Quarkonium production in pA collisions: energy loss, Cronin effect, shadowing and all that

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New Observables in Quarkonium Production

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Motivations

- Charmonia can be used as a hard probe of the nuclear medium since their large mass provide a hard scale
- Clean experimental signature via their decay into lepton pairs
- pA collisions: interesting in itself to study nuclear matter at high density (saturation, ...)
- Also serves as a reference to study 'hot' nuclear matter effects in AA collisions (J/ψ melting, ...)

Nuclear modification

The main observable of interest to study nuclear effects is the nuclear modification factor defined as

$$R_{\mathsf{pA}} = \frac{\mathrm{d}\sigma^{\mathsf{pA}}}{A\,\mathrm{d}\sigma^{\mathsf{pp}}}$$

Some theoretical uncertainties common to pp and pA collisions should cancel in this ratio

Charmonium production is not yet fully understood in pp collisions

$R_{\mathsf{pA}} = 1 \Leftrightarrow$ the nucleus behaves like a superposition of A independent nucleons

Several mechanisms can lead to a nuclear modification of charmonium production:

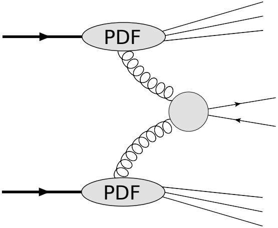
- Modification of the production (nuclear PDFs, energy loss)
- Destruction of bound states in the medium (absorption)

Both kinds of effects can be present at the same time

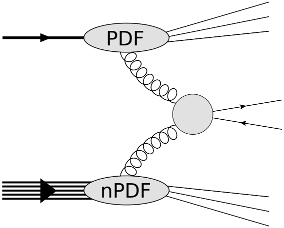
Collinear factorization: nuclear PDFs

This approach is based on the standard pQCD framework

The cross section is a convolution of parton distribution functions with a hard part



proton-proton



proton-nucleus

The nuclear PDF (nPDF) can be written as $f^A(x,Q) = R(x,Q) f^p(x,Q)$

$R(x,Q)$ is the nuclear modification of the free proton PDF

Like PDFs, nPDFs are supposed to be process-independent (can be fitted to some processes and then used for others)

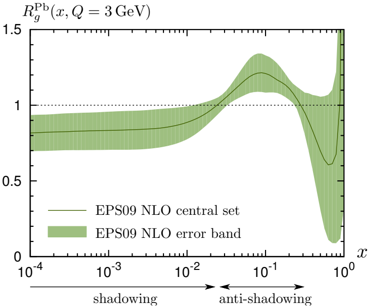
Collinear factorization: nuclear PDFs

There are several nPDF sets available (using various data, LO/NLO, etc)

Typical gluon nPDFs: 4 regions

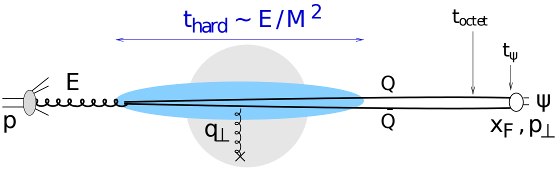
- $x \lesssim 10^{-2}$: shadowing
- $x \sim 10^{-1}$: anti-shadowing
- $0.3 \lesssim x \lesssim 0.7$: EMC effect
- $x \gtrsim 0.7$: Fermi motion

Even modern nPDF fits have quite large uncertainties in the regions of interest for charmonium production (shadowing and anti-shadowing)

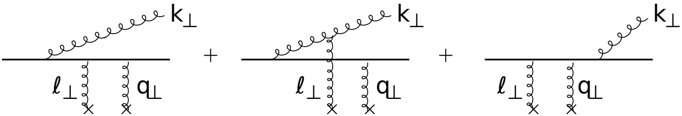


Arleo, Kolevatov, Peigné, Rustamova

This approach is based on the fact that for large formation times all scattering centers in the medium act coherently. Leads to a behaviour $\Delta E \propto E$



The medium-induced coherent radiation spectrum arises from the interference between gluon emission in the initial state and in the final state



$q_\perp$: hard scattering
$k_\perp \ll q_\perp$: soft gluon radiation
$l_\perp \ll q_\perp$: single rescattering to model nuclear transverse momentum broadening, $l_\perp^2 = \Delta p_T^2$

The cross section in pA collisions can be written as

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}^{\psi}}{\mathrm{d}E\,\mathrm{d}^2p_T} = \int_{\varphi}\int_{\varepsilon} \mathcal{P}(\varepsilon, E)\,\frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\psi}}{\mathrm{d}E\,\mathrm{d}^2p_T}\,(E+\varepsilon, p_T - \Delta p_T)$$

The pp cross section is parametrized from experimental data
Both $\mathcal{P}$ and Δp_T involve the transport coefficient $\hat{q}$, which is related to the gluon distribution by

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

Using the power-law behavior $xG(x) \sim x^{-0.3}$ suggested by small x ($x < 10^{-2}$) fits to HERA data, one can write

$$\hat{q}(x) \simeq \hat{q}_0\left(\frac{10^{-2}}{x}\right)^{0.3}$$

where $\hat{q}_0$ is the only free parameter of the model. $\hat{q}_0 = 0.075$ GeV^2/fm from a fit to E866 pW data

$\hat{q}(x)$ is related to the saturation scale by $Q_s^2(x, L) = \hat{q}(x)L$

The bound states may be destroyed by inelastic scatterings with nucleons if they are formed in the nuclear medium

This can be expressed as a survival probability which depends on σ_{abs}

One would expect $\sigma_{\mathsf{abs}} \sim r_{\mathsf{H}}^2$

Very rough estimate: $\sigma_{\mathsf{abs}} \sim \frac{\pi}{M_H^2} \sim 0.5$ mb for J/ψ

The values of σ_{abs} extracted from PHENIX data are much larger than this naive estimate by about one order of magnitude
Arleo, Tram

Data only gives access to the total suppression $\rightarrow$ the value of σ_{abs} depends on the other details of the calculation such as nPDF set

Study of the $\sqrt{s_{J/\psi - N}}$ dependence: σ_{abs} gets smaller at high energy $\rightarrow$ should be negligible at the LHC
Lourenço, Vogt, Woehri

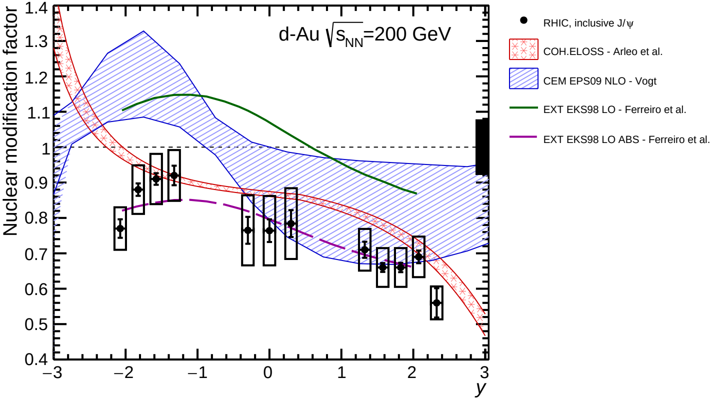
Sharma, Vitev

Phenomenological model including 3 effects implemented by a change of the kinematics of the $a^{(p)} + b^{(A)} \to H + d$ hard process

- Initial state energy loss: radiative loss by the incoming parton in the nuclear medium before the hard interaction. Implemented by an increase of the longitudinal momentum fraction carried by the parton coming from the proton $[\phi_a(x_a)]_{\mathrm{pA}} = \left[\phi_a\left(\frac{x_a}{1-\epsilon_a}\right)\right]_{\mathrm{NN}}$, with $\epsilon_a = \frac{\Delta E_a}{E_a}$
- Nuclear shadowing: uses EKS98 for the EMC effect and Fermi motion regions at large x. At small x the resummation of coherent final-state scatterings is included by changing the longitudinal momentum fraction carried by the parton coming from the nucleus: $(x_b)_{\mathrm{pA}} = (x_b)_{\mathrm{NN}}\left[1 + \frac{\xi_d^2(A^{1/3}-1)}{-\hat{t}+m_d^2}\right]$
- Cronin effect: modeled by including transverse momentum broadening $\langle k_{\mathrm{T}a}^2\rangle_{\mathrm{pA}} = \langle k_{\mathrm{T}}^2\rangle_{\mathrm{NN}} + \langle k_{\mathrm{T}a}^2\rangle_{\mathrm{IS}}$, with $\langle k_{\mathrm{T}a}^2\rangle_{\mathrm{IS}} = \left\langle \frac{2\mu^2 L}{\lambda_a}\right\rangle \xi$

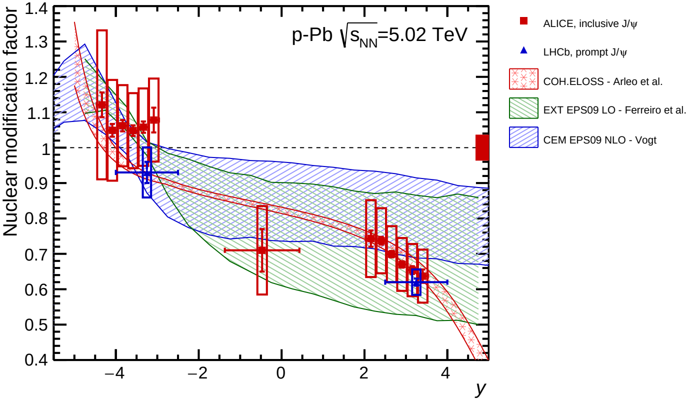
Parameters are related by $\xi_d^2 A^{1/3} \approx \frac{2\mu^2 L}{\lambda_d}$ where μ is related to the gluon density in the nucleus and λ is the mean free path of the parton

The probability distribution $P(\epsilon)$ is derived from the spectrum of medium induced gluon radiation



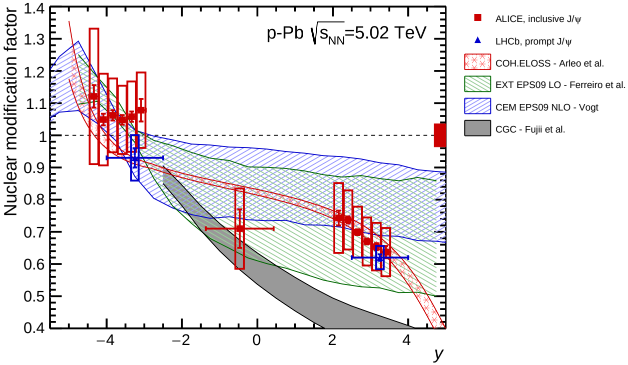
- General behaviour well described by coherent energy loss unless at very backward rapidity
- Calculation based on EPS09 nPDFs: large uncertainty, overestimates R_{dAu} at backward rapidity
- Calculation based on EKS98 nPDFs: no uncertainty given, always above the data. Good agreement with data when adding absorption with $\sigma_{\mathsf{abs}} = 4.2$ mb (much larger than naive expectation)

$R_{\mathrm{pPb}}(y)$: LHC

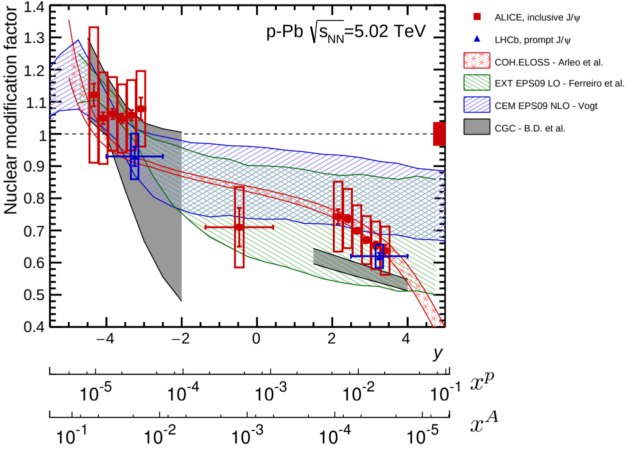


- The three calculations agree rather well with data at backward rapidity
- Forward rapidity: good description by coherent energy loss, hard to conclude for calculations based on nPDFs because of the large uncertainties but the data seems to show a stronger variation with y

$R_{\mathrm{pPb}}(y)$: LHC



$R_{\mathrm{pPb}}(y)$: LHC

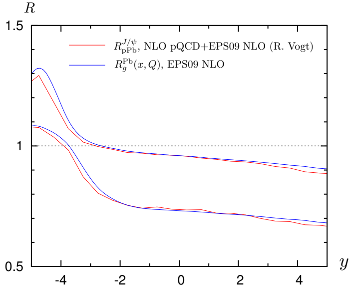


- CGC at forward rapidity: collinear description (PDF) of the proton probed at large x, CGC description of the nucleus probed at small x
- CGC at backward rapidity: collinear description (EPS09 LO nPDF) of the nucleus probed at large x, CGC description of the proton probed at small x (uncertainty: variation of Q between $\frac{1}{2}\sqrt{p_T^2+M^2}$ and $2\sqrt{p_T^2+M^2}$ + EPS09 error band)

$R_{\mathrm{pPb}}(y)$: LHC

The predictions based on nPDFs are very close to what is obtained by simply evaluating R_g at $x = \frac{\sqrt{\langle p_T \rangle^2 + M^2}}{\sqrt{s}} e^{-y}$ and $Q = \sqrt{\langle p_T \rangle^2 + M^2}$ with $\langle p_T \rangle \sim 2$ GeV.

Therefore one can easily estimate the impact of changing the nPDFs



For example the recent nCTEQ15 fit has more shadowing at small x than EPS09 NLO $\rightarrow$ should lead to better agreement at large rapidity but the uncertainty is even larger than EPS09

Nuclear PDFs are still poorly known

We compared inclusive J/ψ from ALICE with prompt J/ψ data from LHCb

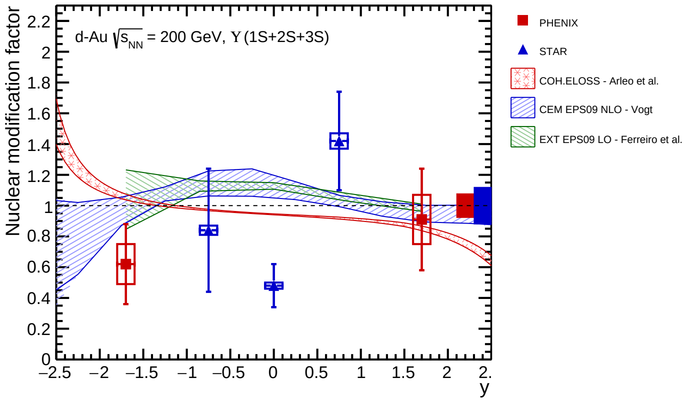
LHCb has measured $R_{\mathrm{pPb}}(y)$ separately for prompt, b decays and inclusive J/ψ

R_{pPb}	$-4.0 < y < -2.5$	$2.5 < y < 4.0$
Prompt J/ψ	$0.93 \pm 0.03 \pm 0.05 \pm 0.05$	$0.62 \pm 0.01 \pm 0.02 \pm 0.03$
J/ψ from b	$0.98 \pm 0.06 \pm 0.07 \pm 0.08$	$0.83 \pm 0.02 \pm 0.04 \pm 0.07$
Inclusive J/ψ	$0.93 \pm 0.03 \pm 0.05 \pm 0.05$	$0.63 \pm 0.01 \pm 0.03 \pm 0.03$

The contribution from b decays does not affect significantly R_{pPb} integrated over p_T

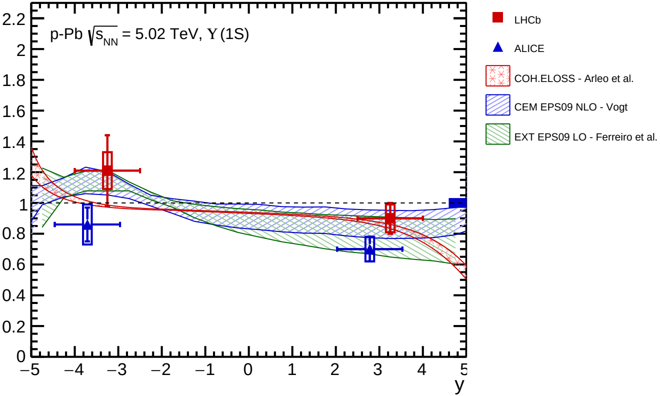
However the b decays fraction grows with p_T ($\sim$ 30% at 15 GeV) so the effect would be larger when looking at $R_{\mathrm{pPb}}(p_T)$ at large p_T

Upsilon $R_{\mathrm{dAu}}(y)$: RHIC



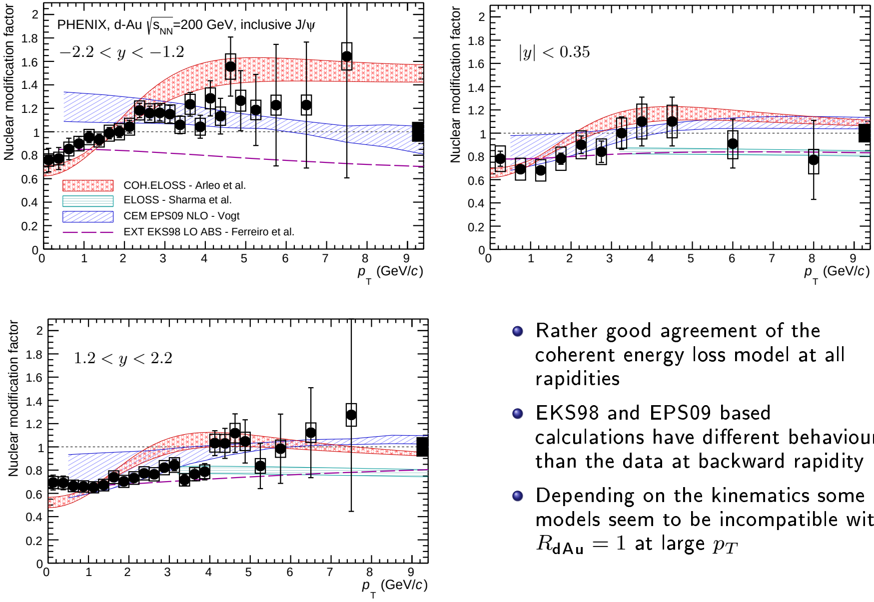
- Models based on nPDFs have a smaller uncertainty than for J/ψ because of the larger Q^2 ...
- ... but the experimental uncertainties are larger
- All the models show a similar agreement with data
- Would be difficult for any model to fit all the data points

Upsilon $R_{\mathrm{pPb}}(y)$: LHC



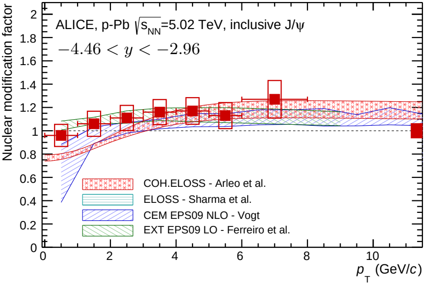
- Only one point at backward and forward rapidity from both ALICE and LHCb
- The central value of ALICE is always below LHCb
- All the models are compatible with data

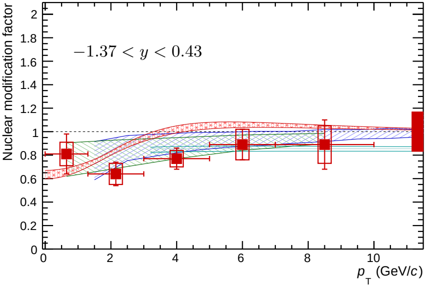
$R_{\mathrm{dAu}}(p_T)$: RHIC

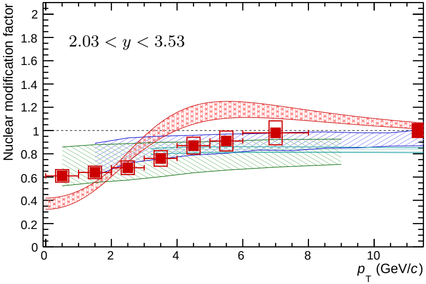


- Rather good agreement of the coherent energy loss model at all rapidities
- EKS98 and EPS09 based calculations have different behaviour than the data at backward rapidity
- Depending on the kinematics some models seem to be incompatible with $R_{\mathrm{dAu}} = 1$ at large p_T

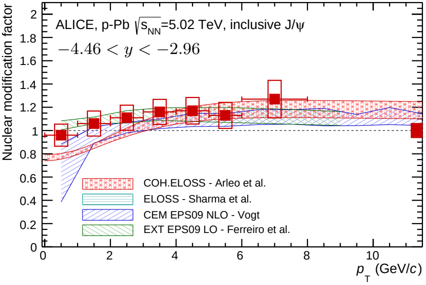
$R_{\text{pPb}}(p_T)$: LHC

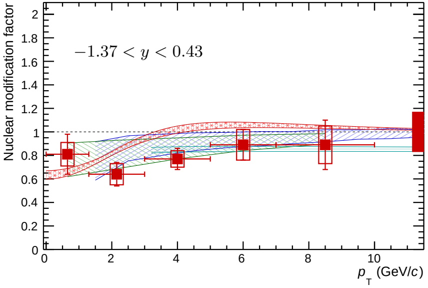


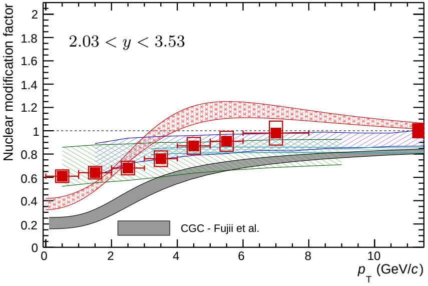




- All models other than coherent energy loss show a reasonable agreement with data
- Coherent energy loss predicts a too strong variations with p_T at forward rapidity (and also slightly at mid-rapidity)







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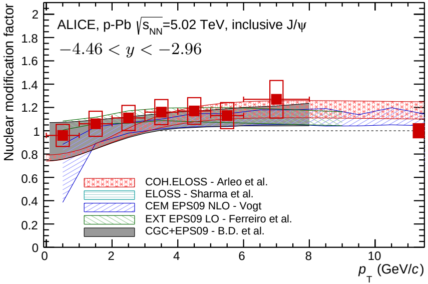
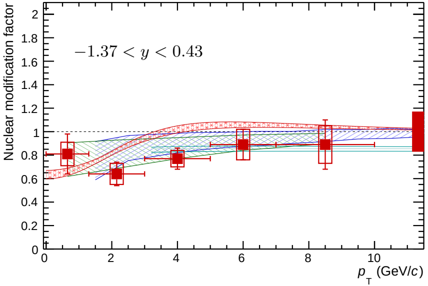
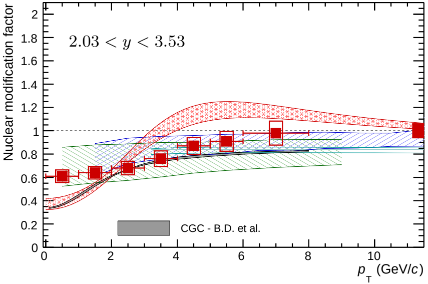
$R_{\mathrm{pPb}}(p_T)$: LHC







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Forward to backward ratio

In addition to R_{pA} one can also study the forward to backward ratio R_{FB}

$$R_{\mathsf{FB}}(y) = \frac{R_{\mathsf{pA}}(y)}{R_{\mathsf{pA}}(-y)}$$

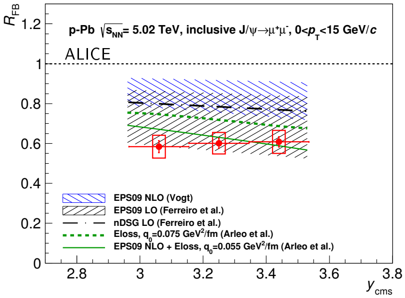
One advantage of this observable is that it is not necessary to rely on a interpolation to get the pp cross section at 5 TeV

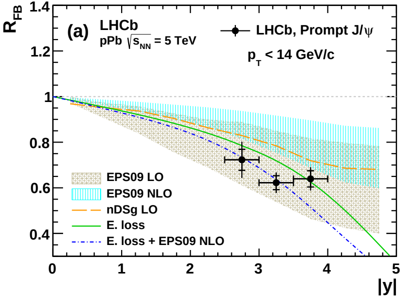
This uncertainty is normally included in the experimental uncertainties

Drawbacks:

- An asymmetric detector coverage in y means reduced statistics
- It is possible for models to describe R_{FB} even if they don't describe R_{pA}
- Comparison of very different domains (e.g. shadowing/anti-shadowing for nPDFs)

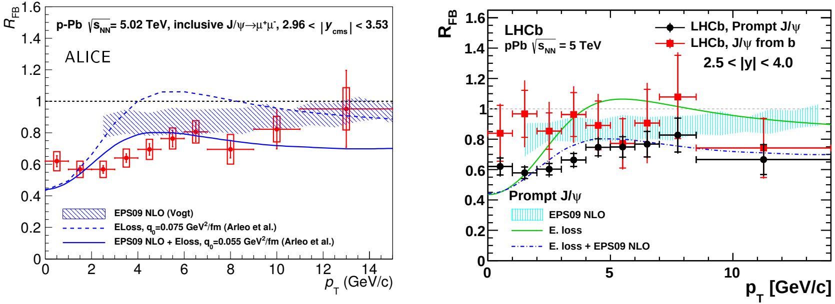
$R_{\mathrm{FB}}(y)$: LHC





- EPS09 NLO based calculation seems to be incompatible with data
- EPS09 LO based calculation is compatible with data but has a large uncertainty
- Coherent energy loss: slope seems too steep compared to ALICE data

$R_{\mathrm{FB}}(p_T)$: LHC



- EPS09 NLO based calculation compatible with data for not too small p_T
- Coherent energy loss: too strong variation with p_T.

Difficult to discriminate between the models based on comparison with data: several models can be compatible with experiments, some don't have predictions for all energies or observables, ...

Main models:

- Collinear factorization: generally compatible with data but very large uncertainties. Need much better constrained nuclear PDFs to conclude
- Coherent energy loss: overall quite good description of the data when only this effect is taken into account. What about mixing with other effects (e.g. nPDFs are supposed to be universal)? Careful analysis needed
- Absorption: expected to be negligible at high energy

A better understanding of the mechanism for bound state formation would be helpful:

- Coherent energy loss assumes long formation times
- Absorption assumes that the bound state is formed in the nuclear medium