The ALICE FoCal upgrade: Connecting the LHC and the EIC

Diffraction and Gluon Saturation at the LHC and the EIC - Trento Workshop

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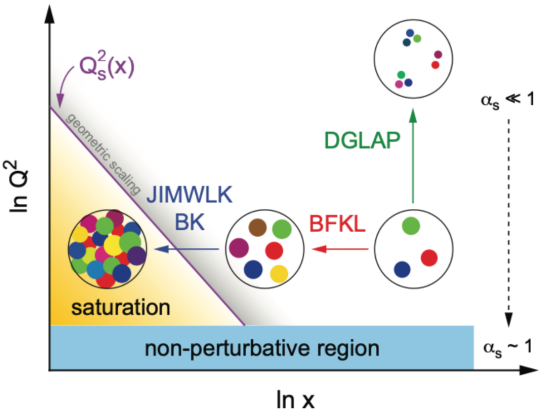
Describing (non)-linear QCD Matter

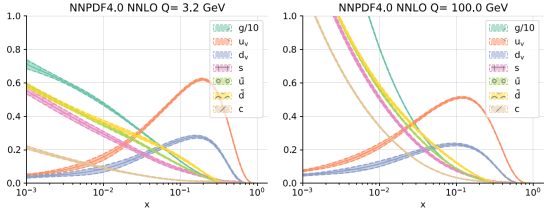
Striving for **universal description**: Theoretical models aim to capture full Q^2-x evolution



ALICE-PUBLIC-2023-001

→ Measurements spanning logarithmically large x and Q^2 range needed

→ Multi-messenger approach using multiple probes at different experiments

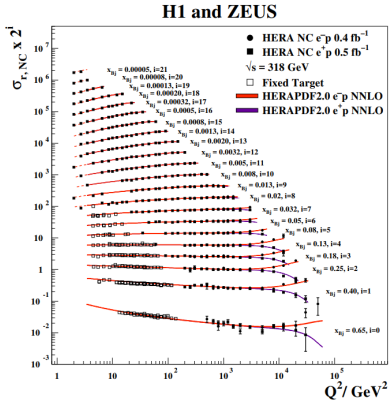


Eur. Phys. J. C (2022) 82 :428

Probing (non)-linear QCD Matter

Established approach: (n)PDF fits

- Used to constrain gluon distributions

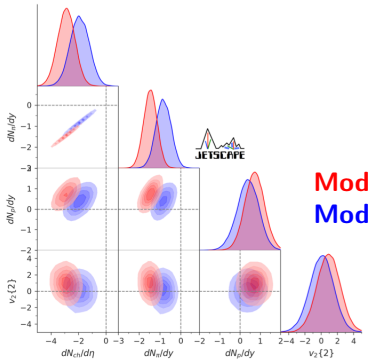


EPJ Web of Conferences 126, 02005 (2016)

Future?

More general approach: Bayesian Inference

- Multi-messenger analysis of data from RHIC+LHC+EIC



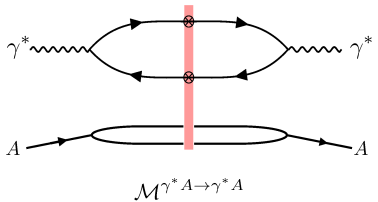
Phys. Rev. C 103 (2021) 5, 054902

Theoretical Connections between DIS and p–A Collisions

DIS in e–A collisions

Inclusive interaction cross section:

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

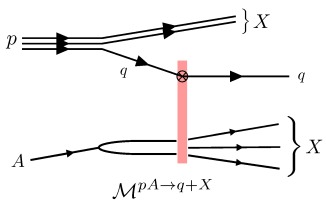


Universe 2021, 7(8), 312

Forward p+A collisions

Scattering amplitude:

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



Universe 2021, 7(8), 312

$\Rightarrow$ Same dipole scattering amplitude $\mathbf{T_{LO}}$!
(Connection includes quadrupoles too)

Upgrades in DIS and p–A Collisions

DIS in e–A collisions:
The Electron-Ion-Collider

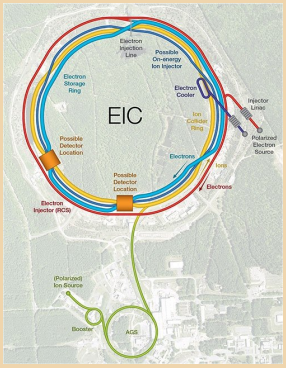
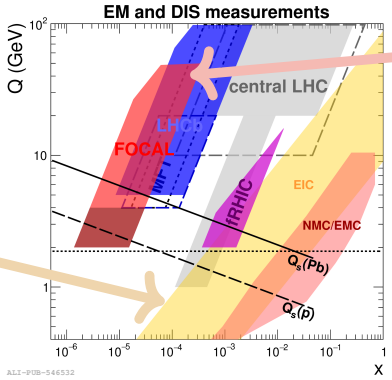
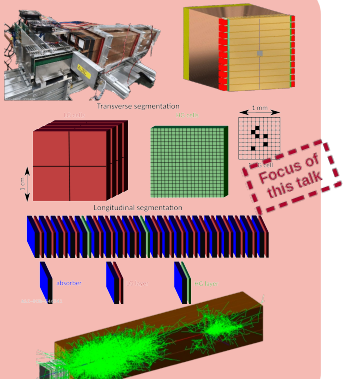


Image credit: DOE



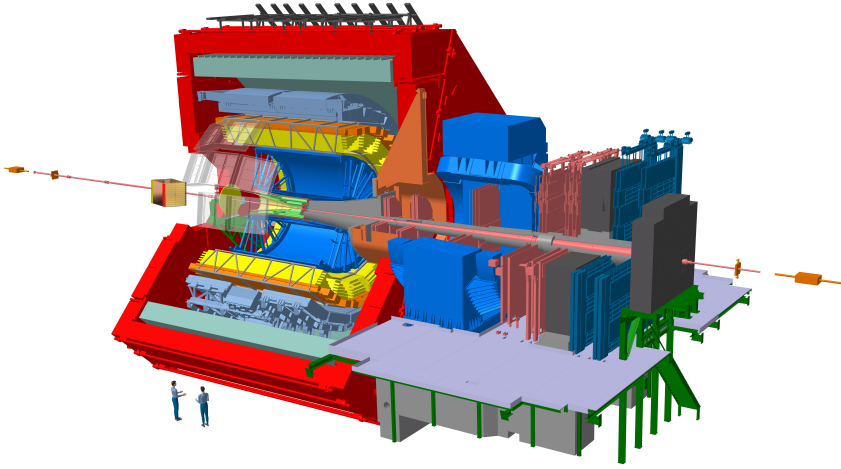
$\Rightarrow$ Large x and Q coverage

Forward p+A collisions:
The ALICE FoCal



CERN-LHCC-2024-004

The ALICE Forward Calorimeter (FoCal)

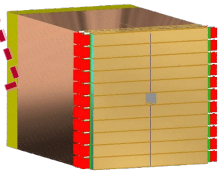


alice-figure.web.cern.ch/node/11222

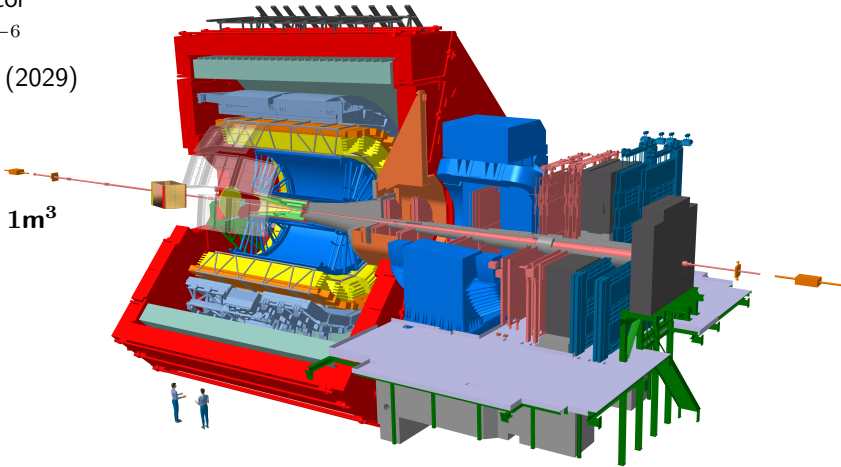
The ALICE Forward Calorimeter (FoCal)

- Upgrade to ALICE detector
- $3.2 < \eta < 5.8 \rightarrow x \sim 10^{-6}$
- Installation before Run 4 (2029)

New: Approved by LHCC



$\sim \mathbf{1m^3}$



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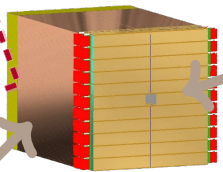
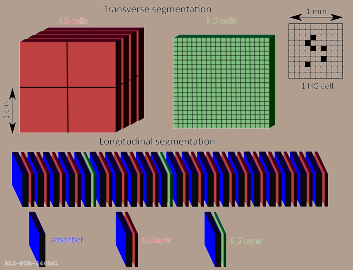


$\sim 1\mathbf{m}^3$

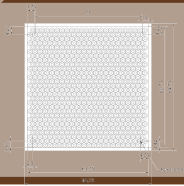
FoCal-E



Highly granular Si-W tracking-calorimeter combining two sensor technologies:

- 18 silicon pad layers (1×1 cm^2)
- Two pixel layers (30×30 μm^2)

FoCal-H



Hadronic scintillating-fibre calorimeter

- Scintillating fibers embedded in Cu tubes (2.5 mm outer diameter)
- Captures full energy of hadronic showers that started in FoCal E
- Enables jet measurements and photon isolation

CERN-LHCC-2024-004

The FoCal Physics Program

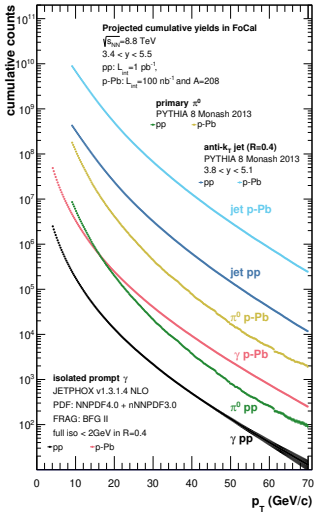
Based on *ALICE-PUBLIC-2023-001*
ALICE-PUBLIC-2023-004

ALICE

Explore non-linear QCD in regime of saturated gluons at low Bjorken-x and constrain nPDFs

Using a multi-messenger approach:

i) Production of π^0, η and vector mesons
ii) Prompt photon production
iii) Jet measurements
iv) γ-jet and γ-hadron correlations
v) Vector meson photoproduction in UPCs
... and more

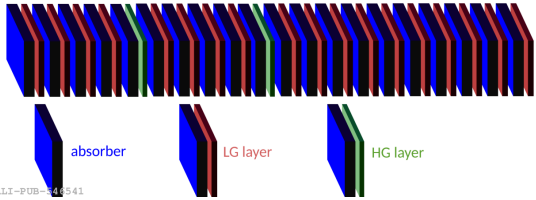


ALI-SIMUL-564283

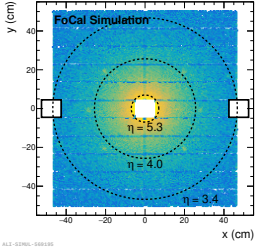
Photon Reconstruction with the FoCal

- Simulation of FoCal-E and FoCal-H detector response to single photons using GEANT3
- Reconstruction efficiency $\approx 90\%$
- Energy resolution saturates at ≈ 3 % for high energies up to $E_\gamma = 1.5$ TeV

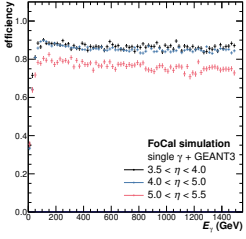
Longitudinal segmentation



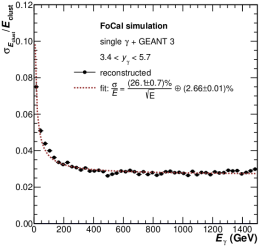
Cluster position



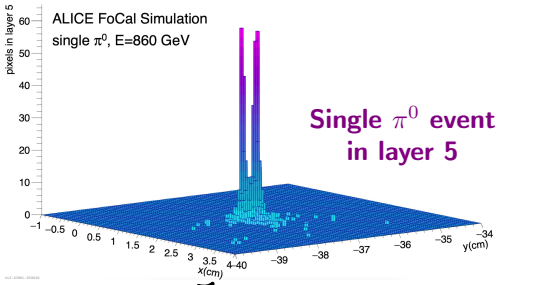
Reconstruction efficiency



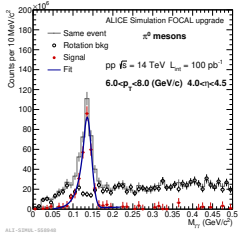
Energy resolution

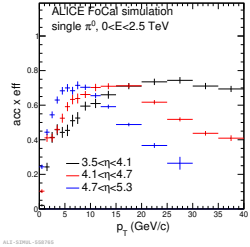


i) Measurement of π^0, η and vector mesons

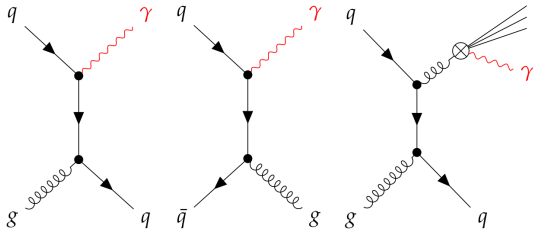


- Measurement of neutral mesons, e.g. π^0, η and ω up to $E_{\text{sim}} = 2$ TeV
- Pixel layers allow measuring photons with less than $d = 5$ mm separation
- Reconstruction efficiency of up to 75%





ii) Prompt Photon Production

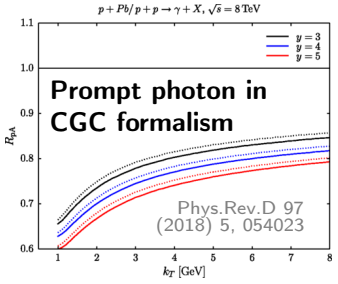


Compton **Annihilation** **Fragmentation**

Direct production
⇒ Direct access to parton, e.g. gluon

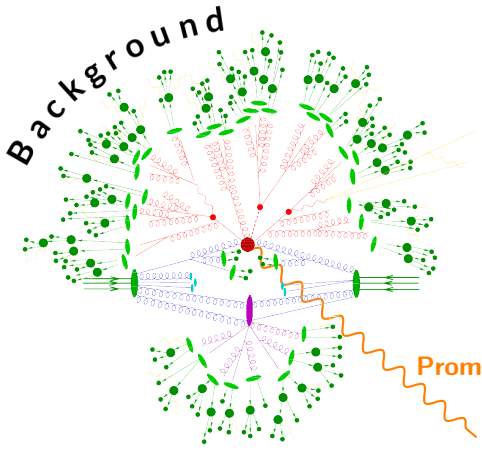
↳ Requires non-perturbative input

- Prompt photons sensitive to gluon (n)PDF
- No strong final state interactions
- Enable investigation of low-x gluons:
  - Shadowing?
  - Non-linear QCD effects (saturation)



⇒ **Key observable in the FoCal physics program to explore the saturation regime**

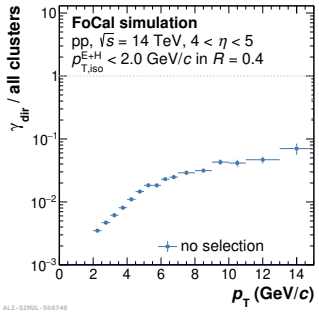
ii) Prompt Photon Identification



Large background of decay photons
→Mostly $\pi^0/\eta \rightarrow \gamma\gamma$

Prog.Part.Nucl.Phys.53:329-338,2004

Signal fraction



ii) Prompt Photon Identification

Isolation
Restrict p_{T} within cone of $R = 0.4$

+

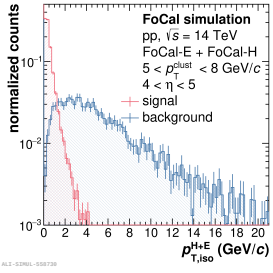
Shower shape
Restrict shower ellipse elongation to reduce merged π^0 clusters

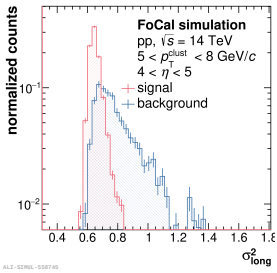
+

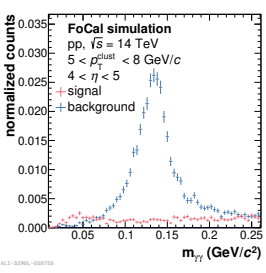
π^0 tagging
Tag decay photons according to inv. mass of cluster pairs

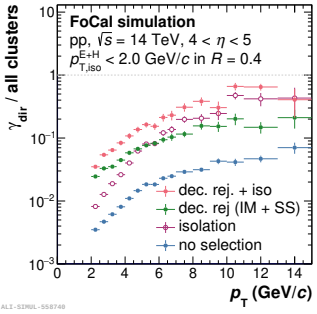
=

Signal fraction
Selections increase signal fraction $\times 11$



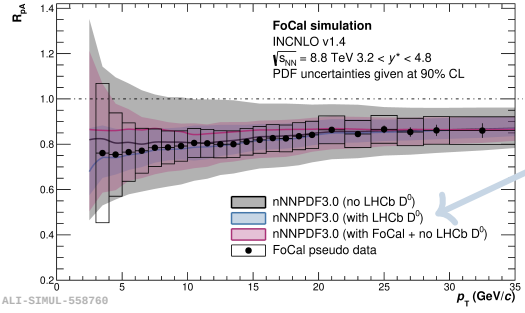






ii) Prompt Photon Physics Impact

- FoCal pseudo data of prompt photon R_{pA}
  - Using NLO+nPDF input
  - Stat. and sys. uncertainties estimated for Run 4
- Expect similar constraints from FoCal for nPDF as LHCb D^0 meson measurement

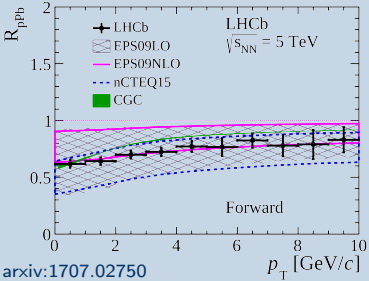


Multiple messengers!

$\gamma_{\mathrm{prompt}} + D^0$

Precise D^0 measurement by LHCb

- Included in nNNPDF3.0



arxiv:1707.02750

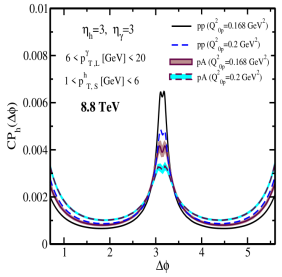
Prompt photons: no final state interaction/hadronization → Clean probe of low-x formalism universality

iii) γ-Hadron Correlations

Theory:

- γ-hadron correlations give insight into low-x gluon dynamics
- $\Delta\phi$ correlation depends on saturation scale

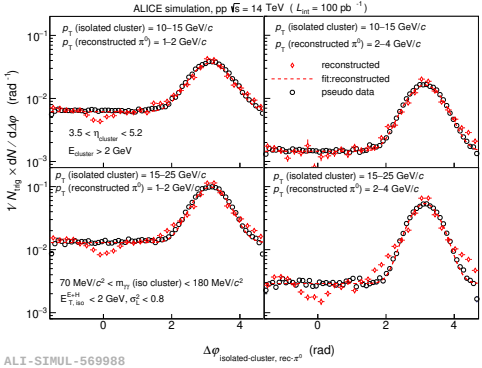
$\Rightarrow$ Expecting **decorrelation** due to saturation



Phys. Rev. D 86, 094016

Experiment:

- γ_{iso}-π^0 correlation in simulated pp collisions
- Precise correlation $\Delta\phi$ peak width measurement

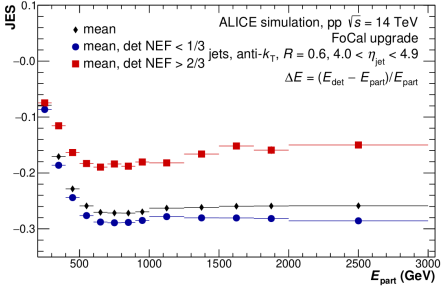


ALI-SIMUL-569988

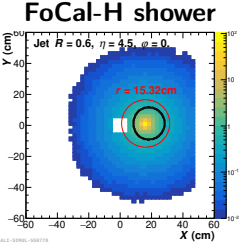
iv) Jet Measurements

- Inclusive and dijet production sensitive to gluon saturation
- Energy Scale (JES) similar to ALICE's EMCal
- Very competitive Energy Resolution (JER) $\sim 12\%$
- Measured Neutral Energy Fraction (NEF) can be used to bias jet sample
  - Determine NEF from overlapping shower energy in FoCal-E and FoCal-H
  - Larger NEF $\rightarrow$ larger JES (JER unchanged)

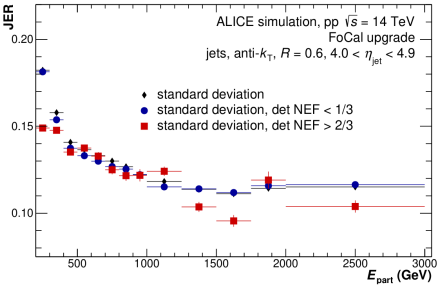
Jet Energy Scale (JES)



FoCal-H shower



Jet Energy Resolution (JER)

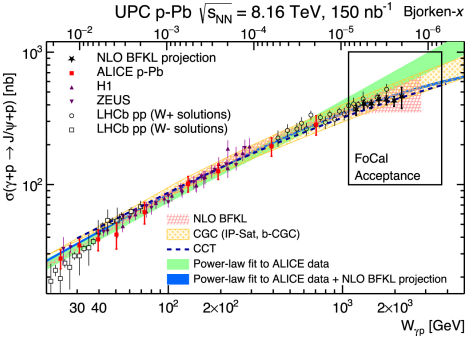


v) Vector Meson Photoproduction in UPCs

ALICE-PUBLIC-2023-004

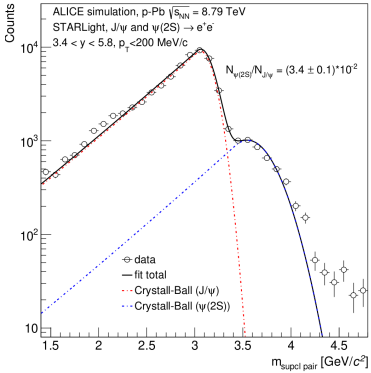
Theory:

- Photoproduction **cross section** of J/ψ in UPCs **proportional to gluon density** squared at LO
- Deviation of cross section from power-law expected from saturation at large $W_{\gamma p}$(low x)



Bylinkin, Nystrand, Tapia Takaki in J. Phys. G (2023) 50 055105

Experiment:



- Extend measurement to unprecedented low-x
- In p–Pb, Pb–p and Pb–Pb collisions
- Reconstruction of J/ψ and ψ(2S) possible

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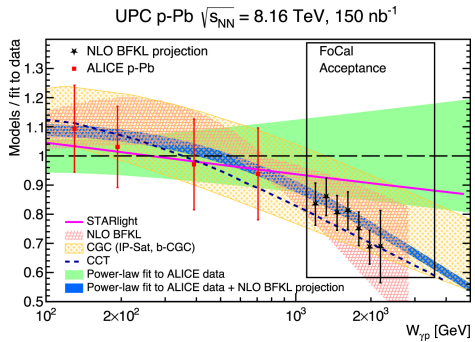

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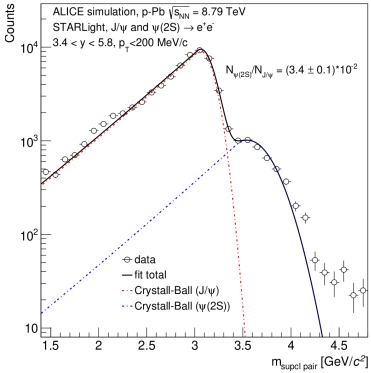

- Extend measurement to unprecedented low-x
- In p–Pb, Pb–p and Pb–Pb collisions
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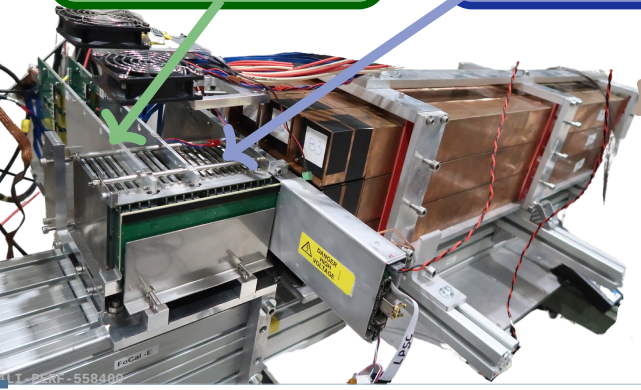
FoCal Prototype

FoCal E Pixels (2 layers)
- ALICE PIxel DEtector (ALPIDE) sensors
- Pixel $\sim 30 \times 30$ μm

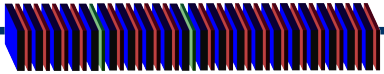
FoCal E Pads (18 layers)
- Si p-type sensors by Hamamatsu
- HGCROC readout

FoCal H (9 modules)
- Scintillating fibers in 668 Cu tubes per module
- SiPM readout

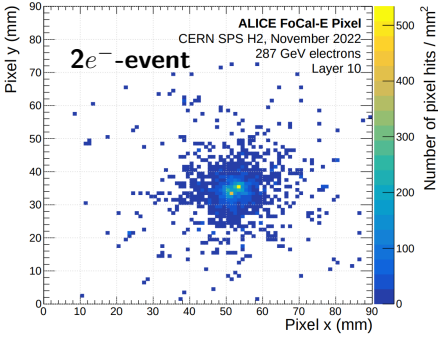


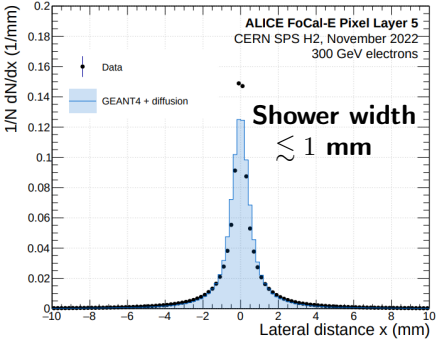
Test beam campaign:
- Full-length prototype tested at CERN PS and SPS
- Electron and hadron beams
- $1 \leq E \leq 350$ GeV
- Prototype performance: arXiv:2311.07413

FoCal Prototype: FoCal-E Pixels



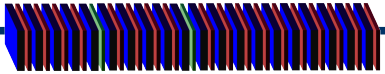
- Excellent shower separation $\mathcal{O}(1\text{mm})$ through two highly granular pixel layers
  - $\rightarrow$ Enables reconstruction of highly boosted $\pi^0 \rightarrow \gamma\gamma$
- Detector response well described by GEANT4 + diffusion model





arXiv:2311.07413

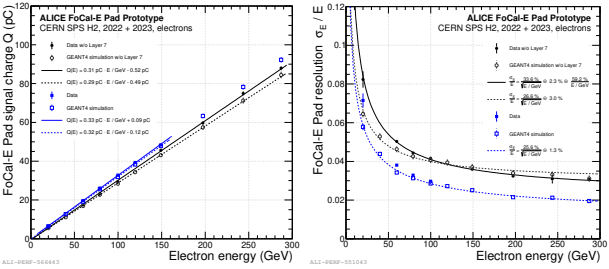
FoCal Prototype: FoCal-E Pad Layers

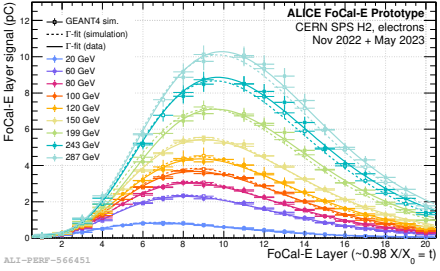


Longitudinal shower profile

e^-

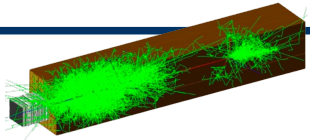
- Key metrics quantified with e^- beam at SPS
- Linear energy response
- Energy resolution less than 3% for $E > 100$ GeV





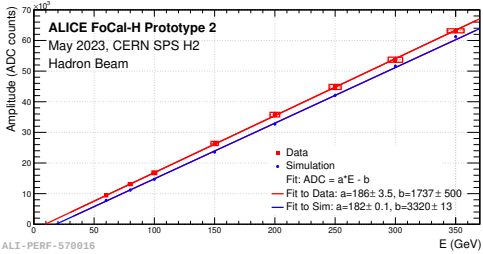
arXiv:2311.07413

FoCal Prototype: FoCal-H

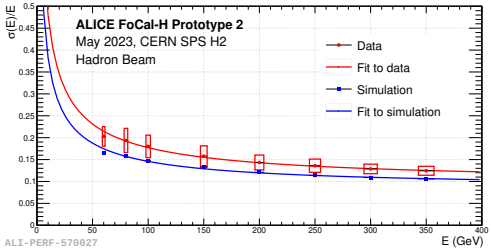


- Performance tested in hadron beam at SPS
- Energy response slope agreement between data and MC
- Energy resolution saturates at $\approx 12\%$
- Slight disagreement with simulation (GEANT4) under investigation

Energy response



Energy resolution



arXiv:2311.07413

Summary

- The "3-in-1" Forward Calorimeter (FoCal) will be installed as an upgrade to ALICE for Run 4
- Simulations demonstrate FoCal's capabilities to probe low-x gluons using various probes
- Test beams show prototype meets physics requirements assumed in simulations

Approved by LHCC

$\Rightarrow$ The FoCal will play a vital role in the global effort with EIC + LHC + RHIC to further our understanding of non-linear QCD evolution

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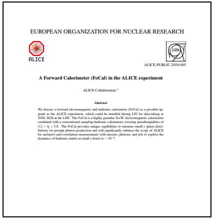
FoCal LOI: cds.cern.ch/record/2719928


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

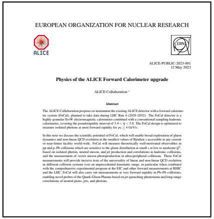
ALICE-PUBLIC-2019-005

A Forward Calorimeter (FoCal) in the ALICE experiment

ALICE Collaboration *

Abstract

FoCal Physics: cds.cern.ch/record/2858858


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE-PUBLIC-2023-001
12 May 2023

Physics of the ALICE Forward Calorimeter upgrade

ALICE Collaboration *

Abstract

Phys. Performance: cds.cern.ch/record/2869141


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE-PUBLIC-2023-004
04 September 2023

Physics performance of the ALICE Forward Calorimeter upgrade

ALICE Collaboration *

Abstract

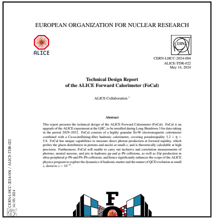
Prototype: arxiv.org/abs/2311.07413


Prepared for submission to JINST

Performance of the electromagnetic and hadronic prototype segments of the ALICE Forward Calorimeter

arXiv:2311.07413v1 [physics.ins-det] 13 Nov 2023

FoCal TDR: cds.cern.ch/record/2890281


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-LHCC-2024-004
ALICE-TDR-022
May 14, 2024

Technical Design Report
of the ALICE Forward Calorimeter (FoCal)

ALICE Collaboration *

Abstract

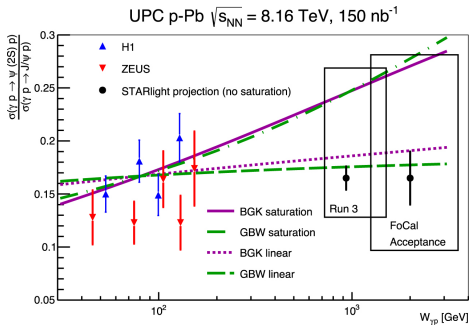
Backup

v) Vector Meson Photoproduction in UPCs (Part 2)

ALICE-PUBLIC-2023-004

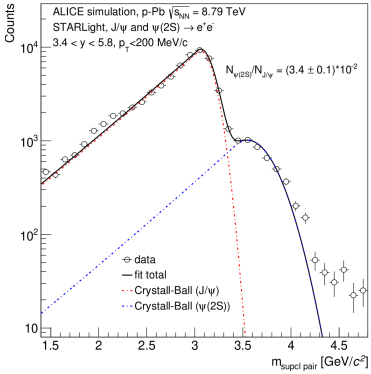
Theory:

- Ratio of $\psi(2S)/J/\psi$ might have even larger sensitivity to gluon saturation than inclusive
- Due to different wave functions and radius dependence of the color dipole



Bylinkin, Nystrand, Tapia Takaki in J. Phys. G (2023) 50 055105

Experiment:



- Extend measurement to unprecedented low-x
- In p–Pb, Pb–p and Pb–Pb collisions
- Reconstruction of J/ψ and ψ(2S) possible