Challenges in Quarkonium Production in p+p and p+Pb Collisions at the LHC

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U.S. DEPARTMENT OF ENERGY | Office of Science

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Outline:

- Quarkonium in p+p
- Quarkonium in p+Pb

Quarkonium in p+p

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

$$\sigma_{J/\psi} = \Sigma_n \sigma_{c\bar{c}[n]} \langle \mathcal{O}^{J/\psi}[n] \rangle$$

Quarkonium Production Schemes

- Color singlet model (CSM)
  - Assume physical color singlet state, normalization is quarkonium wavefunction at origin
  - Disagreement with p_T dependence apparent, including higher order terms does not make significant improvement (see Lansberg's talk)
- Nonrelativistic QCD (NRQCD)
  - Rigorous effective field theory based on 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 becoming available
- k_T factorization
  - Off shell matrix elements and unintegrated gluon distributions

Nonrelativistic QCD Approach

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

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

n sums over all Fock states, singlet and octet; $\sigma_{ce[n]}$ is pair production rate for specific color and spin state, calculated in pQCD; $< O^{J/\psi} [n] >$ is long distance matric 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 ep 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

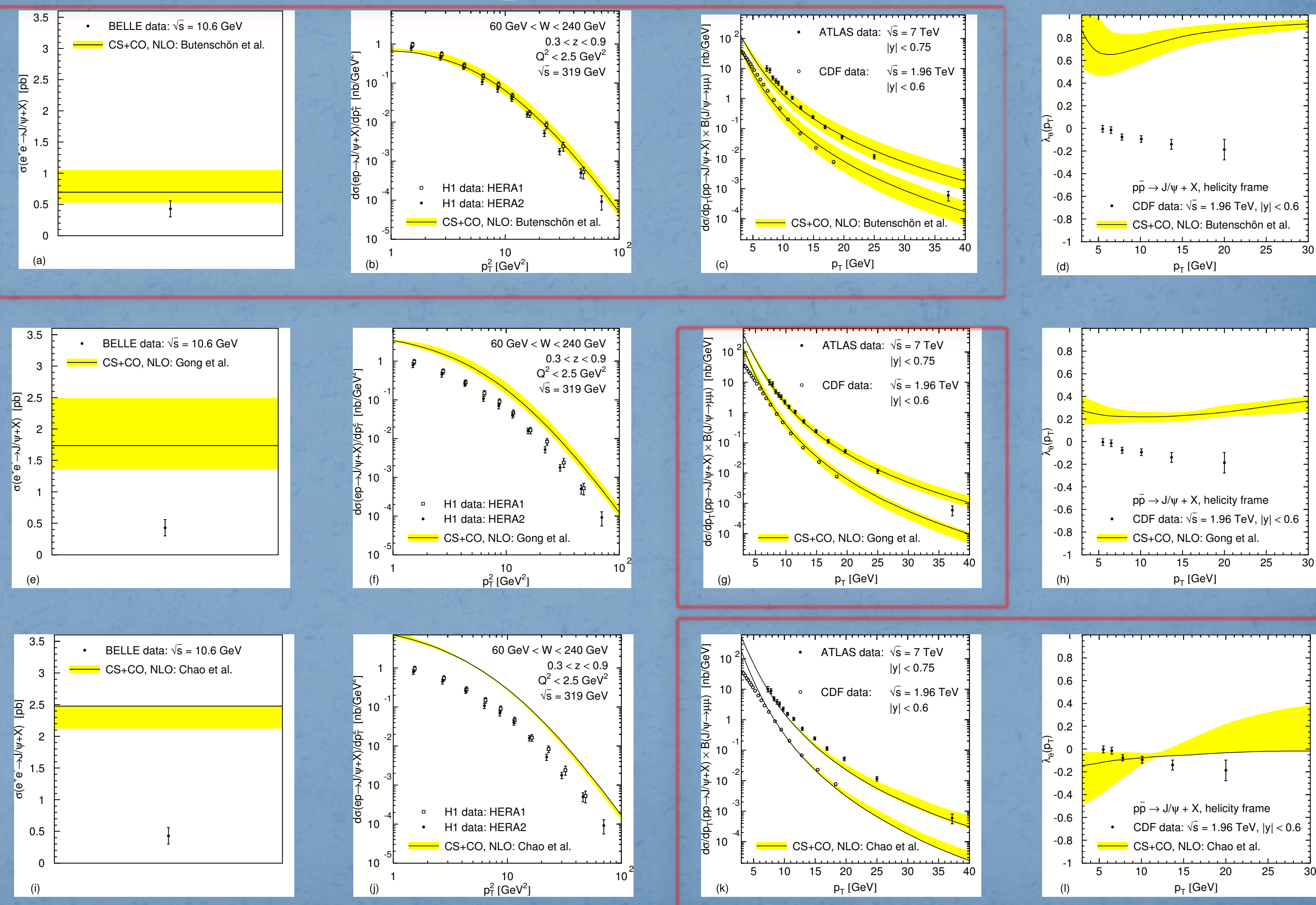
Included in fits

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

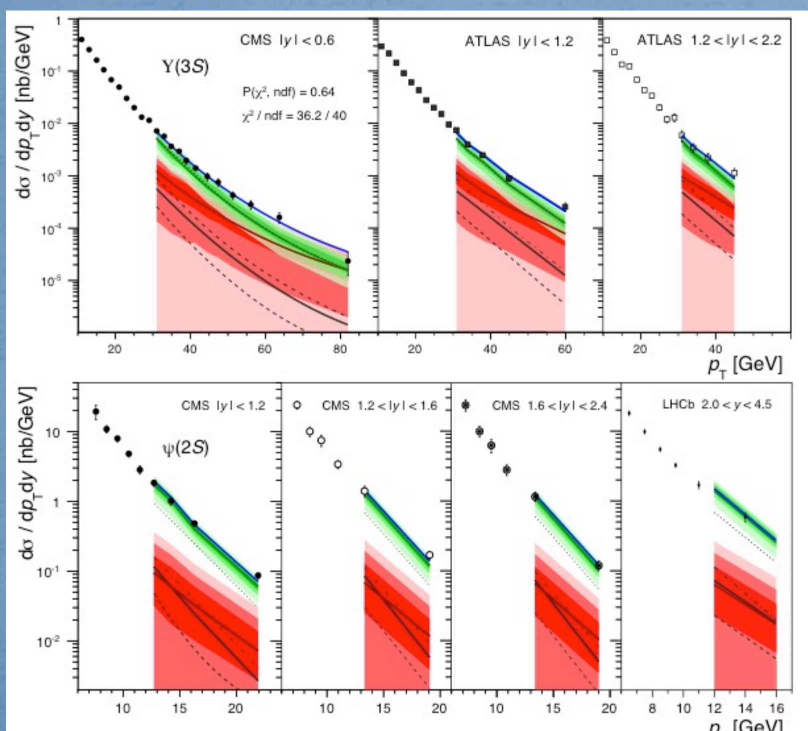


Polarization: fitted or predicted?

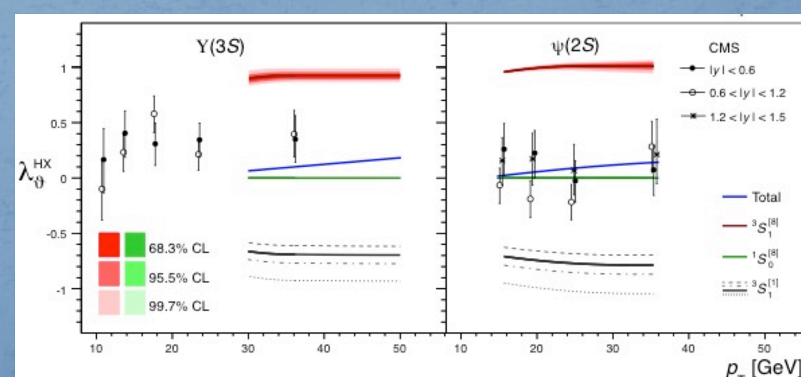
Fitting LDMEs to yields alone does not describe polarization

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



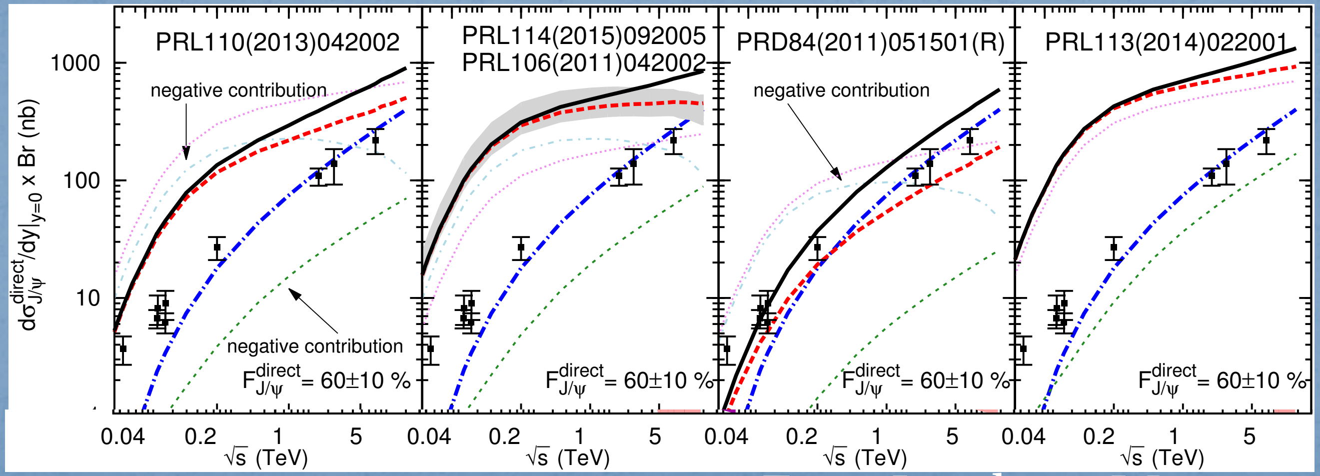
LDMEs fit to yields fail to describe the p_T-integrated rate (no big surprise)

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

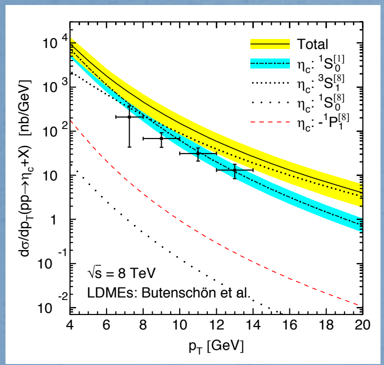


Feng, Lansberg, Wang

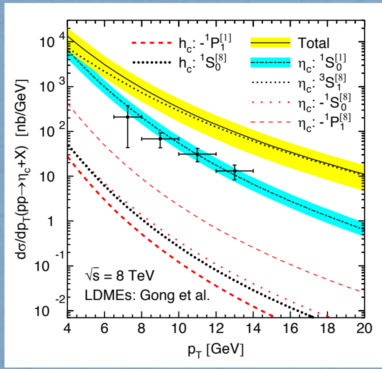
J/ψ LDMEs do not describe η_c

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

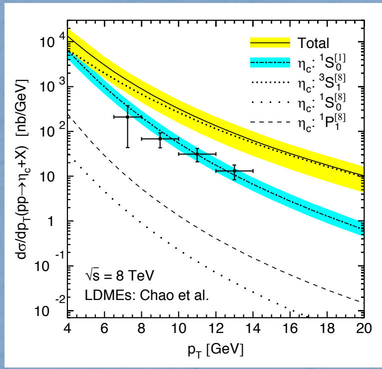
Butenschon & Kniehl



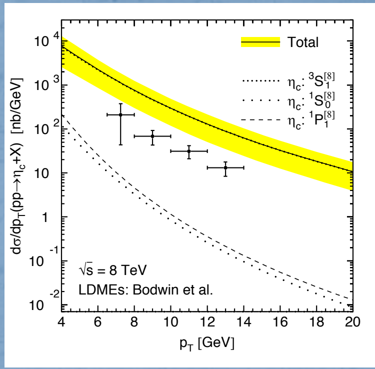
Chao et al



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

Where do we go from here with NRQCD?

- Go beyond current NLO analyses
  - Adopt more parameters such as quark masses and scales
  - Resum logs at high and/or low p_T
  - Look at associated production (although if single inclusive production not described why should associated production be better?)
  - Go to higher order
- Problem with NRQCD factorization?
  - Does not hold for polarized quantities (but this is a pillar of NRQCD)
  - Velocity expansion is too slow
- Some of the data are wrong (are theorists allowed to cherry pick data?)

What about Υ?

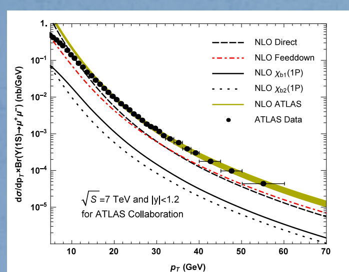
Larger mass, higher scale (smaller coupling) and slower velocity could Make Υ a better candidate for NRQCD

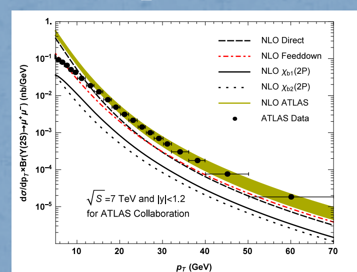
Υ production also allows for more free parameters to allow a description of both production and polarization – only Υ(3S) has little wiggle room

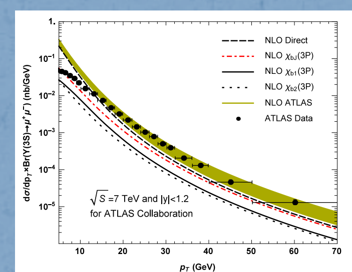
Han et al, p_T > 15 GeV fit

Lansberg et al

ATLAS
|y| < 1.2

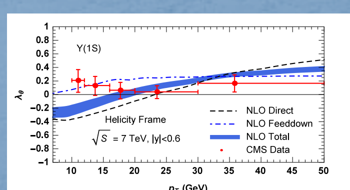


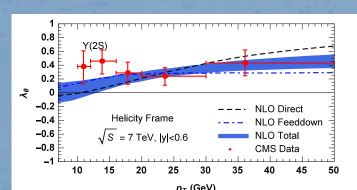


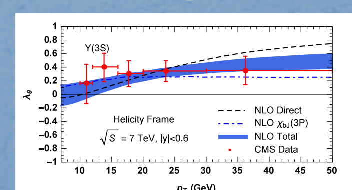


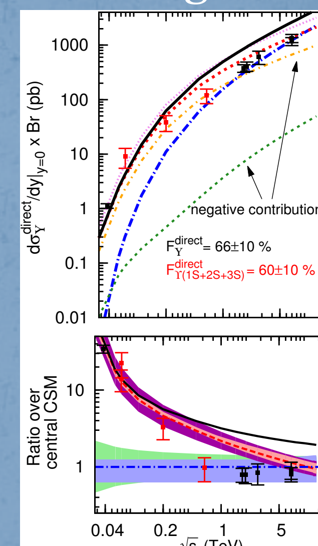
Υ(1S) Υ(2S) Υ(3S)

CMS
|y| < 0.6









Other calculations can give similar agreement with data

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 $Bd\sigma/dy|_{y=0}$ for J/ψ, $Bd\sigma/dy|_{y=0}$ for Υ, only one F_Q for each state of quarkonium family

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

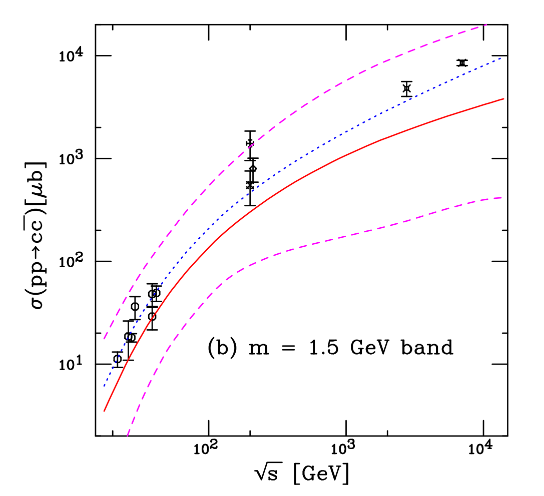
Fitting charm cross section reduces theoretical uncertainties

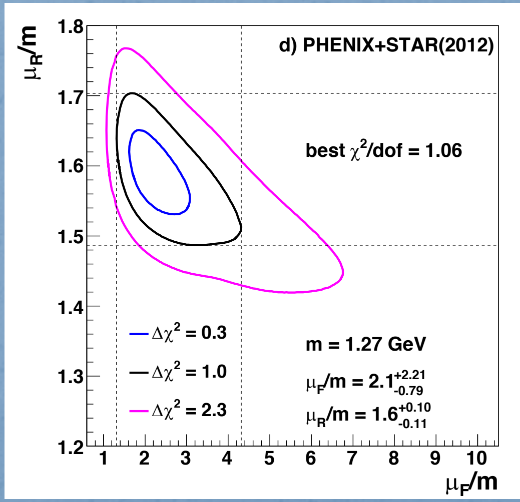
Fit subset of total charm cross section data to obtain best fit values of μ_F/m, μ_R/m

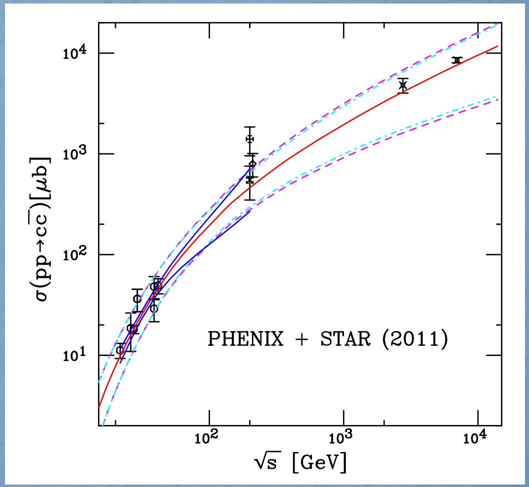
$\Delta\chi^2 = 1$ gives uncertainty on scale parameters, $\Delta\chi^2 = 2.3$ gives one standard deviation on total cross section

LHC results agree well with fit results although not included

No full NNLO cross section, likely to result in large corrections





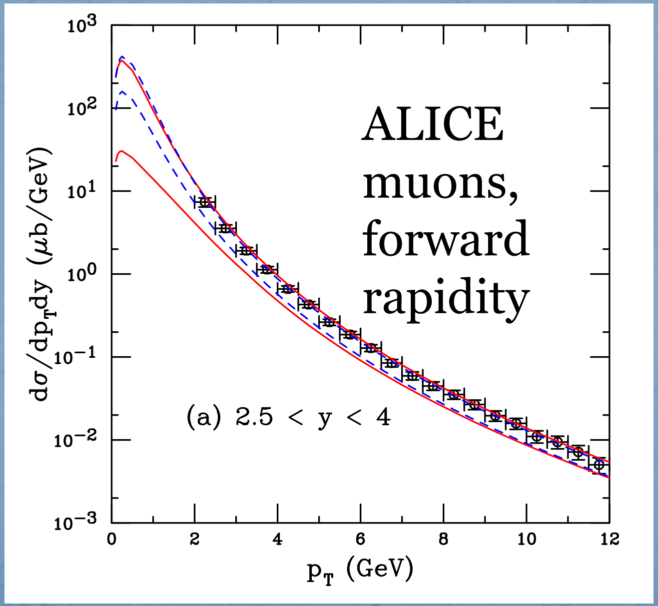


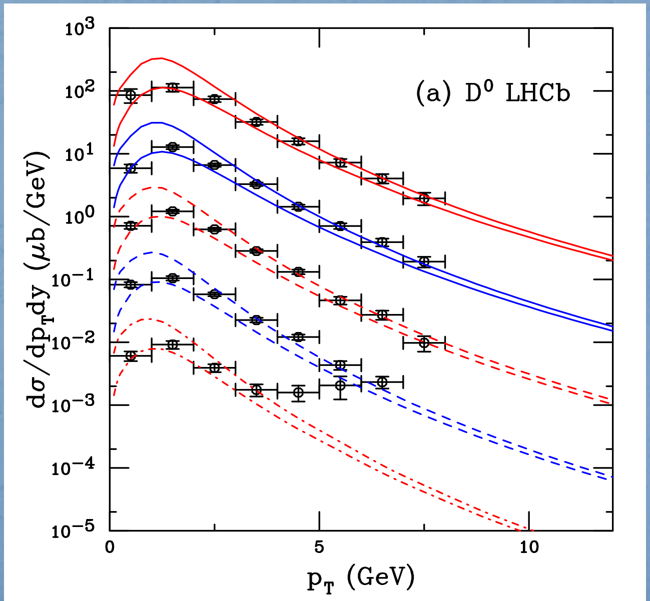
Nelson, Frawley, RV

Open Charm Results at 7 TeV

Excellent agreement with FONLL calculations of distributions in 7 TeV p+p collisions

Using results with m = 1.27 GeV and fitted factorization and renormalization scales instead of fiducial variation of scale by factor of two around m = 1.5 GeV reduces uncertainty band on forward rapidity muons and D^0 p_T distributions without reducing agreement with data

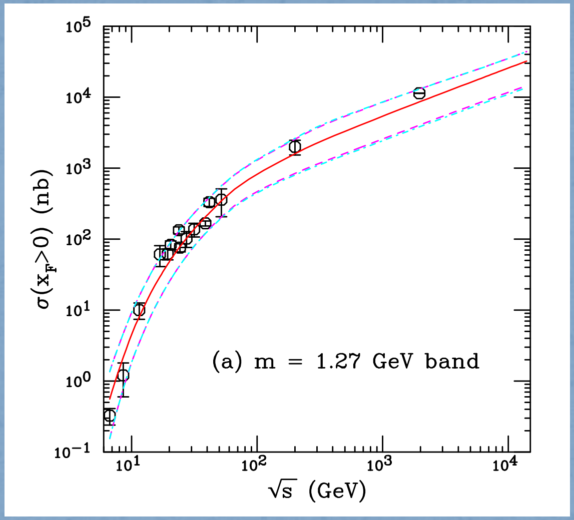




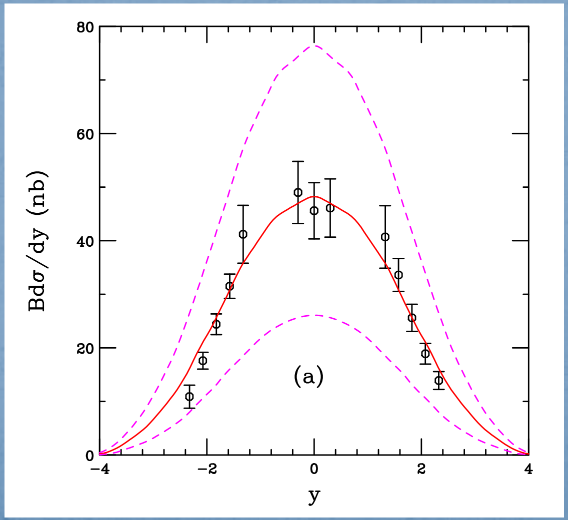
LHCb D^0 2<y<4.5, Δy = 0.5 units

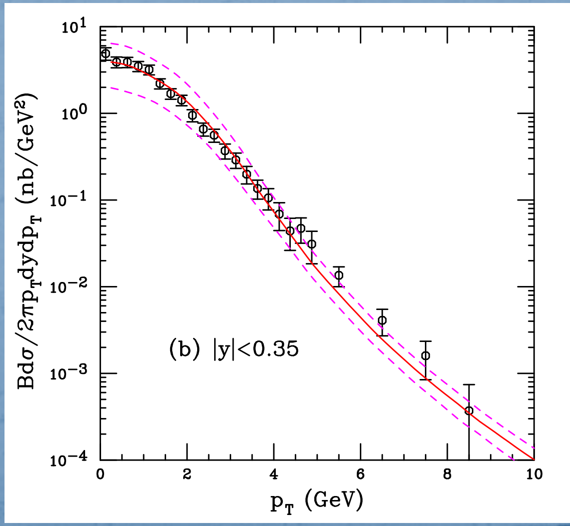
Nelson, Frawley, RV

J/ψ Results in CEM



Nelson, Frawley & RV
Data are from PHENX at RHIC, 0.2 TeV





Improved Color Evaporation Model

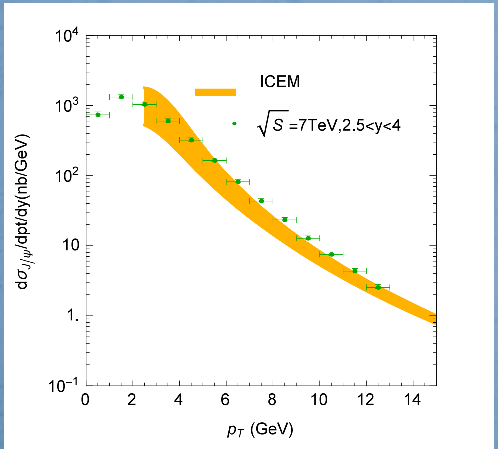
Relates average final state ψ momentum, $\langle p_\psi \rangle$, to quark pair momentum p

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

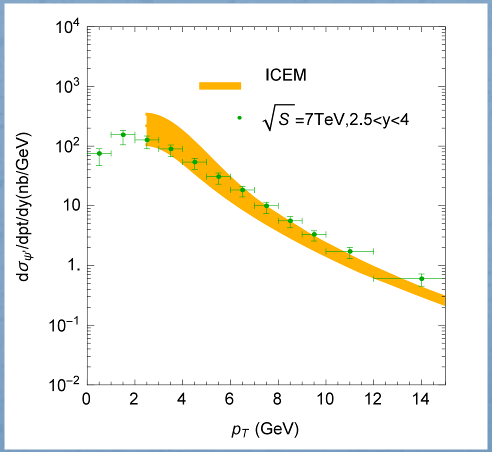
Lower limit on pair mass, M, has to be larger than $\langle p_\psi \rangle$, lower limit on CEM integration has to be increased to M_ψ so that the transverse momentum distribution becomes

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

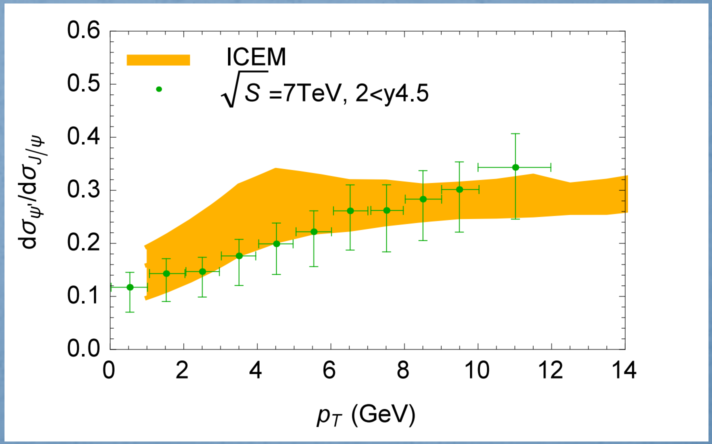
J/ψ



ψ’



ψ’/ψ ratio



LHCb 7 TeV p+p

Y-Q Ma & RV, Phys. Rev. D

Polarization in the CEM

Work done with UC Davis grad student Vincent Cheung

Separate contributions by angular momentum but still integrate over color so no additional parameter fixing is required

First differentiated between longitudinal and transverse polarizations (PRD '17), current work calculates λ for different L and S combinations

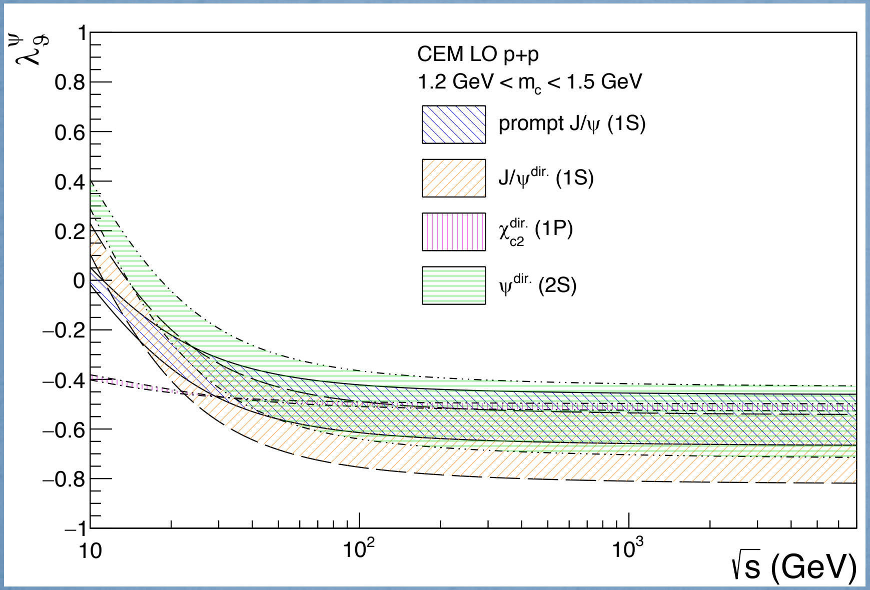
Use Improved CEM to separate dependence of e.g. 1S and 2S states

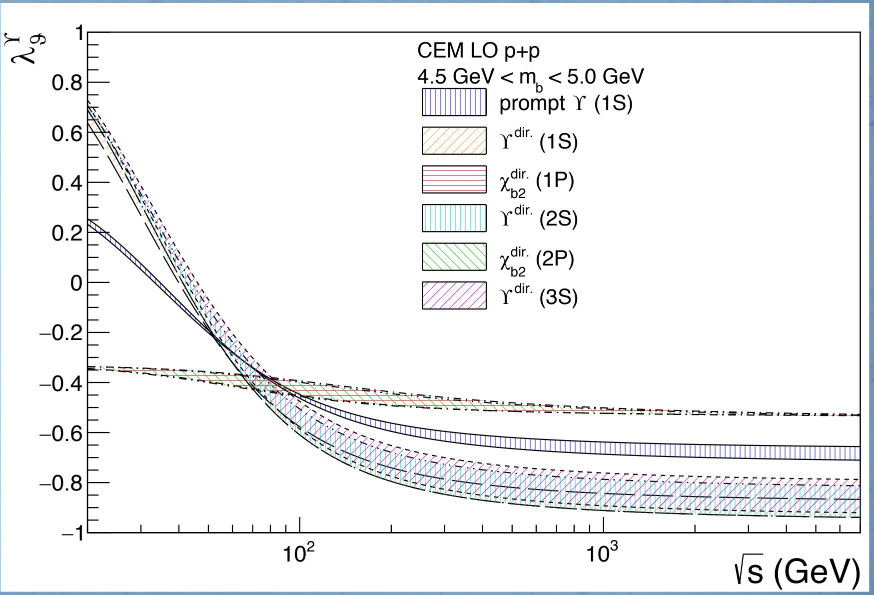
LO so far, thus results only available for center of mass energy and rapidity/x_F, for his dissertation, Vincent will calculate the p_T dependence of the polarization

Polarization in the CEM: energy dep

Dependence of λ on center of mass energy, bands show quark mass dependence, largest source of uncertainty in calculation

χ_c and χ_b states show smallest variation with energy and quark mass





V Cheung & RV, Phys. Rev. D & in preparation

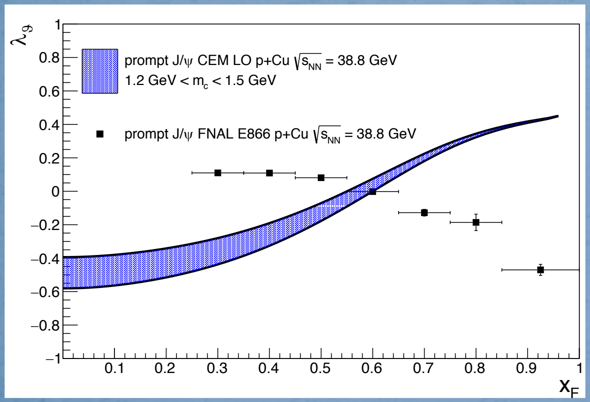
Polarization in the CEM: x_F dep

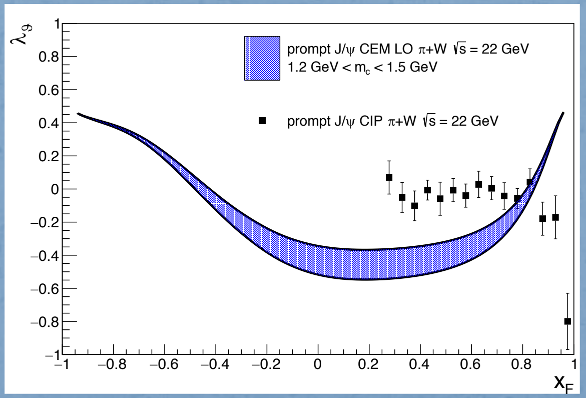
Comparison of calculations with E866 p+Cu J/ψ and Υ data at 38.8 GeV and CIP π + W J/ψ data at 22 GeV

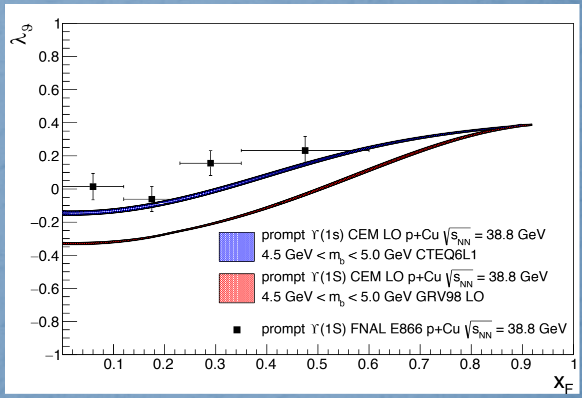
Calculations are LO CEM so no p_T is included thus there is a small kinematic mismatch between calculations

π+*A* and p+*A* are quantitatively different at forward x_F, depend on PDF and energy

Υ agreement is rather good





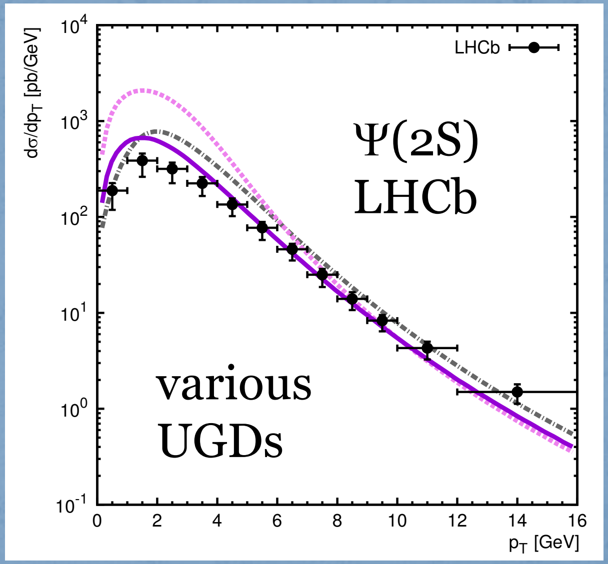


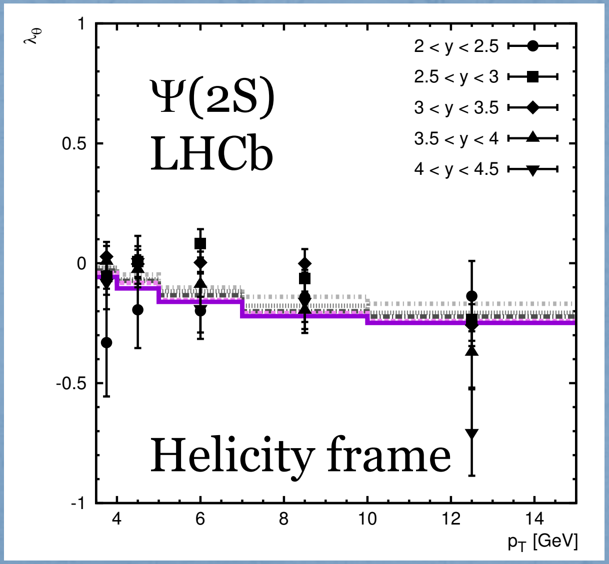
V Cheung & RV, Phys. Rev. D &in preparation

k_T Factorization for Quarkonium

Uses offshell color singlet and color octet matrix elements in NRQCD but with unintegrated gluon distributions to probe lower p_T without resummation

Fits to color octet LDMEs give smaller values than NRQCD with collinear factorization, better agreement with polarization data



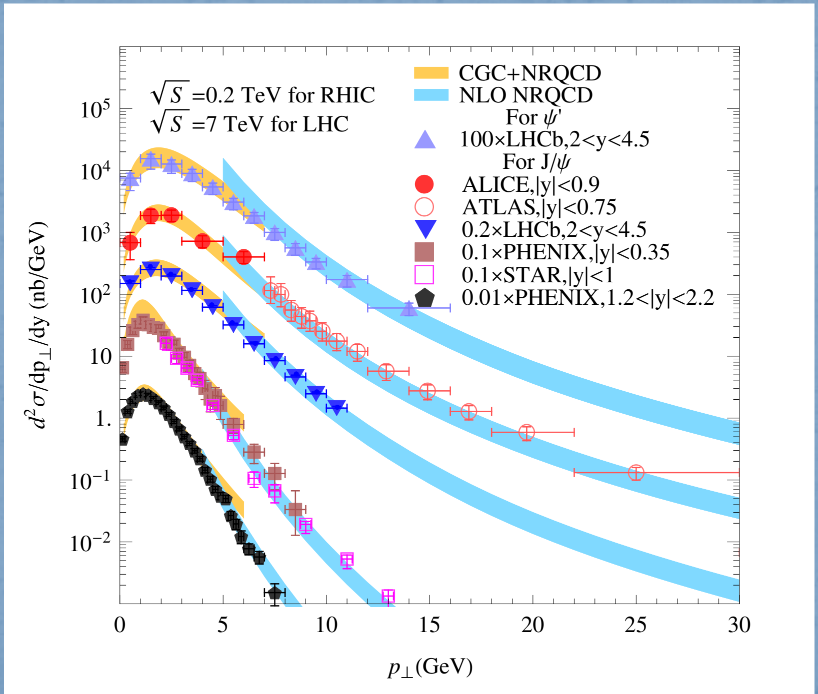


Baronov et al.

Color glass condensate and NRQCD

Uses saturation model of gluon distributions in the proton with NRQCD color octet LDMEs

Saturation physics at low p_T, normal collinear factorization at high p_T, matching at intermediate p_T



Ma and Venugopalan

Summary of Quarkonium in p+p

- Production mechanism still not settled after more than 40 years
- NRQCD has long appeared promising but has many difficulties still remaining
- k_T factorization and color glass model can address low p_T, different mix of LDMEs
- New recent work on color evaporation may be helpful

When the nucleus is a target: p+Pb collisions at the LHC

Nuclear matter effects quantified as 'nuclear suppression factor'

$$R_{pA}(p_T, y) = \frac{1}{A}\frac{d\sigma_{pA}/dp_T dy}{d\sigma_{pp}/dp_T dy}$$

Parton Density in the Initial State

Collinear factorization (DGLAP evolution): parton densities in the nucleus are modified based on global analyses of all data over a wide range of momentum fractions

- Nuclear DIS (electron, muon and neutrino-induced)
- Drell-Yan
- π^0 distributions
- High p_T jets (new, p+Pb 5 TeV data)
- W^+, W^- and Z^0 production (new, p+Pb 5 TeV data)

Global analyses available from various groups: Eskola et al. (EKS98, EPS09, EPPS16 – latest); nDS, nDSg, DSSZ; nCTEQ sets; HKN sets

Saturation, Color Glass Condensate: assumes k_T ordering and evolution in x, important at low x and low Q^2, $Q^2 < Q^2_{sat}$

At high gluon density, recombination of gluons, 2 → 1, competes with gluon emission

Q_{sat} depends on center of mass energy, x, expected to grow as $A^{1/3}$ for nuclei

Hybrid models used to interpolate between low and high x regimes

Cold Matter Energy Loss

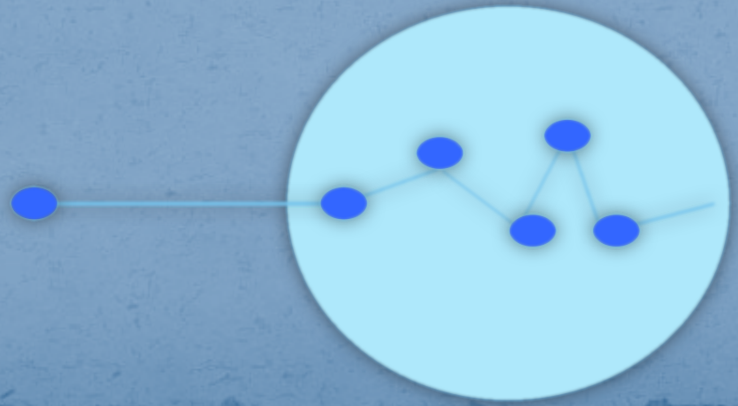
Energy loss in medium: Both initial state (before hard scattering) and final state (after hard scattering) have been considered

$R_{pA} < 1$ (forward rapidity, high p_T)

Cronin effect: Increase in average transverse momentum of the final state due to multiple scattering in the medium

$R_{pA} > 1$ (backward rapidity, low p_T)

Energy loss and Cronin are intertwined and effectively one can cause the other: a loss at high momentum can result in enhancement at low



Additional Cold Matter Effects present for Quarkonium: Size Matters

Nuclear Absorption:

- After heavy flavor pair produced, it can break up due to interactions with nucleons
- Relevant for regions of phase space where quarkonium state is produced in matter, e.g. backward rapidity at the LHC and RHIC

Comovers:

- Quarkonium states break up due to interactions with produced particles
- More loosely bound states are more likely to break up
- Effect increases with collision centrality (comover density)

Both absorption and comover interaction cross sections expected to depend on quarkonium size

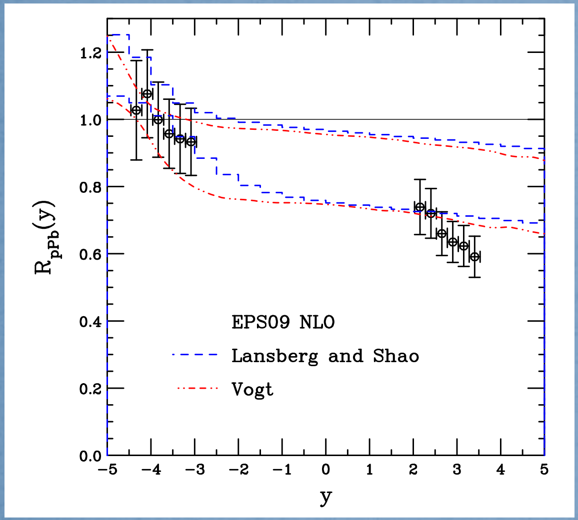
$$\sigma_C/\sigma_{C'} \;\alpha\; (R_C/R_{C'})^2$$

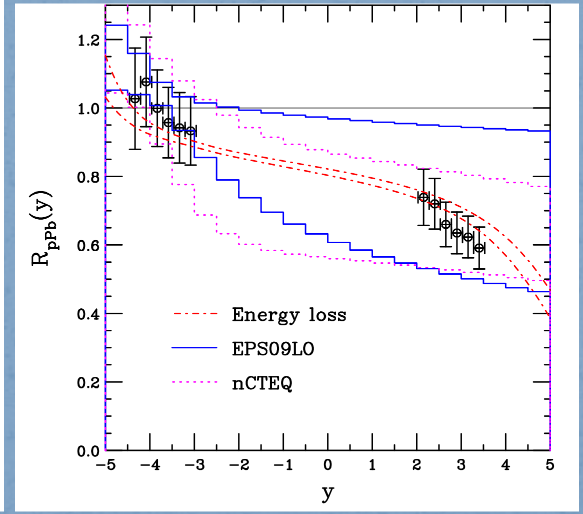
Suppression in p+Pb at 8 TeV: *y* dep

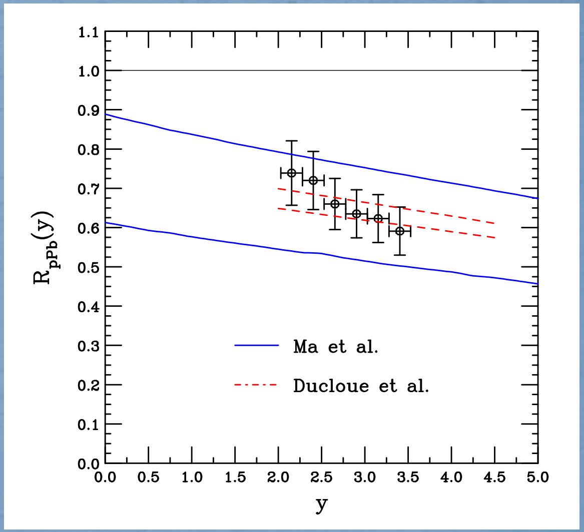
All calculations do a reasonable job of describing preliminary ALICE data

EPS09 NLO is marginal at forward rapidity due to difference in low *x* behavior of CTEQ6M and CTEQ61L

CGC+NRQCD band is larger because different color states shown separately







Collinear factorization: shadowing only and energy loss only

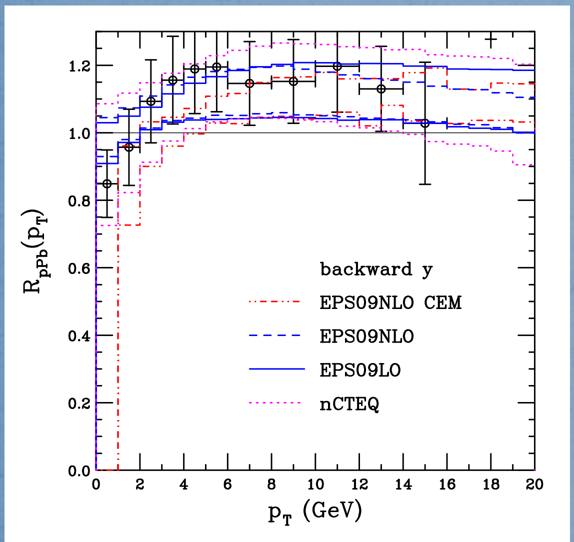
CGC+CEM (Ducloue et al)
CGC+NRQCD (Ma et al)

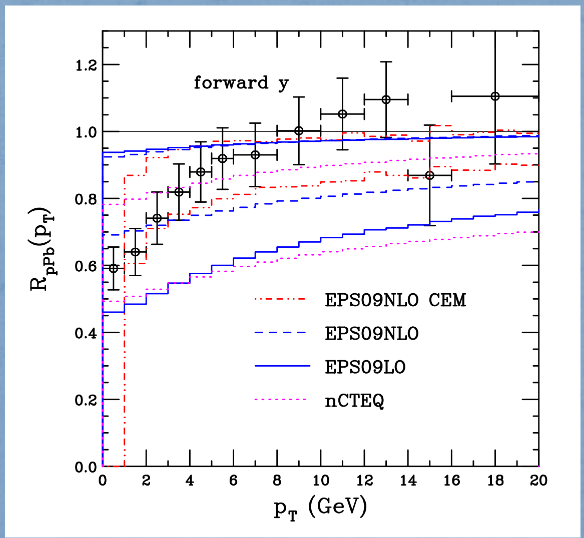
Suppression in p+Pb at 8 TeV: p_T dep

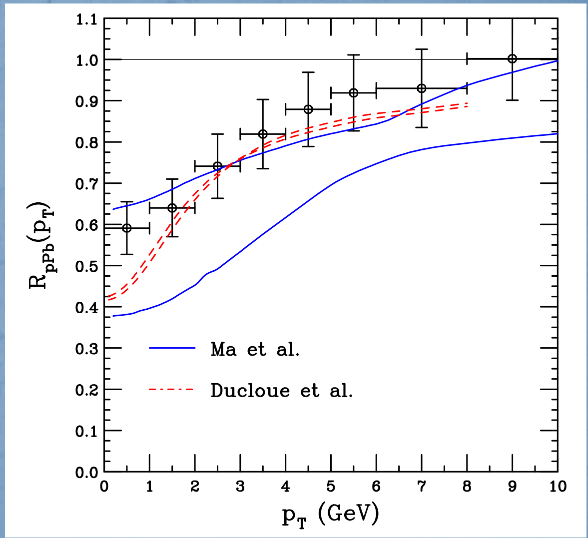
All calculations do a reasonable job of describing preliminary ALICE data

Shadowing uncertainty bands are smaller vs. p_T at backward rapidity

CGC+NRQCD and CGC+CEM calculations have different curvature at low p_T







Collinear factorization: shadowing only
and energy loss only (RV, Lansberg and Shao)

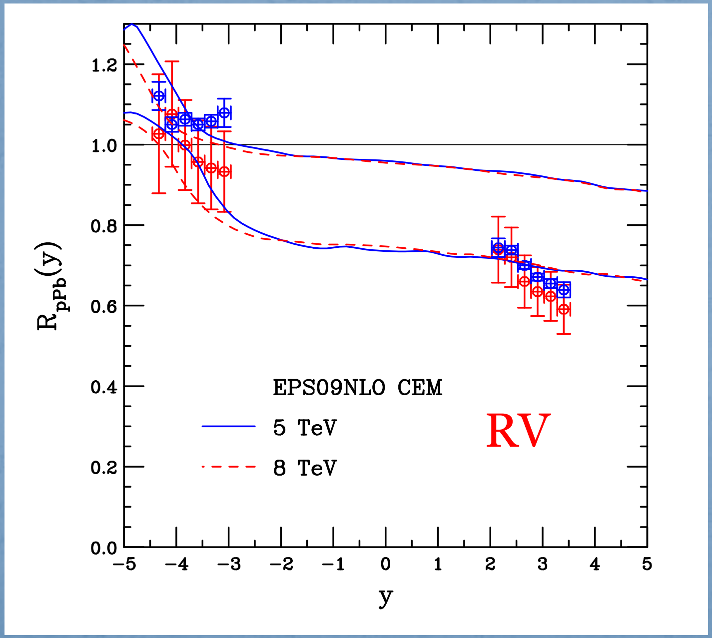
CGC+CEM (Ducloue et al)
CGC+NRQCD (Ma et al)

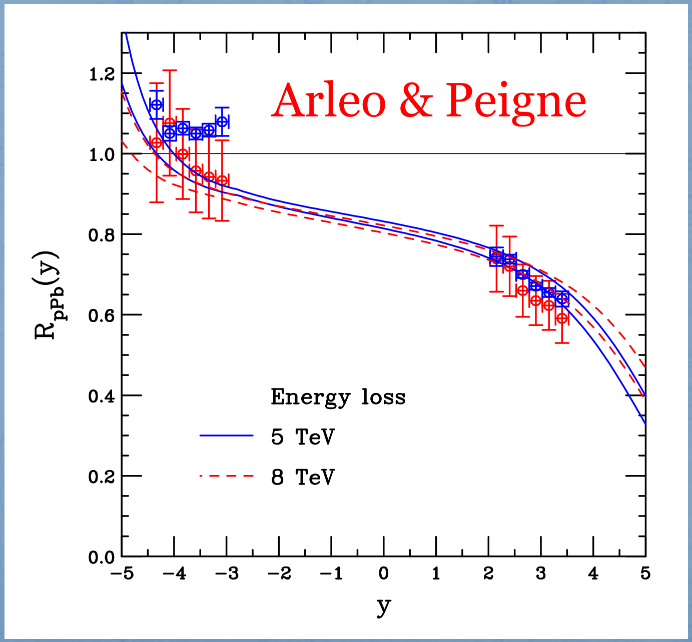
5.02 TeV vs. 8.16 TeV

Comparison is actually 5 vs. 8 TeV, results are shown for cases where the same input models were used in both cases

Only small differences seen in calculations at the two energies, EPS09 NLO CEM is mostly different at backward rapidity, shadowing is maximal at forward y

Data are also rather similar, perhaps more dependence on *y* in backward region

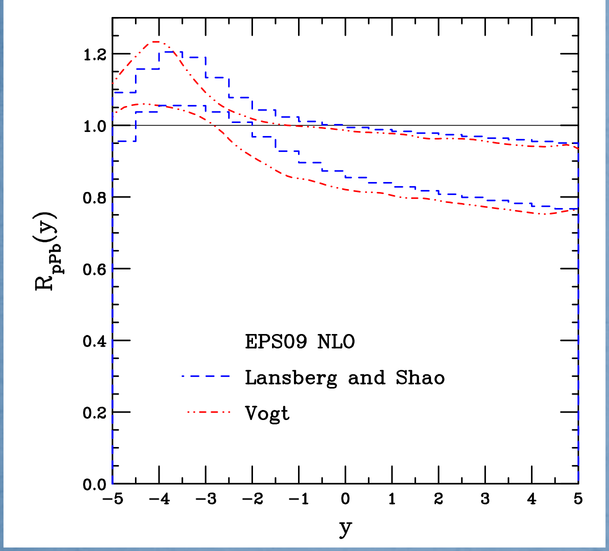


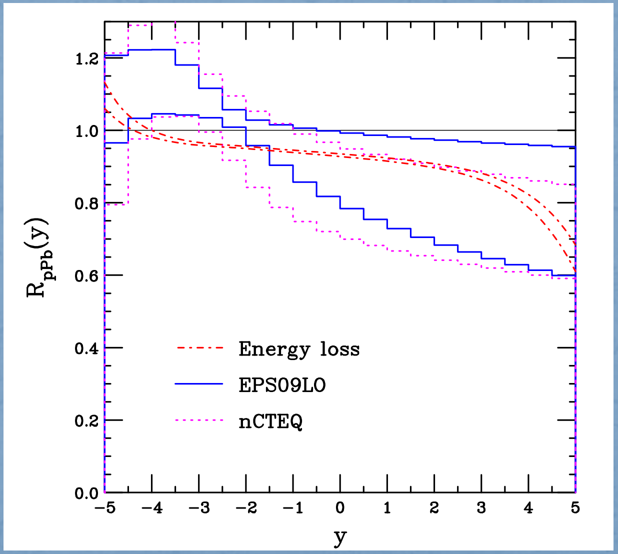


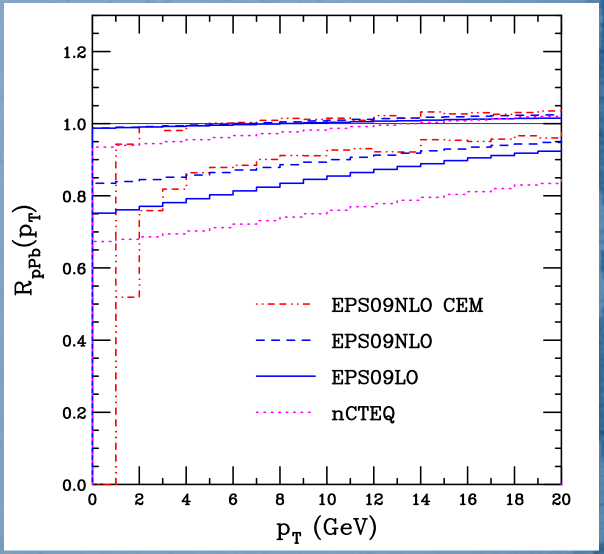
Predictions for Υ(1S) inclusive

Uncertainty bands are smaller for Upsilon results because mass scale is larger, more evolution of nPDFs, somewhat higher *x* as well

All calculations are within uncertainties of each other





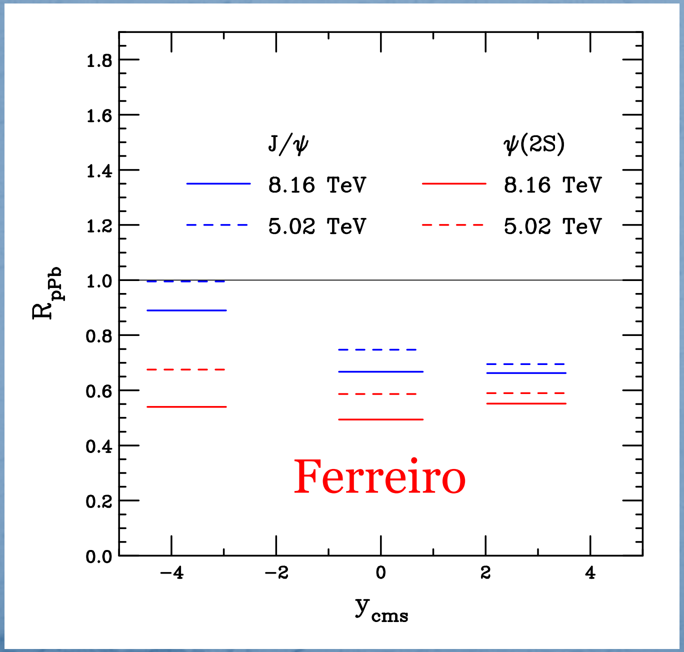


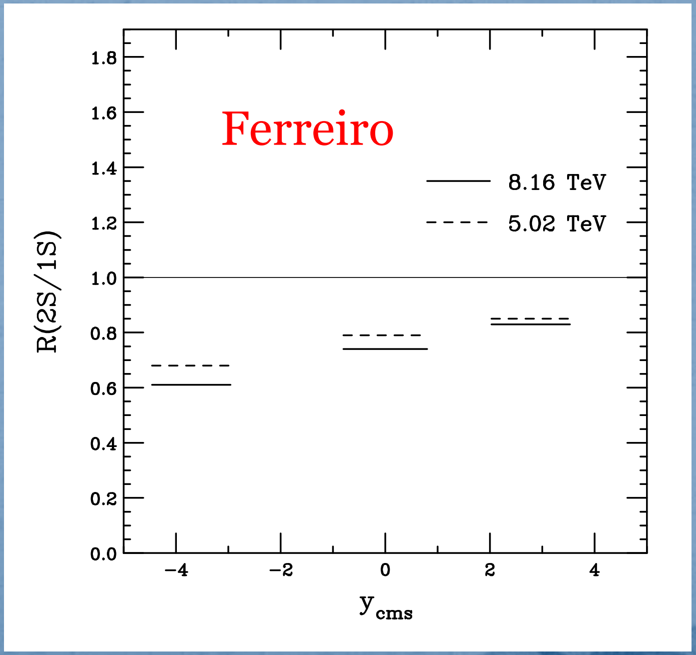
RV, Landsberg and Shao, Arleo and Peigne

Suppression by comovers

Left side compares R_{pPb} in different rapidity regions for the two energies, biggest difference is at backward rapidity, at forward rapidity, difference is negligible

Right side shows double ratio, ψ(2S)/ψ(1S), for the two energies, same trend seen





p+Pb Quarkonium Summary

- Minimum bias results likely too dilute to apply hot matter models but high multiplicity central p+Pb events may be more relevant
- Multiple models can explain the trends in the quarkonium data
- Higher precision data are needed to separate effects and eliminate models – as ever the case