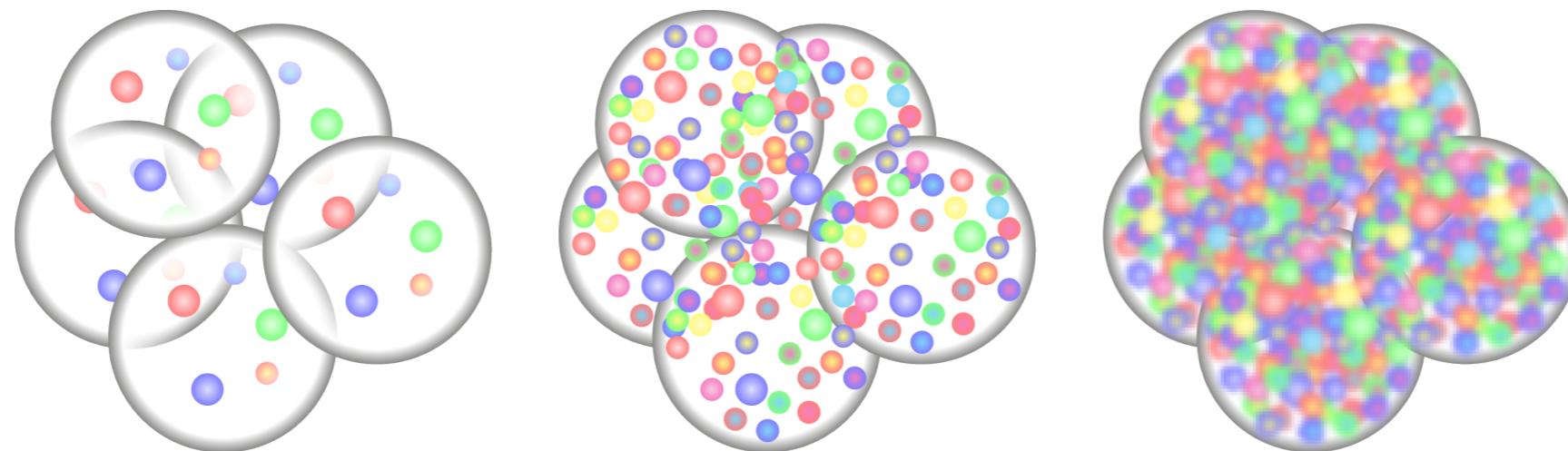




ALICE

Forward Photon Measurements in ALICE at the LHC as a Probe for Low- x Gluons



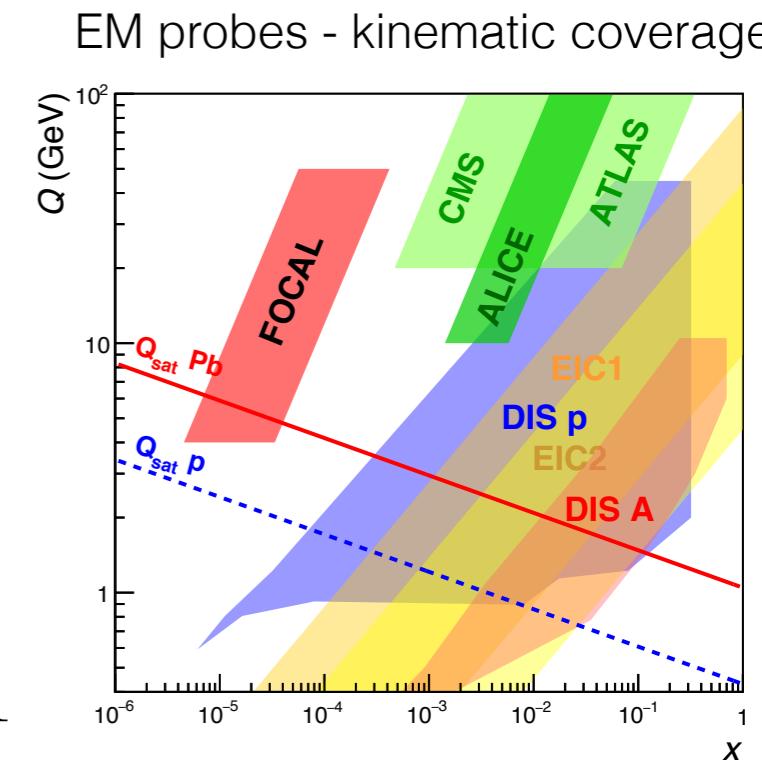
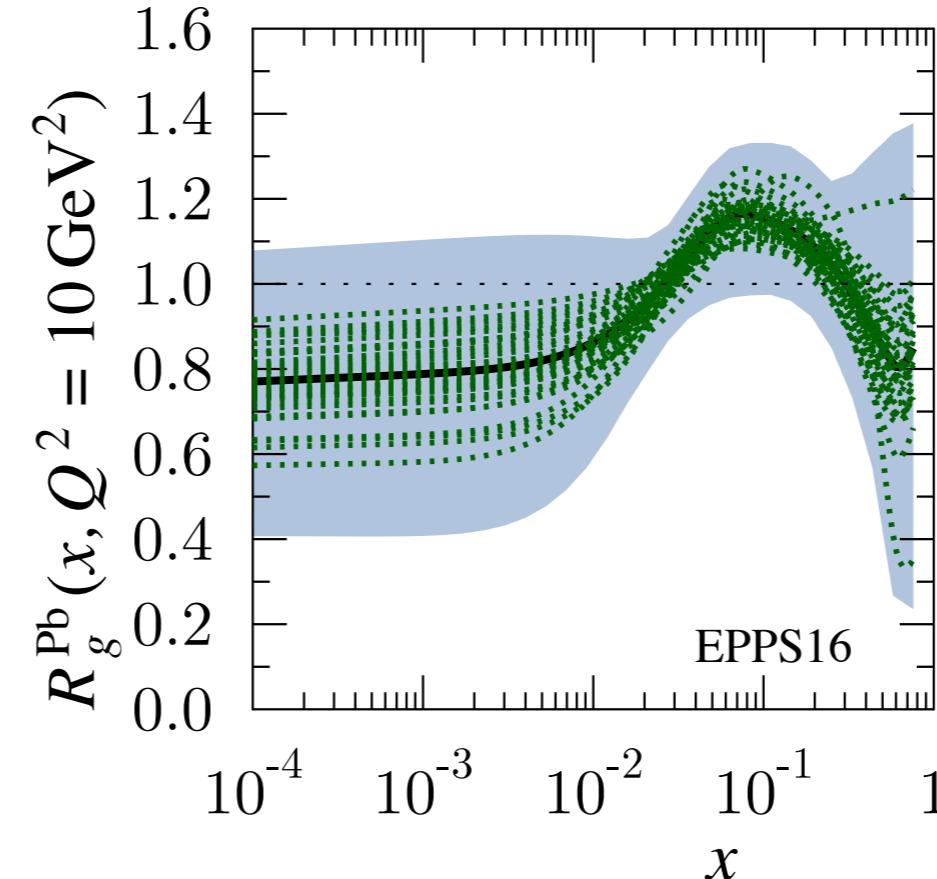
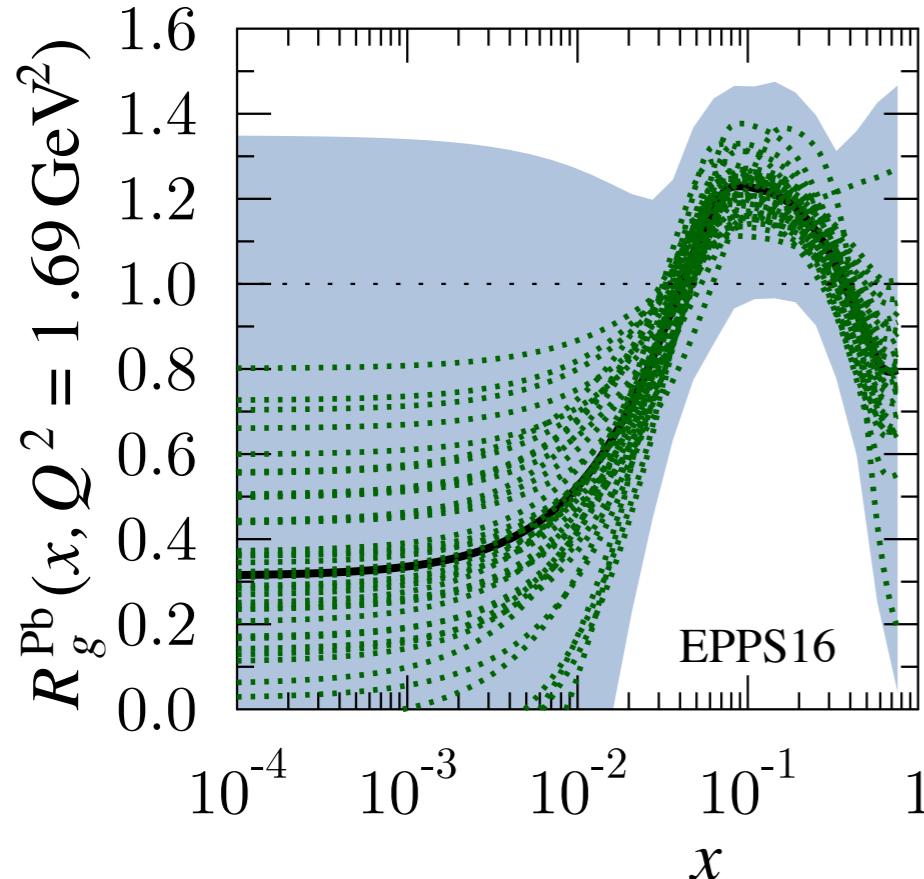
T. Peitzmann (Utrecht University/Nikhef)
for the ALICE Collaboration

Low- x 2019, Nicosia, 26.08.2019

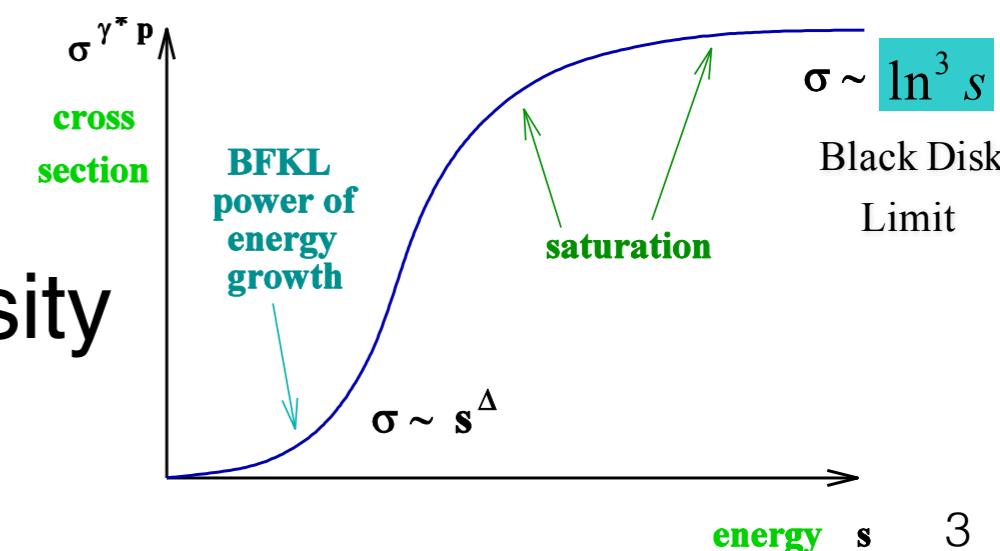
Outline

- Physics case
 - PDF uncertainty (and gluon saturation)
 - experimental probes of PDFs
- FoCal - an ALICE upgrade proposal
 - baseline design, performance
- Research and development
 - high-granularity EM calorimeter
- Summary

PDF Uncertainties and Saturation



- large uncertainties of nPDFs
 - parameterised nuclear modification (unbiased?)
- x -dependence?
 - very little dependence for $x < 10^{-2}$
- **need more experimental data!**
- non-linear effects from high gluon density
- gluon saturation?



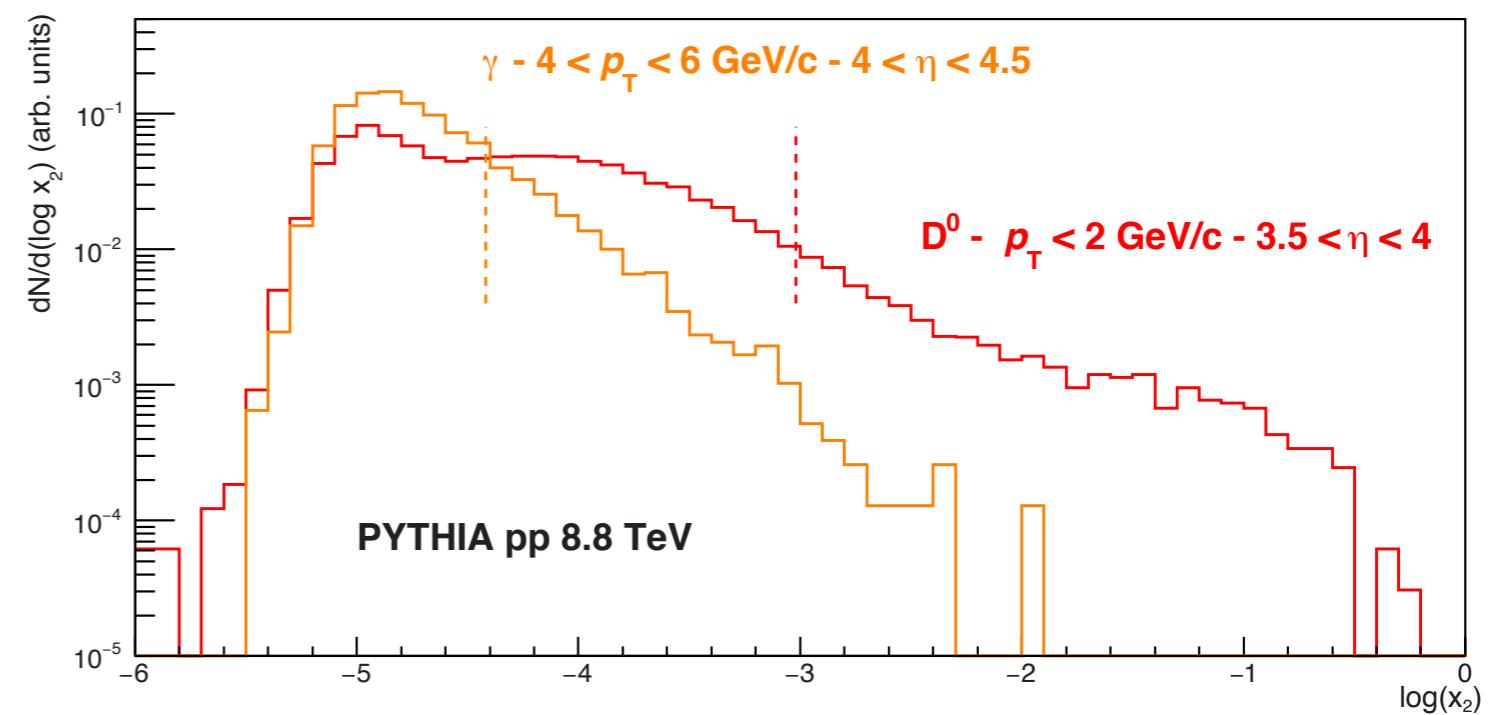
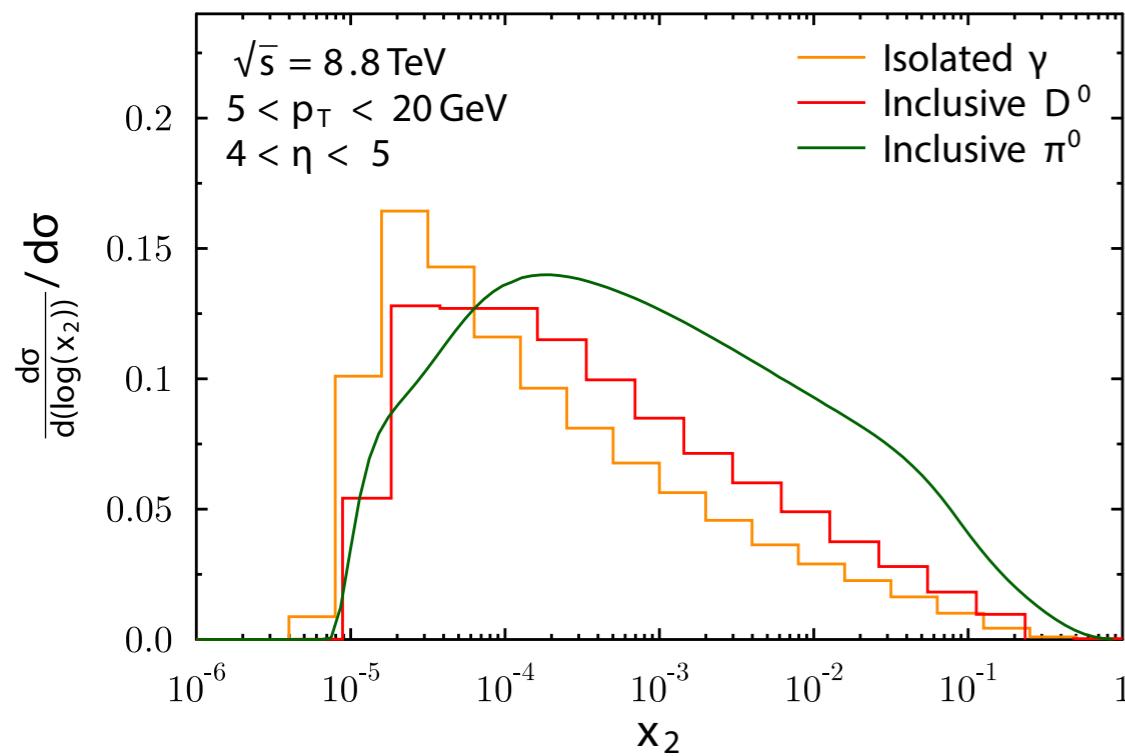
True x-Sensitivity?

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

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

- 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



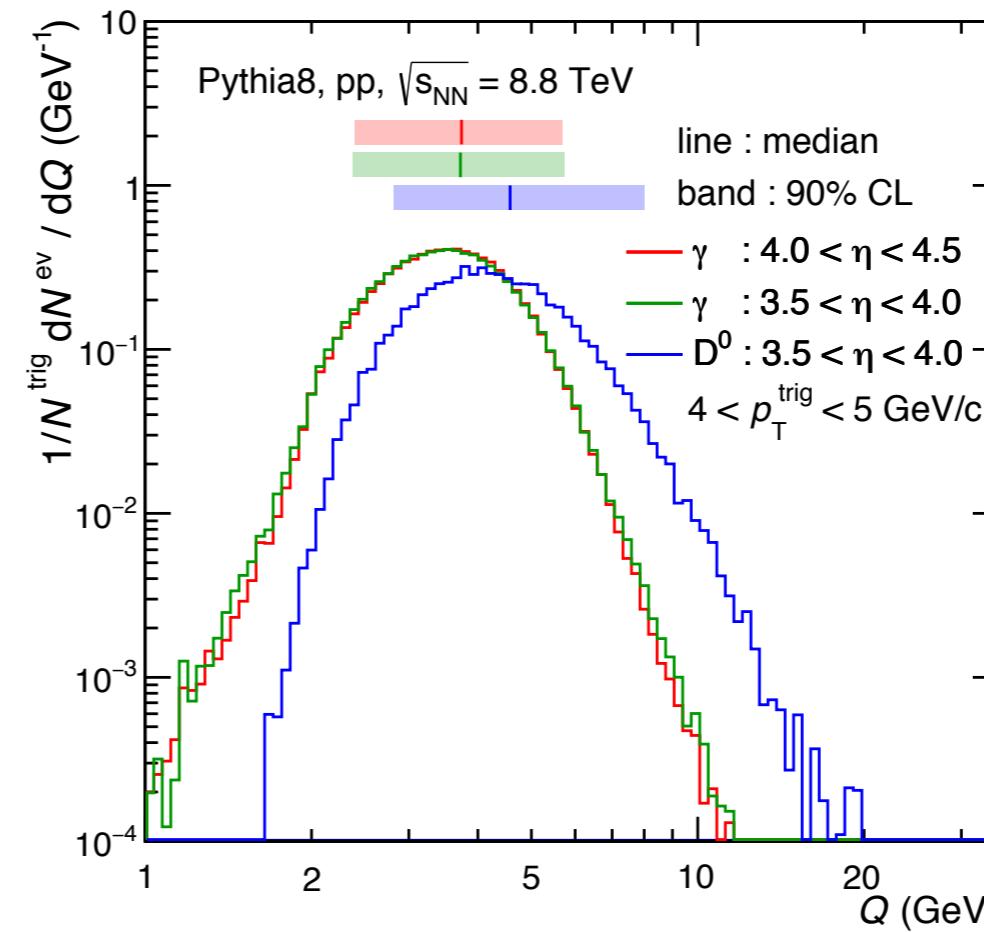
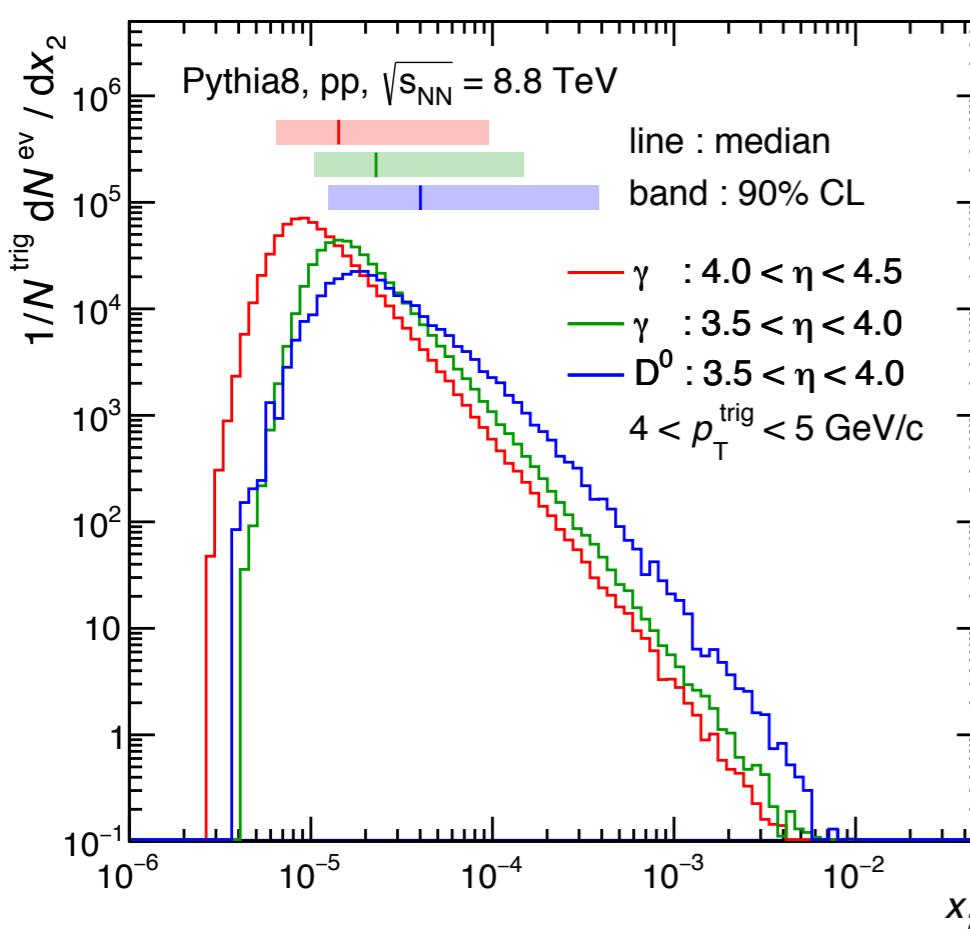
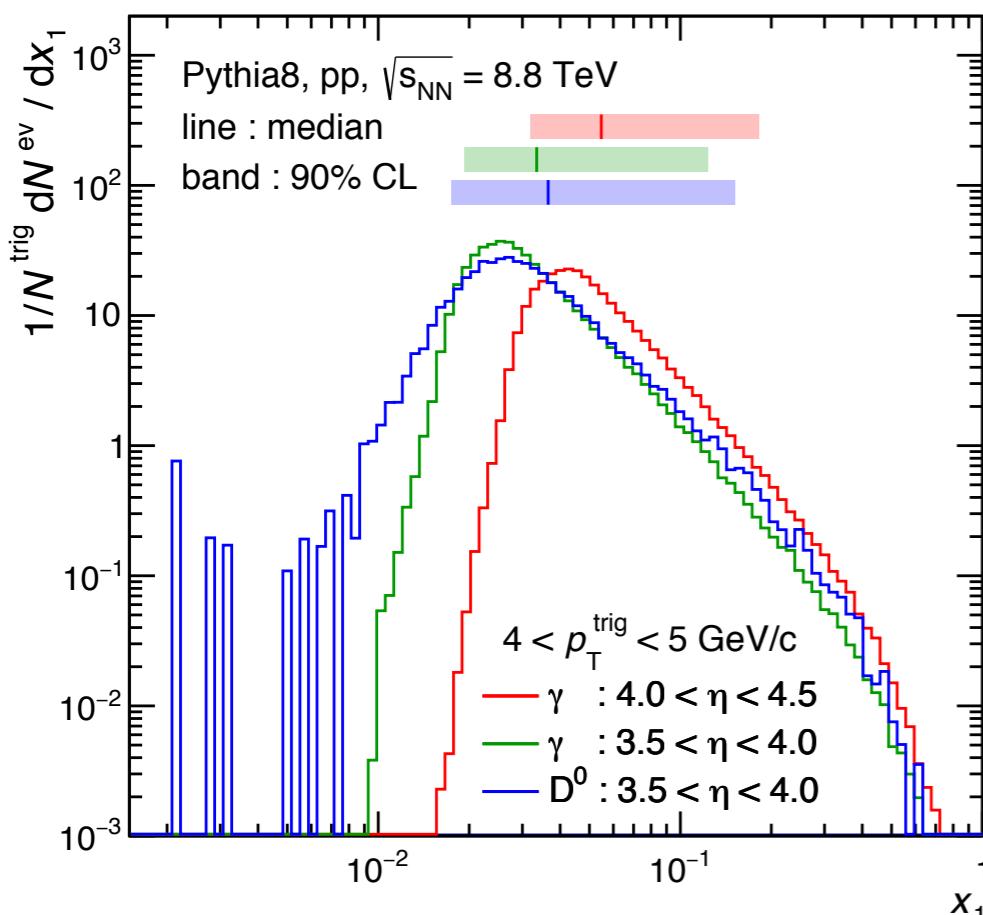
no analytical approximation, taking into account η of recoil parton

x - Q^2 -Sensitivity

PYTHIA pp 8.8TeV
forward measurements

compare LHCb D0 and FoCal
photons

study median of distribution and
90% confidence level limits

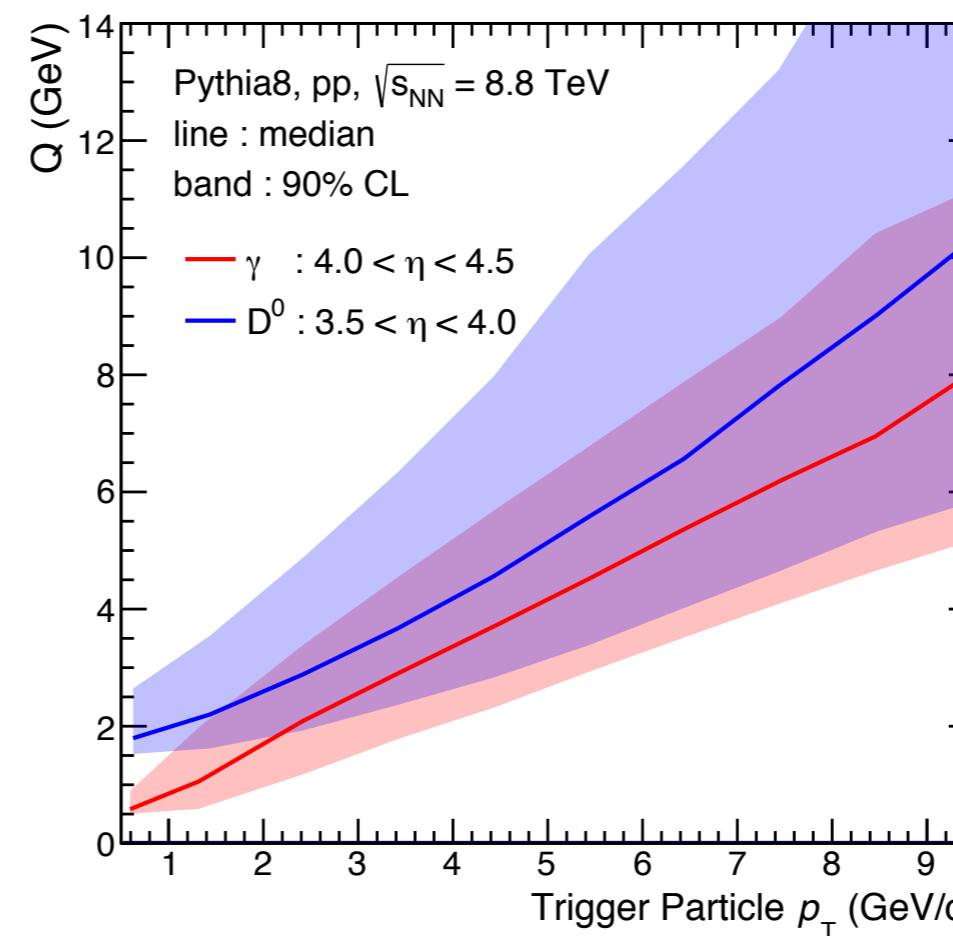
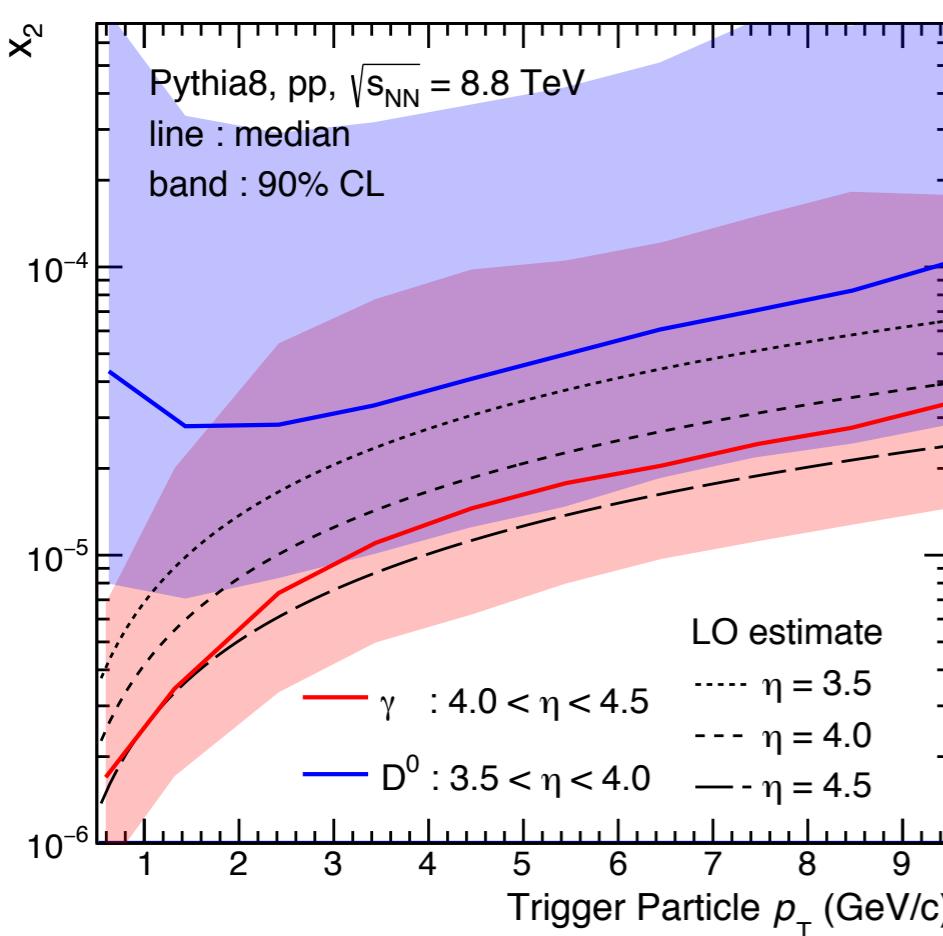
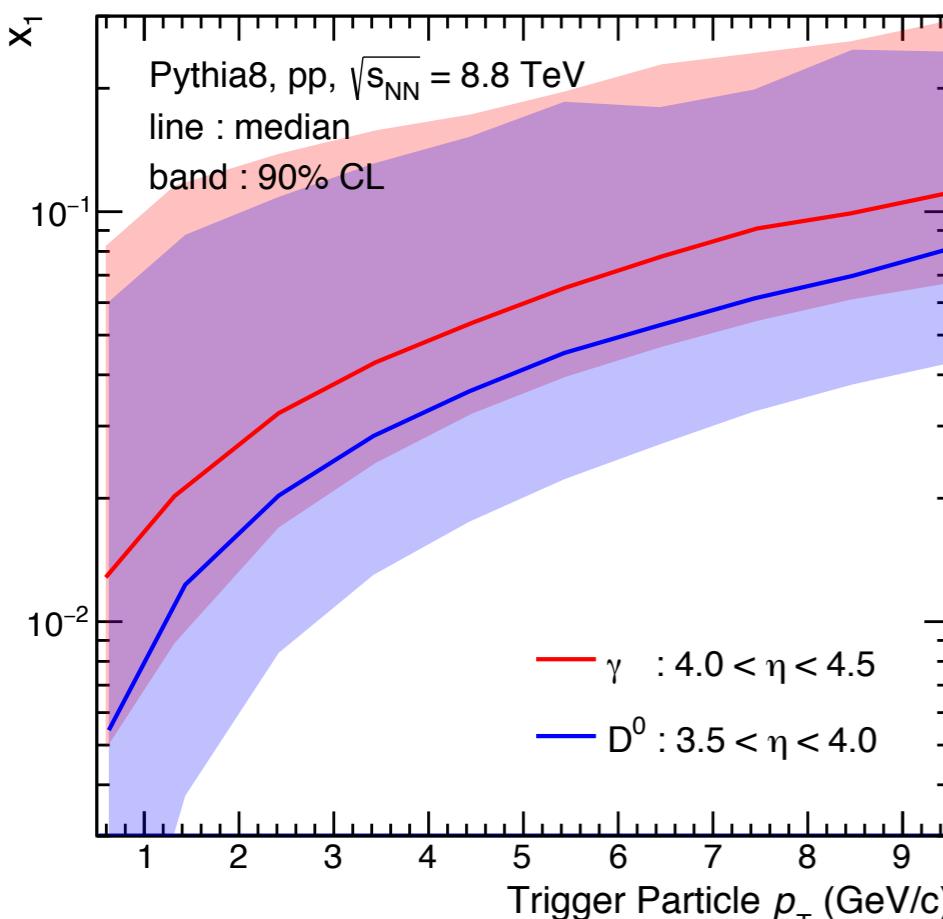


$x\text{-}Q^2$ -Sensitivity

PYTHIA pp 8.8TeV
forward measurements

compare LHCb D0 and FoCal
photons

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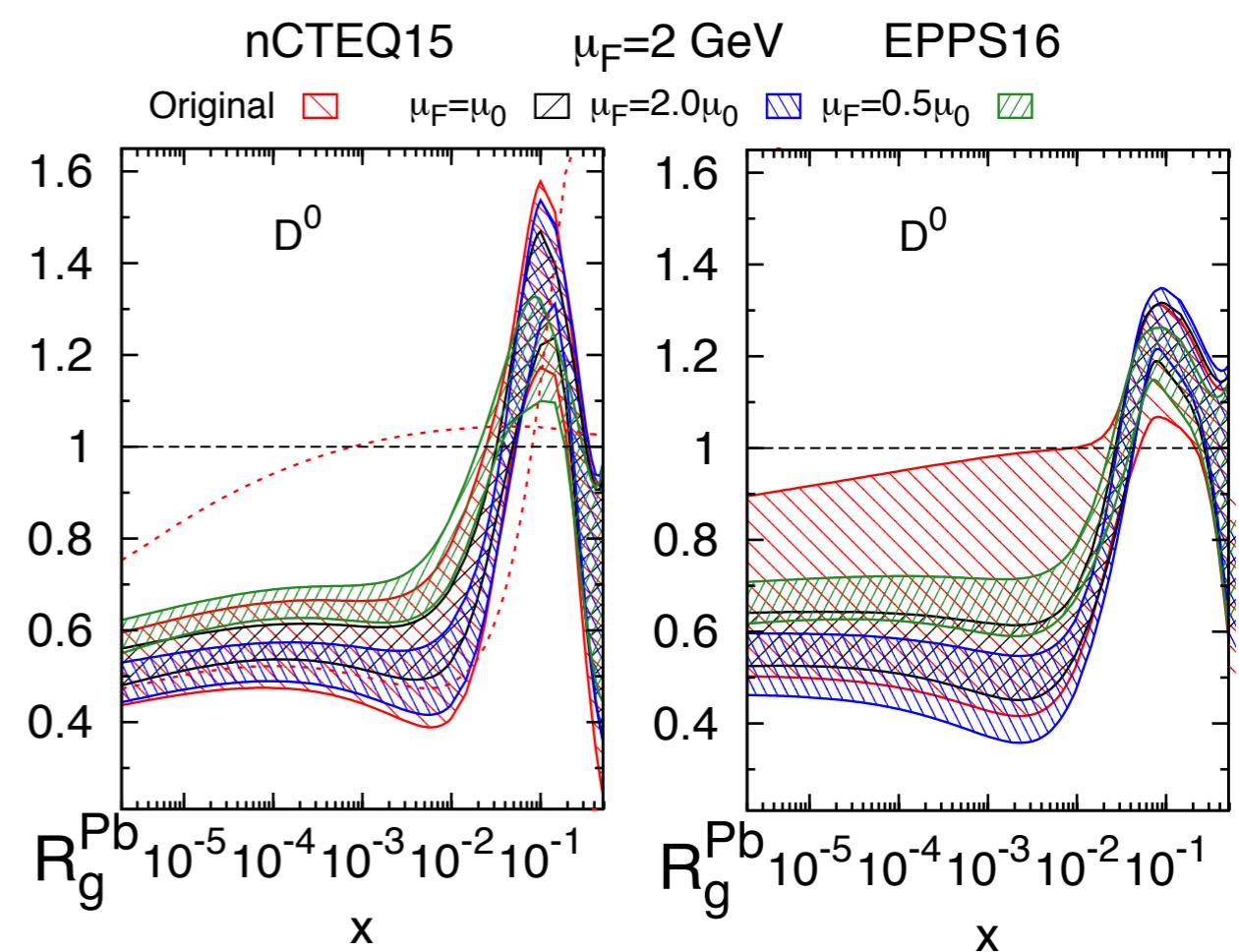
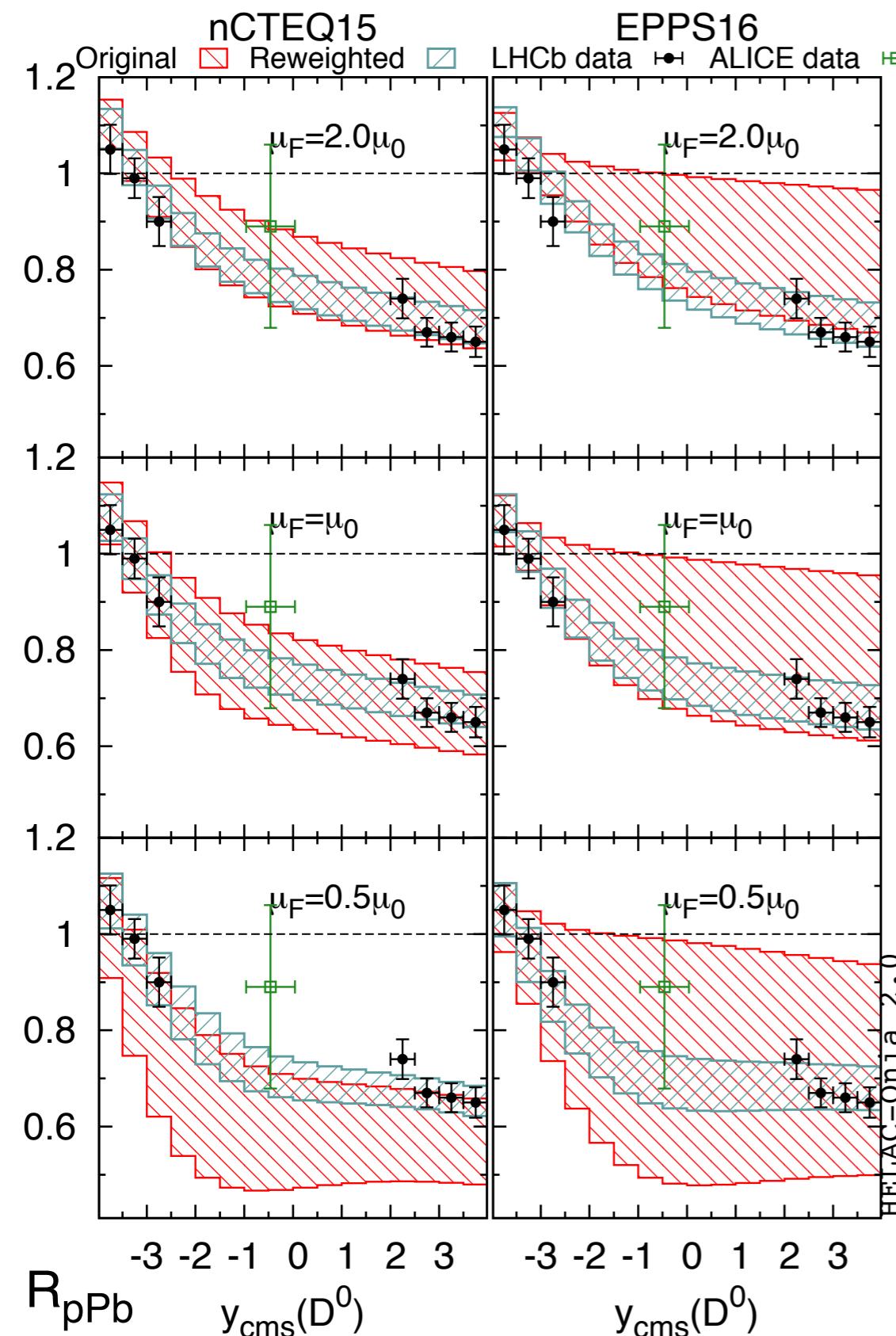




ALICE

PDF Fits Using Charm

- 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 !**

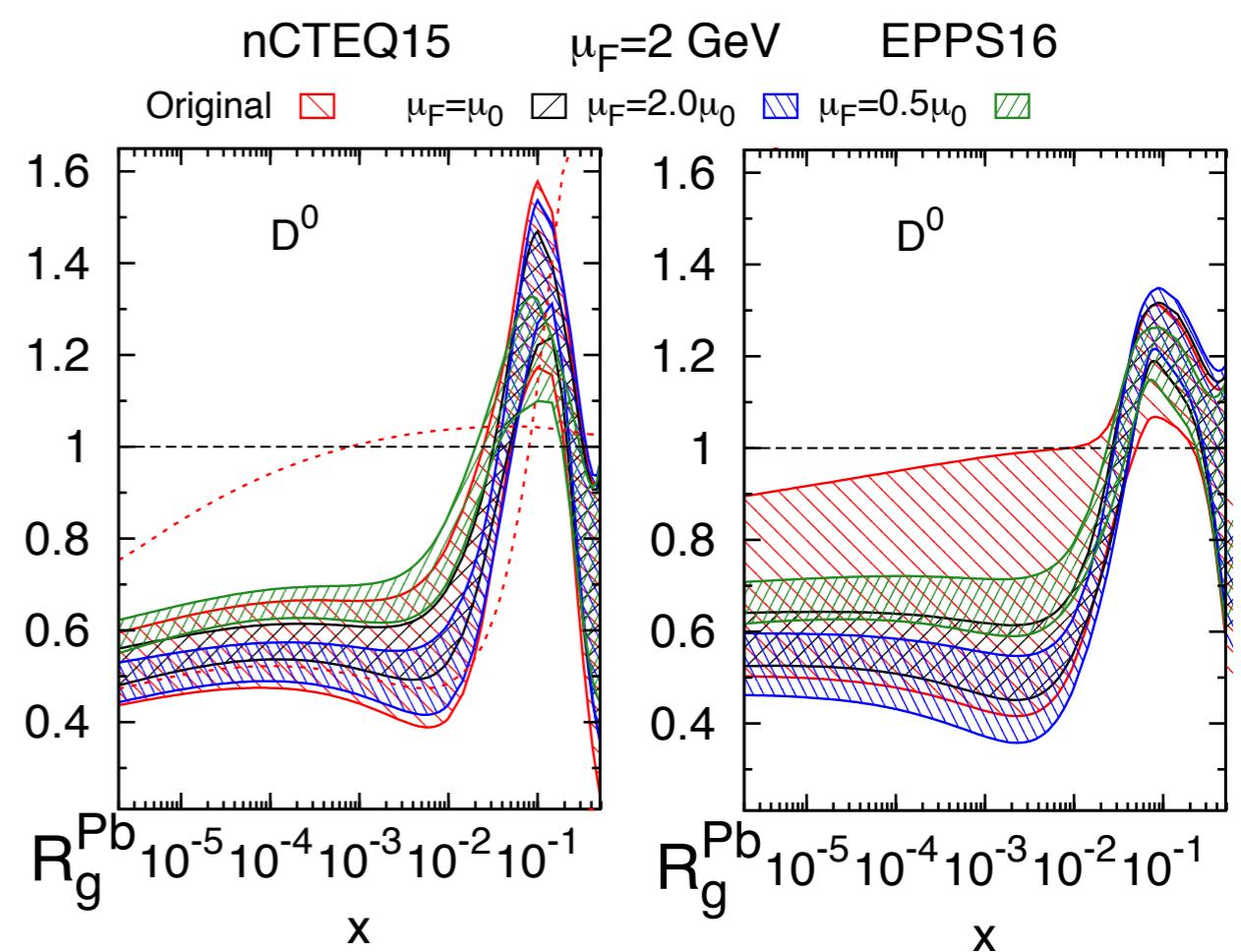
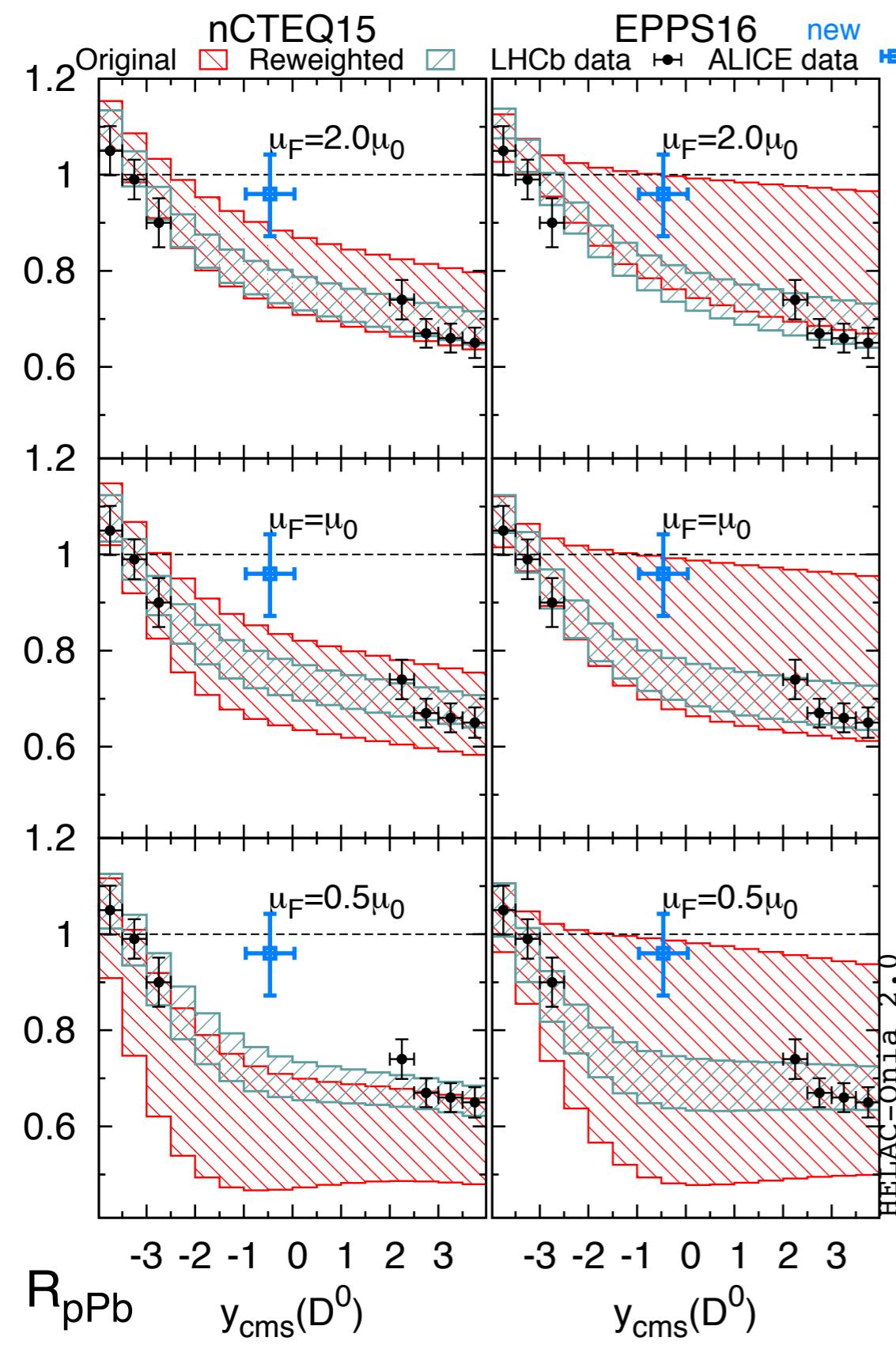




ALICE

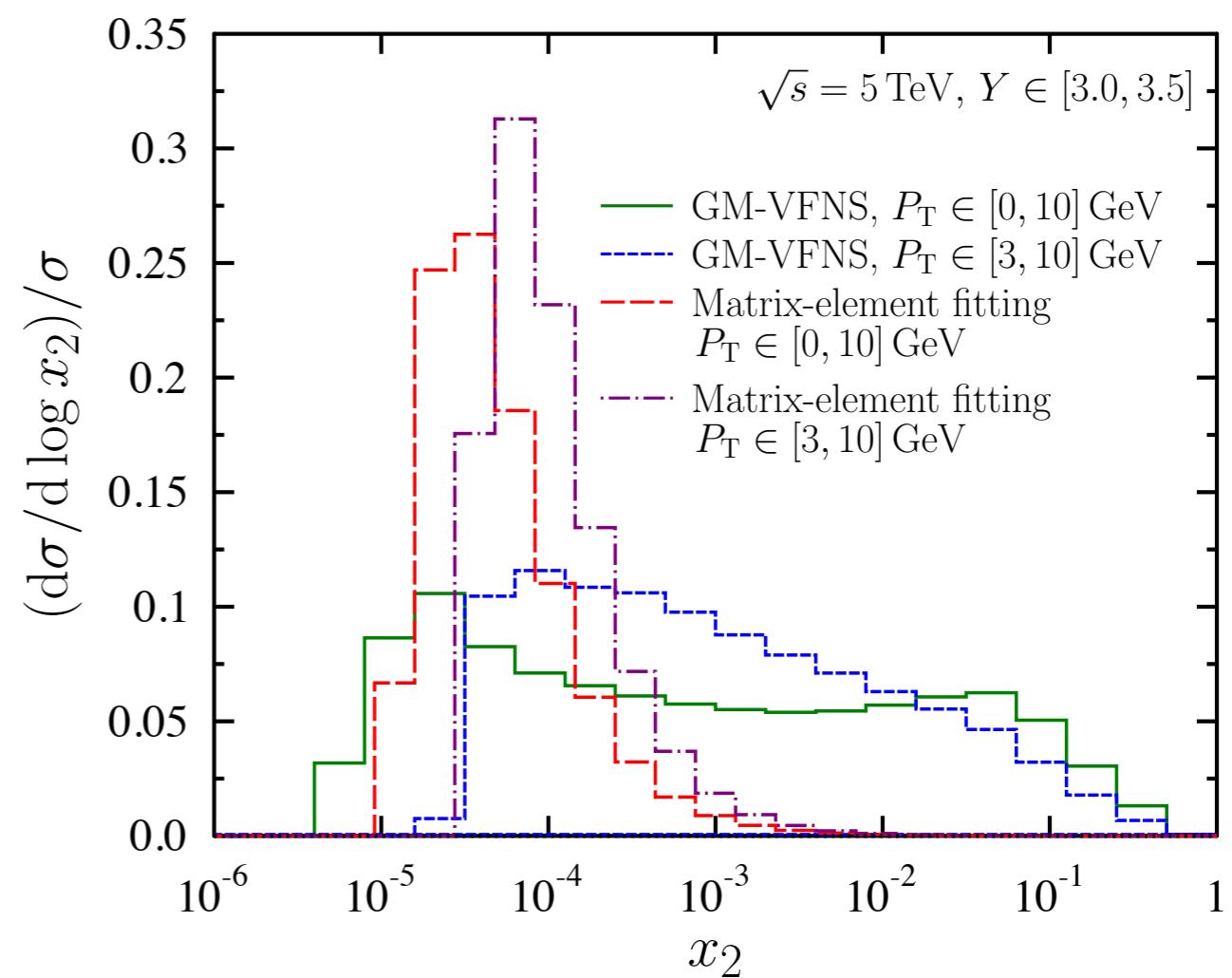
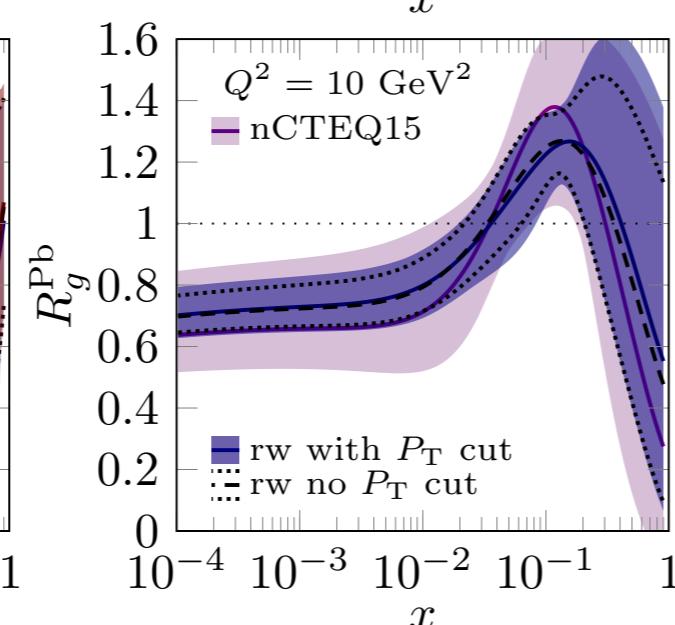
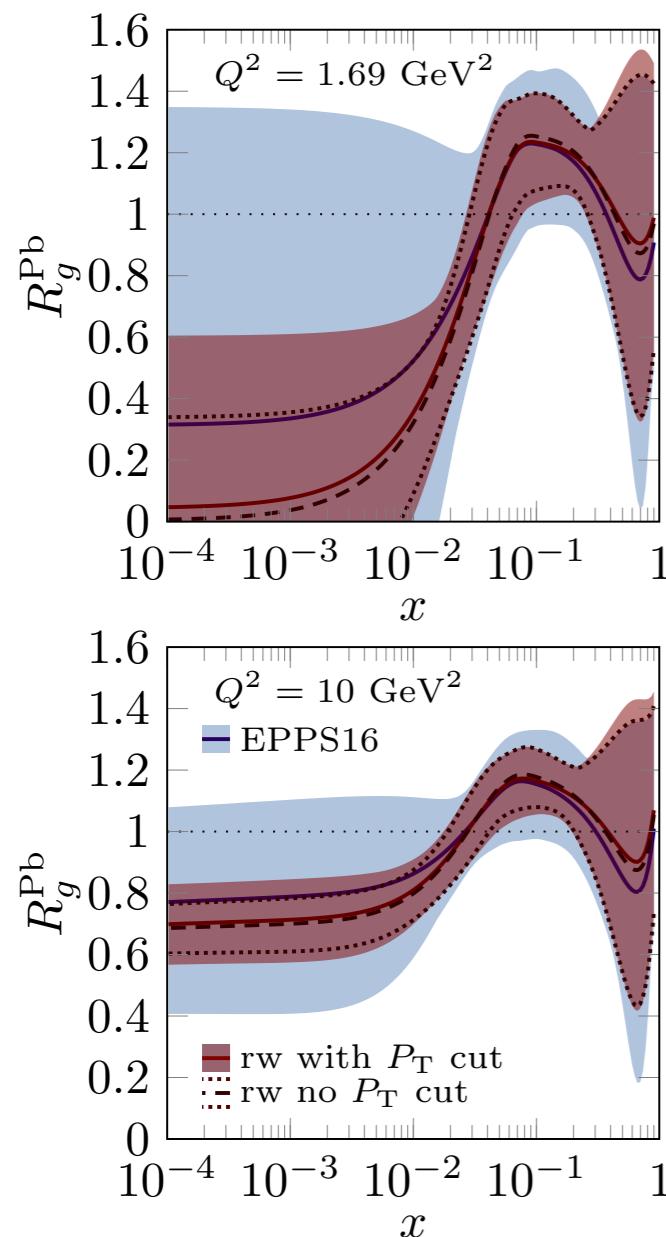
PDF Fits Using Charm

- open charm used in re-weighting
 - fit to LHCb results shows tension with new ALICE results at midrapidity
 - revisit assumptions on shape of parameterisation?**

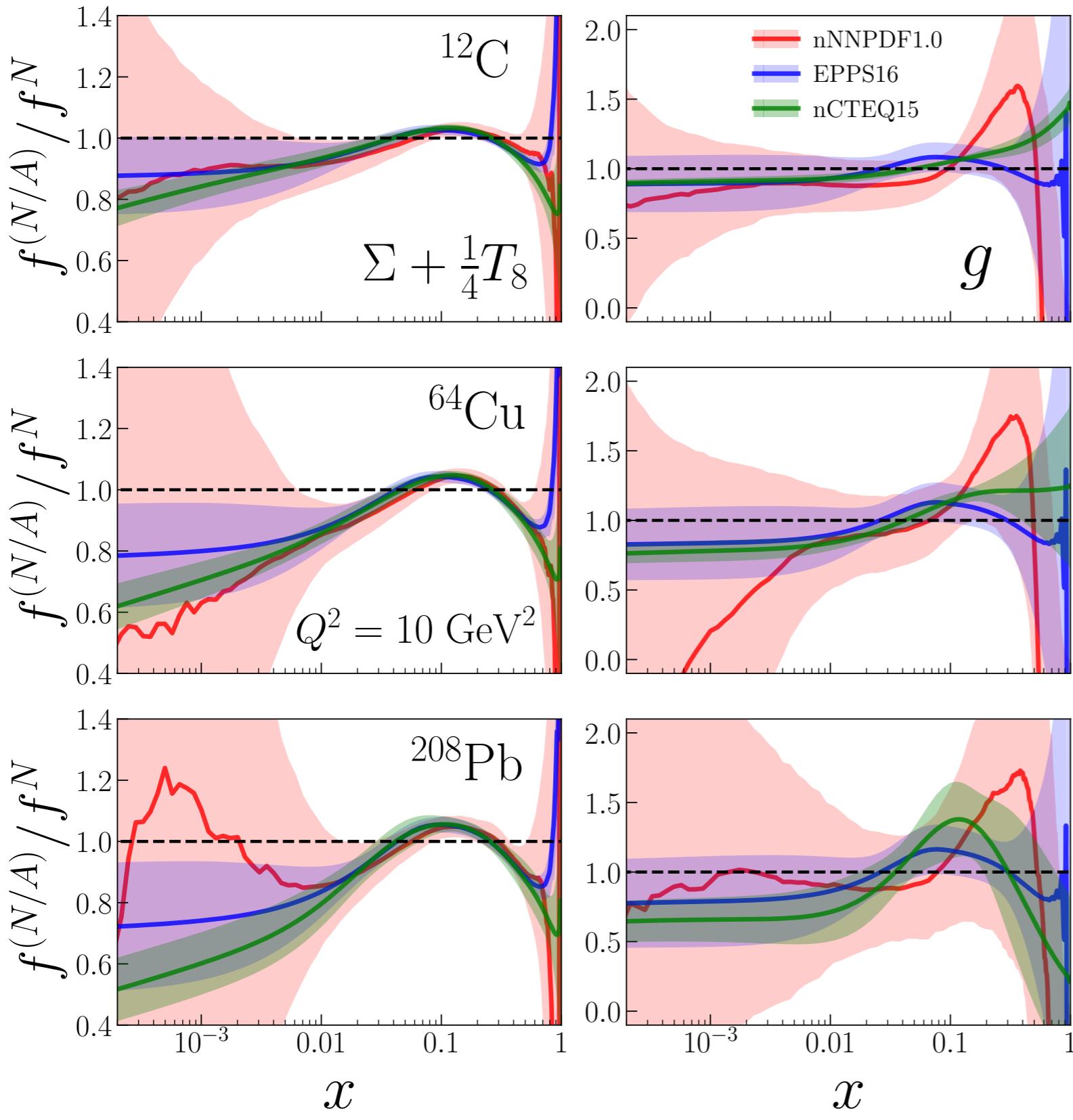


PDF Fits Using Charm II

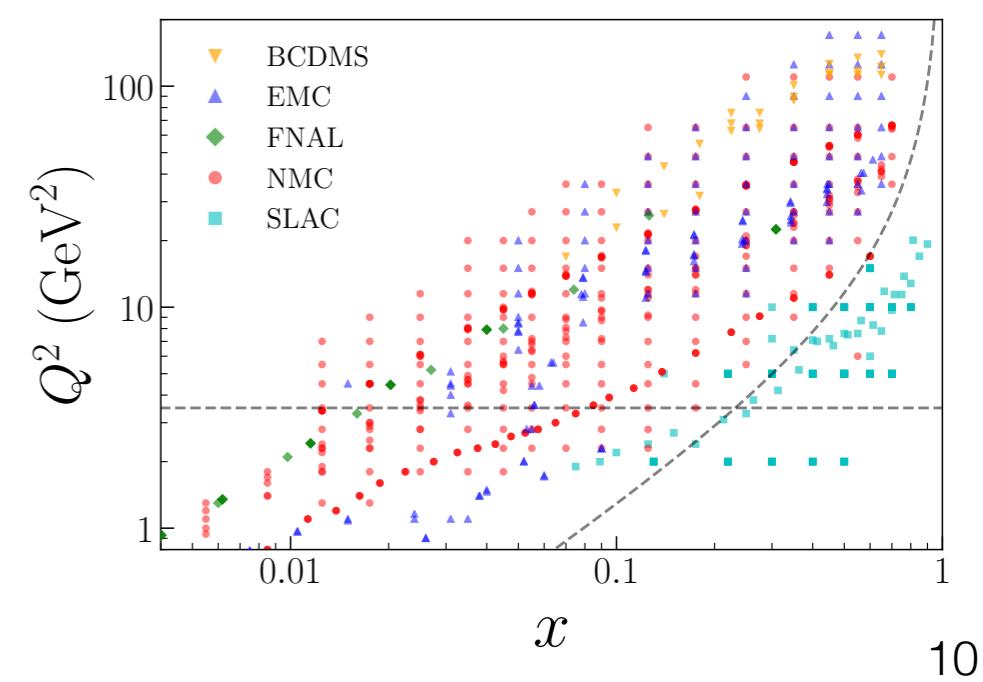
- open charm used in re-weighting
 - new study in GM-VFNS
 - includes production from gluon fragmentation
 - significant contribution from large values of x_2**



Towards More General nPDFs



- **nNNPDF1.0**
 - compared to EPPS16 and nCTEQ15
 - free of assumptions for parameterisation
 - resulting in much larger (more realistic) uncertainty in nuclear PDFs

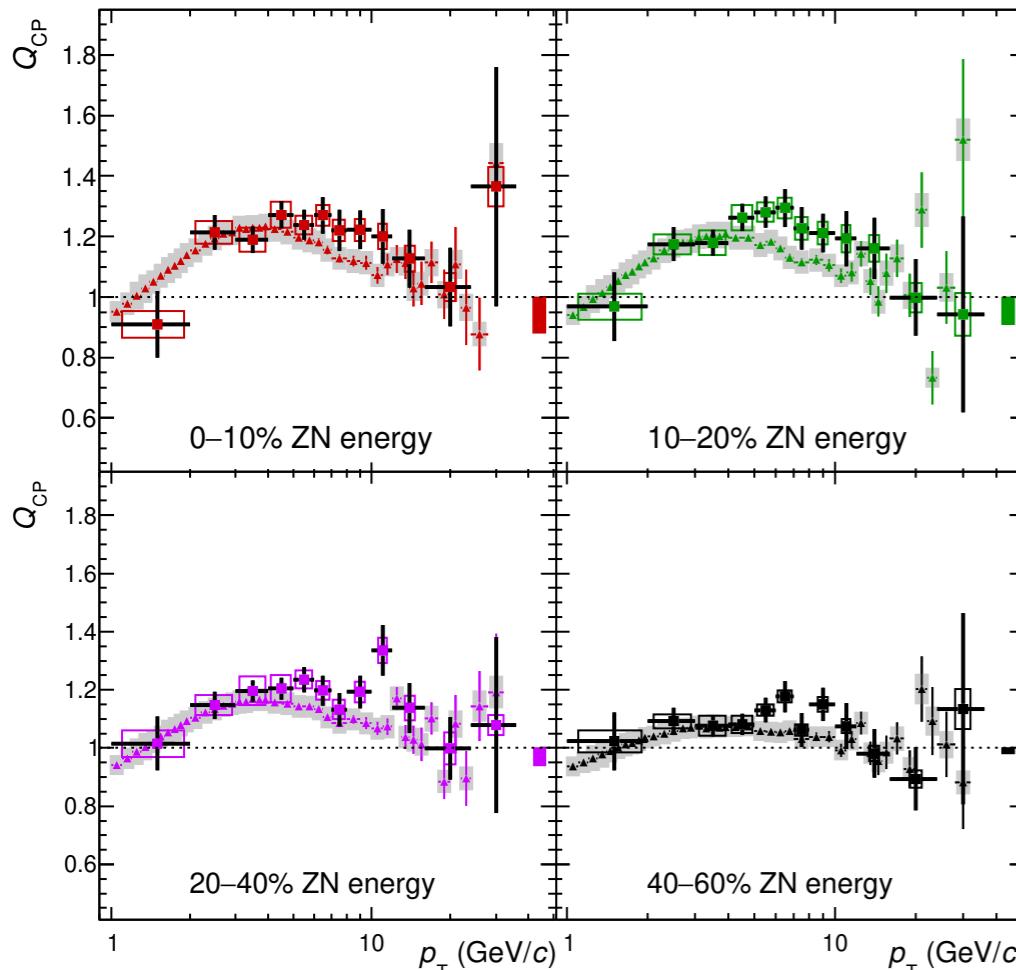




Final-State Modification of Open Charm in p–A?

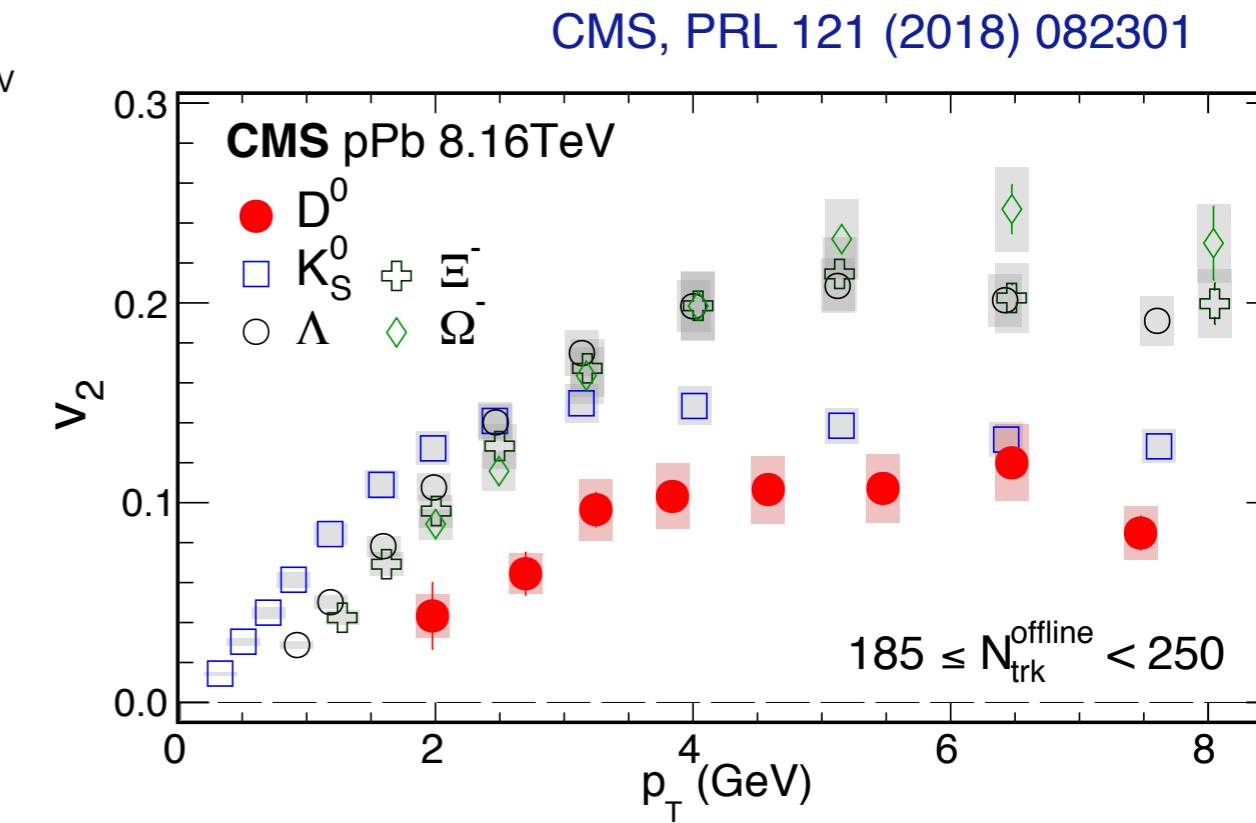
ALICE

ALICE, submitted to JHEP,
arXiv:1906.03425



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

ALICE
p–Pb, $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$
 $-0.96 < y_{\text{cms}} < 0.04$
 ■ Prompt D mesons
 □ Syst. on dN/dp_T
 ■ Syst. on $\langle T_{\text{pPb}} \rangle$
 ▲ Charged particles
 ■ Syst. on dN/dp_T



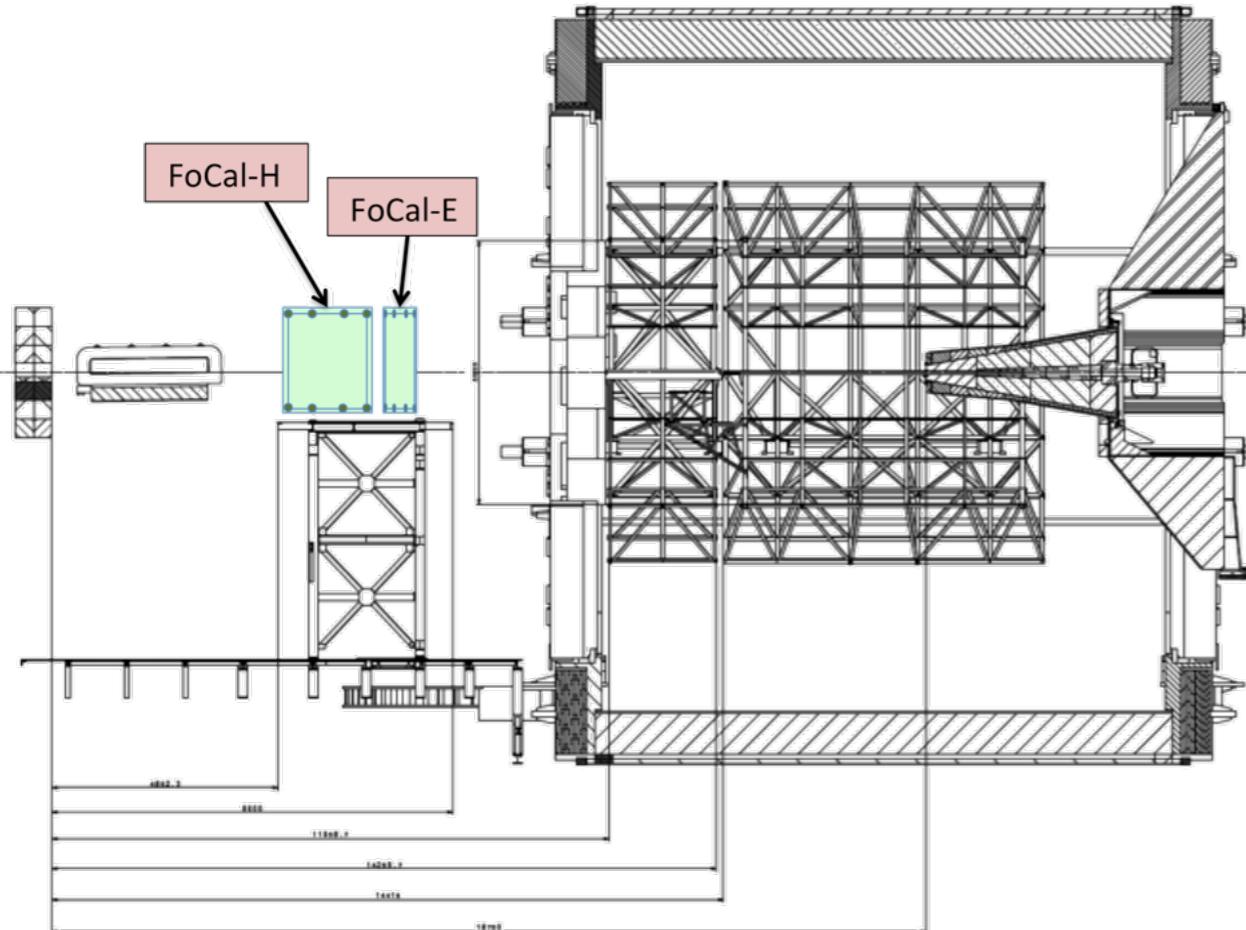
significant v_2 for D mesons,
similar results for HF-decay leptons

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

Low-x Measurements at LHC

- Strong (nuclear) low-x program with various measurements
 - forward production of photons, open charm, DY(?), also UPC
- Important contribution of forward isolated photons
 - potential sensitivity to lower x
 - no final-state modification, suppression of fragmentation
- Opportunity in ALICE
 - needs detector upgrade: FoCal

FoCal in ALICE



FoCal-E: high granularity electromagnetic calorimeter for γ and π^0 measurement

FoCal-H: conventional hadronic calorimeter for isolation and jets

at $z \approx 7\text{m}$: $3.2 < \eta < 5.8$

under internal discussion
possible installation in LS3

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

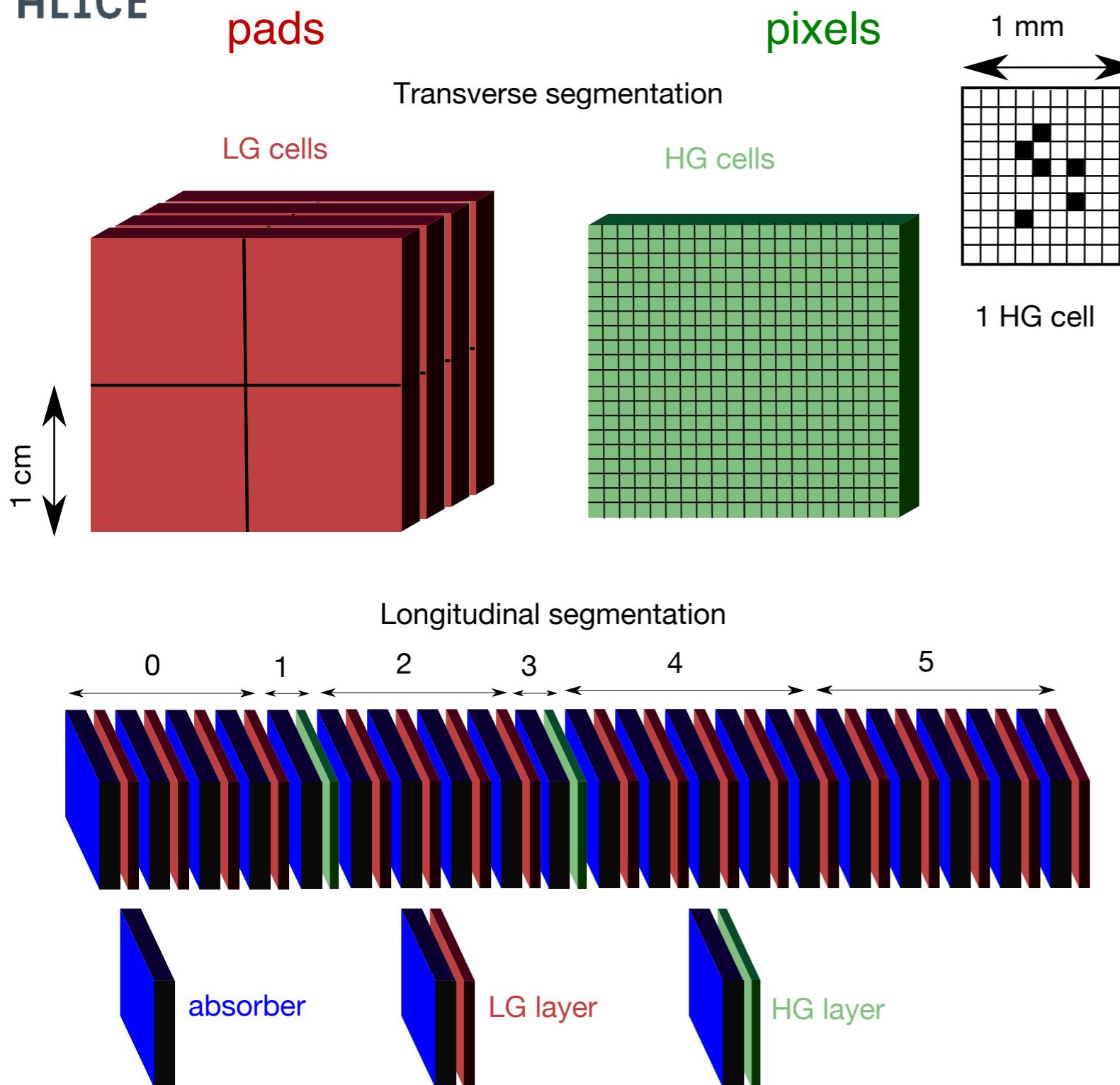
- main challenge: separate γ/π^0 at high energy
- need small Molière radius, high-granularity read-out
 - Si-W calorimeter, effective granularity $\approx 1\text{mm}^2$

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



ALICE

The FoCal Detector – Strawman Design



studied in performance simulations:

20 layers:

$W (3.5\text{mm} \approx 1 X_0) + \text{Si-sensors}$

hybrid design (2 types of sensors)

- **Si-pads** ($\approx 1 \text{ cm}^2$): energy measurement, timing(?)
- **CMOS pixels** ($\approx 30 \times 30 \mu\text{m}^2$): two-shower separation, position resolution

main optimization (to be done):

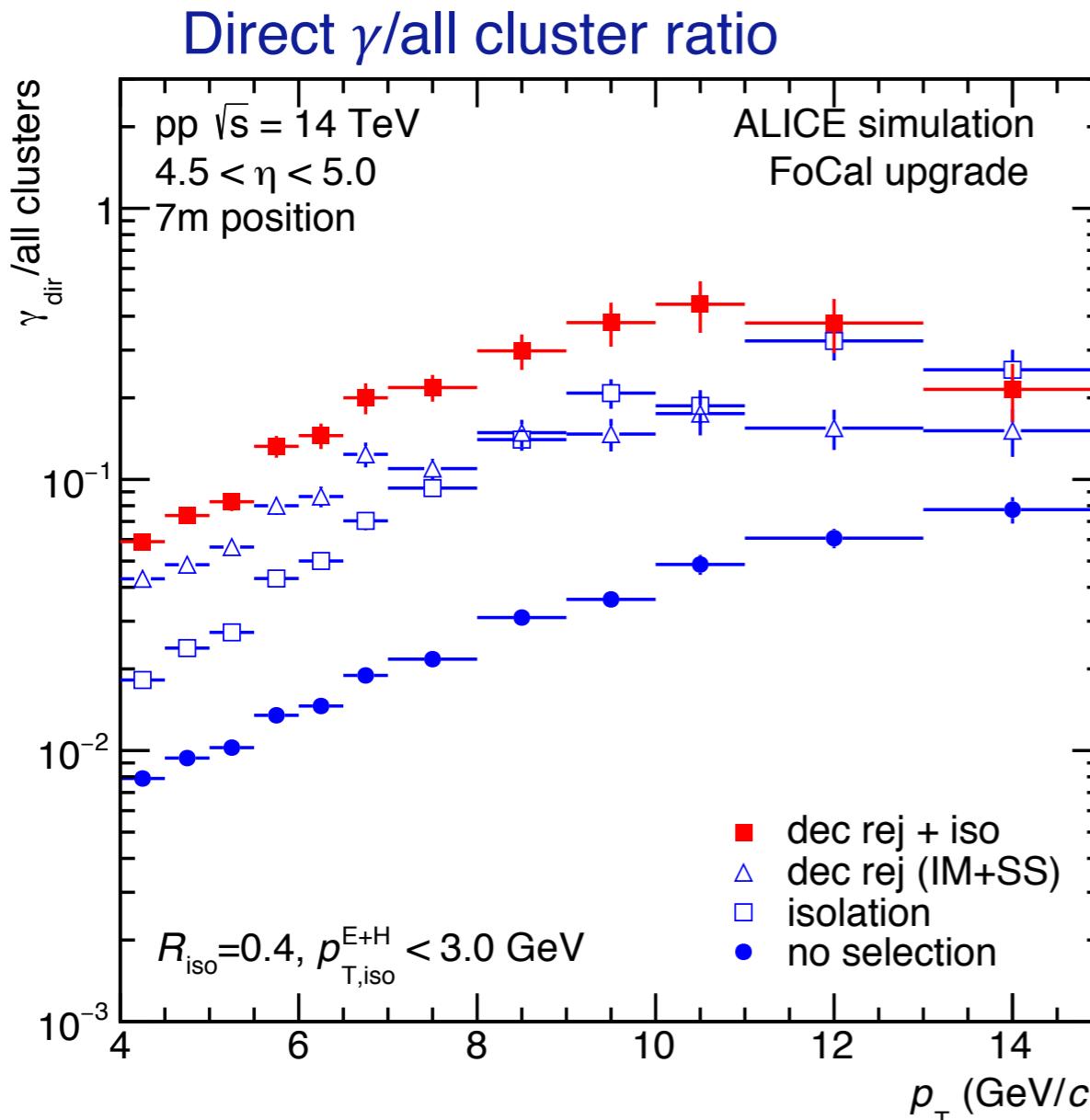
- number of pixel layers and location
- number of pad layers
- maximum separation between layers



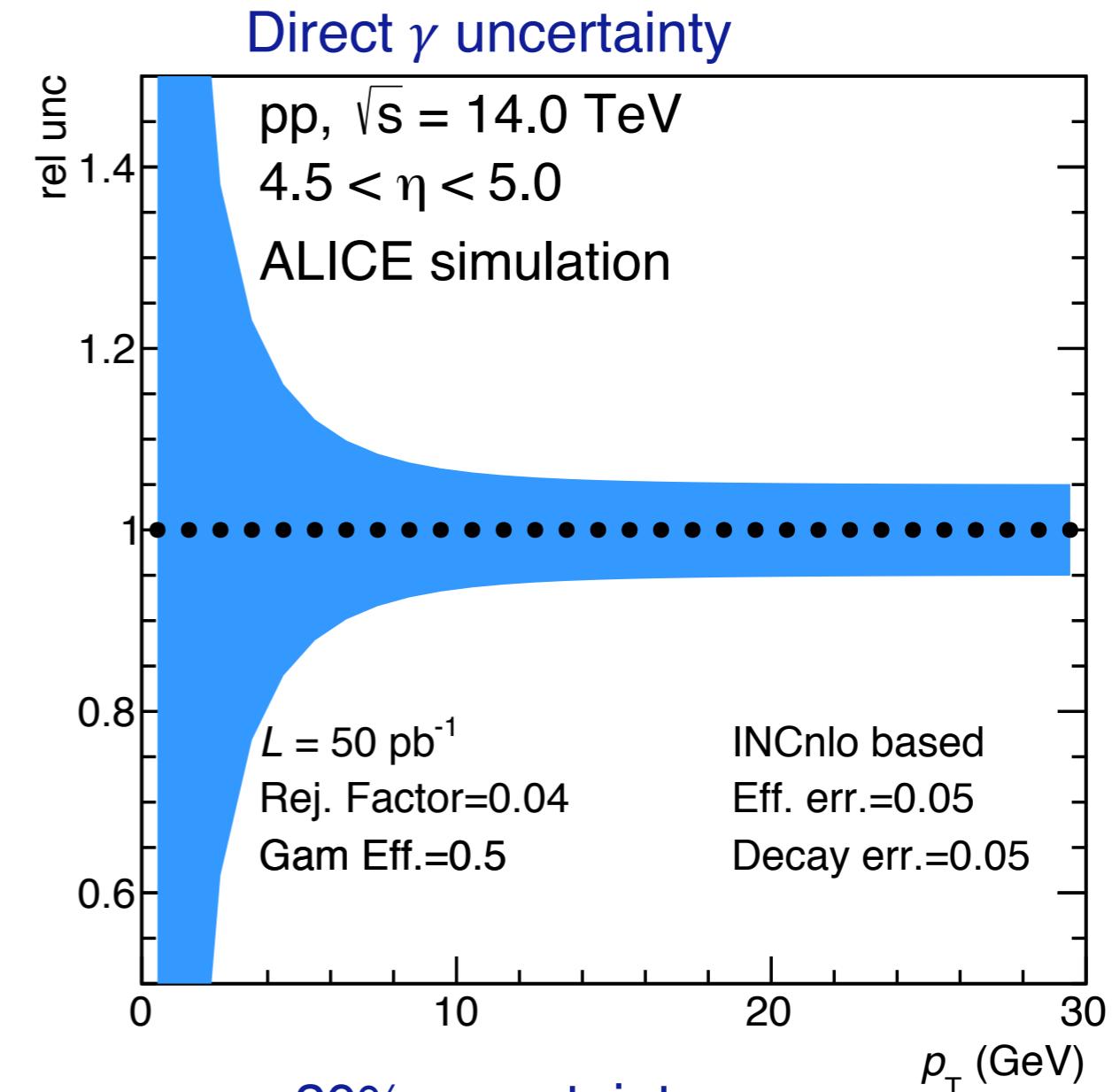
ALICE

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 photon/all > 0.1
for $p_T > 5 \text{ GeV}/c$

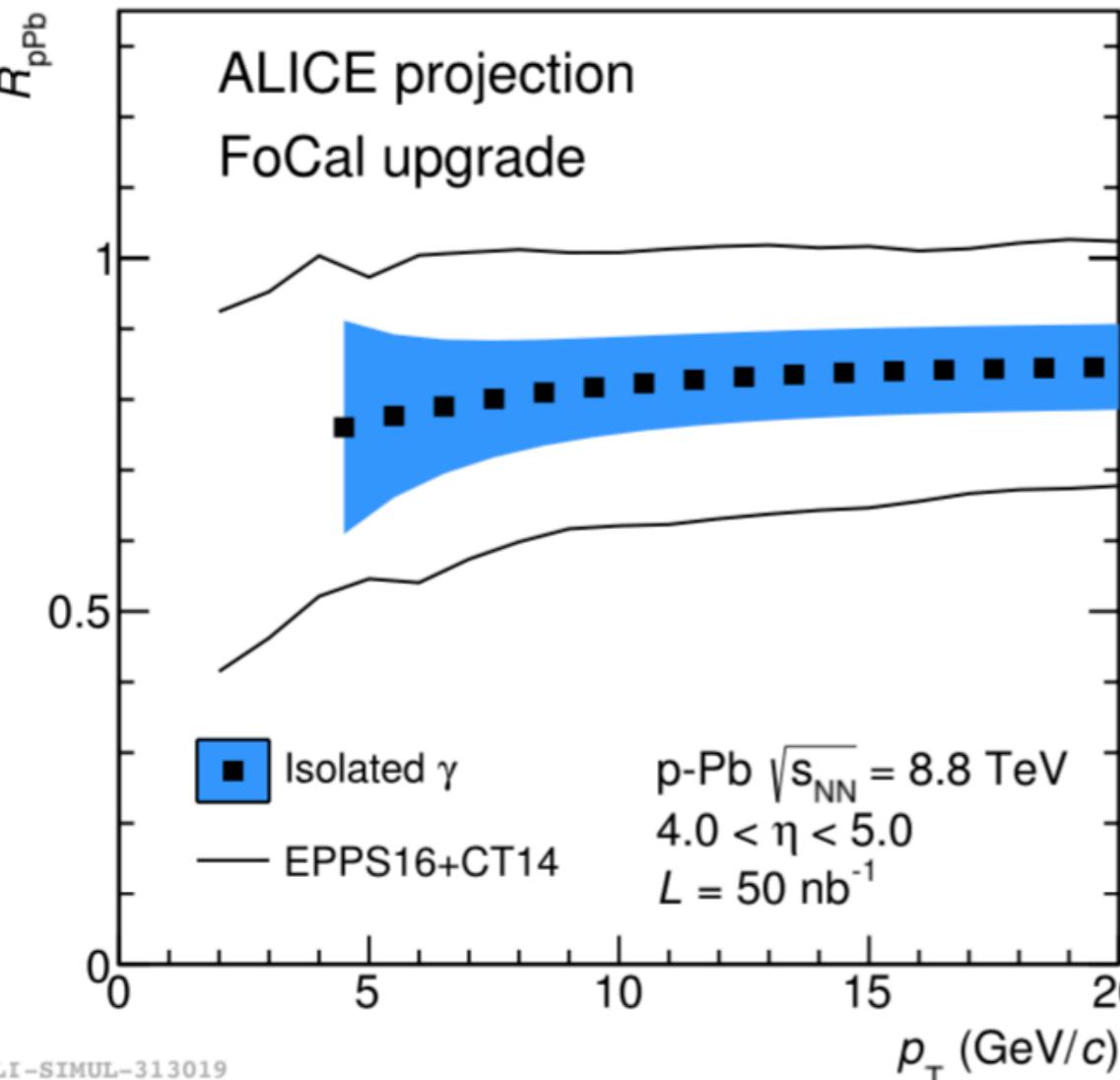


< 20% uncertainty
at $p_T = 4 \text{ GeV}/c$
decreases with increasing p_T



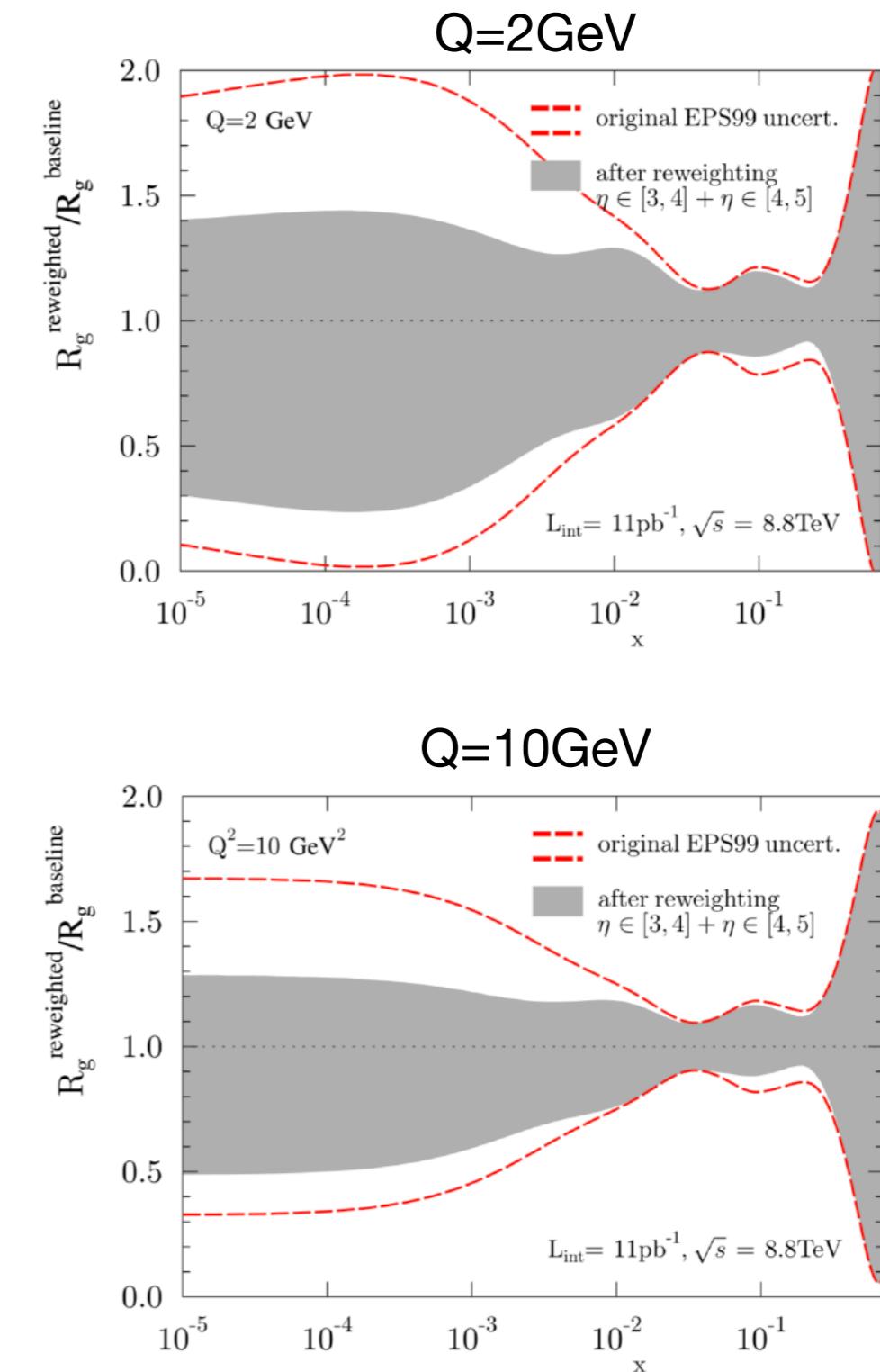
Performance and Impact on EPPS16 nPDF

ALICE



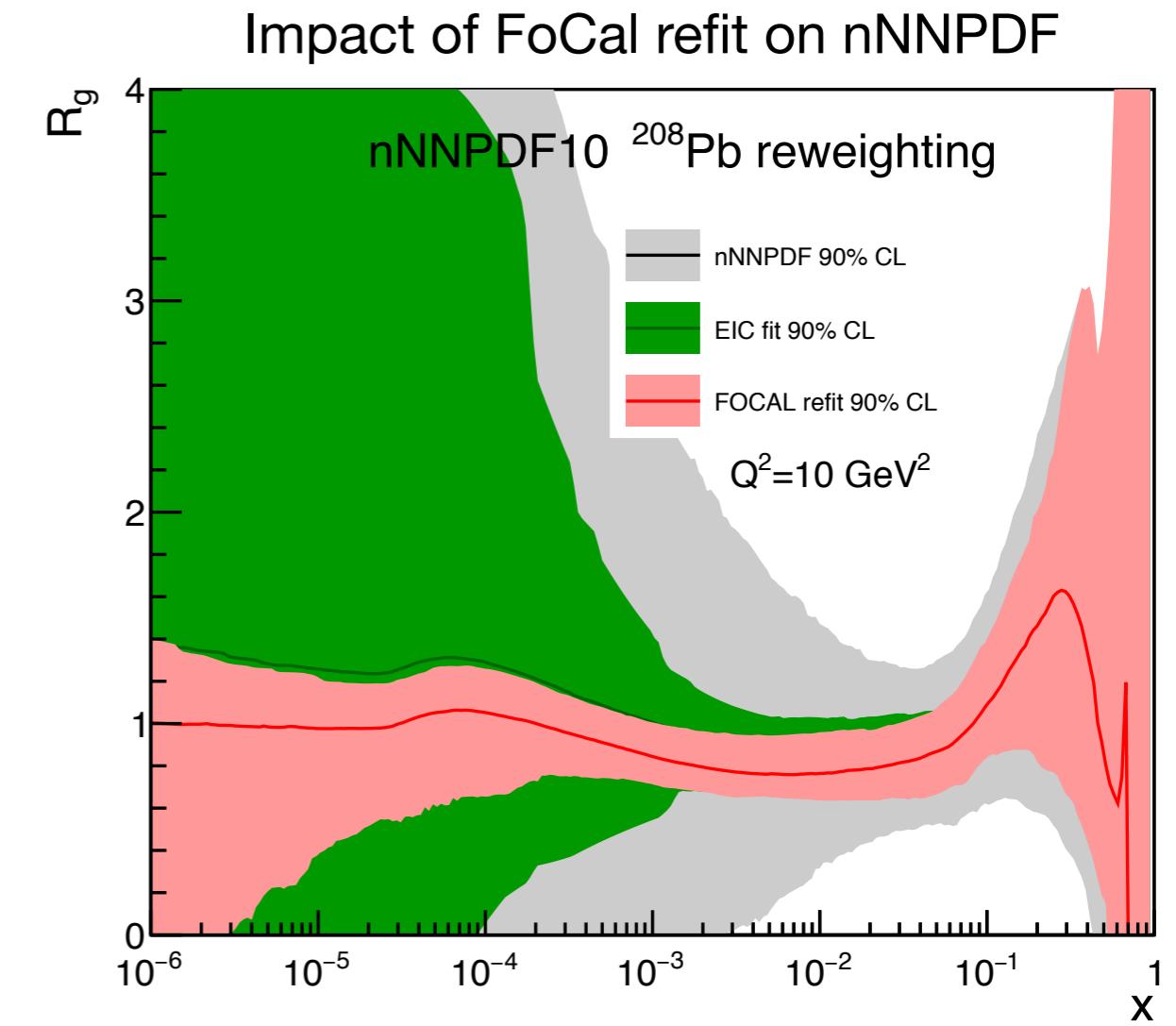
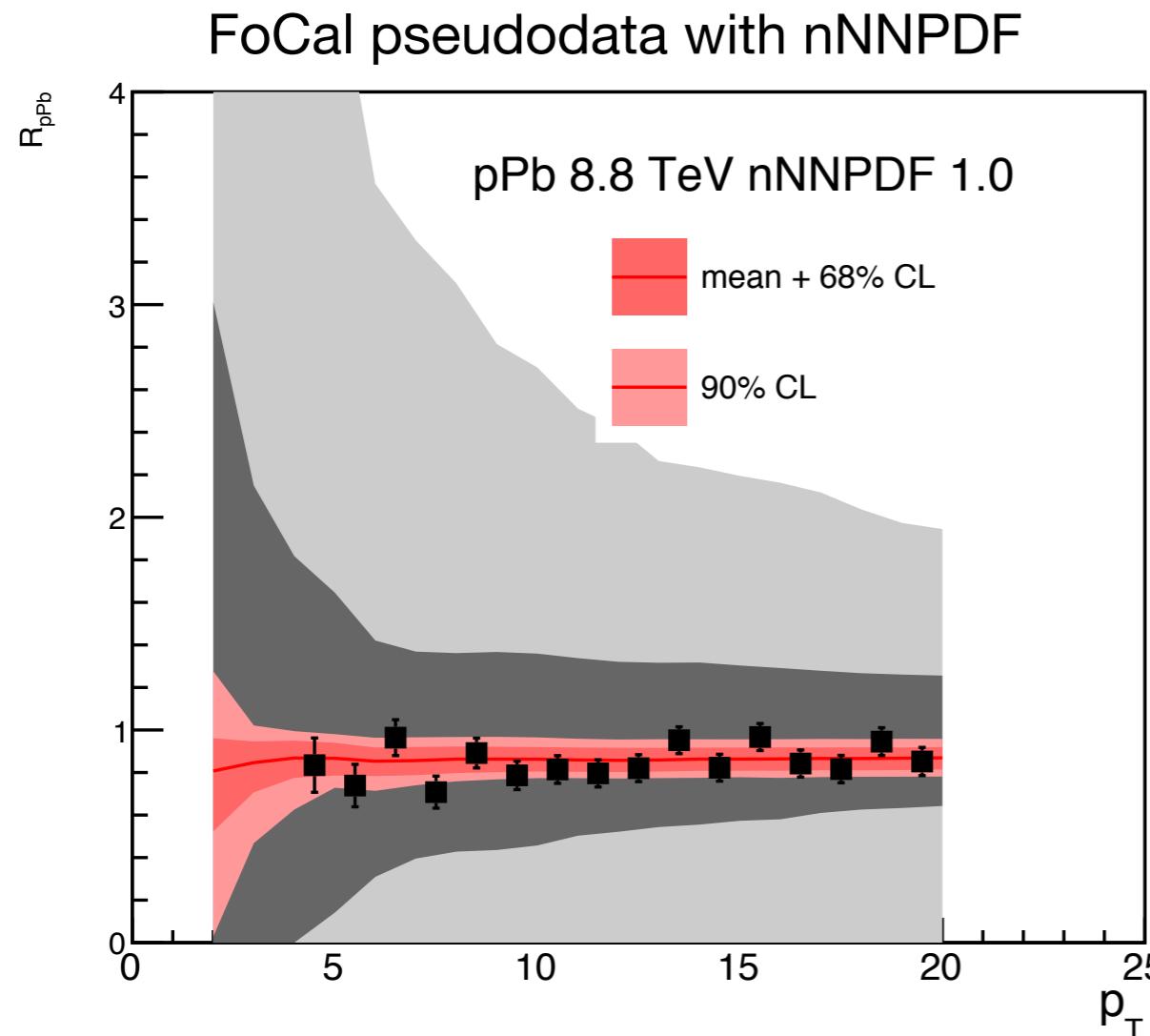
ALI-SIMUL-313019

- Systematic uncertainty $<20\%$ above $6 \text{ GeV}/c$
- Below $\sim 6 \text{ GeV}/c$, uncertainty rises due to increasing background
- Significant improvement (up to factor 2) on EPPS16 gluon PDF
- Similar improvement from open charm
 - Test factorization/universality



Impact on Recent nNNPDF

R. Khalek et al.,
arXiv:1904.00018



Recent nuclear PDFs: nNNPDF minimises theoretical assumptions

- No constraints for $x < 10^{-2}$ from DIS
- FOCAL provides significant constraints over a broad range: $\sim 10^{-5} - 10^{-2}$
- Outperforming significantly the EIC in this aspect



ALICE

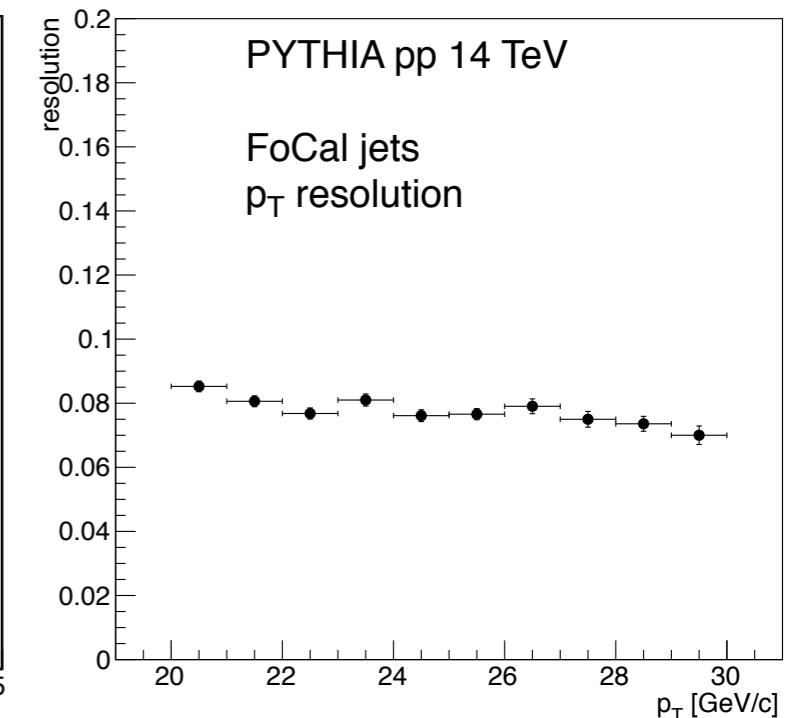
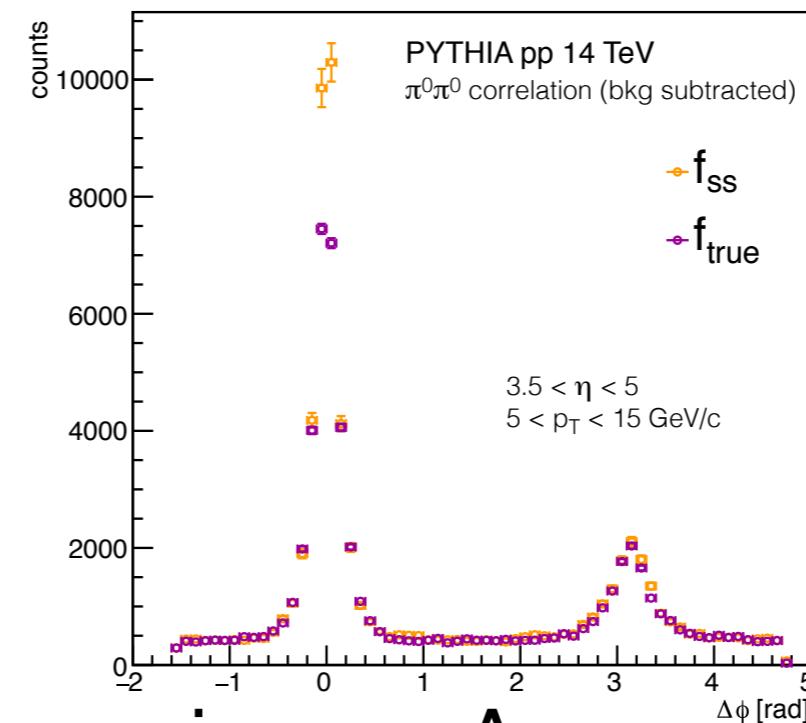
More FoCal Physics Topics

- low-x gluons (n)PDFs, saturation

- direct photon R_{pA}

- $\pi^0-\pi^0$ correlations

- dijet correlations



- ridge/flow-like phenomena in pp, pA

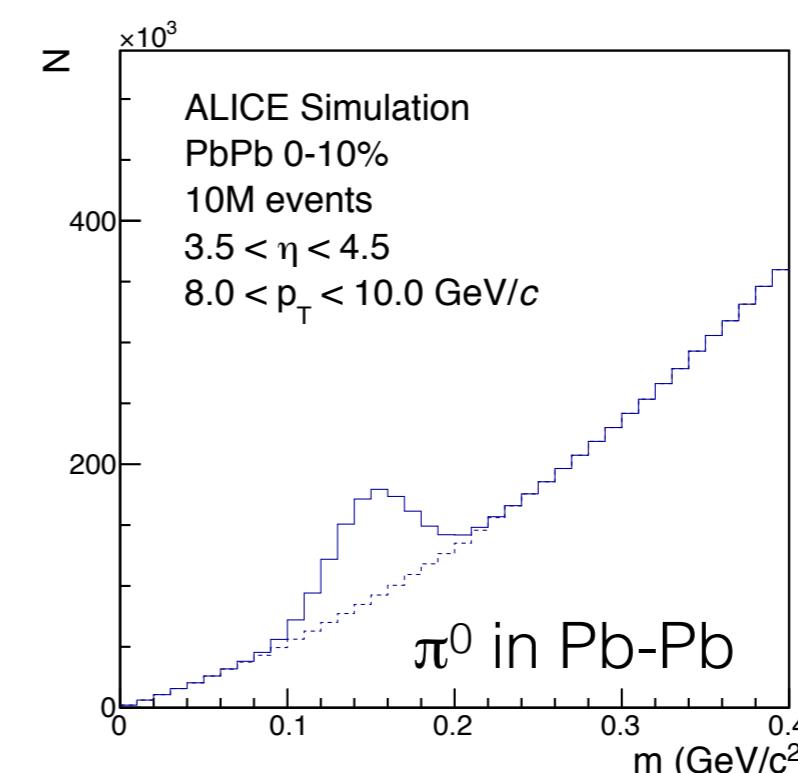
- correlations: forward photon – mid-rapidity hadron

- jet quenching at large y

- neutral pion R_{AA}

- miscellaneous

- reaction plane in Pb–Pb





ALICE

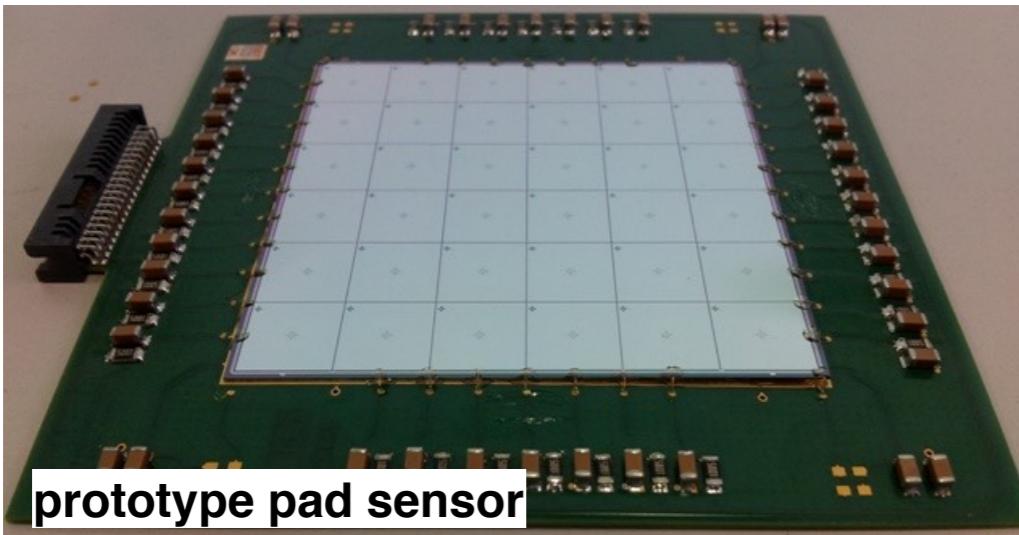
Extensive R&D Program Ongoing

- 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.)

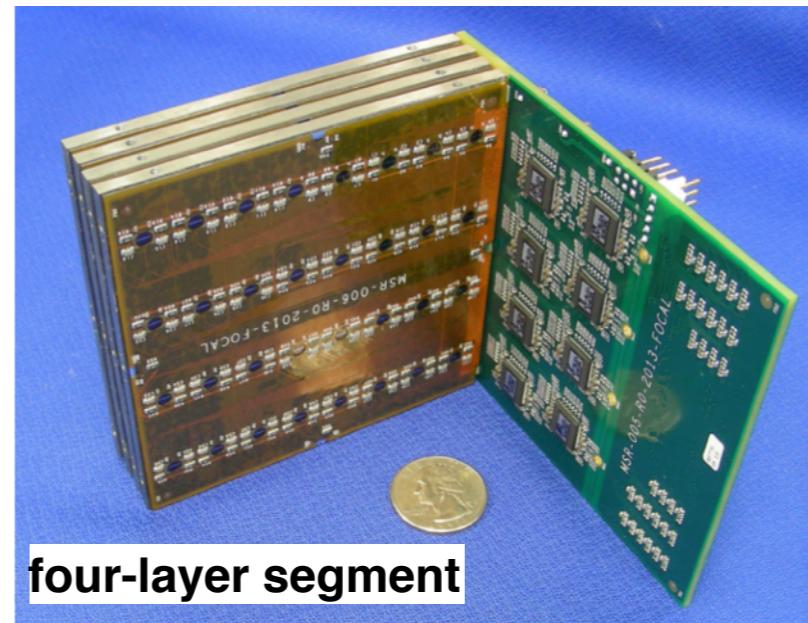


ALICE

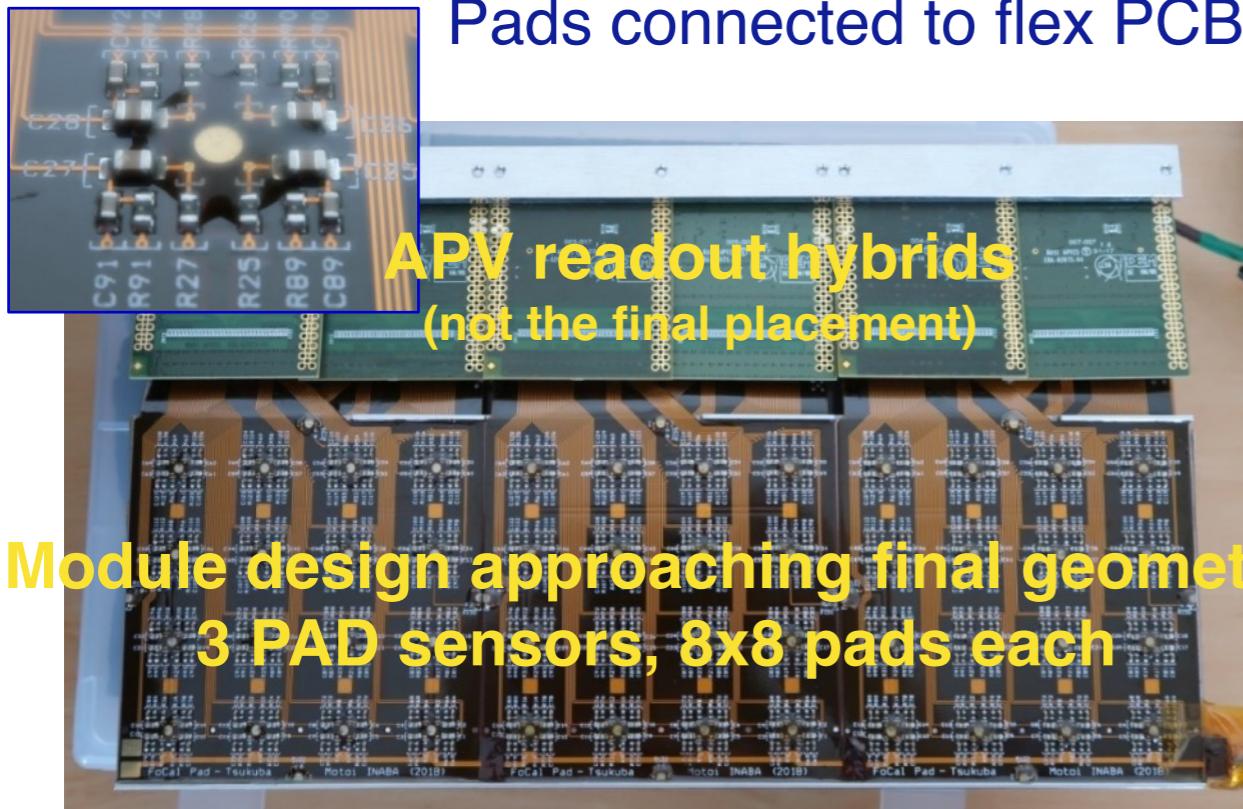
Pad Prototypes



prototype pad sensor



four-layer segment



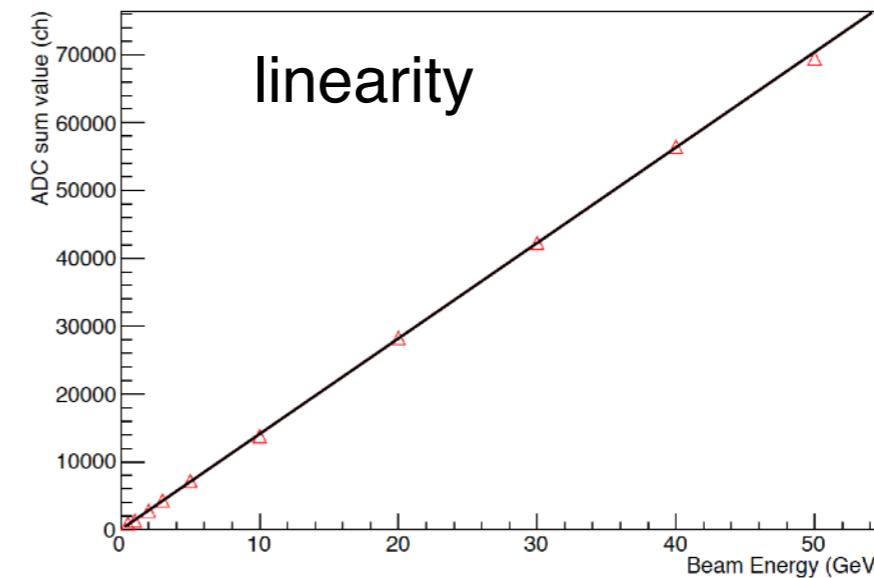
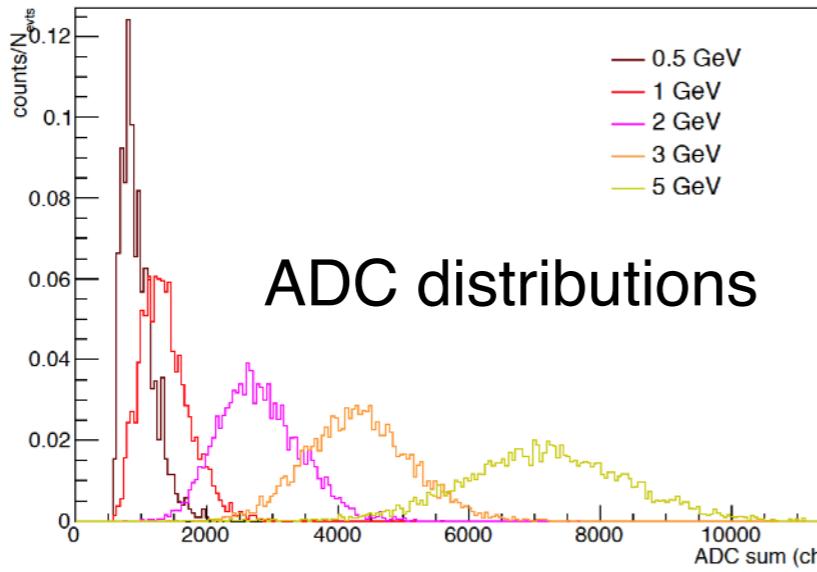
Module design approaching final geometry
3 PAD sensors, 8x8 pads each



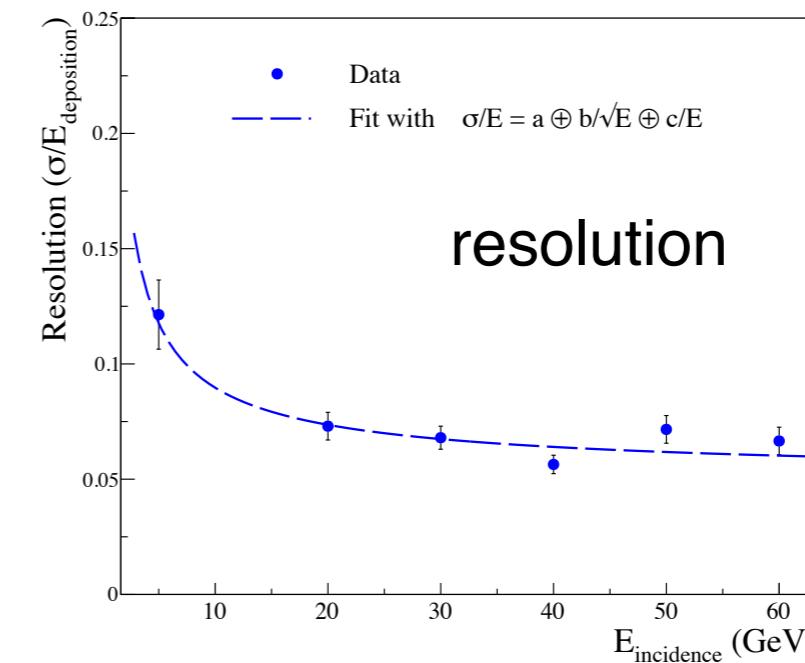
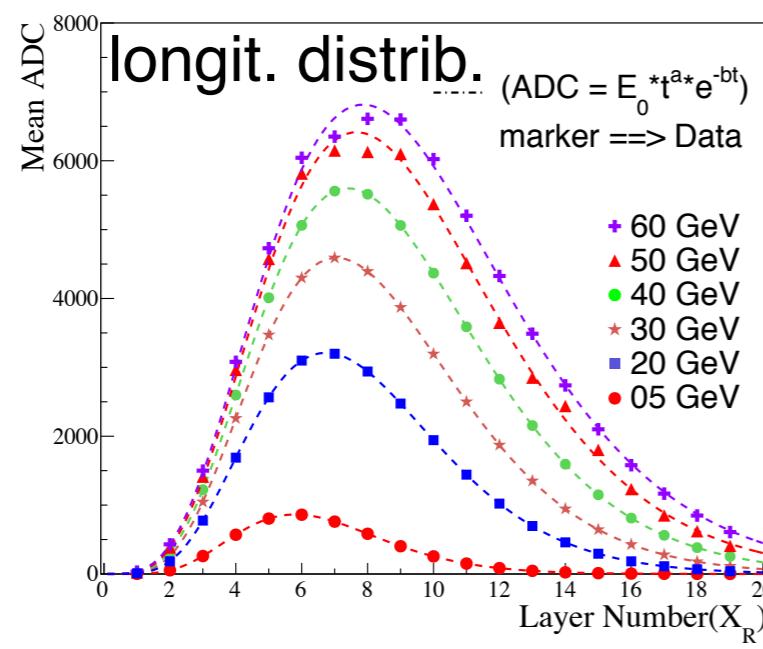
Lots of experience gained over past years
Most recent prototype is close to final design

Large activity in Japan (Tsukuba)
and India (VECC, BARC)

W/Si-Pad Test-Beam Performance



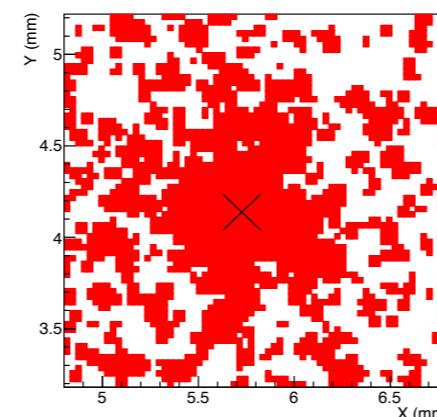
ORNL/Japan Pad prototype with APV/SRS readout



India Pad prototype with custom chip (MANAS/ANUSANSKAR)

test beam performance agrees with simulations
papers on instrumentation in preparation

Towards an Extremely Granular Calorimeter



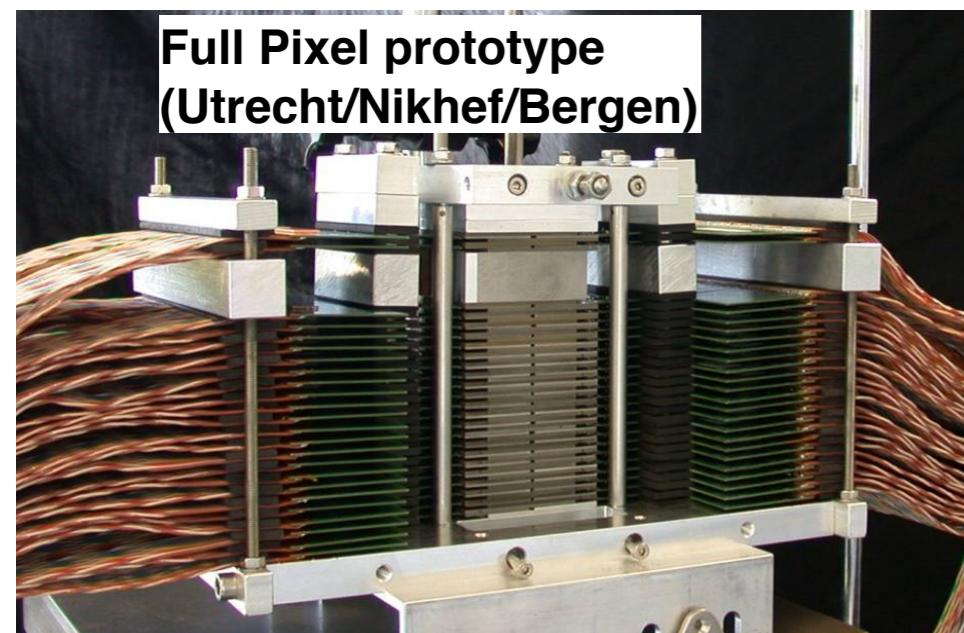
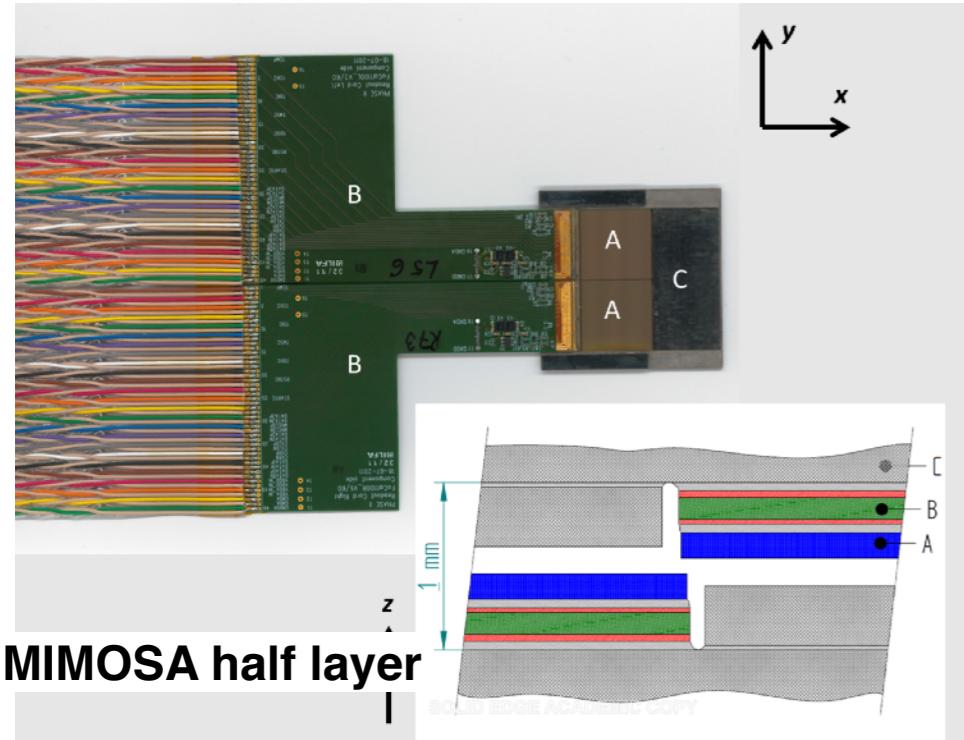
single electron shower
measurement (244 GeV)
in CMOS sensor

~ CMS-HGCAL
pad size (0.5cm^2)

Pixel Prototypes

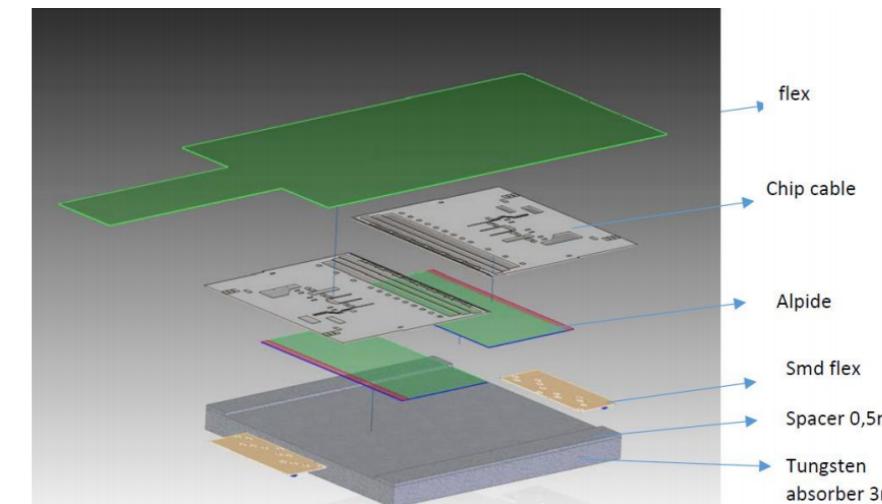
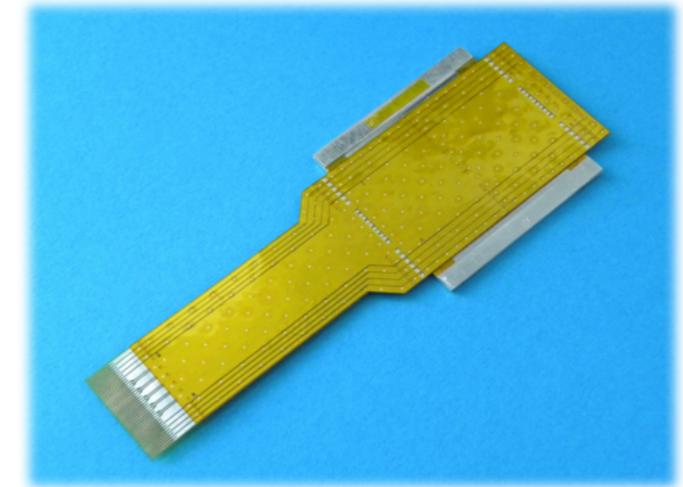
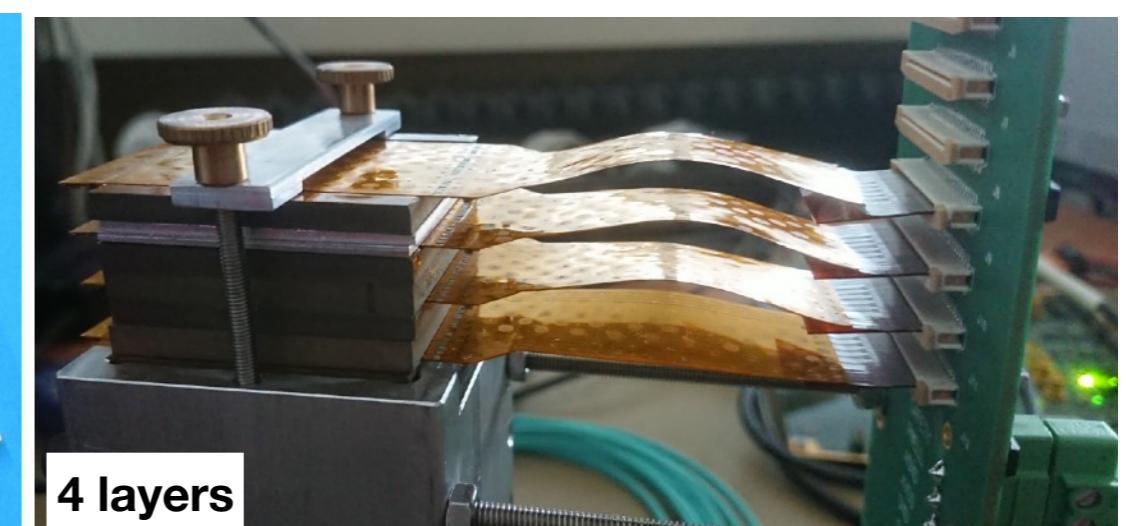
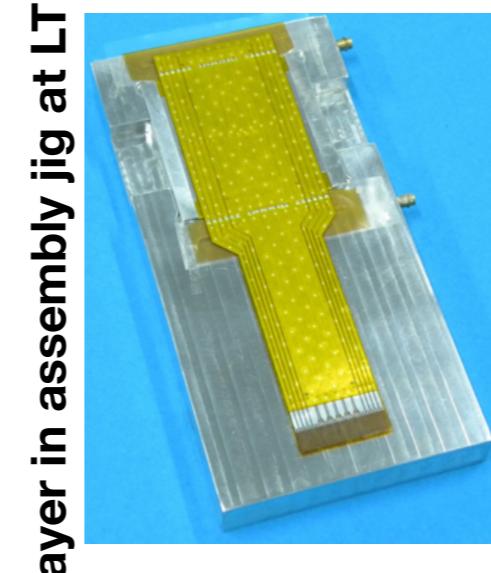
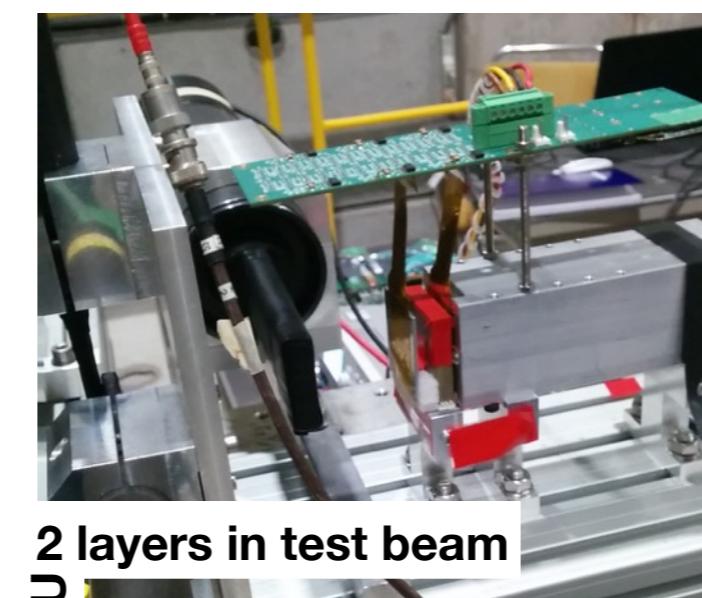
Full pixel - MIMOSA tower

ALPIDE developments



24 layers – 39M pixels

JINST 13 (2018) P01014

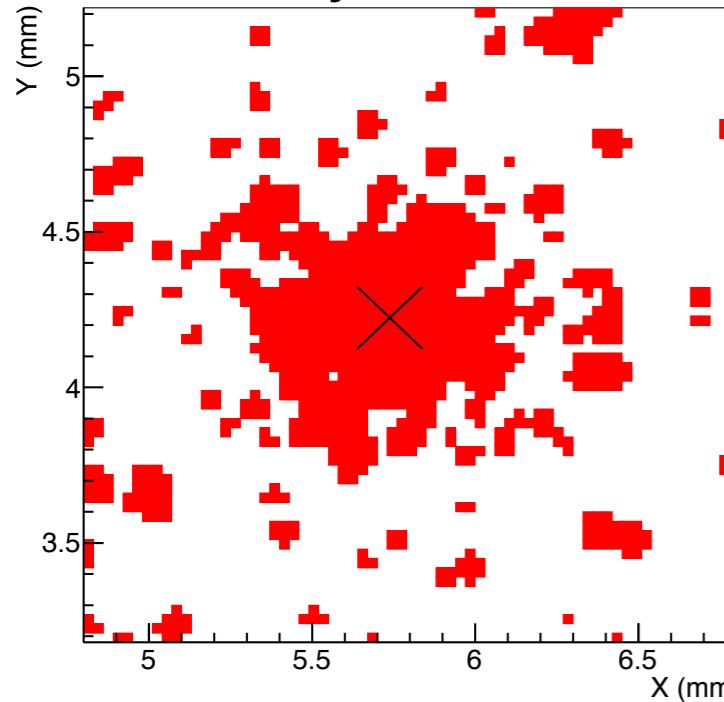




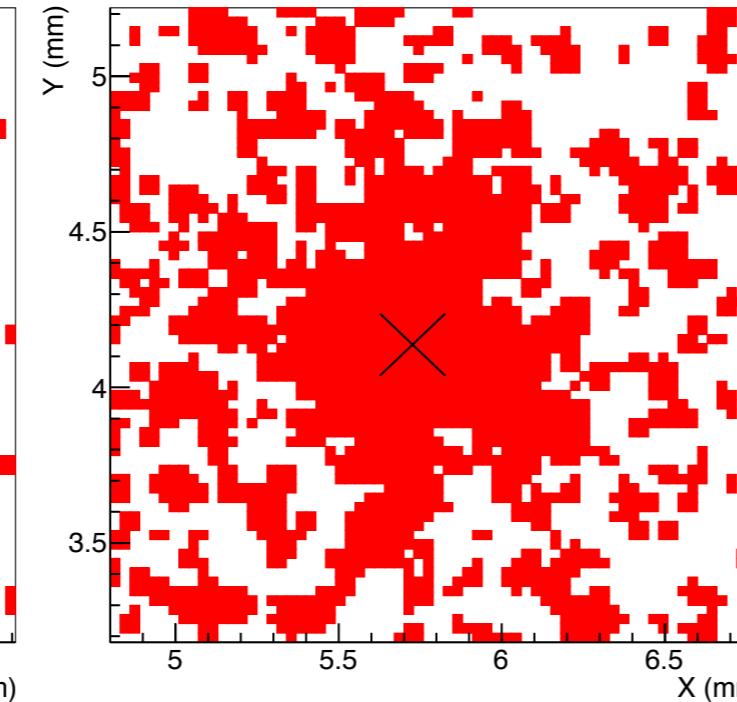
ALICE

Digital Pixel Test-Beam Results

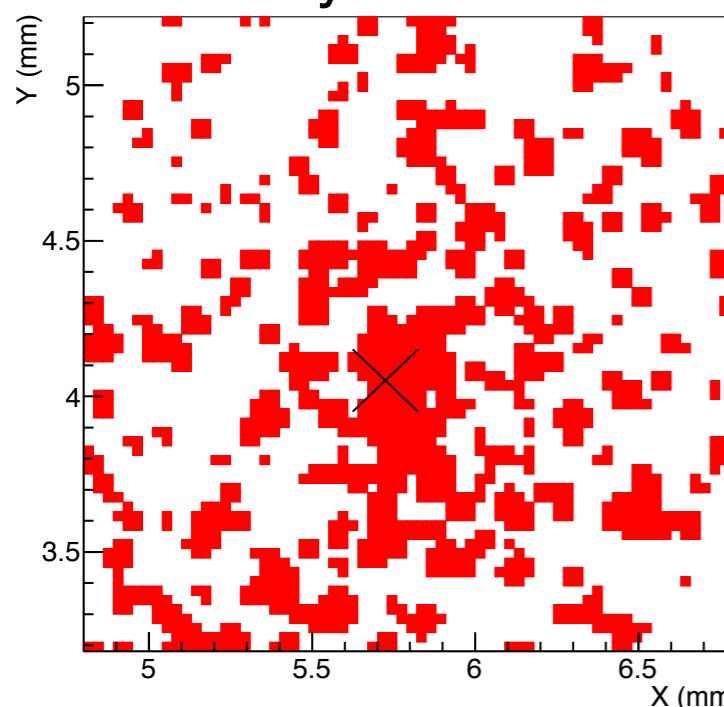
layer 4



layer 8



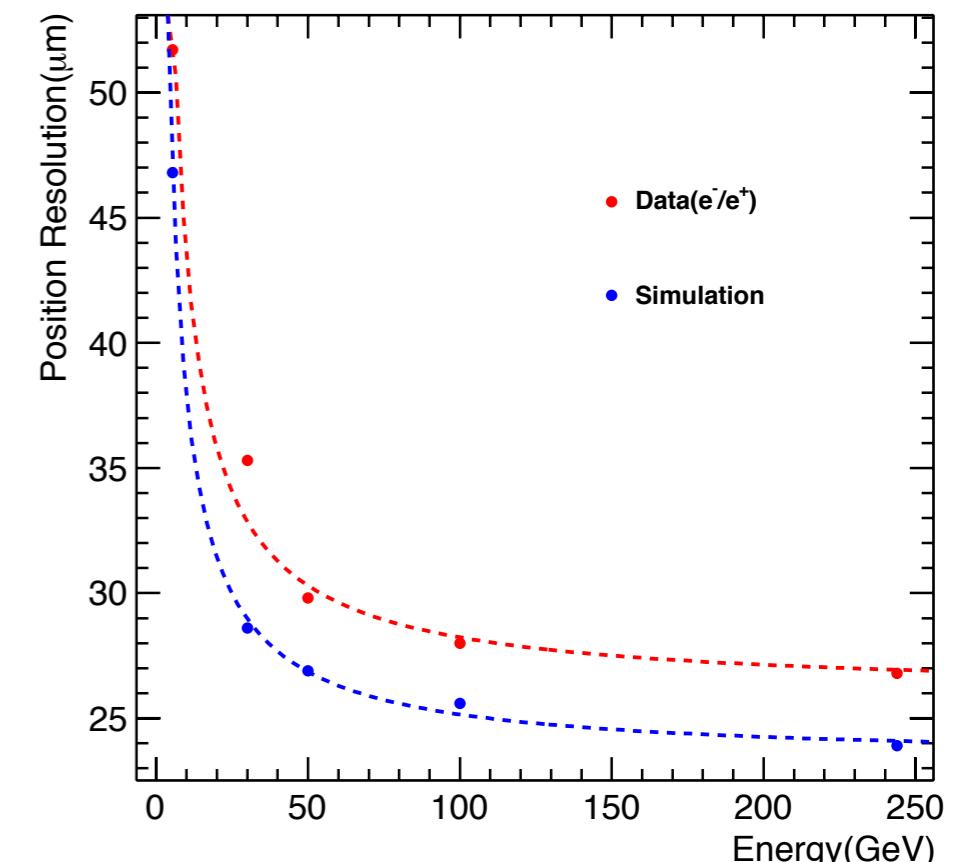
layer 12



244 GeV e^- (@ SPS)
single-event display
in pixel calorimeter

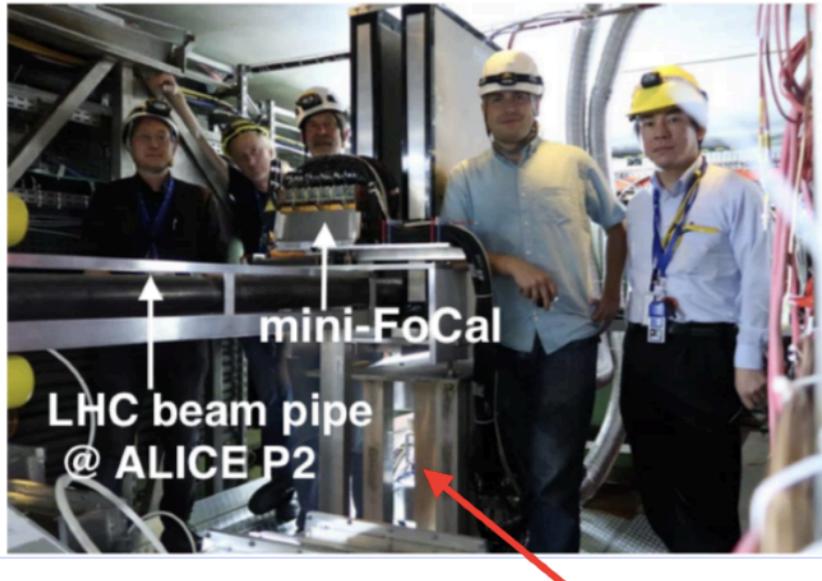
detailed reconstruction
of em showers possible

shower-position resolution



can also provide excellent
two-shower separation

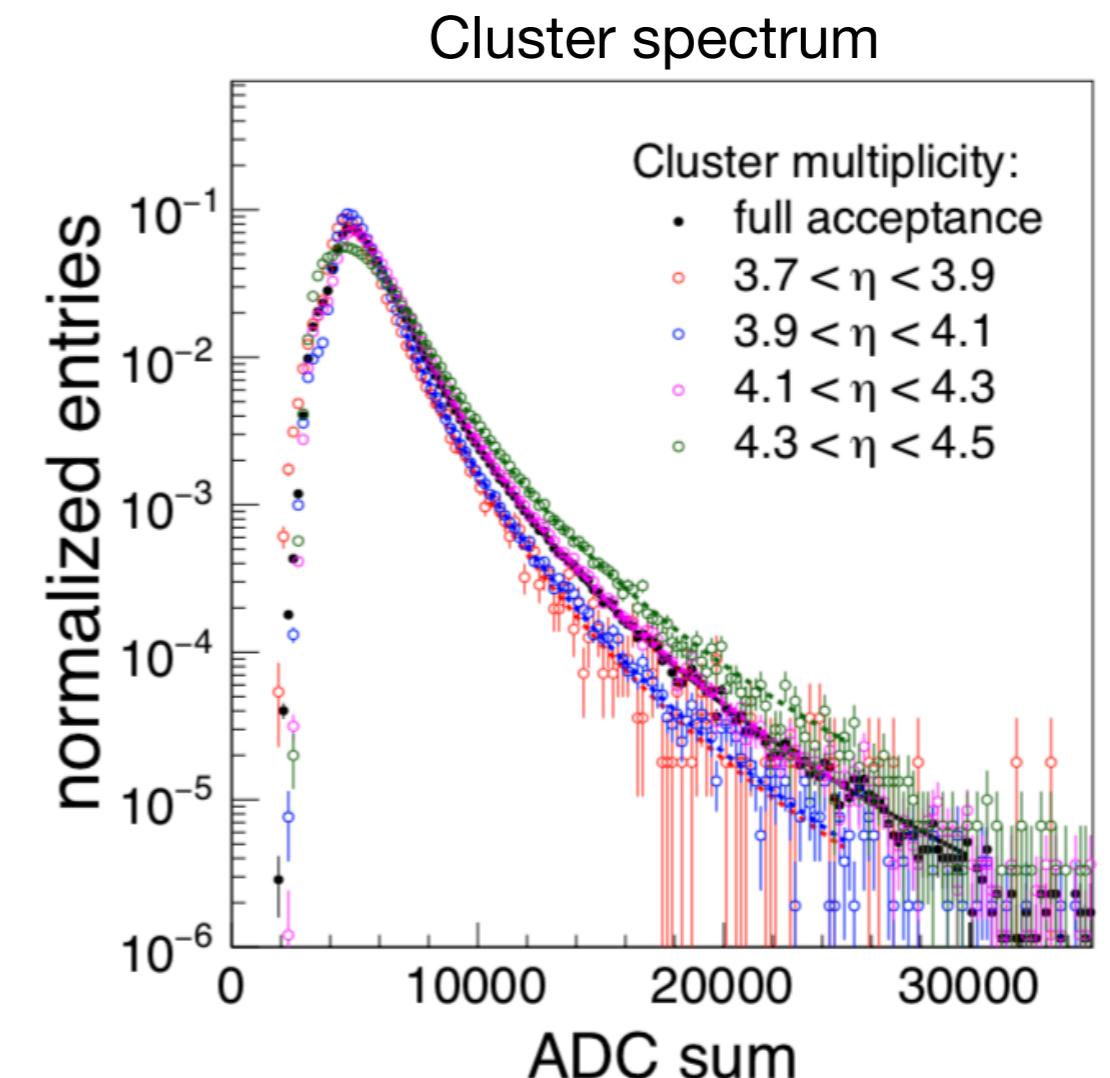
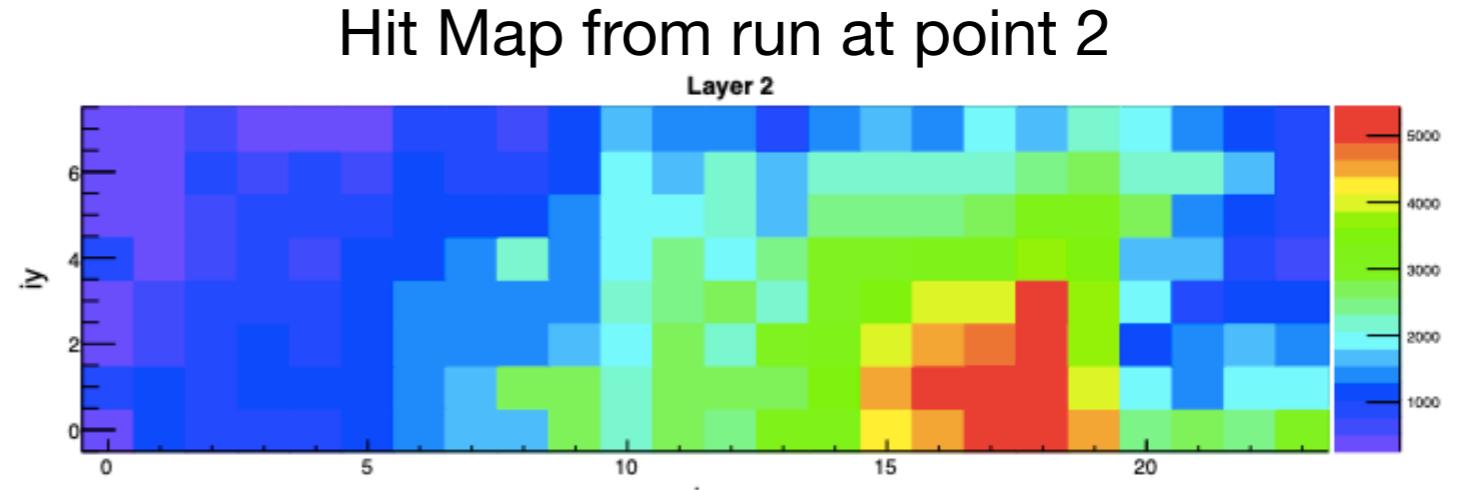
FOCAL prototype in ALICE



SRS system under the table

Goal: measure/verify backgrounds in situ with 13 TeV collisions

- Analysis ongoing
- Calibration based on test beam
- Comparison to MC



Summary

- Large uncertainties in nPDFs at low x
 - revisiting theoretical assumptions
- 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 with prototypes
 - FoCal will be a significant step beyond state of the art in calorimetry

Backup Slides

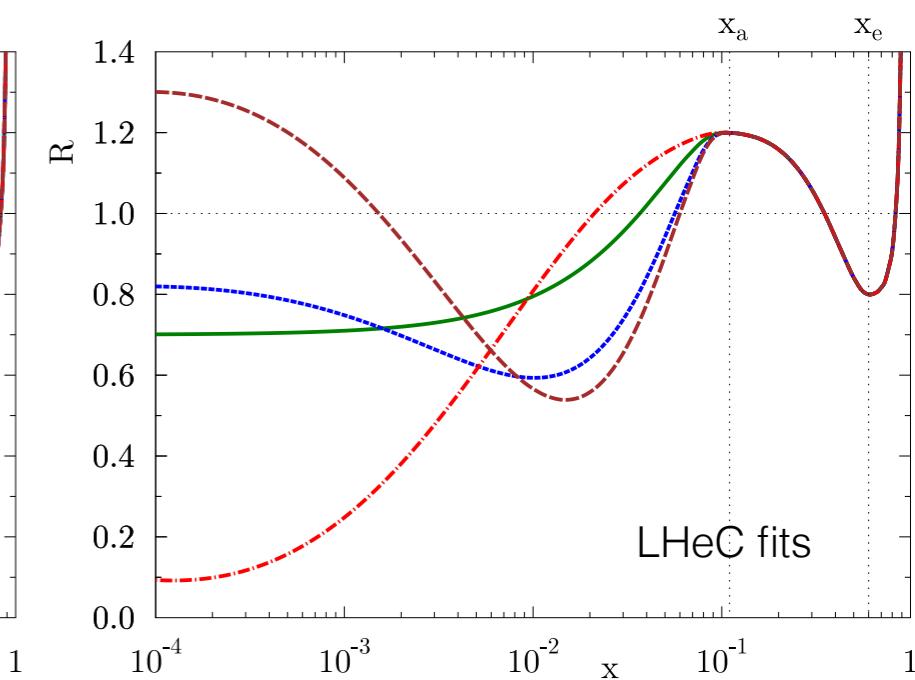
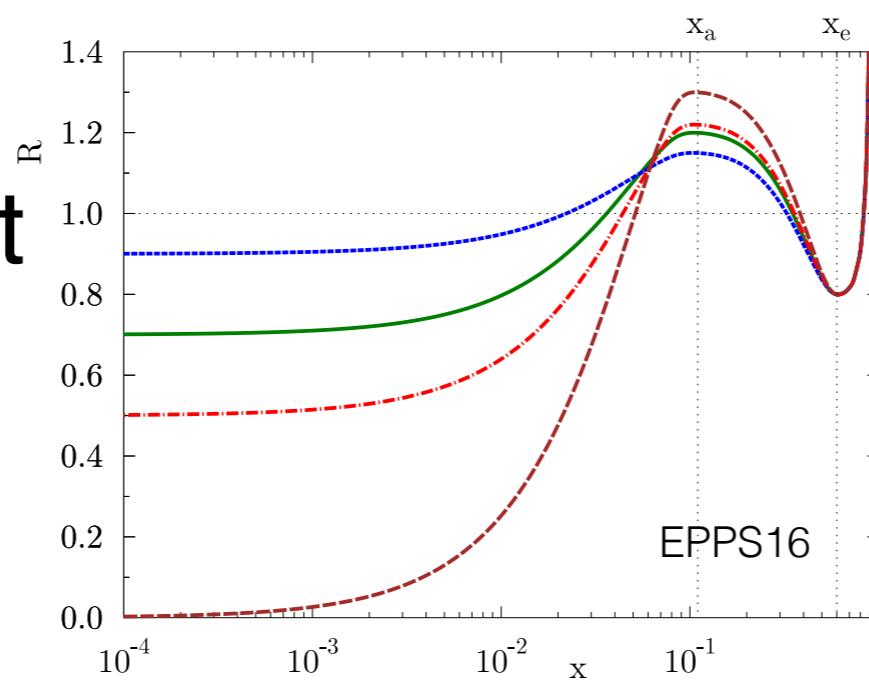
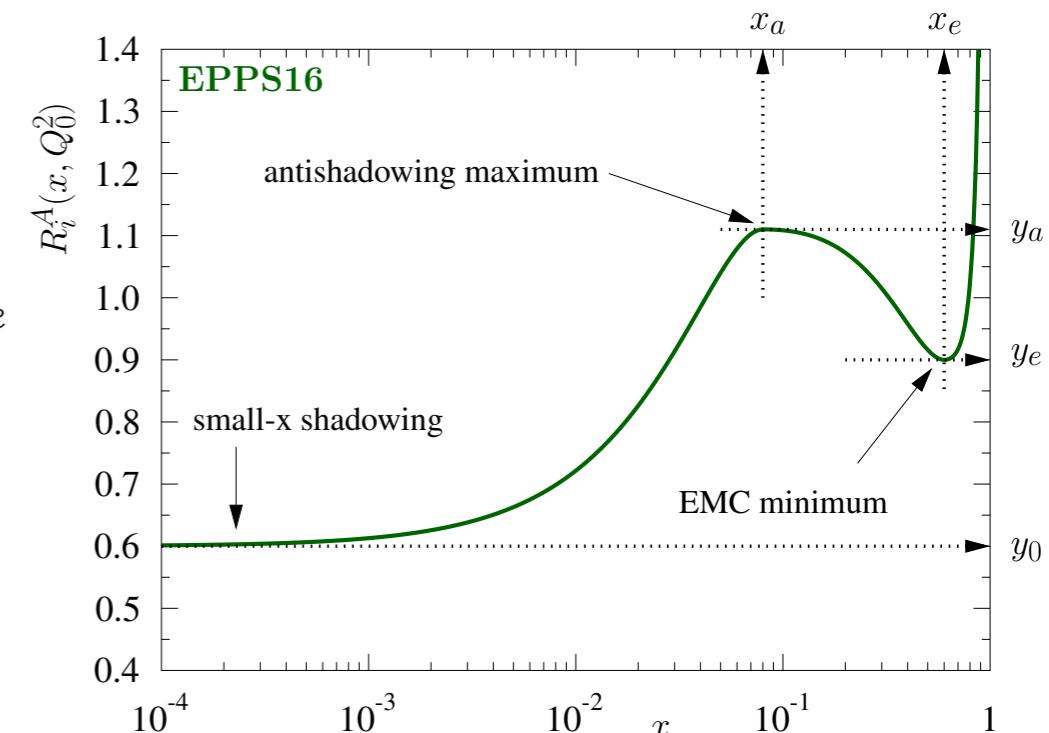
x-Dependence of PDF modification

EPPS16, EPJC 77, 163

$$R_i^A(x, Q^2) = \begin{cases} a_0 + a_1(x - x_a)^2 & x \leq x_a \\ b_0 + b_1x^\alpha + b_2x^{2\alpha} + b_3x^{3\alpha} & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2x)(1 - x)^{-\beta} & x_e \leq x \leq 1 \end{cases}$$

- parameterisation of R_A
 - shape similar to EPS09
 - at low x leads to “plateau” in $\log(x)$

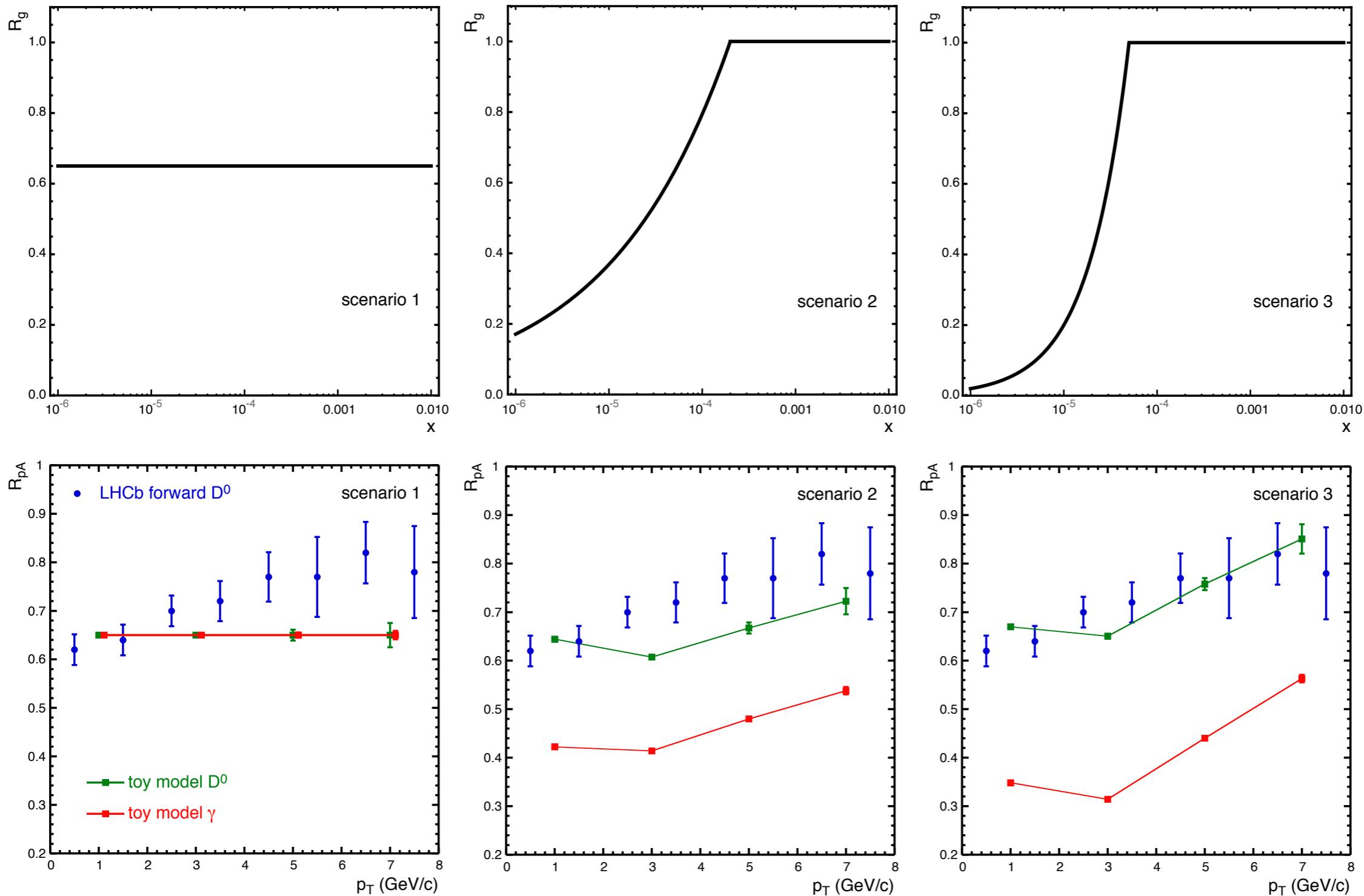
- likely not sufficient
 - more flexible PDF used for LHeC estimates



Influence of x Dependence

parameterise nuclear modification of gluon PDFs

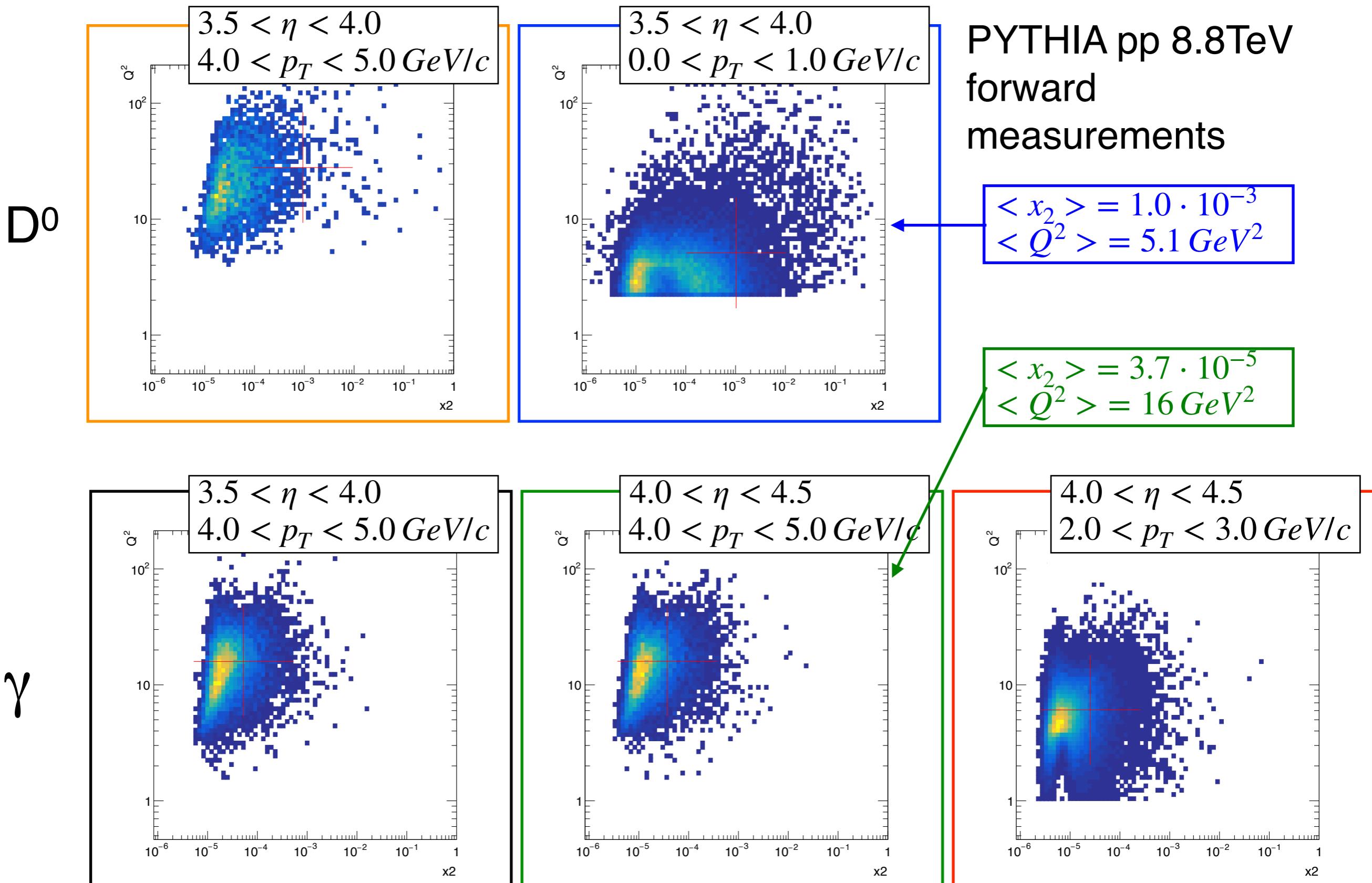
Simple Model based on PYTHIA –
no proper Q^2 dependence



different x-sensitivity of probes
reflected in nuclear modification factor

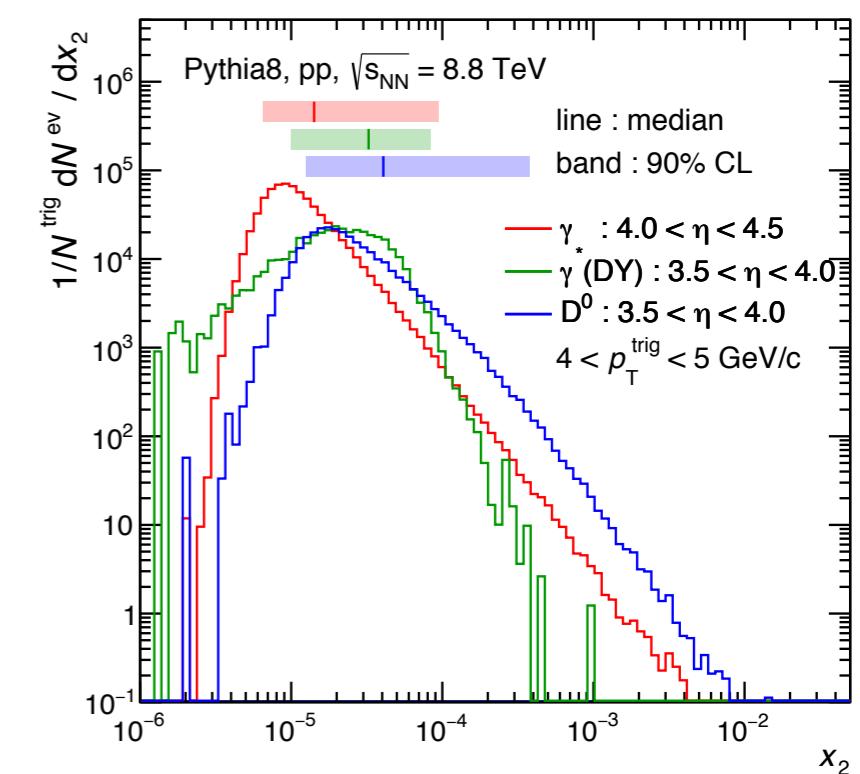
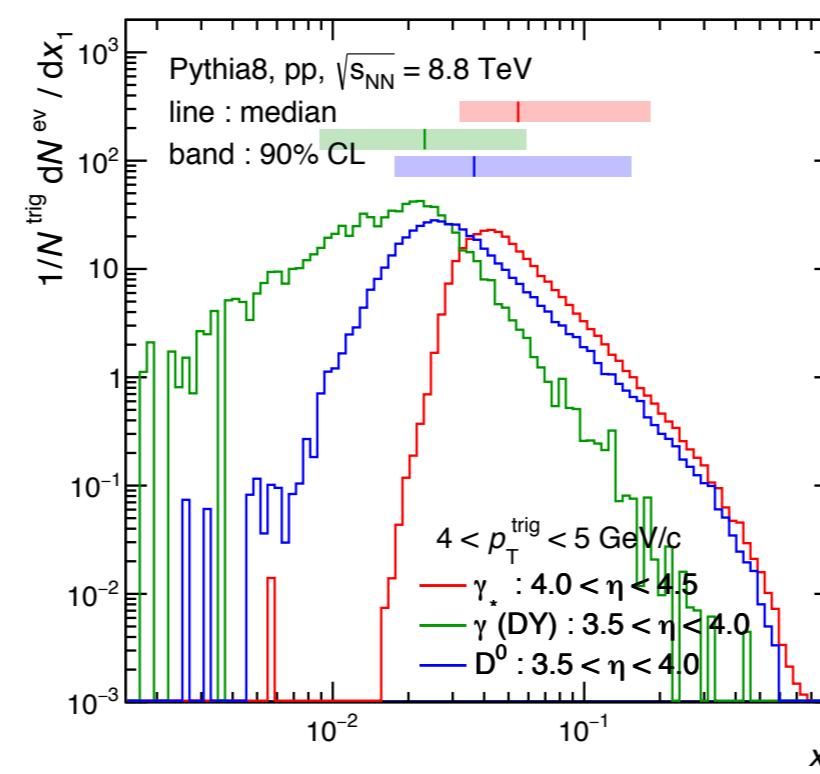
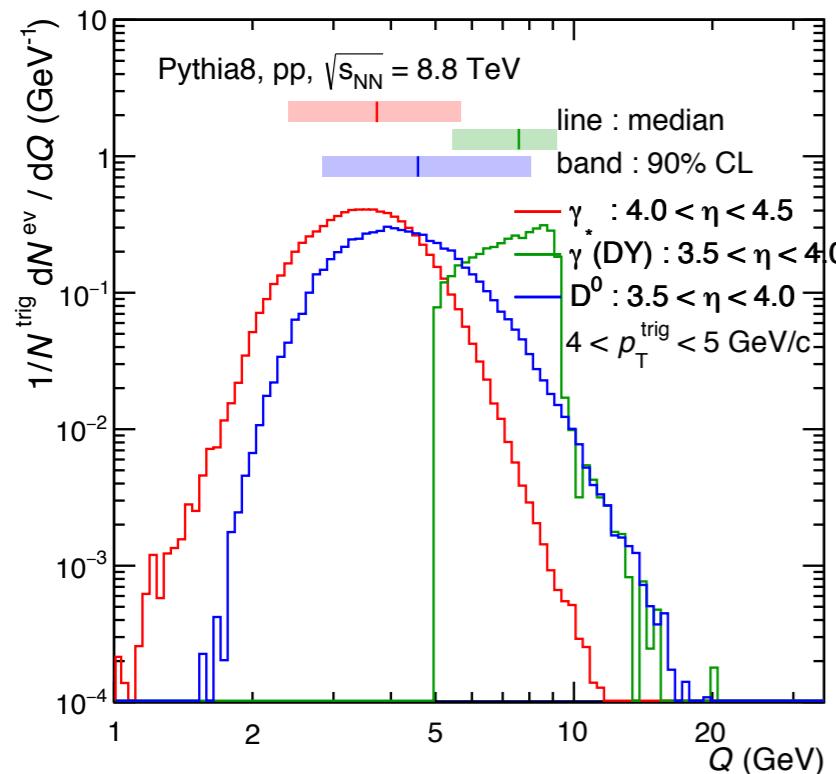
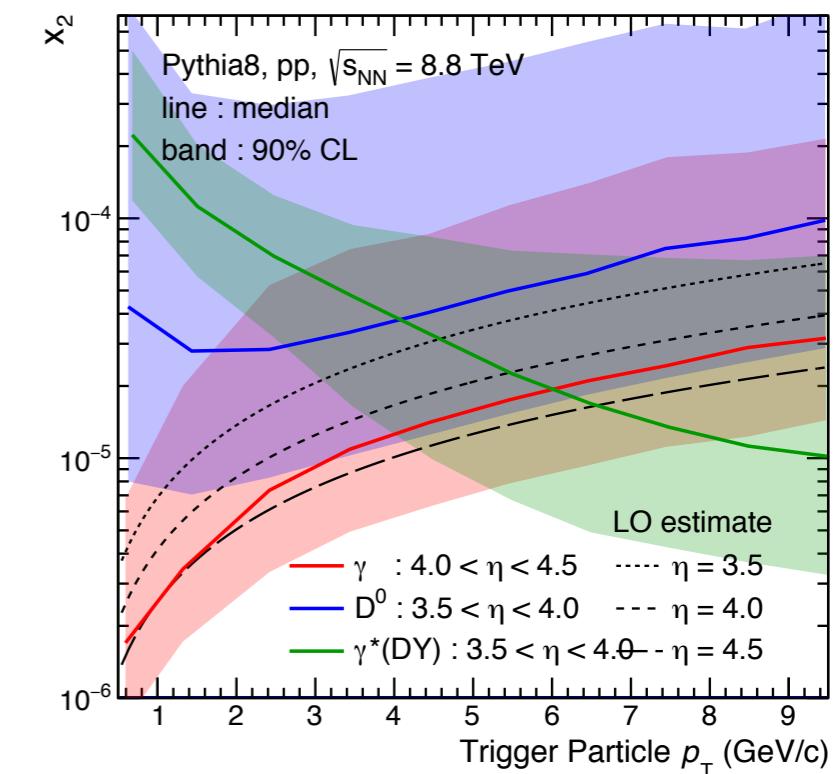
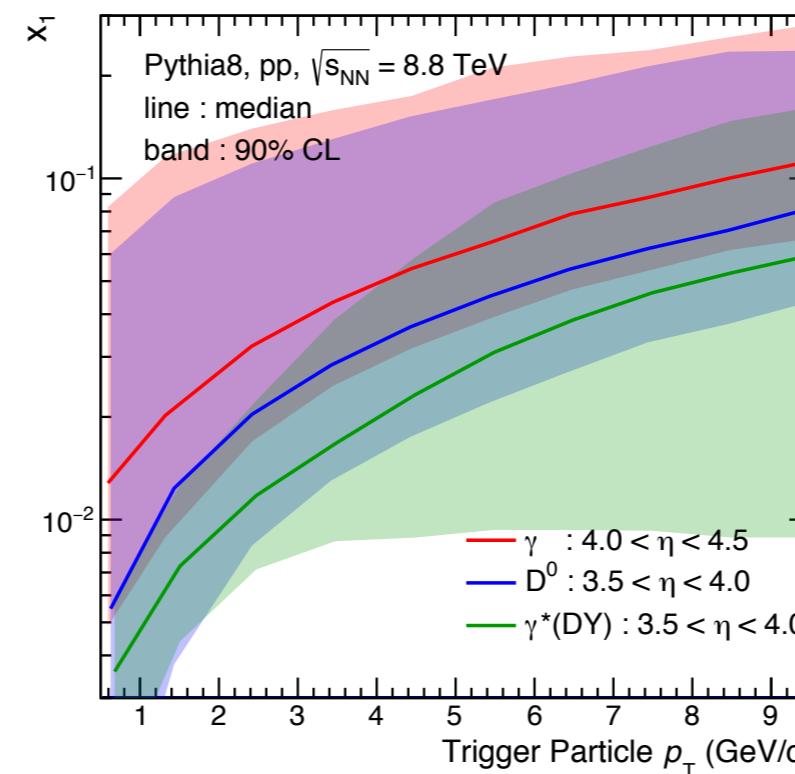
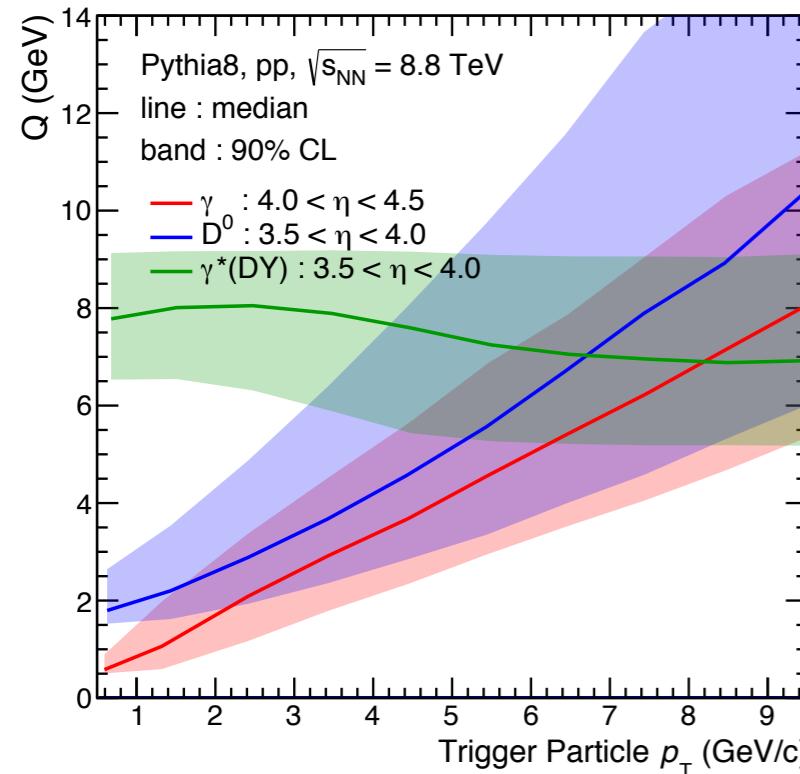
$$R_{pA} = \frac{\int dx d\sigma/dx(p_T, y) \cdot R_g(x)}{\int dx d\sigma/dx(p_T, y)}$$

x - Q^2 -Sensitivity



x - Q^2 -Sensitivity of Drell-Yan

PYTHIA pp 8.8TeV forward measurements



Main Physics Motivation for FoCal (A Hierarchy)

1. prove or refute gluon saturation

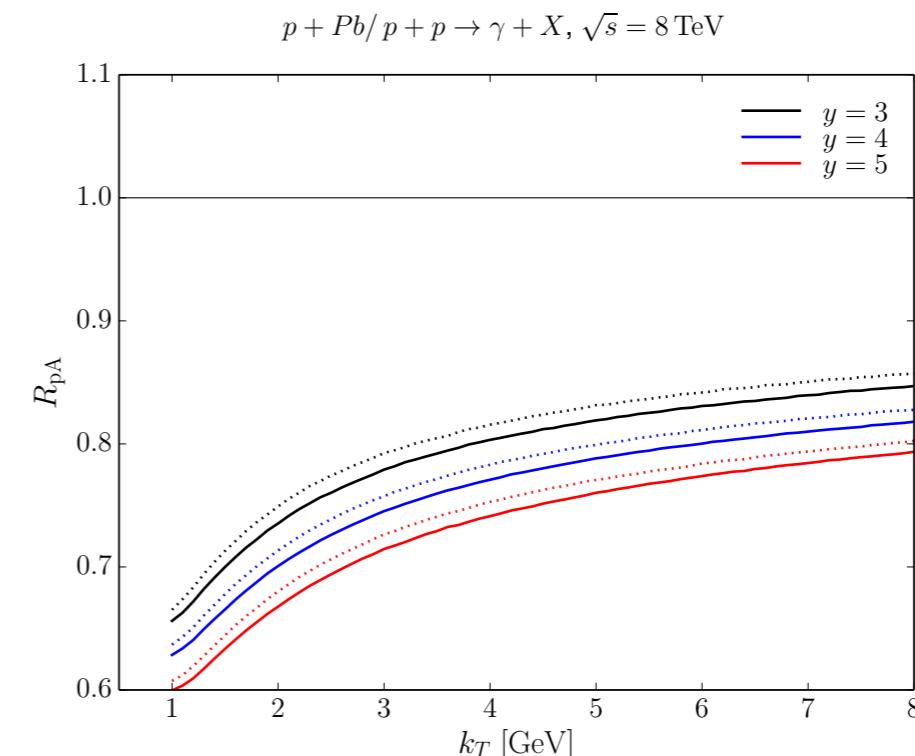
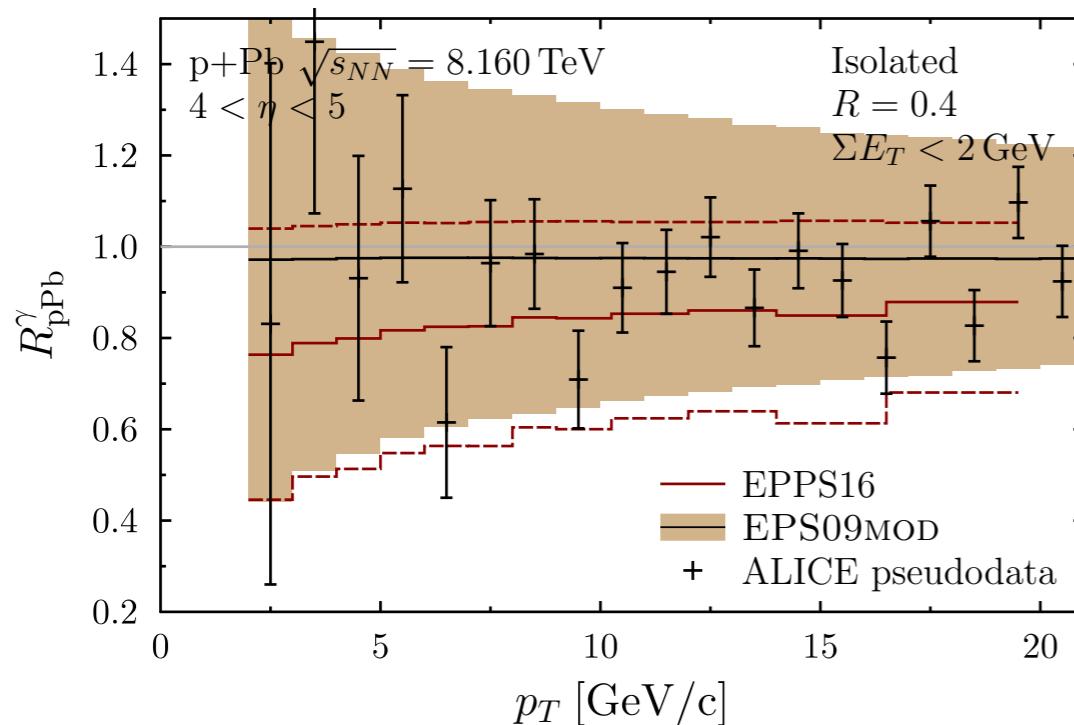
- compare saturation models with linear QCD
- depends on saturation model implementation and flexibility of PDF analytical shape

2. show invalidity of linear QCD at low x

- can all potential measurement outcomes be absorbed in a modified PDF?

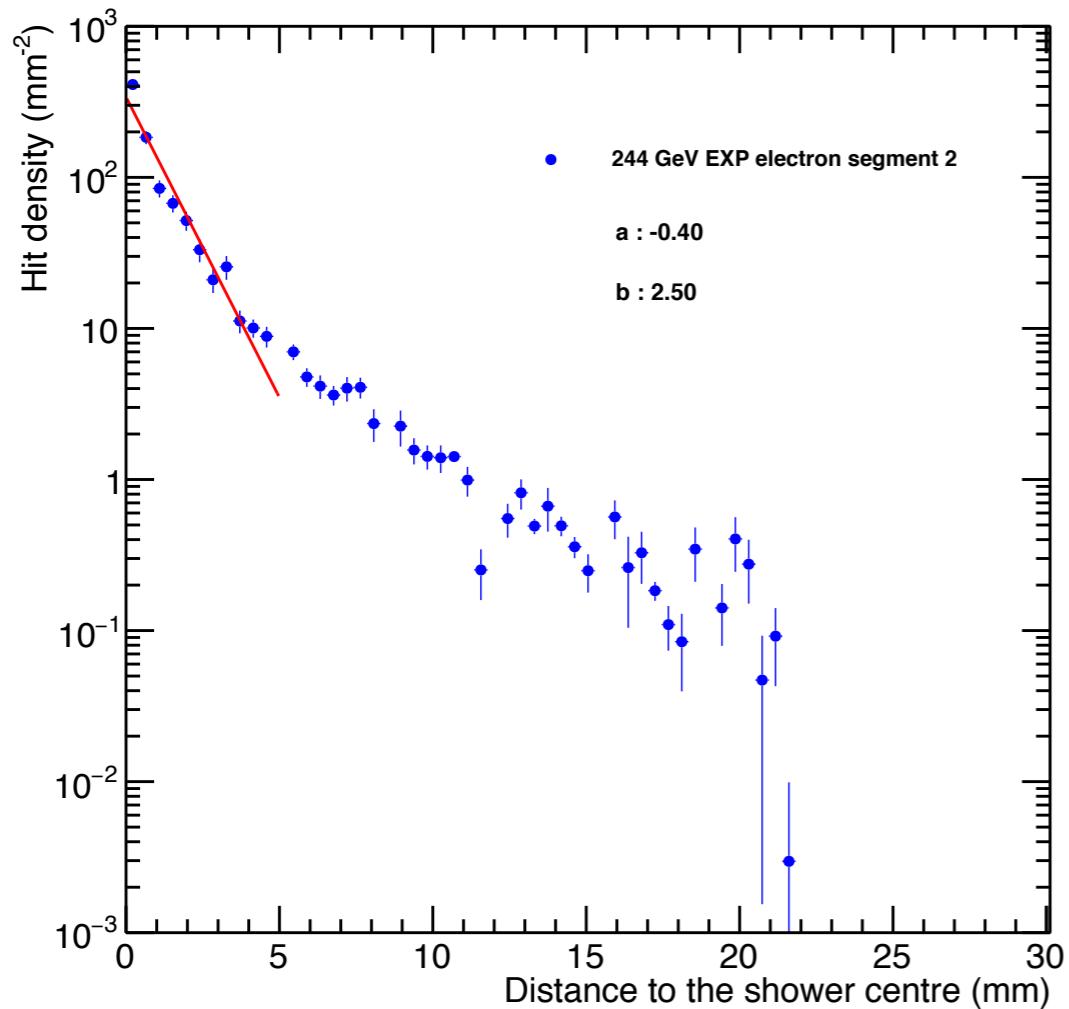
3. constrain the PDFs at low x

- 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?)

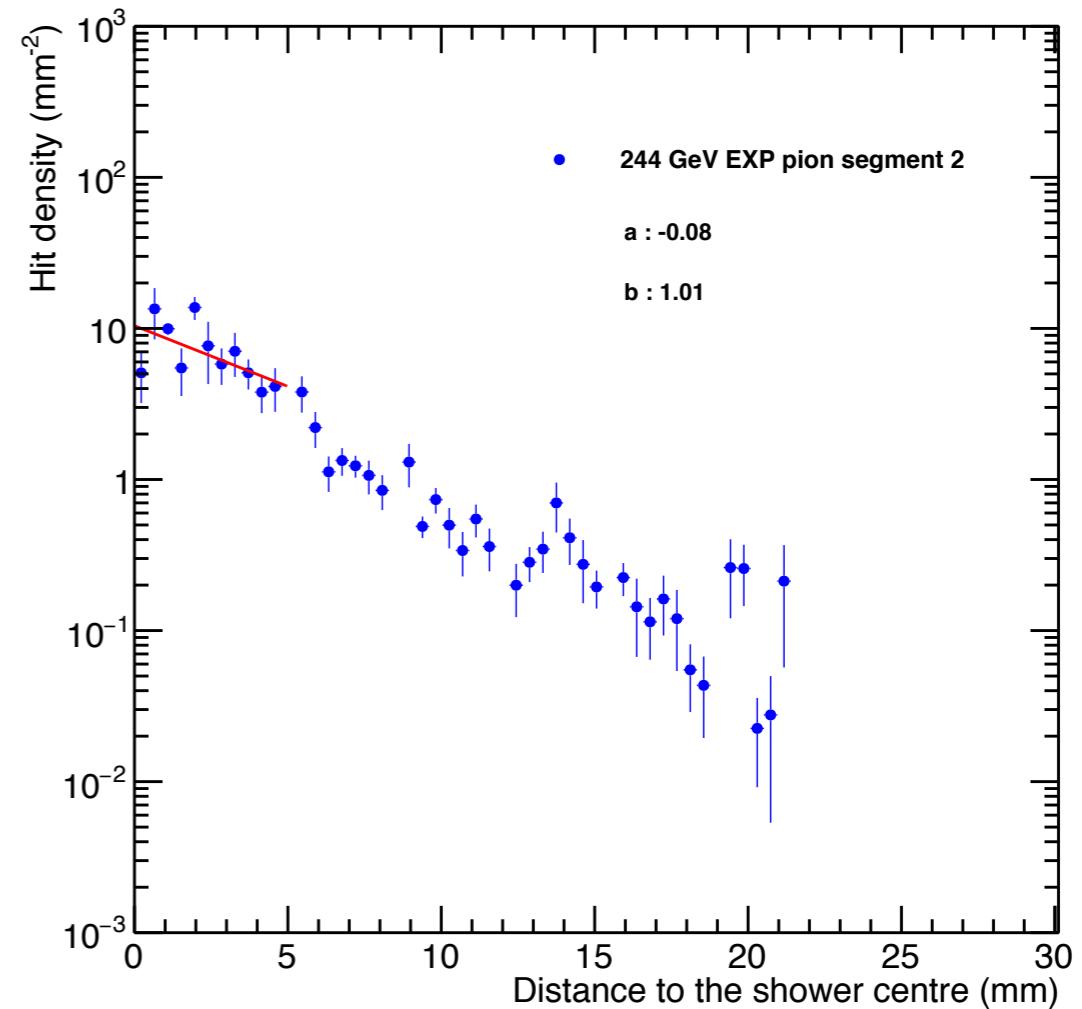


Pixel (HGL) R&D Results: Single Event Profiles

electron



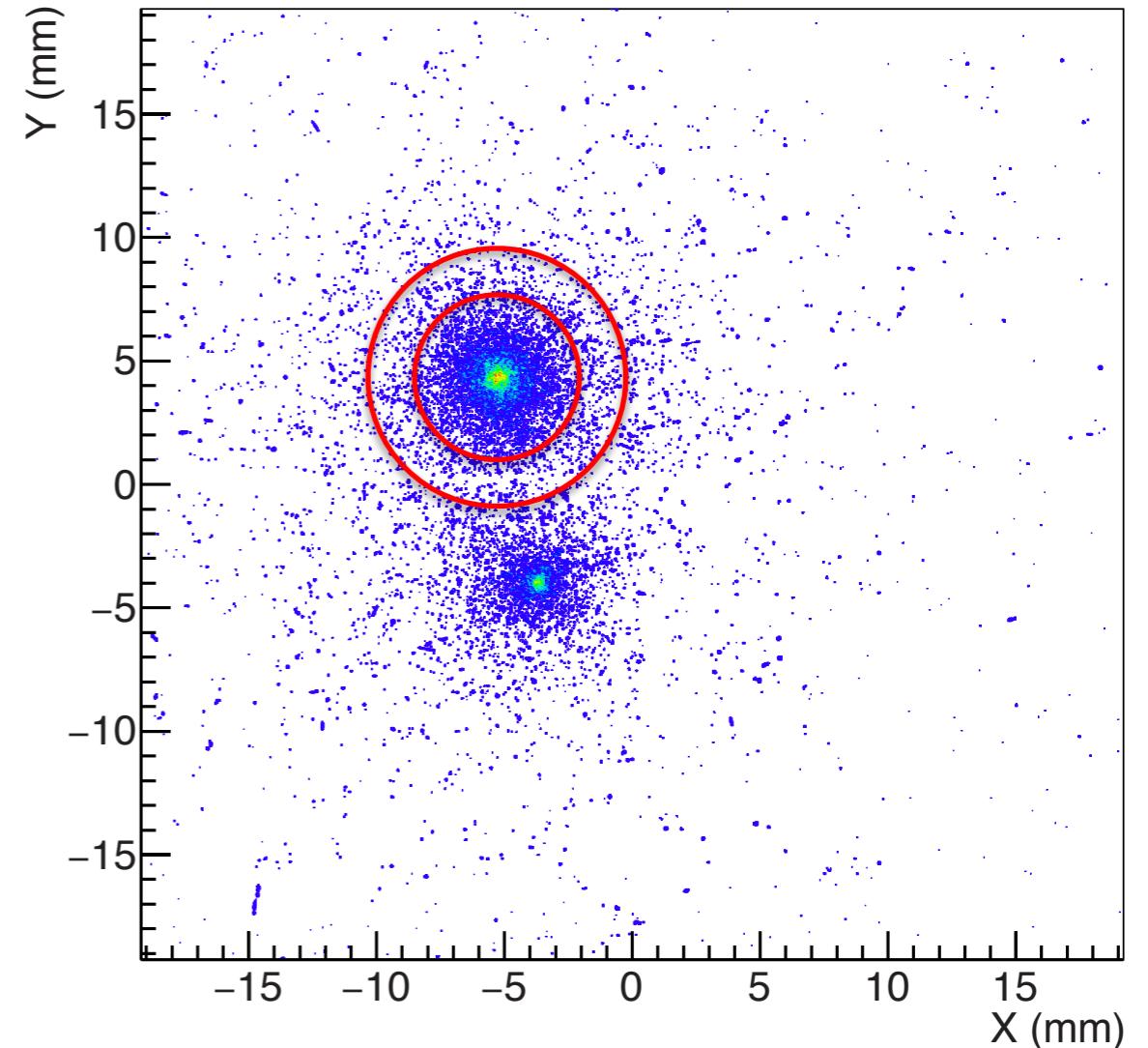
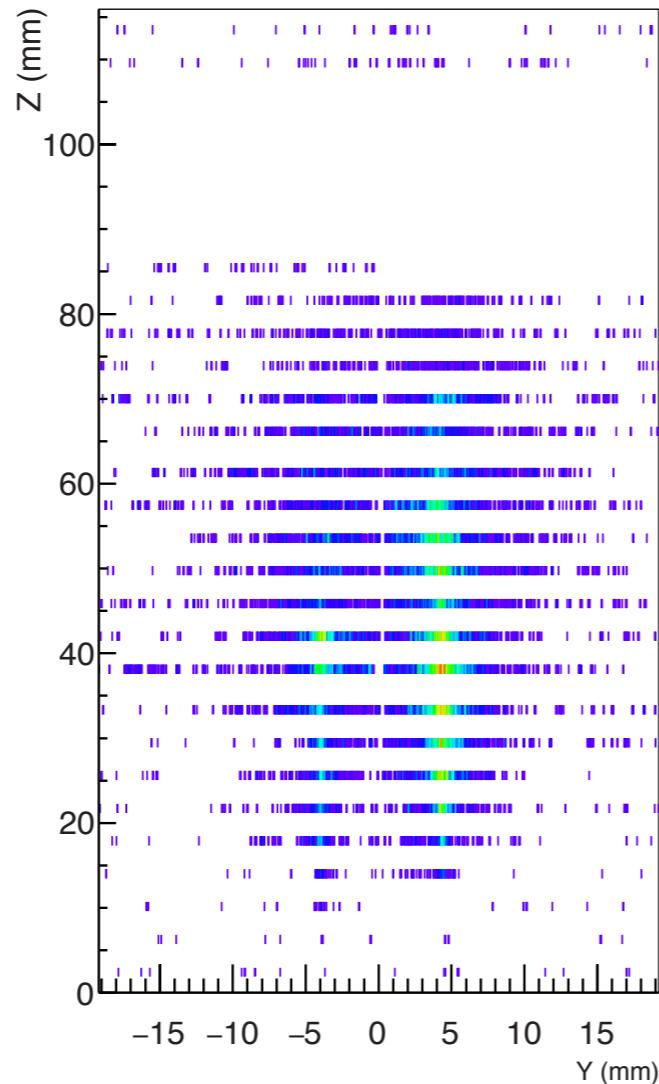
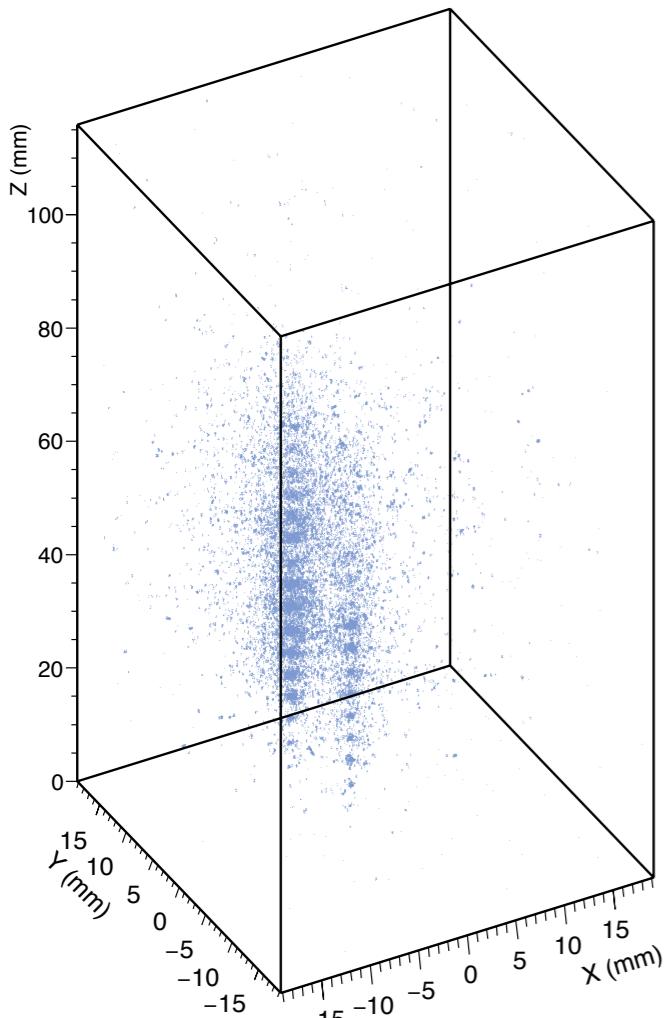
pion



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

Two Shower Separation

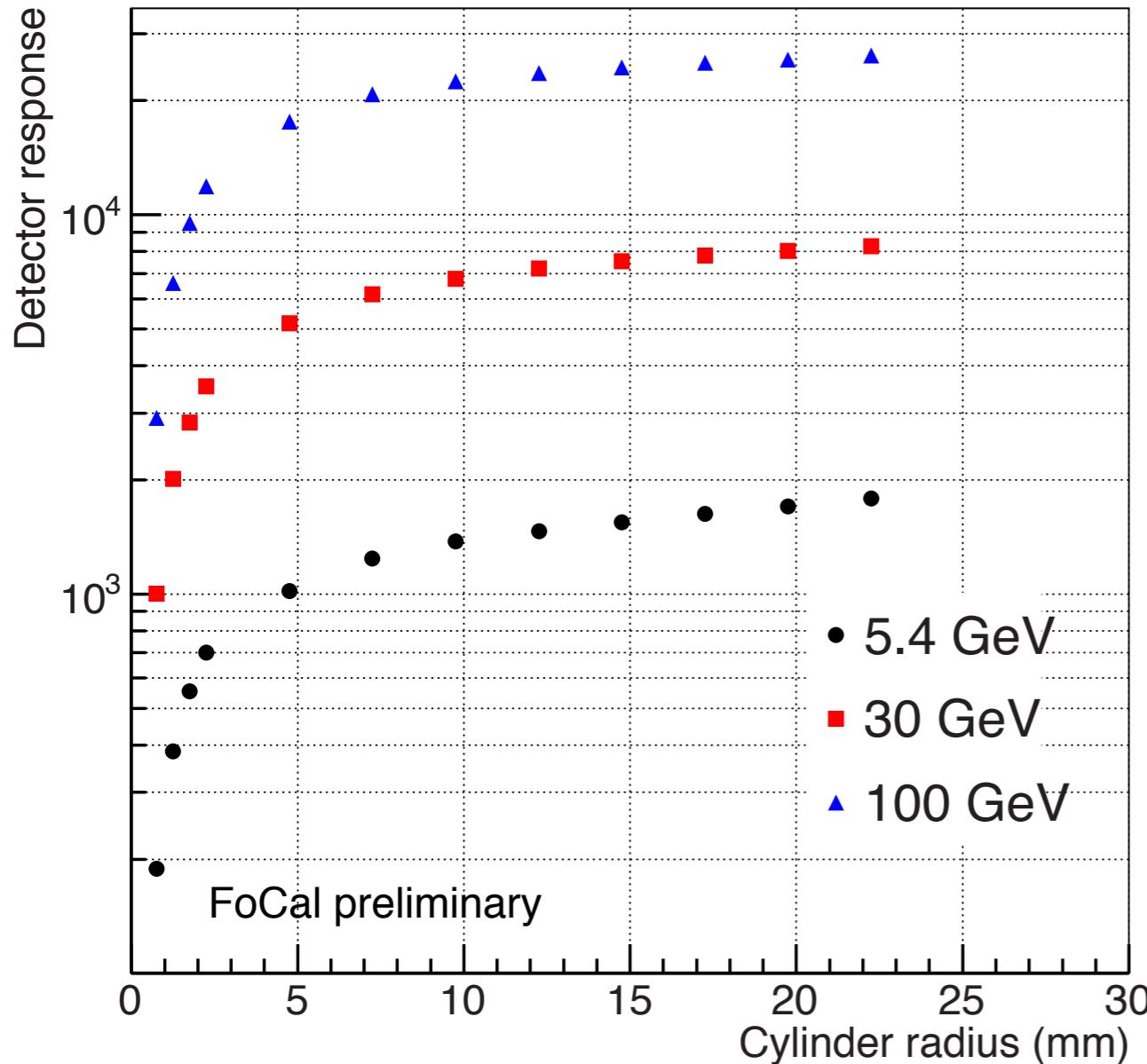
display of single event (with pile-up) from 244 GeV mixed beam



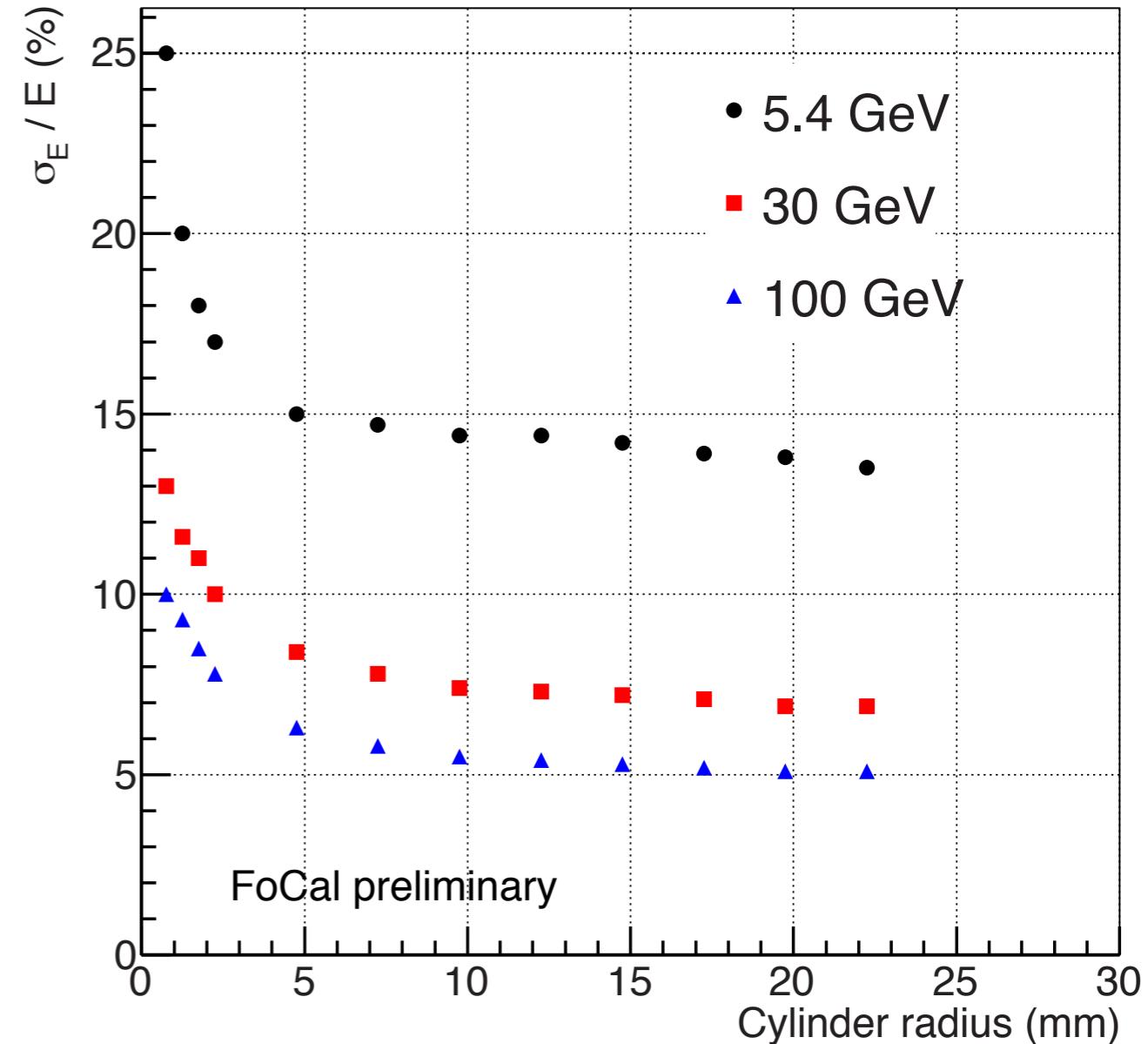
evaluate separation capability: core energy
calculate shower energy in cylinder of finite radius
study as function of radius

R&D Results: Core Energy

detector response (number of hits)



energy resolution



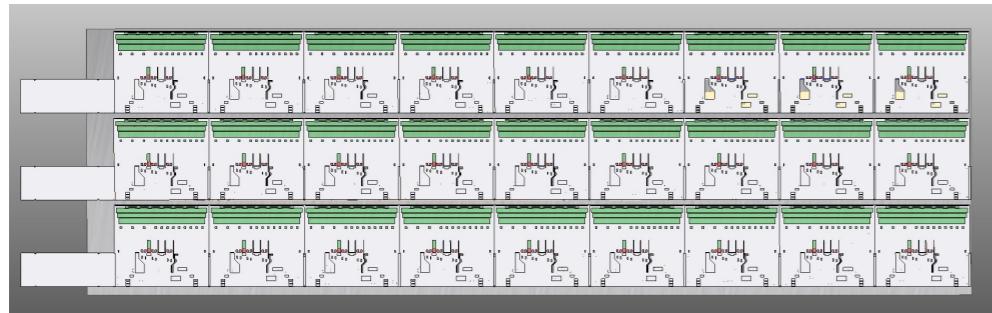
reasonable energy resolution of pixel calorimeter, sufficient for conceptual design

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

Overall conceptual design

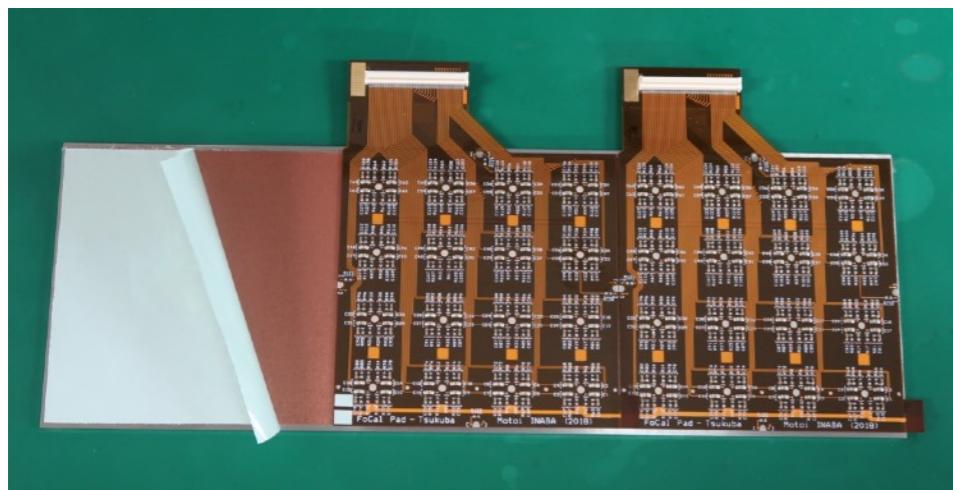
FoCal module: ~28x8 cm

Layout concept for pixel layer

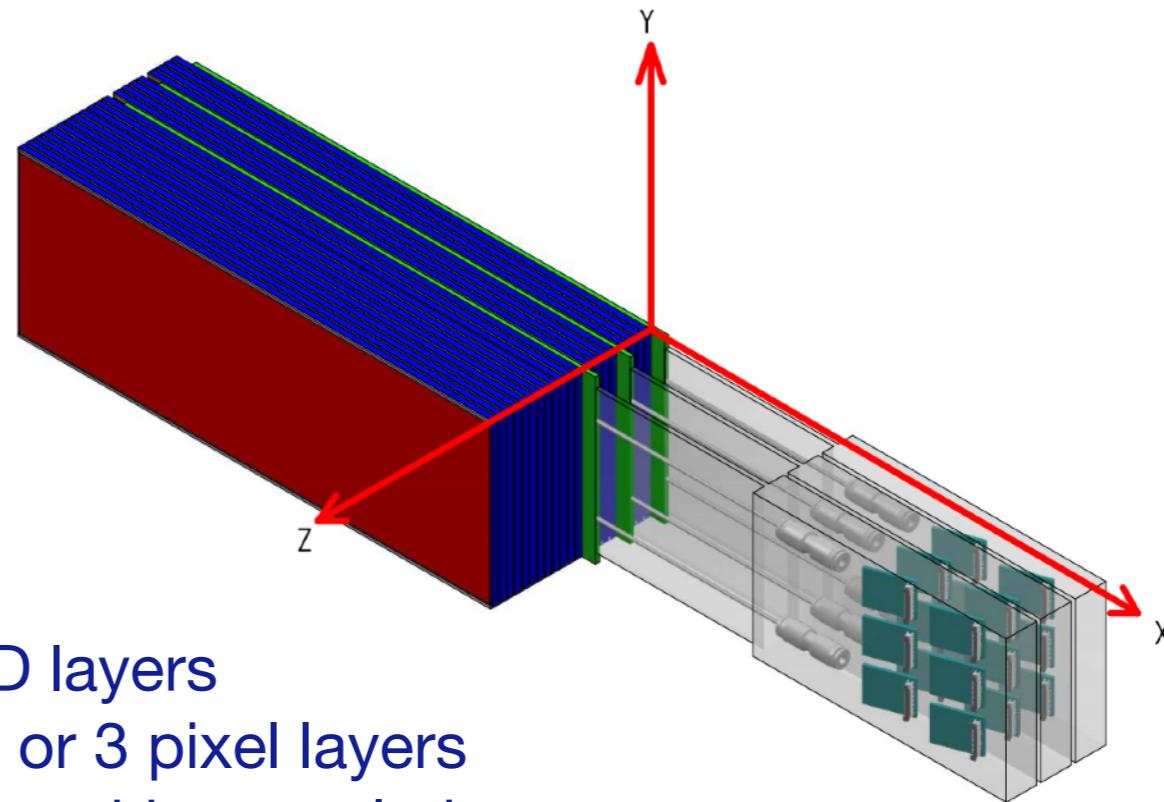


6x9 ALPIDE sensors (2 or 3 layers)

PAD module prototype



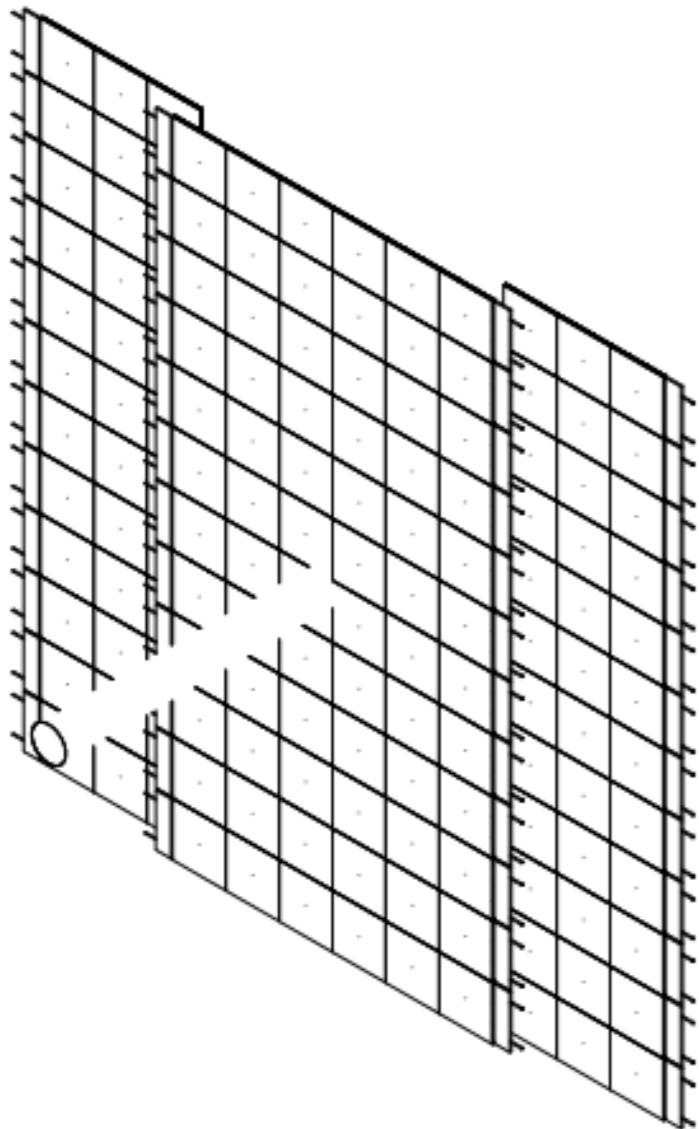
3 sensors: ~9x8 cm



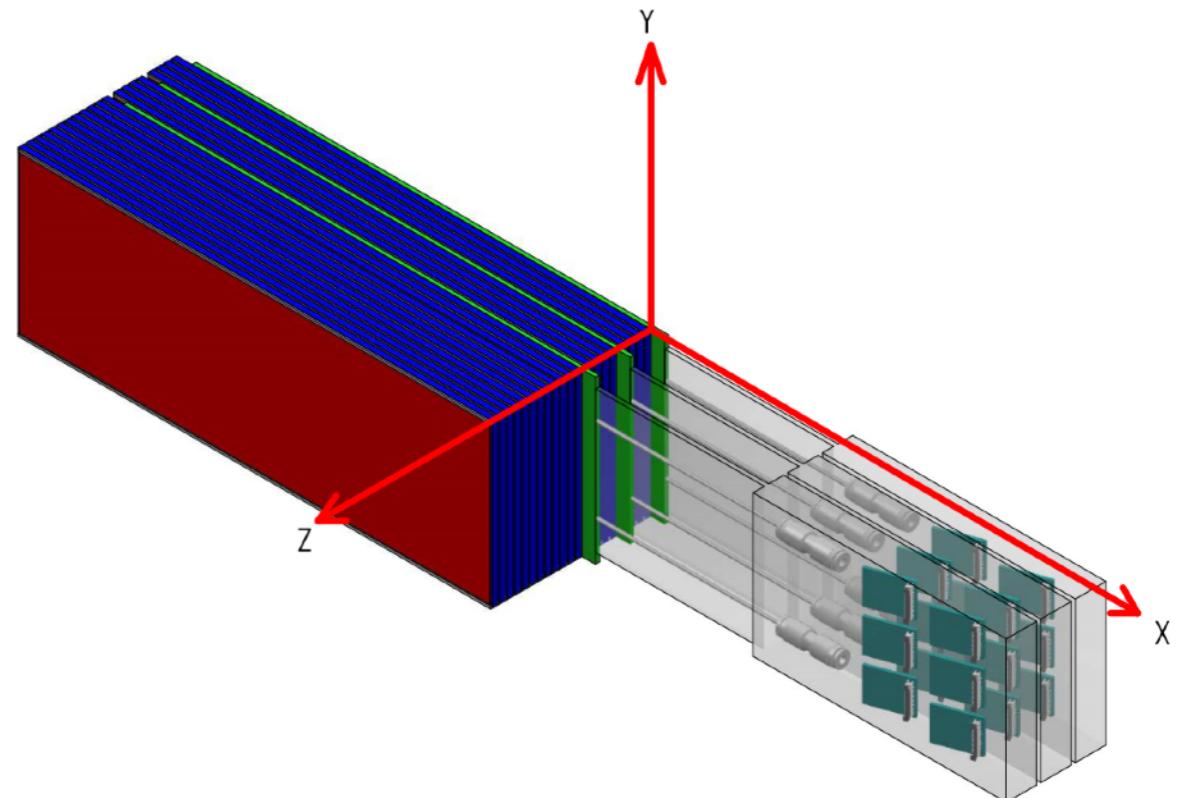
PAD layers
+ 2 or 3 pixel layers
for position resolution

Services/connections
to one side for integration

Integration



Goal/idea: build modules with 3 ‘towers’
Minimize gaps between towers
Stacked vertically into ‘slabs’



PAD layers +
pixel layers for position resolution

Needs work on integration to avoid edges and yet transport outwards signals