Quarkonia Production at Hadron Colliders

- Physics Motivation
- Experimental Details
- J/Ψ Production
- Production of J/Ψ Pairs
- Double Parton Scattering
- ϒ(nS) Production
- Conclusions

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QCD@LHC Workshop - DESY - Hamburg

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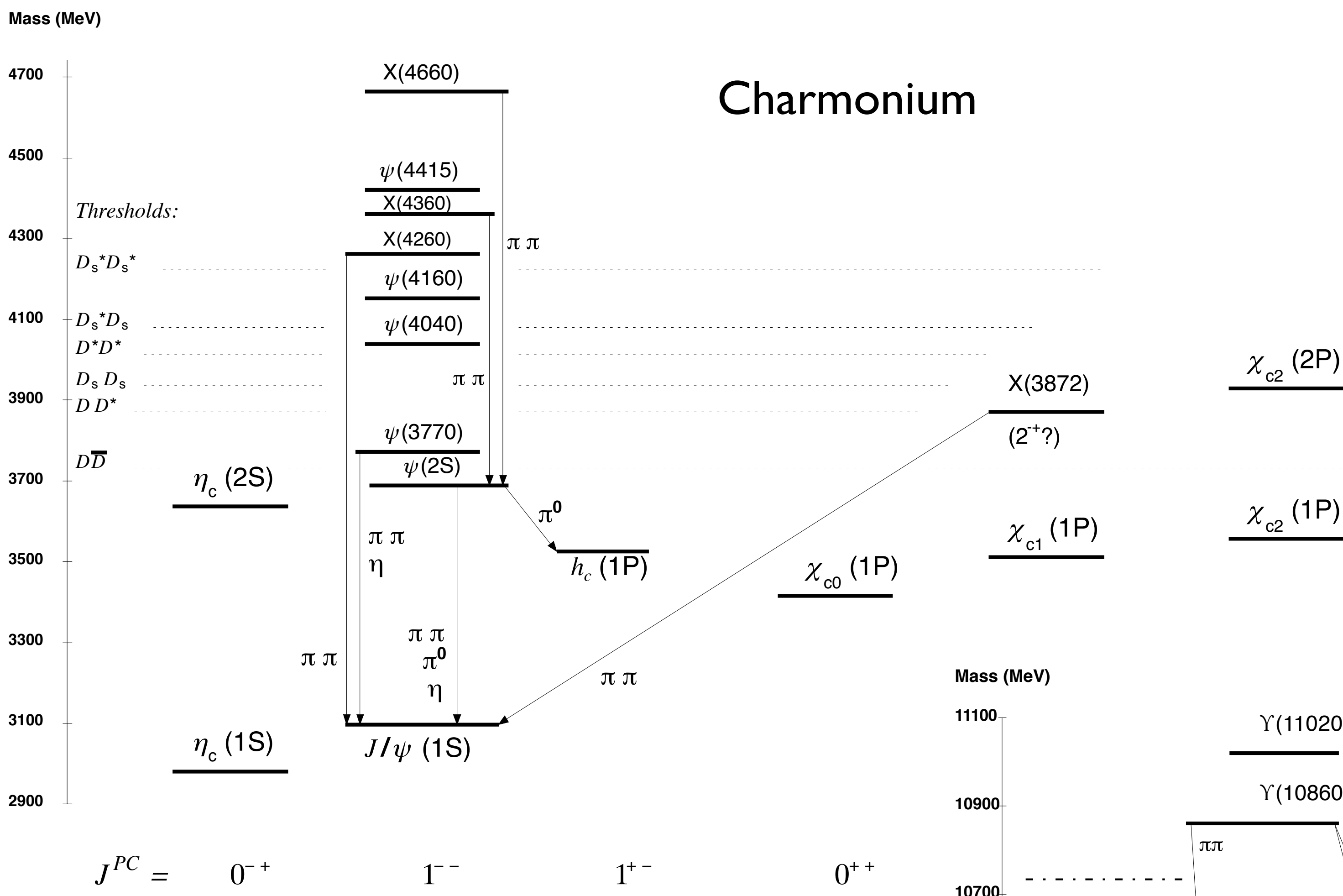
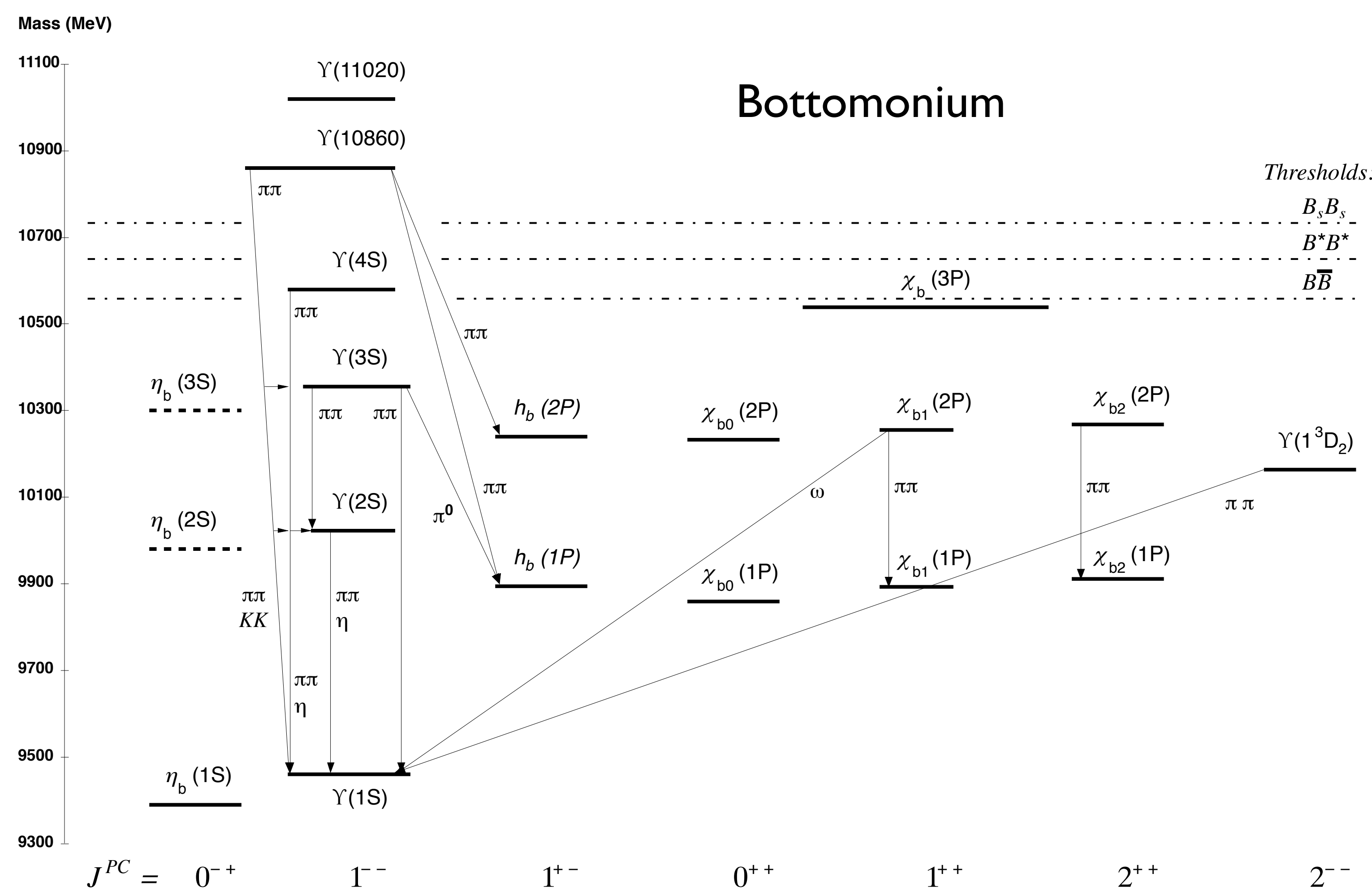




- complex system of states
- provides interesting laboratory for QCD
- production rates influenced by feed-down

In QCD quarkonia production is a multi-scale problem
perturbative expansions possible at high momenta
non-perturbative effects dominate at low momenta

⇒ test interface of perturbative and non-perturbative QCD

⇒ test models of confinement

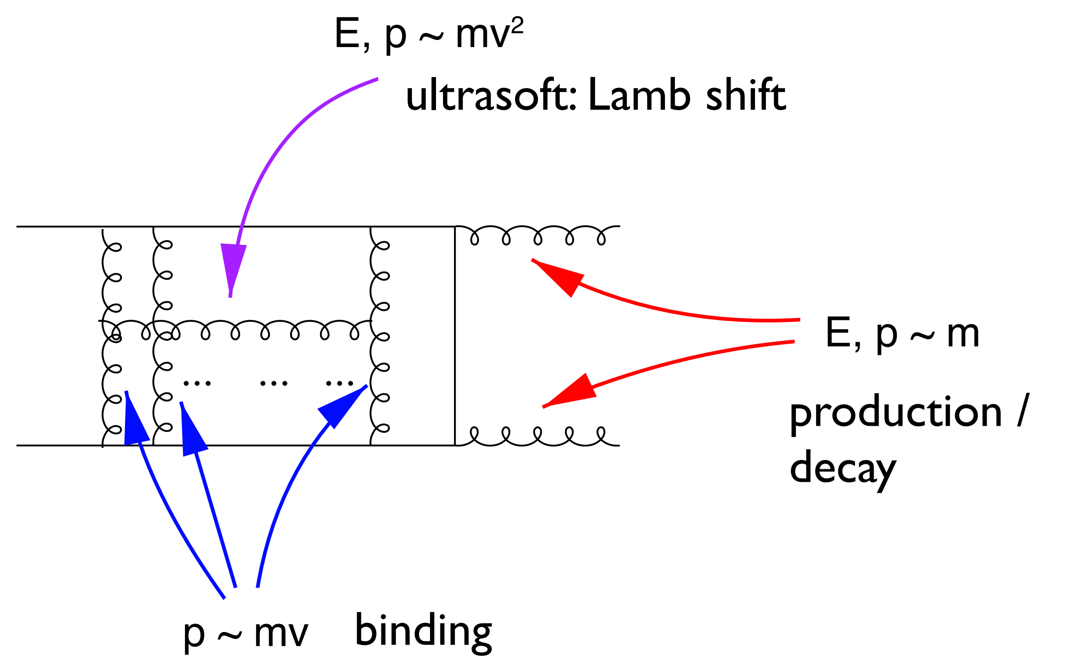
⇒ confront lattice QCD calculations to data

⇒ probe deconfined matter in quark-gluon plasma

Scales:
quarkonia are non-relativistic bound states
v/c ~ 0.3 - 0.1
several associated energy scales:

- partonic mass, m
- partonic momenta, p ~ mv
- hadronic mass ~ binding energy ~ mv^2

production & decay occur at scale m
binding occurs at scales ~ mv
QCD Lamb shift occurs at scales ~ mv^2



EPJC (2011) 71

Polarisation measurements → Pietro Faccioli's talk
Deconfined matter → Ionut Arsene's talk

Quarkonia probe production mechanisms
many flavours of models:
- non-relativistic QCD
- Colour Singlet
- Colour Octet
- Colour Evaporation Model

No model is able to describe all details: rates, polarisations...

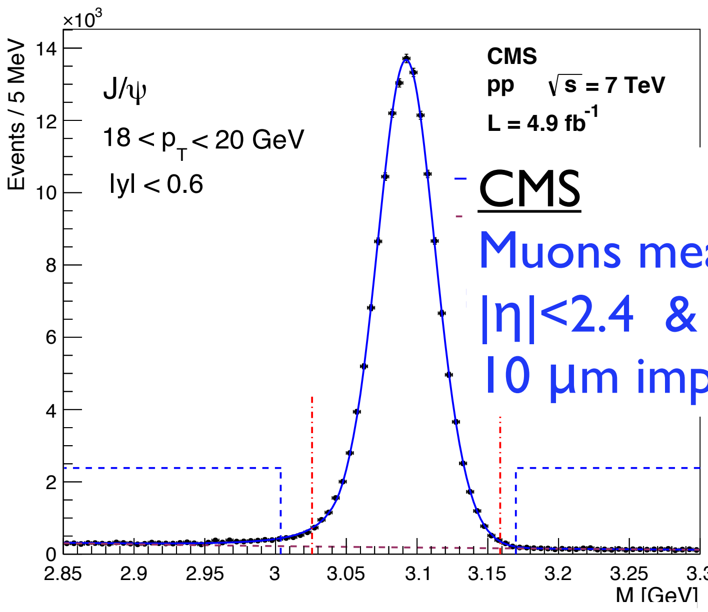
⇒ QCD formulated as a hierarchy of effective field theories
high energy scales integrated out and matched
Factorisation:
qqbar production ⇔ non perturbative evolution into quarkonium

Colour Singlet Model
meson forms if quarks produced in same ang. mom. state as meson
described e^+e^- data well
failed to describe high p_T TeVatron data but NLO / NNLO* improves description

Colour Octet Model
qqbar produced in colour octet state
singlet state evolves from non-perturbative soft gluon emission
yields harder p_T spectrum & larger production cross section than CSM

Colour Evaporation Model
probability to produce quarkonium state independent of quark colour / spin
production cross section is a fraction of the qqbar production

Experiments



CMS

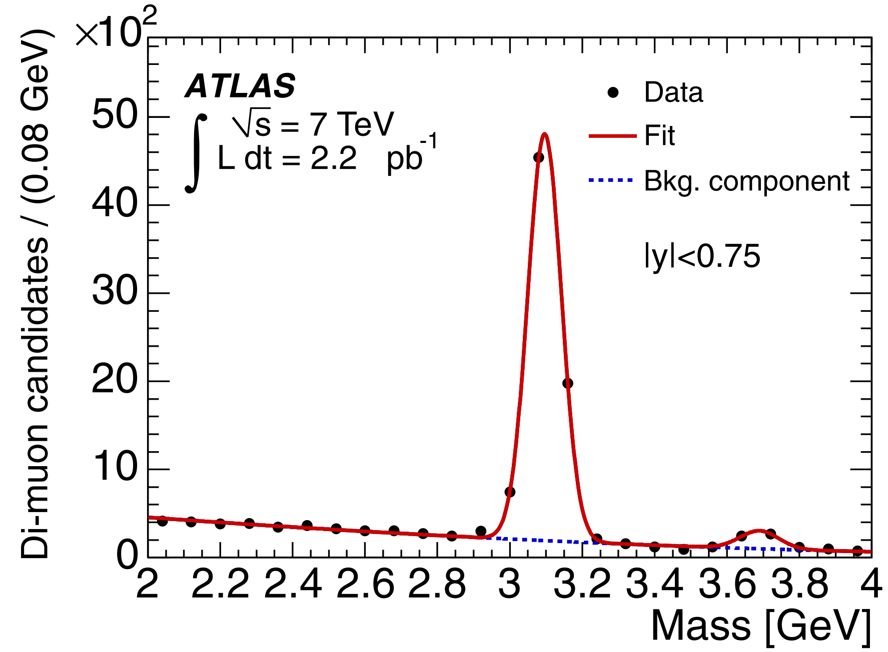
Muons measured:

|η|<2.4 & p_T > 4 GeV

10 μm impact par. resol^n

J/ψ mass resolution

σ = 21 MeV for |y|<0.6



ATLAS

Muons measured:

|η|<2.7 & p_T > 4 GeV

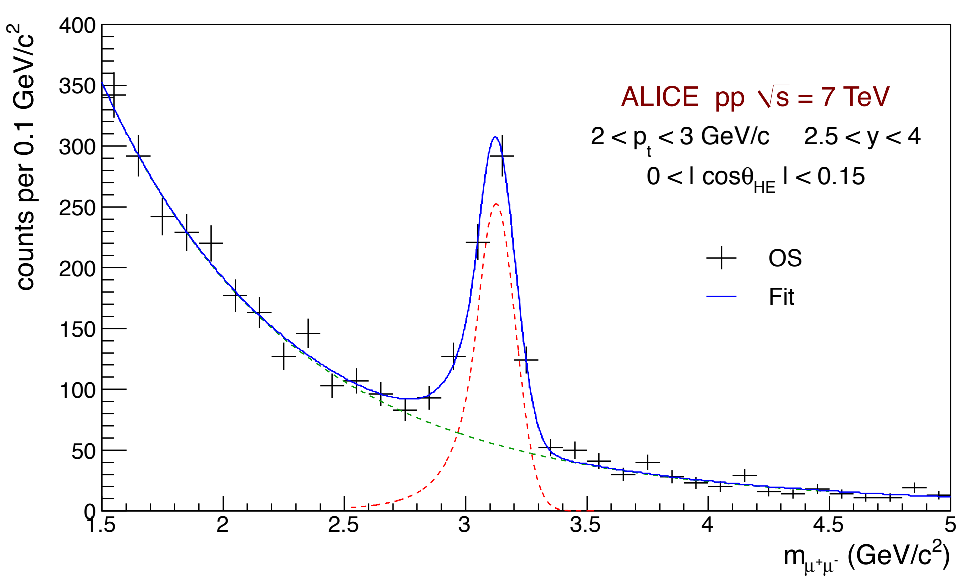
10 μm impact par. resol^n

J/ψ mass resol^n

σ = 46 MeV for |y|<0.75

All four experiments focus quarkonia measurements on muon decay channels

ALICE also has results for electrons |y|<0.9

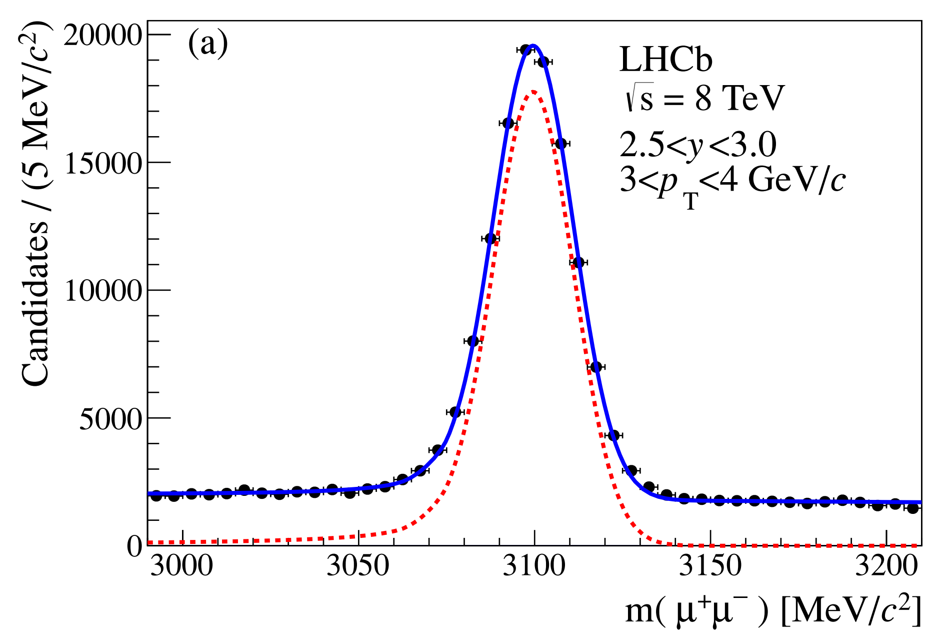


ALICE

Muons measured:

2.5 < η<4 & p_T > 0 GeV

J/ψ mass resol^n σ = 72 MeV



LHCb

Muons measured:

2.5 < η < 4.5

p_T > ~ 4 GeV

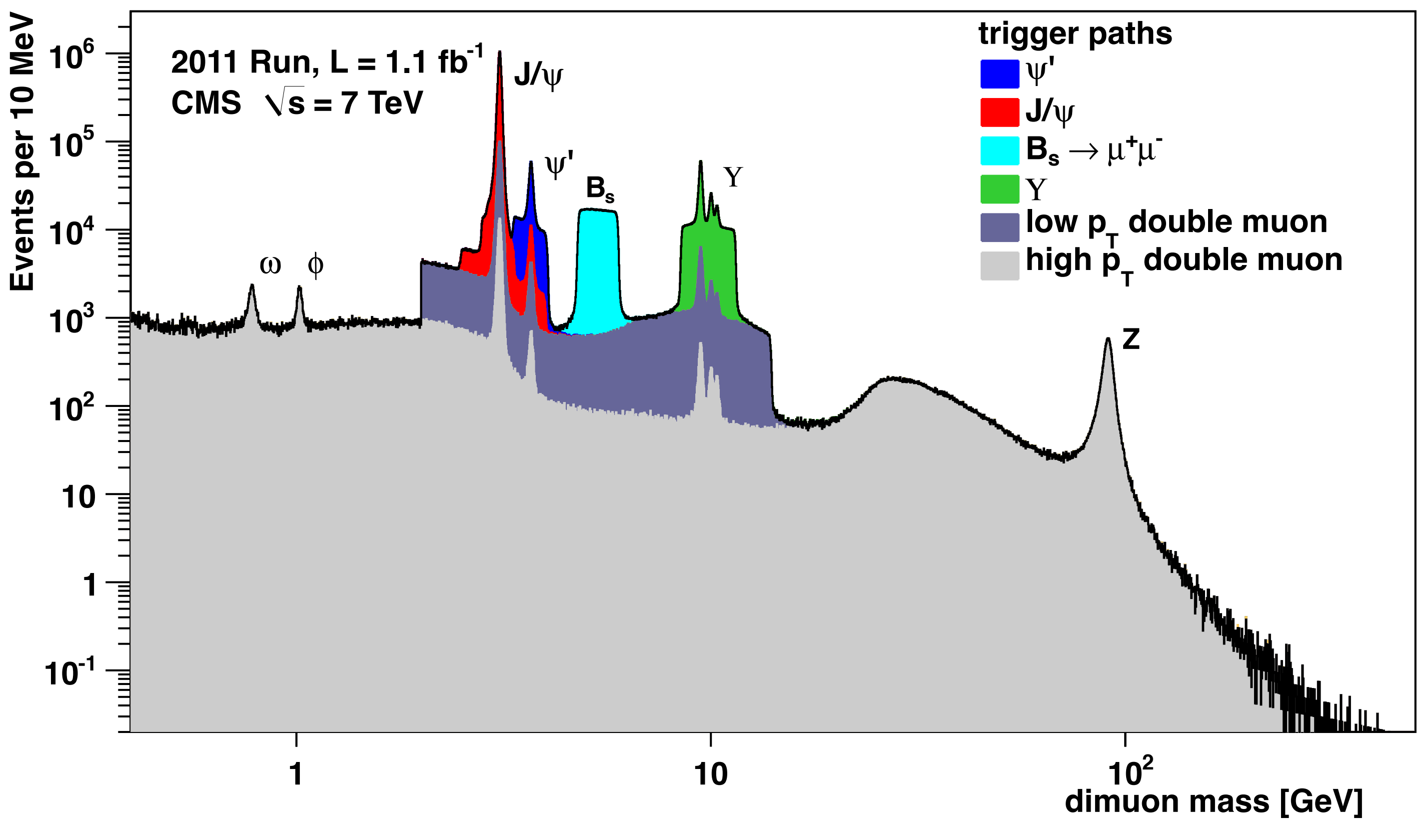
Δp/p = 0.4% - 0.6%

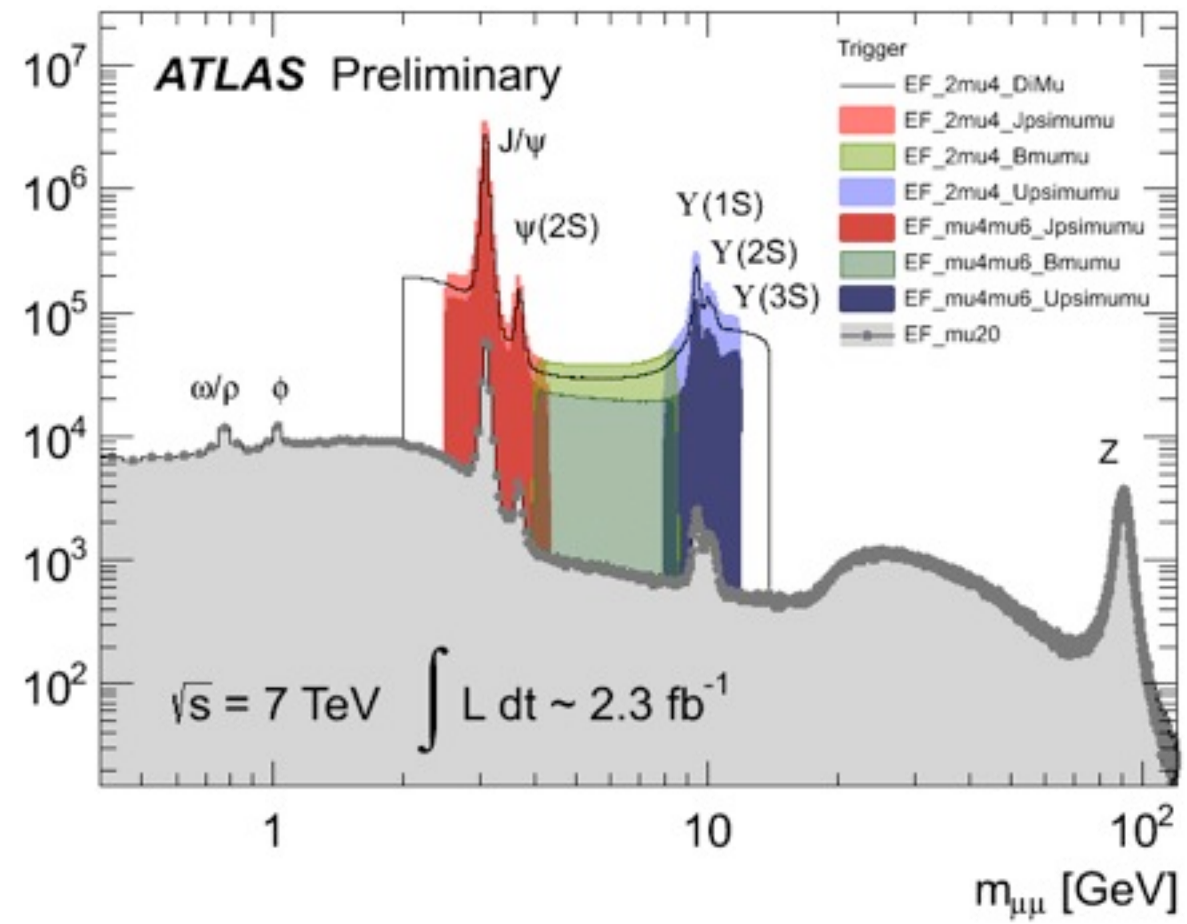
20 μm impact par. resol^n

J/ψ mass resol^n

σ = 14 MeV

Data sets





- High pileup / inst. lumi makes triggering low p_T muons very difficult
- Essential for many studies - calibration, alignment, efficiencies etc
- Large samples of J/ψ and ϒ now collected
- Extended range of production measurements to high meson p_T

J/ψ production measurements $\int \mathcal{L}dt = 2 - 40\ \text{pb}^{-1}$

ϒ(nS) production: $\int \mathcal{L}dt = 2 - 5\ \text{fb}^{-1}$

ϒ(nS) polarisation: $\int \mathcal{L}dt = 5\ \text{fb}^{-1}$

$\sqrt{s}$ = 2.76 TeV / 7 TeV / 8 TeV

ALICE: $\int \mathcal{L}dt = 5\ /\ 15\ \text{nb}^{-1}$ & $1.35\ \text{pb}^{-1}$
minimum bias trigger only

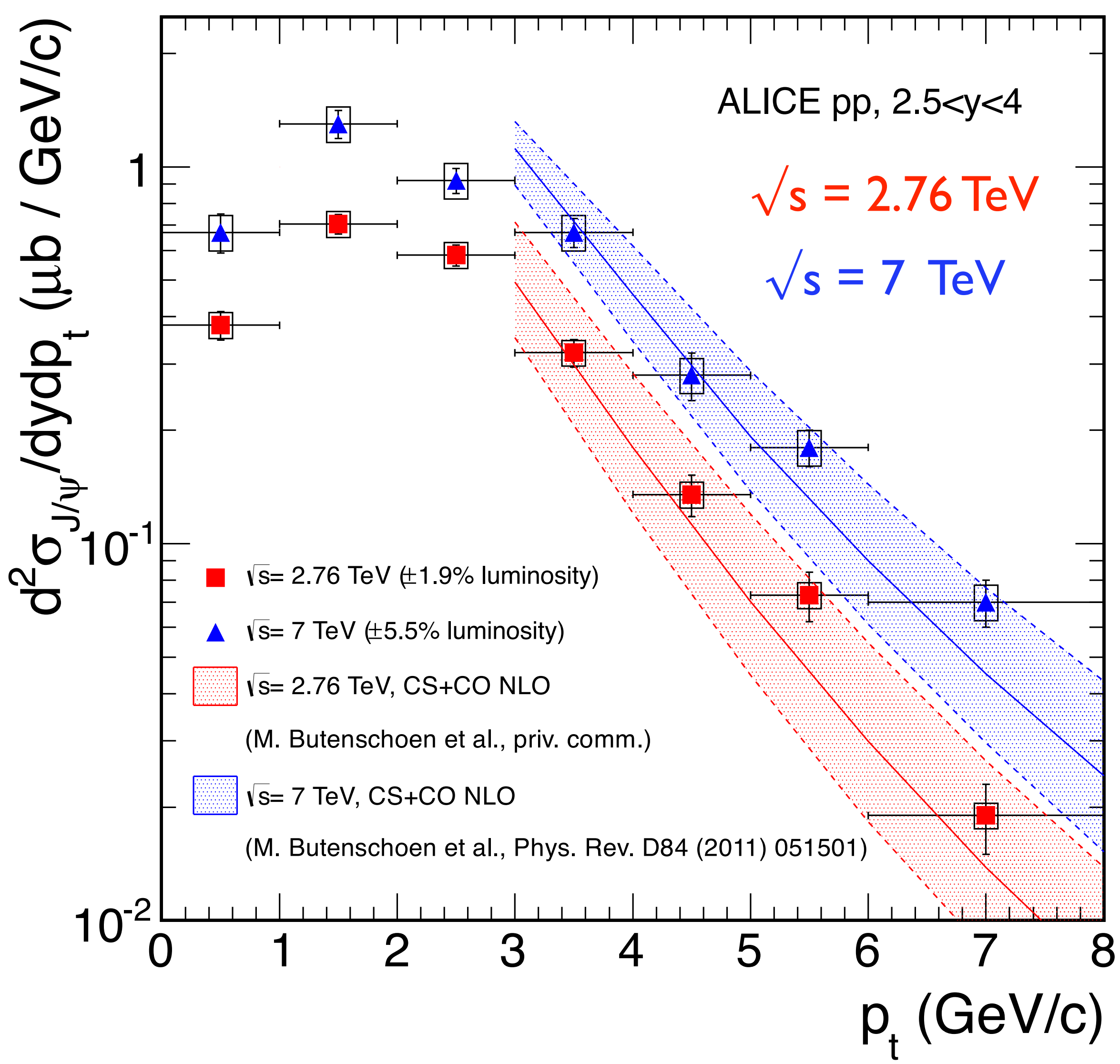
LHCb: $\int \mathcal{L}dt = 18 - 51\ \text{pb}^{-1}$

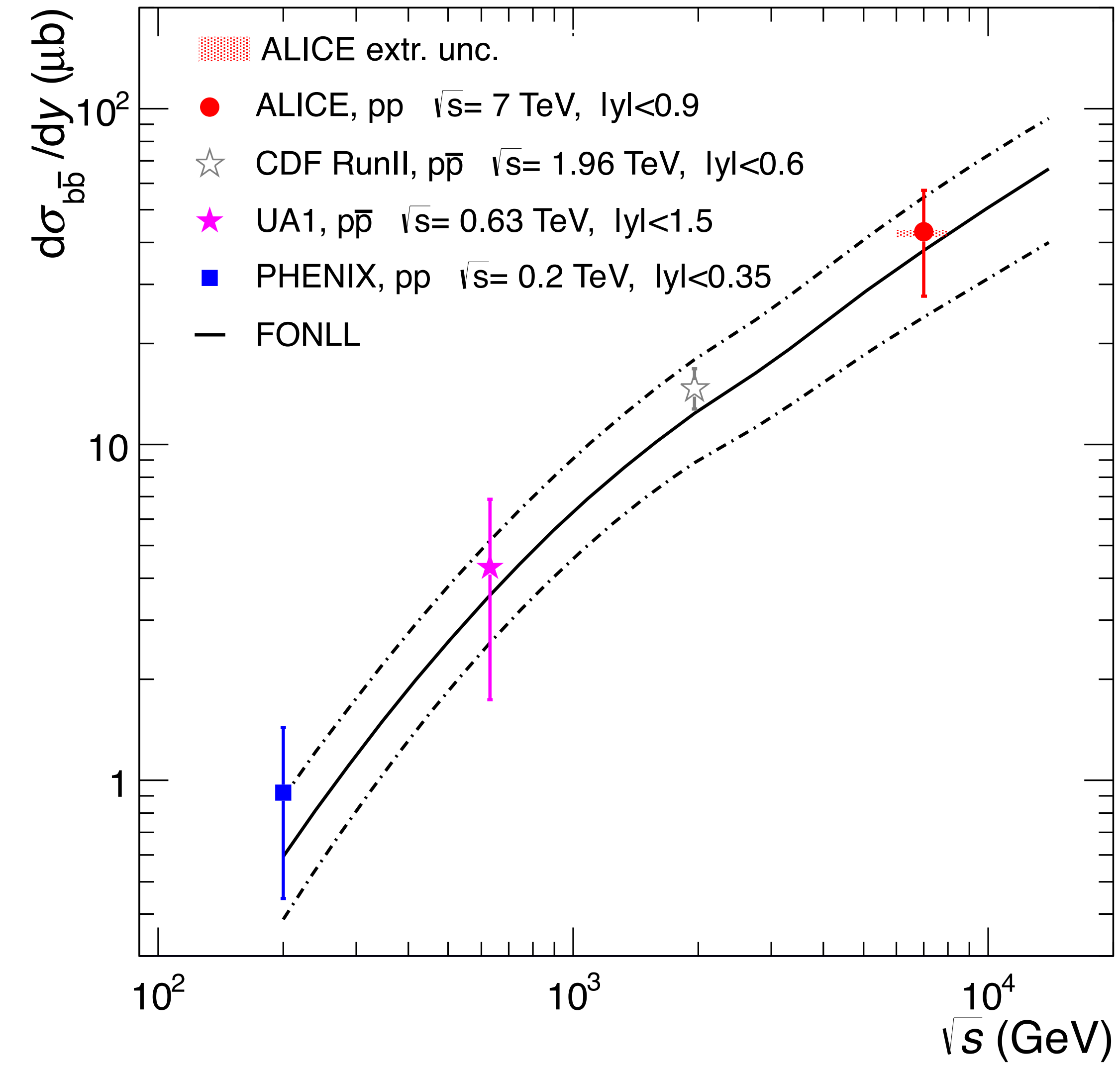
J/Ψ - Inclusive Production

Alice: PLB 718 (2012) 295-306
Alice: JHEP 11 (2012) 065

Measure J/ψ production in pp collisions
Inclusive production (prompt+non-prompt)

CO+CS NLO predicts p_T spectrum well





FONLL model describes b-quark production → decay to b hadrons → J/ψ

FONLL describes inclusive production well
Also described √s dependence

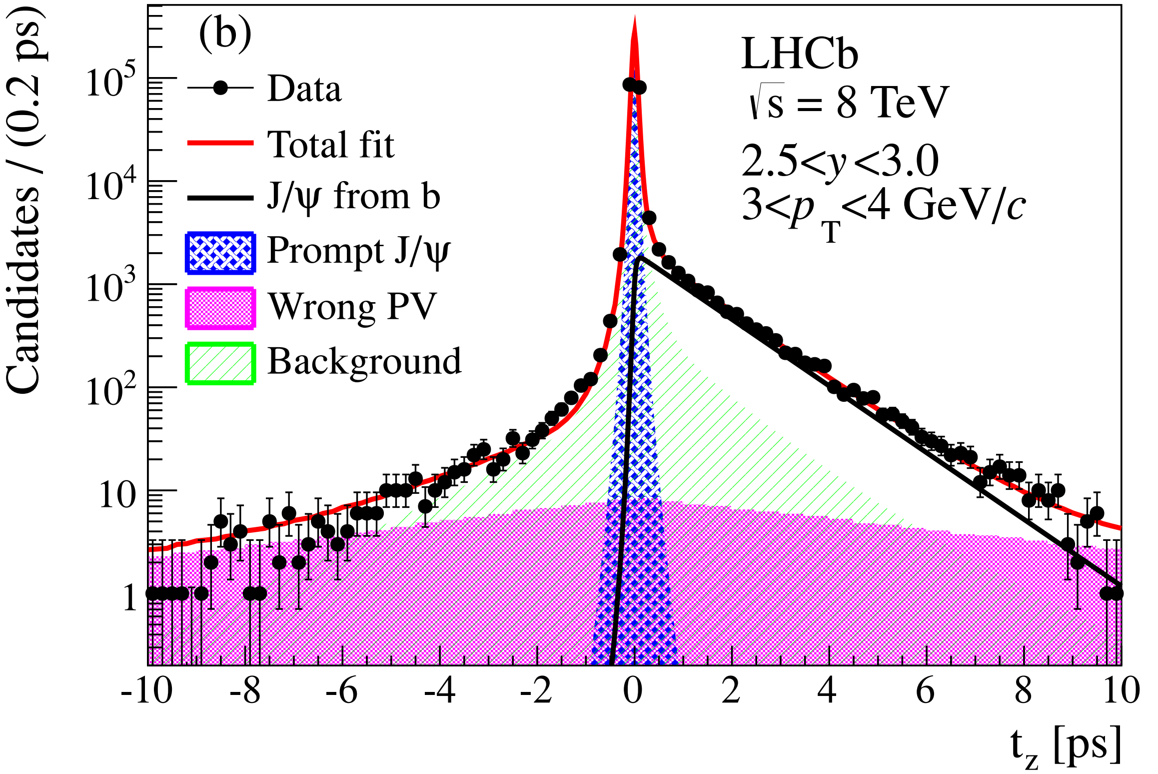
J/Ψ - Prompt and non-Prompt Production

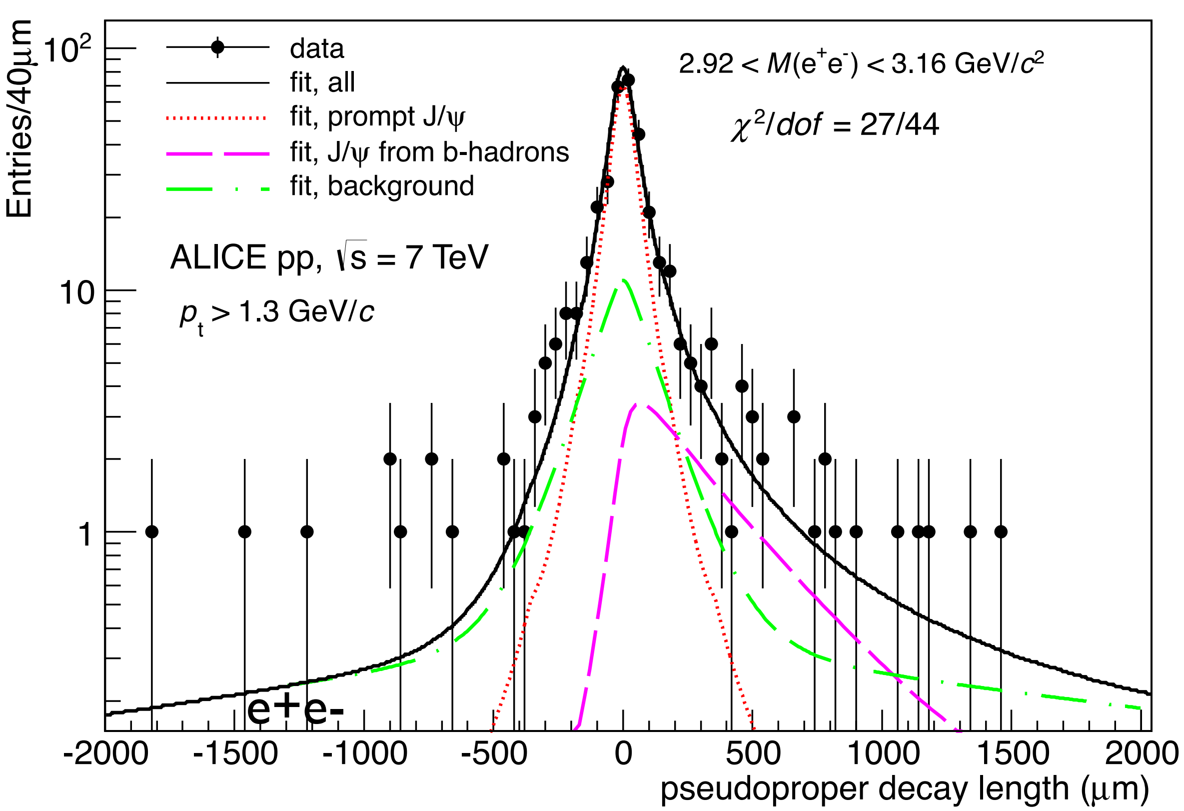
Separate prompt from non-prompt production
test production mechanisms

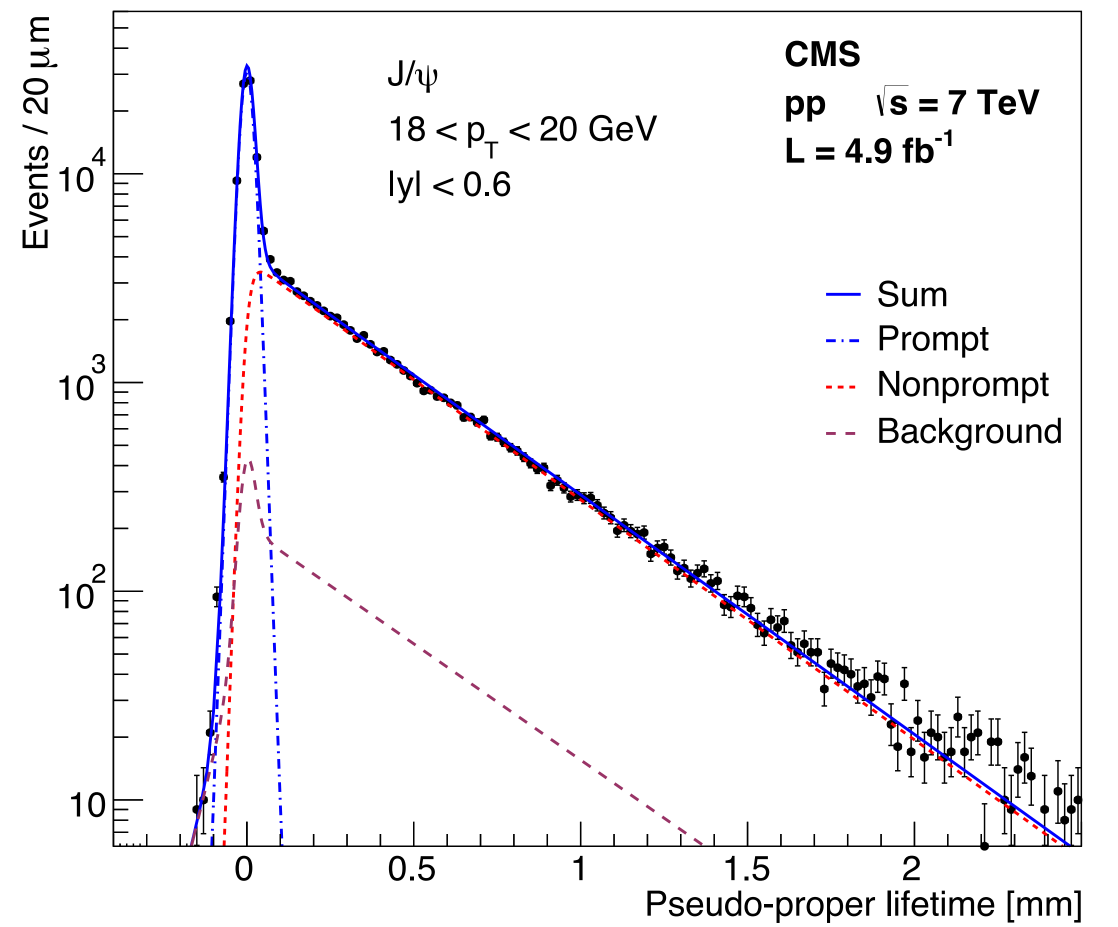
non-prompt: long lived sources eg weak B meson decays
⇒ long exponential tail
prompt: direct QCD production mechanisms
⇒ δ function at t=0

Use pseudo-proper time to separate contributions
→ ATLAS, CMS, ALICE use transverse decay lengths
→ LHCb uses longitudinal

$$t_z = \frac{(z_{J/\psi} - z_{\rm PV}) \times M_{J/\psi}}{p_z}$$







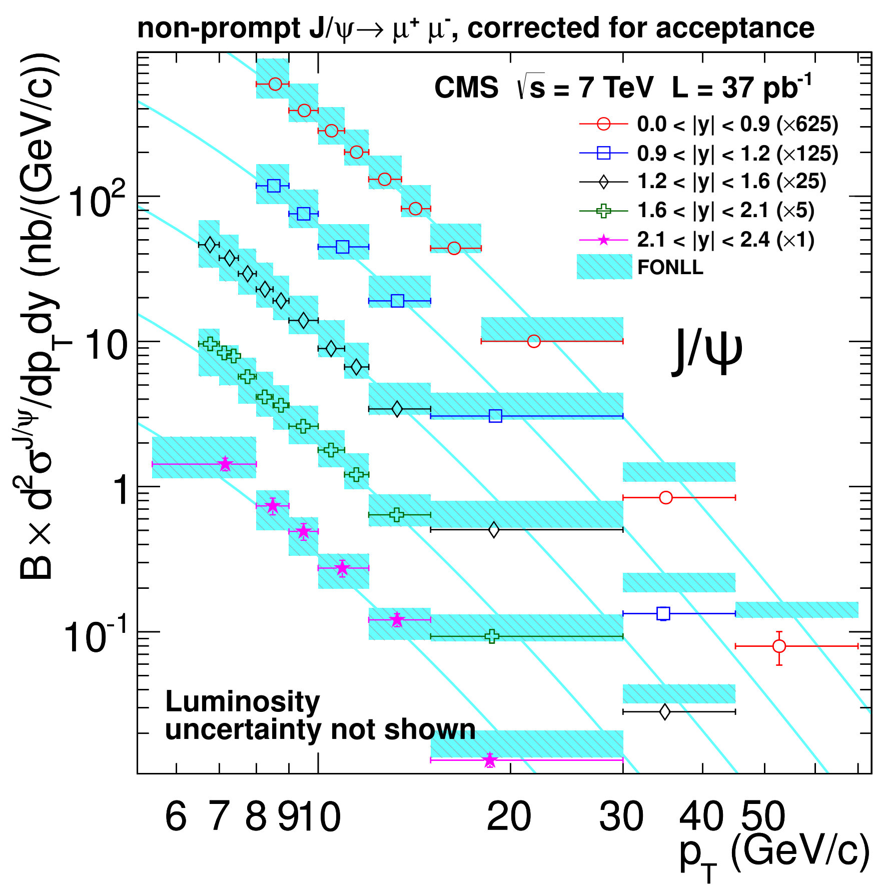
J/Ψ - Non-Prompt Production

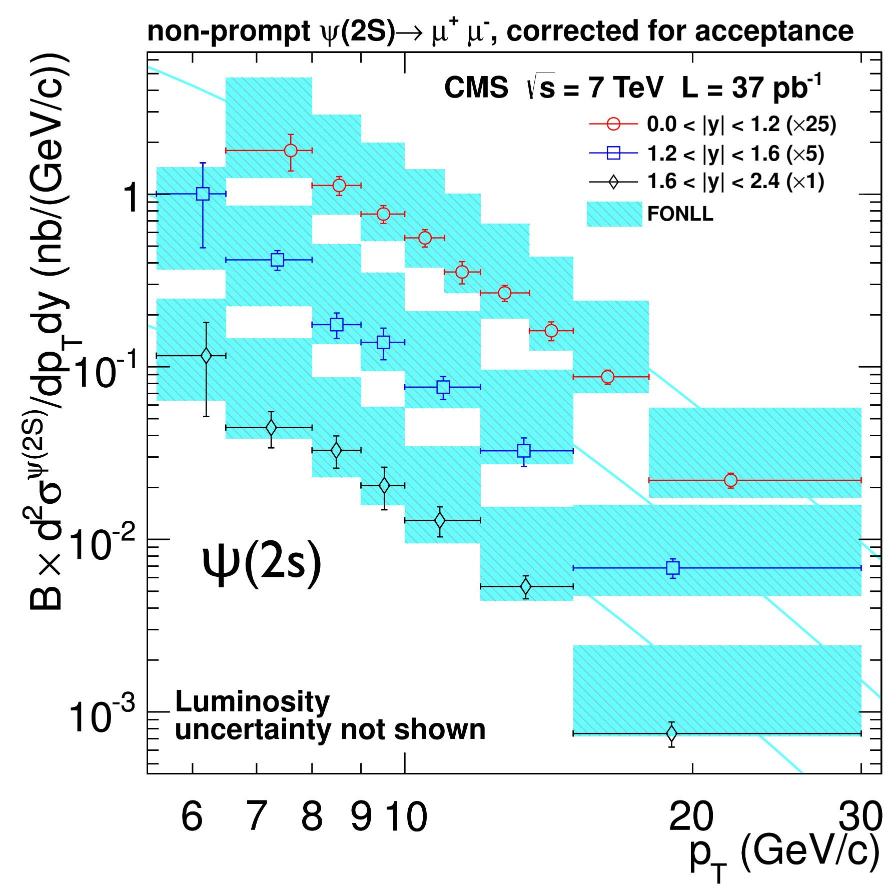
ATLAS & CMS measure production cross sections in y, p_T bins
- $y < 2.4$
- $5 < p_{T,J/\psi} < 70$ GeV
- $\sqrt{s} = 7$ TeV

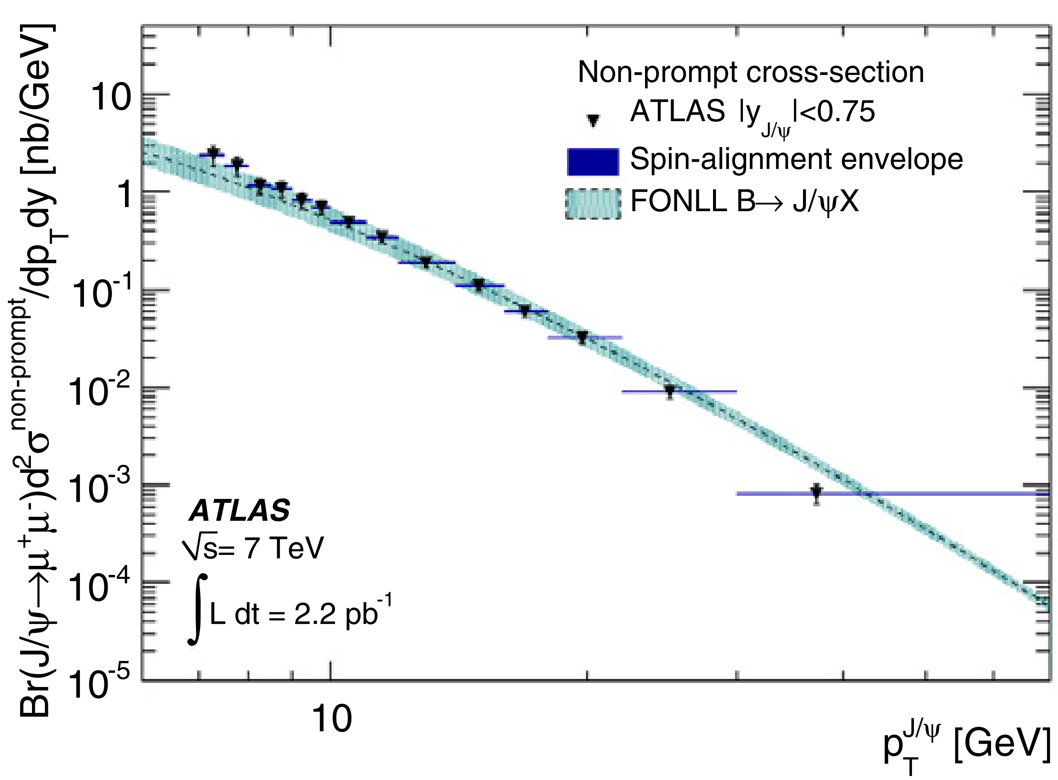
Additional uncertainty from unknown J/ψ spin alignment

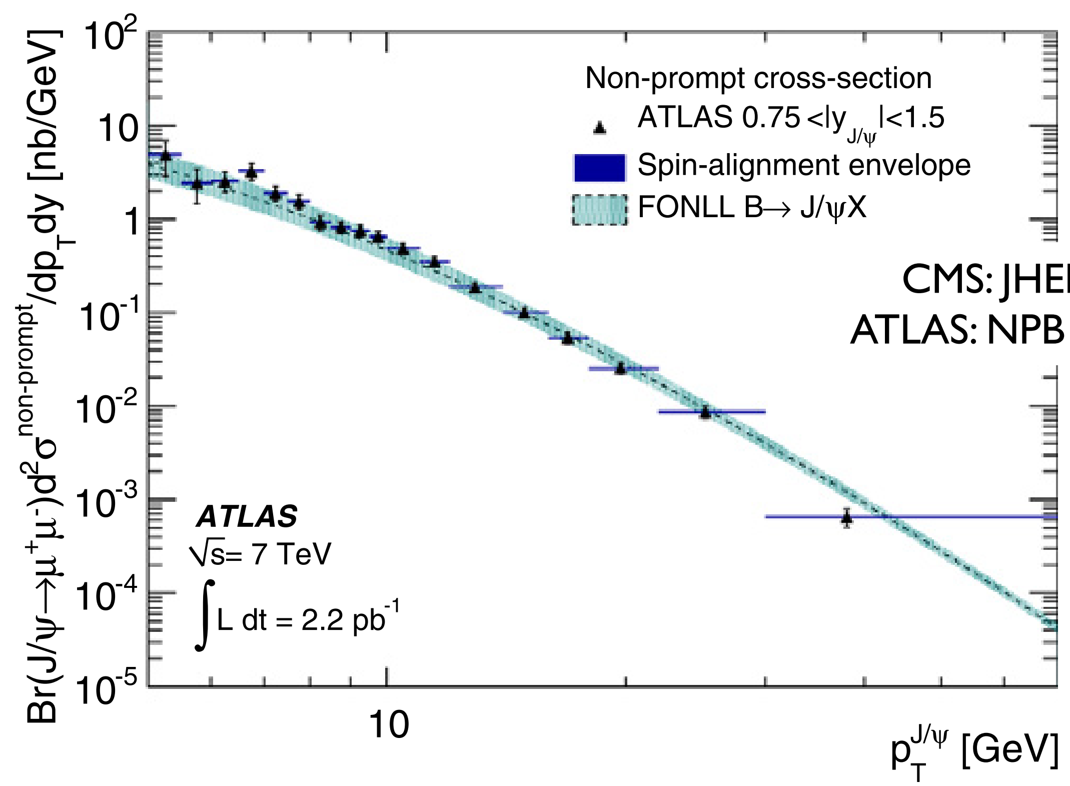
FONLL: b hadron spectrum calc at NLO + NLL resumm. in limit $p_{T,b} > m_b$

non-prompt p_T dependence well described by FONLL









CMS: JHEP 02 (2012) 011
ATLAS: NPB 850 (2011) 387

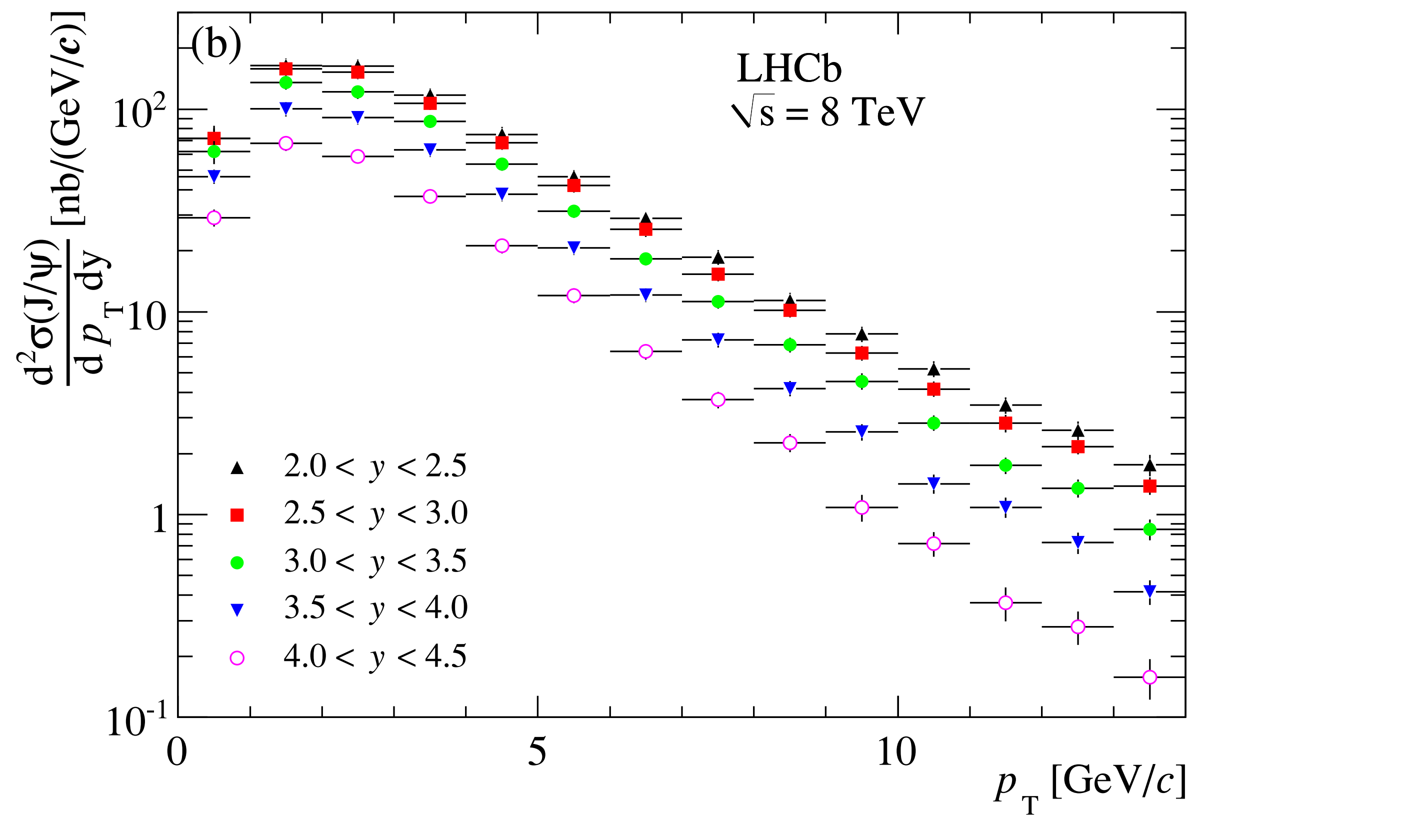
LHCb: JHEP 06 (2013) 064

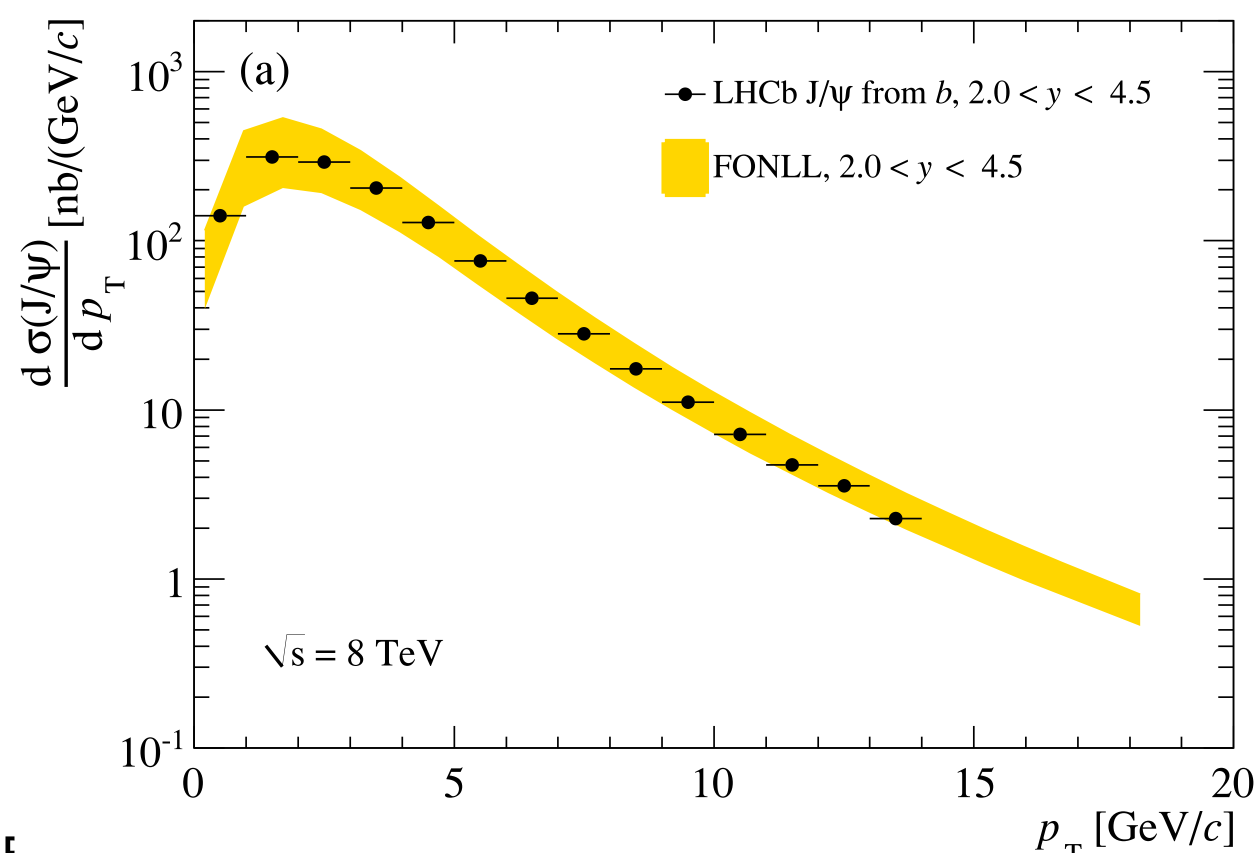
LHCb measures forward high rapidity region

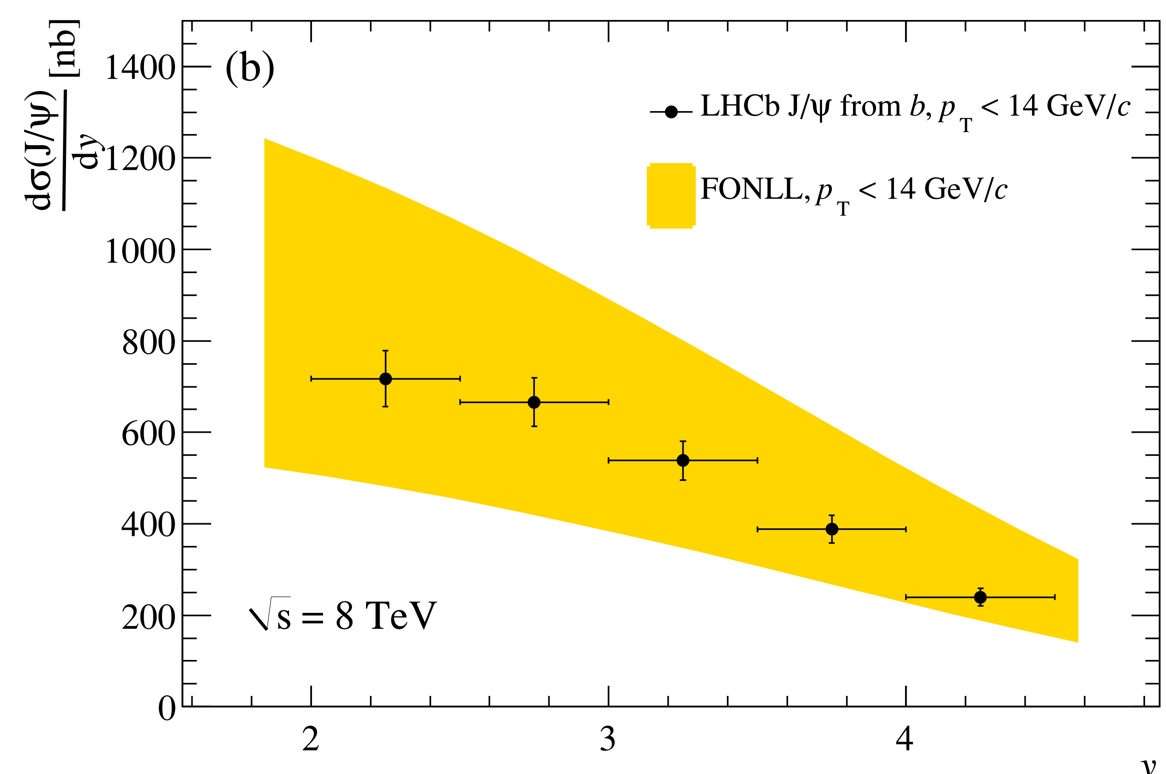
- $2.0 < y < 4.5$
- $0 < p_{T,J/\psi} < 50$ GeV
- $\sqrt{s} = 8$ TeV

At higher y observe increased suppression at high p_T

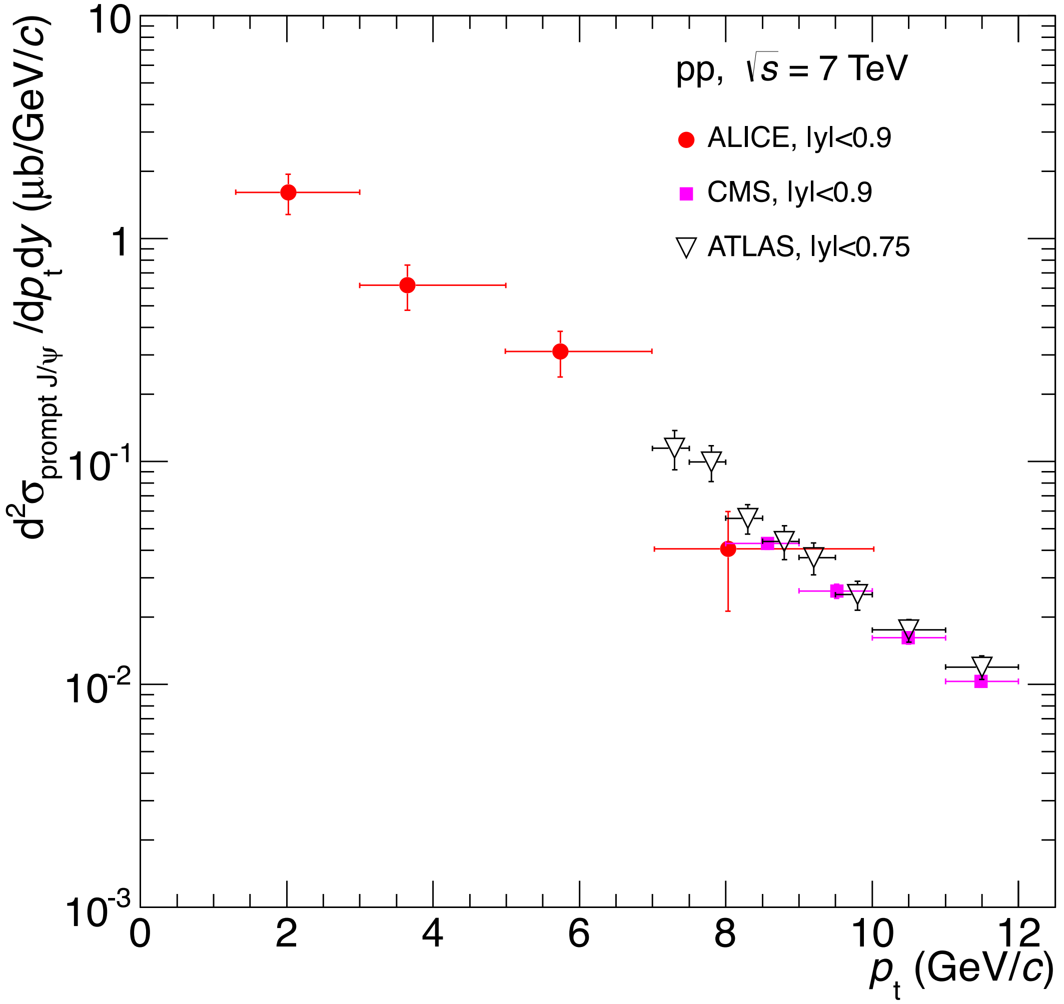
non-prompt J/ψ agrees well with FONLL
Large uncertainties on prediction



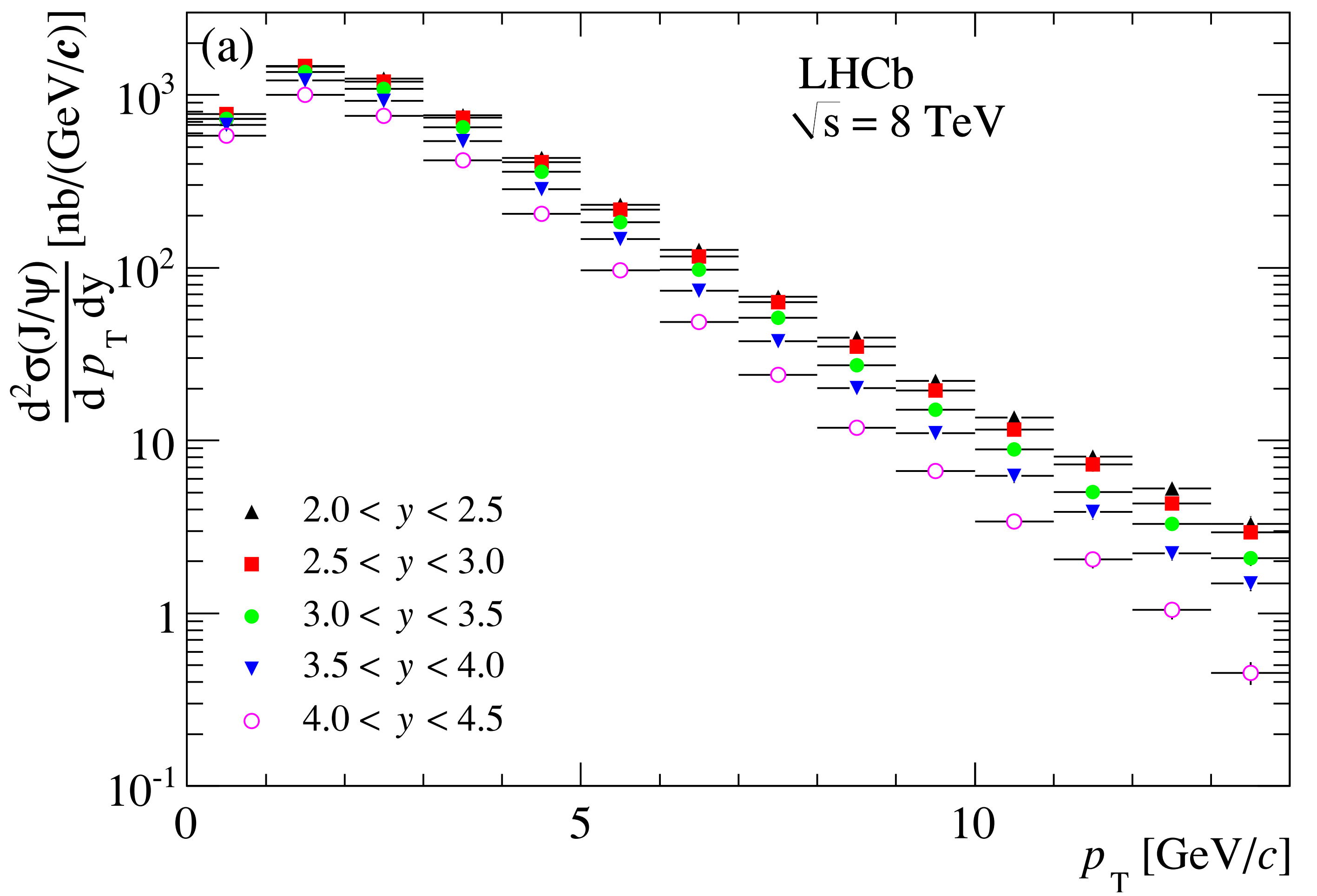




Prompt J/Ψ

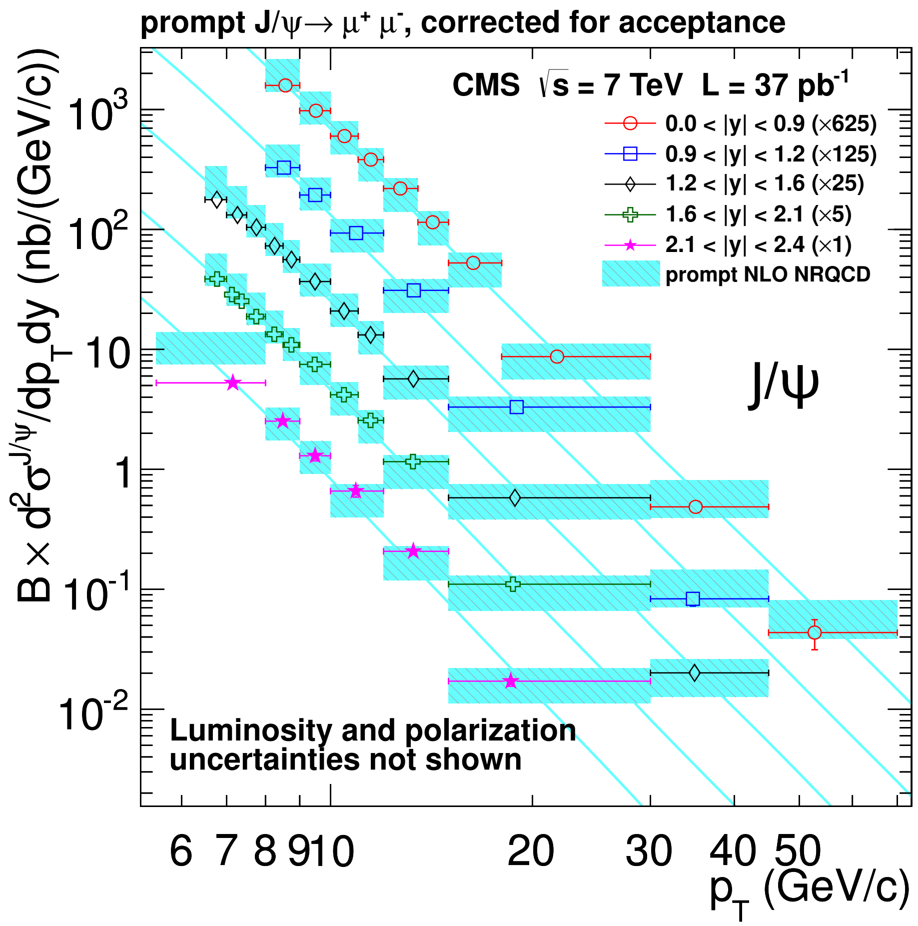


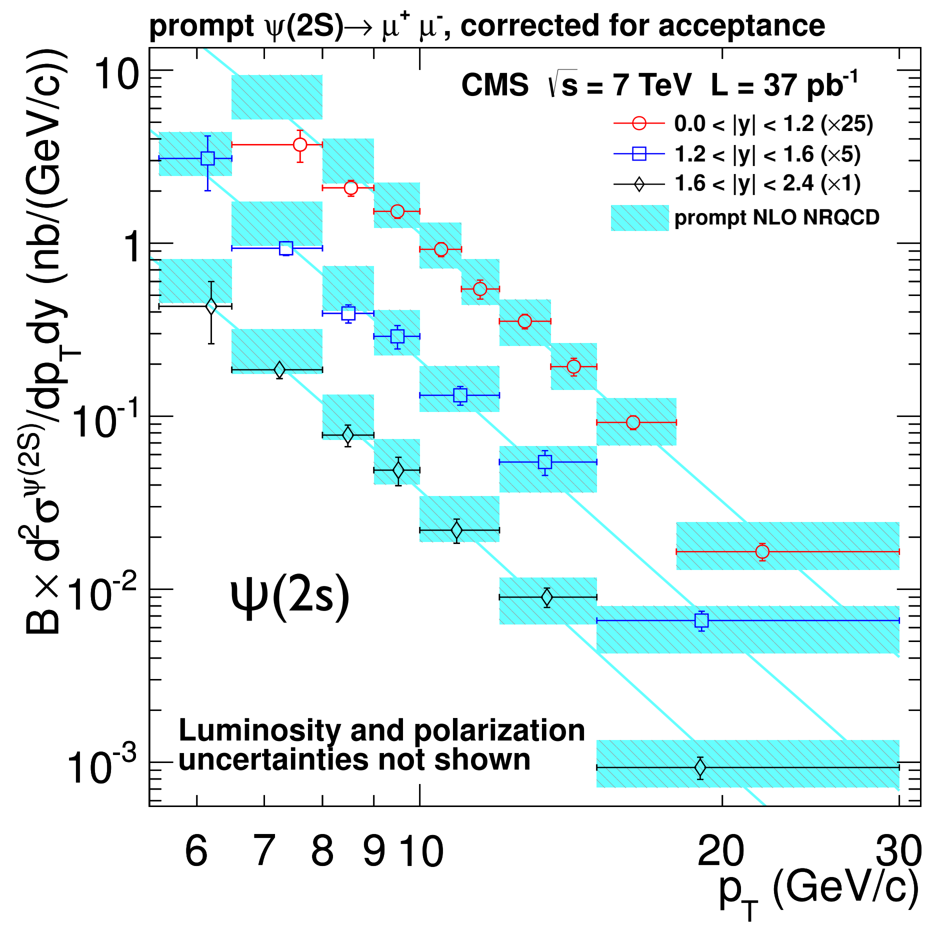
Good agreement between experiments



High p_T prompt production cross section is suppressed as y increases

LHCb: JHEP 06 (2013) 064
Alice: JHEP 1211 (2012) 065



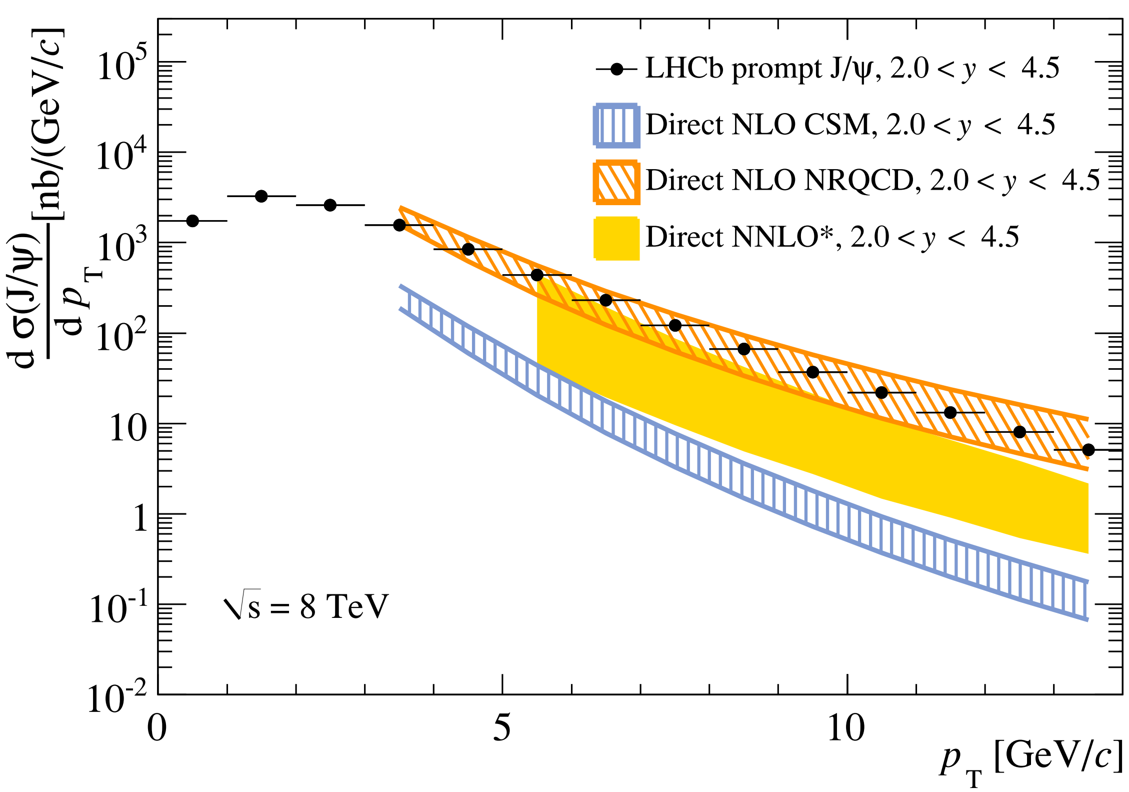


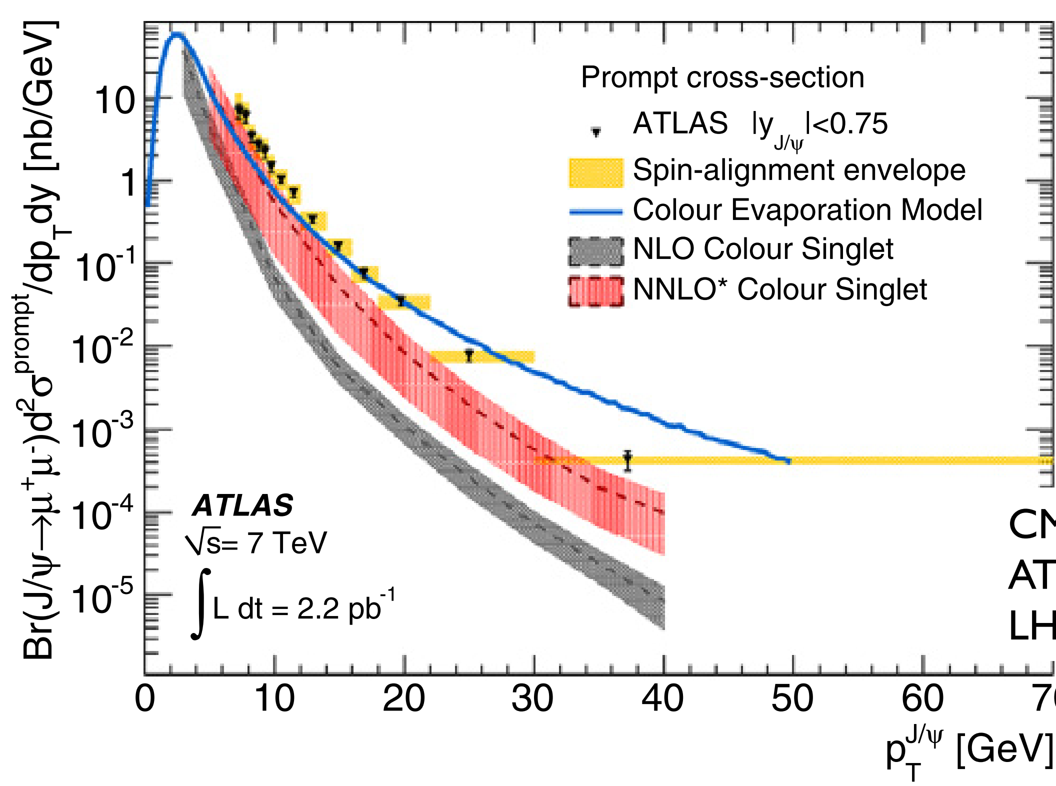
Prompt J/ψ agrees well with NLO NRQCD (octet)

NLO CSM underestimates by ~ factor 10 or more

NNLO* CSM is better but still fails to describe p_T spectrum

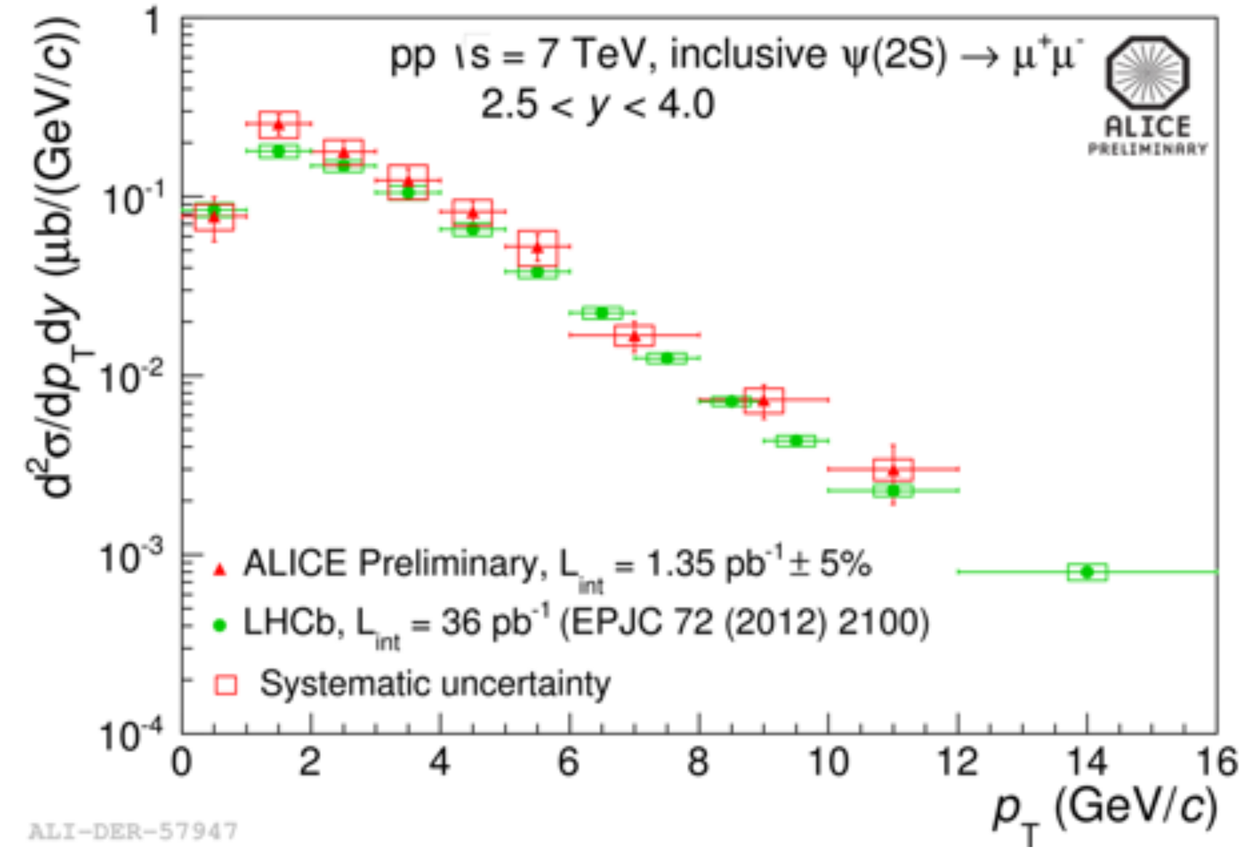
CEM unable to describe complete p_T spectrum

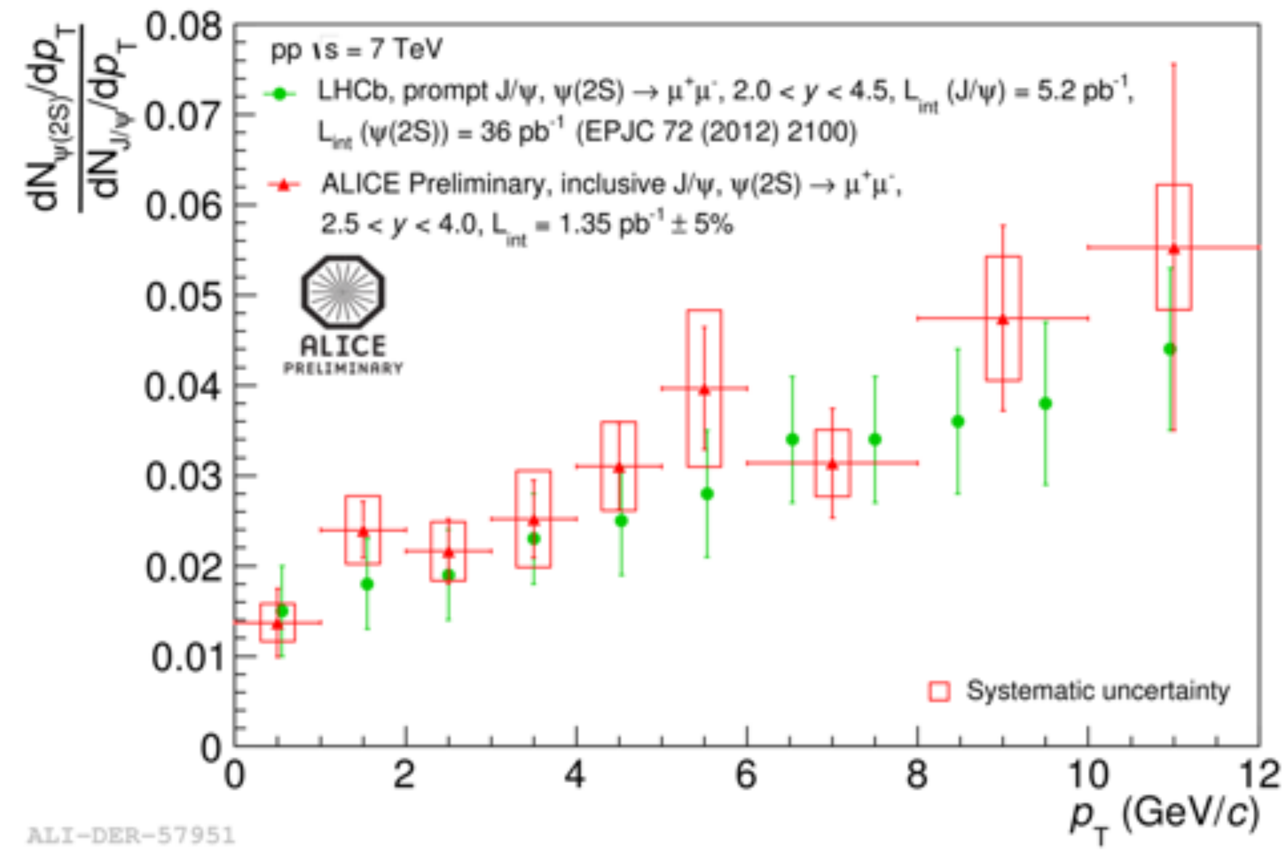




CMS: JHEP 02 (2012) 011
ATLAS: NPB 850 (2011) 387
LHCb: JHEP 06 (2013) 064

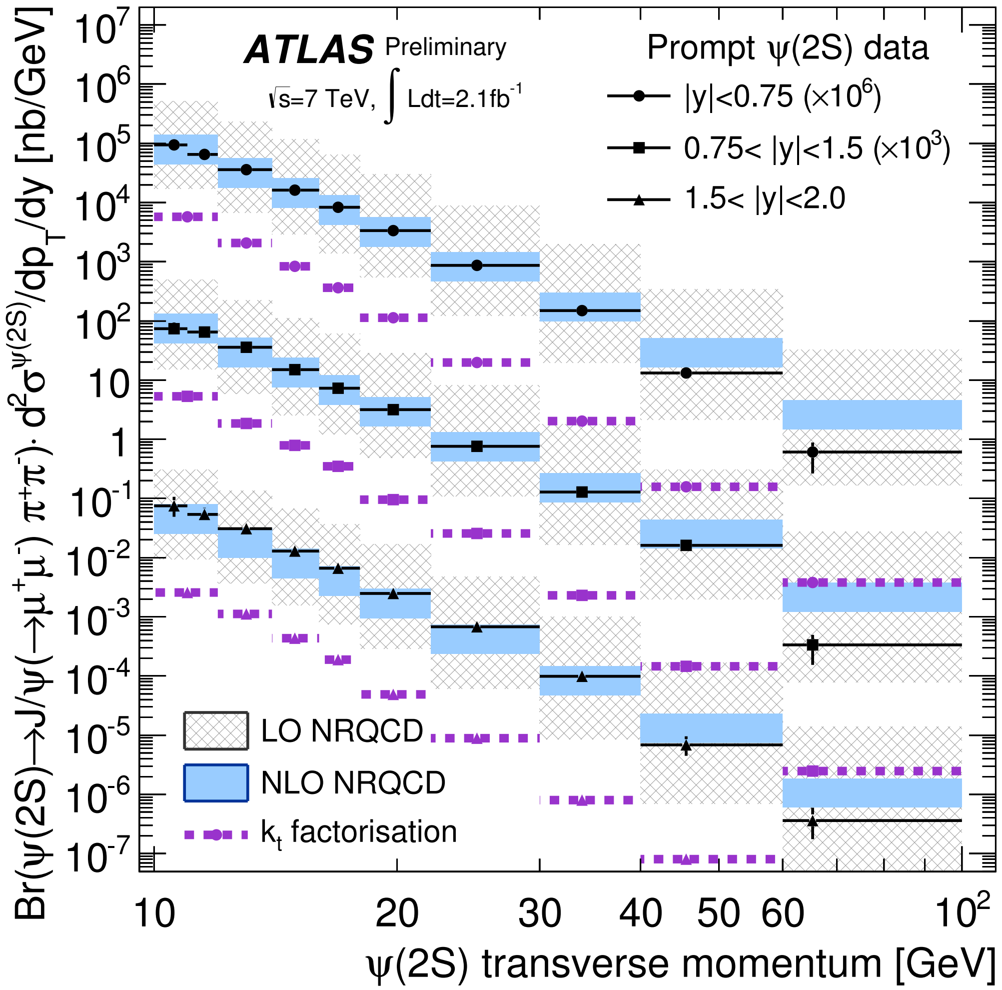
- New result from ALICE on forward ψ(2S) production
- Good agreement with LHCb - prompt production
- Ratio to J/ψ production is ~1% increases at higher p_T

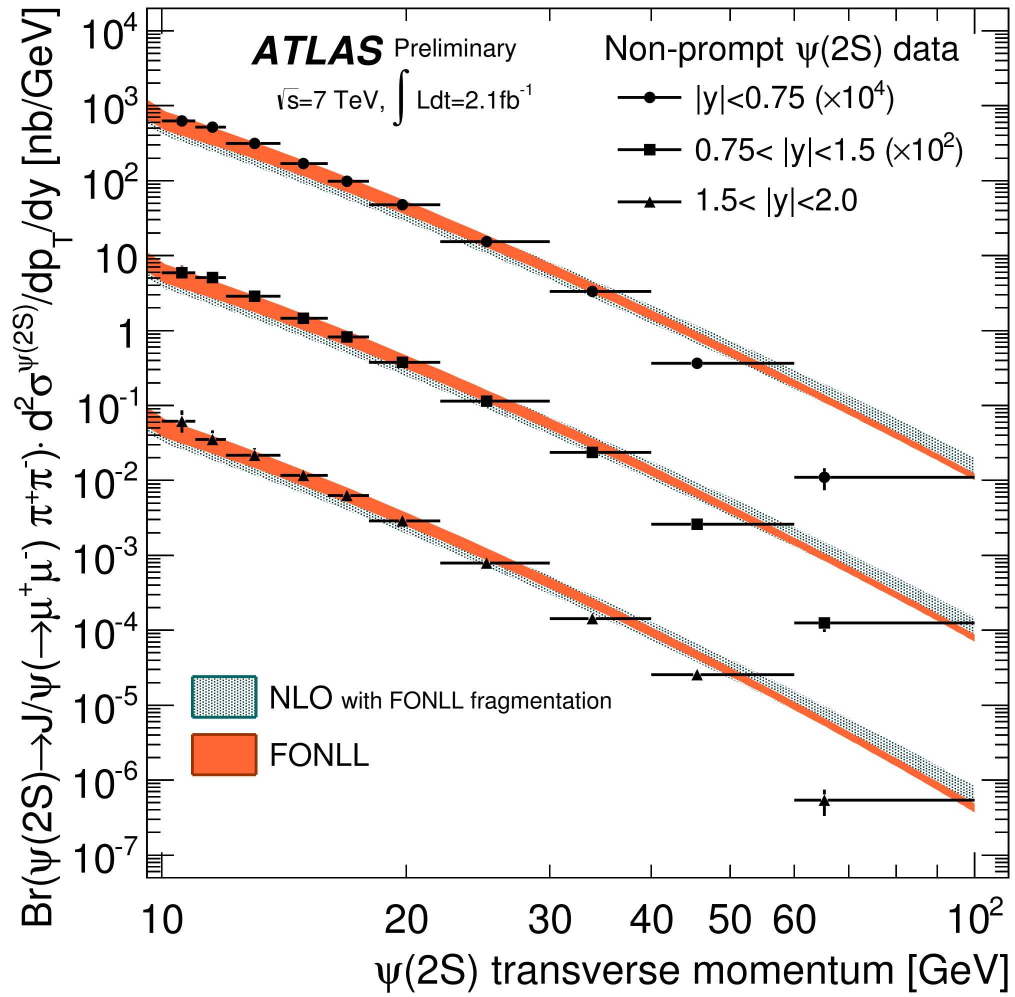




Charmonium Production Ψ(2S)

ATLAS CONF (2013) 094





New result from ATLAS - prompt and non-prompt production of $\psi(2s) \rightarrow J/\psi + \pi\pi$

$\hookrightarrow J/\psi \rightarrow \mu\mu$

$p_T < 100$

$|y| < 2$

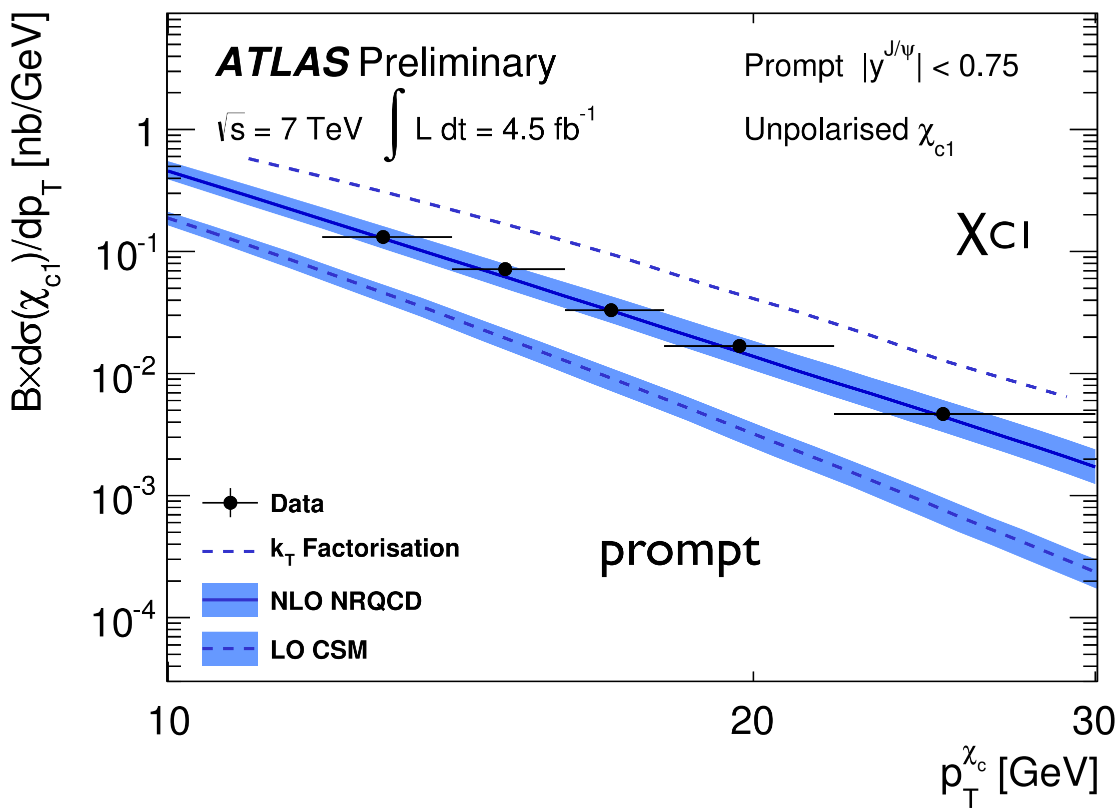
Prompt production has no significant feed-down: higher mass charmonia decay mostly to $D\bar{D}$

NLO NRQCD describes prompt production well - perhaps too high at large p_T

FONLL provides reasonable model for non-prompt production - p_T spectrum too hard

Charmonium Production χ_{c1} & χ_{c2}

ATLAS CONF (2013) 095



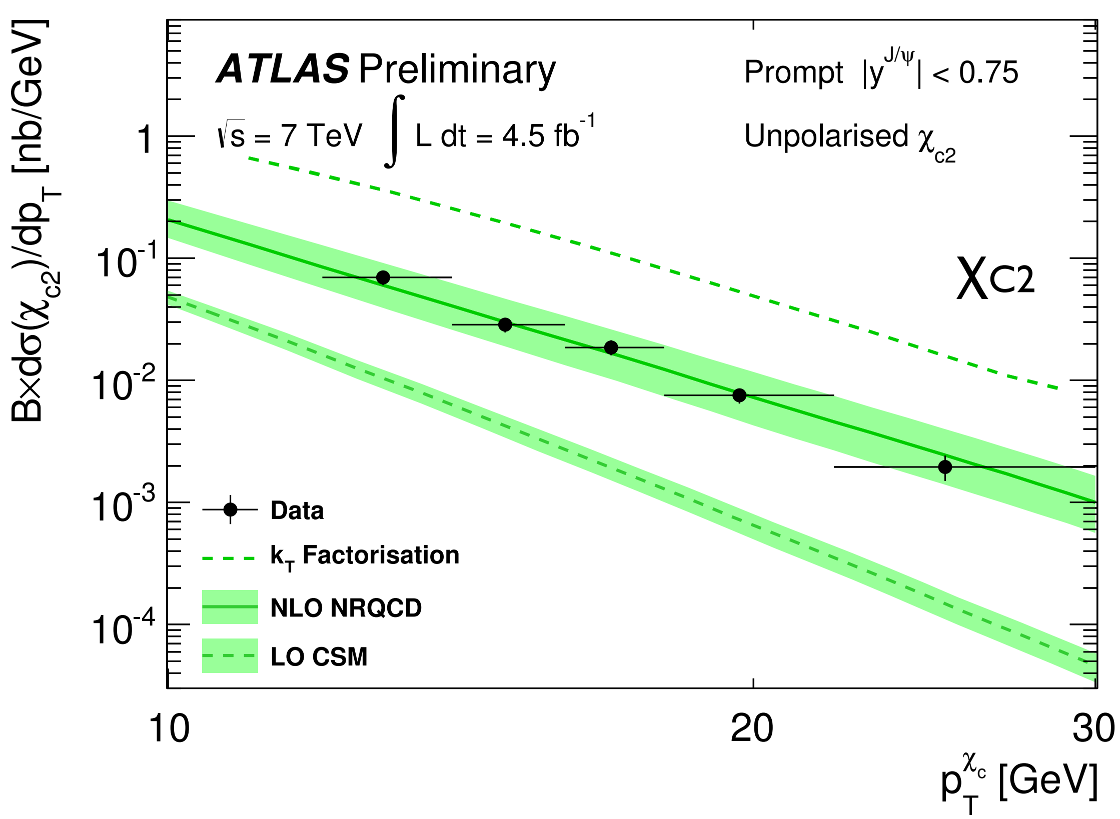
New result from ATLAS $\chi_c \rightarrow J/\psi + \gamma$

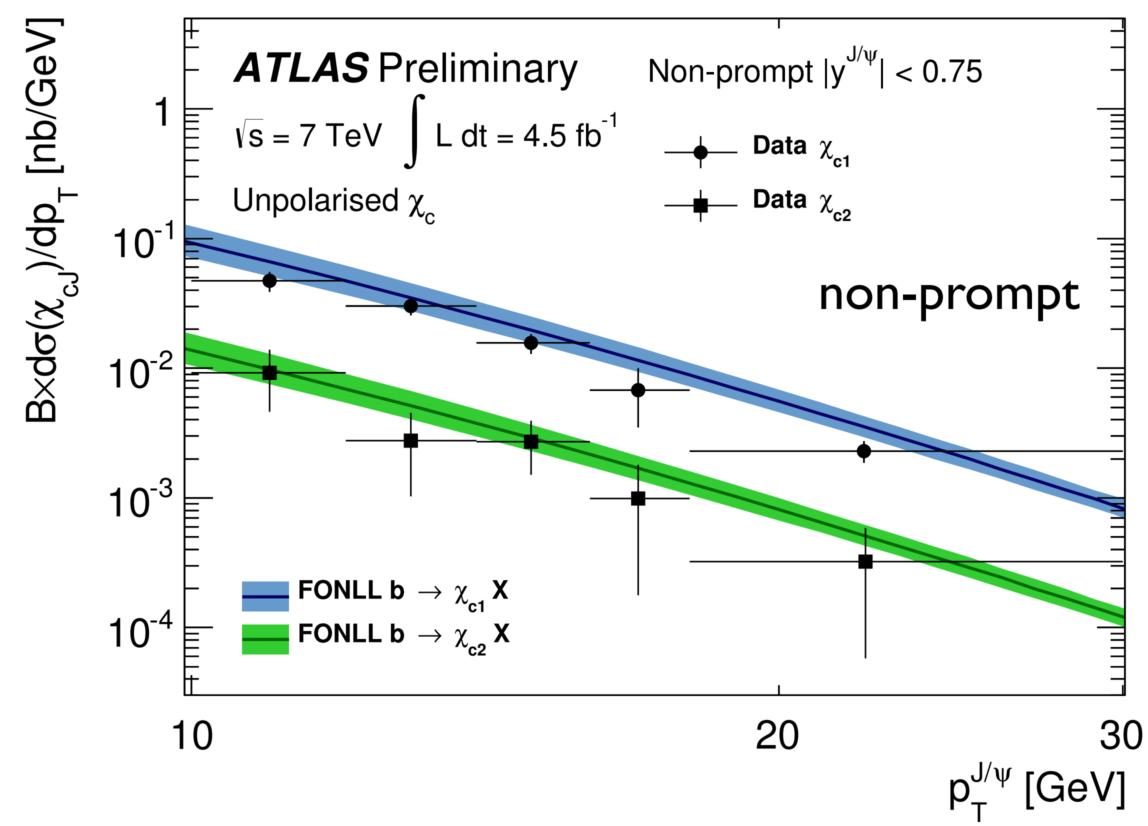
↳ $J/\psi \rightarrow \mu\mu$

↳ $\gamma \rightarrow ee$

NLO NRQCD works well for prompt production

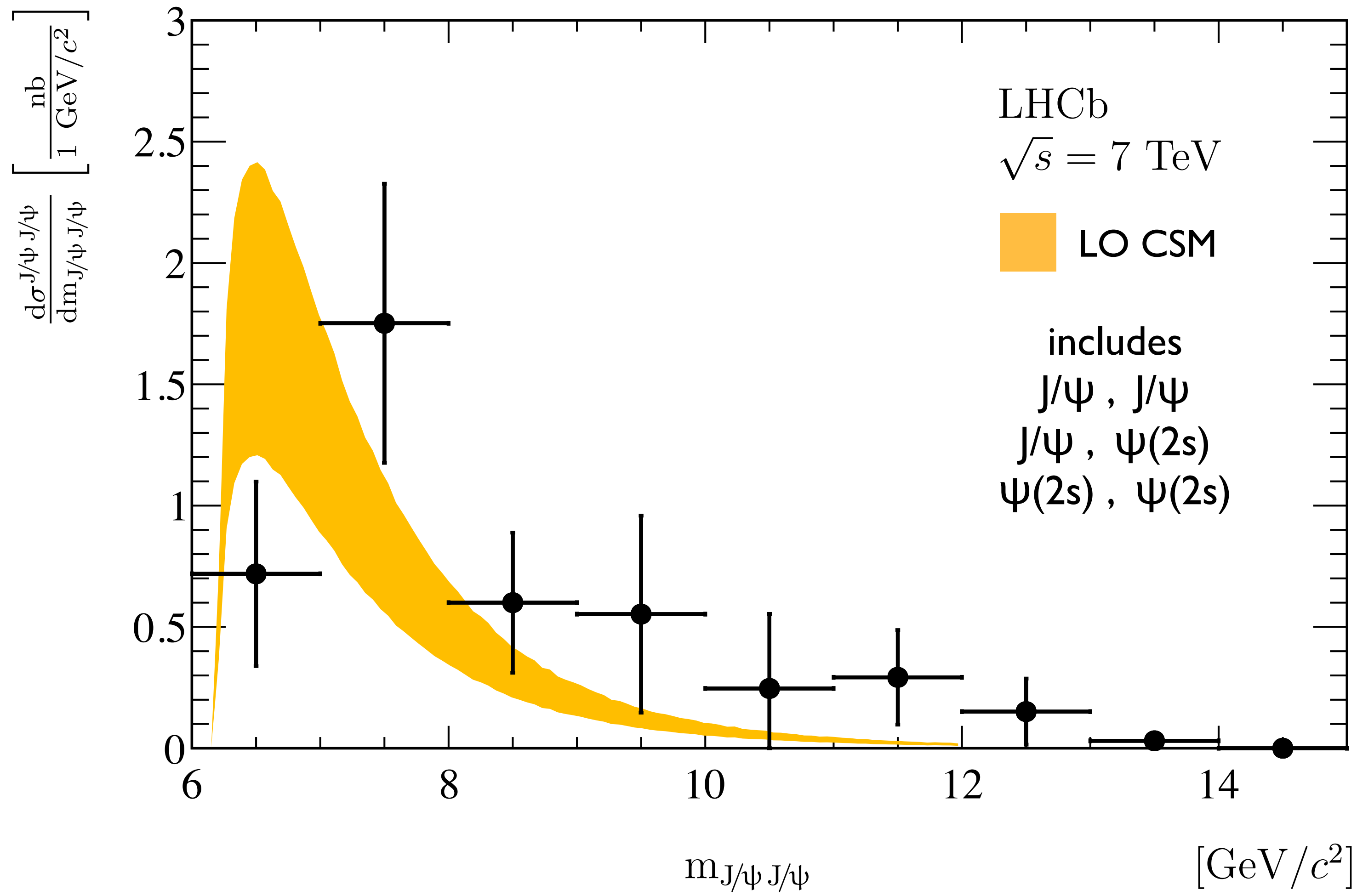
FONLL slightly overestimates non-prompt production





Prompt J/Ψ Pair Production

LHCb: PLB B707 (2012) 52-59



$\int \mathcal{L}dt$ = 35 pb^{-1}

Pair production of prompt J/ψs is process dependent
Could distinguish CO and CSM
Contributions from double parton scattering may be significant

CSM works well - higher statistical precision needed

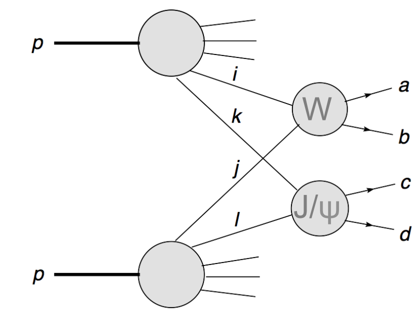
Fiducial selection of J/ψs
2.0 < y < 4.5
p_T < 10 GeV

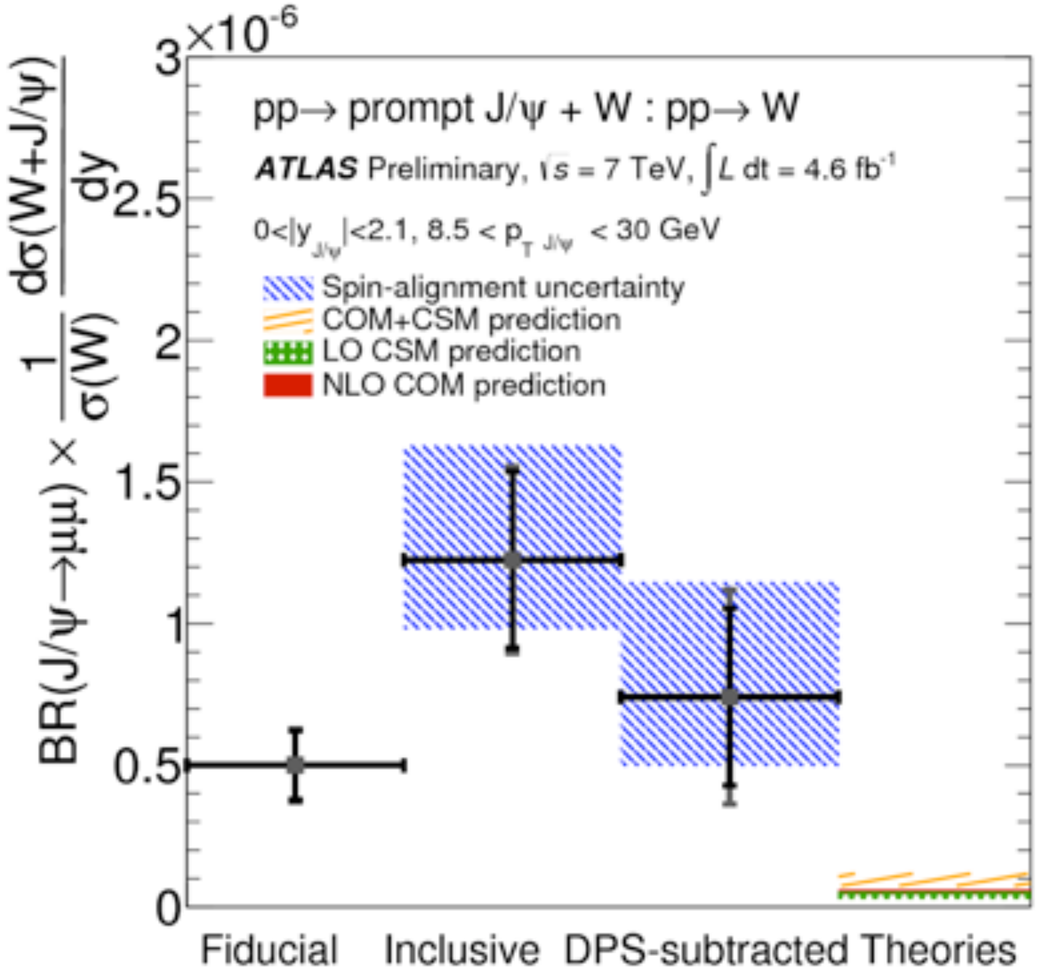
Non-prompt pair production of J/ψs could help understand g→bb splitting
analyses are underway...

Prompt J/Ψ + W± Production

ATLAS-CONF-2013-042

Associated production of J/ψs with $W^{\pm}$ → First observation from ATLAS at 5.3σ
W selects different partonic initial states → different CO / CS contributions
Prediction: pp → W + J/ψ is dominated by CO process
Process is sensitive to double parton scattering: W & J/ψ produced in separate partonic interactions

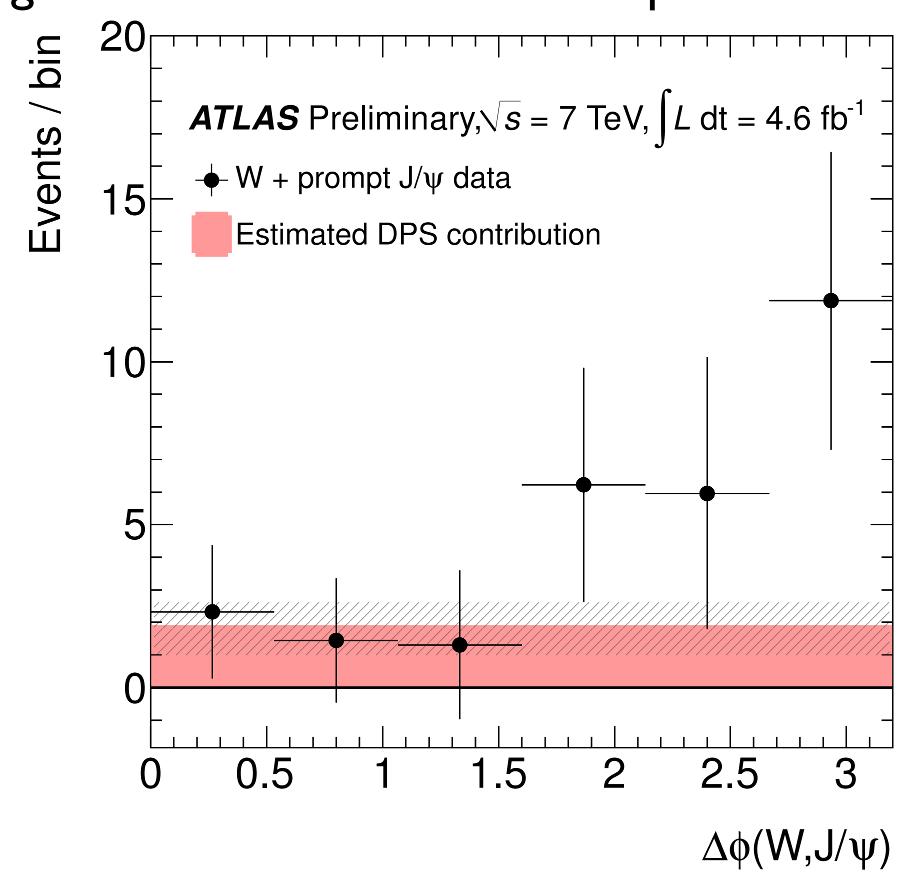




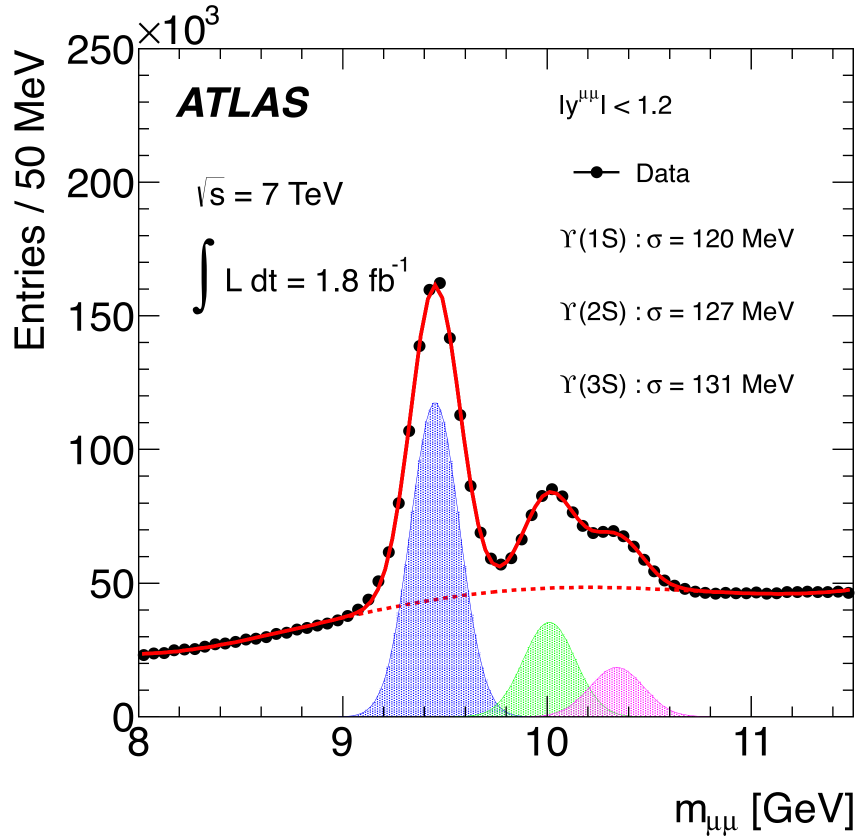
Measure normalised cross section to reduce uncertainties
pile-up estimation: no. additional vertices x σ(J/ψ)/σ(pp)

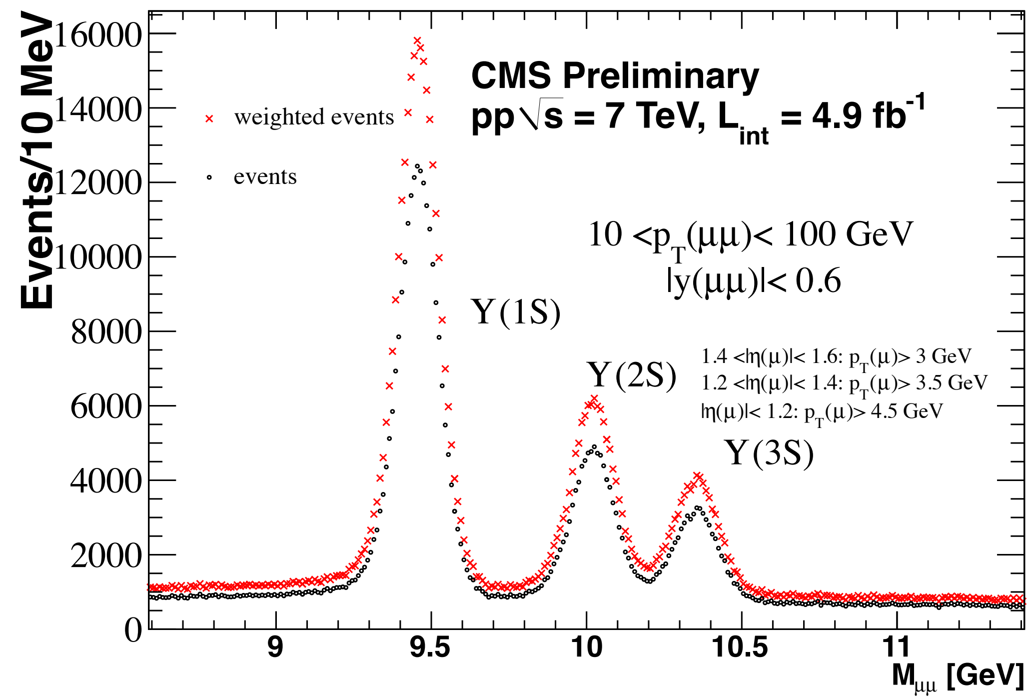
DPS contribution:
$P_{J/\psi\,|\,W} = \sigma_{J/\psi} / \sigma_{eff}$ where $\sigma_{eff} = \sigma_{w+2j}$ measured in data

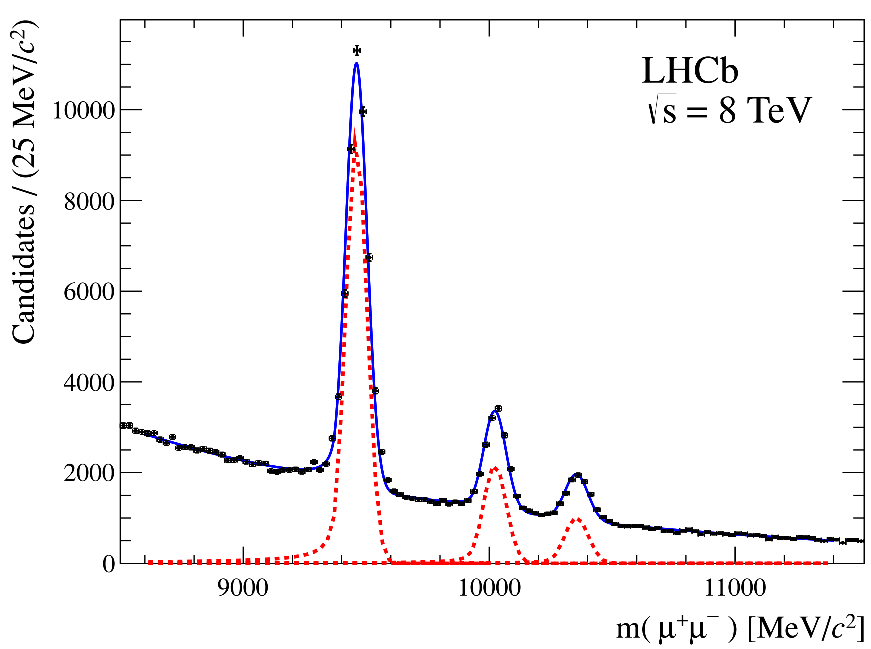
significant DPS contribution expected: flat in Δφ



Combined CO+CS prediction underestimates measurement

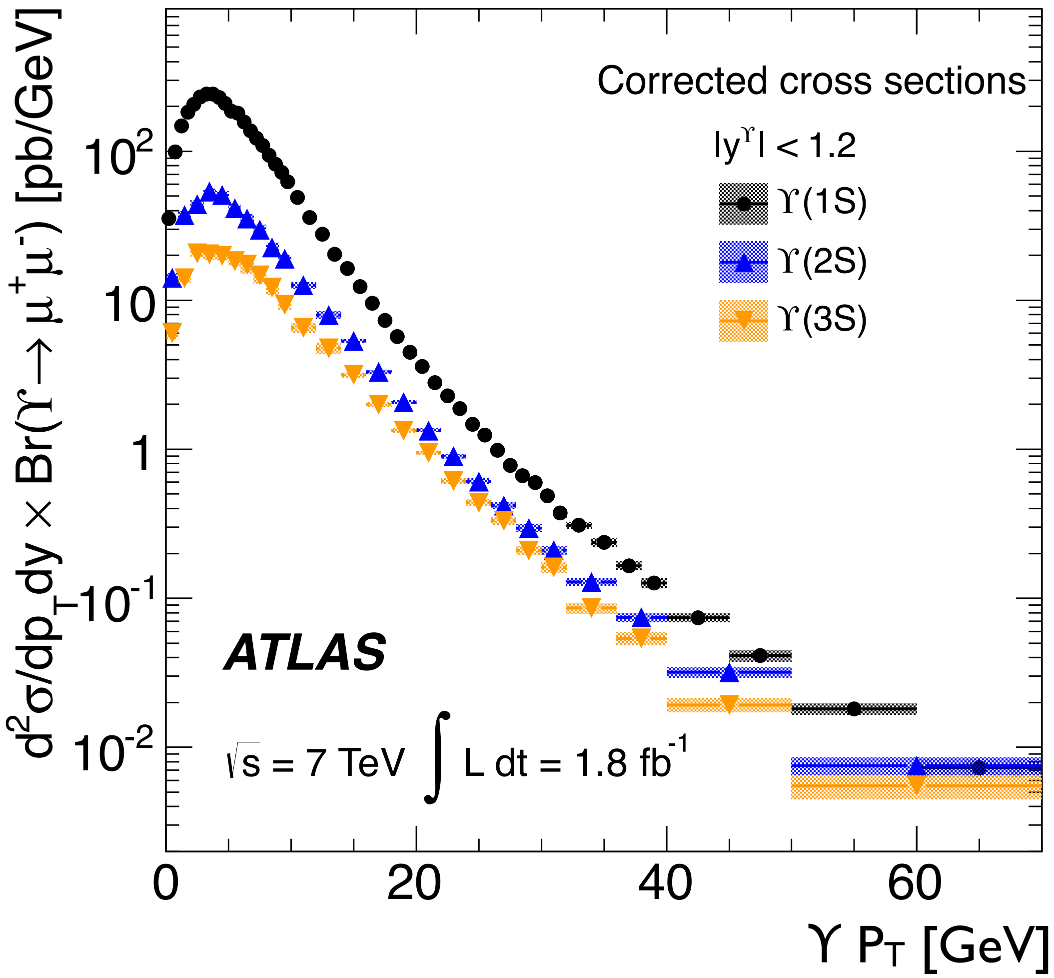


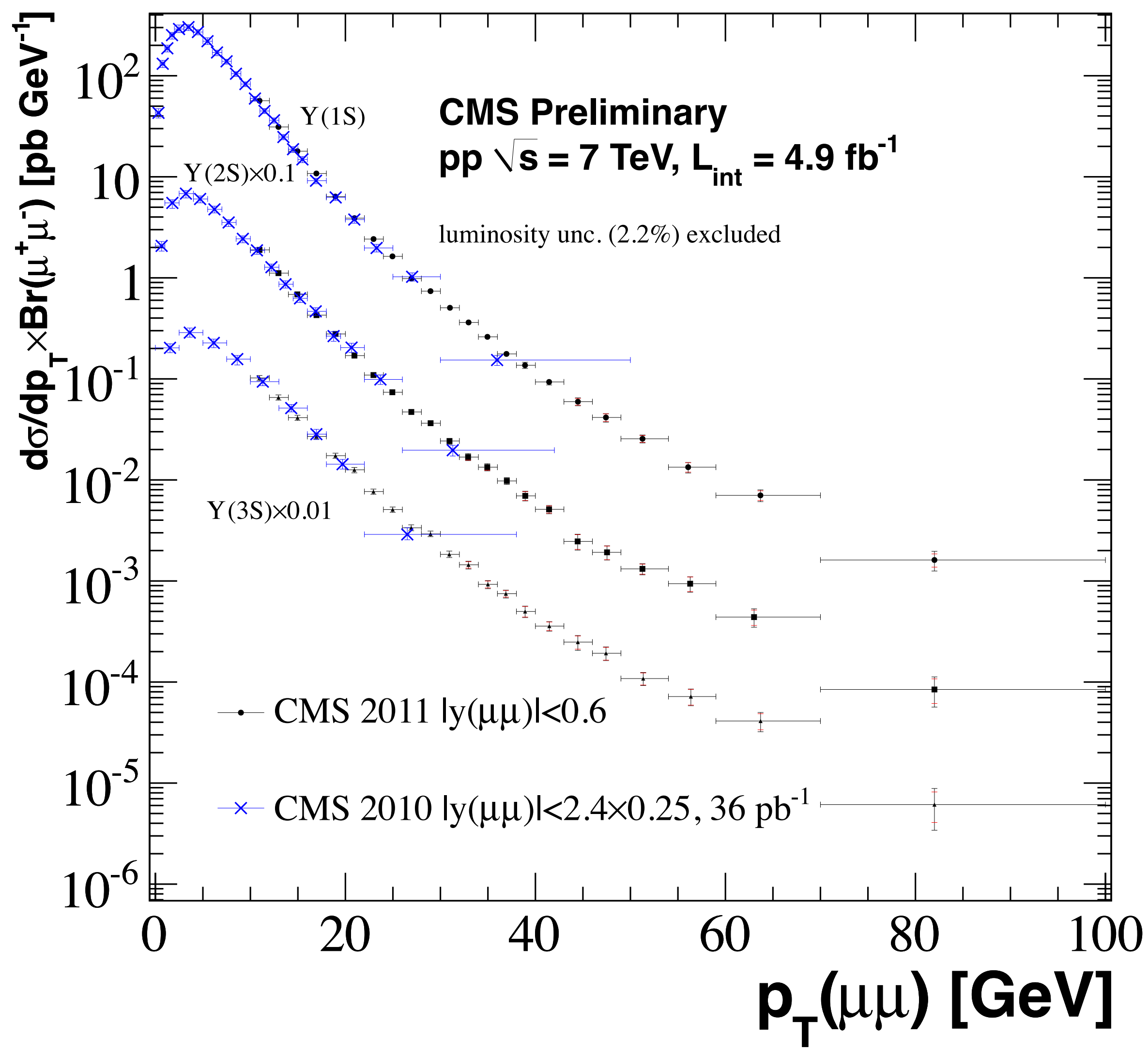


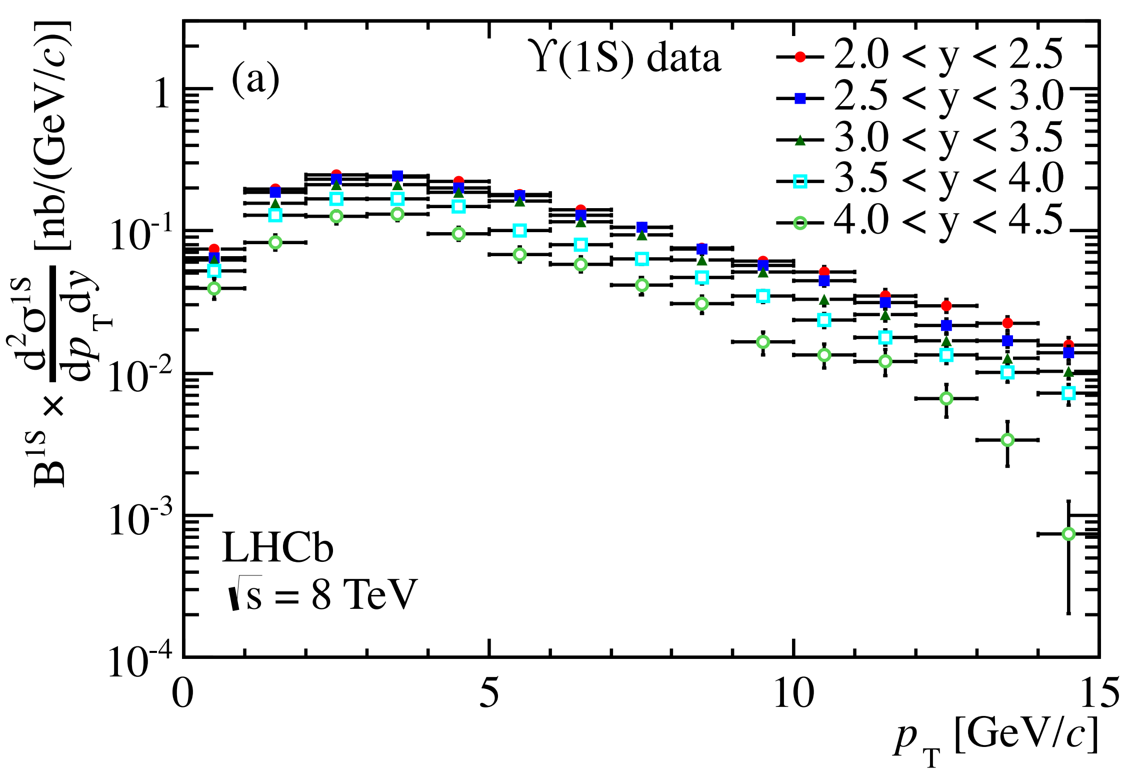


- New measurements of Υ family of mesons
- Expect better theoretical understanding due to large b mass
- Use high stats samples
- Measure production cross sections and polarisation

ATLAS: PRD 87 (2013) 052004
CMS: CMS-PAS-BPH-12-006
LHCb: EPJC (2012) 72:2025
LHCb: JHEP 06 (2013) 064

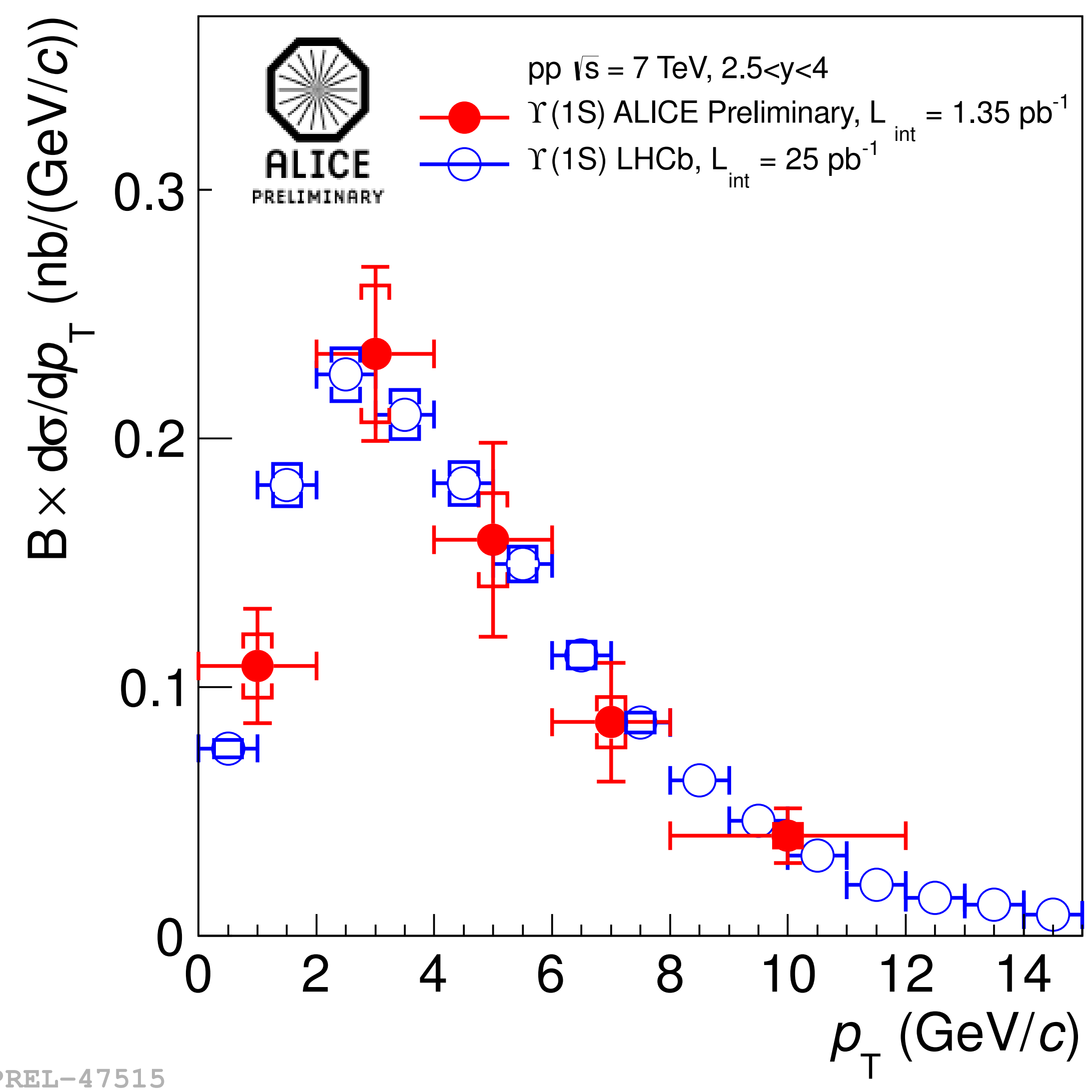


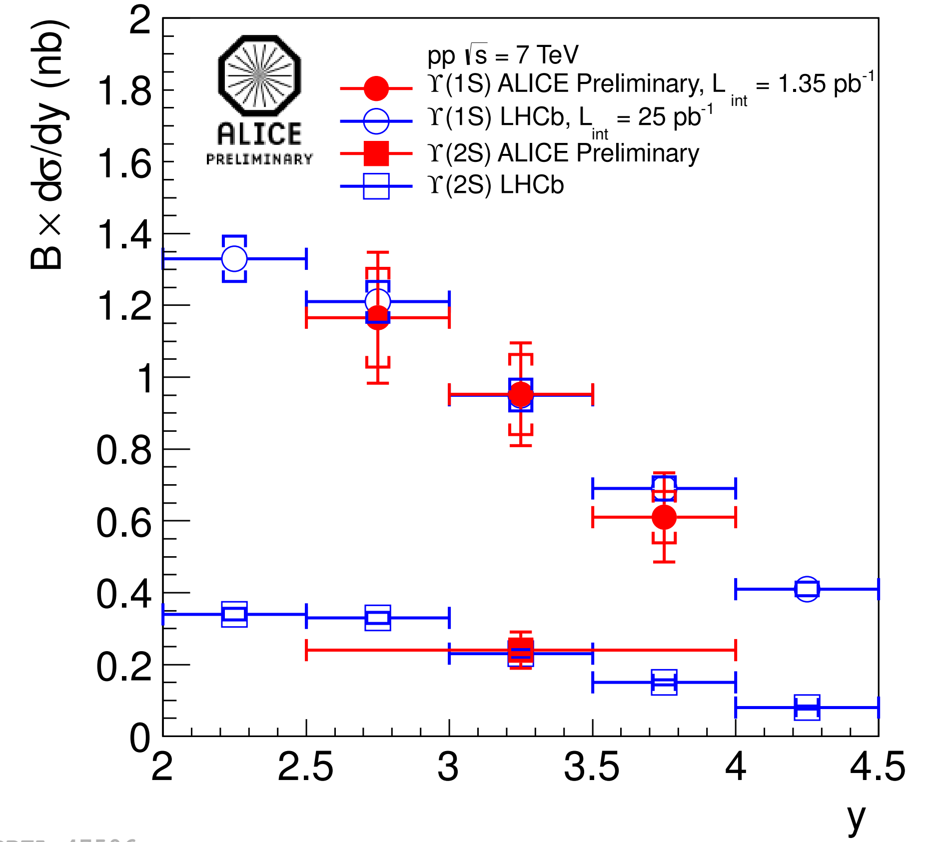


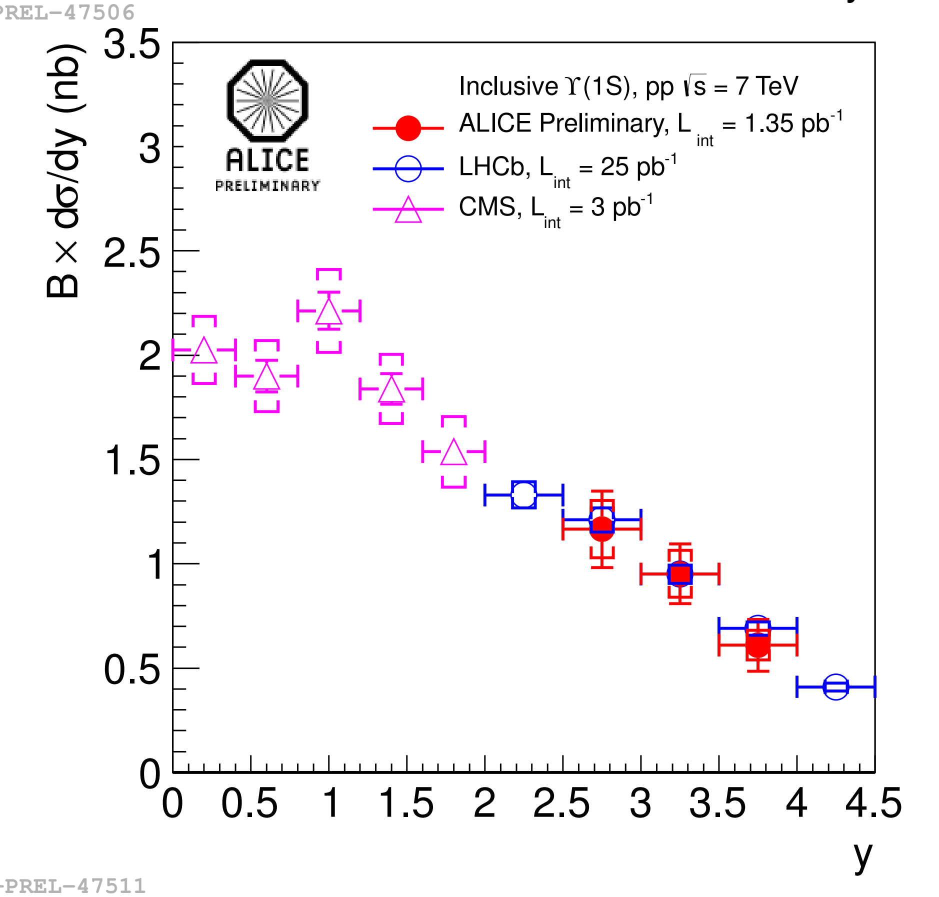


- Corrected cross sections show low p_T peak
- Similar p_T dependence observed for all 3 states
- Cross section falls with increasing y
  → increasing suppression of high p_T tail

Υ(nS) Production

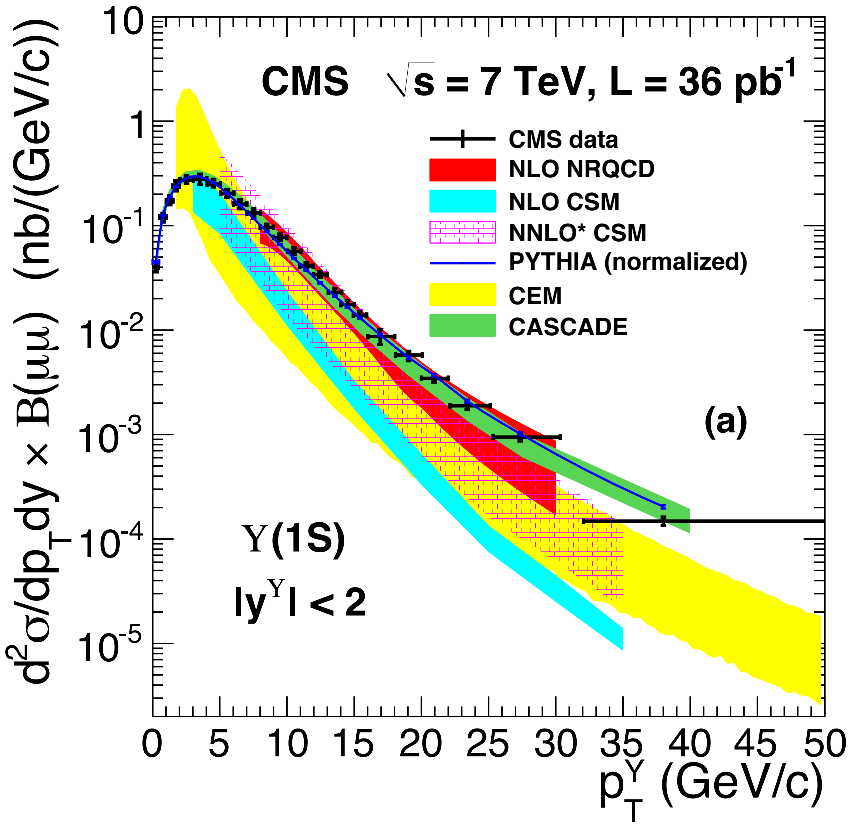


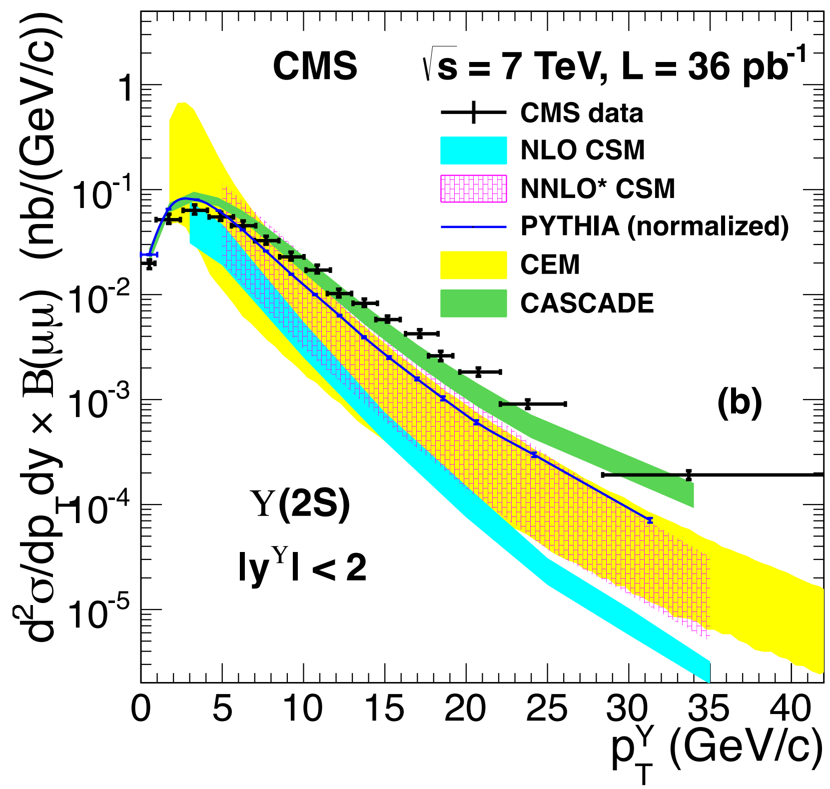


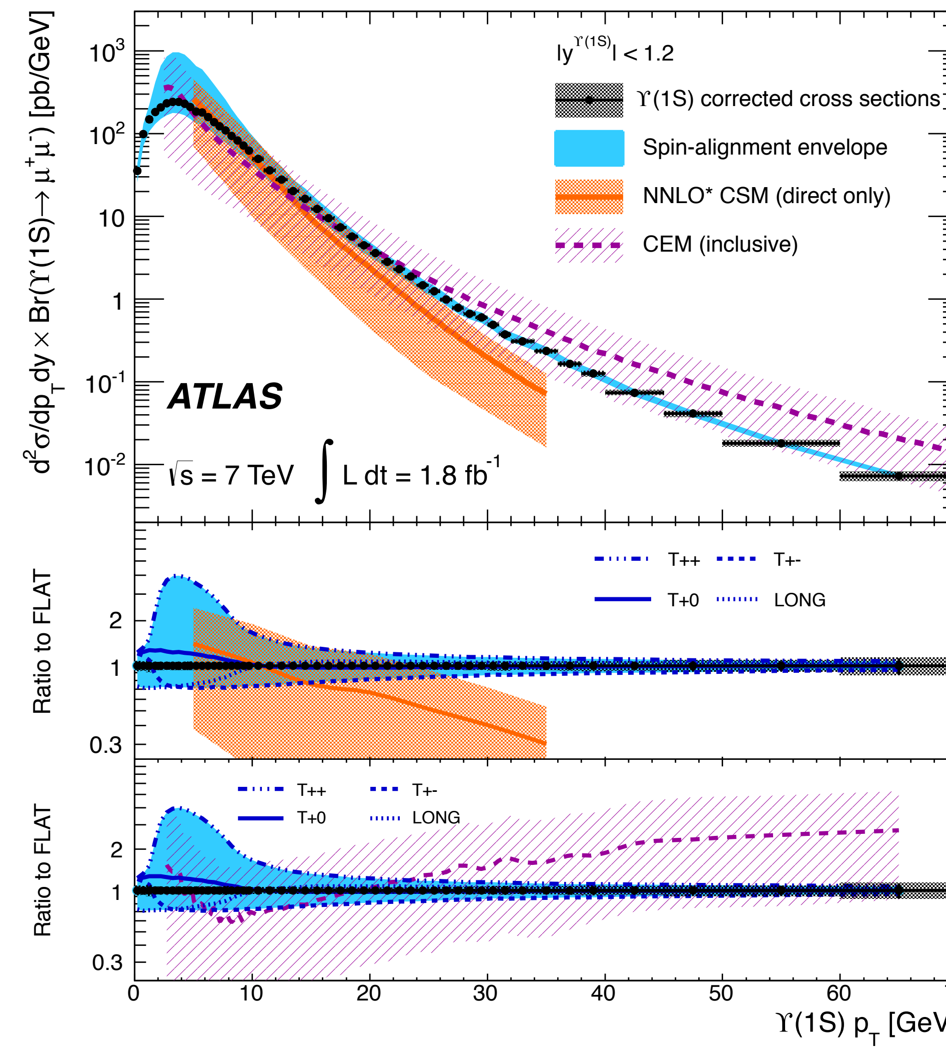


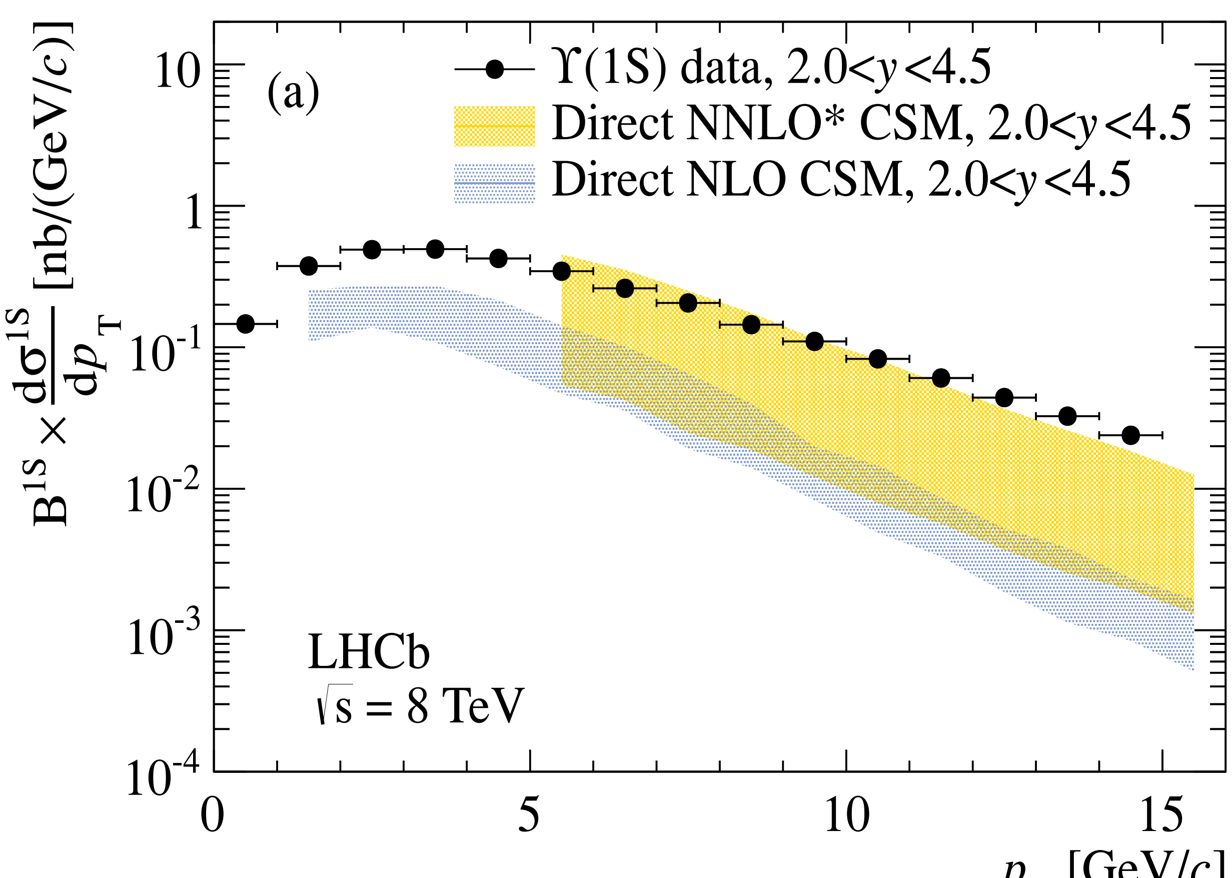
- New pp measurement from ALICE for Υ(1S) and Υ(2S)
- Large uncertainties due to trigger
- Good agreement with CMS & LHCb in central / forward regions

ϒ(nS) Production









- NLO NRQCD works well for p_T> 8 GeV
- CSM, CEM approximate agreement
- None works over full p_T range
- NNLO* CSM: better than it does for J/ψ

ATLAS: PRD 87 (2013) 052004
CMS: arXiv: 1303:5900
LHCb: JHEP 06 (2013) 064

Conclusions

- Production cross sections for J/ψ , ψ(2S) , ϒ(nS) measured at LHC by all experiments
- Kinematic range extended up to p_T ~ 70 GeV and y~4.5
- Good agreement between LHC experiments and TeVatron
- Measurements are mostly systematically limited
- Prompt production well described by NRQCD and the COM
- non-prompt production well described by FONLL

Several interesting measurements underway:
DPS sensitivity from J/ψ associated production with W, Z, J/ψ

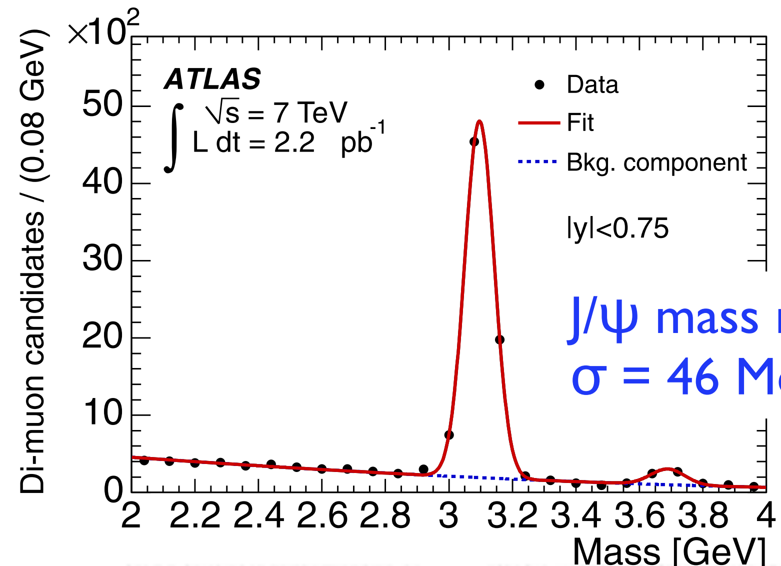
Polarisation measurements for J/ψ and ϒ(nS) discussed in Pietro Faccioli's talk

Quarkonia in PbPb collisions discussed in Ionut Arsene's talk

Extras

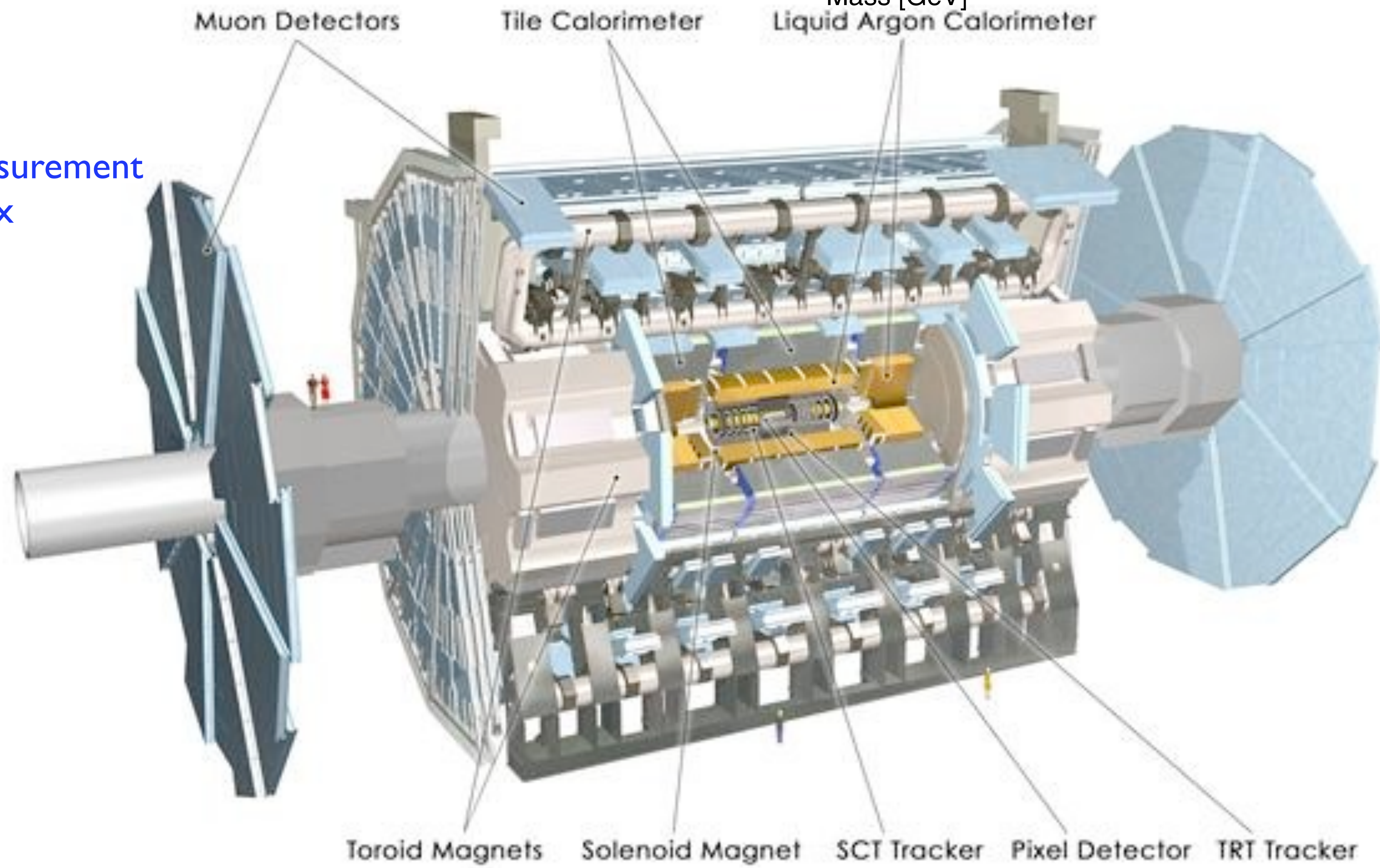
ATLAS

<u>Muon system</u>
trigger system & precision tracking
toroidal B-field ~ 0.5T
$|\eta|<2.7$
transverse impact parameter resolution σ = 10 μm



J/ψ mass resolution
σ = 46 MeV for $|y|<0.75$

<u>Inner detector</u>
Transition radiation tracker:
particle ID, track finding
silicon strips: momentum measurement
silicon pixels: secondary vertex
Solenoidal B-field = 2T
$|\eta|<2.5$

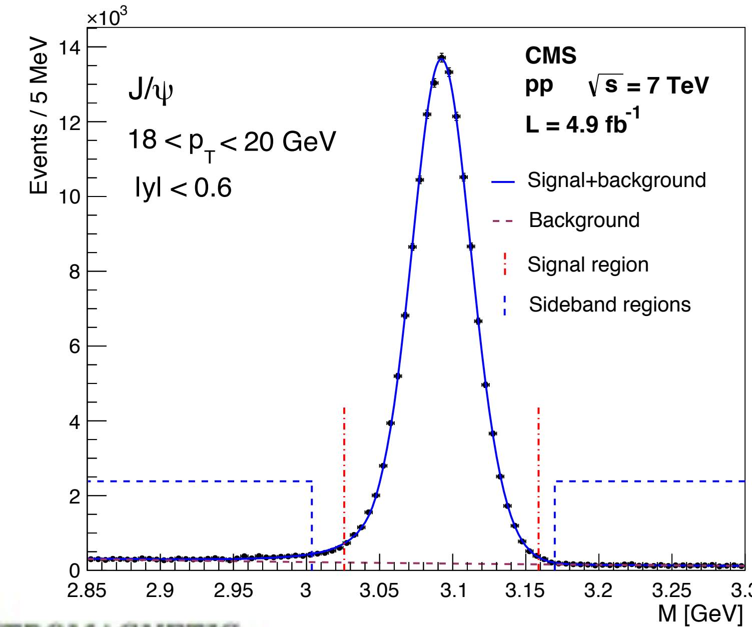


<u>Calorimeters</u>
coverage $|\eta|<4.9$
photons, missing energy

<u>Triggers</u>:
single & dimuon triggers
pT > 4 GeV
opposite sign muons
from common vertex

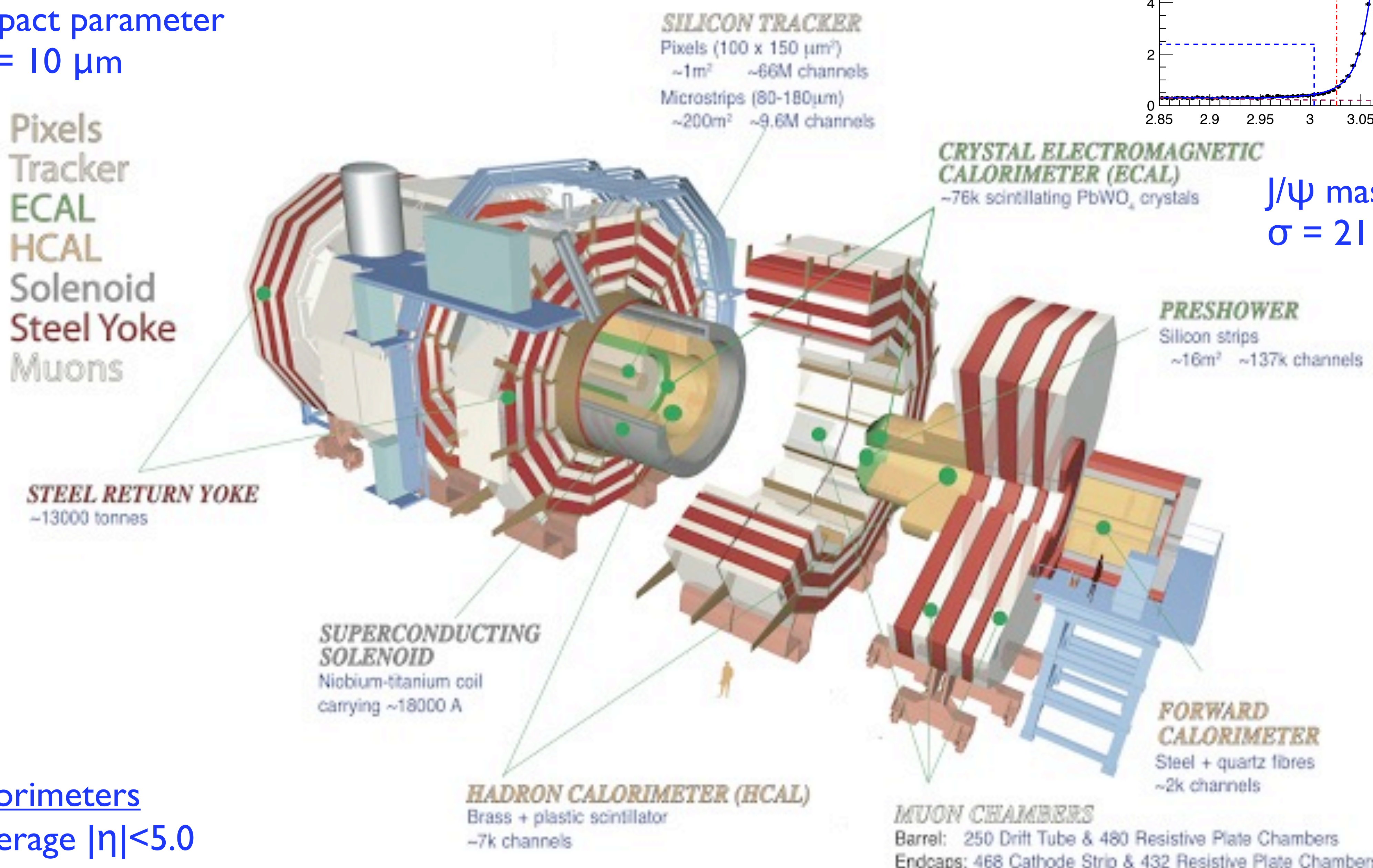
CMS

[Inner detector](#)
silicon strips: momentum measurement
silicon pixels: secondary vertex
Solenoidal B-field = 3.8T
$|\eta|<2.5$

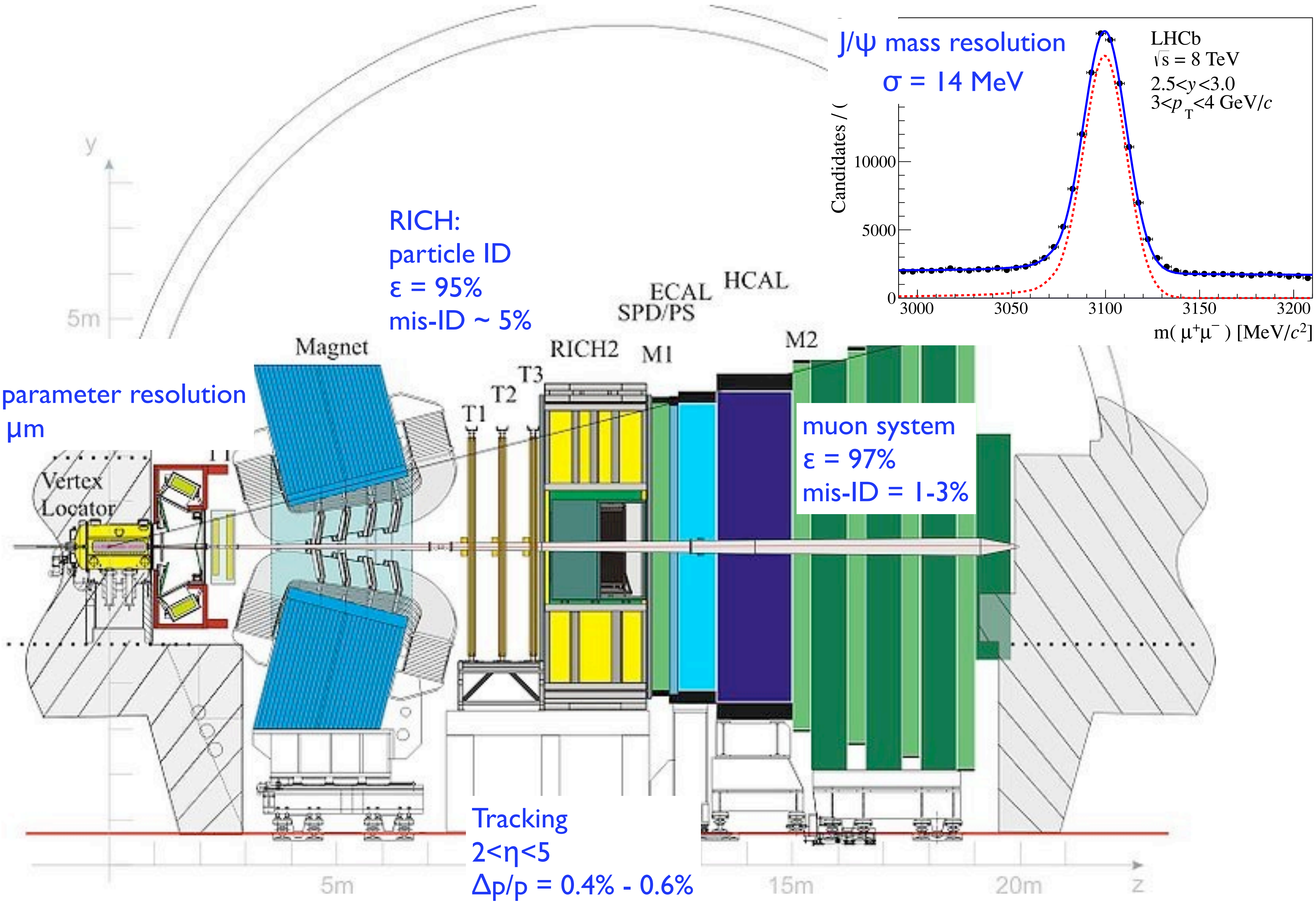


[Muon system](#)
trigger system & precision tracking
$|\eta|<2.4$
steel return yoke provides B-field
transverse impact parameter
resolution σ = 10 μm

J/ψ mass resolution
σ = 21 MeV for $|y|<0.6$



[Calorimeters](#)
coverage $|\eta|<5.0$
photons, missing energy


J/ψ mass resolution
σ = 14 MeV
LHCb
√s = 8 TeV
2.5<y<3.0
3<p_T<4 GeV/c
Candidates / (
10000
5000
0
3000
3050
3100
3150
3200
m(μ+μ−) [MeV/c²]
RICH:
particle ID
ε = 95%
mis-ID ~ 5%
VELO
impact parameter resolution
σ = 20 μm
muon system
ε = 97%
mis-ID = 1-3%
Tracking
2<η<5
Δp/p = 0.4% - 0.6%
y
5m
Magnet
RICH2
ECAL
HCAL
SPD/PS
M1
M2
T1
T2
T3
Vertex
Locator
5m
15m
20m
z

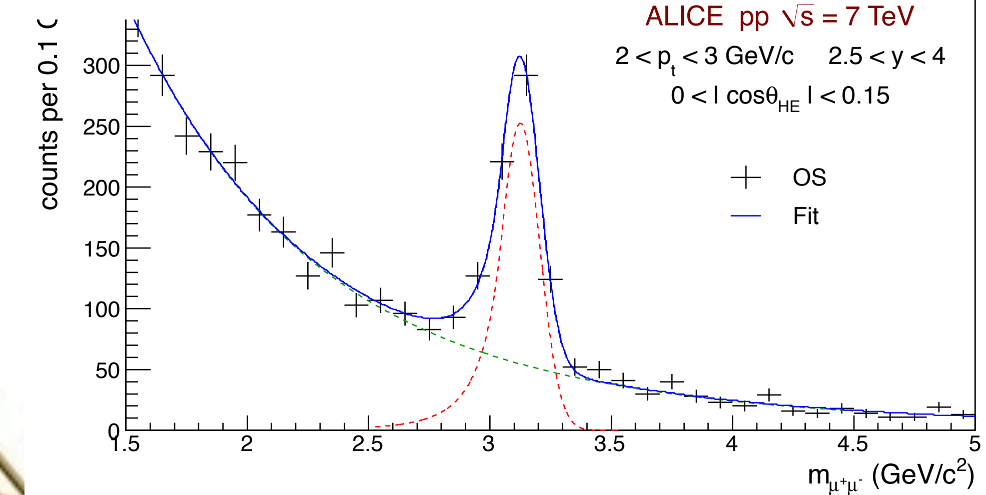
muons measured in forward spectrometer
$2.5 < y < 4$
dipole magnet 3 T.m

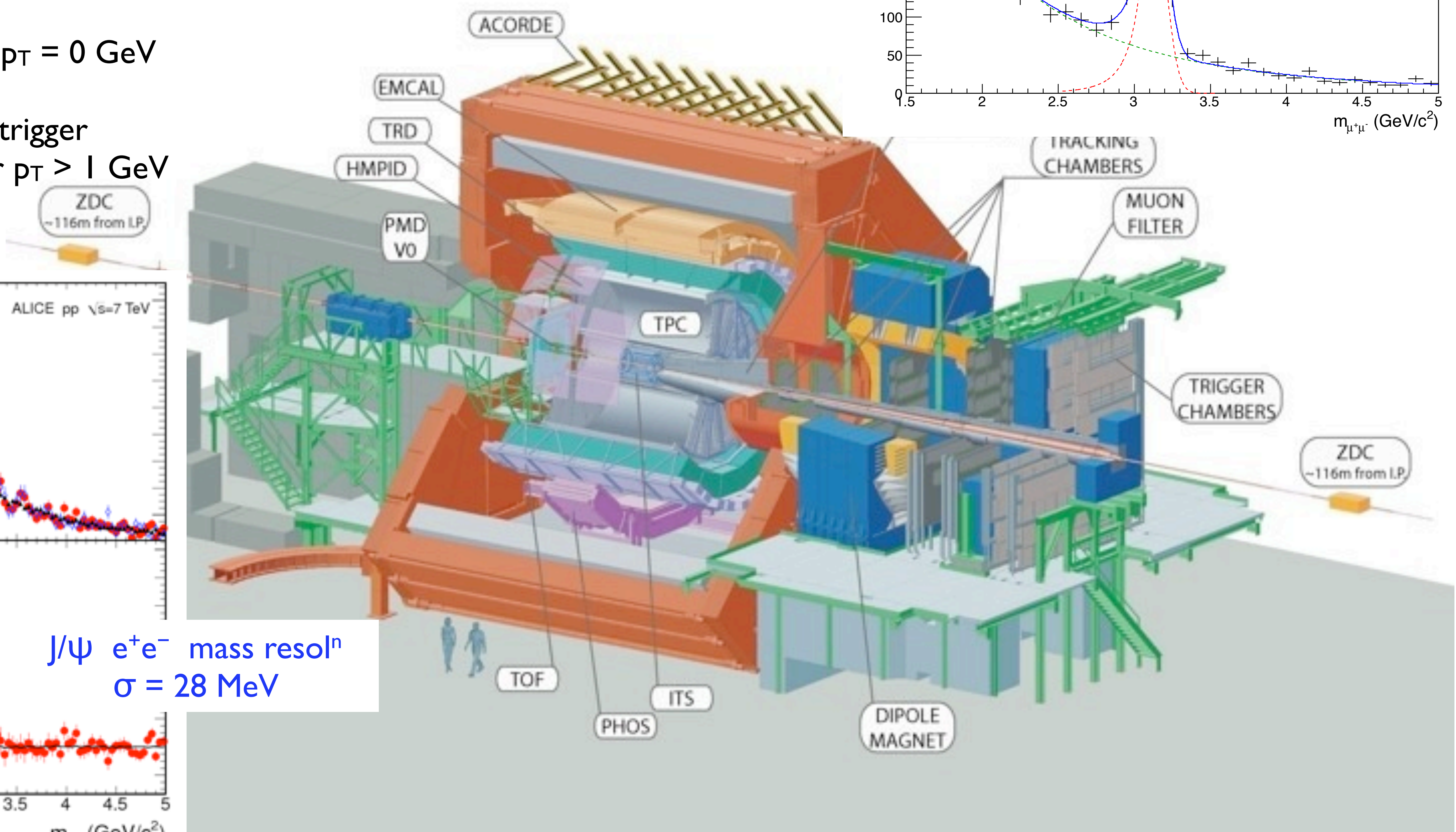
electrons: $|y|<0.9$

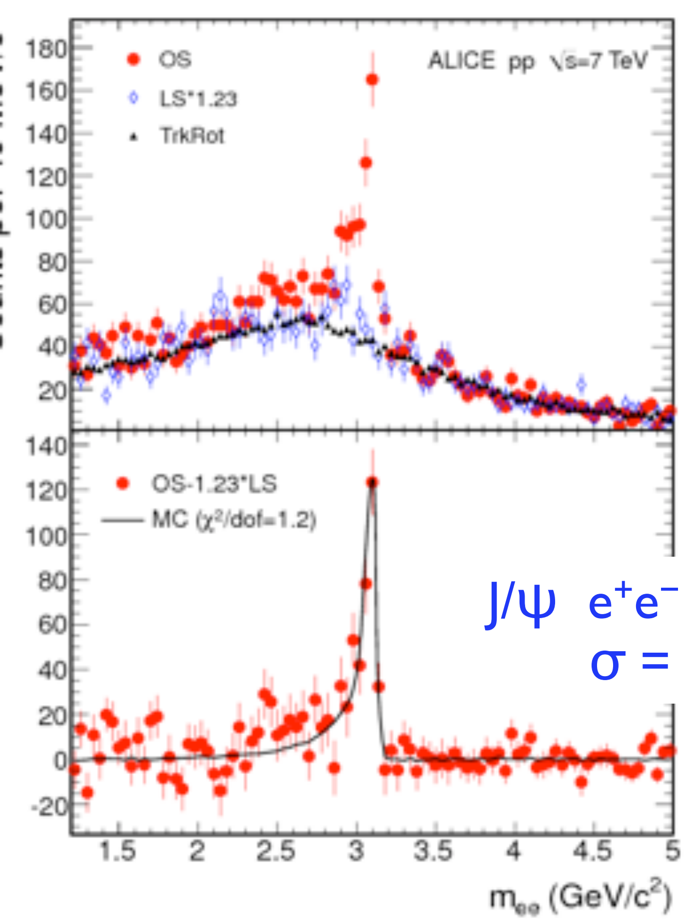
acceptance to p_T = 0 GeV

minimum bias trigger
dimuon trigger p_T > 1 GeV

J/ψ $\mu^+\mu^-$ mass resol^n
σ = 72 MeV



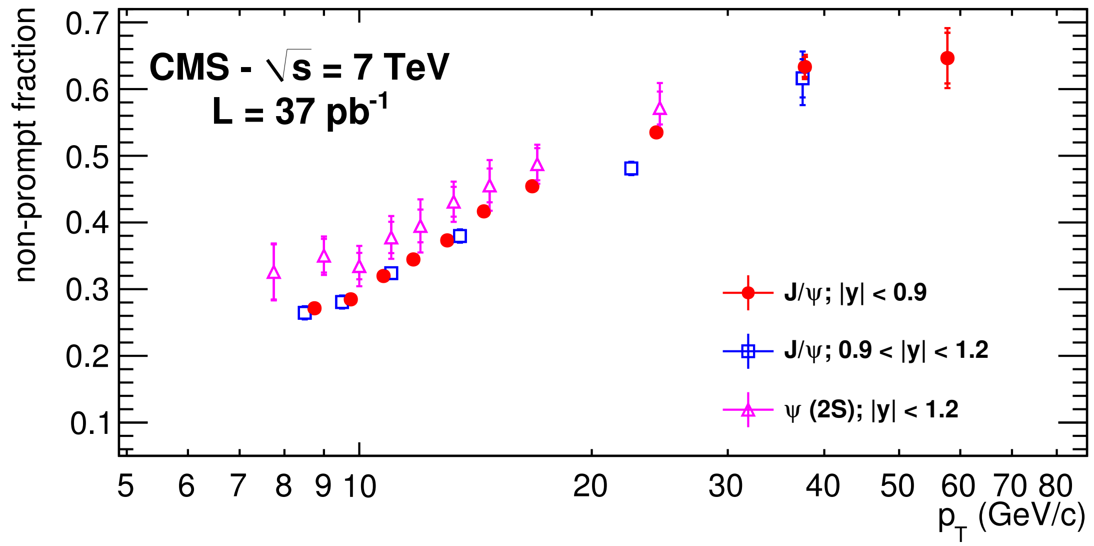


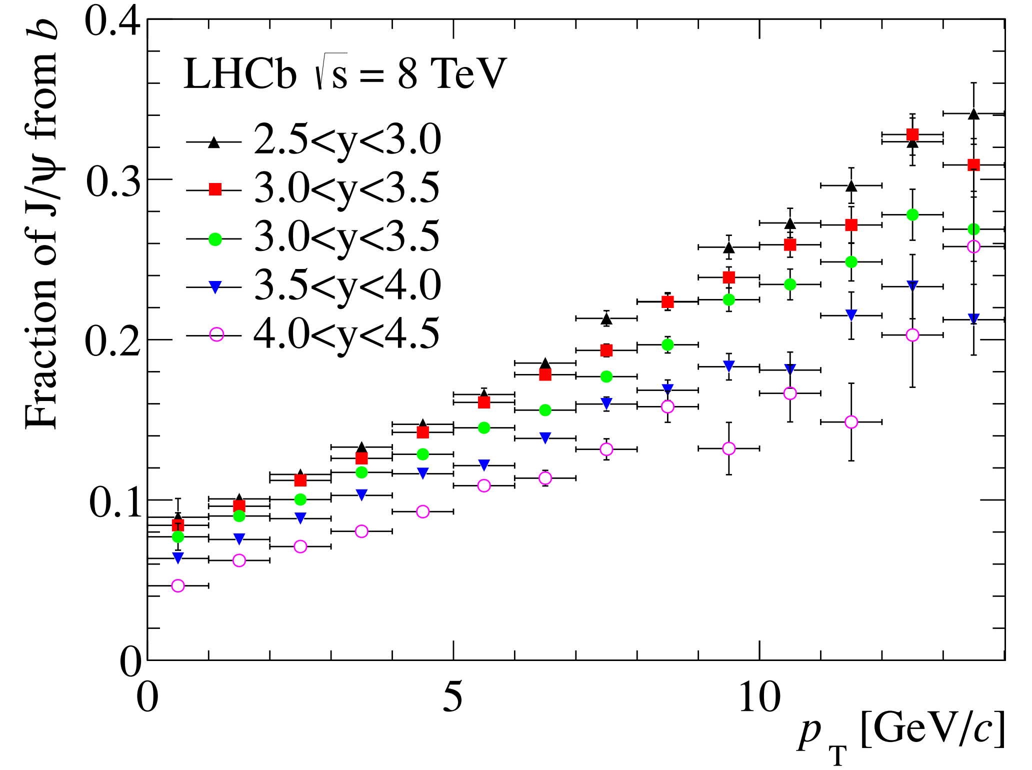


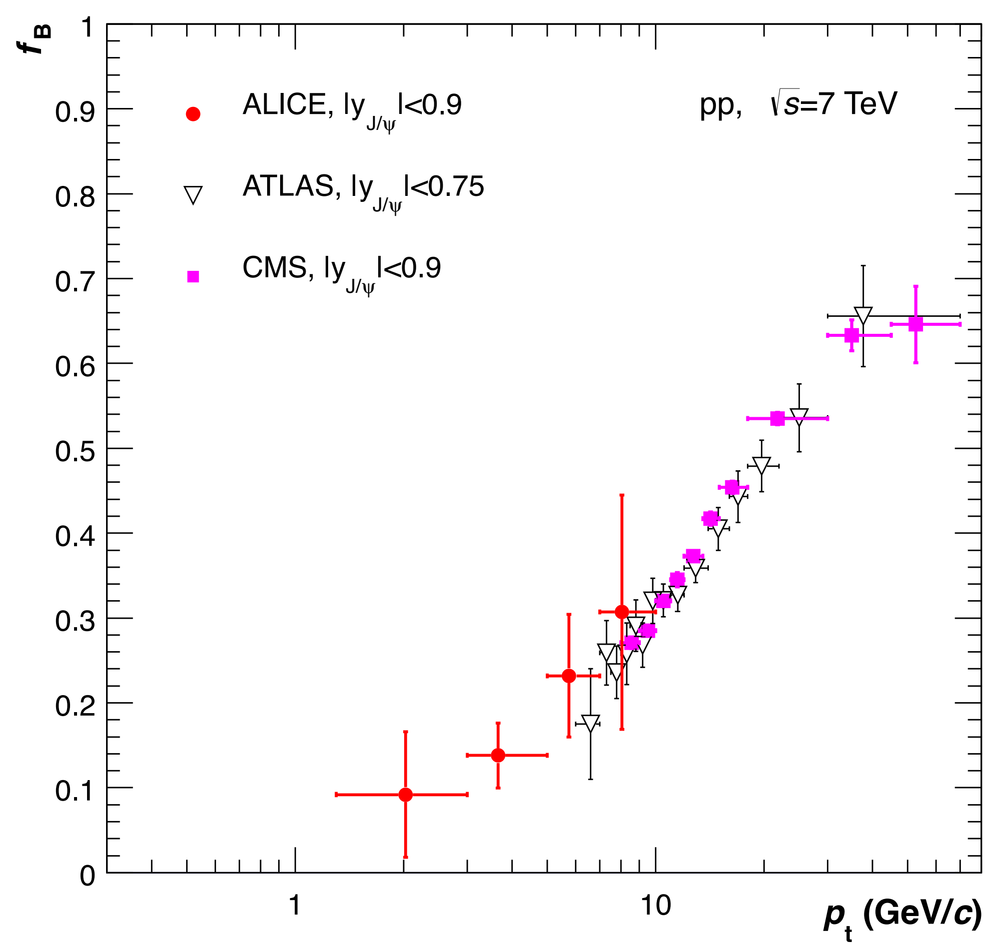
J/ψ e^+e^- mass resol^n
σ = 28 MeV

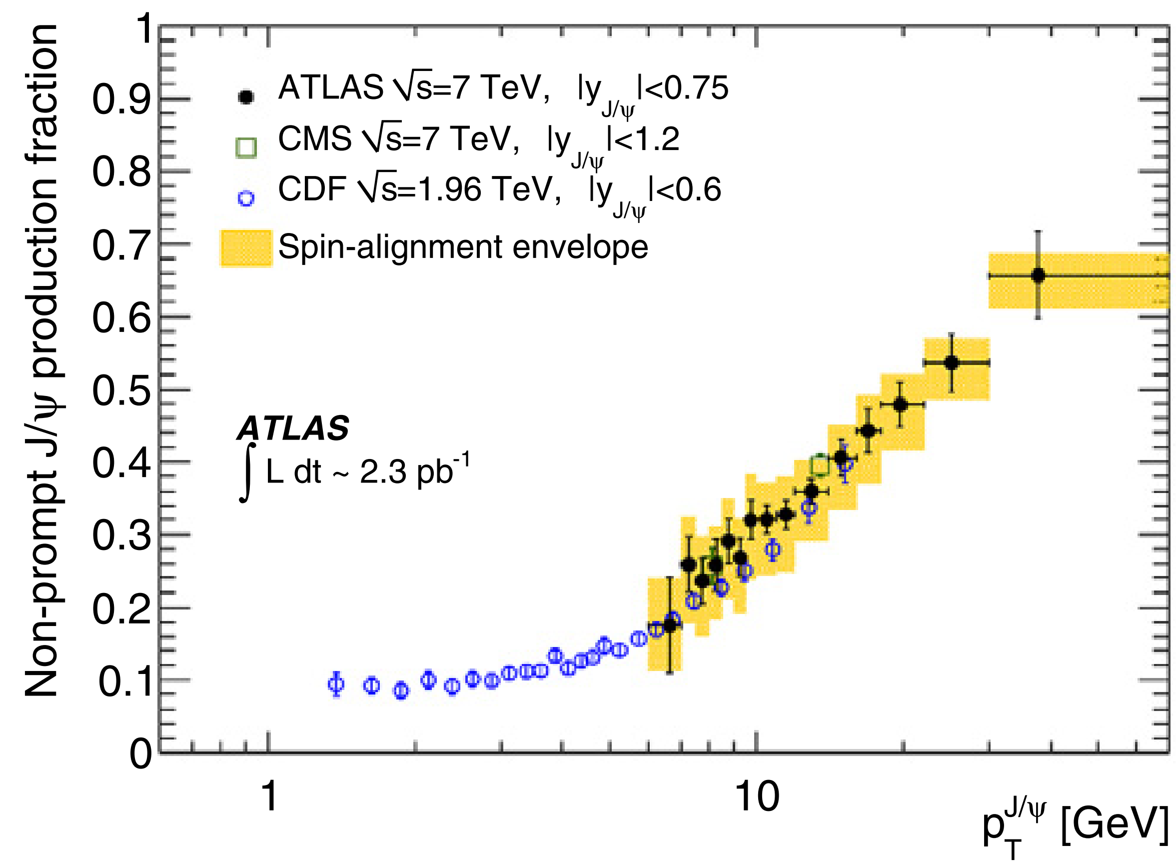
J/Ψ - Non-Prompt Fraction From b

Fraction from b: 10% at low p_T ~70% high p_T
slower increase at high y
little $\sqrt{s}$ dependence
same behaviour for ψ(2s)









Deconfined Matter: J/ψ Suppression

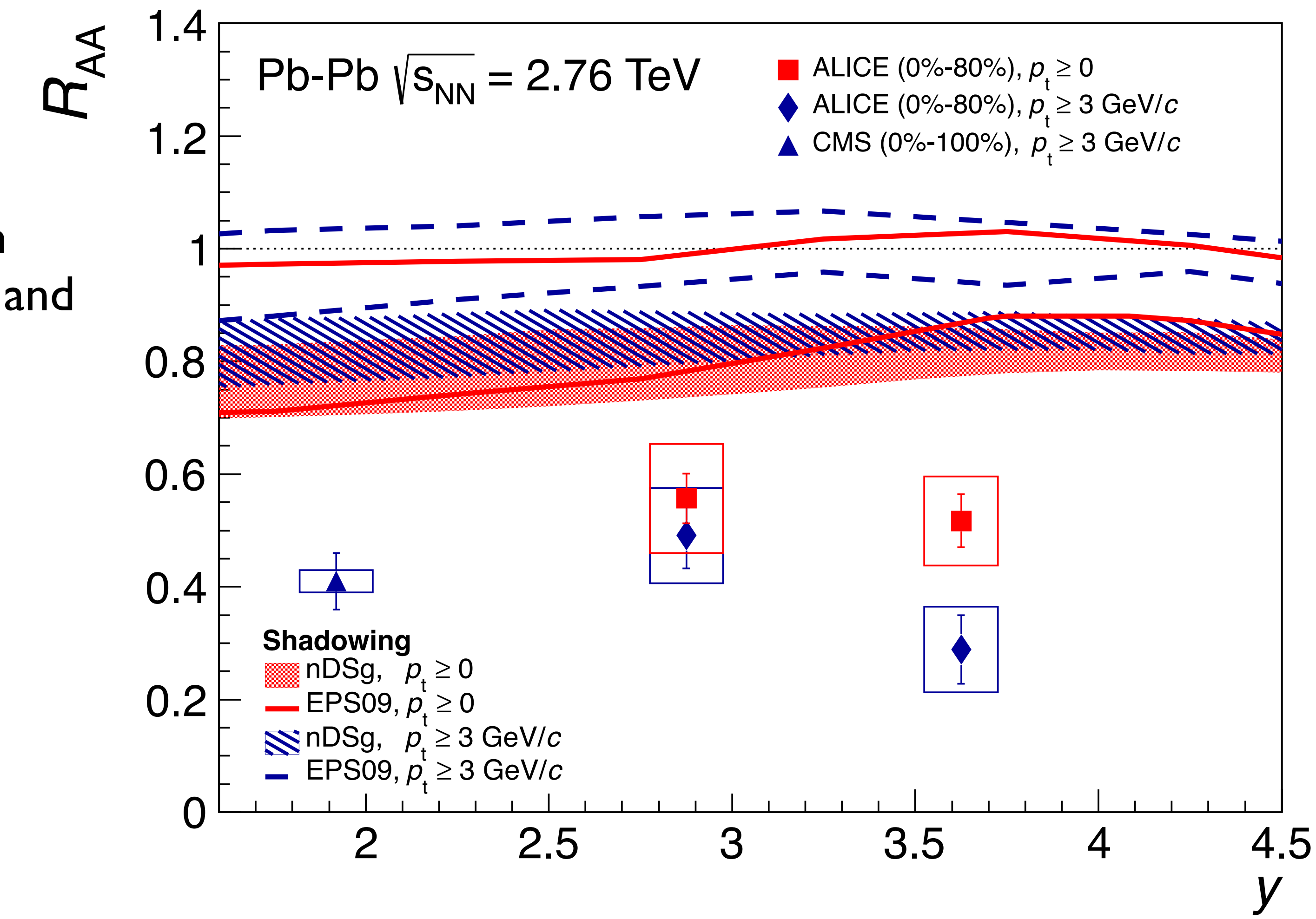
Atlas: PLB 697 (2011) 294–312
CMS: PRL 107 (2011) 052302
Alice: PRL 109 (2012) 072301

Heavy ion collisions provide QCD testbed for deconfined matter
Quark-gluon plasma expected to occur when energy density ~ 1 GeV/fm^3
plasma screens the quark and anti-quark

- → suppression of quarkonia production
- → mesons melt at temperature T relative to meson binding energy
- → ground state J/ψ and ϒ are less suppressed than weakly bound excitations
- → feed-down from excitations will also affect the ground state production rates

CMS: $$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{pp}}} = 0.31^{+0.19}_{-0.15}\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.}),$$

ALICE measure forward rapidity J/ψ suppression
R_{AA} = PbPb rate / pp rate scaled to same $\sqrt{s_{NN}}$ and

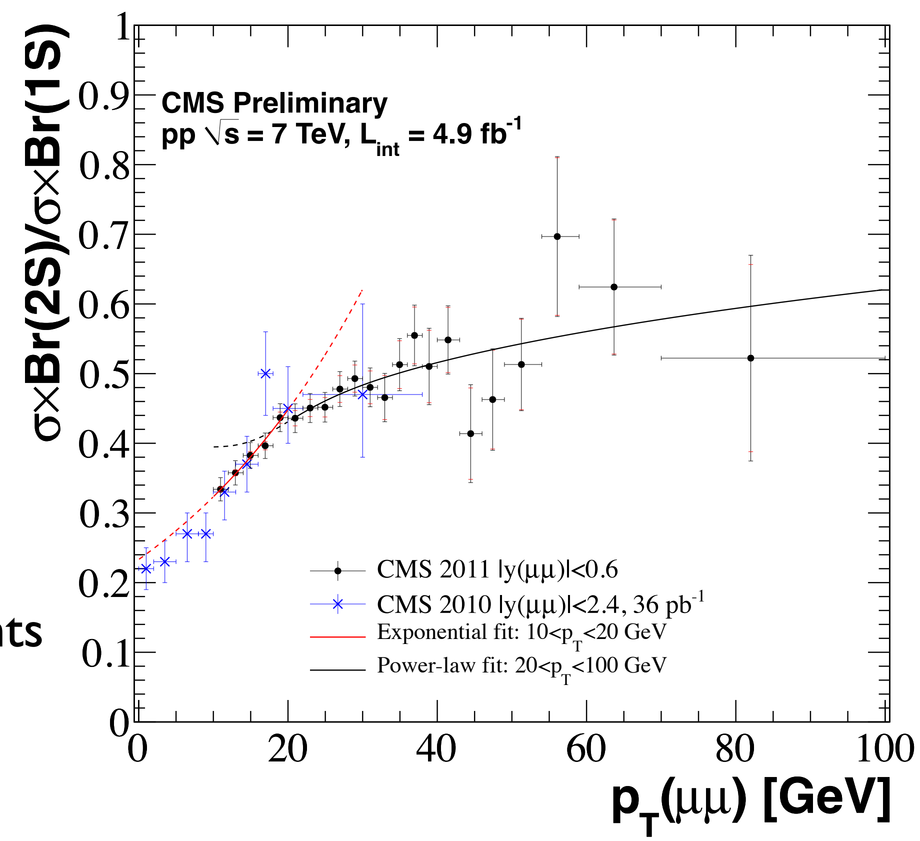


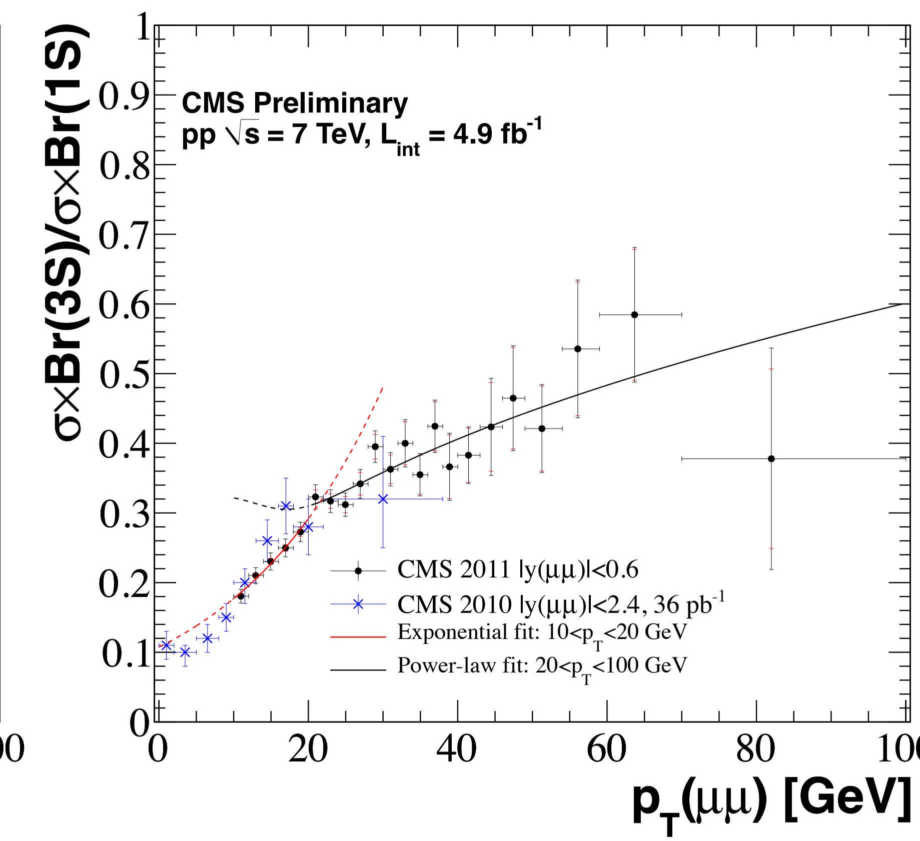
See talk of Ionut Arsene

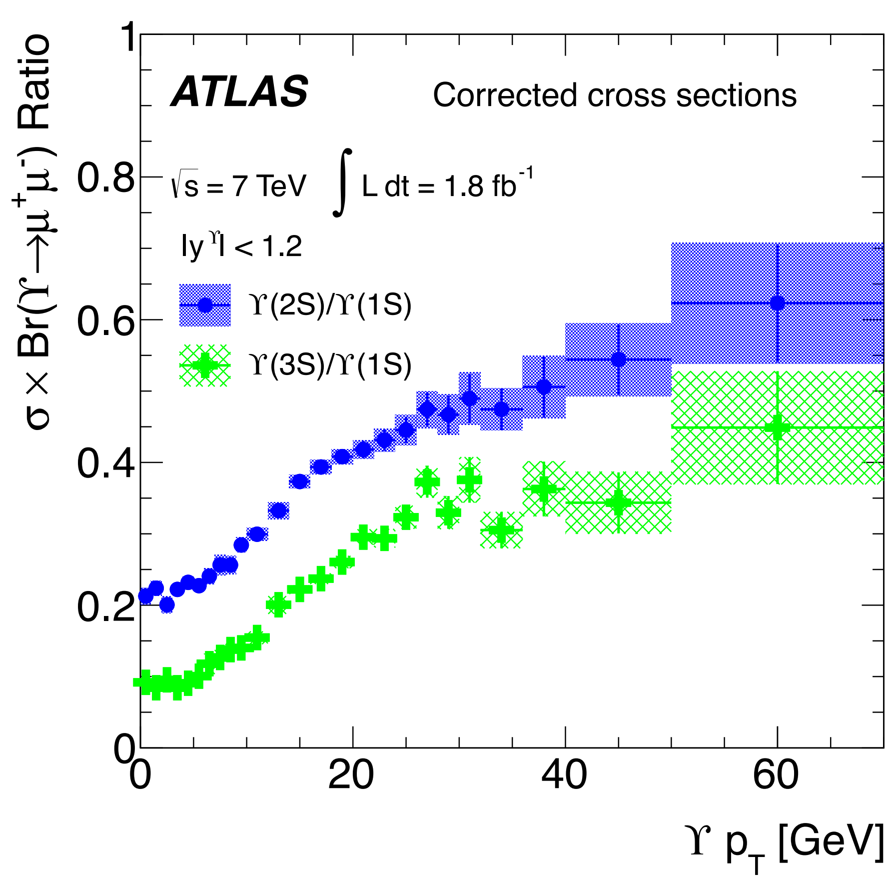
ϒ(nS) Production

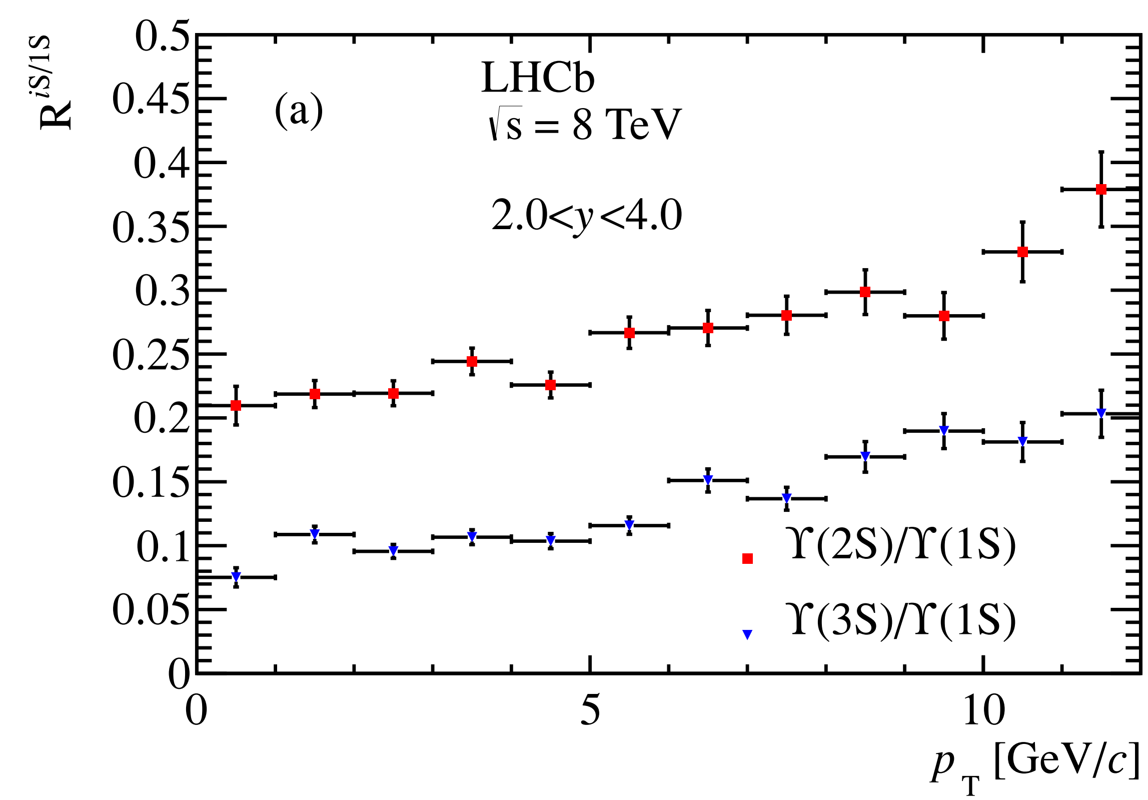
LHCb: JHEP 06 (2013) 064

- Measure ratio of ϒ production rates
- Cancellation of uncertainties in ratio
- Good agreement between experiments
- LHCb measures in different y range

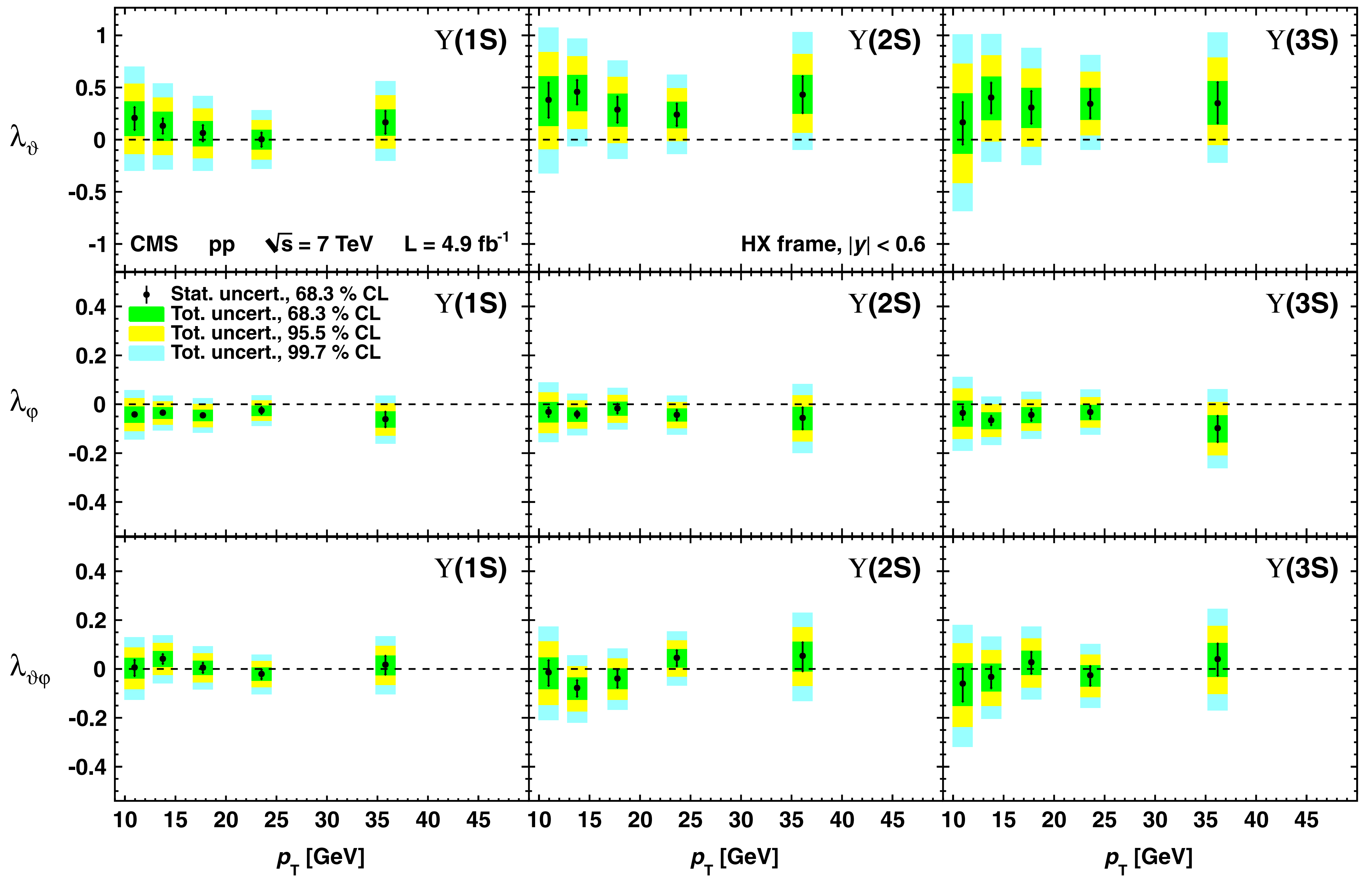








Υ(nS) Polarisation



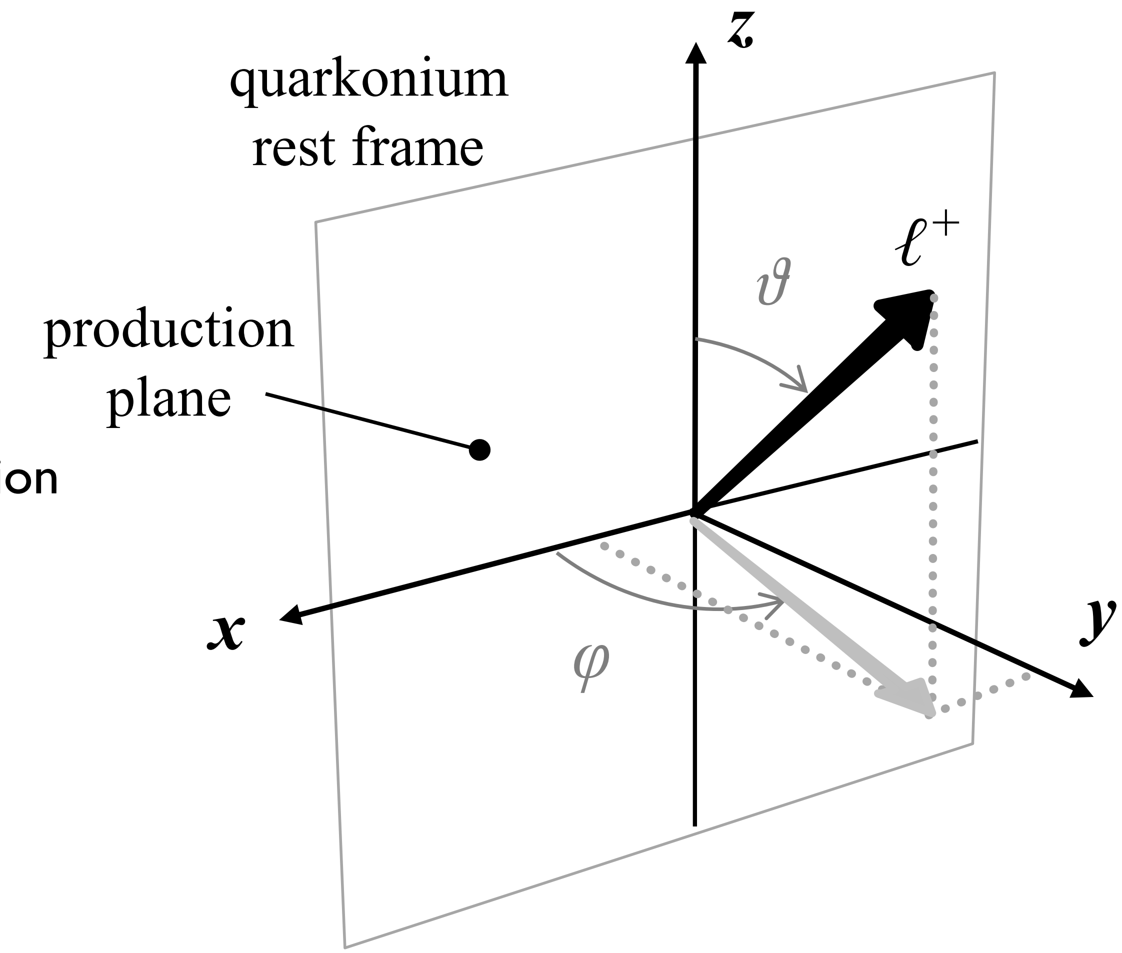
Υ(nS) Polarisation

Theoretical descriptions of quarkonia polarisation have traditionally been difficult

No model successfully describes production rates and polarisation

Try to understand mechanisms producing polarisation

Detector acceptance corrections can strongly depend on polarisation model chosen → uncertainties in production rate measurements

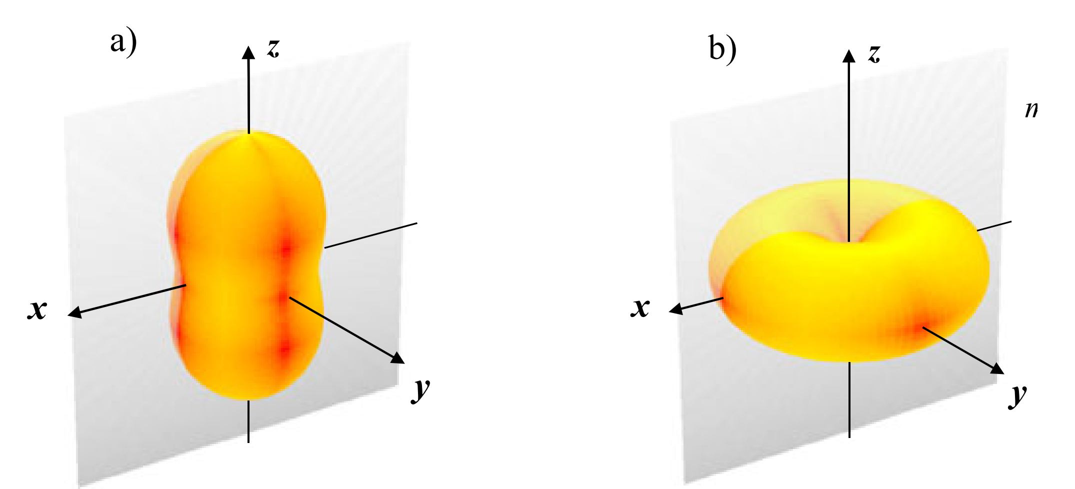


$$\frac{dN}{d(\cos\vartheta)d\varphi} \propto 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi + \lambda_\varphi \sin^2\vartheta\cos 2\varphi.$$

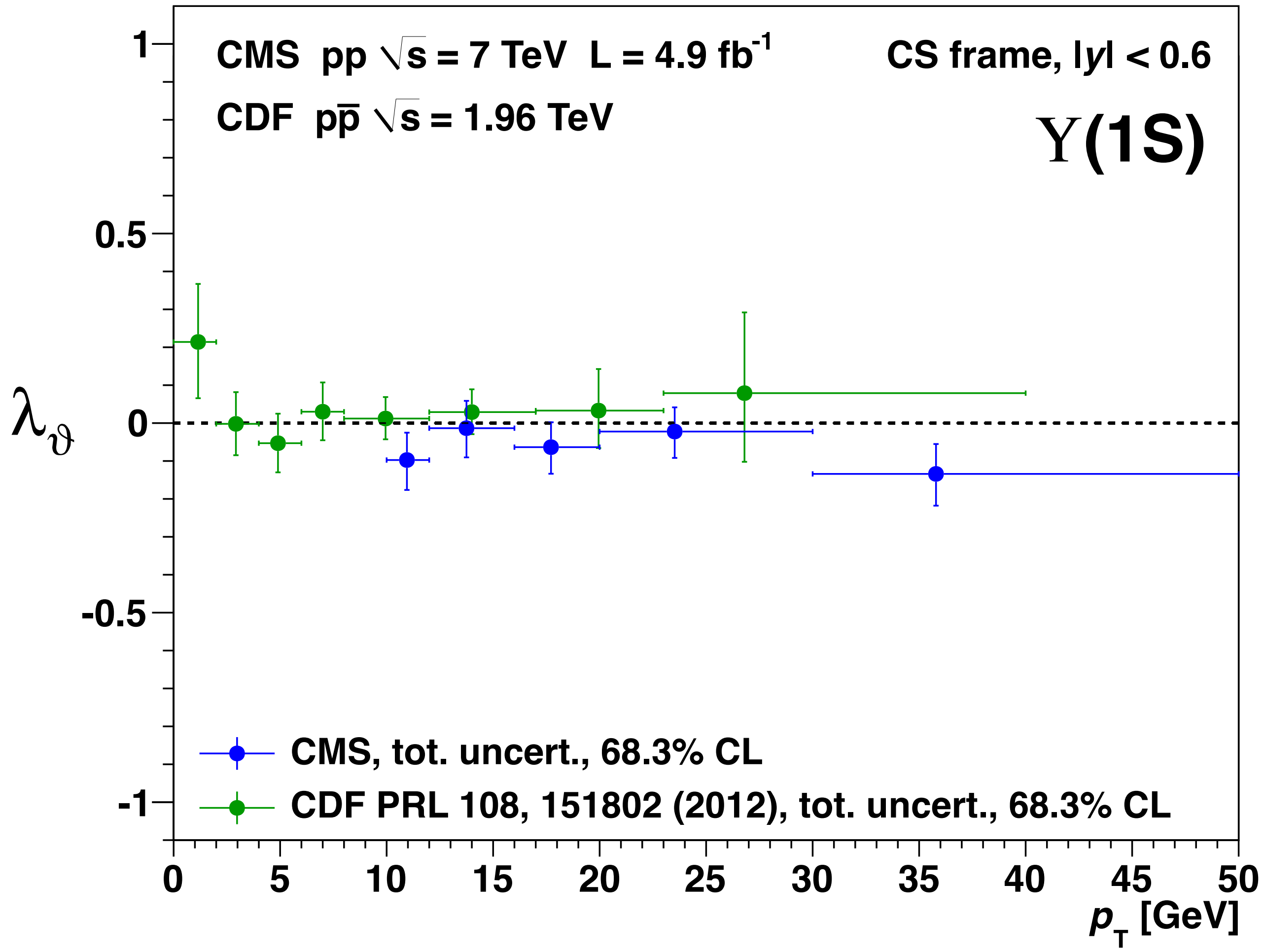
λ are the polarisation parameters in a given frame

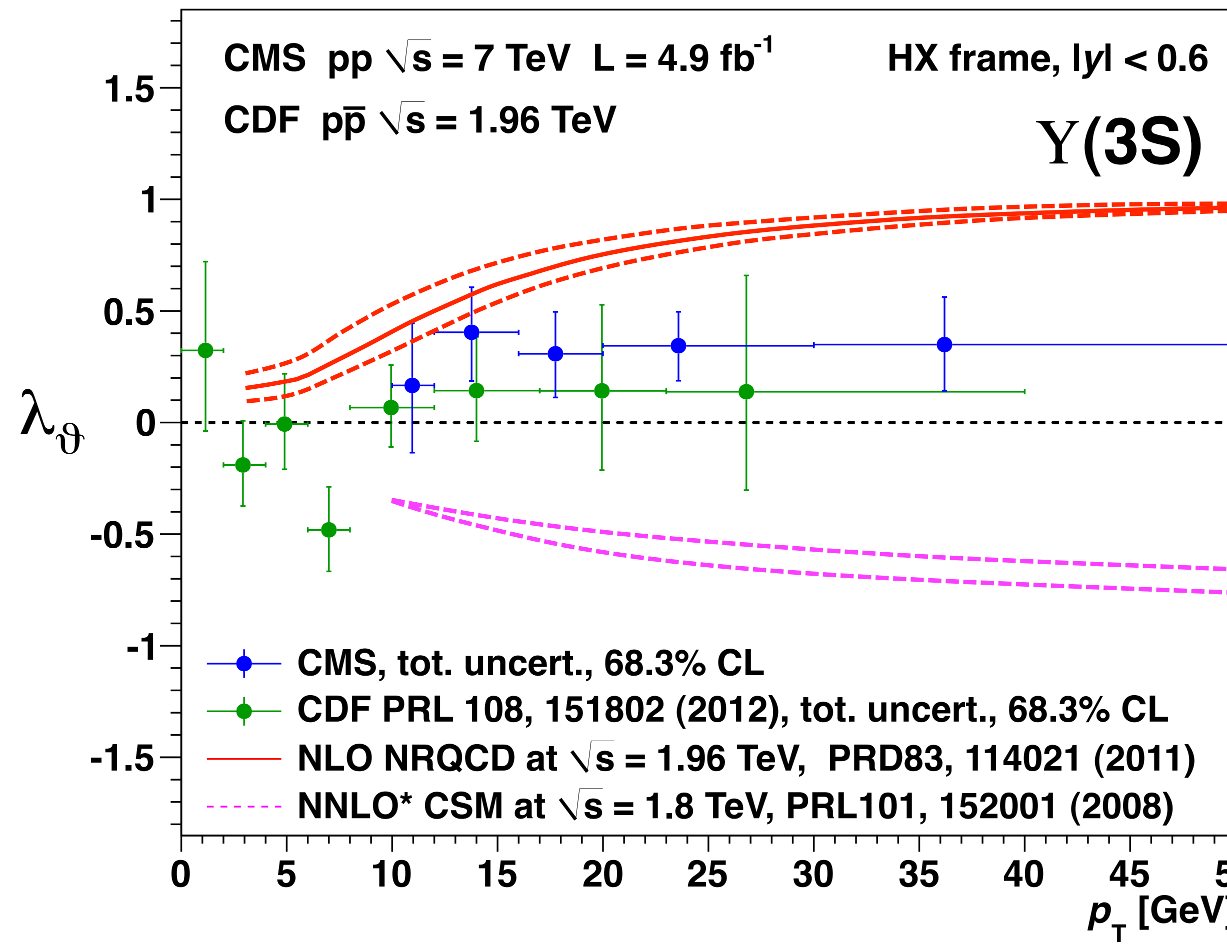
Several different polarisation frames can be defined:

- Centre-of-mass helicity frame HX: z axis in direction of meson
- Collins-Soper frame: CS z axis in direction of relative velocity of incoming partons
- Perpendicular helicity frame: PX z axis ⊥ to Collins-Soper frame z axis



transverse: $\lambda_\theta > 0$ longitudinal: $\lambda_\theta < 0$





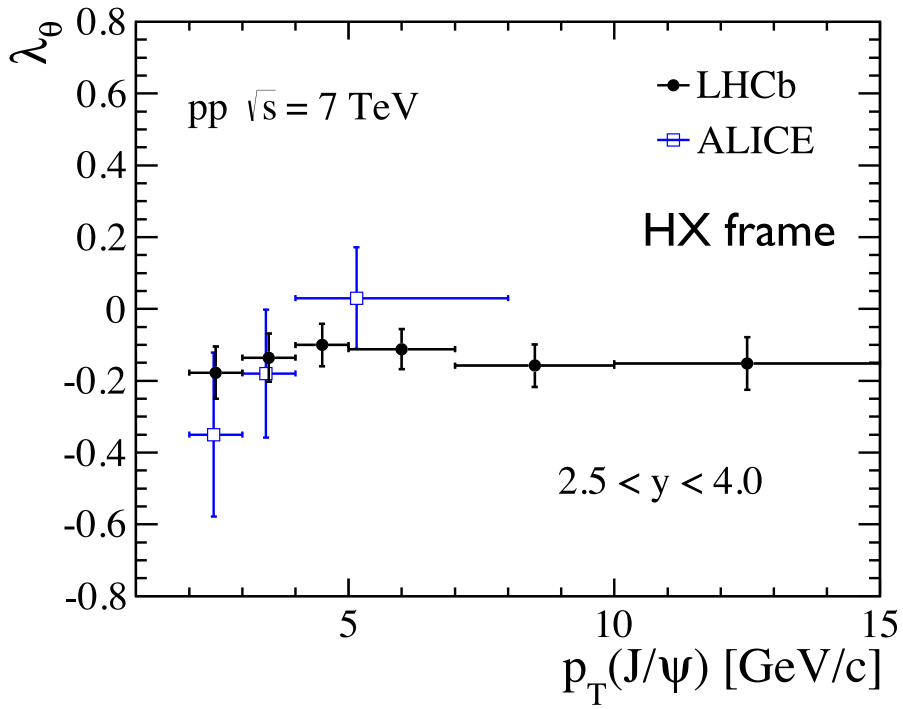
Good agreement between CMS and CDF

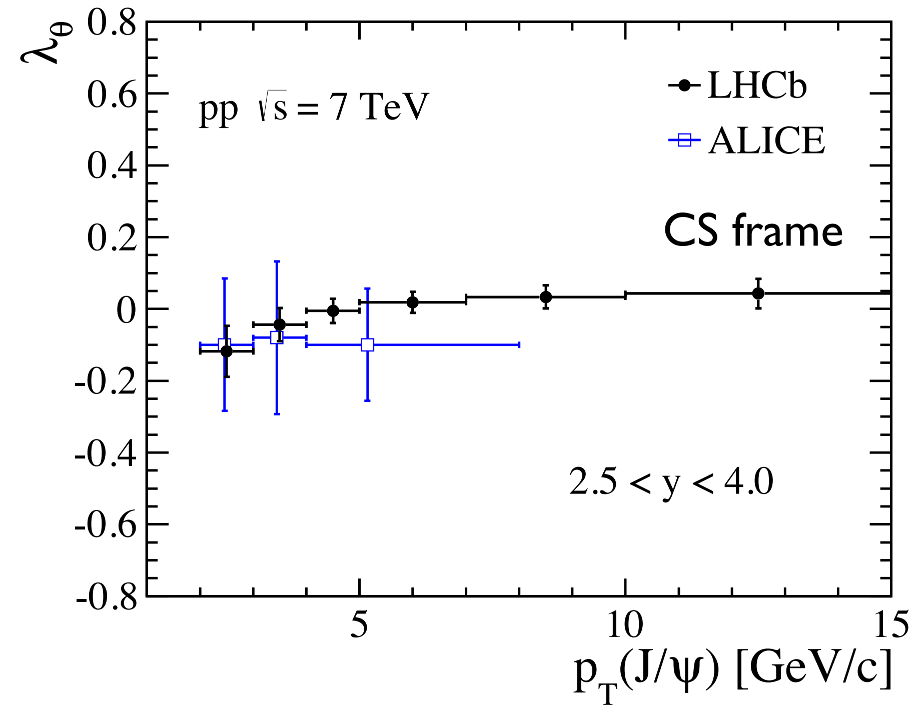
Models do not accurately describe the measurements

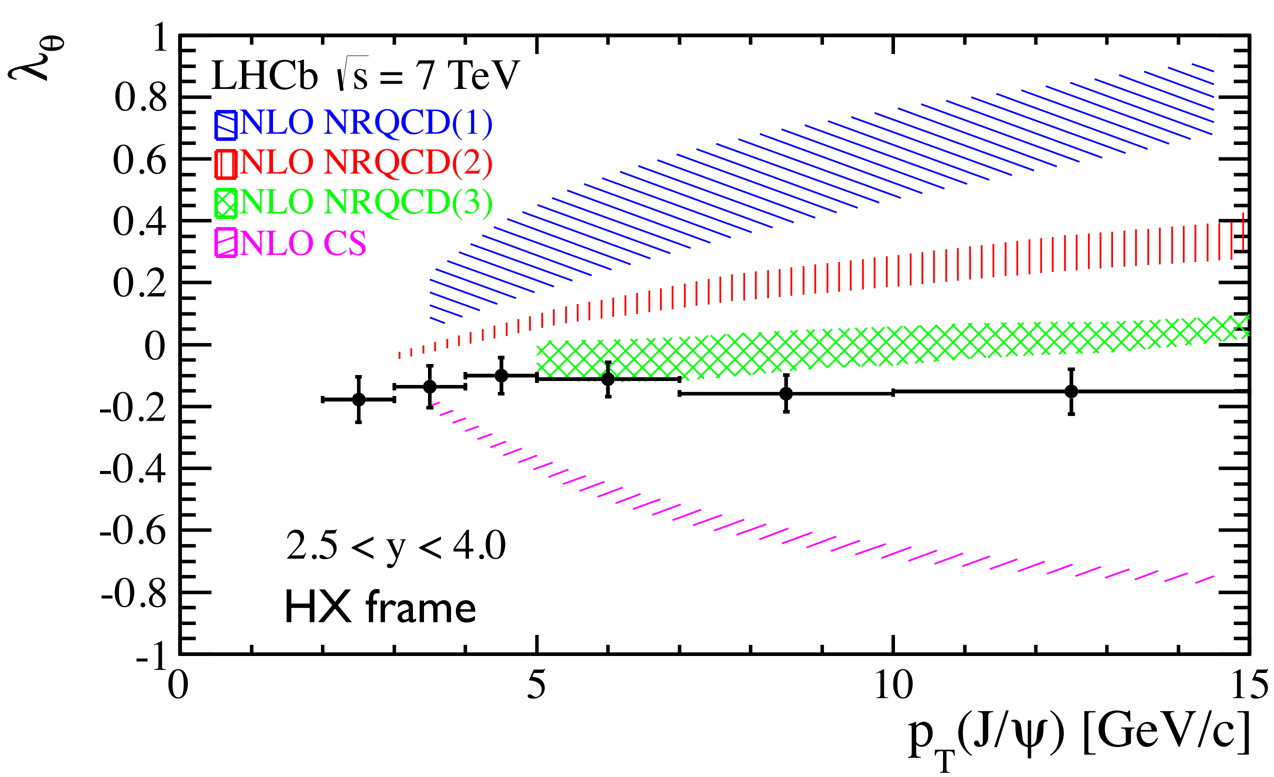
ϒ(3S) is affected by feed-down from $\chi_b(3P)$ ...

J/ψ Polarisation

LHCb arXiv:1307.6379
Alice: PLB 108 (2012) 082001





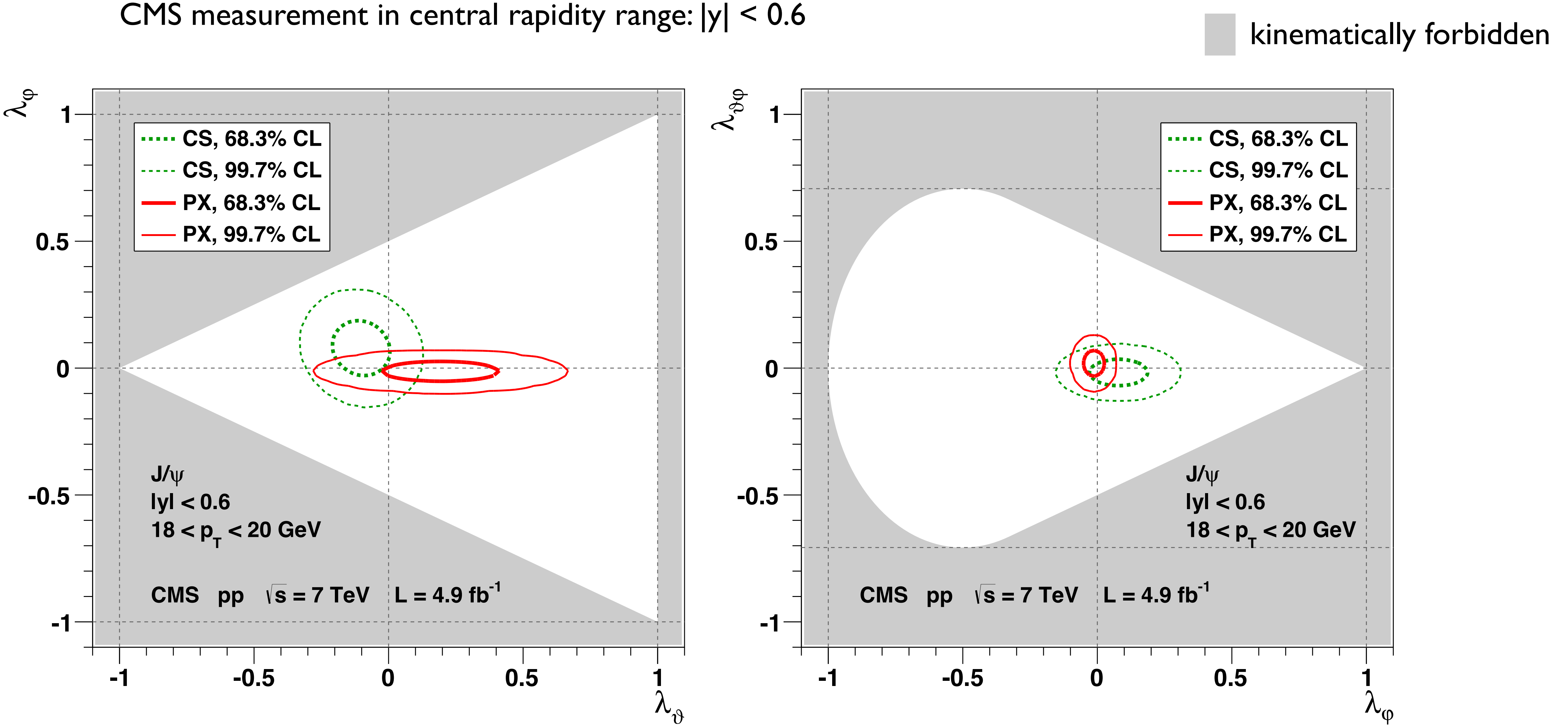


- Prompt J/ψ polarisation measured in HX & CS frames
- Reasonable agreement between experiments
- Small polarisation observed for λ_θ
- Polarisation consistent with zero for $\lambda_{\theta\varphi}$ and λ_φ
- CS cannot describe p_T dependence
- NRQCD (CO) predicts zero polarisation - closest to data

J/ψ Polarisation

CMS arXiv:1307.6070

CMS measurement in central rapidity range: |y| < 0.6



- No significant polarisations observed in either CS or PX frames
- Data disagree with NRQCD predictions (not shown)
- Similar measurements performed for ψ(2s)