Quarkonium production at LHC and Tevatron

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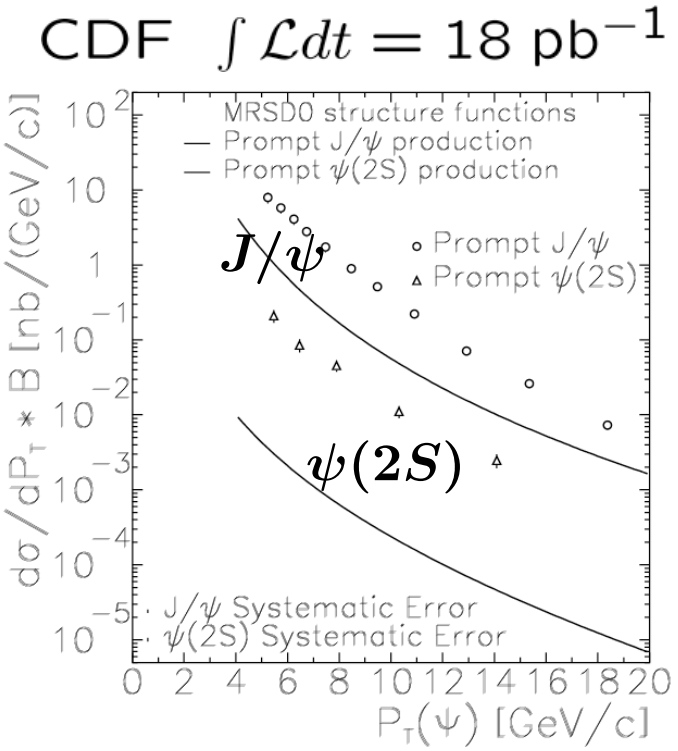
(on behalf of the LHCb Collaboration)

Outline

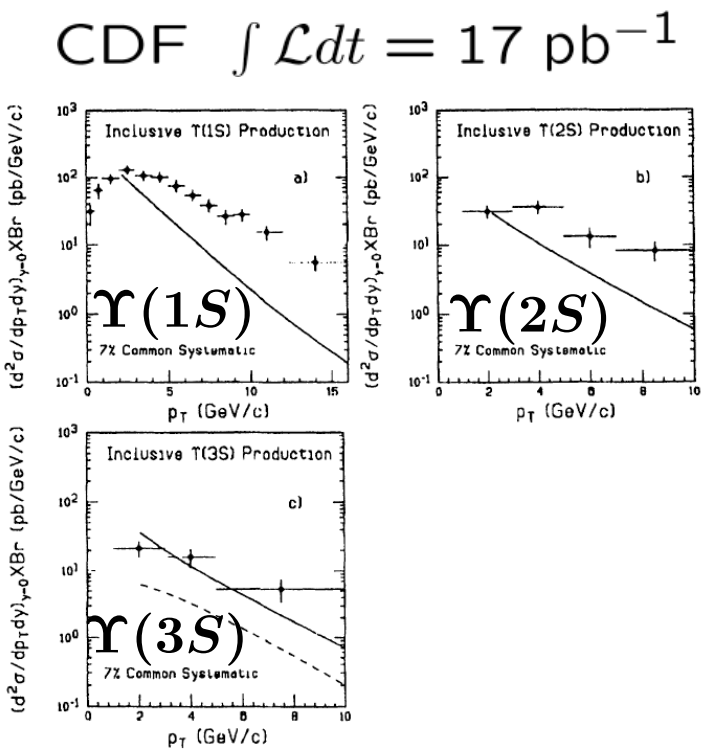
- Introduction
- Production of $J/\psi, \psi(2S), \Upsilon(nS)$
- Polarization measurements
- Production of χ_c and χ_b
- Double charm production
- Summary

Introduction

- Understanding the mechanism of quarkonium production in hadron colliders has been (surprisingly) challenging since the first evidence seen by CDF.



PRL 79 (1997) 572

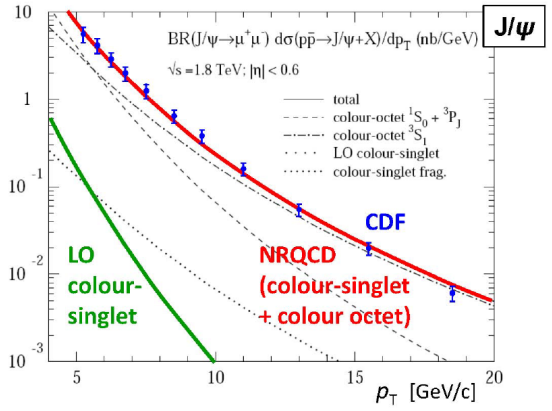


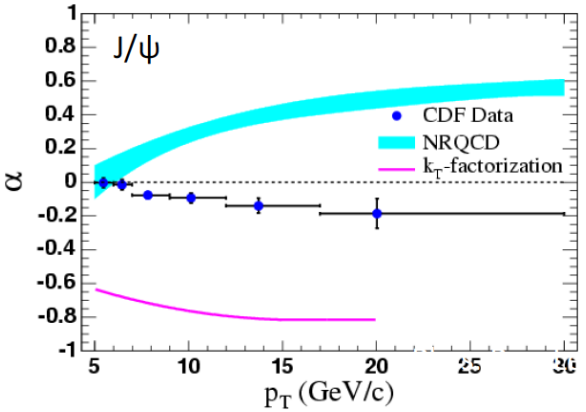
PRL 75(1995) 4358

Introduction

- Color Octet (CO) has been introduced, in addition to Color Singlet (CS), to cope with the large discrepancies:

  - Leading Order: CO dominant ➡ quarkonium transversely polarized





- Nowadays the role of CO vs. CS is still on debate…

  - CS + CO: LO + NLO can reproduce data
  - CS only: LO + NLO + NNLO* not very far from data

NNLO – NNLO* (part. of NNLO) = ?

Introduction (cont'd)

- More observables are proposed: double charm(onium), *p-Pb* collisions at LHC energies…

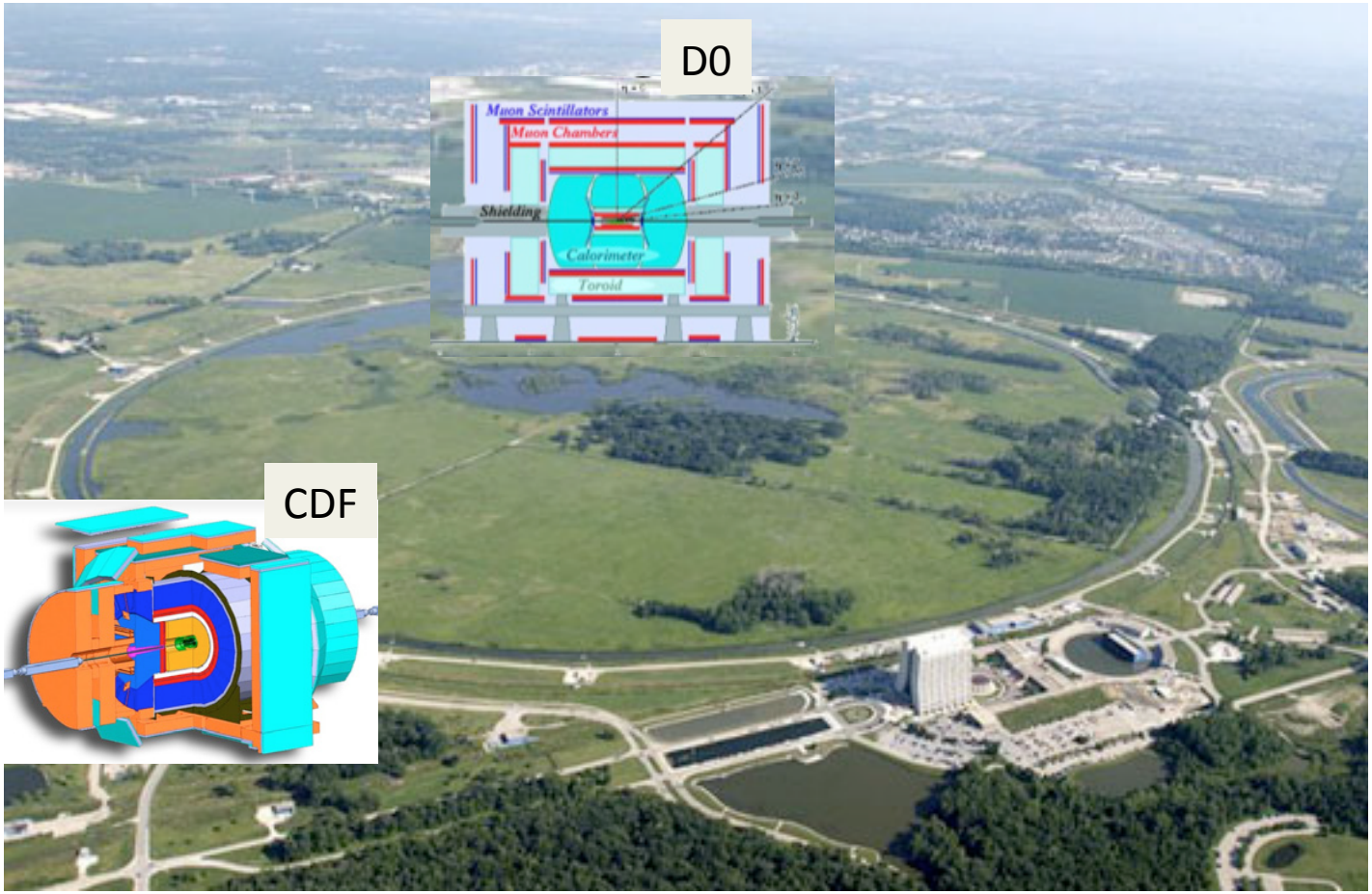
- Meanwhile the production cross-sections (+ polarizations?) of

$$\chi_c, \chi_b, \cdots$$

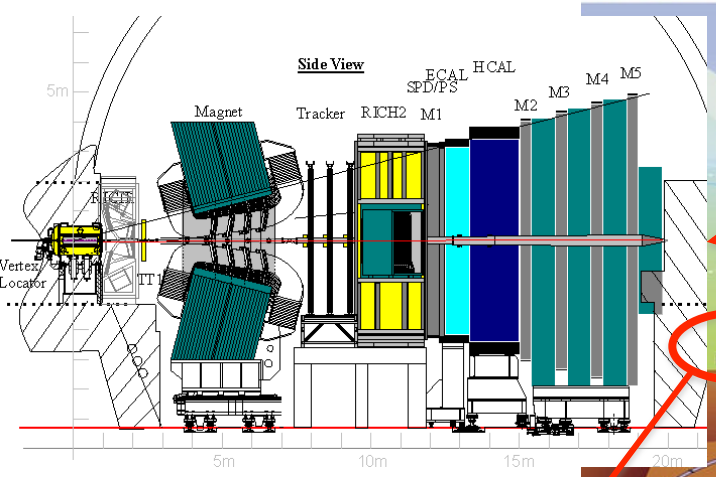
are (going to be?) available, especially at LHC. It may shed new light…

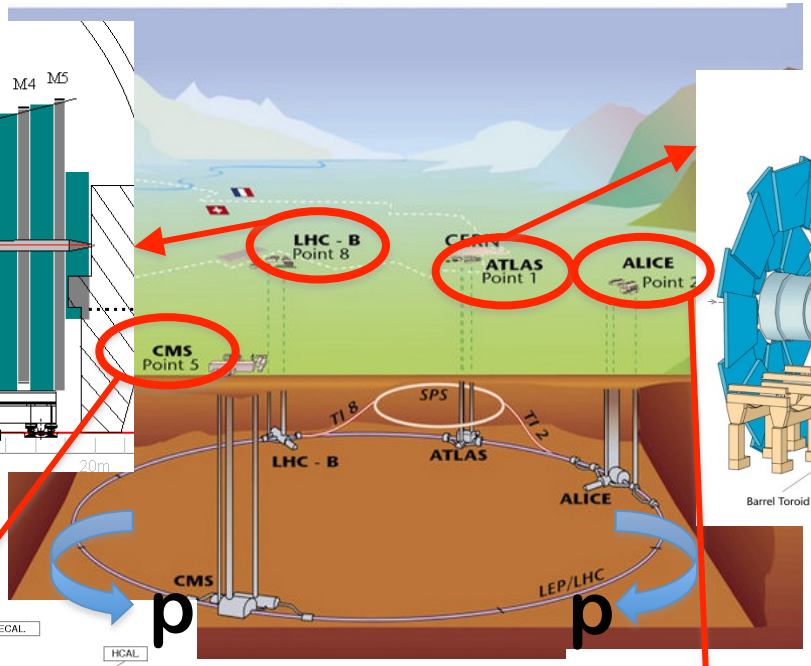
- The interplay between theory and experiment continues.

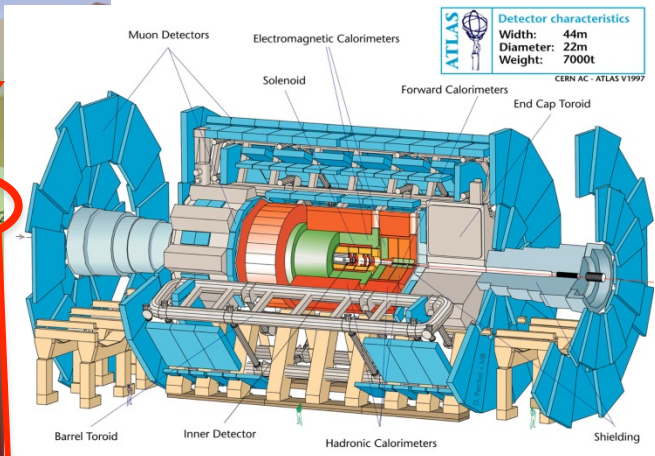
Experiments at Tevatron

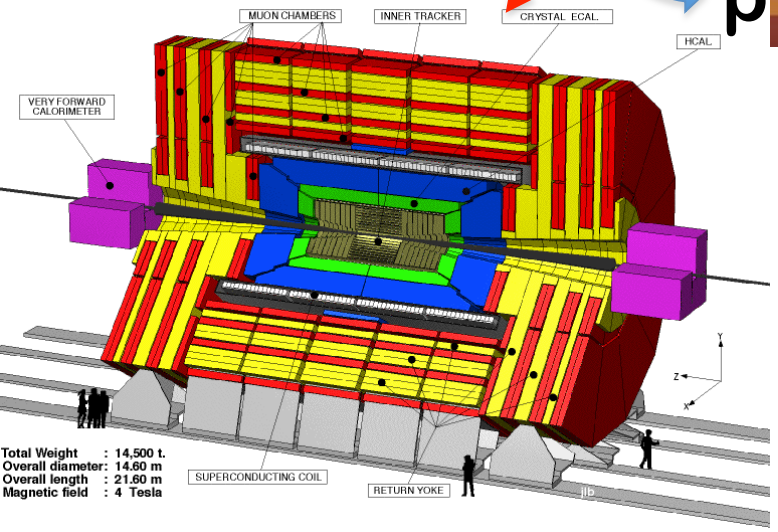


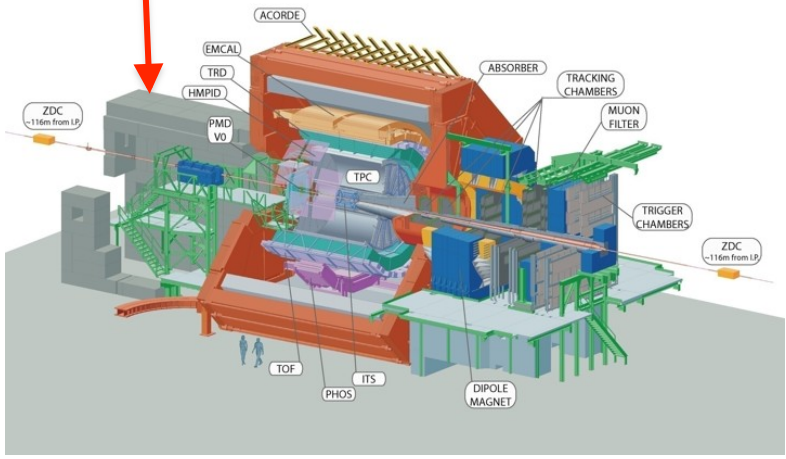
Experiments at LHC









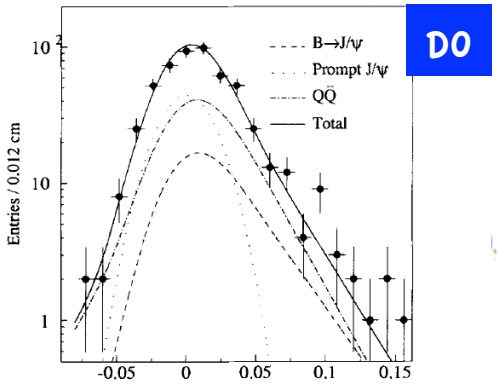


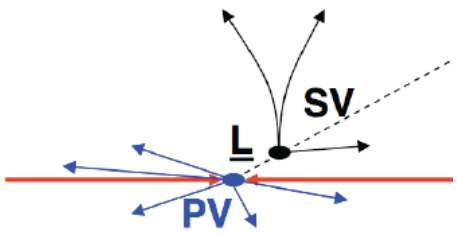
J/ψ production: a short summary

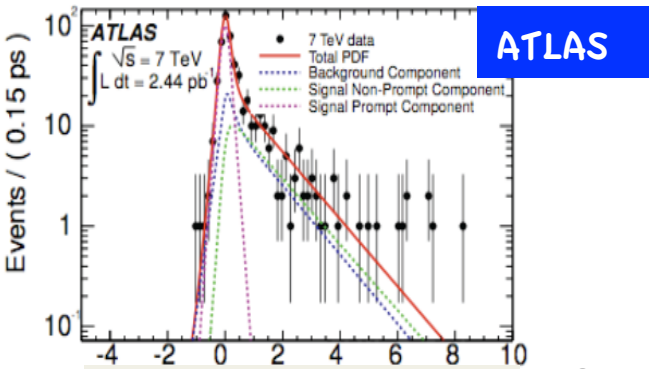
- One of the very first physics results from hadron colliders
- Sources of J/ψ
  - directly produced
  - feed down from χ_c, $\psi(2S)$
  - from *b*-hadron decays

  } Prompt
- Separation of feed down component is challenging experimentally

  ~30% from χ_c at Tevatron, confirmed at LHC
- *b*-component could be separated from the prompt component by a using the lifetime information of b-hadrons



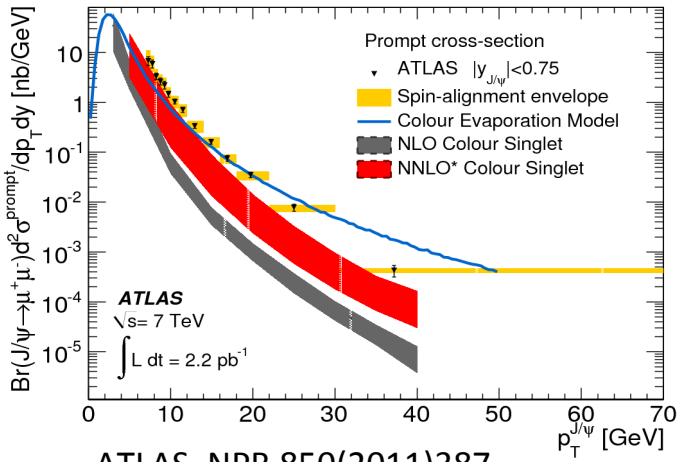




J/ψ production

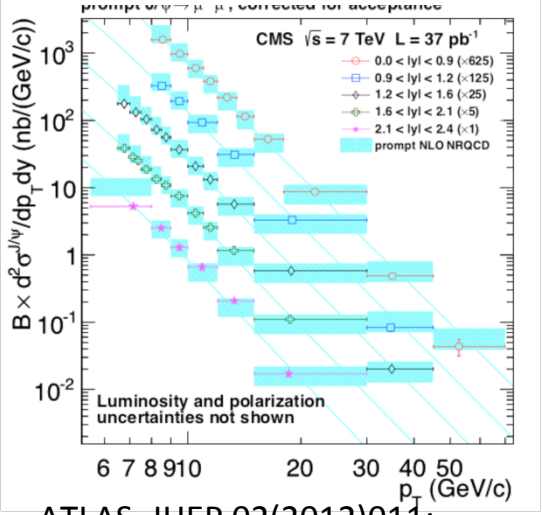
- Theory predictions are in good agreement with data

ATLAS data vs. CS



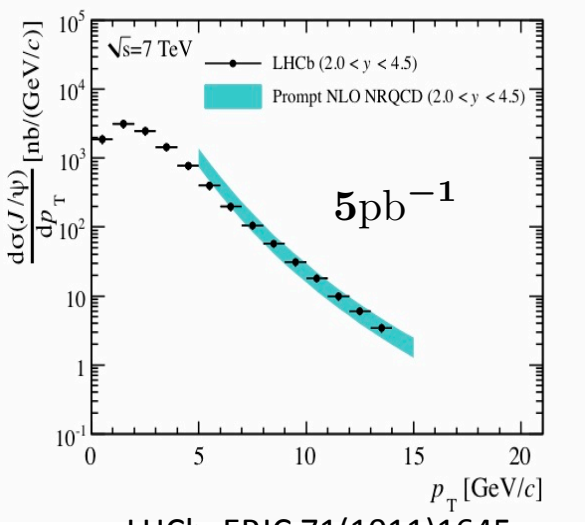
ATLAS, NPB 850(2011)387

CMS data vs. CS+CO



ATLAS, JHEP 02(2012)011;
EPJC 71(2011)1575.

LHCb data vs. CS+CO



LHCb, EPJC 71(1011)1645.

- Huge statistics, dominant uncertainty from unknown polarization. LHC Results will be updated once the polarization measurement is ready.

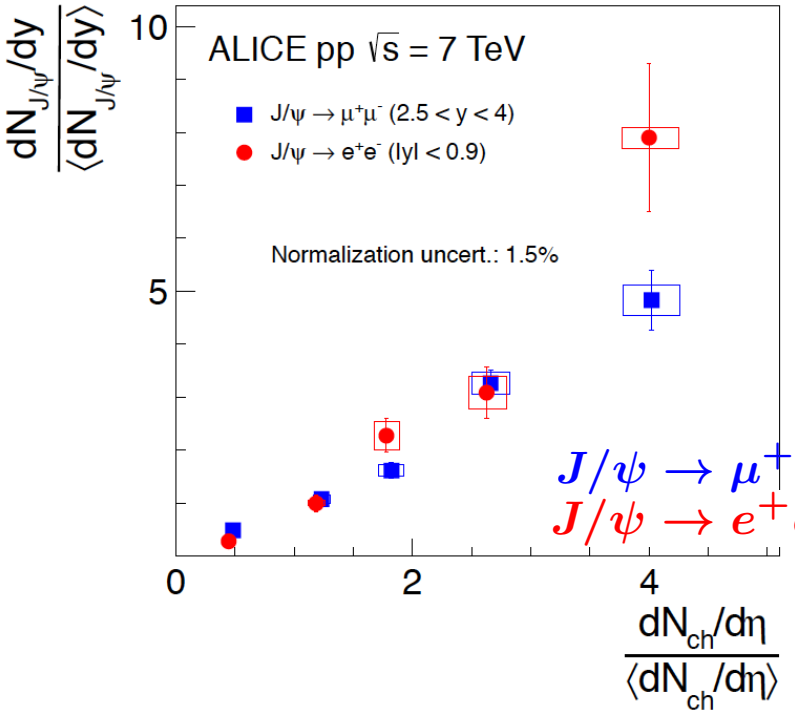
CDF, PRL 79 (1997) 572
D0, PLB 370 (1996) 239

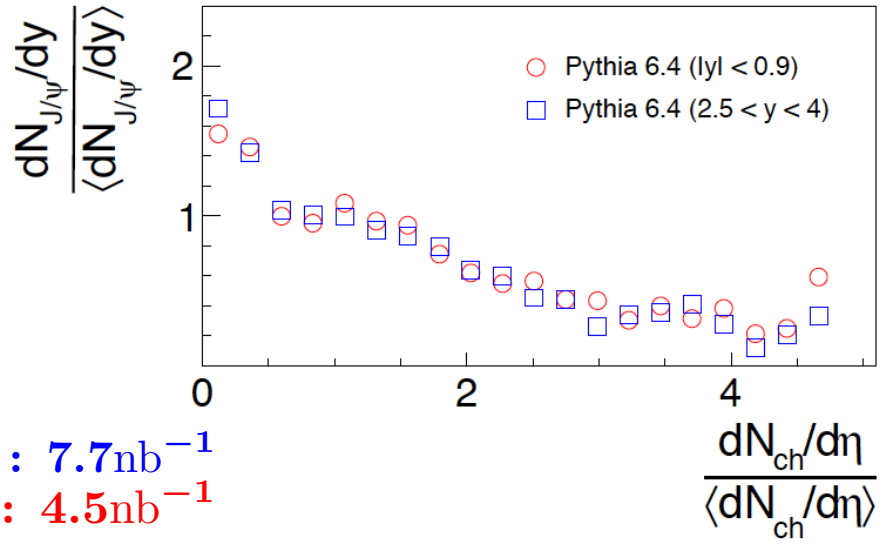
ALICE, PLB 704 (2011) 442; arXiv:1203.3641
ATLAS, NPB 850 (2011) 387
CMS, JHEP 02 (2012) 011; EPJC 71 (2011)1575
LHCb, EPJC 71 (2011) 1645.

J/ψ production

- New ALICE measurement

ALICE, arXiv:1202.2816





$J/\psi \to \mu^+\mu^- : 7.7\mathrm{nb}^{-1}$

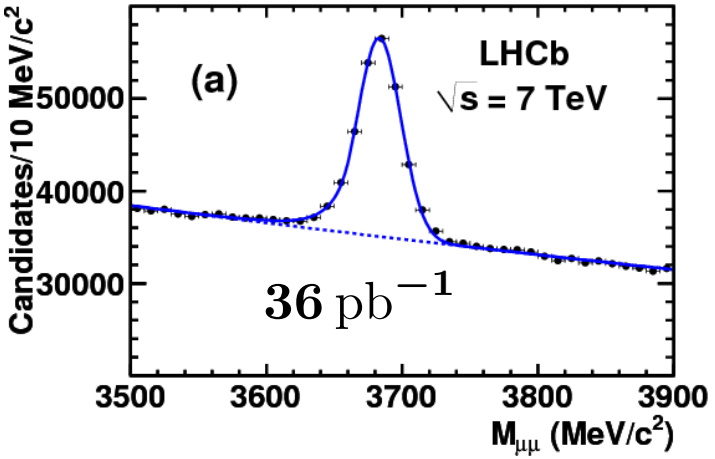
$J/\psi \to e^+e^- : 4.5\mathrm{nb}^{-1}$

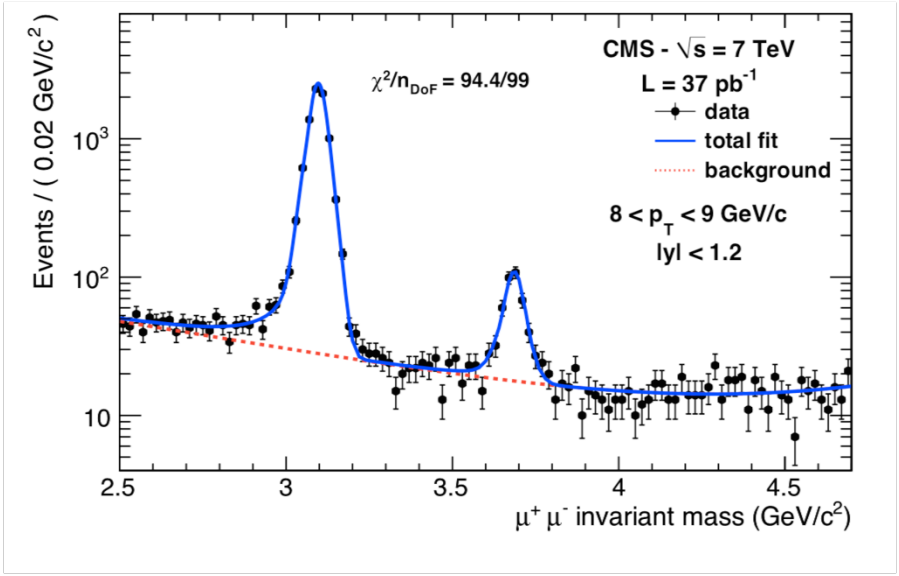
The impact of the measurement is still under discussion

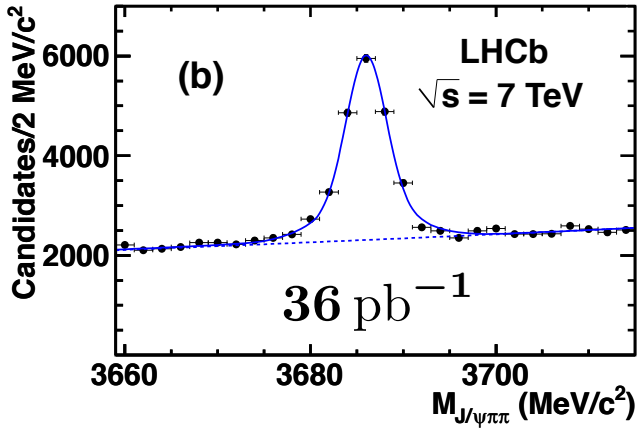
$\psi(2S)$ production

- The prompt component of $\psi(2S)$ doesn't suffer from feed-down from higher mass states: prompt = direct
- May be exploited in two modes

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



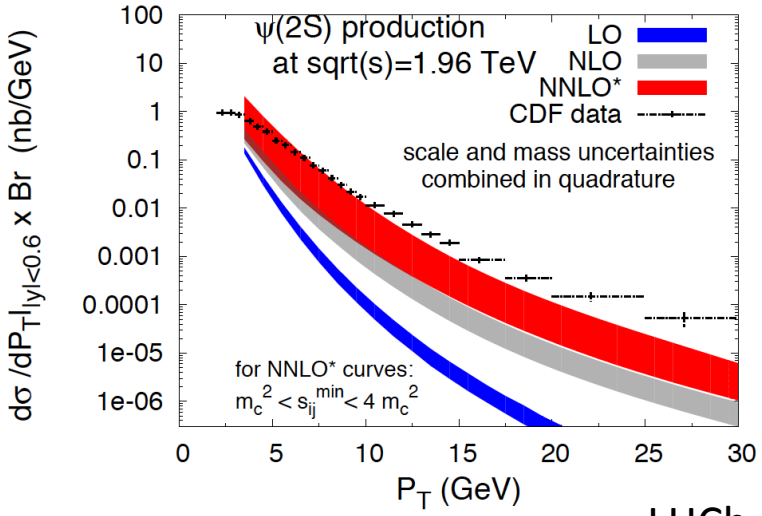




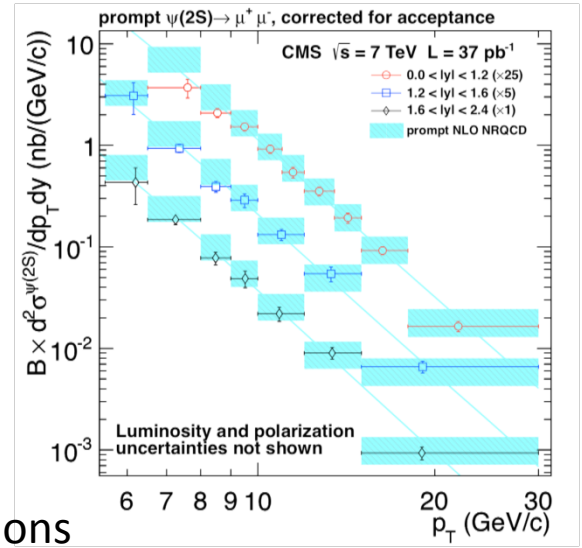
$\psi(2S)$ production

- Reasonable agreement between theory and data

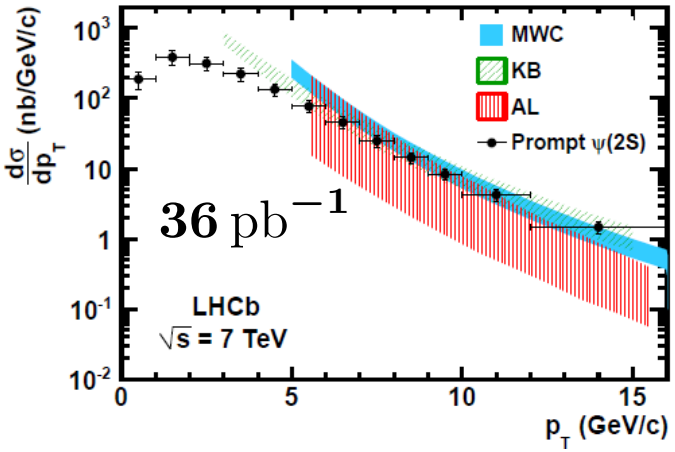
CDF data vs. CS



CMS data vs. CS+CO



LHCb data vs. predictions



CDF, PRD 80 (2009) 031103
CMS, JHEP 02 (2012) 011
LHCb, arXiv:1204.1258

Y.-Q.Ma,K.Wang,K.-T.Chao arXiv:hep-ph/1012.1030

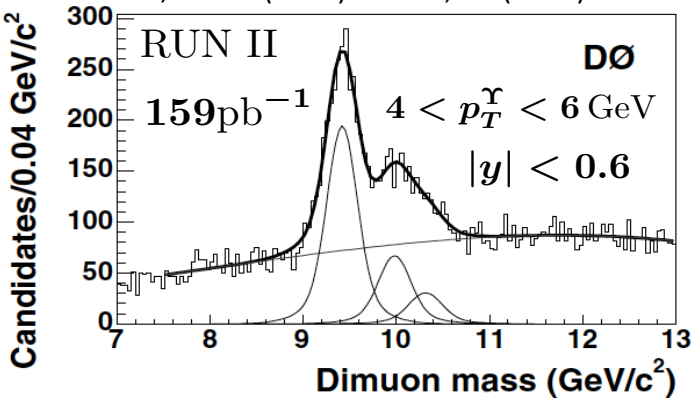
B.Kniehl,M.Butenschön PRL 106 (2011) 022003

P.Artoisenet, PRL 101 (2008) 152001;
J-P.Lansberg Eur. Phys. J. C 61 (2009) 693

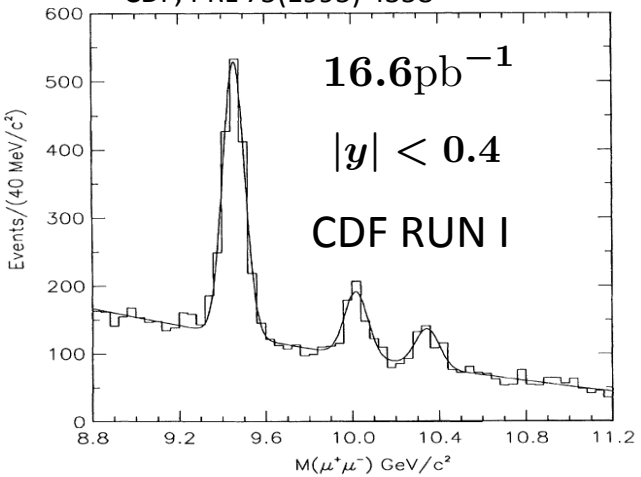
$\Upsilon(nS)$ production

- Three states decaying into $\mu^+\mu^-$: $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$

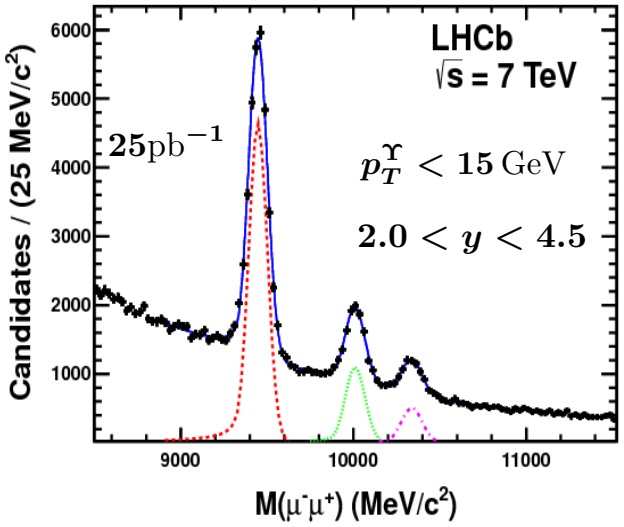
D0, PRL 94(2005)232001;100(2008) 049902



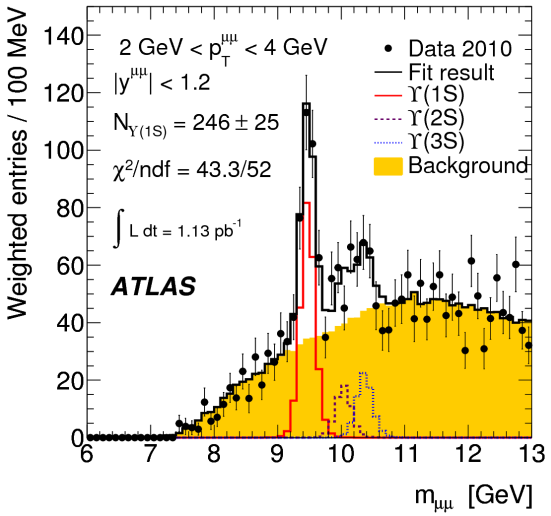
CDF, PRL 75(1995) 4358



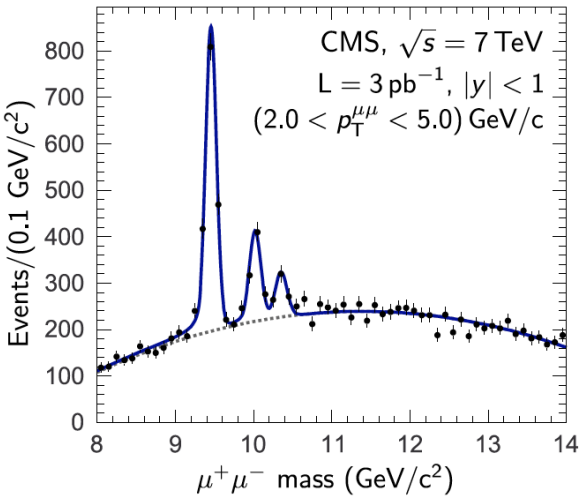
LHCb, arXiv:1202.6579



ATLAS, PLB 705(2011)9

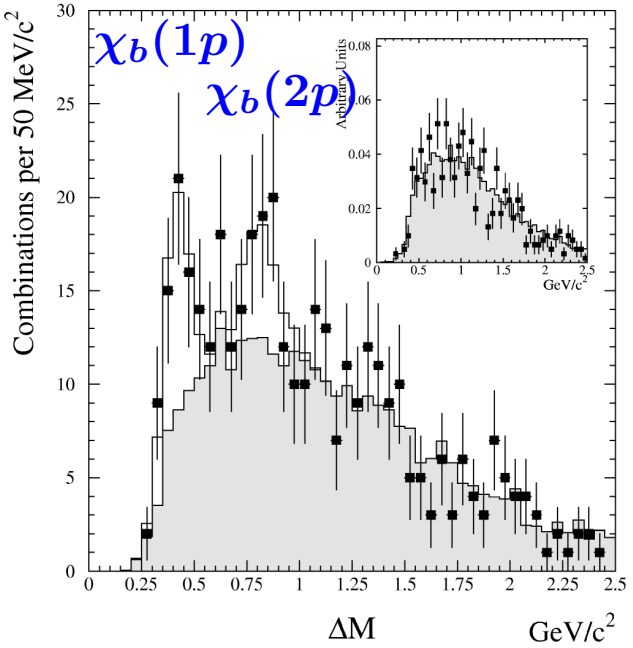


CMS, PRD 83(2011)112004



$\Upsilon(nS)$ production

- $\Upsilon(1S), \Upsilon(2S)$: direct production + feed down



Tevatron RUN I
fraction (%) of $\Upsilon(1S)$ $(p_T^{\Upsilon} > 8\mathrm{GeV})$:

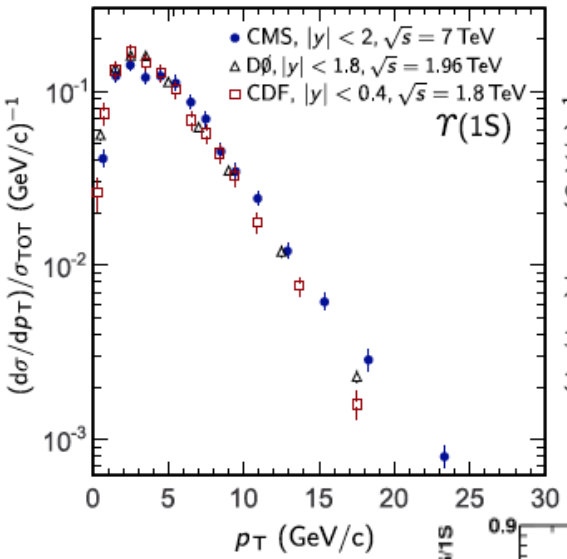
$\chi_b(1P) \to \Upsilon(1S)\gamma$	$27.1 \pm 6.9(\mathrm{stat}) \pm 4.4(\mathrm{syst})$
$\chi_b(2P) \to \Upsilon(1S)\gamma$	$10.5 \pm 4.4(\mathrm{stat}) \pm 1.4(\mathrm{syst})$
direct	$50.9 \pm 8.2(\mathrm{stat}) \pm 9.0(\mathrm{syst})$

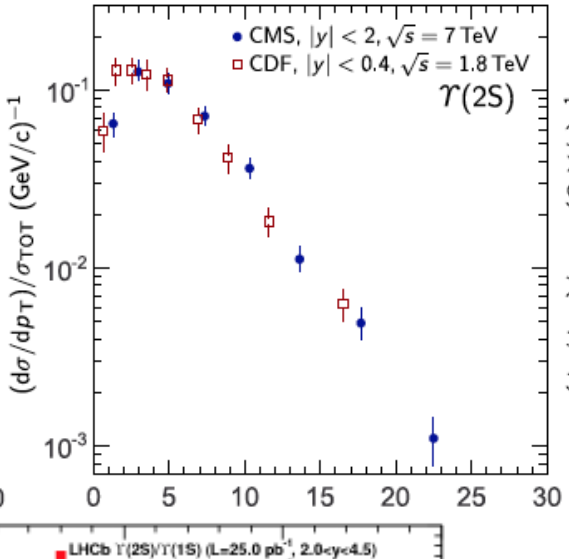
CDF, PRL 84(2000)2094

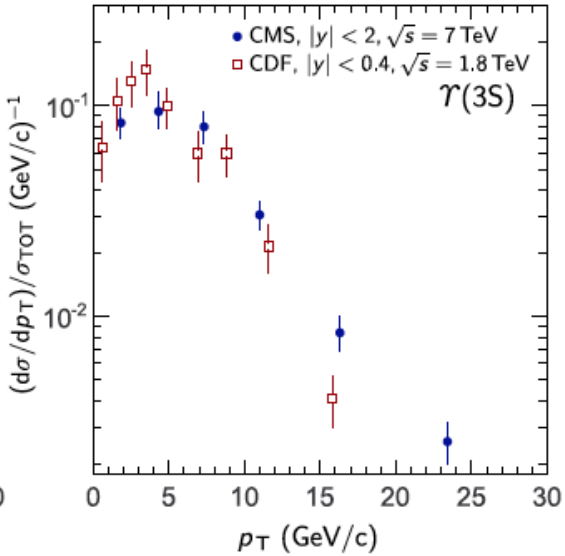
- $\Upsilon(3S)$: ~ direct production

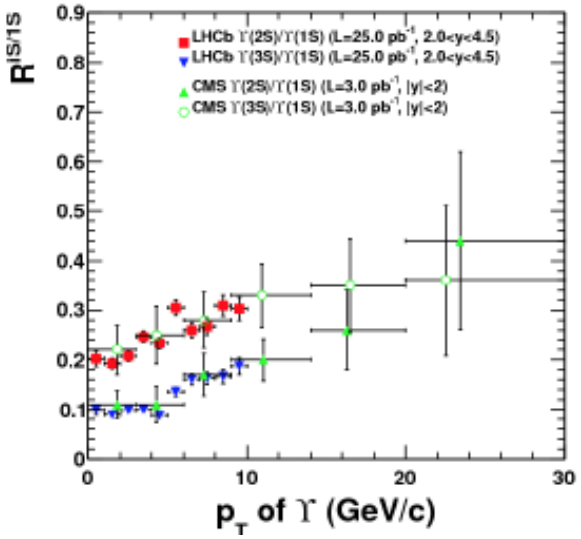
$\Upsilon(nS)$ production

- Measurements in different regions of phase space, different energies, by different experiments…







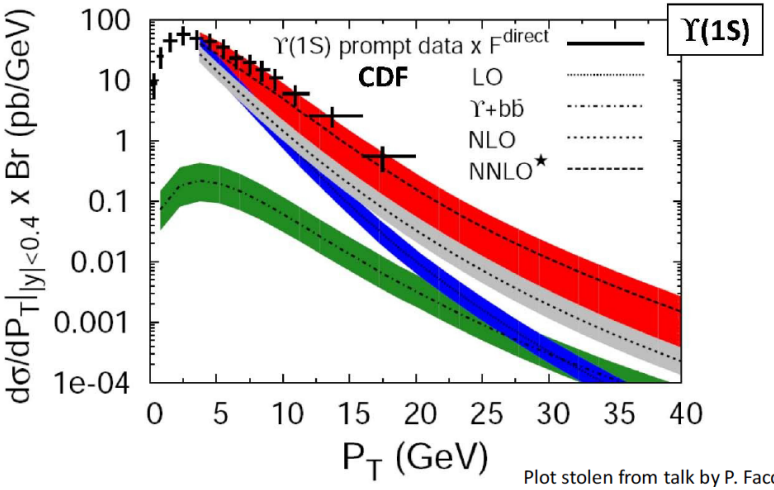


D0, PRL 94(2005)232001; 100(2008) 049902
CDF, PRL 75(1995) 4358
CMS, PRD 83(2011)112004
LHCb, arXiv:1202.6579

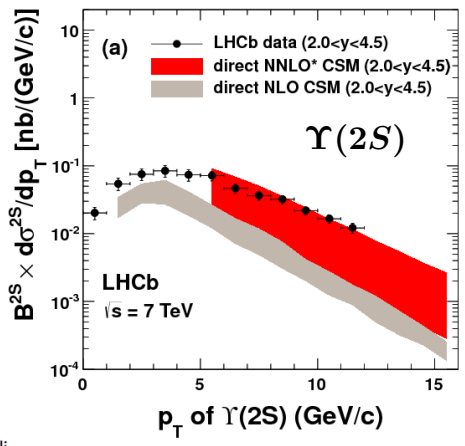
$$R^{iS/1S} = \frac{\sigma(\Upsilon(iS)) \cdot BR(\Upsilon(iS) \to \mu\mu)}{\sigma(\Upsilon(1S)) \cdot BR(\Upsilon(1S) \to \mu\mu)}$$

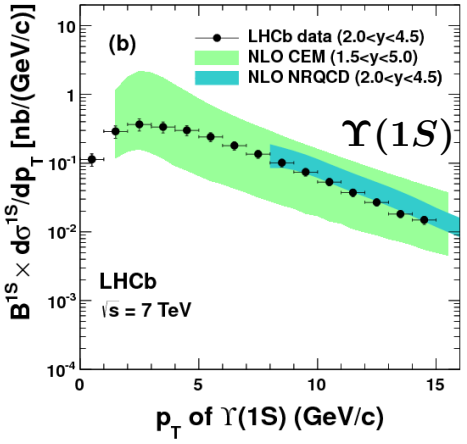
$\Upsilon(nS)$ production

- Reasonable agreements with theory predictions



Plot stolen from talk by P. Faccioli



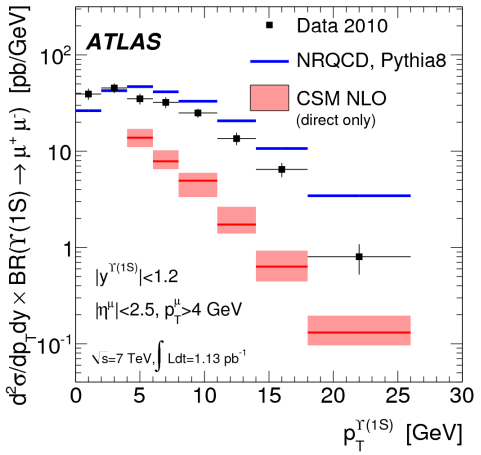


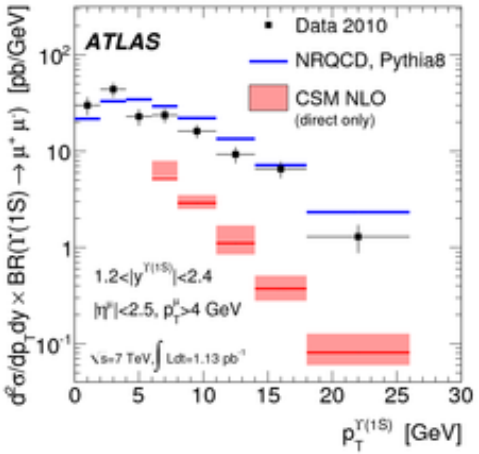
- ATLAS measurement in a kinematic region

  where results less dependent on the unknown polarization

$$|\eta^{\mu}| < 2.5, p_T^{\mu} > 4\,\mathrm{GeV}$$

"NRQCD, Pythia8": CO at LO order + a set of parameters determined from Tevatron data



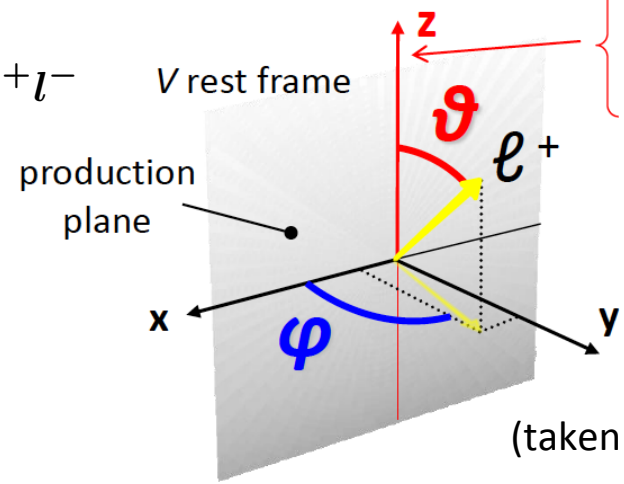


ATLAS, PLB 705 (2011) 9.

Polarization Measurement

- The polarization (spin alignment) of the quarkonium can be determined by the analysis of the angular distribution of the final state leptons

$V \to l^+ l^-$ (V rest frame)



Collins-Soper axis (CS): ≈ dir. of colliding partons
Helicity axis (HX): dir. of V momentum
etc.

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

(taken from P. Faccioli's talk)

- The coefficients are frame dependent, but an invariant characterized the "shape"

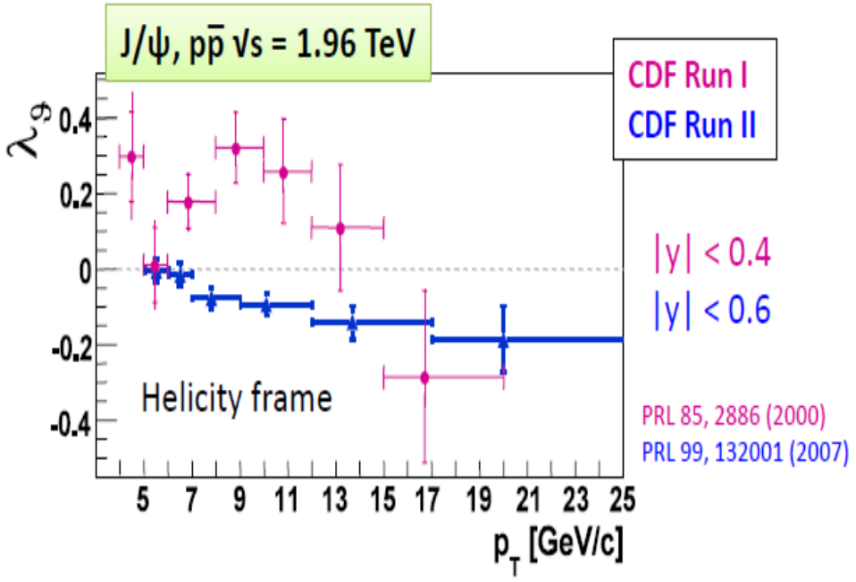
$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

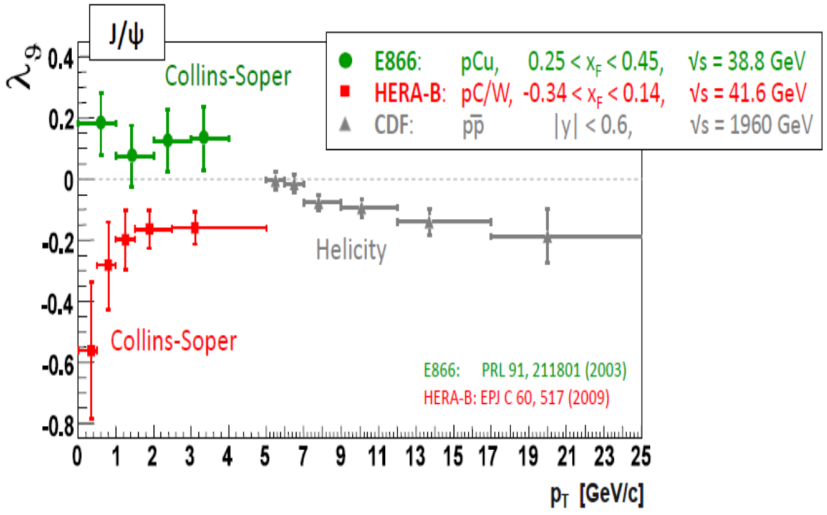
$\tilde{\lambda} = +1$

$\tilde{\lambda} = -1$

Polarization Measurement

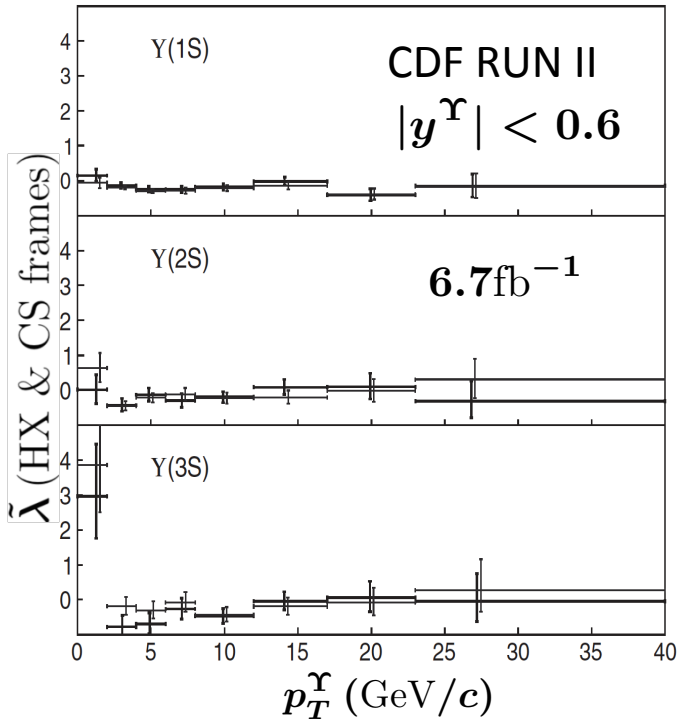
- It was proposed that polarization measurement could shed light on understanding the role of CS vs CO
- Polarization results maybe highly depend on rapidity range, frame,..., and above all the good understanding of the detector

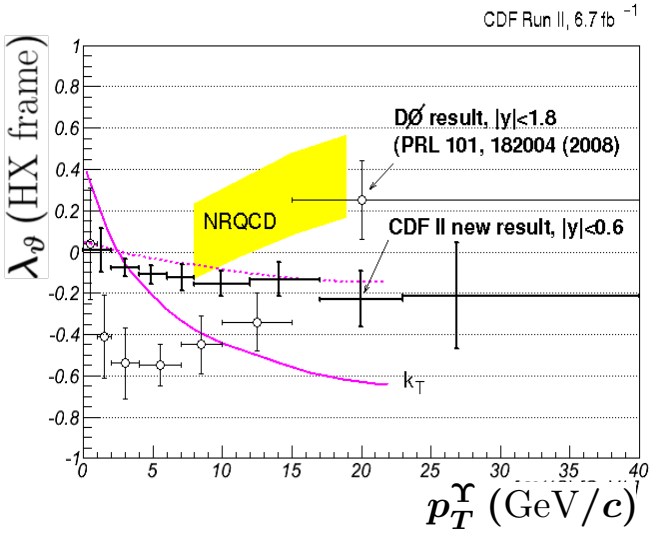




Polarization Measurement

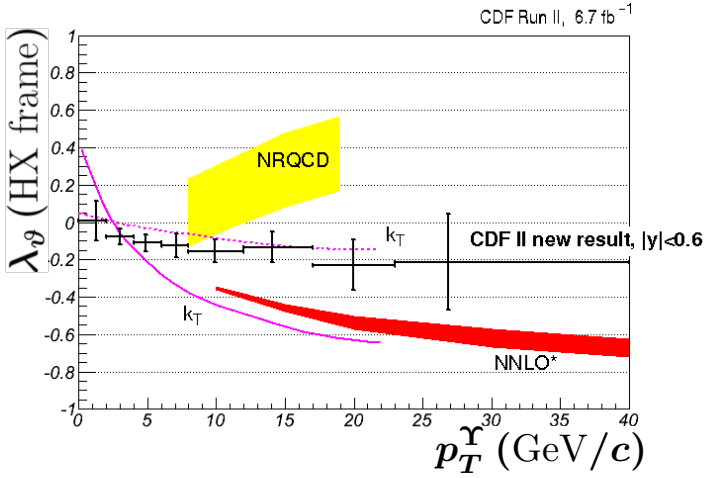
- A "full analysis" on Υ polarization by CDF
- Result not consistent with D0





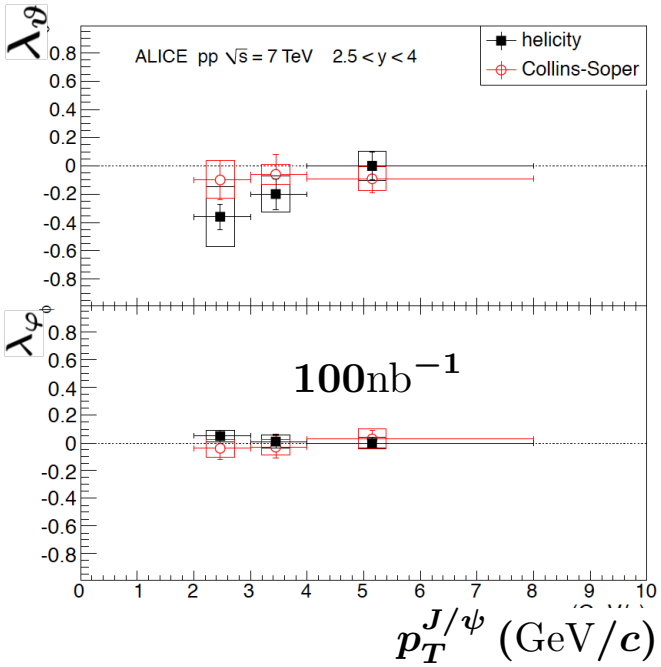
CDF, PRL 108 (2012) 151802
D0, PRL 101 (2008) 182004

- Disagrees with CO at leading order ("NRQCD" in the plot), but close to the CS at NNLO*

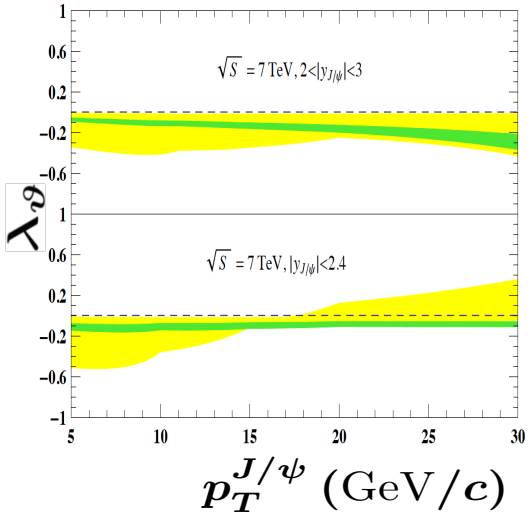


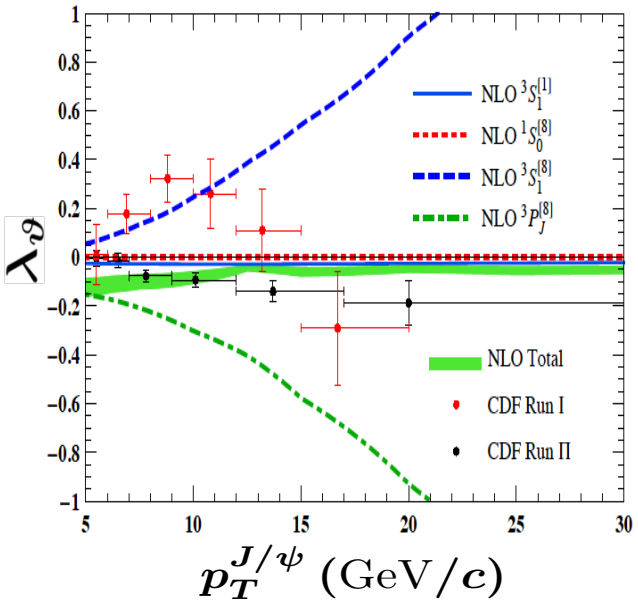
Polarization Measurement

- ALICE released the first J/ψ polarization measurement at LHC



K-T Chao et al., arXiv:1201.4155



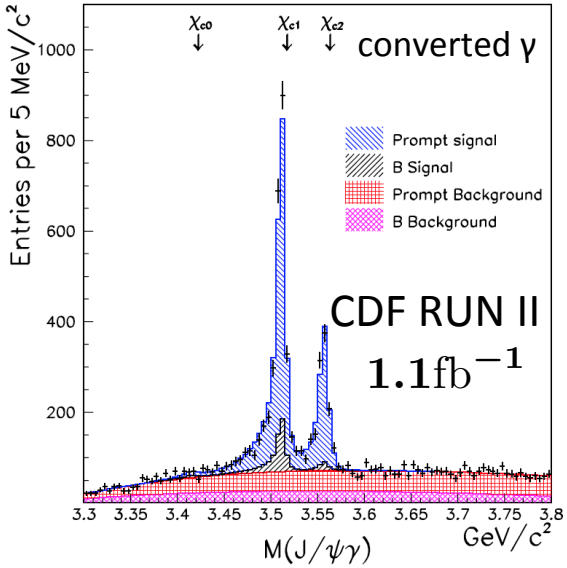


ALICE, PRL 108 (2012)082001

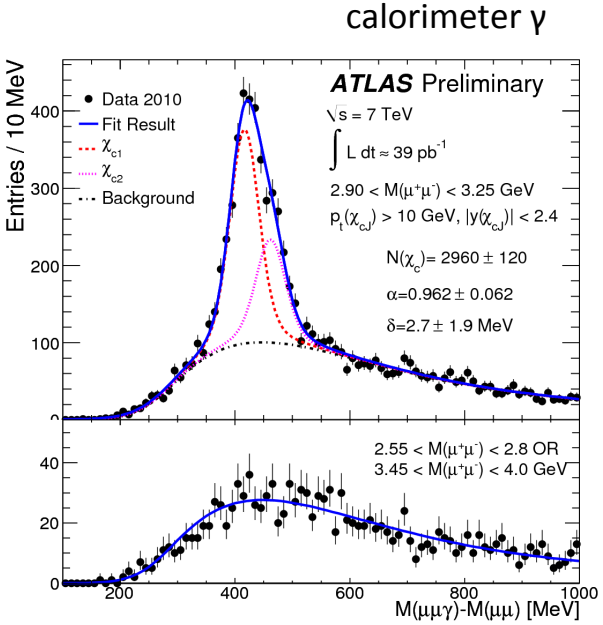
- Results are close to the recent theoretical prediction (NLO CS+CO) with large uncertainties (no feed down in theory). Many terms contribute…

Production of χ_c

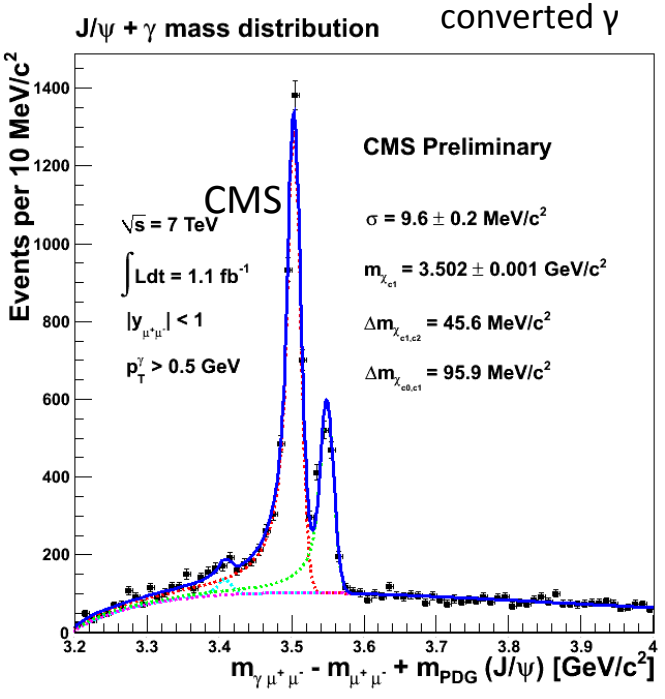
- Decays into $J/\psi + \gamma$, the photon energy resolution is crucial to resolve the χ_{c1}, χ_{c2} states.
- The photon may be measured
  - -in EM Calorimeter: higher eff., poorer resolution
  - -conversions before main tracking system: lower eff., better resolution



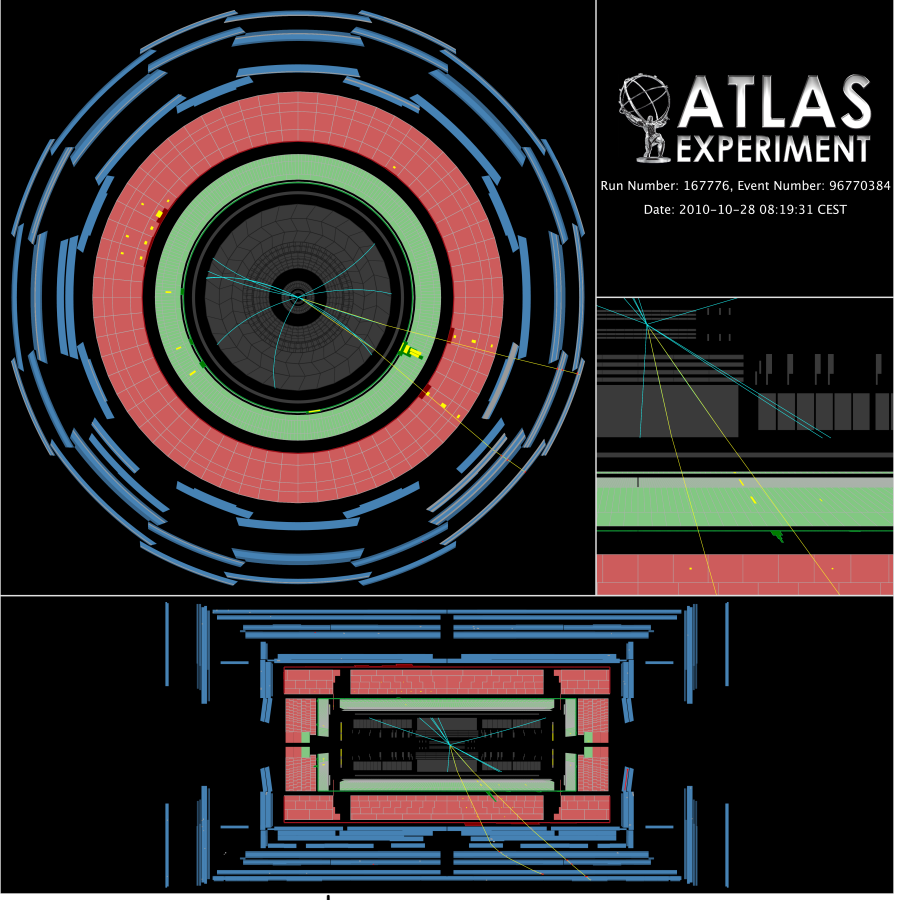
CDF, PRL 98 (2007) 232001



ATLAS-CONF-2012-136

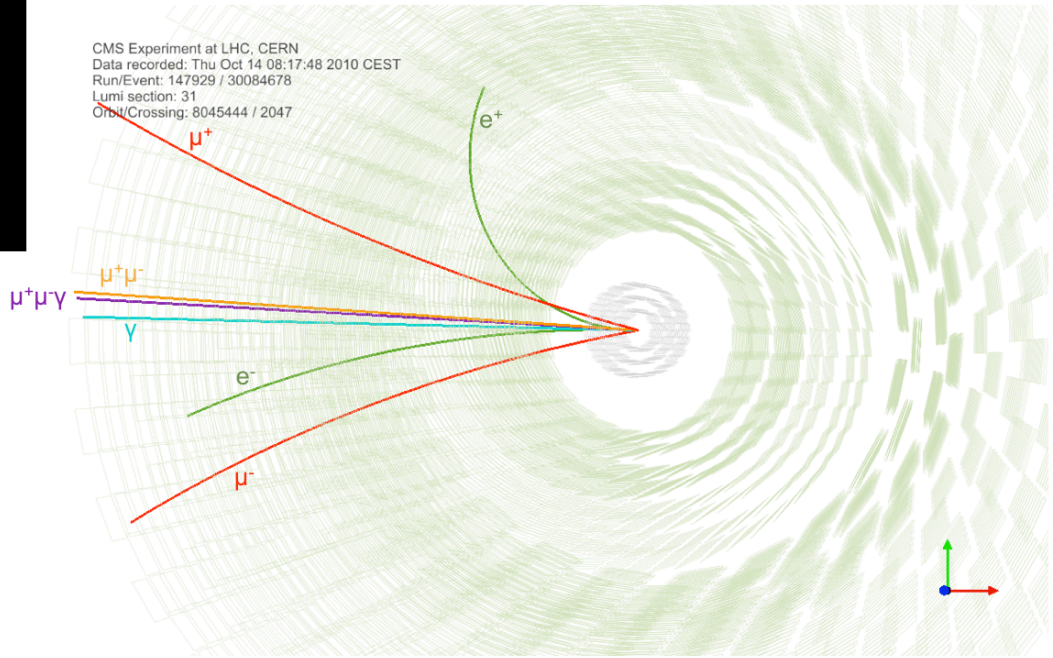


CMS-DP-2011-006



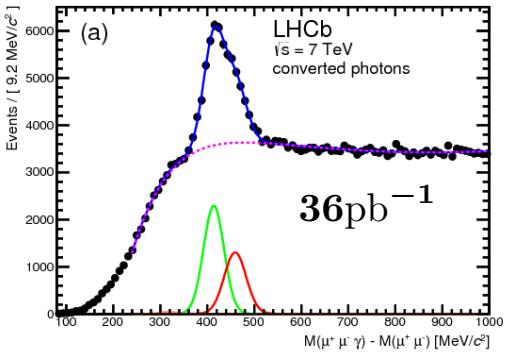
ATLAS $\mu^+\mu^-\gamma$ candidate

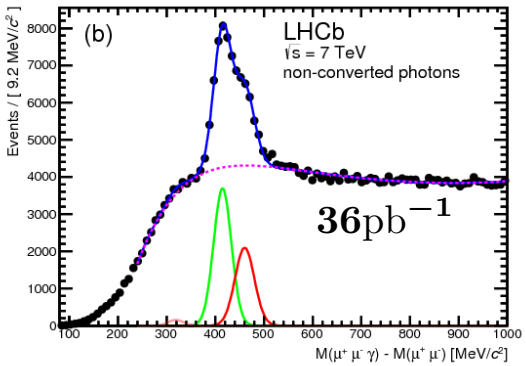
CMS $\mu^+\mu^-\gamma\,(\rightarrow e^+e^-)$ candidate



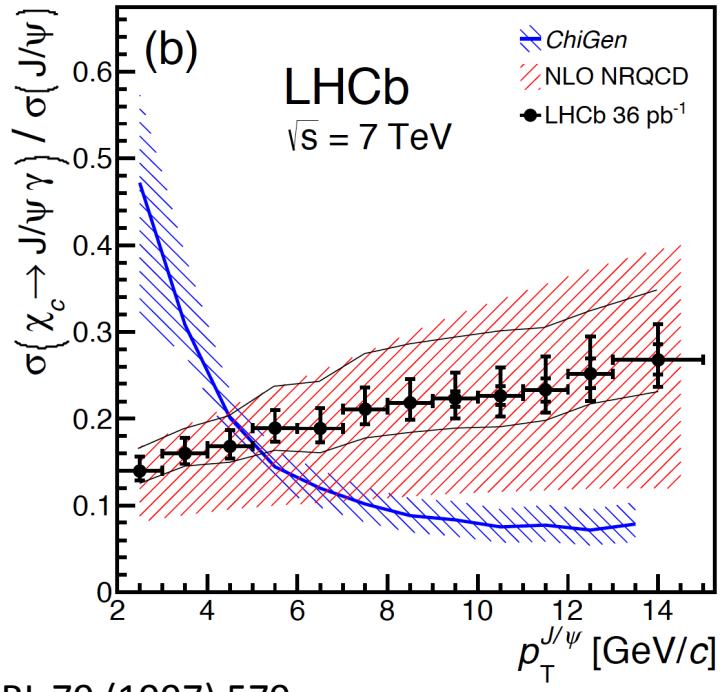
$\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$ at LHCb

- Photon reconstructed in calorimeter only (higher eff., poorer resolution)
- In agreement with CS+CO NLO





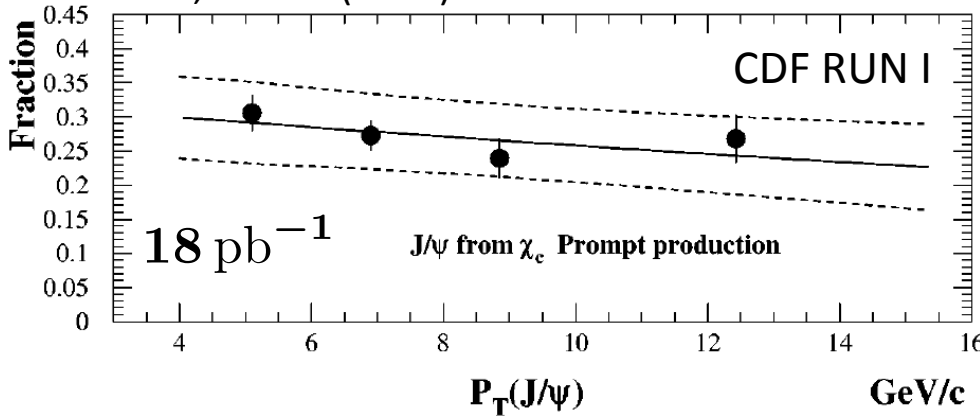
LHCb, arXiv:1202.1462



In figures above ONLY!

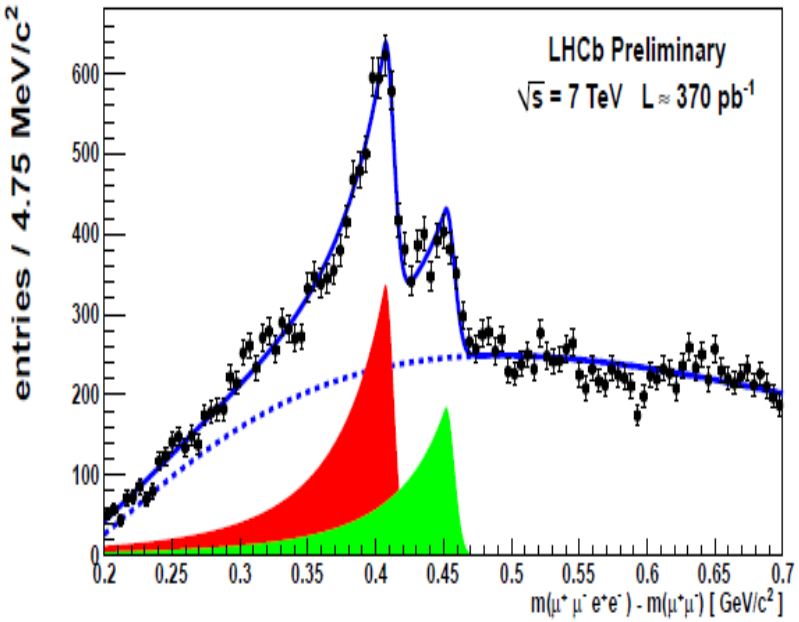
- converted = conversion after the magnet, e^+e^- in the calorimeter
- non-converted = photon in calorimeter

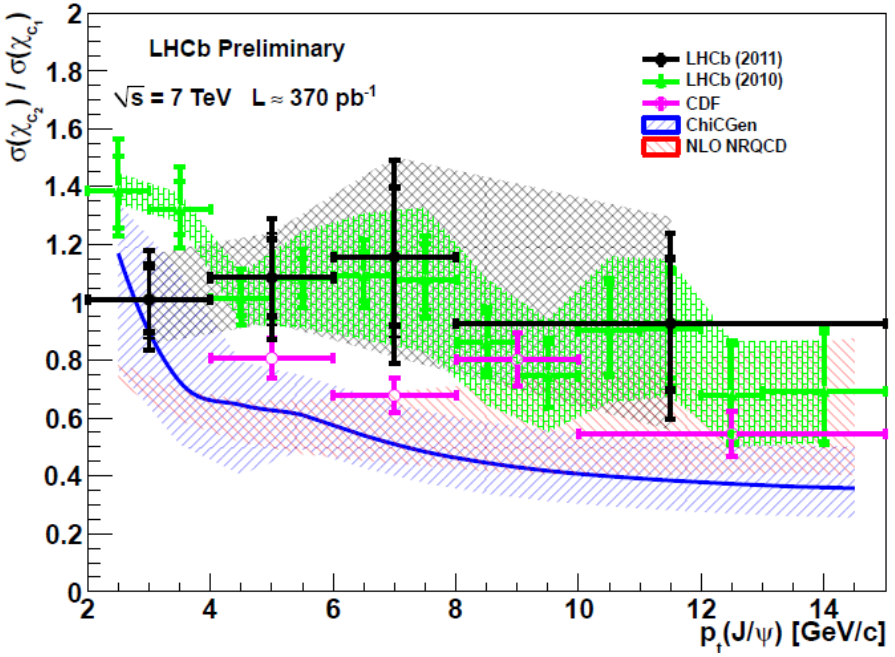
CDF, PRL 79 (1997) 579



$\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at LHCb

- Converted photons are used (better resolution, lower efficiency)
- Results in agreement with CS+CO NLO above 8 GeV





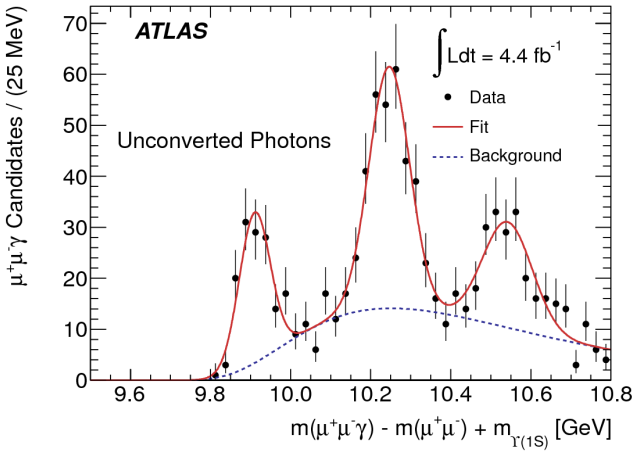
LHCb, arXiv:1202.1080

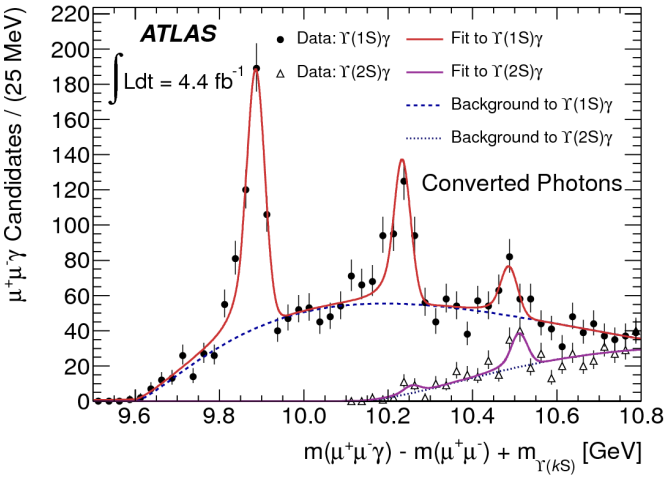
A. Chisholm's talk

New χ_b state

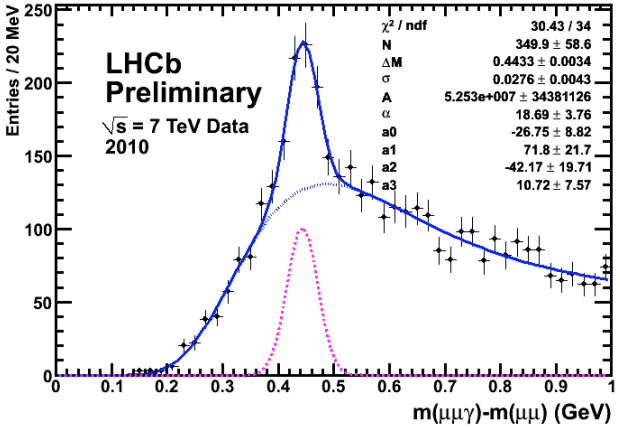
- χ_b states reconstructed from $\chi_b \to \Upsilon(kS) + \gamma$

ATLAS, PRL 108 (2012) 152001





- LHCb observed χ_b states in 2010 data (37 pb^{-1}) with photons in calorimeter. Measurement of χ_b ratios on the way.

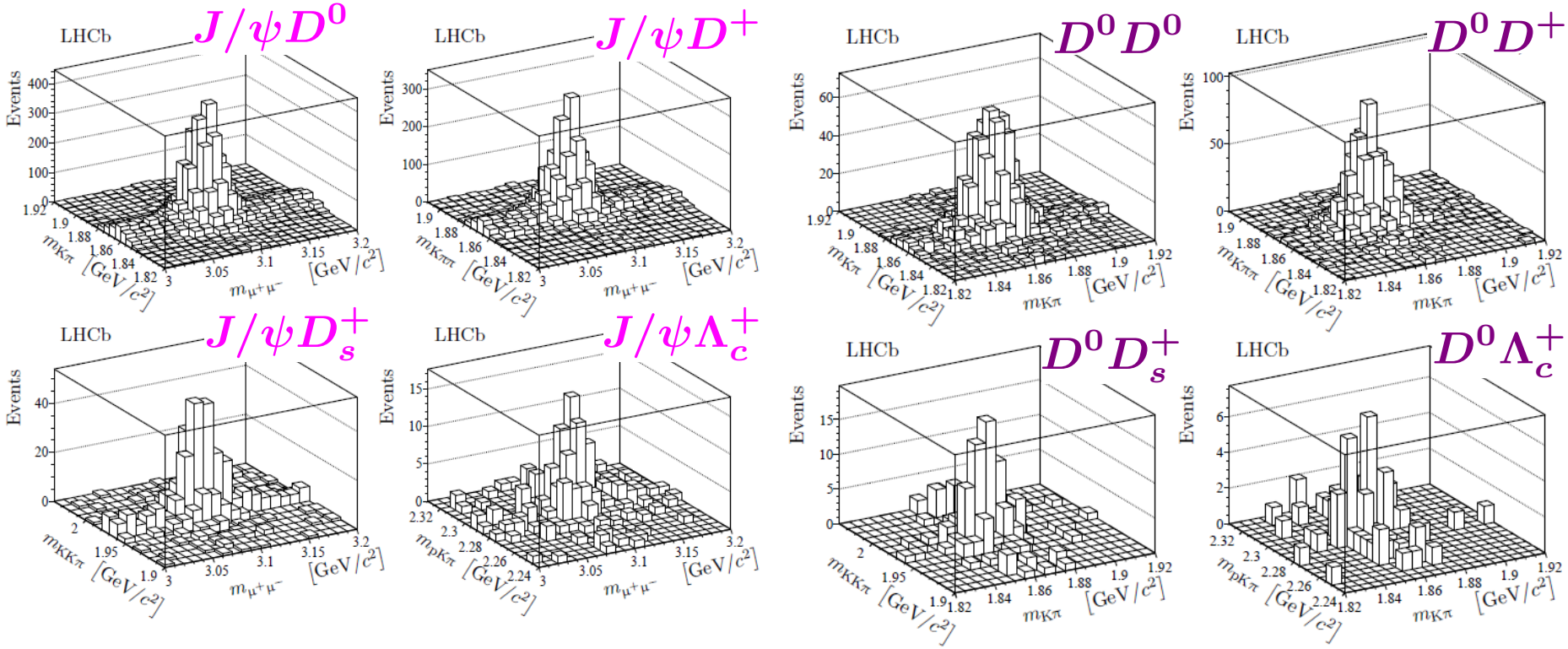


Double charm(onium)

- LHCb made the first observation of double J/ψ production at hadron colliders.

LHCb, PLB 707 (2012) 52

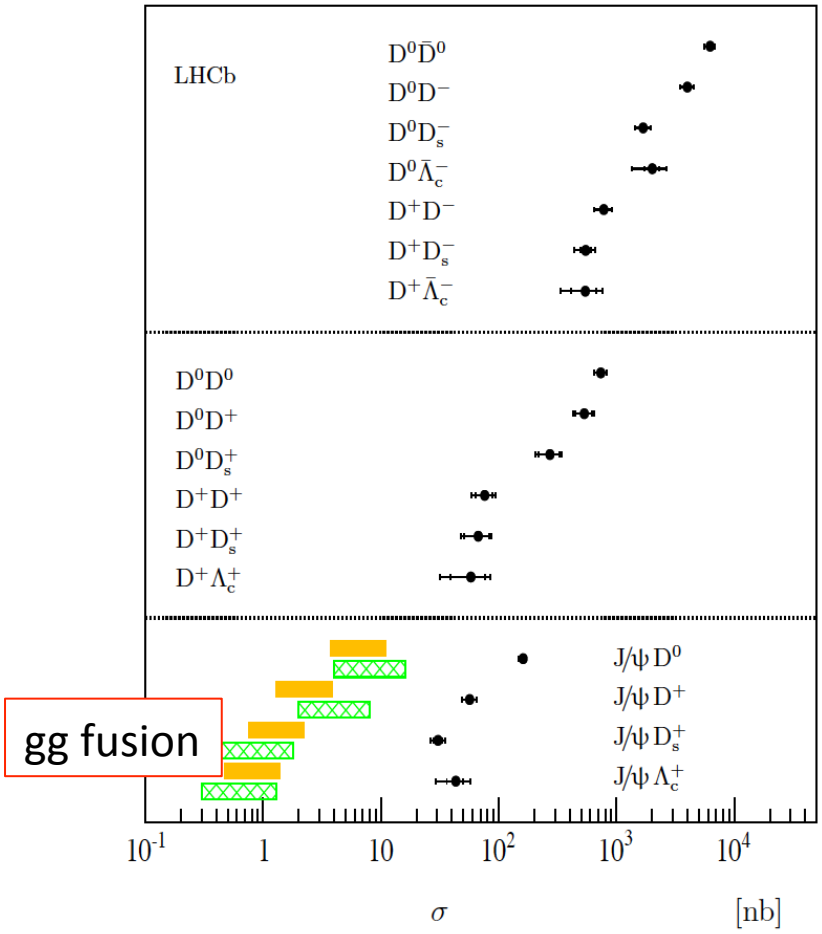
- Many double charm(oium) modes observed with significance > 5σ.

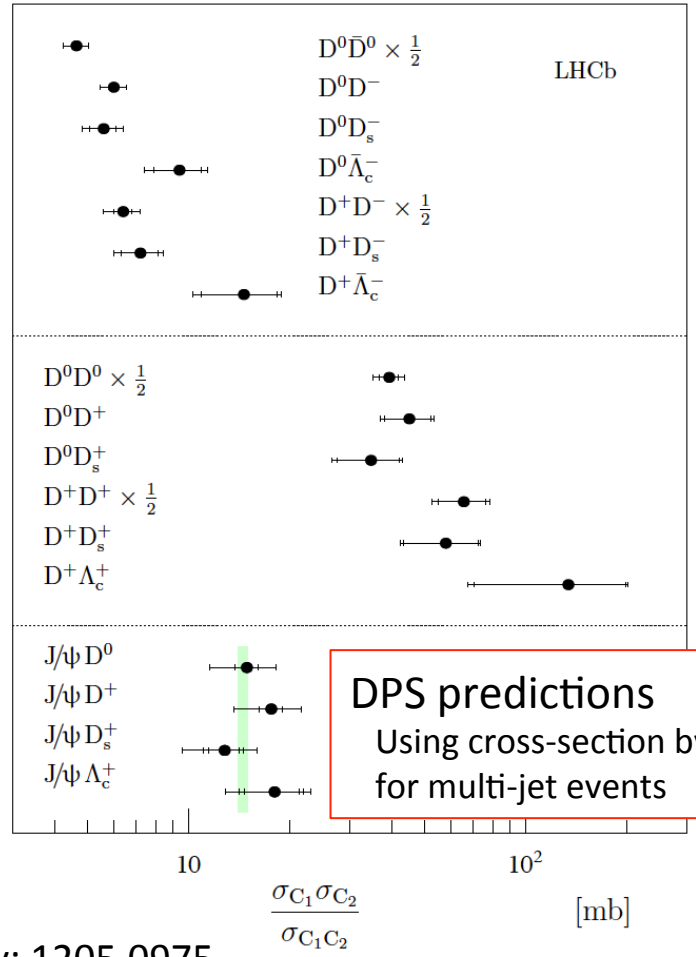


LHCb, arXiv: 1205.0975

Double charm(onium)

- Measured cross-sections suggests Double Parton Scattering (DPS) needed

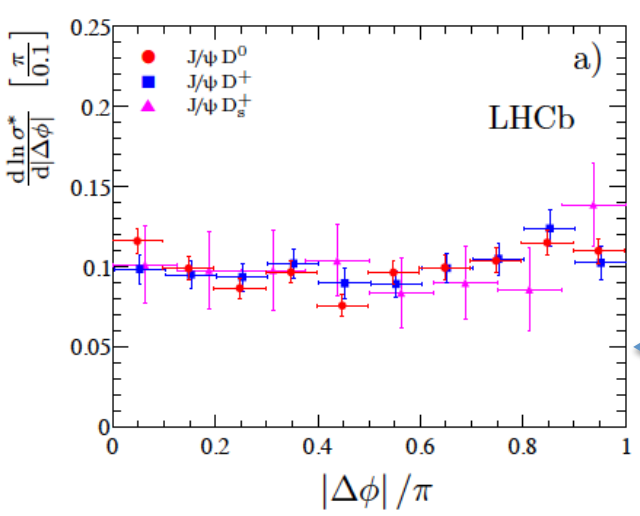




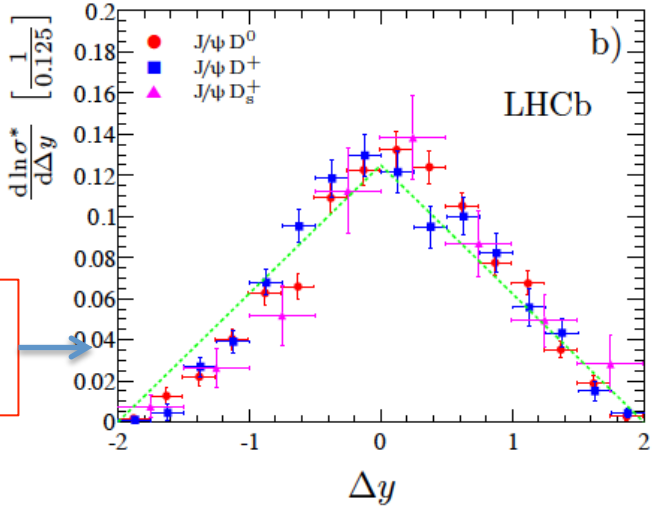
LHCb, arXiv: 1205.0975

Double charm(onium)

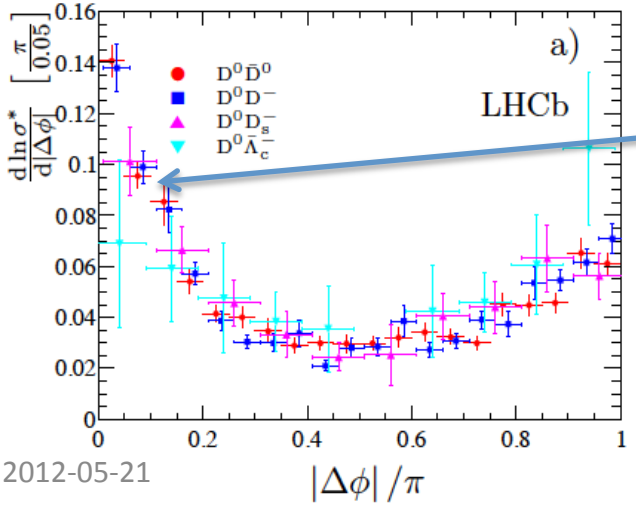
- Correlations reveal some deep insights LHCb, arXiv: 1205.0975

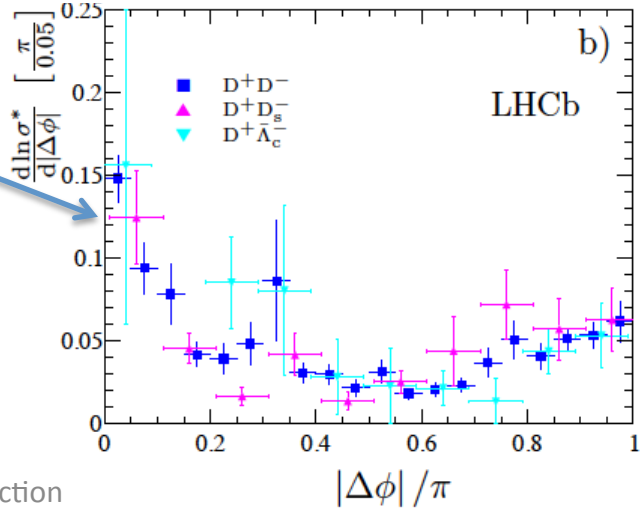


no significant correlations



$g \rightarrow c\bar{c}$

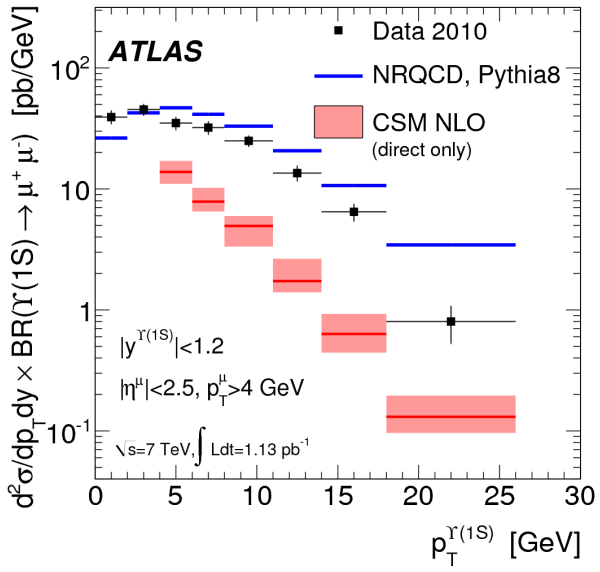


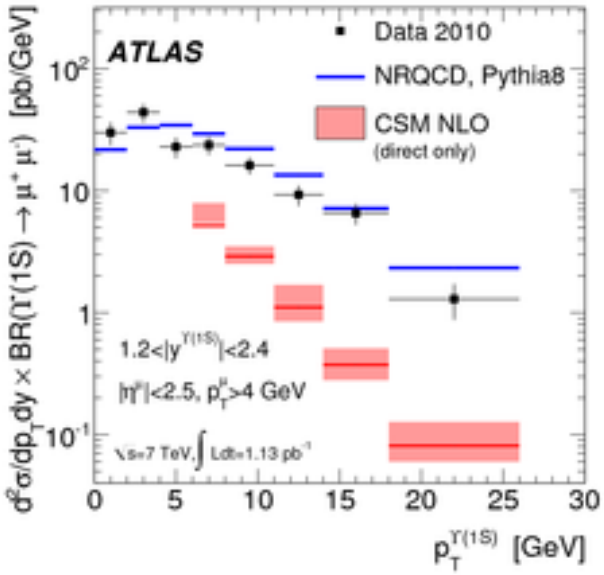


Summary & prospects

- Quakonium production has provided an ideal place to test QCD, many lessons learnt in last 20+ years:
  - high order corrections more important at some phase space region
  - the correct answers may involve many factors, CS+CO
  - simple measurement might not be easy (e.g. polarization)
  - …
- Many more results are going to be produced in LHC
  - polarizations ($J/\psi, \psi(2S), \Upsilon(nS), \cdots$)
  - double Quark(onium) productions
  - new states
  - …
  - *p-Pb* collisions in LHCb
- Stay tuned!

Backup Slides





ATLAS, PLB 705 (2011) 9.

References

PYTHIA 8.135 parameters: PhaseSpace: pTHatMin=1 GeV;
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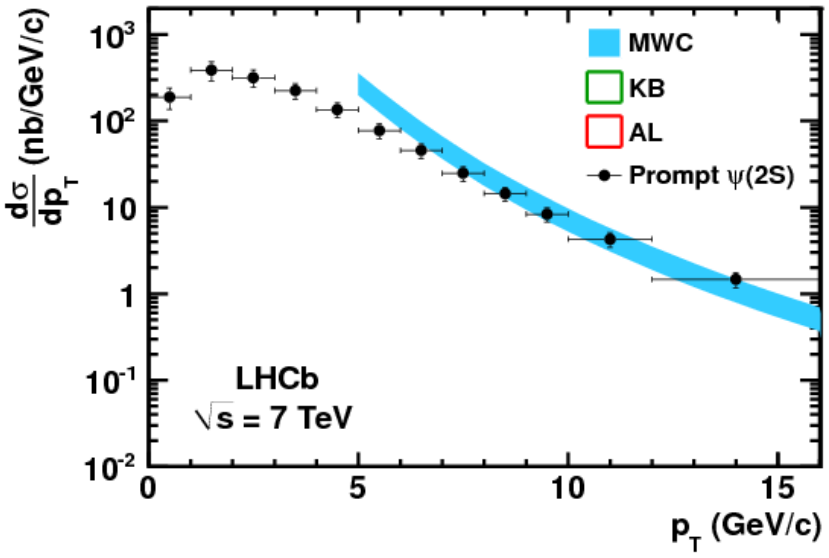
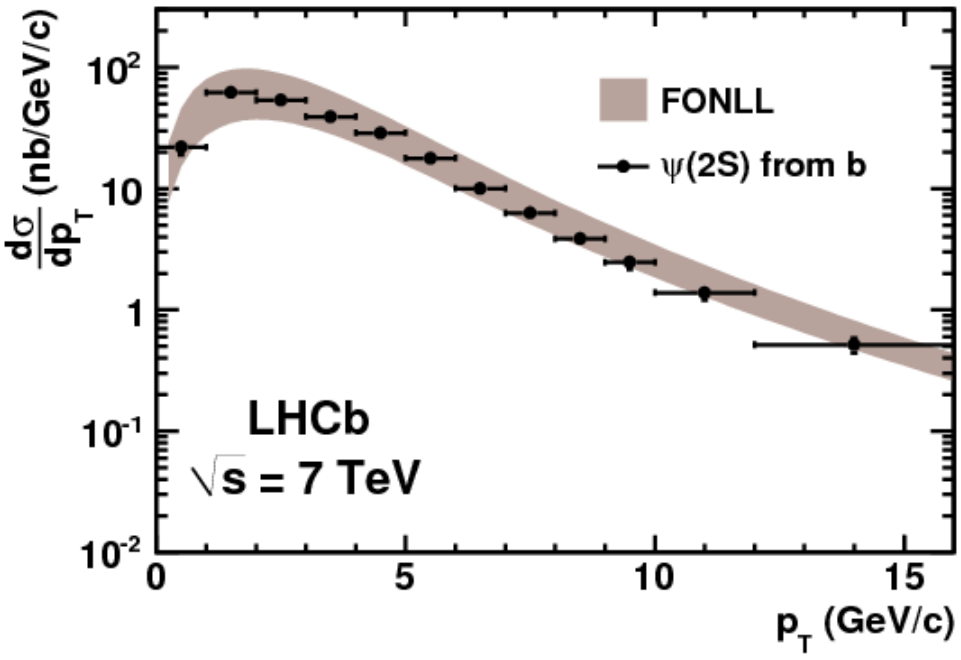
SuppressSmallPT(1.,3,false);
Bottomonium:OUpsilon3P08=0.02;
Bottomonium:Ochib03P01=0.085.

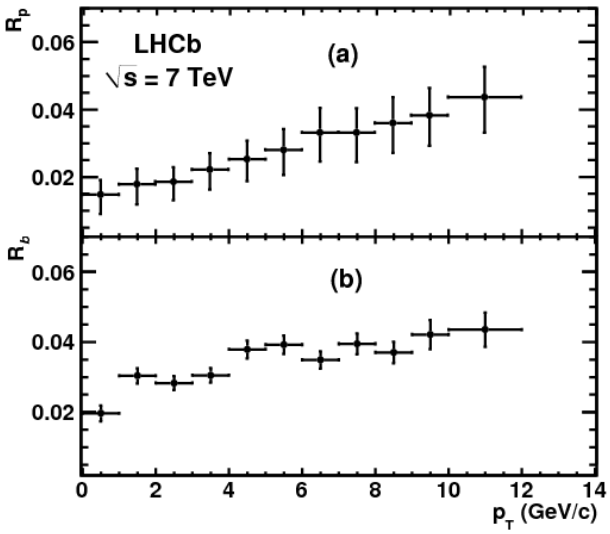
P. Nason et al., arXiv:hep-ph/0003142; A.C. Kraan, arXiv:0807.3123 (hep-ex)

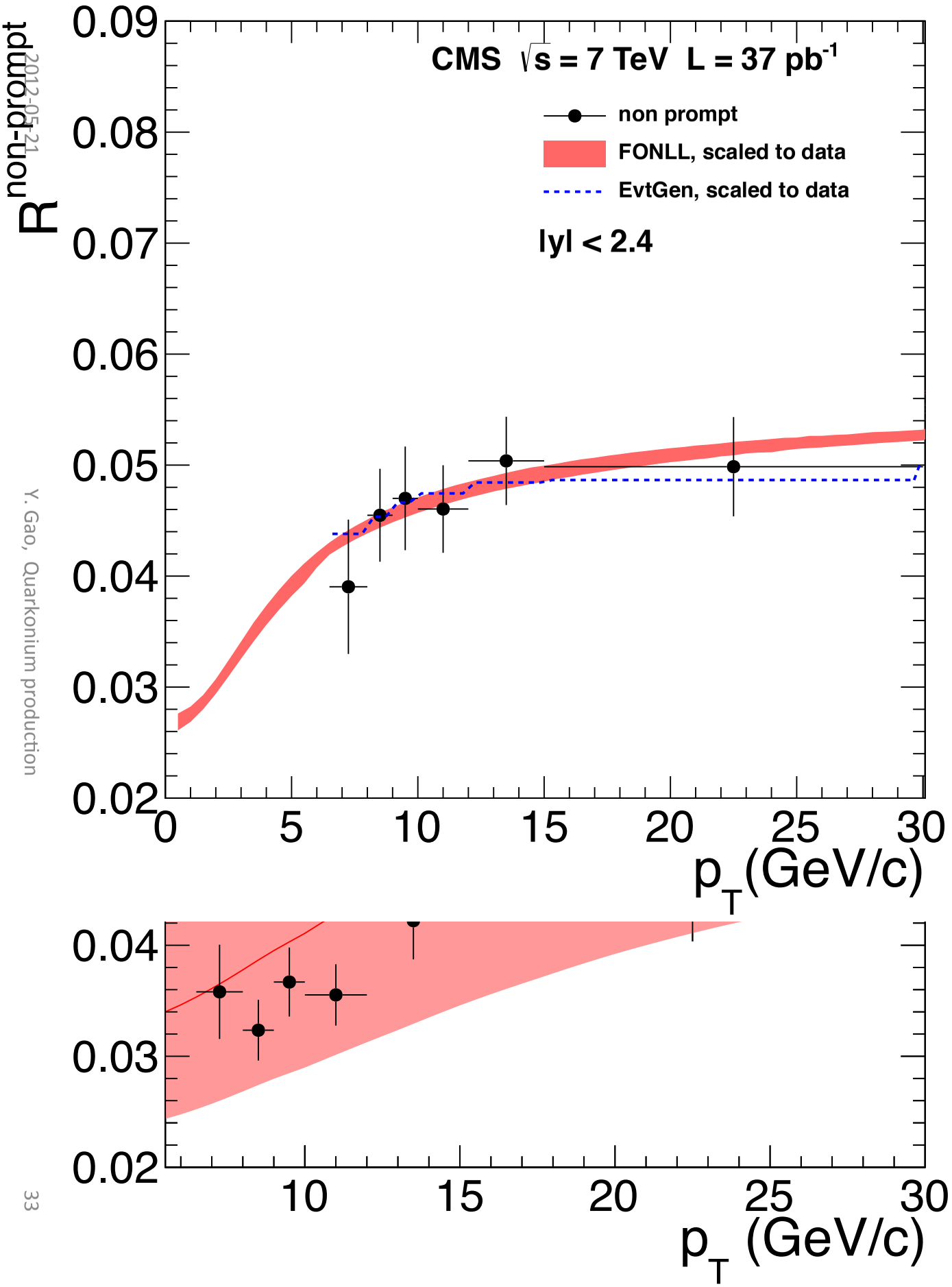
J. Campbell, F. Maltoni, F. Tramontano, Phys. Rev. Lett. 98 (2007) 252002.

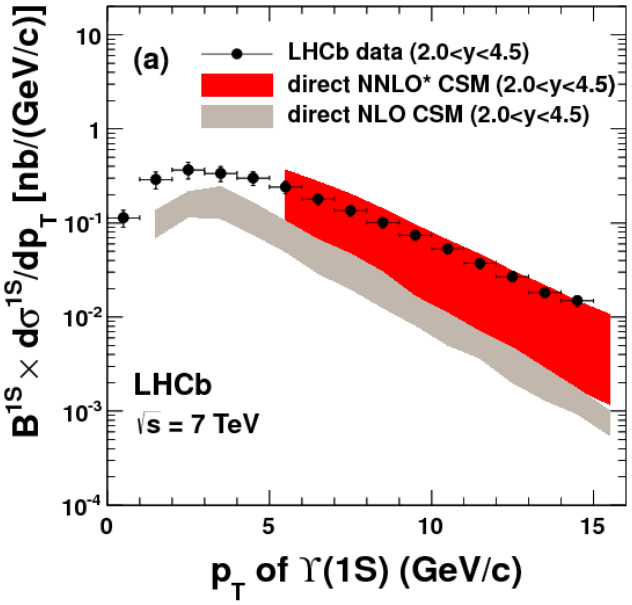
J.M. Campbell, R.K. Ellis, Nucl. Phys. (Proc. Suppl.) 205–206 (2010) 10

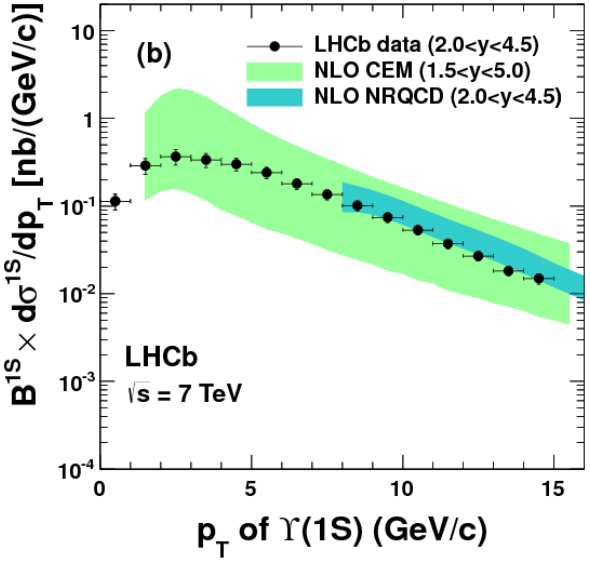

MWC
KB
AL
Prompt ψ(2S)
LHCb
√s = 7 TeV
dσ/dp_T (nb/GeV/c)
p_T (GeV/c)

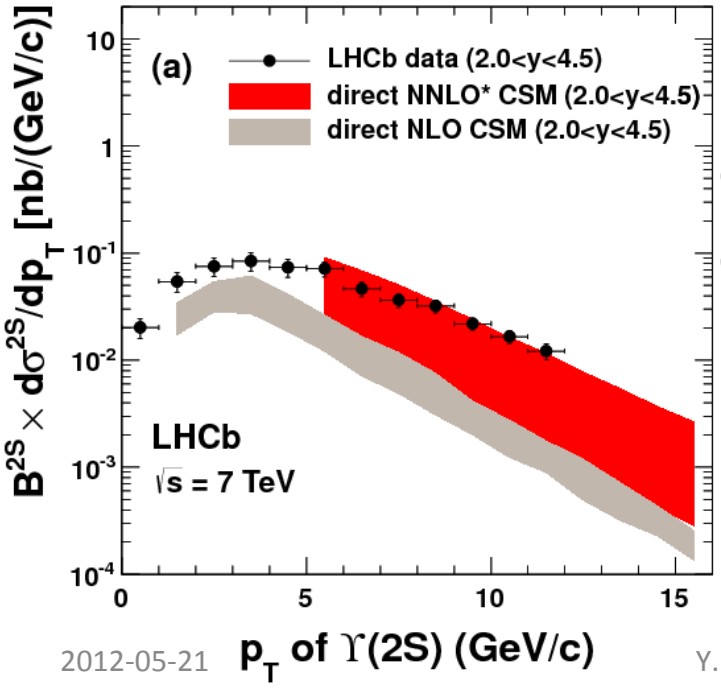

FONLL
ψ(2S) from b
LHCb
√s = 7 TeV
dσ/dp_T (nb/GeV/c)
p_T (GeV/c)

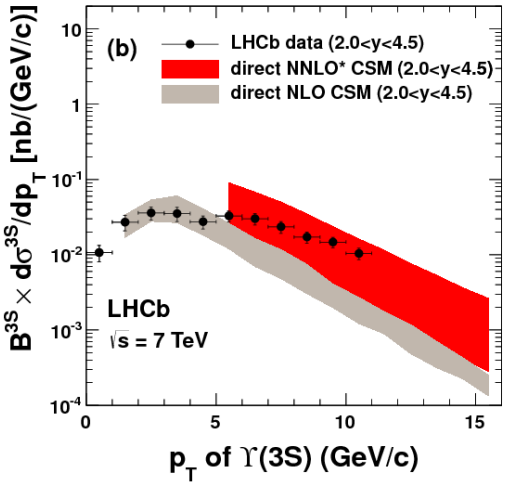

LHCb
√s = 7 TeV
(a)
(b)
R_p
R_b
p_T (GeV/c)

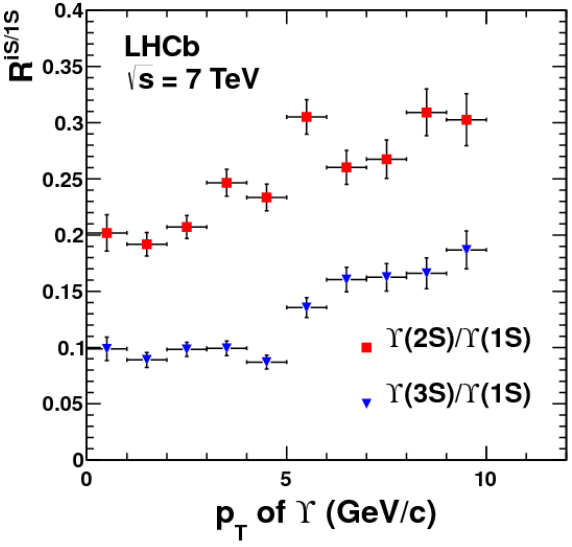

CMS √s = 7 TeV L = 37 pb-1
non prompt
FONLL, scaled to data
EvtGen, scaled to data
|y| < 2.4
R non-prompt
pT (GeV/c)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0
5
10
15
20
25
30

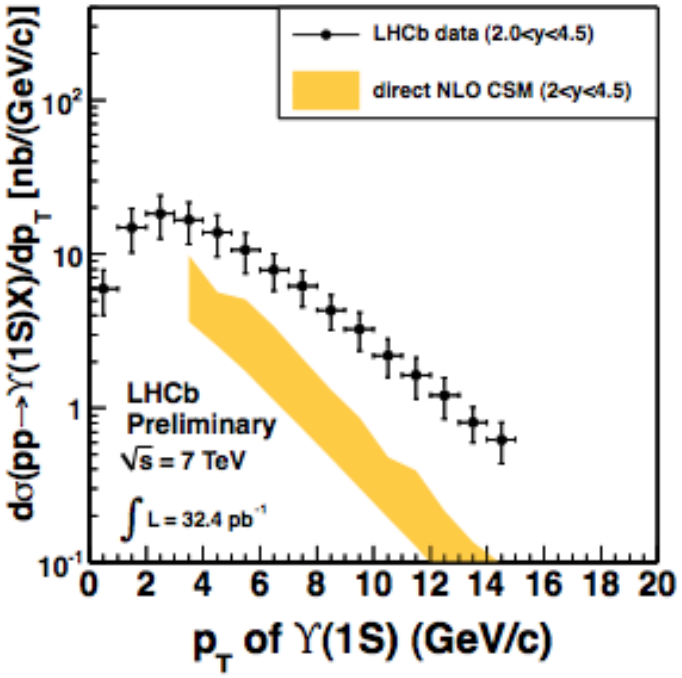

(a)
LHCb data (2.0<y<4.5)
direct NNLO* CSM (2.0<y<4.5)
direct NLO CSM (2.0<y<4.5)
LHCb
√s = 7 TeV
$B^{1S} \times d\sigma^{1S}/dp_T$ [nb/(GeV/c)]
p_T of Υ(1S) (GeV/c)

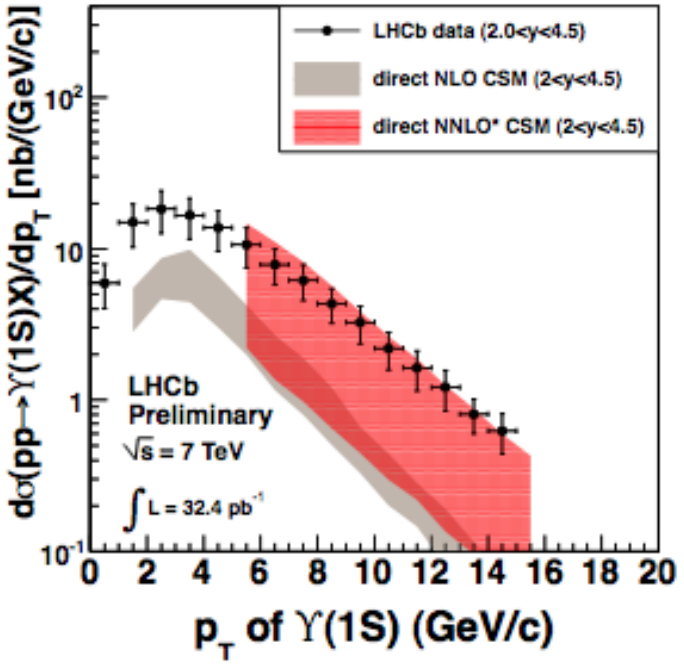

(b)
LHCb data (2.0<y<4.5)
NLO CEM (1.5<y<5.0)
NLO NRQCD (2.0<y<4.5)
LHCb
√s = 7 TeV
$B^{1S} \times d\sigma^{1S}/dp_T$ [nb/(GeV/c)]
p_T of Υ(1S) (GeV/c)

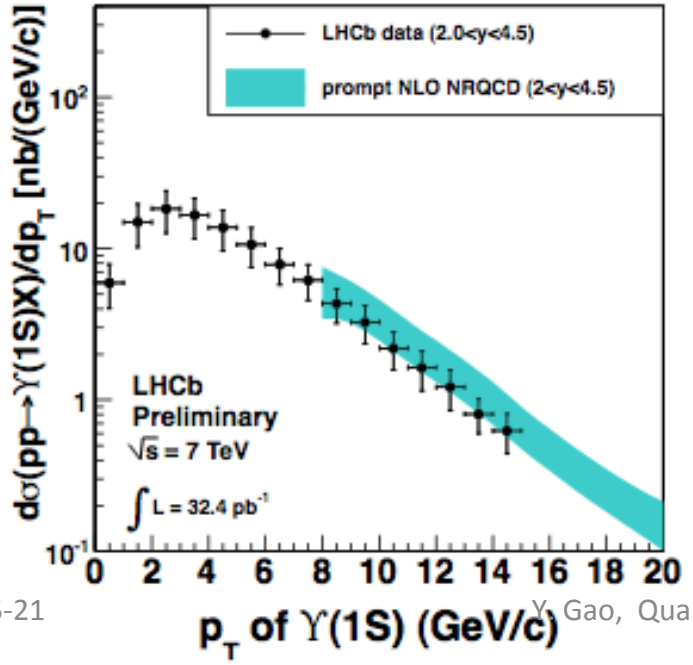

(a)
LHCb data (2.0<y<4.5)
direct NNLO* CSM (2.0<y<4.5)
direct NLO CSM (2.0<y<4.5)
LHCb
√s = 7 TeV
$B^{2S} \times d\sigma^{2S}/dp_T$ [nb/(GeV/c)]
p_T of Υ(2S) (GeV/c)

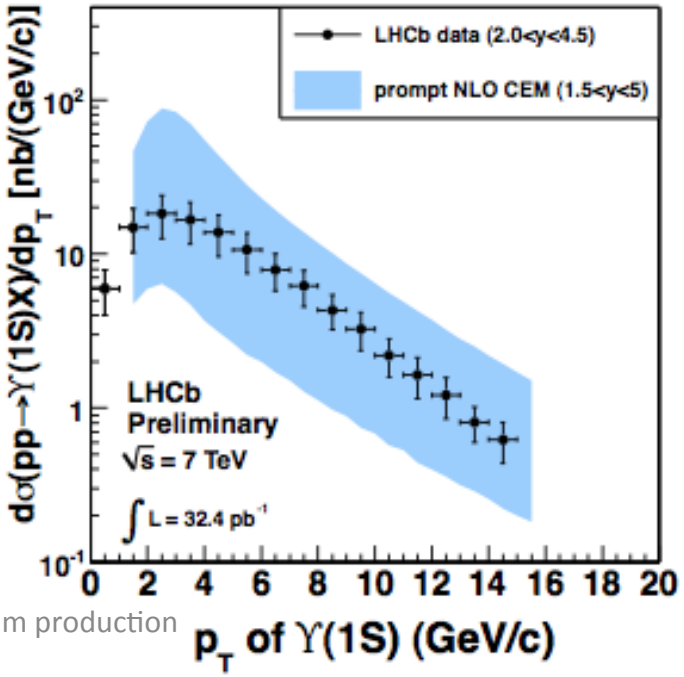

(b)
LHCb data (2.0<y<4.5)
direct NNLO* CSM (2.0<y<4.5)
direct NLO CSM (2.0<y<4.5)
LHCb
√s = 7 TeV
$B^{3S} \times d\sigma^{3S}/dp_T$ [nb/(GeV/c)]
p_T of Υ(3S) (GeV/c)

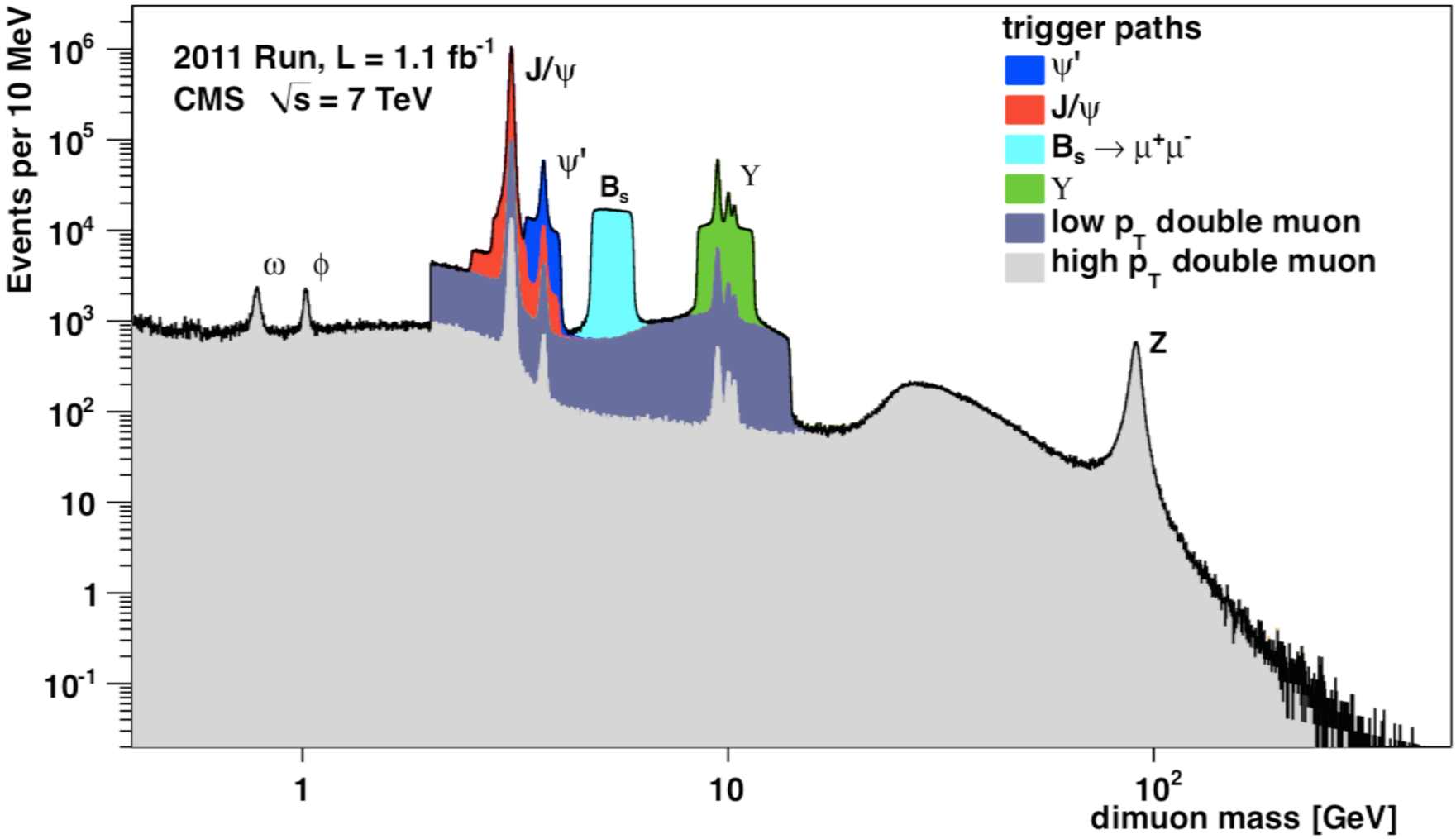

LHCb
√s = 7 TeV
$R^{iS/1S}$
Υ(2S)/Υ(1S)
Υ(3S)/Υ(1S)
p_T of Υ (GeV/c)

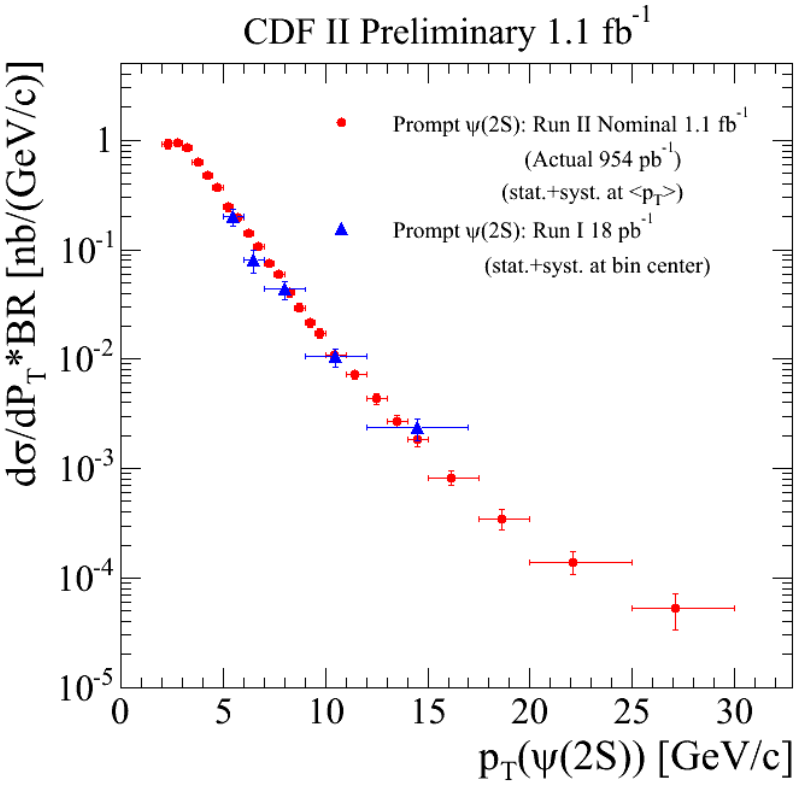

LHCb data (2.0<y<4.5)
direct NLO CSM (2<y<4.5)
LHCb
Preliminary
√s = 7 TeV
∫ L = 32.4 pb⁻¹
dσ(pp→Υ(1S)X)/dp_T [nb/(GeV/c)]
p_T of Υ(1S) (GeV/c)

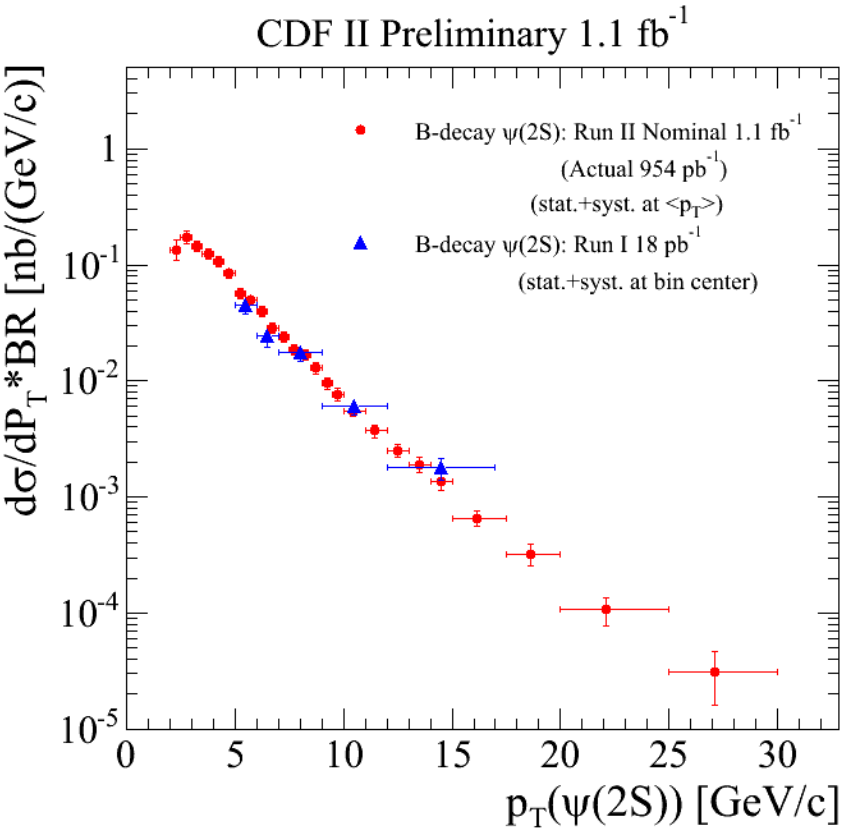

LHCb data (2.0<y<4.5)
direct NLO CSM (2<y<4.5)
direct NNLO* CSM (2<y<4.5)
LHCb
Preliminary
√s = 7 TeV
∫ L = 32.4 pb⁻¹
dσ(pp→Υ(1S)X)/dp_T [nb/(GeV/c)]
p_T of Υ(1S) (GeV/c)


LHCb data (2.0<y<4.5)
prompt NLO NRQCD (2<y<4.5)
LHCb
Preliminary
√s = 7 TeV
∫ L = 32.4 pb⁻¹
dσ(pp→Υ(1S)X)/dp_T [nb/(GeV/c)]
p_T of Υ(1S) (GeV/c)

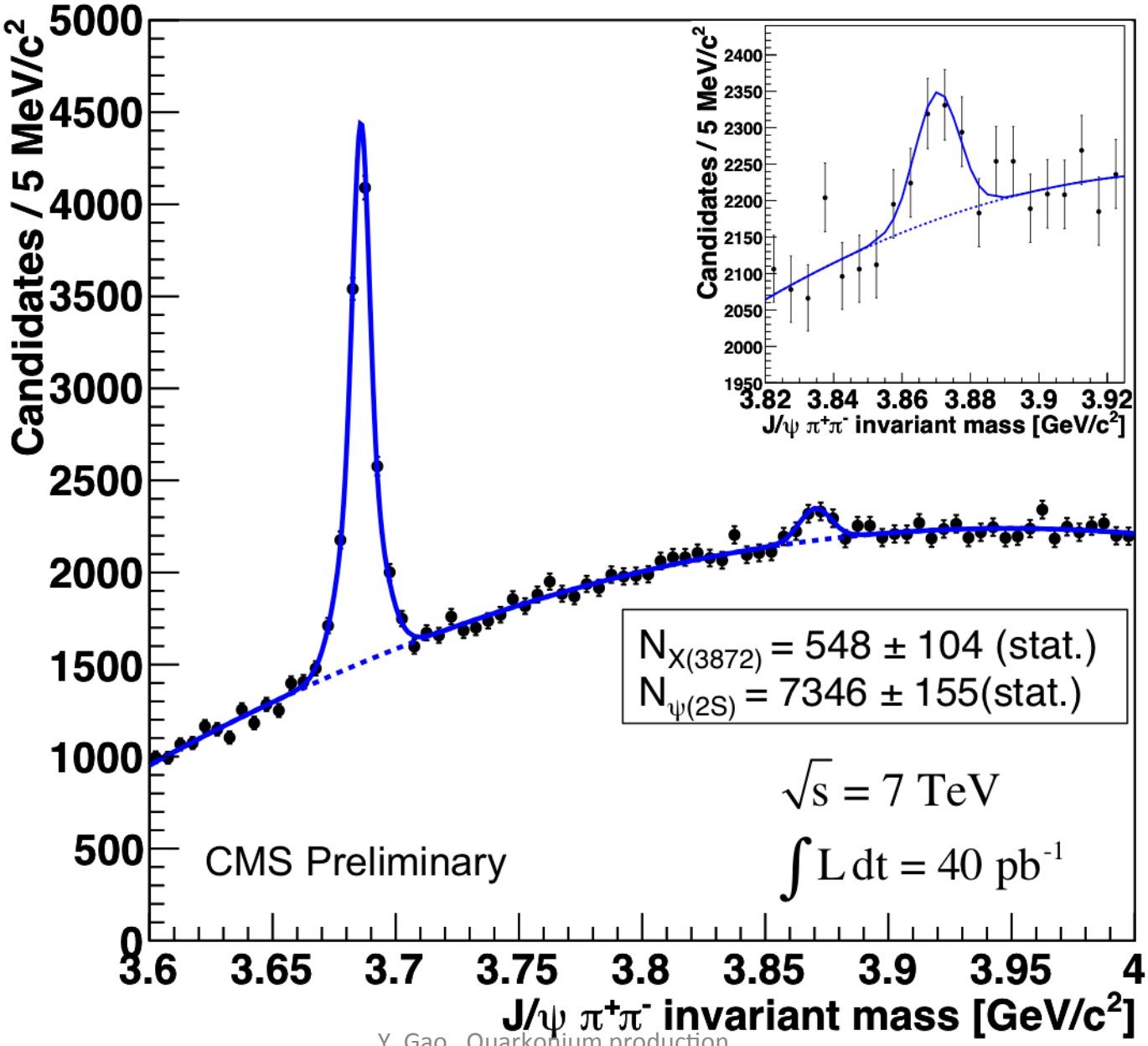

LHCb data (2.0<y<4.5)
prompt NLO CEM (1.5<y<5)
LHCb
Preliminary
√s = 7 TeV
∫ L = 32.4 pb⁻¹
dσ(pp→Υ(1S)X)/dp_T [nb/(GeV/c)]
p_T of Υ(1S) (GeV/c)

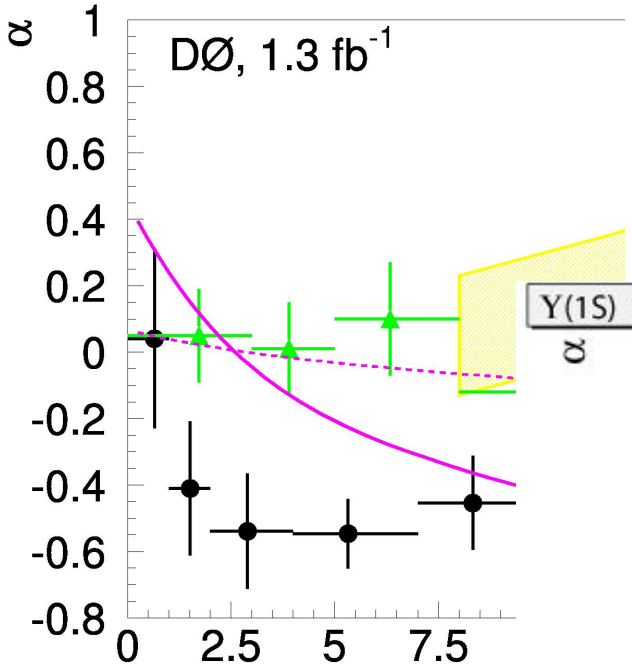

2011 Run, L = 1.1 fb-1
CMS √s = 7 TeV
Events per 10 MeV
dimuon mass [GeV]
trigger paths
ψ'
J/ψ
Bs → μ+μ-
Υ
low pT double muon
high pT double muon
ω
ϕ
J/ψ
ψ'
Bs
Υ
Z

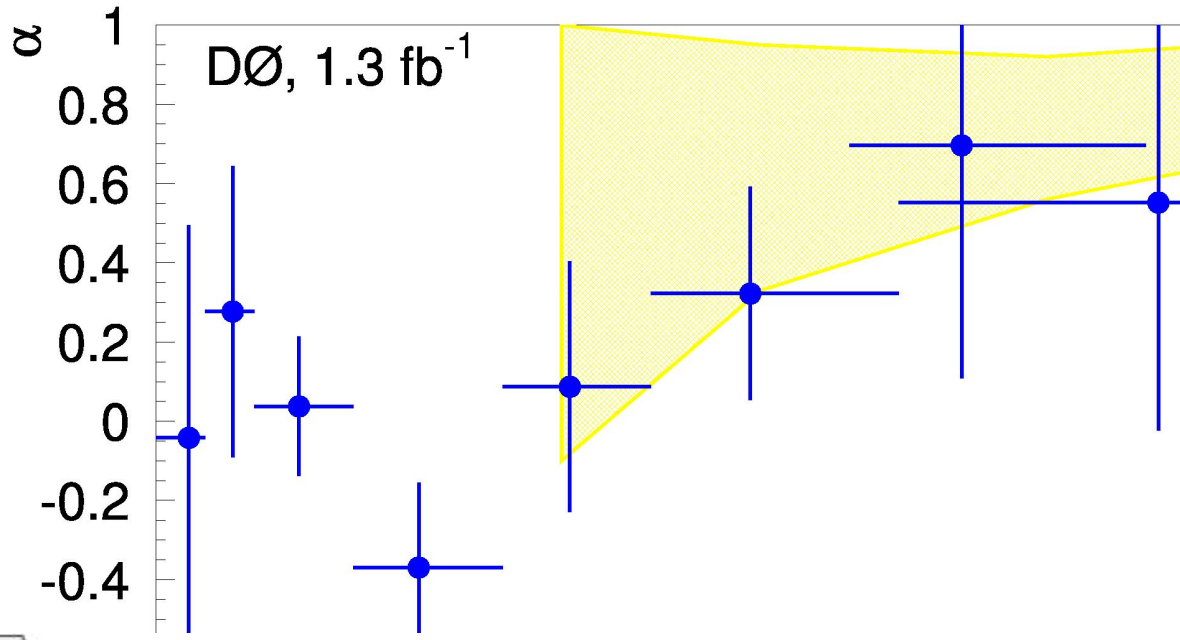

CDF II Preliminary 1.1 fb-1
Prompt ψ(2S): Run II Nominal 1.1 fb-1
(Actual 954 pb-1)
(stat.+syst. at <pT>)
Prompt ψ(2S): Run I 18 pb-1
(stat.+syst. at bin center)
dσ/dPT*BR [nb/(GeV/c)]
pT(ψ(2S)) [GeV/c]

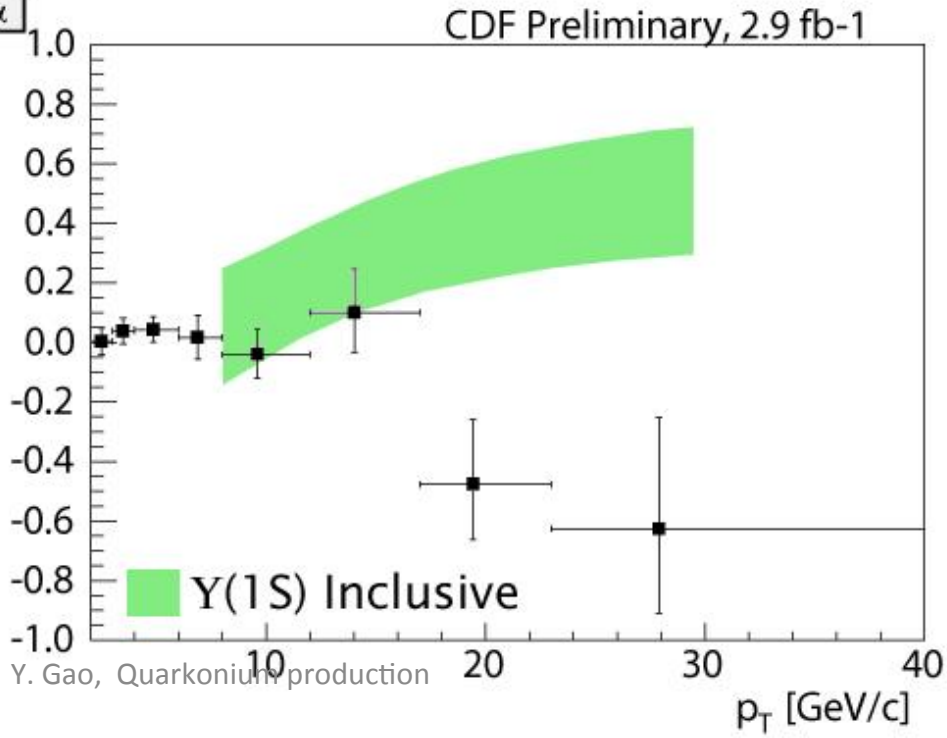

CDF II Preliminary 1.1 fb-1
B-decay ψ(2S): Run II Nominal 1.1 fb-1
(Actual 954 pb-1)
(stat.+syst. at <pT>)
B-decay ψ(2S): Run I 18 pb-1
(stat.+syst. at bin center)
dσ/dPT*BR [nb/(GeV/c)]
pT(ψ(2S)) [GeV/c]

CMS PAS BPH-10-018




α
DØ, 1.3 fb-1
Y(1S) α
0
2.5
5
7.5

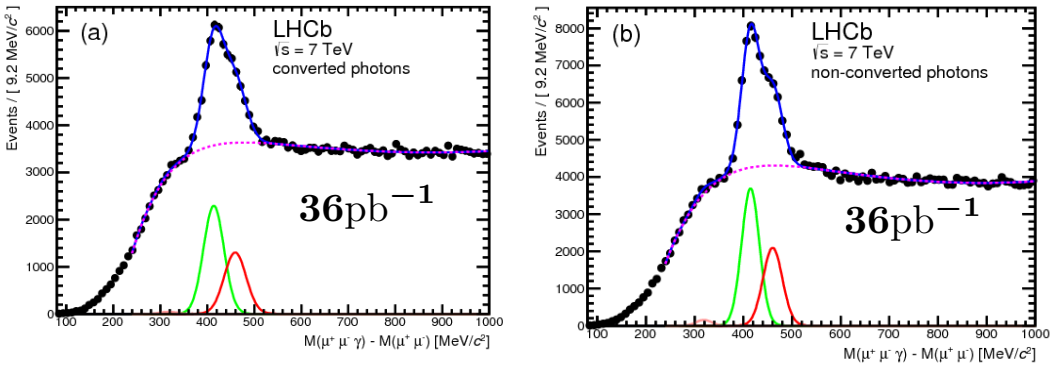

α
DØ, 1.3 fb-1

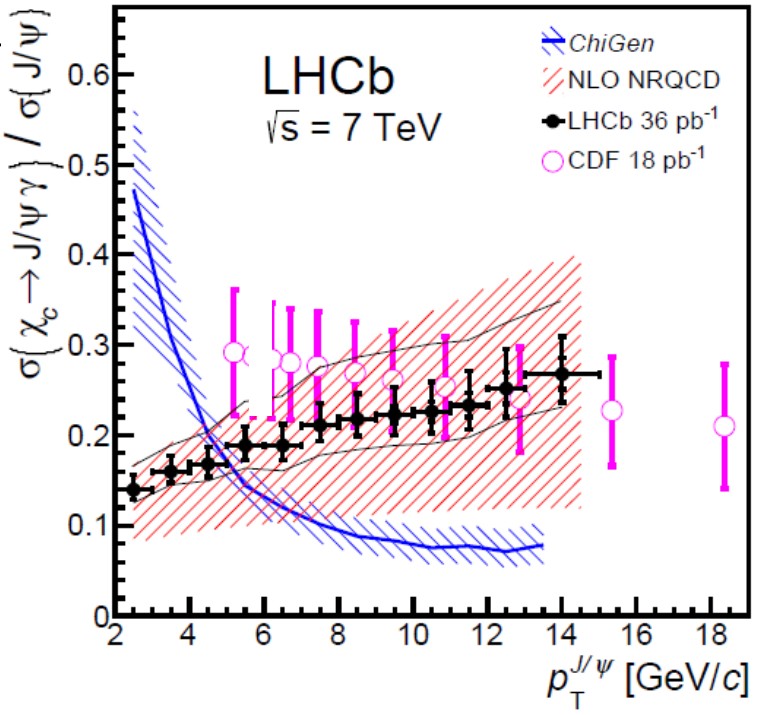

CDF Preliminary, 2.9 fb-1
Y(1S) Inclusive
pT [GeV/c]

D0 Collab. PF

$\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$ at LHCb

- Photon reconstructed in calorimeter only (higher eff., poorer resolution)
- Results in agreement with CS+CO NL





In figures above ONLY!

- converted = conversion after the magnet, e^+e^- in the calorimeter
- non-converted = photon in calorimeter

LHCb, arXiv:1202.1462
CDF, PRL 79 (1997) 579