Heavy flavour and Drell-Yan production in pA collisions in LHCb

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Workshop on LHCb Heavy Ion and Fixed Target physics

CERN – January 2017

Outline

- Context
  - Origin of quarkonium suppression in pA collisions at the LHC
- Coherent energy loss in nuclei
  - Quarkonium suppression in pA collisions
- Disentangling shadowing from coherent energy loss
  - Why Drell-Yan production
  - Results
- Personal wishlist

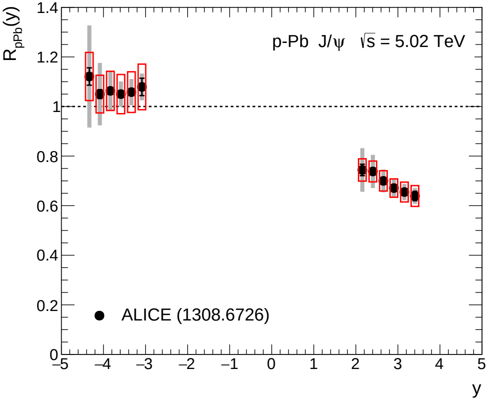
References

- FA, 1612.07987 (brief discussion on hard processes in pA)
- FA, S. Peigné, 1204.4609, 1212.0434 (quarkonia), 1512.01794 (DY), 1504.07428 (LHC fixed-target)
- See also FA, S. Peigné, 1204.4609, 1407.5054, w/ T. Sami, 1006.0818, w/ R. Kolevatov and M. Rustamova, 1304.0901, 1402.1671

Context

ALICE and LHCb measured J/ψ production in pPb collisions at 5 TeV

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



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

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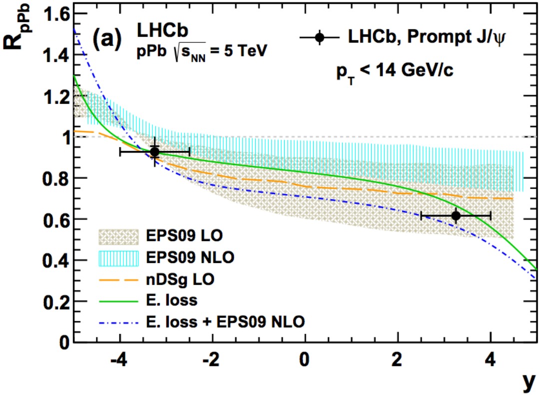

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Possible explanations

- 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 pA data at fixed-target energies (NA3, E866) $\rightarrow$ another effect at work which needs to be understood

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Issue

- Large uncertainties do not allow for precise predictions of nPDF 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

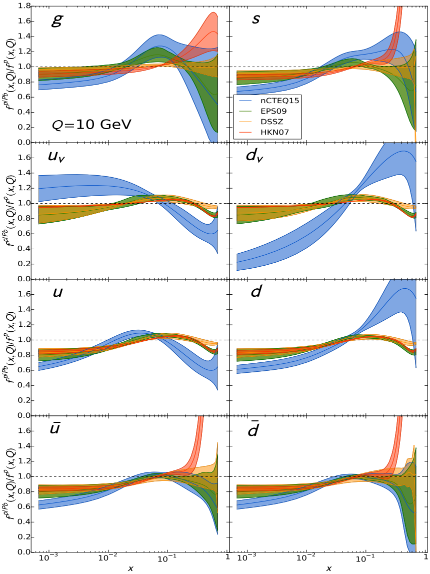
Schienbein, Mon 9 15:30

- Obtained from global fits based on DGLAP evolution
  - EPS09, DSSZ, nCTEQ15...
- Depletion ('shadowing') expected at small x
- Poor constraints, especially at small-x and in the gluon channel
- Crucial need to use LHC pPb data

[Paukkunen Zurita, 1402.6623]

[Eskola et al. EPPS16 1612.05741]

[nCTEQ15, 1509.00792]



Some observables sensitive to nPDF at the LHC

Basically all hard processes, especially at rather low Q^2 !

Particularly within easy reach in LHCb

- Heavy-quarkonia (ψ, Υ)
  - including exciting states
- Open heavy-flavour
  - D, B,... and non-prompt J/ψ
- Drell-Yan at rather low mass $M = \mathcal{O}(10 \text{ GeV})$

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What makes these observables & LHCb that interesting ?

- Small masses & forward acceptance (small x)
  - access to the 'saturation' region, $M \gtrsim Q_s \propto x^{-0.3}$, where shadowing is expected to be maximal

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

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

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A simple approximation **[FA, S. Peigné, 1512.01794]**

$$R_{\mathrm{pA}}^{\psi}(y) = R_g^{\mathrm{Pb}}(x_2, Q = M_\psi)$$

$$x_2 = M_\psi \; e^{-y}/\sqrt{s}$$

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- x_2 given by LO kinematics, precise value not crucial as R_g is flat at low $x \lesssim 10^{-2}$
- Should be accurate within $\mathcal{O}\,(1\%) \ll$ nPDF uncertainties
- R_g^{Pb} given by global fits (EPS09, DSSZ, nCTEQ15), band computed from the spread of 30-50 uncertainty sets

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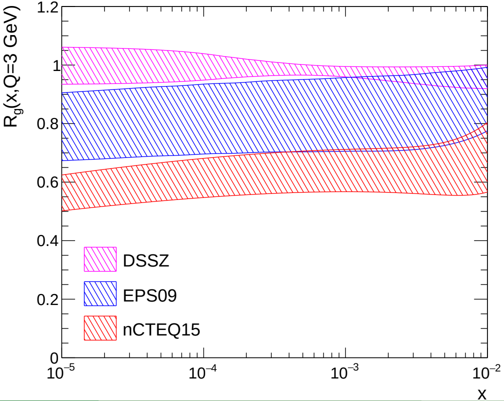
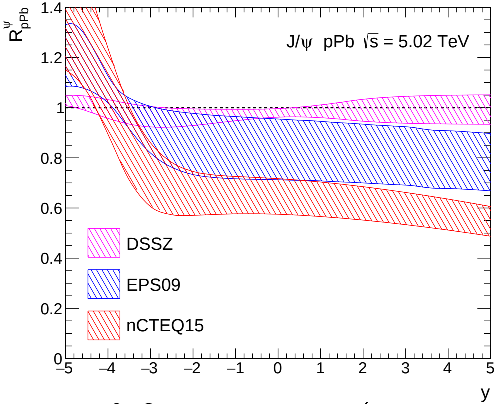
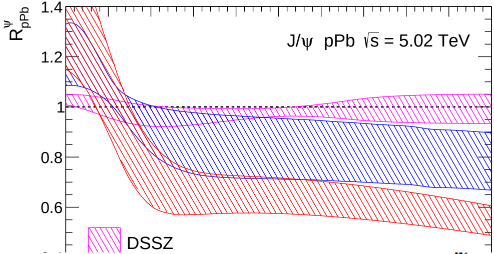


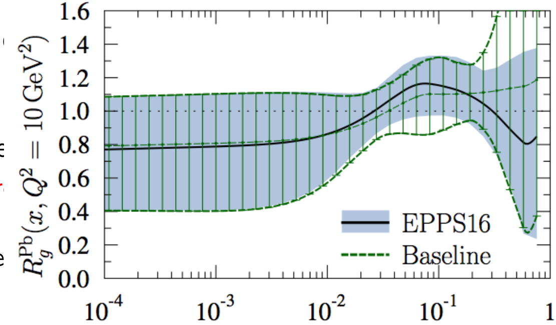
nPDF effects on J/ψ in pPb at LHC



- 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
  - Even more dramatic with EPPS16

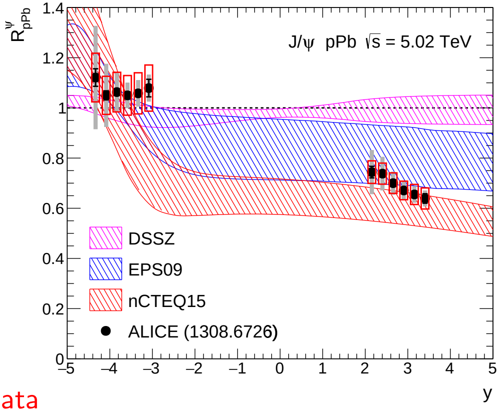
nPDF effects on J/ψ in pPb at LHC





- Match very we ... PS09)
- Widespread pr ... ng
  - At $y = 5$: ... TEQ15
  - Even more

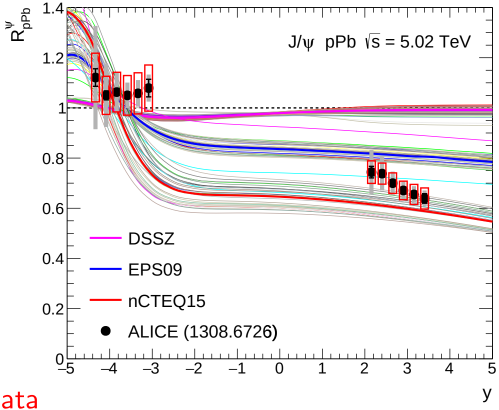
nPDF effects on J/ψ in pPb at LHC



Comparing to data

- DSSZ alone cannot explain the forward suppression
- Apparent agreement with some uncertainty sets of EPS09/nCTEQ15

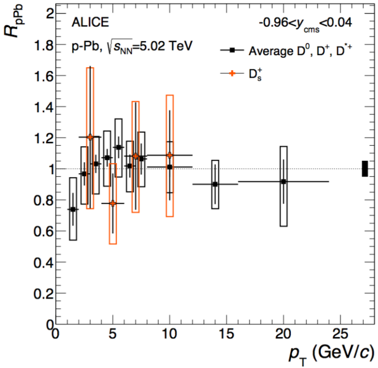
nPDF effects on J/ψ in pPb at LHC

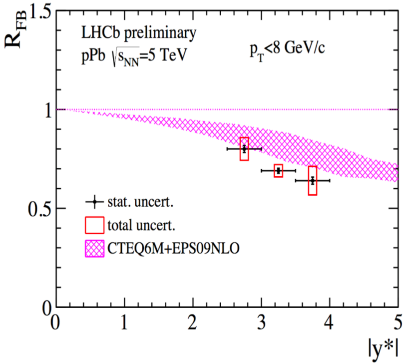


Comparing to data

- 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

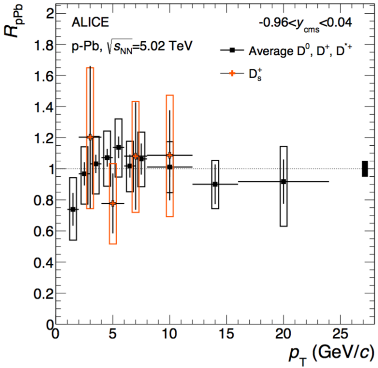
nPDF effects on D mesons in pPb at LHC

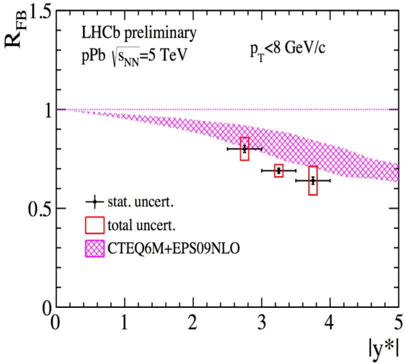




- Little or no suppression at mid-rapidity **[ALICE 1605.07569]**
- forward/backward rapidity asymmetry measured by LHCb **[LHCb-CONF-2016-003]**
  - EPS09 slightly above the data

nPDF effects on D mesons in pPb at LHC





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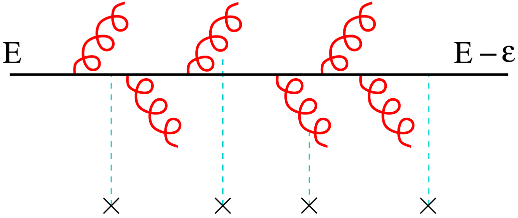
Let us now discuss coherent energy loss effects

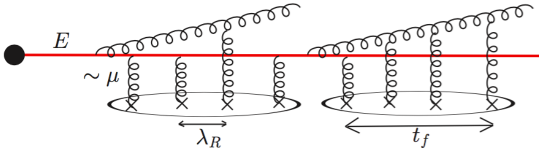
Energy loss-es

On top of momentum broadening, parton multiple scattering in nuclei induces gluon radiation → energy loss in cold nuclear matter



Initial/final state energy loss

LPM regime, small formation time $t_f \lesssim L$



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

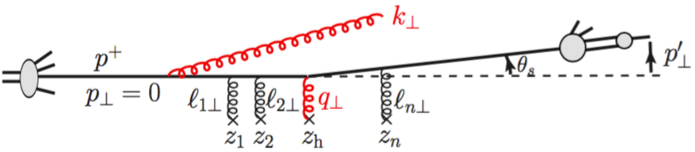
- Energy dependence at most logarithmic
- Best probed in
  - Hadron production in nuclear semi-inclusive DIS
  - Drell-Yan in pA collisions at low energy
- Should be negligible in pA at the LHC
  - fractional energy loss $\Delta E_{\text{LPM}}/E \sim 1/E \ll 1$
  - . . . could play a role in fixed target experiments !

Fully coherent energy loss

Interference between initial and final state, large formation time $t_f \gg L$

[FA Peigné Sami 1006.0818]

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



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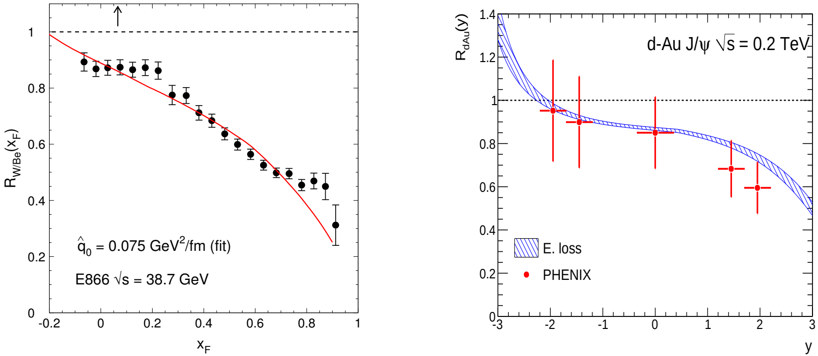
$$\Delta E_{\text{coh}} \propto \alpha_s \frac{\sqrt{\hat{q}\ L}}{M_\perp}\ E \quad (\gg \Delta E_{\text{LPM}})$$

- Important at all energies, especially at large rapidity
- Needs color in both initial & final state
  - no effect on W/Z nor Drell-Yan, no effect in DIS
- Hadron production in pA collisions
  - applied to quarkonia, other processes currently investigated
- Power suppressed: negligible when $M_\perp \gg \sqrt{\hat{q}L}$
  - weaker effects on Υ, let alone on jets

Quarkonia

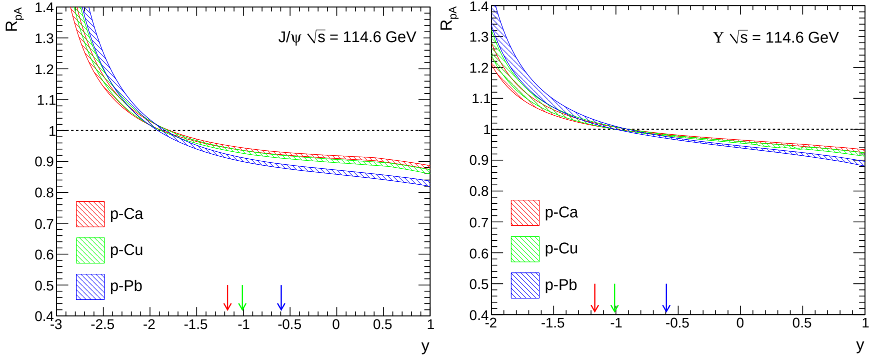
Simple fully coherent energy loss model able to solve the longstanding issue of J/ψ forward suppression pA data **[FA Peigné, 1212.0434]**



- Good agreement with all (E866, PHENIX…) quarkonium pA data
  - Wide range in $\sqrt{s}$ and rapidity
- no nPDF calculation can explain these data

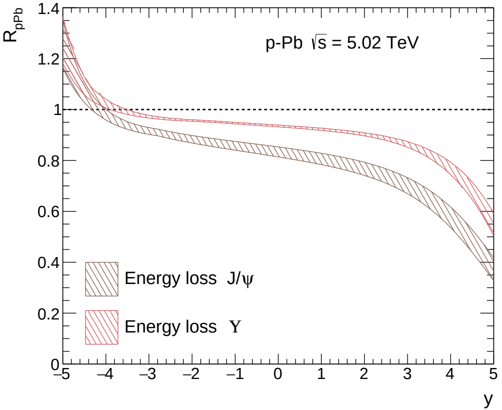
LHC predictions (fixed-target)

[FA, S. Peigné, 1504.07428]



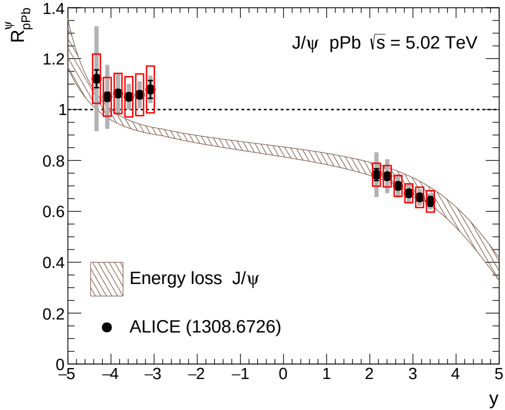
- Suppression could already be seen even at $y = 1$
- Enhancement (?) at negative rapidity
  - although beyond the validity domain of the model

LHC predictions (collider)



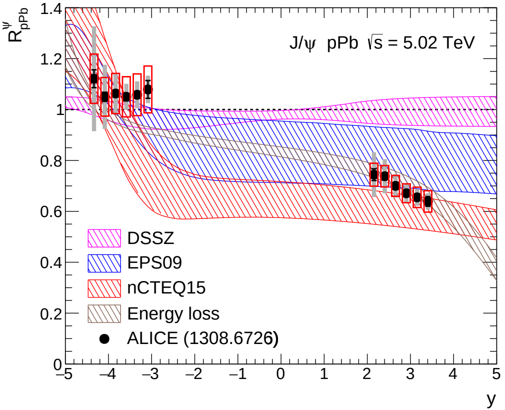
- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- Smaller suppression expected in the Υ channel

LHC predictions (collider)



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

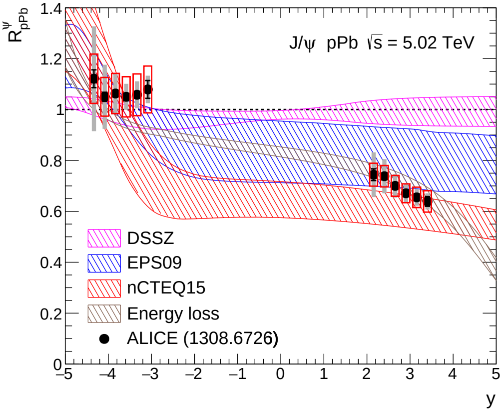
So, what quenches J/ψ ?



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

How to disentangle two physical processes with a single observable ?

So, what quenches J/ψ ?



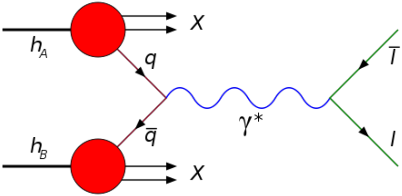
Idea: Use the Drell-Yan process ! **[FA, S. Peigné, 1512.01794]**

Why ?

Shadowing and energy loss effects on DY should be very different

Drell-Yan

A golden probe of sea quark (and gluon) shadowing



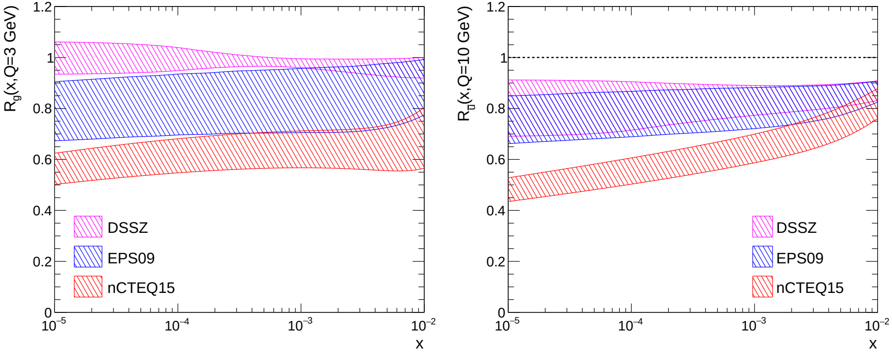
- Low scale $Q \sim 10$ GeV can be reached
  - better than weak bosons, jets, prompt photons
  - mass can be varied
- Very well understood in QCD
  - better than light or heavy hadrons
  - discovered in 1970 at the AGS...

Drell-Yan

Sidney Drell (1926 – 2016)

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)



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

Coherent energy loss effects on DY

- At LO, no color in the final state → no interference effects in gluon emission
  - no coherent energy loss effects expected
- The different color structures in DY and J/ψ production make coherent energy loss act very differently on both processes

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

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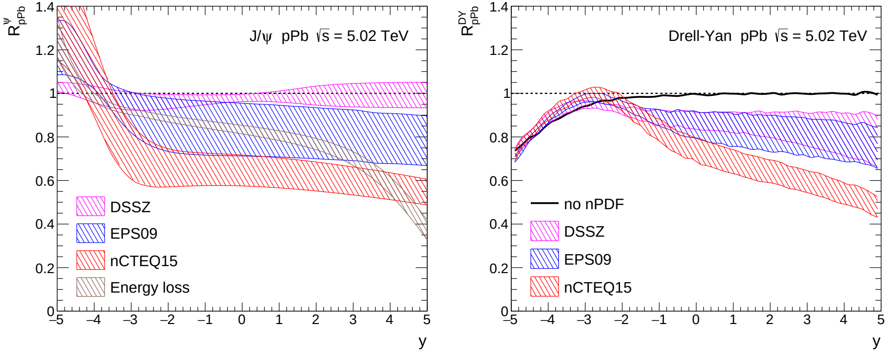
Procedure

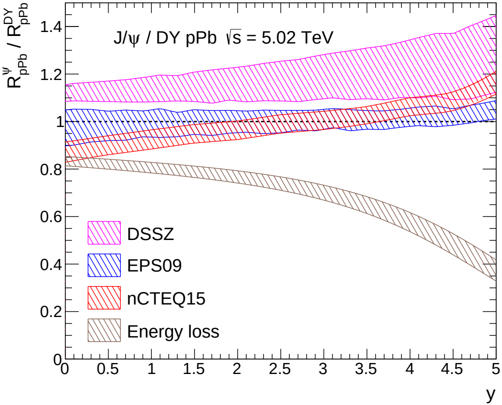
- Compute nPDF and coherent energy loss effects on J/ψ
- Compute nPDF effects on DY at NLO
- Assume no coherent energy loss effects on DY

Comparing J/ψ and DY



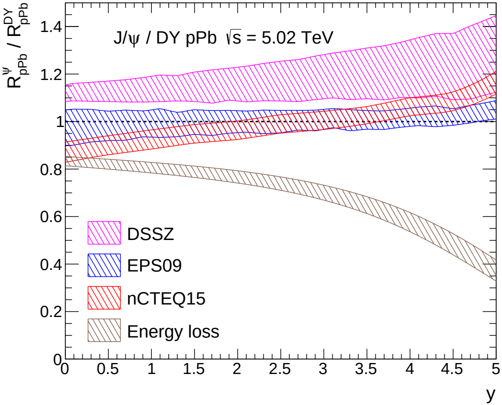
- As expected, qualitatively similar shadowing effects on J/ψ and DY using EPS09 and nCTEQ15 (unlike DSSZ)
- Noticeable isospin effects in the Pb fragmentation region ($y < 0$)
  - Pb poorer in up valence quarks than protons leading to suppression

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

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



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

Experimentally

DY pPb measurement should ideally occur

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

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

Counting rates

- Around 1000 pairs in $2.5 < y < 4$ using $\mathcal{L}_{\rm int} = 15$ nb^{-1}
  - Good statistical accuracy

What next ? A brief wishlist

- Comparing different masses
  - $R_{pA}(J/\psi)/R_{pA}(\Upsilon)$, $R_{pA}(D)/R_{pA}(B)$, $R_{pA}(\mathrm{DY})$ vs. M_{DY}
  - $R_{pA}(J/\psi)/R_{pA}(\mathrm{DY})$
- Quarkonium spectroscopy
  - $R_{pA}(\psi')$, but also $R_{pA}(\chi_{c1})$, $R_{pA}(\chi_{c2})$
- Light hadrons
  - $R_{pA}(h)$ at large rapidity ?
- Going exotic
  - R_{pA} of tetraquarks and pentaquarks ?
- Variables
  - Usual R_{pA} in minimum bias collisions
  - As a function of rapidity, integrated over transverse momentum
  - Nuclear broadening $\langle p_\perp^2 \rangle_{pA} - \langle p_\perp^2 \rangle_{pp}$

Summary

- Two nuclear effects are currently debated: nPDF (and saturation) and coherent energy loss
  - Only the latter can explain lower energy J/ψ data
  - At LHC, the large nPDF uncertainties prevent a firm conclusion
  - ... although future Drell-Yan data could be extremely useful
- Theorists need help from data (and experimentalist colleagues!)
  - LHCb appears the best experiment due to the variety of measurements accessible (open/hidden heavy flavour, DY,...) and forward acceptance
- Never forget about lower collision energy data !
  - Comparing different $\sqrt{s}$ is decisive, instead of focusing on LHC only
  - Promising measurements with SMOG, as important as LHC

Medium-induced gluon spectrum

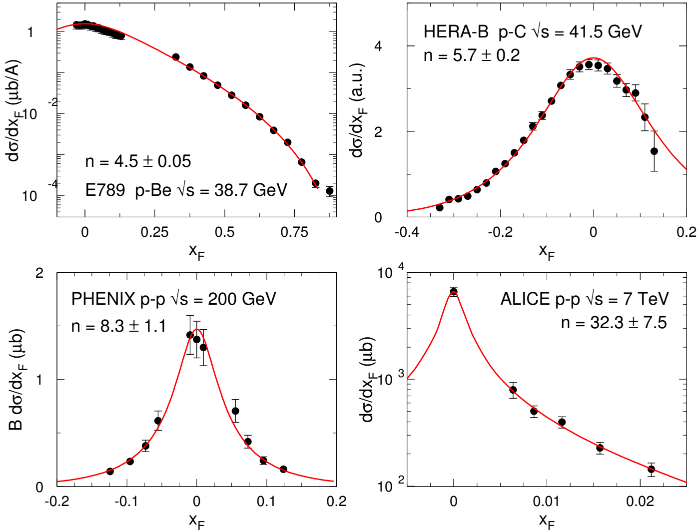
Gluon spectrum $dI/d\omega \sim$ Bethe-Heitler spectrum of massive (color) charge

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

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

- $\Delta E \propto E$ 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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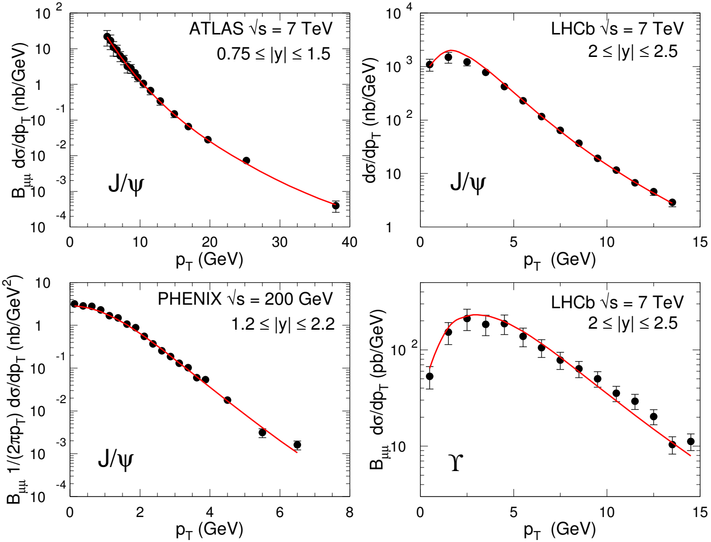

Quenching weight

- Usually one assumes independent emission → 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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For $\omega_i \sim \omega_j \Rightarrow$ emissions i and j are not independent

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

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

- $\mathcal{P}(\epsilon)$ 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]**

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

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 $\mathrm{GeV}^2/\mathrm{fm}$
- Parameter ("slope") of the pp cross section to be varied within its uncertainty extracted from the fit of pp data

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Uncertainty band determined from the independent variation of $\hat{q}_0$ and n (4 error sets)

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

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

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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

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

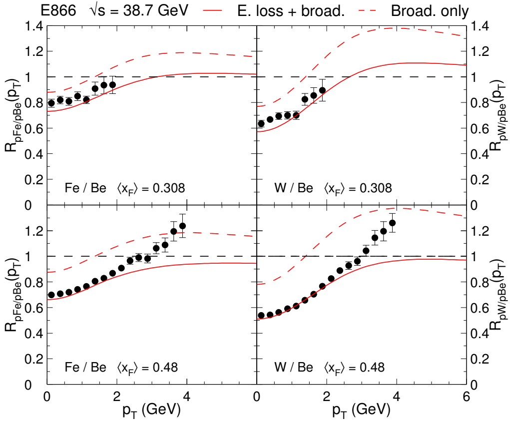
- pp cross section fitted from experimental data

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

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

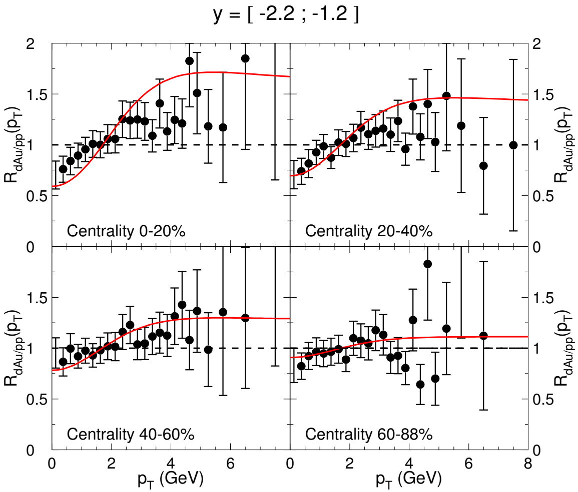
$$R_{\rm pA}^{\psi}(y, p_\perp) \simeq R_{\rm pA}^{\rm loss}(y, p_\perp)\cdot R_{\rm pA}^{\rm broad}(p_\perp)$$

$p_\perp$ dependence at E866



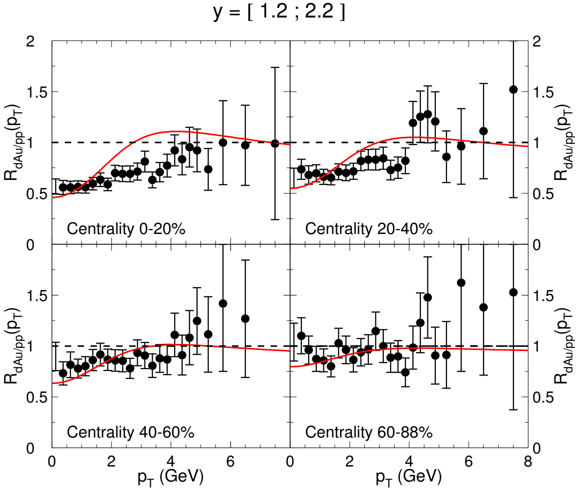
- Good description of E866 data (except at large $p_\perp$ and large x_F)
- Broadening effects only not sufficient to reproduce the data

$p_\perp$ dependence at RHIC



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

$p_\perp$ dependence at RHIC

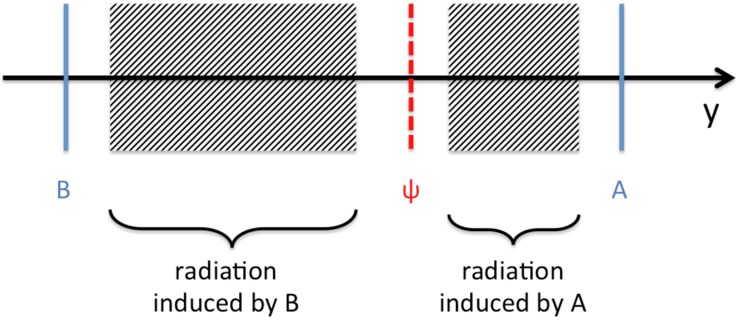


- Good description of $p_\perp$ and centrality dependence at $y = 1.7$

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

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

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

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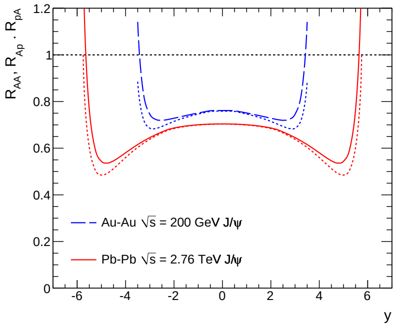
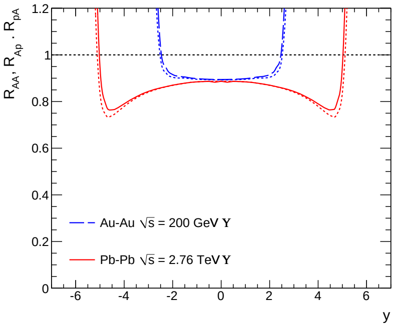
A good approximation (at not too large y)

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

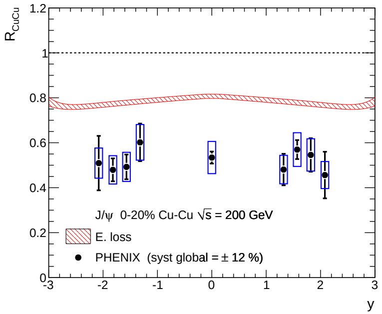
Rapidity dependence in A A collisions

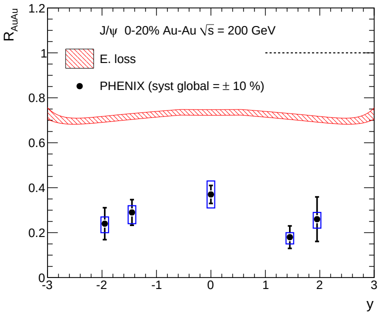




- Rather pronounced suppression, especially for J/ψ
- R_{AA} slightly decreasing at not too large y
- Fast increase at edge of phase space due to energy gain fluctuations

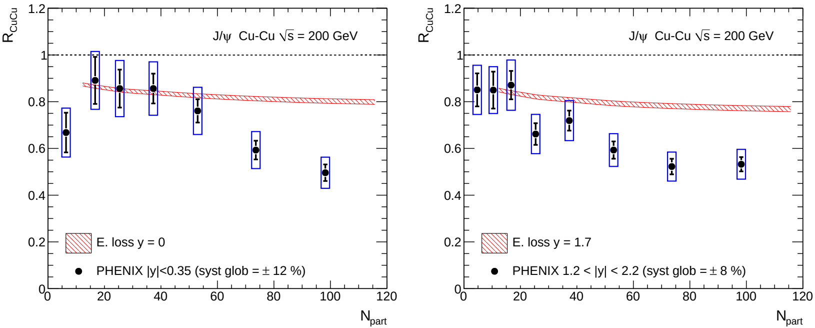
Rapidity dependence in A A collisions at RHIC





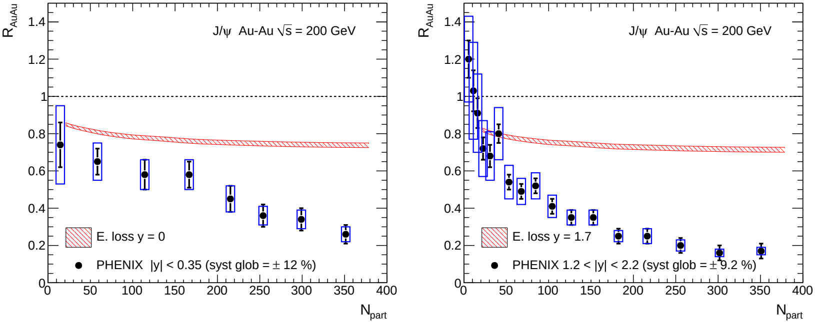
- Disagreement in both Cu Cu and Au Au collisions
- Disagreement more pronounced in Au Au collisions

Centrality dependence in A A collisions at RHIC



- Disagreement only in most central Cu Cu collisions

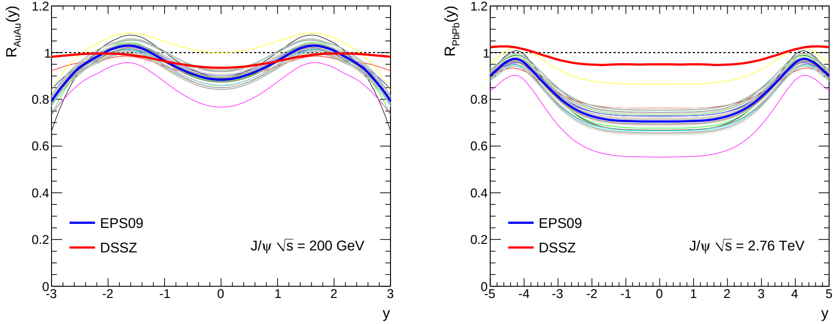
Centrality dependence in A A collisions at RHIC



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

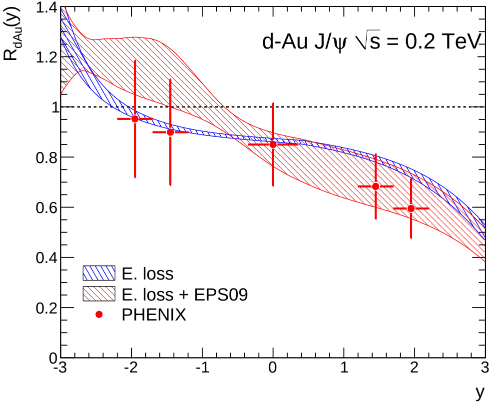
nPDF effects

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

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