Exploring the Frontier of Low-$x$ Physics: The ALICE FoCal upgrade
LHC Forward Physics Workshop

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Describing (non)-linear QCD Matter

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

→ Measurements spanning logarithmically large $x$ and $Q^2$ range needed
→ Multi-messenger approach using multiple probes at different experiments

ALICE-PUBLIC-2023-001
**ALICE Upgrades**

**ALICE 2**
- ITS2 upgrade
- New TPC readout
- New muon forward tracker
- Continuous readout

**ITS3 + FoCal**
- Curved wafer-scale silicon sensors
- Forward Calorimeter → Low-\(x\) reach

**ALICE 3**
- Retractable vertex detector
- Data taking in runs 5 & 6
- Entirely new experiment

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Carlos Lacasta, XIII CPAN days talk

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The ALICE FoCal upgrade
July 15, 2024
The ALICE Forward Calorimeter (FoCal)
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- Upgrade to ALICE detector
- $3.2 < \eta < 5.8 \rightarrow x \sim 10^{-6}$
- Installation before Run 4 (2029)

New: Approved by LHCC

$\sim 1m^3$

alice-figure.web.cern.ch/node/11222
The ALICE Forward Calorimeter (FoCal)

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Highly granular Si-W tracking-calorimeter combining two sensor technologies:
- 18 silicon pad layers (1 \(\times\) 1 cm\(^2\))
- Two pixel layers (30 \(\times\) 30 \(\mu\)m\(^2\))

Hadronic scintillating-fibre calorimeter
- Scintillating fibres 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

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The ALICE FoCal upgrade

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The FoCal Physics Program

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

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

⇒ Large \(x\) and \(Q\) coverage
The FoCal Physics Program

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

Using a multi-messenger approach:

i) Production of $\pi^0$, $\eta$ and vector mesons

ii) Prompt photon production

iii) Jet measurements

iv) $\gamma$-jet and $\gamma$-hadron correlations

v) Vector meson photoproduction in UPCs

... and more

⇒ Large $x$ and $Q$ coverage

Based on

ALICE-PUBLIC-2023-001
ALICE-PUBLIC-2023-004
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 $\approx 3\%$ for high energies up to $E_\gamma = 1.5 \text{ TeV}$
i) Measurement of $\pi^0$, $\eta$ and vector mesons

- Measurement of neutral mesons, e.g. $\pi^0$, $\eta$ and $\omega$ 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%

**ALICE FoCal Simulation**

Single $\pi^0$ event in layer 5
ii) Prompt Photon Production

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

**Direct production**

\[ \Rightarrow \text{Direct access to parton, e.g. gluon} \]

\[ \Rightarrow \text{Key observable in the FoCal physics program to explore the saturation regime} \]
ii) Prompt Photon Identification

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

Prompt photon signal

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

Signal fraction

FoCal simulation
$\gamma s = 14$ TeV, $4 < \eta < 5$
$p_{T,iso}^{E+H} < 2.0$ GeV/$c$ in $R = 0.4$

$\gamma_{dir}$ / all clusters

$\gamma_{dir}$ / all clusters

$0.05$ $0.1$ $0.15$ $0.2$ $0.25$

normalized counts

$0.000$ $0.005$ $0.010$ $0.015$ $0.020$ $0.025$ $0.030$ $0.035$

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ii) Prompt Photon Identification

**Isolation**
Restrict $p_T$ within cone of $R = 0.4$.

**Shower shape**
Restrict shower ellipse elongation to reduce merged $\pi^0$ clusters.

$\pi^0$ **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! $\gamma_{\text{prompt}} + D^0$

Precise $D^0$ measurement by LHCb
- Included in nNNPDF3.0

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

⇒ Expecting **decorrelation** due to saturation

**Experiment:**
- \(\gamma_{iso}-\pi^0\) correlation in simulated pp collisions
- Precise correlation \(\Delta \phi\) peak measurement

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**Diagram:**
- ALICE simulation, pp \(\sqrt{s} = 14\) TeV (\(\int L = 100\) pb\(^{-1}\))
- \(p_{T}\) (isolated cluster) = 10–15 GeV/c
- \(p_{T}\) (reconstructed \(\pi^0\)) = 1–2 GeV/c
- \(p_{T}\) (reconstructed \(\pi^0\)) = 2–4 GeV/c

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Phys. Rev. D 105, 114052
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)

Jet Energy Resolution (JER)
v) Vector Meson Photoproduction in UPCs

Theory:

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

Experiment:

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

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

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

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

FoCal-H (9 modules)
- Scintillating fibres 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
  → Enables reconstruction of highly boosted $\pi^0 \rightarrow \gamma\gamma$
- Detector response well described by GEANT4 + diffusion model

$2e^-\text{-event}$

Shower width $\lesssim 1\text{ mm}$

arXiv:2311.07413
FoCal Prototype: FoCal-E Pad Layers

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

**Longitudinal shower profile**

$e^-$
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
• 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  

⇒ 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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**Summary**

- FoCal LOI: cds.cern.ch/record/2719928  
- FoCal Physics: cds.cern.ch/record/2858858  
- Phys. Performance: cds.cern.ch/record/2869141  
- Testbeam: arxiv.org/abs/2311.07413v1  
- FoCal TDR: cds.cern.ch/record/2890281

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