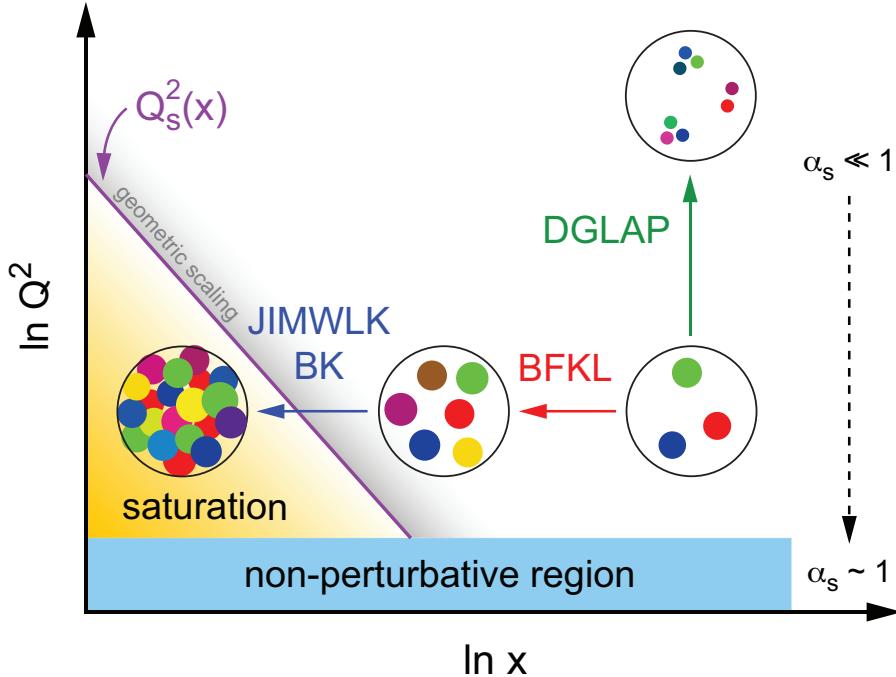


Low-x physics program of the ALICE FoCal upgrade

Peter Jacobs
Lawrence Berkeley National Laboratory

for the ALICE Collaboration





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

How do we test it experimentally?

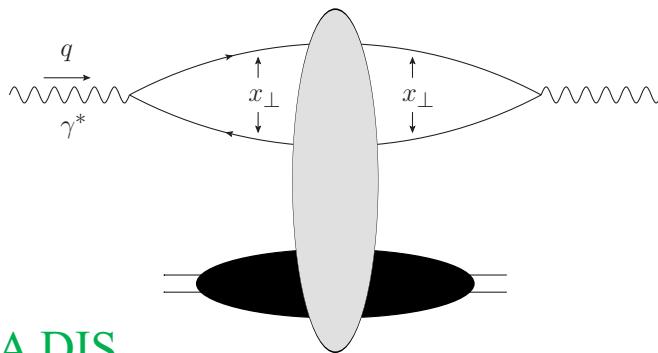
QCD phenomena evolve only logarithmically in x and Q^2

→ 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

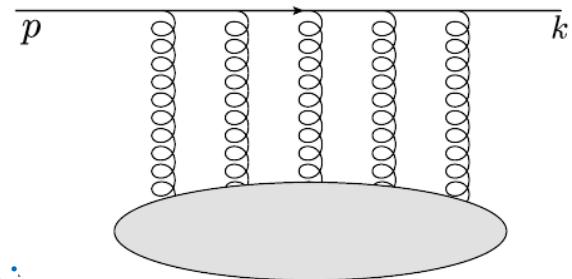


e+A DIS

- Interaction cross section
- Structure Functions F_2, F_L

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

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



Forward p+A:

- Inclusive π^0 , jet, direct γ ,
- γ +jet
- balanced di-jet,...

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

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. D 66 (2002) 014021

Kovchegov and A. H. Mueller, Nucl. Phys. B 529 (1998) 451

Kopeliovich, Raufisen and Tarasov, Phys. Lett. B 503 (2001) 91

The ALICE Forward Calorimeter (FoCal) upgrade

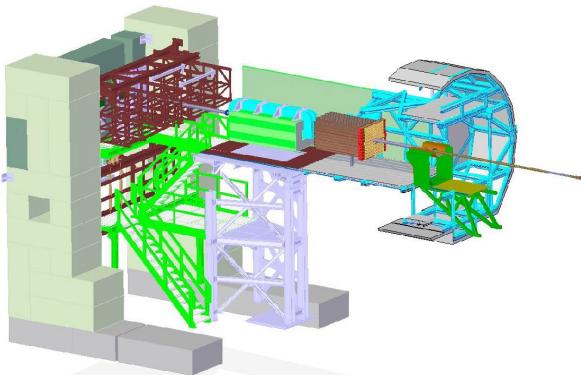
FoCal-E: high granularity Si-W sampling calo

FoCal-H: conventional metal-scintillator sampling calo

Letter of Intent: CERN-LHCC-2020-009

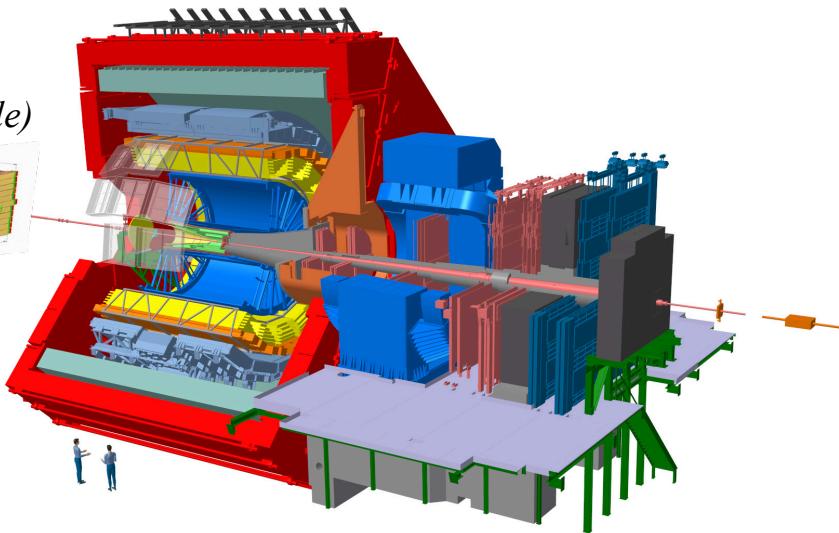
Installation: LHC Long Shutdown 3

Operation: LHC Run 4 (start 2029)



FoCal
(not to scale)

$3.4 < \eta < 5.8$



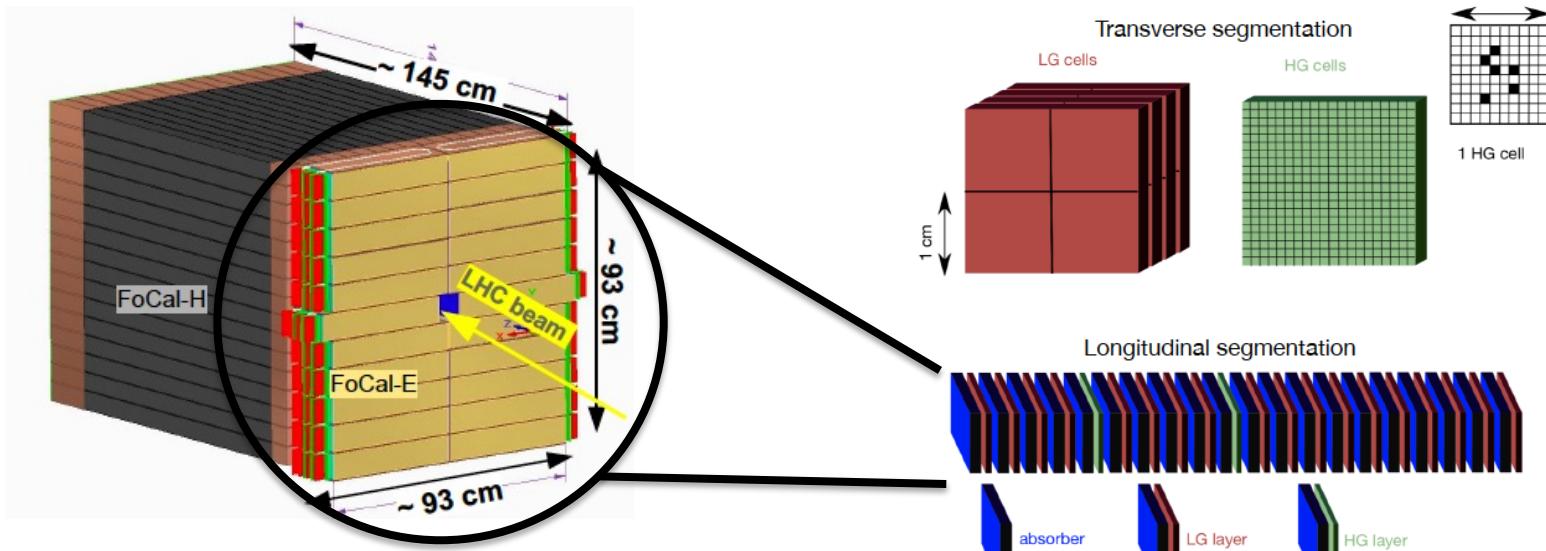
Main physics goal: study universal structure of matter at low- x

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

Observables:

- π^0 and other neutral mesons
- Isolated direct photons
- Jets
- UPCs: $J/\psi, \psi', \Upsilon$
- Z, W
- Correlations

FoCal-E detector

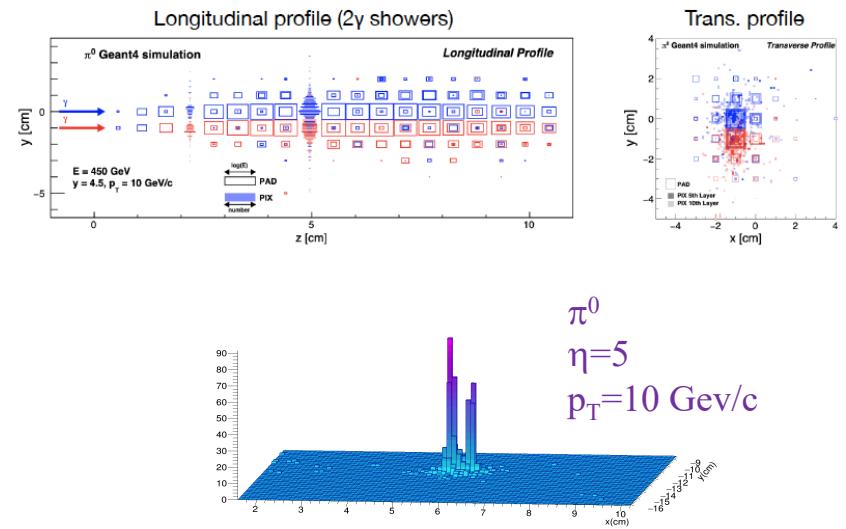


Separate γ/π^0 at high energy:

π^0 ($p_T=10$ GeV, $\eta=4.5$): two- γ separation $\sim 5\text{mm}$
 → need small Molière radius, high granularity

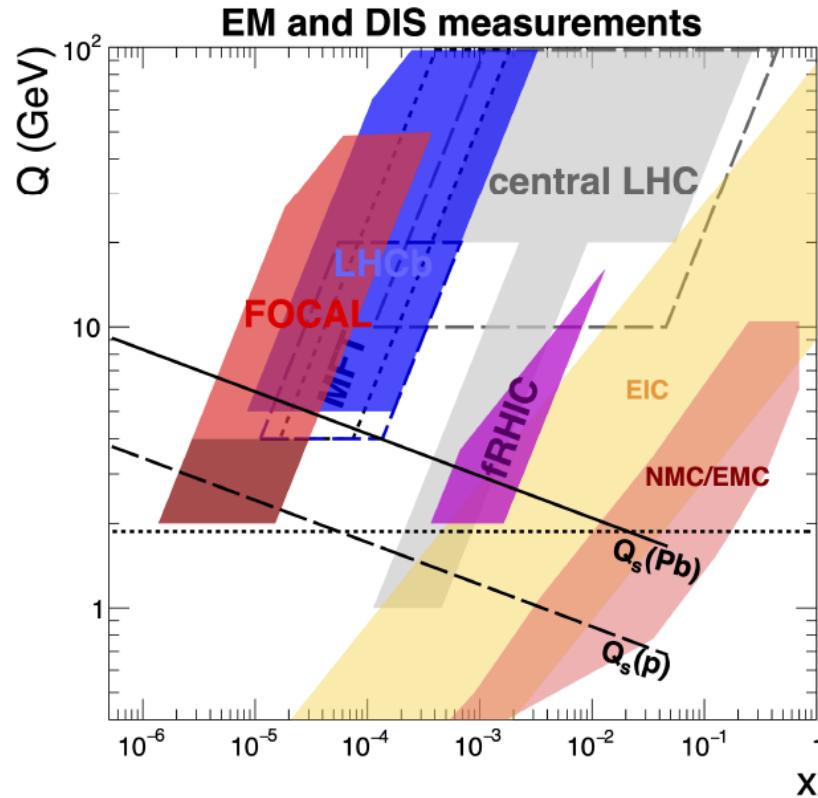
FoCal-E:

- W absorber: 20 layers $\sim 20 X_0$
- Si sensor:
 18 low-granularity pad layers
 2 high-granularity pixel layers ($3 \times 30 \mu\text{m}^2$)
 → effective granularity $\approx 1 \text{ mm}^2$

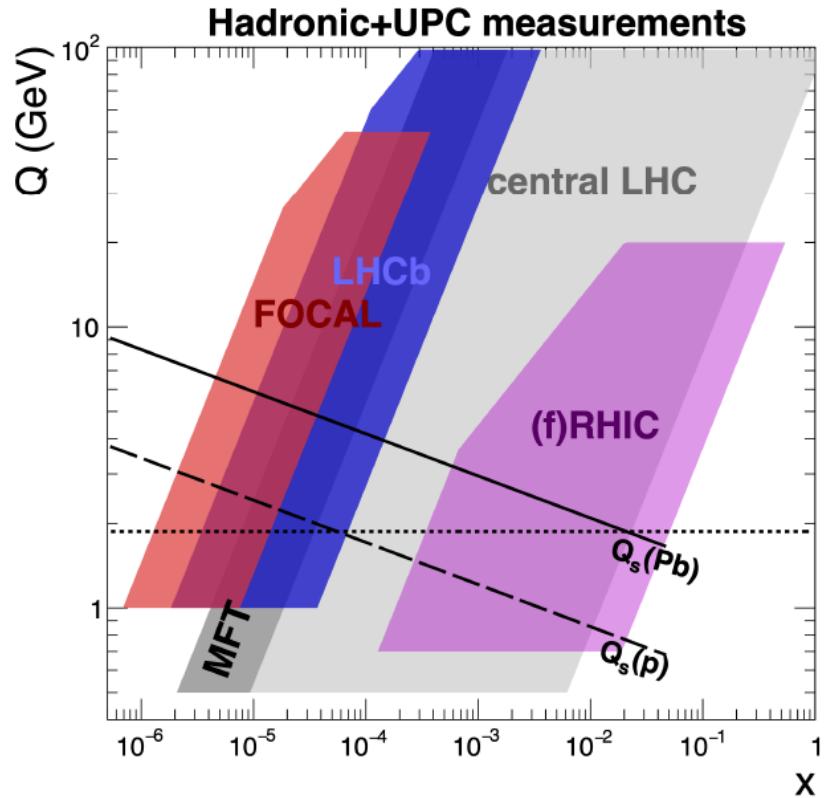


π^0
 $\eta=5$
 $p_T=10$ GeV/c

Low- x probes: experimental acceptance



EM in hadronic collisions:
direct γ , DY

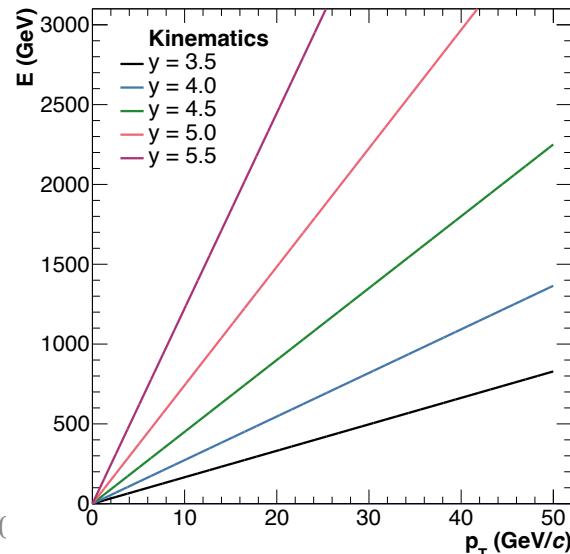


Production rate projections for Run 4

Integrated luminosity: current projections

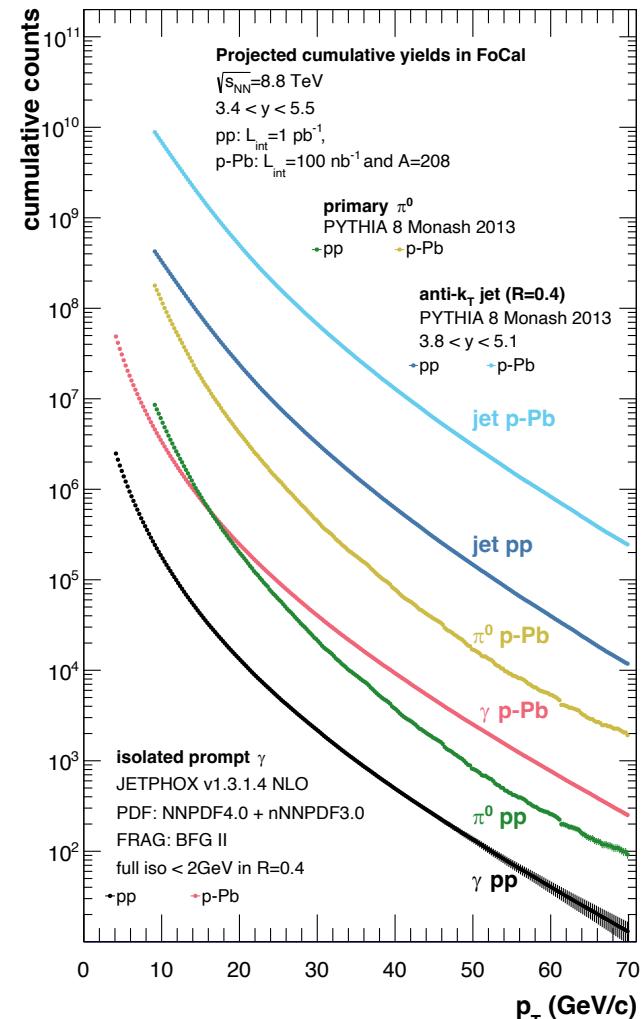
- pp at $\sqrt{s}=8.8$ TeV: 1 week, $\mathcal{L}_{\text{int}}=4 \text{ pb}^{-1}$;
- p-Pb at $\sqrt{s}=8.8$ TeV: 3 weeks, $\mathcal{L}_{\text{int}}=300 \text{ nb}^{-1}$;
(both p-Pb and Pb-p)
- Pb-Pb at $\sqrt{s}=5.02$ TeV: 3 months, $\mathcal{L}_{\text{int}}=7 \text{ nb}^{-1}$;
- pp at $\sqrt{s}=14$ TeV: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

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

Inclusive channel rates
“Round number” int lumi

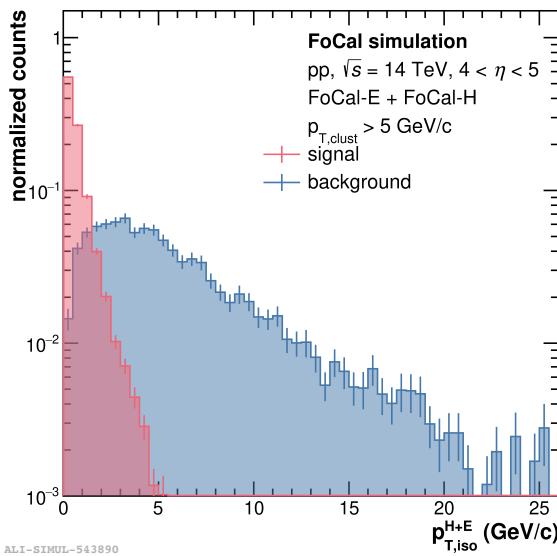


FoCal performance: direct photons:

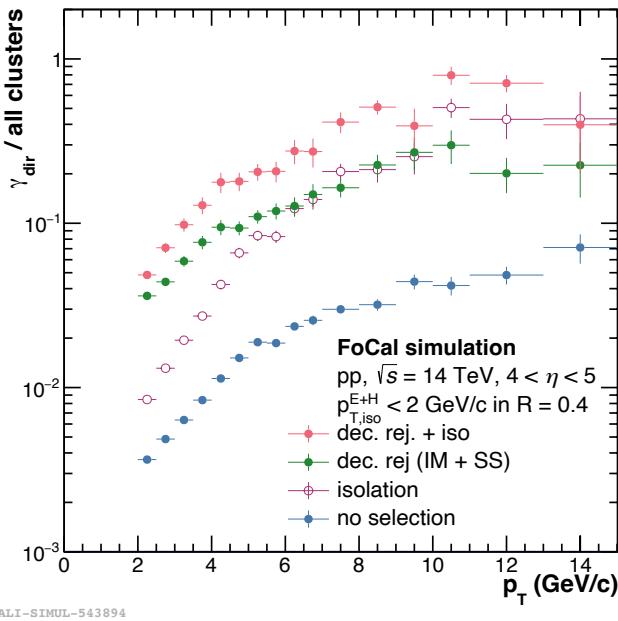
Prompt photon PID cuts:

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

Isolation p_T

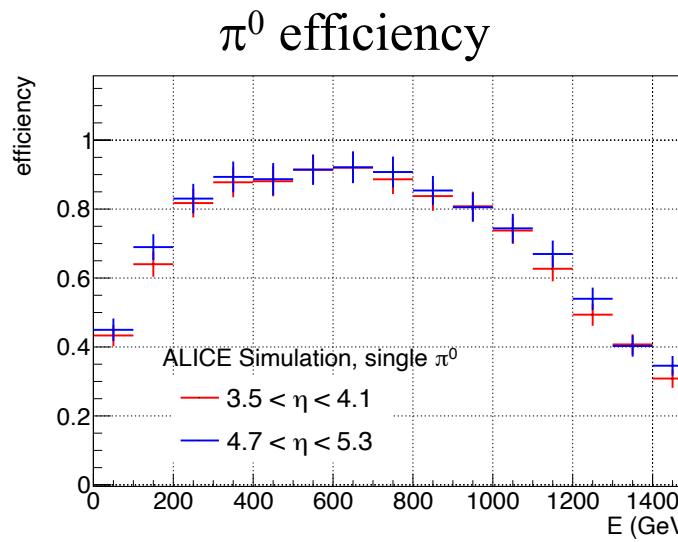


6/20/23



Background rejection: factor ~ 10

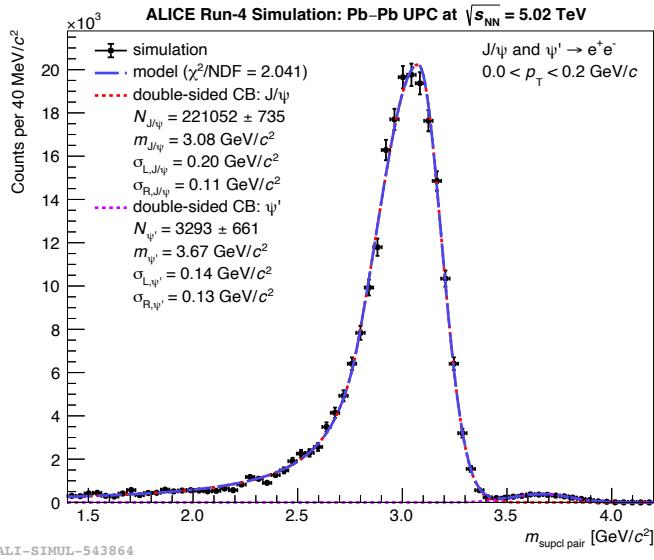
$\gamma_{\text{dir}}/\text{all} > 50\% \rightarrow$ high precision measurement



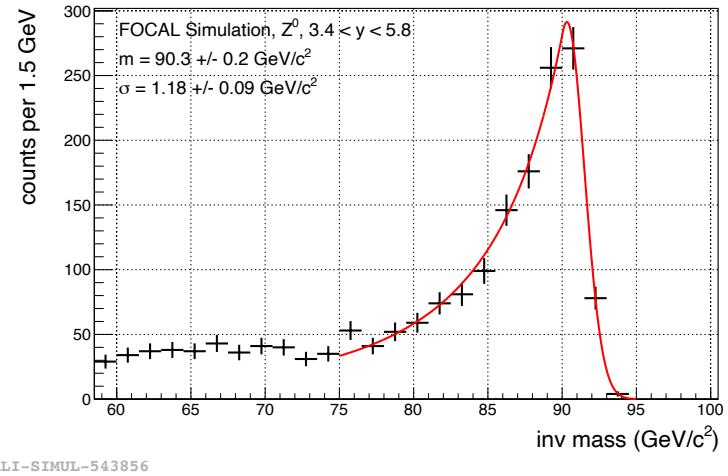
Good π^0 efficiency

Other channels being explored

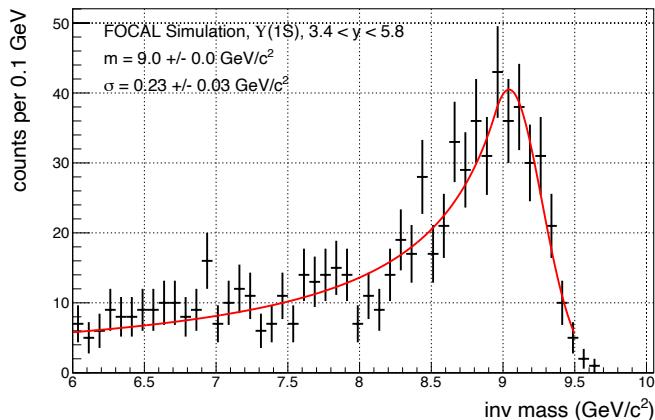
$J/\psi \rightarrow e^+e^-$ (UPC)



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

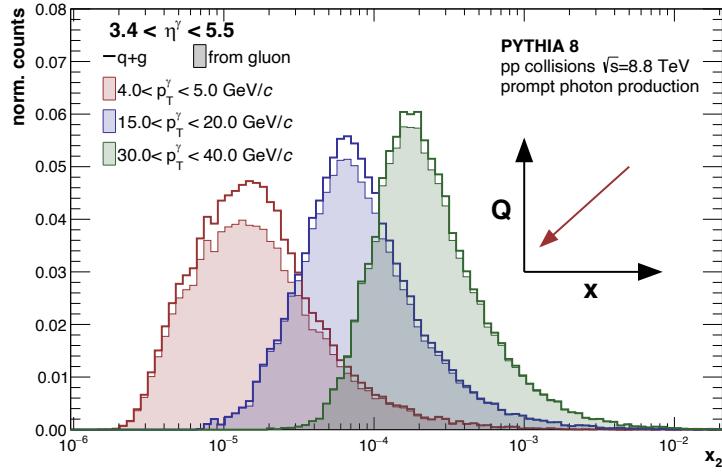


$\Upsilon(1s) \rightarrow e^+e^-$

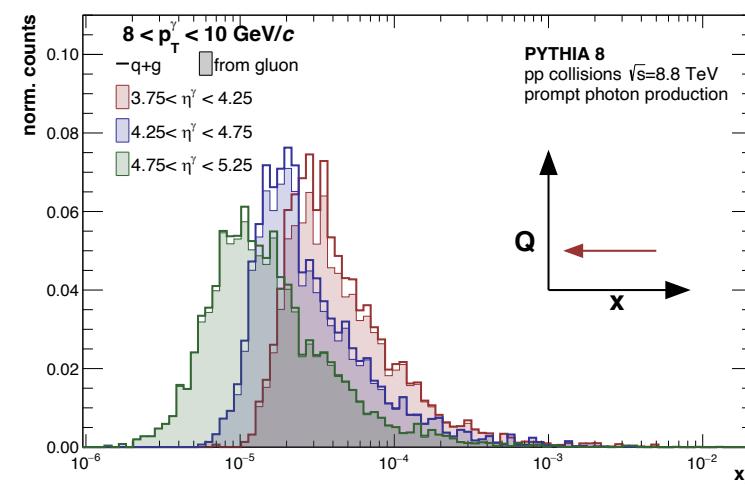


Partonic kinematics: γ in FoCal

p_T dependence

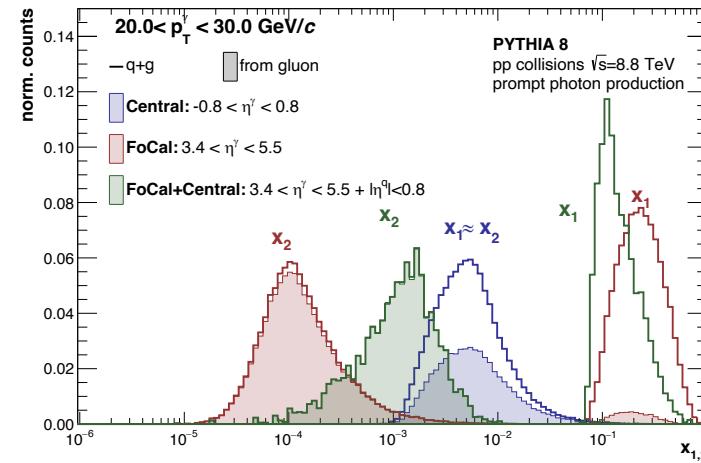
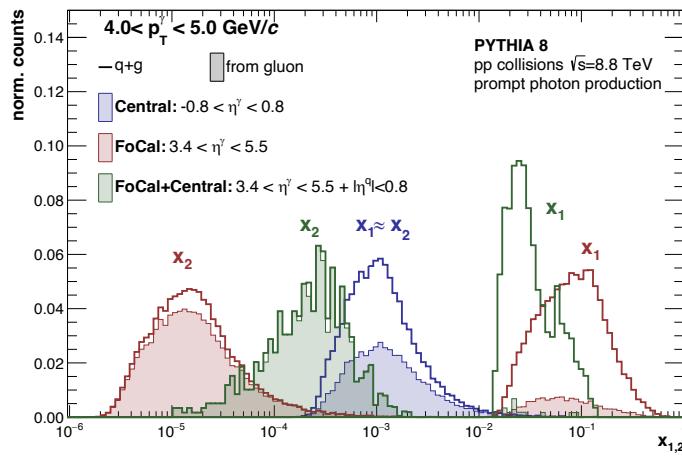


Inclusive γ_{dir}



η dependence

$\gamma+\text{jet}$: FoCal vs Central Barrel



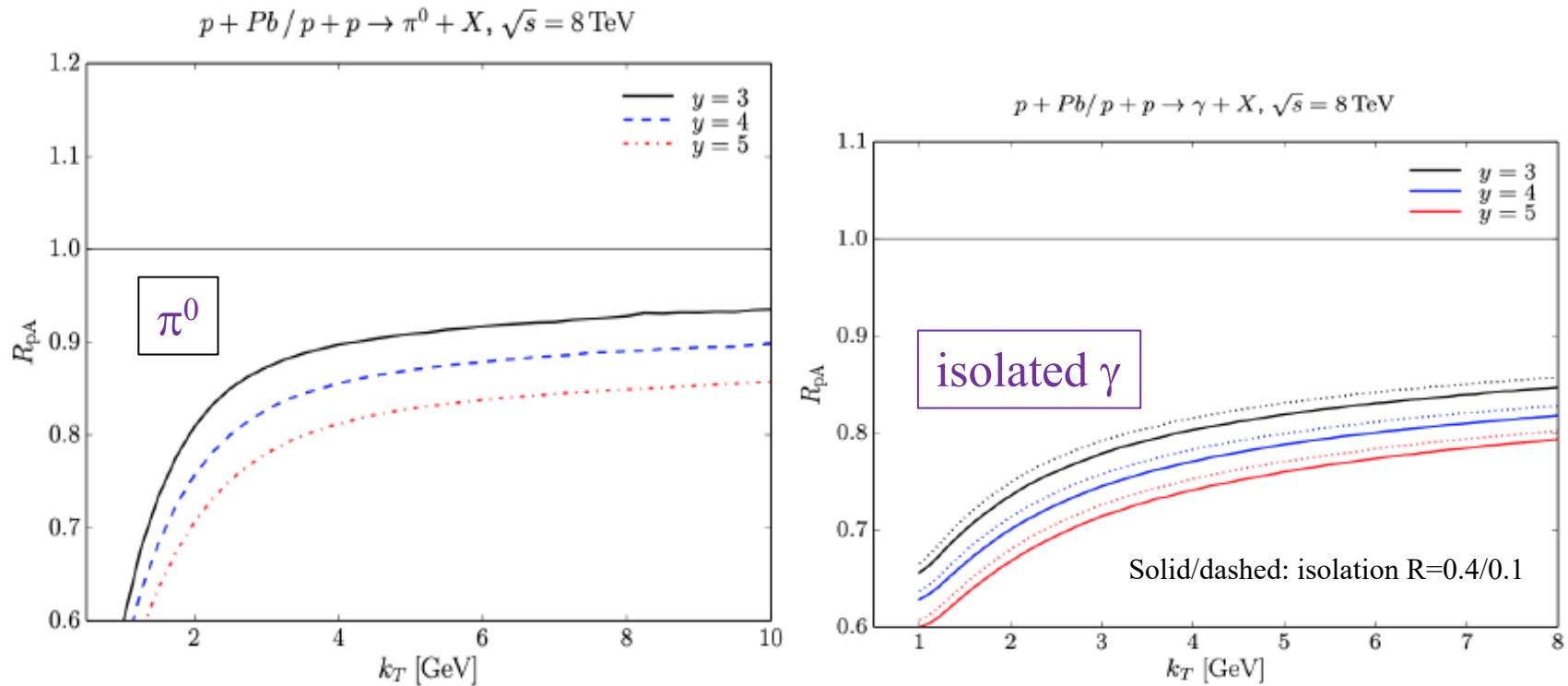
FoCal has flexibility to tune partonic kinematics over significant range
 → overlap with EIC kinematics

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 : $p_T \gg Q_{\text{sat}}$
- Direct γ : $qg \rightarrow \gamma g$; $k_T \sim Q_{\text{sat}}$

Authors: picture may change @ NLO

Also measurable by
LHCb in less forward
acceptance

Lesson for FoCal: both measurements should be done

Forward di-jet

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

- k_T provides knob to dial between saturation and linear QCD
- $\gamma + \text{jet}$: 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)

van Hameren, *Comput. Phys. Commun.* 224 (2018) 371

van Hameren et al., *JHEP* 12 (2016) 034

Kotko et al., *JHEP* 09 (2015) 106

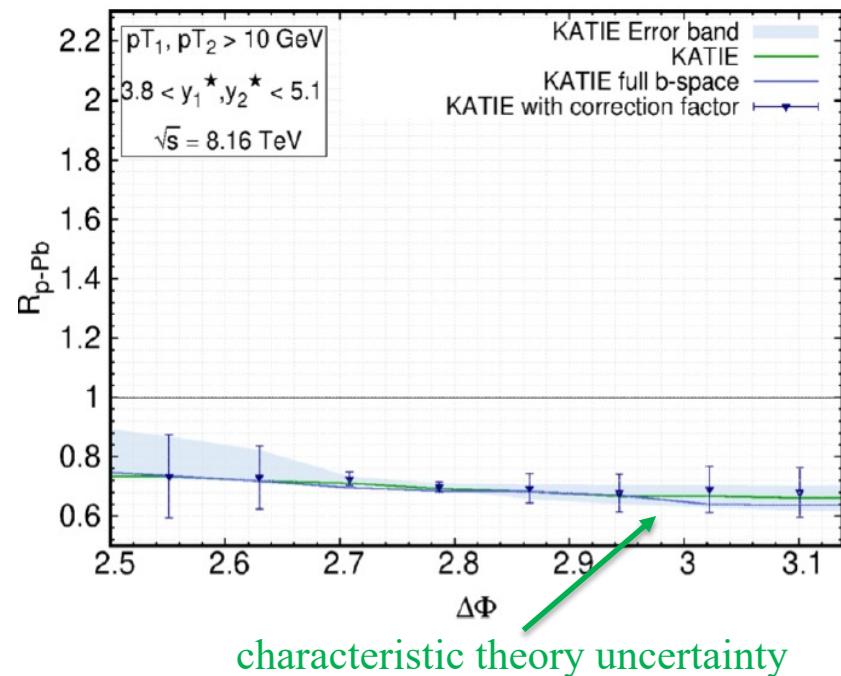
Al-Mashad et al., *arXiv:2210.06613*

Mäntysaari and Paukkunen, *Phys. Rev. D* 100 (2019) 114029

Liu et al. *JHEP* 07 (2022) 041

Wang et al. *arXiv:2211.08322*

Balanced di-jet acoplanarity

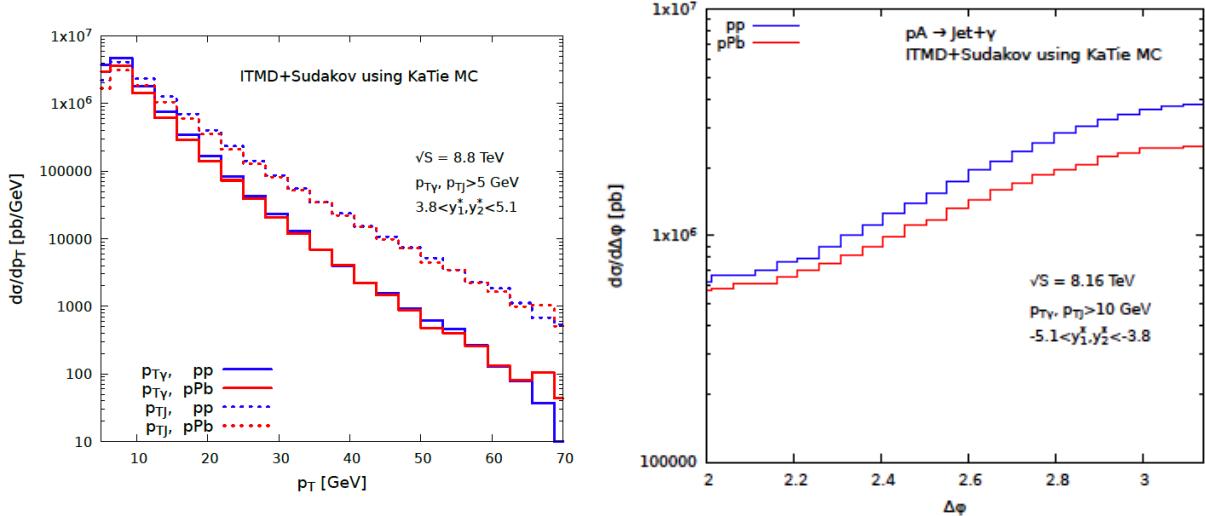


Forward γ +jet

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

γ +jet distributions:

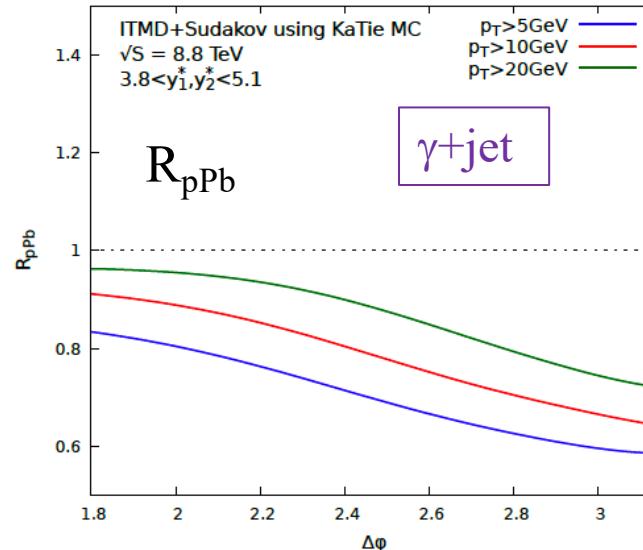
- P-Pb vs pp
- p_T : negligible modification
- $\Delta\phi$: b-to-b suppression



γ +jet: R_{pPb} vs $\Delta\phi$

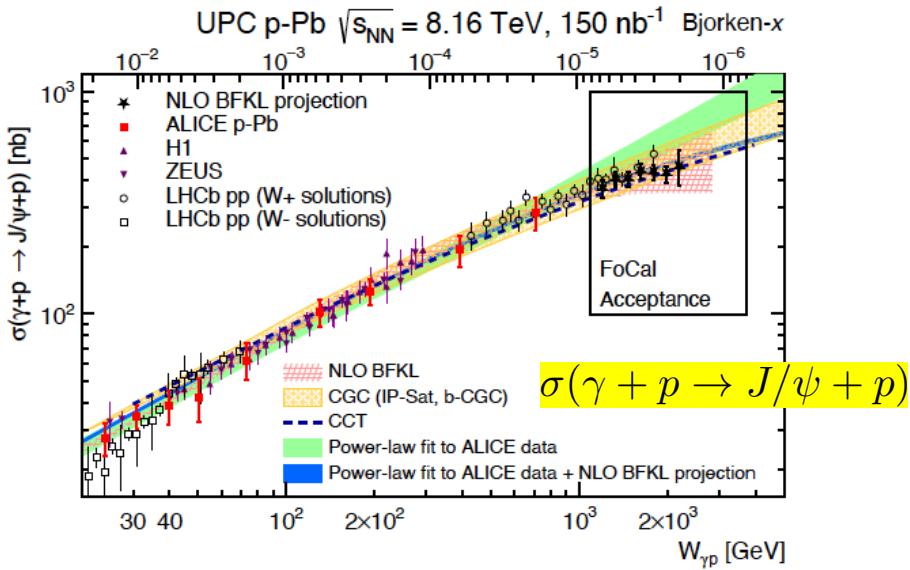
- recoil jet p_T dependence

Compare to di-jet: dipole vs quadrupole TMD



FoCal UPCs: photoproduction of J/ψ , ψ'

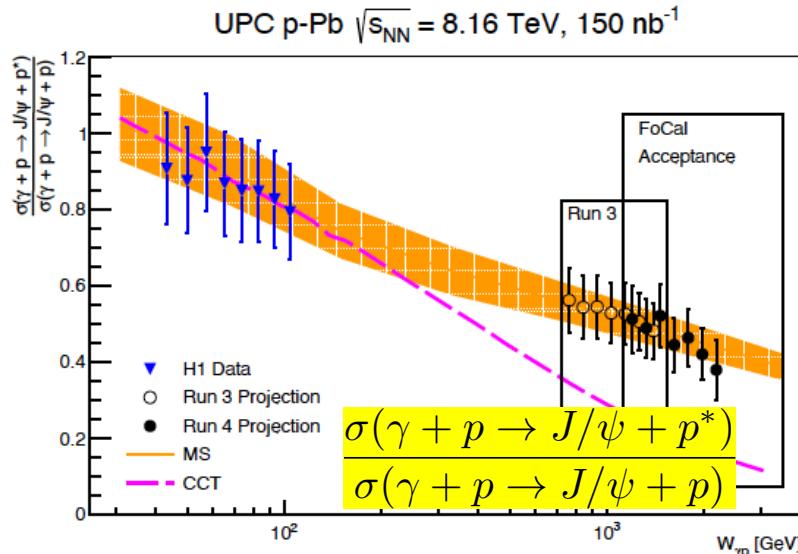
A. Bylinkin, J. Nystrand and D. Tapia Takaki, J. Phys. G 50 (2023) 055105



$W_{\gamma p}$ = 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

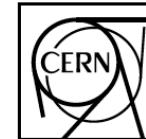
FoCal public documentation

Letter of Intent: CERN-LHCC-2020-009

<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 $p_T \gtrsim 4 \text{ GeV}/c$. This document presents the performance of the FoCal to measure isolated photons and other selected observables.

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

In preparation:

- performance note
- Technical Design Report (TDR)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

1
2 ALICE

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

3 Performance of the ALICE Forward Calorimeter upgrade

4 ALICE Collaboration *

5 Abstract

6 The ALICE Collaboration proposes to instrument the existing ALICE detector with a forward calorime-
7 ter system (FoCal), planned to take data during LHC Run 4 (2029–2032). The FoCal detector is a
8 highly-granular Si+W electromagnetic calorimeter combined with a conventional sampling hadronic
9 calorimeter, covering the pseudo-rapidity interval of $3.4 < \eta < 5.8$. The FoCal design is optimized
10 to measure isolated photons at most forward rapidity for $p_T \gtrsim 4 \text{ GeV}/c$. This document presents the
11 performance of the FoCal to measure isolated photons and other selected observables.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

1
2 ALICE

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

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

5 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

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

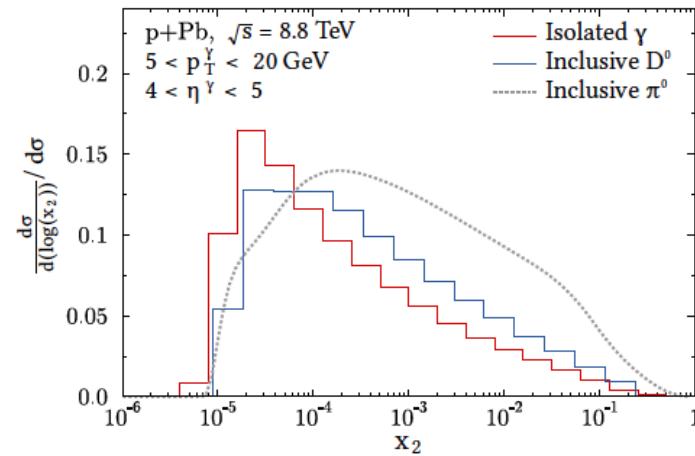
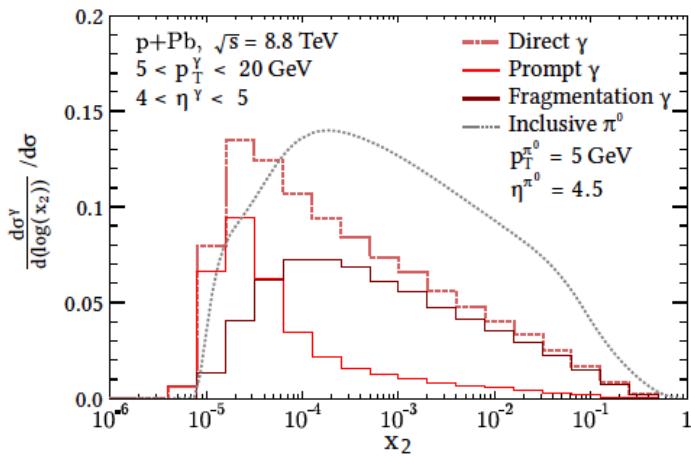
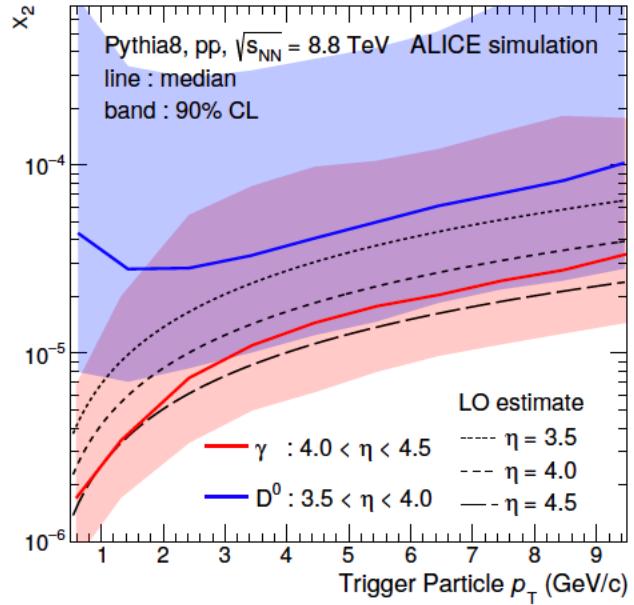
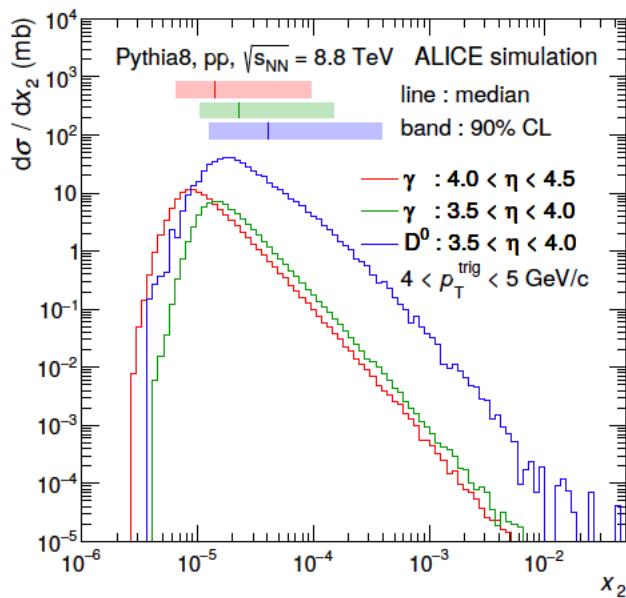
“...pA collisions can serve as a gateway to the EIC as far as saturation physics is concerned, and it also plays an important and complementary role in the study of these two fundamental gluon distributions (Weiszacker-Williams and Dipole)... The small-x factorization in DIS and pA collisions is expected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

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in $p+A$	$\gamma+jet$ in $p+A$	dijet in $p+A$
quadrupole	–	–	+	–	–	+
dipole	+ (purple)	+ (green)	–	+	+	+

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 $p+A$ collisions. Here the + and – signs indicate that the corresponding gluon distributions appear and do not appear in certain processes, respectively.

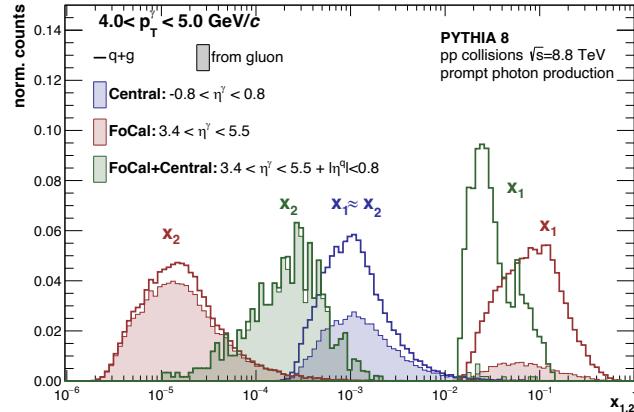
Probes unpolarized gluon TMD distributions

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

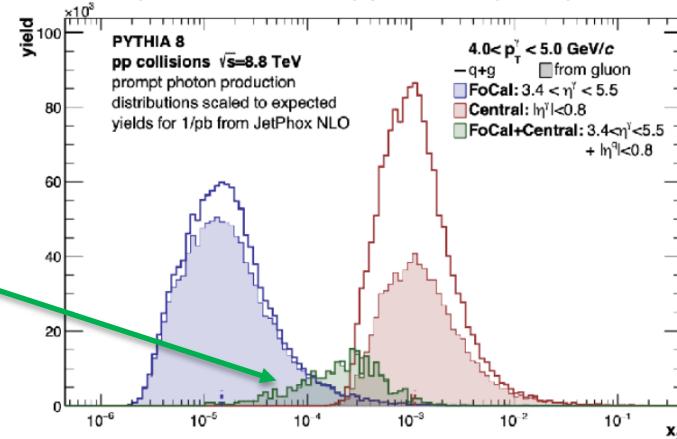


γ +jet rates: forward/central

x -coverage (probability)

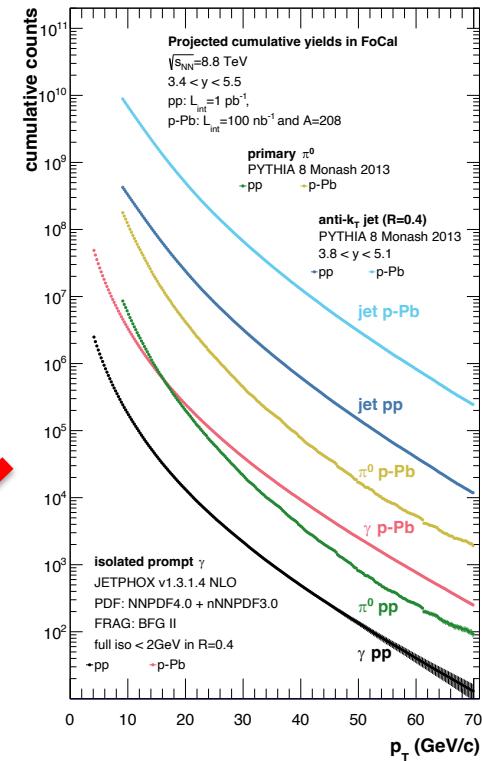


$\times 10^3$ Expected counts of γ -jet events per 1/pb



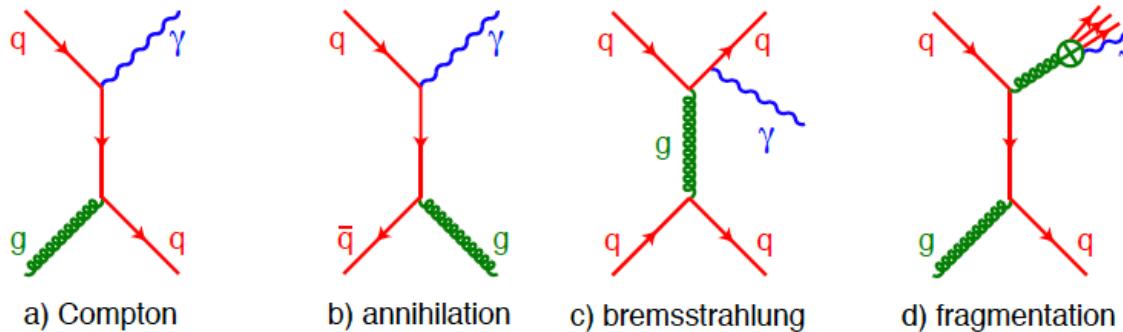
γ : FoCal
jet: central

Trigger rates

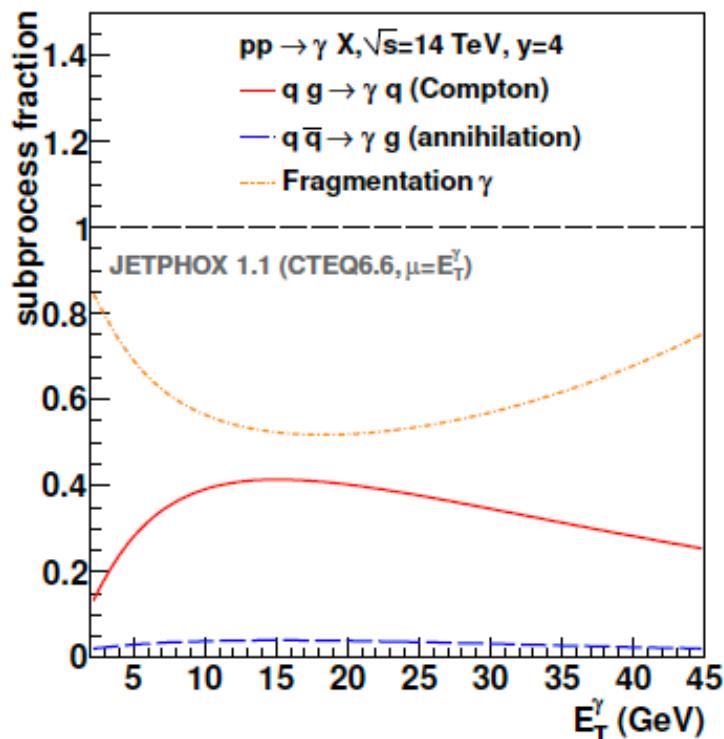


Significant rate of γ +jet coincidences forward/central

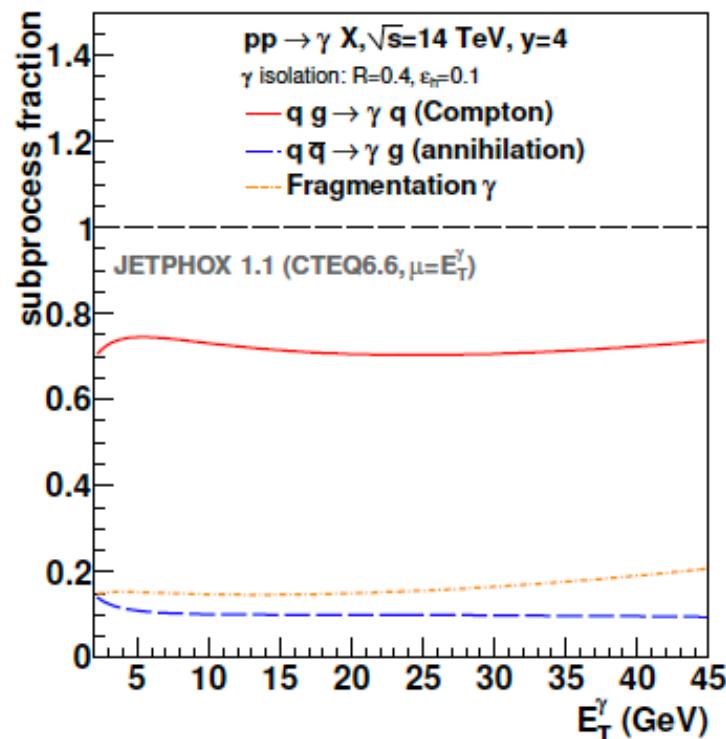
Forward direct γ : partonic processes



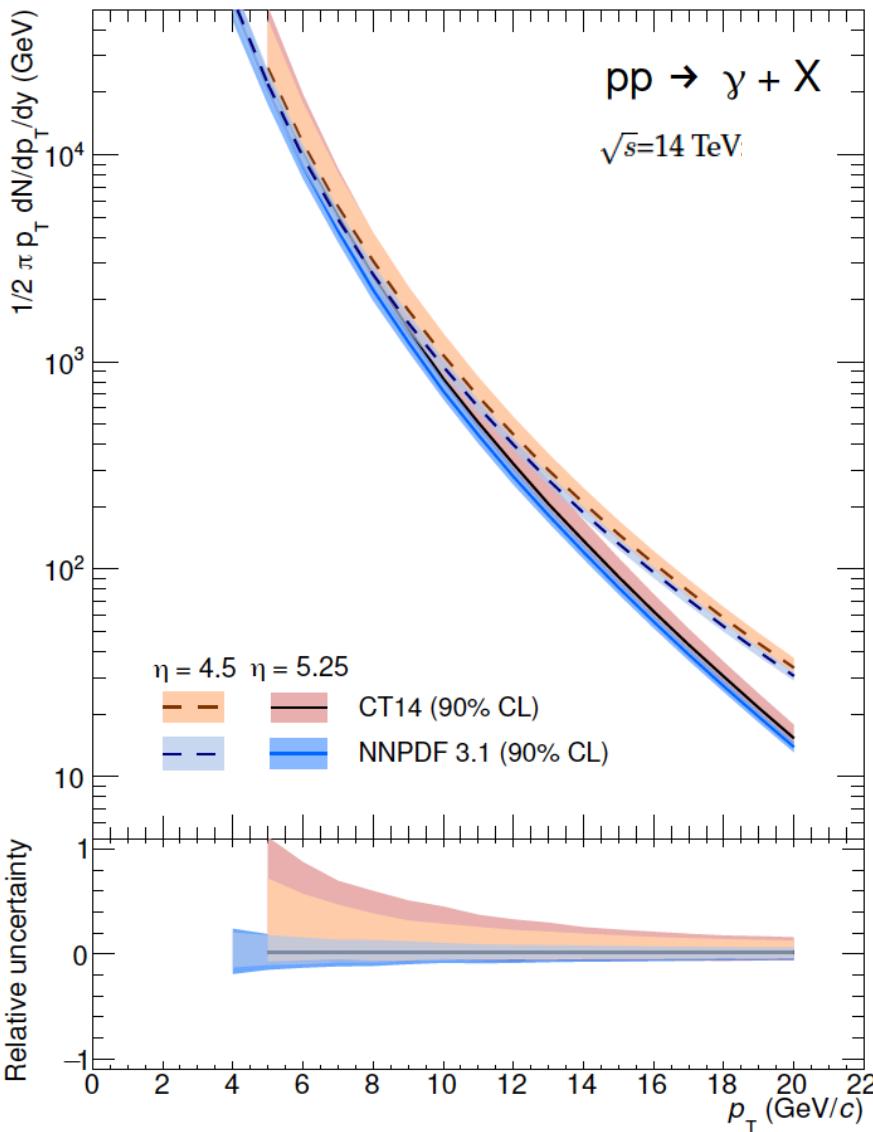
No isolation



Isolated ($R=0.4$, cut=10%)



14 TeV pp collisions: forward isolated photons



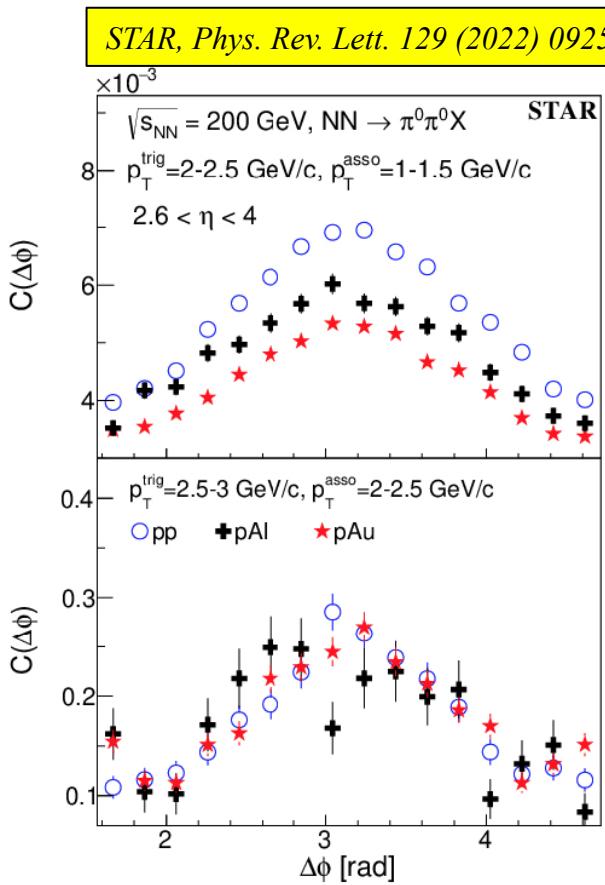
Compare two recent PDF fits: tension in FoCal acceptance

- FoCal provides unique constraints of pp PDFs

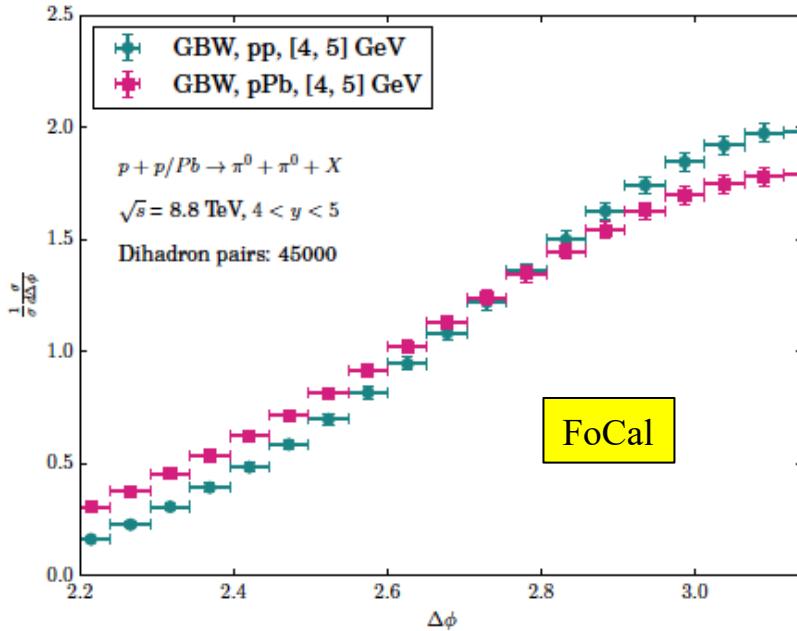
FoCal probes $x \sim 5 \times 10^{-7}$

- sensitive to saturation effects even in pp collisions?

Di-hadron correlations RHIC and LHC



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.