High-Granularity EM Calorimetry for Forward Measurements

T. Peitzmann (Utrecht University/Nikhef)

Outline

• Physics case for FoCal proposal in ALICE
• FoCal baseline design, performance
• R&D: high-granularity EM calorimeter
• Summary
PDF Uncertainties and Saturation

- Large uncertainties of nPDFs
  - Parameterised nuclear modification
  - Recently updated to allow more freedom (e.g. flavour dependence)

- $x$-dependence?
  - Very little dependence for $x < 10^{-2}$

- Non-linear effects from high gluon density
- Gluon saturation?
**x-Sensitivity – Charm vs. Photons?**

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$y$</th>
<th>$p_T$ (GeV/c)</th>
<th>$z$</th>
<th>$x_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>0.2</td>
<td>4</td>
<td>2</td>
<td>0.3</td>
<td>$1.2 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>8.8</td>
<td>0</td>
<td>2</td>
<td>0.3</td>
<td>$1.5 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>jet</td>
<td>8.8</td>
<td>4</td>
<td>20</td>
<td>1</td>
<td>$8.3 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>8.8</td>
<td>4</td>
<td>2</td>
<td>0.3</td>
<td>$2.8 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$D$</td>
<td>8.8</td>
<td>4</td>
<td>0</td>
<td>0.5</td>
<td>$1.5 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>8.8</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>$1.7 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>8.8</td>
<td>4.5</td>
<td>4</td>
<td>1</td>
<td>$1.0 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 8.8$ TeV

$5 < p_T < 20$ GeV

$4 < \eta < 5$

*LO kinematics estimates provide rather lower limit for $x_2$*

*but: higher orders contribute significant tail towards large $x_2$*

*compare $D^0$ (LHCb) and prompt $\gamma$ (FoCal)*

*expect better sensitivity for photons*

*x-distributions from NLO pQCD*

*x-distributions from PYTHIA*

\[
x_{1,2} \approx \frac{2m_T}{\sqrt{s}} \exp (\pm y)
\]

no analytical approximation, taking into account $\eta$ of recoil parton
$x$-$Q^2$-Sensitivity

**D0**

3.5 $< \eta < 4.0$
4.0 $< p_T < 5.0$ GeV/c

3.5 $< \eta < 4.0$
0.0 $< p_T < 1.0$ GeV/c

PYTHIA pp 8.8TeV forward measurements

$< x_2 > = 1.0 \cdot 10^{-3}$
$< Q^2 > = 5.1$ GeV$^2$

3.5 $< \eta < 4.0$
4.0 $< p_T < 5.0$ GeV/c

4.0 $< \eta < 4.5$
4.0 $< p_T < 5.0$ GeV/c

$< x_2 > = 3.7 \cdot 10^{-5}$
$< Q^2 > = 16$ GeV$^2$

3.5 $< \eta < 4.0$
4.0 $< p_T < 5.0$ GeV/c

4.0 $< \eta < 4.5$
2.0 $< p_T < 3.0$ GeV/c
FoCal in ALICE

electromagnetic calorimeter (FoCal-E) for $\gamma$ and $\pi^0$ measurement

preferred scenario:
- at $z \approx 7m$ (outside solenoid magnet)
  $3.3 < \eta < 5.3$
- add hadronic calorimeter (FoCal-H)

under internal discussion
possible installation in LS3

advantage in ALICE: forward region not instrumented, “unobstructed view”

- main challenge: separate $\gamma/\pi^0$ at high energy
- need small Molière radius, high-granularity read-out
  - Si-W calorimeter, effective granularity $\approx 1\text{mm}^2$

note: two-photon separation from $\pi^0$ decay ($p_T = 10 \text{ GeV}/c$, $y = 4.5$, $\alpha = 0.5$) is $d = 2 \text{ mm}$!
The FoCal Detector – Strawman Design

studied in performance simulations:

20 layers: 
W (3.5mm ≈ 1 X₀) + Si-sensors

hybrid design (2 types of sensors)
• **Si-pads** (≈ 1 cm²):
  energy measurement, timing(?)
• **CMOS pixels** (≈ 30x30 µm²):
  two-shower separation, position resolution

<table>
<thead>
<tr>
<th>pixel/pad size</th>
<th>Si-pads</th>
<th>Si-pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>total # pixels/pads</td>
<td>≈ 2.5 x 10⁵</td>
<td>≈ 2.5 x 10⁹</td>
</tr>
<tr>
<td>readout channels</td>
<td>≈ 5 x 10⁴</td>
<td>≈ 2 x 10⁶</td>
</tr>
</tbody>
</table>

assuming ≈ 1 m² detector surface
Direct $\gamma$ Performance in pp

- combined rejection (invariant mass + shower shape, isolation)
- combined suppression of background relative to signal: factor $\approx 10$
  - largely $p_T$-independent

### Direct $\gamma$/all cluster ratio

**pp $\sqrt{s} = 13$ TeV**
- $4.0 < \eta < 5.0$
- 7m position

**ALICE simulation**
- FoCal upgrade

**$R_{iso}=0.4, \ p_T^{E+H} < 3.0$ GeV**

$\gamma_{dir}$/all clusters vs $p_T$ (GeV/c)

---

### Direct $\gamma$ uncertainty

**p-Pb, $\sqrt{s} = 8.8$ TeV**
- $4.0 < \eta < 5.0$

**ALICE simulation**

$L = 50$ nb$^{-1}$
- Rej. Factor=0.03
- Gam Eff.=0.4
- INCnlo based
- Eff. err.=0.05
- Decay err.=0.05

$\approx 20\%$ uncertainty
at $p_T = 4$ GeV/c

decreases with increasing $p_T$

**direct photon/all > 0.1**

for $p_T > 4$ GeV/c
Uncertainties can be improved significantly
Still some discussion ongoing:
choice of $\Delta \chi^2$, effect of DGLAP evolution, shape of parameterisation

Work in progress!
Extensive R&D Program Ongoing

• requires to go beyond state of the art
  • pixel sensors needed for pion rejection (two-shower separation)
  • Si-pads needed for energy resolution and timing
• proof of principle demonstrated
  • successful test of first digital pixel calorimeter (JINST 13 (2018) P01014)
  • investigating several options for pad sensor readout
• ongoing test-beam program
  • test setup with pads currently in ALICE cavern
• still significant R&D steps necessary
  • modifications to ALPIDE sensor
  • optimisation of pad readout
  • general design (minimisation of Molière radius, etc.)
FoCal R&D: Si-pad readout

pad layer prototypes

several calorimeter prototypes with pad readout from different groups

extensive test beam campaigns

recently installed 27 cm x 9 cm full depth prototype in ALICE cavern measurements in pp collisions performance under realistic conditions?

most important issue: readout electronics with sufficient dynamic range (~16bit?) plan to investigate several avenues: SAMPA, CMS-HGCal, ATLAS-VMM, …
W/Si-Pad Test-Beam Performance

ORNL/Japan Pad prototype with APV/SRS readout

India Pad prototype with custom chip (MANAS/ANUSANSKAR)

test beam performance agrees with simulations
papers on instrumentation in preparation
Developing an Extremely Granular Calorimeter

- go beyond state of the art
  - current technologies do not exploit the potential for two-shower separation
- digital pixel calorimeter
  - ~ mm effective cell size useful
  - analog read-out difficult on mm scale
  - use pseudo-analog value from pixel counting:
    requires order of magnitude smaller pixel sizes
FoCal R&D: Si-W CMOS pixel

24-layer prototype with MIMOSA sensors
39M pixels, 30µm pitch

- half layer with two sensors and 1.5mm W
- two half layers mounted together with opposite orientation to minimise dead areas
- total layer thickness ≈ 1 X₀
- full active layer with readout boards within 1mm

A: MIMOSA sensor, B: PCB, C: tungsten

most important issue: readout speed/bandwidth
MIMOSA sensor much too slow, now moving to ALPIDE sensor
- synergy with ALICE ITS upgrade
- needs chip design steps

preparing prototypes with current ALPIDE
- full pixel prototype
- hybrid (pixel/pad) prototype

four layers with flex-cable mounting
very high hit density in shower core
  • not possible to reconstruct single shower particles from pixel clusters
  • have to use number of hits as response (not number of clusters)
  • saturation (overlap of clusters) likely for very high energy

Single Event Hit Distribution - FoCal Pixel Prototype

layer 4

layer 8

layer 12

244 GeV e⁻
average hit densities as a function of radius for different layers

- low energy: early shower maximum, profiles broaden and decay with depth
- high energy: profiles broaden with depth, increase up to shower maximum

shower measurements with unprecedented detail!
R&D - Energy Resolution

\[ \frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E/\text{GeV}}} \oplus \frac{c}{E/\text{GeV}} \]

\[ a = (2.95 \pm 1.65)\% \]
\[ b = (28.5 \pm 3.8)\% \]
\[ c = 6.3\% \]

noise term \( c \) compatible with pedestal width (fixed in fit)

recent work on improved calibration

slightly worse than MC simulation, not unexpected

reasonable energy resolution
- better results expected from LGL
- note: sampling fraction < 1/1000
- possibly still improve calibration, better sensor (ALPIDE) in the future

proof of principle of digital calorimetry

https://arxiv.org/abs/1708.05164
R&D - Position Resolution

Calculate difference of position from
- cluster in layer 0 and
- center of gravity of shower in layers 1 - 23

Single shower position resolution obtained from width of residuals can also provide excellent two-shower separation.
R&D Results: Core Energy

detector response (number of hits)  energy resolution

reasonable energy resolution of pixel calorimeter, sufficient for conceptual design

response and resolution for core energy hardly affected down to $r = 5\text{mm}$: adequate for very high particle density
Pixel (HGL) R&D Results: Single Event Profiles

electron showers have well defined profile, very narrow shower core
pion showers show much larger fluctuation, often much wider
Summary

• Forward photon measurements at LHC provide unique opportunity for low-x physics
  • complementarity with open charm: some advantages for photons
  • needs detector upgrade: proposed FoCal detector in ALICE
  • more physics opportunities with FoCal
• Extensive R&D to go beyond state of the art
  • significant steps on pad sensor readout
  • towards digital pixel calorimetry
    • proof of principle
    • working towards a full-scale detector
  • strong potential for future photon, electron, and jet measurements
Backup Slides
Recent: PDF Fits Using Charm

- open charm used in re-weighting
- significant reduction of uncertainties
- significant suppression – on the low side of current PDFs
- significant pQCD uncertainties (scale, fragmentation)
- relies on shape of parameterisation: very little $x$-dependence at low $x$!

Kusina et al., arXiv:1712.07024
x-Dependence of PDF modification

EPPS16, EPJC 77, 163

\[ R_i^A(x, Q^2) = \begin{cases} 
  a_0 + a_1 (x - x_a)^2 & x \leq x_a \\
  b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \leq x \leq x_e \\
  c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \leq x \leq 1 
\end{cases} \]

- parameterisation of \( R_A \)
  - shape similar to EPS09
  - at low \( x \) leads to “plateau” in \( \log(x) \)

- likely not sufficient
  - more flexible PDF used for LHeC estimates

Helenius, Paukkunen, Armesto, arXiv:1606.09003
Influence of $x$ Dependence

parameterise nuclear modification of gluon PDFs

Simple Model based on PYTHIA – no proper $Q^2$ dependence

different $x$-sensitivity of probes
reflected in nuclear modification factor

$$R_{pA} = \frac{\int dx \frac{d\sigma}{dx}(p_T, y) \cdot R_g(x)}{\int dx \frac{d\sigma}{dx}(p_T, y)}$$
Main Physics Motivation for FoCal (A Hierarchy)

1. prove or refute gluon saturation
   • compare saturation models with linear QCD
   • depends on saturation model implementation and flexibility of PDF analytical shape

2. show invalidity of linear QCD at low $x$
   • can all potential measurement outcomes be absorbed in a modified PDF?

3. constrain the PDFs at low $x$
   • nuclei, also protons
     • main observable: nuclear modification factor $R_{pA}$ of direct photons
       • saturation stronger in nuclei
       • possibly non-existent in protons (calculation of reference in models?)

\[ R_{pA} \]

\[ \sqrt{s_{NN}} = 8.160 \text{ TeV} \]
\[ 4 < p < 5 \]
\[ \Sigma E_T < 2 \text{ GeV} \]

\[ p + Pb / p + p \rightarrow \gamma + X, \sqrt{s} = 8 \text{ TeV} \]

CGC Calculation: Ducloué, Lappi, Mäntysaari, arXiv:1210.02206
Final-State Modification of Open Charm in p–A?

- mechanism for modifications still unclear, possibly final-state interaction!
- relation between initial- and final-state kinematics may be obscured
- introduces additional systematic uncertainty


ALICE Preliminary

- p–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Average $D^0$, $D^+$, $D^{*+}$
- Charged particles

nuclear modification for D mesons
similar to charged hadrons,
deviation from $N_{\text{coll}}$ scaling at low $p_T$

significant $v_2$ for D mesons,
similar results for HF-decay leptons

- mechanism for modifications still unclear, possibly final-state interaction!
- relation between initial- and final-state kinematics may be obscured
- introduces additional systematic uncertainty
Sensor and Readout

MAPS sensor: MIMOSA23 (IPHC) full frame readout

in-pixel micro-circuits
charge collecting diode
particle

read out via 4 Spartan and 2 Virtex FPGAs
continuous data stream of 8GB/s

current sensor too slow (642 µs/frame)
  • real detector will likely use derivative of ALPIDE (ALICE-ITS upgrade)
Two Shower Separation

display of single event (with pile-up) from 244 GeV mixed beam

evaluate separation capability: core energy
calculate shower energy in cylinder of finite radius
study as function of radius
Detector Response

- minimum ionising particle (MIP) peak from pion tracks

- pedestal: noise distribution of full prototype

- response to electrons from SPS test beam

- calculated from per-event hit density distributions
detector response from integrated event-wise hit densities

- fit with linear and power law function, good linearity (power $\beta = 0.98$)

Note - not yet corrected:
- different calibration for low and high energy
- small effects of saturation at high energy
extract cumulative distributions both per layer and integrated

• some lateral leakage at higher energy

small Moliere radius: \( R_M \approx 11 \text{mm} \)

\( \approx 75\% \) of hits within \( R = 5\text{mm} \), 50\% within \( R = 3\text{mm} \), …
R&D - Hadron Rejection

longitudinal shower shape: cut on position of shower start

further discrimination via transverse shower shape: slope

hadron rejection for realistic pion momentum spectrum:
- cases of high deposited energy suppressed from low interaction probability
- additional rejection for low deposited energy from shower shape

$\pi$ (E_{dep} \approx 30$ GeV)
More FoCal Physics Topics

- low-x gluons (n)PDFs, saturation
  - direct photon $R_{pA}$
- $\pi^0$-$\pi^0$ correlations
- dijet correlations

- ridge/flow-like phenomena in pp, pA
  - correlations: forward photon – mid-rapidity hadron

- jet quenching at large y
  - neutral pion $R_{AA}$

- miscellaneous
  - reaction plane in Pb–Pb