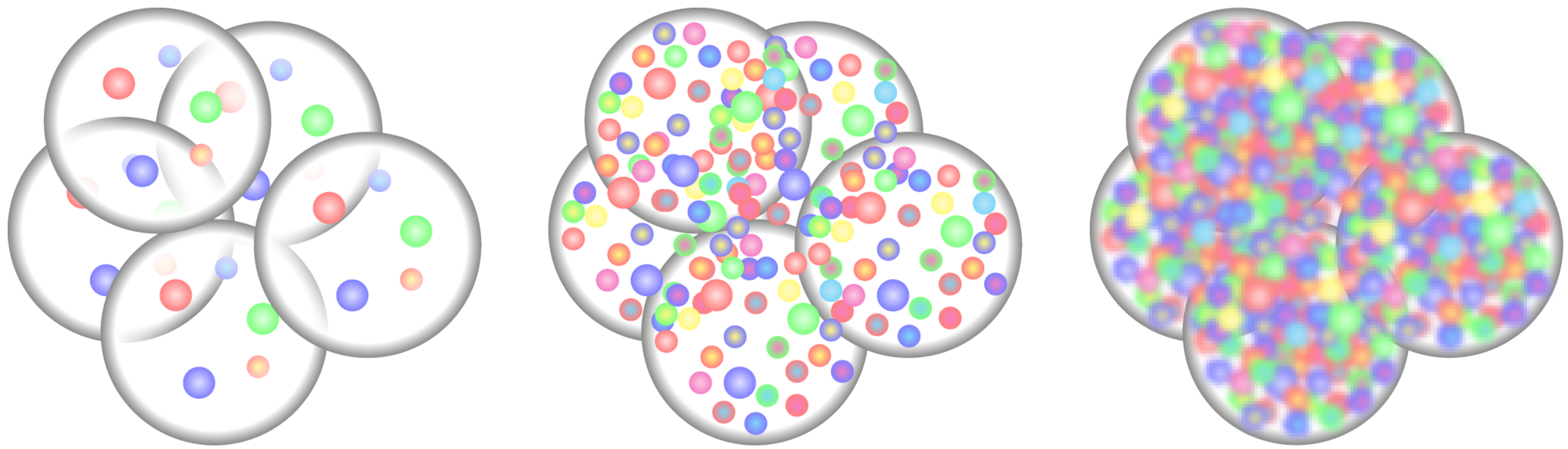


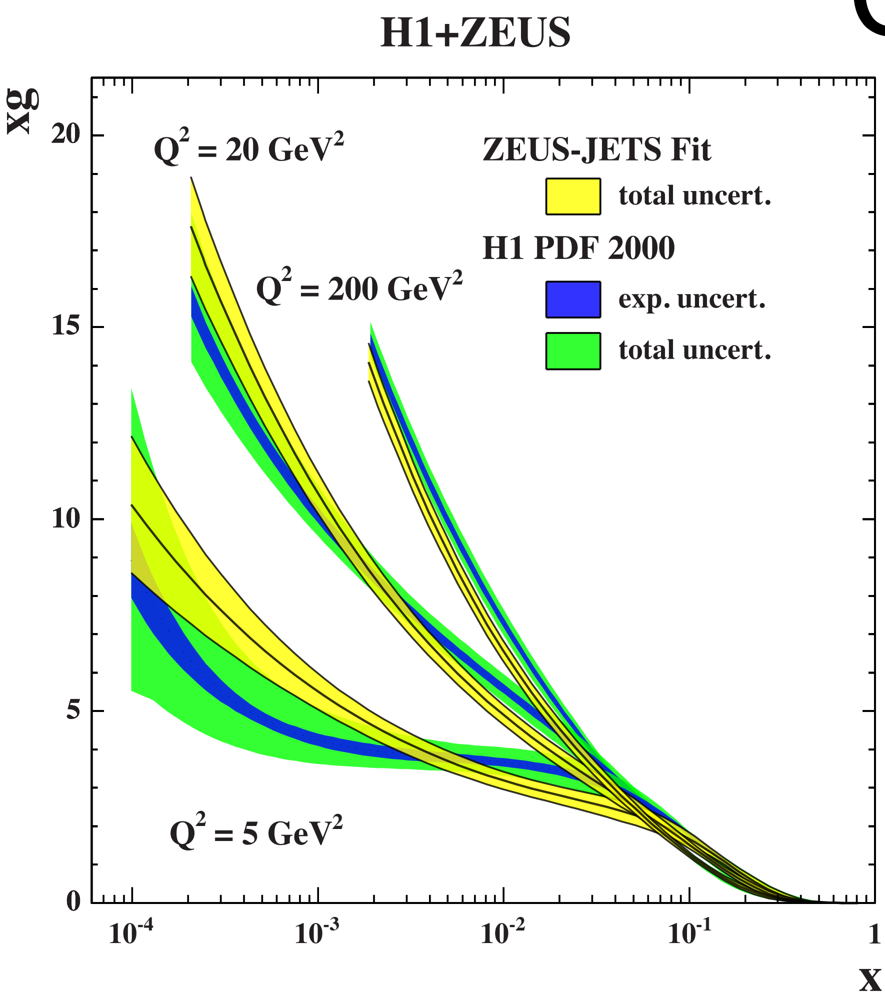
Opportunities for Forward Photon Measurements in ALICE at the LHC

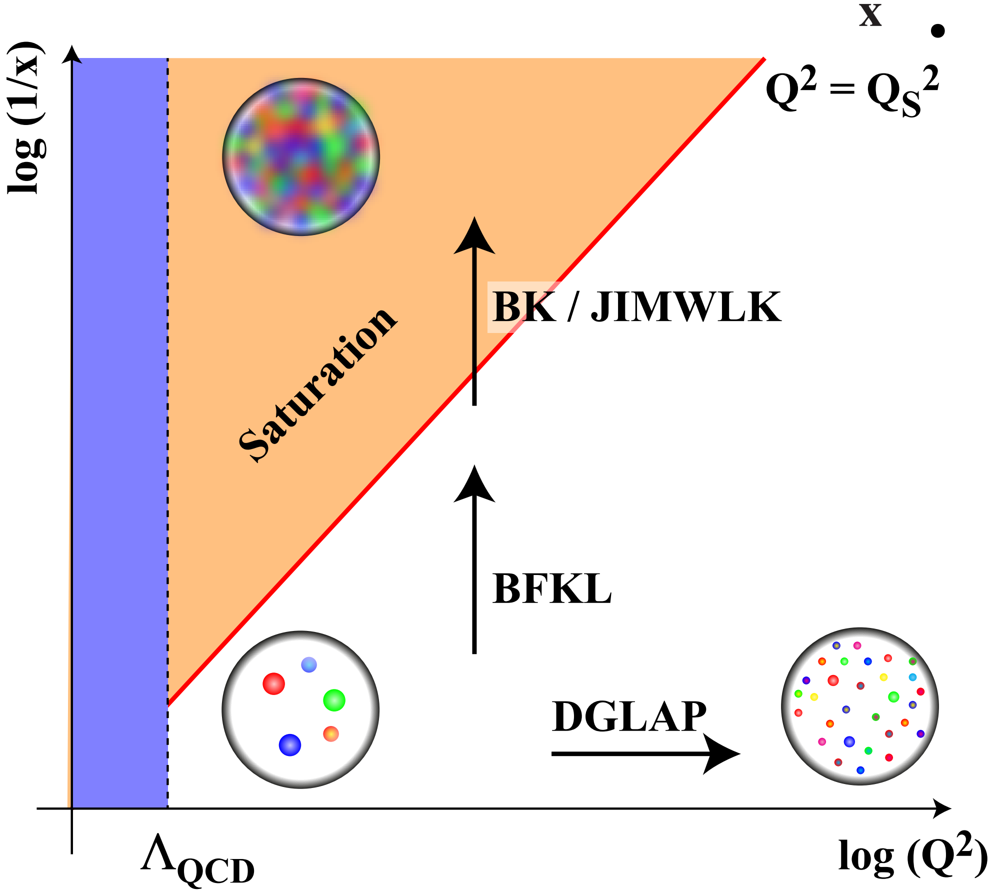
T. Peitzmann (Utrecht University/Nikhef)

Outline

- Introduction
  - low-x physics, gluon saturation
  - first results from LHC
- Saturation signals
  - PDF uncertainties?
  - range of validity of saturation models?
  - charm vs photons?
- FoCal - an ALICE upgrade proposal
  - baseline design: performance studies
  - progress on detector R&D
- Summary

Gluon Saturation



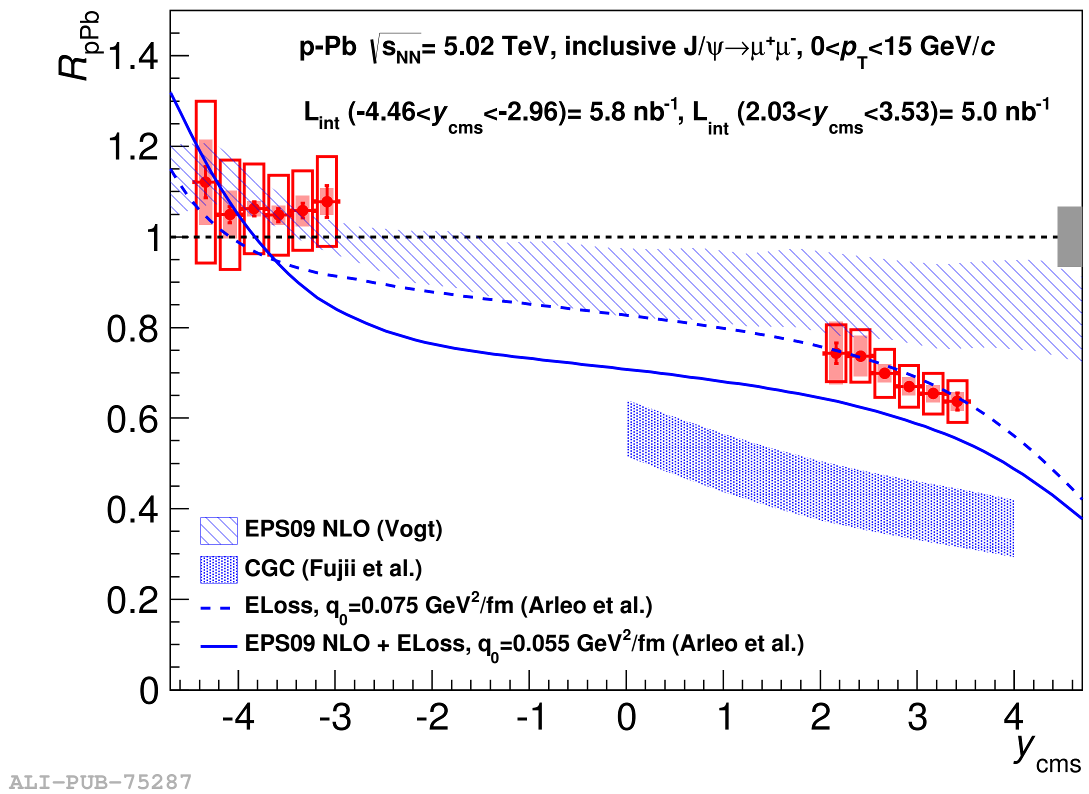


- from evolution equations (DGLAP, BFKL):
  - gluon density increases with Q^2 and $1/x$
    - leads to very high gluon density
    - problems with unitarity(?)
- for high density non-linear processes become important
- gluon saturation below saturation scale
  - enhanced in nuclei

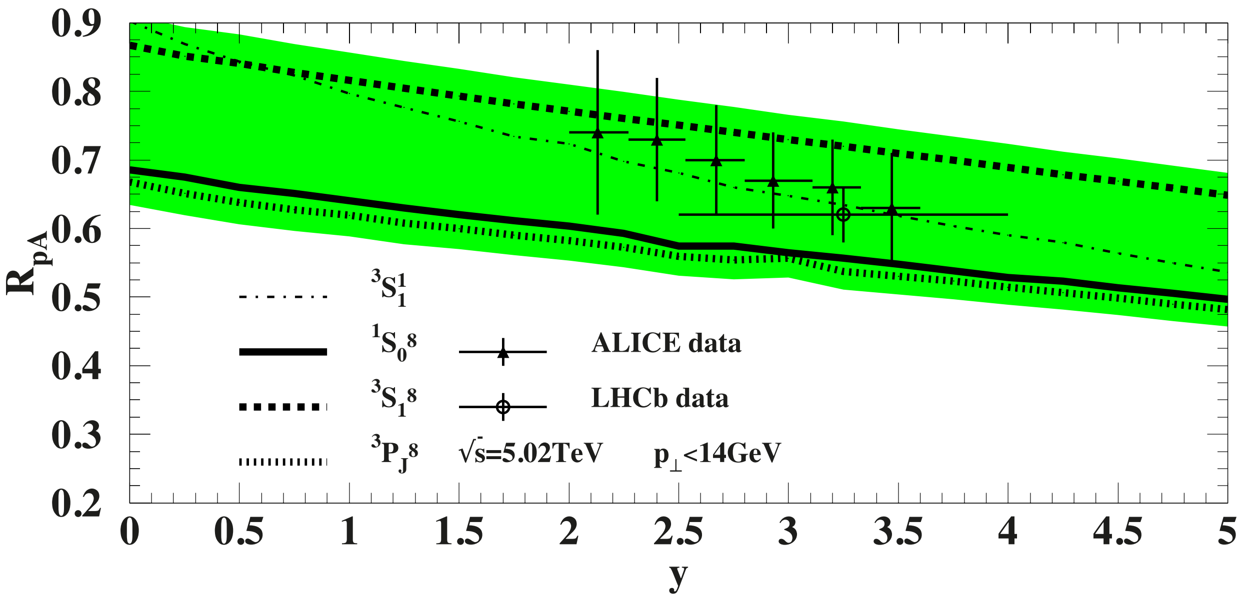
$$Q_s^2(x) \approx \frac{\alpha_S}{\pi R^2} xG(x, Q^2) \propto A^{1/3} \cdot x^{-\lambda}$$

Results from p-Pb at LHC (1)

ALICE, JHEP02 (2014) 073



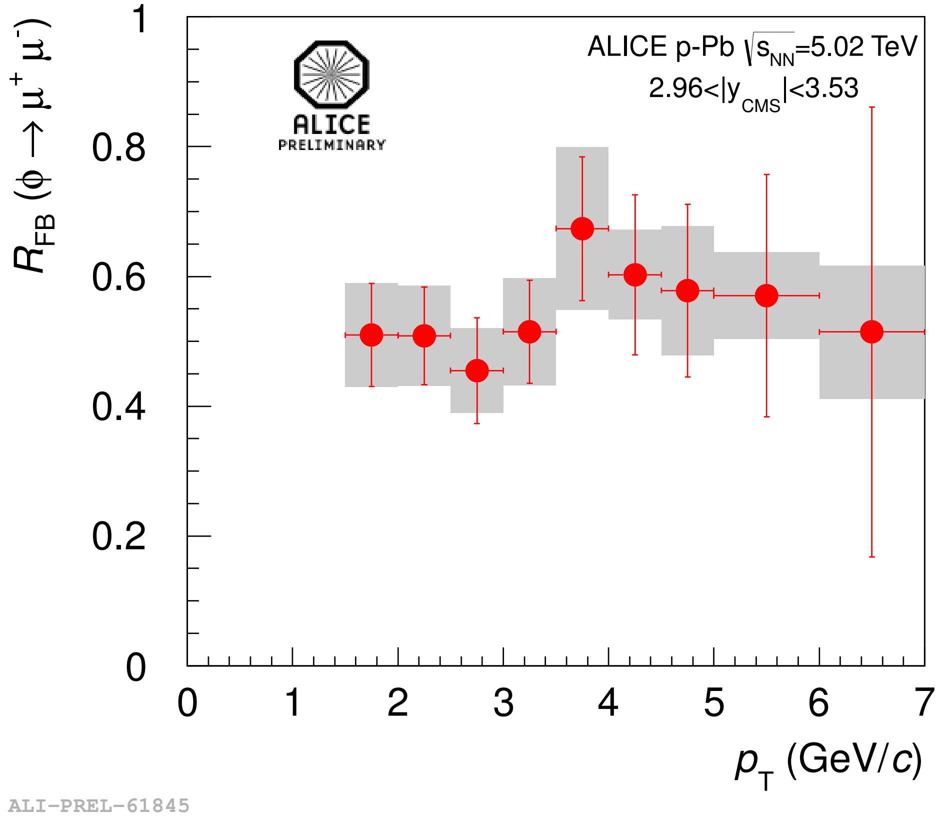
Ma, Venugopalan, Zhang, arXiv:1503.07772



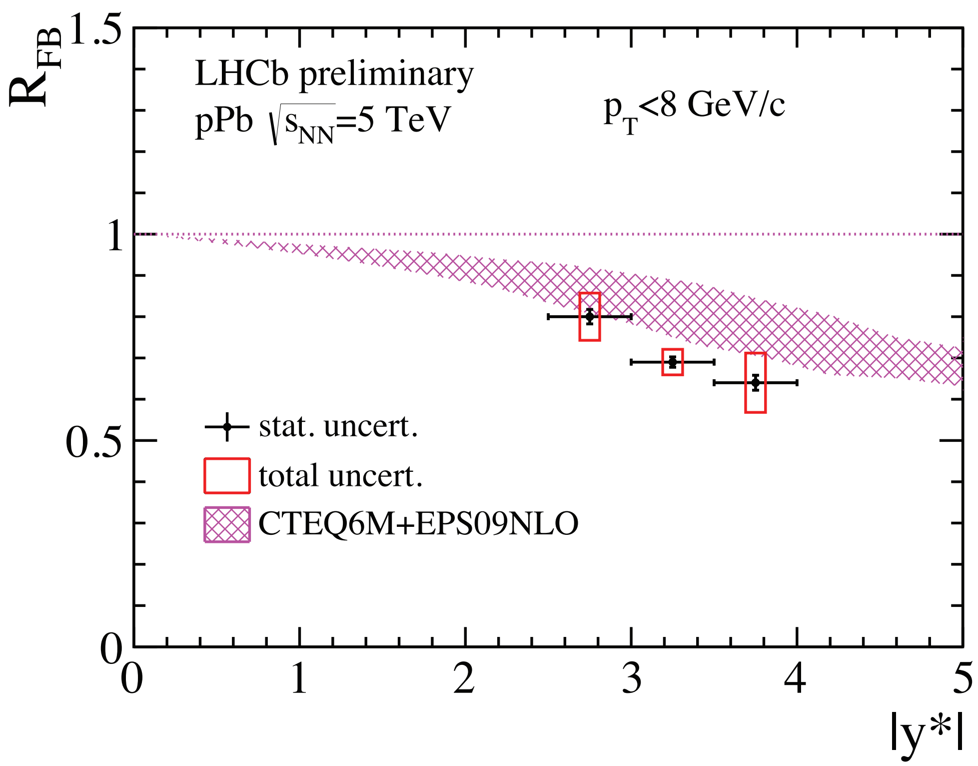
$$R_{pA} = \frac{dN/dp_T(pA)}{< N_{coll}(pA) > dN/dp_T(pp)}$$

- nuclear modification factor RpPb for charmonium
- J/ψ suppressed at forward rapidity
  - consistent with shadowing (EPS09)
  - not described by one CGC calculation (state of the art?)
- description by CGC
  - needs refined calculations
  - uncertainties due to population of different quantum states
- not conclusive

Results from p-Pb at LHC (2)



LHCb-CONF-2016-003



- forward/backward ratio R_{FB}

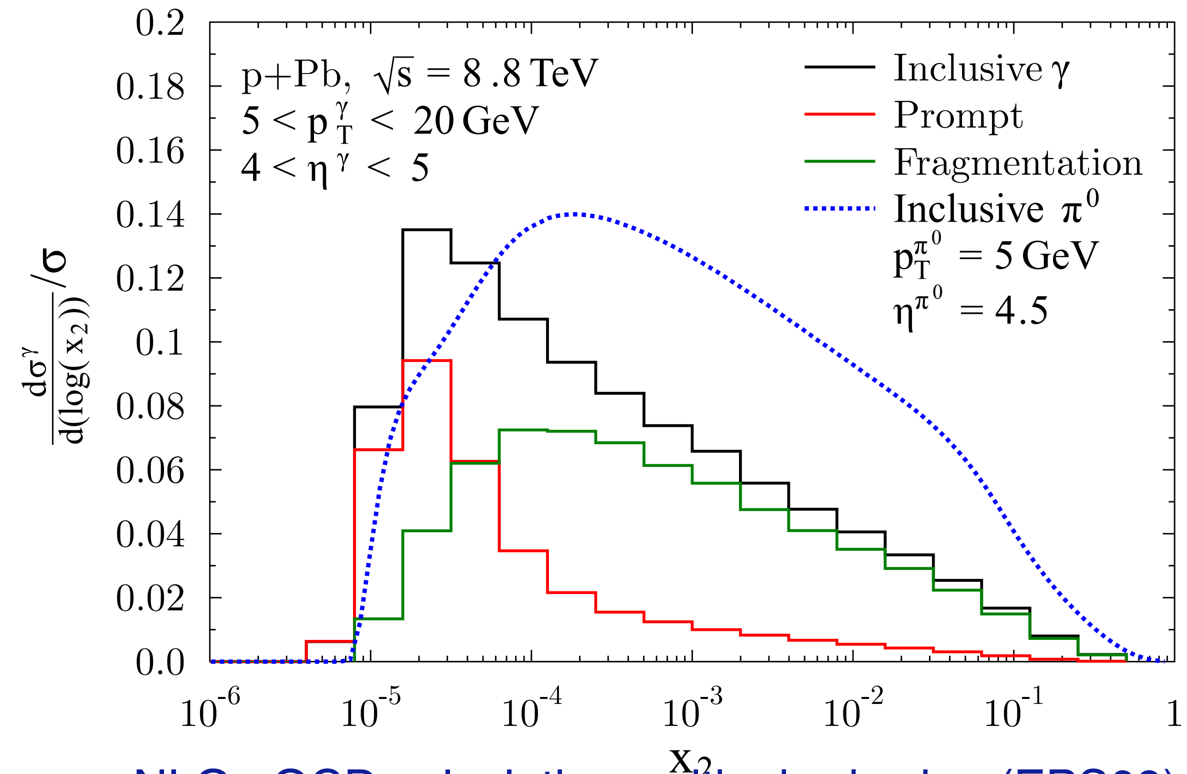
$$R_{FB} = \frac{dN/dp_T(\mathrm{p-going})}{dN/dp_T(\mathrm{Pb-going})}$$

for ϕ-mesons in ALICE (dimuons) and for open charm in LHCb

- ϕ strongly suppressed at forward rapidity
  - interpretation unclear
- prompt D^0 suppressed
  - comparison with shadowing (EPS09): consistent, but data slightly more suppressed

Signals of Saturation?

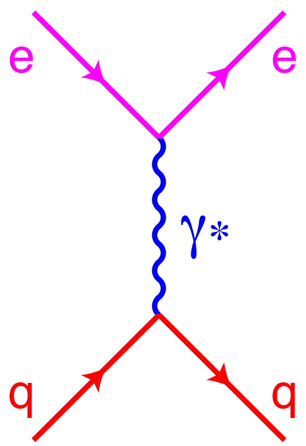
- cleaner observables: EM probes (direct photons, Drell-Yan)
  - no final state interaction
  - well-understood production process
  - well-defined kinematics
- advantage of direct photons: large cross section
  - forward p–A measurement of DY likely not possible with expected luminosity



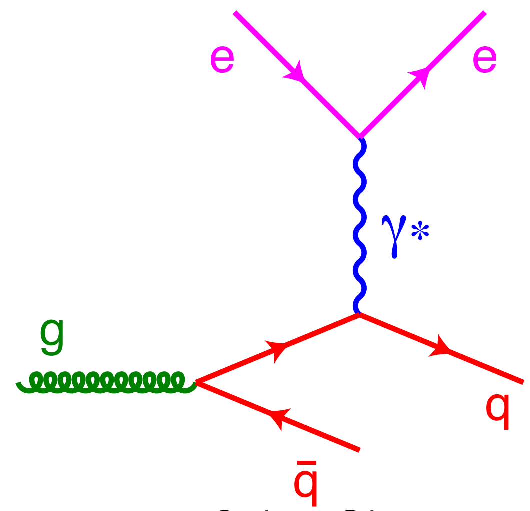
NLO pQCD calculations with shadowing (EPS09)
Helenius, Eskola, Paukkunen, arXiv:1406.1689

- interpretation of hadronic observables remains inconclusive
  - final state modifications in p–A collisions?
  - production process not fully understood for many hadrons
  - kinematic relation to Bjorken-x uncertain (e.g. fragmentation)
- best alternative candidate: open charm
  - direct sensitivity to gluons
  - final state interactions?

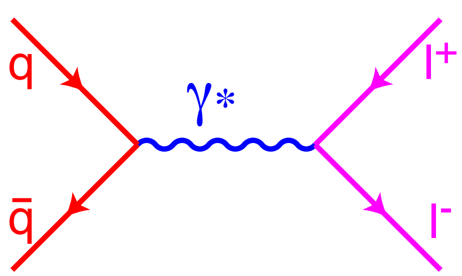
Electromagnetic Processes



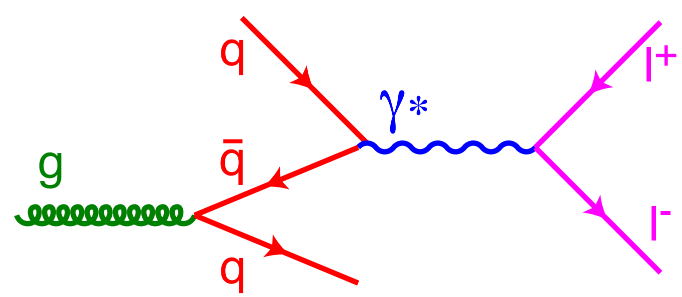
DIS (LO)



DIS (NLO)

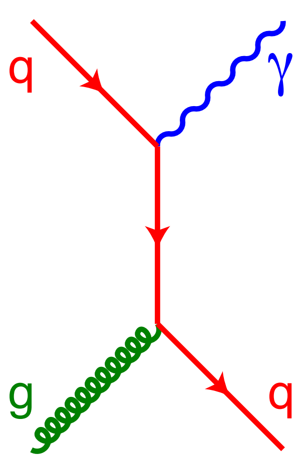


DY (LO)



DY, virtual Compton (NLO)

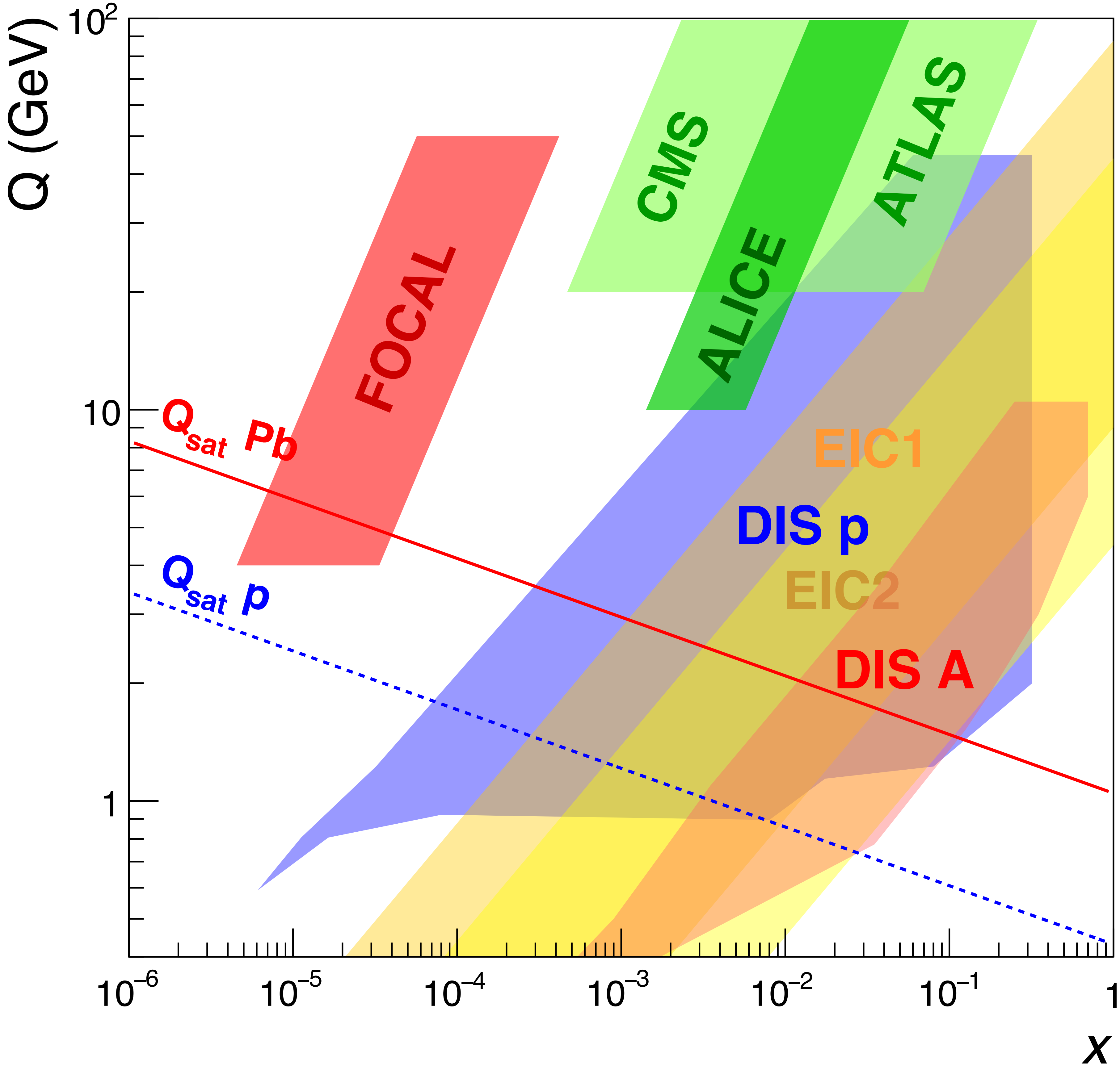
- DIS and Drell-Yan are equivalent processes
  - crossing symmetry
  - sensitivity to gluons only at NLO
    - e.g. virtual qg-Compton
- main disadvantage of DY: very low cross section
  - not accessible in pA



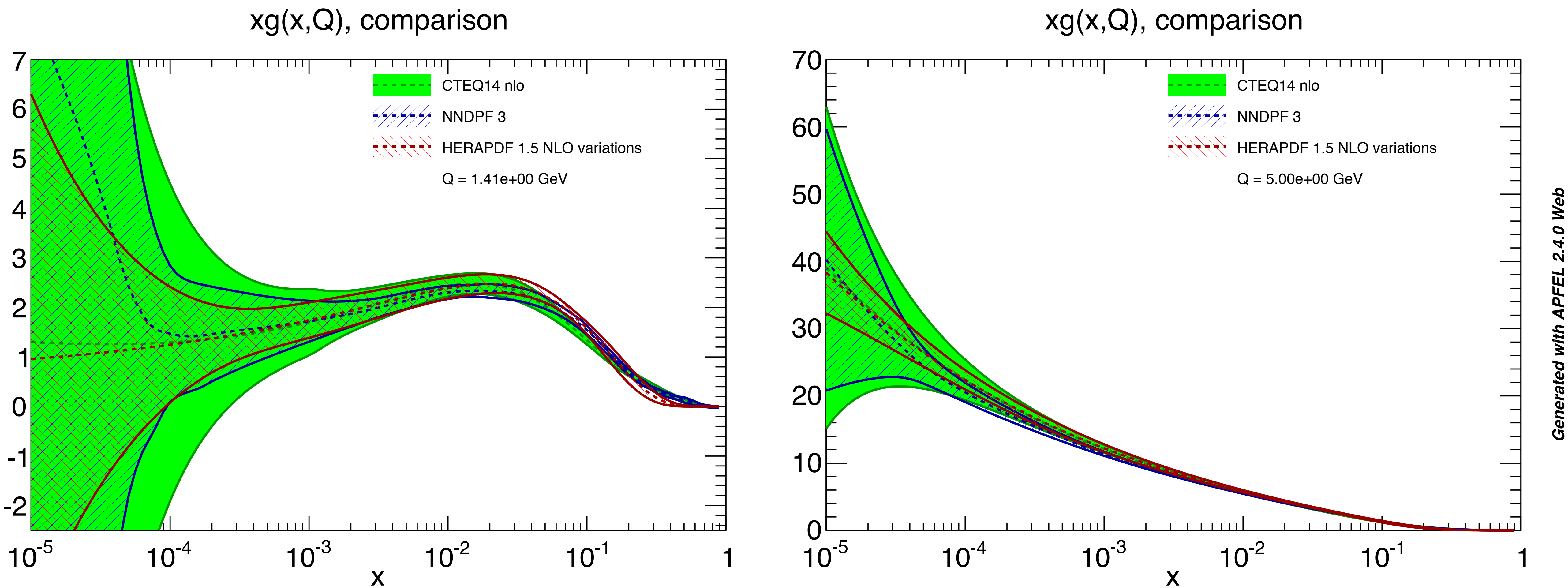
direct-γ, Compton (LO)

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

EM Probes: Kinematic Coverage



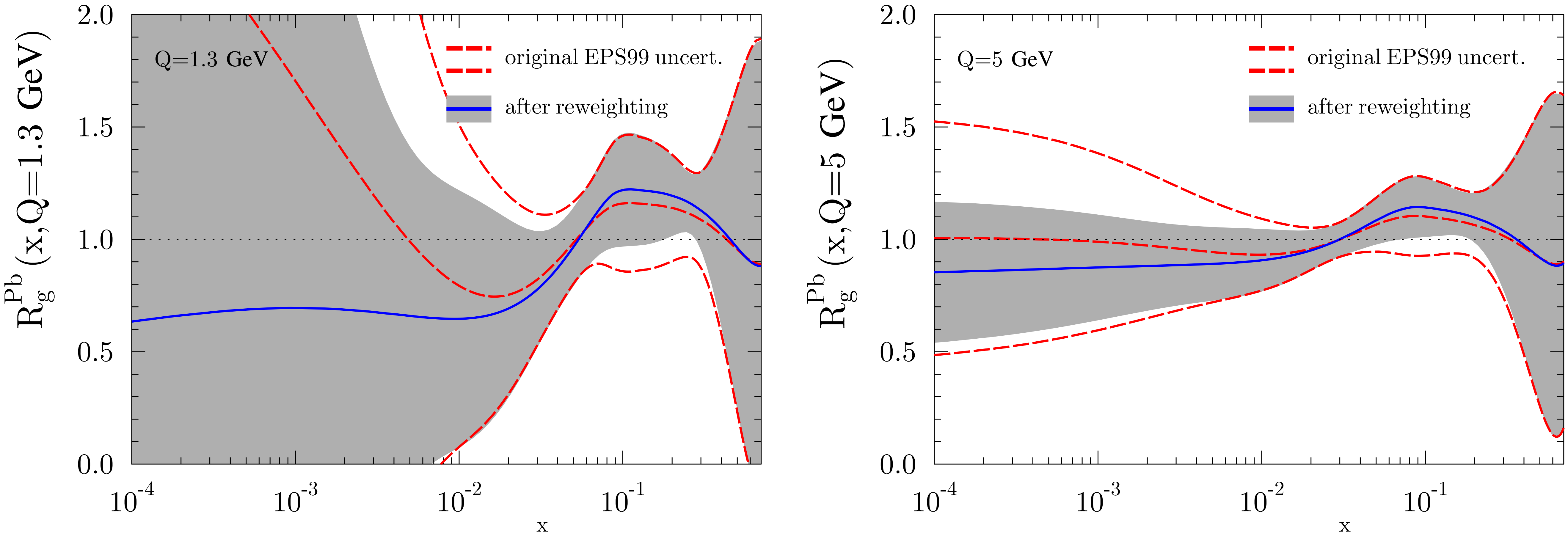
Gluon Densities at Low x (Protons)



- at Q = 1.41 GeV, g(x) essentially unconstrained for $x < 10^{-4}$
- apparent uncertainty significantly reduced at slightly larger Q (5 GeV)
  - not from more data constraints!
  - strong role of QCD evolution

- careful: we want to test QCD evolution!

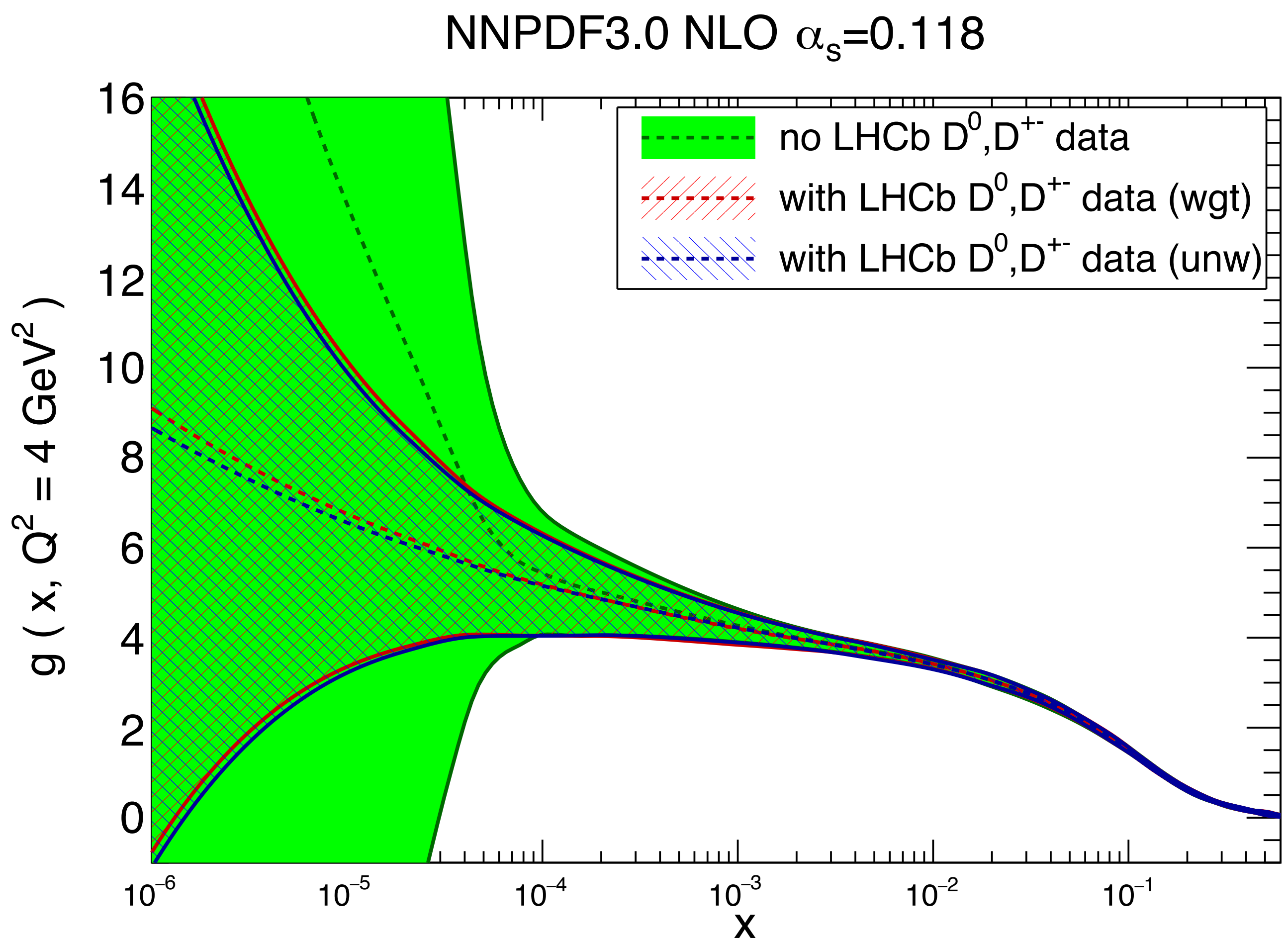
Gluon Densities at Low x (Nuclei)

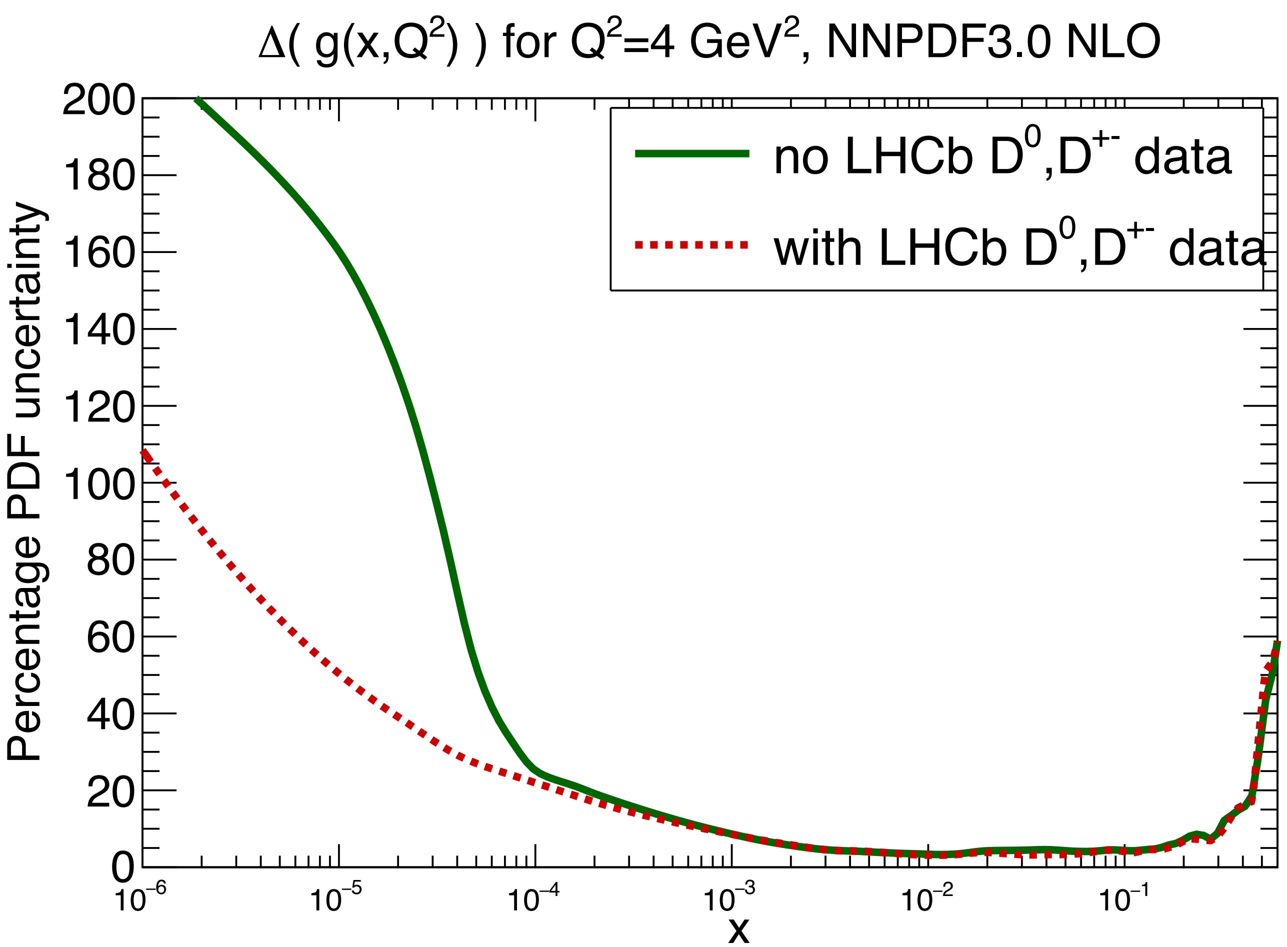


H. Paukkunen, I. Helenius, priv. communication

- at Q = 1.3 GeV, g(x) essentially unconstrained for $x < 10^{-2}$
  - old PDF sets in nuclei did not allow sufficient freedom
  - new parameterisations under way – still not equivalent flexibility as NNPDFs

Impact of Forward Open Charm

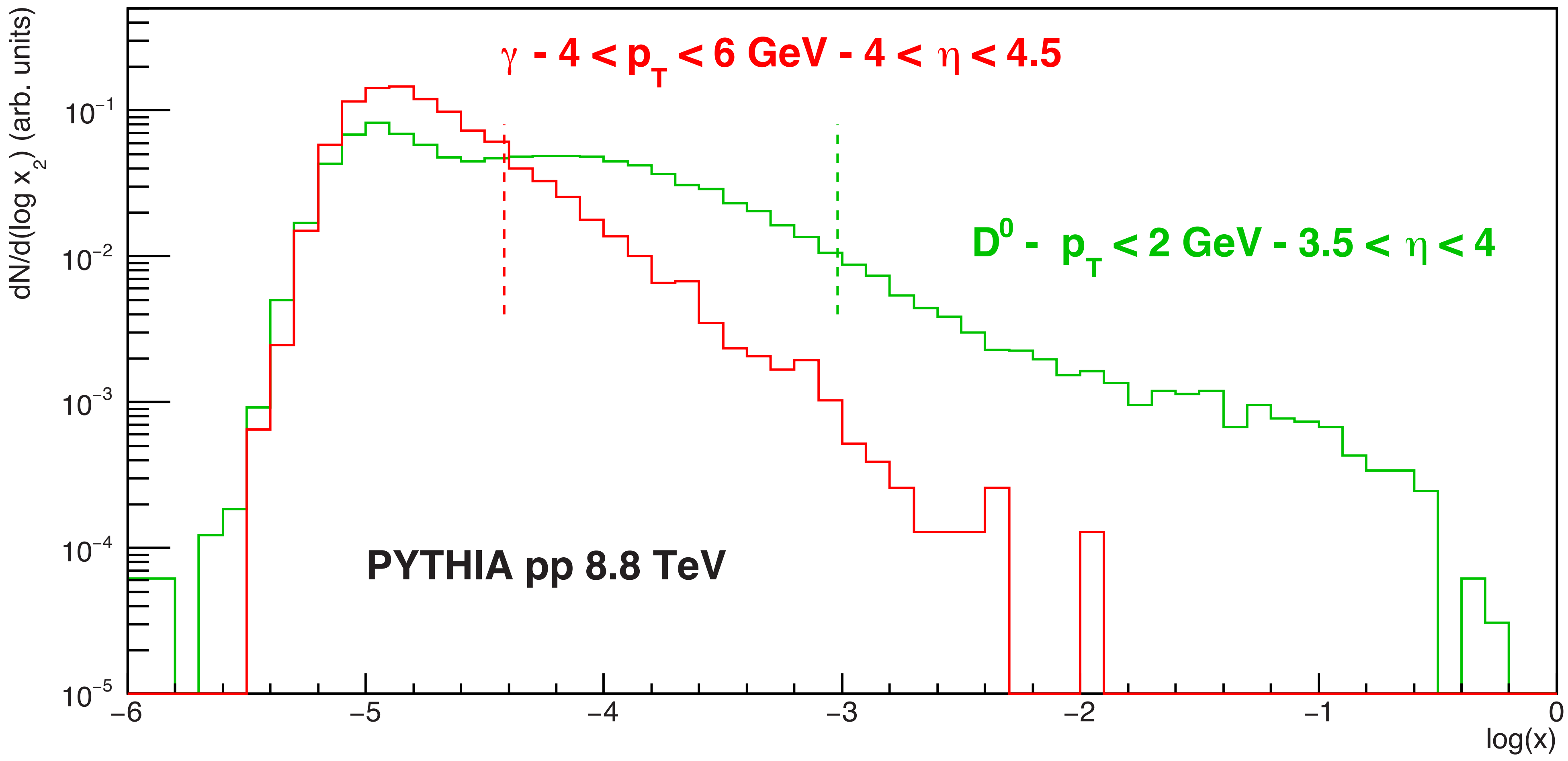




R. Gauld et al., arXiv 1506.08025

- usage of forward D measurements by LHCb can constrain gluon distribution
  - fit uses normalisation at low y, high p_T
- how much of the constraints due to data?

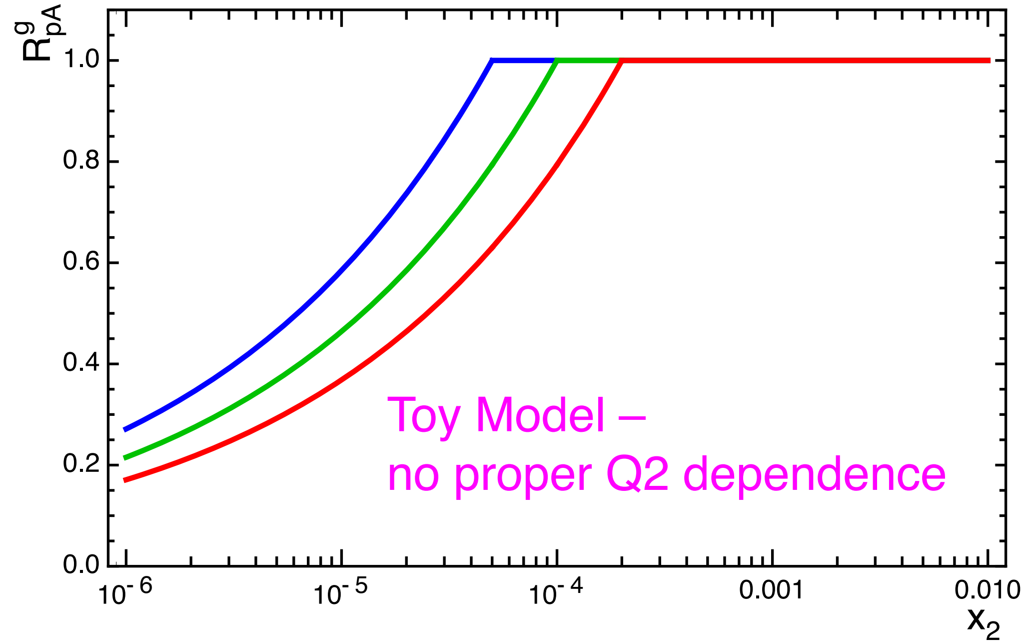
x-Sensitivity

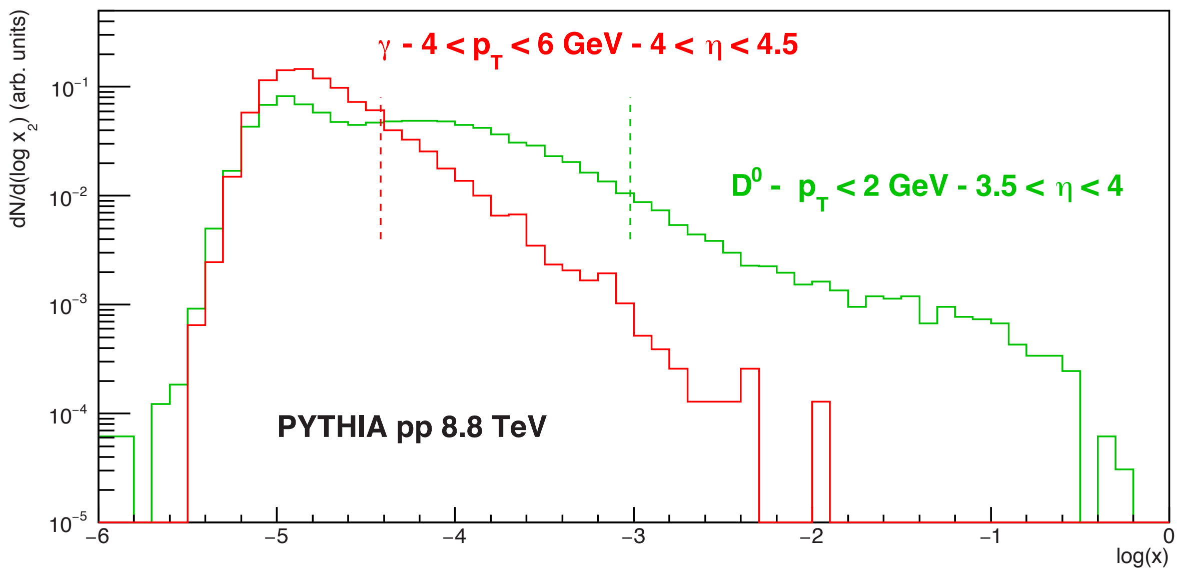


- x_2 distributions for forward production
  - LO production from PYTHIA
  - D^0 (LHCb) vs prompt γ (FoCal)
- apparent maximum at $x \approx 10^{-5}$
  - beware of log(x) scale!
  - significantly larger mean value
- significant advantage of proposed direct photon measurement relative to charm in LHCb

Parameterised Nuclear Modification

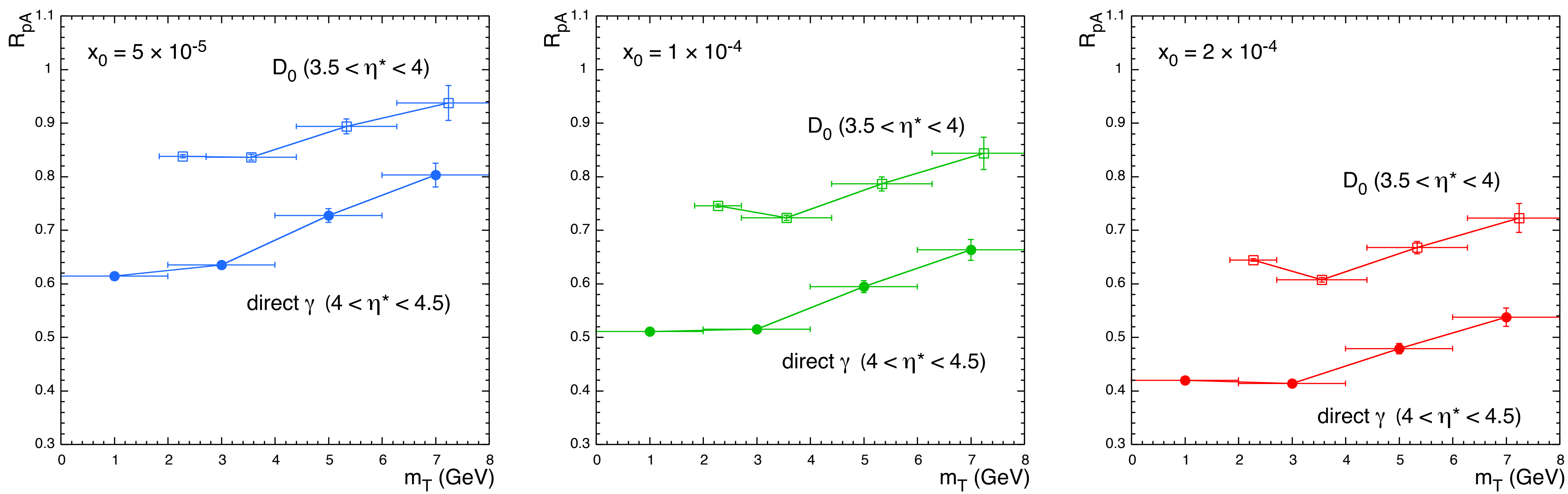
assume nuclear modification of gluon PDFs





fold with gluon x distribution for a given observable in pp collisions (PYTHIA)

from ratio of integrals obtain nuclear modification of observable



More Realistic Nuclear Modification?

naive recipe to compare gluon density from saturation models:

calculate “effective gluon PDFs” (thanks to Elena Petreska)

$$xG(x, Q^2) = \int^Q \frac{d^2 k_T}{\pi} \Phi(x, k_T)$$

GBW-model:

$$xG_{\mathrm{GBW}}(x, Q^2) = \frac{N_c}{2\pi^3 \alpha_s} \pi R^2 Q_s^2(x) \left[1 - \left(1 + \frac{Q^2}{Q_s^2(x)} \right) e^{-Q^2/Q_s^2(x)} \right]$$

MV-model ($k_T >> Q_s$):

$$xG_{\mathrm{MV}}(x, Q^2) = \frac{N_c}{4\pi^2 \alpha_s} \pi R^2 Q_s^2(x) \log \left(\frac{Q^2}{\Lambda^2} \right)$$

with:

$$Q_{sp}^2(x) = Q_{s0}^2(x) \left(\frac{x_0}{x} \right)^\lambda$$

Nuclear Modification of Gluon PDFs

calculate with: $Q^2_{sA}(x) = cA^{1/3}Q^2_{sp}(x)$

$$Q^2_{s0}(x) = 1\,\mathrm{GeV}^2; \;\; x_0 = 3.04 \cdot 10^{-4}; \;\; \lambda = 0.288$$

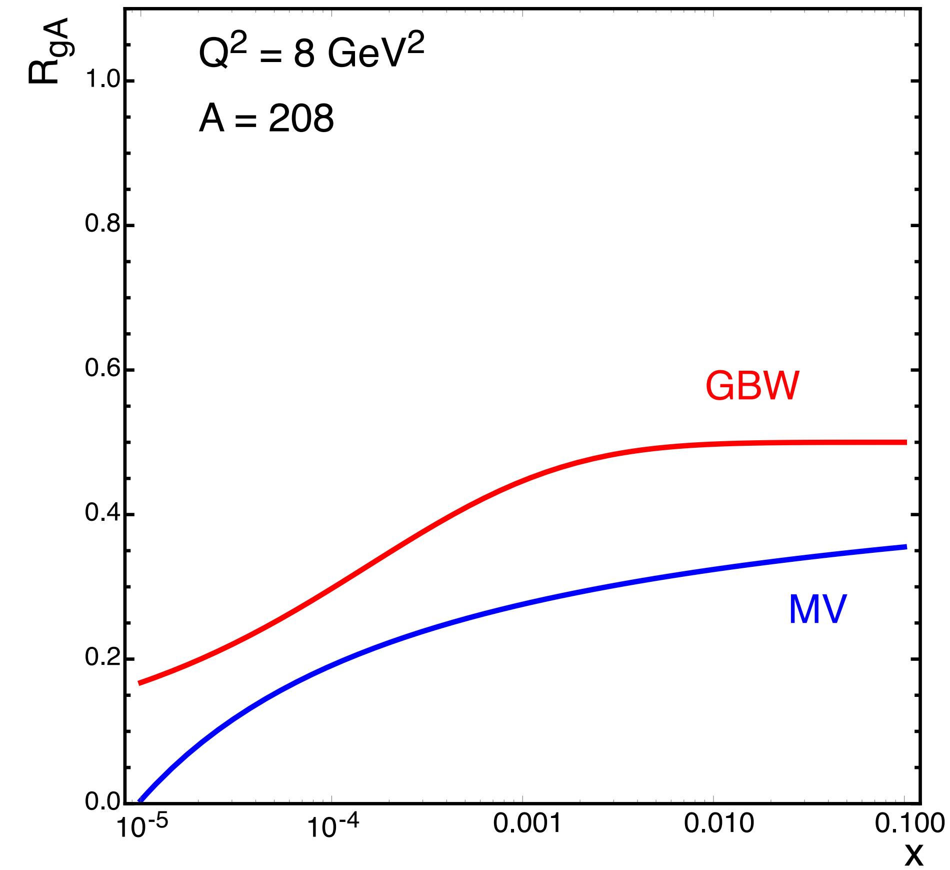
$$c = 0.5$$

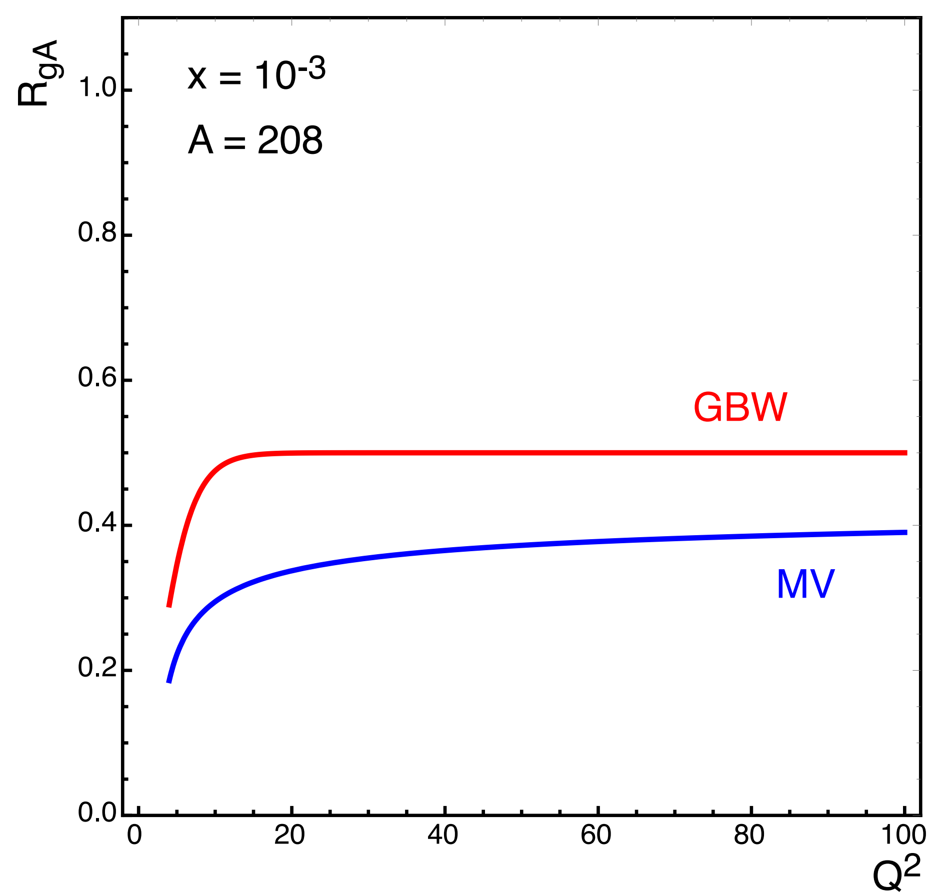
limited range of applicability (if at all)

models do not have proper high-*x* and high-Q^2 limits!

calculations using similar approximations will not be able to properly describe observables with broad *x*-Q^2-distributions of initial partons

“better” saturation models with correct asymptotic limits available?





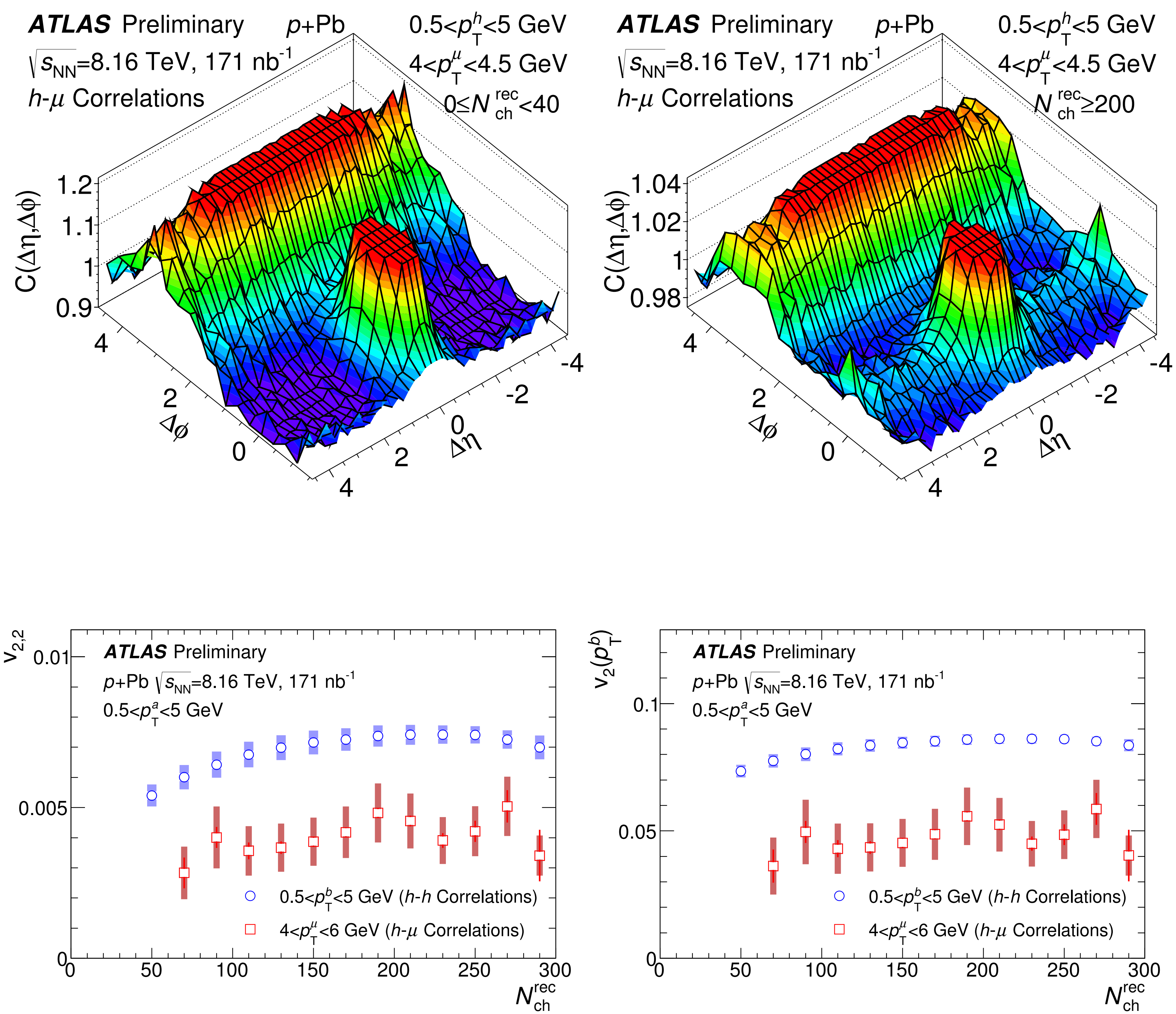
Final State Nuclear Modification of HF in p–Pb?

recent results from ATLAS (presented at QM2017): ATLAS-CONF-2017-006

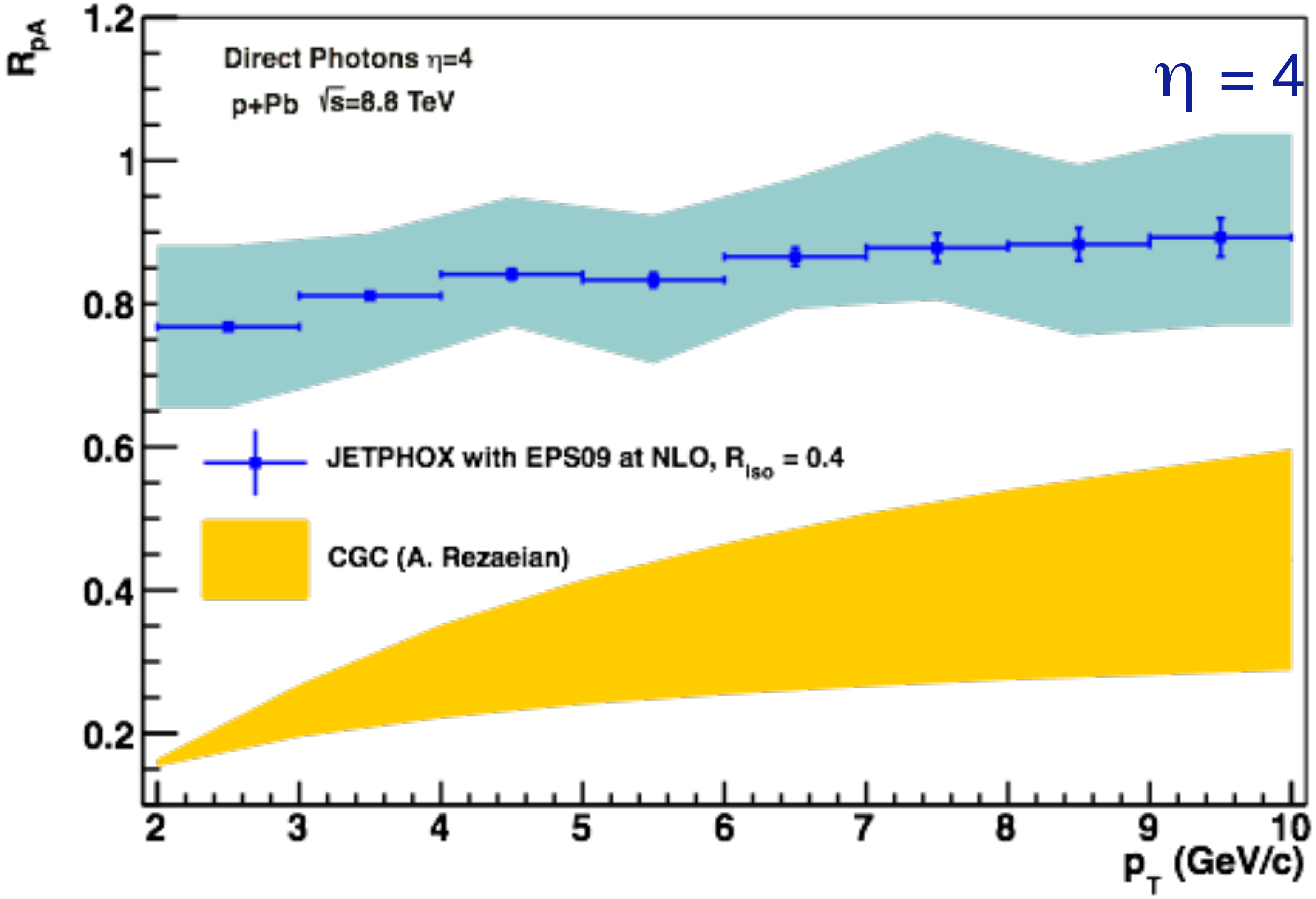
study of h-μ angular correlations, observe flow-like correlation of muons in high multiplicity p–Pb (muons dominated by heavy flavour)

heavy flavour suffering final state modification in pPb?

still useful as initial state probe?



Starting Point Now: nPDF/DGLAP vs CGC



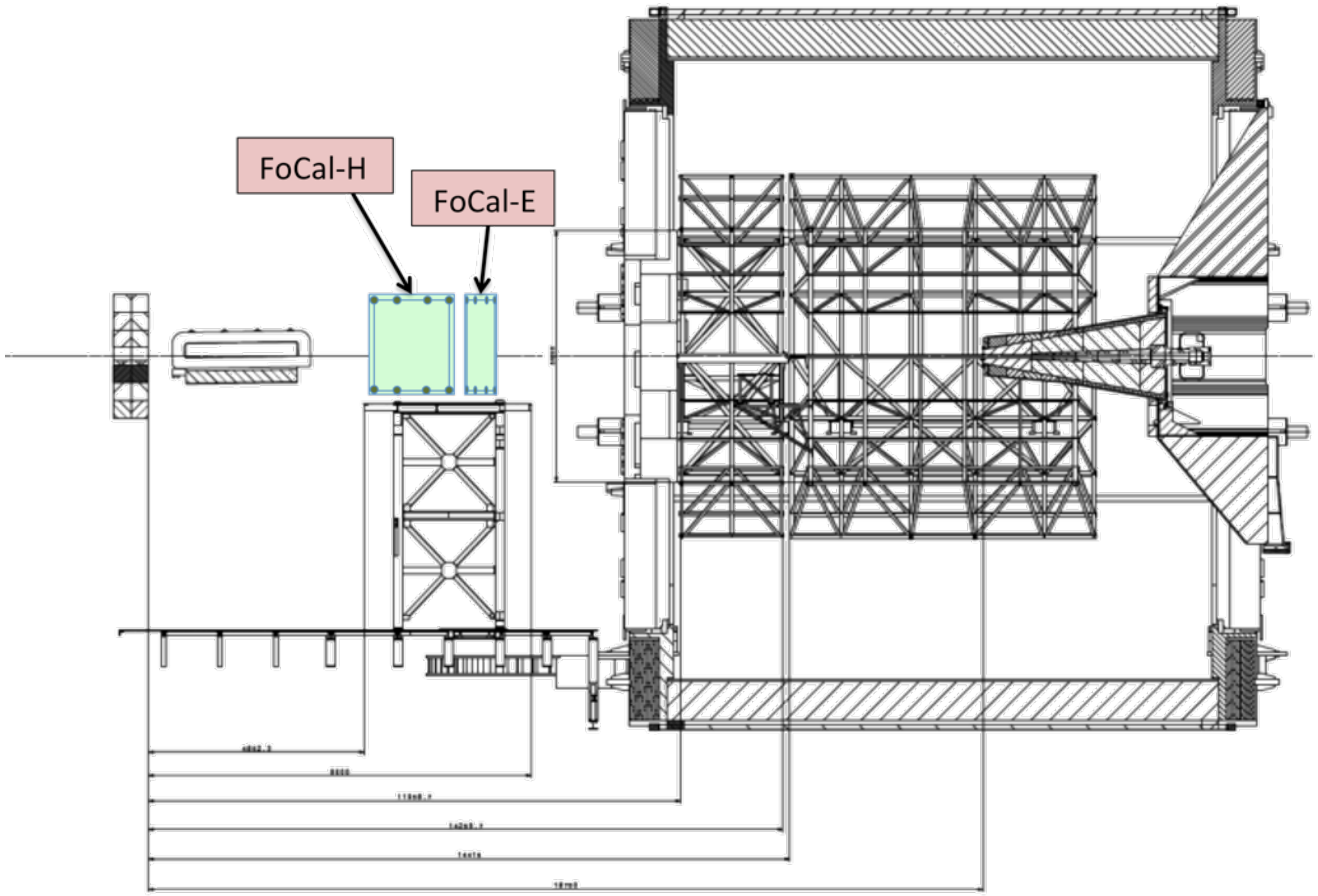
two scenarios for forward γ production in p+A at LHC:

- normal nuclear effects
  linear evolution, shadowing
- saturation/CGC
  running coupling BK evolution

Rezaeian, PLB 718, 1058

- strong suppression in direct γ R_{pA}
  - clean signal for isolated photons
- signals expected at forward η, low-intermediate p_{T}

FoCal in ALICE



electromagnetic calorimeter for γ and π^0 measurement

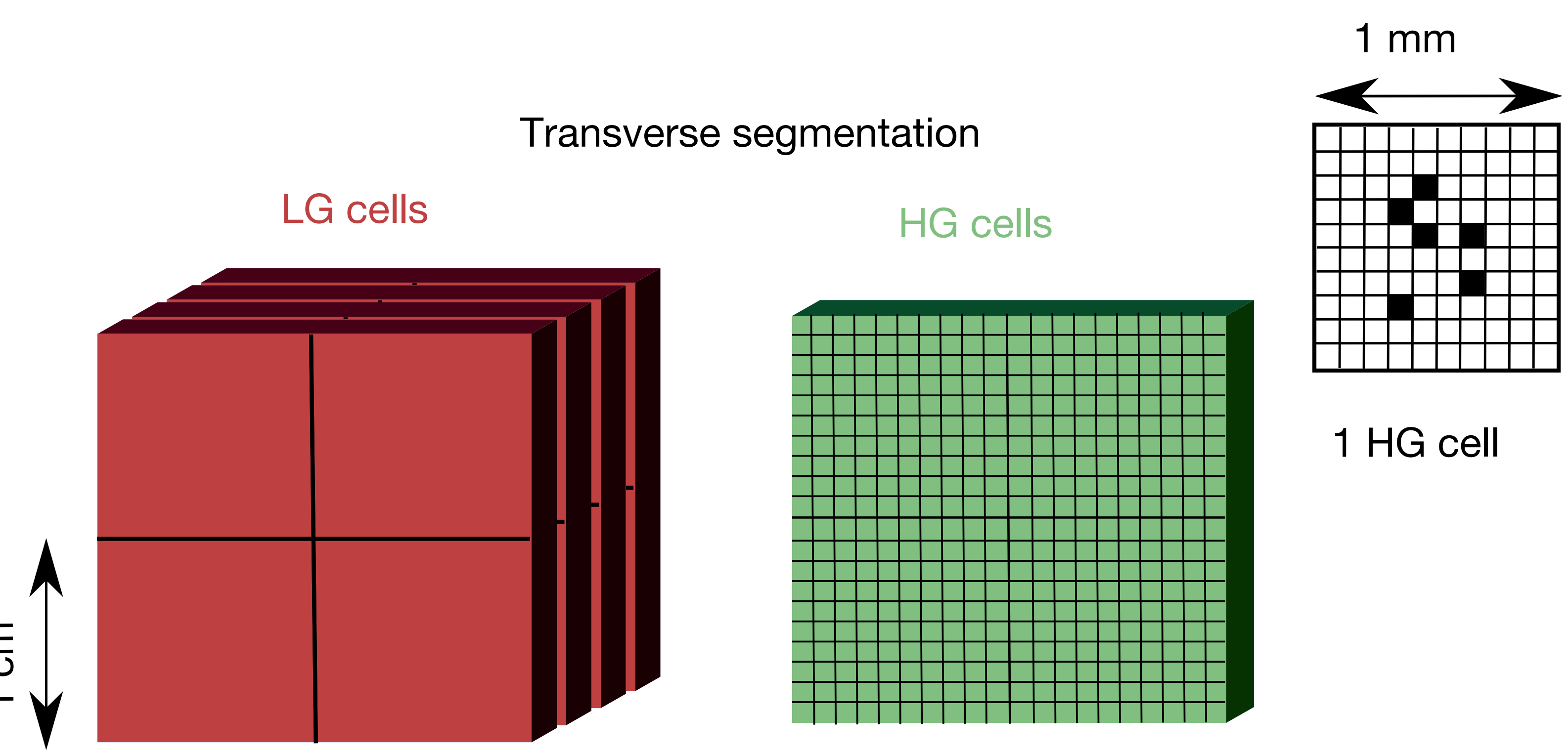
preferred scenario:
- at z ≈ 7m (outside magnet)
  $3.3 < \eta < 5.3$
  (space to add hadr. calorimeter)

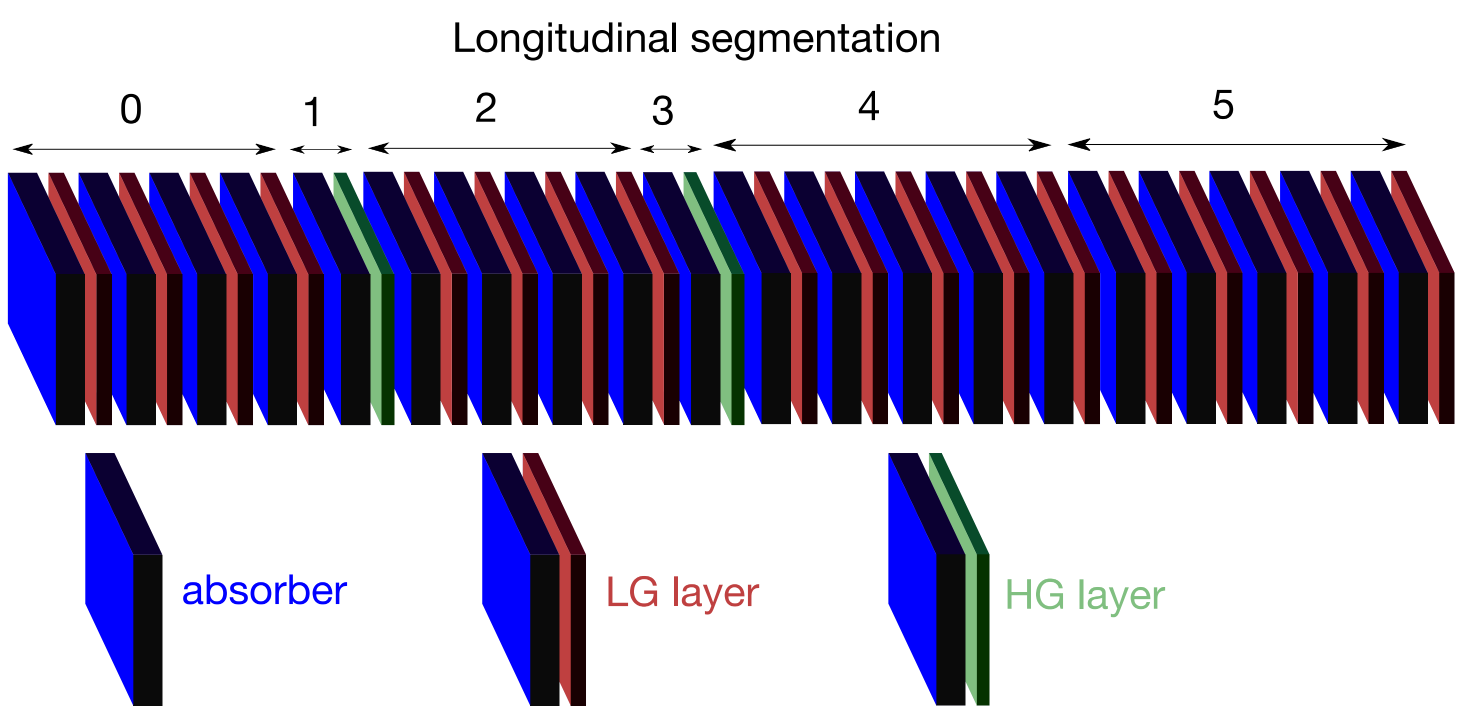
under internal discussion
possible installation in LS3

- 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!

FoCal Strawman Design





studied in performance simulations:

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

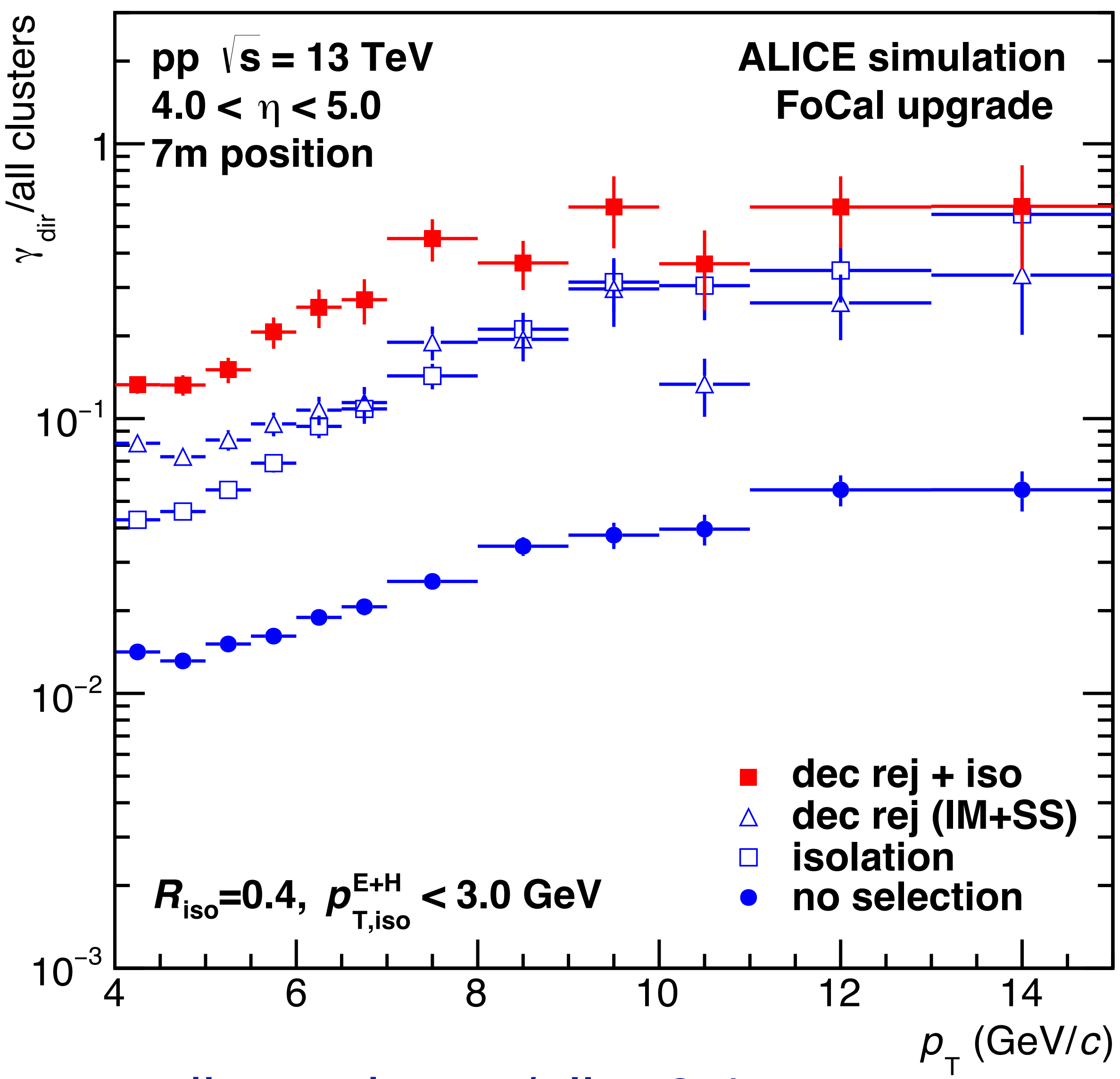
	LG	HG
pixel/pad size	≈ 1 cm^2	≈ 30x30 μm^2
total # pixels/pads	≈ 2.5 x 10^5	≈ 2.5 x 10^9
readout channels	≈ 5 x 10^4	≈ 2 x 10^6

assuming ≈ $1m^2$ detector surface

Direct γ Performance in pp

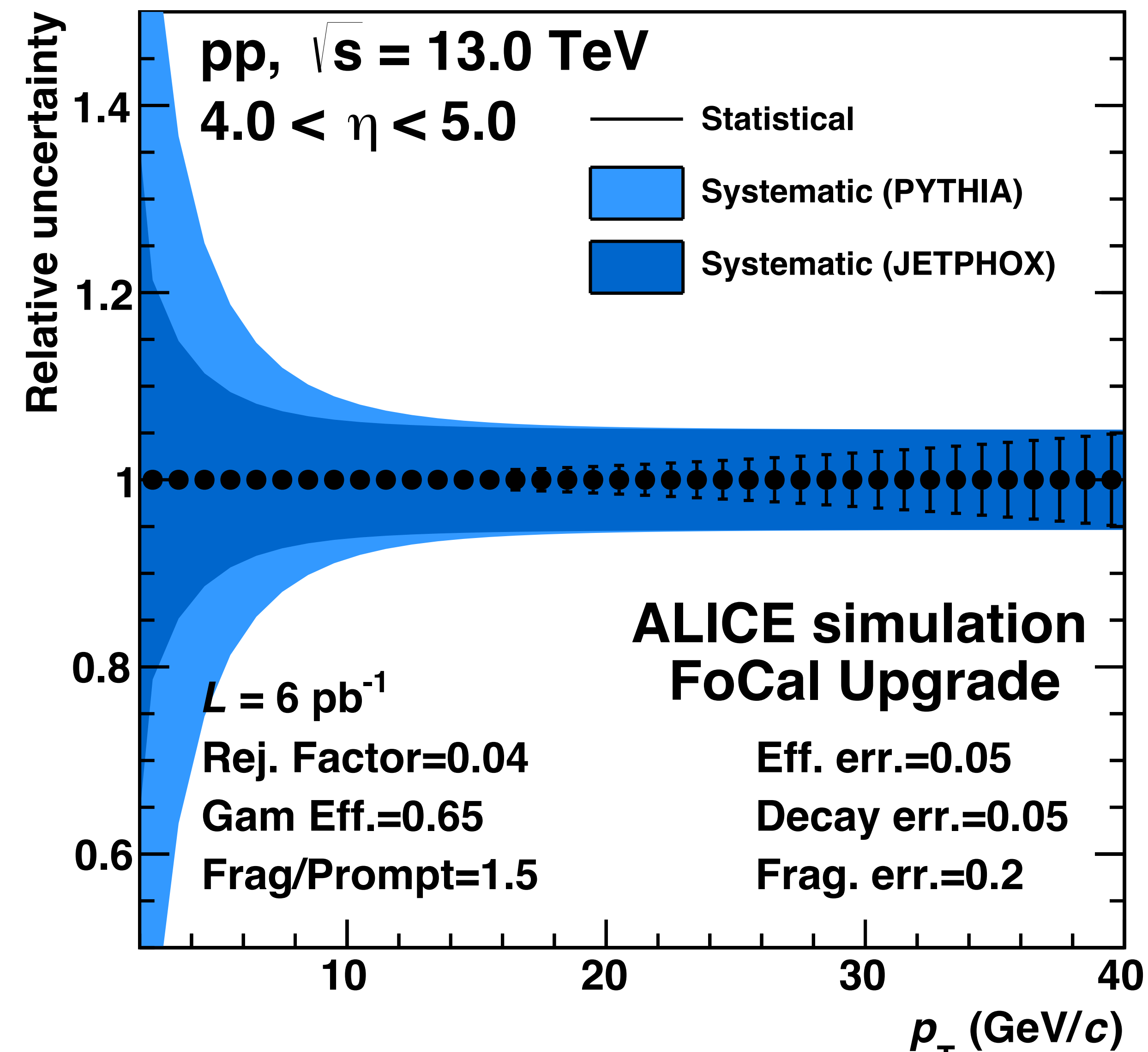
- combined rejection (invariant mass + shower shape, isolation)
- rejection factor ≈25, direct photon efficiency ≈80%
  - largely p_T-independent

Direct γ/all cluster ratio



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

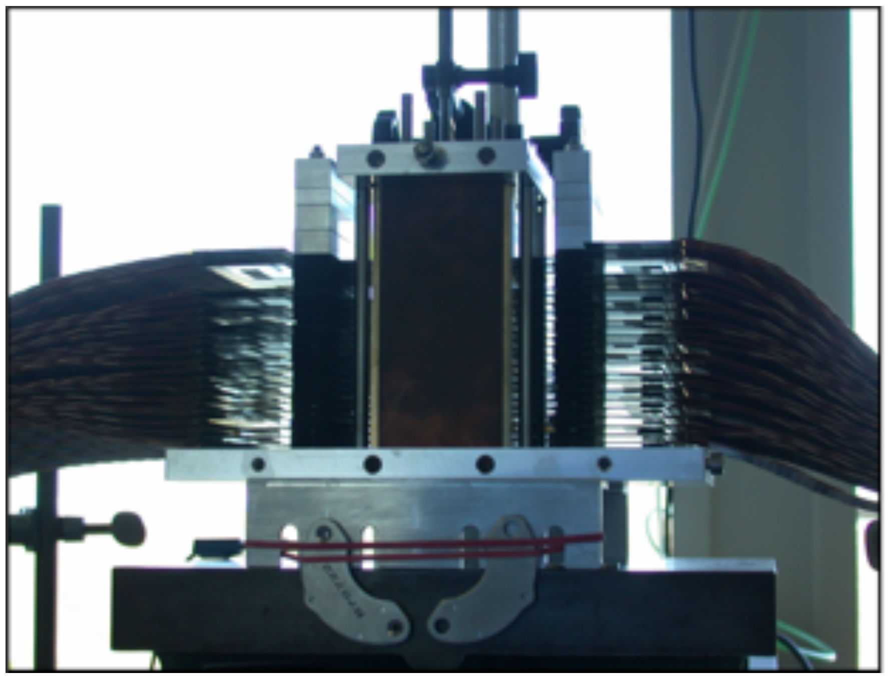
Direct γ uncertainty



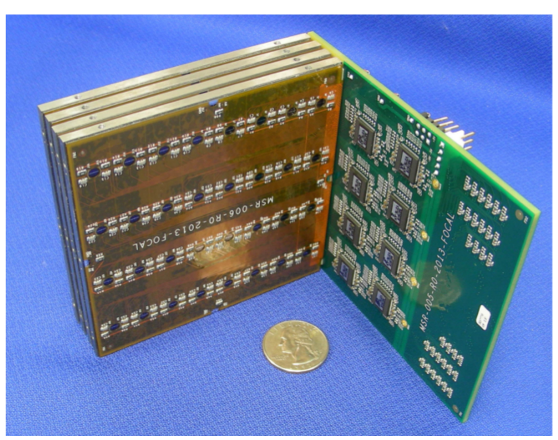
20-40% uncertainty
at p_T = 4 GeV/c
decreases with increasing p_T

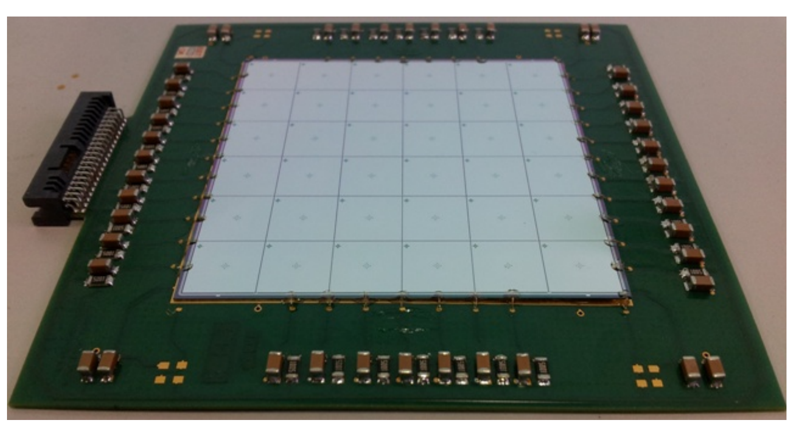
FoCal R&D: Si-W pixel and pad readout

24 layer pixel detector



Pad layer integration





Several groups involved:

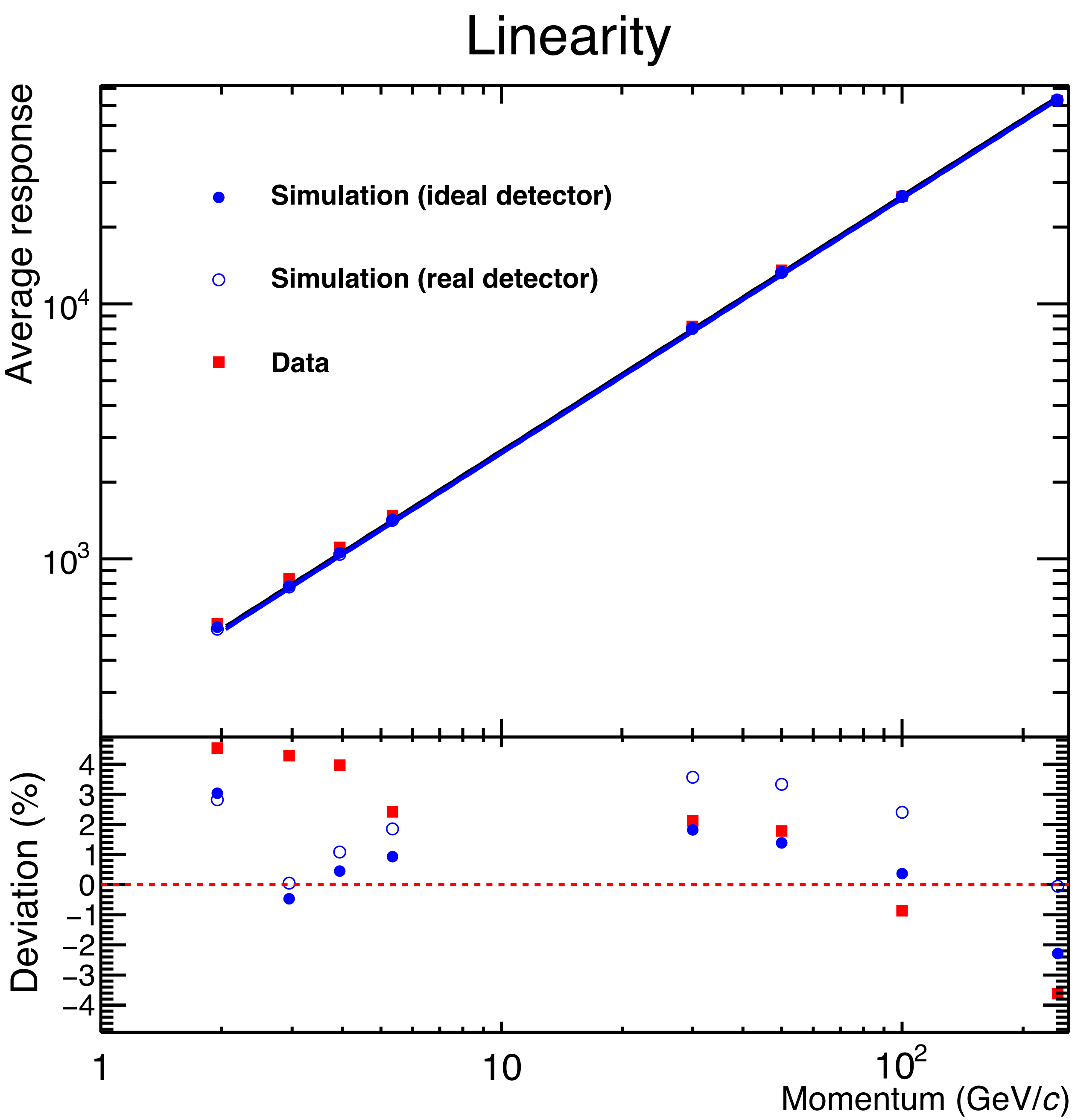
- Full prototype with pixel detectors CMOS (MIMOSA) 39M pixels, 30µm pitch
  - use synergy with R&D for ALICE ITS upgrade
- Full prototype with pad readout

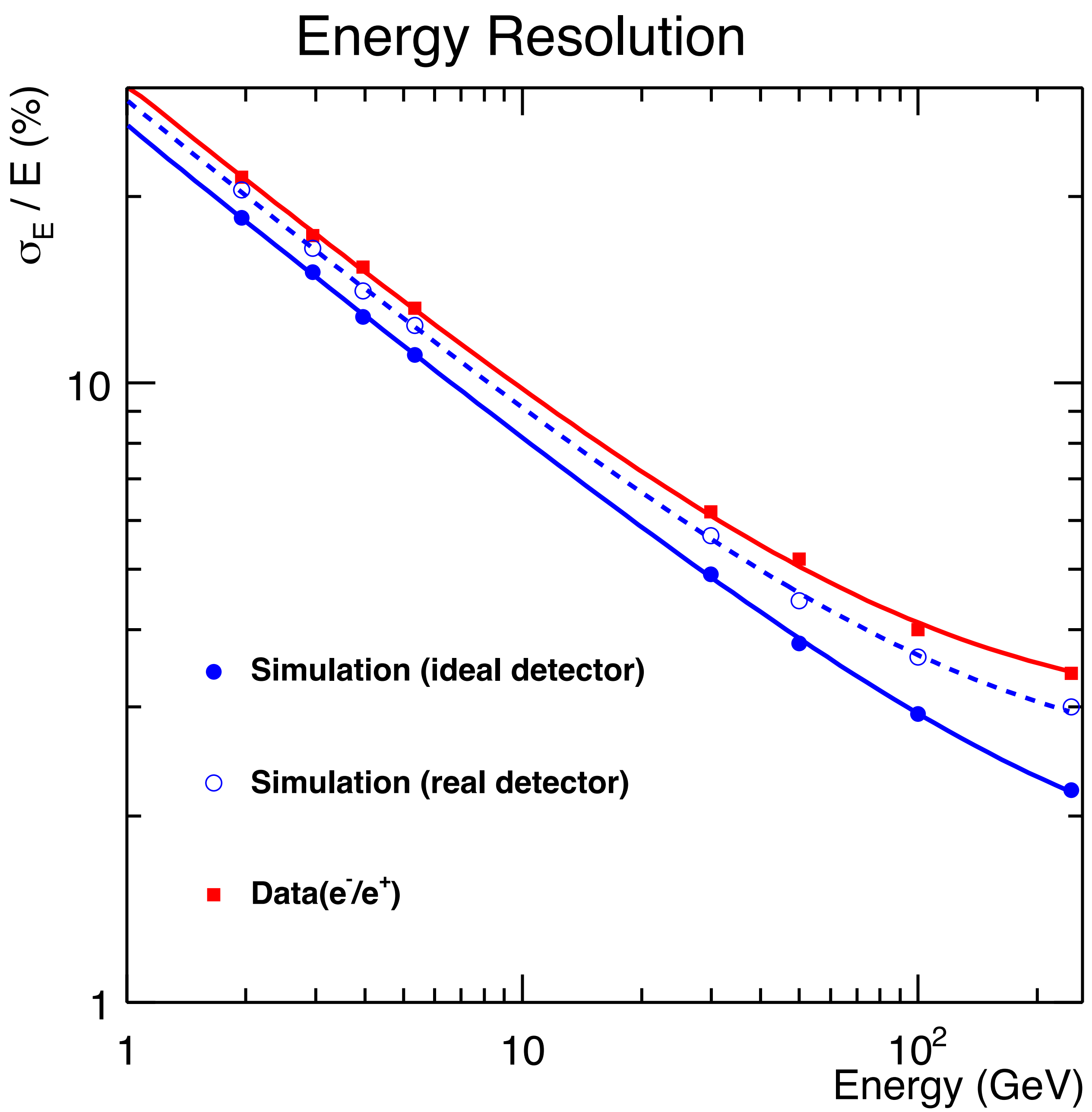
Performed systematic tests:

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

Utrecht/Nikhef (Netherlands),
Bergen (Norway),
Tsukuba, Nara (Japan),
ORNL (US)

R&D - Energy Linearity and Resolution



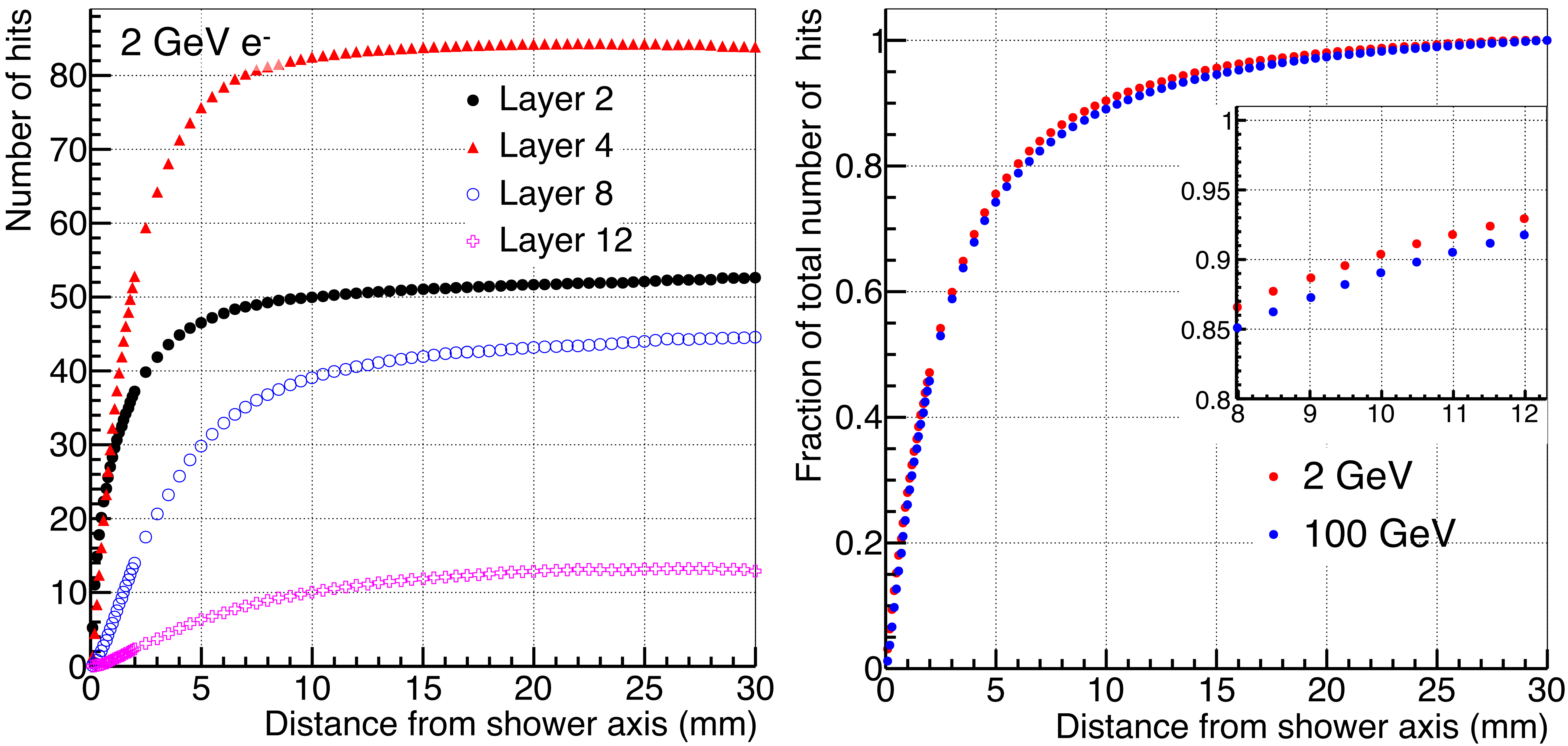


good linearity and energy resolution

- note: different calibration for low and high energy
- possibly still improve calibration
- effects of saturation seen at 244 GeV – to be corrected

proof of principle of digital calorimetry

R&D - Cumulative Lateral Profiles



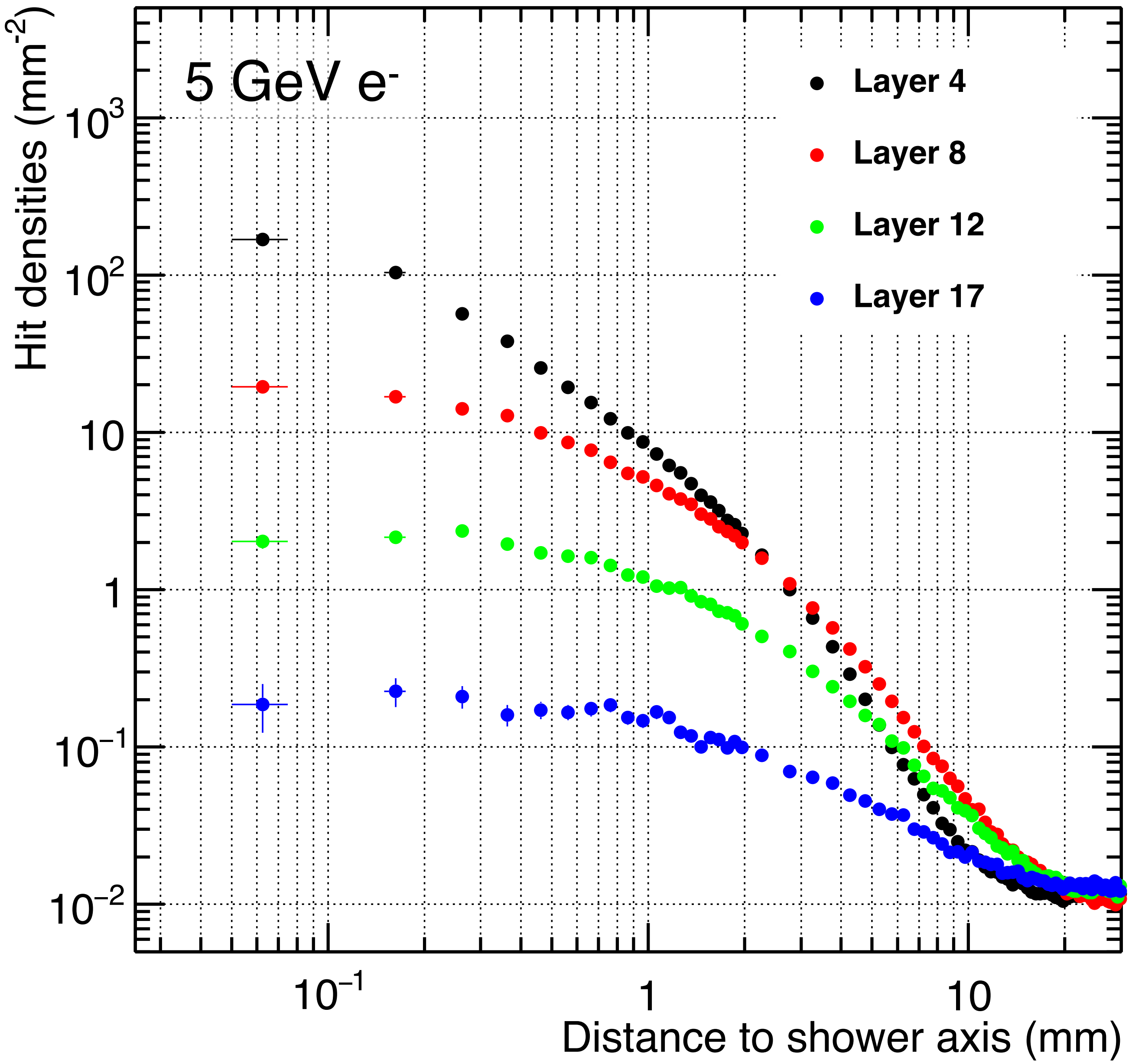
extract cumulative distributions both per layer and integrated

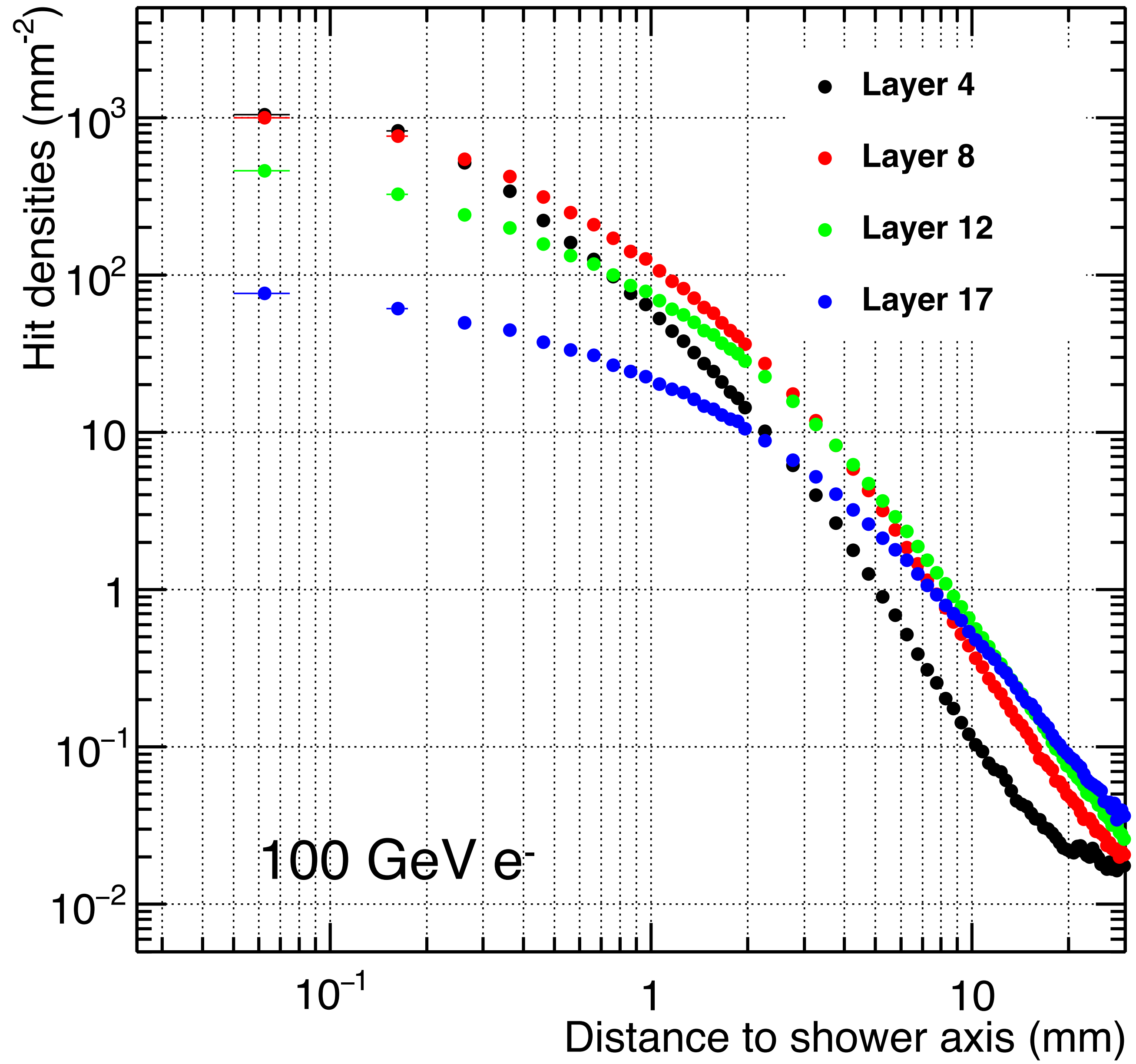
- some lateral leakage at higher energy

small Moliere radius: $R_M \approx 11$mm

$\approx$ 75% of hits within R = 5mm, 50% within R = 3mm, …

R&D - Lateral Profiles





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

- low energy: early shower max, profiles broaden and decay with depth
- high energy: profiles broaden with depth, increase up to shower max

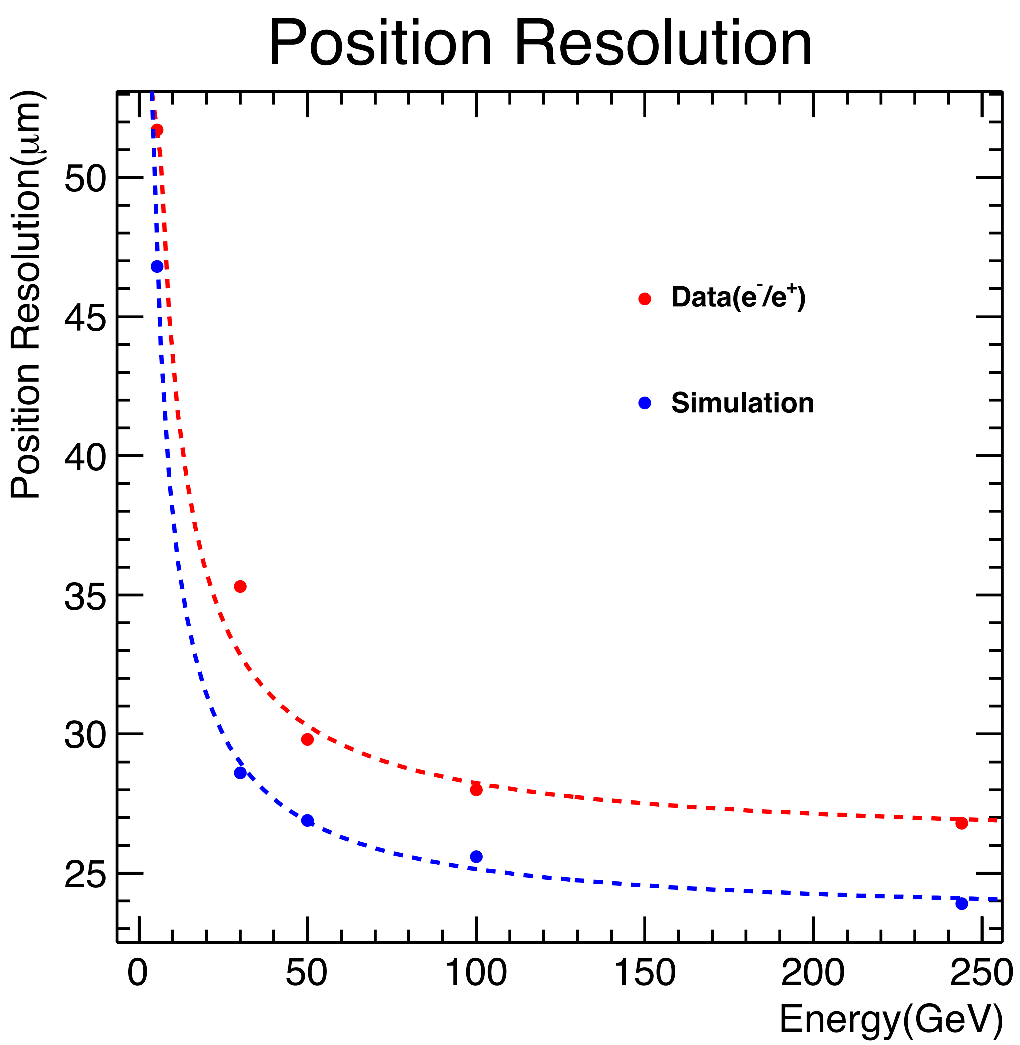
shower measurements with unprecedented detail!

R&D - Position Resolution and Shower Separation

calculate difference of position from

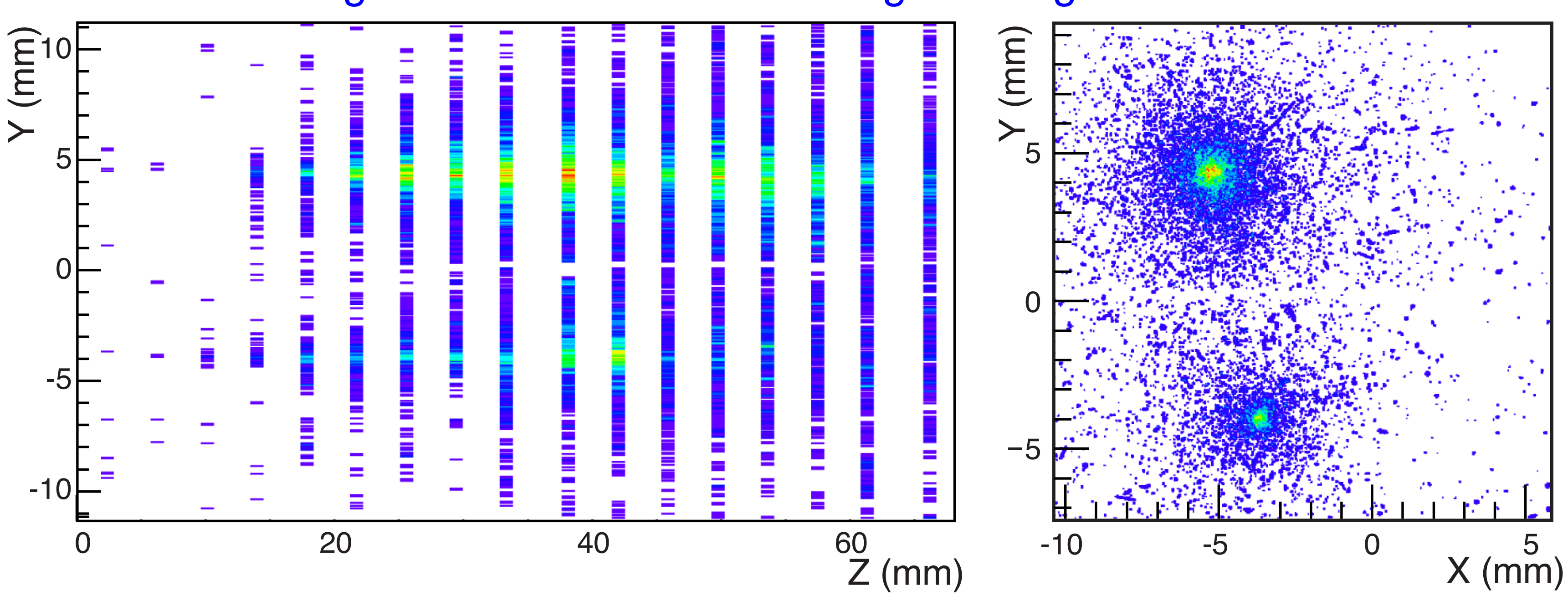
- cluster in layer 0 and
- center of gravity of shower in layers 1 - 23

single shower position resolution obtained from width of residuals



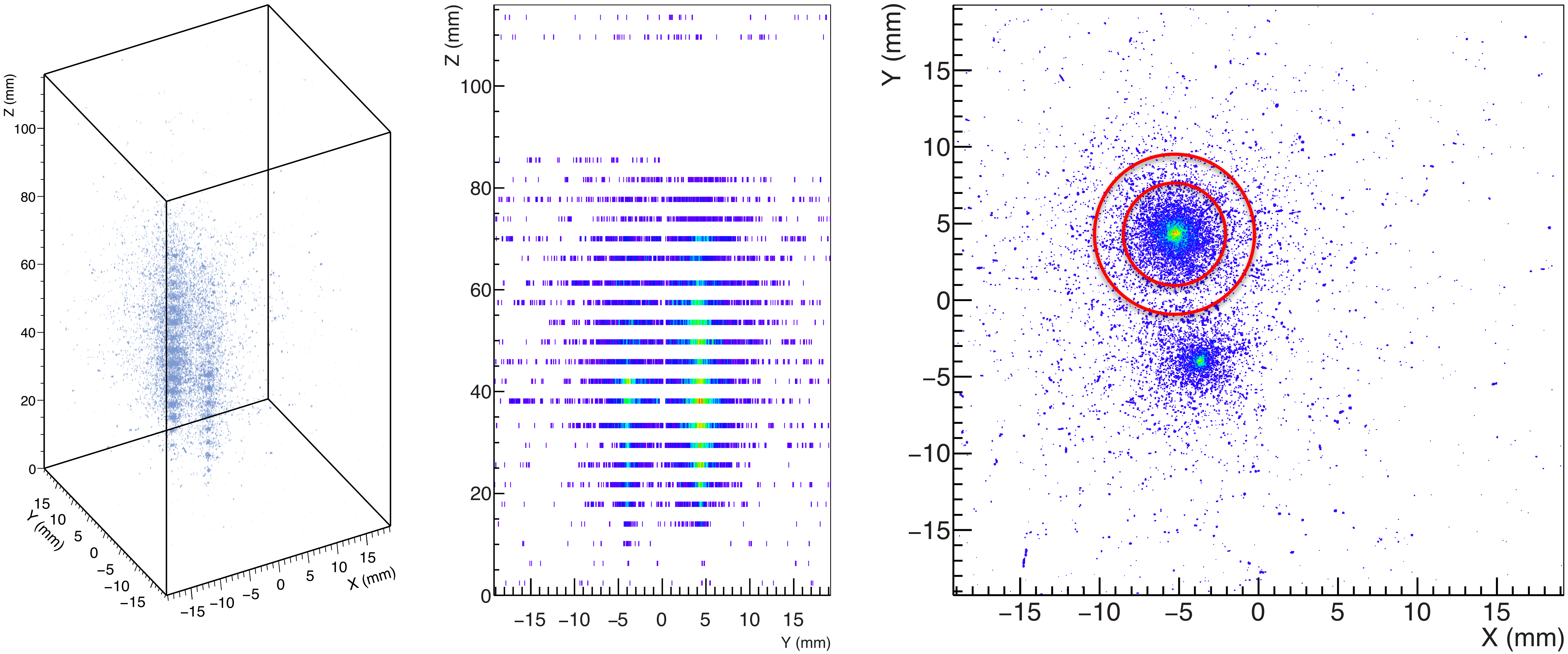
can provide excellent two-shower separation

single-event from data: two neighbouring showers



Two Shower Separation

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



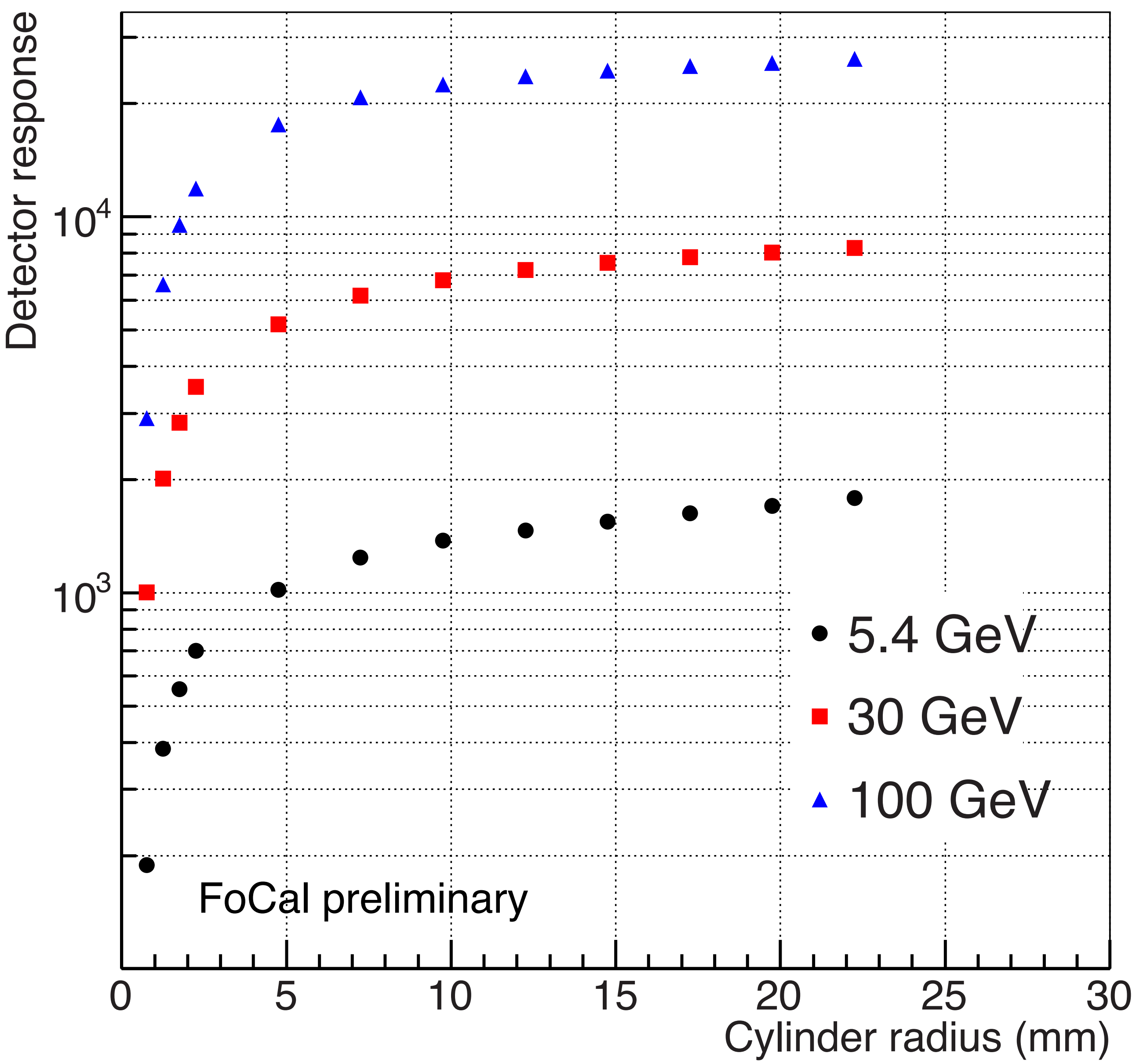
evaluate separation capability: core energy

calculate shower energy in cylinder of finite radius

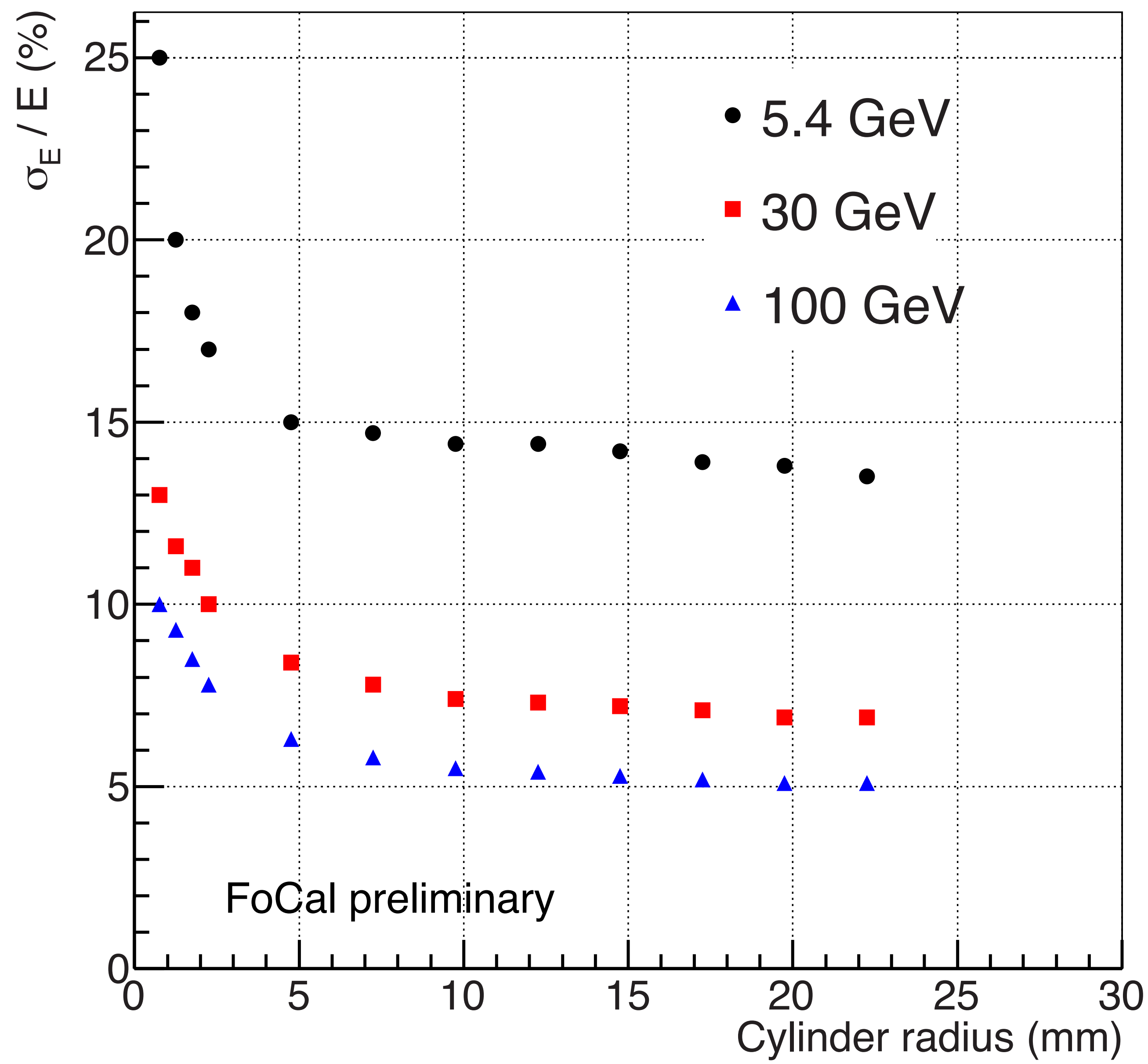
study as function of radius

R&D Results: Core Energy

detector response (number of hits)



energy resolution



reasonable energy resolution of pixel calorimeter, sufficient for conceptual design

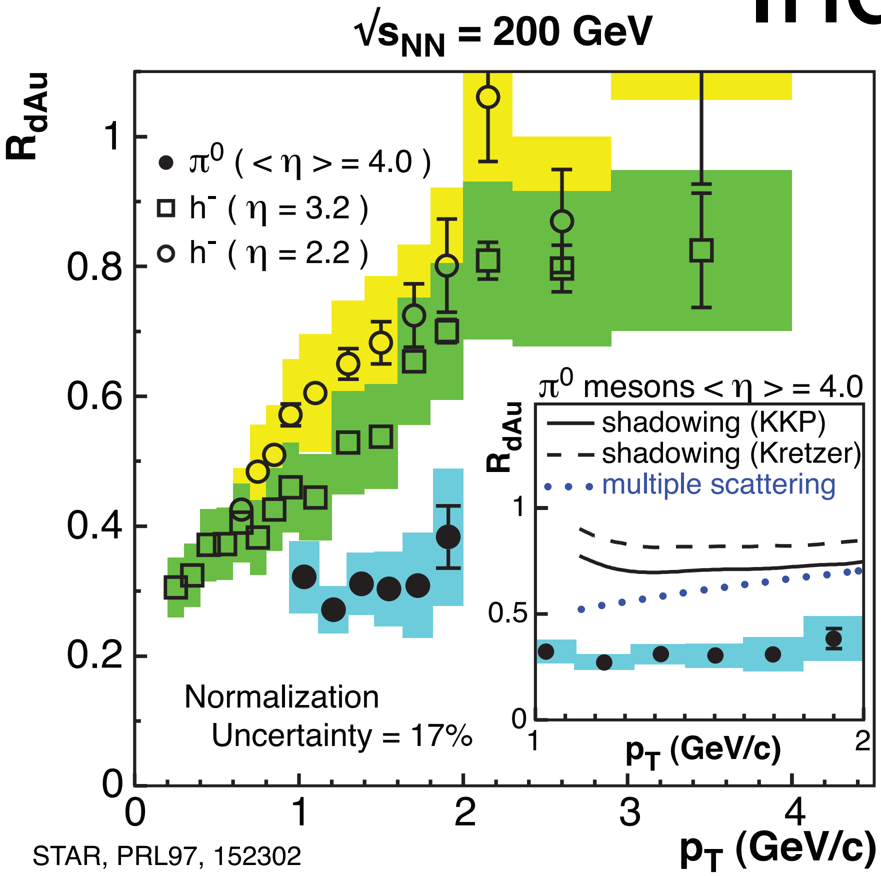
response and resolution for core energy hardly affected down to r = 5mm:
adequate for very high particle density

Summary

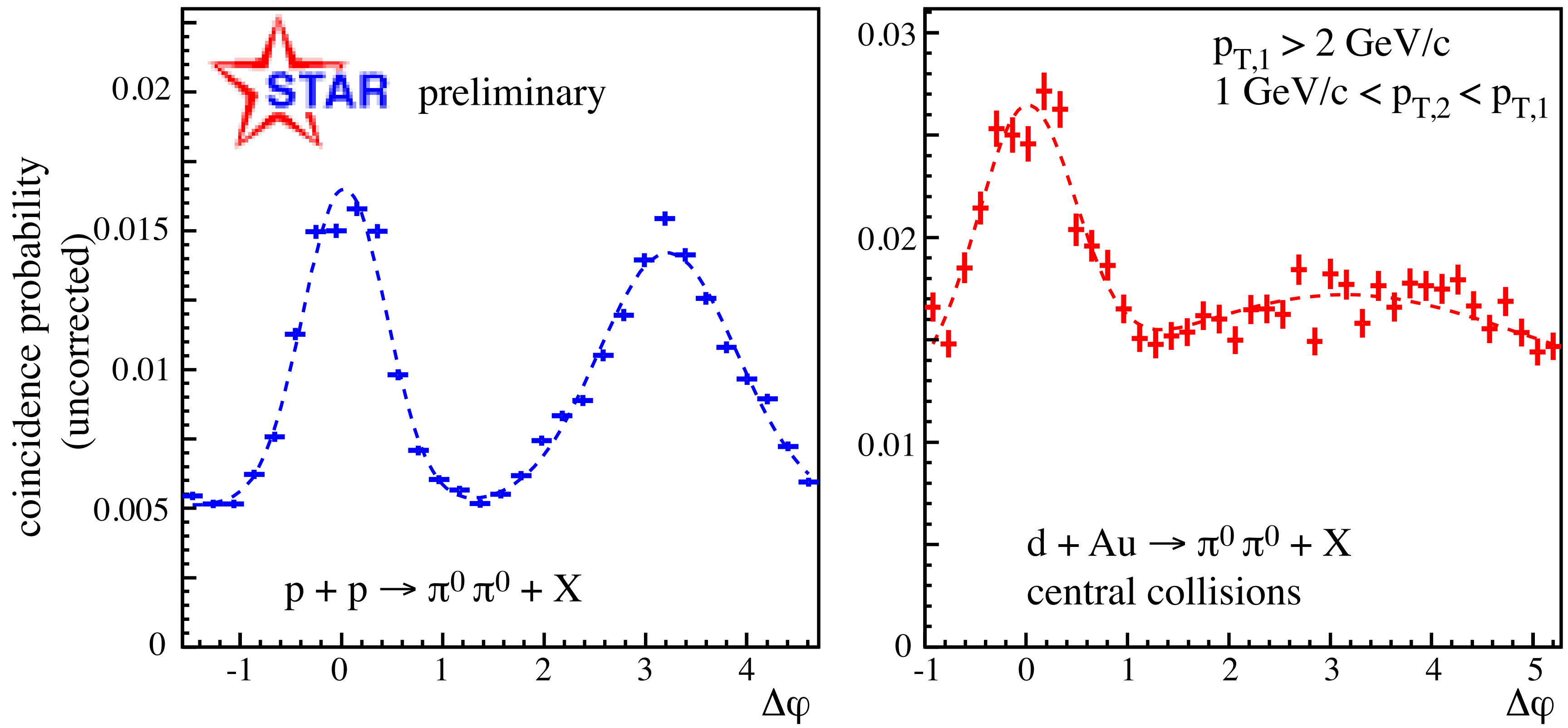
- LHC forward measurements provide unique opportunity for low-x physics
  - hadronic probes inconclusive
    - best bet: open charm (?)
  - advantage of EM probes: sensitivity to initial state, clean production process
- need better understanding of PDF uncertainties, role of QCD evolution, and saturation models
- measurement needs detector upgrade at LHC
  - proposed FoCal detector in ALICE
    - opportunity for forward direct photon measurement
    - particle density/kinematics require extremely high granularity: feasible with SiW pixel calorimeter

Backup Slides

Indications from RHIC



STAR, Braidot, Ogawa et al.



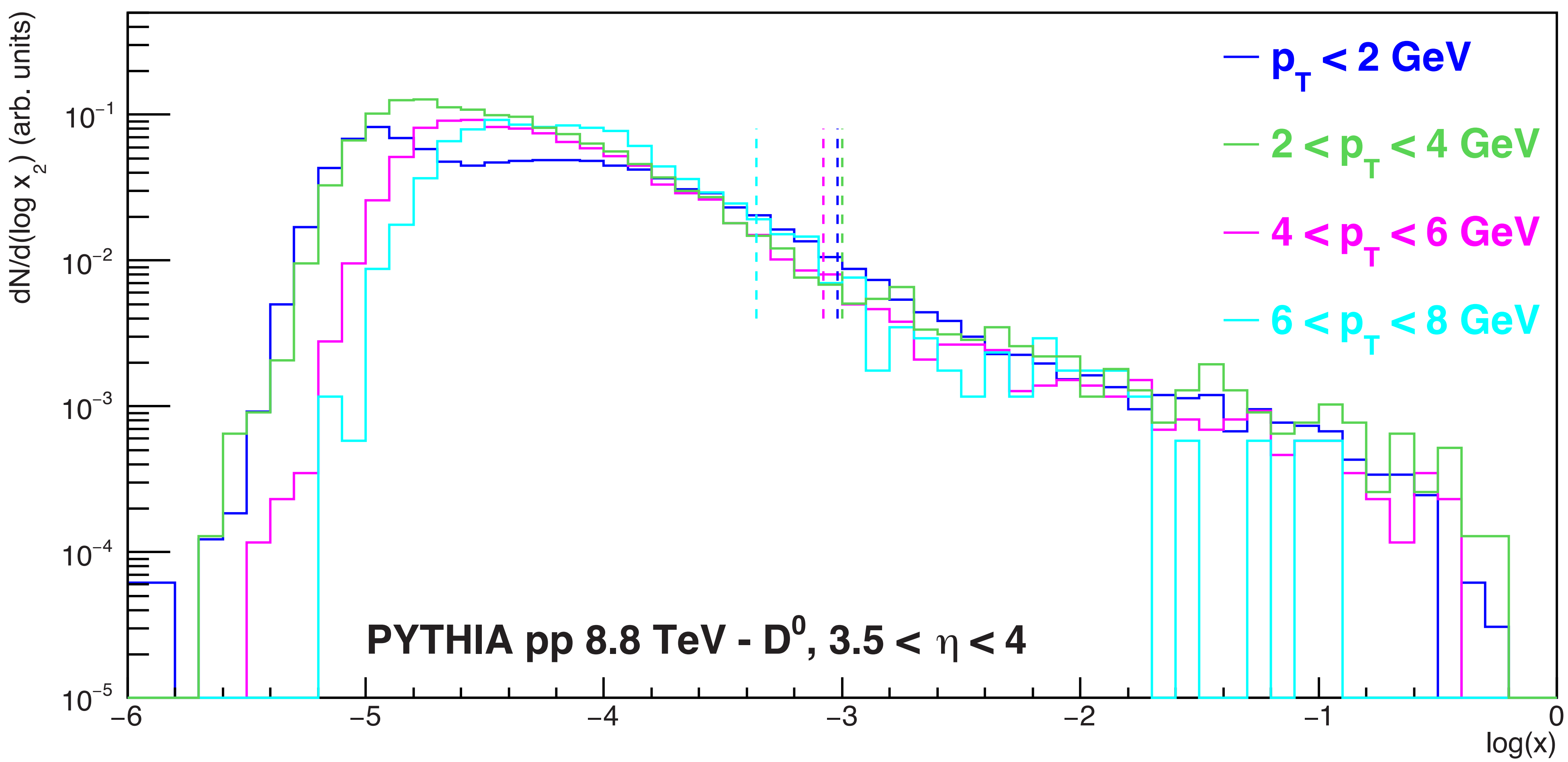
R_{dA}: strong suppression of hadron yield at forward rapidity

di-hadron correlations: broadening/suppression of away-side peak in dAu

$$R_{dA} = \frac{dN/dp_T(dA)}{< N_{coll}(dA) > dN/dp_T(pp)}$$

- qualitatively consistent with CGC, but ...
  - very low p_T, close to kinematic limit, hadron observable (final state interactions)!
- extend p_T and y range (not possible at RHIC)

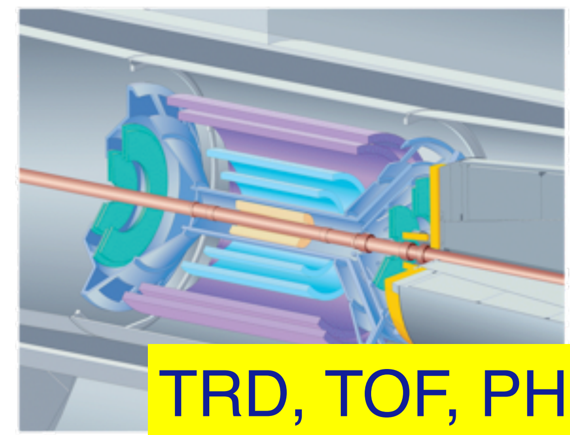
x-Sensitivity



- x_2 distributions for forward charm production
- weak p_T dependence

ALICE Detector & Upgrades

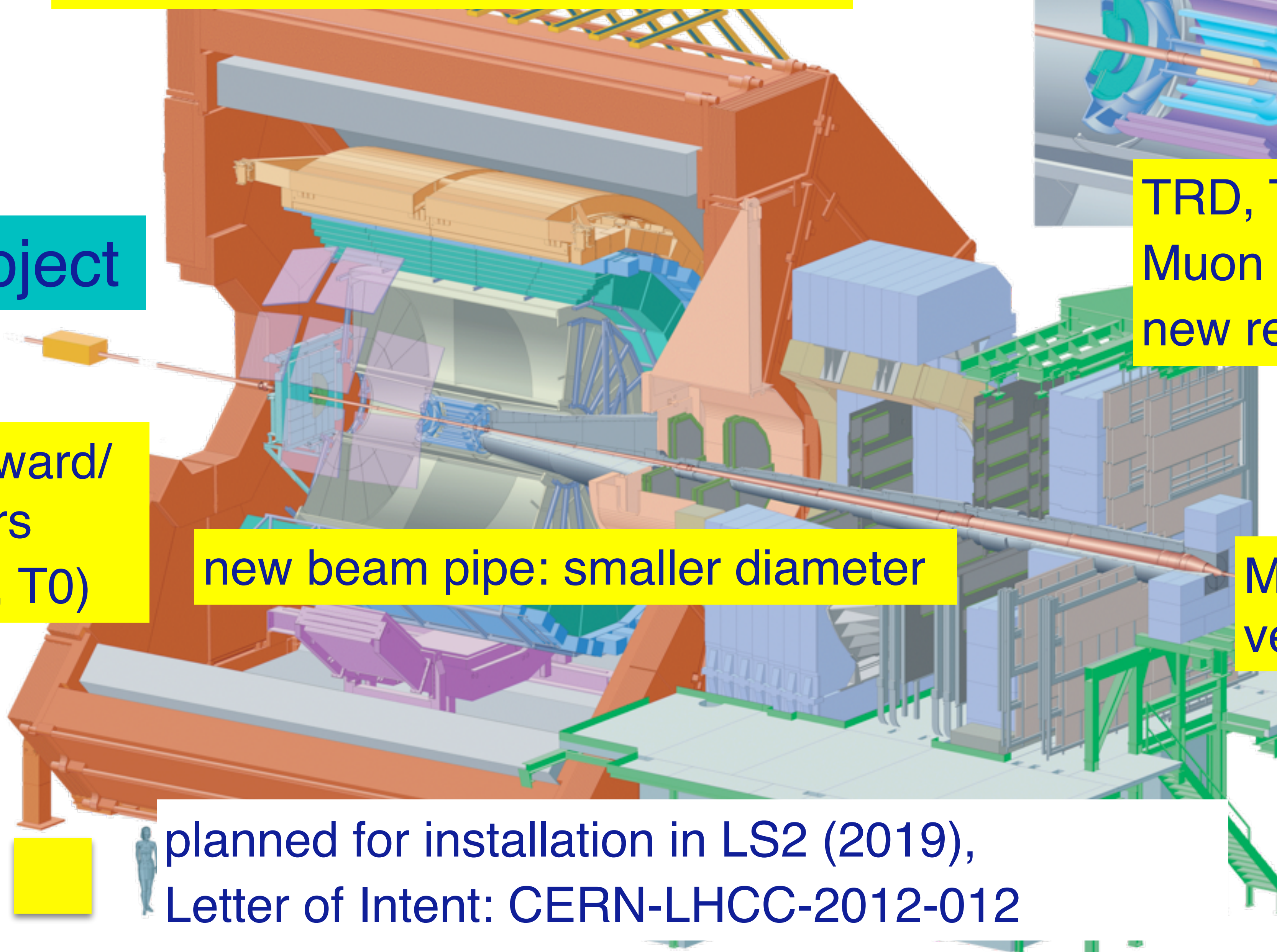
new ITS: high resolution, low material budget



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

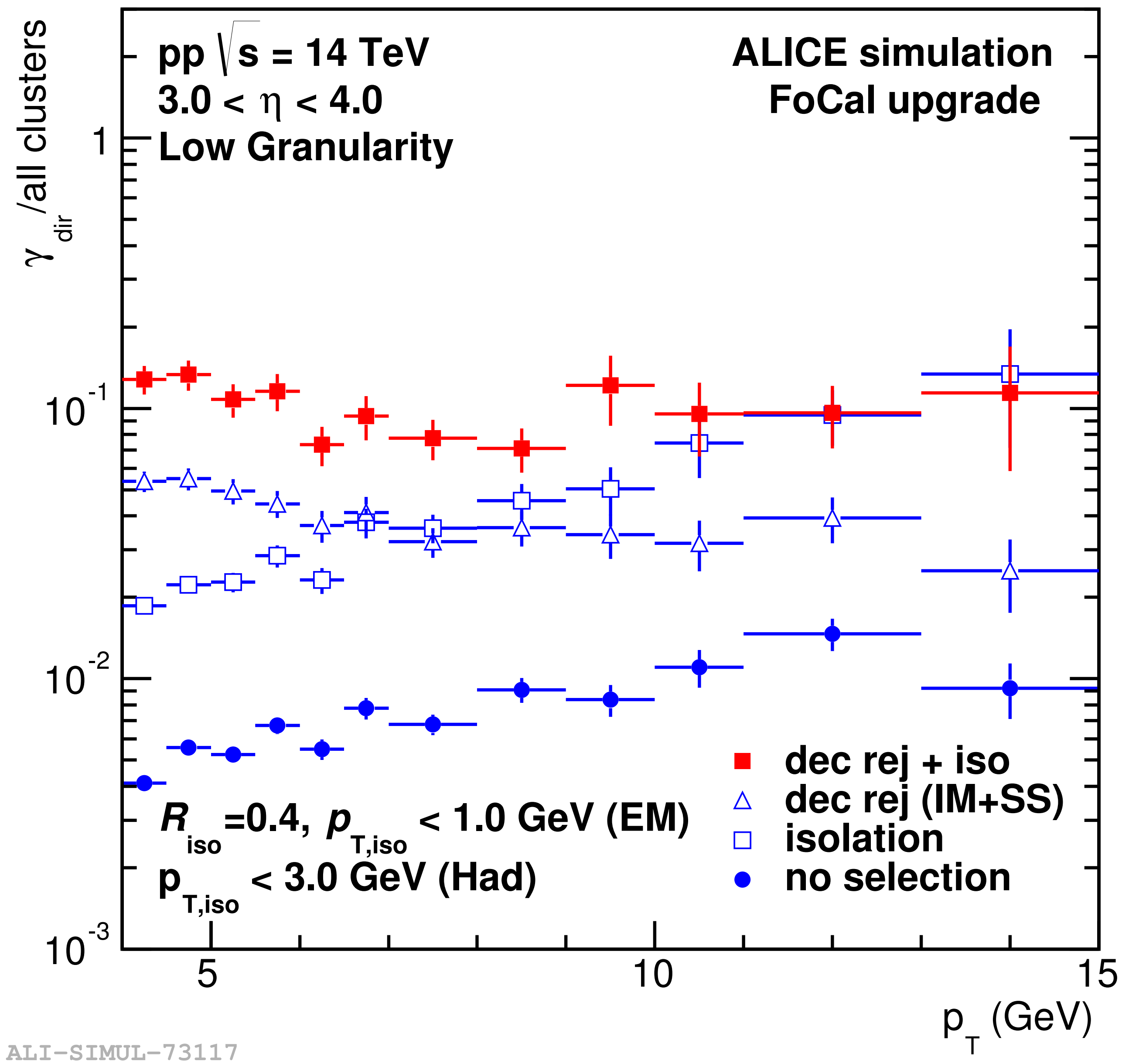
MFT: secondary vertexing for muons

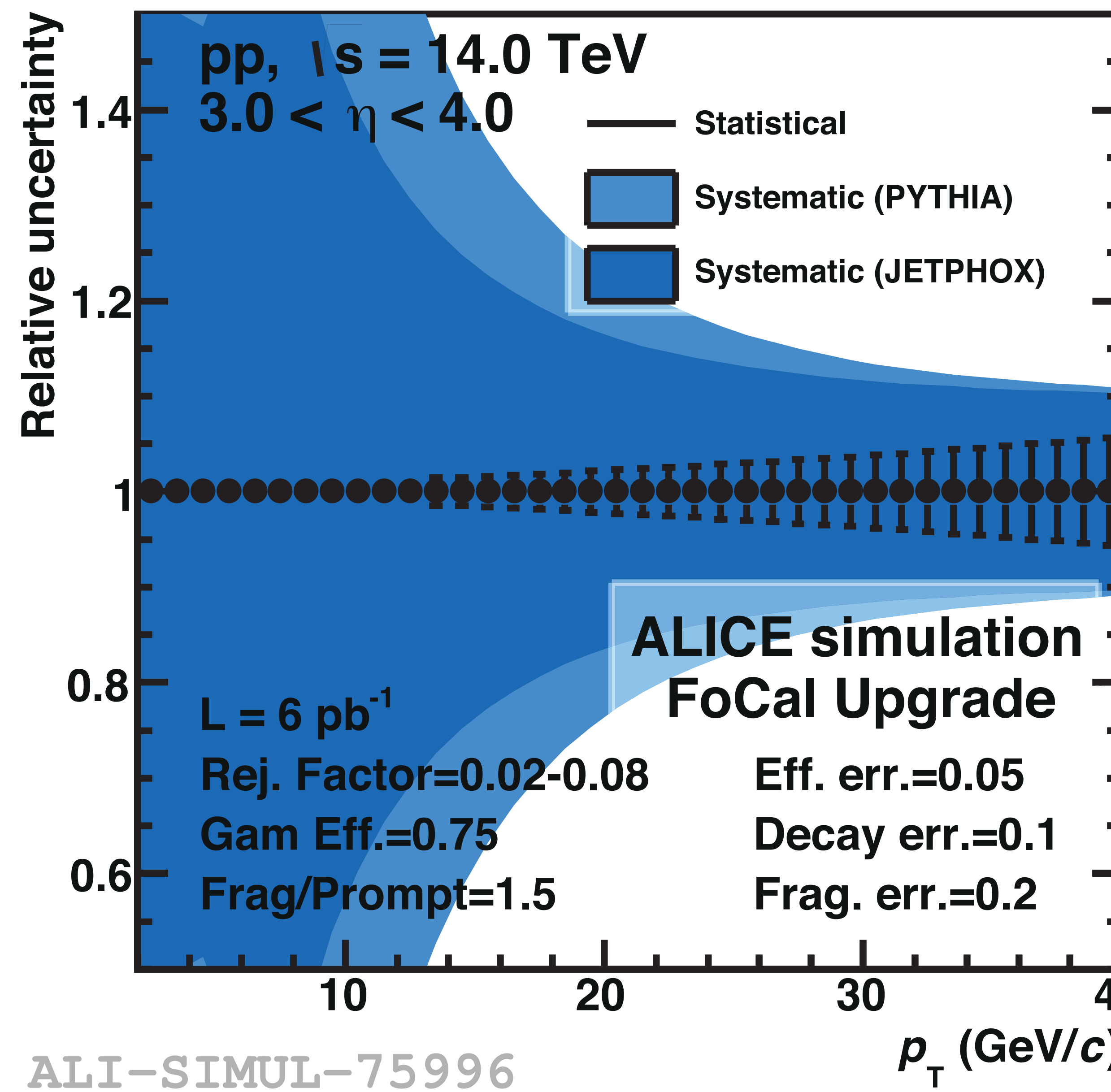
planned for installation in LS2 (2019), Letter of Intent: CERN-LHCC-2012-012

under internal review

ALICE

Low Granularity Measurement



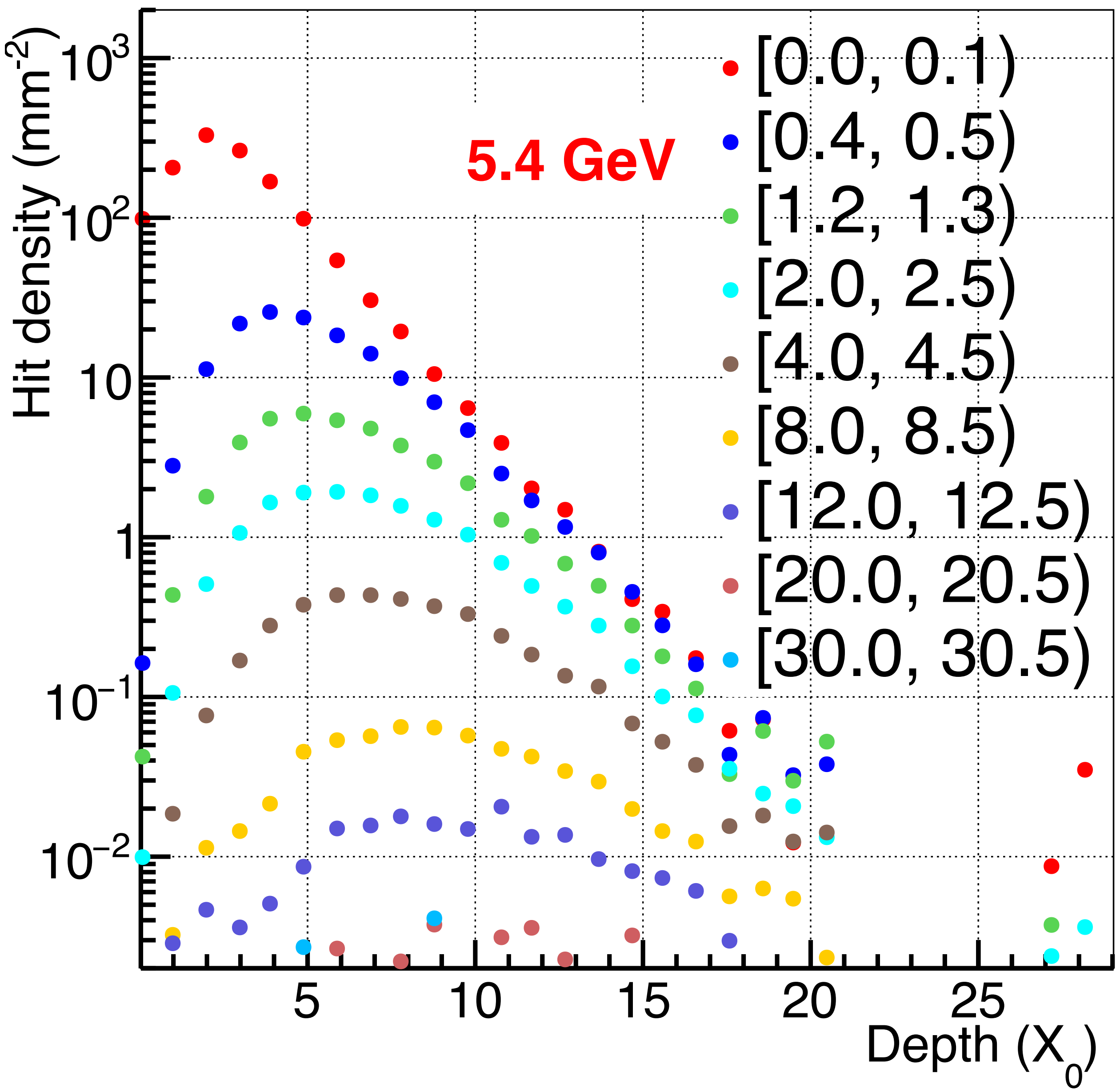


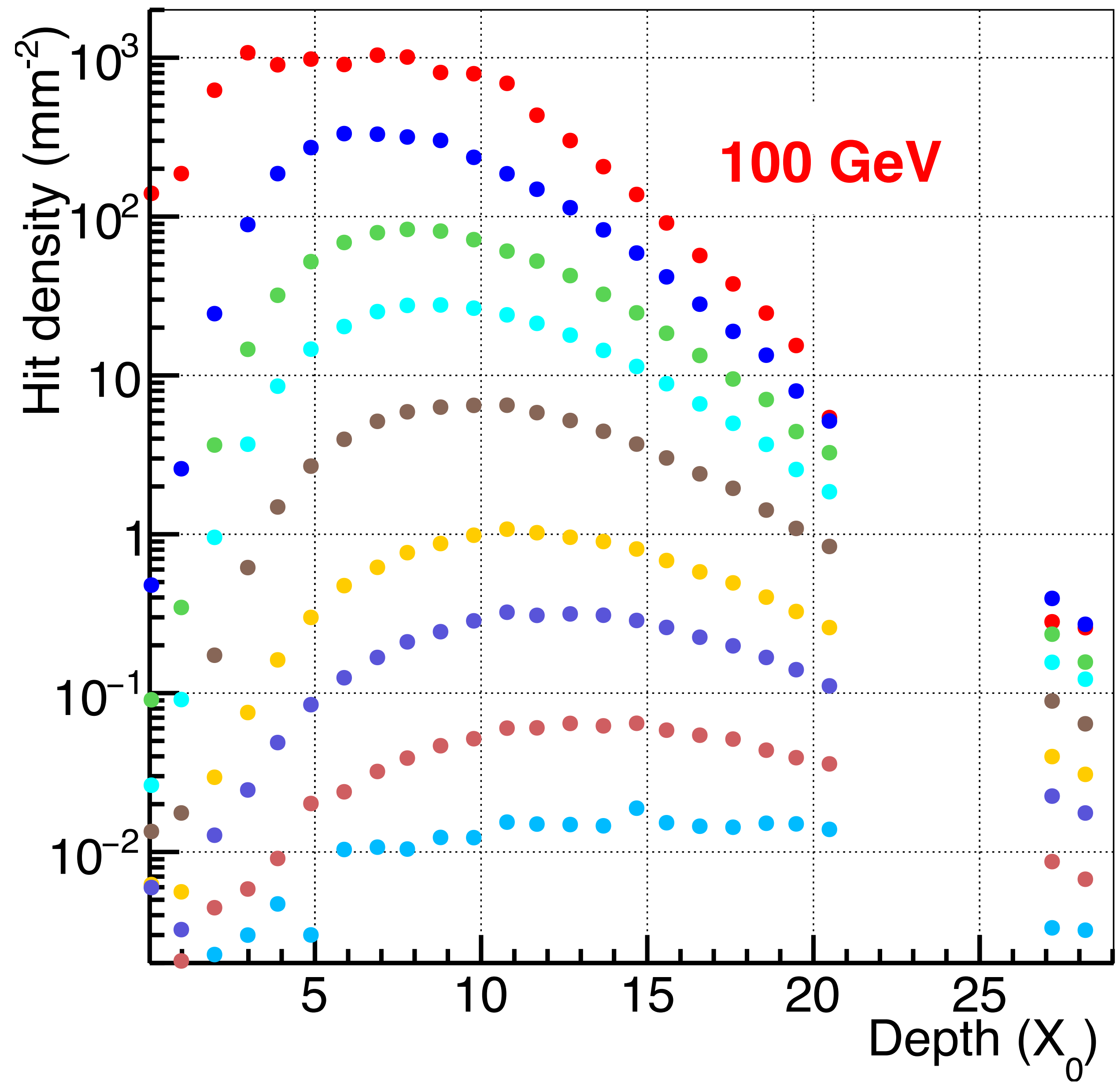
low granularity (1cm2) does not allow efficient decay rejection
direct photon/all ≈ 0.1
for all pT

significant measurement not possible at low pT

NB: conditions similar to LHCb

Longitudinal Profiles



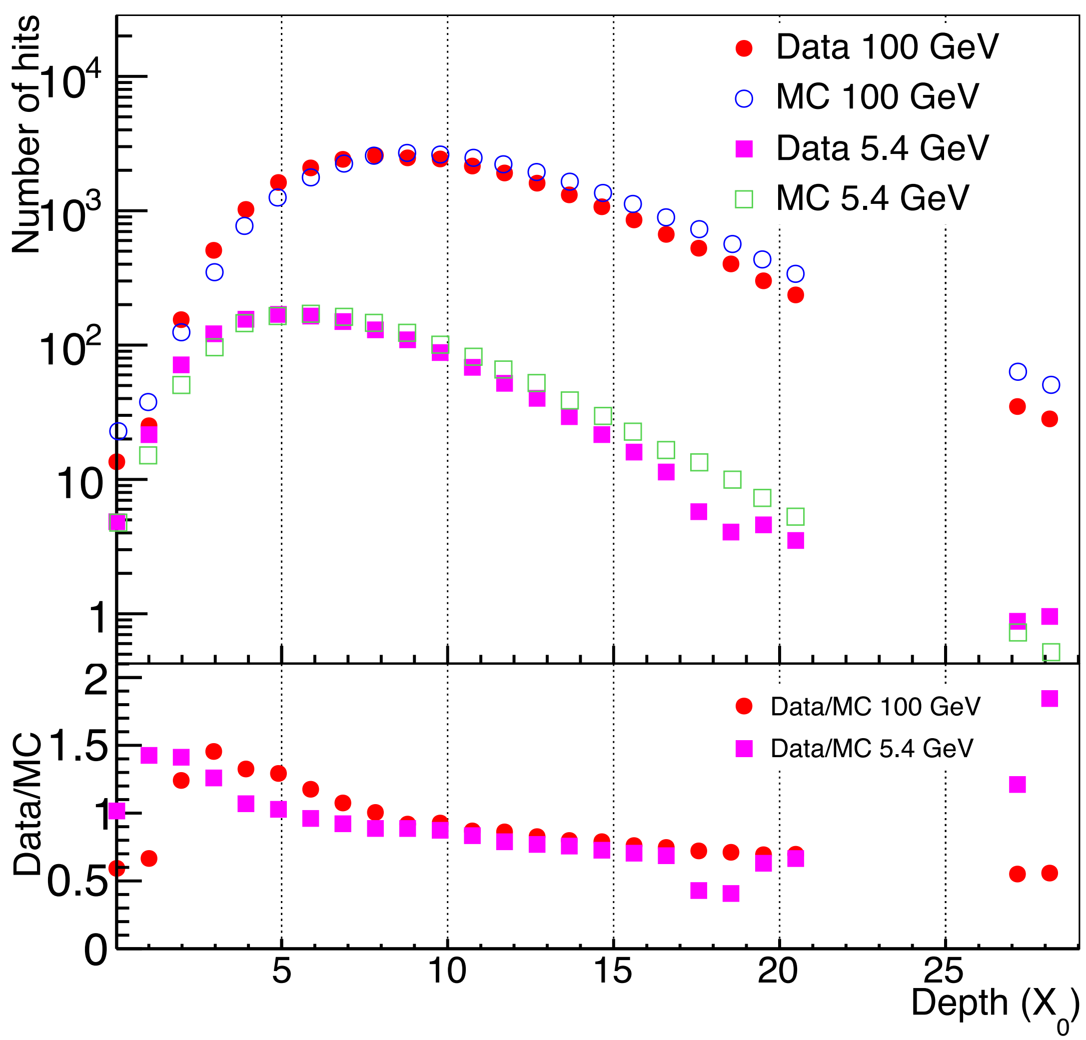


average hit densities as a function of depth for different radial positions

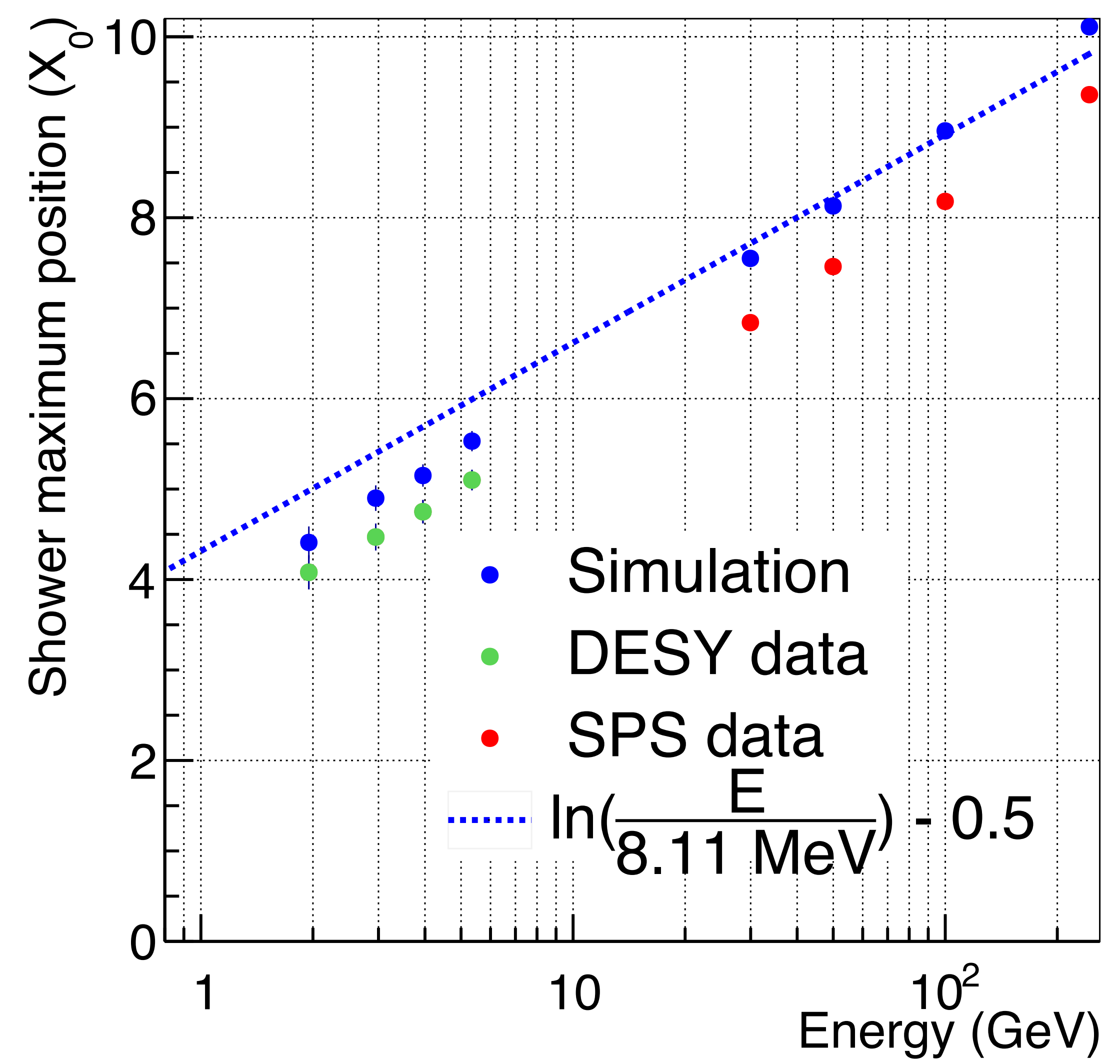
- different view of 3-dimensional info

Longitudinal Profiles - MC Comparison

Longitudinal Profile



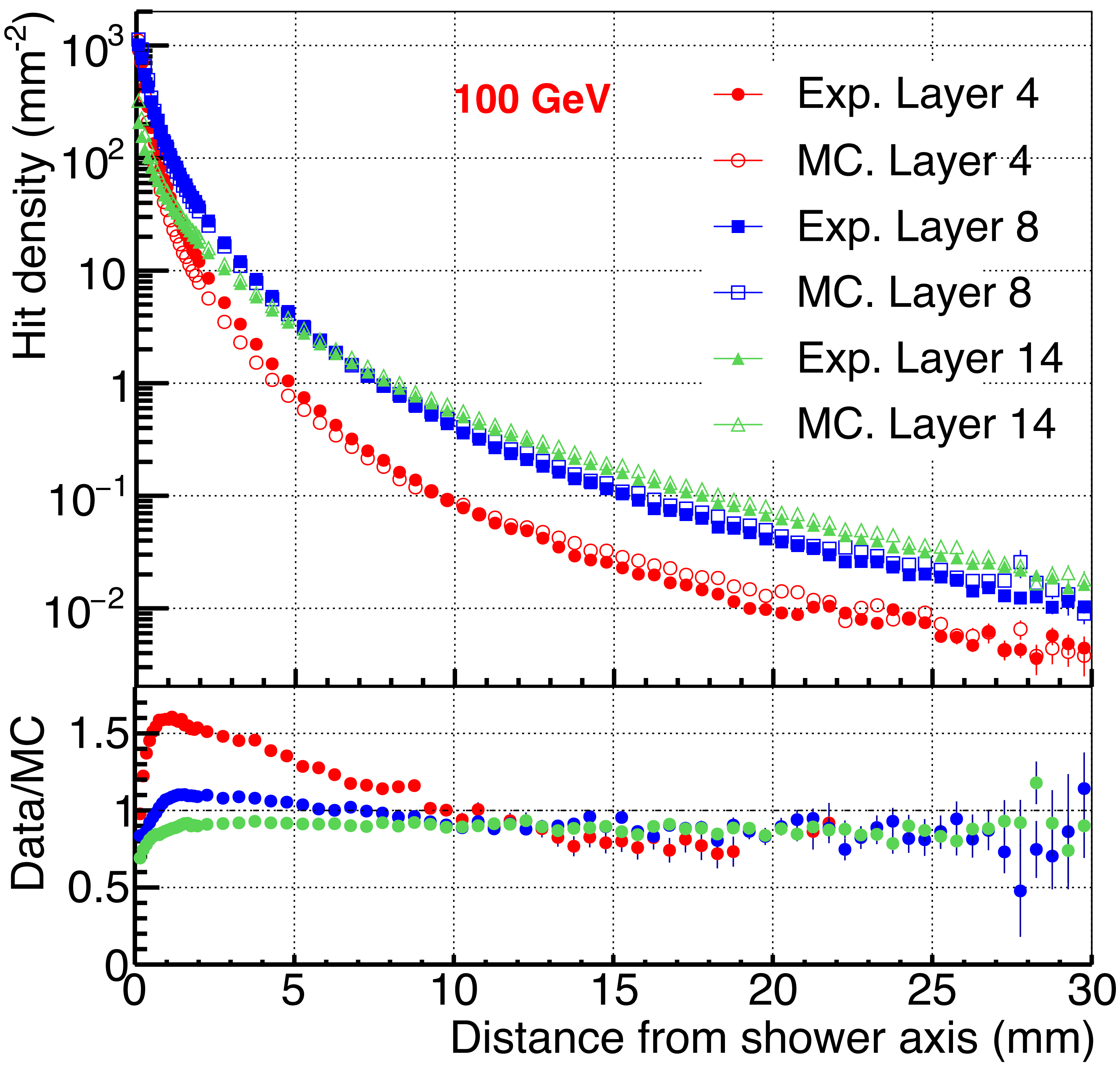
Shower Maximum



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!

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?