^{-2}$$

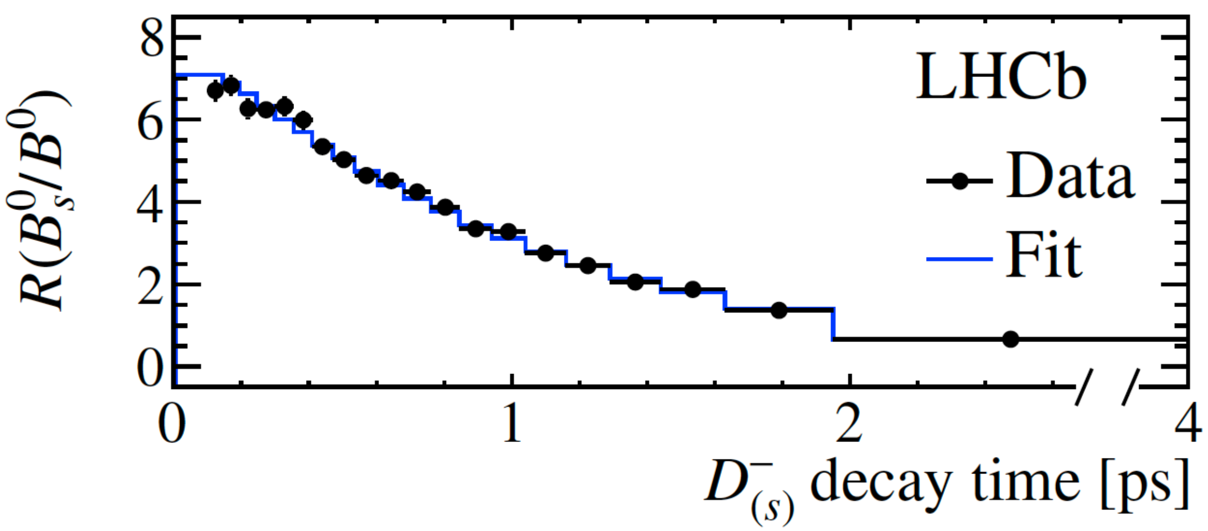
B_s^0 and D_s^+ lifetimes (LHCb)

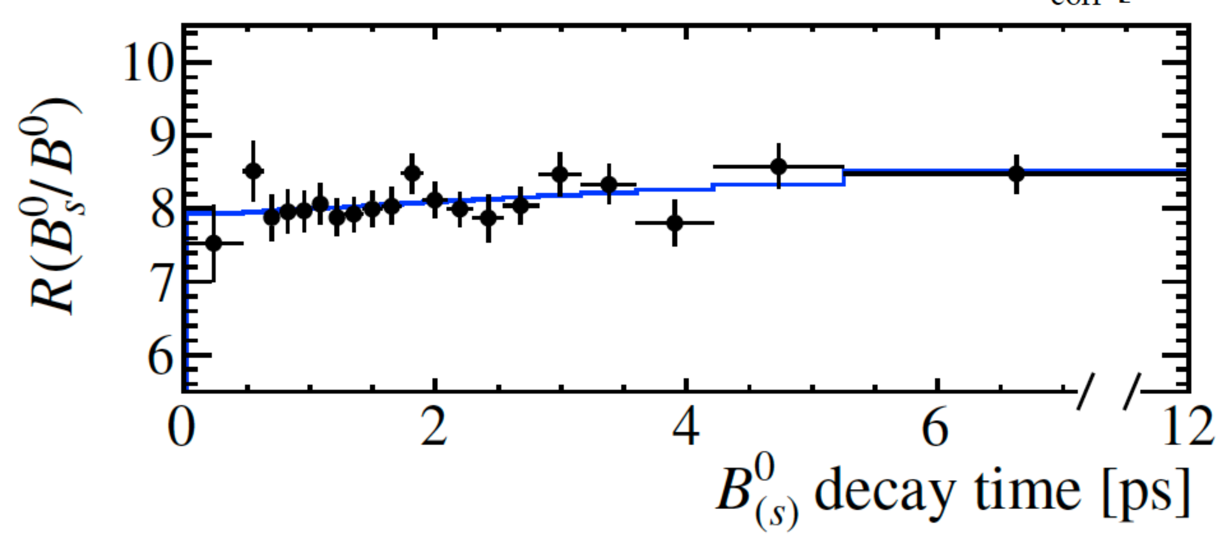
- run I data, 3fb^{-1}
- tests for HQE: validation and refinement using lifetime measurements
- "Flavour-specific" B_s^0 lifetime: single exponential fit in flavour specify final state
- so far, best measurement from LHCb using $B_s^0 \to D_s^- \pi^+$
- Semi-lep: higher yields, but with large systematics
- Novel Method! Use ratio of yields of $B_s^0 \to D_s^{(*)-} \mu^+ \nu$ wrt to $B^0 \to D^{(*)-} \mu^+ \nu$ as a function of decay time

☞ get both B_s^0 and D_s^+ lifetimes by $\Delta\Gamma$ obtained from the fit



arXiv:1705.03475, acc. by PRL





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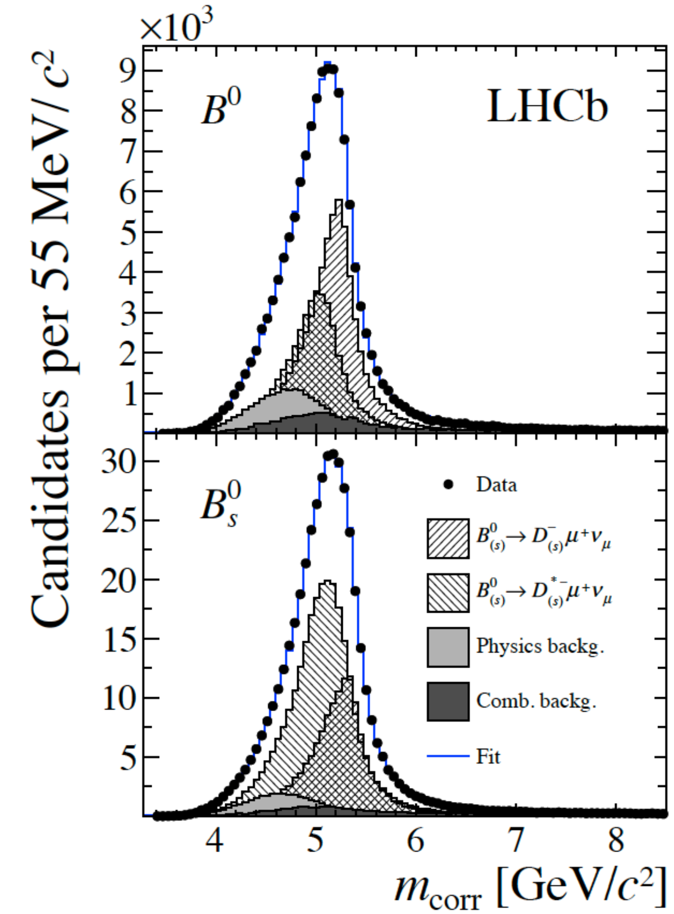
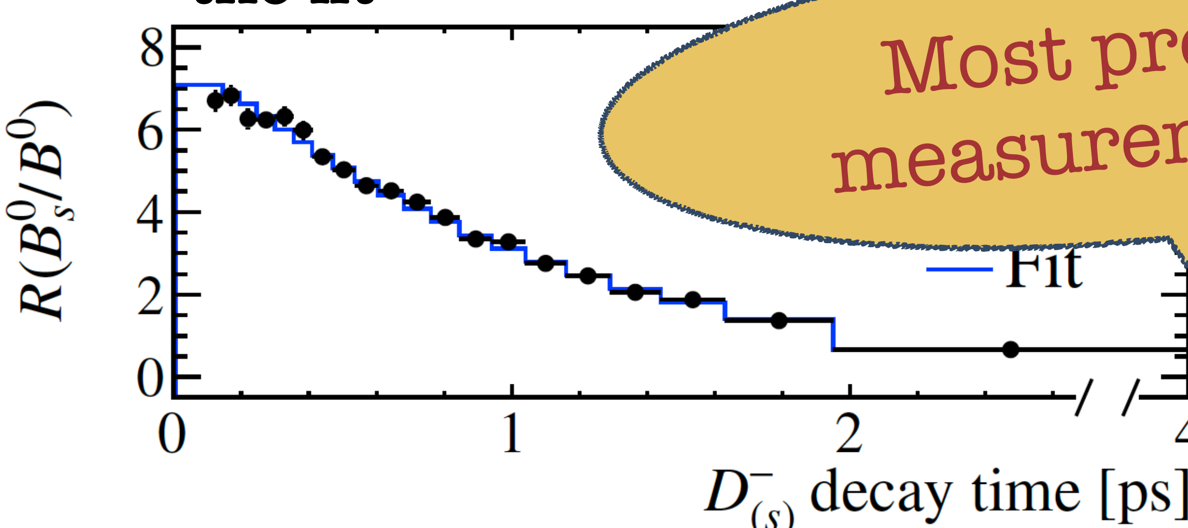
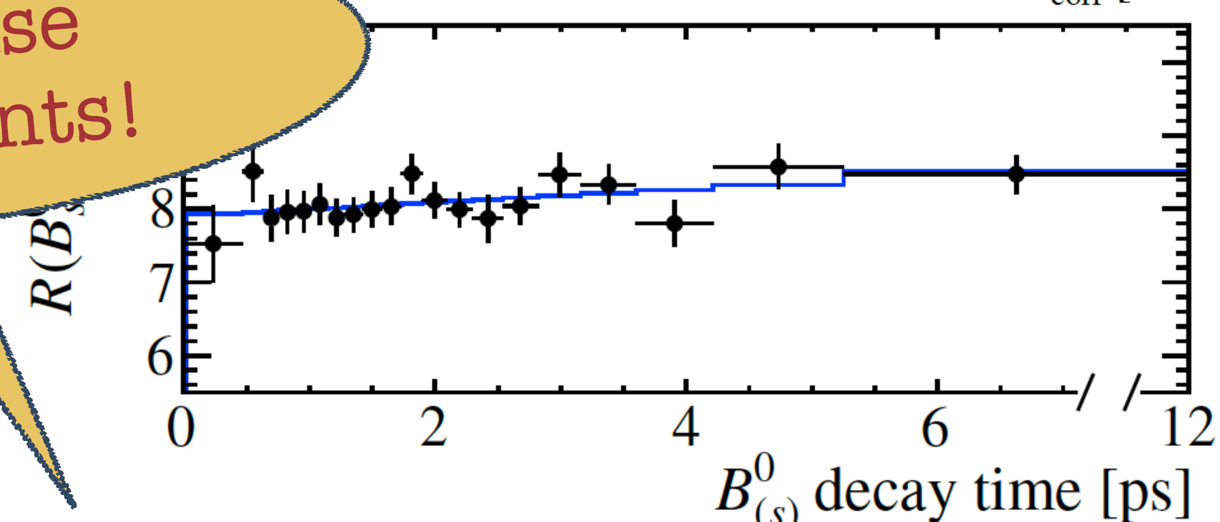


arXiv:1705.03475, acc. by PRL





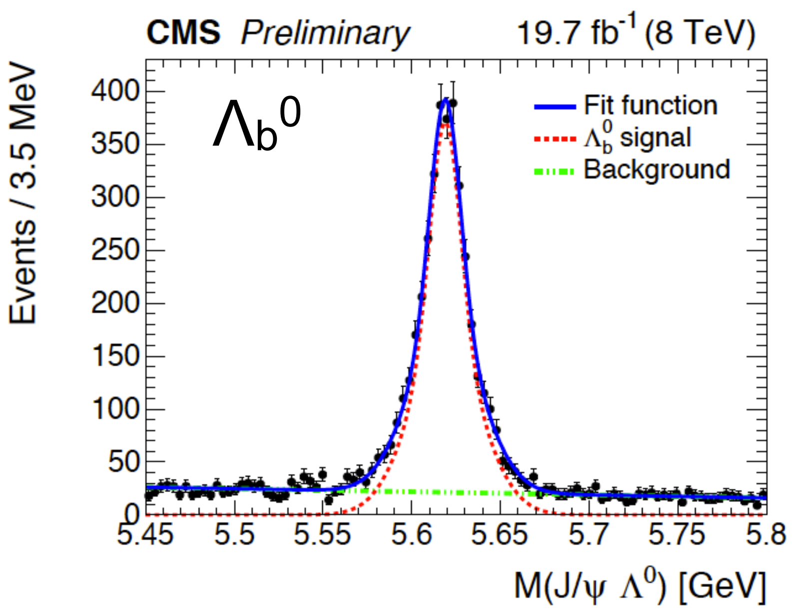
Most precise measurements!

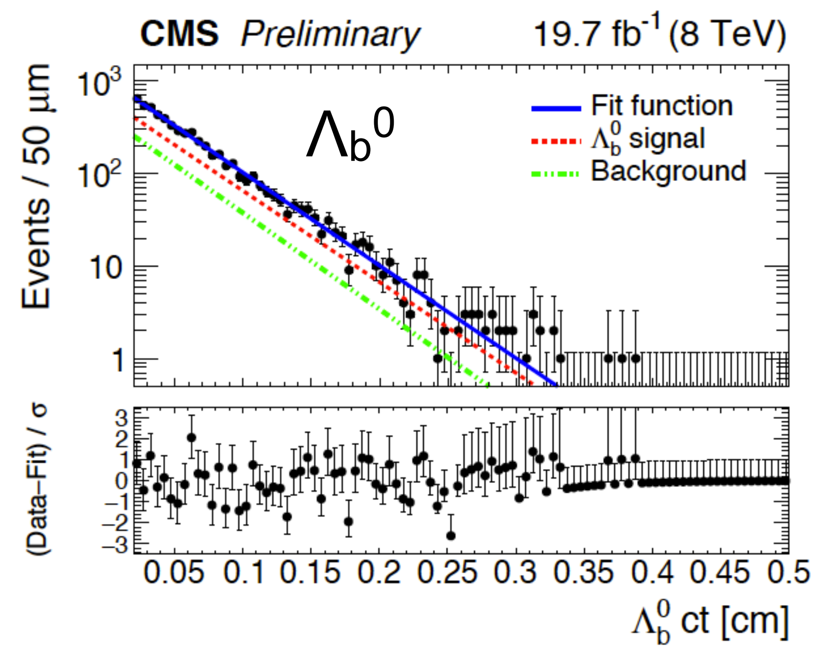
$$\tau_{B_s^0}^{\rm fs} = 1.547 \pm 0.013_{\rm stat} \pm 0.010_{\rm syst} \pm 0.004_{\tau_B}\ {\rm ps}$$
$$\tau_{D_s^-} = 0.5064 \pm 0.0030_{\rm stat} \pm 0.0017_{\rm syst} \pm 0.0017_{\tau_D}\ {\rm ps}$$

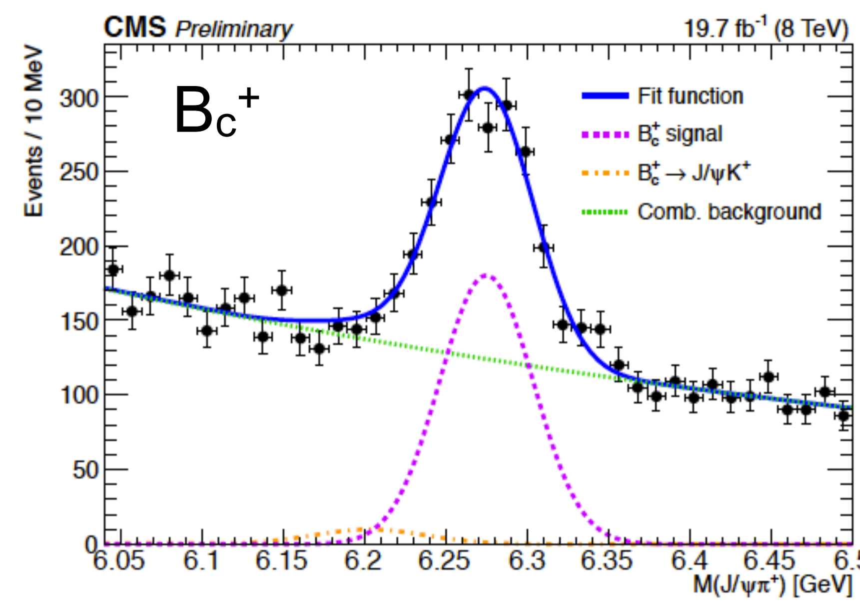
b-hadron lifetimes (CMS)

CMS-PAS-BPH-13-008 (2017)

- CMS measures b-hadron lifetimes with 19.7 fb^{-1} @ 8 TeV
- Uses final states with $J/\psi \rightarrow \mu^+\mu^-$







$$c\tau_{B^0} = 453.0 \pm 1.6\ (\text{stat})\ \pm 1.5\ (\text{syst})\ \mu\text{m}\ (\text{in } J/\psi K^*(892)^0)$$

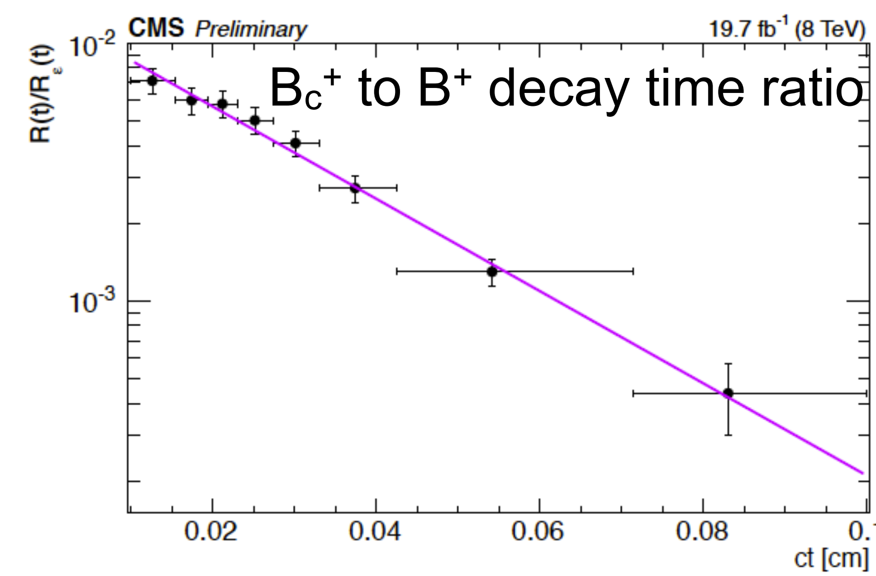
$$c\tau_{B^0} = 457.8 \pm 2.7\ (\text{stat})\ \pm 2.7\ (\text{syst})\ \mu\text{m}\ (\text{in } J/\psi K_S)$$

$$c\tau_{B^0_s} = 504.3 \pm 10.5\ (\text{stat})\ \pm 3.7\ (\text{syst})\ \mu\text{m}\ (\text{in } J/\psi \pi^+\pi^-)$$

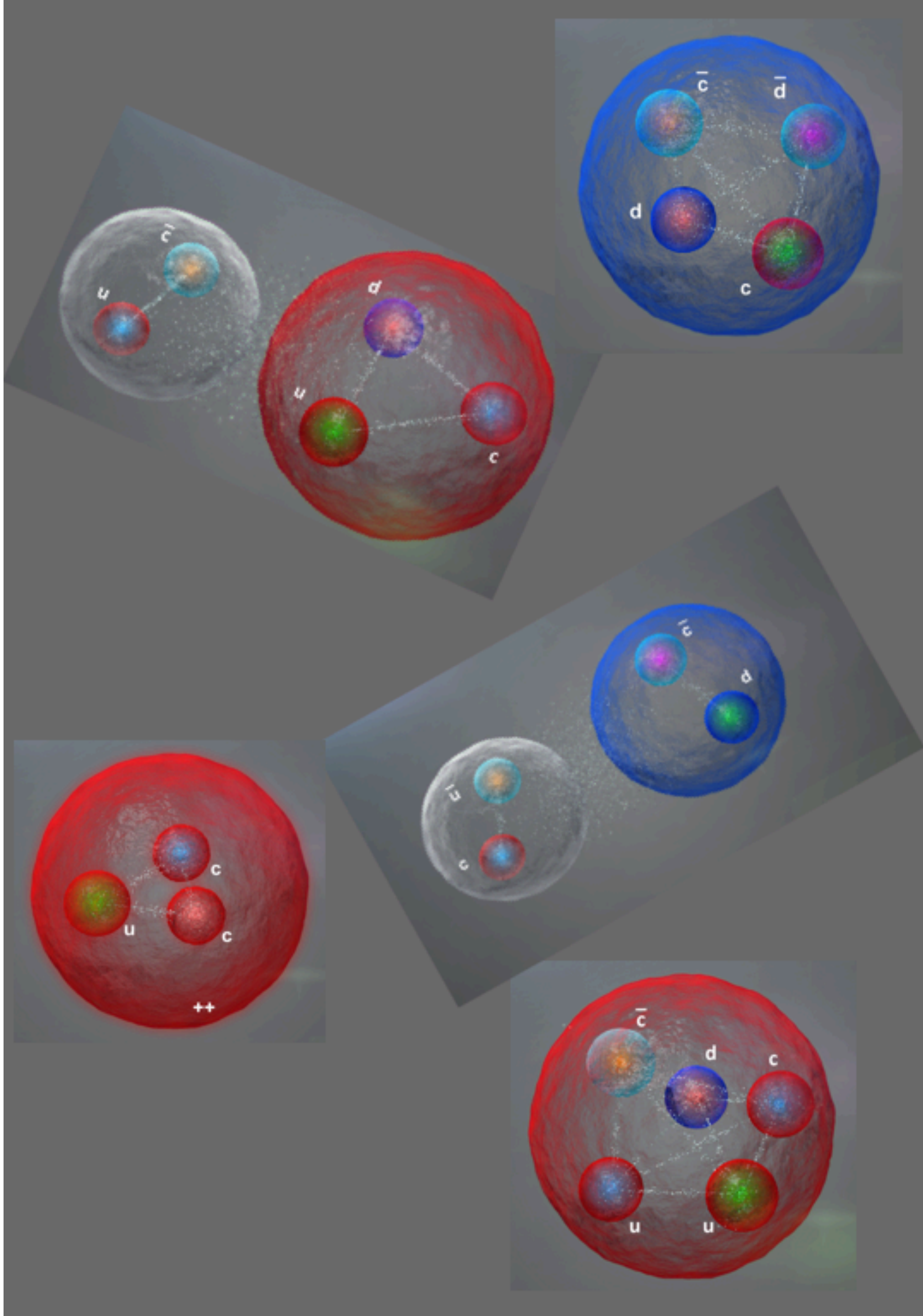
$$c\tau_{B^0_s} = 443.9 \pm 2.0\ (\text{stat})\ \pm 1.2\ (\text{syst})\ \mu\text{m}\ (\text{in } J/\psi \phi(1020))$$

$$c\tau_{\Lambda^0_b} = 443.1 \pm 8.2\ (\text{stat})\ \pm 2.7\ (\text{syst})\ \mu\text{m}$$

$$c\tau_{B^+_c} = 162.3 \pm 8.2\ (\text{stat}) \pm 4.7\ (\text{syst}) \pm 0.1(\tau_{B^+})\ \mu\text{m}$$

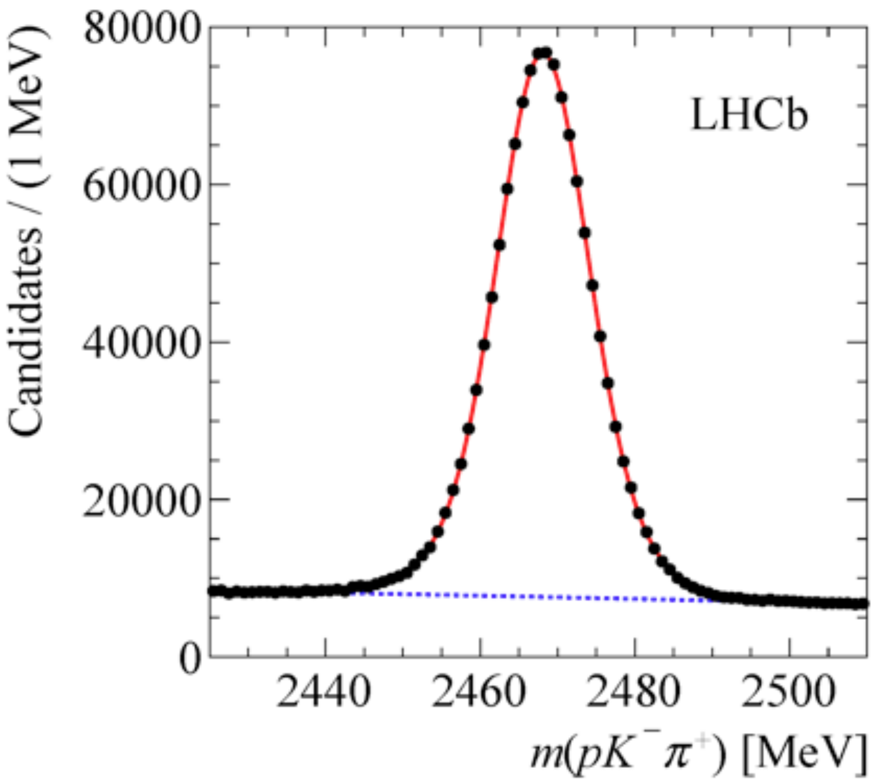


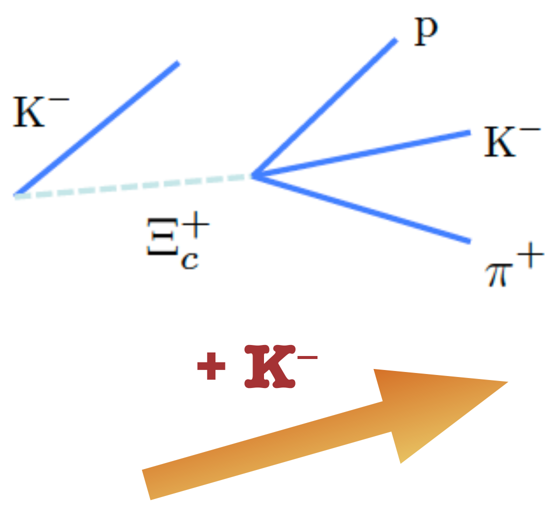
Flavour & More Flavour: spectroscopy



Excited Ω_c States (LHCb)

- Take a $\Xi_c^+ (\to p K^- \pi^+)$ and add a K^-





PRL 118 (2017) 182001

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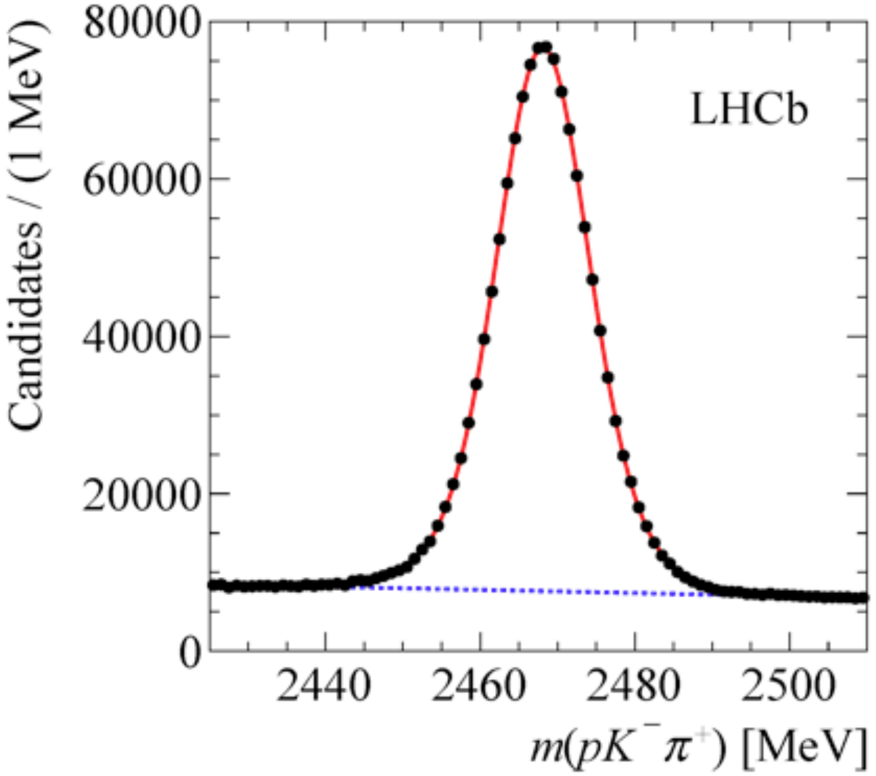
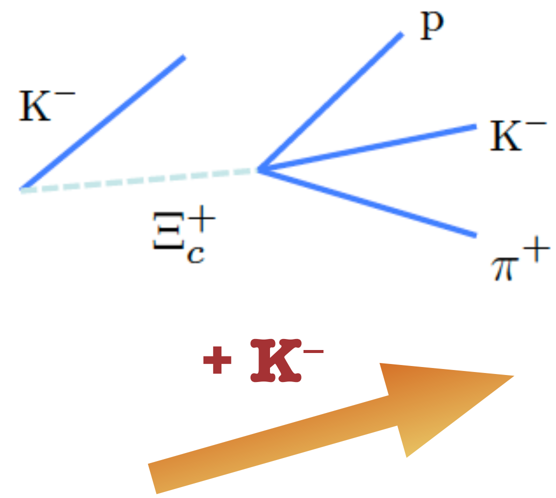
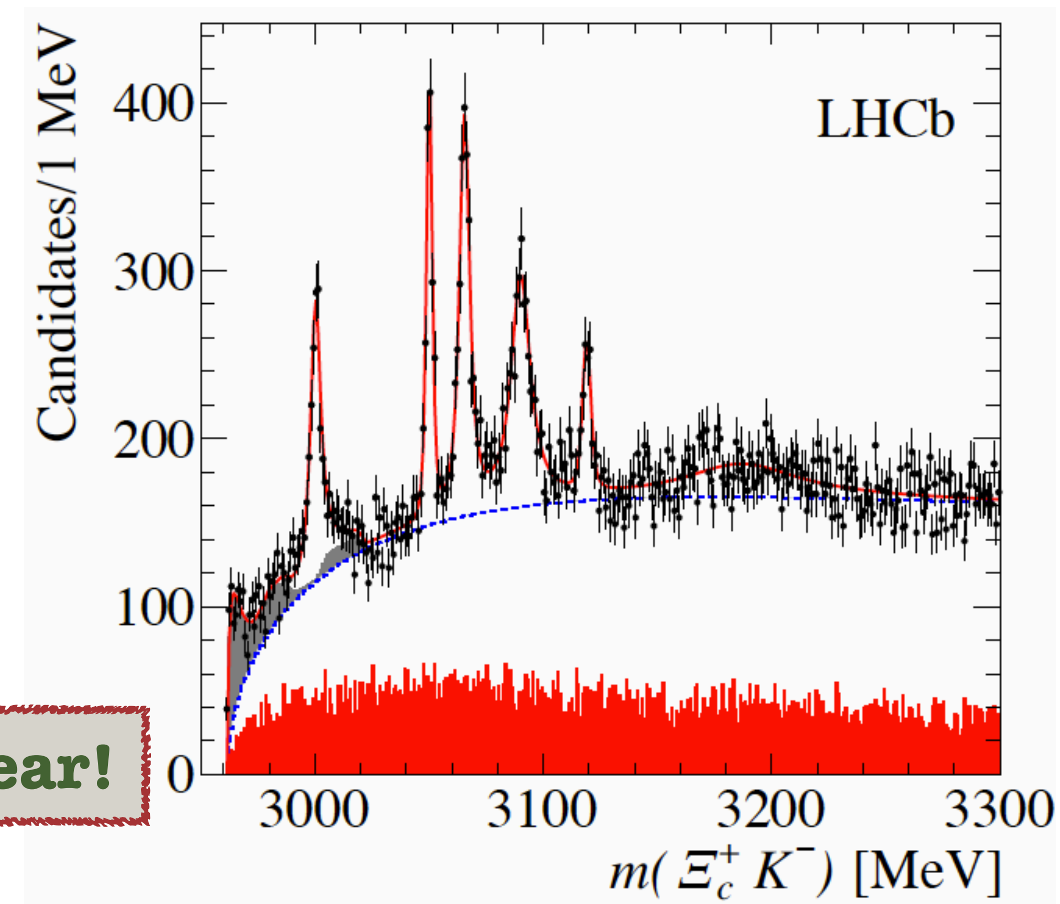




Five Ω^* states appear!



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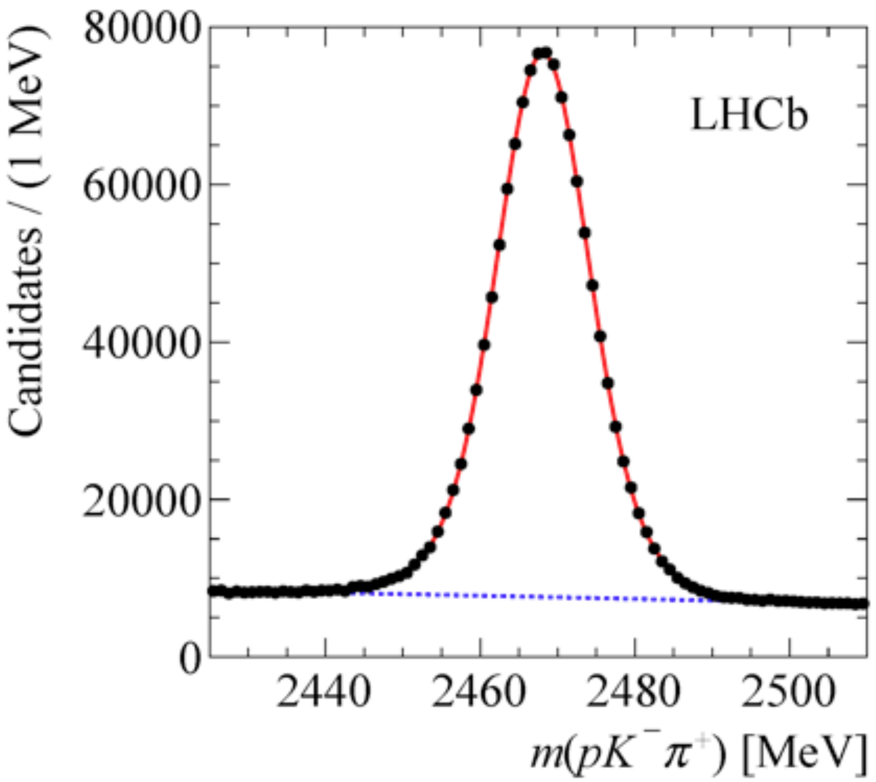

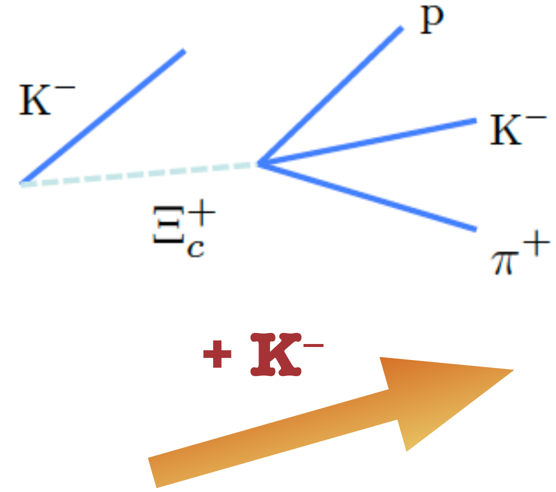

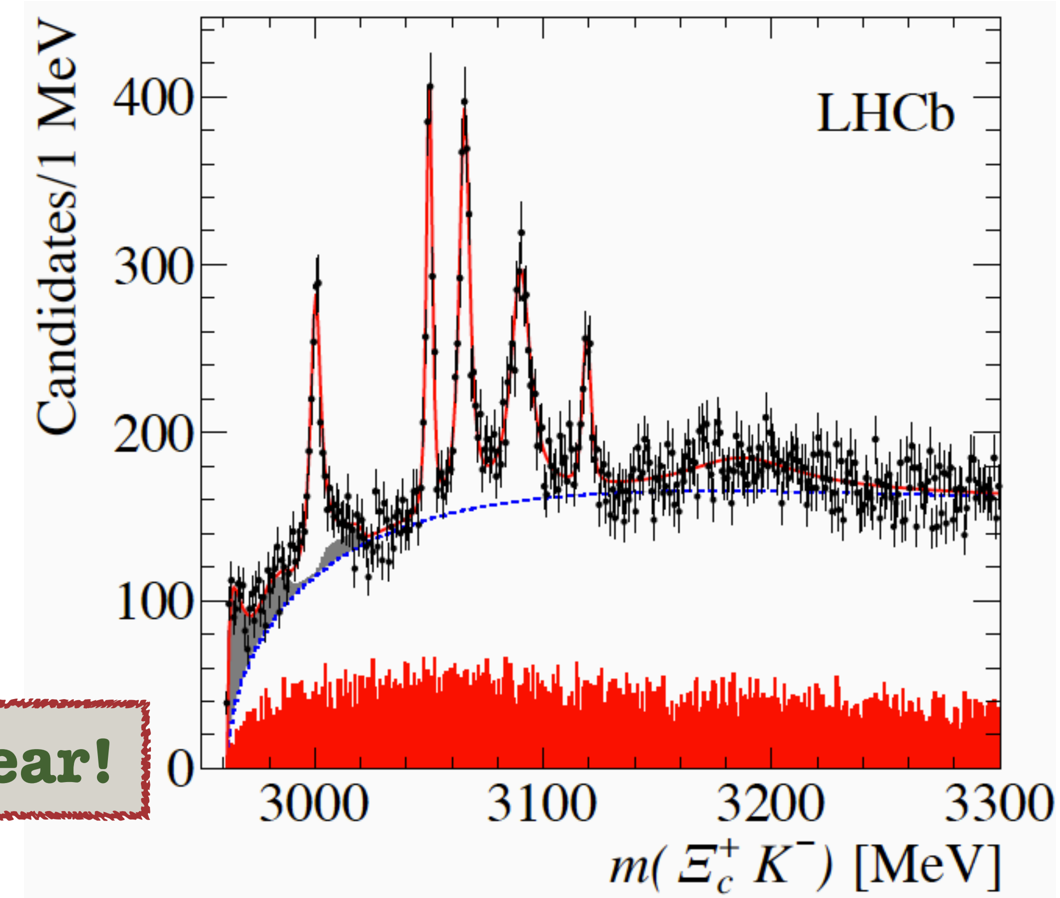

PRL 118 (2017) 182001

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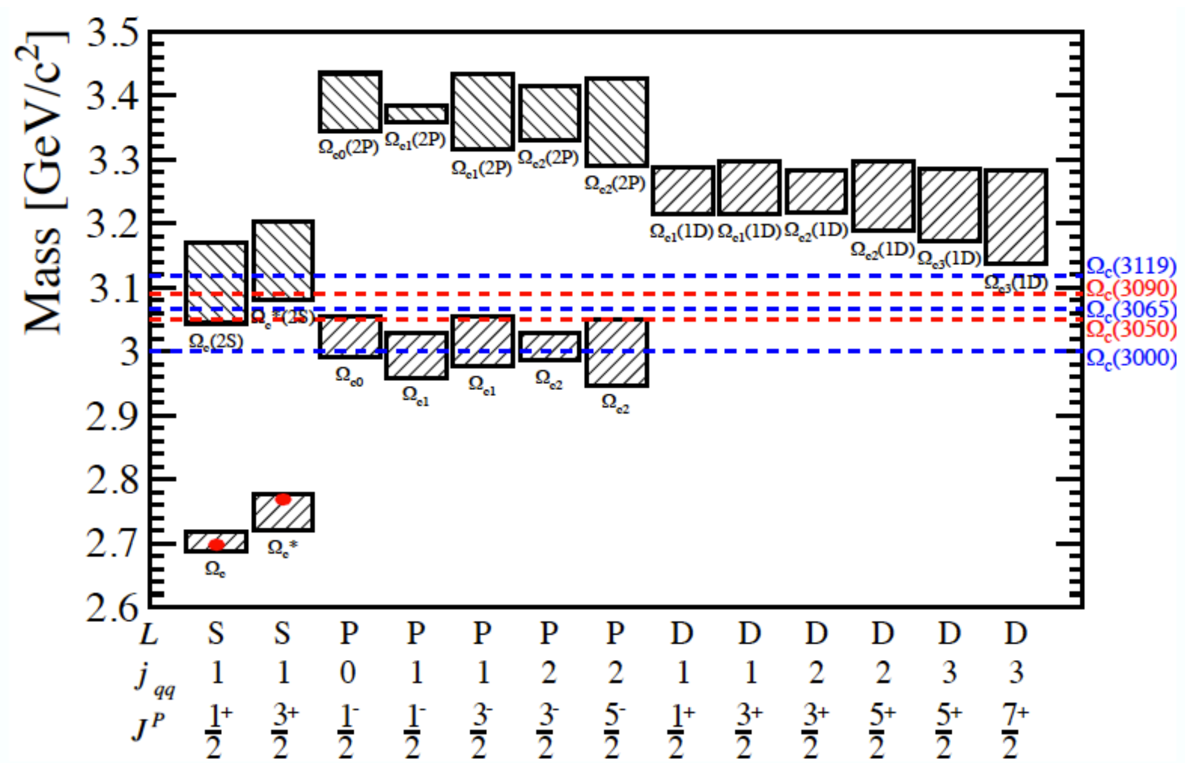
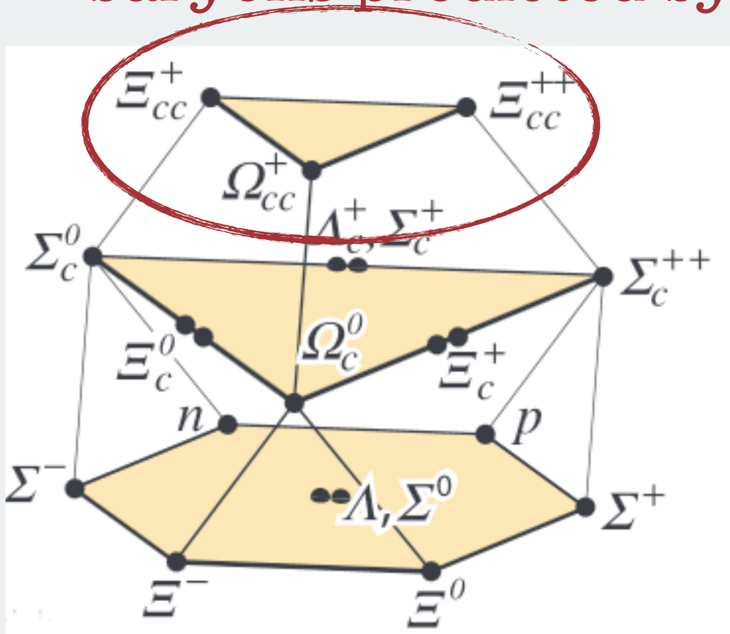


$\Omega_c(3000)$ $\Omega_c(3050)$ $\Omega_c(3066)$ $\Omega_c(3090)$ $\Omega_c(3119)$

- Quantum numbers yet to be determined
  - multi-body decay or production via heavy hadron
- Also indication of a broader structure at ~3.2 GeV

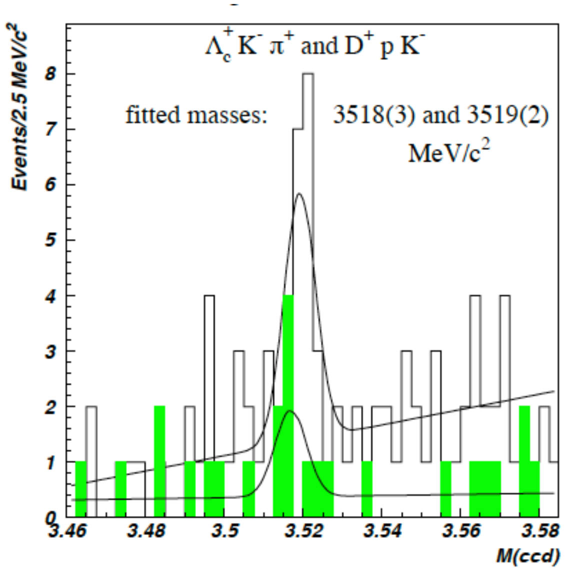
Ξ^{++}_{cc} observation!

3 weakly-decaying doubly charmed baryons predicted by constituent-quark model



SELEX (2002,2005) claimed observation of Ξ^{+}_{cc}

- not confirmed by other experiments



PLB 628 (2005) 18-24

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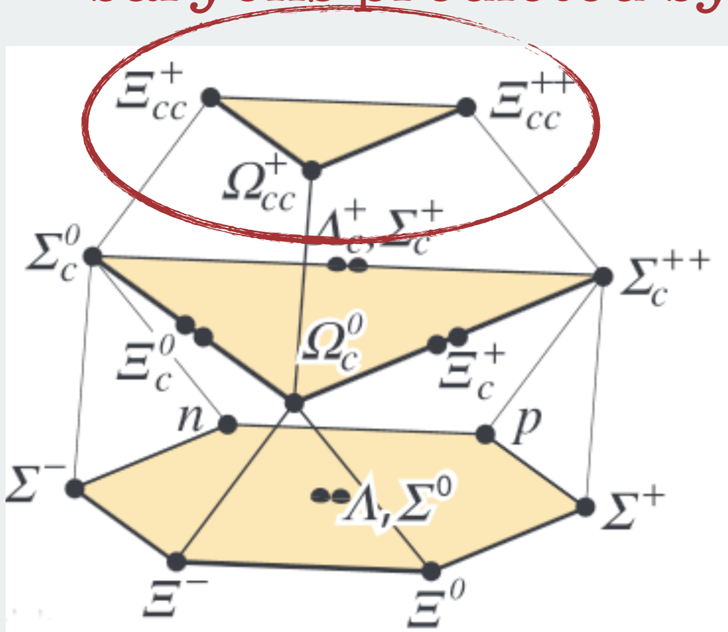

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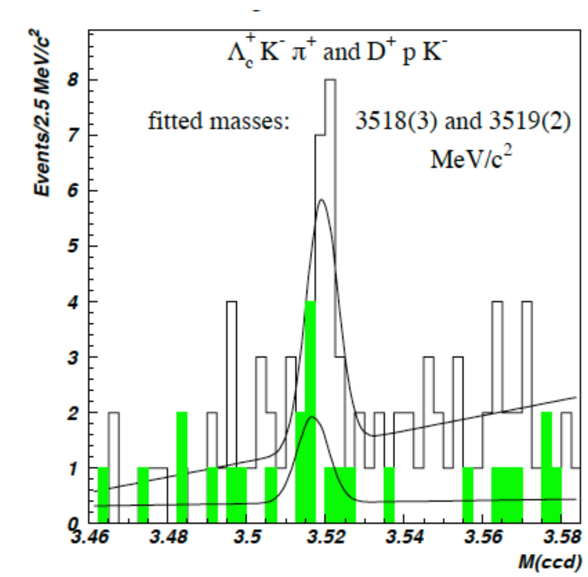


PLB 628 (2005) 18-24

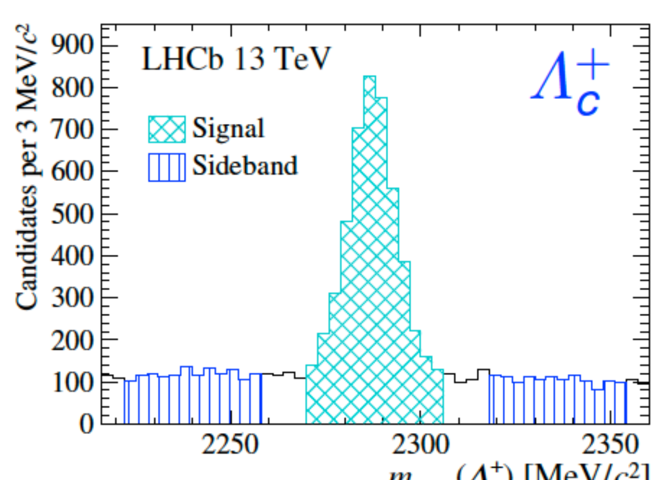
☞ **LHCb searches for Ξ^{++}_{cc} through $\Lambda_c^+(\rightarrow pK^-\pi^+)\ K^-\pi^+\pi^+$**

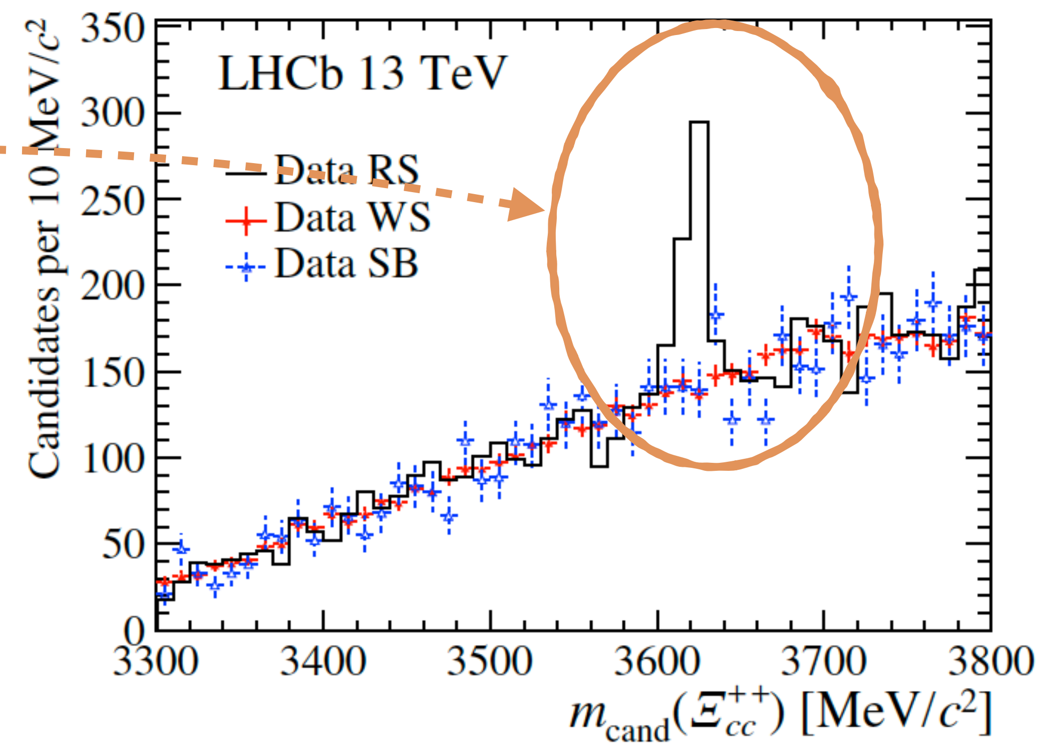
PRL 11 (2017) 180001

(run II data, 1.7 fb^{-1})

- reconstruct also "wrong-sign" $\Lambda_c^+ K^- \pi^+ \pi^-$
- check of Λ_c^+ sidebands

clear structure appears at ~ 3620 GeV!





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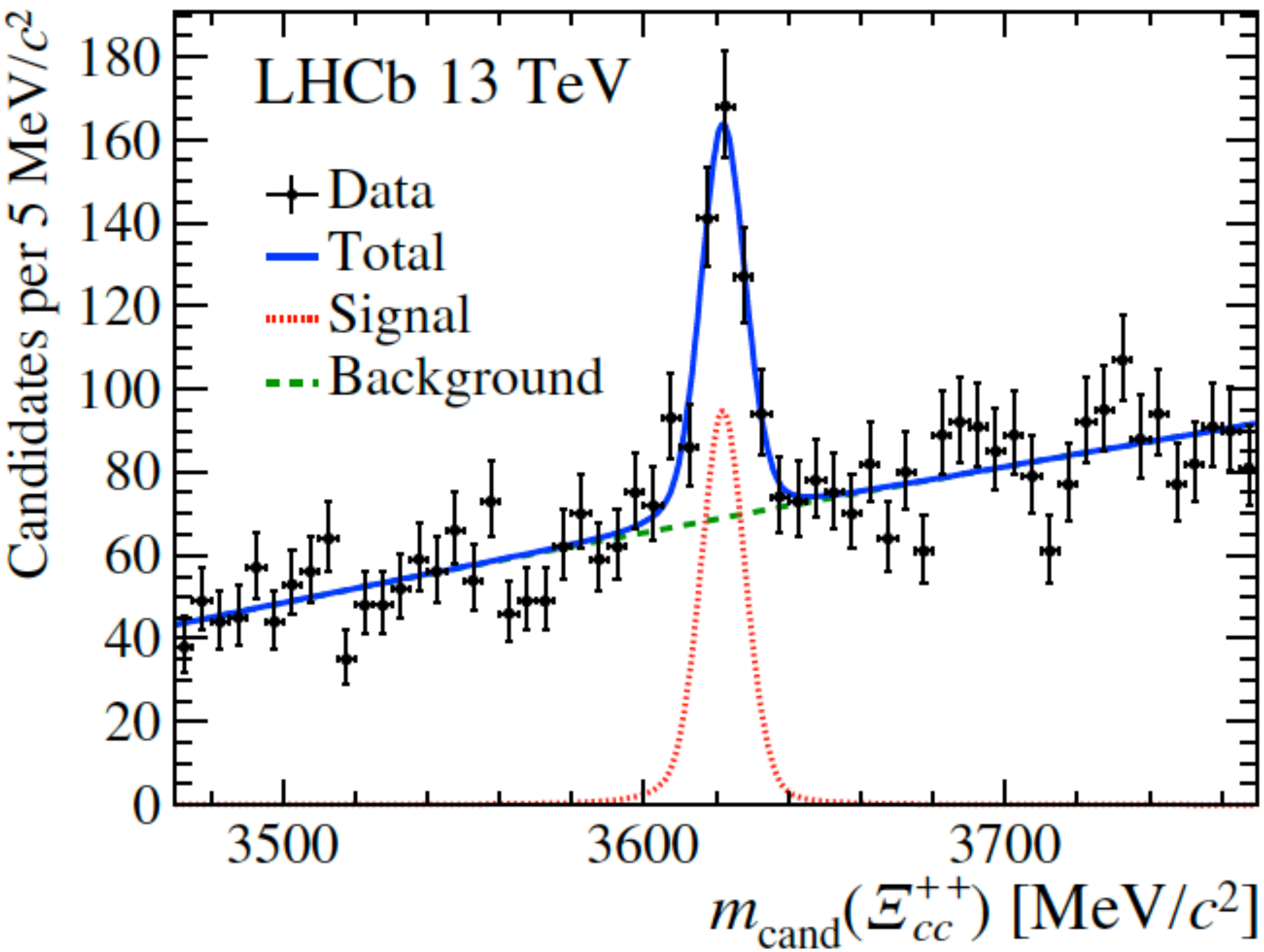
PRL 11 (2017) 180001



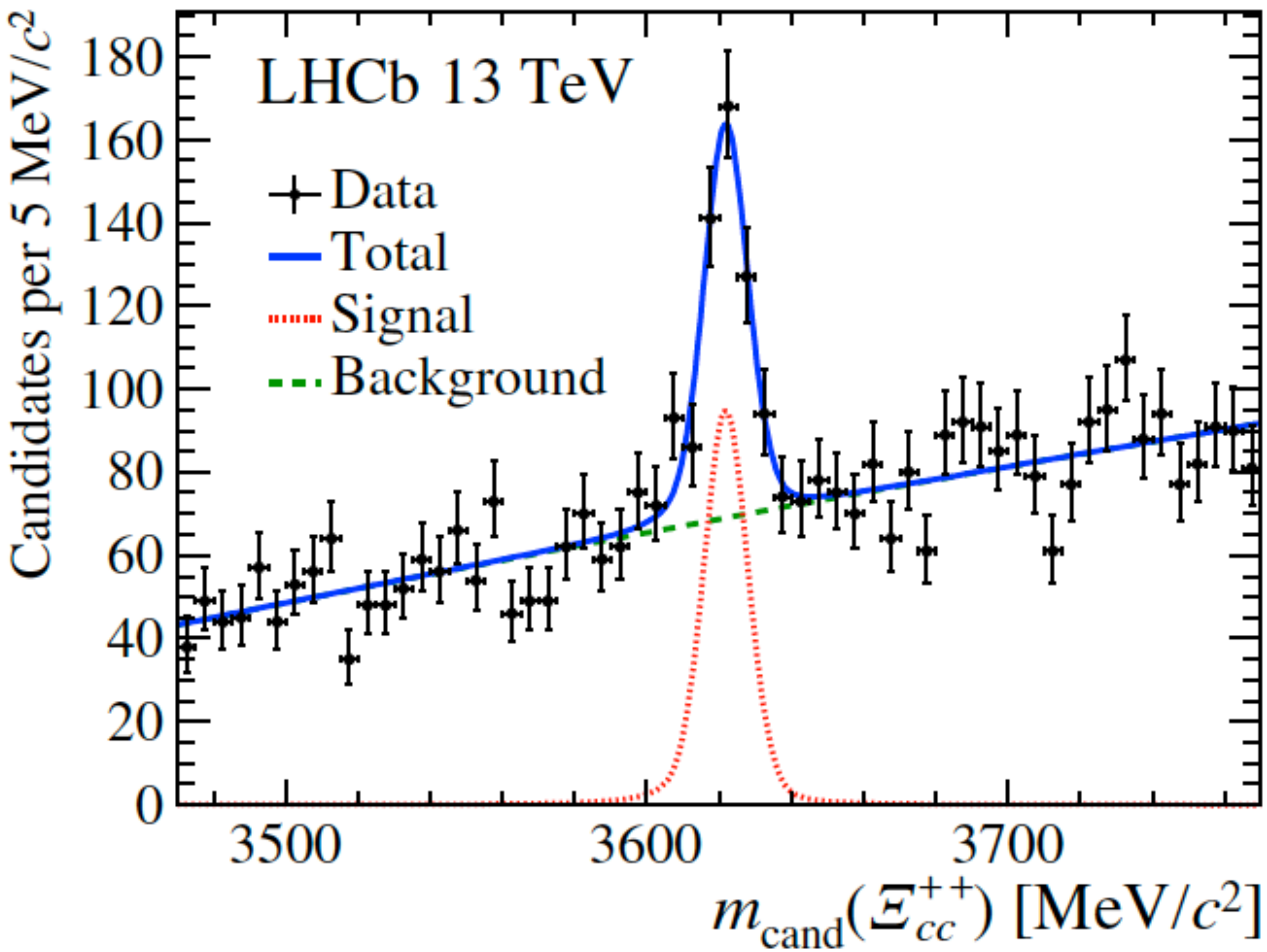
- signal stays strong under decay-time cut: it's a weak decay!
- confirmed with run I data
- follow-up analyses are on their way!

$m(\Xi^{++}_{cc})$ =

3621.40 ± 0.72 (stat) ± 0.21 (syst) ± 0.14 (Λ_c^+) MeV

Ξ^{++}_{cc} observation!

PRL 11 (2017) 180001



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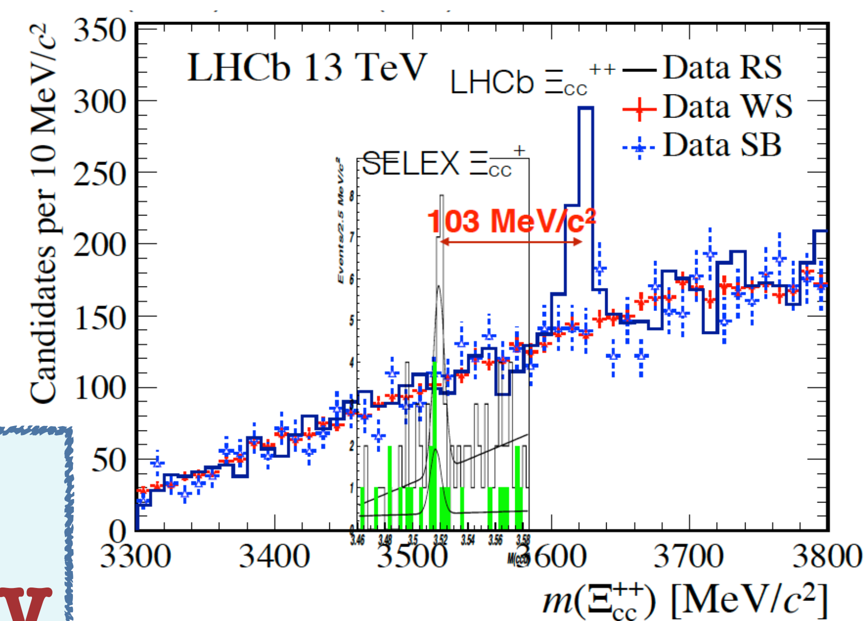
Compared to SELEX "Ξ^{+}_{cc}": 100MeV mass split inconsistent with being isospin partners



$m(\Xi^{++}_{cc})$ =

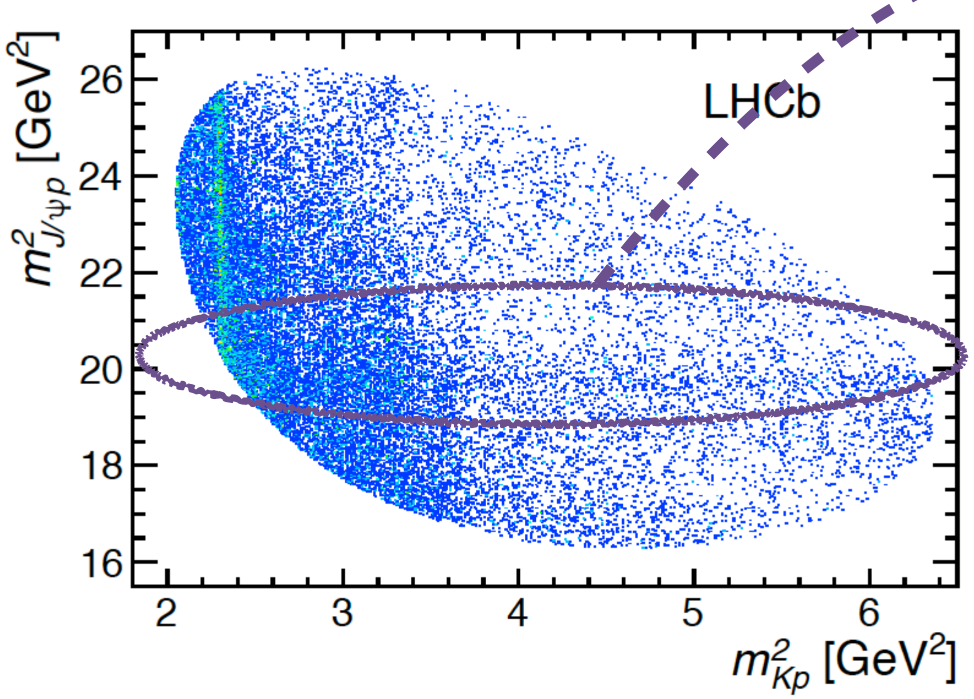
$3621.40 \pm 0.72(stat) \pm 0.21(syst) \pm 0.14(\Lambda_c^+)$ MeV

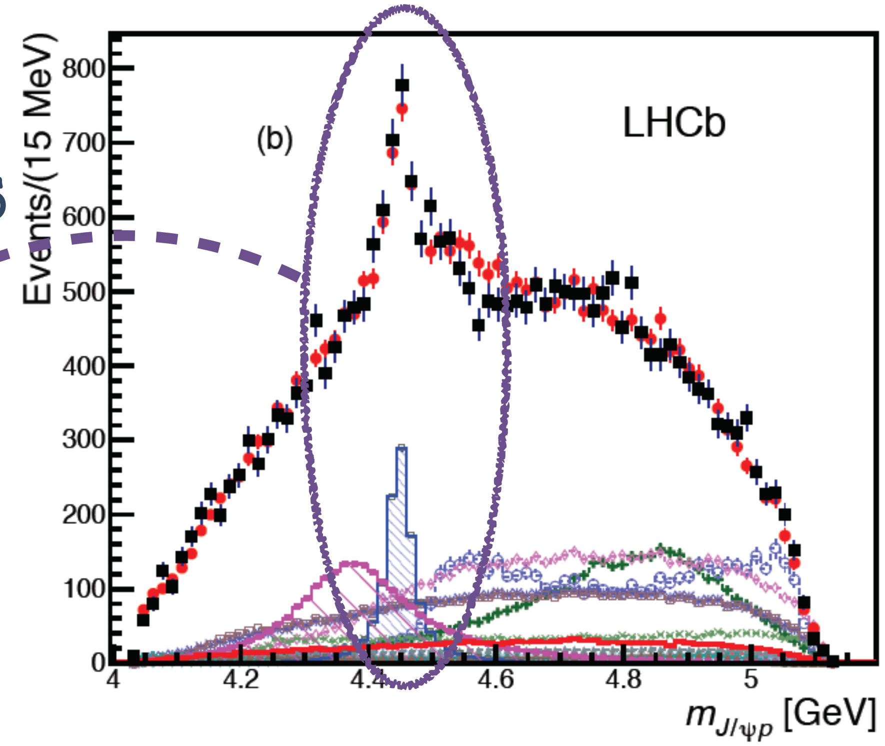
Pentaquarks are out there

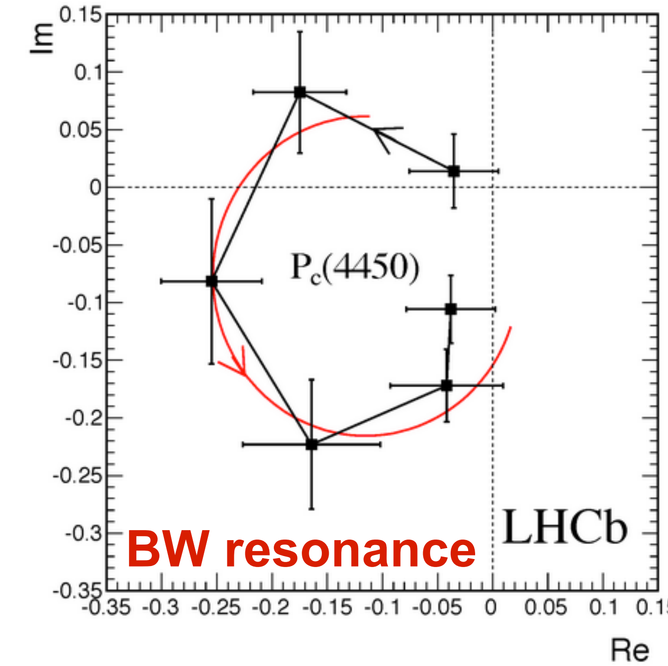
not quite news, still amazing!

- Study of $\Lambda_b^0 \rightarrow J/\psi\, p\, K^-$
- Initial observation of two pentaquark states back in 2015

PRL 115 (2015) 072001







$P_c(4550)^+$ – narrow
$P_c(4380)^+$ – wider
opposite parities

- In a model independent approach, data is inconsistent as being described by Λ^* resonances only
- Search in similar channel, $\Lambda_b^0 \rightarrow J/\psi\, p\, \pi^-$, show evidence for both states at ~3σ

PRL 117 (2016) 082002
PRL 117 (2016) 082003

$c\bar{c}uud$

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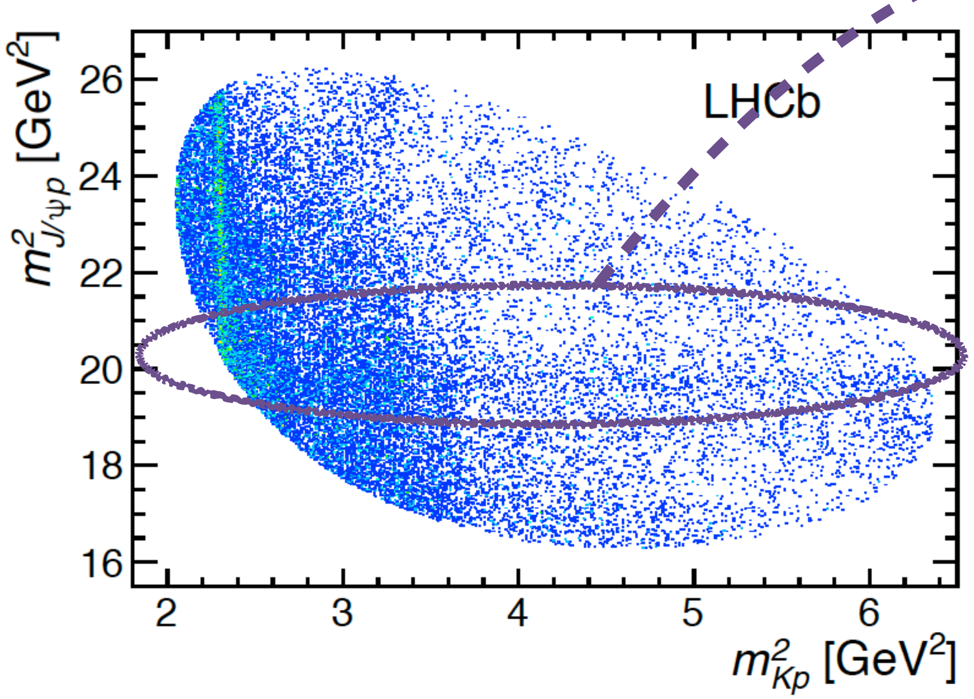

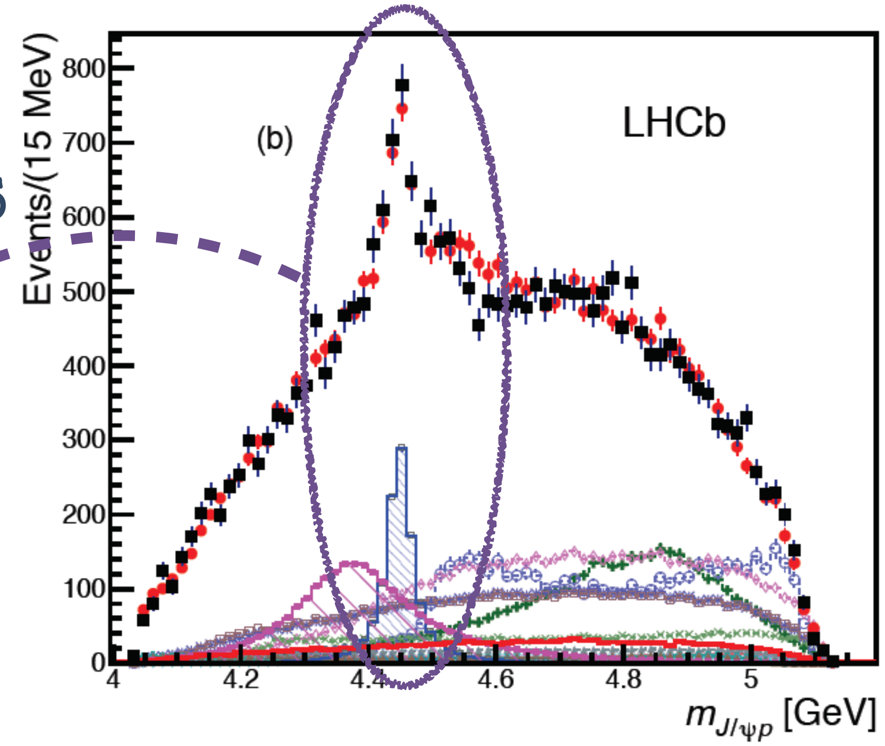

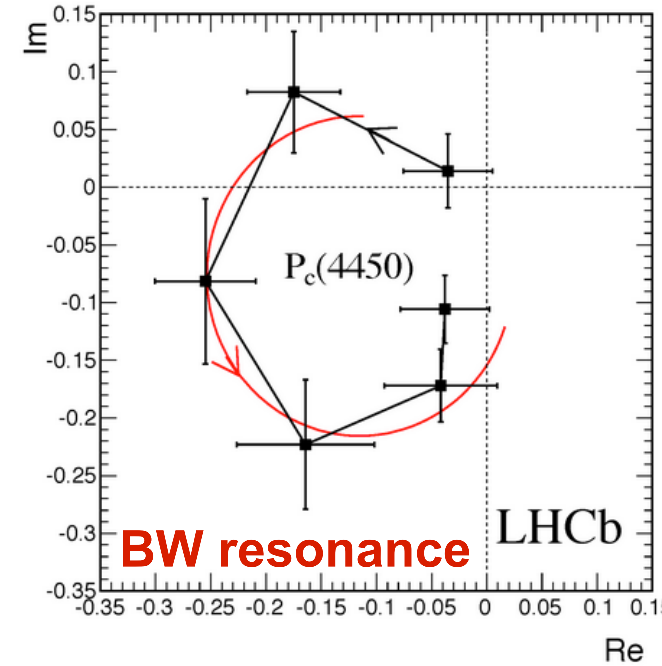

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What's next?

$c\bar{c}uud$

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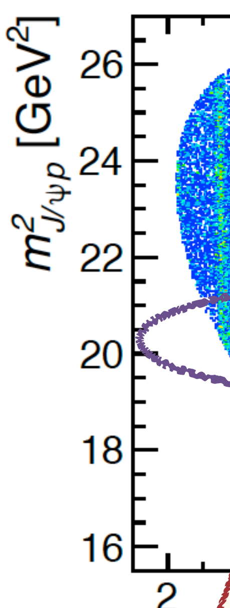

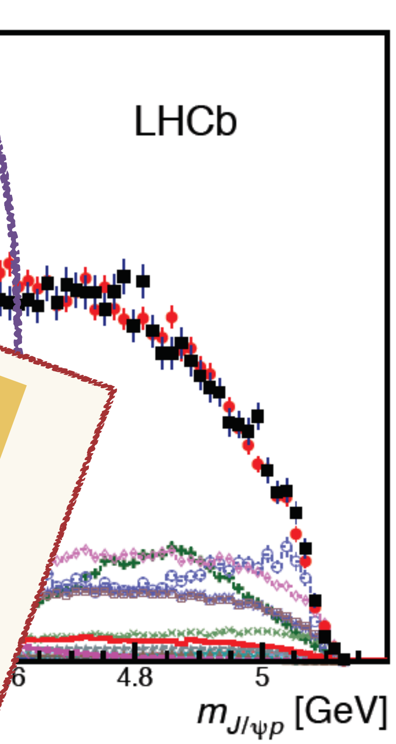

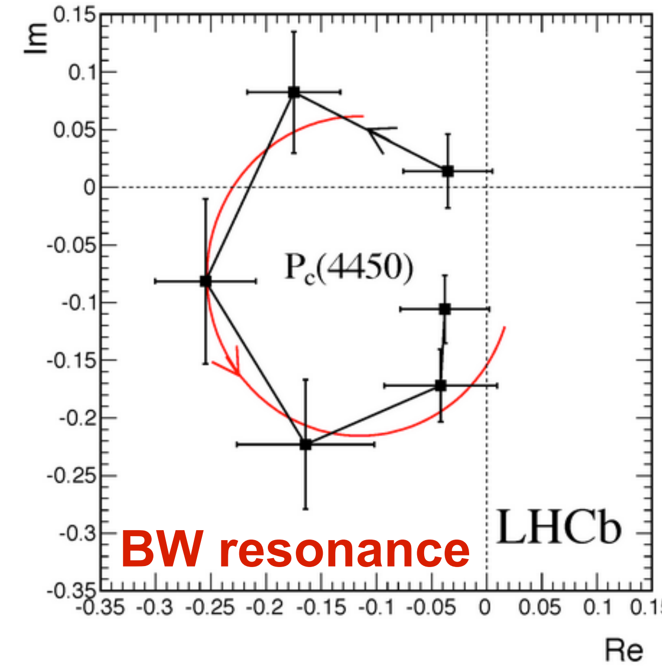

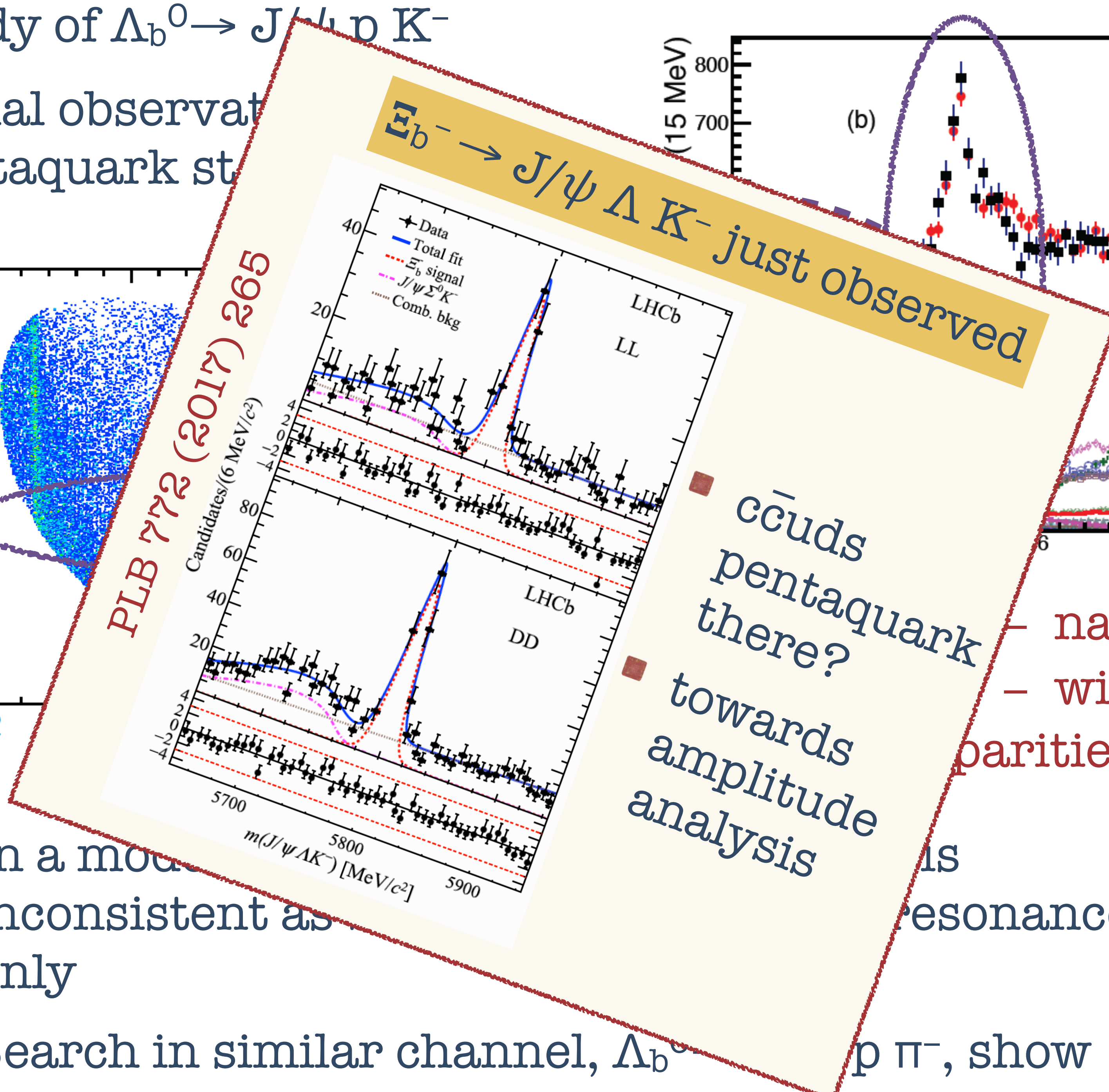

– narrow
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PRL 117 (2016) 082002
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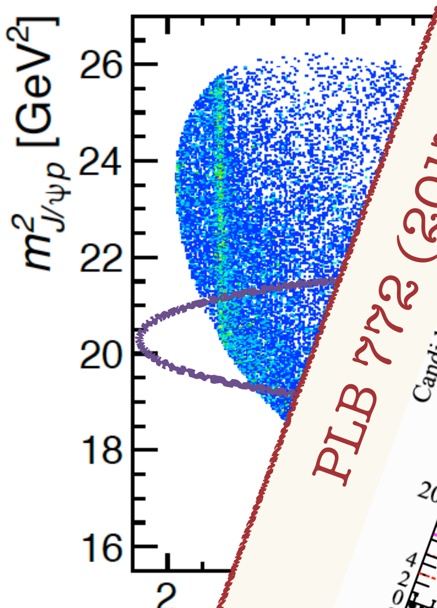
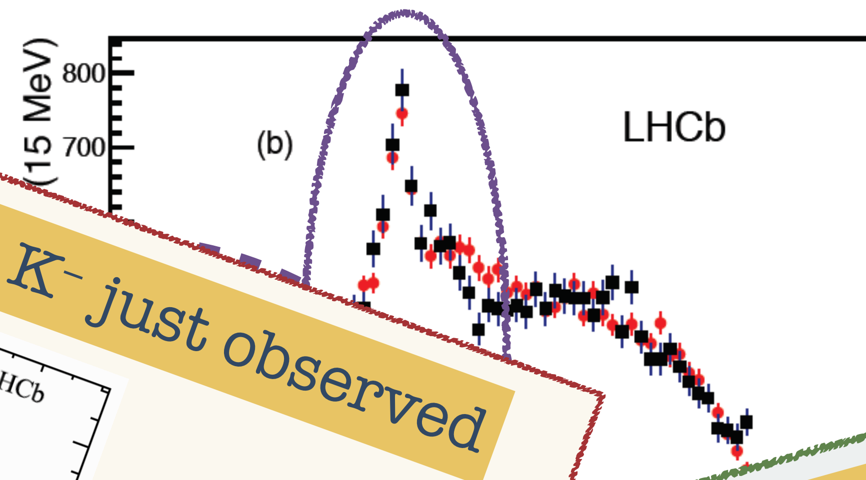
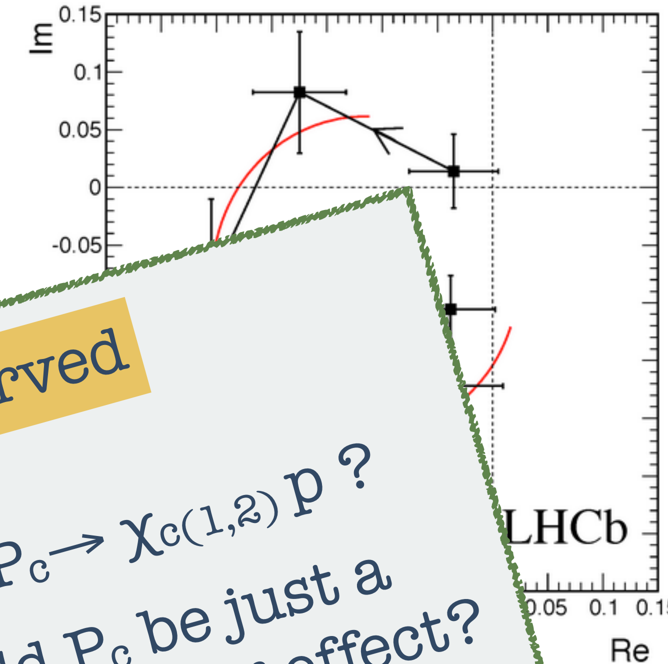
PRL 115 (2015) 072001







- In a mod…
  inconsistent as…
  only
- Search in similar c…
  evidence for both st…

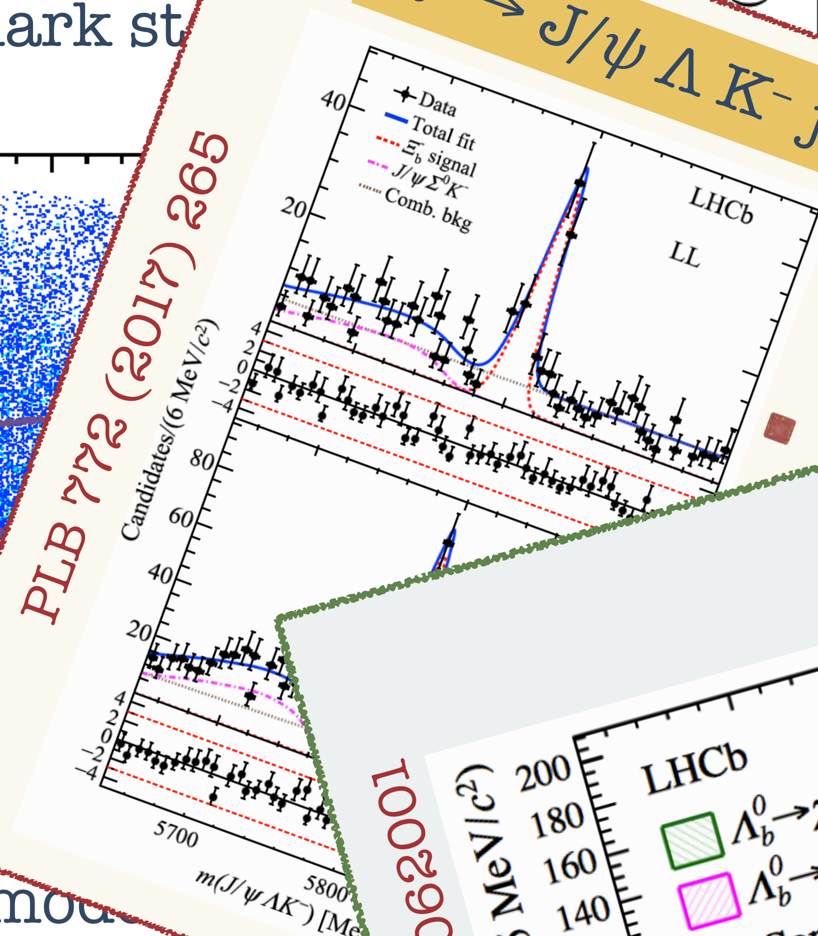
PRL 117 (2016) 082002
PRL 117 (2016) 082003

…ad

…next?

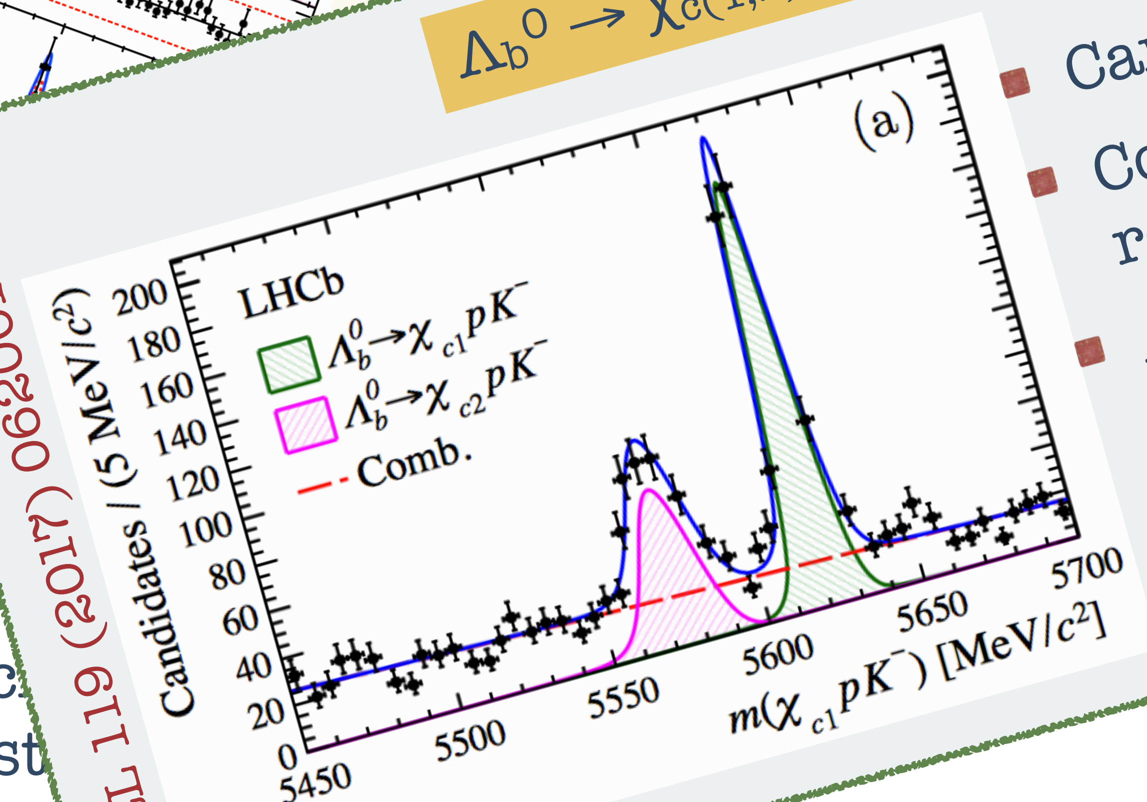
$\Xi_b^- \to J/\psi\, \Lambda\, K^-$ just observed

PLB 772 (2017) 265



$\Lambda_b^0 \to \chi_{c(1,2)}\, pK^-$ just observed

PRL 119 (2017) 062001



- Can $P_c \to \chi_{c(1,2)}\, p$?
- Could P_c be just a rescattering effect?
- Again, amplitude analysis is the next move

Exotic: X → J/ψ φ

- X(4140) first seen by CDF as a narrow state, and then by CMS and D0;

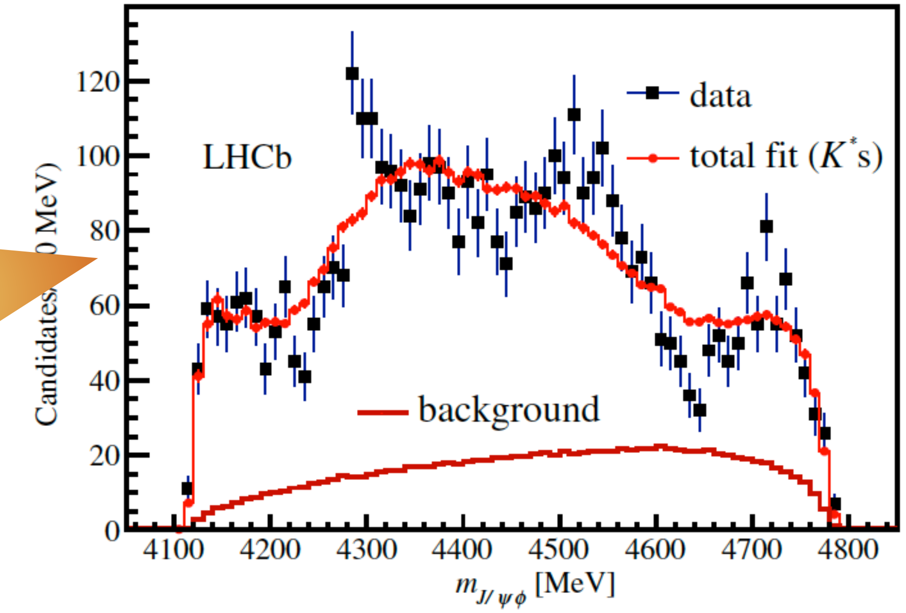
CDF, PRL 102 (2009) 242002, arXiv:1101.6058
CMS, PLB 734 (2014) 261; D0, PRD 89 (2014) 012004

- no evidence from BaBar, Belle, BESIII and LHCb (0.37 fb^{-1})

LHCb studies $B^+ \to J/\psi\, \varphi\, K^+$

- full run I data; 6D amplitude analysis

Data cannot be described by
$K^{*+} \to \varphi\, K^+$ resonances only



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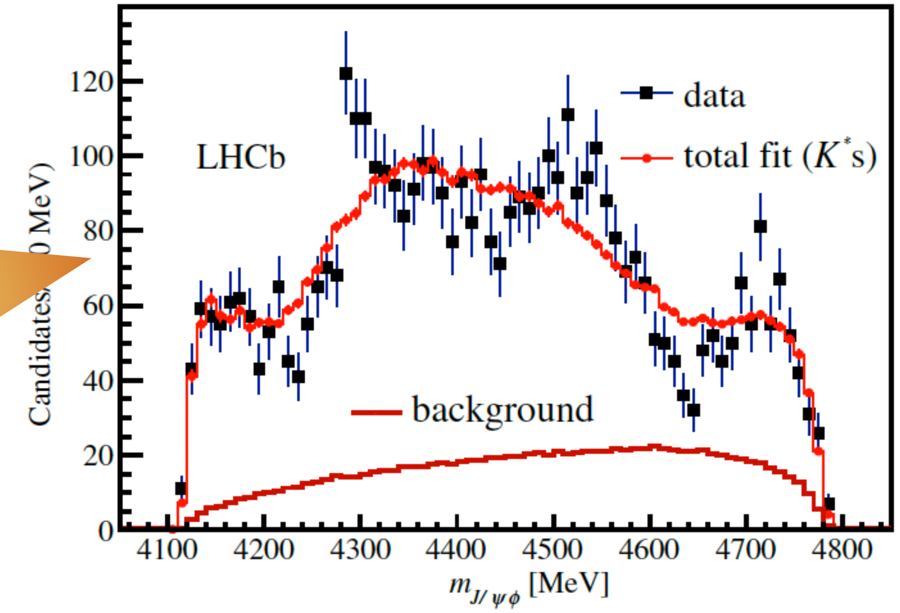

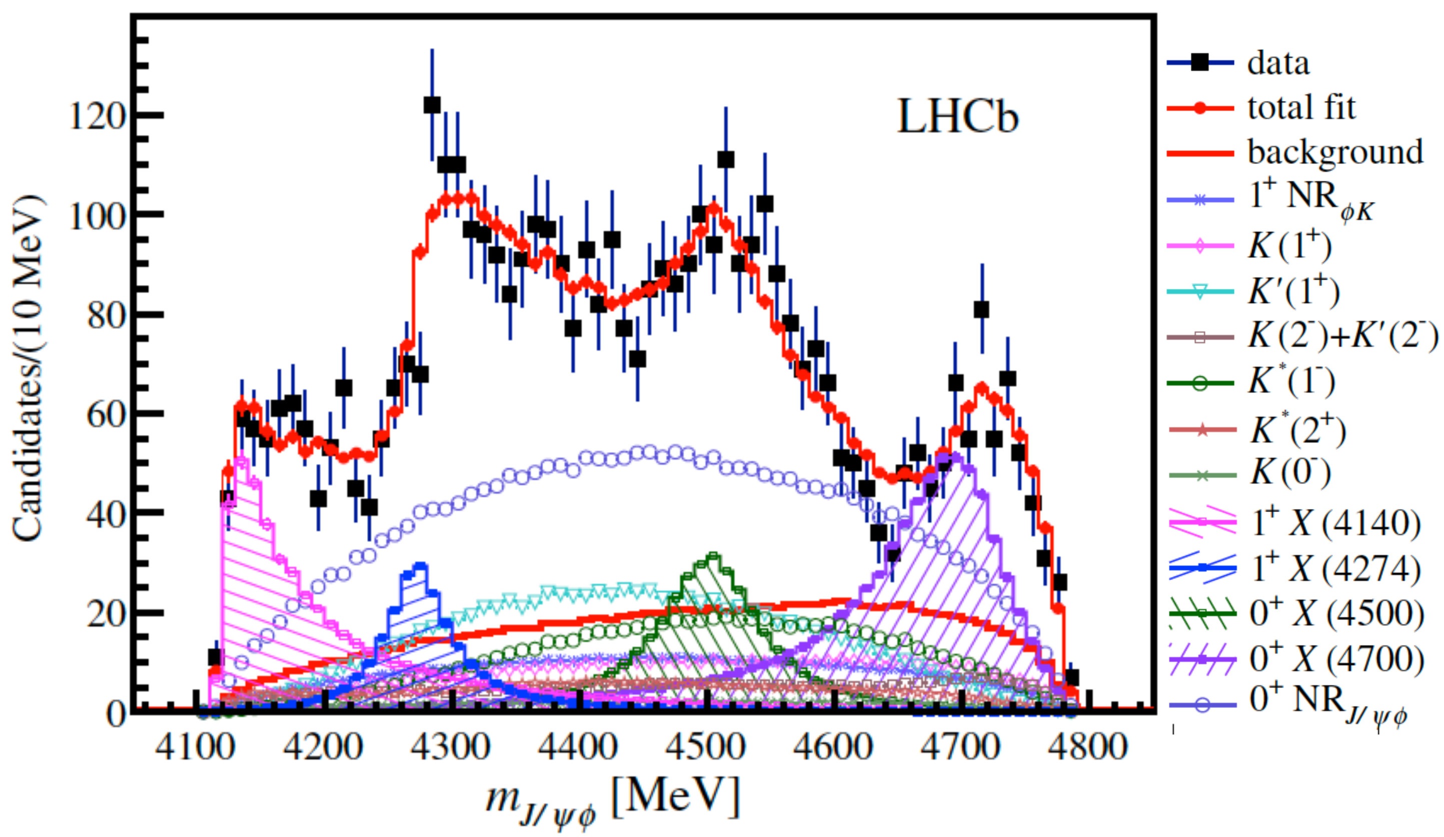

Four exotic states found:

- ☑ **X(4140)** 1^{++}
- ☑ **X(4500)** 0^{++}
- ☑ **X(4274)** 1^{++}
- ☑ **X(4700)** 0^{++}

tetraquarks or $D_s^* D_s^*$ molecules?

X(4140) as a cusp effect ?

Exotic: X → J/ψ φ

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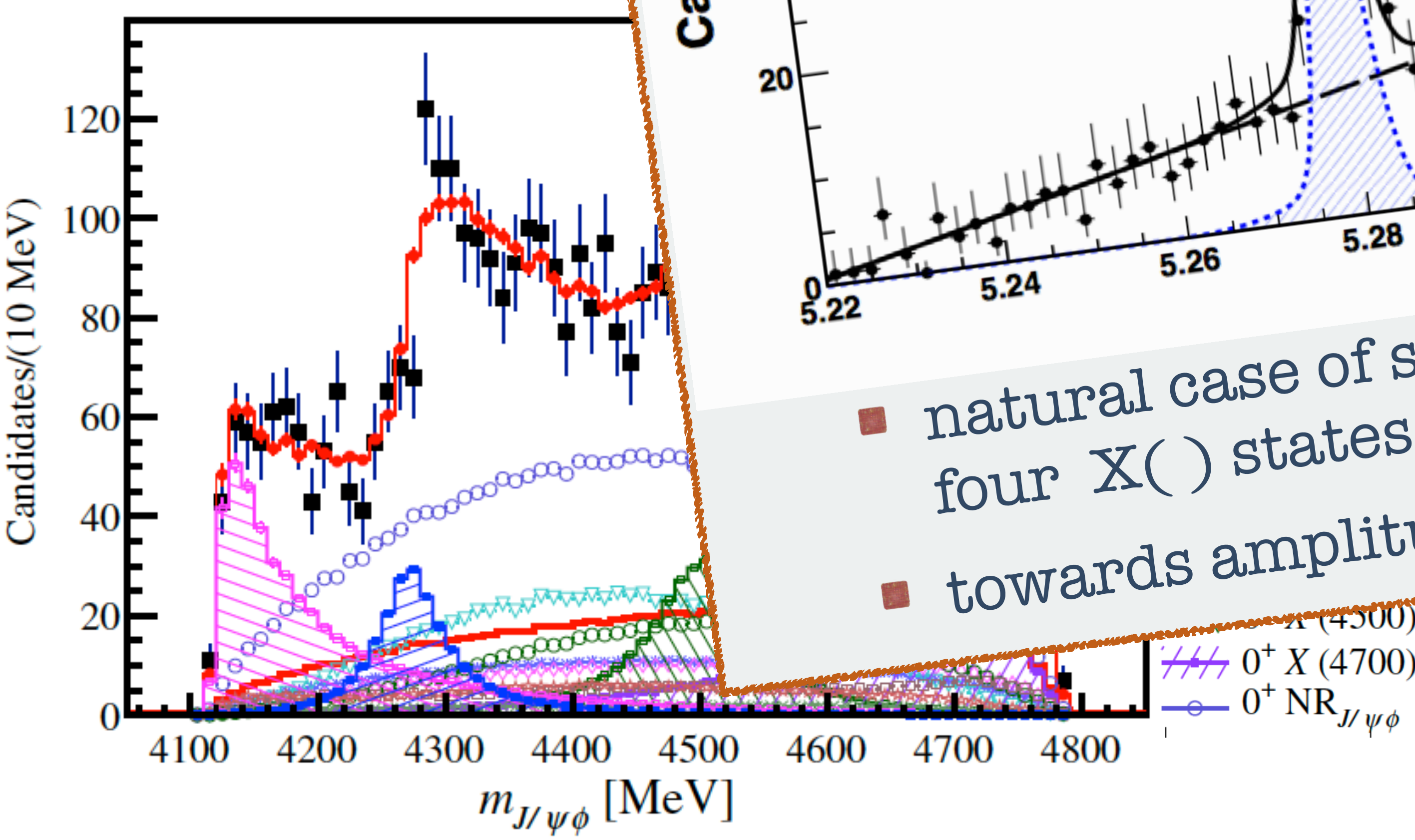
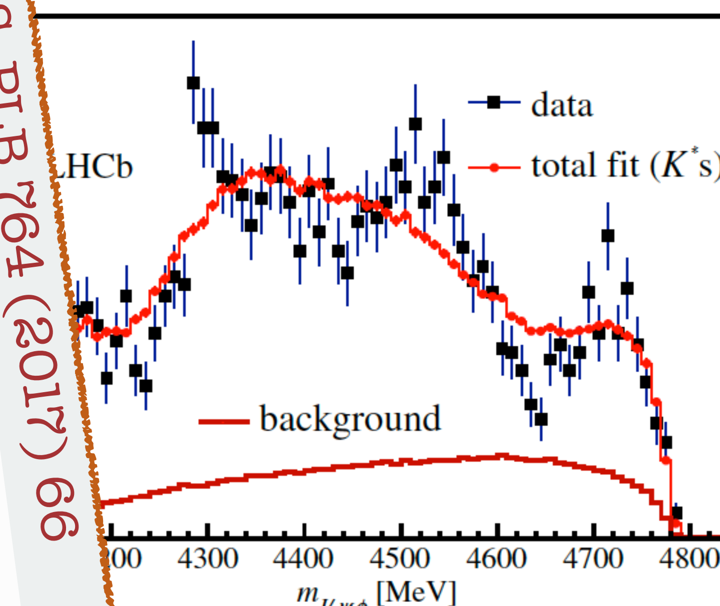
  CDF, PRL 10…) 242002, arXiv:1101.6058
  …) 261; D0, PRD 89 (2014) 012004
- no evidence fro…

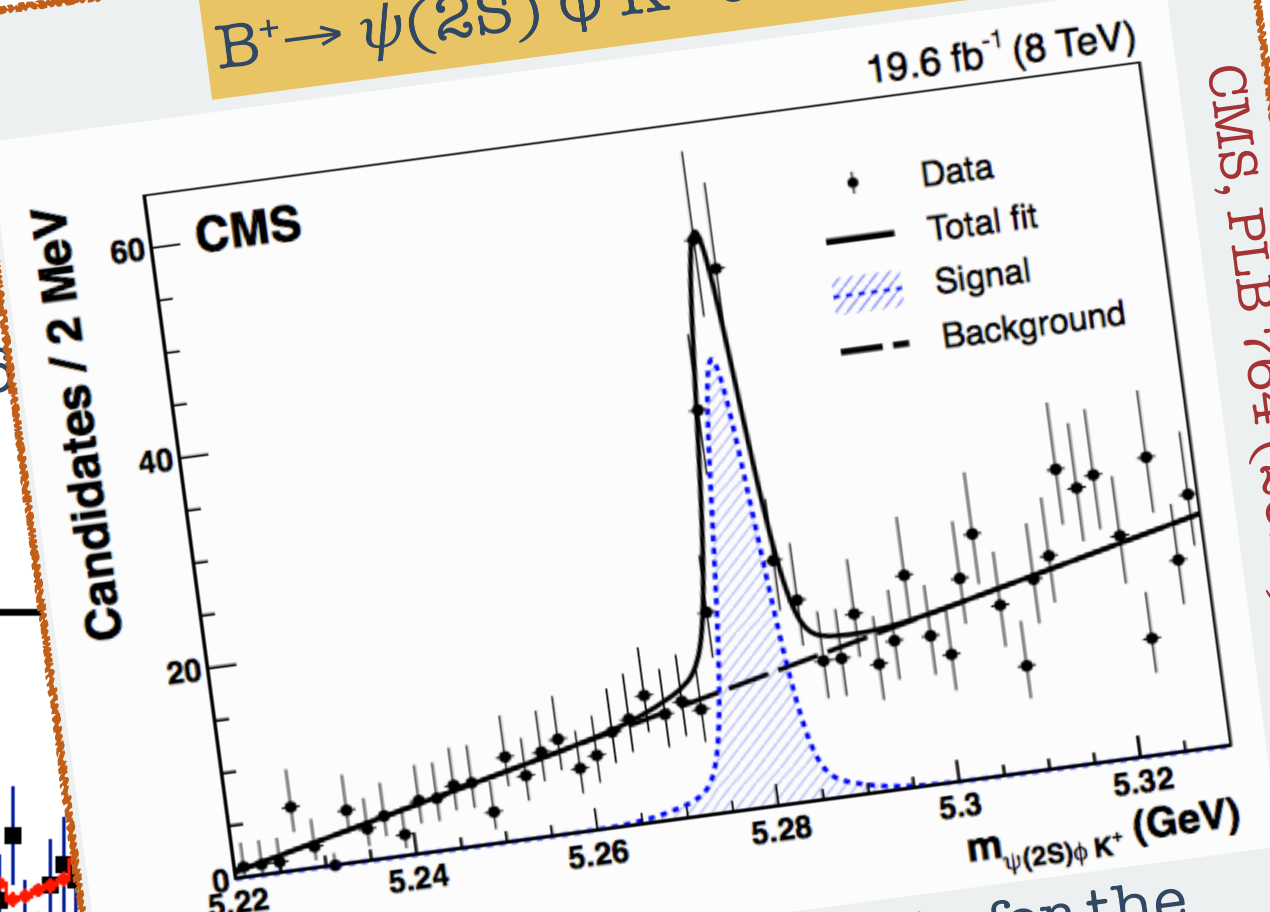
LHCb stud…

- full run I data; 6…





B⁺→ ψ(2S) φ K⁺ observed



CMS, PLB 764 (2017) 66

- natural case of study for the four X( ) states observed
- towards amplitude analysis

… states found:

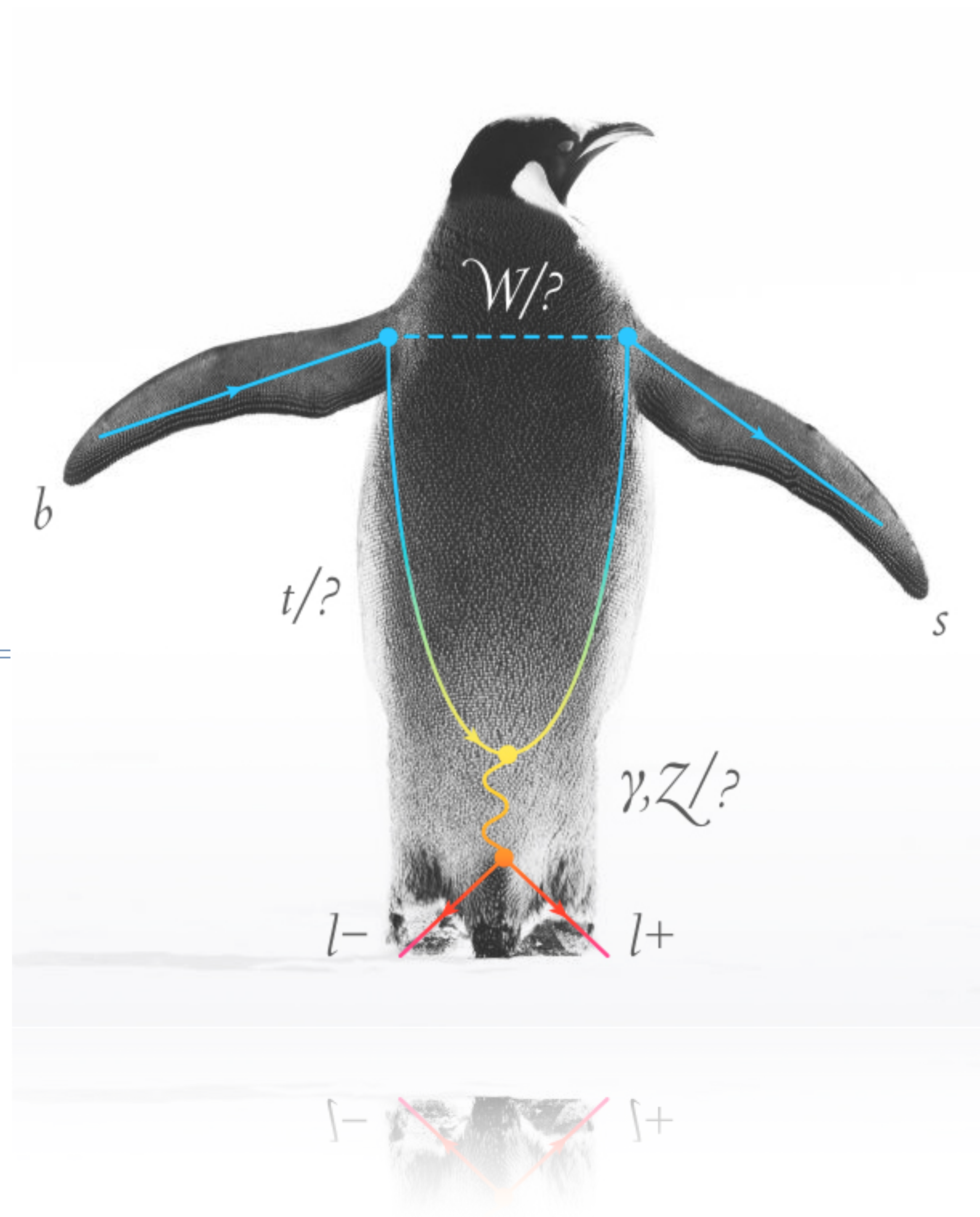
- … 1⁺⁺ ☑ **X(4500)** 0⁺⁺
- … 1⁺⁺ ☑ **X(4700)** 0⁺⁺

tetraquarks or $D_s^* D_s^*$ molecules?

X(4140) as a cusp effect ?

Rare Decays & Lepton Universality

Olena Shmahalo/Quanta Magazine. Source photo: Christopher Michel



Rare decays. Why?

- Rare or forbidden decays within the Standard Model pose ideal environments for the search of New Physics processes

- The b-hadron processes, in particular, access/probe different energy scales!

0.2GeV......	4GeV......	80GeV......	~ 100 TeV ?
Λ_{QCD}	Λ_b	Λ_{EW}	Λ_{NP}
(non-perturbative regime)	(b mass)	(W mass)	(new physics scale)

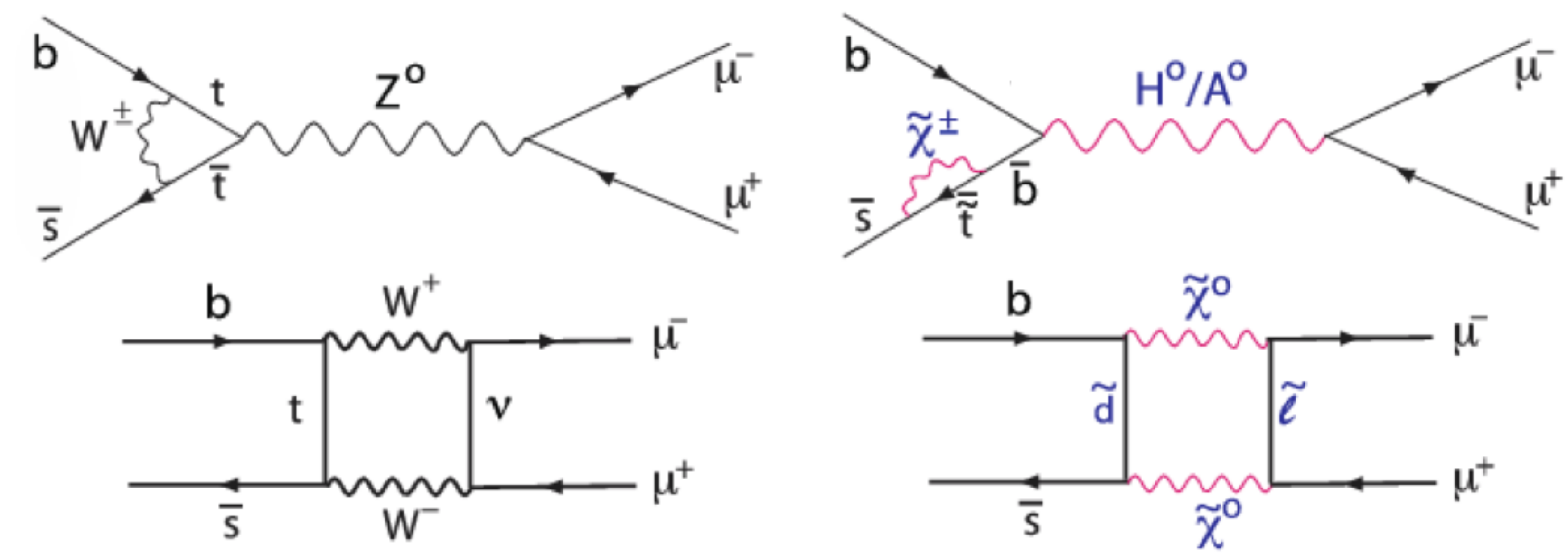
- New particles and/or new interactions could significantly enhance (or decrease) the SM expectations
  - this was the case of $K_L \to \mu^+\mu^-$: its tiny rate led to the prediction of charm through the GIM mechanism

- Not shown here (see backup): news from LHCb
  - new limits on $K_S \to \mu^+\mu^-$ and $B_{(s)} \to \tau^+\tau^-$
  - 1st observation of $D^0 \to \pi\pi\mu\mu$ and $D^0 \to KK\mu\mu$

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

- very rare in the SM:
  - GIM, loop and helicity suppressed
- effects of NP could enhance rate considerably

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



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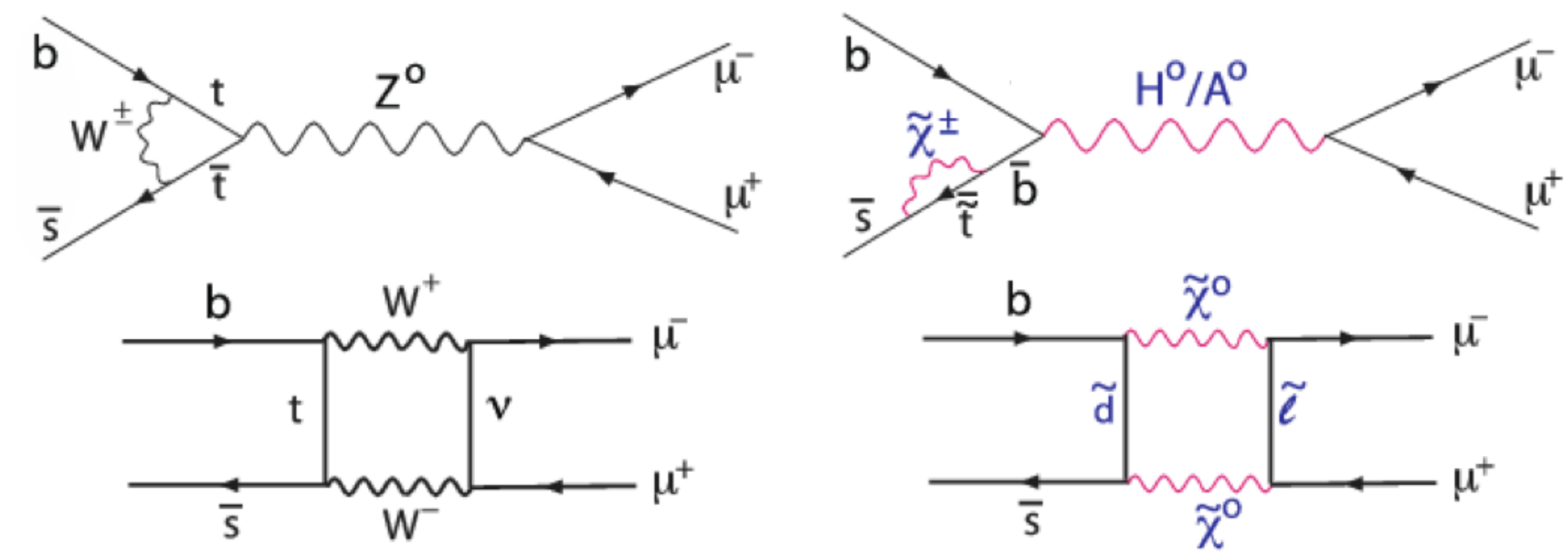
  - GIM, loop and helicity suppressed
- effects of NP could enhance rate conside-rably



- 1st observation from a combined analysis of CMS and LHCb, full run I data:

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

CMS & LHCb, Nature 522 (2015) 68

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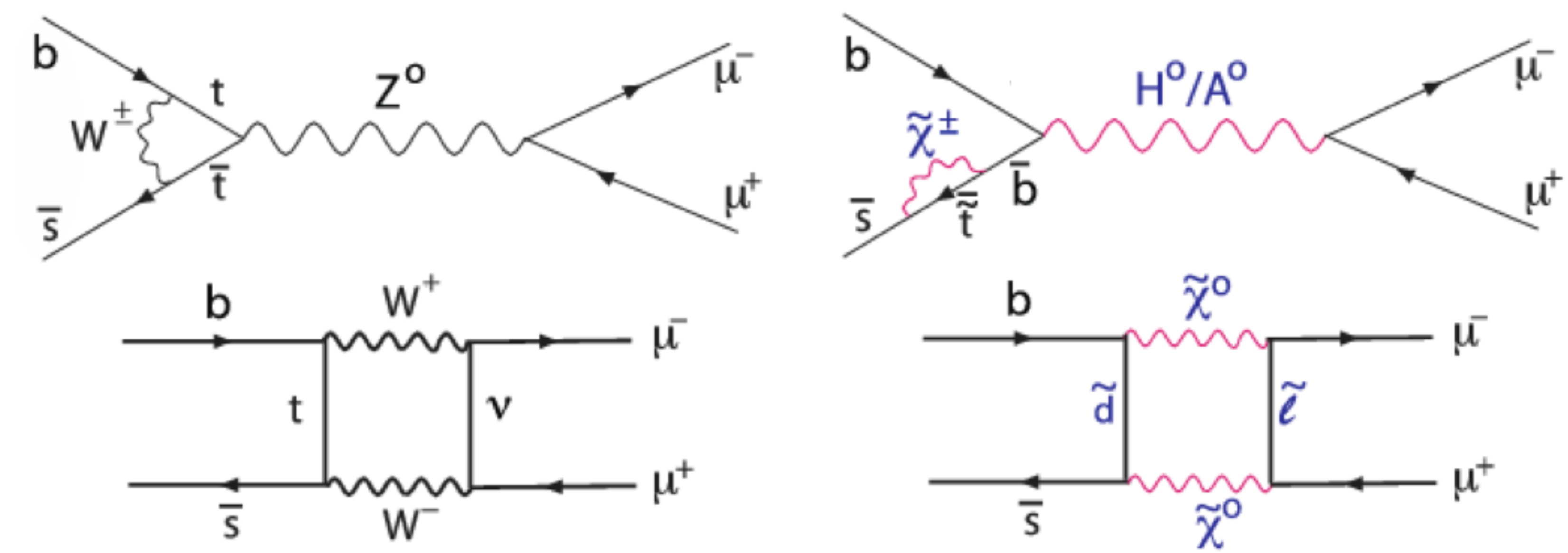

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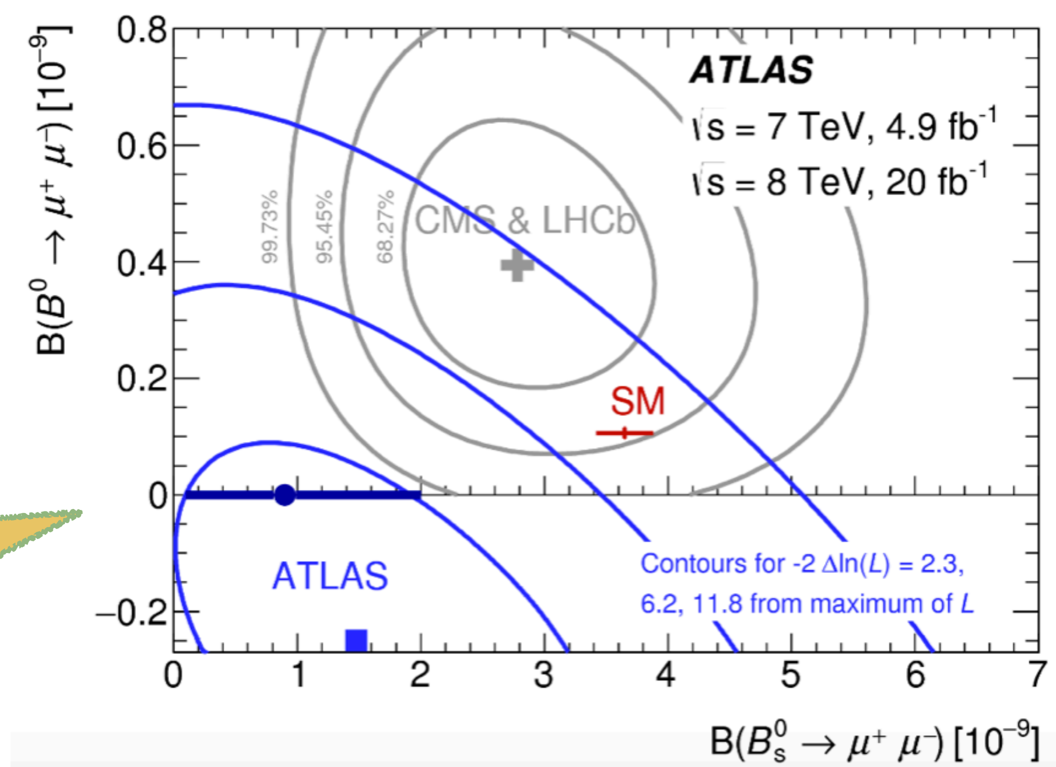
- ATLAS recently joined the game

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ (95\%CL)}$$



CMS & LHCb, Nature 522 (2015) 68

EPJC 76 (2016) 513

$B_{(s)} \to \mu^+ \mu^-$: LHCb run I+II

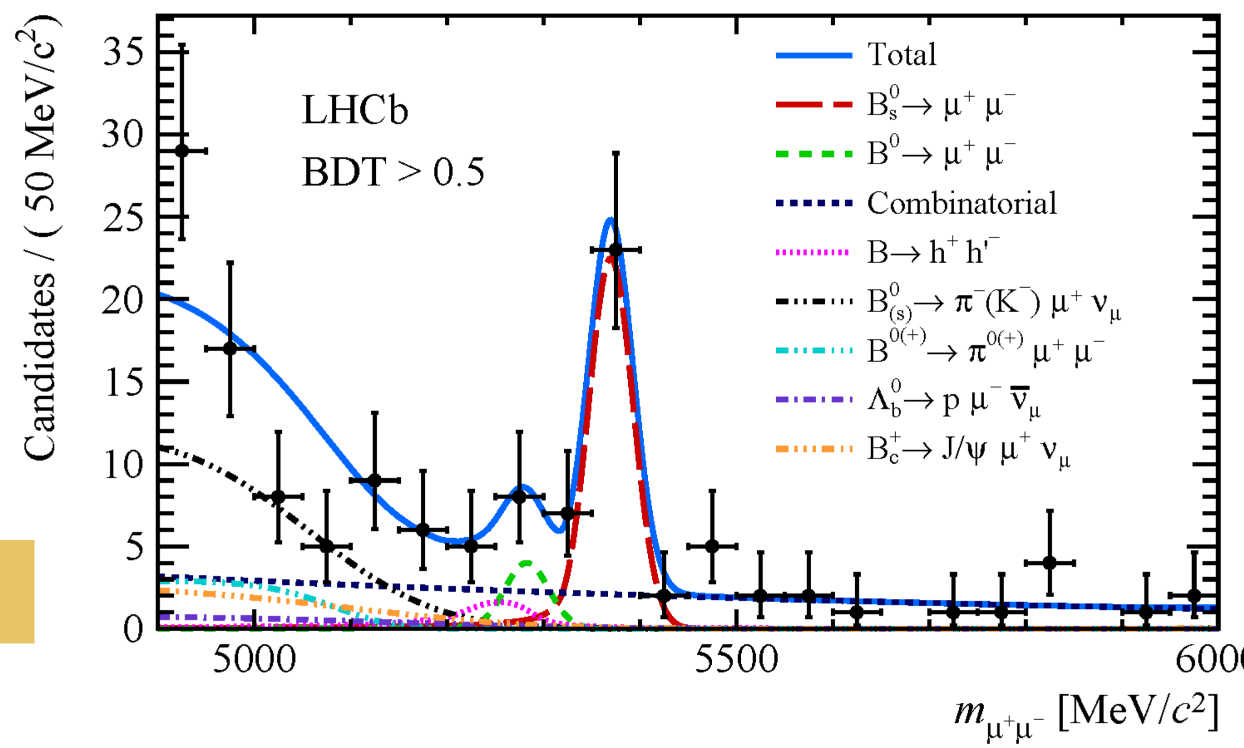
- New LHCb measurement includes 3.0fb^{-1} (run I) + 1.4 fb^{-1} (run II)

PRL 118 (2017) 191801

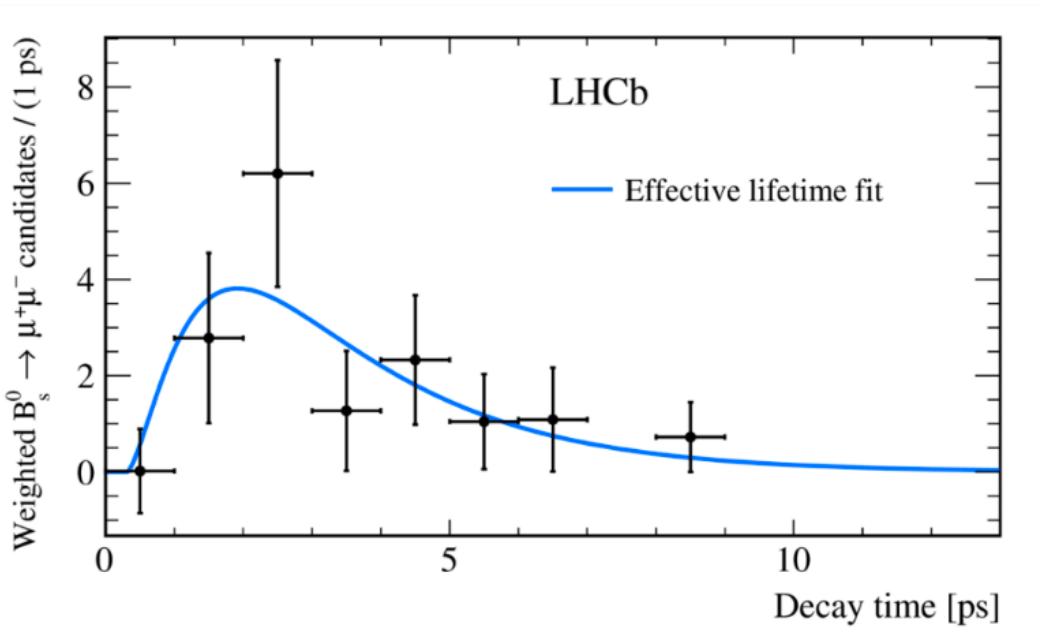
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

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

7.8σ observation from a single experiment



- First measurement of effective lifetime:



- In the SM, only the heavy-mass B_s eigenstate decays to μμ

$$\tau(B_s^0 \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\ \text{ps}$$

- Precision not yet sufficient for probing NP, but open path for future measurements

$B_{(s)} \to \mu^+\mu^-$: LHCb run I+II

- New LHCb measurement includes $3.0\,\text{fb}^{-1}$ (run I) + $1.4\,\text{fb}^{-1}$ (run II)

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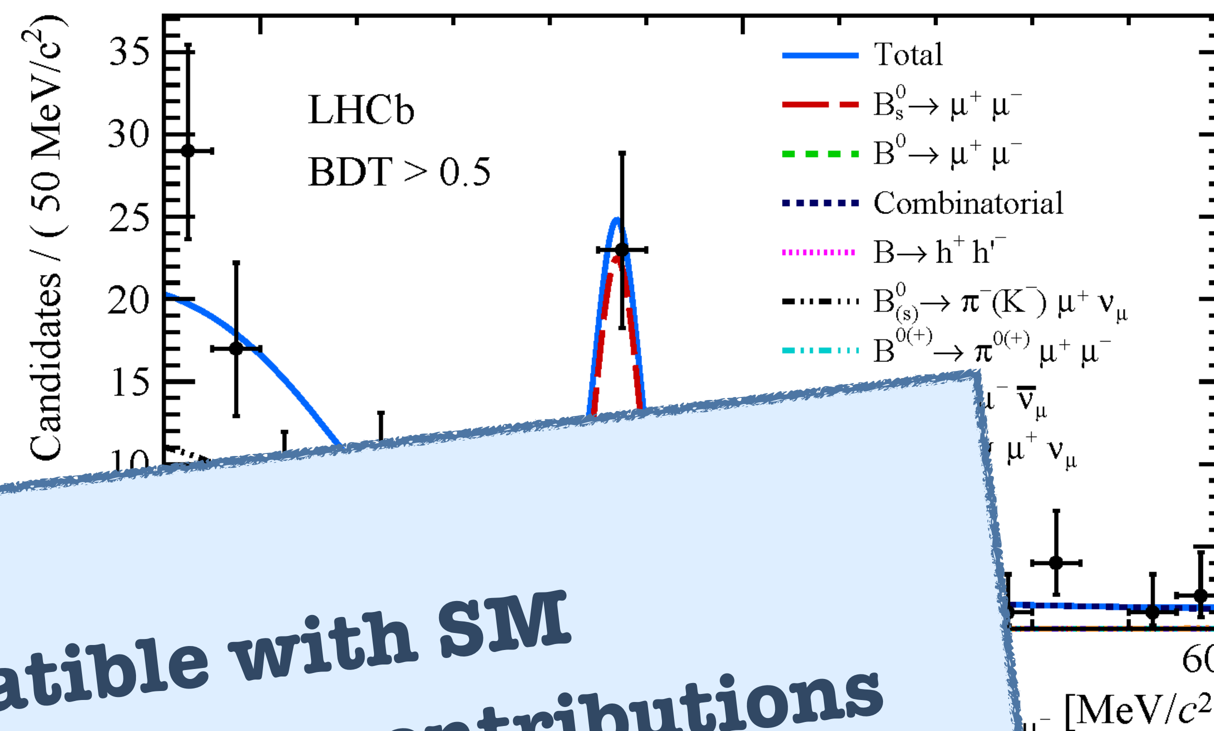


PRL 118 (2017) 191801

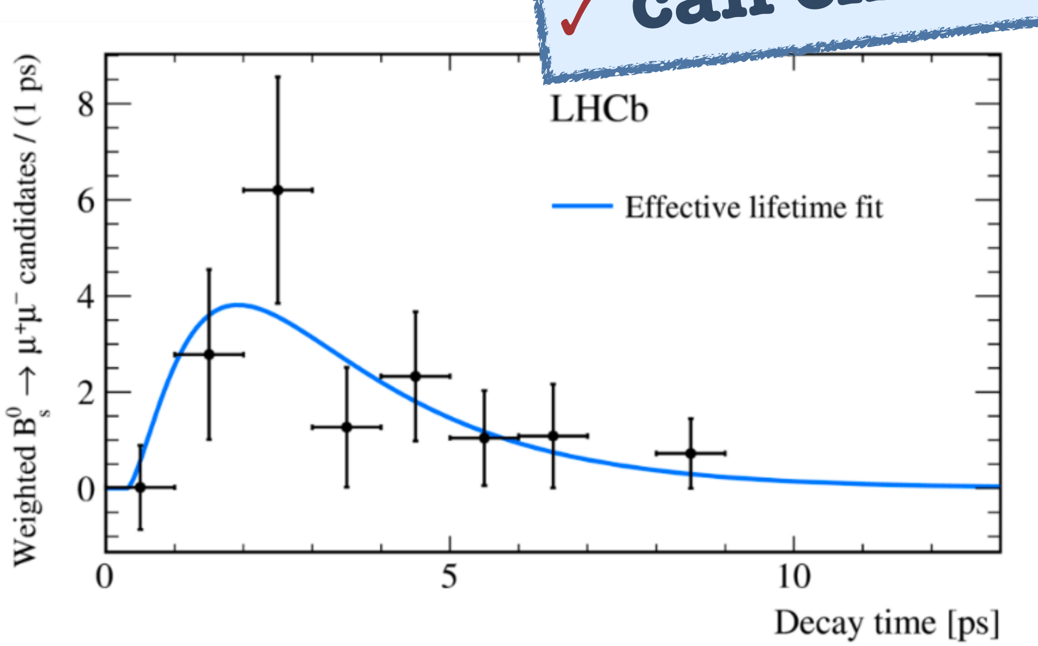
7.8σ observation f

So far:

✓ **all results compatible with SM**

✓ **can exclude large scalar contributions**

- First mea…



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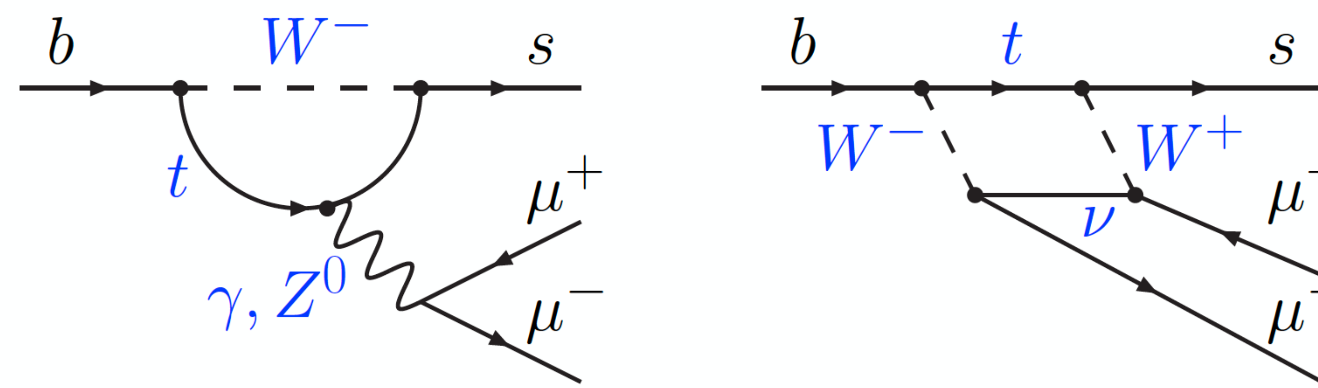
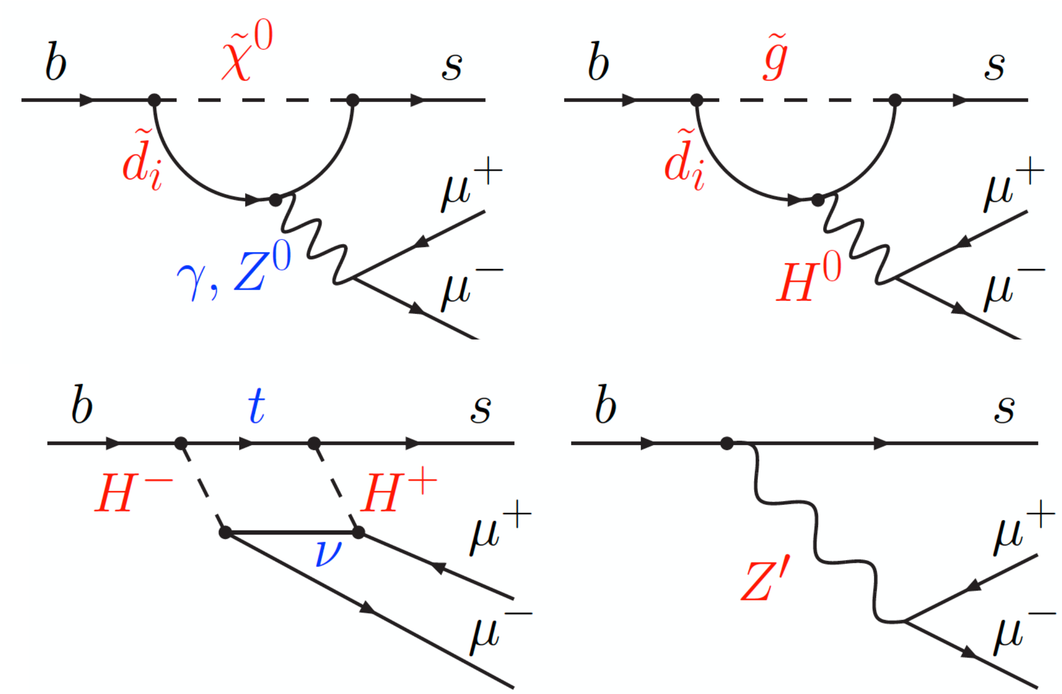
$b \to s\, \ell^+ \ell^-$ processes

- rare decays, occurring through effective FCNC at the SM



- NP processes via new particles in loops or new interactions

- theoretical description through effective Hamiltonian:



$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i [\underbrace{C_i(\mu)\mathcal{O}_i(\mu)}_{\text{Left-handed part}} + \underbrace{C_i'(\mu)\mathcal{O}_i'(\mu)}_{\text{Right-handed part}}]$$

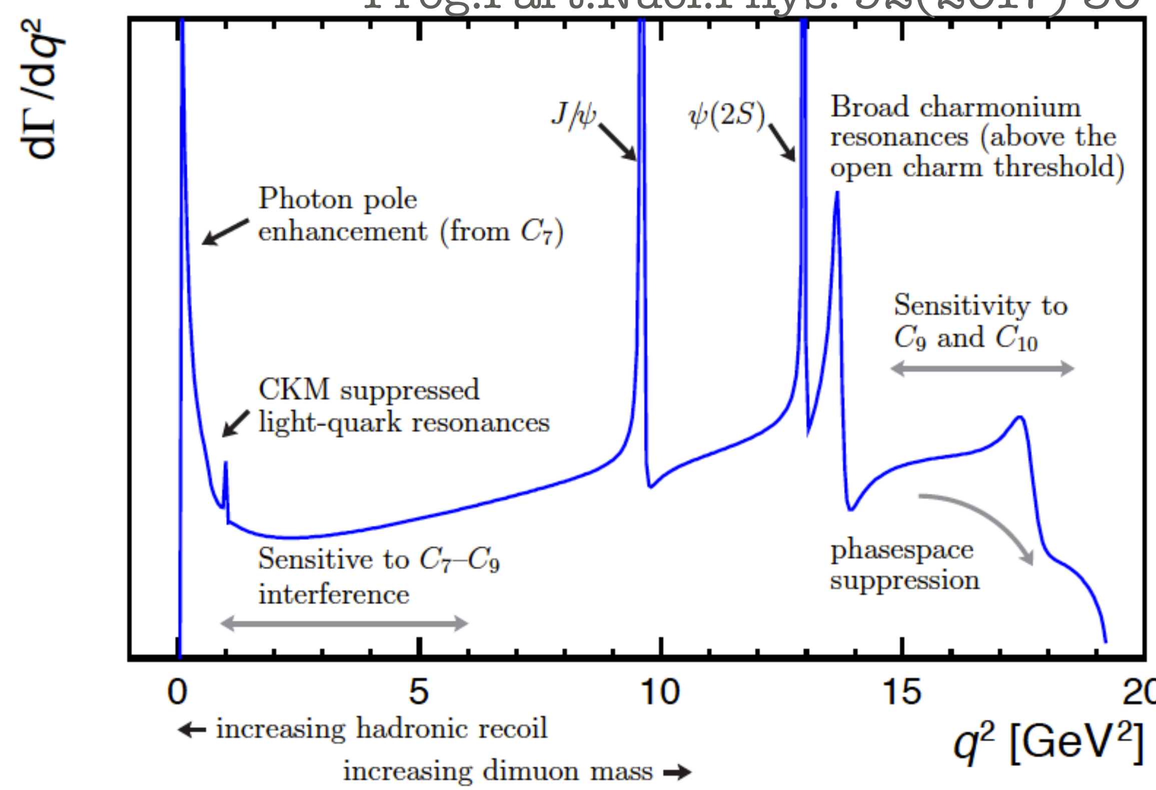
➡ Wilson coefficients C_i : short distance effects, sensitive to NP

➡ Operators $\mathcal{O}_i$: effective 4-fermion interactions

$b \to s \ell^+ \ell^-$ processes

Blake, Lanfranchi, Straub, Prog.Part.Nucl.Phys. 92(2017) 50

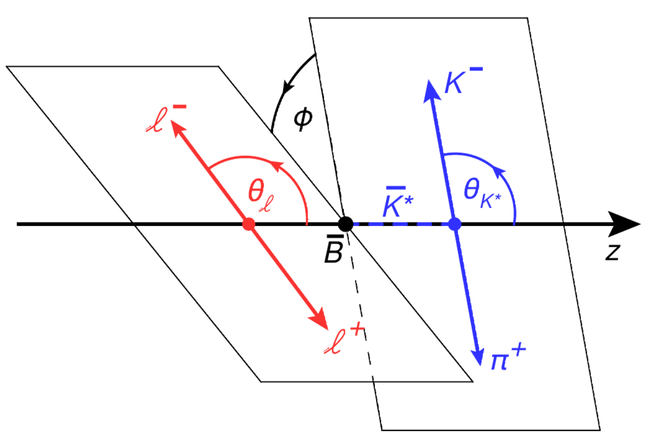
- Measurement of differential branching fractions $d\Gamma/dq^2$
  - SM predictions suffer from hadronic uncertainties
  - regions of q^2 sensitive to different processes



- many decays to be studied:
  $B^{0(+)} \to K^{(*)0(+)} \mu^+\mu^-$, $B_s \to \varphi\, \mu^+\mu^-$, $B^+ \to \pi^+ \mu^+\mu^-$, $\Lambda_b \to \Lambda\, \mu^+\mu^-$, …

- Angular Analysis (eg $\mathbf{B^0 \to K^{*0} \mu^+\mu^-}$) with many observables sensitive to NP

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



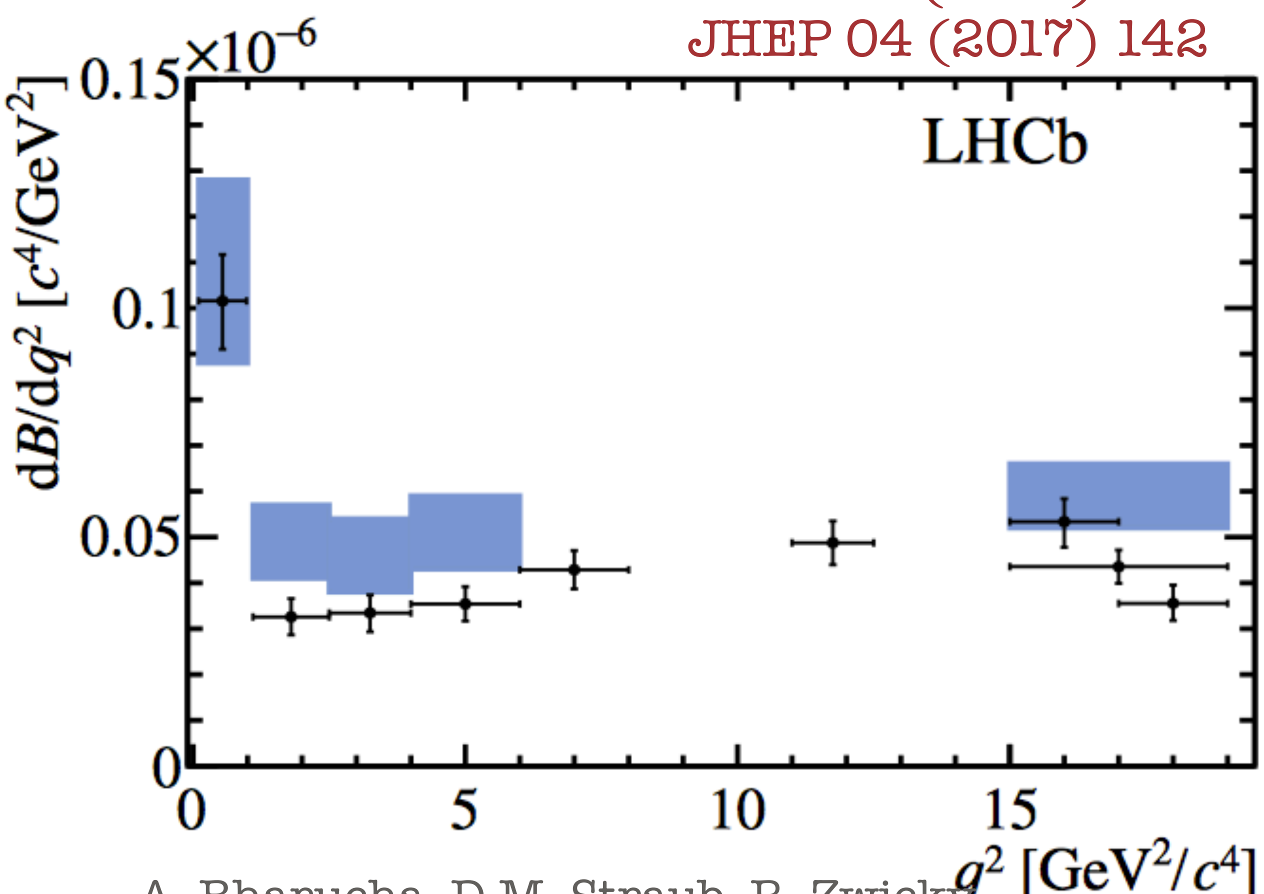
- F_L, A_{FB}, S_i → functions of Wilson coefficients and sensitive to NP
- to reduce hadronic uncertainties, redefine: (among others)

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

$B^0 \to K^{0*}\mu^+\mu^-$ dBR/dq^2

LHCb run I analysis, 3fb^{-1}

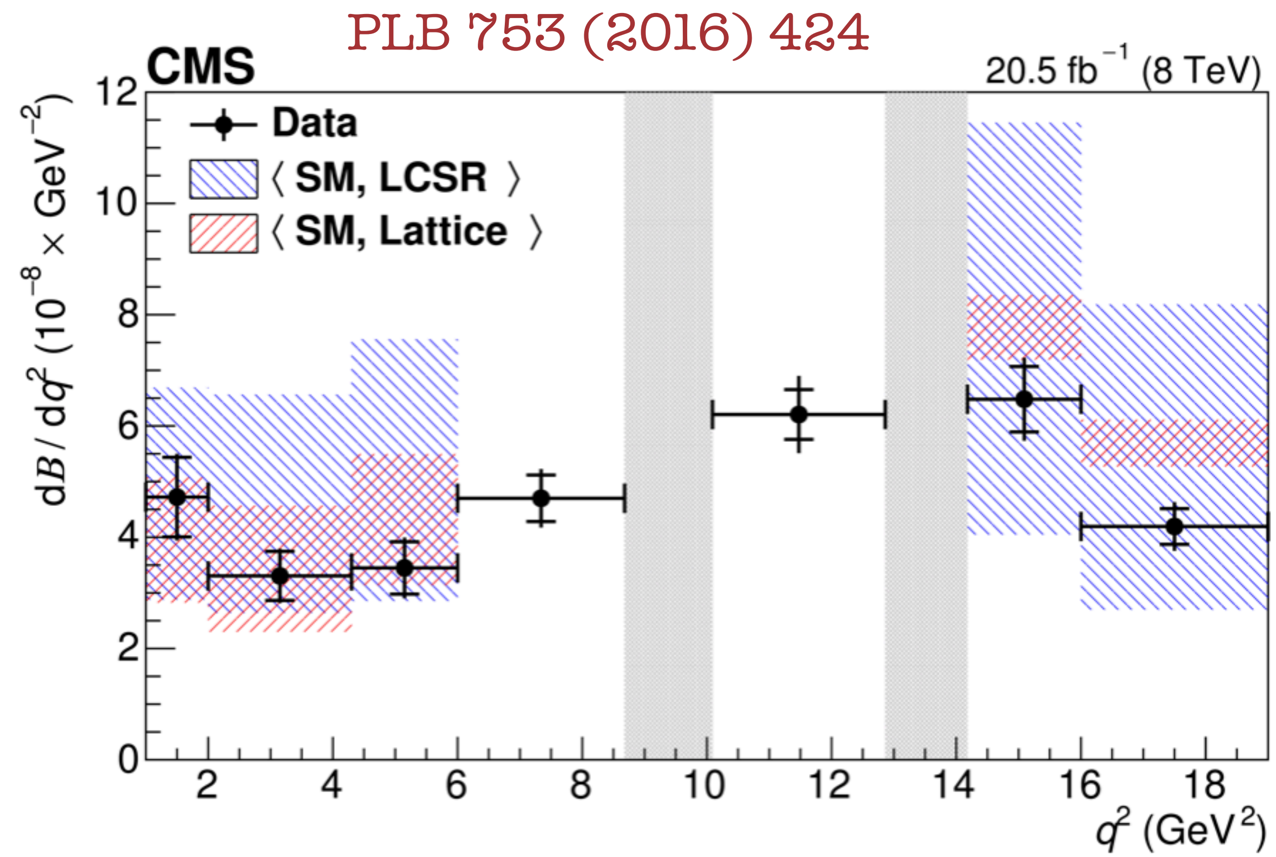
JHEP 11 (2016) 047
JHEP 04 (2017) 142



A. Bharucha, D.M. Straub, R. Zwicky, JHEP 08 (2016) 098
R.R. Horgan et al, PRD 89 (2014)094501

CMS, 8 TeV, 20.5 fb^{-1}

PLB 753 (2016) 424



C. Bobeth, G. Hiller, D. van Dyk, JHEP 07 (2010) 098, PRD87 (2012) 034016

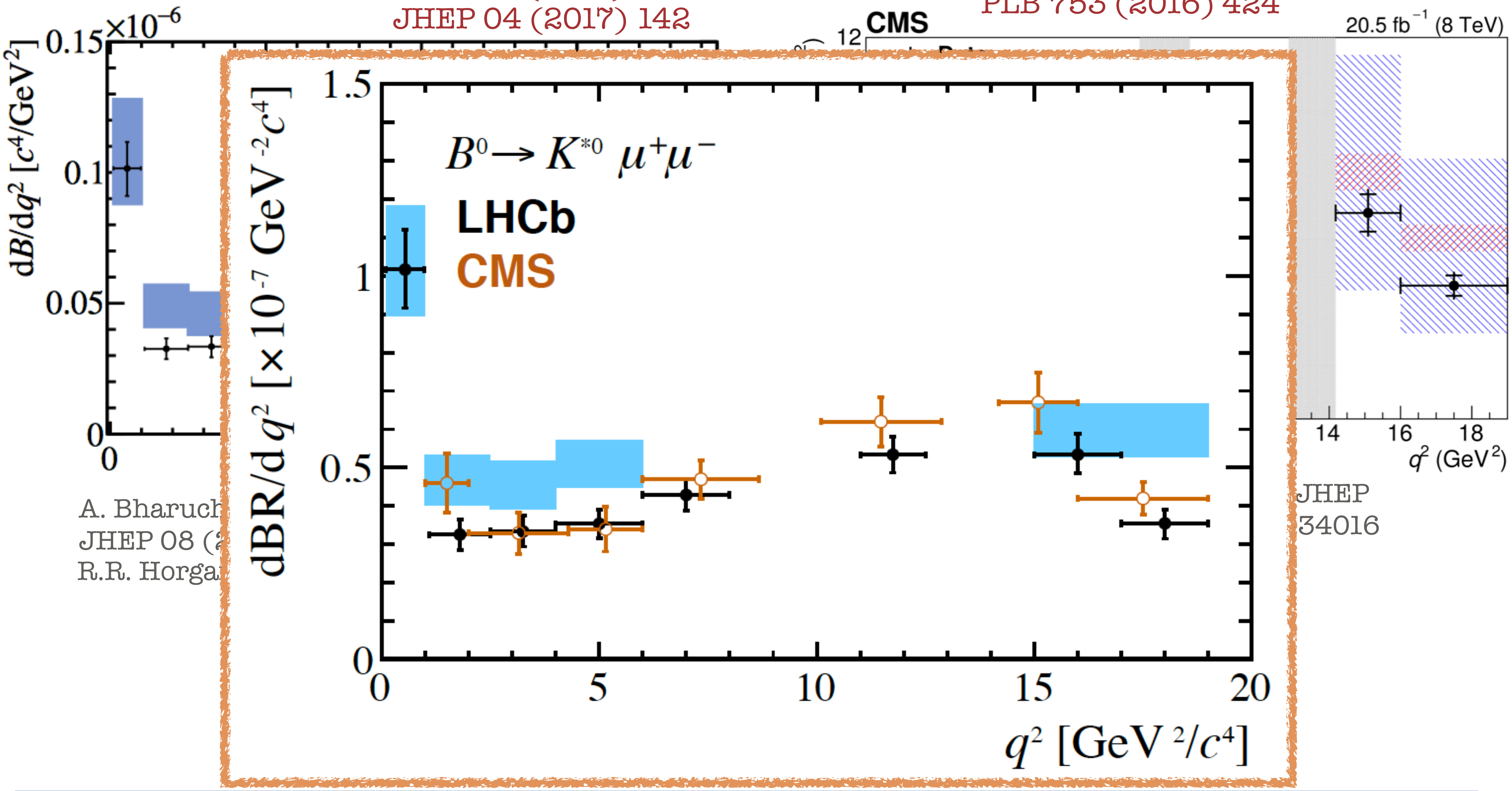
$B^0 \rightarrow K^{0*}\mu^+\mu^-$ dBR/dq^2

LHCb run I analysis, 3fb^{-1}

CMS, 8 TeV, 20.5 fb^{-1}

JHEP 11 (2016) 047
JHEP 04 (2017) 142

PLB 753 (2016) 424



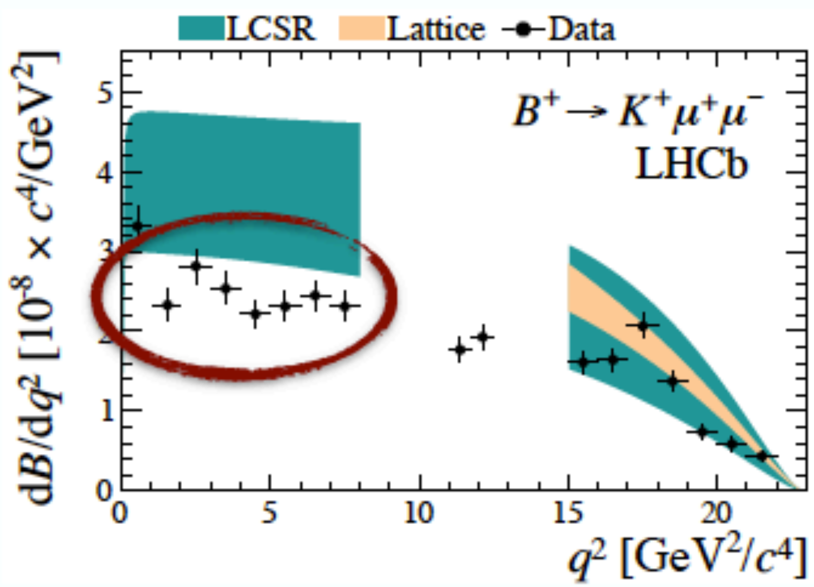
A. Bharuch…
JHEP 08 (2…
R.R. Horga…

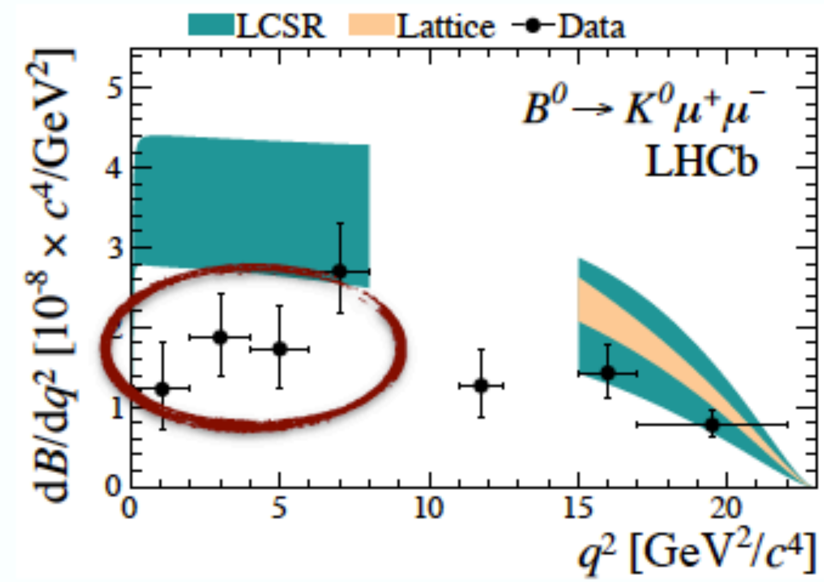
JHEP
…34016

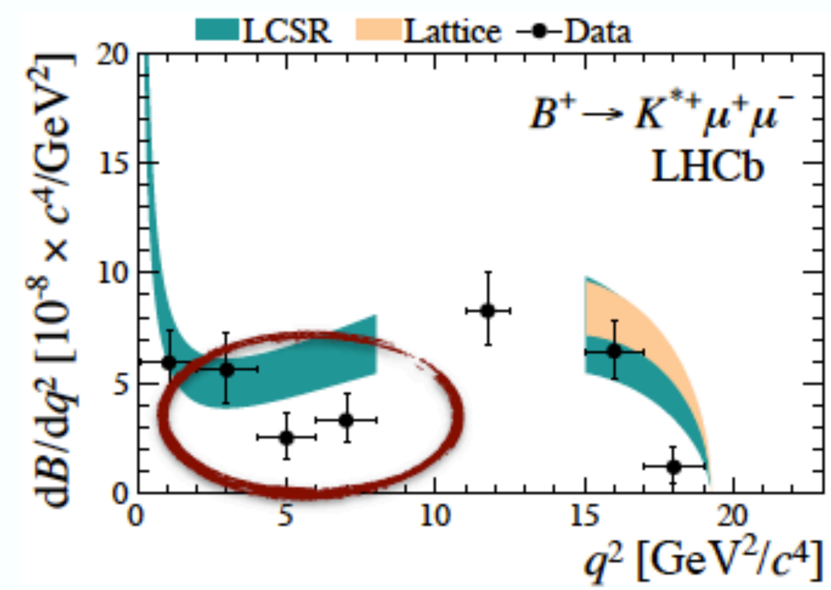
dBR/dq² , a pattern?

- Various b→sμμ transitions from LHCb

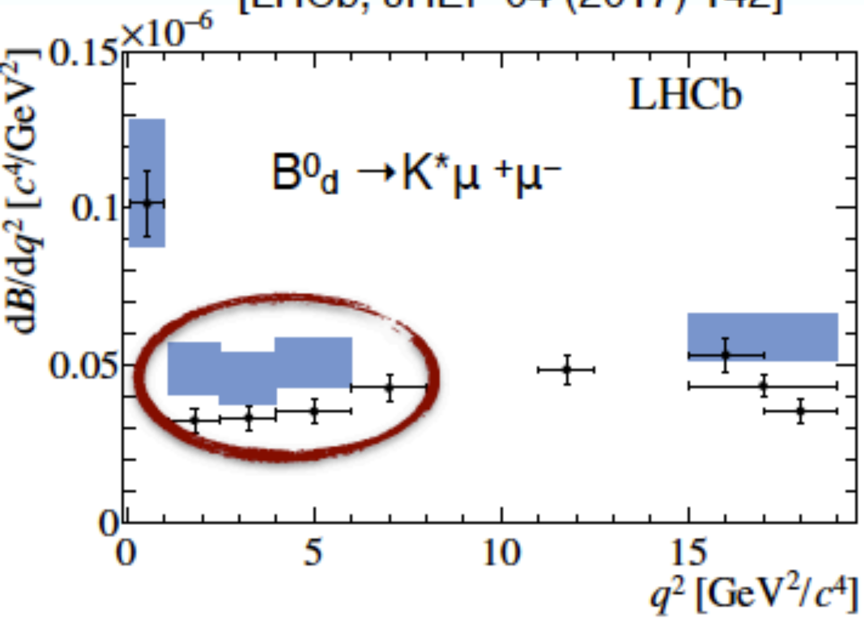
[LHCb, JHEP 06 (2014) 133]



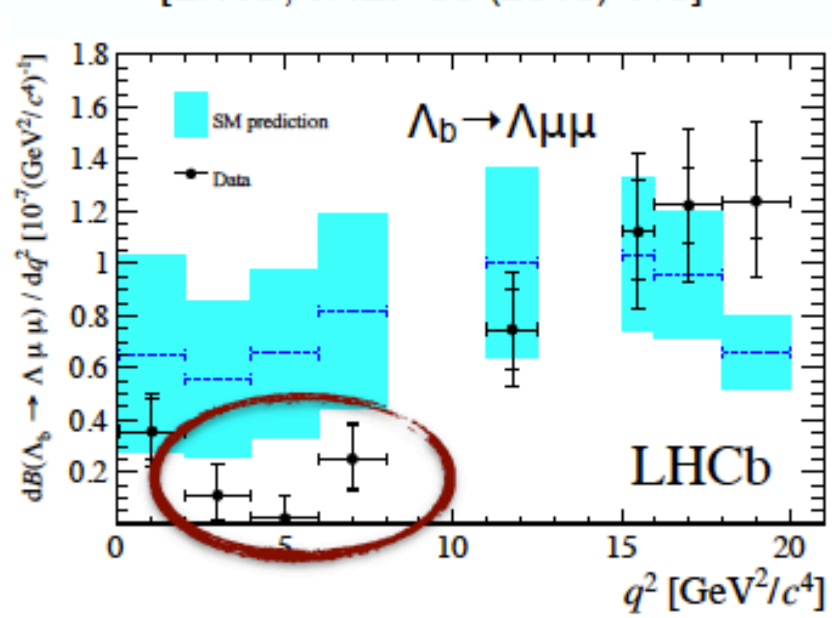




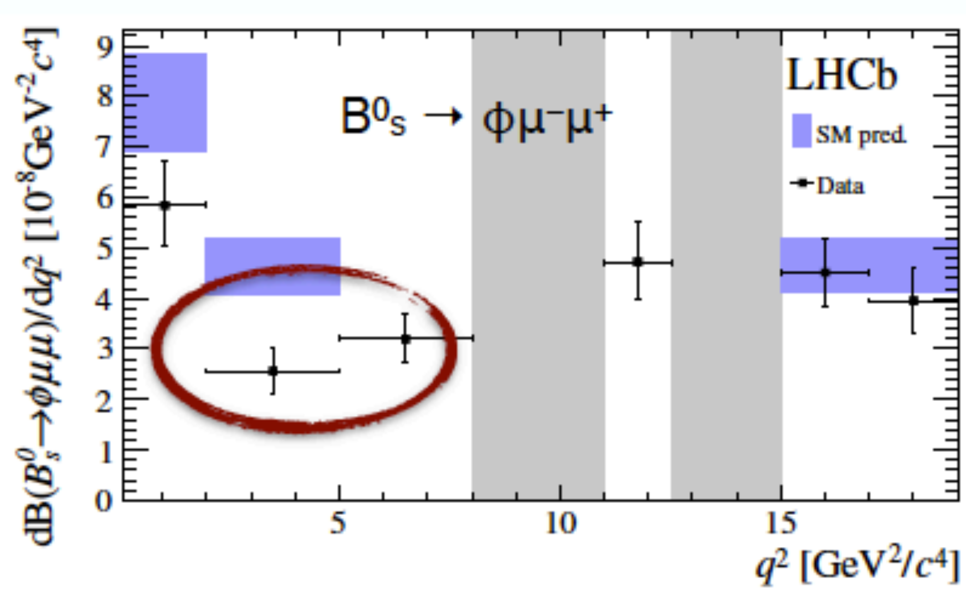
[LHCb, JHEP 11 (2016) 047]
[LHCb, JHEP 04 (2017) 142]



[LHCb, JHEP 06 (2015) 115]



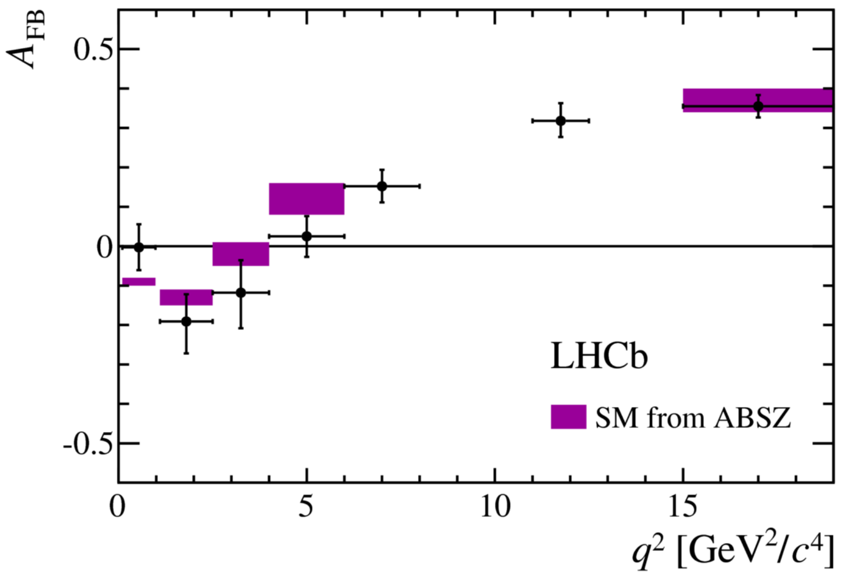
[LHCb, JHEP 09 (2015) 179]

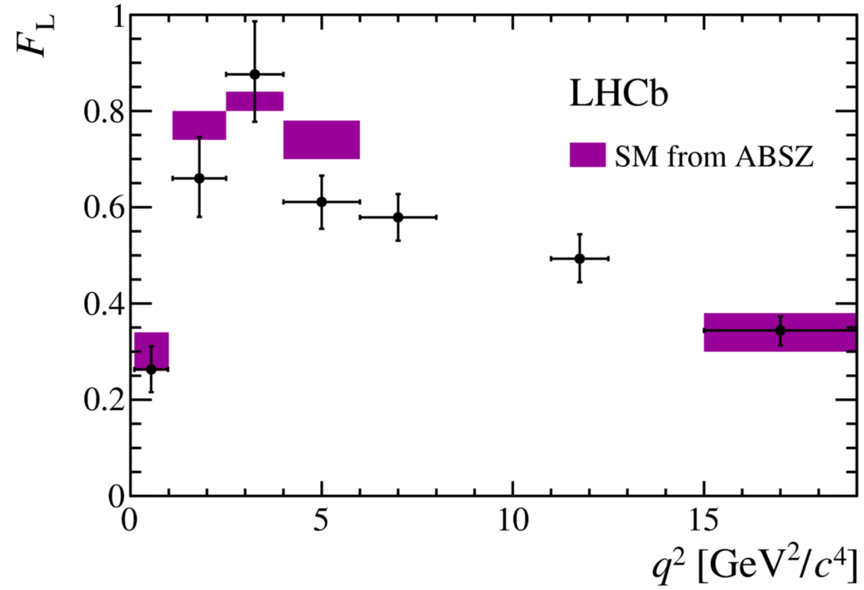


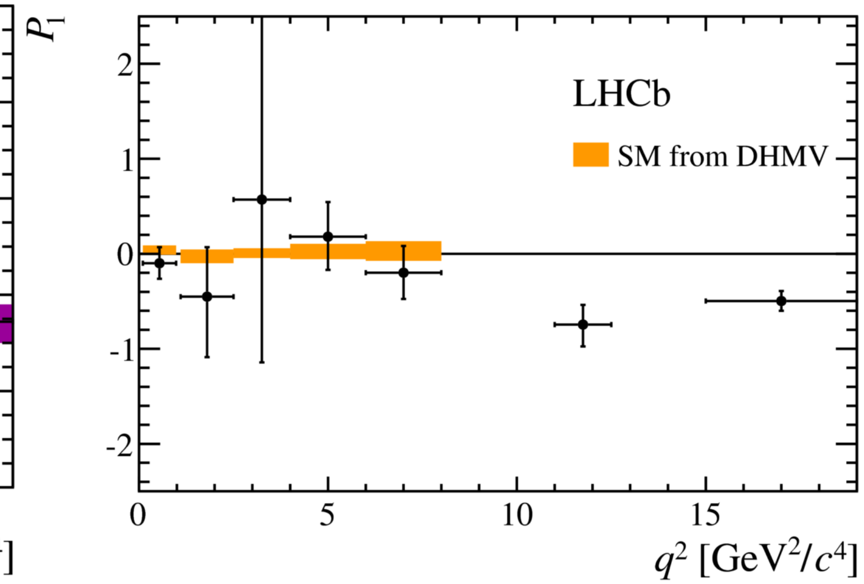
➡ **measurements show tendency of values below SM predictions**

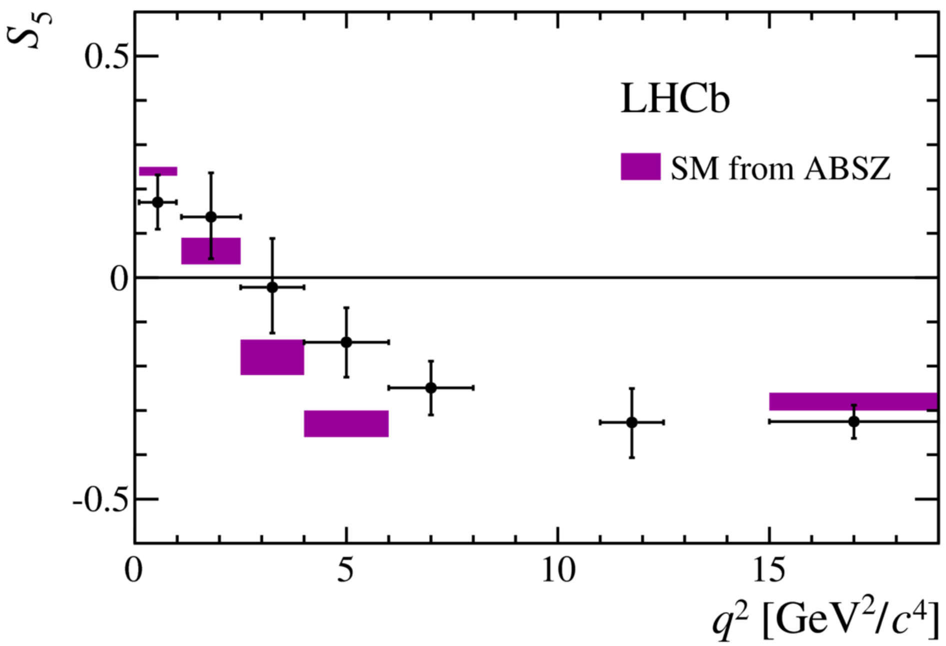
$B^0 \to K^* \mu^+\mu^-$ angular analysis - LHCb

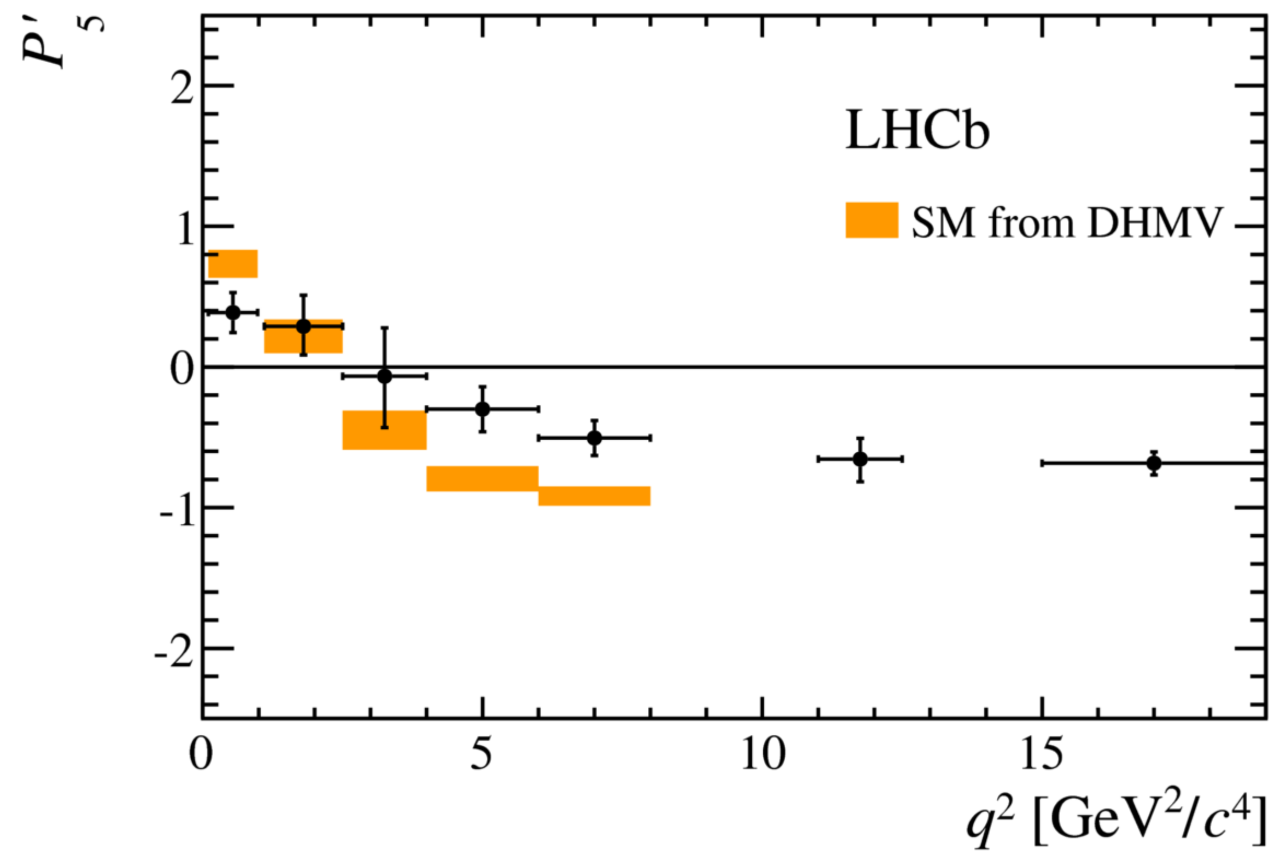
JHEP 02 (2016) 104





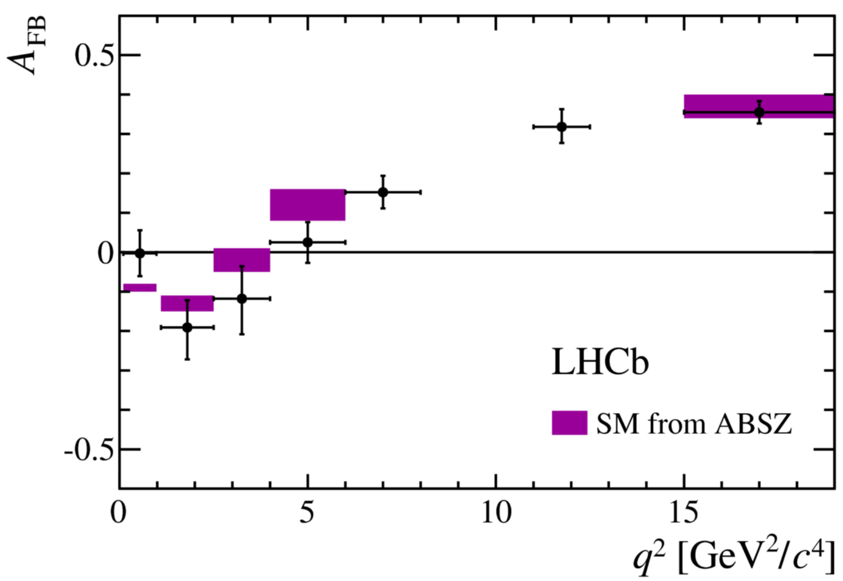


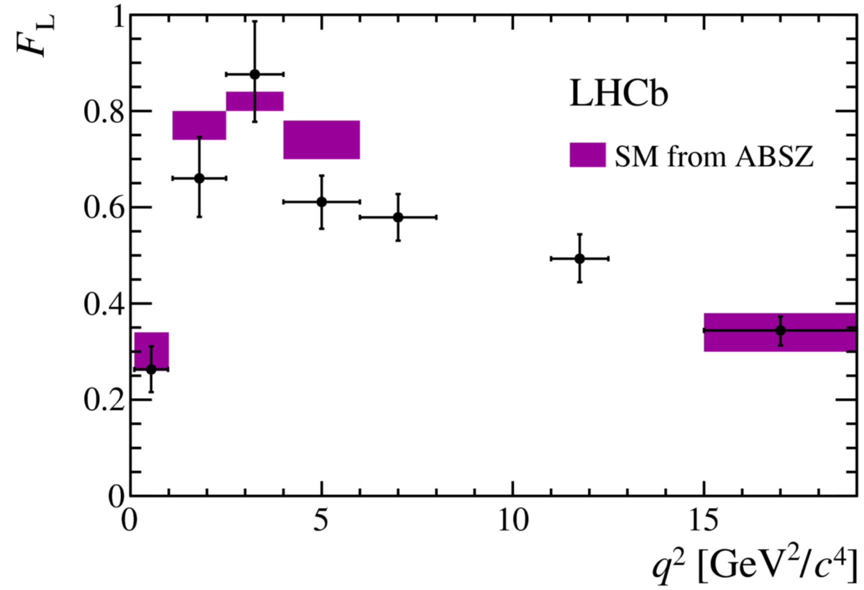


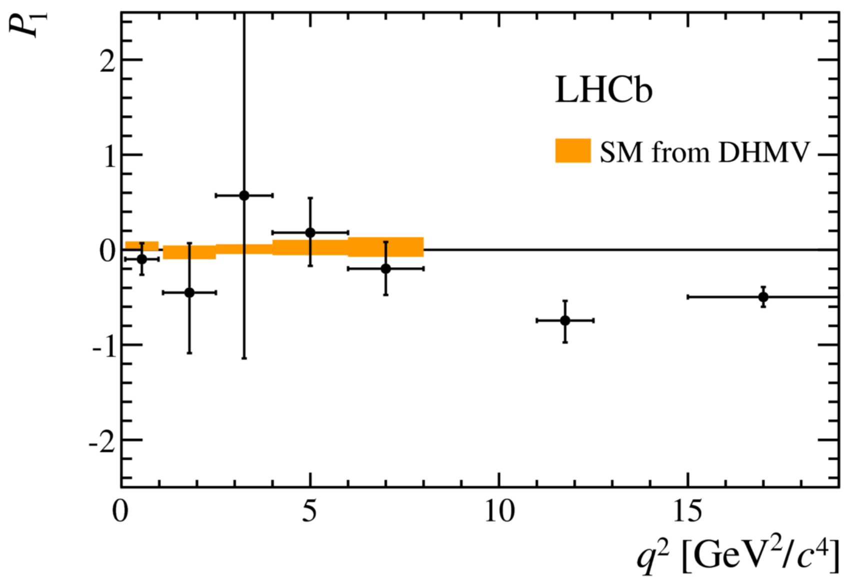


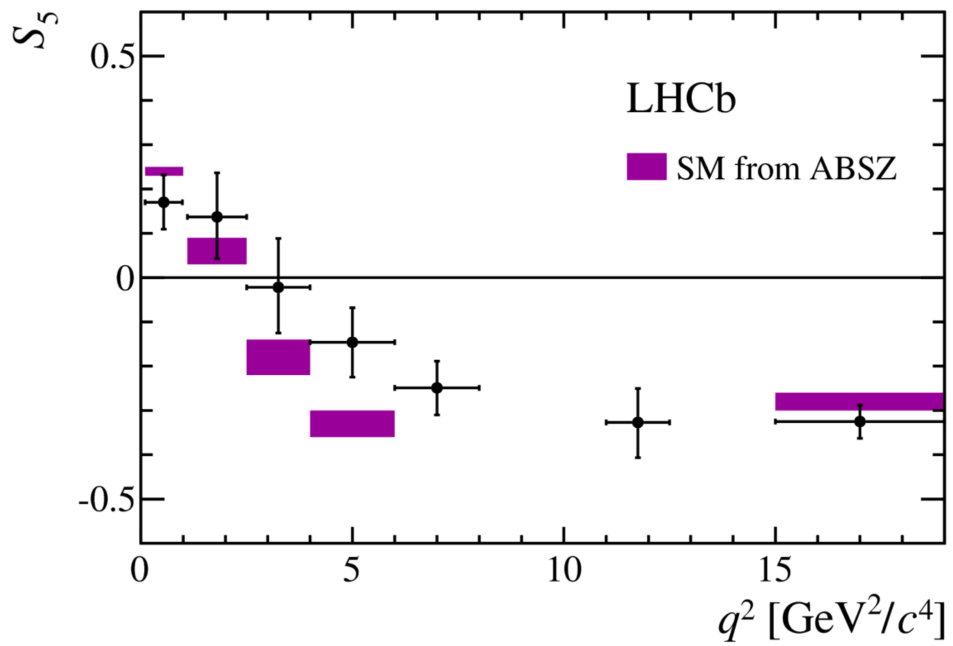
$B^0 \rightarrow K^*\mu^+\mu^-$ angular analysis - LHCb

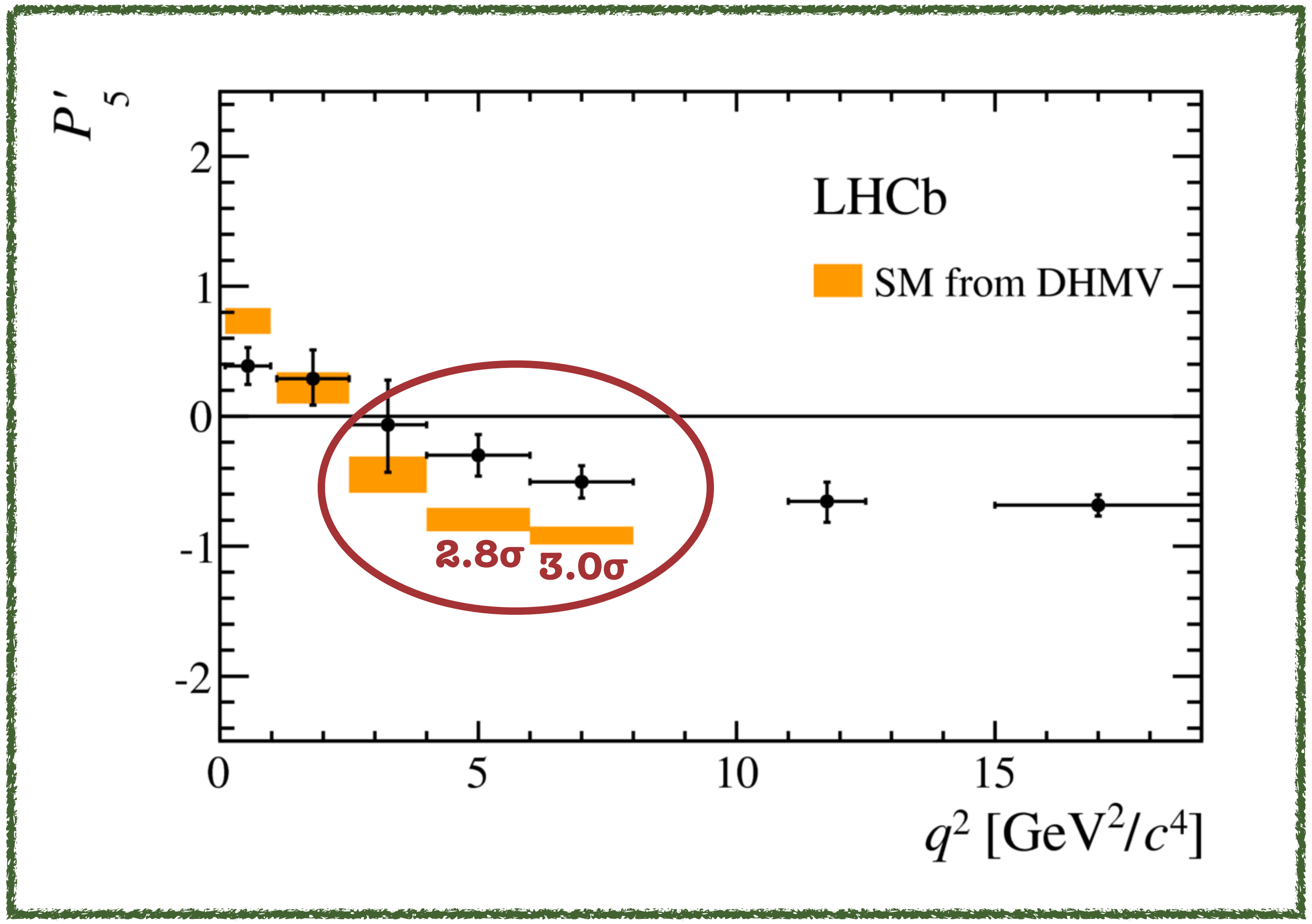
JHEP 02 (2016) 104





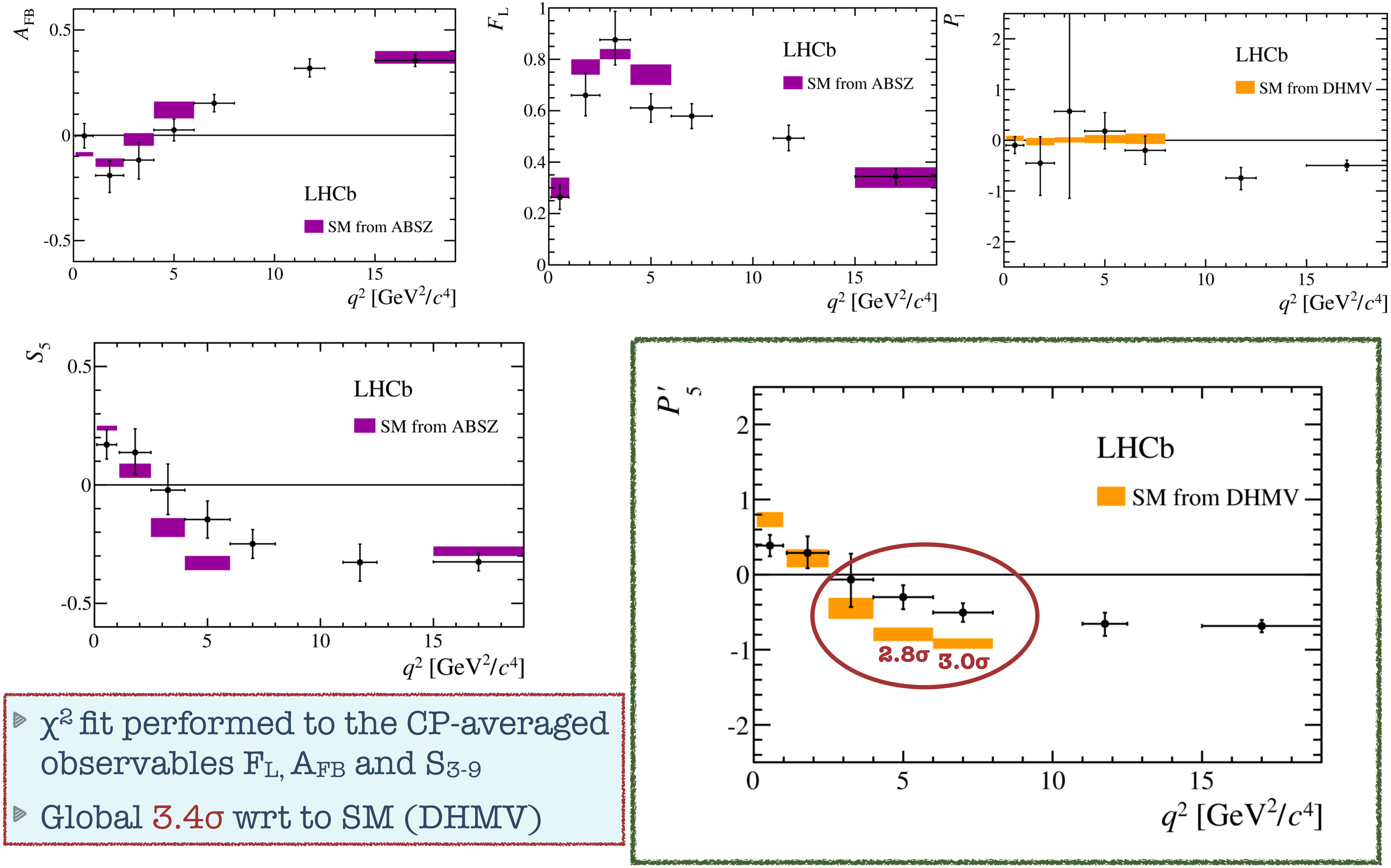






$B^0 \to K^*\mu^+\mu^-$ angular analysis - LHCb

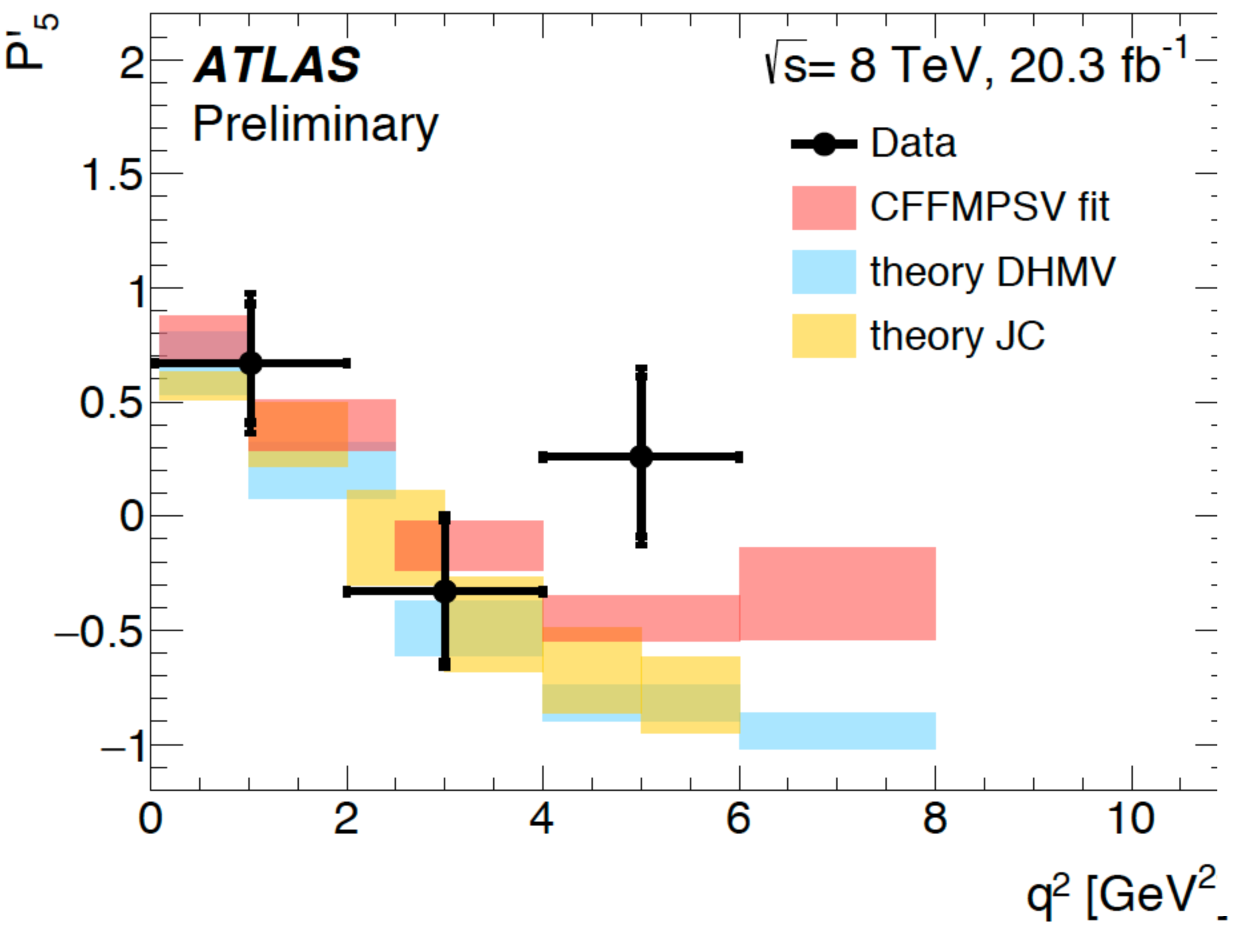
JHEP 02 (2016) 104



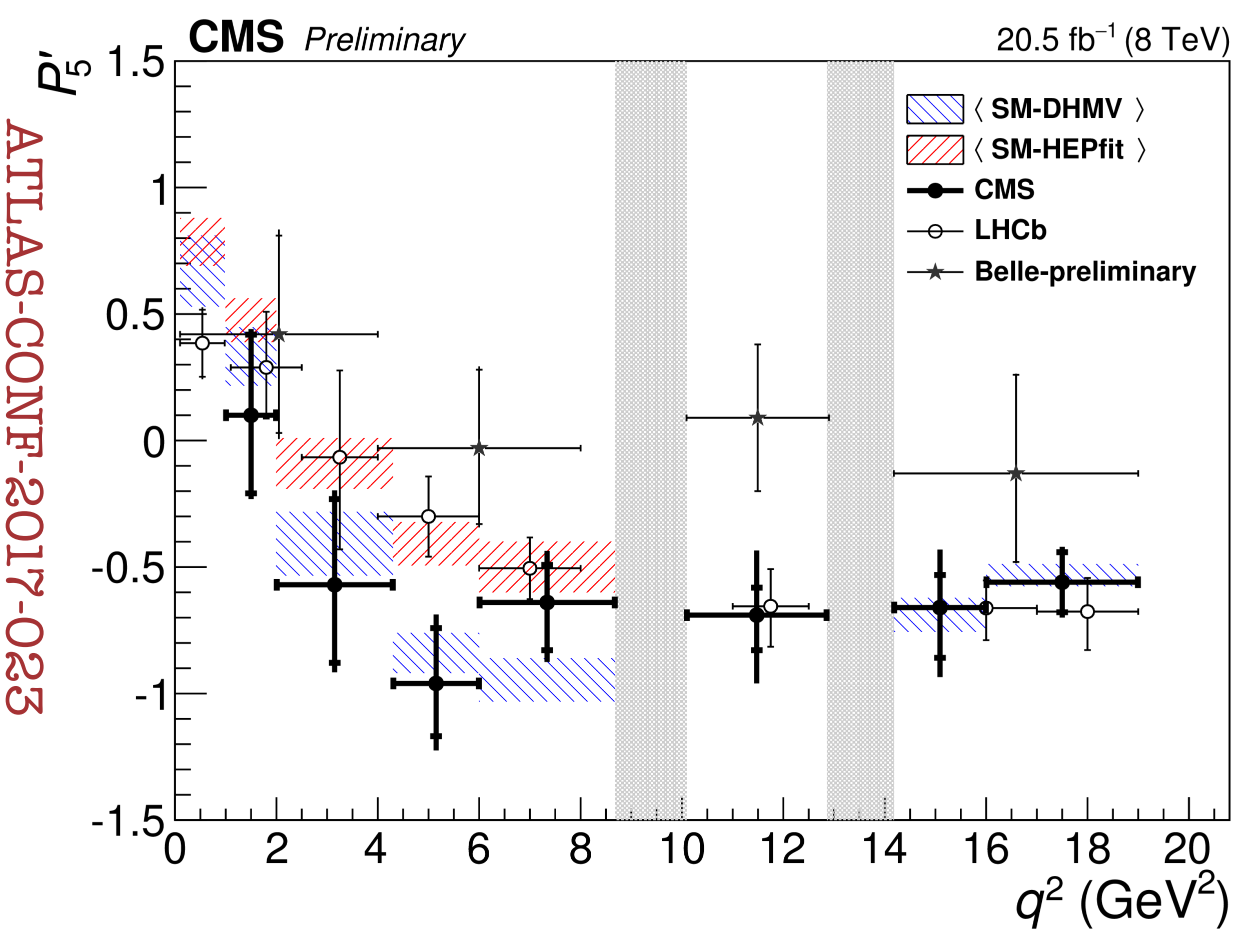
- χ^2 fit performed to the CP-averaged observables F_L, A_{FB} and S_{3-9}
- Global 3.4σ wrt to SM (DHMV)

$B^0 \to K^*\mu^+\mu^-$ angular analysis - ATLAS and CMS

- CMS and ATLAS have recently presented their results on this matter:



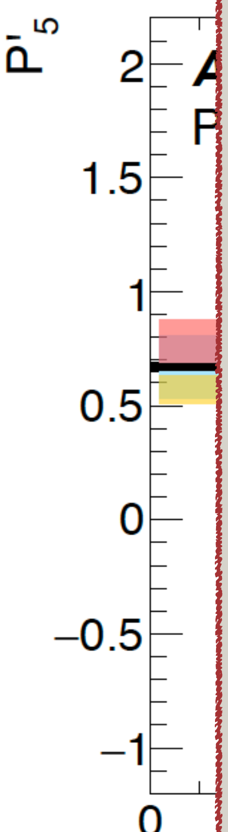
ATLAS-CONF-2017-023



CMS-PAS-BPH-15-008 (2017)

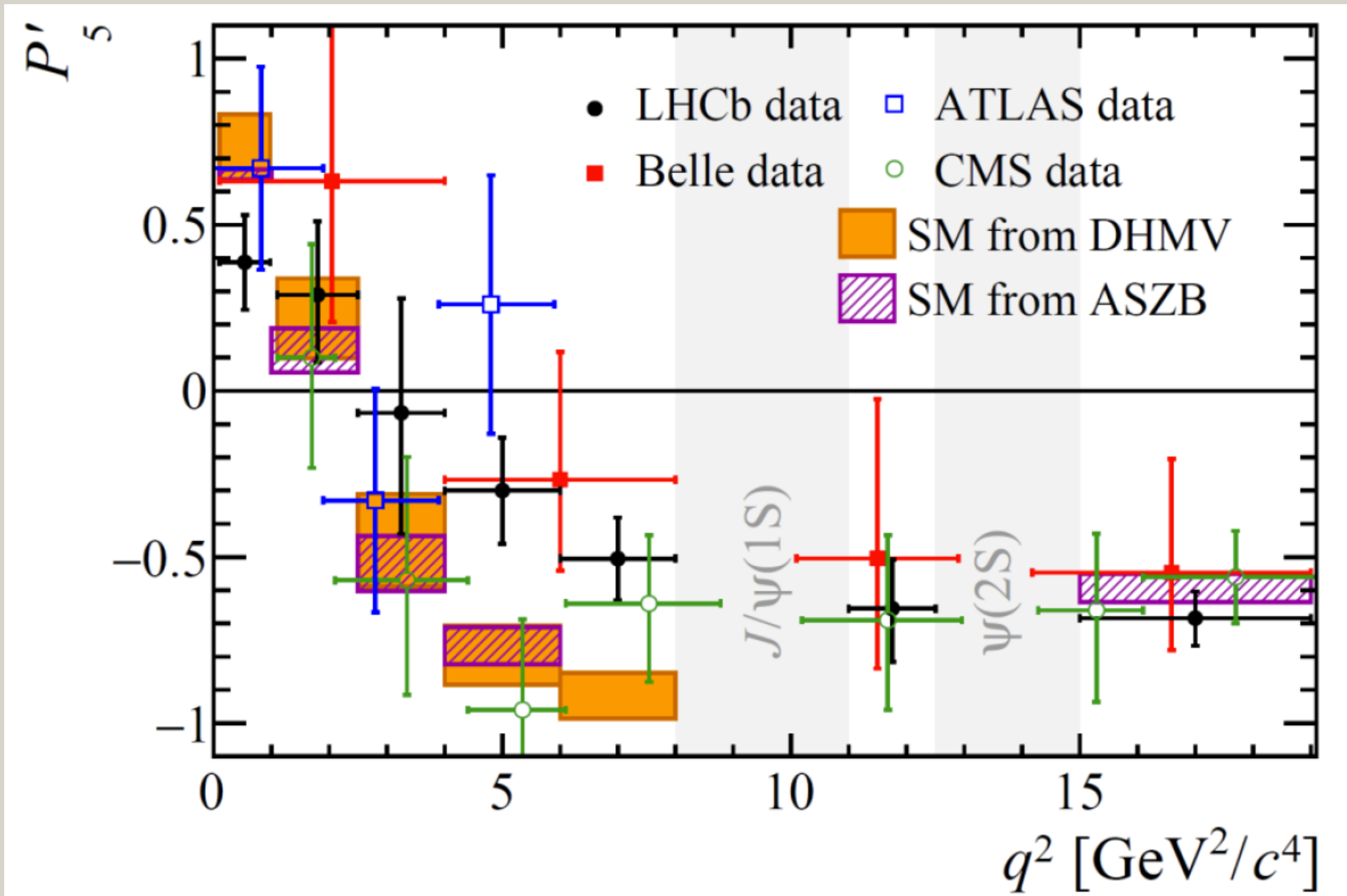
- ATLAS show this (same) tendency of higher P_5' within 4-6 GeV²
- CMS with better agreement SM predictions

$B^0 \to K^*\mu^+\mu^-$ angular analysis - ATLAS and CMS



All together ...

DHMV: JHEP 12 (2014) 125, JHEP 10 (2016) 075
ASZB: EPJC 75 (2015) 382, JHEP 08(2016) 098



LHCb: JHEP 02 (2016) 104
Belle: BELLE-CONF-1603
ATLAS: ATLAS-CONF-2017-023
CMS: CMS-PAS-BPH-15-008

Lepton Universality: R(K)

- apart from the mass, the charged leptons are copies of one another in the SM ⇒ Lepton Universality (LU)

  equal couplings of W and Z to e, μ, τ

- within the SM, amplitudes of processes involving leptons must be identical after correcting for phase space
- lepton universality might be broken by mass dependent couplings
  ⇒ signs for NP
- For semileptonic decays, robust tests rely on ratio of branching ratios for same final state differing only on the lepton flavour

  ☞ hadronic uncertainties cancel

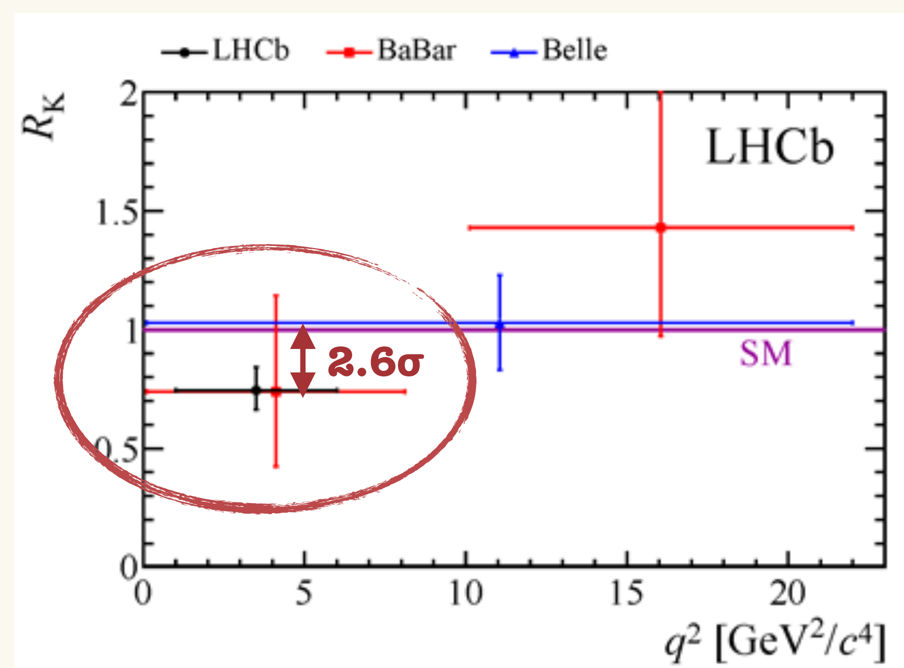
LHCb 2014 (remembering) :

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

measure through double ratio using $B^+ \to K^+ J/\psi(\ell^+\ell^-)$

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

($1\ \mathrm{GeV}^2 < q^2 < 6\ \mathrm{GeV}^2$)



PRL 113 (2014) 151601

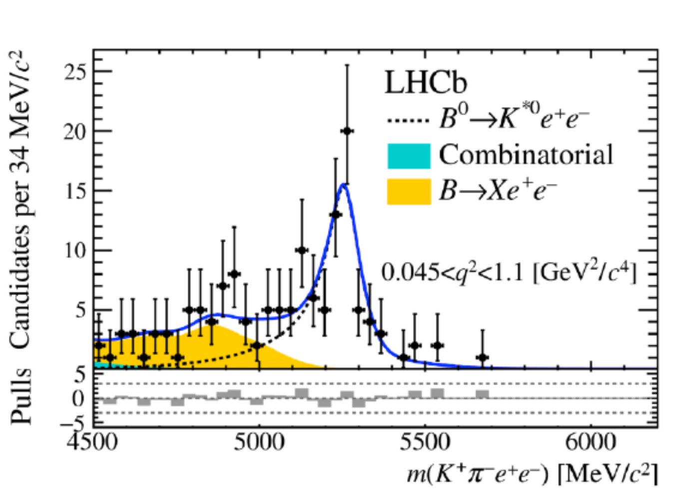
R(K*) - LHCb

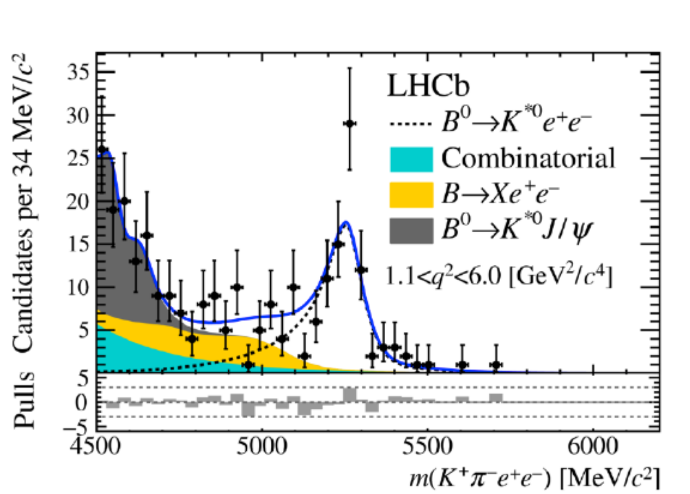
- LHCb uses the same old $B^0 \to K^* \mu^+\mu^-$, now together with $B^0 \to K^* e^+e^-$ for LU studies

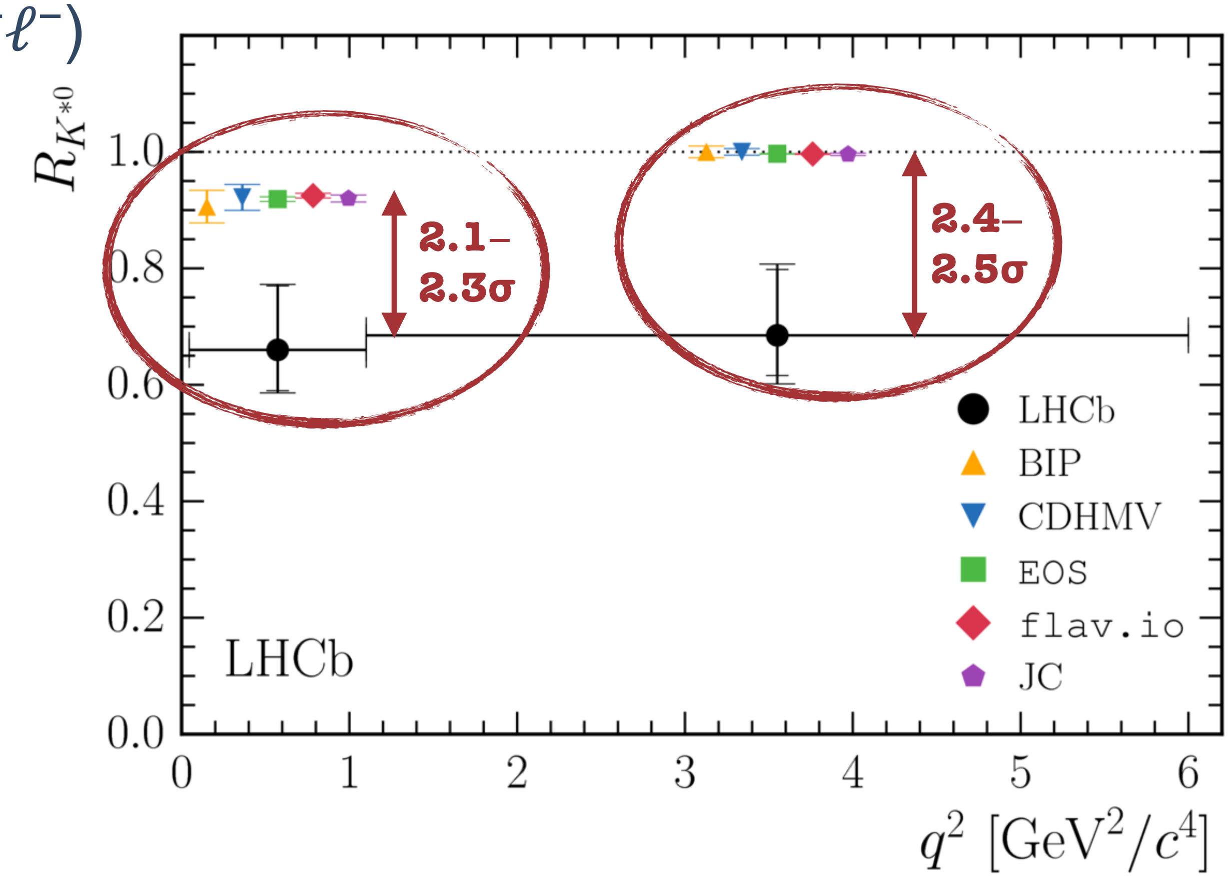
$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

- take the double ratio using $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ as control channels

- Measures in two bins of q^2





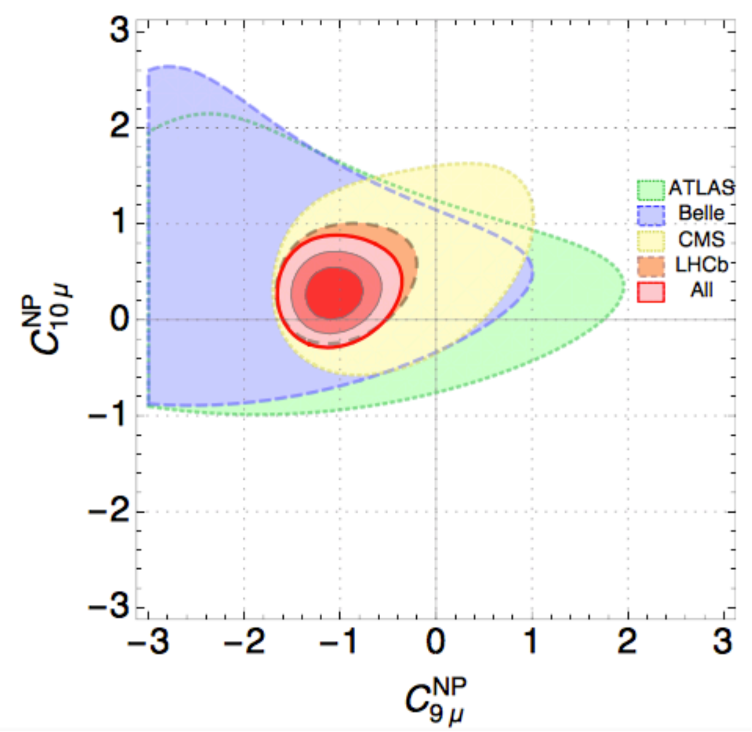


arXiv:1705.05802

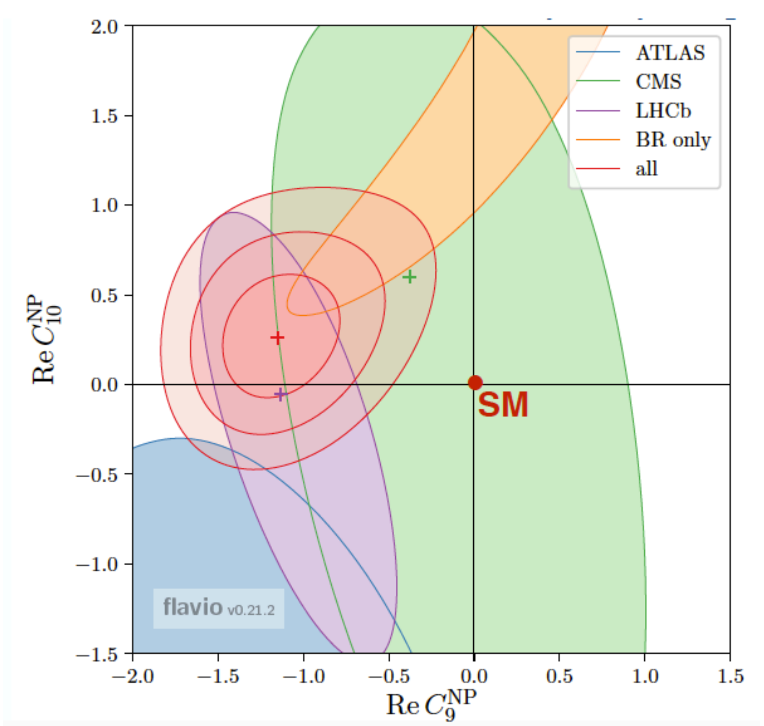
	low- q^2	central- q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]

Global Fits

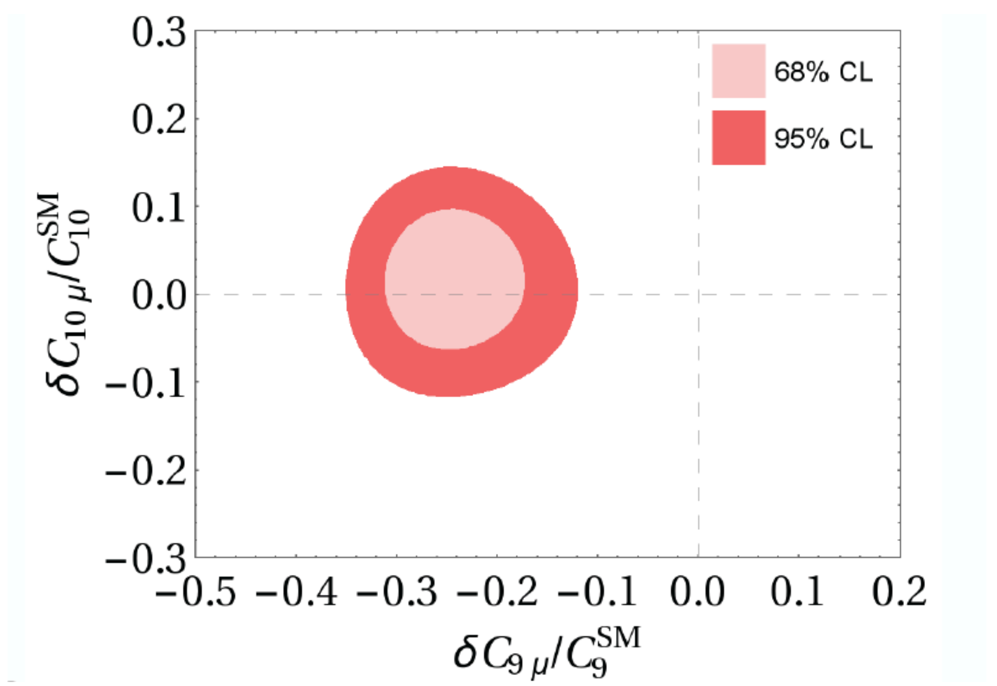
- Global fits to Wilson coefficients provide info on NP contributions
- Several attempts to interpret results
- Use available $B \to \mu\mu$, $b \to s\gamma$, $b \to s\ell\ell$ data: ~ 100 observables



B. Capdevila et al, arXiv:1704.05340



Altmannshofer et al. EPJC 77 (2017) 377

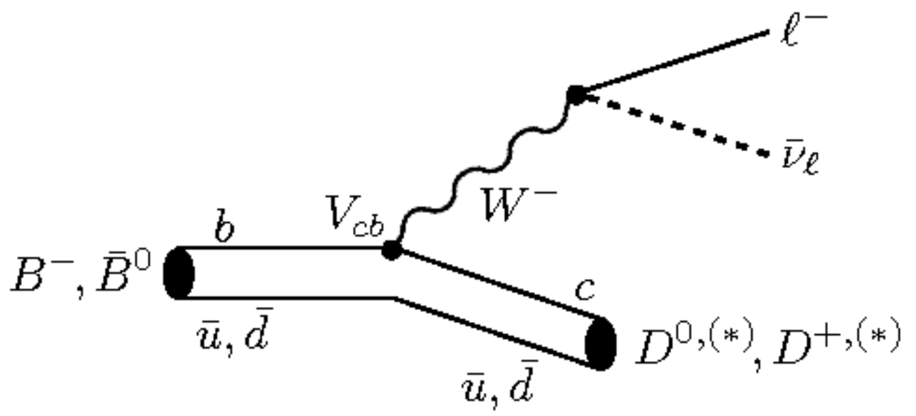


Hurth et al., arXiv:1705.06274

Preference for NP in C_9 at the 4–5σ level

LU: $B \to D^{(*)} \ell \nu$

- a tree-level process, abundant, but a challenge in a hadron machine due to the missing neutrinos (especially for the τ channel)

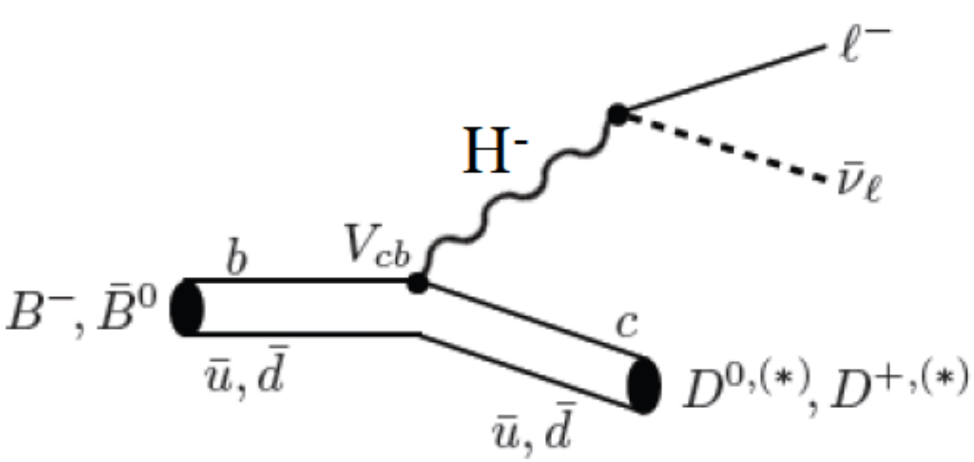


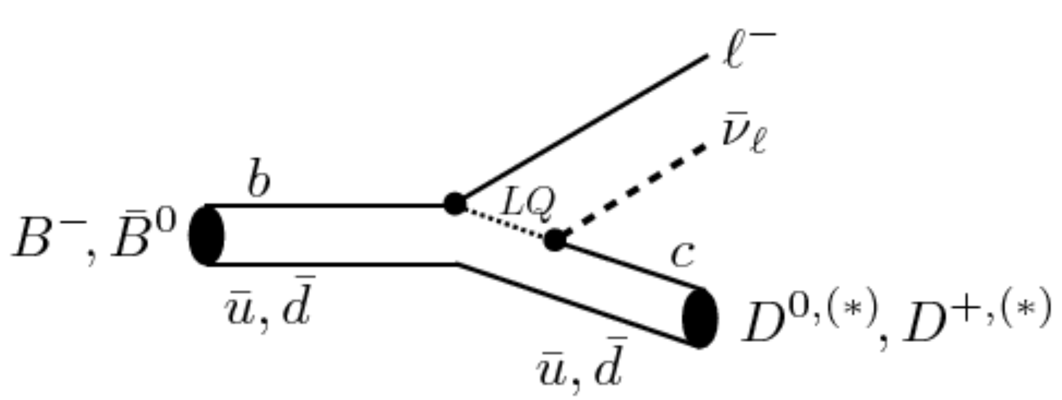
- Measuring the ratio $$R_{D^{(*)}} = \frac{\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)}$$

- very clean SM prediction: $$R_{D^*}^{(\mathrm{SM})} = 0.252 \pm 0.003$$
  - ☞ cancellation of B→ D* form factor uncertainties

    (value differ from 1 due to phase space)

- many NP scenarios could change this ratio, e.g. leptoquarks, charged Higgs





LU: $B \to D^{(*)} \ell \nu$

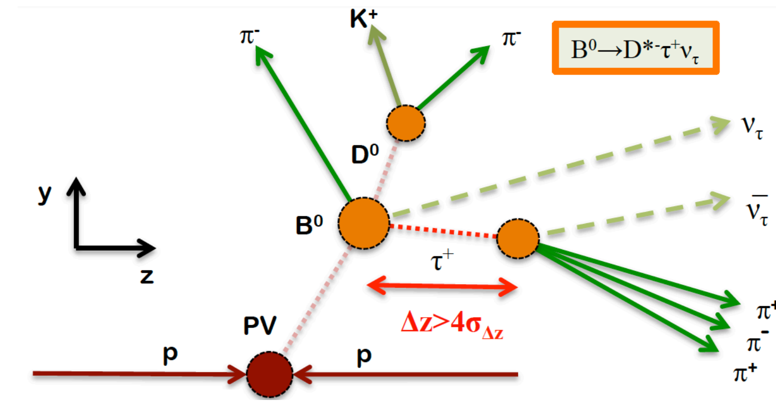
- Babar (2012) was the first to report results with some tension wrt SM
- This year inputs from Belle and LHCb

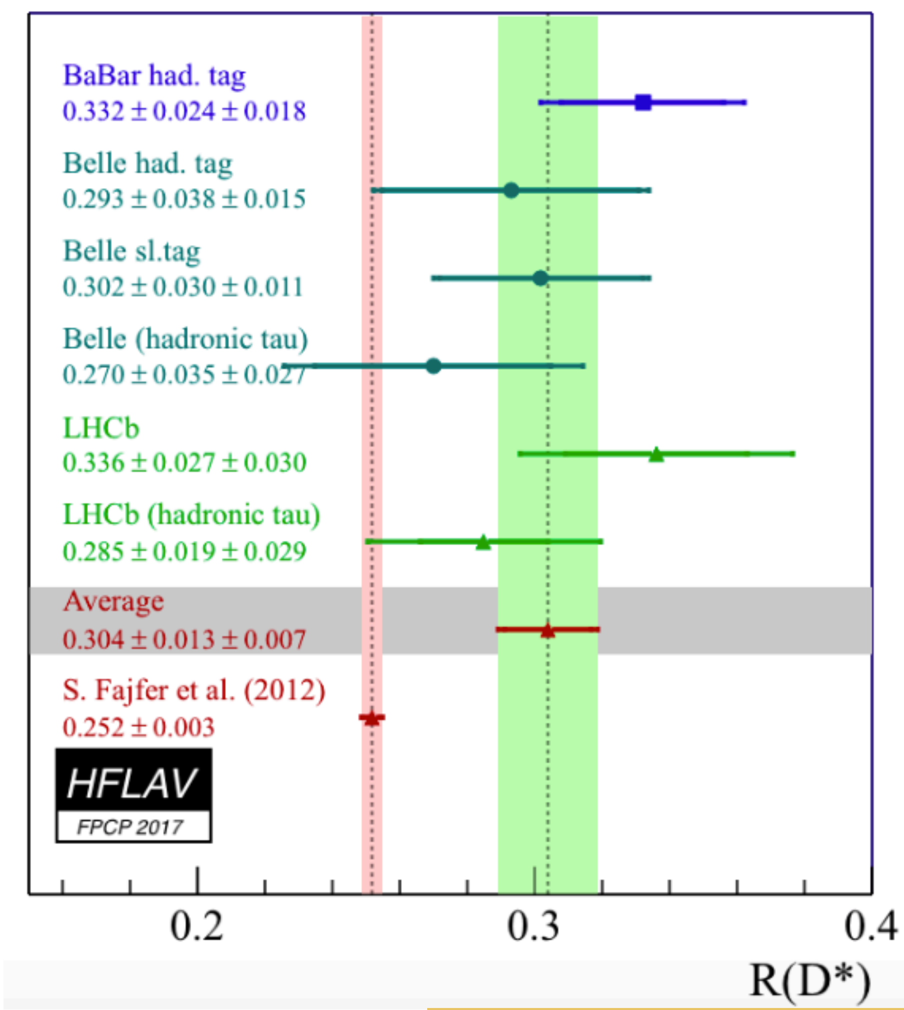
LHCb looks at $\tau \to \pi\pi\pi\nu$ final state

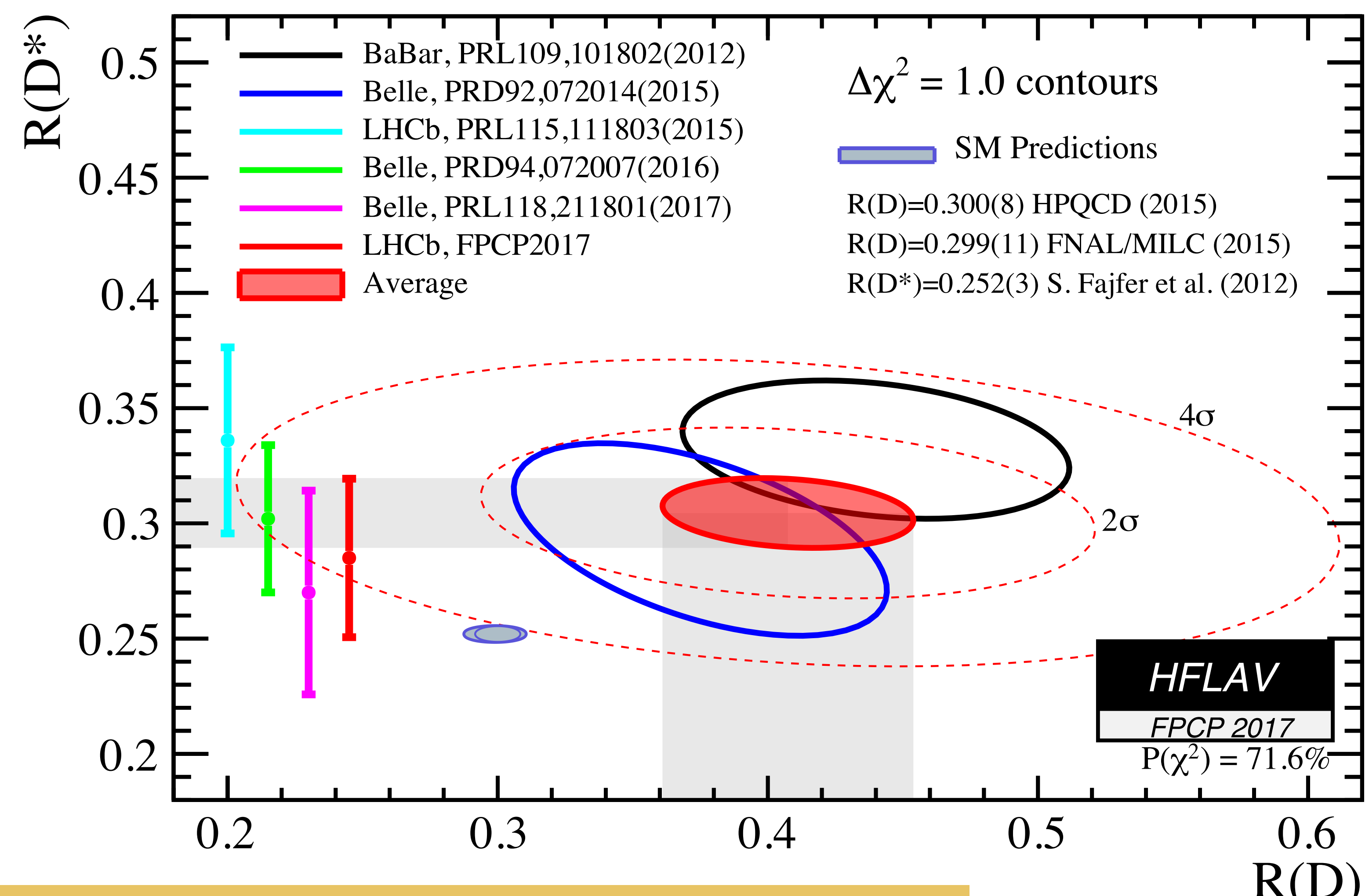
new

arXiv:1708.08856

$$R_{D^*} = 0.285 \pm 0.019 \pm 0.025 \pm 0.014$$







4.1σ level of discrepancy with the SM prediction

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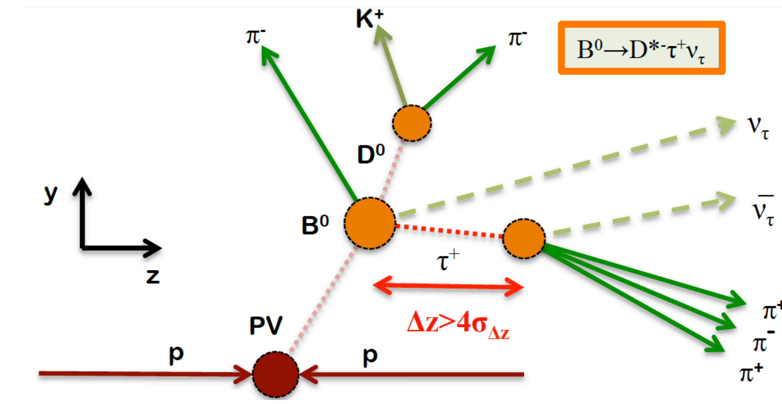
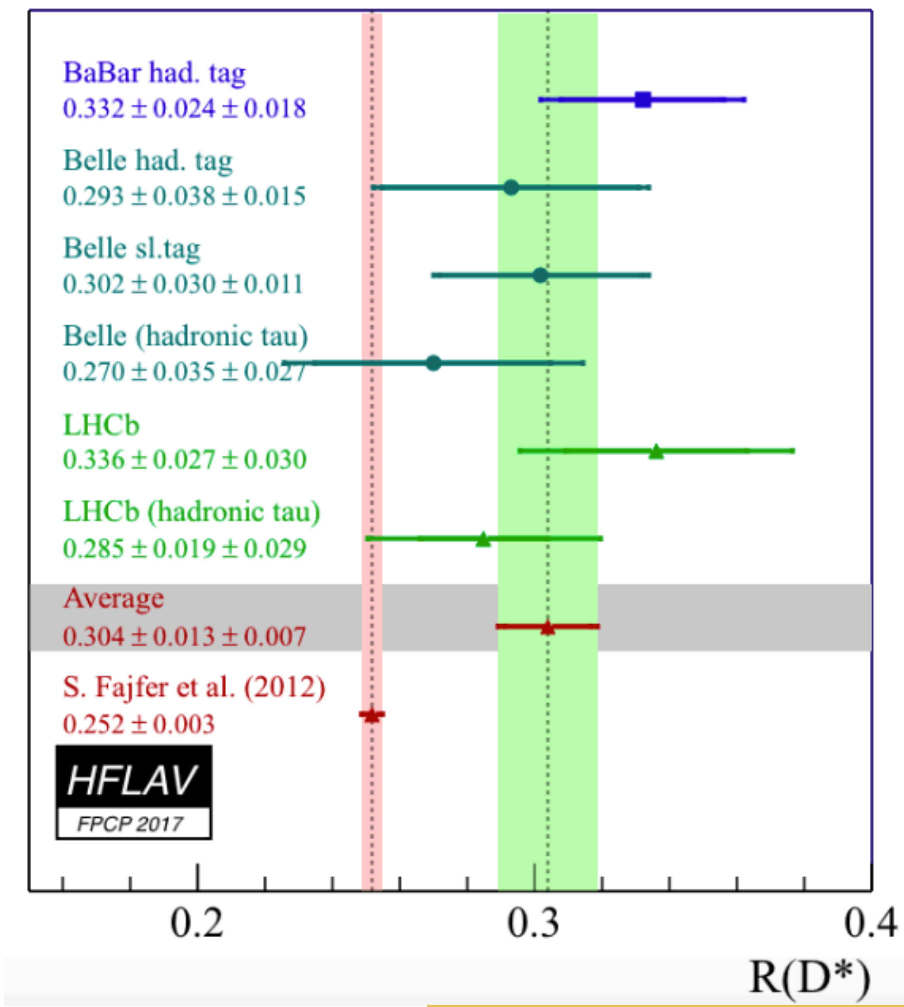
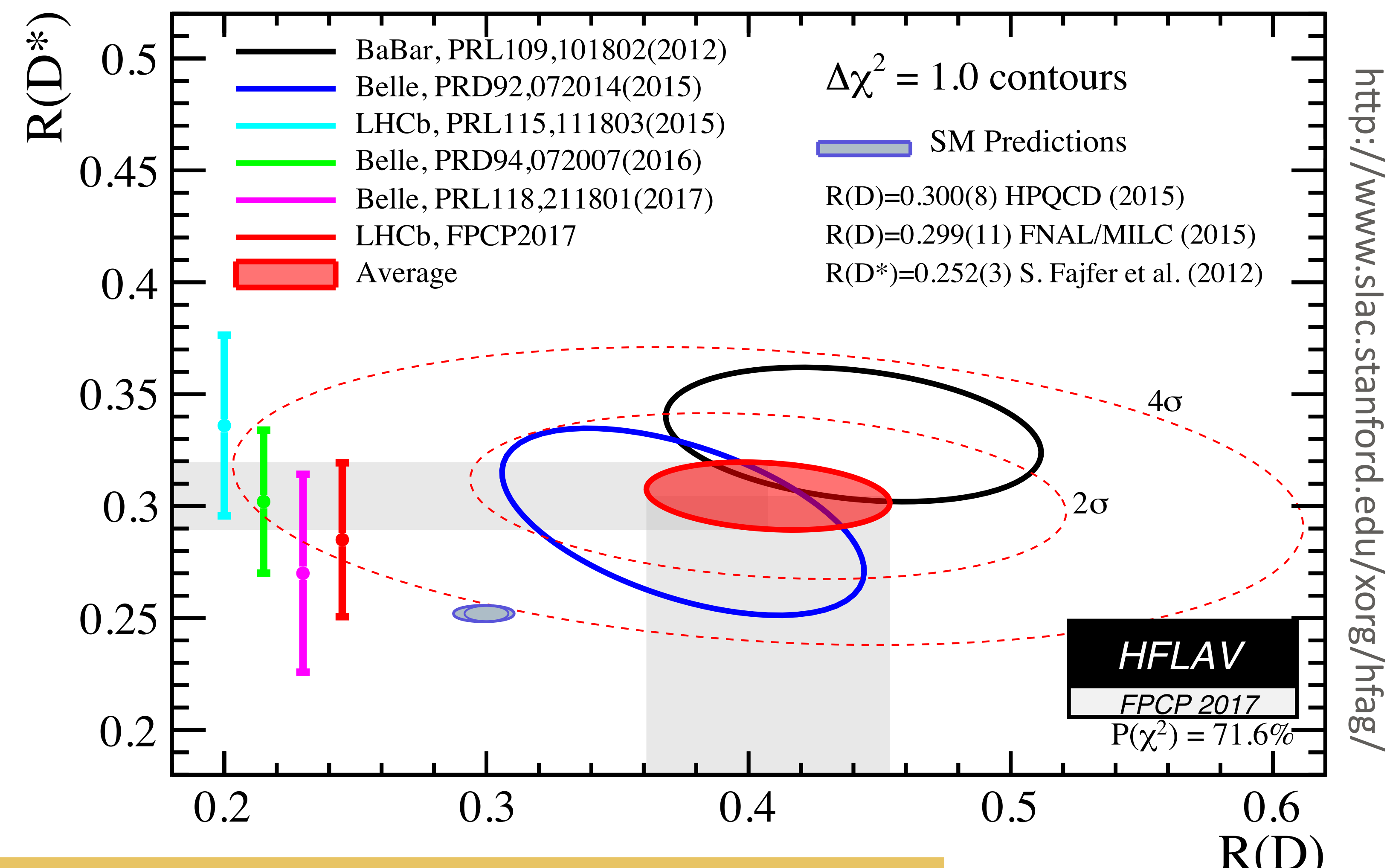


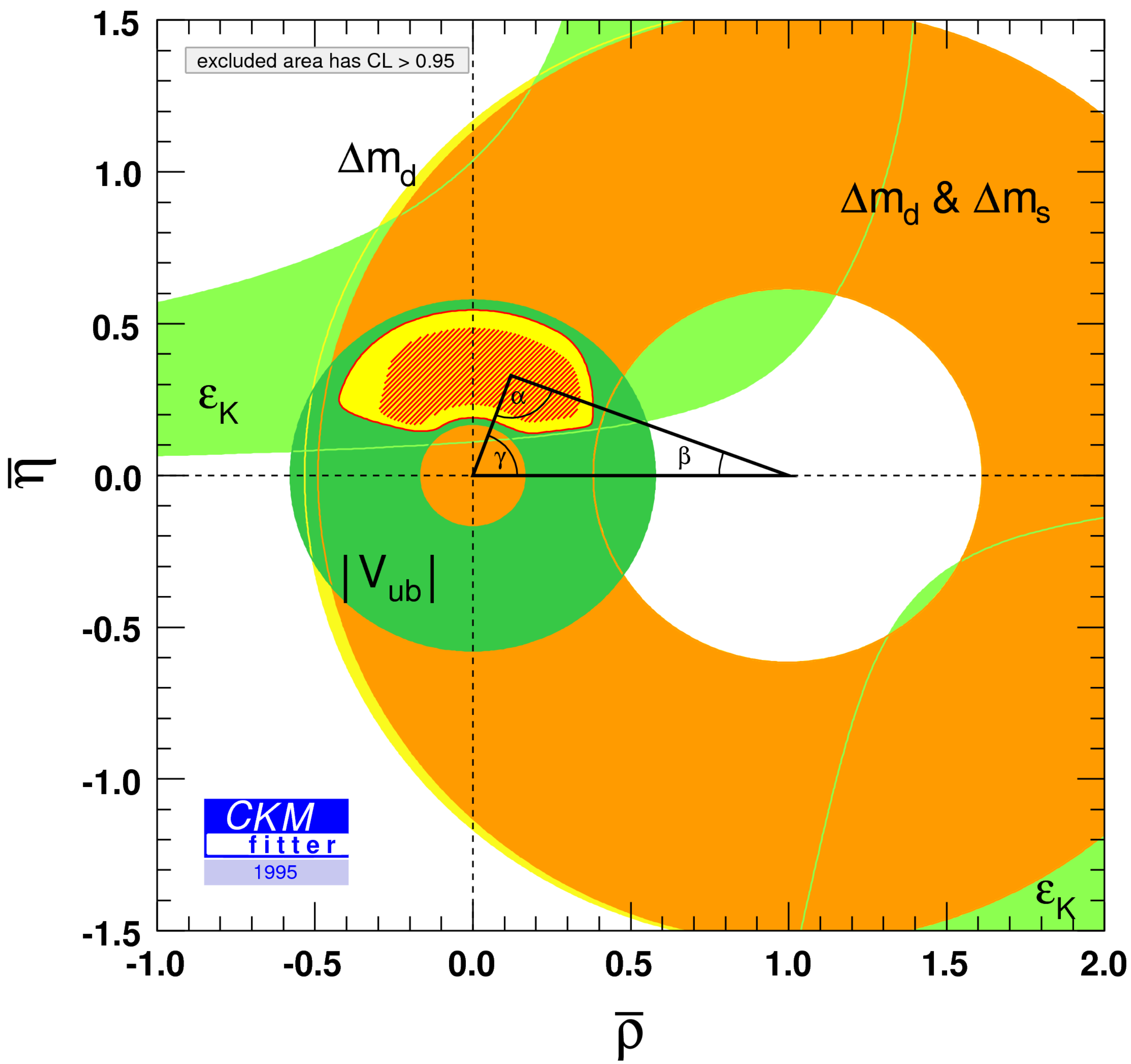




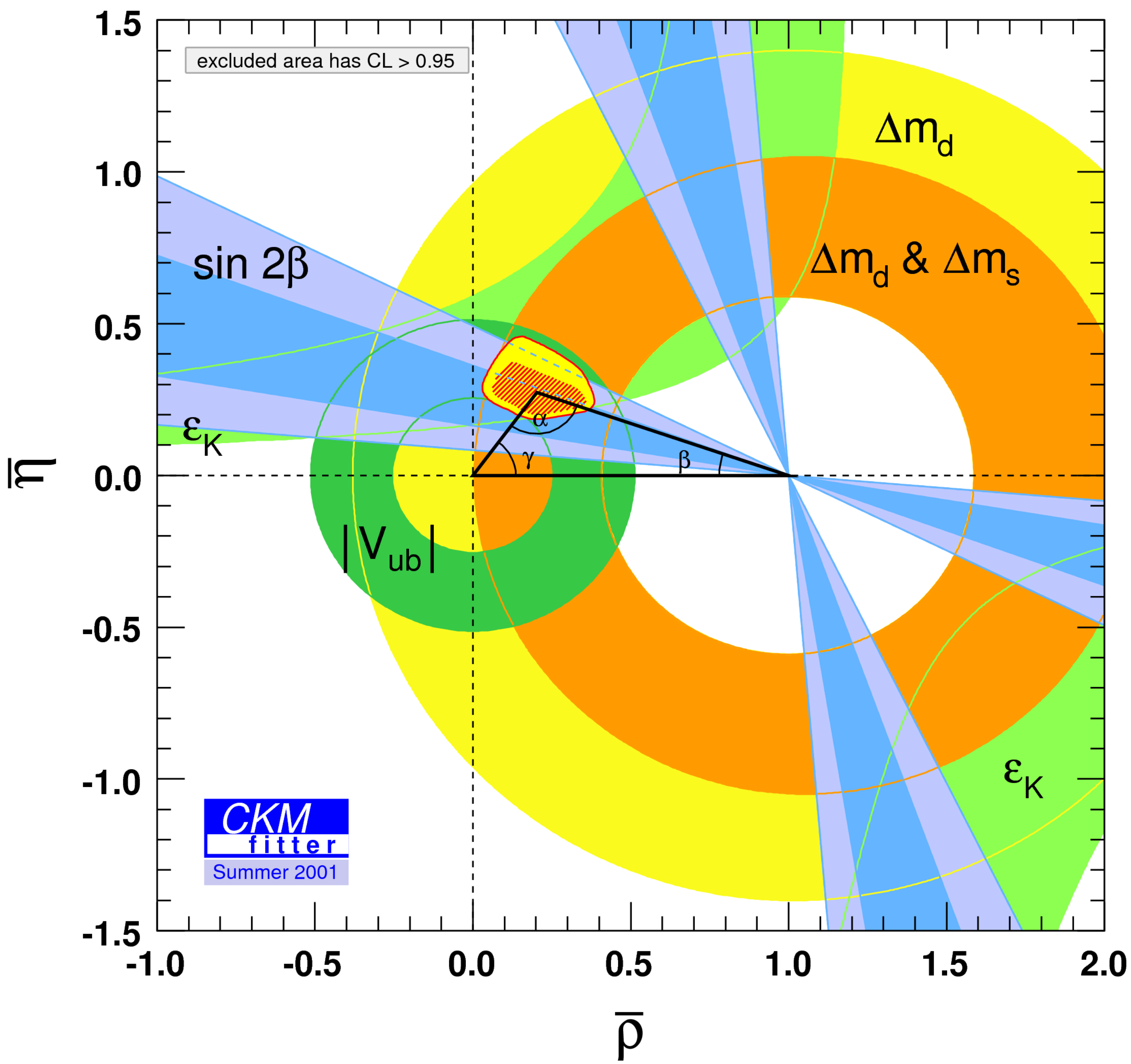
4.1σ level of discrepancy with the SM prediction

Highlights on CP violation

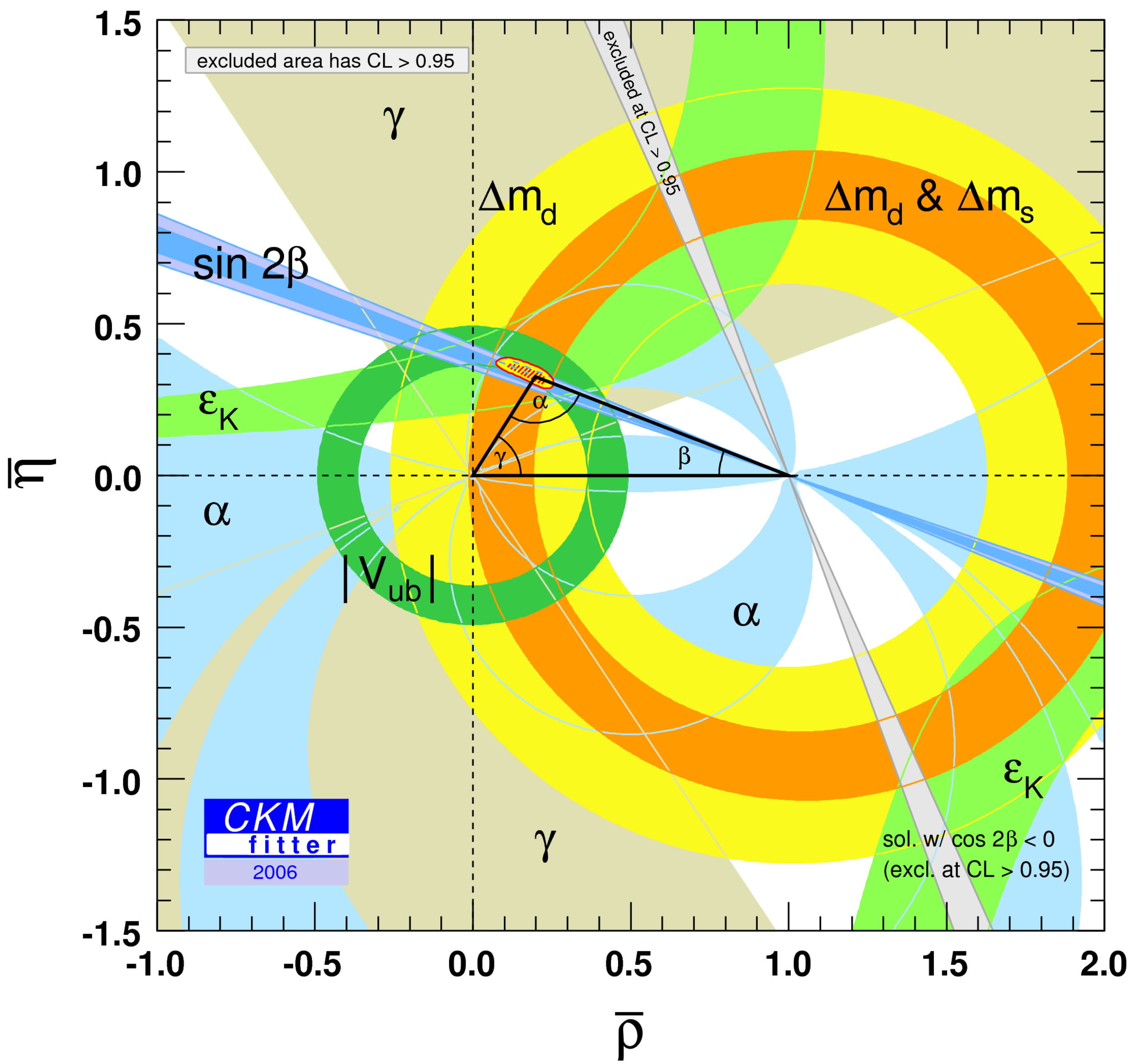
Highlights on CP violation



Highlights on CP violation



Highlights on CP violation



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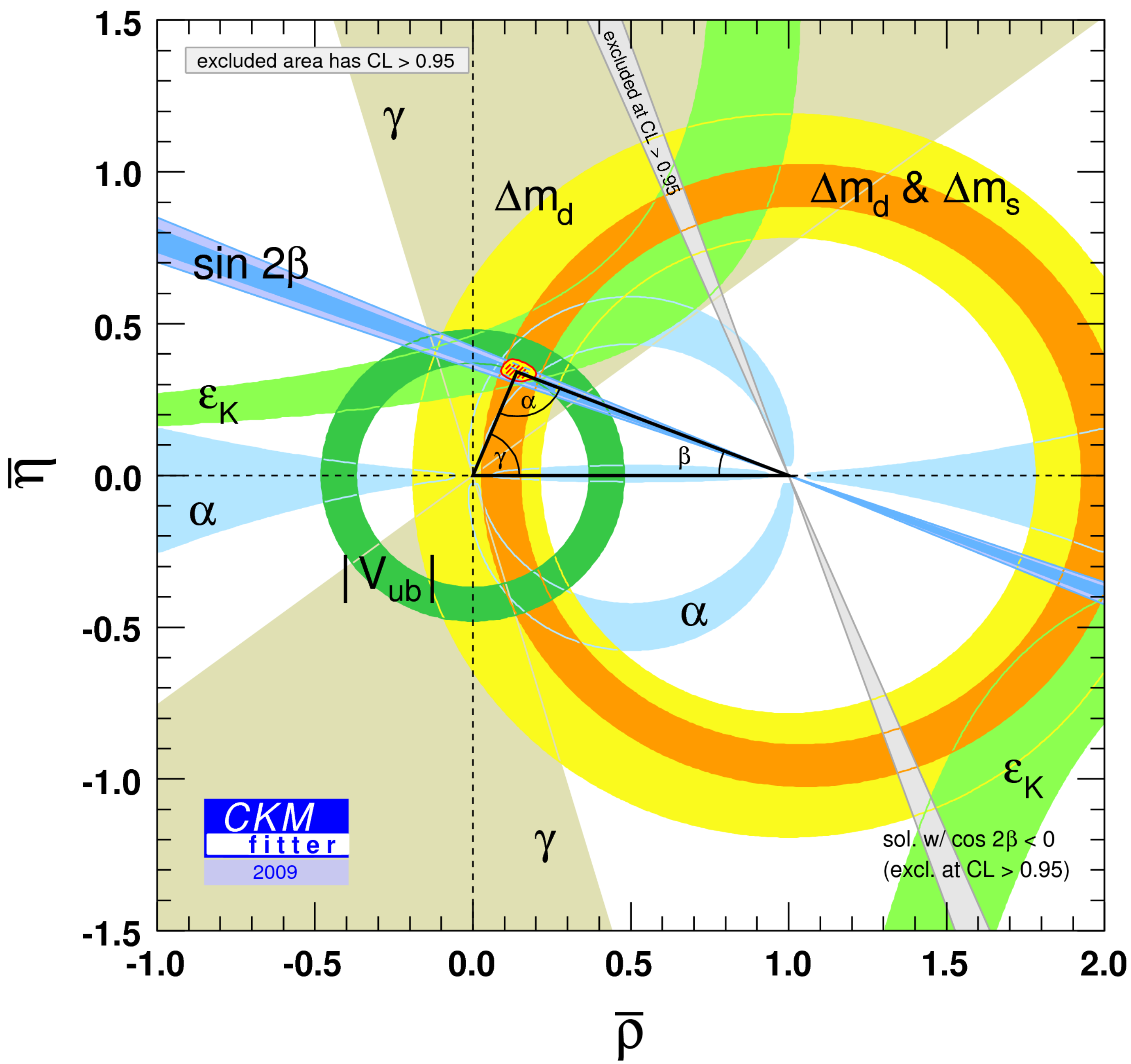

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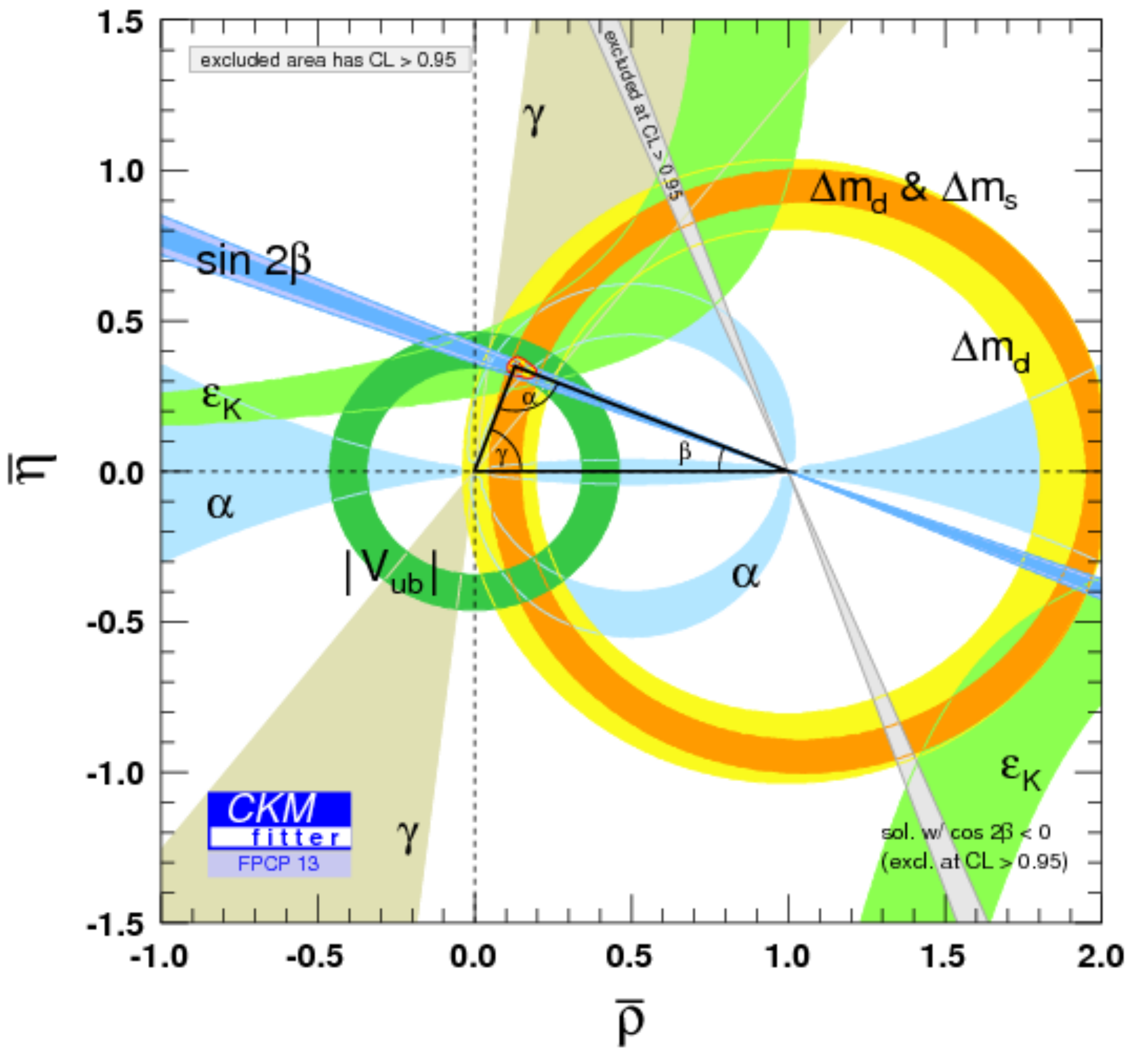

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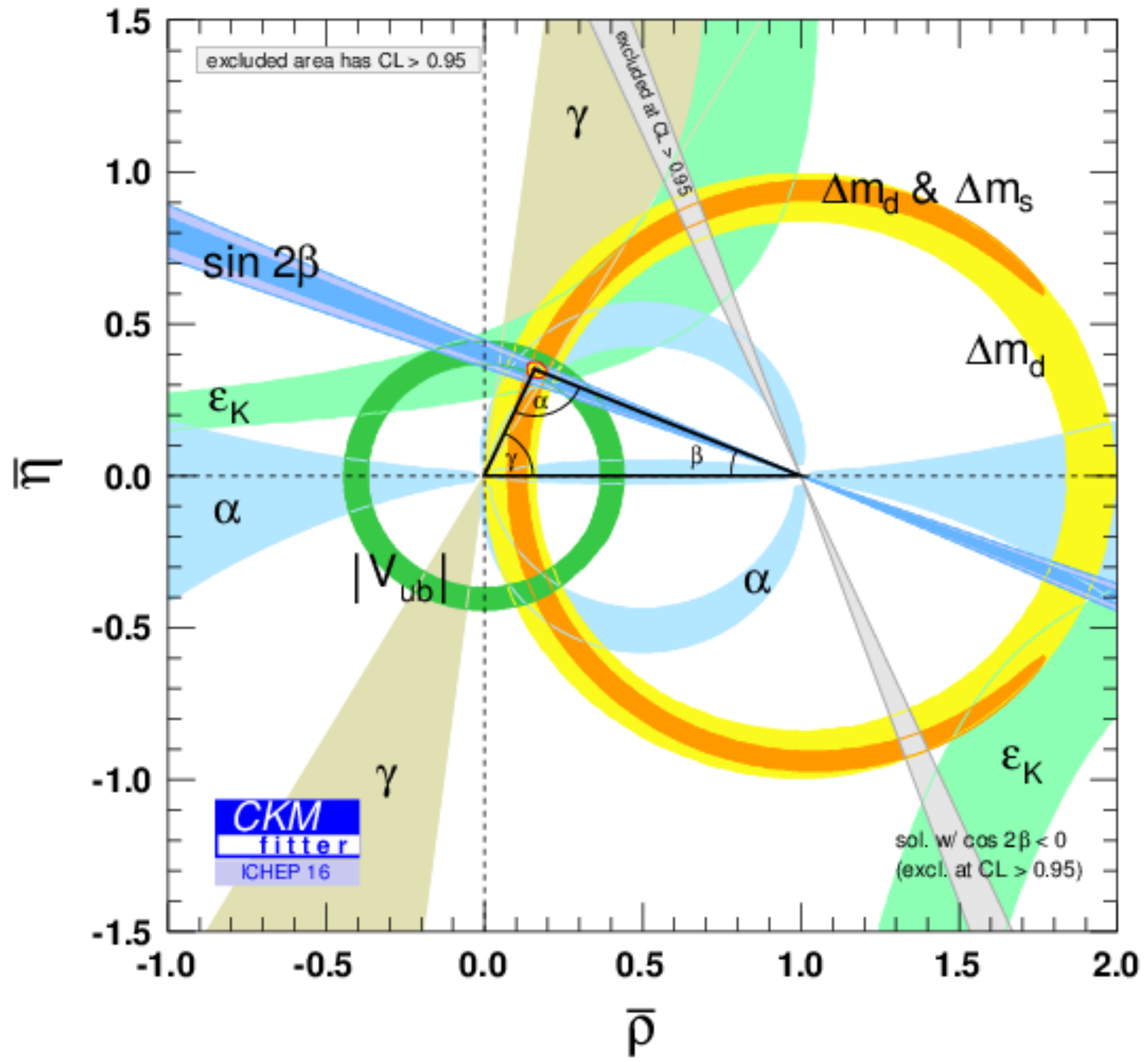


CP violation in one slide

- In the Standard Model, CP violation rises by the CKM mechanism:

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

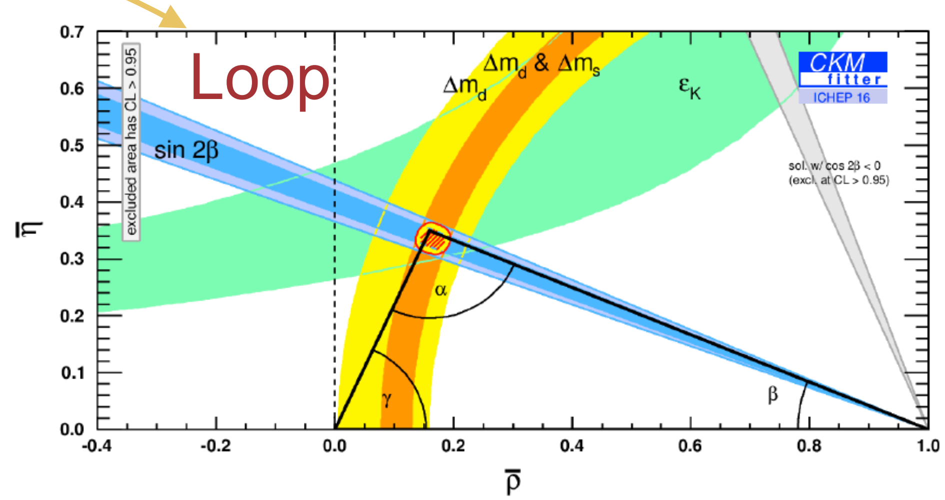
- The complex nature of the CKM matrix is responsible for sizeably CP violation effects in kaons and b-hadron processes
- Tiny effects predicted for charm!
- Angles α, β and γ follow from the orthogonality relation

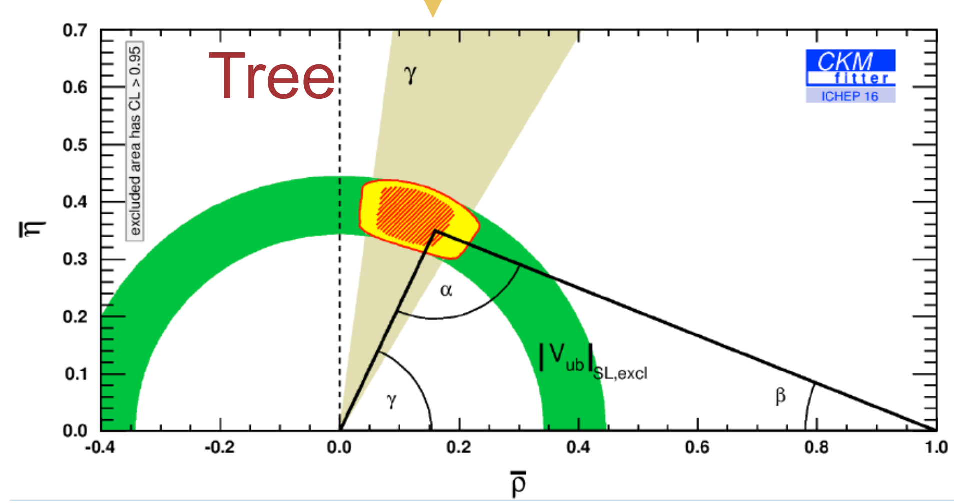
$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$ "The unitary Triangle"

- **Over constraining the Unitary Triangle (sides and angles) is vital to test SM description of CP violation**

γ is the least known angle accessible interference of tree decays

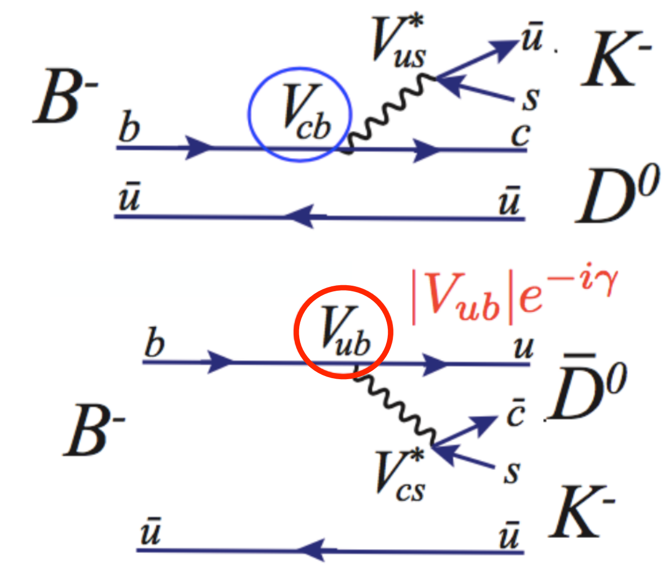
sin(2β) accessible via mixing-decay interference





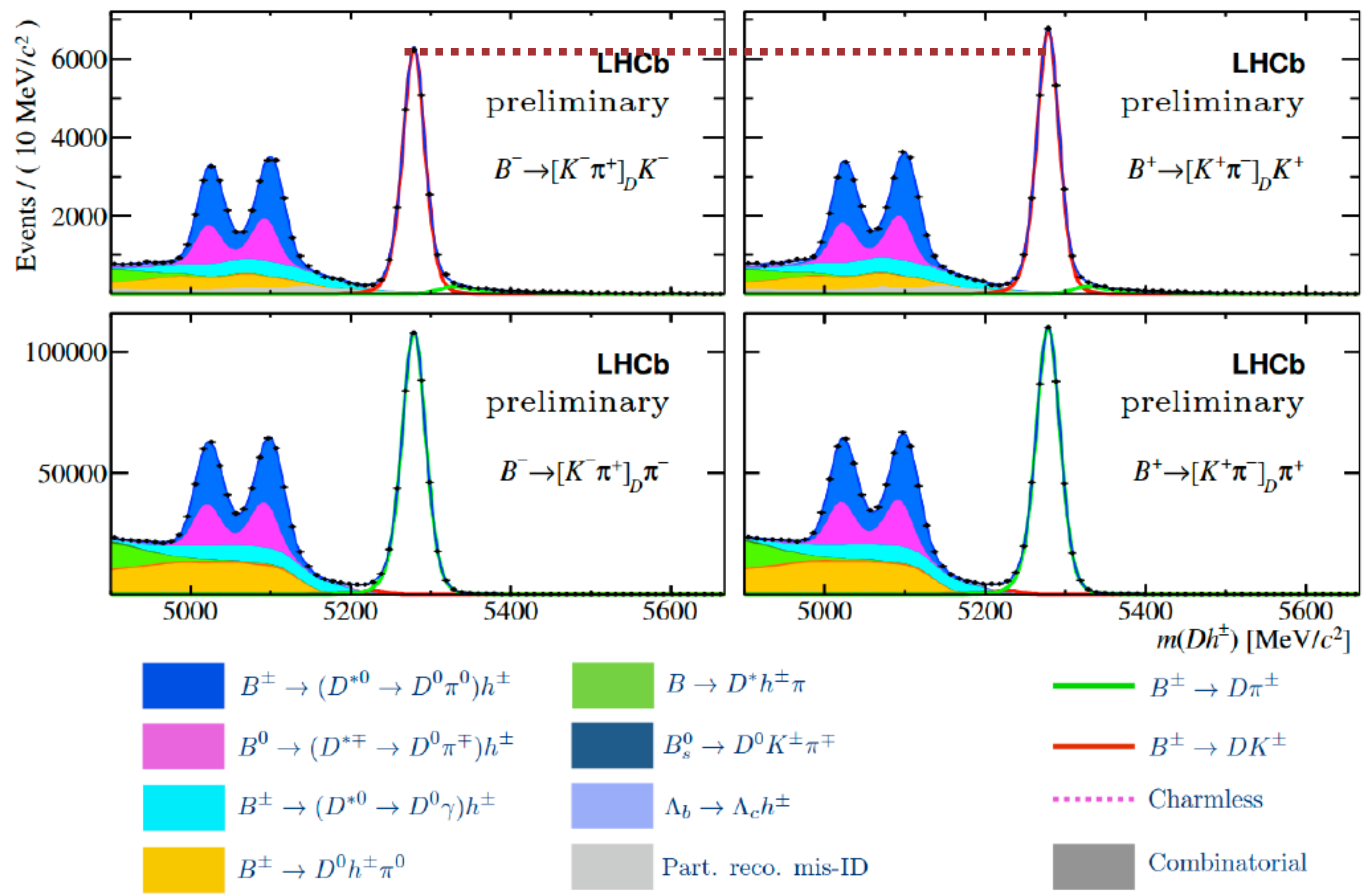
Progresses in angle γ

- its measurement relies on in the interference between b→u and b→ c diagrams – where D^0 and $\bar{D}^0$ go to a common final state
- several methods exist (GLW, ADS, GGSZ,...) depending on the final state used
- need to combine many decay modes!

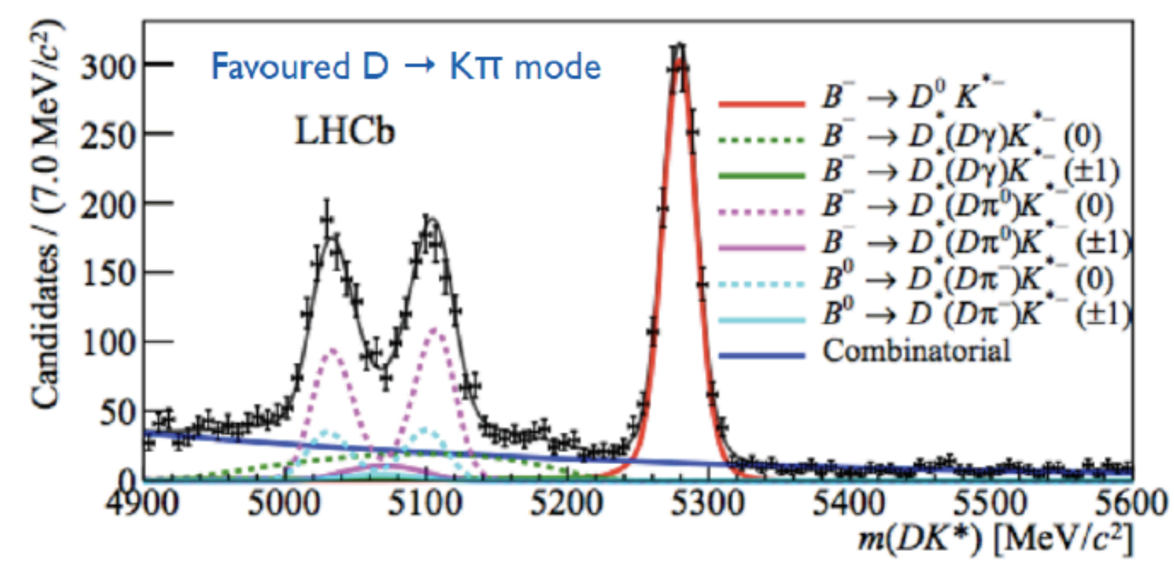


New results using $B^\pm \to D^{(*)0}K^\pm$ and $B^\pm \to DK^{*\pm}$ using full run I ($3fb^{-1}$) + run II data from LHCb

LHCb-PAPER-2017-021



LHCb-PAPER-2017-030



Progresses in angle γ

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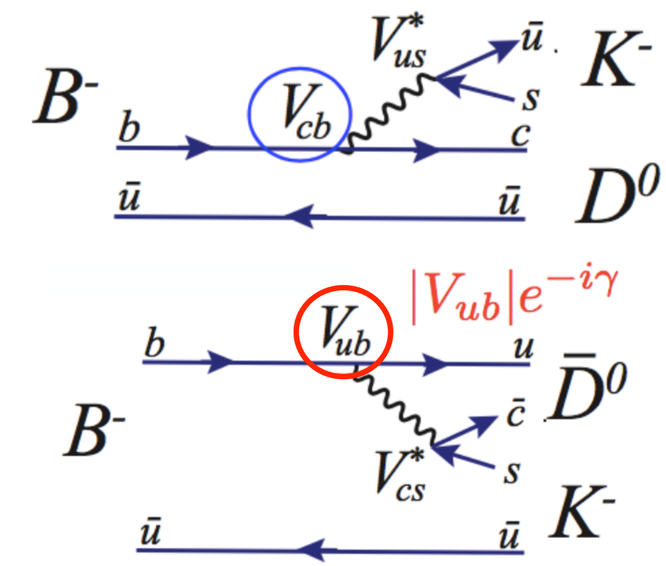
- several methods exist (GLW, A... on the final state
- need to combine

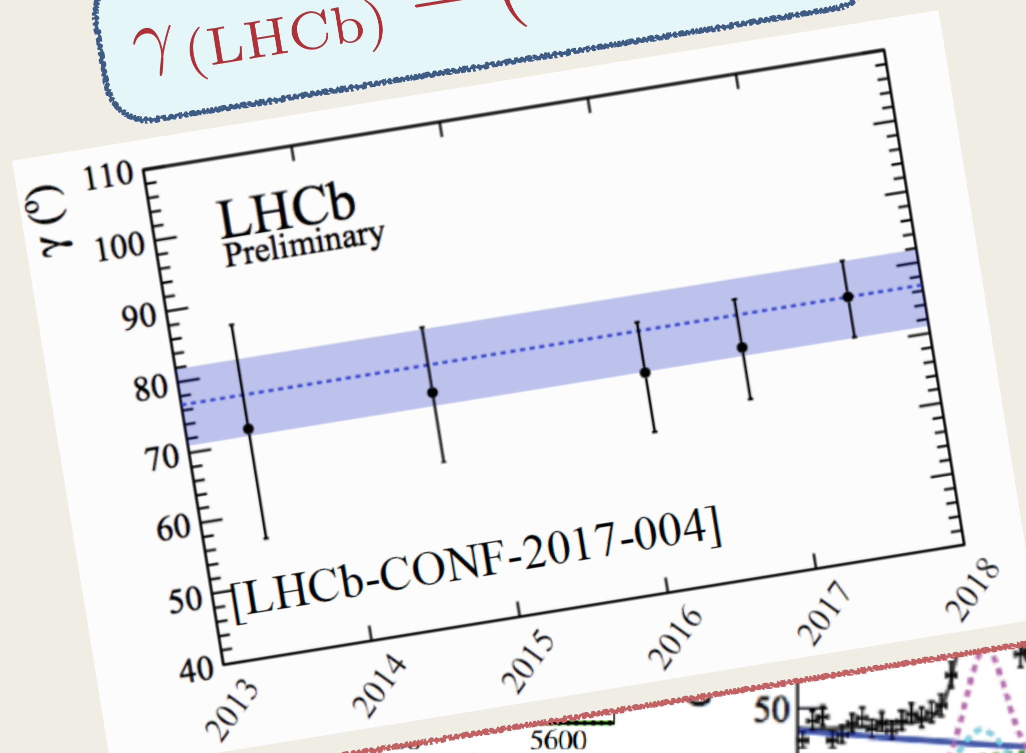


New ... ± using
full r...

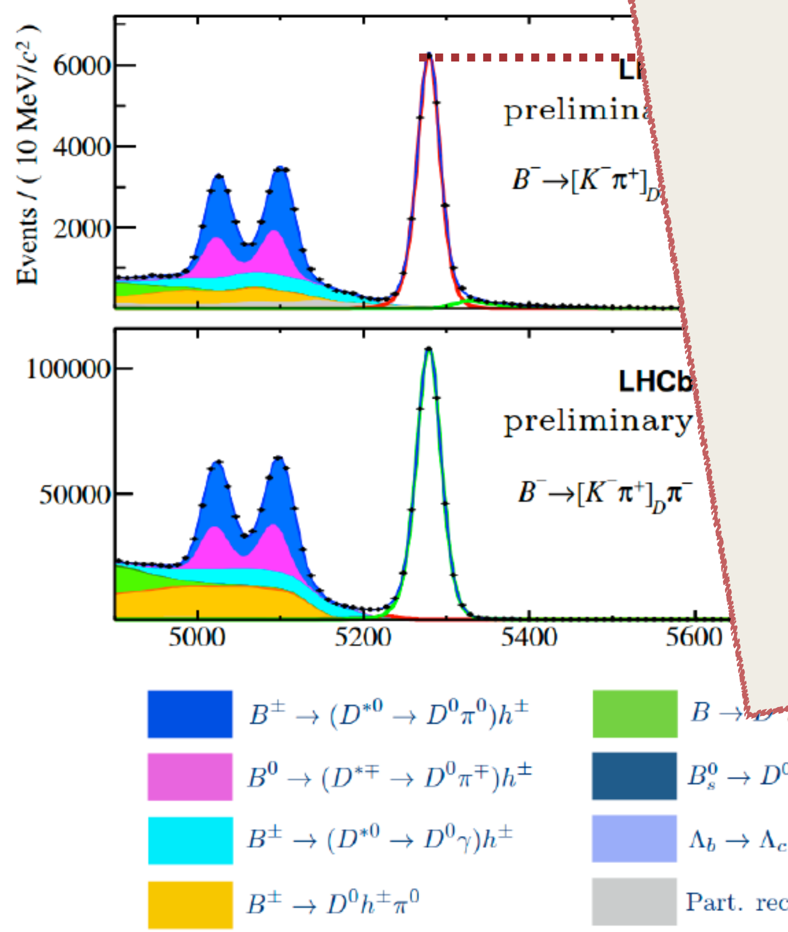
new

γ combination from all LHCb measurements gives the most precise value to date

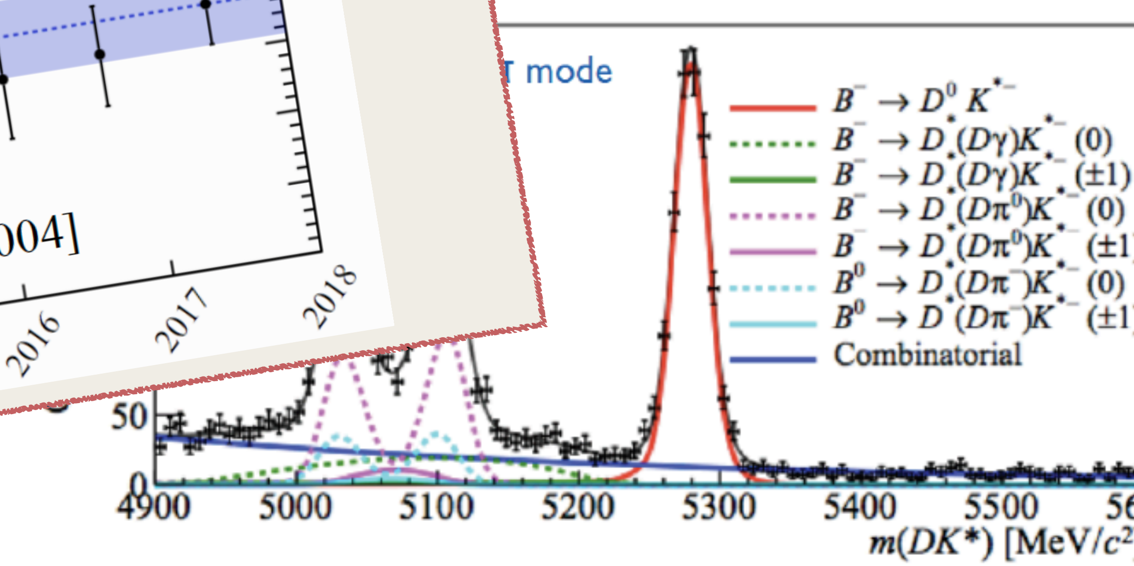
$$\gamma\,(\mathrm{LHCb}) = (76.8^{+5.1}_{-5.7})^\circ$$



LHCb-PAPER-2017-021

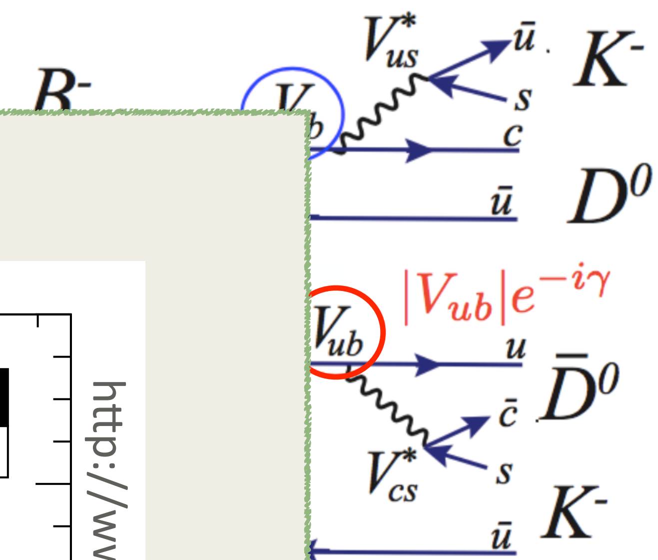


LHCb-PAPER-2017-030

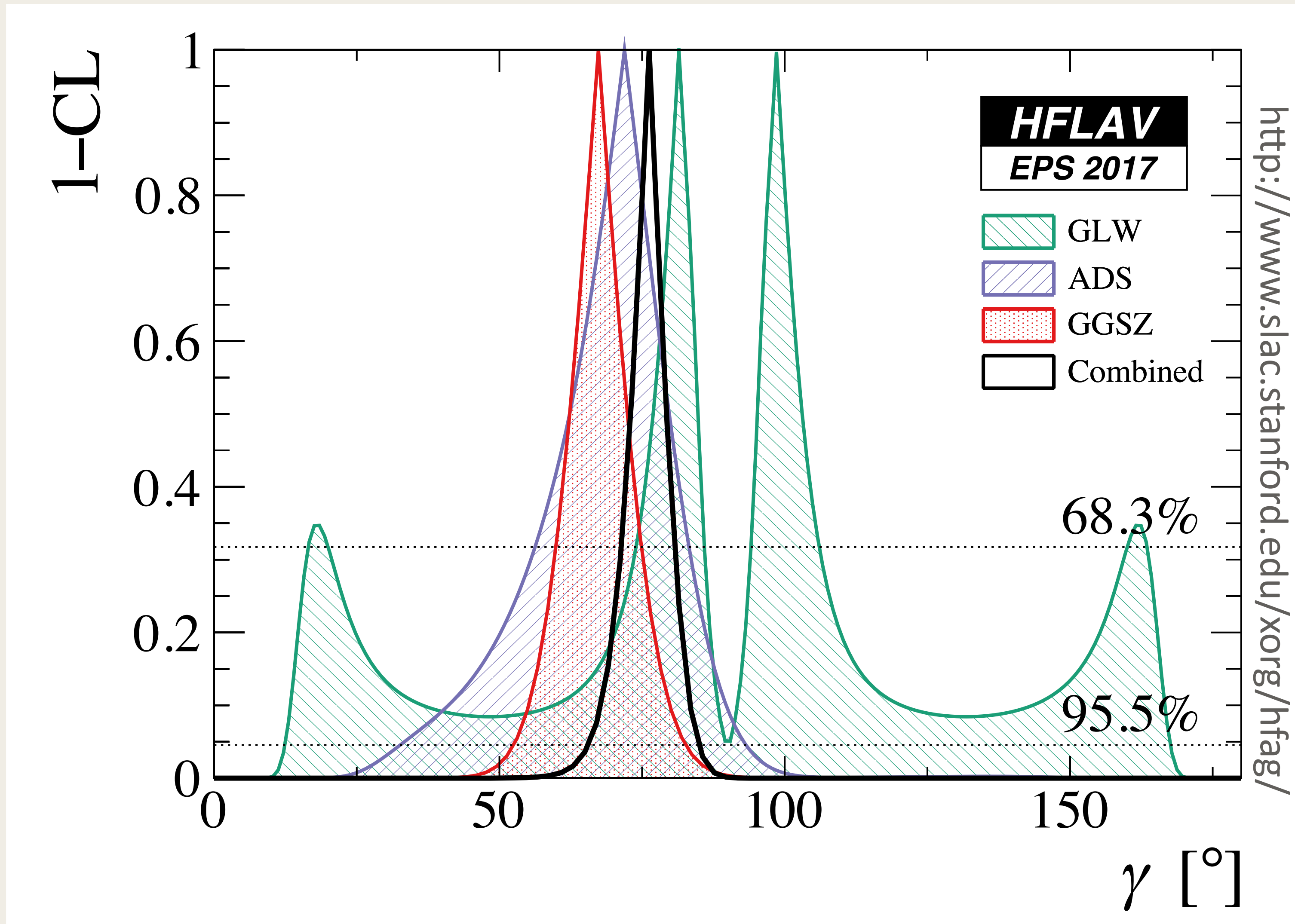


Progresses in angle γ

- its measurement relies on in the interference between $b \to u$ and b… common fi…
- several me… on the fina…
- need to co…

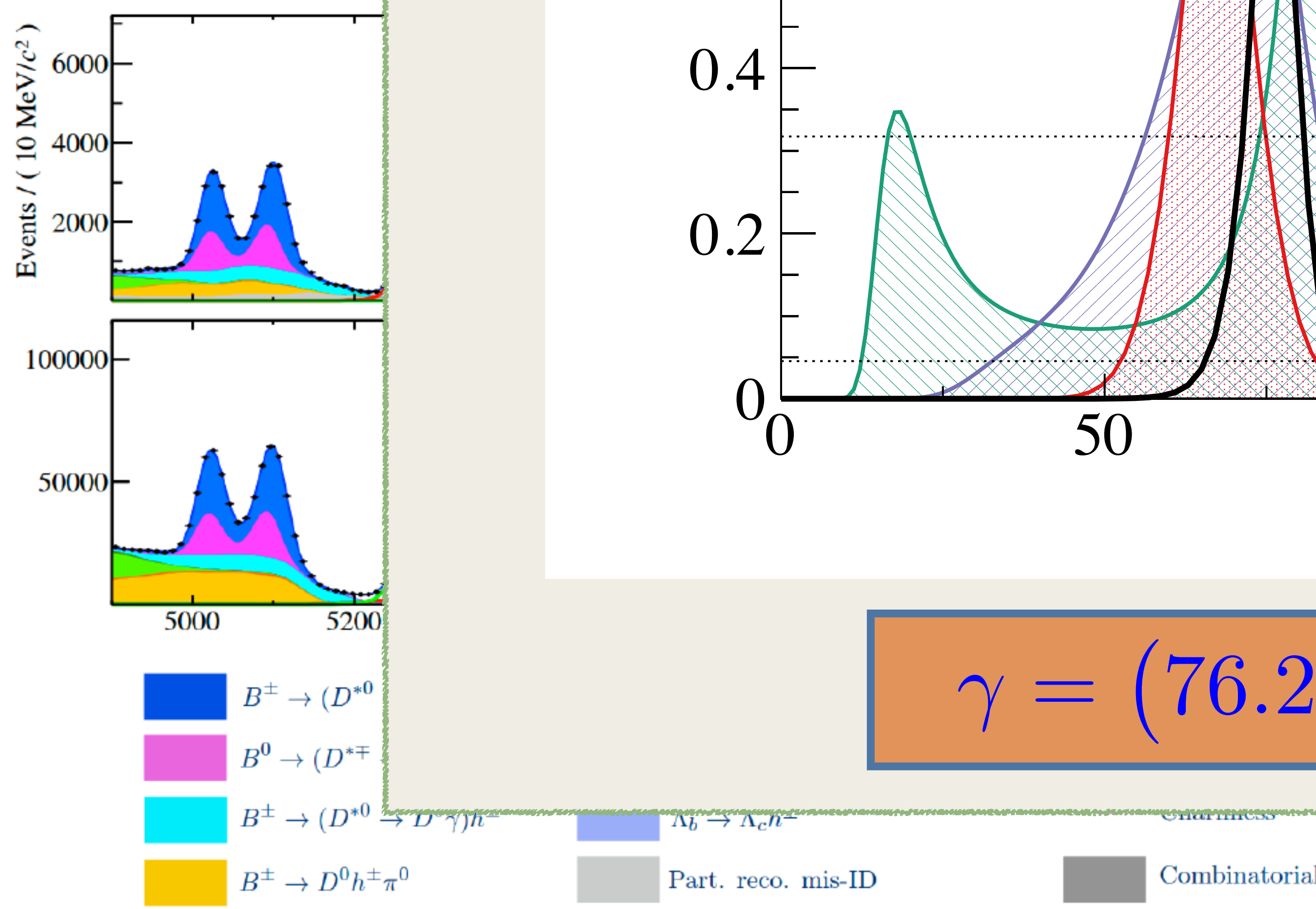


World average by HFLAV

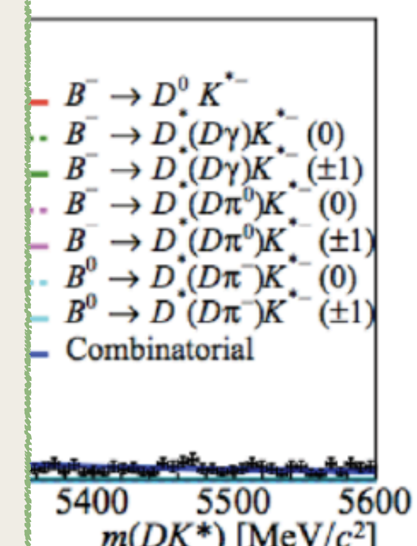


$$\gamma = \left(76.2^{+4.7}_{-5.0}\right)^\circ$$

LHCb-PAPER-2017-021



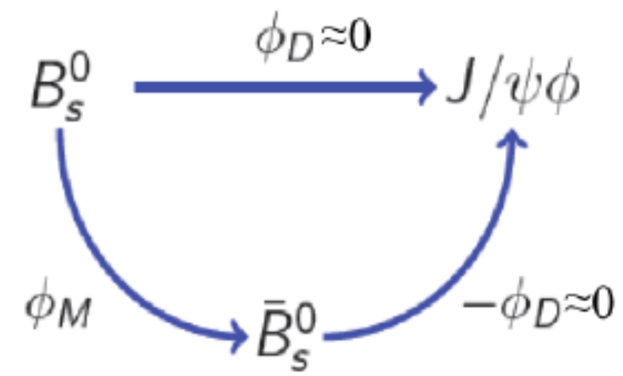
…PER-2017-030



Mixing and CP̸ in B_s: $\Delta\Gamma_s$ and phase φ_s

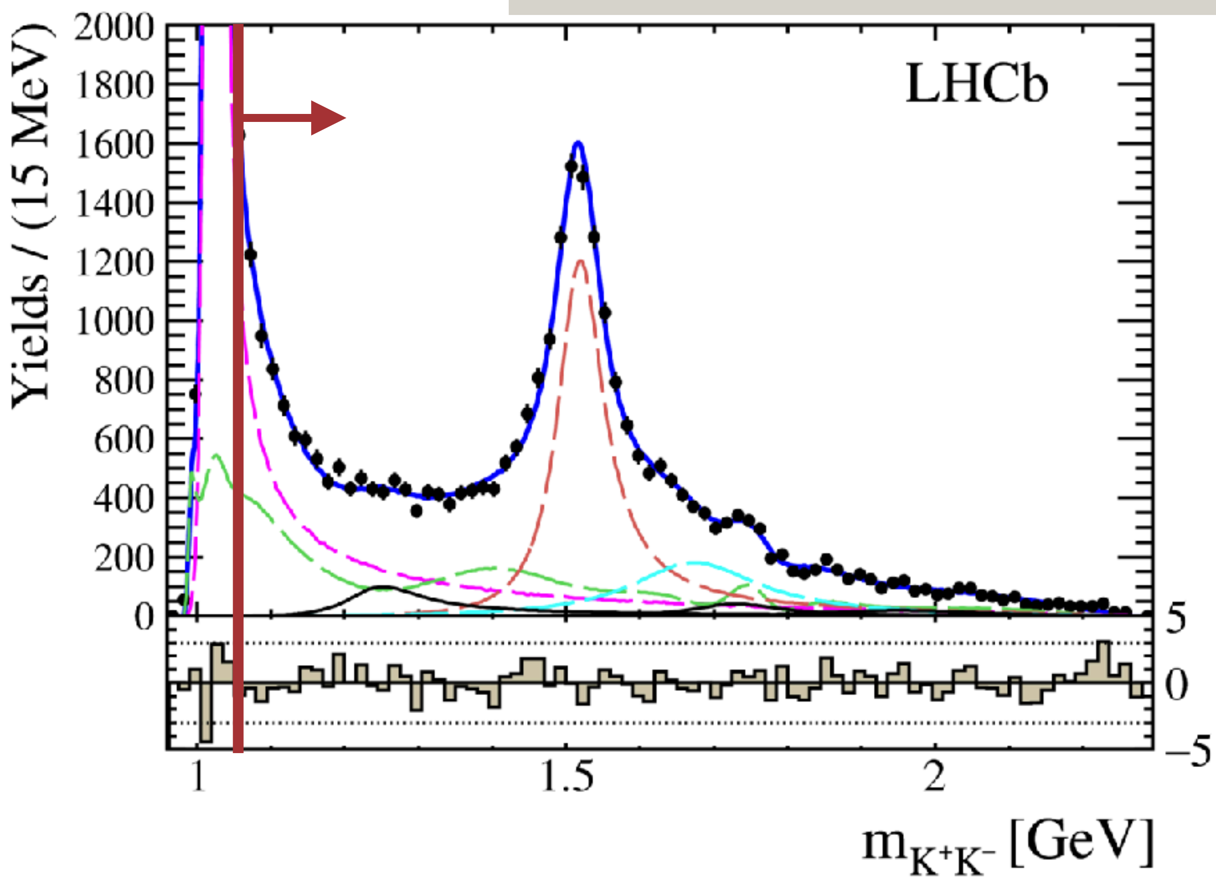
$$\phi_s \overset{SM}{=} -2\beta_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

$\Gamma_s = (\Gamma_L+\Gamma_H)/2 \quad \Delta\Gamma_s = \Gamma_L - \Gamma_H$



- SM predicts φ_s = – 36.3±1.3 mrad
- Appears through the interference between mixing and decay in $B_s \to J/\psi\varphi$
- Good place for search for NP in loops!
- Efforts from many experiments: D0, CMS, ATLAS, CMS and LHCb

New LHCb result: exploits m(KK) > 1.05 GeV



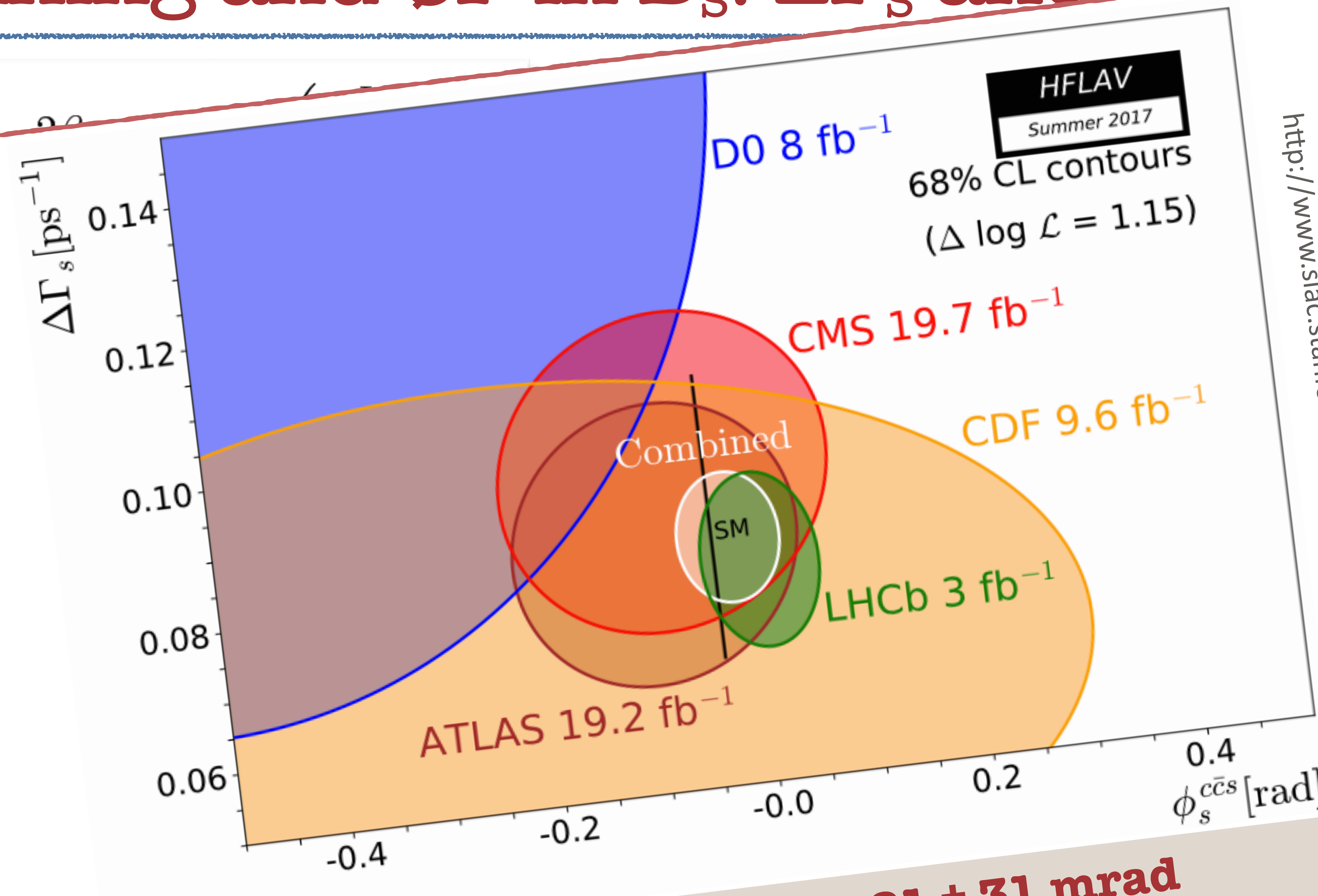
Parameter	Value
Γ_s [ps^{-1}]	$0.650 \pm 0.006 \pm 0.004$
$\Delta\Gamma_s$ [ps^{-1}]	$0.066 \pm 0.018 \pm 0.010$
ϕ_s [mrad]	$119 \pm 107 \pm 34$
$\lvert\lambda\rvert$	$0.994 \pm 0.018 \pm 0.006$

arXiv:1704.08217

- LHCb combined result adding $J/\psi\varphi$, $J/\psi\pi\pi$:

φ_s = 1 ± 37 mrad

Mixing and $\not{C}\not{P}$ in B_s: $\Delta\Gamma_s$ and phase φ_s



φ_s = -21 ± 31 mrad

$\Delta\Gamma_s$ = +0.090±0.005 ps^{-1}

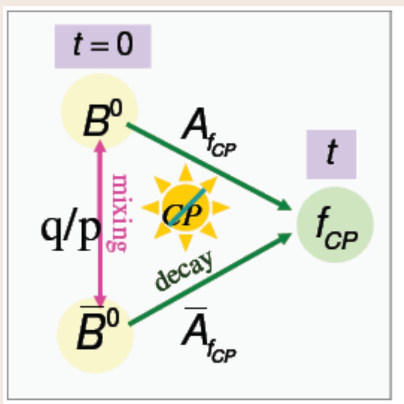
➡ LHCb dominates average

latest results from LHC:
CMS: PLB 757 (2016) 97
ATLAS: JHEP 08 (2016) 147
LHCb: PRL 113 (2014) 211801, PLB 736 (2014) 186, PRL 114 (2015) 041801, PLB 762 (2016) 253, arXiv:1704.08217

… and plenty of other $\not{C}\not{P}$ results

… and plenty of other $\not{CP}$ results

News on sin(2β)

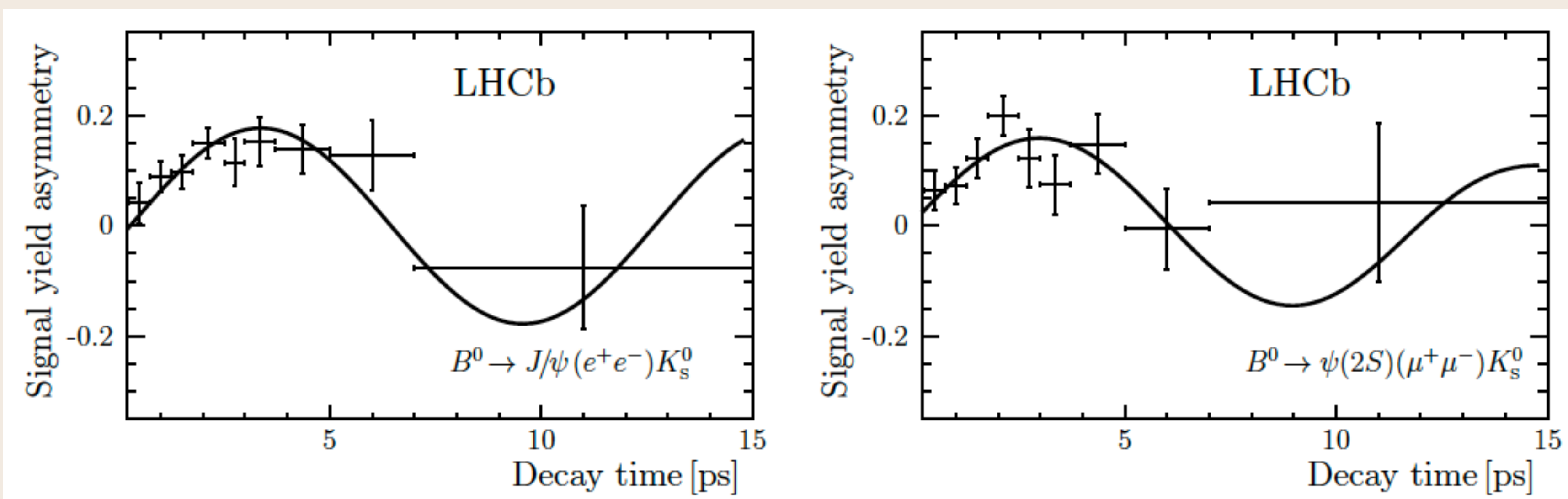


Golden mode $B^0 \to J/\psi(\to\mu^+\mu^-)K_S$

new

LHCb now includes $J/\psi(\to e^+e^-)K_S$ and $\psi(2S)(\to\mu^+\mu^-)K_S$

LHCb-PAPER-2017-029

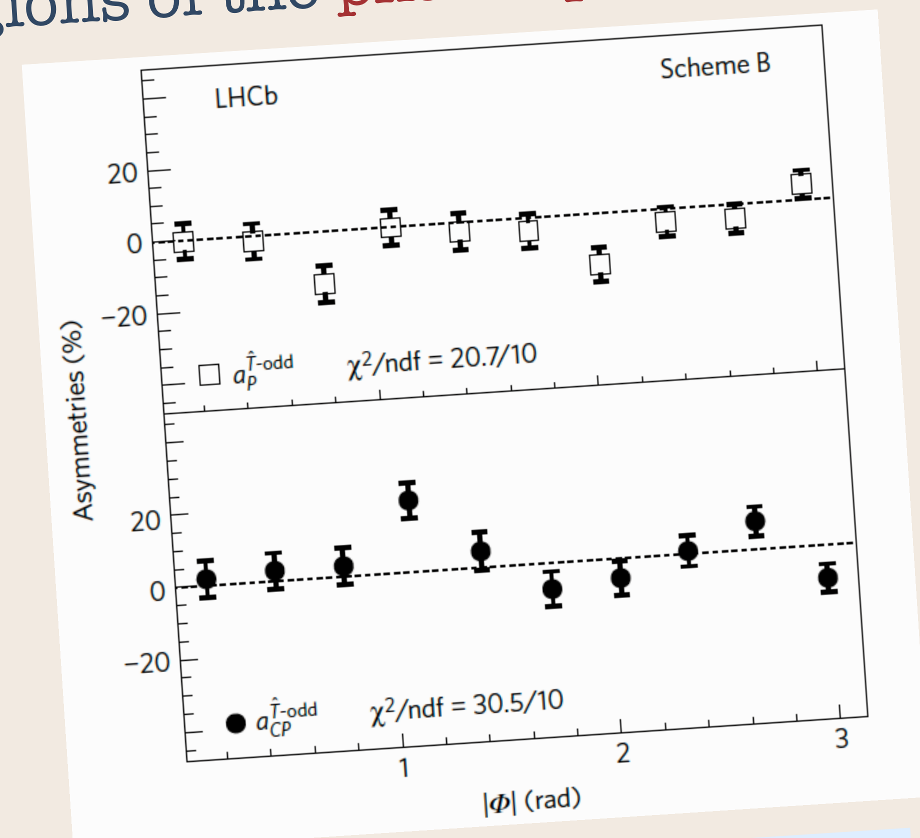


S = +0.758 ± 0.034 C = – 0.017 ± 0.029

… and plenty of other $\not{C}\not{P}$ results

CP Violation in Baryons

- LHCb studies the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^-K^+K^-$ (1st observation) in regions of the phase space



Nature Phys. 13 (2017) 391

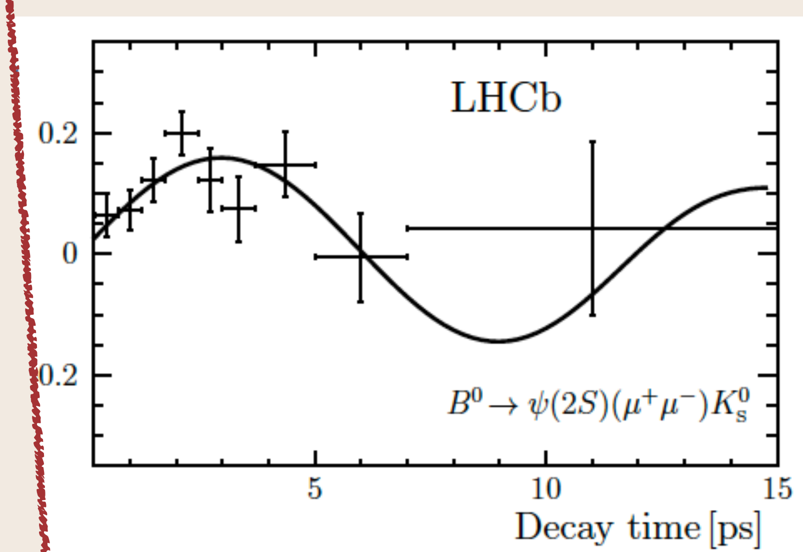
☞ **Evidence for localised CP asymmetries at 3.3σ**

… sin(2β)

… → $J/\psi(\to\mu^+\mu^-)K_S$

…les $J/\psi(\to e^+e^-)K_S$ and

new



LHCb-PAPER-2017-029

C = – 0.017± 0.029

… and plenty of other CP̸ results

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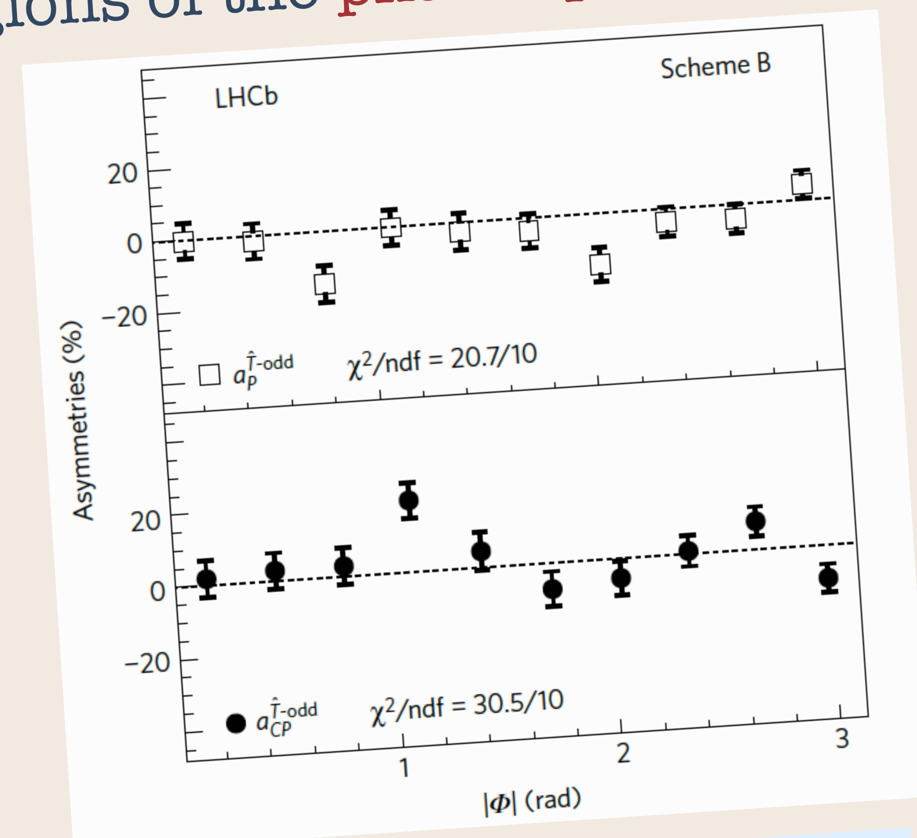


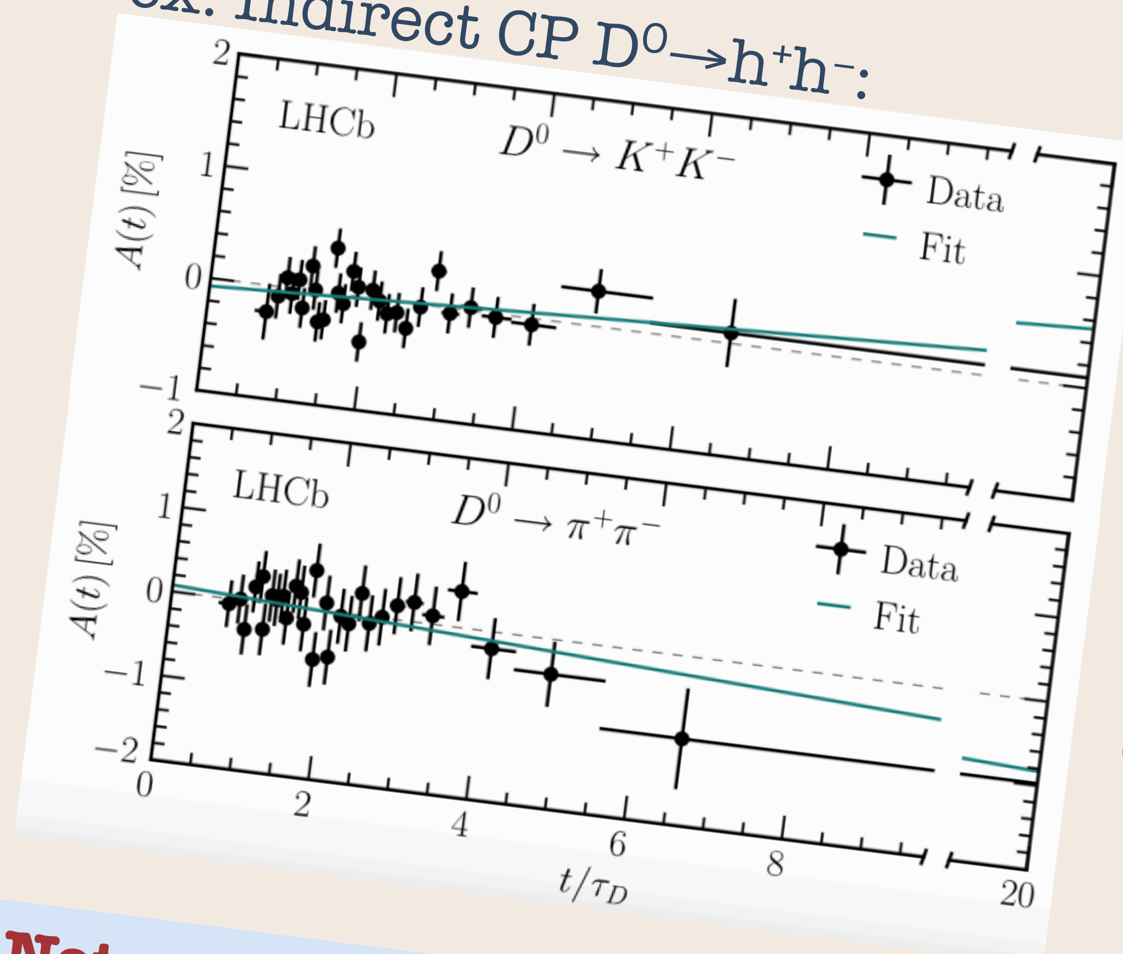
Nature Phys. 13 (2017) 391

☞ **Evidence for localised CP asymmetries at 3.3σ**

Charm Decays

- Tiny expectations within the SM model
- Sensitivities have reached 10^{-3} – 10^{-4} level!

ex: Indirect CP $D^0 \to h^+h^-$:



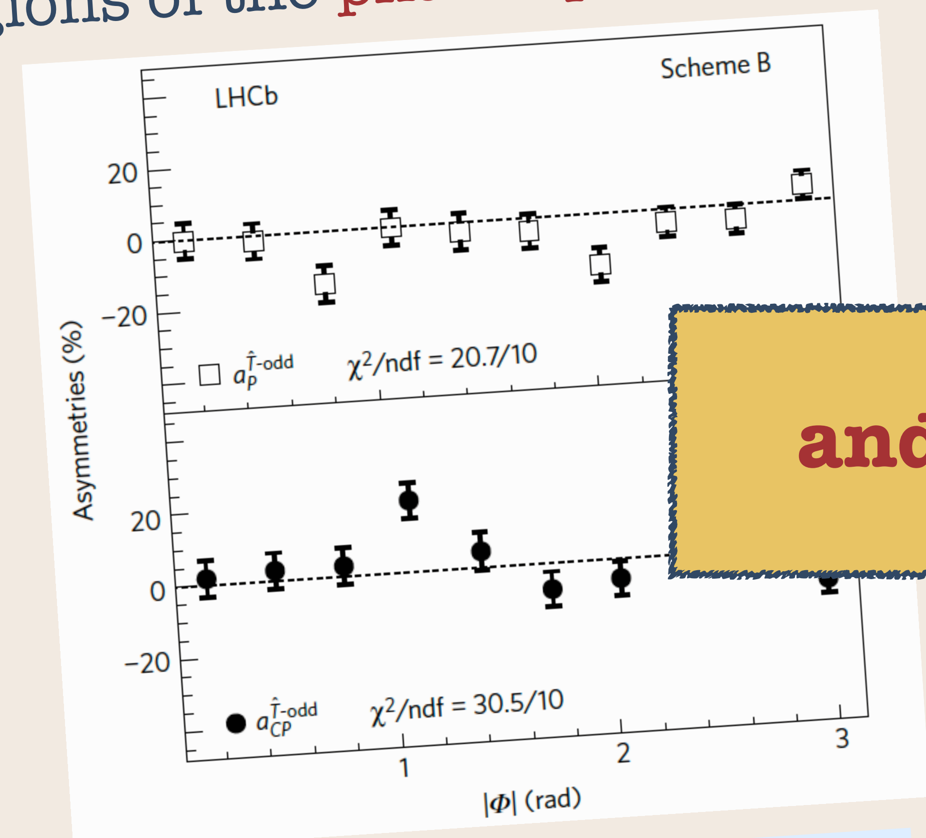
PRL 118 (2017) 261803

Not evidence yet for CP̸ in charm

… and plenty of other $\not{C}\not{P}$ results

CP Violation in Baryons

- LHCb studies the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^-K^+K^-$ (1st observation) in regions of the phase space



Nature Ph… (2017) 391

☞ **Evidence for localised CP asymmetries at 3.3σ**

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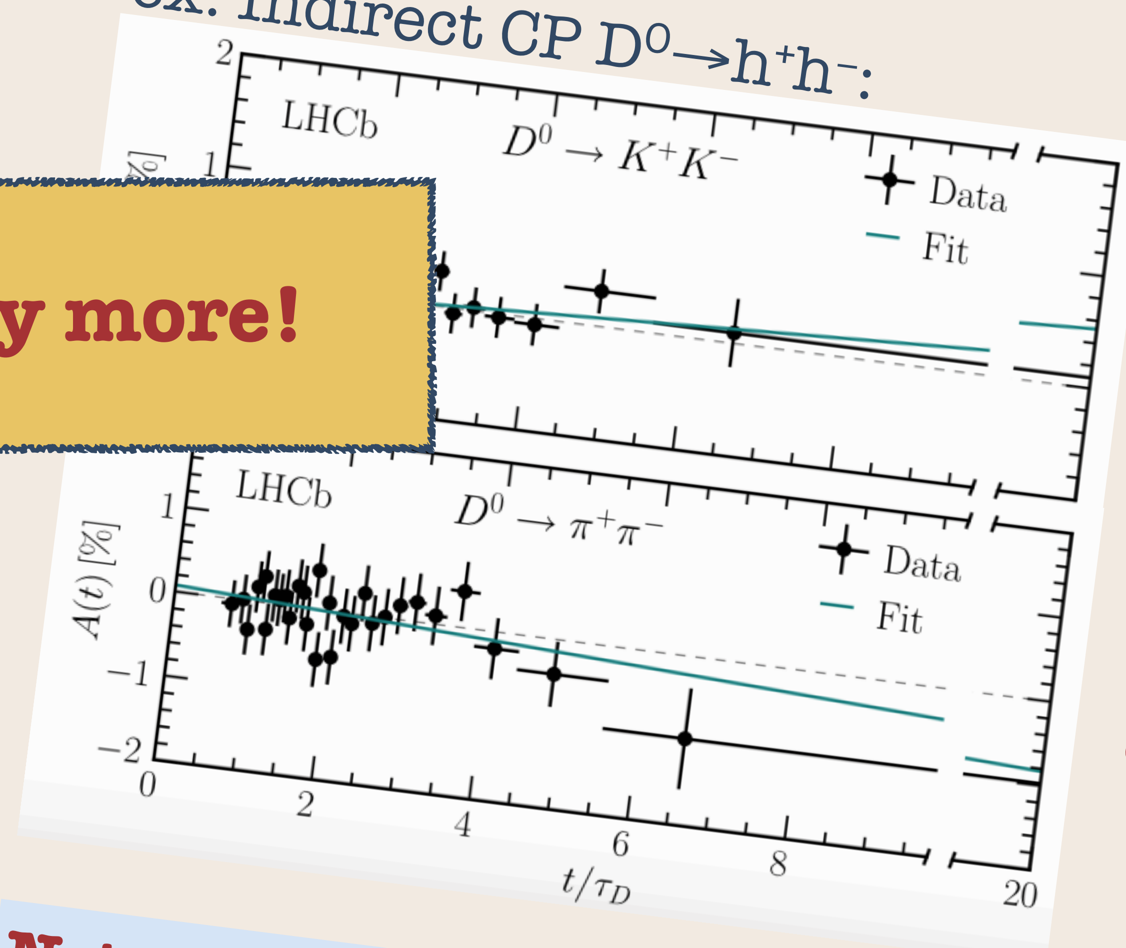


PRL 118 (2017) 261803

Not evidence yet for $\not{C}\not{P}$ in charm

and many more!

Concluding …

- Flavour Physics: a path into the PRECISION FRONTIER
  - ➡ Precise measurements of flavour observables are a key element to test the Standard Model
- A comprehensive study in the heavy quark sector is emerging with many interesting results
  - ➡ "just" QCD is still surprising us with new states
  - ➡ CKM sector responding extremely well to the imposed tests
  - ➡ A few intriguing anomalies at the 2–4σ level in the b-sector involving leptons
- **A flavourful run I in LHC!** And run II is coming strong already

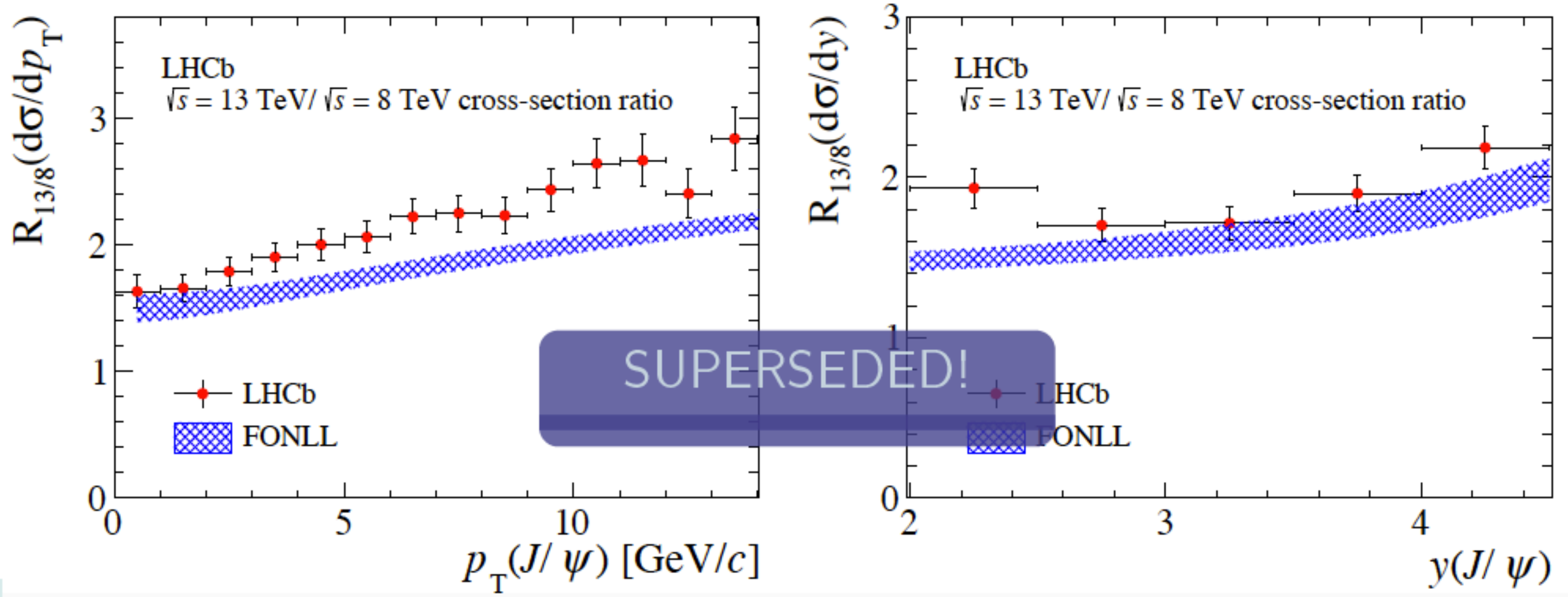
…. and no prejudices: LHC experiments experimenting all roles

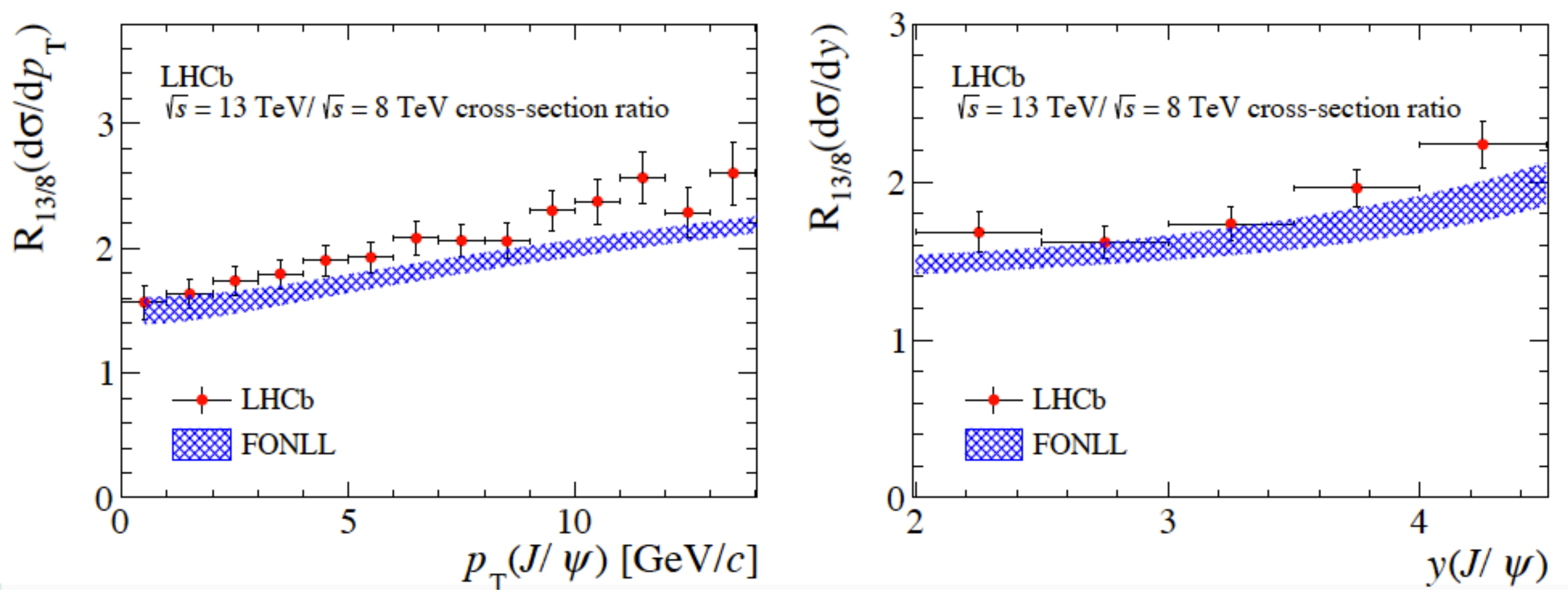
- CMS and ATLAS contributing "beautifully" - competitive in key measurements with di-muons
- LHCb empowering itself in EW bosons, Higgs, heavy ions,… (not mentioned here)
- ALICE with many results on flavour production in pp collisions (not shown here today)

Backups

J/ψ production @ 13 TeV - LHCb

13 to 8 TeV ratio — J/ψ-from-b



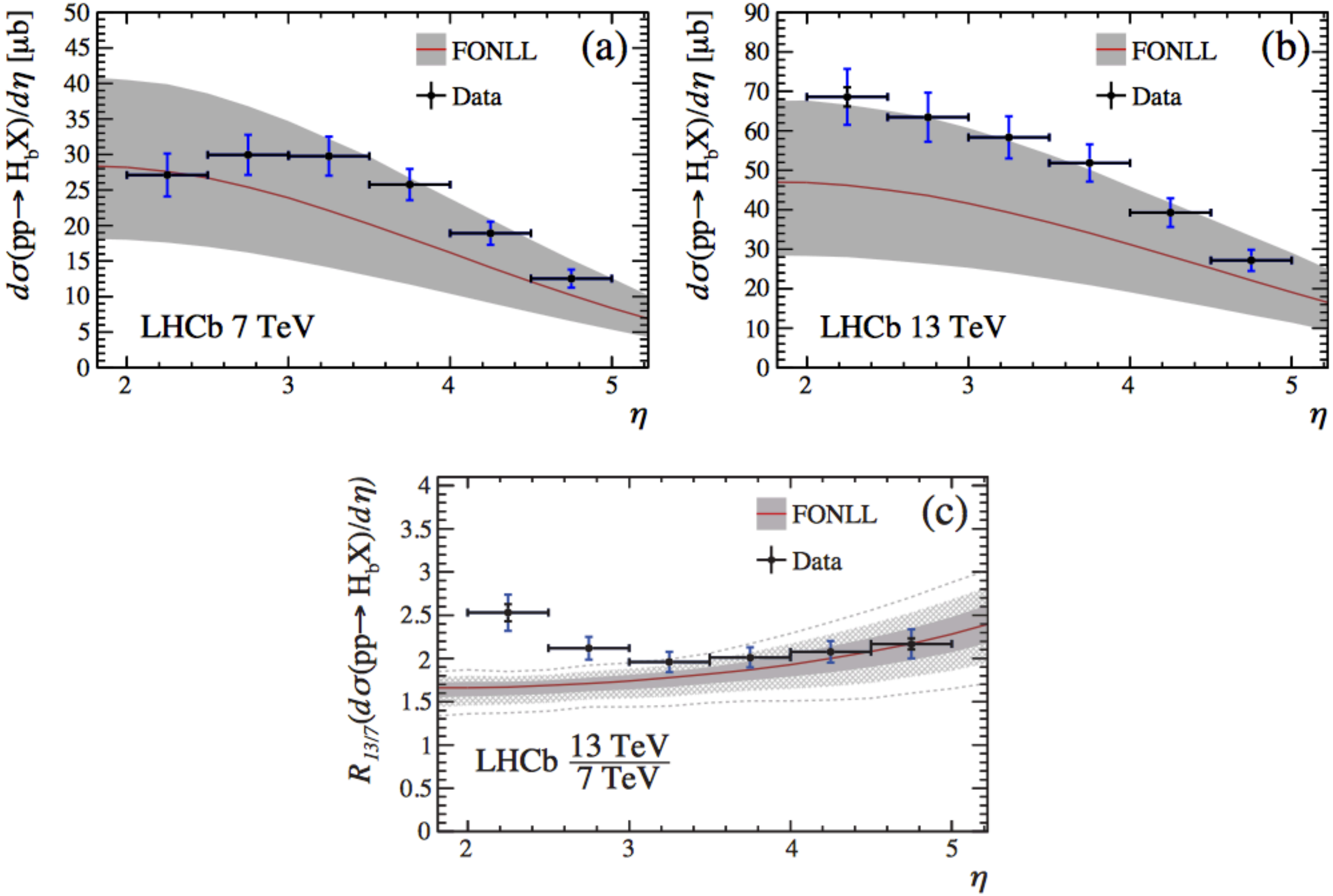


JHEP 10 (2015) 172;
Erratum JHEP 1705 (2017) 063

NRQCD: JHEP 05 (2015) 103
FONLL: JHEP 10 (2012) 137

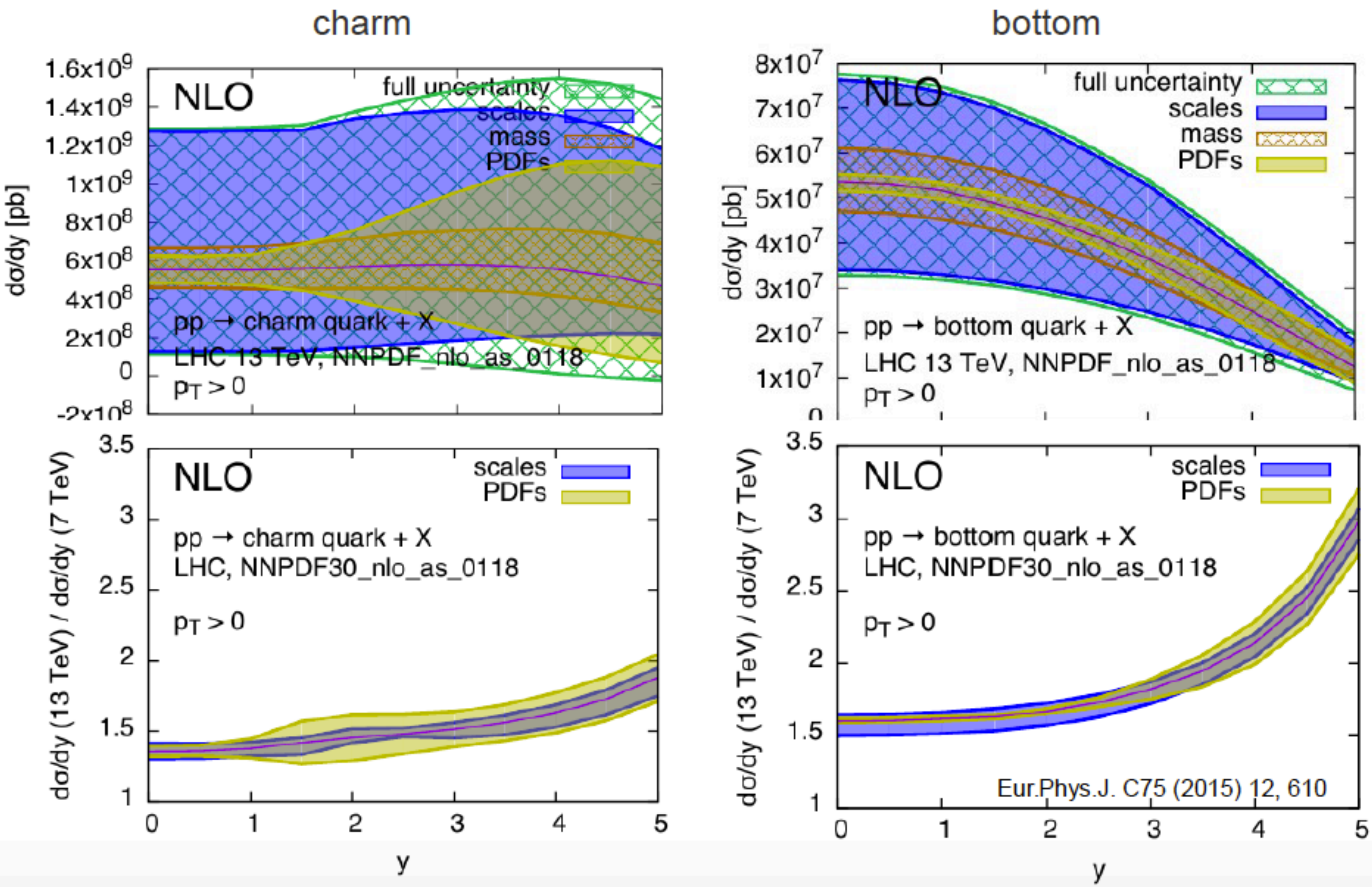
b-hadron cross-section at 7 and 13 TeV

Phys. Rev. Lett. 118, 052002 (2017)



- Erratum being prepared, bug in simulation will affect low η @13 TeV, result will likely be in agreement with FONLL

Cancellation of uncertainties in x-section ratios

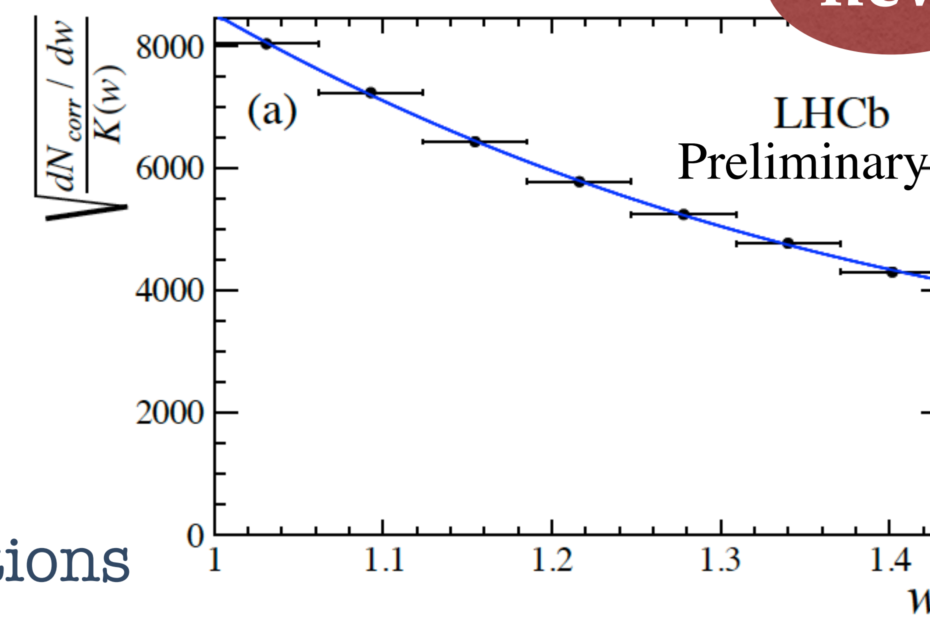


$\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu$ decay rate shape (LHCb)

new

- Decay described by 6 form-factors
- In HQET, these are expressed by the Isgur-Wise (IW) function $\xi_B(w)$

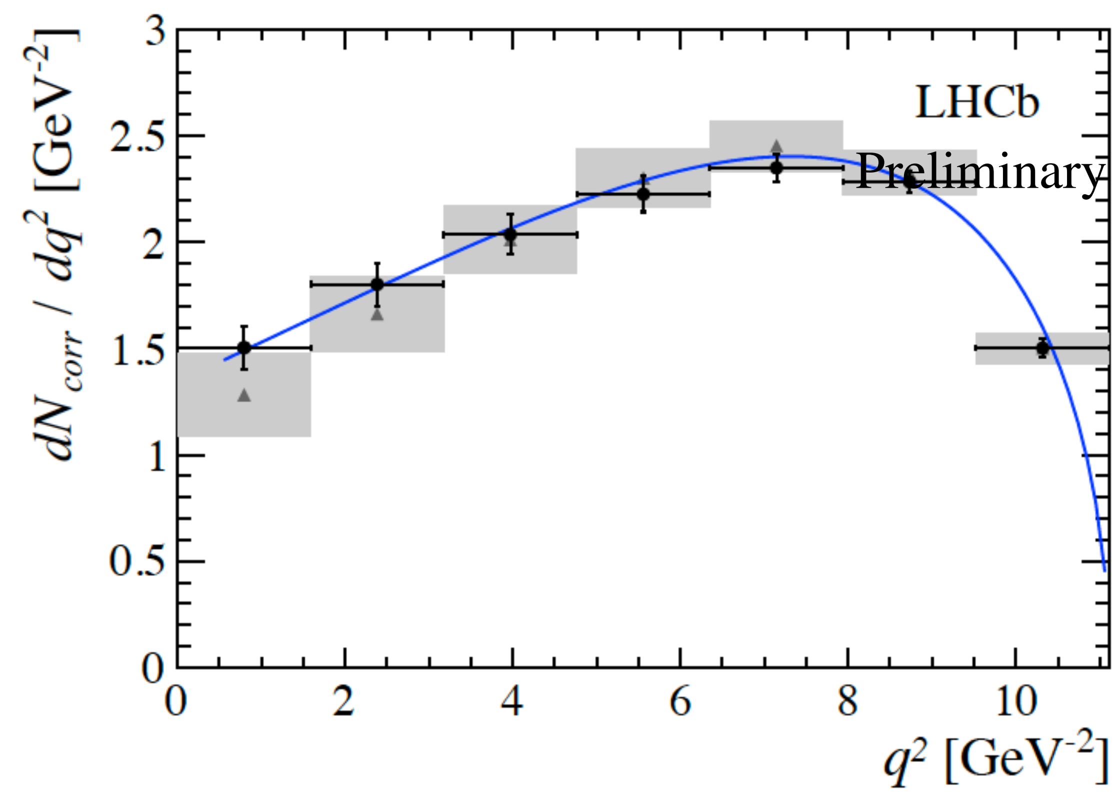
$$\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w) \qquad w = \frac{m^2_{\Lambda_b^0} + m^2_{\Lambda_c^+} - q^2}{2m_{\Lambda_b^0} m_{\Lambda_c^+}}$$



LHCb-PAPER-2017-016

- Slope of $\xi_B(w)$ at $w = 1$ (zero recoil) - ρ^2 : predictions coming from different approaches

Model	ρ^2
Lattice [1]	$1.2^{+0.8}_{-1.1}$
QCD sum rules [2]	1.35 ± 0.13
HQET [2]	1.51



- LHCb obtains

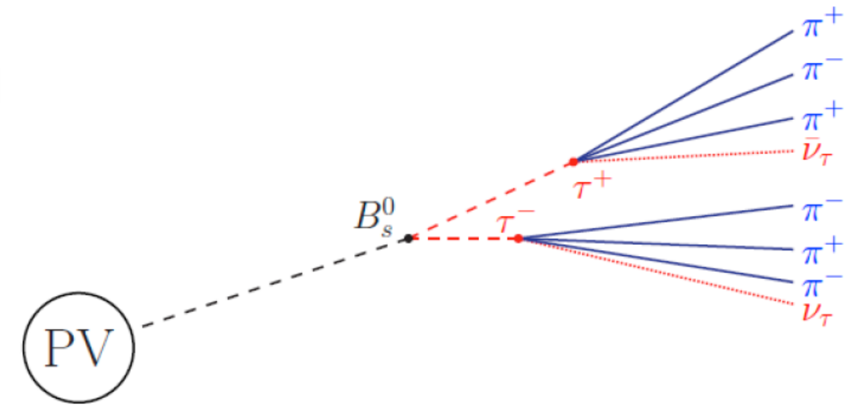
$$\rho^2 = 1.63 \pm 0.07 \pm 0.08$$

- agrees well with predictions
- Lattice (grey) provides very good description, as well as single form-factor (blue, HQET)
- Precise determination of $|V_{cb}|$ in the future, with normalisation channel

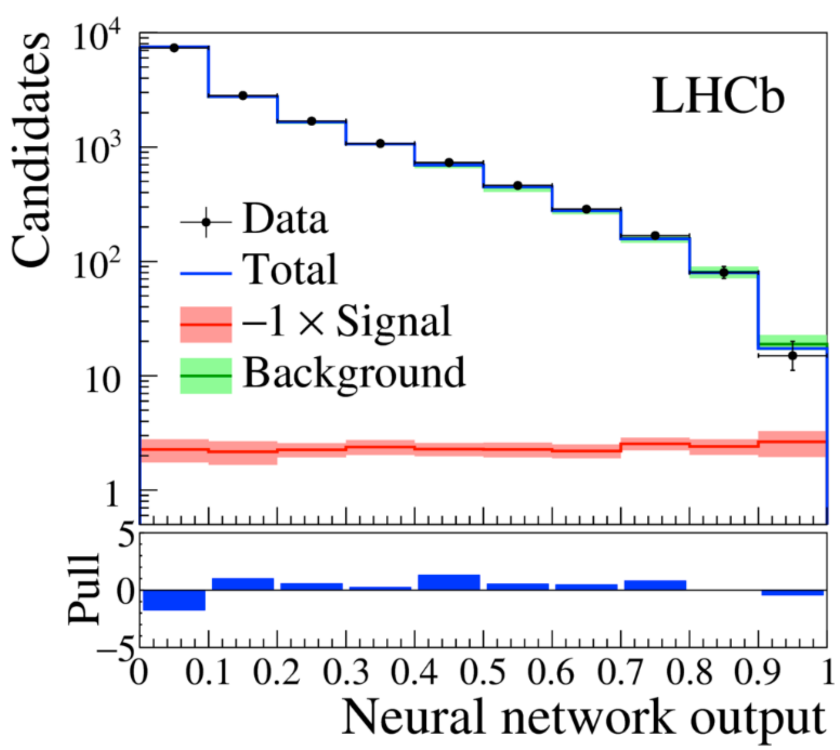
$B_{(s)} \to \tau^+ \tau^-$

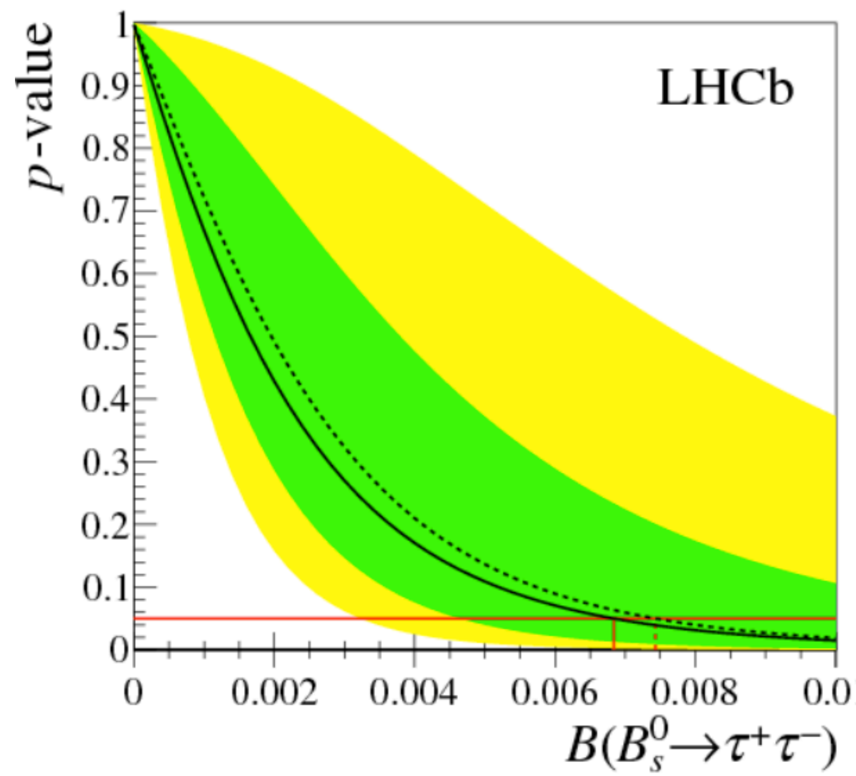
- Higher expected branching ratios than $B_{(s)} \to \mu\mu$

$$\mathcal{B}(B^0 \to \tau^+\tau^-)_{\rm SM} = (2.22 \pm 0.19) \times 10^{-8}$$
$$\mathcal{B}(B^0_s \to \tau^+\tau^-)_{\rm SM} = (7.73 \pm 0.49) \times 10^{-7}$$



- But very challenged due to the neutrinos in the final state
- LHCb reconstruct as $\tau \to \pi\pi\pi\,\nu$, with full run I data





PRL 118 (2017) 251802

- Best limit for $B^0 \to \tau^+\tau^-$ and First limit for $B_s \to \tau^+\tau^-$:

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

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ @ } 95\% CL$$

$K_S \to \mu^+\mu^-$ search - LHCb

new

- K_S has a very tiny BR predicted by the SM

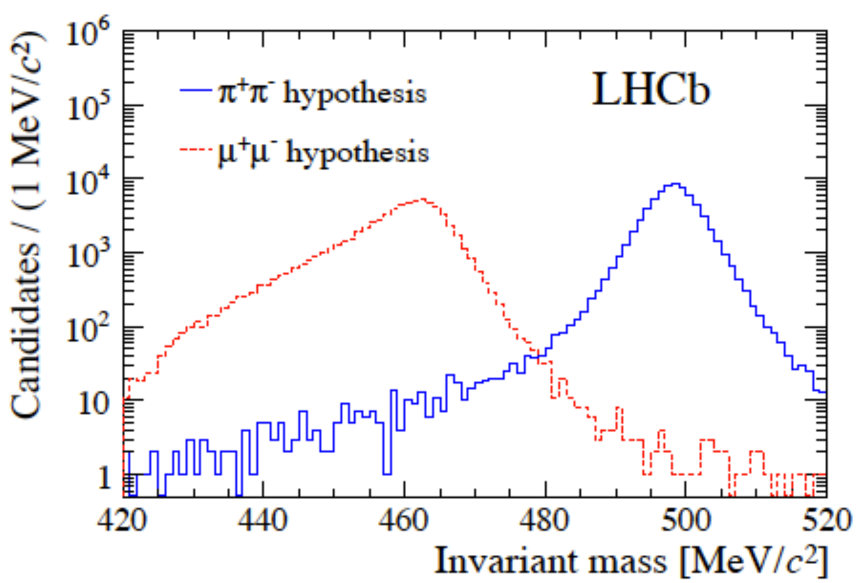
$$\mathcal{B}(K^0_S \to \mu^+\mu^-)_{SM} = (5.0 \pm 1.5) \times 10^{-12}$$

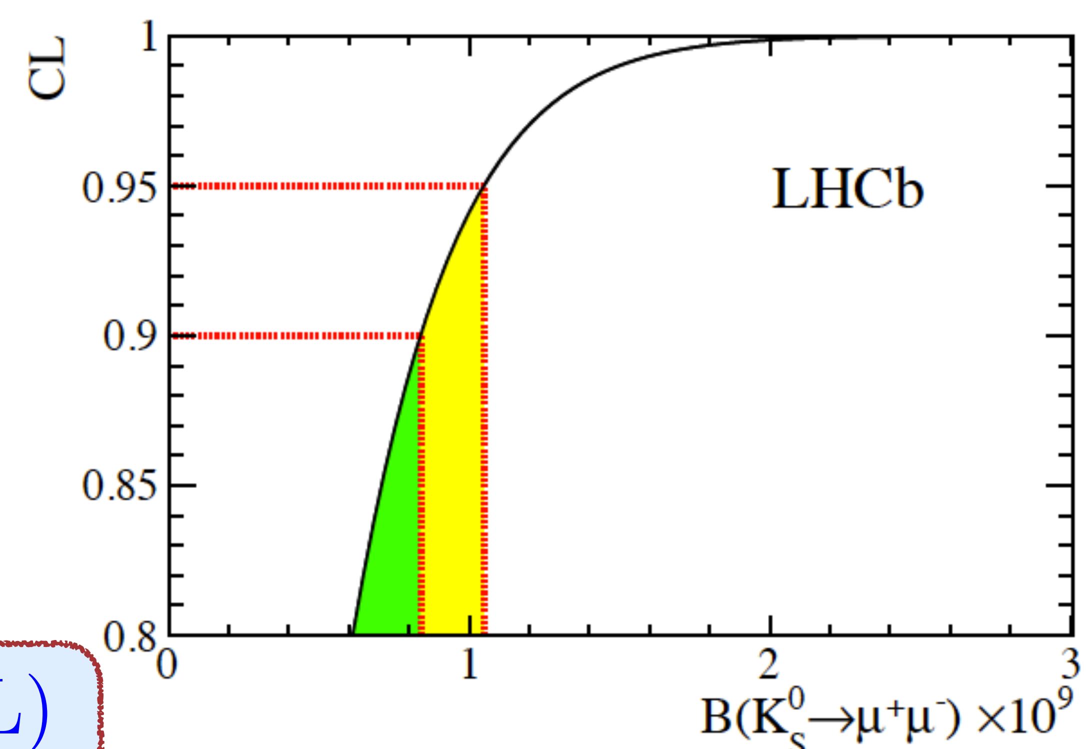
Isidori et al, JHEP 01(2004) 009

  - ➡ a flavour-changing neutral current (FCNC) process, further supressed due to small CP violation; dominated by long-distance effects

- New Physics (NP) with scalars could enhance the BR up to 10^{-10}, with a 10^{-11} observation not conflicting with present bounds in other FCNC processes
- Previous best limit set by LHCb (1 fb^{-1}): 9.0×10^{-9} (90%CL)

New LHCb analysis: full run I data (3 fb^{-1})



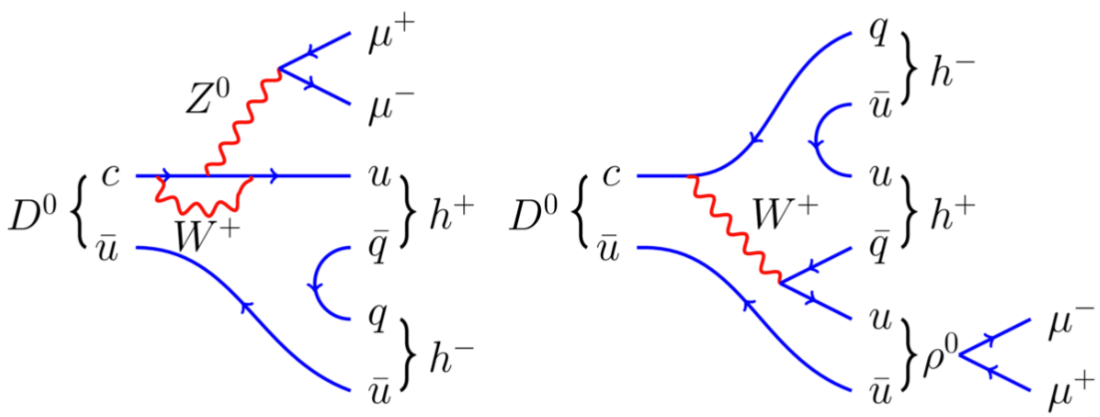


arXiv:1706.00758

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 1.0 \times 10^{-9} \quad (95\%\ \text{CL})$$

Observation of $D^0 \to h^+h^-\mu^+\mu^-$ - LHCb

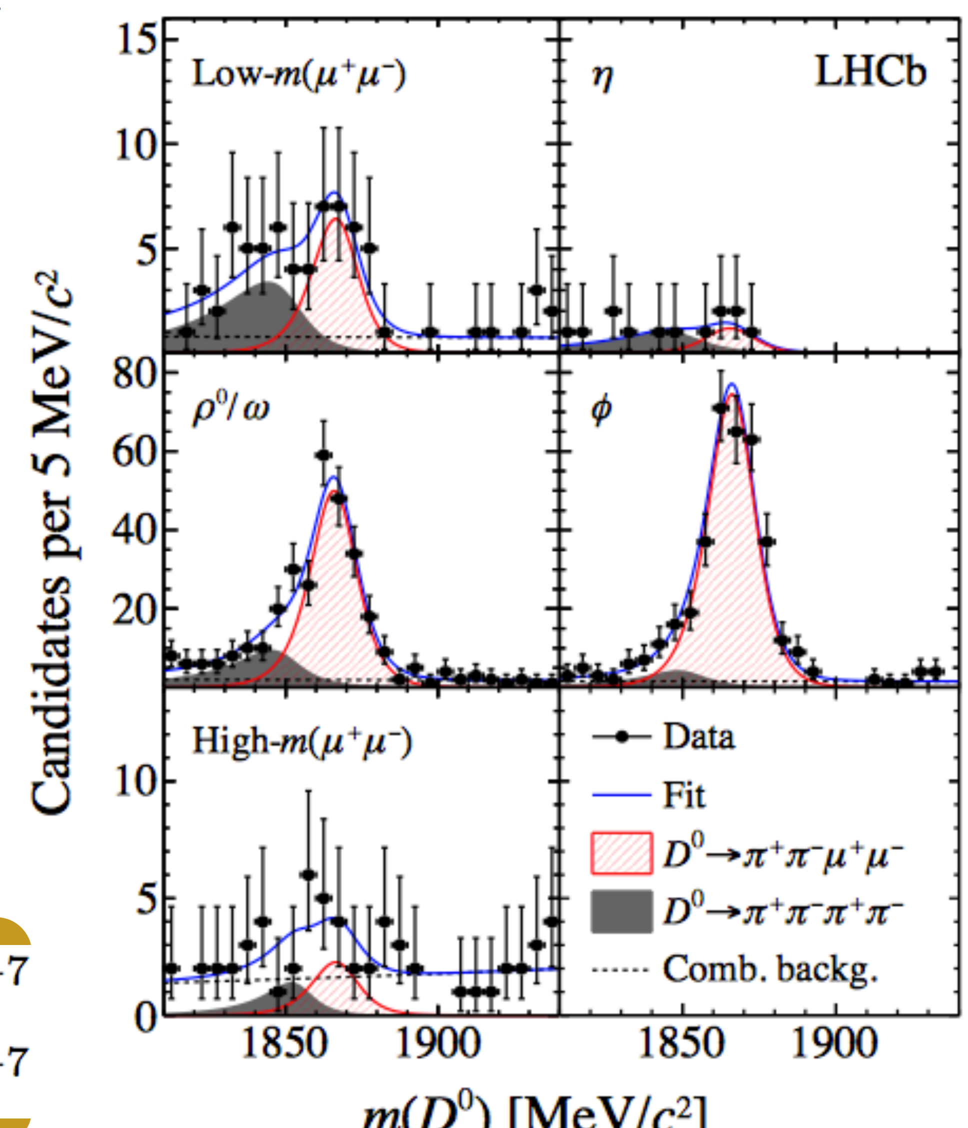
- $D^0 \to K^+K^-\mu^+\mu^-$ and $D^0 \to \pi^+\pi^-\mu^+\mu$ searched for with 2 fb^{-1} @ 8 TeV



- In the SM, short-distance contributions (away from resonances) expected at $\mathcal{O}(10^{-2})$
- but long-distance effects, with resonances decaying to μμ, can enhance rates considerably

First observation reported by LHCb!

$D^0 \to \pi^+\pi^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	< 525	$7.8 \pm 1.9 \pm 0.5 \pm 0.8$
η	525–565	$< 2.4\ (2.8)$
ρ^0/ω	565–950	$40.6 \pm 3.3 \pm 2.1 \pm 4.1$
ϕ	950–1100	$45.4 \pm 2.9 \pm 2.5 \pm 4.5$
High mass	> 1100	$< 2.8\ (3.3)$
$D^0 \to K^+K^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	< 525	$2.6 \pm 1.2 \pm 0.2 \pm 0.3$
η	525–565	$< 0.7\ (0.8)$
ρ^0/ω	> 565	$12.0 \pm 2.3 \pm 0.7 \pm 1.2$



$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

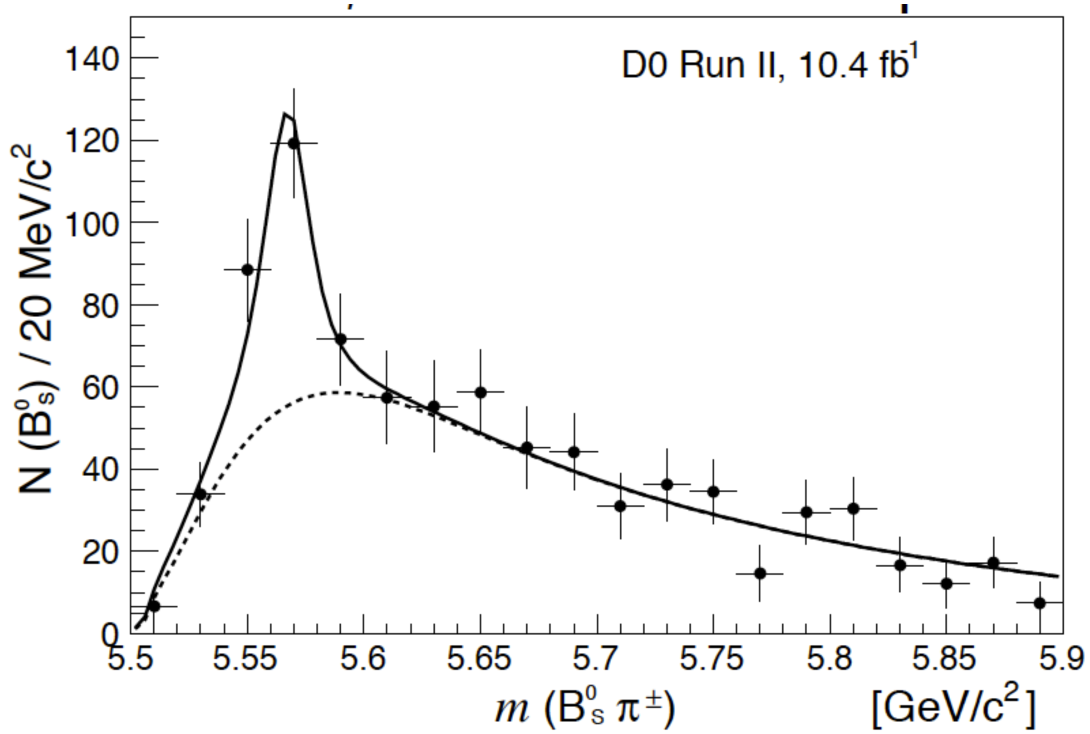
The puzzled X(5568): new $B_s^0 \pi^\pm$ state ?

- D0 observed a peak in the $B_s^0(\to J/\psi\ \varphi)\,\pi^\pm$ mass spectrum:

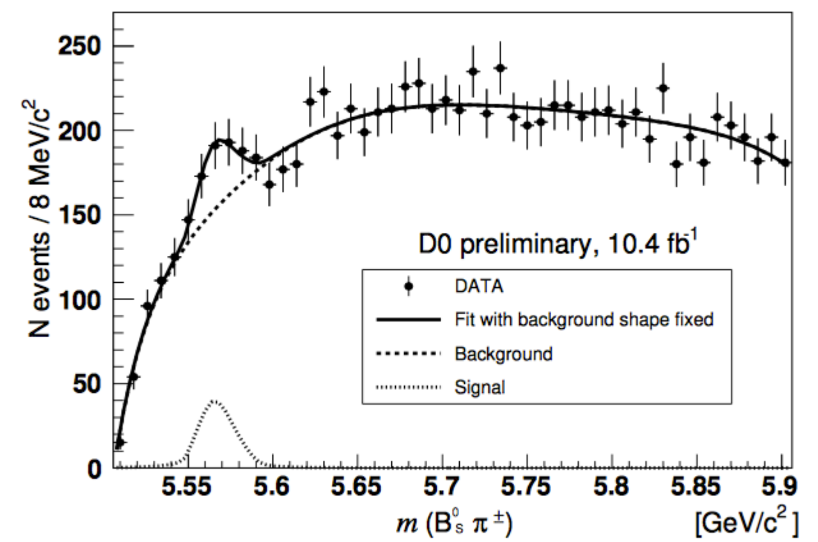
$$m = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV} \qquad \Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \text{MeV}$$

almost 9% of total B_s production coming X(5568) !

PRL 117 (2016) 022003



- Recently also seen using $B_s^0(\to D_s^-\mu^+X)\ \pi^+$:



D0 note 6496-CONF

$\bar{b}\,s\,\bar{d}\,u$

or

$b\,\bar{s}\,\bar{d}\,u$

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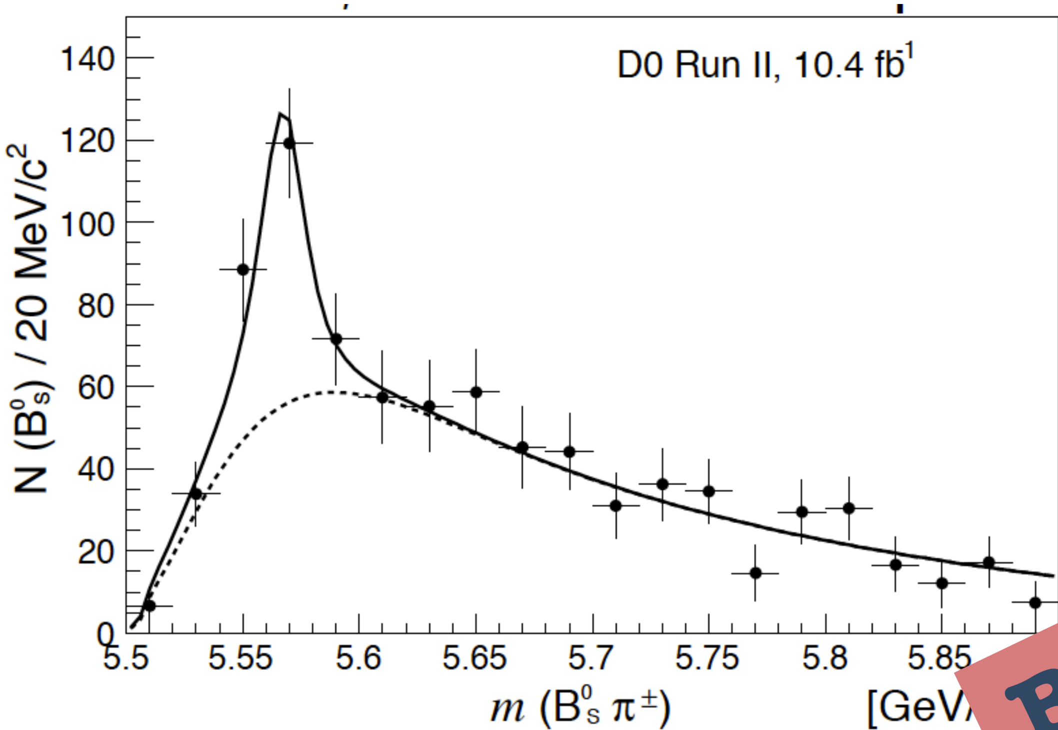
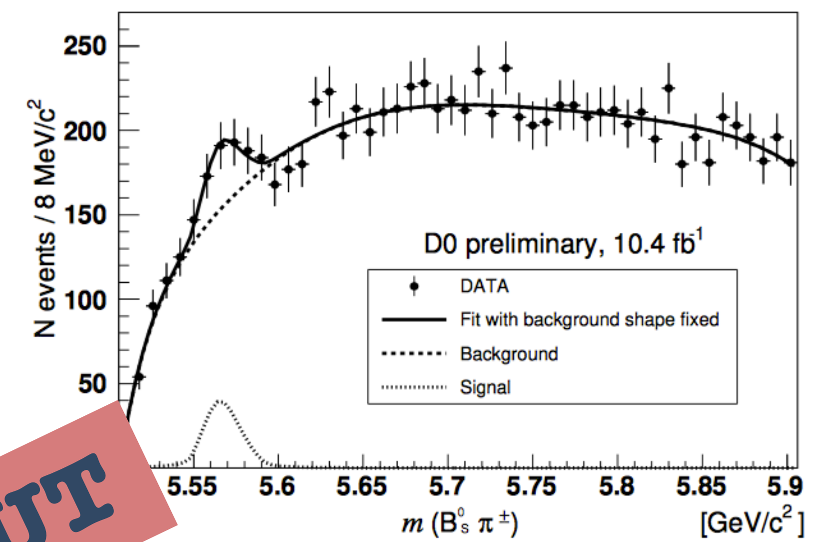
PRL 117 (2016) 022003



BUT

- Recently also seen using $B_s^0(\rightarrow D_s^- \mu^+ X)\ \pi^+$:



D0 note 6496-CONF

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or

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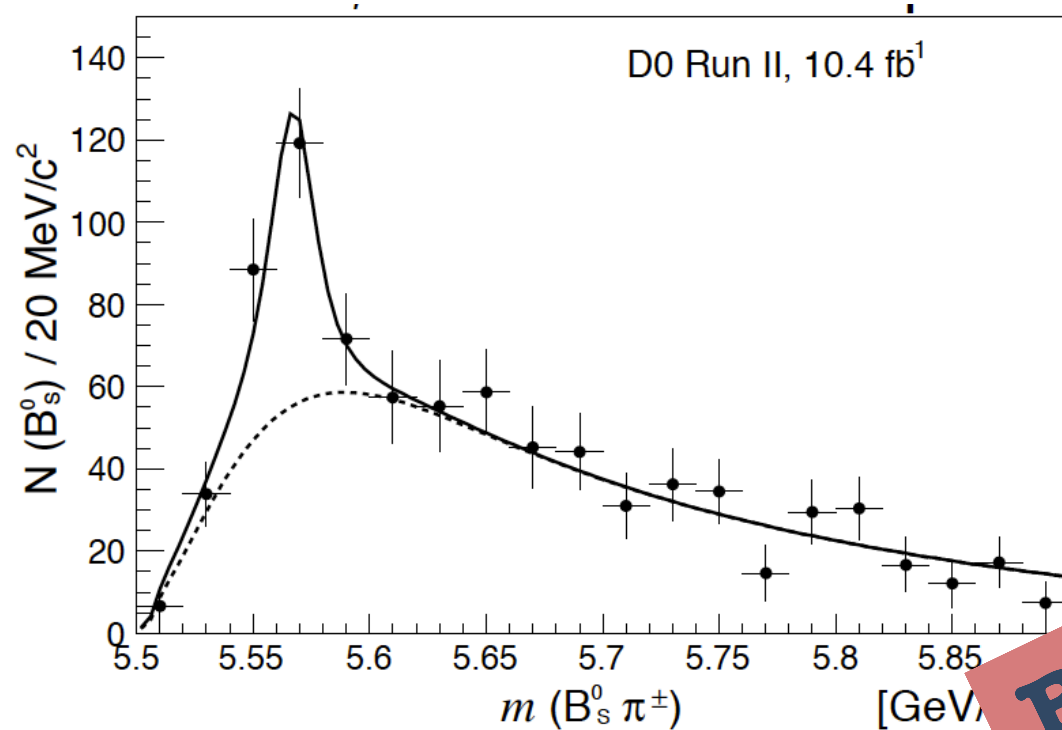
PRL 117 (2016) 022003



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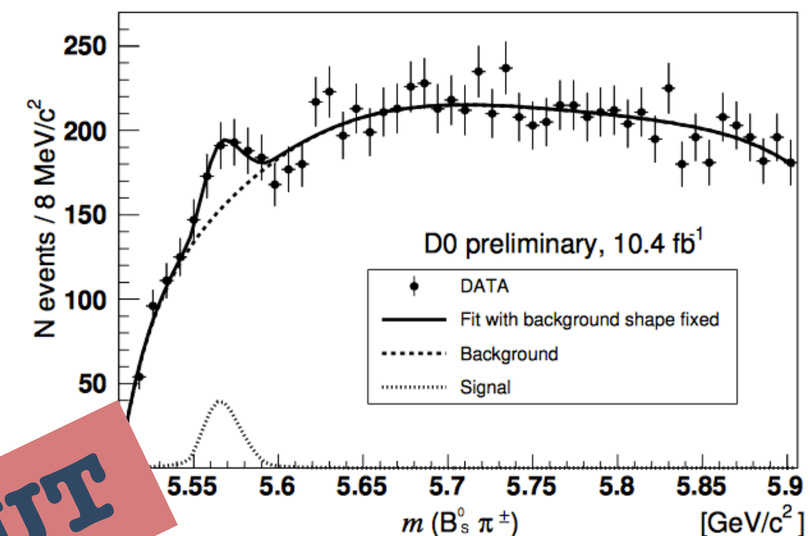


D0 note 6496-CONF

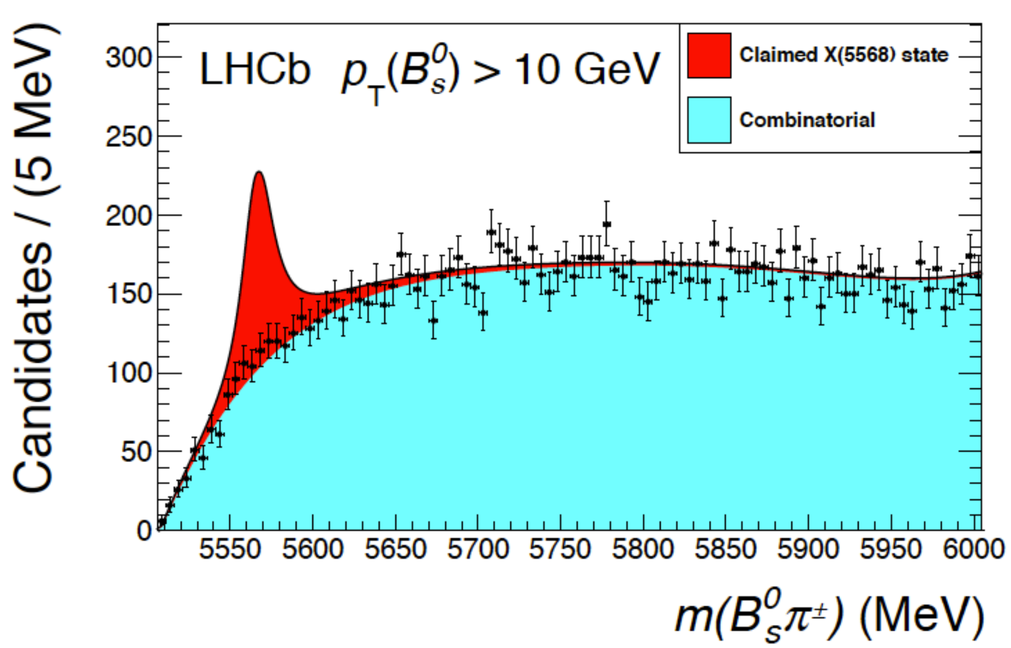
$\bar{b}\,s\,\bar{d}\,u$

or

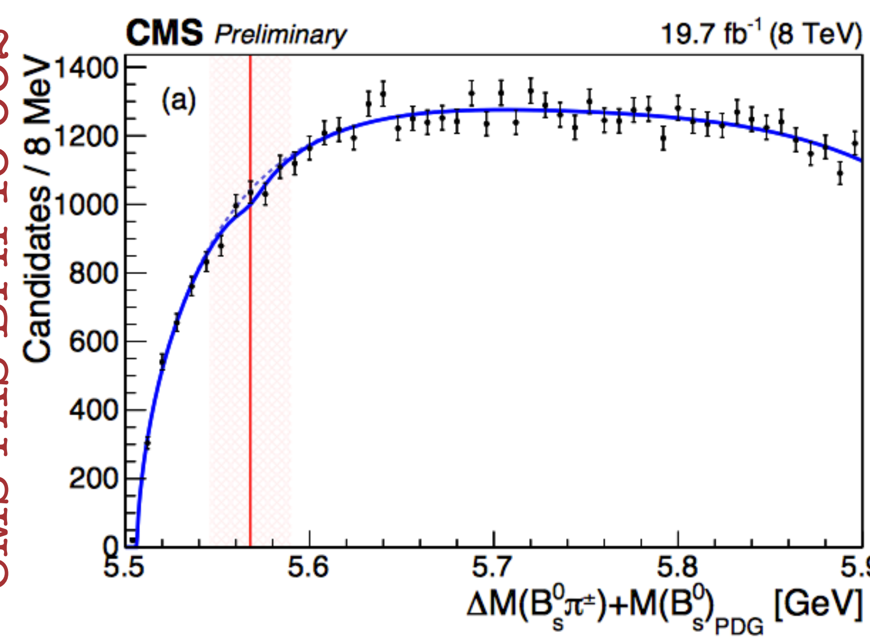
$b\,\bar{s}\,\bar{d}\,u$

BUT

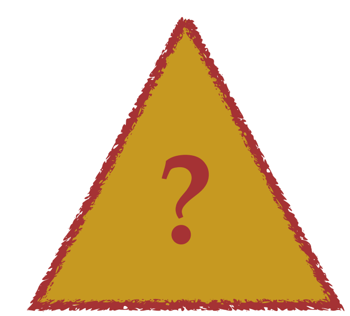
PRL 117 (2016) 152003



CMS-PAS-BPH-16-002

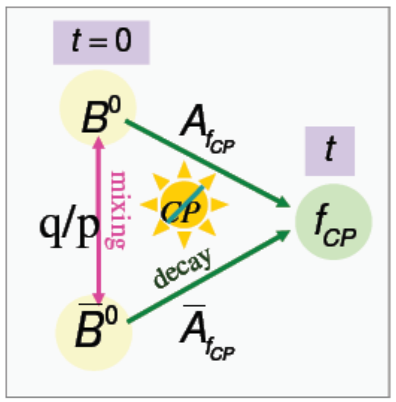


Not seen by LHCb, not seen by CMS!



… and also in sin(2β)

- The discovery mode of CP violation in B mesons (BaBar and Belle) was $B^0 \to J/\psi K_S$: interference of mixing and decay

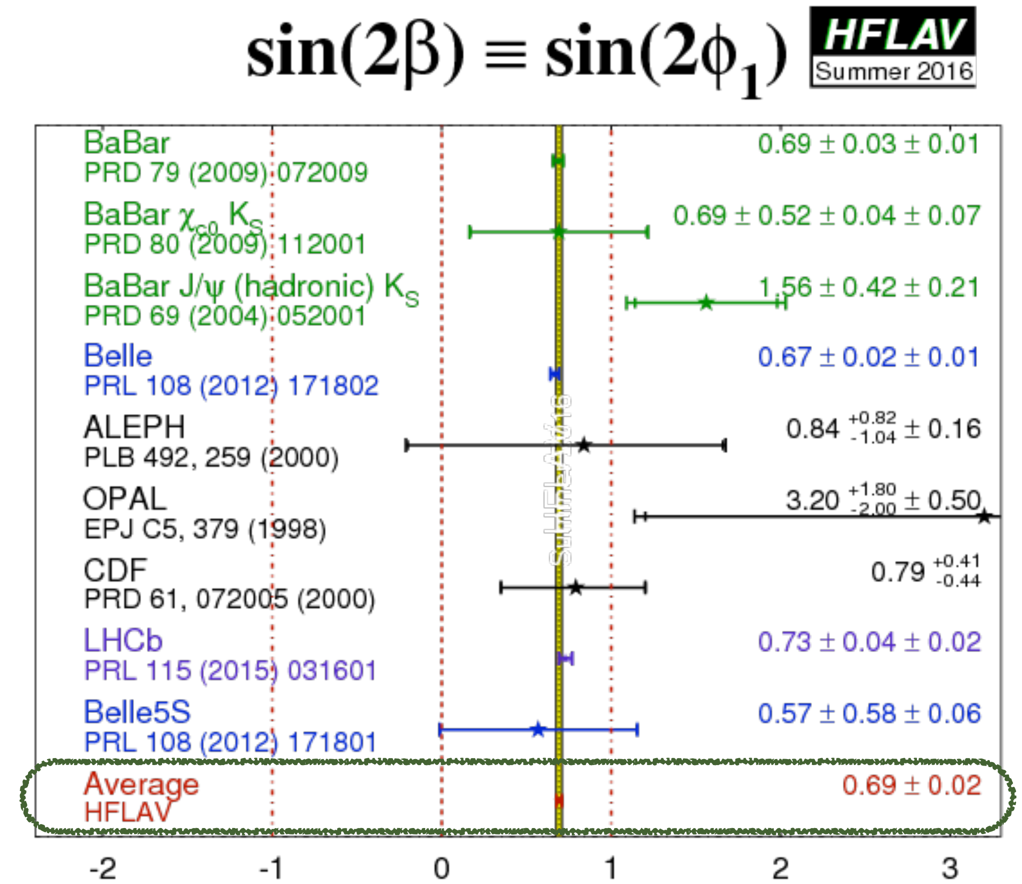


$$\mathcal{A}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\bar{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$

$$= S \sin(\Delta m t) - C \cos(\Delta m t)$$

S ~sin(2β)

$C \approx 0$



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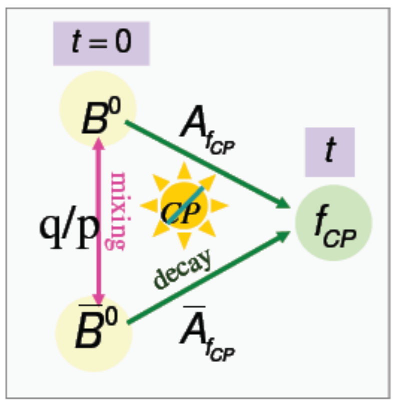

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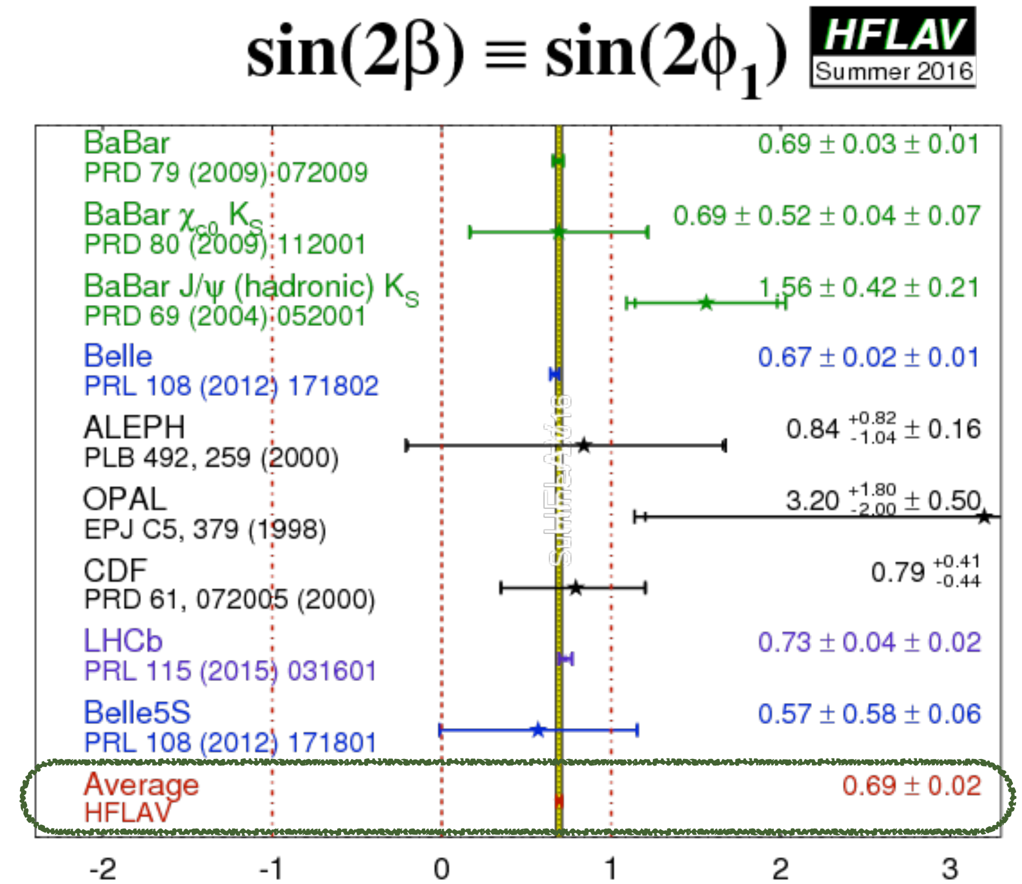
$$S \sin(\Delta m t) - C \cos(\Delta m t)$$

$\sim \sin(2\beta)$ $\quad C \approx 0$

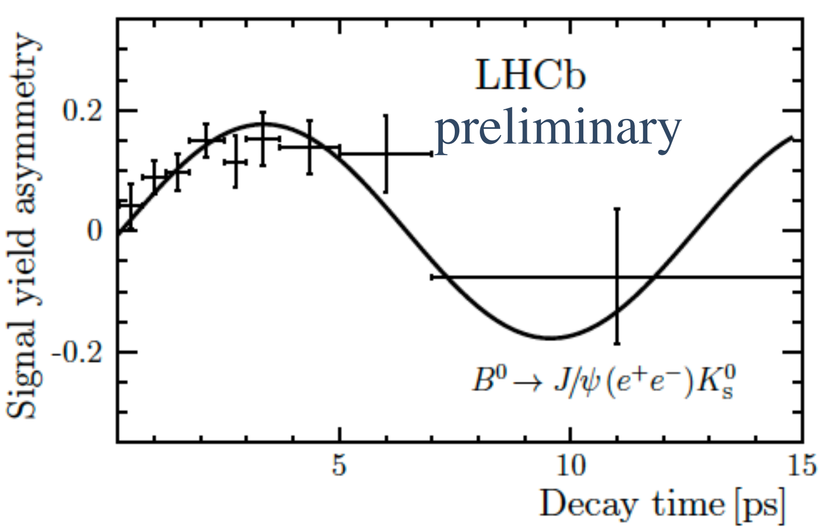
$\sin(2\beta) \equiv \sin(2\phi_1)$

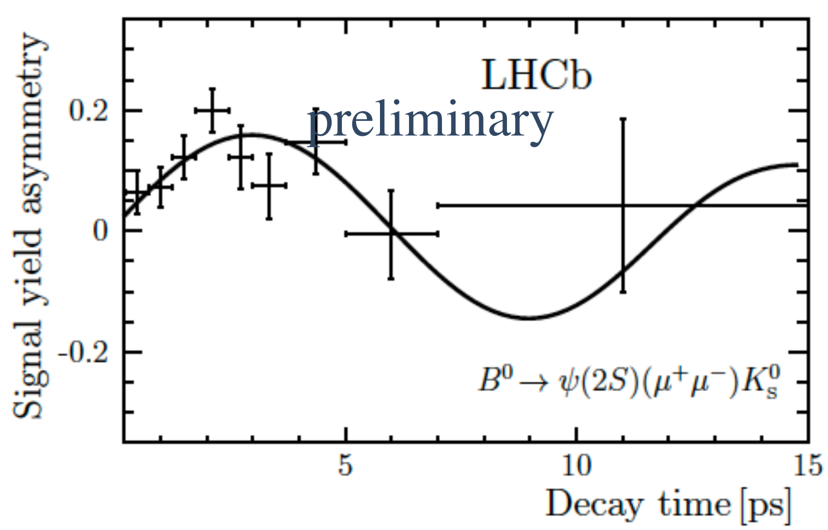


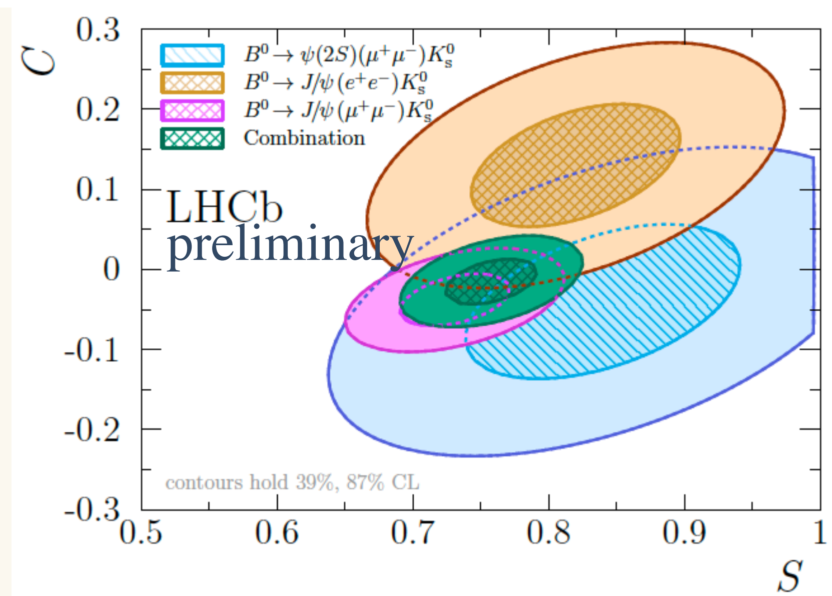
LHCb now includes $J/\psi(\to e^+e^-)K_S$ and $\psi(2S)(\to\mu^+\mu^-)K_S$

new

LHCb-PAPER-2017-029





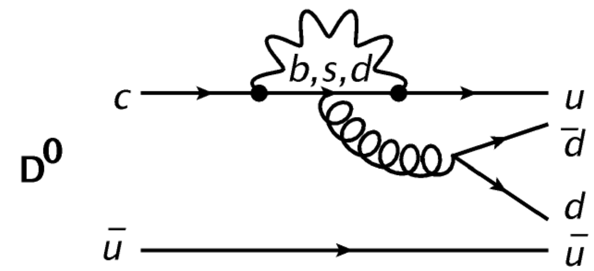


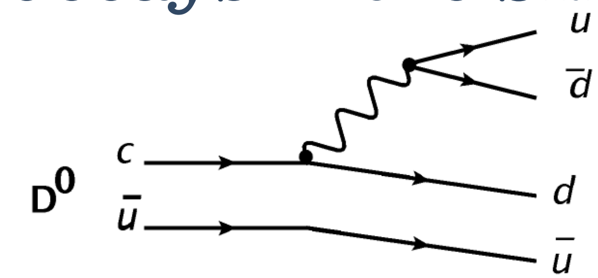
- ➡ mild tension (2σ) with sin(2β) from the B-factories
- ➡ improves the overall consistency with the CKM sector

S = +0.758 ± 0.034
C = − 0.017 ± 0.029

CP violation in charm

- CP violation in charm occurs in Cabibbo suppressed decays in the SM
- Tiny effects! Tree diagram largely dominates over penguin
- Observation of asymmetries $\mathcal{O}$(%) points towards NP long-distance effects difficult to estimate though

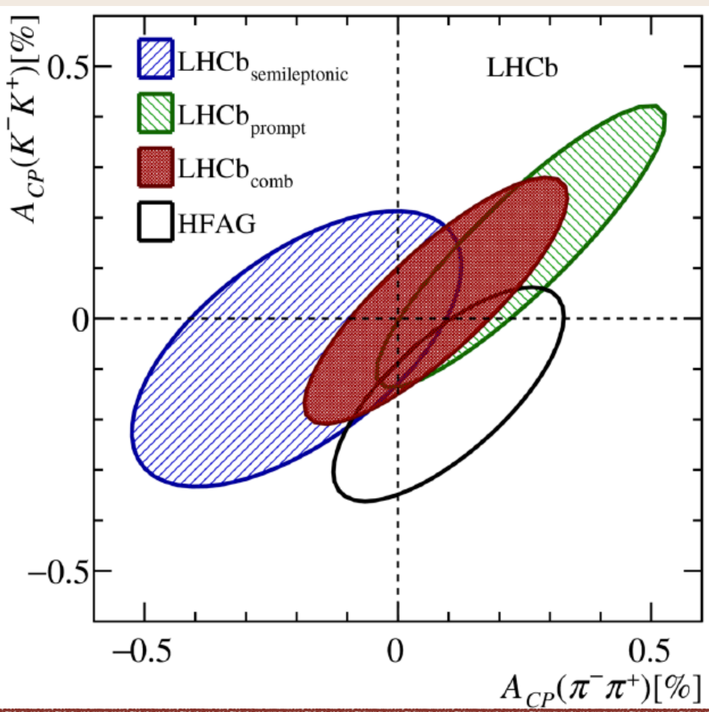




LHCb has huge charm samples ➠ unprecedent sensitivities

Direct CPV in $D^0 \to h^+h^-$

PLB 767 (2017) 177

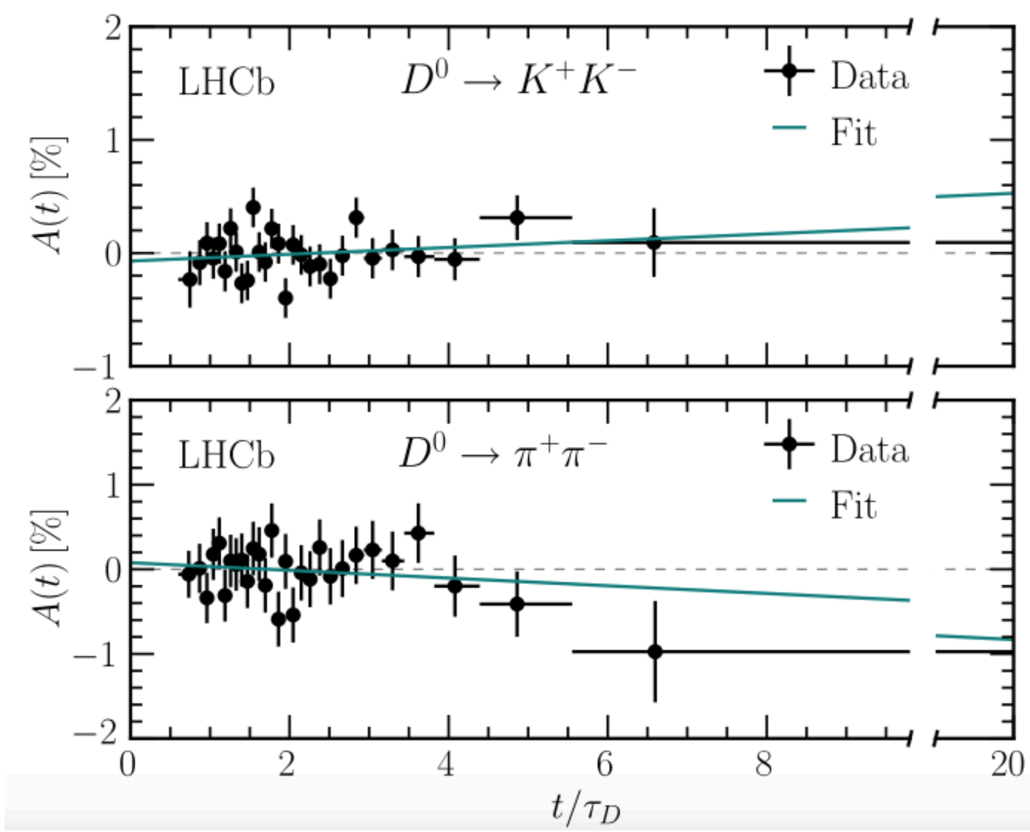


$A_{CP}(KK) = (0.04 \pm 0.12 \pm 0.10)\%$

$A_{CP}(\pi\pi) = (0.07 \pm 0.14 \pm 0.11)\%$

Indirect CP violation in $D^0 \to h^+h^-$

PRL 118 (2017) 261803



$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$

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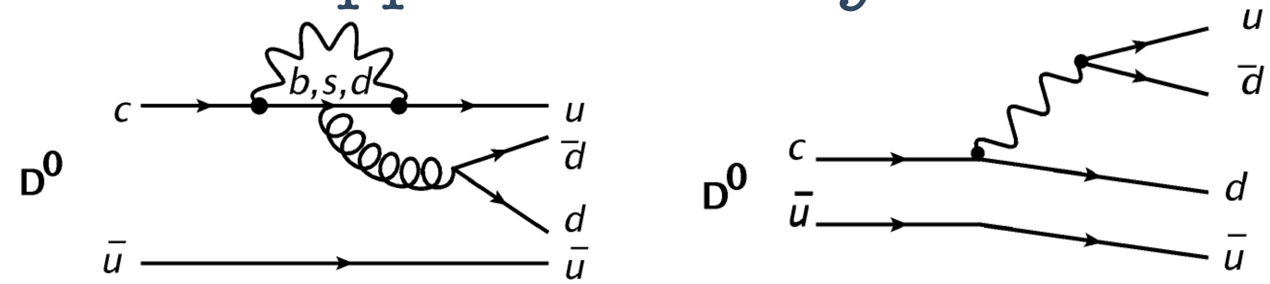

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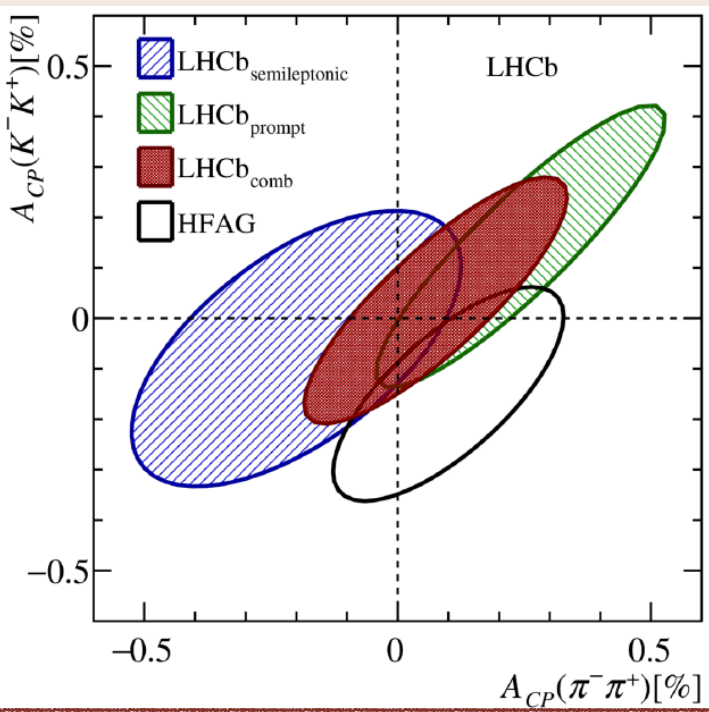

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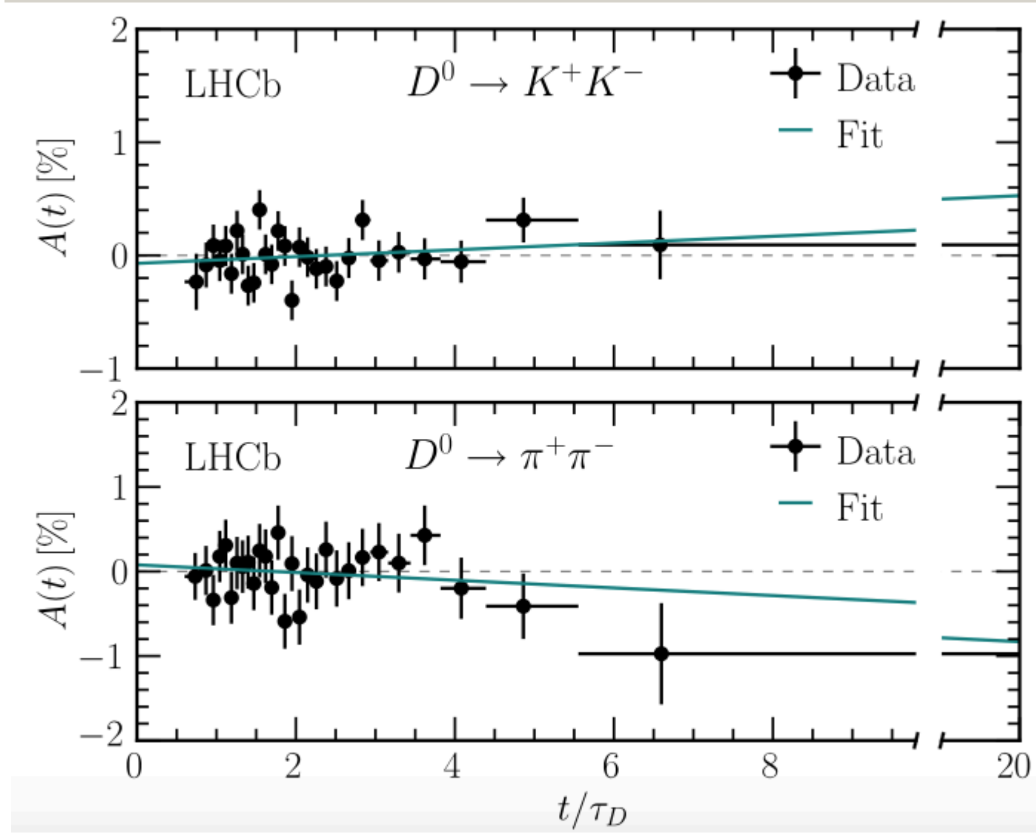

PRL 118 (2017) 261803

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Sensitivities have reached $10^{-3} - 10^{-4}$ level!

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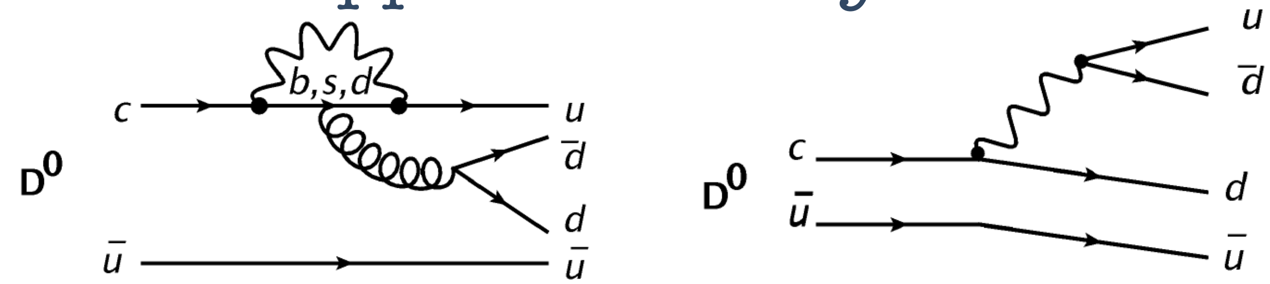

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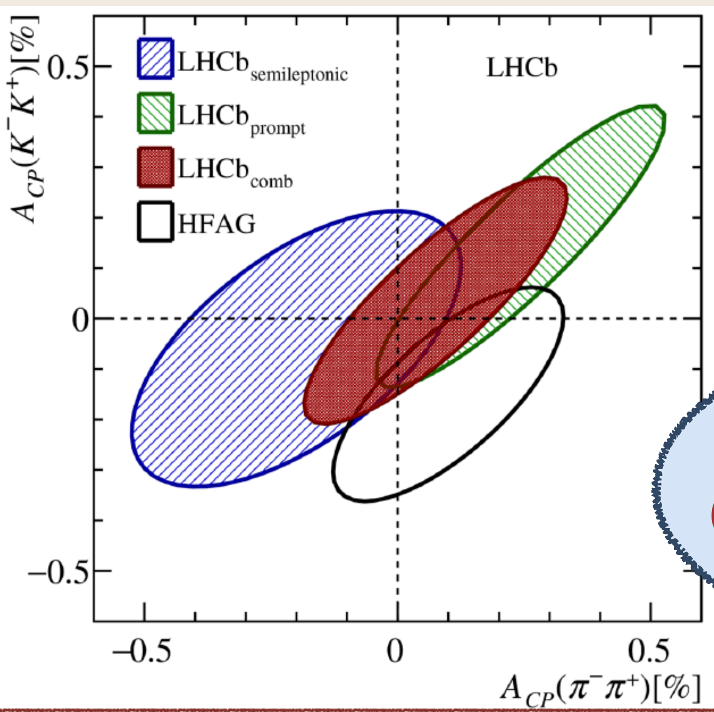

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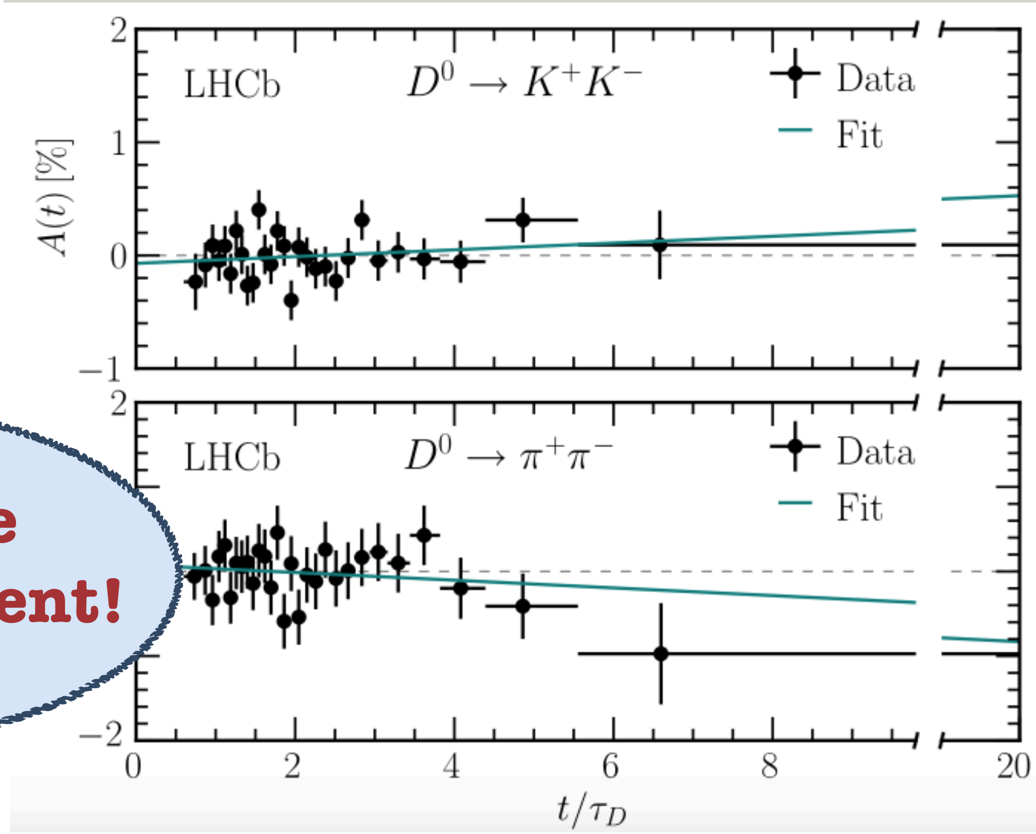
most precise CPV measurement!

Indirect CP violation in $D^0 \to h^+h^-$



PRL 118 (2017) 261803

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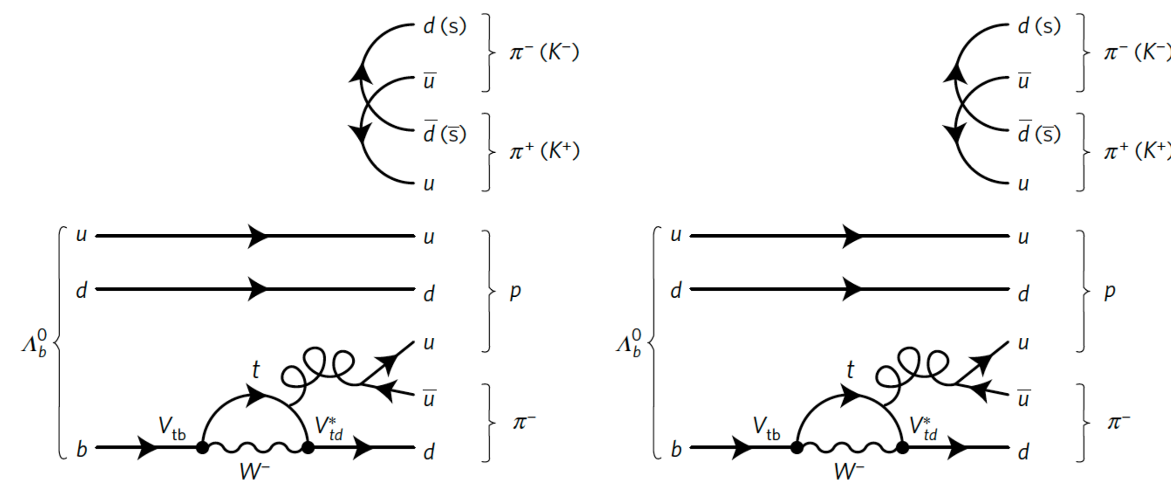
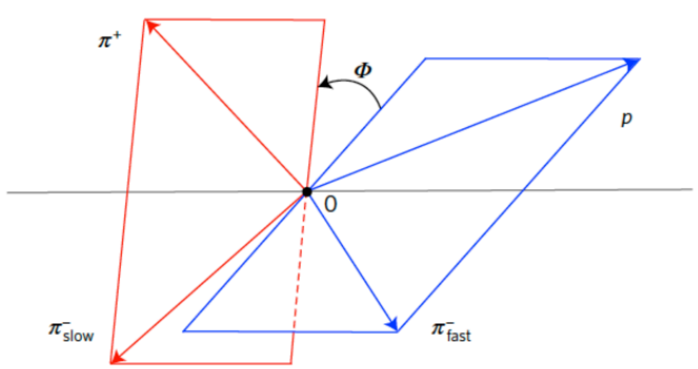
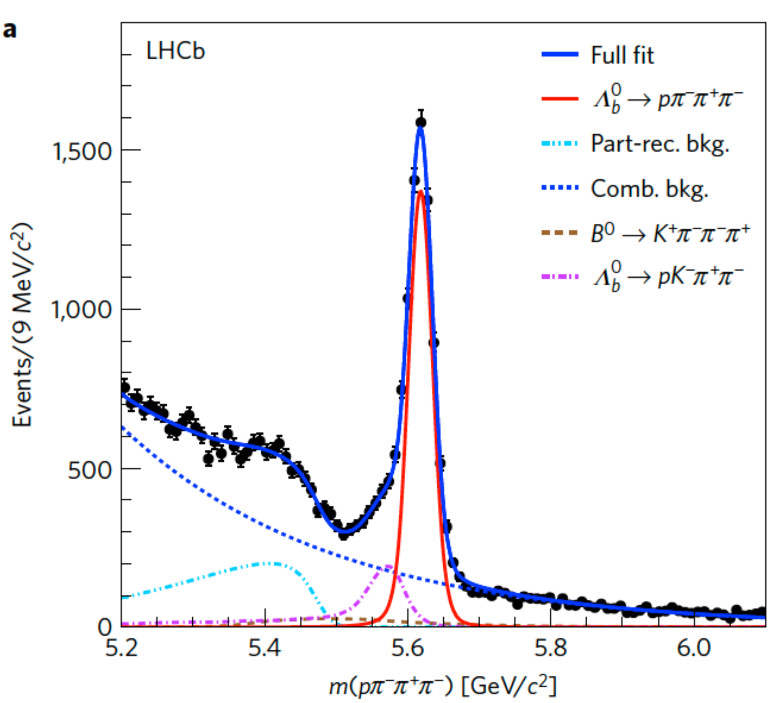
Sensitivities have reached $10^{-3} - 10^{-4}$ level!

CP violation in baryons

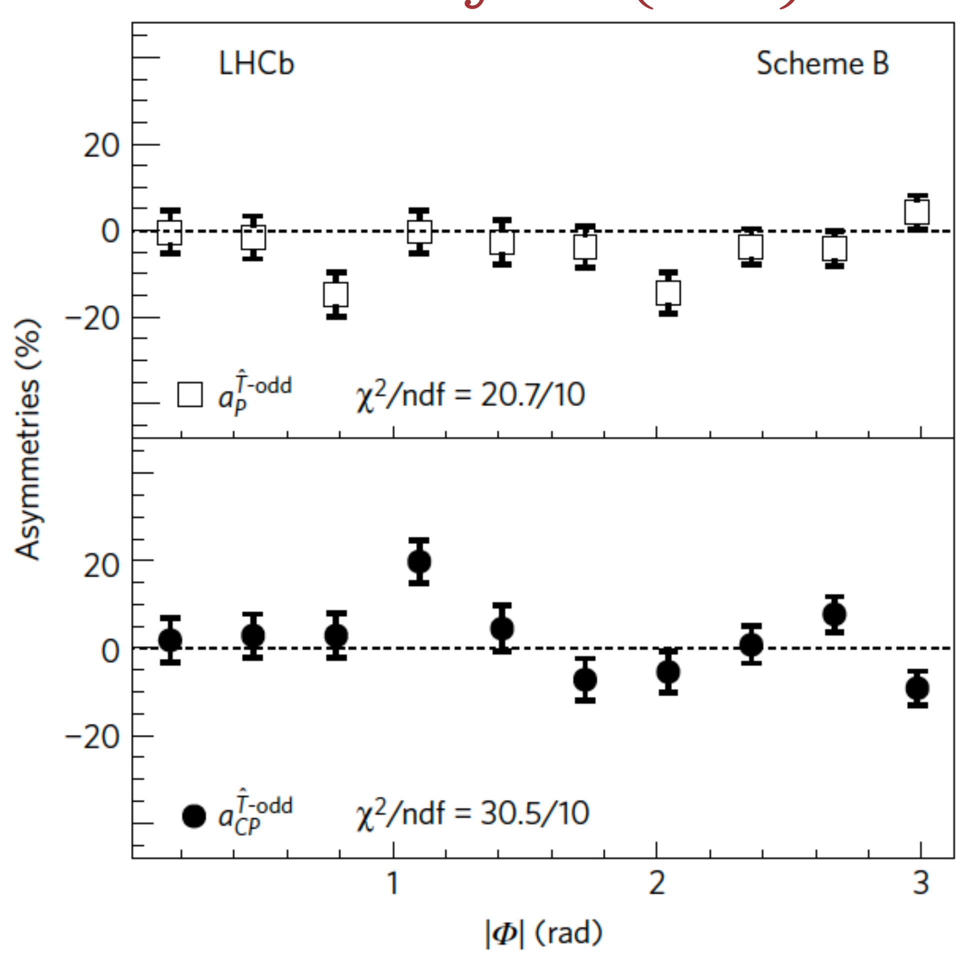
- CP violation was not yet observed in baryon decays
- LHCb studies the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^-K^+K^-$ decays (1st observation)
- CP observables: asymmetries in triple products of the type $C_{\hat{T}} = \vec{p}_p \cdot \left(\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}\right)$







Nature Phys. 13 (2017) 391



➡ no evidence for integrated CP asymmetries in both channels

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ studied in regions of the phase space:

☞ **Evidence for localised CP asymmetries at 3.3σ**