Probing cold nuclear matter effects with Drell-Yan production in pA collisions

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Prospects on various aspects of the dilepton probe in hadronic physics

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Outline

- Probing initial-state energy loss with DY at fixed-target energies
- Probing nPDF with DY at LHC
- Probing transverse momentum broadening with quarkonia and DY

References

- FA, C. Naïm, S. Platchkov, 1810.05120
- FA, S. Peigné, 1512.01794
- FA, C. Naïm, 2004.07188

Context

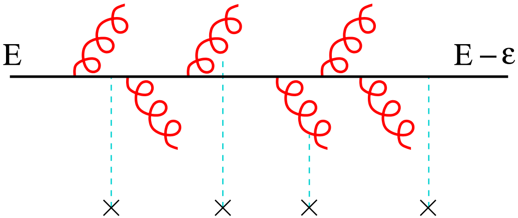
Various nuclear effects at work in J/ψ and DY production in pA collisions

Possible explanations

- Initial-state energy loss in nuclear matter (LPM regime)
- Nuclear parton distribution functions (nPDF)
- Fully coherent energy loss (FCEL) in nuclear matter – not in DY !
- . . . not mutually exclusive

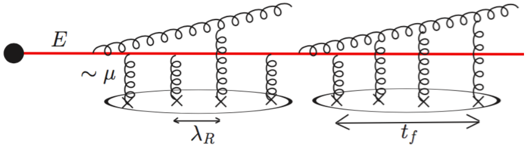
Energy loss-es

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 $t_f \lesssim L$



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

- 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 collisions at the LHC
  - fractional energy loss $\Delta E_{\mathrm{LPM}}/E \sim 1/E \ll 1$
  - Could play a role in fixed-target experiments

Fully coherent energy loss (FCEL)

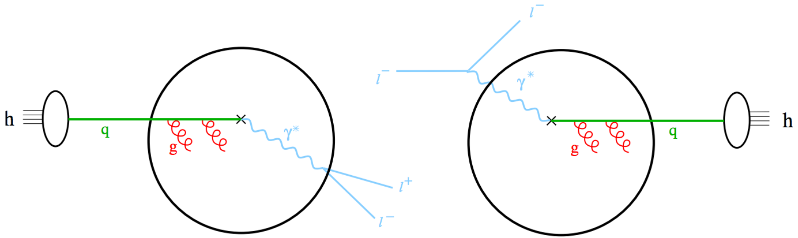
Interference between initial and final state: large formation time $t_f \gg L$

[FA Peigné Sami 1006.0818]

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

- 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, open heavy-flavour hadrons

Parton energy loss in hard processes



- **Drell-Yan process** : $\mathrm{hA} \to \ell^+\ell^- + \mathrm{X}$
  - Initial-state energy loss: LPM regime
- **Hadrons in SIDIS** : $\mathrm{eA} \to \mathrm{e} + \mathrm{h} + \mathrm{X}$
  - Final-state energy loss: LPM regime
- **Hadrons in pA** : $\mathrm{hA} \to \mathrm{q/g}(\to \mathrm{h}') + \mathrm{X}$
  - Initial/final state radiation interference: FCEL regime

Probing initial-state energy loss with Drell-Yan

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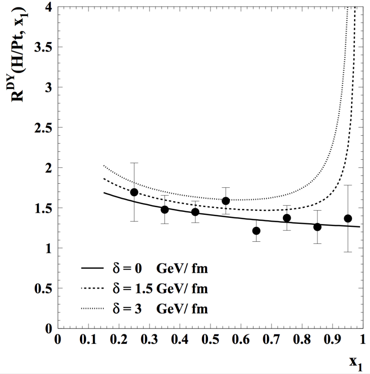
- Drell-Yan is sensitive to initial-state energy loss
  - sensitivity only at low energy
  - Low-energy experiments (e.g. COMPASS/E906) ideal in this respect



- 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

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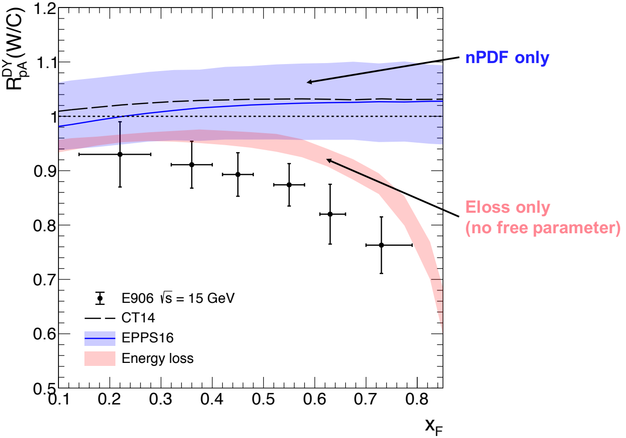
Recent analysis **[FA Naïm Platchkov, 1810.05120]**

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

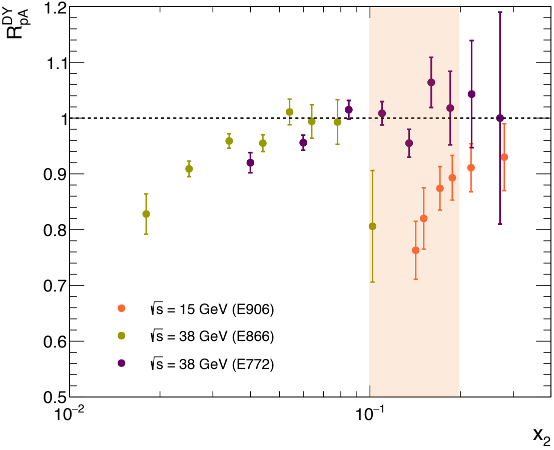
Comparison with E906 preliminary data



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

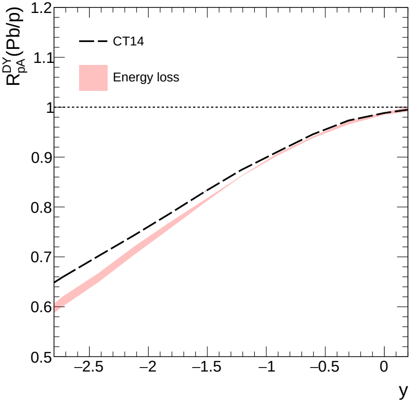
Violation of QCD factorization in DY

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



- 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

- 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]**

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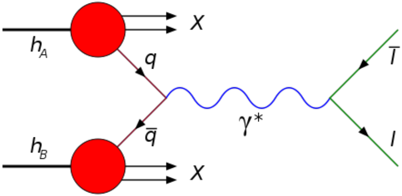
Problem: significant energy loss effects expected on all hadrons

☞ Strong case for dilepton production !

Drell-Yan at LHC

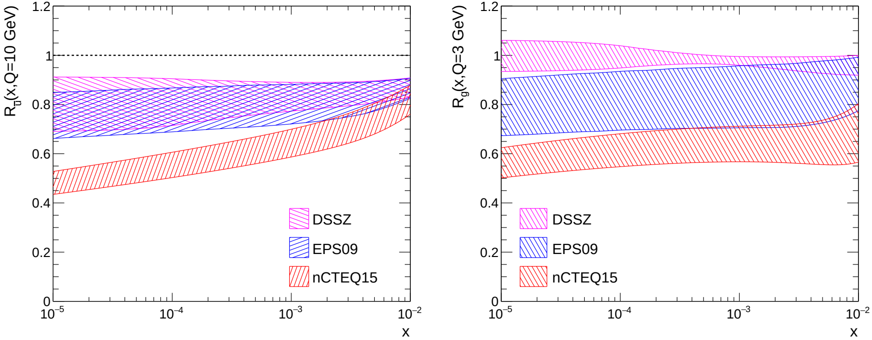
A golden probe of sea quark (and gluon) shadowing



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

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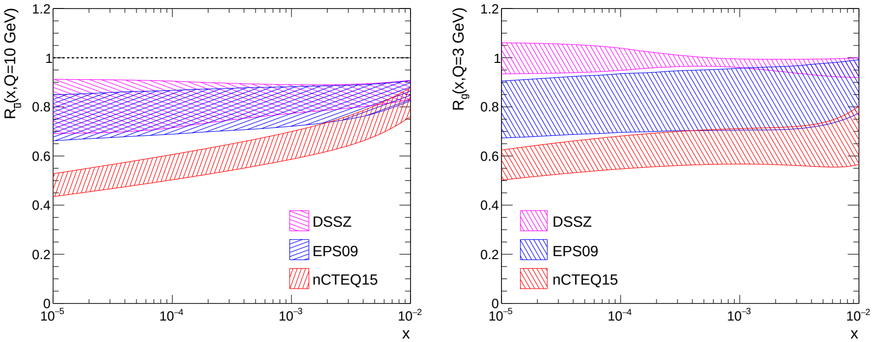
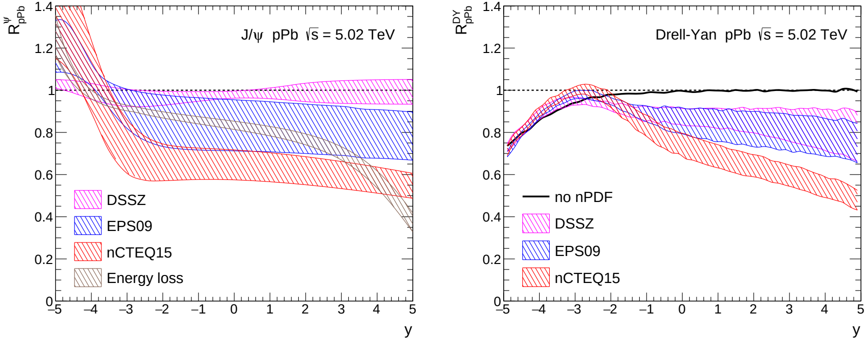


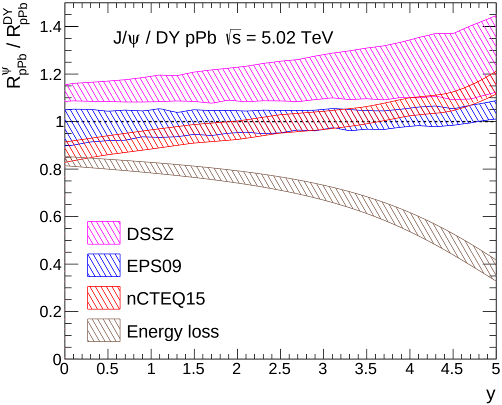
nPDF	$R^{\psi} \simeq R^{\mathrm{DY}}$	$\to \mathcal{R}^{\psi/\mathrm{DY}} \simeq 1$
Energy loss	$R^{\psi} < 1$; $R^{\mathrm{DY}} \gtrsim 1$	$\to \mathcal{R}^{\psi/\mathrm{DY}} < 1$

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 ($y < 0$)

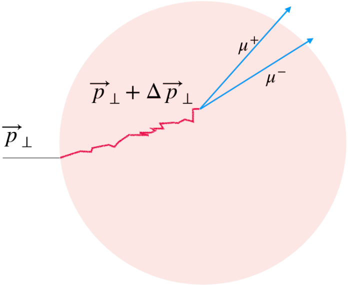
Double ratio $\mathcal{R}^{\psi/\mathrm{DY}}$



- Spectacular difference between shadowing and coherent energy loss
- Significantly reduced nPDF uncertainty due to correlated observables
- This observable should clarify the respective role of both effects
- First DY pPb data by CMS (yet at high M and low y) B. Diab, 2.20pm

Probing multiple scattering with quarkonia and DY

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



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

- 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

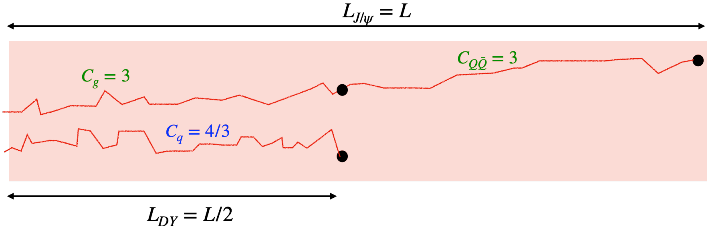
World data analysis in hA collisions **[FA Naïm, 2004.07188]**

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

Colorimetry

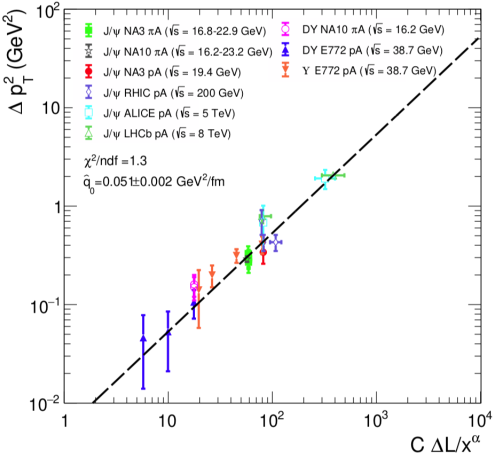
Broadening depends on initial and final Casimir color factors

$$\Delta p_{\perp}^{2} = \frac{C_R + C_{R'}}{2N_c} \left(\hat{q}_{\mathrm{A}} L_{\mathrm{A}} - \hat{q}_p L_p\right)$$



Process	Collision	$\mathcal{C}$
Drell-Yan	πA/pA	$C_F/2$
Quarkonium	πA	$(C_F + N_c)/2$
Quarkonium	pA	N_c

Scaling



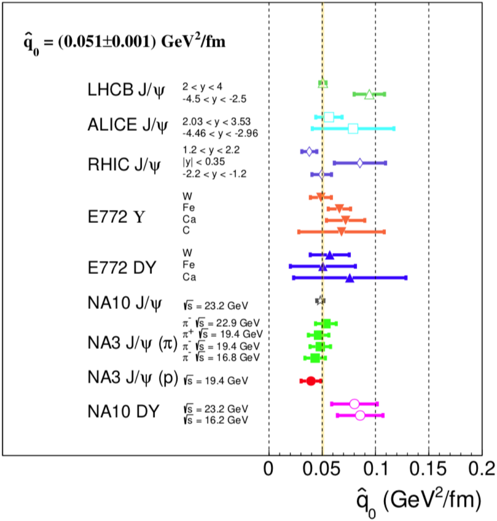
- Simple model used

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

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

$$\hat{q}_0 = 0.051 \pm 0.002 \,\mathrm{GeV}^2/\mathrm{fm}$$

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

Drell-Yan is a versatile tool to investigate cold nuclear matter effects

- LPM energy loss probed in DY production at low energy
  - First evidence in E906 data
- nPDF best probed with color neutral final states (DY, W, Z)
  - Hadrons in pA collisions problematic to extract nPDF
- Multiple scattering and $p_\perp$ broadening
  - Scaling observed from low to high energy
  - Consistency between broadening and energy loss