Low-x physics program of the ALICE FoCal upgrade

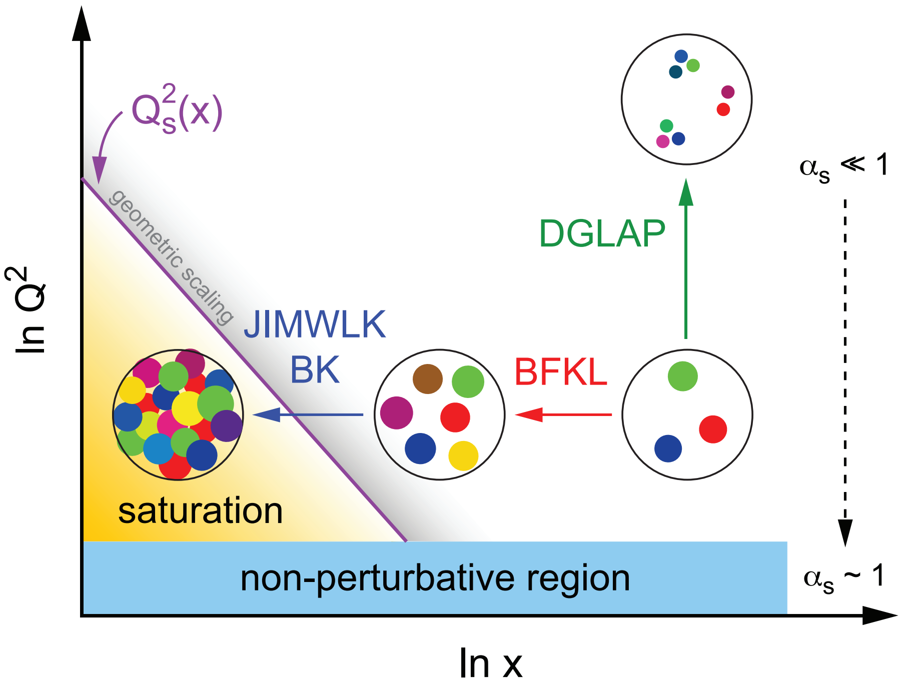
Peter Jacobs
Lawrence Berkeley National Laboratory
for the ALICE Collaboration

SURGE Collaboration Meeting

The frontier of cold QCD

Virtual photon

Collider event



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

How do we test it experimentally?

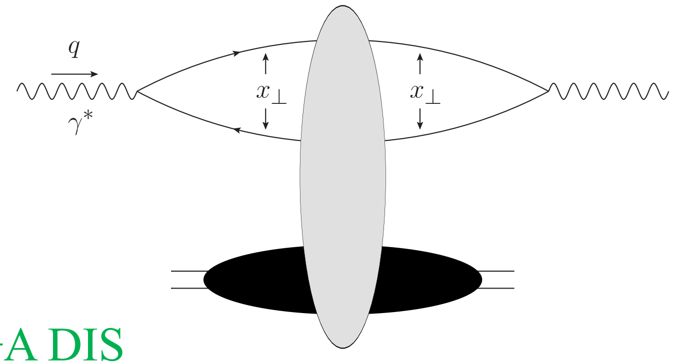
QCD phenomena evolve only logarithmically in x and Q^2

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

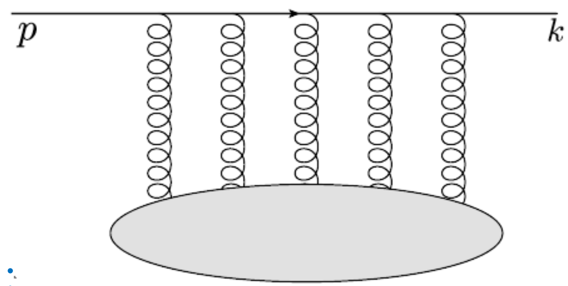
Universality: correct theoretical description must self-consistently describe measurements of **multiple observables at low (x,Q^2) in multiple collision systems**

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

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,…

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

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

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

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

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

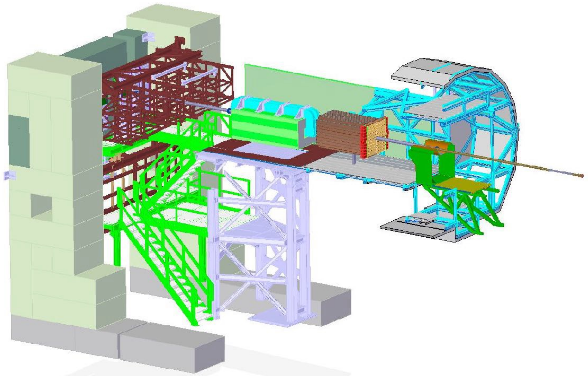
Table 7.2: The process dependence of two gluon distributions (i.e., the Weizsäcker-Williams (WW for short) and dipole (DP for short) distributions) in e+A(e+p) and p+Acollisions. Here the + and − signs indicate that the corresponding gluon distributions appear and do not appear in certain processes,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

Probes unpolarized gluon TMD distributions

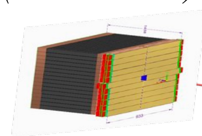
The ALICE Forward Calorimeter (FoCal) upgrade

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

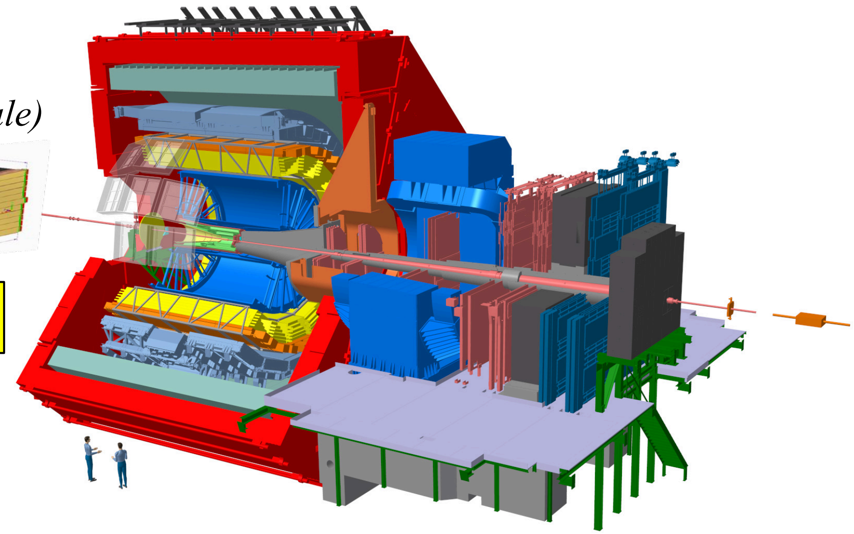
FoCal-E: high granularity Si-W sampling calo
FoCal-H: conventional metal-scintillator sampling calo



FoCal
(not to scale)



$3.4<\eta<5.8$

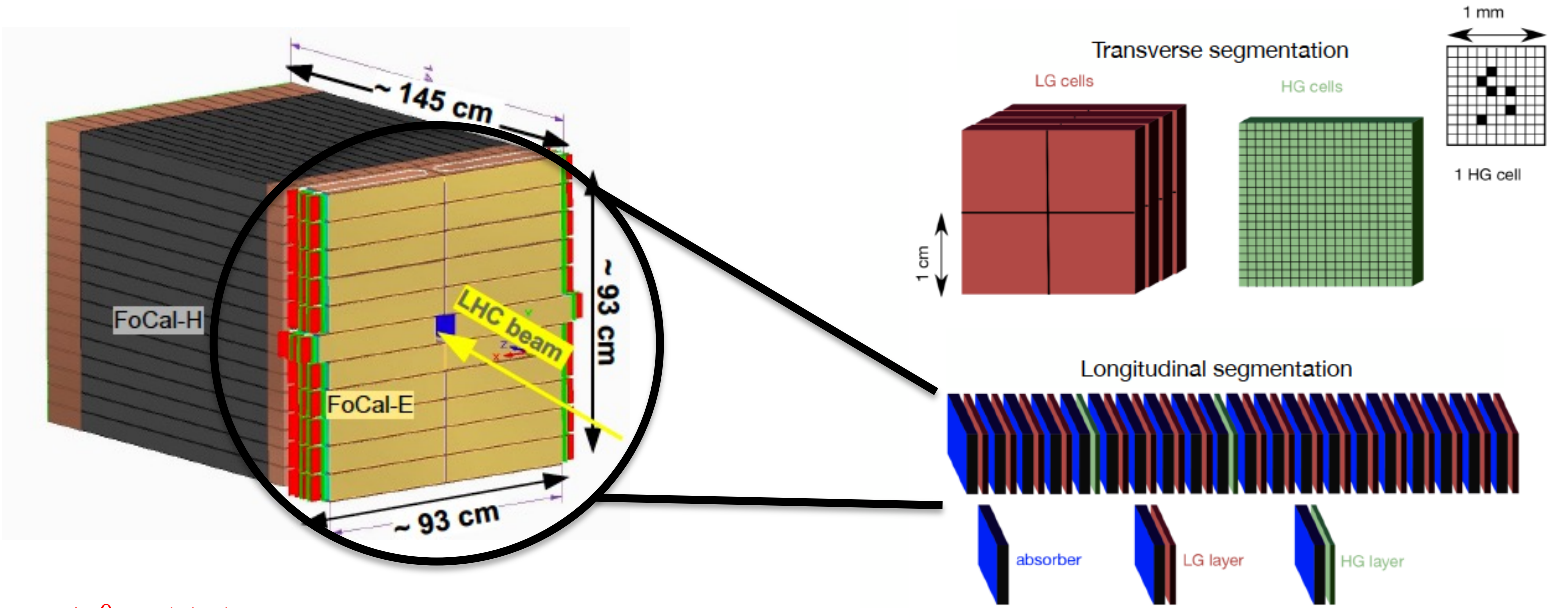


Main physics goal: study universal structure of matter at low-*x*

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

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

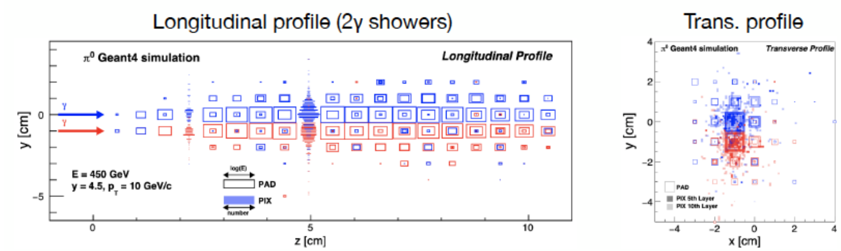
FoCal-E detector



Separate γ/π^0 at high energy:

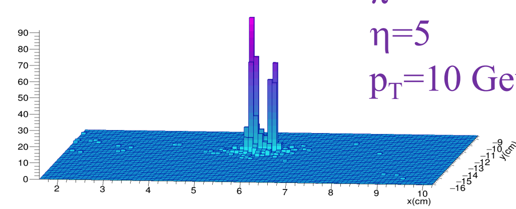
π^0 (p_T=10 GeV, η=4.5): two-γ separation ~5mm

→ need small Molière radius, high granularity



FoCal-E:

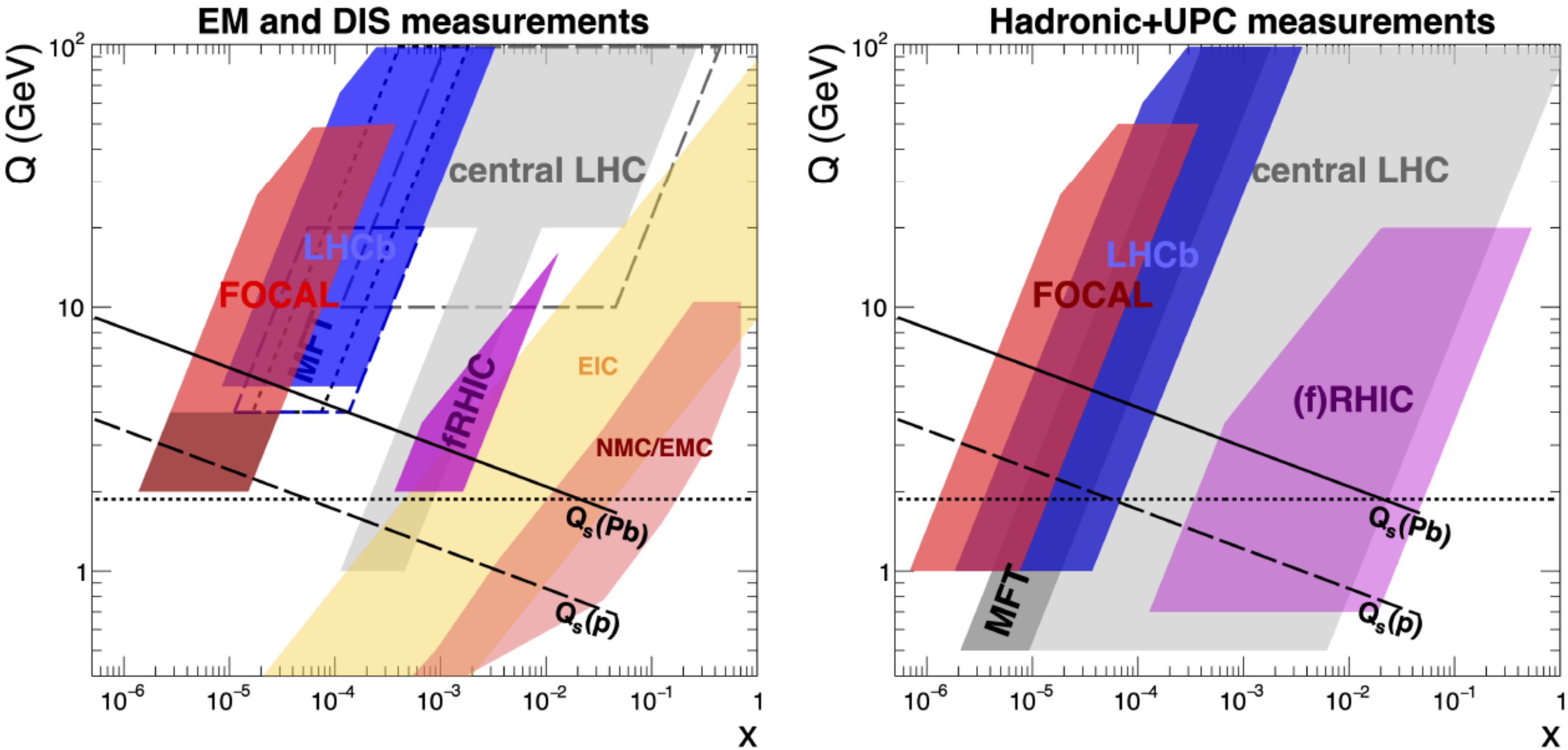
- W absorber: 20 layers ~ 20 X_0
- Si sensor:
  - 18 low-granularity pad layers
  - 2 high-granularity pixel layers (30 x30 μm^2)
  - → effective granularity ≈ 1 mm^2



π^0
η=5
p_T=10 Gev/c

IS'23 talk on technical design and test beam results:
https://indico.cern.ch/event/1043736/contributions/5363764/

Low-x probes: experimental acceptance



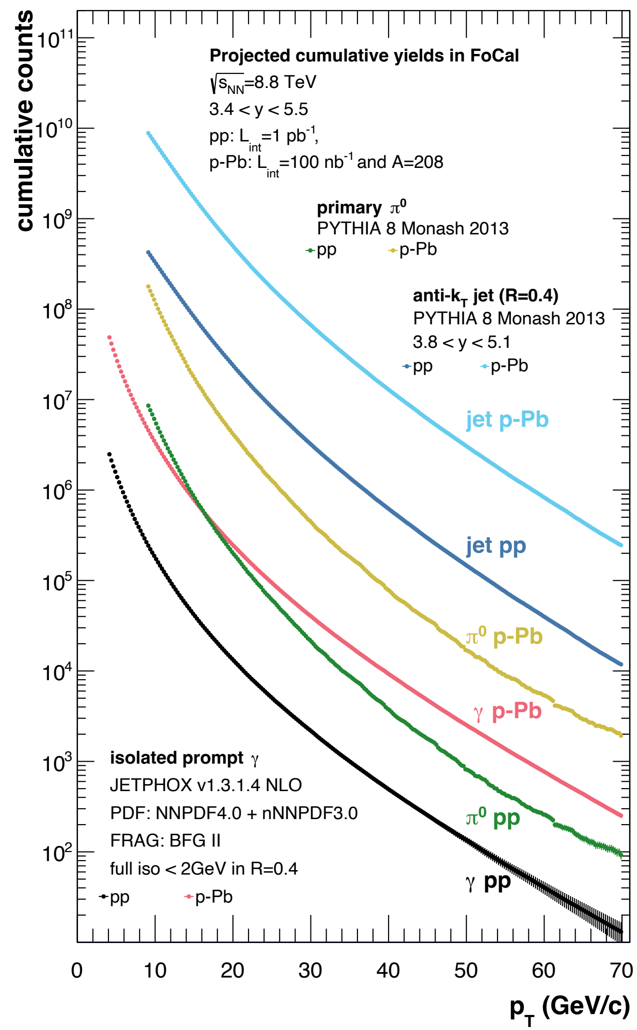
EM in hadronic collisions:
direct γ, DY

Production rate projections for Run 4

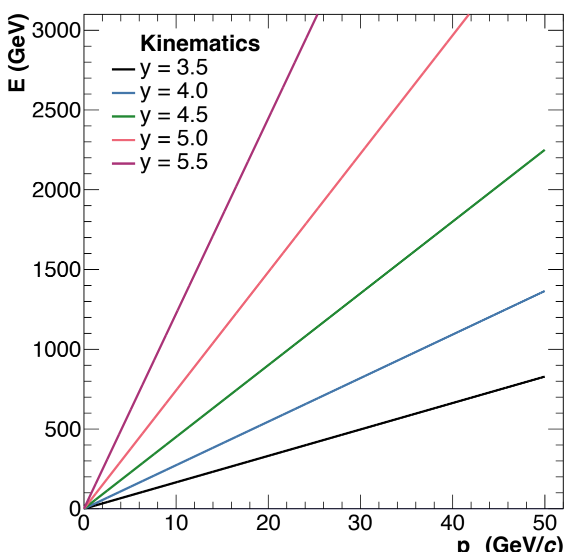
Integrated luminosity: current projections

- 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



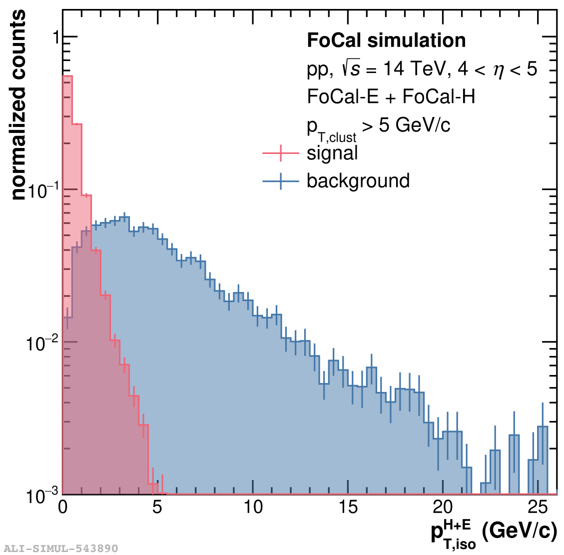
Forward kinematics:
large energy deposition
in calorimeter

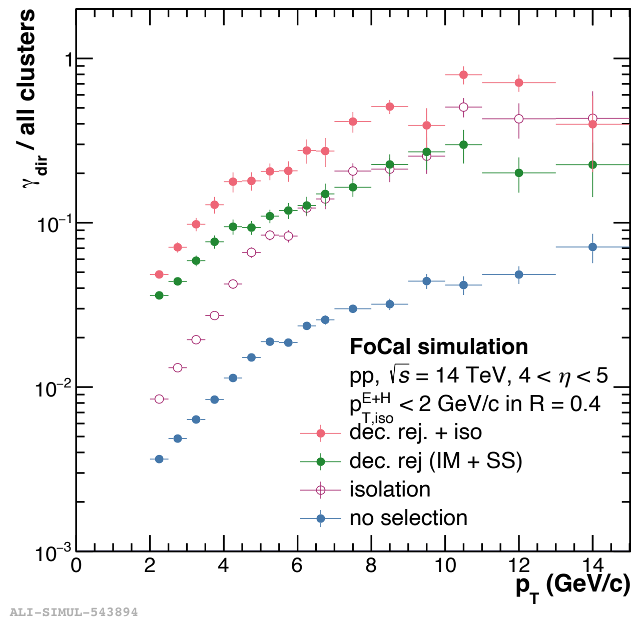
FoCal performance: direct photons:

Prompt photon PID cuts:

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

Isolation p_T

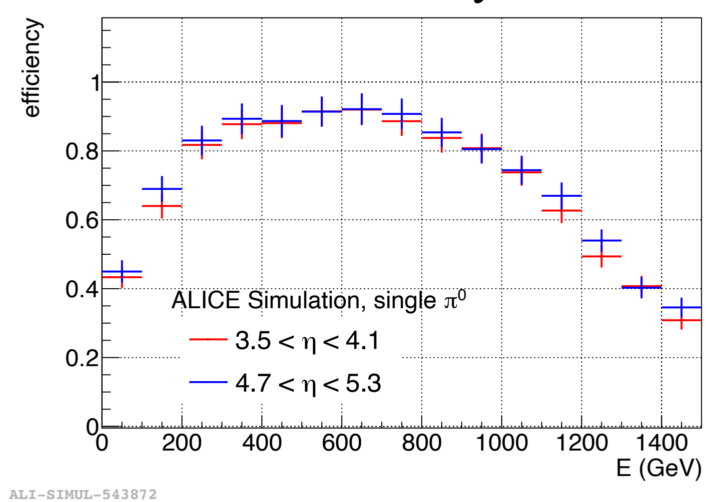




Background rejection:factor~10

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

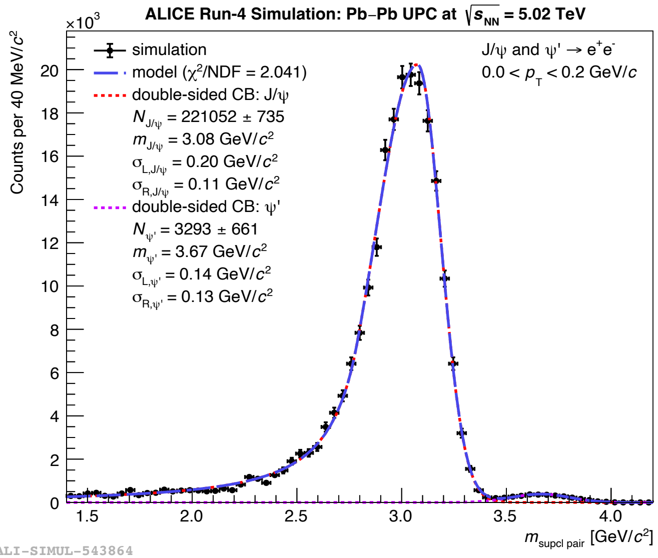
π^0 efficiency



Good π^0 efficiency

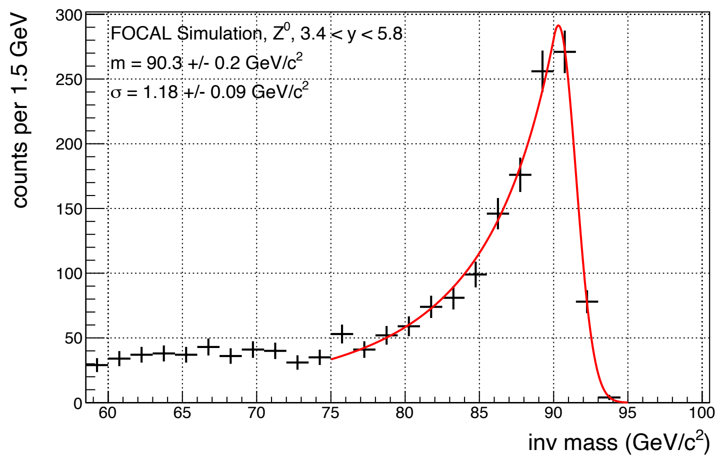
Vector mesons, Z-bosons

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



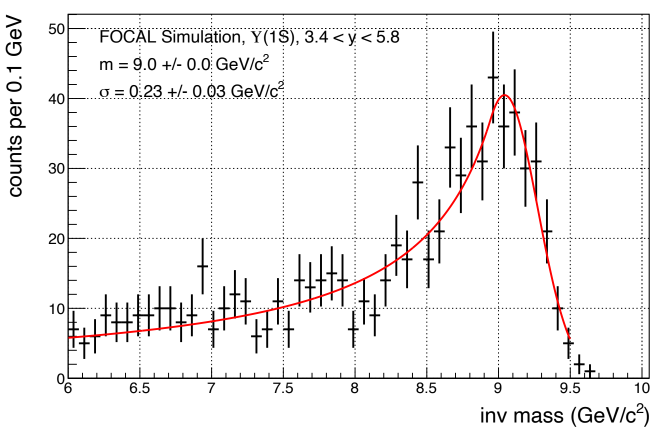
ALI-SIMUL-543864

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



ALI-SIMUL-543856

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



ALI-SIMUL-543860

Jet measurement performance

Forward jet measurements provide key probes of saturation

FoCal: calorimetric jet reconstruction in FoCal-E and FoCal-H

Challenging measurement at very forward η:

- Forward phase space is "geometrically compact"
- But transverse size of calorimetric jet shower is independent of η

Work in progress:

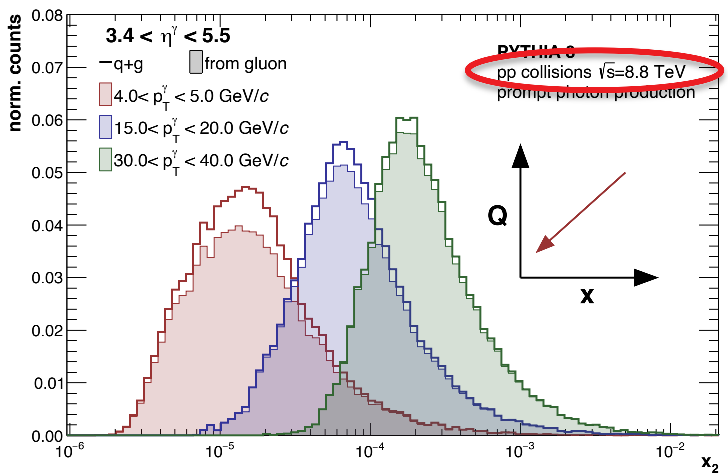
- How large R is needed for good JER and JES?
- Phase space for coincidence channels? (e.g. ~balanced di-jets and gamma+jet)
- In-situ jet energy scale calibration: γ+jet, Z+jet

Detailed study of jet performance is underway

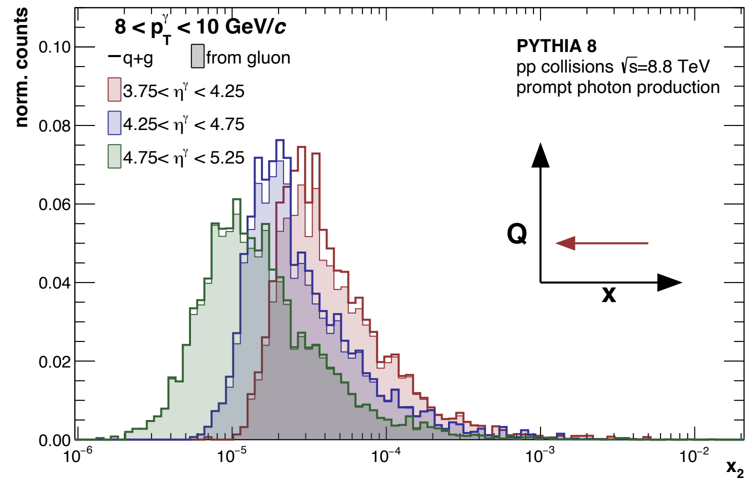
Partonic kinematics: γ in FoCal

Inclusive γ_{dir}

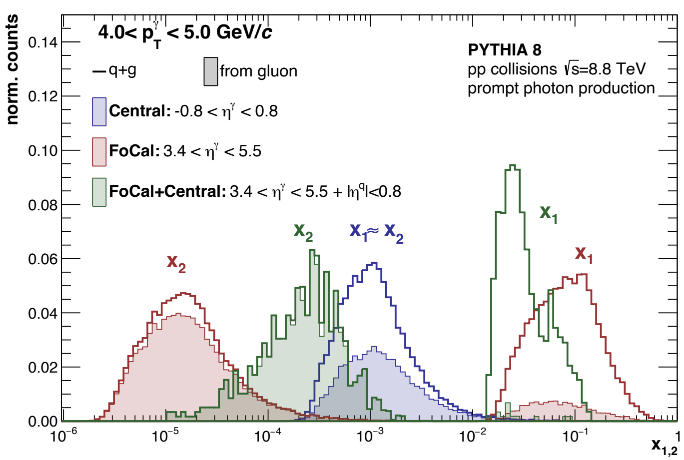
p_T dependence

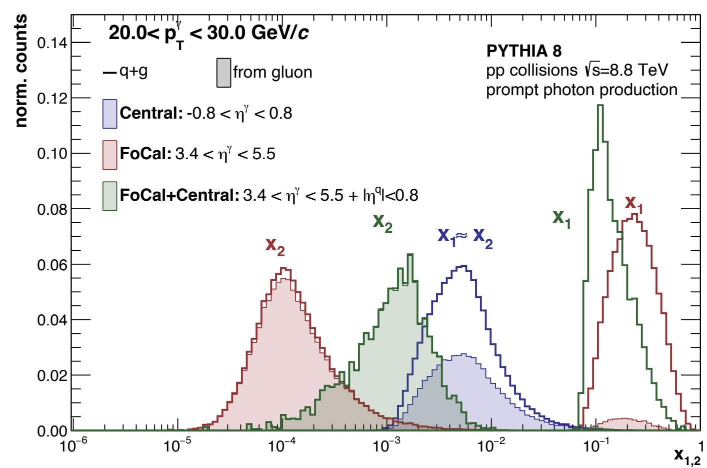


η dependence



γ+jet: FoCal vs Central Barrel

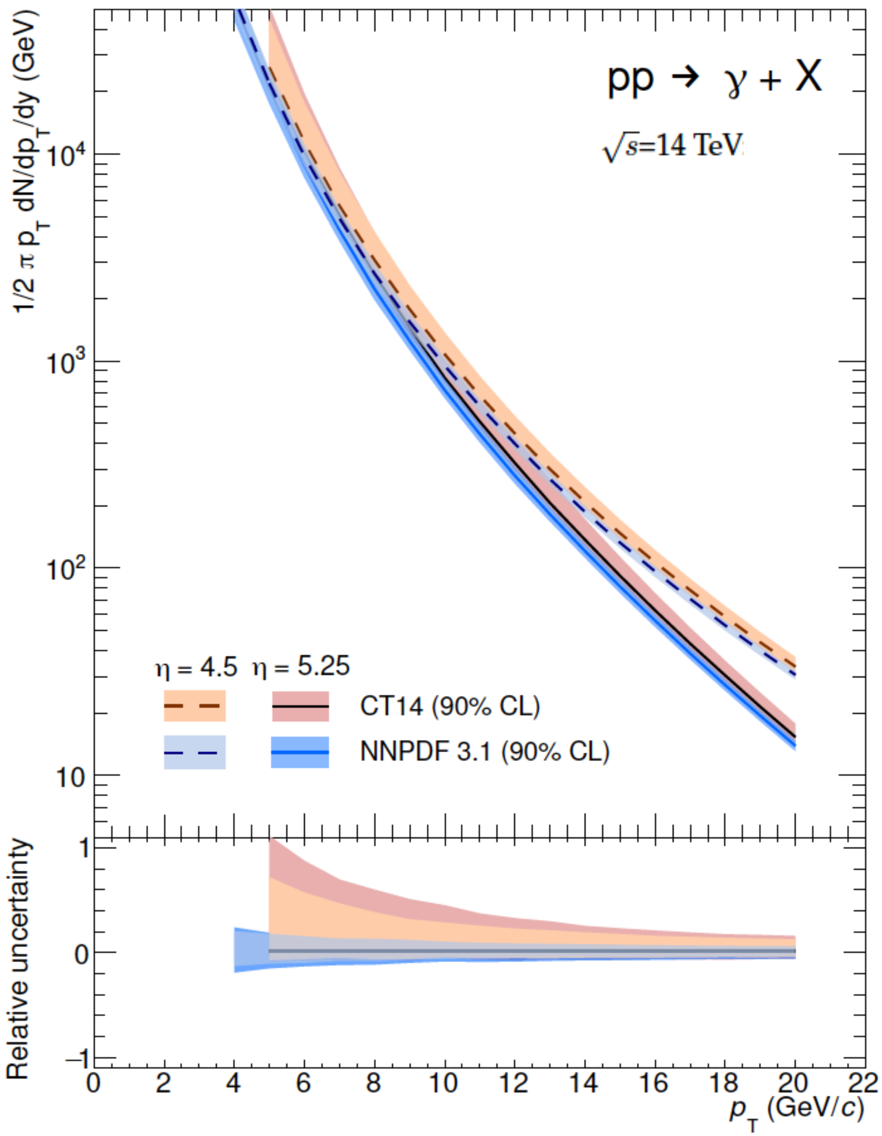




FoCal has flexibility to tune partonic kinematics over significant range

→ overlap with EIC kinematics

Forward isolated photons in pp @ 14 TeV



Compare two recent PDF fits: tension in FoCal acceptance

- FoCal provides unique constraints of pp PDFs

FoCal probes $x \sim 5\text{x}10^{-7}$

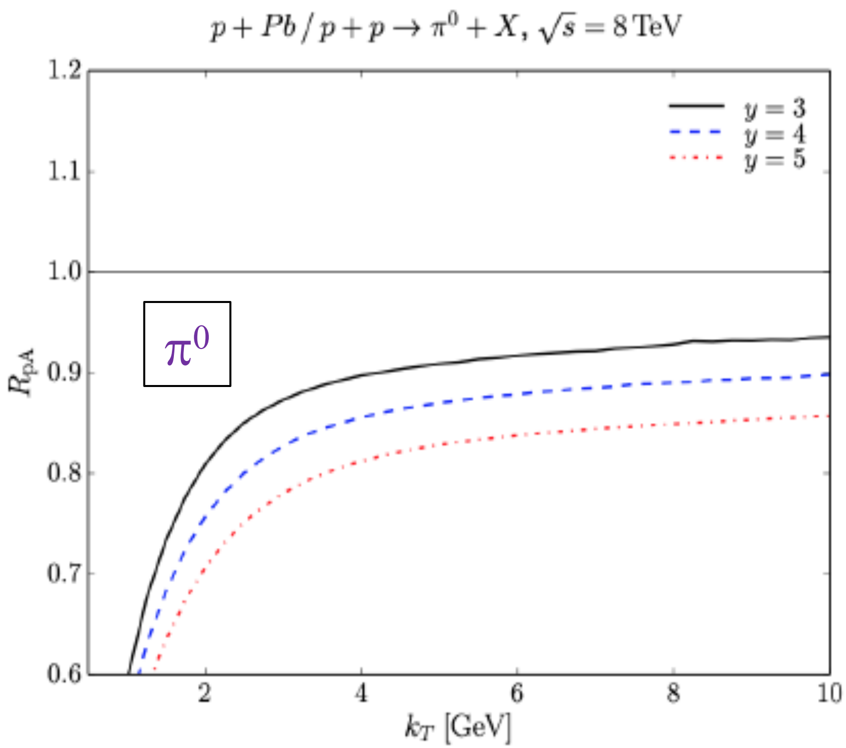
- sensitive to saturation effects even in pp collisions?

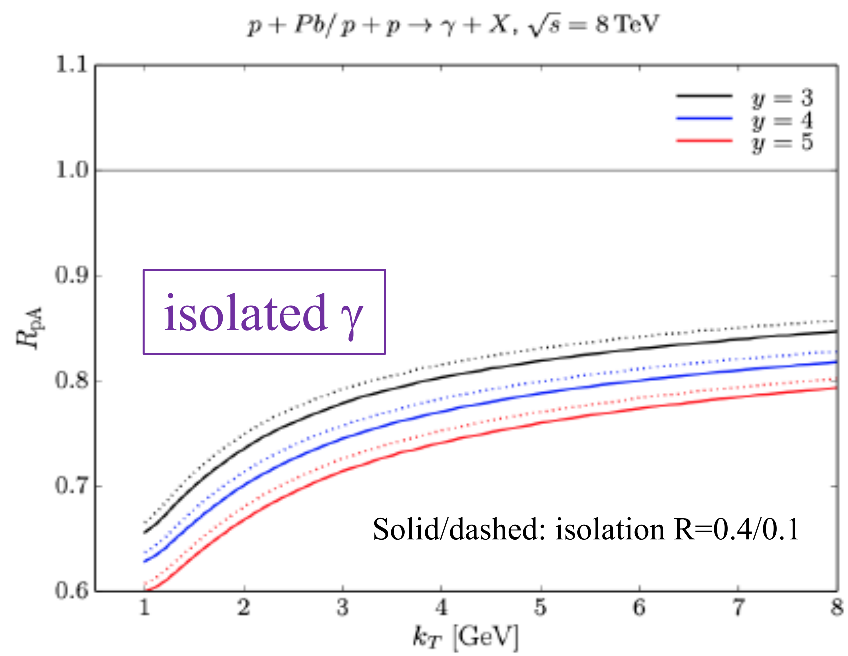
Selected theory calculations of saturation effects that can be probed by FoCal

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

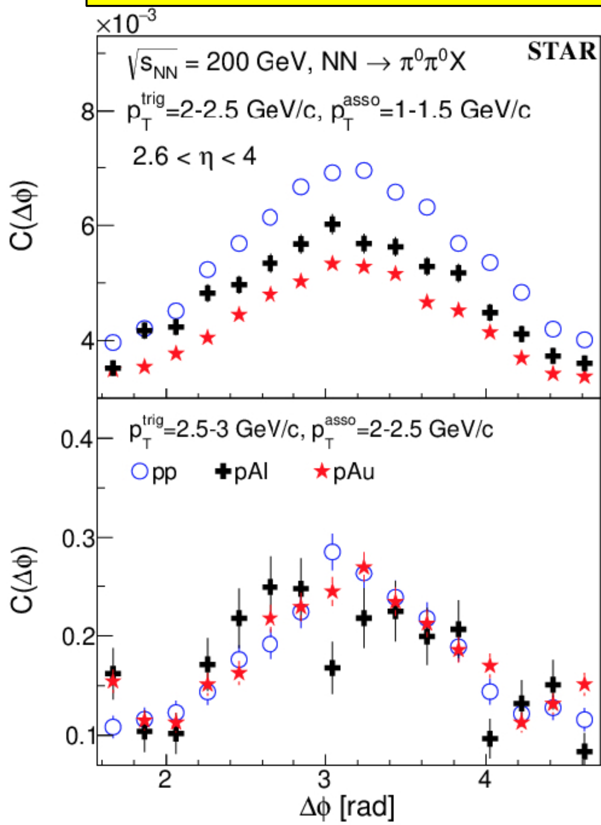
Authors: picture may change @ NLO

Also measurable by LHCb in less forward acceptance

Lesson for FoCal: both measurements should be done

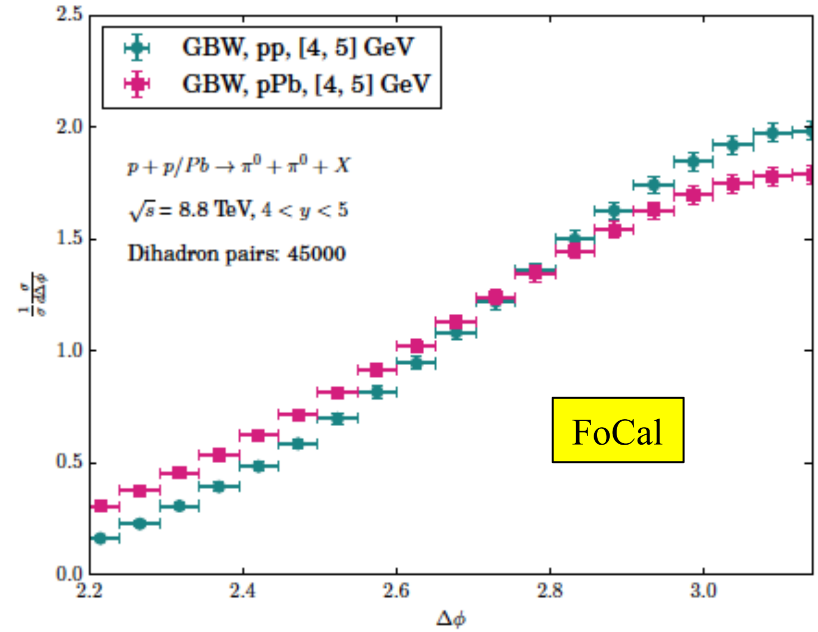
Di-hadron correlations RHIC and LHC

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.

Forward di-jet

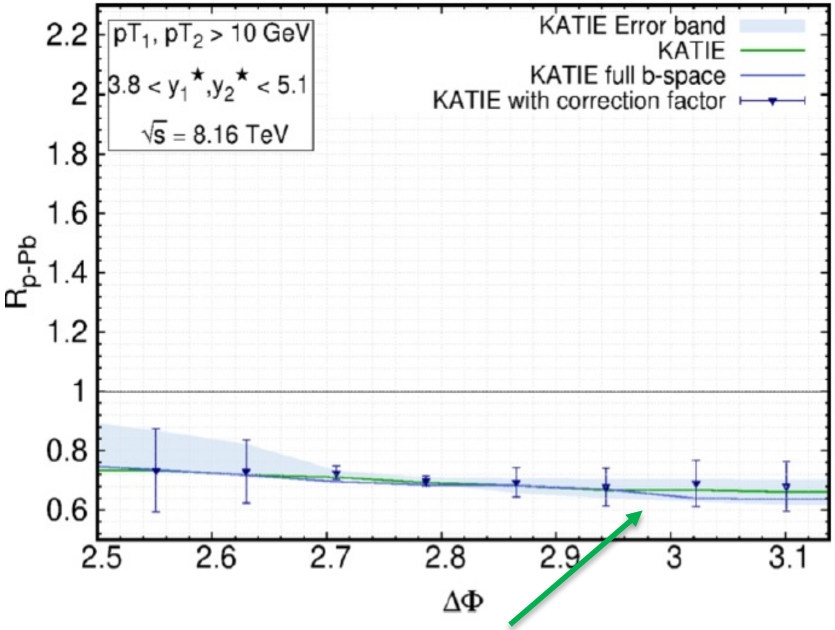
γ+jet, balanced di-jet at low-x: $k_T \sim Q_{sat}$

- 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

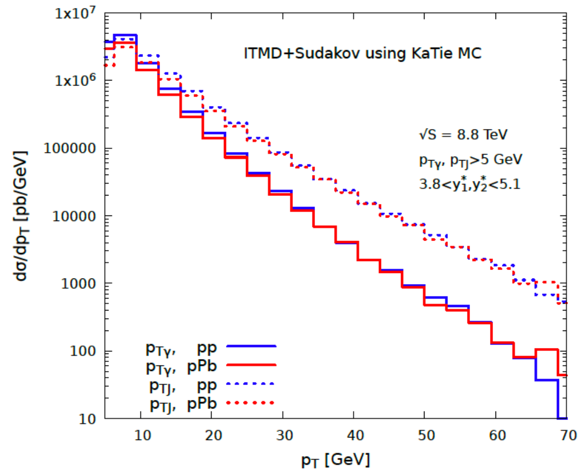
van Hameren, Comput. Phys. Commun. 224 (2018) 371
van Hameren et al., JHEP 12 (2016) 034
Kotko et al., JHEP 09 (2015) 106
Al-Mashad et al., arXiv:2210.06613
Mäntysaari and Paukkunen, Phys. Rev. D 100 (2019) 114029
Liu et al. JHEP 07 (2022) 041
Wang et al. arXiv:2211.08322

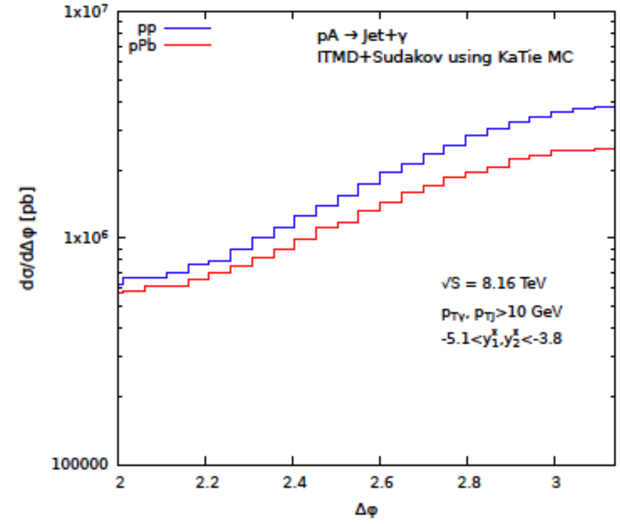
Forward γ+jet

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

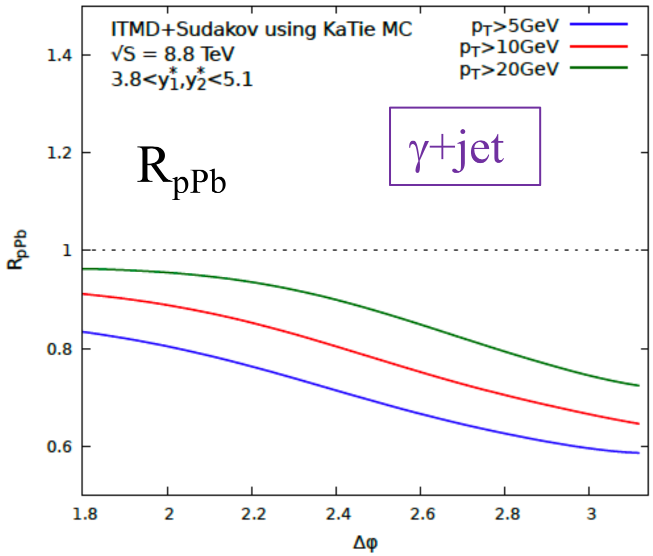




γ+jet: R_{pPb} vs Δϕ

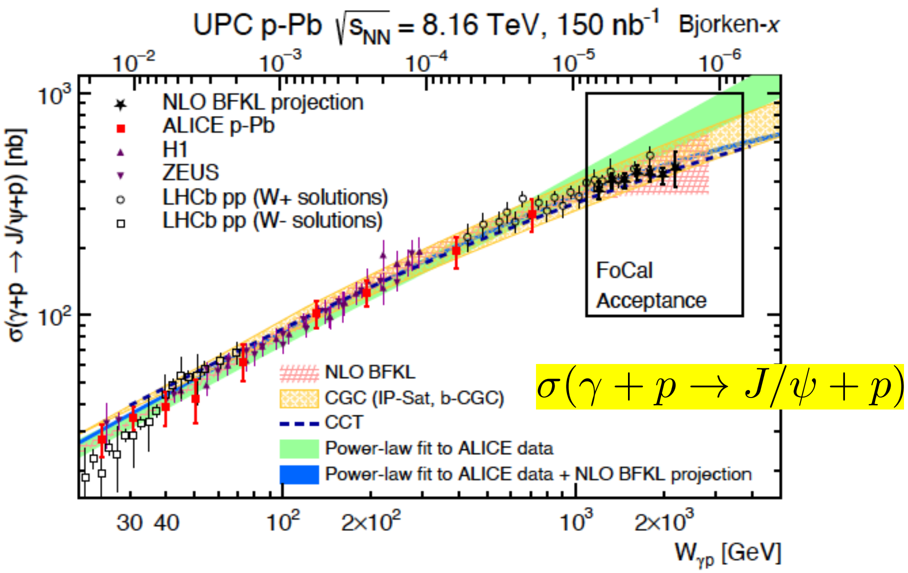
- recoil jet p_T dependence

Compare to di-jet: dipole vs quadrupole TMD



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

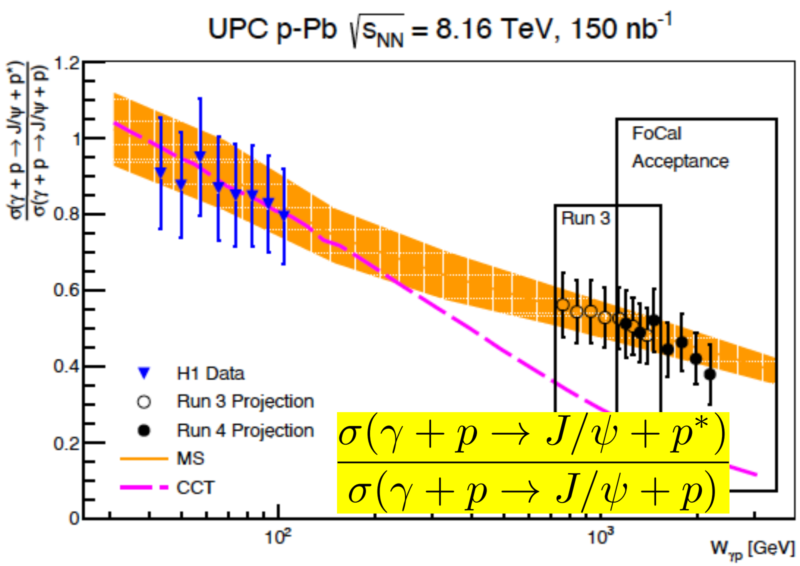
A. Bylinkin, J. Nystrand and D. Tapia Takaki, J. Phys. G 50 (2023) 055105



$W_{\gamma p}$ = 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

FoCal public documentation

Letter of Intent (2020): CERN-LHCC-2020-009

In preparation:

- performance note
- Technical Design Report (TDR)

FoCal Physics Public Note

https://inspirehep.net/literature/2661418

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 $p_T \gtrsim 4$ 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

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE-PUBLIC-2023-DRAFT v0.0
June 14, 2023

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 pseudo-rapidity interval of $3.4 < \eta < 5.8$. The FoCal design is optimized to measure isolated photons at most forward rapidity for $p_T \gtrsim 4$ GeV/c. This document presents the performance of the FoCal to measure isolated photons and other selected observables.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-LHCC-2022-XXX
ALICE-PUBLIC–DRAFT v0.0
June 15, 2023

Technical Design Report:
A Forward Calorimeter (FoCal) in the ALICE experiment

ALICE Collaboration *

Summary

FoCal has unique coverage:

- broad scan of (x,Q^2), including low x and low p_T
- observables: photons, neutral hadrons, jets, and their correlations

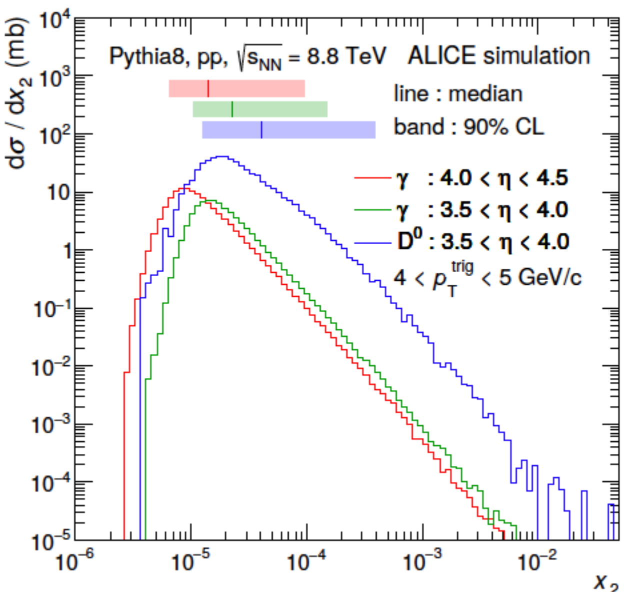
Deep theoretical connection between e-A DIS and forward p-Pb

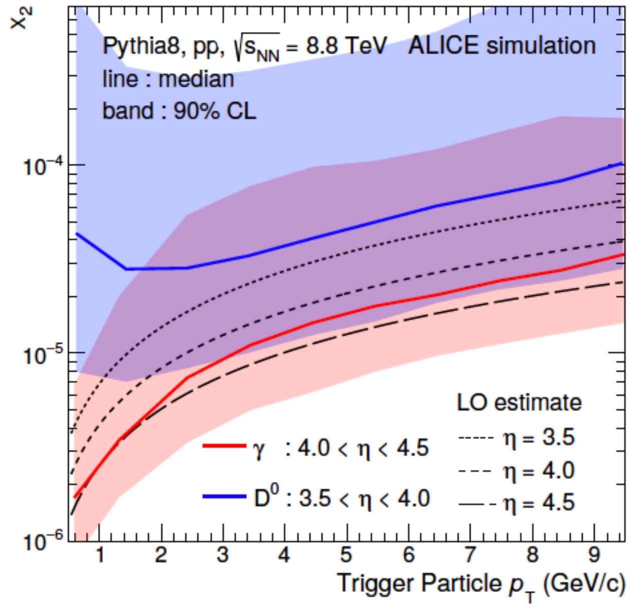
- probe the same dipole/quadrupole+medium interactions
- NLO calculations needed for many channels

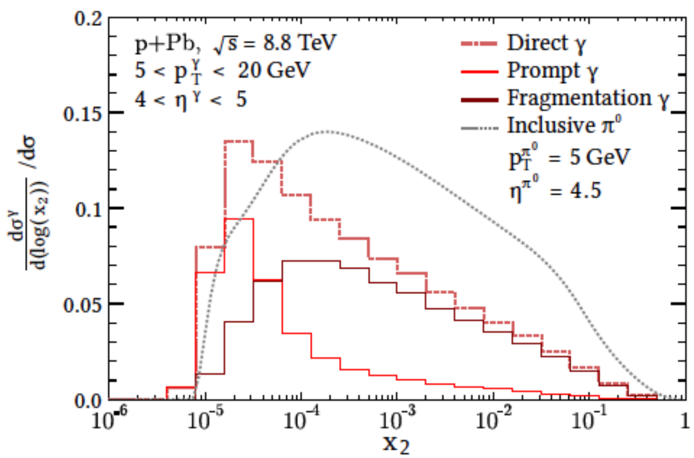
EIC and FoCal are complementary → comprehensive program to explore non-linear QCD evolution

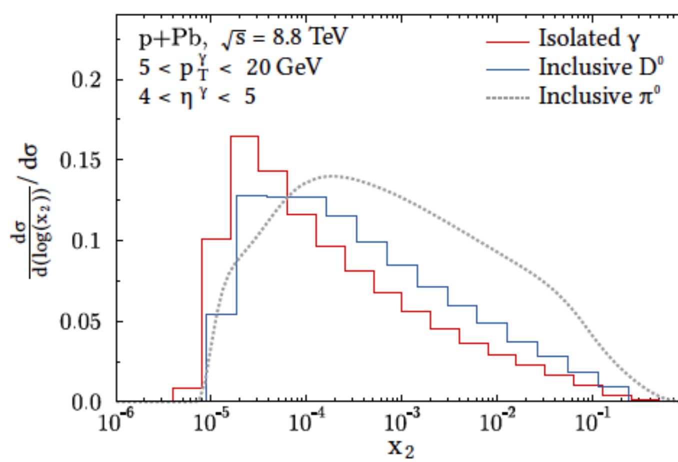
Backup

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



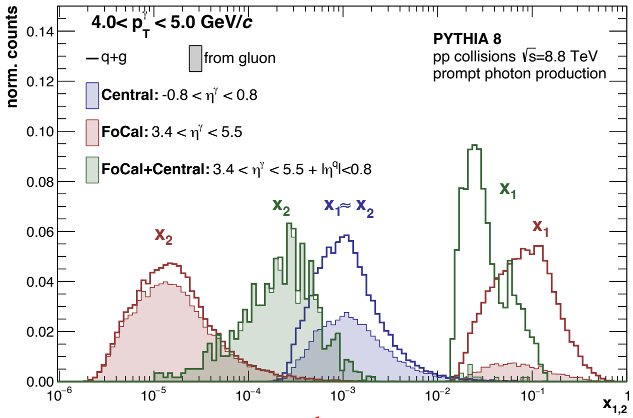




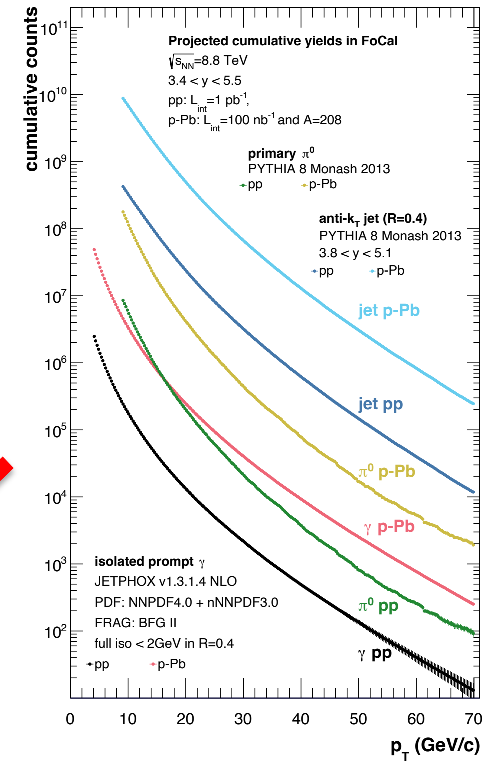


γ+jet rates: forward/central

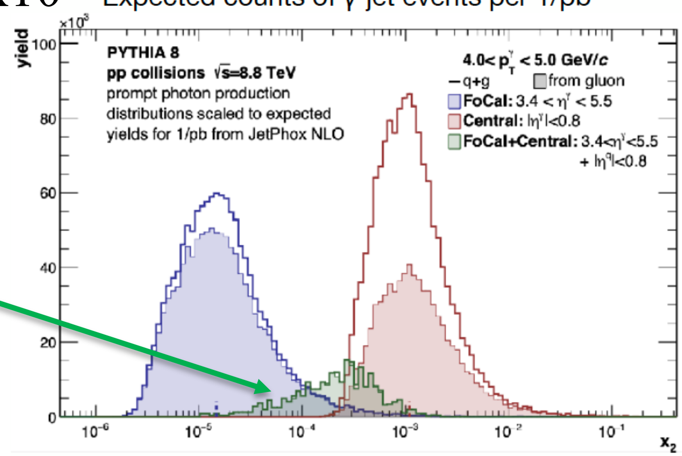
x-coverage (probability)



Trigger rates



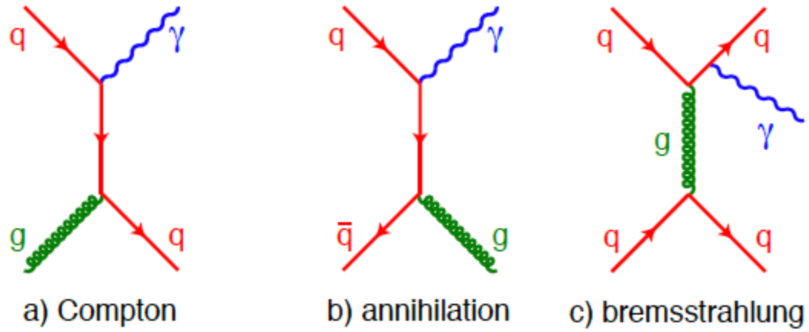
x10^3 Expected counts of γ-jet events per 1/pb



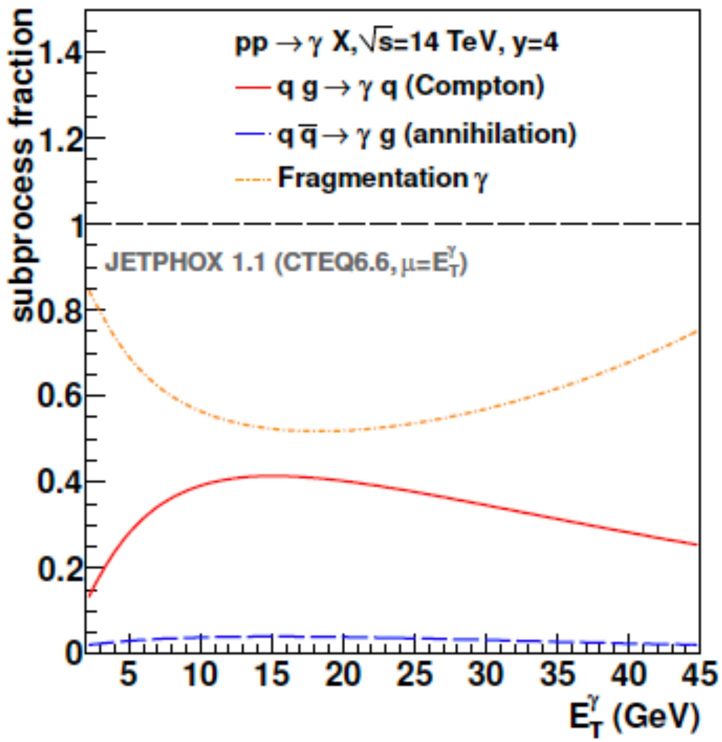
γ: FoCal
jet: central

Significant rate of γ+jet coincidences forward/central

Forward direct γ: partonic processes



No isolation



Isolated (R=0.4, cut=10%)