Heavy Flavour Production & Spectroscopy at LHCb

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on behalf of LHCb

Les Rencontres de Physique de la Vallée d'Aoste
LaThuile, March 2017

MANCHESTER 1824
The University of Manchester

LHCb

Outline

- Production – introduction
- J/ψ from jets
- double J/ψ at 13TeV
- b-production at 13TeV
- b-hadron production asymmetry

- Spectroscopy - introduction
- News on pentaquarks
- Family X→J/ψϕ

- Summary

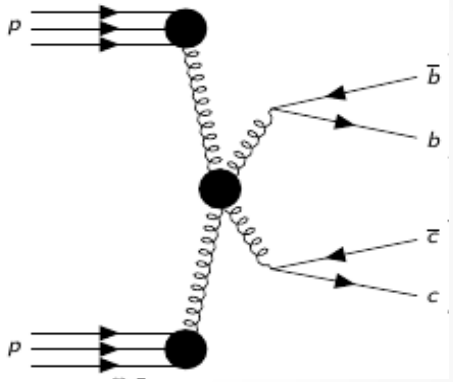
Production of heavy flavours (b & c)

- How much & how produced (hadrons/quarkonia, jets)
- Total & diff. x-sections, asymmetries, particle correlations

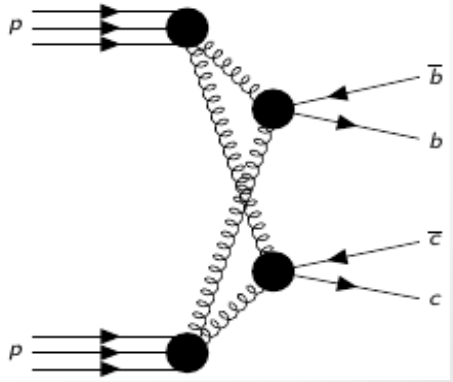
⇨ dominant: gluon-gluon fusion via SPS
- important for sensitivities of NP searches
- huge x-sections O(mb) produced forward/backward ⇨ LHCb design

⇨ SPS + sub-dominant (DPS, CEP, weak prod.)
- probes of QCD in both perturbative & non-perturbative (!) regimes
- test production & fragmentation models used in simulations

Single Parton Scattering (SPS)

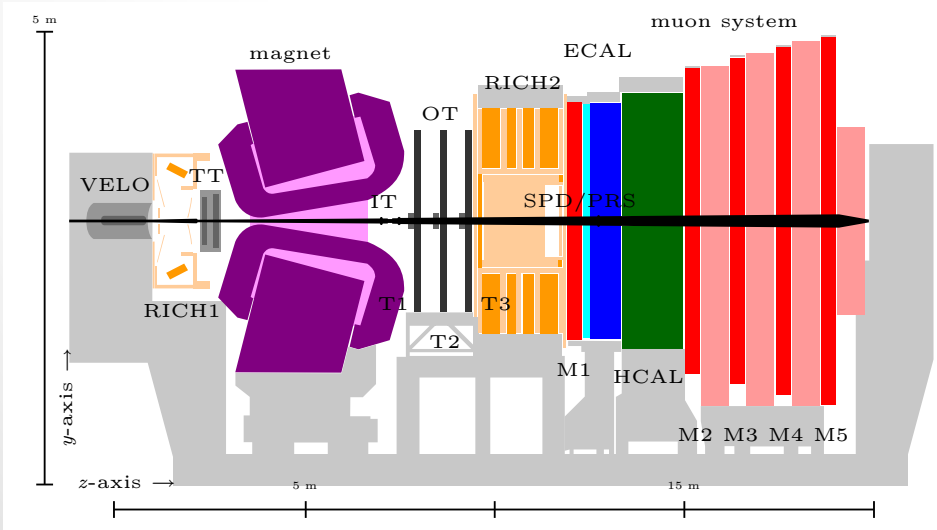


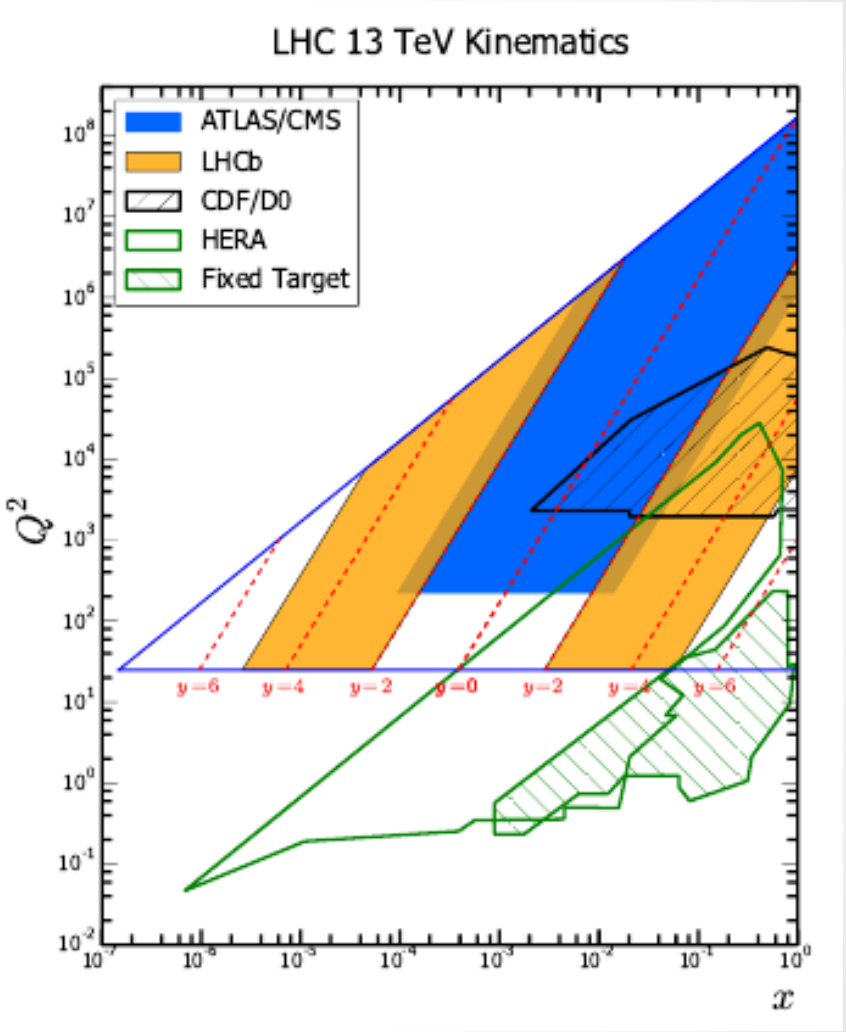
Double Parton Scattering (DPS)



Unique input from LHCb

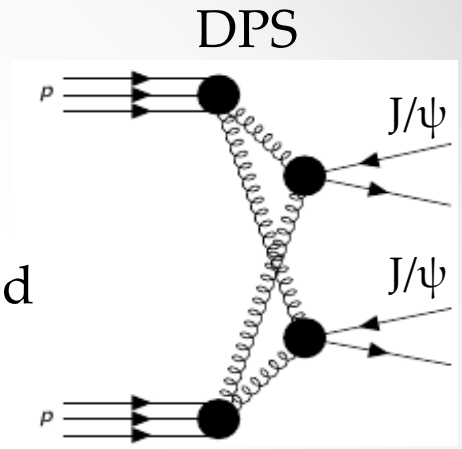
- LHCb: forward spectrometer $2<\eta<5$
  ⇨ complements Atlas/CMS
- Probes partons with low/high momentum fraction (Bjorken x)
- Gluon PDF at $x<10^{-4}$ has large uncertainties





arXiv:1612.07451

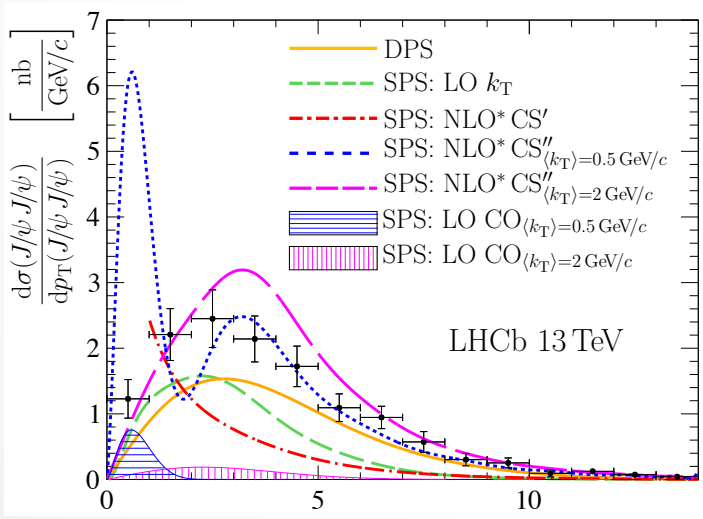
Double J/ψ @ √s=13TeV

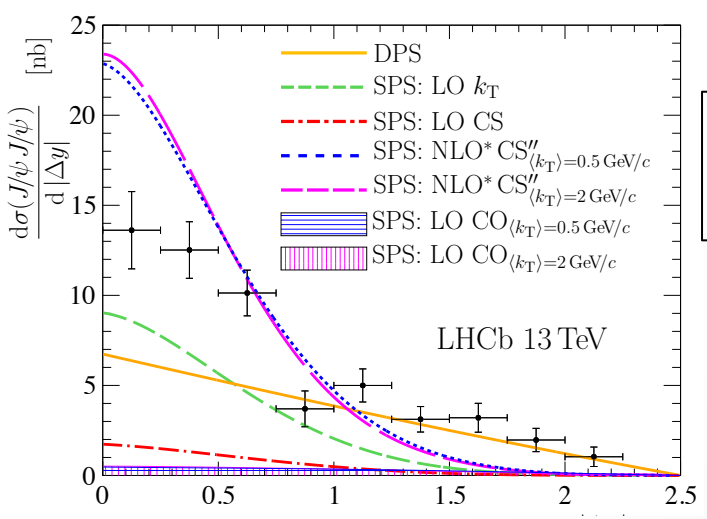


- Contribution from Double Parton Scattering
- J/ψ's independent unless partons in proton correlated
  ⇨ overlap of partons: σ_{eff} ~O(10mb). Universal?
- Prompt J/ψ (not from b)

$$\sigma(J/\psi\ J/\psi) = 13.5 \pm 0.9 \pm 0.8\ \text{nb}$$

$$\frac{\sigma(J/\psi\ J/\psi)}{\sigma(J/\psi)} = (8.9 \pm 0.6 \pm 0.7) \times 10^{-4}$$



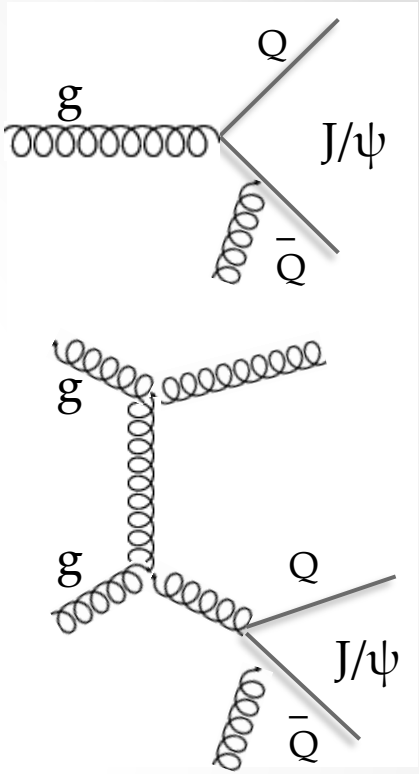


DPS
SPS: other

- SPS & DPS contribute. DPS disentangled ⇨σ_{eff}: 9-14 mb (model dep)

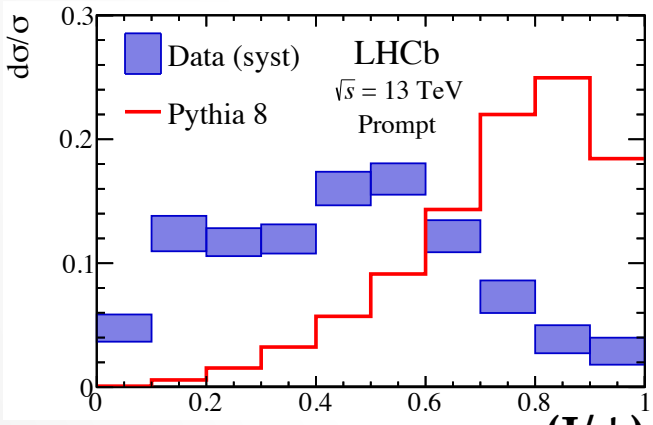
arXiv:1701.05116
submitted to PRL

J/ψ in jets @ √s=13TeV

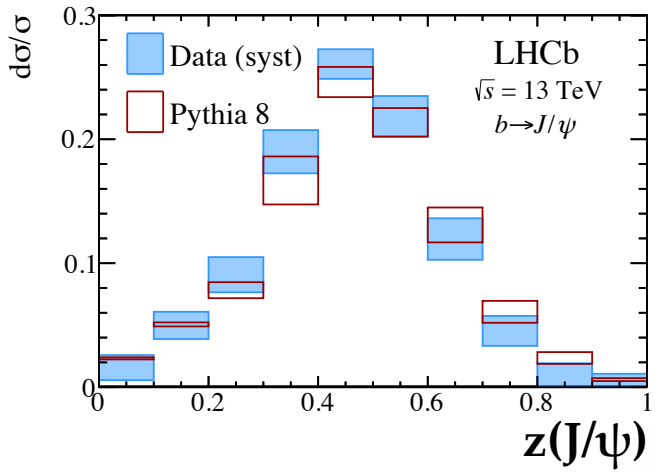


- J/ψ from direct parton scattering (isolated) or through parton showers (in jets)?
- b,c-jet tagging: displaced vertex + MVA (ε~65%, 25%)
- **$z(J/\psi)=p_T(J/\psi)/p_T(jet)$**

J/ψ in c-jets (prompt)



J/ψ in b-jets

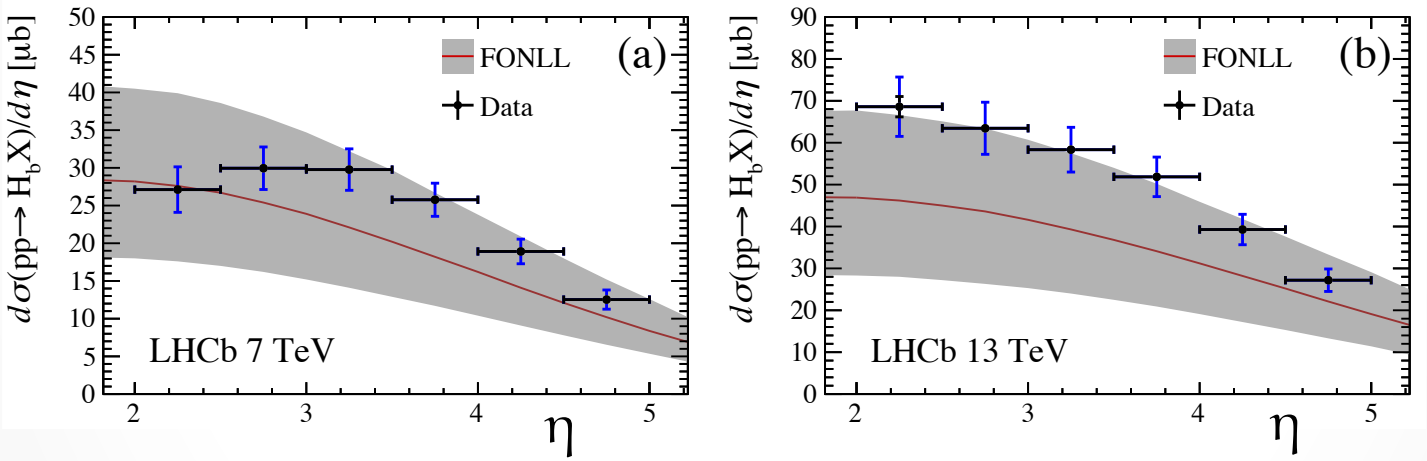


- Prompt J/ψ less isolated than in Pythia generator (used in LHCb)
  ⇨ J/ψ from parton showers
- Explains lack of J/ψ polarisation? (Longstanding puzzle)

PRL 118, 052002 (2017)

b-quark production @ √s=7&13TeV

- $b\bar{b}$ x-section: $pp \to H_b X$ with semileptonic decays:
  $H_b \to D\mu X$, $D_s\mu X$, $\Lambda_c\mu X$ ⇨ B, B_s and Λ_b
- Others: B_c~0.1%, baryons Ξ_b , Ω_b~25% of Λ_b
- Signal from M(charm) and IP(charm+μ)

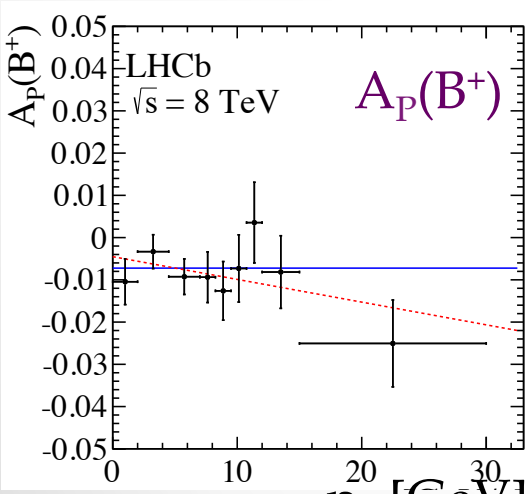


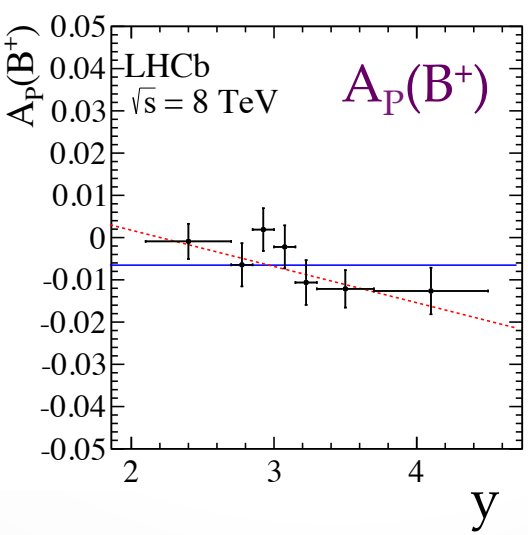
- Total 7TeV: $\sigma_{b\bar{b}} = 72 \pm 0.3 \pm 6.8$ μb 13TeV: $\sigma_{b\bar{b}} = 154 \pm 1 \pm 14$ μb
- Ratio 13/7: 2.14 ± 0.02 ± 0.13 (Prediction: 1.8 ± 0.2)
- $b\bar{b}$ x-section extrapolated to full η: ~600 μb @13TeV

New Asymmetry in b & $\underline{b}$ production @ 7, 8TeV

$$A_P(H_b) = \frac{\sigma(H_b) - \sigma(\overline{H_b})}{\sigma(H_b) + \sigma(\overline{H_b})}$$

- Important also for CP violation studies
- pp collisions ⇨ more b-baryons ⇨ more anti-B to compensate
- Measure signal asymmetry for:
- $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B_s^0 \to D_s^- \pi^+$
- M(B) and decay time for $B^0_{(s)}$ to account for B-oscillations
- Asymmetry significance up to 2.5σ



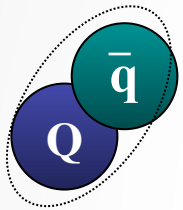


Production asymmetries @ 8TeV

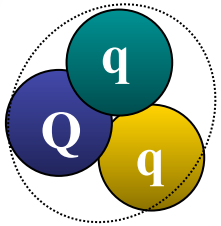
$$A_P(B^+) = (-0.7 \pm 0.1 \pm 0.3)\%$$
$$A_P(B^0) = (-1.4 \pm 0.5 \pm 0.1)\%$$
$$A_P(B_s^0) = (-2.0 \pm 1.9 \pm 0.6)\%$$
$$A_P(\Lambda_b^0) = (+3.4 \pm 1.6 \pm 0.8)\%$$

Spectroscopy of heavy flavours

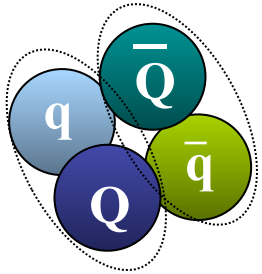
- QCD is generous…
- Conventional hadrons Exotic = more complex; also allowed



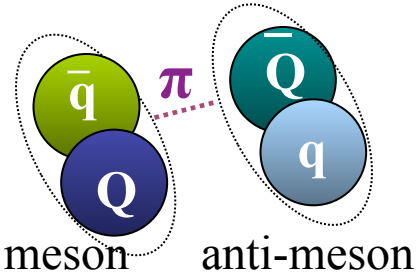
Mesons



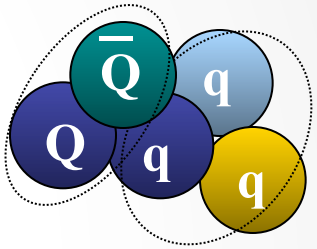
Baryons



Tetraquarks

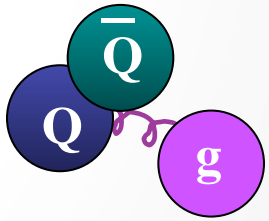


Molecules



Pentaquarks

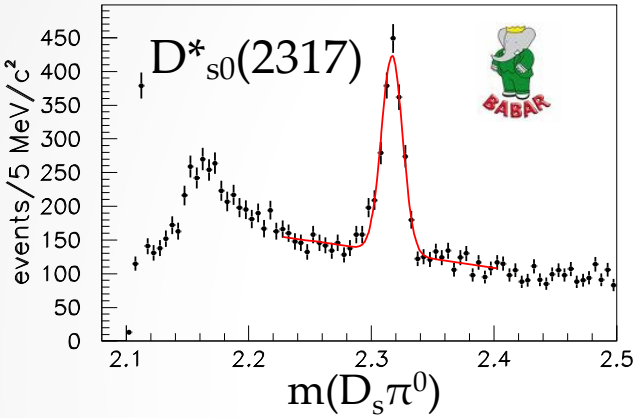
- Trends in spectroscopy studies:
  more excited and more complex hadrons
- Tests of potential models, lattice QCD
- Can we correctly model hadron multiplets?
  masses, widths, transitions/decays
- Can we understand exotics?

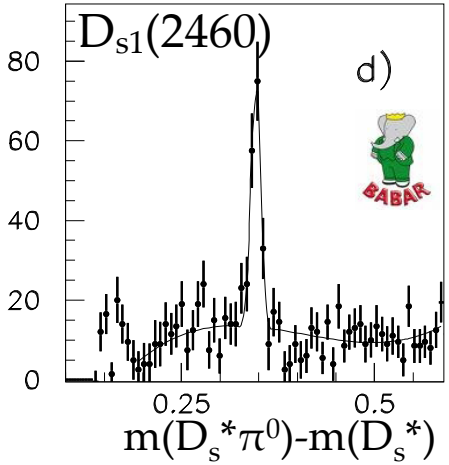


Gluon hybrids

Spectroscopy Renaissance: thanks to Belle & BaBar

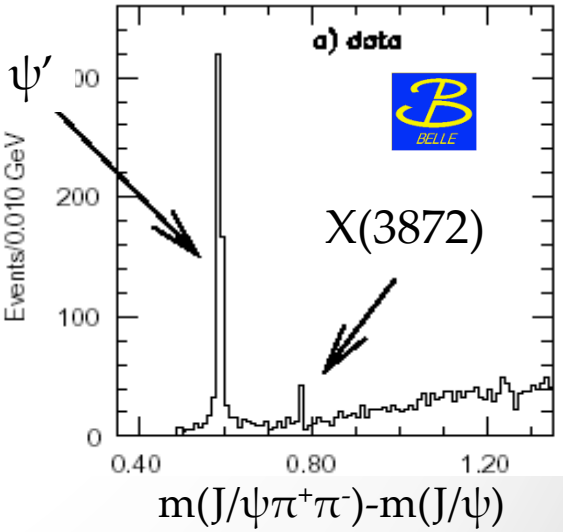
- Excited D_s mesons: didn't fit any models



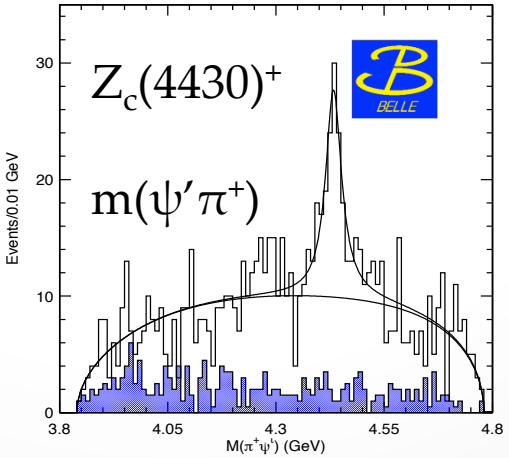


PRL 90, 242001 (2003)
PRD69, 031101 (2004)
PRL 91, 262001 (2003)
PRL100, 142001 (2008)

- Charmonium-like **X,Y** states at ~4 GeV:
  c$\underline{c}$ or 4-quarks?

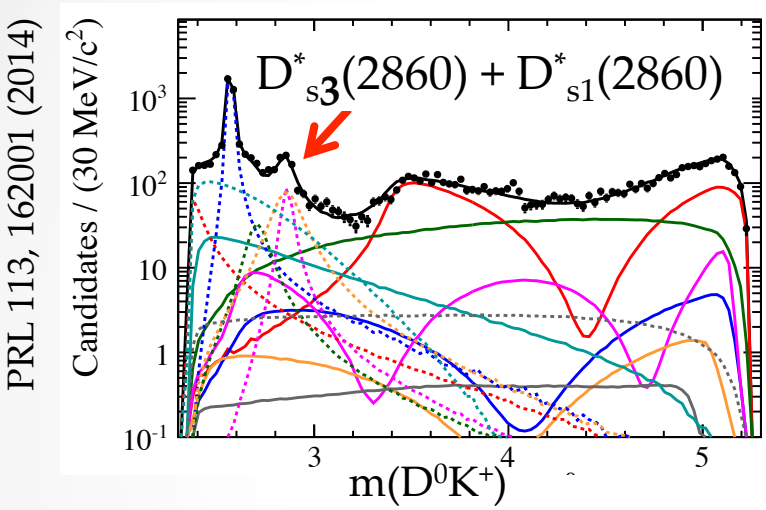


- 'Charged' quarkonia $\mathbf{Z^+}$
  must be 4-quark states!
  $Z_c(4430)^+$: [c$\underline{c}$u$\underline{d}$]

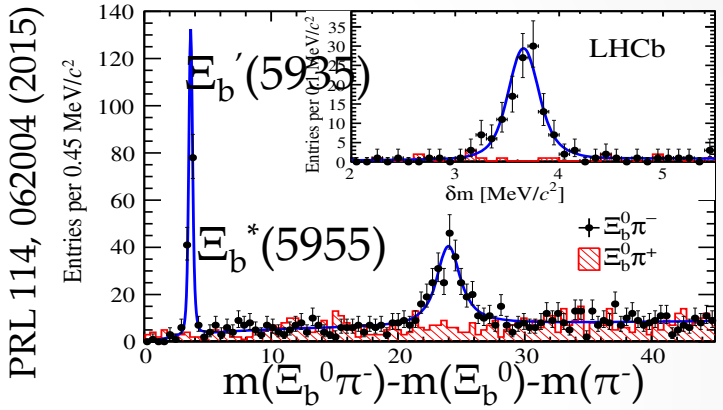


From LHCb, with precision, model indep. & extras

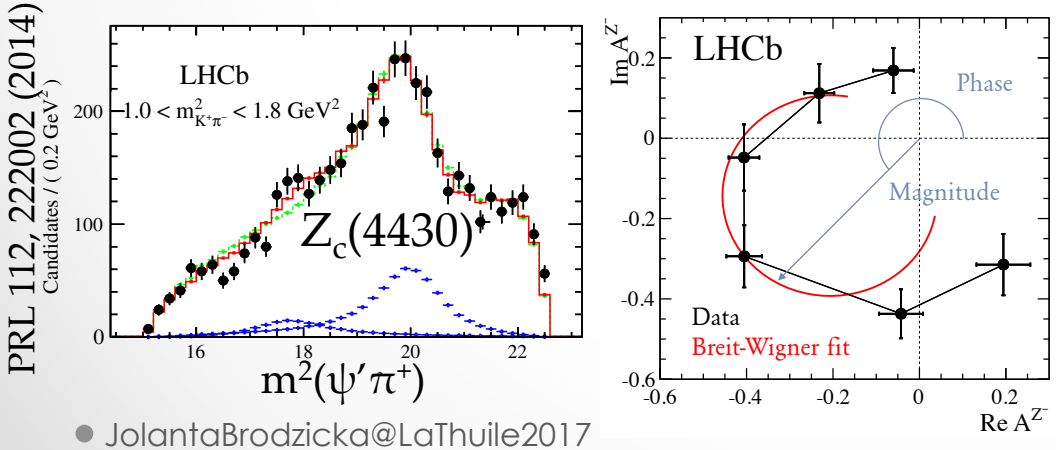
- 1st spin-3 charm meson



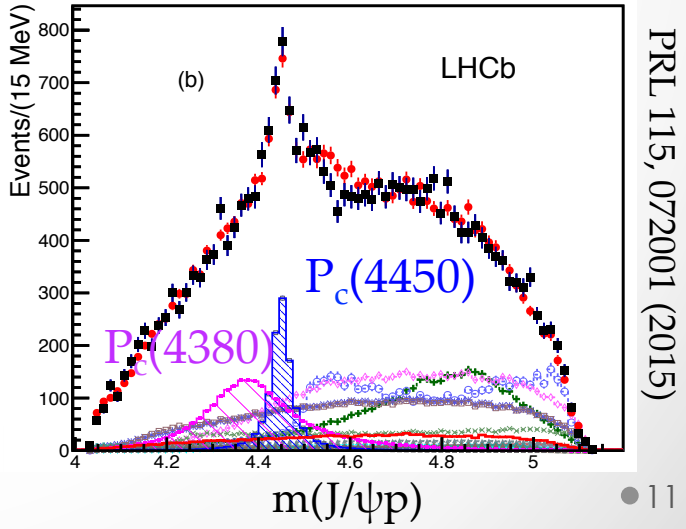
- $\Xi^*_b \to \Xi_b \pi$ baryons: pure & precise



- $Z_c(4430)^+$ exists & has resonance nature



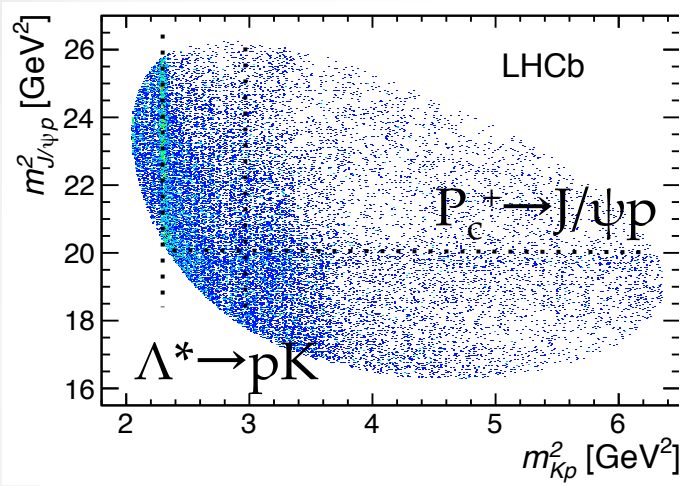
- Pentaquarks! LHCb flagship

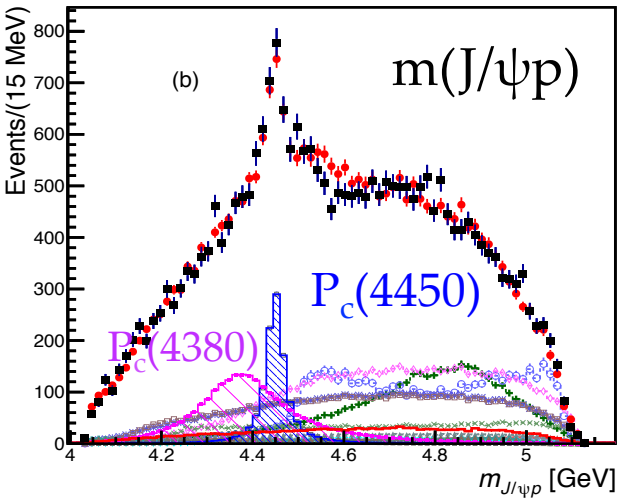


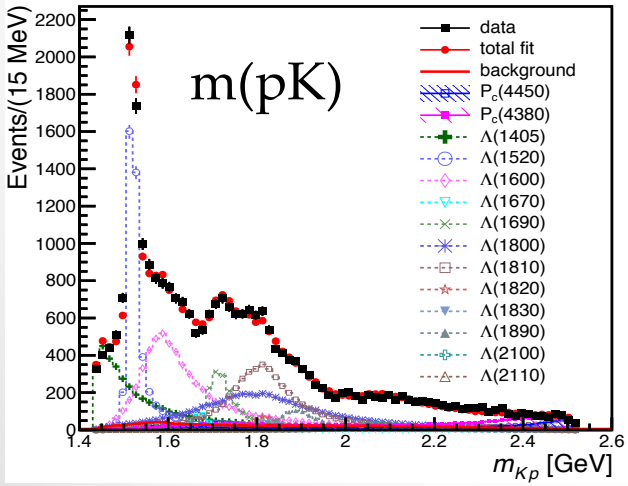
PRL 115, 072001 (2015)

Pentaquarks: at first sight

- $\Lambda_b \to J/\psi p K$; 6-dim amplitude analysis







$P_c(4380)^+$

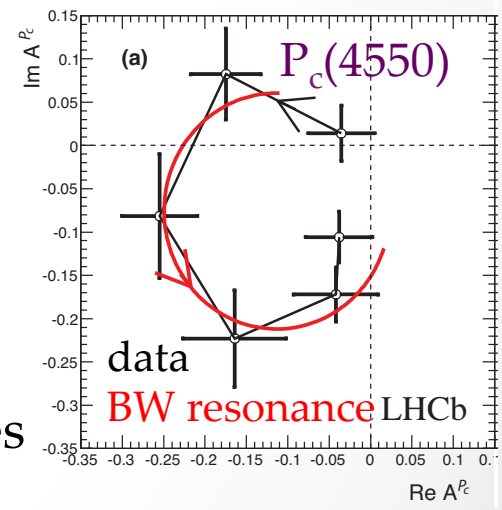
$M = 4380 \pm 8 \pm 29$ MeV

$\Gamma = 205 \pm 18 \pm 86$ MeV

$P_c(4550)^+$

$M = 4450 \pm 2 \pm 2$ MeV

$\Gamma = 39 \pm 5 \pm 19$ MeV



- $P_c(4380)$ $P_c(4550)$:

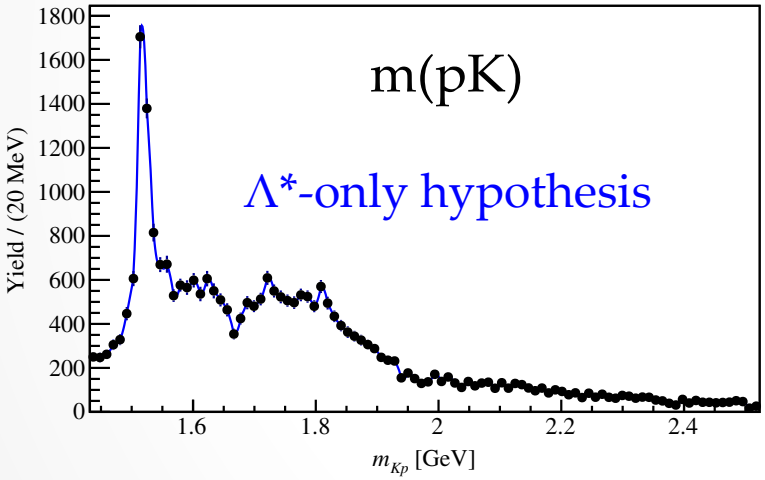
J=3/2, 5/2; opposite P-parities

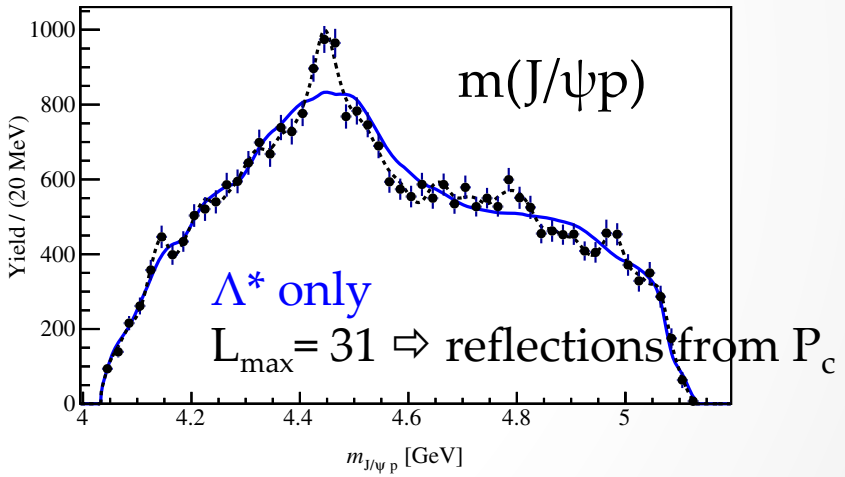
- Min. quark content **[ccuud]**
- Tightly bound or baryon+meson molecule?

PRL 117, 082002 (2016)

Pentaquarks: model indep. approach

- Did we model pK resonances in $\Lambda_b \rightarrow J/\psi pK$ well enough?
- Describe $\Lambda^* \rightarrow pK$ with minimal assumption
- m(Kp) vs. $\cos\theta_{\Lambda^*}$ ⇨ Angular moments $\langle P_L \rangle$ of Λ^* helicity angle
  rank $L \leq 2J_{max}$ where J_{max} is max spin of Λ^*; depends on m(Kp)



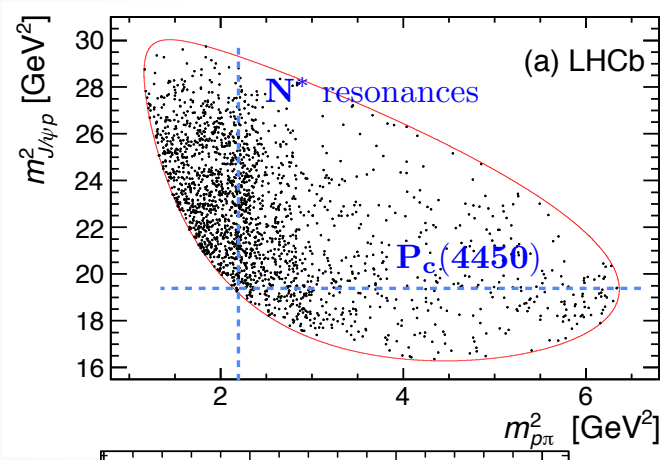


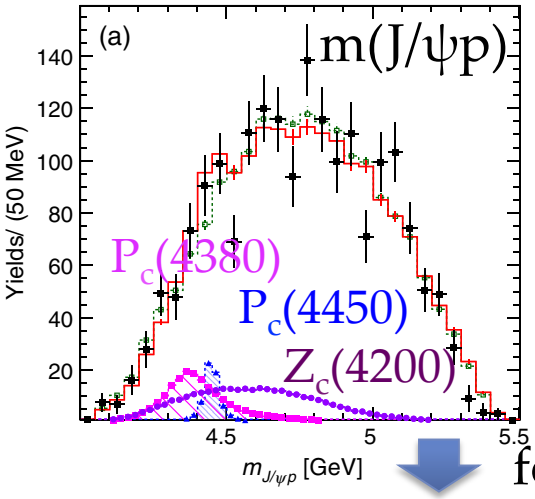
- Data inconsistent with only Λ^*'s at **10σ**
  ⇨ Pentaquarks needed!

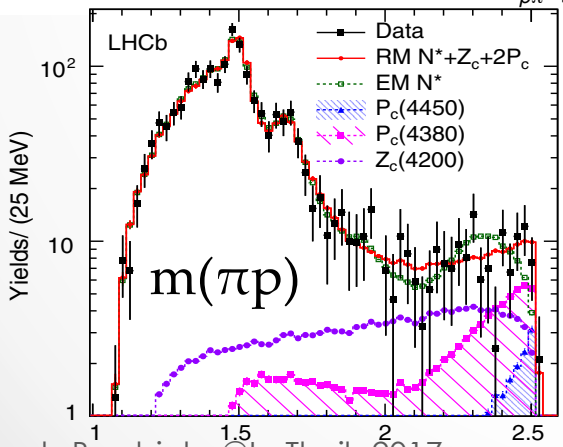
PRL 117, 082003 (2016)

Pentaquarks: produced elsewhere?

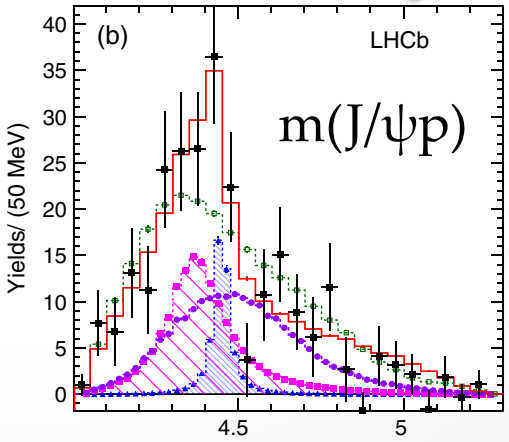
- Study of $\Lambda_b \to J/\psi p \pi^-$ (before $\Lambda_b \to J/\psi p K^-$)
- More complicated dynamics: $N^* \to p\pi$ + $P_c^+ \to J/\psi p$ + $Z_c^- \to J/\psi \pi^-$
- Contribution from exotics ~3σ (with systematics)





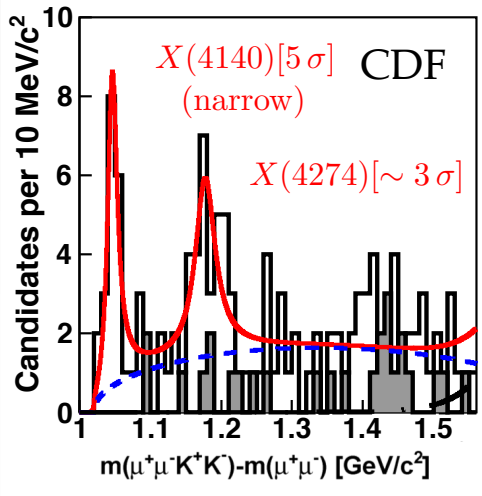


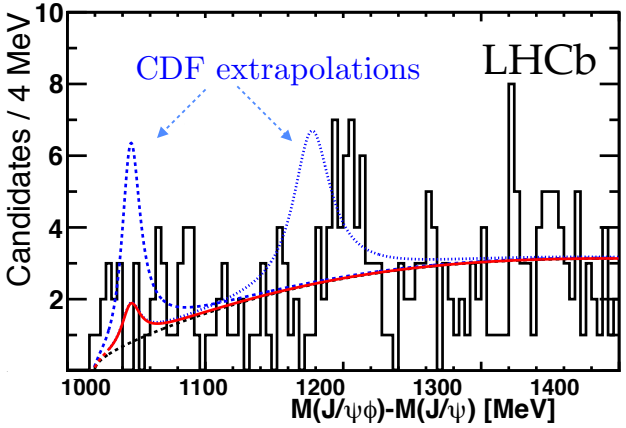
for large m(πp)

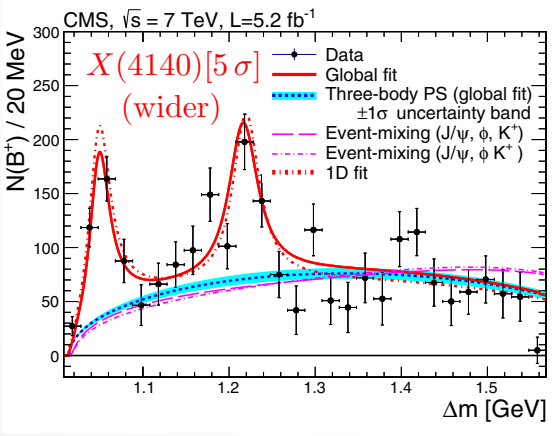


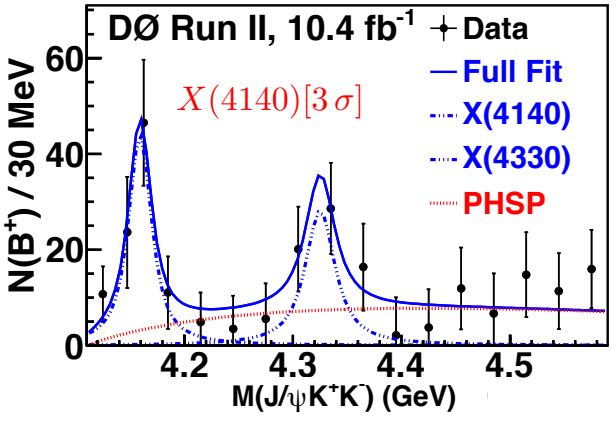
Puzzling X→J/ψφ

CDF arXiv: 1101.6058
LHCb PRD 85, 091103 (2012)
CMS PLB 734, 261 (2014)
D0 PRD 89, 012004 (2014)







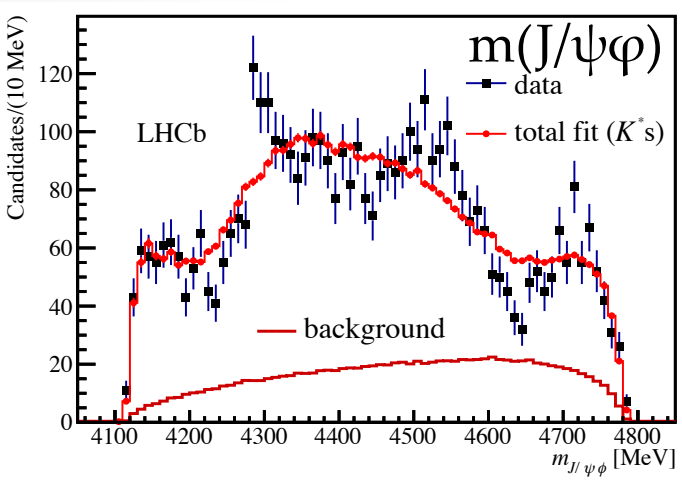


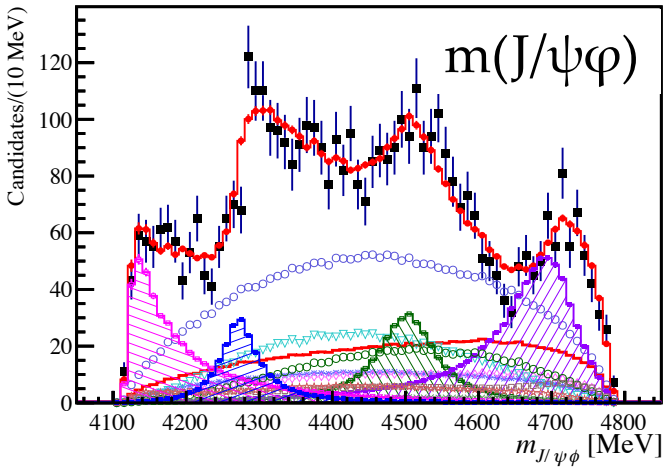
- No evidence seen by Belle/Babar

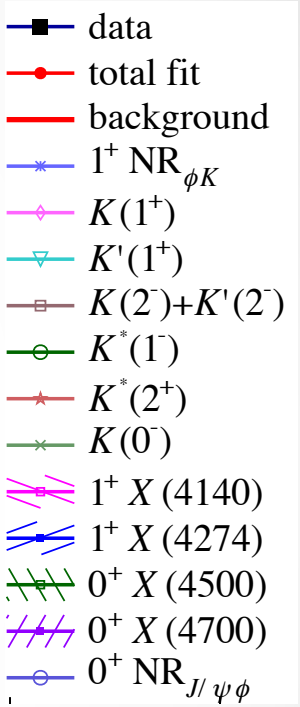
X→J/ψφ Family

PRL 118, 022003 (2017)
PRD 95, 012002 (2017)

- B_s→J/ψφK, 6-dim amplitude analysis
- K*→φK only: don't describe data







- **Four X→J/ψφ needed**; broader than seen by CDF/CMS

State	Signif	J^{PC}	M [MeV]	Γ [MeV]
X(4140)	8.4σ	1^{++}	$4160 \pm 4^{+5}_{-3}$	$83 \pm 21^{+21}_{-14}$
X(4274)	5.8σ	1^{++}	$4273 \pm 8^{+17}_{-4}$	$56 \pm 11^{+8}_{-11}$
X(4500)	6.1σ	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
X(4700)	5.6σ	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

- All won't fit $c\bar{c}$ spectrum
- $D_s^*D_s^*$ molecules or tetraquarks?

- No single model can acommodate them all

Summary

Production

- Many news in strong production of b&c
- Understand more J/ψ production
- Also weak production (W + $Q\underline{Q}$ jets) and $t\underline{t}$ prodcution

  PLB 767 (2017) 110-120
- Heavy flavours in nuclear collisions

Spectroscopy

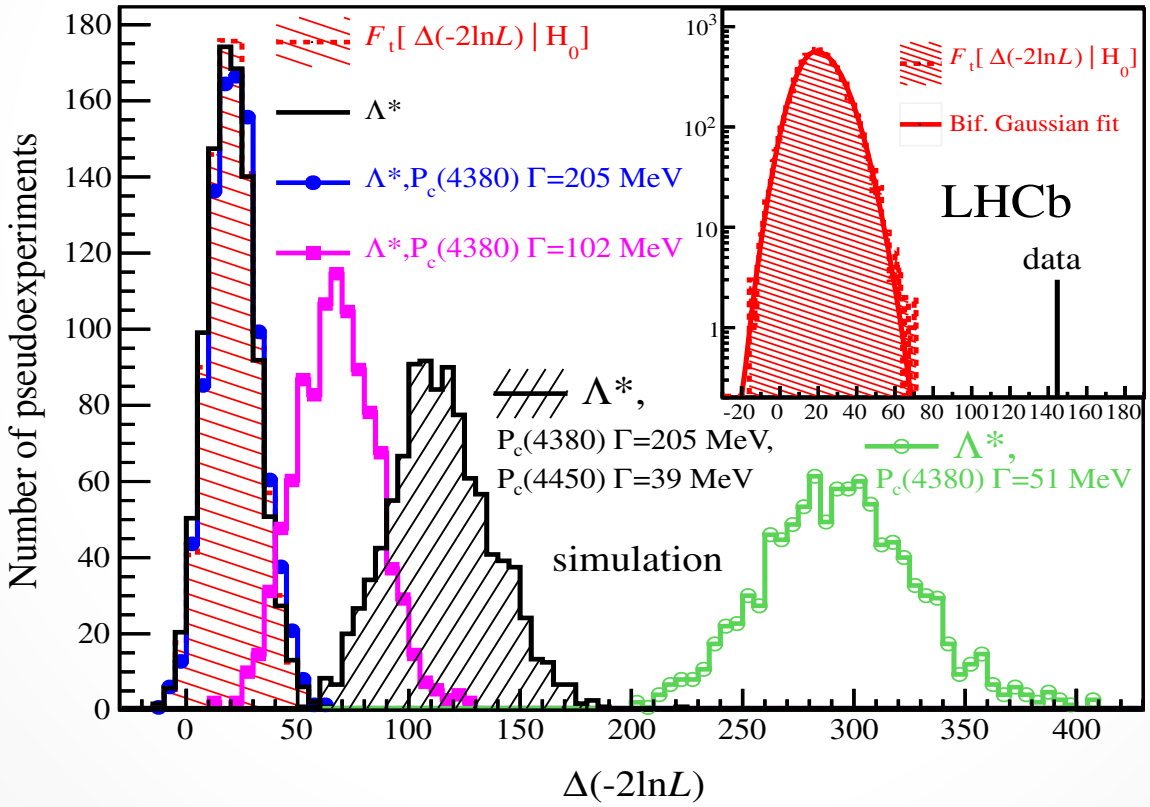
- Exploring & x-checking pentaquarks
- More $c\underline{c}$-like states: four $X \rightarrow J/\psi\varphi$
- Also 'conventional' spectroscopy

  excited $\Lambda_c \rightarrow D^0 p$ arXiv:1701.07873; $D^{**} \rightarrow D\pi$ arXiv:1608.01289
- Missing: Ξ_{cc}, Ξ_{bc}, …
- Ready for surprises

Backups

Pentaquarks: model indep. approach

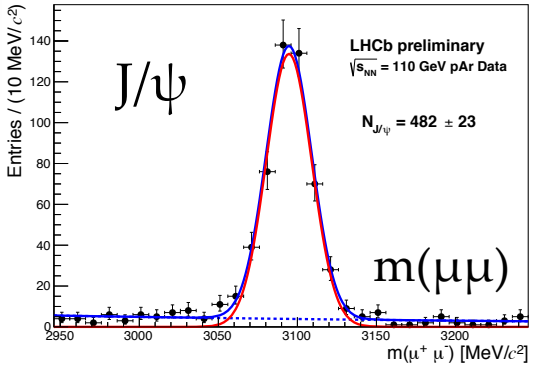
- Test sensitivity to different P_c scenarios based on ampl. models

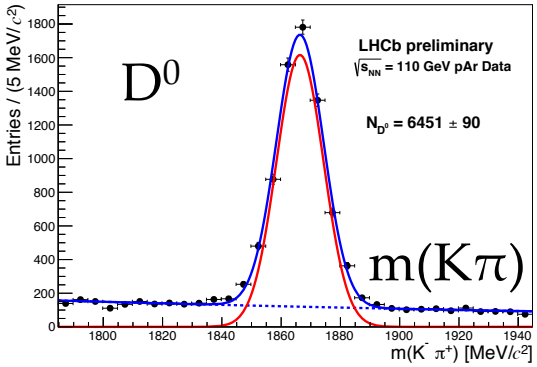


LHCb-CONF-2017-001

J/ψ and D from pAr @ $\sqrt{s_{NN}}$=110GeV

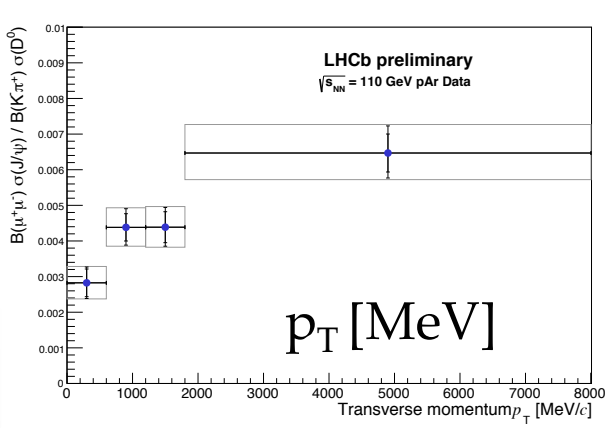
- First results from LHCb in fixed-target mode
- Proton collisions on gas injected into a beam pipe
- Signals

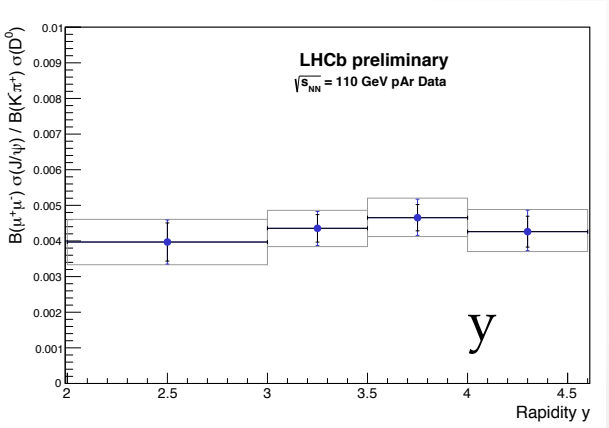




~20 hours data taking!

- $\sigma(J/\psi)/\sigma(D^0)$





- Way to probe QQ production in high density/temp QCD

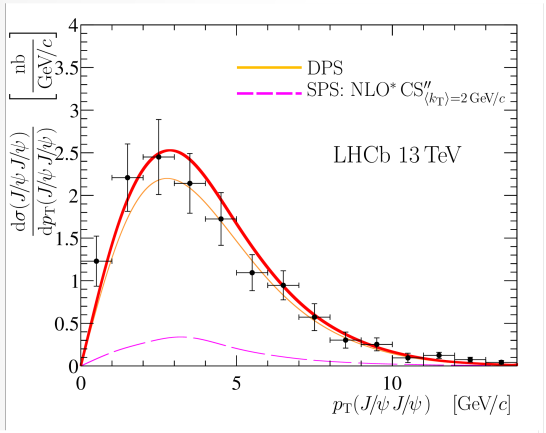
arXiv:1612.07451

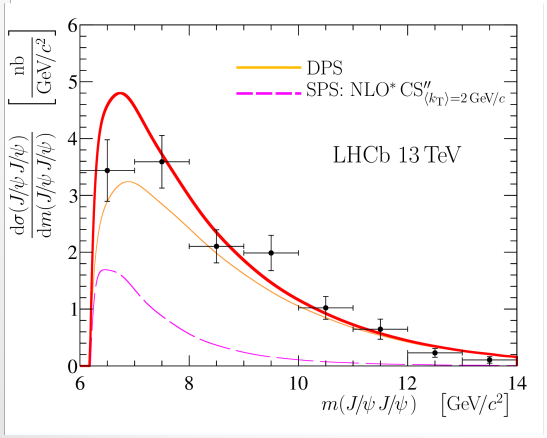
Disentangling DPS and SPS

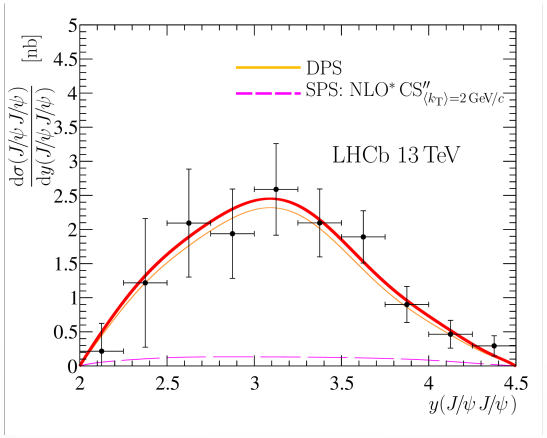
- Example of templated fits for (best?) SPS model
- σ_{eff} [mb]

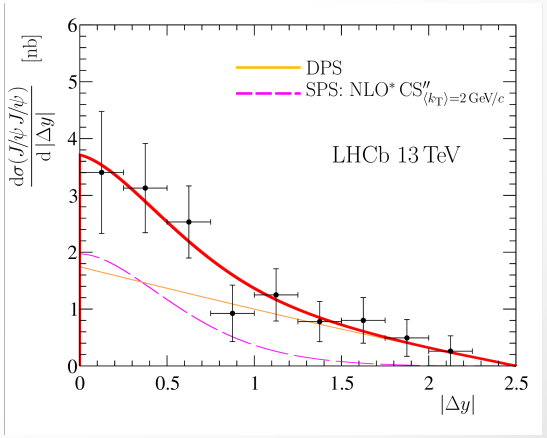
Variable	LO k_{T}	NLO* CS″ $\langle k_{\mathrm{T}}\rangle = 2\,\mathrm{GeV}/c$	NLO* CS″ $\langle k_{\mathrm{T}}\rangle = 0.5\,\mathrm{GeV}/c$
$p_{\mathrm{T}}(J/\psi\,J/\psi)$	11.3 ± 1.6	10.1 ± 4.4	11.0 ± 1.3
$y(J/\psi\,J/\psi)$	—	9.2 ± 3.9	10.0 ± 3.9
$m(J/\psi\,J/\psi)$	11.4 ± 1.2	11.3 ± 1.5	11.3 ± 1.5
$\lvert\Delta y\rvert$	14.4 ± 4.9	14.0 ± 4.4	14.2 ± 4.7

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v} = \sigma_{\mathrm{DPS}} F_{\mathrm{DPS}}(v) + \sigma_{\mathrm{SPS}} F_{\mathrm{SPS}}(v)$$









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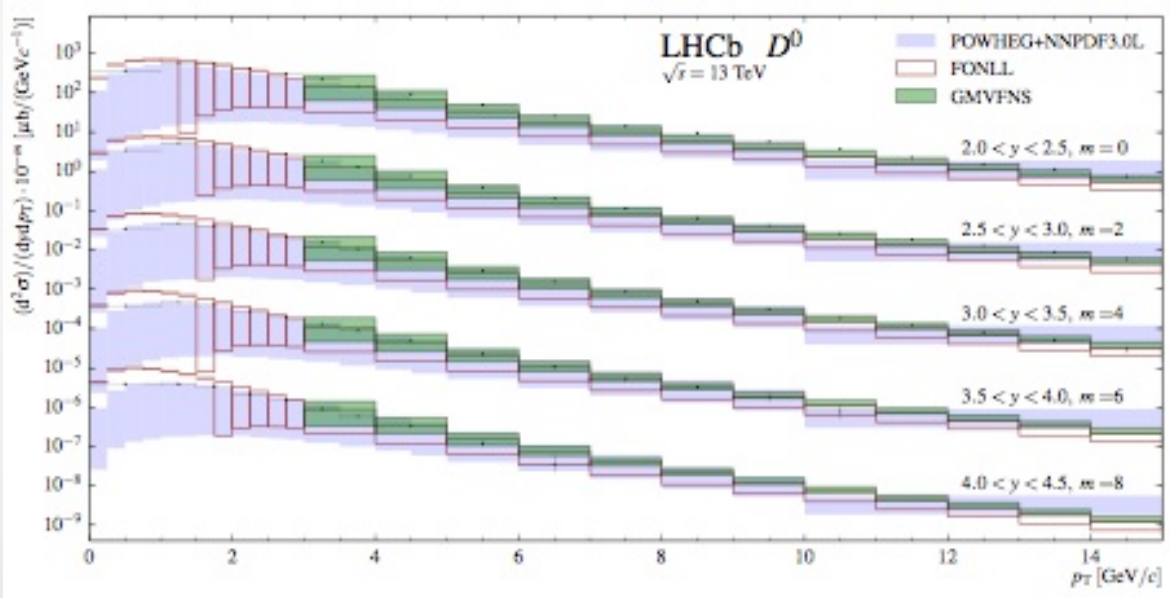
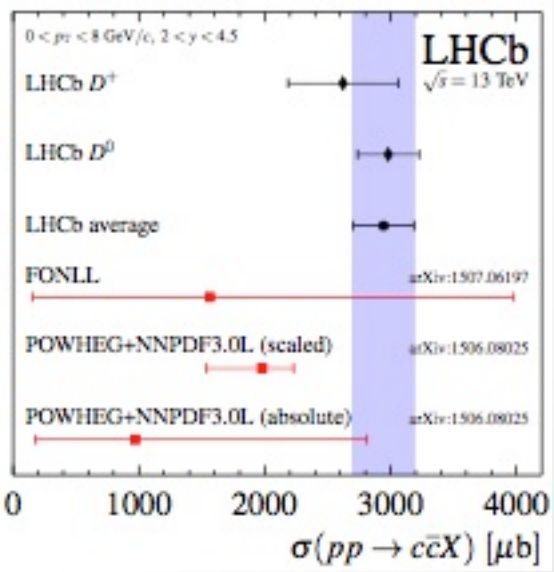
open charm @ 13TeV

- charm promptly produced in pp, $1<p_T<8$GeV
- exclusive decays of D^0, D^+, D_s and D^{*+}

$$\begin{aligned}
\sigma(pp \to D^0 X) &= 2460 \pm 3 \pm 130\,\mu\text{b} \\
\sigma(pp \to D^+ X) &= 1000 \pm 3 \pm 110\,\mu\text{b} \\
\sigma(pp \to D_s^+ X) &= 460 \pm 13 \pm 100\,\mu\text{b} \\
\sigma(pp \to D^{*+} X) &= 880 \pm 5 \pm 140\,\mu\text{b}
\end{aligned}$$





- extrapolation to inclusive charm

$$\sigma(pp \to c\bar{c}X)_{p_T<8\ \text{GeV/c},\,2.0<y<4.5} = 2940 \pm 3 \pm 180 \pm 160\,\mu\text{b}$$