



Production measurements at LHCb



AGH UNIVERSITY OF SCIENCE
AND TECHNOLOGY

Bartłomiej Rachwał
on behalf of LHCb collaboration

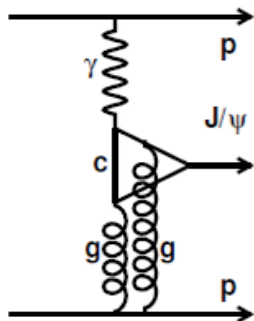
XXIII Cracow EPIPHANY Conference
9-12 January 2017

Production measurements:

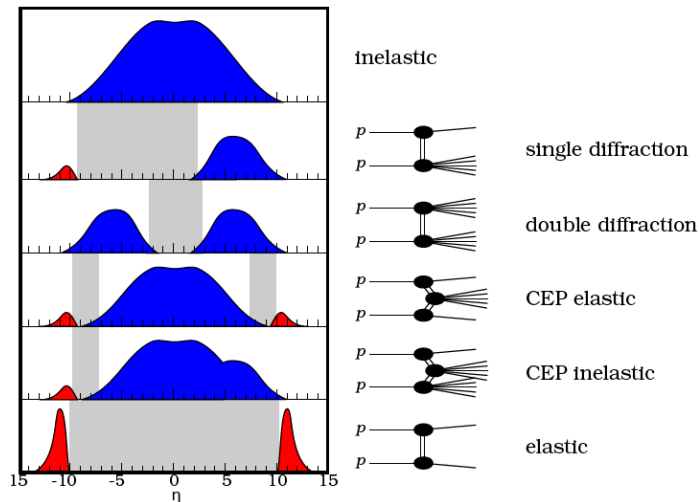
- yield important information on perturbative and non-perturbative processes
- QCD regimes non-perturbative part:
 - many parameters rely on experiment
 - test models and provide an input to tune simulation
- Constraining the parton distribution functions (PDFs)
- Central Exclusive Production (CEP) measurements:
 - very clean experimental final states
 - sensitivity to gluon distribution at low Bjorken-x ($\sim 5 \cdot 10^{-6}$)

Exchange of neutral, colourless objects

γ - pomeron fusion



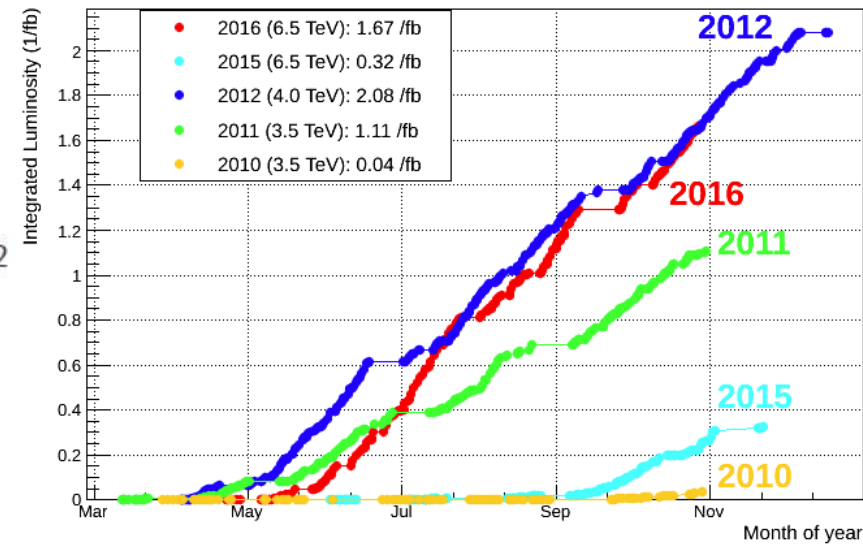
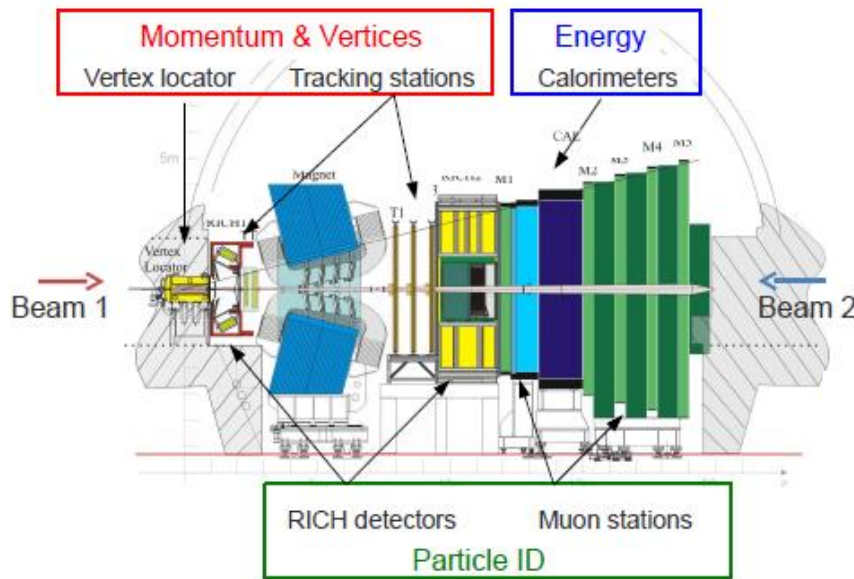
Event Signatures



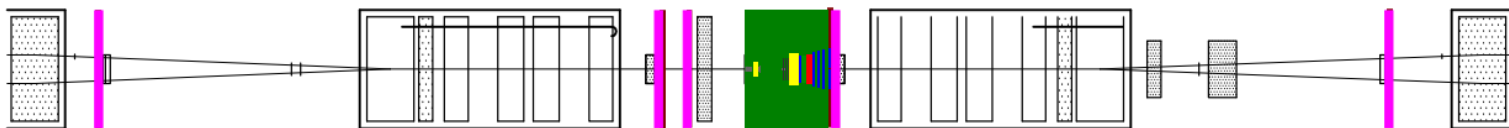
Run 2 production results including CEP studies

- Open charm: D^0 , D^+ , D_s , D^{*+}
JHEP 03 (2016) 159, Erratum: JHEP 09 (2016) 013
- Bottom
arXiv:1612.05140
- Quarkonia:
 J/ψ , J/ψ pairs and exclusive J/ψ , $\psi(2S)$
JHEP 10 (2015) 172, LHCb-CONF-2016-007, arXiv:1612.07451v1
- Z boson
JHEP 09 (2016) 136

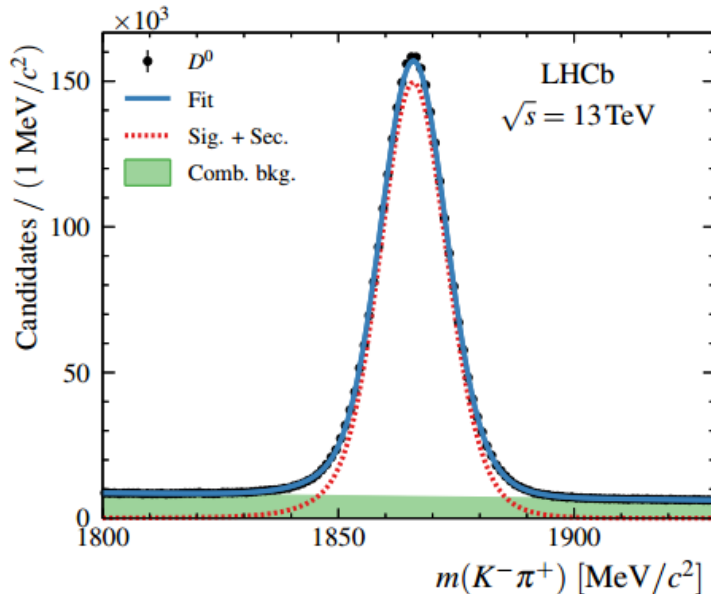
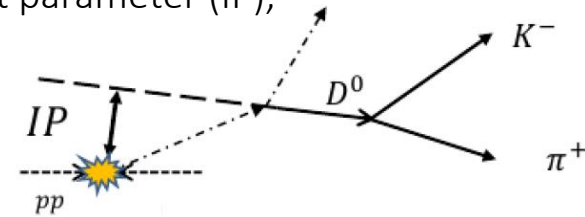
- Single arm spectrometer – designed for precision measurements in b and c physics
- Fully instrumented in the forward region ($2 < \eta < 5$)
- Some detection capability in backward region ($-3.5 < \eta < -1.5$)
- Very flexible trigger \rightarrow able to trigger on low momentum objects, dedicated CEP trigger lines



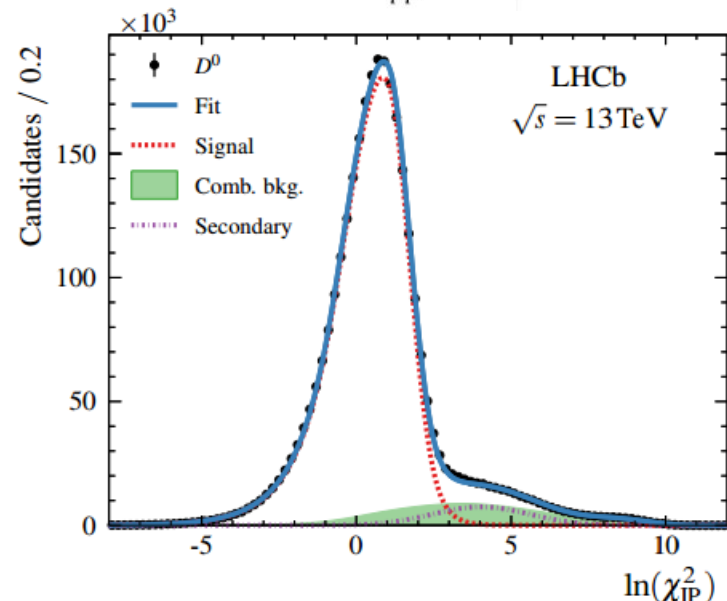
Run 2: additional scintillators upstream and downstream (up to 114 m): HeRSChE stations



- Measurements of the cross-sections for the prompt production of D^0, D^+, D_s^+ and D^{*+} mesons based on $4.98 \pm 0.19 \text{ pb}^{-1}$ data sample.
- Handled decay modes:
 $D^0 \rightarrow K^- \pi^+, D^+ \rightarrow K^- \pi^+ \pi^+, D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+, D_s^+ \rightarrow \phi (K^- K^+) \pi^+$
- Charm mesons from the decays of b -hadrons (secondary charm) are considered as a background process,
- The minimum distance of a track to a primary vertex, the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$
- Signal extraction: subsequent fits to invariant mass and $\ln(\chi_{IP}^2)$

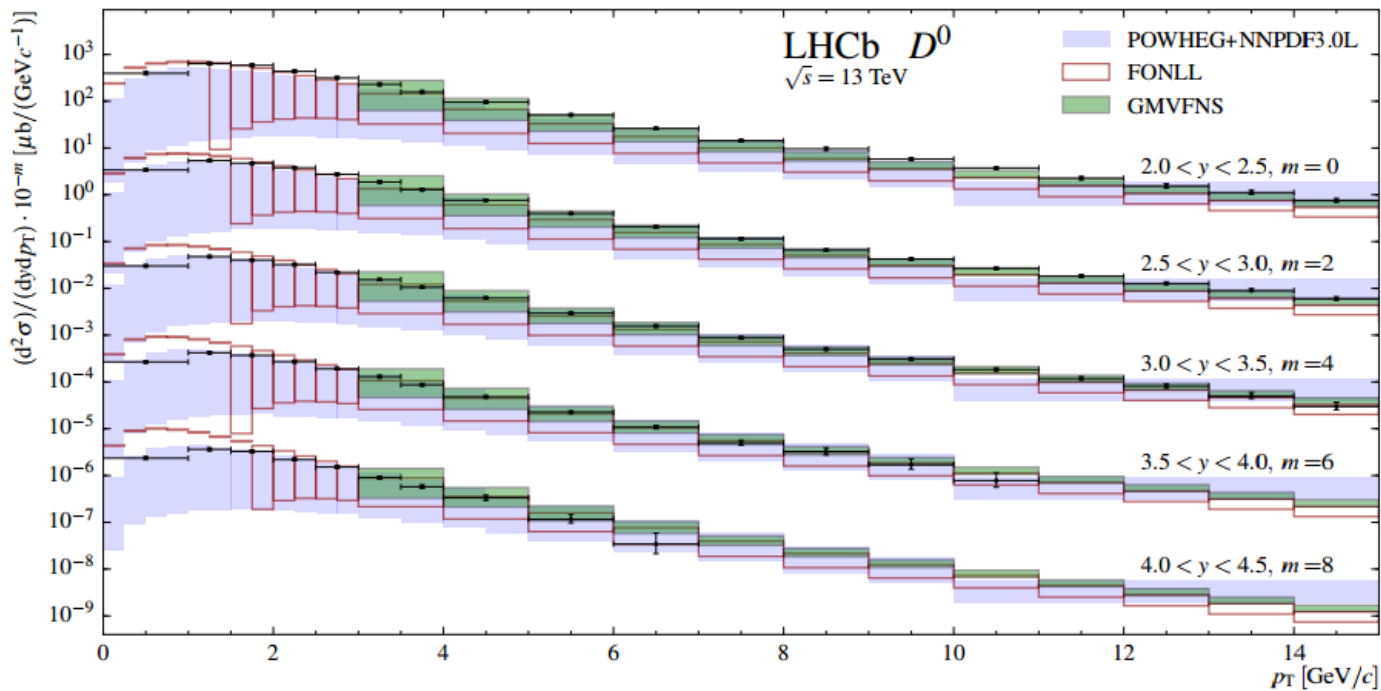


Sig.: Crystal Ball + Gaussian
Bgd.: first order polynomial



Sig.: bifurcated Gaussian + exp tail
Secodaries.: Gaussian

- Double differential cross-sections are measured in the accessible phase-space: $2.0 < y < 4.5$ and $0 < p_T < 15$ GeV/c
- Predictions show large uncertainties at low p_T , data tends to lie at upper end



Predictions:

- fixed order next-to-leading logarithms (**FONLL**) Eur. Phys. J. C75 (2015) 610
- general mass variable flavor number scheme (**GMVFNs**) Eur. Phys. J. C72 (2012) 2082
- modified NNPDF3.0 using 7 TeV LHCb results (**POWHEG+NNPDF3.0L**) JHEP11 (2015)

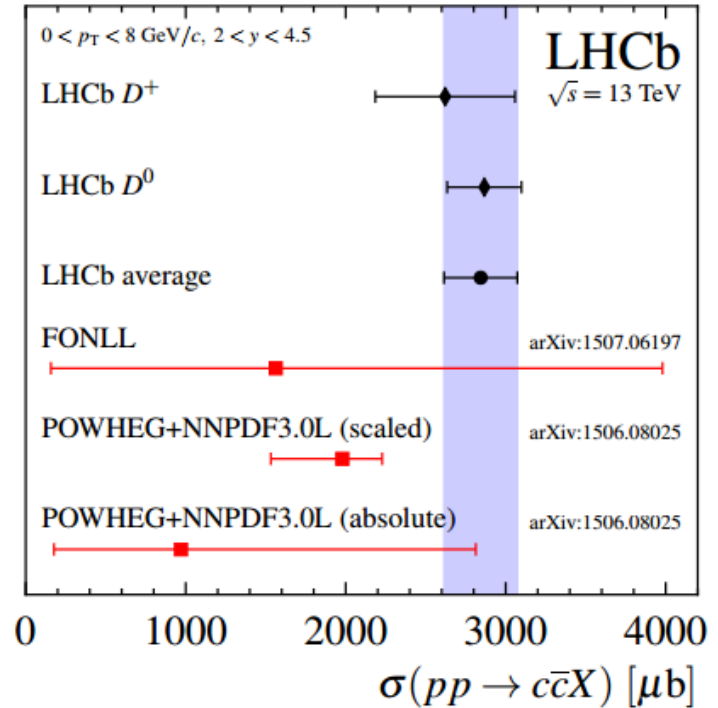
Previous LHCb measurement: $2.0 < y < 4.5$ for $0 < p_T < 8$ GeV/c, Nucl. Phys. B871 (2013)

- The total cc -bar production cross-section, $\sigma(pp \rightarrow c\bar{c}X)$, is calculated using the fragmentation fractions from e^+e^- colliders.

- The combination of the D^0 and D^+ measurements gives:

$$\sigma(pp \rightarrow c\bar{c}X) = 2840 \pm 3 \pm 170 \pm 150 \mu\text{b}$$

\swarrow statistical \swarrow fragmentation fraction
 \swarrow systematic



Predictions:

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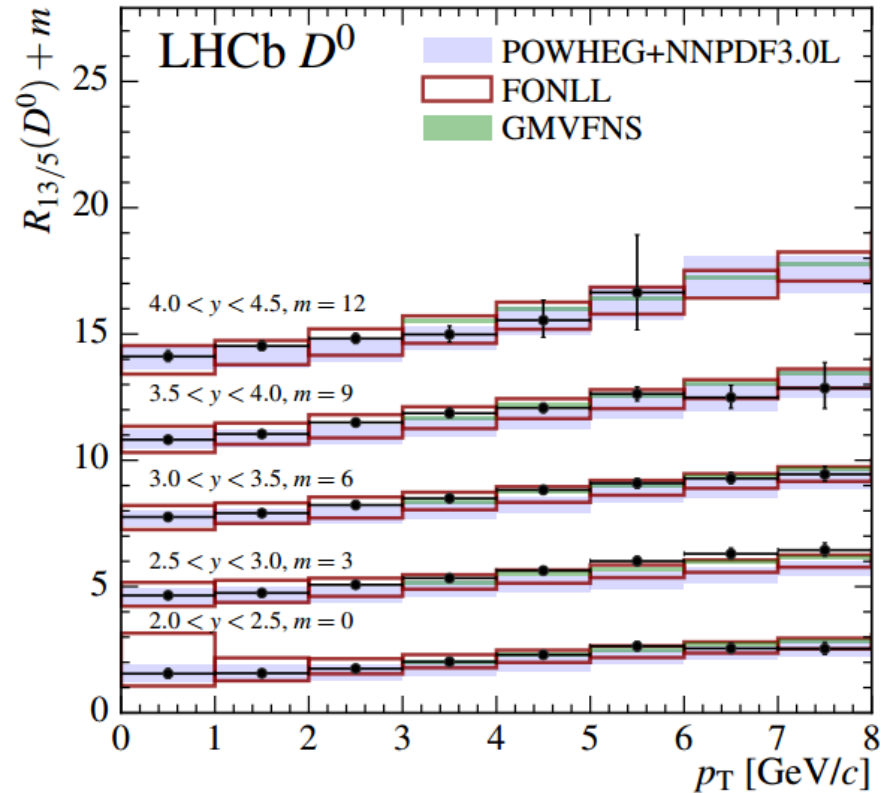
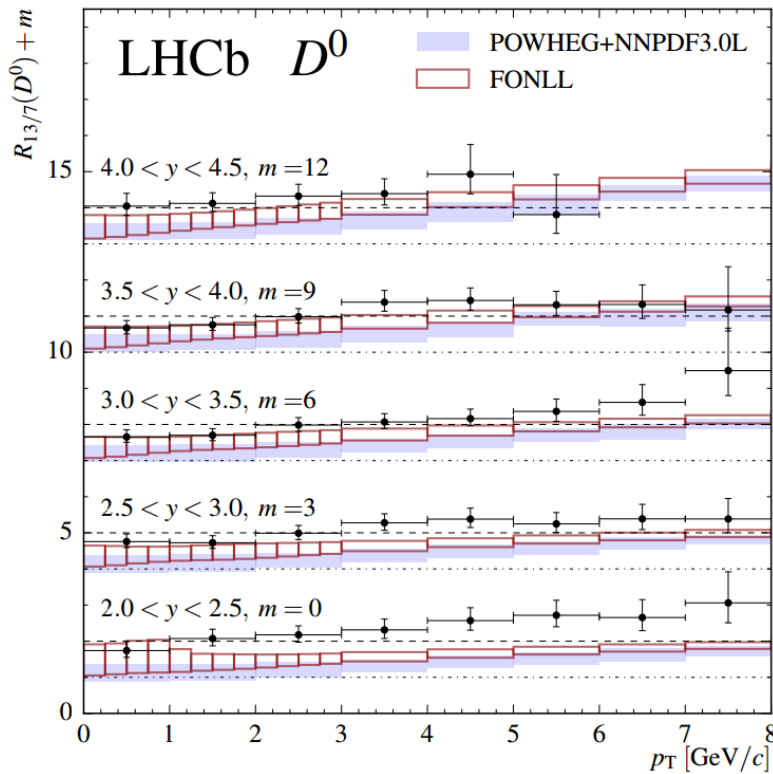
The “absolute” predictions - based on calculations of the 13 TeV cross-section

The “scaled” predictions - based on calculations of the 13 to 7 TeV ratio multiplied with the LHCb results at 7 TeV

Previous LHCb measurement: $2.0 < y < 4.5$ for $0 < p_T < 8 \text{ GeV}/c$, Nucl. Phys. B871 (2013)

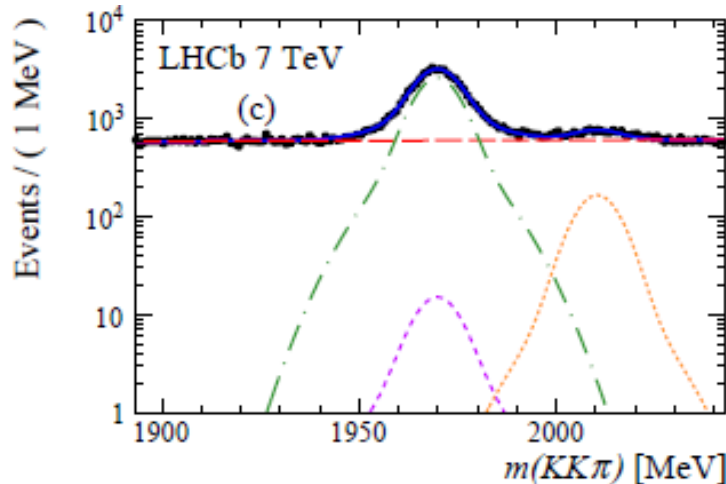
- Experimental and theory uncertainties partially cancel;
- 13/7 TeV: predictions show tendency to lie below the data, most prominent at low rapidity;
- 13/5 TeV: data well described;

arXiv: 610.02230

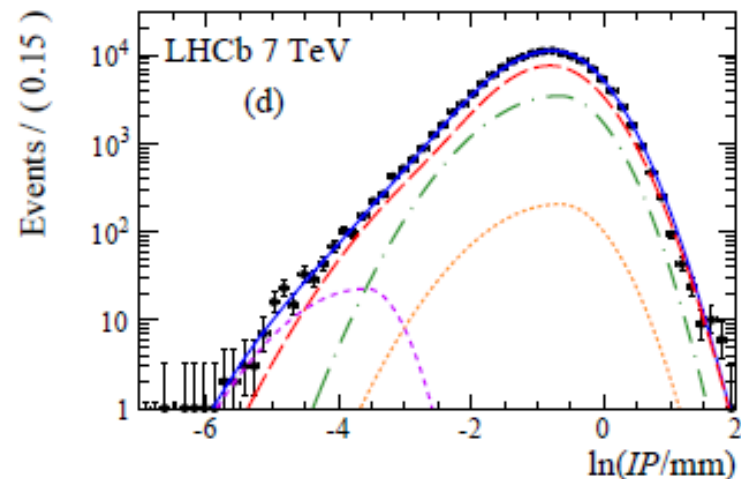


- Production cross-sections for the average of b -flavored and \bar{b} -flavored based on $284.104 \pm 86 \text{ pb}^{-1}$ @ 7 TeV and $4.60 \pm 18 \text{ pb}^{-1}$ @ 13 TeV data samples
- Performed by determined the signal yields of b decays into a charm hadron plus a muon that is detached from the PV;
- Handled decay modes:
 $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow K^+ K^- \pi^+$ and $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\ln(\text{IP})$ distribution of the charm-hadron to separate prompt charm from D -from b -hadron; signal extraction: simultaneous fit to invariant mass and $\ln(\text{IP})$

D_s^+ from b , prompt D_s^+ , D^{*+}



Sig.: double-Gaussian
 Bgd.: first order polynomial



Sig.: bifurcated Gaussian

Total cross-section

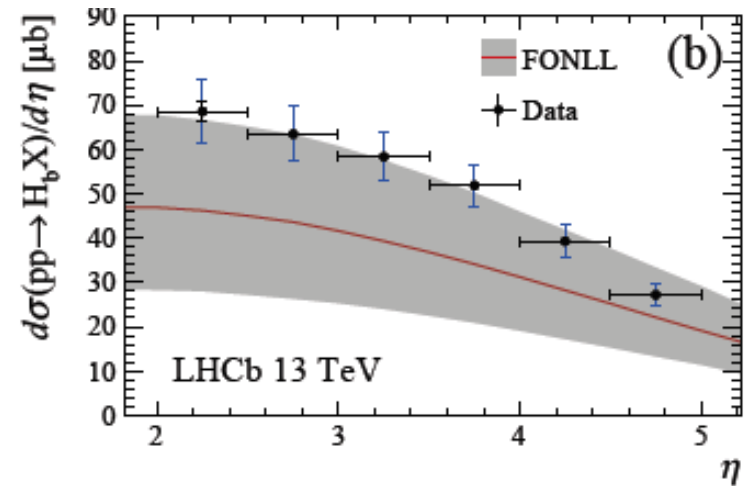
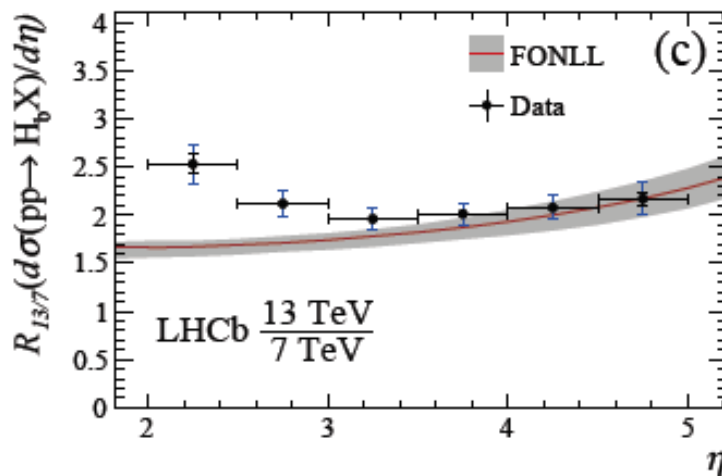
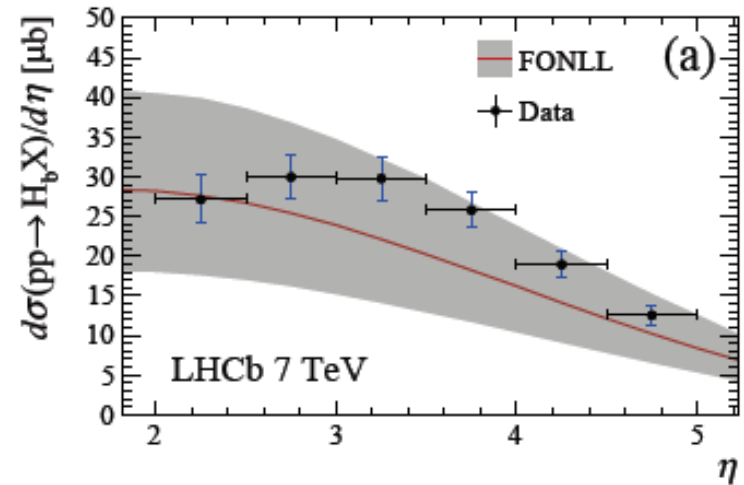
$$\sigma(pp \rightarrow H_b X) \text{ in } 2 < \eta(H_b) < 5$$

$$\sigma(7 \text{ TeV}) = 72.0 \pm 0.3 \pm 6.8 \mu\text{b}$$

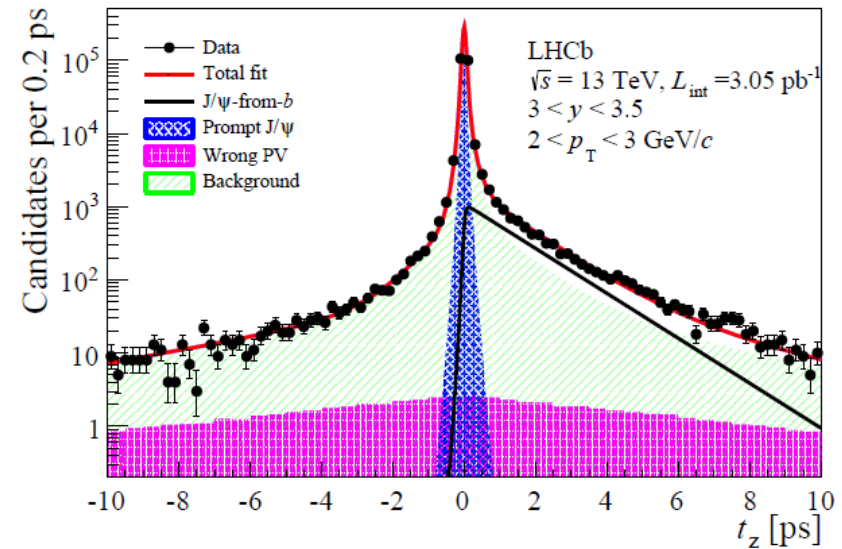
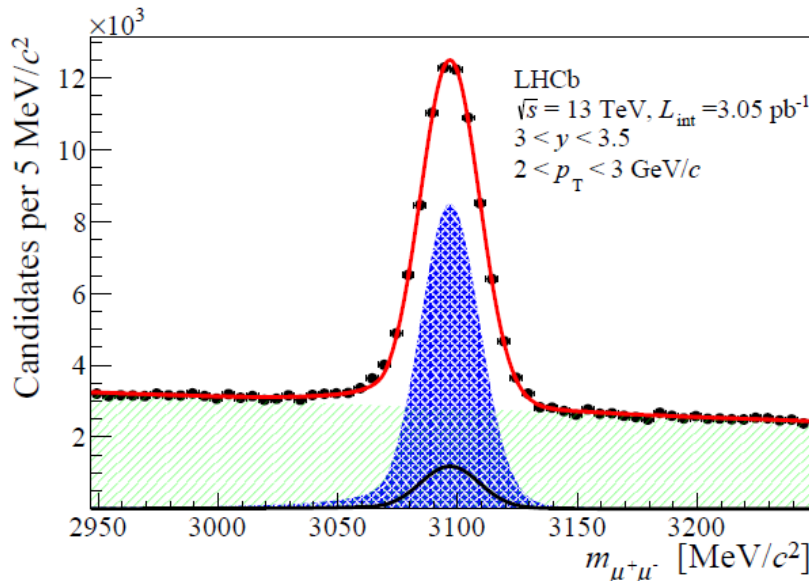
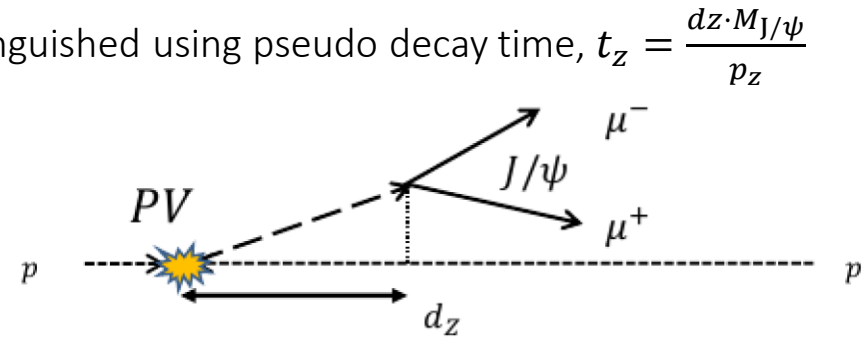
$$\sigma(13 \text{ TeV}) = 154.3 \pm 1.5 \pm 14.3 \mu\text{b}$$

$$\sigma_{13/7} = 2.14 \pm 0.02 \pm 0.13$$

- uncertainty largely reduced in ratios between different energies
- ratio: tension with theoretical predictions, especially at low η



- Based on triggered candidates, w/o offline processing
- Fiducial region:
 $p_T < 14 \text{ GeV}$ and $2 < y < 4.5$
- Data sample: $3.05 \pm 0.12 \text{ pb}^{-1}$
- Prompt J/ψ and J/ψ -from b decays are distinguished using pseudo decay time, $t_z = \frac{dz \cdot M_{J/\psi}}{p_z}$
- Handling J/ψ decaying to $\mu^+ \mu^-$ final states
- Signal yield determination:
 simultaneous fit to invariant mass and t_z

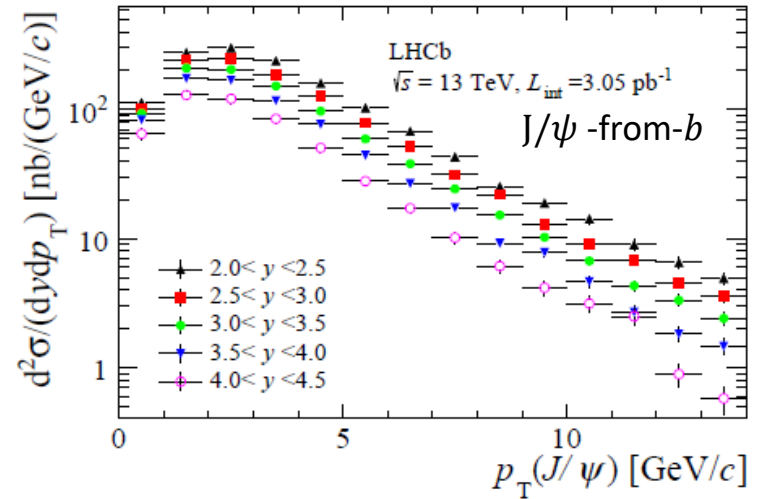
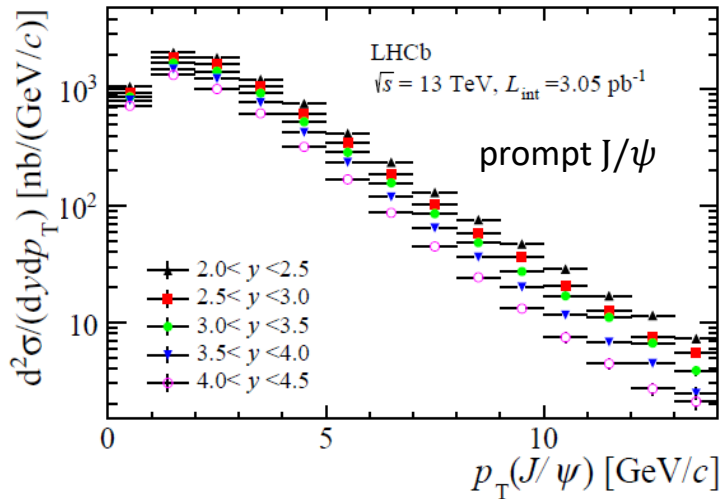


$$\sigma_{\text{prompt}} = 15.30 \pm 0.03 \pm 0.86 \mu\text{b}$$

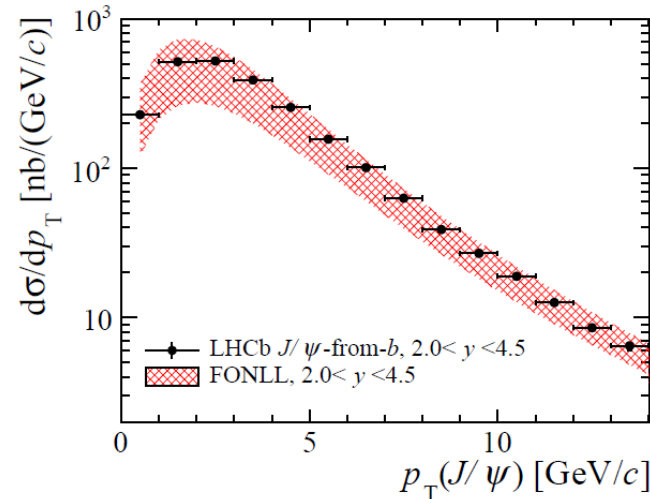
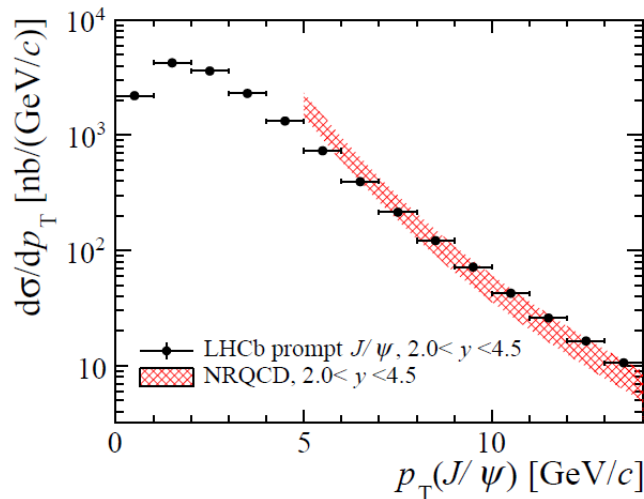
$$\sigma_{\text{from } b} = 2.34 \pm 0.01 \pm 0.13 \mu\text{b}$$

Extrapolation to the full kinematic region

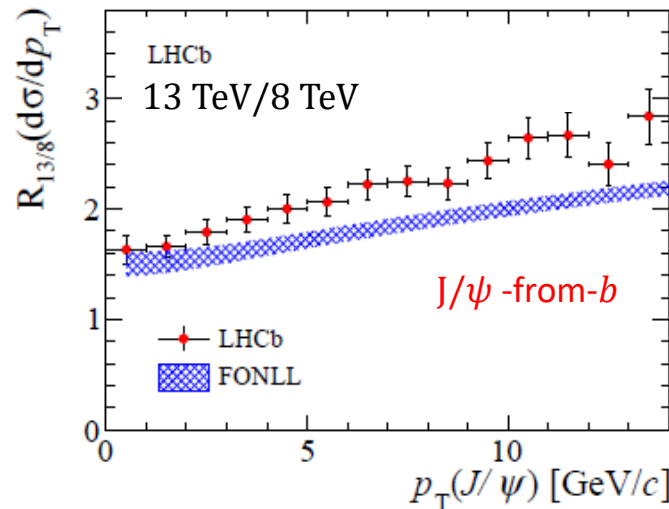
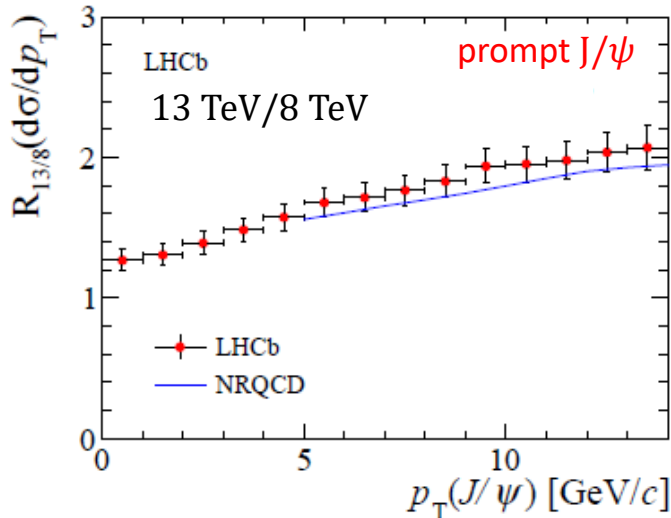
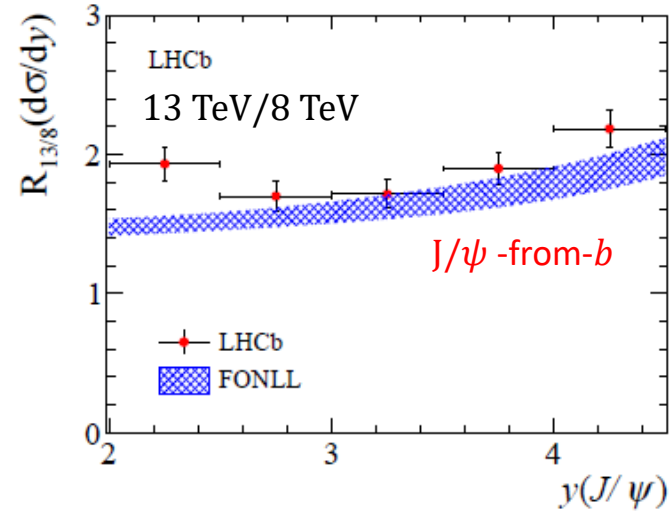
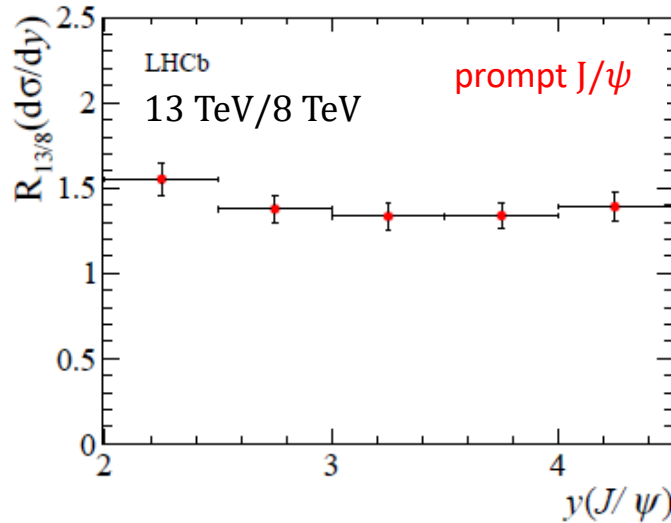
$$\sigma(pp \rightarrow b\bar{b}X) = 515 \pm 2 \pm 53 \mu\text{b}$$



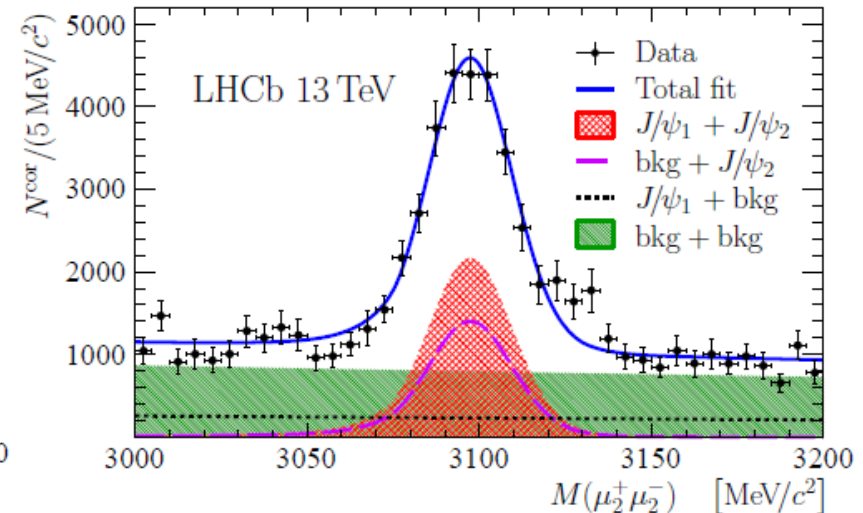
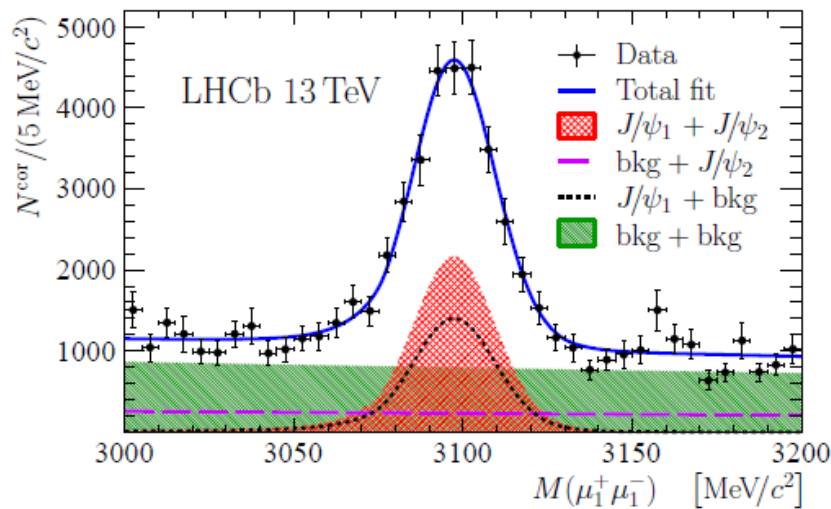
- Good agreement is found between the measurements and the theoretical calculations:



- In the cross-section ratios, many of the systematic uncertainties cancel because of correlations between the two measurements
- predictions below the data, most pronounced at low y for J/ψ from b

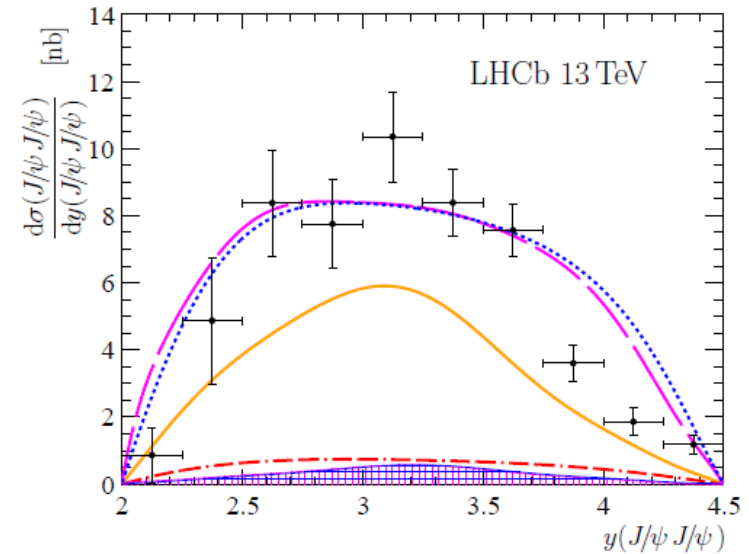
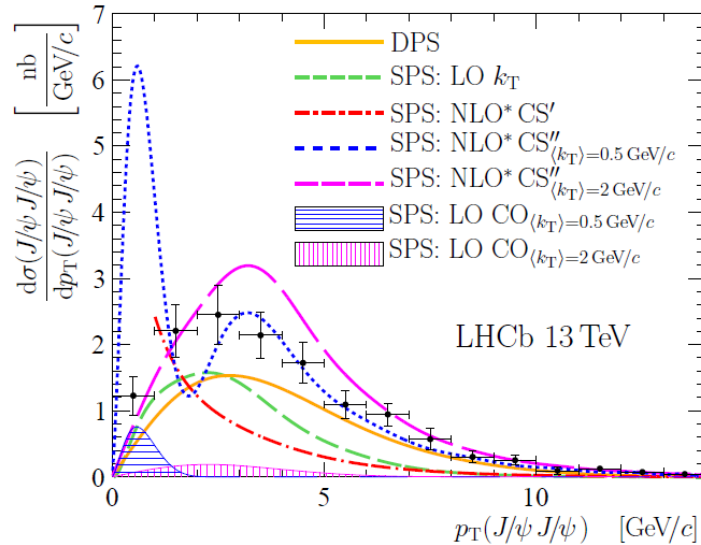


- Fiducial region: $p_T < 10 \text{ GeV}/c$ and $2.0 < y < 4.5$
- Based on $279 \pm 11 \text{ pb}^{-1}$ data sample
- Signal yield determination:
fit to the two-dimensional $(M(\mu_1^+ \mu_1^-), M(\mu_2^+ \mu_2^-))$ mass distribution
- The fraction of candidates with J/ψ mesons from b -hadron decays is determined* to be 5.8%
* with the help of simulation validated with data



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

- Comparisons with theoretical predictions for the differential cross-sections
- Neither the DPS nor any of the SPS models can describe the differential shapes.



In addition series of comparisons computed (see in the backup):

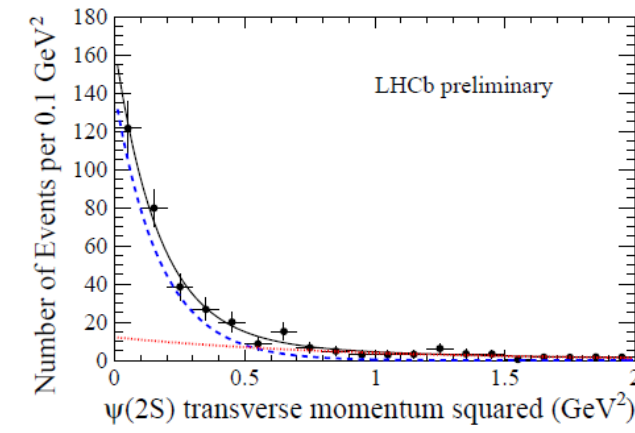
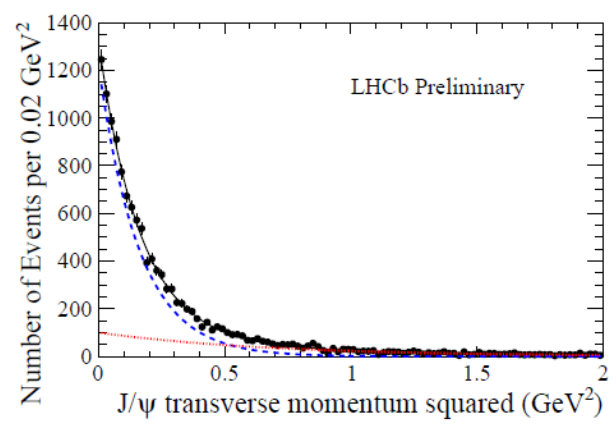
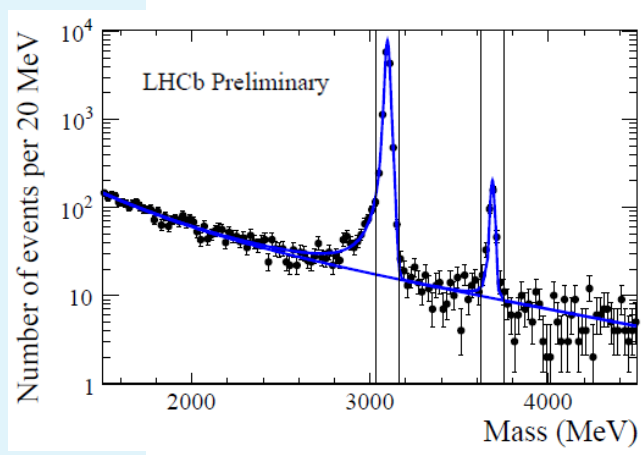
- ✓ $d\sigma(J/\psi J/\psi)/d|\Delta y|$
- ✓ $d\sigma(J/\psi J/\psi)/d|\Delta\phi|$
- ✓ $d\sigma(J/\psi J/\psi)/dA_T, A_T - p_T$ asymmetry
- ✓ $d\sigma(J/\psi J/\psi)/dm(J/\psi J/\psi)$
- ✓ $d\sigma(J/\psi J/\psi)/dy(J/\psi J/\psi)$
- ✓ $d\sigma(J/\psi J/\psi)/2 dy(J/\psi J/\psi)$
- ✓ ... and more with requirement on $p_T(J/\psi J/\psi)$

DPS - double parton scattering
 SPS - single parton scattering

 LO CS - leading-order colour-singlet
 LO CO - leading-order colour-octet
 NLO*CS - next-to-leading-order colour-singlet

- A fit to the differential cross-sections using simple DPS plus SPS models indicates a significant DPS contribution.

- HERSCHEL veto used \rightarrow backgrounds are significantly reduced compared to previous LHCb measurements ($\sim 50\%$)
- Both muons within pseudorapidity region $2 < \eta < 4.5$
- Background sources
 - \rightarrow non-resonant dimuon (continuum) $\rightarrow J/\psi \quad 0.009 \pm 0.001$
 - $\rightarrow \psi(2S) \quad 0.175 \pm 0.018$
 - \rightarrow feed-down of CEP χ_c or $\psi(2S)$ to $J/\psi \quad \rightarrow \quad 0.059 \pm 0.003$
 - \rightarrow non-exclusive (remnants of p dissociation) \rightarrow estimated from the fit to the p_T^2 after continuum and feed-down bgd subtraction:

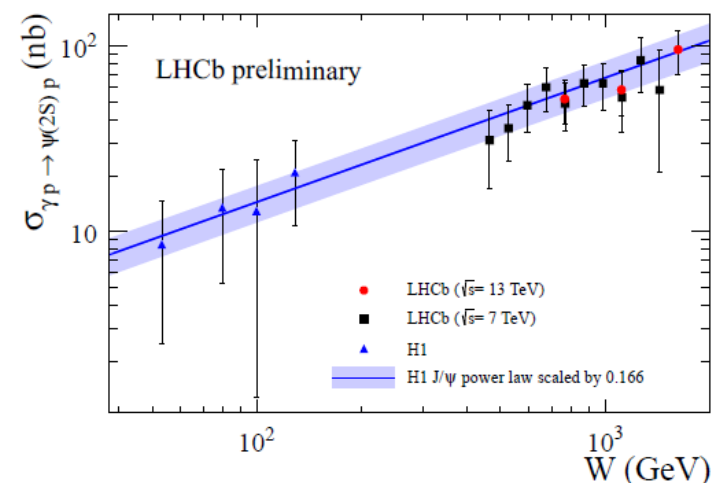
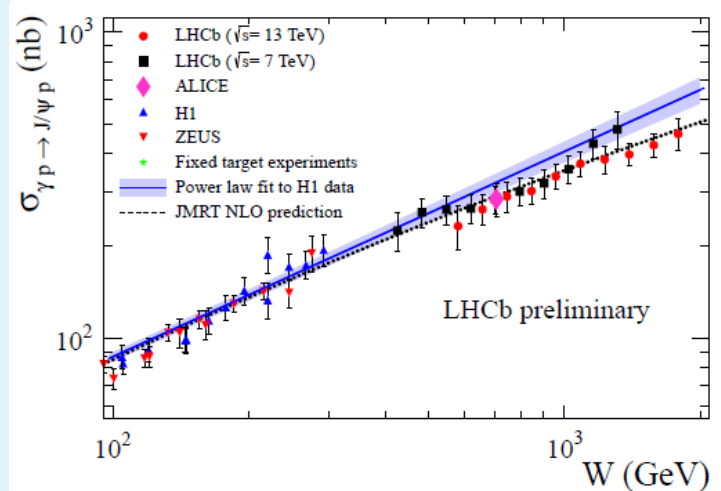
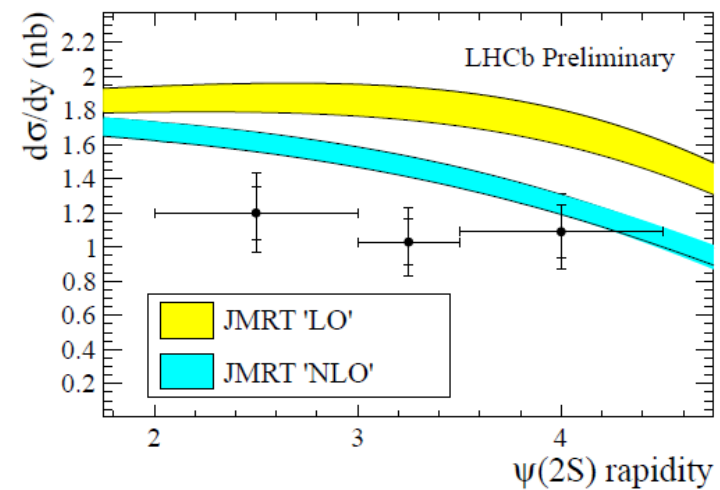
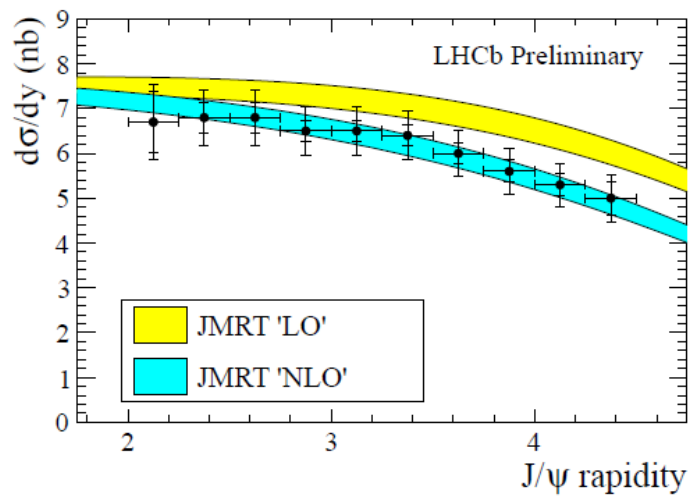


Two exponential functions, one to describe signal and one for the proton dissociation component.

$$\sigma_{J/\psi \rightarrow \mu^+ \mu^-} (2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$

$$\sigma_{\psi(2S) \rightarrow \mu^+ \mu^-} (2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \pm 0.6 \pm 0.4 \text{ pb}$$

the third uncertainty is due to the accuracy of the luminosity determination.



W - the centre-of-mass energy of the photon-proton system

- The inclusive Z boson cross-section for decays to a **dimuon and dielectron** final states
 → statistically independent samples with largely independent systematic uncertainties

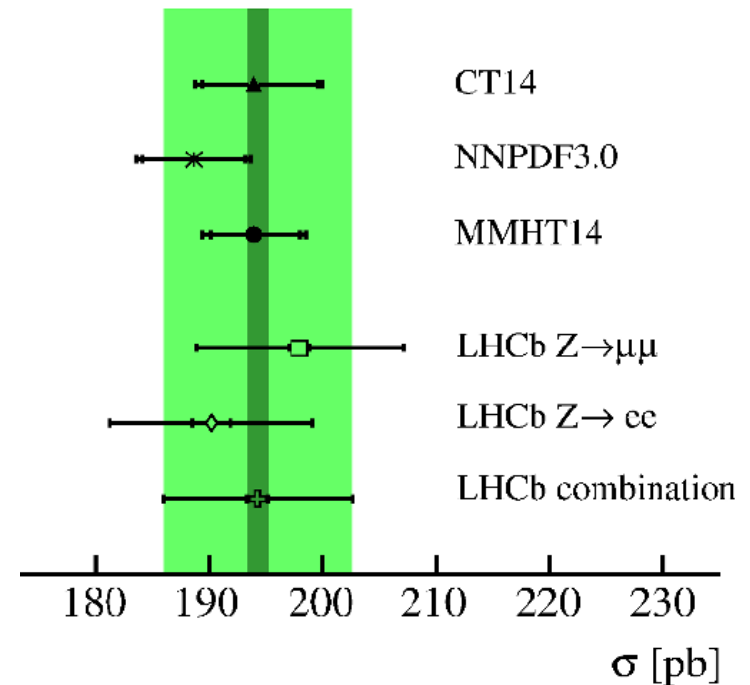
- Fiducial region
 $60 < m(l\bar{l}) < 120 \text{ GeV}$
 $p_T(l) > 20 \text{ GeV}/c$
 $2.0 < \eta < 4.5$

- $\sigma_Z^{\mu\mu} = 198.0 \pm 0.9 \pm 4.7 \pm 7.7 \text{ pb}$
- $\sigma_Z^{ee} = 190.2 \pm 1.7 \pm 4.7 \pm 7.4 \text{ pb}$
- $\sigma_Z^{ll} = 194.3 \pm 0.9 \pm 3.3 \pm 7.6 \text{ pb}$

the third uncertainty is due to the accuracy of the luminosity determination.

- Fixed-order predictions with PDF sets:
 CT14, Phys. Rev. D 93 (2016) 033006
 NNPDF3.0, JHEP 04 (2015) 040
 MMHT14, Eur. Phys. J. C 75 (2015) 204

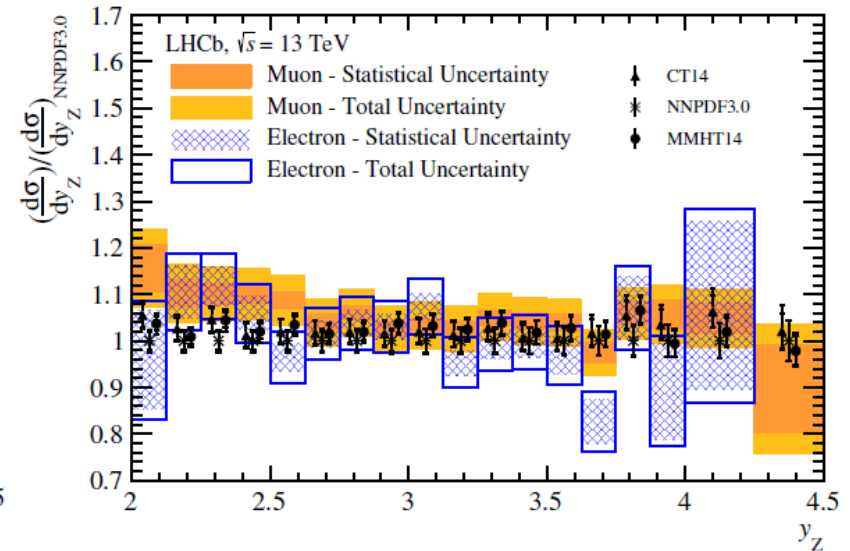
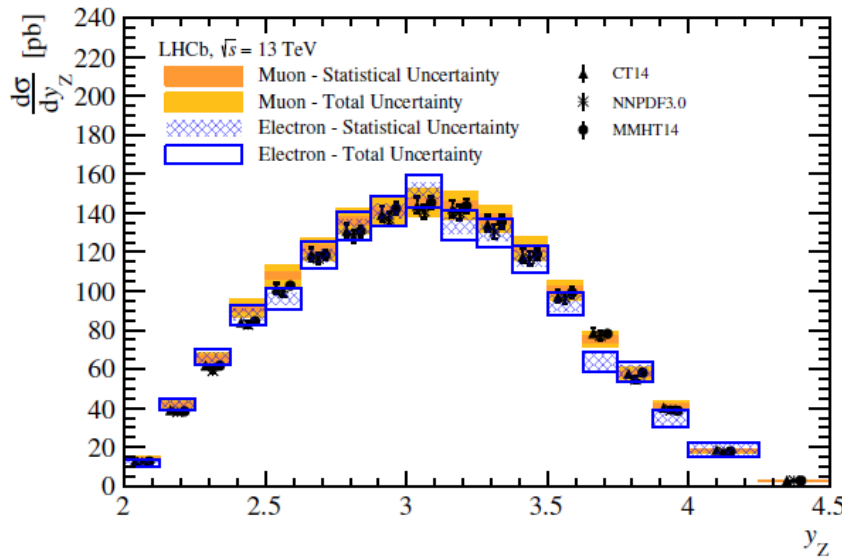
- Fixed-order predictions describe the LHCb data well for a range of PDF sets.



Measured as functions of the Z boson

- rapidity,
- transverse momentum (see backup)
- the angular variable ϕ_η^* (see backup)

$$\phi_\eta^* \equiv \tan(\phi_{\text{acop}}/2)/\cosh(\Delta\eta/2)$$
 acoplanarity angle $\phi_{\text{acop}} \equiv \pi - \Delta\phi$
 $\Delta\phi$ the difference in azimuthal angle of the two leptons
 $\Delta\eta$ the difference in pseudorapidity of the two leptons



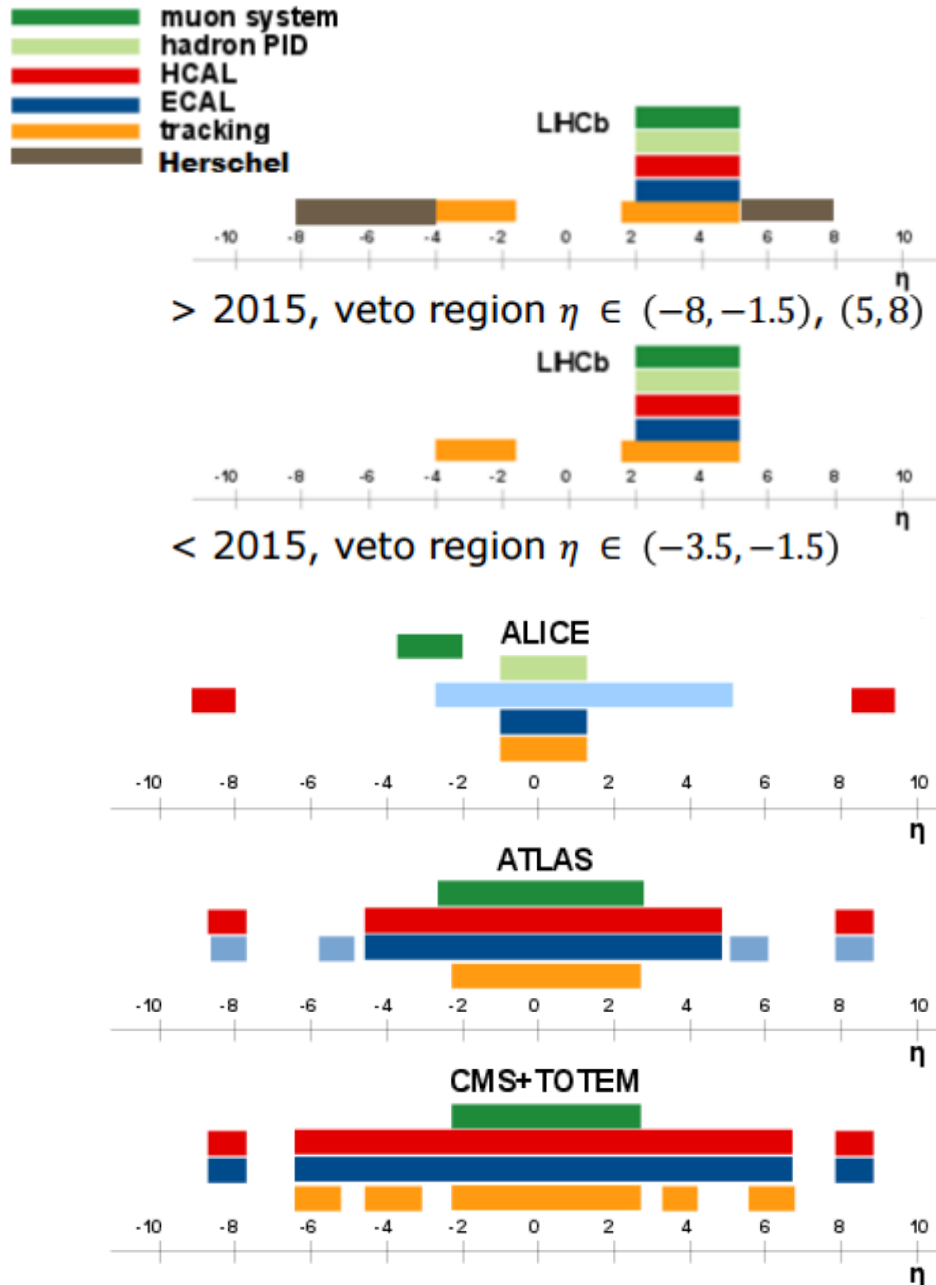
- Plot on the right shows the same information to the one on the left, divided by the NNPDF3.0 predictions
- The measured differential cross-section is slightly larger than the NLO pQCD predictions at lower rapidities

Run 2 results on production of

- heavy flavour: charm and beauty
- quarkonia: J/ψ , J/ψ pairs, exclusive J/ψ , $\psi(2S)$
- Z boson

- Exclusive production
new detectors → better control of inelastic backgrounds

Backup



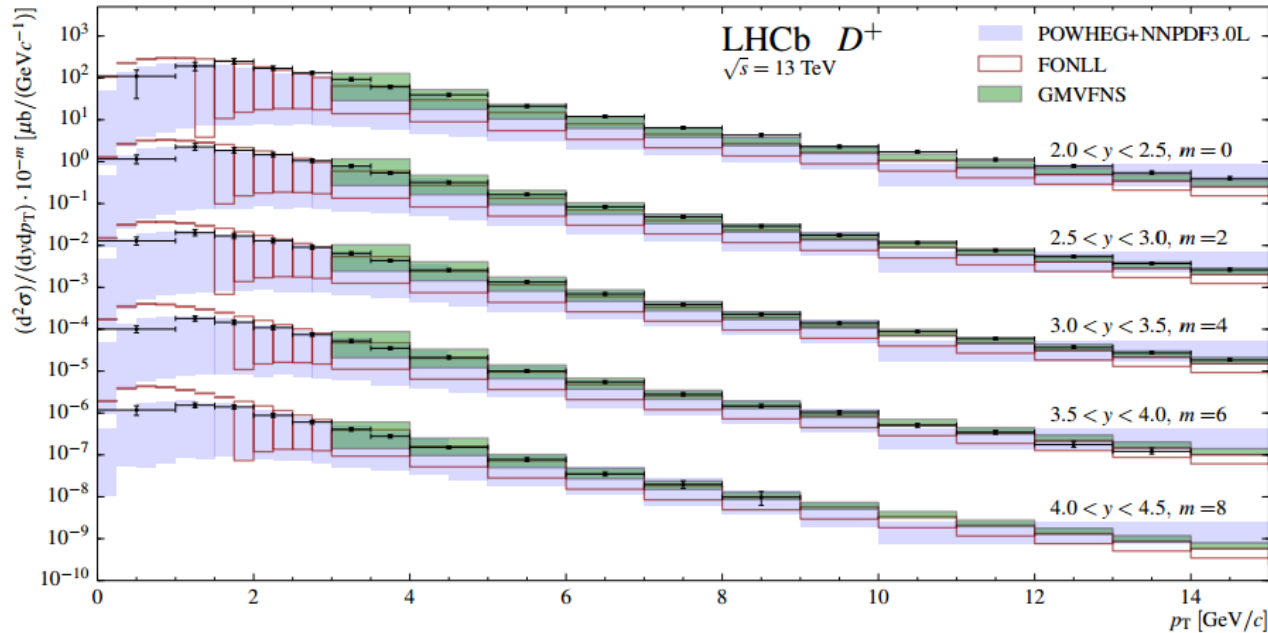
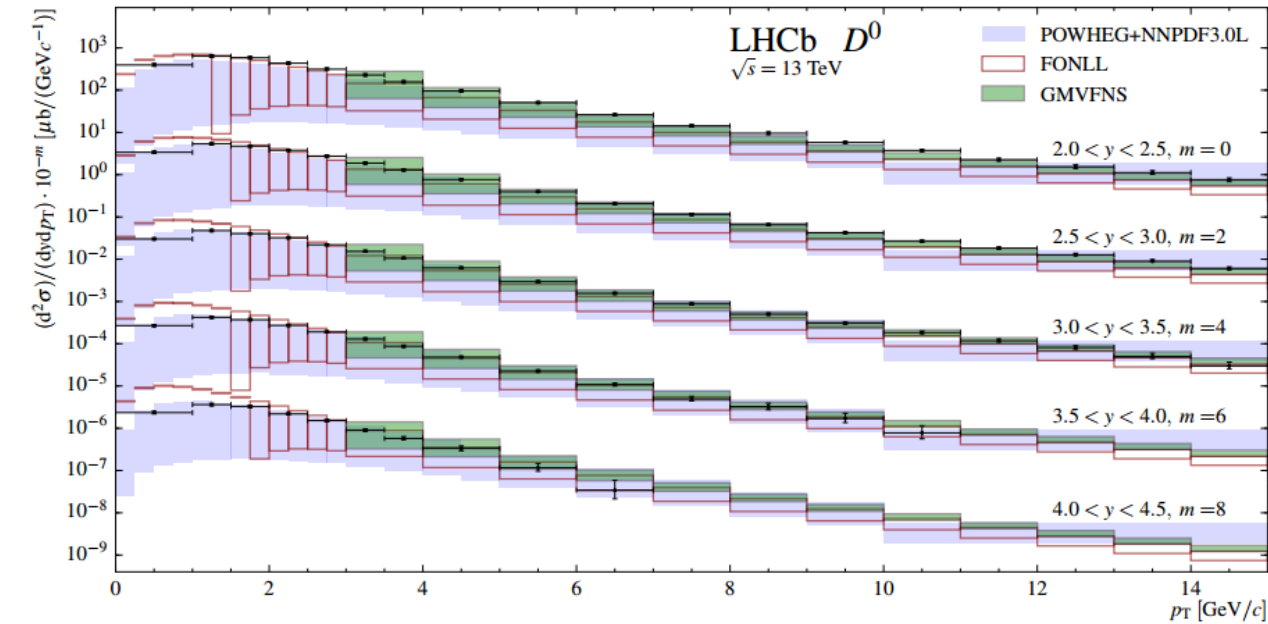
ATLAS and CMS

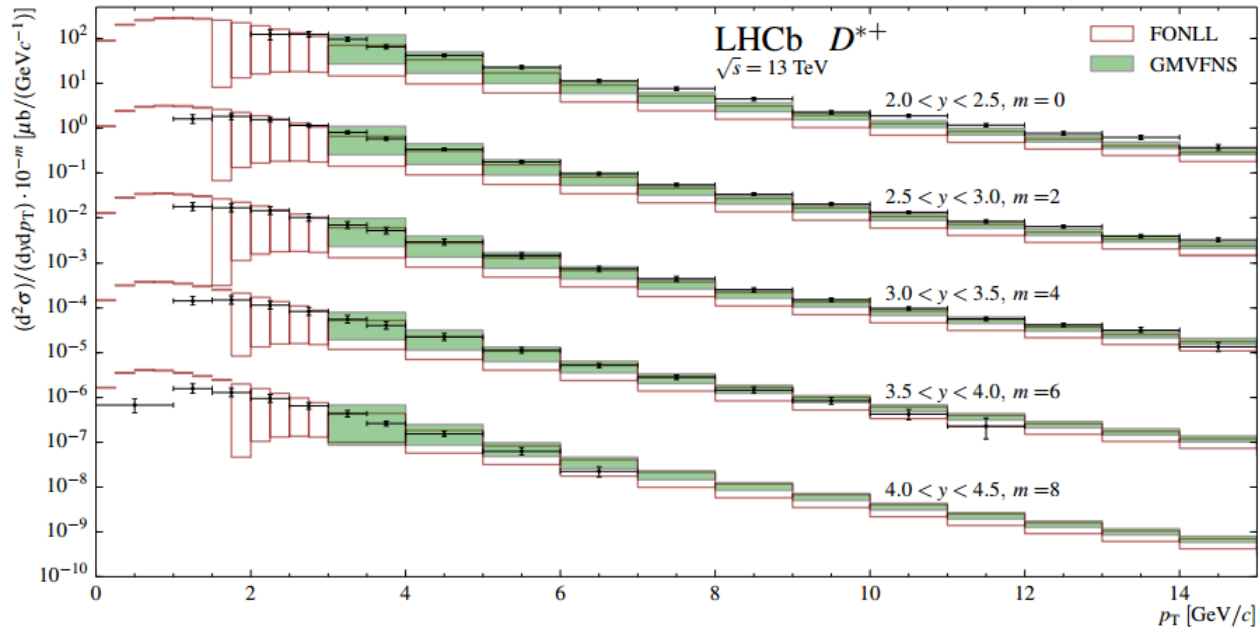
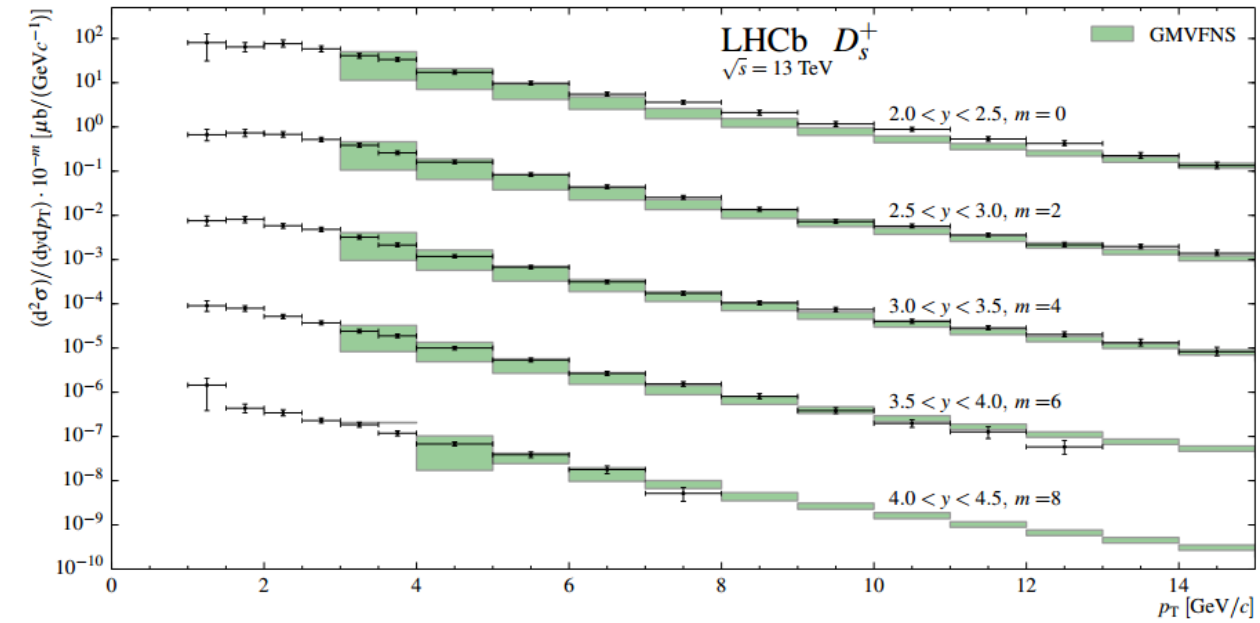
- precision tracking and muon identification in central region
- forward calorimetry - measurements of electrons and jets for $|\eta| < 5$

LHCb

- coverage for $2 < \eta < 5$ – excellent tracking and particle identification low p_T , low mass triggers
- Expanded veto region using HeRSChEL up to $|\eta| < 8$

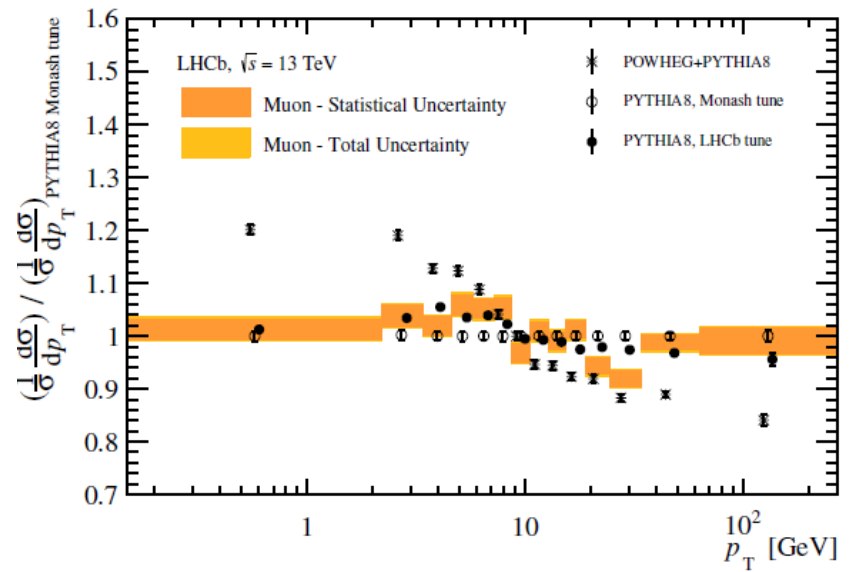
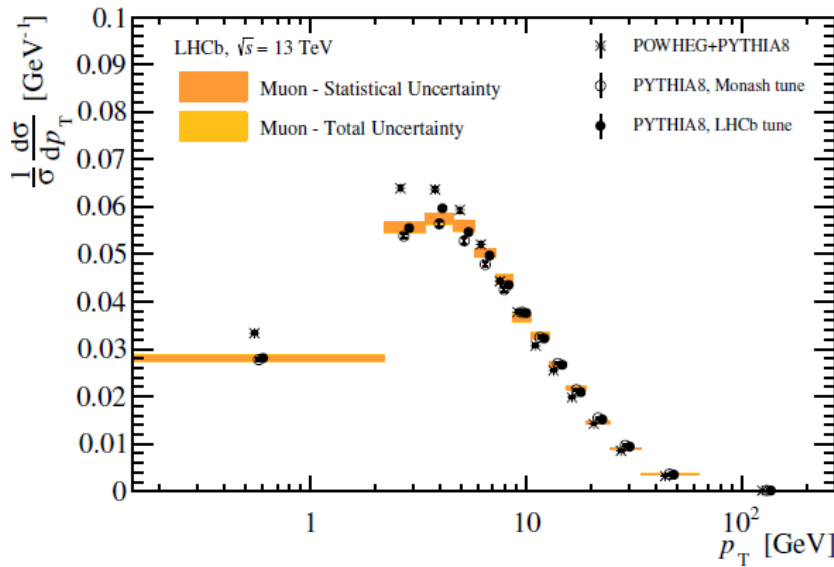
→ complementary measurements





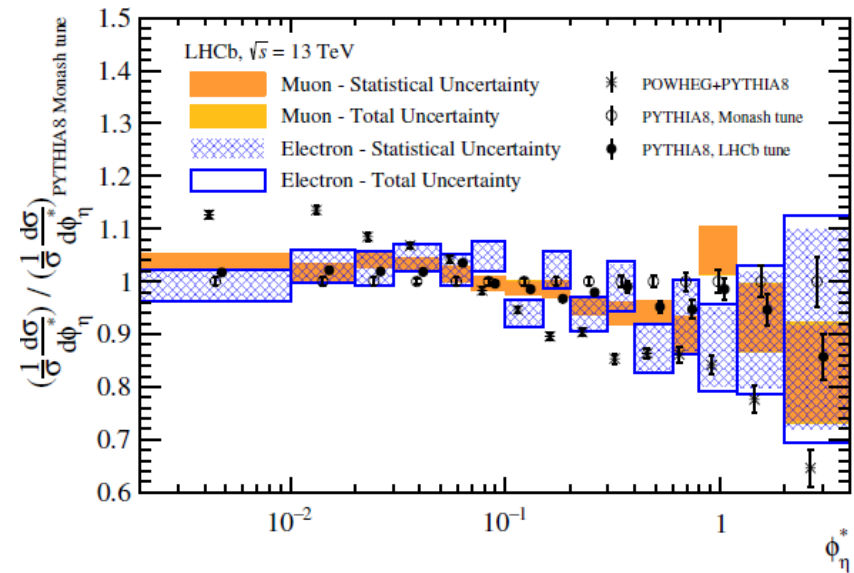
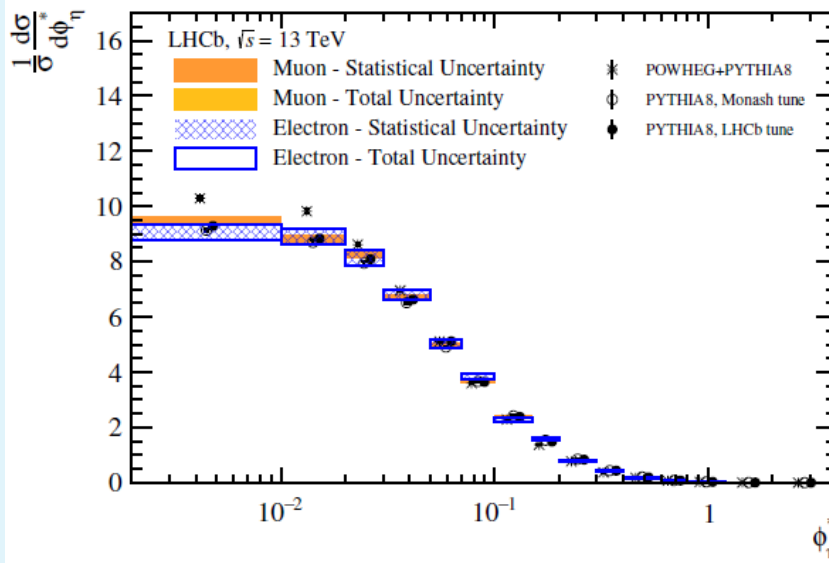
Measured as functions of the Z boson

- rapidity,
- **transverse momentum**
- the angular variable ϕ_η^*



Measured as functions of the Z boson

- rapidity,
- transverse momentum
- the angular variable ϕ_η^*



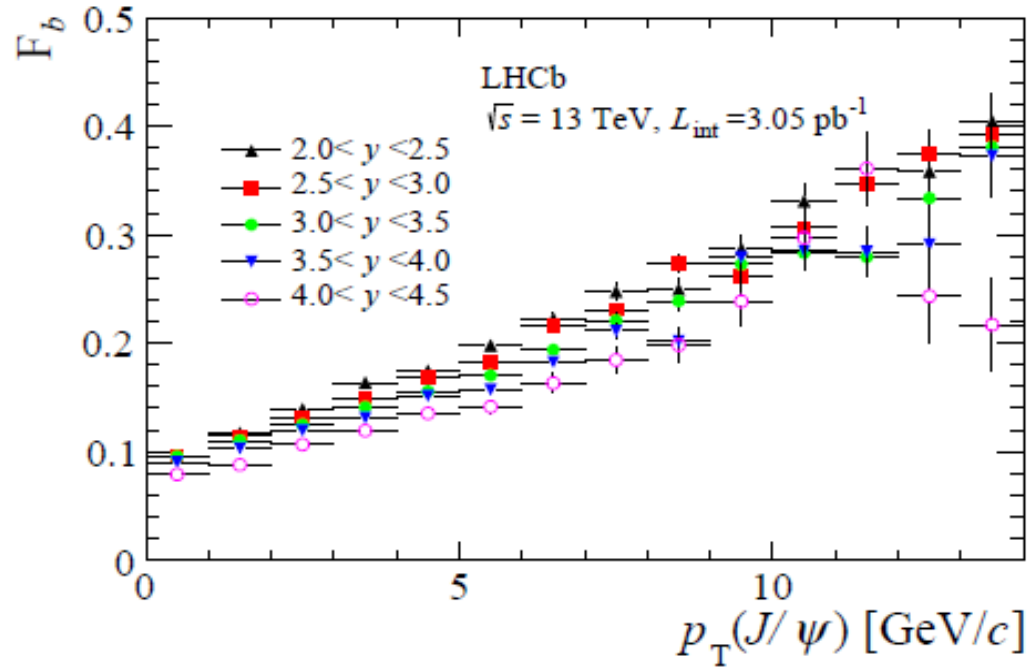
$$\phi_\eta^* \equiv \tan(\phi_{\text{acop}}/2)/\cosh(\Delta\eta/2)$$

$$\text{acoplanarity angle } \phi_{\text{acop}} \equiv \pi - \Delta\phi$$

$\Delta\phi$ the difference in azimuthal angle of the two leptons

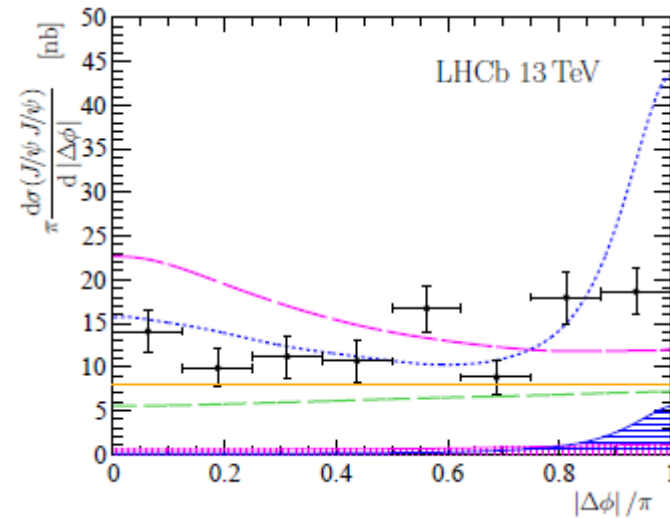
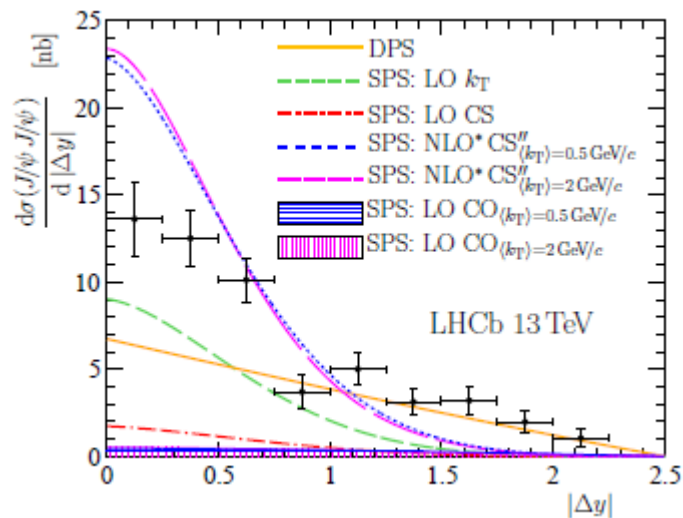
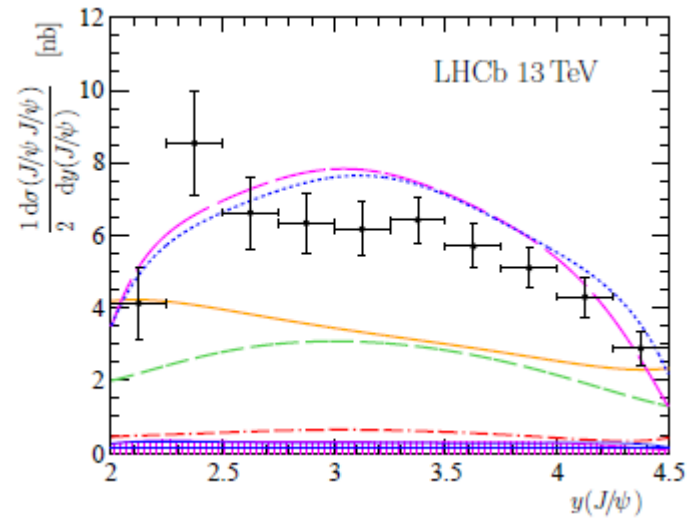
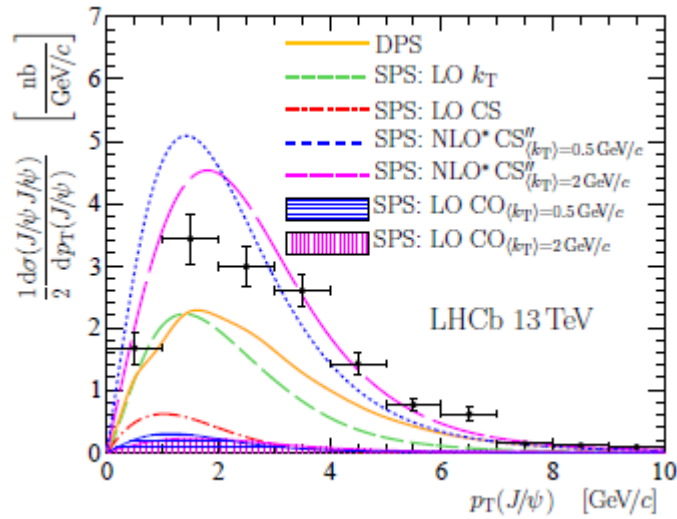
$\Delta\eta$ the difference in pseudorapidity of the two leptons

Fraction of J/ψ -from- b



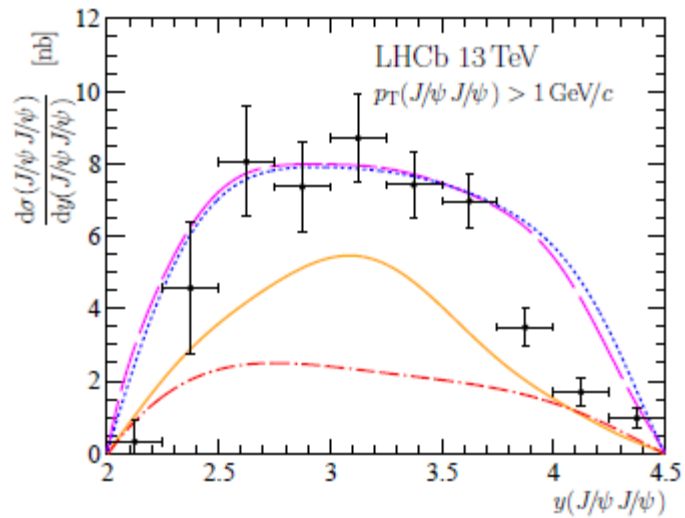
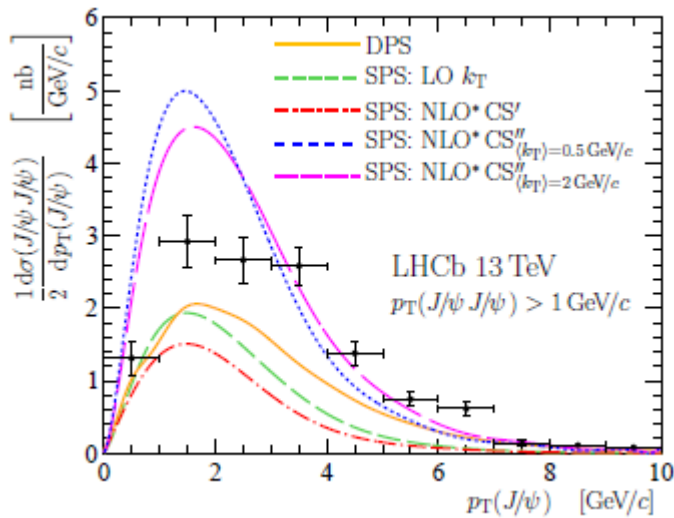
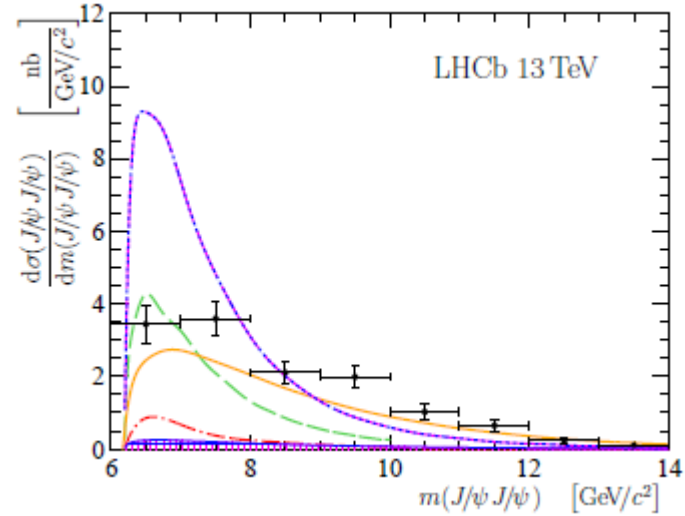
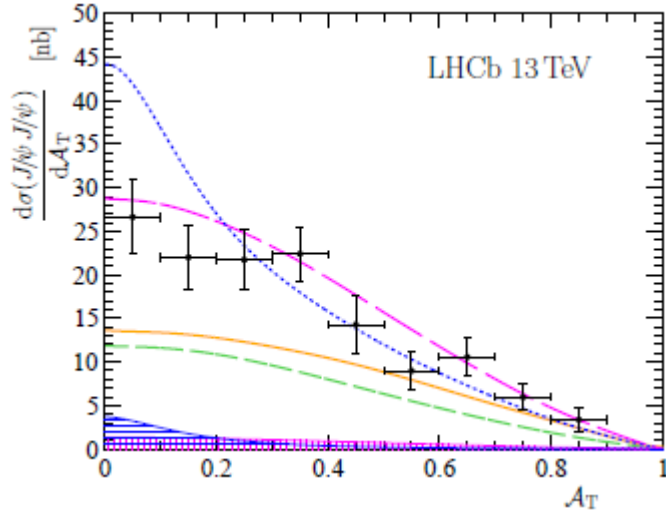
Comparisons between measurements and theoretical predictions for the differential cross-sections

arXiv:1612.07451v1



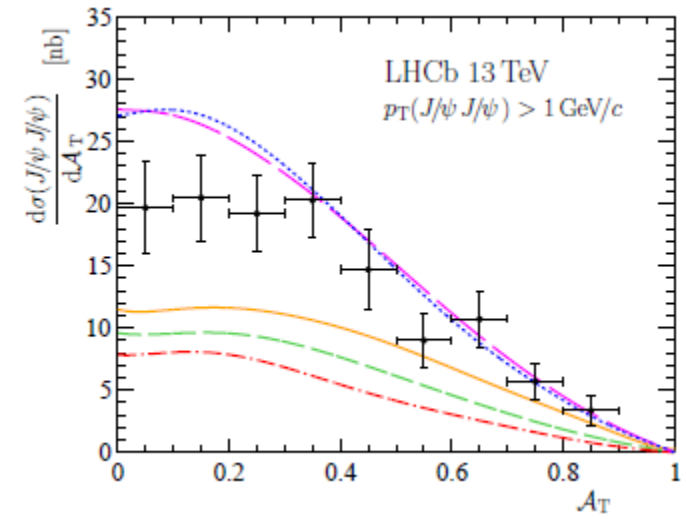
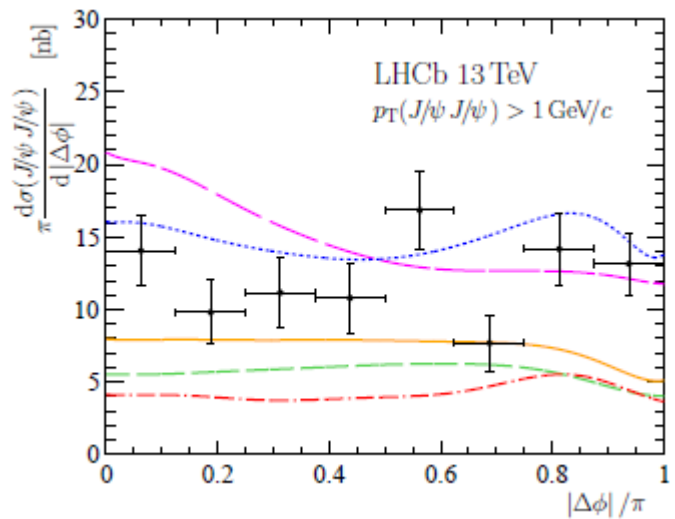
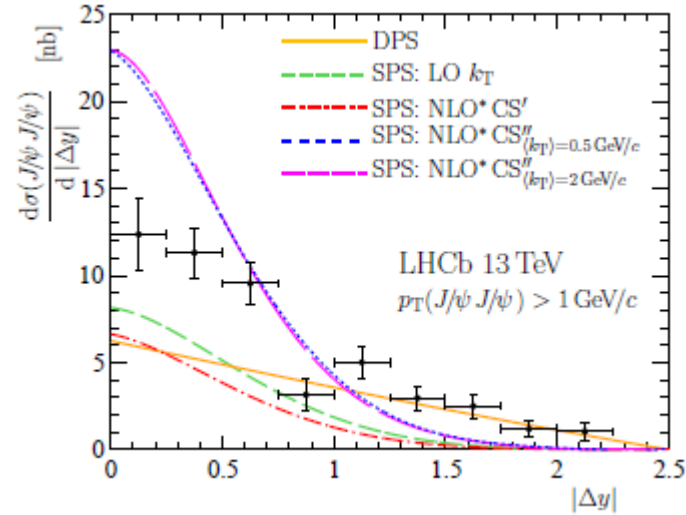
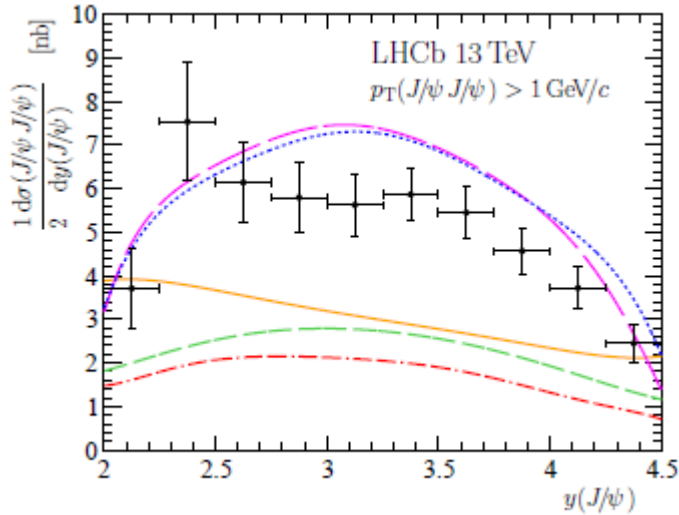
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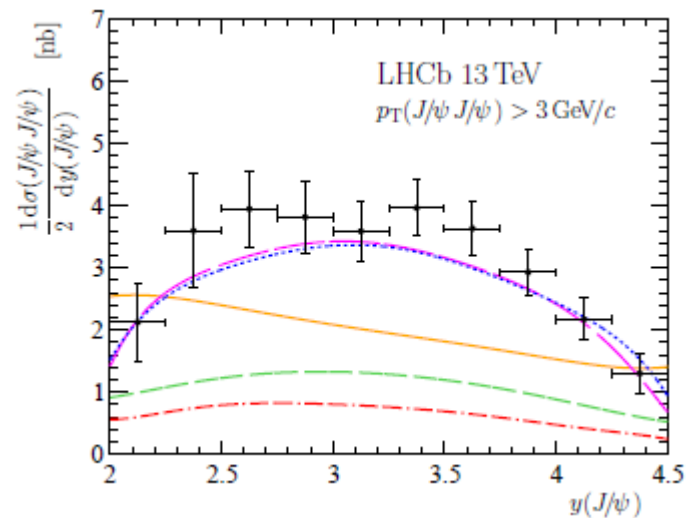
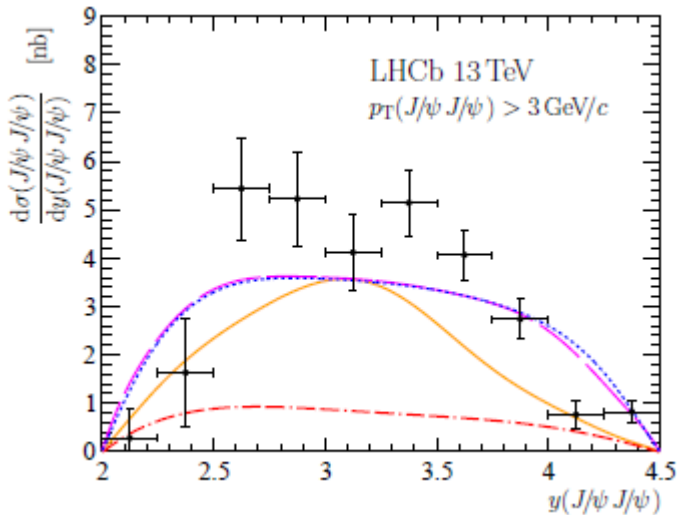
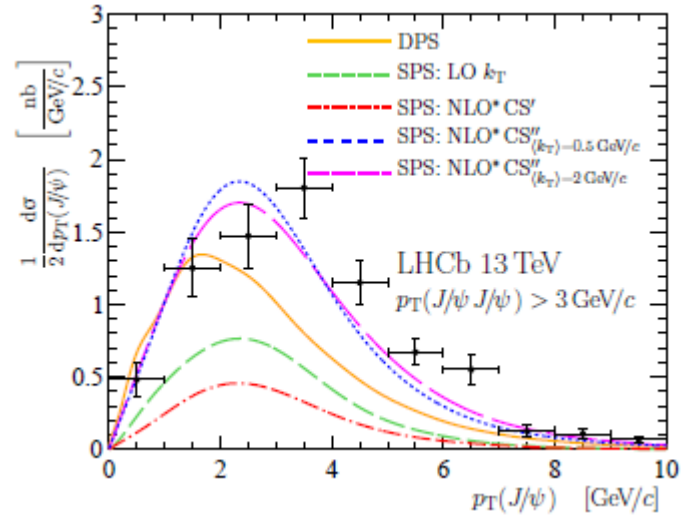
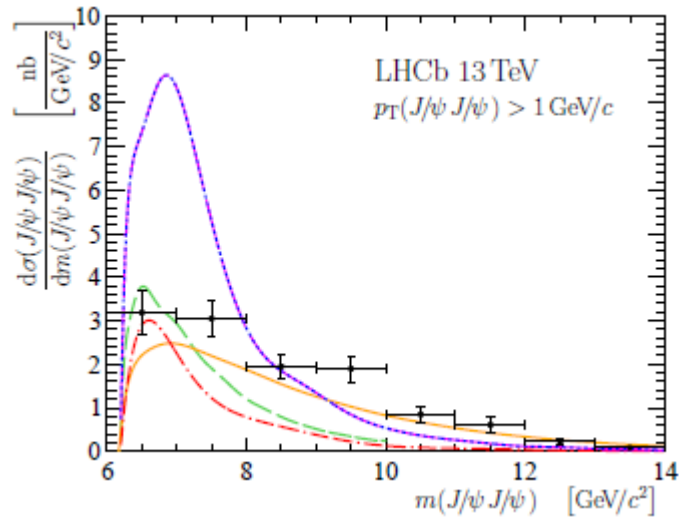
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