Probing cold nuclear matter effects with quarkonium and DY production

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Outline

- Probing fully coherent energy loss with quarkonia at all energies
- Probing LPM energy loss with DY at fixed-target energies
- Probing nPDF with DY at LHC
- Probing transverse momentum broadening with quarkonia and DY

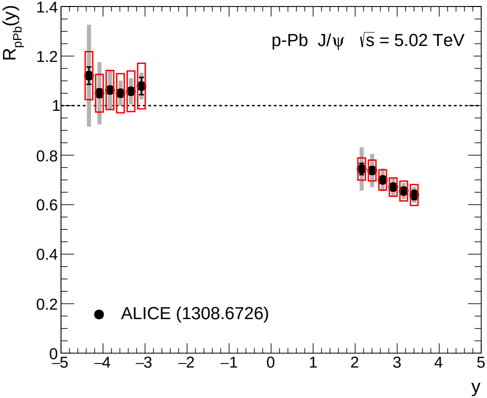
References

- FA, S. Peigné, 1204.4609, 1212.0434
- FA, C. Naïm, S. Platchkov, 1810.05120
- FA, S. Peigné, 1512.01794
- FA, C. Naïm, in preparation

Context

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

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



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- No (or modest) nuclear modification at backward rapidity

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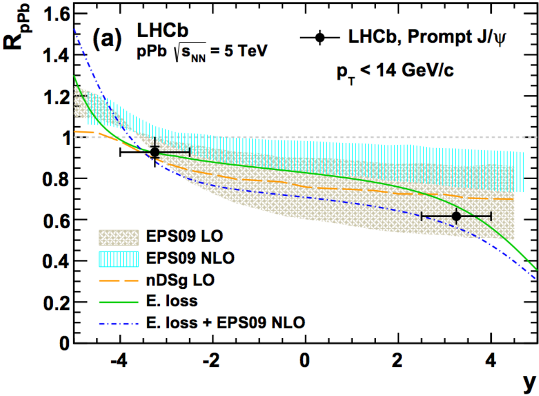

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- Shadowing of nuclear parton distribution functions (nPDF)
- Coherent energy loss in nuclear matter
- ...or both (not mutually exclusive)

Note: nPDF calculations fail to reproduce J/ψ suppression pA data due to lack of x_2 scaling $\rightarrow$ another effect at work to be understood

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Possible exp

- Shadow
- Coherer
- . . . or b

:)

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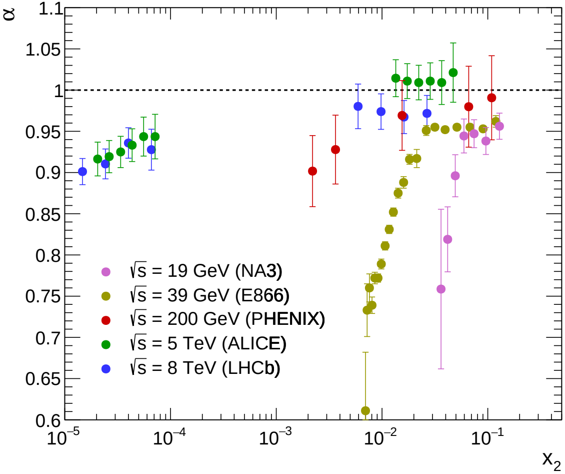

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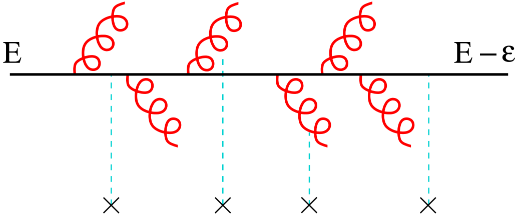
Issue

- Large uncertainties do not allow for precise predictions of nPDF effects on J/ψ at LHC (even more true with EPPS16)
- Then, how to disentangle the effects of nPDF v. energy loss?

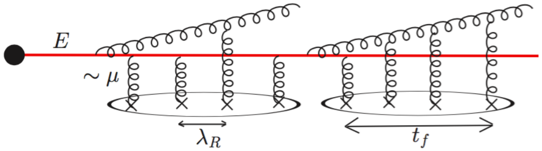
Energy loss-es

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 $t_f \lesssim L$



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

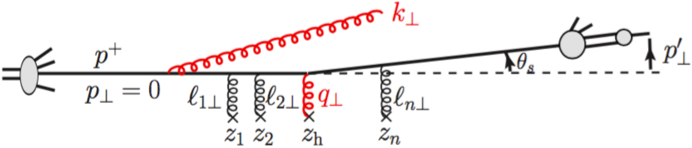
- Energy dependence at most logarithmic
- Best probed in
  - Hadron production in nuclear semi-inclusive DIS
  - Drell-Yan in pA collisions at low energy
- Should be negligible in pA at the LHC
  - fractional energy loss $\Delta E_{\text{LPM}}/E \sim 1/E \ll 1$
  - . . . could play a role in fixed target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

Fully coherent energy loss

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

[FA Peigné Sami 1006.0818]

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



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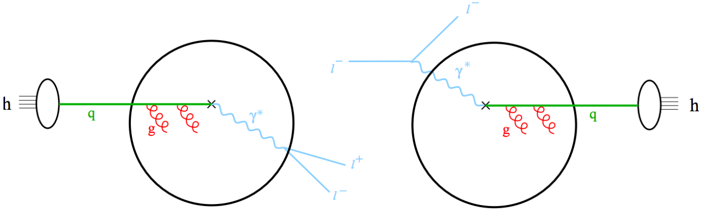
- Important at all energies, especially at large rapidity
- Needs color in both initial & final state
  - no effect on W/Z nor Drell-Yan, no effect in DIS
- Hadron production in pA collisions
  - applied to quarkonia
  - light hadrons currently investigated **[FA Peigné, in preparation]**
- Power suppressed: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

Parton energy loss in hard processes



Drell-Yan process : $\text{hA} \to \ell^+\ell^- + \text{X}$

- Initial state LPM energy loss

Hadrons in SIDIS : $\text{eA} \to \text{e} + \text{h} + \text{X}$

- Final LPM energy loss

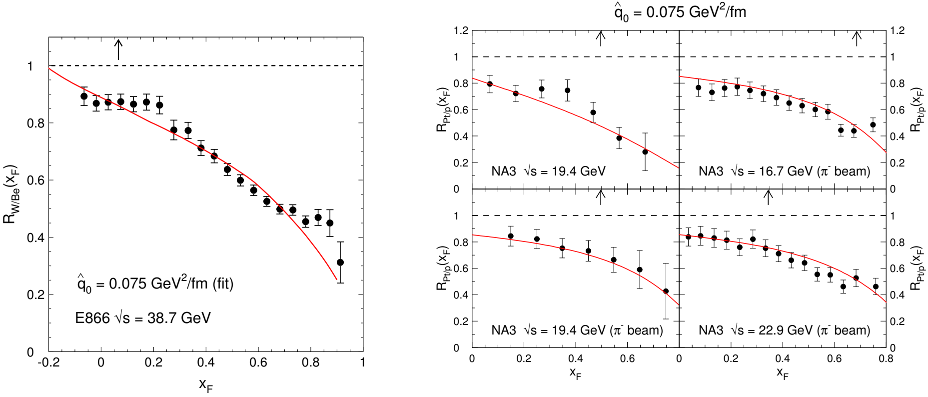
Hadrons in hA : $\text{hA} \to \text{q/g}(\to \text{h}') + \text{X}$

- Initial/final state interference fully coherent energy loss

Probing fully coherent energy loss with quarkonia

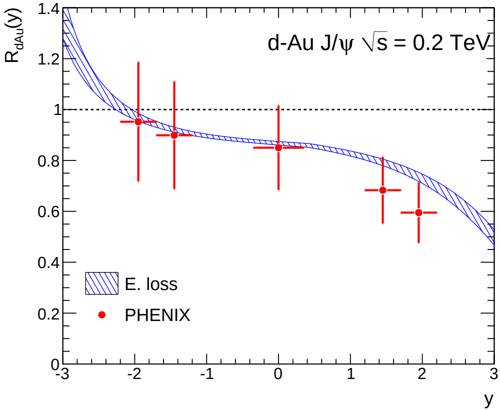
Comparing to low energy pA and πA data

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



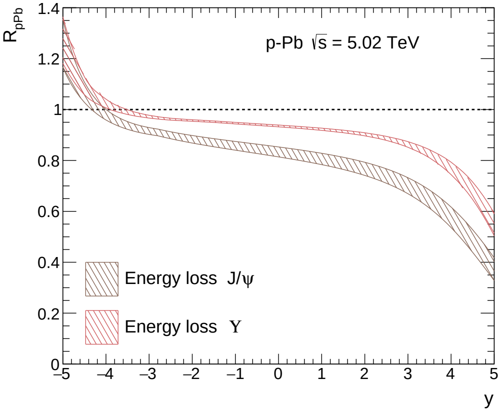
- Good agreement with E866, NA3, NA60, HERA-B data
- no nPDF global fit can explain these data

RHIC predictions ($\sqrt{s} = 200$ GeV)



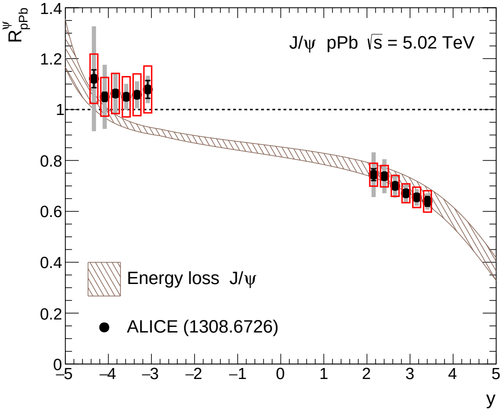
- Good agreement for R_{pA} vs rapidity
- Small uncertainty coming from the variation of the pp cross section and the transport coefficient

LHC predictions ($\sqrt{s} = 5$ TeV)



- 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

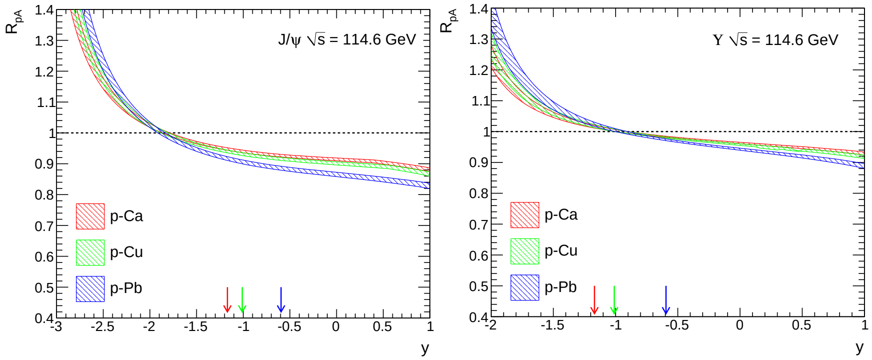
LHC predictions ($\sqrt{s} = 5$ TeV)



- Very good agreement with ALICE and LHCb results, despite large uncertainty on normalization
- Data at $y \gtrsim 4$ would be helpful

LHC predictions (fixed-target)

[FA Peigné, 1504.07428]



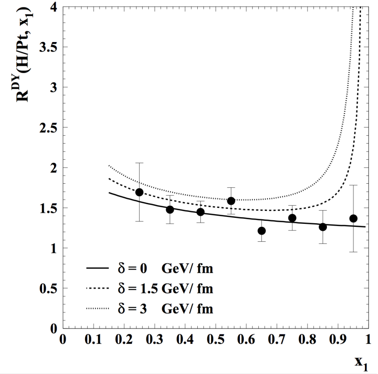
- Suppression could already be seen even at $y = 1$
- Enhancement (?) at negative rapidity
  - although beyond the validity domain of the model

Probing LPM energy loss with Drell-Yan

Probing LPM energy loss with Drell-Yan

- Drell-Yan is sensitive to LPM energy loss
  - sensitivity only at low energy !
  - COMPASS/E906 ideal in this respect

Naïm, Thu 5, 10:00



- NA3 data (1983!) allow to set constraints on the amount of $\hat{q}$

  [FA, hep-ph/0201066**]**

- More precise data on a large x_F range would help

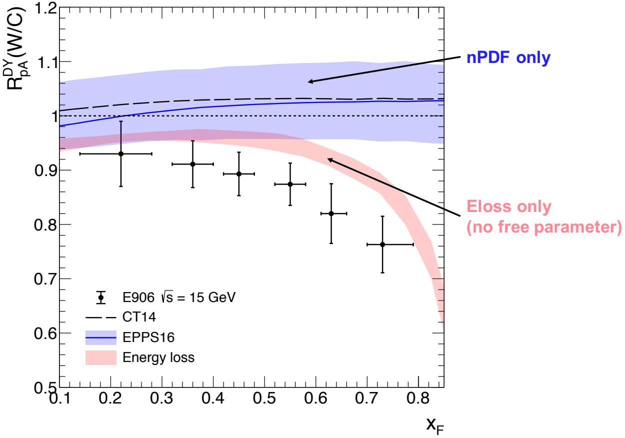
Probing LPM energy loss with Drell-Yan

- Drell-Yan is sensitive to LPM energy loss
  - sensitivity only at low energy !
  - COMPASS/E906 ideal in this respect — Naïm, Thu 5, 10:00

Recent analysis **[FA Naïm Platchkov, 1810.05120]**

- Drell-Yan cross section at NLO
- $\mathcal{P}(\epsilon)$: quenching weight related to the LPM gluon spectrum
- $\hat{q}_0 = [0.07 - 0.09]\,\text{GeV}^2/\text{fm}$ fixed $\rightarrow$ no free parameter in the model !

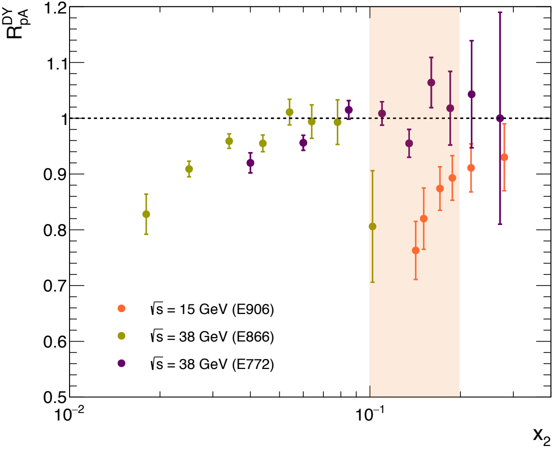
Comparison with E906 preliminary data



- Clear disagreement with nPDF expectations
- Qualitative agreement of energy loss shape and E906
  - First hints of energy loss in DY data

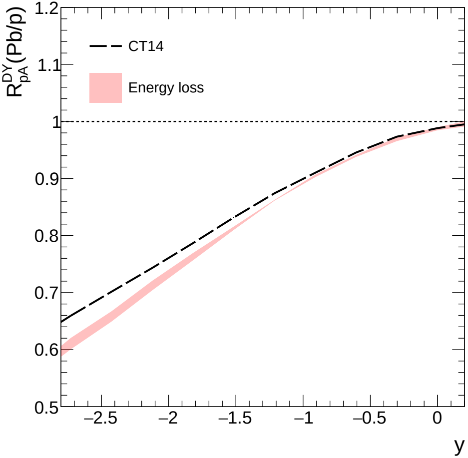
Violation of QCD factorization in DY

Factorization leads to x_2 scaling: $R_{pA}^{DY} = R_{pA}(x_2, \sqrt{s}) = R_{pA}(x_2)$



- No x_2 scaling between E866/E772 and E906 data
- Violation of QCD factorization in DY in pA collisions at low energy

LPM energy loss in DY at fixed-target LHC



- Visible effect ($\sim 10\%$) beyond isospin corrections
  - Almost as large as nPDF (nCTEQ) effects
- Need to be taken into account for clean nPDF extraction

Probing nPDF with Drell-Yan

Which processes ?

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

Particularly within easy reach in LHCb

- Heavy-quarkonia (ψ, Υ) **[Kusina et al. 1712.07024]**
  - including exciting states
- Open heavy-flavour **[Eskola et al. 1906.02512]**
  - D, B,... and non-prompt J/ψ
- Drell-Yan at rather low mass $M = \mathcal{O}(10 \text{ GeV})$ **[FA Peigné, 1512.01794]**

What makes these observables & LHCb that interesting ?

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

Which processes ?

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

Problem: significant energy loss effects expected on all hadrons

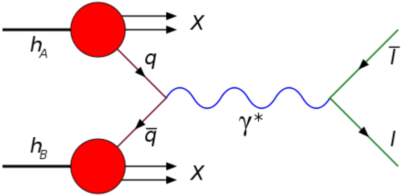
[FA Peigné, in preparation]

How to reliably extract nPDF in pA collisions?

- Include energy loss effects in nPDF global fit analyses
  - Tempting, but ambitious (and vice versa)
- Focus on color neutral final states
  - Drell-Yan, weak bosons, diphotons
- Focus on color neutral initial state
  - Ultra-peripheral collisions — Goncalves, Fri 6, 10:35

Drell-Yan at LHC

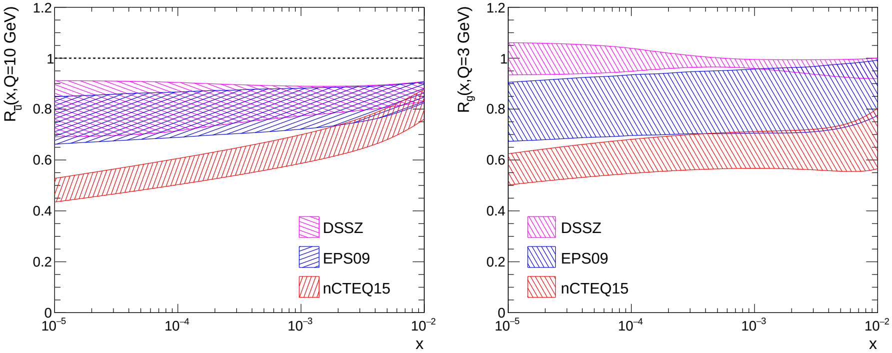
A golden probe of sea quark (and gluon) shadowing



- 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 hadron production

Shadowing effects on DY

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



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

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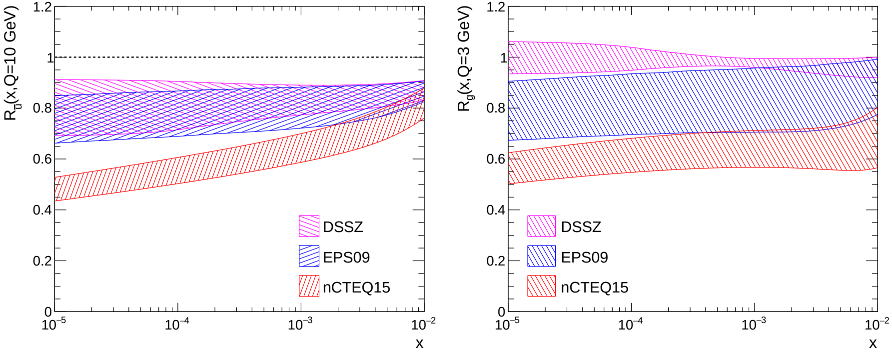
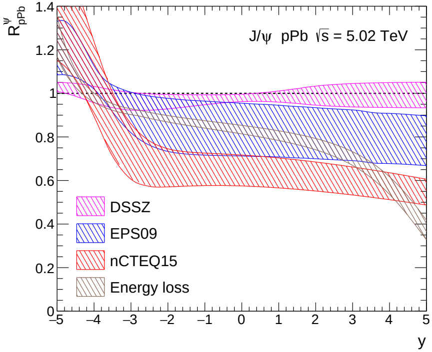
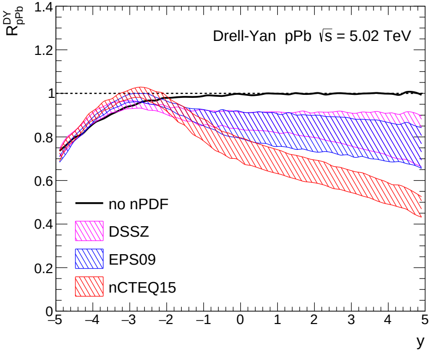


nPDF	$R^{\psi} \simeq R^{\mathrm{DY}}$	$\to \mathcal{R}^{\psi/\mathrm{DY}} \simeq 1$
Energy loss	$R^{\psi} < 1 \; ; \; R^{\mathrm{DY}} \gtrsim 1$	$\to \mathcal{R}^{\psi/\mathrm{DY}} < 1$

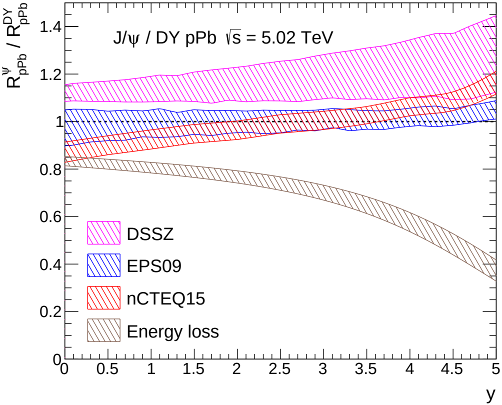
Comparing J/ψ and DY





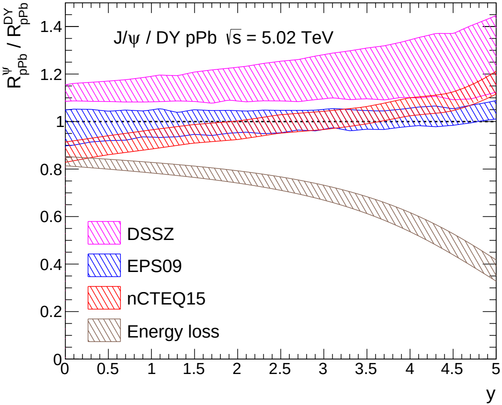
- As expected, qualitatively similar shadowing effects on J/ψ and DY using EPS09 and nCTEQ15 (unlike DSSZ)
- Noticeable isospin effects in the Pb fragmentation region ($y < 0$)

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

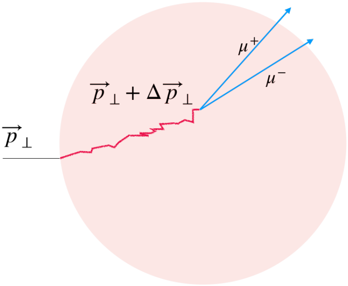
Double ratio $\mathcal{R}^{\psi/\mathrm{DY}}$



- This observable should clarify the respective role of both effects
- LHCb appears to be the best experiment in this respect
  - Around 1000 pairs in $2.5 < y < 4$ using $\mathcal{L}_{\text{int}} = 15\ \text{nb}^{-1}$

Probing multiple scattering with quarkonia and DY

$p_\perp$ broadening as a probe for transport coefficient



$$\Delta p_\perp^2 = \left\langle p_\perp^2 \right\rangle_{\mathrm{hA}} - \left\langle p_\perp^2 \right\rangle_{\mathrm{hp}} = \hat{q}(x) L$$

- At high energy

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

$p_\perp$ broadening phenomenology

Goals

- Independent extraction of the transport coefficient
- Check consistency between radiative energy loss and $p_\perp$ broadening
- Probe x dependence of the gluon distribution and saturation scale

World data analysis in hA collisions **[FA Naïm, in preparation]**

- From SPS to LHC
- Drell-Yan, J/ψ, Υ data
  - Probing different color states

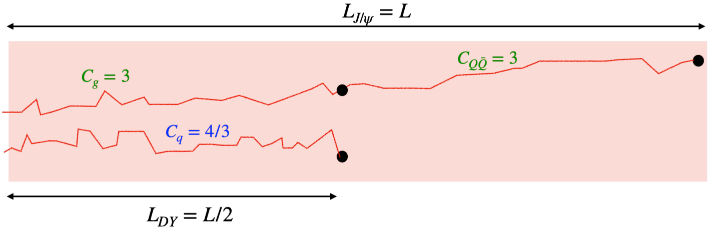
Data analysed

Exp.	Beam	$\sqrt{s}$ (GeV)	Process	A
NA3	p	19.3	J/ψ	Pt
	π^-	16.7/19.3/22.9		
	π^+	19.3		
NA10	π^-	16.2/23.1	DY	W
		23.1	J/ψ	
E772	p	38.7	DY	Ca, Fe, W
			Υ	Ca, Fe, W
RHIC	d	200	J/ψ	Au
ALICE	p	5020	J/ψ	Pb
LHCb	p	8160	J/ψ	Pb

Colorimetry

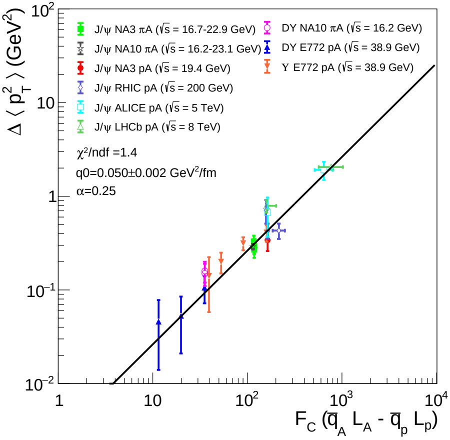
Broadening depends on initial and final Casimir color factors

$$\Delta p_\perp^2 = \frac{C_R + C_{R'}}{2N_c}\,(\hat{q}_A L_A - \hat{q}_p L_p)$$



Process	Collision	$C_R + C_{R'}$
Drell-Yan	π A	C_F
Drell-Yan	p A	C_F
Quarkonium	π A	$C_F + N_c$
Quarkonium	p A	$N_c + N_c$

Scaling



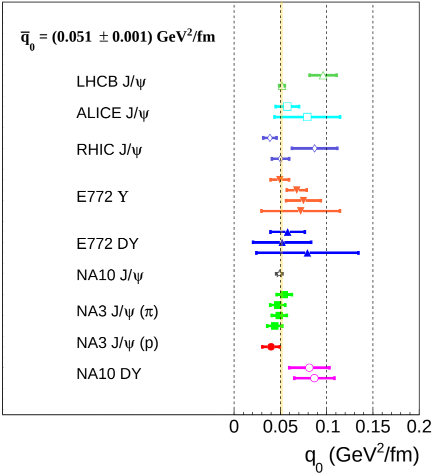
- Simple model used

$$\hat{q}_g(x) = \hat{q}_0 \left[\frac{10^{-2}}{x}\right]^{0.25}$$

- Linear scaling according to expectations
- Extraction of $\hat{q}_0$

$$\hat{q}_0 = 0.050 \pm 0.002\,\mathrm{GeV}^2/\mathrm{fm}$$

Extraction of transport coefficient for each experiment



- Good consistency within all data points
  - Universal transport coefficient
- Consistent with $\hat{q}$ from coherent energy loss

Summary

DY and quarkonia versatile tools to investigate cold nuclear matter effects

- Fully coherent energy loss successfully reproduce quarkonium world data in nuclear collisions
- LPM energy loss probed in DY production at low energy
  - First evidence in E906 data
- nPDF best probed in
  - color neutral final states (DY and weak bosons)
  - DIS or UPC events
- Multiple scattering and $p_\perp$ broadening
  - Scaling observed from low to high energy
  - Consistency between broadening and energy loss