Probing nPDF and fully coherent radiation through electromagnetic signals at the LHC

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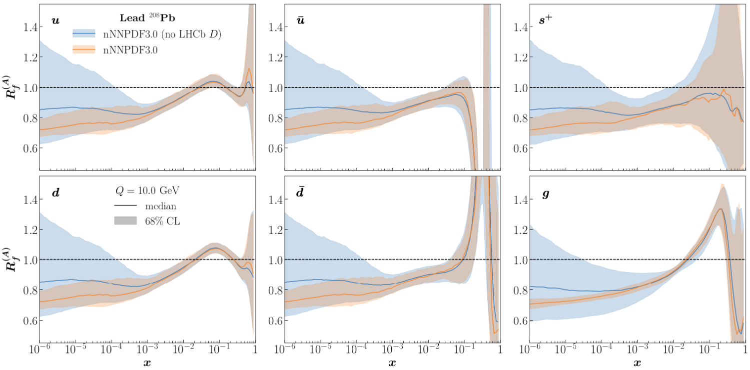
Work in progress with D. Bourgeais, M. Guilbaud, G. Jackson, V. Valencia

nuclear Parton Distribution Functions

- Parton distribution functions are modified in nuclei
  - Evidence at large x from EMC/NMC measurements in DIS
  - Expected depletion at small x (shadowing)
- nPDF cannot be calculated, extracted from data global fits
  - F_2 in eA, Drell-Yan, W/Z, jets, hadrons in pA collisions
  - Several sets: nCTEQ15, EPPS21, nNNPDF3.0...

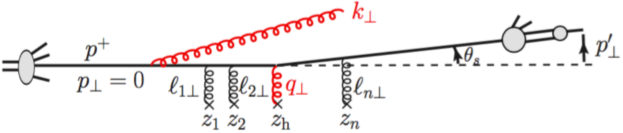
nuclear Parton Distribution Functions



- Poor constraints from data at small x — nNNPDF, 2201.12363
- Strong constraints given by forward D-meson LHCb data
  - key measurements. . . but affected by fully coherent energy loss

Fully Coherent Energy Loss

- **Induced gluon radiation** due to multiple scattering in nuclei



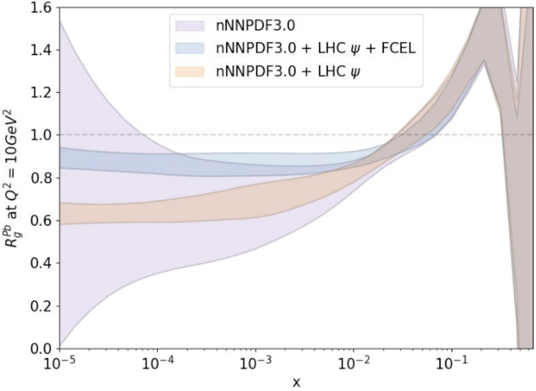
- Average energy loss $\Delta E_{\text{FCEL}} \propto \alpha_s \; (Q_s/M_\perp) \; E$
  - Important at all collision energies, especially at large y
- Needs color in both initial & final state
  - No effect in DIS on nuclei nor Drell-Yan at leading order
- Applied to a variety of processes in pA collisions
  - quarkonia (2012-2014), light hadrons (2020), open heavy-flavour hadrons (2021), atmospheric neutrinos from π/D decays (2021)

Which nPDF global fit strategy

- Given the existence of FCEL, how should nPDF be extracted ?

✓ **Include FCEL** in the pQCD calculation and then extract nPDF
  - Stronger constraints from all measurements available
  - First attempt using J/ψ data

Which nPDF global fit strategy



Arleo Avez HP23 + work in progress

☞ Extracting nPDF from J/ψ data depends strongly on whether FCEL is included or not

Which nPDF global fit strategy

- Given the existence of FCEL, how should nPDF be extracted ?

✓ **Include FCEL** in the pQCD calculation and then extract nPDF
  - Stronger constraints from all measurements available
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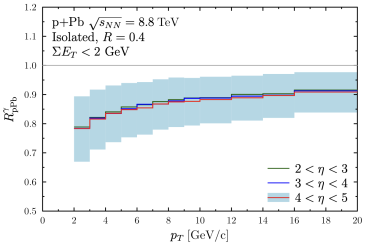
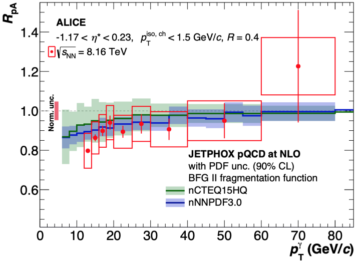
✓ Investigate only observables **poorly sensitive** or **insensitive** to FCEL
  - F_2 in DIS, weak bosons, jets in pA collisions
  - prompt photons and Drell-Yan ☞ this talk

Prompt photons and nPDF

- Prompt photons in pA long been thought as a good probe of nPDF
  FA Gousset 2008, FA Eskola Paukkunen Salgado 2011, Helenius Eskola Paukkunen 2014
  - Sensitive to the gluon nPDF through Compton scattering $qg \to q\gamma$
  - nPDF at small x and small Q accessible at LHC
  - recent measurements at low $p_\perp$ by ALICE



Helenius Eskola Paukkunen 1406.1689



ALICE 2502.18054

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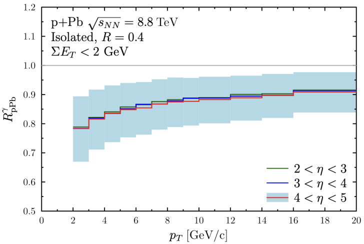
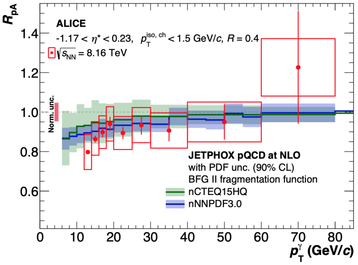




☞ What about FCEL effects on prompt photons ?

Modelling FCEL quenching

For a generic scattering channel α: $\mathrm{ab} \to [\,\mathrm{c}(\xi)\,\mathrm{d}(1-\xi)\,]_{\mathrm{R}}$

$$\frac{d\sigma^{\mathrm{R}}_{\mathrm{pA}}(y)}{dy\,d\xi} = \int_0^{x_{\max}} dx\; \frac{\mathcal{P}_{\mathrm{R}}(x)}{1+x}\, \frac{d\sigma^{\mathrm{R}}_{\mathrm{pp}}(y+\ln(1+x),\xi)}{dy\,d\xi}$$

$$\mathcal{P}_{\mathrm{R}}(\epsilon) \simeq \left.\frac{dI(\epsilon)}{d\epsilon}\right|_{\mathrm{R}} \exp\left\{-\int_{\epsilon}^{\infty} d\omega\; \left.\frac{dI(\omega)}{d\omega}\right|_{\mathrm{R}}\right\}$$

$$\omega\left.\frac{dI}{d\omega}\right|_{\mathrm{R}} \simeq (C_{\mathrm{a}} + C_{\mathrm{R}} - C_{\mathrm{b}})\,\frac{\alpha_s}{\pi}\left[\ln\left(1+\frac{Q^2_{s\mathrm{A}}}{M^2_{\xi}}\frac{E^2}{\omega^2}\right) - \mathrm{pp}\right]$$

FA Peigné 1212.0434

- Valid in the pointlike dijet approximation for which gluon radiation does not probe the dijet
- Induced gluon spectrum computed beyond the pointlike approximation for a generic process $1\,2 \to 3 \ldots n$ Jackson Peigné Watanabe 2312.11650

Modelling FCEL quenching

For a generic scattering channel α: $\mathrm{ab} \to [\,\mathrm{c}(\xi)\,\mathrm{d}(1-\xi)\,]_{\mathrm{R}}$

$$\frac{d\sigma_{pA}^{R}(y)}{dy\,d\xi} = \int_0^{x_{max}} dx\, \frac{\mathcal{P}_{R}(x)}{1+x}\, \frac{d\sigma_{pp}^{R}(y+\ln(1+x),\xi)}{dy\,d\xi}$$

- Summing over the color probabilities ρ_{R_α} for a given channel

$$R_{pA}^{\alpha}(y,p_\perp) \simeq \sum_{R_\alpha} \rho_{R_\alpha}(\xi)\, R_{pA}^{R_\alpha}(y,p_\perp)$$

- Summing over scattering channels α

$$R_{pA}(y,p_\perp) \simeq \sum_{\alpha} f_\alpha(y,p_\perp) \sum_{R_\alpha} \rho_{R_\alpha}(\xi)\, R_{pA}^{R_\alpha}(y,p_\perp)$$

  - Channel fractions f_α computed in pQCD at LO

Prompt photons at leading order

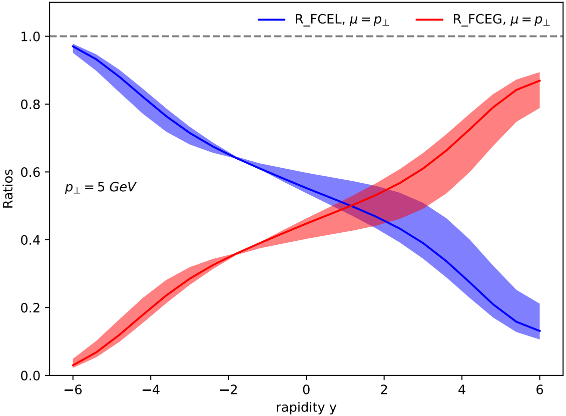
- 2 direct photon channels at LO: Compton scattering and annihilation
  - Different color representations R… but only 1 irrep per channel
  - Crucial difference between $q^p g^A$ and $g^p q^A$ scattering

Process	Initial state	R	Color factor
Compton	$g^p\, q^A \to q\,\gamma$	**3**	$N_c + C_F - C_F = N_c$
	$q^p\, g^A \to q\,\gamma$	**3**	$C_F + C_F - N_c = -1/N_c$
Annihilation	$q^p\, \bar{q}^A \to g\,\gamma$	**8**	$C_F + N_c - C_F = N_c$
	$\bar{q}^p\, q^A \to g\,\gamma$	**8**	$C_F + N_c - C_F = N_c$

☞ Competition between Fully Coherent Energy Loss (FCEL)

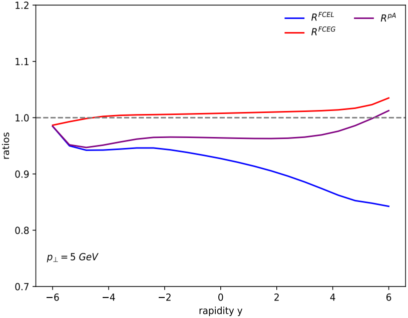
and Fully Coherent Energy Gain (FCEG)

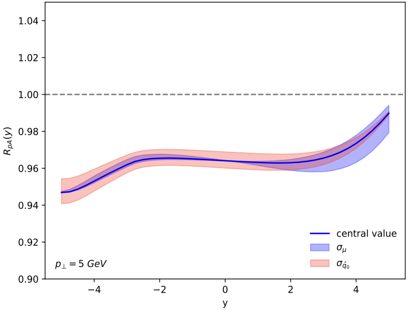
Prompt photons at leading order



- $q^p\, g^A \to q\, \gamma$ naturally dominates at forward rapidity
  - Mostly energy gain at $y > 0$ and energy loss at $y < 0$
- Little PDF & scale dependence on the channel fractions

FCEL/FCEG effects on prompt photons

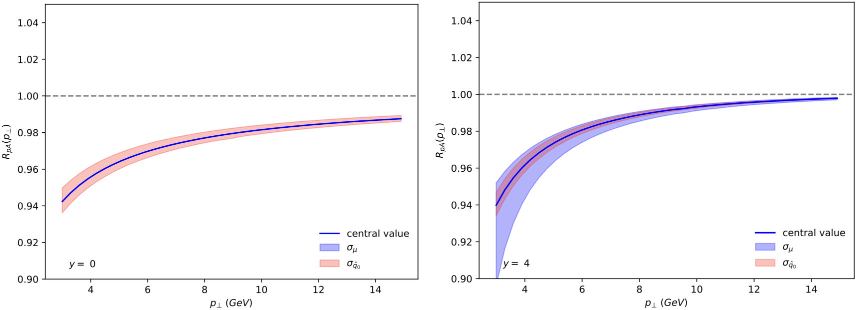




Rapidity dependence

- Stronger effect at negative rapidity
  - $R_{\text{pA}} \simeq 0.94 - 0.96$ at $y = -5$ and $p_\perp = 5$ GeV
- At positive rapidity, FCEL and FCEG mostly compensate
- Small theoretical uncertainty

FCEL/FCEG effects on prompt photons



Transverse momentum dependence

- Tiny effect at large $p_\perp$ ($\Delta E \propto Q_s/p_\perp$)
- Larger scale dependence at small $p_\perp$ and forward rapidity

Going virtual: Drell-Yan process

- Energy loss (gain) effects on prompt photons small but not negligible
- ...but effects on Drell-Yan should be vanishingly small
  - At LO, $q\bar{q} \to \gamma^\star$ insensitive to FCEL
  - At NLO, real emission should lead to $\Delta E \propto Q_s/\sqrt{Q^2 + p_\perp^2} \ll 1$
  - Low mass DY in pA collisions at LHC ideal probe of nPDF at small x

FA Peigné, 1512.01794

LHC data

- CMS data in pPb collisions ($M > 15$ GeV) CMS 2102.13648
- LHCb data in pp collisions at low mass LHCb-CONF-2012-013
- Prospects to measure low-mass DY in pPb with LHCb Runs 3/4 data

LHCb-CONF-2018-005

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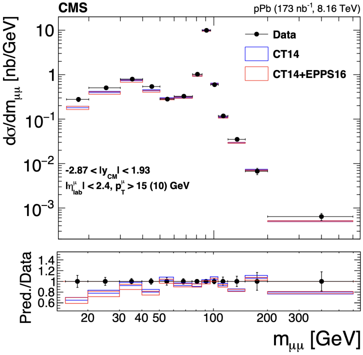

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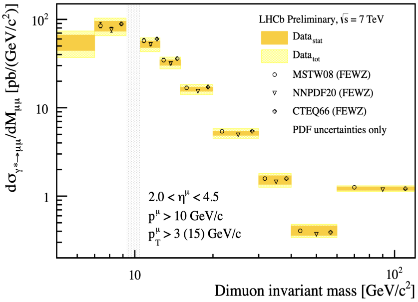

nPDF constraints from DY data

nPDF reweighted according to LHCb Run 3 pseudo-data

- DY computed in pQCD at NLO using DYTurbo and various nPDF sets (EPPS16, nCTEQ15WZ, nNNPDF3.0)

Pseudo-data generation

- Central value given by the average of 3 random nPDF members

$$R_{\text{pA}} = \frac{1}{3}\left[R_{\text{pA}}^{\text{EPPS16}}(k) + R_{\text{pA}}^{\text{nCTEQ15WZ}}(\ell) + R_{\text{pA}}^{\text{nNNPDF}}(m)\right]$$

- Statistical uncertainty obtained from Run 3 luminosity and S/B

$$\delta N_j^{\text{stat}} = \sqrt{\mathcal{L}_{\text{Run 3}}\, N_j \left[1 + \frac{1}{(S/B)_{j,\text{eff}}}\right]}\ ;\ (S/B)_{j,\text{eff}} = 1/30$$

nPDF constraints from DY data

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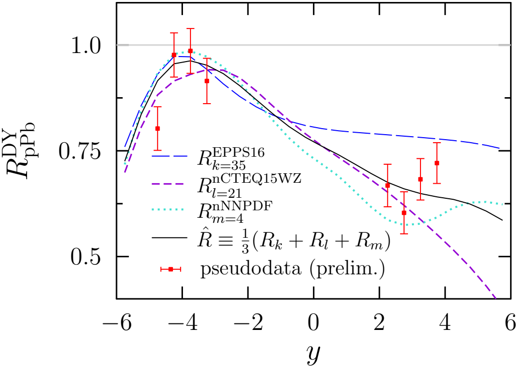
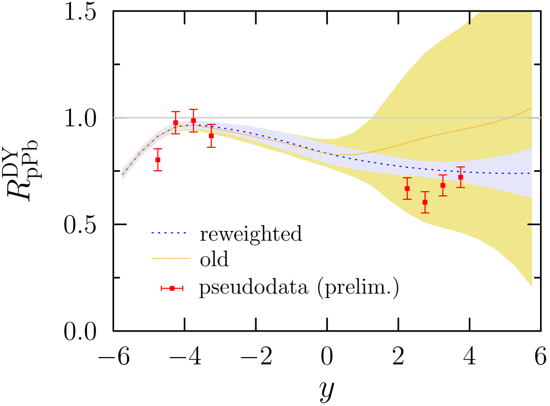
Pseudo-data generation



Reweighting

Using nNNPDF3.0_noD set for the illustration



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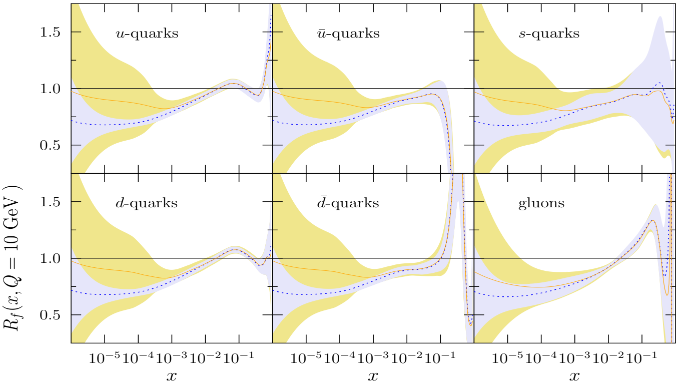
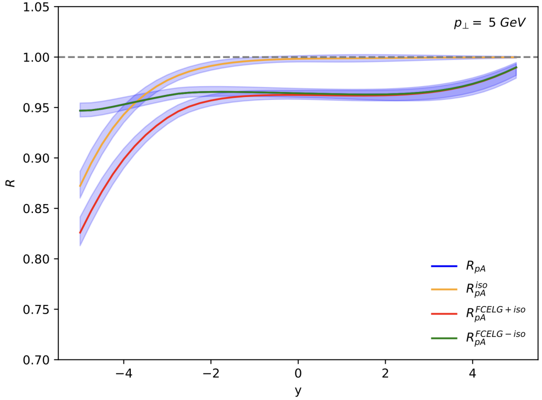


- Significant constraints for both quarks and gluons at small x
- Reminiscent of the constraints from D-mesons, slightly looser...
- ...yet maybe more reliable since unspoiled by FCEL effects

Summary

- Prompt photons proposed as a good probe of nPDF
  - ...but might be affected by FCEL/G
- FCEL/G effects on prompt photons in pA collisions estimated
  - Small but non negligible effect, especially at low $p_\perp$ and $y < 0$
  - Result from a subtle interplay of energy loss and energy gain processes
  - Role of fragmentation photons currently investigated
- Drell-Yan data as the most promising nPDF probe
  - Insensitive to fully coherent medium-induced radiation
  - nPDF reweighting using realistic Run 3 LHCb pseudo-data
  - Significant constraints on both quark and gluon nPDF at small x

Including isospin effects



- Prompt photons suppressed at large negative y due to isospin effects
  - $\sigma(pn \to \gamma\,\mathrm{X}) < \sigma(pp \to \gamma\,\mathrm{X})$ as $d(x) < u(x)$ at large x
- Large effect but small uncertainty