Production & Decay of Heavy Flavours

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ICISE, QUY NHON

PDG particle data group

Introduction

Caveat emptor

I am an experimentalist with a passion for heavy flavour at hadron colliders.

My selection of topics will reflect that!

- HF in this talk
  - Open HF
  - Quarkonia
  - Exotica
  - Polarization

Will not cover (among others):

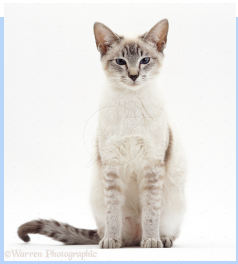
- CP violation & rare decays
- (most) Heavy Ions
- Detailed review of theory advances
- Fixed target results
- HF jet-ology

Apologies for the neglected areas!

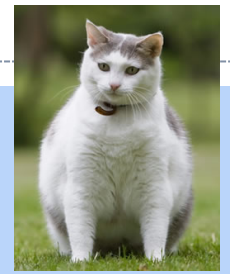
Where are we? Where do we go from here?

HF Production

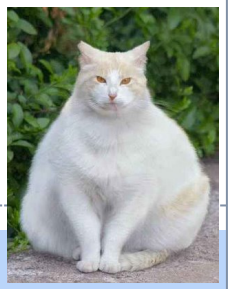
- Nature provides us with light, heavy and super-heavy quarks
  - Will focus here on heavy ones
- HF: experimentally produced from non-HF states ➜
  - Very interesting QCD process
  - BSM physics contributions envisageable
  - ~less interesting for the fundamentalist of flavour (CP/CKM dynamics)



u, d, s



c, b



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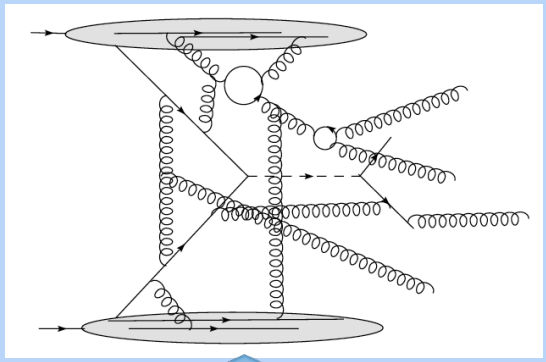
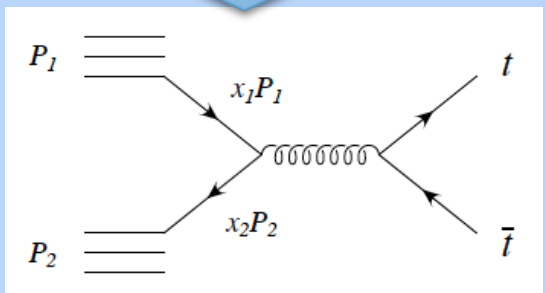




HF Production and QCD

- Increasingly accurate predictions from QCD (e.g. NLO+PS)
- Wider range and higher precision in experimental results ➜ breaking/improving theory possible at higher energies:
  - Large p_T heavy hadrons
  - Heavy quarks in high-p_T jets
- Besides, there are still things to be understood!

Open Heavy Flavour

Cast of Characters

- The zoology and spectroscopy of HF

C_{had}	Mass (GeV)	$c\tau$ (μm)	$B(C_{had} \to lX)$ (%)	$B(C_{had} \to$ Hadrons) (%)
$D^+(c\bar{d})$	1.869	315	17.2	$K^-\pi^+\pi^+$ (9.1)
$D^-(\bar{c}d)$	1.869	315	17.2	$K^+\pi^-\pi^-$ (9.1)
$D^0(c\bar{u})$	1.864	123.4	6.87	$K^-\pi^+$ (3.8)
$\overline{D^0}(\bar{c}u)$	1.864	123.4	6.87	$K^+\pi^-$ (3.8)
$D^{*\pm}$	2.010			$D^0\pi^\pm$ (67.7), $D^\pm\pi^0$ (30.7)
D^{*0}	2.007			$D^0\pi^0$ (61.9)
$D_s^+(c\bar{s})$	1.969	147	8	$K^+K^-\pi^+$ (4.4), $\pi^+\pi^+\pi^-$ (1.01)
$D_s^-(\bar{c}s)$	1.969	147	8	$K^+K^-\pi^-$ (4.4), $\pi^+\pi^-\pi^-$ (1.01)
$\Lambda_c^+(udc)$	2.285	59.9	4.5	ΛX (35), $pK^-\pi^+$ (2.8)
$\Sigma_c^{++}(uuc)$	2.452			$\Lambda_c^+\pi^+$ (100)
$\Sigma_c^+(udc)$	2.451			$\Lambda_c^+\pi^0$ (100)
$\Sigma_c^0(ddc)$	2.452			$\Lambda_c^+\pi^-$ (100)
B_{had}	Mass (GeV)	$c\tau$ (μm)	$B(B_{had} \to lX)$ (%)	$B(B_{had} \to$ Hadrons) (%)
$B^+(u\bar{b})$	5.2790	501	10.2	$\overline{D}^0\pi^-\pi^+\pi^+$ (1.1), $J/\psi K^+$ (0.1)
$B^-(\bar{u}b)$	5.2790	501	10.2	$D^0\pi^+\pi^-\pi^-$ (1.1), $J/\psi K^-$ (0.1)
$B^0(d\bar{b})$	5.2794	460	10.5	$D^-\pi^+$ (0.276), $J/\psi K^+\pi^-$ (0.0325)
$\overline{B^0}(\bar{d}b)$	5.2794	460	10.5	$D^+\pi^-$ (0.276), $J/\psi K^-\pi^+$ (0.0325)
$B_c^+(c\bar{b})$	6.4			$J/\psi\pi^+$ (0.0082)
$B_c^-(\bar{c}b)$	6.4			$J/\psi\pi^-$ (0.0082)
$\Lambda_b^0(udb)$	5.624	368		$J/\psi\Lambda$ (0.047), $\Lambda_c^+\pi^-$ (seen)

R. Vogt

Observables

- ~total cross-sections
  - ⇒ Test pQCD convergence, exclude large logs (small-x?)
- Differential distributions
  - Heavy mesons/hadrons
  - Leptons from HF
  - HF from HF

    (Hb→J/ψX, D_xX)

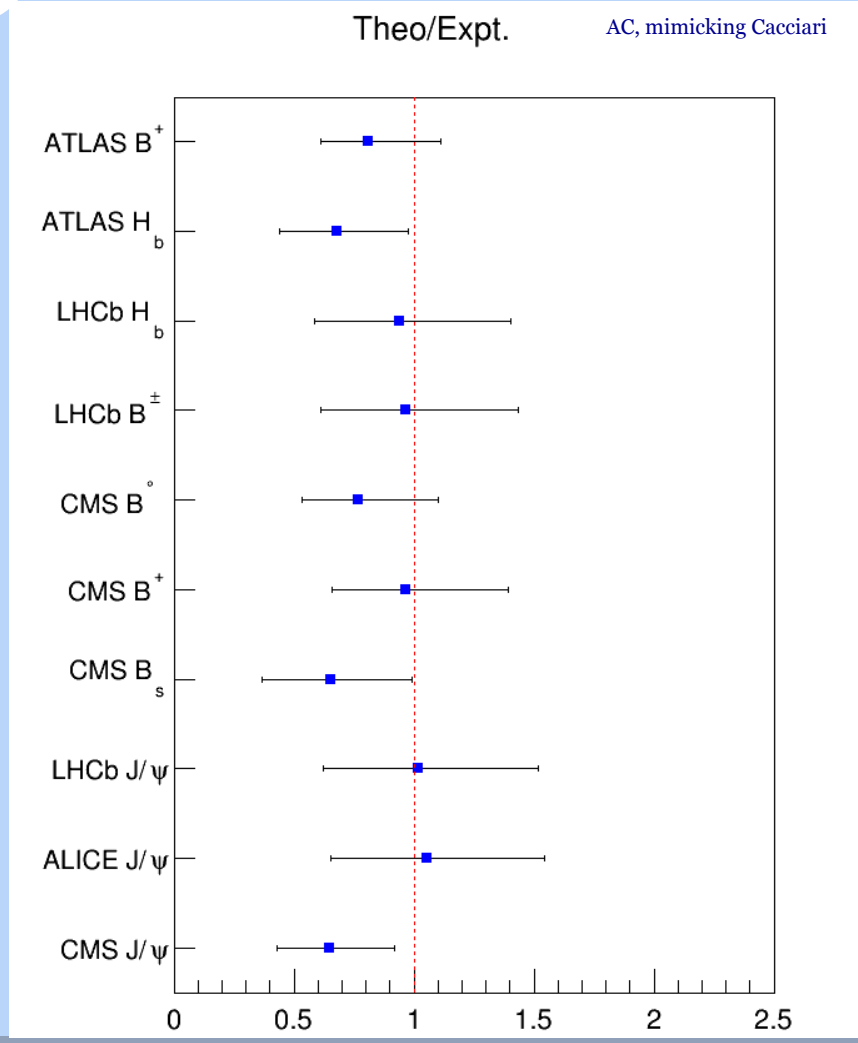
Test universality of NP:
- Decay functions
- Fragmentation functions

Ingredients we fit on data!

The measurement of very high pT (>>20×m) production will test NLL resummation

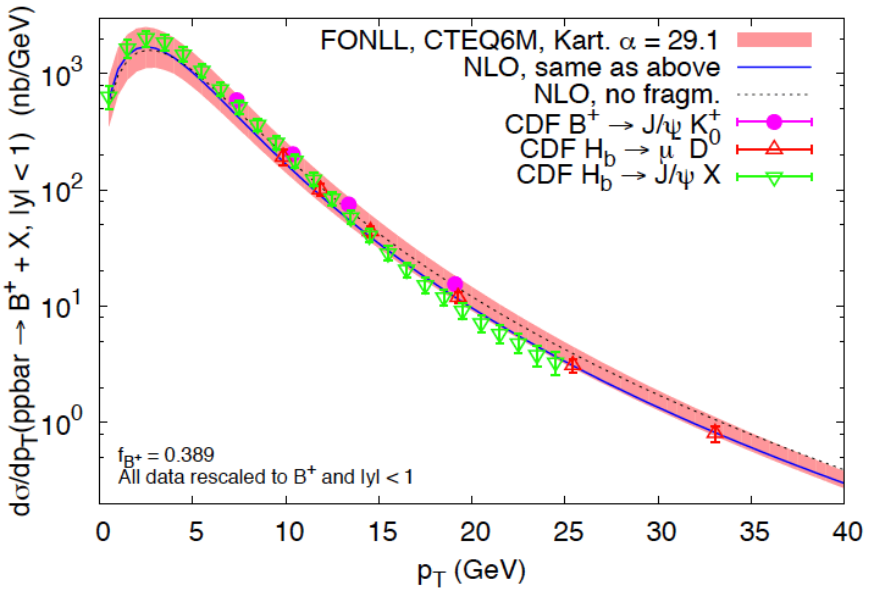
Total Cross Sections

Experiment	Observable σ (pT in GeV)	σ Measured μb	σ FONLL μb
ATLAS JHEP 10(2013)042	B^+ 120>pT>9 $\|y_B\|\leq 2.25$	10.6±0.9	$8.6^{+3.1}_{-2.0}$
ATLAS NPB864(2012)341-381	H_b pT>9 $\|\eta\|\leq 2.5$	$32.7^{+4.6}_{-6.9}$	$22.2^{+9.3}_{-6.3}$
LHCb PLB 694, 209-216 (2010)	H_b $2\leq\eta\leq 6$	75.3±11.4	$70.8^{+33.3}_{-24.4}$
LHCb JHEP 1204 (2012) 093	$B^\pm$ pT<40 $2\leq y\leq 4.5$	41.4±3.4	$40.1^{+19.0}_{-14.5}$
CMS PRL 106 (2011) 252001	B^0 pT>5 $\|y_B\|\leq 2.2$	33.2±4.3	$25.5^{+10.5}_{-7.1}$
CMS PRL 106 (2011) 112001	B^+ pT>5 $\|y_B\|\leq 2.4$	28.1±4.4	$27.2^{+11.2}_{-7.5}$
CMS PRD 84 (2011) 052008	B_s 50>pT>8 $\|y_B\|\leq 2.4$	6.9±0.8 nb	$4.5^{+2.3}_{-1.9}$ nb
LHCb EPJC 71 (2011) 1645	$H_b\rightarrow J/\psi$ pT<14 $2<\|y_\psi\|<4.5$	1.14±0.16	$1.16^{+0.55}_{-0.42}$
ALICE JHEP11(2012)065	$H_b\rightarrow J/\psi$ pT>1.3 $\|y_\psi\|<0.9$	1.26±0.16	$1.33^{+0.59}_{-0.48}$
CMS JHEP 1103 (2011) 090	$H_b\rightarrow J/\psi$ pT>6 $\|y_\psi\|<2.1$	1.32±0.34	$0.855^{+0.28}_{-0.19}$

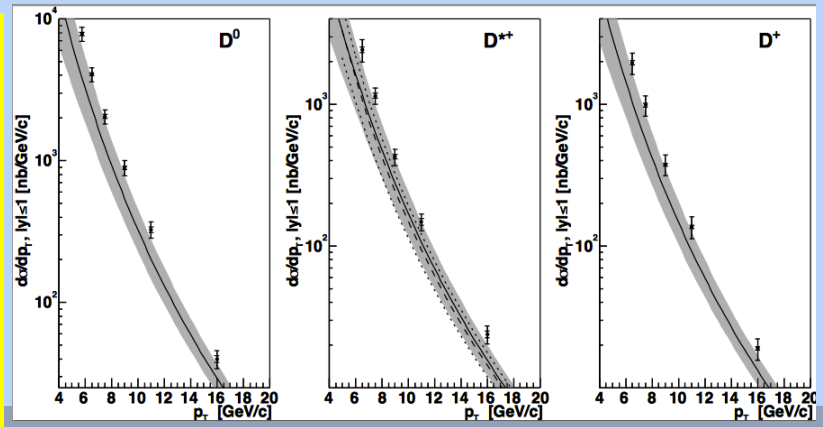


Differential σ: the pre-LHC Era (Tevatron, RHIC)

Cacciari et al., CERN-PH-TH/2011-227



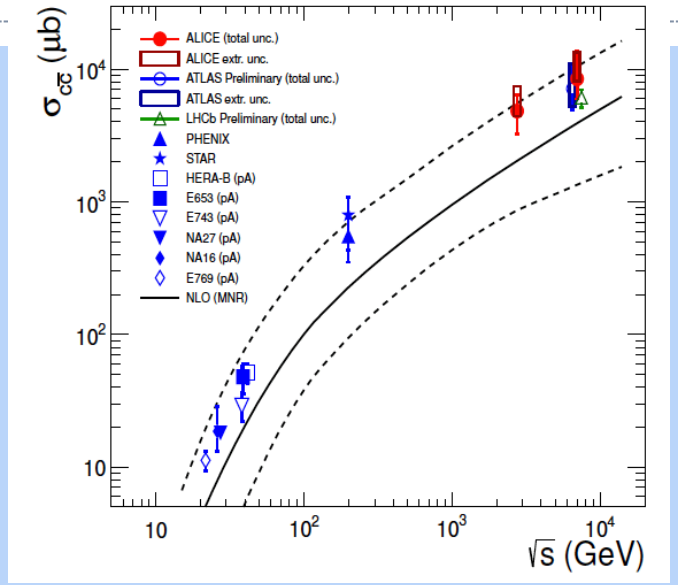
CDF: PRL 91:241804:2003



- Total & diff. HF σ from NLO QCD: accurate prediction
- Fragmentation from e^+e^- (CLEO, Belle, LEP) is predictive when used in hadroproduction
- NLL resummation in hadroproduction not yet probed
  - Needed to extract NP from e^+e^- data

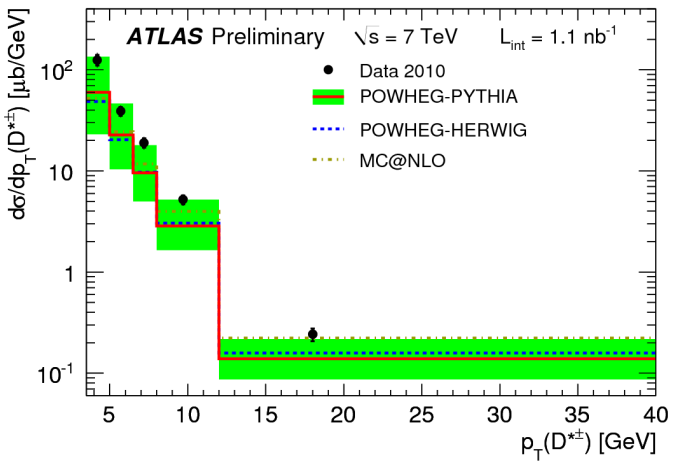
Charm production

ALICE JHEP07 (2012) 191



- Total σ agrees but…
  - large uncertainties
  - Significant theory-based extrapolations

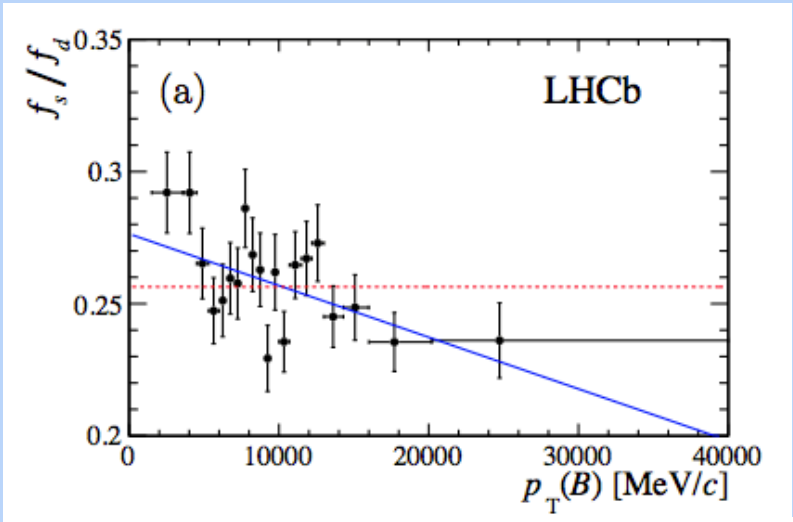
ATLAS-CONF-11-017

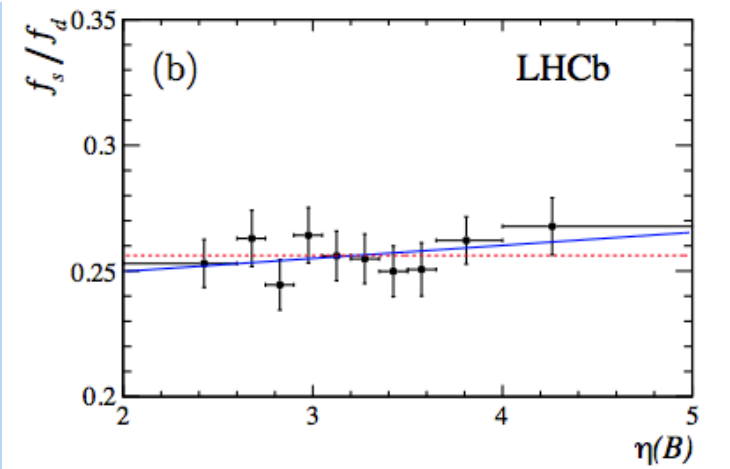


- Differential cross sections consistent but consistently high wrt theory

Fragmentation

Fragmentation Universality?



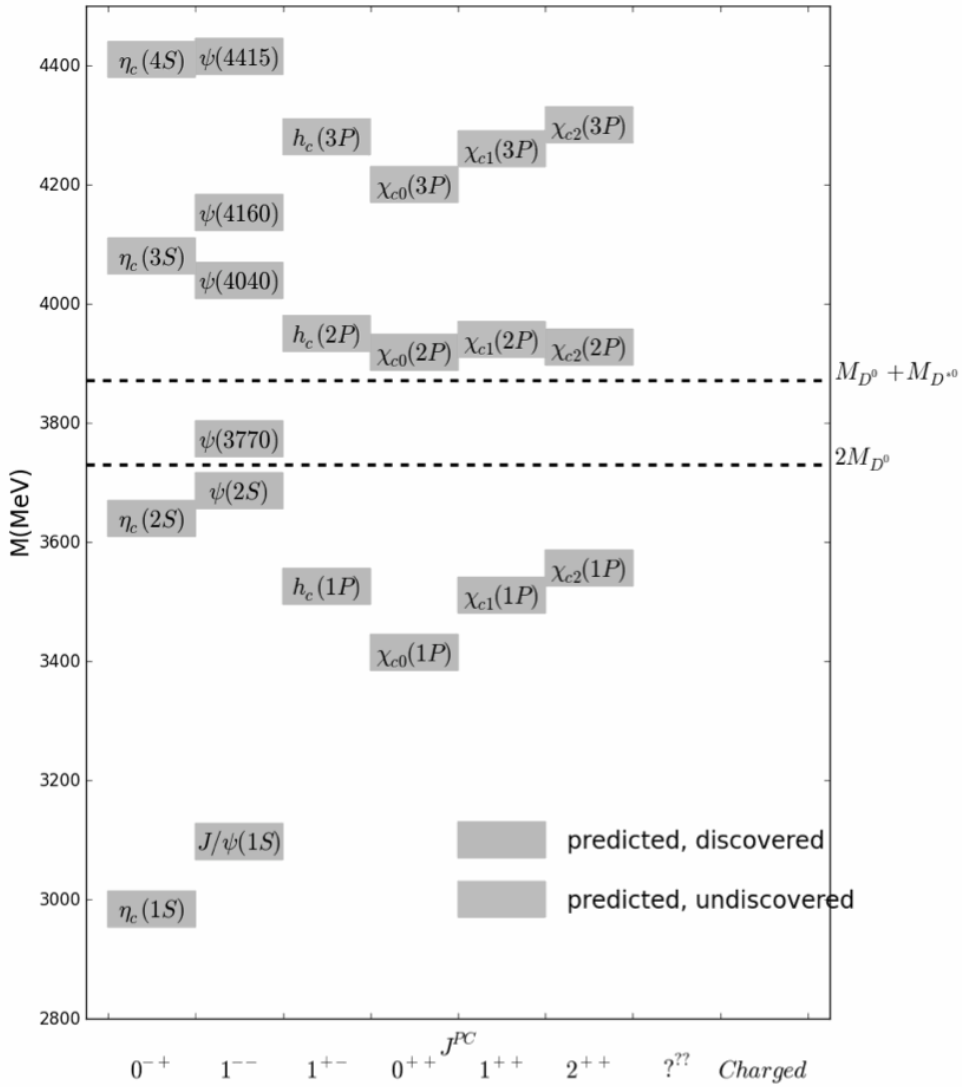


LHCb CERN-PH-EP-2013-006
arXiv 1301.5286

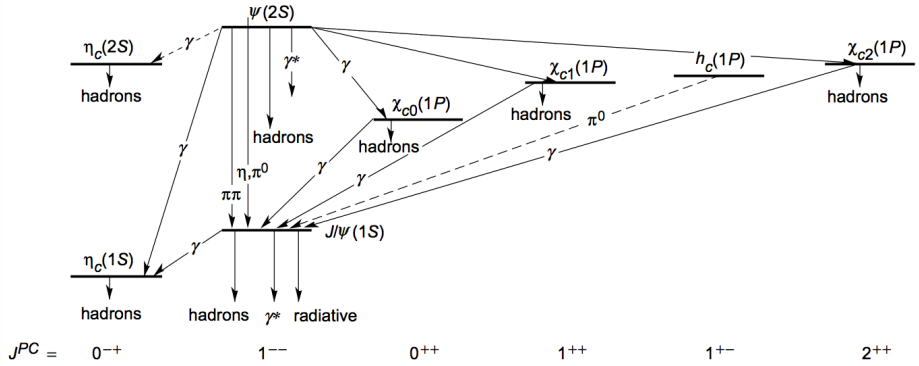
- Input to many BR (including rare decays)
- Precision (B_d, B_u) dominated by B factories
- Several universality assumptions:
  - e^+e^- vs hadroproduction
  - Y vs the rest of the world
  - pT
  - η

Exotica

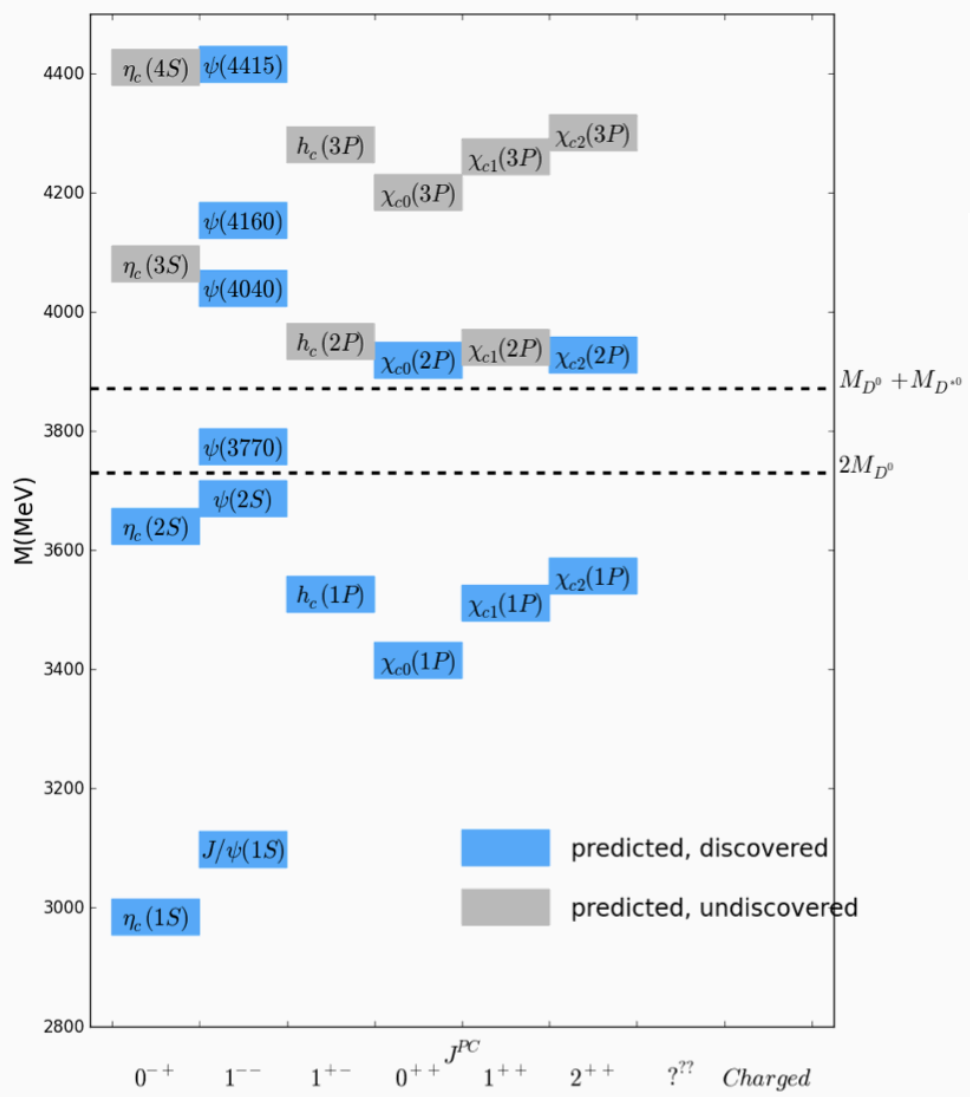
Charmonium Spectroscopy



Significant feed-down to onia production, e.g. J/ψ:



Charmonium Spectroscopy



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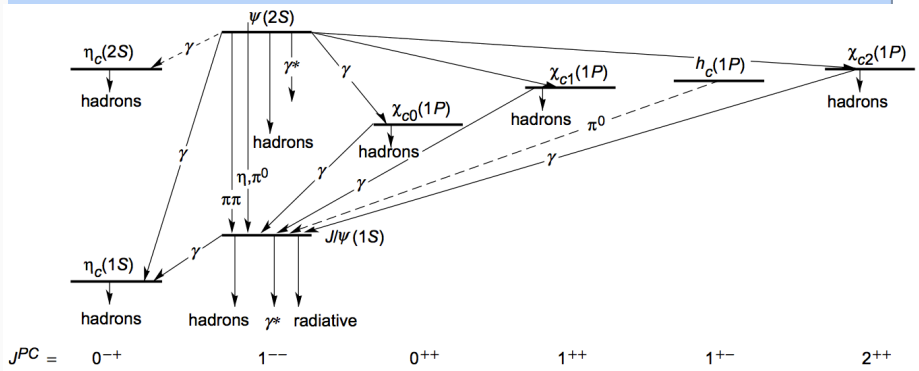
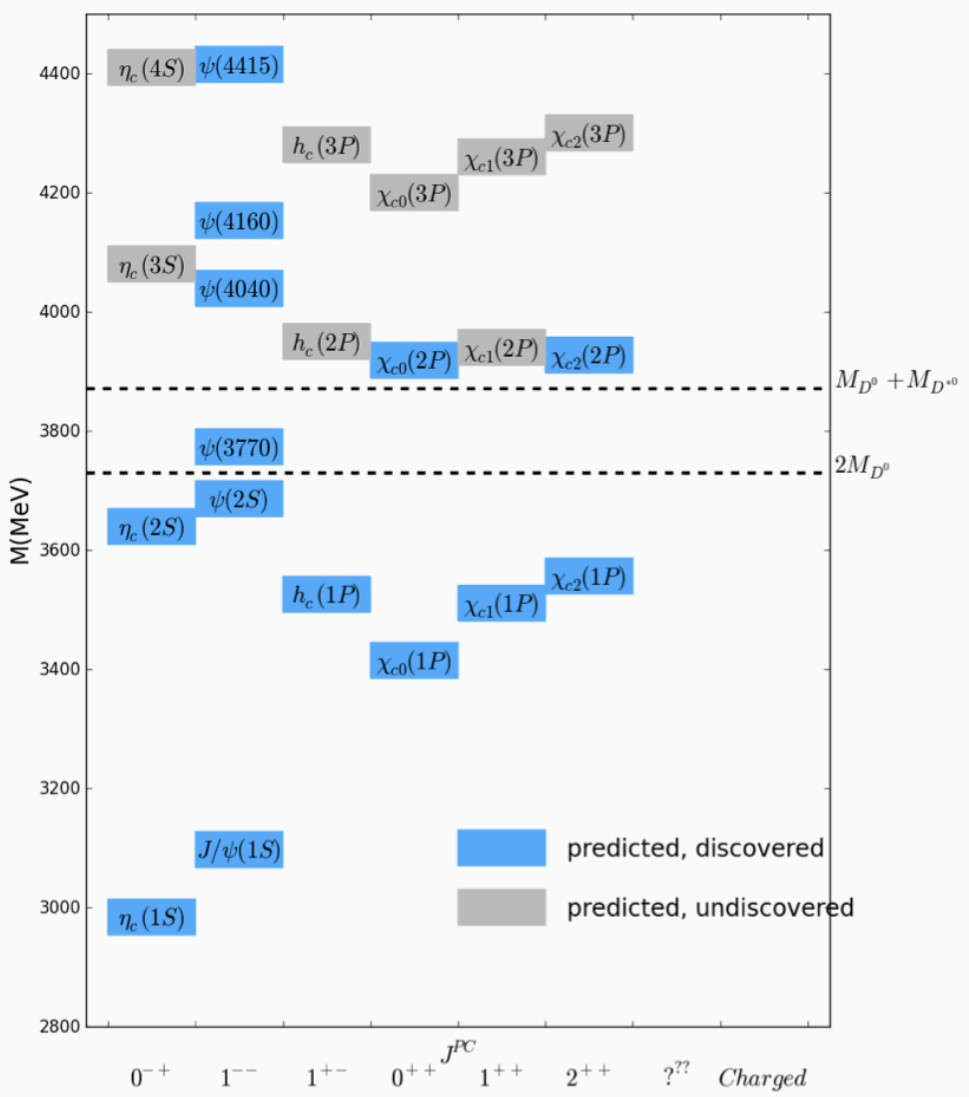
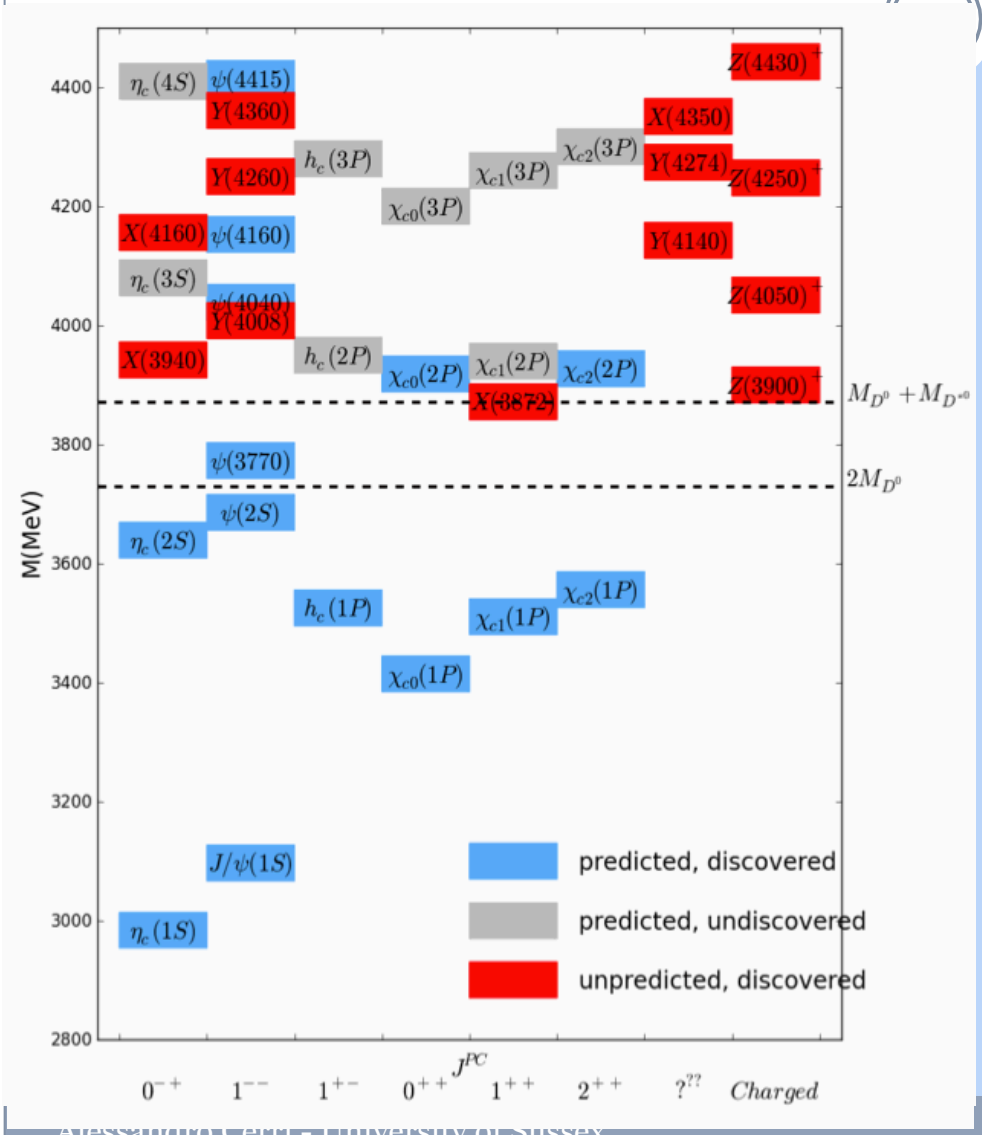


Exotics



- Known knowns:
  - 3 quantum numbers (J^{PC})
  - Nice agreement between prediction and observation…

Exotics

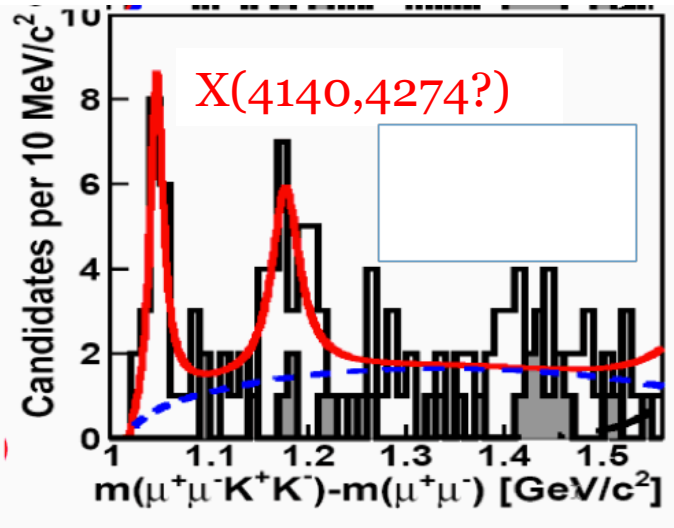


- Known unknowns:
  - X, Y, Z...
  - Charmonium in the final state, but what are they?!?
  - Present in several production mechanisms

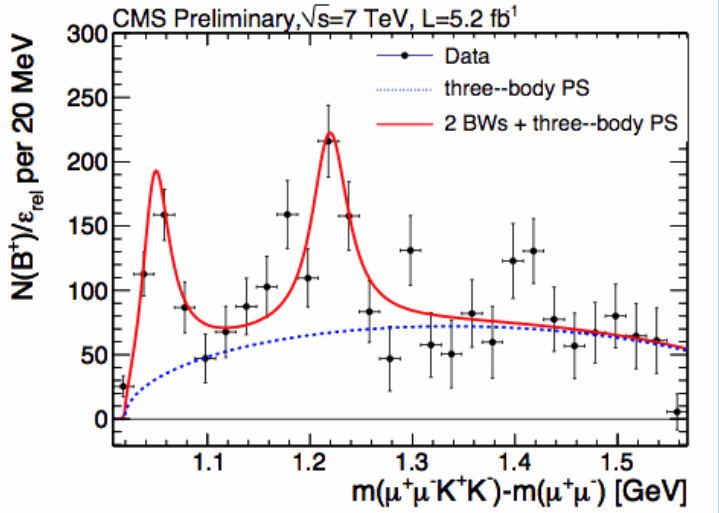
Exotics

- Some not so clearly seen…

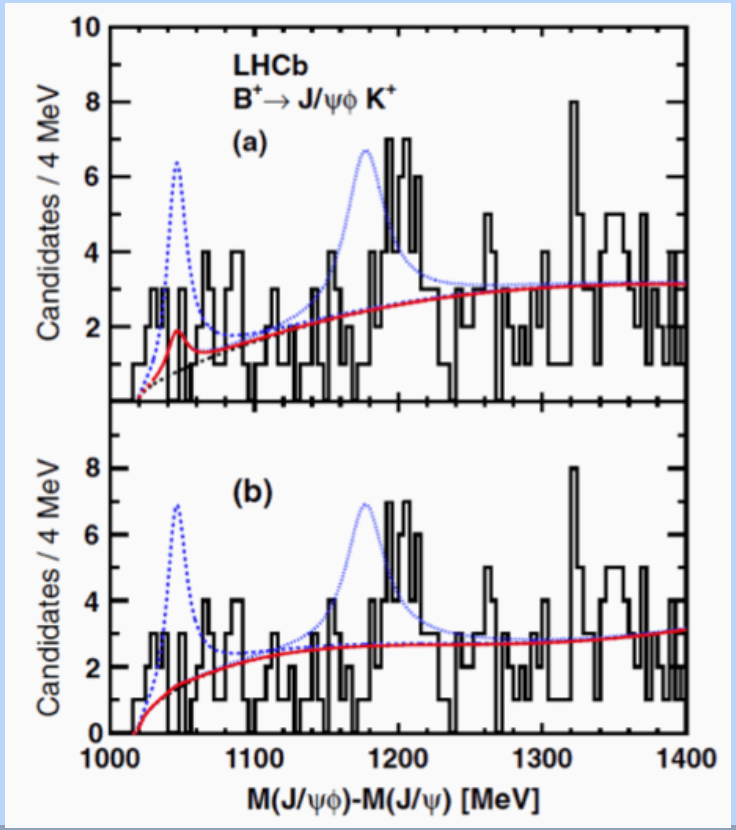
CDF arXiv 1101.6058



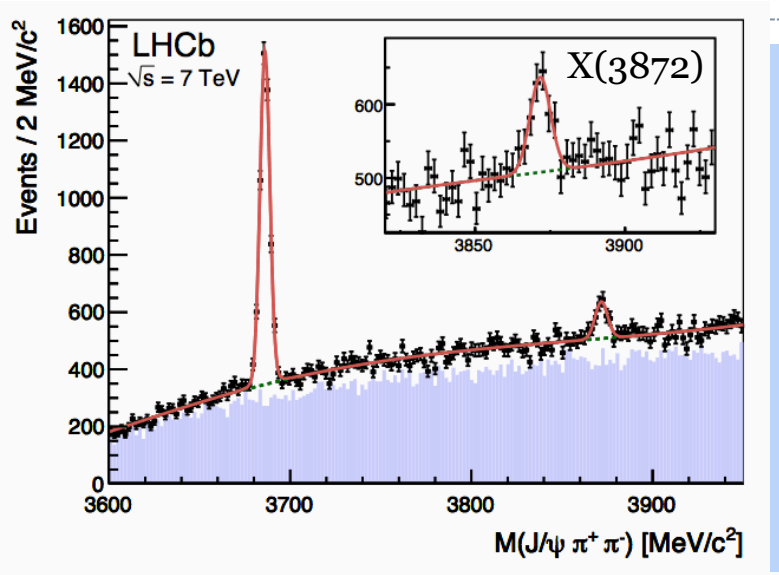
CMS

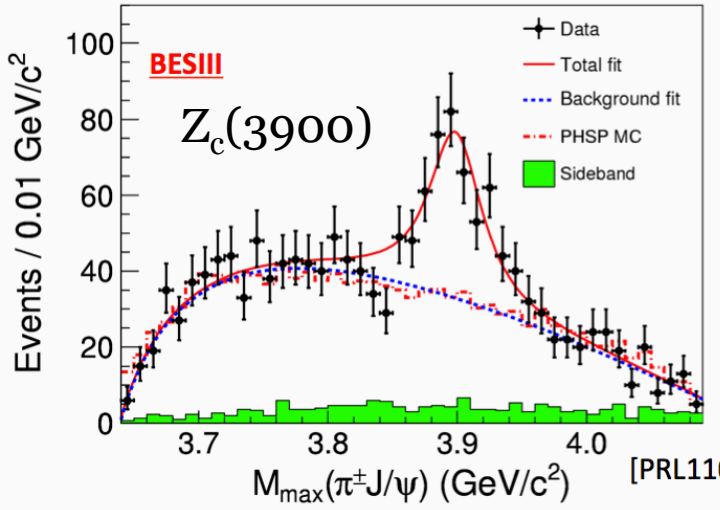


LHCb



Exotics

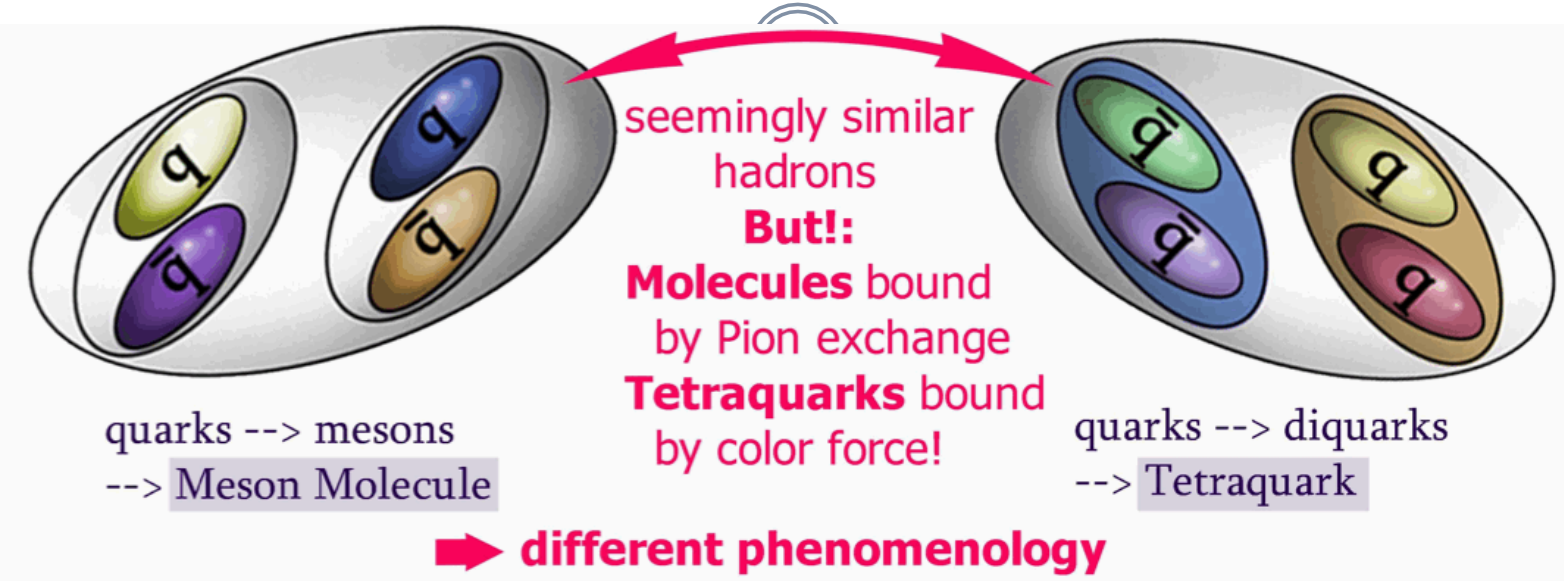


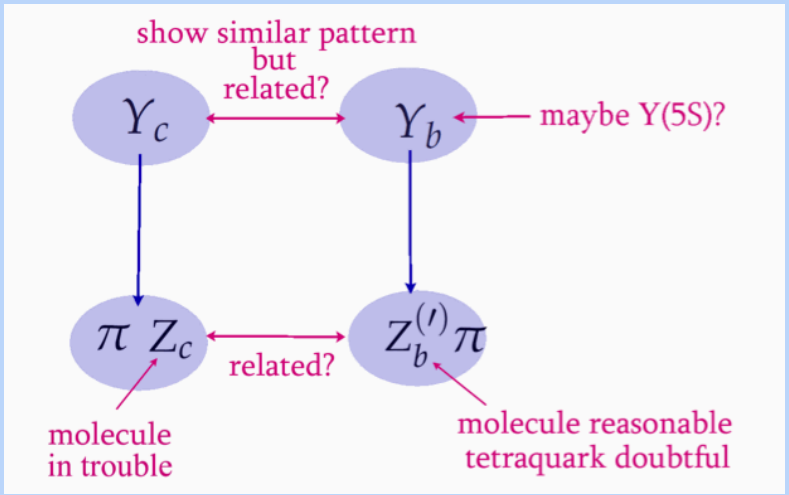


[PRL110, 252001 (2013)]

- Some are definitely here to stay!

Exotics: what model?





- e^+e^- results give no clear indication on "best model"
- Hadroproduction of exotics with mass precision is needed!

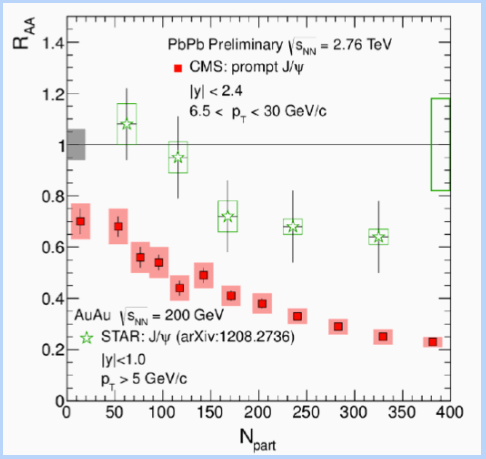
Quarkonia

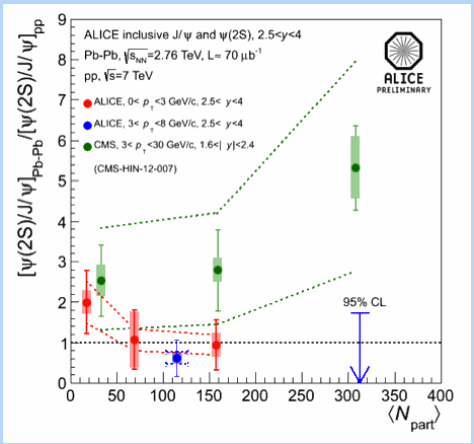
Quarkonia: HI

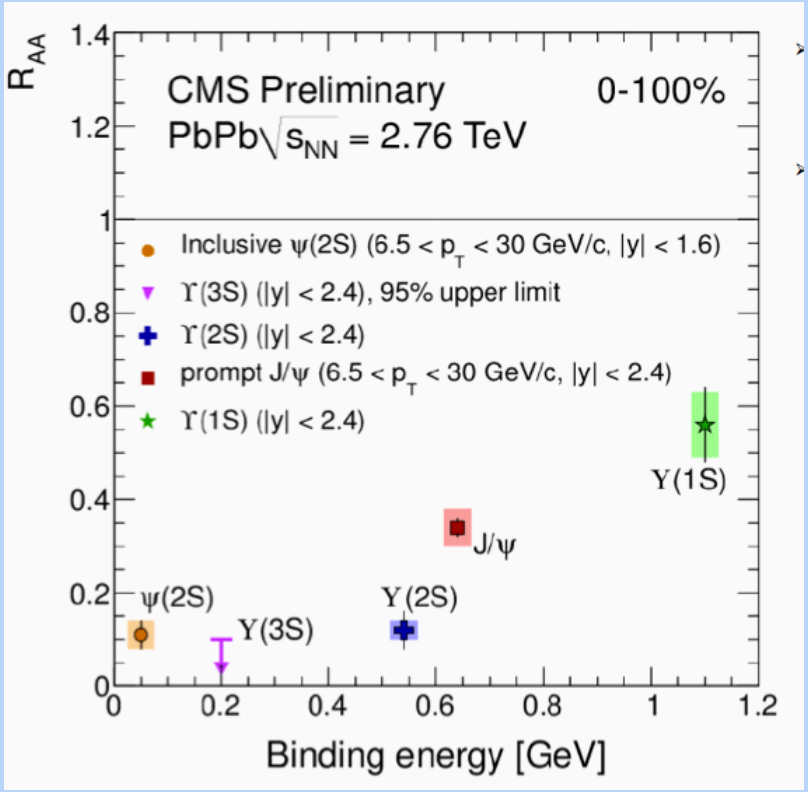
- Spectroscopy predictions very consistent
- Quarkonia used as probe through matter:

"Nuclear Modification Factor"

$$R_{AA} = \frac{d^2 N_{AA}/dp_T dy}{N_{coll} \times d^2 N_{pp}/dp_T dy}$$



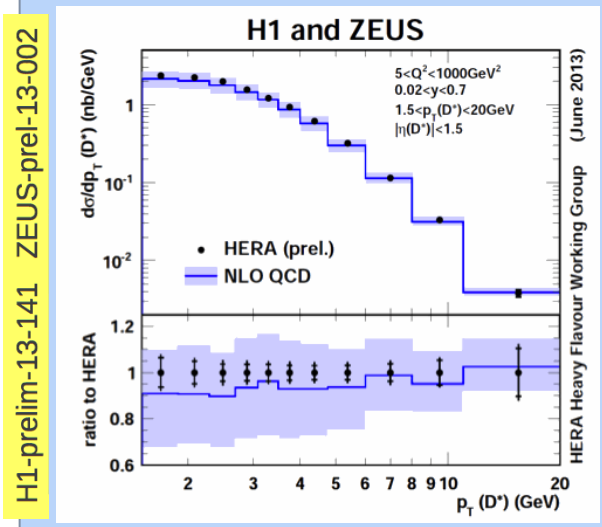




Suppression depends on binding energy!

Quarkonia: HERA

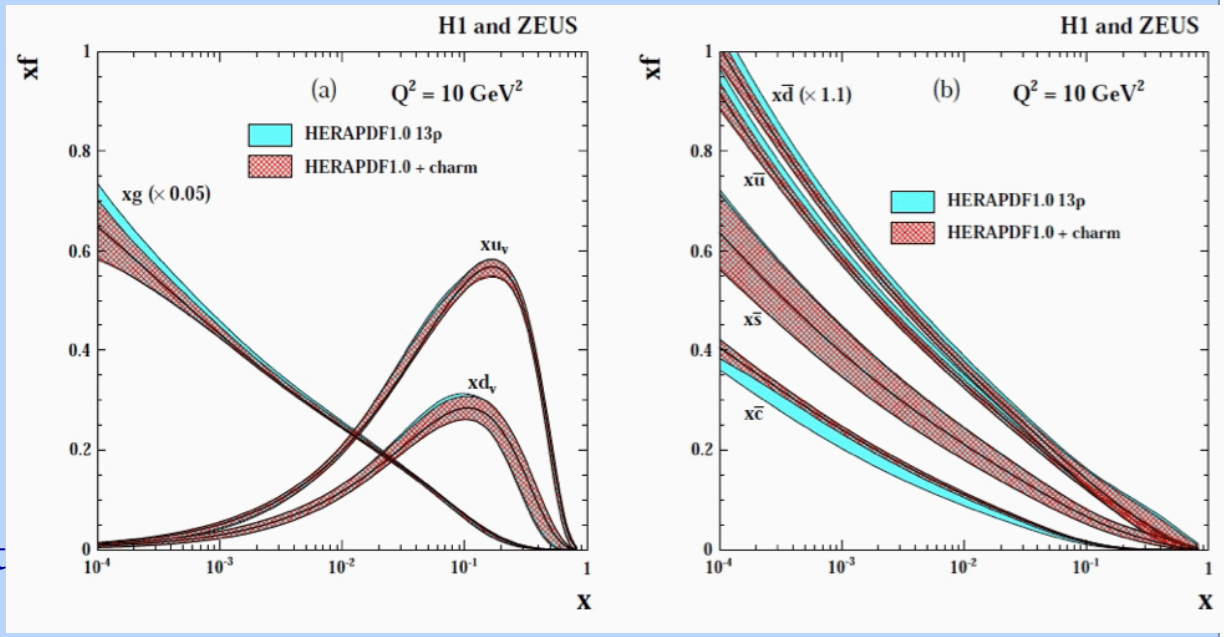
- Spectroscopy predictions very consistent
- Quarkonia used as probe through matter
- Production mechanisms probed in most environments (DIS, photoprod., …)



H1-prelim-13-141 ZEUS-prel-13-002

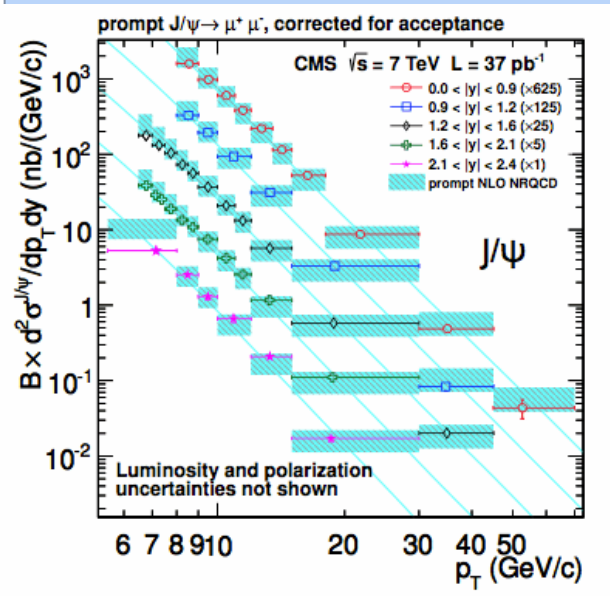
DIS production mechanisms: general agreement, more precision (e.g. full NNLO) sought [expt@5%, theo @10-30%]

PDF fits from HERA/onia data better constrain LHC predictions (e.g. W and Z production)!



Quarkonia PRODUCTION: LHC

- New exciting data available: better coverage, more detailed studies of prompt/non-prompt/direct/indirect



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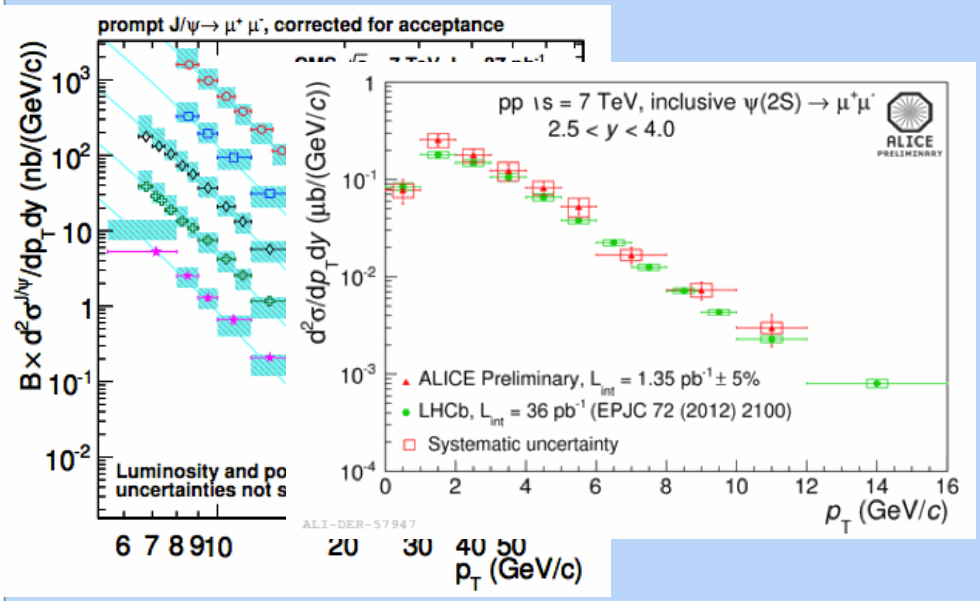

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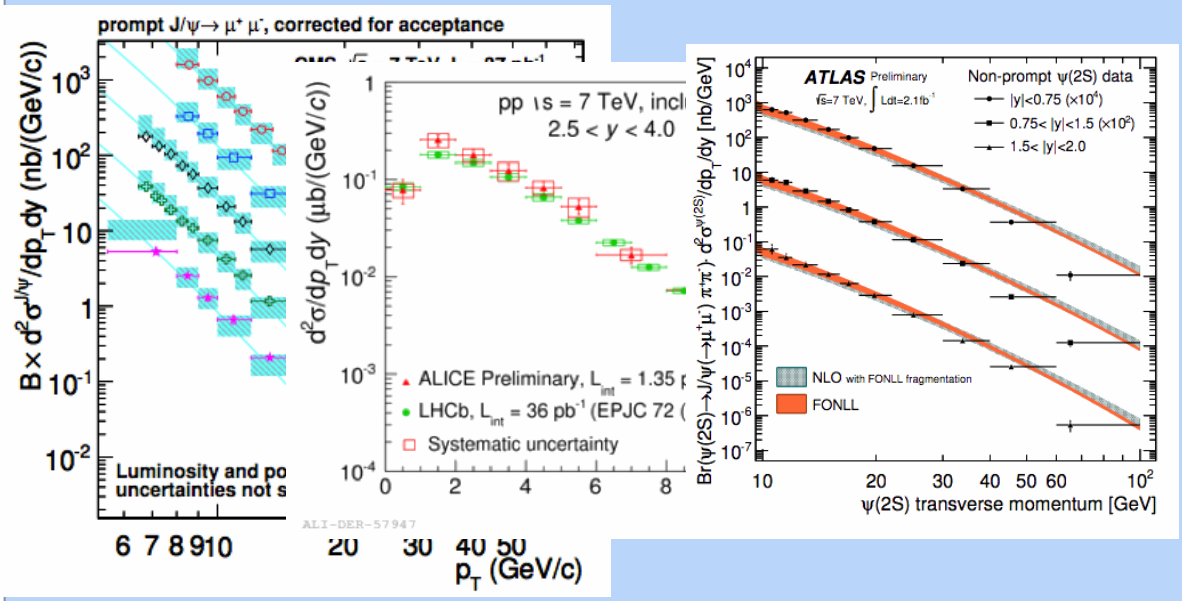

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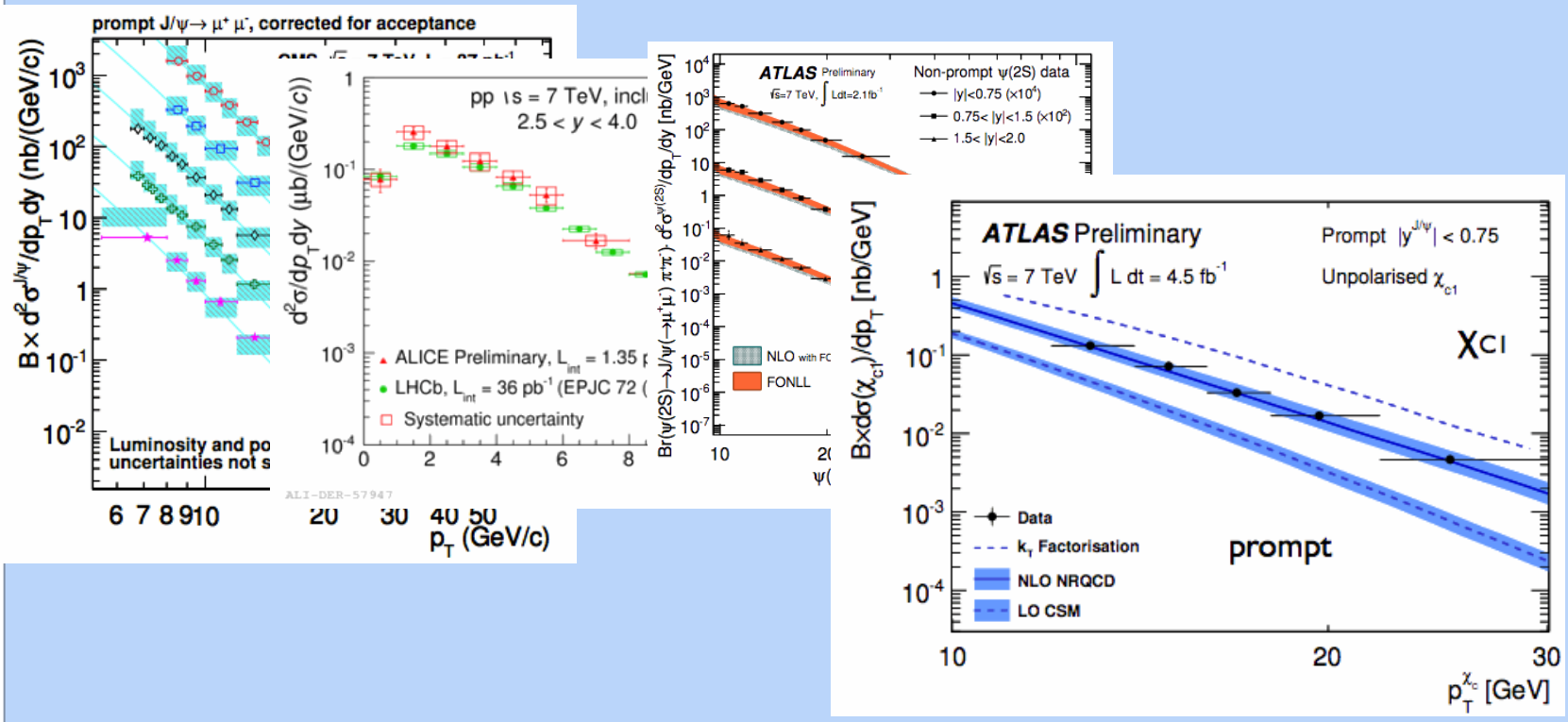

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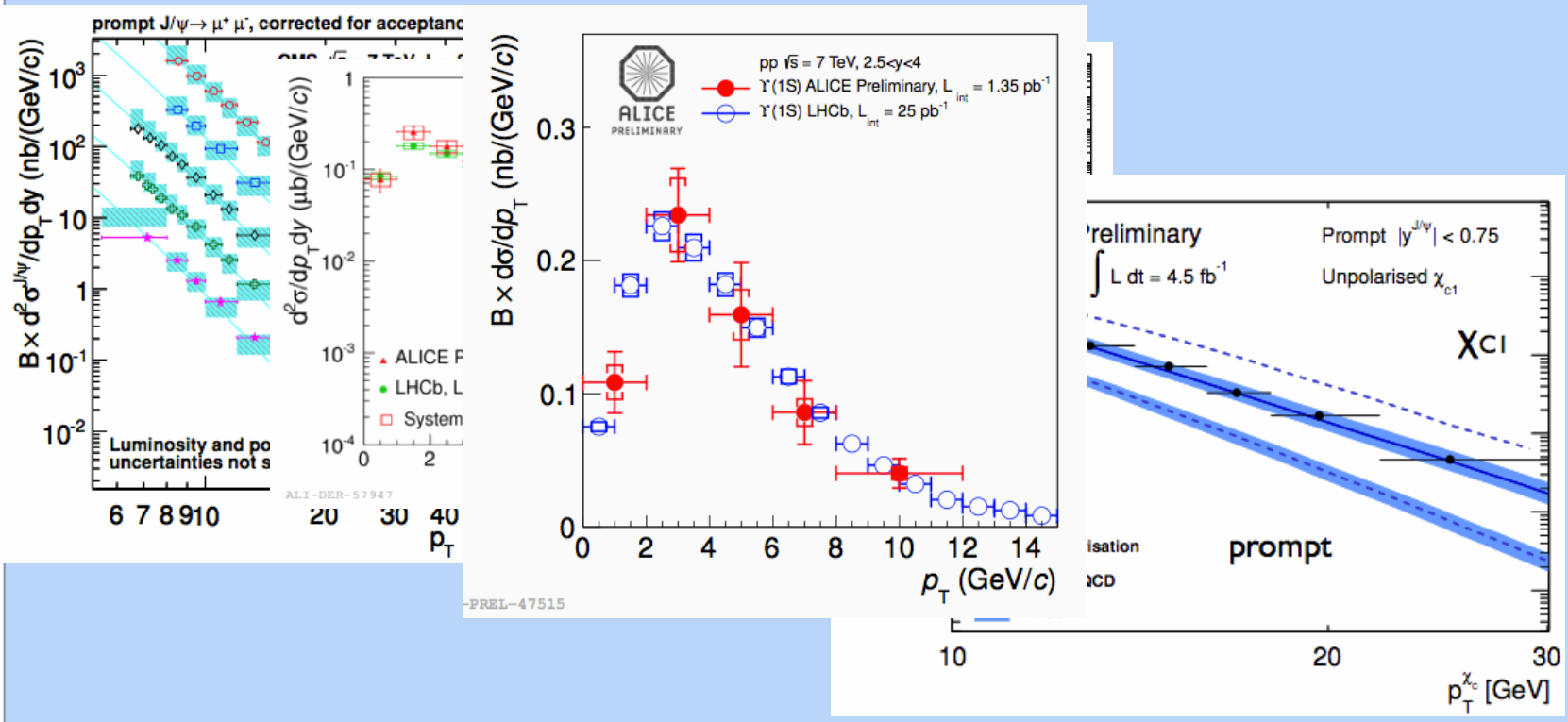

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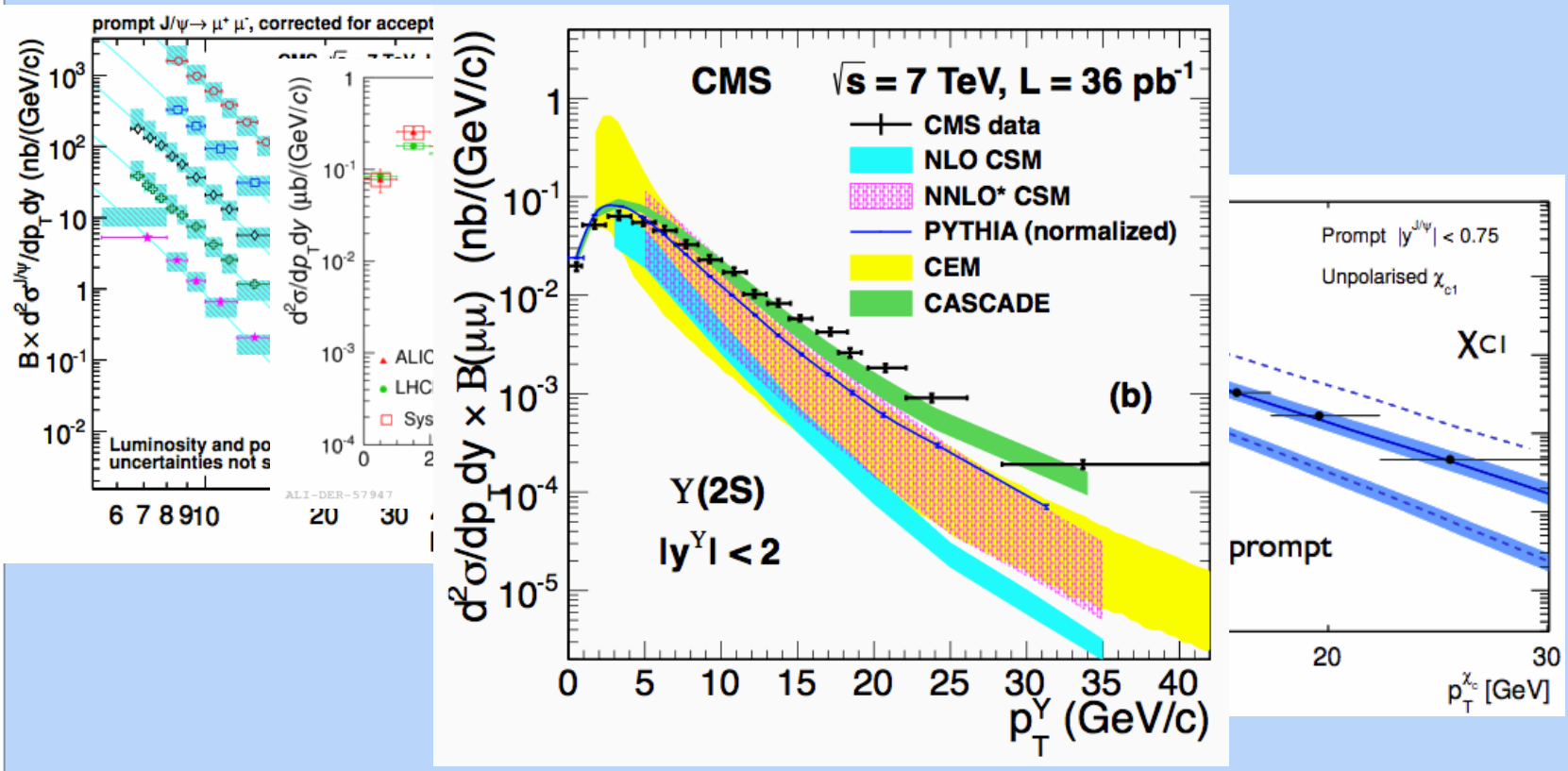

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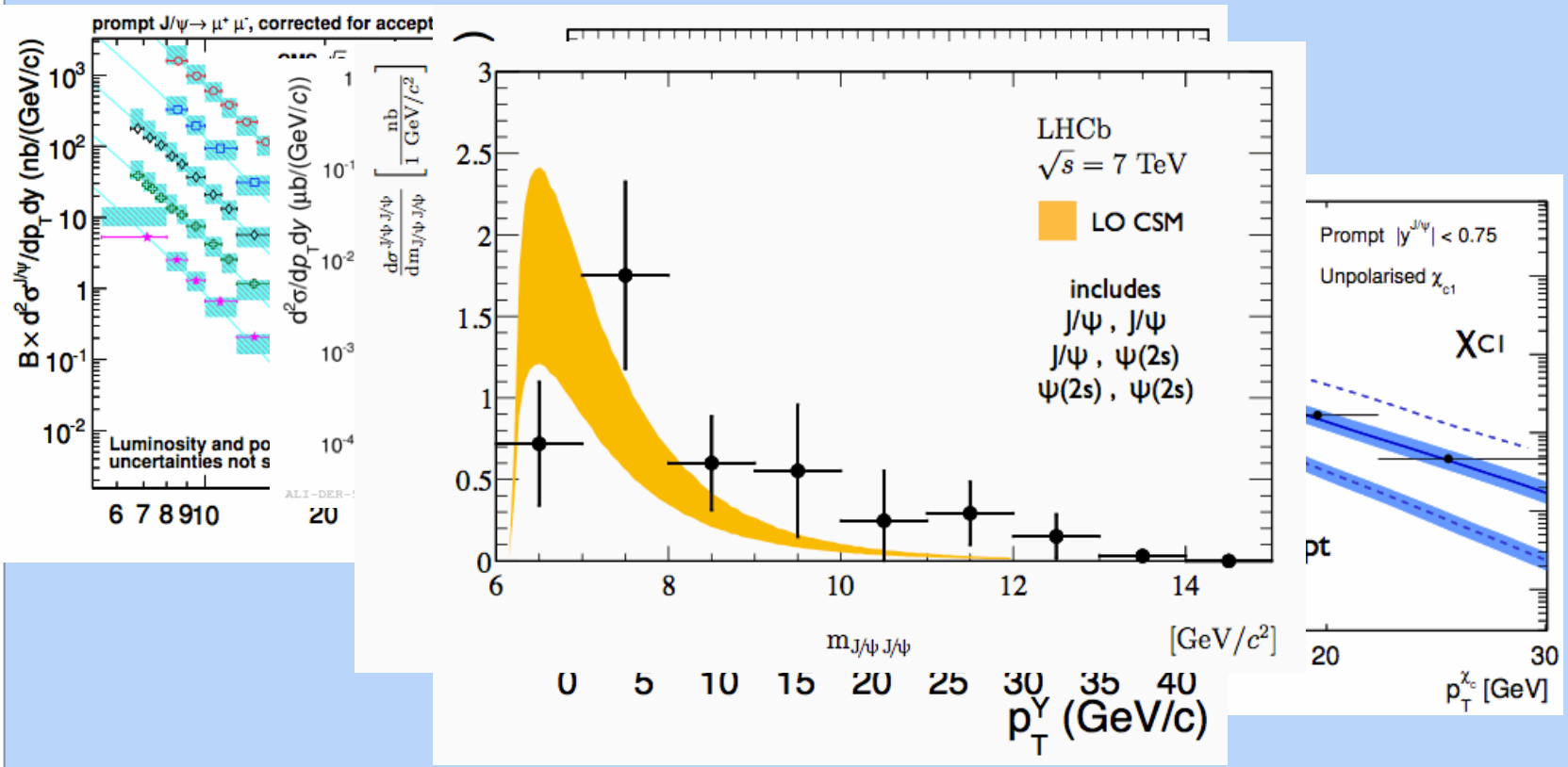

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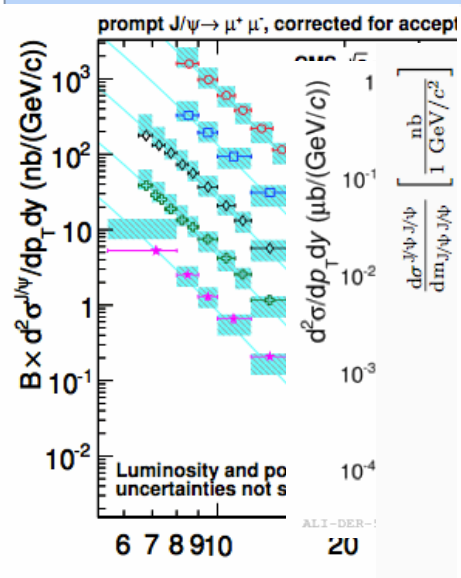
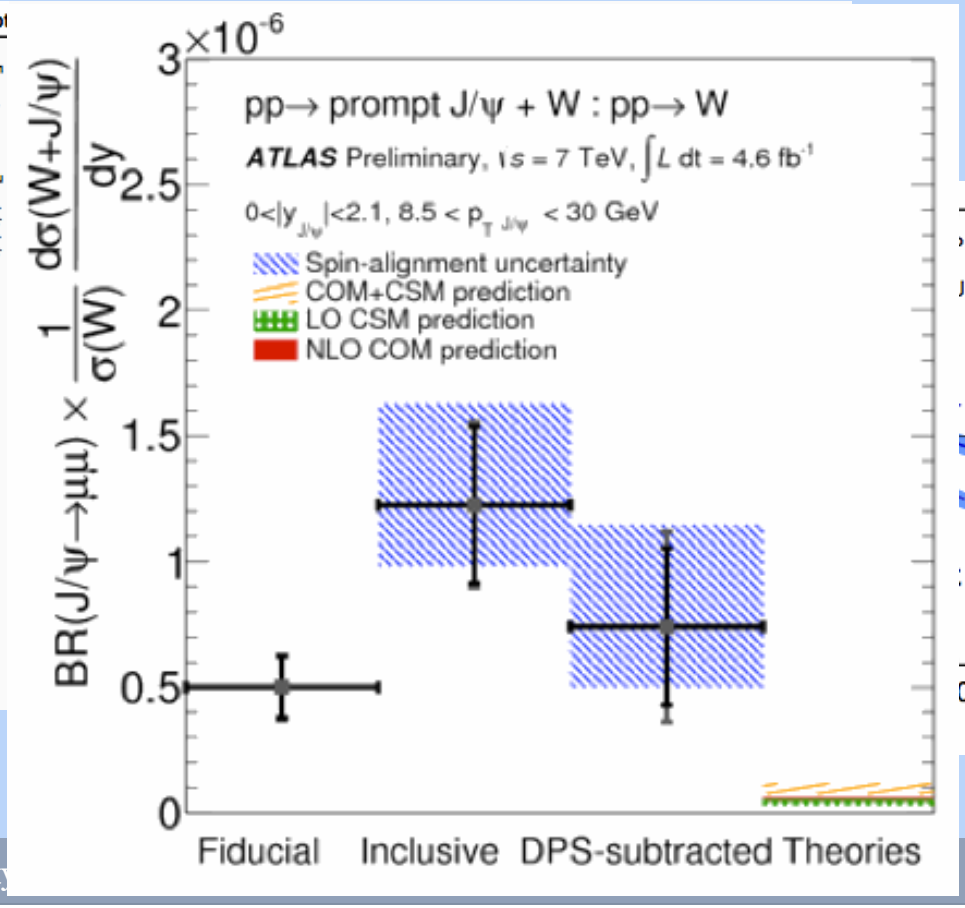
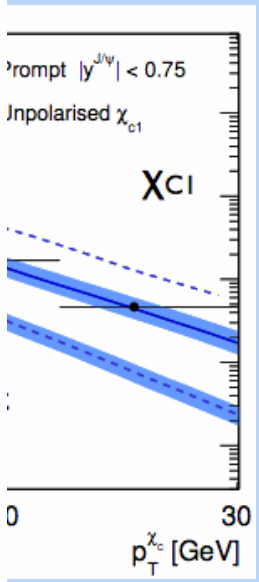
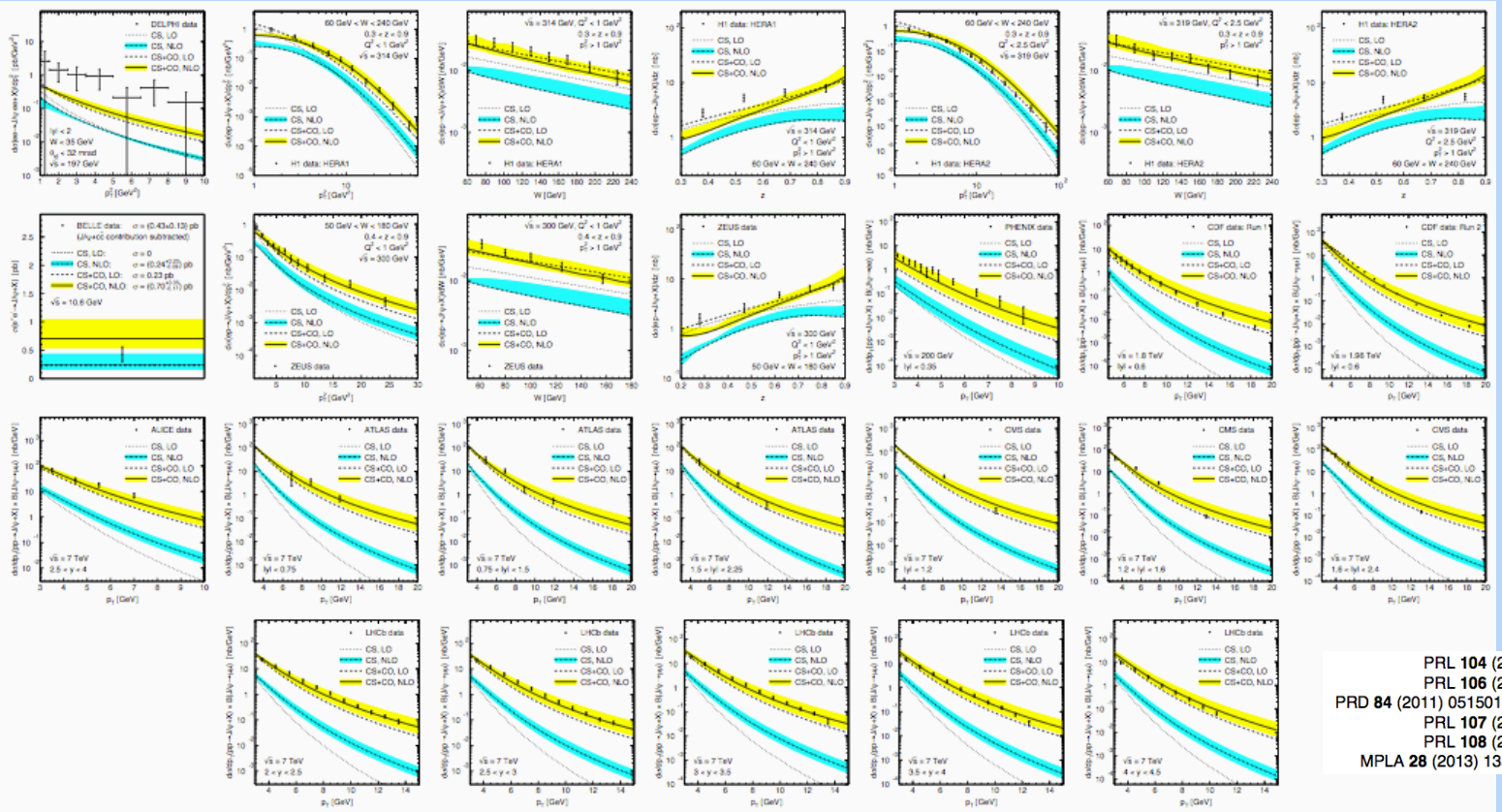






QUARKONIA: production mechanisms

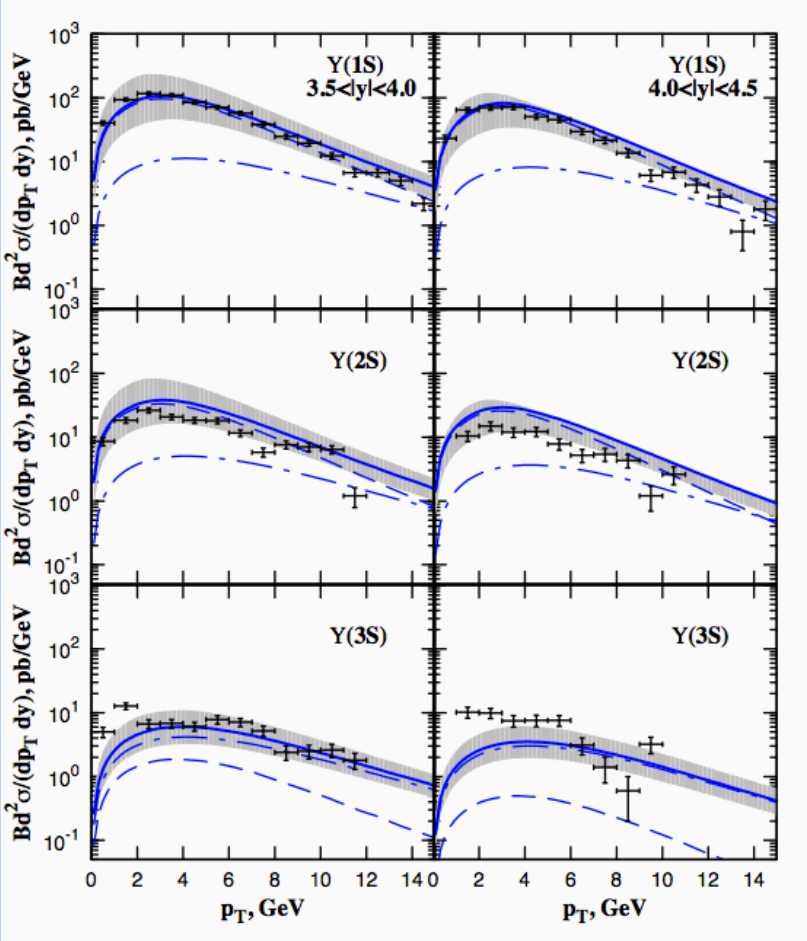
- Global fits are available on the market, looking rather nice across experiments for $c\bar{c}$



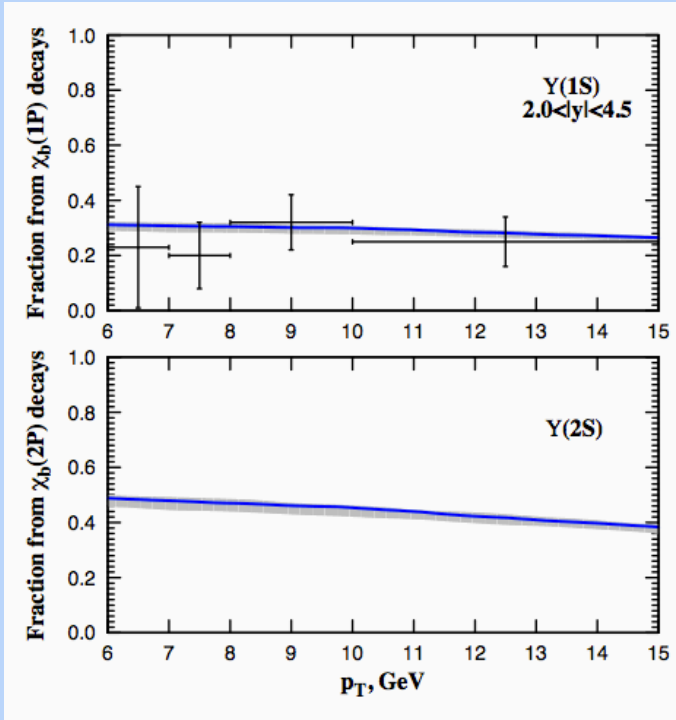
PRL **104** (2010) 072001
PRL **106** (2011) 022003
PRD **84** (2011) 051501 (Rapid Communications)
PRL **107** (2011) 232001
PRL **108** (2012) 172002
MPLA **28** (2013) 1350027 (Brief Reviews)

QUARKONIA: production mechanisms

- ...and $b\bar{b}$



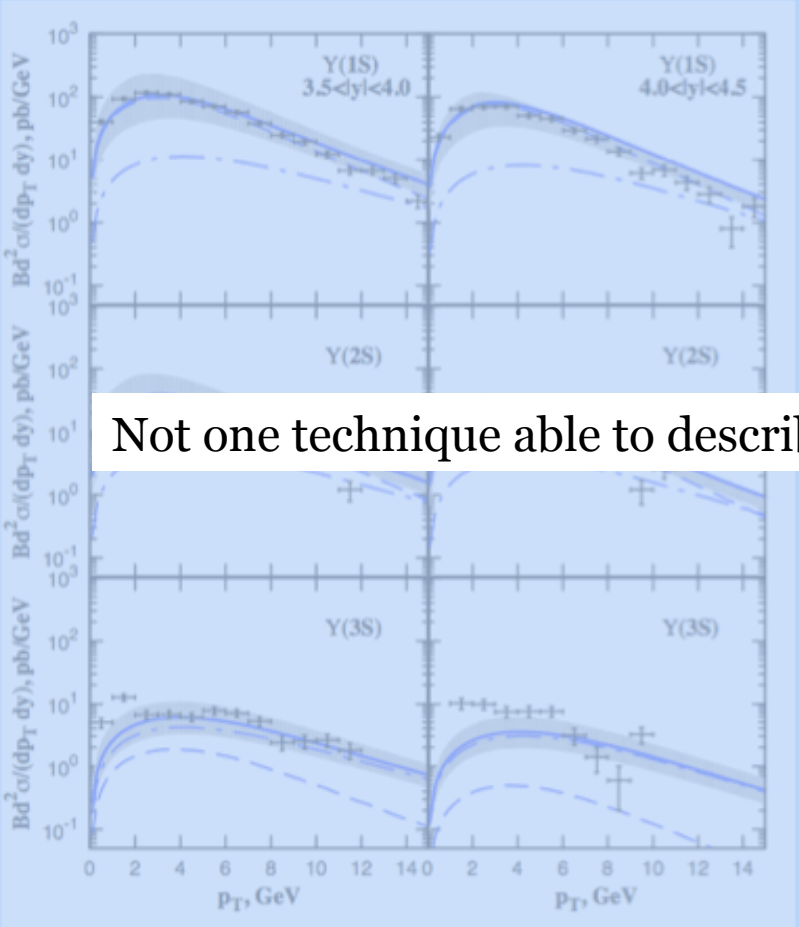
Accounting for direct and non-direct contributions



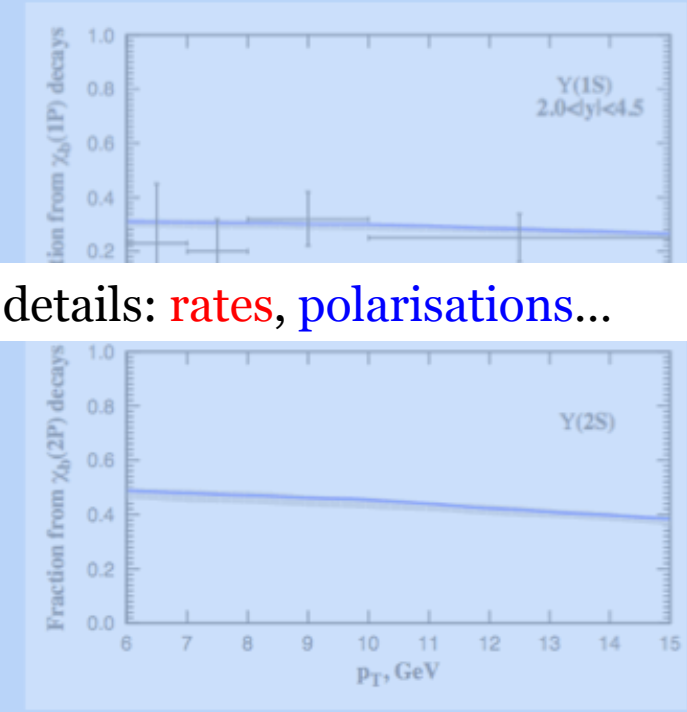
[M. A. Nefedov, V. A. Saleev, A. V. Shipilova, Phys. Rev. D88 (2013) 014003]

A Variety of Techniques…

…and $b\bar{b}$



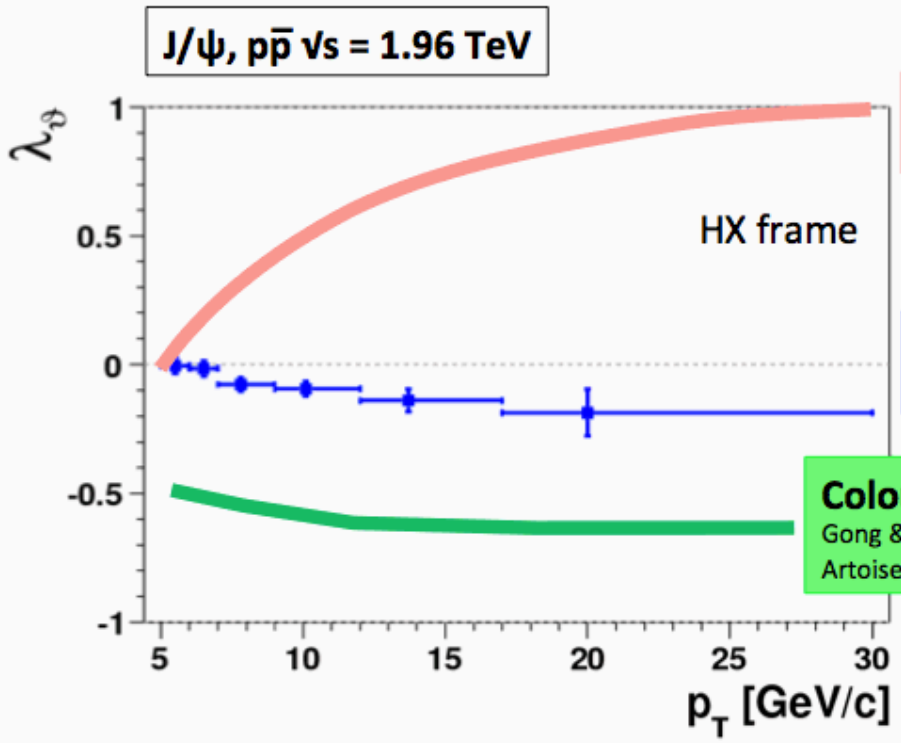
Accounting for direct and non-direct contributions



Not one technique able to describe all details: rates, polarisations…

Quarkonia: the polarization puzzle

Polarization measurements at the Tevatron



NRQCD factorization
Braaten, Kniehl & Lee, PRD62, 094005 (2000)
direct J/ψ

CDF Run II
CDF Coll., PRL 99, 132001 (2007)
direct J/ψ
+ J/ψ *from* χ_c *decays*

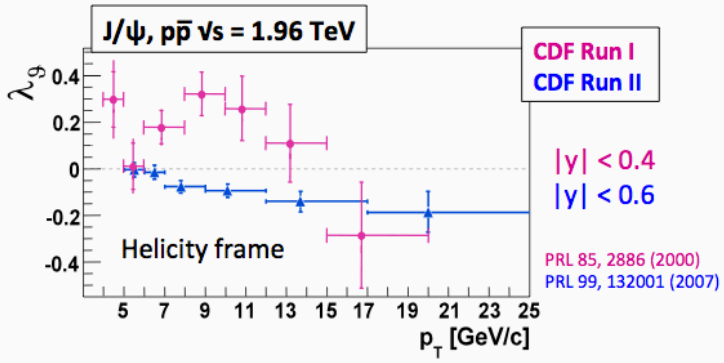
Colour Singlet Model
Gong & Wang, PRL 100, 232001 (2008)
Artoisenet et al., PRL 101, 152001 (2008)
direct J/ψ

⇒ Data and theory
in clear disagreement

Quarkonia

- Not always a matter of theory predictions, but also experimental techniques!

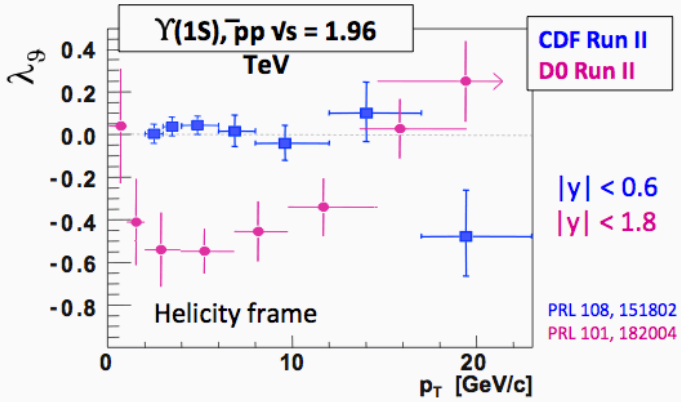
Polarization measurements at the Tevatron



- CDF II vs CDF I

|y| < 0.4
|y| < 0.6

PRL 85, 2886 (2000)
PRL 99, 132001 (2007)



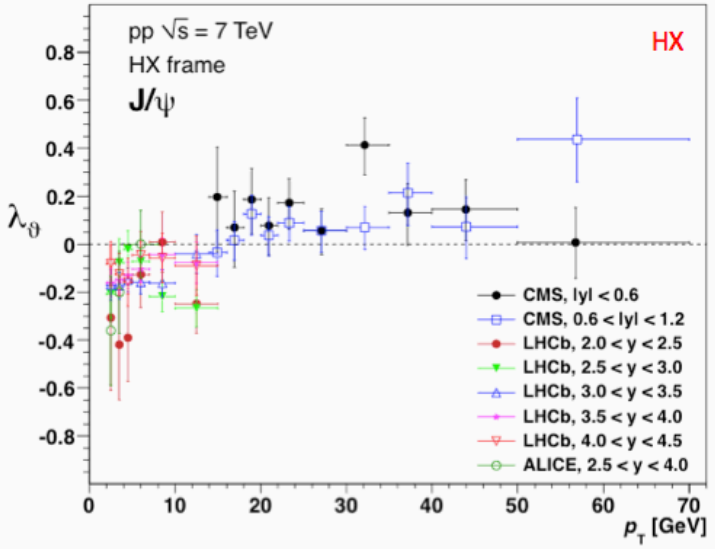
- CDF vs D0

|y| < 0.6
|y| < 1.8

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

⇒ Data and data also in clear disagreement

Improved results needed !



...nevertheless, the polarization problem persists!

Conclusions

- QCD works pretty well!
- Our predictive tools (NLO+PS, FONLL, CEM, CSM, COM…) aren't perfect
- Our experimental data isn't fully consistent with them

- Measure more and better!
- Predict more and better!

"If it ain't broke don't fix it"

- …but it is
- "If it ain't broke, break it first"