Cold Nuclear Matter Effects on Heavy Flavor Production

Ramona Vogt
LLNL and UC Davis

Based on arXiv:1707.09973 [hep-ph]

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Outline

- Effects common to open and hidden heavy flavor
  - nPDF effects (collinear factorization)
  - Saturation effects
- Description of calculations for both heavy flavor and quarkonium
- D and B predictions for 8 TeV
- Description of calculations for quarkonium
- Predictions for J/ψ and Υ at 8 TeV
  - Some comparisons with 5 TeV results

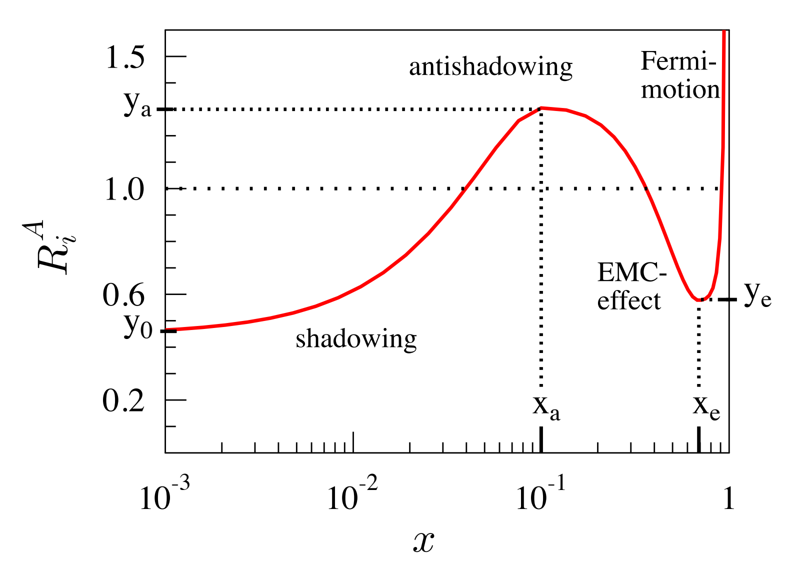
Parton Density in the Initial State

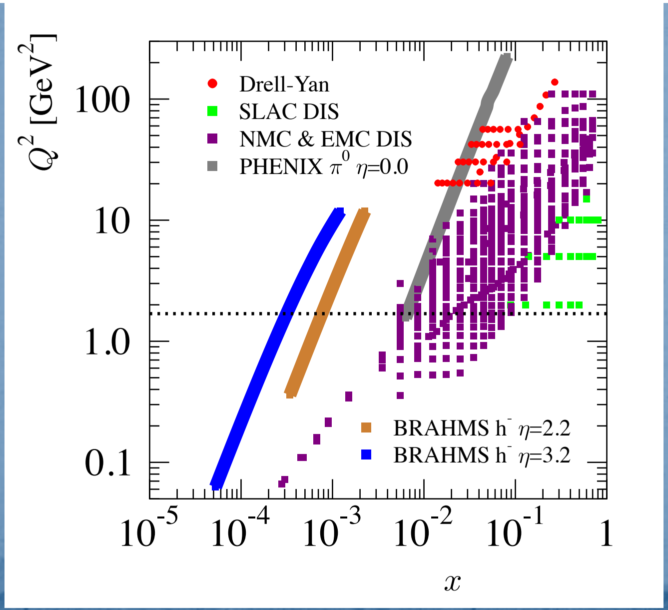
Collinear factorization (DGLAP evolution): parton densities in the nucleus are modified based on global analyses of all data over a wide range of momentum fractions

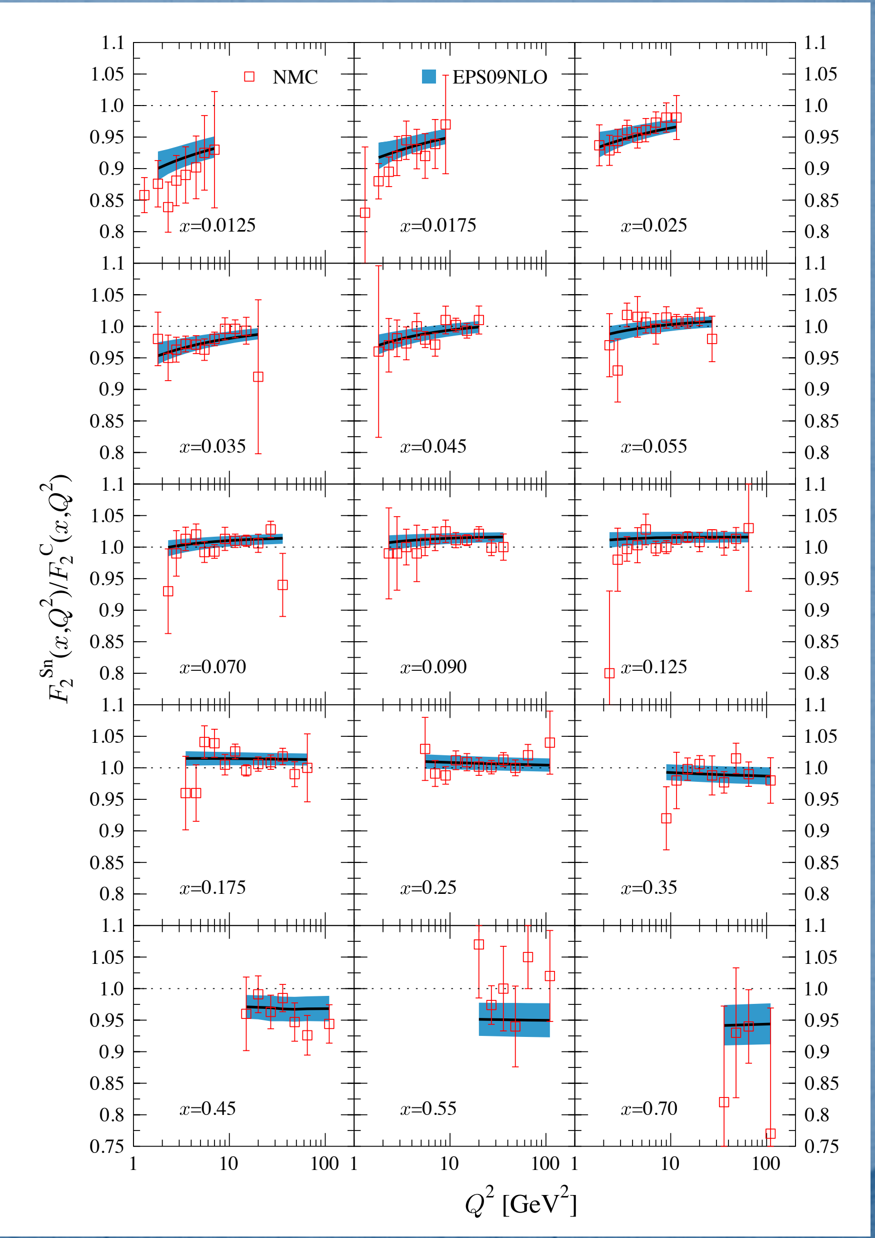
- Nuclear DIS (electron, muon and neutrino-induced)
- Drell-Yan
- π^0 distributions
- High p_T jets (new, p+Pb 5 TeV data)
- W^+, W^- and Z^0 production (new, p+Pb 5 TeV data)

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

EPS09 nPDF analyses

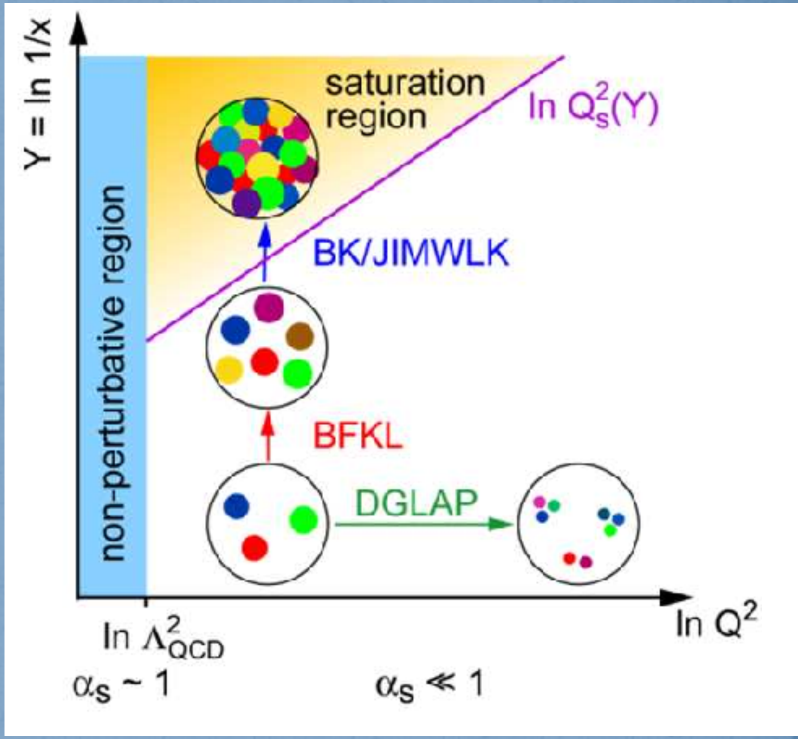






General CGC approach

- 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



Lansberg and Shao approach

- Data driven evaluation of p+p cross sections employing simple parameterization of rapidity and p_T dependence of amplitude with 4 parameters (κ, λ, n, and $\langle p_T \rangle^2$) fit to data and convolution over dominant g+g contribution

$$\overline{|\mathcal{A}(k_1 k_2 \to \mathcal{H} + k_3)|^2} = \frac{\lambda^2 \kappa x_1 x_2 s}{M_{\mathcal{H}}^2} \exp\left[-\kappa \min(p_T^2, \langle p_T \rangle^2)/M_{\mathcal{H}}^2)\right] \times \left(1 + \theta(p_T^2 - \langle p_T^2 \rangle^2) \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_{\mathcal{H}}^2}\right)^{-n}$$

$$\frac{d\sigma(p + p \to \mathcal{H} + X)}{d\Phi_2} = \frac{1}{2s} \int dx_1 dx_2 x_1 f_p(x_1) x_2 f_p(x_2) \overline{|\mathcal{A}(k_1 k_2 \to \mathcal{H} + k_3)|^2}$$

- Same parameters used for p+Pb collisions
- Applied 3 different gluon nPDFs: EPS09 LO, EPS09 NLO, and CTEQ15; no other effects included
- See Lansberg and Shao, Eur. Phys. J. C 77 (2017) 1.

Cold Matter Energy Loss

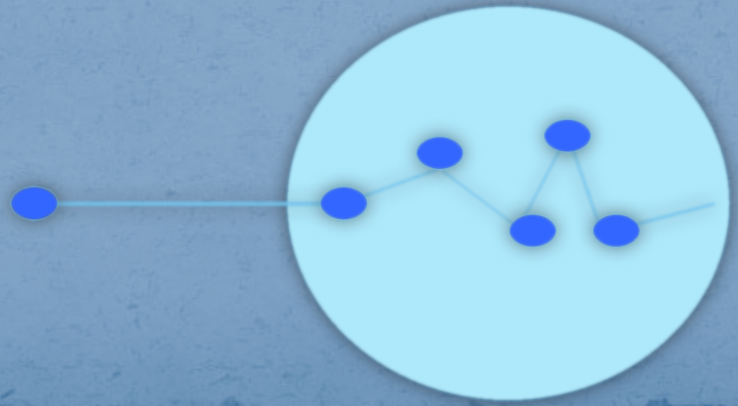
Energy loss in medium: Both initial state (before hard scattering) and final state (after hard scattering) have been considered

$R_{pA} < 1$ (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



Vitev et al approach

Collinear factorization in perturbative QCD, includes:

- Isospin

$$f_{a/A}(x) = \frac{Z}{A} f_{a/p}(x) + \left(1 - \frac{Z}{A}\right) f_{a/n}(x)$$

- Cronin effects (path length varied to simulate stronger or weaker broadening)

$$\langle k_{b,T}^2 \rangle_{pA} = \langle k_{b,T}^2 \rangle_{pp} + \left\langle \frac{2\mu^2 L}{\lambda_{q,g}} \right\rangle \xi$$

- Initial state cold matter energy loss (strength varied to simulate stronger or weaker loss)

$$f_{q/p}(x_a) \to f_{q/p}\left(\frac{x_a}{1-\epsilon_{\rm eff}}\right), \qquad f_{g/p}(x_a) \to f_{g/p}\left(\frac{x_a}{1-\epsilon_{\rm eff}}\right)$$

- Dynamical shadowing

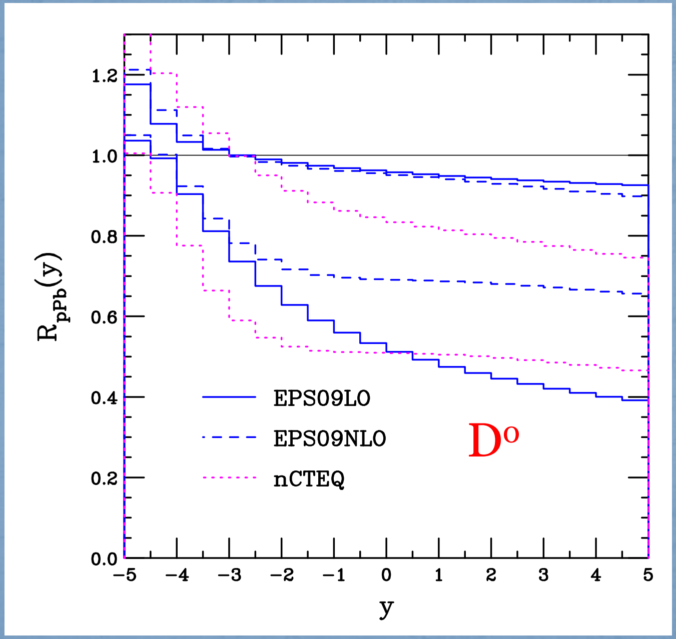
$$x_b \to x_b \left(1 + C_d \frac{\xi^2 (A^{1/3} - 1)}{-\hat{t}}\right)$$

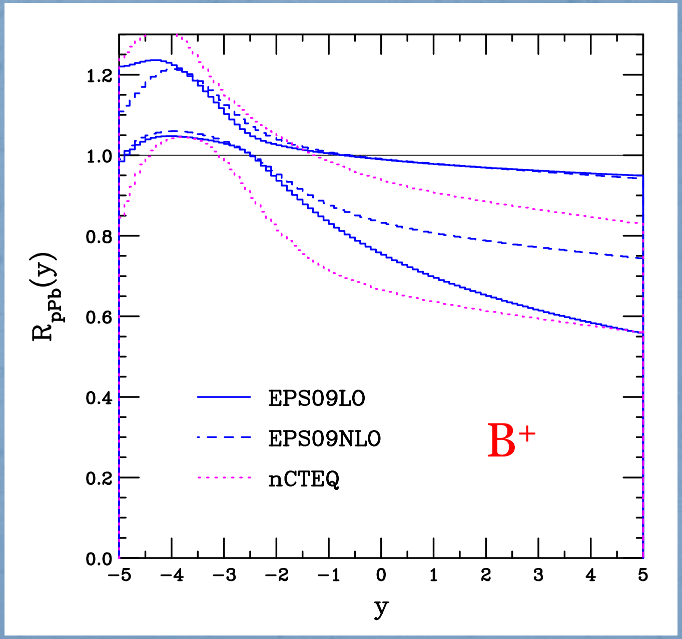
Open heavy flavor

Heavy Flavor Shadowing at 8 TeV

Shadowing only calculations for Dº (left) and B^+ (right) as a function of *y*

Higher mass B moves antishadowing peak at backward rapidity more forward and reduces the strength of the shadowing at forward rapidity





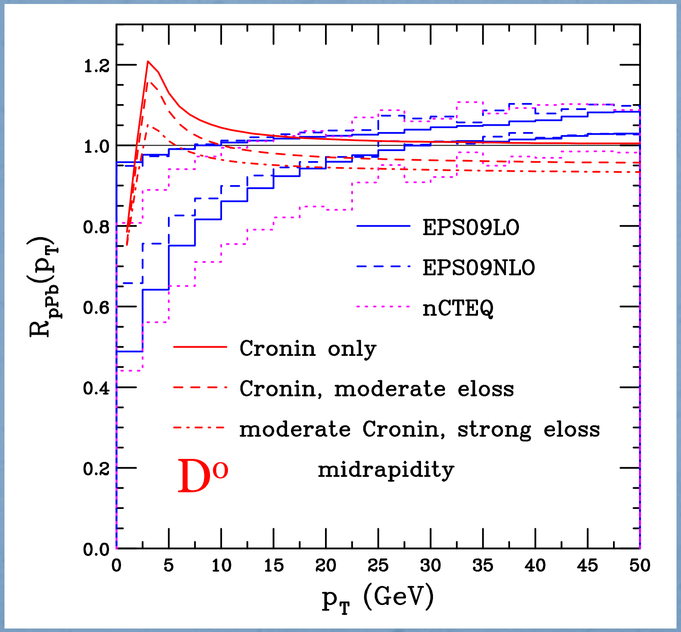
Lansberg and Shao

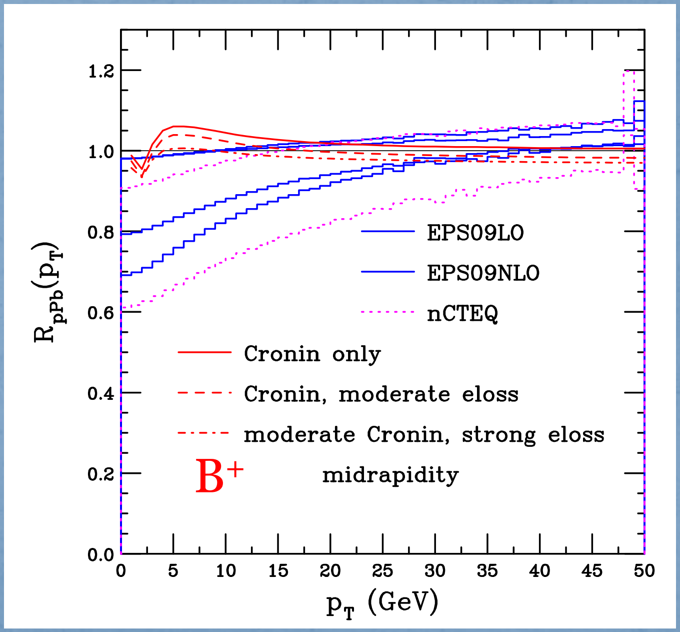
Heavy Flavor: Cronin vs. Shadowing

Cronin, multiple scattering, makes stronger peak for D than for B, heavier quarks do not scatter as strongly

Energy loss reduces Cronin peak

Shadowing only causes suppression at low p_T, Cronin leads to opposite





Lansberg and Shao (shadowing) & Vitev (Cronin)

Quarkonium

EPS09 NLO calculations in CEM

- 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 andΥ 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
- See RV, PRC **92** (2015) 034909 for full details

Arleo and Peigne Energy Loss

p+p production cross section as a function of energy:

$$\frac{1}{A}\frac{d\sigma_{pA}^{\psi}}{dE}(E) = \int_0^{\varepsilon^{\max}} d\varepsilon\,\mathcal{P}(\varepsilon, E, \ell_A^2)\,\frac{d\sigma_{pp}^{\psi}}{dE}(E+\varepsilon)$$

E is energy of pair, ε is energy loss
$\mathcal{P}$ is quenching weight, related to medium-induced coherent energy spectrum, depends on the accumulated transverse momentum transfer due to soft rescatterings in the nucleus, ℓ = qL where q is transport coefficient and L is path length

$$\hat{q}(x_2) \equiv \hat{q}_0 \left[\frac{10^{-2}}{x_2}\right]^{0.3} \quad ; \quad x_2 \equiv \frac{m_T}{\sqrt{s}}\,e^{-y}$$

Production cross section in p+p collisions is parameterized as

$$\frac{d\sigma_{pp}^{\psi}}{dy} \propto \left(1 - \frac{2m_T}{\sqrt{s}}\cosh y\right)^{n(\sqrt{s})}$$

CGC approaches: Ducloue et al

Ducloue et al use CGC + CEM,

$$\frac{d\sigma_{J/\psi}}{d^2p_T dy} = F_{J/\psi} \int_{4m_c^2}^{4m_D^2} dM^2 \frac{d\sigma_{c\bar{c}}}{d^2p_T dy dM^2}$$

The cross section is hybrid between the collinear gluon distribution for the proton and the propagation of the quark-antiquark pair through the medium that is k_T dependent. The hard matrix element is given by Ξ_{coll}.

$$\frac{d\sigma_{c\bar{c}}}{d^2p_T d^2q_T dy_p dy_q} = \frac{\alpha_s^2 N_c}{8\pi^2 d_A} \frac{1}{(2\pi)^2} \times \int \frac{d^2k_T}{(2\pi)^2} \frac{\Xi_{\rm coll}(p_T + q_T, k_T)}{(p_T + q_T)^2} \phi^{q\bar{q},g}_{y_2 = \ln \frac{1}{x_2}}(p_T + q_T, k_T) x_1 g(x_1, Q^2)$$

The values of x_1 and x_2 in the proton and nucleus and the propagation through the medium are give as:

$$x_{1,2} = \frac{\sqrt{p_T^2 + M^2}}{\sqrt{s}} e^{\pm y} \qquad \phi_Y^{q\bar{q},g}(l_T, k_T) = \int d^2b_T \frac{N_c l_\perp^2}{4\alpha_s} S(k_T) S(l_T - k_T)$$

The dipole amplitudes in the Fourier transforms, S, depend on x_2. The impact parameter dependence uses the optical Glauber model.

CGC approaches: Ma et al

Ma et al employ CGC + NRQCD with separation into Color Singlet (CS) and Color Octet (CO) components in a perturbative part (σ) and fitted long distance matrix elements (<*O*>) for momentum state κ:

$$d\sigma_{pA}^{H} = \sum_{\kappa} d\hat{\sigma}_{pA}^{\kappa} \langle \mathcal{O}_{\kappa}^{H} \rangle$$

The singlet and octet components of the cross section are

$$\frac{d\hat{\sigma}_{pA}^{\kappa}}{d^2\boldsymbol{p}_T dy} \overset{\text{CS}}{=} \frac{\alpha_s(\pi \bar{R}_A^2)}{(2\pi)^9(N_c^2-1)} \int\limits_{\boldsymbol{k}_{1T},\boldsymbol{k}_T,\boldsymbol{k}'_T} \frac{\varphi_{p,y_p}(\boldsymbol{k}_{1T})}{k_{1\perp}^2} \times \mathcal{N}_Y(\boldsymbol{k}_T)\mathcal{N}_Y(\boldsymbol{k}'_T)\mathcal{N}_Y(\boldsymbol{p}_T - \boldsymbol{k}_{1T} - \boldsymbol{k}_T - \boldsymbol{k}'_T)\, \mathcal{G}_1^{\kappa},$$

$$\frac{d\hat{\sigma}_{pA}^{\kappa}}{d^2\boldsymbol{p}_T dy} \overset{\text{CO}}{=} \frac{\alpha_s(\pi \bar{R}_A^2)}{(2\pi)^7(N_c^2-1)} \int\limits_{\boldsymbol{k}_{1T},\boldsymbol{k}_T} \frac{\varphi_{p,y_p}(\boldsymbol{k}_{1T})}{k_{1\perp}^2} \mathcal{N}_Y(\boldsymbol{k}_T)\mathcal{N}_Y(\boldsymbol{p}_T - \boldsymbol{k}_{1T} - \boldsymbol{k}_T)\, \Gamma_8^{\kappa},$$

$\mathcal{G}$ and Γ are calculated perturbatively and $\mathcal{N}$ is the dipole forward scattering amplitude while ϕ is the unintegrated gluon distribution,

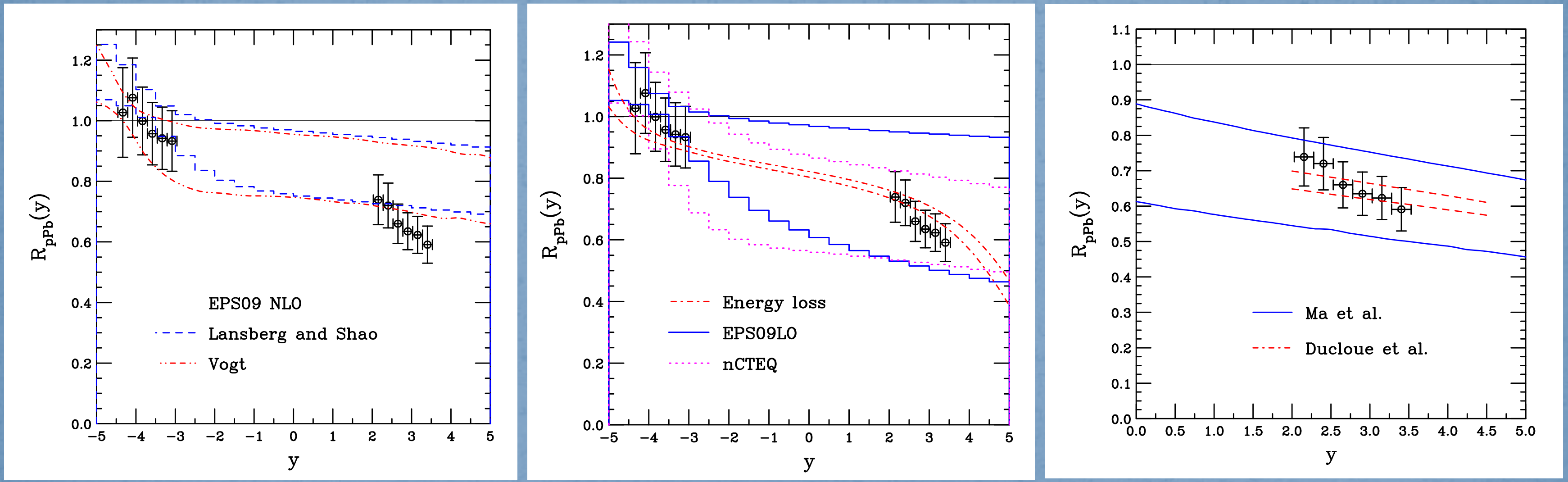
$$\varphi_{p,y_p}(\boldsymbol{k}_{1T}) = \pi \bar{R}_p^2 \frac{N_c k_{1\perp}^2}{4\alpha_s} \widetilde{\mathcal{N}}_{y_p}^{A}(\boldsymbol{k}_{1T})\,.$$

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

All calculations do a reasonable job of describing preliminary ALICE data (add LHCb data plots

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

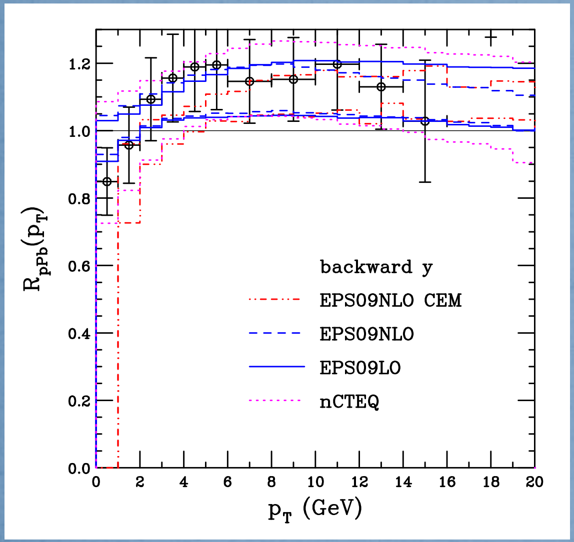
CGC+CEM (Ducloue et al)
CGC+NRQCD (Ma et al)

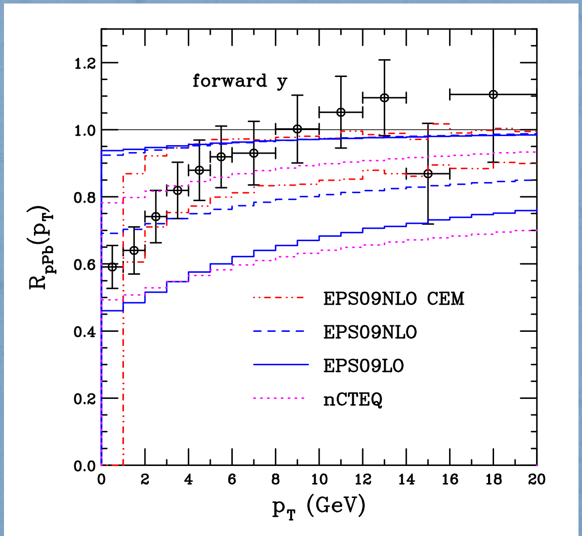
Suppression in p+Pb at 8 TeV: p_T dep

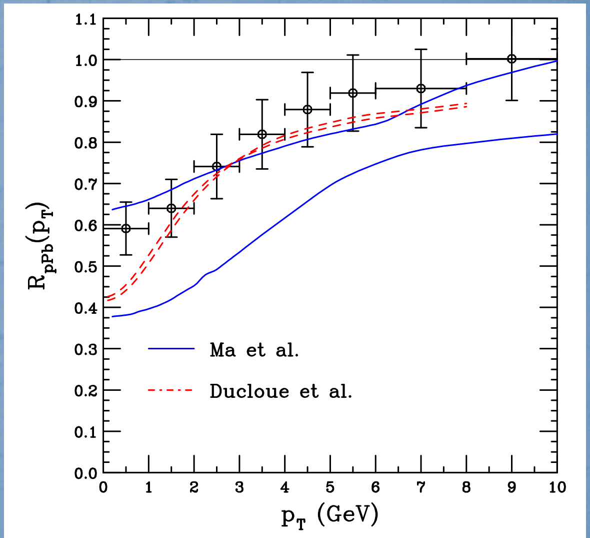
All calculations do a reasonable job of describing preliminary ALICE data

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)

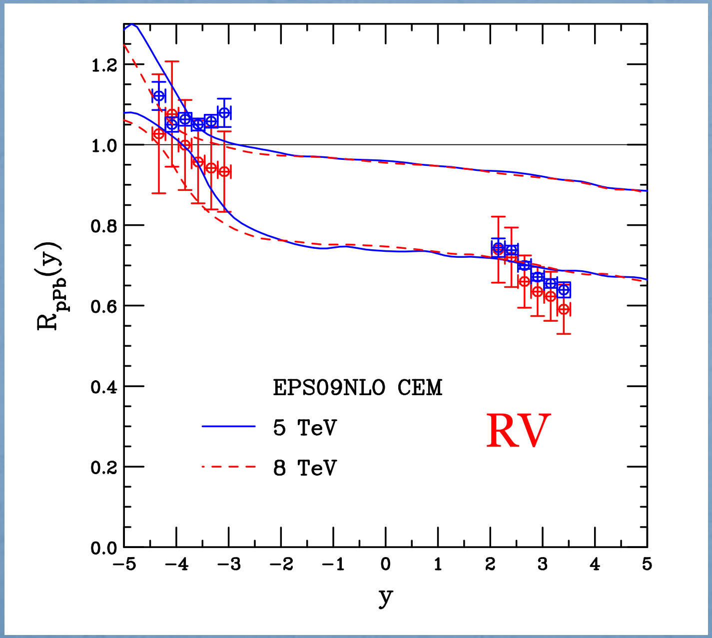
CGC+CEM (Ducloue et al)
CGC+NRQCD (Ma et al)

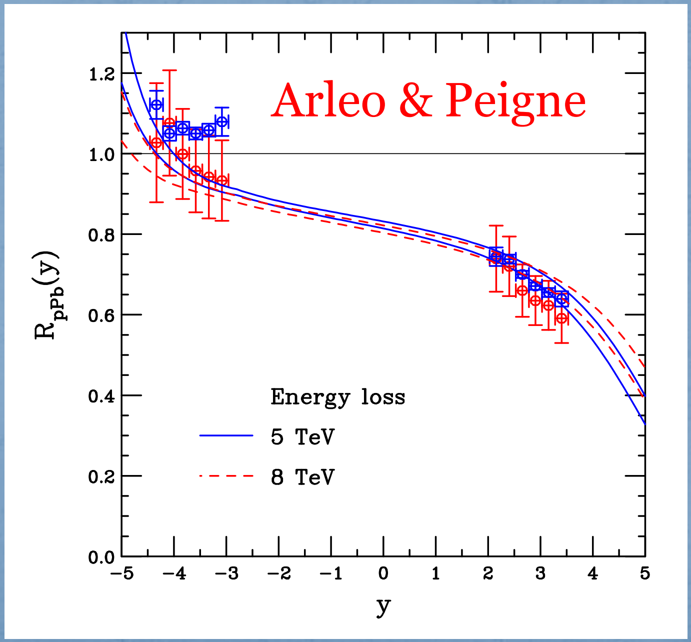
5.02 TeV vs. 8.16 TeV

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

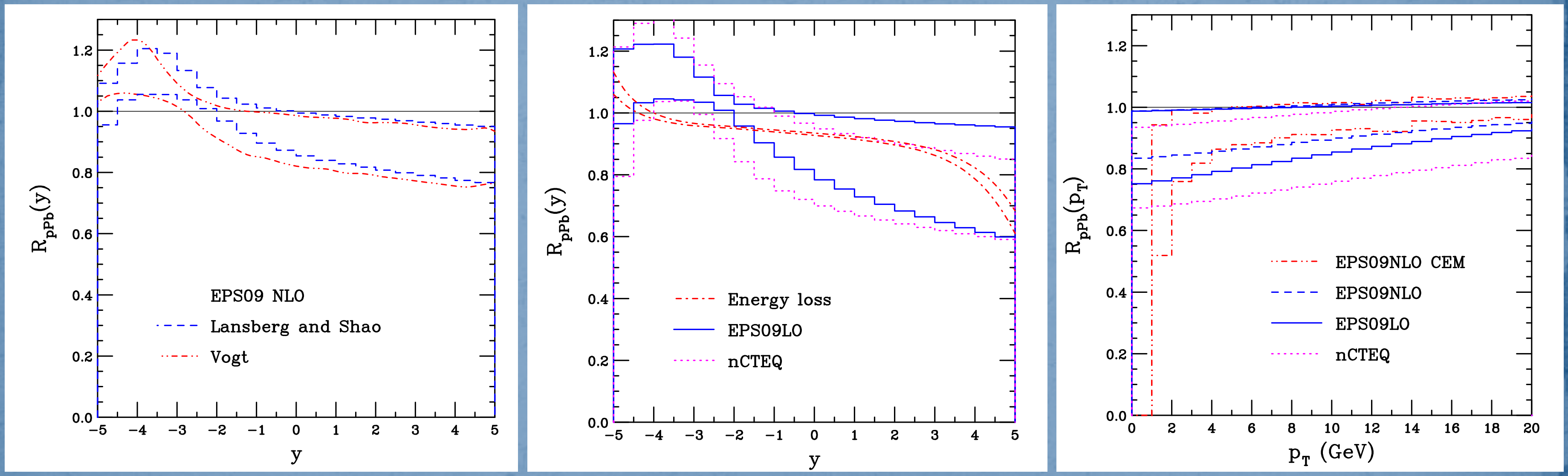




Predictions for Υ(1S) inclusive

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

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
- Possibly 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

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

Comover suppression

J/ψ survival by interactions with comovers determined by rate equation

$$\tau \frac{d\rho^{\psi}}{d\tau}\,(b,s,y) \;=\; -\sigma^{\mathrm{co}-\psi}\;\rho^{\mathrm{co}}(b,s,y)\;\rho^{\psi}(b,s,y)$$

Survival probability S depends on density of comovers and their interaction cross section with quarkonium – cross section was fixed in low energy collisions, does not identify whether comovers are partons or hadrons but they were assumed to be hadrons previously

$$S_{\psi}^{\mathrm{co}}(b,s,y) \;=\; \exp\left\{-\sigma^{\mathrm{co}-\psi}\;\rho^{\mathrm{co}}(b,s,y)\;\ln\left[\frac{\rho^{\mathrm{co}}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

Nuclear suppression factor also includes EPS09 LO shadowing:

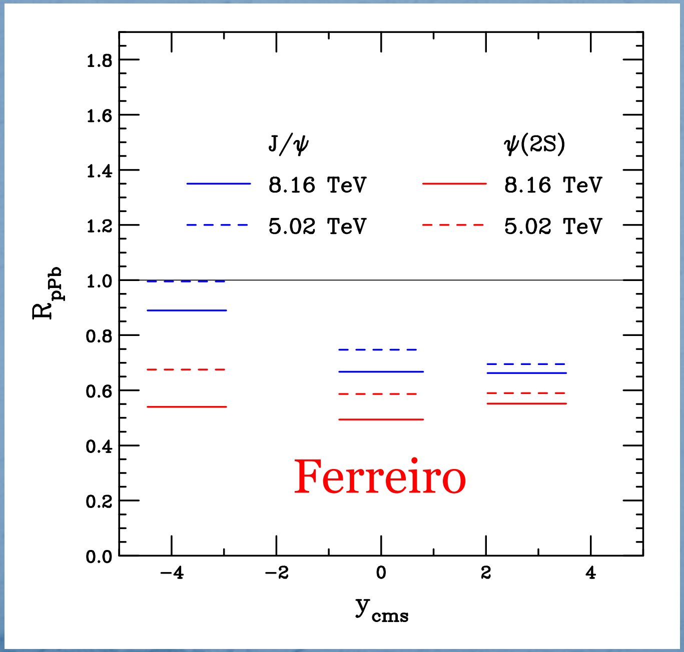
$$R_{pA}^{\psi}(b) = \frac{\int d^2s\,\sigma_{pA}(b)\,n(b,s)\,S_{\psi}^{\mathrm{sh}}(b,s)\,S_{\psi}^{\mathrm{co}}(b,s)}{\int d^2s\,\sigma_{pA}(b)\,n(b,s)}$$

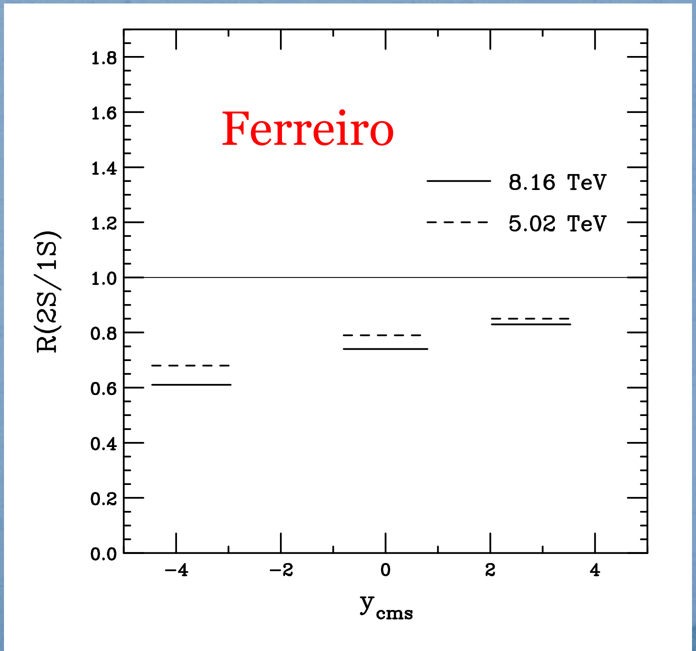
n(b,s) is number of binary collisions and σ_{pA} is inelastic cross section in pA

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





Summary

- Multiple models can explain the trends in the quarkonium data, none include Cronin
- Larger differences between open heavy flavor predictions because multiple scattering taken into account
- Higher precision data are needed to separate effects and eliminate models – as ever the case
- For all results, predictions paper, arXiv:1707.09973 [hep]
- Thanks to all who provided predictions!