

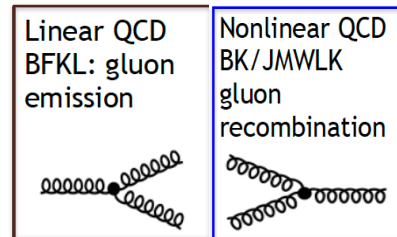
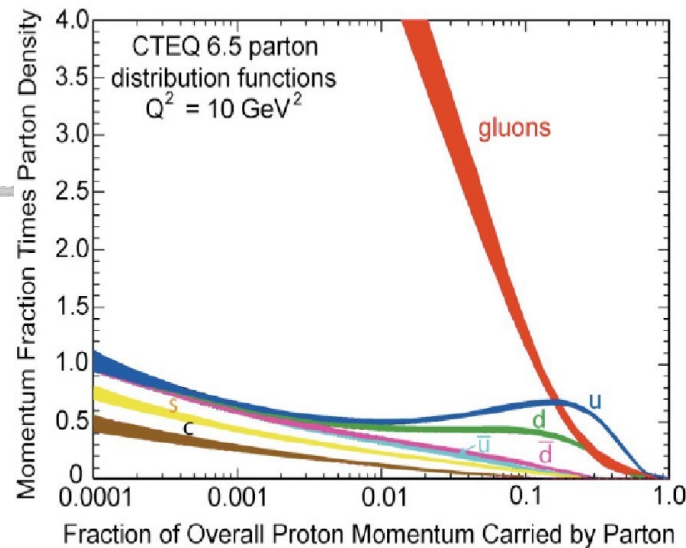
Quarkonium measurements with the Forward Calorimeter in ALICE

Dieter Roehrich
University of Bergen

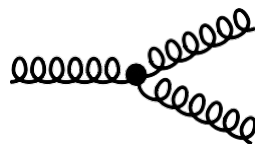


Parton Distribution Function

- 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

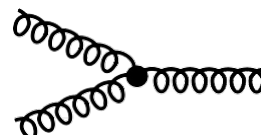


gluon emission



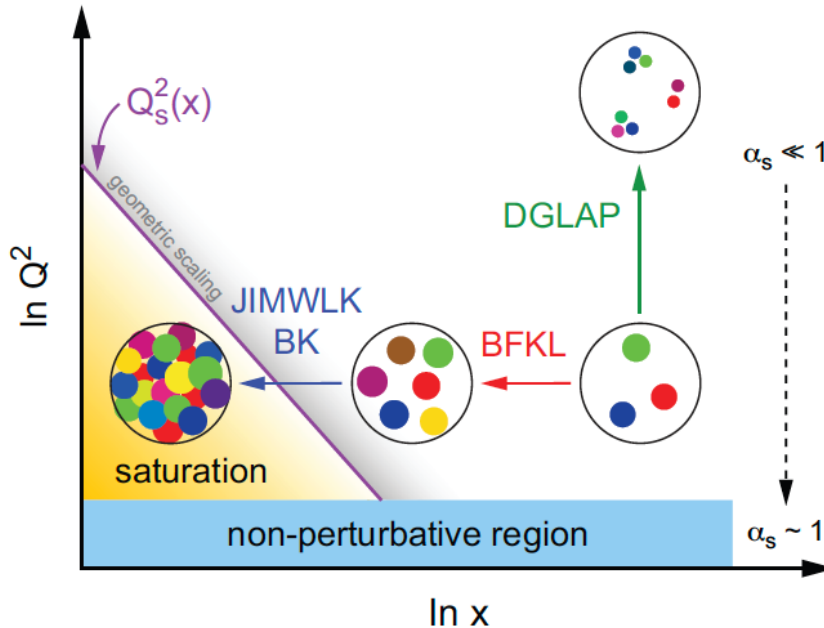
=

gluon recombination



Gluon saturation

- Onset of saturation effects: saturation scale Q_s^2



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

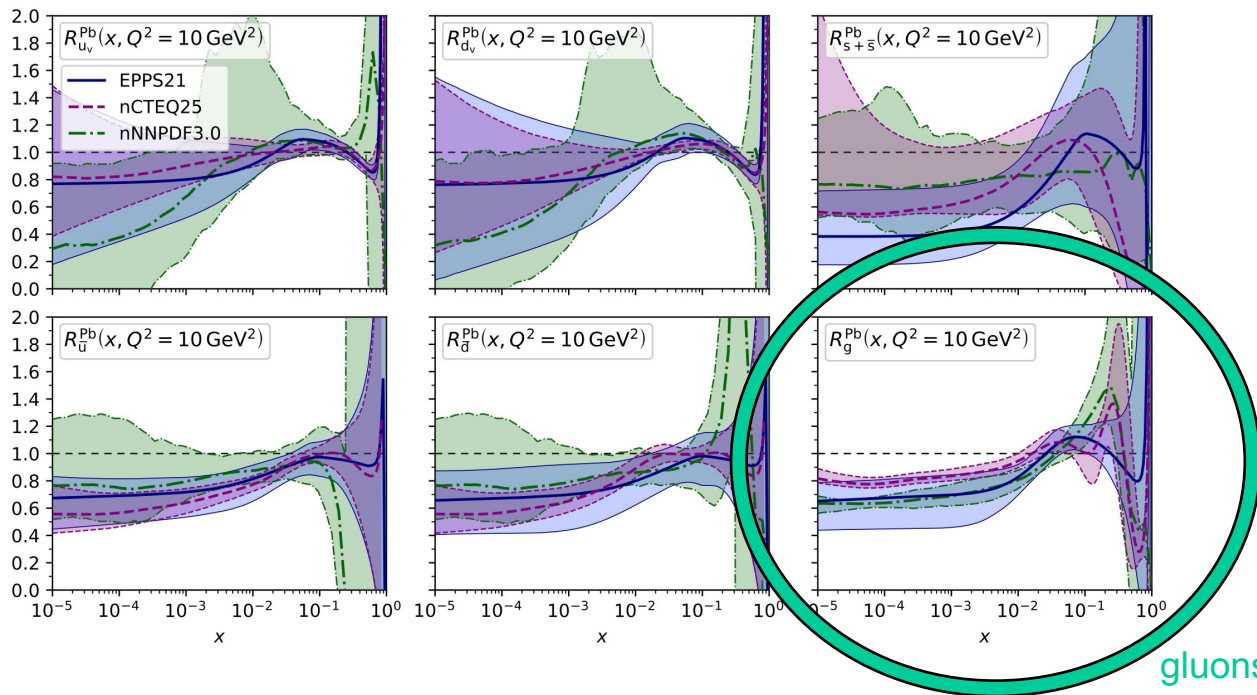
- The effective theory to describe this saturated gluon field:
Color Glass Condensate (CGC)

Nuclear PDFs

- Nuclear PDFs for Pb – state-of-the-art

A. Kusina, IS 2025

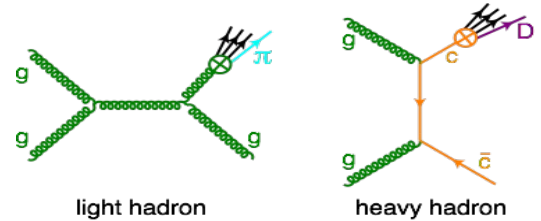
Nuclear modification for lead



A probe for gluon density – direct photons

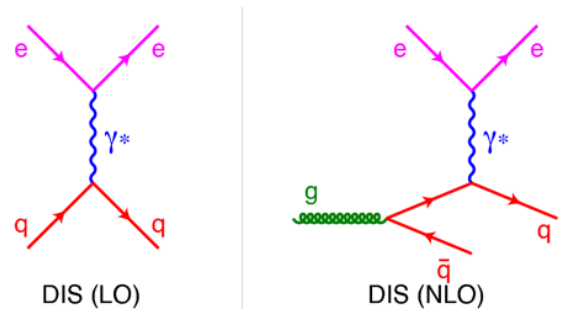
- **Hadronic observables**

- interpretation inconclusive

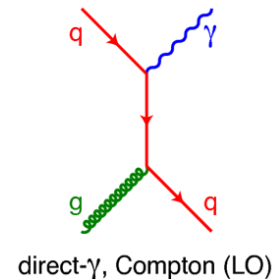


- **Electromagnetic probes**

- Deep-Inelastic Scattering (DIS)
 - » classical PDF method
 - » not sensitive to gluons at LO
 - » gluons from NLO



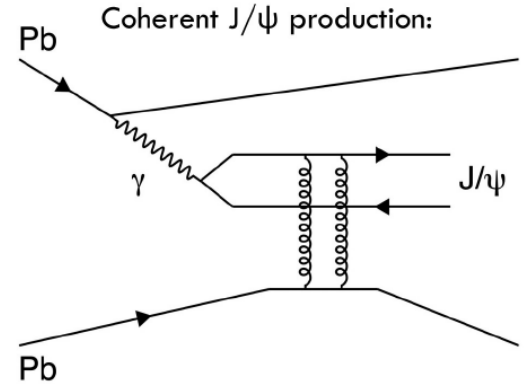
- Photon production in hadronic collisions
 - » sensitive to gluons at LO



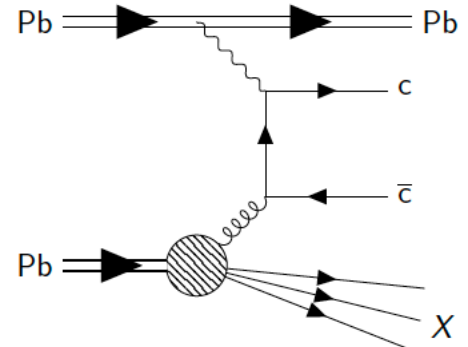
Probes for gluon density - UPCs

- UPCs

- Photoproduction of vector mesons

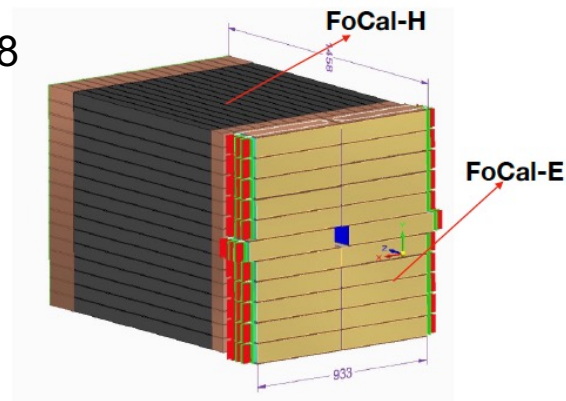
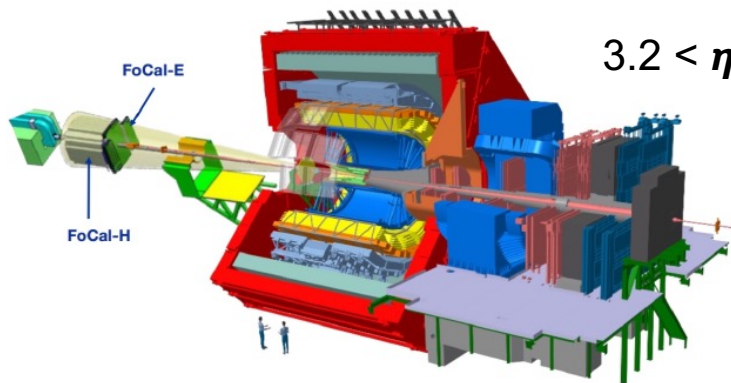


- Charm production in photonuclear interactions



- ...

The Forward Calorimeter - FoCal

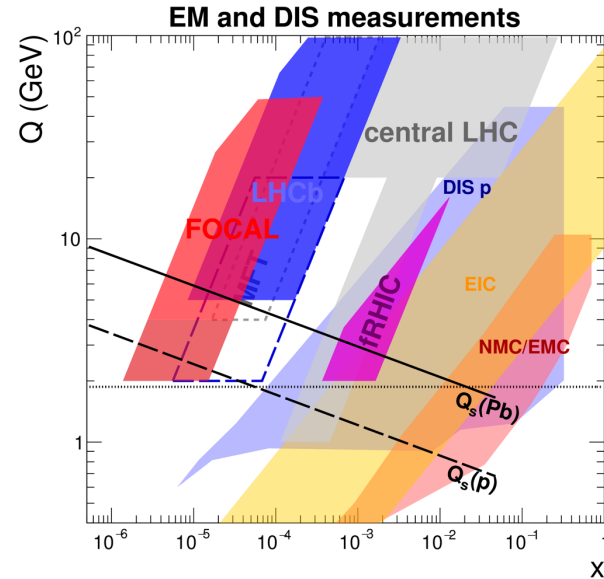


LHC Run 4 - 2030-2033

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

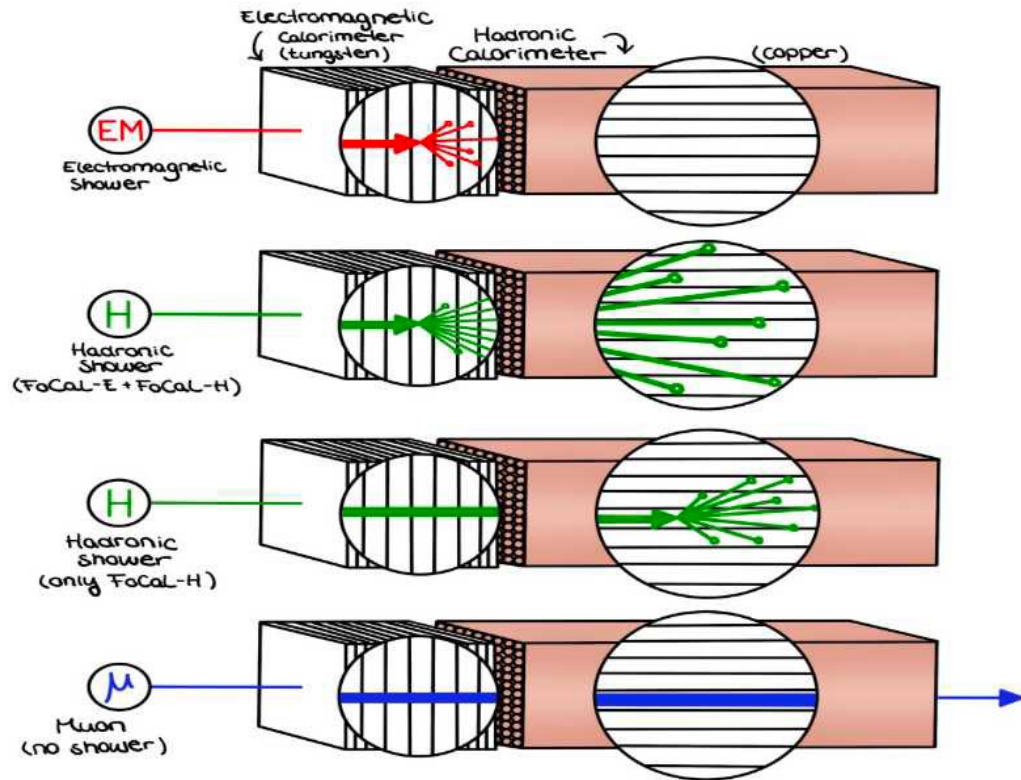
- **Main physics goal:**
Explore non-linear QCD in regime of saturated gluons at low Bjorken- x and constrain nPDFs
- **FoCal capabilities allow explorations of gluon saturation using a multi-messenger approach:**
 - prompt photon production
 - γ -hadron correlations
 - production of π^0 and η vector 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

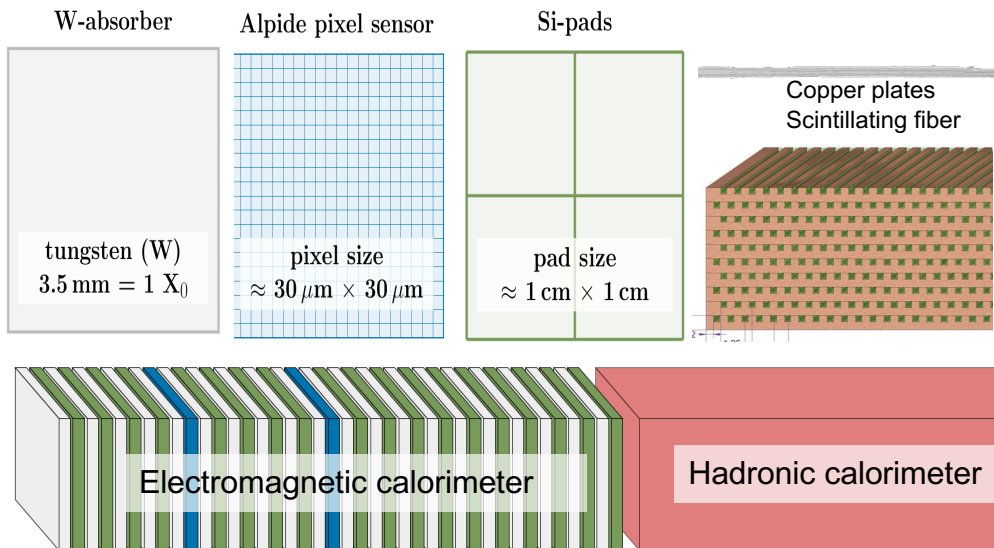
The Forward Calorimeter - FoCal

ECAL: sandwich/shashlik type - HCAL: spaghetti type



- sampling calorimeter

FoCal design



• FoCal-E (electromagnetic):

- **high-granularity Si-W sampling calorimeter combining two readout granularities:**
 - 18 pad layers with silicon pads ($1 \times 1 \text{ cm}^2$)
 - two pixel layers with digital readout (ALPIDE)
- ability to “track” showers
- used to measure photons and π^0

• 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.

FoCal – experimental challenges

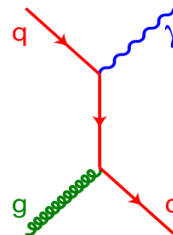
- **Signal**

- Single isolated photons at forward rapidity

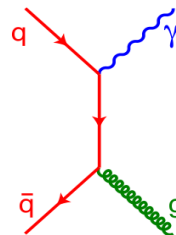
- **Background**

- Isolation from hadronic activity/jets

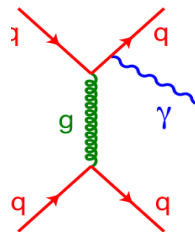
- Discrimination of π^0 decay into two γ



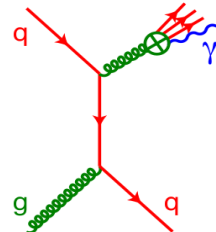
a) Compton



b) annihilation

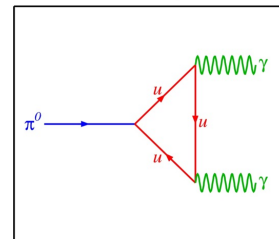


bremsstrahlung



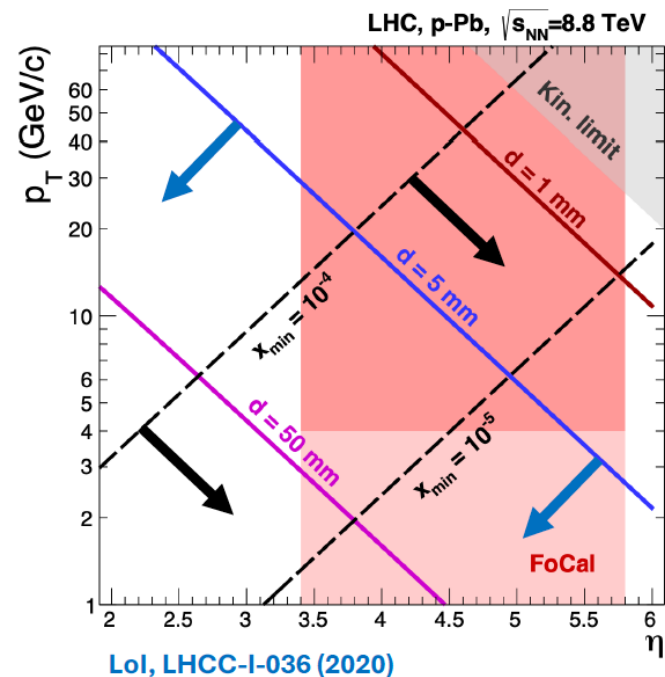
d) fragmentation

π^0 Decay



FoCal – experimental challenges

Summarizing kinematical targets (using π^0 decays):



Neutral pion decay:

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

Minimum cluster distance d_{min}

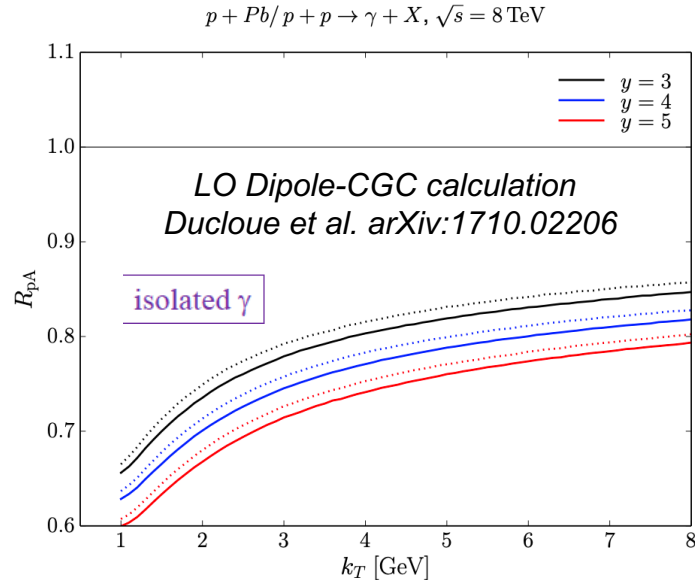
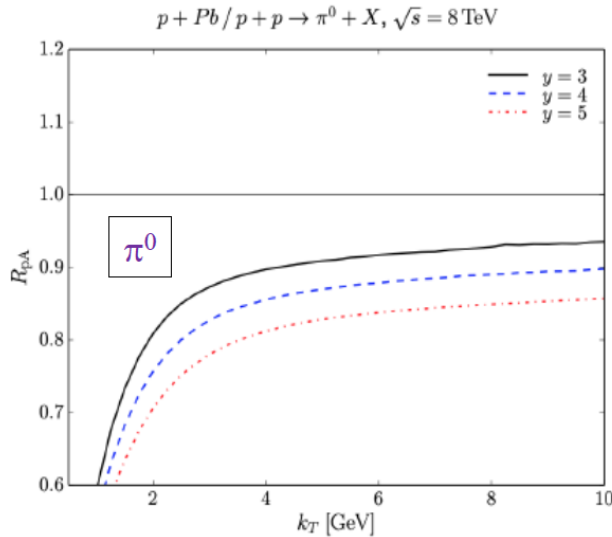
$$p_T < \frac{4 \times (7 \text{ m})}{d_{min}} m_\pi e^{-\eta}$$

Desired x-scale

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

Direct photon production – the key observable

- R_{pPb} : forward π^0 , γ

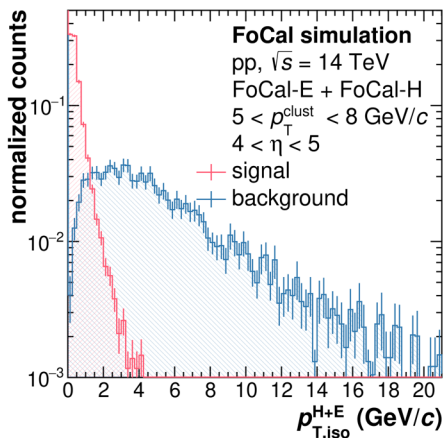


- Significant difference in low p_T suppression between π^0 and direct γ
- Different production channels have different sensitivity to saturation
 - prompt photons directly produced in hard scattering $qg \rightarrow \gamma q$
 - sensitivity to gluon distribution and no strong interaction in final state

Identifying direct photons with FoCal

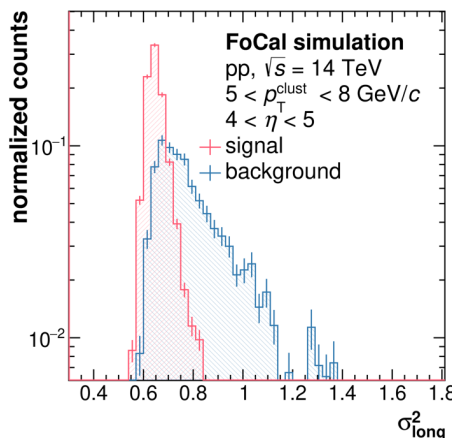
- measurement of isolation energy in FoCal-E and FoCal-H

isolation

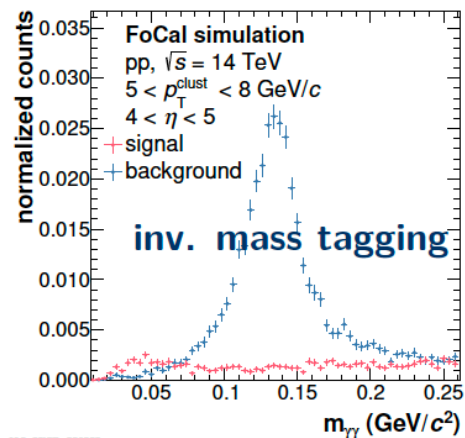


- EM shower shape in 20 layers

shower
shape

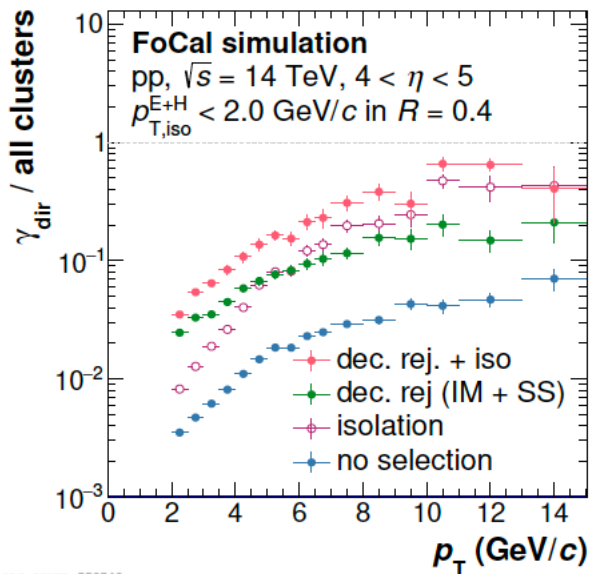


- separation of showers from dominant neutral pion decay background

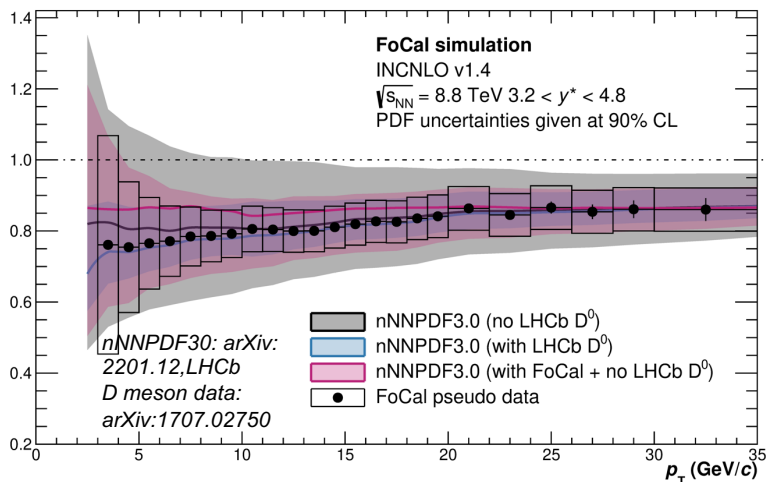


Measurement of direct photon production

- 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

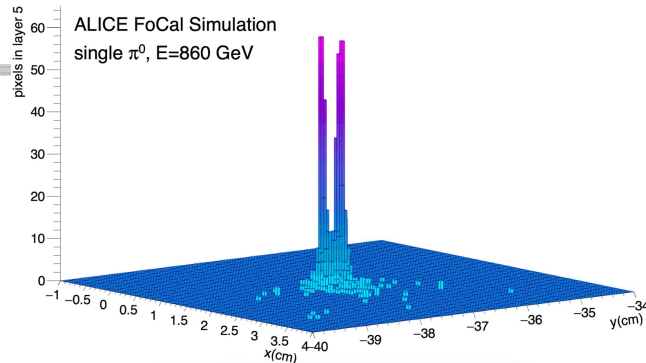


- nPDF+NLO R_{pA} re-weighted using FoCal pseudo data
- reduction of nNNPDF30 uncertainties similar to LHCb D mesons
- strong nPDF constraints at forward rapidities
- multi-messenger approach: different sensitivity to final state effects

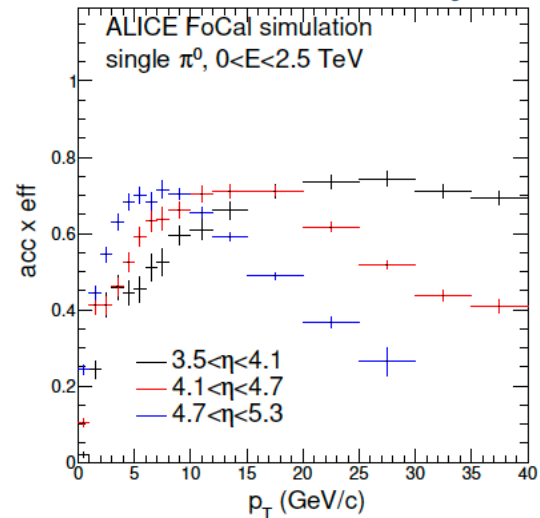


Neutral meson measurements

- 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!

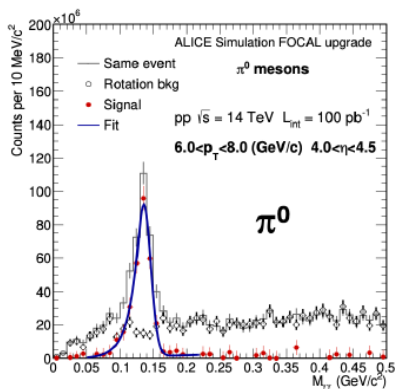


Reconstruction efficiency

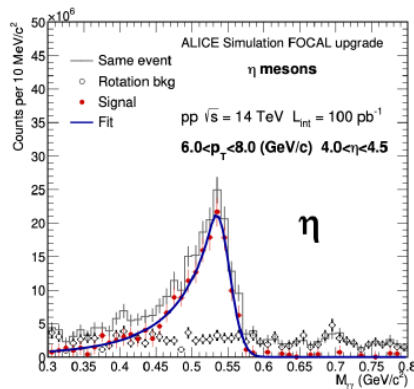


Neutral meson measurements

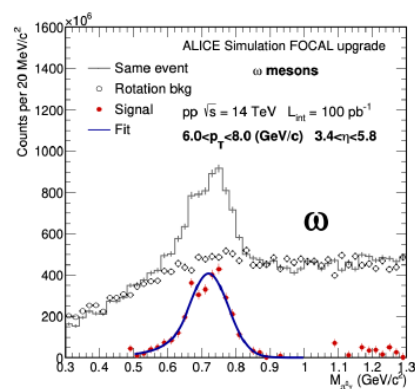
• Invariant mass distributions



ALICE-SIMUL-558948



ALICE-SIMUL-558953



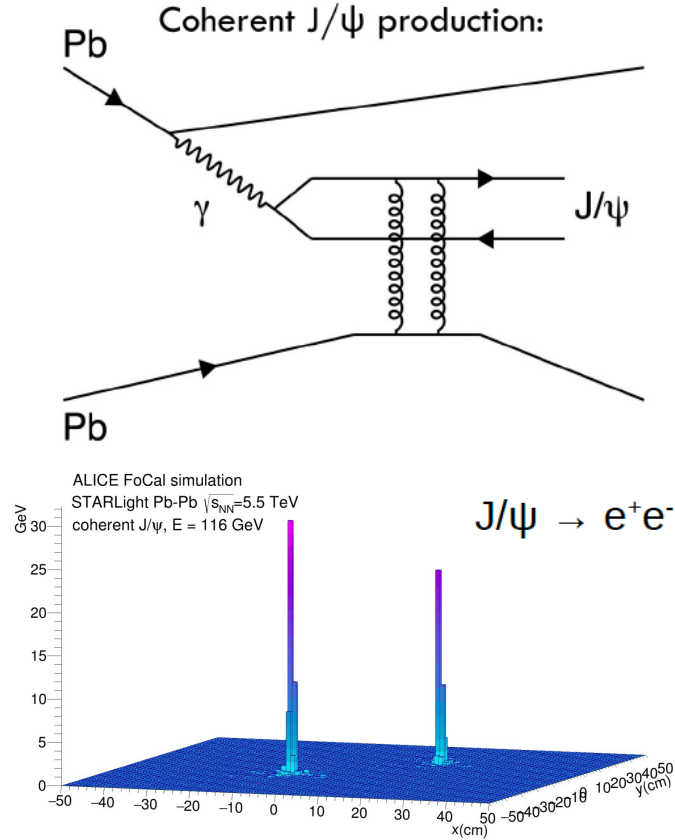
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Prospects of J/Ψ measurements

- **UPC**
- **pp**

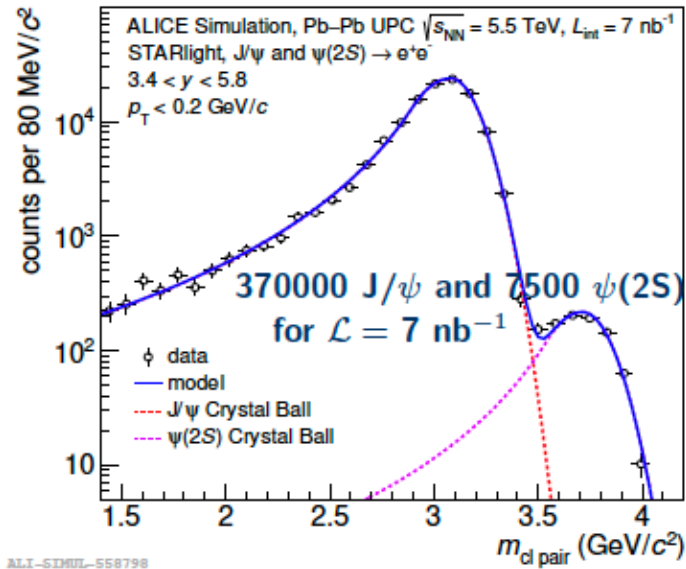
Ultra-Peripheral Collisions with FoCal

- 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:
- $$W_{\gamma p}^2 = 2E_p M_{J/\psi} e^{\pm y}$$
- 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/ψ

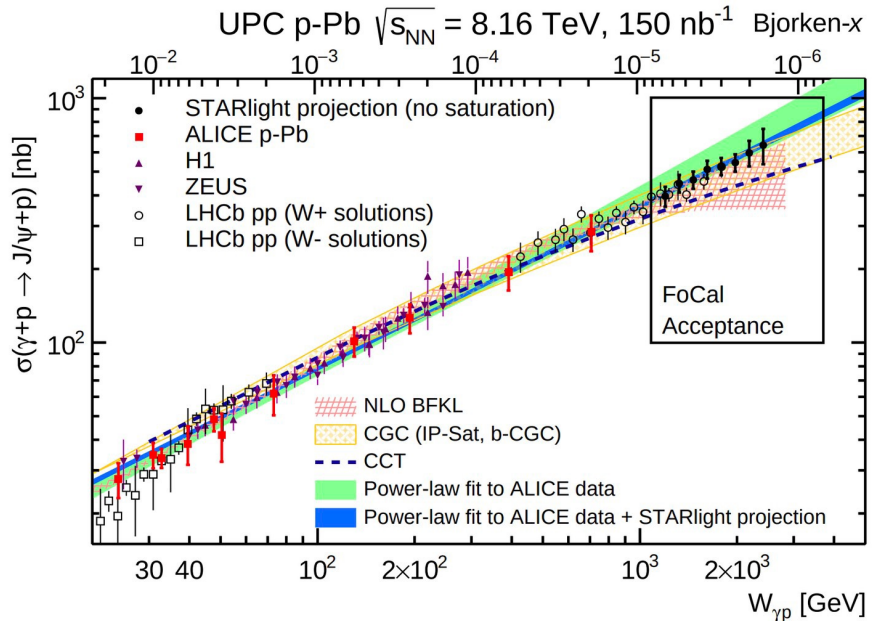


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Vector meson photo-production in UPC

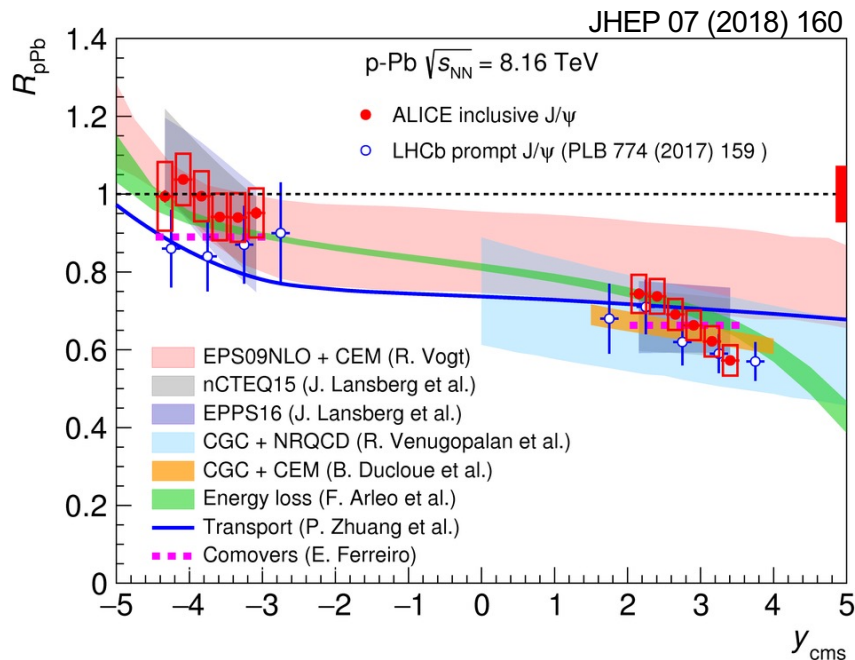
- Photoproduction off protons $\sigma(\gamma p)$ at high- W

- 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

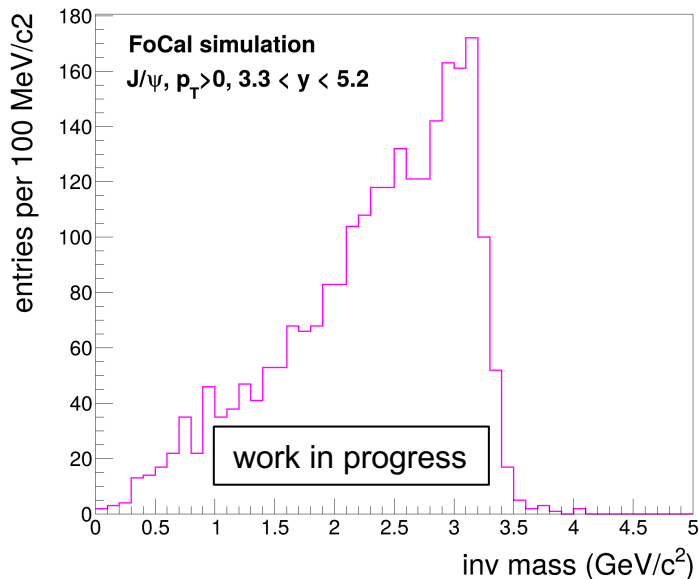
J/ψ - nuclear modification factor in pPb



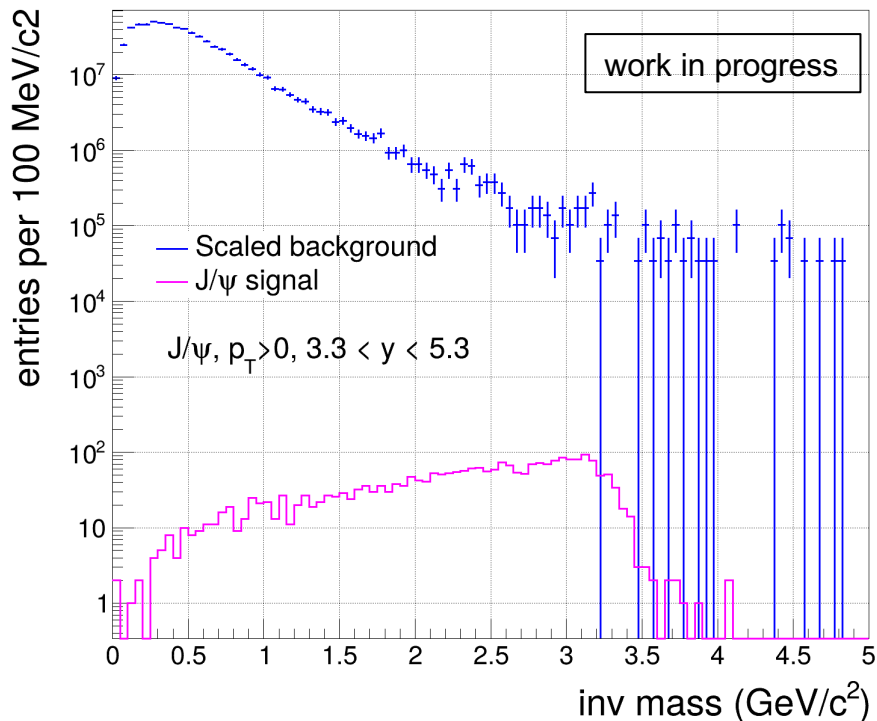
- Data at $y=5$ will allow to distinguish different scenarios/models

J/ Ψ invariant mass distribution - pp

- **Signal shape**
 - Full simulation (Pythia + GEANT) and reconstruction

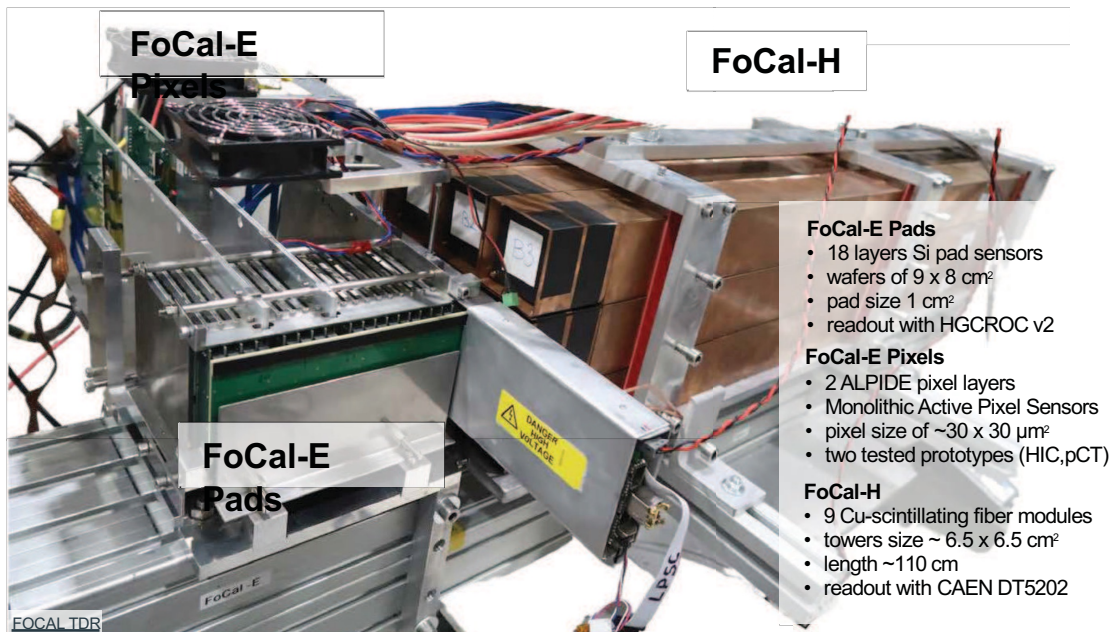


J/ψ invariant mass distribution - pp



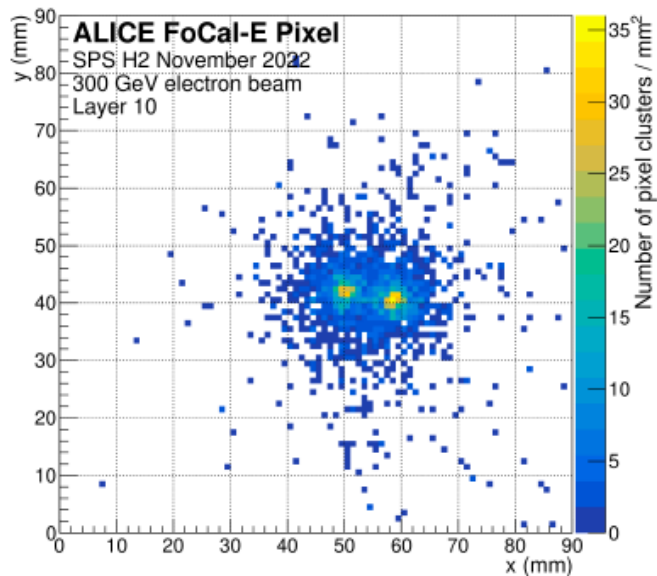
- **Combinatorial background**
 - Mainly due to π^0 decays
 - Background reduction strategy: identify pion decay candidates and remove them from the shower list

FoCal prototypes and test beam results



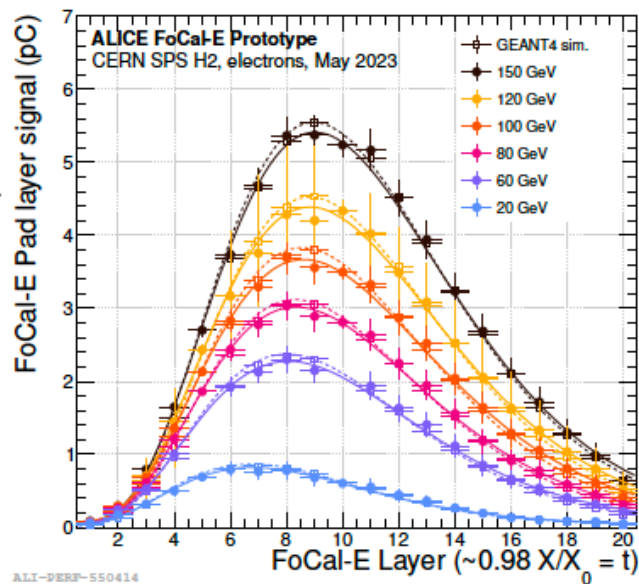
FoCal prototypes and test beam results – FoCal-E

Shower separation in FoCal-E pixels



ALI-CONF-529586

Longitudinal shower profile in FoCal-E



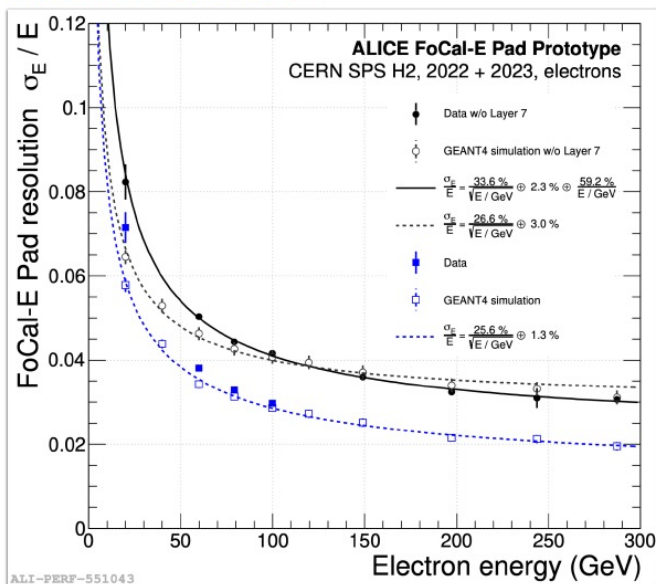
ALI-CONF-550414

FoCal prototypes and test beam results – FoCal-E

Prototype performance



FoCal-E measured resolution



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

• May 2023 Test beam:

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

Data

• Nov 2022 (w/o layer 7) Test beam :

- $\frac{\sigma_E}{E} < 4\%$ for Energies > 100 GeV
- $\frac{\sigma_E}{E} = \frac{33.6\%}{\sqrt{E/\text{GeV}}} \oplus \frac{59.2\%}{E/\text{GeV}} \oplus 2.3\%$

Data w/o Layer 7

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

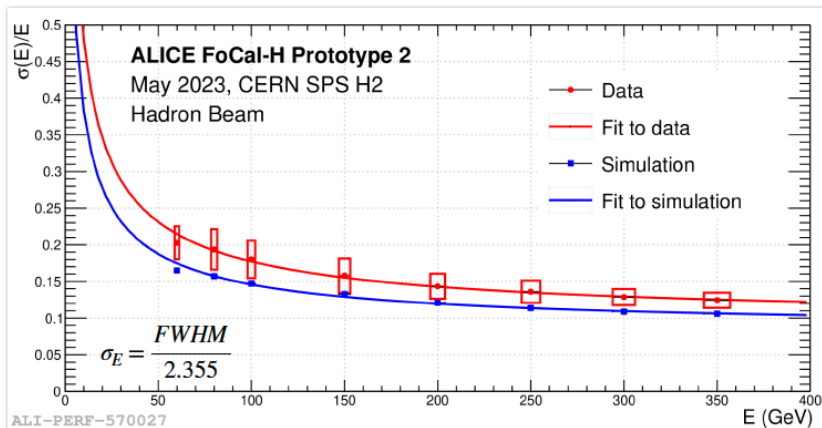
FoCal prototypes and test beam results – FoCal-H



Prototype performance

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

FoCal-H measured resolution



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

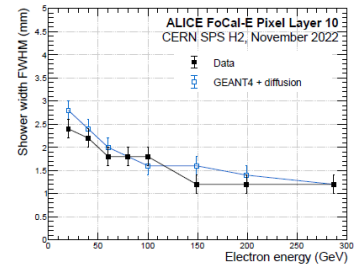
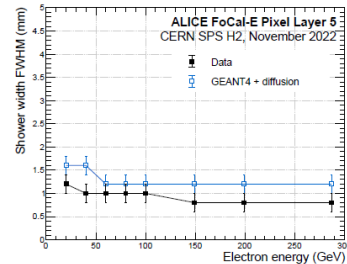
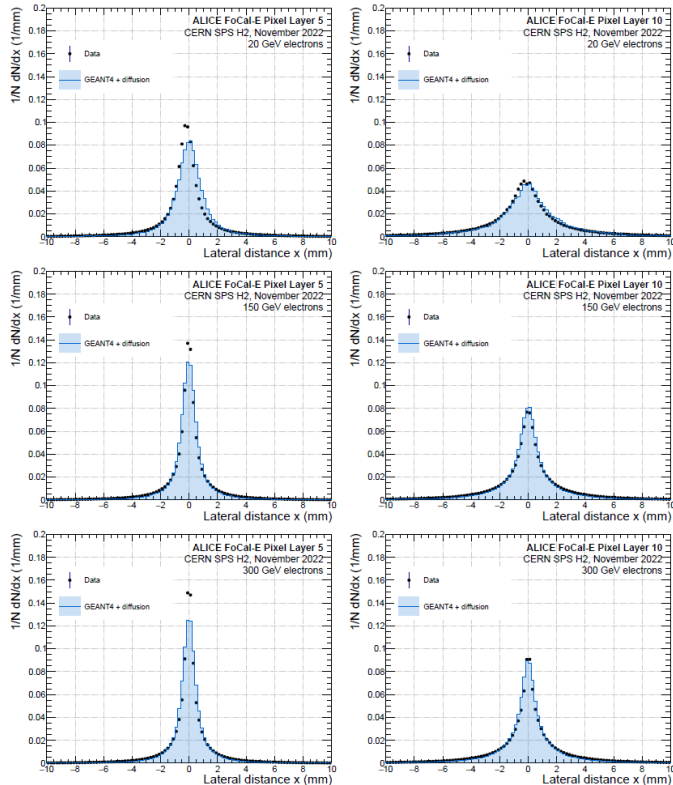
Systematic effect	$\Delta\sigma_{\text{stoch.}}$	$\Delta\sigma_{\text{const.}}$
Fit range	0.02	0.001
Line shape	0.10	0.005
HG-LG matching	0.05	0.003
Gain choice	0.20	0.002
Global energy scale	0.04	0.003
Total (added in quadrature)	0.22	0.007

Resulting parameters:

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

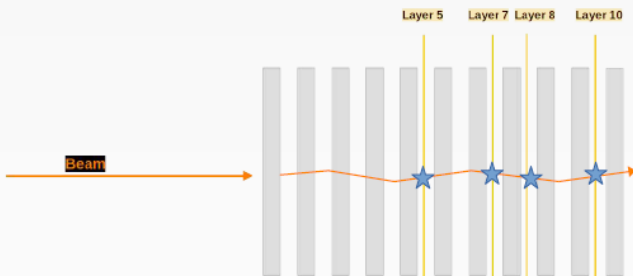
Shower separation

- Lateral shower profiles
 - narrow core + long tails
 - ~1-2 mm shower separation

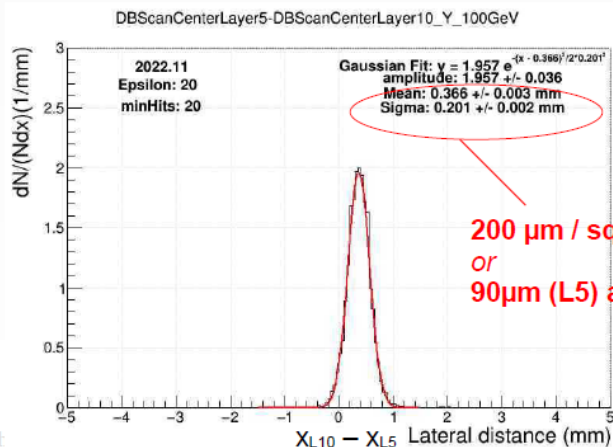


Shower reconstruction

Single shower position resolution σ_{xy}

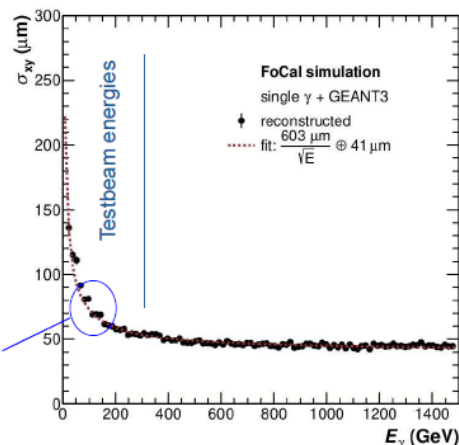


- Determine shower center in L10 relative to shower center determined from other layer(s)
- Plots shows distribution of $X_{10} - X_5$
- Width of distribution is quadratic sum of uncertainties



100 GeV

$\sim 80 \mu\text{m}$



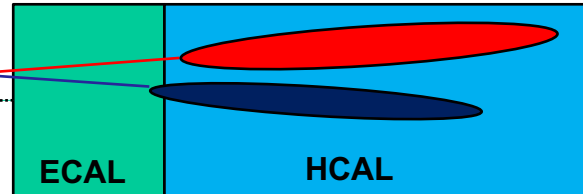
... it is a tracking calorimeter

At forward rapidities (~ 5):

- Can we measure Λ s?



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



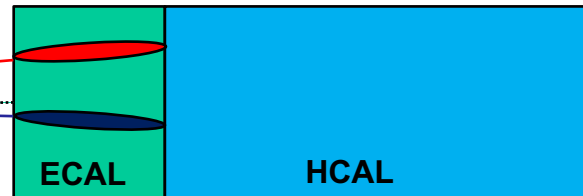
- Charged decay

- Proton and pion tracking in ECAL $\rightarrow$ reconstruction of secondary vertex
- Position and energy of proton and pion shower in HCAL
- $\rightarrow$ Baryon stopping, Λ -polarisation, ...

- Can we separate prompt/non-prompt J/Ψ ?



B^+ ($y=5$, $p_T=10$ GeV/c):
Mean decay length: 7.8 cm



Λ -production at forward rapidities

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



- Measurements:

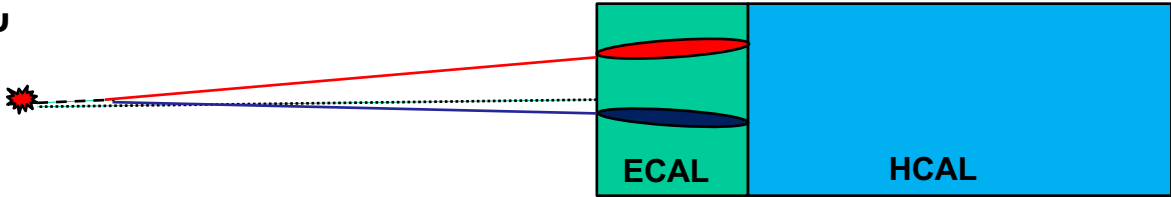
- proton and pion tracks in pixel layers 5 and 10, 5 μm resolution
- Energy of pion and proton shower (no need to separate them)

Λ , $y = 5$	$pT = 2 \text{ GeV}/c$	$pT = 10 \text{ GeV}/c$
E	170 GeV	750 GeV
Typical decay	$p \sim 143 \text{ GeV}$ $\pi^- \sim 26 \text{ GeV}$	$p \sim 630 \text{ GeV}$ $\pi^- \sim 120 \text{ GeV}$
Fraction of decays between IP and FoCal	44%	14%
Track separation at FoCal	$< 2 \text{ mm}$	$< 8 \text{ mm}$
Pointing error at 7 m (IP)	$\sigma = 13 \text{ mm}$ (dominated by MS)	$\sigma = 3 \text{ mm}$ (dominated by position error)

- Reconstruction seems possible

Quarkonium-production at forward rapidities

- J/Ψ



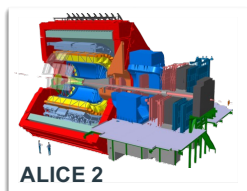
- Measurement

- Energy of electron showers (well separated)
- Position of shower centers in pixel layers 5 and 10, 50 μm resolution

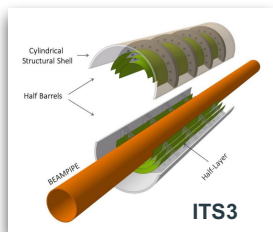
J/Ψ , $y = 5$	$p_T = 2 \text{ GeV}/c$	$p_T = 10 \text{ GeV}/c$
E	274 GeV	777 GeV
Typical decay	$e \sim 137 \text{ GeV}$	$e \sim 390 \text{ GeV}$
Shower separation	5.6 cm	16 cm
Pointing error at 7 m (IP) (dominated by position error)	$\sigma = 2 \text{ cm}$	$\sigma = 2 \text{ cm}$

- Separation prompt/non-prompt J/Ψ maybe doable
- An additional pixel layer in front of FoCal would reduce the pointing error to 4 mm

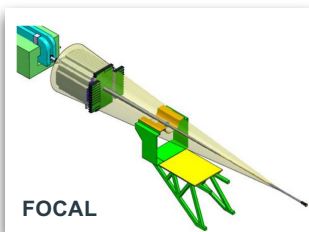
ALICE Upgrade Roadmap



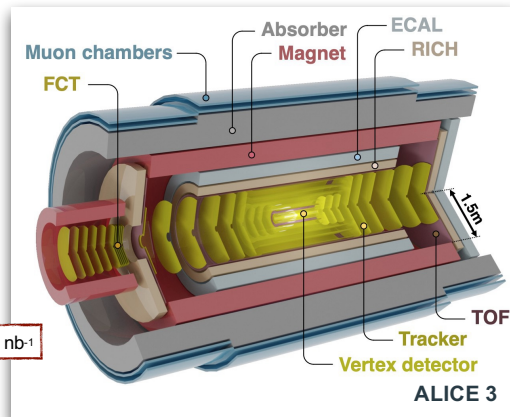
Pb-Pb: 6.2 nb^{-1}
O-O: $500 \mu\text{b}^{-1}$



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



Pb-Pb: $\sim 35 \text{ nb}^{-1}$



LHC Run 3
2022-2026

LS3
2026-2029

LHC Run 4
2030-2034

LS4
2034-2035

LHC Run 5
2036-2041

This is the end