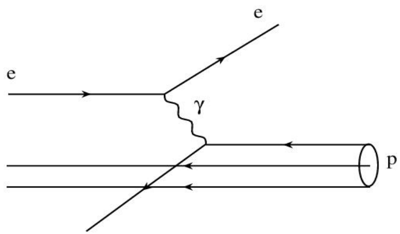
# Probing gluon saturation
# -
# the Forward Calorimeter in ALICE

**Dieter Roehrich**
**University of Bergen**

# QCD matter - proton

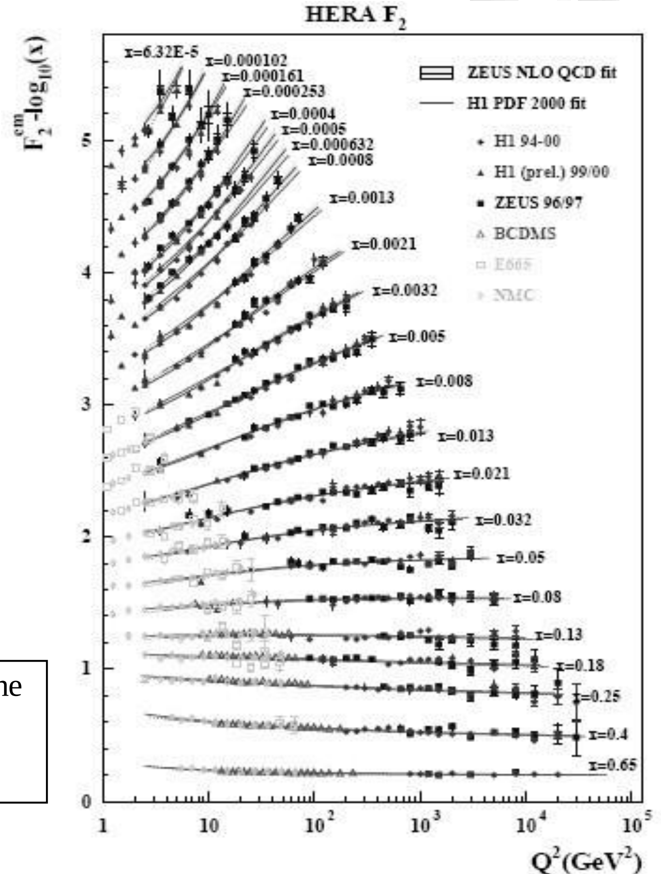
- **What is inside a proton?**
- **Deep-inelastic electron-proton scattering -> elastic electron-quark scattering -> parton model**




- **Cross-section**
  **-> structure functions $F_1$, $F_2$**
  **-> parton distribution function**

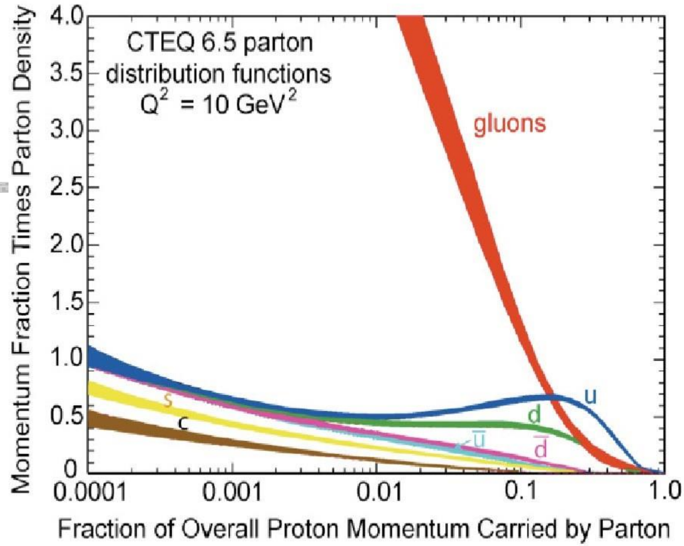
Bjorken x: fraction of the proton momentum carried by the parton (in a frame where the proton is ultra-relativistic)

$Q^2$: momentum transfer

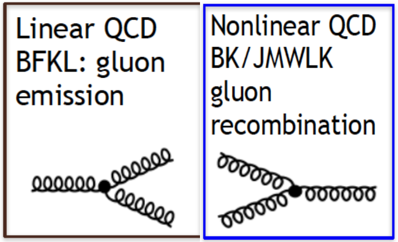


# Gluons

### Parton Distribution Function



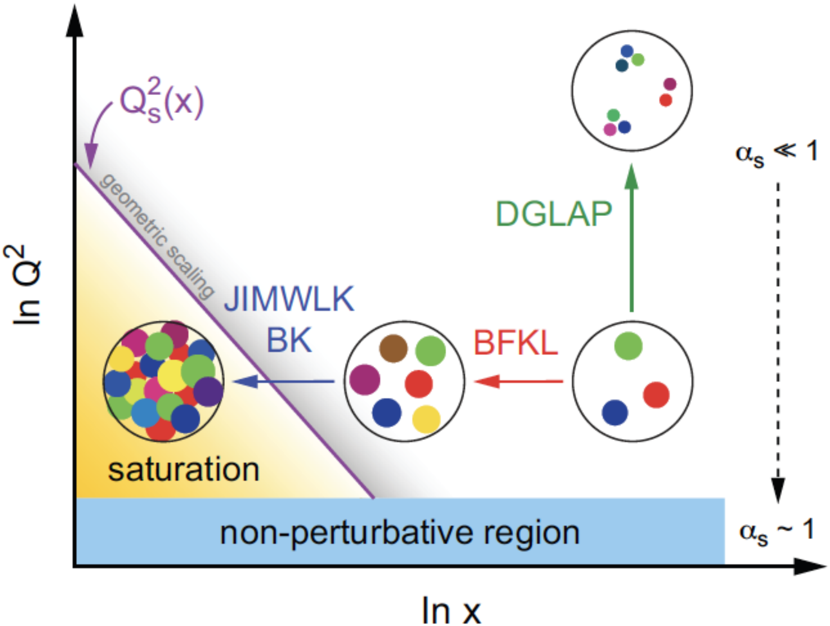

- **QCD at low x:**
  - **parton splitting is described by linear equations: BFKL equation (as well as DGLAP evolution)**
  - **At high enough gluon densities gluons would also recombine**
    **- described by BK/JMWLK equations**




- **Gluon saturation**
  **- dynamical equilibrium between emission and recombination**

# QCD matter – gluon saturation

- **Onset of saturation effects: saturation scale $Q^2_s$**

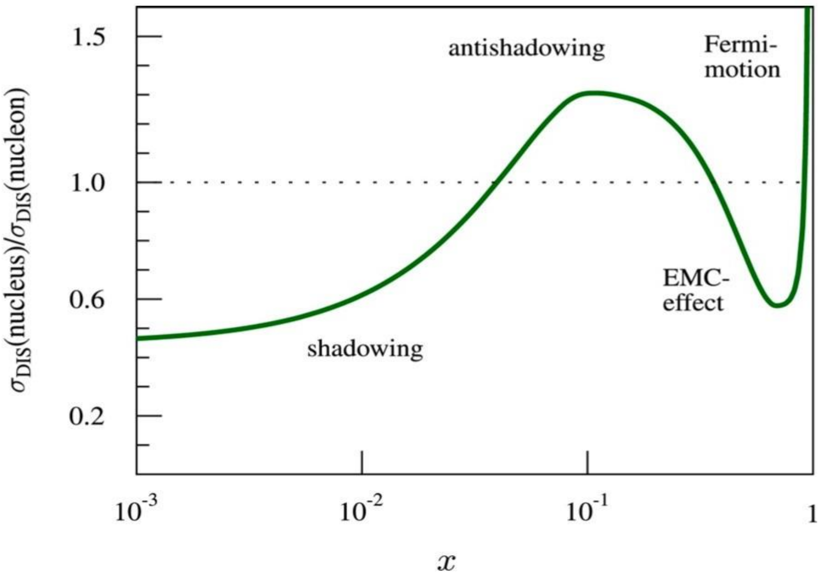



$$Q_s^2 \approx \frac{xG_A(x, Q^2)}{\pi R_A^2}$$

- **The effective theory to describe this saturated gluon field:**
  **Color Glass Condensate (CGC)**

# QCD matter – nuclei

- **Nuclei are not a collection of free protons and neutrons - nuclear shadowing**




- Experimental observation: parton distributions are different for protons and nuclei

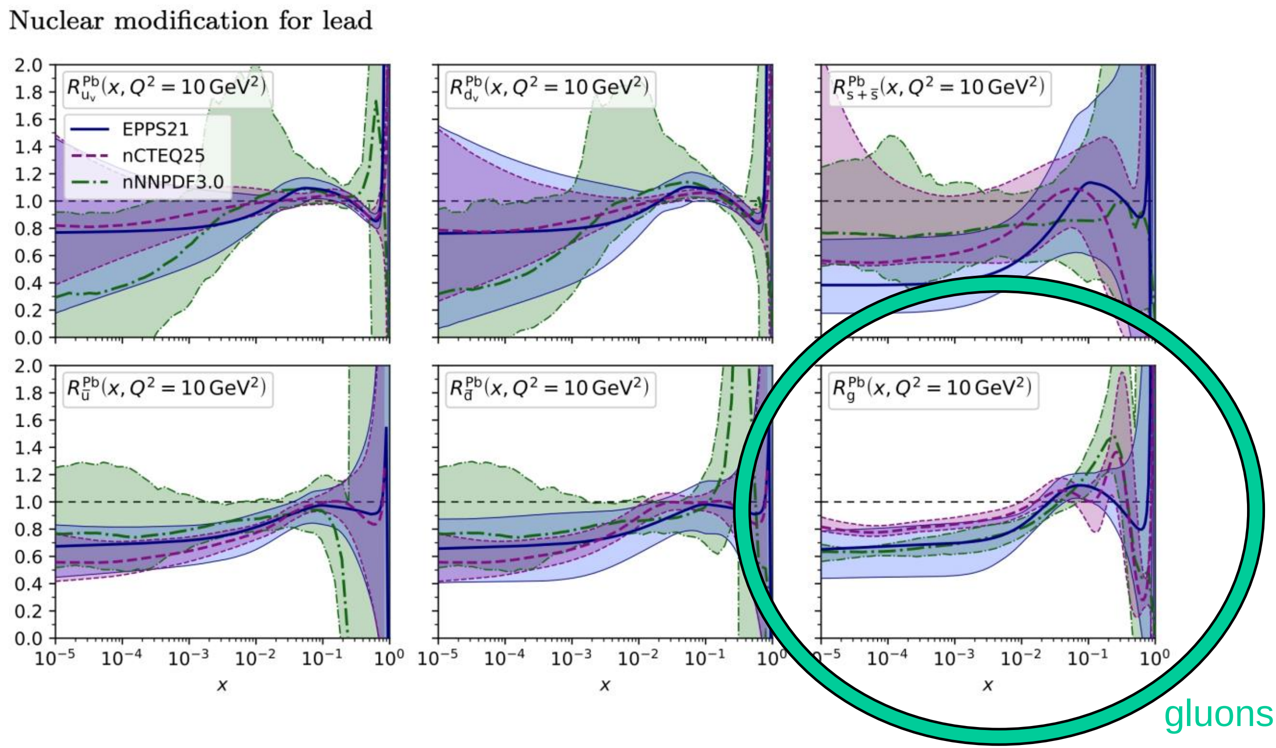
- What is the mechanism responsible for shadowing?

  Gluon saturation?

- **saturation scale $Q^2_s$ is modified in nuclei:** $$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

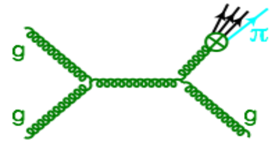
# QCD matter – nuclei

- **Nuclear PDFs for Pb – state-of-the-art** A. Kusina, IS 2025

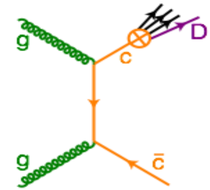


# A probe for gluon density – direct photons

- **Hadronic observables**
  - interpretation inconclusive

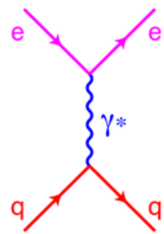


light hadron

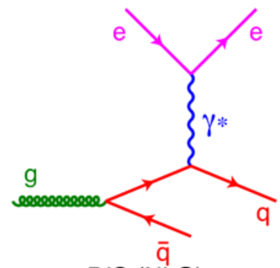


heavy hadron

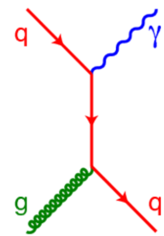
- **Electromagnetic probes**
  - Deep-Inelastic Scattering (DIS)
    - » classical PDF method
    - » not sensitive to gluons at LO
    - » gluons from NLO
  - Photon production in hadronic collisions
    - » sensitive to gluons at LO



DIS (LO)



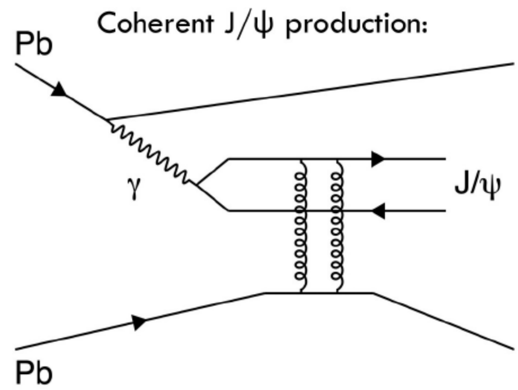
DIS (NLO)

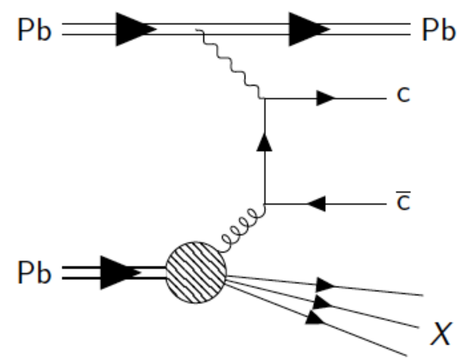


direct-γ, Compton (LO)

# Probes for gluon density - UPCs

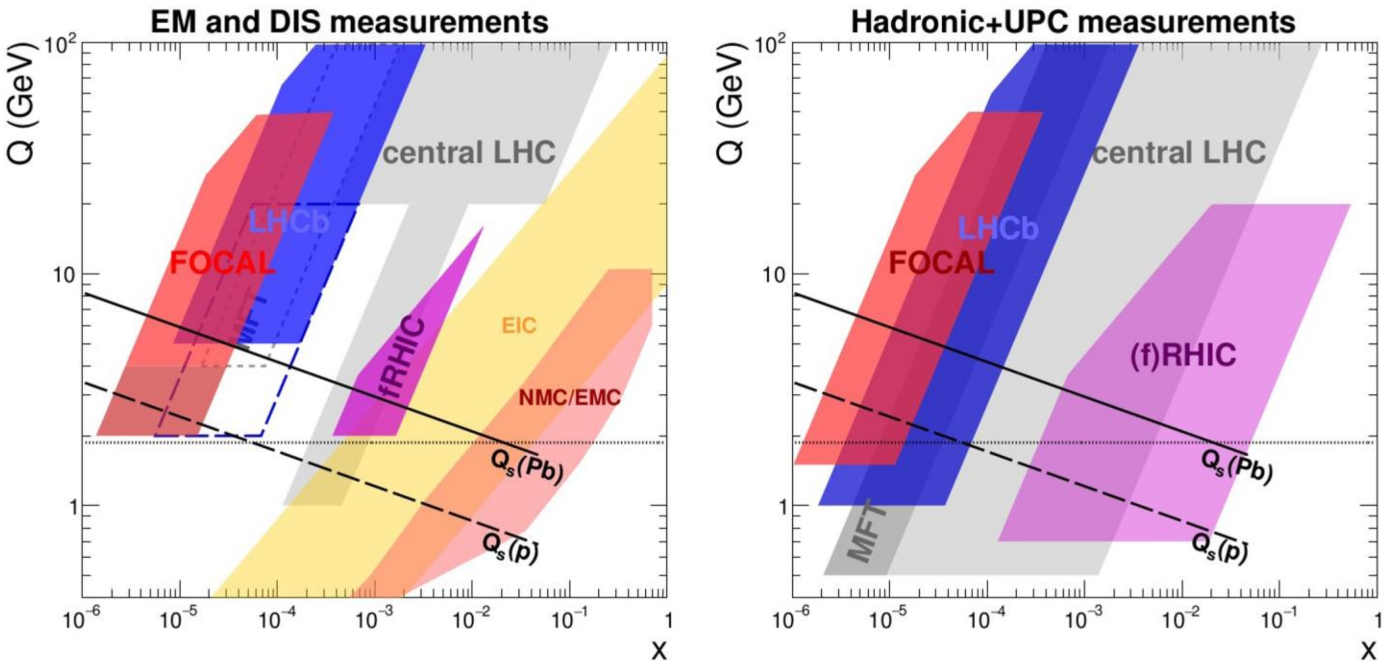
- **UPCs**
  - Photoproduction of vector mesons
  - Charm production in photonuclear interactions
  - …



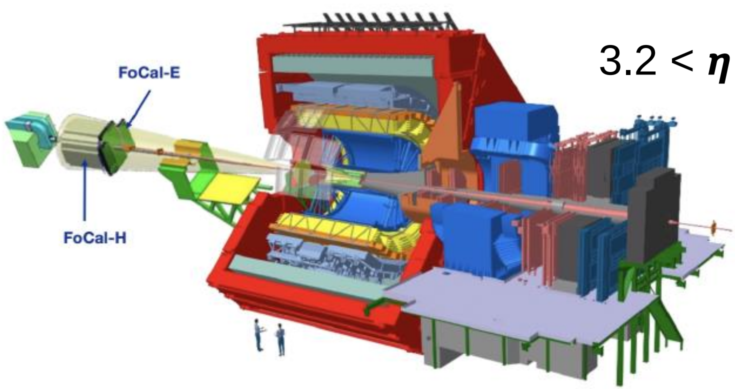
# The Q-x experimental landscape

- **Exploration of nuclear PDFs**



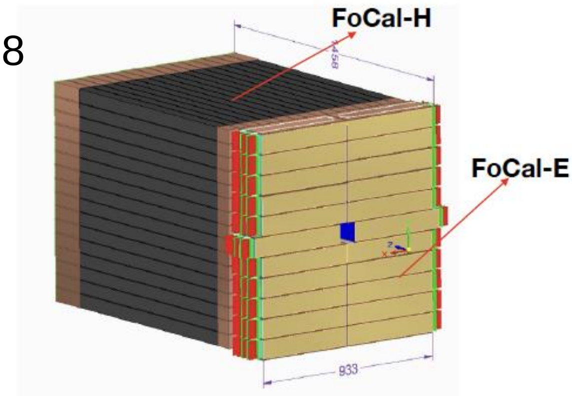

- FoCal at ALICE will explore a unique low-*x* regime reaching $x \sim 10^{-6}$ in nuclear collisions – p+p and pPb – at the LHC

# The Forward Calorimeter - FoCal




LHC Run 4 - 2030-2033

$3.2 < \boldsymbol{\eta} < 5.8$

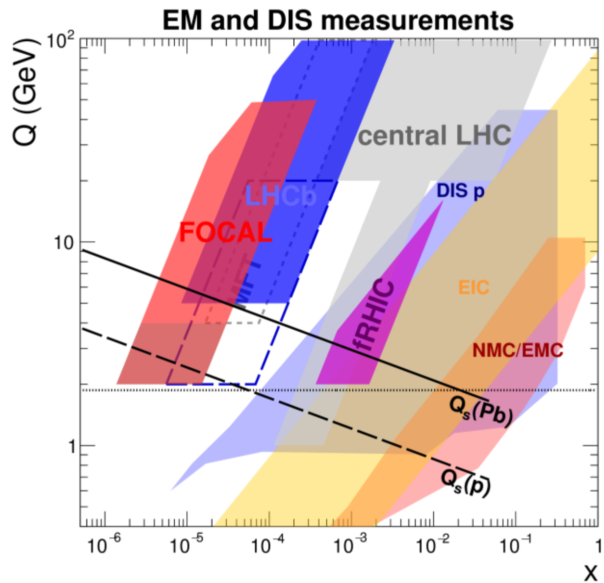



**very forward calorimeter consisting of two parts, an electromagnetic calorimeter (FoCal-E) and a hadronic calorimeter (FoCal-H) located 7m from the IP of ALICE**

# The Forward Calorimeter - FoCal

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

- **FoCal capabilities allow explorations of gluon saturation using a multi-messenger approach:**
  - **prompt photon production**
  - **γ-hadron correlations**
  - **production of $\pi^0$ and $\eta$ vector mesons**
  - **jet measurements (e.g. dijet production)**
  - **vector meson photo-production in Ultra-Peripheral Collisions (UPC)**
  - **... and more ...**

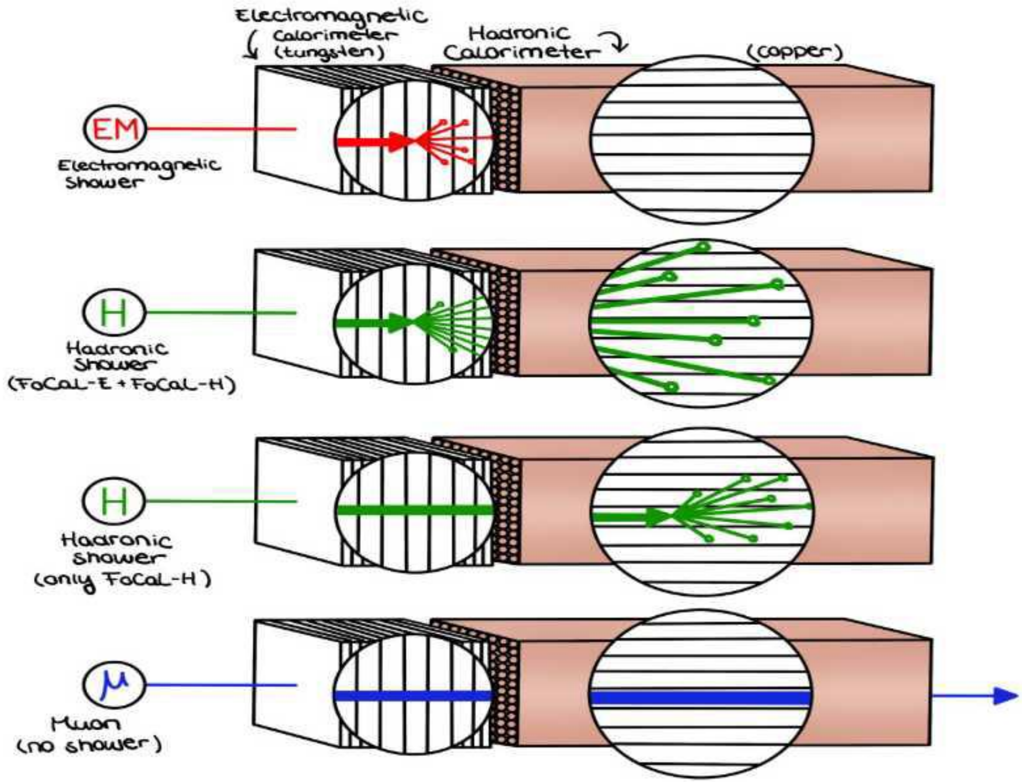



FoCal acceptance allows to reach $x \sim 10^{-6}$, complementing searches for gluon saturation at current and future facilities

# The Forward Calorimeter - FoCal

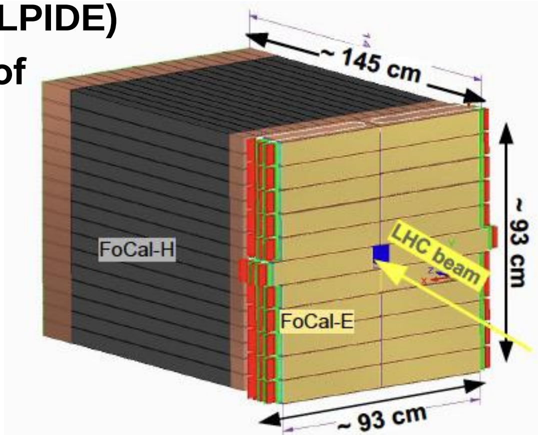
**ECAL: sandwich/shashlik type - HCAL: spaghetti type**

- **sampling calorimeter**



# The Forward Calorimeter - FoCal

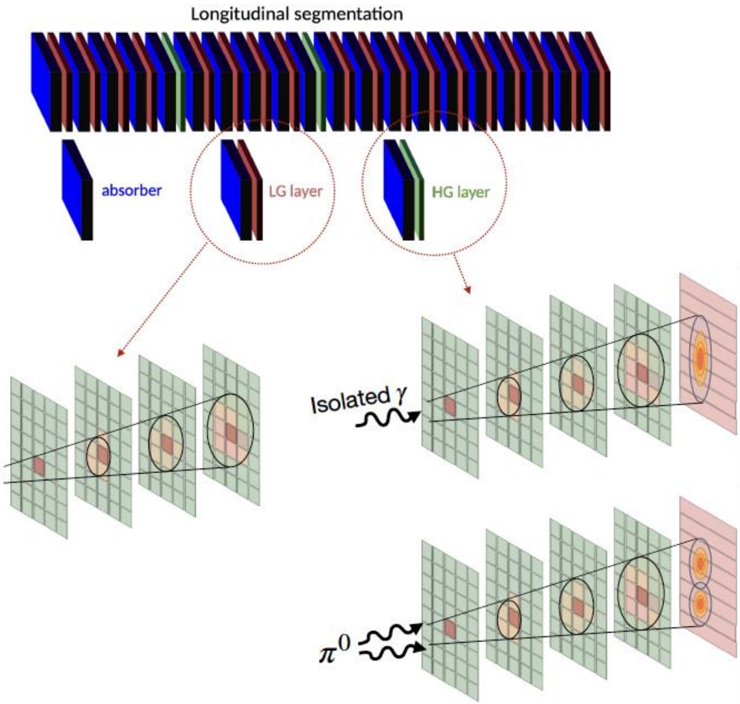
- **FoCal-E (electromagnetic):**
  - **high-granularity Si-W sampling calorimeter combining two readout granularities:**
    - **18 pad layers with silicon pads (1x1 $cm^2$)**
    - **two pixel layers with digital readout (ALPIDE)**
  - **ability to "track" longitudinal component of shower**
  - **used to measure photons and $\pi^0$ (40 µm position resolution)**



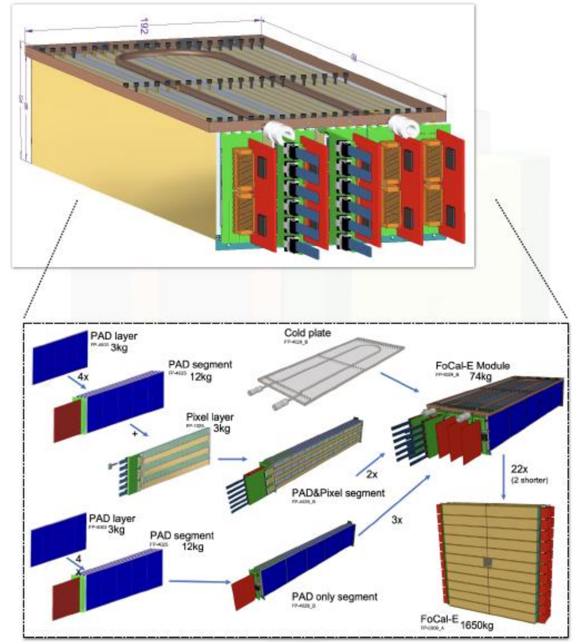

- **FoCal-H (hadronic):**
  - **conventional metal-scintillator hadronic calorimeter behind FoCal-E**
  - **scintillation fibres embedded in Cu sheets**
  - **used to measure photon isolation, jet energy etc.**

# The Forward Calorimeter - FoCal

## Detector concept - FoCal-E

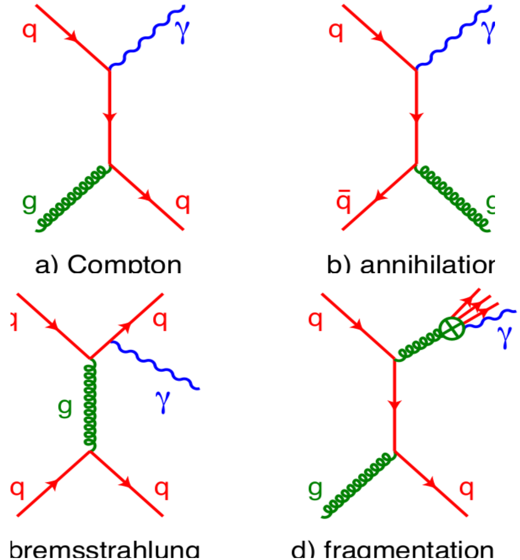



FoCal-E modules assembly

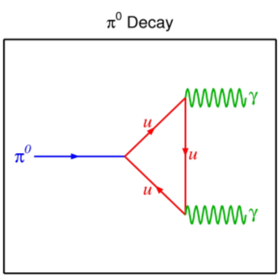


# FoCal – experimental challenges

- **Signal**
  - **Single isolated photons at forward rapidity**

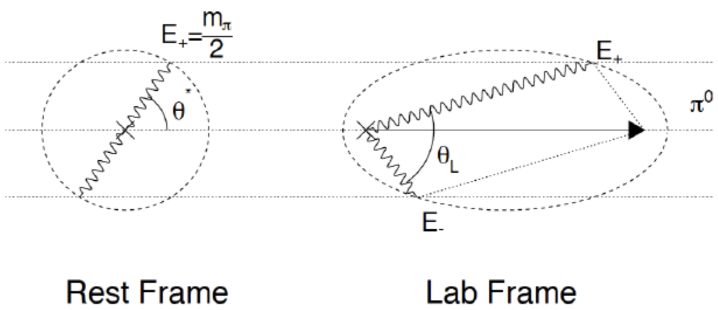



- **Background**
  - **Isolation from hadronic activity/jets**
  - **Discrimination of $\pi^0$ decay into two ɣ**



# FoCal – experimental challenges

## Opening angle between photons from $\pi^0$ decays:




$$\theta_L \sim \frac{2}{\gamma} \sim \frac{2m_\pi}{E_\pi} \sim \frac{2m_\pi}{p_T \cosh(\eta)}$$

**$\pi^0$ kinematic range:**
$1 < p_T < 20$ GeV/c
$3.4 < \eta < 5.8$

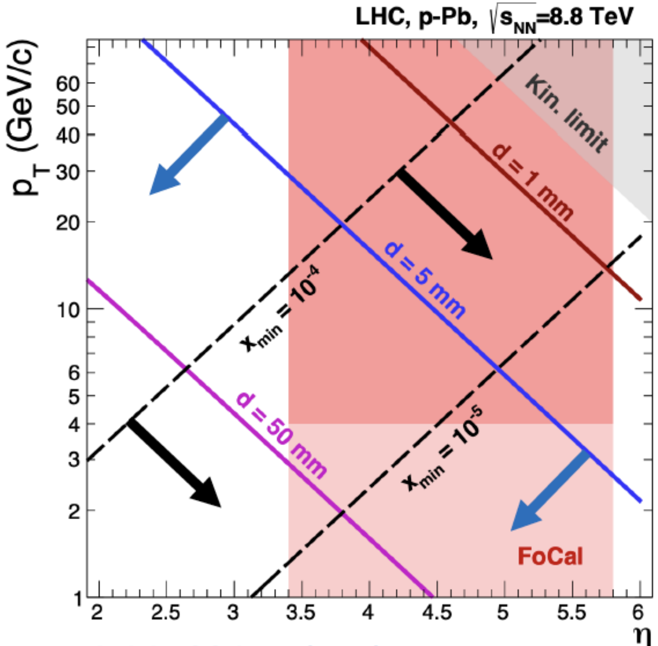
**At FoCal rapidities:**
$15 < E_\pi < 3300$ GeV
$0.005° < \theta_L < 1.25°$

**FoCal 7 m from IP:**
Distance between clusters
$0.06 < d_L < 15$ cm

**Dynamic range for clusters from ~10 GeV up to ~1 TeV.**
**Cluster separation down to mm scale.**

# FoCal – experimental challenges

## Summarizing kinematical targets (using $\pi^0$ decays):




LoI, LHCC-I-036 (2020)

Neutral pion decay:

$$\pi^0 \rightarrow \gamma + \gamma$$

Minimum cluster distance $d_{min}$

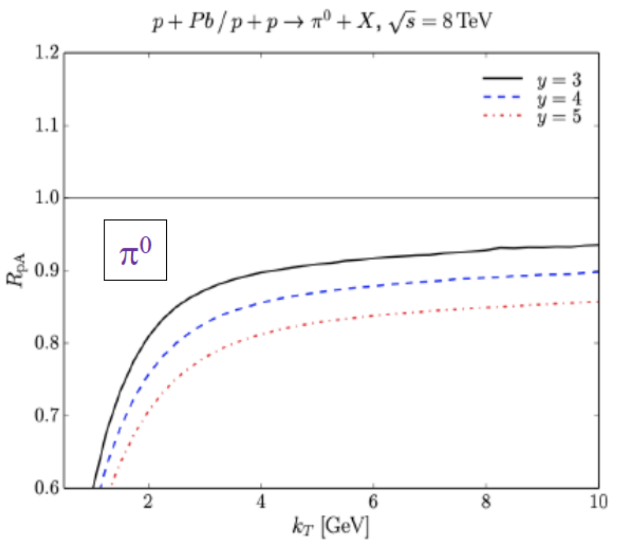
$$p_T < \frac{4\times(7\ \mathrm{m})}{d_{min}} m_\pi e^{-\eta}$$

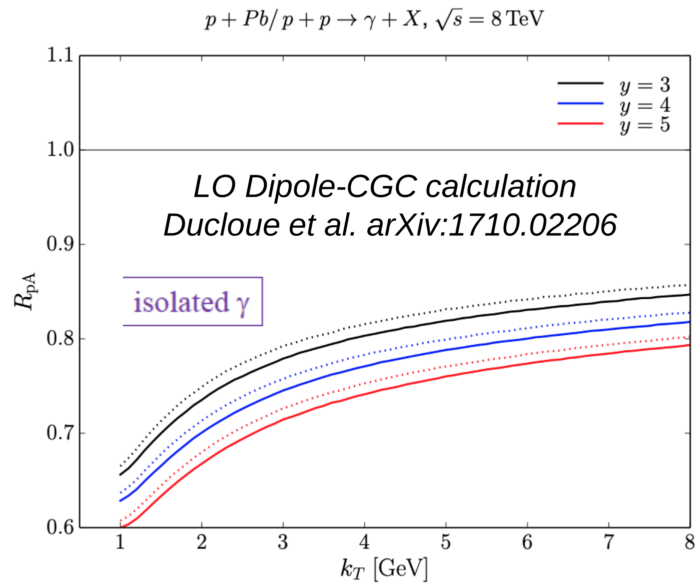
Desired $x$ –scale

$$p_T < \frac{x_{min}\sqrt{s}}{2} e^{+\eta}$$

# Direct photon production – the key observable

- $R_{pPb}$: forward $\pi^0$, $\gamma$



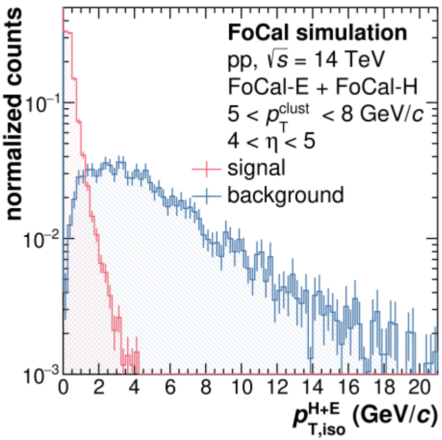




- Significant difference in low $p_T$ suppression between $\pi^0$ and direct $\gamma$
- Different production channels have different sensitivity to saturation
  - prompt photons directly produced in hard scattering qg -> $\gamma$q
  - sensitivity to gluon distribution and no strong interaction in final state
  - Direct photons: $k_T \sim Q_{sat}$ vs $\pi^0$: $p_T \gg Q_{sat}$

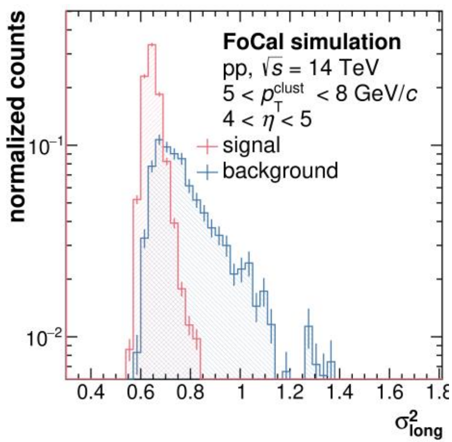
# Identifying direct photons with FoCal

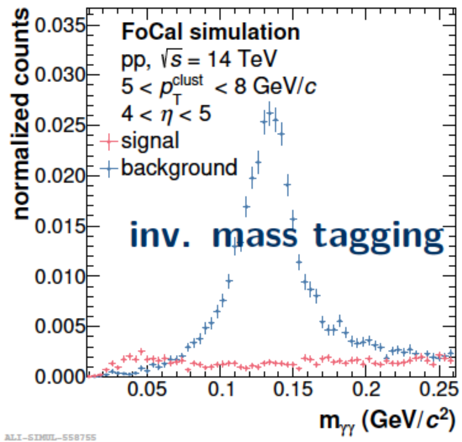
- measurement of isolation energy in FoCal-E and FoCal-H
- EM shower shape in 20 layers
- separation of showers from dominant neutral pion decay background

isolation



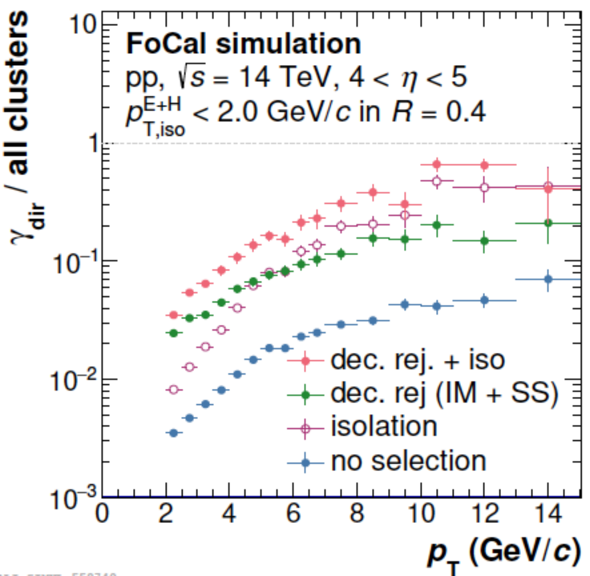

shower shape



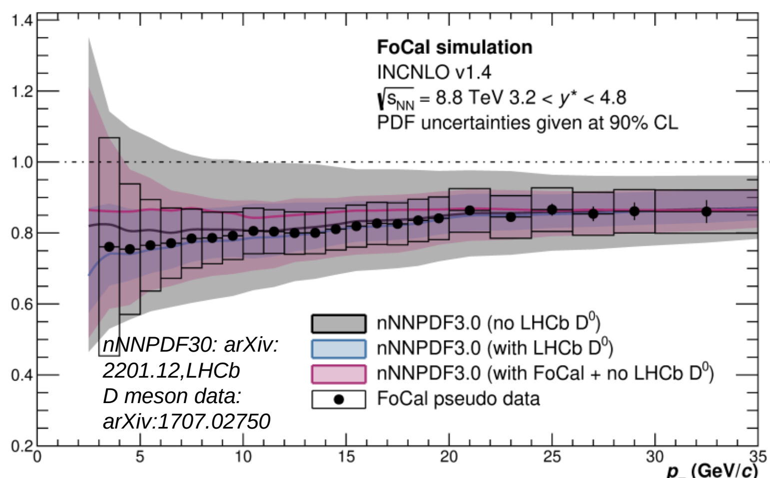



# Measurement of direct photon production

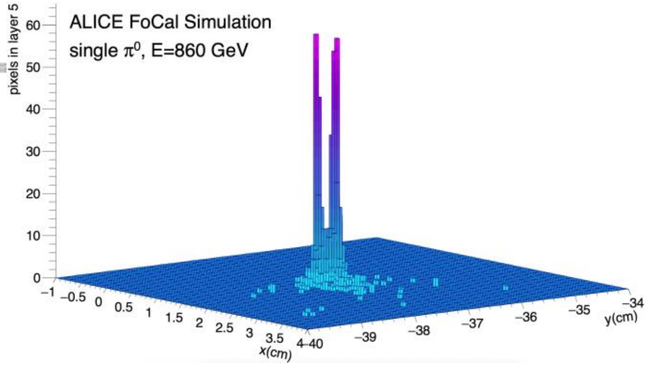
- isolation + shower shape selection + invariant mass tagging allow to increase signal fraction by about factor 11 up to 70% at $p_T$=14 GeV/c




- nPDF+NLO $R_{pA}$ re-weighted using FoCal pseudo data
- reduction of nNNPDF30 uncertainties similar to LHCb D mesons
- strong nPDF constraints at forward rapidities
- multi-messenger approach: different sensitivity to final state effects



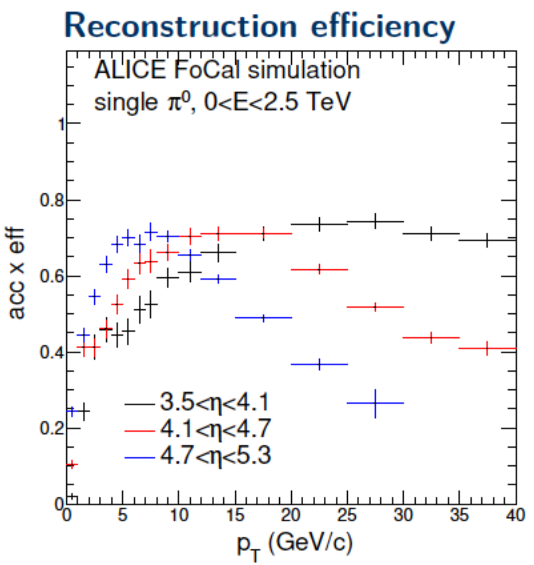
# Neutral meson measurements




- various studies using simulated data and FoCal geometry in GEANT demonstrate FoCal capabilities to measure neutral mesons

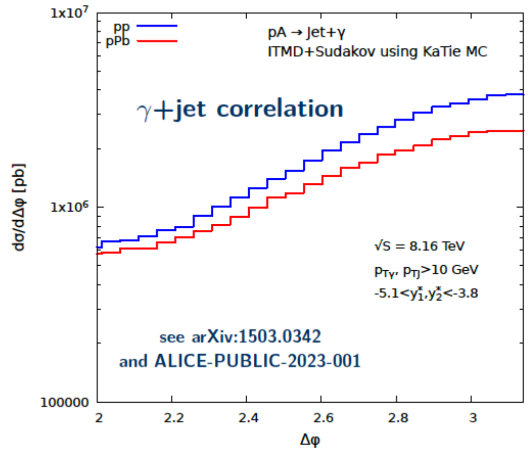
- expected luminosities for Run 4 sufficient to measure over a large energy range of up to 2 TeV, also differentially in rapidity

- highly granular pixel layers allow for efficiencies of up to 80%, even for a photon separation of < 5 mm!

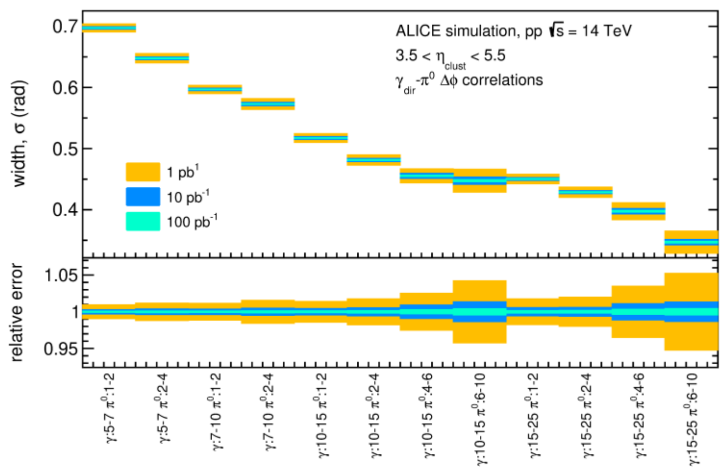


# Measurement of gamma-hadron correlation

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



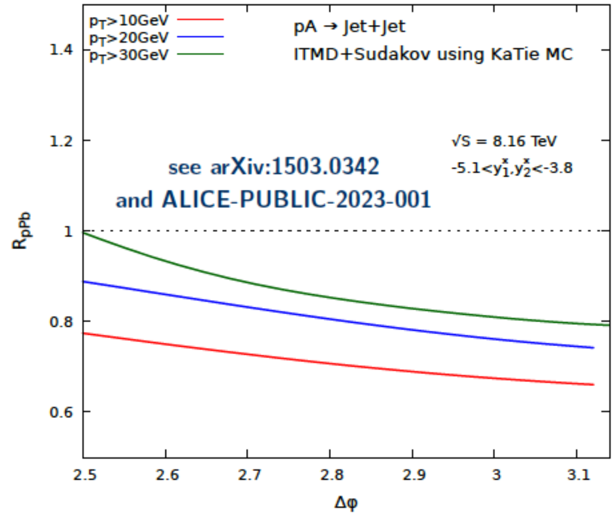

- **FoCal performance**
  - **correlation peak can be measured precisely**
  - **stat. uncertainties of peak width 0.001 rad for expected Run 4 luminosities**
  - **differential measurement feasible in significant number of trigger bins**

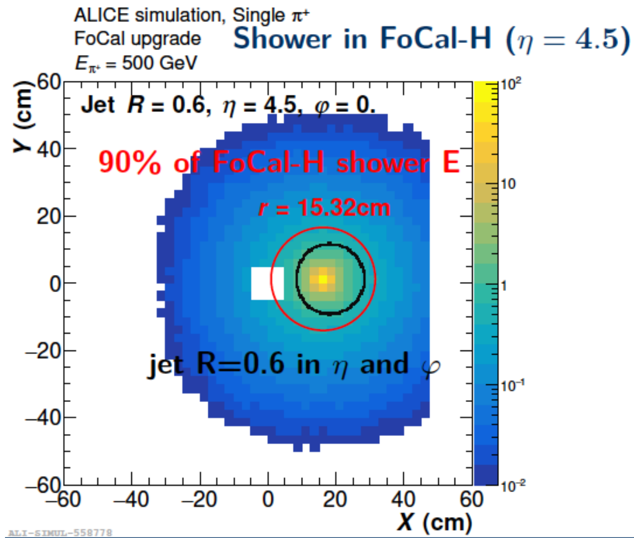


# Jet measurements

- **Jets**
  - **forward incl. jet, gamma+jet and dijet production sensitive to gluon saturation**
  - **dijet especially interesting -> 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 1-2 cm, interaction length FoCal-H 15-20 cm**



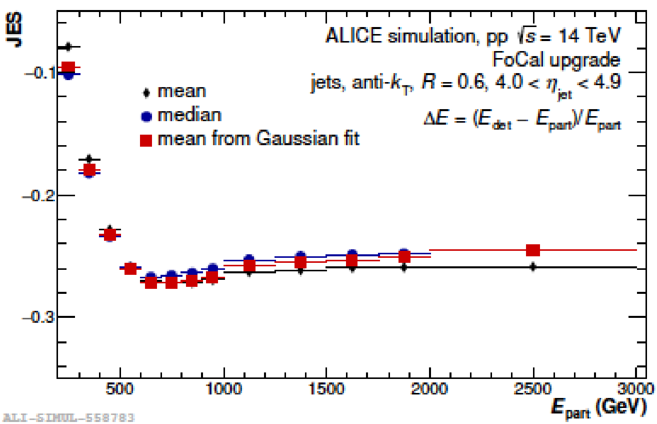



# Jet measurements

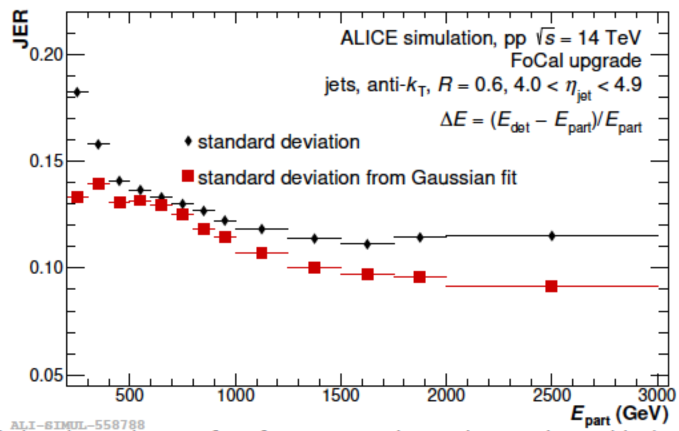
- **Pythia + GEANT studies to quantify FoCal performance for R = 0.6 anti-k$_T$ jets**

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

Jet Energy Scale = mean of $\Delta E$




Jet Energy Resolution = width of $\Delta E$



# Ultra-Peripheral Collisions with FoCal

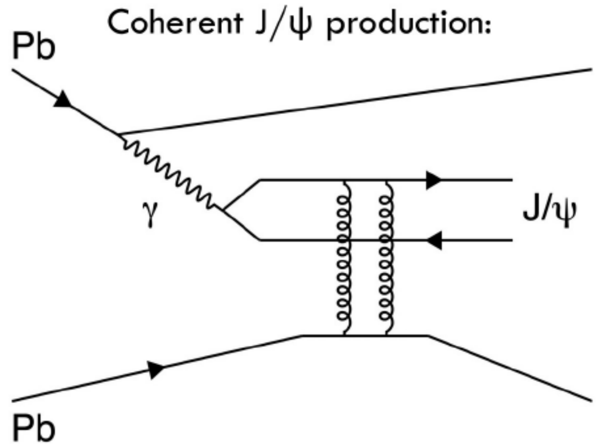
- **Quarkonia (J/ψ, ψ') photoproduction in p-Pb and Pb-Pb collisions**

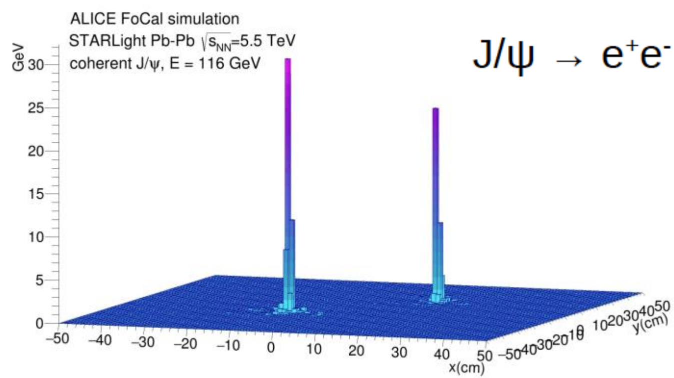
  - UPCs at the LHC probe the hadronic structure over a wide Bjorken-*x* region, **down to $10^{-6}$**

  - **Extension of photon-Pb and photon-proton cross-sections to very high and very low c.m. energy:**

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

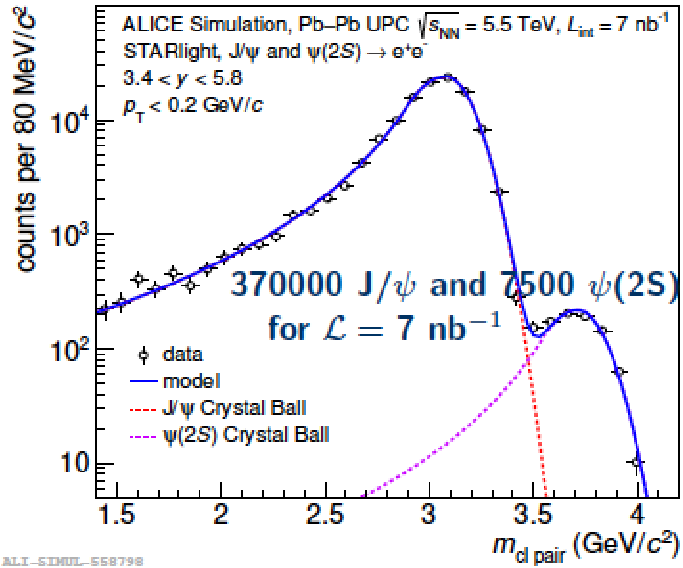
  - **Access to gluon distribution and saturation**



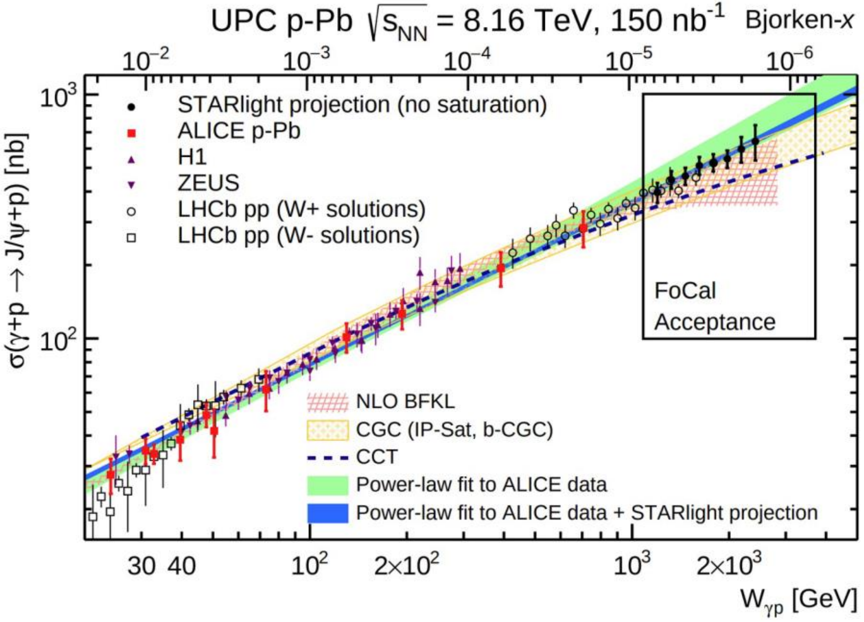
# Vector meson photo-production in UPC

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



# Vector meson photo-production in UPC

- **Photoproduction off protons σ(γ+p) at high-W**
  - **photo-production cross section of vector mesons (e.g. J/psi) in ultra-peripheral collisions is proportional to squared gluon density**

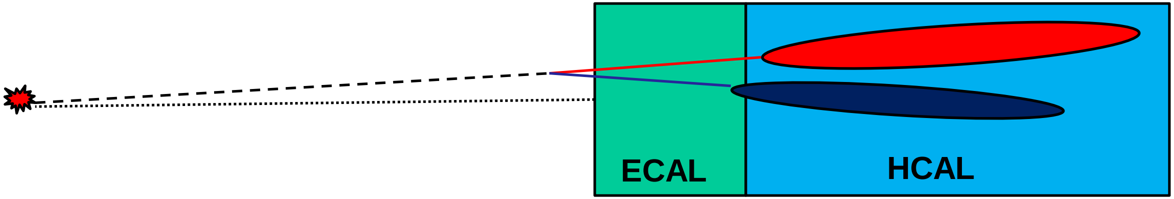



  - **deviation from power-law growth of cross section with increasing $W_{\gamma p}$ expected due to saturation effects**

# Λ-production at forward rapidities

- Detection of $\Lambda + \bar{\Lambda}$ with FoCal

Λ-decay: $\Lambda \rightarrow p + \pi^-$



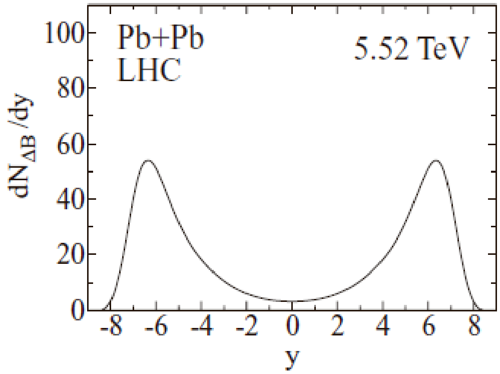

  - Charged decay
    - Proton and pion tracking in ECAL -> reconstruction of secondary vertex
    - Position and energy of proton and pion shower in HCAL
  - Neutral decay
    - Position, direction and energy of neutral pion shower in ECAL
    - Position and energy of neutron shower in HCAL

- Baryon stopping
- Λ-polarisation

# Baryon transport

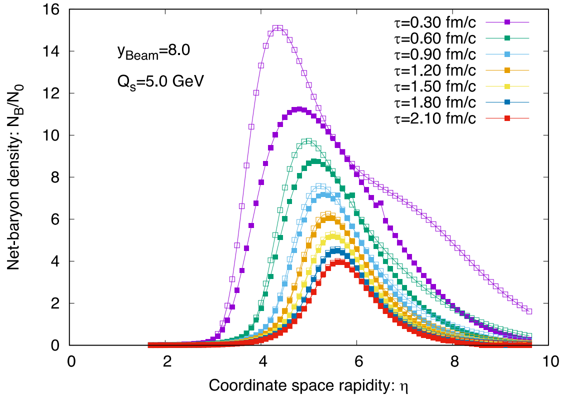
- **Stopping**
  - **quark di-quark (q−qq) string fragmentation and/or junction anti-junction loops?**
  - **Saturation models**
    - **net-baryon fragmentation peak position**

Y. Mehtar-Tani and G. Wolschin, Phys. Rev. C80, (2009) 054905



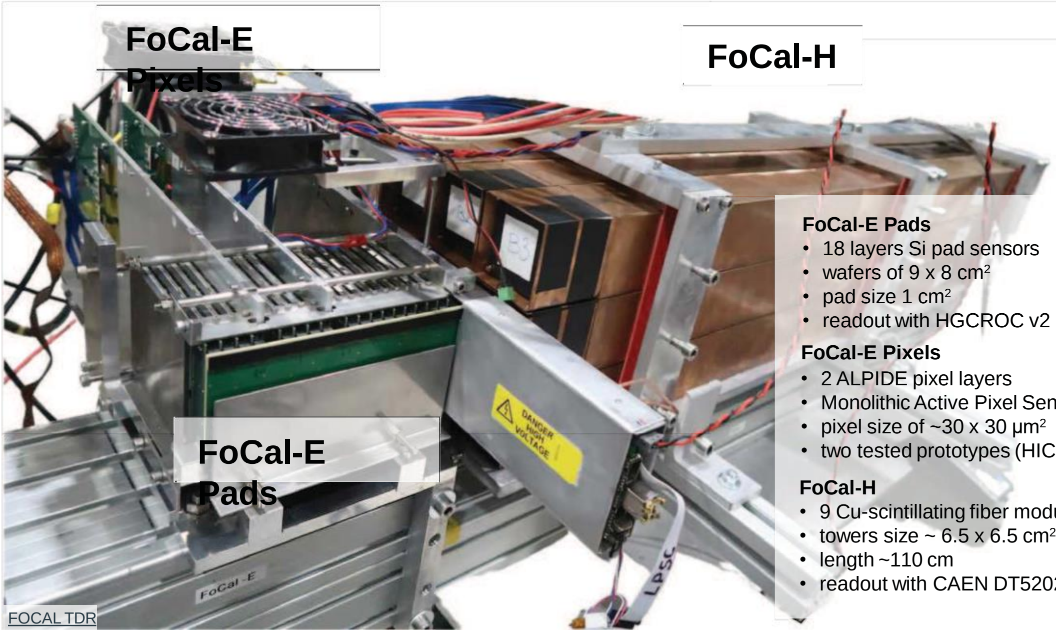

    - **baryon density at forward eta**

L. McLarren, S. Schlichting, S. Sen, arXiv:1811.04089 (2018)




**-> gluon saturation scale**

# FoCal prototypes and 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$^2$
- two tested prototypes (HIC,pCT)

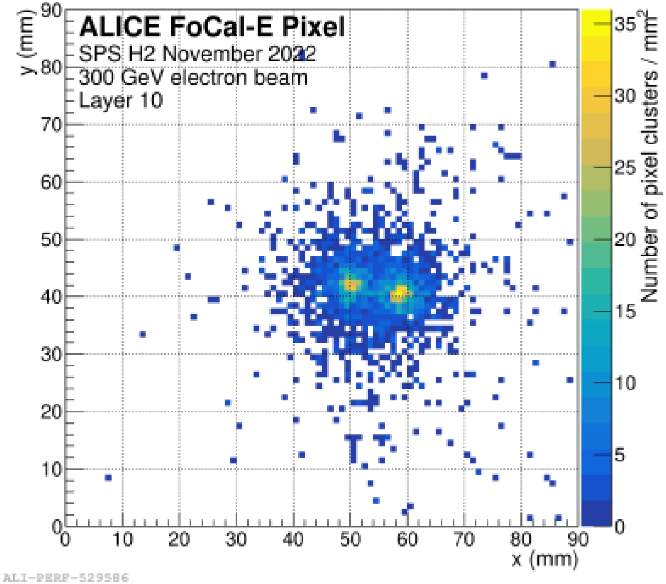
**FoCal-H**
- 9 Cu-scintillating fiber modules
- towers size ~ 6.5 x 6.5 cm$^2$
- length ~110 cm
- readout with CAEN DT5202

ALI-PERF-569144

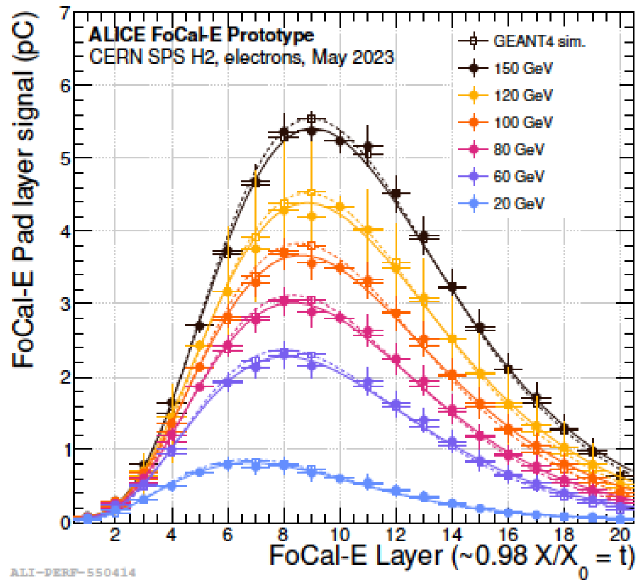
FOCAL TDR

# FoCal prototypes and test beam results – FoCal-E

Shower separation in FoCal-E pixels




Longitudinal shower profile in FoCal-E

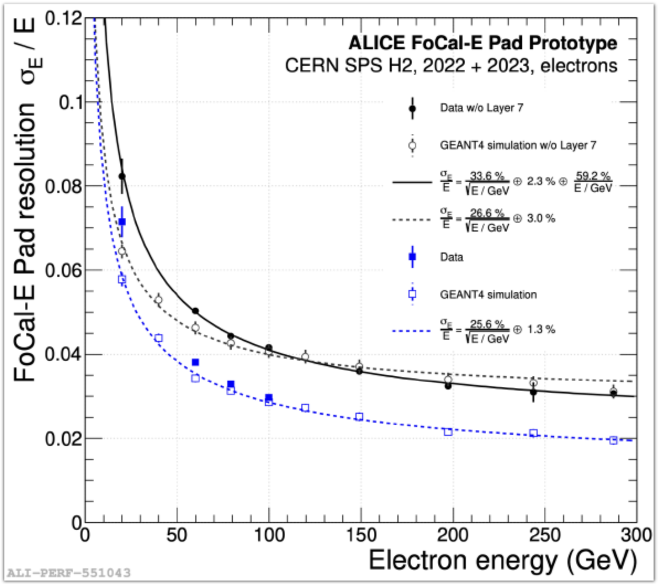


# FoCal prototypes and test beam results – FoCal-E

## Prototype performance

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/GeV}} \oplus b \oplus \frac{c}{E/GeV}$$

**FoCal-E measured resolution**




- **May 2023 Test beam:**
  - $\frac{\sigma_E}{E} < 3\%$ for Energies > 100 GeV
  - 120, 150 GeV not included in fit
  - $\frac{\sigma_E}{E} = \frac{25.6\%}{\sqrt{E/GeV}} \oplus 1.3\%$

Data

- **Nov 2022 (w/o layer 7) Test beam :**
  - $\frac{\sigma_E}{E} < 4$ % for Energies > 100 GeV
  - $\frac{\sigma_E}{E} = \frac{33.6\%}{\sqrt{E/GeV}} \oplus \frac{59.2\%}{E/GeV} \oplus 2.3\%$

Data w/o Layer 7

| Dataset | $\sigma_{stoch.}$ (%) | $\sigma_{const.}$ (%) | $\sigma_{noise}$ (%) | $\chi^2$ | n.d.f. |
|---|---|---|---|---|---|
| Data w/o L7 | $33.6 \pm 1.4$ | $2.27 \pm 0.10$ | $59.20 \pm 35.3$ | 4.4 | 5 |
| GEANT4 simulation w/o L7 | $26.6 \pm 0.9$ | $2.98 \pm 0.13$ | - | 4.6 | 8 |
| GEANT4 simulation w L7 | $25.6 \pm 0.5$ | $1.27 \pm 0.10$ | - | 5.5 | 8 |

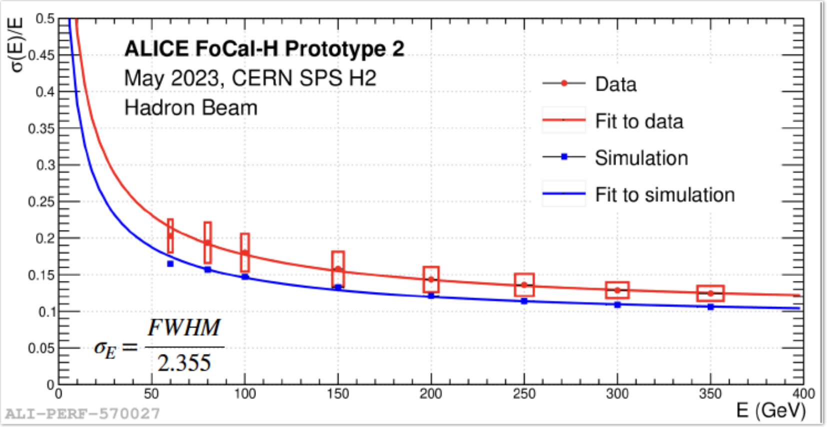
Performance of the electromagnetic and hadronic prototype segments of the ALICE Forward Calorimeter

# FoCal prototypes and test beam results – FoCal-H

## Prototype performance

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/GeV}} \oplus b \oplus \frac{c}{E/GeV}$$

**FoCal-H measured resolution**




| Systematic effect | $\Delta\sigma_{\text{stoch.}}$ | $\Delta\sigma_{\text{const.}}$ |
|---|---|---|
| Fit range | 0.02 | 0.001 |
| Line shape | 0.10 | 0.005 |
| HG-LG matching | 0.05 | 0.003 |
| Gain choice | 0.20 | 0.002 |
| Global energy scale | 0.04 | 0.003 |
| Total (added in quadrature) | 0.22 | 0.007 |

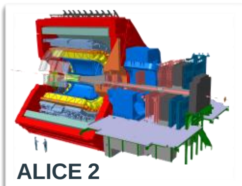
**Resulting parameters:**

- $\sigma_{stoch.} = (148 \pm 2_{stat} \pm 22_{syst})\ \%$
- $\sigma_{const.} = (10.0 \pm 0.13_{stat} \pm 0.7_{syst})\ \%$
- $\sigma_{noise}$ compatible with 0

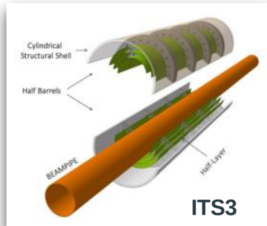
- Results compared with simulations
  - channel-by-channel light Coll. Efficiency spread
  - resolution < 20 % for hadrons > 60 GeV
  - resolution ~10 % for hadrons > 150 GeV

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

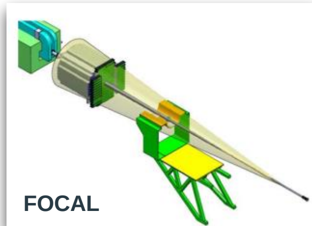
# ALICE Upgrade Roadmap



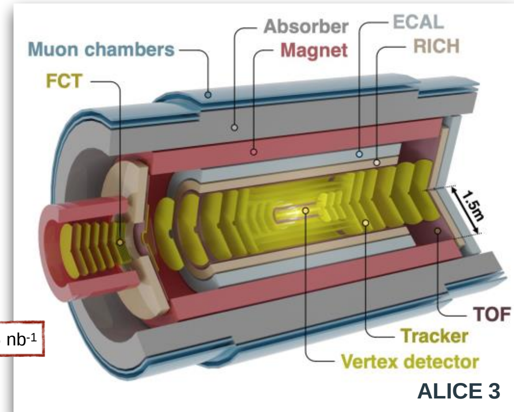

Pb-Pb: 6.2 $nb^{-1}$
O-O: 500 $\mu b^{-1}$




Pb-Pb: 6.8 $nb^{-1}$
p-Pb: 0.6 $pb^{-1}$




Pb-Pb: ~ 35 $nb^{-1}$




# This is the end