Quarkonium and Heavy Flavour Meson Production at 13 TeV at ATLAS

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on behalf of the ATLAS Collaboration

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Outline : Introduction

Charmonium — ATLAS-CONF-2015-030, ATLAS-CONF-2016-0XX (X(3872)), EPJ C76 (2016) 283, JHEP 09 (2014) 079, JHEP 07 (2014) 154

Beauty mesons — ATLAS-CONF-2015-064, PRL 115 (2015) 262001, JHEP 10 (2013) 042

Charmed mesons — NP B907 (2016) 717

Summary

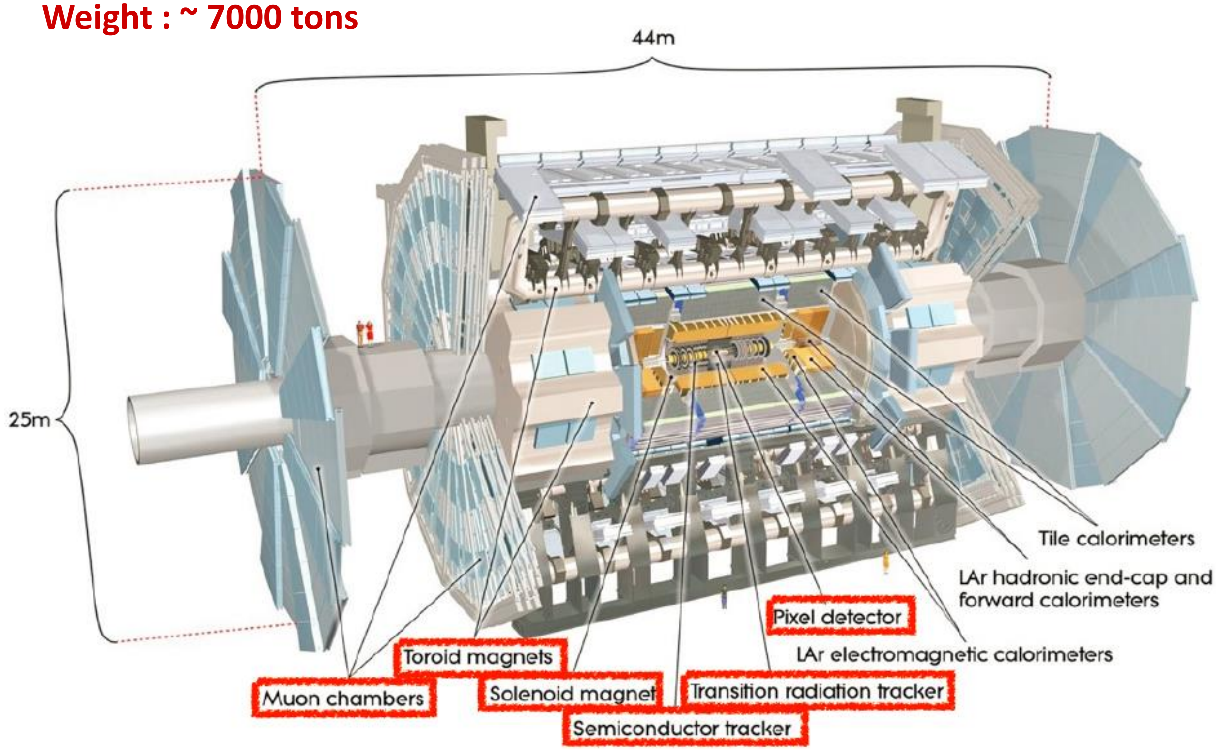
Back-up : additional plots

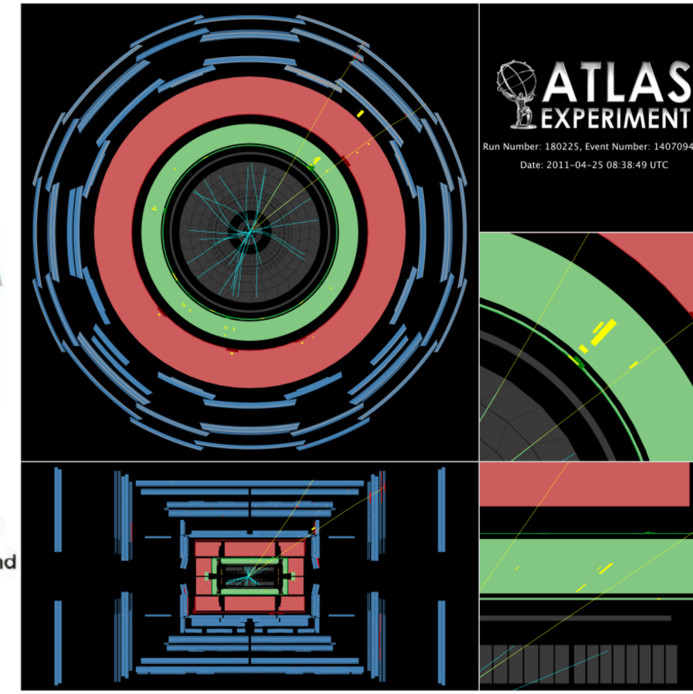
Bottomonium — PR D 87 (2013) 052004

$Z + J/\psi$ — EPJ C 75 (2015) 229

$W + J/\psi$ — JHEP 04 (2014) 172

ATLAS @ LHC





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

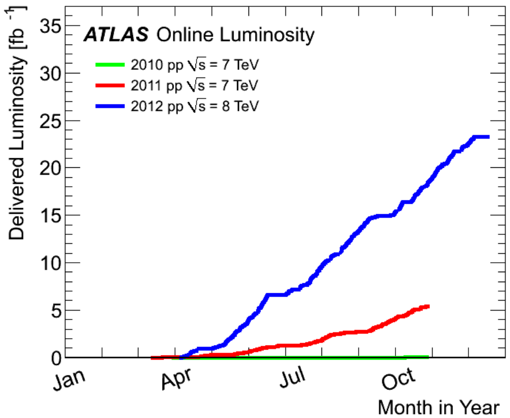
~150 MeV for ϒ

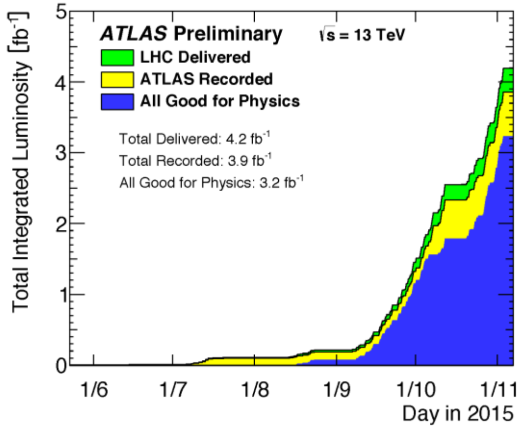
Muon Spectrometr:

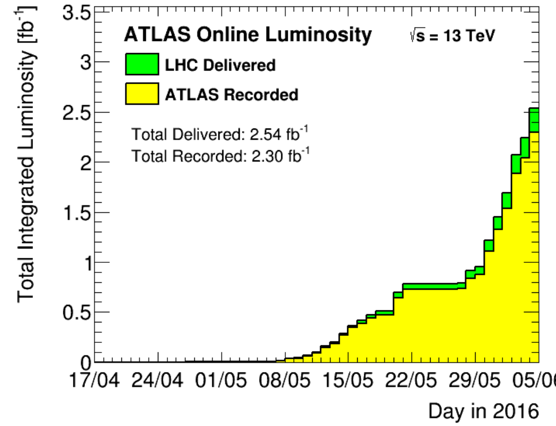
Offline tracking: $|\eta| < 2.7$

Triggering: $|\eta| < 2.4$

Data Taking and HF triggering



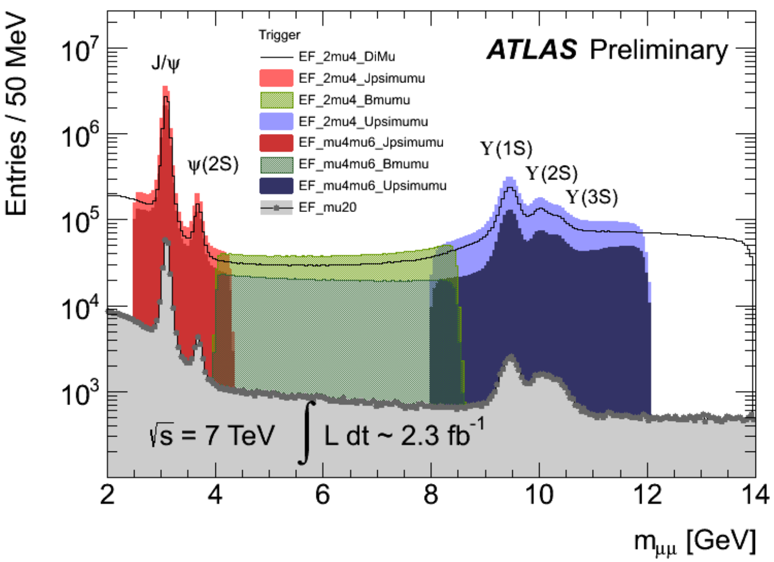


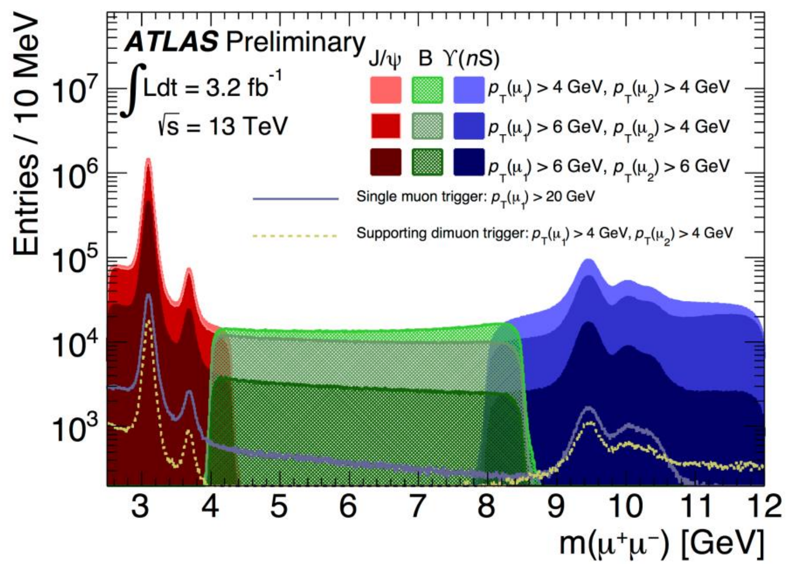


6.76 x 10^{33} cm^{-2} s^{-1}

5.0 x 10^{33} cm^{-2} s^{-1}

8.2 x 10^{33} cm^{-2} s^{-1}



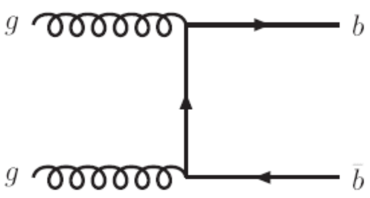


Charmonium production

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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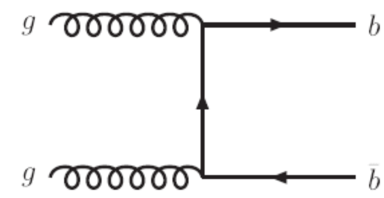
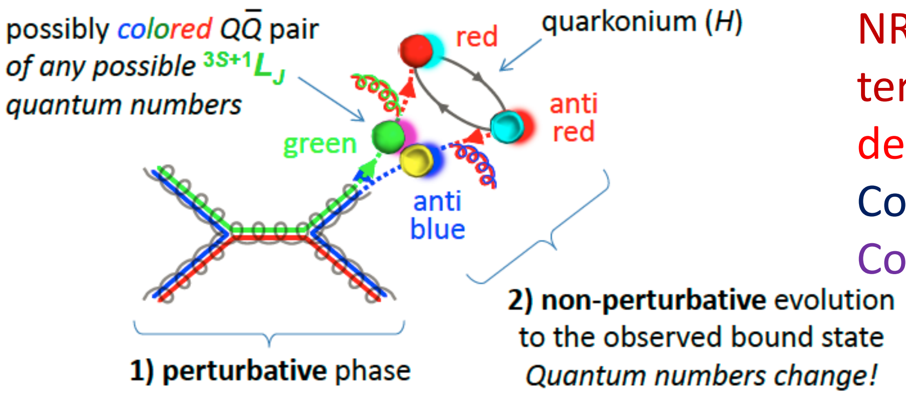


Prompt (not from B decays) – probes specific mechanisms of $Q\bar{Q}$ system production and transformation to a meson



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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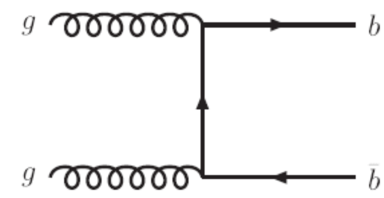

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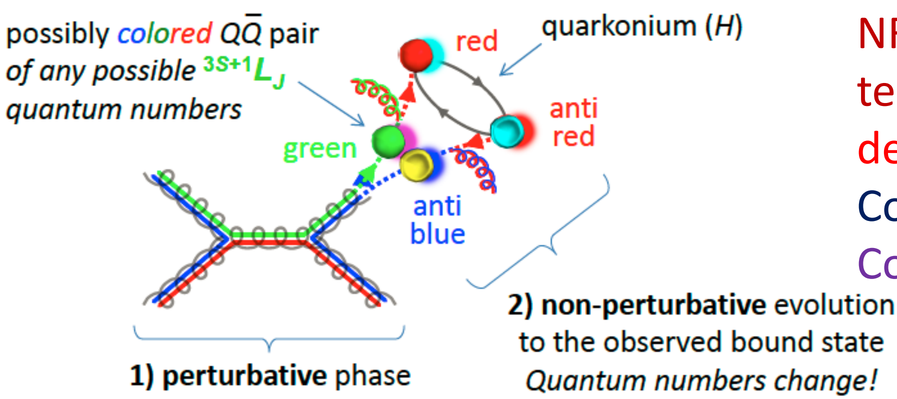

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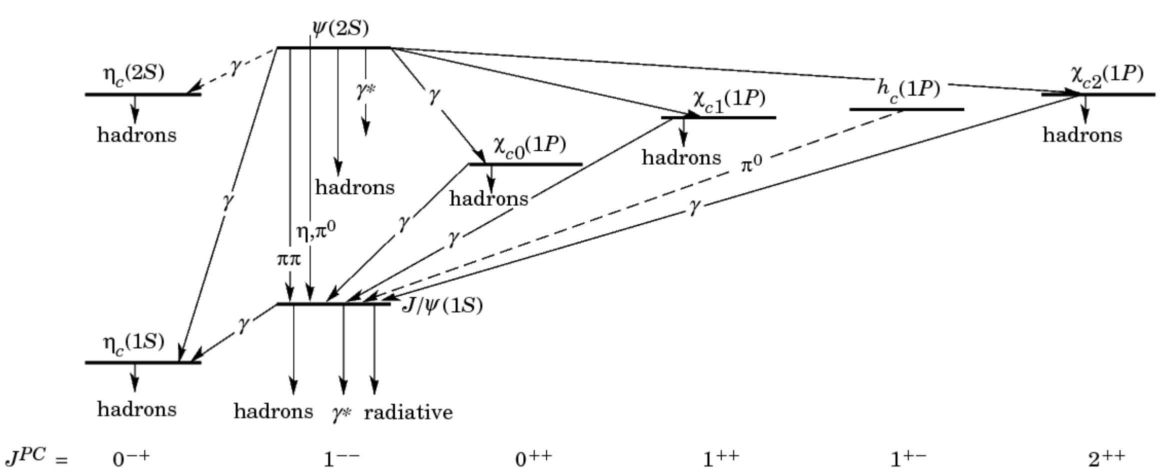
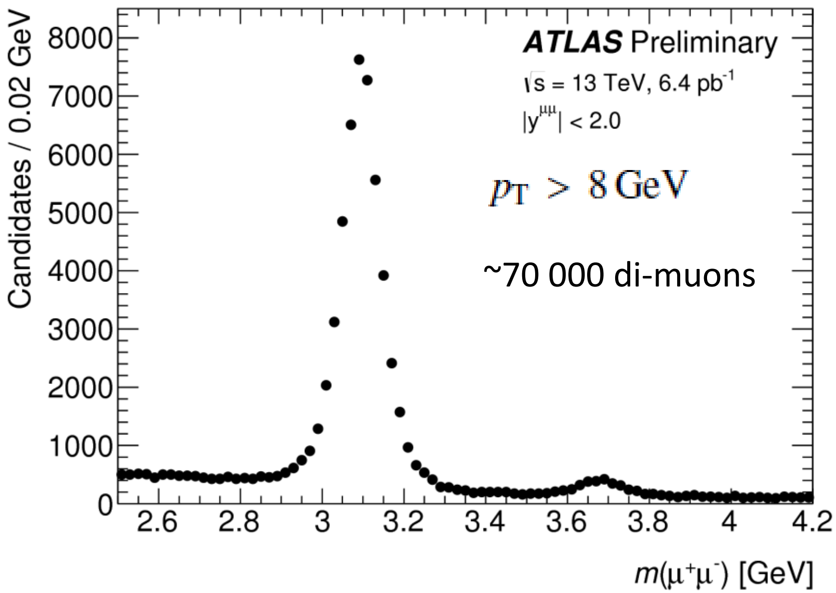


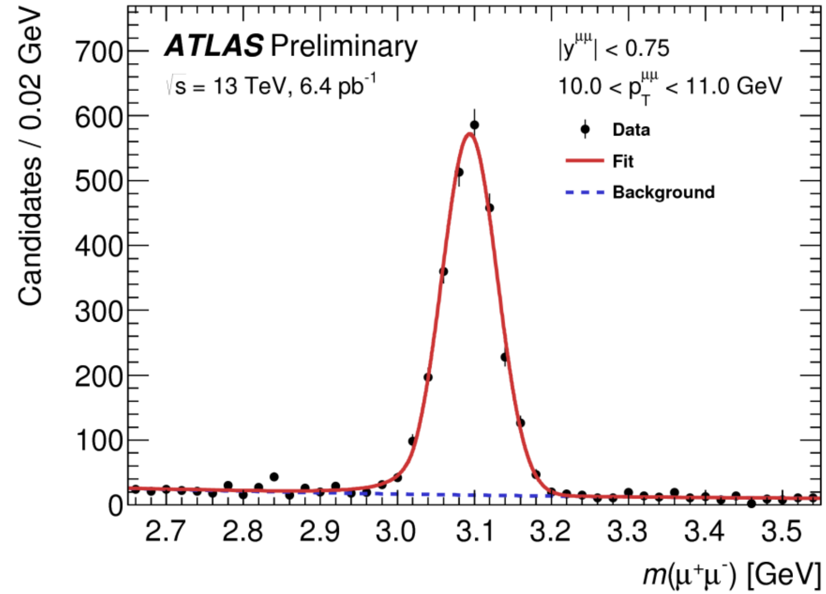
Ψ(2S) – nearly feed-down free

J/ψ – feed-downs ~35%

Charmonium production: J/ψ, 13 TeV

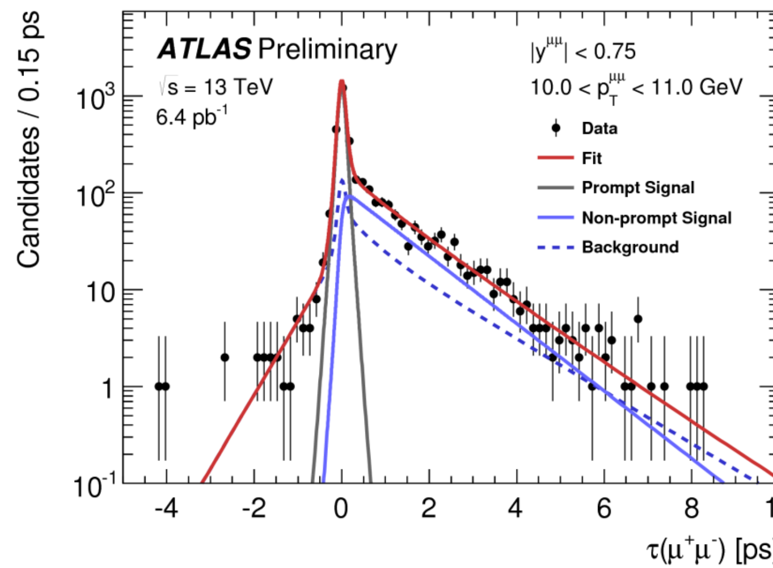
ATLAS-CONF-2015-030



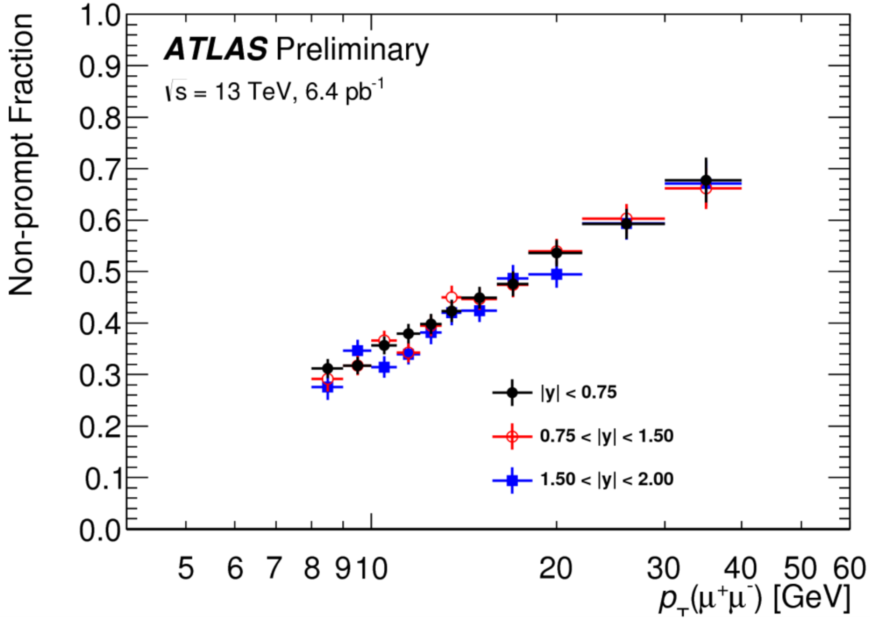


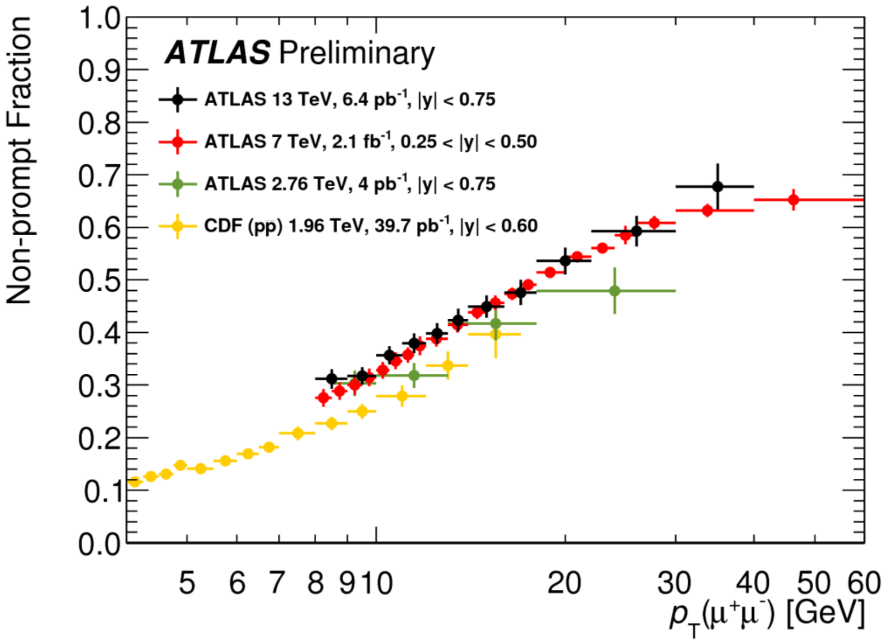
Pseudo-proper decay time:

$$\tau = L_{xy} m_{J/\psi}^{\mathrm{PDG}} / p_{\mathrm{T}}$$



Charmonium production: J/ψ, 13 TeV





Non-Prompt Fraction

$$f_b^{J/\psi} \equiv \frac{pp \to b + X \to J/\psi + X'}{pp \xrightarrow{\text{Inclusive}} J/\psi + X'} = \frac{N^{NP}_{J/\psi}}{N^{NP}_{J/\psi} + N^{P}_{J/\psi}}$$

rises from ~25% till ~60%

No strong dependence from |y| range

No sizeable differences between 7 and 13 TeV results

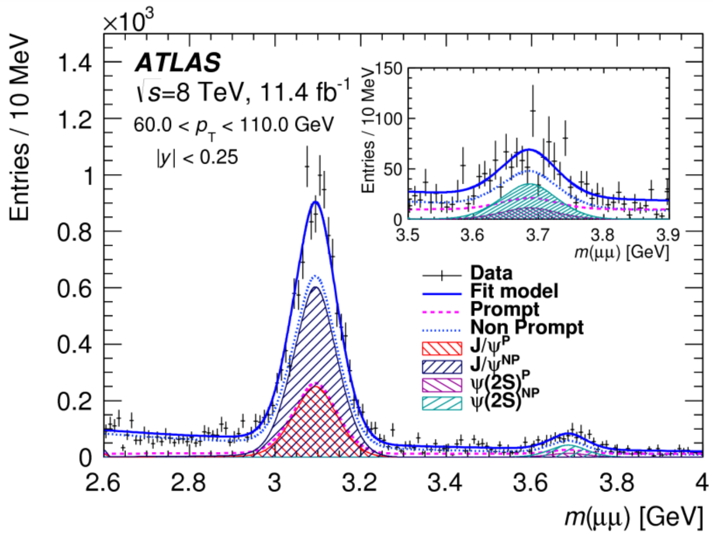
Larger than at smaller *pp* and *p$\bar{p}$* energies

Charmonium production: J/ψ, ψ(2S), χ_c, 7-8 TeV

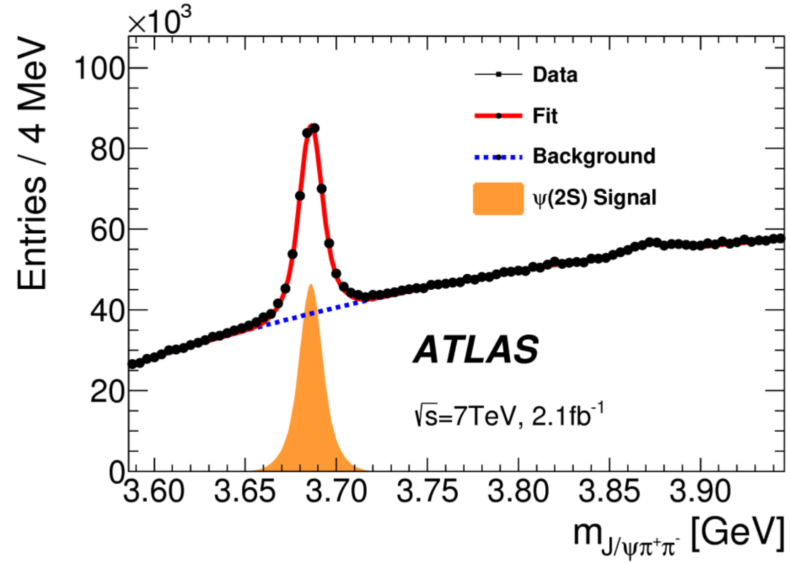
J/ψ and ψ(2S), EPJ C76 (2016) 283
$\chi_{c1/2}$, JHEP 07 (2014) 154

ψ(2S), JHEP 09 (2014) 079
ψ(2S) and X(3872), ATLAS-CONF-2016-0XX

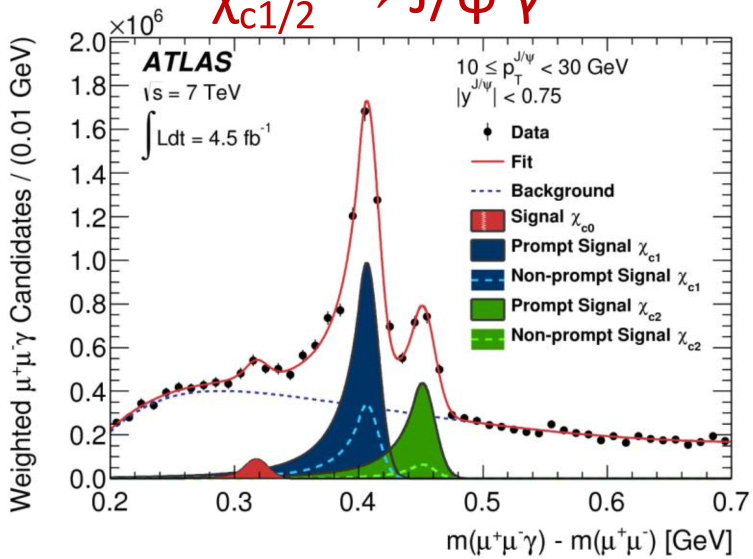
J/ψ, ψ(2S) → $\mu^+\mu^-$

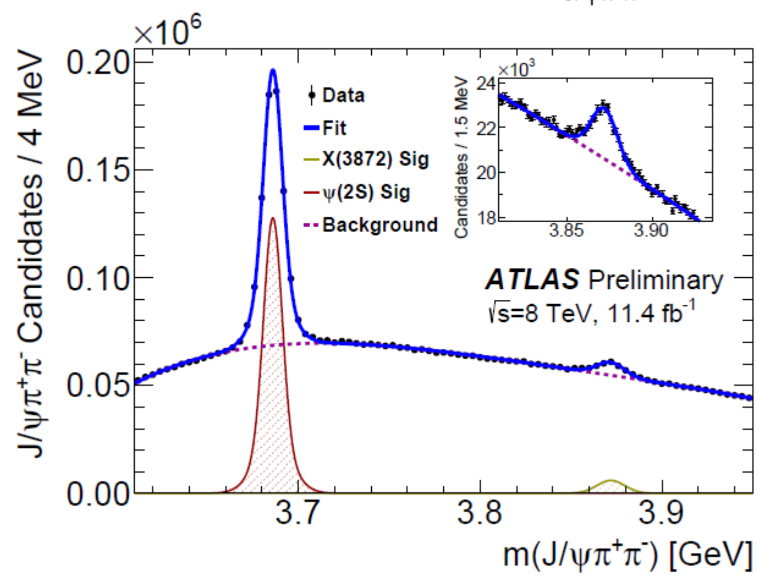


ψ(2S), X(3872) → J/Ψ $\pi^+\pi^-$

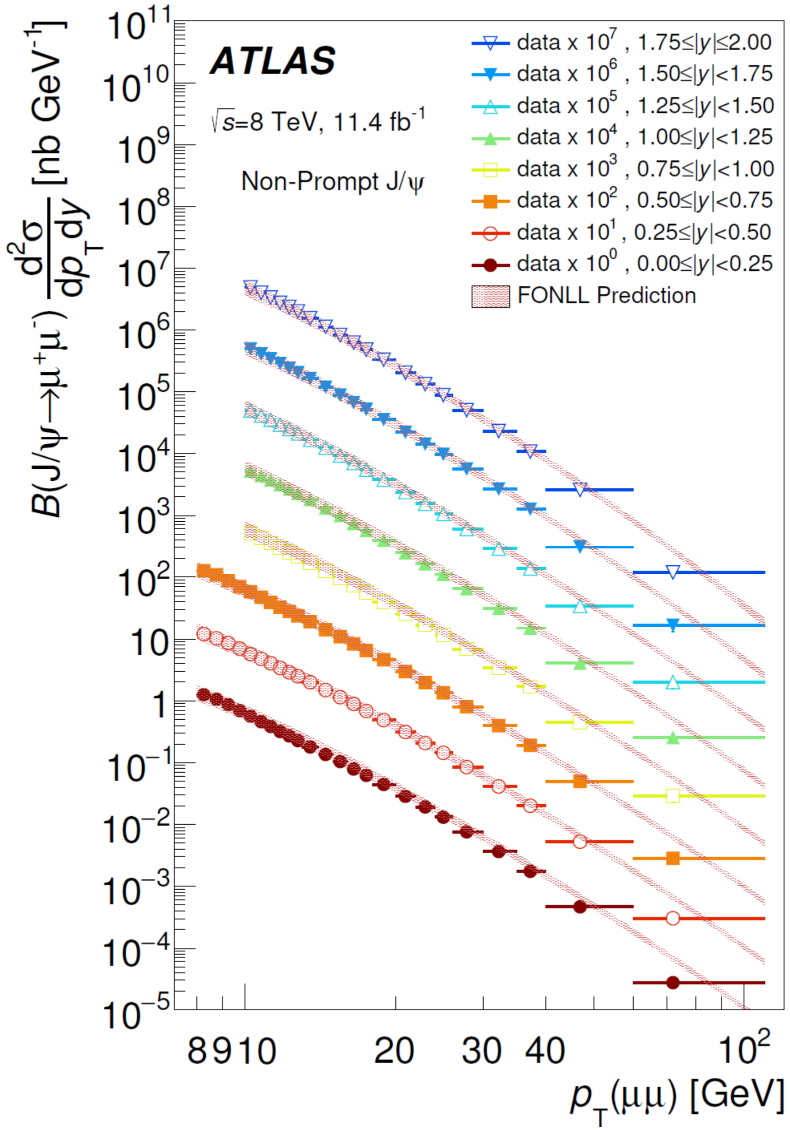


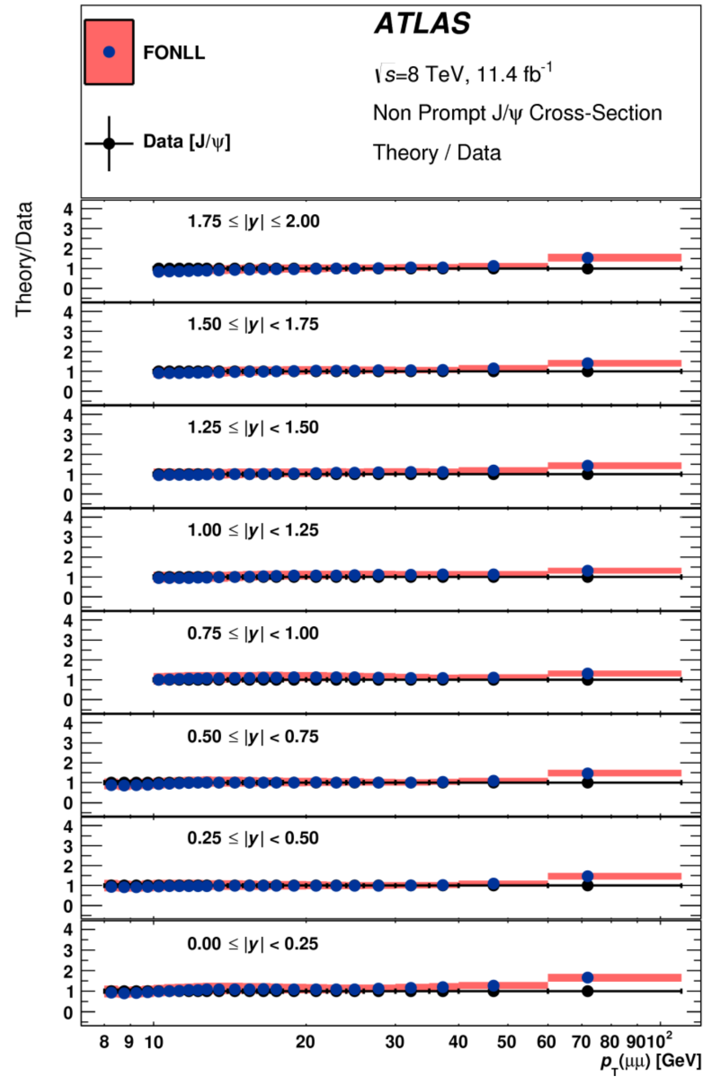
$\chi_{c1/2}$ → J/ψ γ





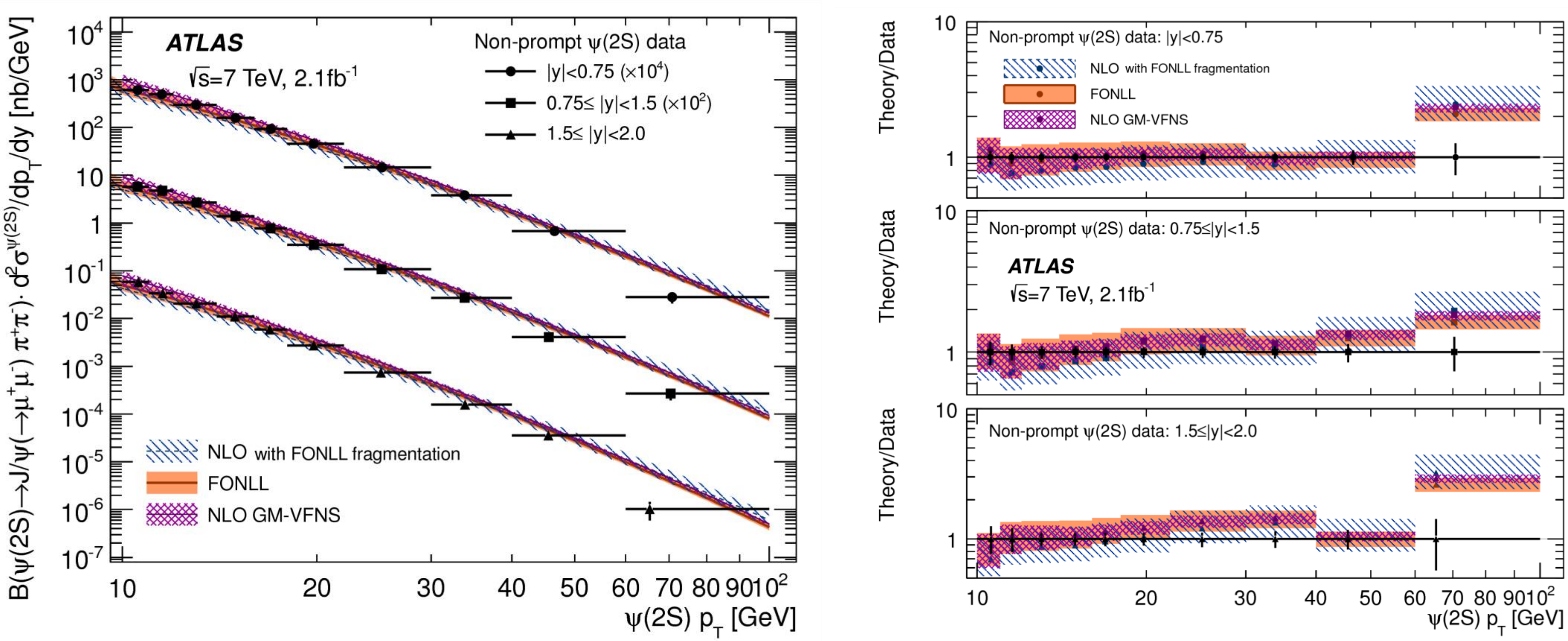
J/ψ (→μ⁺μ⁻), 8 TeV, non-prompt diff. x-sections





- generally, reasonable description by FONLL
- predictions are harder than data

$\psi(2S) \rightarrow J/\psi\ (\rightarrow\mu^+\mu^-)\pi^+\pi^-$, non-prompt diff. x-sections



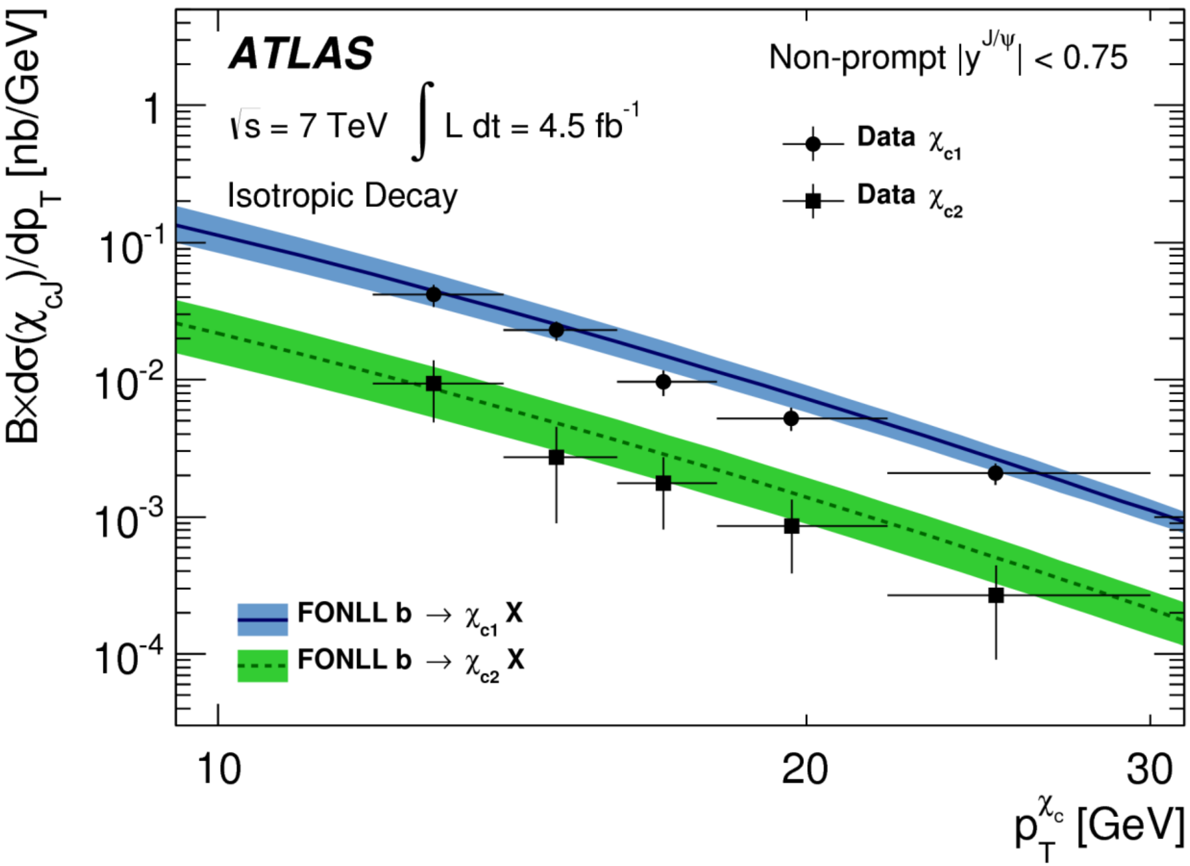
- generally, reasonable description by FONLL and GM-VFNS predictions are harder than data

- NLO with "wrong" (FONLL) fragmentation is even harder

$\chi_{c1/2} \rightarrow J/\psi\ (\rightarrow\mu^+\mu^-)\ \gamma$, non-prompt diff. x-sections

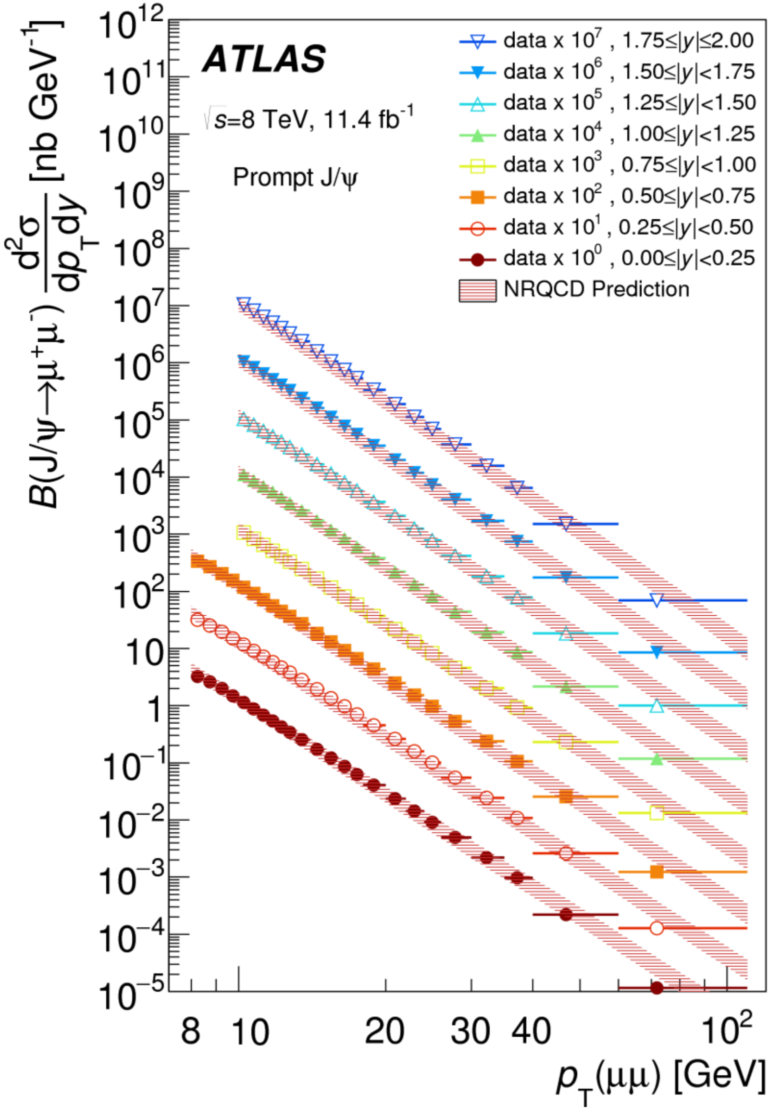
ATLAS, $\chi_{c1/2}$, JHEP 07 (2014) 154

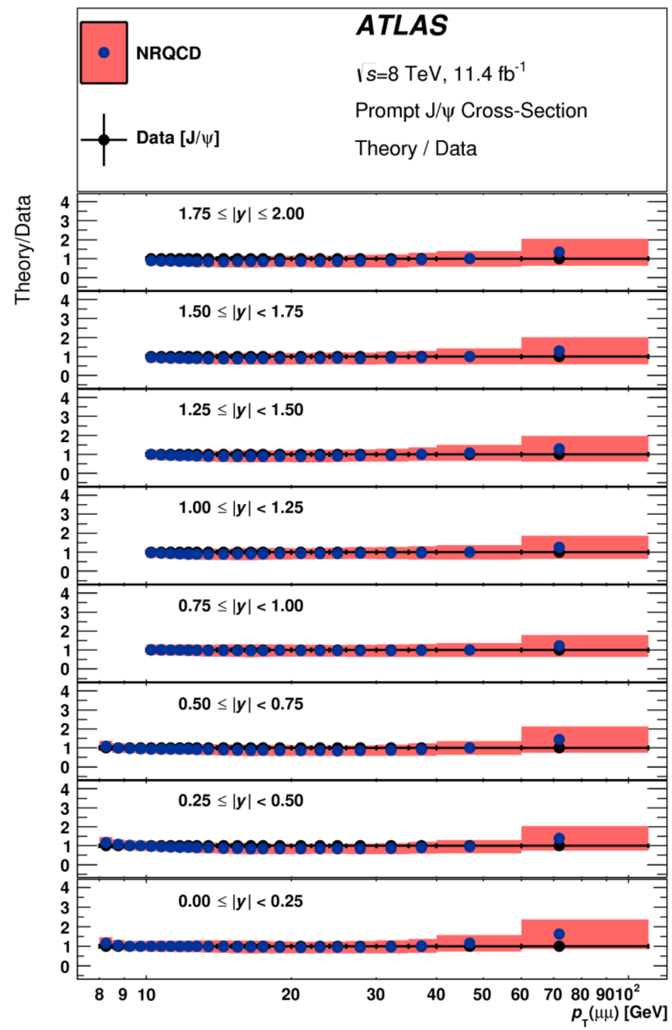
Absolute $\chi_{c1/2}$ cross sections are measured



FONLL describes reasonably (somewhat harder)

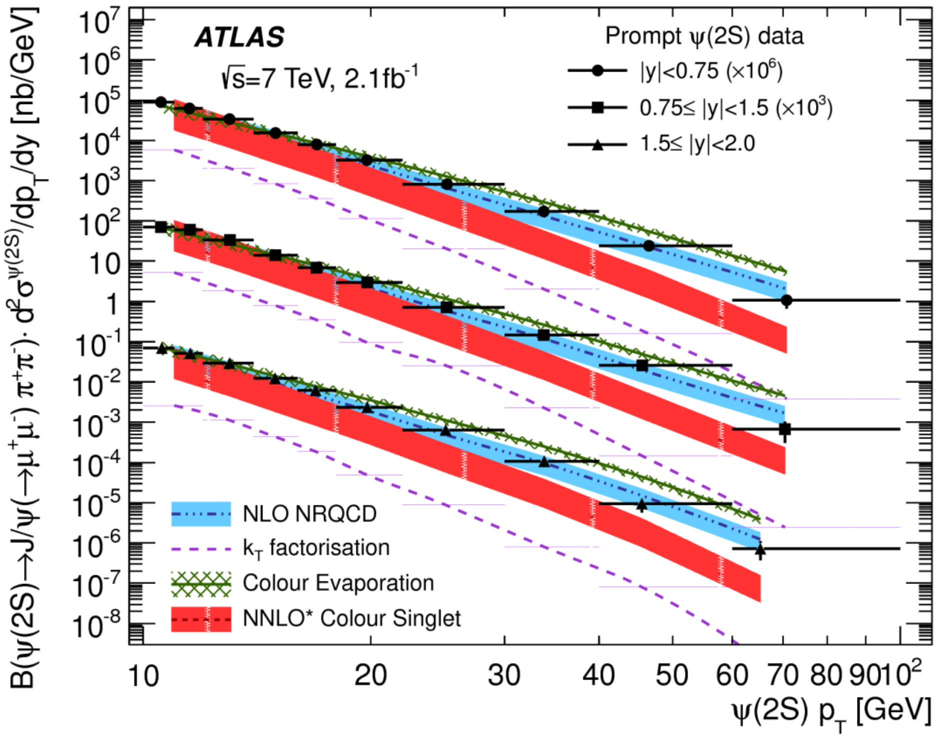
J/ψ, 8 TeV, prompt diff. x-sections

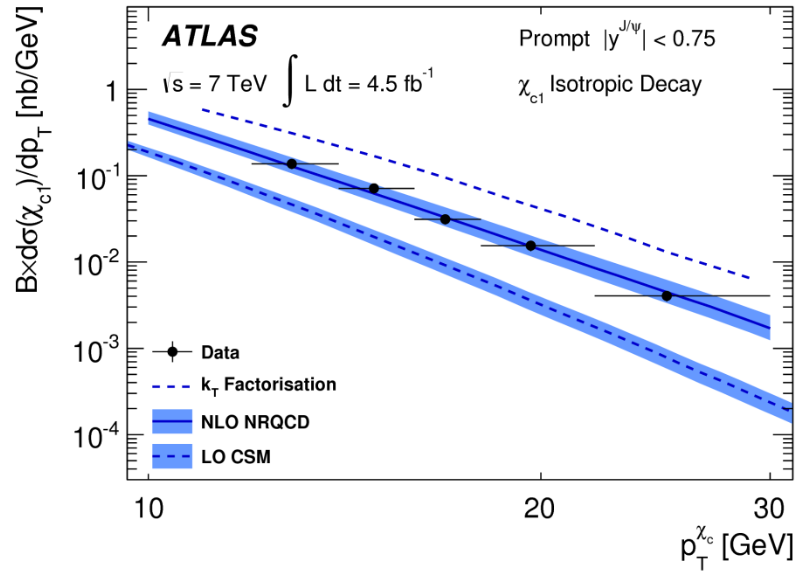


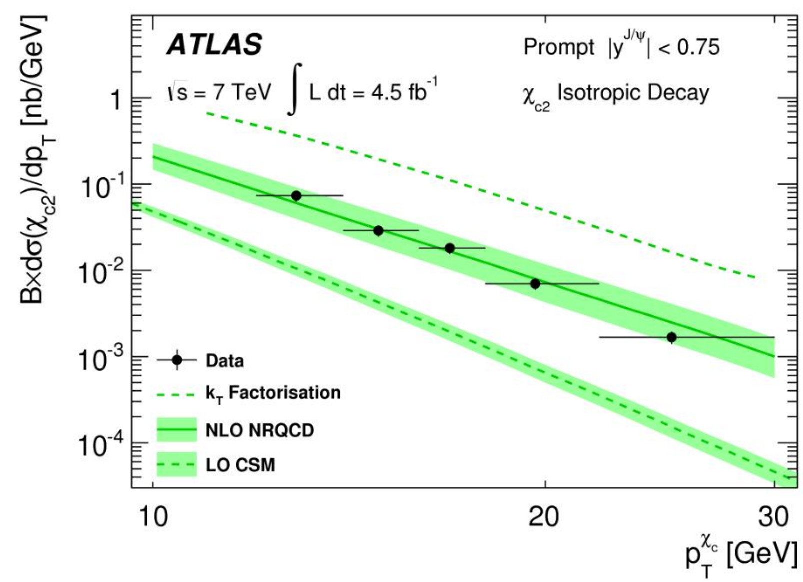


NLO NRQCD (Y.Q. Ma et al.) is generally o.k.

$\psi(2S)$ and $\chi_{c1/2}$, prompt diff. x-sections



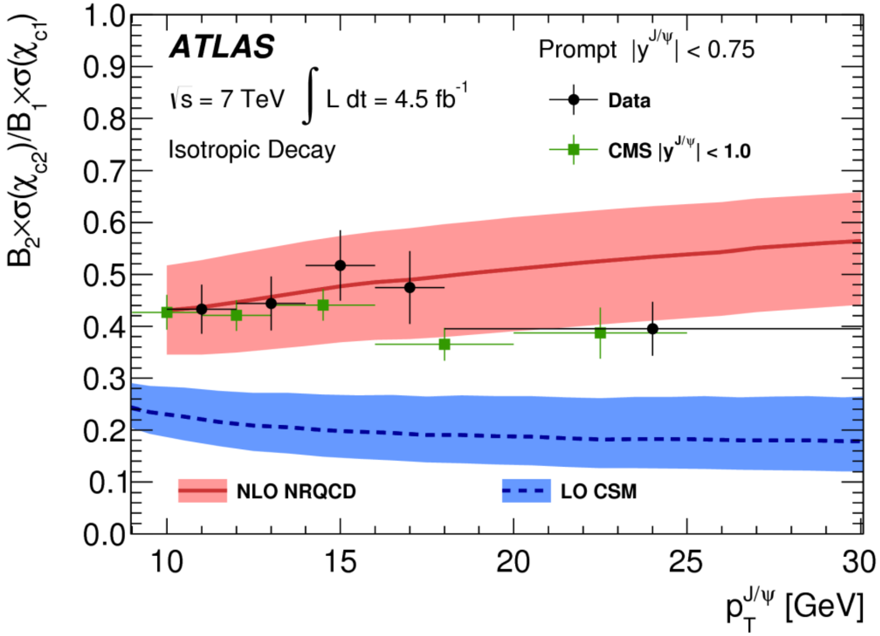




- NLO NRQCD is generally o.k.
- CS is too low even at NNLO*
- CEM is somewhat too hard

k_T –factorization predictions (CS) (Baranov et al.) need to be re-tuned

$\chi_{c1/2} \rightarrow J/\psi\ (\rightarrow \mu^+\mu^-)\ \gamma$, ratios for prompt diff. x-sections

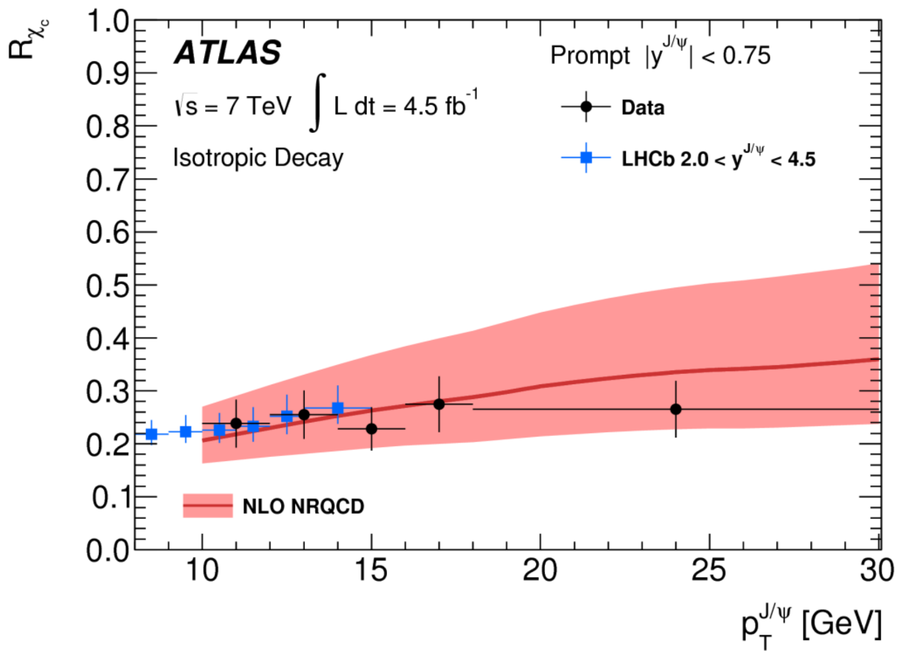


Y.-Q. Ma, K. Wang, and K.-T. Chao

L. A. Harland-Lang and W. J. Stirling

reasonable description by NLO NRQCD

LO CSM does not describe

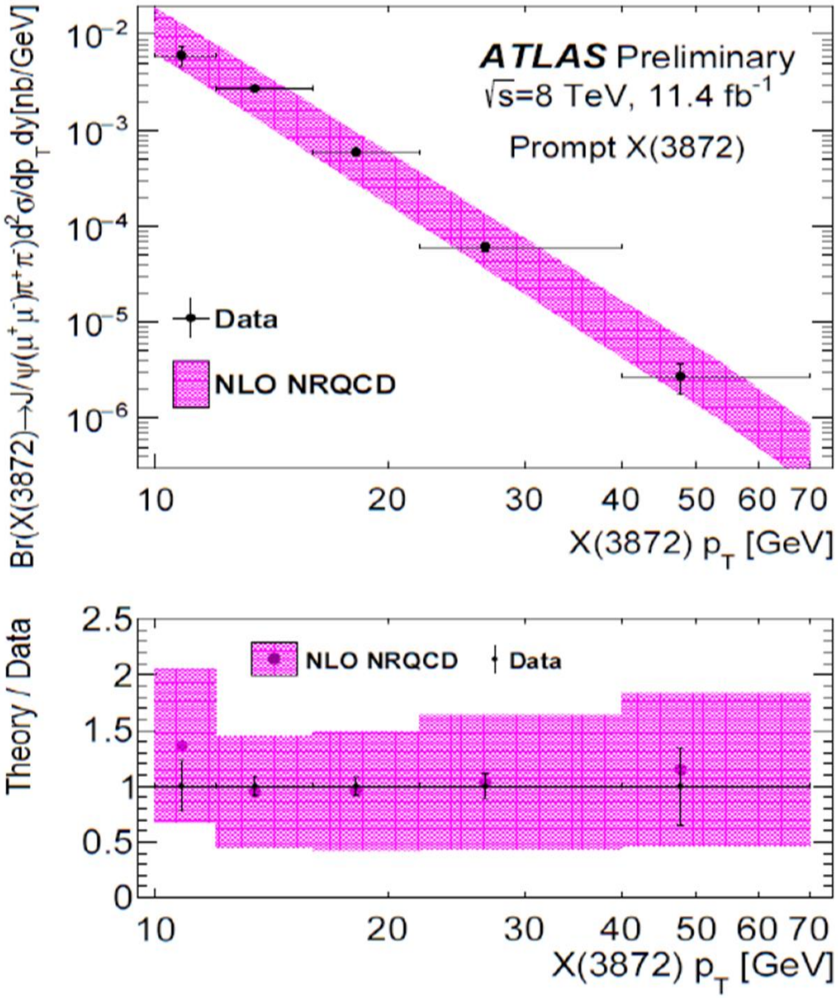


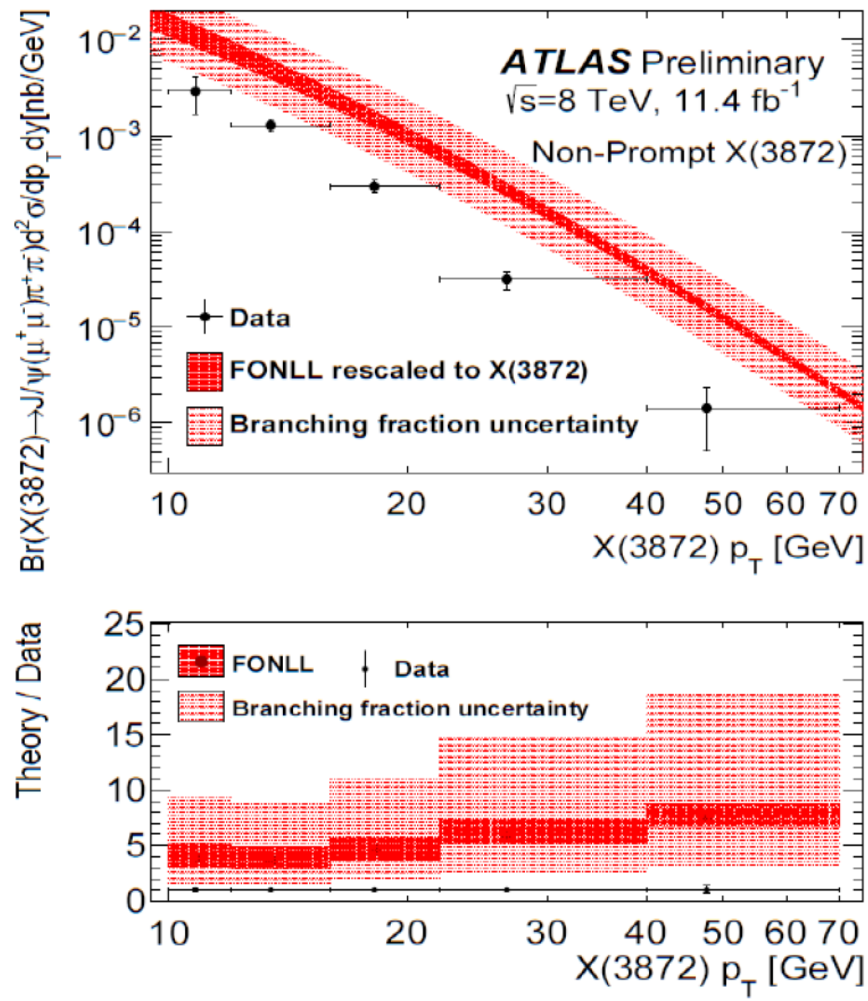
good agreement between LHC experiments

fraction, R_{χ_c}, of prompt J/ψ produced in χ_c decays

X(3872), 8 TeV, prompt/non-prompt diff. x-sections

ATLAS-CONF-2016-0XX



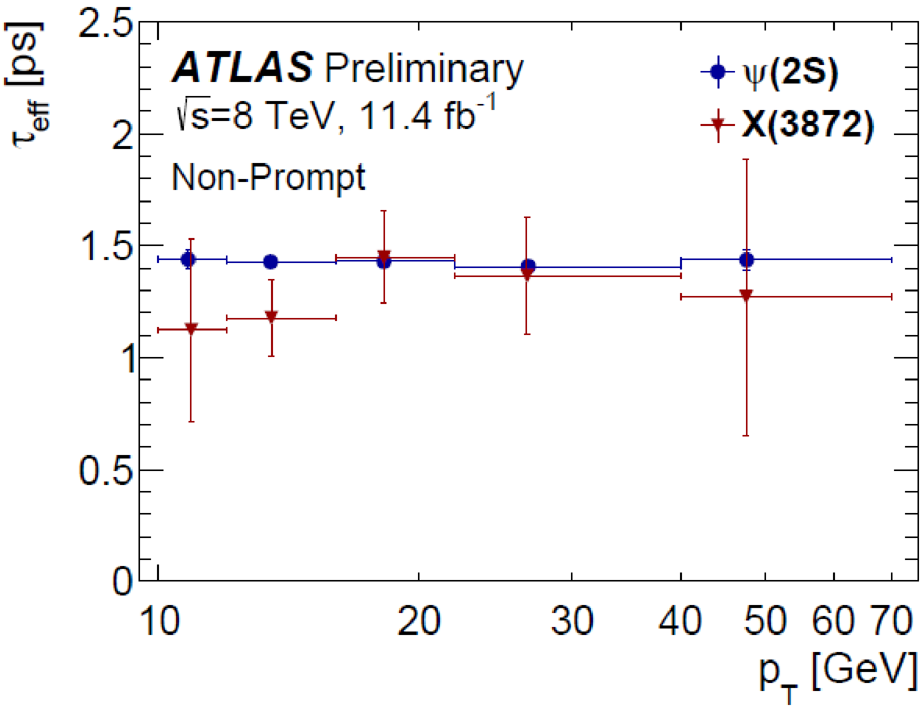


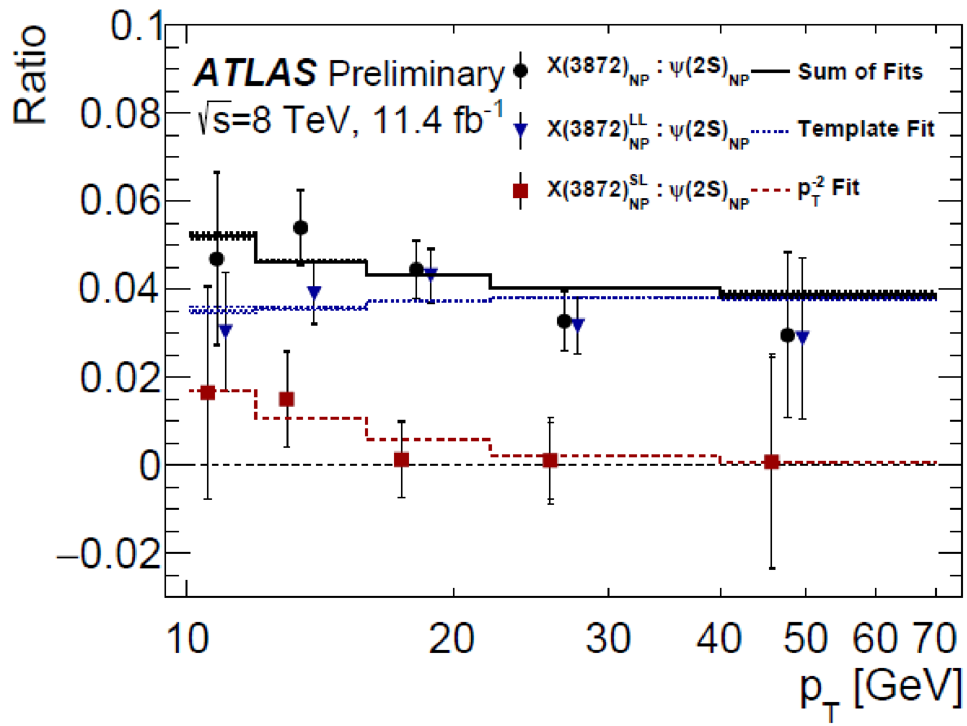
NLO NRQCD (C. Meng et al.), $\chi_{c1}(2P) + D^0\bar{D}^{*0}$,
produced dominantly via $\chi_{c1}(2P)$,
tuned to CMS, is generally o.k.

FONLL, rescaled from ψ(2S), with
$f(B\to X(3872)\to J/\psi\pi^+\pi^-)=(1.9\pm0.8)\times10^{-4}$
(Artoisenet&Braaten with CDF data)
is too high, too hard

X(3872), 8 TeV, indication of enhanced B_c contribution

ATLAS-CONF-2016-0XX





$\tau_{\text{long-lived}}$ = 1.45 ± 0.05 ps

$\tau_{\text{short-lived}}$ = 0.40 ± 0.05 ps

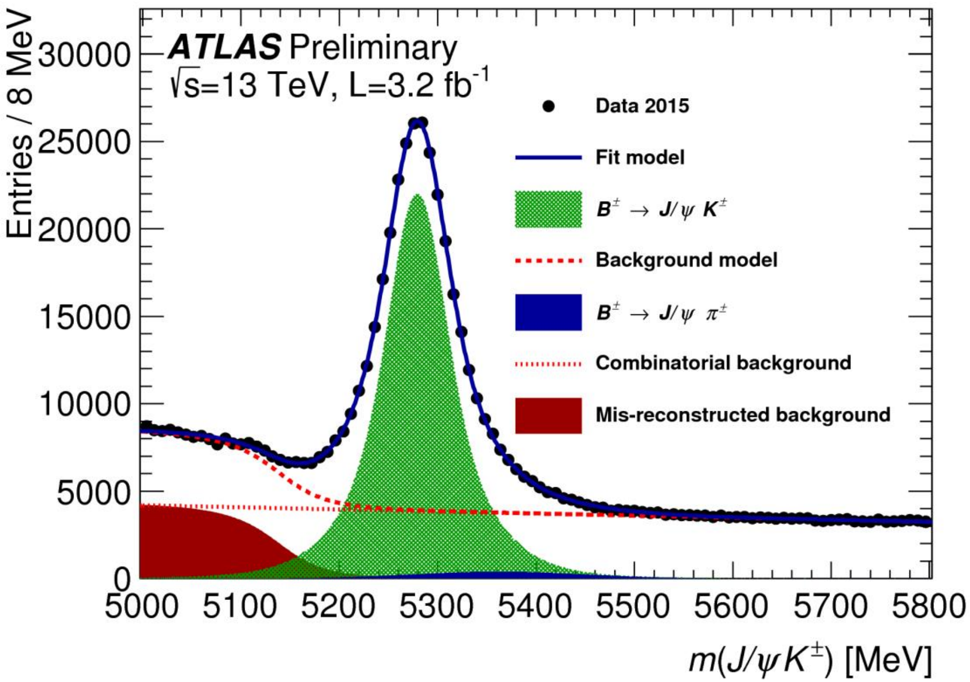
Short-lived component
~ a/p_T^2 (recombination)

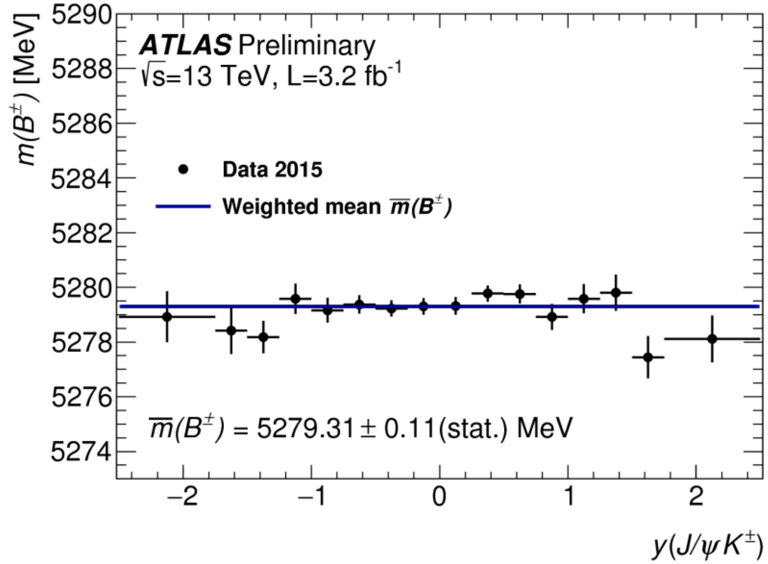
$$\frac{\sigma(pp \to B_c)Br(B_c \to X(3872))}{\sigma(pp \to \text{non}-\text{prompt } X(3872))} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\%$$

Non-prompt X(3872) production suggests enhanced B_c contribution

Beauty meson production: $B^+ \to J/\psi K^+$, 13 TeV

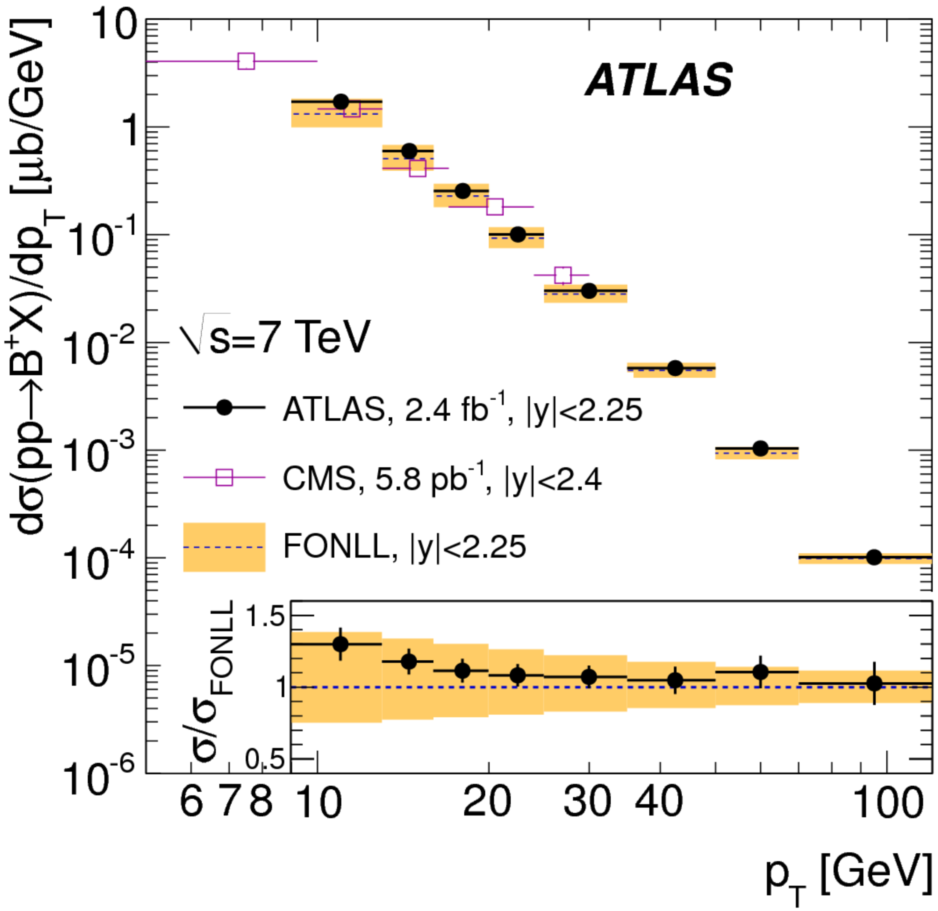
ATLAS-CONF-2015-064

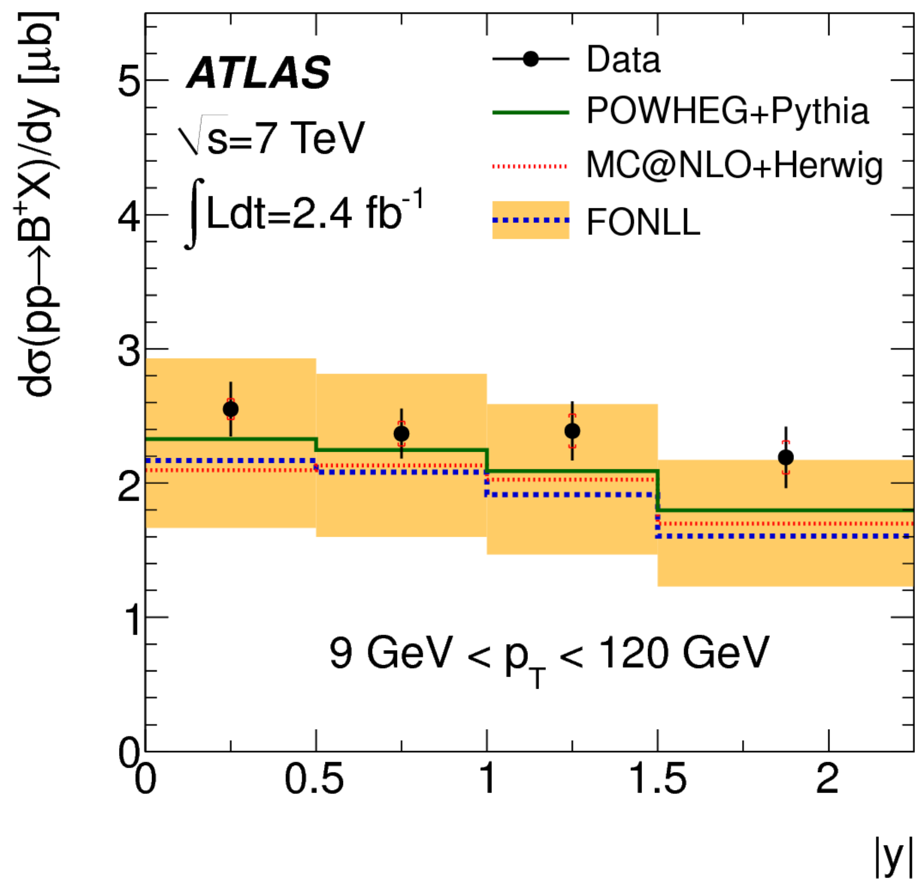




Fit	$B^{\pm}$ mass [MeV]	Fit error [MeV]
Default Fit	5279.31	0.11 (stat.)
$L_{xy} > 0.2$ mm	5279.34	0.09 (stat.)
World Average fit	5279.29	0.15
LHCb	5279.38	0.11 (stat.) ± 0.33 (syst.)

Beauty meson production: $B^+ \to J/\psi K^+$, 7 TeV



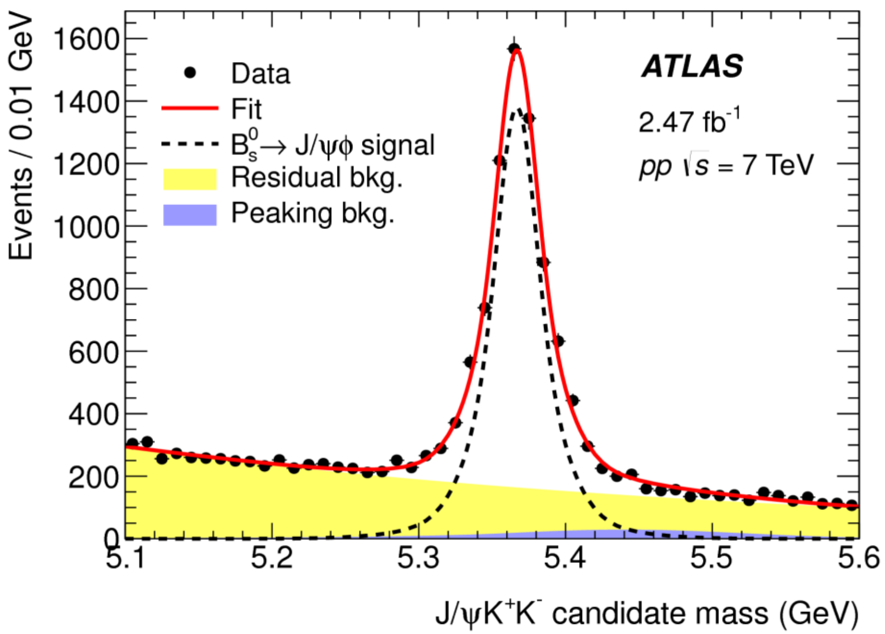


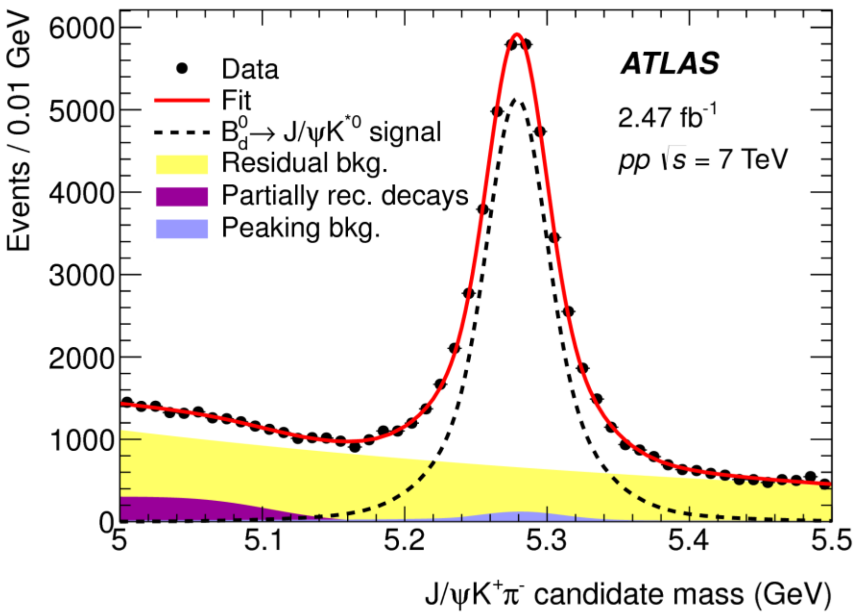
FONLL provides reasonable description although with large theor. uncertainties

Central predictions are somewhat harder

The predictions are normalized to $f(b\to B^+) = 40.1 \pm 1.3\%$ [PDG]

Strangeness suppression in b fragmentation: f_s / f_d, 7 TeV





$$N_{B_s^0} = 6640 \pm 100 \; B_s^0 \to J/\psi\phi$$

$$N_{B_d^0} = 36290 \pm 320 \; B_d^0 \to J/\psi K^{*0}$$

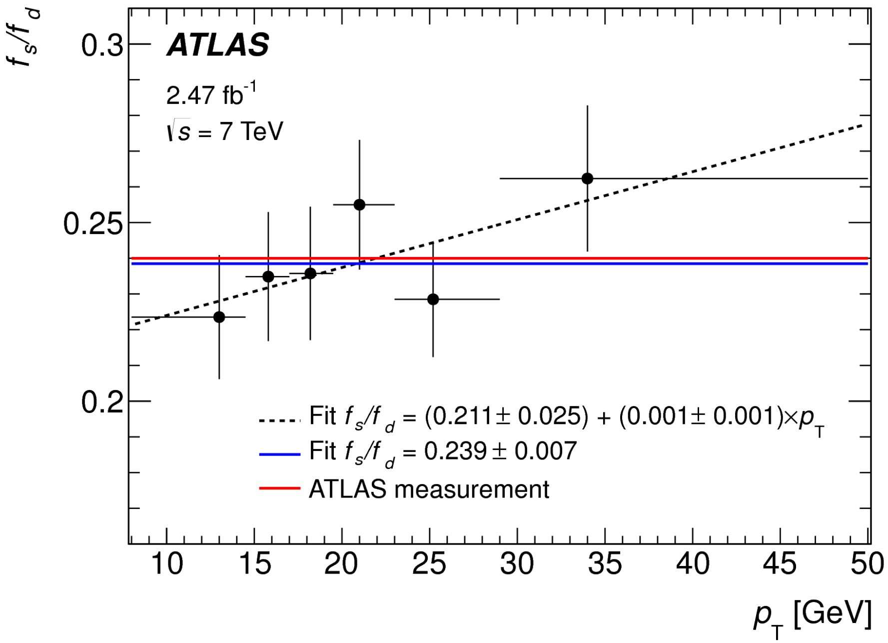
$$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.199 \pm 0.004(\text{stat}) \pm 0.008(\text{sys})$$

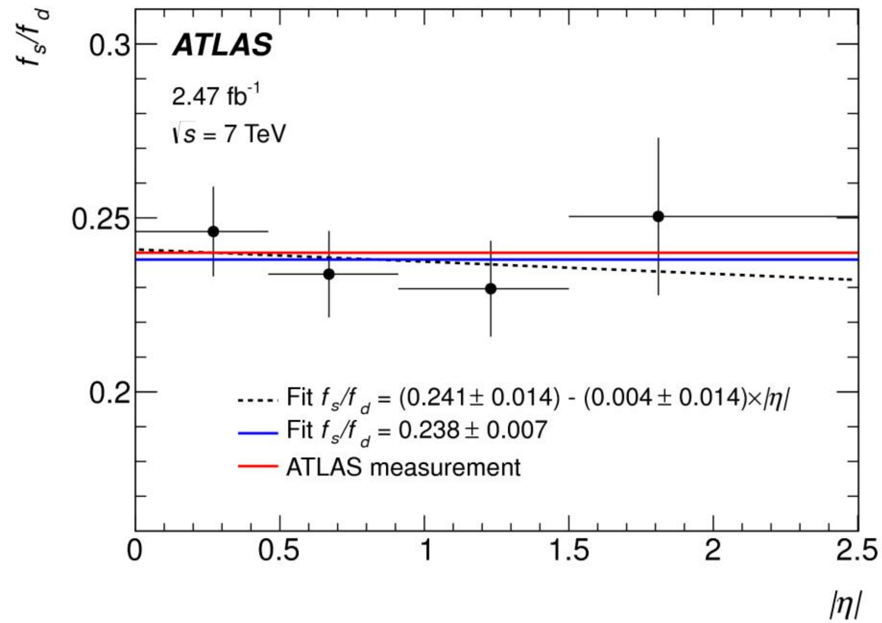
$$\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c)$$

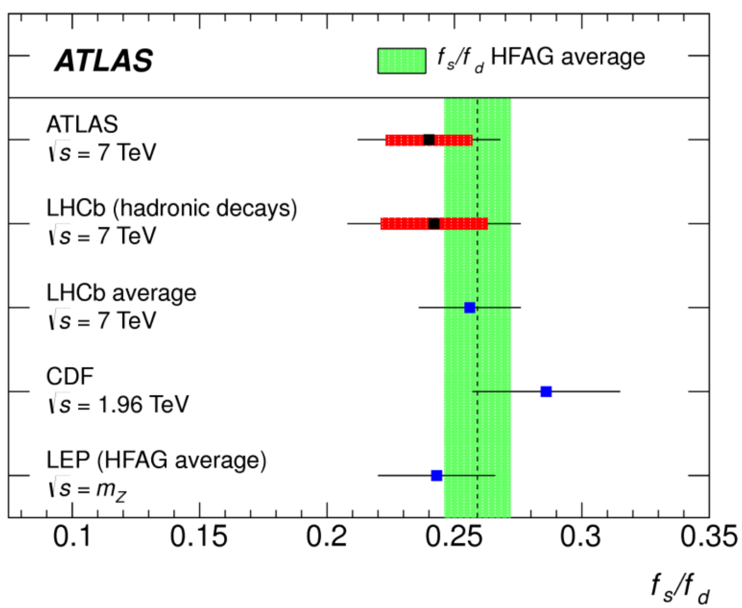
pQCD, X. Liu et al.

$$\frac{f_s}{f_d} = 0.240 \pm 0.004(\text{stat}) \pm 0.010(\text{sys}) \pm 0.017(\text{th})$$

Strangeness suppression in b fragmentation: f_s/f_d, 7 TeV







No sizeable p_T and η dependence

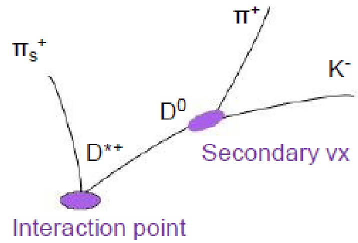
Good agreement with other measurements

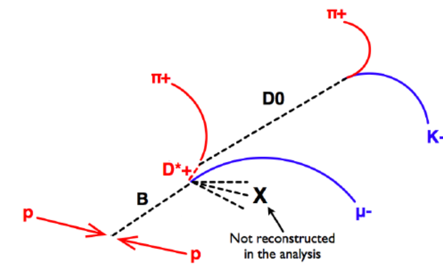
Charmed meson production: $D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$, 7 TeV

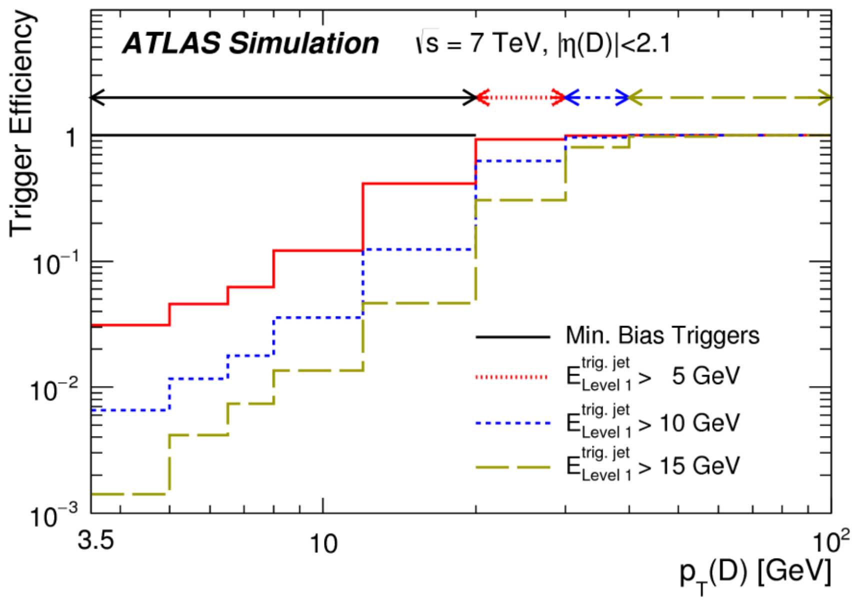
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+) \pi^+$ (+c.c.)

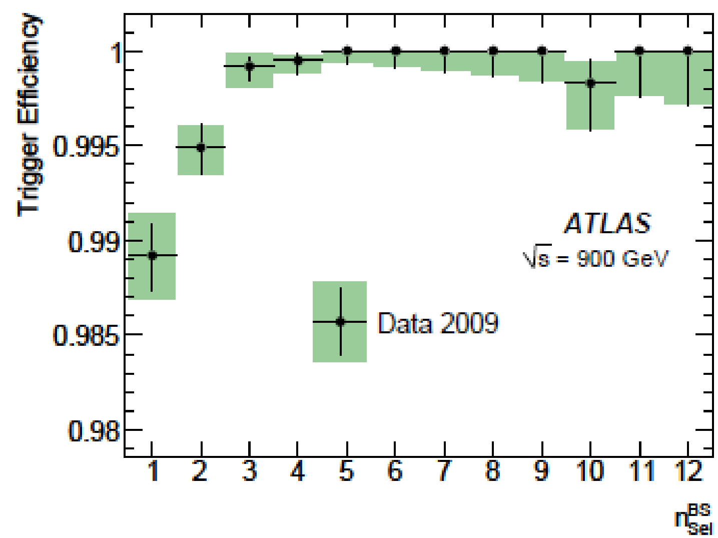
$D^+ \rightarrow K^- \pi^+ \pi^+$ (+c.c.)

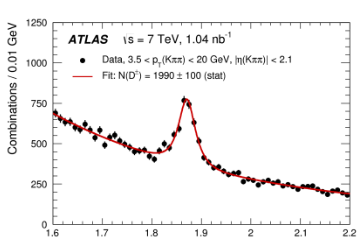
$D_s^+ \rightarrow \varphi \pi^+ \rightarrow (K^- K^+) \pi^+$ (+c.c.)

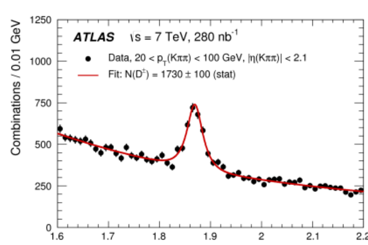


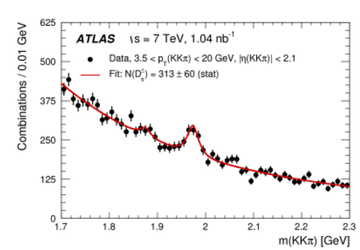


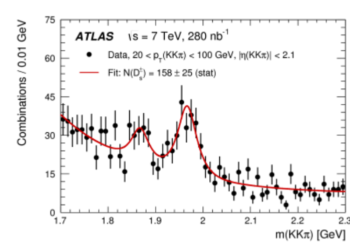












D meson visible x-sections

low-p_T: 3.5 – 20 GeV   high-p_T: 20 - 100 GeV

	$\sigma^{vis}(D^{*\pm})$		$\sigma^{vis}(D^{\pm})$		$\sigma^{vis}(D_s^{*\pm})$	
Range [units]	low-p_T [μb]	high-p_T [nb]	low-p_T [μb]	high-p_T [nb]	low-p_T [μb]	high-p_T [nb]
ATLAS	331 ± 36	988 ± 100	328 ± 34	888 ± 97	160 ± 37	512 ± 104
GM-VFNS	340^{+130}_{-150}	1000^{+120}_{-150}	350^{+150}_{-160}	980^{+120}_{-150}	147^{+54}_{-66}	470^{+56}_{-69}
FONLL	202^{+125}_{-79}	753^{+123}_{-104}	174^{+105}_{-66}	617^{+103}_{-86}	-	-
POWHEG+PYTHIA	158^{+179}_{-85}	600^{+300}_{-180}	134^{+148}_{-70}	480^{+240}_{-130}	62^{+64}_{-31}	225^{+114}_{-69}
POWHEG+HERWIG	137^{+147}_{-72}	690^{+380}_{-160}	121^{+129}_{-64}	580^{+280}_{-140}	51^{+50}_{-25}	268^{+107}_{-62}
MC@NLO	157^{+125}_{-72}	980^{+460}_{-290}	140^{+112}_{-65}	810^{+390}_{-260}	58^{+42}_{-25}	345^{+175}_{-87}

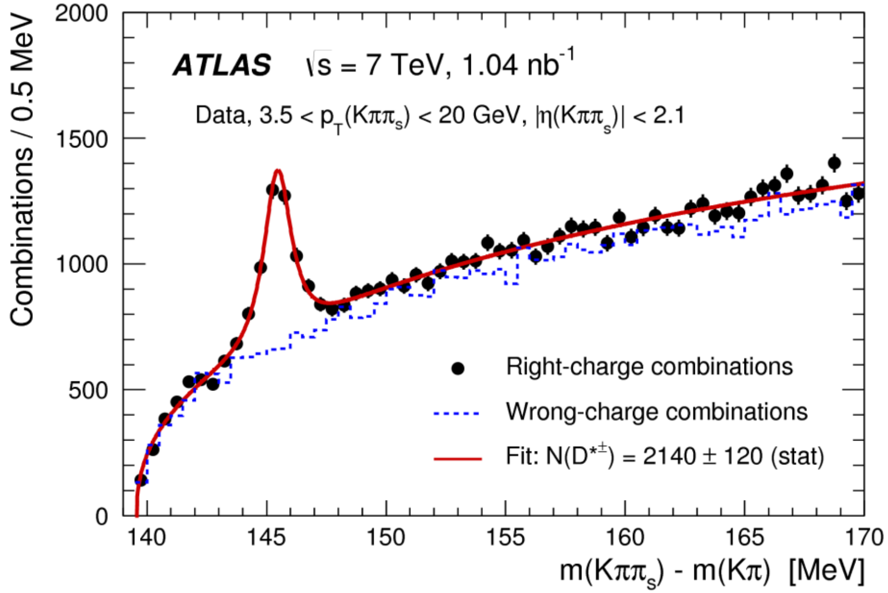
POWHEG+PYTHIA/HERWIG – matched NLO+LL (developed from “massive” NLO)

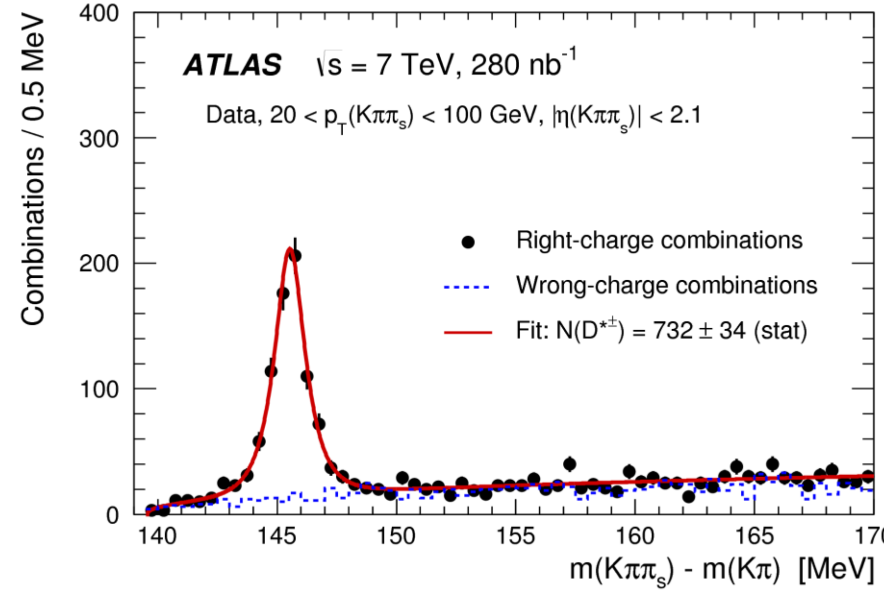
MC@NLO (+HERWIG) – matched NLO+LL (developed from “massive” NLO)

FONLL – matched NLO+NLL (developed from “massive” NLO)

GM-VFNS – developed from “massless” NLO, consider explicitly flavour excitation diagrams, consider fragmentation of light quarks and gluons to *D* mesons

$D^{*\pm}$ signals and visible x-sections





$$\text{Gauss}^{\text{mod}} \propto \exp[-0.5 \cdot x^{1+1/(1+0.5\cdot x)}], \quad \text{where } x = |(\Delta m - m_0)/\sigma|.$$

DATA:

$$\sigma^{\text{vis}}(D^{*\pm}) = 331 \pm 18\,(\text{stat}) \pm 28\,(\text{syst}) \pm 12\,(\text{lum}) \pm 5\,(\text{br})\,\mu\text{b}$$

$$\sigma^{\text{vis}}(D^{*\pm}) = 988 \pm 45\,(\text{stat}) \pm 81\,(\text{syst}) \pm 35\,(\text{lum}) \pm 15\,(\text{br})\,\text{nb}$$

POWHEG+PYTHIA:

$$\sigma^{\text{vis}}(D^{*\pm}) = 158^{+176}_{-81}\,(\text{scale})^{+15}_{-16}\,(m_Q)^{+14}_{-13}\,(\text{PDF} \oplus \alpha_s)^{+19}_{-16}\,(\text{hadr})\,\mu\text{b}$$

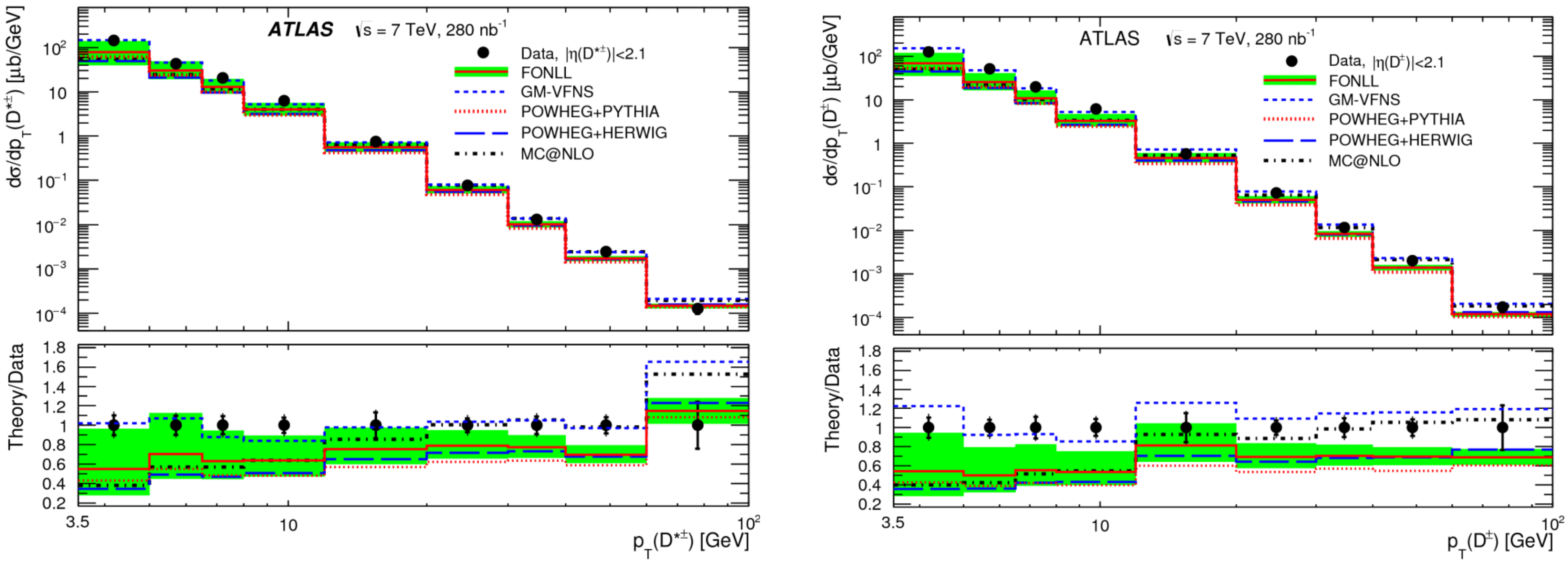
$$\sigma^{\text{vis}}(D^{*\pm}) = 600^{+269}_{-137}\,(\text{scale})^{+15}_{-21}\,(m_Q)^{+25}_{-34}\,(\text{PDF} \oplus \alpha_s)^{+126}_{-111}\,(\text{hadr})\,\text{nb}$$

FONLL:

$$\sigma^{\text{vis}}(D^{*\pm}) = 202^{+119}_{-73}\,(\text{scale})^{+36}_{-27}\,(m_Q) \pm 21\,(\text{PDF}) \pm 5\,(\text{ff})\,\mu\text{b}$$

$$\sigma^{\text{vis}}(D^{*\pm}) = 753^{+116}_{-98}\,(\text{scale})^{+28}_{-18}\,(m_Q) \pm 41\,(\text{PDF}) \pm 17\,(\text{ff})\,\mu\text{b}$$

$D^{(*)\pm}$ differential x-sections vs $p_T(D^{(*)\pm})$



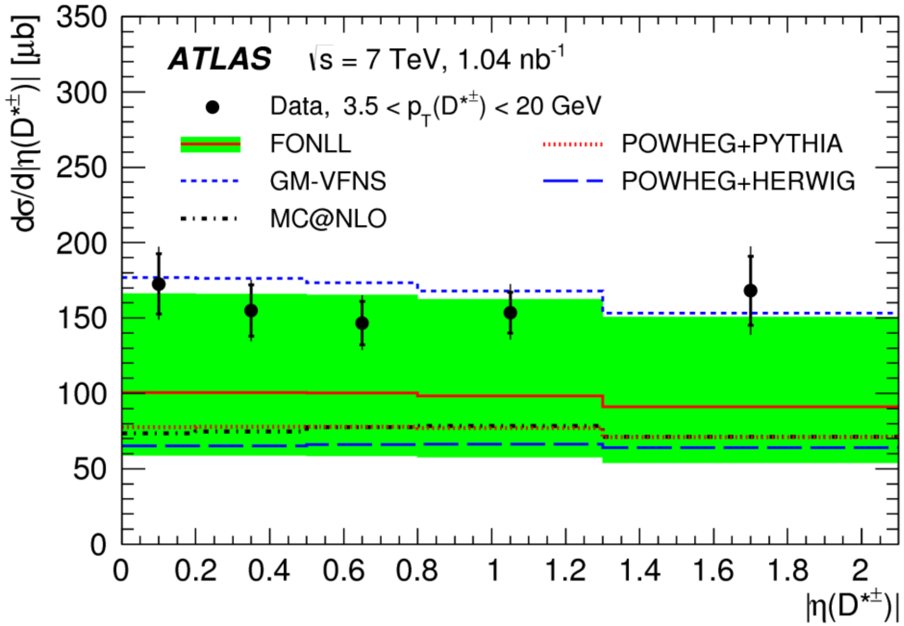
GM-VFNS - agree both in shape and normalization

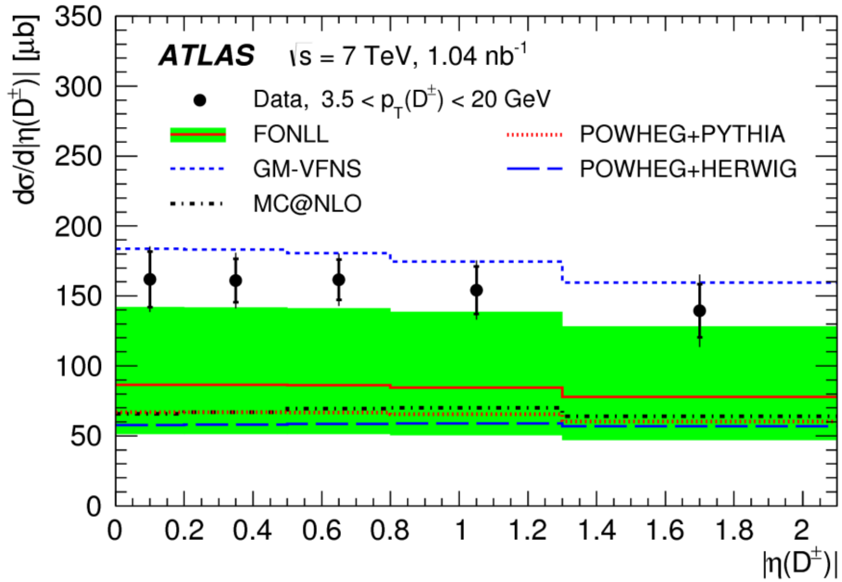
FONLL, POWHEG, MC@NLO - agree within large theoretical uncertainties

MC@NLO - worst shape description

$D^{(*)\pm}$ differential x-sections vs $|\eta(D^{(*)\pm})|$

$3.5 < p_T < 20\,\mathrm{GeV}$



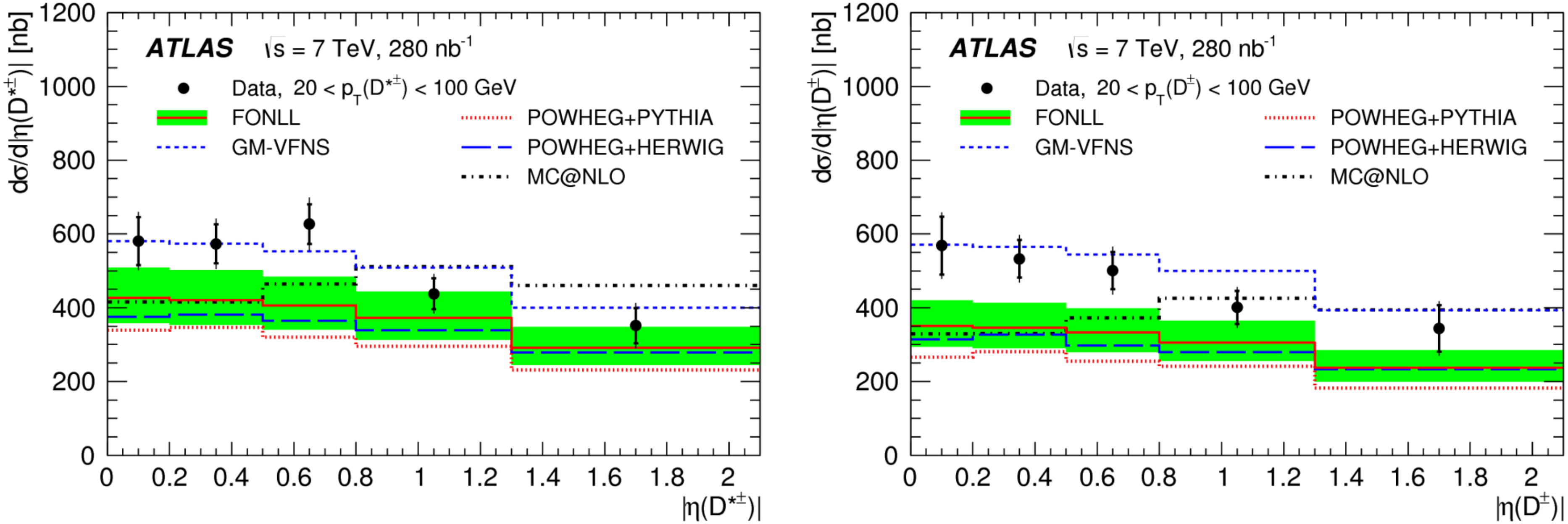


GM-VFNS - agree both in shape and normalization

FONLL, POWHEG, MC@NLO - agree within large theoretical uncertainties

$D^{(*)\pm}$ differential x-sections vs $|\eta(D^{(*)\pm})|$

$20 < p_T < 100\,\mathrm{GeV}$



GM-VFNS - agree both in shape and normalization

FONLL, POWHEG, MC@NLO - agree within large theoretical uncertainties

MC@NLO - worst shape description

Extrapolation with FONLL, total $c\bar{c}$ x-section

$$\sigma_{tot}(D^{(*)}) = \sigma_{pp\to c\bar{c}X\to D^{(*)}X'} = \sigma_{vis}^{DATA}(D^{(*)})\ (1 - f_{b\bar{b}})\ f_{extr}^{NLO,c\bar{c}}$$

$f_{extr}^{NLO,c\bar{c}} \sim 14 - 16$ **(relatively stable)**

$$\sigma_{c\bar{c}} = \sigma_{tot}(D^{(*)})/f(c \to D^{(*)})\ /\ \mathbf{2.}$$

weighted mean from $D^{*\pm}$ and $D^{\pm}$:

$3.5 < p_T(D) < 20$ GeV and $|\eta(D)| < 2.1$

$$\sigma_{c\bar{c}}^{tot} = 8.6 \pm 0.3\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.3\,(\text{lum}) \pm 0.2\,(\text{ff})^{+3.8}_{-3.4}\,(\text{extr})\ \text{mb} \quad (\text{ATLAS})$$

$1 < p_T(D) < 24$ GeV and $|y(D)| < 0.5$

$$\sigma_{c\bar{c}}^{tot} = 8.5 \pm 0.5\,(\text{stat})^{+1.0}_{-2.4}\,(\text{syst}) \pm 0.3\,(\text{lum}) \pm 0.2\,(\text{ff})^{+5.0}_{-0.4}(\text{extr})\ \text{mb} \quad (\text{ALICE})$$

Extrapolation with POWHEG+PYTHIA, fragm. ratios

$$\gamma_{s/d} = \frac{\sigma_{c\bar{c}}^{\rm tot}(D_s^+)}{\sigma_{c\bar{c}}^{\rm tot}(D^{*+}) + \sigma_{c\bar{c}}^{\rm tot}(D^+) - \sigma_{c\bar{c}}^{\rm tot}(D^{*+}) \cdot (1 - \mathcal{B}_{D^{*+}\to D^0\pi^+})} = \frac{\sigma_{c\bar{c}}^{\rm tot}(D_s^+)}{\sigma_{c\bar{c}}^{\rm tot}(D^+) + \sigma_{c\bar{c}}^{\rm tot}(D^{*+}) \cdot \mathcal{B}_{D^{*+}\to D^0\pi^+}}$$

$$P_{\rm v}^d = \frac{\sigma_{c\bar{c}}^{\rm tot}(D^{*+})}{\sigma_{c\bar{c}}^{\rm tot}(D^{*+}) + \sigma_{c\bar{c}}^{\rm tot}(D^+) - \sigma_{c\bar{c}}^{\rm tot}(D^{*+}) \cdot (1 - \mathcal{B}_{D^{*+}\to D^0\pi^+})} = \frac{\sigma_{c\bar{c}}^{\rm tot}(D^{*+})}{\sigma_{c\bar{c}}^{\rm tot}(D^+) + \sigma_{c\bar{c}}^{\rm tot}(D^{*+}) \cdot \mathcal{B}_{D^{*+}\to D^0\pi^+}}$$

$$\gamma_{s/d} = 0.26 \pm 0.05\,({\rm stat}) \pm 0.02\,({\rm syst}) \pm 0.02\,({\rm br}) \pm 0.01\,({\rm extr})\,,$$

$$P_{\rm v}^d = 0.56 \pm 0.03\,({\rm stat}) \pm 0.01\,({\rm syst}) \pm 0.01\,({\rm br}) \pm 0.02\,({\rm extr})\,.$$

$$\gamma_{s/d}^{\rm LEP} = \frac{f(c \to D_s^+)}{f(c \to D^+) + f(c \to D^{*+}) \cdot \mathcal{B}_{D^{*+}\to D^0\pi^+}} = 0.24 \pm 0.02 \pm 0.01\,({\rm br})$$

$$P_{\rm v}^{\rm LEP} = \frac{f(c \to D^{*+})}{f(c \to D^+) + f(c \to D^{*+}) \cdot \mathcal{B}_{D^{*+}\to D^0\pi^+}} = 0.61 \pm 0.02 \pm 0.01\,({\rm br})$$

Summary

- **Charmonium production:** non-prompt fractions are similar at 7 TeV and 13 TeV, larger than those at smaller *pp* and $p\bar{p}$ energies

- **Charmonium x-sections, Non-Prompt:** FONLL and GM-VFNS agree
  Prompt: only NLO NRQCD generally agree

- **X(3872) production, Prompt:** NLO NRQCD ($\chi_{c1}(2P)$ dominance) agrees
  Non-Prompt: FONLL is too high (large *Br* uncert.)
  an indication of enhanced B_c^+ contribution

- **Beauty and charmed meson productions:** strangeness suppression is ~0.25 in both beauty and charm fragmentation

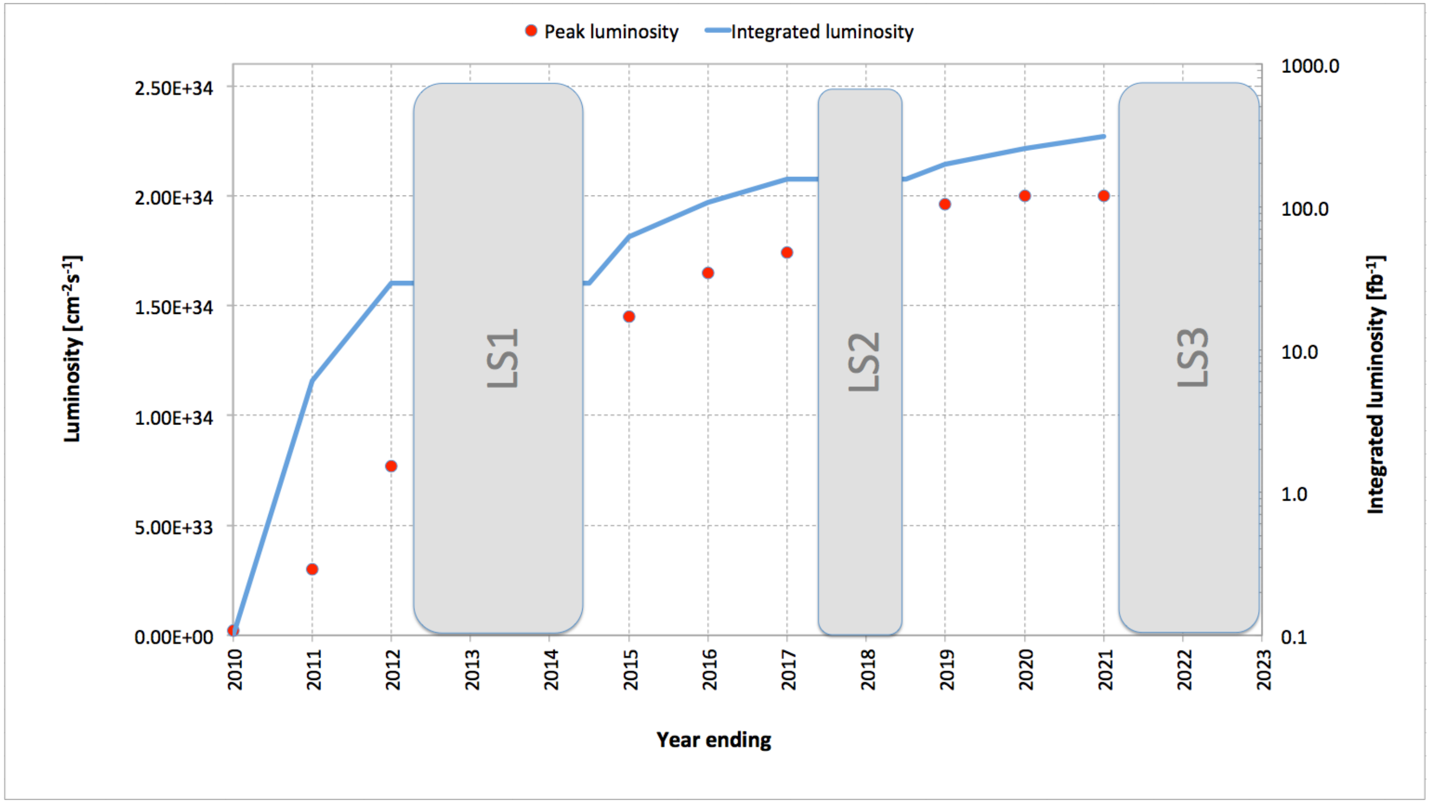
- **Beauty meson x-sections:** FONLL generally agree (somewhat harder, like for charmonium)

- **Charmed meson x-sections:** GM-VFNS agree in shape and norm.,
  FONLL and POWHEG below the data, agree within large theor. uncert.,
  MC@NLO shows the worst shape description

- More results at 13 TeV with up to 25 fb^{-1} by the end of 2016,
  and with ~100 fb^{-1} by Meson 2018

Back-up Slides

LHC



7-8 TeV

13 TeV

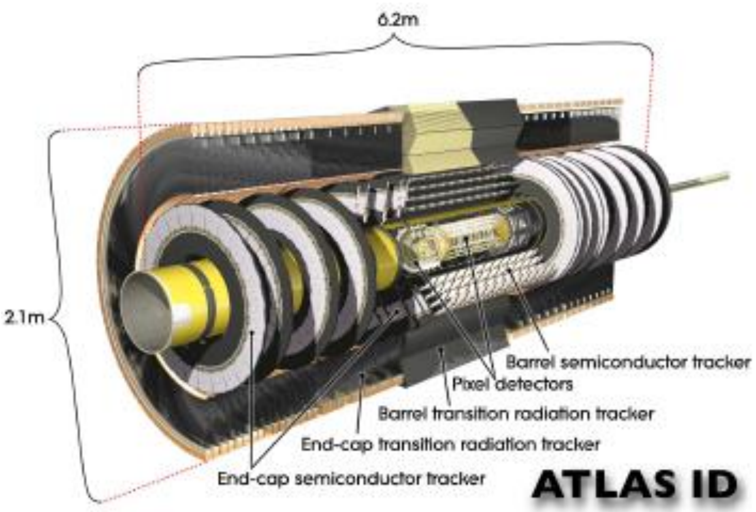
Run 1
25 fb^{-1}

Run 2
100 fb^{-1}

Run 3
300 fb^{-1}

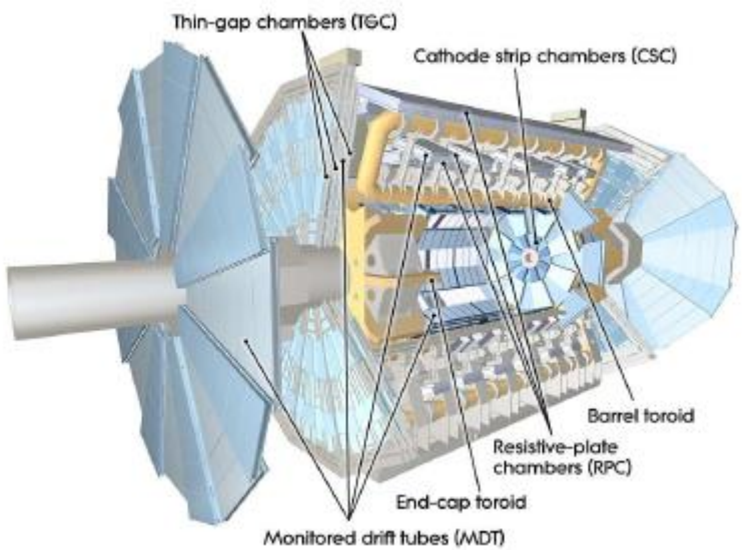
Run 4
HL-LHC
3000 fb^{-1}

Inner Detector and Muon Spectrometer



- Pixel detector: 3 barrel layers, 2 x 3 end-cap discs: $\sigma_{r\phi}$ ~ 10 μm, σ_z ~115 μm
- Semiconductor Tracker (SCT): 4 barrel layers, 2 x 9 end-cap discs: $\sigma_{r\phi}$ ~ 17 μm, σ_z ~115 μm
- Transition Radiation Tracker (TRT): 73 barrel straw layers, 2 x 160 end-cap radial straw discs: $\sigma_{r\phi}$ ~ 130 μm
- All within a 2 T magnetic field

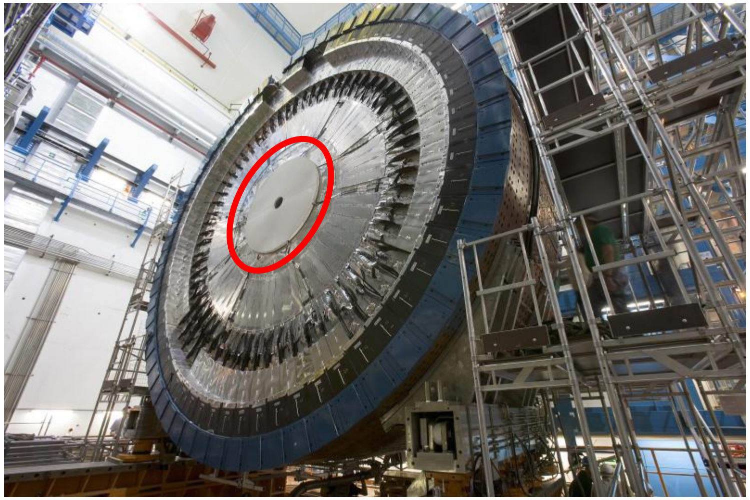
$$\sigma(p_T)/p_T \sim 0.05\% p_T(GeV) \oplus 1\%$$



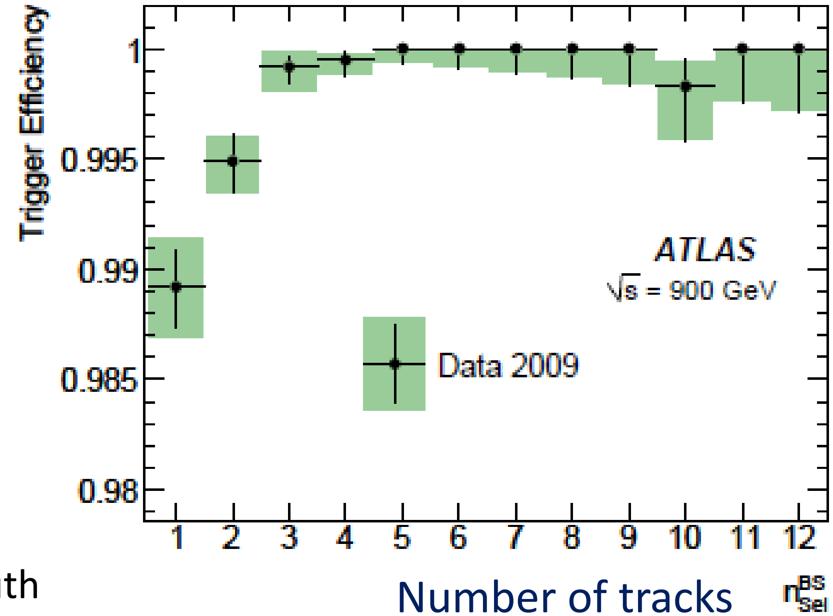
Muon Spectrometer

- Toroidal magnetic field: bending power 1.5-5.5 Tm (barrel) and 1-7.5 Tm (end-cap)
- Precision chambers (Monitored Drift Tubes MDT, Cathod Strip Chambers CSC)
- Fast Trigger layers (Resistive Plate Chambers RPC, Thin Gap Chambers TGC)
- $|\eta| < 2.7$, $\sigma(p_T)/p_T \sim 10\%$ up to 1 TeV

Minimum-Bias Trigger



MinBias Trigger Scintillator at z=±3.56 m
on LAr cryostat; 2 rings with 8 sector in azimuth
2.09<|η|<2.82, 2.82<|η|<3.84



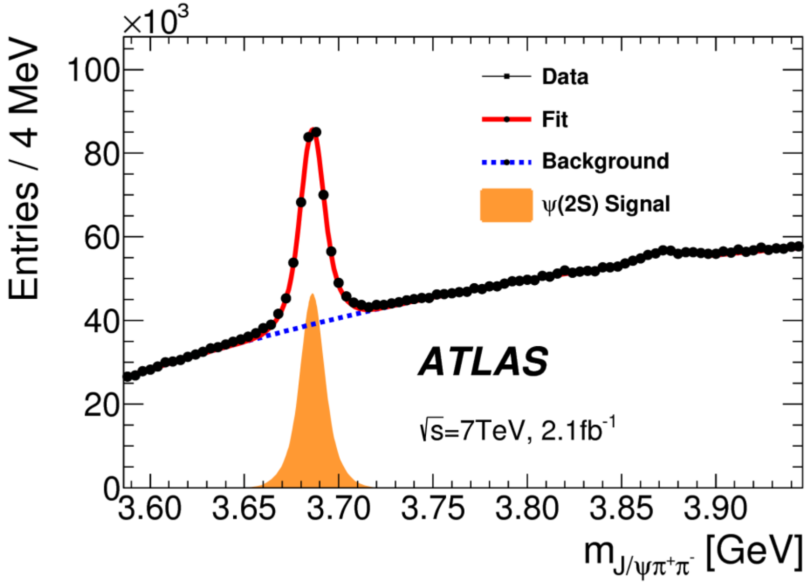
At least one hit above threshold in the Minimum-Bias Trigger Scintillators at each end of the detector

Efficiency is ~100% for events with at least 2 tracks passing beam-spot region

MBTS trigger allow us to measure *D*-mesons production cross-sections without uncertainty originating from trigger efficiency

The trigger is heavily prescaled with luminosity increase

$\psi(2S) \rightarrow J/\psi\ (\rightarrow \mu^+\mu^-)\pi^+\pi^-$



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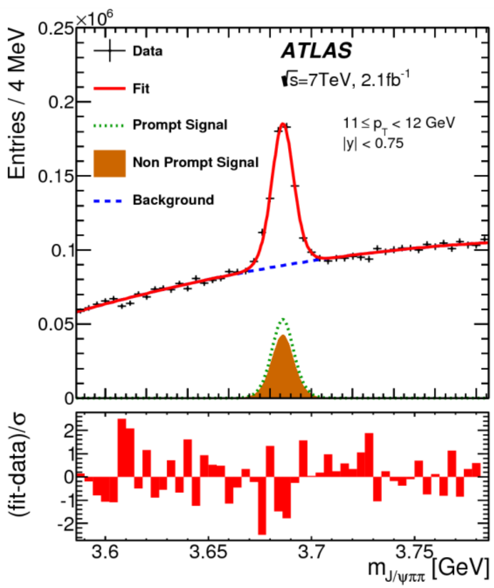
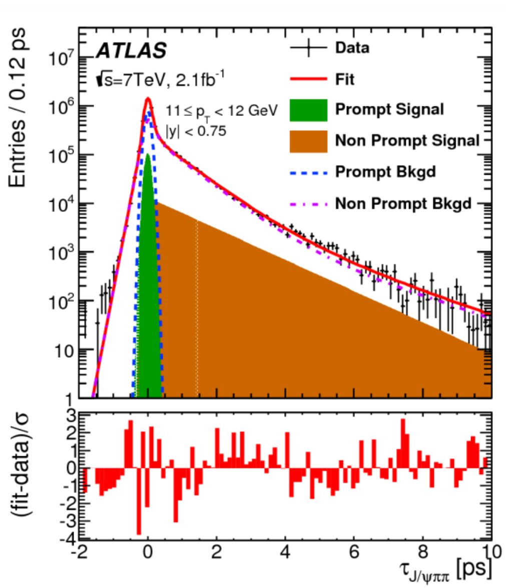
~ 200 000 *ψ(2S)* mesons

- contributes to inclusive J/ψ x-sections
- free from feed-downs of heavier charmonium states

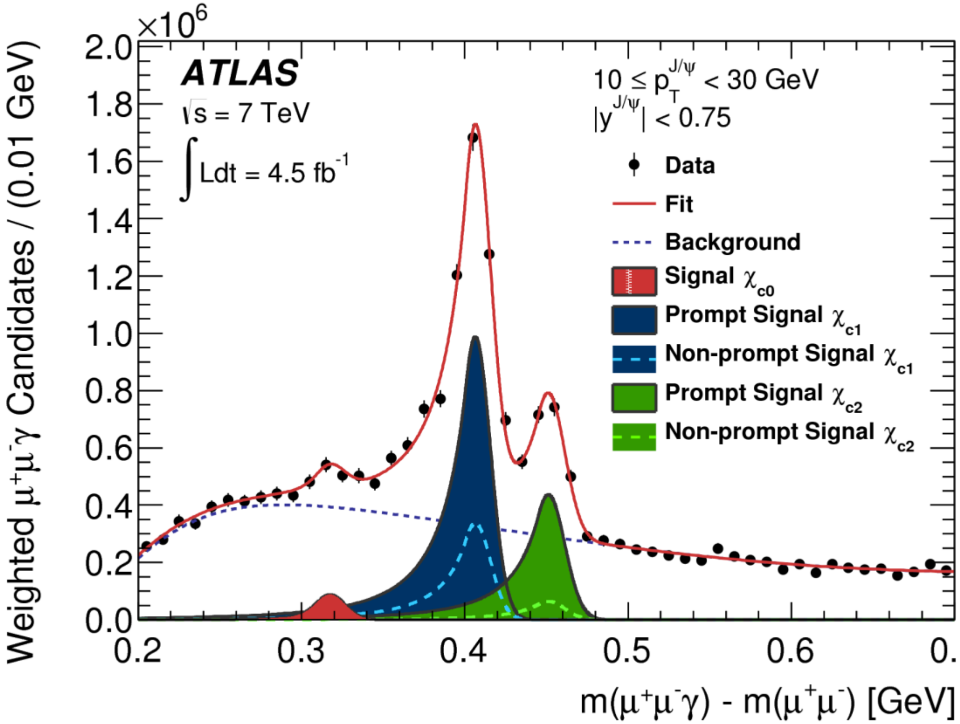




To separate prompt and non-prompt (from B decays) production pseudo-proper lifetime is used

$$\tau = \frac{L_{xy} \cdot m_{J/\psi}}{|\vec{p_T}|} \qquad L_{xy} = \frac{\vec{L} \cdot \vec{p_T}}{|\vec{p_T}|}$$

$\chi_{c1/2} \rightarrow J/\psi\ (\rightarrow \mu^+\mu^-)\ \gamma$



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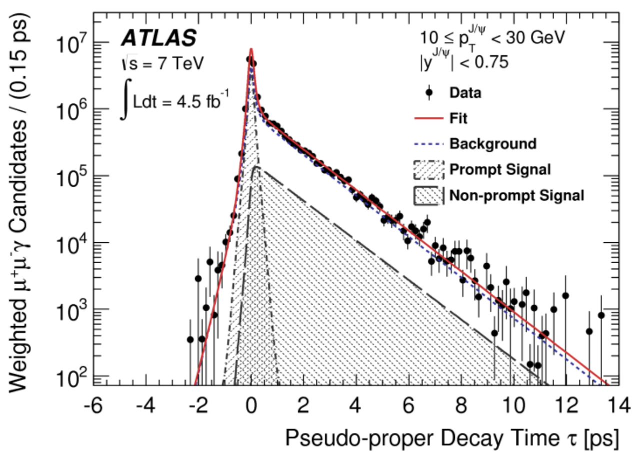
only converted photons

$$p_T^\gamma > 1.5 \text{ GeV and } |\eta^\gamma| < 2.0$$

$$2.95 < m(\mu^+\mu^-) < 3.25 \text{ GeV}$$



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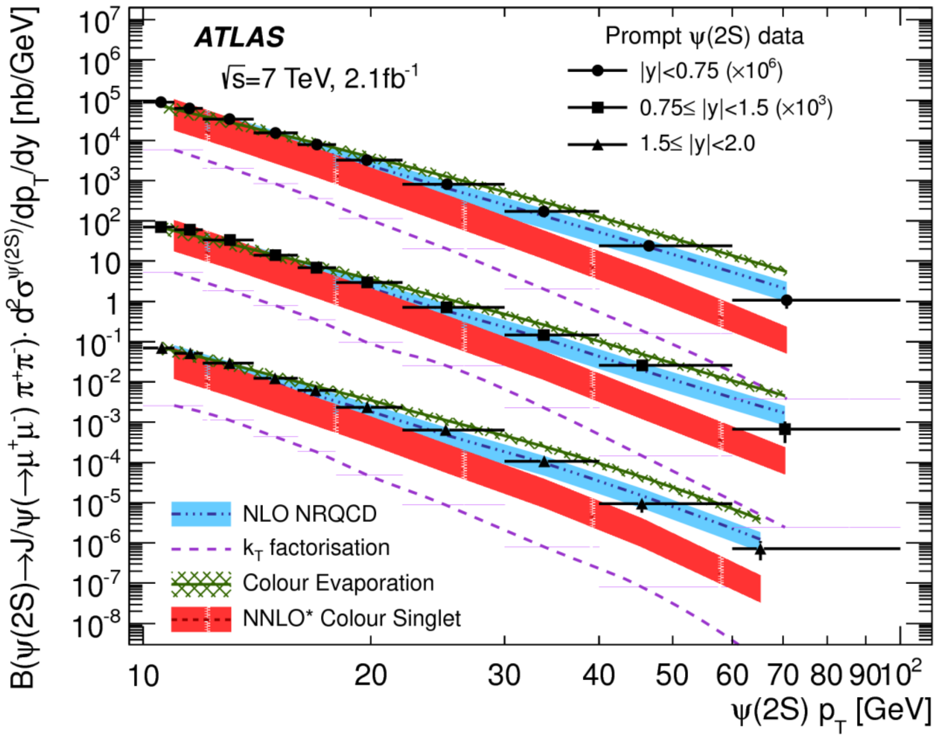
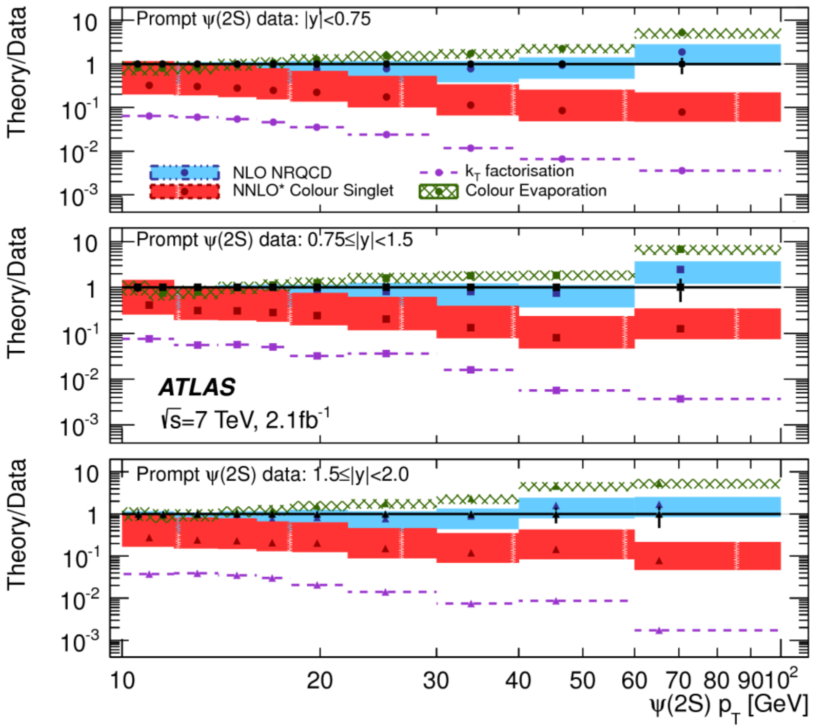
$$\tau = \frac{L_{xy} \cdot m_{J/\psi}}{|\vec{p_T}|} \qquad L_{xy} = \frac{\vec{L} \cdot \vec{p_T}}{|\vec{p_T}|}$$

$\psi(2S) \rightarrow J/\psi\ (\rightarrow\mu^+\mu^-)\pi^+\pi^-$, prompt diff. x-sections



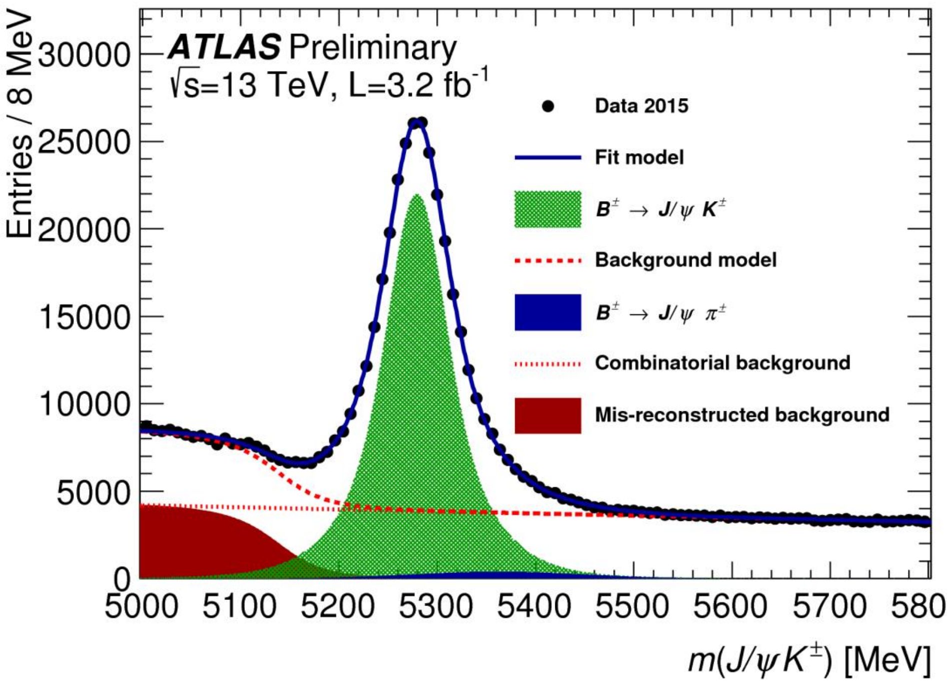


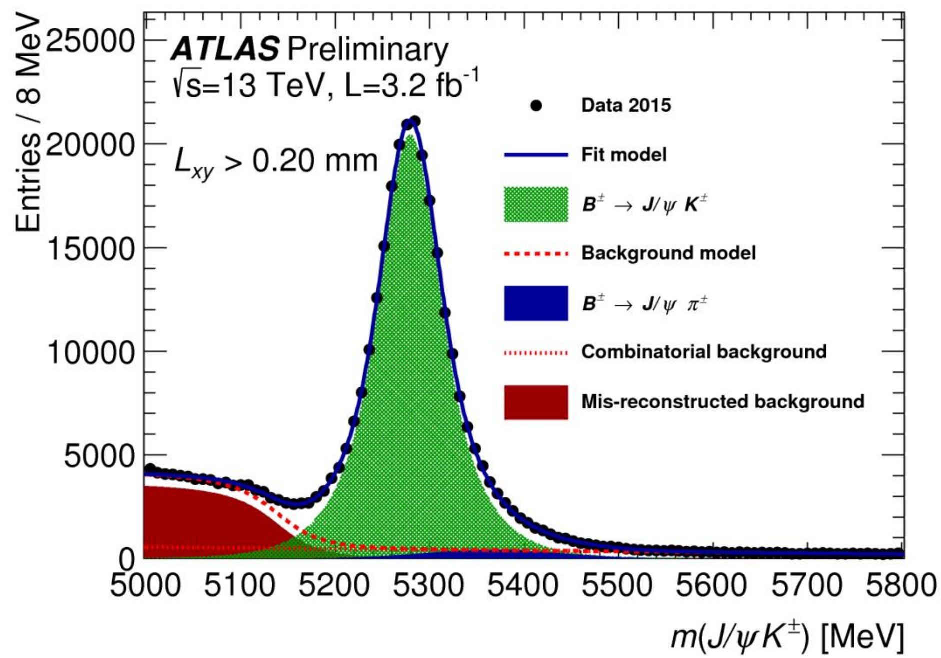
- NLO NRQCD is generally o.k.

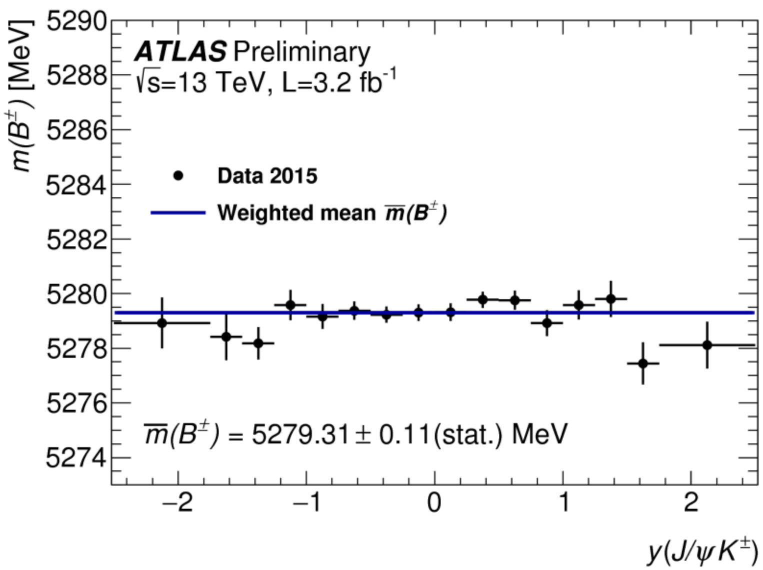
- CS is too low even at NNLO*

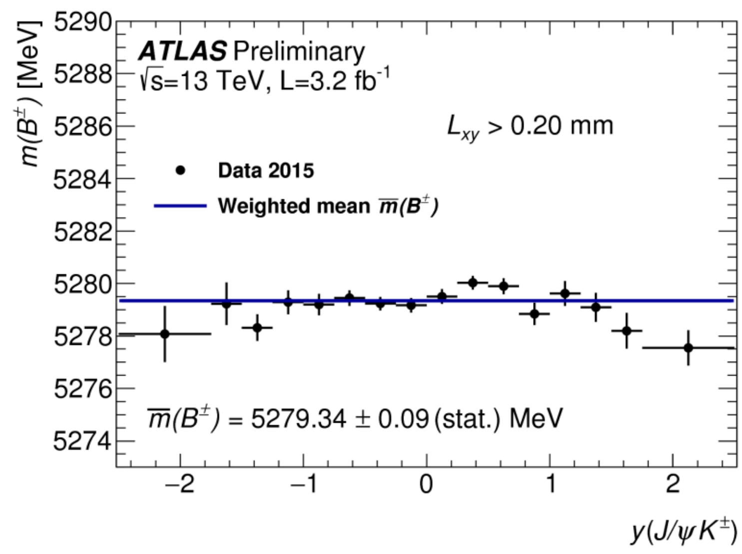
- CEM is somewhat too hard

Beauty hadron production: $B^+ \to J/\psi K^+$, 13 TeV









NLO++ predictions

POWHEG-PYTHIA, POWHEG-HERWIG, MC@NLO(-HERWIG)

- matched NLO+LL calculations
- available as public generators
- use MC fragmentation and decays
- normalized (by us) to LEP fragm. fractions ($f(c \to D)$, $f(b \to D)$)

FONLL from M.Cacciari et al.

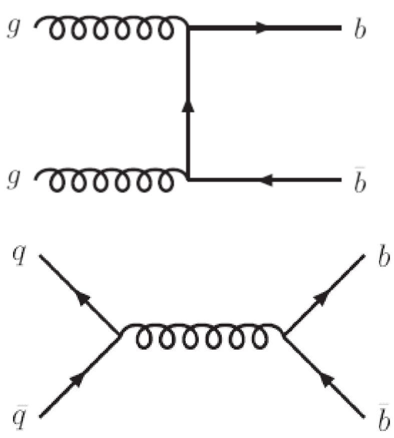
- matched NLO+NLL calculations (developed from "massive" NLO)
- available from public web-form
- use own fits of fragmentation functions
- normalized (by us) to LEP fragm. fractions

GM-VFNS from B.Kniehl et al.

- available from authors by request (developed from "massless" NLO)
- use own fits of fragmentation functions and fragmentation fractions
- consider fragmentation from light quarks and gluons to D mesons
- only scale uncertainties (dominant)

Scales and parameters and set and varied by the predictions authors or in consultations with them

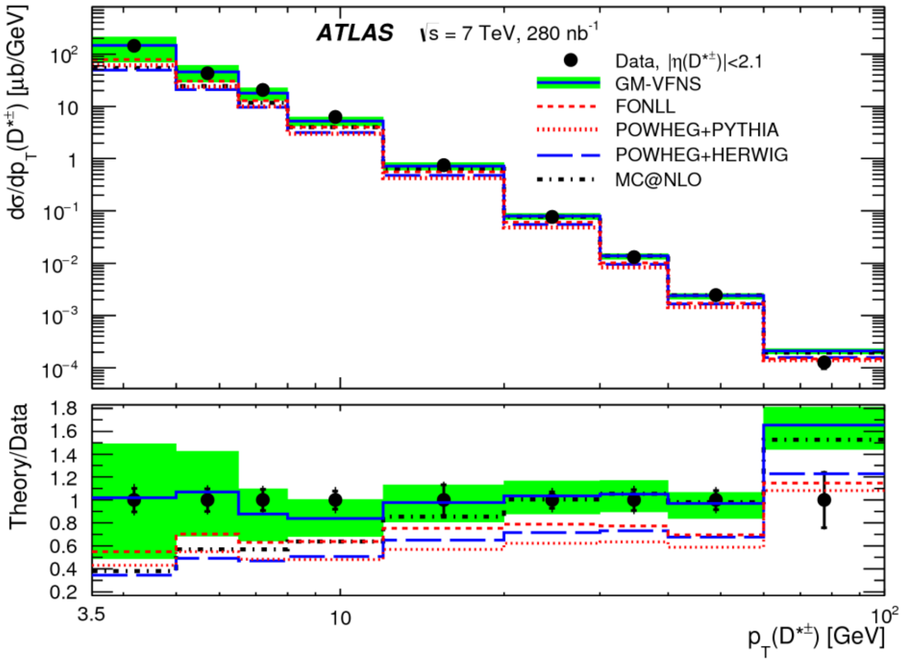
flavor creation
($gg \to Q\bar{Q}$, $q\bar{q} \to Q\bar{Q}$)

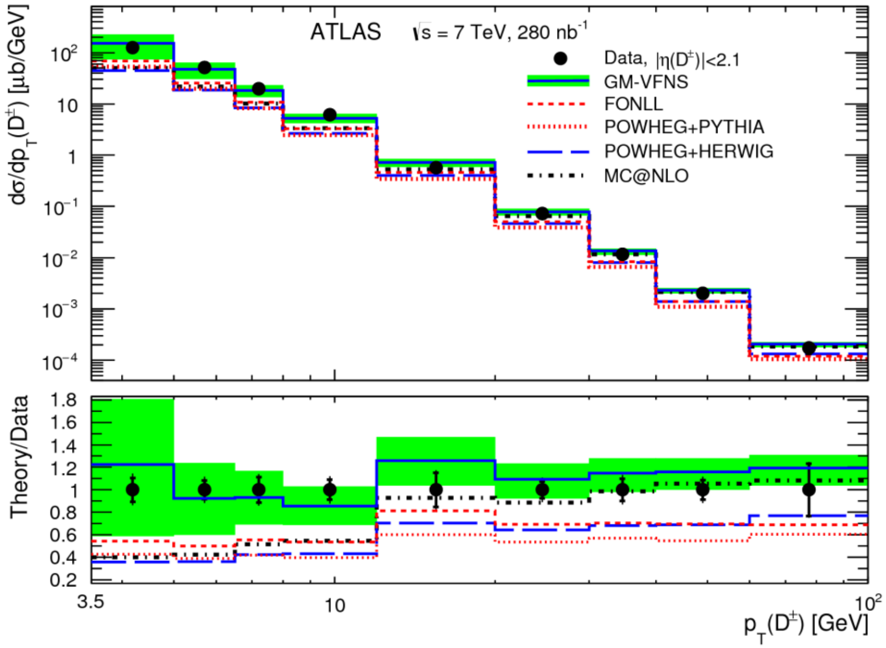


gluon splitting
($g \to Q\bar{Q}$)

flavor excitation
($gQ \to gQ$, $qQ \to qQ$)

$D^{(*)\pm}$ differential x-sections vs $p_T(D^{(*)\pm})$





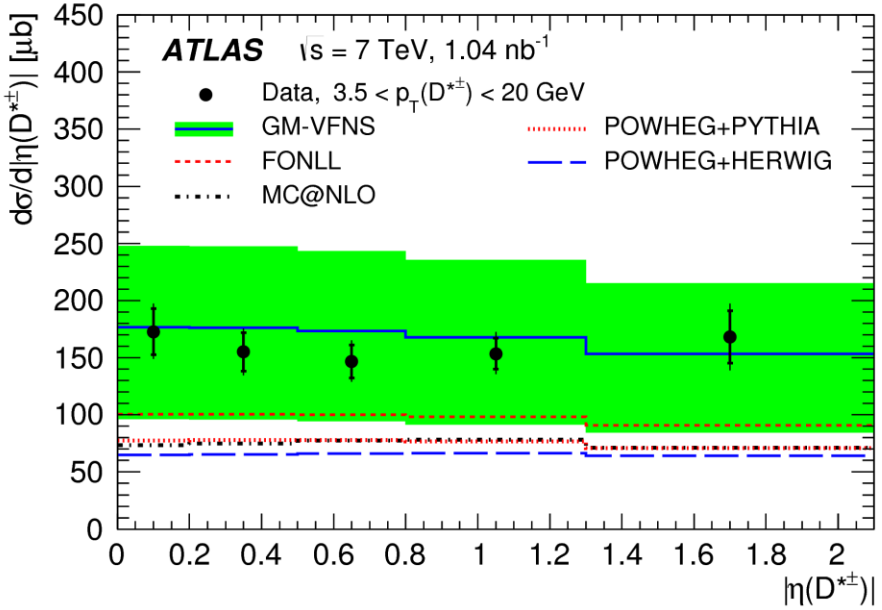
GM-VFNS - agree both in shape and normalization

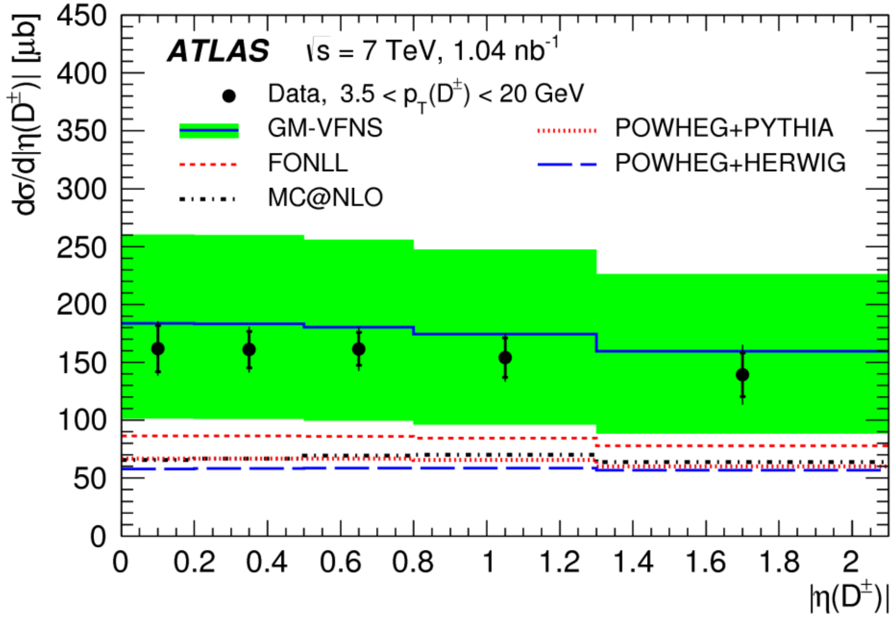
FONLL, POWHEG, MC@NLO - agree within large theoretical uncertainties

MC@NLO - worst shape description

$D^{(*)\pm}$ differential x-sections vs $|\eta(D^{(*)\pm})|$

$3.5 < p_T < 20\,\mathrm{GeV}$



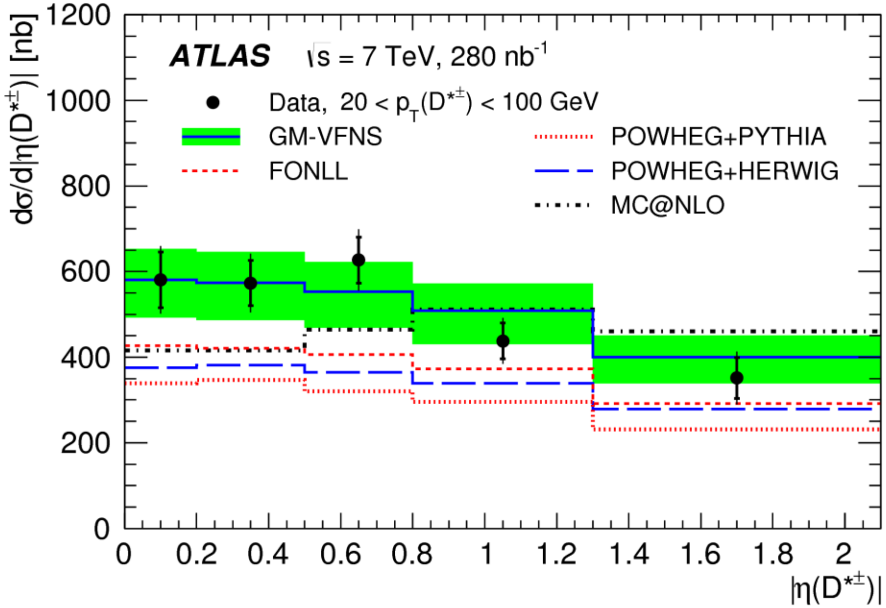


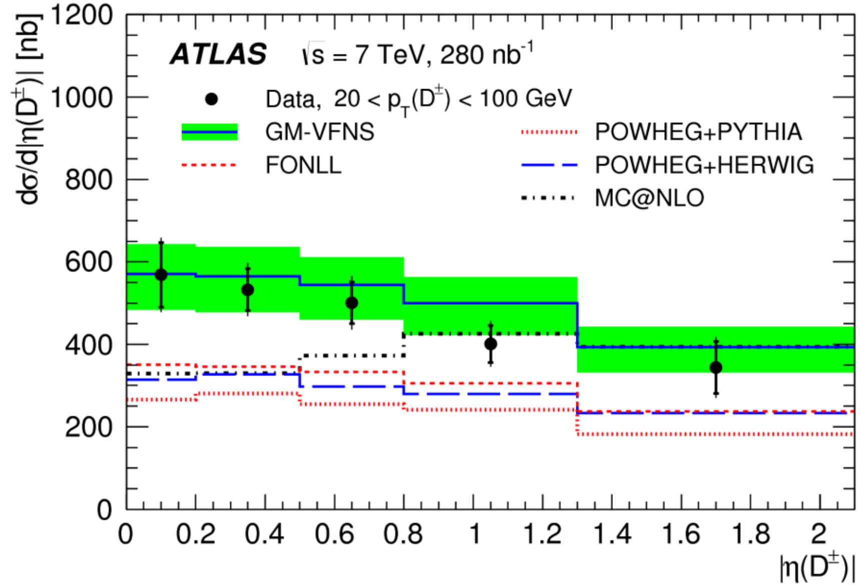
GM-VFNS - agree both in shape and normalization

FONLL, POWHEG, MC@NLO - agree within large theoretical uncertainties

$D^{(*)\pm}$ differential x-sections vs $|\eta(D^{(*)\pm})|$

$20 < p_T < 100\,\mathrm{GeV}$





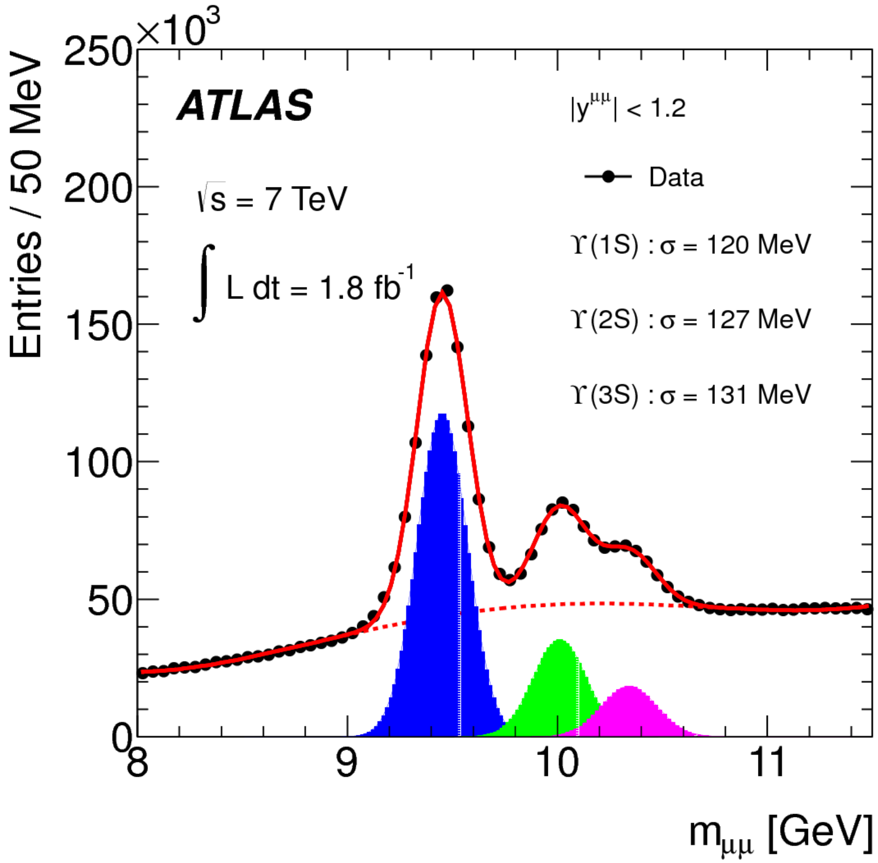
GM-VFNS - agree both in shape and normalization

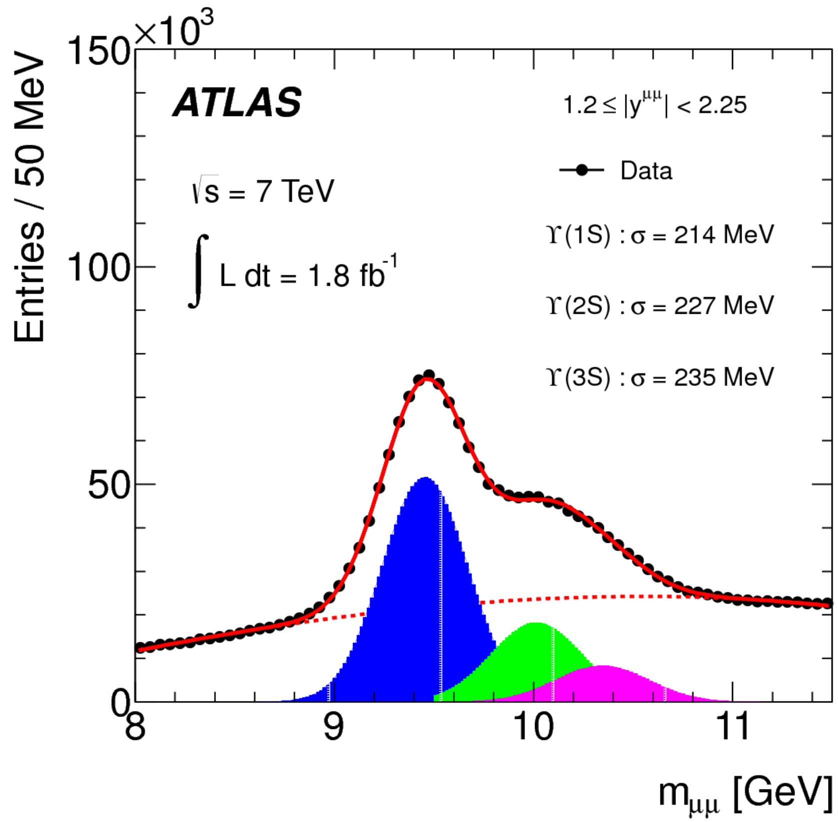
FONLL, POWHEG, MC@NLO - agree within large theoretical uncertainties

MC@NLO - worst shape description

Bottomonium production, 7 TeV

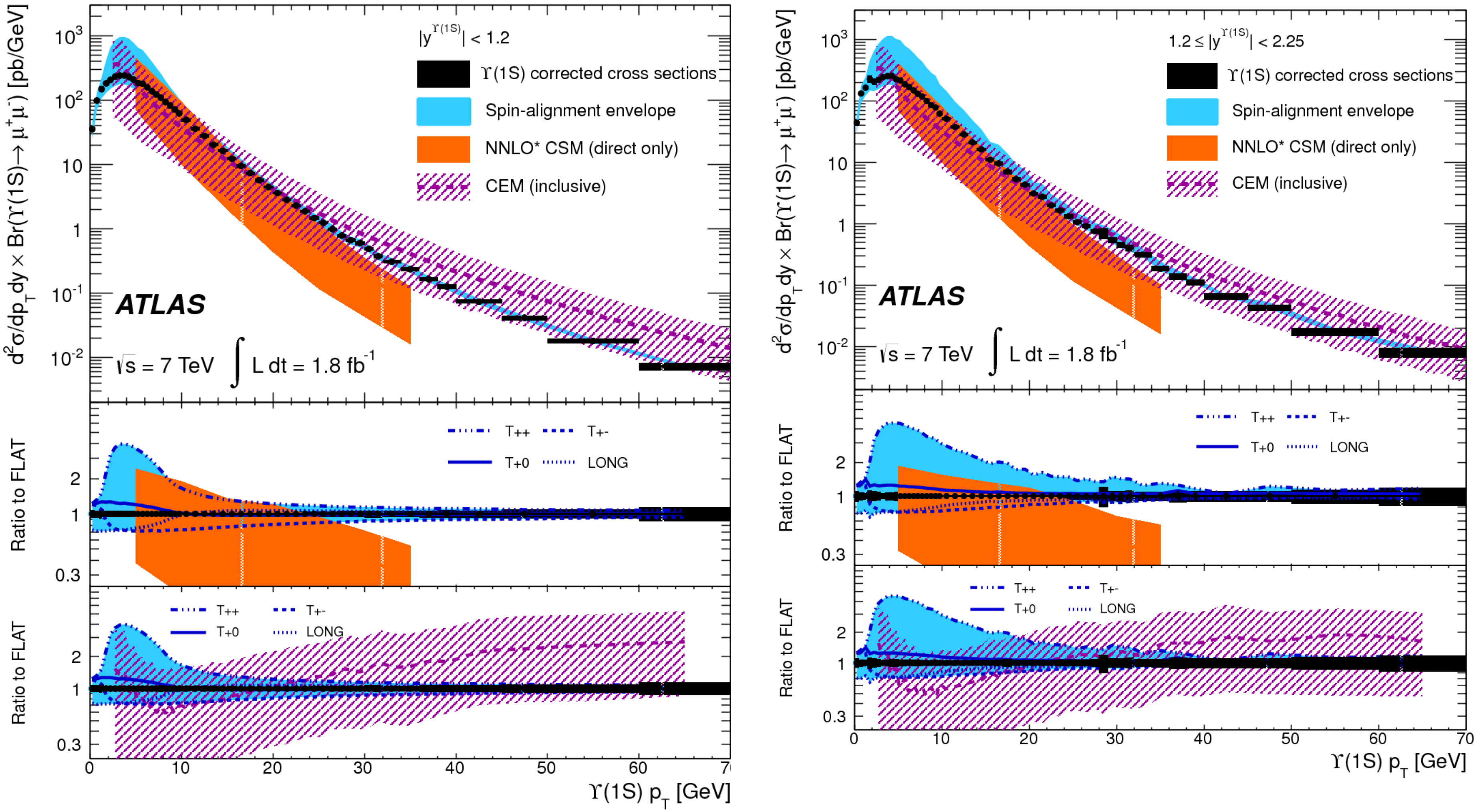
PRD 87 (2013) 052004





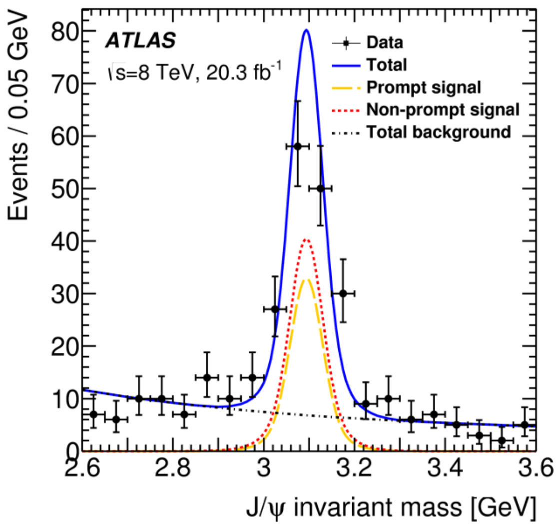
Bottomonium production, 7 TeV

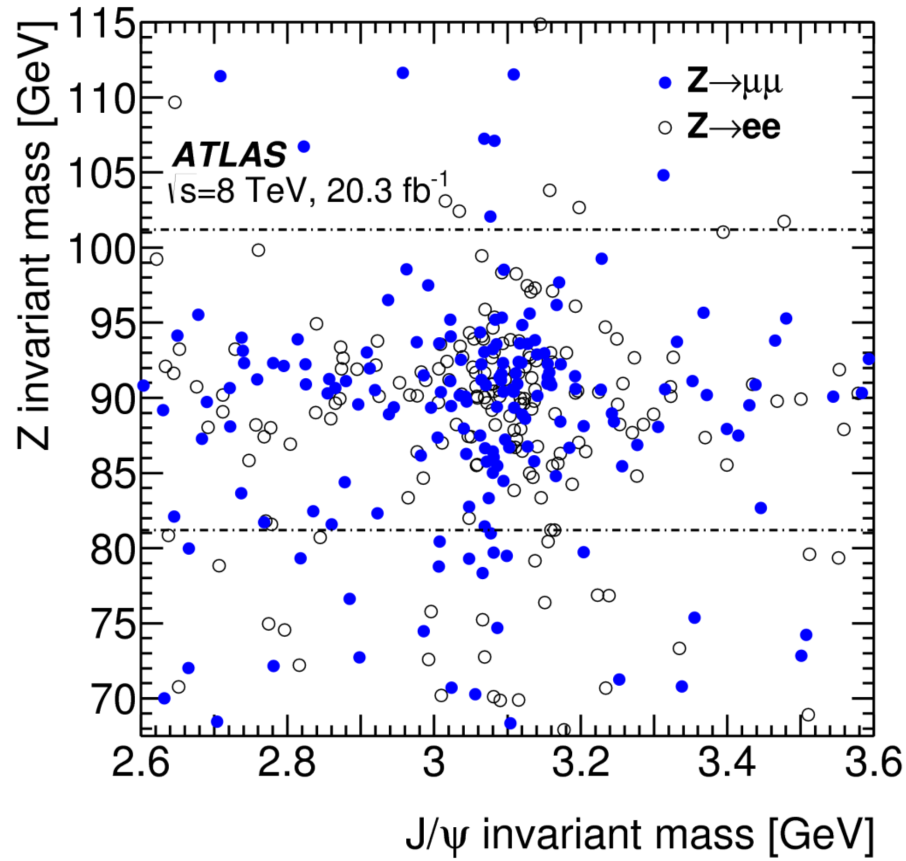
PRD 87 (2013) 052004

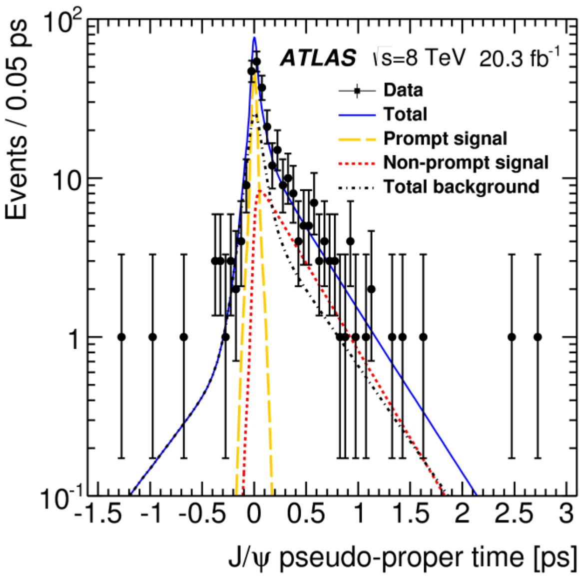


Z + J/ψ production (1st obs.) ATLAS, Z + J/Ψ, arXiv:1412.6428

Prompt component probes mechanisms of $c\bar{c}$ system production and transformation to a meson at high scale; potentially sensitive to Double Parton Scattering (DPS)





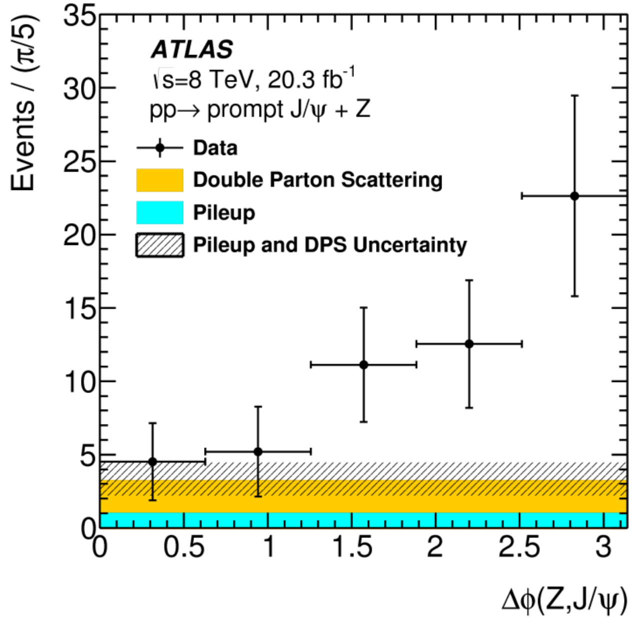


$$8.5 < p_T(J/\psi) < 100 \text{ GeV}$$

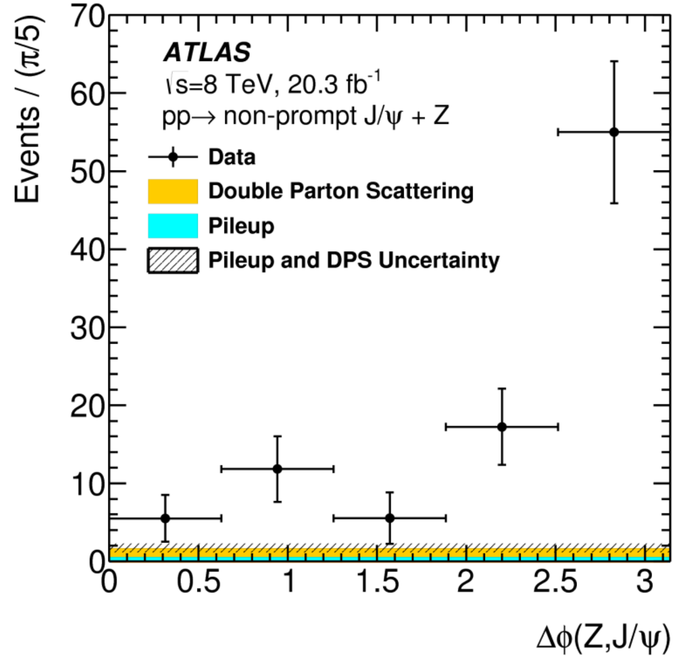
$$|y(J/\psi)| < 2.1$$

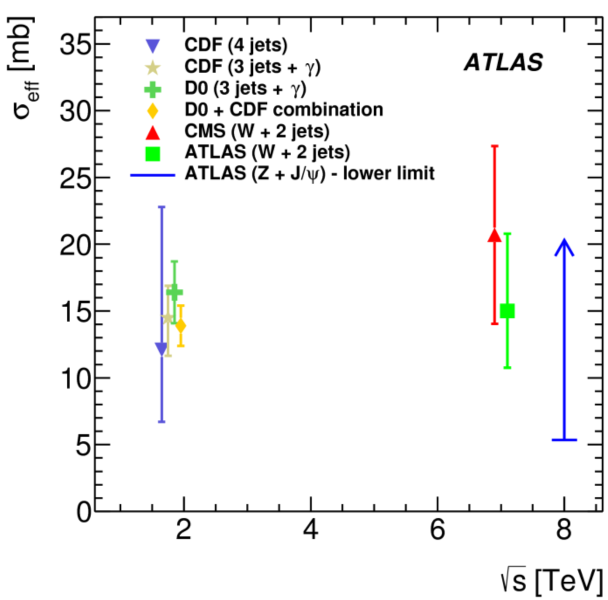
$Z + J/\psi\ (\rightarrow\mu^+\mu^-)$, $\Delta\varphi$ distributions and DPS

Prompt: 56 ± 10



Non prompt: 95 ± 12





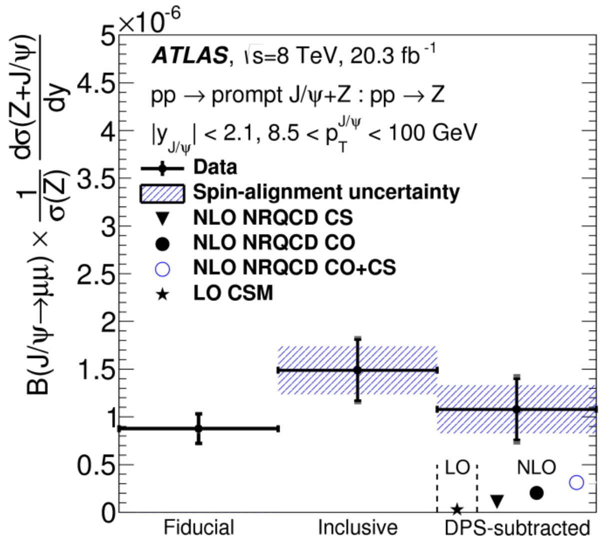
$\sigma_{\rm eff} = 15 \pm 3\,({\rm stat.})^{+5}_{-3}\,({\rm sys.})\,{\rm mb}$ ATLAS (W + 2 jets)

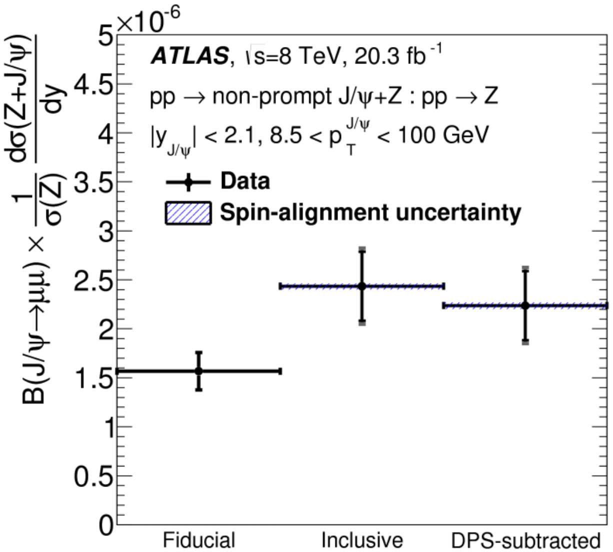
$\sigma_{\rm eff} > 5.3\,{\rm mb}\ \ (3.7\,{\rm mb})\ \ {\rm at}\ 68\%\ \ (95\%)$ ATLAS (Z + J/ψ)

$Z + J/\psi\ (\rightarrow \mu^+\mu^-)$, integrated and diff. cross sections

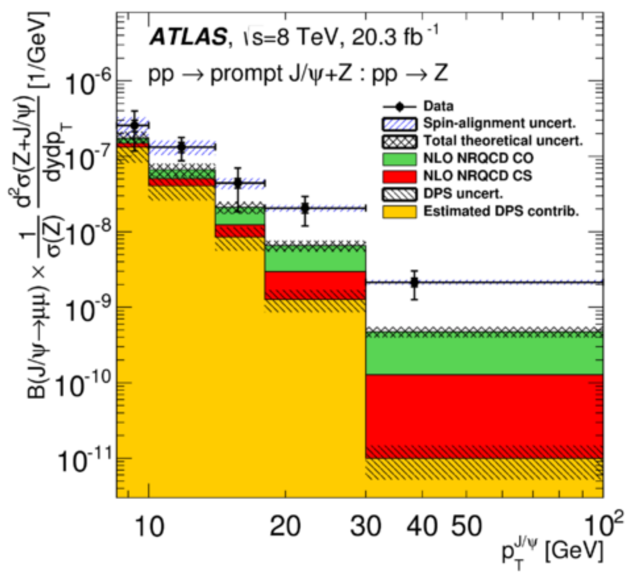
NRQCD: Mao et al.

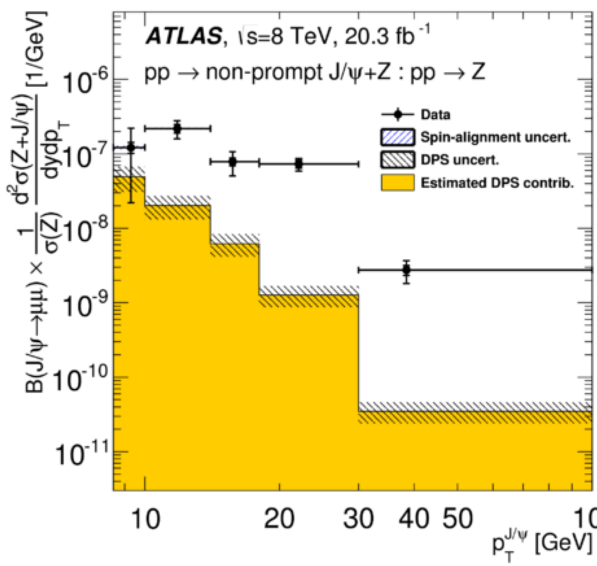
CSM: Gong et al.





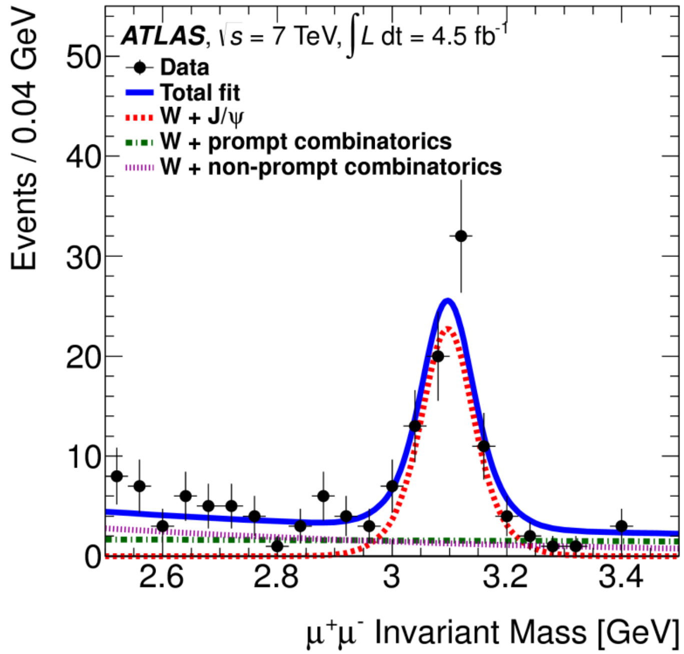
Predictions below data

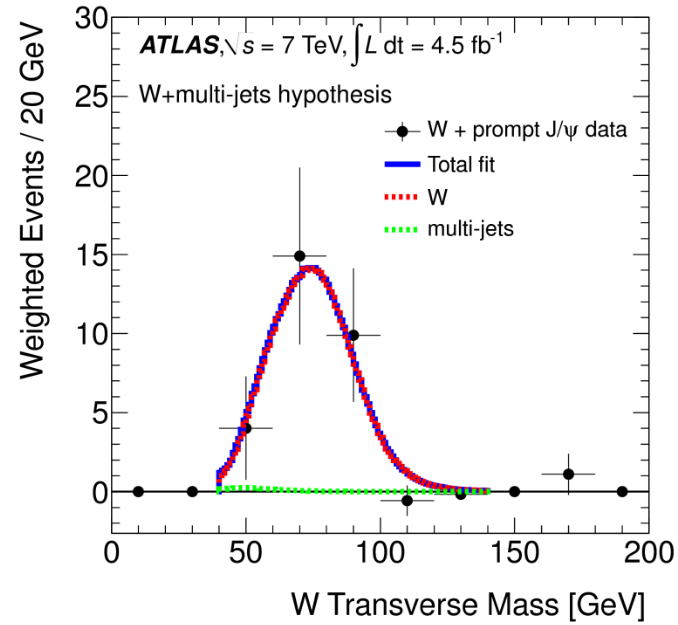




$W + J/\psi\ (\rightarrow \mu^{+}\mu^{-})$

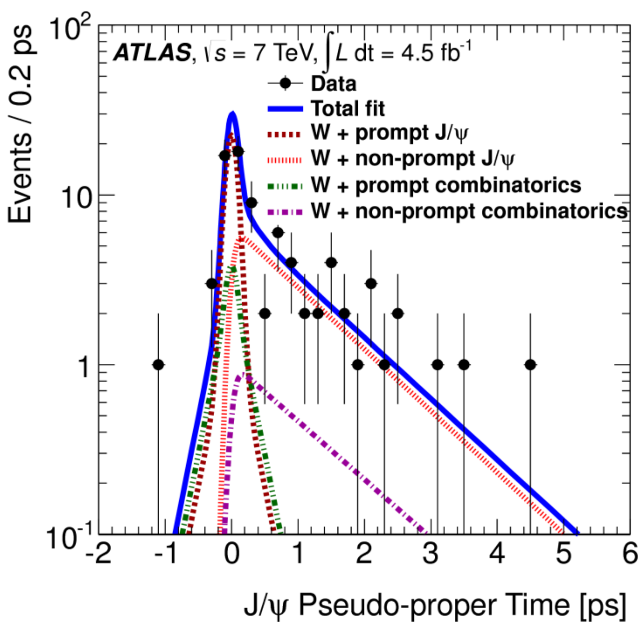
ATLAS, W + J/Ψ, JHEP 04 (2014), 172





$W^{\pm} \rightarrow \mu\nu_{\mu}$

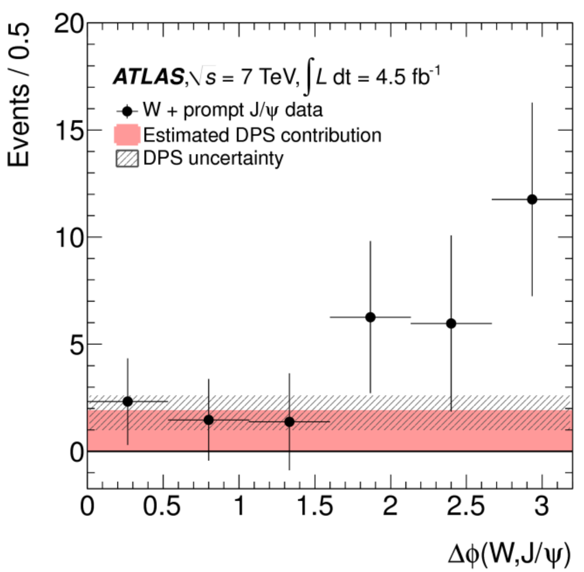
$$m_{\mathrm{T}}(W) \equiv \sqrt{2 p_{\mathrm{T}}(\mu) E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos(\phi^{\mu} - \phi^{\nu_{\mu}})\right)}$$



$0 < |y_{J/\psi}| < 2.1$, $8.5 < p_{T\ J/\psi} < 30$ GeV

$$\tau = \frac{L_{xy} \cdot m_{J/\psi}}{|\vec{p_T}|}$$

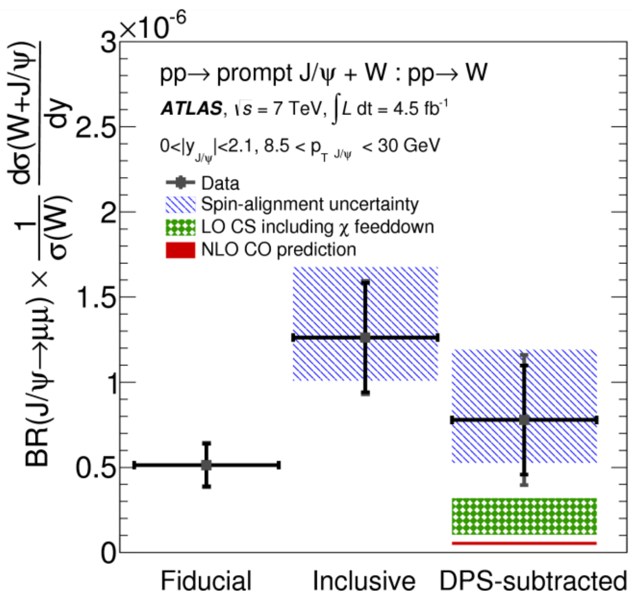
$W + J/\psi$ ($\to\mu^+\mu^-$), $\Delta\varphi$ distr. and rates w.r.t. inclusive W

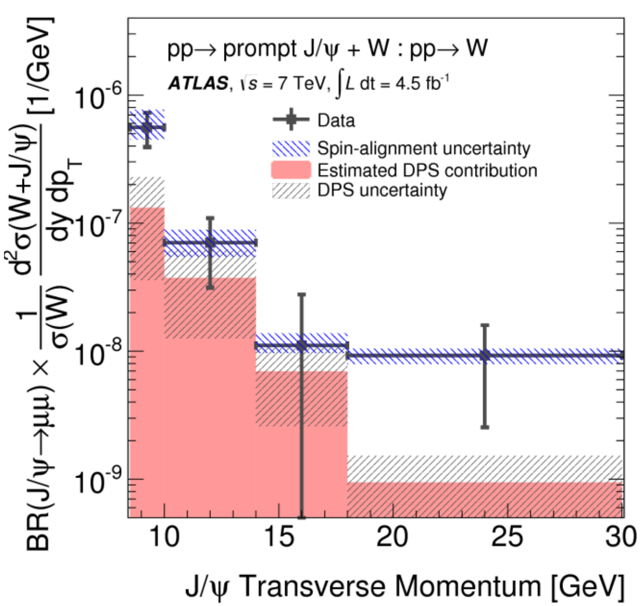


$27.4^{+7.5}_{-6.5}$ $W^{\pm}$ + prompt J/ψ events

DPS: $\sigma_{\rm eff} = 15 \pm 3\,(\text{stat.})^{+5}_{-3}\,(\text{sys.})\,\text{mb}$

10.8 ± 4.2





LO CS: Lansberg et al. NLO CO: Mao et al.