Quark Matter 2023: XXXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions

Forward Calorimeter (FoCal): Physics program and performance

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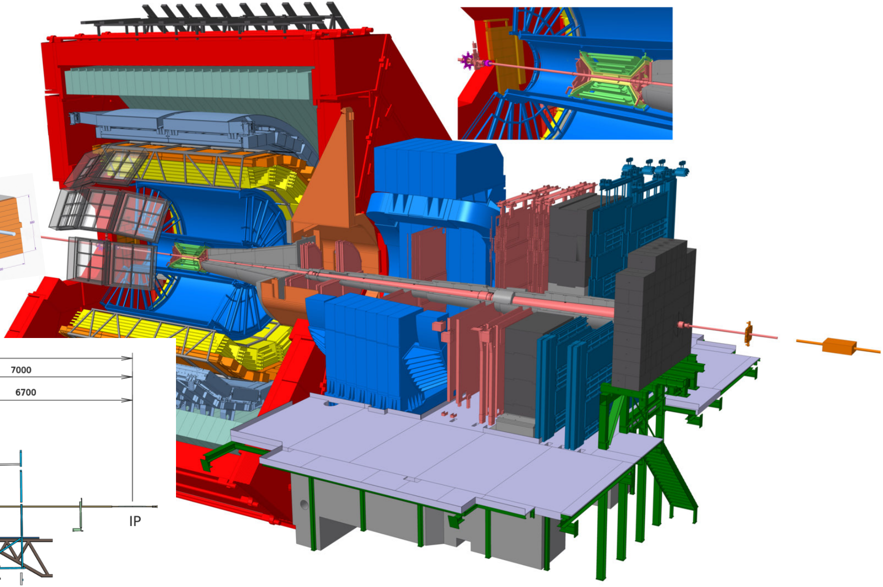
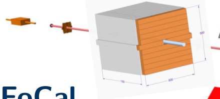
ALICE

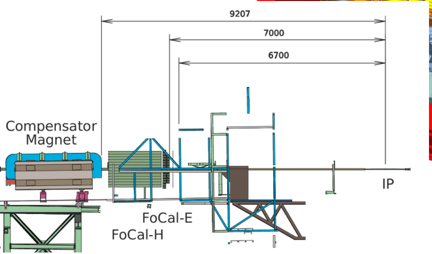
The ALICE detector



not to scale!



FoCal
$3.2 < \eta < 5.8$



Operational in Run 4 (2029) **Further info: FoCal-LoI**

$3.2 < \eta < 5.8$

General:

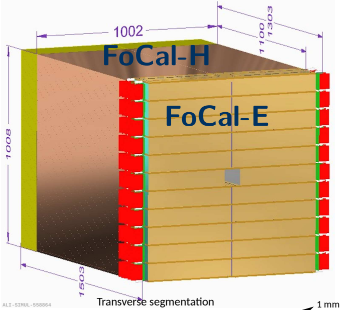
- very forward calorimeter consisting of two parts (FoCal-E and FoCal-H) located $\approx 7\,$m from IP of ALICE

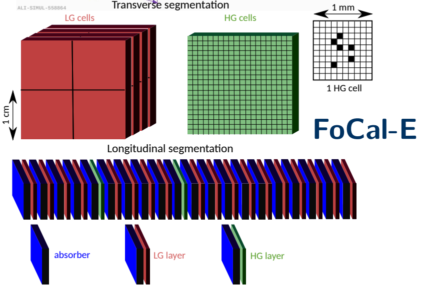
FoCal-E (electromagnetic):

- high-granularity Si-W sampling calorimeter combining two readout granularities:
  - 18 pad layers with silicon pads ($1 \times 1\,$cm^2)
  - two pixel layers with digital readout ($30 \times 30\,\mu$m^2)
- ability to "track" longitudinal component of shower!
- used to measure **photons and** π^0 ($40\,\mu$m position res.)

FoCal-H (hadronic):

- conventional metal-scintilator **hadronic calorimeter** behind FoCal-E
- design using scintillation fibres embeded in Cu tubes
- used to measure **photon isolation, jet energy** etc.





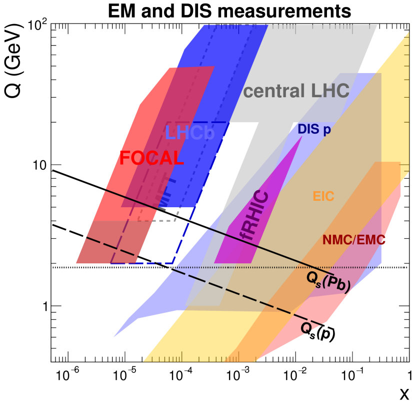
The Forward Calorimeter (FoCal)

Main physics goal: Explore non-linear QCD in regime of saturated gluons at low Bjorken-x + constrain nPDFs

FoCal capabilities allow explorations of gluon saturation using a **multi-messenger approach**:

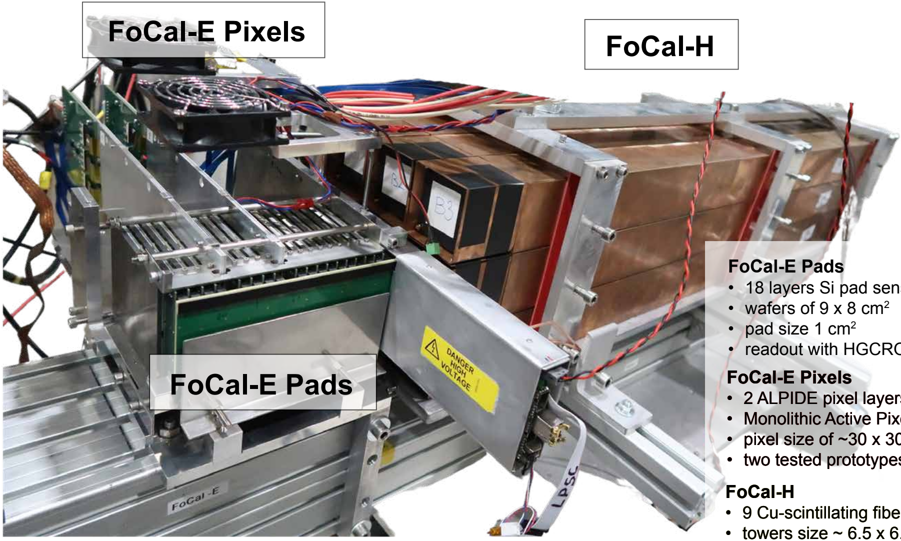
- prompt photon production
- γ-hadron correlations
- production of π^0, η and vector mesons
- jet measurements (e.g. dijet production)
- vector meson photo-production in Ultra-Peripheral Collisions (UPC)
- ... and more ...

see ALICE-PUBLIC-2023-001



- FoCal acceptance allows to reach down to $x \sim 10^{-6}$, complementing searches for gluon saturation at current and future facilities
- deep theoretical connection to EIC physics

FoCal prototype & test beam results



FoCal-E Pads
- 18 layers Si pad sensors
- wafers of 9 x 8 cm^2
- pad size 1 cm^2
- readout with HGCROC v2

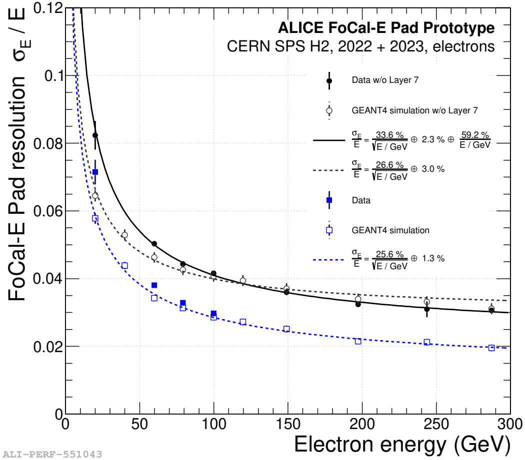
FoCal-E Pixels
- 2 ALPIDE pixel layers
- Monolithic Active Pixel Sensors
- pixel size of ~30 x 30 μm
- two tested prototypes (HIC,pCT)

FoCal-H
- 9 Cu-scintillating fiber towers
- towers size ~ 6.5 x 6.5 cm2
- length ~110 cm
- readout with CAEN DT5202

FoCal prototype tested in electron/hadron beams at SPS in Nov. 2022 and May 2023!

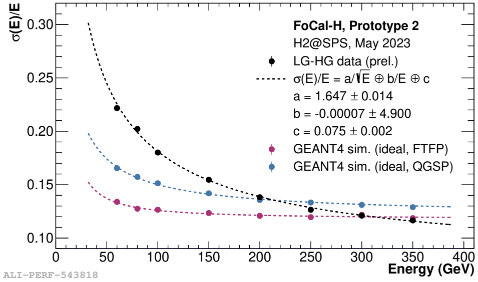
FoCal prototype & test beam results

Energy resolution FoCal-E pads



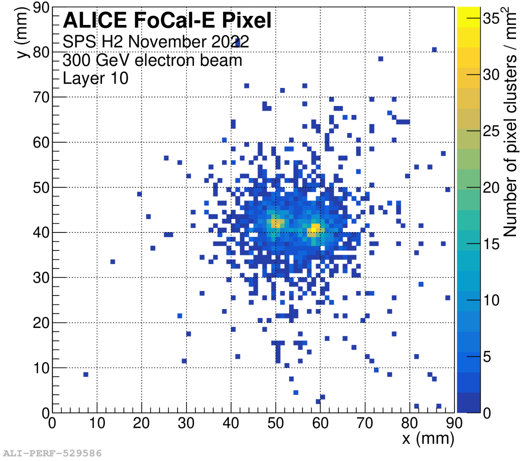
- energy resolution of FoCal-E studied using electron beam from SPS
- energy resolution $< 4\,\%$ for high energies within physics requirement & described by sim.

Energy resolution FoCal-H

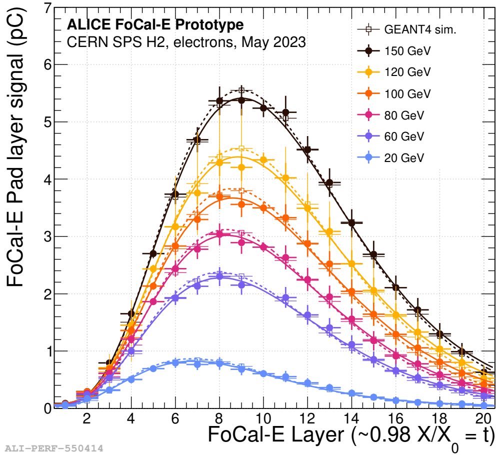


- energy resolution $< 8\,\%$ at high energies
- disagreement with MC under investigation

Shower separation in FoCal-E pixels



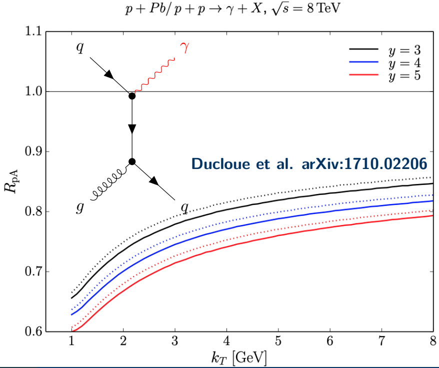
Longitudinal shower profile in FoCal-E



Measurement of prompt photon production

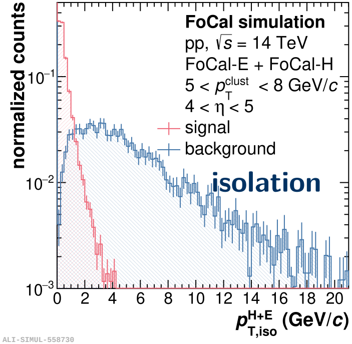
Theory:

- prompt photons directly produced in hard scattering q$g \rightarrow \gamma$q
- sensitivity gluon & no strong interaction in final state
- measurement of prompt photon production at forward y in p–Pb collisions sensitive to gluon saturation



Measuring prompt photons with FoCal:

- FoCal well suited to identify prompt photons:
  1. measurement of isolation energy in FoCal-E and FoCal-H
  2. EM shower shape in 20 layers
  3. separation of showers from dominant $\pi^0 \rightarrow \gamma\gamma$ background



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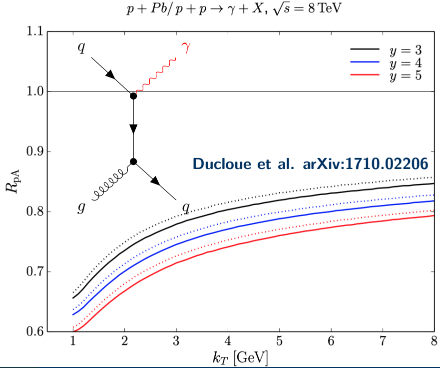

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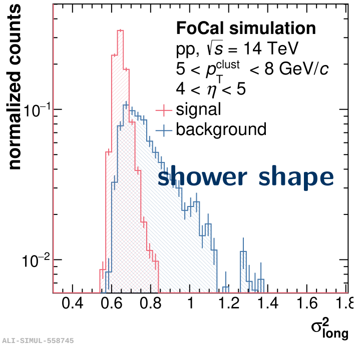

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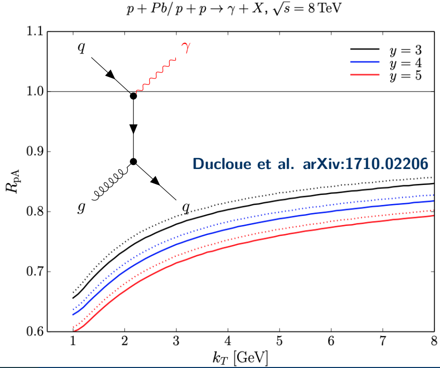

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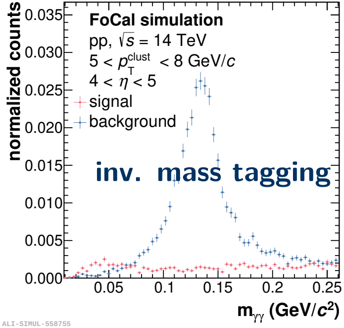
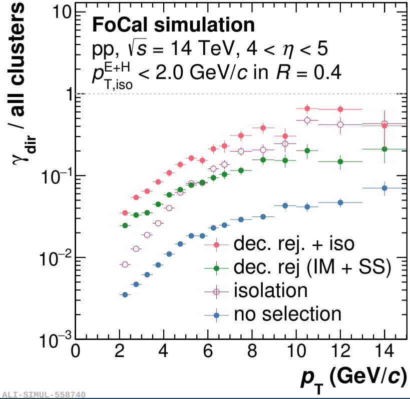
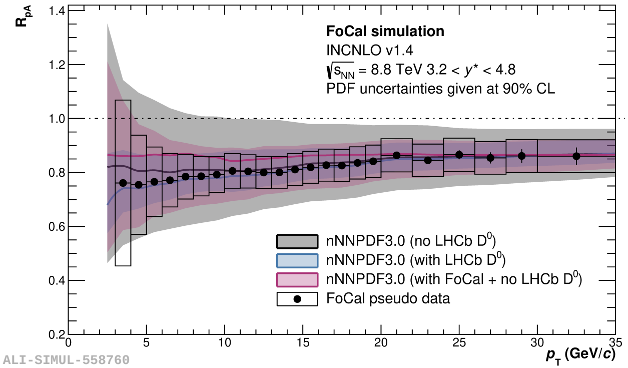


Measurement of prompt photon production

- isolation + shower shape selection + invariant mass tagging allow to **increase signal fraction** by about **factor 11** up to $70\,\%$ at $p_T \sim 14\,\mathrm{GeV}$
- addition untapped potential: machine learning on 3D showers?

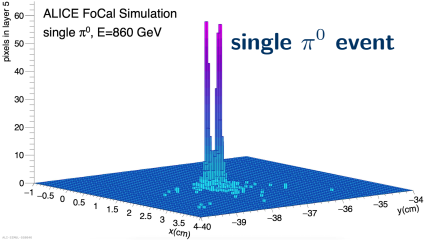


nNNPDF30: arXiv:2201.12 LHCb D meson data: arXiv:1707.02750

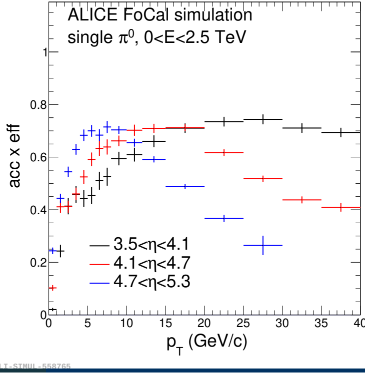


- nPDF+NLO R_{pA} reweighted using FoCal pseudo data
- FoCal photons: reduction of nNNPDF30 uncertainties similar to LHCb D mesons
- strong nPDF constrains at forward rapidities
- multi messenger approach: differing sensitivity to final state effects

Measurement of π^0, η and vector mesons

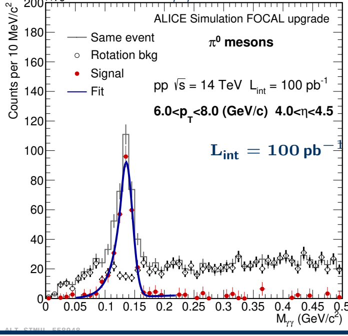


Reconstruction efficiency

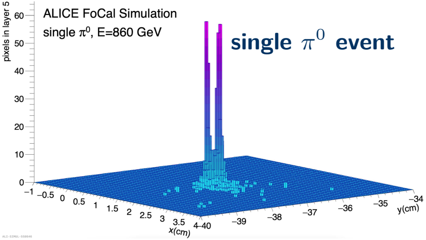


- various studies using simulated data + FoCal geometry in GEANT demonstrate FoCal capabilities to measure e.g. π^0, η and ω mesons
- expected luminosities for Run 4 sufficient to measure over large energy range of **up to 2 TeV**, also differentially in rapidity
- highly granular **pixel layers** allow for efficiencies of up to $80\,\%$, even for photon **separation of $< 5\,$mm!**

$\pi^0 \to \gamma\gamma$ reconstruction

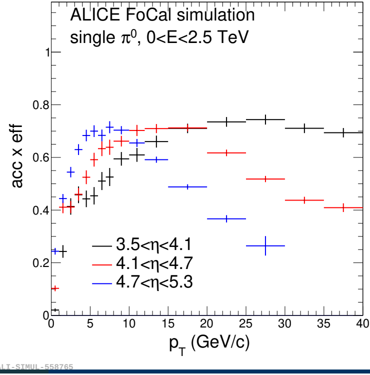


Measurement of π^0, η and vector mesons



single π^0 event

Reconstruction efficiency



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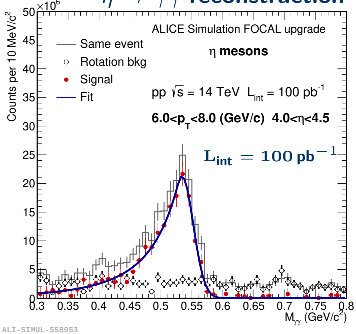
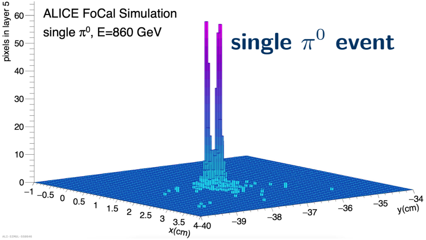
$\eta \rightarrow \gamma\gamma$ reconstruction



Measurement of π^0, η and vector mesons



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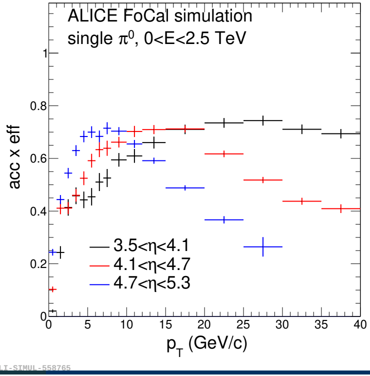

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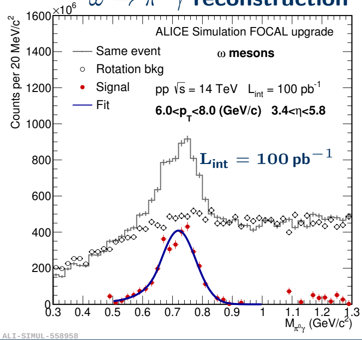
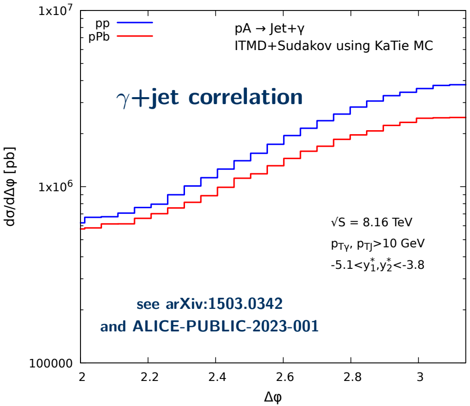
$\omega \to \pi^0\gamma$ **reconstruction**



Measurement of γ-hadron correlation

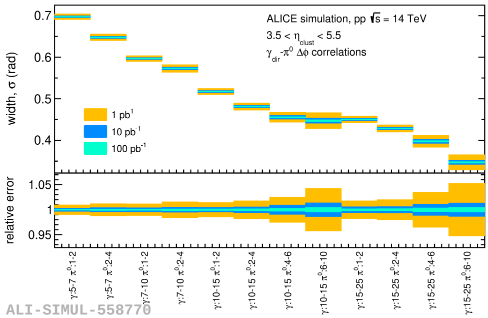
Theory:

- study of γ-hadron correlations offers additional sensitivity to low-x gluon dynamics
- expectation of **yield suppression** and **de-correlation** due to saturation effects



FoCal performance

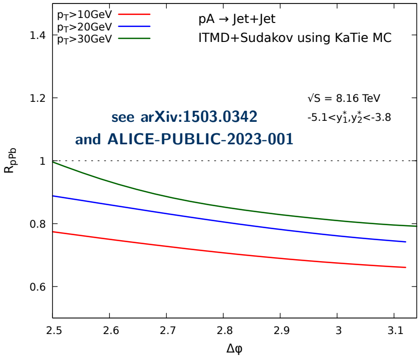
- analysis of γ-π^0 corr. in simulated pp collision events + detector smearing
- correlation peak can be measurement precisely: **stat. uncertainties** of peak width $\sim$ **0.001 rad** for expected Run 4 luminosities
- differential measurement feasible in significant number of trigger bins



Jet measurements

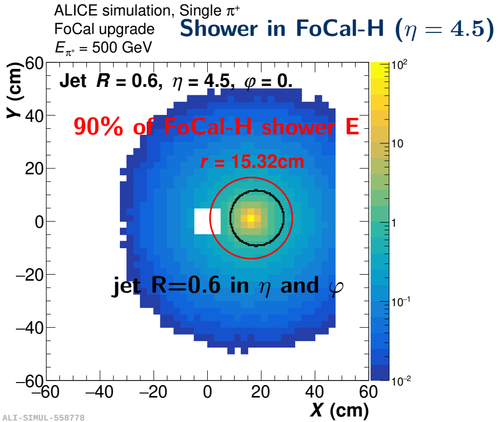
Theory:

- forward incl. jet, γ+jet and dijet production sensitive to gluon saturation
- dijet especially interesting
  $\rightarrow$ momentum imbalance k_T probes Q_{sat}



Kinematic considerations:

- a given jet with resolution parameter R will be **squeezed into an increasingly small geometrical space** at forward rapidities!
- effective Moliere radius FoCal-E $\approx 1-2\,$cm, interaction length FoCal-H $\approx 15-20\,$cm

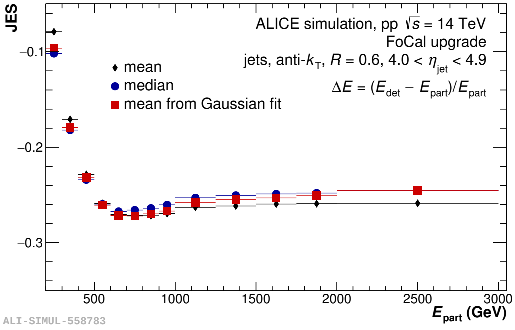


Jet measurements

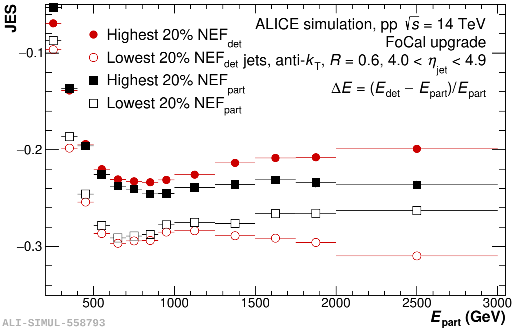
- studies using **Pythia + GEANT** to quantify FoCal perf. for $R = 0.6$ anti-$\mathbf{k}_\mathrm{T}$ jets

$$\Delta E = (E_{\mathbf{det}} - E_{\mathbf{part}})/E_{\mathbf{part}}$$

Jet Energy Scale = mean of ΔE



Jet Energy Scale for different Neutral Energy Fractions (NEF)

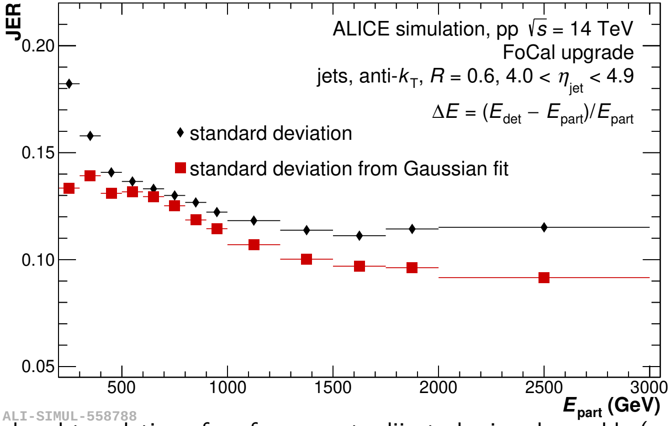


- JES influenced by kinematic considerations + neutral energy fraction

- studies using **Pythia + GEANT** to quantify FoCal perf. for $R = 0.6$ anti-$\mathbf{k}_{\mathrm{T}}$ jets

$$\Delta E = (E_{\mathbf{det}} - E_{\mathbf{part}})/E_{\mathbf{part}}$$

Jet Energy Resolution = width of ΔE



- JER quantified and translation of performance to diject physics observable (e.g. k_{T}) ongoing

Theory:

- photo-production cross section of vector mesons (e.g. J/ψ) in ultra-peripheral collisions **proportional to gluon density**
- **deviation from power-law** growth of cross section with increasing $W_{\gamma p}$ expected due to **saturation effects**

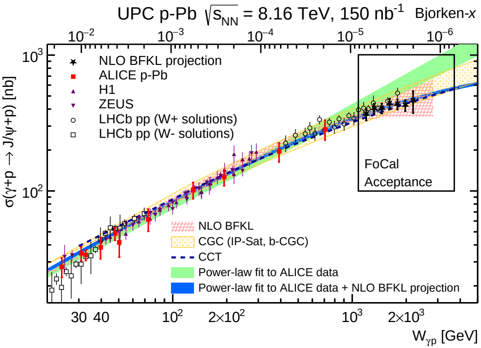
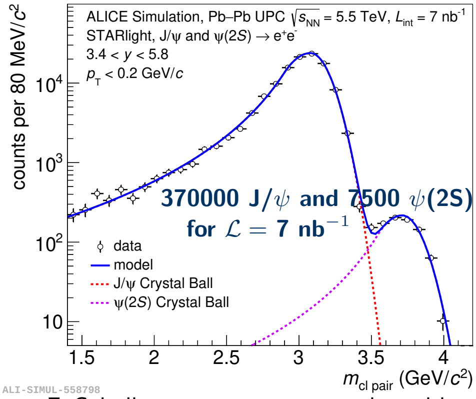


fig. taken from Bylinkin, Nystrand, Takaki arXiv:2211.16107

FoCal performance:



- FoCal allows to access unprecedented low-x, extending existing measurements to $\mathbf{W_{\gamma p}}$ **≈2 TeV (10 GeV) in p-Pb (Pb-p collisions) + Pb-Pb collisions**
- studies with STARLight + GEANT show successful reconstruction of J/ψ and $\psi(2S)$

Vector meson photo-production in UPC

Theory:

- photo-production cross section of vector mesons (e.g. J/ψ) in ultra-peripheral collisions **proportional to gluon density**
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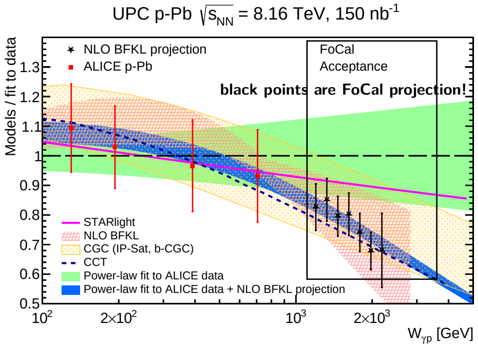

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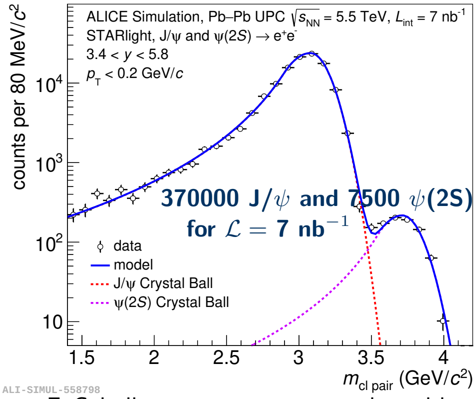

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Summary

Summary:

- the **FoCal detector is a planned calorimeter for the ALICE experiment for Run 4**, covering forward rapidities $3.2 < \eta < 5.8$
- **Goal:** explore gluon saturation at low-x in **multi-messenger approach**, deep connection to EIC physics
- performance studies using simulated collision events + detector simulation **demonstrates FoCal capabilities to probe this regime using a variety of observables!**
- prototype of detector tested in test beams at SPS in 2022 and 2023 show energy resolution meeting physics requirements

Read more:

- FoCal Letter-of-Intent (**CERN-LHCC-2020-009**)
- Physics of the ALICE Forward Calorimeter upgrade (**ALICE-PUBLIC-2023-001**)
- Physics performance of the ALICE Forward Calorimeter upgrade (**ALICE-PUBLIC-2023-004**)
- Technical Design Report (**in preparation**)
- Performance of the electromagnetic and hadronic prototype segments of the ALICE FoCal (**paper in preparation**)

Thank you for your attention & stay tuned!

Backup

Connection to EIC

EIC Yellow Report Sec. 7.5.4:

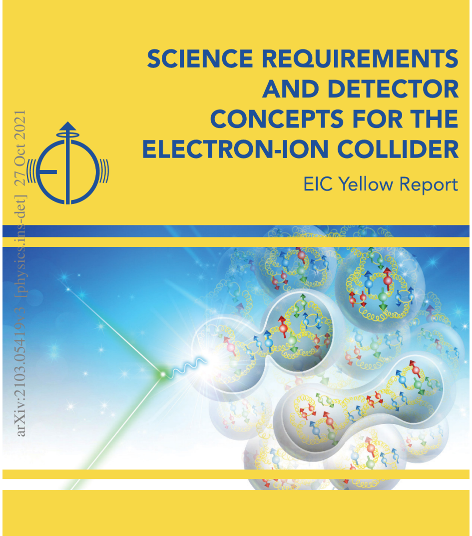
"Meanwhile, pA collisions can serve as a gateway to the EIC as far as saturation physics is concerned, and it also plays an important and complementary role in the study of these two fundamental gluon distributions."

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in p+A	γ+jet in p+A	dijet in p+A
xG_{WW}	−	−	+	−	−	+
xG_{DP}	+	+	−	+	+	+

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+Acollisions. Here the + and − signs indicate that the corresponding gluon distributions appear and do not appear in certain processes, respectively.

the whole picture (EIC + forward LHC/RHIC) will me more than the sum of its parts!

The "bible" of the EIC:



arXiv:2103.05419

Rates in FoCal acceptance

- yields for various observables in FoCal acceptance estimated using expected integrated luminosities for Run 4
- high rates for prompt photons, mesons and jets