Disentangling Shadowing from Coherent Energy Loss using the Drell-Yan Process

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Outline

- Context
  - Origin of quarkonium suppression in p–A collisions at the LHC
- Coherent energy loss in nuclei
  - Quarkonium suppression in p–A collisions
  - Phenomenology
- Disentangling shadowing from coherent energy loss
  - Why Drell-Yan production
  - Results

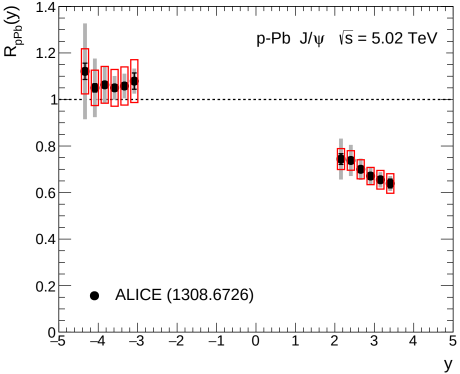
References

- FA, S. Peigné, 1512.01794
- See also FA, S. Peigné, 1204.4609, 1212.0434, 1407.5054, w/ T. Sami, 1006.0818, w/ R. Kolevatov, 1402.1671

Context

ALICE and LHCb measured J/ψ production in p–Pb collisions at 5 TeV

$$R_{\rm pA}(y) \equiv \frac{1}{A}\ \frac{d\sigma_{\rm pA}}{dy}\ \Big/\ \frac{d\sigma_{\rm pp}}{dy}$$



- Rather strong suppression at forward rapidity
- No (or modest) nuclear modification at backward rapidity

Context

ALICE and LHCb measured J/ψ production in p–Pb collisions at 5 TeV

Possible explanations

- Shadowing of nuclear parton distribution functions (nPDF)
- Coherent energy loss in nuclear matter
- . . . or both (not mutually exclusive)
- Note: all nPDF calculations fail to reproduce J/ψ suppression p–A data at lower energy (NA3, E866, RHIC) $\rightarrow$ another effect at work

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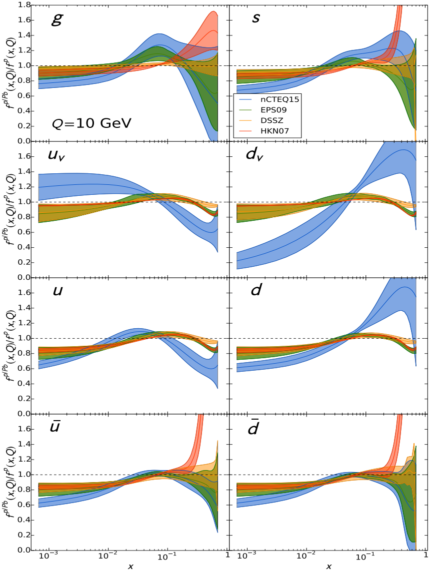
Issue

- Large uncertainties do not allow for precise predictions of shadowing effects on J/ψ at LHC
- Then, how to disentangle the effects of shadowing v. energy loss?

Nuclear Parton Distribution Functions (nPDF)



Parton densities are modified in nuclei

- Obtained from global fits based on DGLAP evolution
  - EPS09, DSSZ, nCTEQ15. . .
- Shadowing (aka saturation) expected at small x
- Poor constraints from data
  - especially for small-x gluons

[nCTEQ15, 1509.00792]

Talks by Morfín (Wed) and Kulagin (Thu)

nPDF effects on forward J/ψ production

- J/ψ production mechanism still unknown (CSM, NRQCD, CEM,...)
- However heavy quark pair production should proceed via gluon fusion

$$g^p g^A \to Q\bar{Q} \to J/\psi + \mathrm{X}$$

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A simple model

$$\begin{aligned} R^{\psi}_{\mathrm{pA}}(y) &= R^{\mathrm{Pb}}_g(x_2, Q = M_\psi) \\ x_2 &= M_\psi \, e^{-y}/\sqrt{s} \end{aligned}$$

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- x_2 given by LO kinematics, precise value not crucial as R_g is flat at low $x \lesssim 10^{-2}$
- R_g^{Pb} given by global fits (EPS09, DSSZ, nCTEQ15), band computed from the spread of 30-50 uncertainty sets

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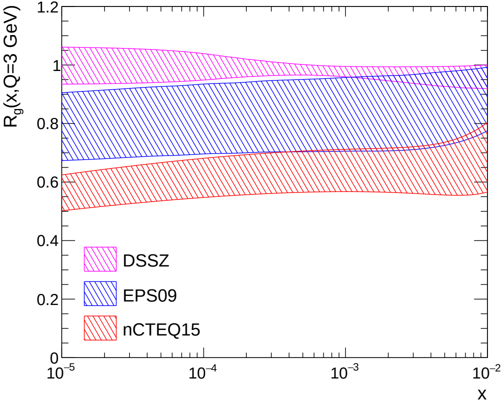
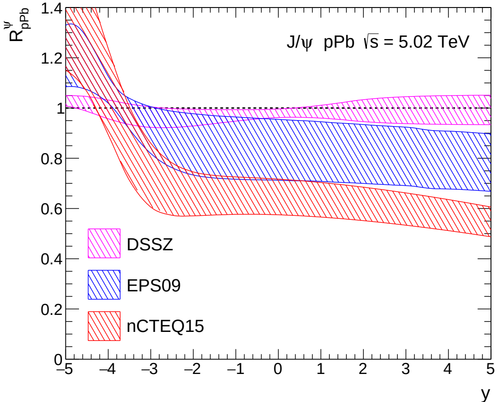
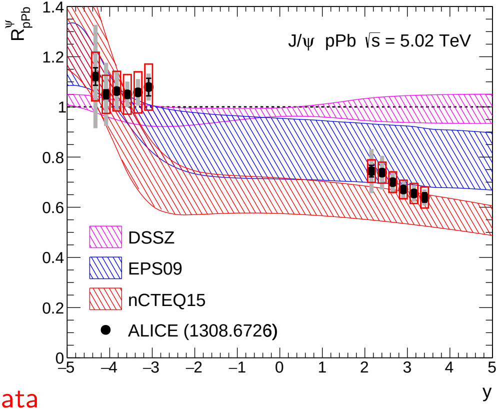


nPDF effects on J/ψ in p–Pb at LHC



- Match very well NLO CEM calculations (by R. Vogt using EPS09)
- Widespread predictions due to uncertainty on gluon shadowing
  - At $y = 5$: $R_{\mathrm{pPb}} \simeq 1$ with DSSZ but $R_{\mathrm{pPb}} \simeq 0.5$–$0.6$ with nCTEQ15

nPDF effects on J/ψ in p–Pb at LHC



Comparing to data

- DSSZ alone cannot explain the forward suppression
- Apparent agreement with some uncertainty sets of EPS09/nCTEQ15
- Side remark: need to compare individual uncertainty sets with data

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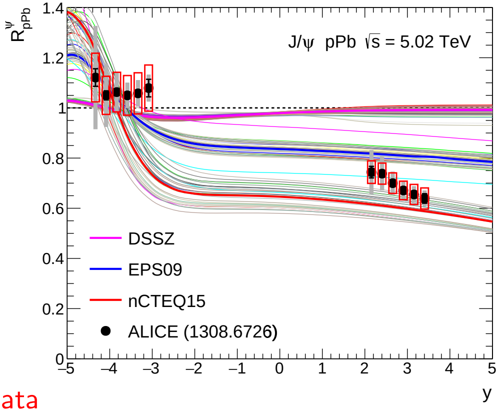

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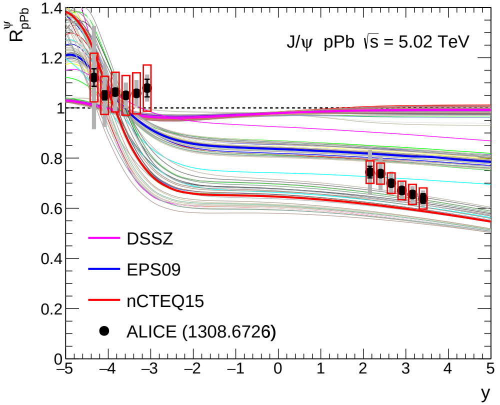

Let us now investigate coherent energy loss effects

Energy loss regimes

- Multiple scattering of the incoming gluon in nuclear matter induces gluon radiation → energy loss
- Different energy loss regimes depending on gluon formation time $t_{\rm f}$

- Landau-Pomeranchuk-Migdal (LPM): $\lambda < t_{\rm f} < L$
  - A group of $(t_{\rm f}/\lambda)$ scattering centers acts as a single radiator

$$\omega < \mu^2 L^2/\lambda \equiv \hat{q} L^2$$

- Fully coherent (large formation time): $t_{\rm f} > L$
  - All scattering centers act coherently as a source of radiation

$$\omega > \hat{q} L^2$$

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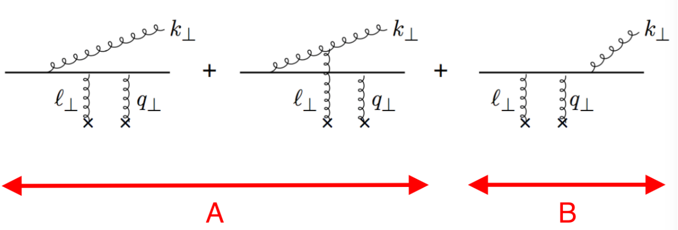
$$\omega > \hat{q} L^2$$

In the remainder of the talk, I focus on coherent energy loss regime

Set-up

Consider an incoming parton scattering at small angle, undergoing a hard process ($q_\perp$) and multiple soft scattering ($\ell_\perp \sim Q_s \ll q_\perp$)



- $|A|^2$ and $|B|^2$ cancel out in the induced spectrum $dI/d\omega$
- Interference terms, $\mathrm{Re}(A\ B^\star)$, do not cancel in the induced spectrum !
- Coherent radiation crucial for $t_f \gg L$
- Gluon spectrum computed rigorously in the opacity expansion (including virtual corrections)

Parametric dependence

LPM energy loss (small formation time $t_f \lesssim L$)

$$\Delta E_{\text{LPM}} \propto \alpha_s \; \hat{q} \; L^2$$

- Hadron production in nuclear DIS
- Particle suddenly accelerated (e.g. jet in QGP)

Coherent energy loss (large formation time $t_f \gg L$)

$$\Delta E_{\text{coh}} \propto \alpha_s \; F_c \; \frac{\sqrt{\hat{q}\; L}}{M_\perp} \; E \quad (\gg \Delta E_{\text{LPM}})$$

- Needs color in both initial & final state (otherwise $F_c = 0$)
- Important at all energies, especially at large rapidity
- Hadron production in p–A collisions

Induced gluon spectrum

Gluon spectrum $dI/d\omega$ for $1 \to 1$ hard forward process

$$\omega \frac{dI}{d\omega}\bigg|_{1\to 1} = \frac{F_c \; \alpha_s}{\pi} \; \ln\left(1 + \frac{\hat{q}L \; E^2}{M_\perp^2 \; \omega^2}\right)$$

- First determined in a simple model, later confirmed rigorously in the GLV opacity expansion

  [FA Peigné Sami, 1006.0818, Peigné FA Kolevatov, 1402.1671]

- Color factor F_c follows from simple color algebra: $F_c = C_R + C_{R'} - C_t$ where R (R') = color rep. of the incoming (outgoing) particle

$$\begin{aligned} g \to g \quad &: \quad F_c = N_c + N_c - N_c = N_c \\ q \to g \quad &: \quad F_c = C_F + N_c - C_F = N_c \\ q \to q \quad &: \quad F_c = C_F + C_F - N_c = -1/N_c \quad (< 0 \,!) \end{aligned}$$

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- Color factor F_c follows from simple color algebra: $F_c = C_R + C_{R'} - C_t$ where R (R') = color rep. of the incoming (outgoing) particle
- Similar expression for 2 particles in the final state ($1 \to 2$ process)

  [Liou Mueller, 1402.1647**]**

  [Peigné Kolevatov, 1405.4241**]**

Phenomenology

Goal

- Explore phenomenological consequences of coherent energy loss
- Approach as simple as possible with the least number of assumptions
- Observables
  - Quarkonium suppression in p–A (and A A) collisions
  - Light hadron production in p–A collisions

Model for quarkonium suppression

Energy shift

$$\frac{1}{A}\frac{d\sigma_{\mathrm{pA}}^{\psi}}{dE}\left(E,\sqrt{s}\right) = \int_0^{\varepsilon_{\max}} d\varepsilon\,\mathcal{P}(\varepsilon, E)\,\frac{d\sigma_{\mathrm{pp}}^{\psi}}{dE}\left(E+\varepsilon,\sqrt{s}\right)$$

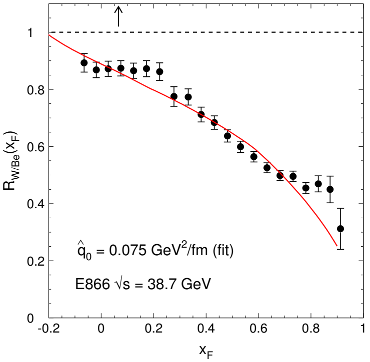
- pp cross section fitted from experimental data
- $\mathcal{P}(\epsilon)$: quenching weight related to the $g \to g$ induced gluon spectrum

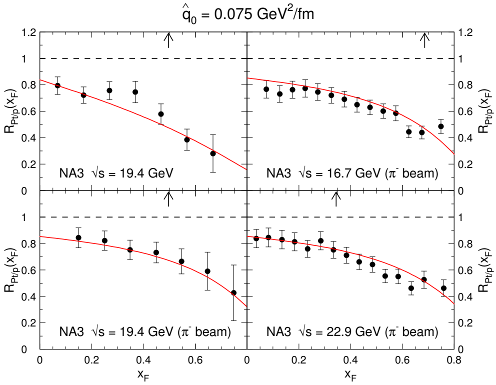
$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega}\,\exp\left\{-\int_{\epsilon}^{\infty} d\omega \frac{dI}{d\omega}\right\}$$

- Length L given by Glauber model
- Transport coefficient

$$\hat{q}(x) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\,\rho\, xG(x) = \hat{q}_0\left(\frac{10^{-2}}{x}\right)^{0.3} \;;\; \hat{q}_0 = 0.075\ \mathrm{GeV}^2/\mathrm{fm}$$

Comparing to low energy p–A data



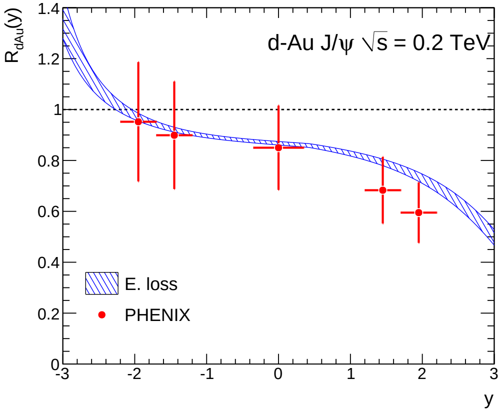


- Good agreement with E866, NA3, NA60, HERA-B data

[FA, S. Peigné, 1212.0434]

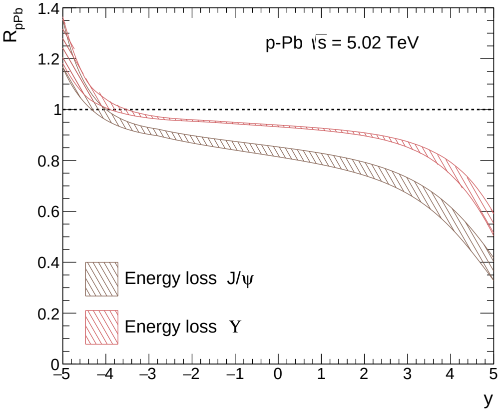
- no nPDF global fit can explain these data

RHIC predictions



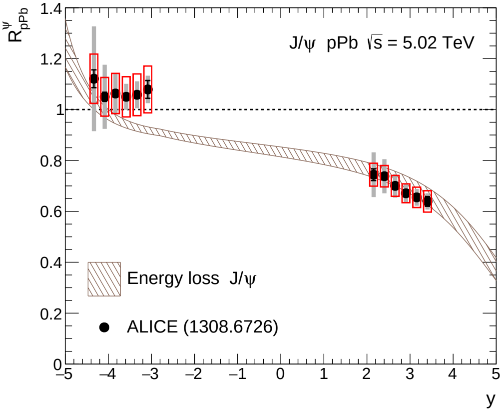
- Good agreement for R_{pA} vs rapidity
- Small uncertainty coming from the variation of the pp cross section and the transport coefficient

LHC predictions



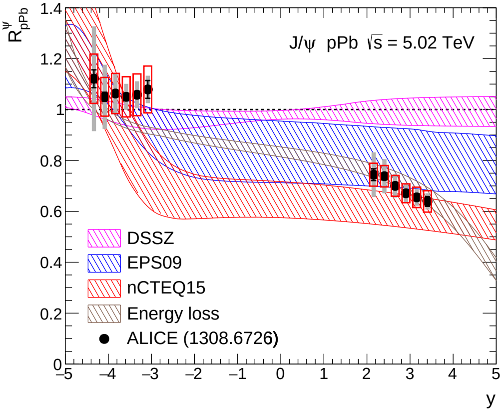
- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- Smaller suppression expected in the Υ channel

LHC predictions



- Very good agreement despite large uncertainty on normalization
- Data at $y \gtrsim 4$ would be helpful

So, what quenches J/ψ ?



- Coherent energy loss model describes well data
- Some nPDF sets also in rough agreement

How to disentangle two physical processes with a single observable ?

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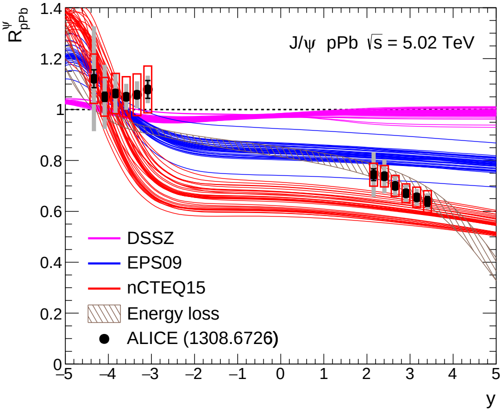

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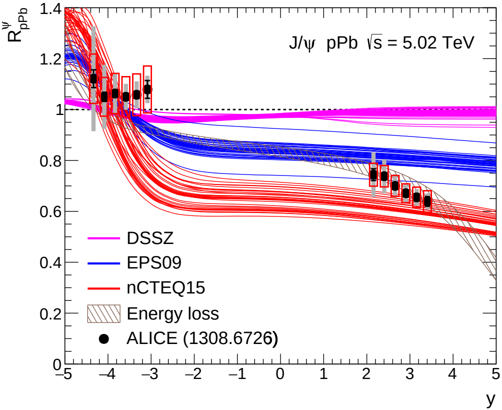

Idea: Use the Drell-Yan process ! **[FA, S. Peigné, 1512.01794]**

Why ?

Shadowing and energy loss effects on DY should be very different

Shadowing effects on DY

- Forward DY sensitive to sea antiquark shadowing: $q^p \bar{q}^A \to \gamma^\star$
- Sea antiquark and gluon shadowing pretty similar (EPS09, nCTEQ15)

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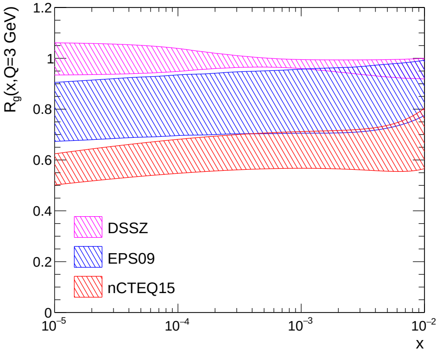

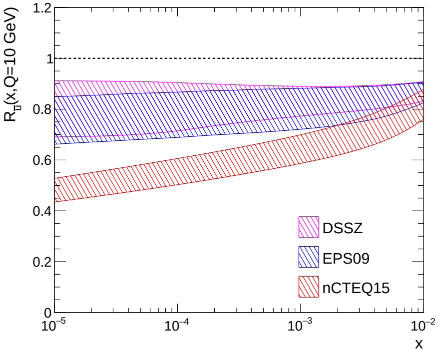

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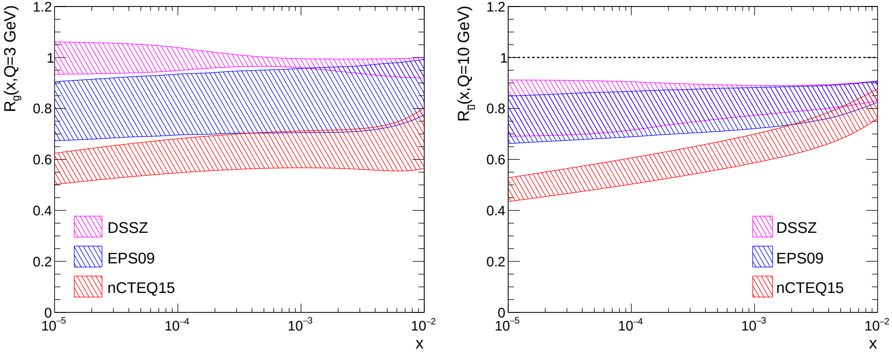

nPDF $\quad R^\psi \simeq R^{\rm DY} \quad \to \quad \mathcal{R}^{\psi/\rm DY} \equiv R^\psi / R^{\rm DY} \simeq 1$

Coherent energy loss effects on DY

- At LO, no color in the final state $\rightarrow$ no interference effects in gluon emission
  - no coherent energy loss effects expected
- At NLO, $qg \rightarrow q\gamma^*$ could be sensitive to coherent medium-induced gluon radiation
  - small $(1/N_c)$ and negative color factor
  - slight DY enhancement expected
- The different color structures in DY and J/ψ production make coherent energy loss act very differently on both processes

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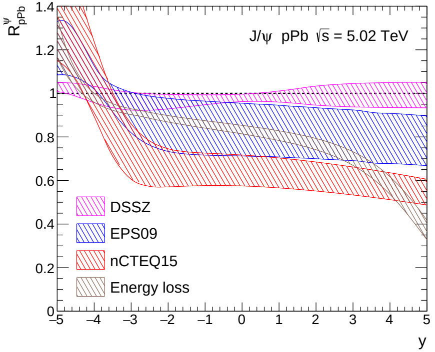
Energy loss $R^{\psi} < 1$; $R^{\mathrm{DY}} \gtrsim 1$ $\rightarrow$ $\mathcal{R}^{\psi/\mathrm{DY}} < 1$

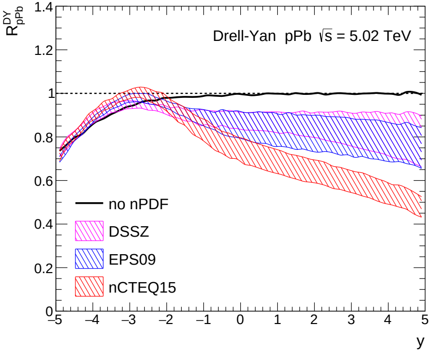
Comparing J/ψ and DY in p–Pb collisions

Procedure

- Compute nPDF (using DSSZ, EPS09, nCTEQ15) and coherent energy loss effects on J/ψ
- Compute nPDF effects on DY at NLO (DYNNLO code)
  - $10 \lesssim M_{\rm DY} \lesssim 20$ GeV to avoid strong background from B decays
- Assume no coherent energy loss effects on DY

Comparing J/ψ and DY





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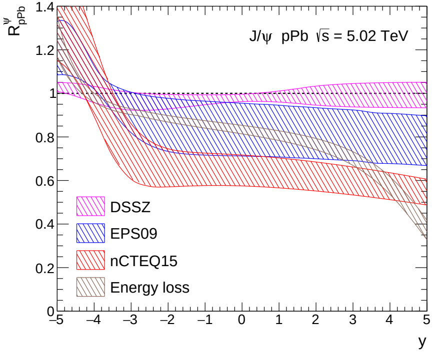
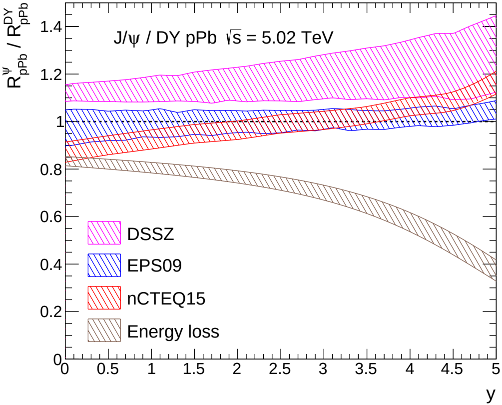


- As expected, qualitatively similar shadowing effects on J/ψ and DY using EPS09 and nCTEQ15 (unlike DSSZ)
- Noticeable isospin effects in the Pb fragmentation region ($y < 0$)
  - Pb poorer in up valence quarks than protons leading to suppression

Double ratio $\mathcal{R}^{\psi/\mathrm{DY}}$



- Spectacular difference between shadowing and coherent energy loss
- Significantly reduced nPDF uncertainty because of the correlation between gluon and sea quark nPDF individual sets

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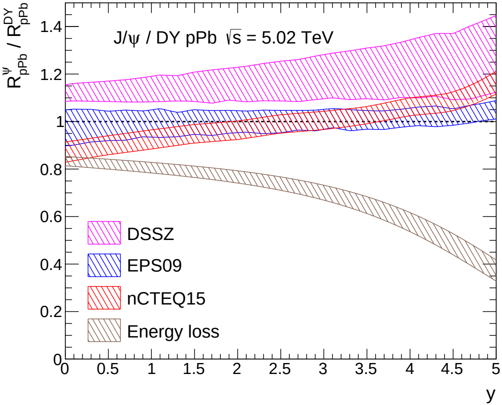

- This observable should clarify the respective role of both effects
  - Implications on light hadron forward suppression in p–Pb collisions
  - Implications on quarkonium suppression in Pb–Pb collisions
- Could also be interesting to measure at lower energy see Platchkov (Sat)

Experimentally

DY p–Pb measurement should ideally occur

- at forward rapidity
- at rather low mass, e.g. $10 \lesssim M_{\mathrm{DY}} \lesssim 20$ GeV

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LHCb appears to be the best experiment in this respect

- Large rapidity acceptance $1.5 \lesssim y \lesssim 4$
- VELO detector can be used to remove B decays and access low mass
- Preliminary measurements already done in p–p collisions
- ATLAS/CMS also useful at mid-rapidity and ALICE with vertex detector upgrade

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Counting rates

- Around 2000 pairs in $3.5 < y < 4$ using $\mathcal{L}_{\mathrm{int}} = 100\ \mathrm{nb}^{-1}$
    - Good statistical accuracy

Summary

- Coherent energy loss could play a decisive role in the suppression of J/ψ in p–A collisions
  - Derived from first principle calculations
  - Good agreement with all existing data from SPS to LHC
- Small-x shadowing might also play a role (at LHC), but current uncertainties due to lack of data do not allow for precise predictions
- DY in p–Pb as a key measurement to clarify the current situation
  - Could easily be performed by LHCb in p–Pb run in 2016
- No coherent energy loss expected in DIS
  - e–A collider ideal tool to probe nPDF

A bound on energy loss ?

Considering an asymptotic charge in a QED model **[Brodsky Hoyer 93]**

- No contribution from large formation times $t_f \gg L$
- Induced gluon radiation needs to resolve the medium

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \qquad \omega \lesssim k_\perp^2 \ L \sim \hat{q} \ L^2$$

  - Bound independent of the parton energy
  - Energy loss cannot be arbitrarily large in a finite medium
  - Apparently rules out energy loss models as a possible explanation

However

- Not true in QED when the charge is deflected
- Not necessarily true in QCD due to color rotation

Medium-induced gluon spectrum

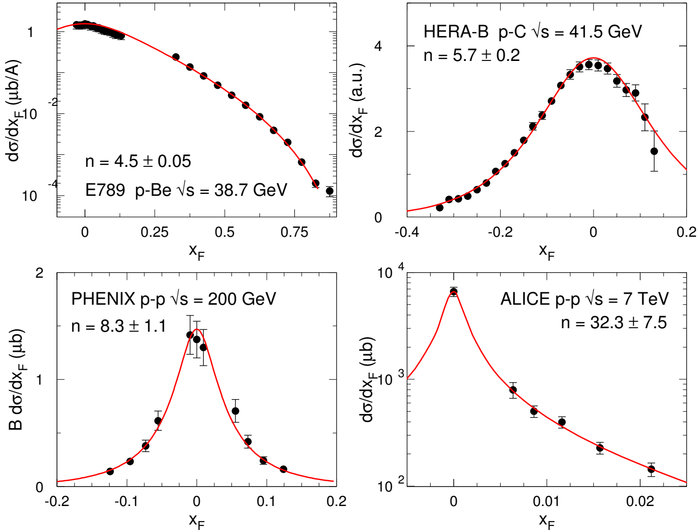
Gluon spectrum $dI/d\omega \sim$ Bethe-Heitler spectrum of massive (color) charge

$$\omega \frac{dI}{d\omega}\bigg|_{\text{ind}} = \frac{N_c \alpha_s}{\pi} \left\{ \ln\left(1 + \frac{E^2 \Delta q_\perp^2}{\omega^2 M_\perp^2}\right) - \ln\left(1 + \frac{E^2 \Lambda_{\text{QCD}}^2}{\omega^2 M_\perp^2}\right) \right\}$$

$$\Delta E = \int d\omega\, \omega\, \frac{dI}{d\omega}\bigg|_{\text{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2} - \Lambda_{\text{QCD}}}{M_\perp} E$$

- $\Delta E \propto E$ neither initial nor final state effect nor 'parton' energy loss: arises from coherent radiation
- Physical origin: broad t_f interval : $L, t_{\text{hard}} \ll t_f \ll t_{\text{octet}}$ for medium-induced radiation

Fit to pp data



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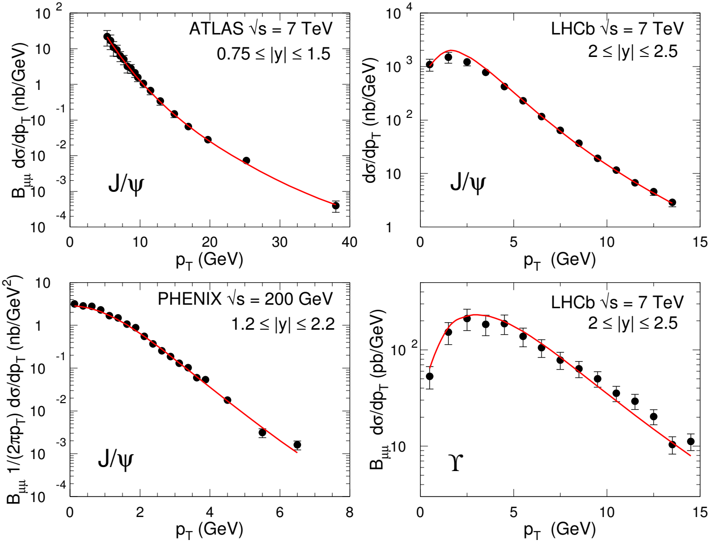

Quenching weight

- Usually one assumes independent emission $\to$ Poisson approximation

$$\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \, \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right)$$

- However, radiating ω_i takes time $t_f(\omega_i) \sim \omega_i / \Delta q_\perp^2 \gg L$

For $\omega_i \sim \omega_j \Rightarrow$ emissions i and j are not independent

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- Usually one assumes independent emission $\rightarrow$ Poisson approximation

$$\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right)$$

- However, radiating ω_i takes time $t_f(\omega_i) \sim \omega_i / \Delta q_\perp^2 \gg L$

For $\omega_i \sim \omega_j \Rightarrow$ emissions i and j are not independent

- For self-consistency, constrain $\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$

$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega} \exp\left\{ - \int_{\epsilon}^{\infty} d\omega \frac{dI}{d\omega} \right\} \qquad \omega \frac{dI}{d\omega}\bigg|_{\rm ind} \simeq \frac{N_c \alpha_s}{\pi} \ln\left(1 + \frac{E^2 \hat{q} L}{\omega^2 M_\perp^2} \right)$$

- $\mathcal{P}(\epsilon)$ scaling function of $\hat{\omega} = \sqrt{\hat{q}L}/M_\perp \times E$

Transport coefficient

$\hat{q}$ related to gluon distribution in a proton **[BDMPS 1997]**

$$\hat{q}(x) = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho\, x G(x, \hat{q} L)$$

For simplicity we assume

$$\hat{q}(x) = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3} \qquad (\hat{q} \text{ frozen at } x \gtrsim 10^{-2})$$

- $\hat{q}_0 \equiv \hat{q}(x = 10^{-2})$ only free parameter of the model
- $\hat{q}(x)$ related to the saturation scale: $Q_s^2(x, L) = \hat{q}(x) L$ **[Mueller 1999]**

Uncertainties

Two sources of uncertainties are identified

- Transport coefficient $\hat{q}_0$ (default 0.075 $\mathrm{GeV}^2/\mathrm{fm}$) to be varied from 0.07 to 0.09 $\mathrm{GeV}^2/\mathrm{fm}$
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Uncertainty band determined from the independent variation of $\hat{q}_0$ and n (4 error sets)

$$\begin{aligned}(\Delta R^+)^2 &= \sum_{k=\hat{q}_0,n} \left[\max\left\{R(S_k^+) - R(S^0), R(S_k^-) - R(S^0), 0\right\}\right]^2 \\ (\Delta R^-)^2 &= \sum_{k=\hat{q}_0,n} \left[\max\left\{R(S^0) - R(S_k^+), R(S^0) - R(S_k^-), 0\right\}\right]^2\end{aligned}$$

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- Largest uncertainty comes from the variation of $\hat{q}_0$ around mid-rapidity
- At very large rapidity (e.g. $y \gtrsim 4$ at LHC), uncertainty coming from n becomes comparable or larger than that coming from $\hat{q}_0$

$p_\perp$ dependence

Most general case

$$\frac{1}{A}\frac{d\sigma_{\rm pA}^{\psi}}{dE\ d^2\vec{p}_\perp} = \int_\varepsilon \int_\varphi \mathcal{P}(\varepsilon, E)\, \frac{d\sigma_{\rm pp}^{\psi}}{dE\ d^2\vec{p}_\perp}\left(E+\varepsilon, \vec{p}_\perp - \Delta\vec{p}_\perp\right)$$

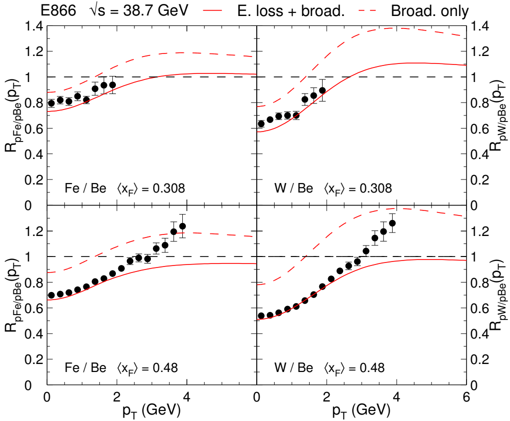
- pp cross section fitted from experimental data

$$\frac{d\sigma_{\rm pp}^{\psi}}{dy\, d^2\vec{p}_\perp} \propto \left(\frac{p_0^2}{p_0^2 + p_\perp^2}\right)^m \times \left(1 - \frac{2M_\perp}{\sqrt{s}}\cosh y\right)^n$$

- Overall depletion due to parton energy loss
- Possible Cronin peak due to momentum broadening

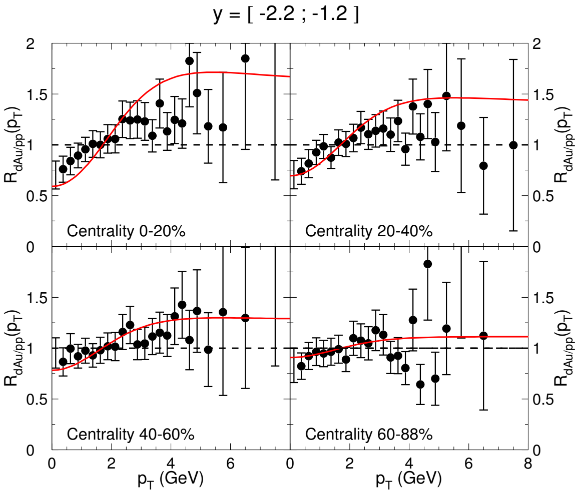
$$R_{\rm pA}^{\psi}(y, p_\perp) \simeq R_{\rm pA}^{\rm loss}(y, p_\perp) \cdot R_{\rm pA}^{\rm broad}(p_\perp)$$

$p_\perp$ dependence at E866



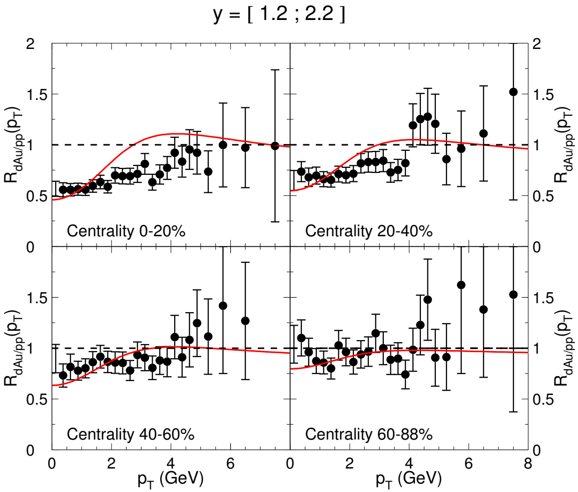
- Good description of E866 data (except at large $p_\perp$ and large x_F)
- Broadening effects only not sufficient to reproduce the data

$p_\perp$ dependence at RHIC



- Good description of $p_\perp$ and centrality dependence at $y = -1.7$

$p_\perp$ dependence at RHIC

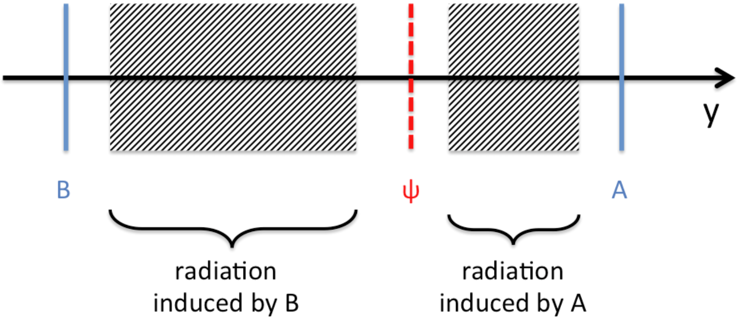


- Good description of $p_\perp$ and centrality dependence at $y = 1.7$

Extrapolation to heavy-ion collisions

Model for A B collisions

- Both incoming (projectile & target) partons lose energy in the (target & projectile) nucleus, respectively
- Two distinct regions of phase space for gluon emission → no interference effects in the radiation induced by nucleus A and B



Extrapolation to heavy-ion collisions

Model for A B collisions

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$$
\frac{1}{A\ B}\frac{d\sigma^{\psi}_{AB}}{dy}\left(y,\sqrt{s}\right) = \int d\ \delta y_B\,\mathcal{P}_B(\varepsilon_B, y)\int d\delta y_A\,\mathcal{P}_A(\varepsilon_A, -y)\,\frac{d\sigma^{\psi}_{\mathrm{pp}}}{dy}\left(y + \delta y_B - \delta y_A, \sqrt{s}\right)
$$

with δy_B defined as $E(y + \delta y_B) \equiv E(y) + \epsilon_B$

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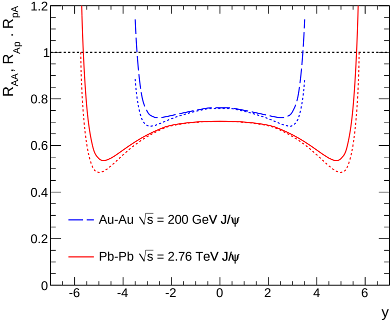
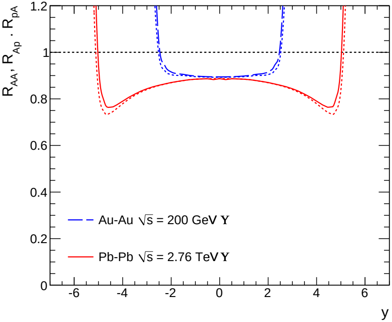
A good approximation (at not too large y)

$$R_{AB}(+y) \simeq R_{Ap}(+y)\times R_{pB}(+y) = R_{pA}(-y)\times R_{pB}(+y)$$

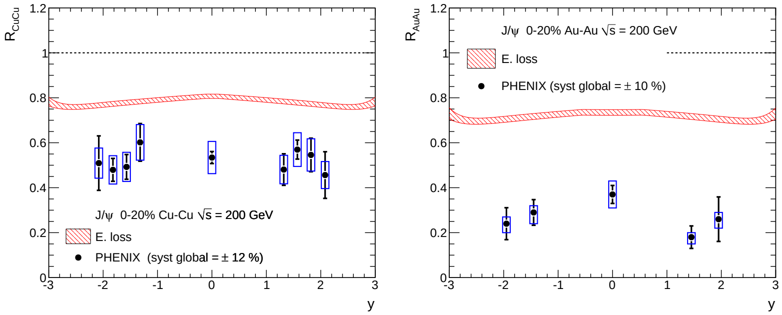
Rapidity dependence in A A collisions





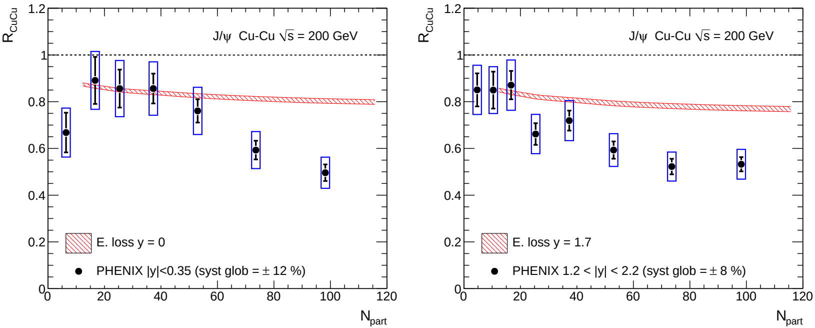
- Rather pronounced suppression, especially for J/ψ
- R_{AA} slightly decreasing at not too large y
- Fast increase at edge of phase space due to energy gain fluctuations

Rapidity dependence in A A collisions at RHIC



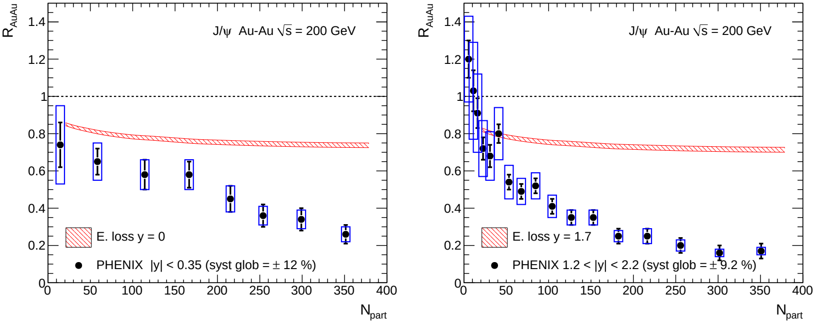
- Disagreement in both Cu Cu and Au Au collisions
- Disagreement more pronounced in Au Au collisions

Centrality dependence in A A collisions at RHIC



- Disagreement only in most central Cu Cu collisions

Centrality dependence in A A collisions at RHIC



- Disagreement only in most central Cu Cu collisions
- Strong disagreement in most central Au Au collisions, fair agreement within uncertainties in peripheral collisions

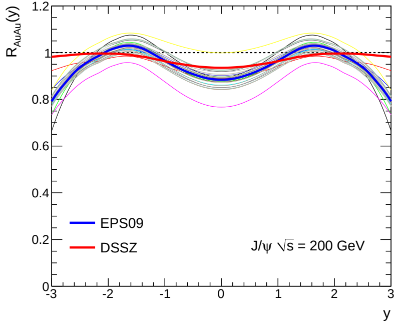
nPDF effects

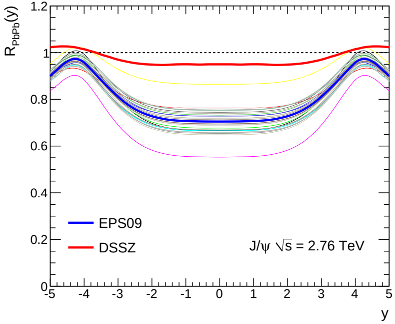
- nPDF effects may affect quarkonium suppression in p–A & A A collisions and could be added (incoherently) to present energy loss effects
- However sill large uncertainty on small x gluon shadowing (within a single set or comparing existing sets)

For simplicity we provided “energy loss only” calculations

nPDF effects

Ratio of gluon densities (using EPS09 NLO, x_1, x_2 given by $2 \to 1$ kin.)





- At RHIC, energy loss is the leading effect
- At LHC
  - Energy loss leading effect as compared to DSSZ
  - Same order of magnitude as EPS09 around mid-rapidity but leading effect at large rapidity

“Diffractive” component in NA3

“In your model, could you reproduce the NA3 diffractive component which is completely FLAT as a function of x_F ?” (Stan)

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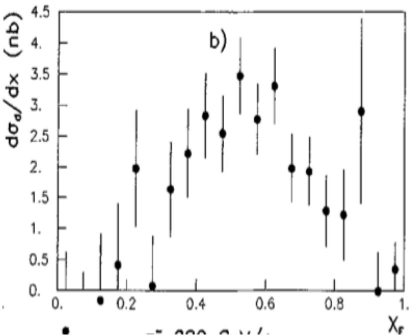

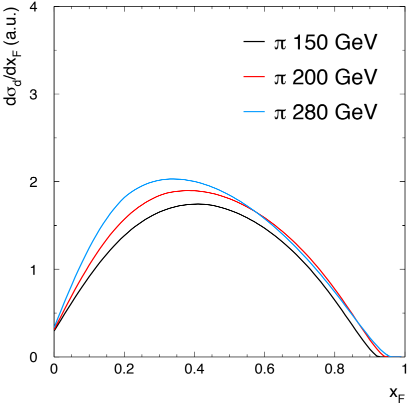

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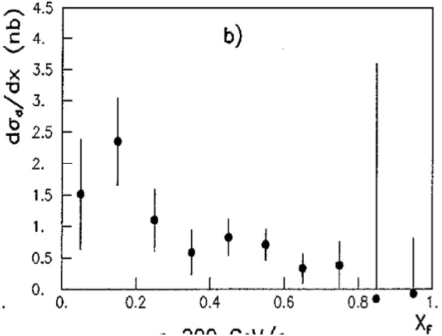
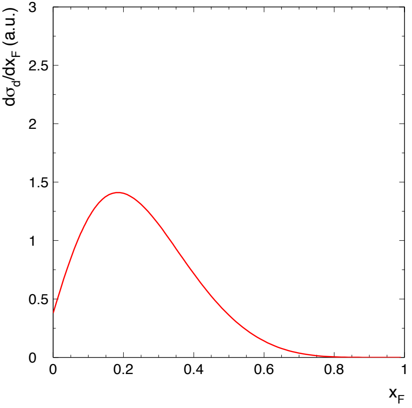
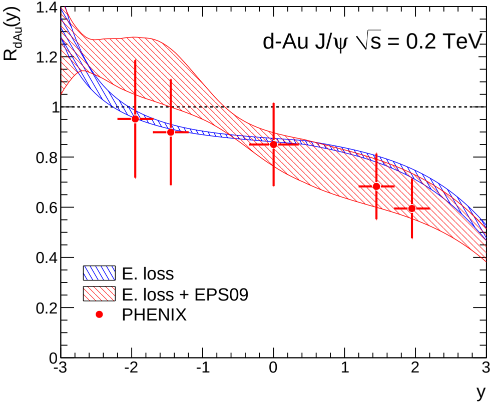




RHIC predictions w/ and w/o EPS09



- Good agreement at all rapidity w/ and w/o EPS09 nPDF

LHC predictions w/ and w/o EPS09