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

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Outline:

- Open heavy flavor
- Quarkonium
- Heavy flavor partons in the proton
- When the nucleus is a target: p+Pb

Open Heavy Flavor

Collinear vs k_T factorization, schematic single inclusive cross section

$$E\frac{d^3\sigma(e)}{d^3p} = E_Q\frac{d^3\sigma(Q)}{d^3p_Q} \otimes D(Q \to H_Q) \otimes f(H_Q \to e)$$

Single Inclusive Production

Single inclusive calculation of heavy flavor: quark; hadron; and semileptonic decay distributions calculated in Fixed-Order Next-to-Leading Log (FONLL) approach (Cacciari and Nason, applied to RHIC w/RV)

Schematically:

$$E\frac{d^3\sigma(e)}{d^3p} = E_Q\frac{d^3\sigma(Q)}{d^3p_Q} \otimes D(Q \to H_Q) \otimes f(H_Q \to e)$$

Single heavy quark cross section only: no $Q\overline{Q}$ pair kinematics

Fragmentation into heavy-flavor hadrons described by FONLL-appropriate fragmentation functions, $D(Q \to H_Q)$, extracted from e^+e^- data

$$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0})G(m, p_T)$$

Includes resummed terms (RS) of order $\alpha_s^2(\alpha_s \log(p_T/m))^k$ (leading log – LL) and $\alpha_s^3(\alpha_s \log(p_T/m))^k$ (NLL) to improve $p_T \gg m$ region

Subtracts fixed-order (FO) terms retaining only logarithmic mass dependence, "massless" limit of FO calculation (FOM0) employs same renormalization scheme, $G(m, p_T)$ interpolates between FO and RS regions for same number of light flavors

Smaller charm cross section than at FO ($n_{\mathrm{lf}} = 3$) since heavy flavor treated as a light degree of freedom ($n_{\mathrm{lf}} = 4$)

Defining Theoretical Uncertainty

Theoretical uncertainties can be large, especially for charm; good for containing full uncertainty range but less so for comparing to high statistics data

FONLL fiducial uncertainty obtained from region of mass and scale that should encompass the true value:

- **For** $\mu_F = \mu_R = m$**, vary mass,** $1.3 < m_c < 1.7$, $4.5 < m_b < 5.0$ **GeV;**
- **For** $m_c = 1.5$ **and** $m_b = 4.75$ **GeV, vary scales independently within a factor of two:** $(\mu_F/m, \mu_R/m) = (1,1)$, **(2,2), (0.5,0.5), (0.5,1), (1,0.5), (1,2), (2,1)**

Fitting the total heavy flavor cross sections (Nelson, Frawley, RV) to reduce scale uncertainties:

- **Take lattice value for** m_c **and** $1S$ **value for** m_b**, 1.27 and 4.65 GeV respectively with** 3σ **mass uncertainty**
- **Vary scales independently within** 1σ **of fitted region:** $(\mu_F/m, \mu_R/m) = (C, C)$, **(H,H), (L,L), (H,C), (C,H), (L,C), (C,L)**

The uncertainty band in all cases comes from the upper and lower limits of mass and scale uncertainties added in quadrature

Fitting charm cross section to reduce theoretical uncertainties

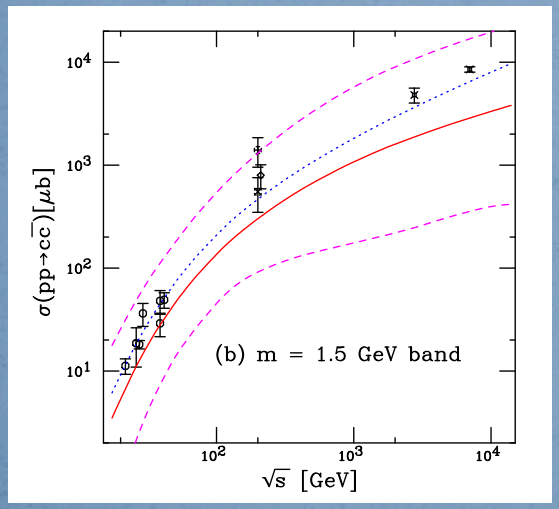
Full NNLO cross section, if known, could still result in large corrections

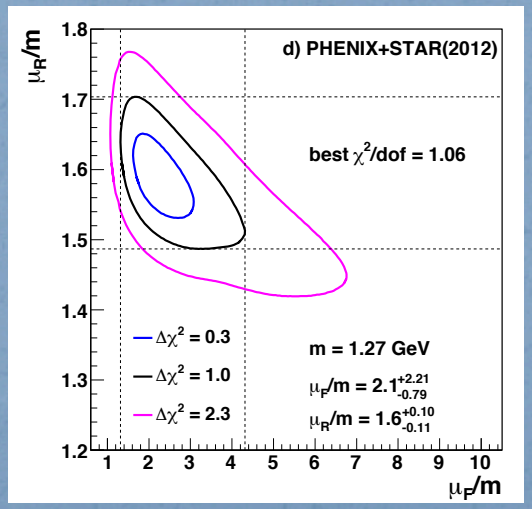
Use subset of $c\bar{c}$ total cross section data for best fit values of μ_F/m and μ_R/m

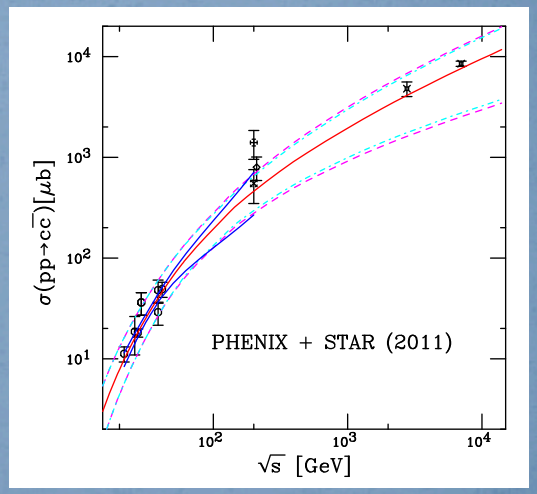
$\Delta\chi^2 = 1$ **gives uncertainty on scale parameters**

$\Delta\chi^2 = 2.3$ **gives one standard deviation on total cross section**

LHC results agrees well with fits although not included in the fits







Nelson, Frawley, RV

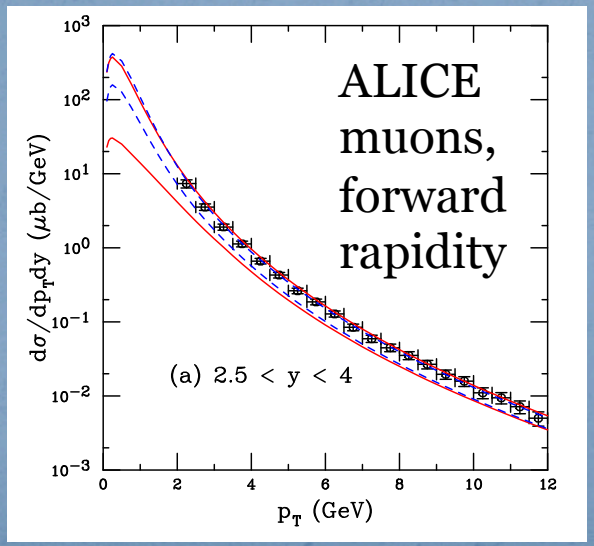
Open Charm Results at 7 TeV

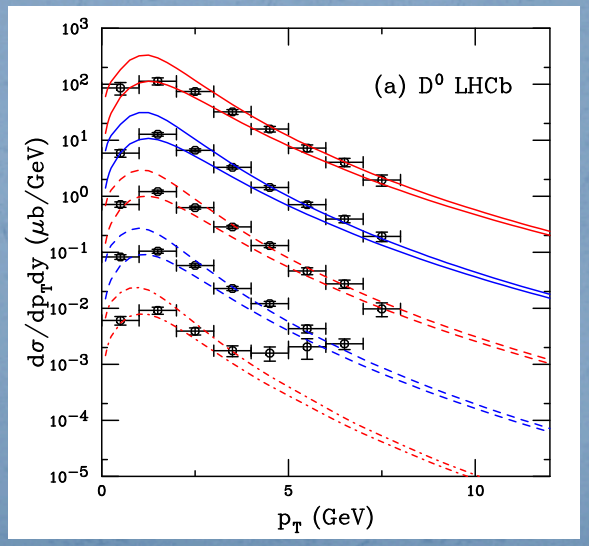
Distributions calculations with FONLL: excellent agreement with $\sqrt{s} = 7$ TeV ALICE pp data on muons in the forward region, $2.5 < y < 4$

(Left) Leptons from semi-leptonic heavy flavor decays from ALICE: contributions from $D \to \mu X$, $B \to \mu X$, $B \to D \to \mu X$, $\sim 10\%$ decay branching ratios

(Right) Forward D^0 distributions from LHCb, divided up into $\Delta y = 0.5$ regions, lowest bin $2.0 < y < 2.5$ has correct normalization, other results are scaled down by factor of 10 for clarity

Using fit results instead of fiducial results $m = 1.5$ GeV gives narrower uncertainty without reducing agreement with data





LHCb
D^0
$2<y<4.5$,
$\Delta y = 0.5$
units

Nelson, Frawley, RV

Other Calculations with Collinear Factorization

Inclusive Production:

GM-VFN scheme:

Kniehl *et al.* **calculate NLO corrections to inclusive charm production using massive or massless charm. They derive the massless limit from massive theory (fixed-flavor number, FFN) and showed that it differs from massless scheme (zero mass, variable flavor number, ZM-VFN) by finite corrections.**

Subtraction terms were adjusted to establish massive theory in $\overline{\mathrm{MS}}$ scheme that approaches the ZM-VFN result at high p_T.

Included contributions from incoming c or $\overline{c}$ quarks as well as those with gluon or light quark fragmentation to charm using DGLAP-evolved nonperturbative fragmentation functions

Exclusive Production:

HVQMNR:

Mangano, Nason and Ridolfi, negative weight Monte Carlo, incomplete cancellation of divergences for heavy quark pairs at low p_T, no resummed terms

Peterson function is default fragmentation function

POWHEG-hvq:

Frixione, Nason and Ridolfi, positive weight Monte Carlo with leading log resummation

Can be run either standalone for NLO events or interfaced to shower Monte Carlos like HERWIG and PYTHIA

k_T Factorization

Exclusive $Q\overline{Q}$ production uses off-shell leading order matrix elements for $g^*g^* \to c\overline{c}$ (Collins and Ellis) together with unintegrated gluon distributions that depend on the gluon transverse momenta as well as the usual dependence on x and factorization scale μ_F

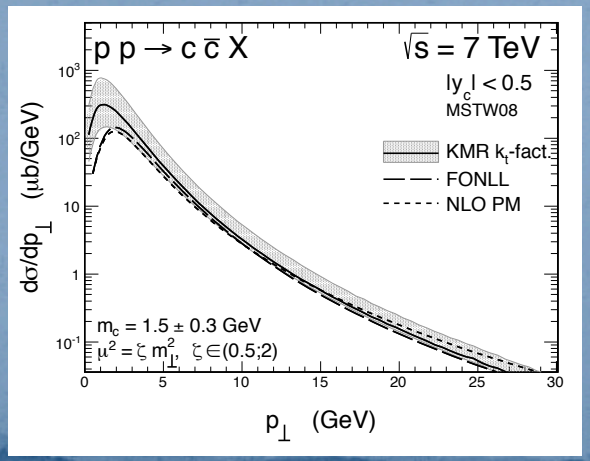
$$\frac{d\sigma(pp \to c\overline{c}X)}{dy_1 dy_2 d^2p_{1T} d^2p_{2T}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2k_{1T}}{\pi} \frac{d^2k_{2T}}{\pi} \overline{|\mathcal{M}_{g^*g^* \to c\,\overline{c}}|^2} \delta^2\left(\vec{k}_{1T} + \vec{k}_{2T} - \vec{p}_{1T} - \vec{p}_{2T}\right) \mathcal{F}_g(x_1, k_{1T}^2, \mu_F^2) \mathcal{F}_g(x$$

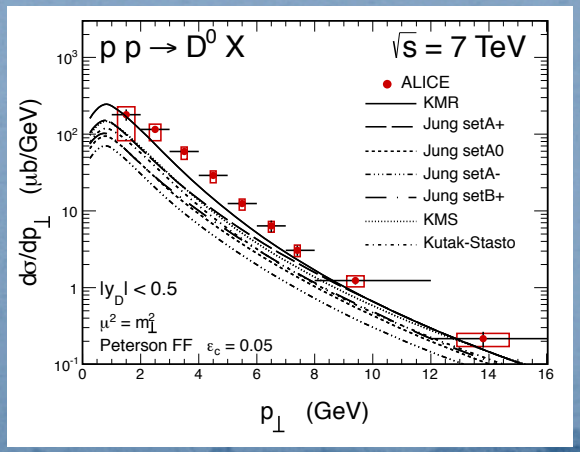
$$\frac{d\sigma(pp \to D\overline{D}X)}{dy_1 dy_2 d^2p_{1T}^D d^2p_{2T}^{\overline{D}}} \approx \int \frac{D_{c\to D}(z_1)}{z_1} \cdot \frac{D_{\overline{c}\to\overline{D}}(z_2)}{z_2} \cdot \frac{d\sigma(pp \to c\overline{c}X)}{dy_1 dy_2 d^2p_{1T}^c d^2p_{2T}^{\overline{c}}} dz_1 dz_2$$

Use Peterson function fragmentation with smaller value of ϵ parameter (harder fragmentation)

Unintegrated gluon distributions depend on LO k_T-integrated parton densities and Sudakov form factor

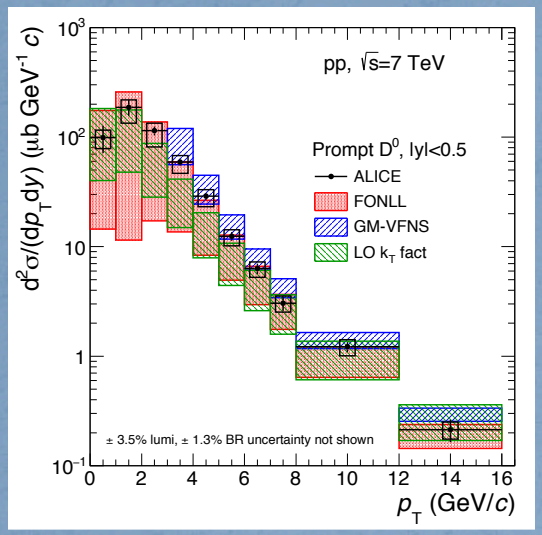
Normalization condition $g(x, \mu_F^2) = \int_0^{\mu^2} dk_T^2\, f_g(x, k_T^2, \mu_F^2)$

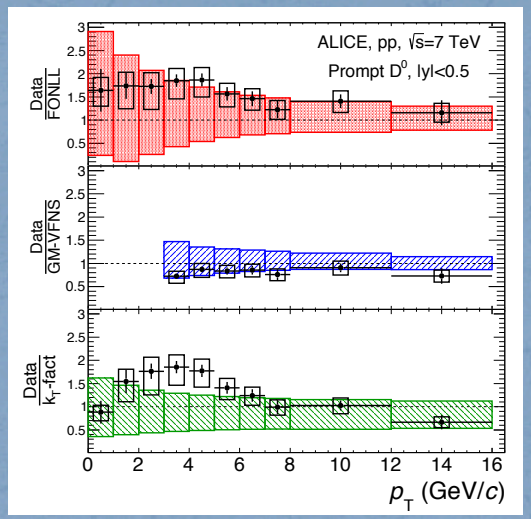




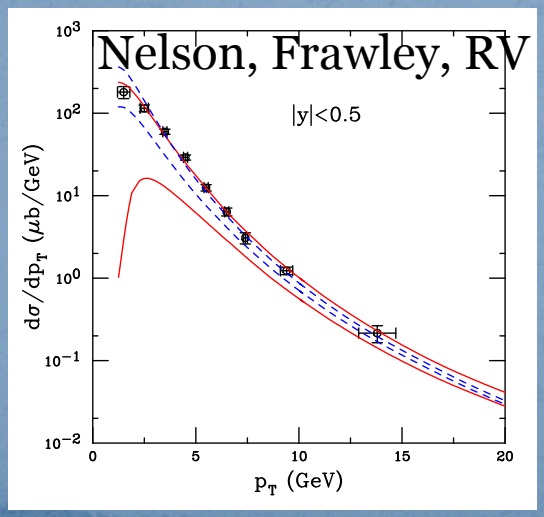
Calculations by Maciula & Szczurek

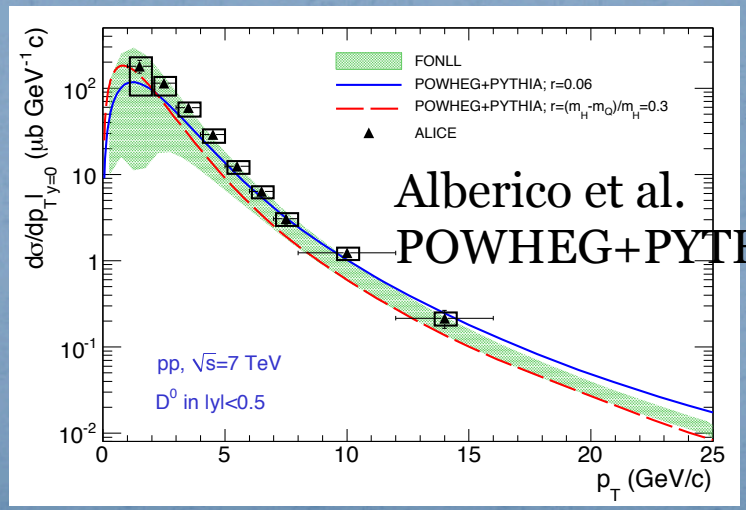
Single D⁰ Results – ALICE





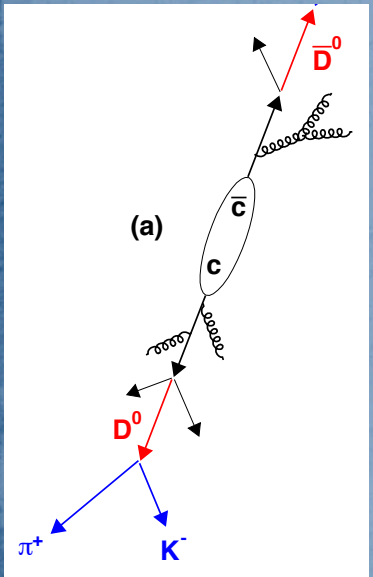
ALICE Collaboration: arXiv:1605.07569, in press

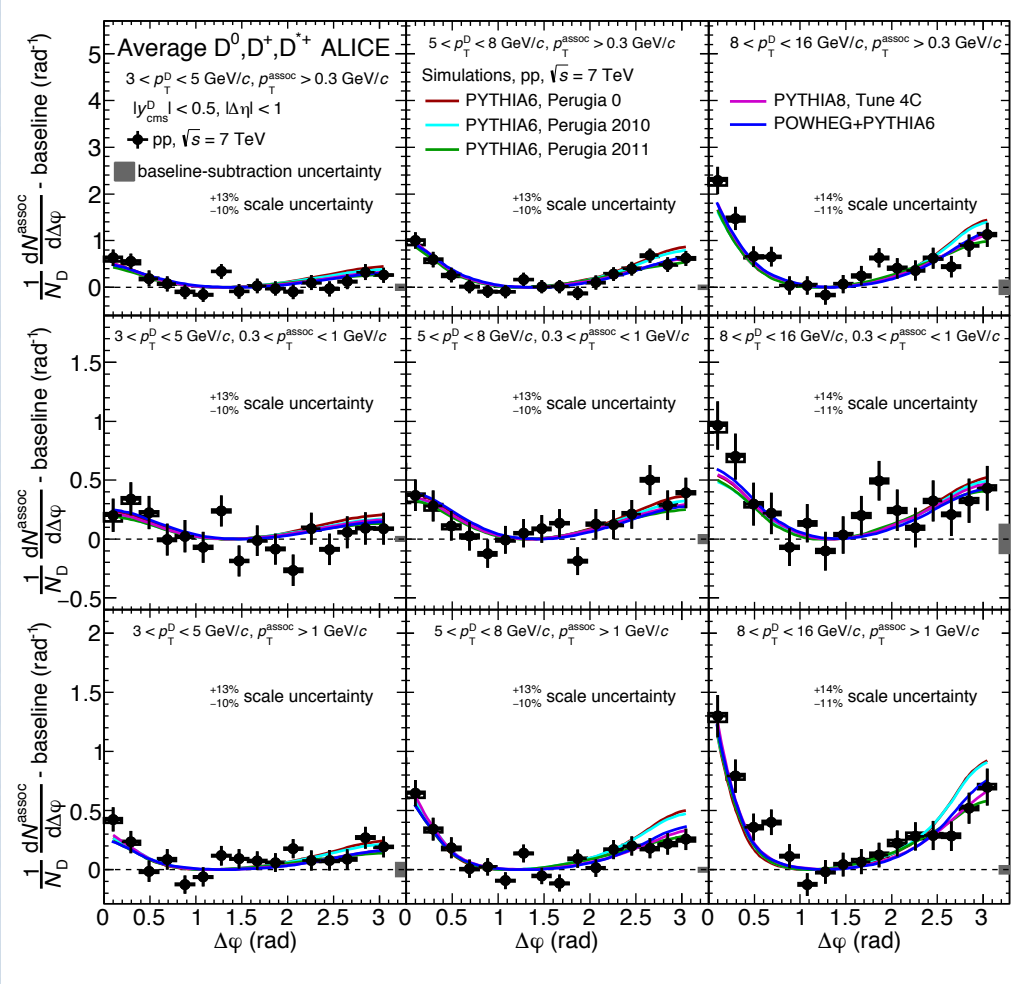




ALICE D-hadron azimuthal correlations

p+p shown at 7 TeV, p+Pb at 5.02 TeV similar





Increasing light hadron trigger p_T

PLB 671 (2009) 361

Increasing D meson p_T

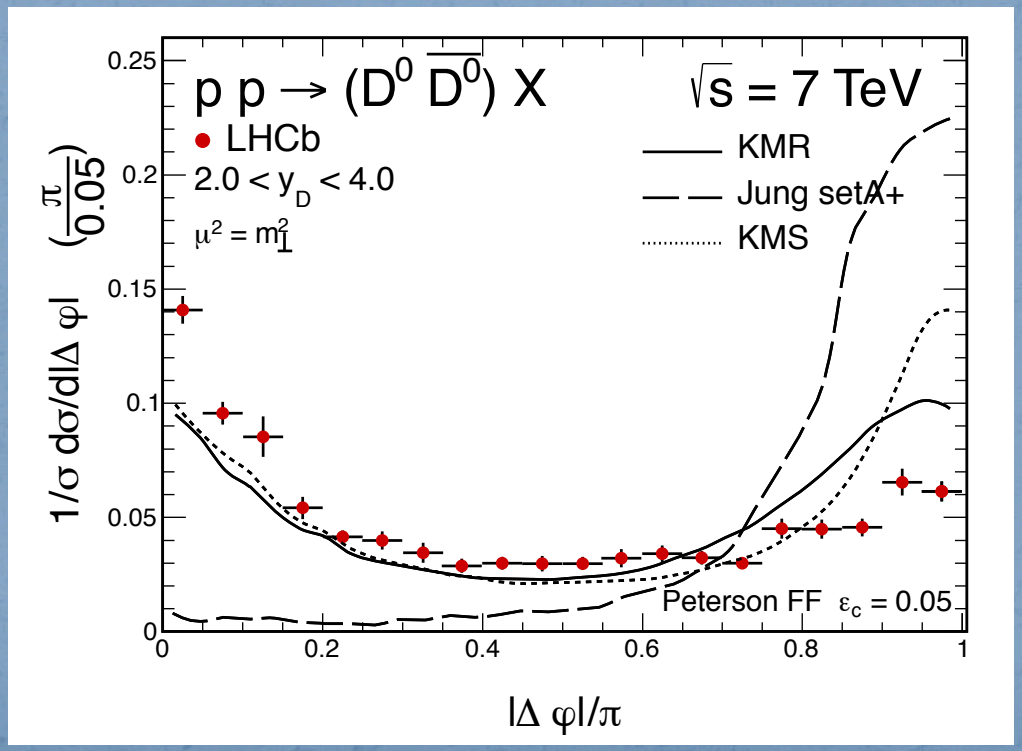
arXiv:1605.06963

LHCb D^0 pair correlations

Pair correlations at forward rapidity in k_T-factorization approach

Correlation similar to ALICE D-hadron correlation at central rapidity

None of the calculations are a good match to the data



Calculations by Maciula & Szczurek

Open Heavy Flavor Summary

- Collinear factorization appears to work very well at LHC, even at low p_T and forward rapidity, for single heavy flavor distributions
- Exclusive NLO calculations, as well as PYTHIA, can explain correlation results
- k_T factorization does not do better than collinear factorization and, in fact, does not do as well at low p_T, even though x is small

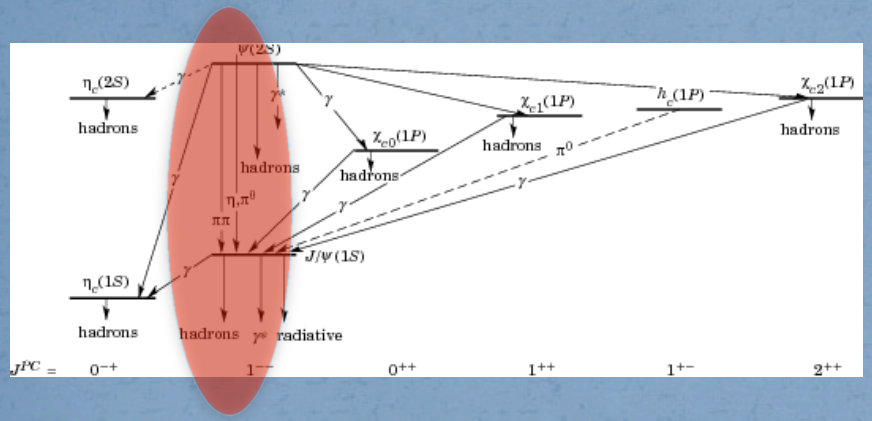
Quarkonium Production

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

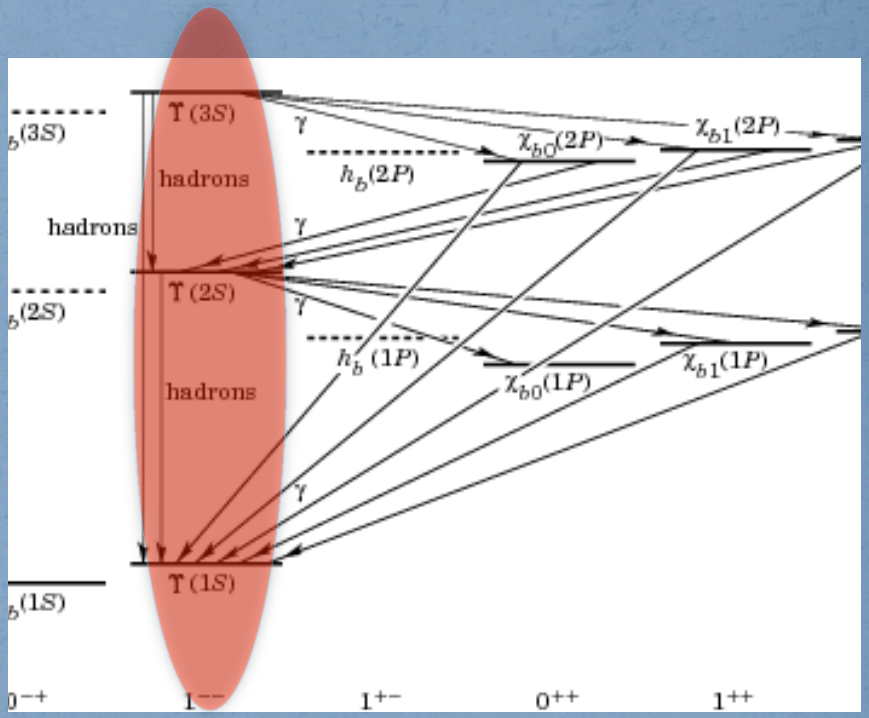
$$\sigma_{J/\psi} = \Sigma_n \sigma_{c\bar{c}[n]} \langle \mathcal{O}^{J/\psi}[n] \rangle$$

Quarkonium Levels

Focus on this talk is primarily on S states



Charmonium



Bottomonium

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
- 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 $e.g.\ J/\psi$**:**

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

Sum over n **is over all Fock states, including color-octet states**

$\sigma_{c\overline{c}[n]}$ **is production rate of** $c\overline{c}$ **pair in a particular color and spin state** n**, calculated in perturbative QCD**

$\langle \mathcal{O}^{J/\psi}[n] \rangle$ **are nonperturbative long distance matrix elemnts (LDMEs) that describe the conversion of** $c\overline{c}[n]$ **state into final state** J/ψ**, assuming that the hadronization does not change the spin or momentum**

The LDMEs are assumed to be <u>universal</u>

NRQCD includes a double expansion in relative velocity of c **and** $\overline{c}$**,** v**, and the strong coupling constant** α_s**, thus the LDMEs scale with definite powers of** v

Leading term in v**,** $n =^3 S_1^{[1]}$**, corresponds to the color singlet model**

Color octet states are subleading terms ${}^1S_0^{[8]}$**,** ${}^3S_1^{[8]}$**, and** ${}^3P_J^{[8]}$

Heavy quark spin symmetry can be used to assign LDMEs to other charmonium states, $e.g.\ \langle \mathcal{O}^{\eta_c}[{}^3S_1^{[8]}] \rangle = \langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}] \rangle$

Mix of color octet terms determined by fitting the LDMEs to data, usually p_T **distributions above some** p_T **cut, and then used to predict other measurements such as the polarization**

NRQCD generally predicts significant transverse polarization

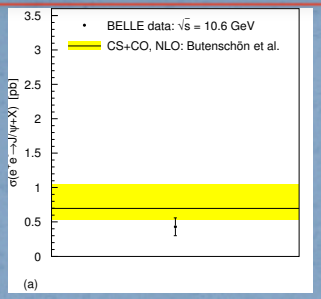
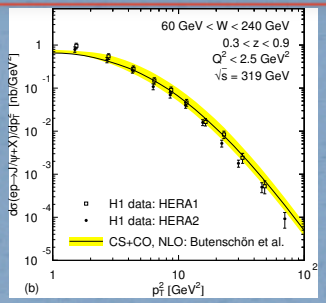
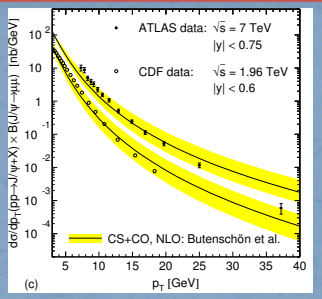
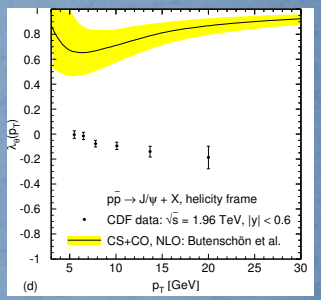
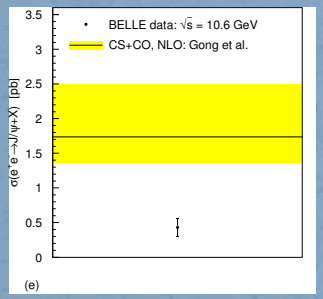
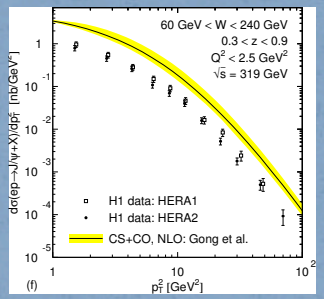
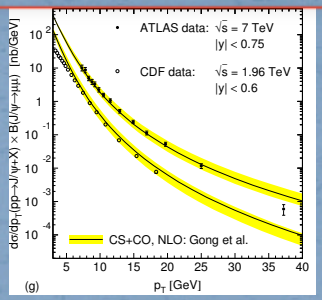
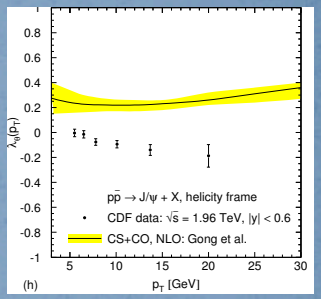
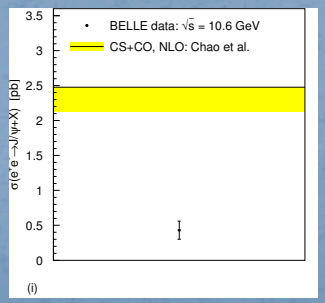
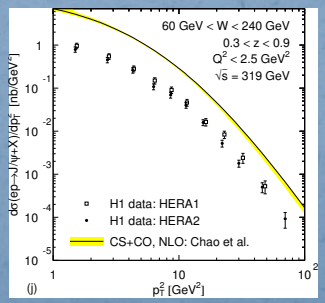
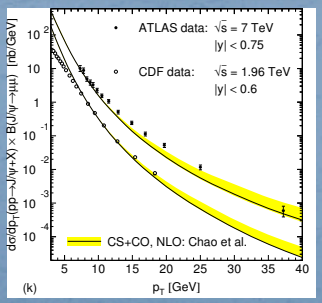
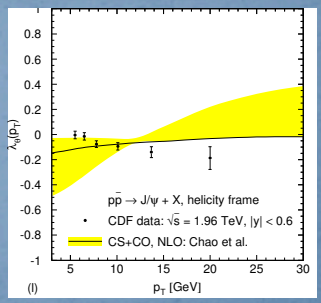
Are the LDMEs Universal?

- 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

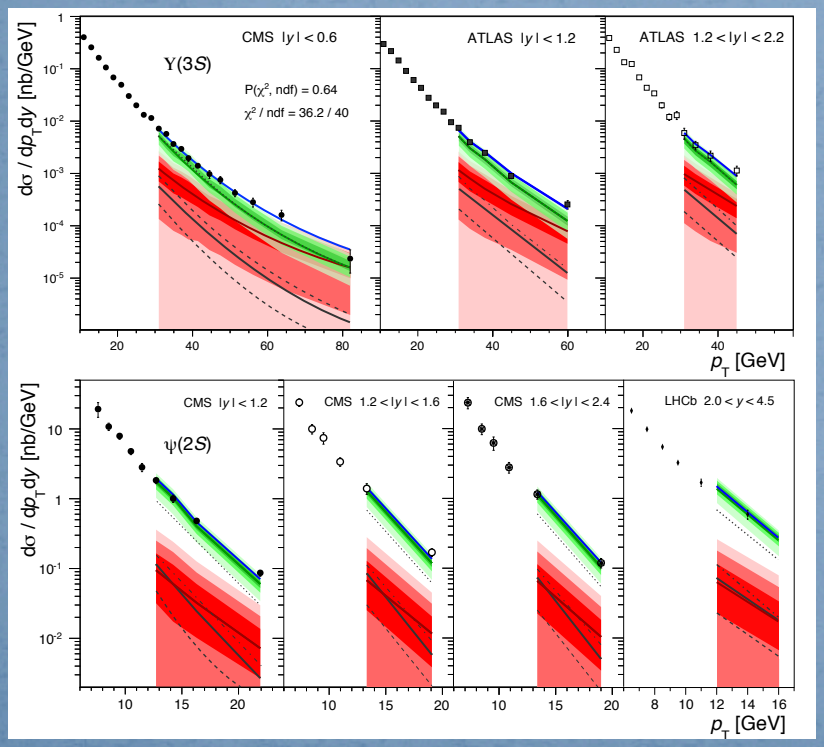
	e^+e^-	ep	pp distribution	pp polarization
Butenschon & Kniehl $p_T > 3$ GeV				
Gong et al $p_T > 5$ GeV				
Chao et al $p_T > 7$ GeV				

Polarization: fitted or predicted?

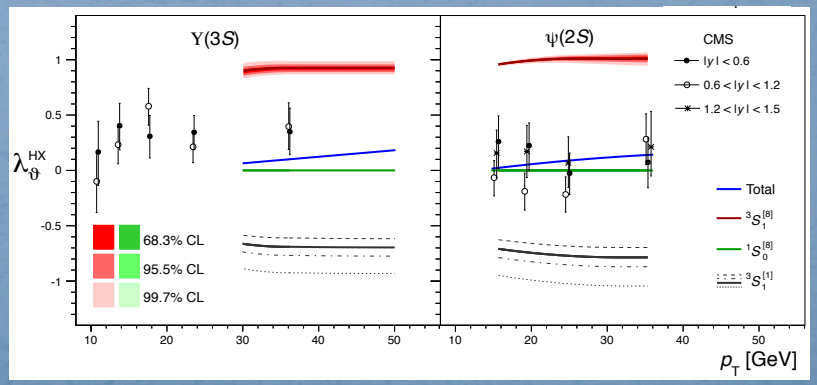
Fitting LDMEs to yields alone does not describe polarization

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



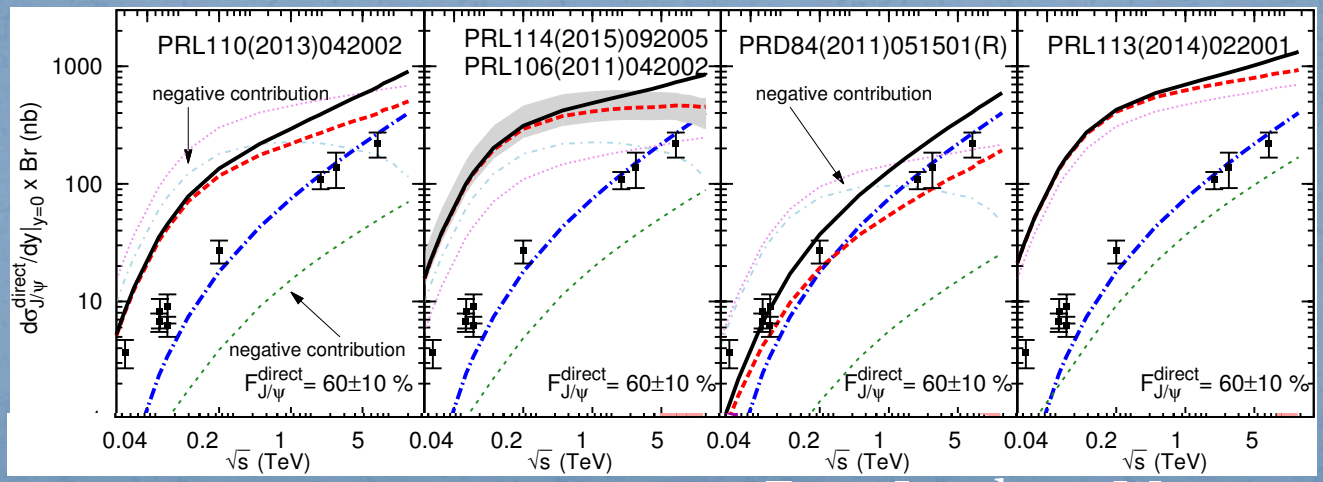
LDMEs fit to yields fail to describe the p_T-integrated rate (no big surprise)

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

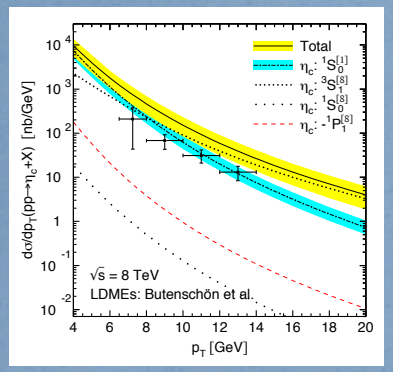


Feng, Lansberg, Wang

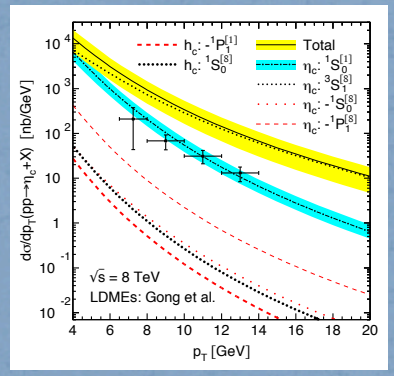
J/ψ LDMEs do not describe η_c

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

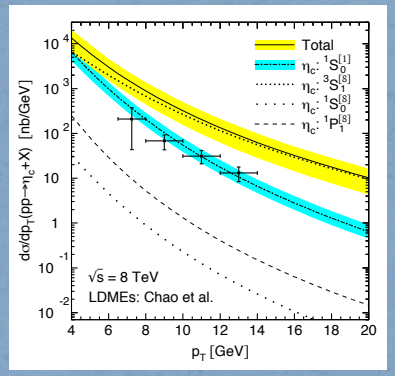
Butenschon & Kniehl



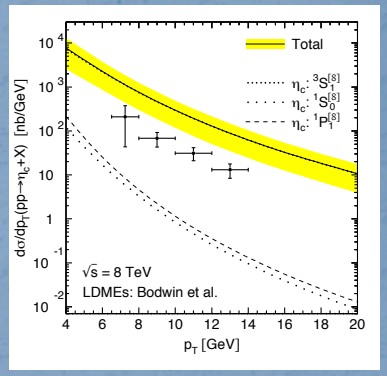
Chao et al



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?

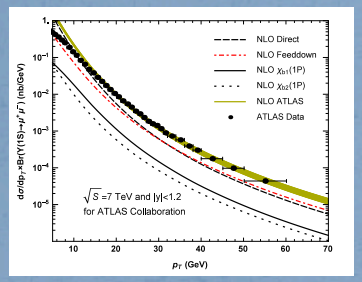
Larger mass, higher scale (smaller coupling) and slower velocity could Make Υ a better candidate for NRQCD

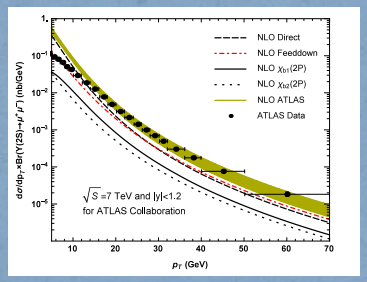
Υ production also allows for more free parameters to allow a description of both production and polarization – only Υ(3S) has little wiggle room

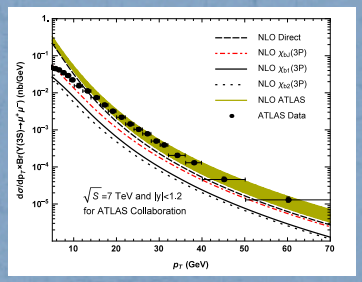
Han et al, p_T > 15 GeV fit

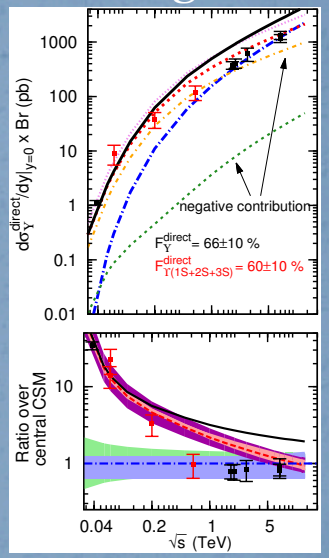
Lansberg et al

ATLAS
|y| < 1.2



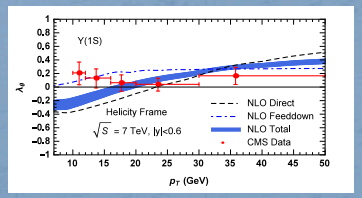


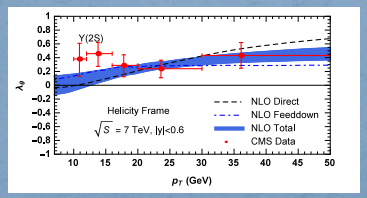


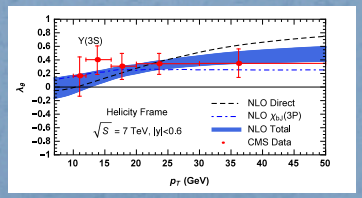


Υ(1S) Υ(2S) Υ(3S)

CMS
|y| < 0.6







Other calculations can give similar agreement with data

Color Evaporation Model

All quarkonium states are treated like $Q\overline{Q}$ ($Q = c, b$) below $H\overline{H}$ ($H = D, B$) threshold

Color and spin have been integrated out in $Q\overline{Q}$ cross section so color is said to be 'evaporated' away during transition from pair to quarkonium state withouth changing kinematics

Distributions for all quarkonium family members generally assumed identical. Thus production ratios should also be independent of $\sqrt{s}$, p_T, x_F.

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

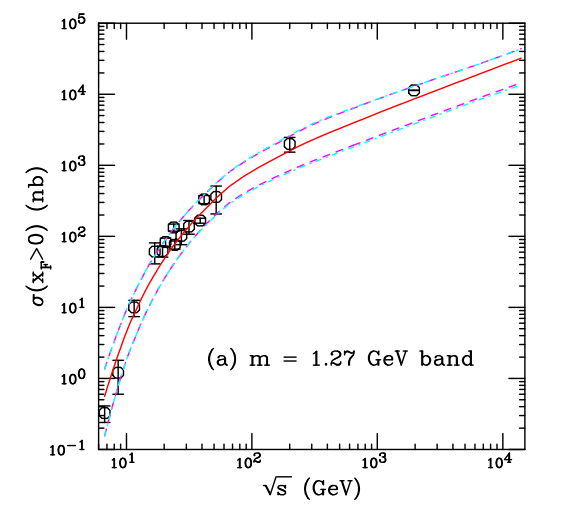
Values of m and μ^2 fixed from NLO calculation of $Q\overline{Q}$ total cross sections

F_Q fixed by comparison of NLO calculation of σ_Q^{CEM} to $\sqrt{s}$ 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

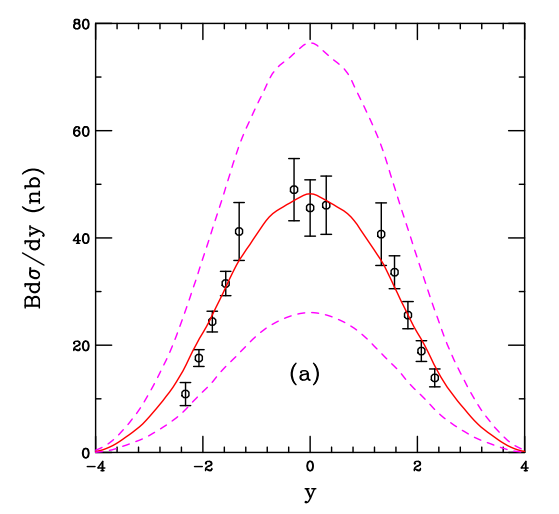
One F_Q for each quarkonium state

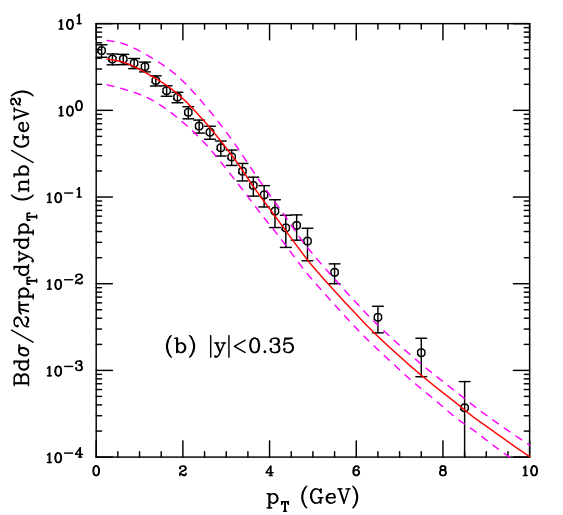
Since spin has been average over, no previous prediction of polarization in CEM

J/ψ Results in CEM



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





New work on CEM

- UC Davis graduate student Vincent Cheung is calculating the polarization at LO in the CEM, look for a paper later this year

- Calculating ψ'/ψ ratio as a function of p_T in a modified CEM where the p_T of the quarkonium state is modified by the ratio of the pair invariant mass to the quarkonium mass (with Y-Q Ma)

Improved Color Evaporation Model

Relates the average final state ψ momentum, $\langle p_\psi \rangle$, to the $c\bar{c}$ pair momentum, p

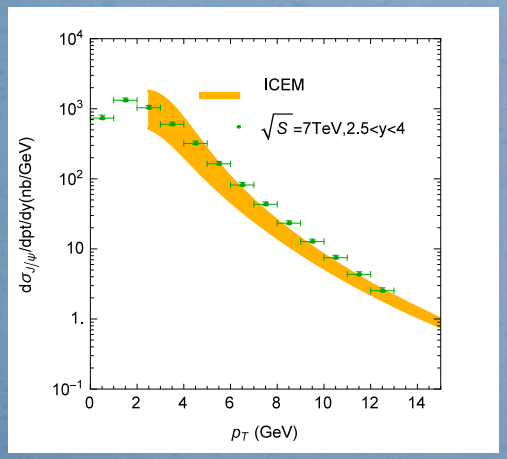
$$\langle p_\psi \rangle = \frac{M_\psi}{M} p + \mathcal{O}(\lambda^2/m_c)$$

Also, since the lower limit on pair mass, M, has to be larger than $\langle p_\psi \rangle$, the lower limit on the CEM integration has to be increased to M_ψ

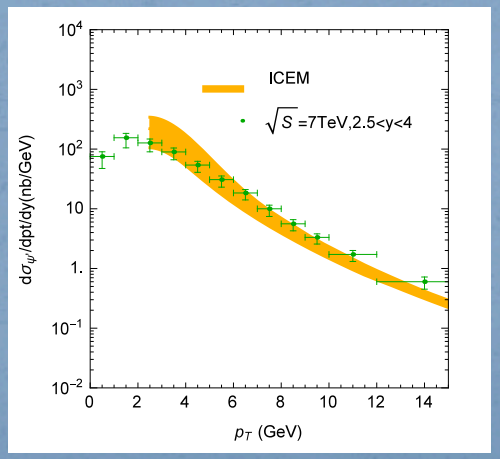
For the transverse momentum distribution, we have

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

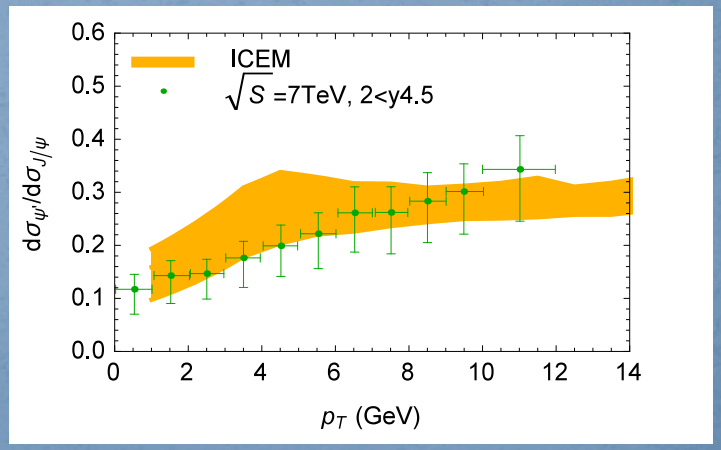
J/ψ



ψ'



ψ'/ψ ratio



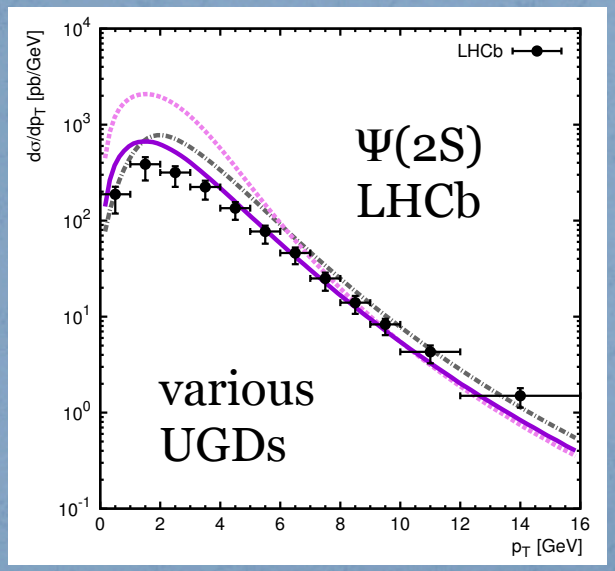
LHCb 7 TeV p+p

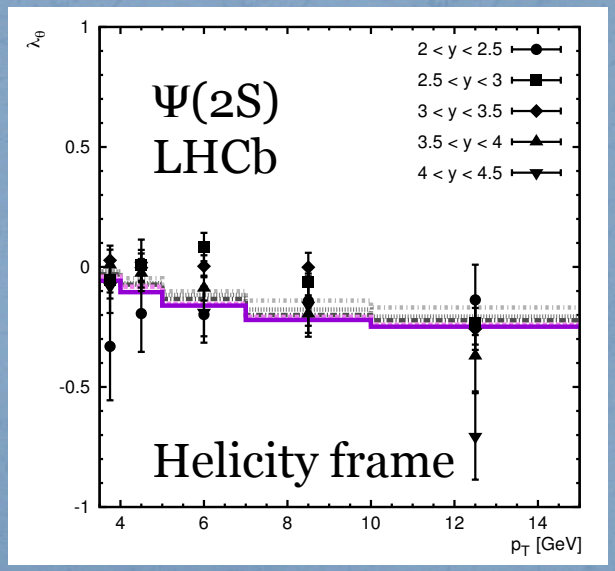
Y-Q Ma & RV, in preparation

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



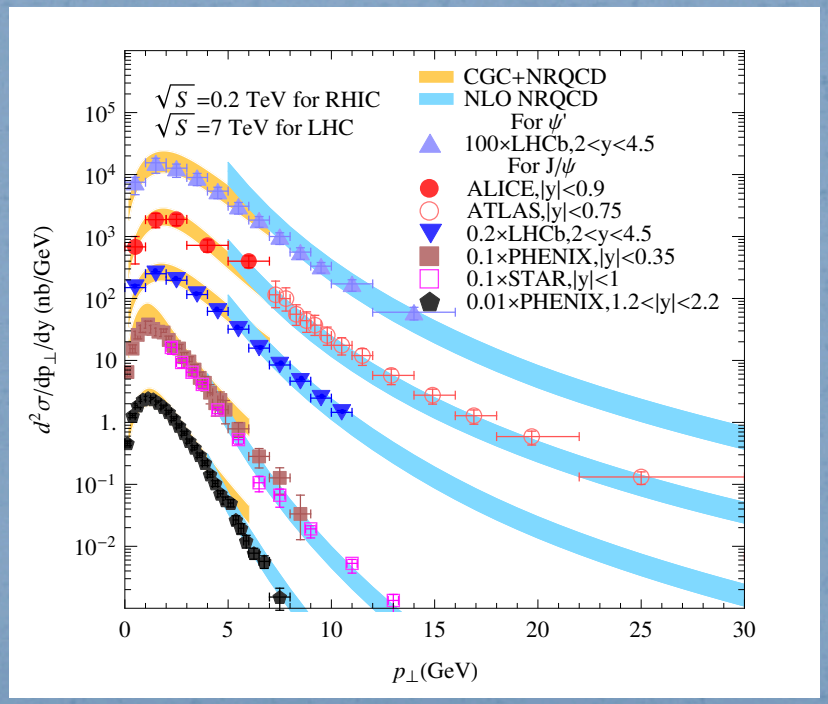


Baronov et al.

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

- 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

Intrinsic Heavy Flavor

An idealized 1% normalized intrinsic charm distribution in a 5-quark $|uudc\overline{c}\rangle$ state

$$c(x) \propto \frac{dP_{\rm ic}(x)}{dx} = 18x^2[\frac{1}{3}(1-x)(1+10x+x^2) + 2x(1+x)\ln x]$$

What is Intrinsic Charm?

Intrinsic Charm – $c\overline{c}$ pairs in the hadron wavefunction liberated by soft interactions – was first proposed by Brodsky, Hoyer, Peterson and Sakai (BHPS) in 1980's, enhances charm production rates in the forward region

The proton wavefunction can be expanded over a complete basis of quark and gluon states with color singlet functions in the Fock components, $|uud\rangle$, $|uudg\rangle \cdots |uudc\overline{c}\rangle$

Dominant Fock components have minimal invariant mass, configurations with equal rapidity are most likely, giving charm quarks a higher fraction of the momentum of the hadron than the light partons

In a 5-quark $|uudc\overline{c}\rangle$ state, assuming heavy quark mass limit, integration over light quarks and $\overline{c}$ gives, assuming the intrinsic charm probability is 1%:

$$c(x) \propto \frac{dP_{\rm ic}(x)}{dx} = 18x^2[\frac{1}{3}(1-x)(1+10x+x^2) + 2x(1+x)\ln x]$$

This probability is still a matter of debate with a number of new analyses in the last several years

Why Intrinsic Charm?

Such an intrinsic charn state could explain anomalously large charm production rates at high momentum fractions, x

- **EMC charm structure function, F_2^c, large at higher x and Q^2**
- **Leading charm asymmetries in hadroproduction (D^- over D^+ in $\pi^- p$ interactions at SPS and FNAL)**
- **Large $pp \to \Lambda_c X$ production cross section at $x_F > 0.5$ at ISR**
- **Double J/ψ production at high x_F in hadroproduction measured by NA3**
- **Doubly-charmed baryon production at forward momentum observed by SELEX**
- **Proposed by Brodsky and Laha as an explanation of astrophysical neutrino rate at high energies seen by Ice Cube**

Early Analyses of Intrinsic Charm

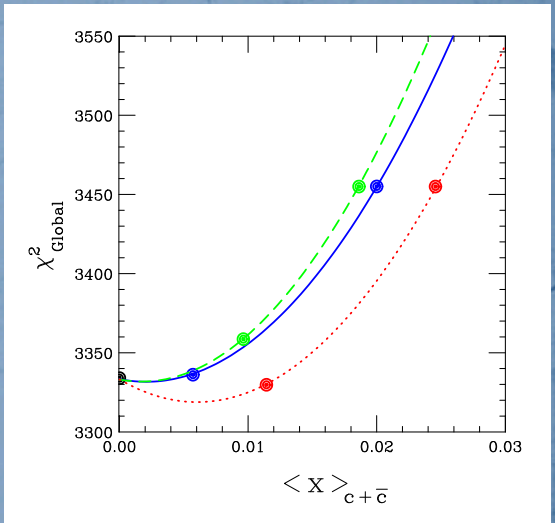
Hoffman and Moore calculated intrinsic charm at NLO for EMC only (1983), include mass effects and scale evolution

Harris, Smith and RV made NLO calculation of extrinsic and intrinsic charm at NLO, 1990, found approximate (0.86 ± 0.60)**% contribution at highest** Q^2 **fitting EMC data only**

Pumplin *et al.* **made first global analysis of proton PDFs (2007) with CTEQ6.6c sets under three assumptions:**

- **BHPS,** $c(x) = \overline{c}(x)$**,**
- **Meson-cloud model,** $|uudc\overline{c}\rangle = |\Lambda_c(udc)\overline{D}^0(u\overline{c})\rangle$ **with** $c(x) \neq \overline{c}(x)$**,**
- **'Sea-like', intrinsic distribution has same shape as radiatively-generated charm,** $c(x) = \overline{c}(x)$**.**

Pumplin results



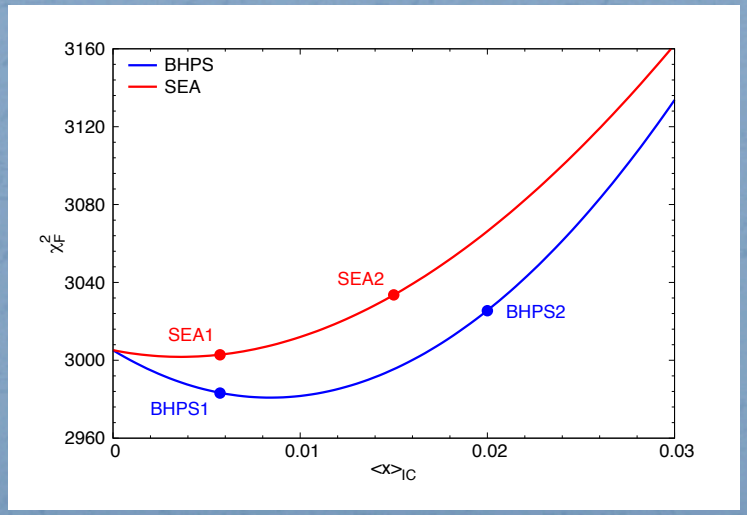
New Global Analyses – Dulat

Dulat *et al.*, **based on CT10 NNLO PDFs, included DIS from fixed-target and HERA, SDIS, Drell-Yan production,** W **charge asymmetry,** Z^0 **rapidity distribution, and inclusive jet measurements**

Found $\langle x \rangle_{c+\bar{c}}(Q_0^2) \leq 0.025$ **for BHPS and** $\langle x \rangle_{c+\bar{c}}(Q_0^2) \leq 0.015$ **for sea-like**

Using penalty factor found that upper limit on BHPS comes from CCFR data while upper limit on sea-like from HERA charm data

$\Delta\chi^2 = 100$ **tolerance**



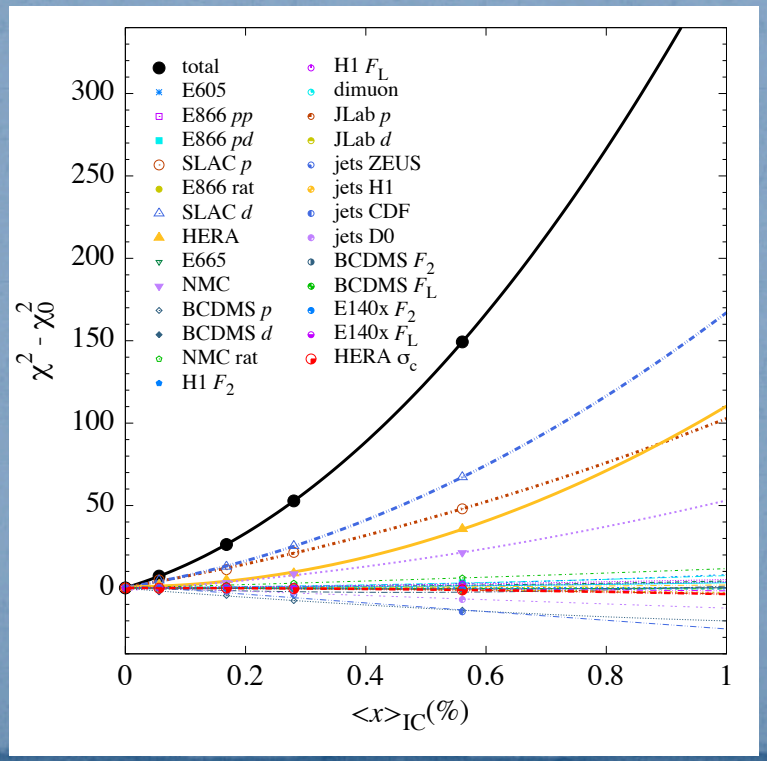
New Global Analyses – Jimenez-Delgado

Jimenez-Delgado *et al.* **used looser kinematic cuts ($Q^2 \geq 1$ GeV^2) and included lower energy data, in particular data with nuclear targets**

Found $\langle x \rangle_{c+\bar{c}} < 0.1\%$ at 5σ level

Employed more stringent tolerance criteria, $\Delta\chi^2 = 1$

Note that if the tolerance criteria was relaxed to that of Dulat *et al.*, **they could also accommodate intrinsic charm at the 1% level**



New Global Analyses – NNPDF Collab.

NNPDF Collaboration (Ball *et al.*) recently compared global analyses with "perturbative charm" and "fitted charm" (intrinsic charm)

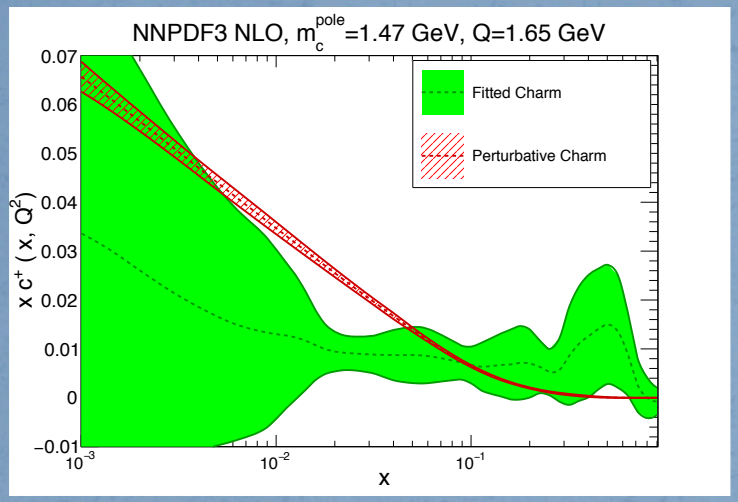
No particular assumption made about shape

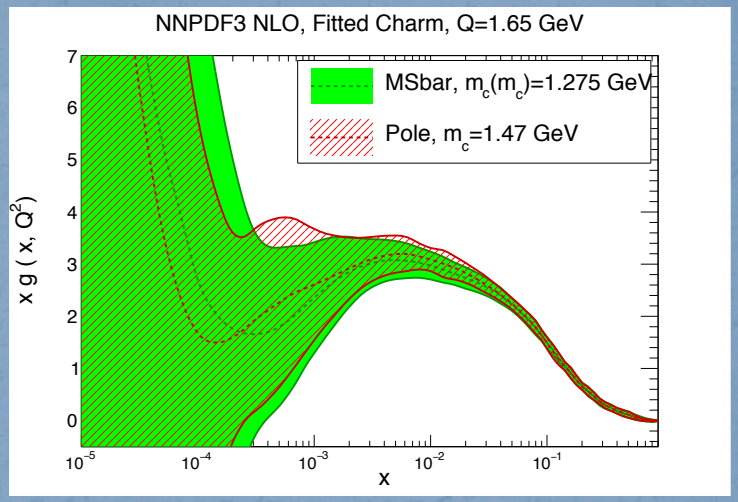
Found that:

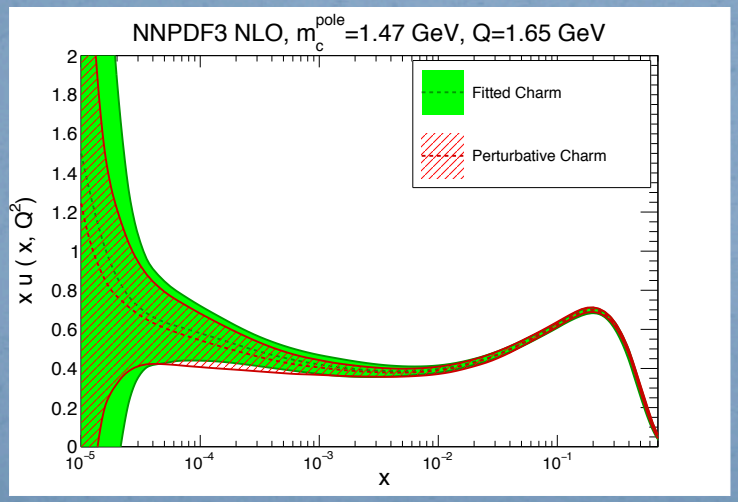
- **Inclusive HERA data, Drell-Yan and fixed-target DIS χ^2 improved with fitted charm,**
- **Tevatron and LHC data were neutral to fitted charm,**
- **EMC F_2^c data could only be described using fitted charm**

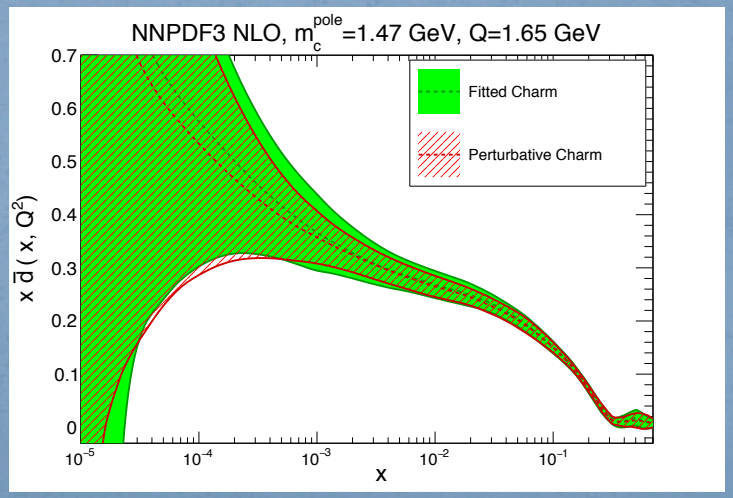
Concluded that charm at low x is perturbative but, at low scales and high x, the data support an intrinsic component

NNPDF Collaboration Results:









arXiv:1605.06515

Intrinsic Heavy Flavor Summary

- Possible high x charm content of proton long suggested
- Global analyses of proton parton densities are making a serious effort to determine the size of the potential effect after more than 35 years
  - Some contentious results but latest NNPDF results with shape-independent analysis favors 'fitted charm'
- Fixed-target program at the LHC with emphasis on forward physics and high statistics may provide data to settle the question

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

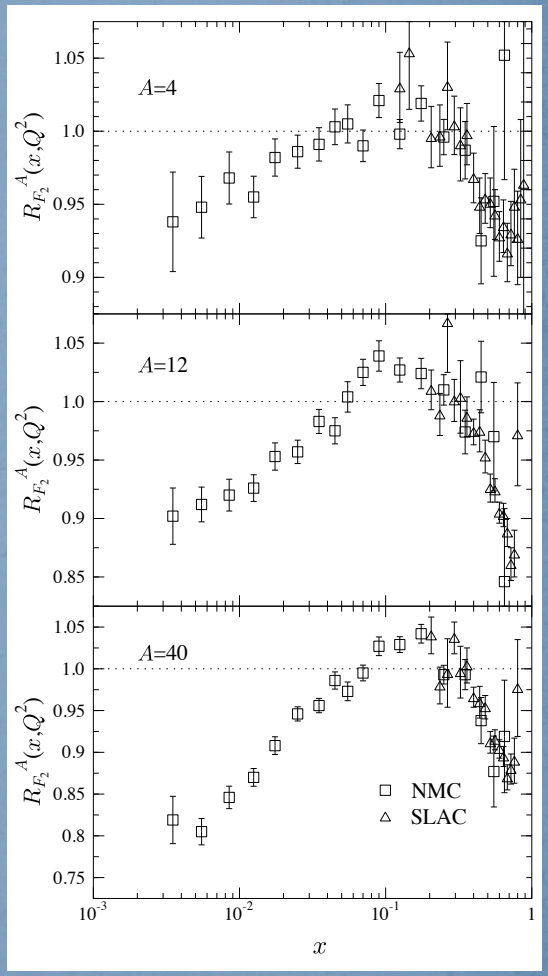
Nuclear matter effects quantified as 'nuclear suppression factor'

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

Nuclear Modifications of Parton Densities (nPDFs): Shadowing

Assumes collinear factorization, DGLAP evolution in Q^2, involves global fits of nuclear PDFs to data with nuclear targets (nuclear DIS, Drell-Yan, π^0 and jet p_T distributions) performed by several groups similar to proton PDF analyses

$$f_{i/A}(x, Q^2) = S_i^A(x, Q^2) f_{i/p}(x, Q^2)$$

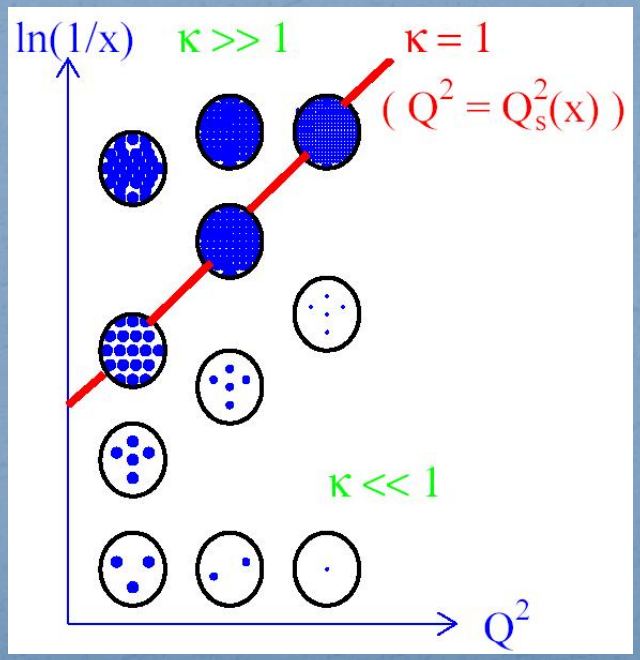


Nuclear Modifications of the parton densities: Saturation

Saturation:

- **Assumes k_T ordering and evolution in x, important at low x and low Q^2, $Q^2 \leq Q^2_{\rm sat}$**
- **At high gluon density, recombination of gluons, $2 \to 1$, competes with gluon emission, $1 \to 2$**
- **Saturation achievable for nucleons and nuclei with $Q_{\rm sat}$ depending on $\sqrt{s}$ and x, expected to grow as $A^{1/3}$ for nuclei, proportional to nuclear radius**
- **Fraction of nucleon/nuclear disk packed with partons, $\kappa = (F_2(x, Q^2)/Q^2)/\pi R^2$**

Hybrid models required to interpolate between the two regimes



Cold Matter Energy Loss

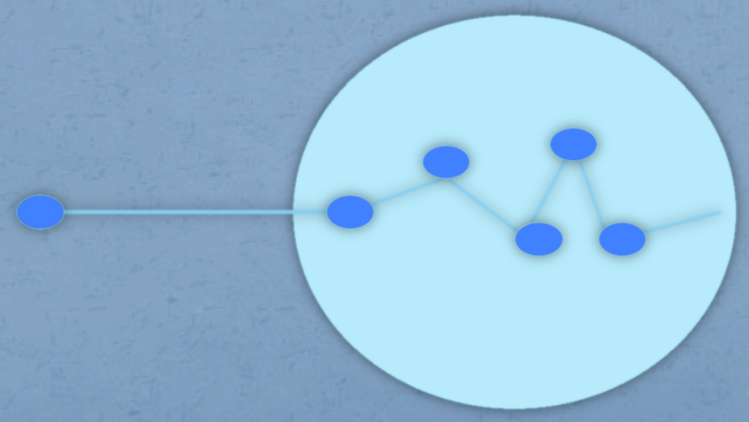
Energy loss in medium: Both initial state (scatterings of the projectile partons with gluons in matter *before* hard scattering) and final state (scattering of produced partons in the medium *after* hard scattering) have been considered

$$R_{pA} < 1 \quad \text{forward rapidity, high } p_T$$

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

$$R_{pA} > 1 \quad \text{low } p_T$$

Energy loss and Cronin are intertwined in cold matter: softening of spectrum at high momentum results in an enhancement at lower momentum



Hot Matter Effects

Assumes that particle density is sufficiently high to produced a quark-gluon plasma in $p + A$ collisions; $e.g.$ transport model calculations of heavy quark propagation in an expanding and cooling deconfined medium

The models can include collisional and/or radiative energy loss in hot matter

The temperature and time evolution of the medium is taken into account

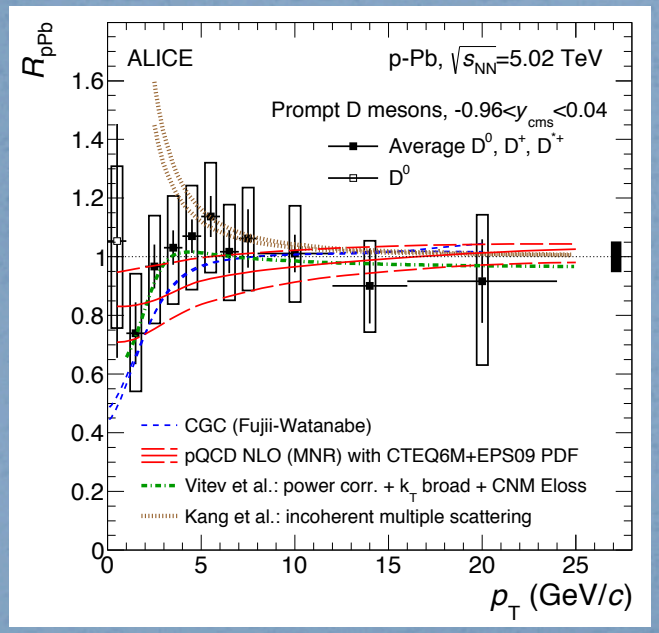
These effects usually included on top of some cold matter effects such as shadowing

The conditions for assuming thermalization should more likely be met for most central (highest multiplicity) p+Pb collisions rather than minimum bias collisions

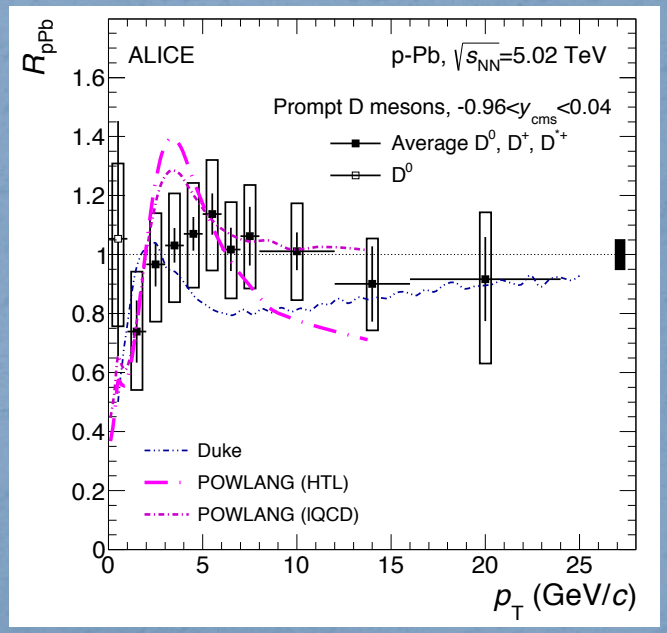
ALICE D mesons in Medium

Most cold matter only calculations do a better job of describing the combined ALICE D meson data than do the hot matter calculations

Cold nuclear matter



Hot QGP medium



arXiv: 1605.07569

Additional Cold Matter Effects present for Quarkonium: Size Matters

Additional final-state effects for quarkonium

Nucleon Absorption

- **After $c\overline{c}$ production, the pair can break up in matter due to interactions with nucleons**
- **Relevant only for regions of phase space where the quarkonium state is produced in matter, *e.g.* for backward rapidity at the LHC**
- **Thus at midrapidity, effective absorption cross section at collider energies is small to negligible**

Comovers

- **Quarkonium states break up due to interactions with produced particles**
- **The more loosely bound the state, the more likely it is to break up**
- **Effect depends on comover density, increases with collision centrality**

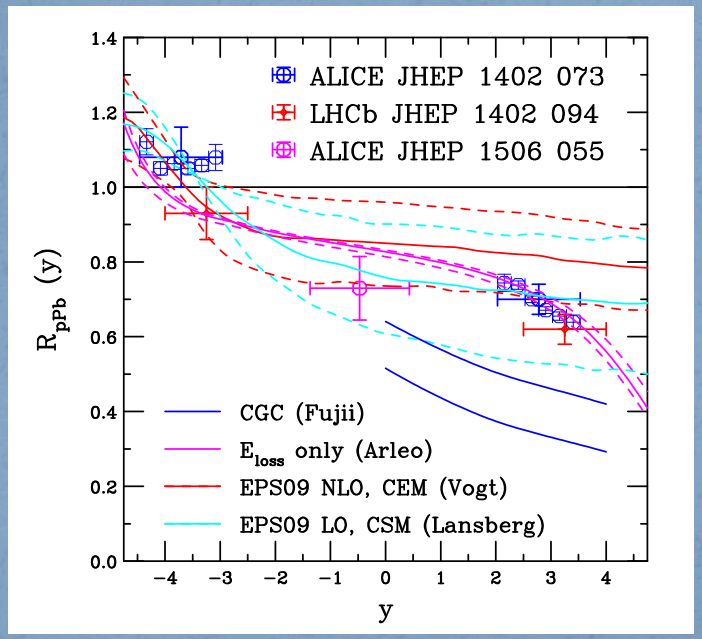
Both absorption and comover interaction cross sections expected to depend on charmonium size,

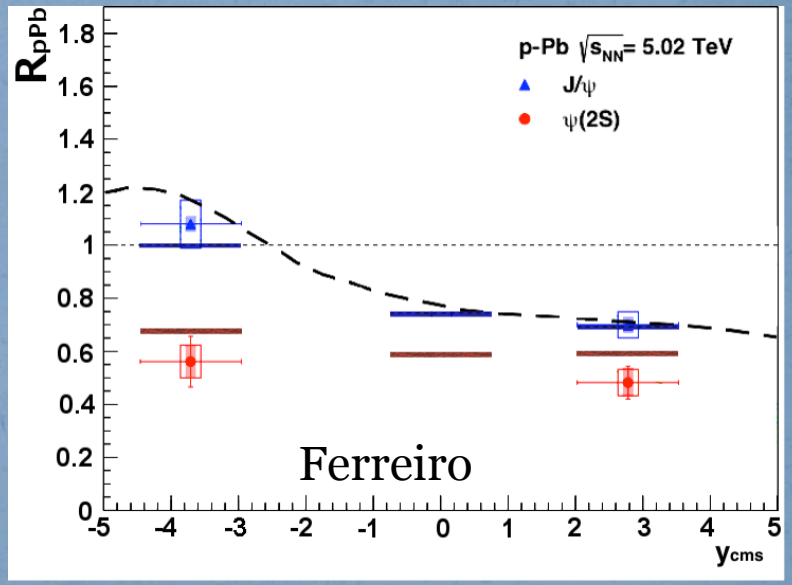
$$\sigma_{C'}/\sigma_C \propto (R_{C'}/R_C)^2$$

Quarkonium Suppression in p+Pb

Ψ(2S) considerable more suppressed than J/ψ, particularly at backward Rapidity, closer to the nucleus, more susceptible to comovers and absorption

See arXiv:1605.09479 for full description of both calculations and model details





Ψ(2S) ALICE data: JHEP 1412 (14) 073

p+Pb 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 open charm and quarkonium data
- Higher precision data are needed to separate effects and eliminate models – as ever the case
- Charm and bottom jet measurements also being studied