Probing QCD with Drell-Yan and quarkonium in nuclear collisions

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This talk

- Introduce various nuclear effects known to affect hard processes in nuclear collisions (pA, $\gamma^\star$A)
  - nuclear parton distribution functions (nPDF)
  - parton energy loss in nuclear matter
- Show how future measurements could be useful to understand these effects
  - Structure functions and hadron production in DIS on nuclei
  - Charmonium and Drell-Yan in pA collisions

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)
- FA, hep-ph/0201066 (DY at fixed target)
- FA, hep-ph/0306235 (hadron production in SIDIS)

Why hard processes in pA collisions ?

Hard processes (with a large energy scale $Q \gg \Lambda_{\rm QCD}$)

$$\mathrm{pp} \to (\mathrm{h}, \gamma, \mathrm{Z}, \ldots) + \mathrm{X}$$

- Great variety
  - Drell-Yan, light/heavy hadrons, photons, W/Z, jets, ...
- 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

Factorization in pA collisions

See the 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 nuclear PDF (nPDF)
  - could be probed in various processes and collision systems (pA, $\gamma^\star$A)
- New scale for power corrections ($\Lambda_{\mathrm{A}} > \Lambda_{\mathrm{p}}$)
  - specific processes like parton energy loss enhanced in pA collisions
  - ...could spoil the extraction of nuclear PDF

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What to expect for nuclear PDF ?

Nuclear parton distribution functions

Discovery of the EMC effect

First evidence of nuclear PDF modifications by EMC in 1983

- Structure functions in D and Fe are different in the range $0.05 \lesssim x \lesssim 0.5$

Nuclear PDF today

- Active field of research!
- nPDF ratios f_i^A / f_i^p extracted from global fits of data
  [DSSZ, nCTEQ15, KA15, EPPS16. . .]
  - Use data on F_2 (DIS), Drell-Yan, hadrons, W/Z, jets (pA collisions)

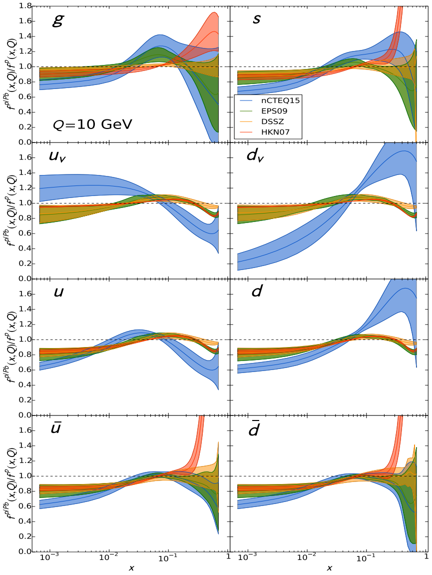
Nuclear Parton Distribution Functions (nPDF)

Parton densities are modified in nuclei

- Depletion ('shadowing') expected at small x
- Poor constraints, especially at small-x and in the gluon channel
- Crucial need to use LHC pPb data

[Eskola et al. EPPS16 1612.05741]

- Future COMPASS data on F_2 could help tremendously!



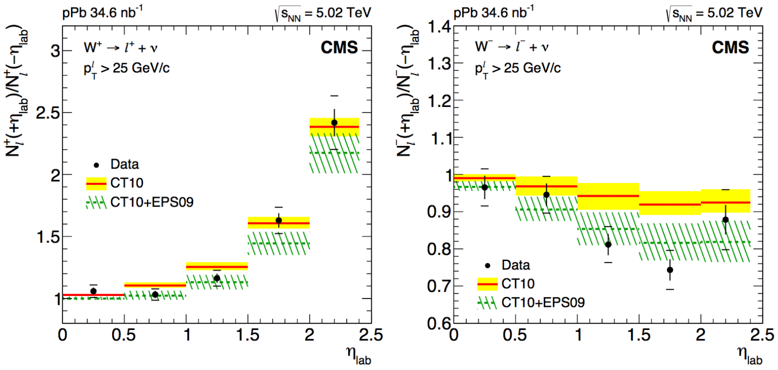
[nCTEQ15, 1509.00792]

Probing nPDF at the LHC

- Ideally, looking for processes sensitive to PDF only
  - Avoid hadron production sensitive to energy loss effects
- Best candidates
  - Weak bosons
  - Jets
  - Drell-Yan

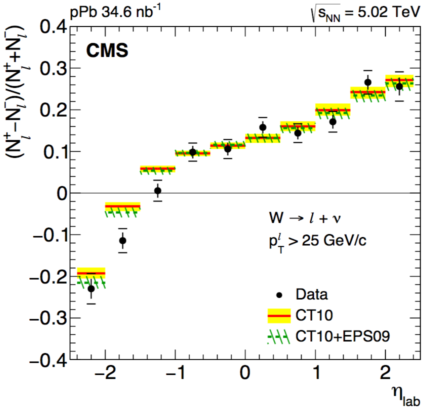
Weak bosons

W/Z measured recently in pPb by ALICE, ATLAS & CMS



- W boson rapidity asymmetry measured by CMS
  - data favor nuclear PDF modifications

Weak bosons



Lepton charge asymmetry

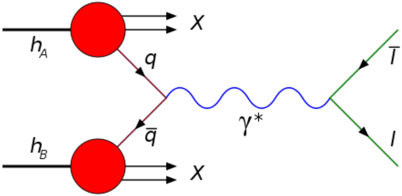
$$\frac{N_\ell^+ - N_\ell^-}{N_\ell^+ + N_\ell^-}$$

- Tension at negative η → 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
  - . . . which could be tested by COMPASS!

Talk Vincent Andrieux, Monday 15:20

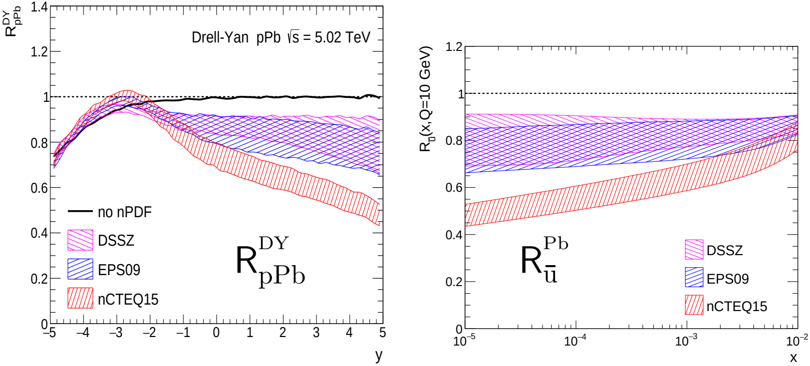
Drell-Yan

A golden probe of sea quark (and gluon) shadowing... at the LHC



- Low scale $Q \sim 10$ GeV can be reached where nPDF effects are largest
  - better than weak bosons, jets, prompt photons
  - mass can be varied
- Very well understood in QCD
  - better than light or heavy hadrons
  - factorization proven for DY

Drell-Yan at the LHC



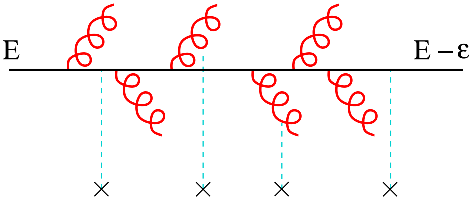
[FA Peigné, 1512.01794]

- NLO calculations using DSSZ, EPS09 and nCTEQ15
  - should reveal sea quark shadowing at low scale
- To be measured by LHCb at fwd/bwd rapidity in pPb Run 2

Parton energy loss

Energy loss-es

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



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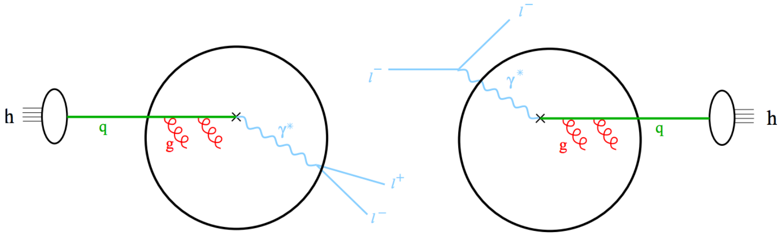


- Could affect many hard processes!
  - Drell-Yan in low energy pA and πA collisions
  - Hadron production in semi-inclusive DIS $\gamma^\star A \to$ h + X
  - Quarkonium in pA collisions at all energy
- Parametric dependence depends on the gluon formation time t_f

Parametric dependence

Small formation time $t_f \lesssim L$ (LPM energy loss)

$$\Delta E_{\rm LPM} \propto \alpha_s \; \hat{q} \; L^2$$

- Drell-Yan in pA and πA collisions
- Hadron production in semi-inclusive DIS on nuclei
- Only relevant at 'low' parton energy since $\Delta E_{\rm LPM}/E \sim 1/E$

Large formation time $t_f \gg L$ (fully coherent energy loss)

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

- Absent in DY and in DIS
- Important for hadron production in pA collisions at all energies

Model for J/ψ suppression from coherent energy loss

Energy shift

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}^{\psi}}{\mathrm{d}E}(E,\sqrt{s}) = \int_0^{\varepsilon_{\max}} \mathrm{d}\varepsilon\,\mathcal{P}(\varepsilon,E)\,\frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\psi}}{\mathrm{d}E}(E+\varepsilon,\sqrt{s})$$

- pp cross section fitted from experimental data
- $\mathcal{P}(\epsilon)$: quenching weight related to induced gluon spectrum

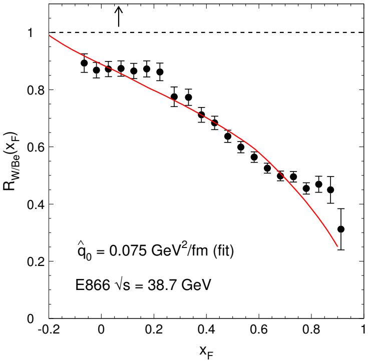
$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega}\,\exp\left\{-\int_{\epsilon}^{\infty} d\omega \frac{dI}{d\omega}\right\}$$

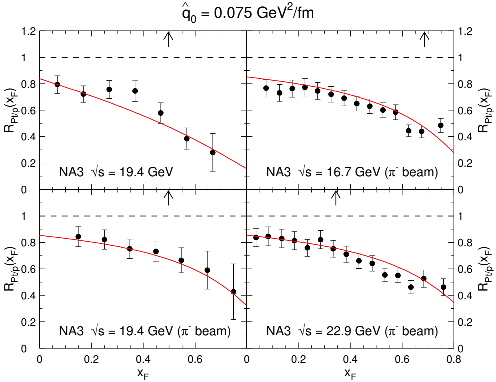
- Medium length L given by Glauber model
- Transport coefficient

$$\hat{q}(x) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\,\rho\, xG(x) = \hat{q}_0\left(\frac{10^{-2}}{x}\right)^{0.3} \;;\; \hat{q}_0 = 0.075\ \mathrm{GeV}^2/\mathrm{fm}$$

Comparing to low energy pA and πA data

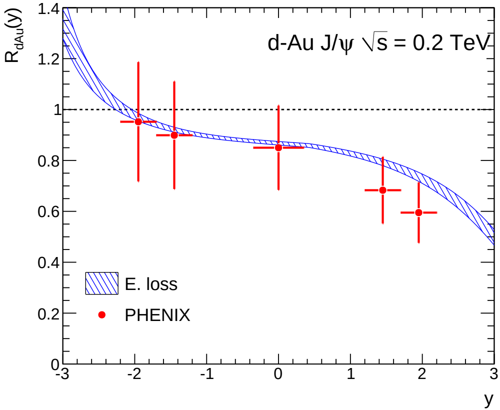
Simple fully coherent energy loss model able to solve the longstanding issue of J/ψ forward suppression pA data **[FA Peigné, 1212.0434]**





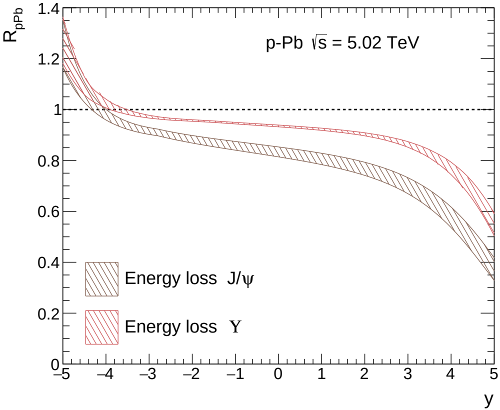
- Good agreement with E866, NA3, NA60, HERA-B data
- no nPDF global fit can explain these data

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



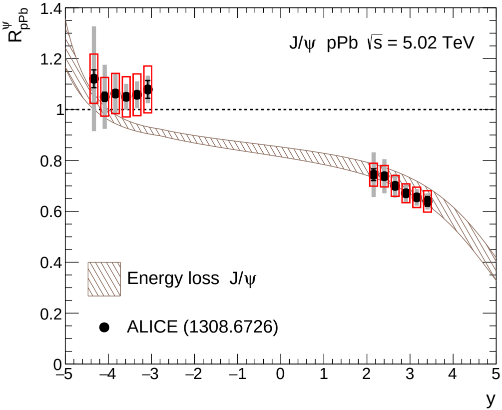
- Good agreement for R_{pA} vs rapidity
- Small uncertainty coming from the variation of the pp cross section and the transport coefficient

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

Probing LPM energy loss: (1) Drell-Yan

- Quarkonium production is sensitive to coherent energy loss
- Drell-Yan is sensitive to LPM energy loss
  - sensitivity only at low energy !
  - COMPASS ideal experiment to probe energy loss in this regime

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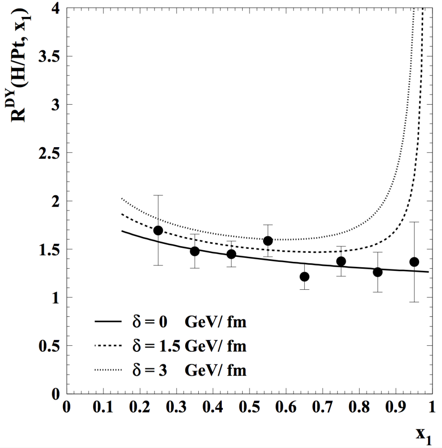


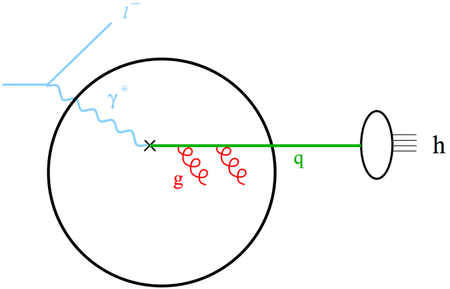
- NA3 data (1983!) allow to set constraints on the amount of energy loss (transport coefficient $\hat{q}$)

  [FA, hep-ph/0201066]

- More precise data on a large x_F range would help

Probing LPM energy loss (2): hadron production in SIDIS

Energy loss can be probed by looking at hadron fragmentation function



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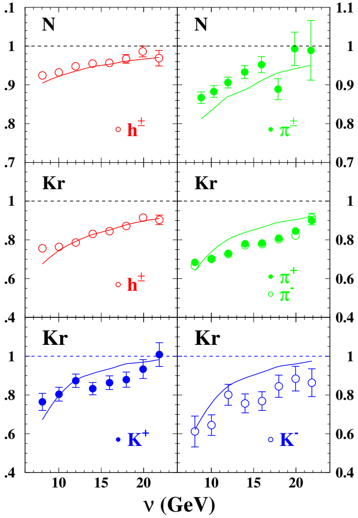

$$\frac{1}{N_A^e}\frac{dN_A^h(\nu, z)}{d\nu\, dz} \simeq D_u^h(z, Q^2, A)$$

- Wealth of data by HERMES and CLAS
- Access to ‘medium-modified’ fragmentation functions due to energy loss effects

[FA, hep-ph/0306235]

Future measurements (?)

- Probing nuclear PDF
  - F_2 in DIS
  - Access quark nPDF at large $x \sim 0.1$
- Probing LPM energy loss
  - Drell-Yan in $\pi^{\pm}$A
  - hadron fragmentation function in semi-inclusive DIS
  - Access transport coefficient, universality of LPM energy loss
- Probing coherent energy loss
  - Quarkonium (and light hadron)
  - Access transport coefficient, parametric dependence of coherent energy loss
- Probing quarkonium production dynamics
  - Compare DY and quarkonium transverse momentum broadening $\langle p_{\perp}^2 \rangle$

Summary

- Hard processes in pA reveal many facets of QCD processes
  - Nuclear PDF, momentum broadening, radiative energy loss. . .
- 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
- Impressive data collected at LHC and earlier. And more to come !
  - . . . pPb Run 2 at $\sqrt{s} = 8.16$ TeV last November
- Not just LHC ! Nuclear effects can also (best!) be studied in. . .
  - DIS on nuclei
  - Low-energy hadron-nucleus collisions

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Thanks !