Fully coherent energy loss in proton-nucleus collisions

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Subatech, Nantes

Cold Nuclear Matter Effects: from the LHC to the EIC

CFNS, Stony Brook, USA – January 2025

Collinear factorization in pA collisions

A nucleus as an ordinary hadron

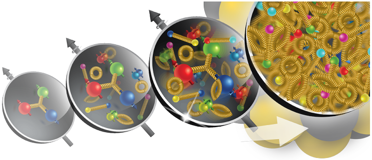
$$\frac{d\sigma_{pA}}{dy\ dQ} = \sum_{i,j} \int dx_1\ f_i^{p}(x_1, \mu) \int dx_2\ f_j^{A}(x_2, \mu) \frac{d\hat{\sigma}_{ij}(Q, \mu')}{dy\ dQ} + \mathcal{O}\left(\frac{\Lambda_A^n}{Q^n}\right)$$

- 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

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

nPDF

- Parton distribution functions are modified in nuclei
  - Evidence at large x from EMC/NMC measurements in DIS
- Extracted from data global fits
  - nuclear DIS: structure functions F_2
  - pA collisions: DY, W/Z, jets, hadrons (π at RHIC, D at LHC)
- Leads to x_2 **scaling** for hadron suppression: $R_{\mathrm{pA}}(x_2, \sqrt{s}) = R_{\mathrm{pA}}(x_2)$
- Expected shadowing at small x_2
  - Leads to hadron suppression at high $\sqrt{s}$ and large y
  - Amount of shadowing poorly known due to lack of data



Probing leading twist nPDF at the LHC

Ideally, looking for processes sensitive to PDF only

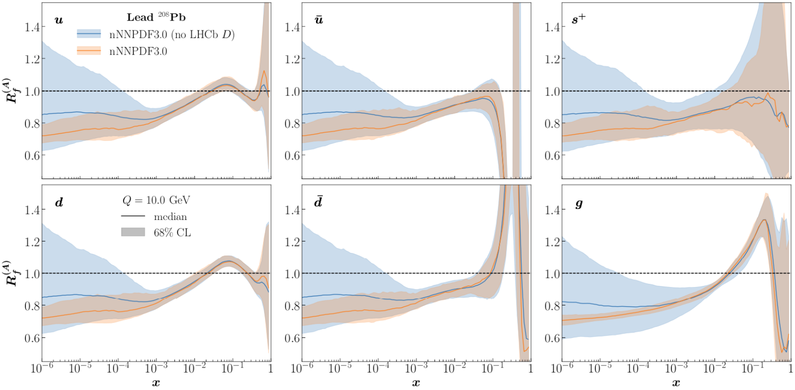
Some requirements (not necessary, but preferable):

- Sufficiently large scale: $Q \gg Q_s \simeq$ few GeV
  - to ensure factorization to be at work
- ... but not too large to keep some sensitivity
  - $f^A / A f^p \simeq 1$ in the Bjorken limit ($Q^2 \to \infty$ at fixed x)
- Favor color-neutral probes
  - avoid energy loss effects

Best candidates

Weak bosons, Jets, Drell-Yan

nNNPDF3.0 (w/ and w/o LHCb D meson data)

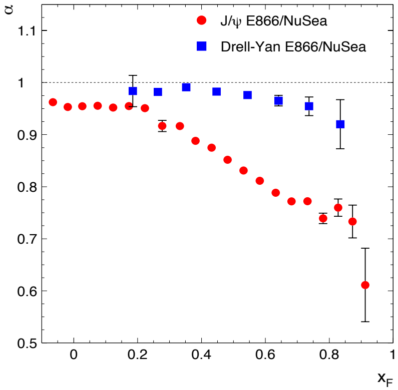


- Strong constraints given by forward D-meson data nNNPDF, 2201.12363
- Several other attempts EPPS21 2112.12462, nCTEQ 2204.09982

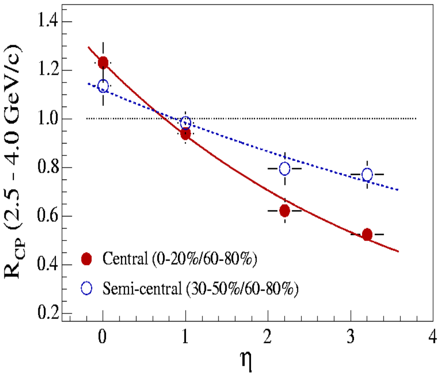
Talks by Kusina and Paukkunen, Tue 14

Nuclear effects beyond nPDF

- Strong light hadron and J/ψ suppression observed at forward rapidity
- Smaller suppression in the Υ channel & much smaller for Drell-Yan



E772 / E866/NuSea



BRAHMS

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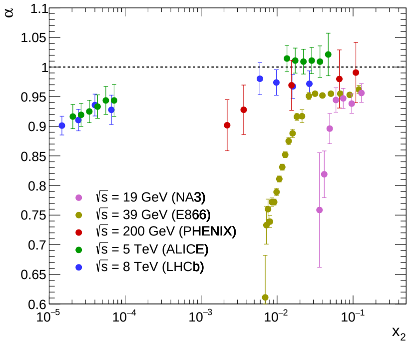
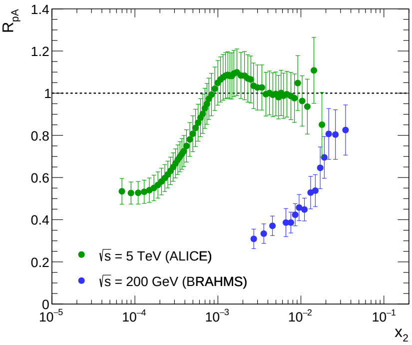


FA Naïm Platchkov 2019



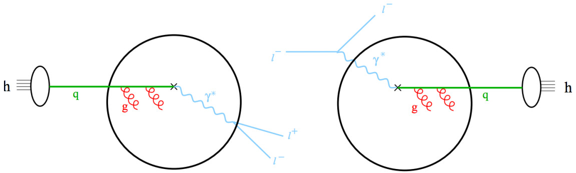
FA Habilitation thesis 2018

☞ Strong violation of x_2 scaling

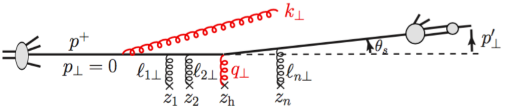
Radiative energy loss in cold nuclear matter

Induced gluon radiation could affect many hard QCD processes!

- Drell-Yan in pA collisions
  - initial-state energy loss
- Hadron production in semi-inclusive DIS $\gamma^\star A \to h + X$
  - final-state energy loss



- Hadron production in pA collisions
  - initial & final state energy loss... and **initial-final state interference**



Radiative energy loss in cold nuclear matter

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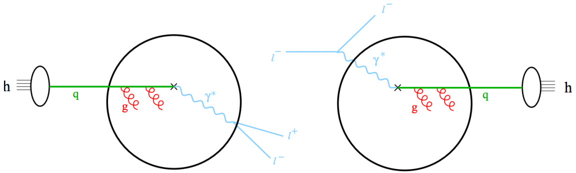

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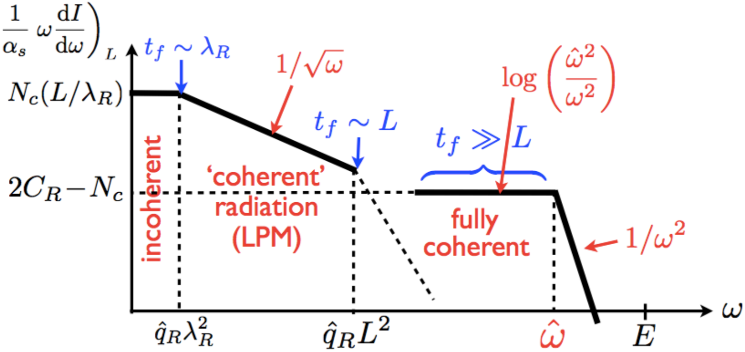
  - initial & final state energy loss... and **initial-final state interference**

☞ How does energy loss depend parametrically on parton energy ?

Fully coherent induced gluon spectrum



Fully coherent induced gluon spectrum

$$\omega \frac{dI}{d\omega}\bigg|_{1\to 1} = \frac{\alpha_s}{\pi} F_c \ln\left(1 + \frac{\hat{q}\, L}{M_\perp^2} \frac{E^2}{\omega^2}\right)$$

FA Peigné Sami 1006.0818 FA Peigné 1212.0434

FA Kolevatov Peigné 1402.1671 Peigné Kolevatov 1405.4241

- First determined in a model, later confirmed in the opacity expansion
- Color factor follows from color algebra: $F_c = C_R + C_{R'} - C_t$
  - R (R') = color rep. of the incoming (outgoing) particle

$$\begin{aligned} g \to g \quad &: \quad F_c = N_c + N_c - N_c = N_c \\ q \to g \quad &: \quad F_c = C_F + N_c - C_F = N_c \\ q \to q \quad &: \quad F_c = C_F + C_F - N_c = -1/N_c \quad (< 0\ !) \end{aligned}$$

- Average energy loss proportional to E !

$$\Delta E_{\text{FCEL}} \propto \alpha_s\, F_c\, \frac{\sqrt{\hat{q}\, L}}{M_\perp}\, E$$

In a nutshell

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

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

- Hadron production in nuclear DIS or Drell-Yan in pA collisions
- Particle suddenly accelerated (e.g. jet in QGP)

Fully coherent energy loss (large formation time $t_f \gg L$)

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

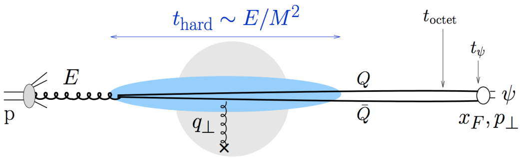
- Important for hadron production in pA collisions at all energies
- Needs color in both initial & final state
    - no effect on W/Z nor Drell-Yan, no effect in DIS
- Power suppressed: negligible when $M_\perp \gg \sqrt{\hat{q}\, L} \sim Q_s$

Phenomenology

Goal

- Explore phenomenological consequences of coherent energy loss
- Approach as simple as possible with the least number of assumptions
- Observable: quarkonium suppression in pA (and AA) collisions

Physical picture and assumptions



- Color neutralization happens on long time scales: $t_{\text{octet}} \gg t_{\text{hard}}$
- In-medium rescatterings do not resolve the octet $Q\bar{Q}$ pair
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$

Model

Energy shift

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

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

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

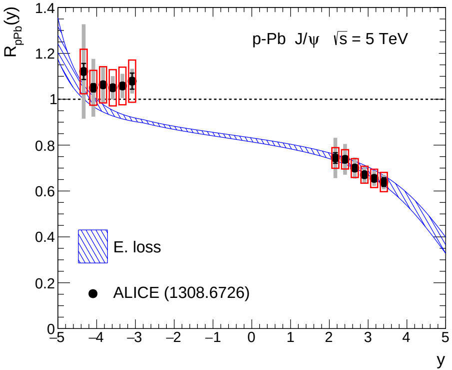
- Length L given by Glauber model
- Transport coefficient

$$\hat{q}(x) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\,\rho\, xG(x) = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3} \quad ; \; \hat{q}_0 = 0.05\text{–}0.09\ \mathrm{GeV}^2/\mathrm{fm}$$

  - $\hat{q}_0$ range in agreement with LPM energy loss and nuclear broadening studies, corresponds to $Q_s \simeq 1.3$–1.8 GeV at LHC at mid-rapidity

LHC predictions

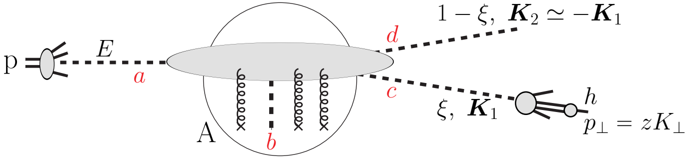
FA Peigné 1204.4609 1212.0434 FA Kolevatov Peigné Rustamova 2003.06337



- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- Very good agreement with LHC data as well with all other J/ψ data at lower energy (NA3, E866, PHENIX...)

From quarkonium to light hadron production

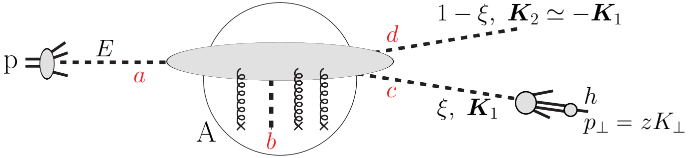
Which differences from quarkonium to single light hadron production?



- Final state made of two partons at leading order
  - Partons produced with opposite and large transverse momenta $K_1 \simeq K_2 \gg \sqrt{\hat{q}L}$ and energy fractions ξ and $1-\xi$
- Use medium-induced gluon spectrum associated to $2 \to 2$ scattering
  - Final state in different color representations R with probability $\rho_{\rm R}(\xi)$
- Hadronization: $z \neq 1$

From quarkonium to light hadron production

Which differences from quarkonium to single light hadron production?



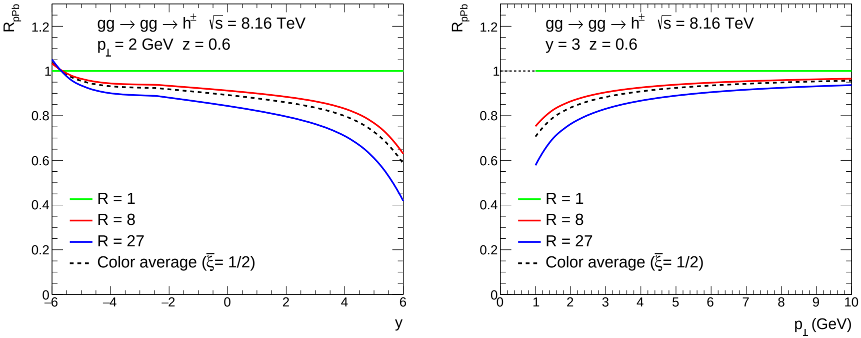
Assuming a smooth variation of ρ and $R^{\mathrm{h}}_{\mathrm{pA}}$ with ξ

$$R^{\mathrm{h}}_{\mathrm{pA}}(y, p_\perp) \simeq \sum_{\mathrm{R}} \rho_{\mathrm{R}}(\xi)\, R^{\mathrm{R}}_{\mathrm{pA}}(y, p_\perp)$$

$$R^{\mathrm{R}}_{\mathrm{pA}}(y, p_\perp) = \int_0^{\delta_{\max}} \mathrm{d}\delta\ \hat{\mathcal{P}}_{\mathrm{R}}\left(x, \frac{\sqrt{\hat{q}L}\,\langle z \rangle}{M_\xi}\right) \frac{\mathrm{d}\sigma^{\mathrm{h}}_{pp}(y+\delta, p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp} \Big/ \frac{\mathrm{d}\sigma^{\mathrm{h}}_{pp}(y, p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp}$$

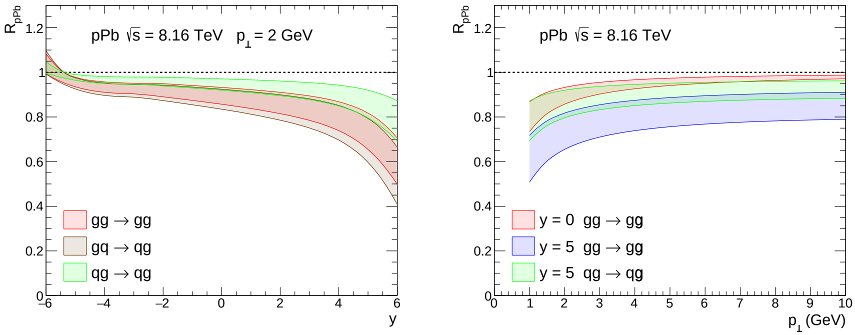
Color dependence

FA Peigné 2003.01987 FA Cougoulic Peigné 2003.06337



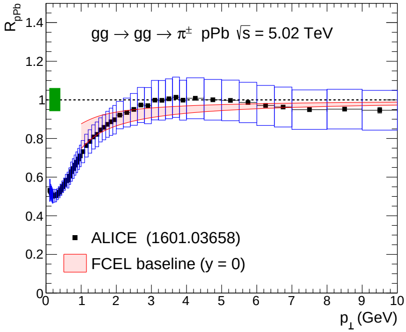
- Rapidity dependence reminiscent of quarkonium suppression
- Significant suppression, especially in the **27** color state
- Color-averaged suppression similar to that of an octet
- Effects weaken at large $p_\perp$

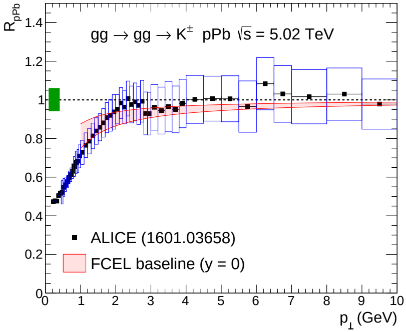
Predictions at LHC



- Significant effects
  - More pronounced at larger y (measurable e.g. by LHCb)
  - Persists up to $p_\perp \simeq 10$ GeV
- All scattering processes can be computed (here most important ones)
- Similar in magnitude to saturation/nPDF effects

Comparison to data



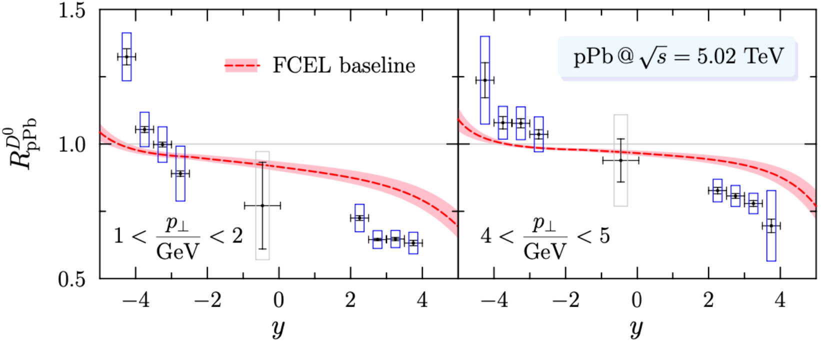


- Precise baseline in agreement with ALICE $\pi^\pm/K^\pm$ & CMS $h^\pm$ data
  - brings constraints on other physical effects
  - disagreement with $p/\bar{p}$ data

From light hadrons to D-mesons

Above model can be simply extended to the case of D mesons

FA Jackson Peigné 2107.05871



- Accounts for half of the suppression
  - Room for nPDF effects
- Small relative uncertainty

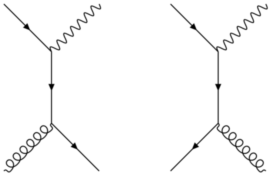
Prompt photons

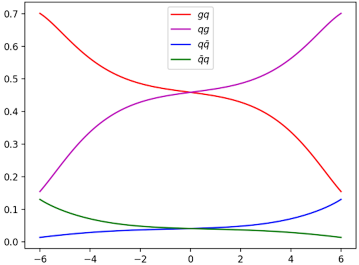
- Prompt photons in pp/pA collisions have long been seen as a good probes of gluon (n)PDF
- However. . . photons also affected by FCEL due to recoiling jet

FA, Bourgeais, Jackson, in progress

At leading order

- Compton scattering ($qg \to \gamma q$) color triplet final state
- Annihilation ($q\bar{q} \to \gamma g$) , color octet final state





Discussion

- FCEL affects D-meson production in pA collisions. . . but nPDF are extracted using D-meson data ignoring FCEL
- How to extract nPDF reliably **given FCEL** ?
  - Use color neutral probes in pA collisions: DY, W/Z
  - Use large-Q^2 measurements: jets, top quarks
  - Use DIS data
  - . . . or include FCEL in nPDF global fits

Reweighting nPDF, w/ and w/o FCEL

Given a new data set, **PDF can be conveniently reweighted**

✗ **Ignore FCEL** :

$$\mathcal{P}(f_{\rm A} \,|\, \text{pQCD} \cap \text{world data})$$

- ‘Statistically good’ fits can be obtained, including LHCb data
- Strong constraints. . . but unreliable result

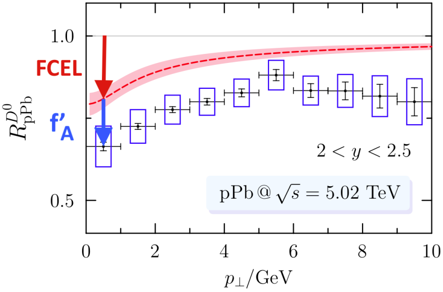
✓ **Include FCEL**

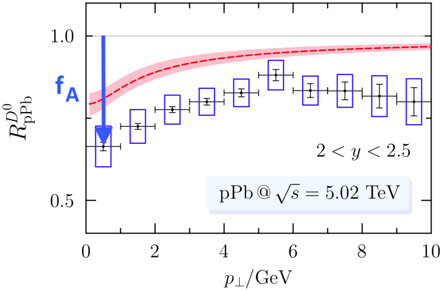
$$\mathcal{P}(f'_{\rm A} \,|\, \text{pQCD} \cap \text{FCEL} \cap \text{world data})$$

- Part of the nuclear dependence cannot be attributed to nPDF
- Different physical processes with different scaling properties
- Resulting nPDF extracted from data **will not be the same**: $f'_{\rm A} \neq f_{\rm A}$

Reweighting nPDF, w/ and w/o FCEL

Given a new data set, **PDF can be conveniently reweighted**



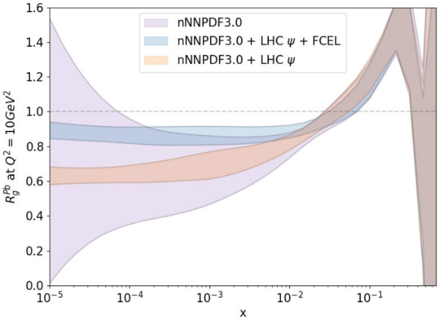


$\mathcal{P}(f'_A \,|\,$ FCEL $\cap$ LHCb data$)$ $\mathcal{P}(f_A \,|\,$ no FCEL $\cap$ LHCb data$)$

$$f'_A \neq f_A$$

A first attempt

Reweighting nPDF w/ and w/o FCEL using J/ψ LHC data



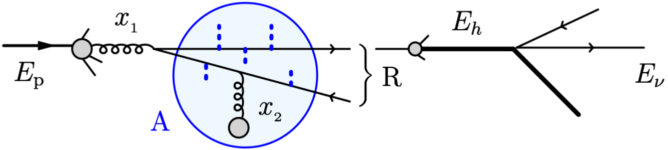
FA Avez Hard Probes 2023 & work in preparation

- Large difference between nPDF alone and nPDF + FCEL
- Similar results for all nPDF sets
- Lesser gluon shadowing when FCEL is included

Atmospheric neutrinos

- HE cosmic rays (protons) collide on $\langle A \rangle \simeq 14.5 \Rightarrow$ Air shower
  - Similar to pA collisions at LHC
- D-meson decay responsible for the atmospheric ν flux

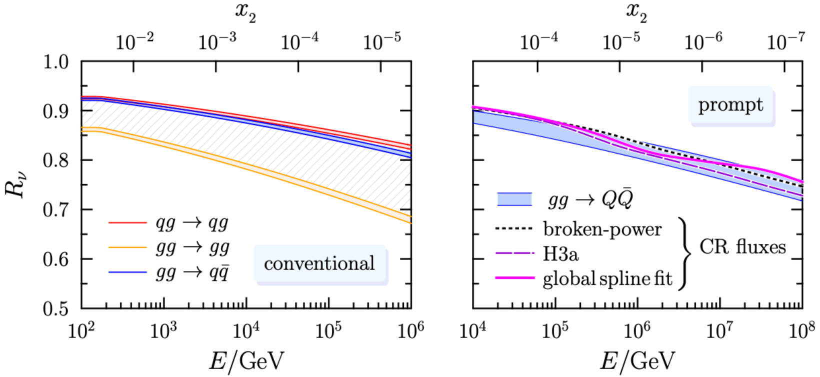
Lipari 1993, Gondolo Ingelman Thunman 1996



Depletion of atmospheric neutrinos from FCEL

$R_\nu \equiv \Phi_\nu^{\mathsf{FCEL}}/\Phi_\nu^{\mathsf{FCEL}} \simeq \int_0^1 \mathrm{d}z\, z^\gamma\, P(z)$

FA Jackson Peigné 2112.10791



- Sizeable depletion of atmospheric ν's
- Similar in size to nPDF / saturation effects
- Reduced background for searches of astrophysical ν's

Summary

- FCEL predicted from first principles **with small uncertainty**
  - $\Delta \propto E$
  - Leads to QCD factorization breaking
- **Affects significantly hadron production** in pA collisions
  - Applied to light hadrons, D-mesons, quarkonia, prompt photons
  - ...and atmospheric neutrino flux through D-meson decays
- Crucial **impact on nPDF extractions**
  - D-meson/quarkonium data cannot be used in global fits, unless FCEL is properly taken into account
  - Electron-ion collider best place to probe nPDF