Hard processes in pA collisions

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Why hard processes in pA collisions?

Hard processes

- Great variety
  - W/Z, Drell-Yan, photons, (b-quark) jets, light/heavy hadrons. . .
- Well known in QCD
  - computed in perturbation theory and systematically compared to pp
  - caveat: hadron production (especially quarkonia) less understood

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pA collisions

- 'Simple' medium: static, known density profile
- Easier measurements (than in AA) due to smaller underlying event
- Small influence of the produced medium on hard processes
  - less true at LHC, less true for (excited) quarkonia

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In short

Closest to (theory/exp) QCD studies in pp, yet with a heavy-ion touch

Flow of the talk

From pp to the heavy-ion touch

- pp/pA collisions in collinear factorization
  - leading twist nPDF analyses
  - observables: W/Z, Drell-Yan, jets
- Beyond collinear factorization: multiple scattering in nuclei
  - Momentum broadening and induced gluon radiation
  - observables: light and heavy-quark hadrons
- Beyond Glauber model
  - event activity in presence of a hard process

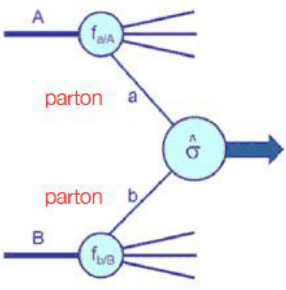
Collinear factorization in pp collisions

Take a large momentum transfer process in pp, scale $Q(= p_\perp, M) \gg \Lambda_{\rm QCD}$

$$\text{pp} \to (\text{h}, \gamma, \text{Z}, \dots) + \text{X}$$

Factorization = approximation

$$\frac{\mathrm{d}\sigma_{\rm pp}}{\mathrm{d}y\ \mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1\ f_i^p(x_1, \mu) \int \mathrm{d}x_2\ f_j^p(x_2, \mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(Q, \mu')}{\mathrm{d}y\ \mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\rm p}^n}{Q^n}\right)$$



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- Predictive power
  - long distance physics encoded into PDF (and FF) which are universal
    - a proton is a proton is a proton (no matter how you struck it)
  - short distance calculable in perturbation theory
- Power corrections due to long range soft gluon interaction
  - process dependent, not universal

What about pA collisions ?

Collinear factorization in pA collisions

A nucleus as an ordinary hadron

$$\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}y\ \mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1\ f_i^p(x_1, \mu) \int \mathrm{d}x_2\ f_j^A(x_2, \mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(Q, \mu')}{\mathrm{d}y\ \mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{A}}^n}{Q^n}\right)$$

- Universal (leading twist) nuclear PDF
  - could be probed in various processes and collision systems (eA, γA, pA)
- New scale for power corrections ($\Lambda_{\mathrm{A}} > \Lambda_{\mathrm{p}}$)
  - higher twist processes enhanced in pA collisions (wrt pp)
  - specific processes could spoil the extraction of (universal) nPDF

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What to expect for f_i^A ? How does it compare to f_i^p ?

PDF of a nucleus

In a super dilute nucleus: f^A given by incoherent sum over nucleon PDF

$$f_i^A = Z\ f_i^p + (A - Z)\ f_i^n$$

$$\mathrm{d}\sigma_{\mathrm{pA}} = Z\ \mathrm{d}\sigma_{\mathrm{pp}} + (A - Z)\ \mathrm{d}\sigma_{\mathrm{pn}} \simeq A\ \mathrm{d}\sigma_{\mathrm{pp}} \Rightarrow R_{pA} \equiv \frac{1}{A}\ \frac{\mathrm{d}\sigma^{\mathrm{pA}}}{\mathrm{d}\sigma^{\mathrm{pp}}} \simeq 1$$

PDF of a nucleus

In a super dilute nucleus: f^A given by incoherent sum over nucleon PDF

$$f_i^A = Z\ f_i^p + (A - Z)\ f_i^n$$

In practice, distance between nucleons much smaller than coherence time at high energy

$$\ell_c \sim \frac{E}{Q^2} \sim \frac{1}{2m_N x_2} \gg 1\ \text{fm}$$

- Onset of nuclear shadowing at small $x_2 \lesssim 10^{-1}$
- Working assumption

$$f_i^A = Z\ R_i^{p/A}\ f_i^p + (A - Z)\ R_i^{n/A}\ f_i^n$$

  - nPDF ratios $R_i^{p/A}(x, Q^2)$ assumed to be universal
  - extracted from (N)LO global fit analysis based on DGLAP evolution

[EKS98, nDS, HKN... EPS09, DSSZ, nCTEQ15, KA15]

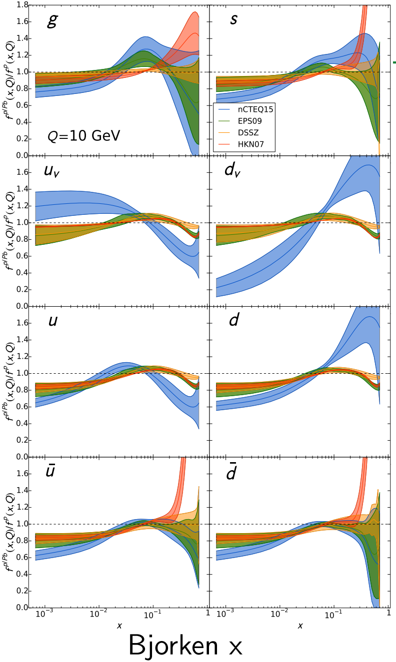
nPDF ratios

- Poor constraints from data, especially at small-x and in the gluon channel
- Strong sensitivity on the parametrization at low scale

  [Helenius Paukkunen Armesto, 1606.09003**]**

- Crucial need to use LHC pPb data to reweight nPDF

  [Paukkunen Zurita, 1402.6623**]**



[nCTEQ15, 1509.00792**]**

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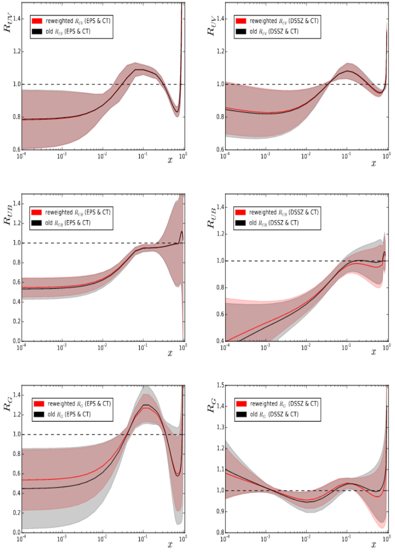

[Armesto et al. 1512.01528**]**

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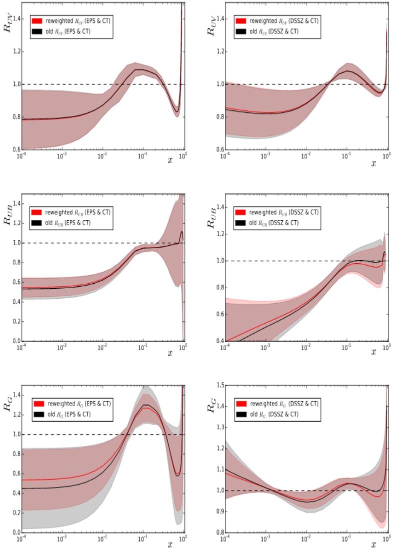
What would be the best processes ?



Probing leading twist nPDF at the LHC

Ideally, looking for processes sensitive to PDF only

Some requirements (not necessary, but preferable):

- Sufficiently large scale: $Q \gg Q_s \simeq$ few GeV
  - avoid non-linear evolution and large power corrections
- ...but not too large to keep some sensitivity
  - $f^A/Af^p \simeq 1$ in the 'Bjorken limit' ($Q^2 \to \infty$ at fixed x)
- Integrated over all $p_\perp$ (or focus on $p_\perp \gg Q_s$)
  - avoid multiple scattering effects e.g. Cronin effect
- Favor color-neutral probes
  - avoid coherent energy loss

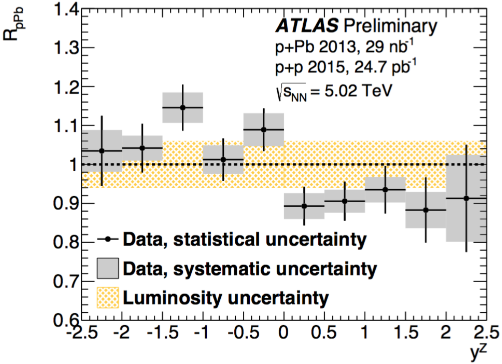
Best candidates

Weak bosons, Jets, Drell-Yan

Weak bosons

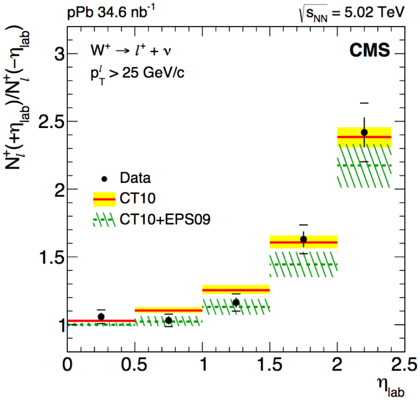
W/Z measured in pPb (and PbPb) by ALICE, ATLAS & CMS

[motivated in Paukkunen Salgado, 1010.5392]



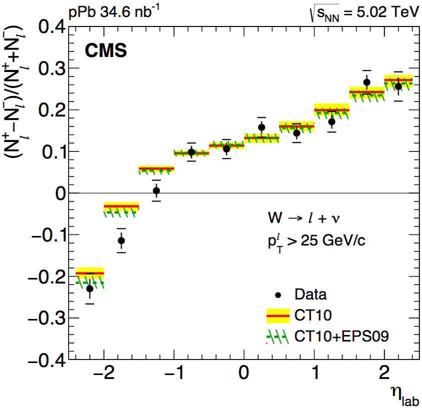
- R_{pA} of Z boson presented by ATLAS
- Slight suppression at forward rapidity (smaller x in Pb)

Weak bosons



- W boson rapidity asymmetry measured by CMS
  - sensitive to $R_d^A(x \sim 10^{-3})$ / $R_u^A(x \sim 10^{-1})$ (W^+ channel)
  - data favor CT10×EPS09
  - also measured by ATLAS

Weak bosons



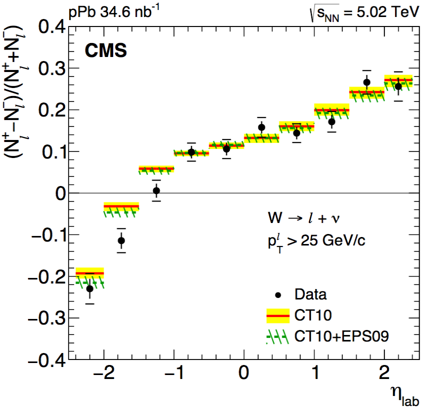
Lepton charge asymmetry

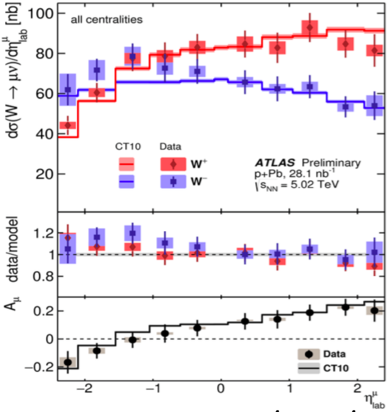
$$\frac{N_\ell^+ - N_\ell^-}{N_\ell^+ + N_\ell^-}$$

- Tension at negative $\eta \to$ possible flavour dependence $R_u^A \neq R_d^A$
  - Isospin symmetry $R_u^A = R_d^A$ often assumed due to lack of data
  - pPb Run 2 should tell
- Simple scaling relates pPb and PbPb cross sections at $y < 0$

[FA Chapon Paukkunen, 1509.03993]

Weak bosons





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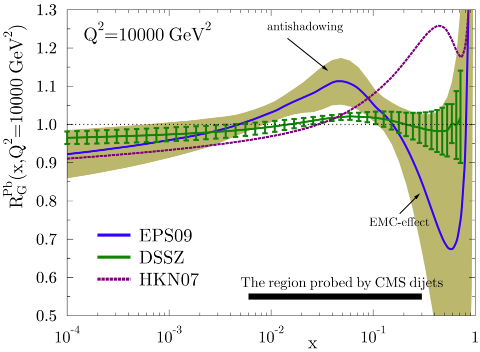
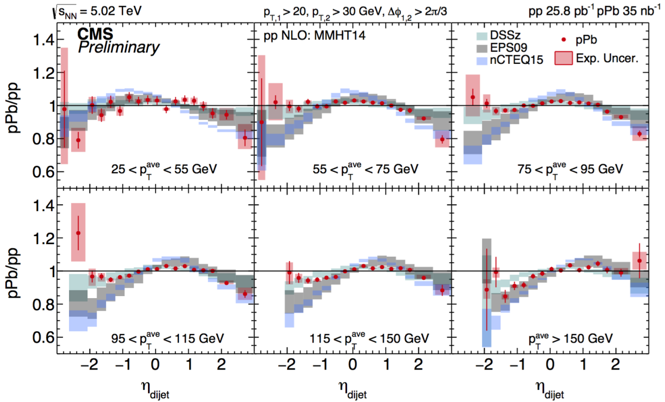
Jets



- Jets in pPb at LHC sensitive to (gluon & valence quark) nPDF, in the vicinity of the anti-shadowing region

[Paukkunen Eskola Salgado, 1408.4563]

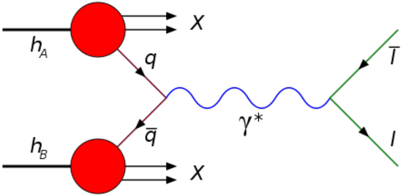
Jets



- Tight constraints brought by CMS dijets
- nPDF effects favored. . . yet no single set reproduces whole dataset
  - crucial data to further constrain x & Q^2 dependence of nPDF
  - other effects at the lowest Q^2 ?

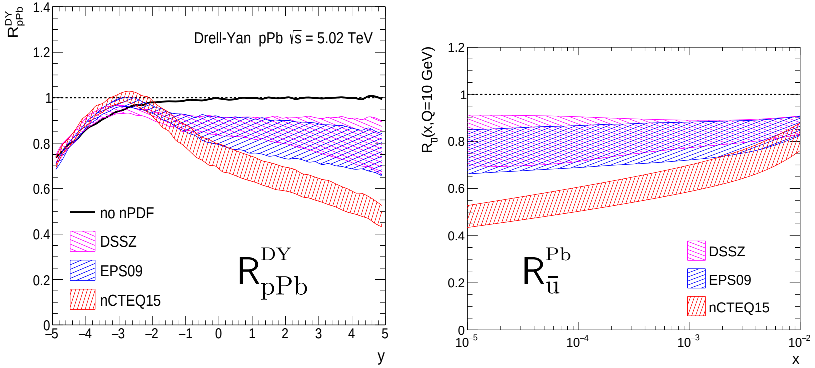
Drell-Yan

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
- Colorless final state at LO
  - small/negligible energy loss in cold matter
- Very well understood in QCD
  - better than light or heavy hadrons

Drell-Yan



[FA Peigné, 1512.01794]

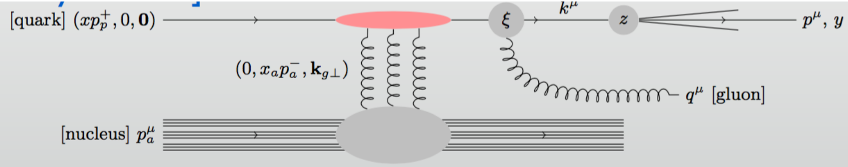
- NLO calculations using DSSZ, EPS09 and nCTEQ15
  - should reveal sea quark shadowing at low scale
  - could be computed in the saturation formalism too
- To be measured by LHCb at fwd/bwd rapidity in pPb Run 2
  - reasonable statistics expected

Beyond leading-twist nPDF

What is not included in leading-twist nPDF ?

- Non-linear QCD evolution
  - all nPDF global fits based on (linear) DGLAP evolution
- Momentum broadening of the fast parton in the nucleus

. . . taken into account in the saturation formalism (CGC)



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. . . taken into account in the saturation formalism (CGC)

- Based on JIMWLK or BK (non-linear) evolution
- Rescattering effects resummed in the dipole formalism
- Based on $k_\perp$ factorization
  - working assumption since $k_\perp$ factorization not proven in QCD
- Several (semi)hard processes investigated
  - light hadrons, open heavy-flavour hadrons, quarkonia, photons. . .

Light hadrons

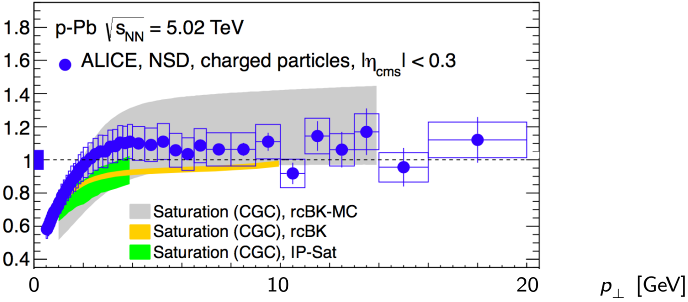
Often used is 'dilute-dense' (hybrid) formalism to model pA collisions

$$\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}y\ \mathrm{d}p_\perp} = \sum_{i=q,g} \int \frac{\mathrm{d}z}{z^2}\, \mathrm{d}x_1\ f_i^p(x_1,\mu)\ \mathcal{F}_{x_g}^{\mathrm{F,A}}(k_\perp)\ D_{h/i}(z,\mu') + \mathcal{O}\left(\alpha_s^2\right)$$

- f_i^p and $D_{h/i}$: ordinary (collinear) PDF and FF – obey DGLAP
- $\mathcal{F}_{x_g}^{\mathrm{F,A}}$: unintegrated gluon PDF – obey BFKL, BK, JIMWLK

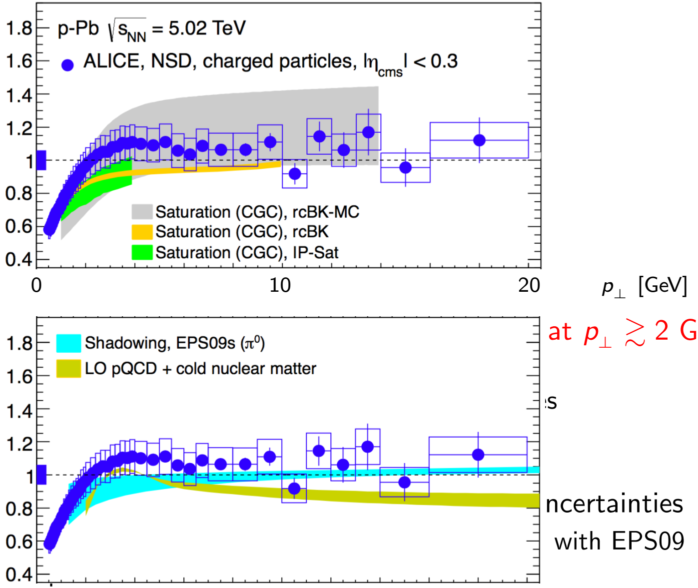
- In practice, many different implementations and working assumptions, leading to slightly different results
- Important recent development on NLO cross section
  - Issue of negativity on the way to be solved

Light hadrons



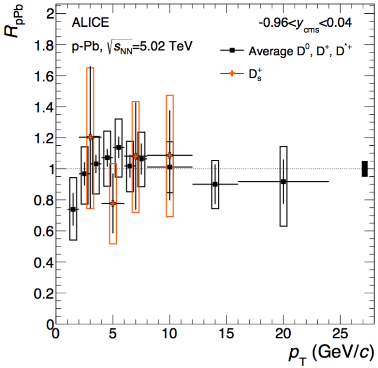
- Mid-rapidity light hadrons show almost no suppression at $p_\perp \gtrsim 2$ GeV but depletion below
  - possible shadowing/saturation at the smallest $p_\perp$ values
  - depletion due to $p_\perp$ broadening
  - $R_{pA} < 1$ also expected due to scaling of soft processes
- Agrees with some CGC calculations, yet large exp/th uncertainties
  - tendency for less suppression than in theory – also true with EPS09
  - what is expected at 8 TeV ?

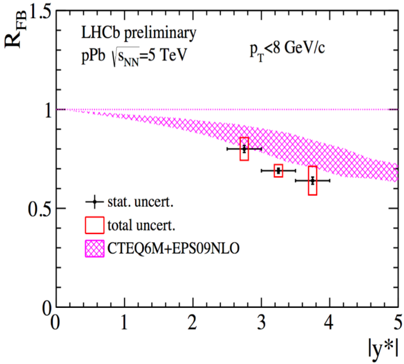
Light hadrons



- Mid-r … at $p_\perp \gtrsim 2$ GeV
  but d…
  - p… …s
  - c…
  - R…
- Agree… …ncertainties
  - t… with EPS09
  - v…

Heavy hadrons – D meson

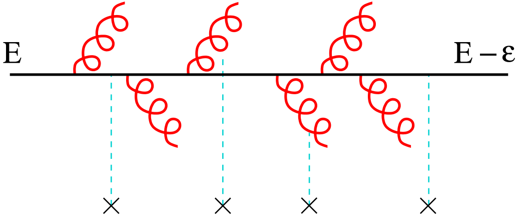




- Little or no suppression at mid-rapidity **[ALICE 1605.07569]**
- forward/backward rapidity asymmetry reported by LHCb **[LHCb-CONF-2016-003]**

Energy loss-es

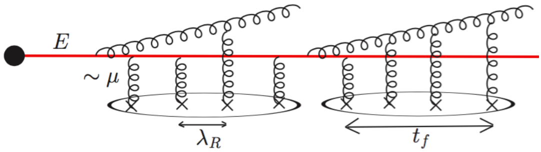
On top of momentum broadening, parton multiple scattering in nuclei induces gluon radiation → energy loss in cold nuclear matter



- presently not taken into account in CGC formalism

Initial/final state energy loss

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



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

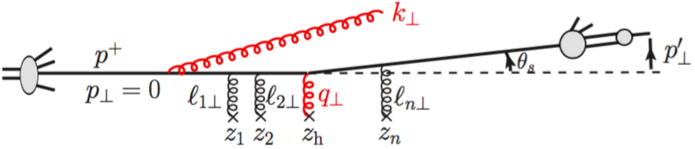
- Energy dependence at most logarithmic
- Best probed in
  - Hadron production in nuclear semi-inclusive DIS
  - Drell-Yan in pA collisions at low energy
  - Jet in QGP
- Should be negligible in pA at the LHC
  - fractional energy loss $\Delta E_{\rm LPM}/E \ll 1$
  - explains why weak bosons and jets almost unmodified in pPb

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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[FA Peigné Sami 1006.0818]

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

- Predicted from first principles
  - Same spectrum obtained in the opacity expansion and in dipole model

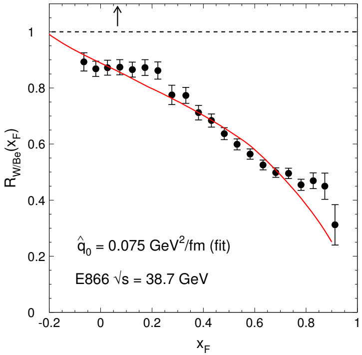
[FA Peigné Kolevatov, 1402.1671, Peigné Kolevatov 1405.4241]

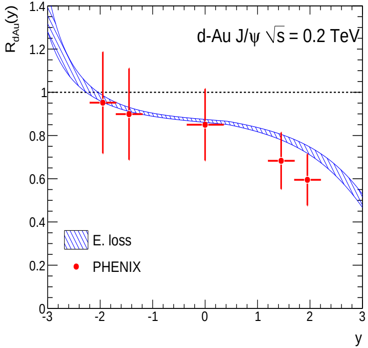
[Liou Mueller 1402.1647, Munier Peigné Petreska 1603.01028]

- 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 $M_\perp \gg \sqrt{\hat{q}\ L} \sim Q_s$
  - no jet suppression in pA

Quarkonia

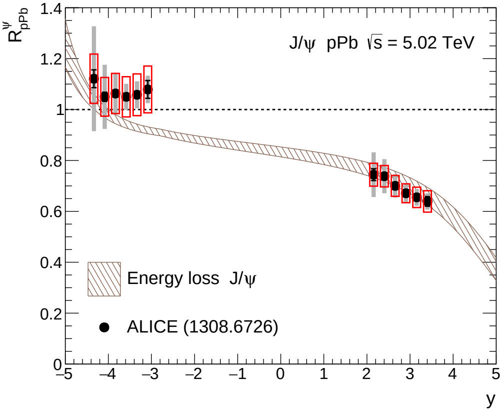
Simple coherent energy loss model able to solve the longstanding issue of J/ψ forward suppression pA data **[FA Peigné, 1212.0434]**





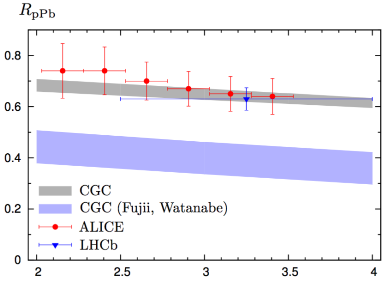
- Good agreement with all (E866, PHENIX. . .) quarkonium pA data
  - Wide range in $\sqrt{s}$ and rapidity
- no nPDF calculation can explain these data

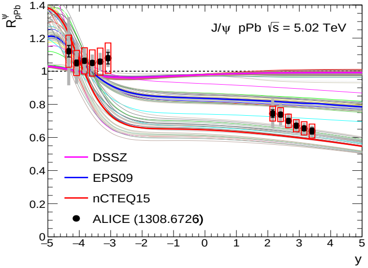
Quarkonia



- Predictions in excellent agreement with ALICE (and LHCb) data
  - especially the trend at large y

Quarkonia





- Updated CGC+CEM calculations now agree with data
  - Also attempts within CGC+NRQCD **[Ma Venugopalan Zhang, 1503.07772]**
- Possible agreement with some nPDF sets too

Event activity in pA

Two ways to investigate the nuclear dependence in pA

- Good old way
  - pA minimum bias collisions on various nuclei
  - easy at fixed target facilities
  - no look at extreme/unusual pA events

- The LHC way
  - bin events in terms of event activity (multiplicity, energy)
  - hope that the event activity is correlated with centrality

Event activity in pA

Factorization theorem appropriate for sufficiently inclusive observables

$$\text{p A} \to (\text{hard process}) + X \qquad (X : \text{not measured})$$

When looking at the event activity, totally different process

$$\text{p A} \to (\text{hard process} + \text{specific event activity}) + X$$

- No reason to expect factorization theorem to apply
- Normalizing with pp becomes dubious since two different processes are compared
- sensitive to multiparticle (soft) dynamics
  - difficult to compute, especially in presence of a hard process

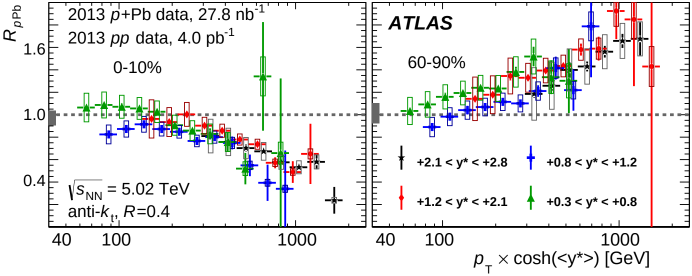
Event activity in pA

Most of the time hard process and event activity factorize

- large 'reservoir' of energy, typically $x_{1,2} \sim Q/\sqrt{s} \ll 1$
- in presence of large rapidity separation

...otherwise such correlations between hard process and underlying activity could be responsible for significant deviations on R_{pA}

Event activity in pA



- Event activity 'bin migration'
  - More hard processes with small event activity (thus less with large)
- Interesting in itself
  - understand the origin of such large hard–soft correlations
  - constraints on MC
  - already many studies on the topic !

[Perepelitsa Steinberg 1412.0976 **Armesto Gülhan Milhano** 1502.02986**]**

[McGlinchey Nagle Perepelitsa 1603.06607 **Kordell Majumder** 1601.02595**]**

Summary

- Hard processes in pA reveal many facets of QCD processes
  - shadowing/saturation, momentum broadening, radiative energy loss. . .
- Impressive data collected at LHC and earlier. And more to come !
- A challenge for theorists: clarify the role of each process on various observables and at different energies
  - still a long way to go. . . but very encouraging progress already made
- pA is exciting in itself.

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- A challenge for theorists: clarify the role of each process on various observables and at different energies
  - still a long way to go...but very encouraging progress already made
- pA is exciting in itself.

  Paraphrasing Feynman:

  > *"pA physics is like sex: sure, it may give some practical results in heavy-ion collisions, but that's not why we do it."*

Summary

- Hard processes in pA reveal many facets of QCD processes
  - shadowing/saturation, momentum broadening, radiative energy loss...
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Merci pour votre attention !