Heavy quark physics at ATLAS and CMS

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on behalf of the ATLAS and CMS Collaborations

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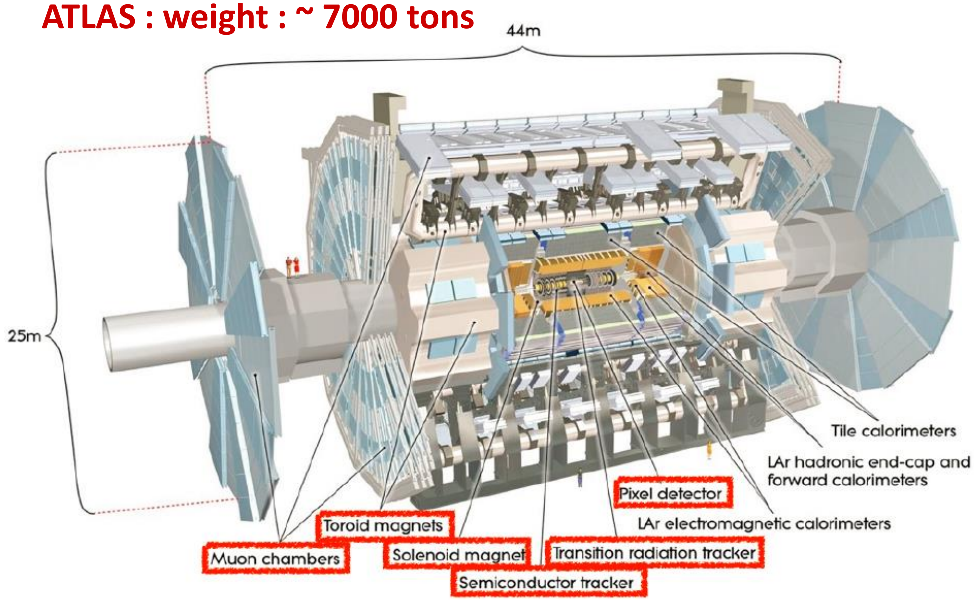
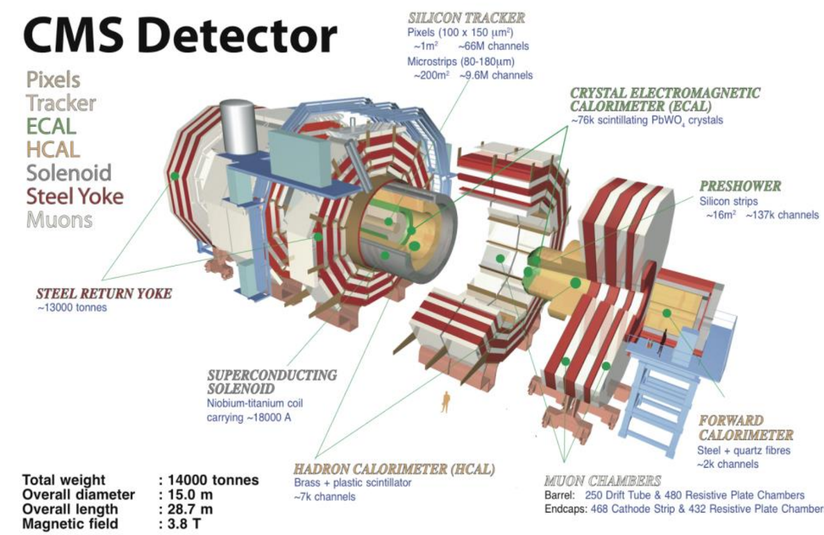
Selected recent results

Outline : ATLAS + CMS @ LHC
- Charm and Beauty meson Production
- Charmonium and Bottomonium production
- Mixing and CP violation
- Rare decays (FCNC)
- Decays and Spectroscopy
- Summary

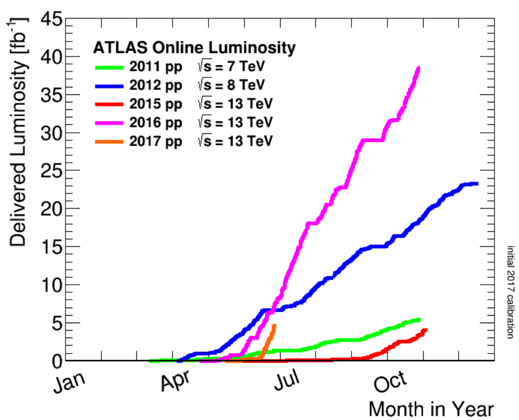
ATLAS+CMS @ LHC

ATLAS : weight : ~ 7000 tons

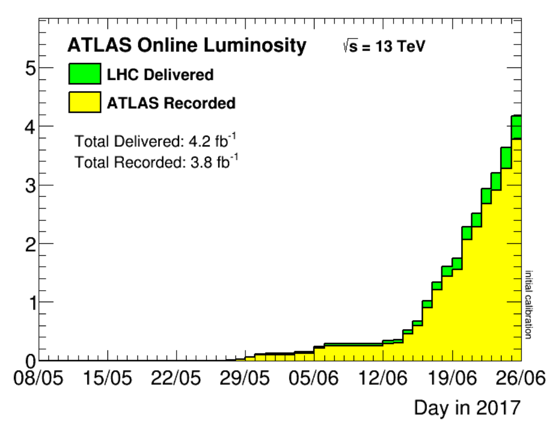


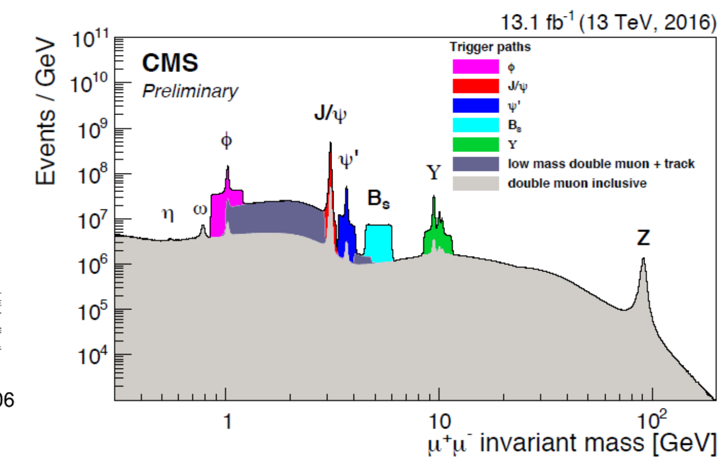


2010 - 2017



2017





L_{max} = 13.8 x 10^{33} cm^{-2} s^{-1}

L_{max} = 15.5 x 10^{33} cm^{-2} s^{-1}

Dimuon triggers

L_{int} ≈ 60 fb^{-1} per experiment

Charm and Beauty meson Production

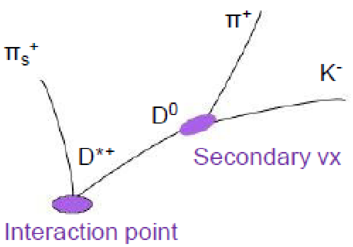
Charmed meson production @ 7 TeV: $D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$

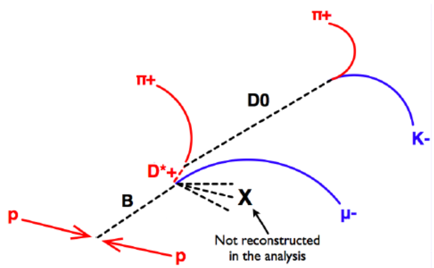
ATLAS, NP B 907 (2016) 717

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

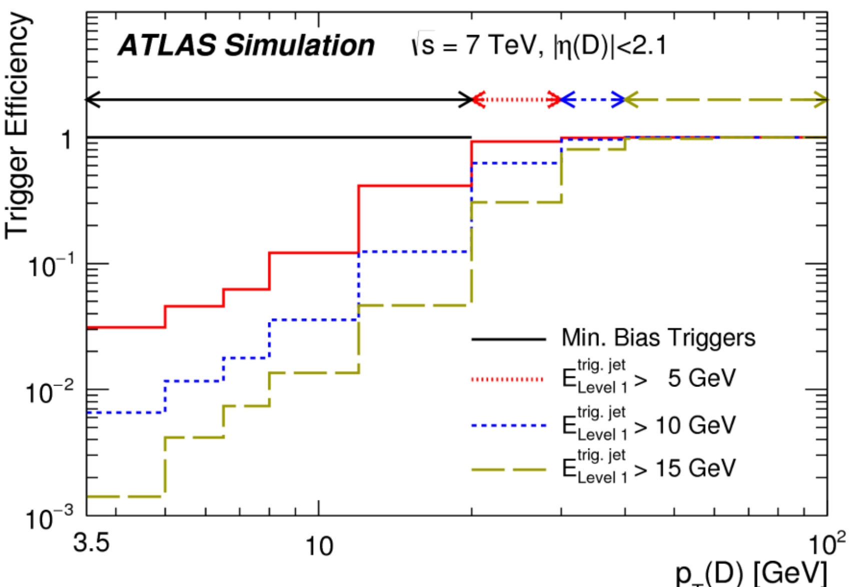
$D^+ \rightarrow K^- \pi^+ \pi^+$ (+c.c.)

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

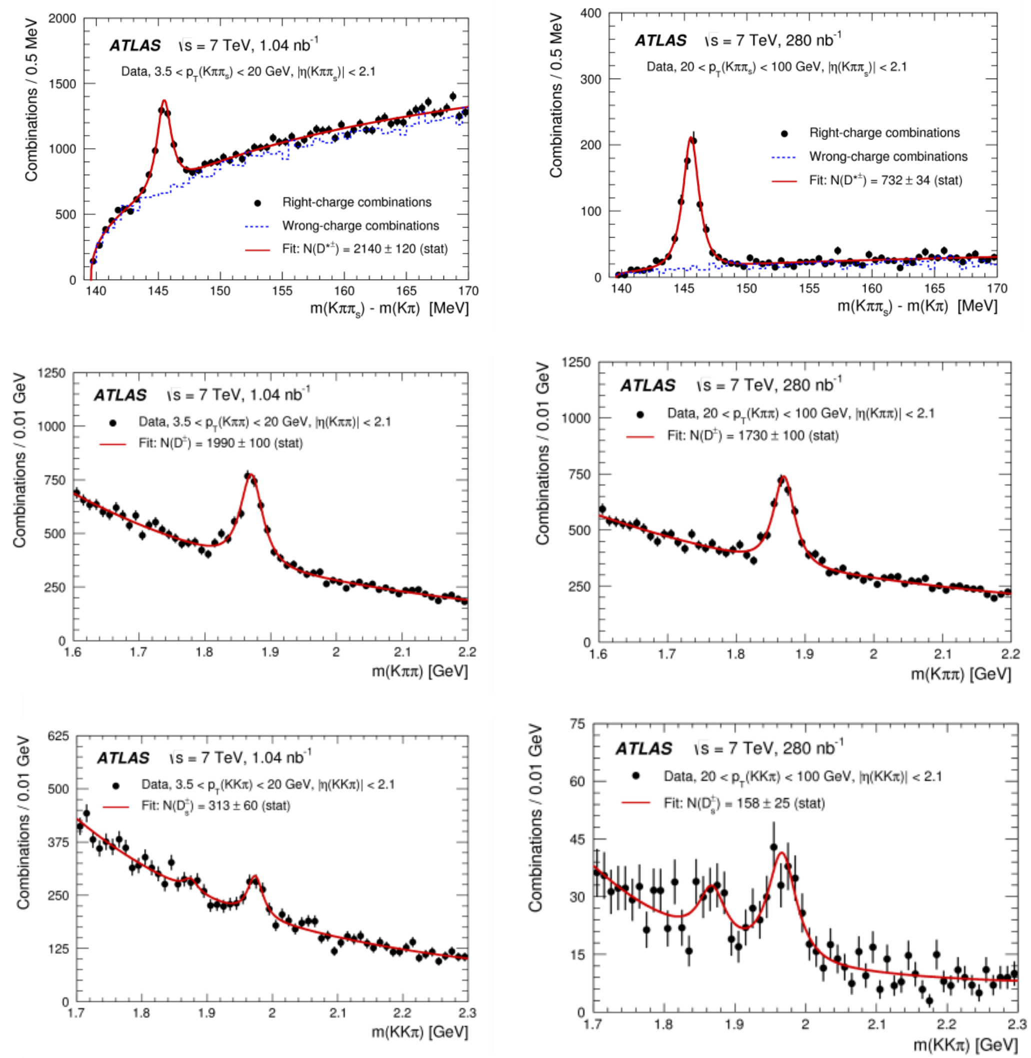




~ 10%



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



D meson visible x-sections

ATLAS, NP B 907 (2016) 717

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}

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

FONLL – matched NLO+NLL (developed from "massive" NLO)

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

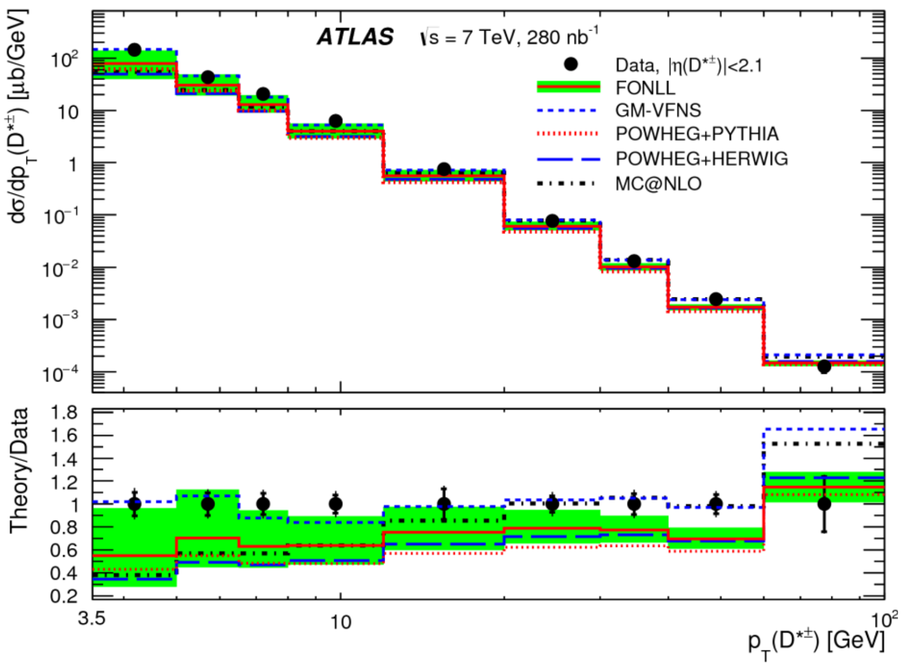
MC@NLO (+HERWIG) – matched NLO+LL (developed from "massive" NLO)

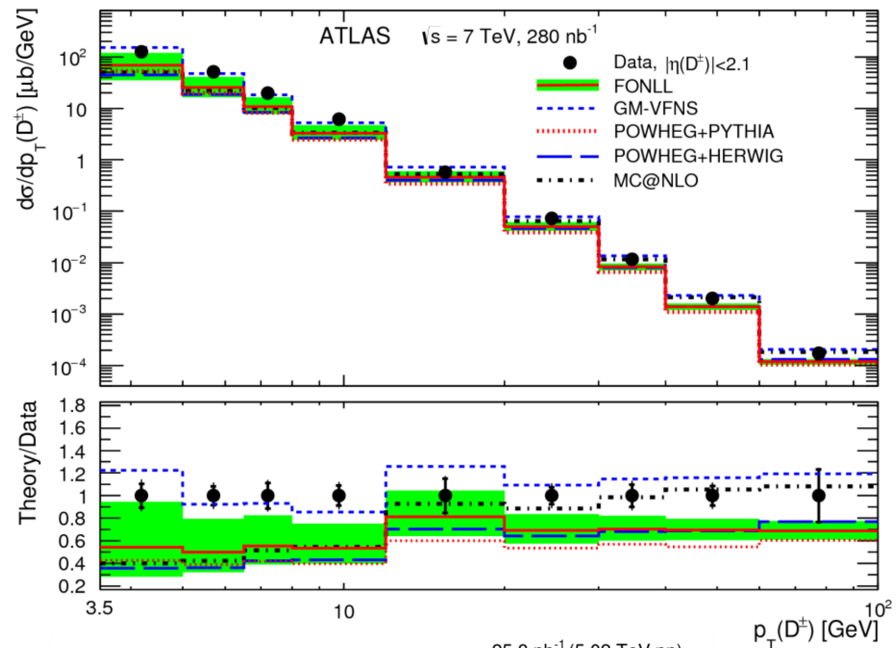
NNLO is in principle available (Czakon et al.),
but not yet numerically stable for masses in the few-GeV range

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

ATLAS, NP B 907 (2016) 717

CMS PAS HIN-16-001

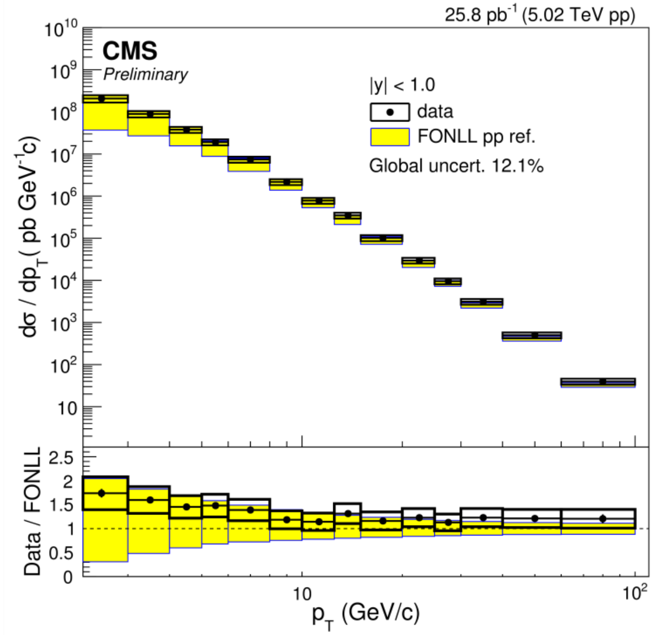




GM-VFNS – agree both in shape and normalization

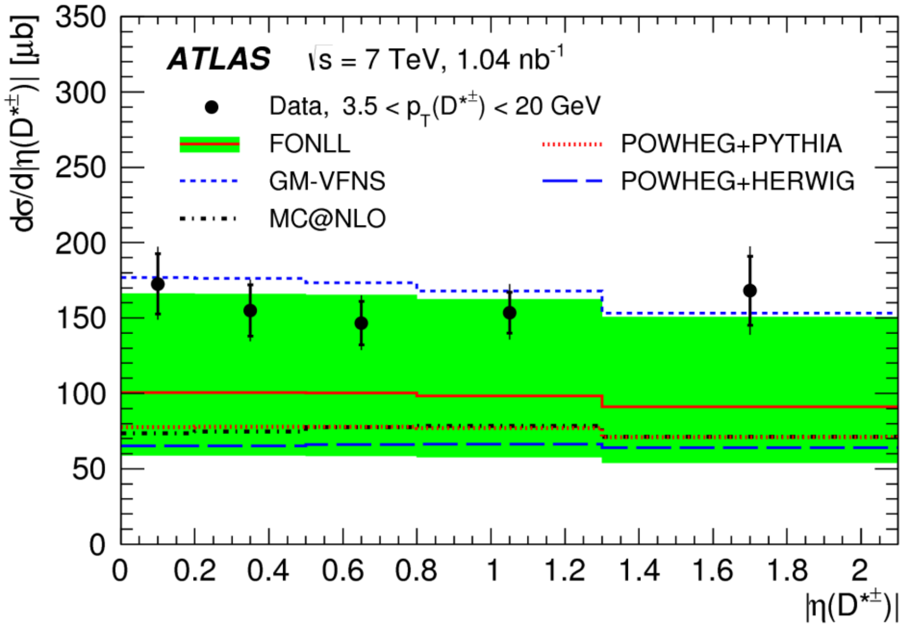
FONLL, POWHEG, MC@NLO – agree within large theoretical uncertainties

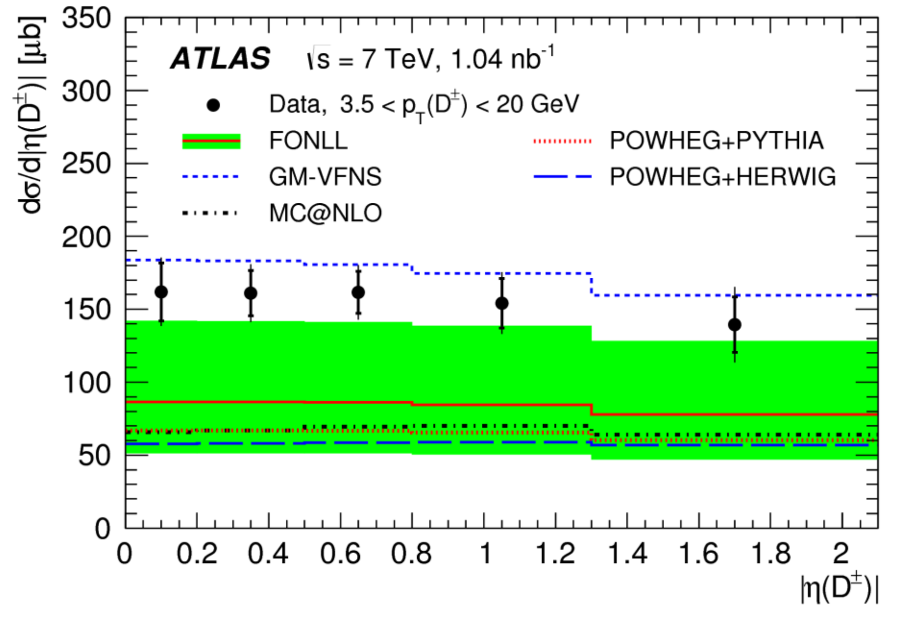
MC@NLO – worst shape description



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

low-p_T: 3.5 – 20 GeV





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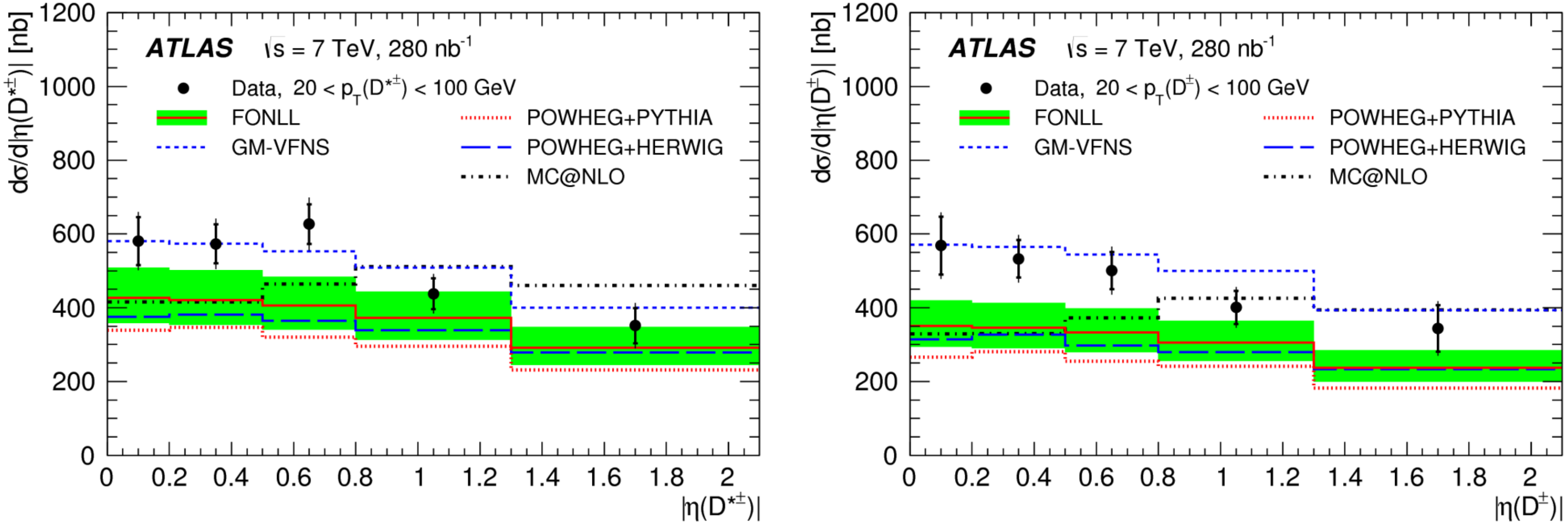
$D^{(*)\pm}$ differential x-sections vs $|\eta(D^{(*)\pm})|$

high-p_T: 20 - 100 GeV



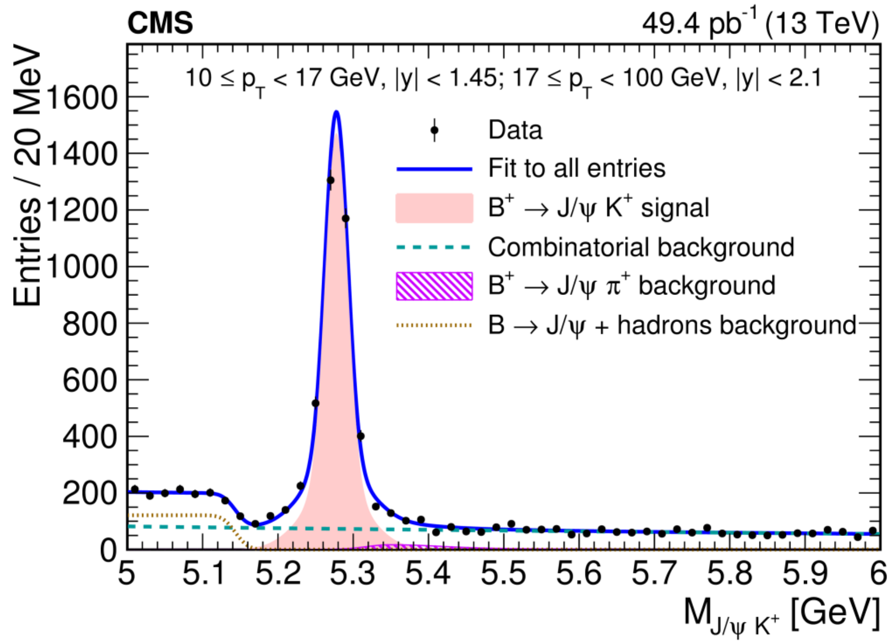
GM-VFNS – agree both in shape and normalization

FONLL, POWHEG, MC@NLO – agree (?) within large theoretical uncertainties

MC@NLO – worst shape description

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

CMS, PLB 771 (2017) 435



$(10 < p_T(B^\pm) < 17$ GeV && $|y(B^\pm)| < 1.45)$ ||
$(17 < p_T(B^\pm) < 100$ GeV && $|y(B^\pm)| < 2.1)$

$N(B^\pm) = 3477^{+86}_{-84}$

Systematic sources	Relative uncertainties (%)
Muon trigger, identification, and reconstruction	6.0–13.7
Detector alignment	2.8
B^+ vertex reconstruction	1.4
Size of simulated samples	0.5–3.9
Track reconstruction efficiency	3.9
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ branching fraction	3.1
Model in likelihood fits	1.0–6.4
Bin-to-bin migration	0.4–3.7
B^+ kinematic distributions	0.4–10.6
Parton distribution functions	0.1–0.7
B^+ lifetime	0.3
Total (excluding the integrated luminosity)	9.1–15.6
Integrated luminosity	2.7

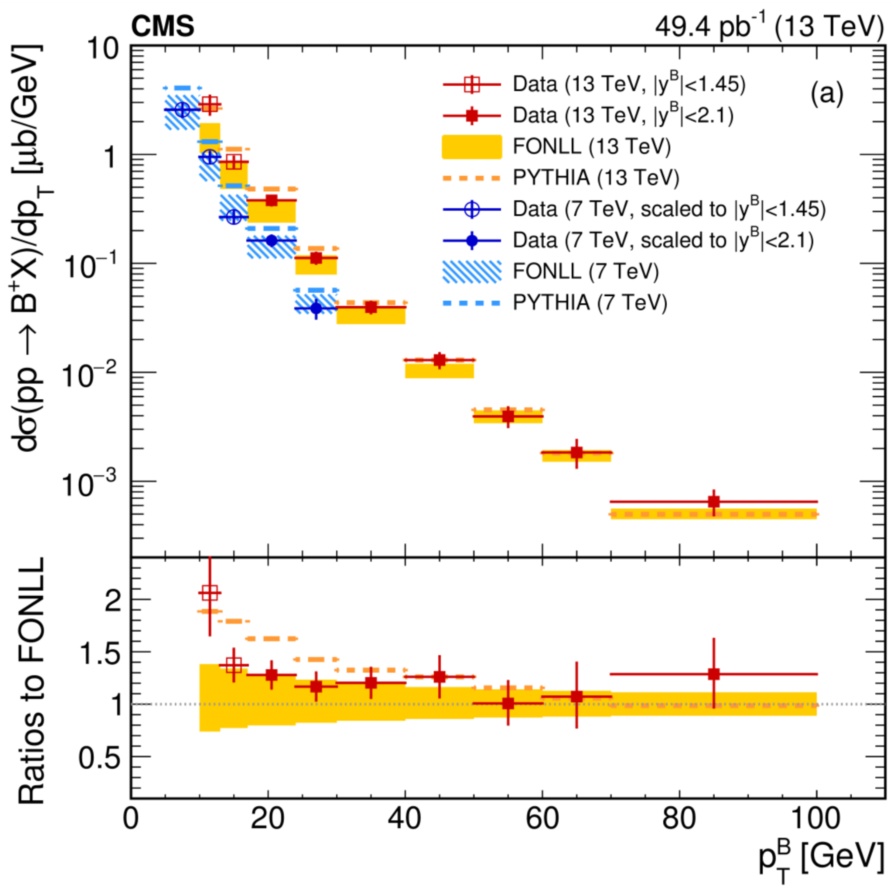
$\sigma(B^+) = 14.9 \pm 0.4\ (\text{stat}) \pm 2.0\ (\text{syst}) \pm 0.4\ (\text{lumi})\ \mu b$

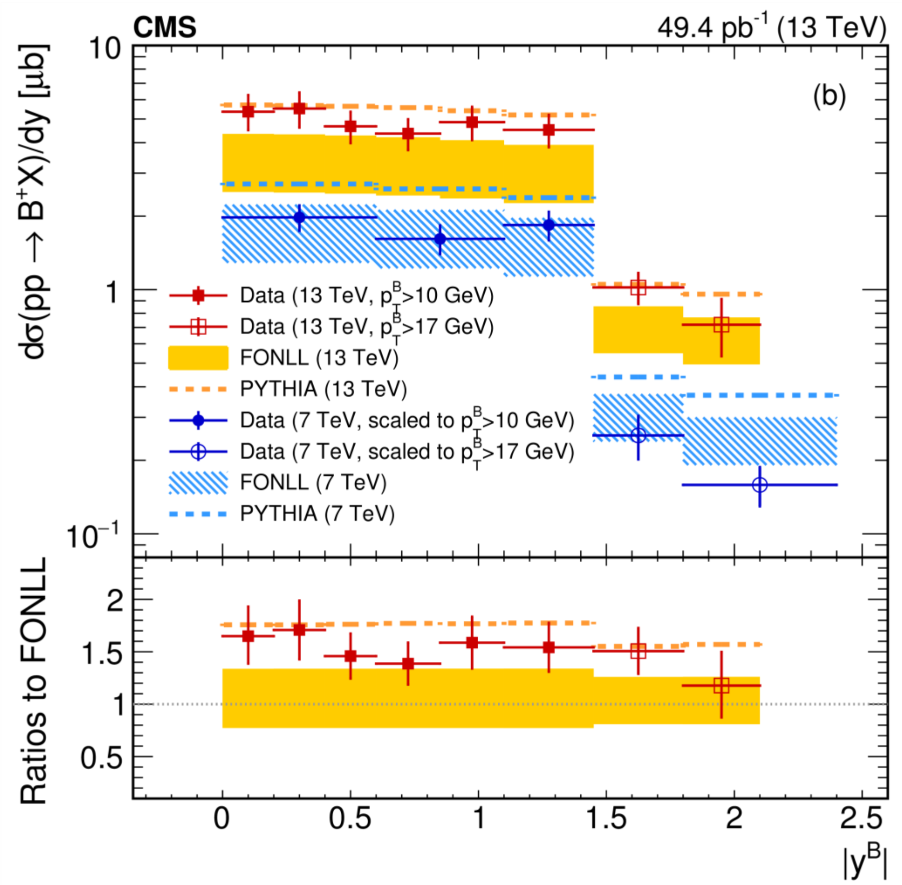
FONLL : $9.9^{+3.3}_{-2.2}\ \mu b$

below but in agreement within large theor. uncertainties

$B^+ \to J/\psi K^+$, 13 TeV

CMS, PLB 771 (2017) 435



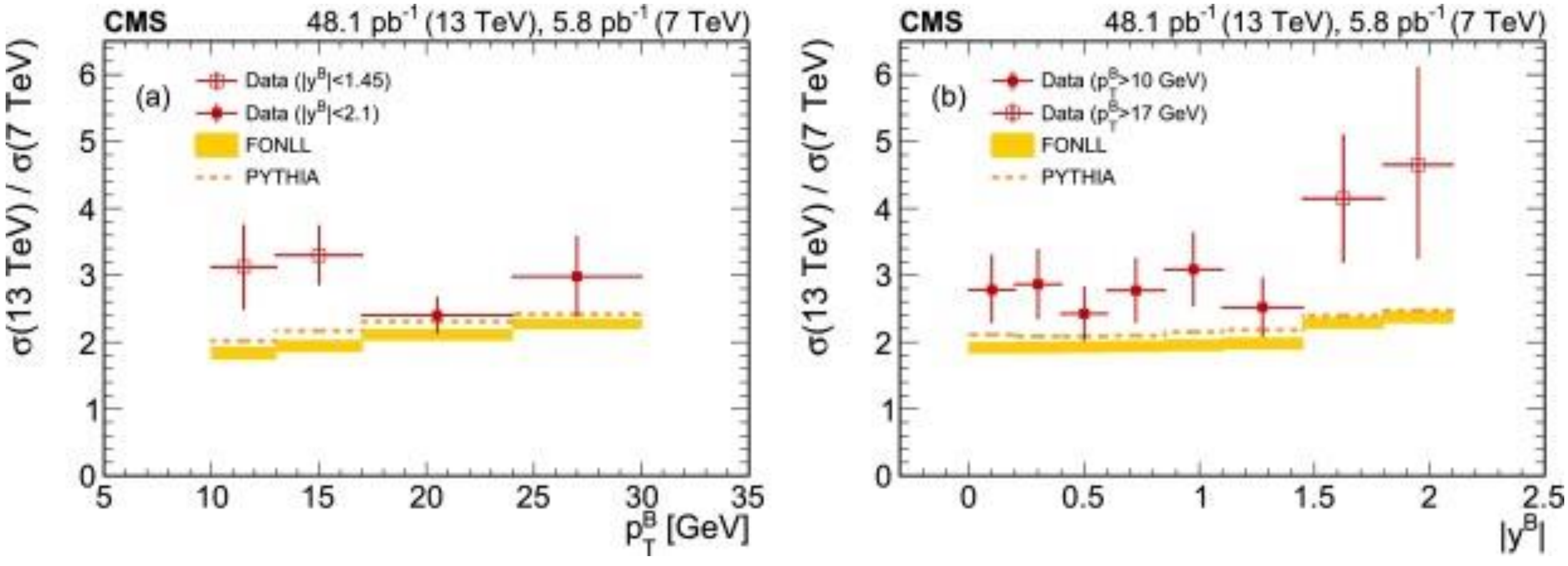


FONLL below the data at low $p_T(B^+)$

Differences are larger at 13 TeV ?

$B^+ \to J/\psi K^+$, 13 TeV

CMS, PLB 771 (2017) 435



DATA tend to prefer higher values compared to FONLL

Measurements of $\sigma^{13\ \mathrm{TeV}}/\sigma^{7\ \mathrm{TeV}}$ are of great interest,
in particular for PDF constraints (see Cacciari et al., EPJ C 75 (2015) 610)

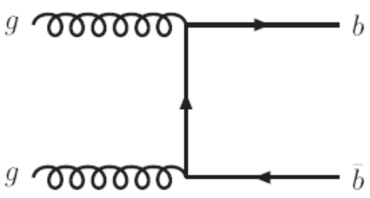
Charmonium and Bottomonium production

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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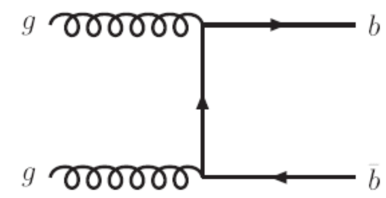
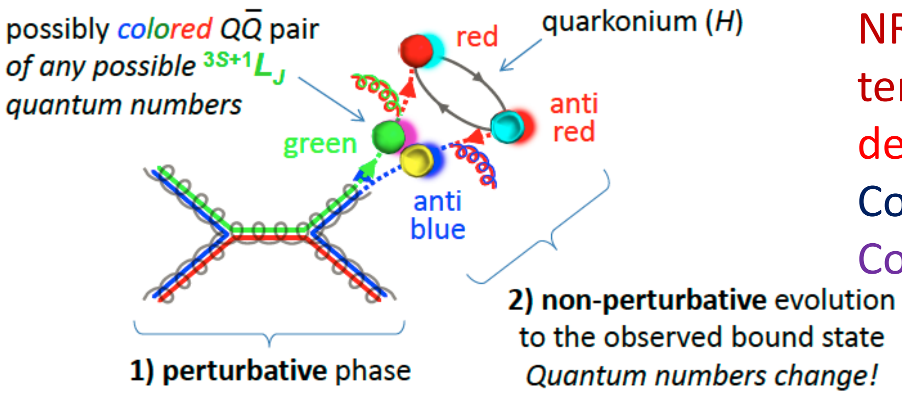


Prompt (not from B decays) – probes specific mechanisms of $Q\bar{Q}$ system production and transformation to a meson



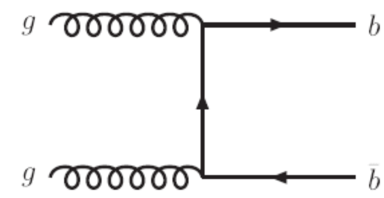
NRQCD: Color Singlet (CS) and Color Octet (CO) terms. Long-distance matrix elements (LDME) determined from experimental data.

Color Singlet Model (CSM) – only CS diagrams.

Color Evaporation Model (CEM) – only one LDME.

Charmonium production

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



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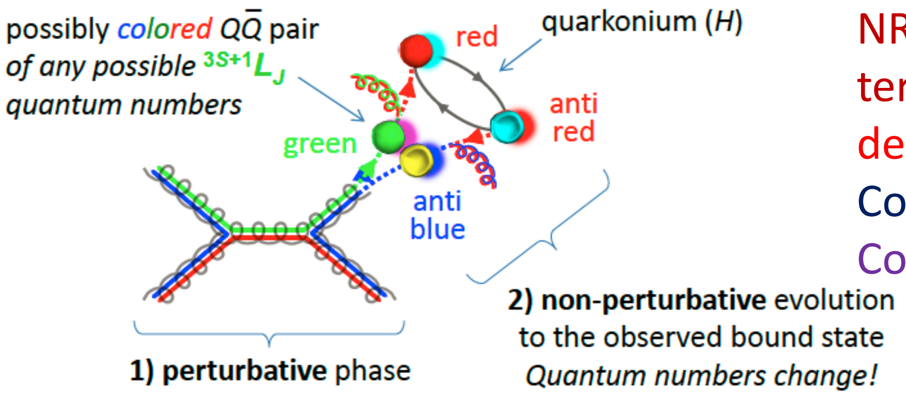

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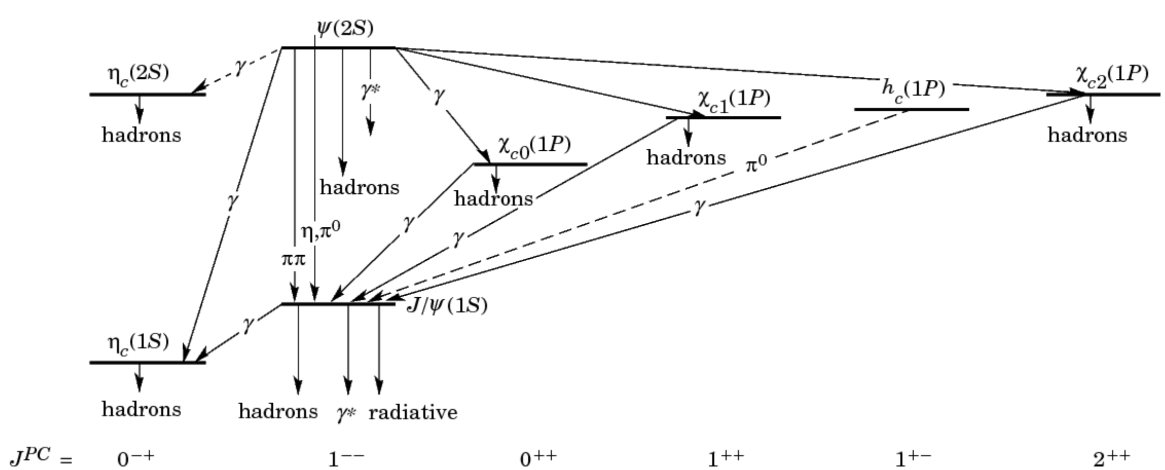
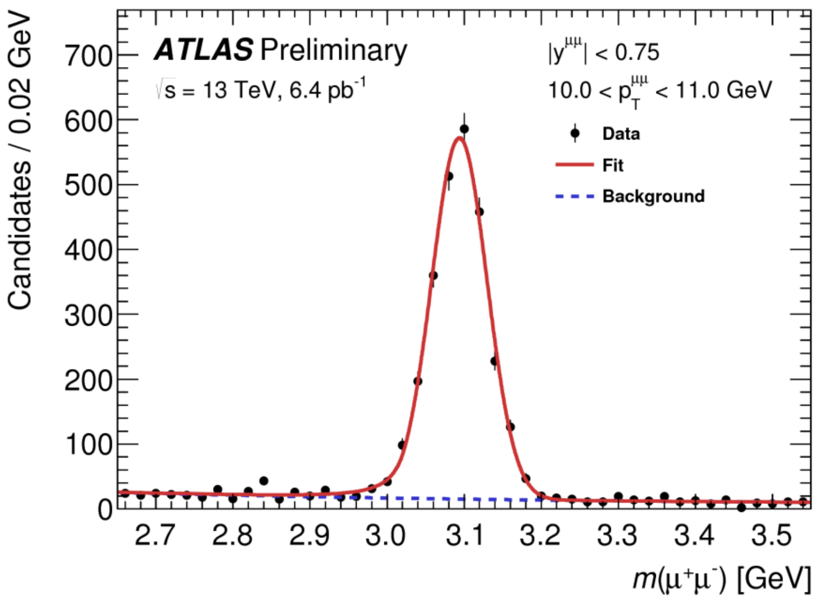


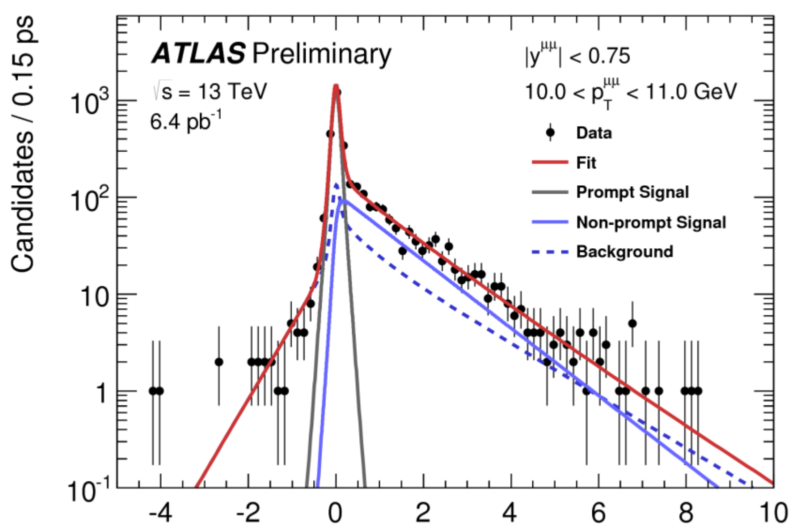
$\Psi(2S)$ – nearly feed-down free

J/ψ – feed-downs ~35%

Onium production @ 13 TeV

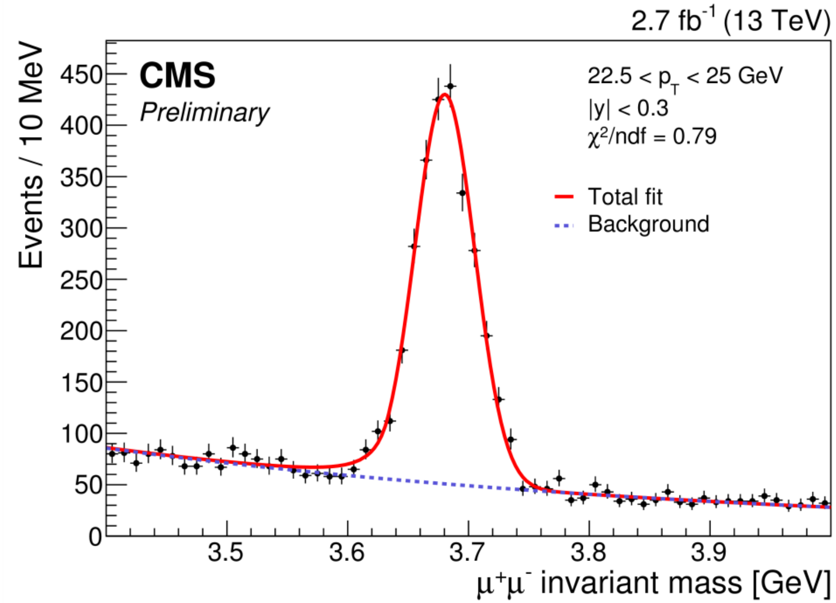
ATLAS-CONF-2015-030

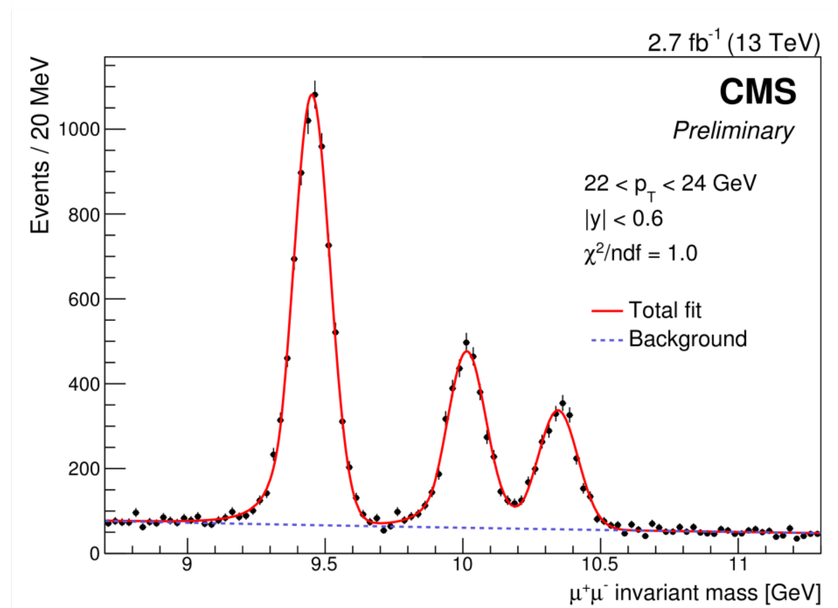




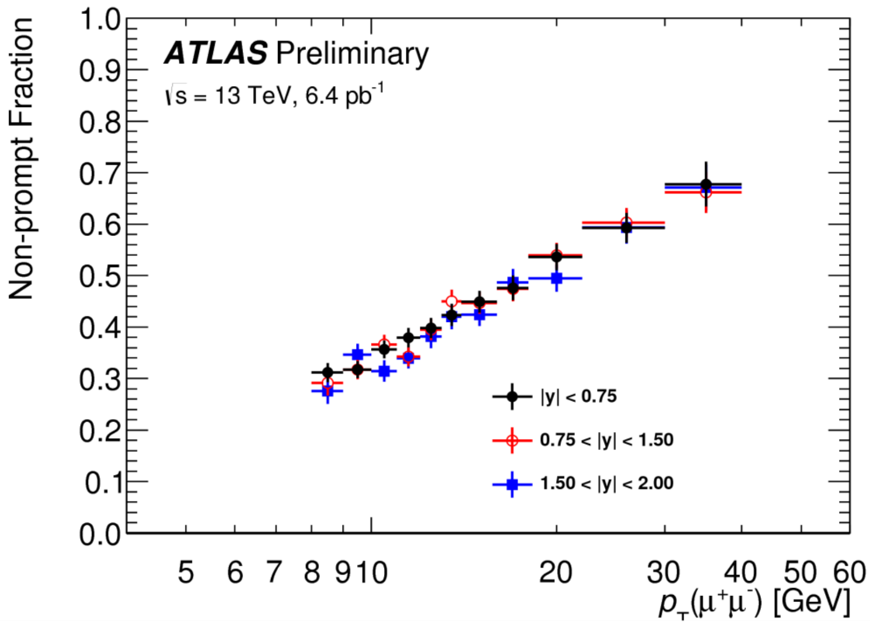
Pseudo-proper decay time: $\tau = L_{xy} m_{J/\psi}^{\mathrm{PDG}} / p_{\mathrm{T}}$

CMS PAS BPH-15-005





Charmonium production @ 13 TeV: J/ψ



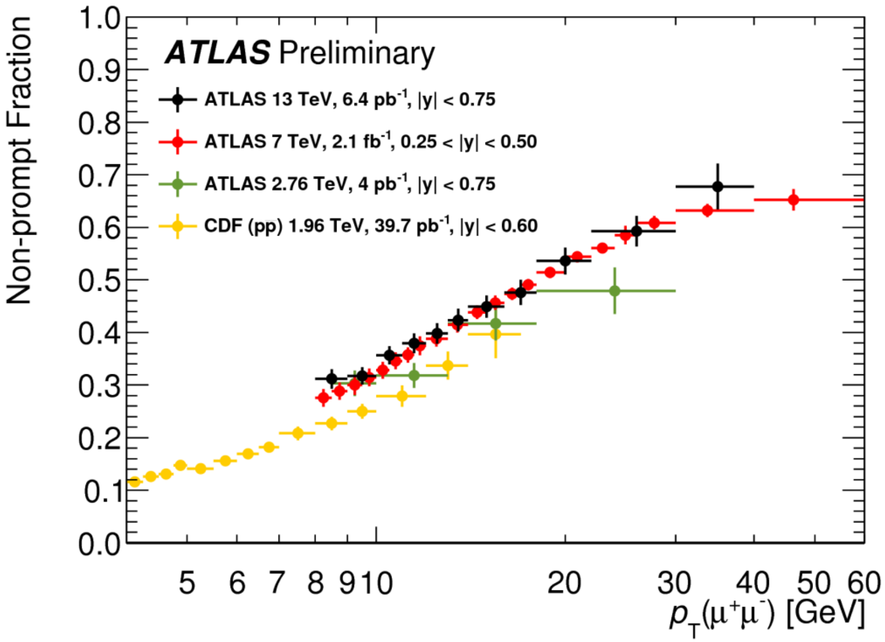
ATLAS-CONF-2015-030

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

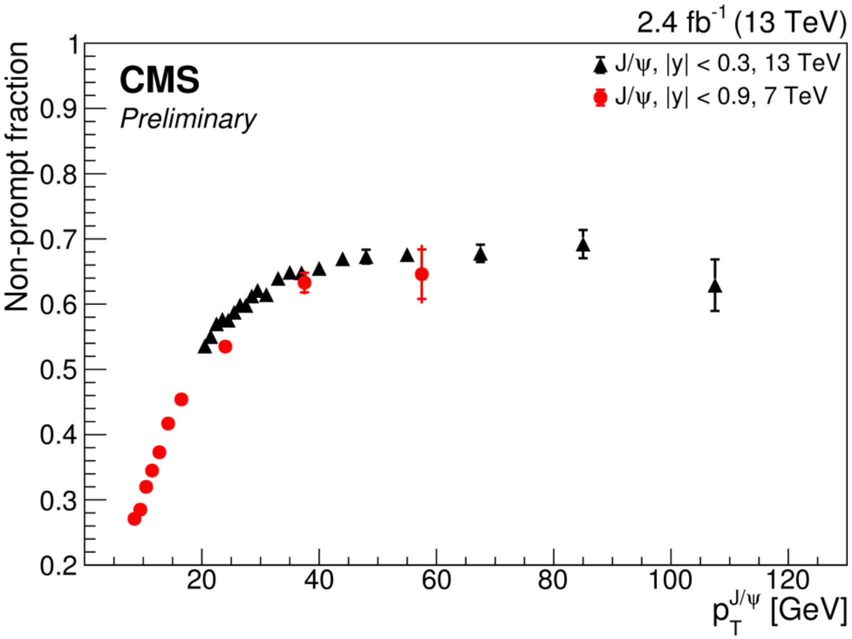


No sizeable differences between 7 and 13 TeV results

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

Charmonium production @ 13 TeV

CMS PAS BPH-15-005

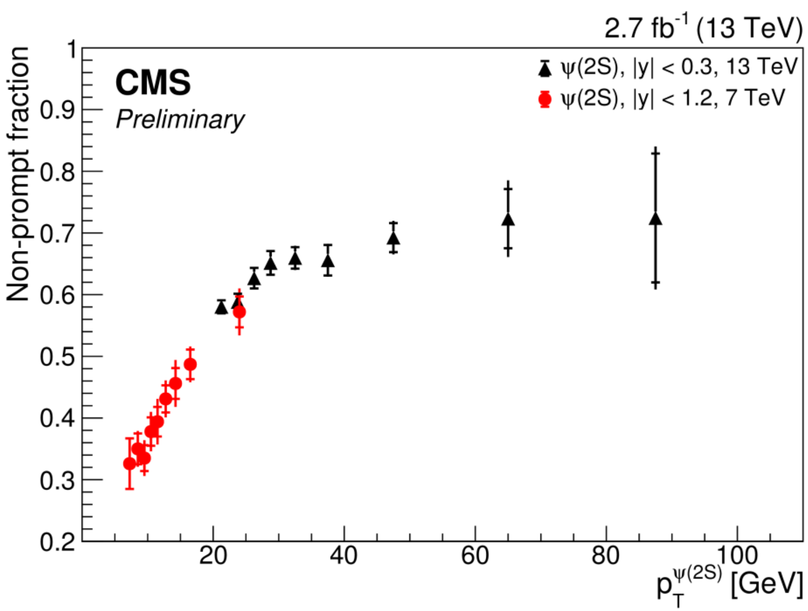


Non-Prompt Fraction

J/ψ

rises from ~25% till ~70%

flattish above 40 GeV



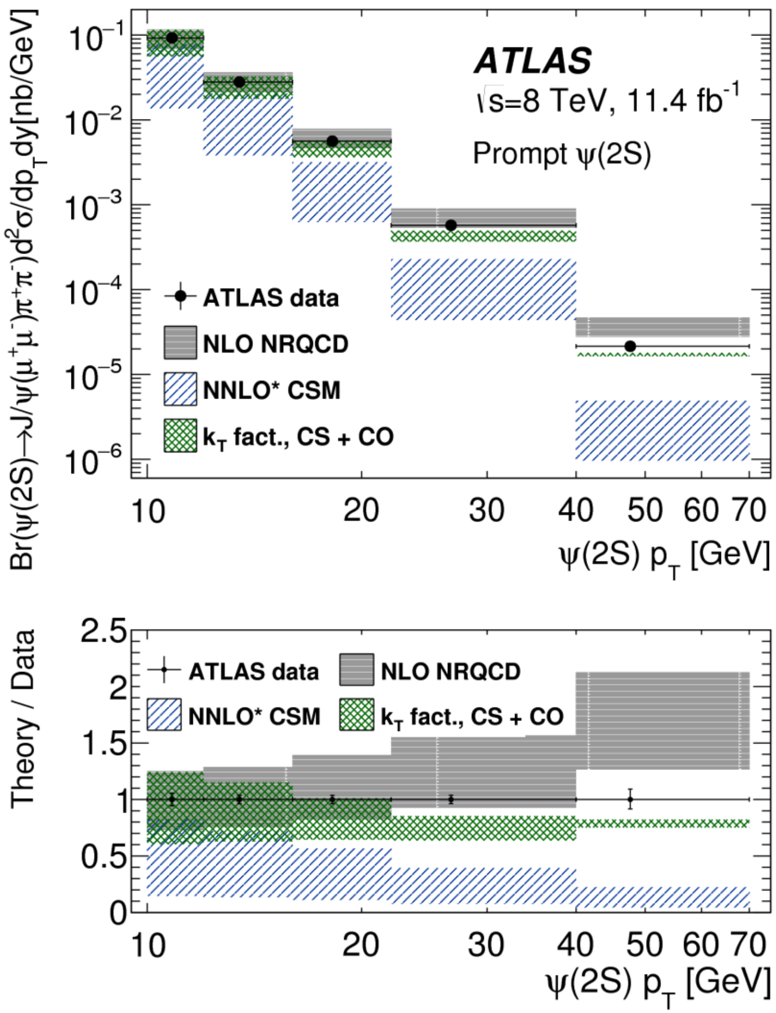
Ψ(2S)

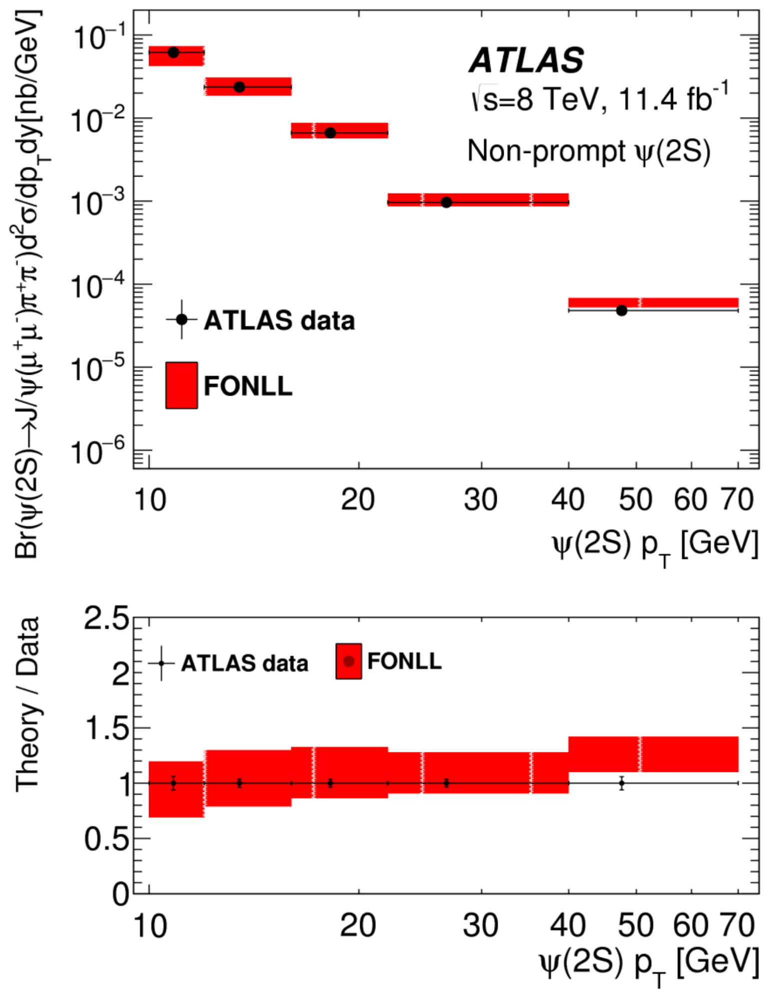
rises from ~30% till ~70%

flattish above 40 GeV

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

ATLAS, JHEP 01 (2017) 117



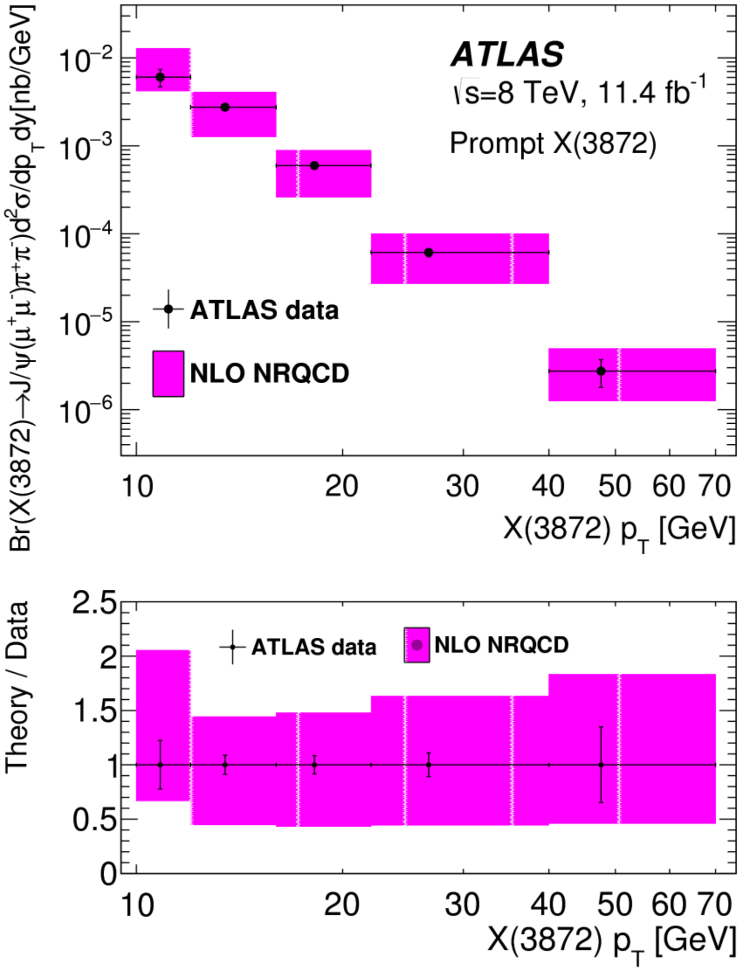


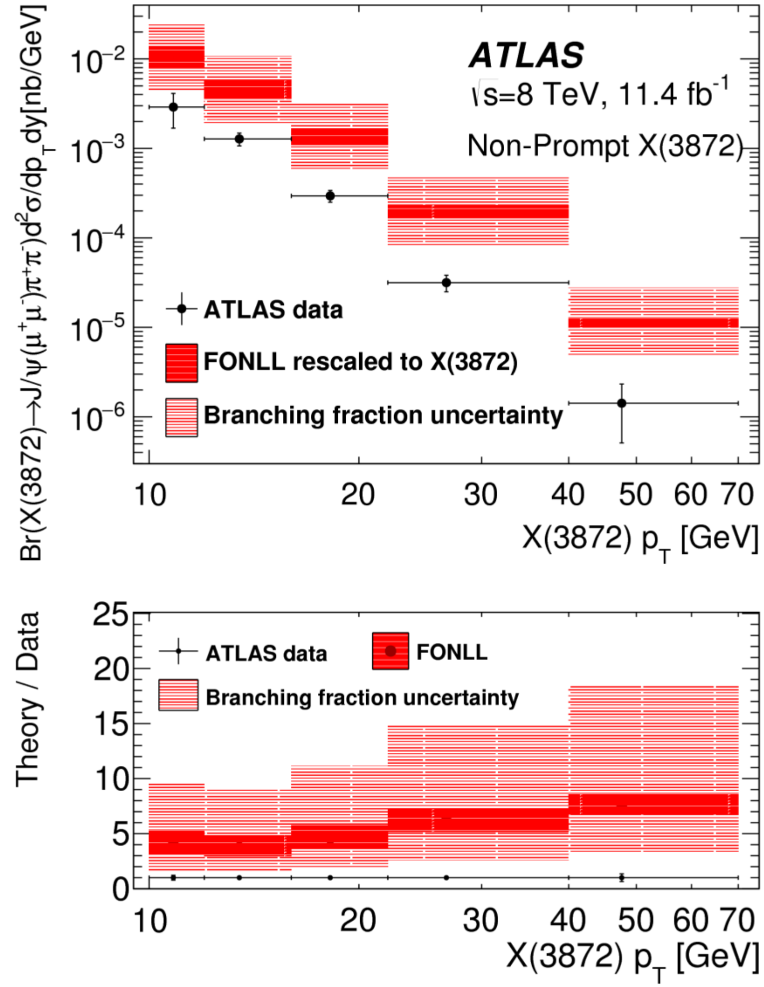
- NLO NRQCD is generally o.k.
- CS is too low even at NNLO*
- new k_T – factorization predictions (CS + CO) in fair agreement

FONLL is generally o.k.

X(3872) $(\rightarrow J/\psi\pi^+\pi^-)$, 8 TeV, prompt/non-prompt diff. x-sections

ATLAS, JHEP 01 (2017) 117



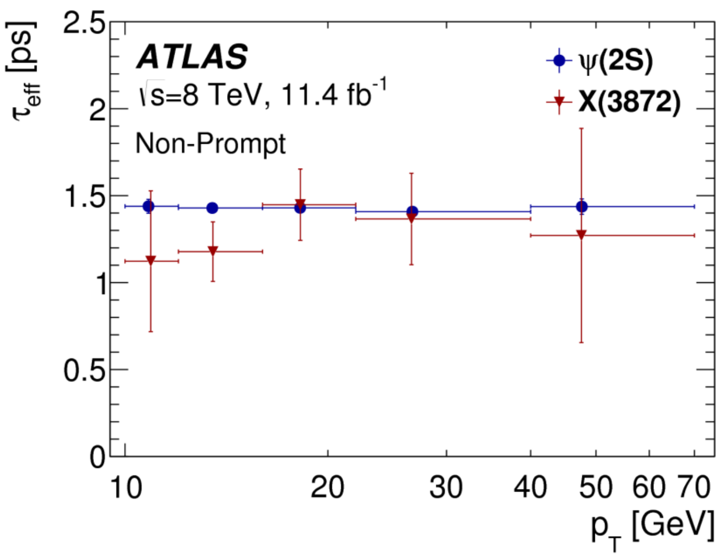


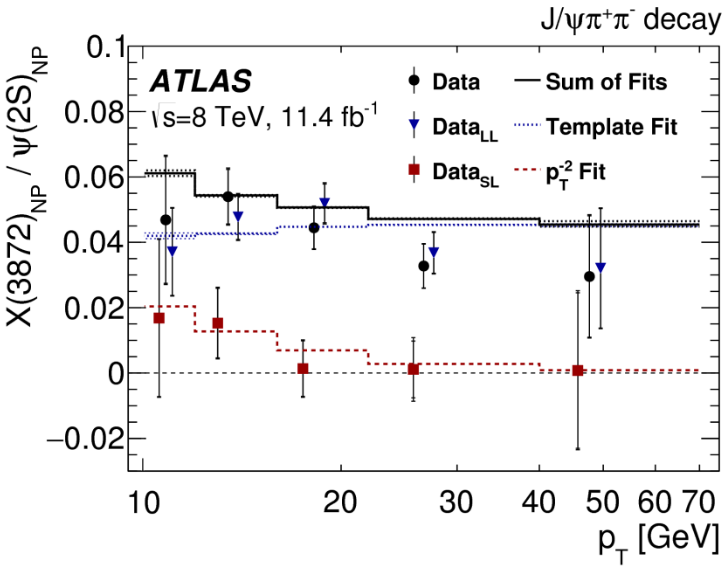
NLO NRQCD (C. Meng et al.), $\chi_{c1}(2P) + D^0\bar{D}^{*0}$,
produced dominantly via $\chi_{c1}(2P)$,
tuned to CMS, is generally o.k.

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

Enhanced B_c contribution to non-prompt X(3872) production

ATLAS, JHEP 01 (2017) 117

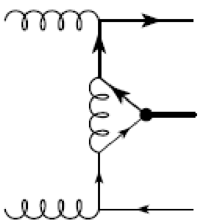




$\tau_{\text{long-lived}} = 1.45 \pm 0.05$ ps

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

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



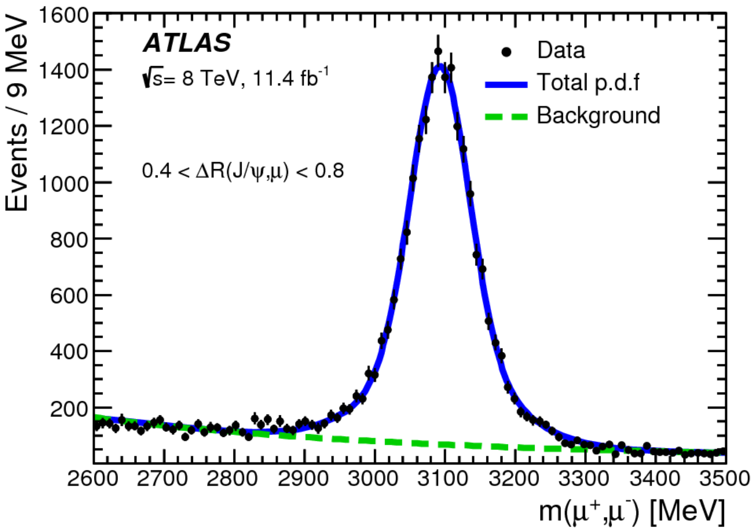
$$\frac{\sigma(pp \to B_c)Br(B_c \to X(3872))}{\sigma(pp \to \text{non}-\text{prompt}\ X(3872))} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\%$$

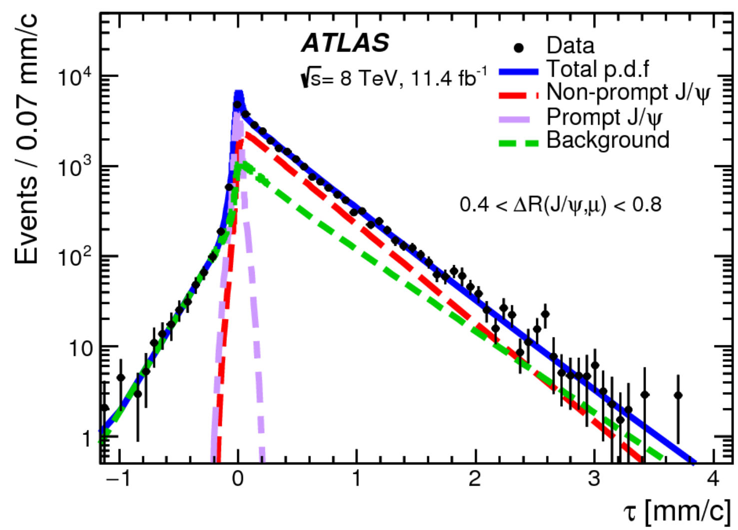
Enhanced *B_c* contribution to non-prompt X(3872) production ?

Measurement of $b\bar{b} \to J/\psi\ \mu^{\pm}$

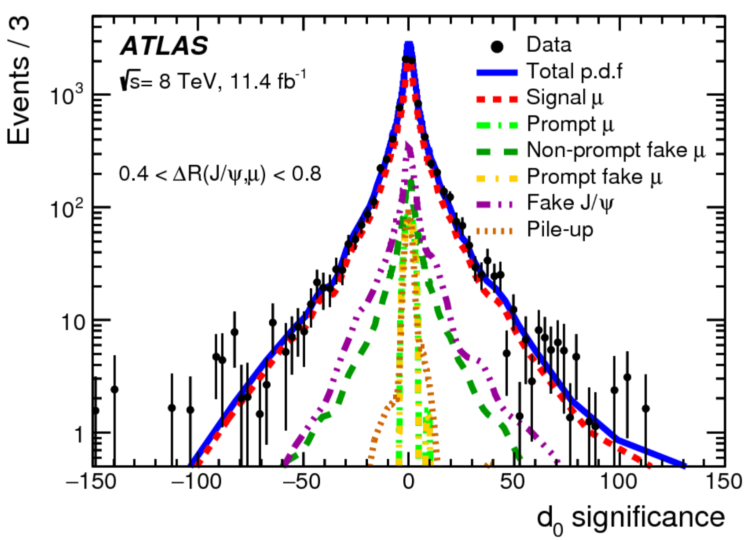
ATLAS, arXiv:1705.03374

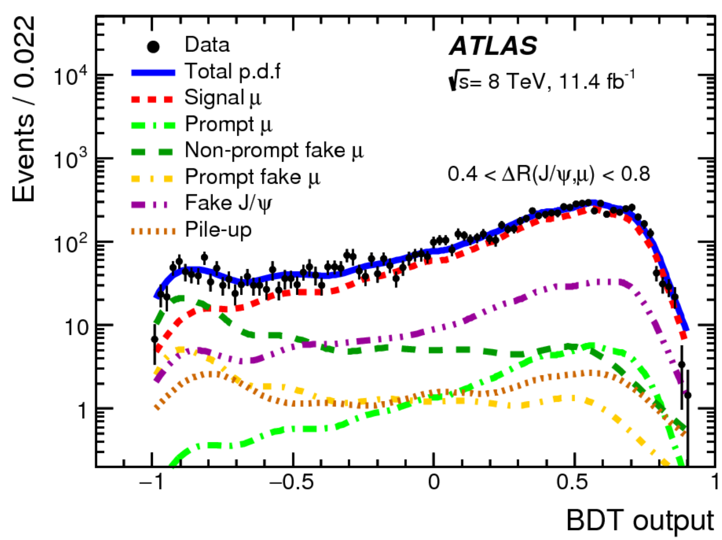
Probes $b\bar{b}$ production dynamics





τ > 0.25 ps





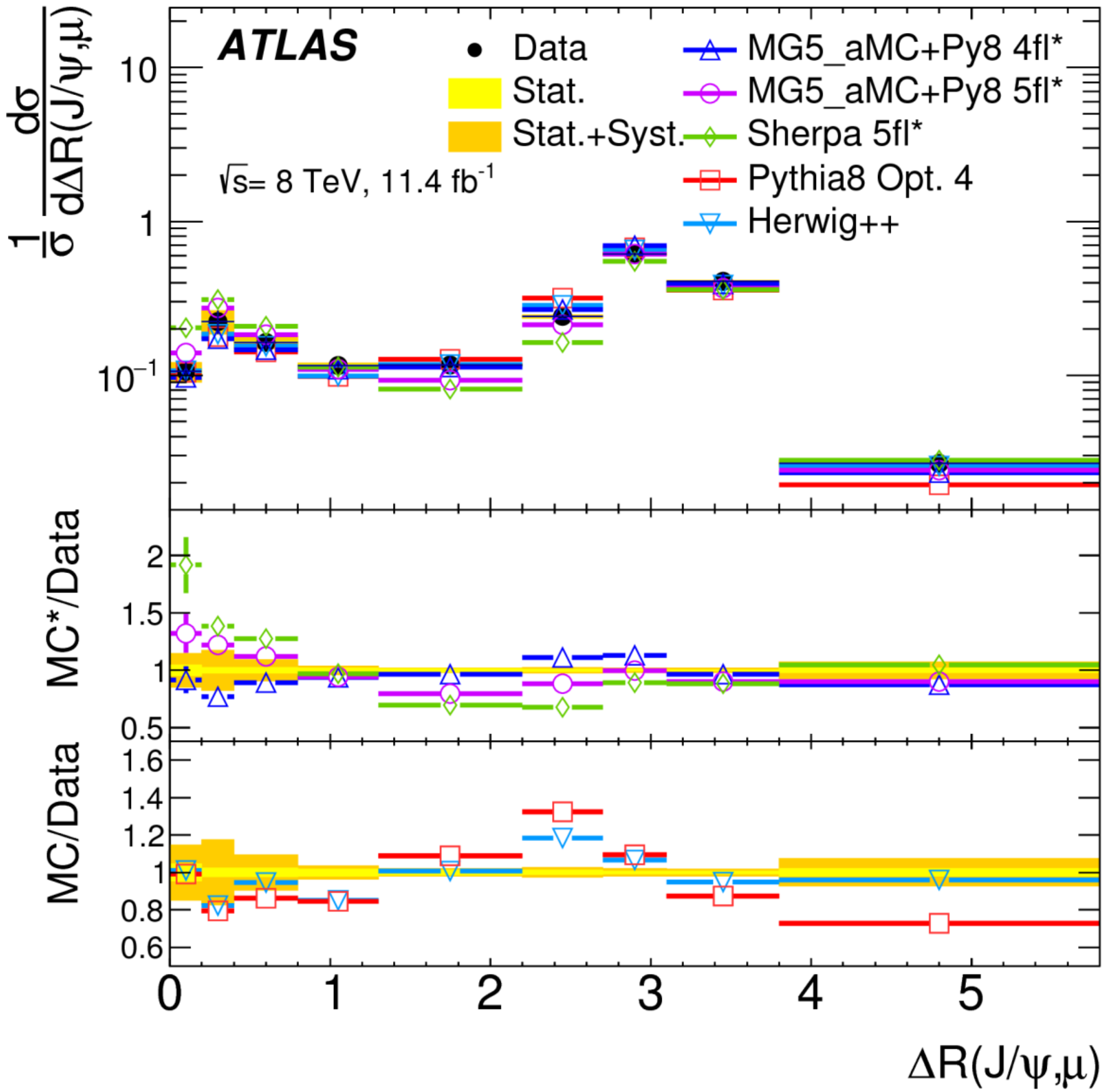
2D fit to $d_0(\mu)/\sigma(d_0)$ and BDT output

Measurement of $b\bar{b} \to J/\psi\ \mu^{\pm}$

ATLAS, arXiv:1705.03374

Differential x-sections in ΔR, Δφ, Δy, y_{boost}, Mass, p_T, M/p_T, p_T/M

Probes small opening angles of $b\bar{b}$



Predictions have a large spread

Neither is perfect

MadGraph5_aMC@NLO+Pythia8

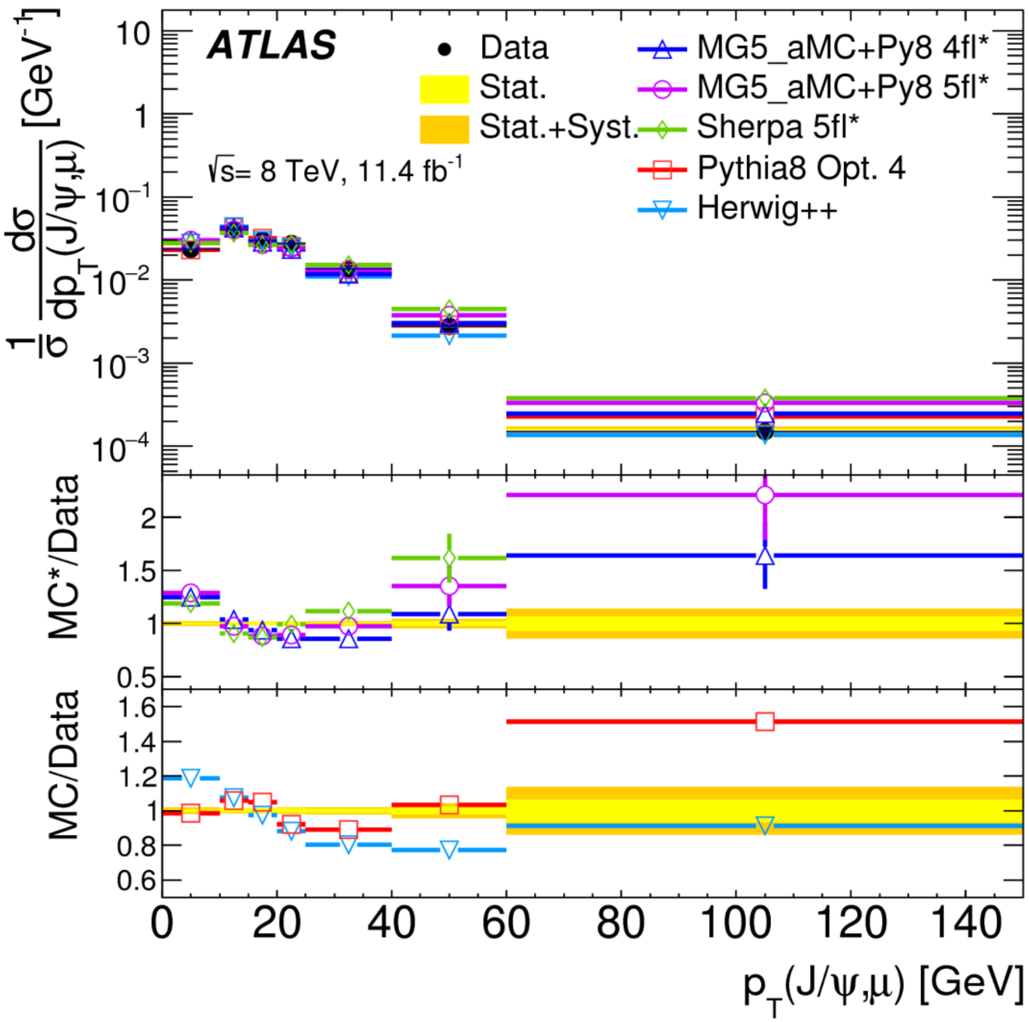
in fair agreement for ΔR

Other predictions demonstrate some deviations

Measurement of $b\bar{b} \rightarrow J/\psi\ \mu^{\pm}$

ATLAS, arXiv:1705.03374

Differential x-sections in ΔR, $\Delta\varphi$, Δy, y_{boost}, Mass, p_T, M/p_T, p_T/M



MadGraph5_aMC@NLO+Pythia8 too high at large p_T

4-flavour predictions agree better than 5-flavour predictions at large p_T

Theor. uncertainties are not yet available

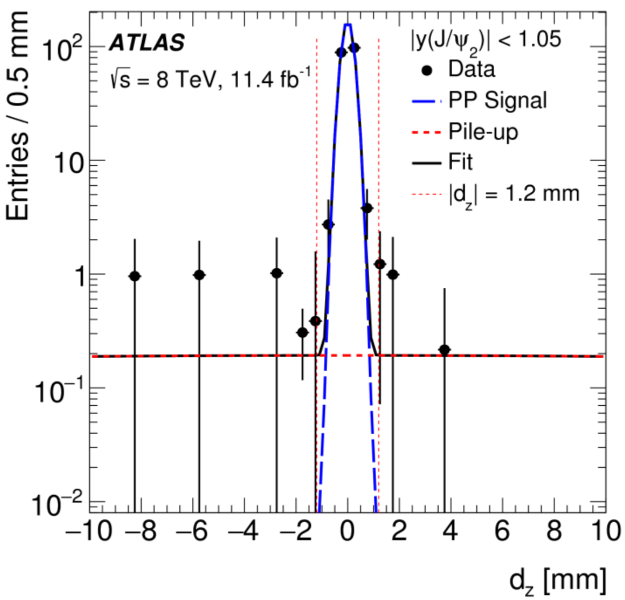
$J/\psi + J/\psi$ prompt production

ATLAS, EPJ C 77 (2017) 76

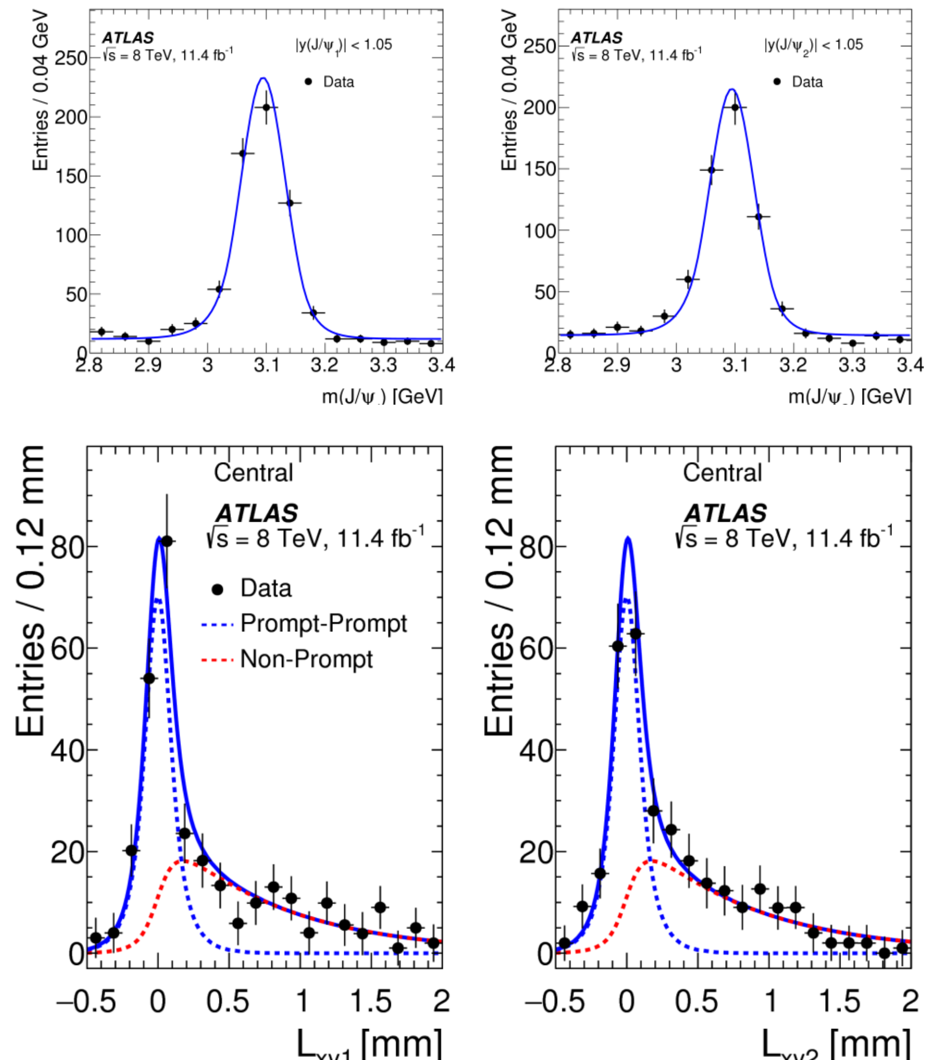
Probes specific mechanisms of $c\bar{c}c\bar{c}$ system production and transformation to 2 mesons; potentially sensitive to Double Parton Scattering (DPS)

$p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$

$|d_z| < 1.2$ mm, remaining pile-up (0.5-1.0%) subtracted



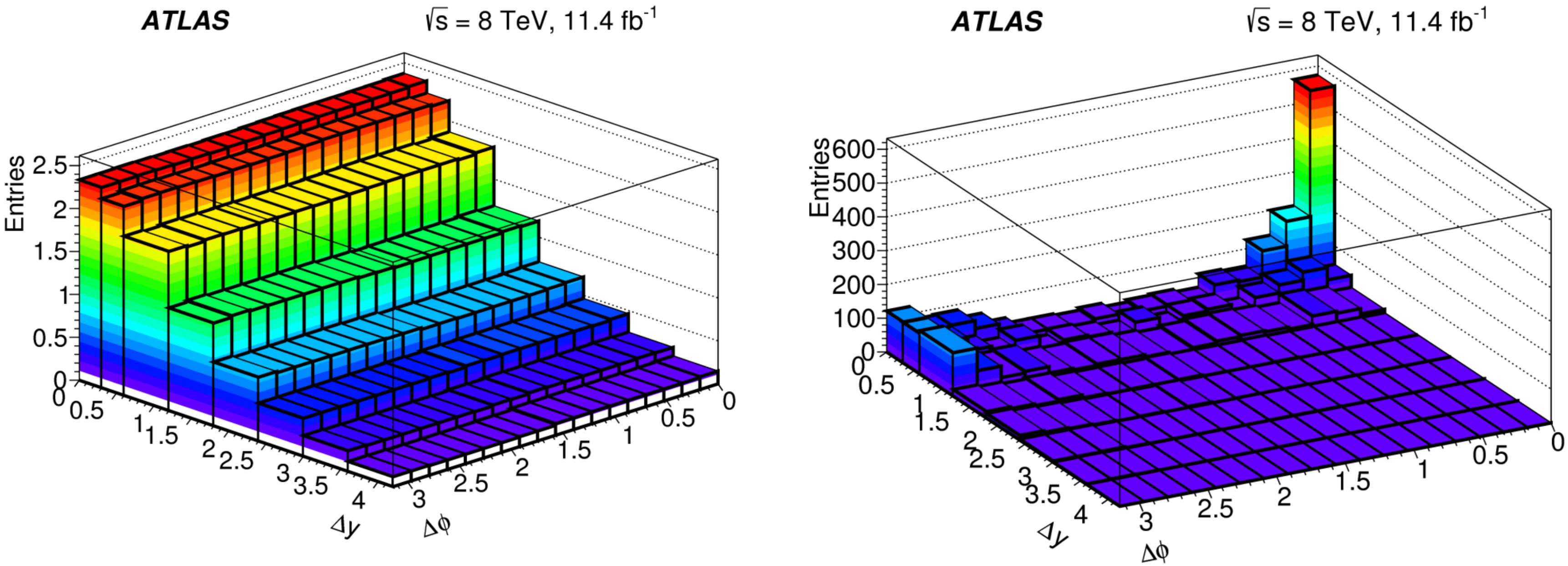
1160 ± 70 prompt J/ψ pairs



$J/\psi + J/\psi$ prompt production

ATLAS, EPJ C 77 (2017) 76

Data-driven SPS/DPS separation



J/ψ mesons from different events

DPS template normalized to data in the DPS-dominant region: $\Delta y > 1.8$ && $\Delta\varphi < \pi/2$

SPS template obtained by subtraction of the DPS template from data

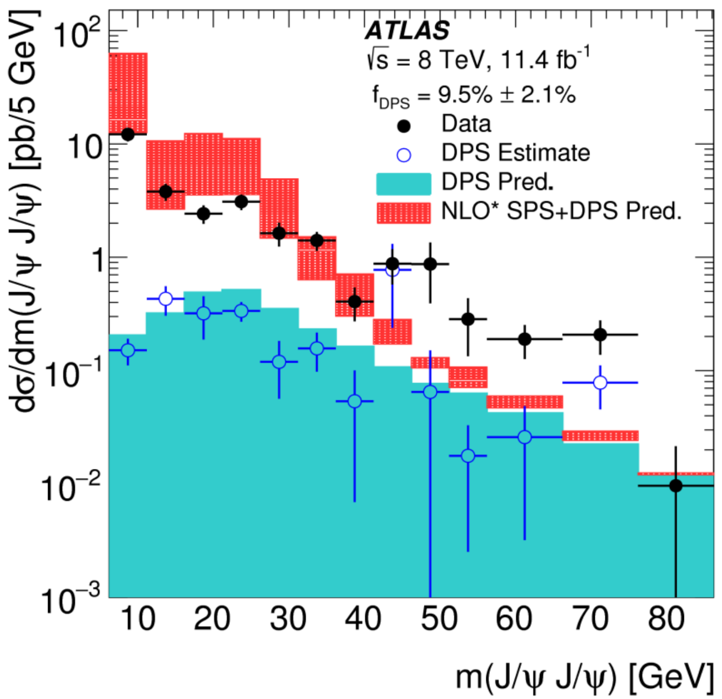
$$w_{\mathrm{DPS}}(\Delta\phi,\ \Delta y) = \frac{N_{\mathrm{DPS}}(\Delta\phi,\ \Delta y)}{N_{\mathrm{Data}}(\Delta\phi,\ \Delta y)}$$

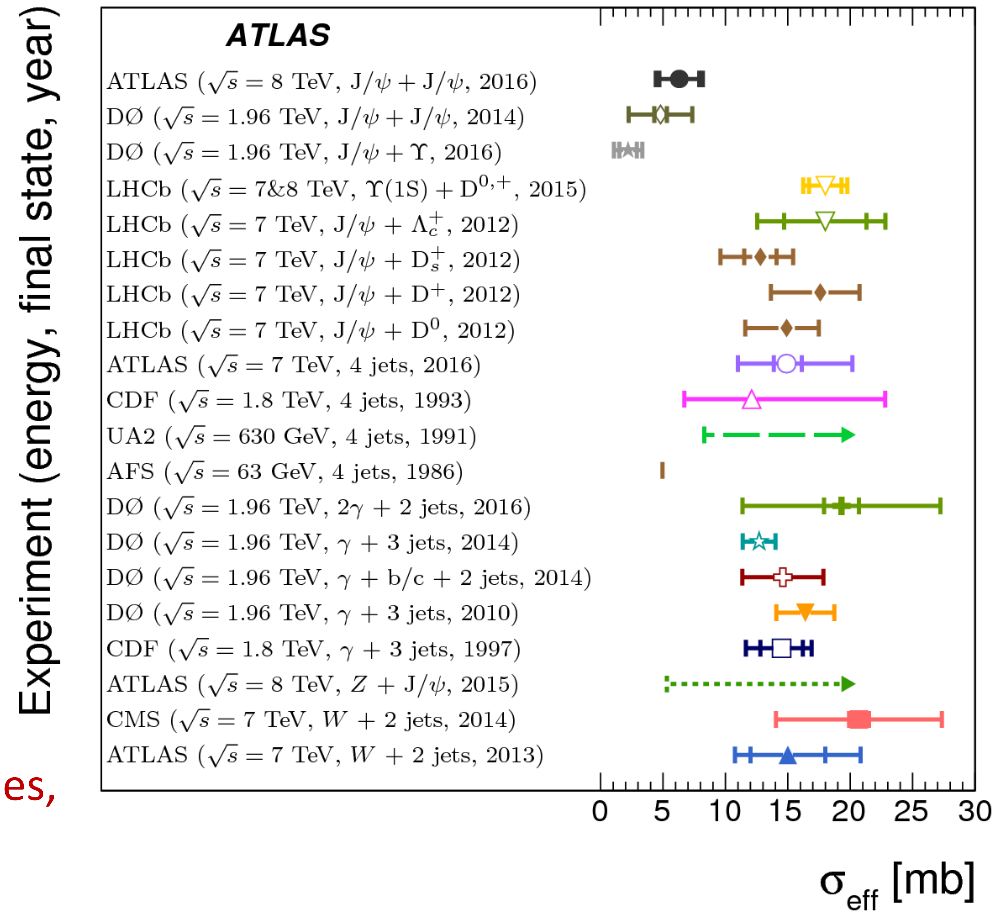
$$w_{\mathrm{SPS}}(\Delta\phi,\ \Delta y) = \frac{N_{\mathrm{SPS}}(\Delta\phi,\ \Delta y)}{N_{\mathrm{Data}}(\Delta\phi,\ \Delta y)}$$

J/ψ + J/ψ prompt production

ATLAS, EPJ C 77 (2017) 76

CMS, JHEP 09 (2014) 094





LO DPS (Borschensky, Kulesza) agrees

NLO* SPS (Lansberg, Shao) generally agrees, below at large Δy and m(J/ψ J/ψ)

$$\sigma_{\rm eff} = \frac{1}{2}\frac{\sigma_{J/\psi}\sigma_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\rm DPS}}$$

$\sigma_{\rm eff}$ = 6.3 ± 1.6 (stat) ± 1.0 (syst) mb

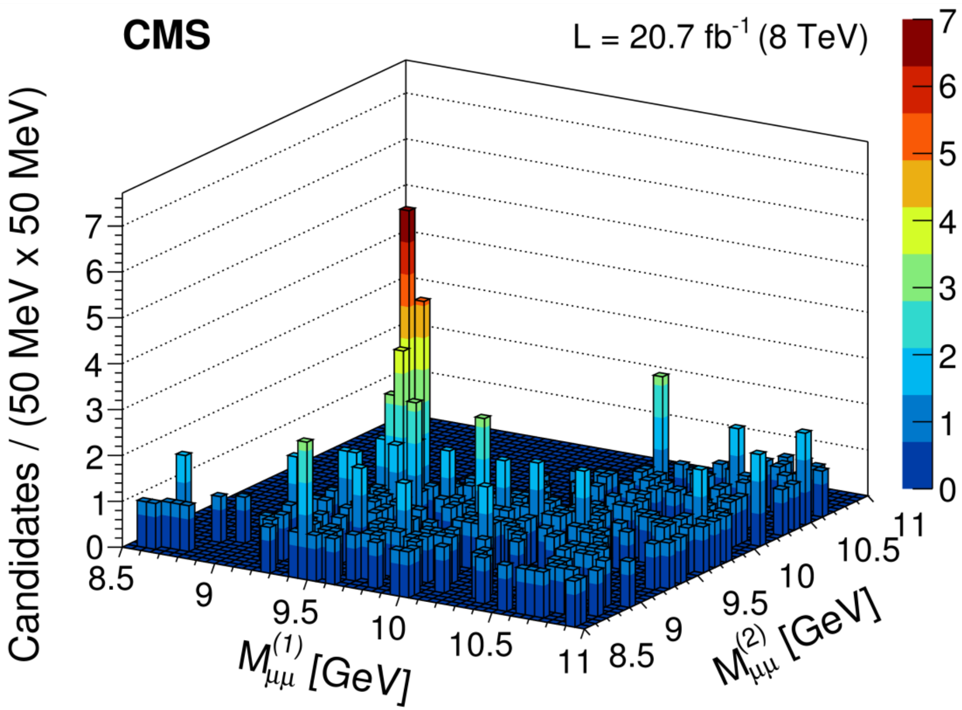
LHCb (13 TeV, *J/ψ+J/ψ*, NLO* CS) : 10.2 ± 1.0 mb

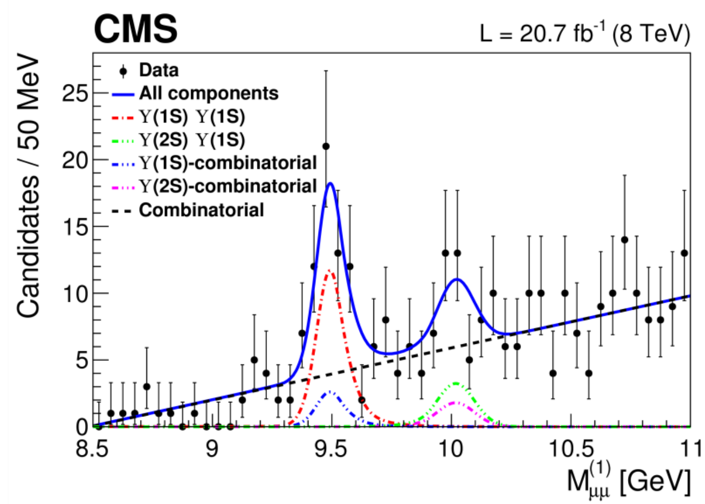
CMS-based (√s=7 TeV, *J/ψ+J/ψ*) : 8.2 ± 2.2 mb

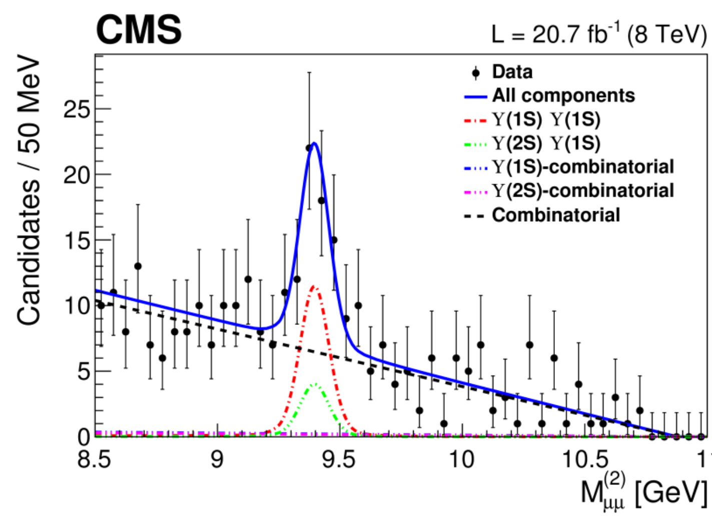
smaller than jet-related $\sigma_{\rm eff}$ measurements

$\Upsilon(1S) + \Upsilon(1S)$ production

CMS, JHEP 05 (2017) 013







$$\sigma_{\text{fid}} = 68.8 \pm 12.7\,(\text{stat}) \pm 7.4\,(\text{syst}) \pm 2.8\,(\mathcal{B})\,\text{pb}$$

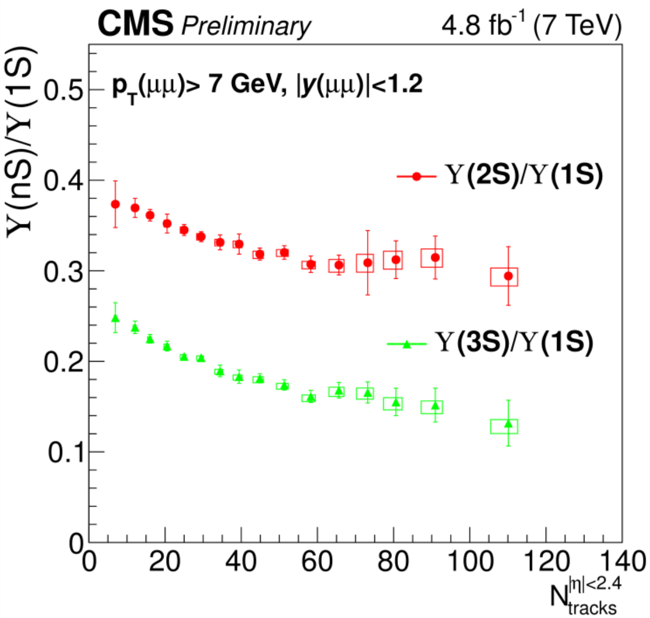
Two estimations of σ_{eff} of DPS:

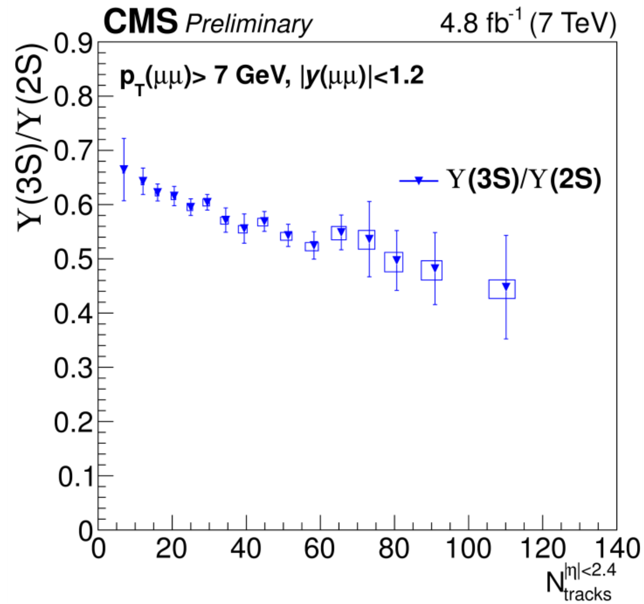
$\sigma_{eff} \approx 6.6$ mb, $\sigma_{eff} \approx 2.3$ mb

- agree with other quarkonium measurements
- smaller than jet-related measurements

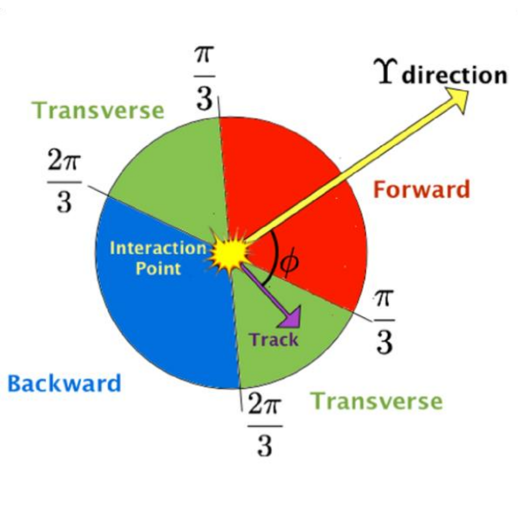
ϒ(nS) dependence on charged particle multiplicity in pp collisions

CMS PAS BPH-14-009

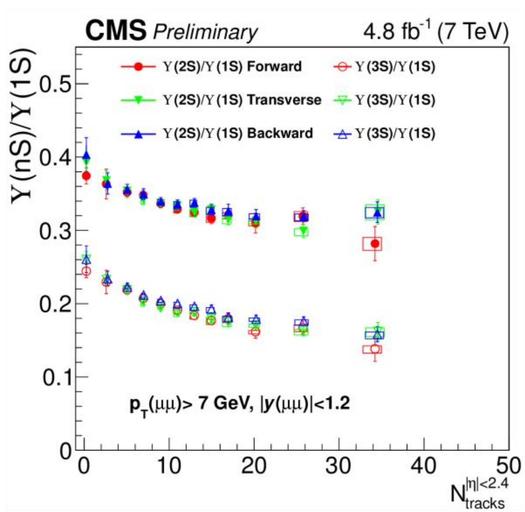




Clear suppression with increase of multiplicity



(a)



(b)

No dependence from tracks direction

Connected with the underlying event itself?

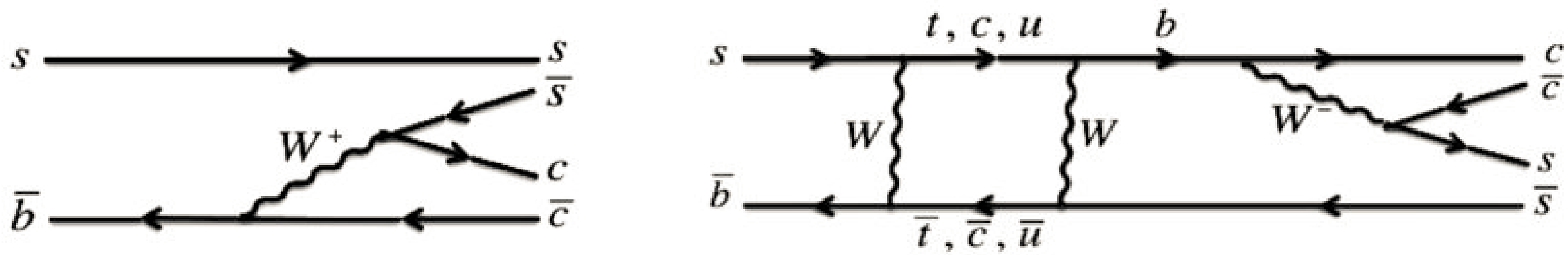
Mixing and CP violation

Measurements of CP violation with $B_s \to J/\psi\varphi$

The time evolution of B_s meson mixing is characterized by

- ✓ the mass difference Δm_s of the heavy (B_H) and light (B_L) mass eigenstates
- ✓ the CP-violating mixing phase φ_s
- ✓ the width difference of $\Delta\Gamma_s = \Delta\Gamma_L - \Delta\Gamma_H$

Interference between the B_s decays amplitudes to the CP eigenstates $J/\psi\varphi$ or via mixing gives rise to a measurable CP violating phase φ_s



SM:

$$\phi_s \simeq -2\beta_s = -0.0363^{+0.0016}_{-0.0015}\ \text{rad} \qquad \beta_s \doteq \arg[-(V_{ts}V^*_{tb})/(V_{cs}V^*_{cb})]$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.087 \pm 0.021\ \text{ps}^{-1}$$

New Physics could modify φ_s and $\Delta\Gamma_s$ / Δm_s If new particles contributes to box diagrams

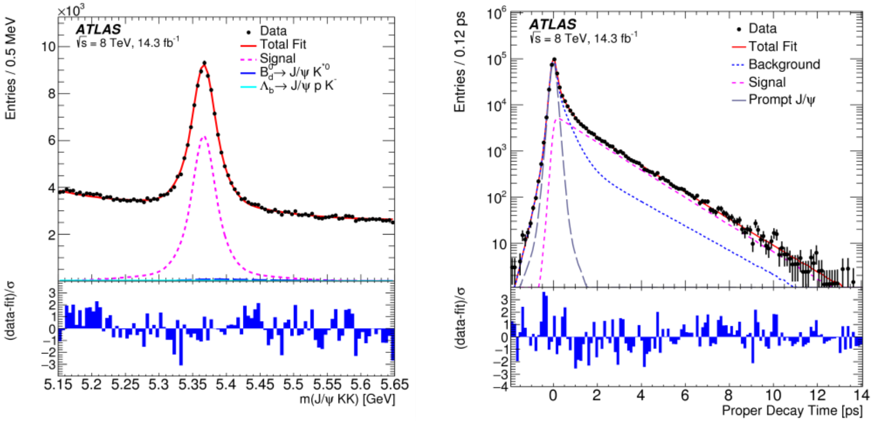
$PS \to VV$ decay gives orbital angular momentum $L = 0$, 1 or 2

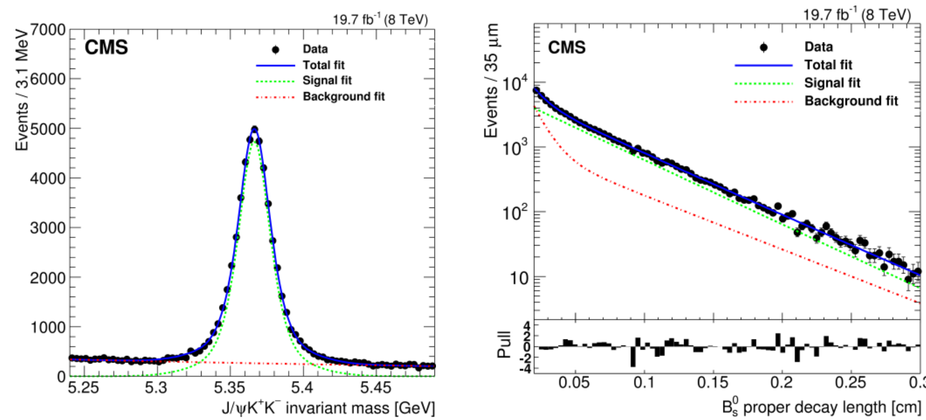
$L = 0$ or 2 are CP-even

$L = 1$ is CP-odd

Measurements of CP violation with $B_s \to J/\psi\varphi$

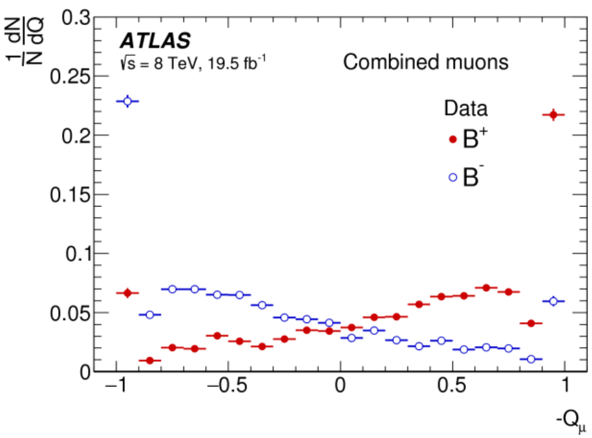
ATLAS, JHEP 08 (2016) 147 | **CMS, PLB 757 (2016) 97**





~ 74900 B_s^0 mesons | **~ 49200 B_s^0 mesons**

Flavour tagging tuned using $B^+ \to J/\psi K^+$



Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Combined μ	4.12 ± 0.02	47.4 ± 0.2	0.92 ± 0.02
Electron	1.19 ± 0.01	49.2 ± 0.3	0.29 ± 0.01
Segment-tagged μ	1.20 ± 0.01	28.6 ± 0.2	0.10 ± 0.01
Jet-charge	13.15 ± 0.03	11.85 ± 0.03	0.19 ± 0.01
Total	19.66 ± 0.04	27.56 ± 0.06	1.49 ± 0.02

ATLAS

$$\mathcal{D} = P(B|Q) - P(\bar{B}|Q) = 2P(B|Q) - 1 \qquad T = \epsilon\mathcal{D}^2$$

$$\mathcal{P}_{\text{tag}} = (1.307 \pm 0.031\,(\text{stat}) \pm 0.007\,(\text{syst}))\,\%$$

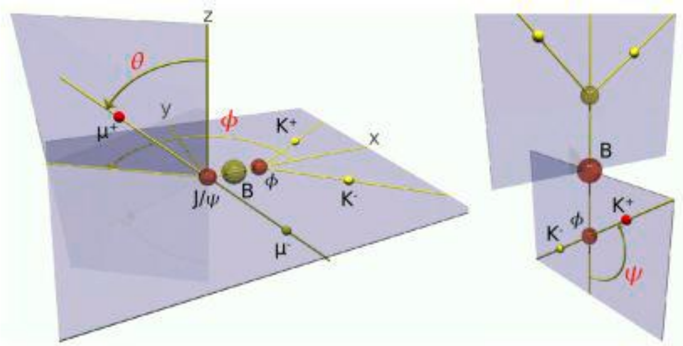
CMS

μ±, e±, jet-charge

Measurements of CP violation with $B_s \to J/\psi\varphi$

ATLAS, JHEP 08 (2016) 147

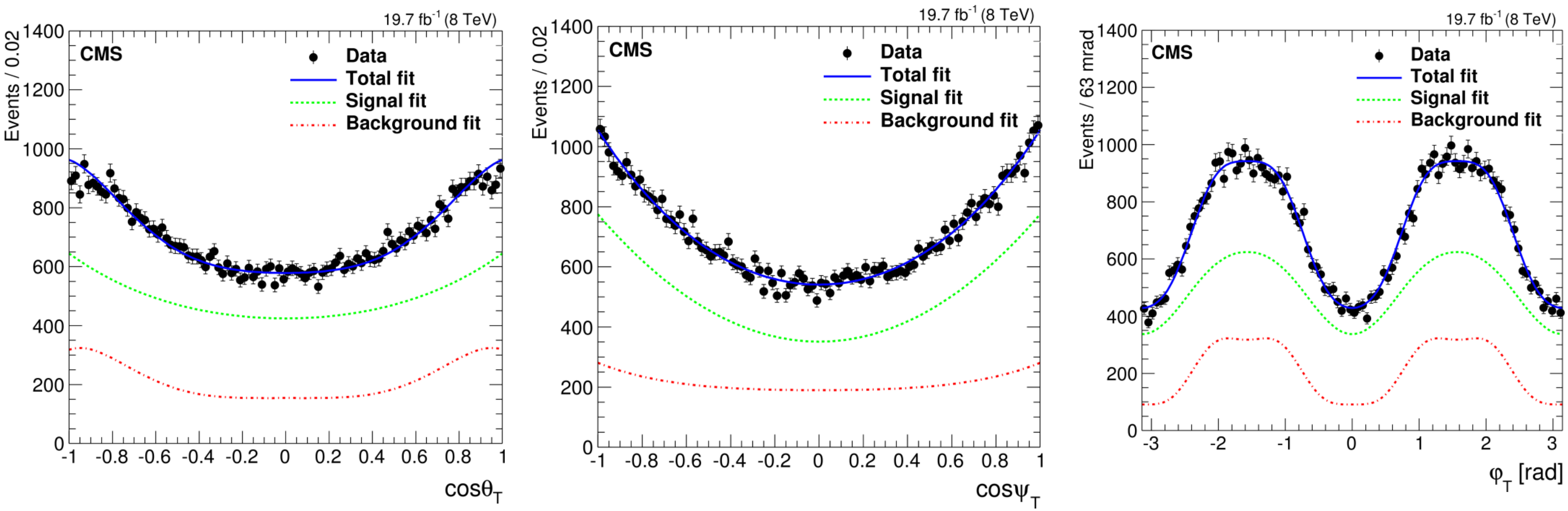
CMS, PLB 757 (2016) 97



time-dependent, flavour-tagged angular analysis

~25 free parameters
projections are shown

Three transversity angles



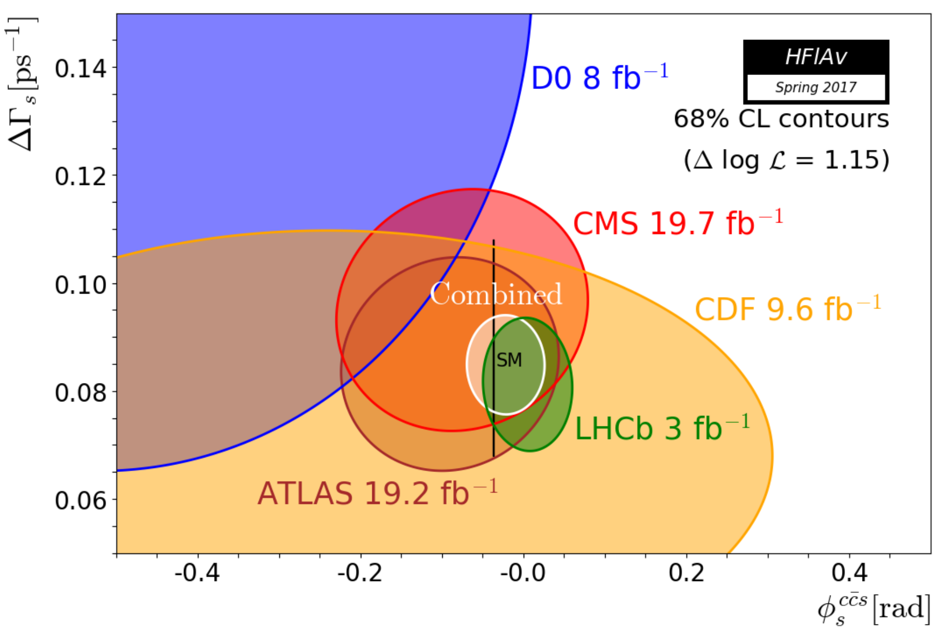
Measurements of CP violation with $B_s \to J/\psi\varphi$

ATLAS, JHEP 08 (2016) 147

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.110	0.082	0.042
$\Delta\Gamma_s$[ps^{-1}]	0.101	0.013	0.007
Γ_s[ps^{-1}]	0.676	0.004	0.004
$\|A_\parallel(0)\|^2$	0.230	0.005	0.006
$\|A_0(0)\|^2$	0.520	0.004	0.007
$\|A_S(0)\|^2$	0.097	0.008	0.022
$\delta_\perp$ [rad]	4.50	0.45	0.30
$\delta_\parallel$ [rad]	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	−0.08	0.03	0.01

CMS, PLB 757 (2016) 97

Parameter	Fit result
ϕ_s [rad]	-0.075 ± 0.097
$\Delta\Gamma_s$ [ps^{-1}]	0.095 ± 0.013
$\|A_0\|^2$	0.510 ± 0.005
$\|A_S\|^2$	$0.012^{+0.009}_{-0.007}$
$\|A_\perp\|^2$	0.243 ± 0.008
$\delta_\parallel$ [rad]	$3.48^{+0.07}_{-0.09}$
$\delta_{S\perp}$ [rad]	$0.37^{+0.28}_{-0.12}$
$\delta_\perp$ [rad]	2.98 ± 0.36
$c\tau$ [μm]	447.2 ± 2.9



[HFAG Preliminary]

Good agreement with SM

$\phi_s = -21 \pm 31$ mrad

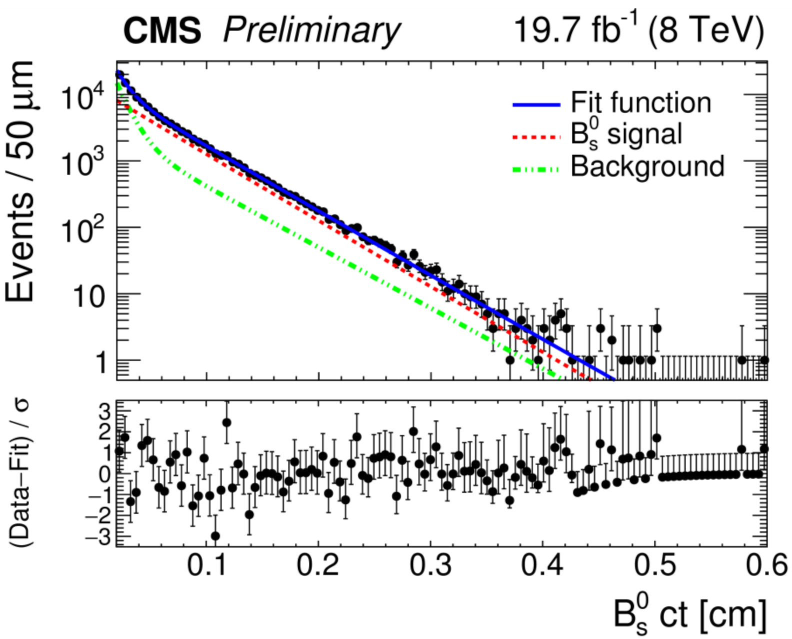
[HFAG Preliminary]

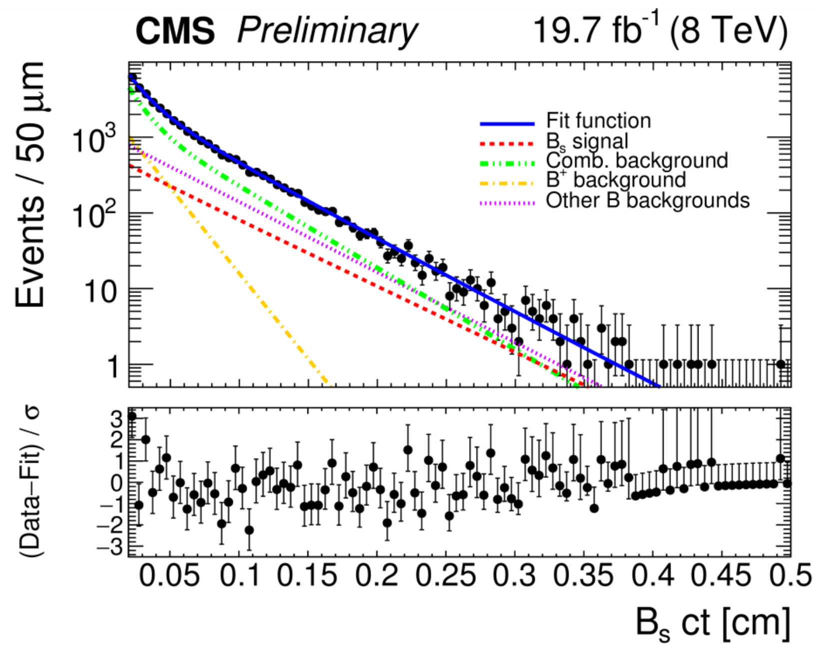
SM: $-0.0363^{+0.0016}_{-0.0015}$ rad

a lot of room for improvement

Precision measurements of B lifetimes in $B \longrightarrow J/\psi X$ decays

CMS PAS BPH-13-008





$B_s \longrightarrow J/\psi\varphi$

mixture of 2 CP-even ($\approx B_L$)
and one CP-odd ($\approx B_H$)

$B_s \longrightarrow J/\psi\pi^+\pi^-$

$0.9240 < m(\pi^+\pi^-) < 1.0204$ GeV,
dominated by $f_0(980)$
CP-odd ($\approx B_H$)

$$c\tau_{B^0_s} = 443.9 \pm 2.0\,(\text{stat}) \pm 1.2\,(\text{syst})\ \mu\text{m}\ (\text{in } J/\psi\phi(1020))$$

$$c\tau_{B^0_s} = 504.3 \pm 10.5\,(\text{stat}) \pm 3.7\,(\text{syst})\ \mu\text{m}\ (\text{in } J/\psi\pi^+\pi^-)$$

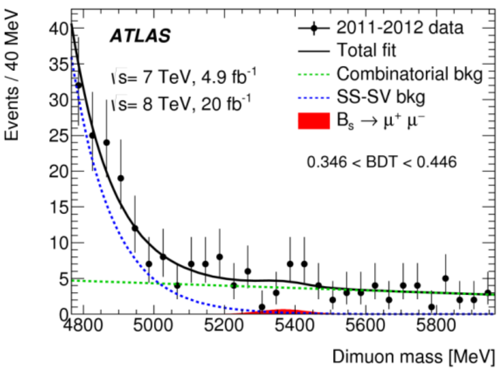
$$\Gamma_H = c/c\tau_{B^0_s} = 0.594 \pm 0.012\,(\text{stat}) \pm 0.004\,(\text{syst})\ \text{ps}^{-1}$$

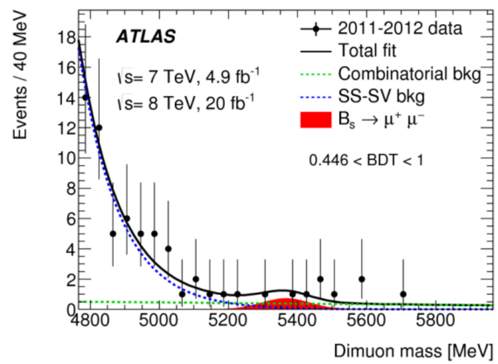
neglecting CPV

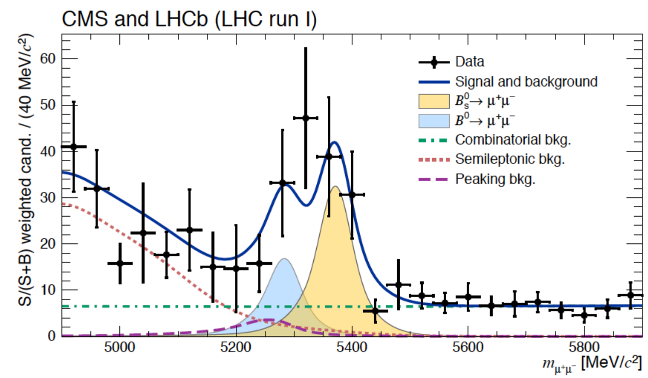
Rare Decays (FCNC)

$B_{(s)}^0 \to \mu^+\mu^-$ (FCNC, CKM and helicity suppressed)

ATLAS, EPJC 76 (2016) 513 **CMS+LHCb, Nature (2015) 14474**







$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(0.9^{+1.1}_{-0.8}\right) \times 10^{-9}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.0 \times 10^{-9} \text{ (95\% CL)}$$

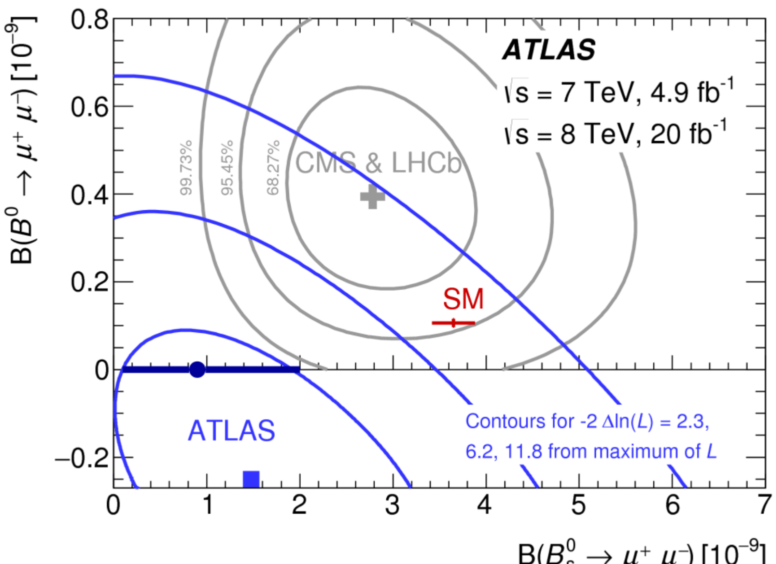
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ (95\% CL)}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$ 6.2 σ

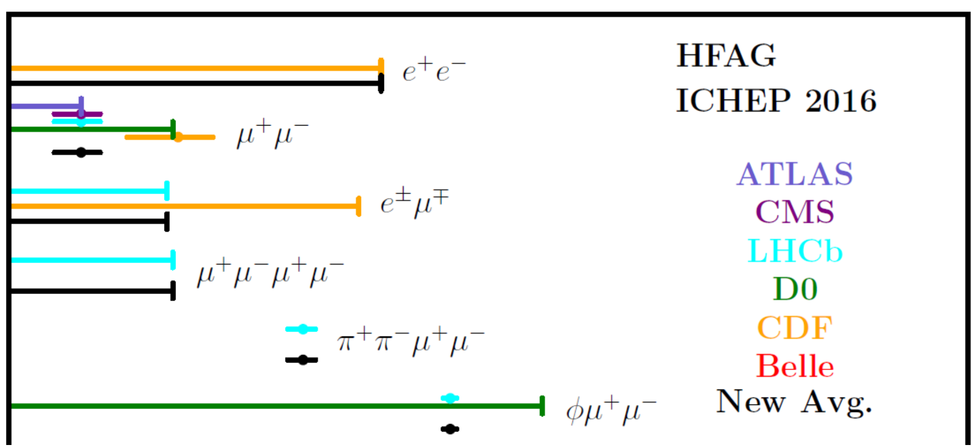
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$ 3.2 σ

$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.06 \pm 0.09) \times 10^{-10}$$



agree within 2 σ



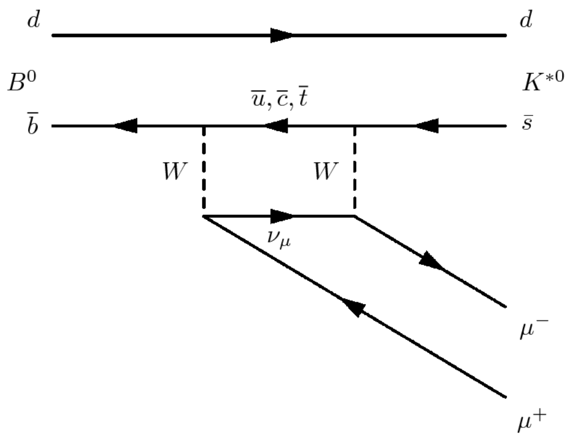
Run II data to clarify the situation

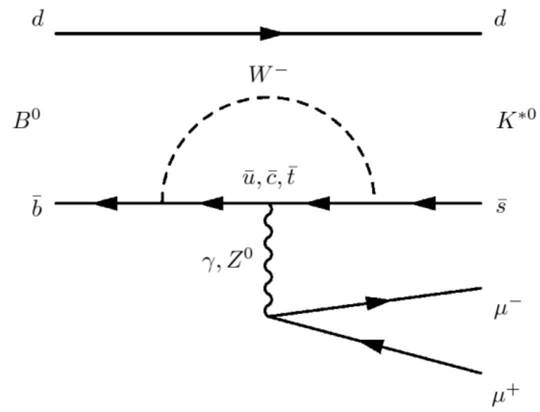
$B^0 \to K^{*0} \mu^+\mu^-$ (FCNC)

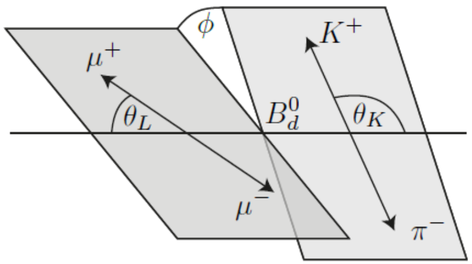
ATLAS-CONF-2017-023

CMS, PLB 753 (2016) 013

CMS PAS BPH-15-008







$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Bigg[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Bigg]. \quad (1)$$

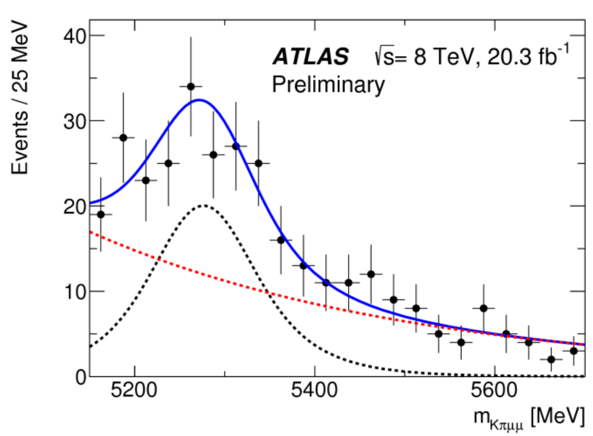
$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}$$
$$P_3 = -\frac{S_9}{1-F_L}$$
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

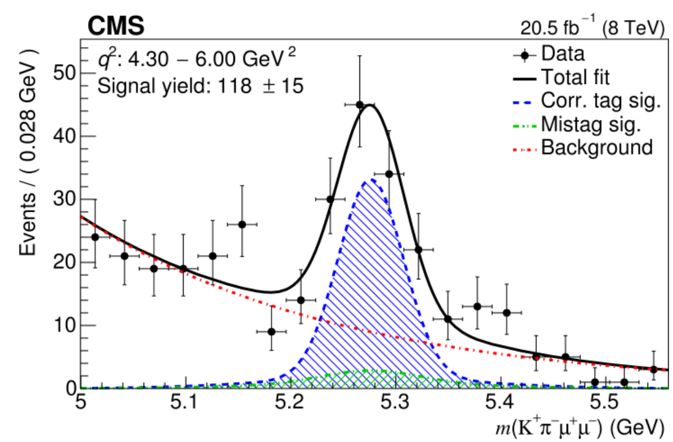
to reduce theor. uncert.

F_L – fraction of longit. polarised K*'s

S_i – angular coefficients

Full angular analysis Performed in bins of $q^2 = m^2(\mu^+\mu^-)$

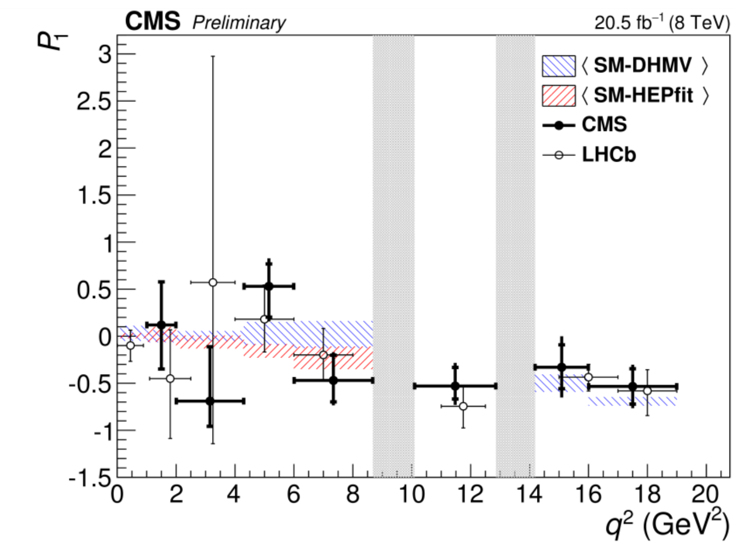


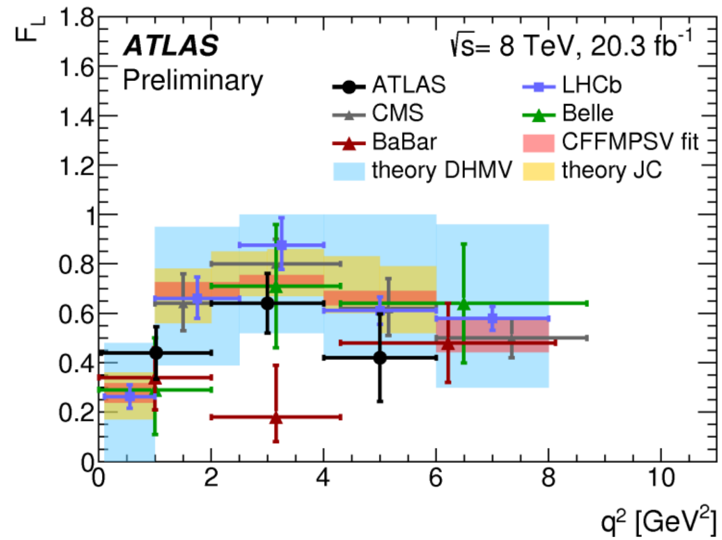


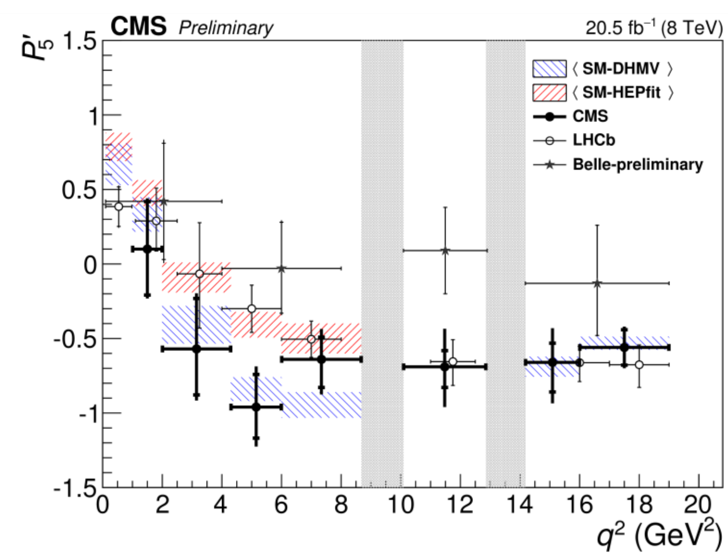
$B^0 \rightarrow K^{*0} \mu^+\mu^-$ (FCNC)

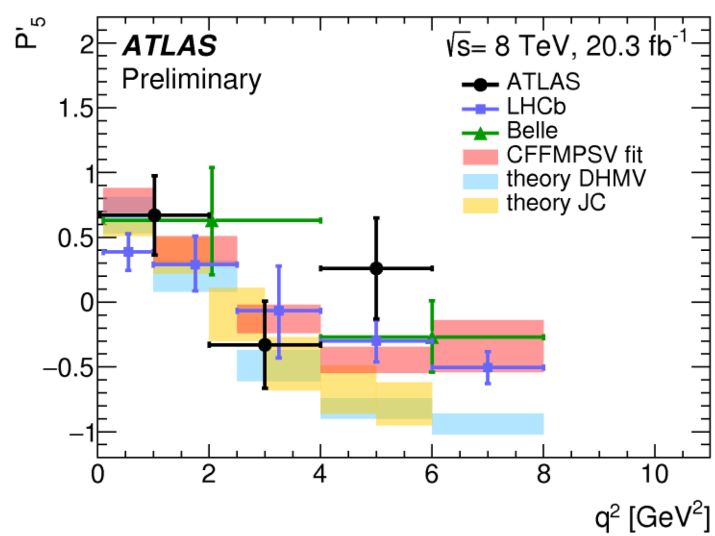
ATLAS-CONF-2017-023

CMS, PLB 753 (2016) 013
CMS PAS BPH-15-008









More data are needed!

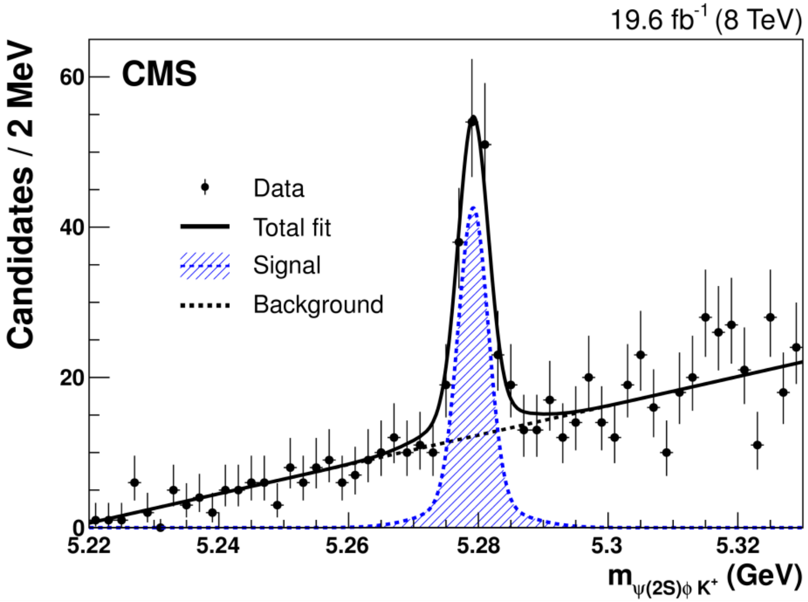
Fair agreement with SM in most distributions/bins

~2.5 σ deviation in P_5' for $4 < q^2 < 6$ GeV² in ATLAS (similar to LHCb and Belle)

Decays and Spectroscopy

Observation of $B^+ \to \psi(2S)\varphi(1020)K^+$

CMS, PLB 764 (2017) 66



(140 ± 15) signal events

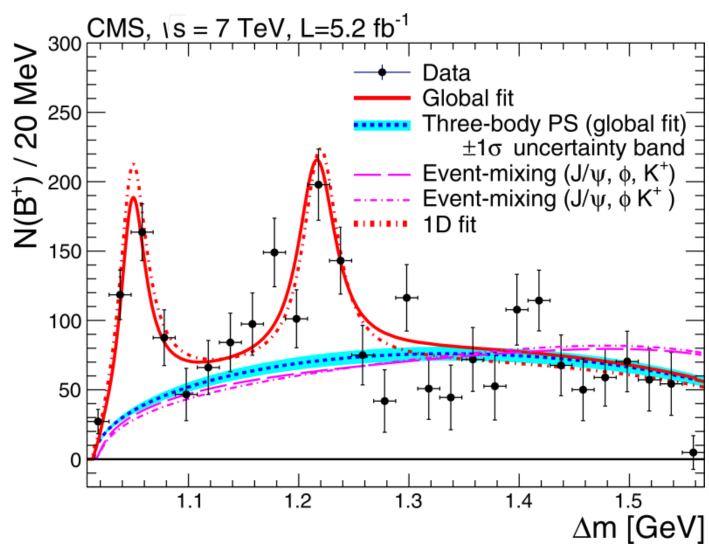
Branching fraction:

$$(4.0 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.2\,(\mathcal{B})) \times 10^{-6}$$

using normalization to $B^+ \to \psi(2S)K^+$

Can be used in searches for resonances in $m(\psi(2S)\varphi)$ with more data

CMS, PLB 734 (2014) 66

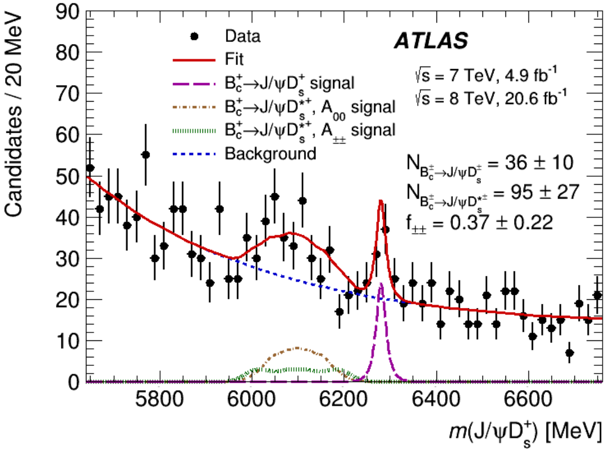


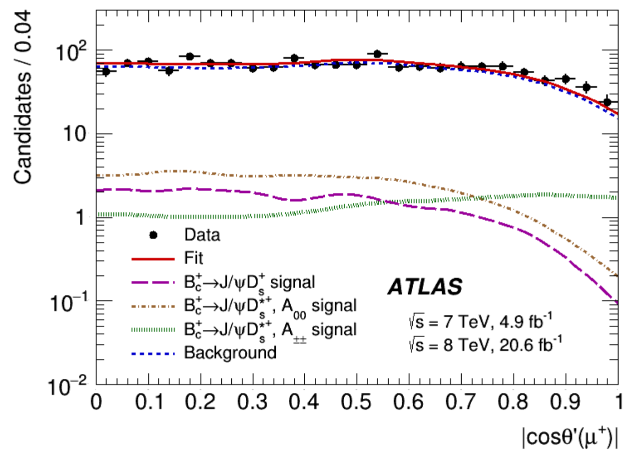
CDF, D0, LHCb, CMS and BaBAr reported possible structures in $m(J/\psi\varphi)$ using $B^+ \to J/\psi\varphi(1020)K^+$

$\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

Measurement of $B_c^+ \to J/\psi\, D_s^{(*)+}$

ATLAS, EPJ C 75 (2016) 1





2D unbinned fit

helicity angle θ′ : between μ^+ and D_s^+ in $\mu^+\mu^-$ rest frame

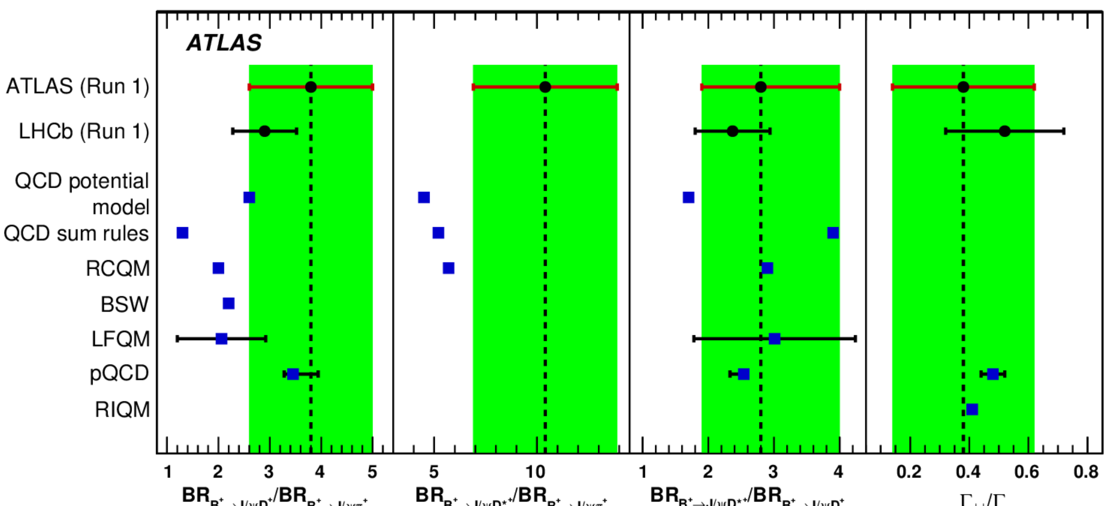
Normalization mode: $B_c^+ \to J/\psi\, \pi^+$

$$\mathcal{R}_{D_s^+/\pi^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^+}}{\mathcal{B}_{B_c^+\to J/\psi \pi^+}} = 3.8 \pm 1.1\ (\text{stat.}) \pm 0.4\ (\text{syst.}) \pm 0.2\ (\text{BF})$$

$$\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi \pi^+}} = 10.4 \pm 3.1\ (\text{stat.}) \pm 1.5\ (\text{syst.}) \pm 0.6\ (\text{BF})$$

$$\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi D_s^+}} = 2.8^{+1.2}_{-0.8}\ (\text{stat.}) \pm 0.3\ (\text{syst.})$$

$$\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23\ (\text{stat.}) \pm 0.07\ (\text{syst.})$$



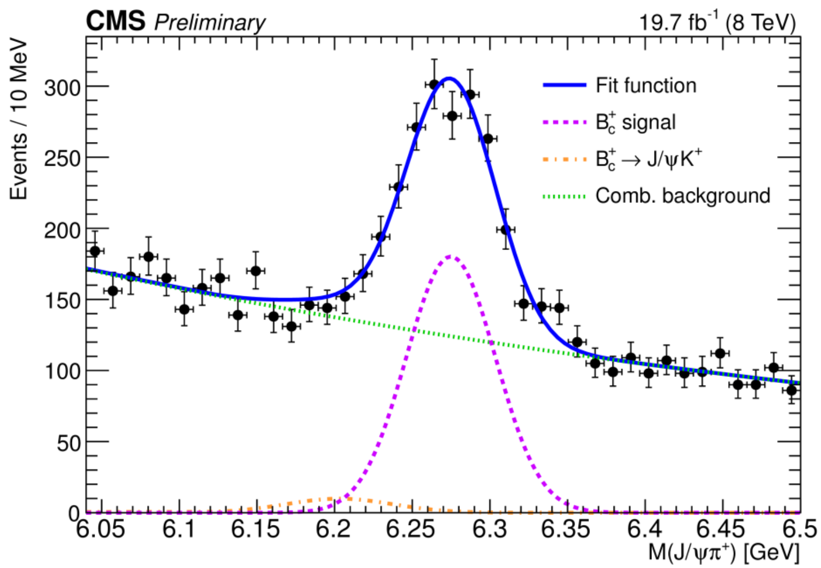
Reasonable agreement with LHCb

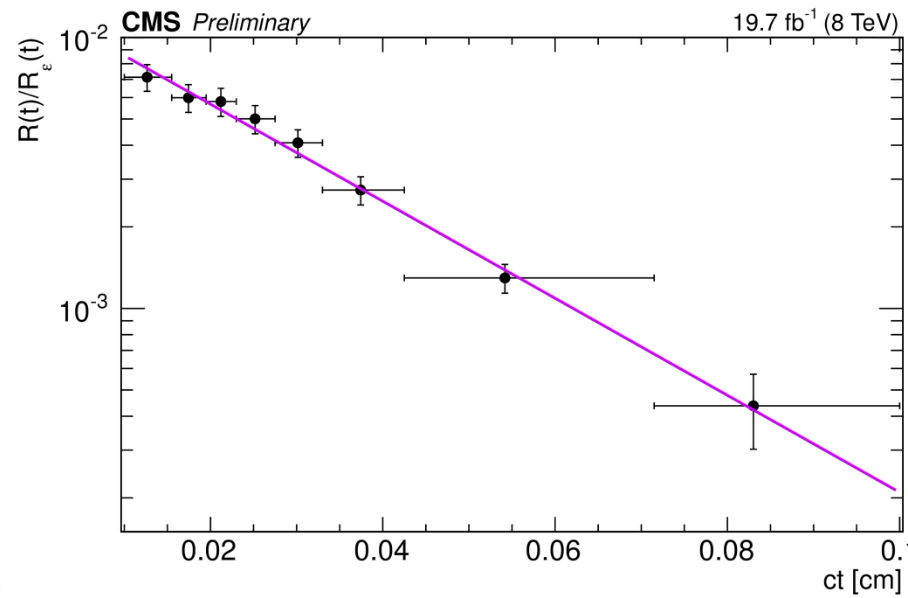
Some predictions are below but within 2 σ

Experimental precision can (will) be improved!

Precision measurement of B_c lifetime

CMS PAS BPH-13-008





$$c\tau_{B_c^+} = 162.3 \pm 8.2\ (\mathrm{stat}) \pm 4.7\ (\mathrm{syst}) \pm 0.1\ (\tau_{B^+})\ \mu m$$

$$\frac{N_{B_c^+}(t)}{N_{B^+}(t)} = \mathcal{R}(t) = \frac{\epsilon_{B_c^+}(t) r(t) \otimes E_{B_c^+}(t)}{\epsilon_{B^+}(t) r(t) \otimes E_{B^+}(t)}$$

In agreement with the LHCb measurements

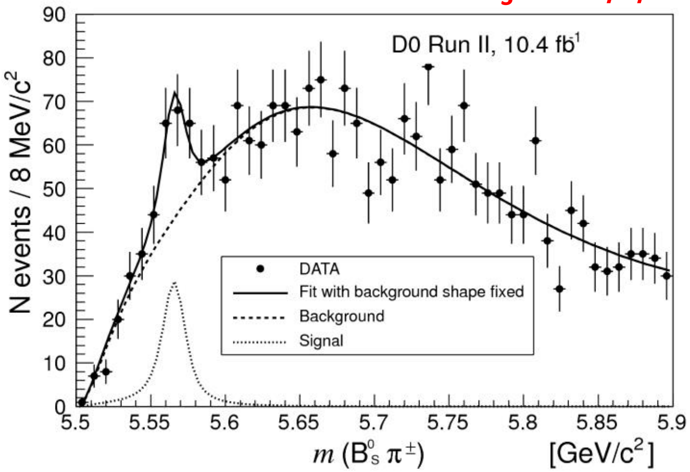
Higher previous Tevatron measurements

Precise value is important to constraint new physics behind $B \to D^{(*)} \tau \nu$ anomalies

VALUE (10^{-12} s)	DOCUMENT ID		TECN	COMMENT
0.507 ±0.009 OUR EVALUATION				
0.507 ±0.009 OUR AVERAGE				
0.5134 ±0.0110 ±0.0057	[1,2] AAIJ	15G	LHCB	pp at 7, 8 TeV
0.509 ±0.008 ±0.012	[3] AAIJ	14G	LHCB	pp at 8 TeV
0.452 ±0.048 ±0.027	[2] AALTONEN	13	CDF	$p\bar{p}$ at 1.96 TeV
0.448 $^{+0.038}_{-0.036}$ ±0.032	[4] ABAZOV	09H	D0	$p\bar{p}$ at 1.96 TeV
0.463 $^{+0.073}_{-0.065}$ ±0.036	[4] ABULENCIA	06O	CDF	$p\bar{p}$ at 1.96 TeV
0.46 $^{+0.18}_{-0.16}$ ±0.03	[4] ABE	98M	CDF	$p\bar{p}$ 1.8 TeV

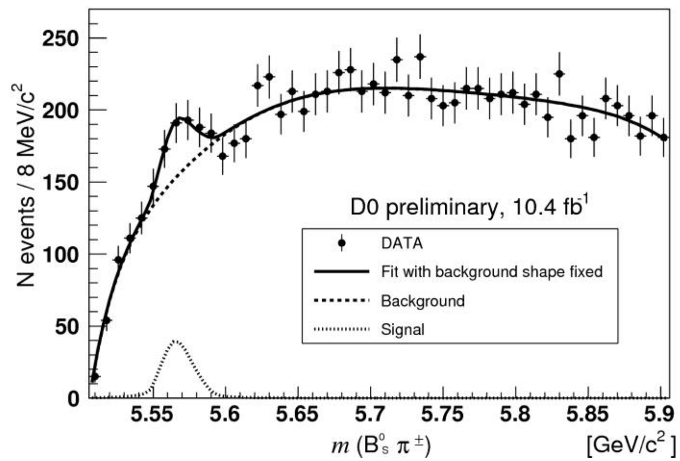
Search for $X(5568) \to B_s\pi^\pm$ CMS PAS BPH-16-002

$B_s \to J/\psi\varphi$

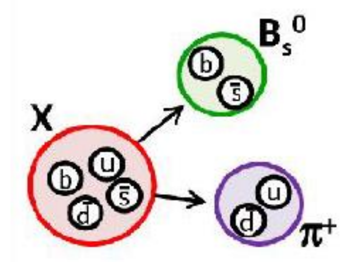


$\rho_X = (8.4 \pm 1.9 \pm 1.4)\%$

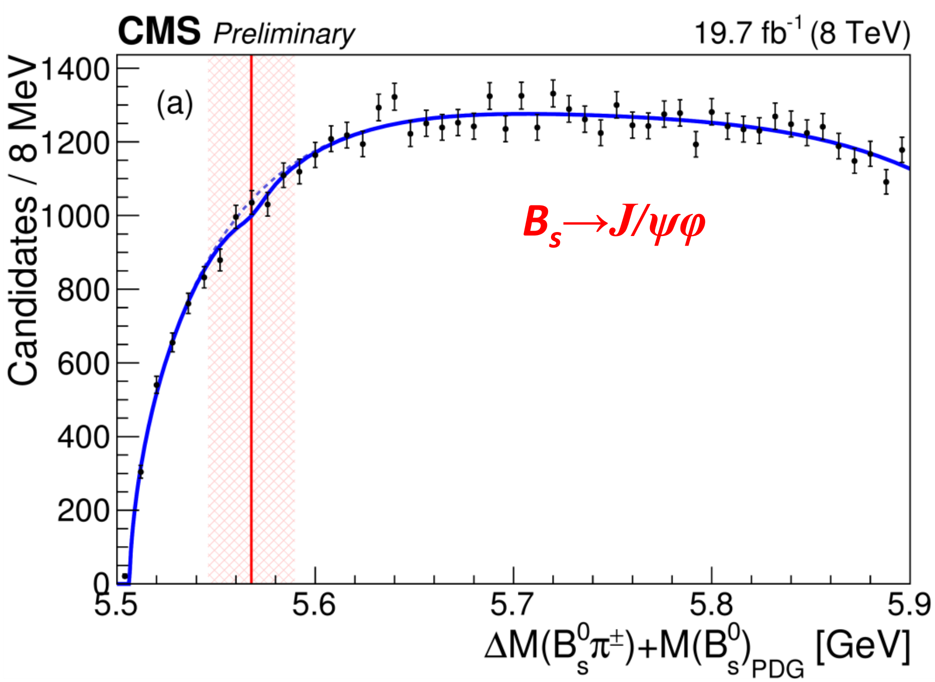
$B_s \to D_s^+\mu^- X$



$\rho_X = (7.6\ ^{+2.8}_{-2.4}\ ^{+0.6}_{-1.7})\%$



$p_T(B_s) > 10$ GeV



$B_s \to J/\psi\varphi$

$\rho_X^{CMS} < 3.9$ % at 95% CL

$\rho_X^{LHCb} < 2.4$ % at 95% CL

$p_T(B_s) > 10$ GeV

No results from CDF and ATLAS yet

Summary : main messages

- **Charmed meson x-sections:** GM-VFNS agree in shape and norm.
  Beauty meson x-sections: FONLL generally agrees
  Charmonium x-sections, Prompt: NLO NRQCD generally agrees

- **CP violation:** precise measurements φ_s and $\Delta\Gamma_s$
  good agreement with SM, higher precision is needed

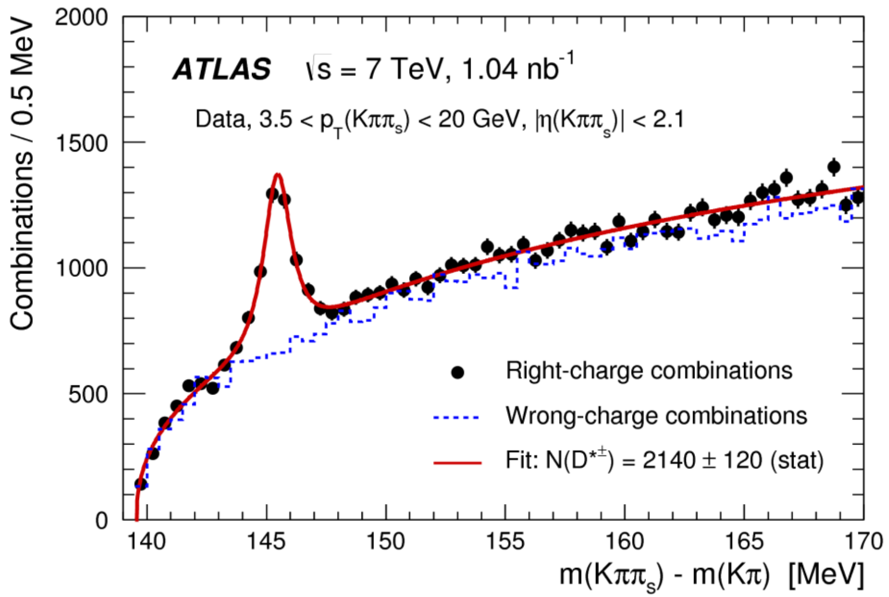
- $B_{(s)}^0 \to \mu^+\mu^-$: observed by CMS+LHCb, agree with SM
  ATLAS agrees with CMS+LHCb and SM on the level of 2 σ
  $B^0 \to K^{*0}\,\mu^+\mu^-$: generally agree with SM, tensions on the level of 2.5 σ in one bin for ATLAS (similar to LHCb and Belle)

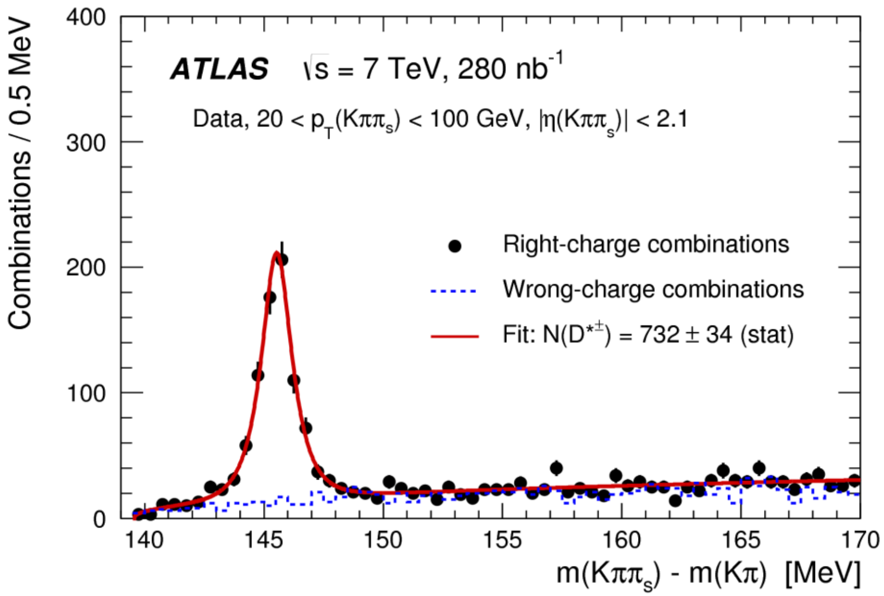
- $X(5568) \to B_s\pi^{\pm}$: no signal in CMS data, $\rho_X^{CMS} < 3.9\,\%$ at 95% CL
  in agreement with LHCb and contradiction to D0

- New exciting results for summer/fall conferences

Back-up Slides

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





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

DATA:

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

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

POWHEG+PYTHIA:

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

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

FONLL:

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

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

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 $D^{\pm}$:

$3.5 < p_{\mathrm{T}}(D) < 20$ GeV and $|\eta(D)| < 2.1$

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

$1 < p_{\mathrm{T}}(D) < 24$ GeV and $|y(D)| < 0.5$

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

Extrapolation with POWHEG+PYTHIA, fragm. ratios

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

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

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

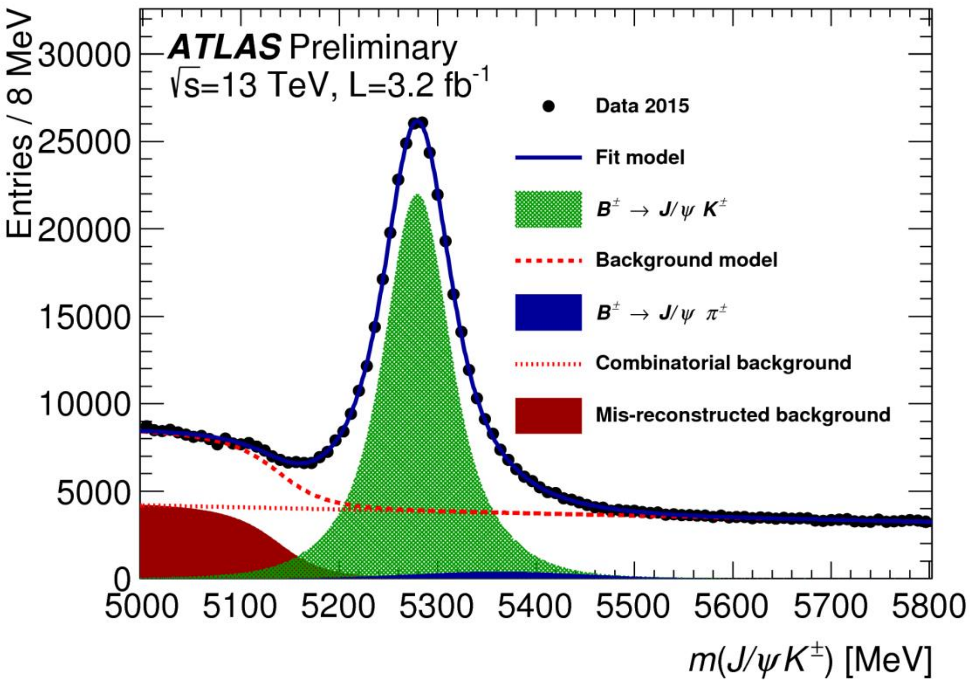
$$P_{\rm v}^d = 0.56 \pm 0.03\,({\rm stat}) \pm 0.01\,({\rm syst}) \pm 0.01\,({\rm br}) \pm 0.02\,({\rm extr})\,.$$

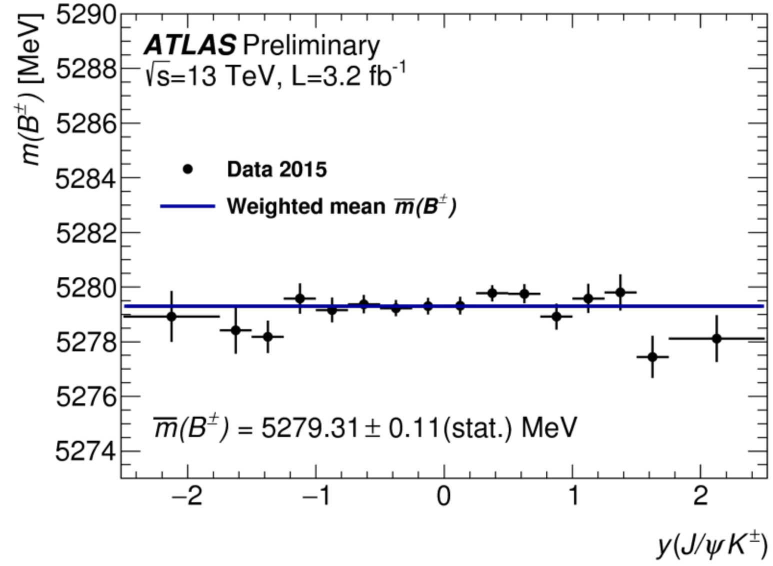
$$\gamma_{s/d}^{\rm LEP} = \frac{f(c\to D_s^+)}{f(c\to D^+) + f(c\to D^{*+})\cdot\mathcal{B}_{D^{*+}\to D^0\pi^+}} = 0.24 \pm 0.02 \pm 0.01\,({\rm br})$$

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

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

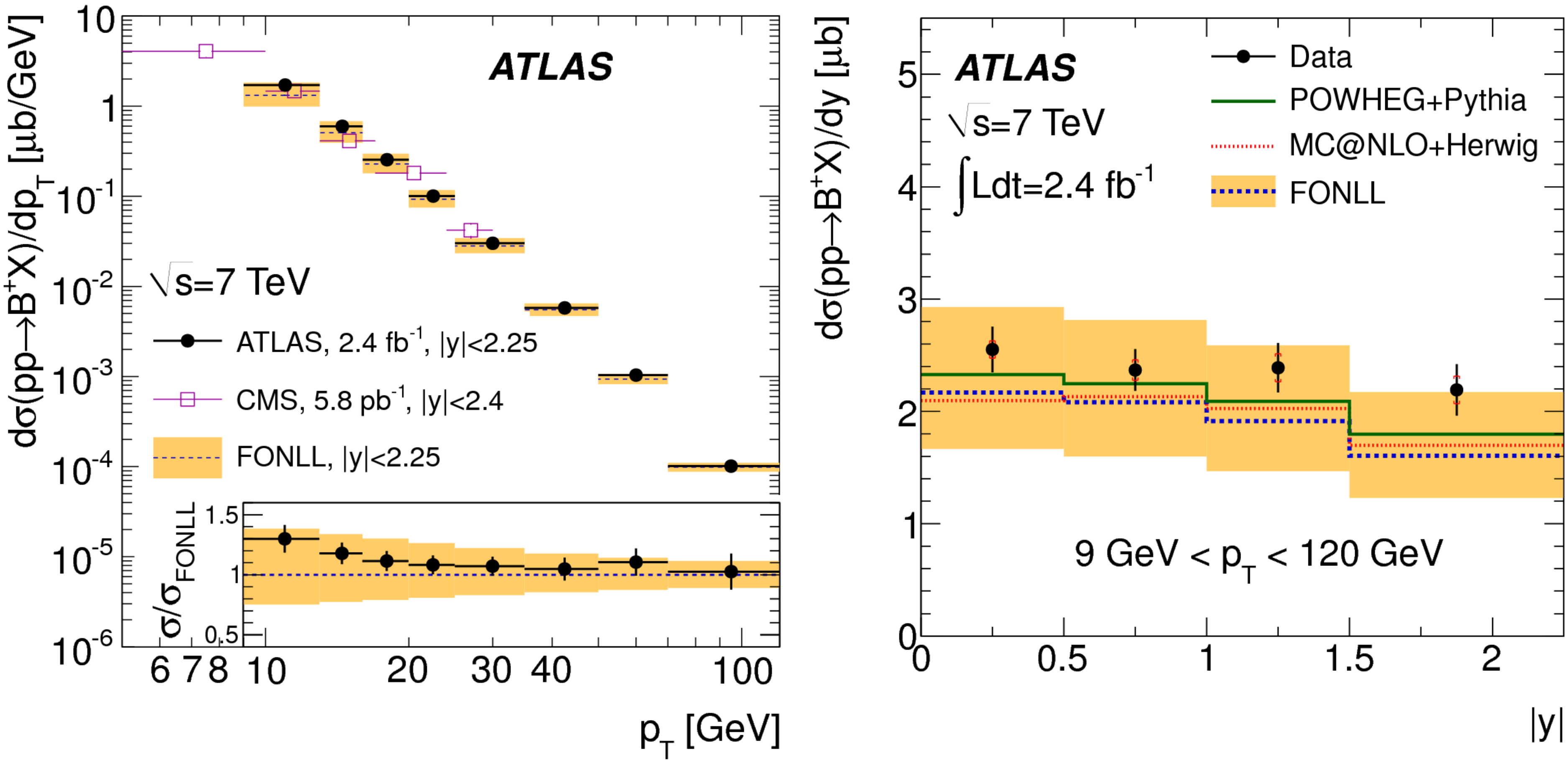
ATLAS-CONF-2015-064





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

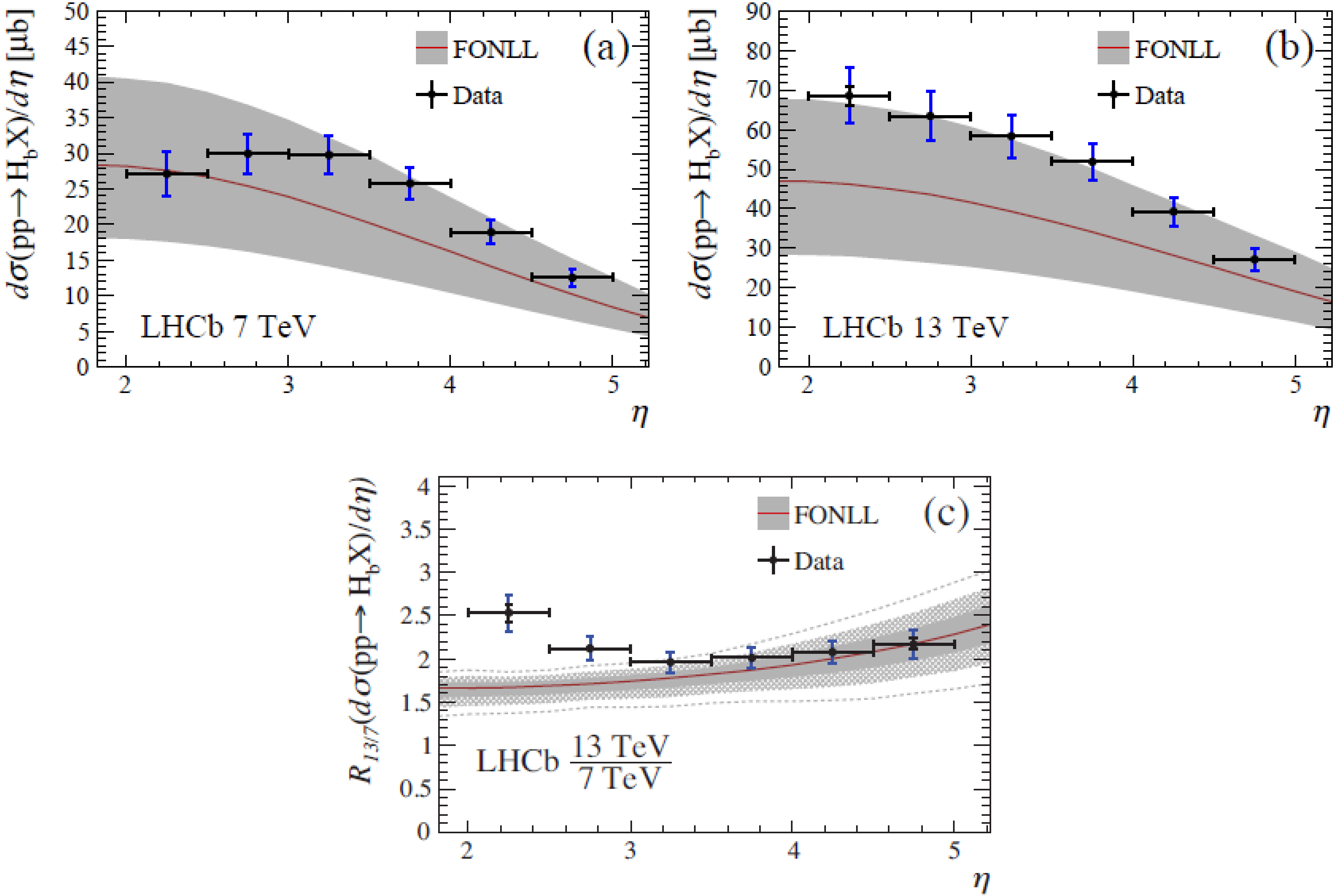


FONLL provides reasonable description although with large theor. uncertainties

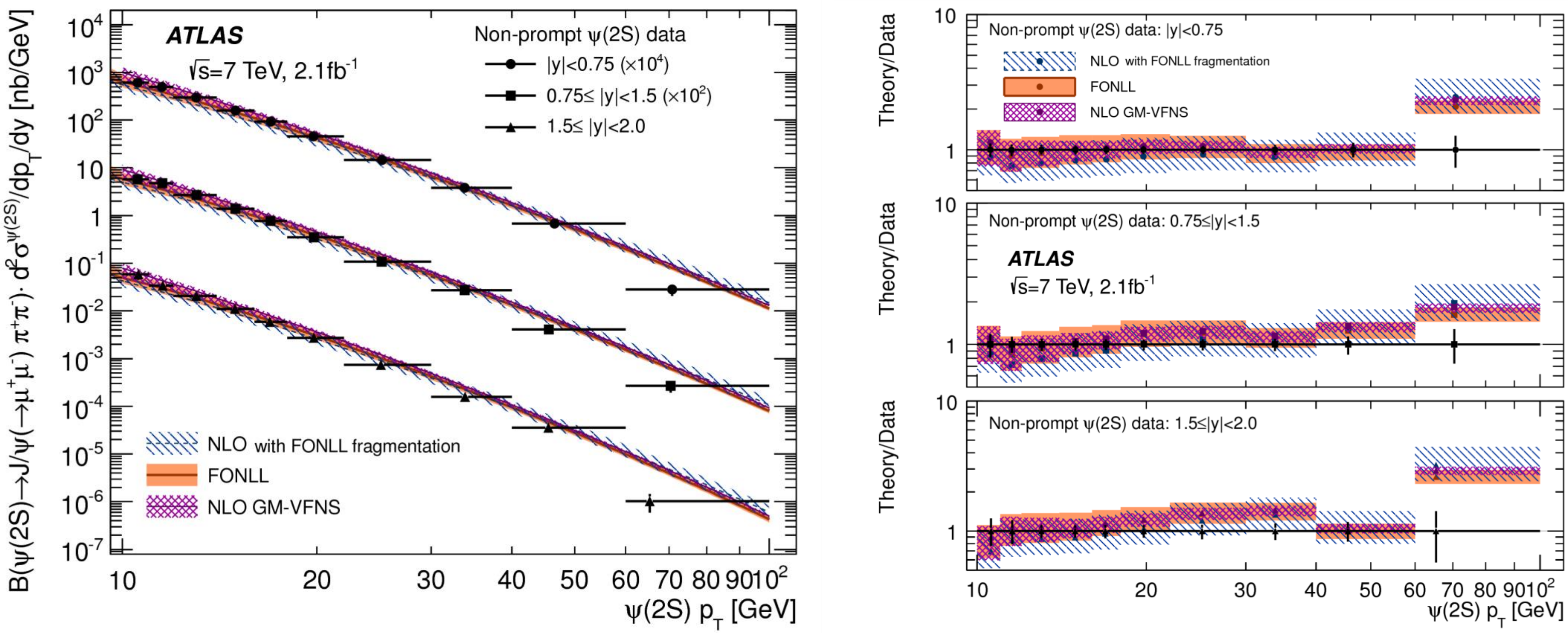
Central predictions are somewhat harder

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

LHCb, Phys. Lett. 118 (2017) 052002



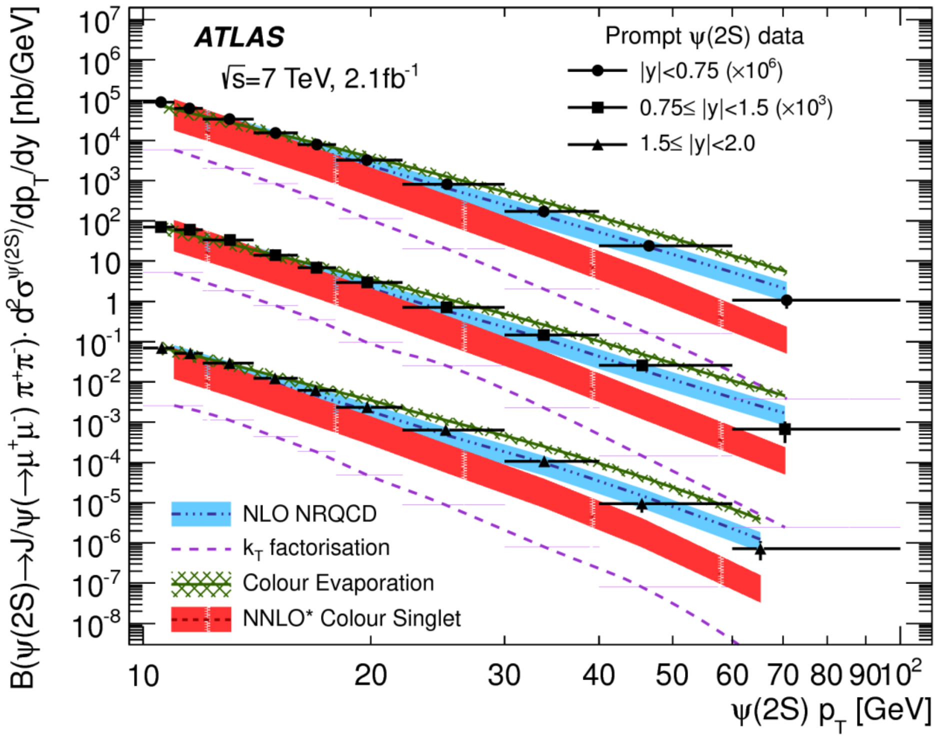
$\psi(2S) \rightarrow J/\psi\ (\rightarrow\mu^{+}\mu^{-})\pi^{+}\pi^{-}$, non-prompt diff. x-sections

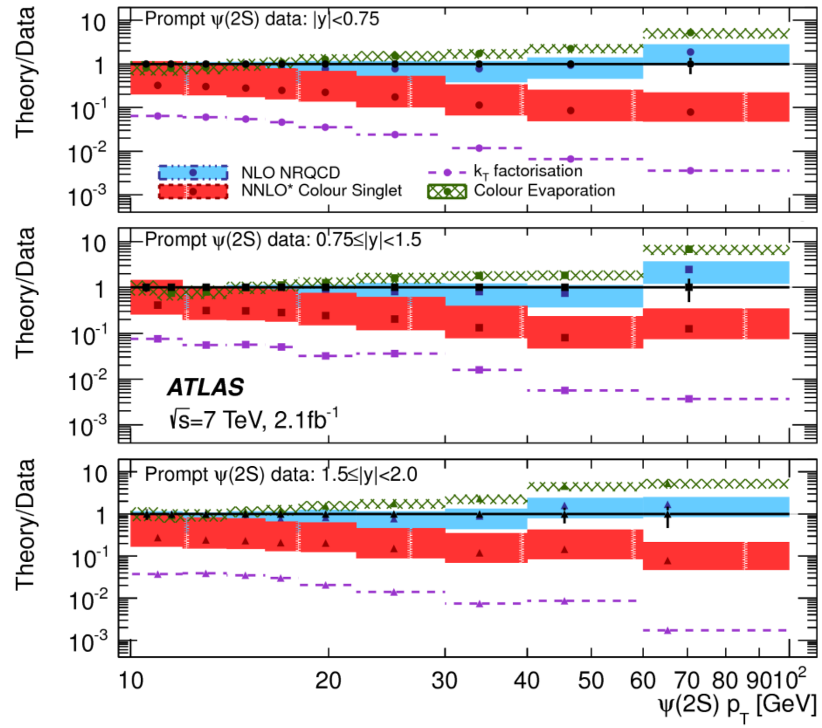


- generally, reasonable description by FONLL and GM-VFNS predictions are harder than data

- NLO with “wrong” (FONLL) fragmentation is even harder

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



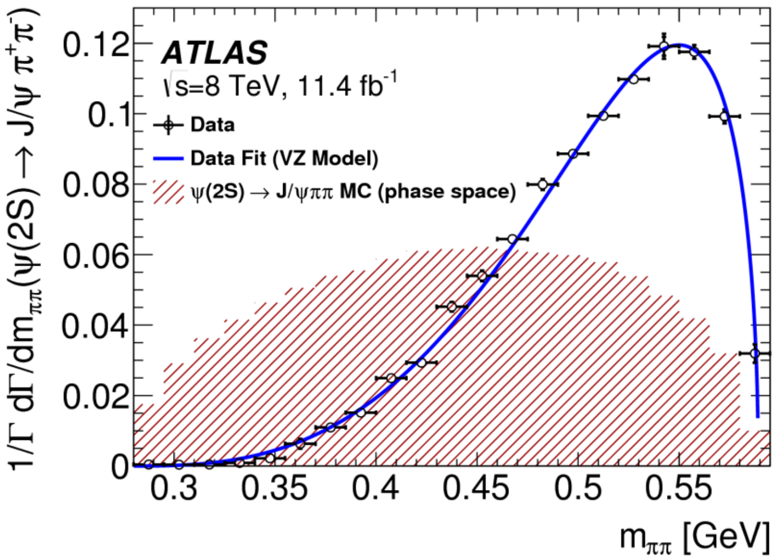


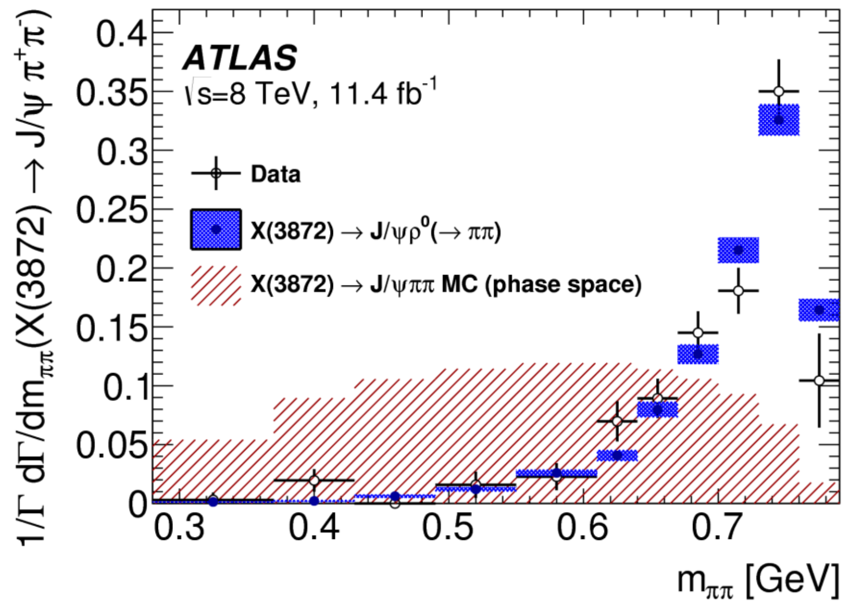
- NLO NRQCD is generally o.k.

- CS is too low even at NNLO*

- CEM is somewhat too hard

$m(\pi^+\pi^-)$ in $\psi(2S)$, $X(3872) \rightarrow J/\psi\ \pi^+\ \pi^-$, 8 TeV





$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS}$$

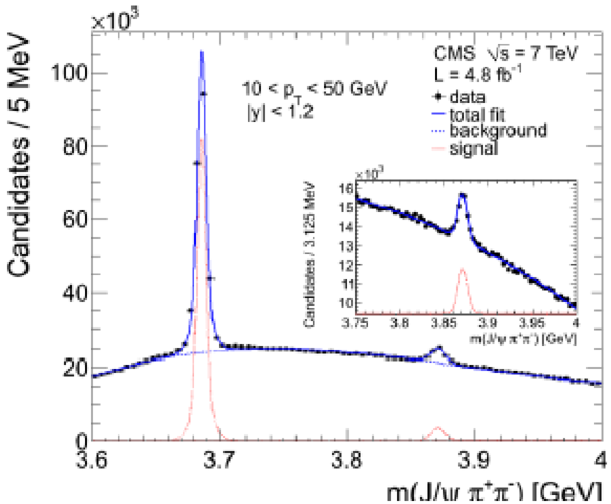
ρ^0 dominance

$$\lambda = 4.16 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{sys})$$

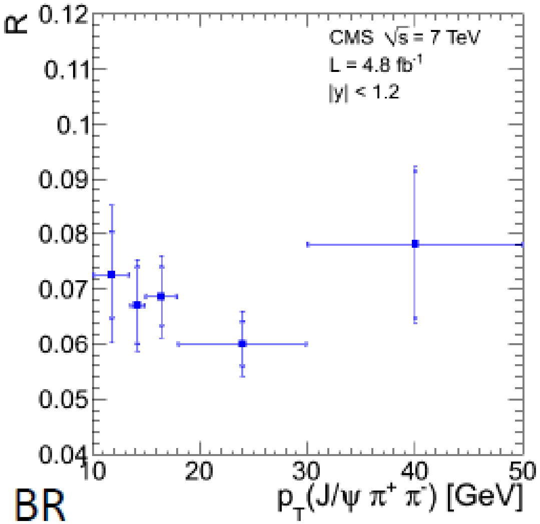
Voloshin-Zakharov distribution

CMS: JHEP 04 (2013) 154

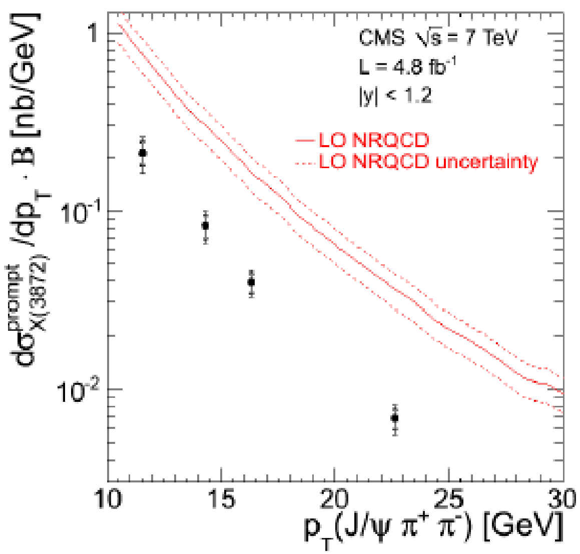
X(3872) Production via decays to $J/\psi\,\pi^+\pi^-$



Assuming $J^{PC} = 1^{++}$
unpolarised

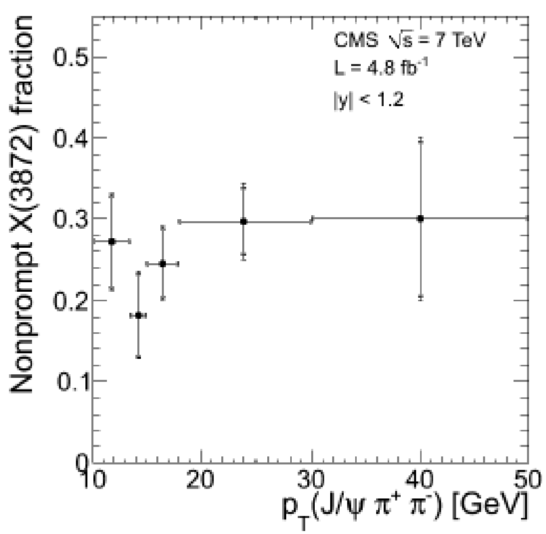


Ratio to $\psi(2S)$ times BR



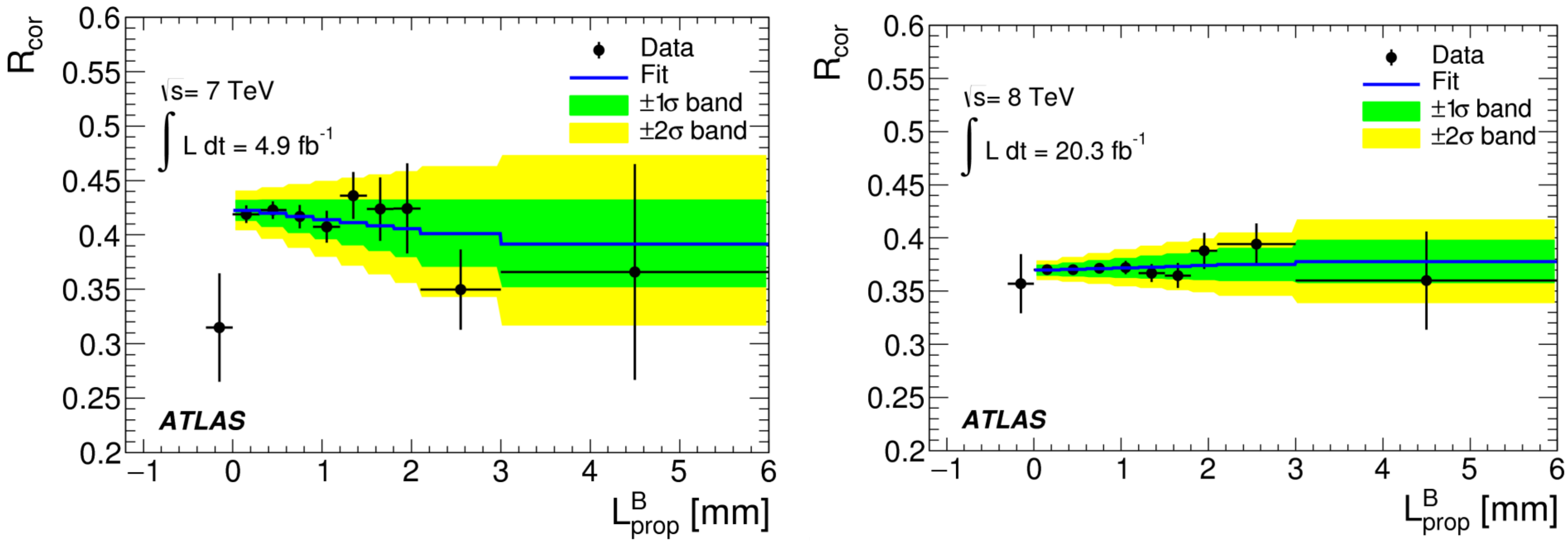
NRQCD:
significantly
Exceeds
measured
value

pT shape ok



$B^0 \longrightarrow J/\psi K^0_S/K^{*0}$ results

ATLAS, JHEP 06 (2016) 081



$$\Gamma[t, J/\psi K_S] \propto e^{-\Gamma_d t}\left[\cosh\frac{\Delta\Gamma_d t}{2} + \cos(2\beta)\sinh\frac{\Delta\Gamma_d t}{2} - A_P \sin(2\beta)\sin(\Delta m_d t)\right]$$

$$\Gamma[t, J/\psi K^{*0}] \propto e^{-\Gamma_d t}\cosh\frac{\Delta\Gamma_d t}{2}$$

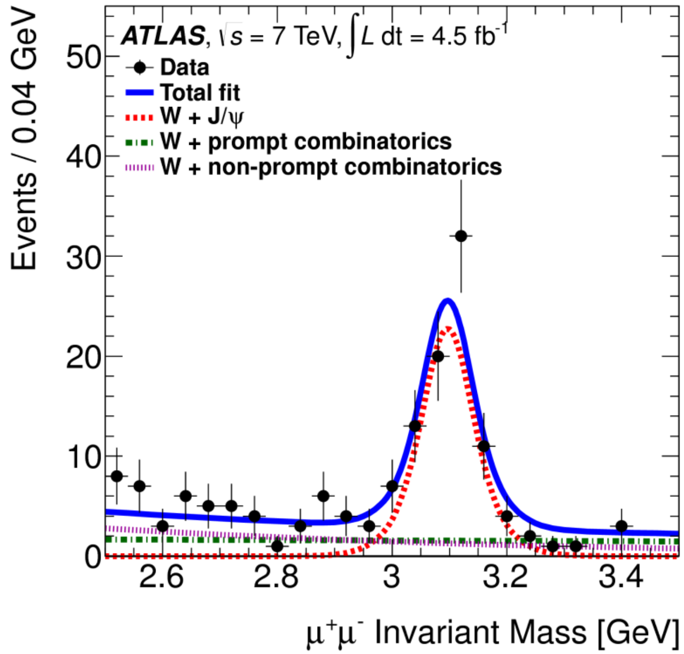
$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1\ (\text{stat.}) \pm 0.9\ (\text{syst.})) \times 10^{-2}$$

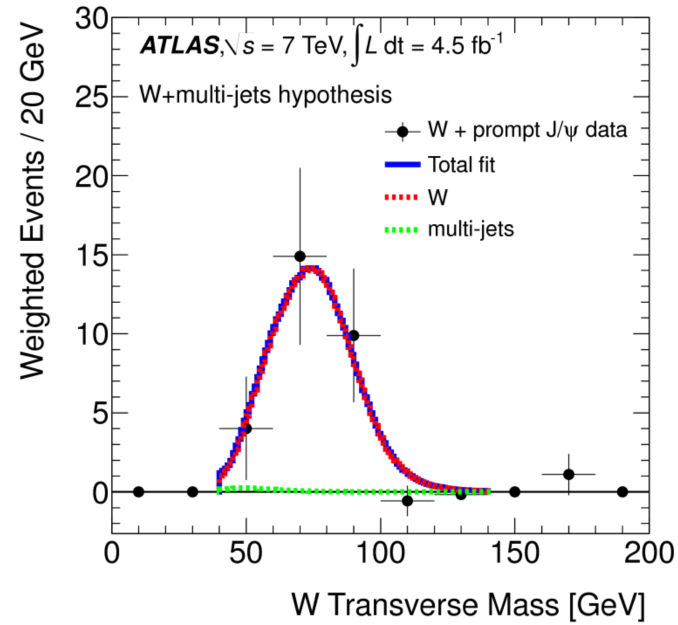
$s \times \Delta\Gamma_d/\Gamma_d$ = –0.002 ± 0.010

from DELPHI, BABAR, Belle, ATLAS and LHCb

$W + J/\psi\ (\to\mu^+\mu^-)$

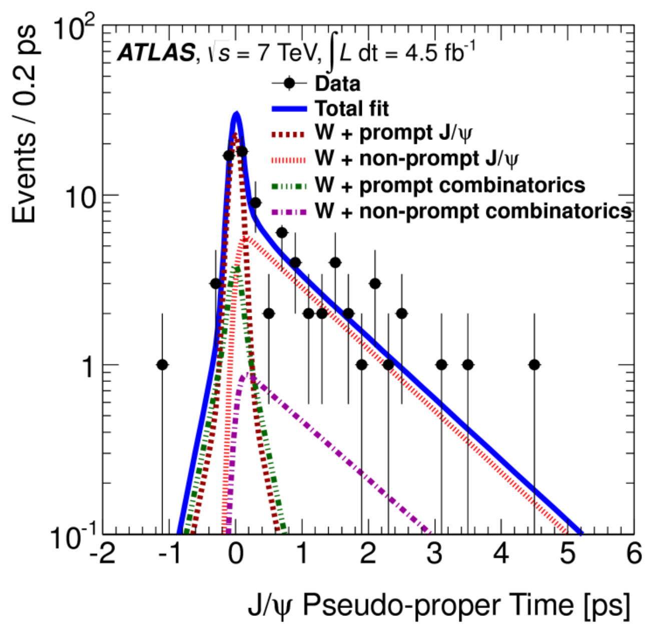
ATLAS, JHEP 04 (2014), 172





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

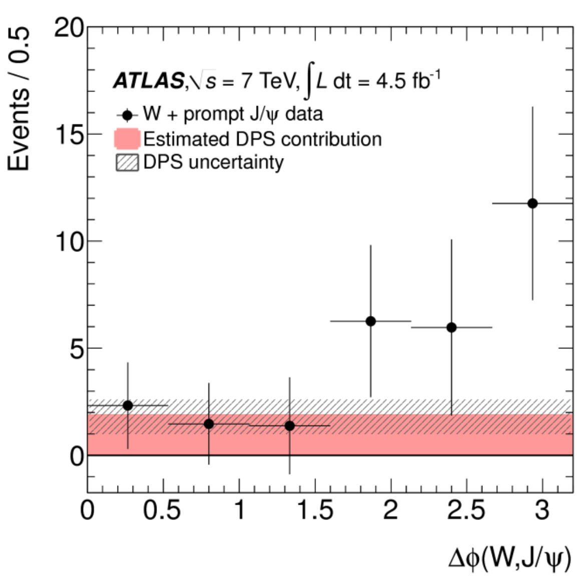
$$m_{\rm T}(W) \equiv \sqrt{2 p_{\rm T}(\mu) E_{\rm T}^{\rm miss}\left(1-\cos(\phi^{\mu}-\phi^{\nu_{\mu}})\right)}$$



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

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

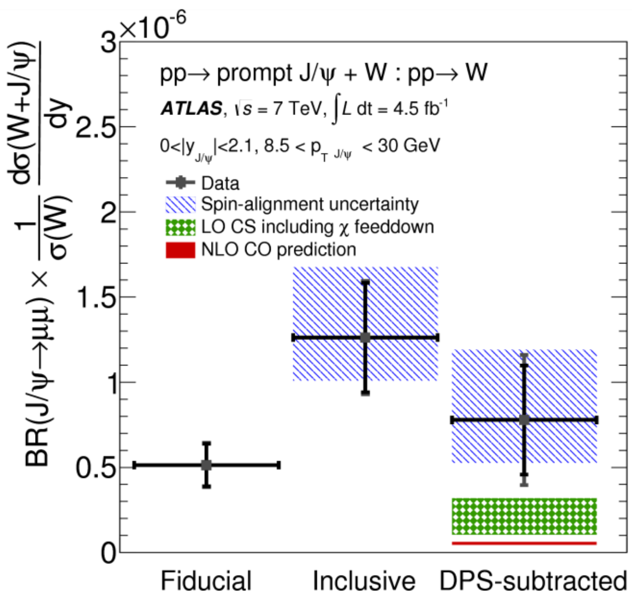
W + J/ψ (→μ⁺μ⁻), Δφ distr. and rates w.r.t. inclusive W

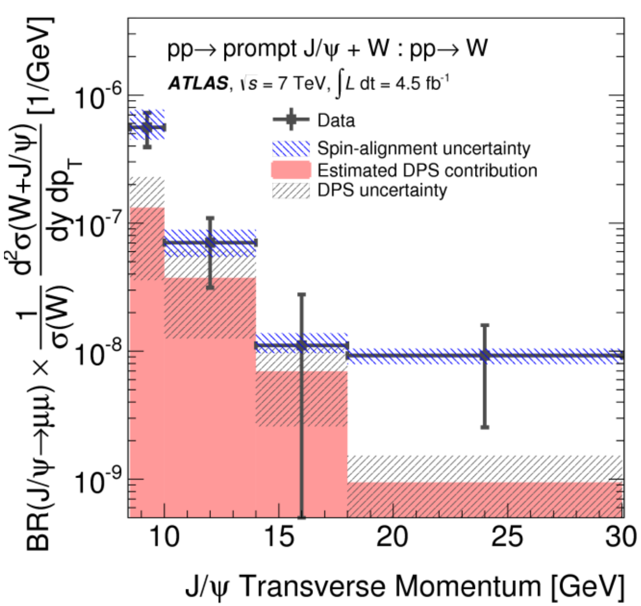


$27.4^{+7.5}_{-6.5}\ W^{\pm} + \text{prompt } J/\psi$ events

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

10.8 ± 4.2

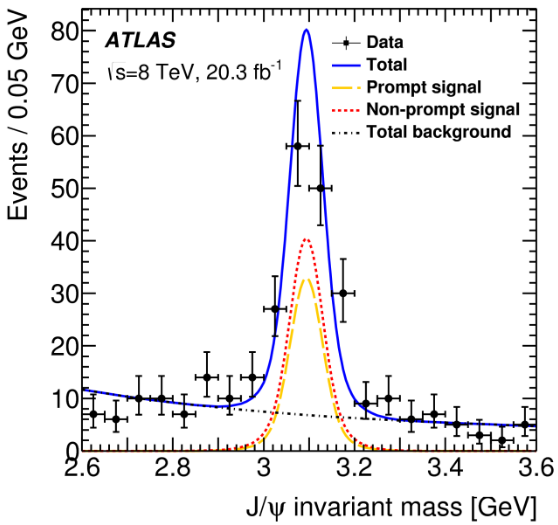


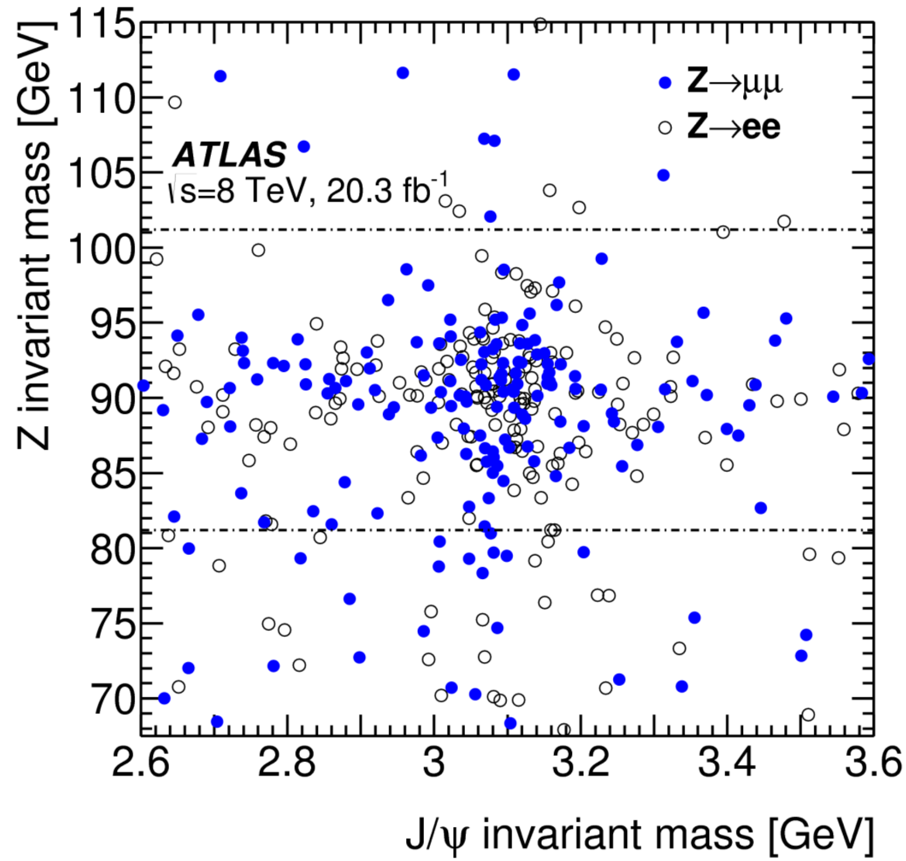


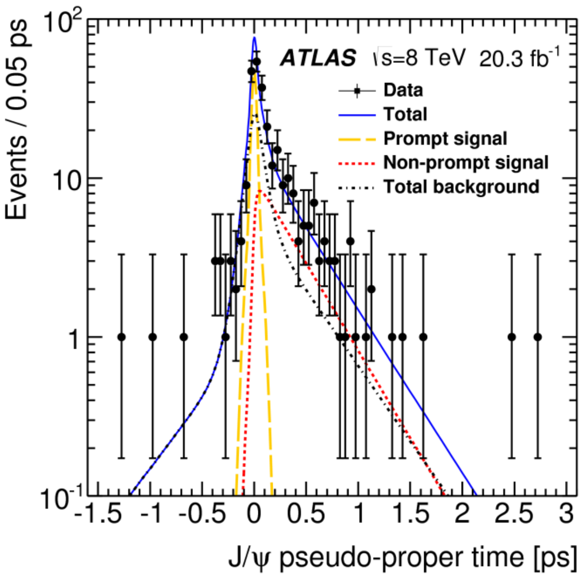
LO CS: Lansberg et al. NLO CO: Mao et al.

Z + J/ψ production (1st obs.) **ATLAS, EPJ C 75 (2015) 229**

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)





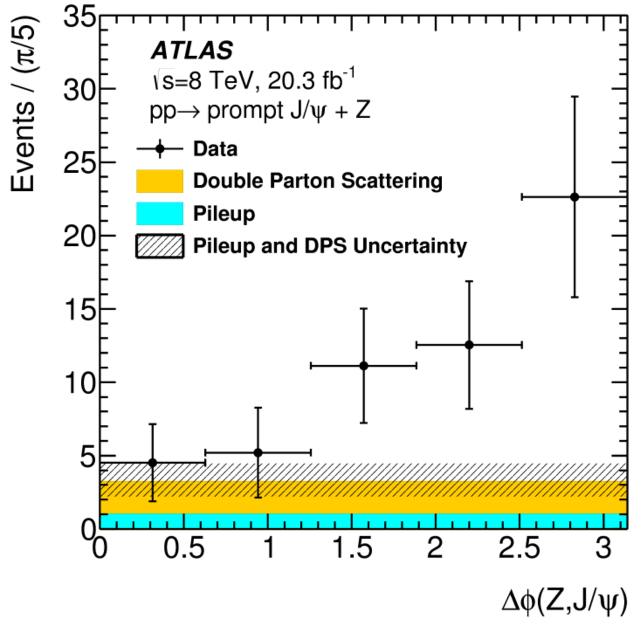


$$8.5 < p_{\mathrm{T}}(J/\psi) < 100 \ \mathrm{GeV}$$

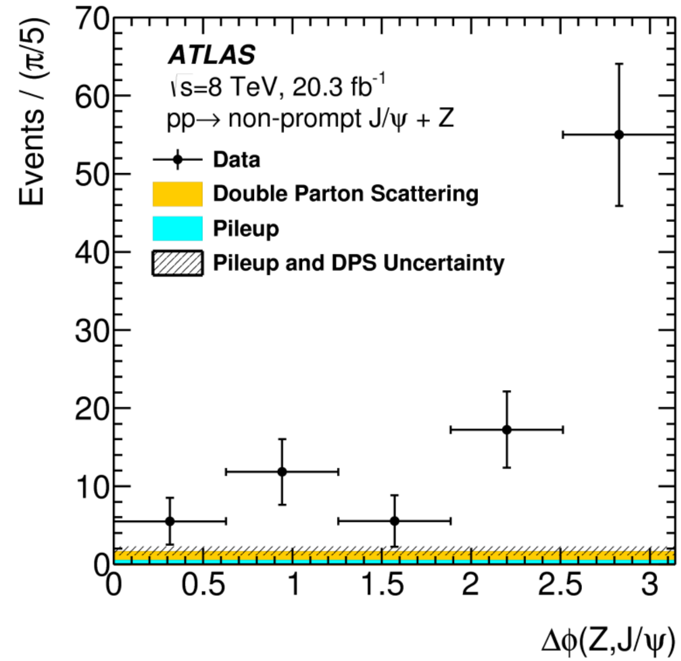
$$|y(J/\psi)| < 2.1$$

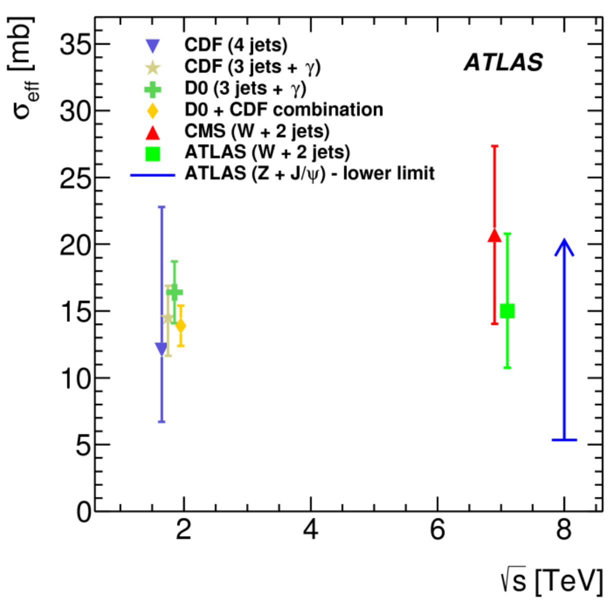
$Z + J/\psi\ (\rightarrow\mu^+\mu^-)$, $\Delta\varphi$ distributions and DPS

Prompt: 56 ± 10



Non prompt: 95 ± 12





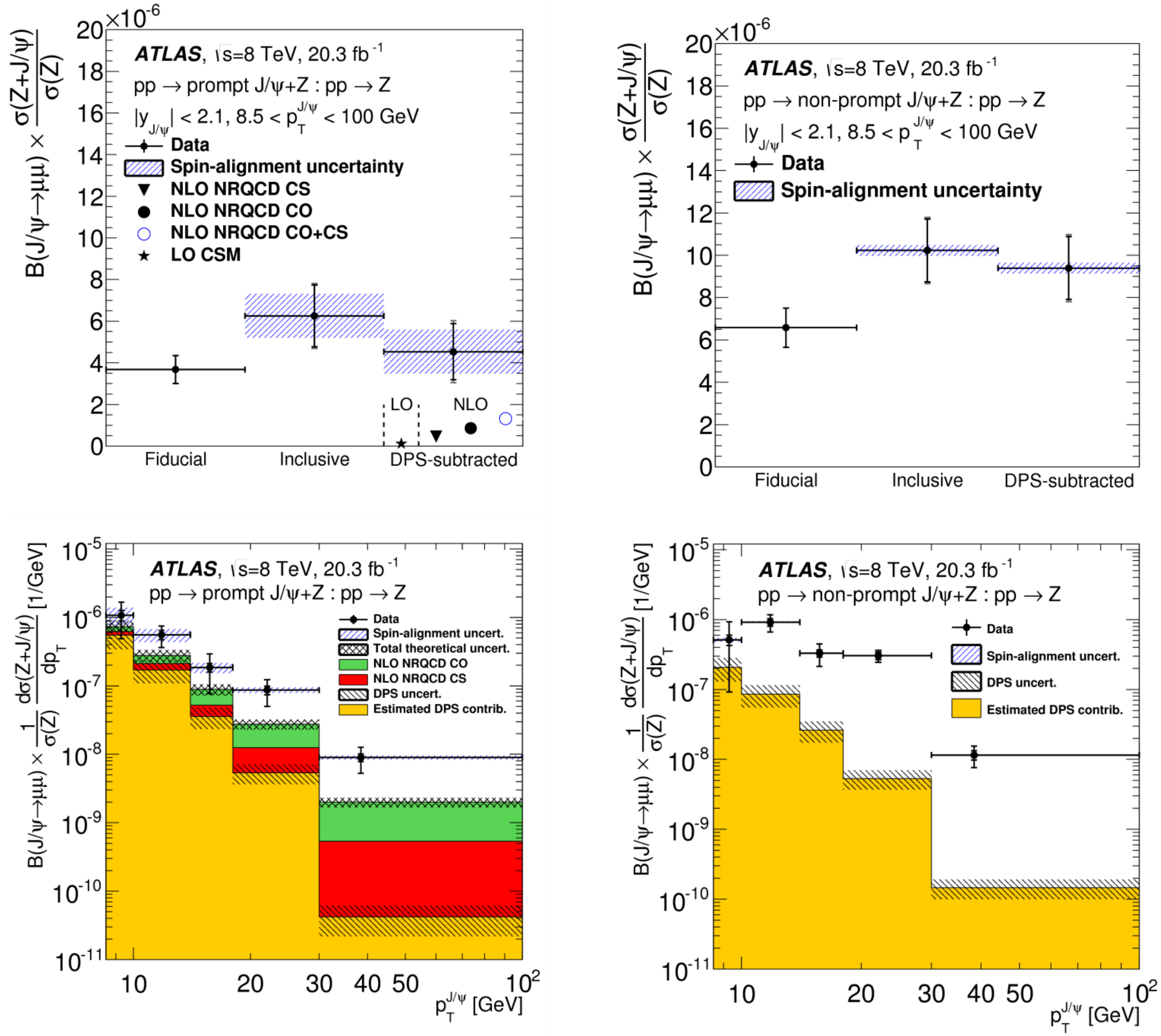
$\sigma_{\rm eff} = 15 \pm 3\,(\text{stat.})^{+5}_{-3}\,(\text{sys.})\,\text{mb}$ ATLAS (W + 2 jets)

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

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

NRQCD: Mao et al.

CSM: Gong et al.



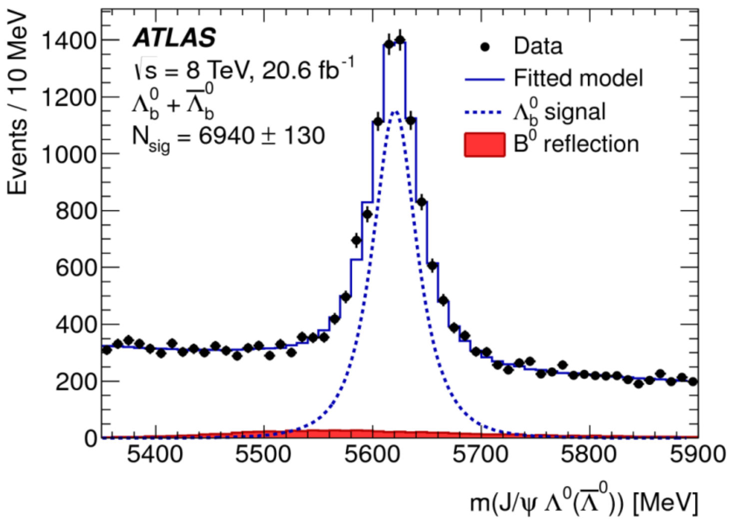
Predictions below data

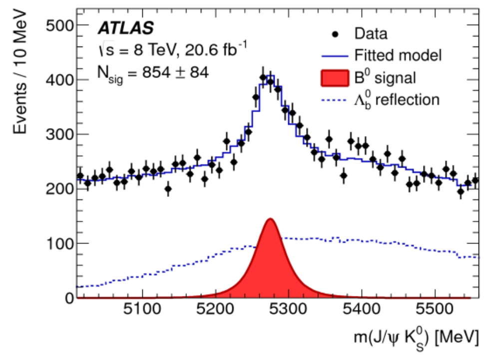
Observation of $\Lambda_b \to \psi(2S)\,\Lambda^0$

ATLAS, PLB 751 (2015) 63

$p_T(\Lambda_b)$ > 10 GeV $|\eta(\Lambda_b)| < 2.1$

2-vertex cascade fit with 2 mass constraints (charmonium and Λ^0/K^0_S)

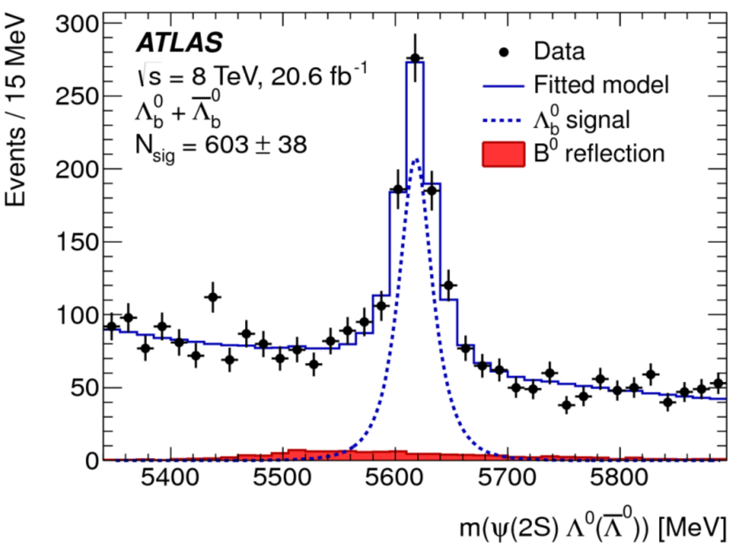


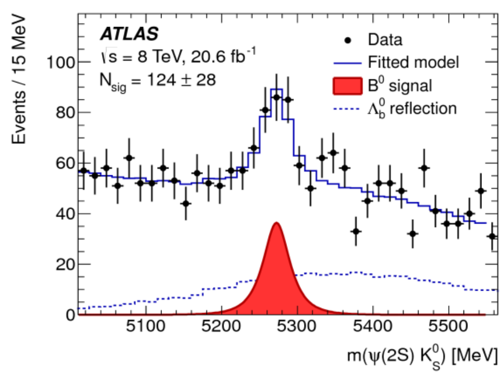


$m(\mu^+\mu^-)$ within ±200 MeV of $m(J/\psi)_{PDG}$

$N(\Lambda_b \to J/\psi\,\Lambda^0)$ = 6940 ± 130

$Prob(\Lambda_b)| > Prob(B^0)$





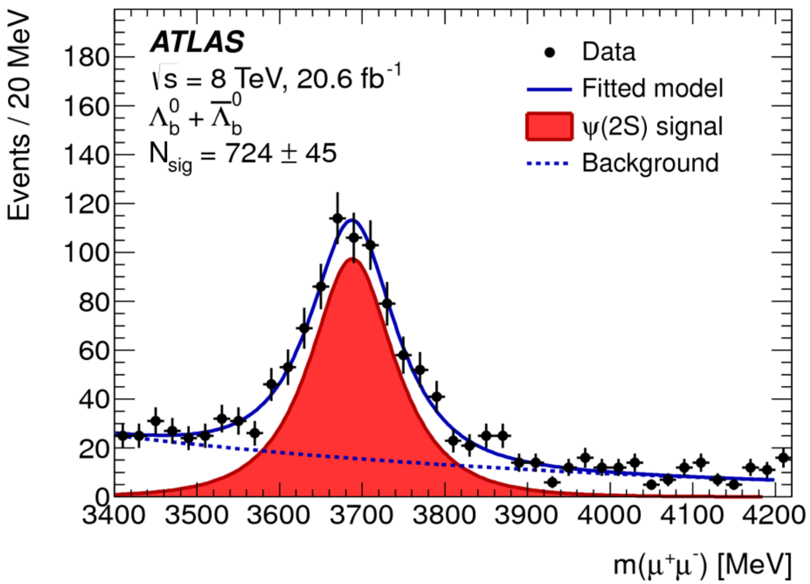
$m(\mu^+\mu^-)$ within ±200 MeV of $m(\psi(2S))_{PDG}$

$N(\Lambda_b \to \psi(2S)\,\Lambda^0)$ = 603 ± 38

Is it really $\Lambda_b \rightarrow \psi(2S)\, \Lambda^0$?

ATLAS, PLB 751 (2015) 63

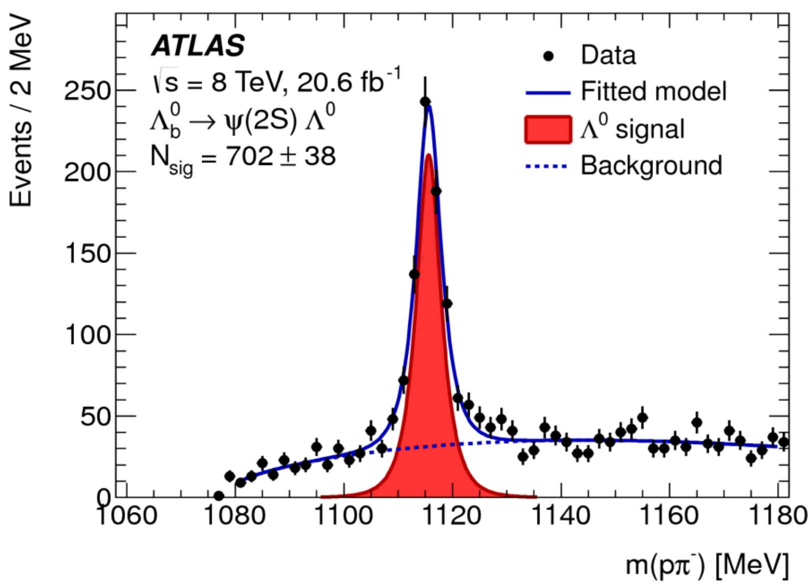
(not $\Lambda_b \rightarrow \mu^+\mu^- p\, \pi^-$, $\mu^+\mu^- \Lambda^0$, $\psi(2S)\, p\, \pi^-$)



Cascade fit w/o constraint on charmonium mass

N(ψ(2S)) = 724 ± 45

in events within ±3 σ of $m(\Lambda_b)_{PDG}$



Cascade fit w/o constraint on Λ^0 mass

N(Λ^0) = 702 ± 38

in events within ±3 σ of $m(\Lambda_b)_{PDG}$

Measurement of $\Gamma(\Lambda_b \to \psi(2S)\,\Lambda^0)/\Gamma(\Lambda_b \to J/\psi\,\Lambda^0)$

ATLAS, PLB 751 (2015) 63

$$\frac{\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \to J/\psi\,\Lambda^0)} = 0.501 \pm 0.033(\text{stat}) \pm 0.016(\text{syst}) \pm 0.011(\mathcal{B})$$

Lies in the range 0.5-0.8 measured for the branching ratios of analogous B meson decays [PDG].

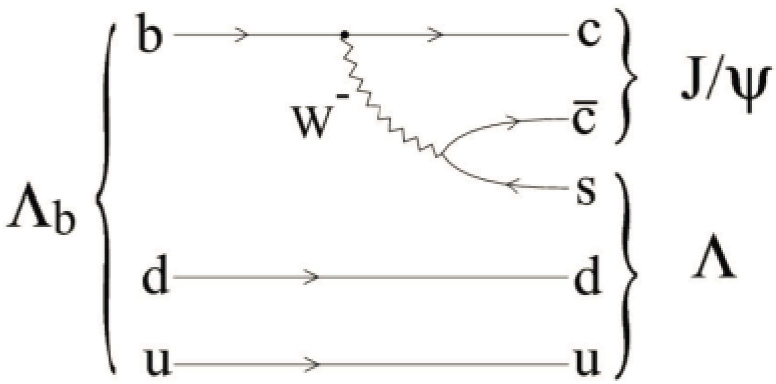
The covariant quark model prediction (0.8 ± 0.1),
T. Gutsche et al., PRD 88 (2013) 114018
T. Gutsche et al., PRD 92 (2015) 114008
is quite above (~3 σ)

Other calculations?

$\Lambda_b \rightarrow J/\psi\ (\mu+\mu-)\ \Lambda^0\ (p\pi^-)$

ATLAS, PRD 89 (2014) 092009

CMS PAS BPH-15-005



Four possible helicity amplitudes:

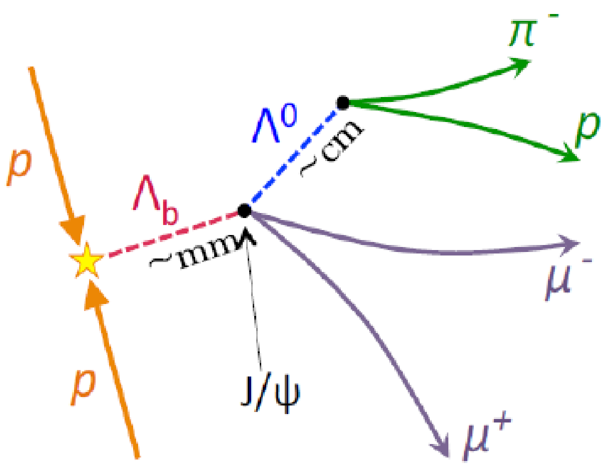
Amplitude	$\lambda_{J/\psi}$	λ_Λ
a_+	0	1/2
a_-	0	-1/2
b_+	-1	-1/2
b_-	1	1/2

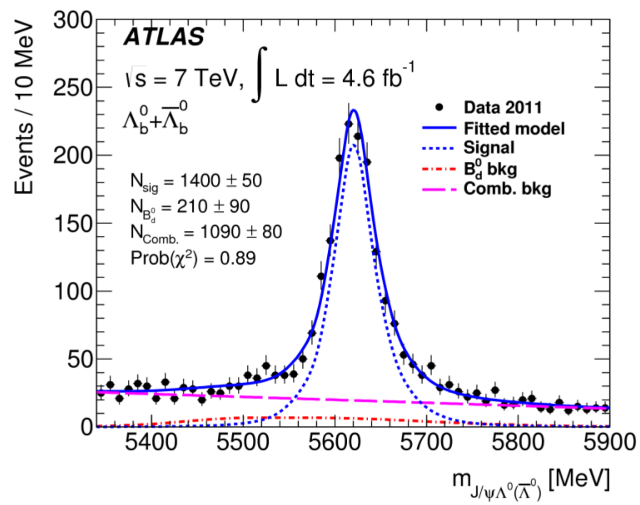
Parity violation is a well-known feature of weak interactions. It is **not maximal in decays of hadrons** due to the presence of **strongly coupled spectator quarks**

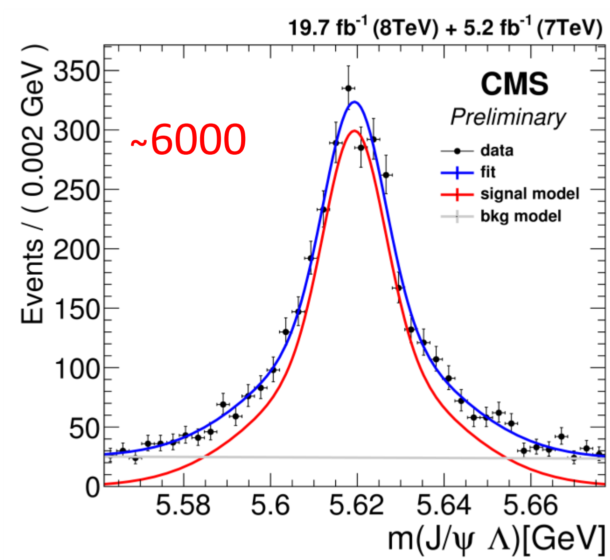
$$|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2 = 1.$$

Parity violating asymmetry parameter

$$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$







$\Lambda_b \rightarrow J/\psi\ (\mu+\mu-)\ \Lambda^0\ (p\pi^-)$

Full angular PDF

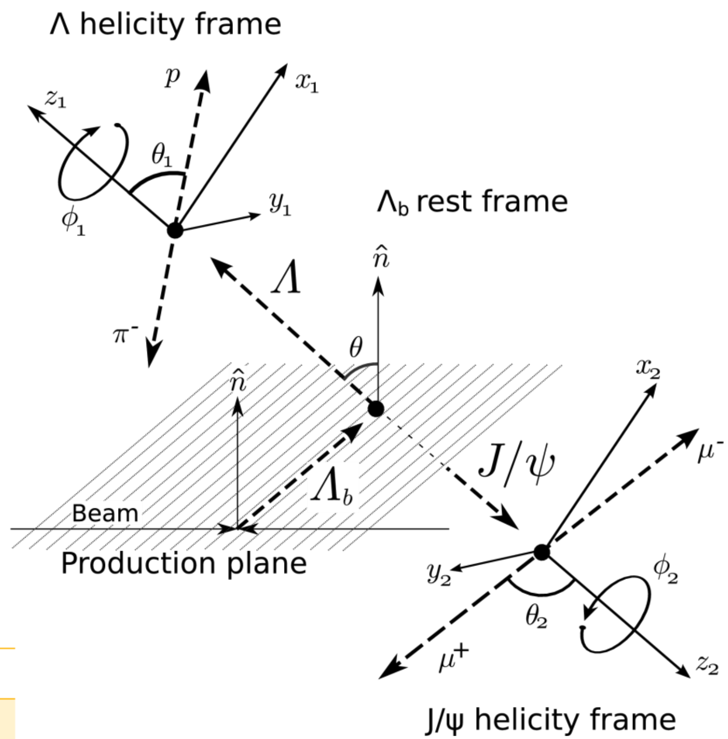
$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega)$$

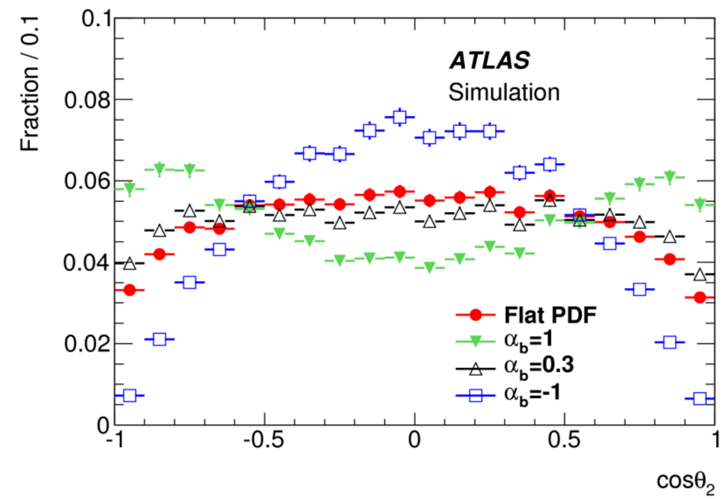
f_{1i} : bilinear functions of the four helicity amplitudes $\vec{A}$
f_{2i} : functions of polarization P of Λ_b and decay parameter α_Λ of Λ, where $\alpha_\Lambda = 0.642 \pm 0.013$
F_i : functions of decay angles $\Omega(\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2)$

i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
2	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	α_Λ	$\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
6	$-a_+a_+^* + a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta_1$
18	$3/\sqrt{2}\,\mathrm{Re}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1 \sin\theta_2 \cos\theta_2 \cos(\phi_1 + \phi_2)$
19	$-3/\sqrt{2}\,\mathrm{Im}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1 \sin\theta_2 \cos\theta_2 \sin(\phi_1 + \phi_2)$

$$\chi^2 = \sum_i \sum_j (\langle F_i \rangle^{\exp} - \langle F_i \rangle) V_{ij}^{-1} (\langle F_j \rangle^{\exp} - \langle F_j \rangle)$$

as no solution with real parameters





$\Lambda_b \rightarrow J/\psi\ (\mu+\mu-)\ \Lambda^0\ (p\pi^-)$

ATLAS, PRD 89 (2014) 092009

CMS PAS BPH-15-005

Results ATLAS

$$\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$$

$$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst}),$$
$$|a_-| = 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}),$$
$$|b_+| = 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst}),$$
$$|b_-| = 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst}).$$

CMS

$$P = 0.00 \pm 0.06(stat) \pm 0.02(syst),$$
$$\alpha_1 = 0.12 \pm 0.13(stat) \pm 0.06(syst), \alpha_b = -\alpha_1$$
$$\alpha_2 = -0.93 \pm 0.04(stat) \pm 0.04(syst),$$
$$\gamma_0 = -0.46 \pm 0.07(stat) \pm 0.04(syst),$$

$$|T_{-0}|^2 = 0.51 \pm 0.03(stat) \pm 0.02(syst),$$
$$|T_{+0}|^2 = -0.02 \pm 0.03(stat) \pm 0.02(syst),$$
$$|T_{--}|^2 = 0.46 \pm 0.02(stat) \pm 0.02(syst),$$
$$|T_{++}|^2 = 0.05 \pm 0.04(stat) \pm 0.02(syst).$$

✓α_b value consistent with LHCb: 0.05 ± 0.17(stat) ± 0.07(syst) (PLB 724 (2013) 27)

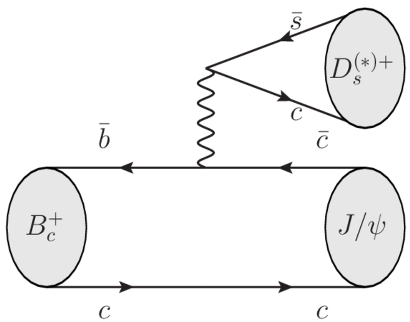
✓intermediate between pQCD (-(0.14 -0.17)) and HQET (0.78) predictions

✓ large $|a_-|$ and $|b_+|$ suggest negative helicity for Λ^0

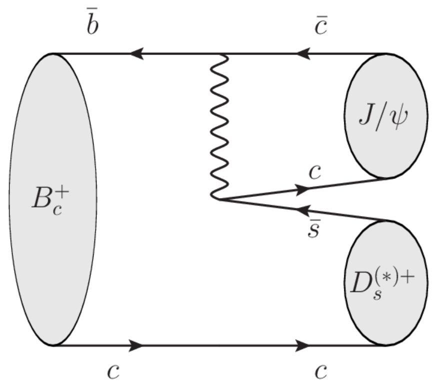
Amplitude	$\lambda_{J/\psi}$	λ_Λ
a_+	0	1/2
a_-	0	-1/2
b_+	-1	-1/2
b_-	1	1/2

Study of $B_c^+ \to J/\psi\ D_s^{(*)+}$

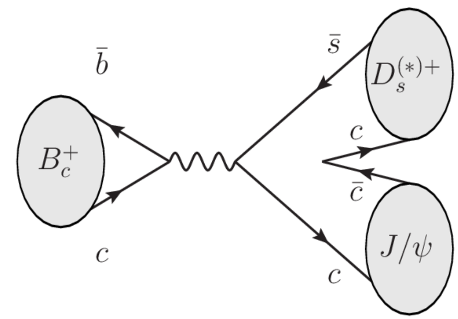
ATLAS, EPJ C 75 (2016) 1



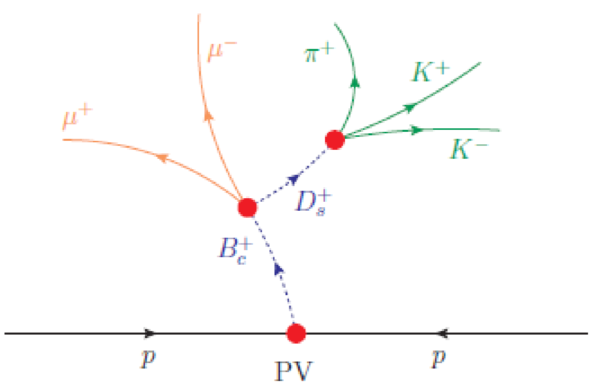
Spectator



Colour-suppressed



Annihilation



$p_T(B_c) > 15$ GeV $|\eta(B_c)| < 2$

$m(K^+K^-)$ within ±7 MeV of $m(\varphi)_{PDG}$

2-vertex cascade fit with 2 mass constraints (J/ψ and D_s)

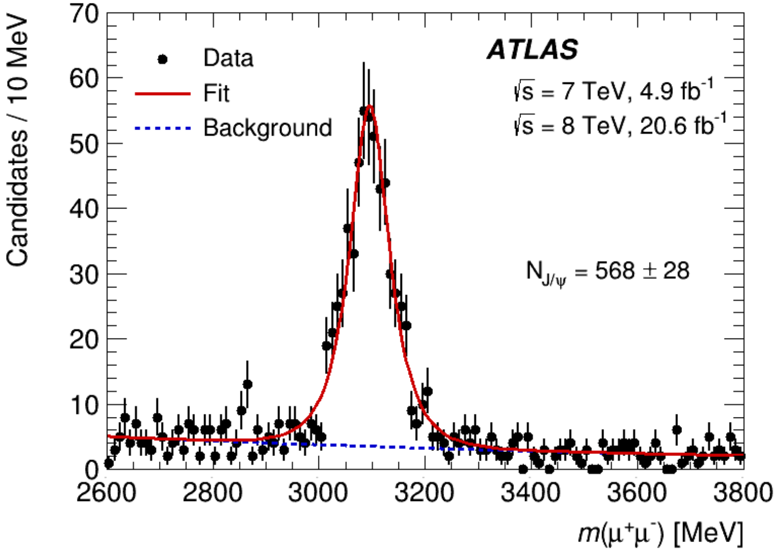
in case of $D_s^* \to D_s\ \pi^0/\gamma$: π^0/γ escapes detection

3 helicity amplitudes for PS → V + V decay: A_{00}, A_{++}, A_{--}

Is it really $B_c^+ \rightarrow J/\psi\ D_s^{(*)+}$?

ATLAS, EPJ C 75 (2016) 1

(not $B_c^+ \rightarrow \mu^+\mu^-\ \varphi\ \pi^+,\ \mu^+\mu^-\ D_s^+,\ J/\psi\ \varphi\ \pi^+$)

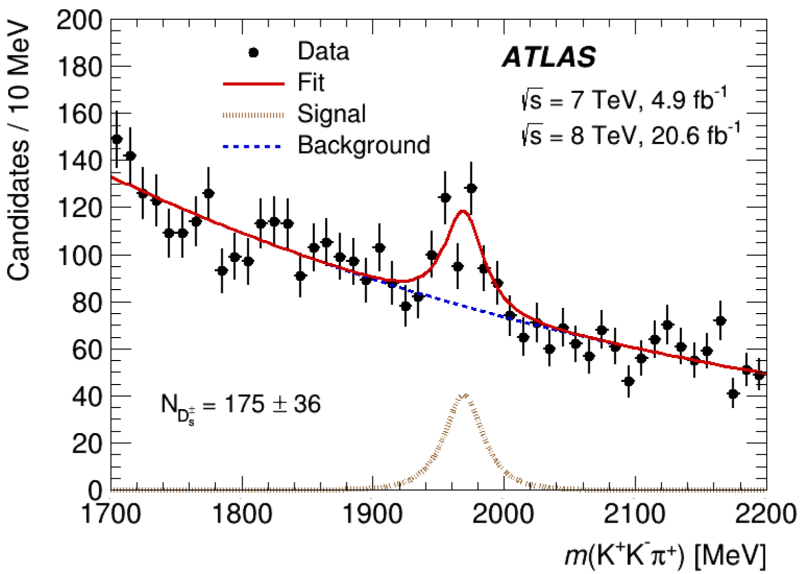


Cascade fit w/o mass constraints

events with 5.9 < m(J/ψ D_s^+) < 6.4 GeV

N(J/ψ) = 568 ± 28

a lot of J/ψ in background



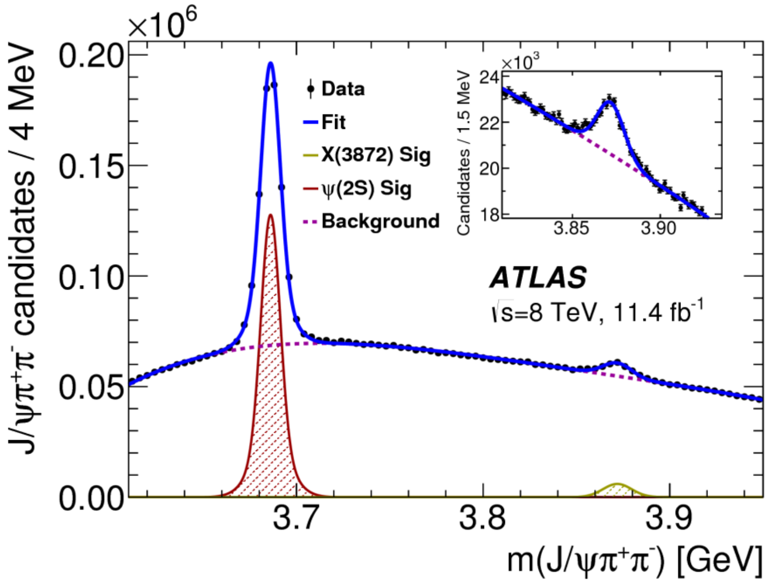
N(D_s^+) = 175 ± 36

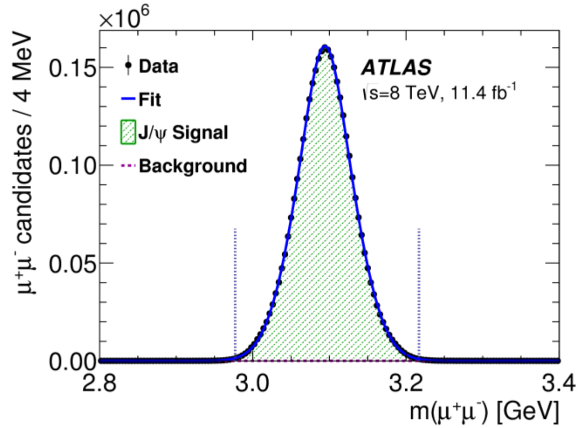
non-significantly above

$N(B_c^+ \rightarrow J/\psi\ D_s^+) + N(B_c^+ \rightarrow J/\psi\ D_s^{*+})$

Study of X(3872) (and ψ(2S)) → J/ψ π⁺π⁻

ATLAS, JHEP 01 (2017) 117





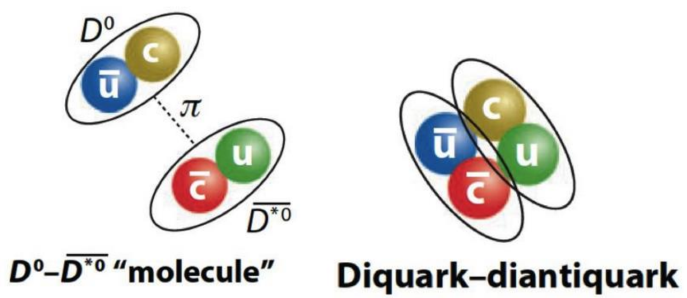
3.6 M of *J/ψ*

470 k of *ψ(2S)*

30 k of *X(3872)*

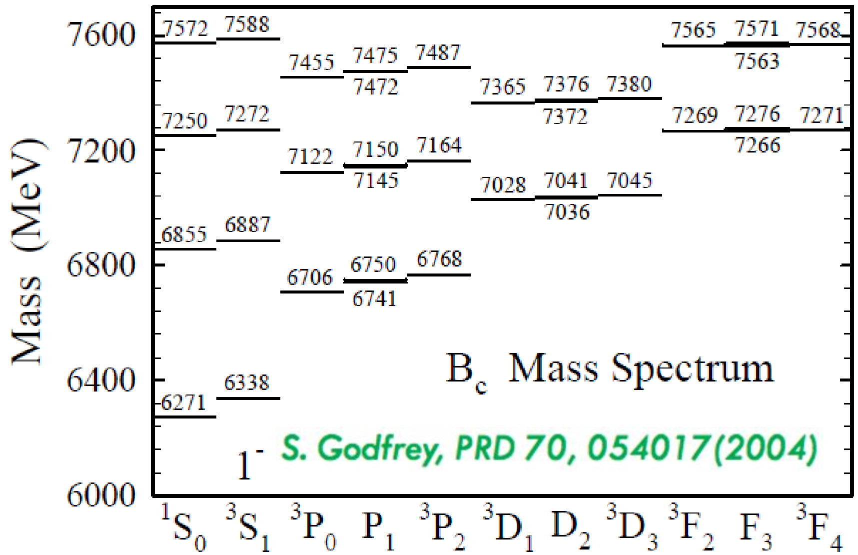
$10 < p_T(\psi(2S)/X(3872)) < 70$ GeV

$|y(\psi(2S)/X(3872))| < 0.75$



Observation of excited B_c ($\to B_c \pi^+ \pi^-$)

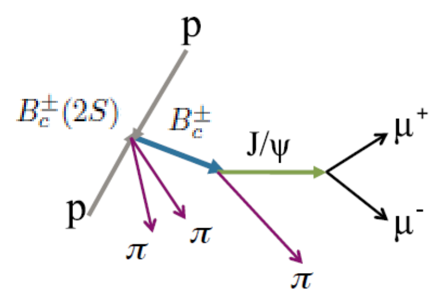
ATLAS, PRL 113 (2014) 212004



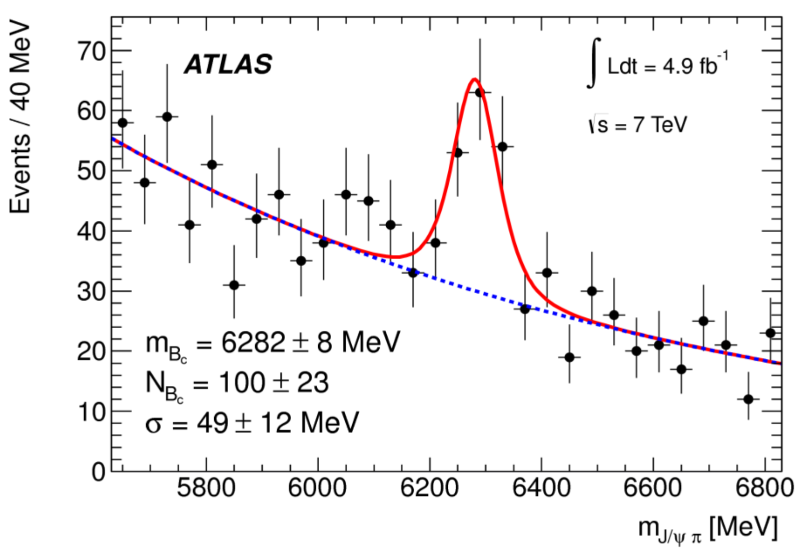
Large B_c family is expected although only ground state has been known until today

$B_c^{\pm}(2S)$ 6835–6917 MeV

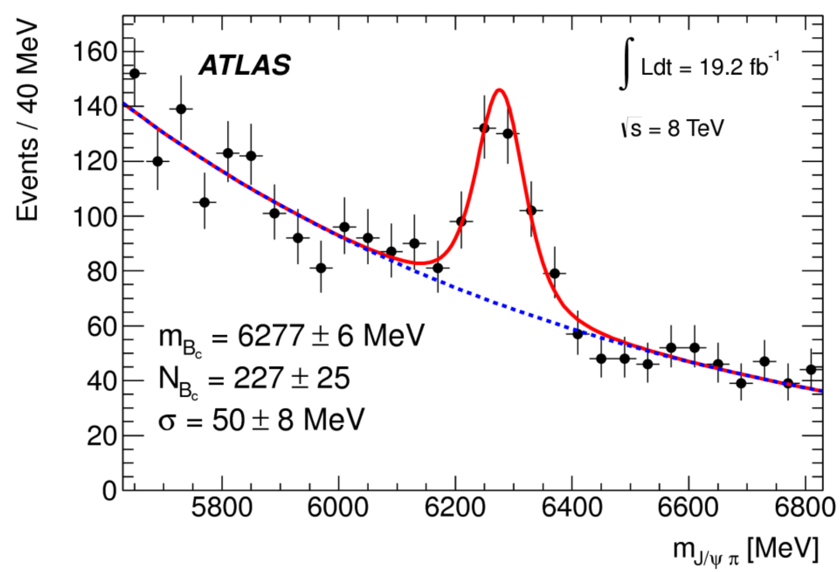
$2S/1S \simeq 0.6 \quad 2^1S_0 \to 1^1S_0 + \pi\pi$



$p_T(\pi)$ > 4 GeV, $m(J/\psi)$ constrained to PDG



$p_T(B_c)$ > 15 GeV

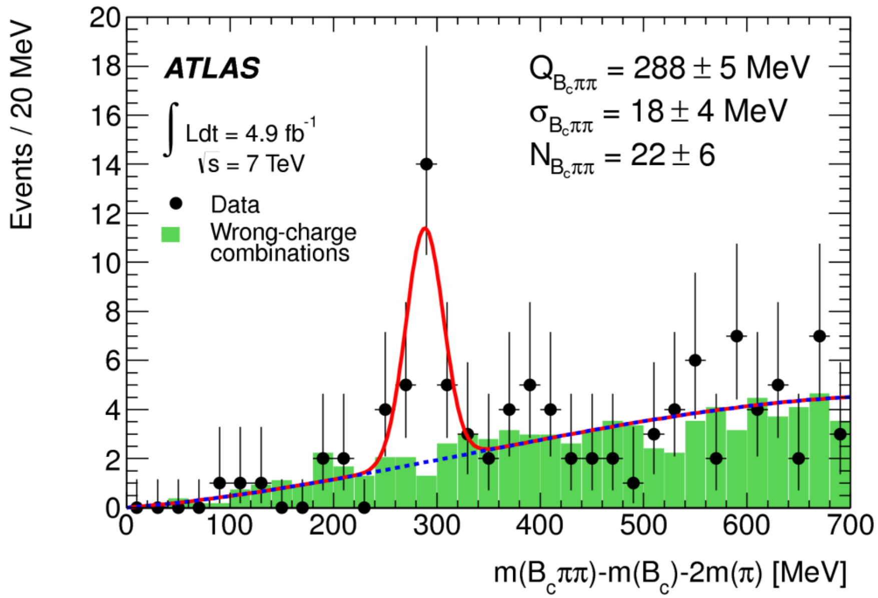


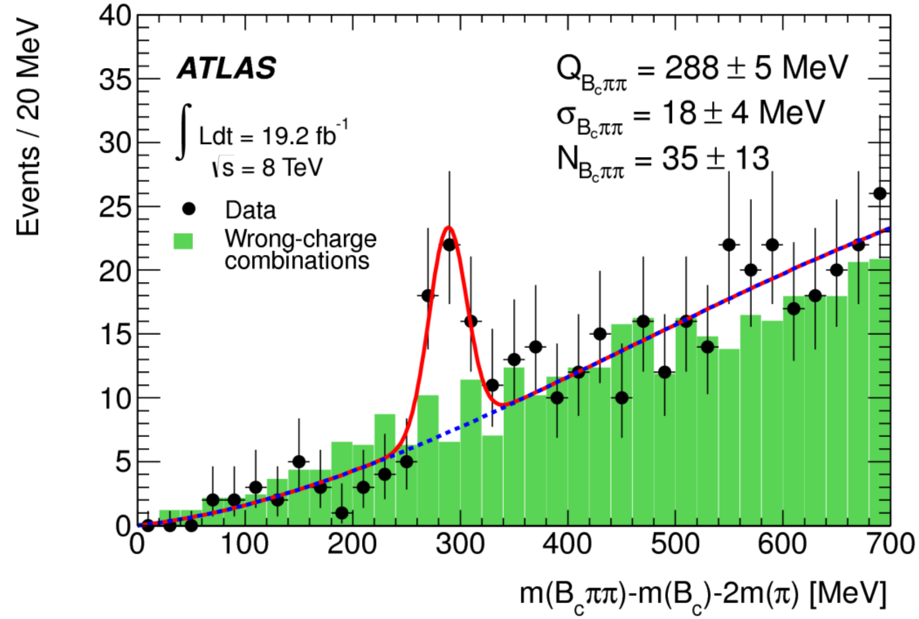
$p_T(B_c)$ > 18 GeV

Observation of excited B_c ($\longrightarrow B_c\pi^+\pi^-$)

ATLAS, PRL 113 (2014) 212004

$p_T(\pi^\pm)$ > 400 MeV, $m(J/\psi)$ constrained to PDG





Significance from Δln*L* of pseudo-experiments: 5.4 σ (local)
5.2 σ (“look elsewhere”)

Q = 288.3 ± 3.5 ± 4.1 MeV
M = 6842 ± 4 ± 5 MeV

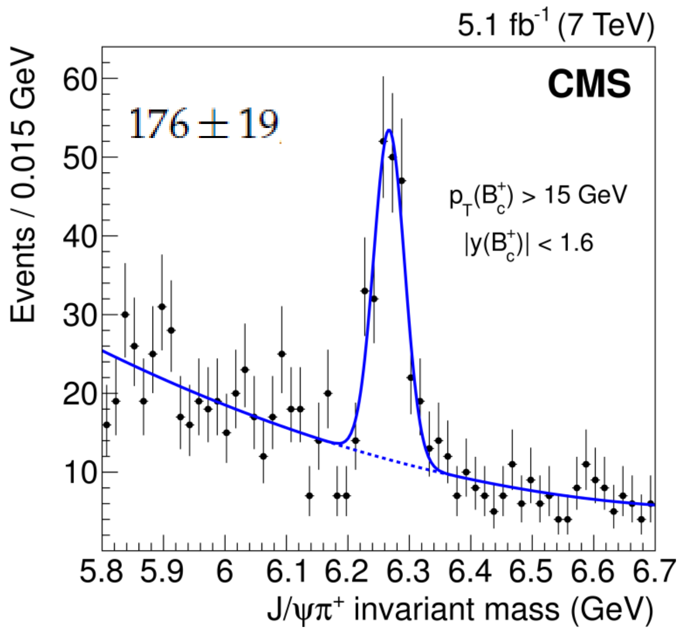
Both mass value and decay mode agree with expectations for $B_c^\pm(2S)$

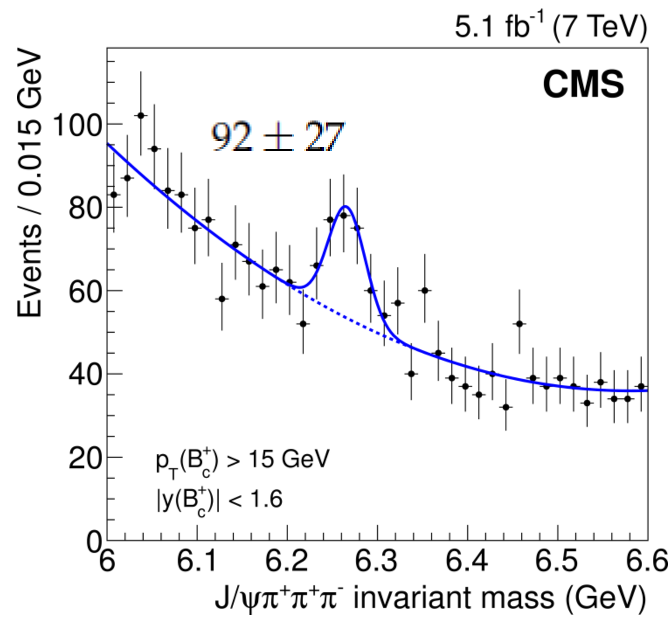
Measurements of

CMS, JHEP 01 (2015) 063

$$R_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = \frac{Y_{B_c^+ \to J/\psi\pi^+}}{Y_{B^+ \to J/\psi K^+}}$$

$$R_{B_c} = \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = \frac{Y_{B_c^+ \to J/\psi\pi^+\pi^+\pi^-}}{Y_{B_c^+ \to J/\psi\pi^+}}$$





$p_T > 15\,\mathrm{GeV}$

$|y| < 1.6$

$$R_{c/u} = [0.48 \pm 0.05\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}) \pm 0.05\,(\tau_{B_c})]\%$$

differs from the LHCb value

$[0.68 \pm 0.10\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}) \pm 0.05\,(\tau_{B_c})]\%$

$p_T > 4\,\mathrm{GeV},\ 2.5 < \eta < 4.5$

$$R_{B_c} = 2.55 \pm 0.80\,(\mathrm{stat}) \pm 0.33\,(\mathrm{syst})^{+0.04}_{-0.01}\,(\tau_{B_c})$$

agrees with the LHCb value