Heavy flavour production and spectroscopy at the LHC

WARWICK

M. Kreps on behalf of ALICE, ATLAS, CMS, LHCb

LHCP, Lund, Sweden, 13-18 June, 2016

Physics Department

- Open charm and beauty production
- Associated production
- Open charm spectroscopy
- Exotic spectroscopy
- Lot of details in parallel sessions, here just summary

Heavy quark production

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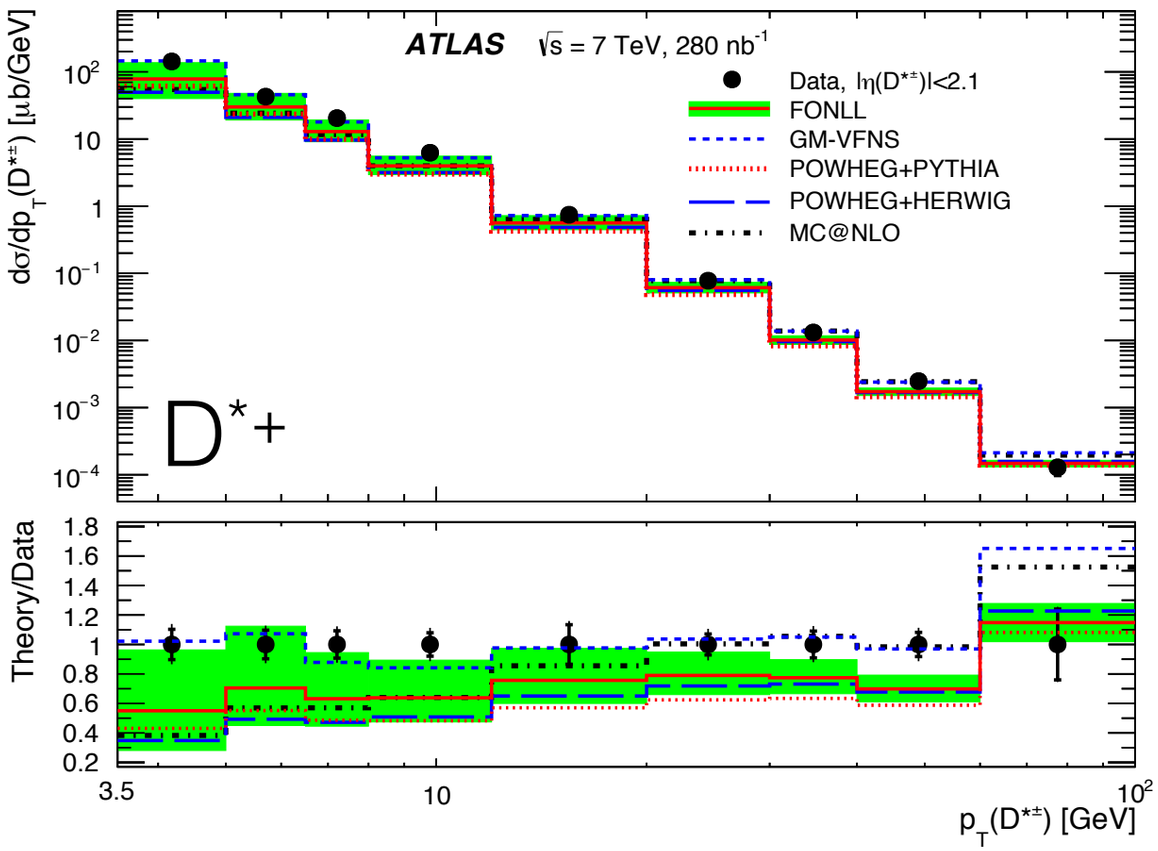
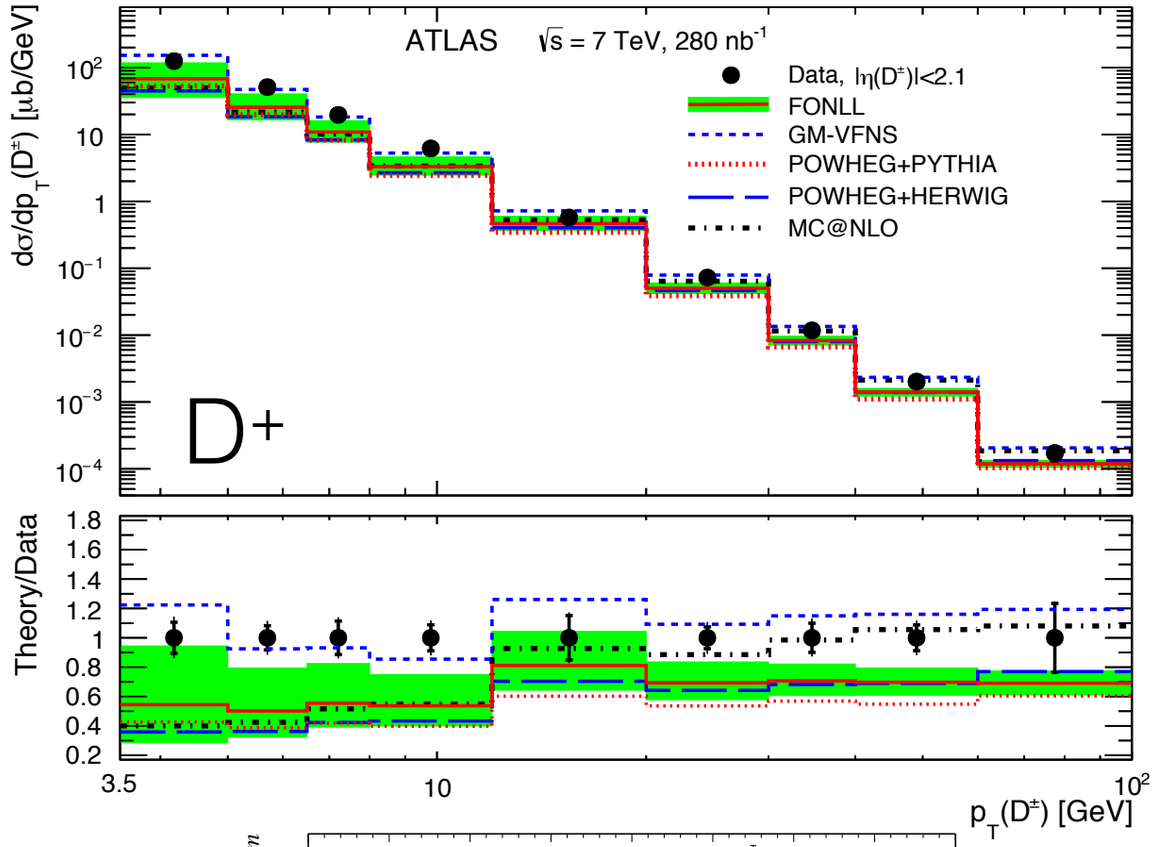
- Heavy quark production measurements provide important tests of QCD
- At LHC gluon-gluon fusion dominates and thus can help to constrain low-x gluon PDF
- Hadronisation hard to predict, need measurements
  - Many things we do at LHC involve hadrons at some point (voluntarily or involuntarily)
- Long standing puzzles exists
  - Often some measurements can be described, but others not
- For quarkonia two contributions are considered
  - Colour singlet
  - Colour octet
  - Predicting both cross-section and polarisation in the same time is not easy
- With LHC samples, we can probe also double parton scattering using quarkonia pairs
- Heavy quark production plays also important role in heavy-ion physics
- I will concentrate on pp interactions
- Leave heavy-ion side (see talk by A. Mischke on Tuesday)

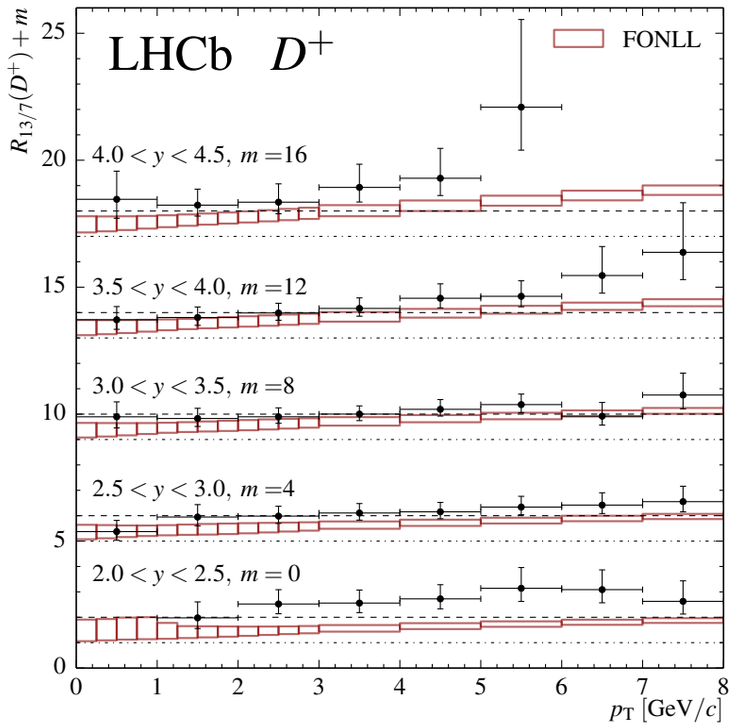
Open charm production

NP B907, 717
JHEP 1603(2016) 159





- ATLAS joins in open charm x-section measurements in central region
- Done using D^+, D^{*+} and D_s
- Compare to expectations
  - Fragmentation based on experimental data
- Complementary y range to LHCb



Open charm production

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1605.06963

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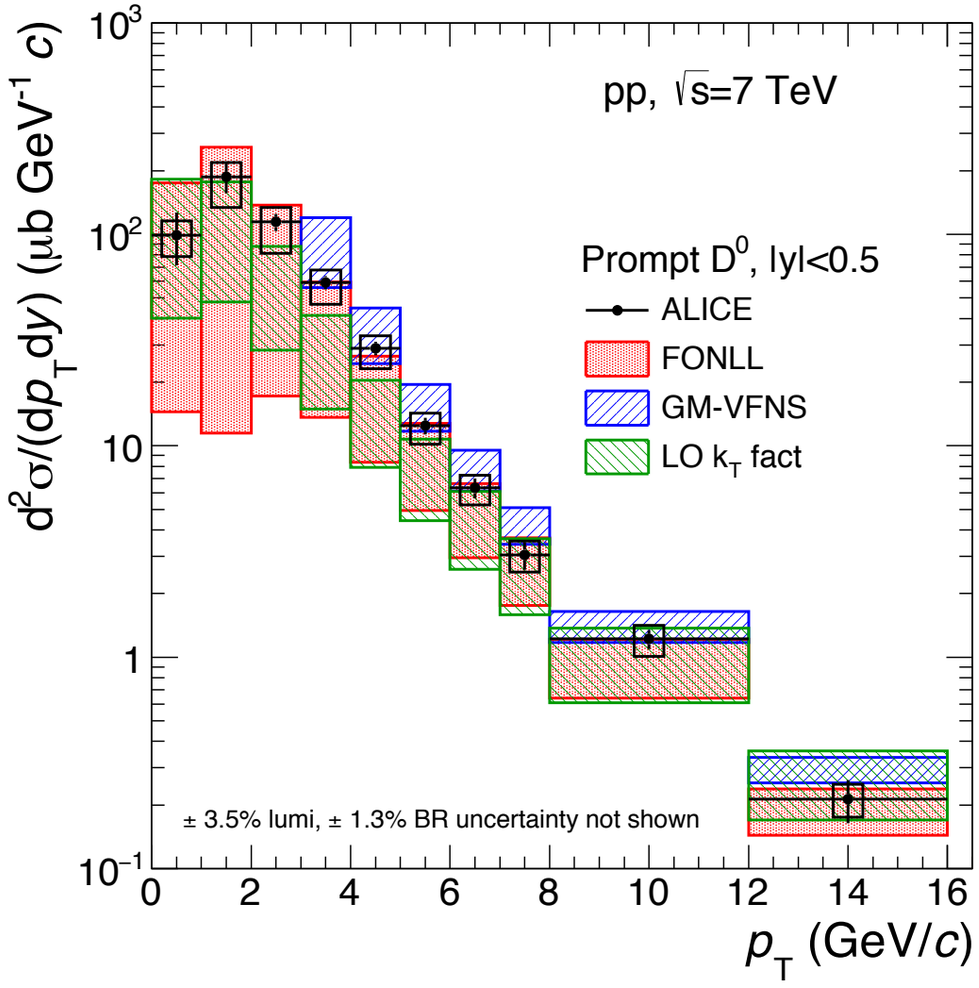
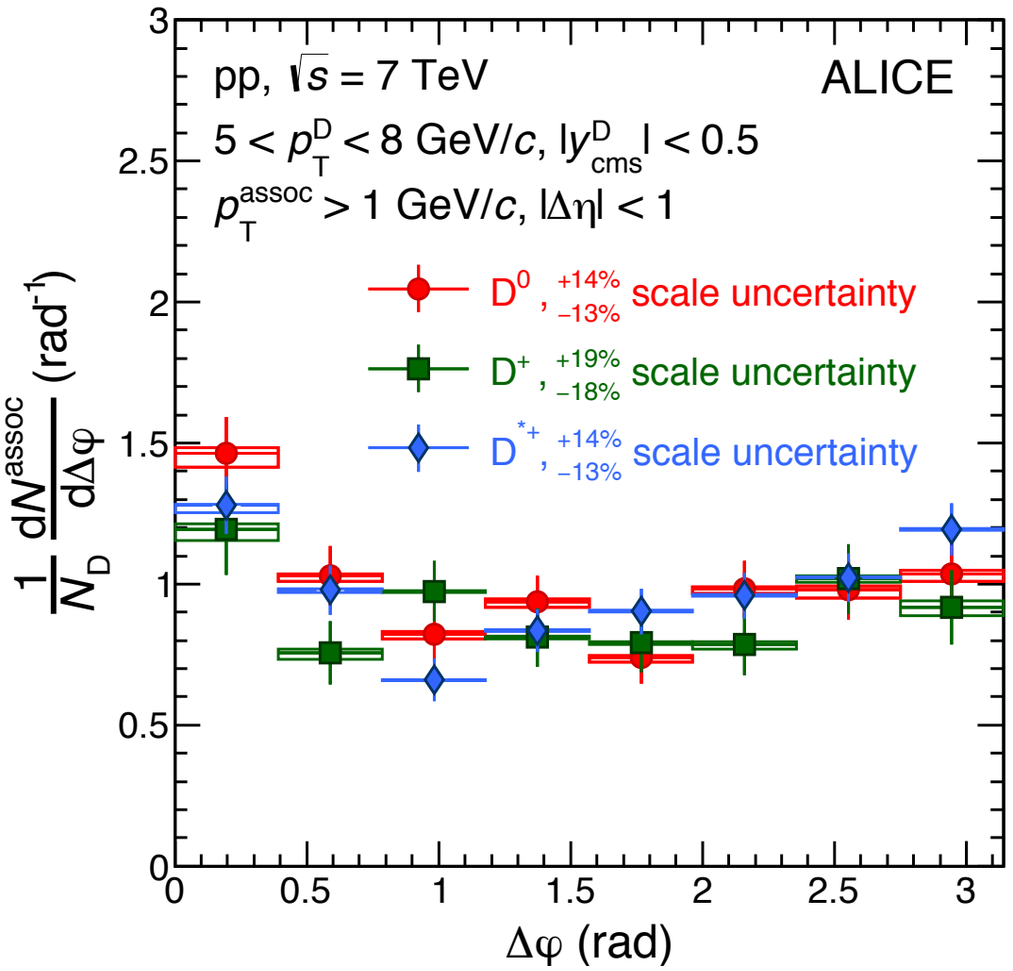
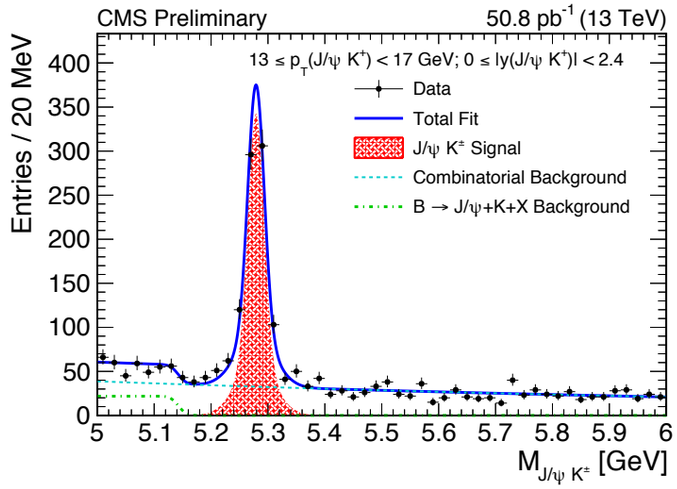


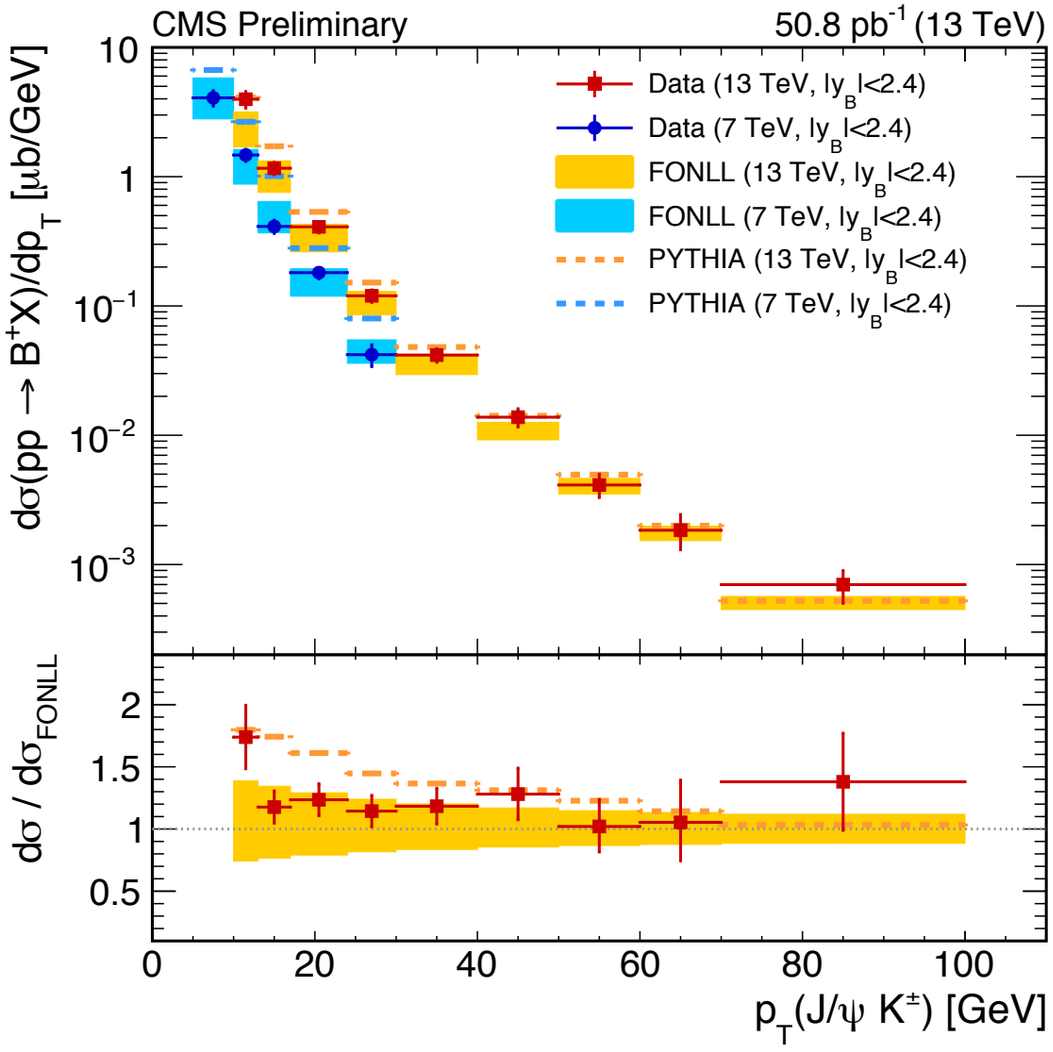


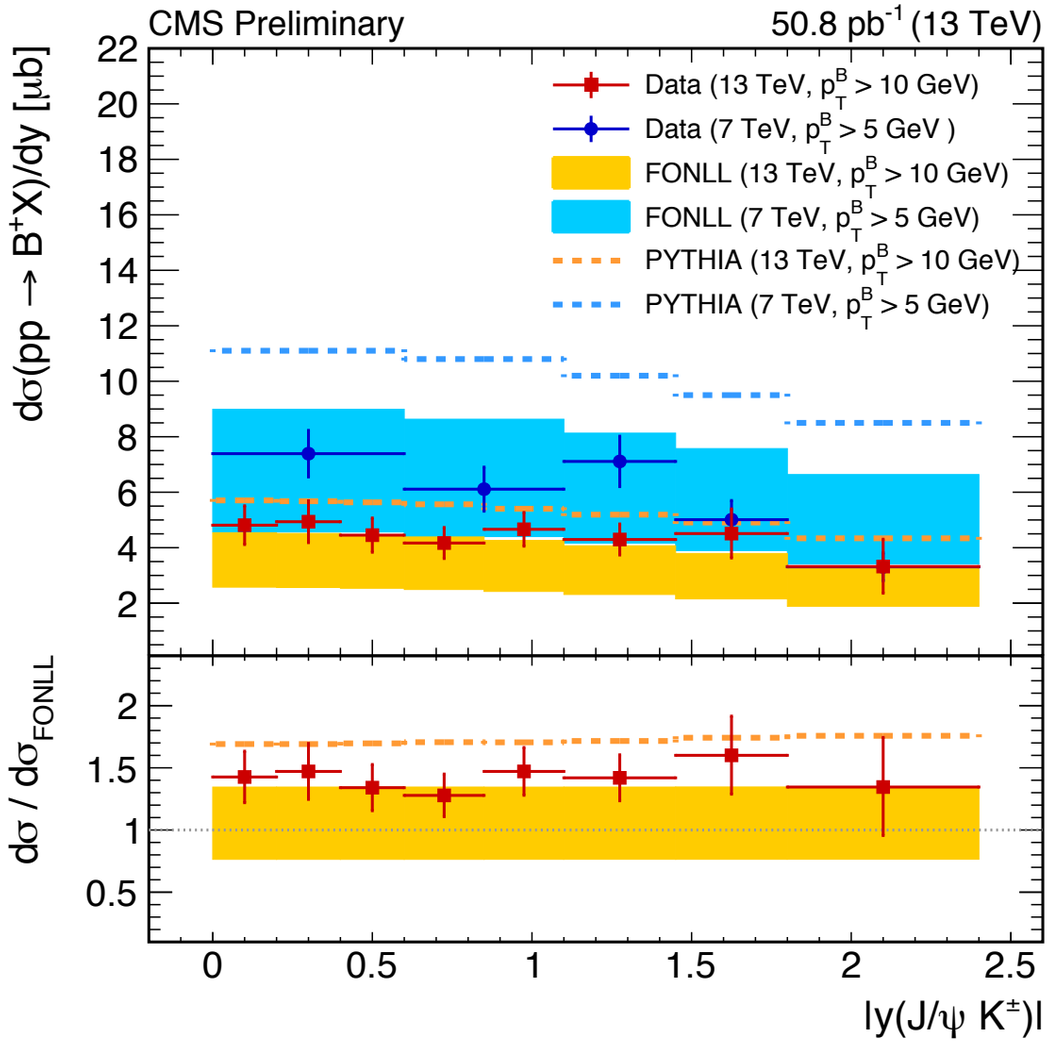
- ALICE measures open charm production at central rapidity
- Could go down to zero transverse momentum
- Useful measurement of correlation between open charm and charge particles
  - Probes fragmentation of quarks into hadrons in some details

Open beauty production

- B^+ x-section at 13 TeV from CMS
- Reaches unprecedented p_T range
- FONLL agrees in shape, total cross-section bit below data (but within uncertainties)

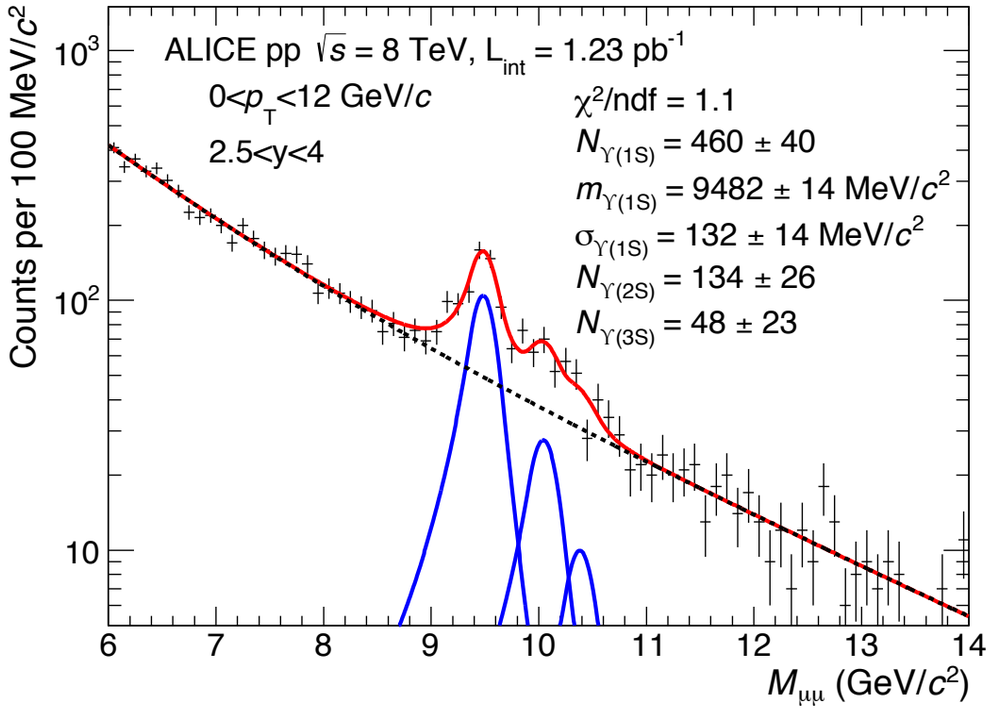


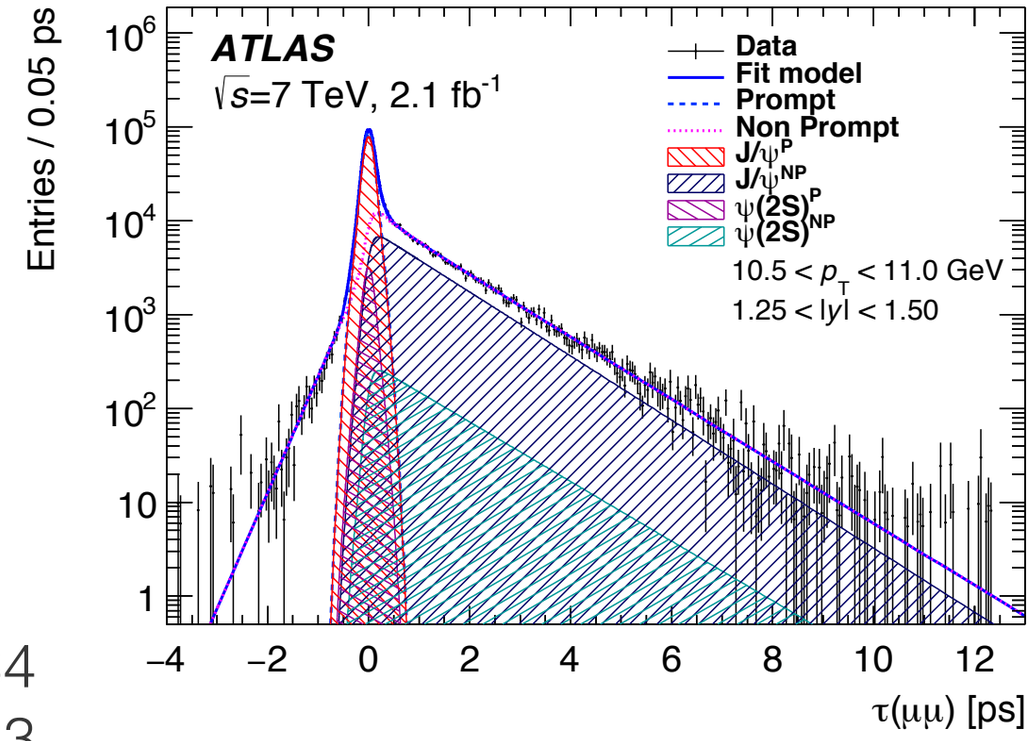


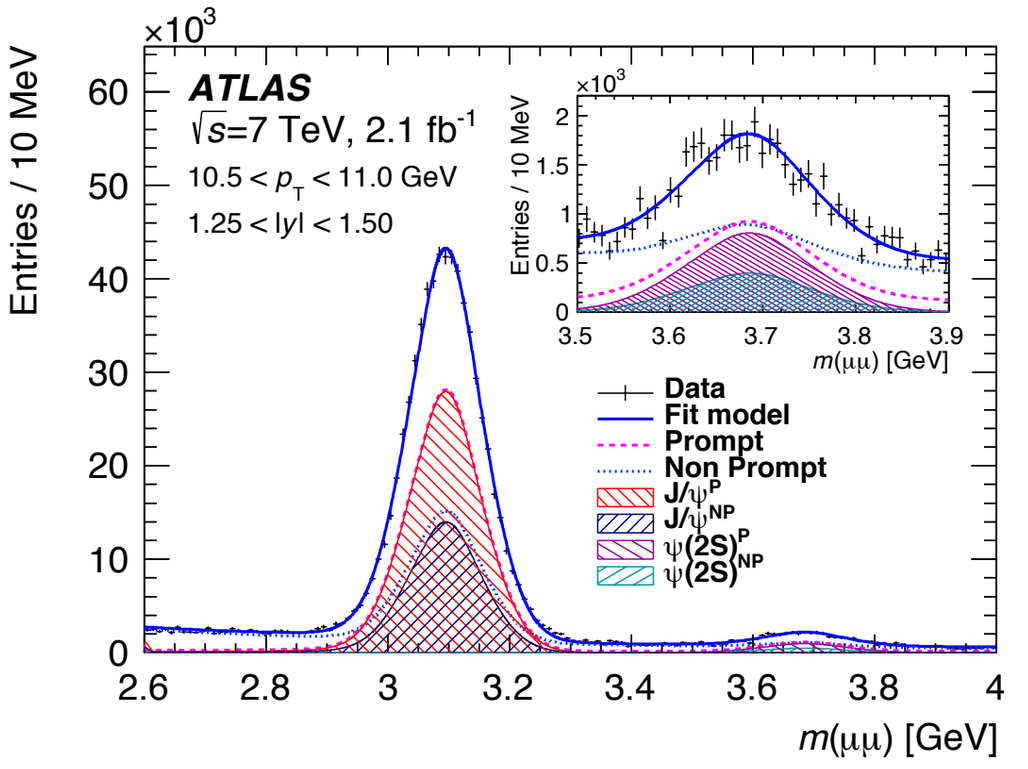


Experimental issues in quarkonia production

- Good mass resolution helps
  - Upsilon states can overlap
- For charmonia need to separate prompt production from b-hadron decays
  - Typically fit pseudo-decay-time distribution
- Going to higher p_T background shape changes





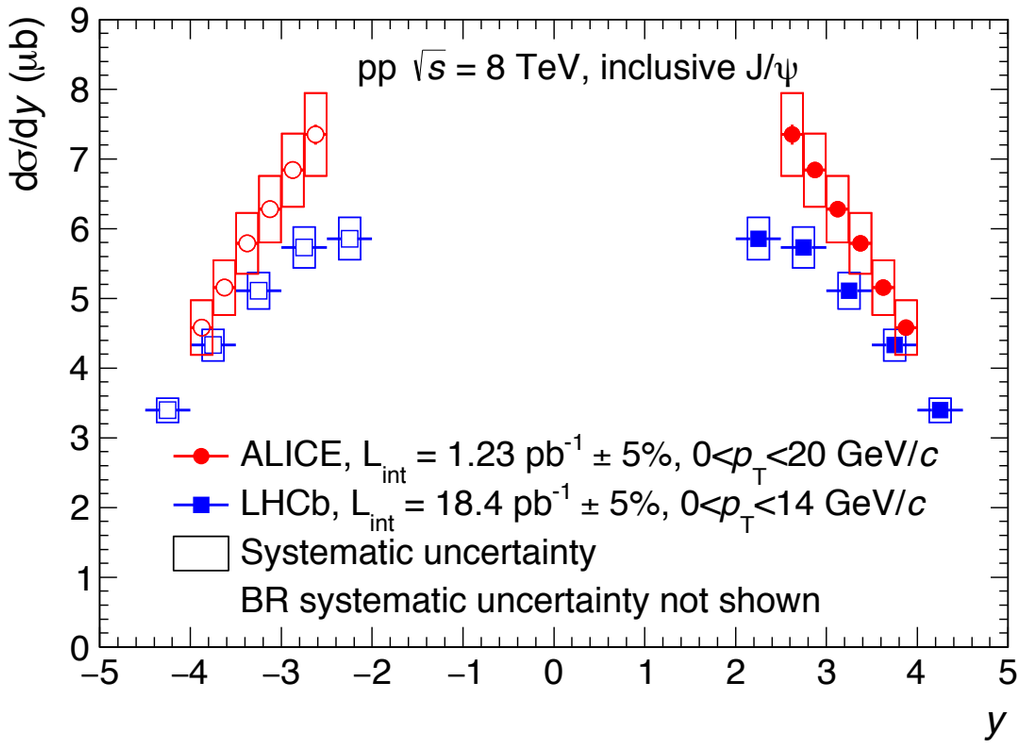


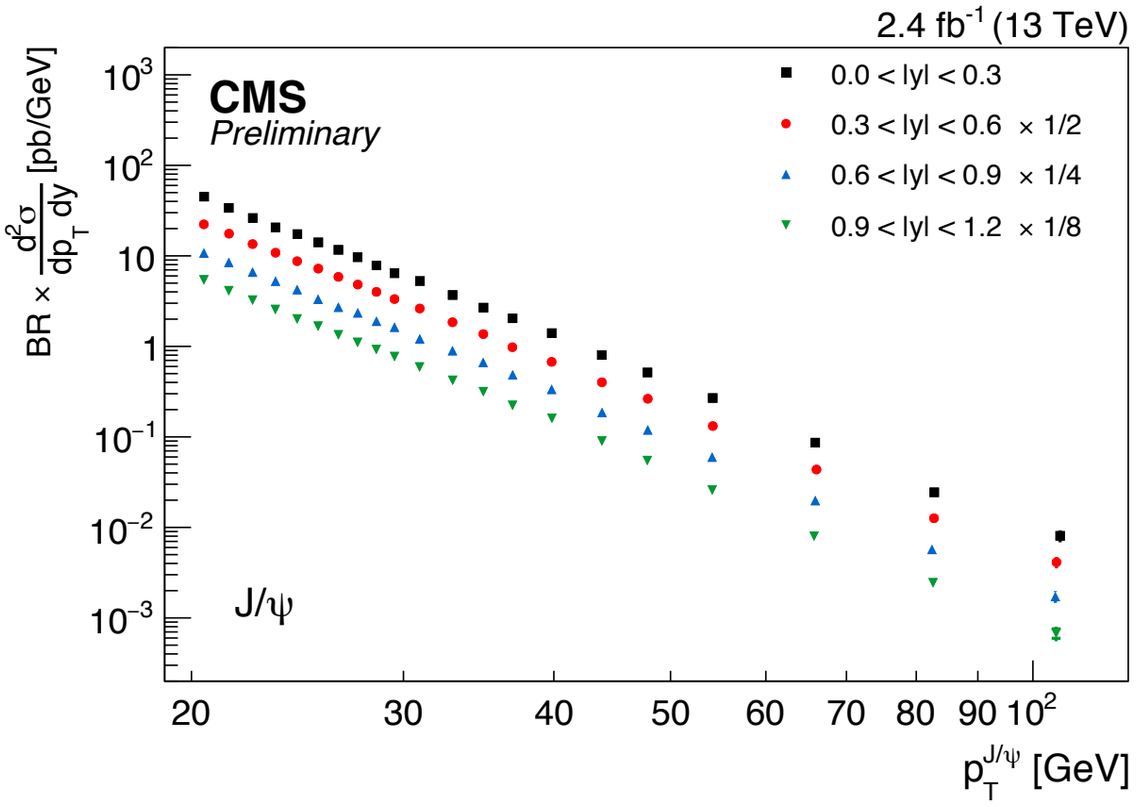
EPJC76, 184
EPJC76, 283

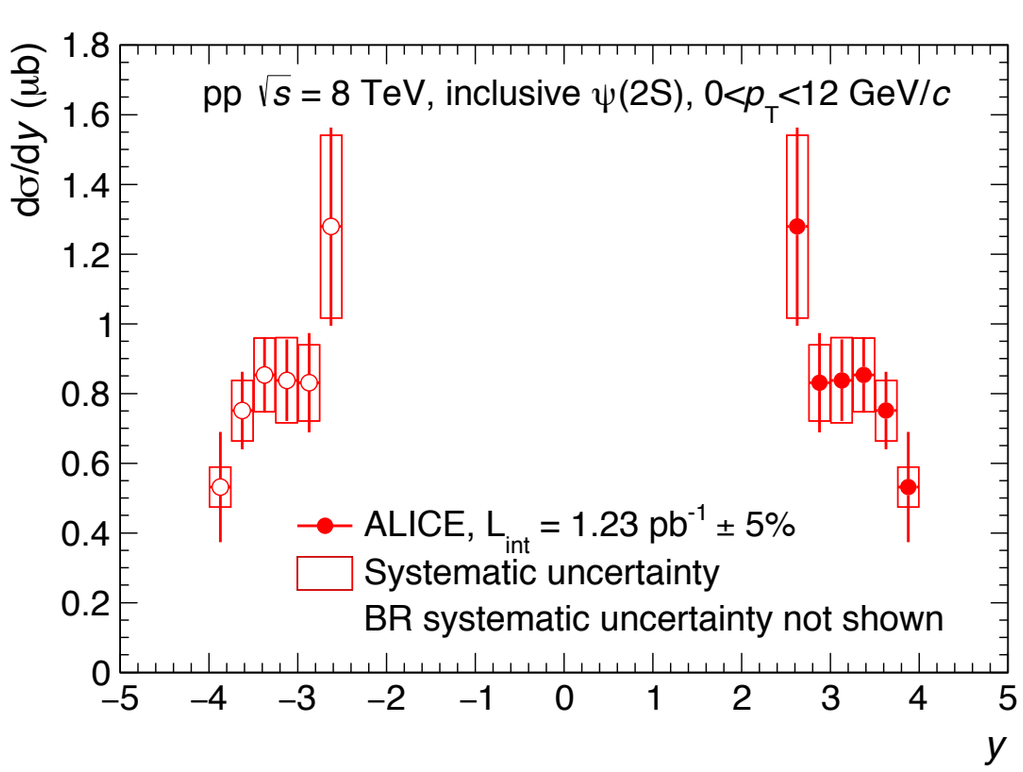
Charmonia production

- ALICE/LHCb cover different rapidity region compared to ATLAS/CMS
- ALICE and LHCb agree on J/ψ cross-section
- ALICE/LHCb measures down to low p_T
- ATLAS/CMS high p_T, significantly extended compared to previous measurements

EPJC76, 184
CMS-PAS-BPH-15-005
JHEP 1306(2013) 064

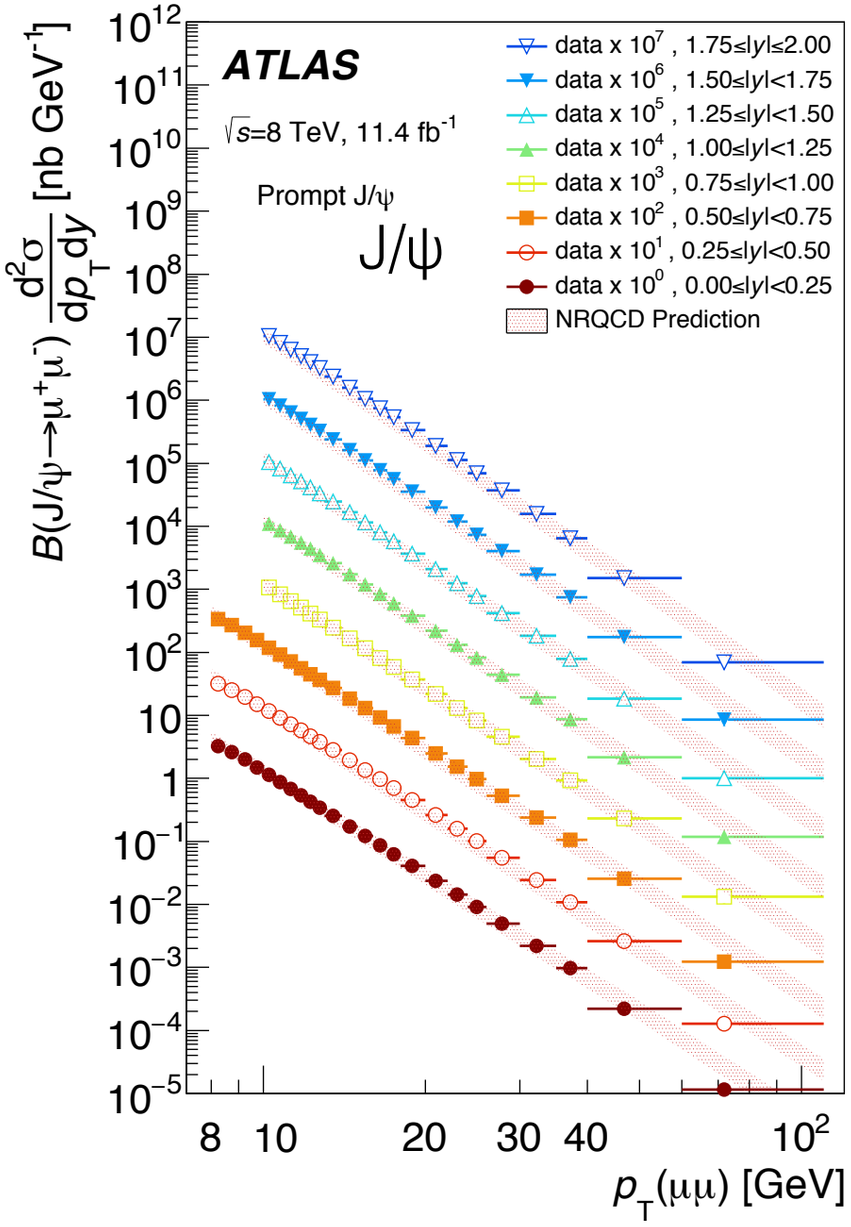


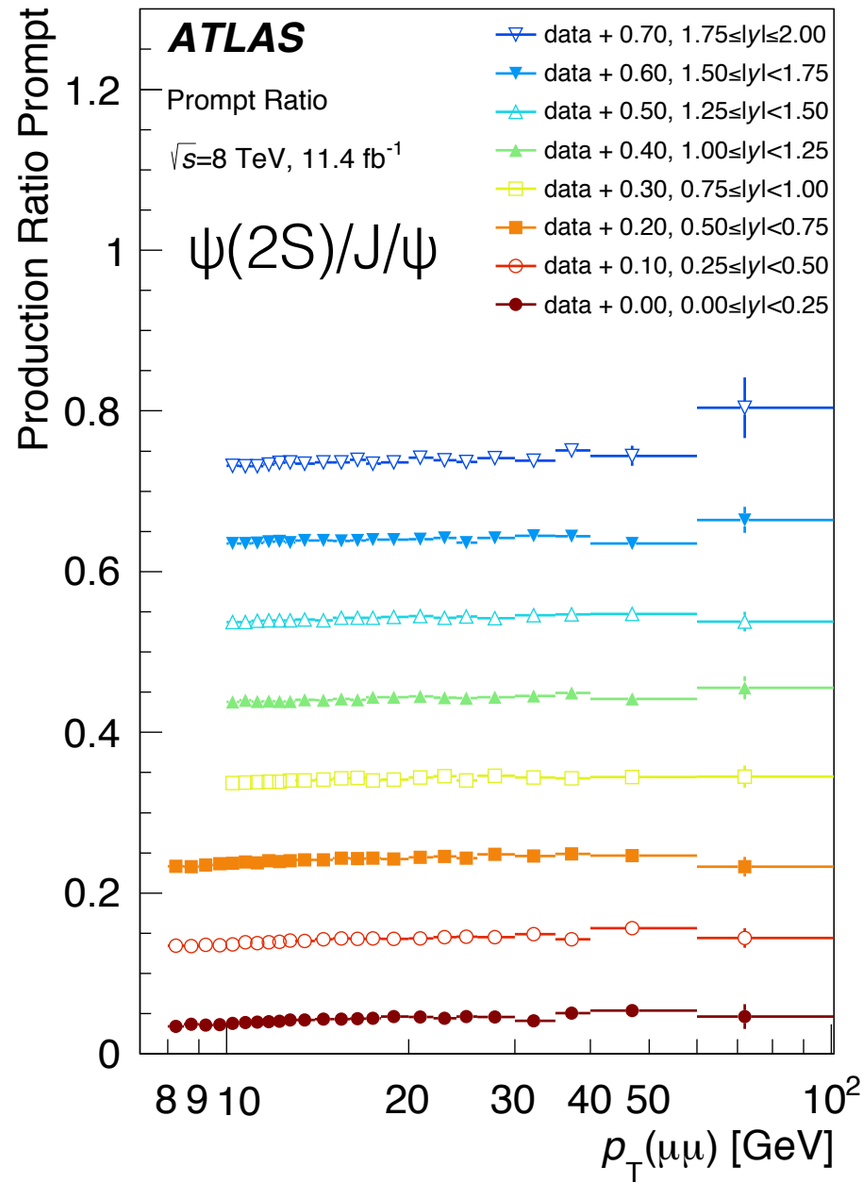




Charmonia

EPJC76, 283





- Detailed information over wide phase-space region
- Cross-section reasonably agrees with prediction
- Polarisation measurements in such details will be important

Bottomium

CMS-PAS-BPH-15-005
JHEP 1511(2015) 103

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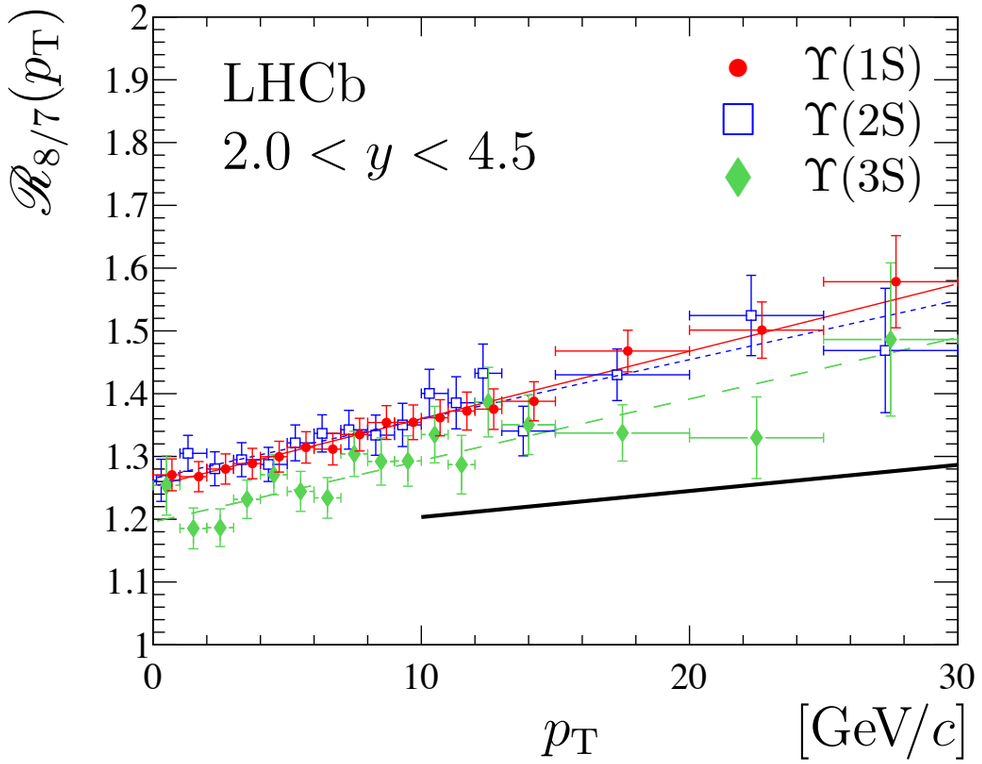
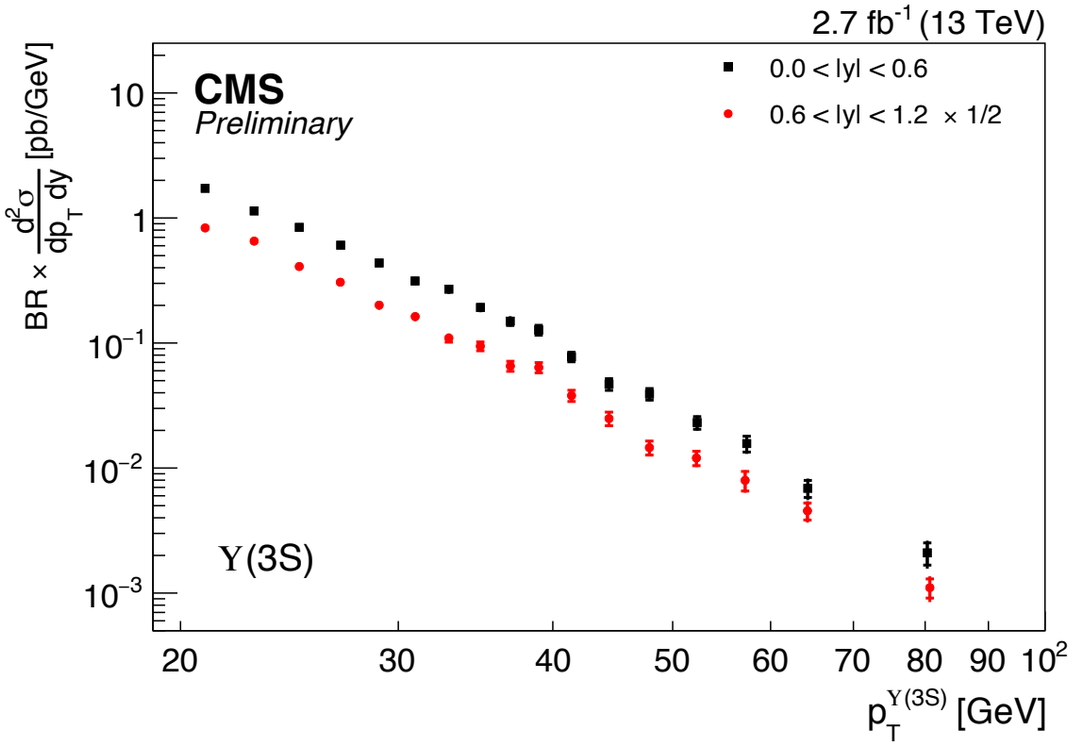
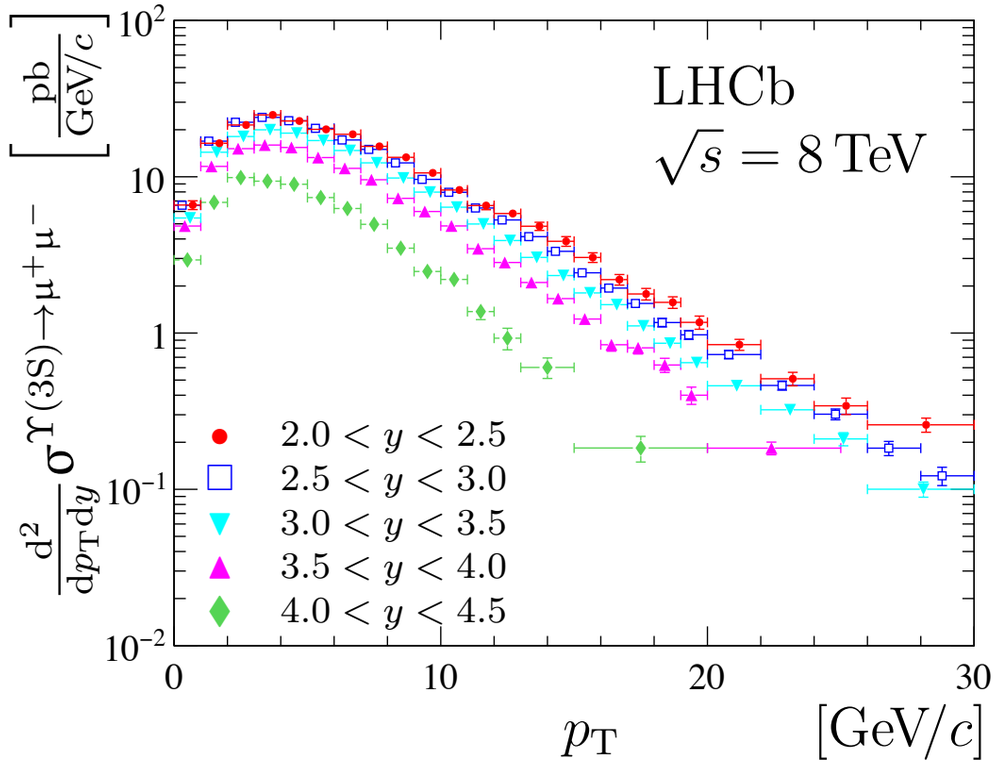
- Typically Y(1S), Y(2S) and Y(3S) measured in single analysis
- Similar to charmonia, detailed data exists over large fraction of phase space
- Going from 7 TeV to 8 TeV data do not fully agree with prediction







Associated production

CMS-PAS-BPH-14-008
arXiv:1510.05949

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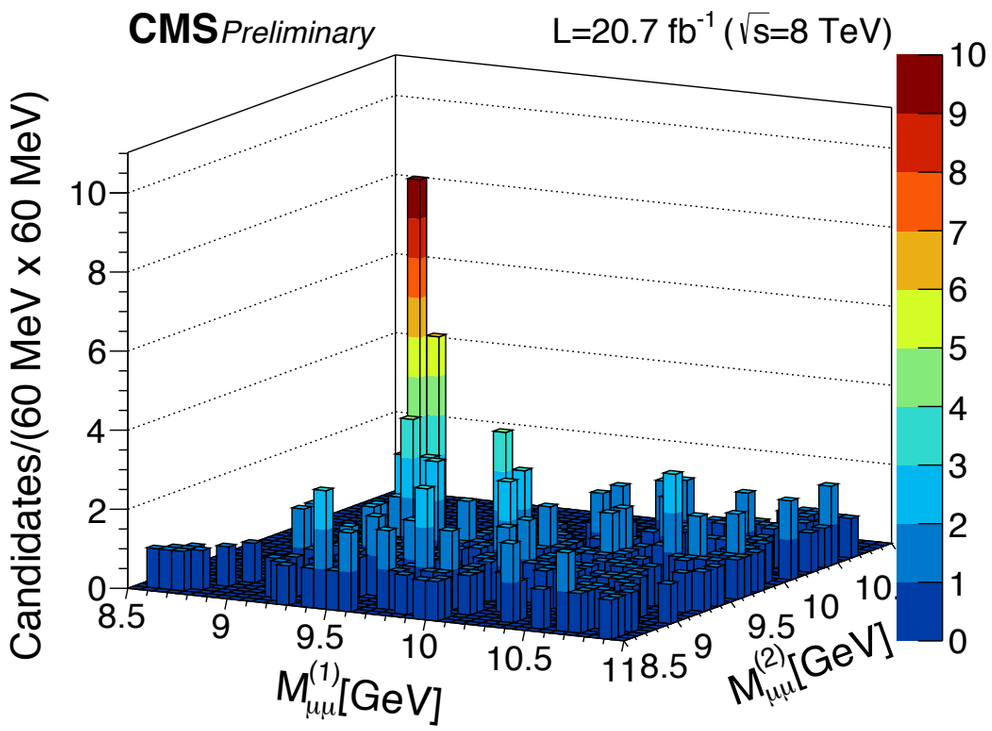
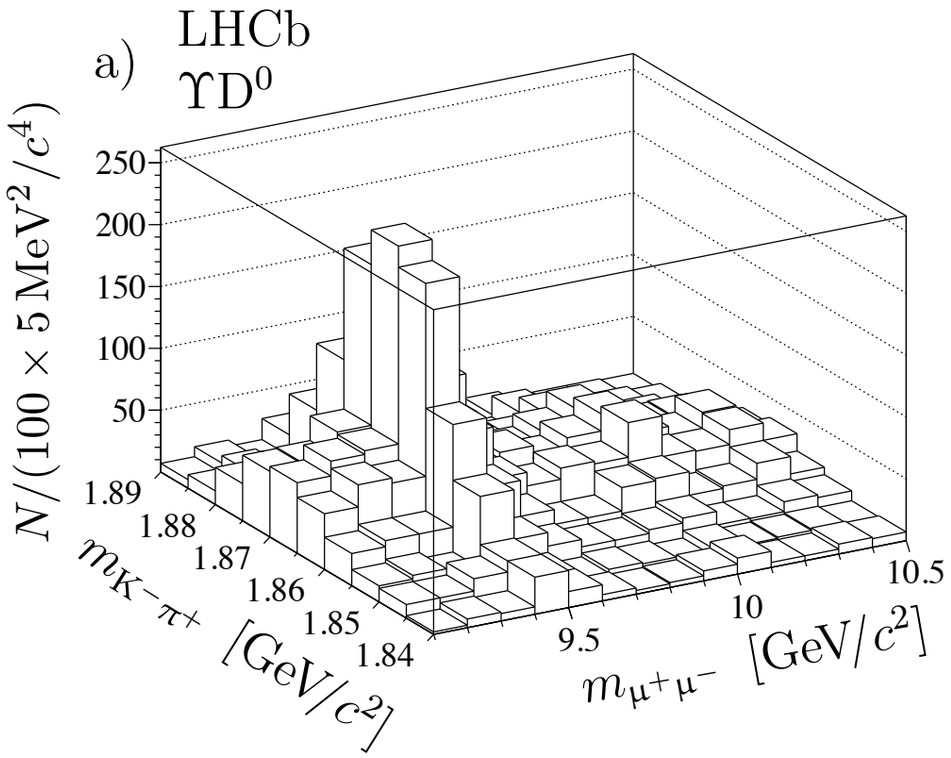
- In 1982 production of J/ψJ/ψ was seen for the first time
- Production of two pairs of heavy quarks is useful tool to study double parton scattering
  - These can be produced also in single parton scattering with gluon splitting to second pair
- CMS observes Y(1S) pair production for the first time
- LHCb for the first time observes bottomia produced with open charm hadron





Spectroscopy

Pentaquark states

arXiv:1604.05708
PRL 115, 072001

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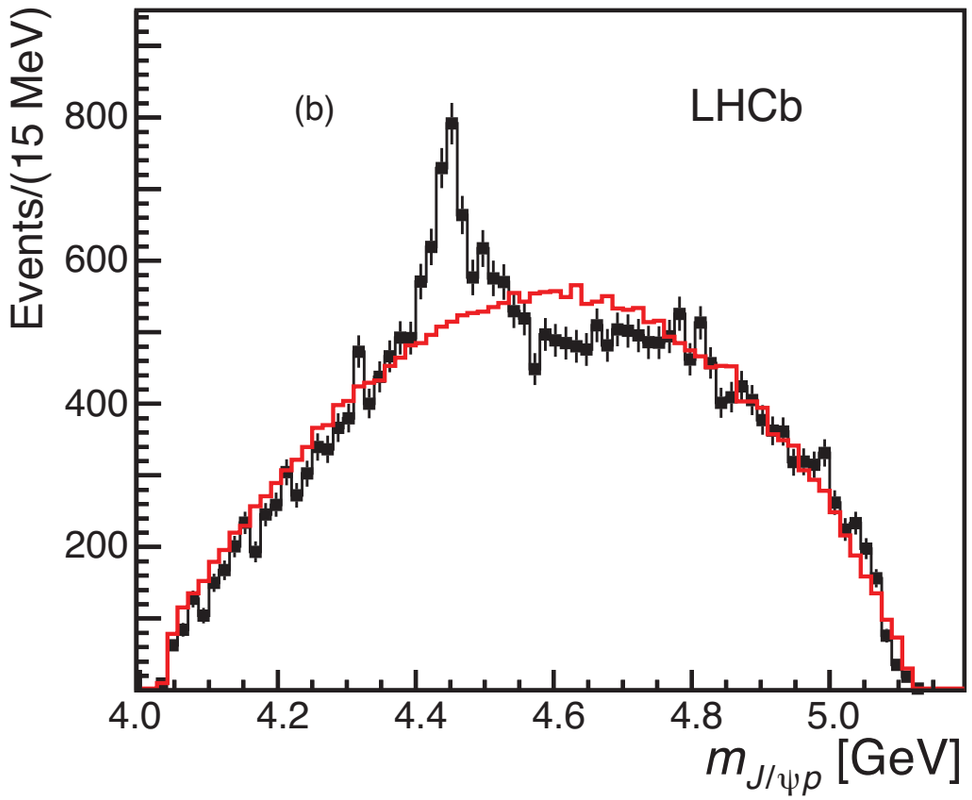
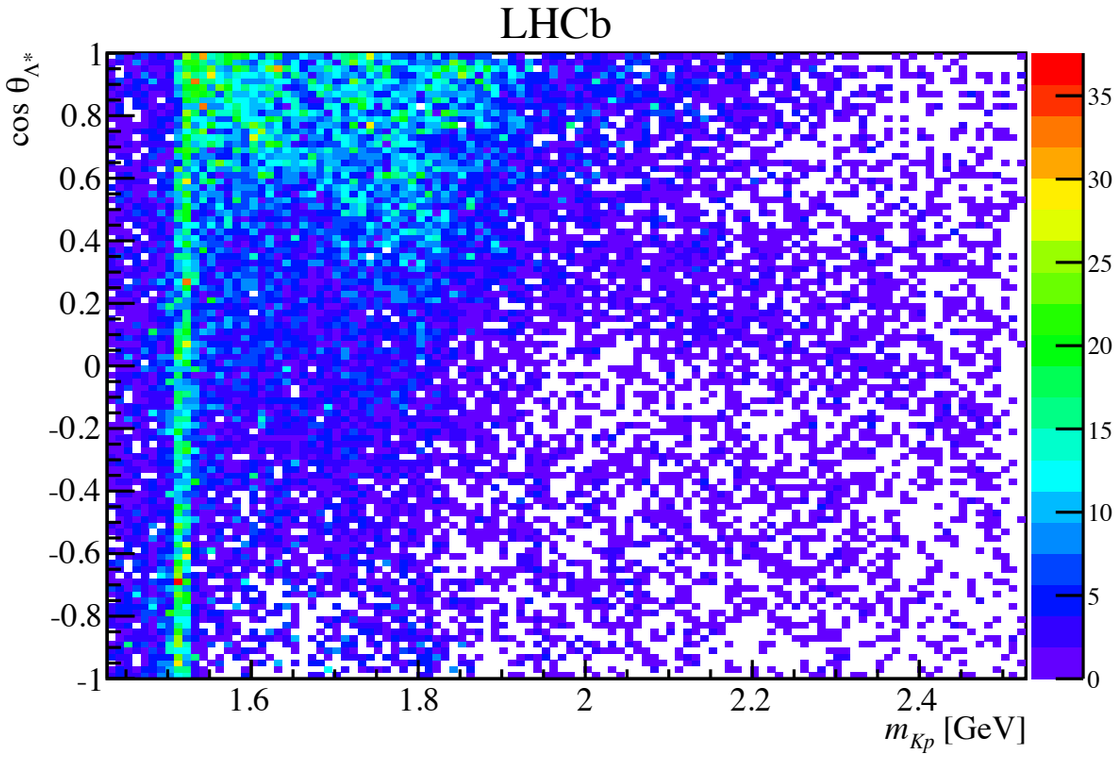
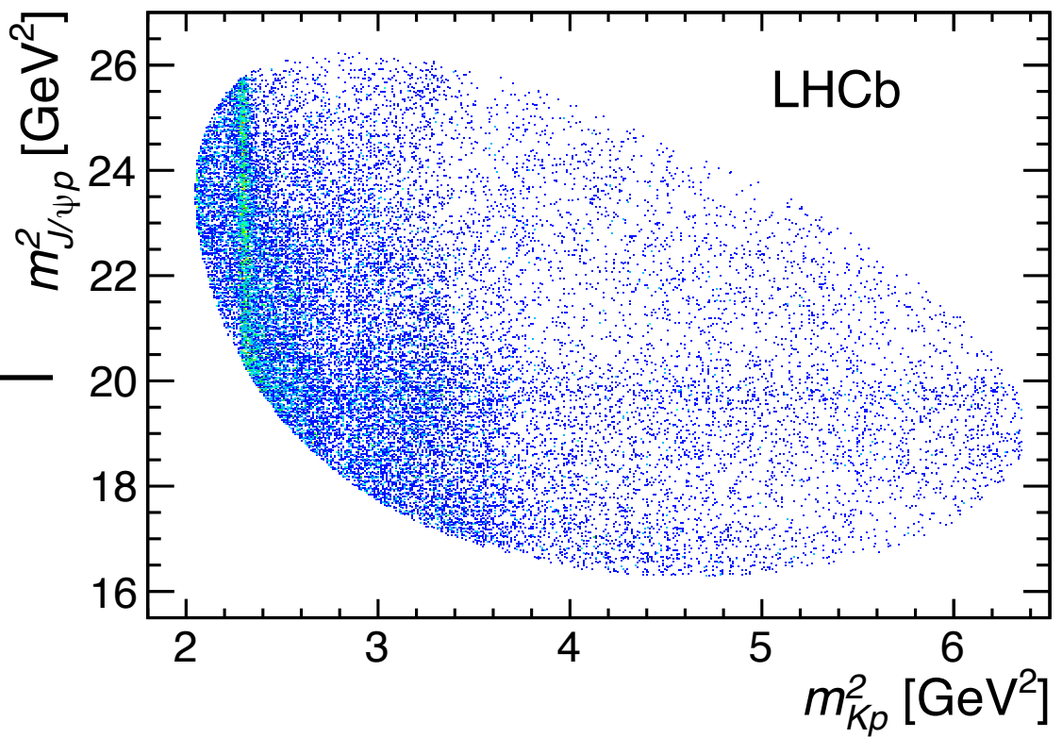
- Last summer LHCb observed two pentaquark states in $\Lambda_b \rightarrow J/\psi pK$ decays
- Original analysis used amplitude fit
  - Sensitive, but depends on assumptions on resonances shapes
- Can do model independent test in the same decay







Pentaquark states

arXiv:1604.05708

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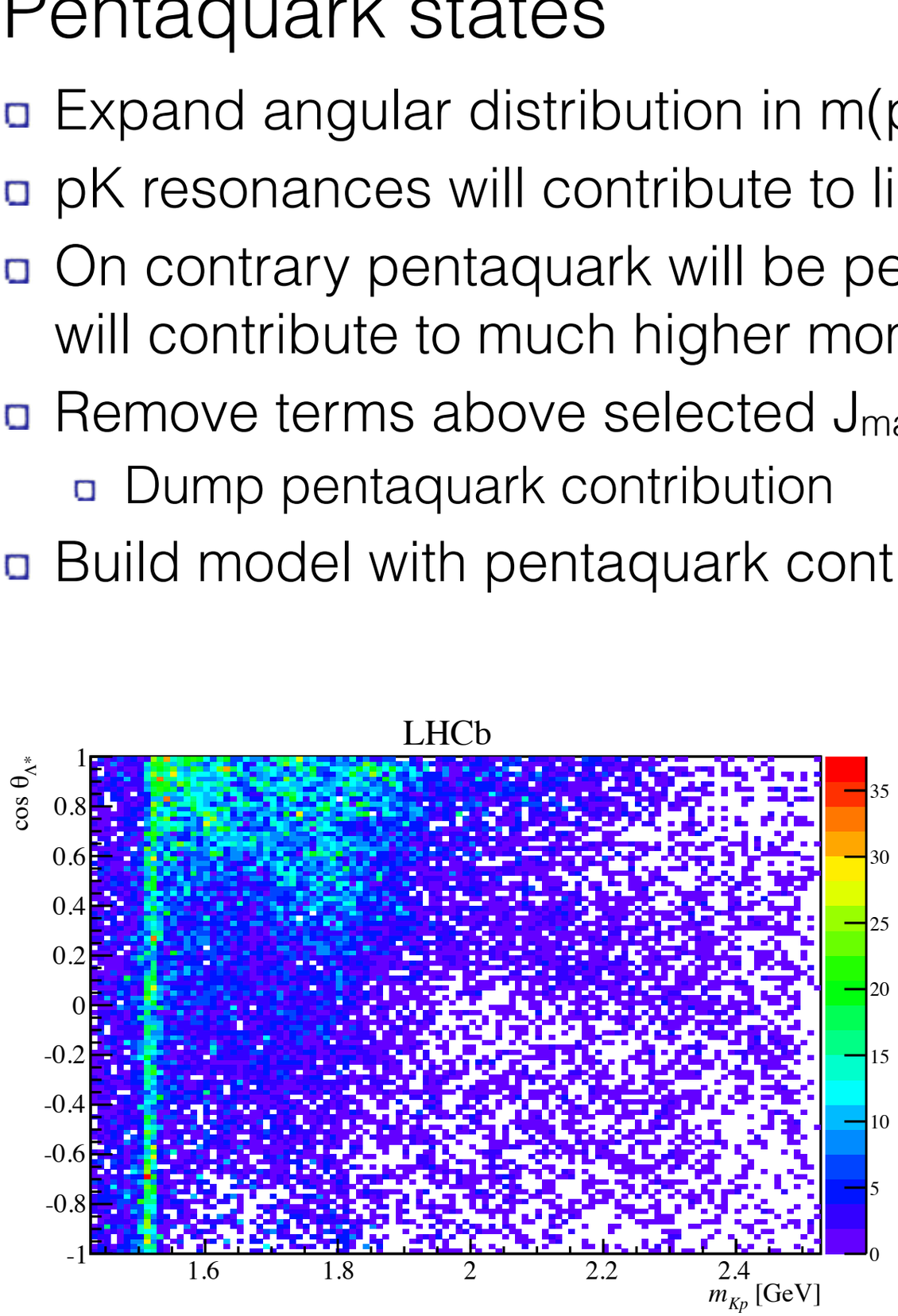
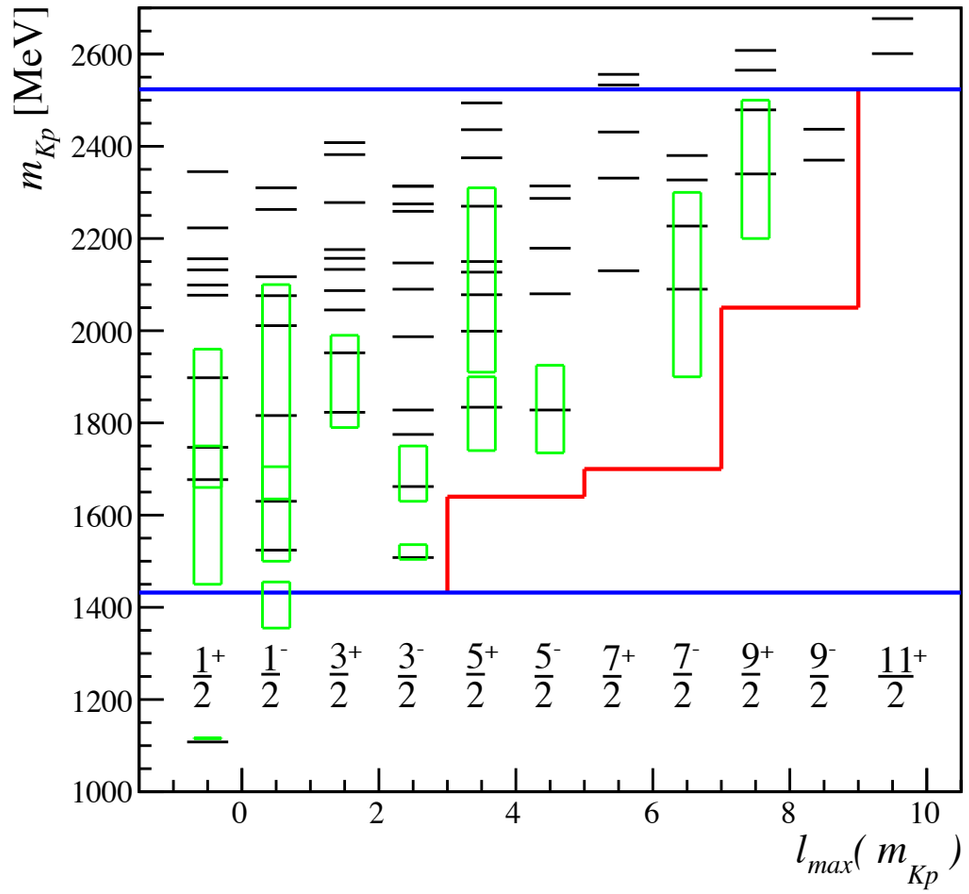
- Expand angular distribution in m(pK) bins in Legendre polynomials
- pK resonances will contribute to limited number of terms (up to 2×spin)
- On contrary pentaquark will be peaking in angular distribution and thus will contribute to much higher moments
- Remove terms above selected J_{max}
  - Dump pentaquark contribution
- Build model with pentaquark contribution suppressed





Pentaquark states

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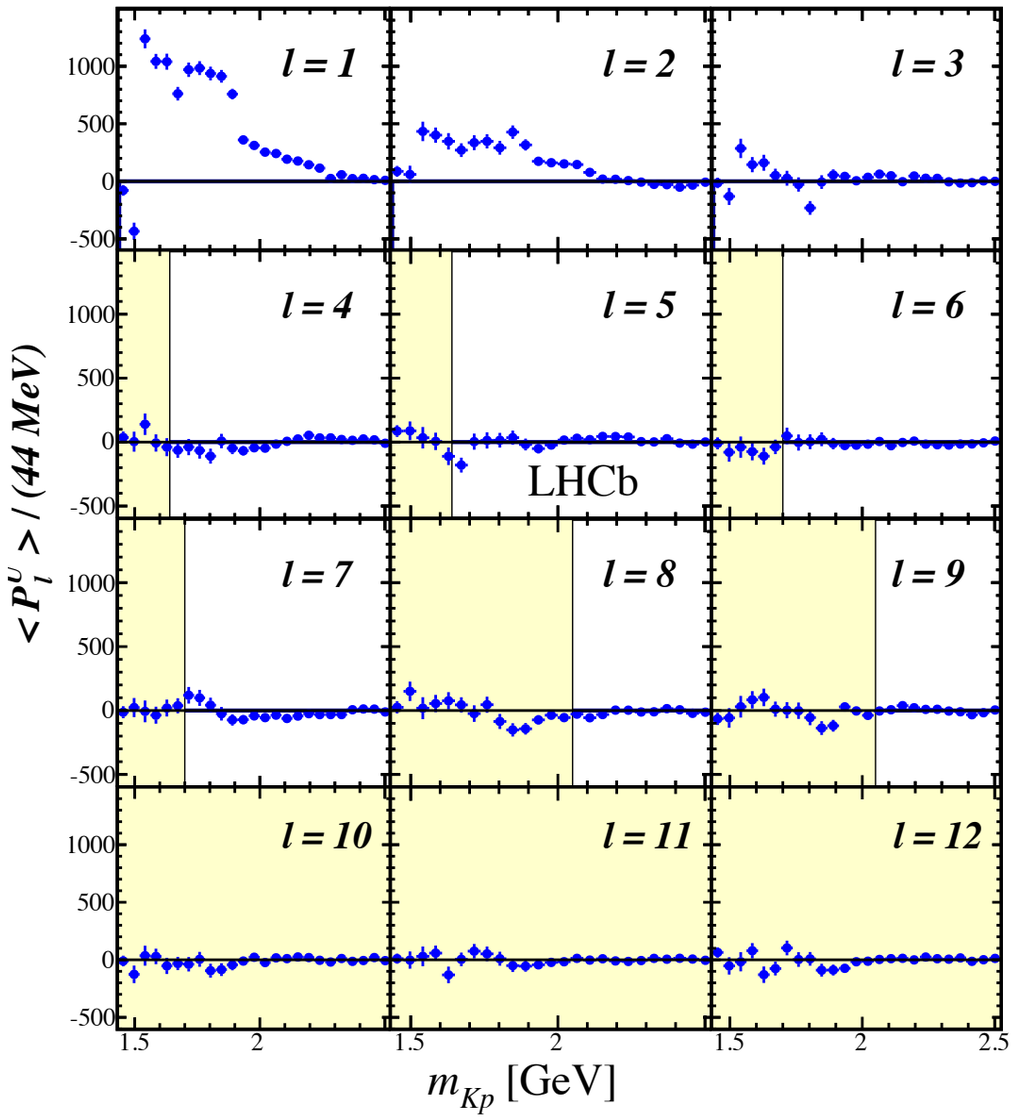

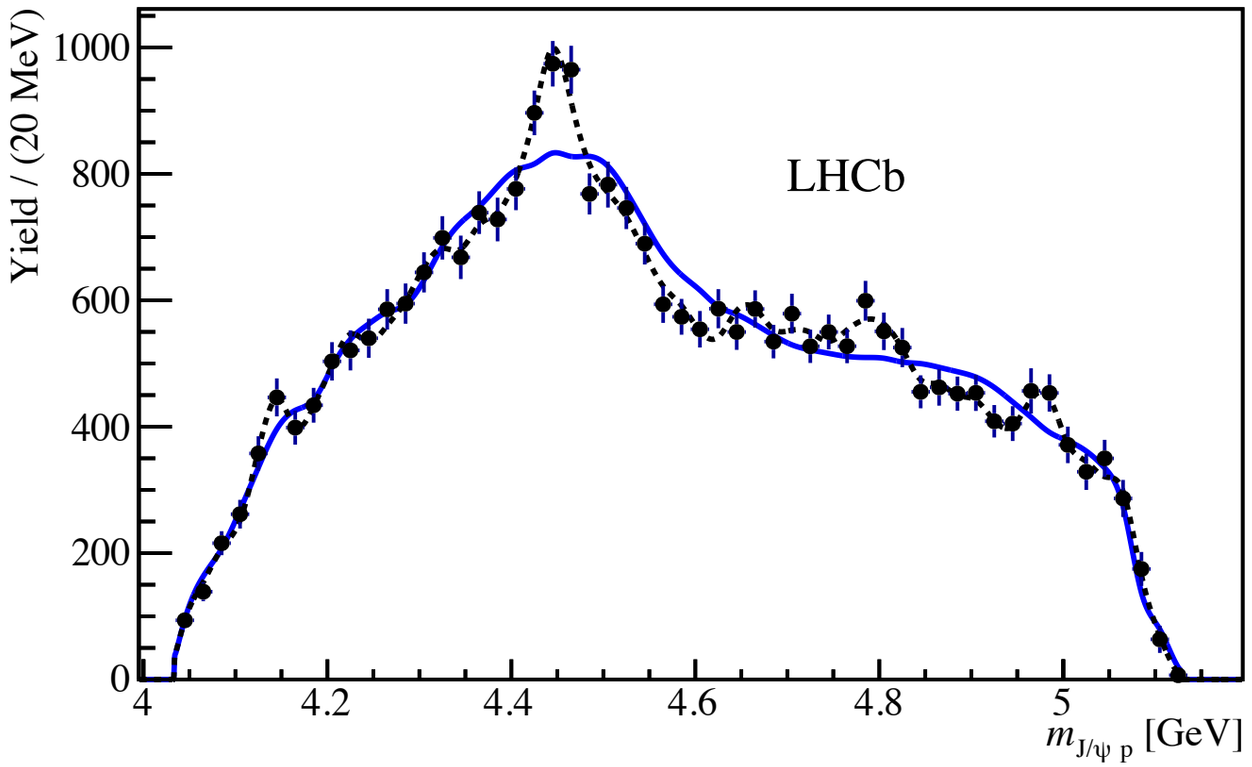

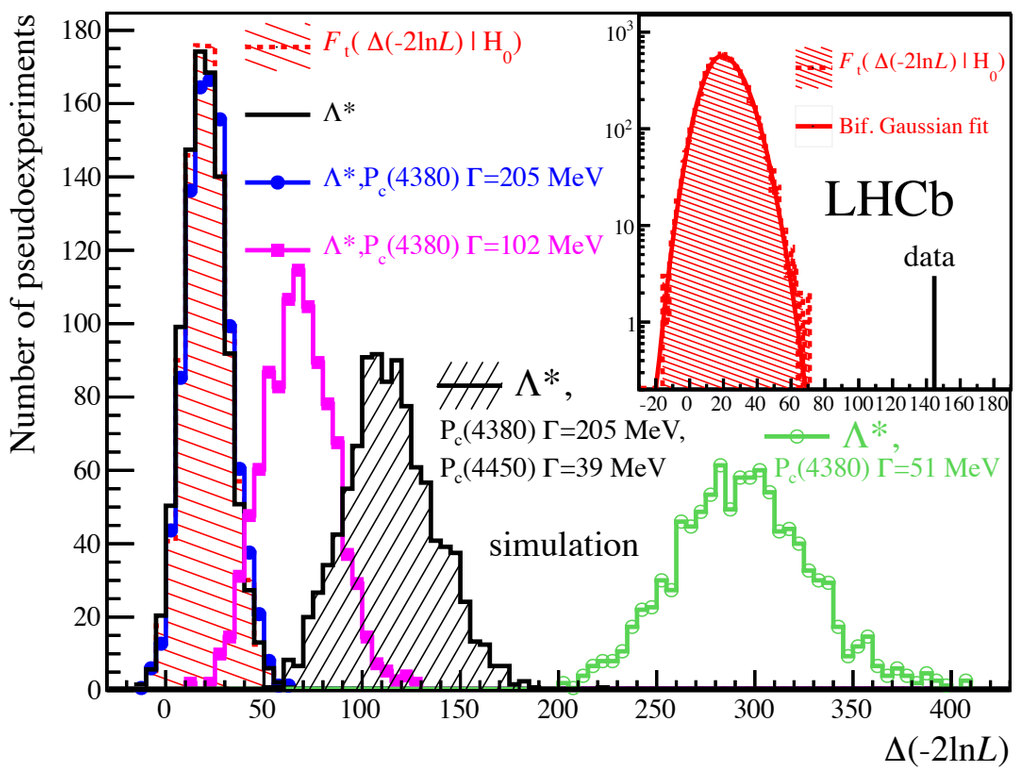

- Model independent analysis confirms pentaquark contributions
- Can quantify significance using pseudo-likelihood (>9σ)

Pentaquark states

LHCb-PAPER-2016-015 (in preparation)

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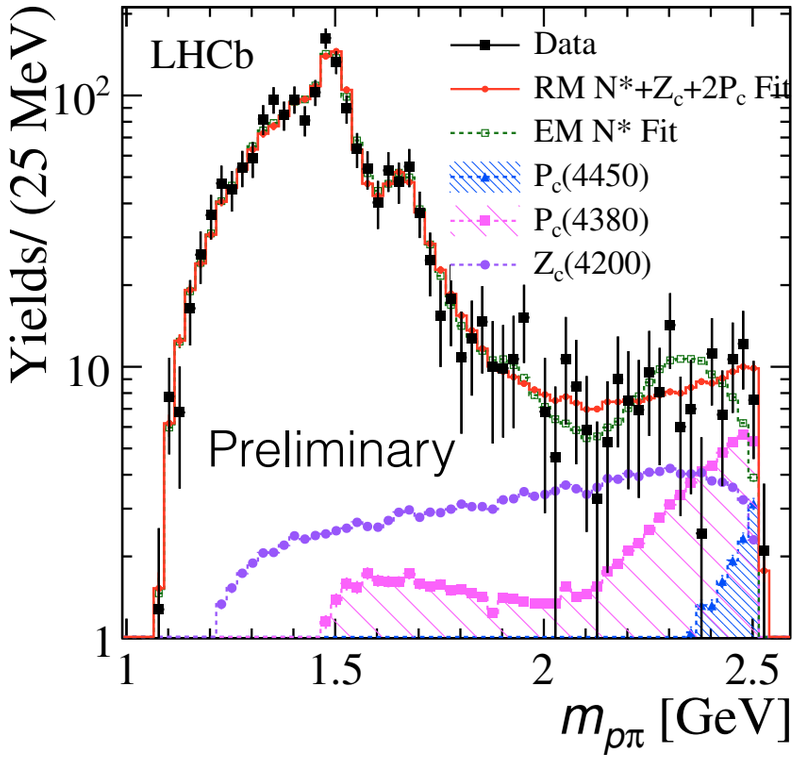
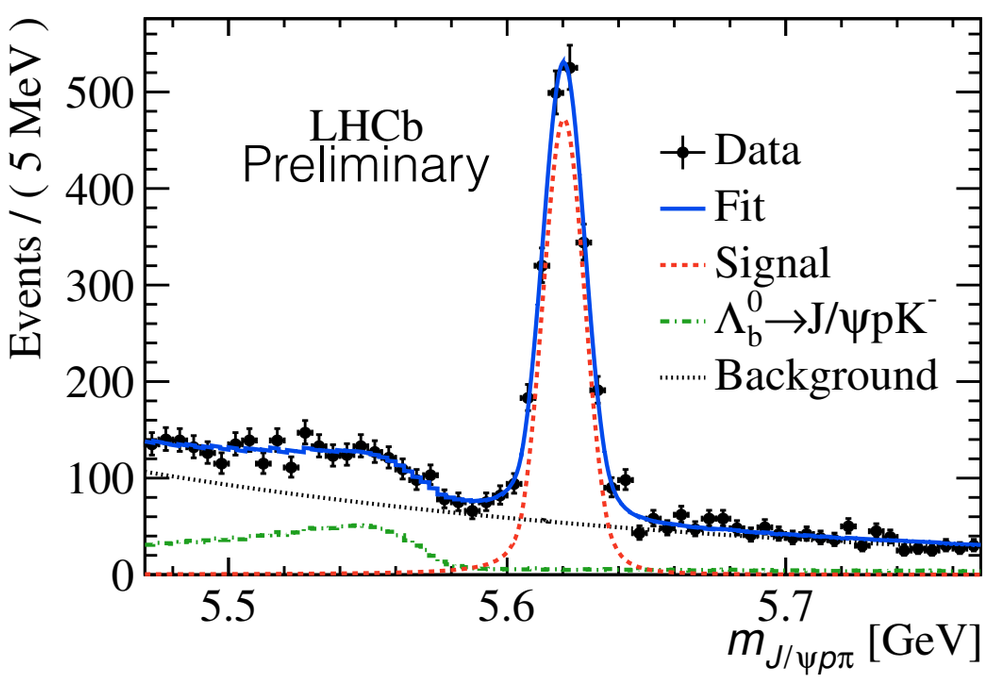
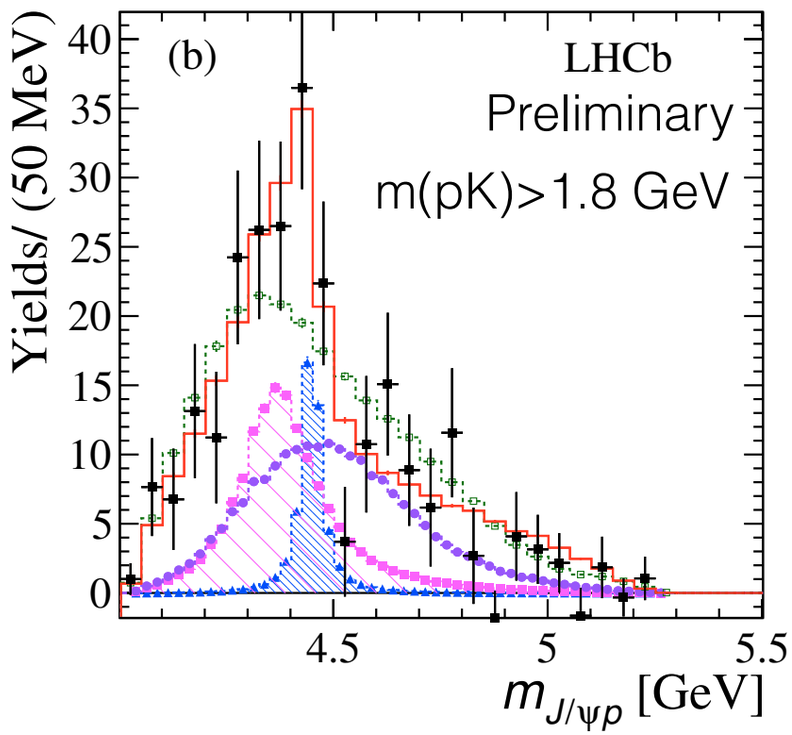
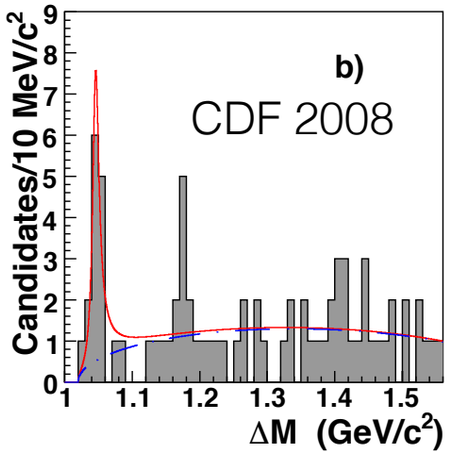
- Study Cabibbo suppressed $\Lambda_b \to J/\psi p \pi$ decays
- Statistics about factor 10 lower
- Possible $J/\psi\pi$ states in addition to $p\pi$ and $J/\psi p$
- Fit with two pentaquark and $Z_c(4200)$ about 3.1σ better than fit without exotic contributions
  - Without $Z_c(4200)$ in the fit, 3.3σ evidence for pentaquark states
- Consistent with $\Lambda_b \to J/\psi p K$ decays

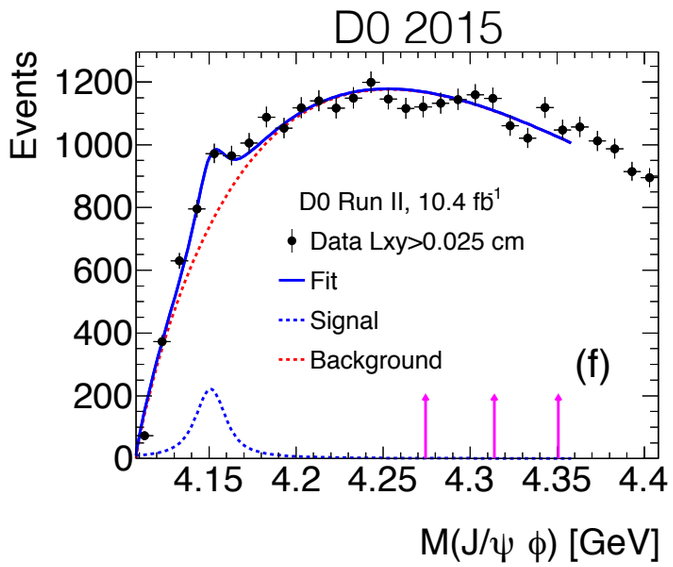


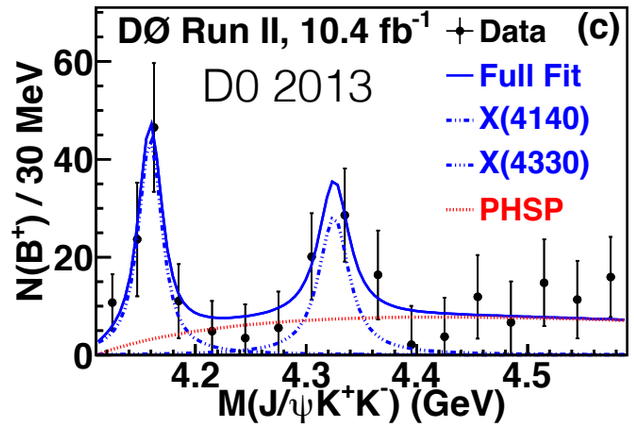


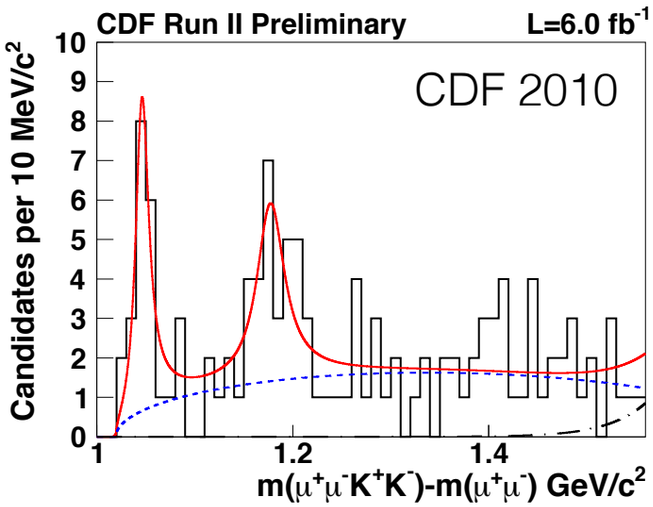


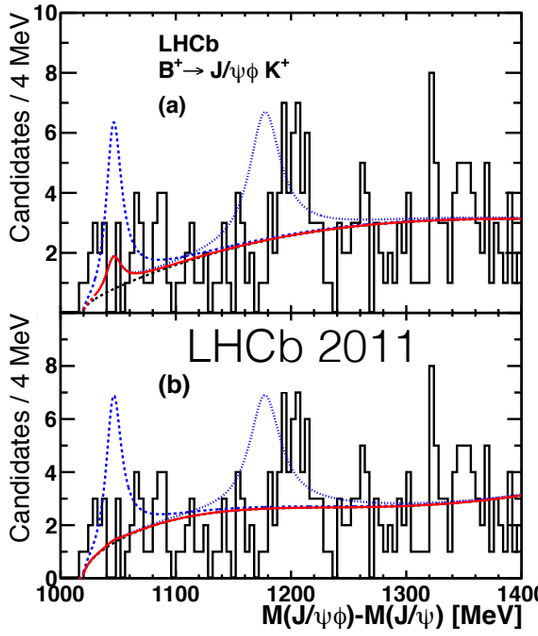
X(4140)→J/ψϕ state

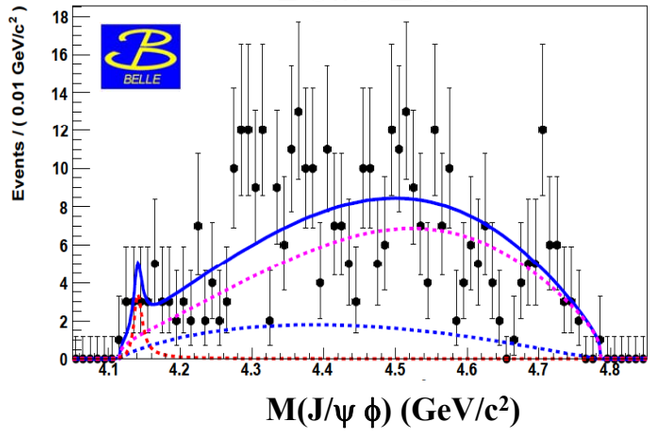


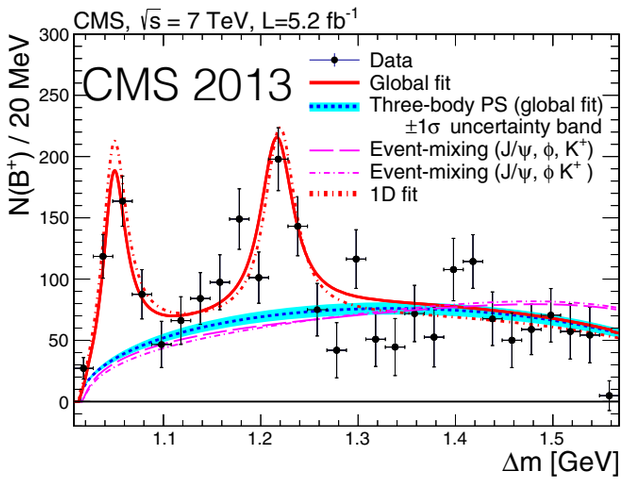


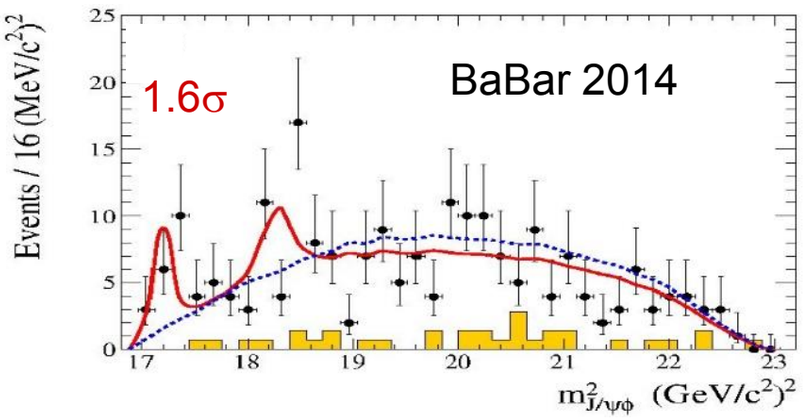












- X(4140)→J/ψϕ claimed first by CDF in B⁺→J/ψϕK
- Seen by some experiments, but not others
- Confusing situation

X(4140)→J/ψϕ state

LHCb-PAPER-2016-019/009 (in preparation)

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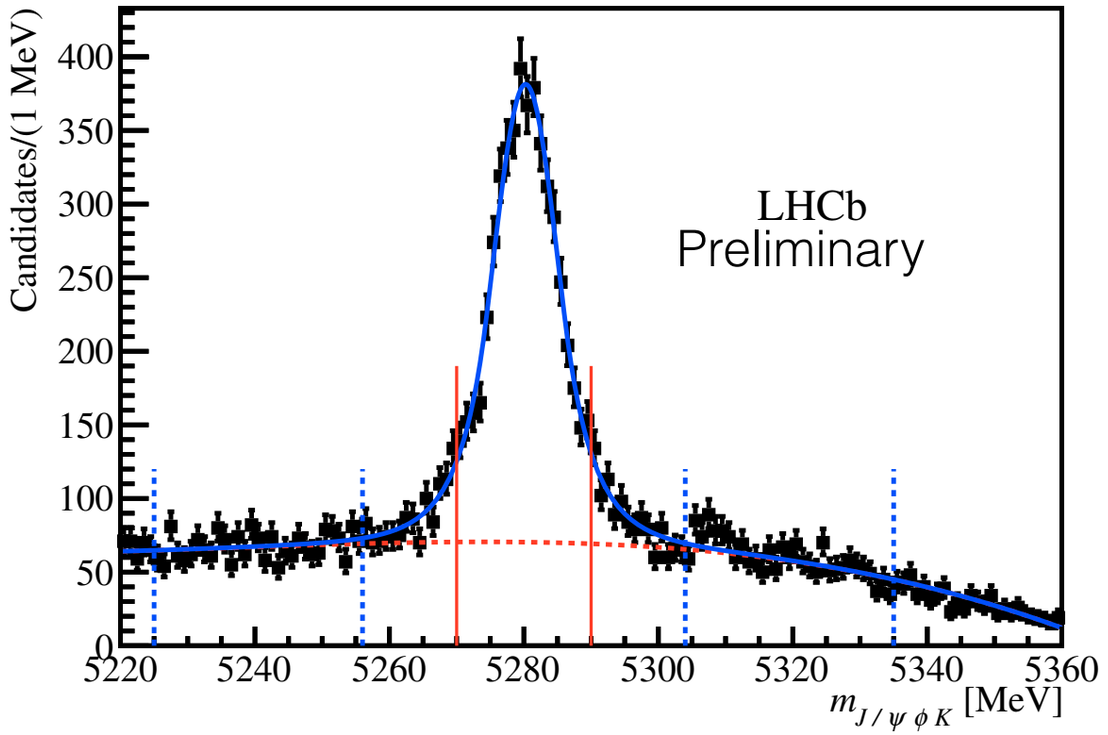
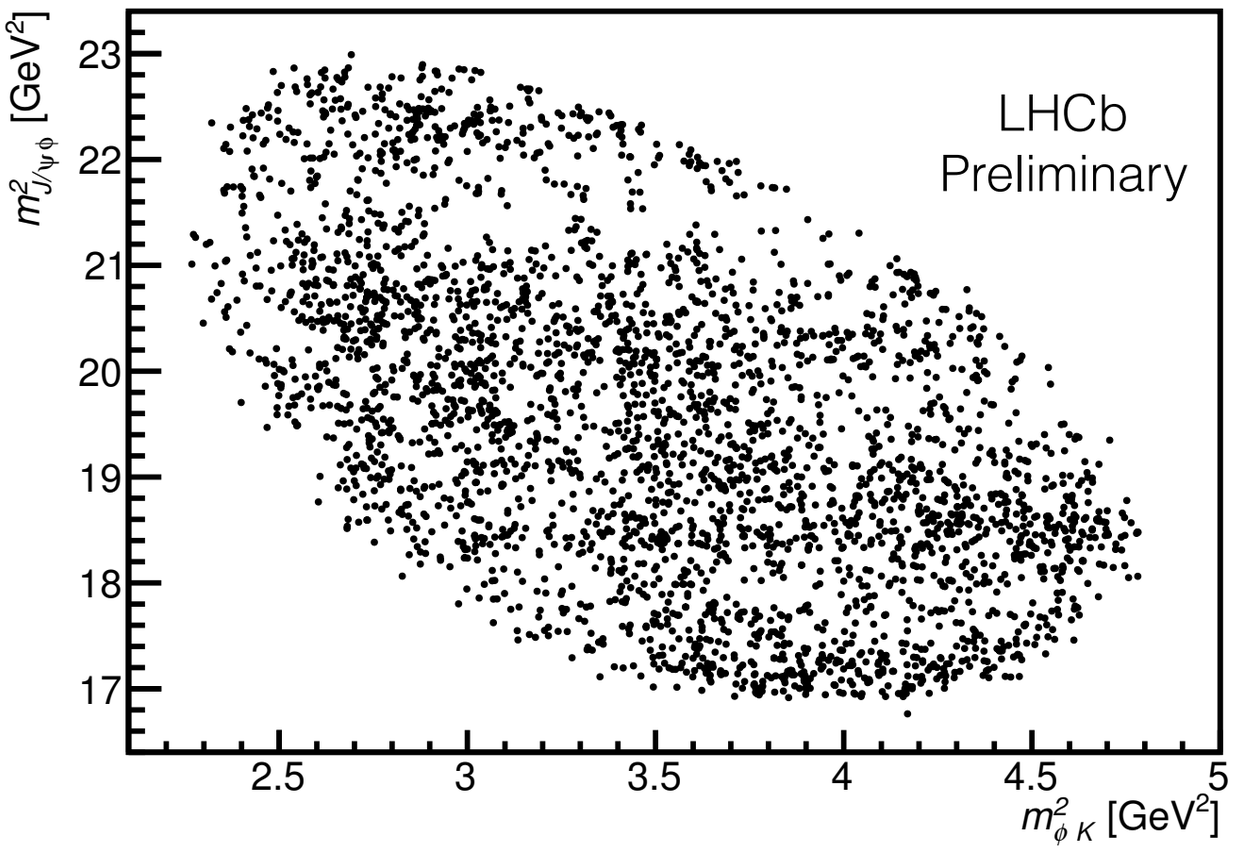
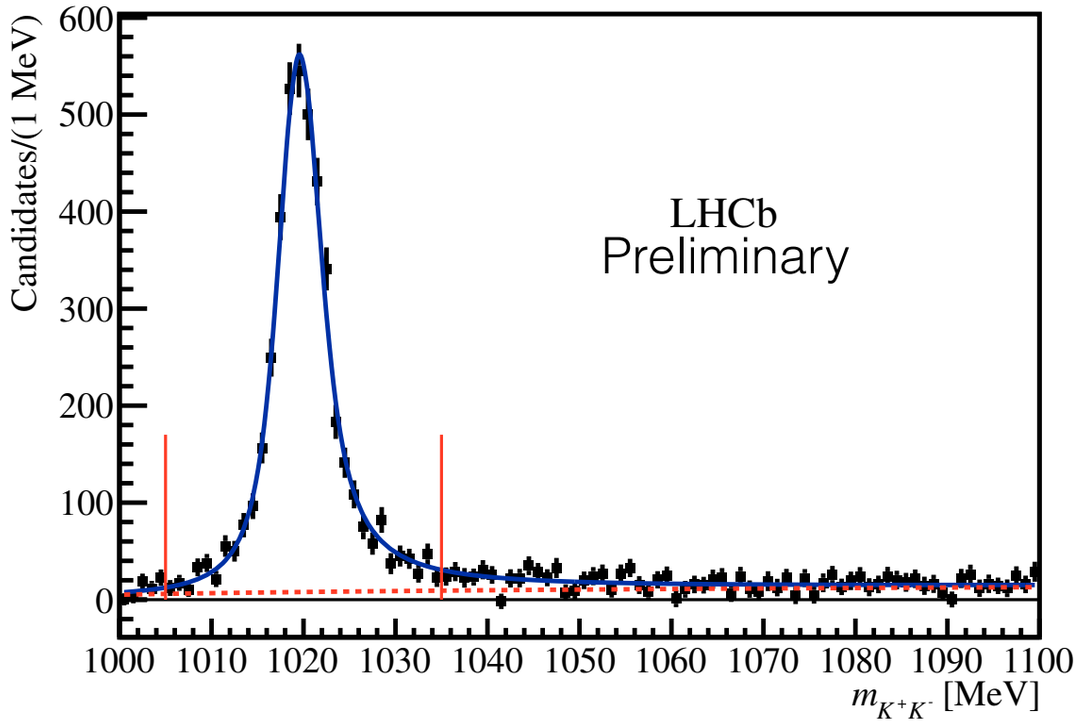
- LHCb performs amplitude analysis of $B^+ \to J/\psi\phi K$ decays
- Selection removes events when two KK combinations are consistent with ϕ
- Modelling becomes tricky as there is little information on $K^* \to \phi K$ resonances







X(4140)→J/ψϕ state

LHCb-PAPER-2016-019/009 (in preparation)

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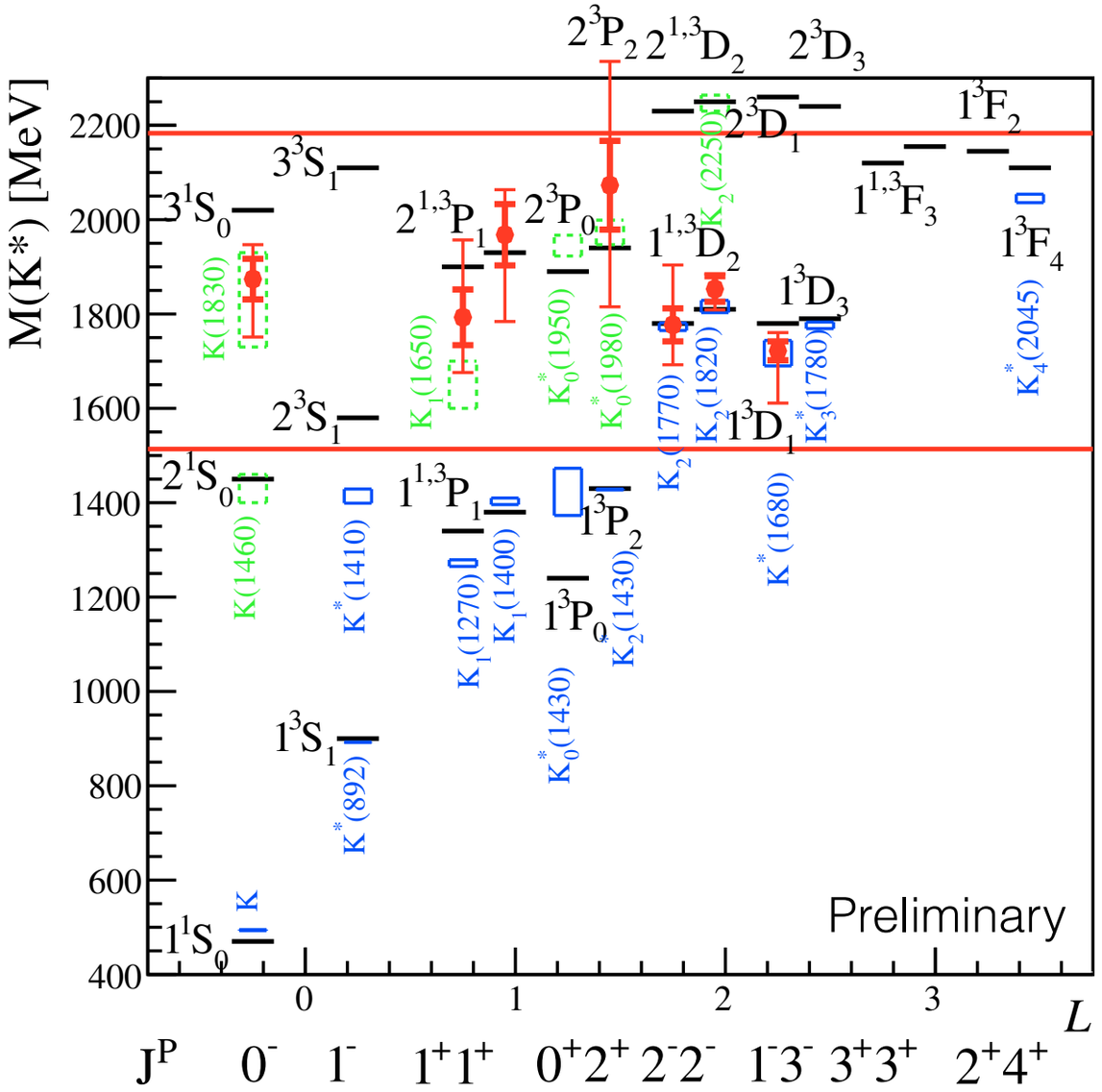

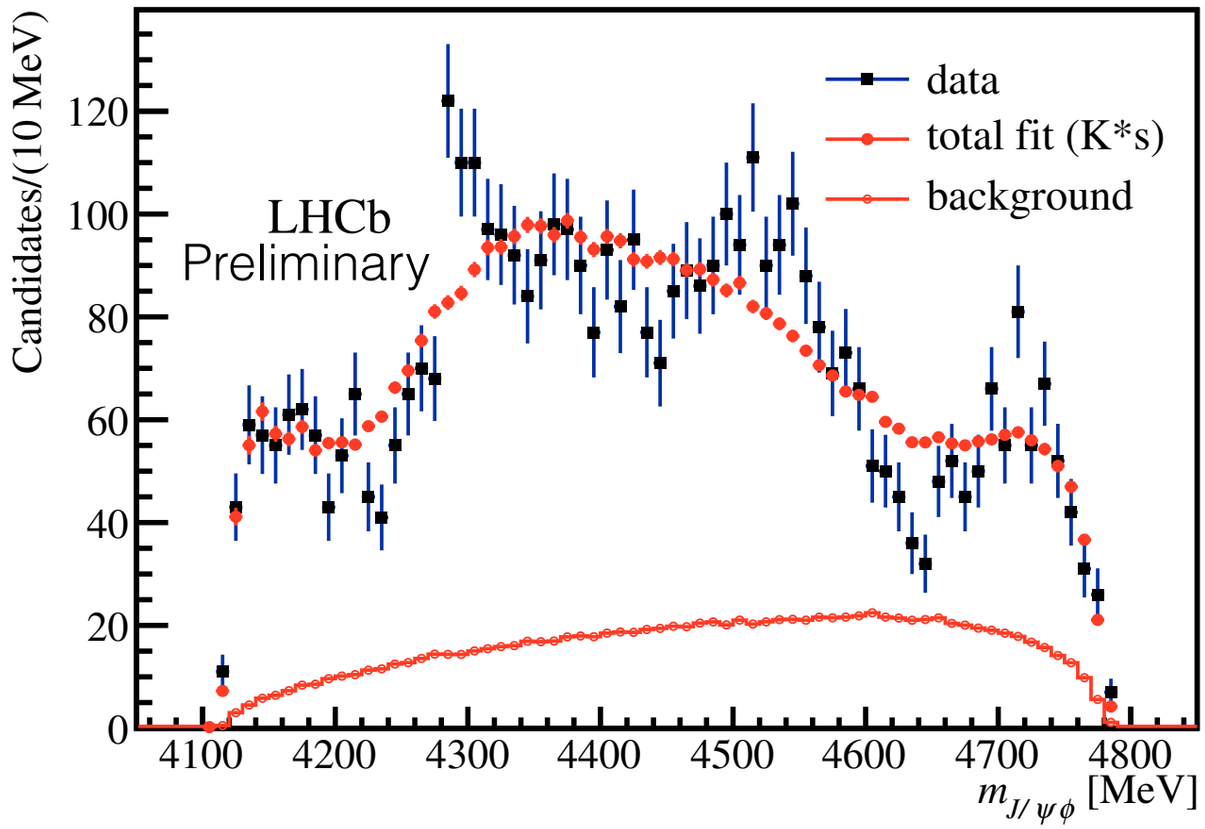

- Fit with ϕK resonances only could not describe data
- Adding more ϕK resonances does not improve description

X(4140)→J/ψϕ state

LHCb-PAPER-2016-019/009 (in preparation)

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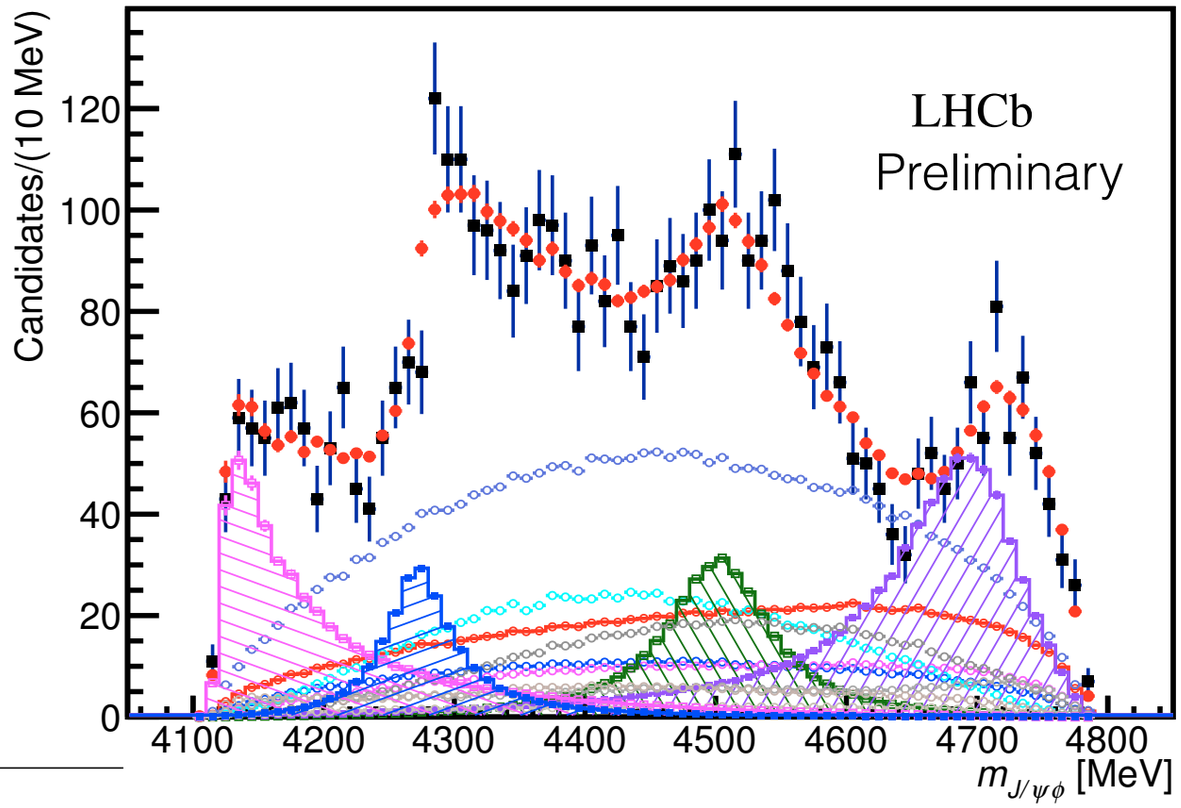
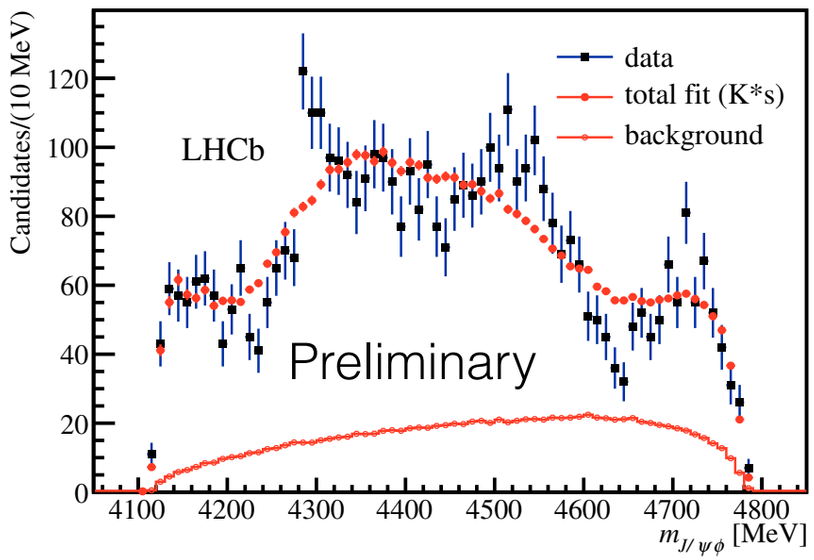
- Need 4 exotic contributions to describe data
- X(4140) possibly $D_sD_s^*$ cusp
- Some disagreement in parameters compared to previous experiments
  - Possibly due to missing interference effects in 1D fits



Contribution	sign. or Ref.	M_0 MeV	Γ_0 MeV	Fit results F.F. %
All $X(1^+)$				$16\pm3\,^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13\pm3.2\,^{+4.7}_{-2.0}$
ave.	Table 1	4146.9 ± 2.3	17.8 ± 6.8	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF	[25]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS	[22]	$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	
All $X(0^+)$		Preliminary		$28\pm\ 5\,^{+\ 7}_{-\ 7}$
$\mathrm{NR}_{J/\psi\phi}$	6.4σ			$46\pm11\,^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$



Conclusions

- Lot of detailed data on heavy flavour hadrons production
- High precision should help models development to settle open questions
- Clear evidence for associated/pair production of heavy quark pairs
  - Hopefully it will help to pinpoint extent of double parton scattering
- Pentaquark states confirmed in
  - model independent study
  - decays of $\Lambda_b \rightarrow J/\psi p \pi$
- Amplitude analysis of $B^+ \rightarrow J/\psi \phi K$ decays reveals rich "exotic" structure
  - Interpretation of these is rather unclear at this moment

- Chiara Zampolli: HF production at ALICE
- Vincenzo Canale: HF production at ATLAS
- Bazar Bartosik: HF production at CMS
- Max Neuner: HF production at LHCb
- Roberta Cardinale: Spectroscopy at LHCb
- Paulo Iengo: Spectroscopy at ATLAS
- Alexis Pompili: Spectroscopy at CMS
- Antonello Polosa: Spectroscopy interpretation

WARWICK

BACKUP

D_{sJ} spectroscopy

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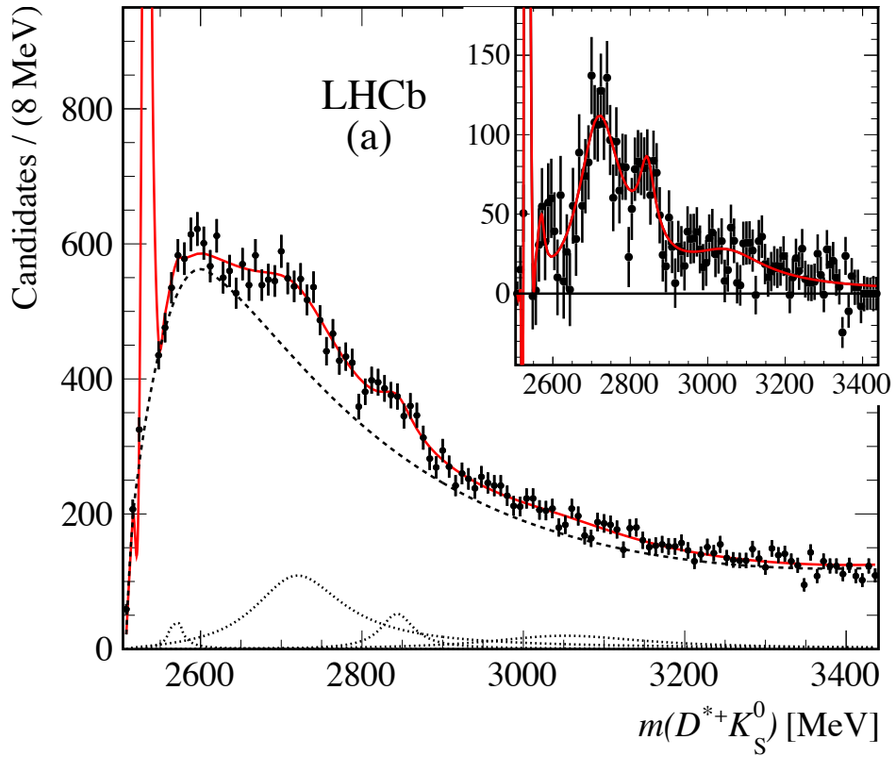
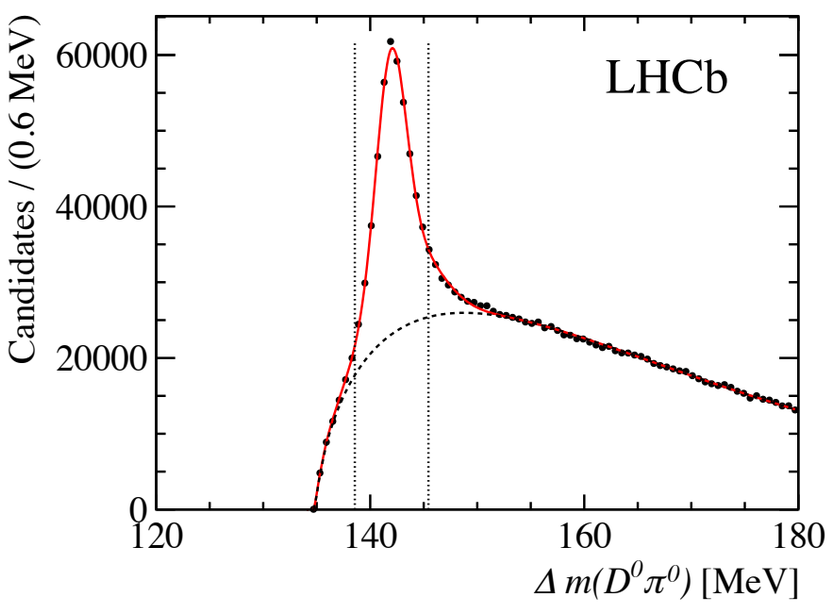
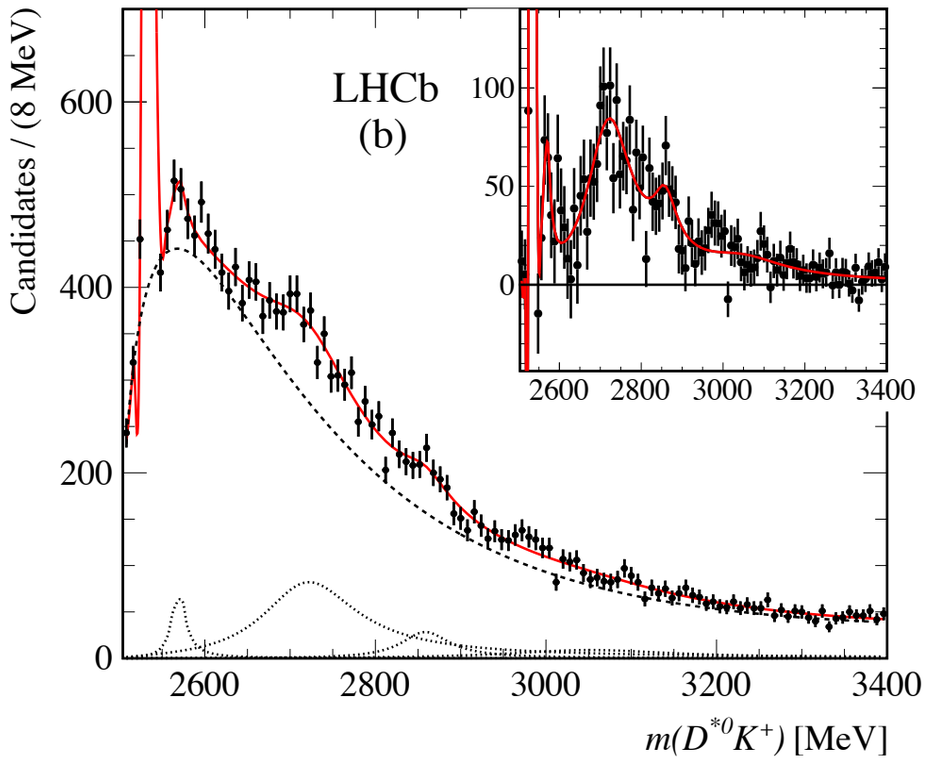
WARWICK

- Open charm spectroscopy has unanswered questions
- Not all expected states observed
- Some D_{sJ} states below DK threshold
- Studies both in prompt production and B decays
- Prompt production has higher statistics, but more difficult background
- B decays provide better handle on J^P



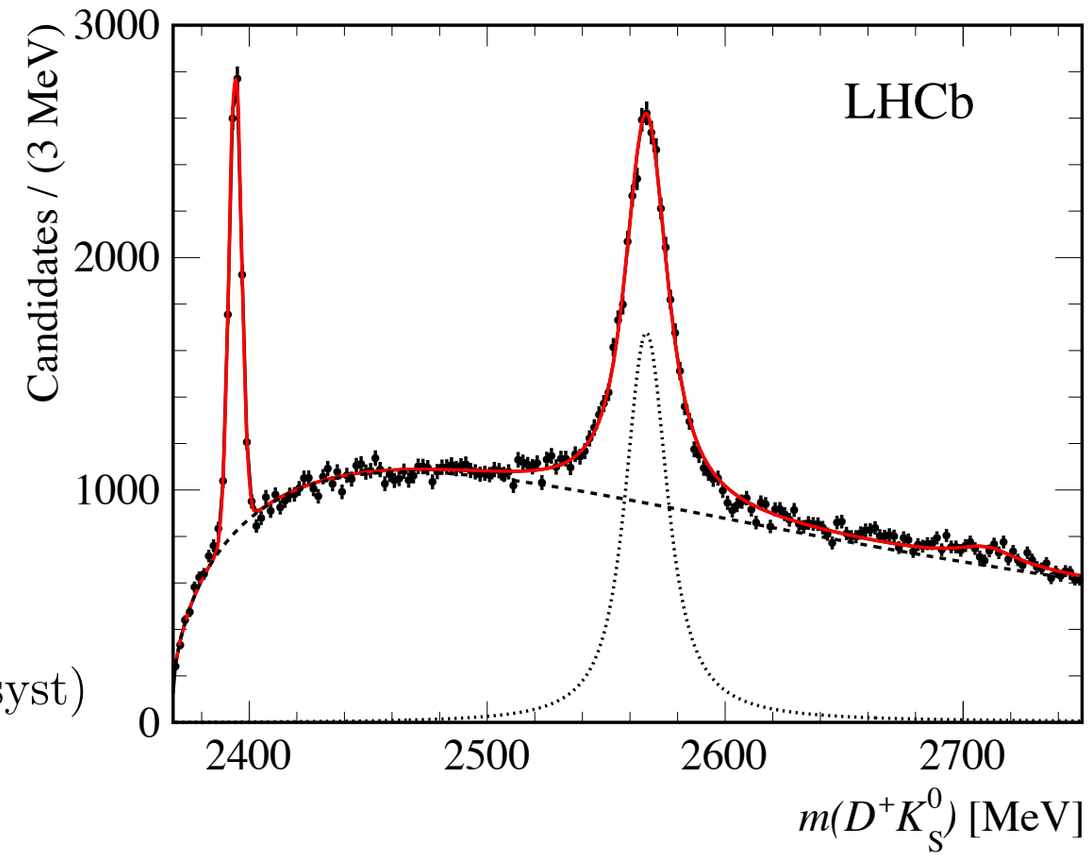


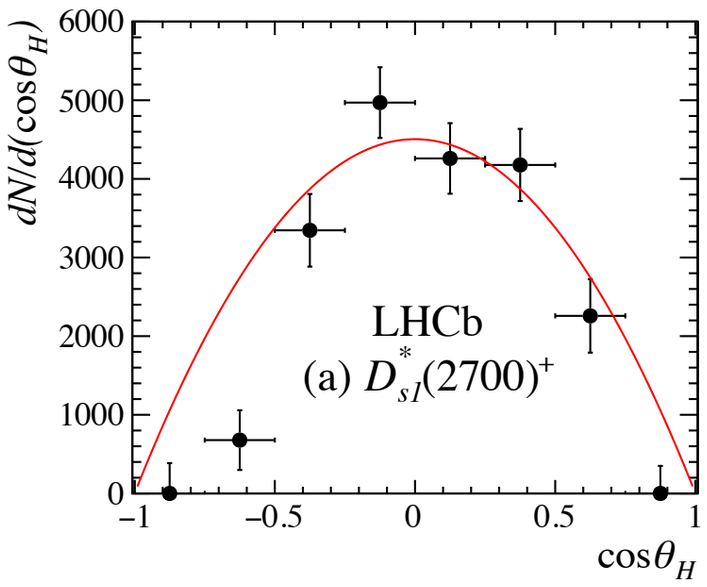


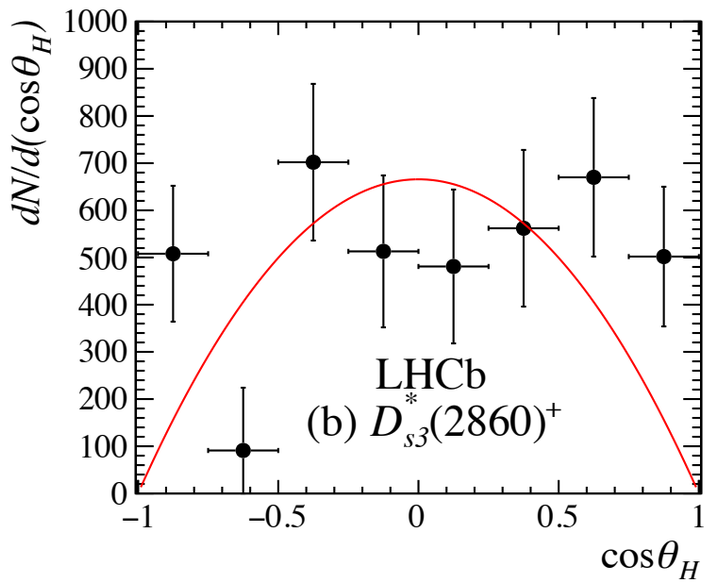
D_{sJ} spectroscopy

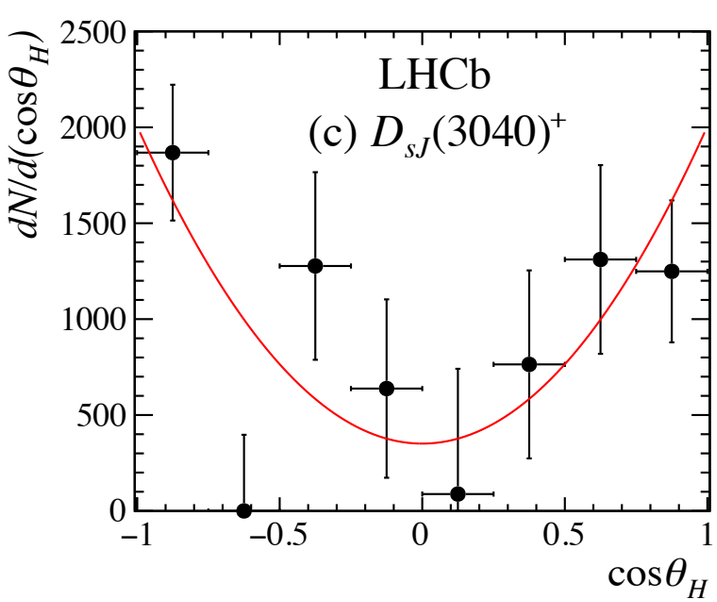
- First observation of $D_{sJ}(2573) \rightarrow D^+K_S$
- In decays to D^* can use angular distributions to probe spin-parity
  - Separate natural spin-parity (0^+,1^-, 2^+, …) from unnatural spin-parity (0^-,1^+, 2^-, …)
- Measured

$$\frac{\mathcal{B}(D^*_{s2}(2573)^+ \to D^{*+}K^0_S)}{\mathcal{B}(D^*_{s2}(2573)^+ \to D^+K^0_S)} = 0.044 \pm 0.005\,(\text{stat}) \pm 0.011\,(\text{syst})$$





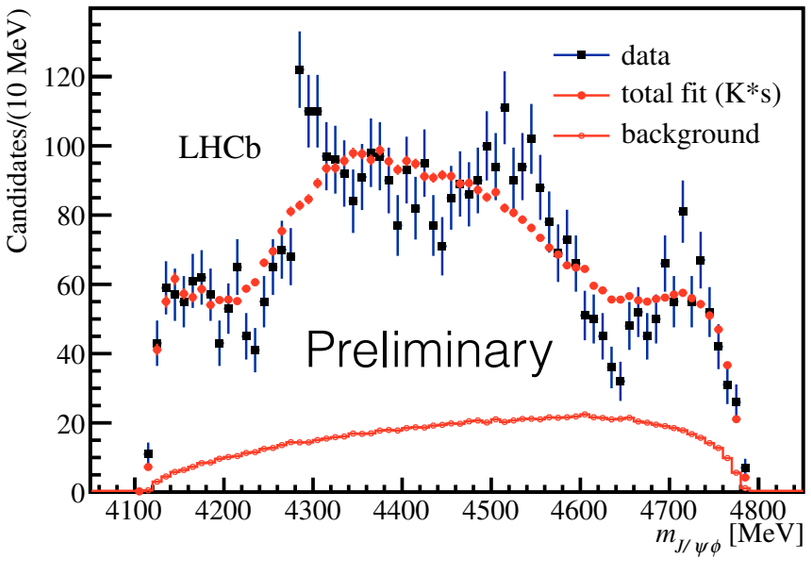


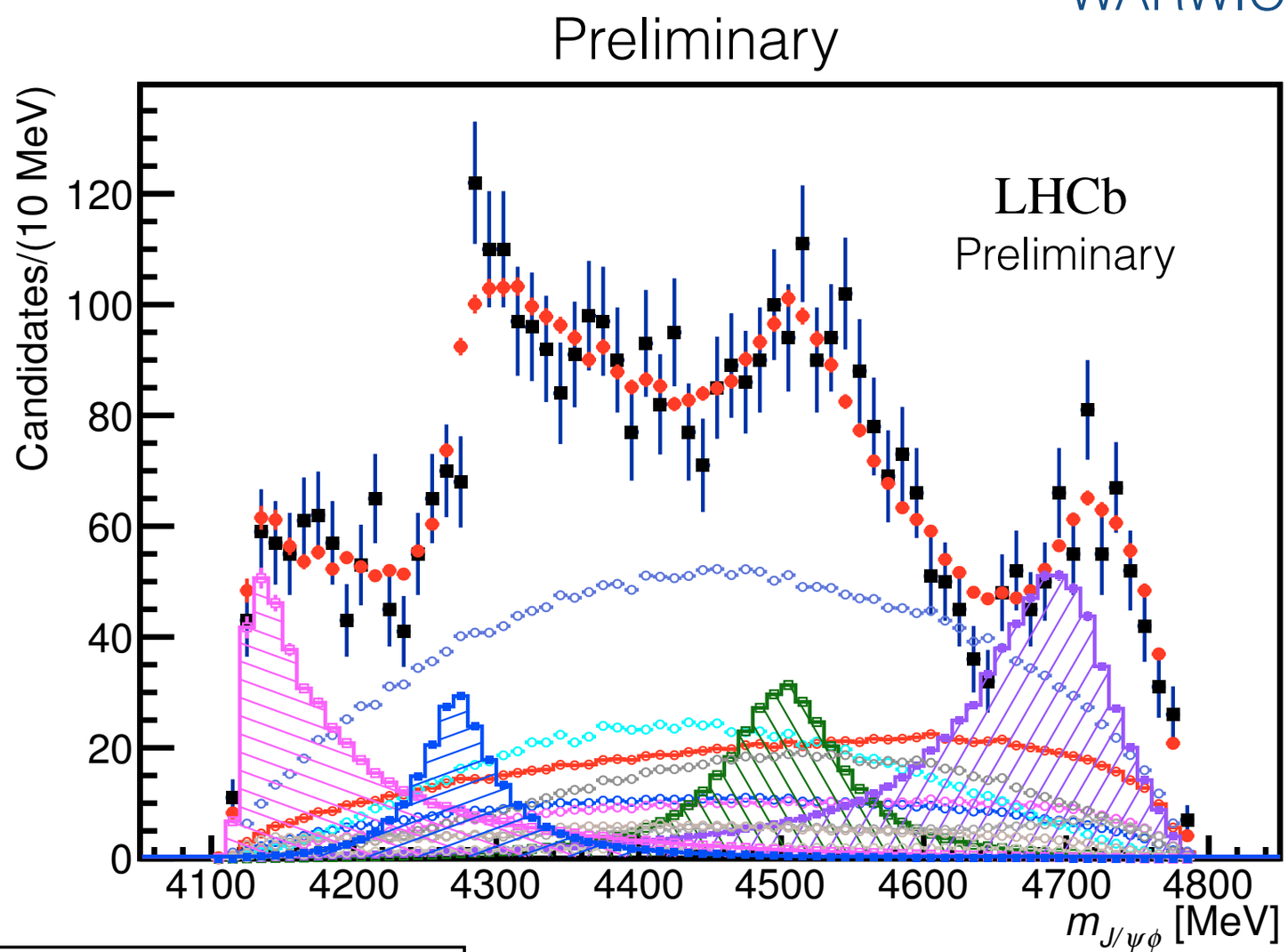


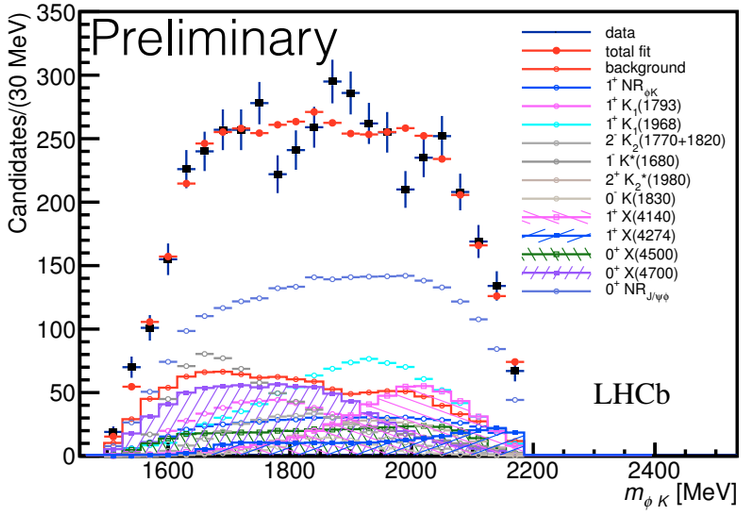
X(4140)→J/ψϕ state

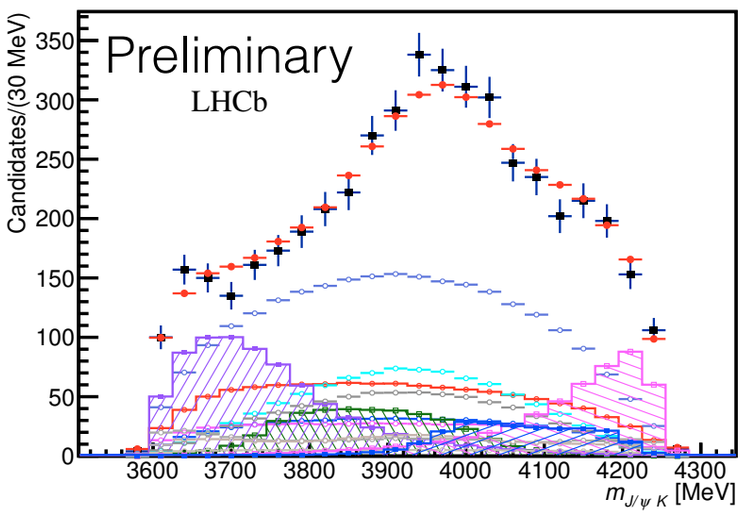
LHCb-PAPER-2016-019/009 (in preparation)

WARWICK





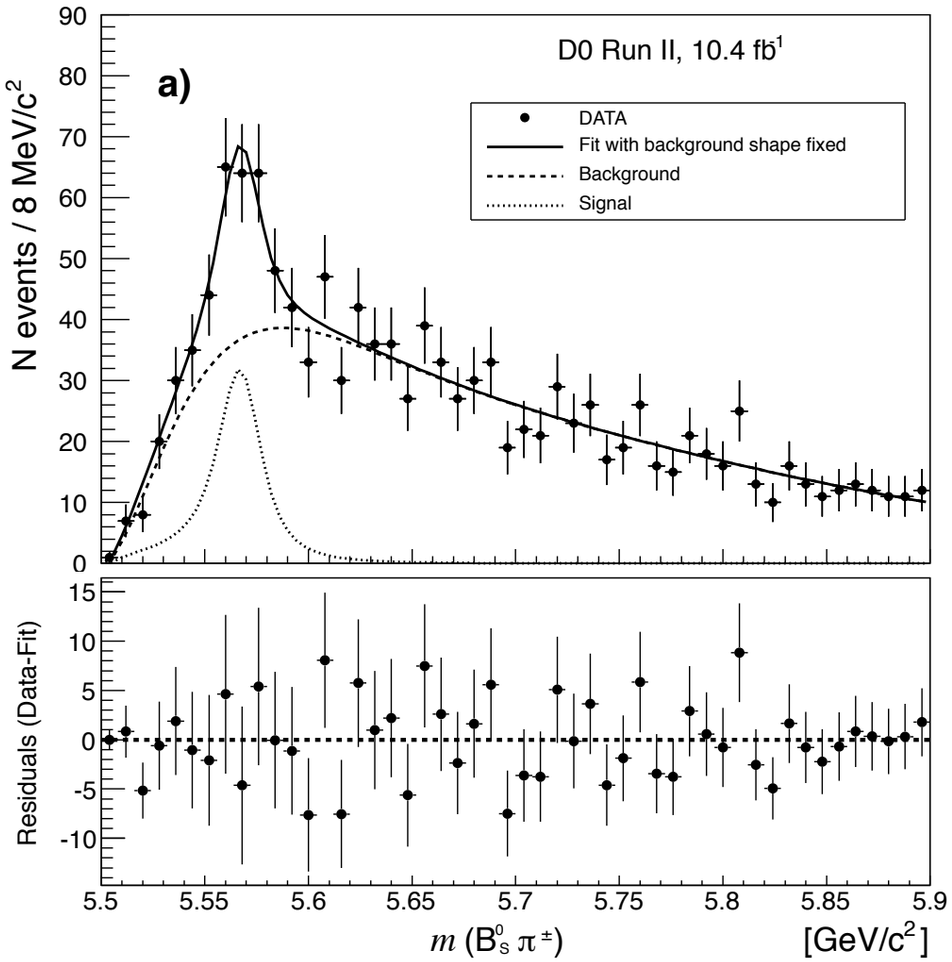


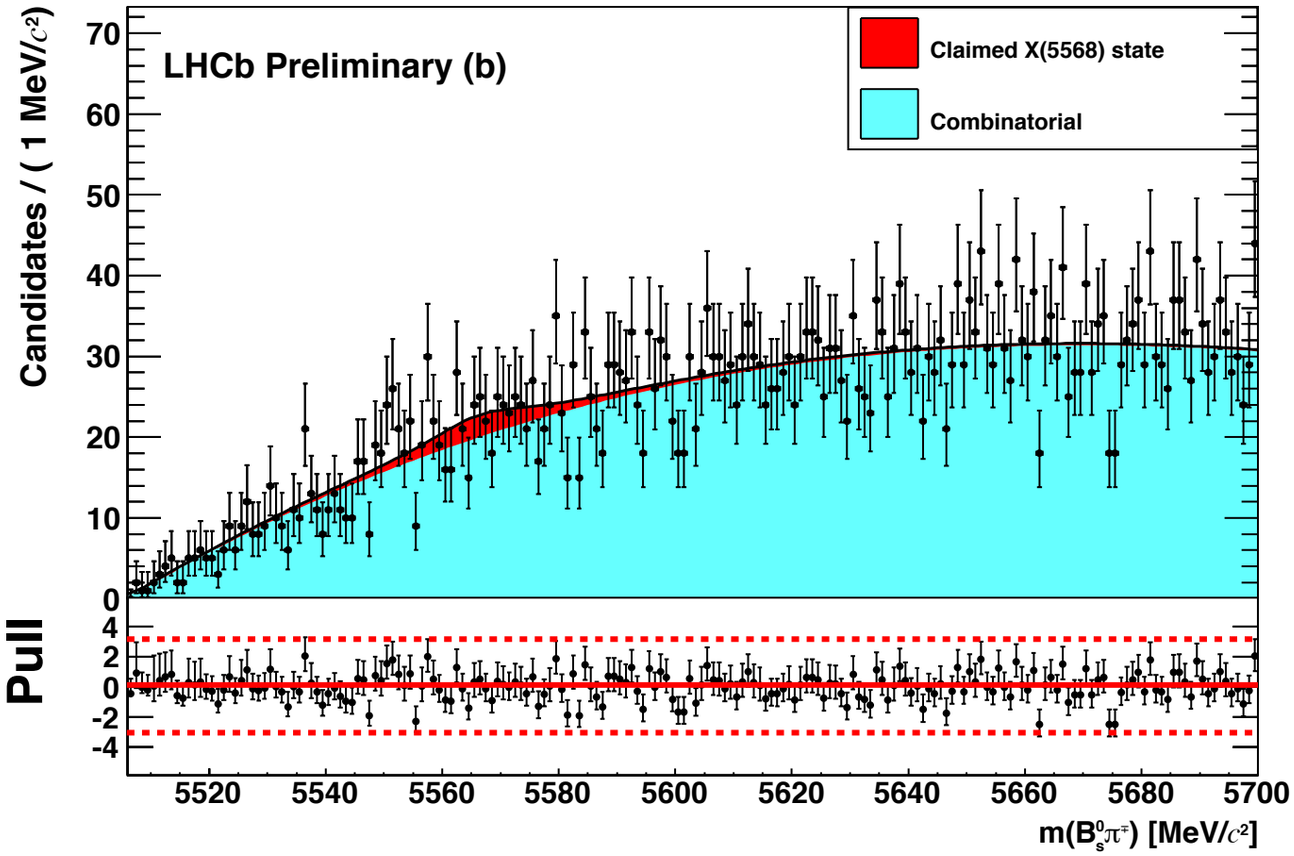


Structure in $B_s\pi$ spectrum?

LHCb-CONF-2016-004

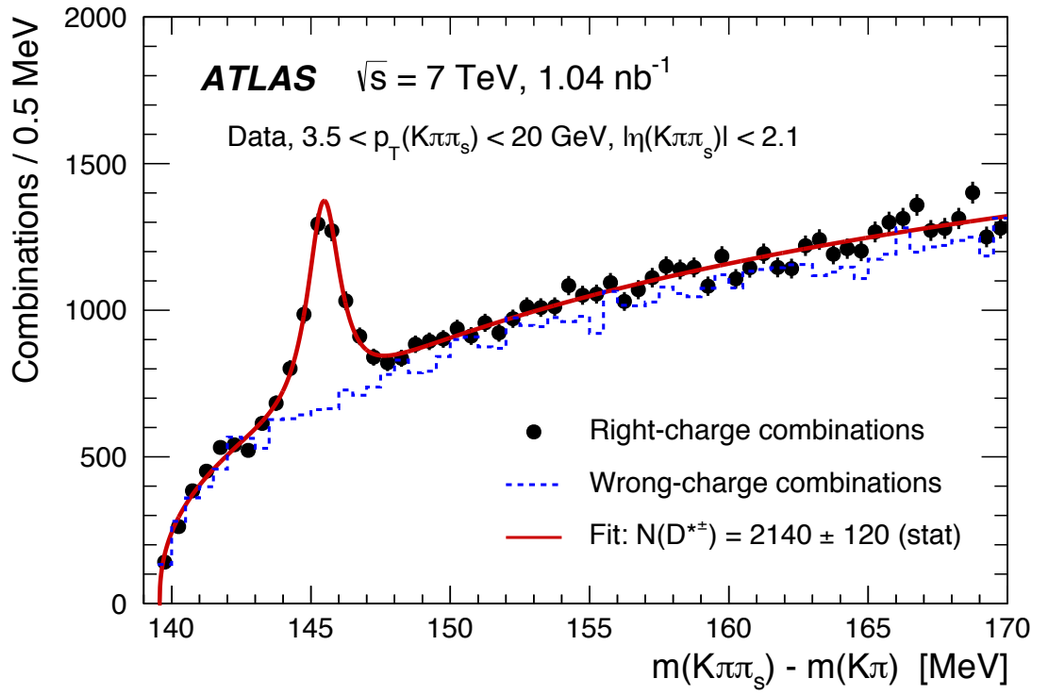
- D0 collaboration claimed state decaying to $B_s\pi^+$
- LHCb has large data sample to check it
  - 112600 B_s events (LHCb) vs. 5582 (D0)
- No state seen in place of D0 state

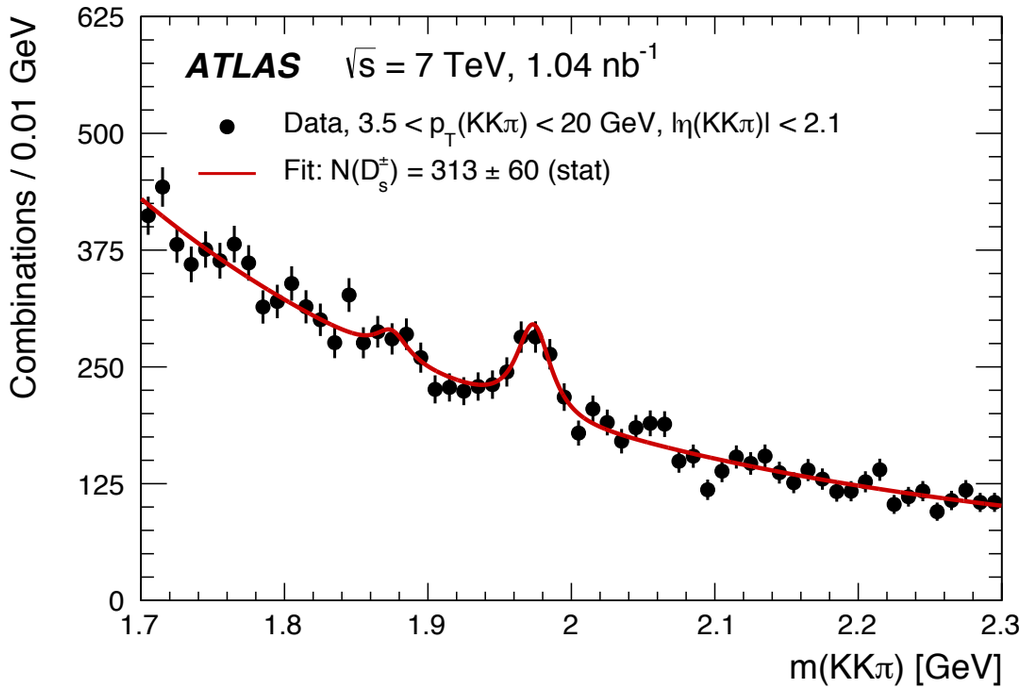


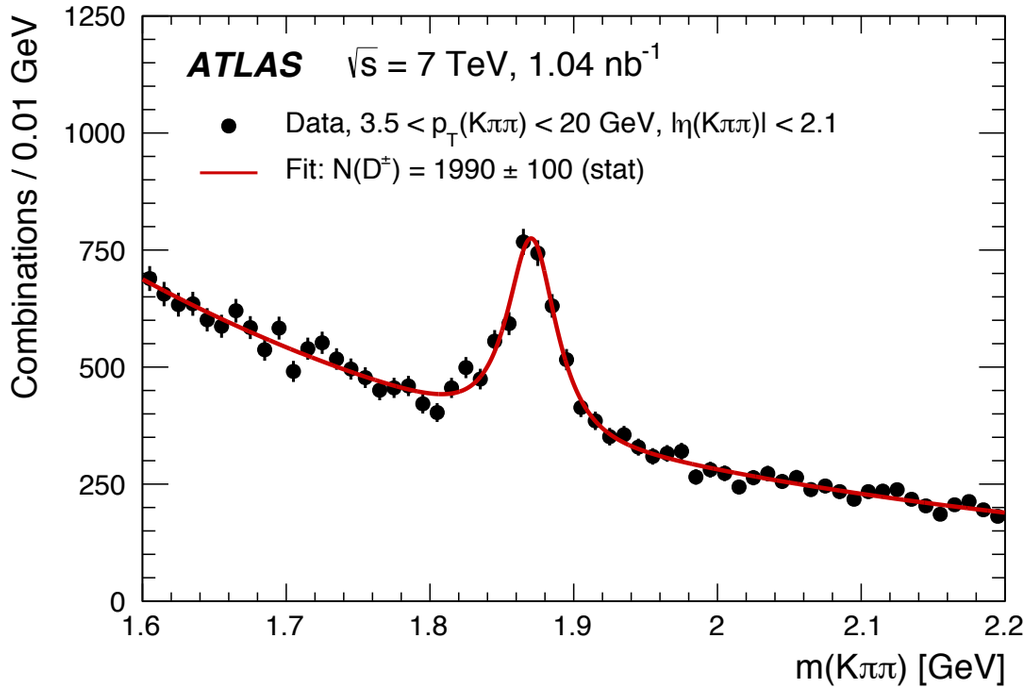


Open charm production

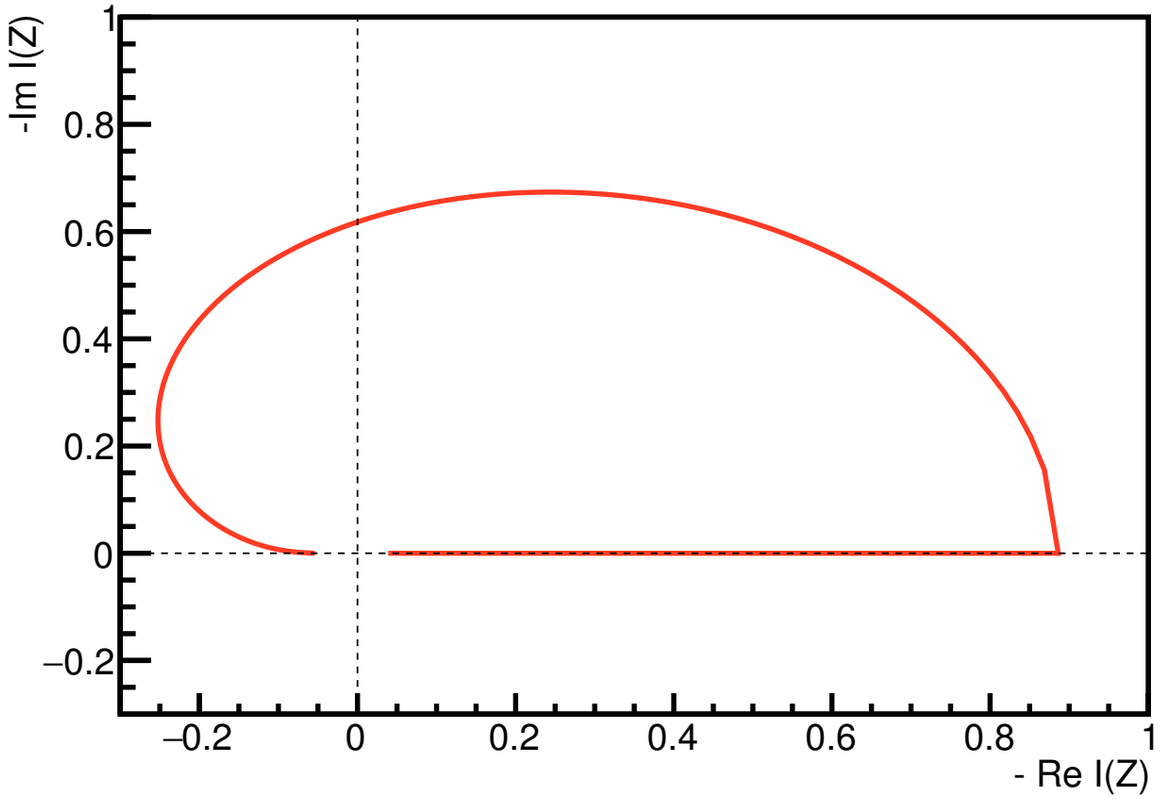
- ATLAS joins in open charm x-section measurements in central region
- Done using D^+, D^{*+} and D_s
- Compare to expectations
  - Fragmentation based on experimental data
- Can use results to extract fragmentation fractions

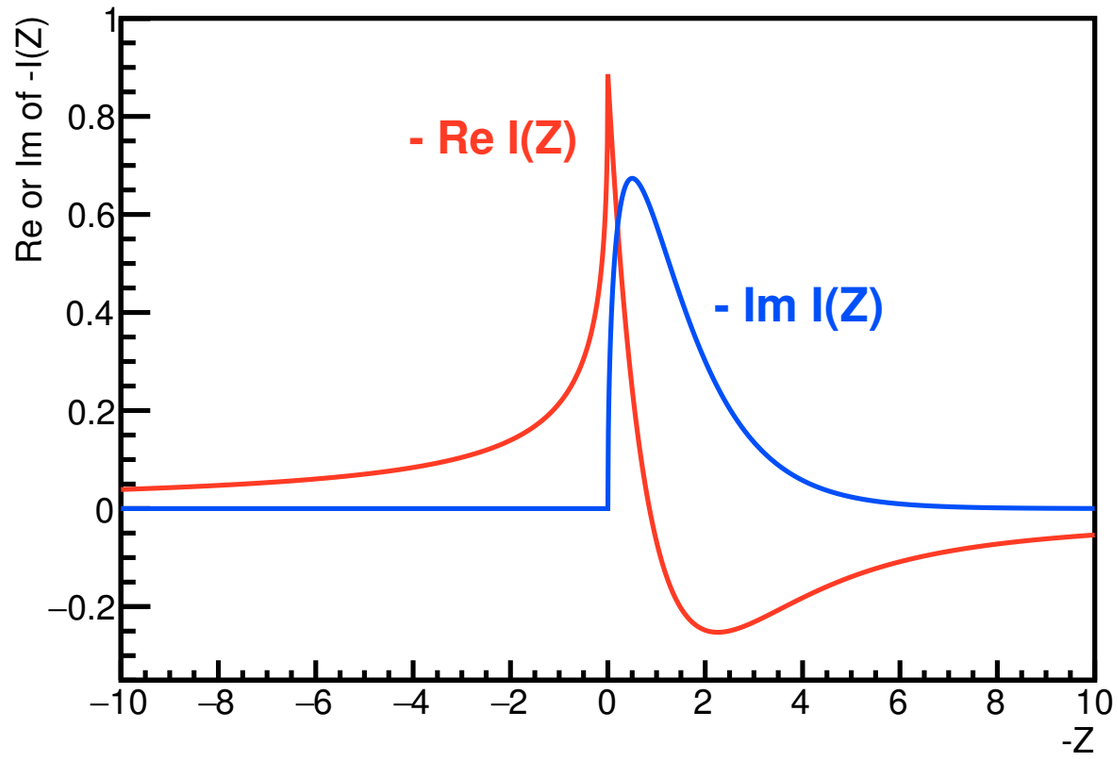




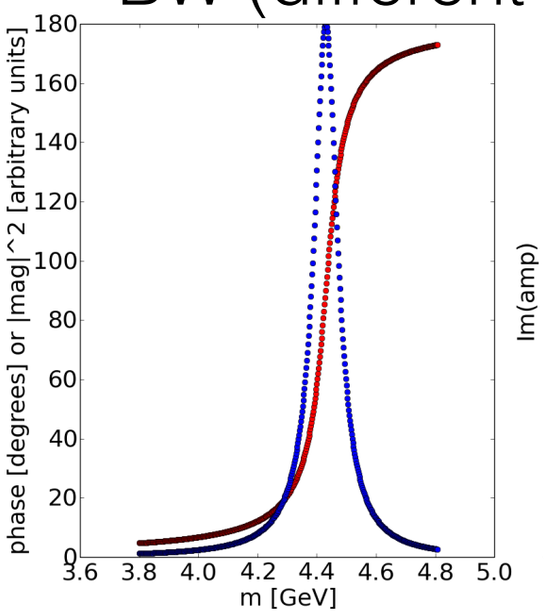


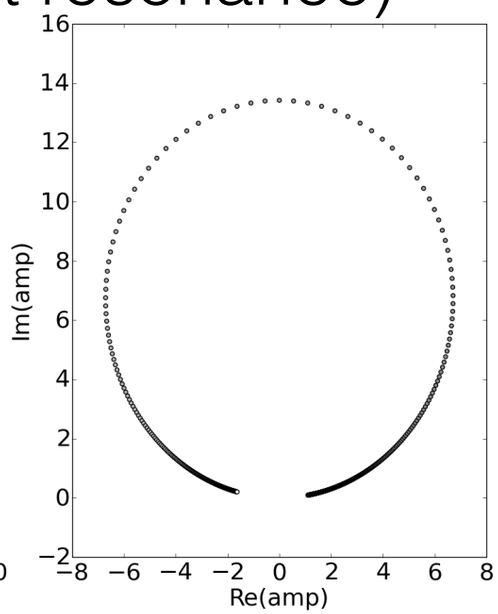
X(4140) CUSP





BW (different resonance)





- Cusp model from Swanson: 1504.07952