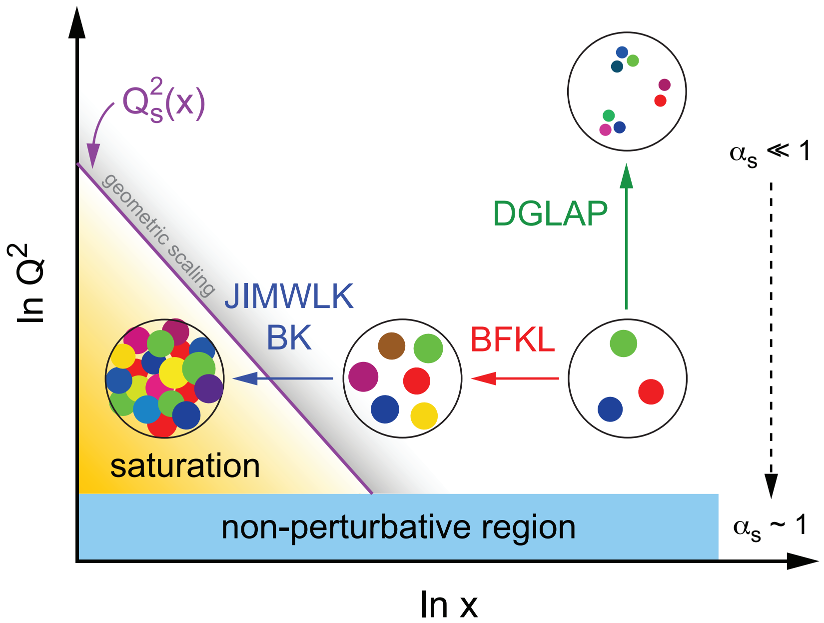
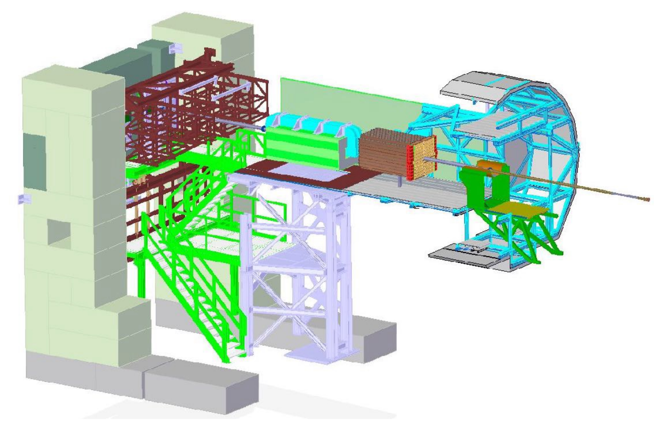
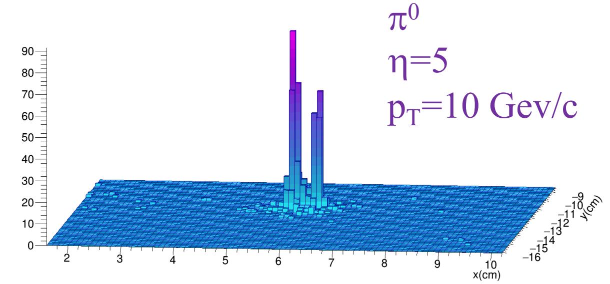
Search for non-linear QCD evolution: FoCal and the EIC

Peter Jacobs, LBNL

2nd International Workshop on Forward Physics and Forward Calorimeter Upgrade
Tsukuba, March 13-15 2023







This is not an official ALICE or FoCal talk

- presents my personal view only

However, it is based on extensive work by the FoCal collaboration, most recently as presented at the US DOE Science Review of the FoCal project (January ‘23)

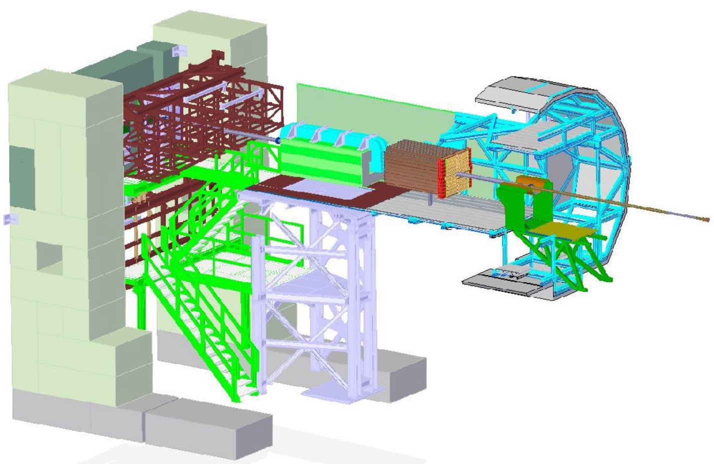
See also talk by Daniel T-T on UPCs

ALICE Public Note is in preparation

ALICE Forward Calorimeter (FoCal)
Science proposal

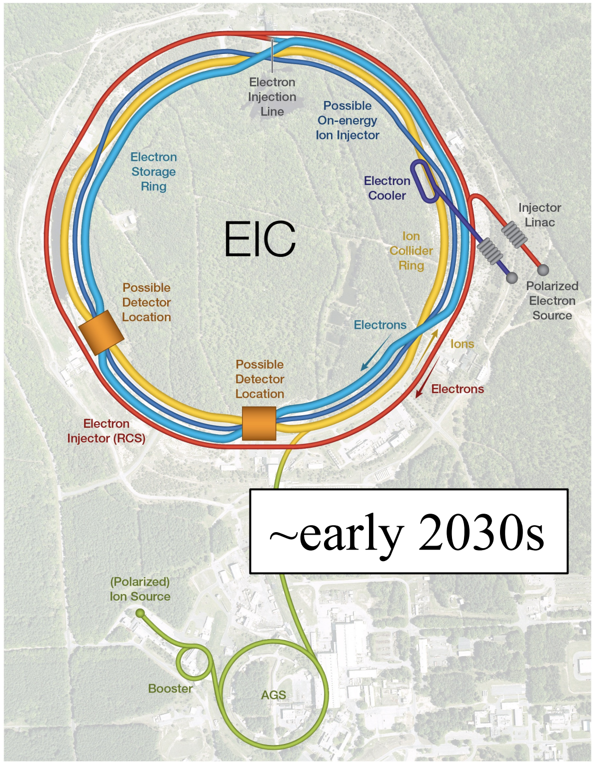
ALICE-USA Collaboration
(Dated: January 23, 2023)

We propose to instrument the existing ALICE detector with a forward calorimeter system (FoCal), enabling a new and unique program at the LHC focused on small-x gluon dynamics of hadrons and nuclei. The FoCal detector is a highly-granular Si+W electromagnetic calorimeter combined with a conventional sampling hadronic calorimeter, covering the pseudorapidity interval of $3.4 < \eta < 5.5$. The FoCal design is optimized to measure isolated photons at most forward rapidity for $p_T < 20$ GeV/c. The FoCal will provide theoretically well-motivated observables in pp and p–Pb which are sensitive to the gluon distribution at small x at low to moderate Q^2, based on isolated photon, neutral meson, and jet production and correlations in hadronic collisions, and the measurement of vector meson photoproduction in ultra-peripheral collisions. The FoCal scientific program provides a broad exploration of gluon dynamics and non-linear QCD evolution at the lowest values of Bjorken x that will be accessible at any current or near-future facility world-wide. The FoCal measurements, combined with the comprehensive experimental program at the EIC and other forward measurements at RHIC and the LHC, will enable incisive tests of the universality of linear and non-linear QCD evolution in different collision systems over an unprecedented kinematic range. The FoCal will also carry out measurements at very forward rapidity in Pb–Pb collisions, enabling novel probes of the Quark-Gluon Plasma based on jet quenching phenomena and long-range correlations of neutral pions, jets, and photons. We discuss the scientific potential and the expected performance of the FoCal, and present the contribution to the FoCal project proposed by the ALICE-USA collaboration in the context of the international FoCal effort.



~2029

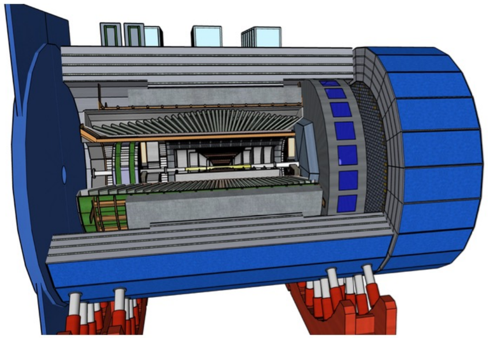
Complementary?

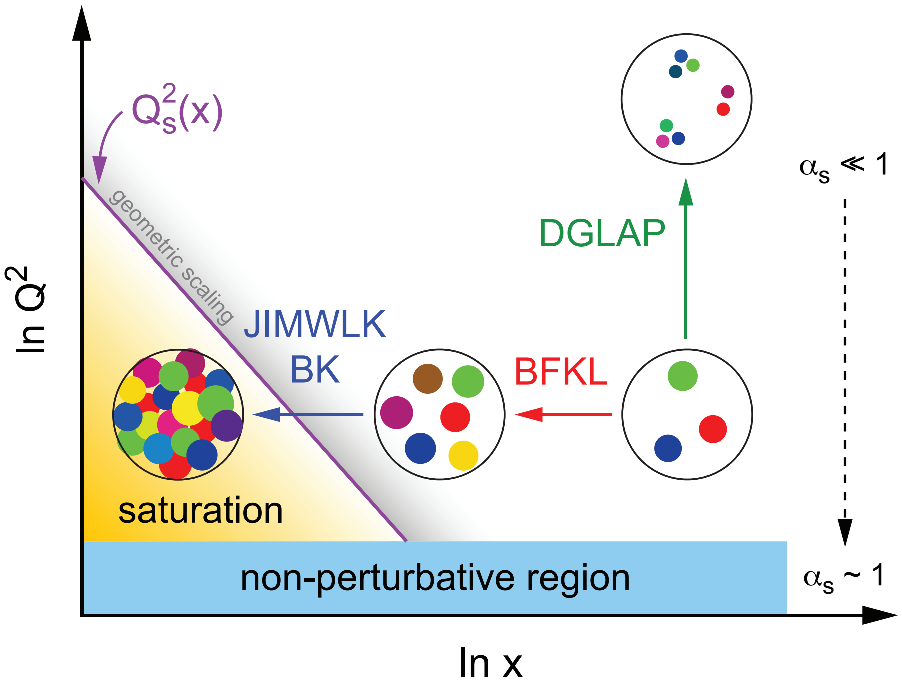


~early 2030s

EIC **C**omprehensive **C**hromodynamics **E**xperiment
Collaboration Detector Proposal

Consider low-x physics…





Is this the correct description of the low-x structure of matter?

How do we test it experimentally?

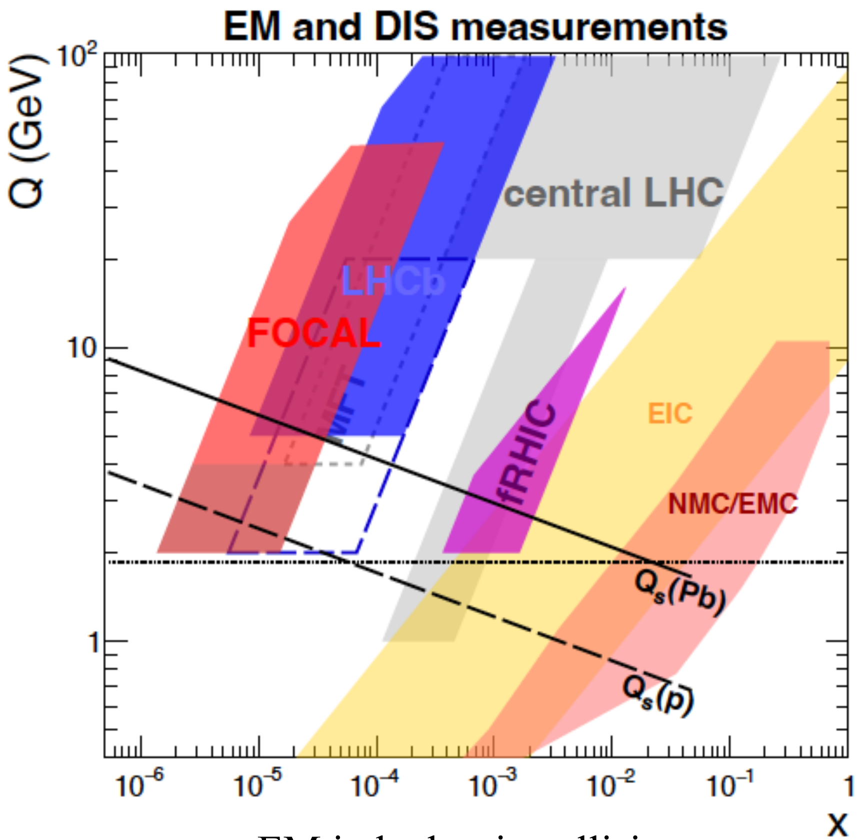
QCD phenomena evolve only logarithmically in x and Q^2

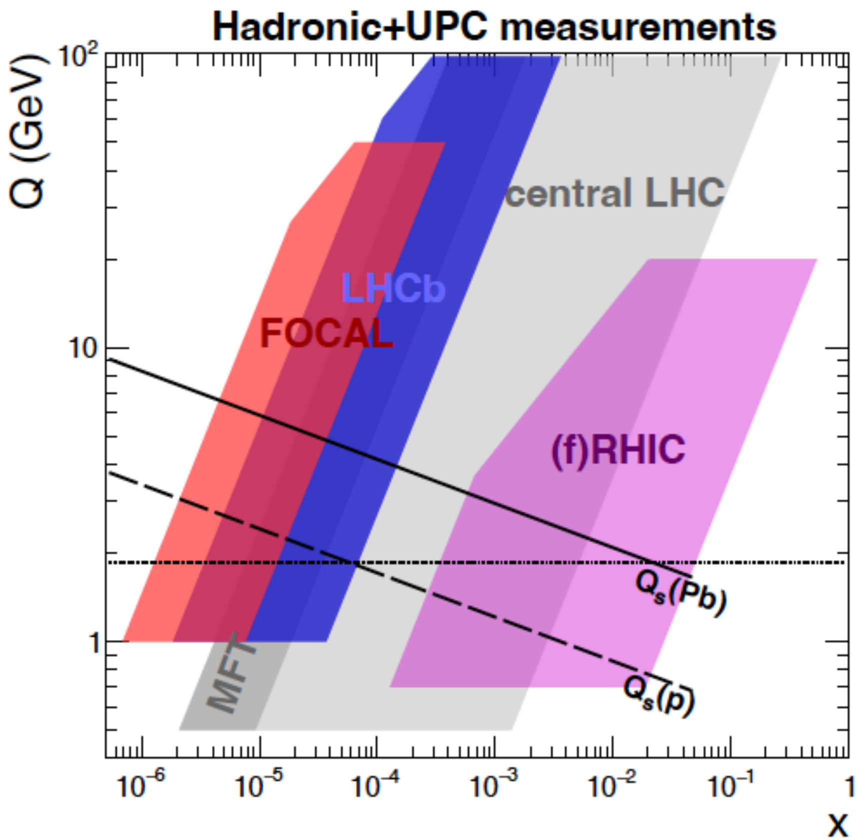
→ experimental study of non-linear QCD evolution requires **"logarithmically broad" coverage in (x,Q^2)**

Universality: correct theoretical description must self-consistently describe measurements of **multiple observables at low (x,Q^2) in multiple collision systems**

Multi-messenger program: combine measurements from e+A DIS and diffractive interactions at EIC, with forward p+A collisions at RHIC and LHC

Current and future saturation experiments: acceptance





EM in hadronic collisions:
direct γ, DY

Exploring non-linear QCD evolution: FoCal measurement strategy

Observables must be clearly interpretable theoretically:

- theoretical description must factorize
- measurements probe the same QCD operators as probed by corresponding measurements in e+A DIS

Observables must have high statistical precision and systematic accuracy (~10%) over a wide kinematic range

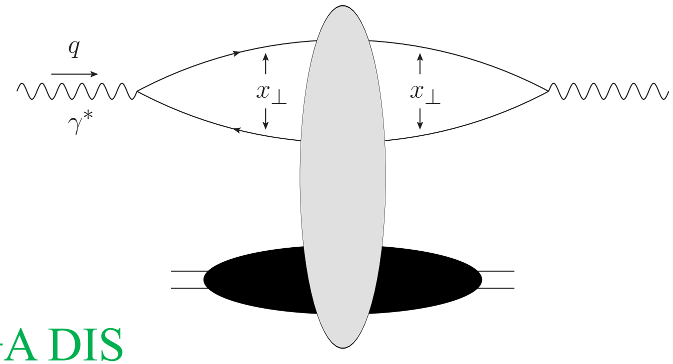
- wide kinematic range: from low (x,Q^2) where saturation effects are expected to high x or Q^2 where saturation effects are expected to be negligible

Minimize sensitivity to poorly-controlled non-perturbative effects in theory calculations, especially modeling of hadronization.

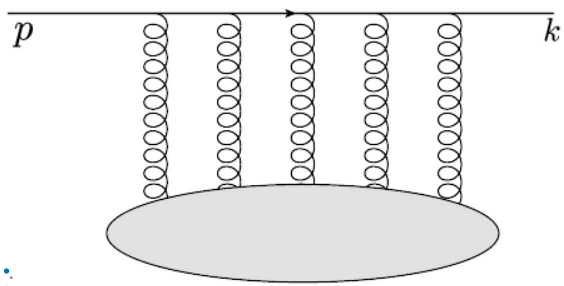
Collision systems:

- p+p @ 5, 8.8 and 14 TeV
- p+Pb @ 8.8 TeV; (both p+Pb and Pb+p)

Theoretical interpretability: dipole formalism



e+A DIS
- Interaction cross section
- Structure Functions F_2, F_L



Forward p+A:
- Inclusive π^0, jet, direct γ,
- γ+jet
- balanced di-jet,…

$$\sigma_{\gamma^* T} = \int_0^1 \mathrm{d}z \int \mathrm{d}^2\mathbf{r}_\perp |\psi^{\gamma^*\to q\bar{q}}(z,\mathbf{r}_\perp)|^2 \sigma_{\mathrm{dipole}}(x,\mathbf{r}_\perp)$$

$$\sigma^{\mathrm{LO}}_{\mathrm{dipole}}(x,\mathbf{r}_\perp) = 2\int \mathrm{d}^2\mathbf{b}\, T_{\mathrm{LO}}(\mathbf{b}+\frac{\mathbf{r}_\perp}{2}, \mathbf{b}-\frac{\mathbf{r}_\perp}{2})$$

$$|M|^2_{\mathrm{LO}} \propto \int \mathrm{d}^2\mathbf{b}\, \mathrm{d}^2\mathbf{r}_\perp e^{i\mathbf{p}_\perp\cdot\mathbf{r}_\perp} T_{\mathrm{LO}}(\mathbf{b}+\frac{\mathbf{r}_\perp}{2}, \mathbf{b}-\frac{\mathbf{r}_\perp}{2})$$

Multiple processes in e+A DIS and forward p+A are described theoretically by the same dipole-medium (or quadrupole-medium) interaction cross section → calculable at NLO

Compare e+A DIS and forward p+A: incisive universality tests

Dipoles in DIS:
Gribov, Sov. Phys. JETP 30 (1970) 709-717
Bjorken and Kogut, Phys. Rev. D 8 (1973) 1341
Frankfurt and Strikman, Phys. Rept. 160 (1988) 235
A. H. Mueller, Nucl. Phys. B 335 (1990) 115
Nikolaev and Zakharov, Z. Phys.C 49 (1991) 607

Dipoles in particle production:
Kopeliovich, Tarasov and Schafer, Phys. Rev. C 59 (1999) 1609
Gelis and Jalilian-Marian, Phys. Rev. D66 (2002) 014021
Kovchegov and A. H. Mueller, Nucl. Phys. B 529 (1998) 451
Kopeliovich, Raufeisen and Tarasov, Phys. Lett. B 503 (2001) 91

EIC Yellow Report: e+A DIS vs forward p+A

Nucl. Phys. A1026 (2022) 122447

Sect. 7.5.4: Low-x gluons and factorization in eA (ep) vs pA and AA

"…pA collisions can serve as a gateway to the EIC as far as saturation physics is concerned, and it also plays an important and complementary role in the study of these two fundamental gluon distributions (Weiszacker-Williams and Dipole)…The small-x factorization in DIS and pA collisions is expected to hold at higher order [1228], since the higher-order corrections do not generate genuine new correlators in the large Nc limit."

quadrupole

dipole

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in p+A	γ+jet in p+A	dijet in p+A
xG_{WW}	−	−	+	−	−	+
xG_{DP}	+	+	−	+	+	+

Table 7.2: The process dependence of two gluon distributions (i.e., the Weizsäcker-Williams (WW for short) and dipole (DP for short) distributions) in e+A(e+p) and p+Acollisions. Here the + and − signs indicate that the corresponding gluon distributions appear and do not appear in certain processes, respectively.

Probes several TMD gluon distributions

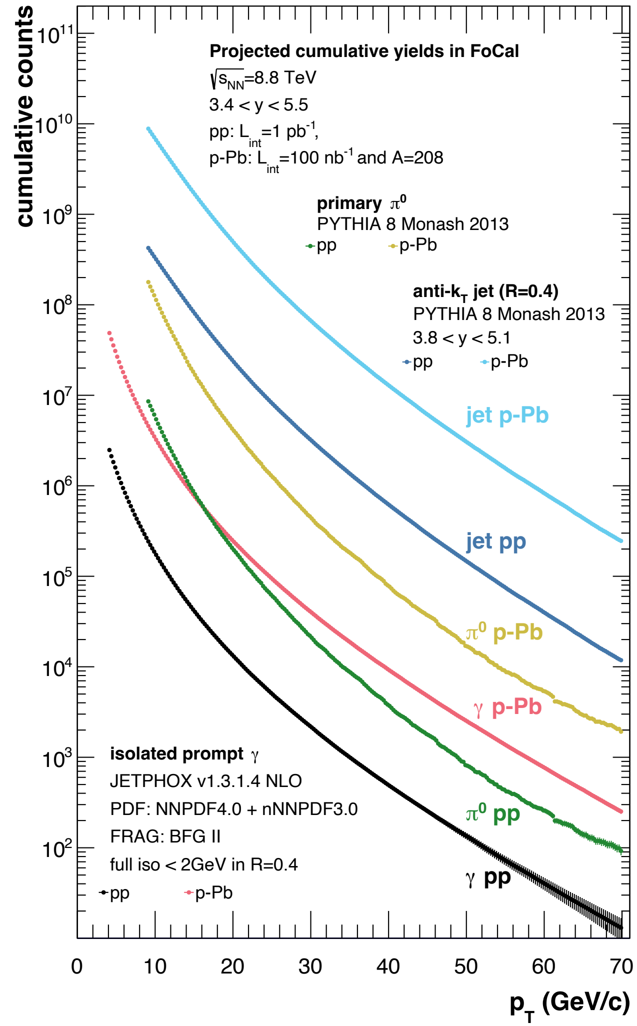
Production rate projections for Run 4

Current int lumi projections

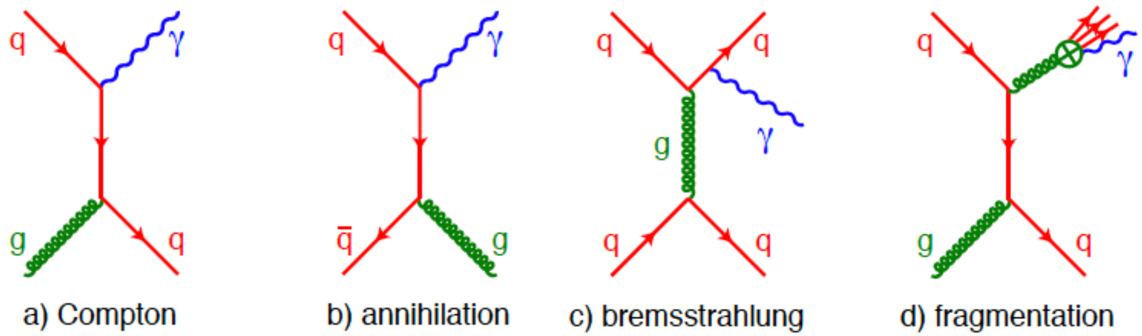
- pp at $\sqrt{s}$=8.8 TeV: 1 week, $\mathcal{L}$=4 pb^{-1};
- p–Pb at $\sqrt{s}$=8.8 TeV: 3 weeks, $\mathcal{L}$=300 nb^{-1}; (both polarities)
- Pb–Pb at $\sqrt{s_{NN}}$=5.02 TeV: 3 months; $\mathcal{L}$=7 nb^{-1};
- pp at $\sqrt{s}$=14 TeV: ≈ 18 months, $\mathcal{L}$=150 pb^{-1};

Significant rate for inclusive γ, π^0 and jet production, from very low to very high p_T

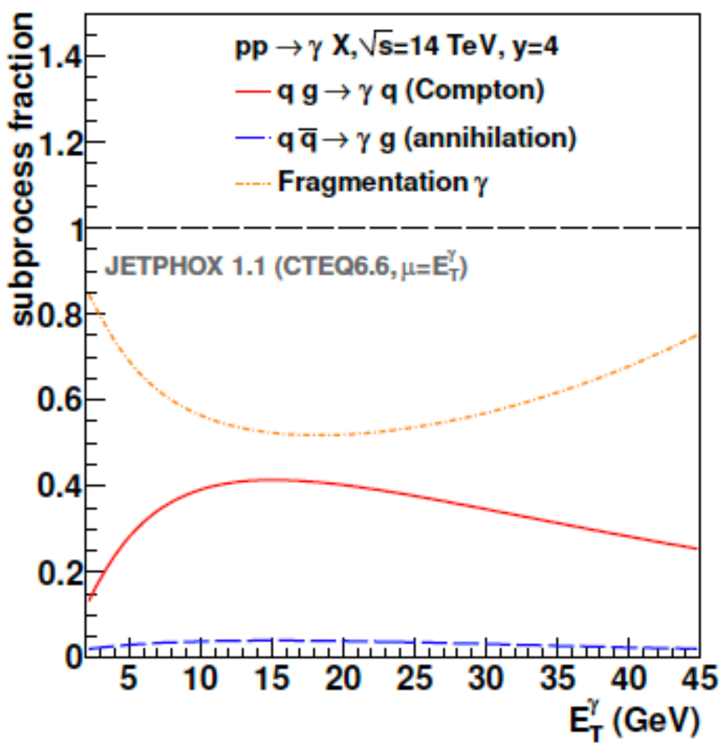
Inclusive channel rates
“Round number” int lumi



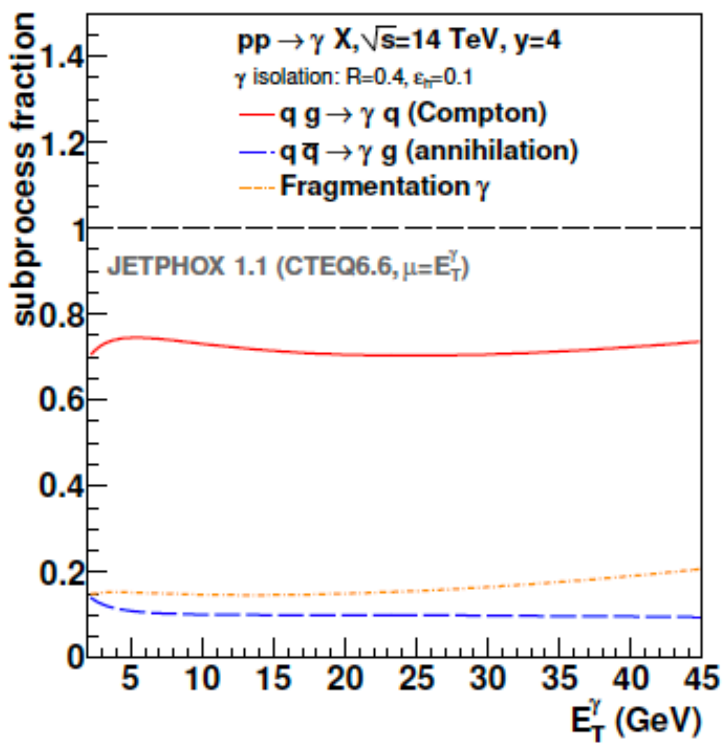
Forward direct γ: partonic processes



No isolation



Isolated (R=0.4, cut=10%)



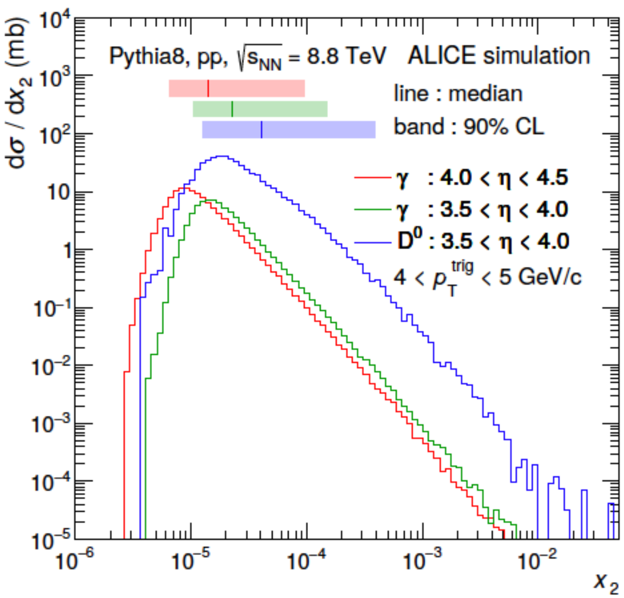
Partonic kinematics

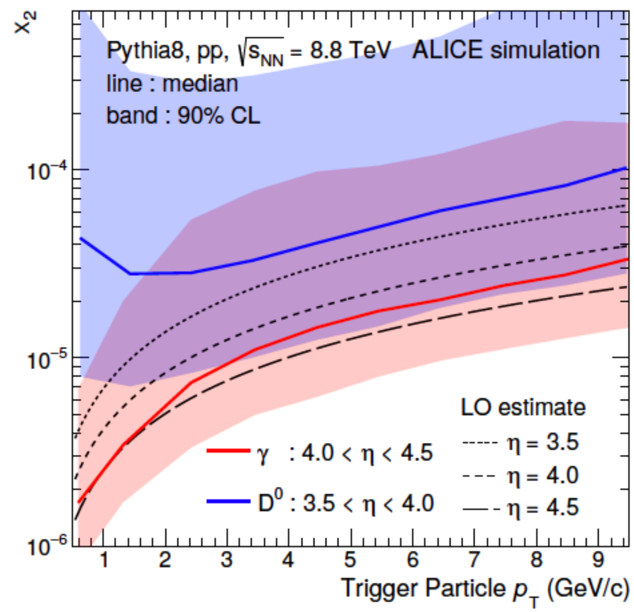
What is the reach in *x* for specific observables?

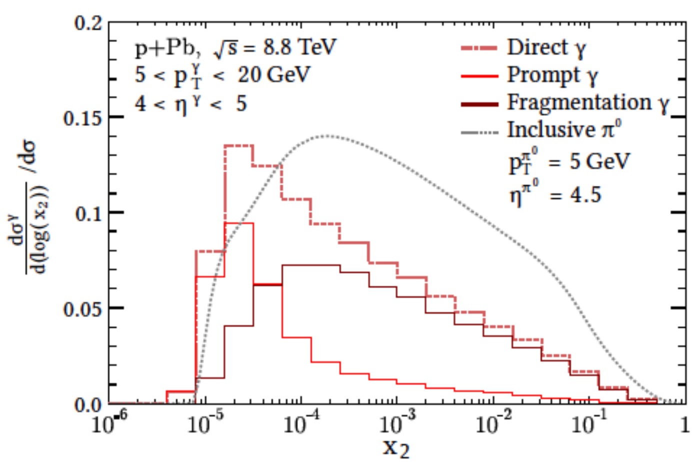
PYTHIA-generated events for pp collisions at 8.8 TeV

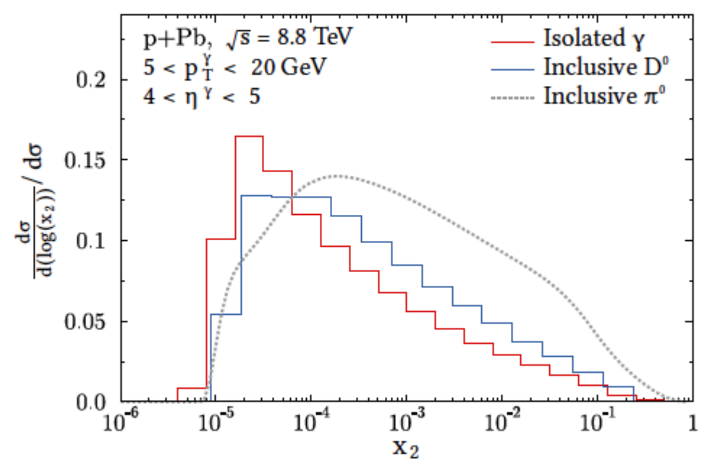
LO estimate: $$x_{1,2} \approx \frac{2p_{\mathrm{T}}}{\sqrt{s}} \exp(\pm y)$$

Partonic kinematics:
γ, π^0 (FoCal); D-meson (LHCb)



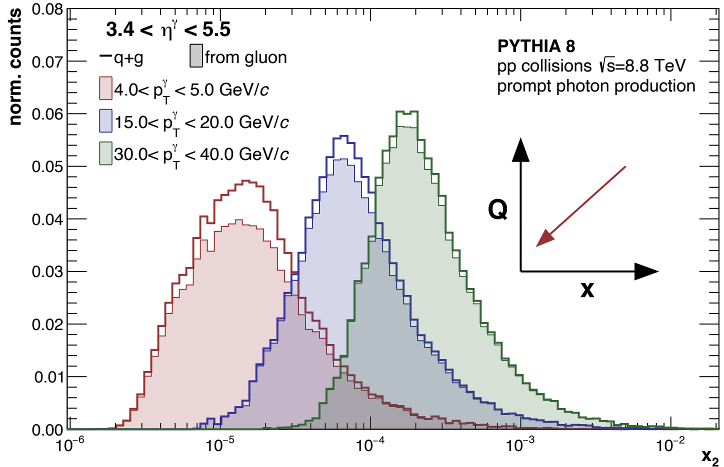




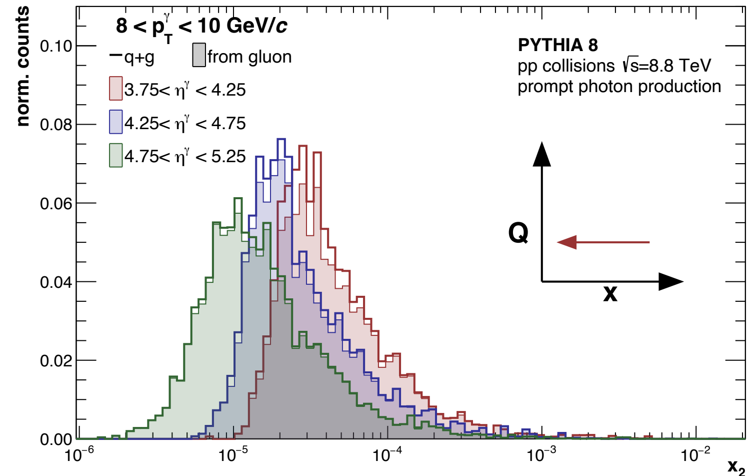


Partonic kinematics: γ in FoCal

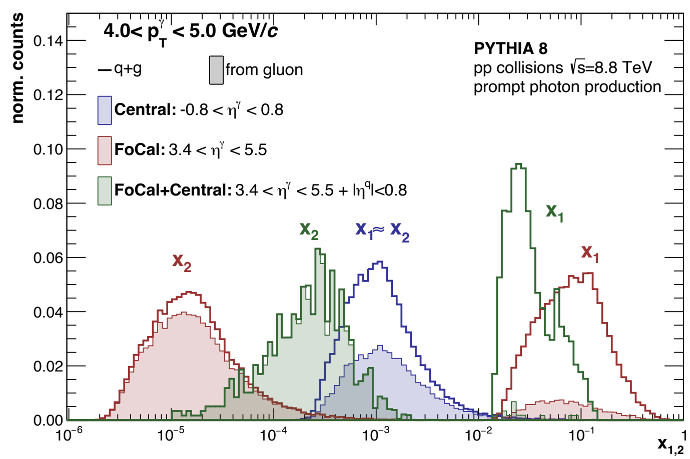
p_T dependence

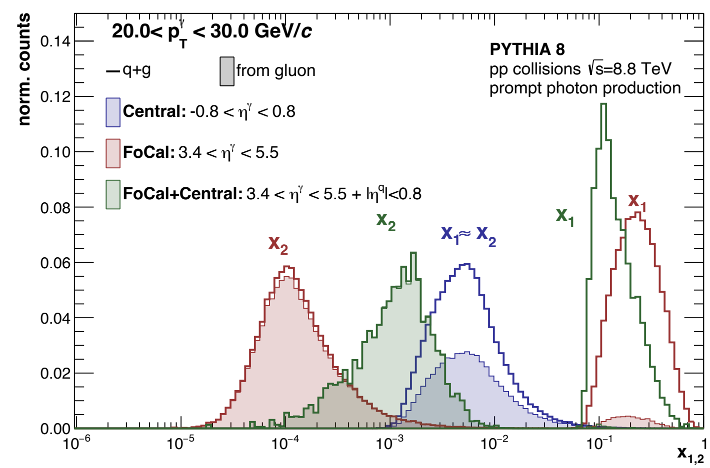


η dependence



FoCal vs Central Barrel

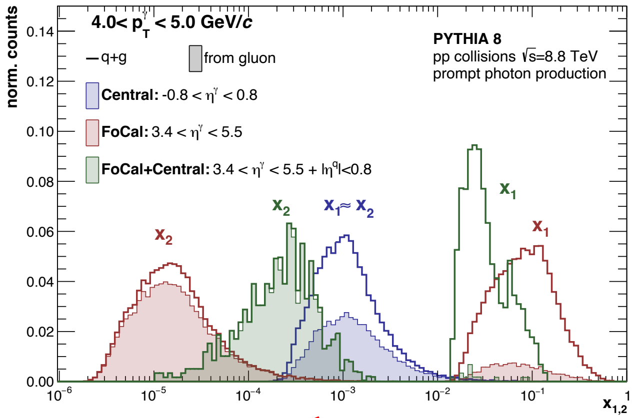




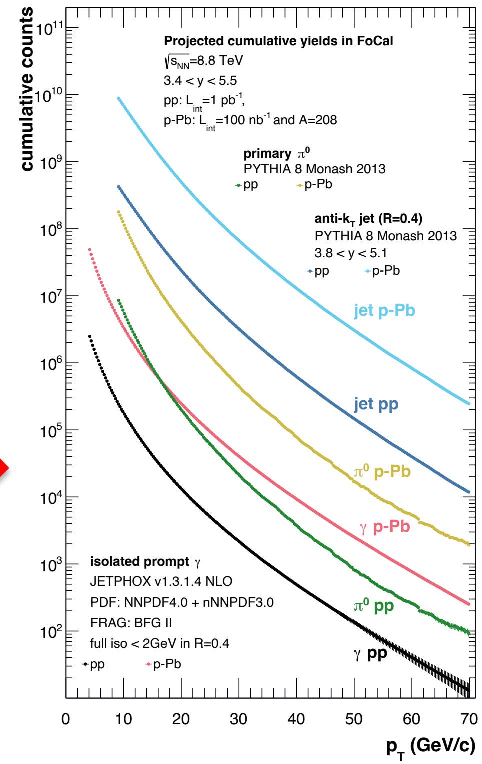
FoCal has flexibility to tune partonic kinematics over significant range
→ overlap with EIC kinematics

γ+jet rates: forward/central

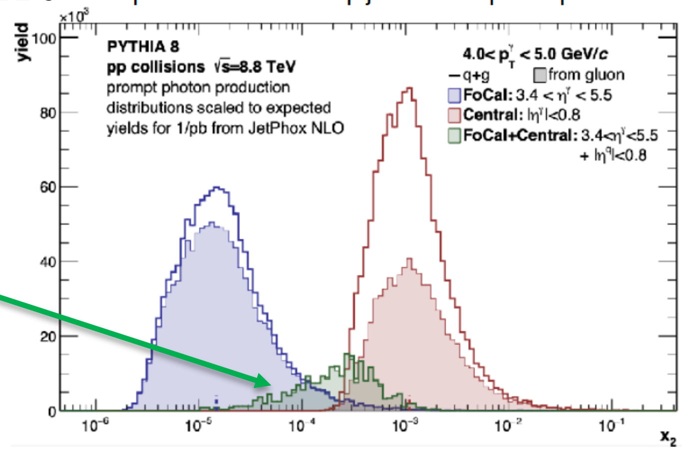
x-coverage (probability)



Trigger rates



x10^3 Expected counts of γ-jet events per 1/pb



γ: FoCal
jet: central

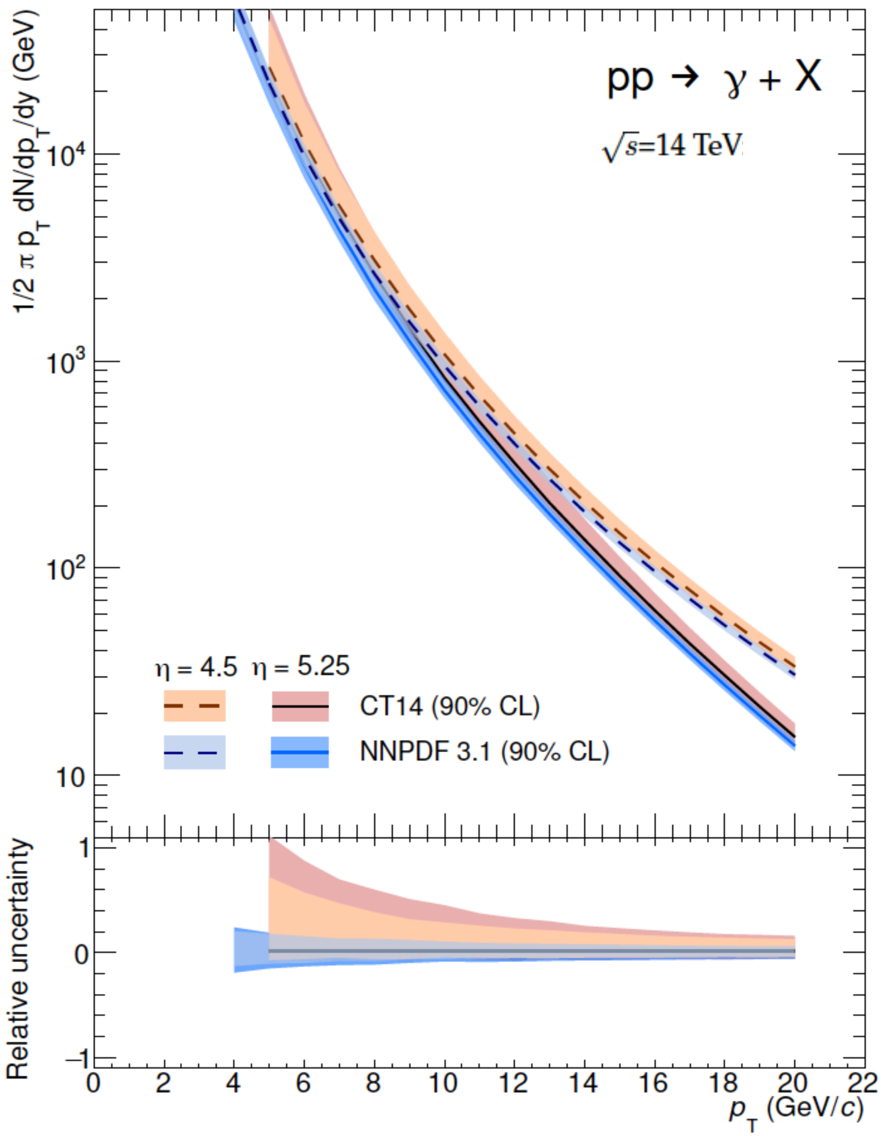
Significant rate of γ+jet coincidences forward/central

Predictions for selected FoCal measurements of saturation in hadronic collisions

This is a rapidly developing topic.

These calculations provide the best current estimate of the magnitude of saturation effects that FoCal could see.

14 TeV pp collisions: forward isolated photons



Compare two recent PDF fits: tension in FoCal acceptance

- FoCal provides unique constraints of pp PDFs

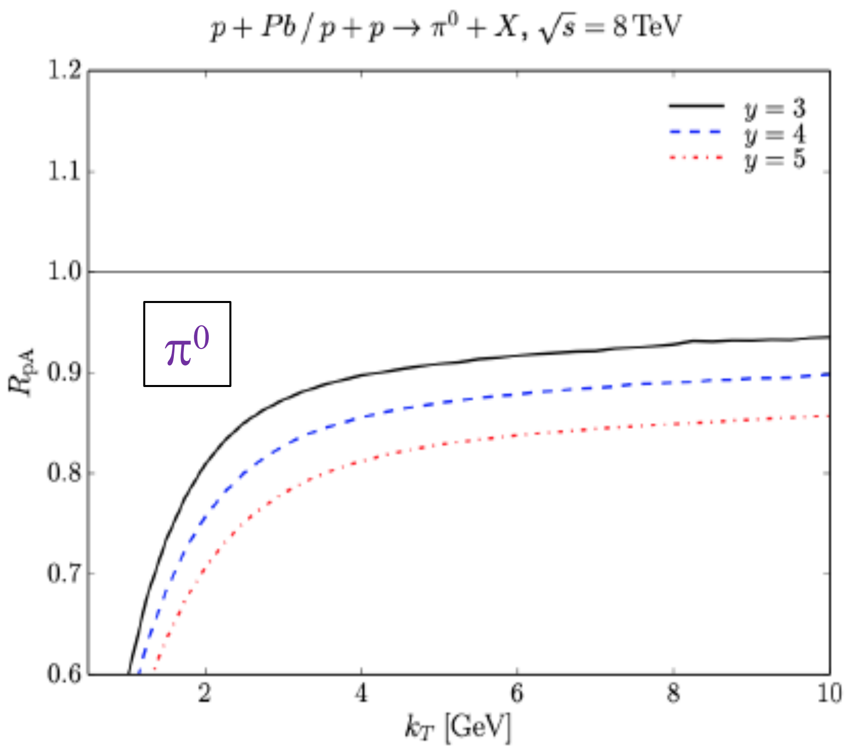
FoCal probes *x* ~5x10^{-7}

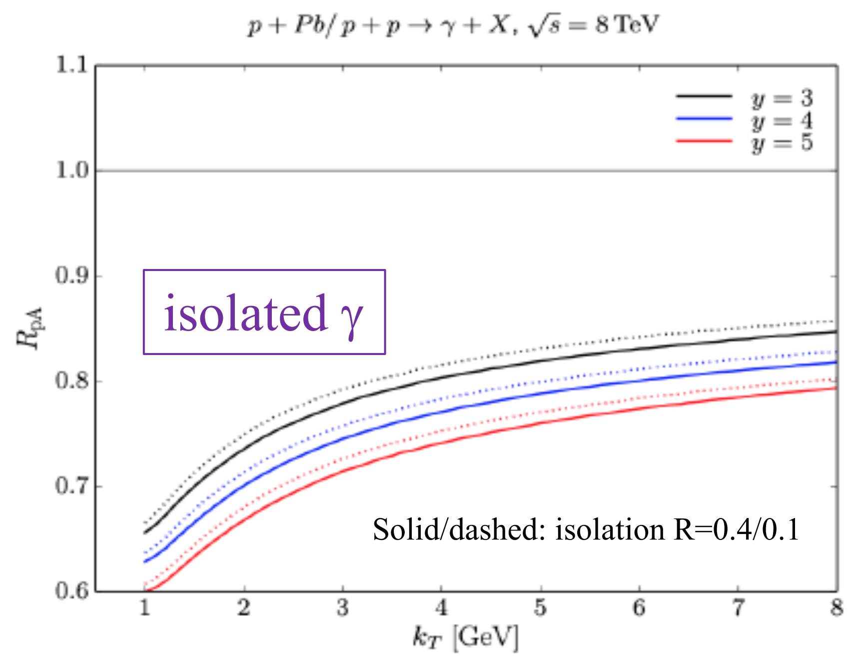
- sensitive to saturation effects even in pp collisions?

R_{pPb}: forward π^0, γ

Ducloué, Lappi, and Mäntysaari, Phys. Rev. D97 (2018) 054023

LO Dipole-CGC calculation





Significant difference in low p_T suppression between π^0 and isolated γ

Different production channels have different sensitivity to saturation

- π^0: $p_T >> Q_{sat}$
- Direct γ: $qg \rightarrow \gamma g$; $k_T \sim Q_{sat}$

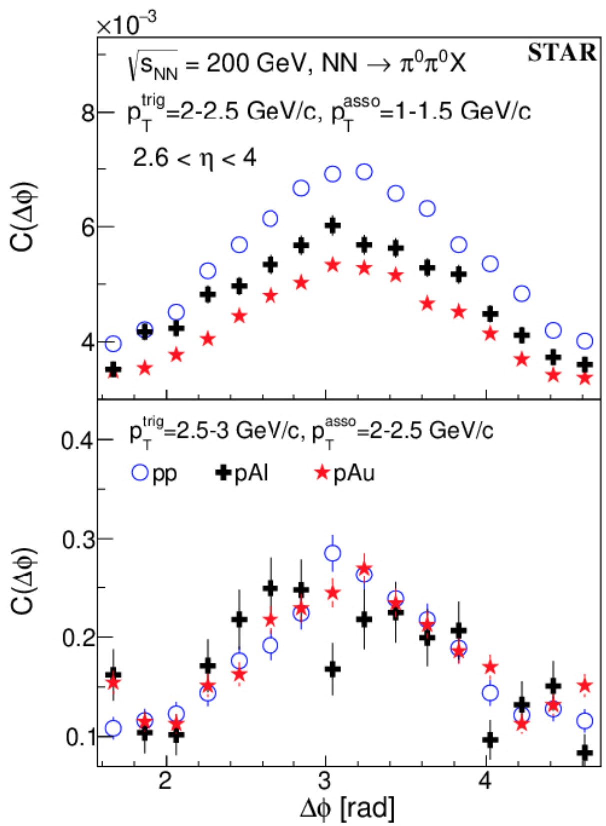
Authors: picture may change @ NLO

Lesson for FoCal: both measurements should be done

Also measurable by LHCb in less forward acceptance

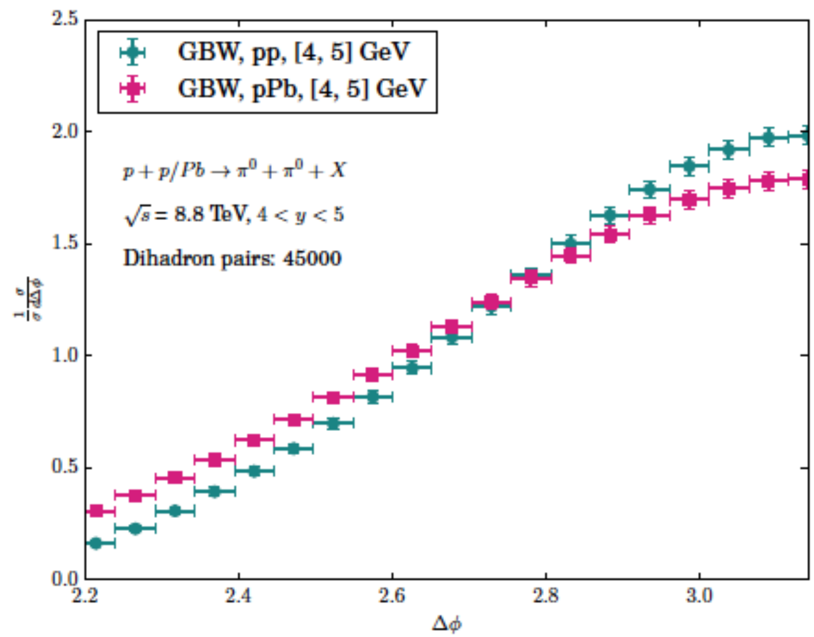
Di-hadron correlations RHIC/LHC

STAR, Phys. Rev. Lett. 129 (2022) 09250



- A-dependent recoil yield suppression
- no significant azimuthal broadening (!)

Stasto, Wei, Xiao, and Yuan, Phys. Lett. B784 (2018) 301



Dilute-dense LO + Sudakov

- probes quadrupole operator
- fits STAR data similar to left panel

Small broadening effect: experimentally challenging

- NLO needed for theory uncert.

Forward γ+jet, di-jet

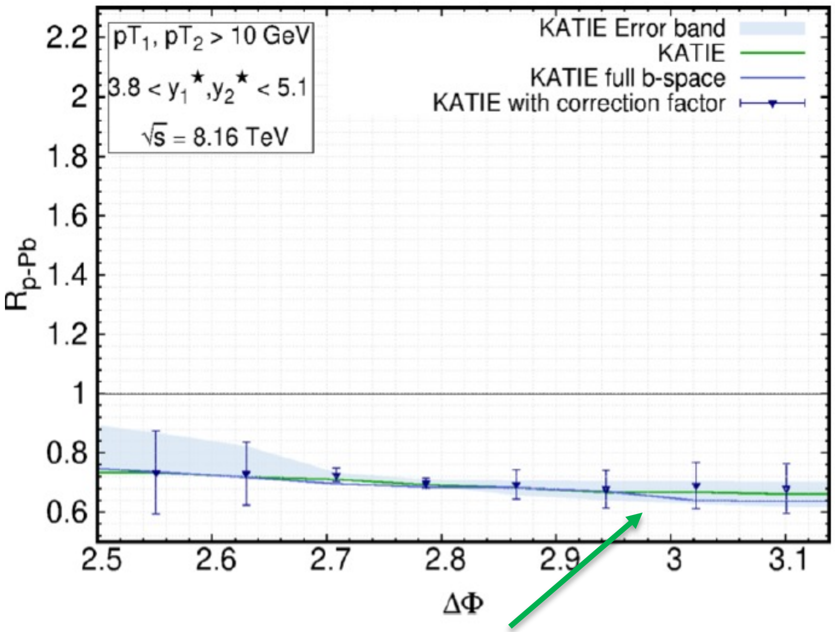
γ+jet, balanced di-jet at low-x: $k_T \sim Q_{sat}$

- k_T provides knob to dial between saturation and linear QCD
- γ+jet: dipole TMD gluon distribution
- di-jet: multiple TMD distributions

KaTie (Kotko et al.)

- Improved TMD (iTMD) framework
- Sudakov resummation
- NP effects: jet showering, hadronization (PYTHIA)

Balanced di-jet acoplanarity



characteristic theory uncertainty

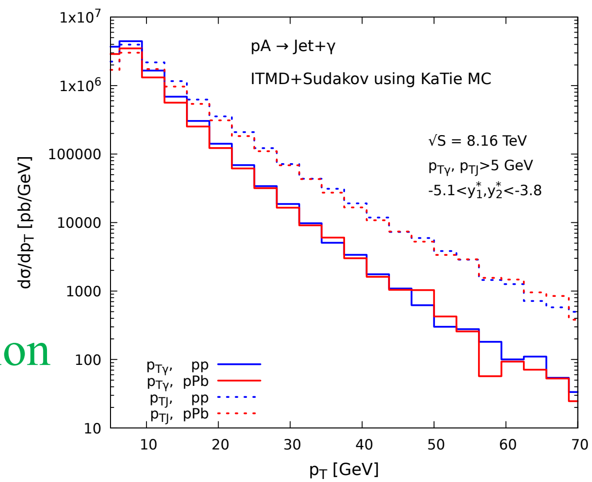
van Hameren, Comput. Phys. Commun. 224 (2018) 371
van Hameren et al., JHEP 12 (2016) 034
Kotko et al., JHEP 09 (2015) 106
Al-Mashad et al., arXiv:2210.06613
Mäntysaari and Paukkunen, Phys. Rev. D 100 (2019) 114029
Liu et al. JHEP 07 (2022) 041
Wang et al. arXiv:2211.08322

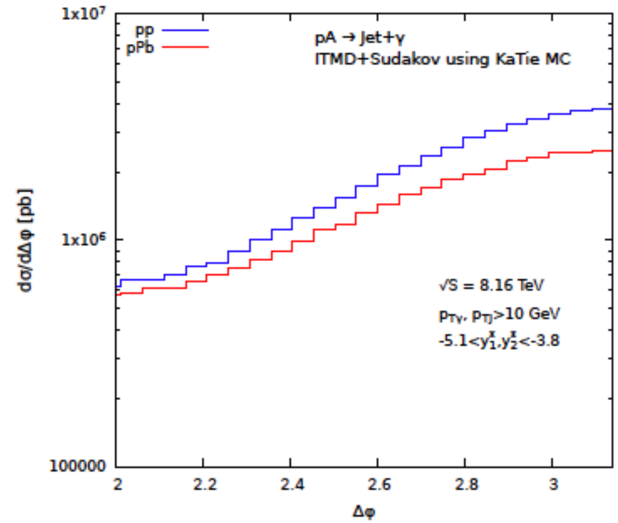
Forward γ+jet, di-jet cont'd

KaTie calculations (Kotko et al., unpublished)

γ+jet distributions:

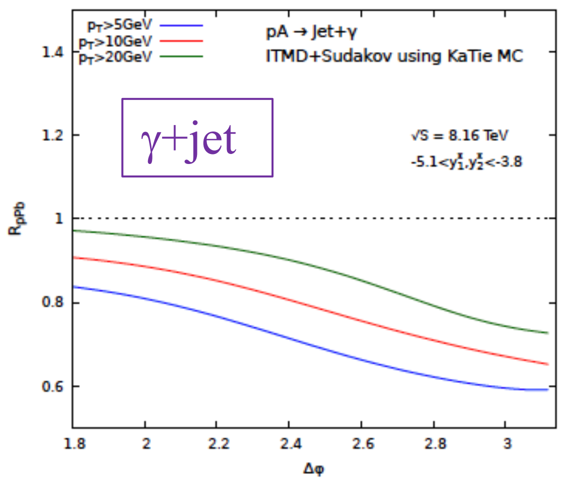
- pPb vs pp
- p_T: negligible modification
- $\Delta\phi$: b-to-b suppression

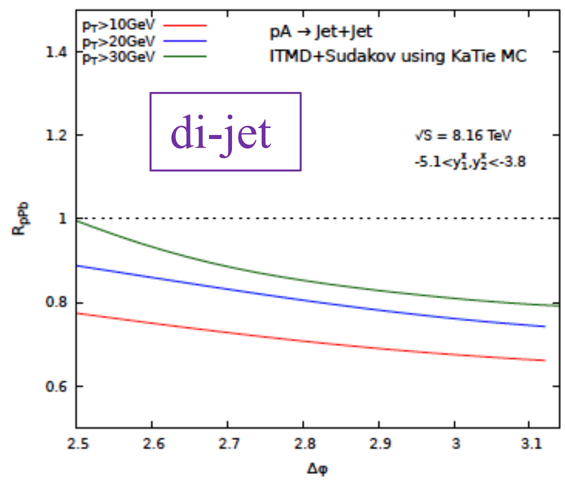




R_{pPb} vs $\Delta\phi$

- γ+jet, di-jet: quantitatively different distributions
- Different color flow probes different physics: dipole vs quadrupole TMD

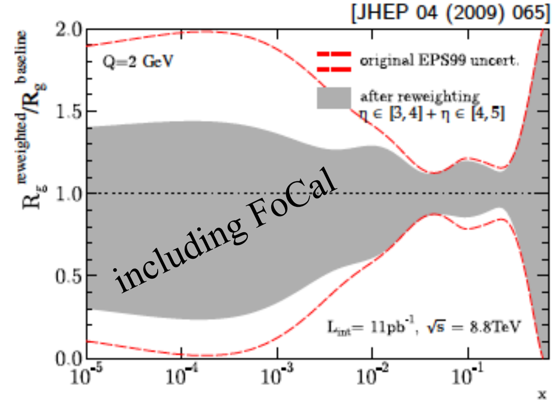


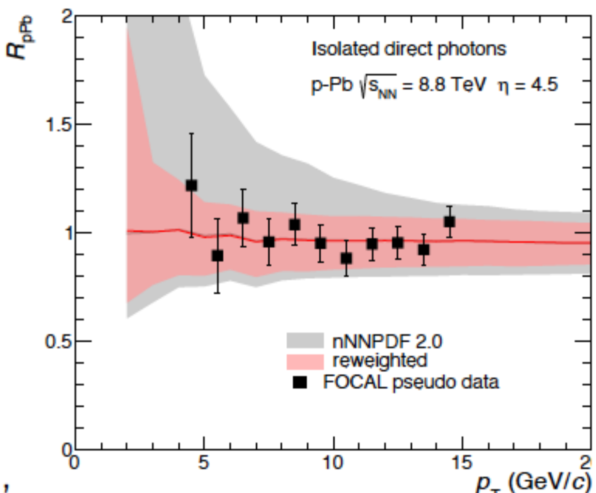


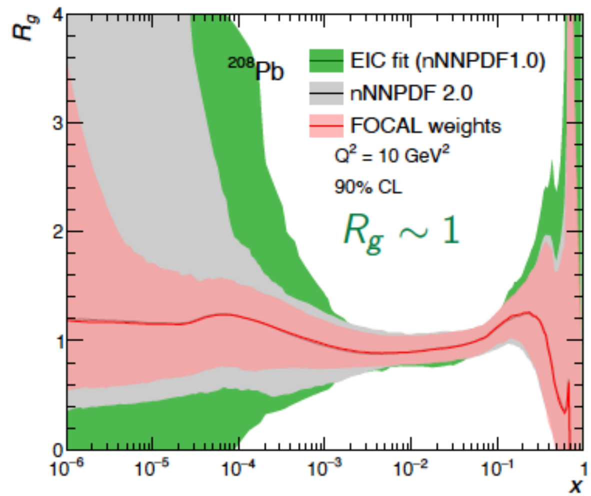
Lesson for FoCal: both measurements should be done

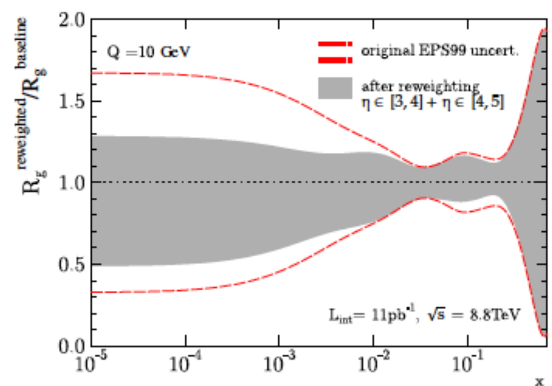
Impact of FoCal on nuclear PDFs

- Excerise: Quantify possible impact of high precision FoCal measurements
- Inclusion of pseudo-data projections using INCNLO allows to estimate impact on nuclear pdfs
- Systematic uncertainties dominated by purity at low p_T
- Potential to reduce significantly uncertainties at low-x even compared to EIC
- Significantly lower $R_{pA} \sim 0.8$ would shift R_g significantly









Reweighting follows approach in [arXiv:1909.05338]

F. Bock (ORNL) | FoCal: photons & jets | January 25, 2023 | 10 / 17

R_g = nuclear modification of gluon PDF

Impact of FoCal on nuclear PDFs

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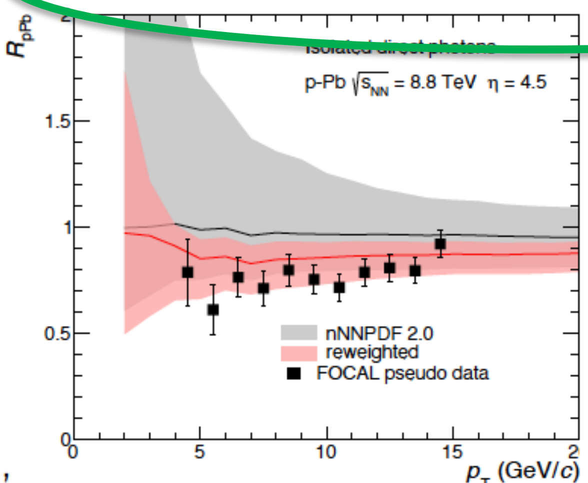
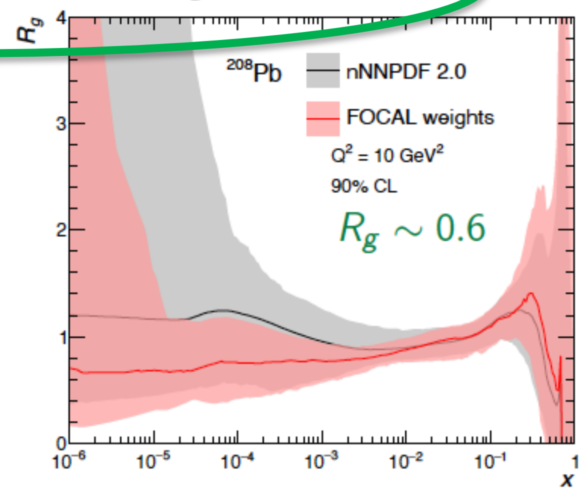
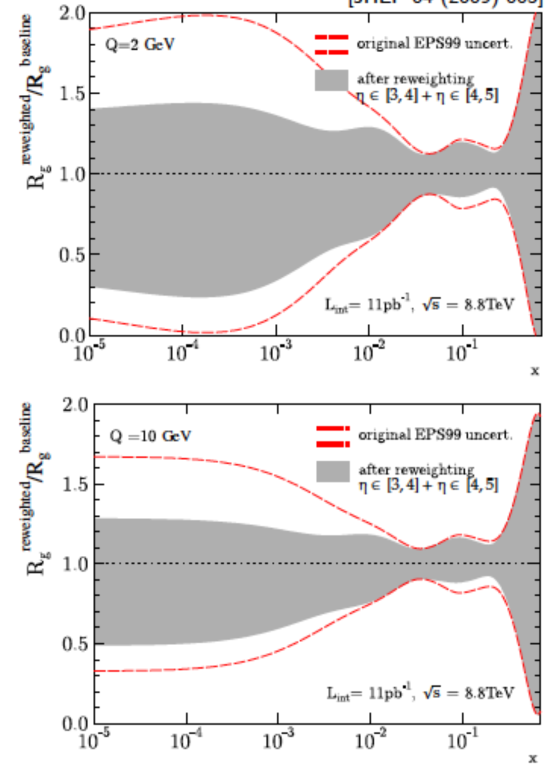
[JHEP 04 (2009) 065]







Reweighting follows approach in [arXiv:1909.05338]

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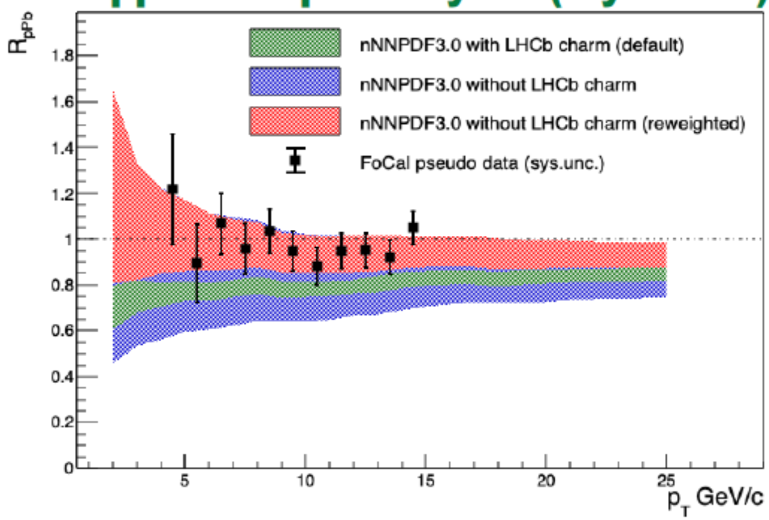
Example of global analysis using nNNPDF3.0

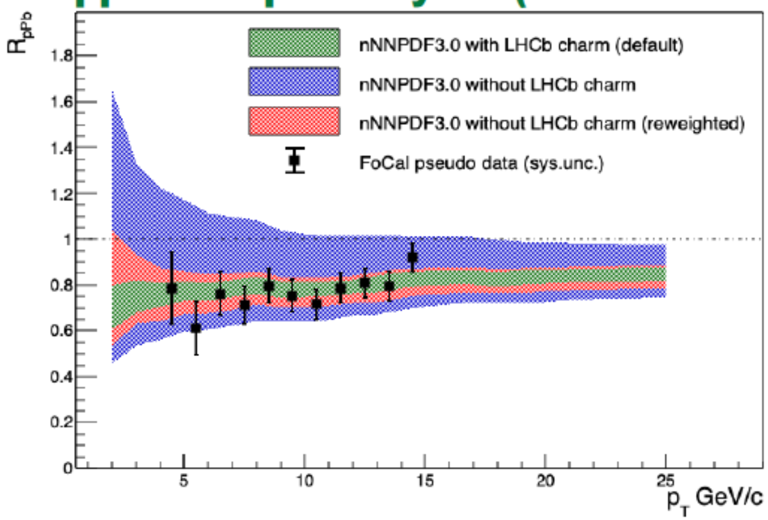
Reweighting follows approach in [arXiv:1909.05338]

[arXiv:2201.12363v2]

Un-Suppressed photon yield (toy-model)



Suppressed photon yield (from nNNPDF2.0)



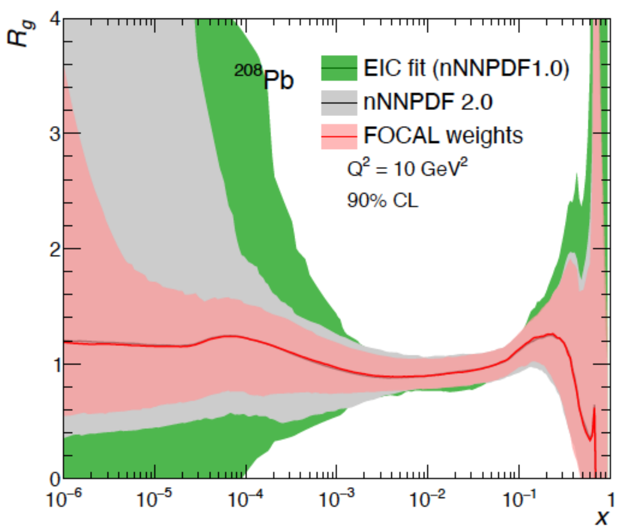
Validate or in-validate factorization/universality

- Non-linear dynamics, if present, could be reabsorbed in the nuclear PDF fit
- To discriminate linear from non-linear evolution may need to go beyond nPDF fits in collinear approximation

Saturation is multi-messenger: how to discriminate linear from non-linear evolution?

Global nPDF fits may not be the full story

- Armesto et al '22: use eA DIS F_2 and F_L to discriminate linear/non-linear evolution; poor discrimination due to ambiguity in initial conditions
- Not included in colinear nPDF fits:
  - angular decorrelation (acoplanarity),
  - Jet substructure
  - Energy-energy correlators
  - ….



Alternative: Bayesian inference

Illustration: Multisystem Bayesian constraints on the transport coefficients of QCD matter

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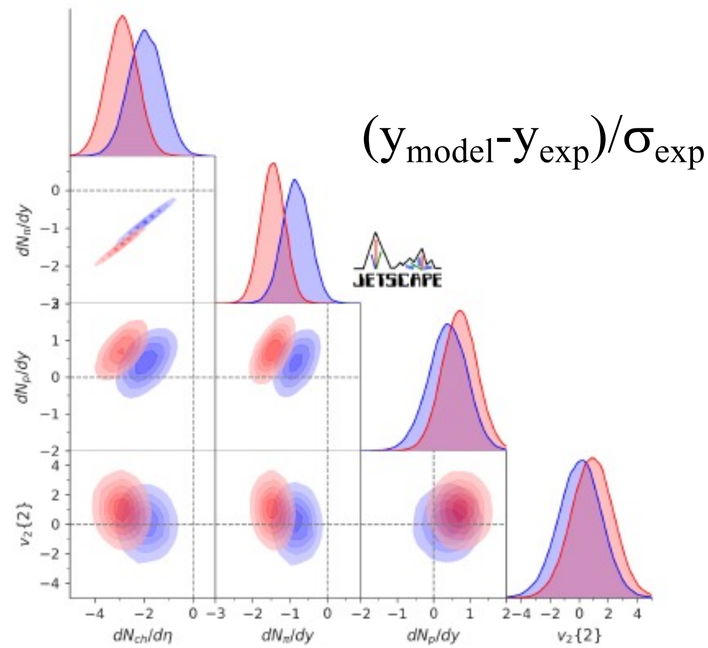


Needs significant development for EIC + fRHIC + fLHC

Summary

Deep theoretical connection between e+A DIS and forward p+Pb for photons, hadrons, jets and correlations

- Probe the same dipole/quadrupole+medium interactions

FoCal has unique forward coverage with huge kinematic reach, from low to high p_T: broad scan of (x,Q^2)

- Complementary to EIC
- Essential for comprehensive universality tests of linear/non-linear evolution

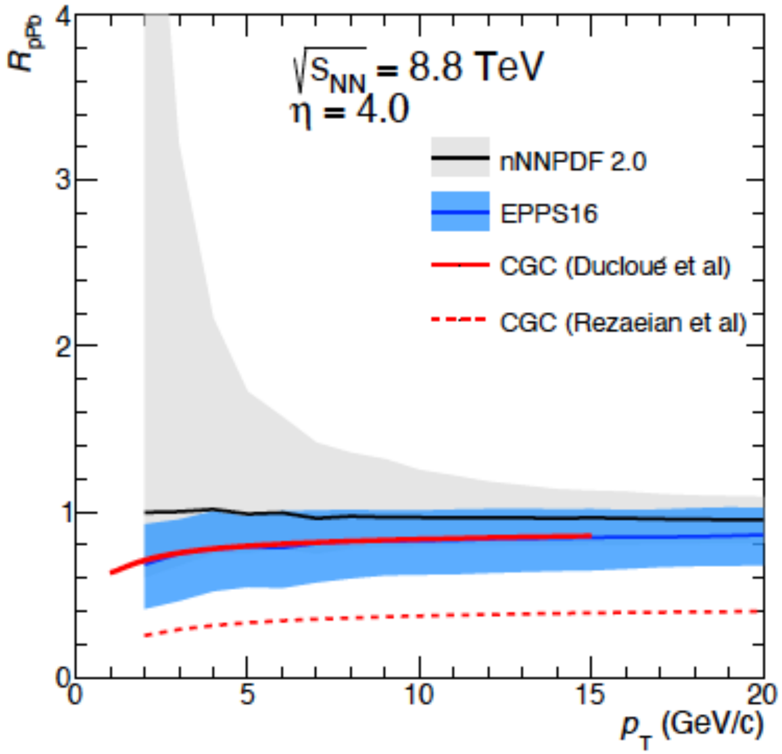
Theory status: NLO calculations needed for many channels

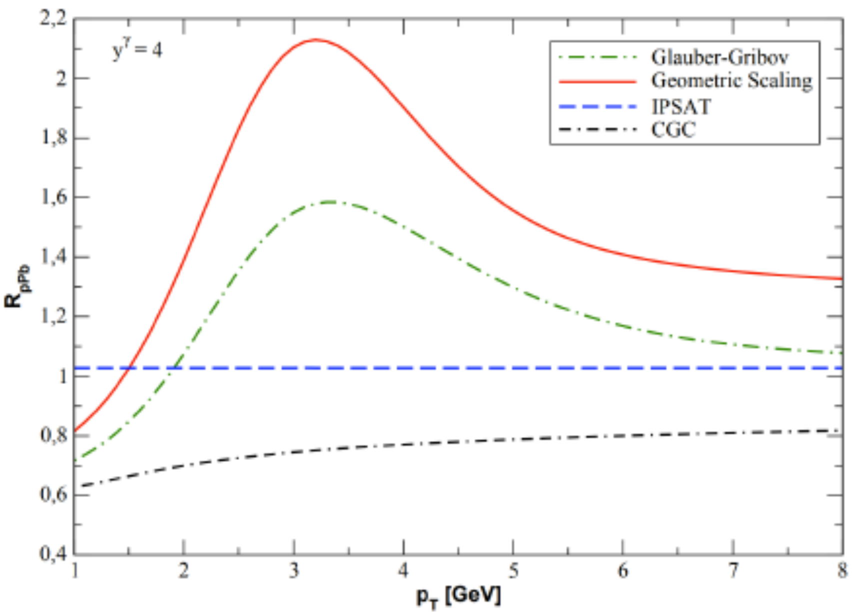
Rigorous comparison between theory calculations and high-dimensional, multi-messenger datasets to discriminate linear from non-linear evolution

- Global nPDF fits
- Bayesian inference
- …

Backup

Isolated γ R_{pPb}: linear vs non-linear evolution





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π^0 and D-mesons from LHCb