ATLAS results on charmonium and B_c and exotic heavy hadrons

Leonid Gladilin (Moscow State Univ.)
on behalf of the ATLAS Collaboration

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Pittsburgh, USA

Outline : **Introduction**

J/ψ & ψ(2S) at 13 TeV — **ATLAS-CONF-2019-047**

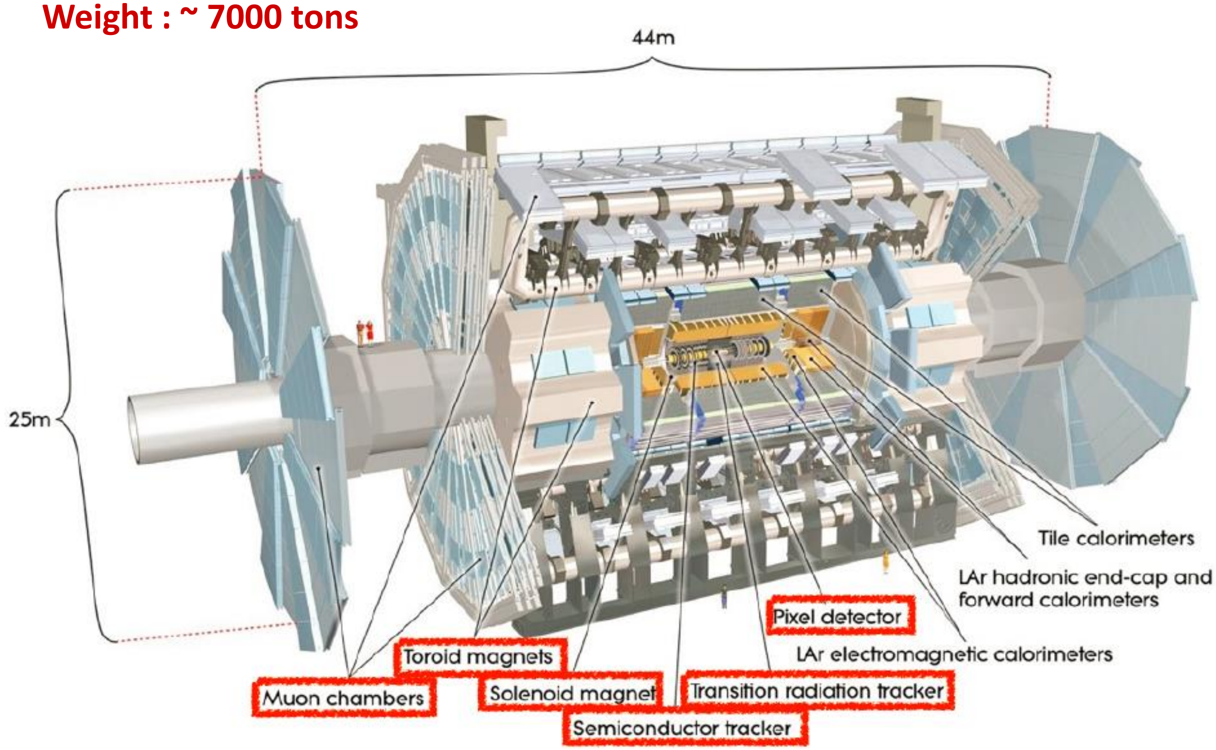
B_c^+ / B^+ at 8 TeV — **arXiv:1912.02672 (subm. to PRD)**

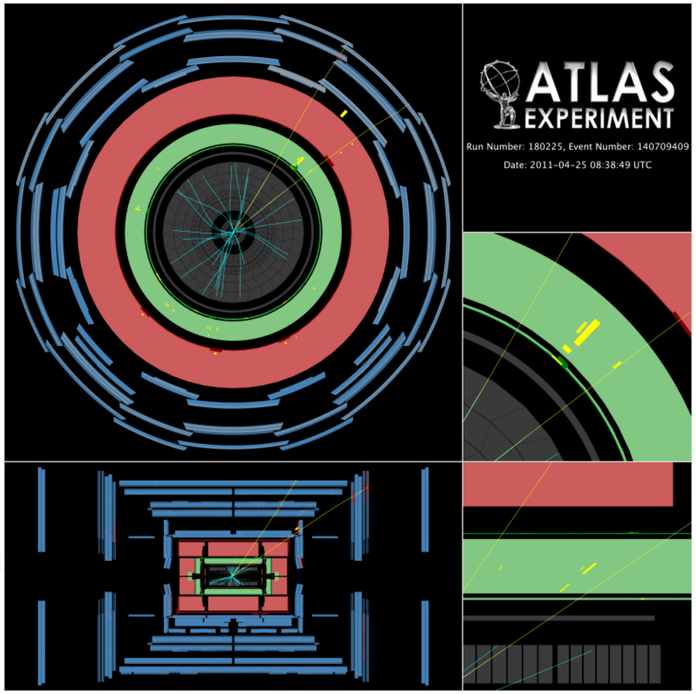
P_c^+ at 7-8 TeV — **ATLAS-CONF-2019-048**

Summary

ATLAS @ LHC

Weight : ~ 7000 tons





Inner Detector (Pixel+SCT+TRT):

$p_T > 0.4$ (0.1) GeV, $|\eta| < 2.5$

New for Run 2:

Insertable B-layer (IBL) – inner-most pixel layer (r = 33 mm) and thinner beam-pipe

$m(\mu^+\mu^-)$ resolution: ~50 MeV for J/ψ

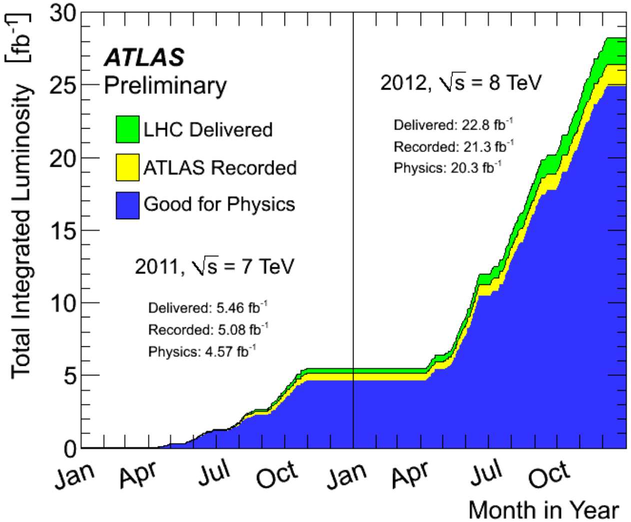
~150 MeV for Υ

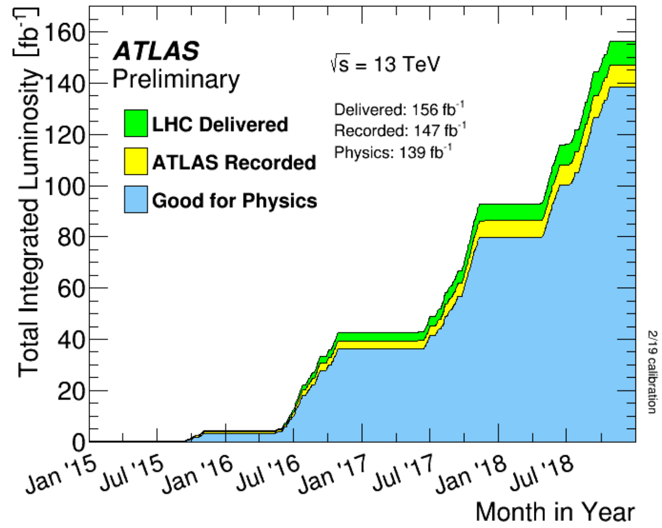
Muon Spectrometr:

Offline tracking: $|\eta| < 2.7$

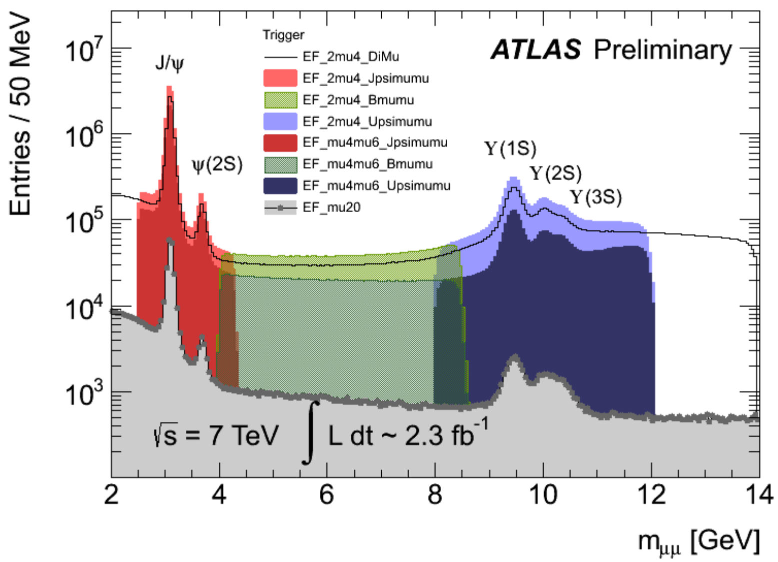
Triggering: $|\eta| < 2.4$

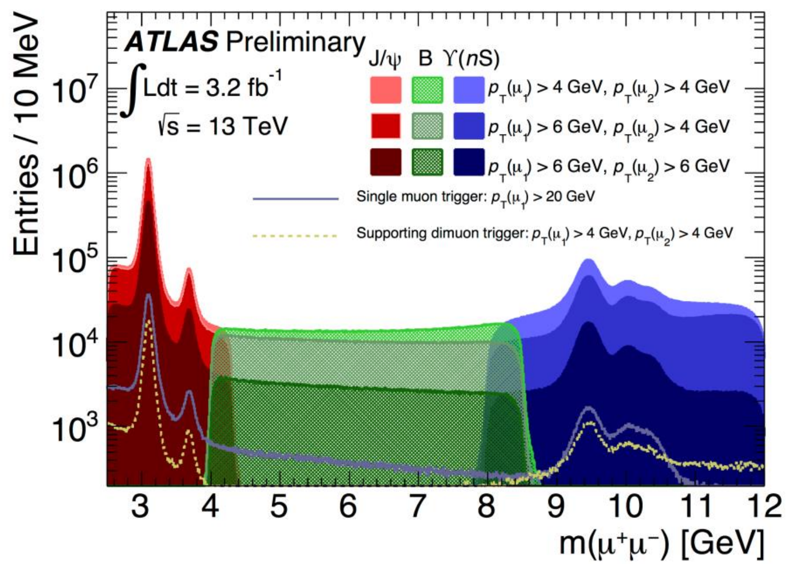
Data Taking and Heavy Flavor triggering





Peak Lumi: 7.73 x 10^{33} cm^{-2} s^{-1} **21.0 x 10^{33} cm^{-2} s^{-1}**





Charmonium production at 13 TeV with 139 fb^{-1}

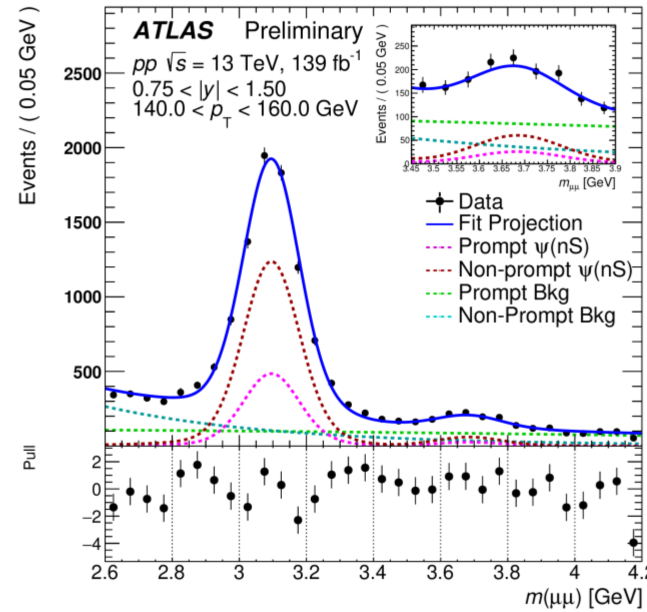
Uses a single-muon trigger, with threshold at 50 GeV, un-prescaled on the full integrated luminosity of Run II, 139 fb^{-1}

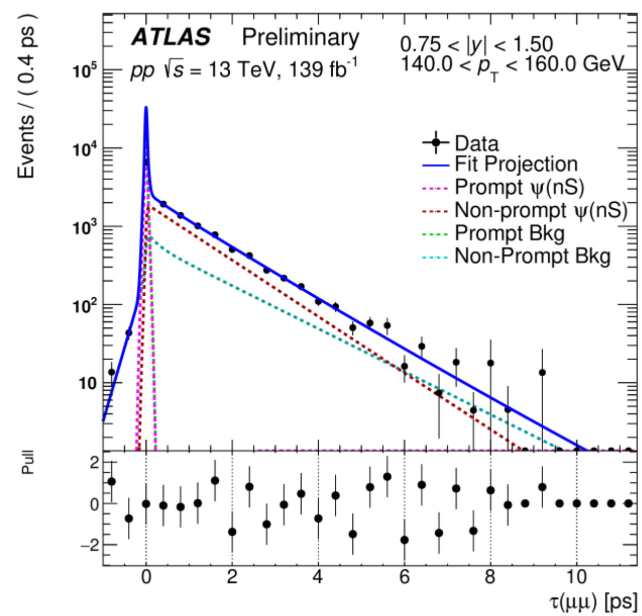
p_T range covered: 60-360 GeV for J/ψ in 11 bins
(60-140 GeV for ψ(2S))

Rapidity range |y| < 2 covered in three bins

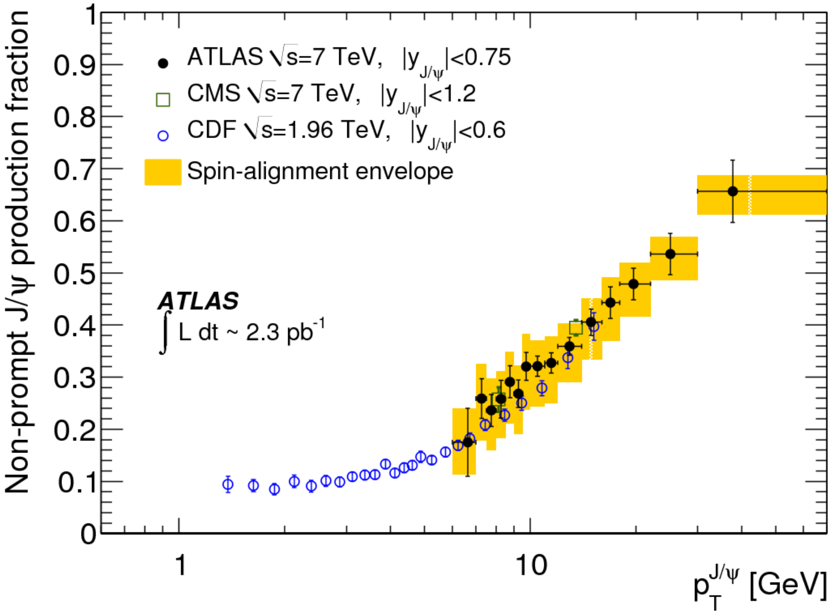
Yields for J/ψ and ψ(2S), prompt and non-prompt (from B decays), determined using 2D fit (mass and "pseudo-proper" lifetime)

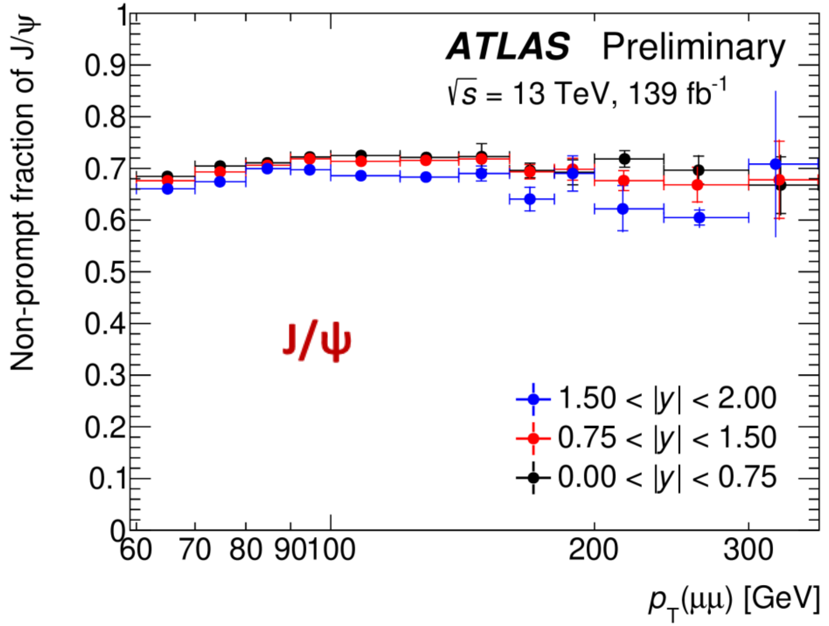
$$\tau = \frac{m\, L_{xy}}{c\, P_T}$$





Charmonium non-prompt fractions



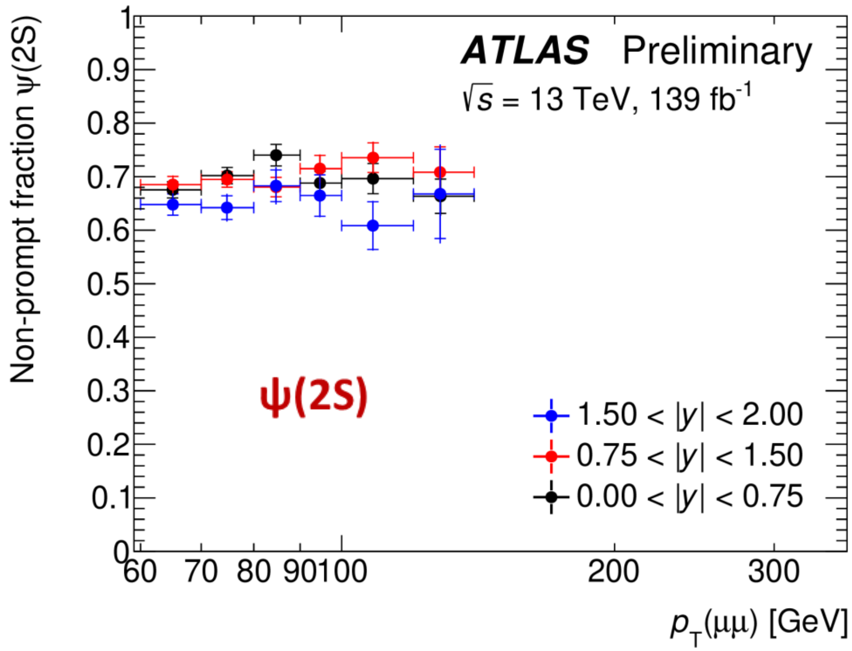


Plateau ~0.7 for p_T >~ 40 GeV

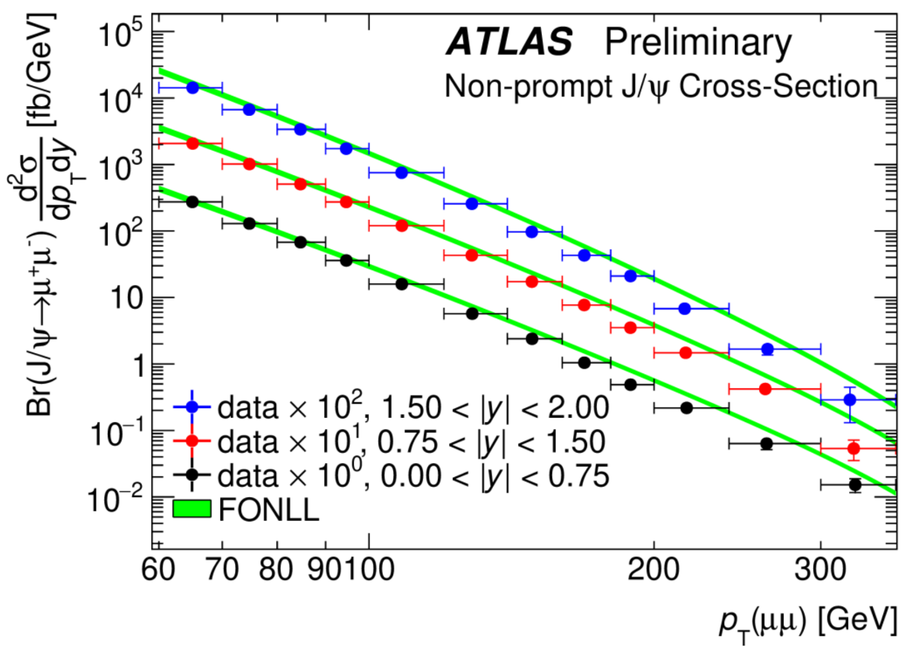
Similar behavior in pp and p$\bar{p}$ collisions for √s from 1.96 TeV till 13 TeV

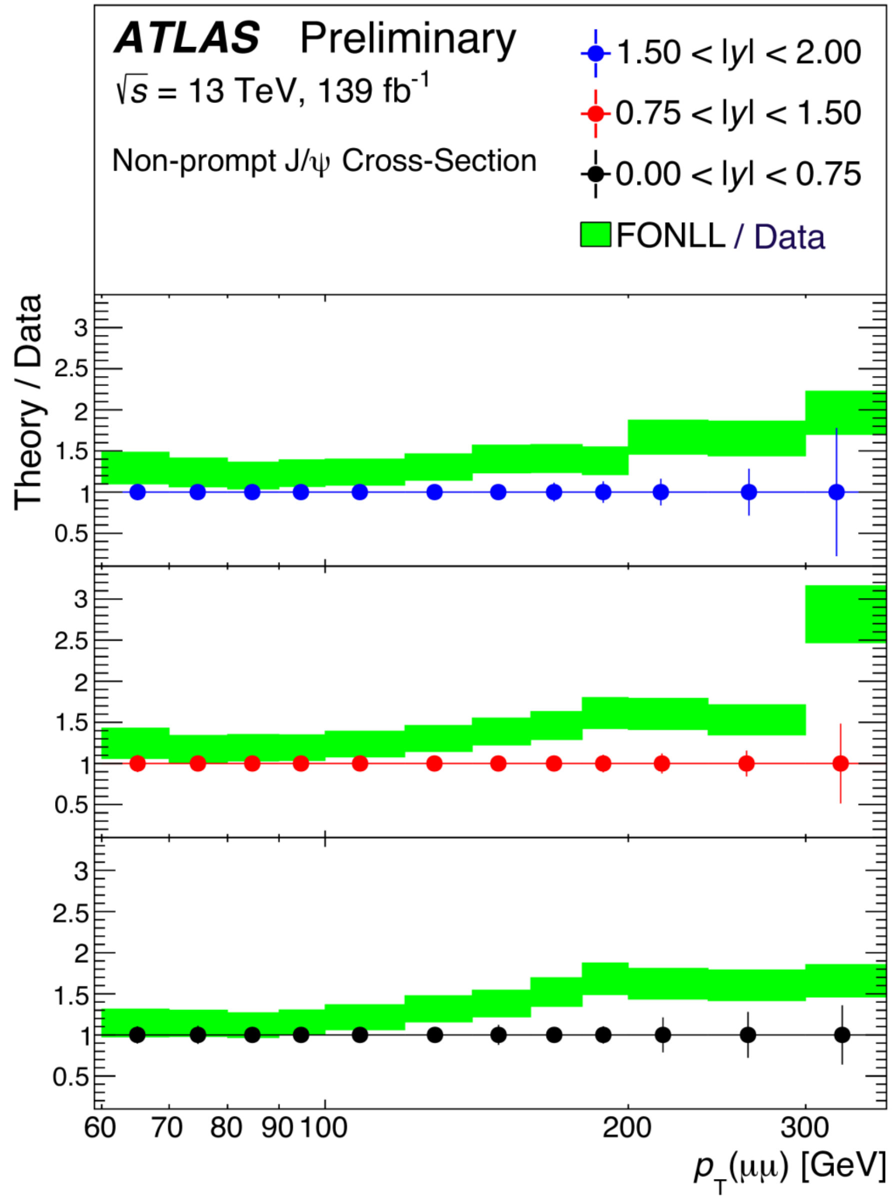
No strong dependence from rapidity

Similar for J/ψ and ψ(2S)



Charmonium non-prompt x-sections



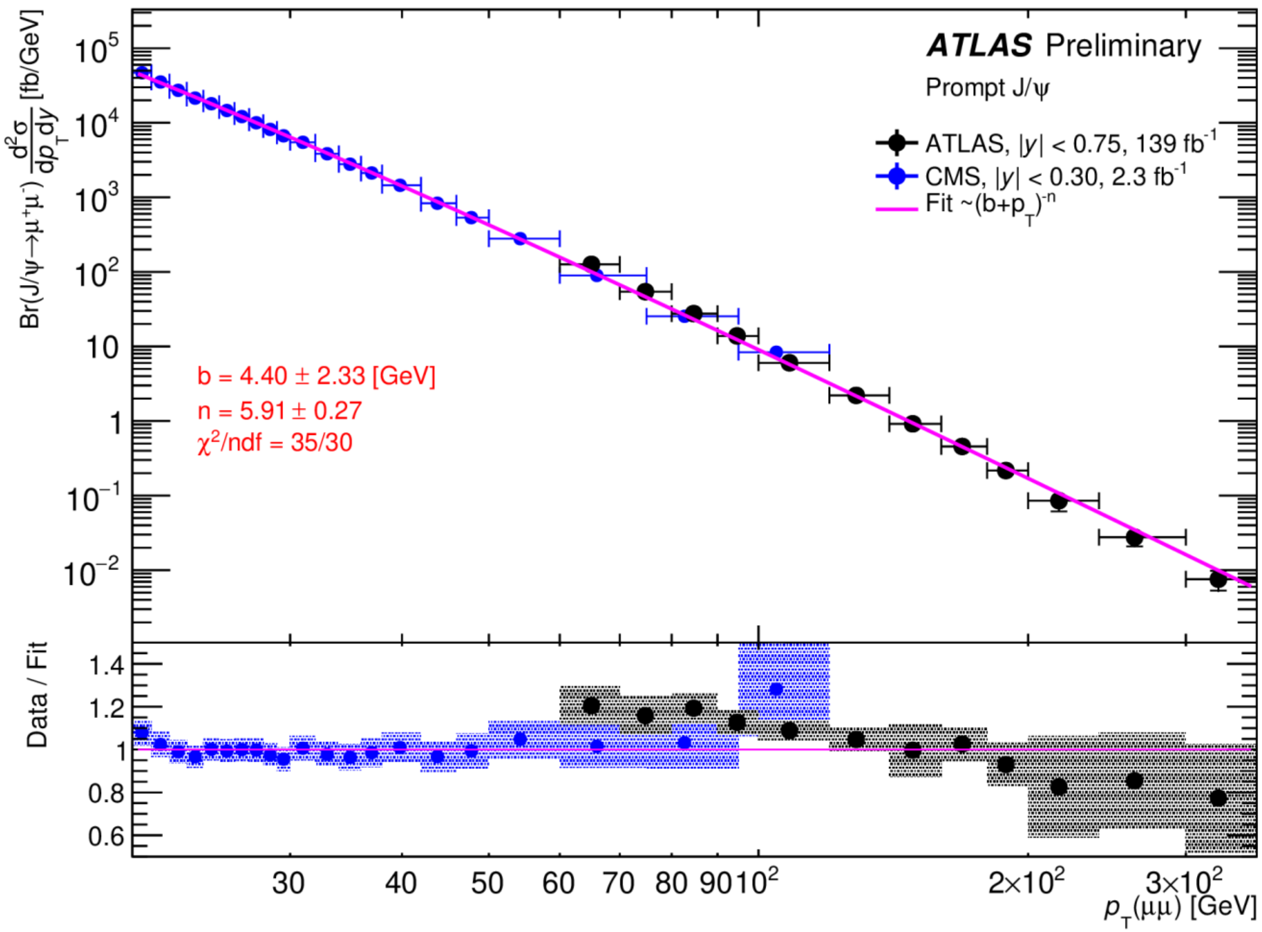


FONLL predictions in general agreement, too high at high p_T

Deviations from data up to ~2

NNLO?
New fragmentation tuning?
Fixing of technical FONLL problems at high p_T?

Charmonium prompt x-sections



ATLAS and CMS agree in the range of overlap

Can be described by simple parametrization

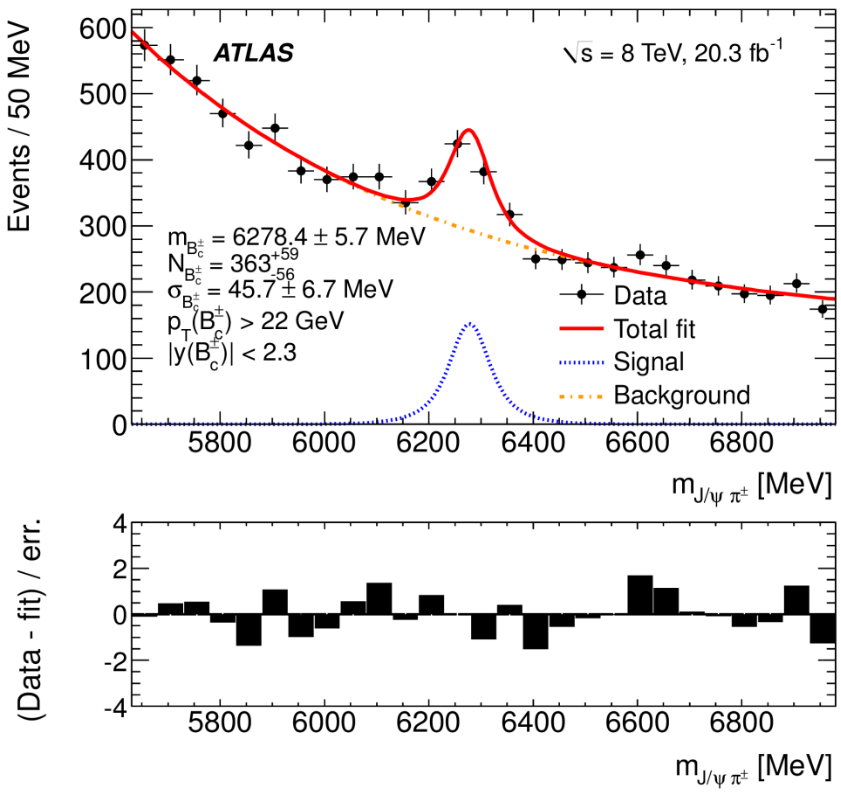
$\sim(b+p_T)^{-n}$

with b=4.4 and n=6

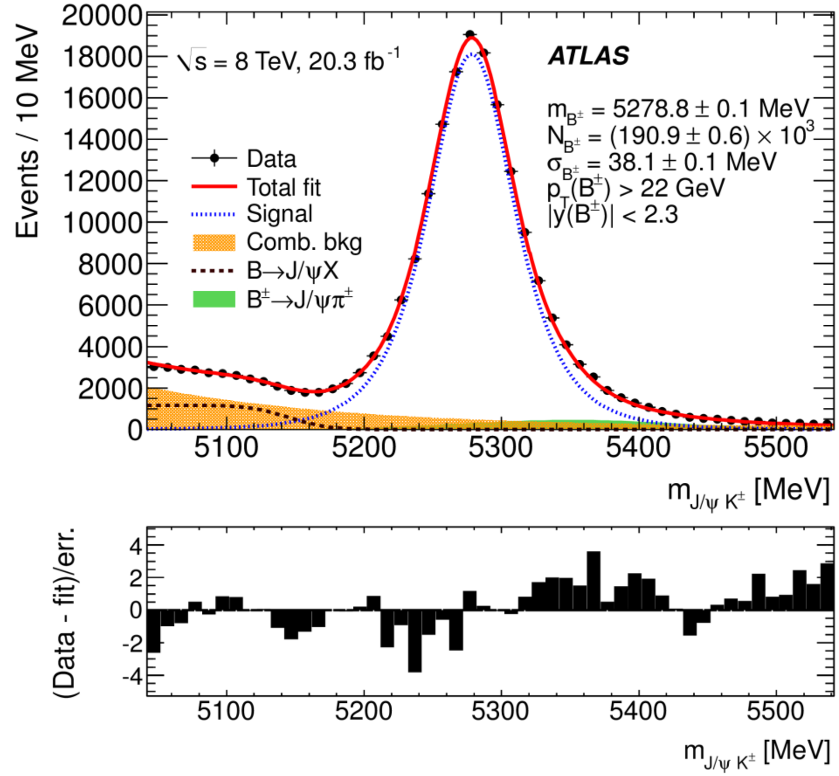
Waiting NRQCD predictions for high-p_T charmonium production

B_c^+ / B^+ x-section ratios at 8 TeV with 20 fb^{-1}

$B_c^+ \to J/\psi\ \pi^+$



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



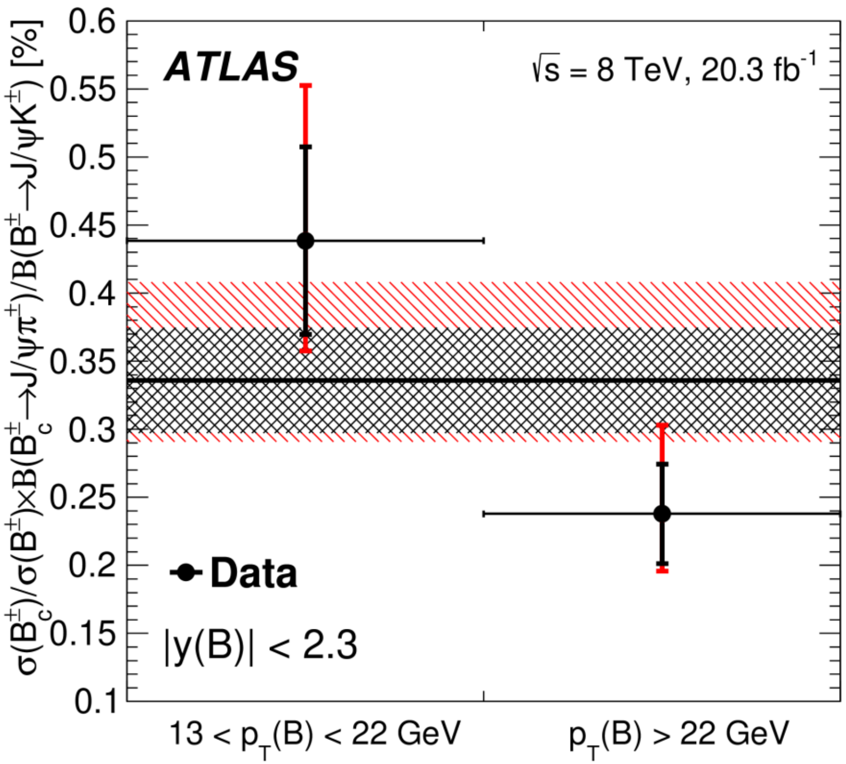
B_c^+ and B^+ yields measured using di-muon trigger

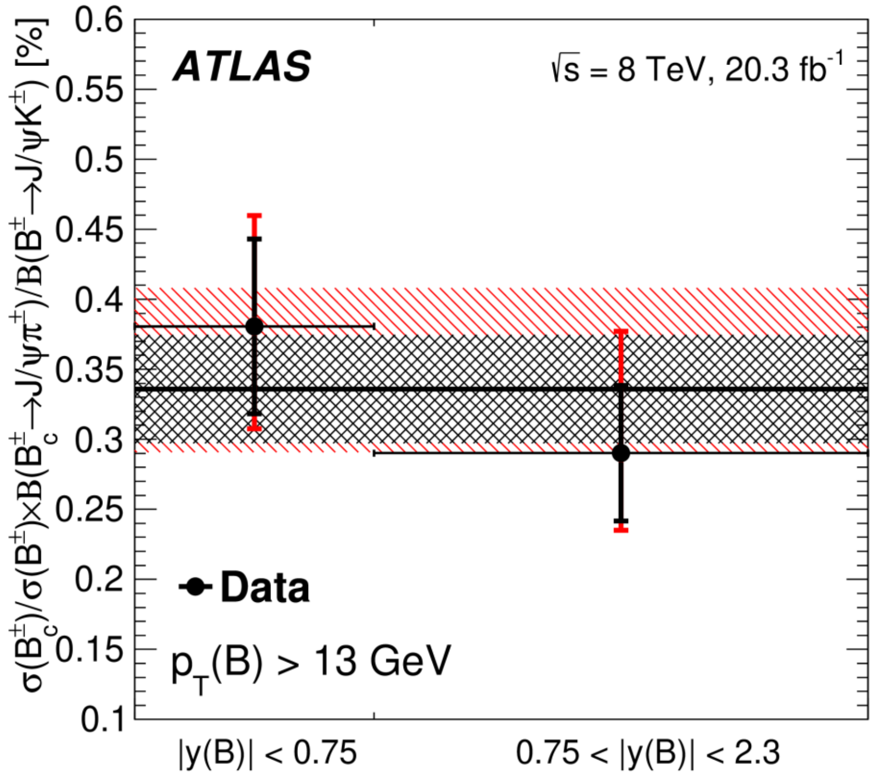
Their ratios, corrected for acceptances and efficiencies, measured in two p_T bins (13-22 GeV, >22 GeV) and two |y| bins (<0.75, 0.75-2.3)

B_c^+ / B^+ x-section ratios at 8 TeV

$$\frac{\sigma(B_c^\pm)\cdot\mathcal{B}(B_c^\pm\to J/\psi\pi^\pm)}{\sigma(B^\pm)\cdot\mathcal{B}(B^\pm\to J/\psi K^\pm)} = (0.34\ \pm\ 0.04_{\,\mathrm{stat}}\ {}^{+0.06}_{-0.02}{}_{\,\mathrm{syst}}\ \pm\ 0.01_{\mathrm{lifetime}})\%$$

Compatible with CMS/LHCb





The ratio decreases with p_T

No significant |y| dependence

Differences in production?
hadronization?

B_c^+ / B^+ x-section ratios at LHC

$$\frac{\sigma(B_c^\pm)\cdot\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm)\cdot\mathcal{B}(B^\pm \to J/\psi K^\pm)} =$$

0.683 ± 0.018 ± 0.009 **pT < 20 GeV**, 2.0 < |y| < 4.5 LHCb at 8 TeV

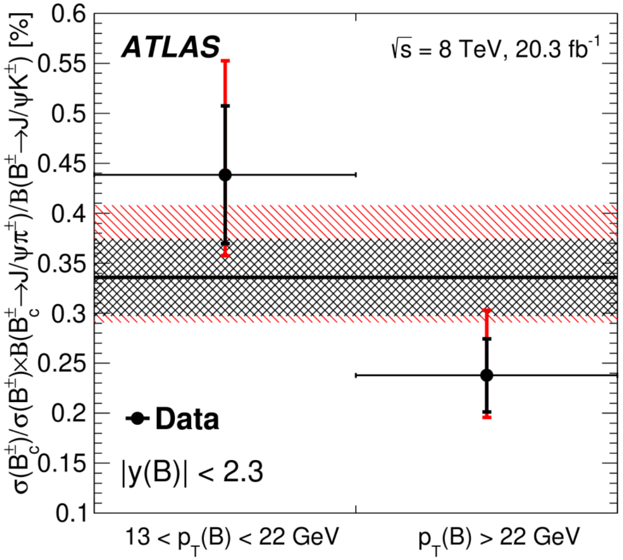
0.48 ± 0.05 ± 0.03 ± 0.05 **pT > 15 GeV**, |y| < 1.6 CMS at 7 TeV

0.44 ± 0.07 $^{+0.09}_{-0.04}$ ± 0.01 **13 < pT** < 22 GeV, |y| < 2.3 ATLAS at 8 TeV

0.24 ± 0.04 $^{+0.05}_{-0.01}$ ± 0.01 **pT > 22 GeV**, |y| < 2.3 ATLAS at 8 TeV

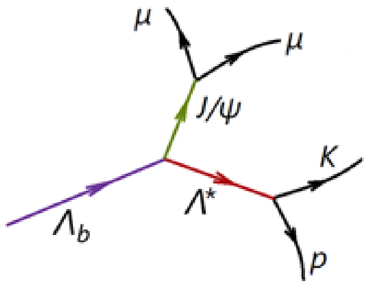
The ratio decreases with p_T

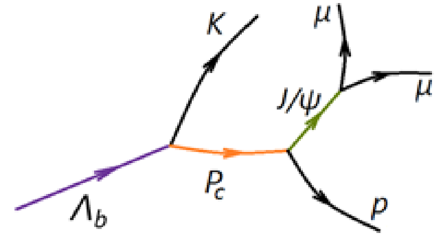
Differences in production?
hadronization?

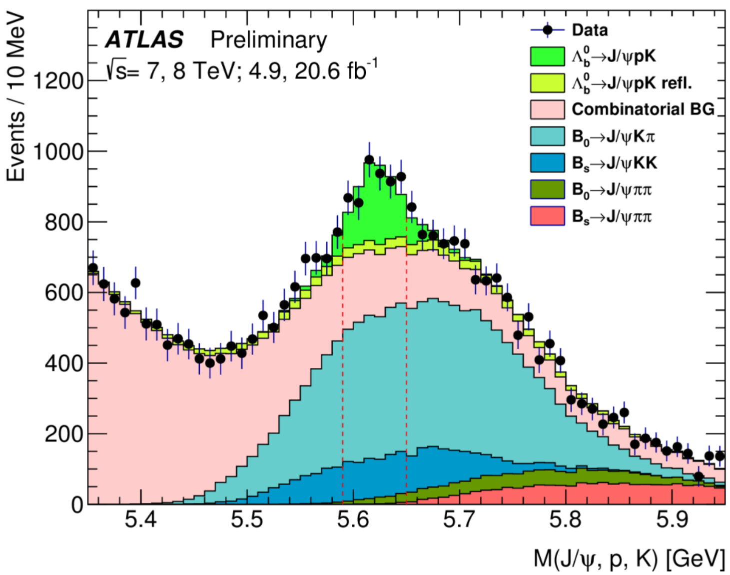


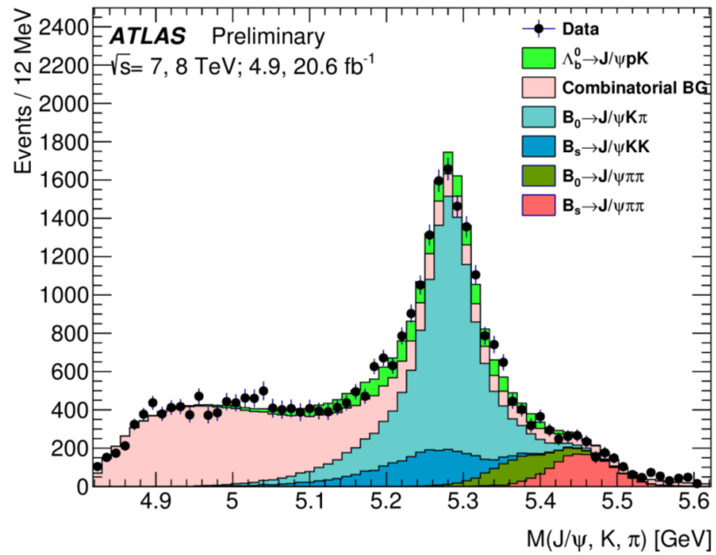
Pentaquarks with hidden charm ($c\bar{c}uud$) at 7 - 8 TeV with 25 fb^{-1}

m(Kπ) > 1.55 && m(πK) > 1.55 → m(pK) > 2.0 GeV





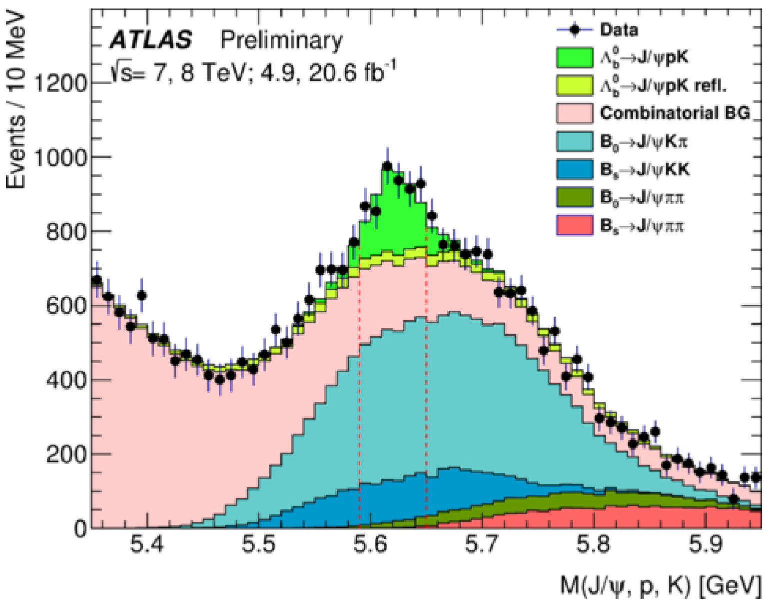




$\Lambda_b \to J/\psi\, p\, K^-$ signal is seen on the top of

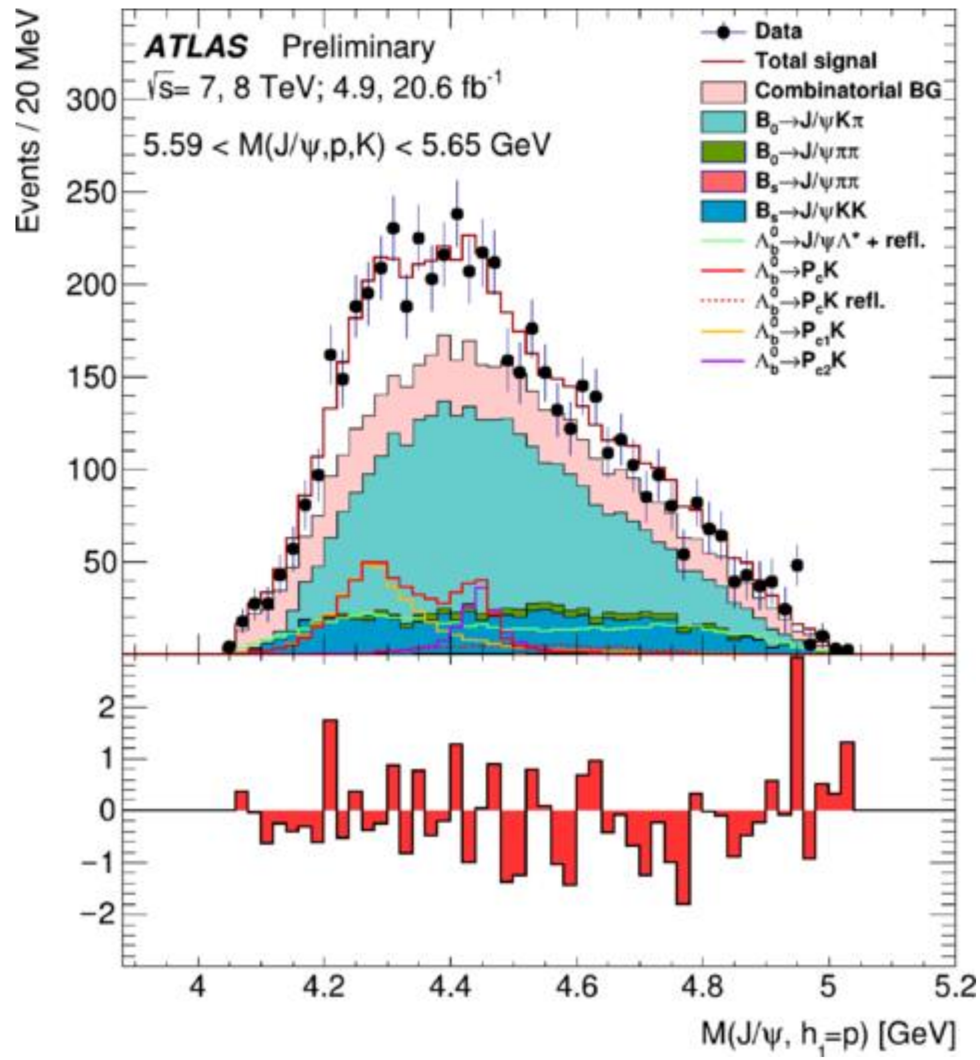
- **large combinatorial background**
- **very large $B \to J/\psi\, K^+ \pi^-$ contribution**
- **large $B_s \to J/\psi\, K^+ K^-$ contribution**
- **tails from small $B \to J/\psi\, \pi^+ \pi^-$ and $B_s \to J/\psi\, \pi^+ \pi^-$ contributions**

P_c^+ at 7 - 8 TeV



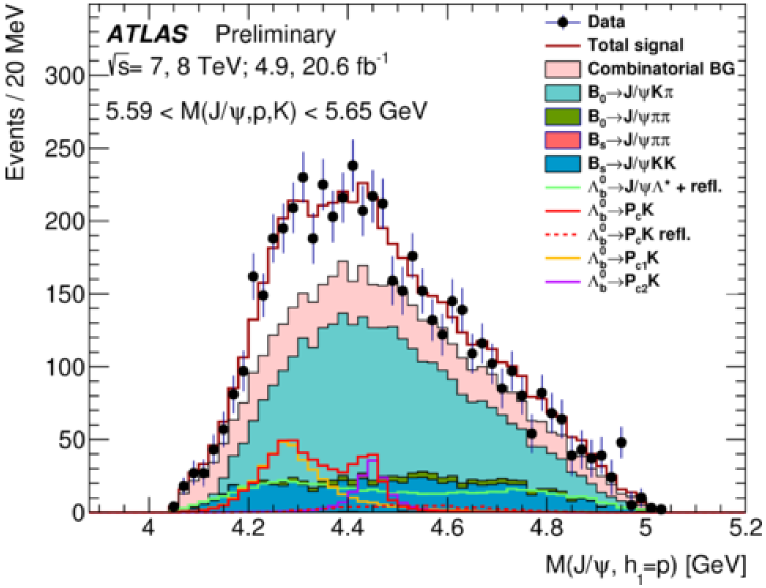
$N(\Lambda_b \to J/\psi, p, K) = 2270 \pm 300$

$N(B^0 \to J/\psi, K, \pi) = 10770$,
$N(B_s \to J/\psi, K, K) = 2290$,
$N(B^0 \to J/\psi, \pi, \pi) = 1070$,
$N(B_s \to J/\psi, \pi, \pi) = 1390$;

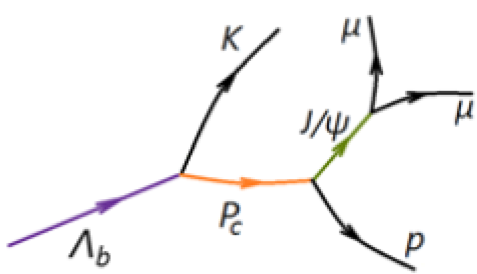


1010±140 direct $\Lambda_b \to J/\psi, p, K$

$\Lambda_b \to J/\psi, p, K$ decays analysis: 2 pentaquark hypothesis



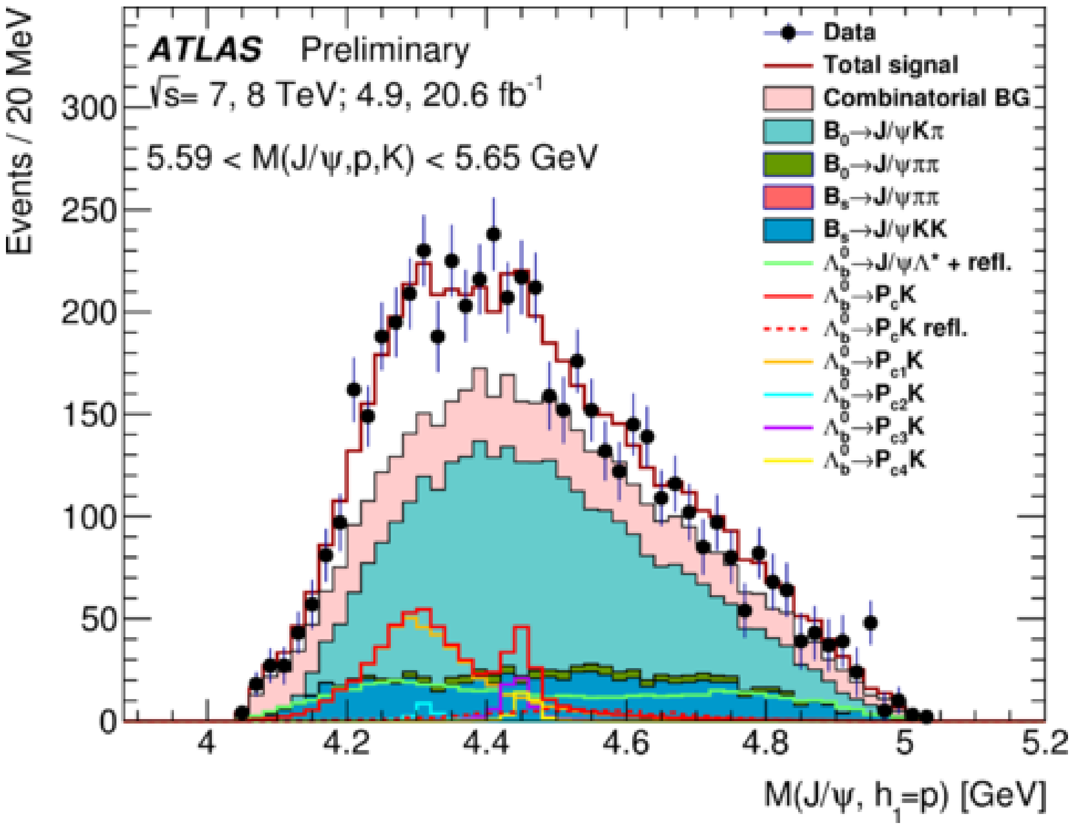
$\chi^2/N_{dof} = 49.0/43$ (p-value= 0.25)



P_c signal parameters and yields from fit:

Parameter	Value	LHCb value
$N(P_{c1})$	400^{+130}_{-140}(stat)$^{+110}_{-100}$(syst)	–
$N(P_{c2})$	150^{+170}_{-100}(stat)$^{+50}_{-90}$(syst)	–
$N(P_{c1}+P_{c2})$	540^{+80}_{-70}(stat)$^{+70}_{-80}$(syst)	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}$(stat)$^{+0.2}_{-0.1}$(syst) rad	–
$m(P_{c1})$	4282^{+33}_{-26}(stat)$^{+28}_{-7}$(syst) MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

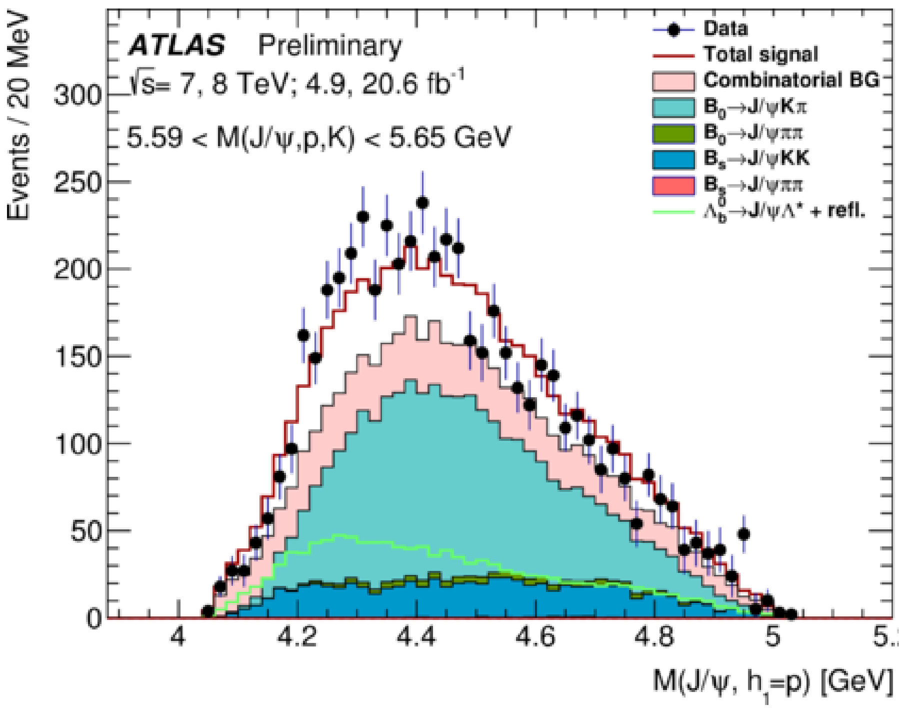
$\Lambda_b \rightarrow J/\psi,p,K$ decays analysis: 4 pentaquark hypothesis

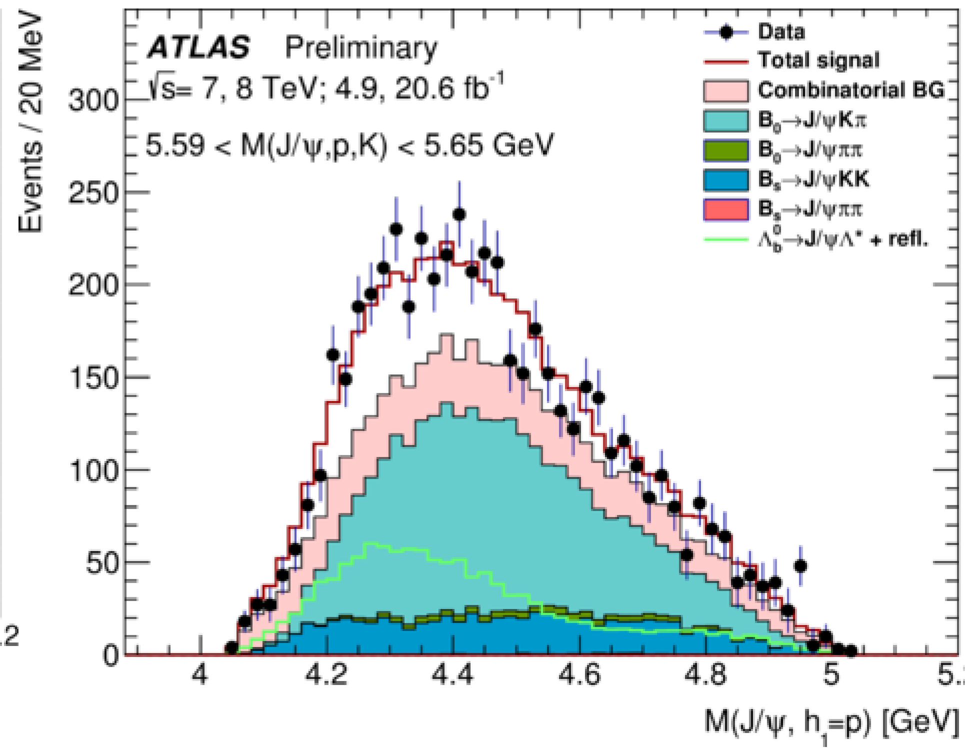


Similar fits (no interference, Breit-Wigner amplitudes) has been performed on our data with masses, widths and relative yields of narrow states fixed to LHCb values. Parameters of $P_c(4380)$ kept free.

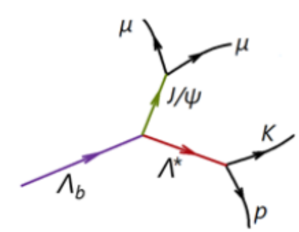
ATLAS data is consistent with LHCb Run II results.

No pentaquark fits: extended Λ* decay model





Projection of 2D M(J/ψ,p) vs M(J/ψ,K) + 1D M(p,K) fit w/o pentaquarks using extended Λ* decay model (left)



Result of 1D χ2 M(J/ψ,p) fit with the same model (right): $\chi^2/NDF = 42.0/23$

p-val = 9.1 x 10^{-3}

This model shows a ‘border-line agreement’ with data.

Summary

J/ψ & ψ(2S) at 13 TeV

non-prompt fraction: plateau ~0.7 for p_T >~ 40 GeV

non-prompt x-sections: FONLL predictions too high at high p_T

prompt x-sections: $\sim(b+p_T)^{-n}$**, waiting for NRQCD**

B_c^+ / B^+ at 8 TeV

~0.3% (σ * Br)

the ratio decreases with p_T

no significant |y| dependence

P_c^+ at 7-8 TeV

measured parameters of two pentaquarks agree with LHCb;

do not contradict to the 3 narrow pentaquarks LHCb measurement;

model w/o pentaquarks in border-line agreement (p-val = 9.1×10^{-3})

New exciting results for summer/fall conferences

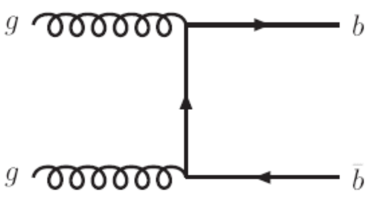
Back-up Slides

Charmonium production

Non-prompt (from B decays) – probes open b quark production, fragmentation and B-decay kinematics

FONLL, matched NLO+NLL ("massive" NLO + resummation)

GM-VFNS ("massless" NLO + mass-dependent terms)



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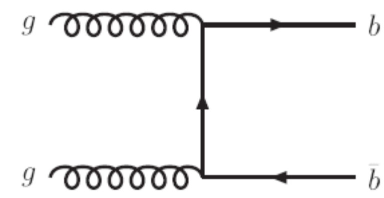
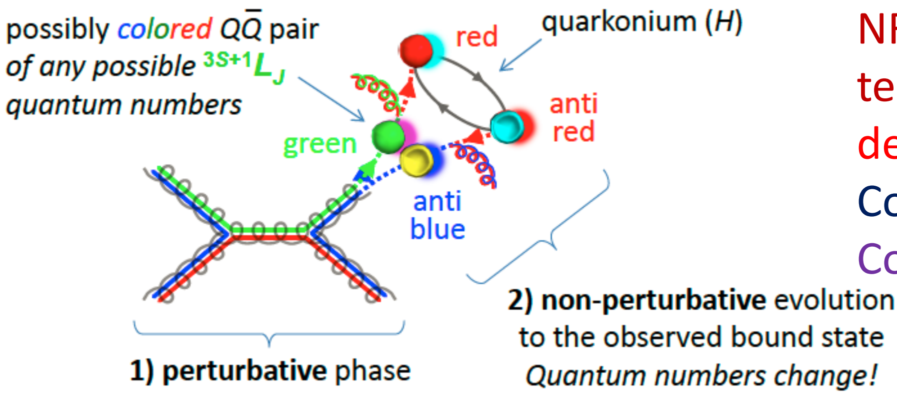


Prompt (not from B decays) – probes specific mechanisms of $Q\bar{Q}$ system production and transformation to a meson



NRQCD: Color Singlet (CS) and Color Octet (CO) terms. Long-distance matrix elements (LDME) determined from experimental data.

Color Singlet Model (CSM) – only CS diagrams.

Color Evaporation Model (CEM) – only one LDME.

Charmonium production

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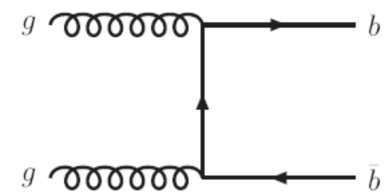

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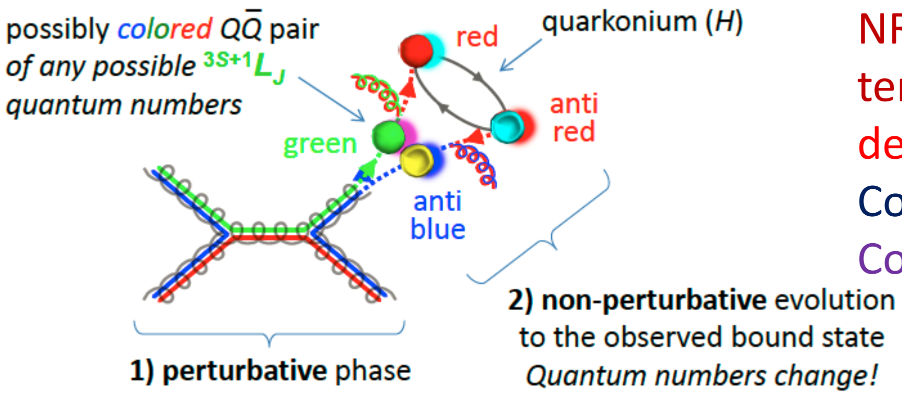

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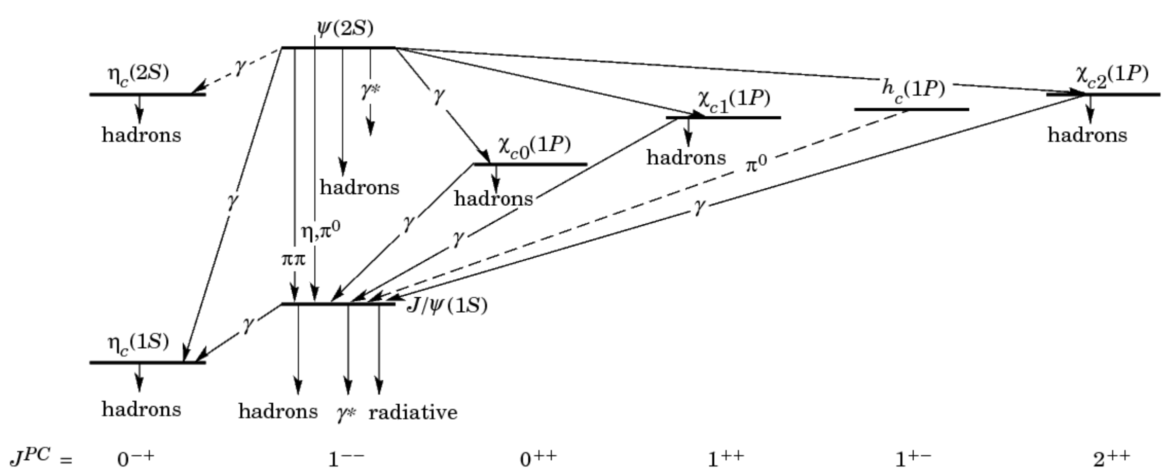
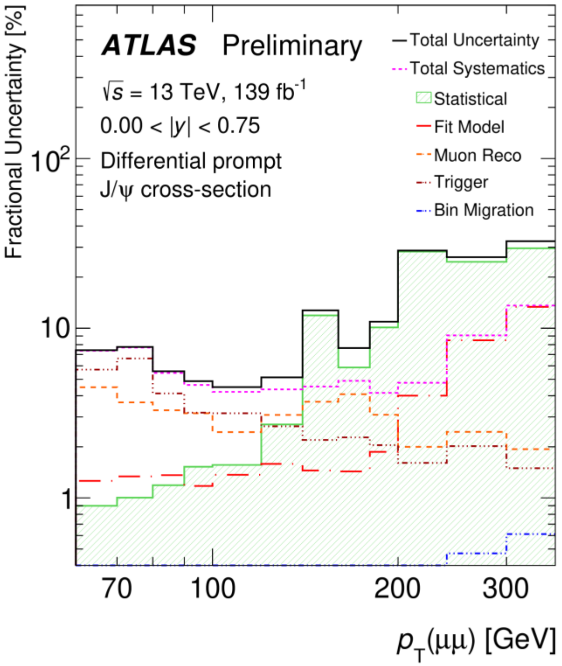
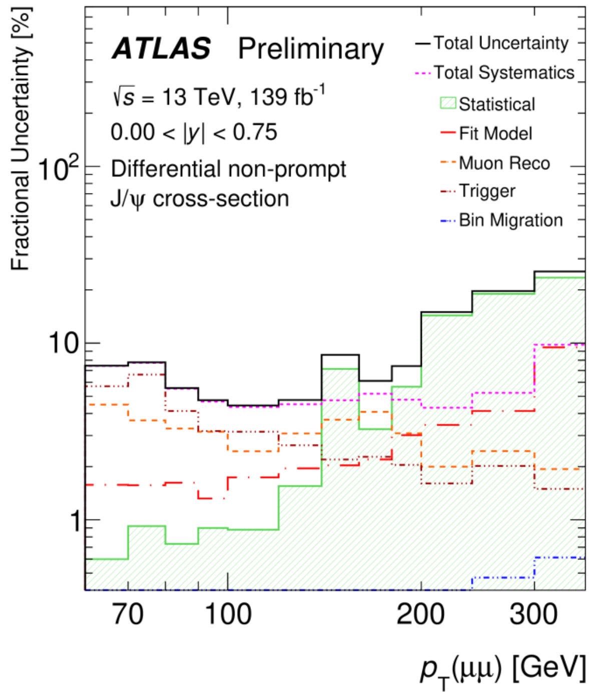
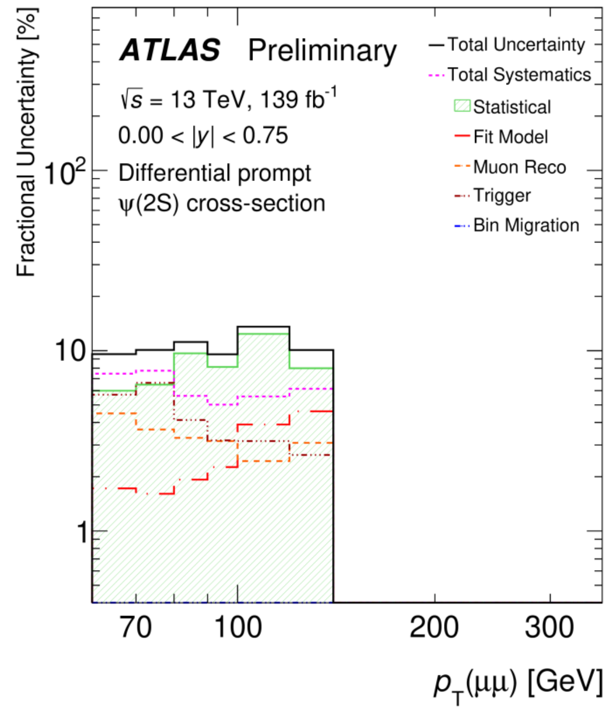


Ψ(2S) – nearly feed-down free

J/ψ – feed-downs ~35%







- Systematics due to fit model variation, muon and track reconstruction efficiency determination, trigger efficiency determination, and bin-to-bin migration have been studiec
- Systematic uncertainties dominate for J/ψ up to pT of about 140 GeV
- At higher pT of J/ψ, and also for full range of pT for ψ(2S), statistical errors are dominant.
- Overall uncertainties for J/ψ start at the level of 5-7%, increasing at the highest pT to 30%
- For ψ(2S), uncertainties fairly stable at around 10%

B_c^+ / B^+ x-section ratios at 8 TeV with 20 fb^{-1}

Source of uncertainty	Uncertainty value			
	$B_c^{\pm}$		$B^{\pm}$	
	$13\,GeV < p_T < 22\,GeV$	$p_T > 22\,GeV$	$13\,GeV < p_T < 22\,GeV$	$p_T > 22\,GeV$
Signal model of the fit	2.4%	1.1%	0.1%	0.2%
CS and PRD components	$^{+19.3\%}_{-2.4\%}$	$^{+19.9\%}_{-2.4\%}$	0.5%	0.5%
Background model of the fit	1.7%	1.2%	0.2%	0.2%
Trigger and reconstruction effects	0.9%	0.8%	1.2%	1.2%
B-meson lifetime uncertainty	1.1%	0.9%	$< 0.1\%$	$< 0.1\%$

Source of uncertainty	Uncertainty value			
	$B_c^{\pm}$		$B^{\pm}$	
	$\lvert y\rvert < 0.75$	$0.75 < \lvert y\rvert < 2.3$	$\lvert y\rvert < 0.75$	$0.75 < \lvert y\rvert < 2.3$
Signal model of the fit	2.5%	2.8%	0.1%	0.2%
CS and PRD components	$^{+11.2\%}_{-2.4\%}$	$^{+23.2\%}_{-2.4\%}$	0.5%	0.5%
Background model of the fit	2.8%	1.3%	0.2%	0.2%
Trigger effects and reconstruction effects	1.1%	1.0%	1.2%	1.1%
B-meson lifetime uncertainty	1.0%	0.9%	$< 0.1\%$	$< 0.1\%$

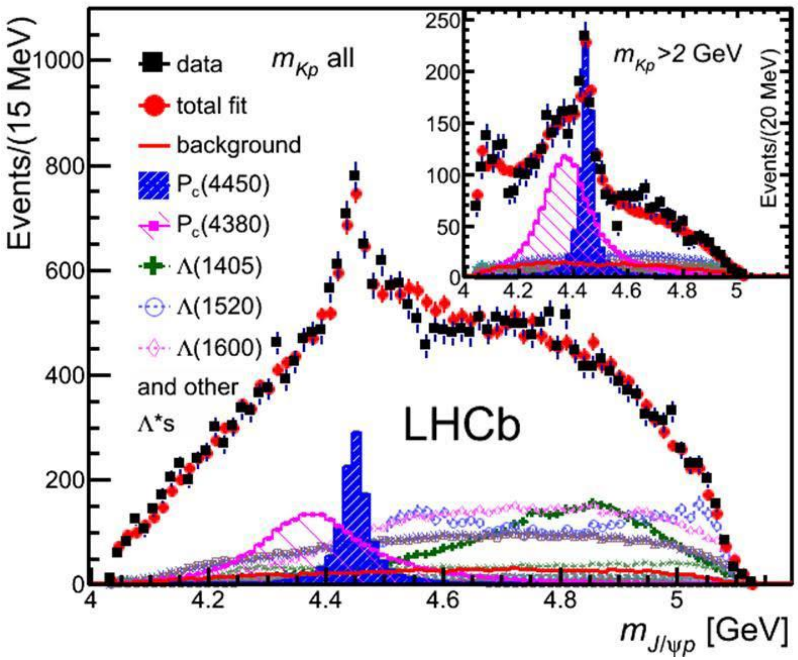
LHCb results on pentaquarks with hidden charm

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays PRL **115**, 072001 (2015)

Model-Independent Evidence for $J/\psi p$ Contributions to $\Lambda_b^0 \to J/\psi p K^-$ Decays PRL **117**, 082002 (2016)

Study of the production of Λ_b^0 and $\overline{B}^0$ hadrons in pp collisions and first measurement of the $\Lambda_b^0 \to J/\psi pK^-$ branching fraction 2016 *Chinese Phys. C* **40** 011001

Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \to J/\psi p\pi^-$ Decays PRL **117**, 082003 (2016)



$m_1 = 4380 \pm 8 \pm 29$ MeV, $\Gamma_1 = 205 \pm 18 \pm 86$ MeV,

$m_2 = 4449.8 \pm 1.7 \pm 2.5$ MeV, $\Gamma_2 = 39 \pm 5 \pm 19$ MeV.

Significance is convincing

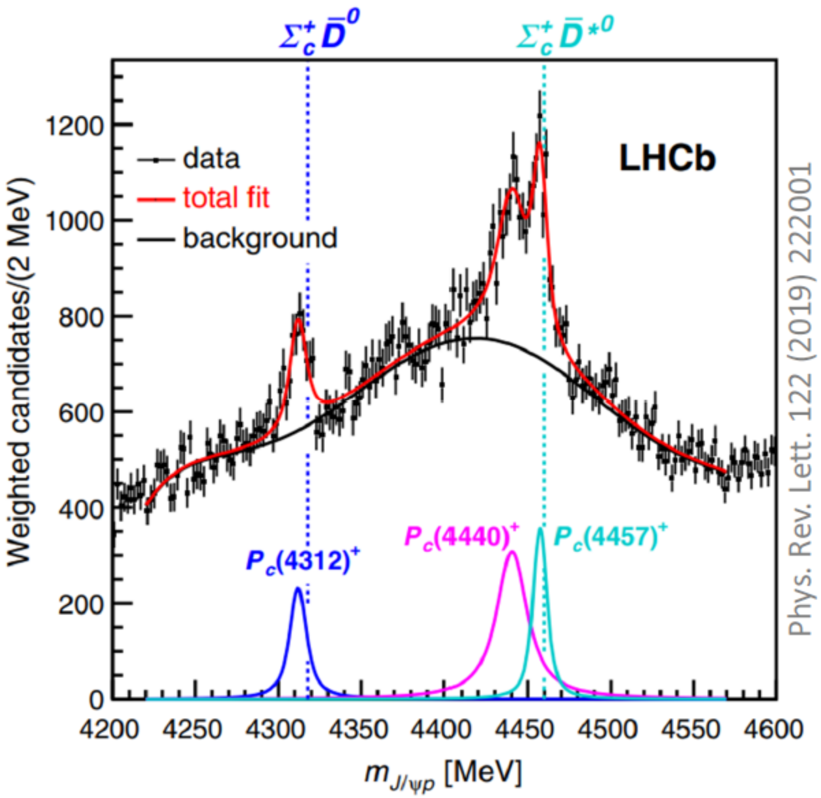
However, in PDG

Status: *

* Evidence of existence is poor.

Observation of a narrow pentaquark state, Pc(4312)+, and of two-peak structure of the Pc(4450)+

Phys. Rev. Lett. 122, 222001 (2019) arXiv:1904.03947 [hep-ex]



LHCb selected 9 times more Λ_b candidates in Run II compared to Run I.

The $J/\psi p$ mass resolution is 2.3-2.7 MeV (RMS) in 4.3-4.6 GeV region.

New data showed evidence for a new narrow state: $P_c(4312)$.

Moreover, the former $P_c(4450)$ state revealed substructure: 2 narrow states $P_c(4440)$ and $P_c(4457)$ have been observed.

Signal parameters are obtained using non-coherent sum of Breit-Wigner amplitude.

Presence of the broad state $P_c(4380)$ is not confirmed…

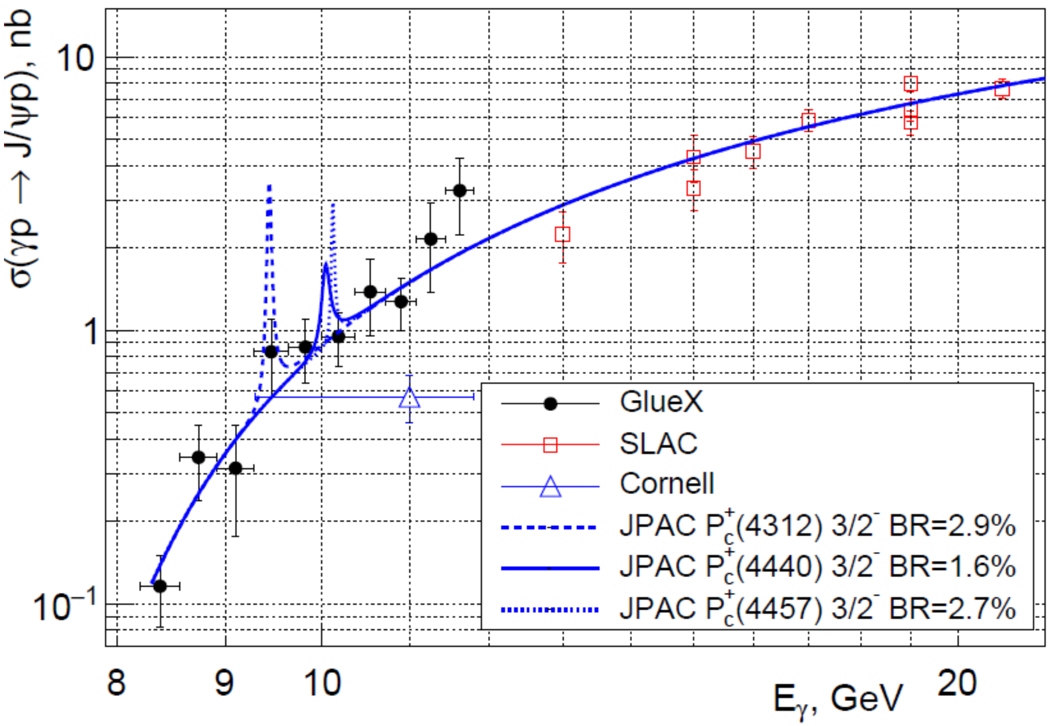
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Helicity formalism is not (yet) used in Run II analyses

First measurement of near-threshold J/ψ exclusive photoproduction off the proton

Phys. Rev. Lett. 123, 072001 (2019) arXiv:1905.10811 [nucl-ex] (The GlueX Collaboration)

We report on the measurement of the $\gamma p \to J/\psi p$ cross section from $E_\gamma = 11.8$ GeV down to the threshold at 8.2 GeV using a tagged photon beam with the GlueX experiment. We find the total cross section falls toward the threshold less steeply than expected from two-gluon exchange models. The differential cross section $d\sigma/dt$ has an exponential slope of 1.67 ± 0.39 GeV^{-2} at 10.7 GeV average energy. The LHCb pentaquark candidates P_c^+ can be produced in the s-channel of this reaction. We see no evidence for them and set model-dependent upper limits on their branching fractions $\mathcal{B}(P_c^+ \to J/\psi p)$ and cross sections $\sigma(\gamma p \to P_c^+) \times \mathcal{B}(P_c^+ \to J/\psi p)$.



	$\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, %	
	p.t.p. only	total
$P_c^+(4312)$	2.9	4.6
$P_c^+(4440)$	1.6	2.3
$P_c^+(4457)$	2.7	3.8

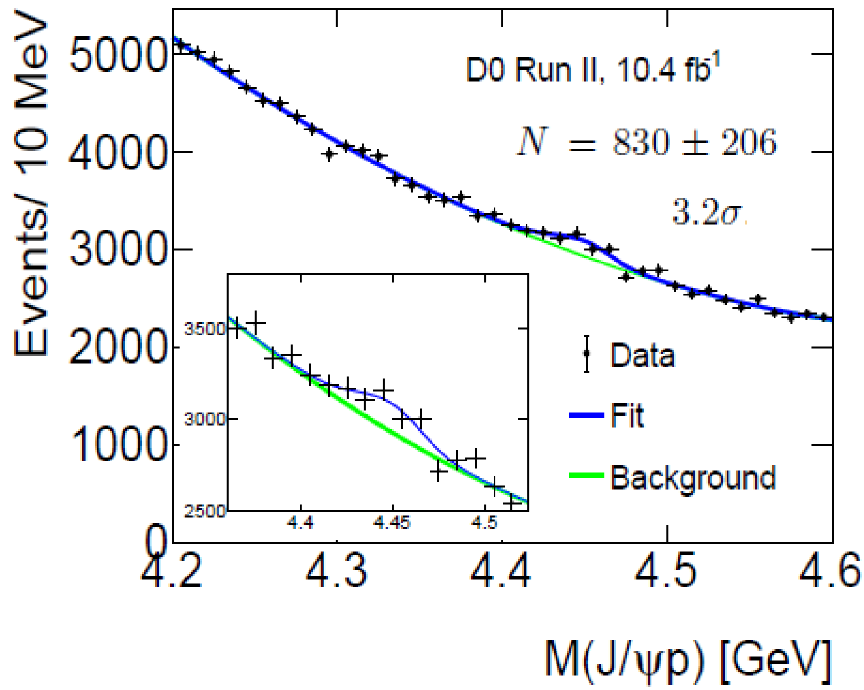
upper limits for the P_c^+ states

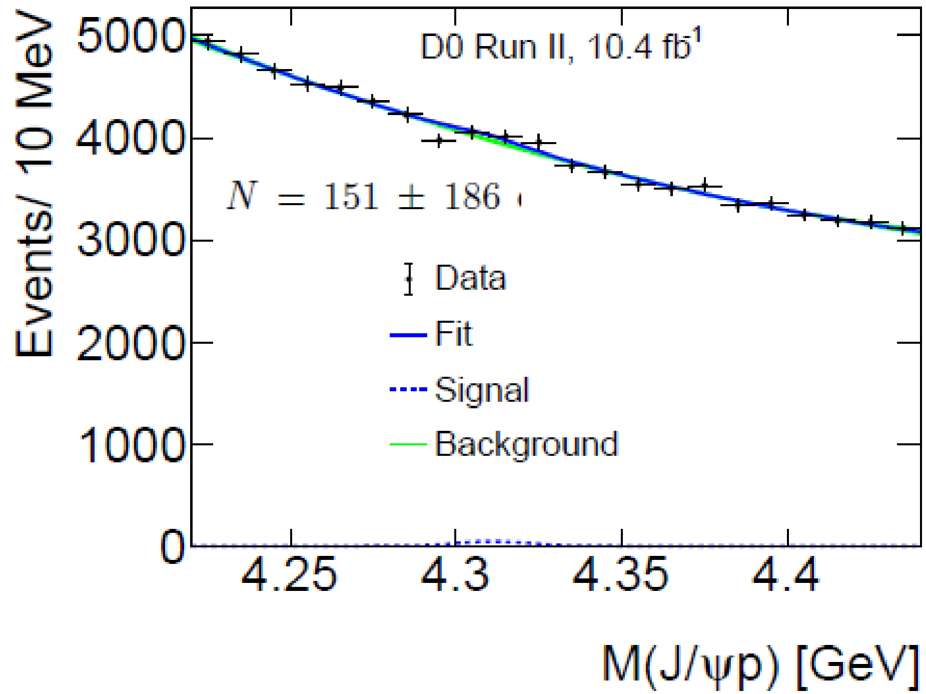
at 90% confidence level

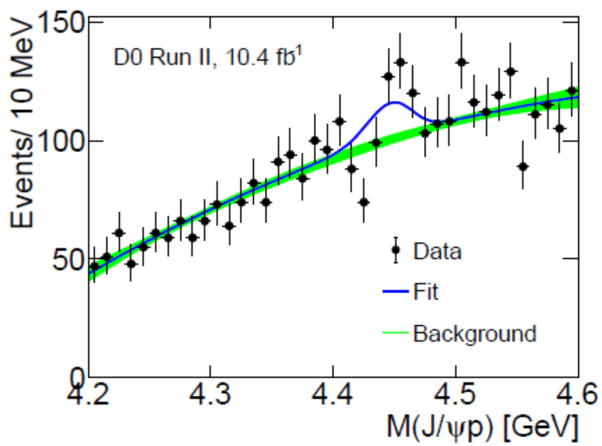
Inclusive production of the P_c resonances in $p\bar{p}$ collisions (The D0 Collaboration*)

arXiv:1910.11767 [hep-ex]

"displaced vertex" candidates with a superimposed fit







candidates of the decay $\Lambda_b^0 \to J/\psi p K^-$

82 ± 37

2.3σ

Selection criteria

- $\chi^2(H_b)/N_{\text{dof}} < 2$, where χ^2 is the quality of the fit to the H_b topology with $N_{\text{dof}} = 8$.
- $L_{xy}(H_b) > 0.7$ mm, where $L_{xy}(H_b)$ is the transverse decay length of the H_b vertex measured from the primary vertex.
- $p_{\text{T}}(H_b)/\sum p_{\text{T}}(\text{track}) > 0.2$, where the sum in the denominator is taken over all tracks originating from the primary vertex (tracks of the H_b candidate are included in the sum). The requirement removes a sizeable fraction of combinatorial background while having a smaller effect on the signal due to the characteristic hard fragmentation of b quarks.
- $p_{\text{T}}(p) > 2.5$ GeV and $p_{\text{T}}(K^-) > 1.8$ GeV, assuming proton and kaon masses for the additional tracks in turn.
- $\cos\theta_{P_c} < 0.5$, where θ_{P_c} is the angle between J/ψ momentum in the P_c candidate rest frame and P_c candidate momentum in Λ_b candidate rest frame;
- $\cos\theta_{\Lambda_b} < 0.8$, where θ_{Λ_b} is the angle between P_c candidate momentum and Λ_b candidate momentum in laboratory frame;
- $|\cos\theta_{\Lambda^*}| < 0.85$,
  where θ_{Λ^*} is the angle between kaon momentum in $\Lambda^* \to pK$ candidate rest frame and Λ^* candidate momentum in Λ_b candidate rest frame.

$$p_{\text{T}}(\mu^\pm) > 4\,\text{GeV},\ |\eta(\mu^\pm)| < 2.3.$$

The kinematic range of the H_b measurement is fixed to

$$p_{\text{T}}(H_b) > 12\,\text{GeV},\ |\eta(H_b)| < 2.1.$$

Fit structure – iterations of 4 steps

1. To tune parameters of B and B_s decays (background):

Unbinned likelihood for the sum

[2D m(J/ψ K π)+m(J/ψ π K)] + [2D m(J/ψ K K)+m(J/ψ π π)] + overall normalization
[2D m(J/ψ π_1)+m(J/ψ π_2)] + [1D m(Kπ)] + [1D m(πK)] + B signal mass region
[2D m(J/ψ K_1)+m(J/ψ K_2)] + [1D m(KK)] B_s signal mass region

2. To determine number of Λ_b baryons

χ^2 fit of m(J/ψ p K^-) (fully statistically correct)

3. To tune Λ* parameters (Λ_b signal region)

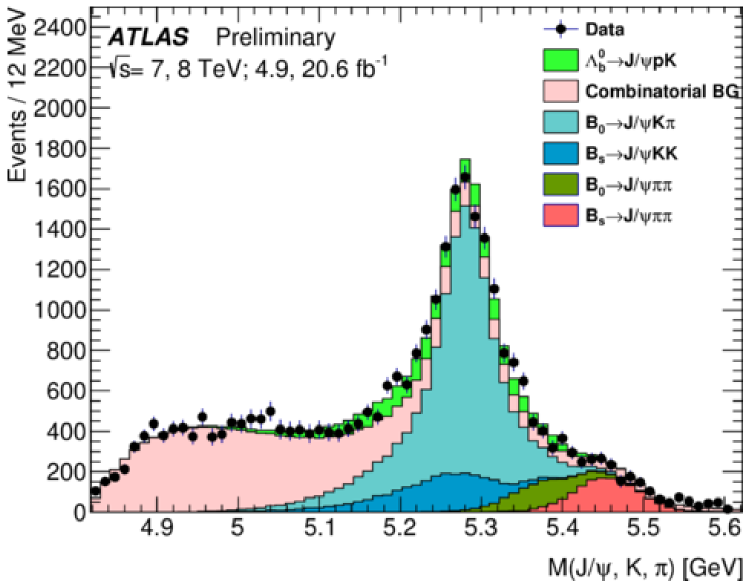
Unbinned likelihood fit for the sum

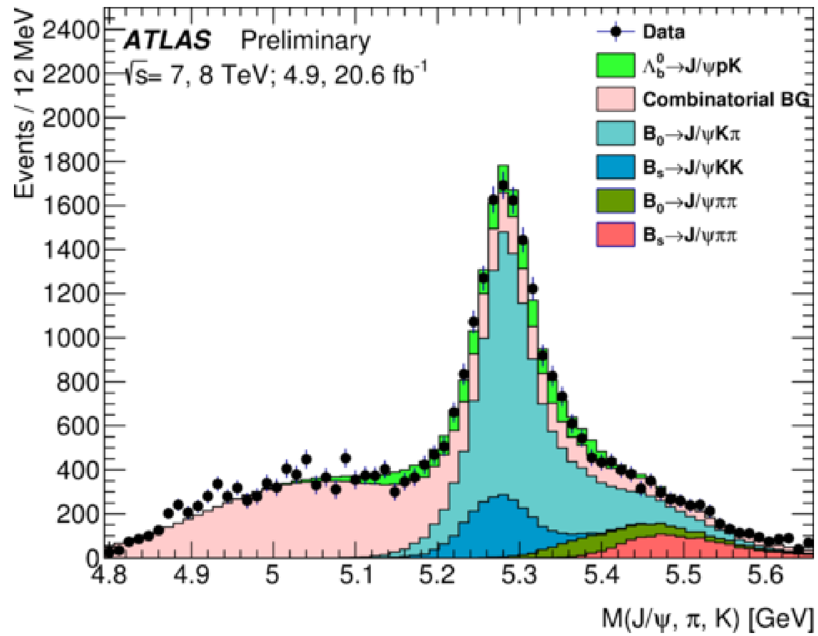
[2D m(J/ψ p)+m(J/ψ K)] + [1D m(pK)]

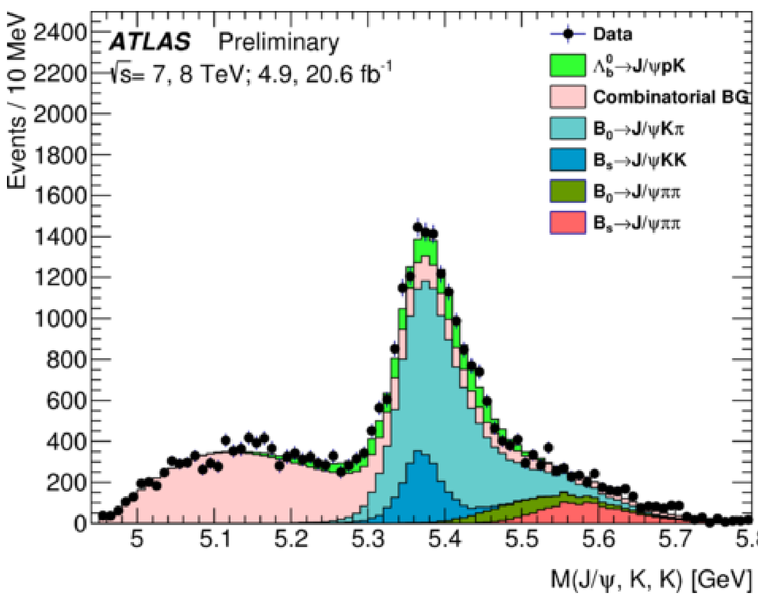
4. To determine pentaquark parameters (Λ_b signal region)

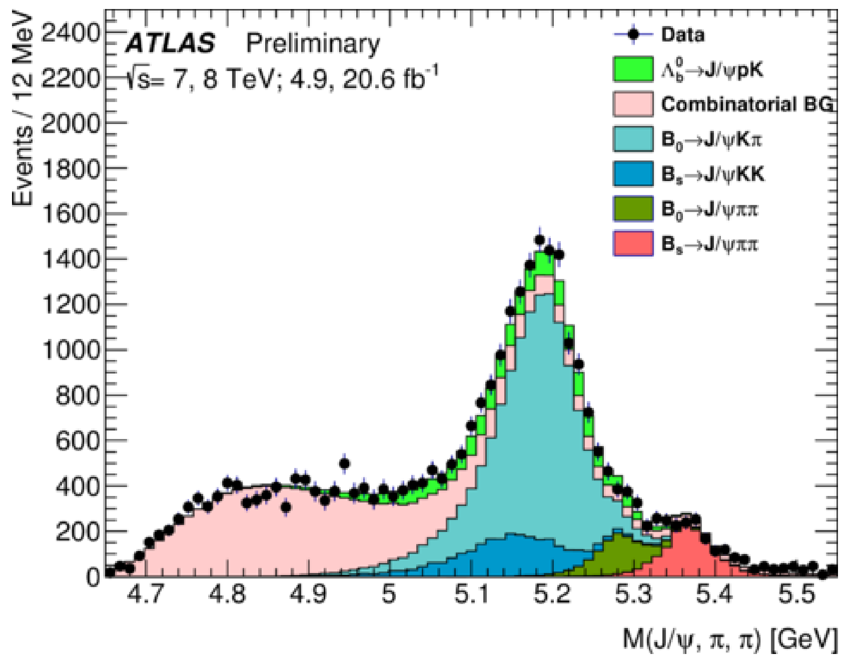
χ^2 fit of m(J/ψ p) (fully statistically correct)

Step 1 : To tune parameters of B and Bs decays (background):

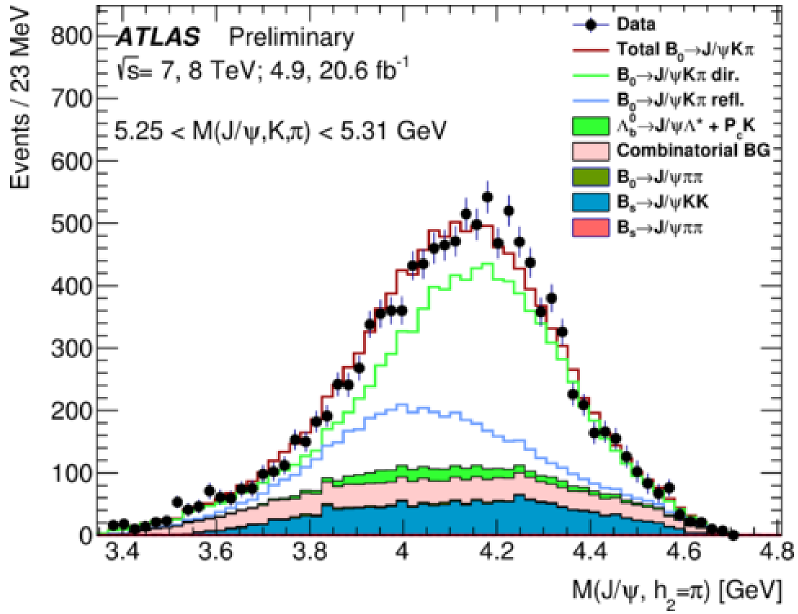


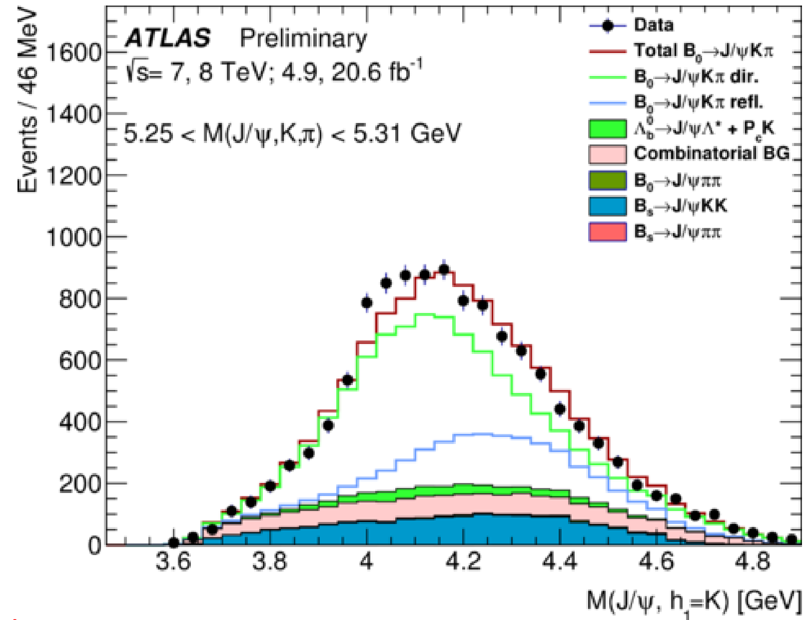




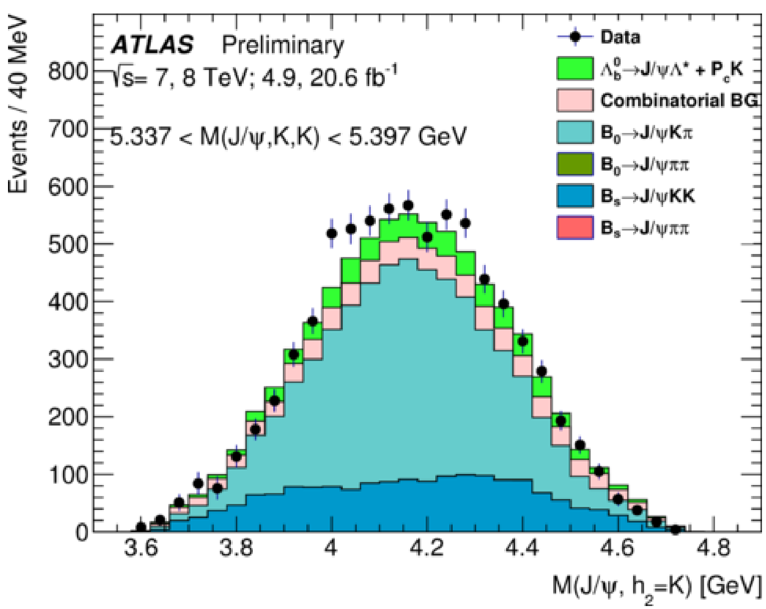


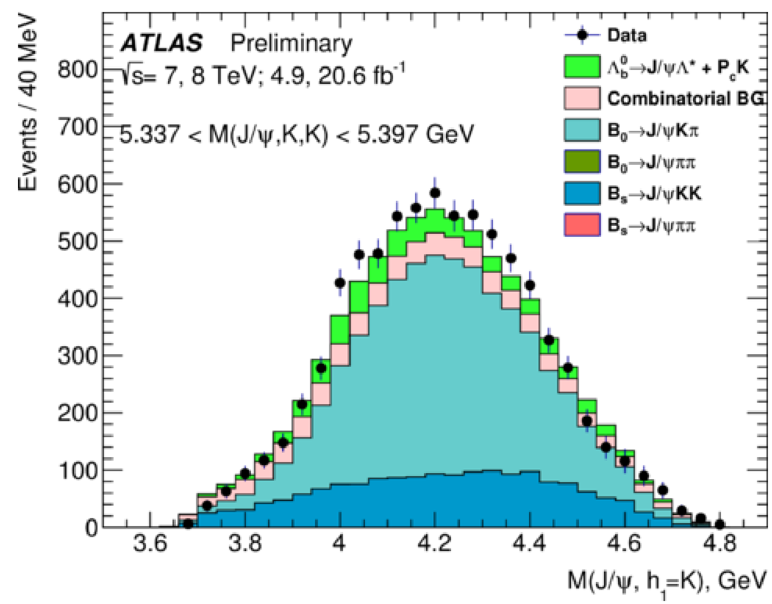
Step 1 : To tune parameters of B and Bs decays (background):





Is X(4200)± here?





Summary of systematic uncertainties

Source	$N(P_{c1})$	$N(P_{c2})$	$N(P_{c1}+P_{c2})$	$\Delta\phi$
Number of $\Lambda_b^0 \to J/\psi p K^-$ decays (δ_1)	$^{+1.8}_{-0.6}\%$	$^{+6.6}_{-9.2}\%$	$^{+1.6}_{-0.8}\%$	$^{+0.3}_{-0.0}\%$
Pentaquark modelling (δ_2)	$^{+21}_{-0}\%$	$^{+1}_{-22}\%$	$^{+8.7}_{-4.4}\%$	$^{+1.6}_{-0.0}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling (δ_3)	$^{+14}_{-2}\%$	$^{+5}_{-44}\%$	$^{+9.2}_{-9.1}\%$	$^{+3.6}_{-1.6}\%$
Combinatorial background (δ_4)	$^{+0.7}_{-4.0}\%$	$^{+18}_{-5}\%$	$^{+4.2}_{-4.8}\%$	$^{+3.2}_{-0.0}\%$
B meson decays modelling (δ_5)	$^{+13}_{-25}\%$	$^{+28}_{-35}\%$	$^{+1.6}_{-9.3}\%$	$^{+0.5}_{-2.1}\%$
Total systematic uncertainty	$^{+28}_{-25}\%$	$^{+35}_{-61}\%$	$^{+14}_{-15}\%$	$^{+5.1}_{-2.7}\%$

Source	$m(P_{c1})$	$\Gamma(P_{c1})$	$m(P_{c2})$	$\Gamma(P_{c2})$
Number of $\Lambda_b^0 \to J/\psi p K^-$ decays (δ_1)	$^{+0.06}_{-0.03}\%$	$^{+3.5}_{-2.5}\%$	$^{+0.07}_{-0.04}\%$	$^{+7}_{-13}\%$
Pentaquark modelling (δ_2)	$^{+0.6}_{-0.0}\%$	$^{+18}_{-0}\%$	$^{+0.2}_{-0.0}\%$	$^{+0}_{-33}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling (δ_3)	$^{+0.23}_{-0.05}\%$	$^{+9.2}_{-1.2}\%$	$^{+0.24}_{-0.02}\%$	$^{+2}_{-62}\%$
Combinatorial background (δ_4)	$^{+0.03}_{-0.15}\%$	$^{+0}_{-11}\%$	$^{+0.01}_{-0.17}\%$	$^{+22}_{-4}\%$
B meson decays modelling (δ_5)	$^{+0.24}_{-0.00}\%$	$^{+21}_{-21}\%$	$^{+0.27}_{-0.14}\%$	$^{+17}_{-57}\%$
Total systematic uncertainty	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$