High-Granularity EM Calorimetry for Forward Measurements

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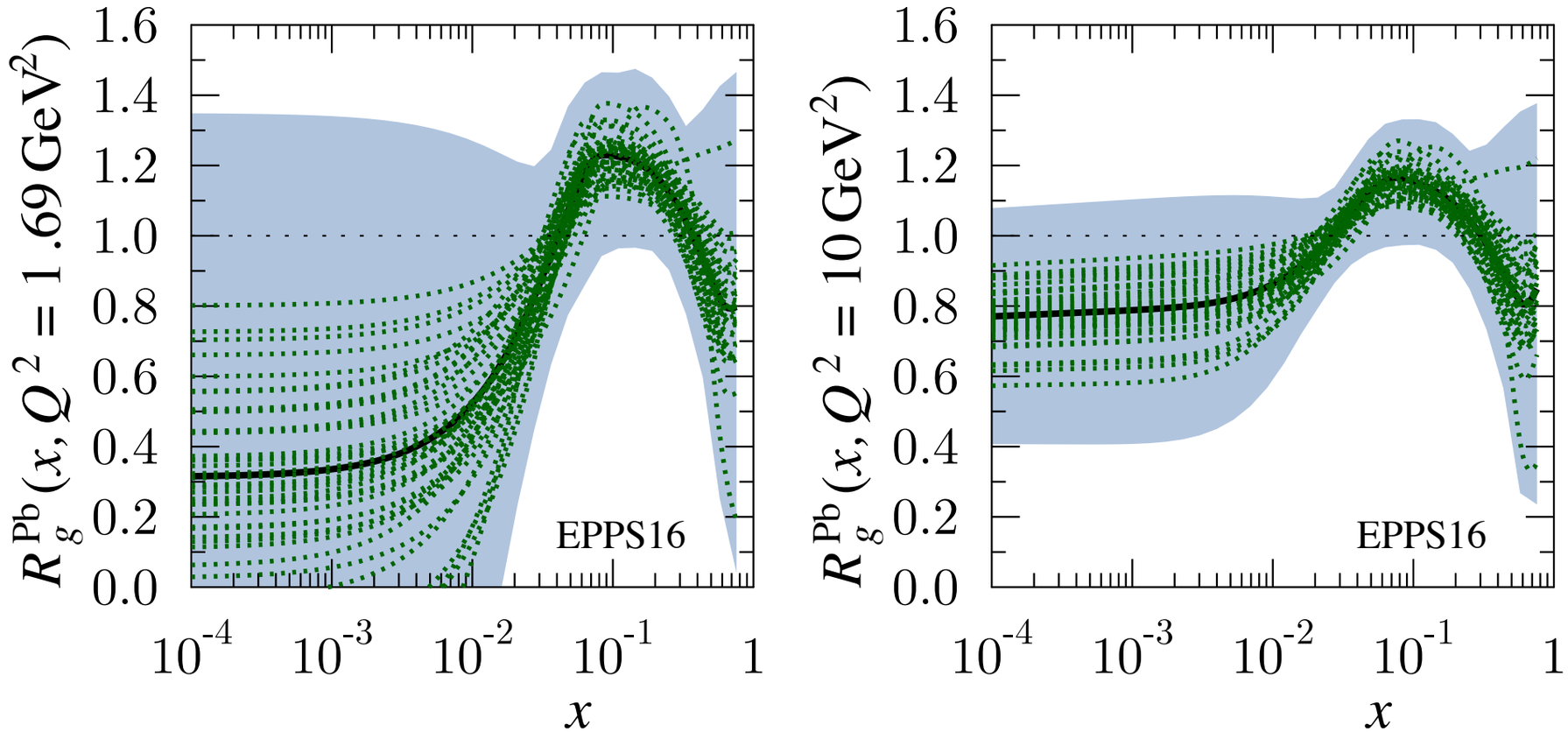
Outline

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

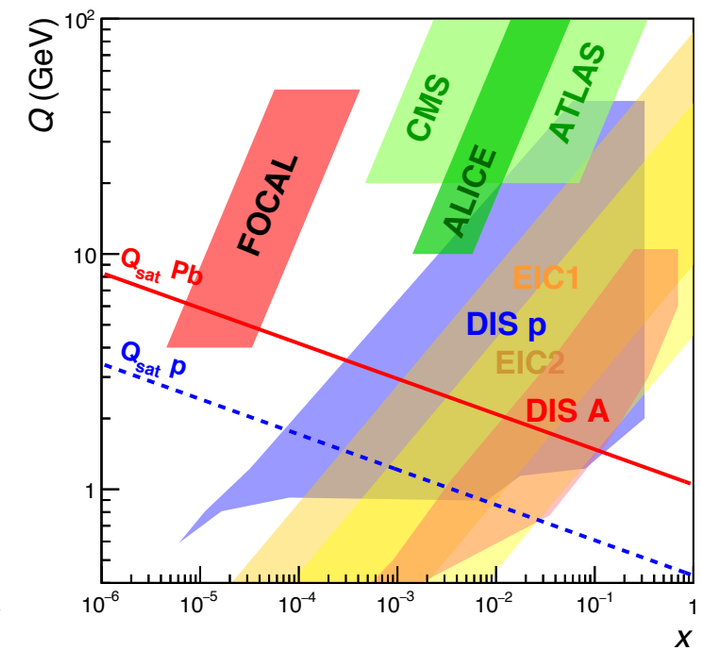
CFNS Forward Workshop 2018, Stony Brook, 17.10.2018

EPPS16, EPJC 77, 163

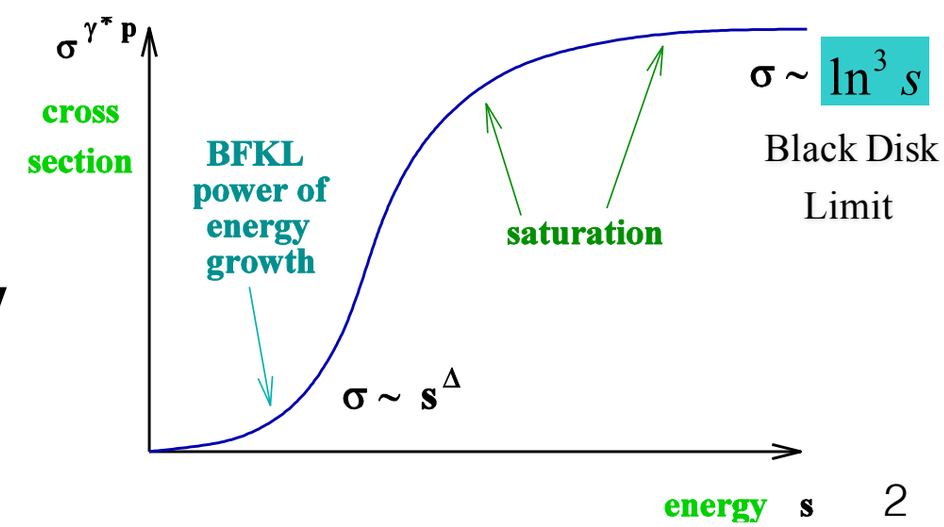
PDF Uncertainties and Saturation



EM probes - kinematic coverage



- 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?

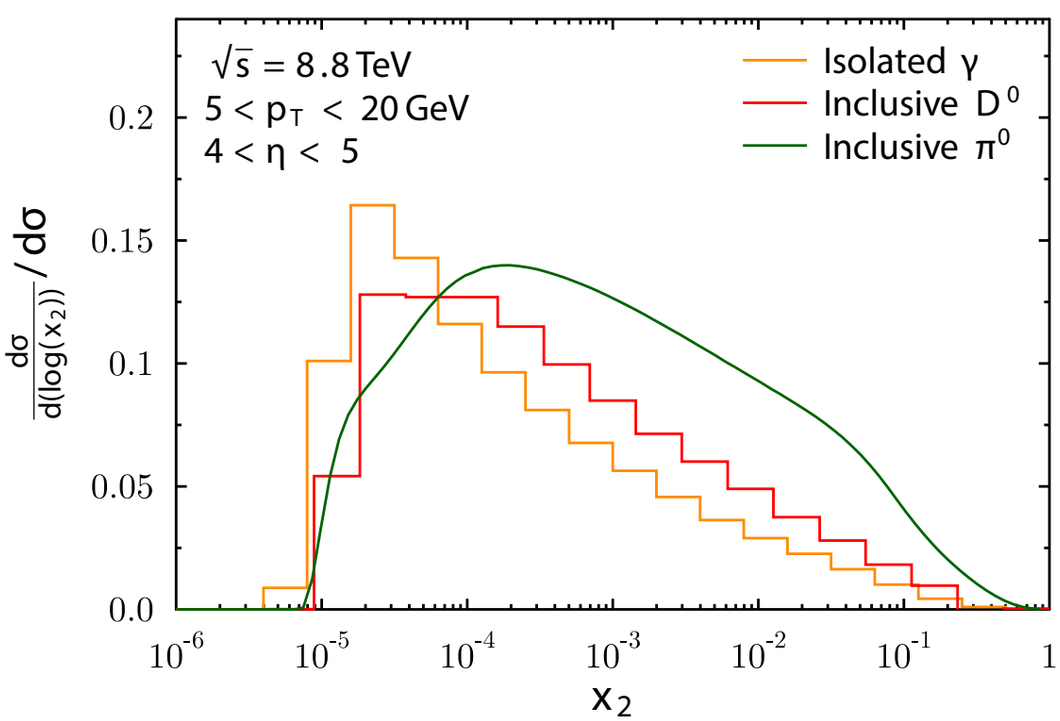
	$\sqrt{s}$ (TeV)	y	p_T (GeV/c)	z	x_2
π	0.2	4	2	0.3	$1.2 \cdot 10^{-3}$
π	8.8	0	2	0.3	$1.5 \cdot 10^{-3}$
jet	8.8	4	20	1	$8.3 \cdot 10^{-5}$
π	8.8	4	2	0.3	$2.8 \cdot 10^{-5}$
D	8.8	4	0	0.5	$1.5 \cdot 10^{-5}$
γ	8.8	4	4	1	$1.7 \cdot 10^{-5}$
γ	8.8	4.5	4	1	$1.0 \cdot 10^{-5}$

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

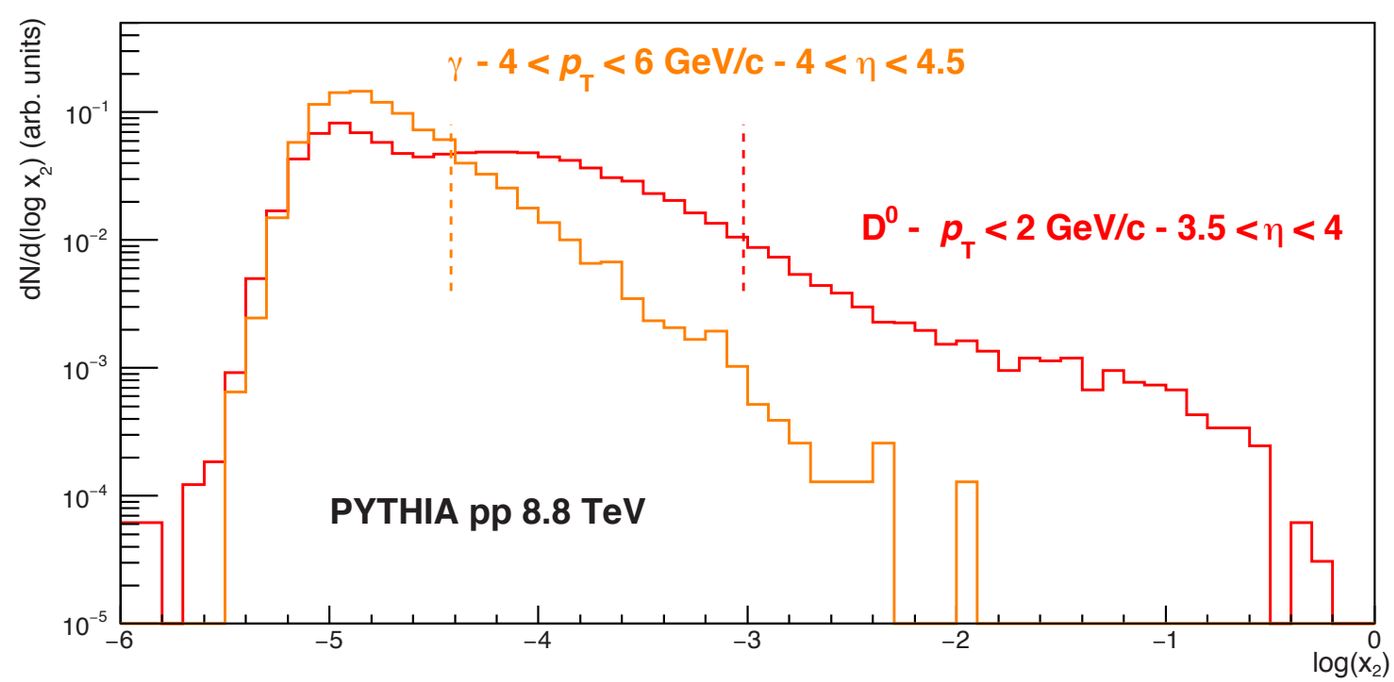
- LO kinematics estimates provide rather lower limit for x_2
- but: higher orders contribute significant tail towards large x_2

- compare D^0 (LHCb) and prompt γ (FoCal)
- expect better sensitivity for photons

- *x*-distributions from NLO pQCD



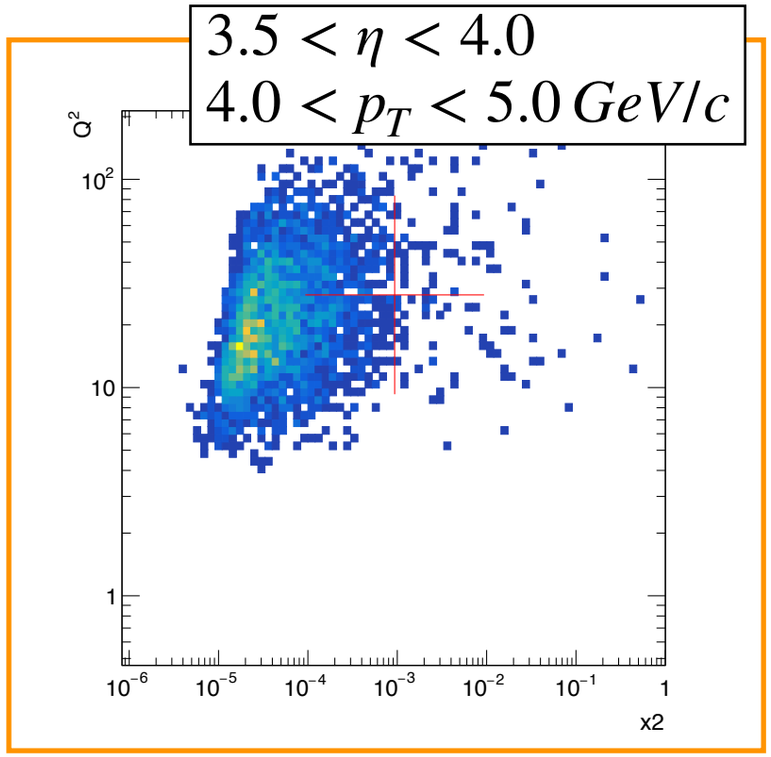
- *x*-distributions from PYTHIA

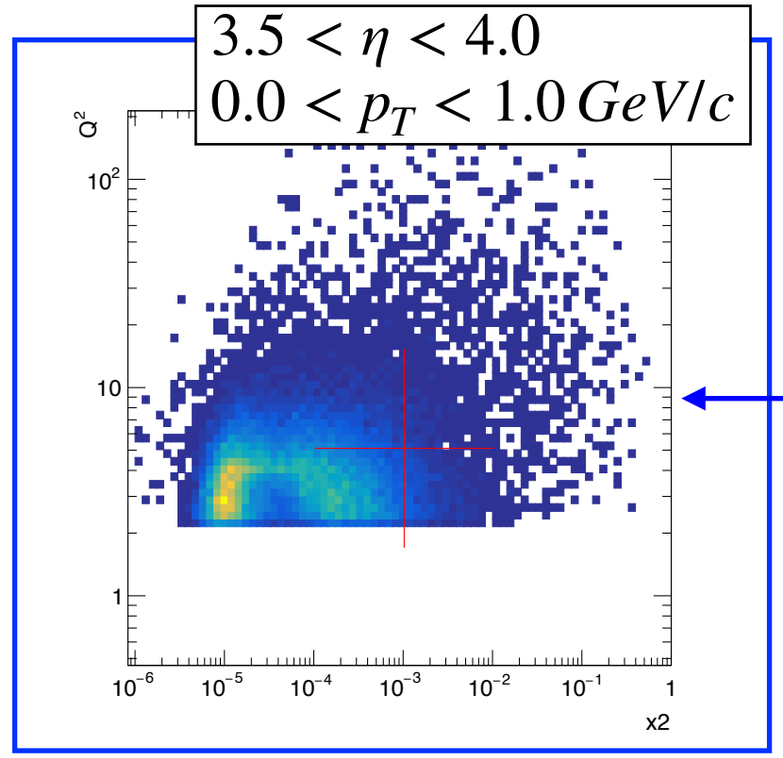


no analytical approximation, taking into account η of recoil parton

x-Q^2-Sensitivity

D^0



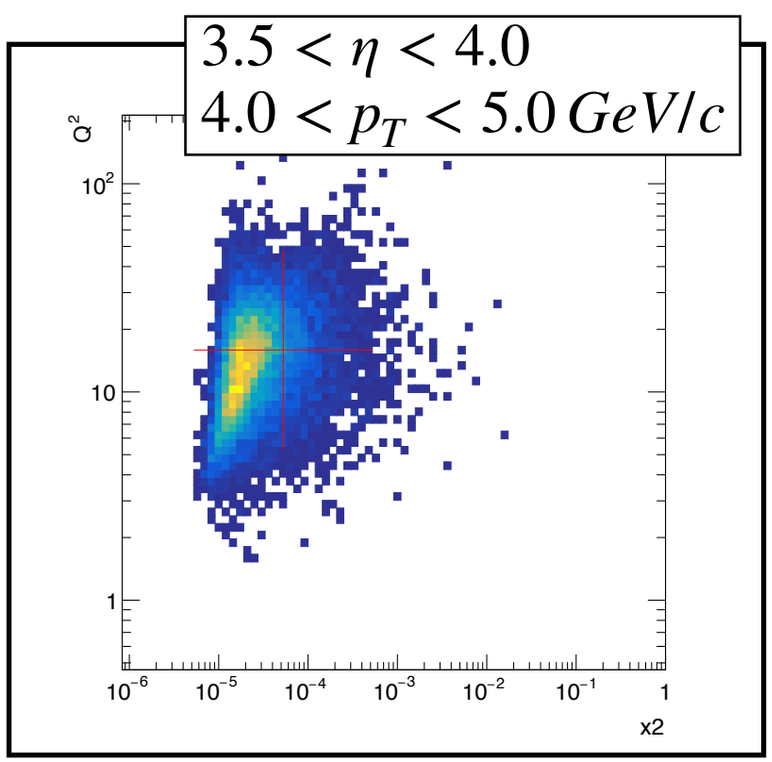


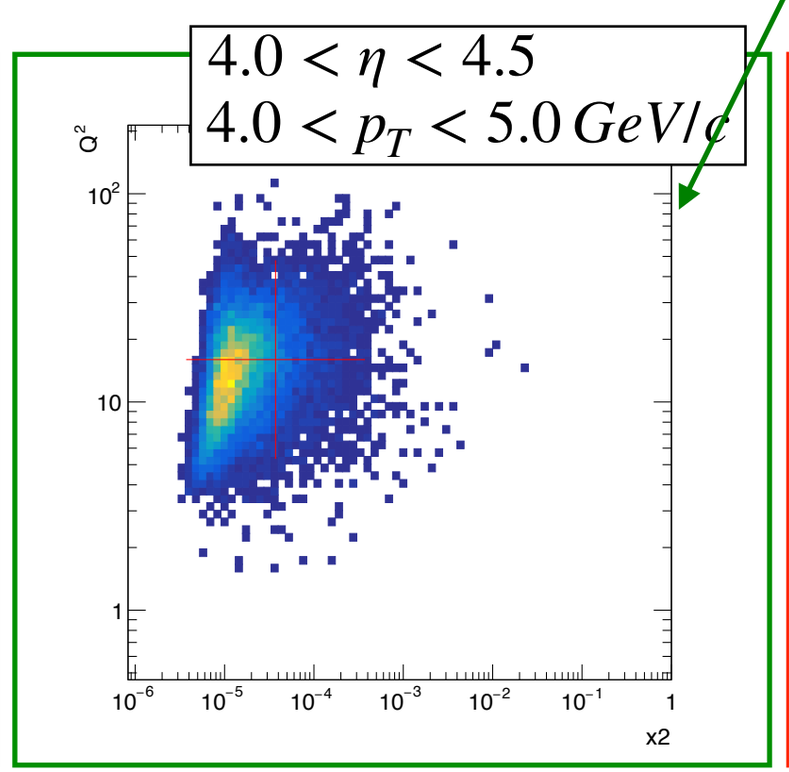
PYTHIA pp 8.8TeV forward measurements

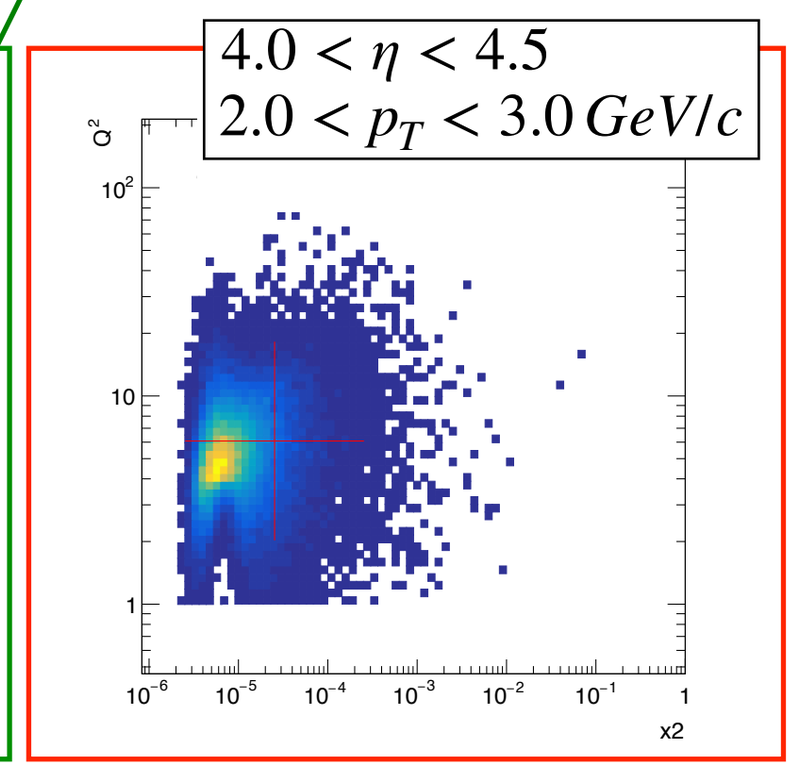
$< x_2 > = 1.0 \cdot 10^{-3}$
$< Q^2 > = 5.1\, GeV^2$

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

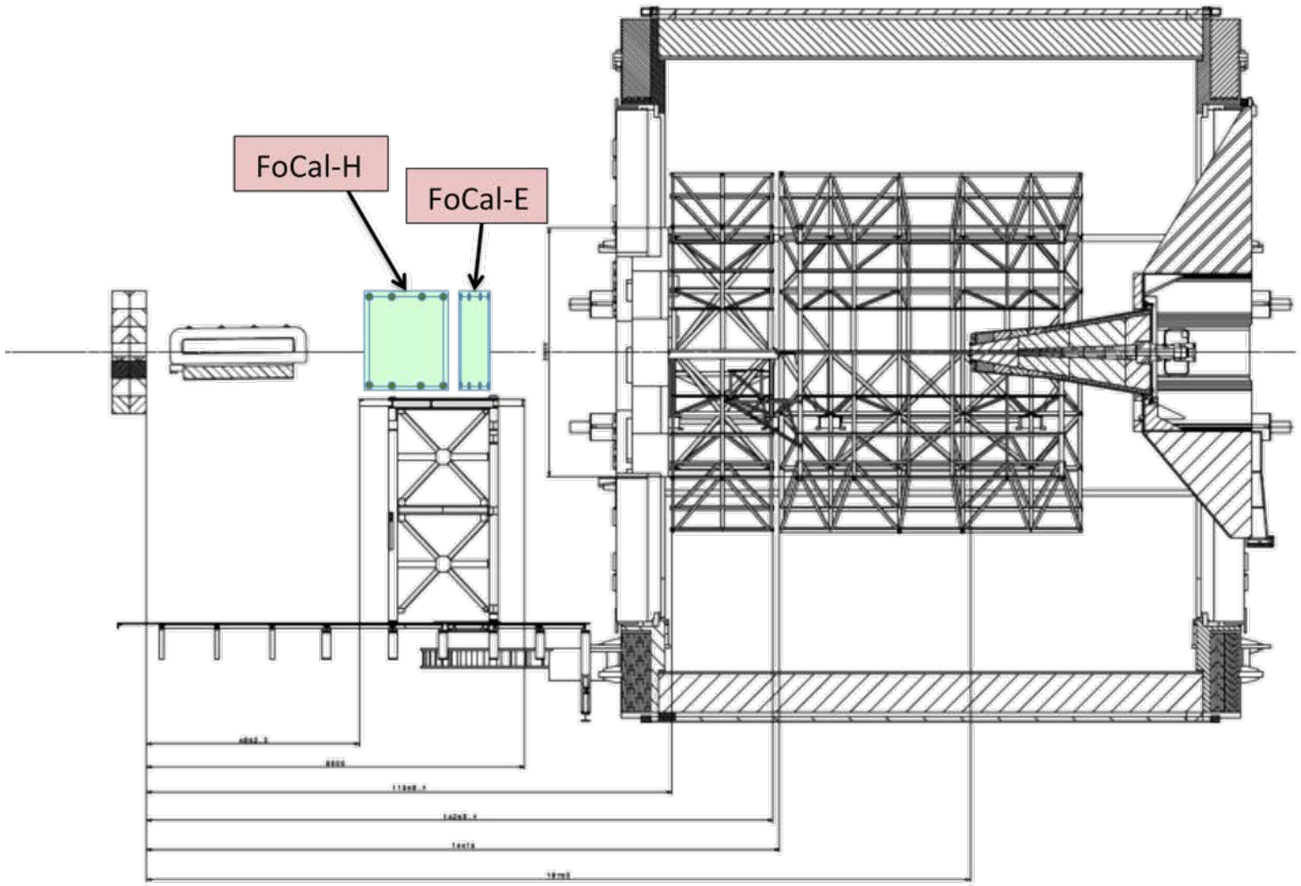
γ







FoCal in ALICE



electromagnetic calorimeter (FoCal-E) for γ and π^0 measurement

preferred scenario:

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

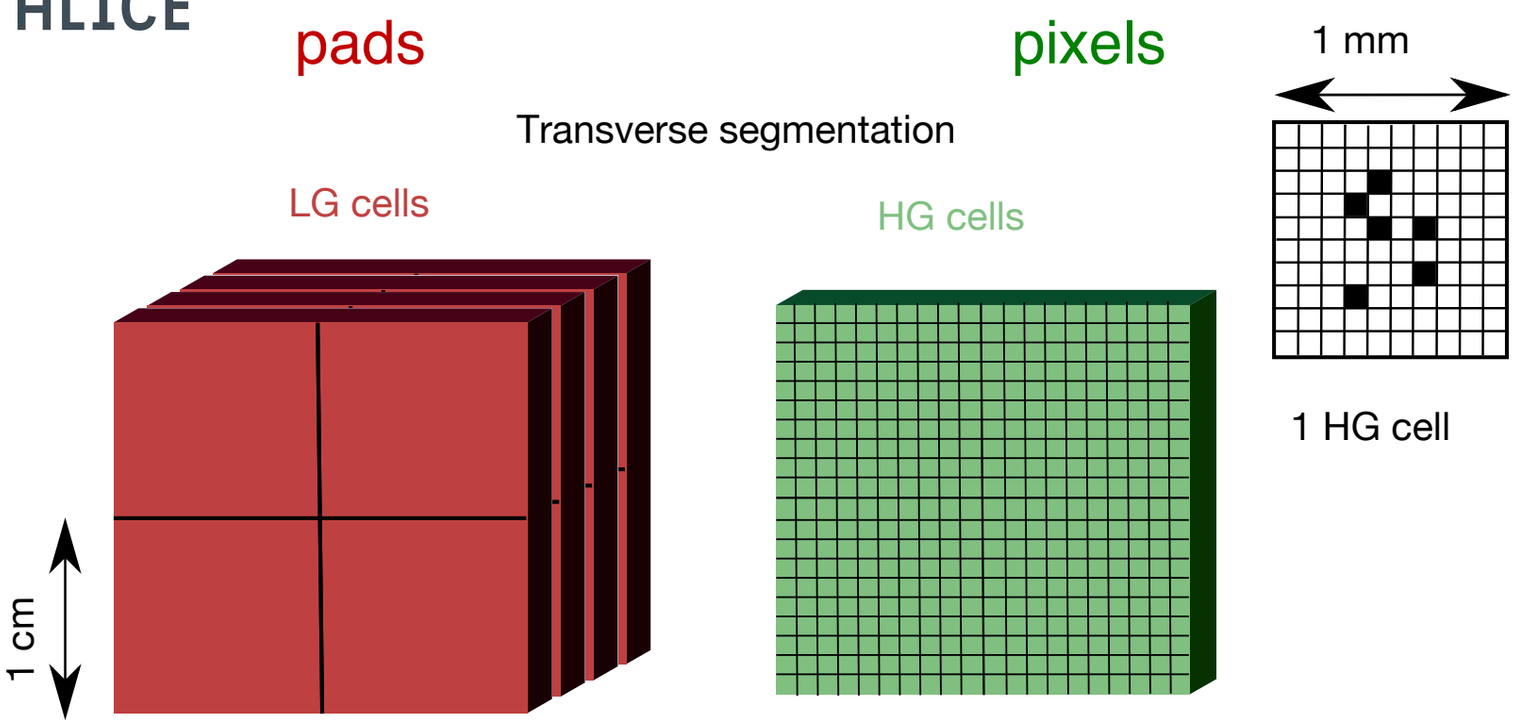
under internal discussion
possible installation in LS3

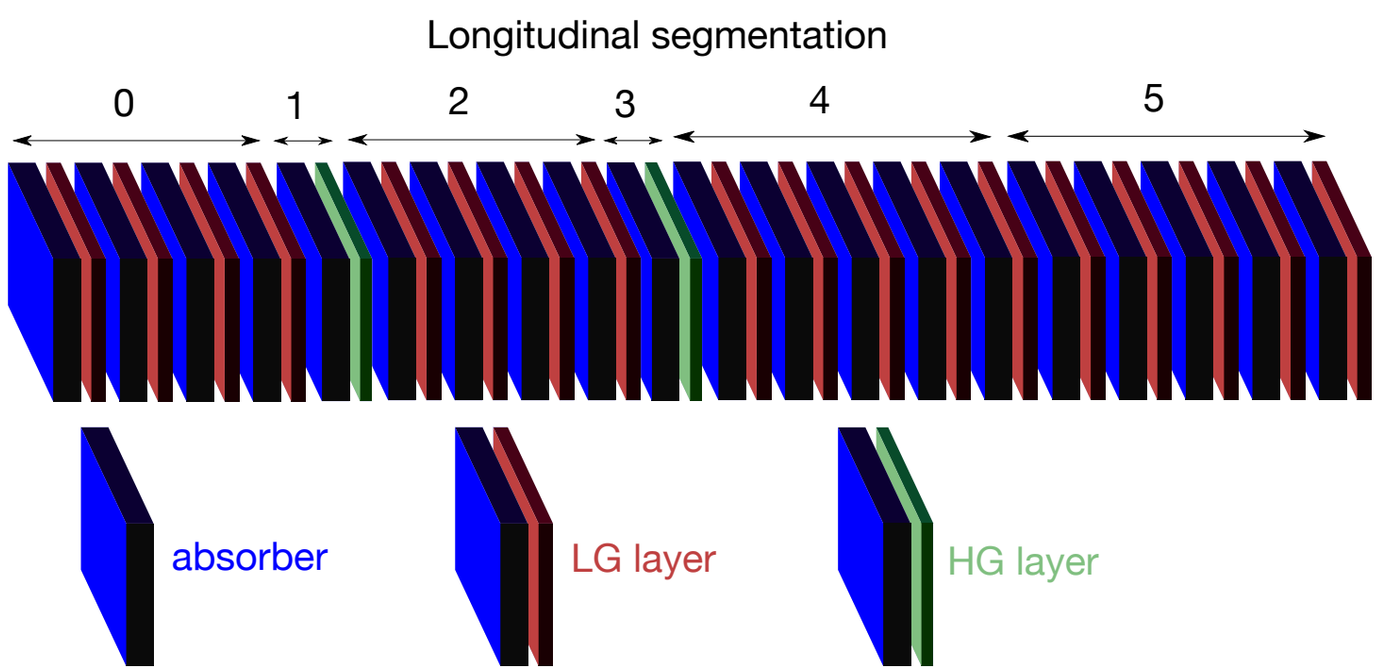
advantage in ALICE: forward region not instrumented, “unobstructed view”

- main challenge: separate γ/π^0 at high energy
- need small Molière radius, high-granularity read-out
  - Si-W calorimeter, effective granularity ≈ 1mm^2

note: two-photon separation from π^0 decay (p_T = 10 GeV/c, y = 4.5, α = 0.5) is d = 2 mm!

The FoCal Detector – Strawman Design





studied in performance simulations:

20 layers:
W (3.5mm ≈ 1 X_0) + Si-sensors

hybrid design (2 types of sensors)

- **Si-pads** (≈ 1 cm²):
  energy measurement, timing(?)
- **CMOS pixels** (≈ 30x30 μm^2):
  two-shower separation, position resolution

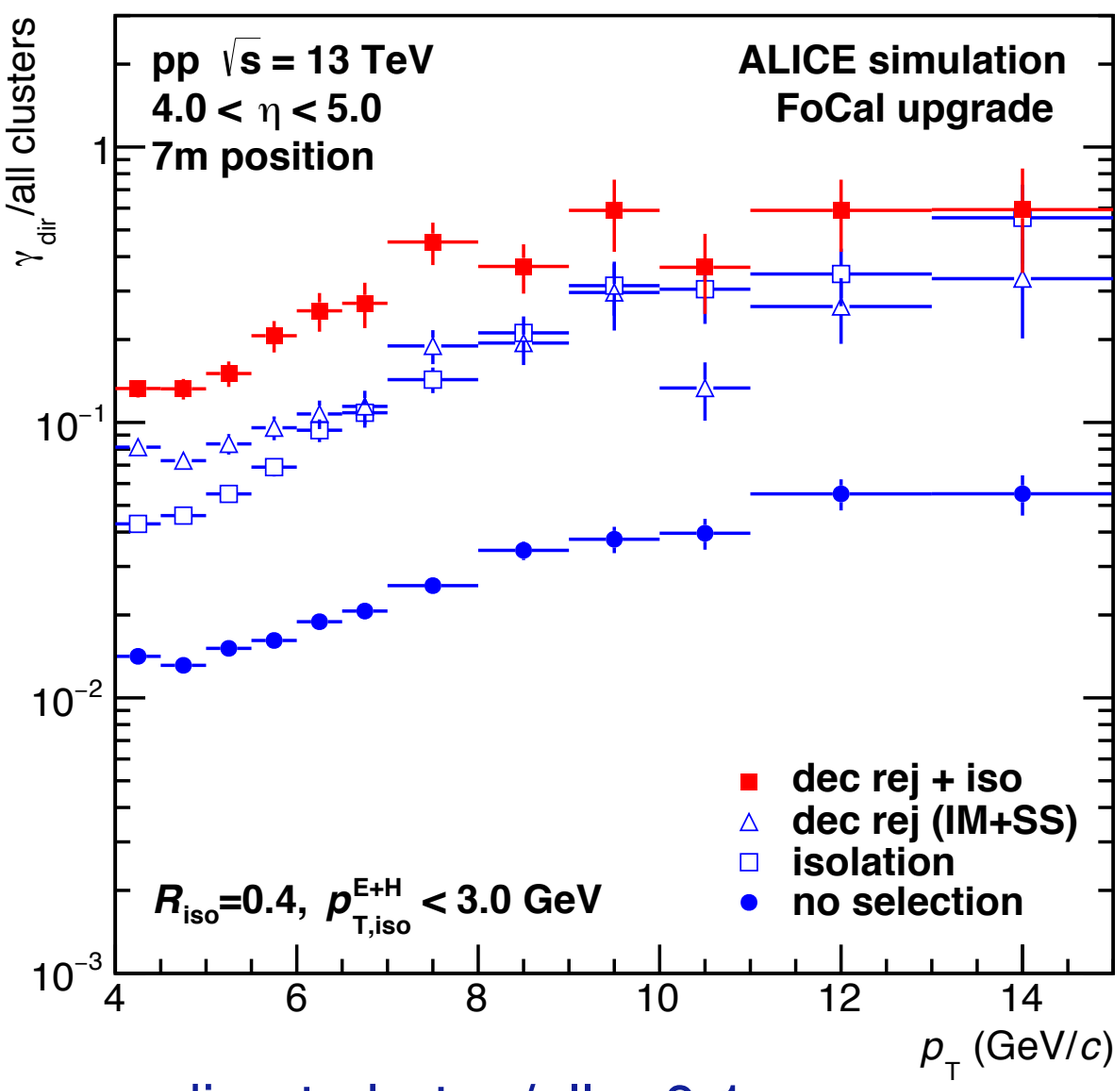
	Si-pads	Si-pixels
pixel/pad size	≈ 1 cm²	≈ 30x30 μm²
total # pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9
readout channels	≈ 5 x 10^4	≈ 2 x 10^6

assuming ≈ 1m² detector surface

Direct γ Performance in pp

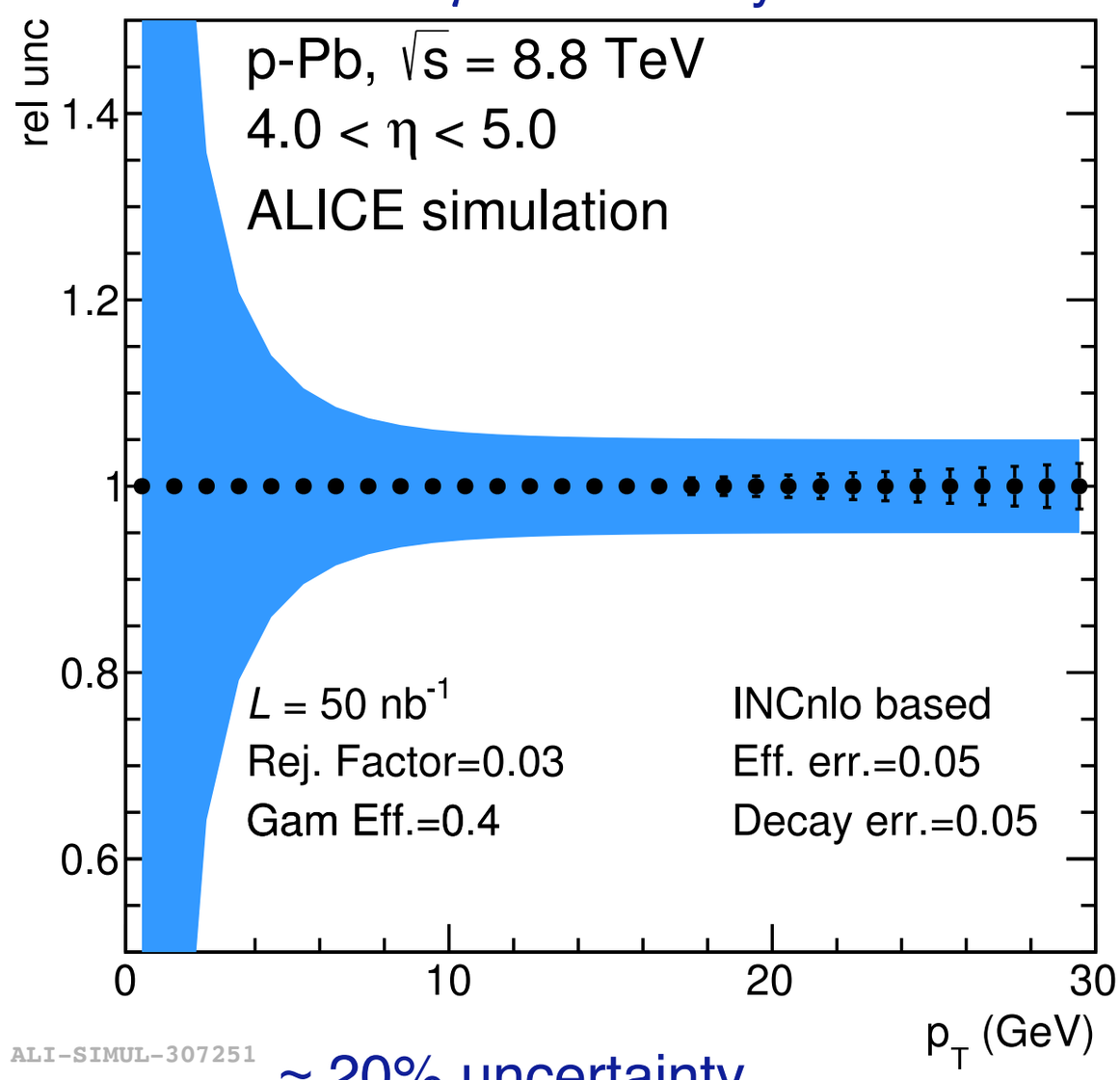
- combined rejection (invariant mass + shower shape, isolation)
- combined suppression of background relative to signal: factor ≈ 10
  - largely p_T-independent

Direct γ/all cluster ratio



direct photon/all > 0.1
for p_T > 4 GeV/c

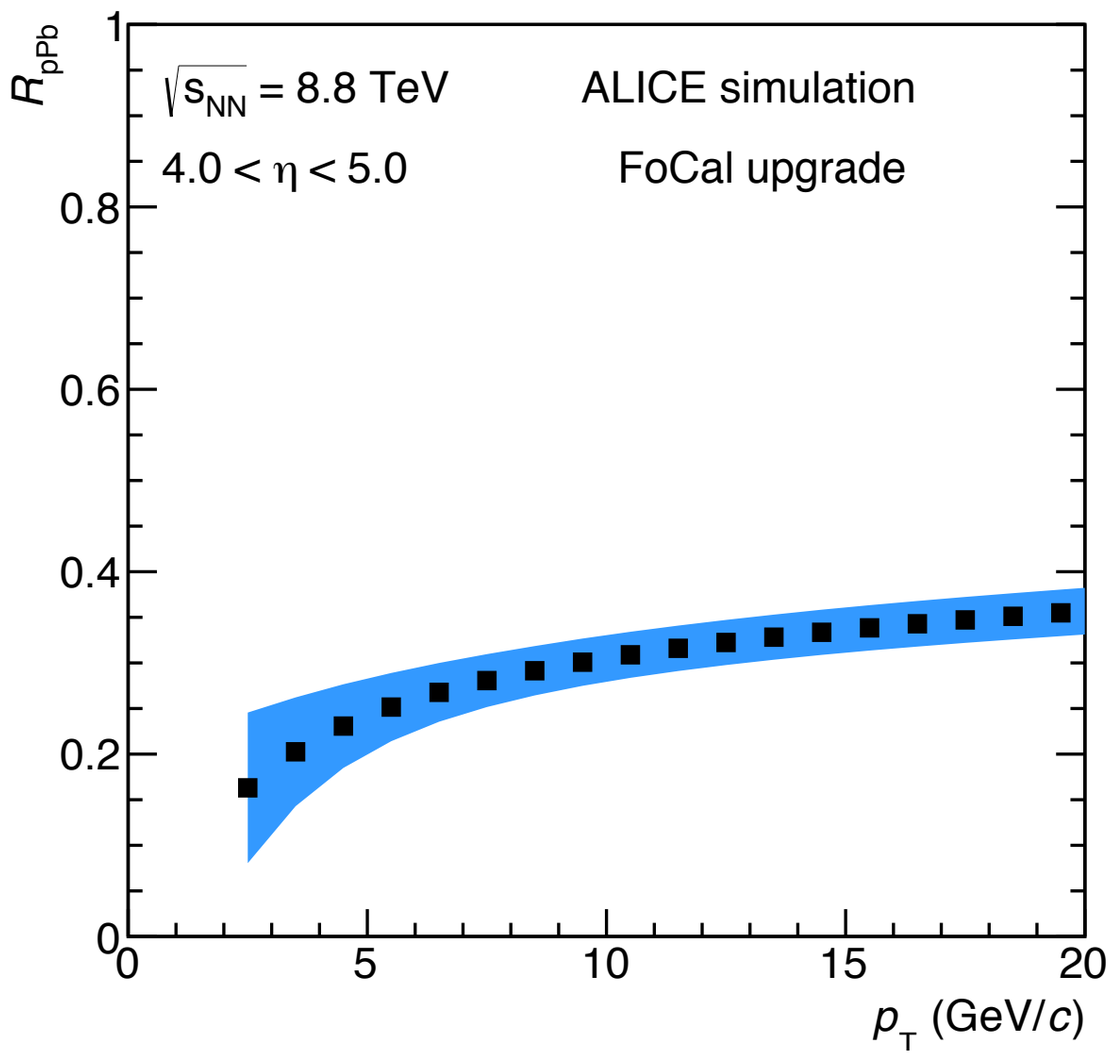
Direct γ uncertainty



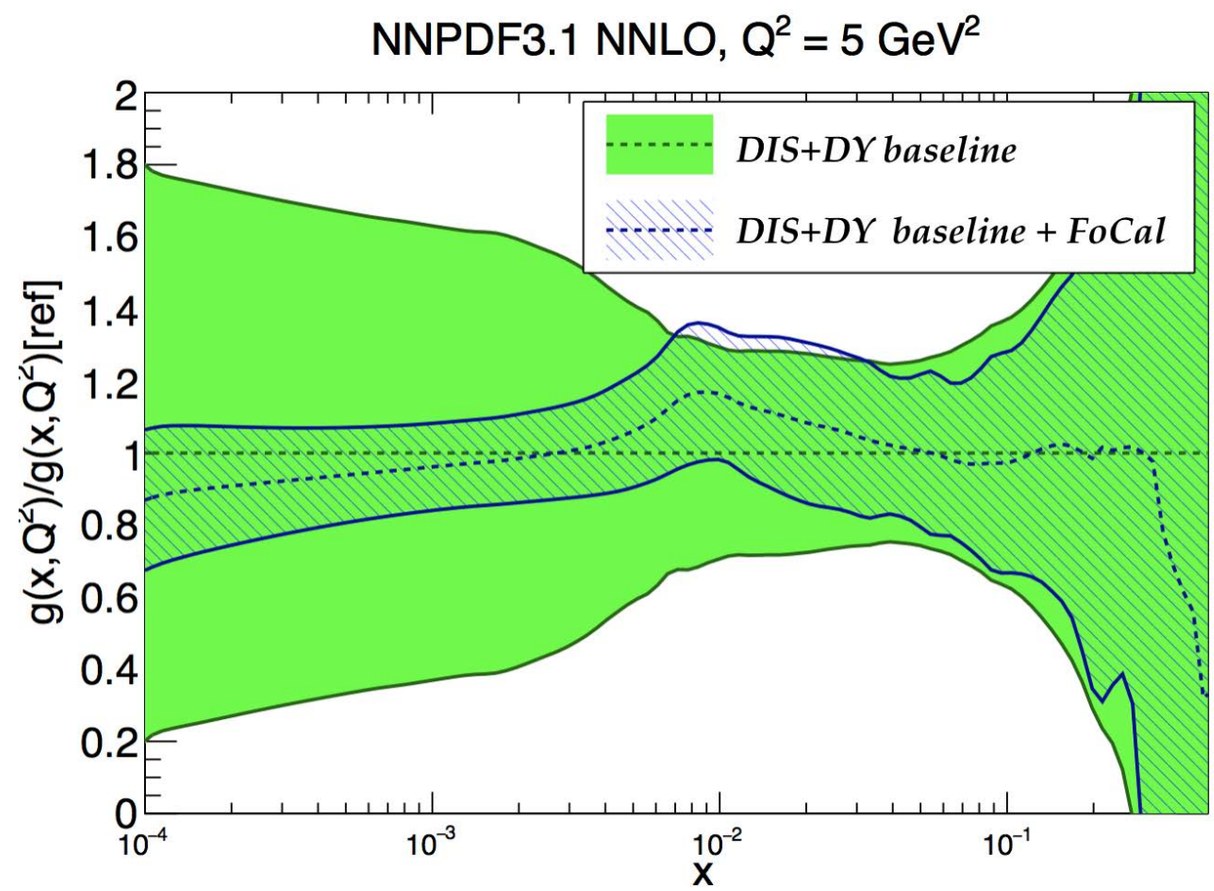
≈ 20% uncertainty
at p_T = 4 GeV/c
decreases with increasing p_T

Impact of Forward Photons on nPDFs

Performance estimate of FoCal measurement



uncertainty of nPDFs without/with FoCal
J. Rojo et al, priv. comm.,
arXiv 1610.09373,1706.00428,1802.03021



Uncertainties can be improved significantly

Still some discussion ongoing:
choice of $\Delta\chi^2$, effect of DGLAP evolution, shape of parameterisation

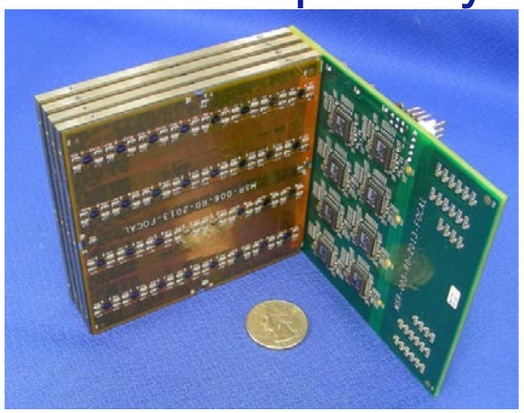
Work in progress!

Extensive R&D Program Ongoing

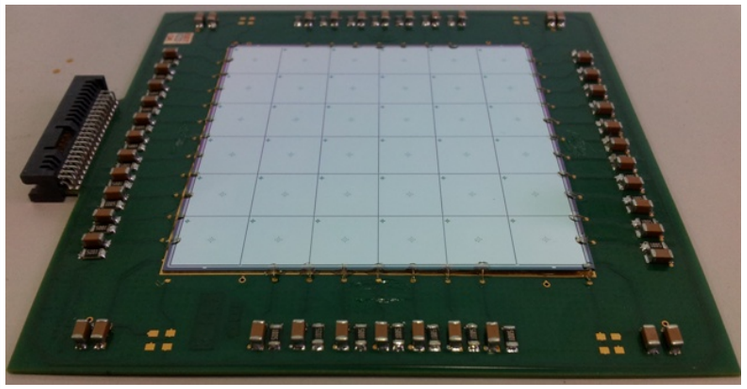
- requires to go beyond state of the art
  - pixel sensors needed for pion rejection (two-shower separation)
  - Si-pads needed for energy resolution and timing
- proof of principle demonstrated
  - successful test of first digital pixel calorimeter (JINST 13 (2018) P01014)
  - investigating several 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

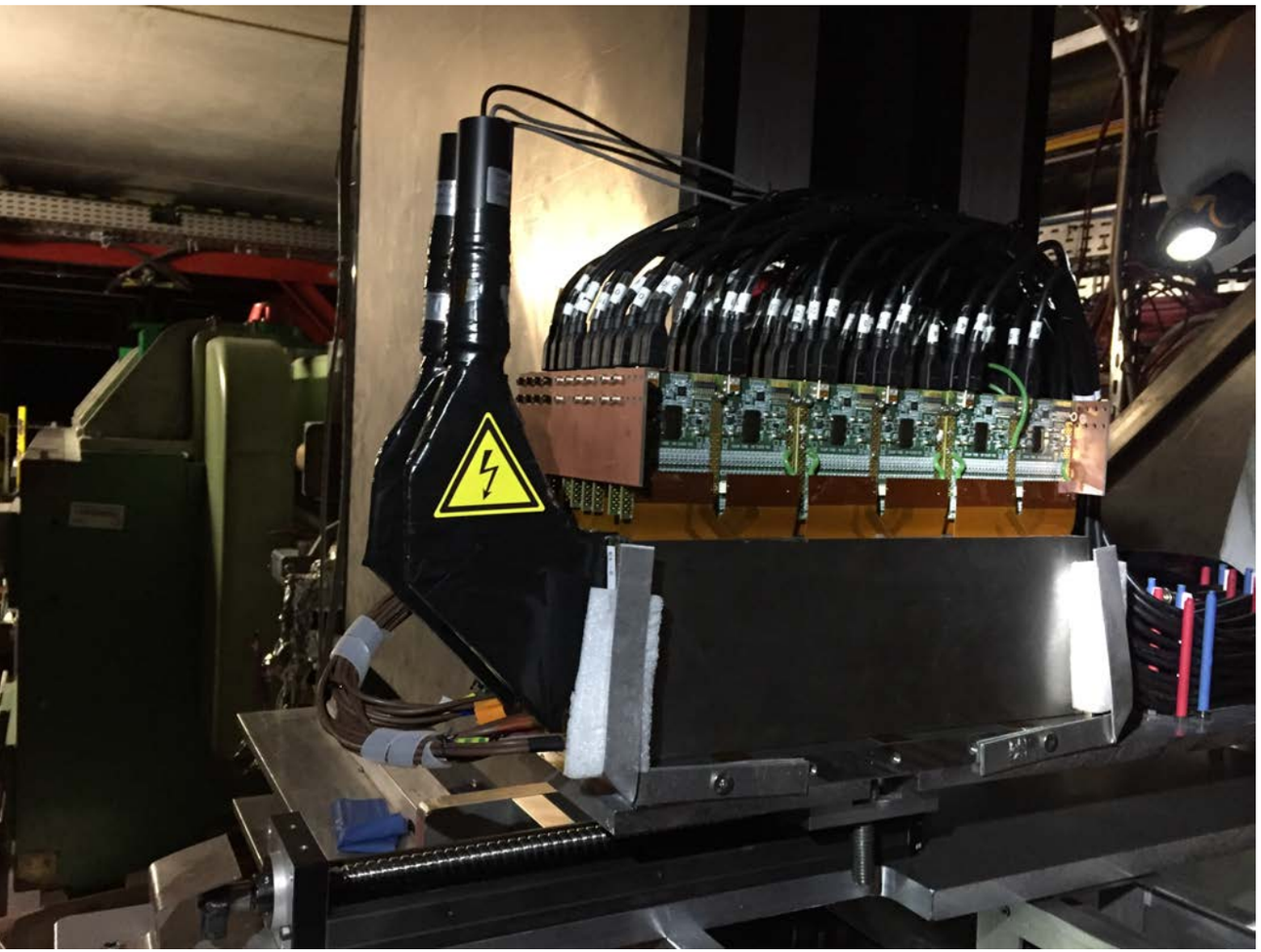


ORNL/Tsukuba



Kolkata/Mumbai

miniFoCal in ALICE cavern



several calorimeter prototypes with pad readout from different groups

extensive test beam campaigns

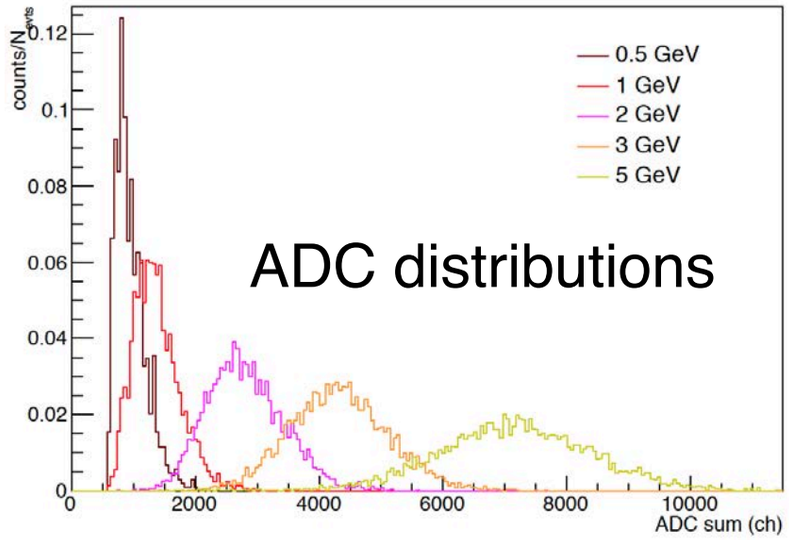
recently installed 27 cm x 9 cm full depth prototype in ALICE cavern

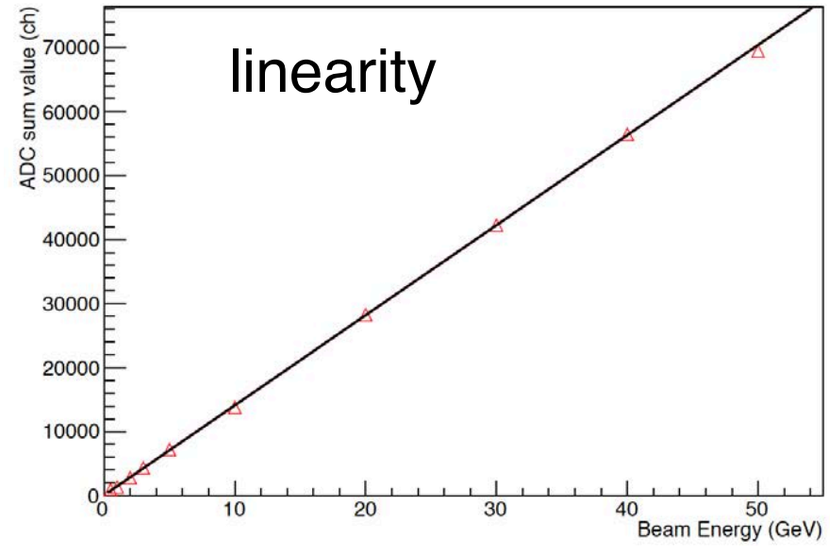
- measurements in pp collisions
- performance under realistic conditions?

most important issue:
readout electronics with sufficient dynamic range (~16bit?)

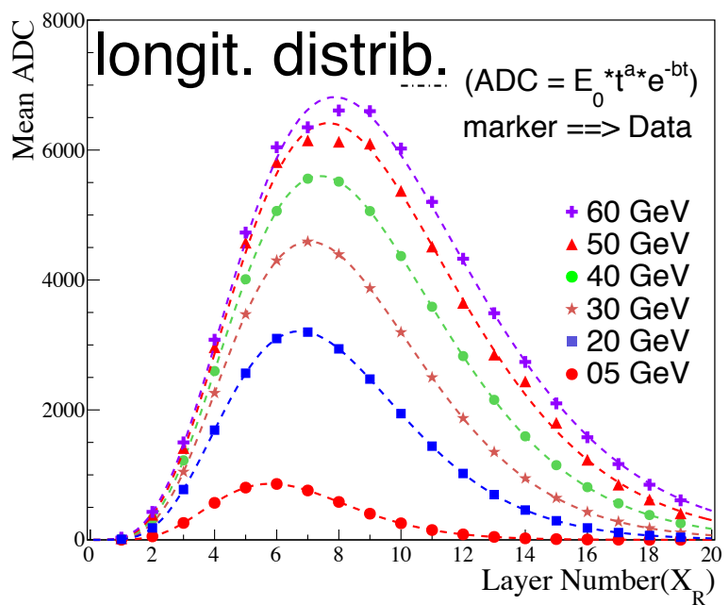
- plan to investigate several avenues: SAMPA, CMS-HGCal, ATLAS-VMM, …

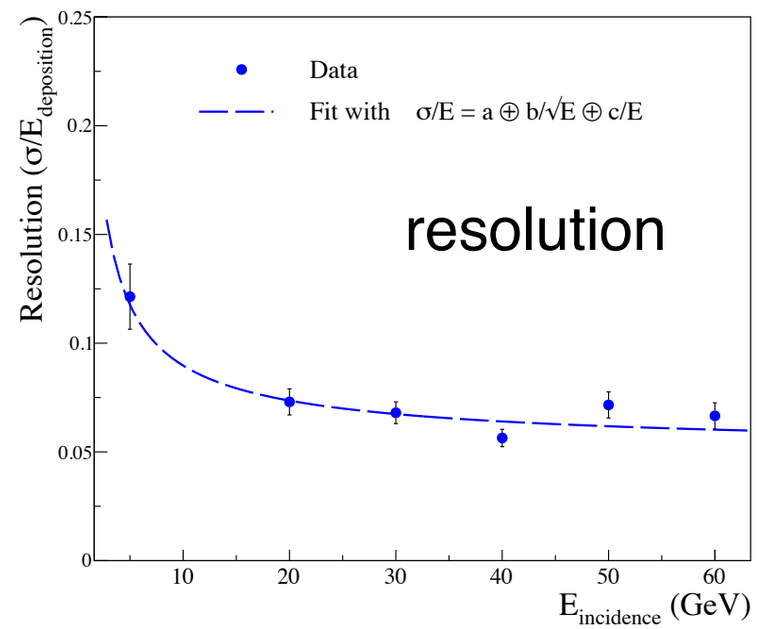
W/Si-Pad Test-Beam Performance





ORNL/Japan Pad prototype with APV/SRS readout

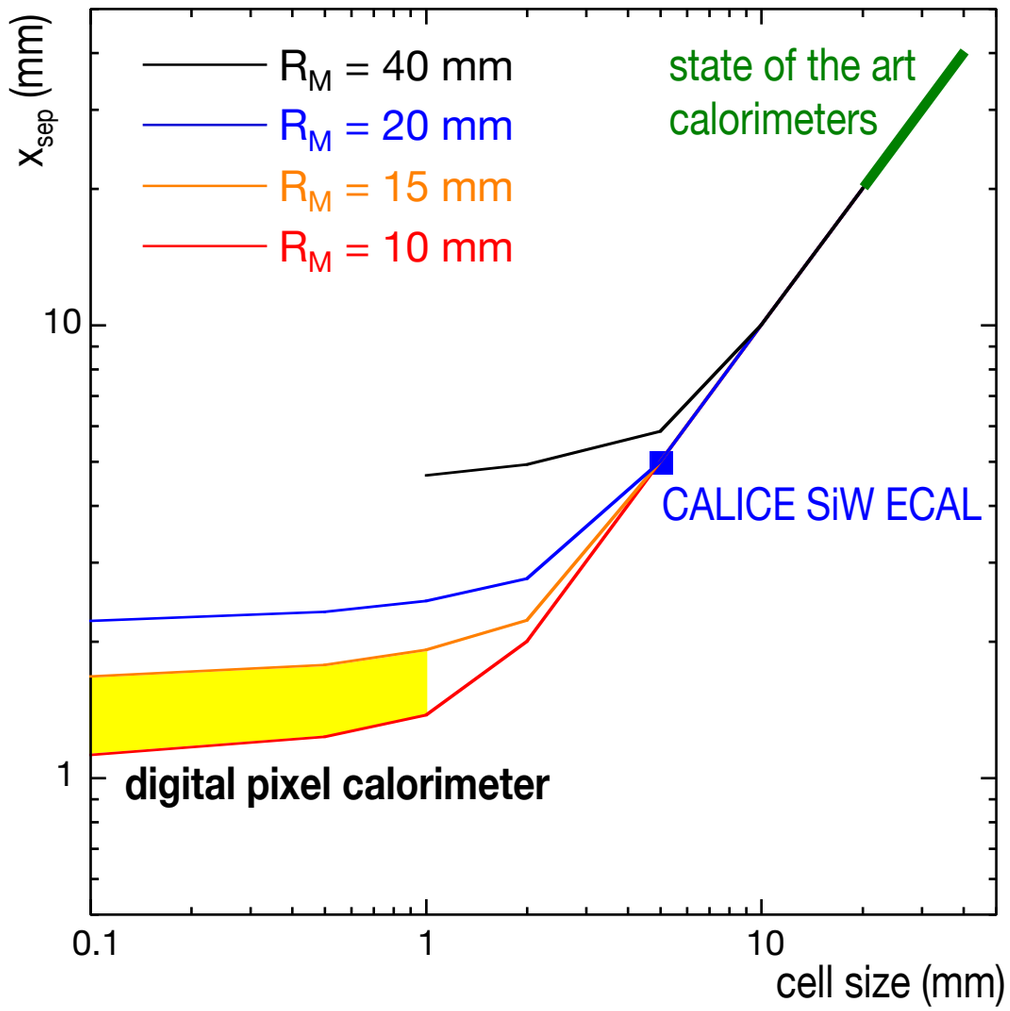




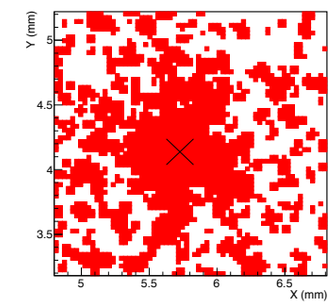
India Pad prototype with custom chip (MANAS/ANUSANSKAR)

test beam performance agrees with simulations
papers on instrumentation in preparation

Developing an Extremely Granular Calorimeter



~ CMS-HGCAL
pad size (0.5cm²)

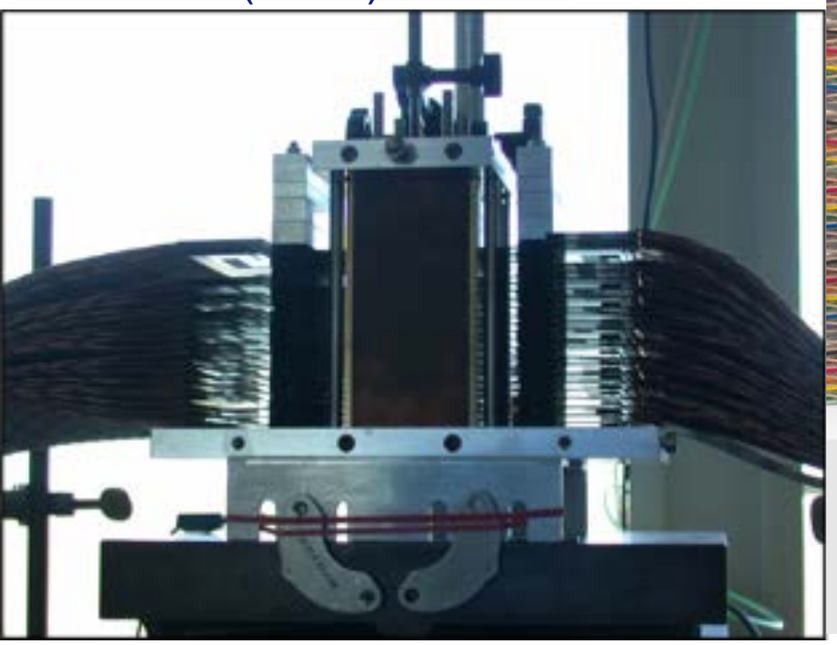


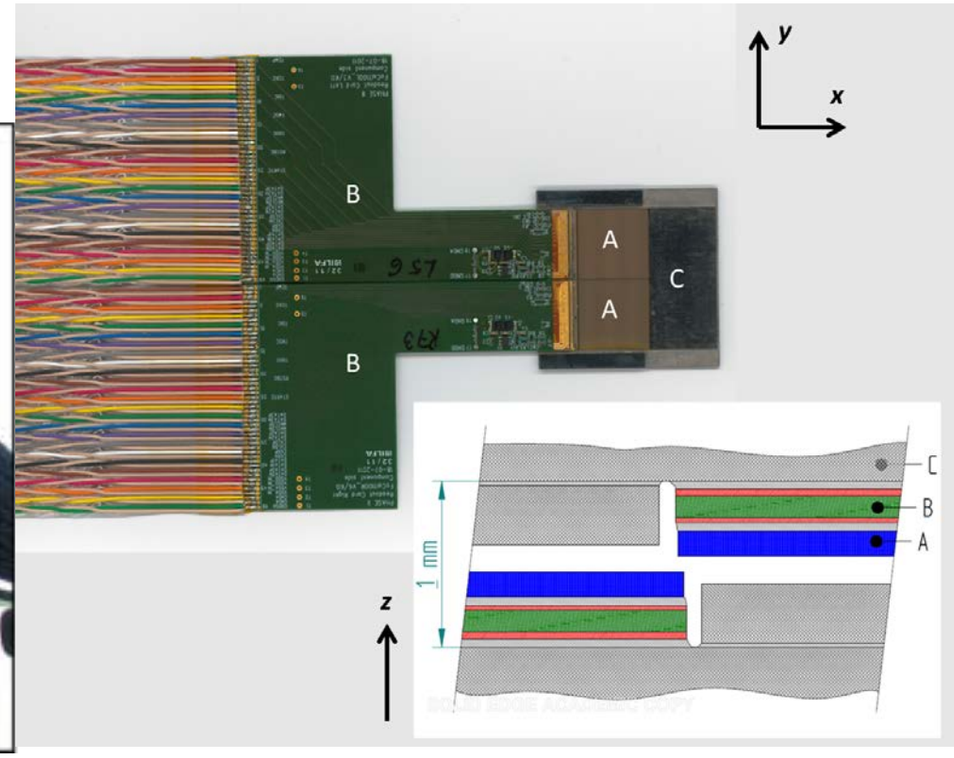
single electron shower measurement (244 GeV) in CMOS sensor

- 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

Utrecht/Nikhef, Bergen
JINST 13 (2018) P01014





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 X_0
- full active layer with readout boards within 1mm

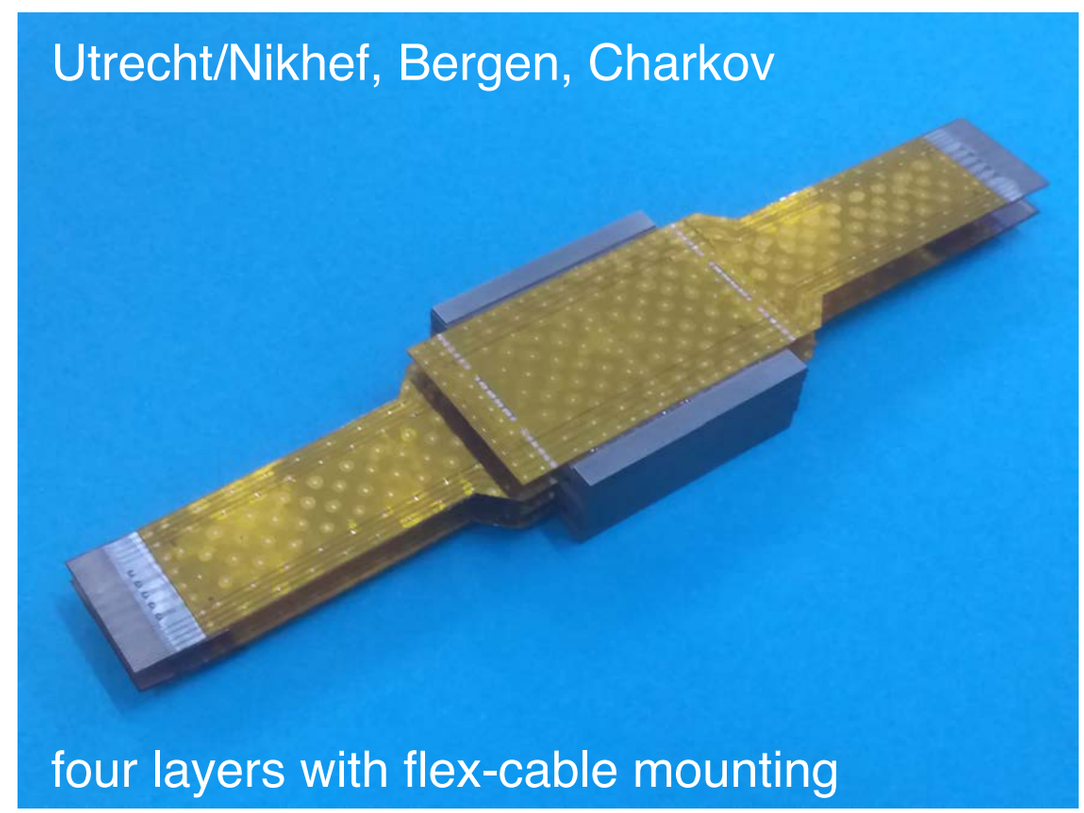
A: MIMOSA sensor, B: PCB, C: tungsten

most important issue: readout speed/bandwidth
MIMOSA sensor much too slow,
now moving to ALPIDE sensor

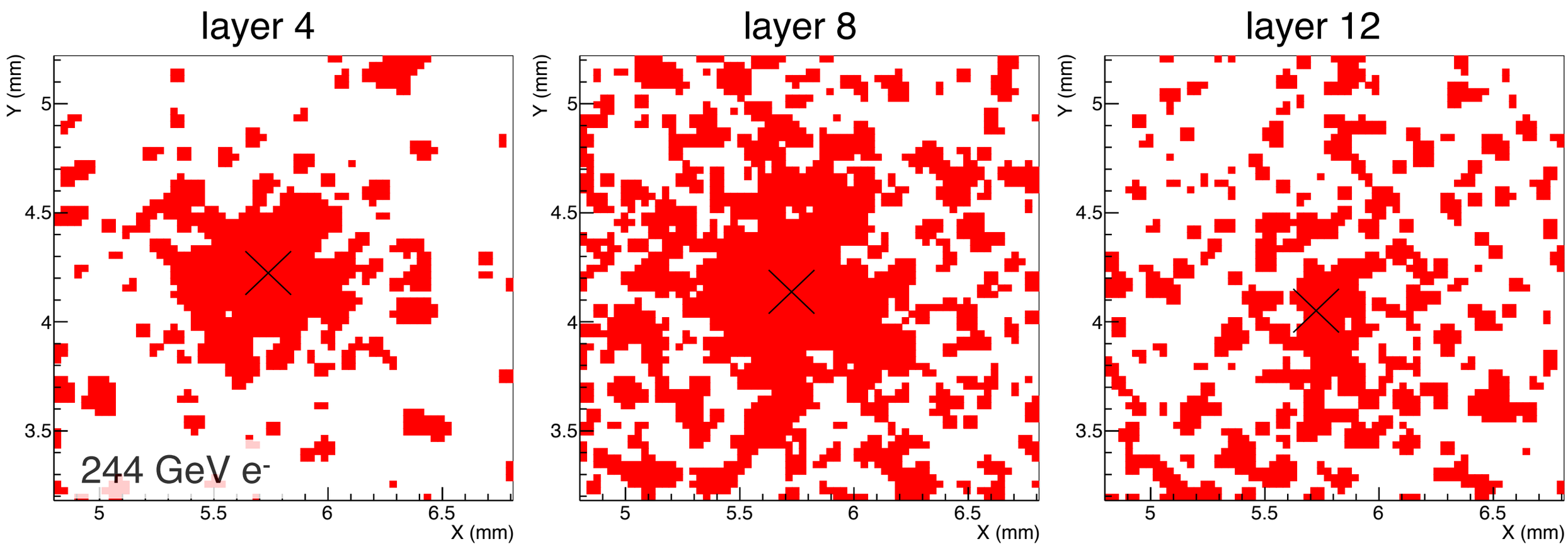
- synergy with ALICE ITS upgrade
- needs chip design steps

preparing prototypes with current ALPIDE

- full pixel prototype
- hybrid (pixel/pad) prototype



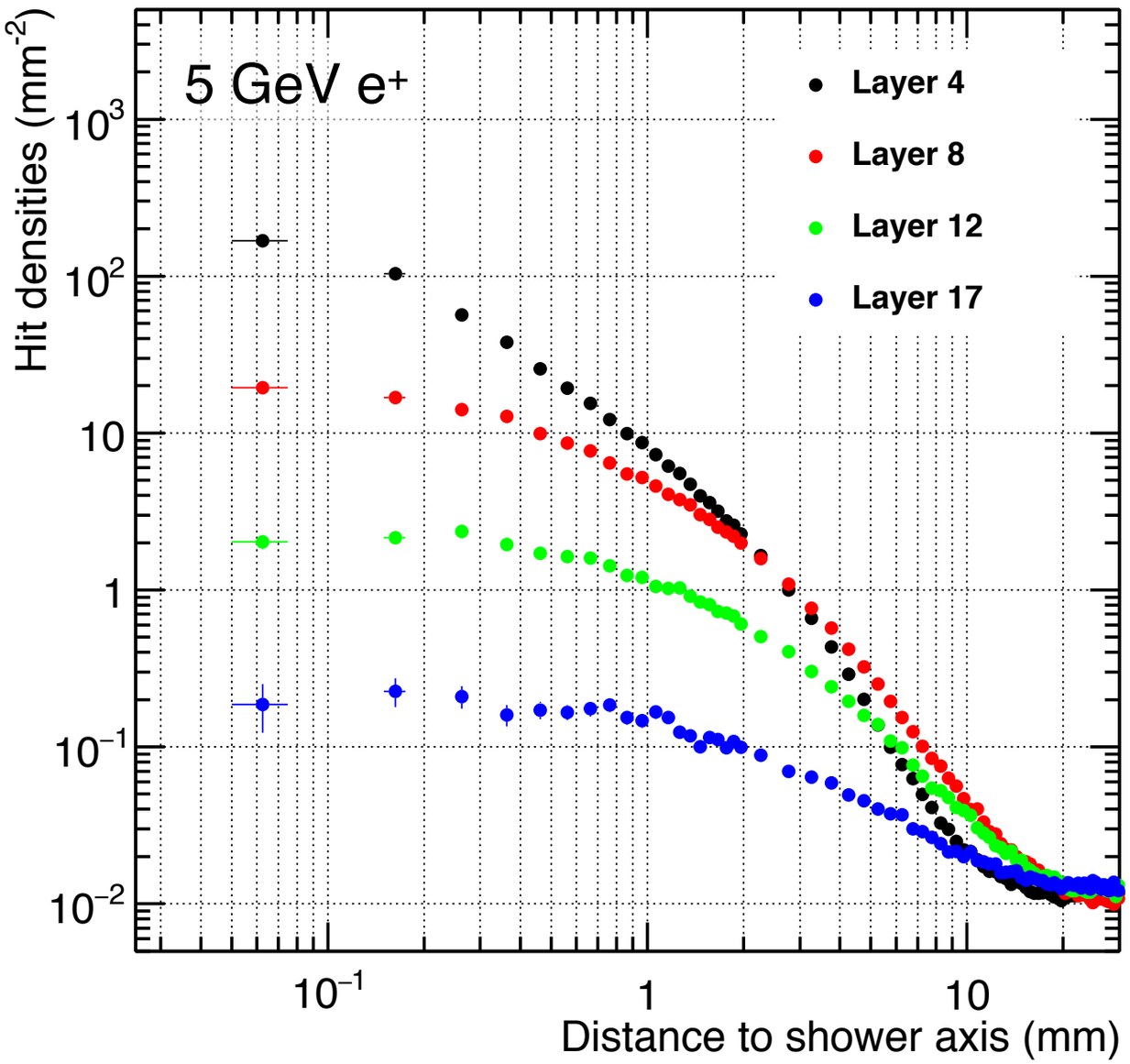
Single Event Hit Distribution - FoCal Pixel Prototype

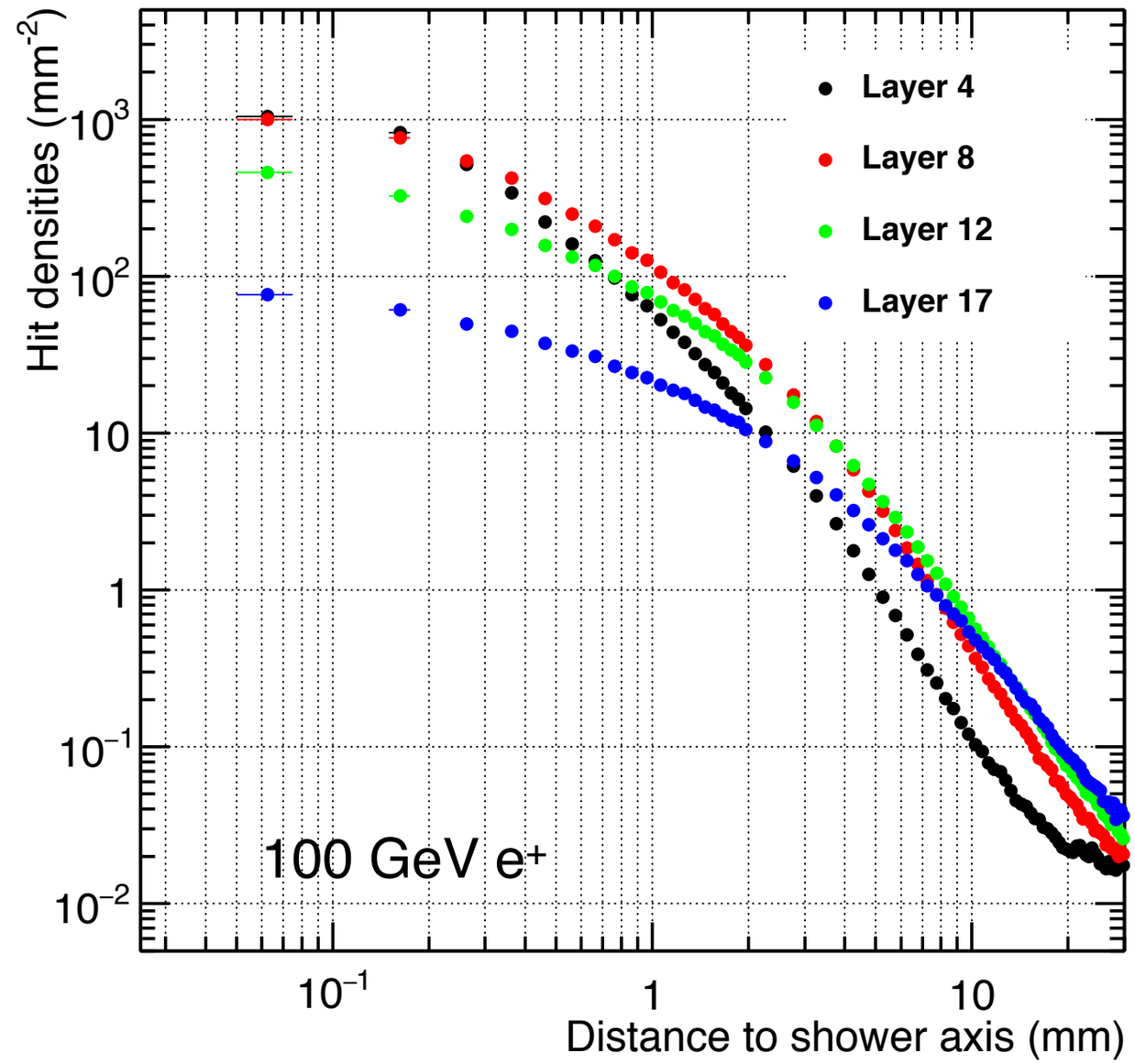


very high hit density in shower core

- 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

R&D - Lateral Profiles



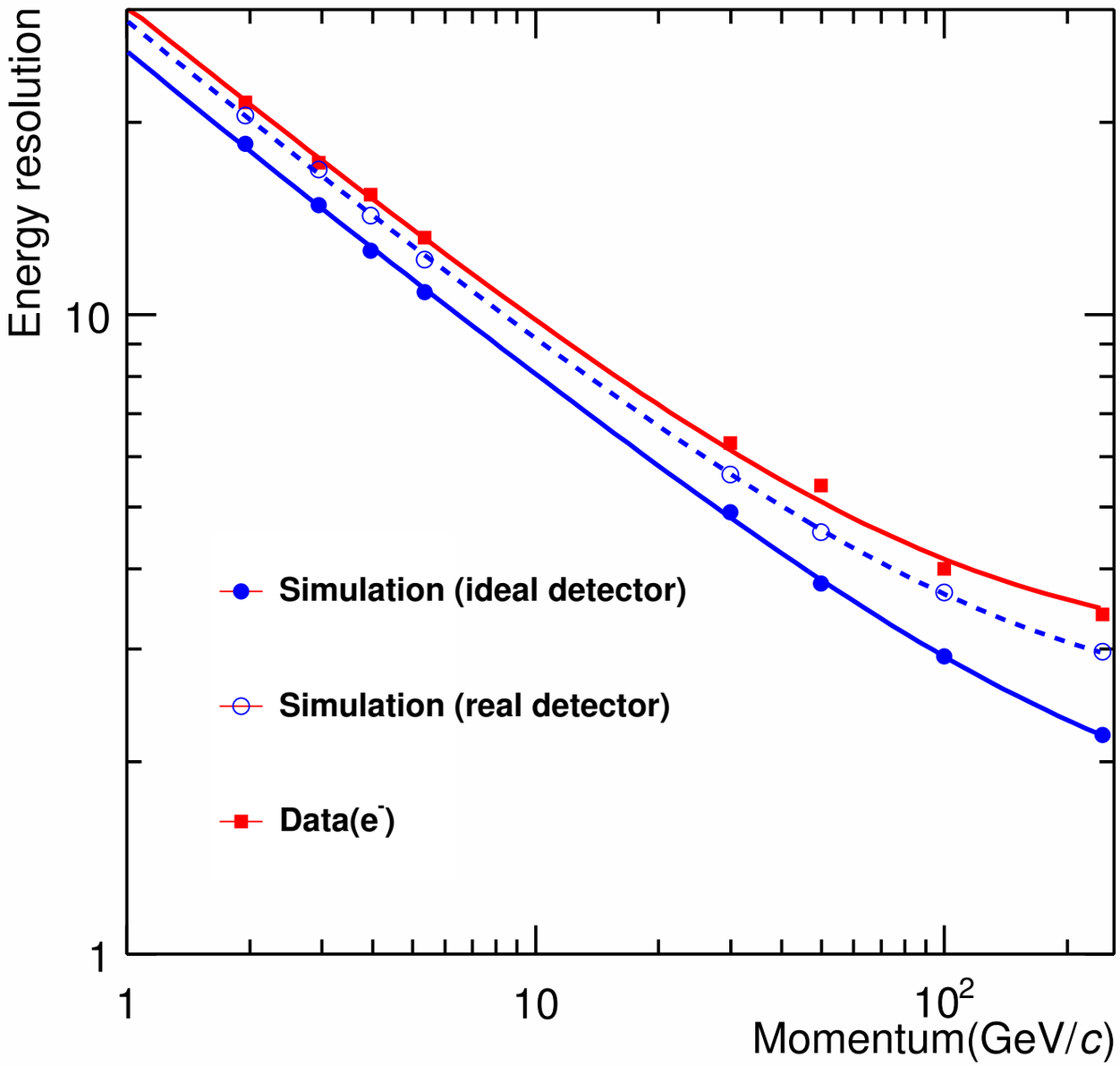


average hit densities as a function of radius $\frac{dN_{\text{hit}}}{dA}(r)$ for different layers

- 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



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

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

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

recent work on improved calibration

slightly worse than MC simulation,
not unexpected

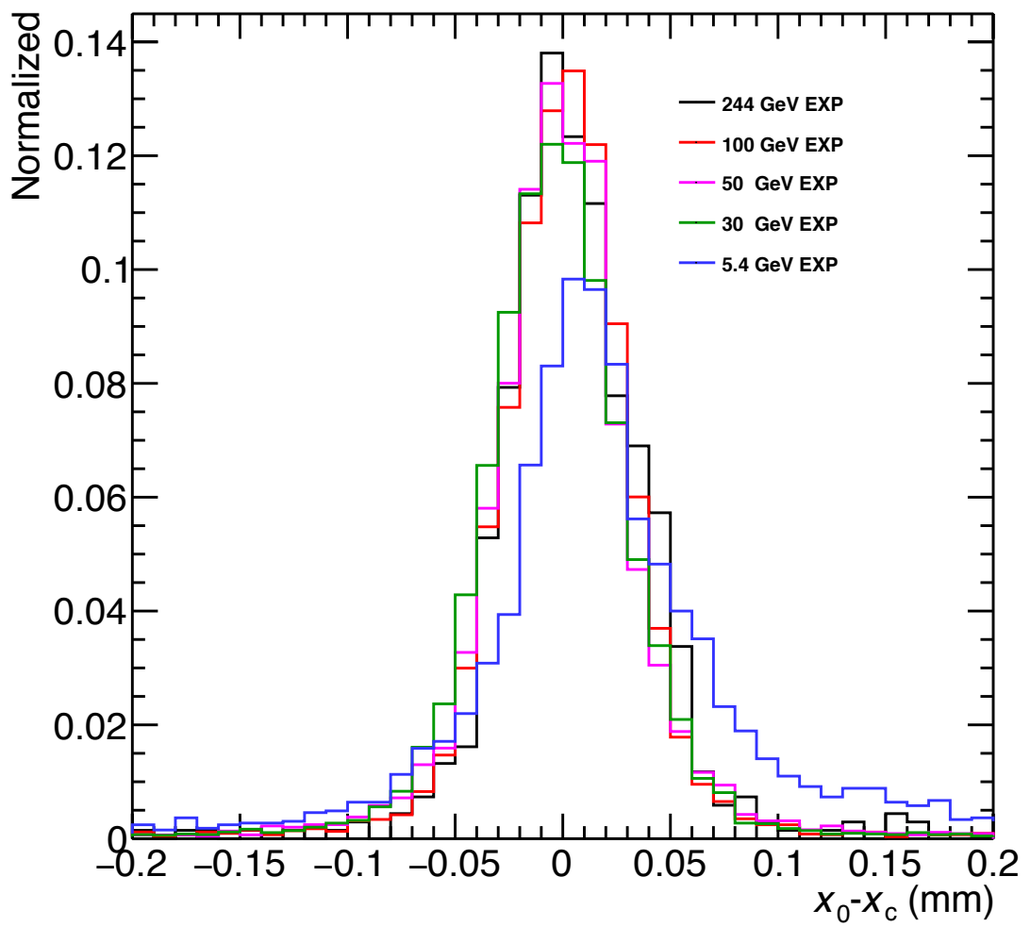
reasonable energy resolution

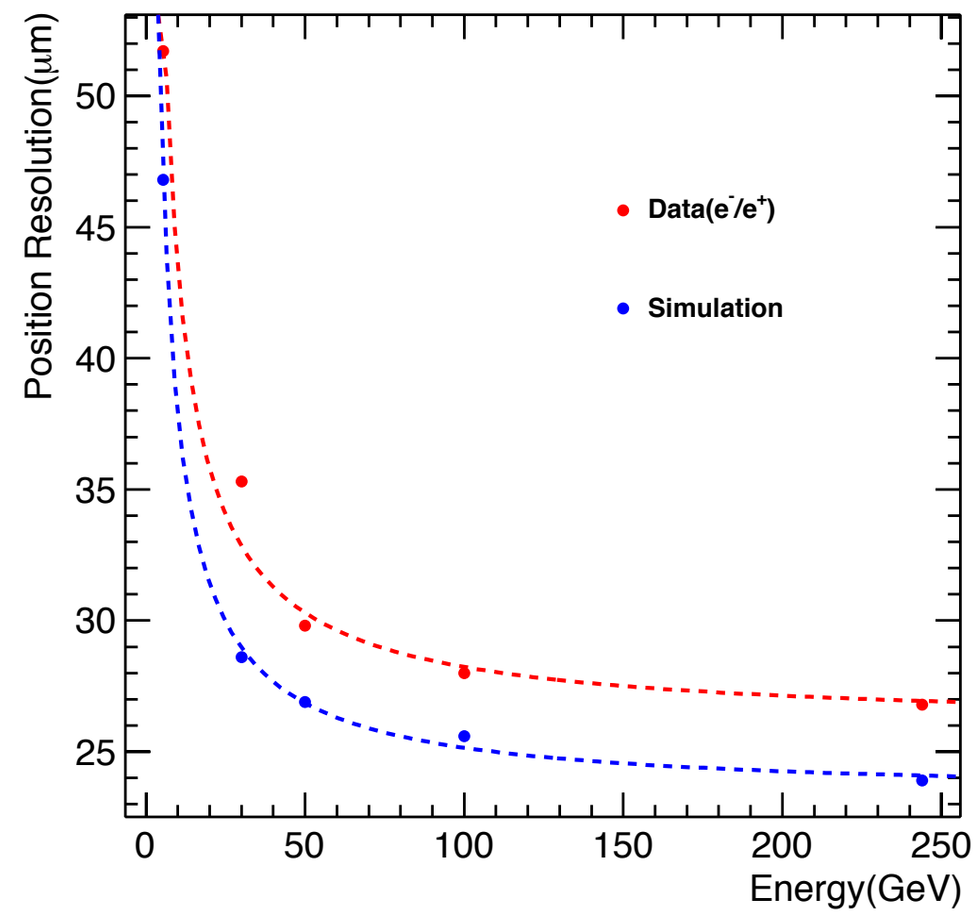
- better results expected from LGL
- note: sampling fraction < 1/1000
- possibly still improve calibration, better sensor (ALPIDE) in the future

proof of principle of digital calorimetry

first paper published: JINST 13 (2018) P01014
https://arxiv.org/abs/1708.05164

R&D - Position Resolution





calculate difference of position from

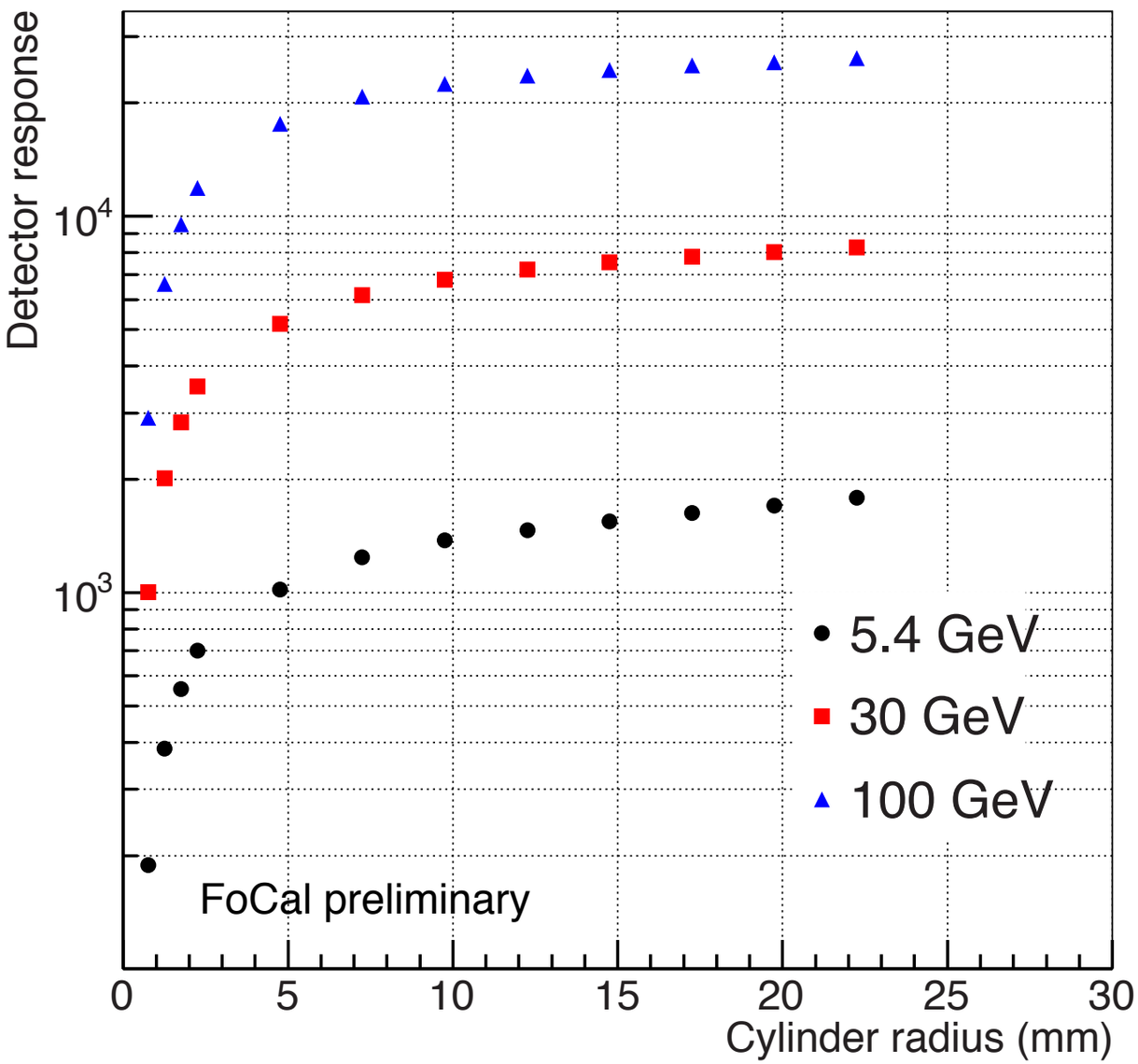
- cluster in layer 0 and
- center of gravity of shower in layers 1 - 23

single shower position resolution obtained from width of residuals

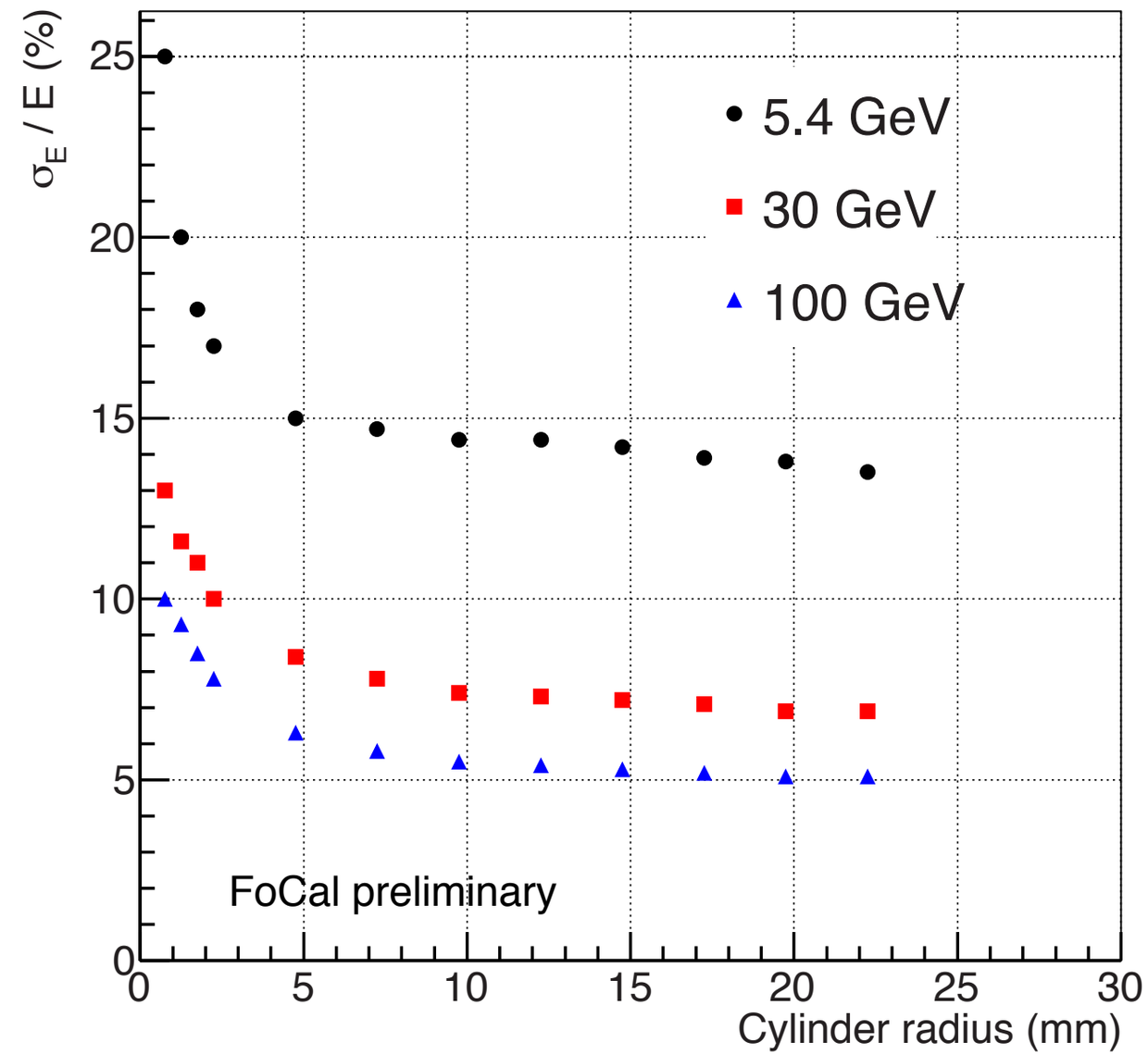
can also provide excellent two-shower separation

R&D Results: Core Energy

detector response (number of hits)



energy resolution

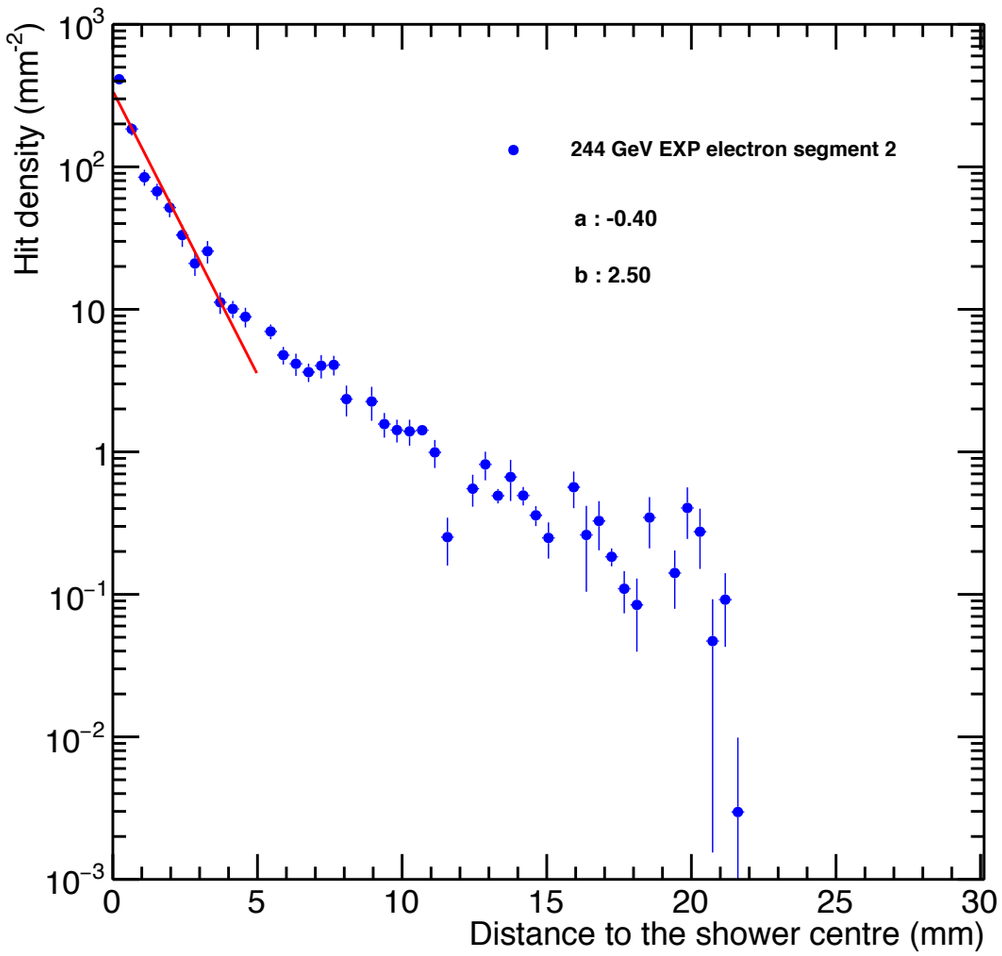


reasonable energy resolution of pixel calorimeter, sufficient for conceptual design

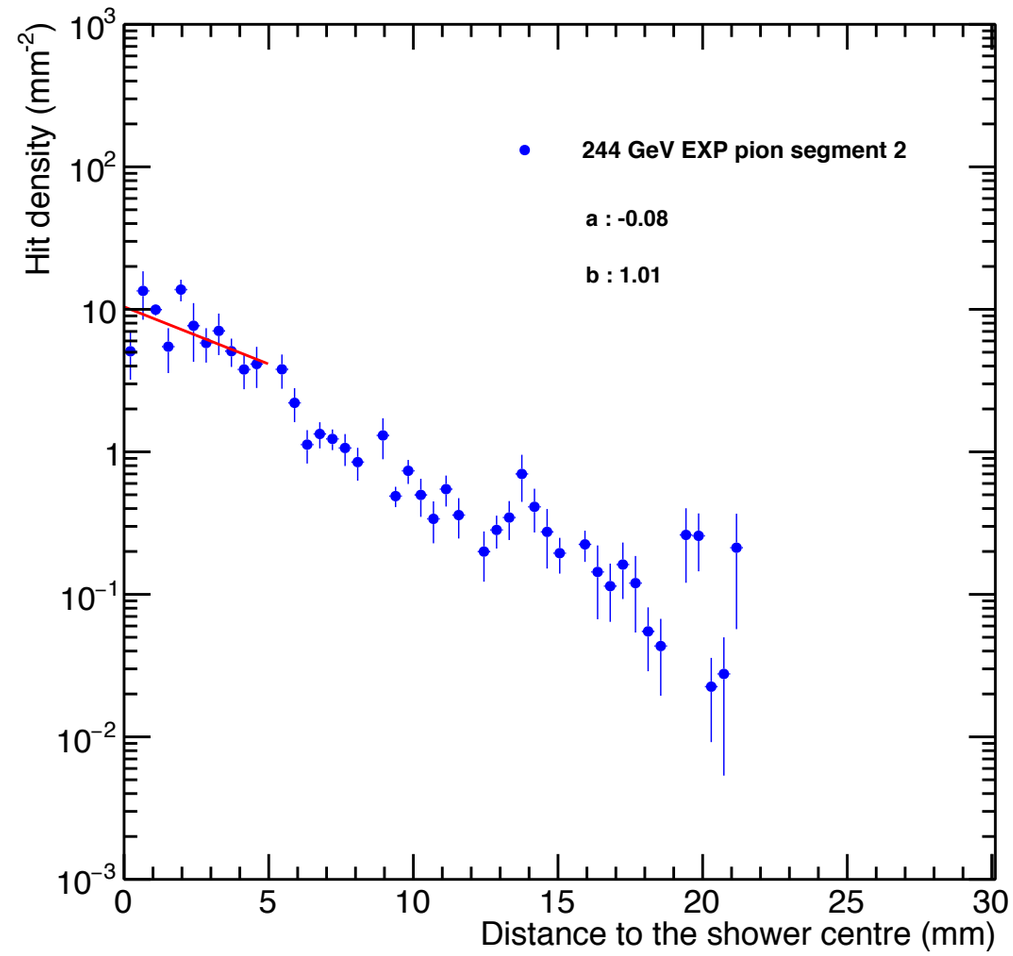
response and resolution for core energy hardly affected down to r = 5mm:
adequate for very high particle density

Pixel (HGL) R&D Results: Single Event Profiles

electron



pion



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

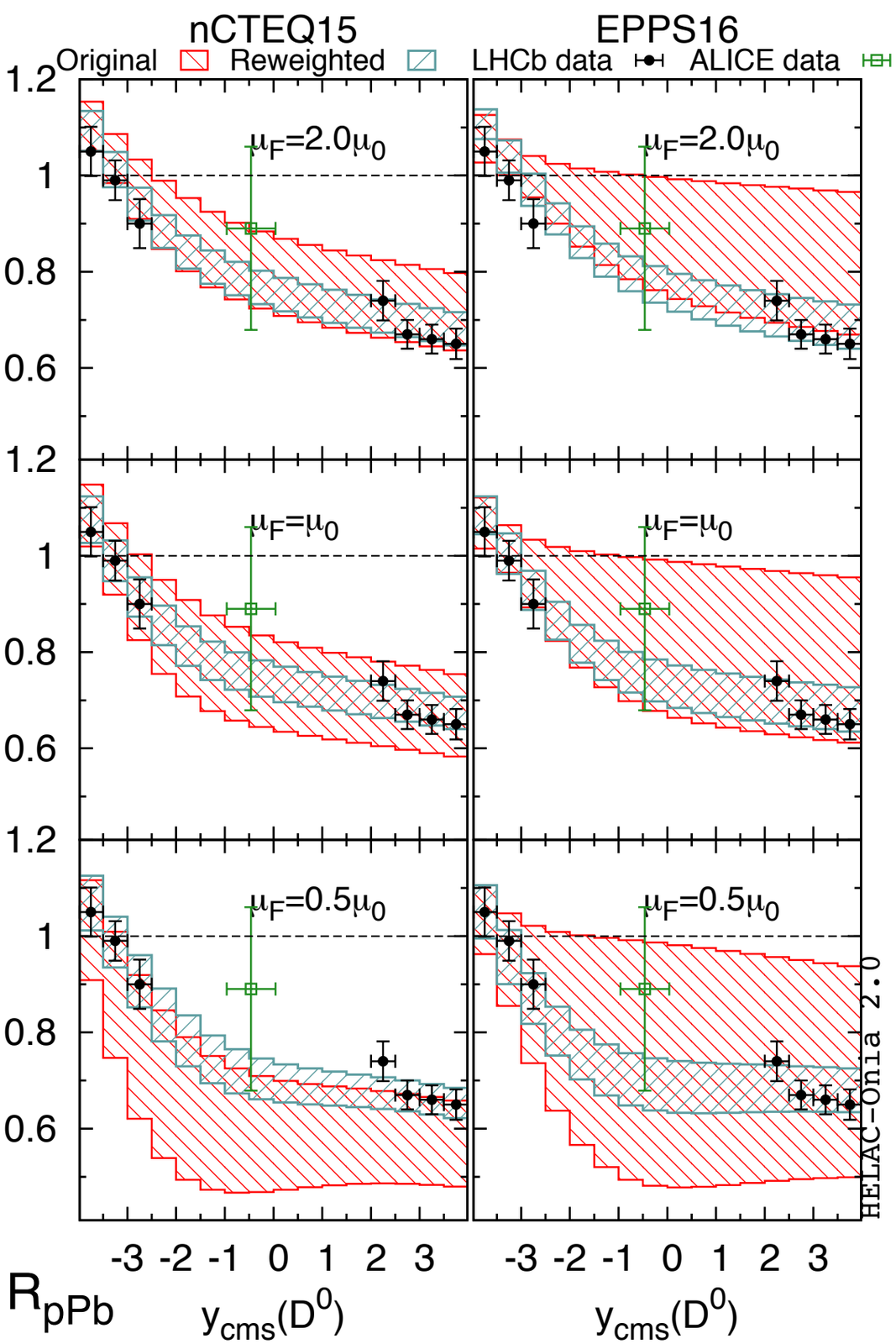
Summary

- 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

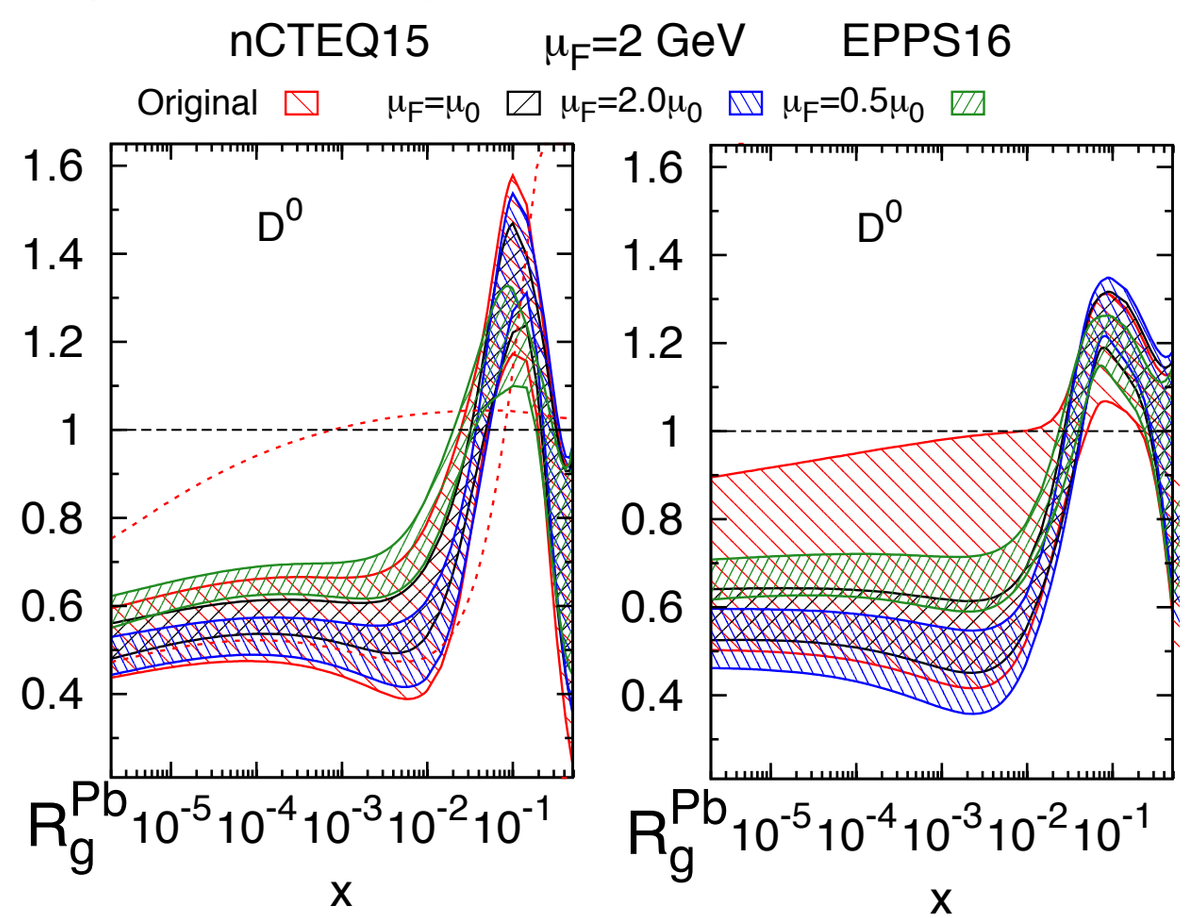
Backup Slides

Recent: PDF Fits Using Charm

Kusina et al., arXiv:1712.07024



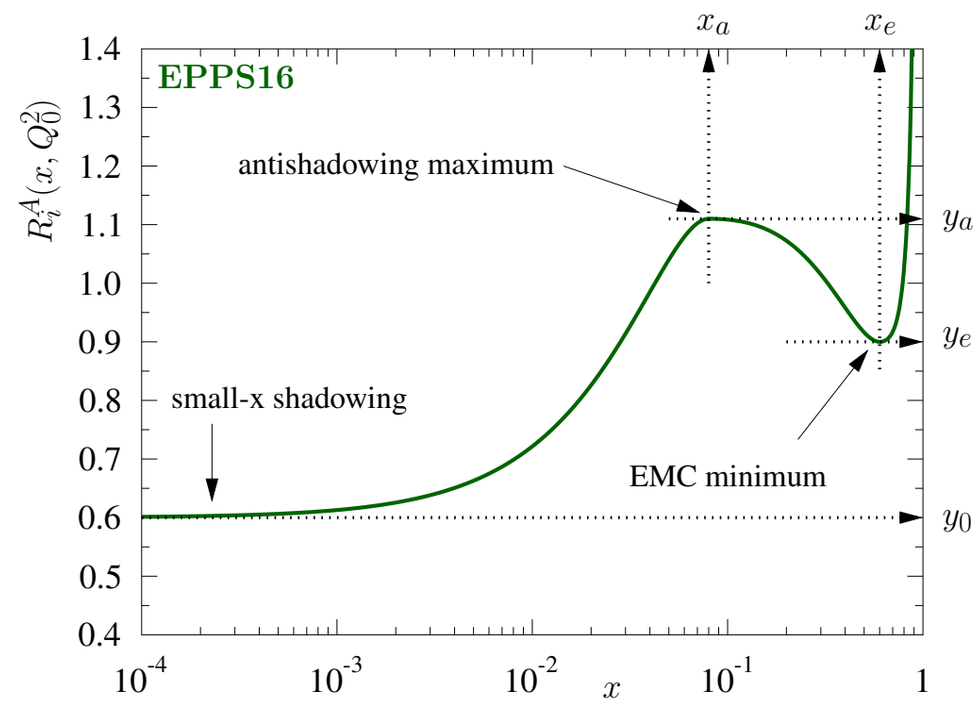
- open charm used in re-weighting
  - significant reduction of uncertainties
  - significant suppression – on the low side of current PDFs
  - significant pQCD uncertainties (scale, fragmentation)
  - relies on shape of parameterisation: very little *x*-dependence at low *x*!



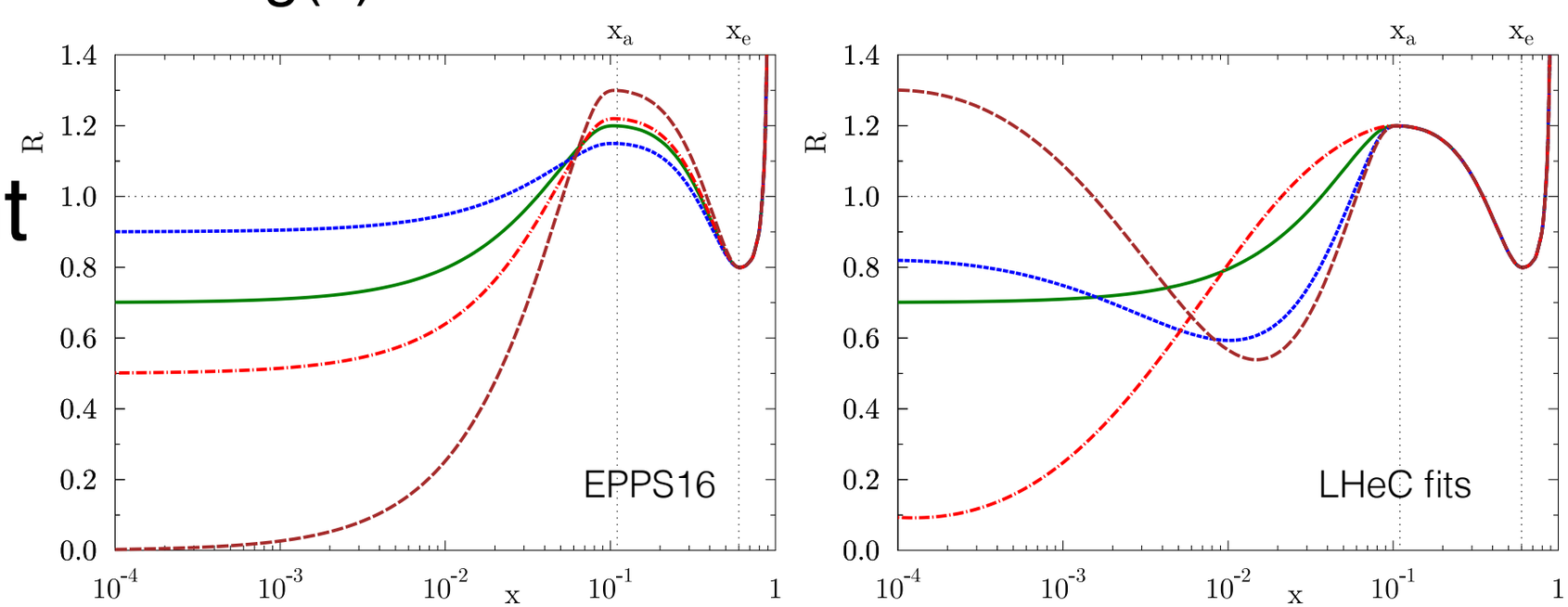
x-Dependence of PDF modification

EPPS16, EPJC 77, 163

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



- 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

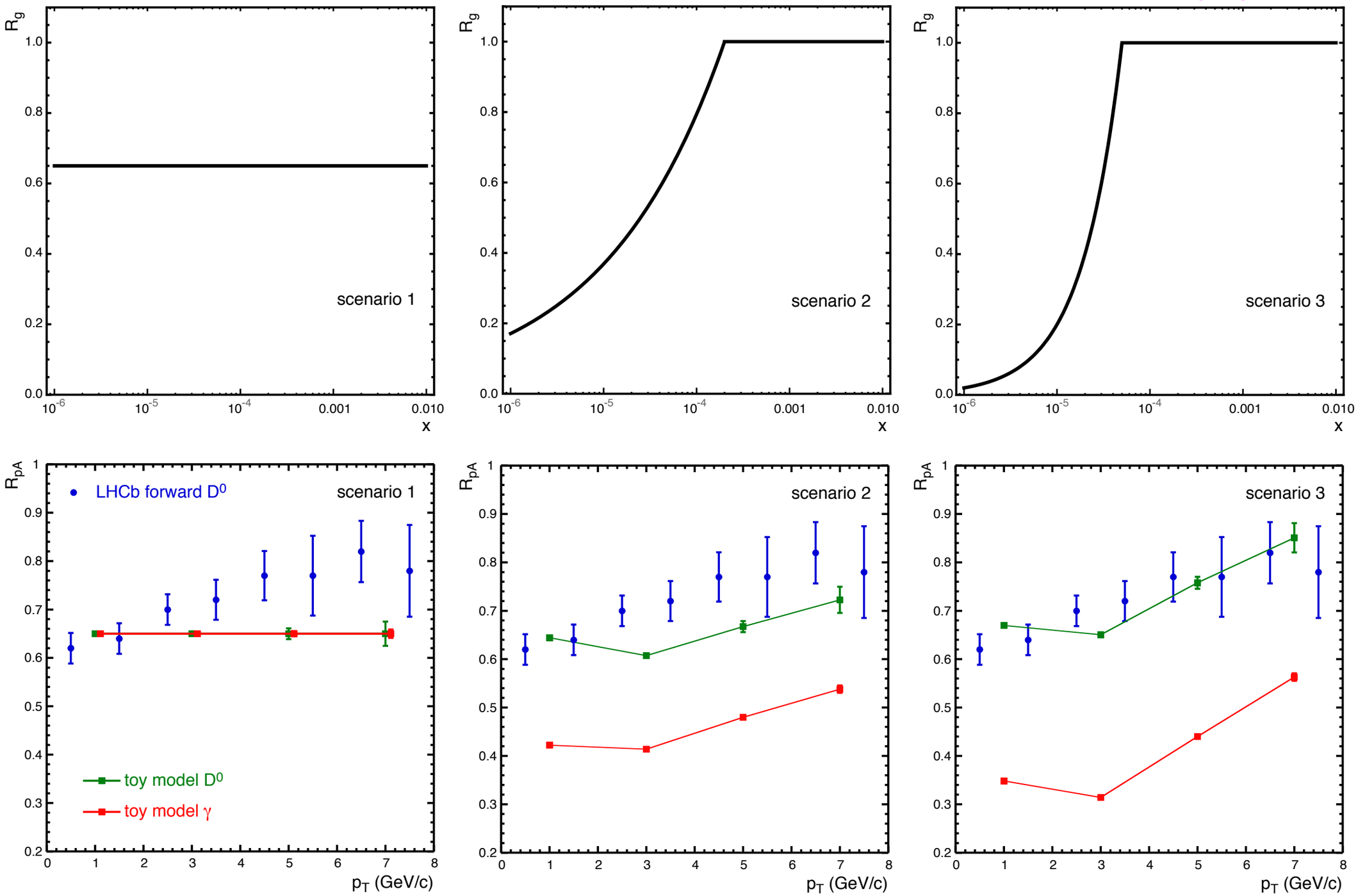


Helenius, Paukkunen, Armesto, arXiv:1606.09003

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

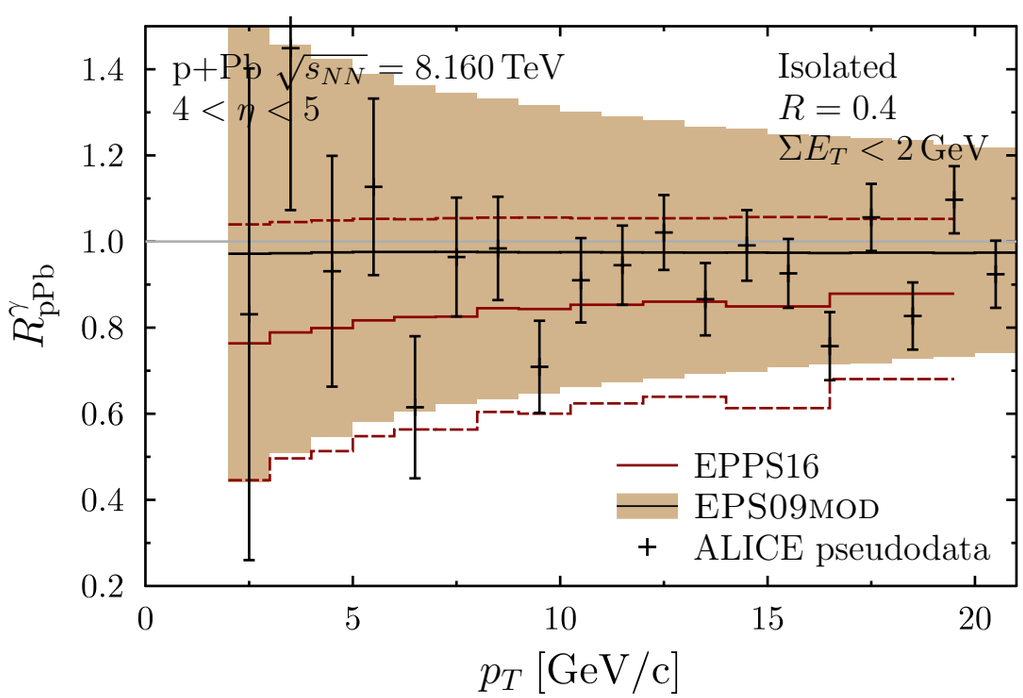
reflected in nuclear modification factor

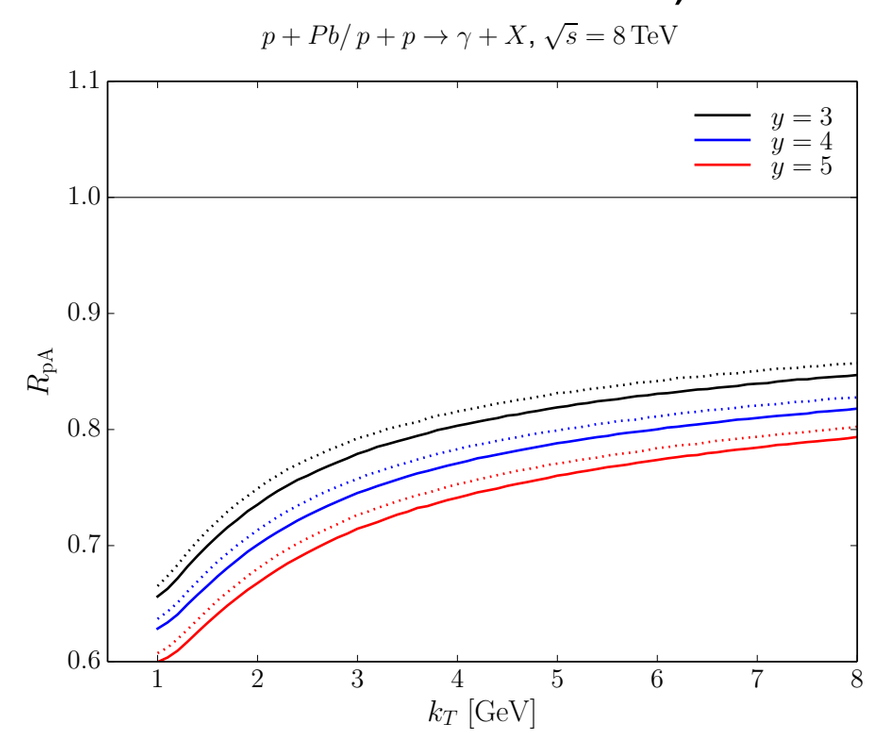
$$R_{pA} = \frac{\int dx \; d\sigma/dx(p_T, y) \cdot R_g(x)}{\int dx \; d\sigma/dx(p_T, y)}$$

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

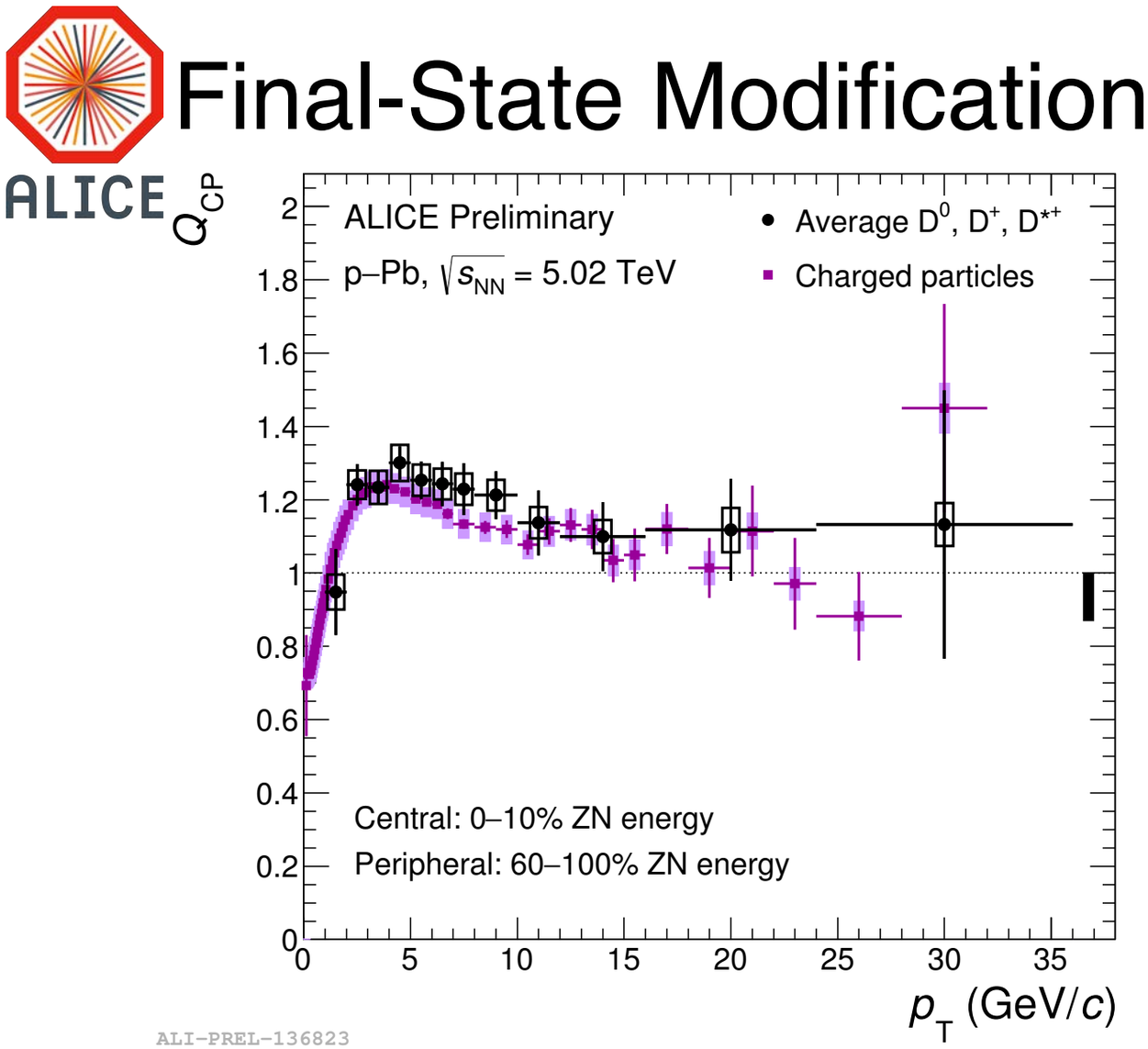
- main observable: nuclear modification factor R_{pA} of direct photons
  - saturation stronger in nuclei
  - possibly non-existent in protons (calculation of reference in models?)





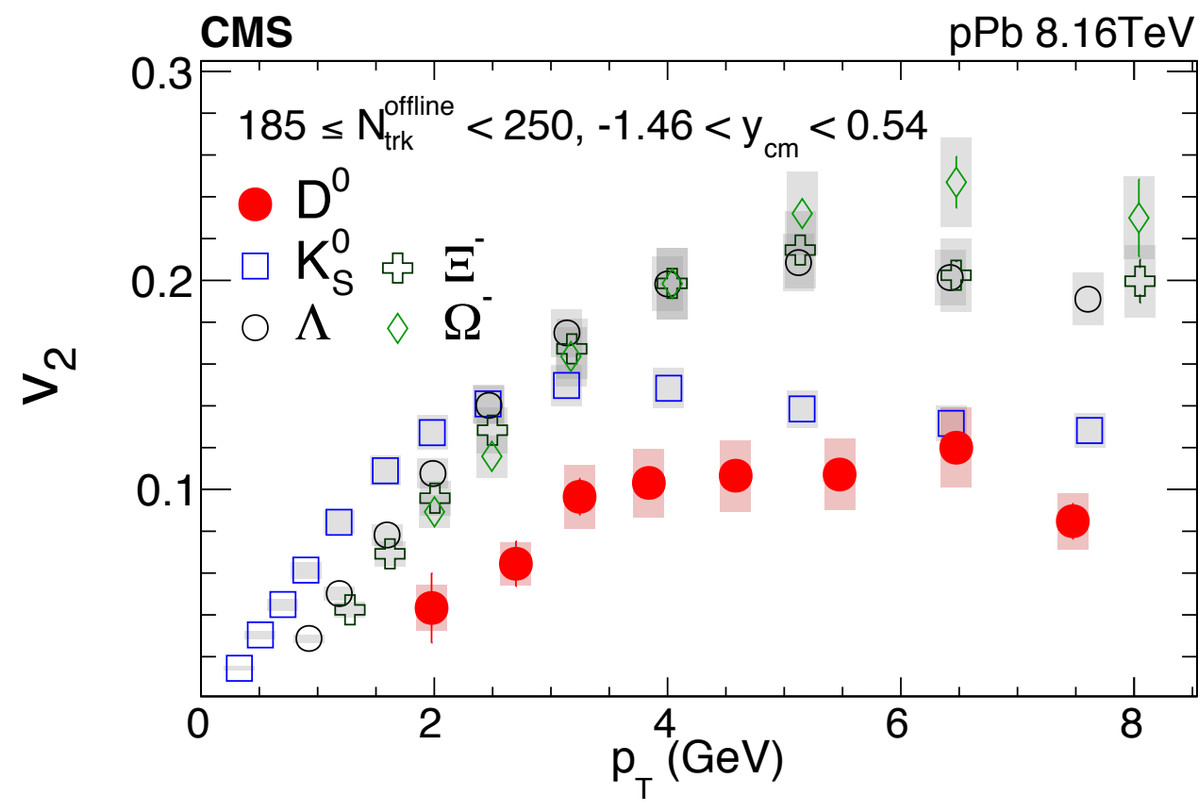
CGC Calculation: Ducloué, Lappi, Mäntysaari, arXiv:1210.02206

Final-State Modification of Open Charm in p–A?



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

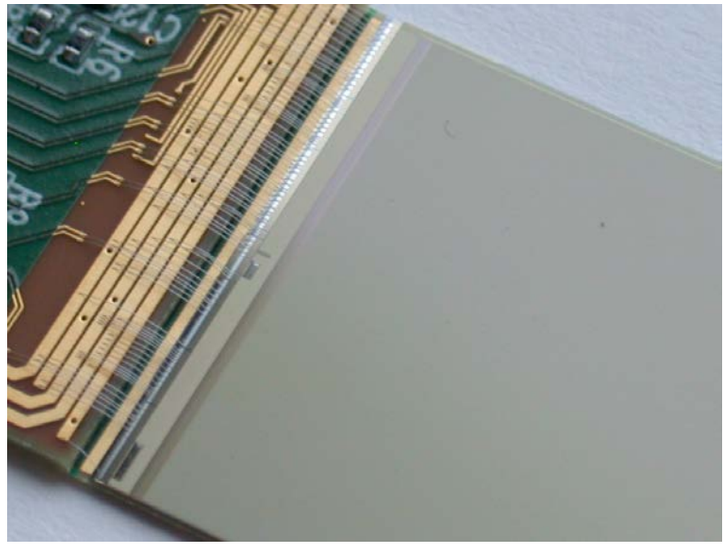
CMS Collaboration, CERN-EP-2018-076

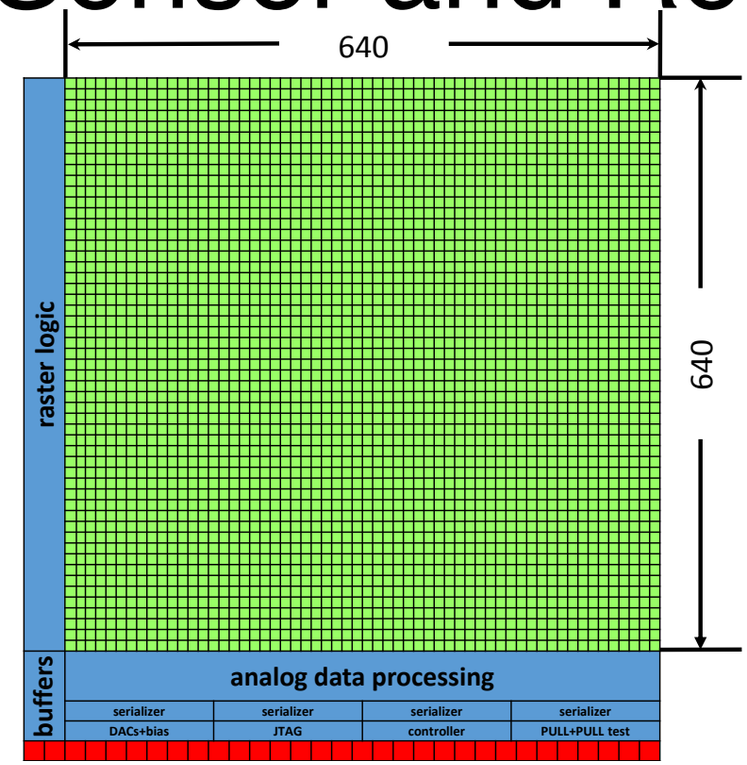


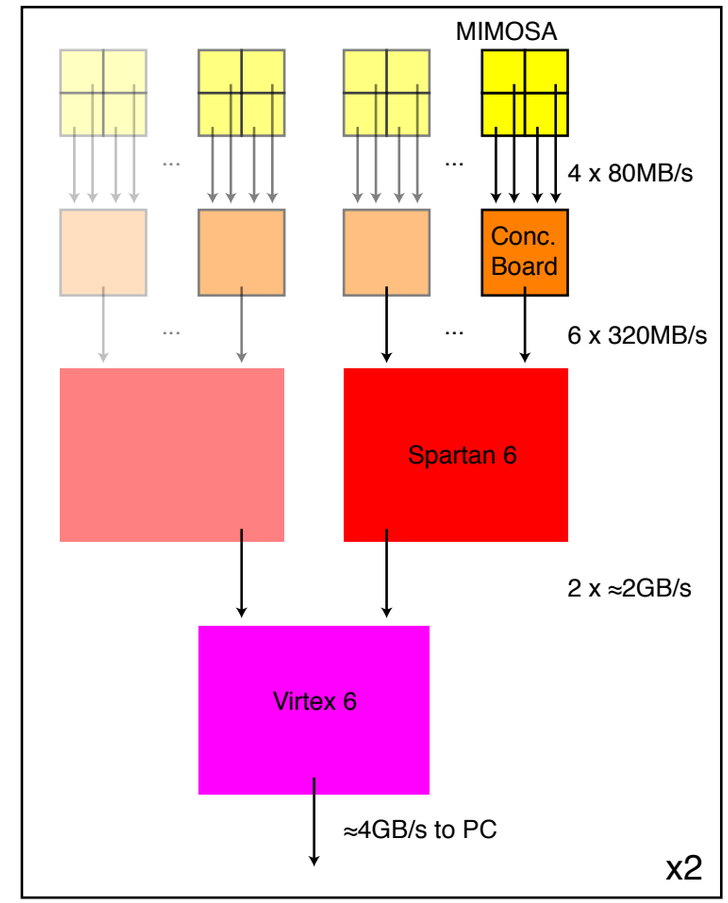
significant v_2 for D mesons,
similar results for HF-decay leptons

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

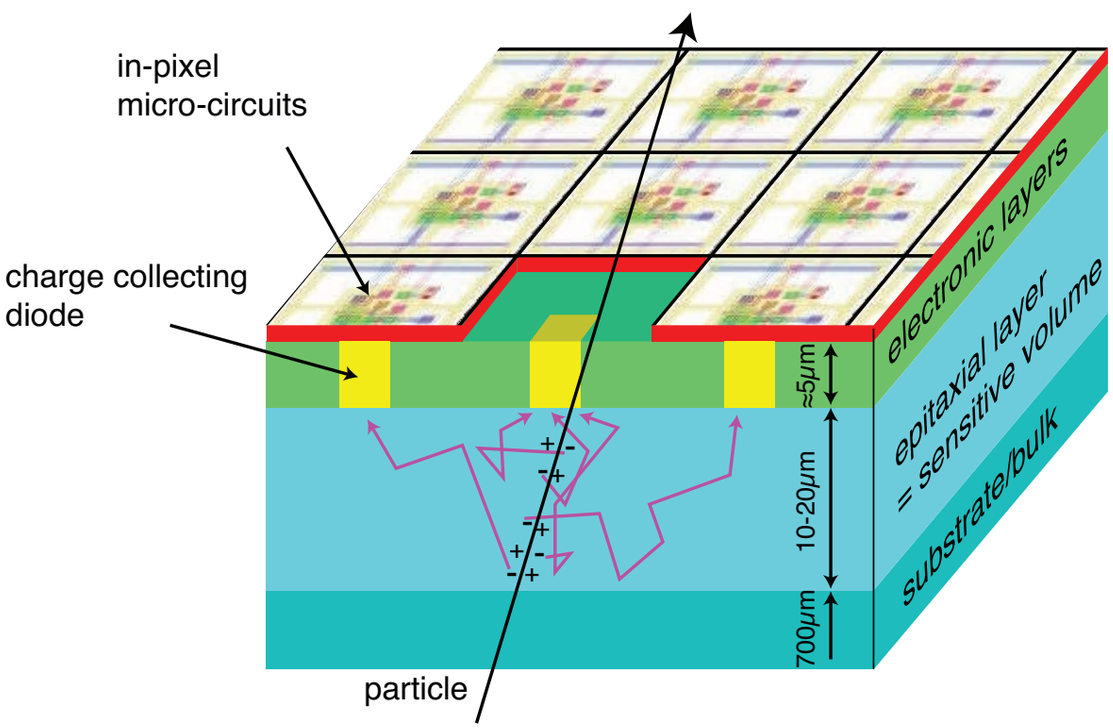
Sensor and Readout







MAPS sensor:
MIMOSA23 (IPHC)
full frame readout



read out via 4 Spartan and 2 Virtex FPGAs

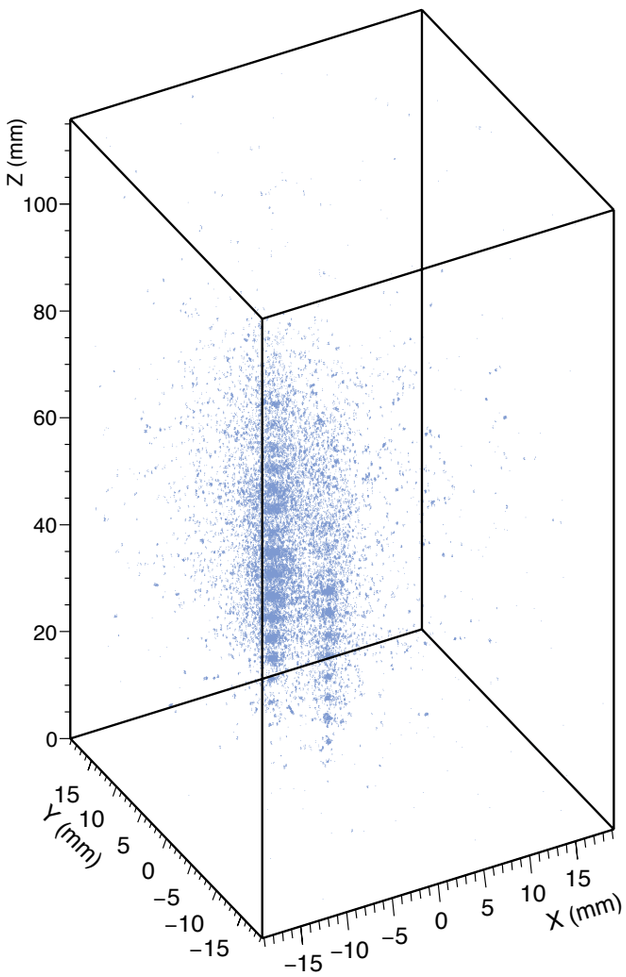
continuous data stream of 8GB/s

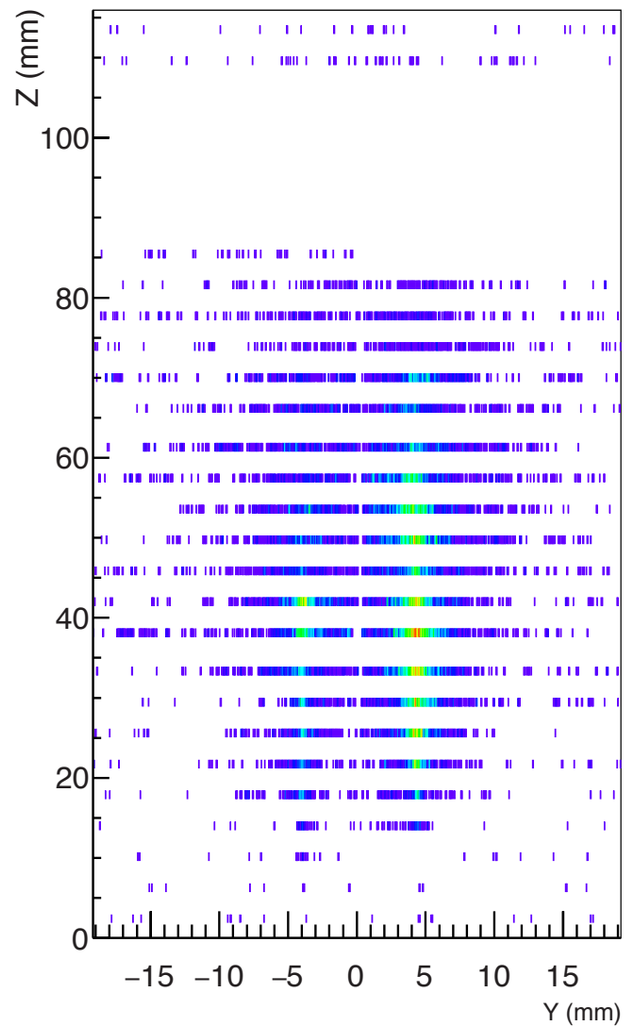
current sensor too slow (642 μs/frame)

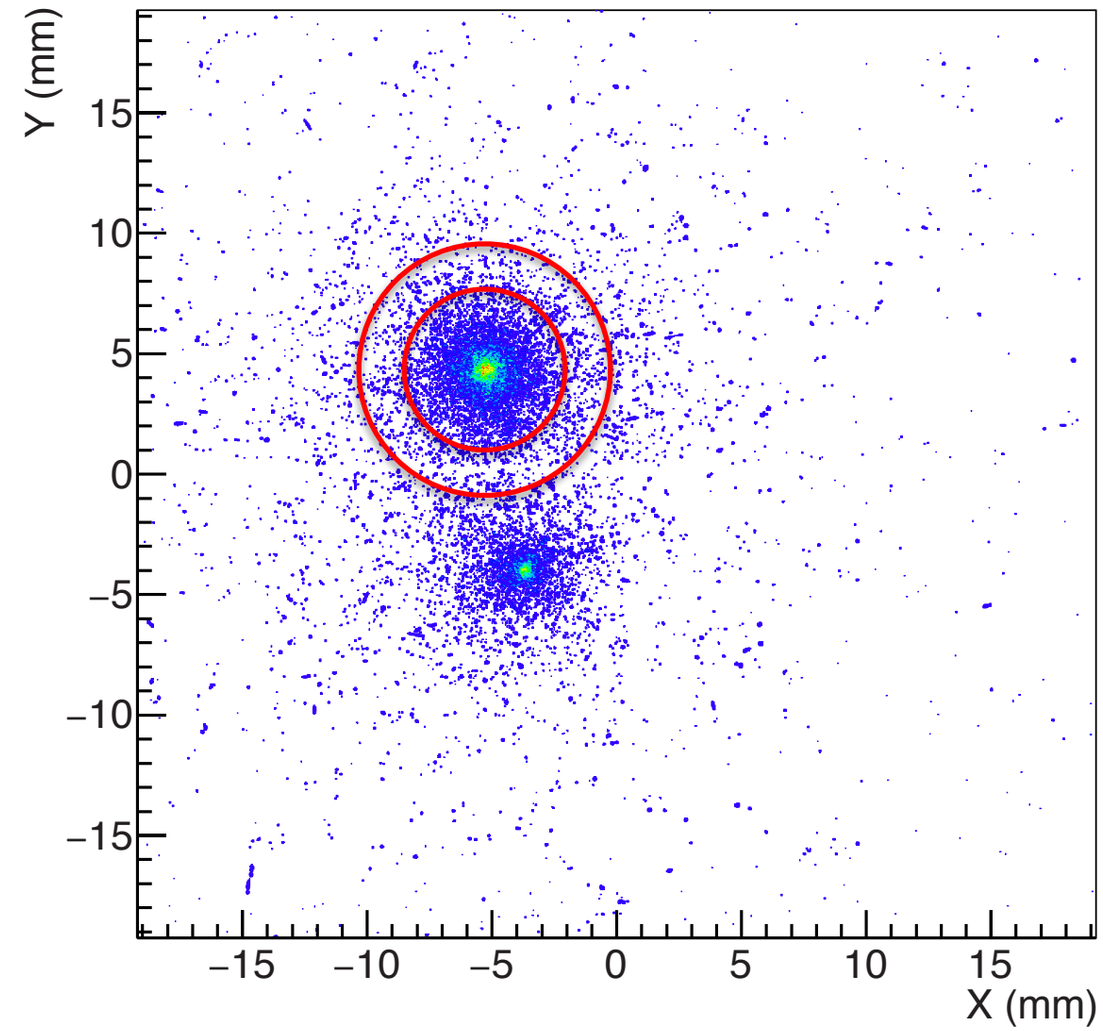
- real detector will likely use derivative of ALPIDE (ALICE-ITS upgrade)

Two Shower Separation

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



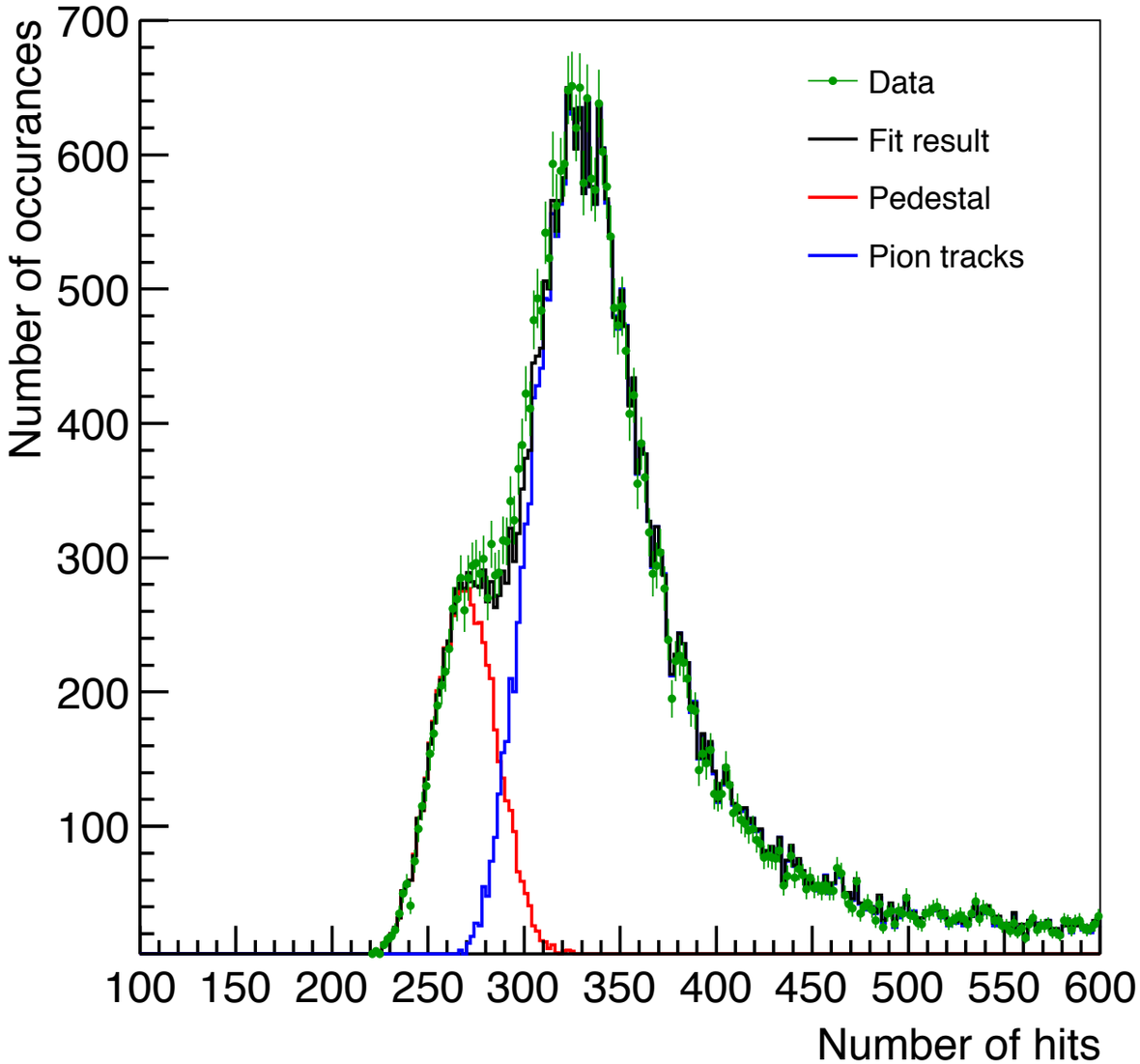


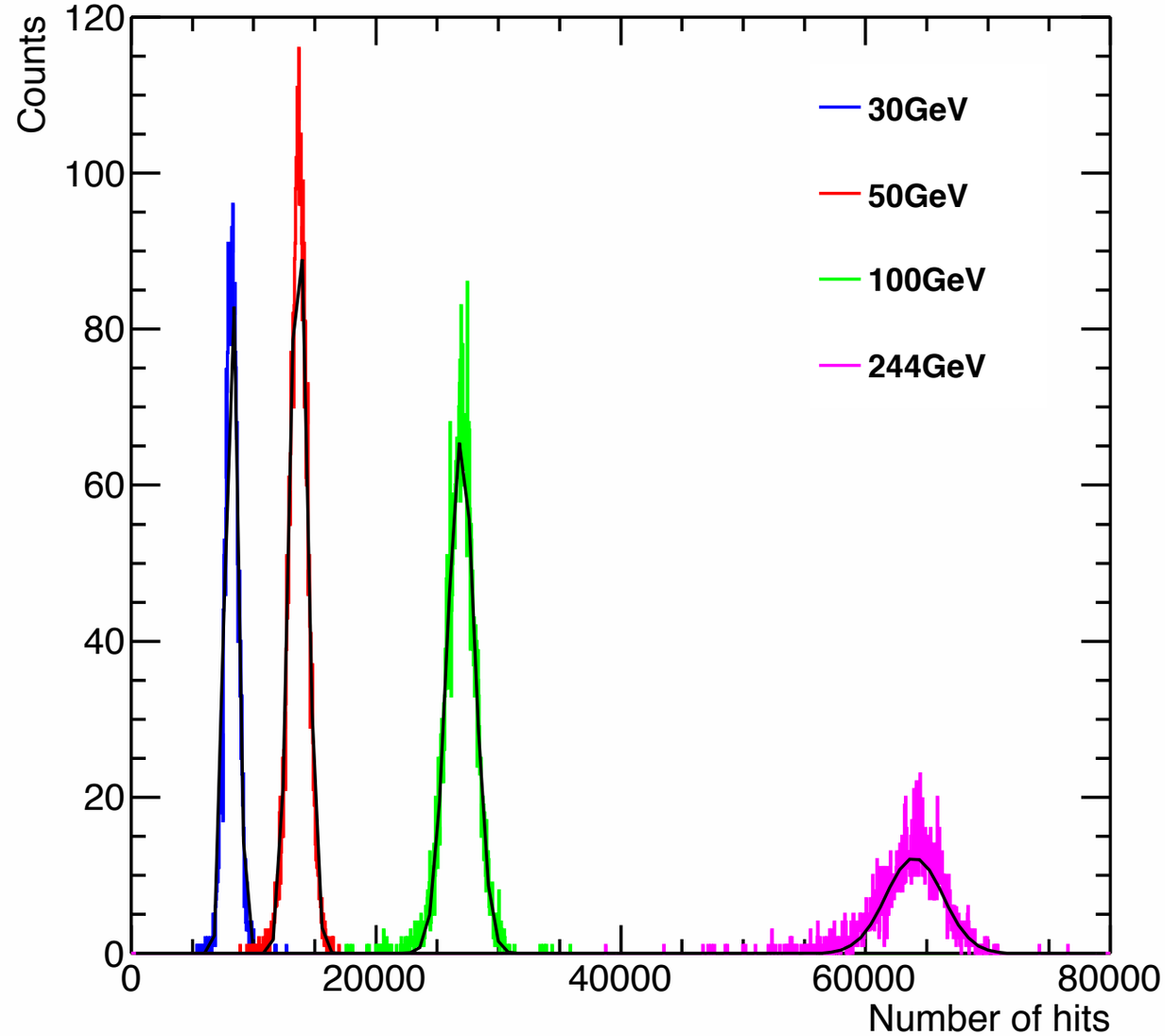


evaluate separation capability: core energy

- calculate shower energy in cylinder of finite radius
- study as function of radius

Detector Response





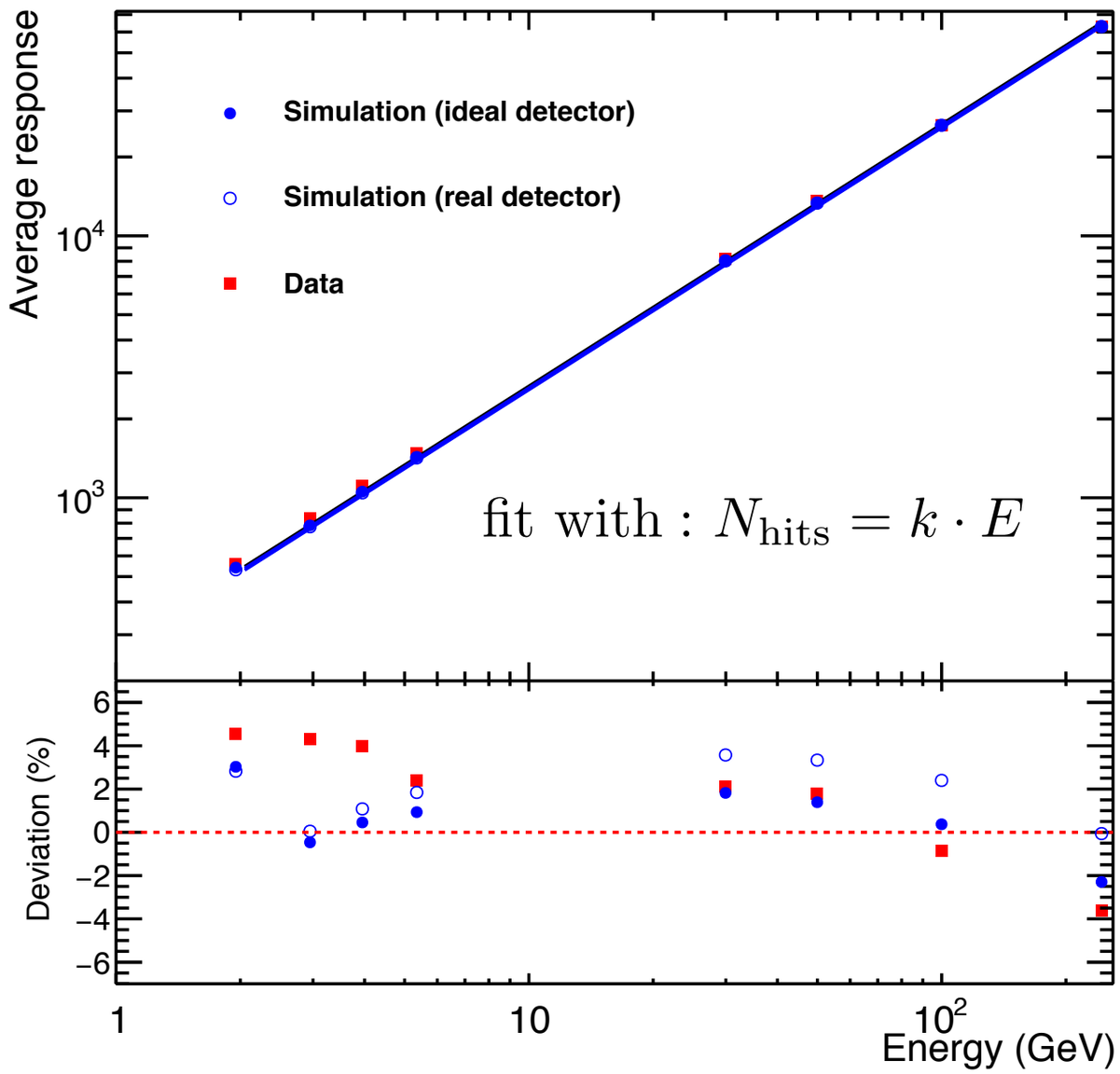
- minimum ionising particle (MIP) peak from pion tracks

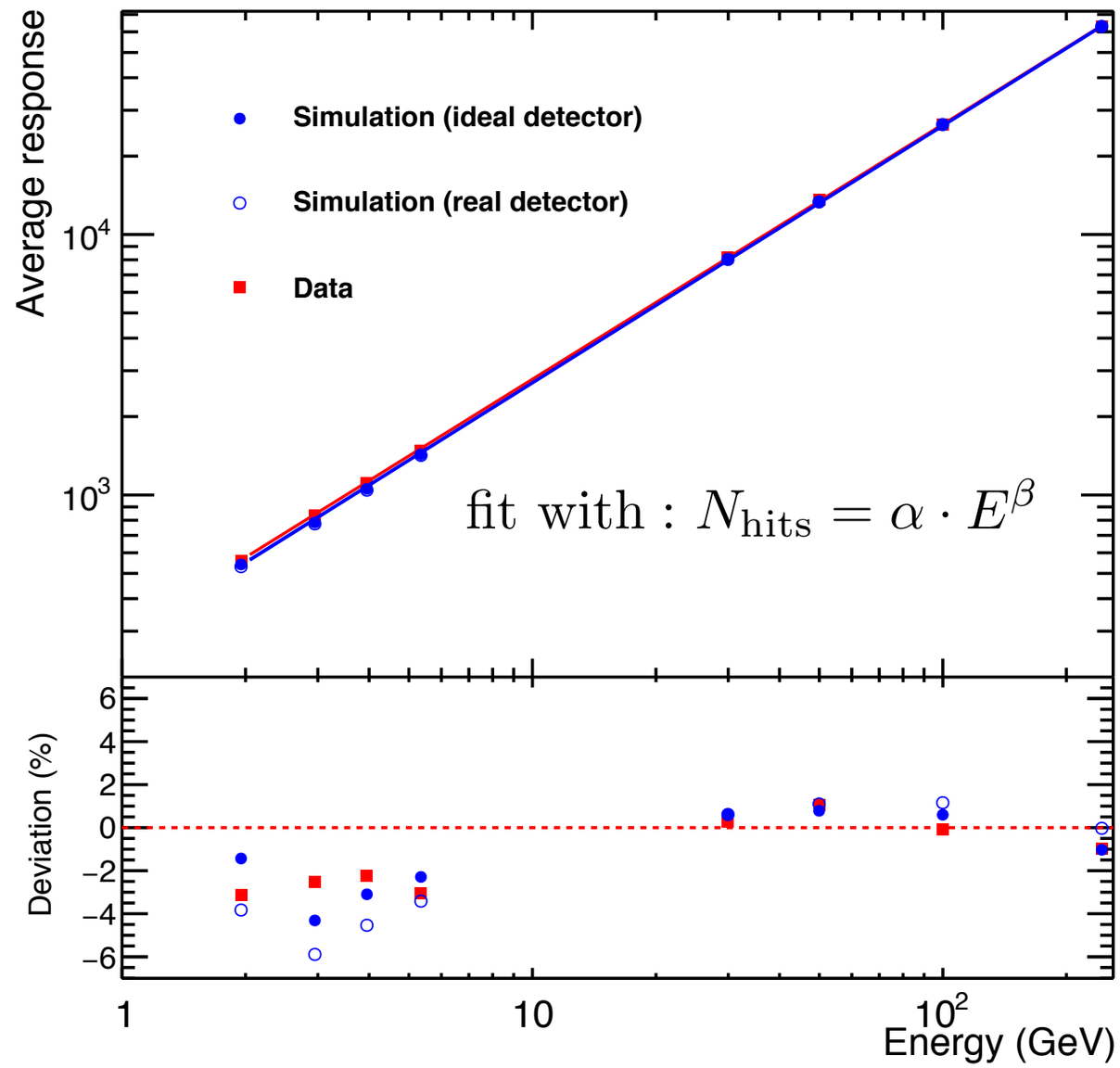
- pedestal: noise distribution of full prototype

- response to electrons from SPS test beam

- calculated from per-event hit density distributions

R&D - Energy Linearity





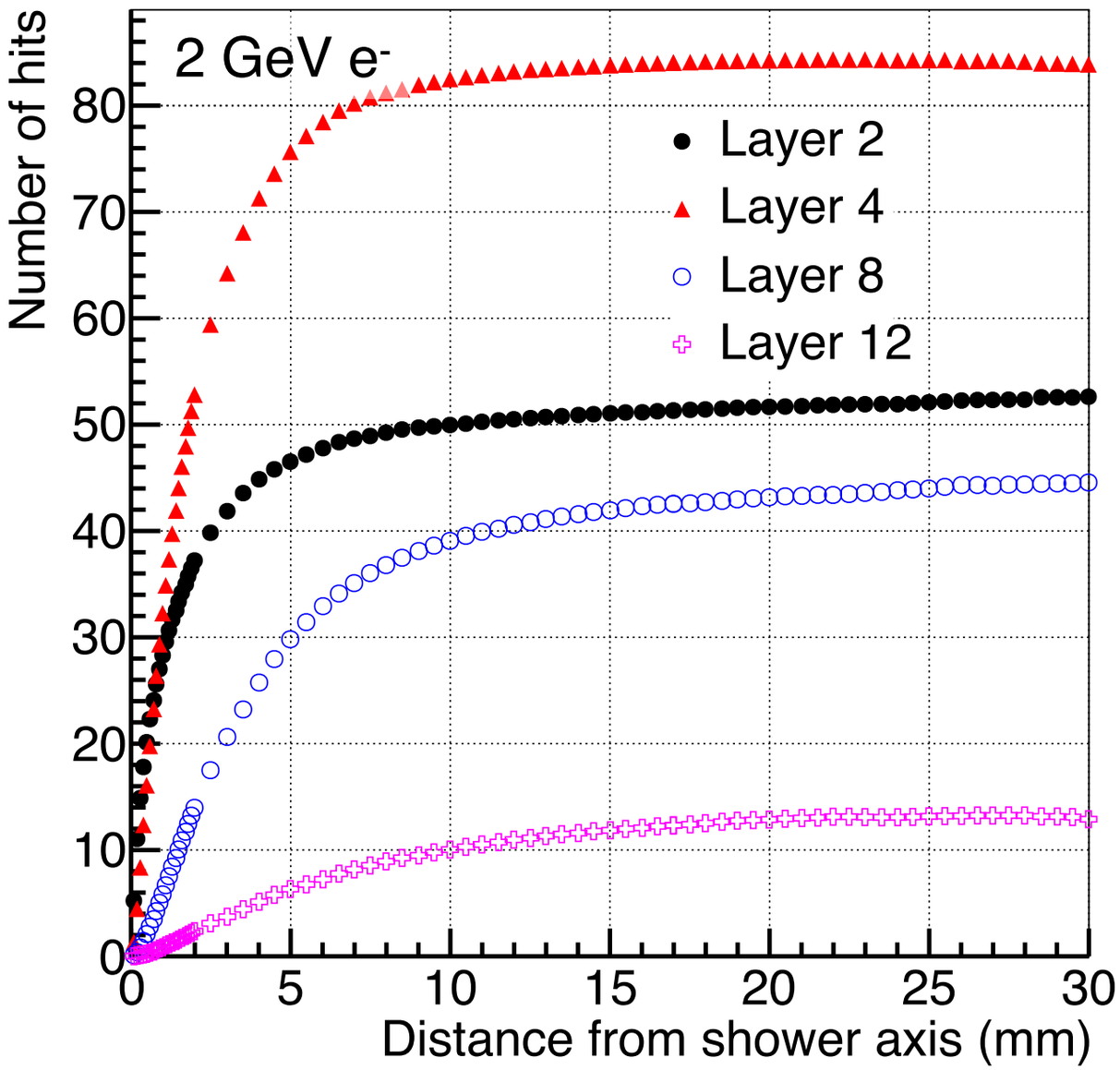
detector response from integrated event-wise hit densities

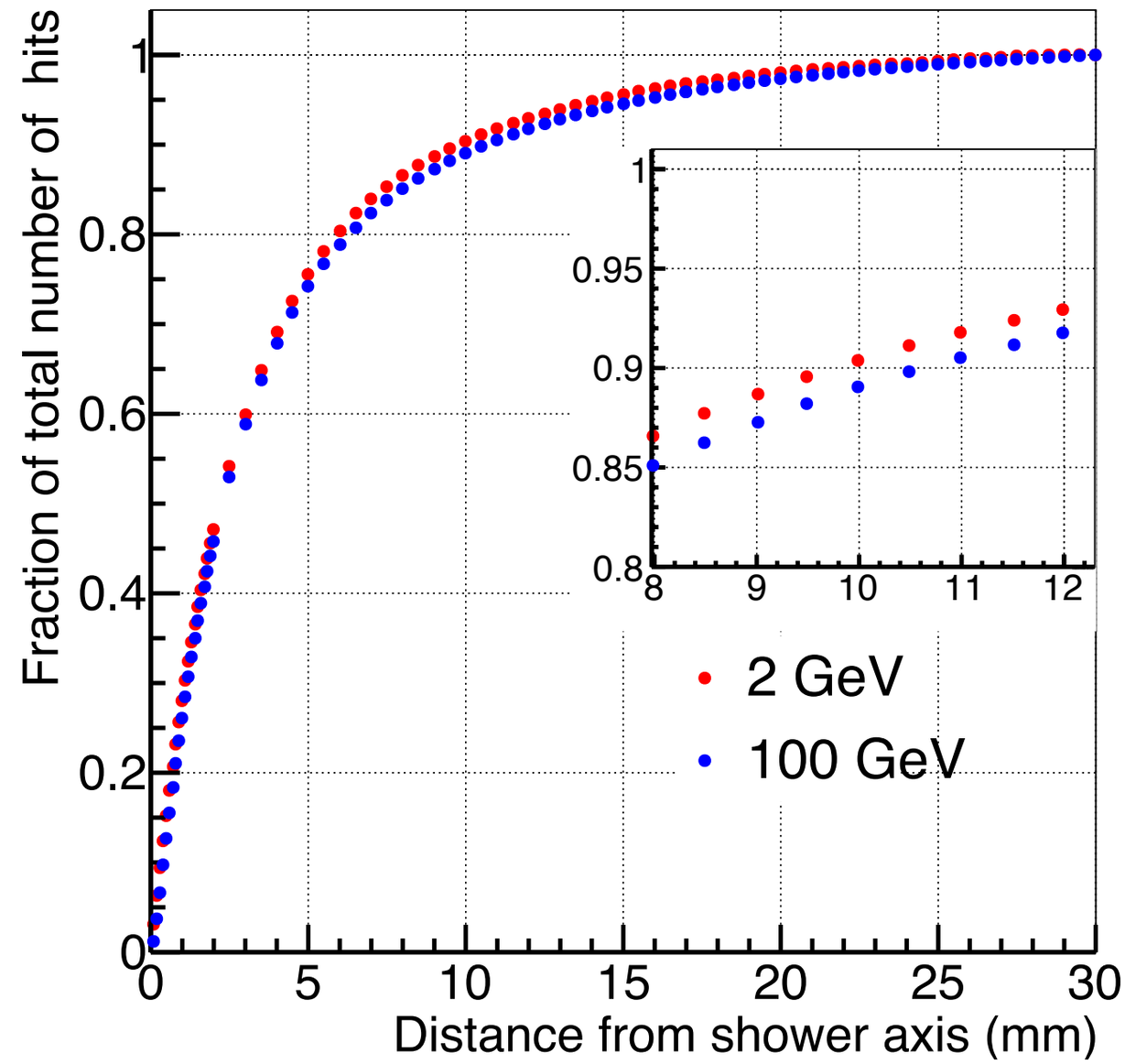
- fit with linear and power law function, good linearity (power β = 0.98)

note - not yet corrected:

- different calibration for low and high energy
- small effects of saturation at high energy

R&D - Cumulative Lateral Profiles





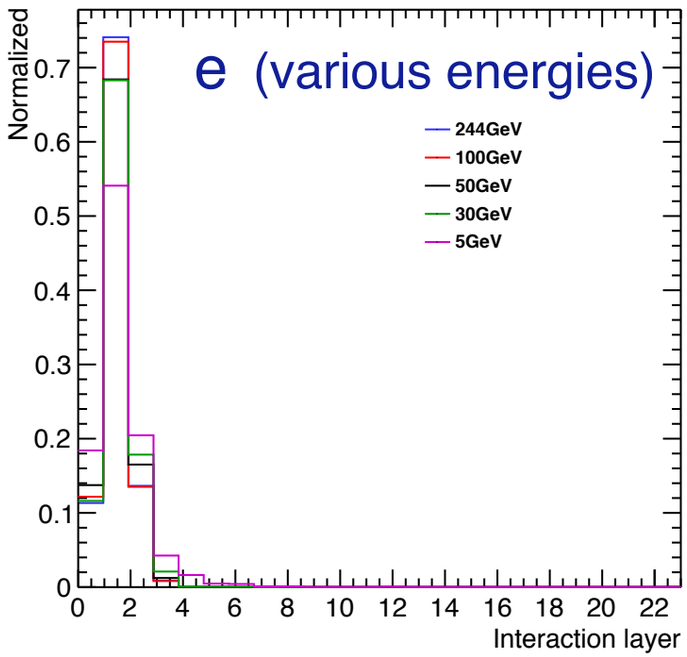
extract cumulative distributions both per layer and integrated

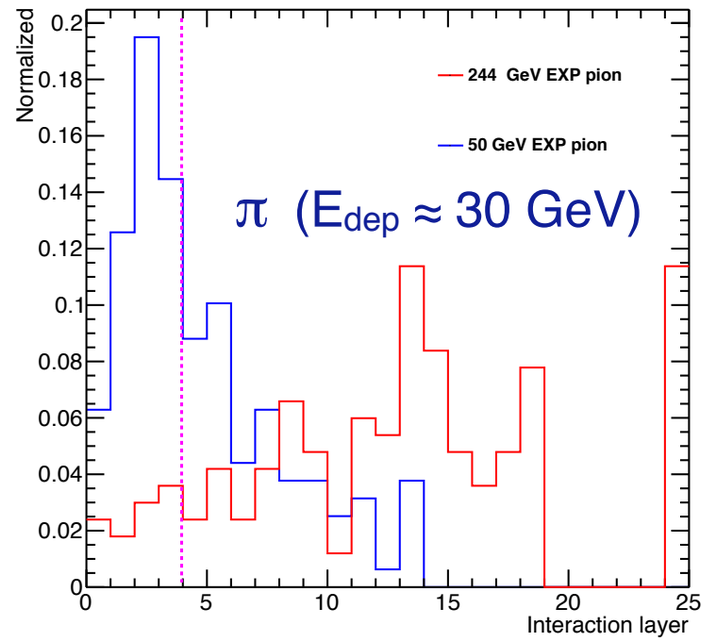
- some lateral leakage at higher energy

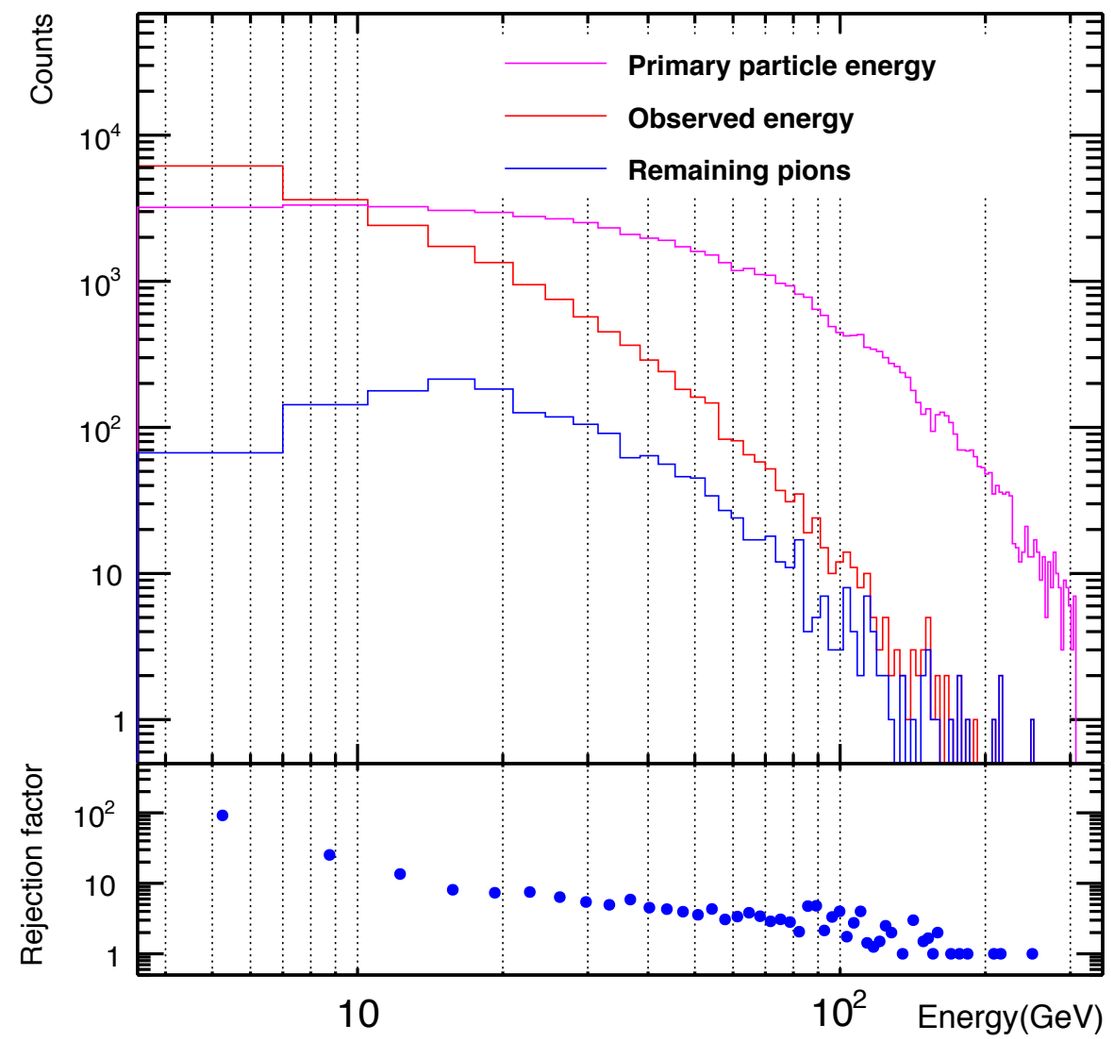
small Moliere radius: $R_M \approx 11$mm

≈ 75% of hits within R = 5mm, 50% within R = 3mm, …

R&D - Hadron Rejection







longitudinal shower shape:
cut on position of shower start

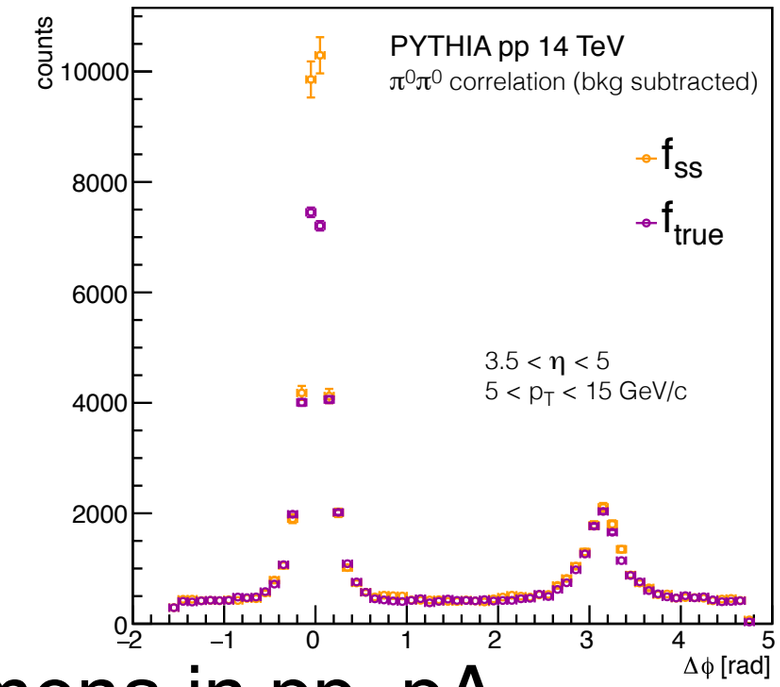
further discrimination via
transverse shower shape: slope

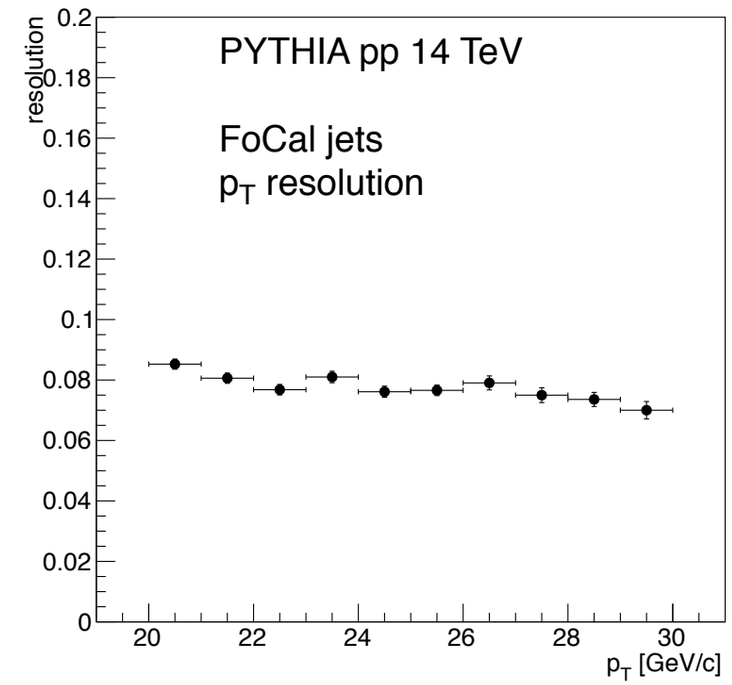
hadron rejection for realistic pion momentum spectrum:

- cases of high deposited energy suppressed from low interaction probability
- additional rejection for low deposited energy from shower shape

More FoCal Physics Topics

- low-x gluons (n)PDFs, saturation
  - direct photon R_{pA}
  - π^0-π^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