Forward physics at the LHC: pp to AA

Peter Jacobs
Lawrence Berkeley National Laboratory

WE-Heraeus-Seminar:
Forward Physics and QCD at the LHC and EIC
Physikzentrum Bad Honnef
Oct 23-27 2023

Forward QCD physics at the LHC: pp to ~~AA~~ pA

Peter Jacobs
Lawrence Berkeley National Laboratory

The organizers asked me to talk about forward LHC physics "from pp to AA" but I only got as far as "from pp to p+Pb"

- this is already a broad topic, and I think is where the greatest interest lies in forward physics at the LHC

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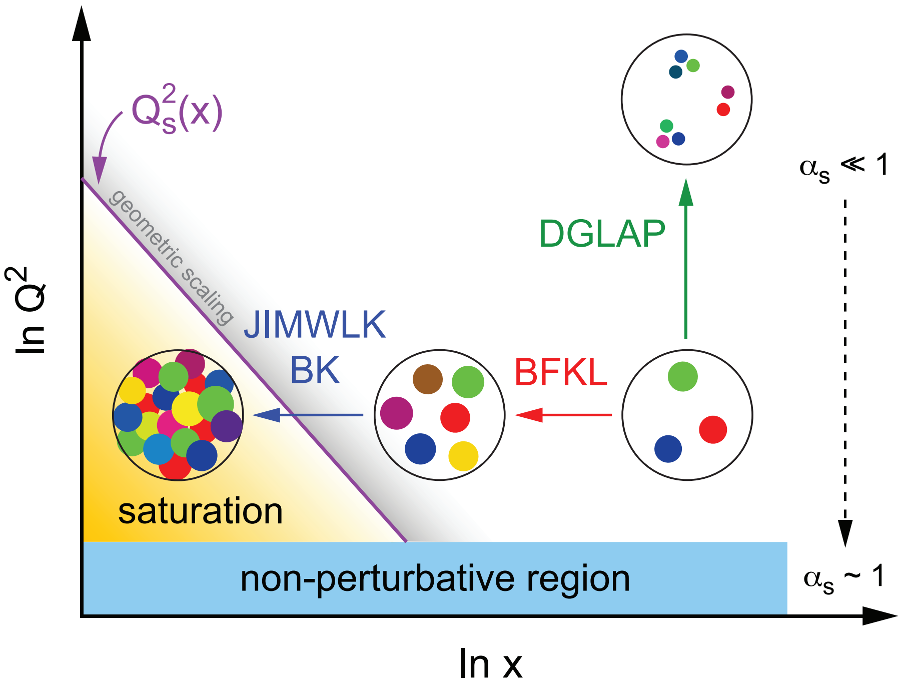
My goal for this talk: present key current and future LHC measurements which probe low-x physics

Very much a work in progress:

- challenging to formulate a comprehensive picture
- that's the focus of this workshop



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

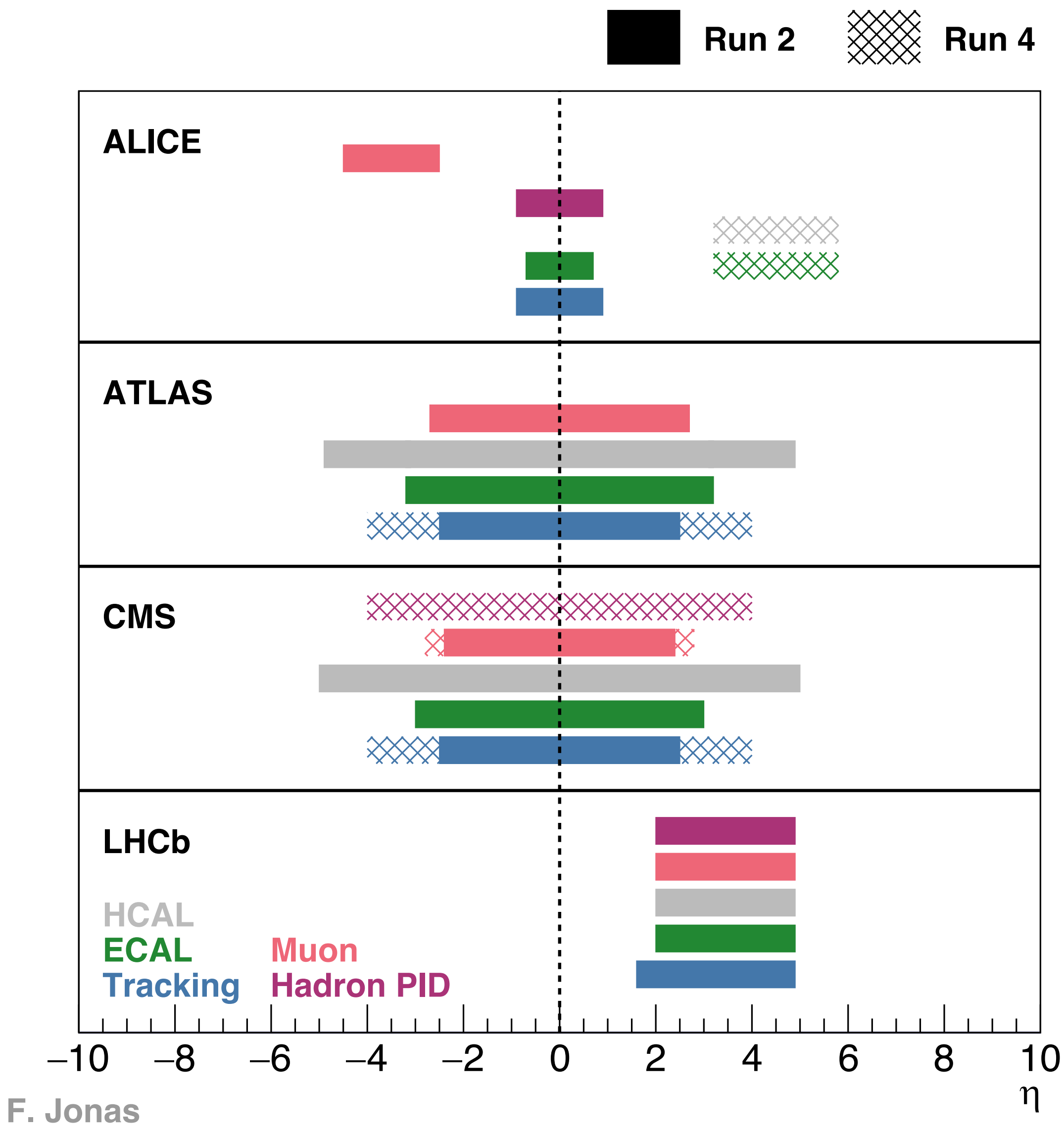
→ experimental study of non-linear QCD evolution requires **"logarithmically broad" coverage in (x,Q^2)**

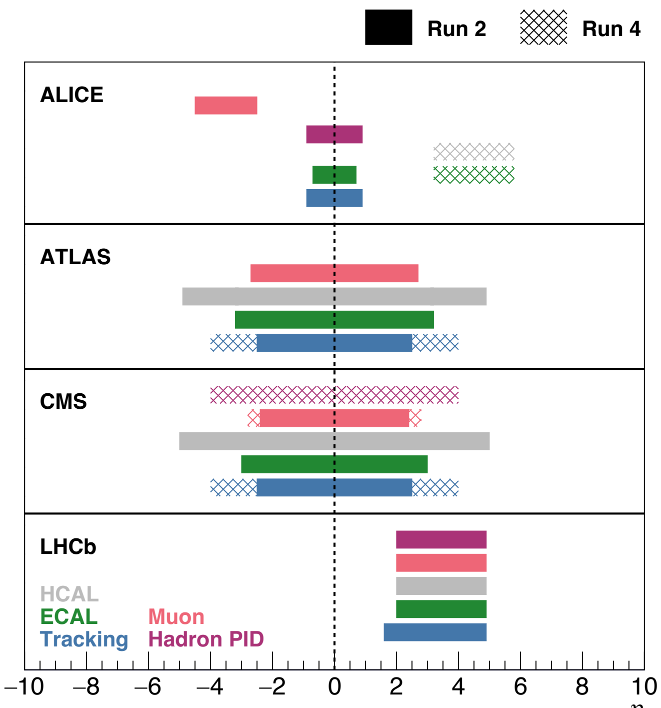
Universality: correct theoretical description must self-consistently describe measurements of **multiple observables at low (x,Q^2) in multiple collision systems**

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

LHC experimental coverage

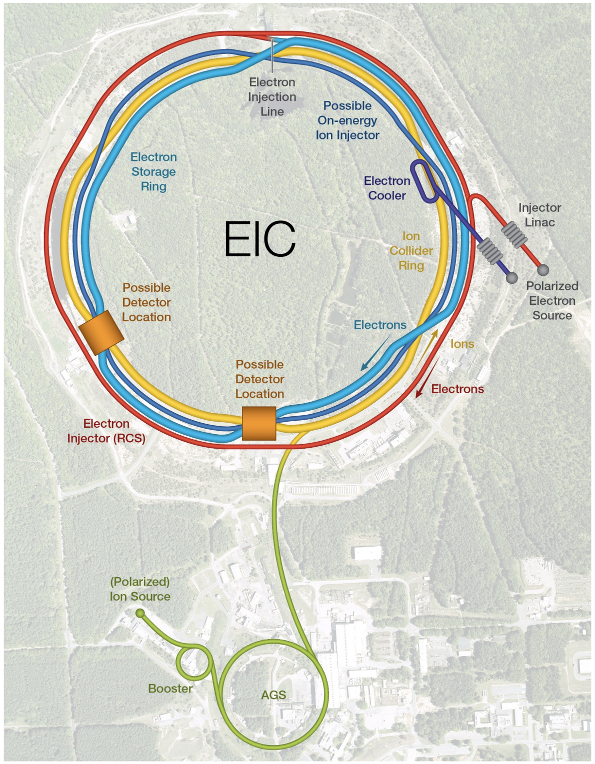
Detectors sensitive to low-x observables



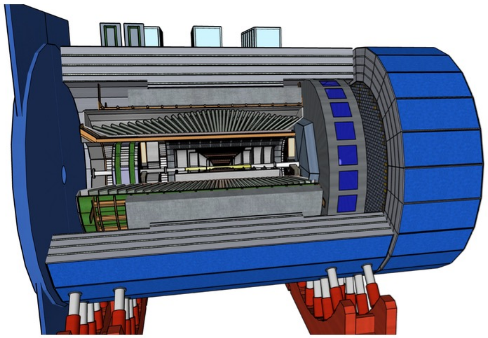


F. Jonas

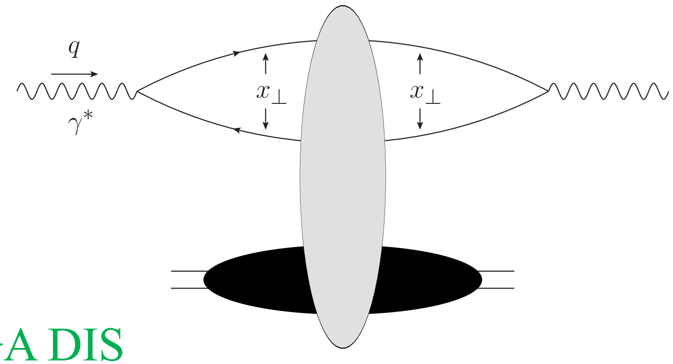
Complementary
for low-x physics?

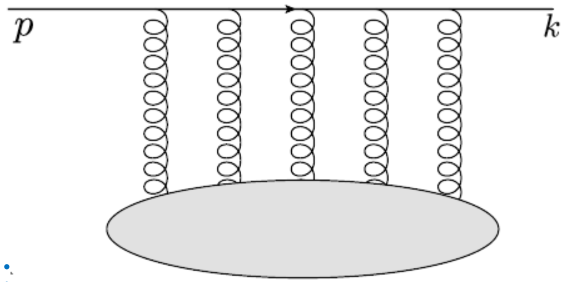


EIC Comprehensive Chromodynamics Experiment
Collaboration Detector Proposal



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,…

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

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

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

Multiple processes in e-A DIS and forward p-A are described theoretically by the same dipole-medium forward scattering amplitude T_{LO} → calculable beyond LO

Compare e-A DIS and forward p-A: universality

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

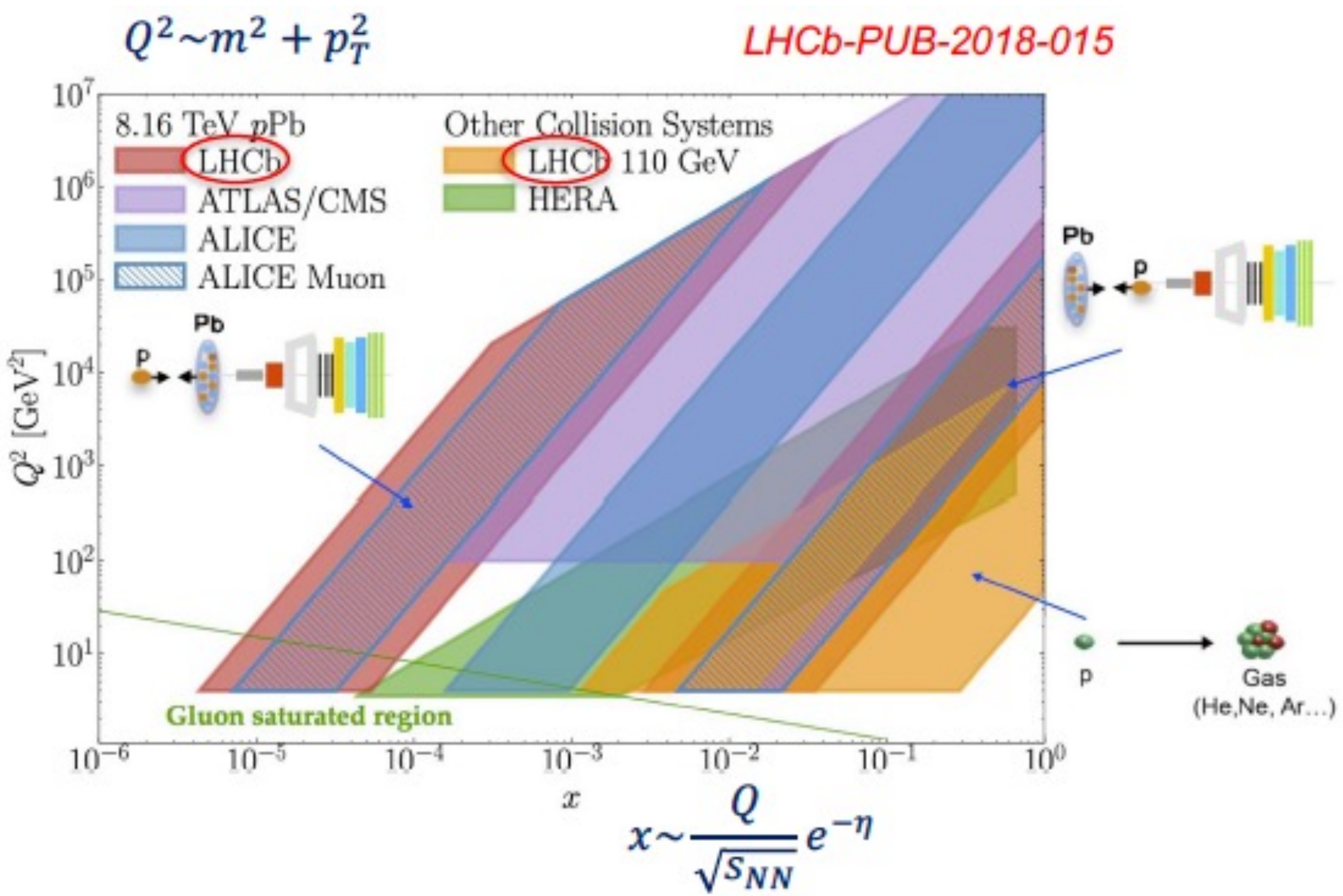
"…pA collisions can serve as a gateway to the EIC as far as saturation physics is concerned, and it also plays an important and complementary role in the study of these two fundamental gluon distributions (Weiszacker-Williams and Dipole)…The small-x factorization in DIS and pA collisions is expected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

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

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.

Forward pA probes unpolarized gluon TMD distributions

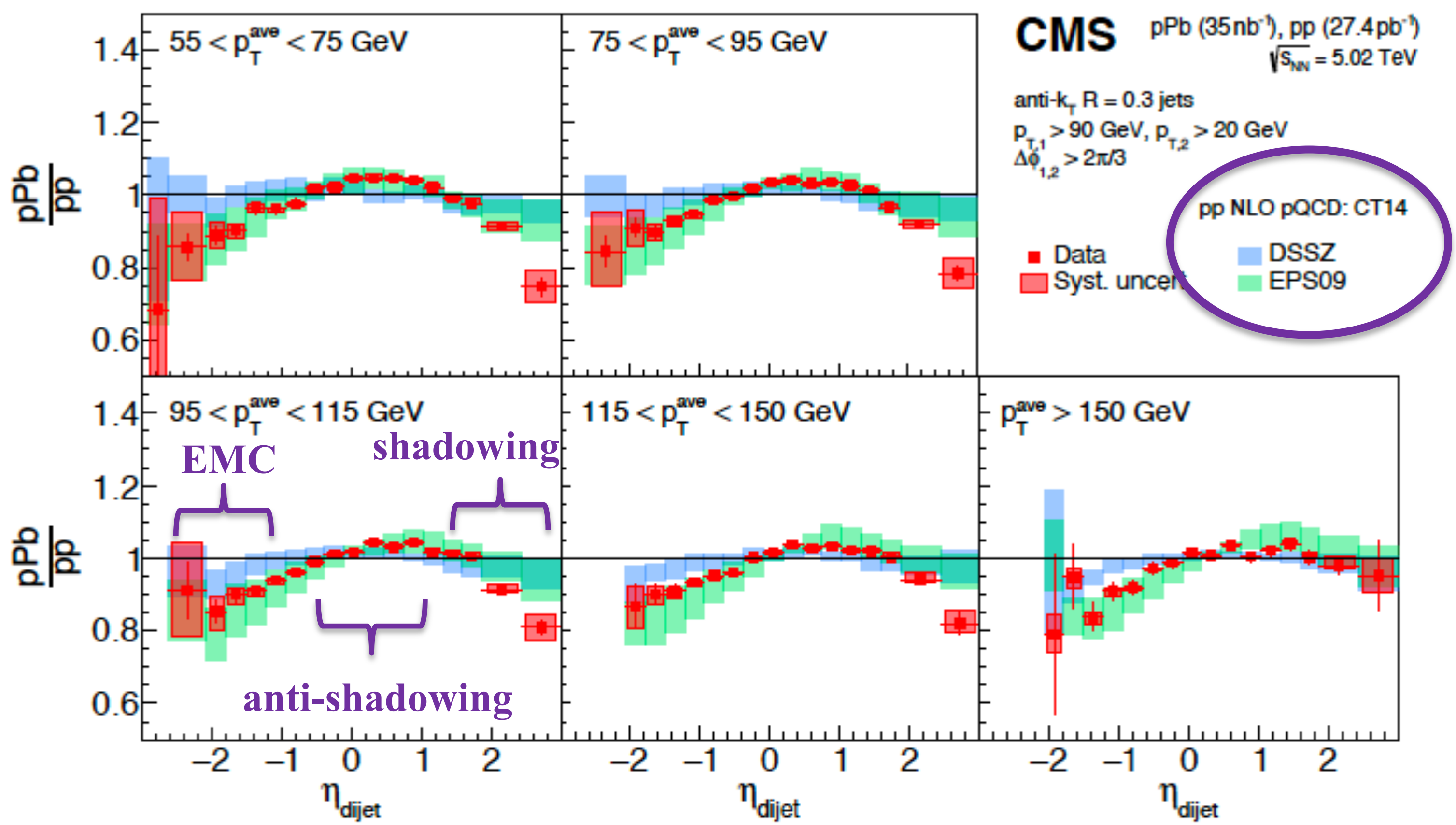
LHC Run 2 results



CMS: forward di-jets in p+Pb

Phys. Rev. Lett. 121, 062002 (2018)
arXiv:1805.04736

$\eta>0$: proton direction
→ low-x in Pb

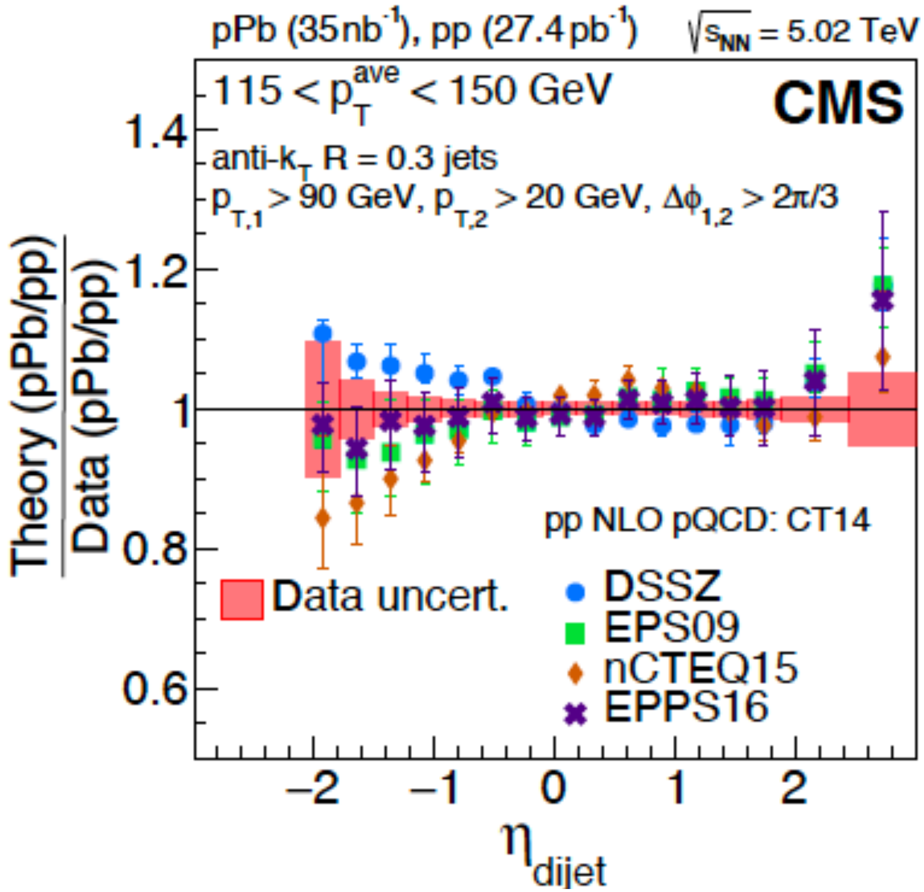


EPS09: gluon EMC effect based on PHENIX π^0
DSSZ: does not incorporate gluon EMC effect

} gluon EMC effect directly observable!

CMS: forward di-jets in p+Pb

Phys. Rev. Lett. 121, 062002 (2018)
arXiv:1805.04736



Significant discrimination of nPDF implementations

DSSZ w/o gluon EMC effect: disfavored

EPS09: EMC implementation compatible with data

nCTEQ15: overshoots EMC and anti-shadowing effects

EPPS16 similar to EPS09 w/ relaxed constraints; larger nPDF uncertainties

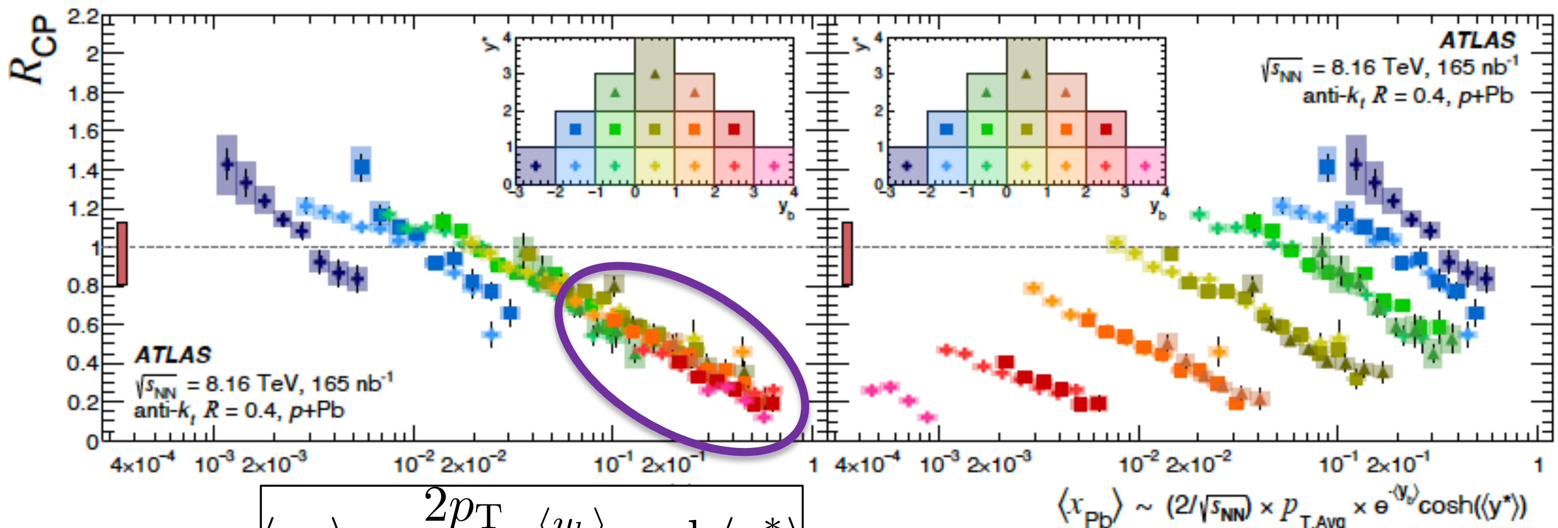
ATLAS: forward di-jets in p+Pb

arXiv:2309.00033

Events classified by Event Activity (EA) based on forward E_T ("centrality")

R_{CP}: ratio of yields for high/low EA

- scaled by Glauber-model factor assuming EA is geometric in origin



$$\langle x_p \rangle \sim \frac{2p_{\mathrm{T}}}{\sqrt{s}} e^{\langle y_b \rangle} \cosh\langle y^* \rangle$$

Di-jet kinematics:

y_b=pair boost

y*=half-separation in rapidity

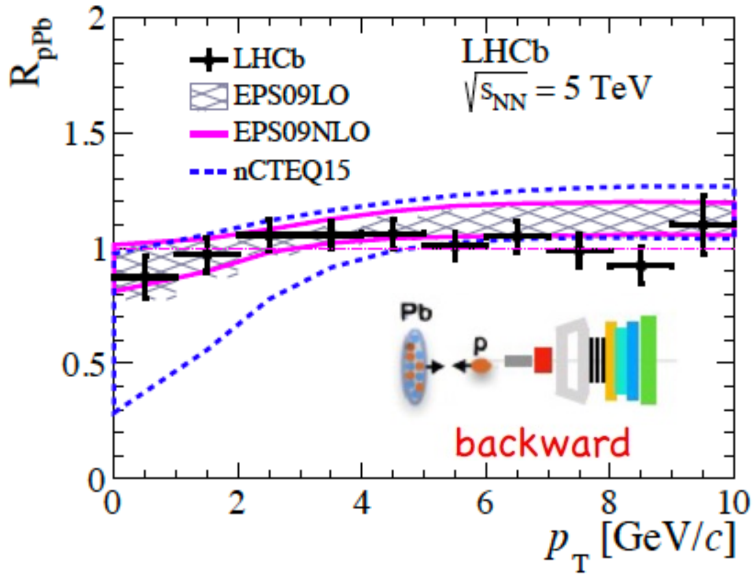
Striking scaling of high-EA yield suppression at large $\langle x_p \rangle$

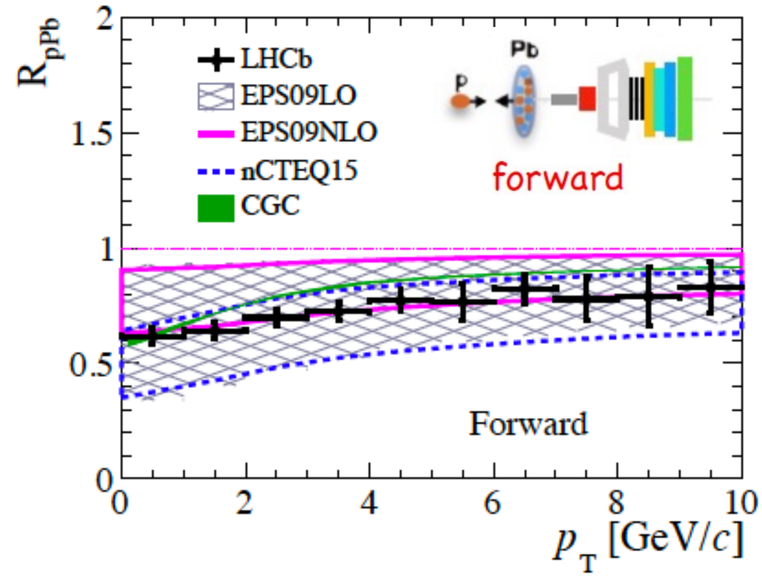
Driven by color fluctuations in proton wavefunction

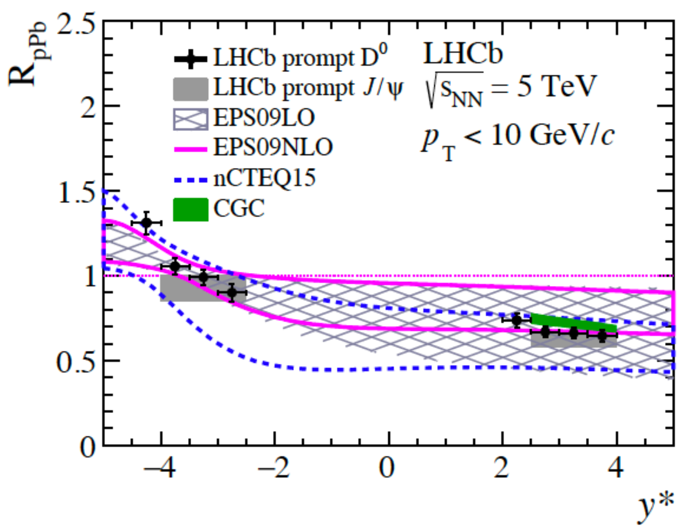
→ new probe of color transparency

LHCb: D^0 production in p+Pb

JHEP 10 (2017) 090
arXiv:1707.02750





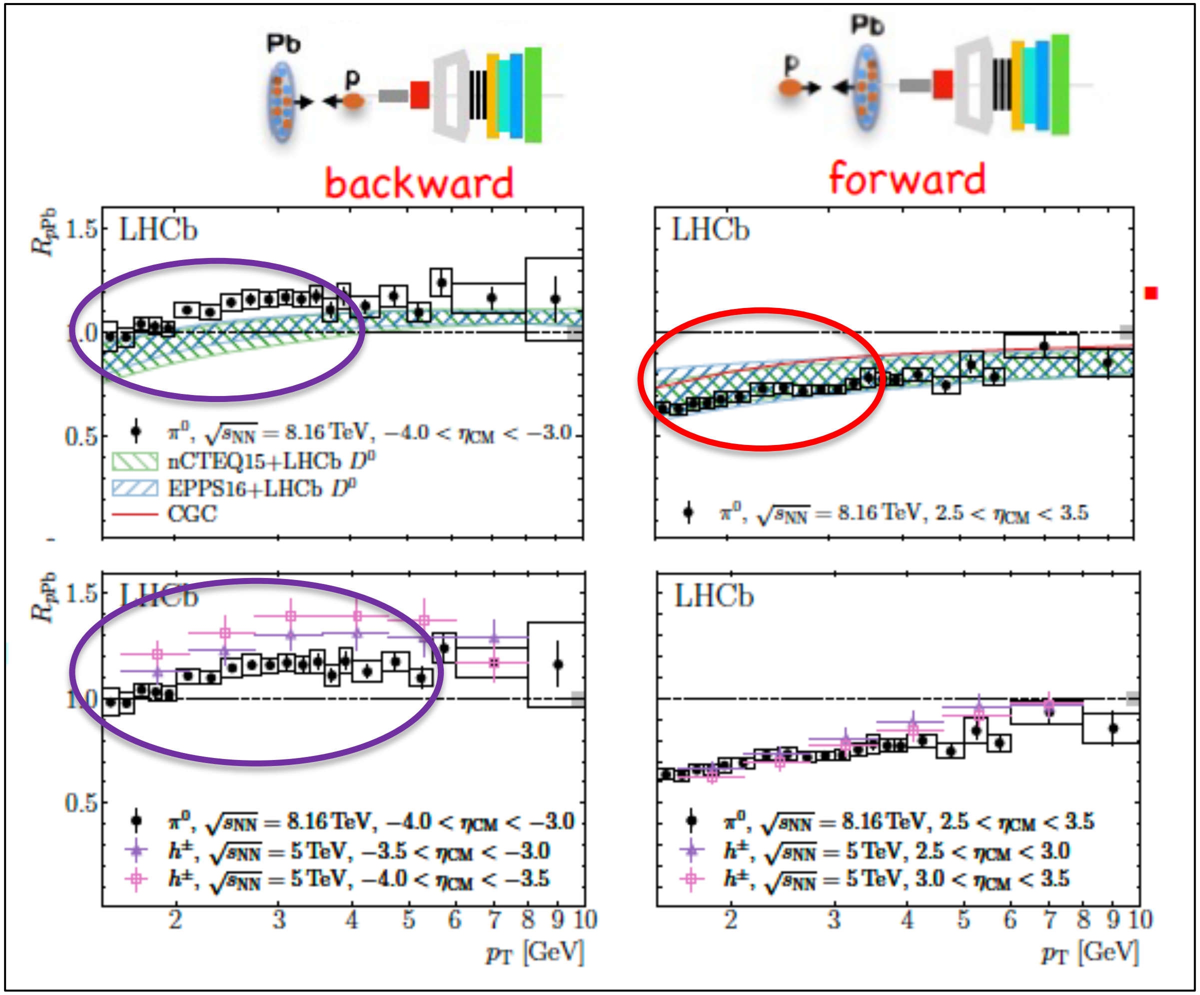


Data uncertainties are smaller than theory uncertainties → significant constraints on nPDFs

(Data from 2017, see next slides)

LHCb: π^0 production in p+Pb

PRL 131 (2023) 042302
arXiv:2204.10608



nCTEQ15, EPPS16: both incorporate LHCb D^0 data

Forward (Pb low-x):

- good agreement w/ both linear QCD and CGC

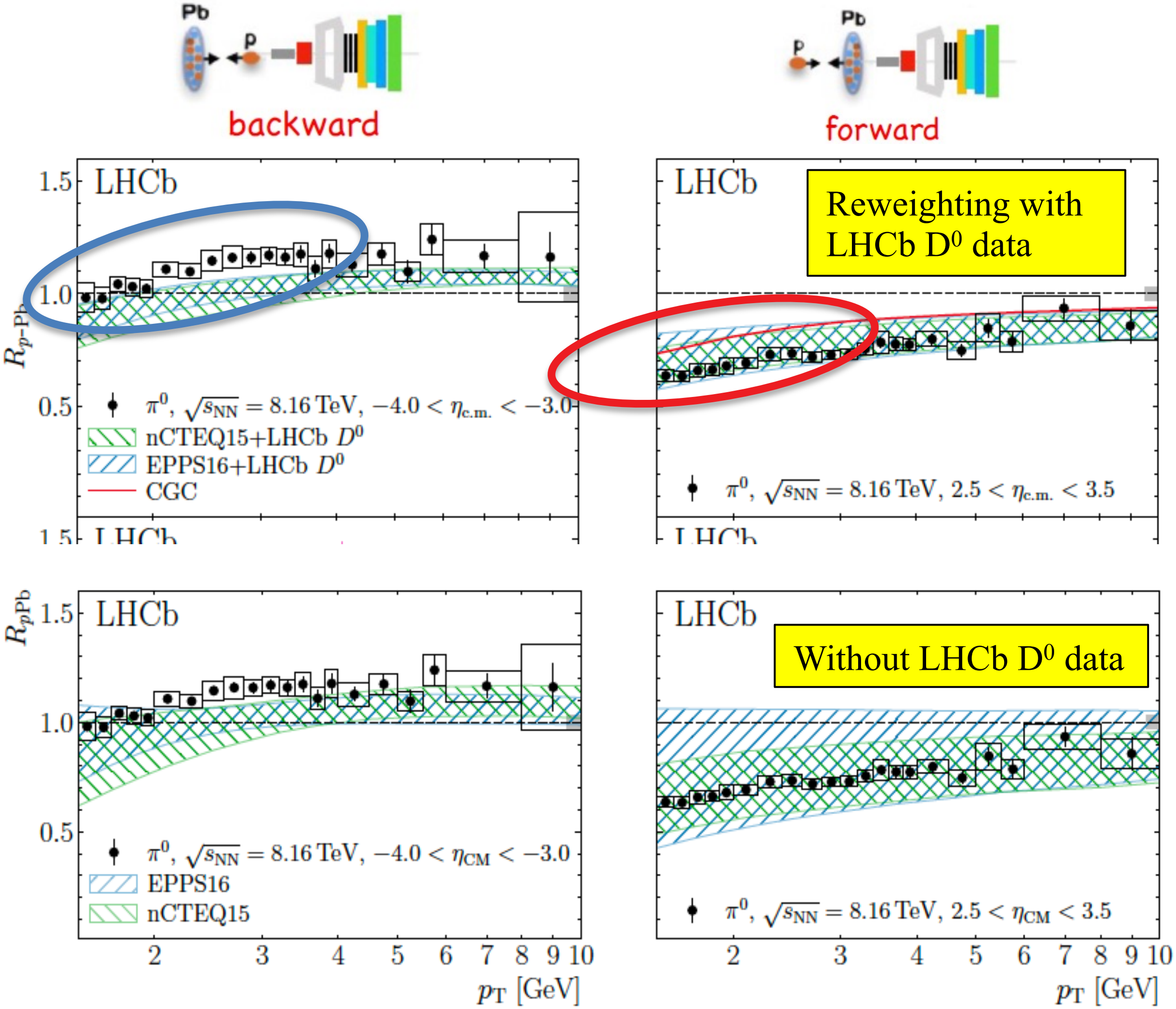
Backward (Pb high-x):

- poorer agreement: additional nPDF constraints
- ch hadron yield enhanced vs π^0
- characteristic of heavy-ion collisions → radial flow? baryon enhancement?

nPDFs: impact of LHCb D^0 data

PRL 131 (2023) 042302
arXiv:2204.10608

Compare nPDFs to LHCb π^0 data with and without reweighting by LHCb D^0 data



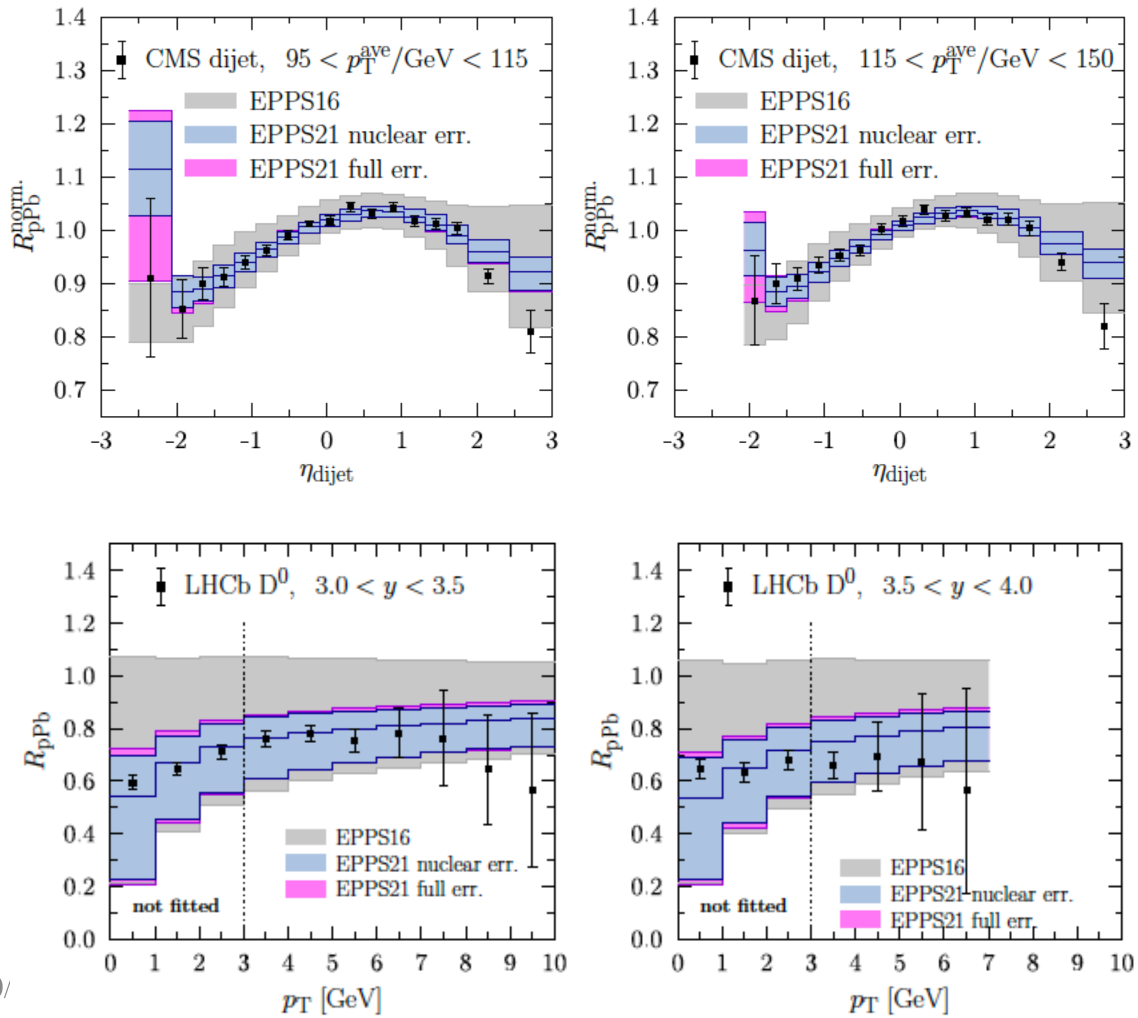
Anti-shadowing (backward): minor improvement, still some tension

Low-x: marked reduction in systematic uncertainties

Eskola et al., EPJ C82 (2022) 5, 413
arXiv:2112.12462

EPPS21

Includes LHC p+Pb data:
- 5 TeV: CMS forward di-jet, LHCb D^0 @ 5 TeV;
- 8 TeV: CMS W

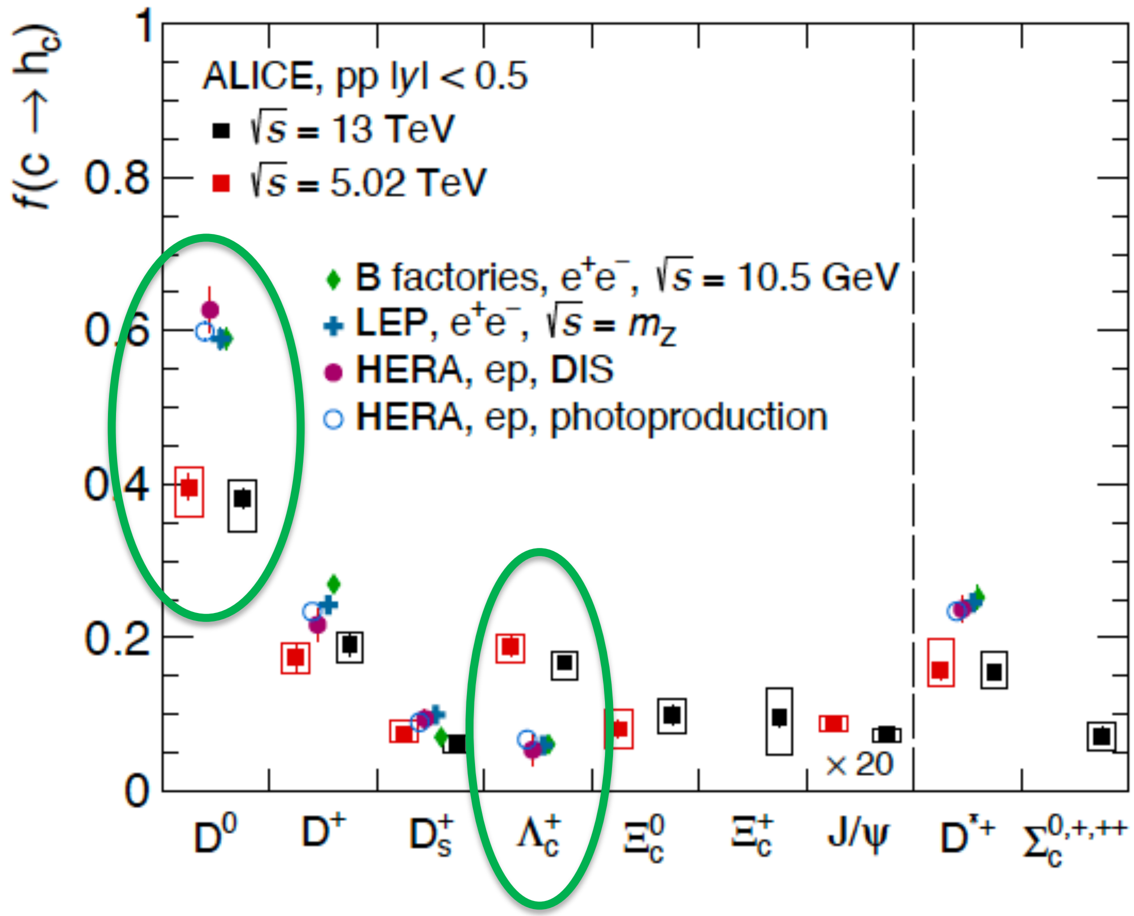


Dramatic improvement in uncertainties relative to EPPS16

ALICE: charm fragmentation in p+p

arXiv:2308.04877

Measure all final states containing charm that have significant yield
→ determine branching fractions $f(c \to h_c)$



Larger fraction of charm branches to baryons in pp than in e^+e^- and ep
→significant effect of hadronic environment

Word of caution: $c \to D^0$ fragmentation is not universal (!)

Effect has not been taken into account in current nPDF fits

- how does this affect theory uncertainties??

LHCb: beauty fragmentation in pp

arXiv:2310.12278 (posted last Friday!)

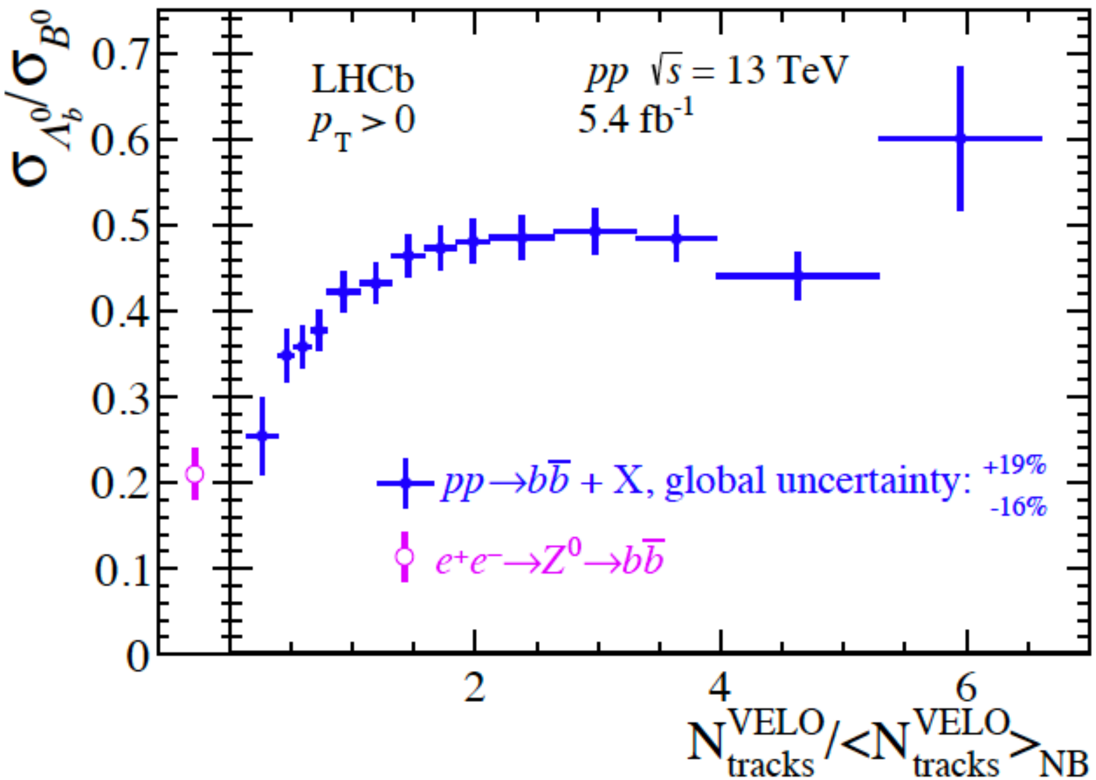
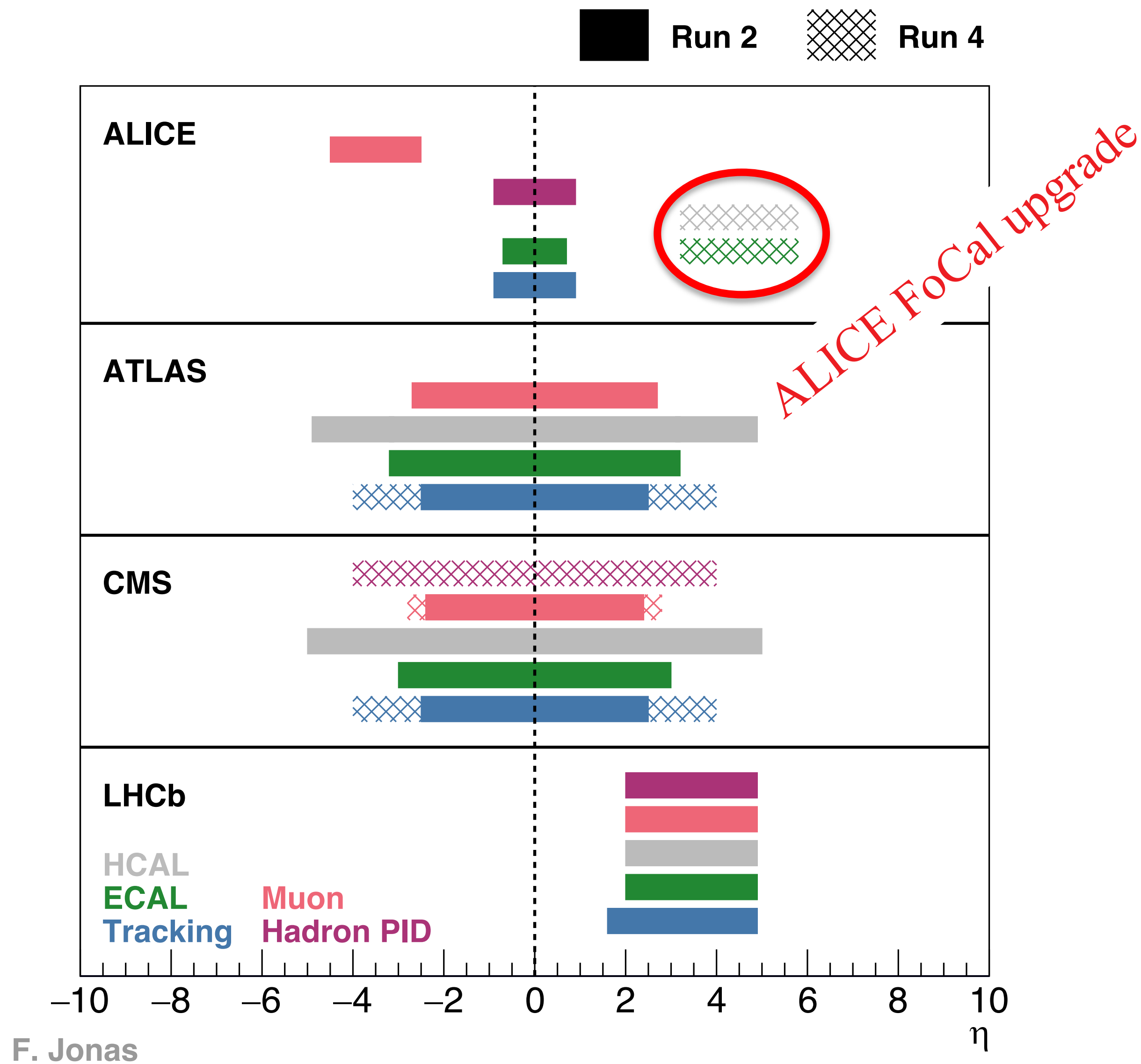


Figure 3: Ratio of Λ_b^0 to B^0 cross-sections as a function of the total track multiplicity measured in the VELO detector (blue). The purple point indicates the value measured in e^+e^- collisions at LEP [60].

Ratio of beauty baryon/meson yield vs Event Activity

Same picture in the beauty sector: relative branching into baryons vs. mesons depends on the hadronic environment!

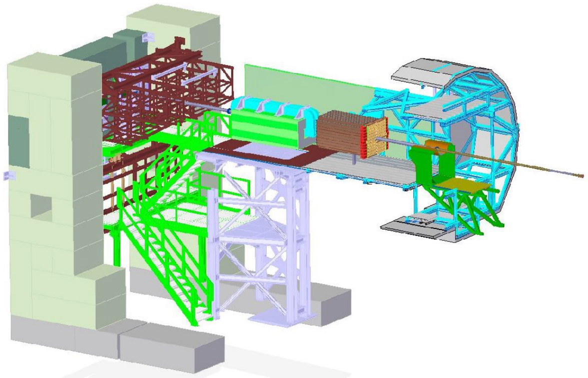
LHC Run 4 projections



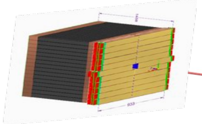
The ALICE Forward Calorimeter (FoCal) upgrade

Florian Jonas poster/flash talk

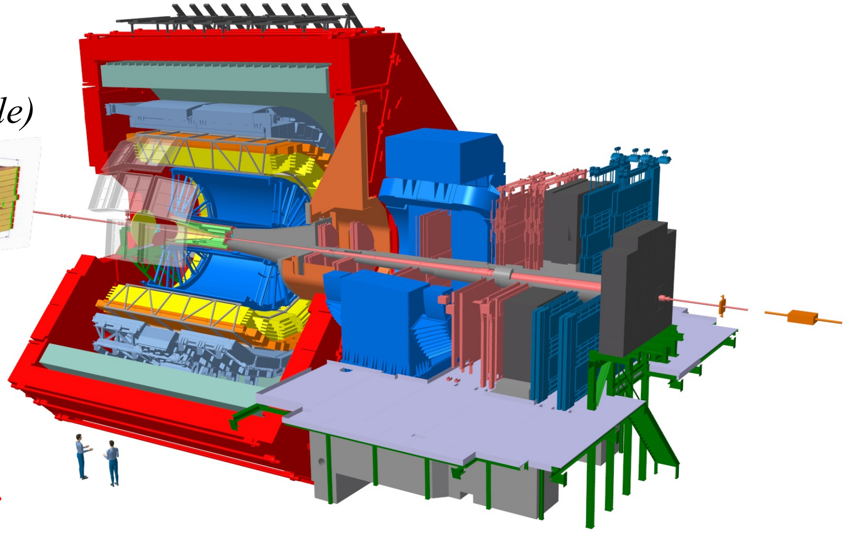
FoCal-E: high granularity Si-W sampling calo
FoCal-H: conventional metal-scintillator sampling calo



FoCal
(not to scale)



3.4<η<5.8



Main physics goal: study universal structure of matter at low-x

Flagship measurement: isolated direct photons for p_T>~2 GeV/c at very forward η

Installation: LHC Long Shutdown 3
Operation: LHC Run 4 (start 2029)

Observables:
- π^0 and other neutral mesons
- Isolated direct photons
- Jets
- UPCs: J/ψ, ψ', ϒ
- Z, W
- Correlations

FoCal documents

Letter of Intent: CERN-LHCC-2020-009

ALICE-PUBLIC-2023-001
https://inspirehep.net/literature/2661418

ALICE

ALICE-PUBLIC-2023-001
12 May 2023

Physics of the ALICE Forward Calorimeter upgrade

ALICE Collaboration *

Abstract

The ALICE Collaboration proposes to instrument the existing ALICE detector with a forward calorimeter system (FoCal), planned to take data during LHC Run 4 (2029–2032). The FoCal detector is a highly-granular Si+W electromagnetic calorimeter combined with a conventional sampling hadronic calorimeter, covering the pseudorapidity interval of $3.4 < \eta < 5.8$. The FoCal design is optimized to measure isolated photons at most forward rapidity for $p_{\mathrm{T}} \gtrsim 4$ GeV/c.

In this note we discuss the scientific potential of FoCal, which will enable broad exploration of gluon dynamics and non-linear QCD evolution at the smallest values of Bjorken x accessible at any current or near-future facility world-wide. FoCal will measure theoretically well-motivated observables in

ALICE-PUBLIC-2023-004

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

ALICE-PUBLIC-2023-004
04 September 2023

Physics performance of the ALICE Forward Calorimeter upgrade

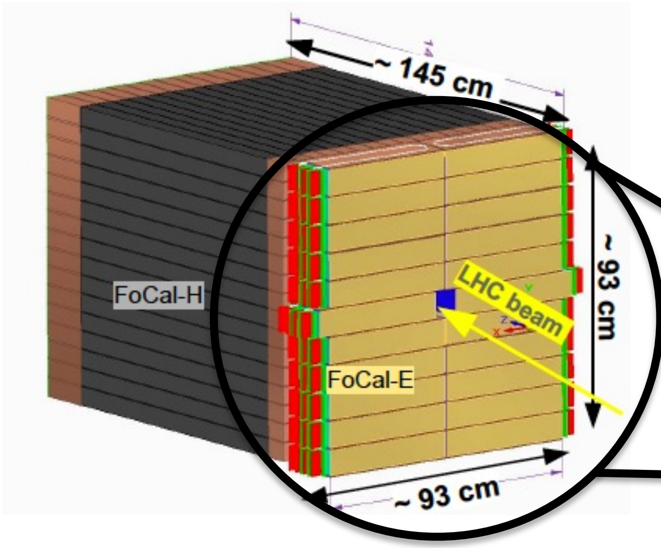
ALICE Collaboration *

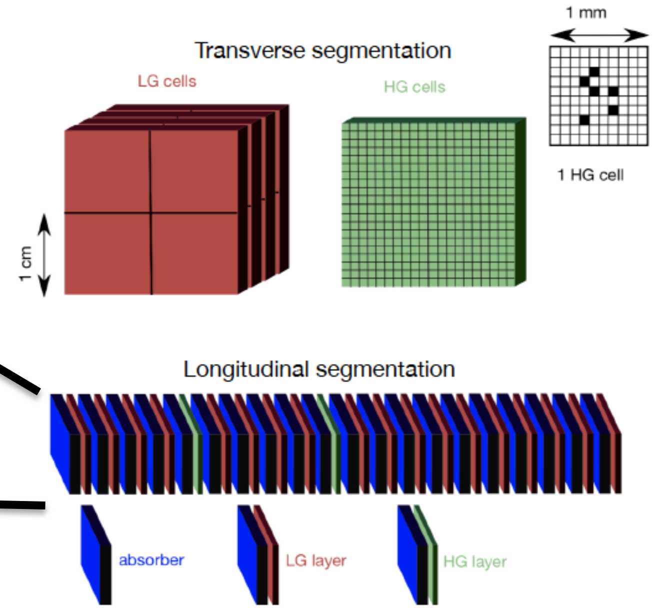
Abstract

The ALICE Collaboration proposes to instrument the existing ALICE detector with a forward calorimeter system (FoCal), planned to take data during LHC Run 4 (2029–2032). The FoCal detector is a highly-granular Si+W electromagnetic calorimeter combined with a conventional sampling hadronic calorimeter, covering the pseudorapidity interval of $3.2 < \eta < 5.8$. The FoCal design is optimized to measure isolated photons at forward rapidity for $p_{\mathrm{T}} \gtrsim 4$ GeV/c, as well as neutral hadrons, vector mesons, and jets. Measurements of the inclusive distributions and correlations of these observables probe the structure of matter down to $x \sim 10^{-6}$, providing incisive tests of linear and non-linear QCD evolution at low x. This document presents current projections of the FoCal measurement performance for these observables.

Technical Design Report (TDR) in preparation

FoCal-E detector



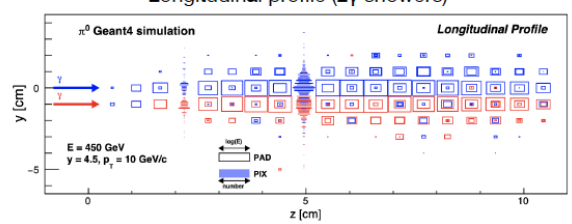


Separate γ/π^0 at high energy:

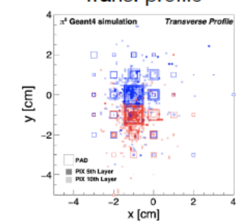
π^0 (p_T=10 GeV, η=4.5): two-γ separation ~5mm

→ need small Molière radius, high granularity

Longitudinal profile (2γ showers)

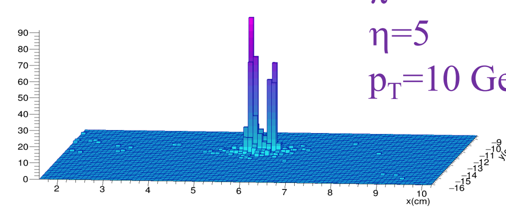


Trans. profile



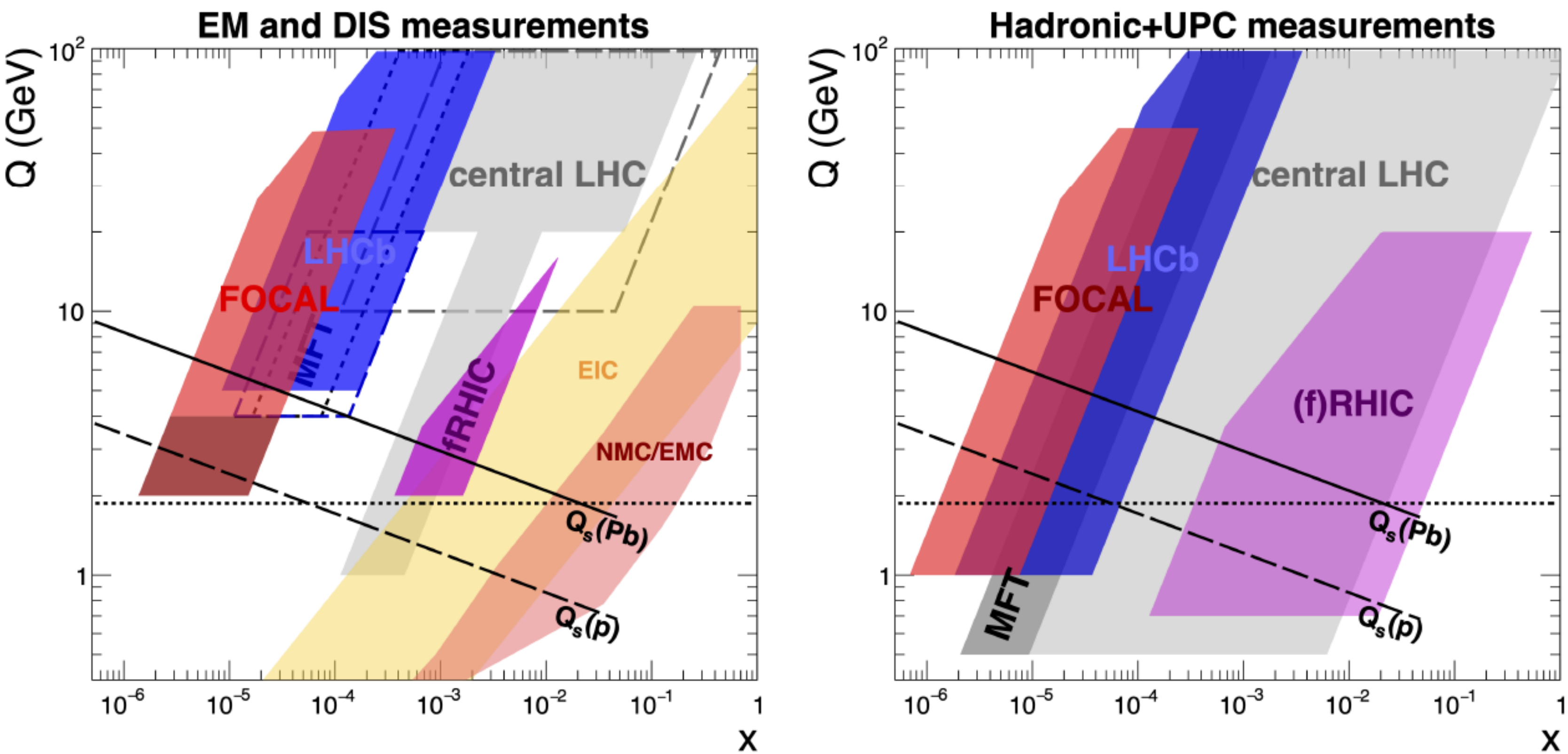
FoCal-E:

- W absorber: 20 layers ~ 20 X_0
- Si sensor:
  - 18 low-granularity pad layers
  - 2 high-granularity pixel layers (3 x30 μm^2)
  - → effective granularity ≈ 1 mm^2



π^0
η=5
p_T=10 Gev/c

Run 4 experimental acceptance



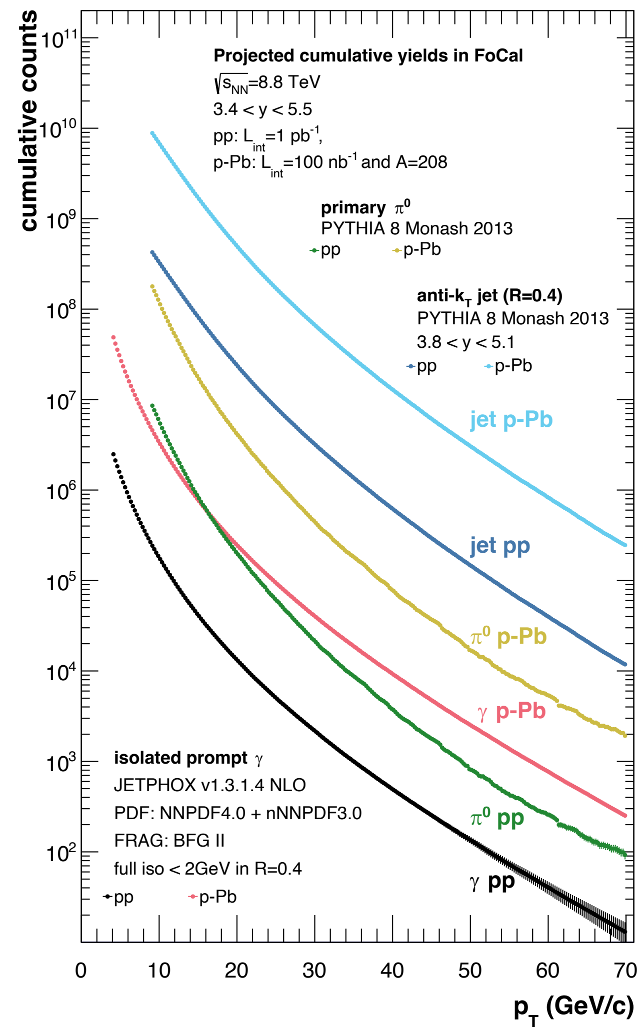
EM in hadronic collisions:
direct γ, DY

FoCal production rate projections

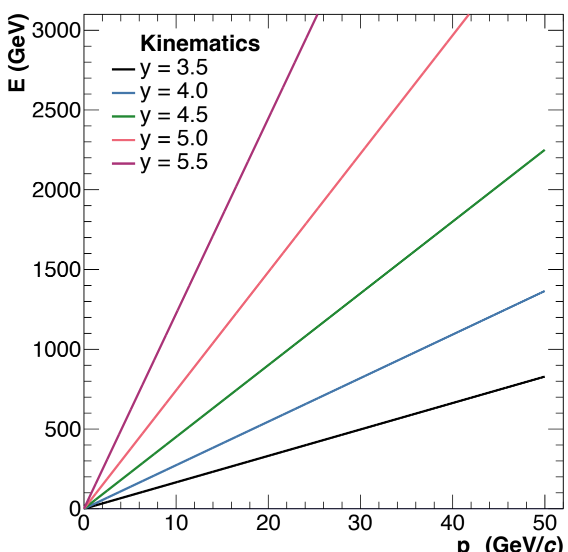
Integrated luminosity: current projections

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

Inclusive channel rates "Round number" int lumi



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



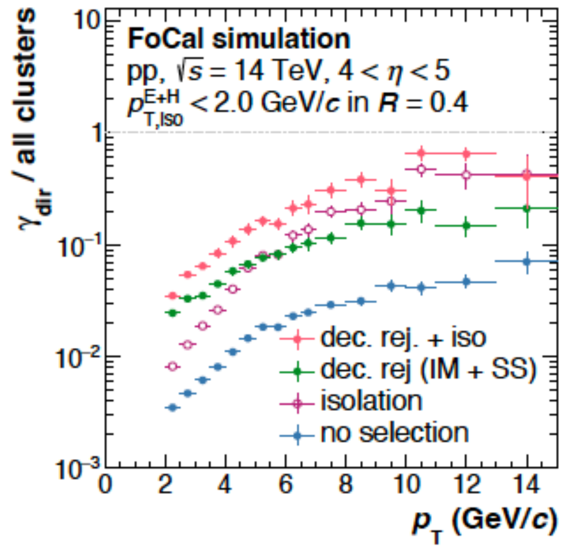
Forward kinematics: large energy deposition in calorimeter

FoCal direct photon performance

Florian Jonas poster/flash talk

Prompt photon PID cuts:

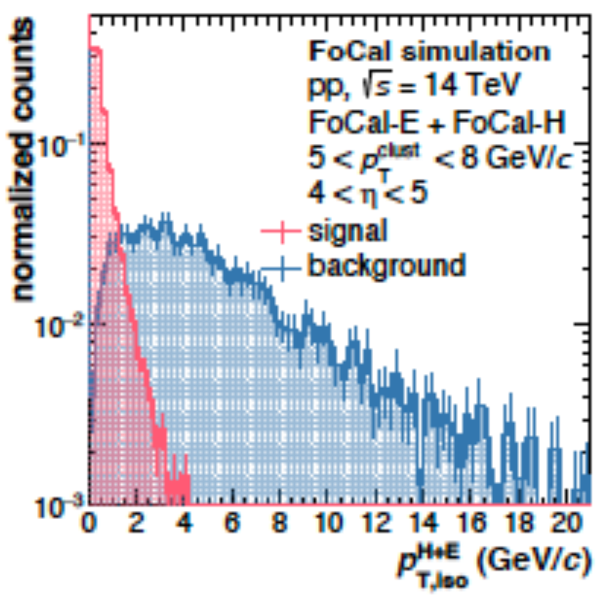
- invariant mass (IM)
- shower shape (SS)
- isolation: EM + Hadronic



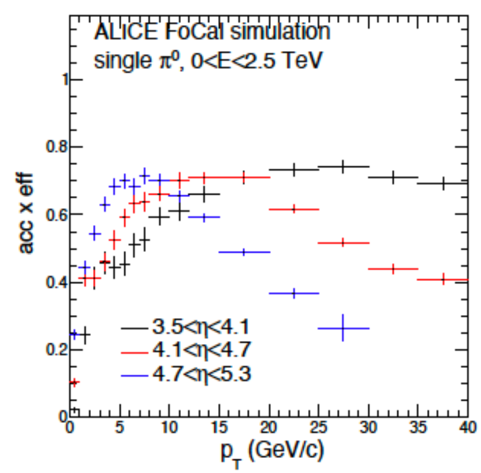
Background rejection:factor~10

γ_{dir}/all >50% → high precision measurement

Isolation p_T



π^0 efficiency

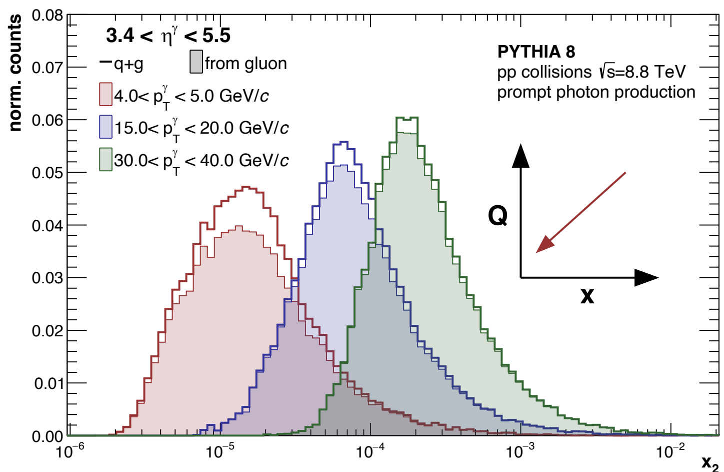


Good π^0 efficiency

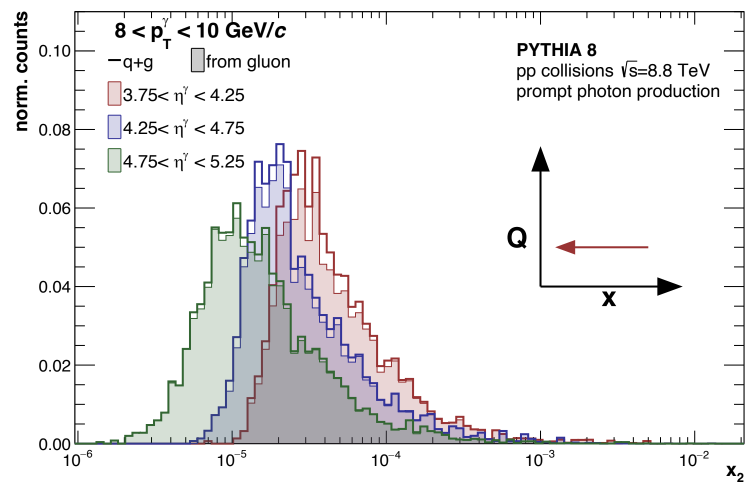
Partonic kinematics: γ in FoCal

Inclusive γ_{dir}

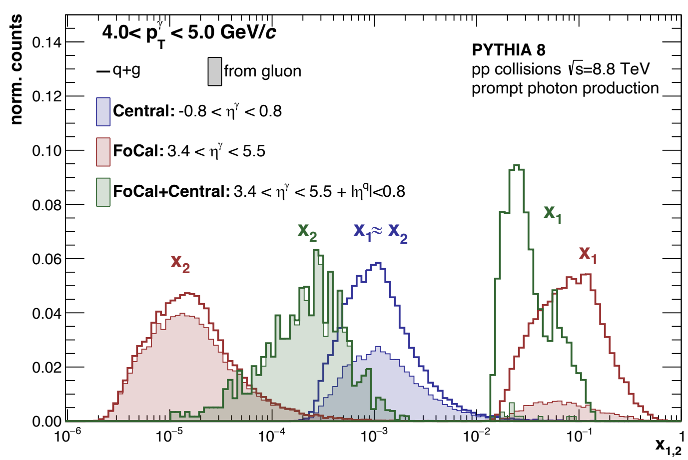
p_T dependence

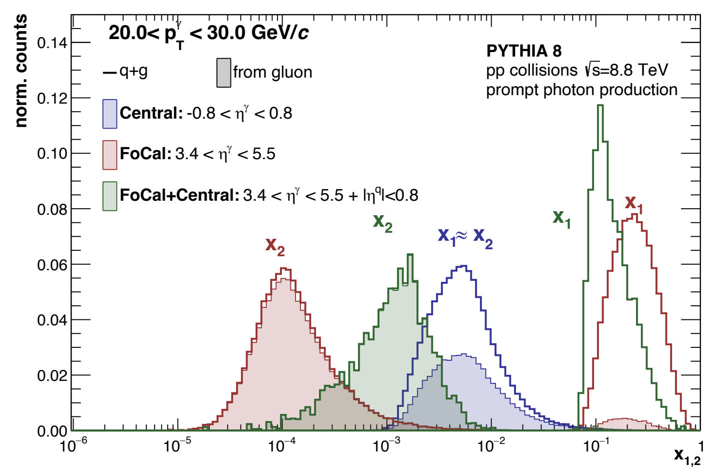


η dependence



γ+jet: FoCal vs Central Barrel



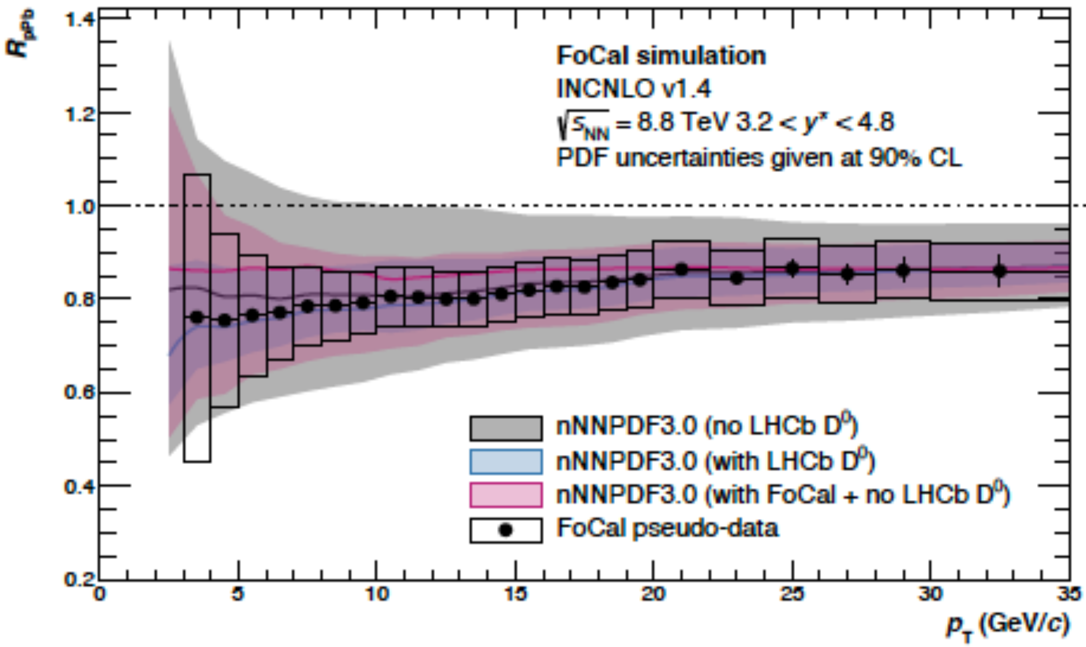


FoCal has flexibility to tune partonic kinematics over significant range
$\rightarrow$ overlap with EIC kinematics

FoCal and nPDFs

Florian Jonas poster/flash talk

Bayesian reweighting of nNNPDF3.0 using FoCal pseudo-data



Significant reduction in uncertainties

Systematically independent of D-meson constraint

- no hadronization effects

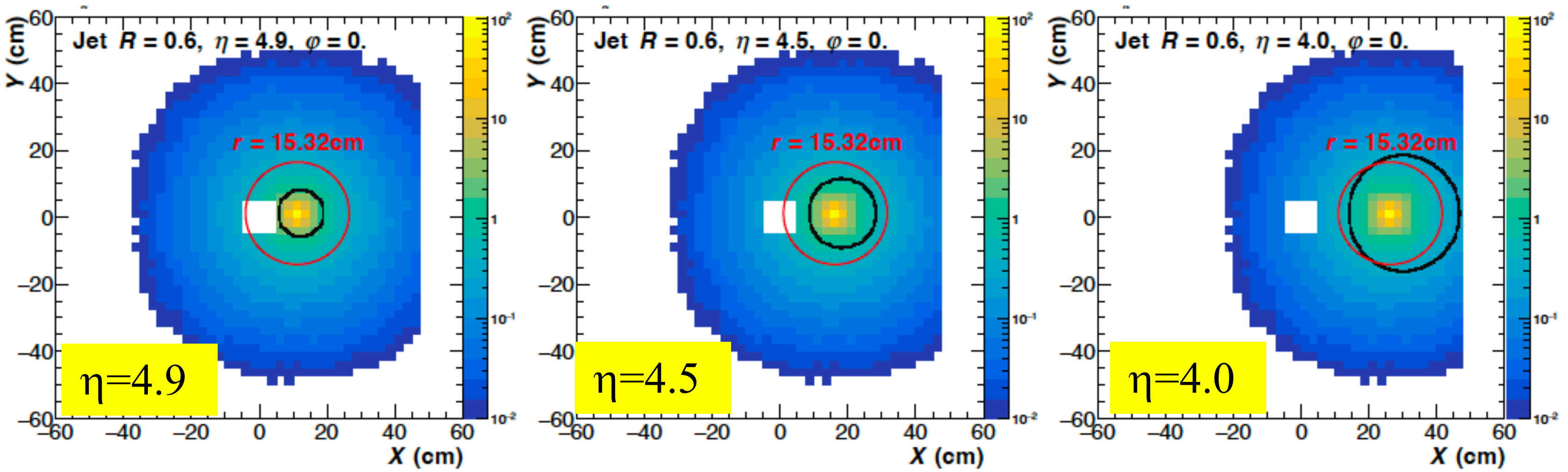
→ Universality test of low-*x* formalisms

Jets in FoCal

Very forward jet measurements are extremely challenging:

- hadronic shower transverse profile width ~15 cm, independent of η
- but profile in (x,y) of jet with fixed R in (η,ϕ) shrinks at high η

Average hadronic shower profile of single π^+ with E=500 GeV in FoCal at various η

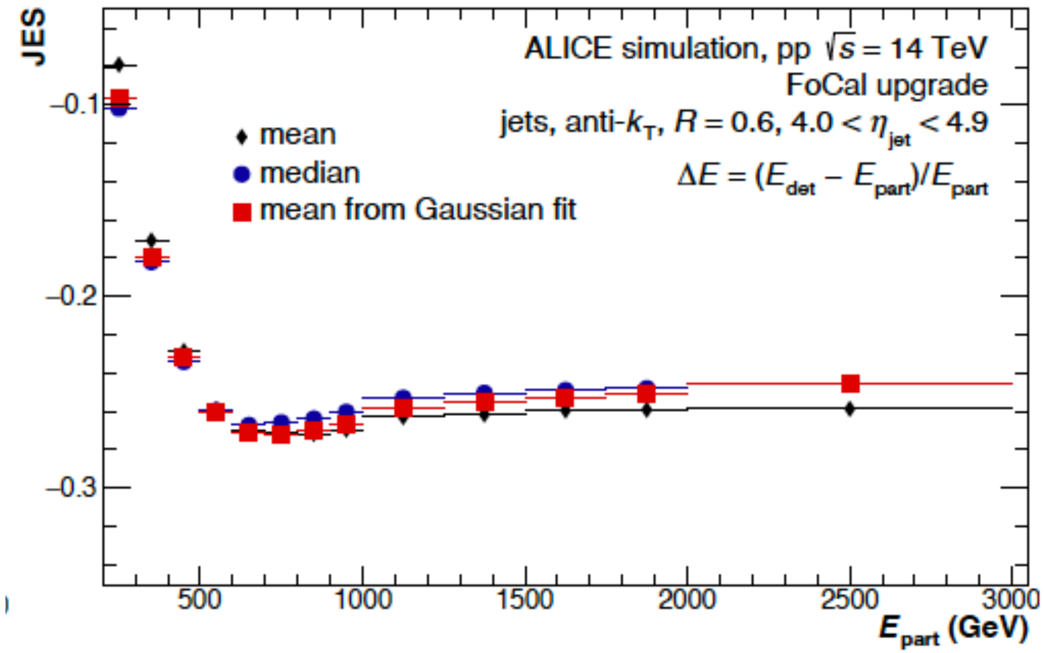


Black: contour of jet with R=0.6 in (η,ϕ)

Red: nuclear interaction length of Cu; contains ~81% of shower energy

Jets in FoCal: Jet Energy Scale

Jet performance metric: $\mathrm{JES} = \frac{E^{\mathrm{jet}}_{\mathrm{measured}} - E^{\mathrm{jet}}_{\mathrm{truth}}}{E^{\mathrm{jet}}_{\mathrm{truth}}}$



Misses >25% of jet energy

- complex calibration
- systematics of model-dependent corrections?

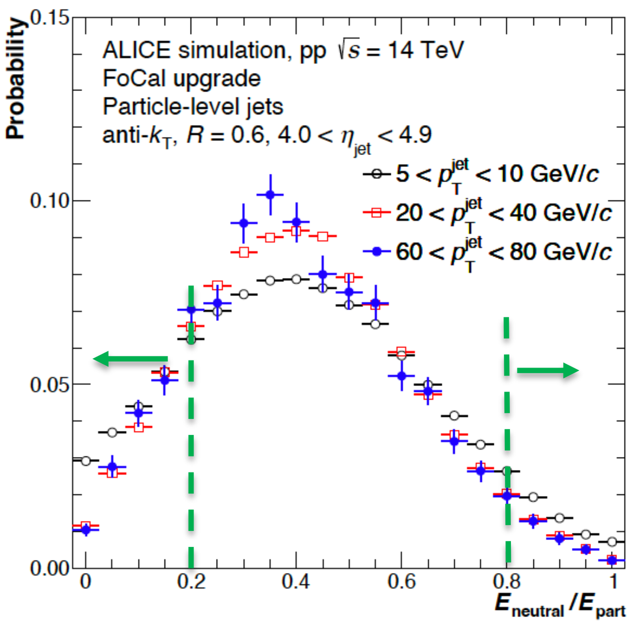
JES mitigation: Neutral Energy Fraction

NEF: fraction of jet energy carried by EM shower

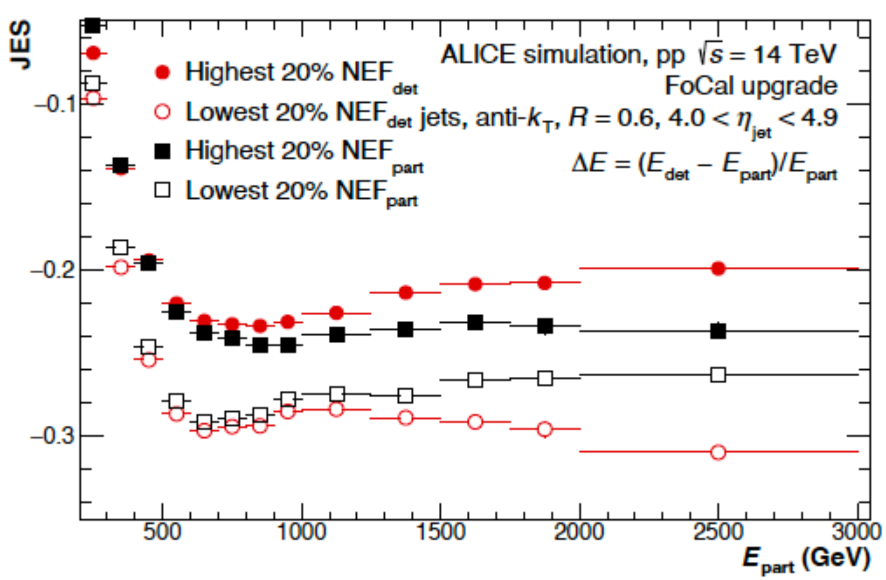
Mitigation strategy:

- utilize tighter transverse profile of EM shower and excellent FoCal-E spatial resolution
- bias jet selection by Neutral Energy Fraction (NEF)

NEF probability



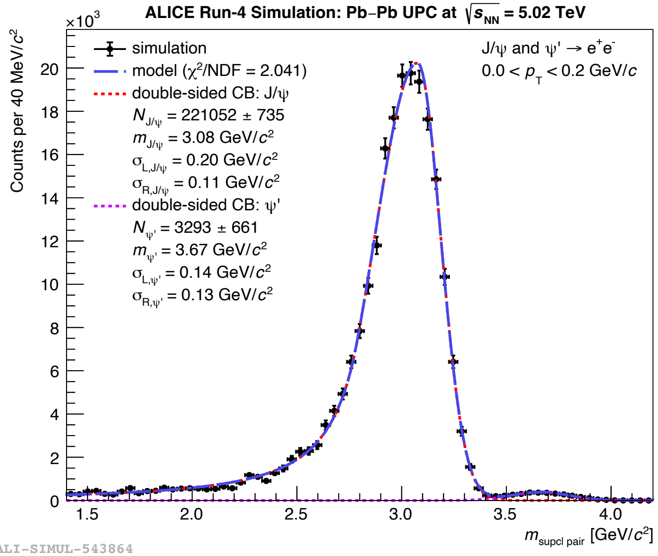
JES



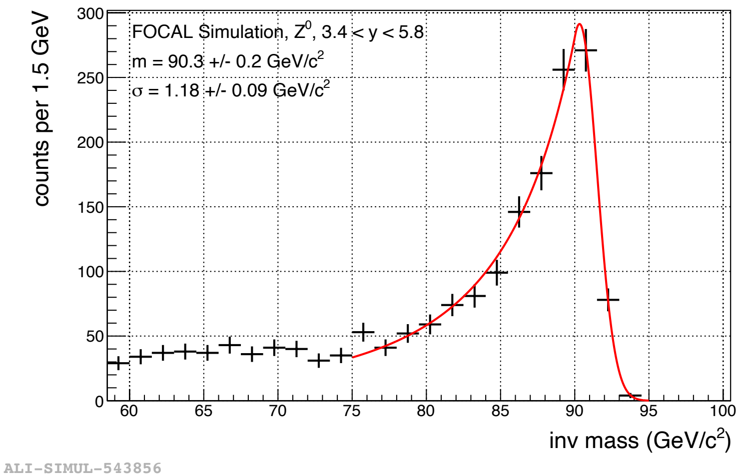
Theory issues: does NEF cut break factorization? How to model?

Other channels under study

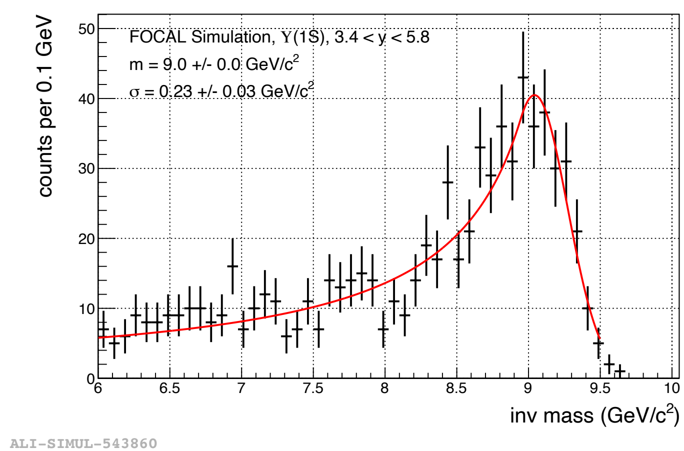
$J/\psi \to e^+e^-$ (UPC)



$Z^0 \to e^+e^-$



$\Upsilon(1s) \to e^+e^-$

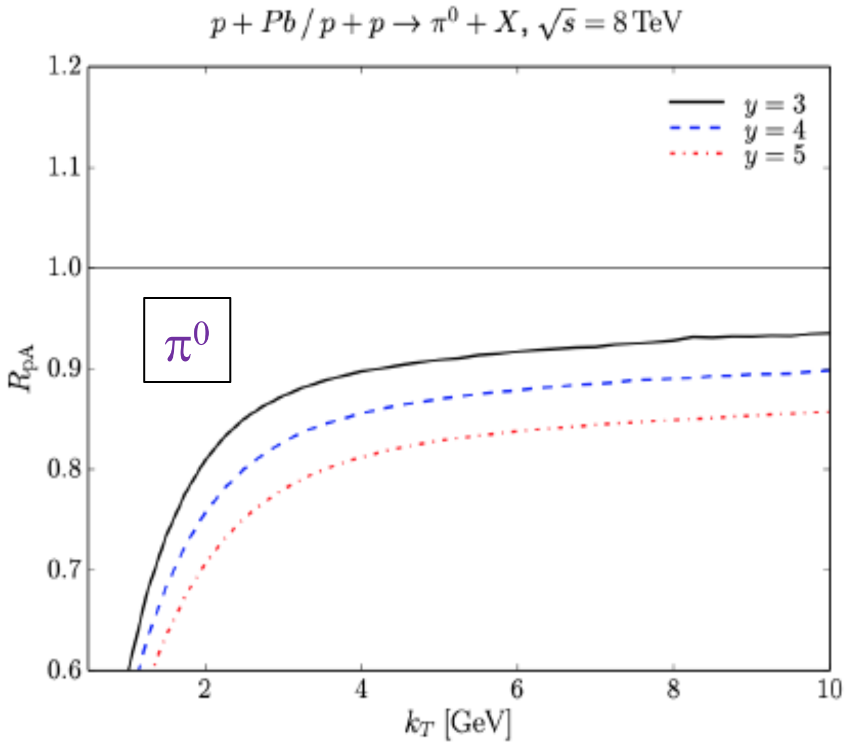


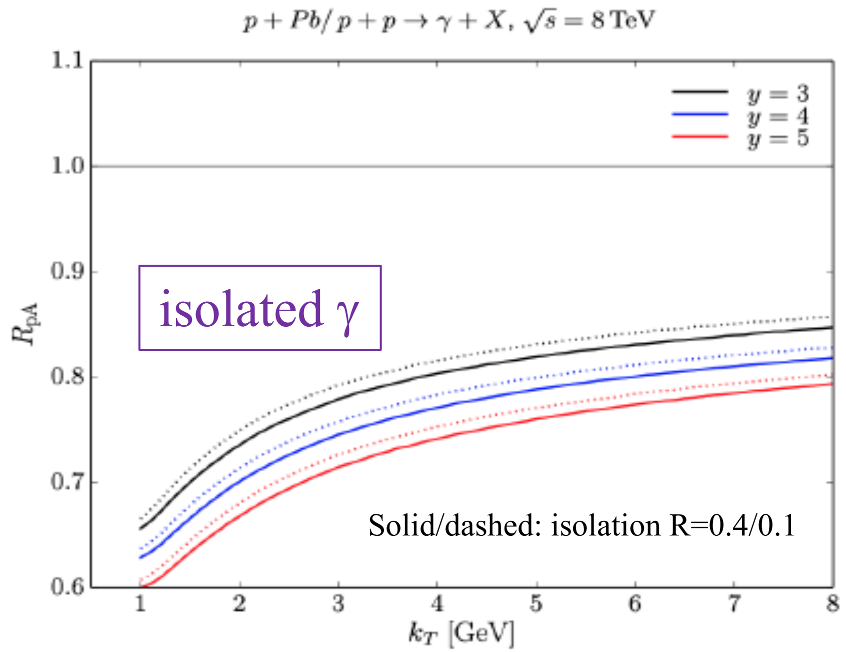
Selected theory calculations of saturation effects that can be probed by FoCal

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: $qg \to \gamma g$; $k_T \sim Q_{sat}$

Authors: picture may change @ NLO

Lesson for FoCal/LHCb: both measurements should be done

Forward di-jets

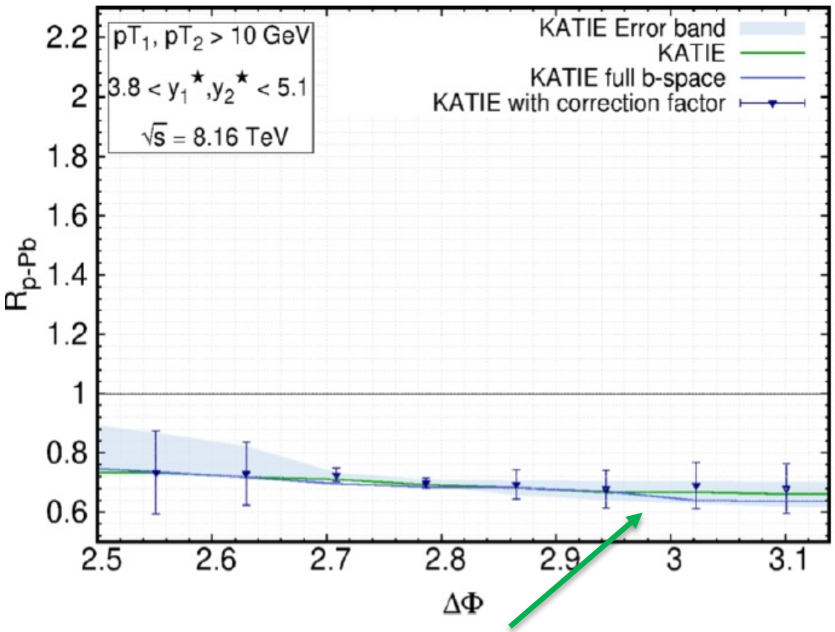
γ+jet, balanced di-jet at low-x: $k_T \sim Q_{sat}$

- 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

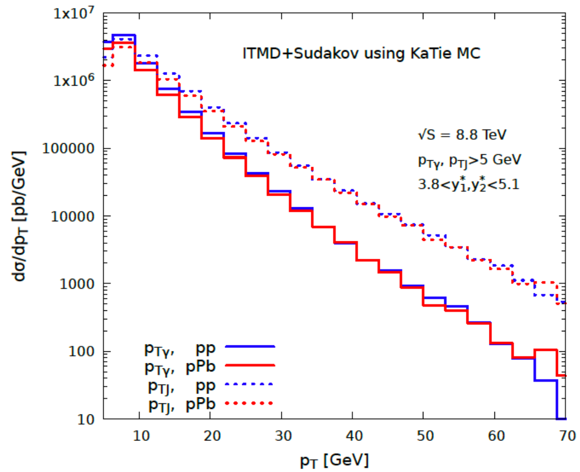
van Hameren, Comput. Phys. Commun. 224 (2018) 371
van Hameren et al., JHEP 12 (2016) 034
Kotko et al., JHEP 09 (2015) 106
Al-Mashad et al., arXiv:2210.06613
Mäntysaari and Paukkunen, Phys. Rev. D 100 (2019) 114029
Liu et al. JHEP 07 (2022) 041
Wang et al. arXiv:2211.08322

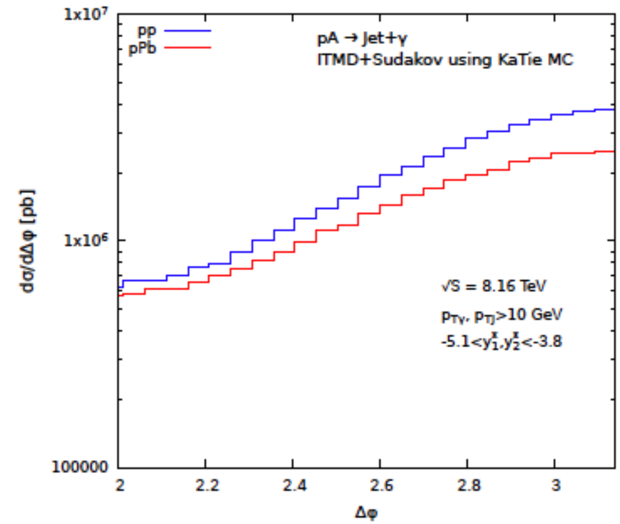
Forward γ+jet

KaTie calculations (I. Ganguli et al., arXiv:2306.04706)

γ+jet distributions:

- P-Pb vs pp
- p_T: negligible modification
- Δϕ: b-to-b suppression

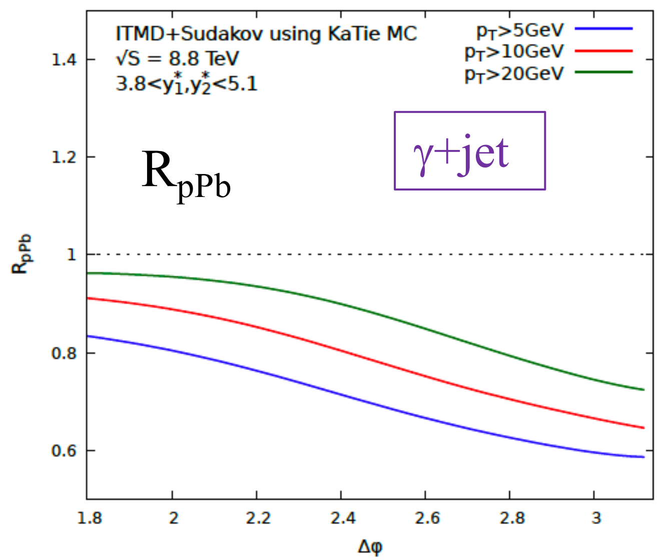




γ+jet: R_{pPb} vs Δϕ

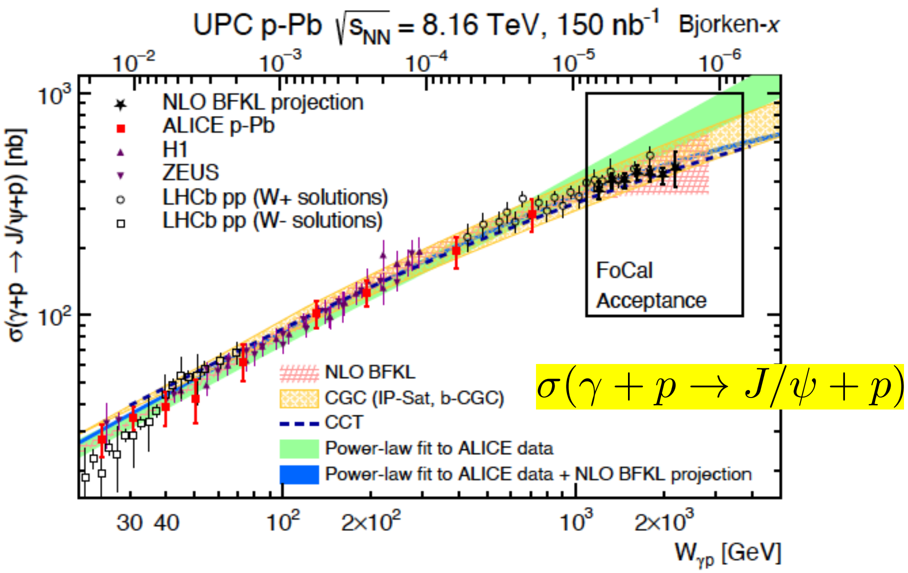
- recoil jet p_T dependence

Compare to di-jet: dipole vs quadrupole TMD



UPCs in FoCal: photoproduction of $J/\psi, \psi'$

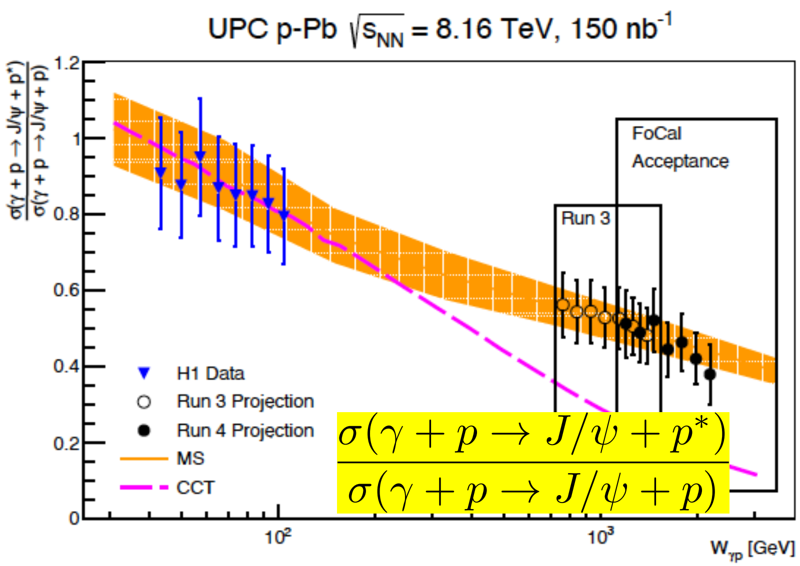
A. Bylinkin, J. Nystrand and D. Tapia Takaki, J. Phys. G 50 (2023) 055105



$W_{\gamma p}$ = photon − proton CM energy

FoCal extends reach in $W_{\gamma p}$

Explores region where saturation effects may be significant



Coherent vs incoherent scattering: dissociative production

Final comments: discriminating non-linear from linear QCD evolution

Fast-forward 10 years: lots of beautiful new data on ep, eA, and pA from EIC+forward RHIC/LHC.

How will we use these heterogenous datasets optimally to search for saturation and quantify its effects?

Non-linearity via DIS structure fns

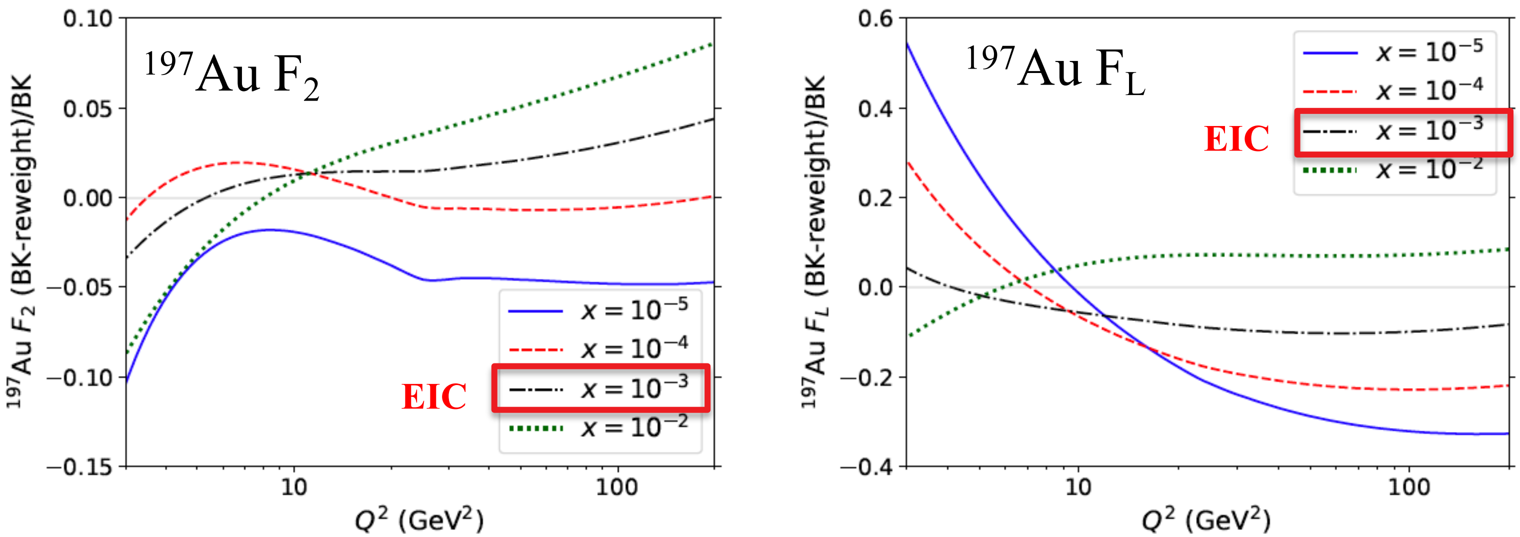
Armesto et al.
PRD 105 (2022) 11, 114017
arXiv:2203.05846

Example: what is the sensitivity of DIS Structure Functions for discriminating linear and non-linear evolution?

Toy model:

- Compute F_2 and F_L in EIC and LHeC kinematics; no exp. uncert
- Both collinear factorization and CGC (non-linear) approaches
- Match at $x \sim 10^{-2}$ and $Q^2 \sim 10 Q_s^2$
- Evolve away from matching region and compare

Relative difference of nonlinear and linear evolution



EIC: F_2 difference ~few percent; F_L difference ~10% → challenging

Global analysis of saturation data

Common approach: global nPDF fit to Struct. Fns.

- limited sensitivity to non-linear evolution: see previous slide

Many saturation observables do not map directly onto nPDFs:

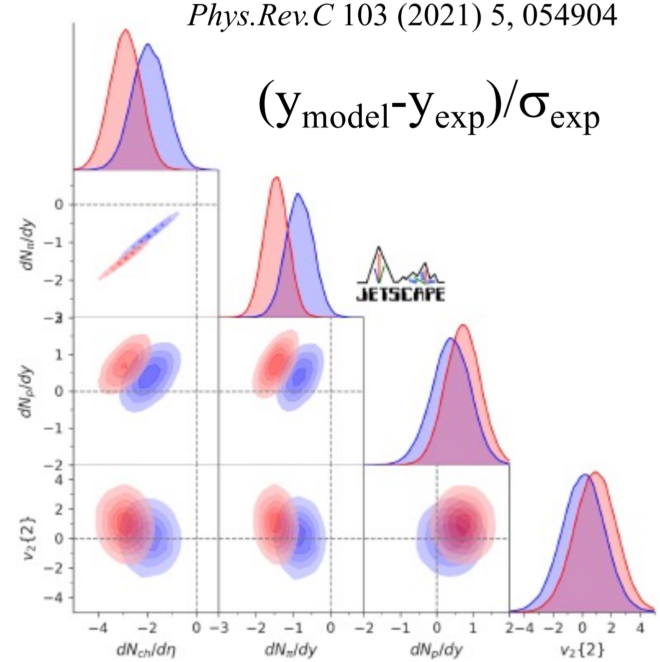
- angular decorrelation (acoplanarity),
- Jet substructure
- Energy-energy correlators
- ….

More general approach: Bayesian Inference

Instructive example from heavy-ion physics:

- Bayesian Inference using two different models of Quark-Gluon Plasma dynamics with broad array of low-p_T data
- Extract transport coefficients and uncertainties
- Re-predict experimental observables
- Models are not equally successful!

JETSCAPE
Phys.Rev.C 103 (2021) 5, 054904



→ needs significant development for EIC + fRHIC + fLHC

Summary

Forward p+A at the LHC: deep theoretical connection to EIC low-x physics

- universality tests of low-x formalisms

Run 2 data

- jets, D-mesons, π^0
- strong constraints on nPDFs
- potential issue: non-universality of charm/beauty fragmentation

ALICE/FoCal upgrade for Run 4:

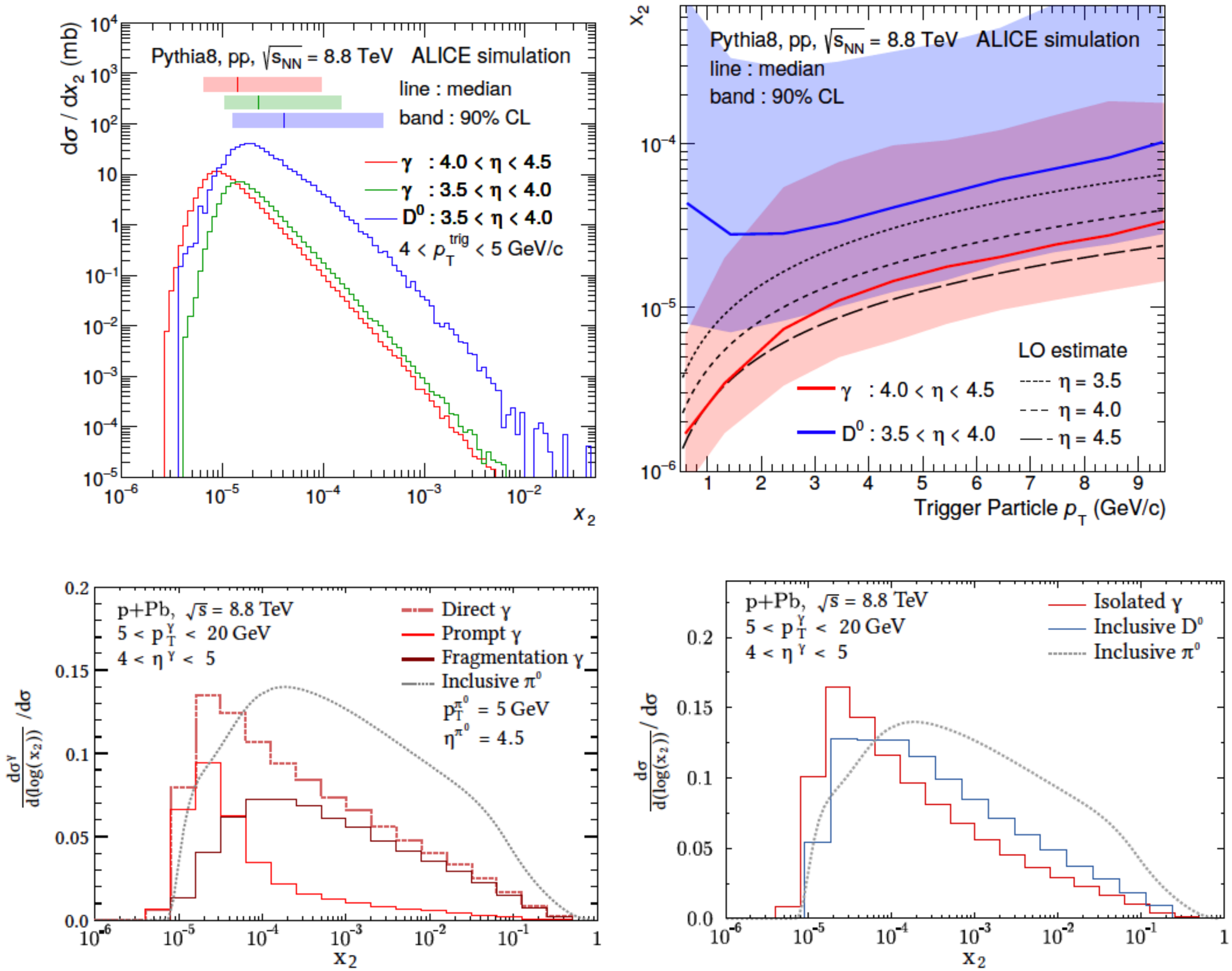
- direct photons, jets, mesons + correlations; UPCs
- lower reach in x
- new universality tests

Key issue: global analysis

- how do we best exploit these vast and heterogeneous datasets to explore linear vs non-linear evolution at low-x?

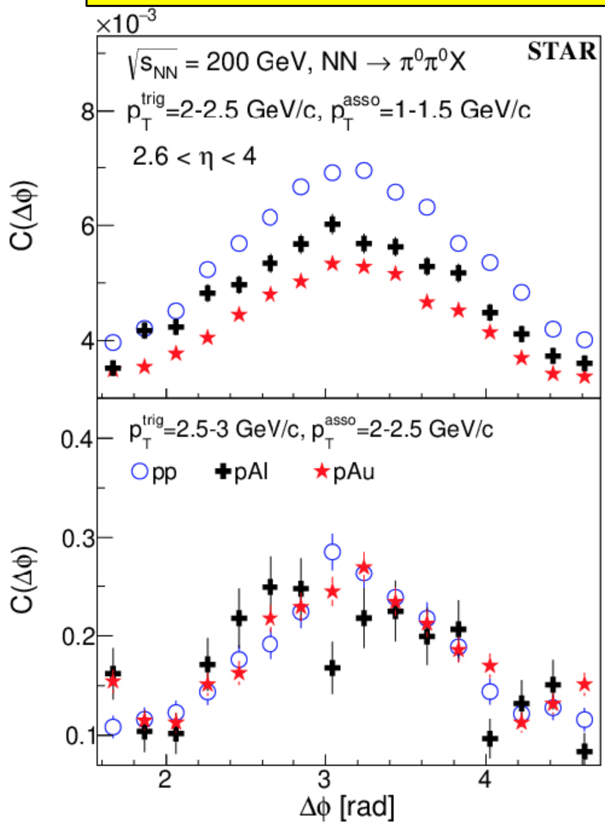
Backup

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



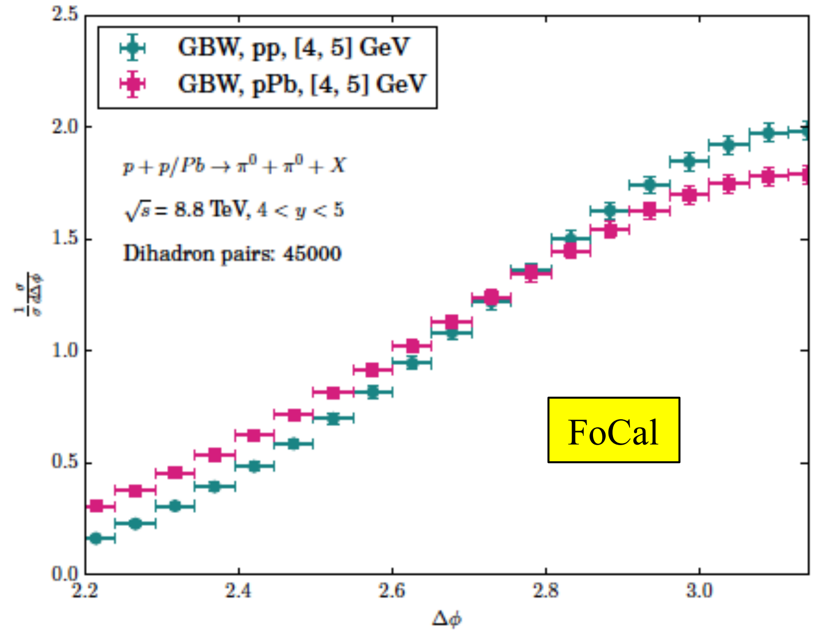
Di-hadron correlations RHIC and LHC

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



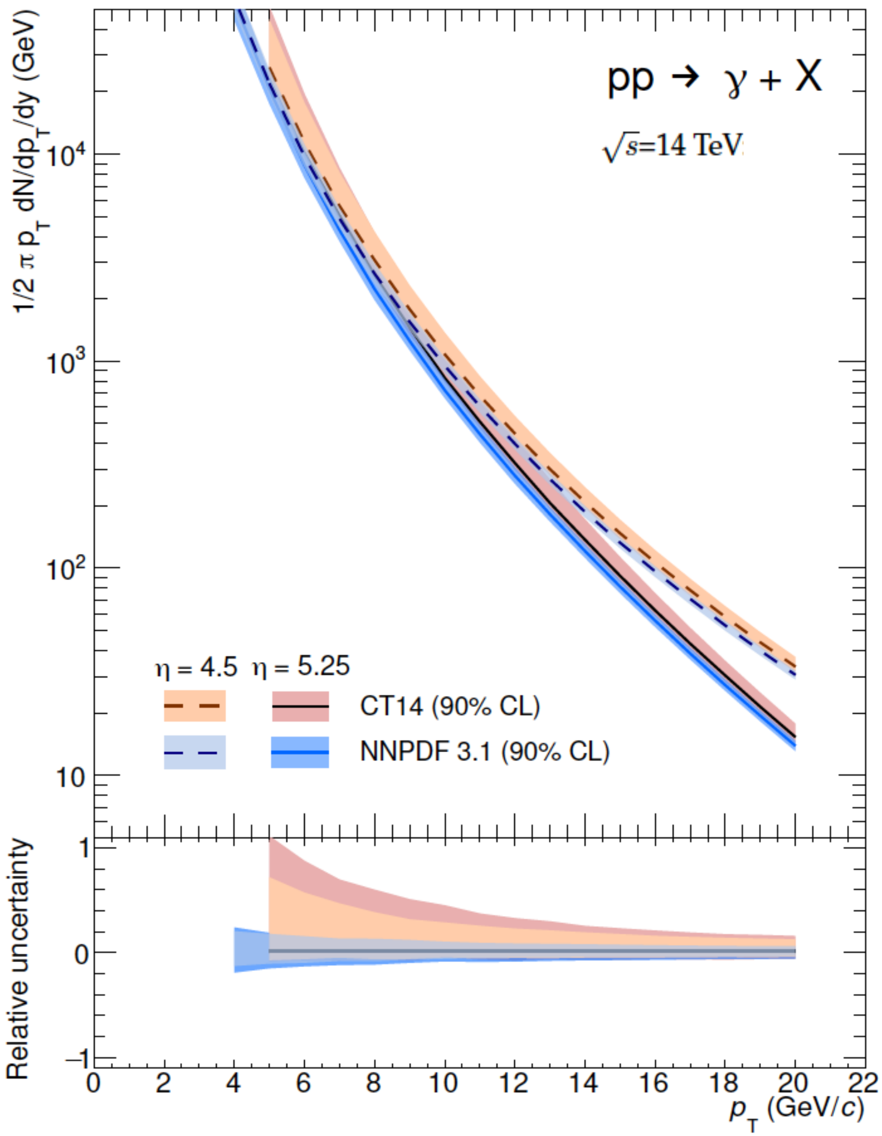
Dilute-dense LO + Sudakov

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

Small broadening effect: experimentally challenging

- NLO needed for theory uncert.

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?