A Forward Calorimeter in ALICE (FoCal)

Ionut-Cristian Arsene (University of Oslo) on behalf of the ALICE Collaboration

UPC 2023, 10-15 December, Playa del Carmen, Yucatán, Mexico
ALICE upgrades timeline

2022-2025
- Run 3
- LS3

2029-2032
- Run 4
- LS4

2035-2038
- Run 5
- LS5

2040-2041
- Run 6

ALICE 2

Phase IIb Upg

ALICE 3

FoCal and ITS3

FoCal LoI: ALICE, LHCC-I-036 (2020)
ITS3 LoI: CERN-LHCC-2019-018

ALICE3 Loi: CERN-LHCC-2022-009
Why FoCal?

Main goal: explore non-linear gluon evolution and nPDFs at low Bjorken-x

LoL: ALICE, LHCC-I-036 (2020)
Physics case: ALICE-PUBLIC-2023-001
Physics performance: ALICE-PUBLIC-2023-004
FoCal observables in hadronic collisions

- Main measurement: isolated direct photons in pp and p-Pb collisions
- Complementary observables:
  - $\pi^0$
  - Jets
  - Quarkonia, $Z^0$ and $W^\pm$
  - correlations

ALICE, LHCC-I-036 (2020)
FoCal observables in UPC

- **Quarkonia (J/ψ, ψ’) photoproduction**
  - Extension of photon-Pb and photon-proton cross-sections to very high and very low c.m. energy
  - Bjorken-$x$ reach down to $\sim 10^{-6}$, discrimination power for saturation models
- Other photon induced processes also measurable:
  - Low mass vector mesons,
  - $\gamma\gamma \rightarrow ee$,
  - Inclusive photo-nuclear and diffractive di-jets,
  - Light-by-light scattering,...

Many thanks to Alexander Bylinkin, Joakim Nystrand and Daniel Tapia Takaki!
The ALICE detector (Run 3 setup)
The ALICE detector + FoCal

• Forward calorimeter (3.2<\eta<5.8)
  • Electromagnetic: FoCal-E
  • Hadronic: FoCal-H
FoCal design challenges

- Discriminate direct photons and decay photons (mainly from $\pi^0$)
  - Requires: small Moliere radius, high granularity readout

- Suppress bremsstrahlung and fragmentation photons
  - Requires: measurement of hadronic showers
FoCal structure

**FoCal-E (electromagnetic)**
- High granularity Si-W calorimeter
- Longitudinal segmentation (20 layers)
  - 3.5mm W in each layer ($1 \times X_0$)
  - 18 pad layers (1x1 cm$^2$)
    - Energy measurement
    - 2 pixel layers (30x30 μm$^2$)
    - Two shower separation

**FoCal-H (hadronic)**
- Metal-scintillator using “spaghetti” design
- Scintillation fibers embedded in Cu tubes
- Photon isolation, hadronic jet components
FoCal prototype for test beams

Small prototype built for performance tests
- FoCal-E
  - ~ 9 x 8 cm$^2$ transverse size
  - 18 pad layers
  - 2 pixel layers
- FoCal-H
  - 9 Cu-scintillator towers
  - ~ 20 x 20 cm$^2$ transverse size

FoCal prototype tested in electron/hadron beams at SPS in Nov 2022 and May 2023
Energy resolution in beam tests

- FoCal-E: energy resolution < 4% at high energies
- FoCal-H: energy resolution < 15% at high energy
  - Disagreements with MC under investigation
Transverse and longitudinal shower profiles

Two-shower separation in FoCal-E pixels

Longitudinal shower profile in FoCal-E
Performance in hadronic collisions

ALICE FoCal Simulation

pp $\sqrt{s}=14$ TeV

leading $\pi^0$, $E = 530$ GeV, no pile-up
Phase-space coverage

- Direct photons measured in FoCal vs. D-mesons in LHCb
- Photon-hadron correlations combining FoCal and central-rapidity acceptance significantly extends the coverage in $x$

$LHCb D^0$: JHEP10(2017)090
Direct photons

Isolation energy in FoCal-E and FoCal-H

Signal fraction up to ~70% at $p_T \sim 14$ GeV/c
- Still untapped potential by using additional more sophisticated methods
Prompt photon $R_{pPb}$

- nPDF+NLO $R_{pPb}$ reweighted using FoCal pseudo data
- Reduction of nNNPDF30 uncertainties similar to LHCb $D^0$ mesons
Light mesons

- Neutral pion efficiency of up to $\sim 70\%$
- High efficiency for the reconstruction of other light mesons: $\eta$, $\omega$
Jet energy scale (JES) and jet energy resolution (JER) quantified using Pythia + GEANT for $R=0.6$ anti-$k_T$ jets

\[ \Delta E = \frac{(E_{\text{det}} - E_{\text{part}})}{E_{\text{part}}} \]

- Jet energy scale (JES) and jet energy resolution (JER) quantified using Pythia + GEANT for $R=0.6$ anti-$k_T$ jets
Ultra-peripheral collisions

J/ψ $\rightarrow$ e$^+$e$^-$

ALICE FoCal simulation
STARLight Pb-Pb $\sqrt{s_{NN}}$=5.5 TeV
coherent J/ψ, E = 116 GeV
Vector meson photo-production in UPC

- High efficiency (~80%) for J/ψ measurement in e⁺e⁻
- Coverage up to y~5.5

**Pb-Pb @ 5.36 TeV, L = 7/nb**

<table>
<thead>
<tr>
<th>VM</th>
<th>(\sigma(\text{Pb} + \text{Pb} \rightarrow \text{Pb} + \text{Pb} + \text{VM}))</th>
<th>(\sigma(3.4 \leq \eta_{1,2} \leq 5.8))</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho^0)</td>
<td>5.0 b</td>
<td>20 (\mu)b</td>
<td>140,000</td>
</tr>
<tr>
<td>(\phi)</td>
<td>440 mb</td>
<td>10 (\mu)b</td>
<td>70,000</td>
</tr>
<tr>
<td>J/ψ</td>
<td>39 mb</td>
<td>53 (\mu)b</td>
<td>370,000</td>
</tr>
<tr>
<td>(\psi(2S))</td>
<td>7.5 mb</td>
<td>1.1 (\mu)b</td>
<td>7,500</td>
</tr>
<tr>
<td>(\Upsilon(1S))</td>
<td>94 (\mu)b</td>
<td>5.0 nb</td>
<td>35</td>
</tr>
</tbody>
</table>

**p-Pb, Pb-p @ 8.8 TeV, L = 150/nb**

<table>
<thead>
<tr>
<th>VM</th>
<th>(\sigma(p + \text{Pb} \rightarrow p + \text{Pb} + \text{VM}))</th>
<th>(\sigma(3.4 \leq \eta_{1,2} \leq 5.8))</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho^0)</td>
<td>35 mb</td>
<td>140 nb</td>
<td>21,000</td>
</tr>
<tr>
<td>(\phi)</td>
<td>1.7 mb</td>
<td>51 nb</td>
<td>7,700</td>
</tr>
<tr>
<td>J/ψ</td>
<td>98 (\mu)b</td>
<td>400 nb</td>
<td>60,000</td>
</tr>
<tr>
<td>(\psi(2S))</td>
<td>16 (\mu)b</td>
<td>8.9 nb</td>
<td>1,300</td>
</tr>
<tr>
<td>(\Upsilon(1S))</td>
<td>220 nb</td>
<td>0.38 nb</td>
<td>60</td>
</tr>
<tr>
<td>Pb → FoCal</td>
<td>Pb → FoCal</td>
<td>Pb → FoCal</td>
<td>Pb → FoCal</td>
</tr>
<tr>
<td>(\rho^0)</td>
<td>35 mb</td>
<td>17 nb</td>
<td>2,600</td>
</tr>
<tr>
<td>(\phi)</td>
<td>1.7 mb</td>
<td>5.3 nb</td>
<td>800</td>
</tr>
<tr>
<td>J/ψ</td>
<td>98 (\mu)b</td>
<td>36 nb</td>
<td>5,400</td>
</tr>
<tr>
<td>(\psi(2S))</td>
<td>16 (\mu)b</td>
<td>0.53 nb</td>
<td>80</td>
</tr>
<tr>
<td>(\Upsilon(1S))</td>
<td>220 nb</td>
<td>0.67 pb</td>
<td>~ 0</td>
</tr>
</tbody>
</table>

Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107
**J/ψ and ψ(2S) reconstruction in Pb-Pb**

- Ground and excited charmonium states can be separated
- Coherent and incoherent components can be extracted from the $p_T$ distribution
- Very large photoproduced quarkonia sample expected to be measured with FoCal
- Potential of improving the mass and $p_T$ resolution

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**Graphs:**

1. **Left Graph:**
   - ALICE Simulation, Pb–Pb UPC $\sqrt{s_{NN}} = 5.5$ TeV, $L_{int} = 7$ nb$^{-1}$
   - STARlight, $J/\psi$ and $\psi(2S) \rightarrow e^+e^-$
   - $3.4 < y < 5.8$
   - $p_T < 0.2$ GeV/c

2. **Right Graph:**
   - ALICE Simulation, Pb–Pb UPC $\sqrt{s_{NN}} = 5.5$ TeV, $L_{int} = 7$ nb$^{-1}$
   - STARlight, $J/\psi$ and $\psi(2S) \rightarrow e^+e^-$
   - $3.4 < y < 5.8$
   - $2.8 < m_{\text{cl pair}} < 3.4$ GeV/c$^2$
   - Data
   - Coh $J/\psi$
   - Inc $J/\psi$
   - Feed-down from coh $\psi'$
   - Feed-down from inc $\psi'$

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**Notes:**

- Data points are shown with symbols, and models are shown as lines.
- The graphs illustrate the distributions of mass and $p_T$ for $J/\psi$ and $\psi(2S)$ in Pb–Pb collisions at high energies.
- The simulations are performed with STARlight software, which allows for detailed comparison between experimental data and theoretical predictions.
Coherent $J/\psi$ photoproduction in Pb-Pb UPC

**Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107**

- Extension of the measurement to $y \sim 5.5$, very good stat. uncertainties
- Interference between quark and gluon contributions largest in the FoCal acceptance

Flett, Jones, Martin, Ryskin and Teubner, arXiv:1908.08398
Photo-nuclear cross-section $\sigma(\gamma+\text{Pb})$

Emitter-target ambiguity solved using measurements in ZDC neutron emission classes
Photo-nuclear cross-section $\sigma(\gamma+\text{Pb})$

**ALICE, JHEP 10 (2023) 119**

- Combined FoCal + ZDC analysis
  - coverage in $W_{\gamma\text{Pb}}$ to be extended both towards low and high values
J/$\psi$ and $\psi'$ reconstruction in p-Pb and Pb-p

- Simulation studies done with realistic expectations of quarkonia yields
- $\psi(2S)/J/\psi$ ratio expected to be measured with about 3% and 12% statistical uncertainty in p-Pb (low-$W_{\gamma p}$) and Pb-p (high-$W_{\gamma p}$), respectively
Photoproduction off protons $\sigma(\gamma+p)$ at high-$W$

- FoCal extends coverage in $W_{\gamma p}$ up to about 2 TeV
- Large lever arm for discriminating linear vs saturation scenarios
Energy dependence of the $\psi(2S)/J/\psi$ ratio

Ratio has a good discrimination power between linear vs saturation models in the range of very high-$W_{\gamma p}$

Limitation due to the expected low $\psi(2S)$ yields ($\sim12\%$ stat.uncert.)
Dissociative to exclusive $J/\psi$ photoproduction ratio

- Probe of the fluctuations in the proton target configurations
- Reduction of the dissociative/exclusive ratio towards high c.m. provides a signature of gluon saturation

*Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107*

UPC $p$-$p$ $\sqrt{s_{NN}} = 8.16$ TeV, 150 nb$^{-1}$

- Figure showing data and theoretical predictions for the dissociative to exclusive ratio as a function of $W_{\gamma\gamma}$.

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Production off proton in Pb-p at low-$W_{\gamma p}$

Coverage down to $W_{\gamma p}$~12 GeV with Pb-p at 8.16 TeV, overlap with E401 data

With an eventual run at 1.26 TeV, measurements could fill the gap between low energy data points and LHC experiments
Summary

- FoCal is a planned ALICE upgrade for the LHC Run-4 covering forward rapidities
- Main goal: explore gluon content at low-x using multiple measurements
- Hadronic collisions
  - Isolated direct photons
  - Jets
  - Mesons, quarkonia, weak bosons
  - Correlations
- Main probes studied so far in UPC (Pb-Pb, p-Pb, Pb-p)
  - Coherent and incoherent J/ψ and ψ(2S)
  - Combined FoCal with ZDC and other ALICE detectors to tag neutron emission and dissociative production off protons
Backup