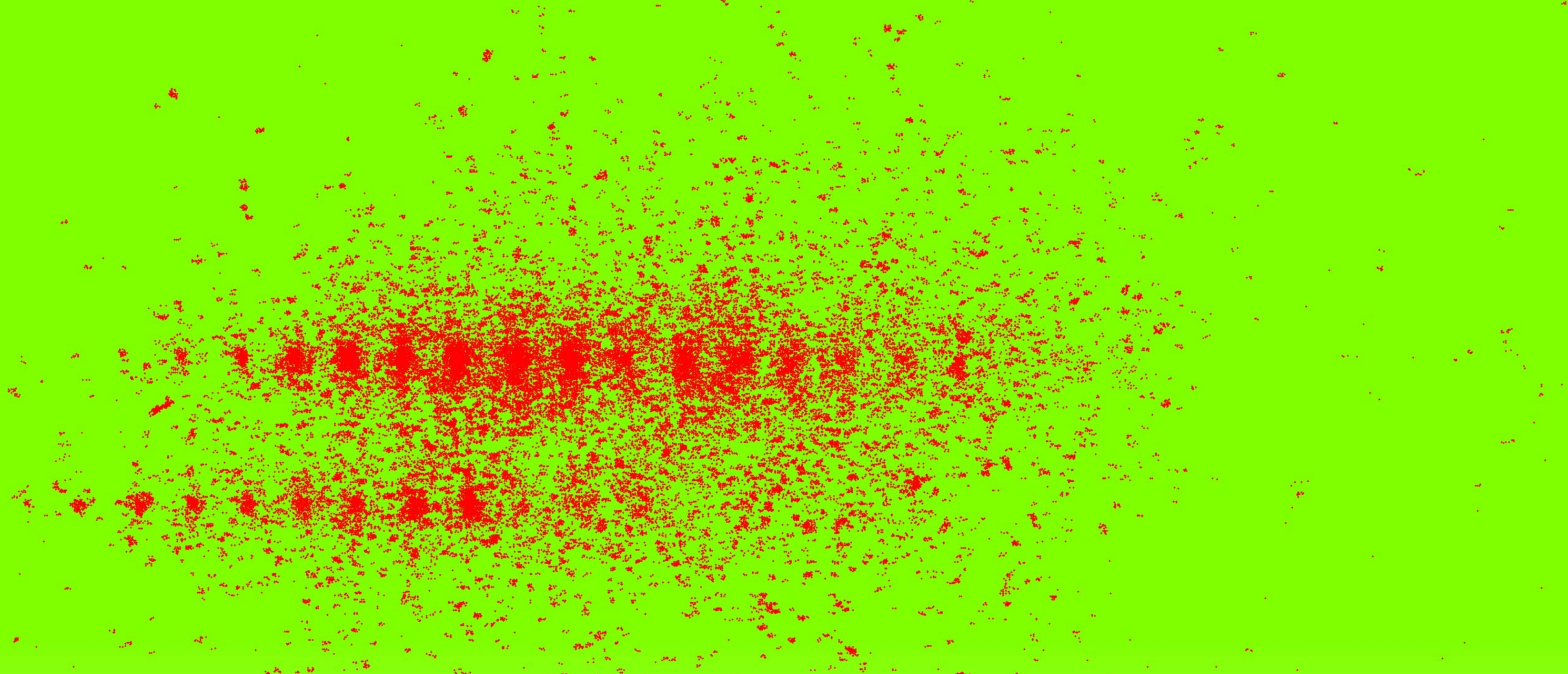


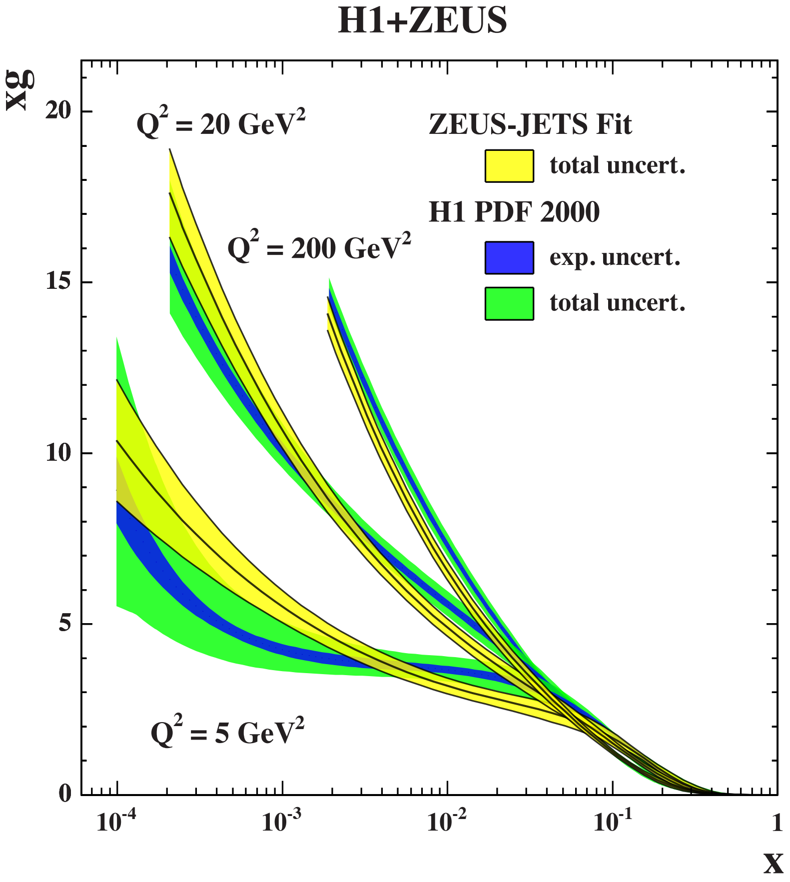
High granularity digital Si-W electromagnetic calorimeter for forward direct photon measurements at LHC

T. Peitzmann (Utrecht University/Nikhef)
for the ALICE FoCal Collaboration

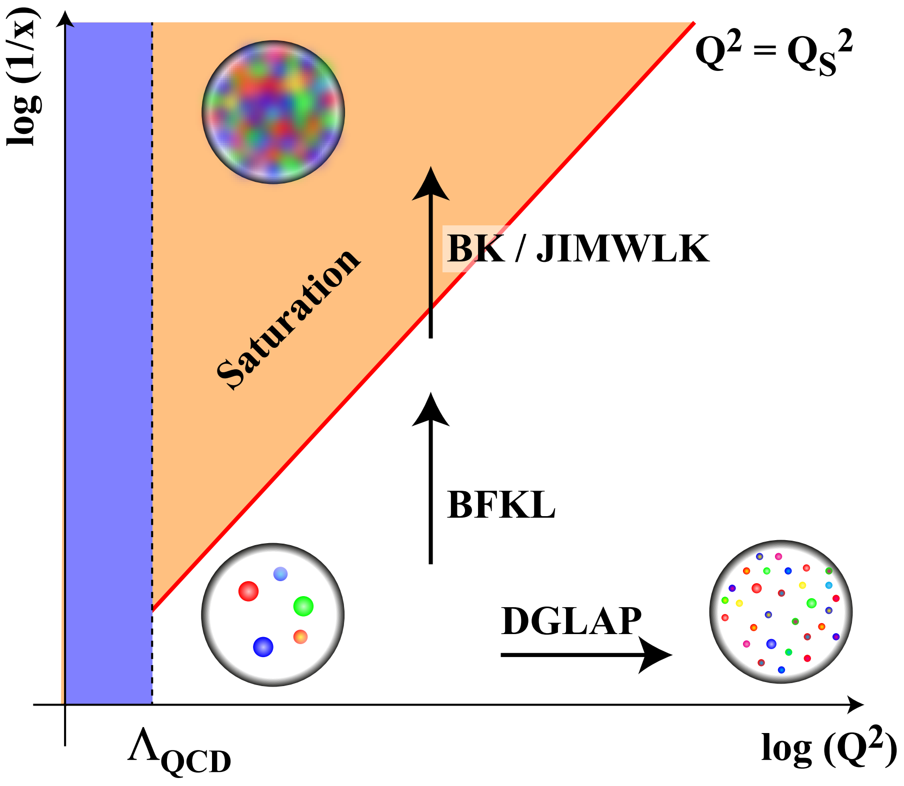
Outline

- Introduction
    - photons as a probe for gluon saturation
- FoCal - an ALICE upgrade proposal
    - baseline design
    - performance
- Research and Development
    - high-granularity digital EM calorimeter
- Summary

Photons as Probe for Gluon Saturation

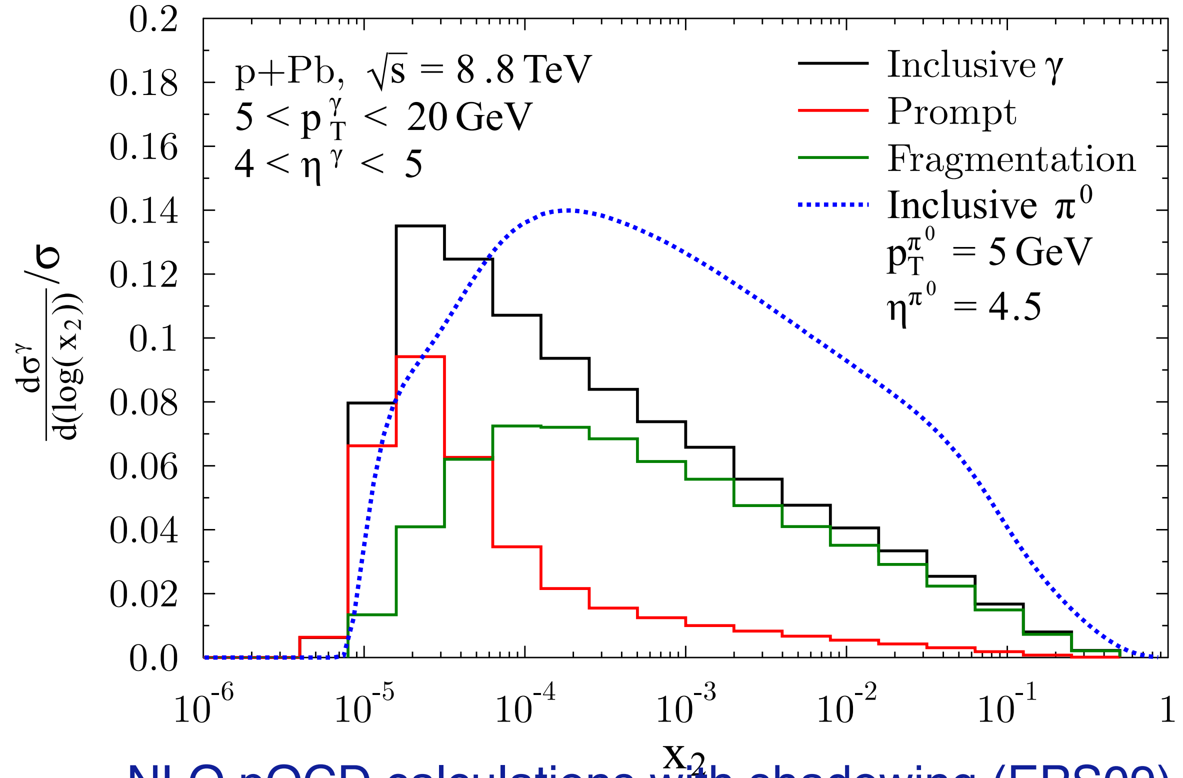


- from QCD evolution (DGLAP, BFKL):
  - gluon density increases with Q^2 and $1/x$
    - leads to very high gluon density
    - problems with unitarity(?)
- for high density non-linear processes become important
- gluon saturation below saturation scale
  - enhanced in nuclei $$Q_s^2(x) \approx \frac{\alpha_S}{\pi R^2} xG(x,Q^2) \propto A^{1/3} \cdot x^{-\lambda}$$



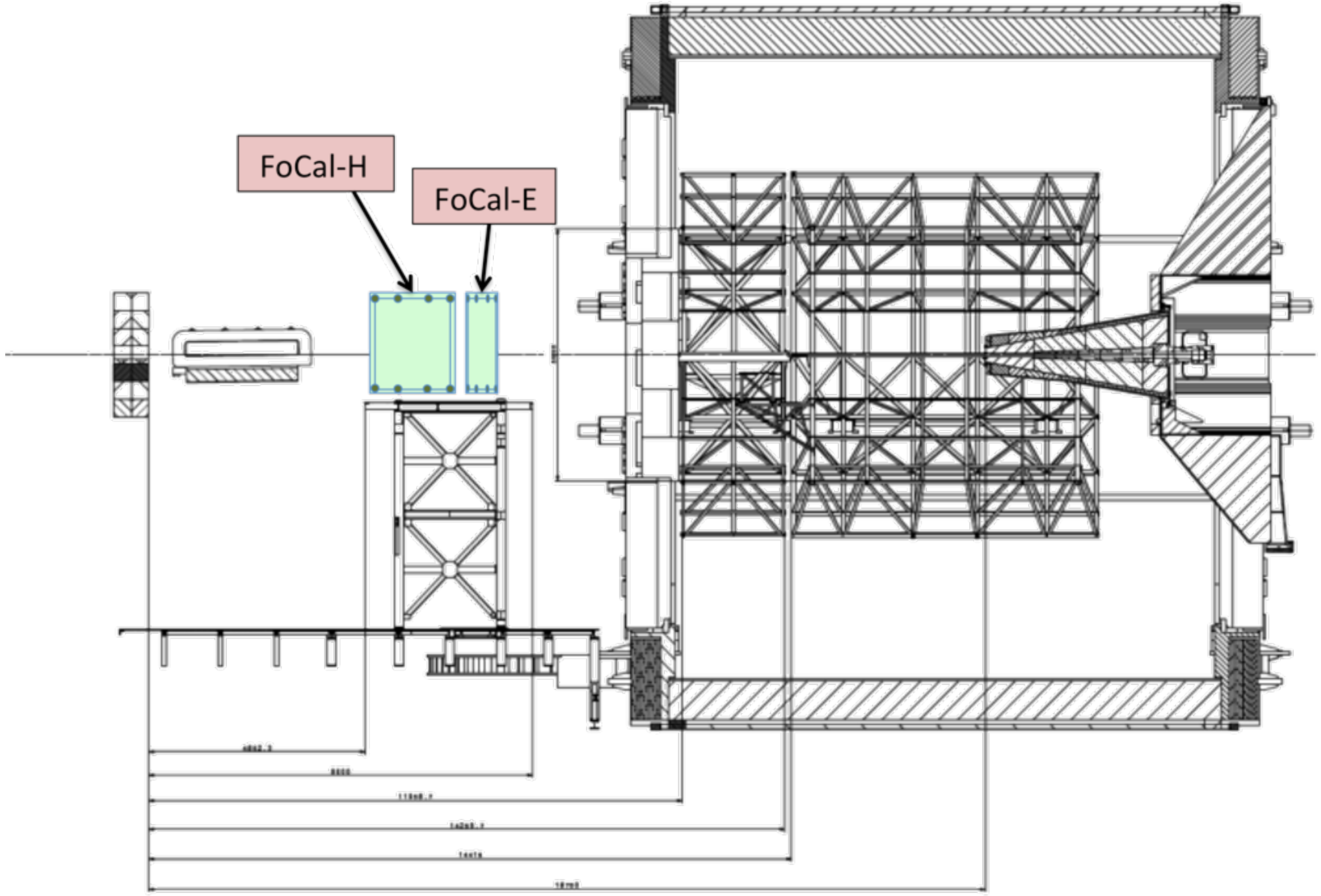
most promising probe: forward direct photons

clear sensitivity for small *x*, no final state interaction



NLO pQCD calculations with shadowing (EPS09)
Helenius, Eskola, Paukkunen, arXiv:1406.1689

FoCal in ALICE



electromagnetic calorimeter for γ and π^0 measurement

preferred scenario:

- at $z \approx 7$m (outside solenoid magnet) $3.3 < \eta < 5.3$ (space to add hadronic calorimeter)

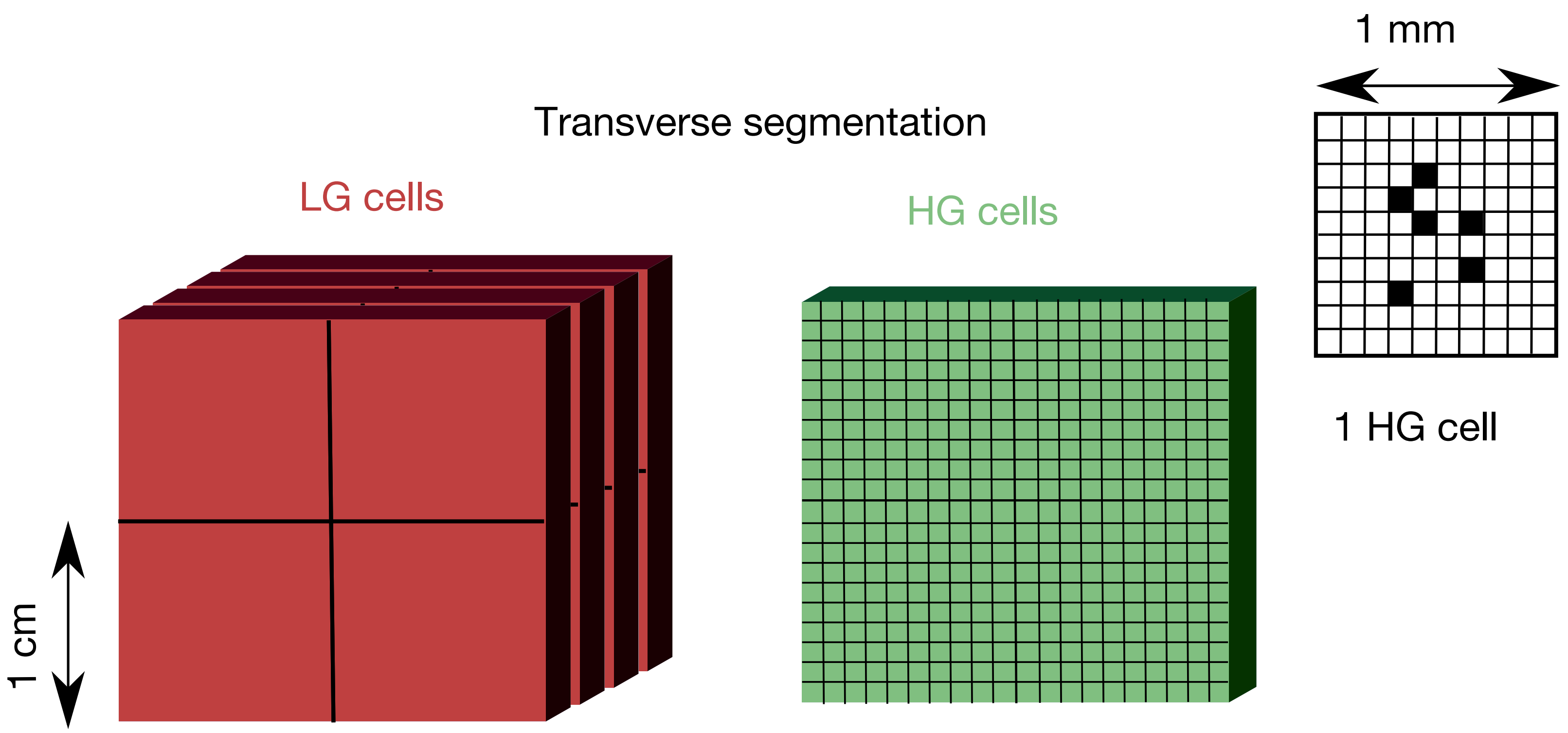
under internal discussion
possible installation in LS3

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 $\approx 1\,\mathrm{mm}^2$

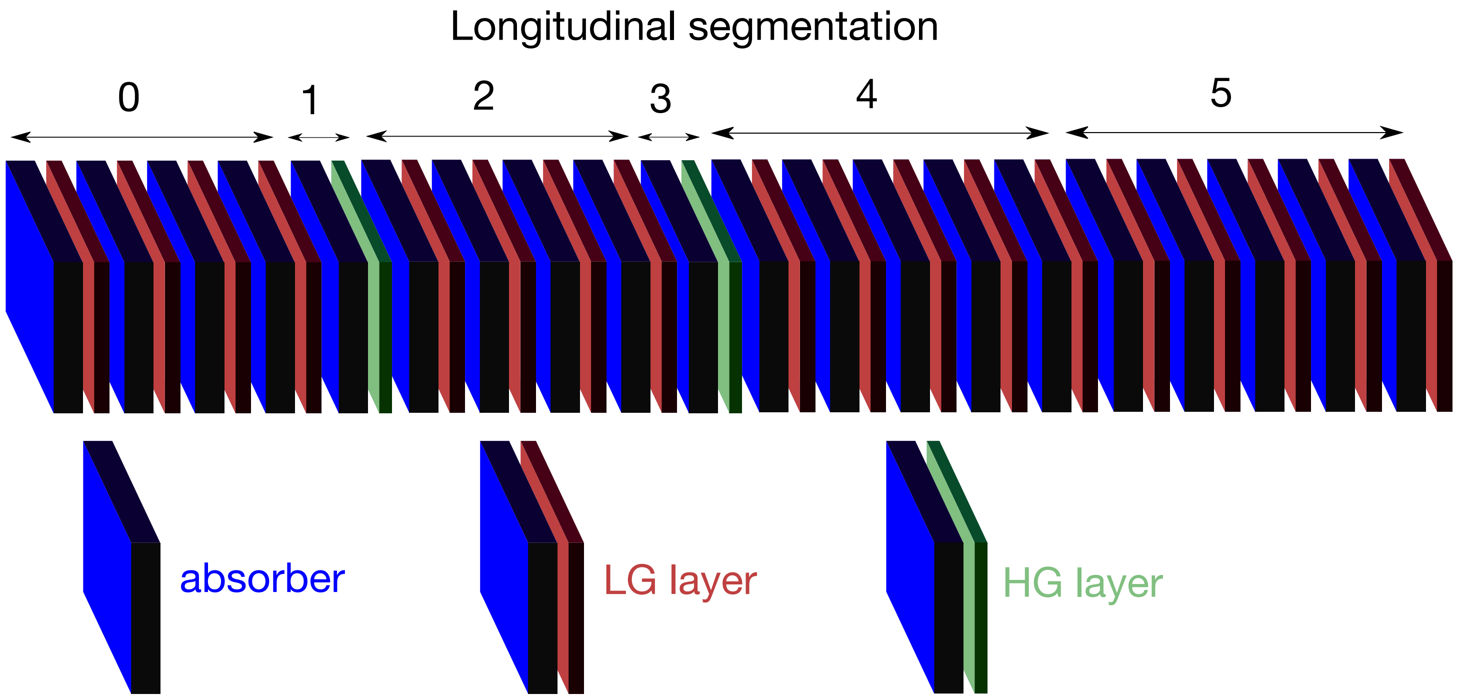
note: two-photon separation from π^0 decay ($p_T = 10$ GeV/c, $y = 4.5$, $\alpha = 0.5$) is d = 2 mm!

FoCal Strawman Design



studied in performance simulations:

20 layers: W (3.5mm ≈ 1 X0) +
Si-sensors (2 types)
low granularity (LG), Si-pads
high granularity (HG), pixels
(e.g. CMOS-MAPS)



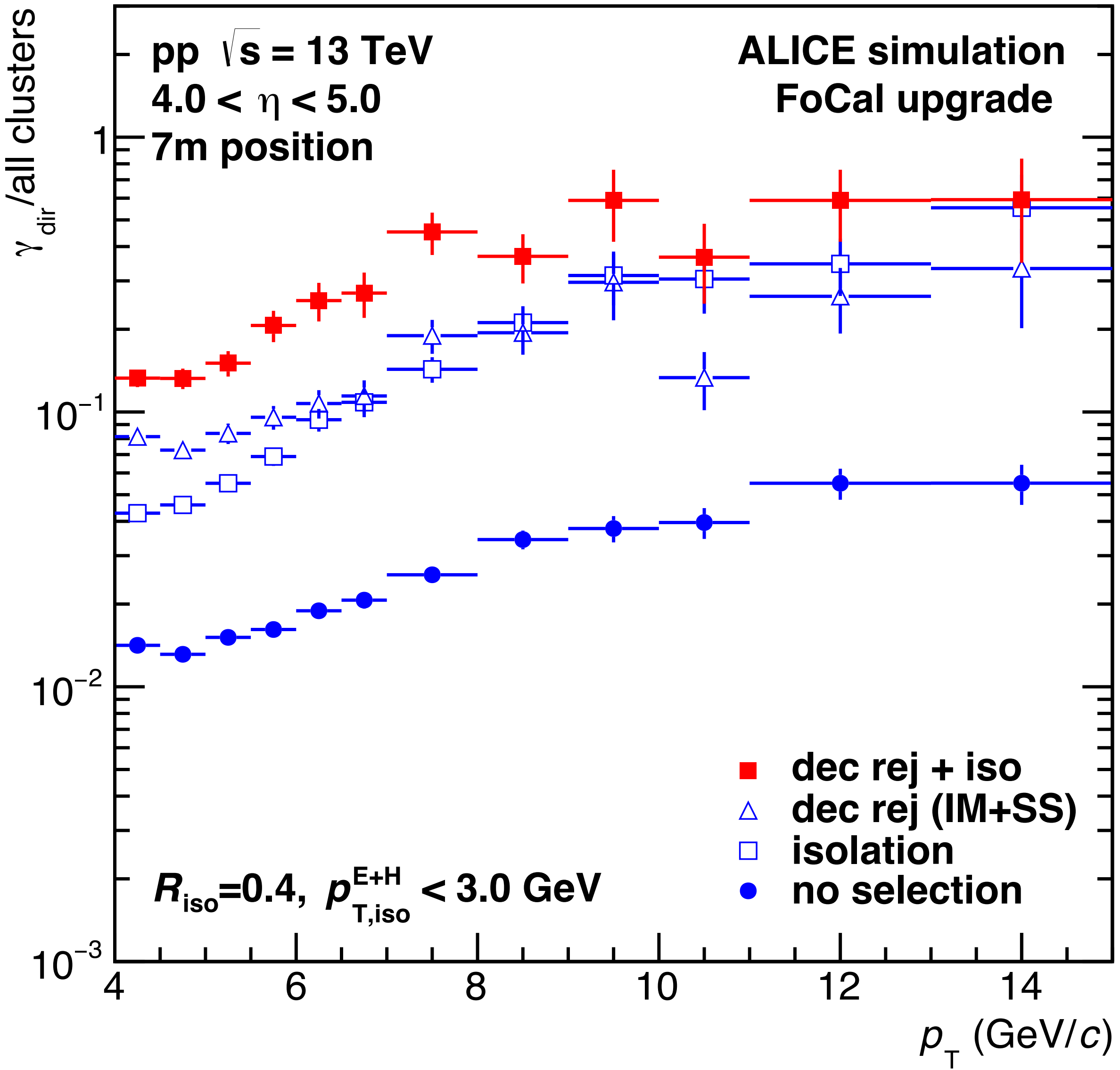
	LG	HG
pixel/pad size	≈ 1 cm^2	≈ 30x30 μm^2
total # pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9
readout channels	≈ 5 x 10^4	≈ 2 x 10^6

assuming ≈ 1m^2 detector surface

Direct γ Performance in pp

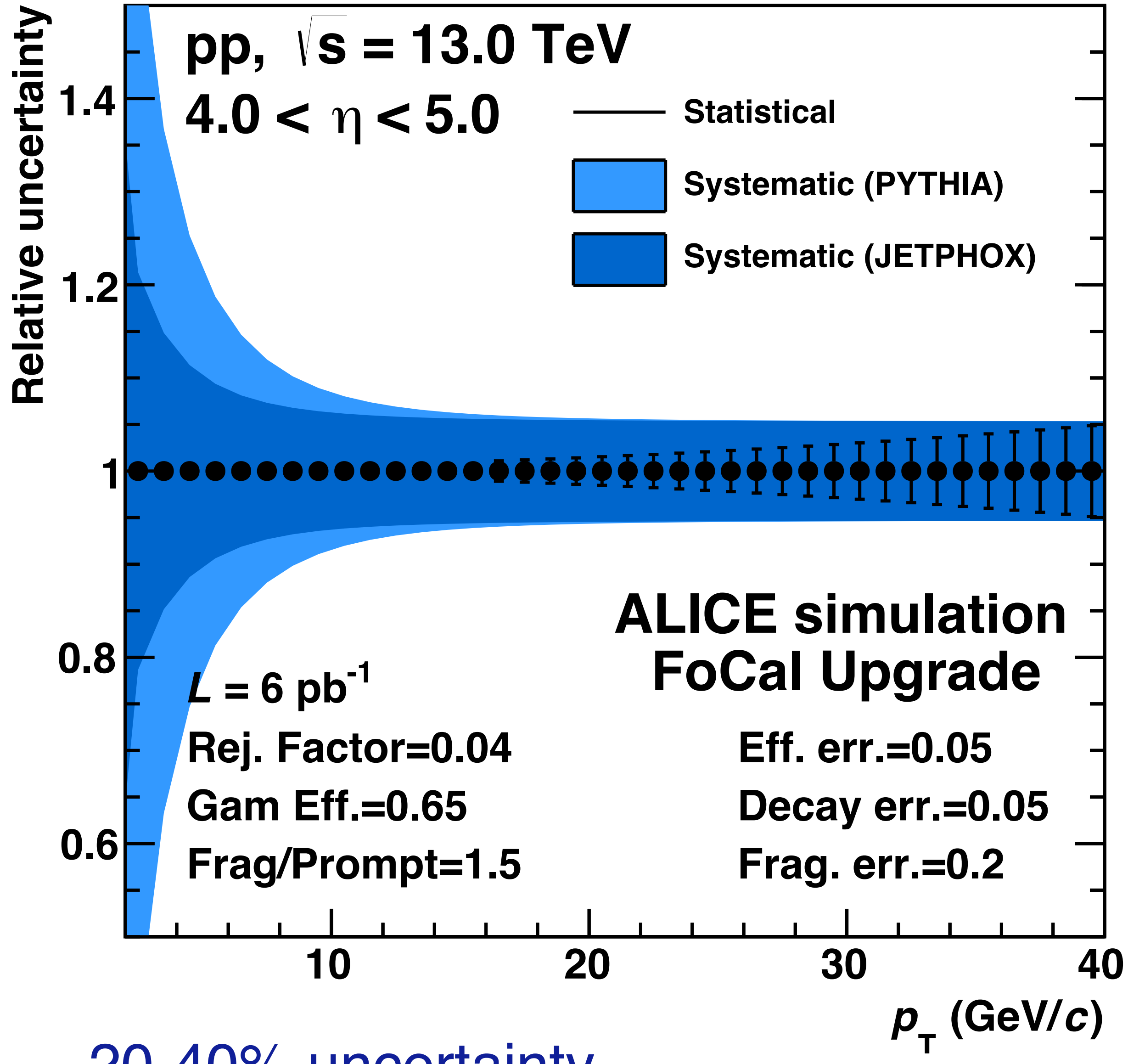
- combined rejection (invariant mass + shower shape, isolation)
- combined suppression of background relative to signal: factor ≈ 10
  - largely p_T-independent

Direct γ/all cluster ratio



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

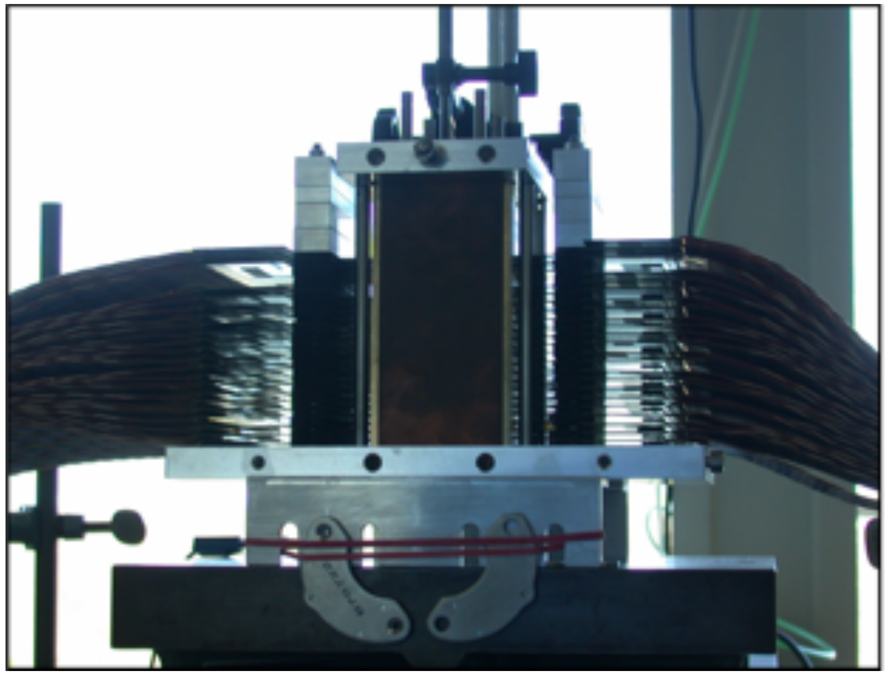
Direct γ uncertainty



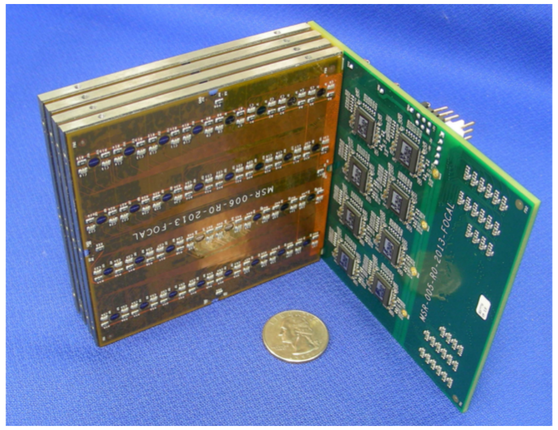
20-40% uncertainty
at p_T = 4 GeV/c
decreases with increasing p_T

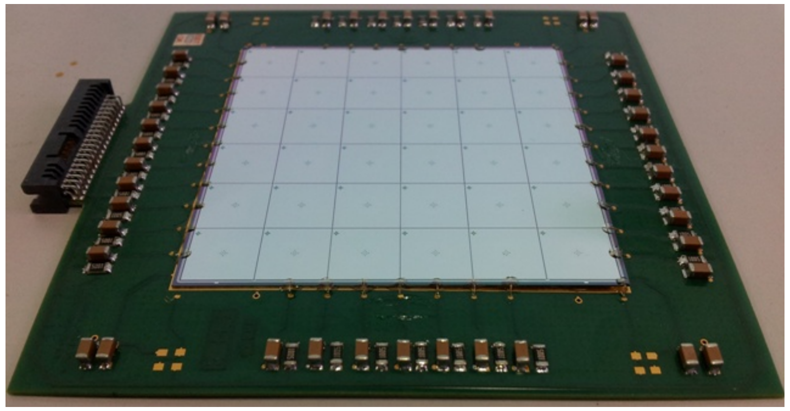
FoCal R&D: Si-W pixel and pad readout

24 layer pixel detector



Pad layer integration





Several groups involved:
- Full prototype with pixel detectors CMOS (MIMOSA) 39M pixels, 30µm pitch
  - use synergy with R&D for ALICE ITS upgrade
- Full prototype with pad readout

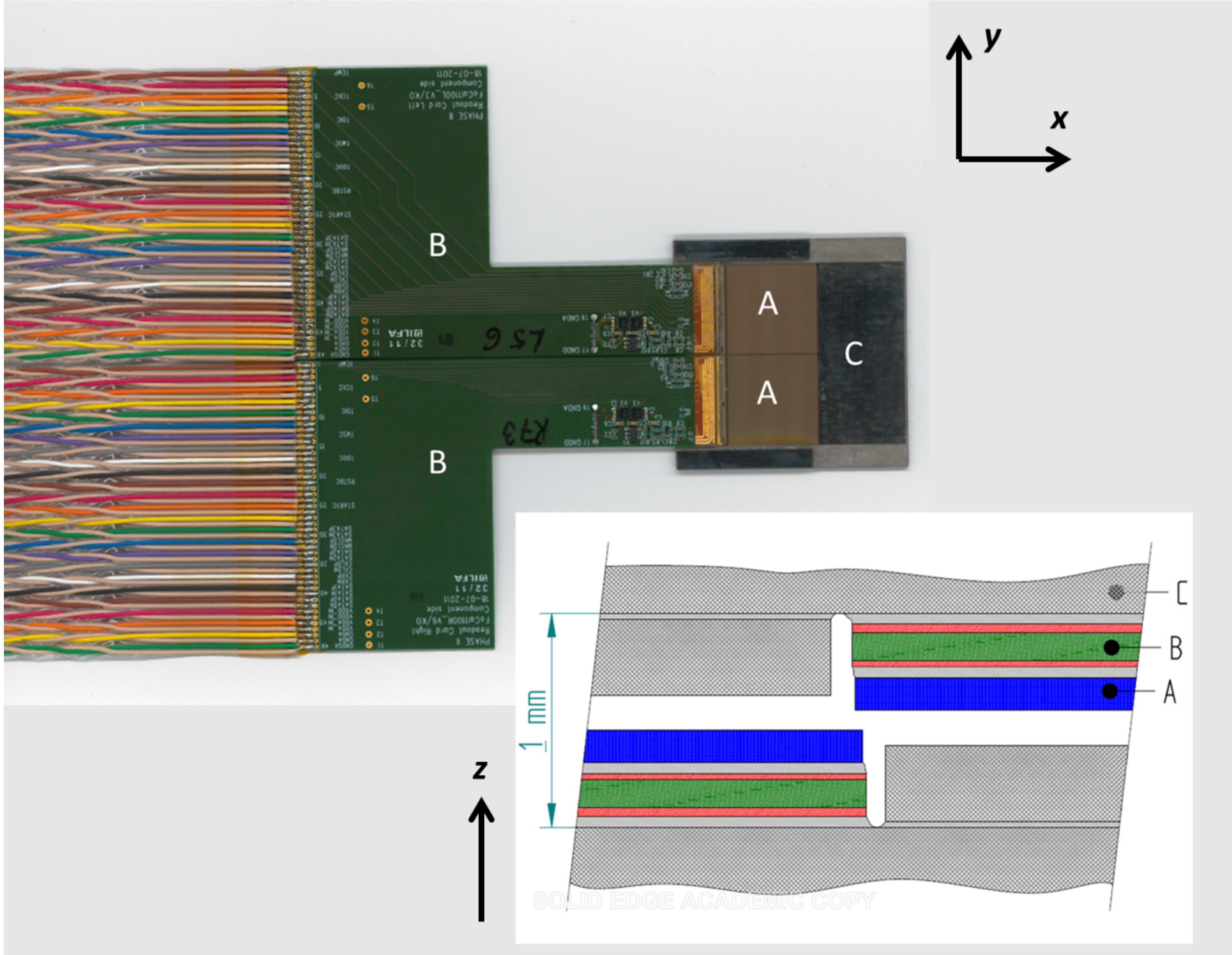
Performed systematic tests:
- Test beam data from 2 to 250 GeV (DESY, PS, SPS)
- Cosmic muons

Utrecht/Nikhef (Netherlands),
Bergen (Norway),
Tsukuba, Nara, Hiroshima (Japan),
ORNL (US)
VECC Kolkata,
BARC Mumbai (India)

R&D with High-Granularity Digital Calorimeter Prototype

R&D Activities with Si-pad/W Calorimeter Prototypes (Japan/ORNL, India) not covered here

Prototype Design



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

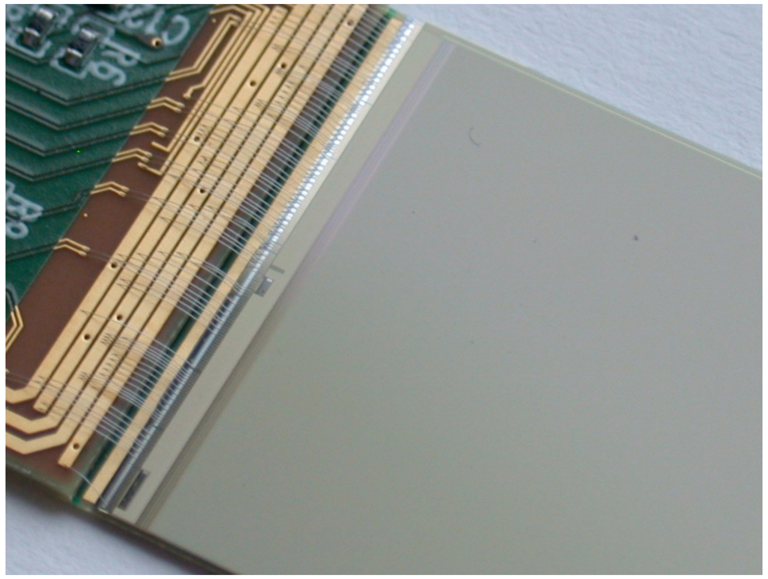
full active layer with readout boards within 1mm

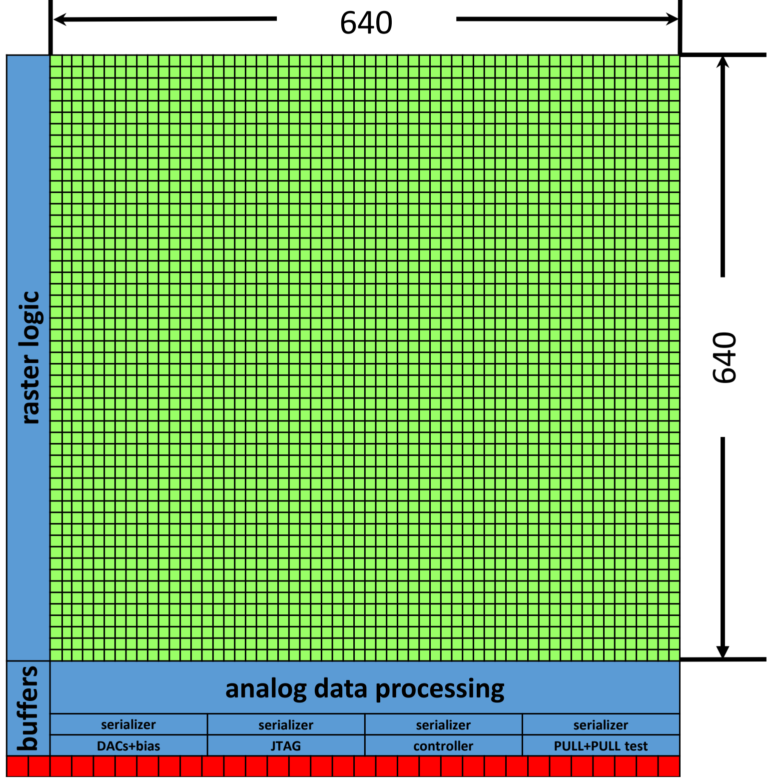
A: MIMOSA sensor
B: PCB
C: tungsten

extremely compact design

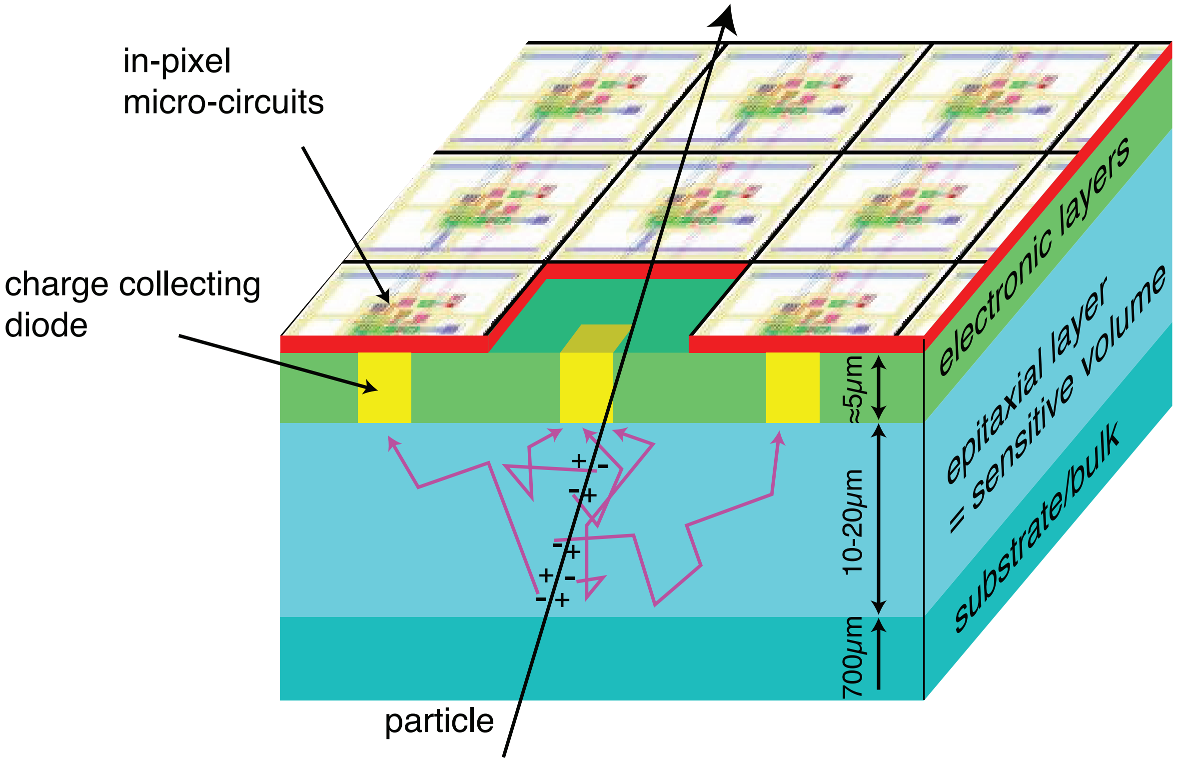
- allows for high pixel density and small Moliere radius

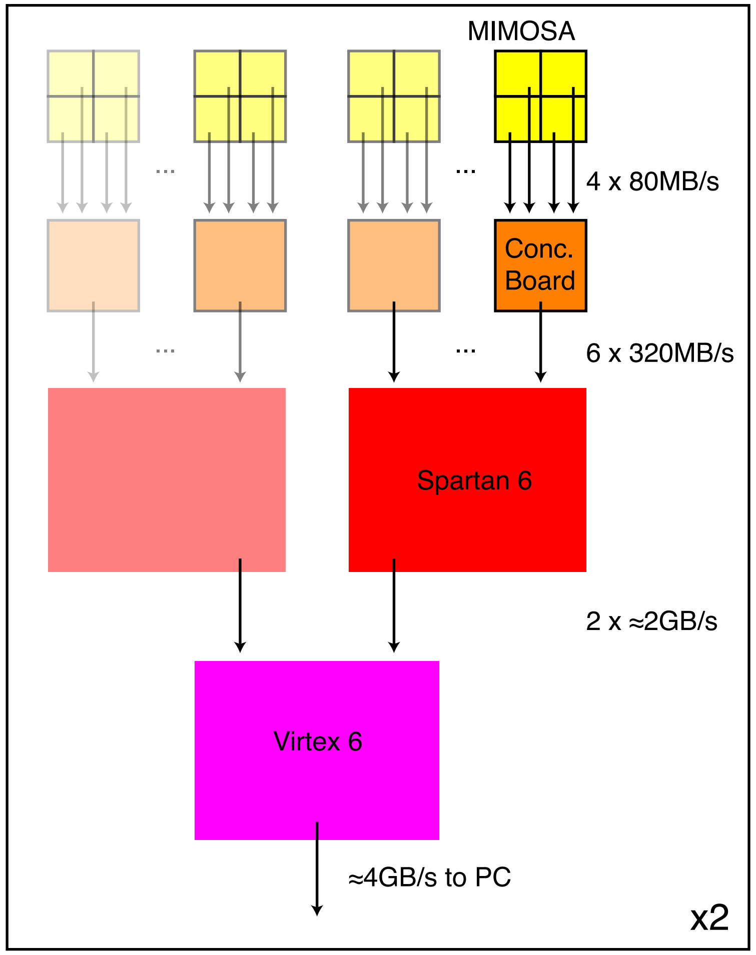
Sensor and Readout





MAPS sensor:
MIMOSA23 (IPHC)
full frame readout





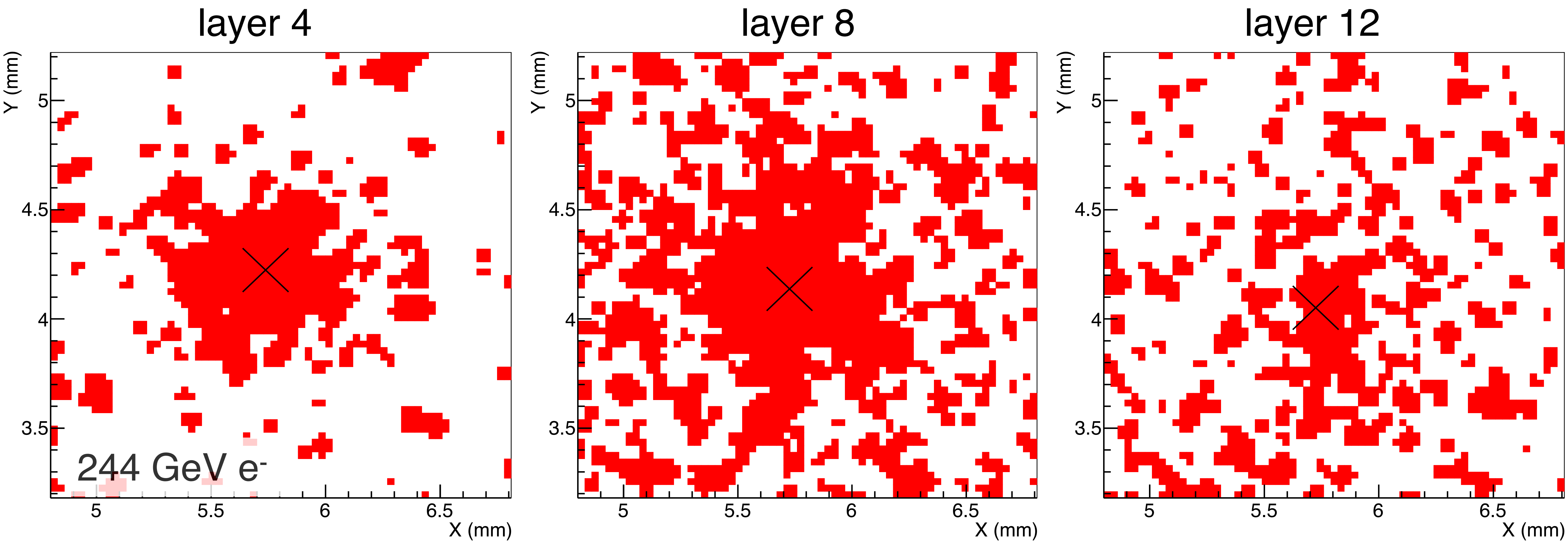
read out via 4 Spartan and 2 Virtex FPGAs

continuous data stream of 8GB/s

current sensor too slow (642 μs/frame)

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

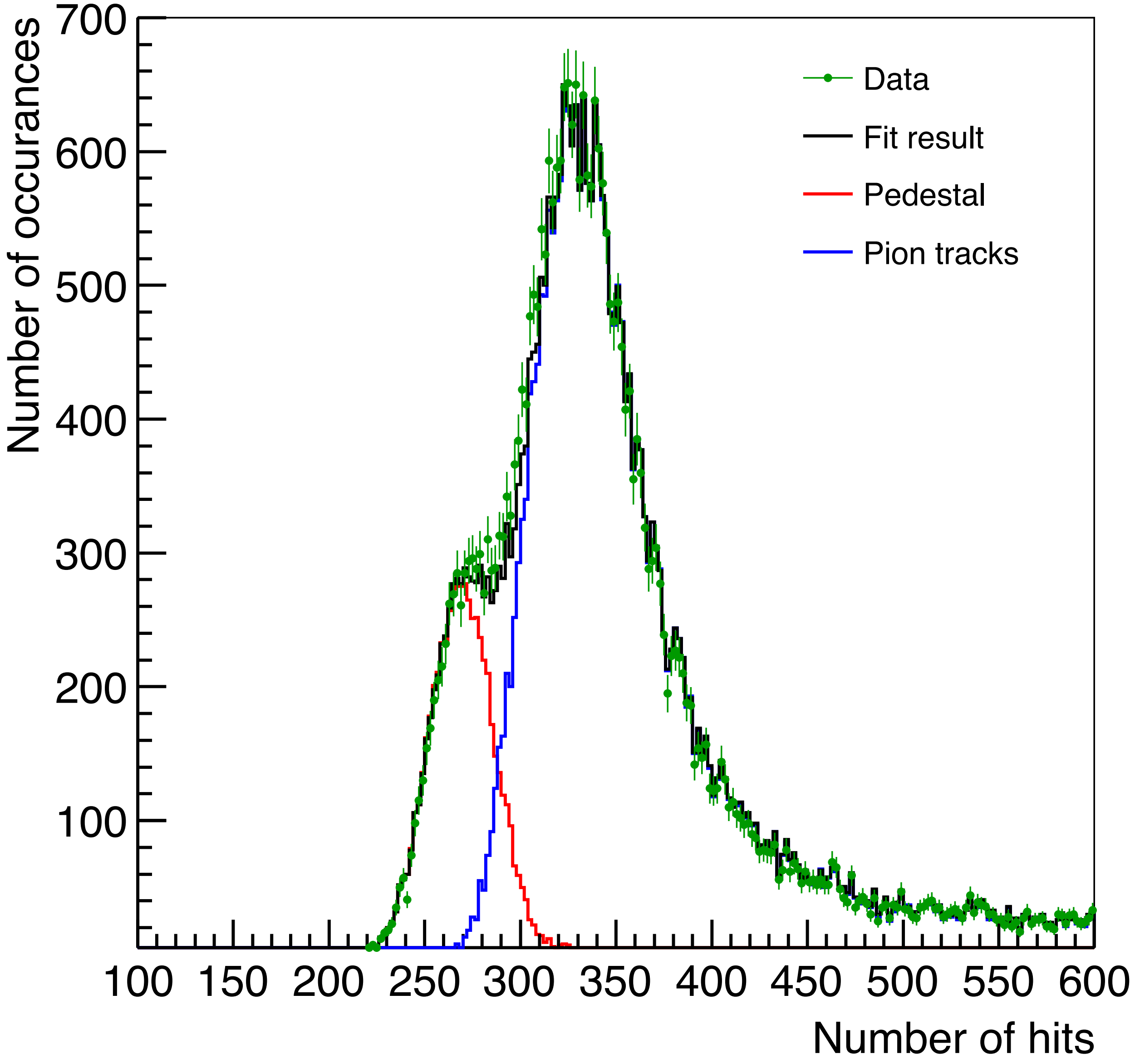
Single Event Hit Distribution

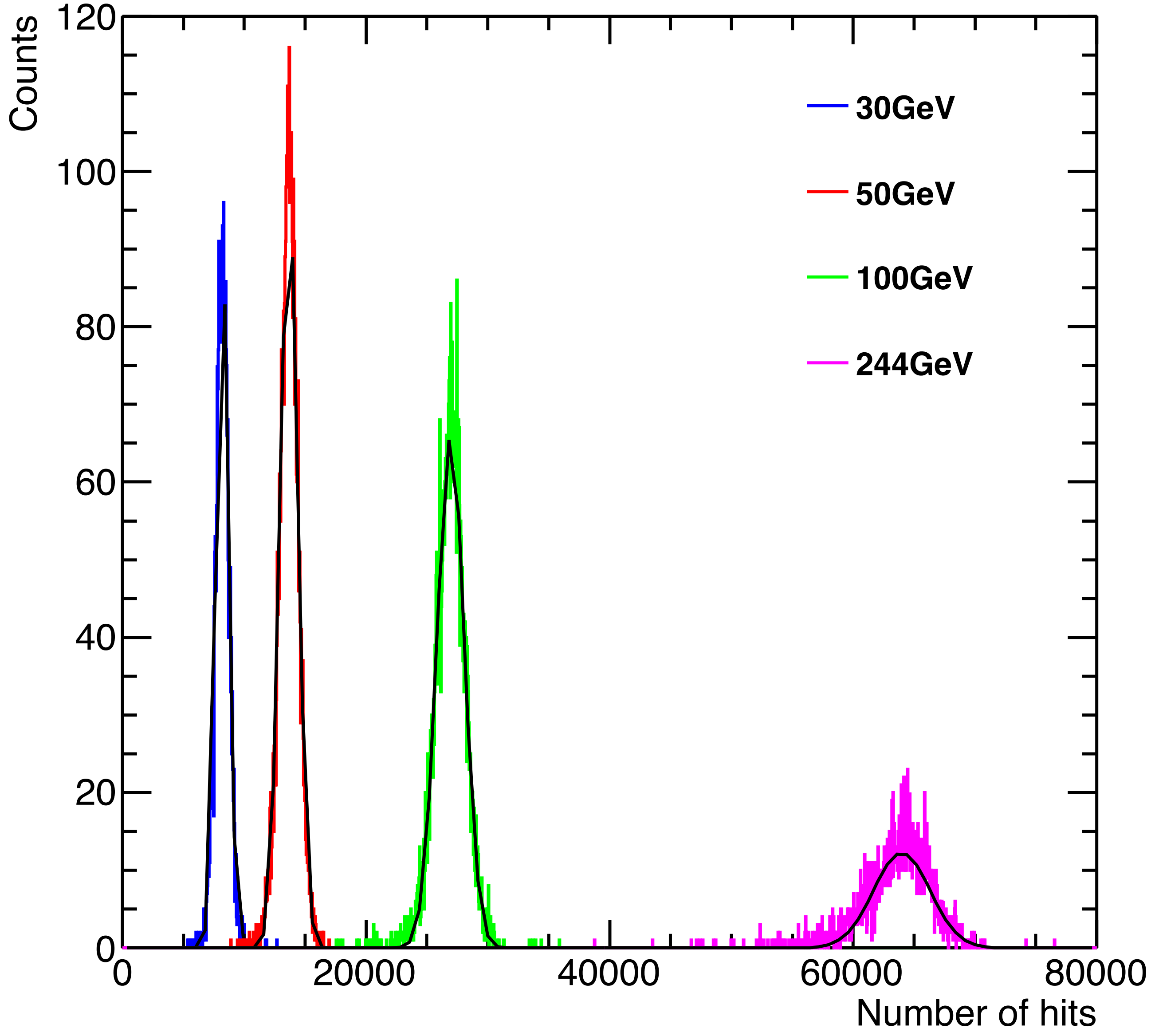


very high hit density in shower core

- 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

Detector Response





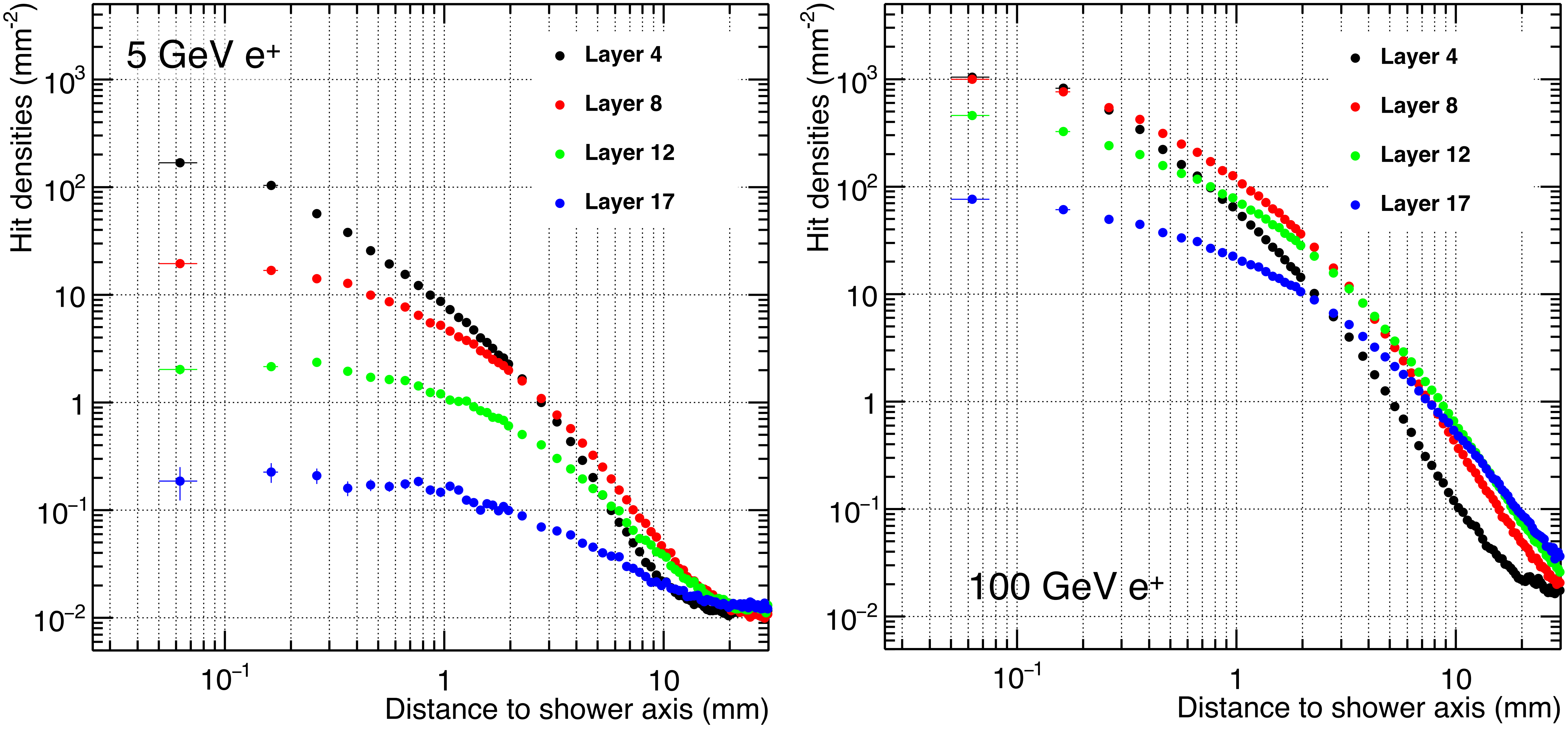
- minimum ionising particle (MIP) peak from pion tracks

- pedestal: noise distribution of full prototype

- response to electrons from SPS test beam

- calculated from per-event hit density distributions

R&D - Lateral Profiles

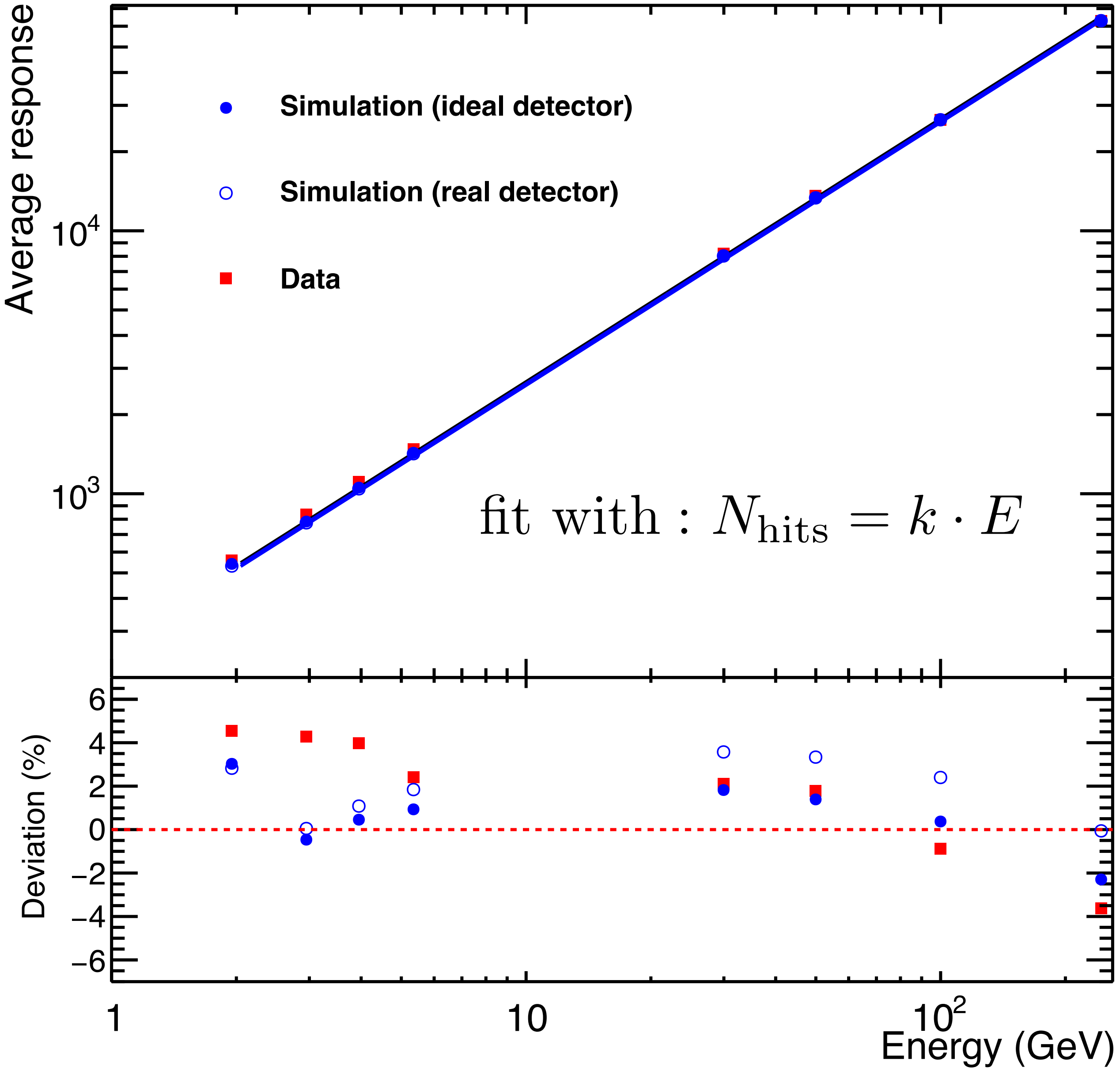


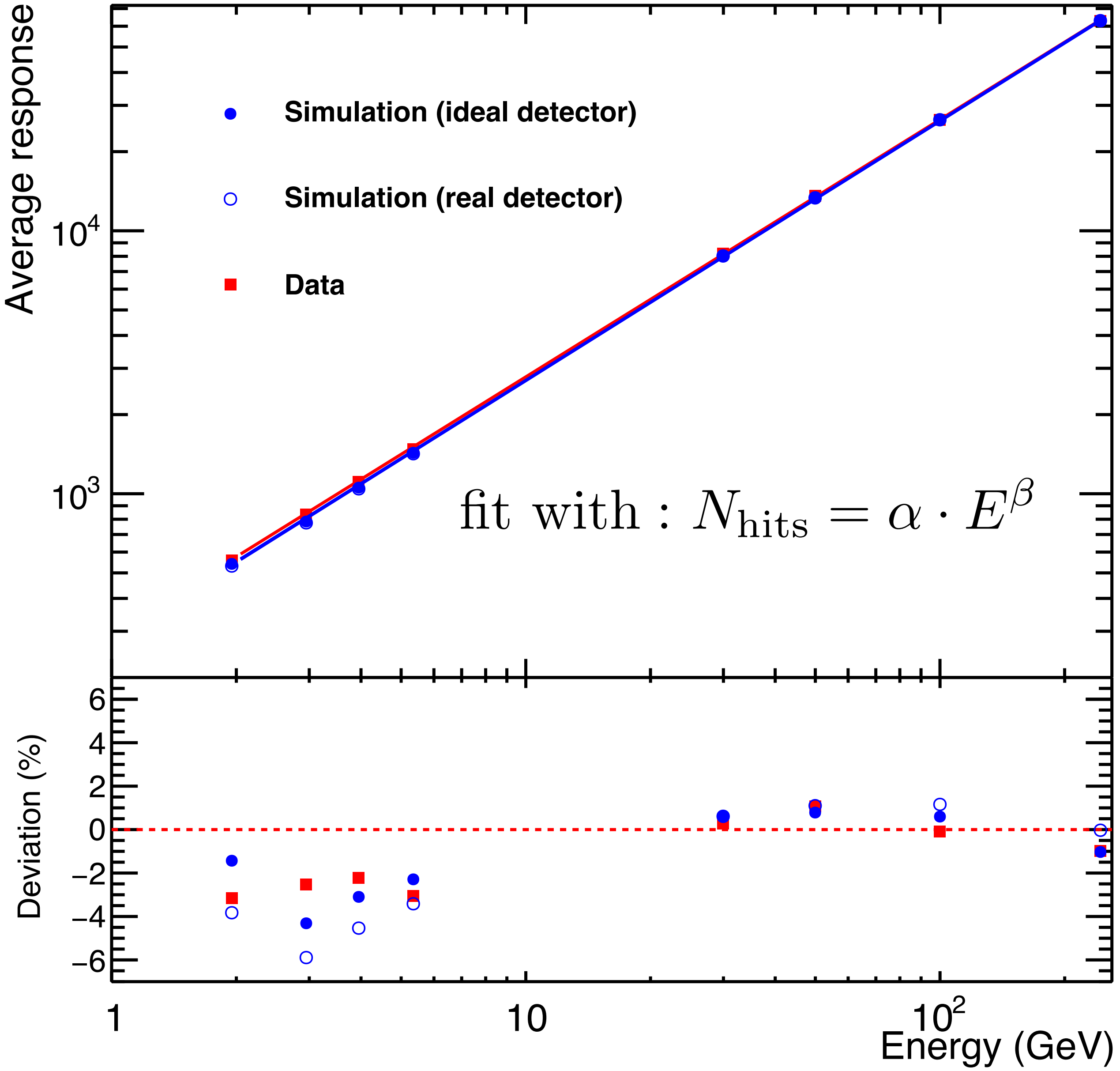
average hit densities as a function of radius for different layers $\frac{dN_{\mathrm{hit}}}{dA}(r)$

- 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 Linearity





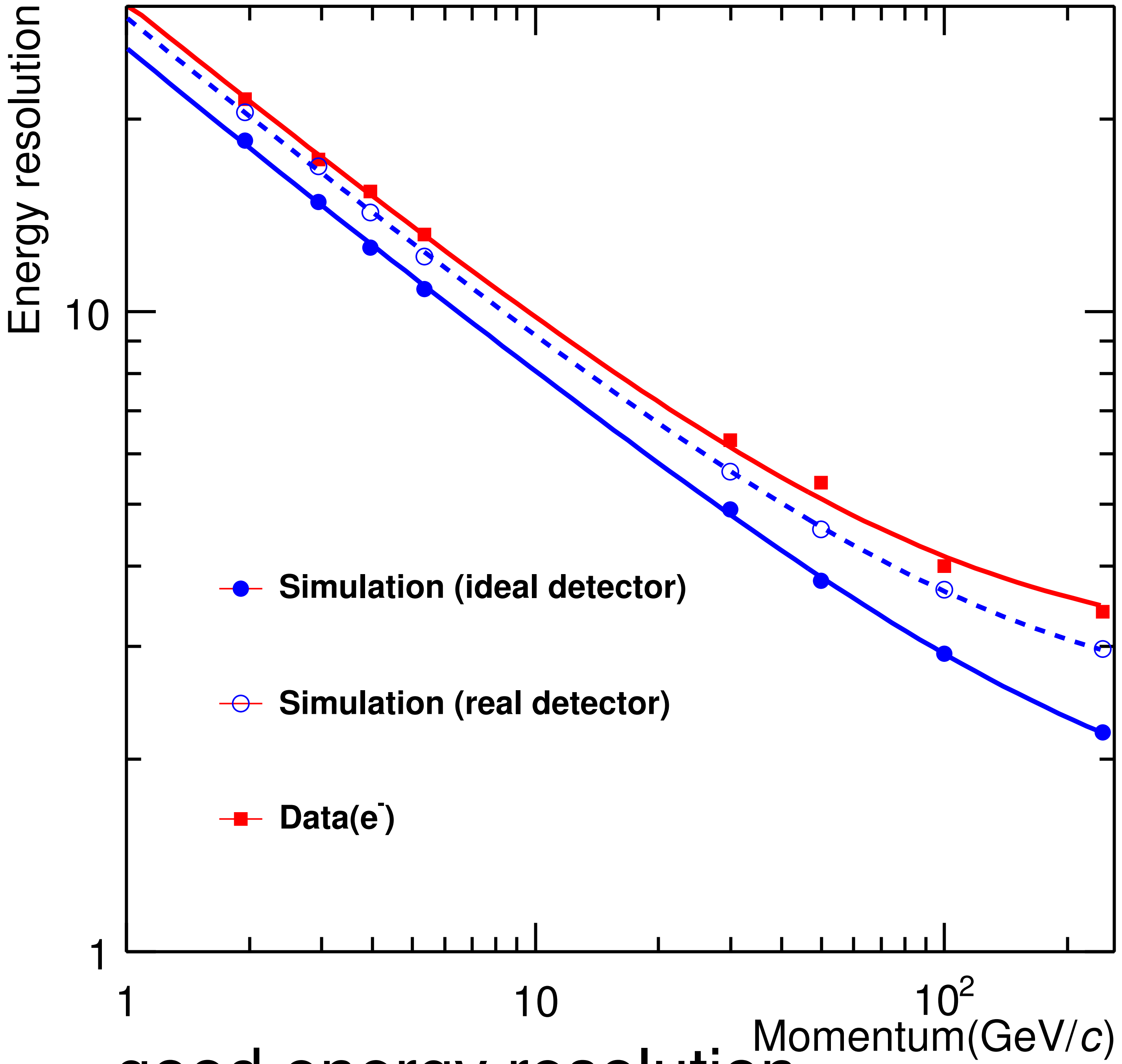
detector response from integrated event-wise hit densities

- 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 - 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

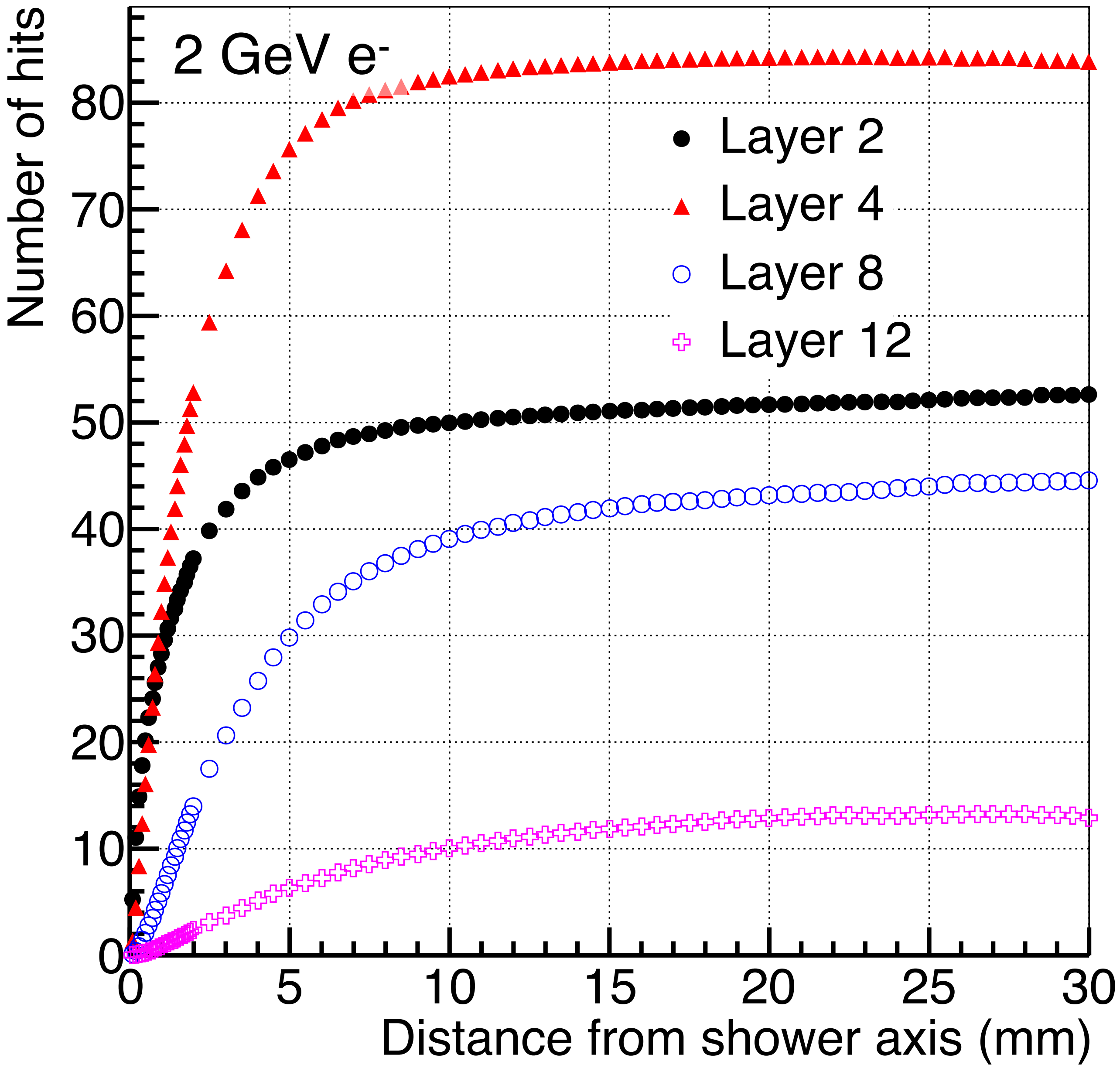
slightly worse than MC simulation, not unexpected

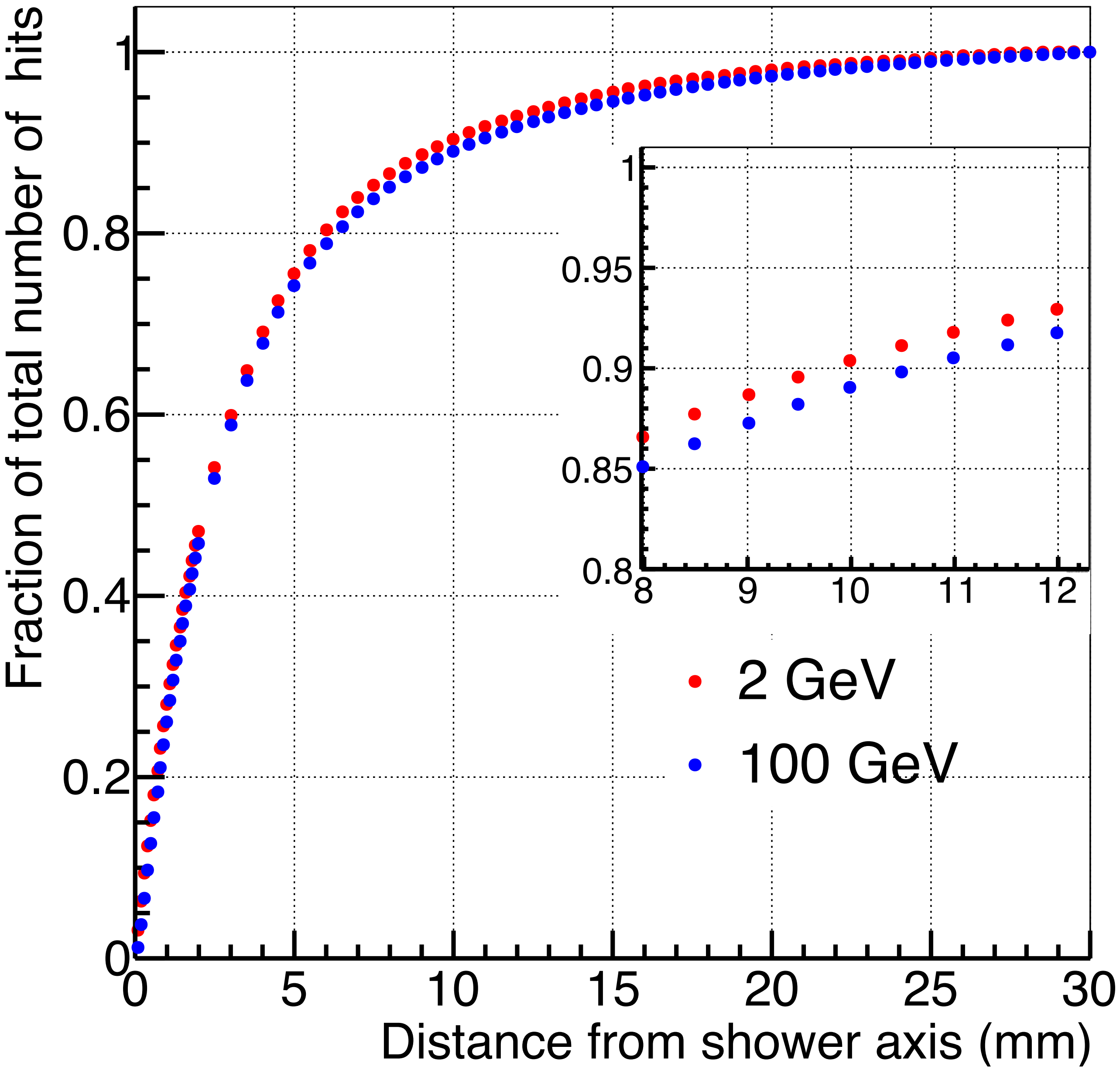
good energy resolution

- certainly sufficient for forward detector
- note: sampling fraction < 1/1000
- possibly still improve calibration, better sensor (ALPIDE) in the future

proof of principle of digital calorimetry

R&D - Cumulative Lateral Profiles





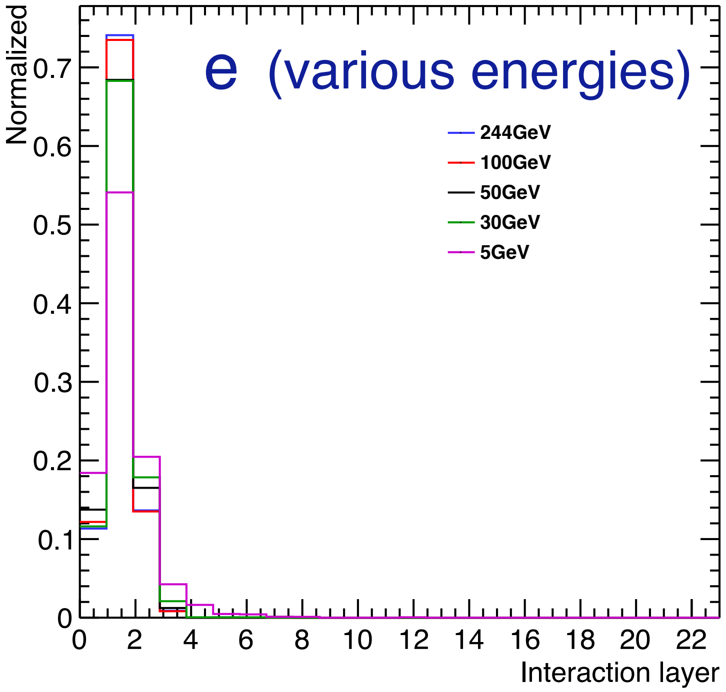
extract cumulative distributions both per layer and integrated

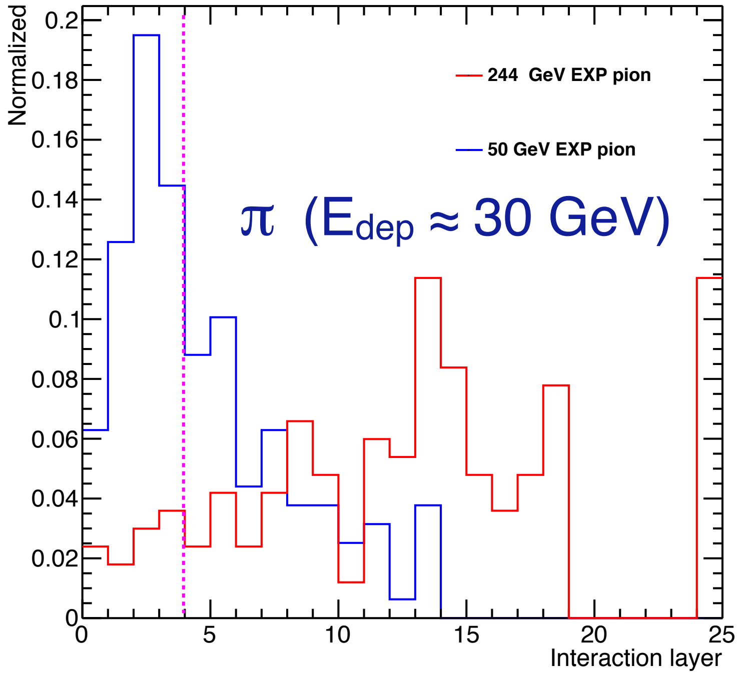
- some lateral leakage at higher energy

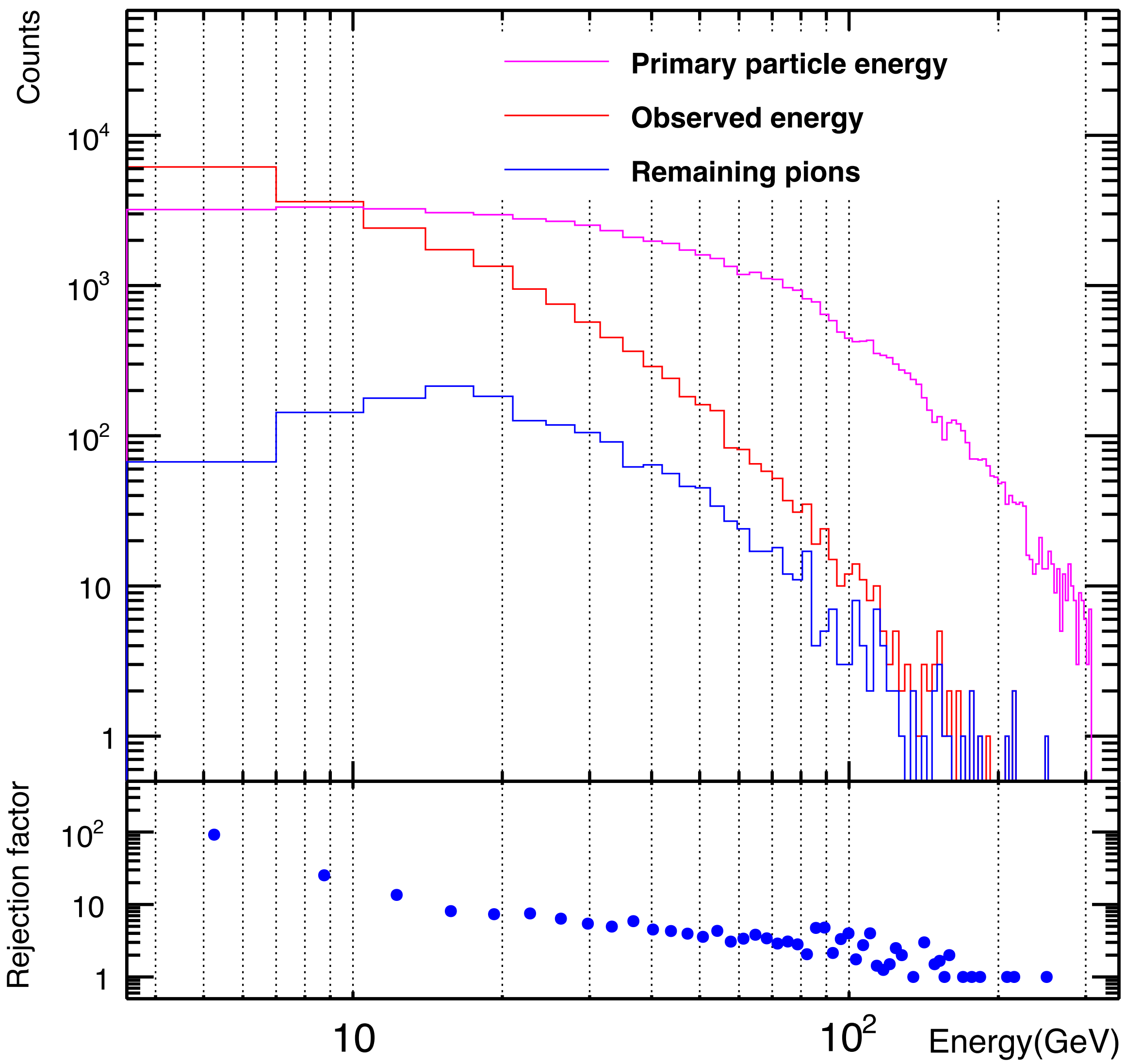
small Moliere radius: $R_M \approx$ 11mm

$\approx$ 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:

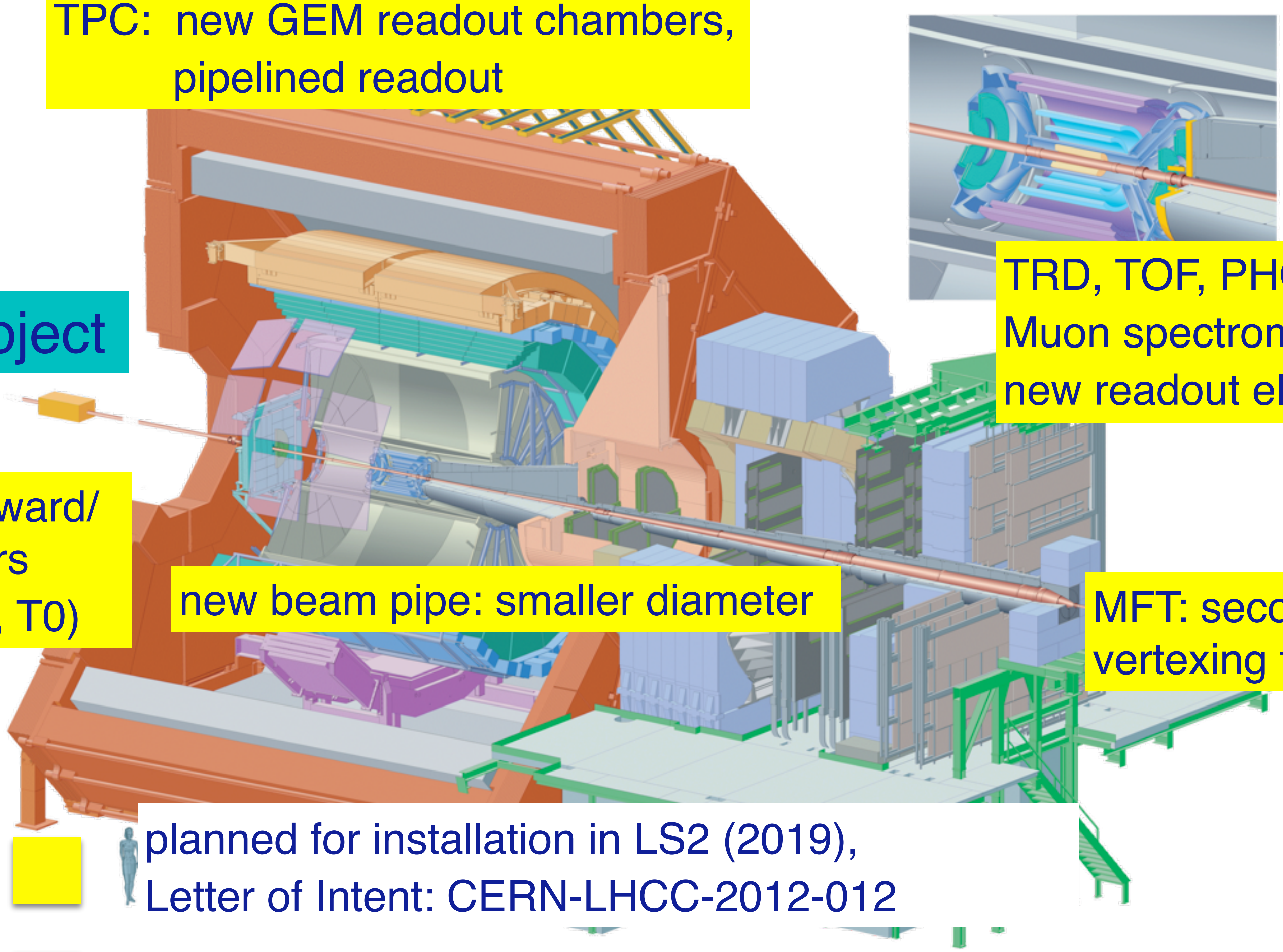
- cases of high deposited energy suppressed from low interaction probability
- additional rejection for low deposited energy from shower shape

Summary

- Forward photon measurements at LHC provide unique opportunity for low-x physics
    - needs detector upgrade: proposed FoCal detector in ALICE
- Extensive R&D with high granularity digital calorimeter prototype
    - proof of principle of digital calorimetry
    - unique detector: smallest R_M, highest granularity
    - enormous potential (two-shower separation, hadron rejection, PFA?)
    - should allow tuning of GEANT parameters
    - *see also:*
        - *N. van der Kolk (talk today, 15:20)*
        - *first paper submitted to JINST, https://arxiv.org/abs/1708.05164*
- Next steps
    - develop fast sensor (ALPIDE)
    - more corrections (saturation, improved calibration)
    - …

Backup Slides

ALICE Detector & Upgrades



new ITS: high resolution,
low material budget

TPC: new GEM readout chambers,
pipelined readout

FoCal project

TRD, TOF, PHOS, EMCal,
Muon spectrometer:
new readout electronics

Upgrade of forward/
trigger detectors
(ZDC, VZERO, T0)

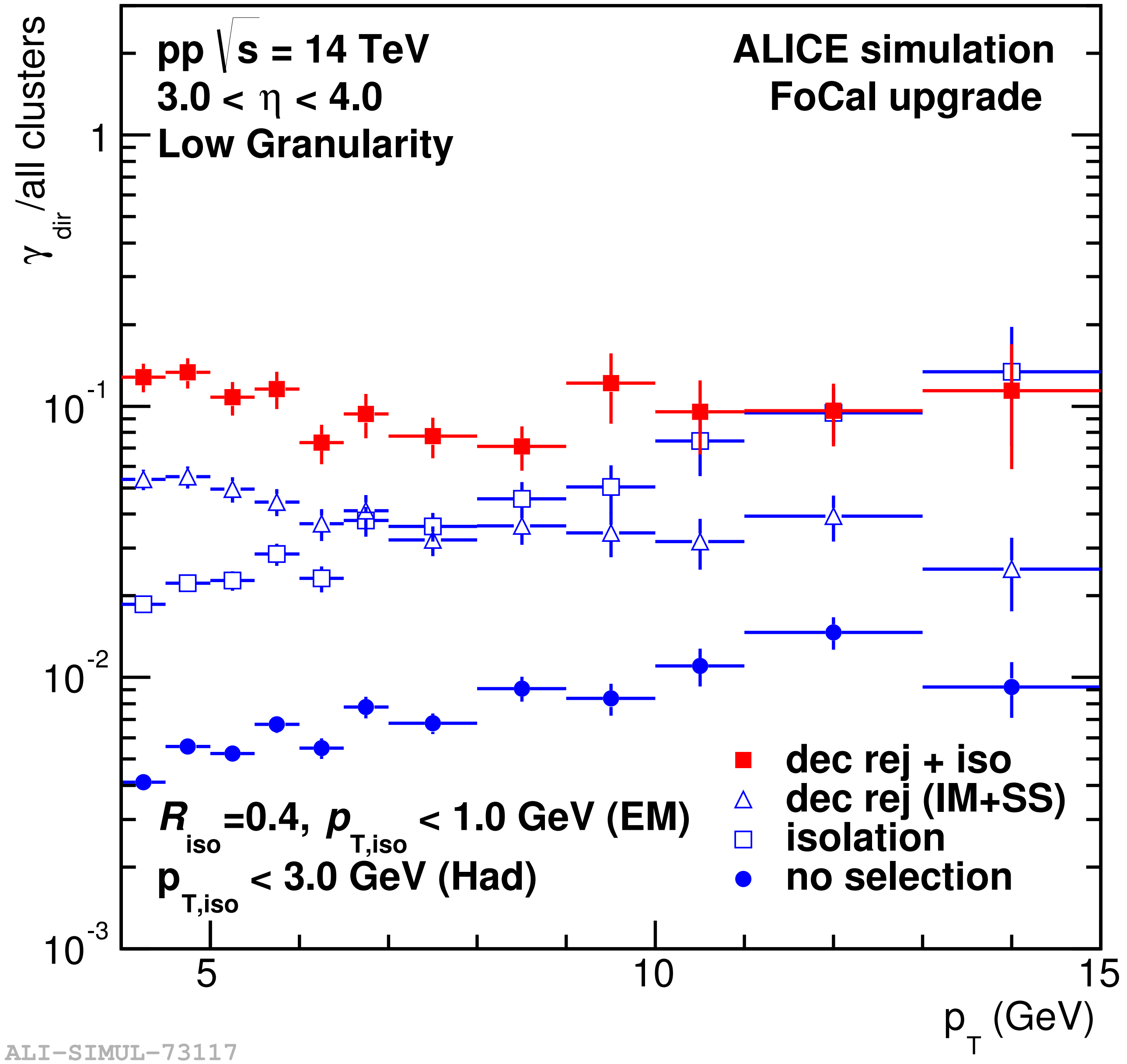
new beam pipe: smaller diameter

MFT: secondary
vertexing for muons

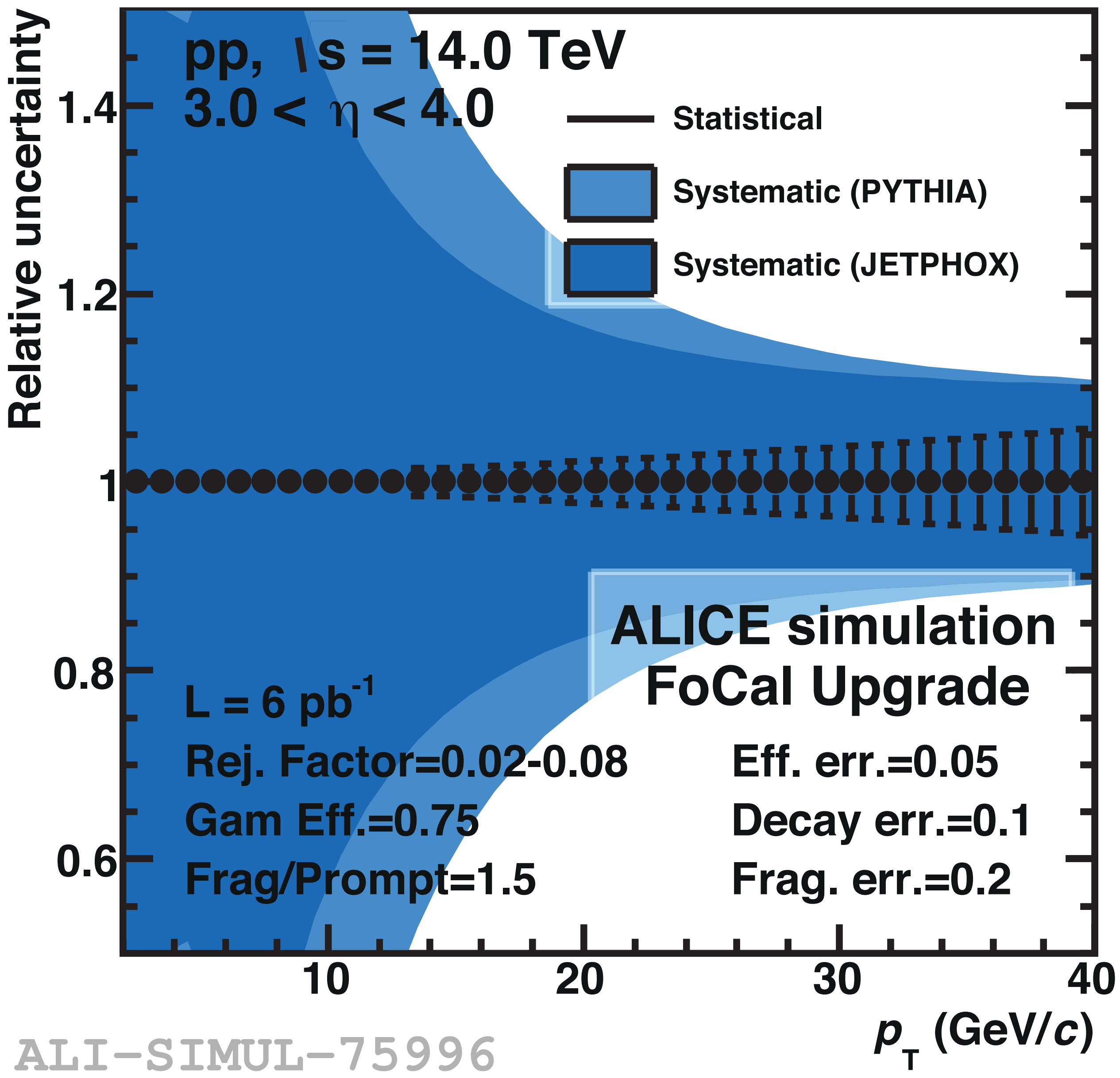
🟨 planned for installation in LS2 (2019),
Letter of Intent: CERN-LHCC-2012-012

🟦 under internal review

Low Granularity Measurement



ALI-SIMUL-73117



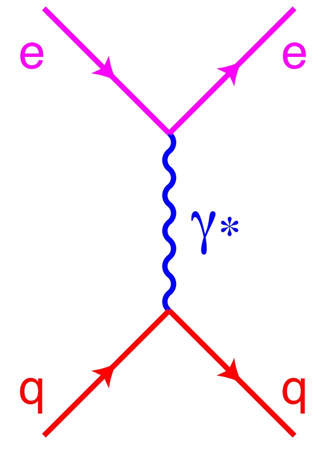
ALI-SIMUL-75996

low granularity (1cm2) does not allow efficient decay rejection
direct photon/all ≈ 0.1
for all pT

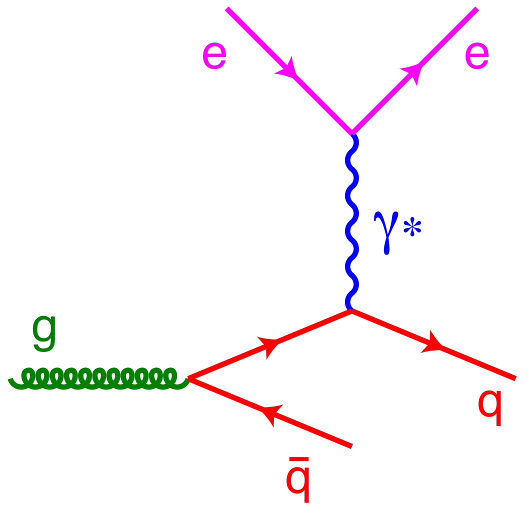
significant measurement not possible at low pT

NB: conditions similar to LHCb

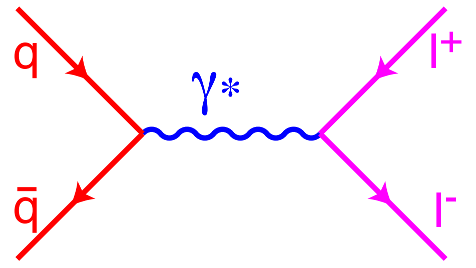
Electromagnetic Processes



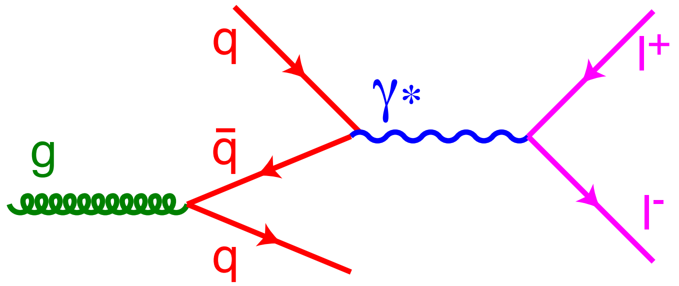
DIS (LO)



DIS (NLO)

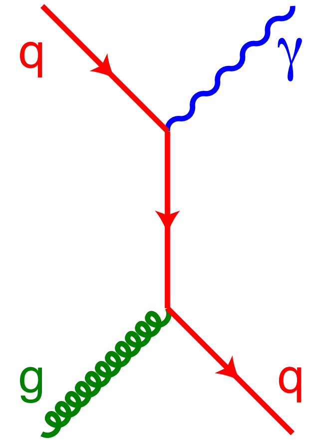


DY (LO)



DY, virtual Compton (NLO)

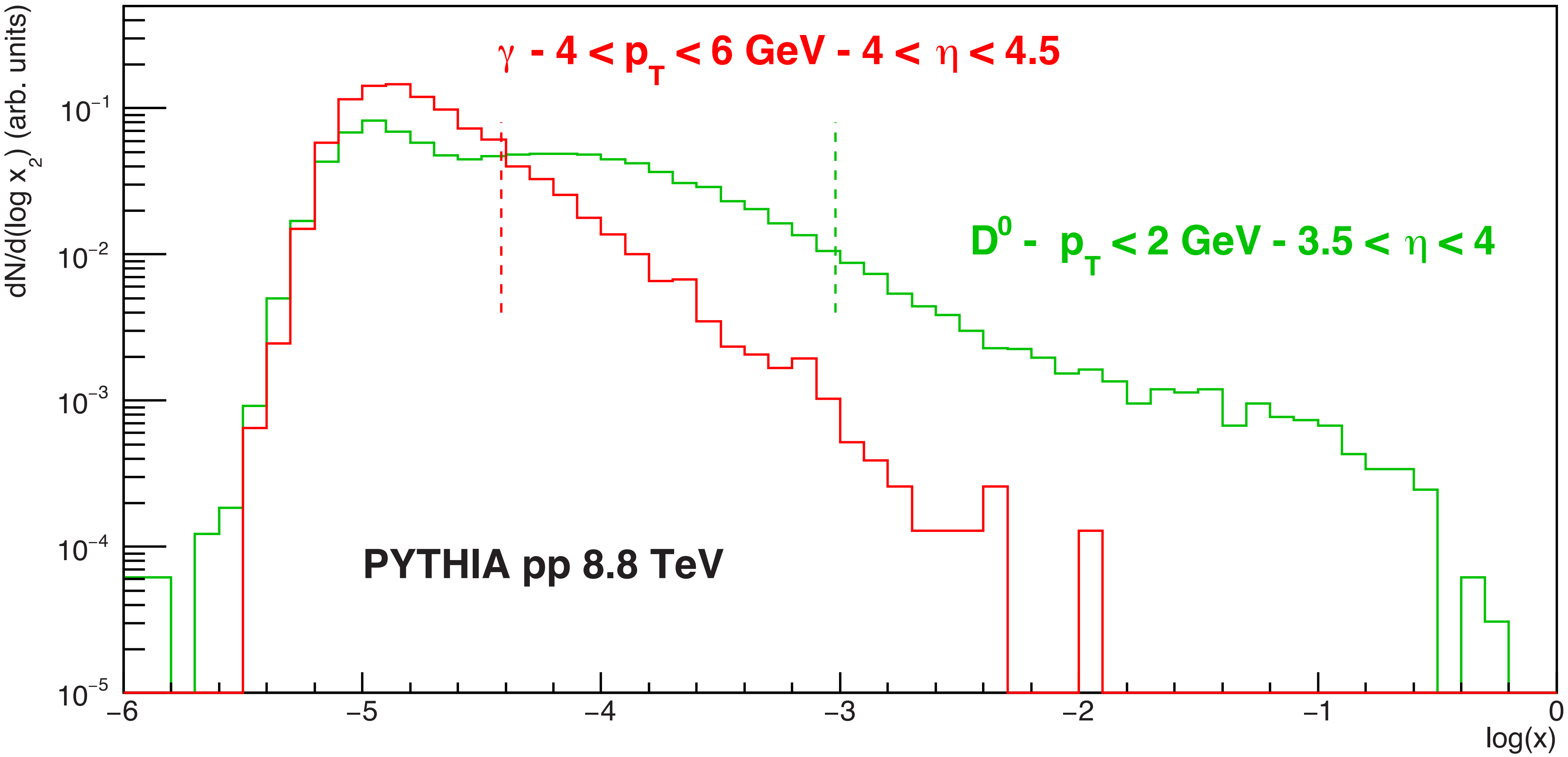
- DIS and Drell-Yan are equivalent processes
  - crossing symmetry
  - sensitivity to gluons only at NLO
    - e.g. virtual qg-Compton
- main disadvantage of DY: very low cross section
  - not accessible in pA



direct-γ, Compton (LO)

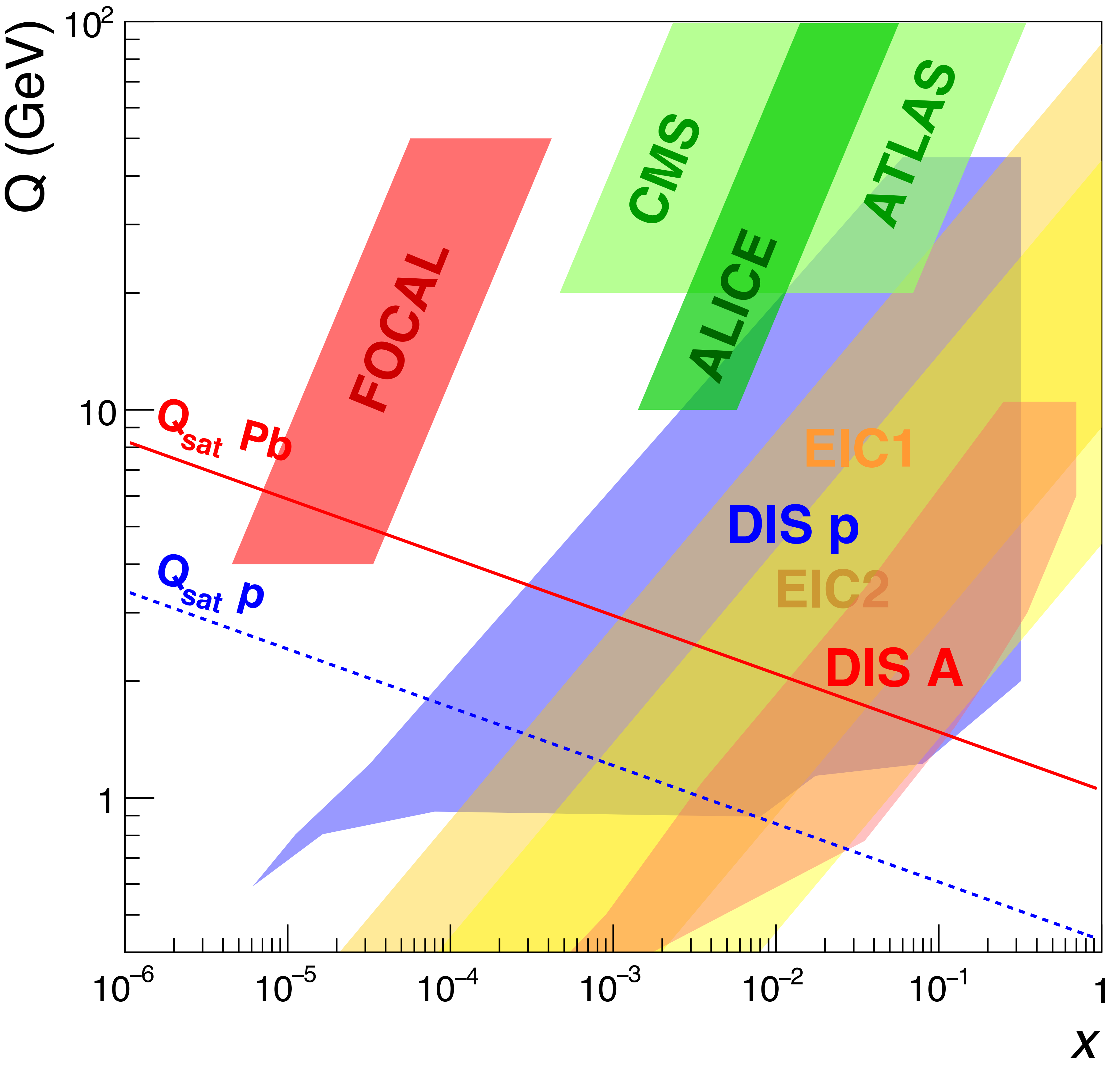
- real photons: sensitivity to gluons at LO, clear kinematic relation
  - higher order corrections?

x-Sensitivity

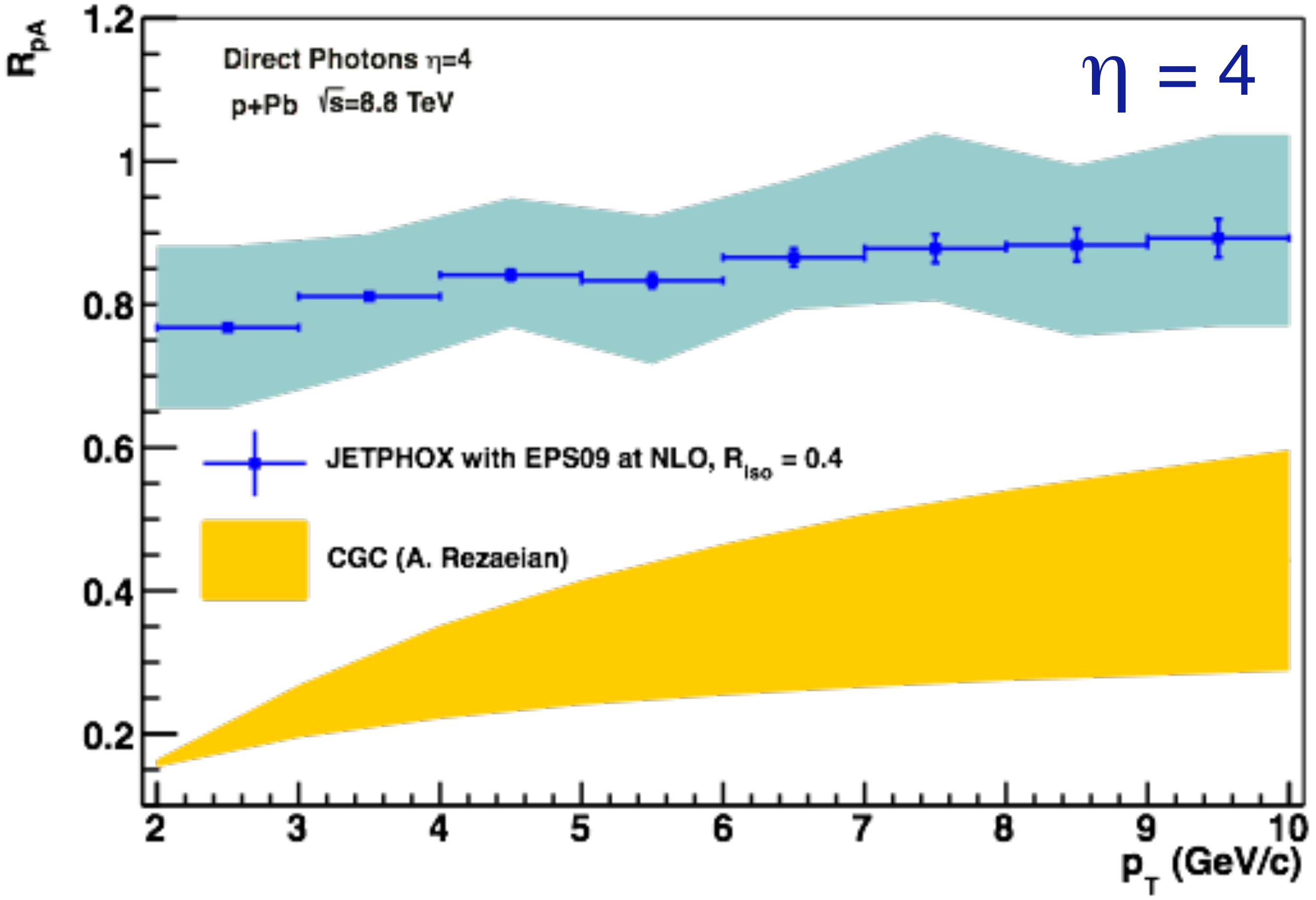


- x_2 distributions for forward production
  - LO production from PYTHIA
  - D^0 (LHCb) vs prompt γ (FoCal)
- apparent maximum at $x \approx 10^{-5}$
  - beware of log(x) scale!
  - significantly larger mean value
- significant advantage of proposed direct photon measurement relative to charm in LHCb

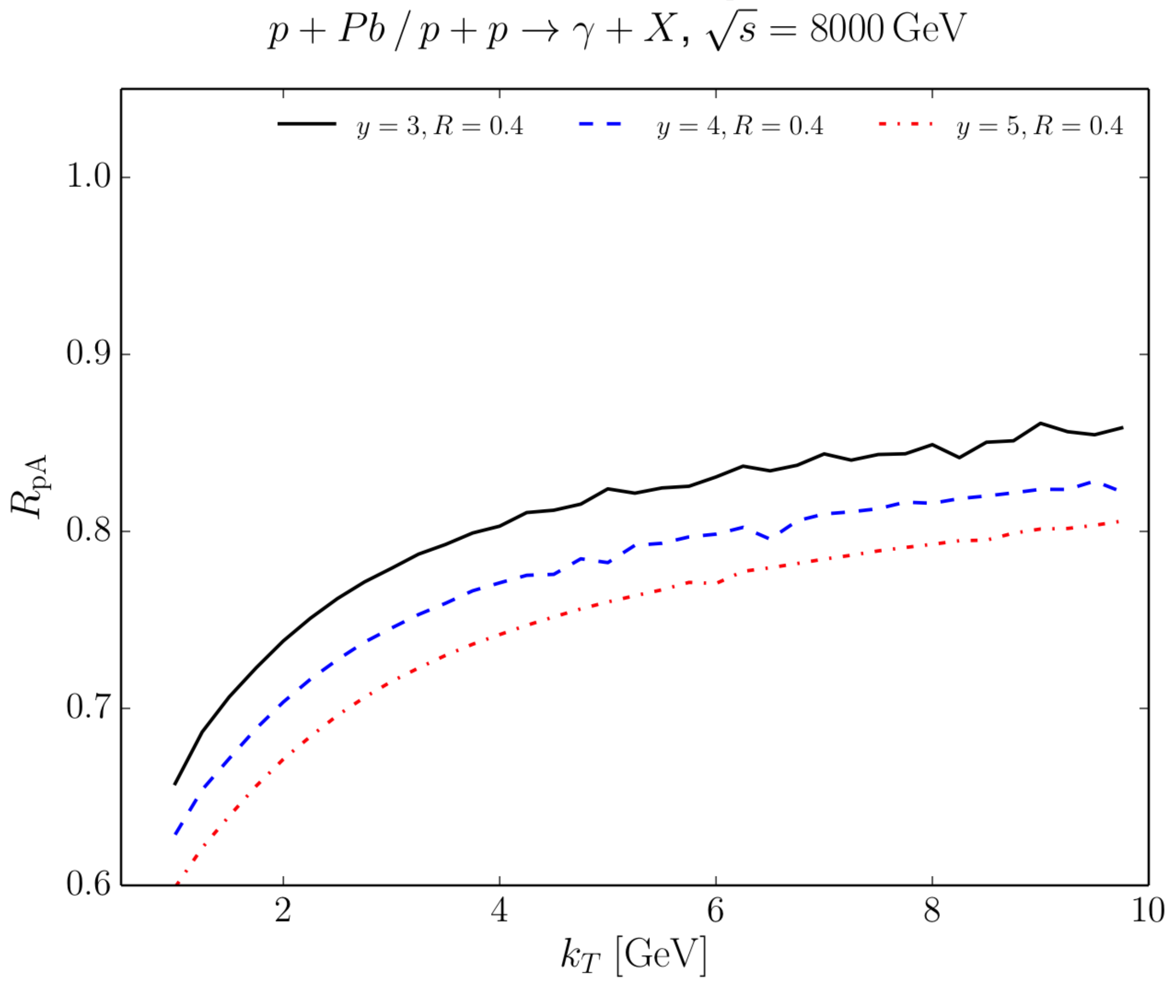
EM Probes: Kinematic Coverage



Theoretical Expectations for R_{pPb}



nPDF: JETPHOX+EPS09, CGC: A.Rezaeian, PLB 718, 1058



CGC: B. Ducloué, RBRC workshop June 2017

early CGC calculation:

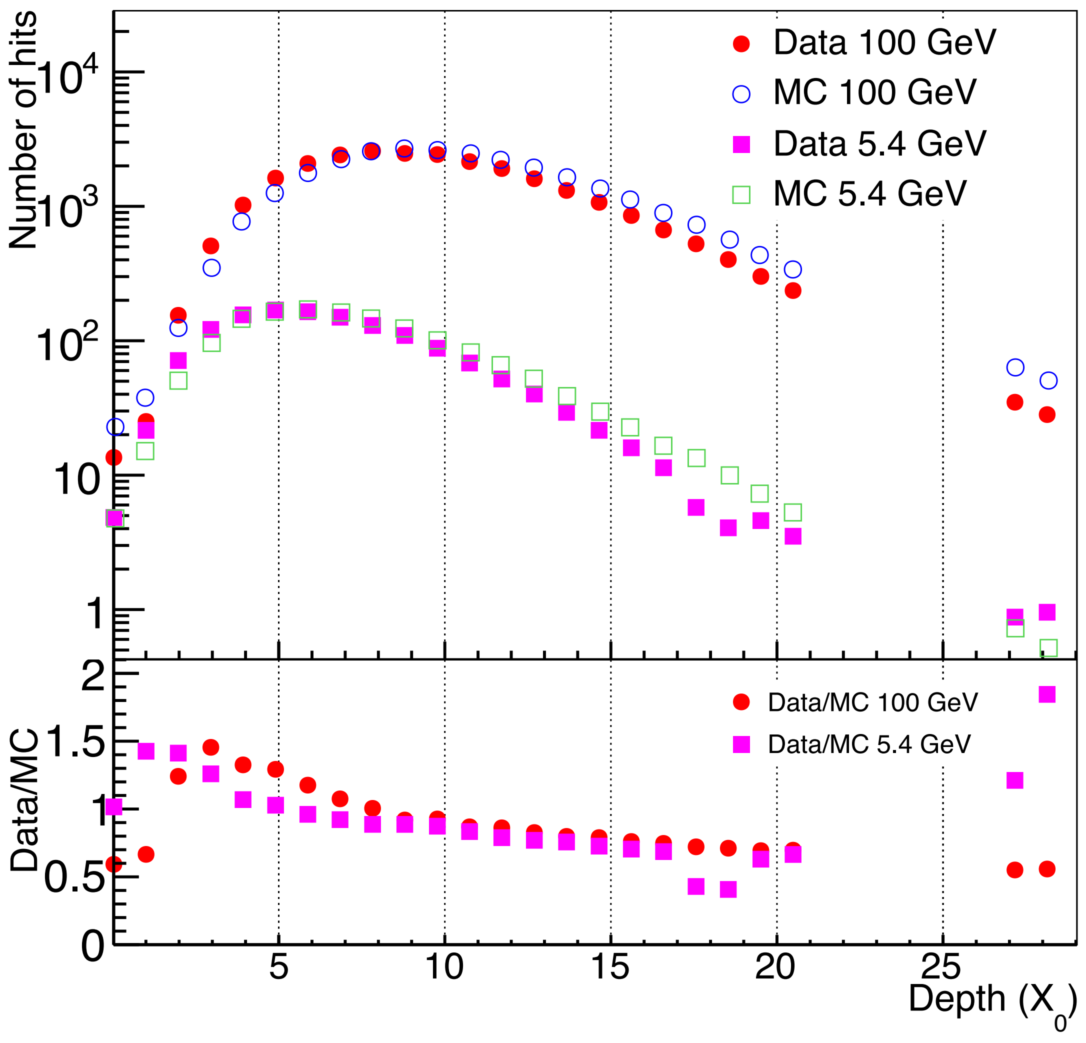
strong suppression of photon production $R_{pPb} \approx 0.2\text{-}0.4$

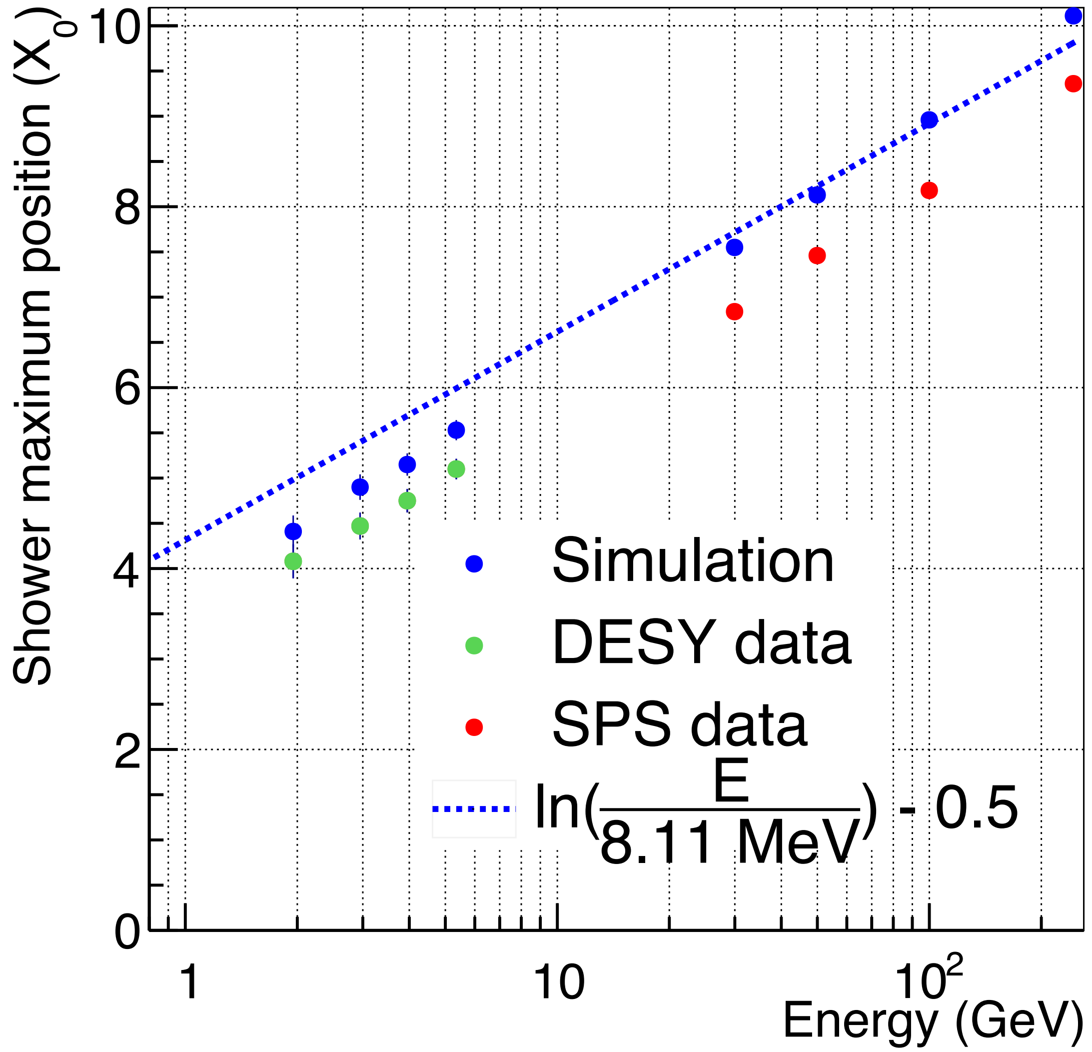
recent CGC calculation:

shows larger $R_{pPb} \approx 0.7\text{-}0.8$

currently large uncertainty in CGC prediction,
but also larger uncertainty in nuclear PDFs (EPPS16)

Longitudinal Profiles - MC Comparison

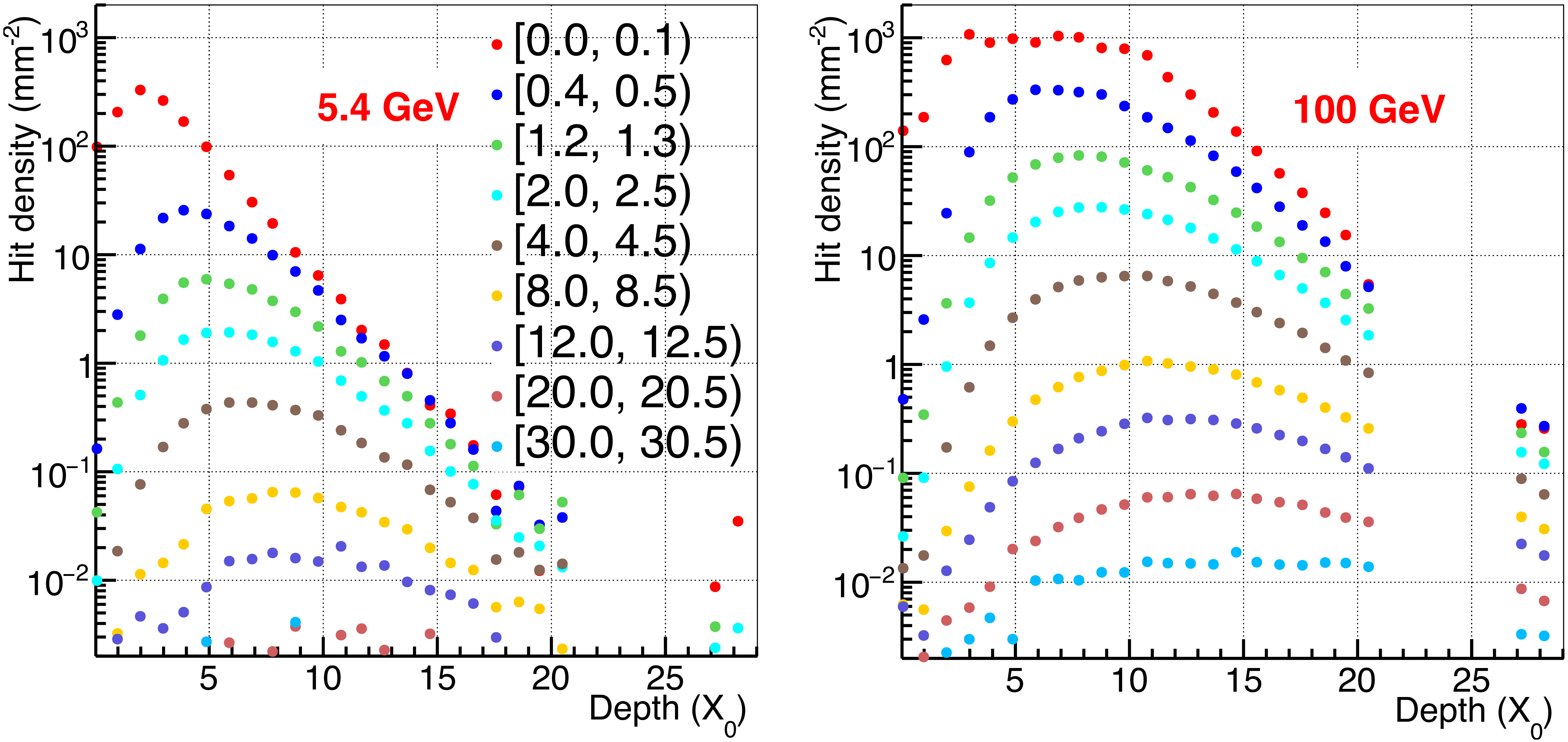

Longitudinal Profile


Shower Maximum

significant difference between data and MC

- larger number of hits in data for early layers
- shower maximum reached earlier than in MC
- similar effect observed in CALICE AHCAL!

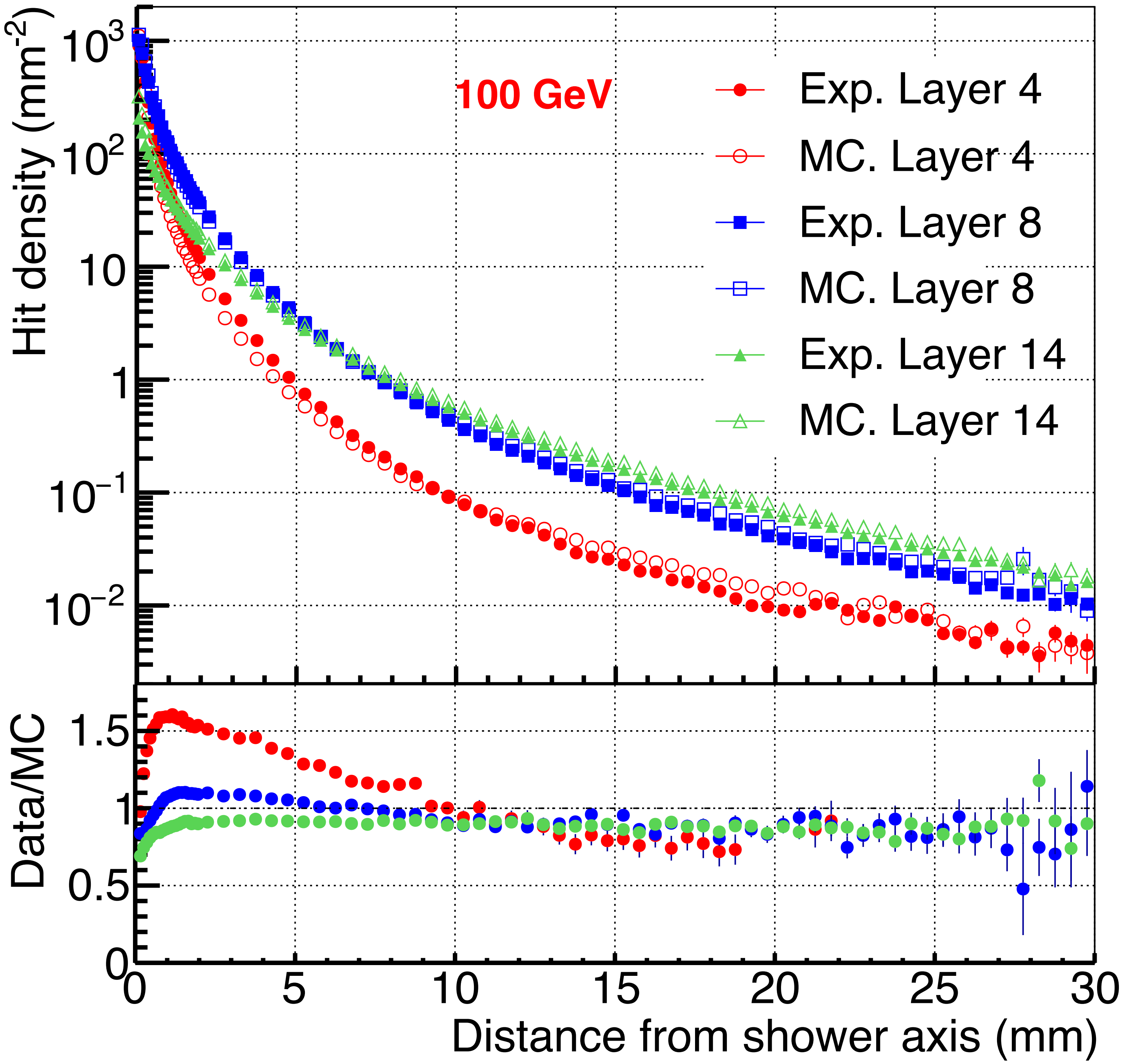
Longitudinal Profiles



average hit densities as a function of depth
for different radial positions

- different view of 3-dimensional info

Lateral Profiles - MC Comparison



also differences to MC in lateral profiles

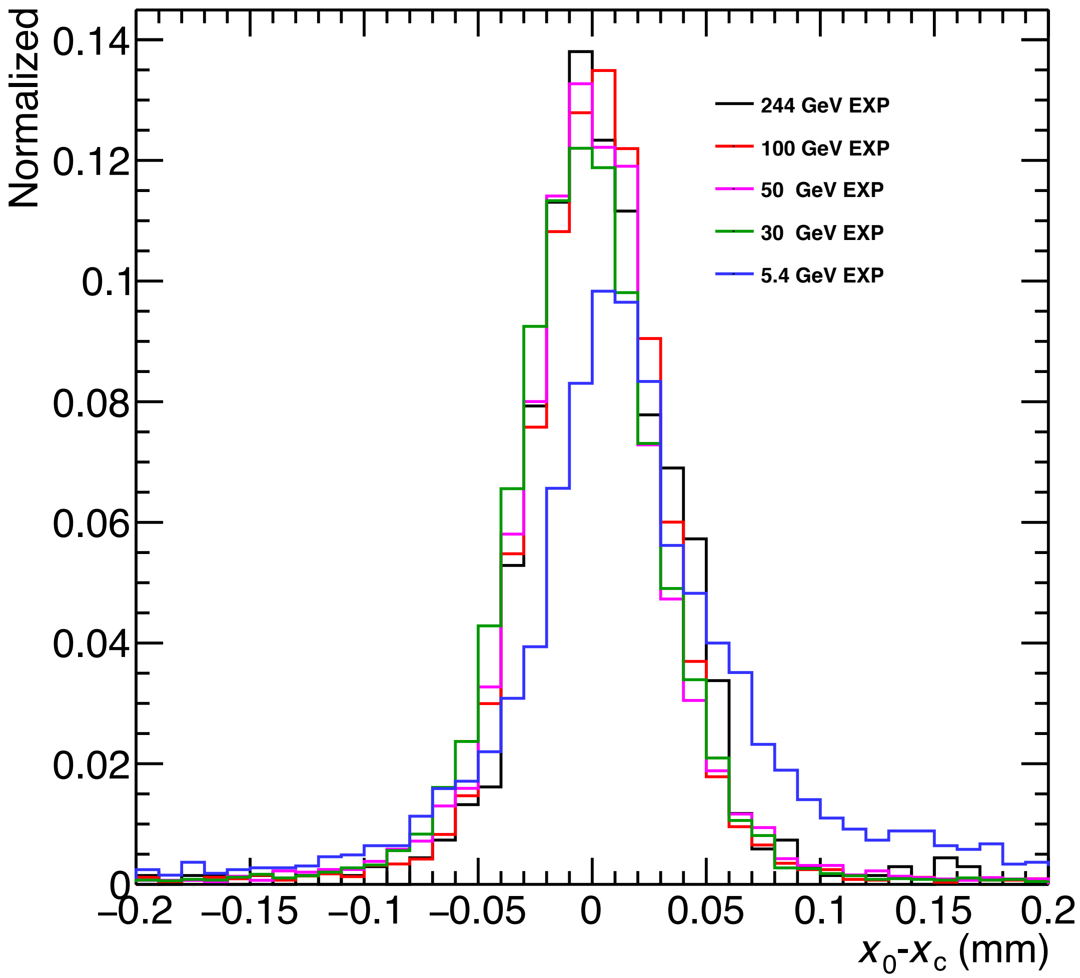
consistent with difference in longitudinal profiles: larger number of hits in early layers

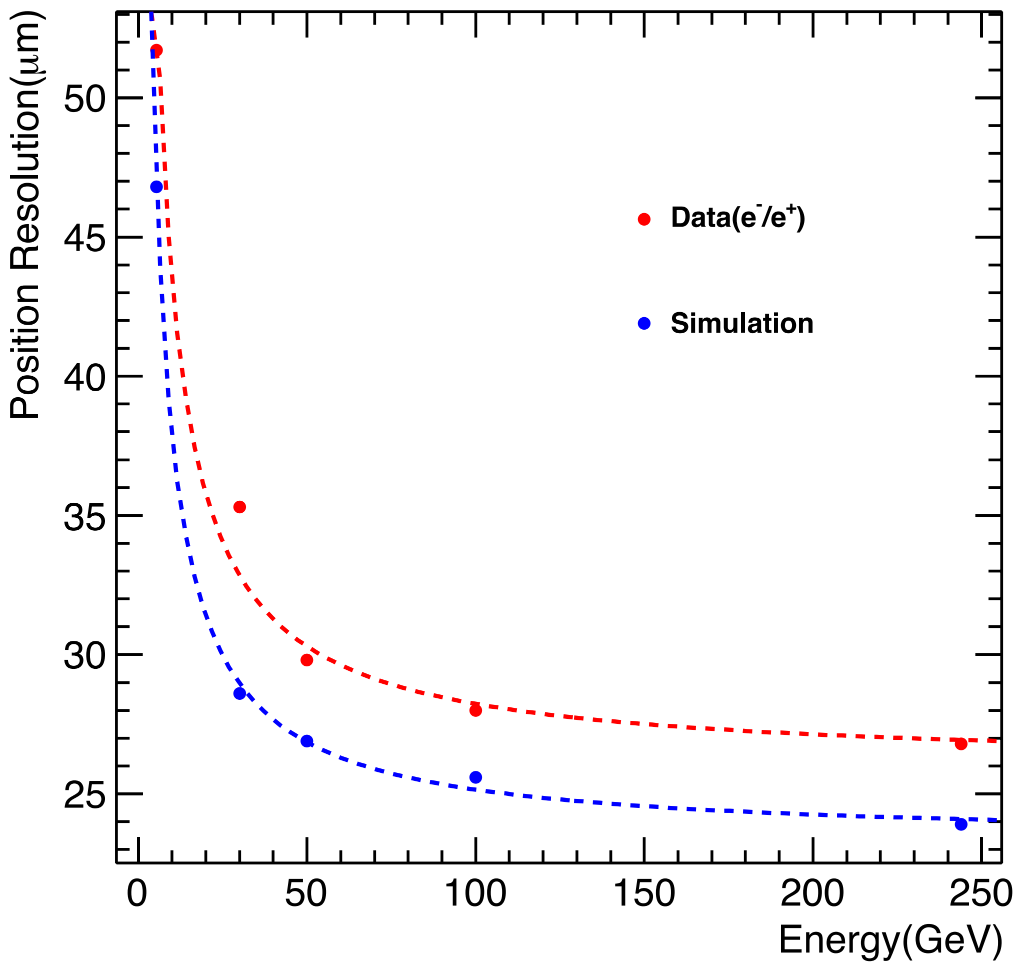
more details significant?

- narrower profiles?
- drop in hit density in central core?

possible issues: imperfect implementation of charge diffusion in MC?

R&D - Position Resolution





calculate difference of position from

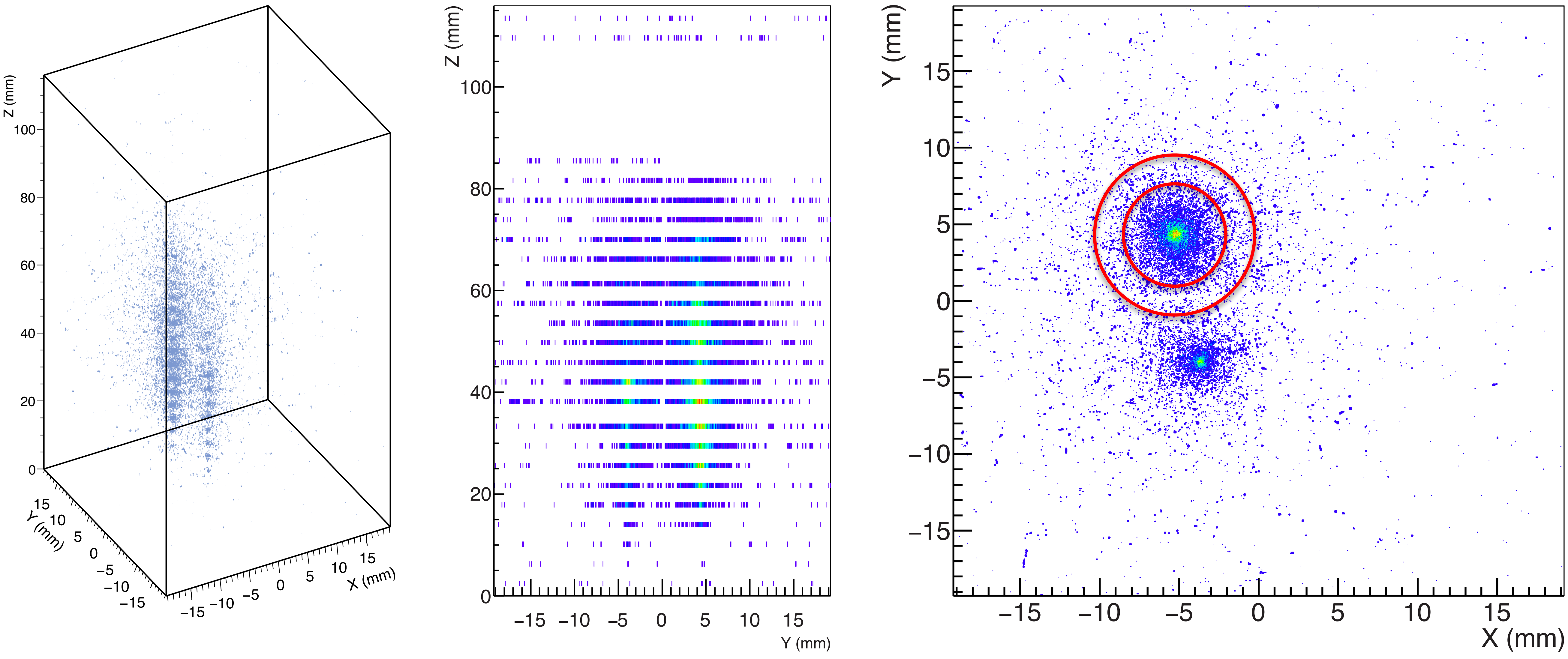
- cluster in layer 0 and
- center of gravity of shower in layers 1 - 23

single shower position resolution obtained from width of residuals

can also provide excellent two-shower separation

Two Shower Separation

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

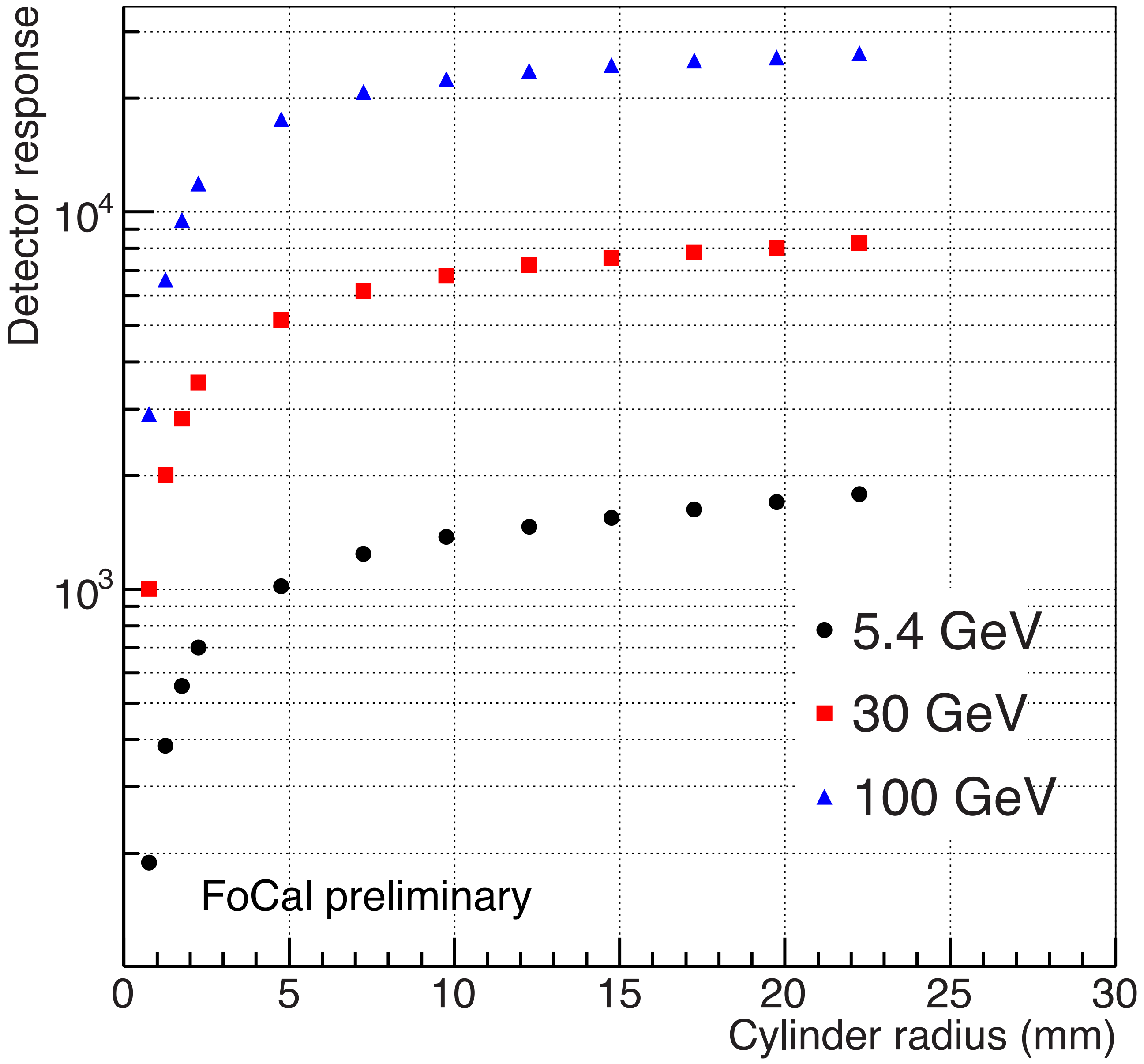


evaluate separation capability: core energy

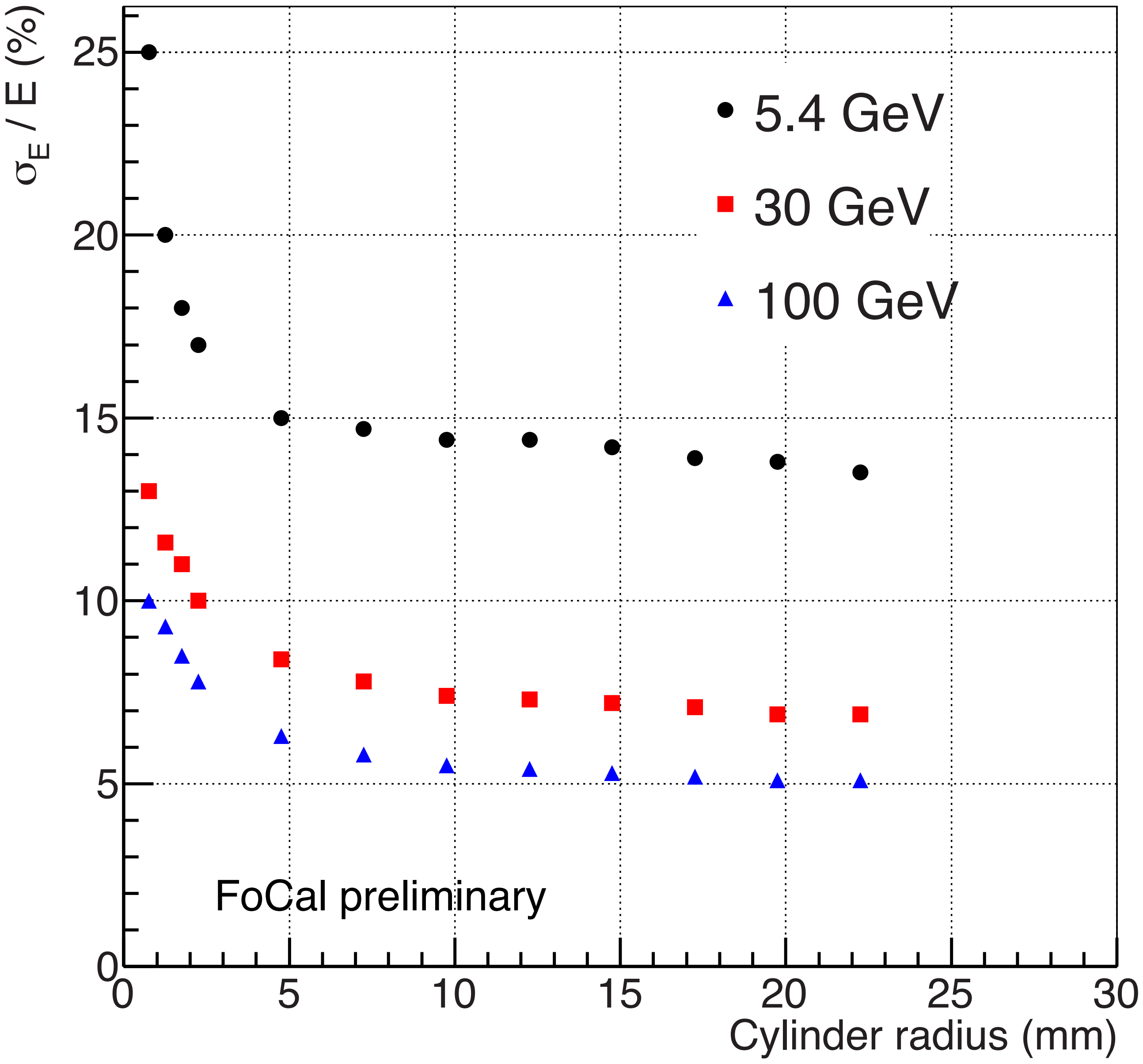
- calculate shower energy in cylinder of finite radius
- study as function of radius

R&D Results: Core Energy

detector response (number of hits)



energy resolution

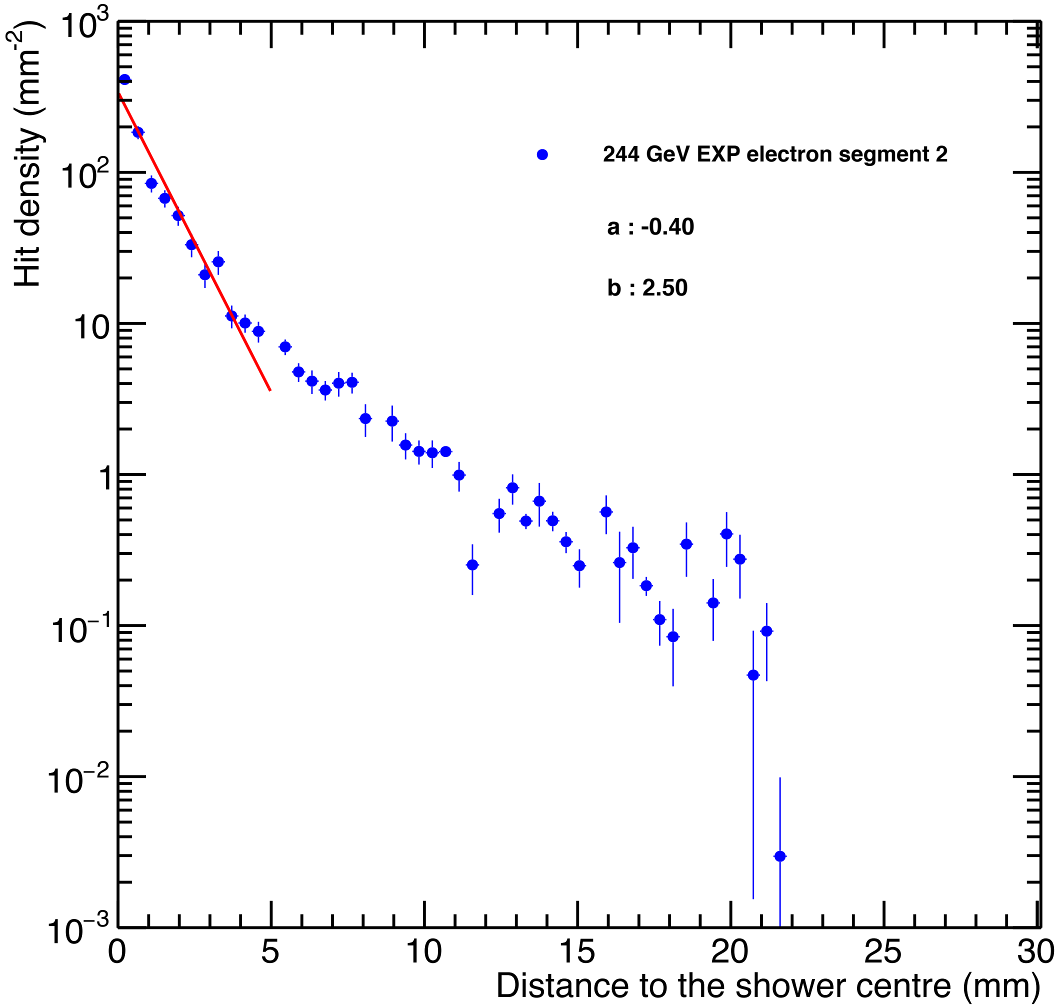


reasonable energy resolution of pixel calorimeter, sufficient for conceptual design

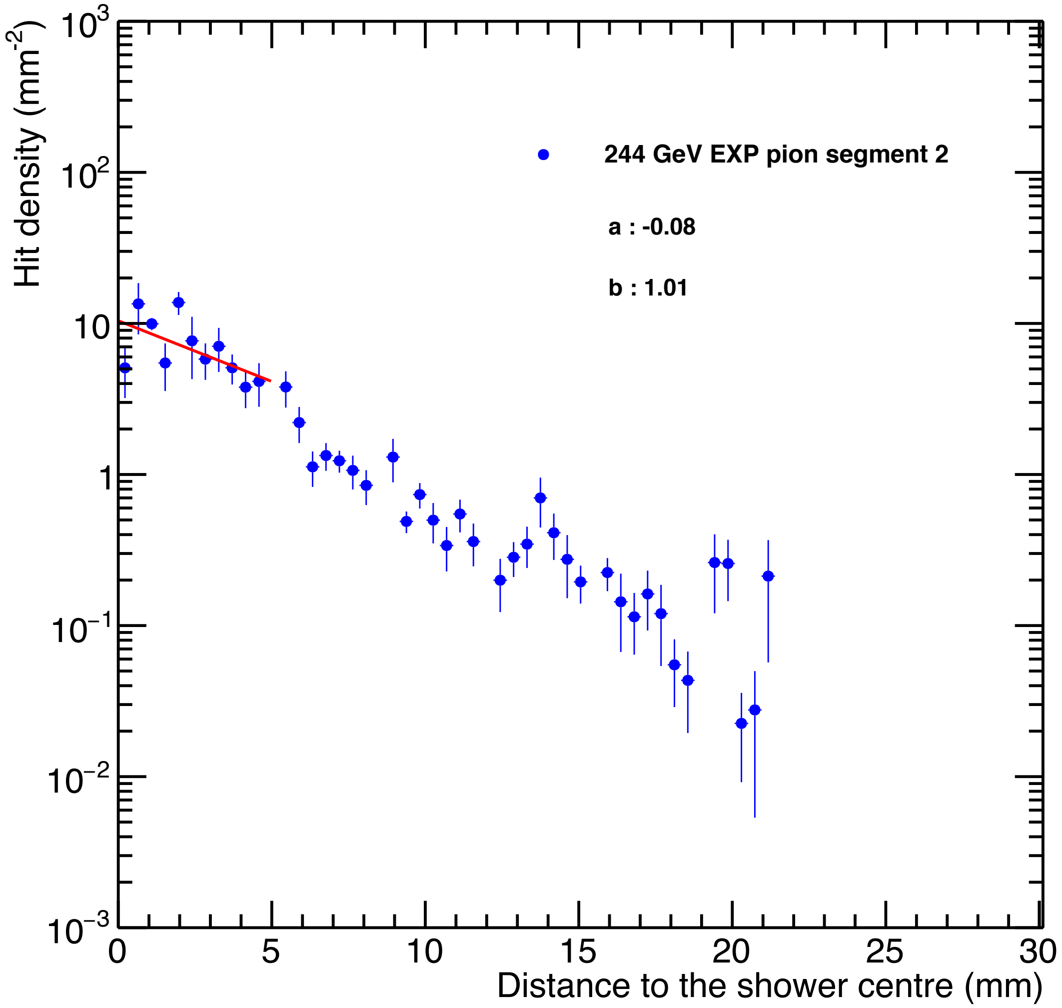
response and resolution for core energy hardly affected down to r = 5mm:
adequate for very high particle density

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