Cold Matter Quarkonium Production in the Improved Color Evaporation Model

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Quarkonium Production Schemes

- Color singlet model (CSM)
  - Assume physical color singlet state, normalization is quarkonium wavefunction at origin
  - Disagrees with p_T dependence, higher order terms show no significant improvement
- Nonrelativistic QCD (NRQCD)
  - Rigorous effective field theory, factorization of soft and hard scales
  - Expansion of cross section in velocity and strong coupling
  - Not clear that NRQCD factorization agrees with data
- Color evaporation model (CEM)
  - Does not separate states into color or spin on average
  - Fewer parameters than NRQCD (one per state)
  - New results available in improved CEM, including polarization
- k_T factorization
  - Off shell matrix elements, unintegrated gluon distributions all approaches

This talk will focus on the improved color evaporation model results

p+p collisions

Traditional Color Evaporation Model

All quarkonium states treated like heavy quark pairs (*Q = c, b*) below heavy hadron (*H = D, B*) threshold

Color and spin are averaged over in pair cross section so color is 'evaporated' during transition from quark pair to quarkonium without changing kinematics

Distributions for quarkonium family members assumed identical

$$\sigma_Q^{\rm CEM} = F_Q \sum_{i,j} \int_{4m^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 \; f_{i/p}(x_1,\mu^2) \; f_{j/p}(x_2,\mu^2) \; \hat{\sigma}_{ij}(\hat{s})$$

Values of quark mass, m, and scale, μ, fixed from NLO calculation of heavy quark pair cross section

Scale factor F_Q fixed by comparison of $\sigma_Q^{\rm CEM}$ to energy dependence of J/ψ and Υ cross sections, $\sigma(x_F > 0)$ and $B d\sigma/dy|_{y=0}$ for J/ψ, $B d\sigma/dy|_{y=0}$ for Υ, only one F_Q for each state of quarkonium family

Spin always summed over so no previous predictions of polarization in CEM

Based on: Nelson, RV, Frawley, PRC87 (2013) 014908

Improved Color Evaporation Model

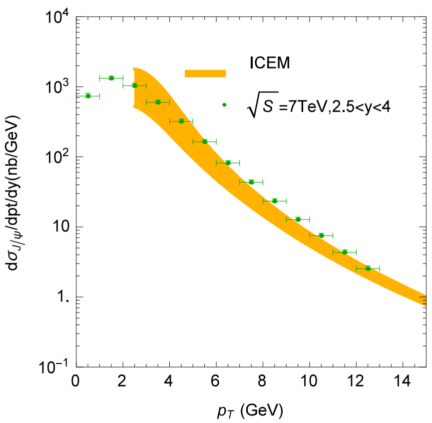
Relates average final state ψ momentum, $\langle p_\psi \rangle$, to quark pair momentum *p*

$$\langle p_\psi \rangle = \frac{M_\psi}{M} p + \mathcal{O}(\lambda^2/m_c)$$

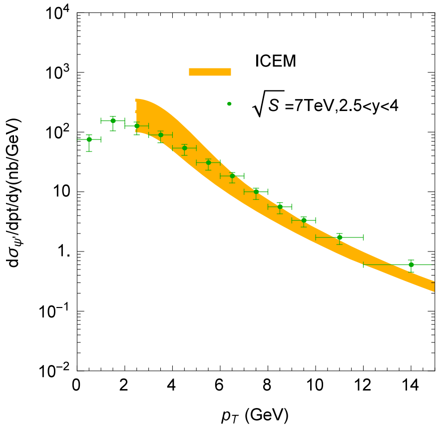
Lower limit on pair mass, *M*, has to be larger than $\langle p_\psi \rangle$, lower limit on CEM integration has to be increased to M_ψ so that the transverse momentum distribution becomes

$$\frac{d\sigma_\psi(p)}{dp_T} = F_\psi \int_{M_\psi}^{2m_D} dM \frac{M}{M_\psi} \frac{d\sigma_{c\bar{c}}(M,p')}{dM dp'_T}\Big|_{p'_T=(M/M_\psi)p_T}$$

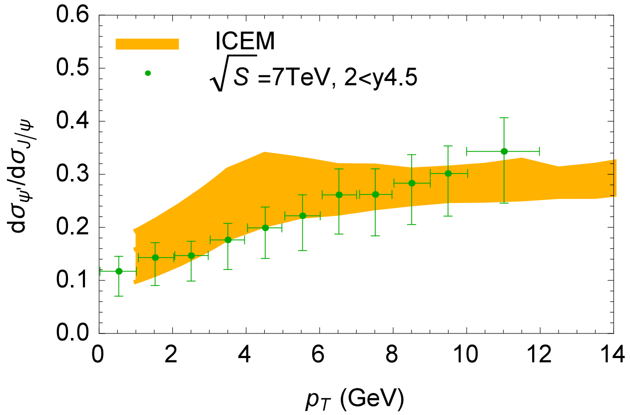
J/ψ



ψ'



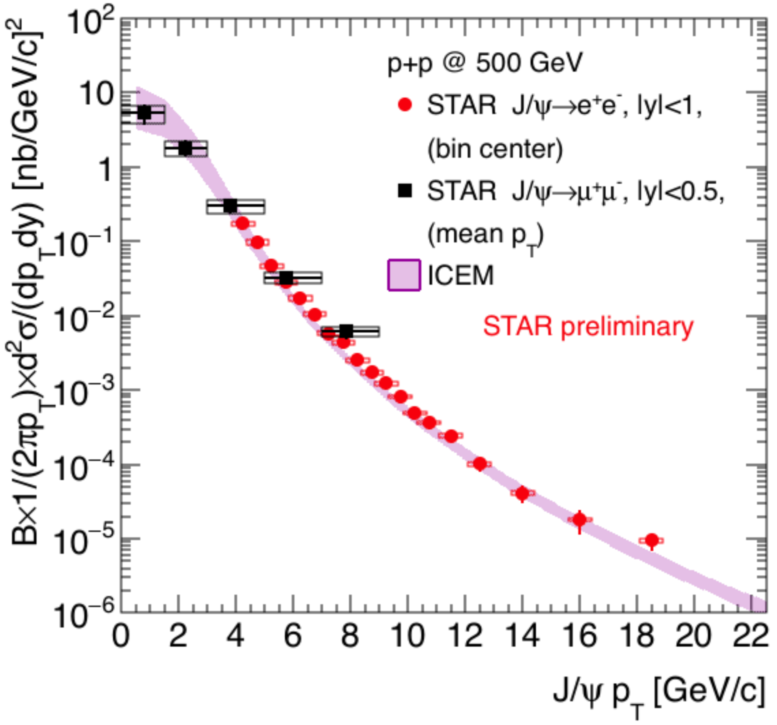
ψ'/ψ ratio

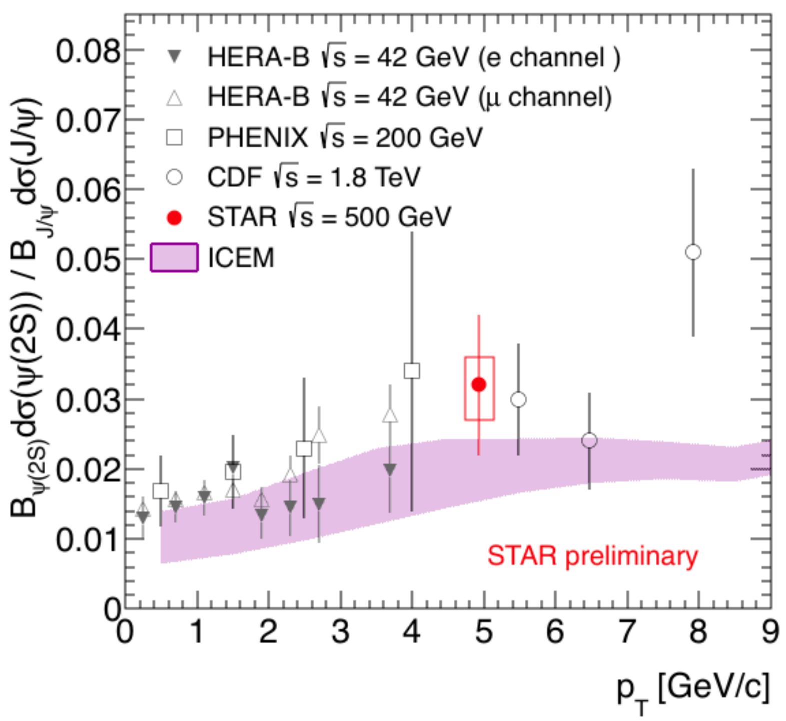


LHCb 7 TeV p+p

Y-Q Ma & RV, PRD95 (2016) 114029

J/ψ ICEM results for STAR at 500 GeV





Compliments of Z. Tang

ICEM in k_T factorization approach

- First calculated p_T dependence of quarkonium polarization in ICEM: work of UCD student V. Cheung (PRD95 (17) 074021; 96 (17) 054014; 98 (18) 114029; 99 (19) 034007)
- Reggeized gluons, off shell MEs and unintegrated gluon distribution

$$\begin{aligned}\sigma &= F_Q \int_{m_Q^2}^{4m_H^2} d\hat{s} \int dx_1 \int dx_2 \int dk_{1T}^2 \int dk_{2T}^2 \int \frac{d\phi_1}{2\pi} \int \frac{d\phi_2}{2\pi} \\ &\times \ \Phi_1(x_1, k_{1T}, \mu_1)\Phi_2(x_2, k_{2T}, \mu_2)\hat{\sigma}(\mathcal{R}+\mathcal{R} \to Q\overline{Q})\delta(\hat{s} - x_1 x_2 s + |\vec{k}_{1T} + \vec{k}_{2T}|^2)\end{aligned}$$

$$\begin{aligned}\mathcal{A}(\mathcal{R}+\mathcal{R} \to Q\overline{Q}) &= \epsilon^\mu(k_1)\epsilon^\nu(k_2)\mathcal{A}_{\mu,\nu}(g+g \to Q\overline{Q}) \\ \mathcal{A}_{L=0} &= \frac{1}{2}\int_{-1}^{1} dx \mathcal{A}(x = \cos\theta)\end{aligned}$$

$$k_1 = (x_1, s, \vec{k}_{1T}, x_1 s) \qquad k_2 = (x_2 s, \vec{k}_{2T}, -x_2 s)$$

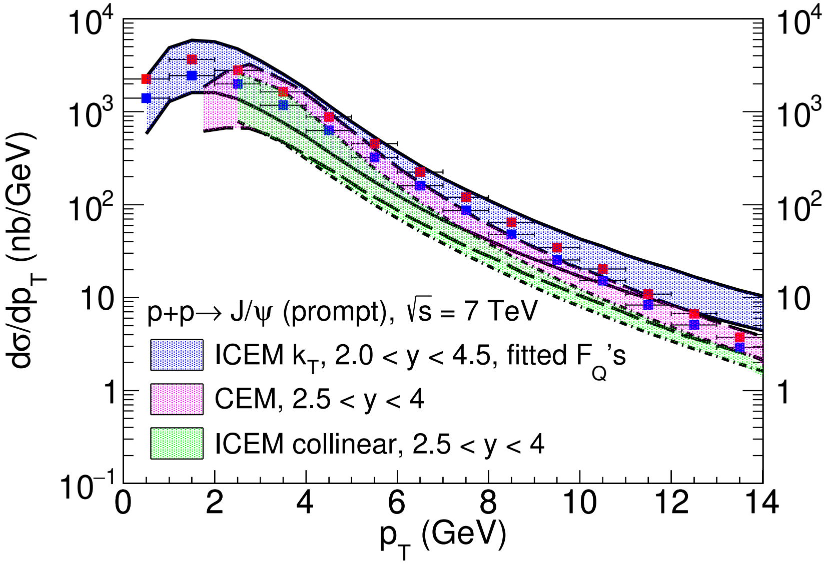
$$\epsilon(k_1) = (0, \vec{k}_{1T}/|k_{1T}|, 0) \qquad \epsilon(k_2) = (0, \vec{k}_{2T}/|k_{2T}|, 0)$$

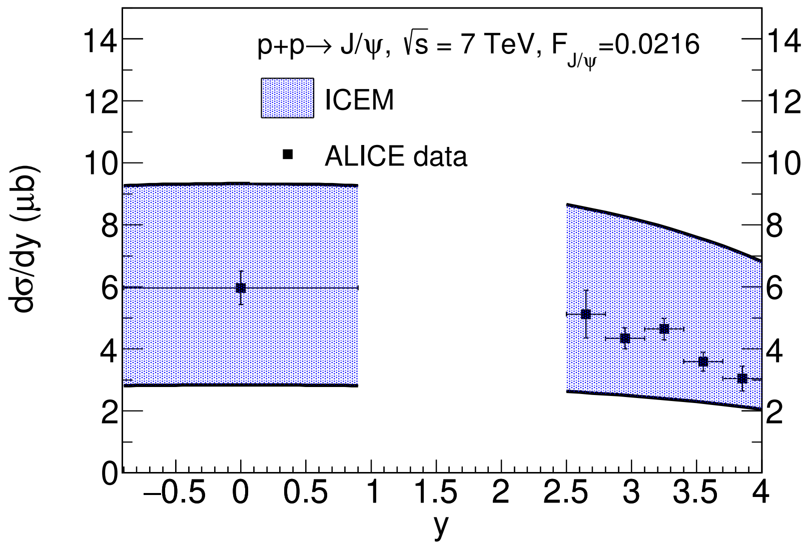
- Still LO; for NLO, go back to collinear factorization, also include all contributions (q-qbar and (q+qbar)g)

J/ψ in k_T factorized ICEM vs. other CEM calculations

Somewhat faster decrease of the CEM and collinear factorization
ICEM calculation likely due to the higher lower limit on y, 2.5 instead of 2;
possibly also due to use of unintegrated gluon PDFs in k_T factorization

In collinear factorization calculation, results shown only above p_T ~ 2-2.5 GeV;
$p_T \rightarrow 0$ in k_T factorization



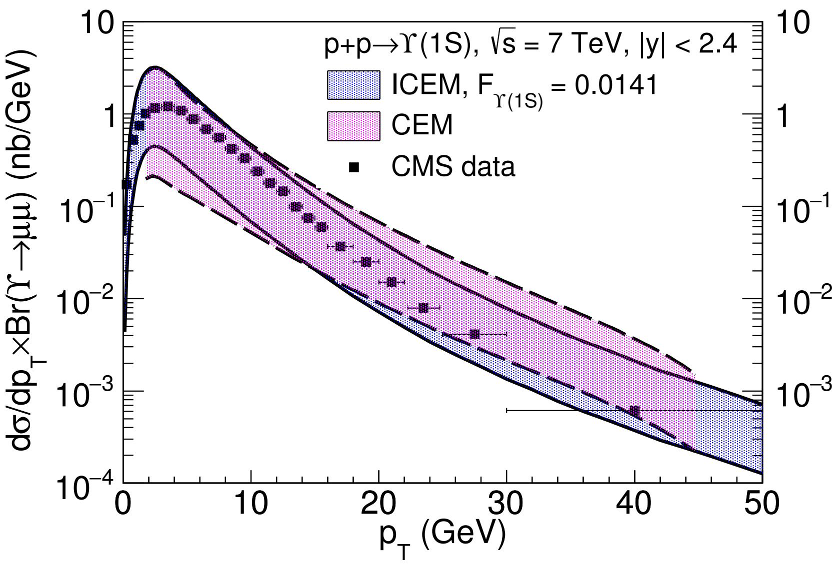


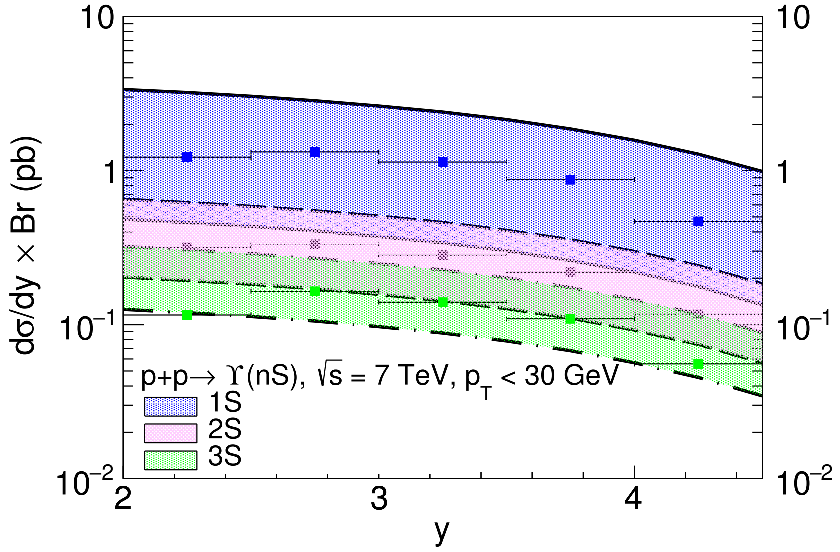
Combined mass and renormalization scale uncertainties

Υ in k_T factorized ICEM vs. other CEM calculations

Some difference in p_T slopes but the agreement between the two approaches is good

Comparison of rapidity distributions is to forward LHCb data only for all 3 Υ S states, agreement is good in all cases



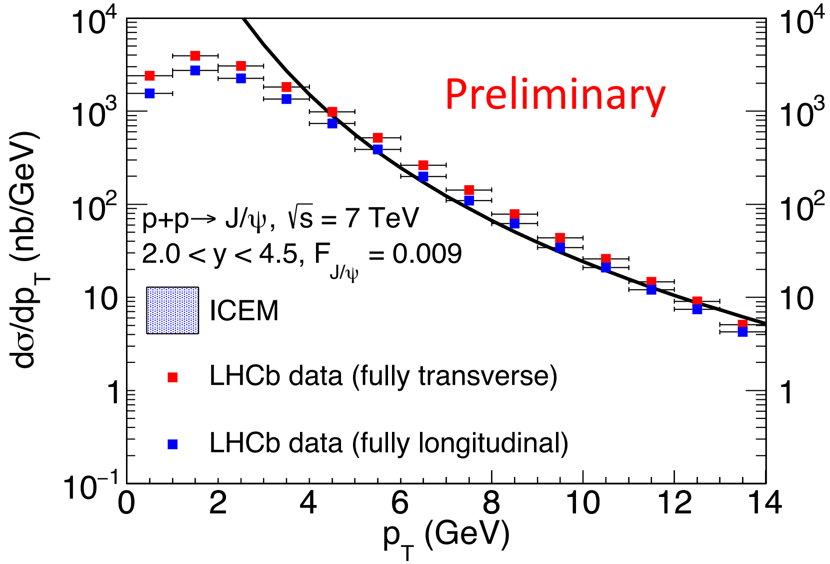


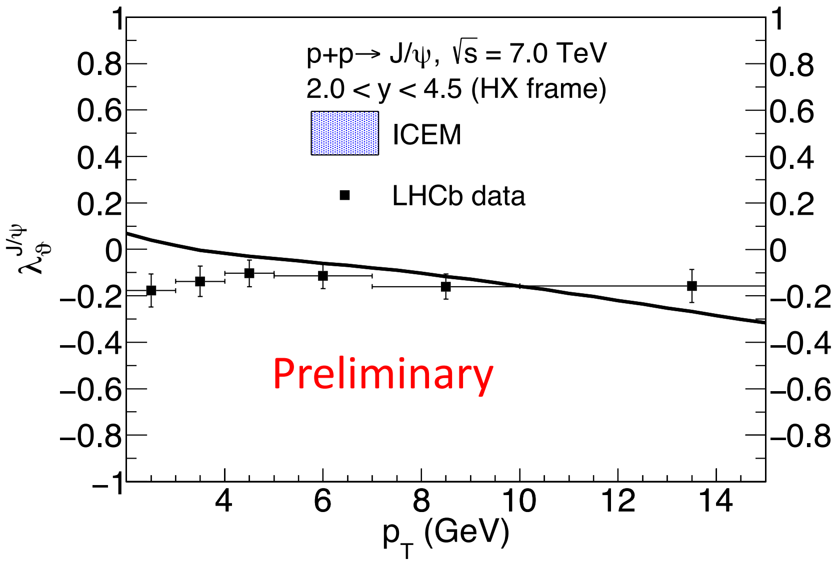
Combined mass and renormalization scale uncertainties

New: NLO ICEM collinear factorization

Preliminary results shown for LHCb J/ψ distributions

Mass, renormalization and factorization scale uncertainties yet to be added





V. Cheung and RV, in progress

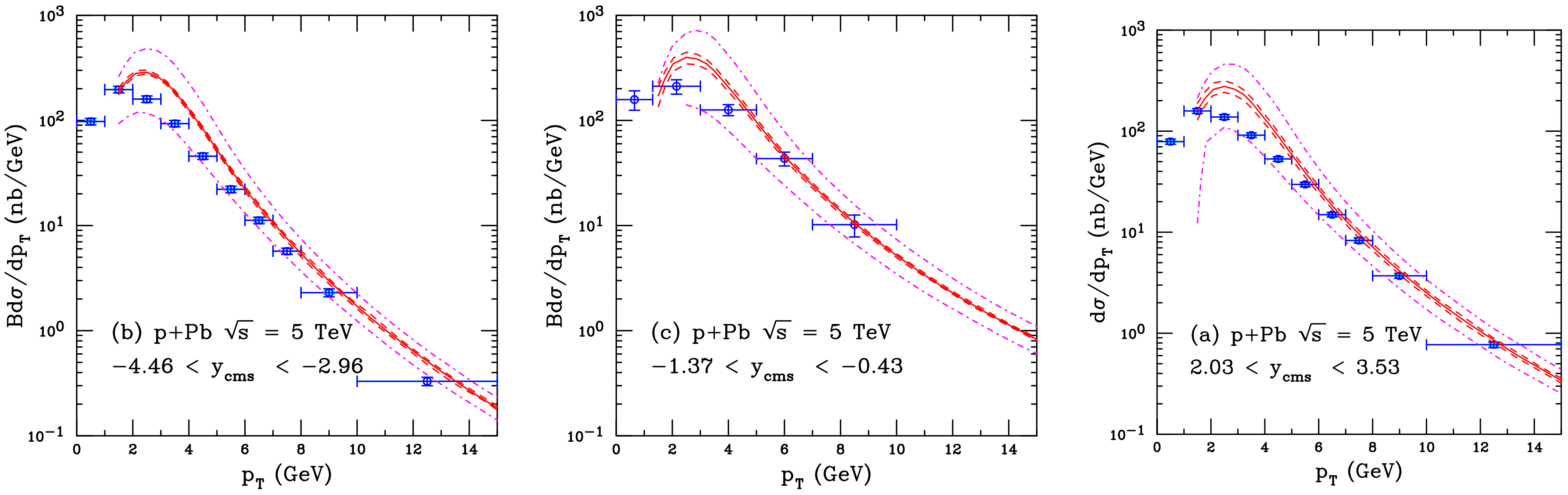
p+Pb collisions

Follows RV, PRC 92 (15) 034909

nPDFs effects on quarkonium

- Quarkonium production calculated in CEM (similar in ICEM)
- Modification of p_T and rapidity distributions studied with EPS09 NLO and other available nPDFs (only EPS09 shown here)
- EPS09 has 15 parameters, 31 sets, uncertainties added in quadrature for each +/- set resulting from changing each parameter by 1 standard deviation
- New results for this meeting in Pb+Pb calculated with EPPS16 – larger uncertainty bands expected because now 20 parameters, 40 error sets
- nPDF uncertainties small compared to mass and scale uncertainties

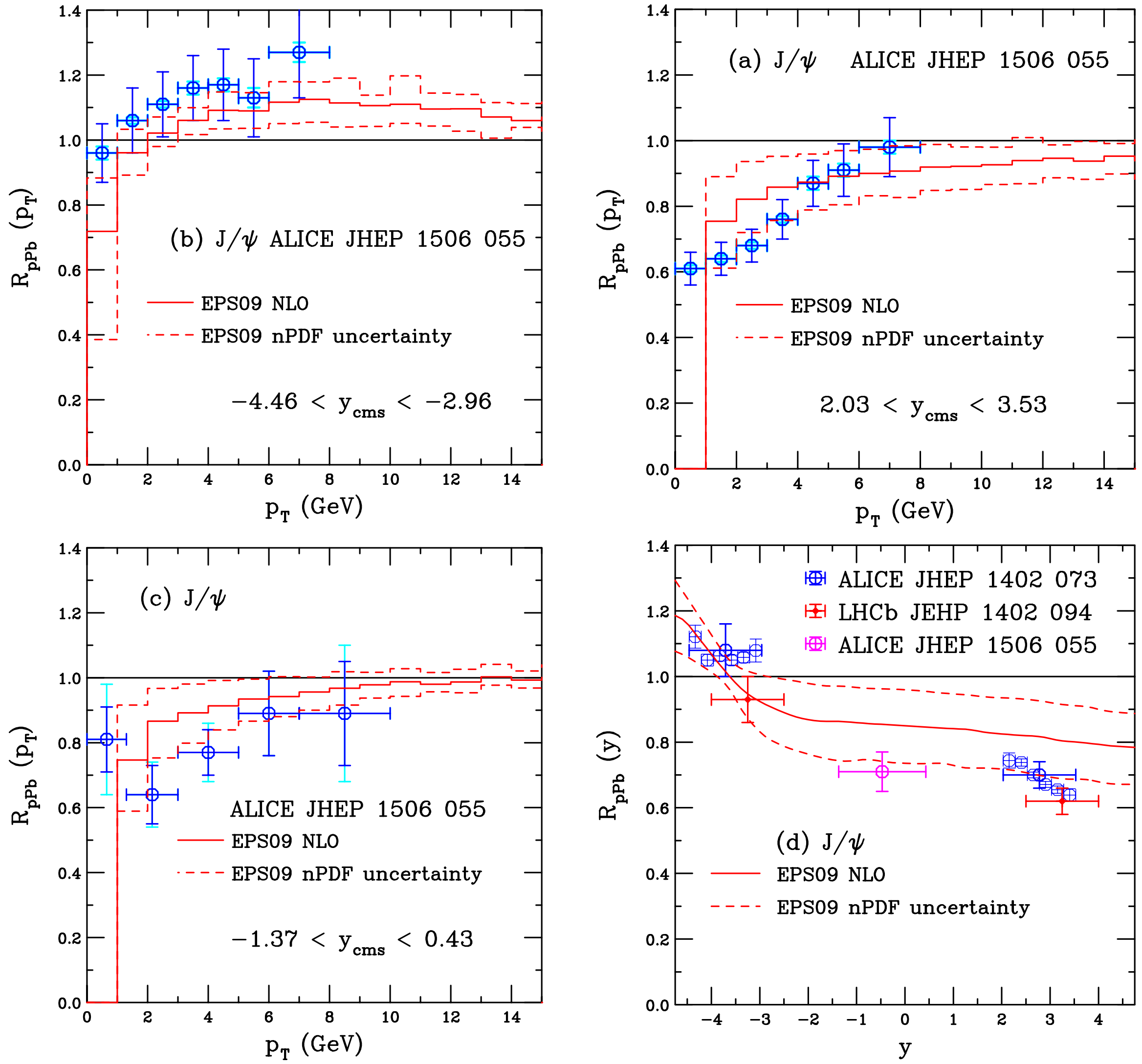
J/ψ p_T distributions in p+Pb @ 5 TeV



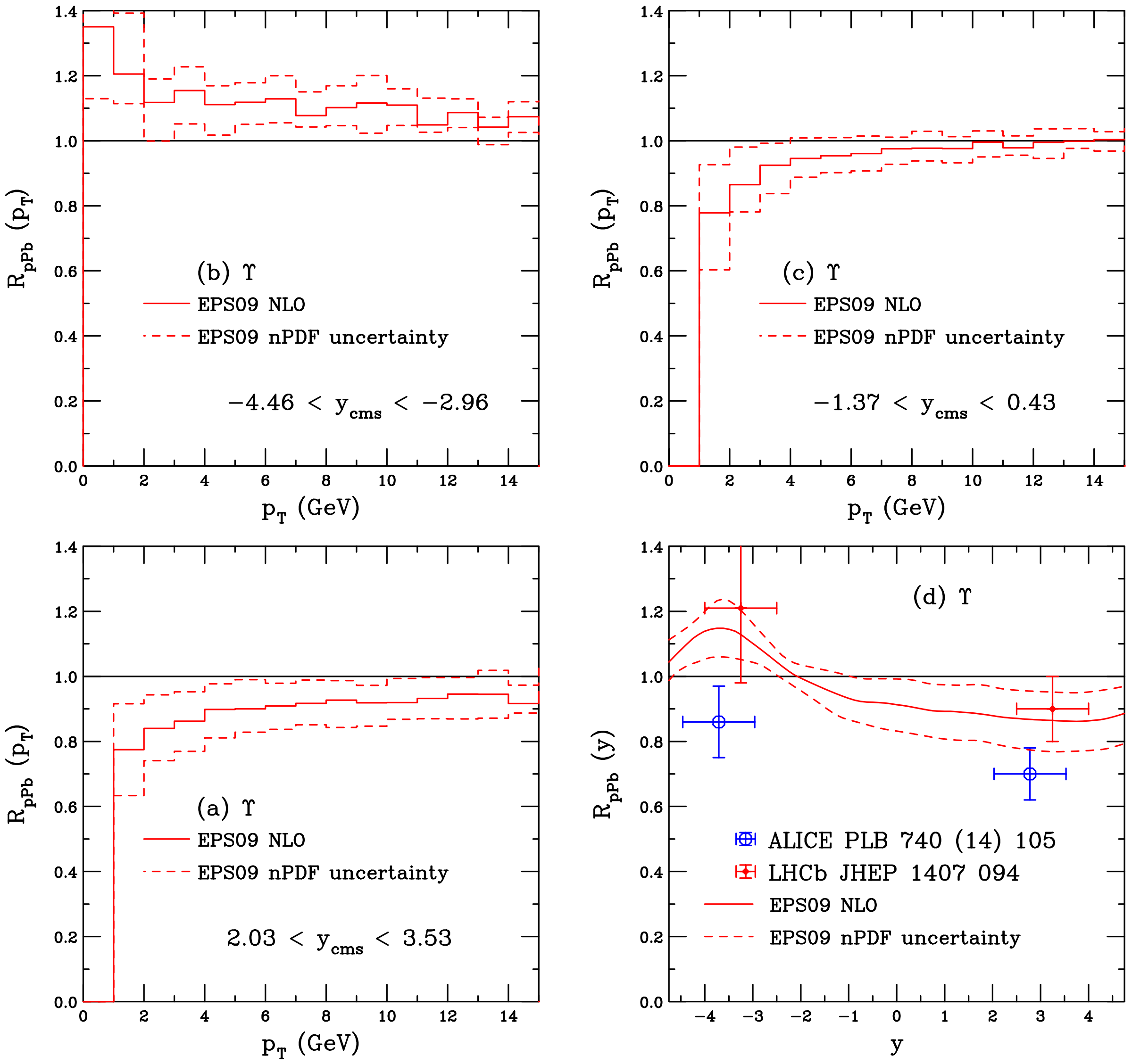
The p_T distributions at backward (left), central (middle) and forward (right) rapidities measured by ALICE at 5.02 TeV

The dashed magenta lines are the mass and scale uncertainties added in quadrature taking the upper and lower limits of the mass and scale combinations Excursions from the central value; the red curves inside this band shows the EPS09 NLO nPDF uncertainties

J/ψ shadowing in p+Pb @ 5 TeV



Υ shadowing in p+Pb @ 5 TeV



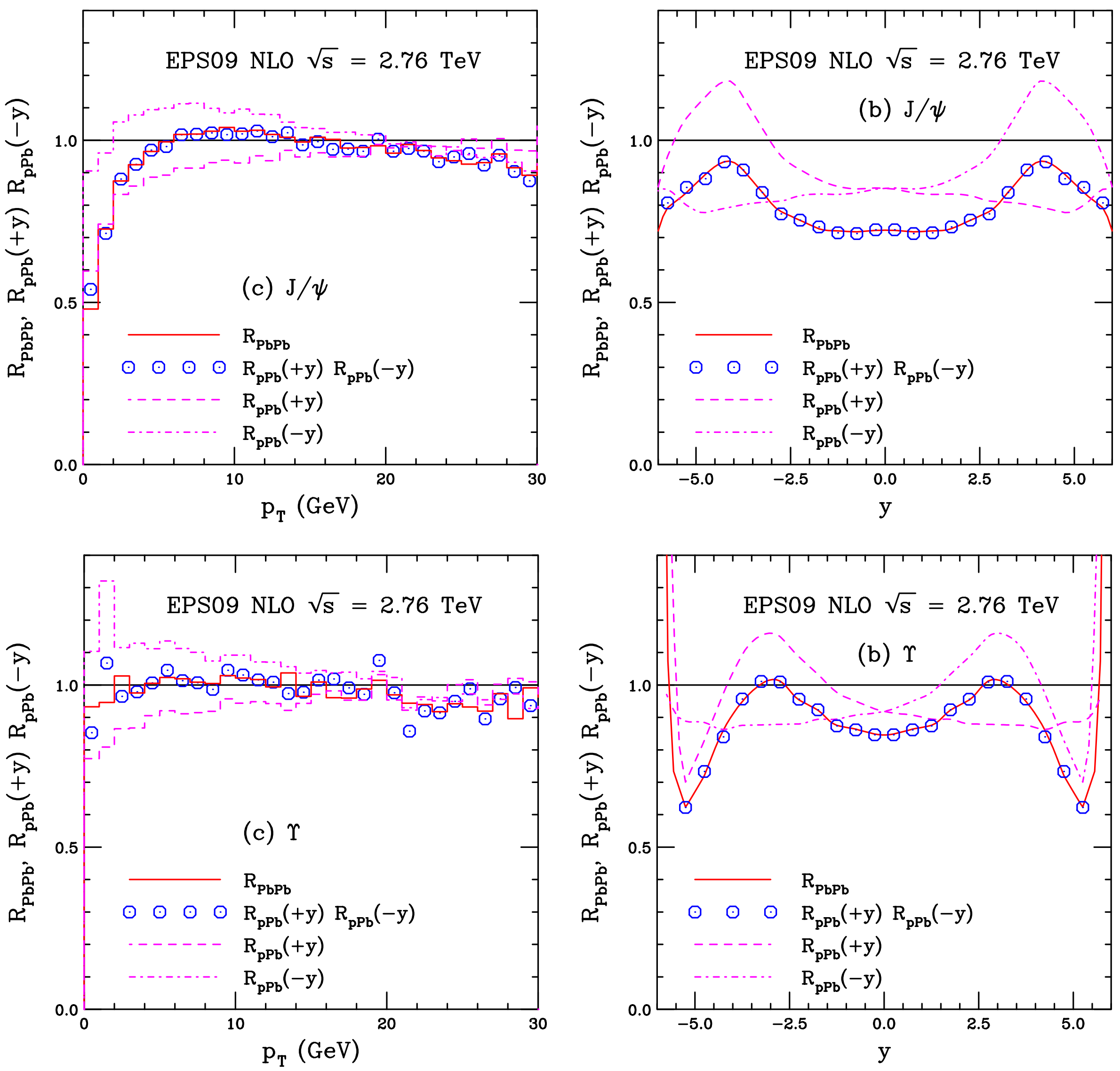
nPDF effects in Pb+Pb collisions

- nPDFs applied to both nuclei, the initial Pb distributions don't talk to each other before the collision in collinear factorization approach

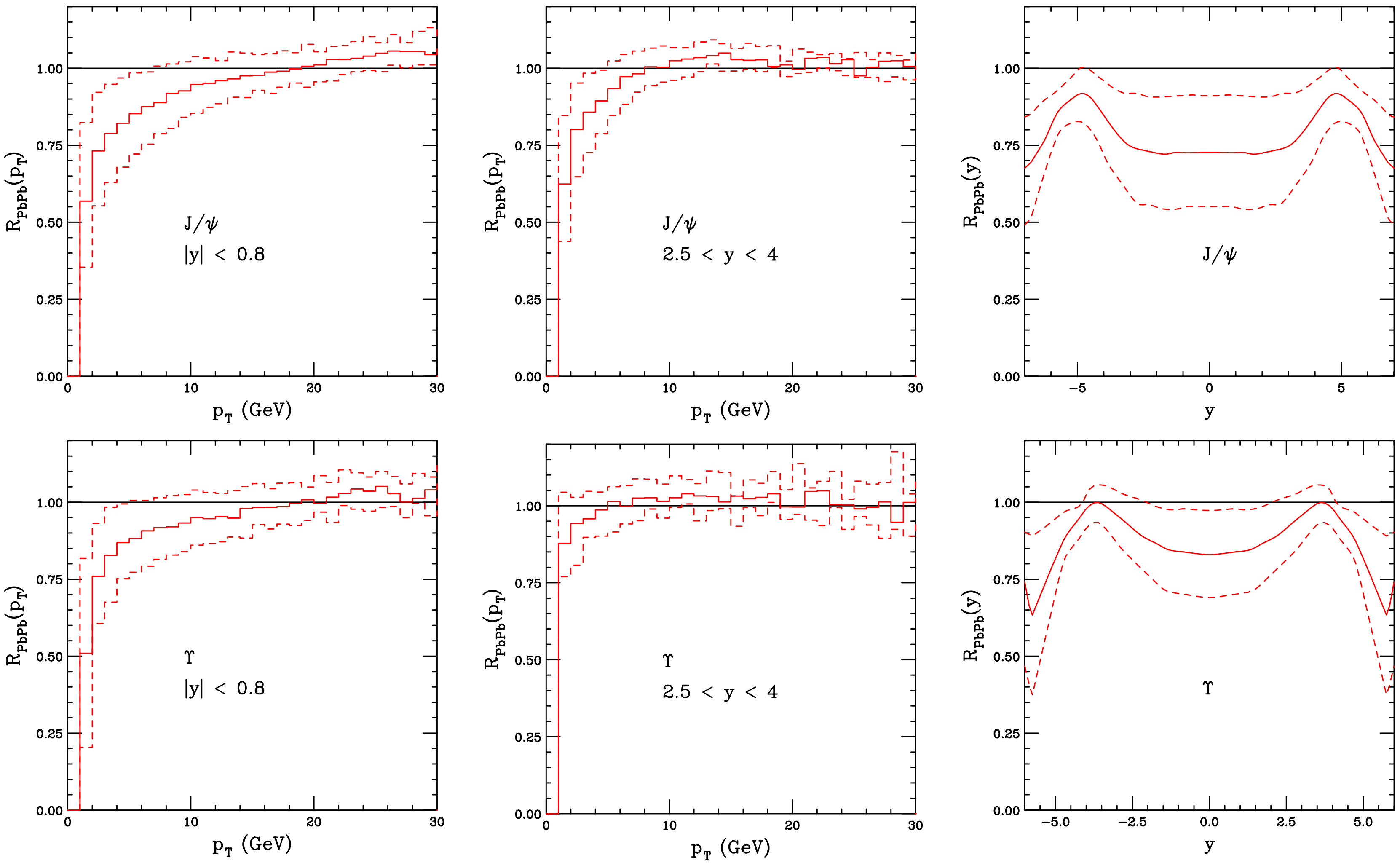
- The effects then factorize, effectively multiplication of p+Pb ratio by Pb+p ratio to obtain R_{AA}, both in p_T and rapidity

- Note also now that the results are symmetric around midrapidity, like p+p, whereas the p+Pb results are shifted in the LHC

J/ψ & Υ in Pb+Pb @ 2.76 TeV



J/ψ & Υ in Pb+Pb @ 5 TeV



That’s all folks…

Nonrelativistic QCD Approach

NRQCD factorization theorem for e.g. J/ψ:

$$\sigma_{J/\psi} = \Sigma_n \, \sigma_{c\epsilon[n]} <\mathcal{O}^{J/\psi}[n]>$$

n sums over all Fock states, singlet and octet; $\sigma_{c\epsilon[n]}$ is pair production rate for specific color and spin state, calculated in pQCD; $<\mathcal{O}^{J/\psi}[n]>$ is long distance matrix element (LDME) describing conversion to final state J/ψ assuming that hadronization does not change spin or momentum

LDMEs are assumed to be universal

Cross section is a double expansion in relative velocity of the pair, *v*, and strong coupling constant α_s, LDMEs scale with powers of *v*

Color singlet, $n = {}^3S_1^{[1]}$, is leading term in v, color octet states (${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$) are subleading, octet LDMEs determined by fitting LDMEs to data, these are then used to predict observables such as polarization, LDMEs of other states through heavy quark spin symmetry

NRQCD predicts strong transverse polarization at high p_T

Are the LDMEs Universal?

- The fit results depend on the energy scales of the process described, e.g. whether analysis is global or not and whether or not e^+e^- and *e*p data also included
- The fit results depend on the p_T scale, whether the minimum p_T is 3, 5, or 7 GeV
- The fit results depend on whether or not polarization is fitted or predicted
- Fits to p_T distributions do not describe the total cross sections
- Using LDMEs fitted to J/ψ results with heavy quark spin symmetry does not translate well to other states, e.g. η_c

LDMEs depend on process and scale

State of the art as of 1404.3723

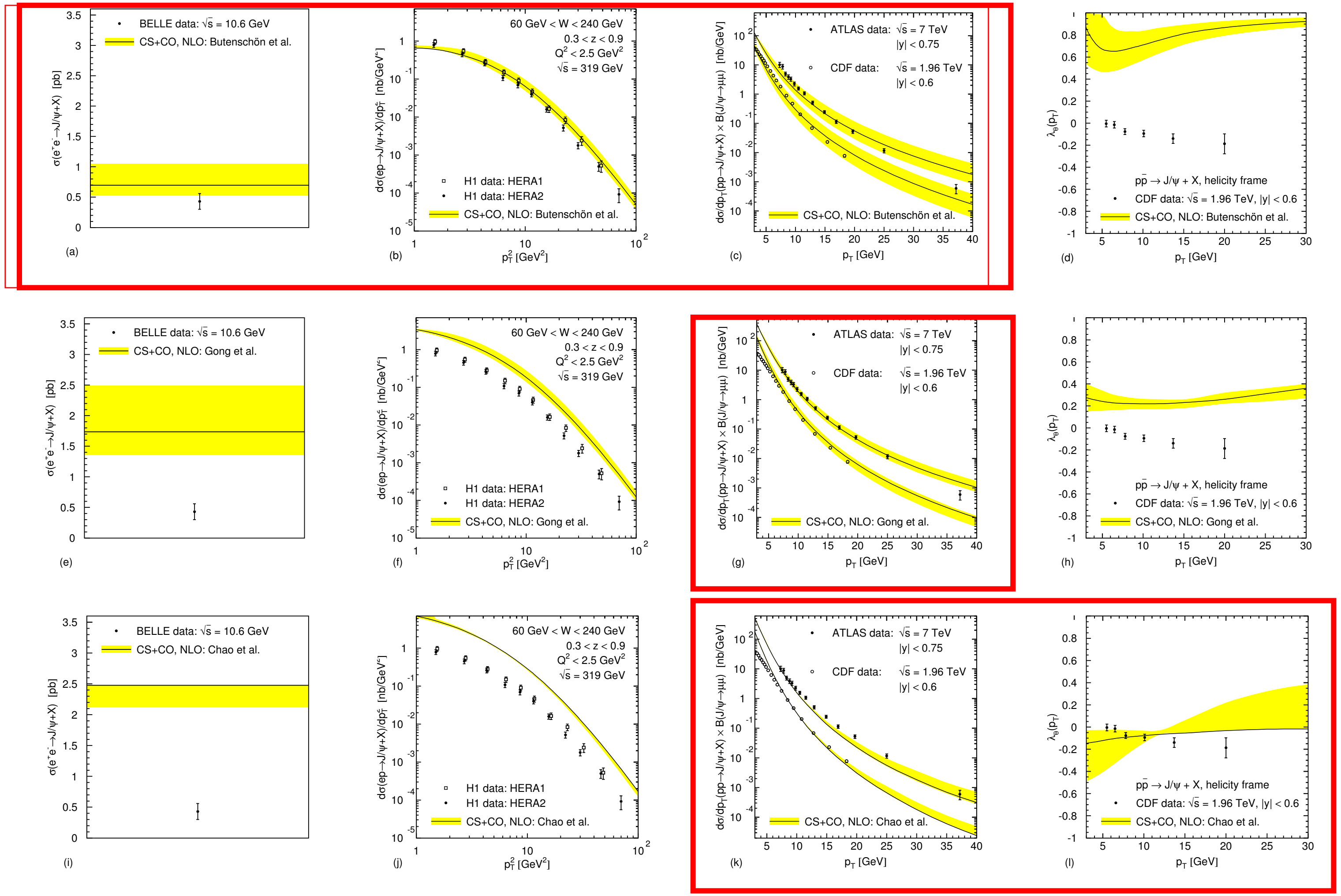
Included in fits

e^+e^- | *ep* | pp distribution | pp polarization

Butenschon & Kniehl $p_T > 3$ GeV

Gong et al $p_T > 5$ GeV

Chao et al $p_T > 7$ GeV

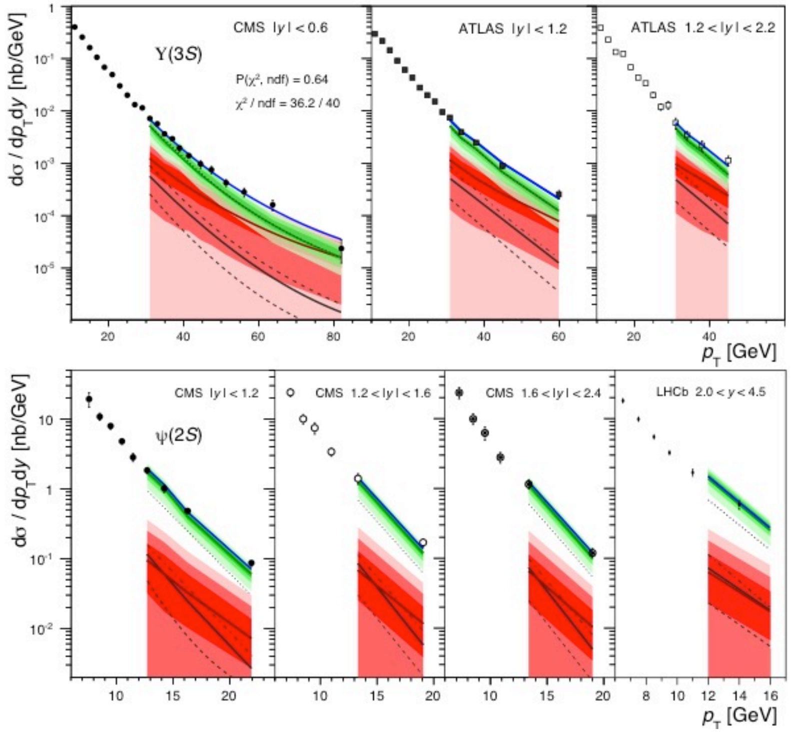


Polarization: fitted or predicted?

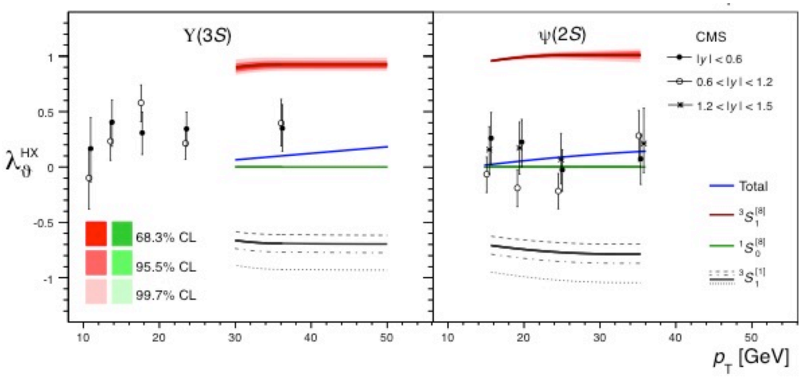
Fitting LDMEs to yields alone does not describe polarization

A combined fit to the two requires a higher p_T cut

This can be taken to the extreme, as in Faccioli et al where favorable p_T cut chosen



By looking only at excited states and $p_T/m > 3$, one can achieve a longitudinally polarized result



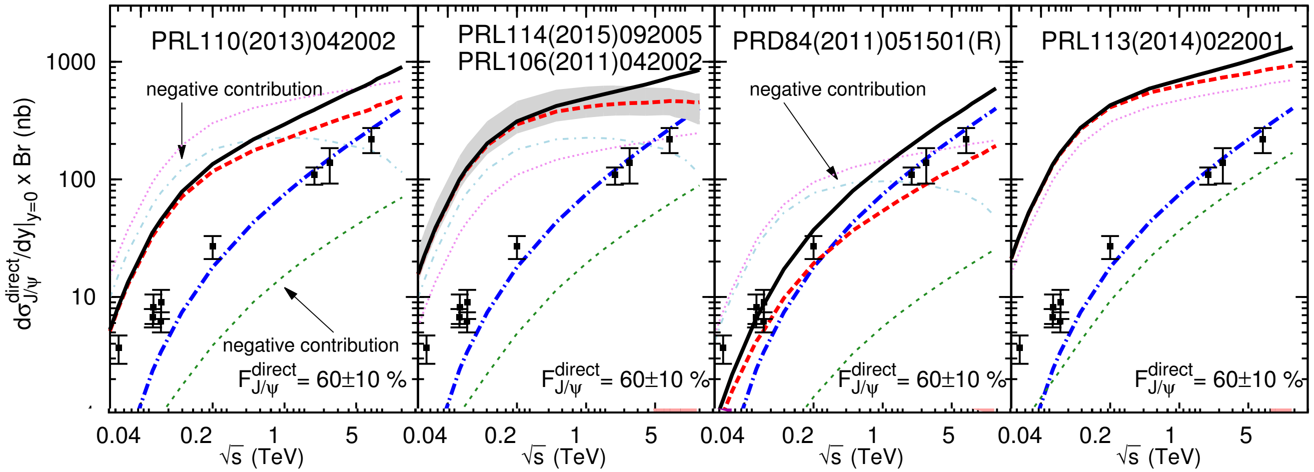
LDMEs fit to yields fail to describe the p_T-integrated rate (no big surprise)

LDMEs extracted from p_T distributions cannot describe center-of-mass energy dependence of *y=0* cross section

Lowest p_T cut (p_T > 3 GeV) comes closest to data here yet is furthest off on polarization

No low p_T resummation of logarithms included so far

Gang et al. | Chao et al. | Butenschon and Kniehl | Bodwin et al

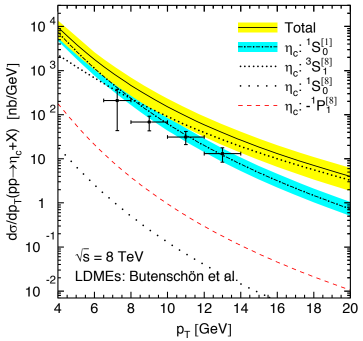


Feng, Lansberg, Wang

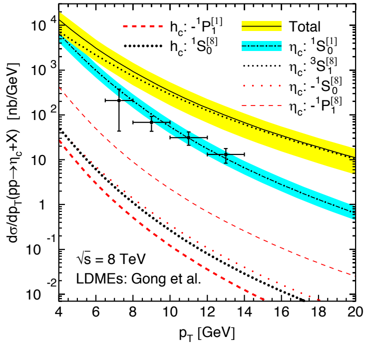
J/ψ LDMEs do not describe η_c production

If one takes heavy-quark spin symmetry LDMEs to apply to η_c production, all results so far overpredict LHCb η_c yields

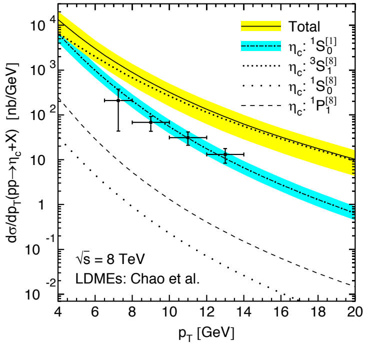
Butenschon & Kniehl



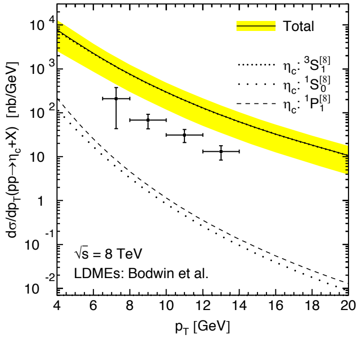
Chao et al



Gong et al



Bodwin et al



Calculations by Butenschon & Kniehl

If heavy-quark spin symmetry is given up, one can fit η_c LDMEs independently but then LDMEs are not universal, do not describe other processes

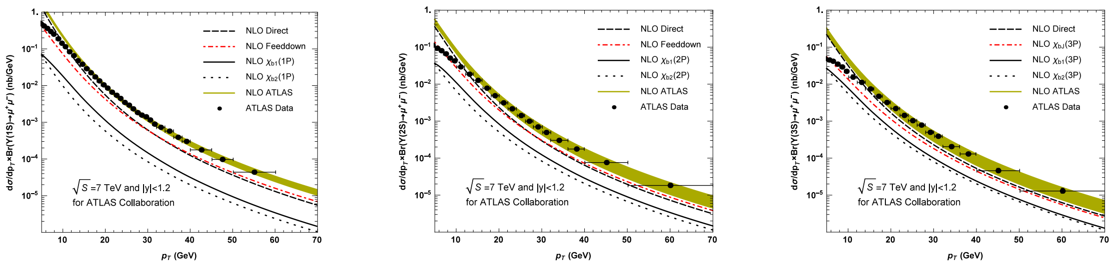
What about Υ?

Larger mass, higher scale (smaller coupling) and slower velocity could
Make Υ a better candidate for NRQCD

Υ production also allows for more free parameters to allow a description of both production and polarization – only Υ(3S) has little wiggle room

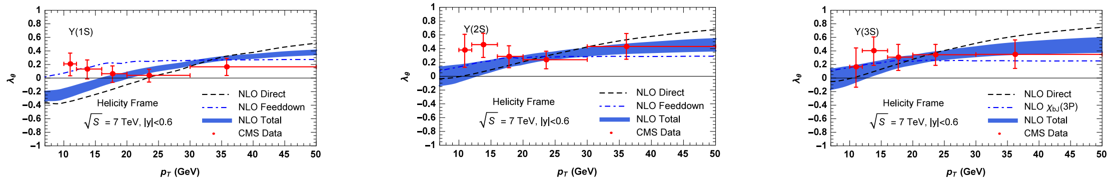
Han et al, p_T > 15 GeV fit

ATLAS
|y| < 1.2

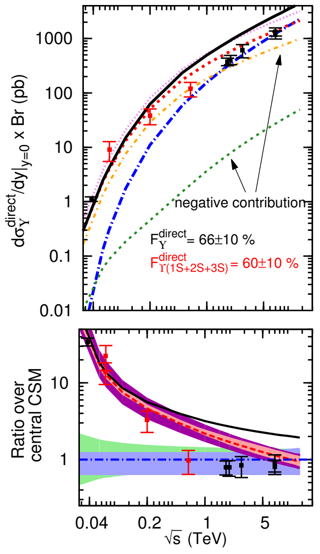


Υ(1S)

CMS
|y| < 0.6



Lansberg et al



Other calculations can give similar agreement with data