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 \( Q(= p_{\perp}, M) \gg \Lambda_{\text{QCD}} \)

\[
\text{pp} \rightarrow (h, \gamma, Z, \ldots) + X
\]

Factorization = approximation

\[
\frac{d\sigma_{pp}}{dy \ dQ} = \sum_{i,j} \int dx_1 \ f_i^P(x_1, \mu) \int dx_2 \ f_j^P(x_2, \mu) \frac{d\hat{\sigma}_{ij}(Q, \mu')}{dy \ dQ} + O \left( \frac{\Lambda_n^p}{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

\[
\frac{d\sigma_{pA}}{dy \, dQ} = \sum_{i,j} \int dx_1 \, f_i^p(x_1, \mu) \int dx_2 \, f_j^A(x_2, \mu) \frac{d\hat{\sigma}_{ij}(Q, \mu')}{dy \, dQ} + \mathcal{O}\left(\frac{\Lambda_A^n}{Q^n}\right)
\]

- **Universal (leading twist) nuclear PDF**
  - could be probed in various processes and collision systems (eA, γA, pA)
- **New scale for power corrections (\(\Lambda_A > \Lambda_p\))**
  - higher twist processes enhanced in pA collisions (wrt pp)
  - specific processes could spoil the extraction of (universal) nPDF
Collinear factorization in pA collisions

A nucleus as an ordinary hadron

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What to expect for \(f_i^A\) ? How does it compare to \(f_i^p\) ?
In a super dilute nucleus: $f^A_i$ given by \textit{incoherent sum} over nucleon PDF

$$f^A_i = Z f^p_i + (A - Z) f^n_i$$

$$d\sigma_{pA} = Z d\sigma_{pp} + (A - Z) d\sigma_{pn} \simeq A d\sigma_{pp} \Rightarrow R_{pA} \equiv \frac{1}{A} \frac{d\sigma_{pA}}{d\sigma_{pp}} \simeq 1$$
In a super dilute nucleus: \( f^A \) given by incoherent sum over nucleon PDF

\[
f^A_i = Z f^p_i + (A - Z) f^n_i
\]

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

\[
f^A_i = Z R^{p/A}_i f^p_i + (A - Z) R^{n/A}_i f^n_i
\]

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

[Ref: EKS98, nDS, HKN... EPS09, DSSZ, nCTEQ15, KA15]
nPDF ratios

- Poor constraints from data, especially at small-$x$ and in the gluon channel
  Armesto, Fri 23 14:00

- 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: $Q \gg Q_s \approx \text{few GeV}$
  - avoid non-linear evolution and large power corrections
- ...but not too large to keep some sensitivity
  - $f^A / Af^p \approx 1$ 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)

Dumancic, Sat 24 14:20
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

Dumancic, Sat 24 14:20
Weak bosons

![Graph showing lepton charge asymmetry](image)

- 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 $y < 0$

  \[
  \frac{N^+ - N^-}{N^+ + N^-}
  \]

  [FA Chapon Paukkunen, 1509.03993]
Weak bosons

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  [FA Chapon Paukkunen, 1509.03993]
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

Lee, Sun 25 9:10

- 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
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)
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)
- 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

\[
\frac{d\sigma_{pp}}{dy \, dp_\perp} = \sum_{i=q,g} \int \frac{dz}{z^2} \, dx_1 \, f_i^p(x_1, \mu) \, \mathcal{F}^{F,A}_{xg}(k_\perp) \, D_{h/i}(z, \mu') + \mathcal{O}(\alpha_s^2)
\]

- \(f_i^p\) and \(D_{h/i}\): ordinary (collinear) PDF and FF – obey DGLAP
- \(\mathcal{F}^{F,A}_{xg}\): 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

Beuf, Mon 26 17:00
Zhu, Sat 24 11:20
Lappi, Sat 24, 11:40
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 show almost no suppression at $p_{\perp} \gtrsim 2$ GeV but depletion below this value. 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?

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Heavy hadrons – D meson

- Little or no suppression at mid-rapidity
- Forward/backward rapidity asymmetry reported by LHCb

[ALICE 1605.07569]

[Hard Probes 2016] 14 / 22
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 $t_f \ll L$

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

- Energy dependence at most logarithmic
  - corrections able to change the parametric dependence?

- 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 $\Delta E_{\text{LPM}}/E \ll 1$
  - explains why weak bosons and jets almost unmodified in pPb

[Kolbe Horowitz, 1511.09313]
Coherent energy loss

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

\[ \Delta E_{\text{coh}} \propto \alpha_s \sqrt{\frac{q}{M_{\perp}}} \frac{L}{E} \quad \left( \gg \Delta E_{\text{LPM}} \right) \]
Coherent energy loss

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

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

- 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 \( M_{\perp} \gg \sqrt{q} L \sim Q_s \)
  - no jet suppression in pA
Simple coherent energy loss model able to solve the longstanding issue of $J/\psi$ forward suppression pA data

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

- especially the trend at large $y$
Updated CGC+CEM calculations now agree with data

Ducloué, Sat 24 12:00

Also attempts within CGC+NRQCD [Ma Venugopalan Zhang, 1503.07772]

Possible agreement with some nPDF sets too

Ferreiro, Mon 26 16:30
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

\[ p\,A \rightarrow (\text{hard process}) + X \quad (X : \text{not measured}) \]

When looking at the event activity, totally different process

\[ p\,A \rightarrow (\text{hard process + specific event activity}) + X \]

- 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!

[Perpeletia Steinberg 1412.0976 Armesto Gulhan Milhano 1502.02986]
[McGlinchey Nagle Perpeletia 1603.06607 Kordell Majumder 1601.02595]
Before concluding

With more time I would have also mentioned

- Hot medium effects on hard processes in pA at LHC
- Focus also on RHIC and fixed-target experiments (FNAL, SPS)
- Double parton scattering

Usual disclaimer: apologies for not being able to cover all studies and to those whose work is under- or mis-represented.
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
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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.”
Thanks for your attention!