The Forward Calorimeter project in ALICE

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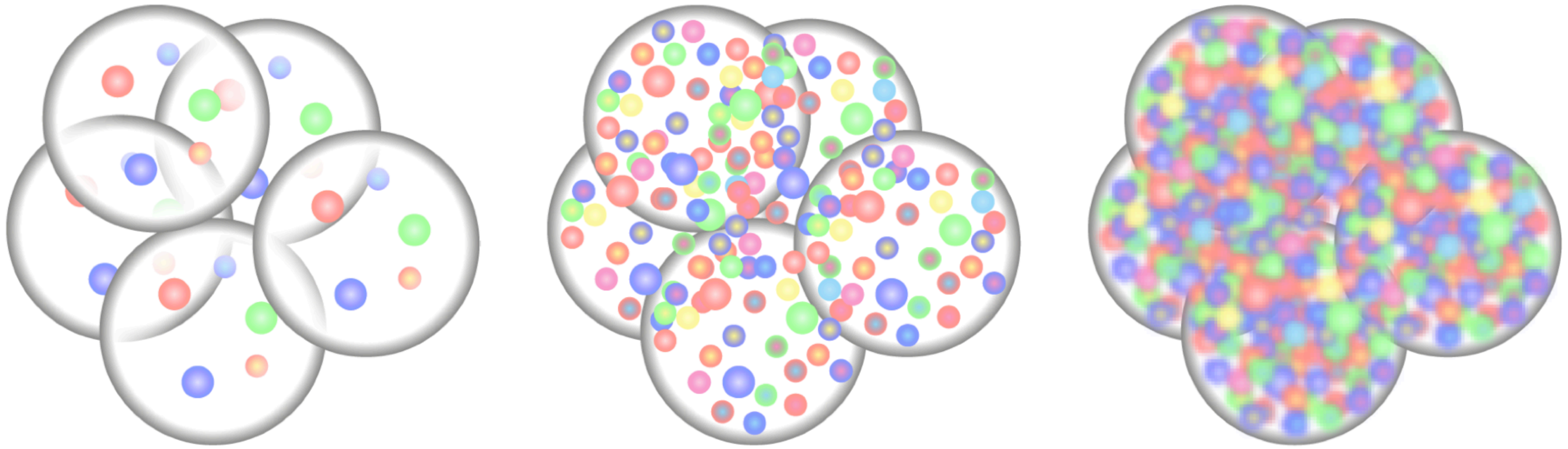
on behalf of the FoCal collaboration

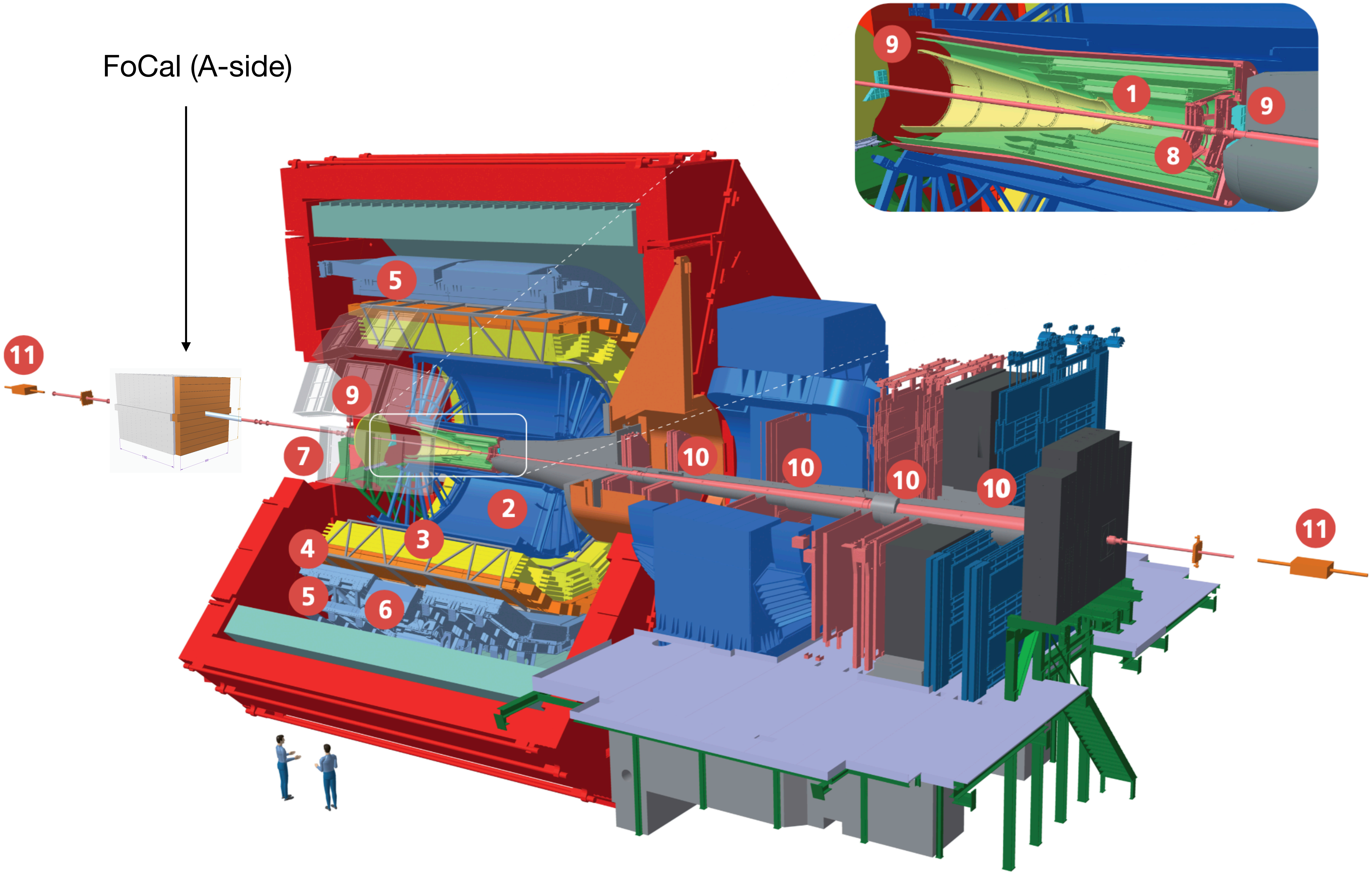
05.08.2020 (v1)

Letter-of-Intent: https://cds.cern.ch/record/2719928

1. Introduction



ALICE schematics


FoCal (A-side)

1 **ITS** | Inner Tracking System

2 **TPC** | Time Projection Chamber

3 **TRD** | Transition Radiation Detector

4 **TOF** | Time Of Flight

5 **EMCal** | Electromagnetic Calorimeter

6 **PHOS / CPV** | Photon Spectrometer

7 **HMPID** | High Momentum Particle Identification Detector

8 **MFT**| Muon Forward Tracker

9 **FIT** | Fast Interaction Trigger

10 **Muon Spectrometer**

11 **ZDC** | Zero Degree Calorimeter

The FoCal proposal

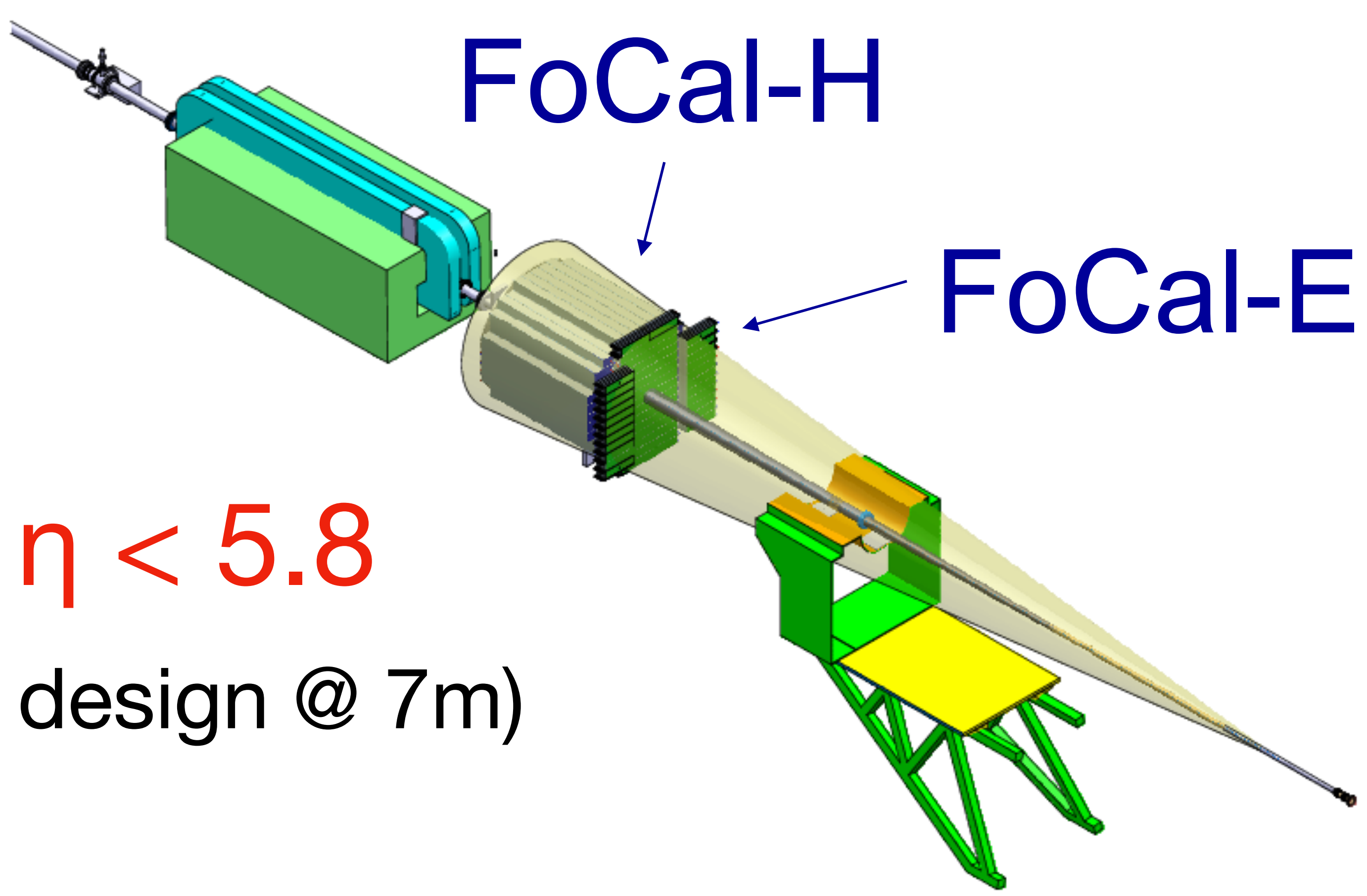
FoCal-E: high-granularity Si-W sampling calorimeter for photons and π^0
FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets

Observables:

- π^0 (and other neutral mesons)
- Isolated (direct) photons
- Jets (and di-jets)
- J/ψ (Υ) in UPC
- W, Z
- Event plane and centrality

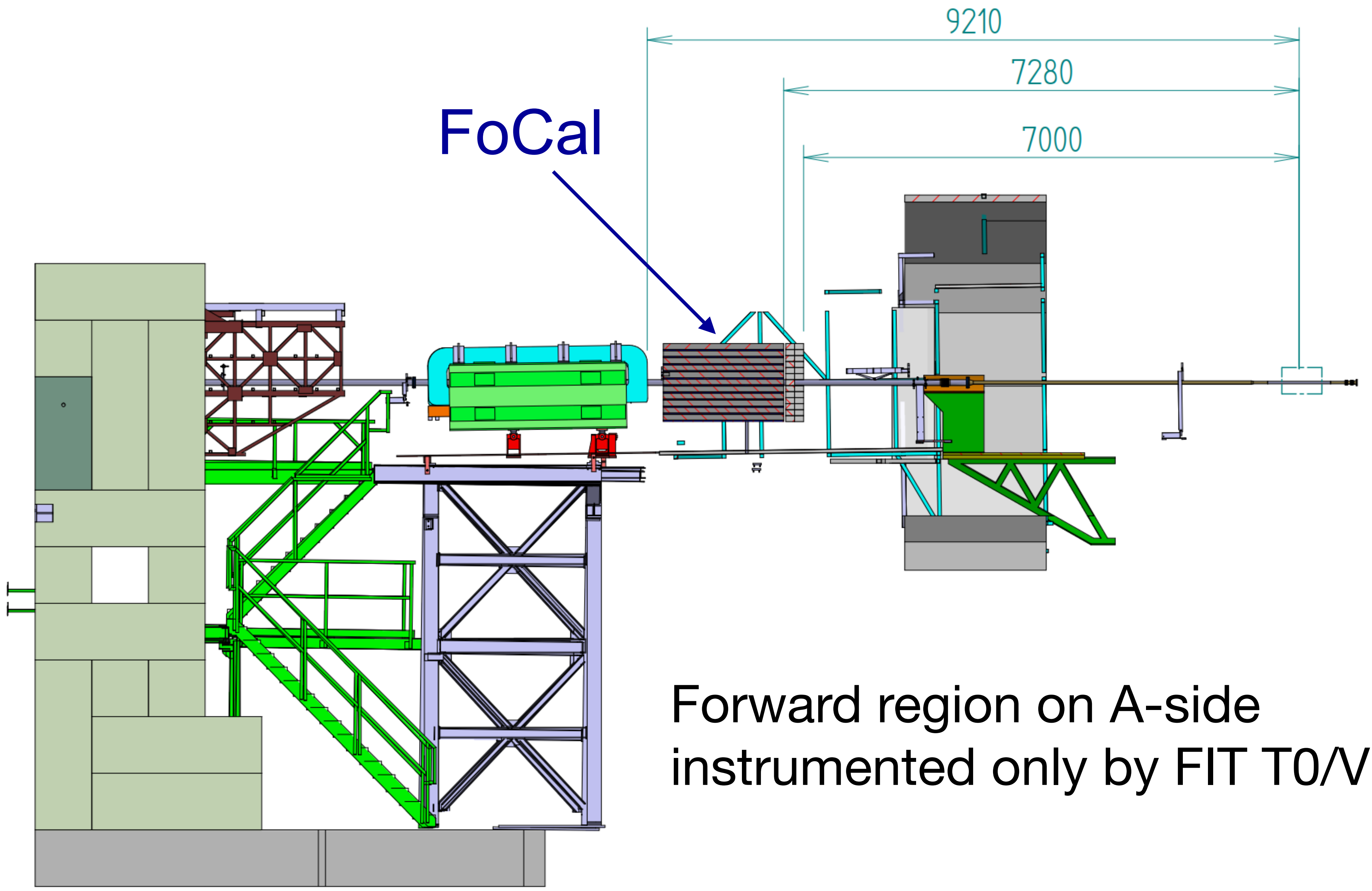
Letter of Intent:

CERN-LHCC-2020-009



$3.4 < \eta < 5.8$

(baseline design @ 7m)



Forward region on A-side instrumented only by FIT T0/V0

Physics programme

1. Quantify nuclear modification of the gluon density at small-x
   - Isolated photons in pp and pPb collisions

2. Explore non-linear QCD evolution
   - Azimuthal π^0-π^0 and isolated photon-π^0 (or jet) correlations in pp and pPb collisions

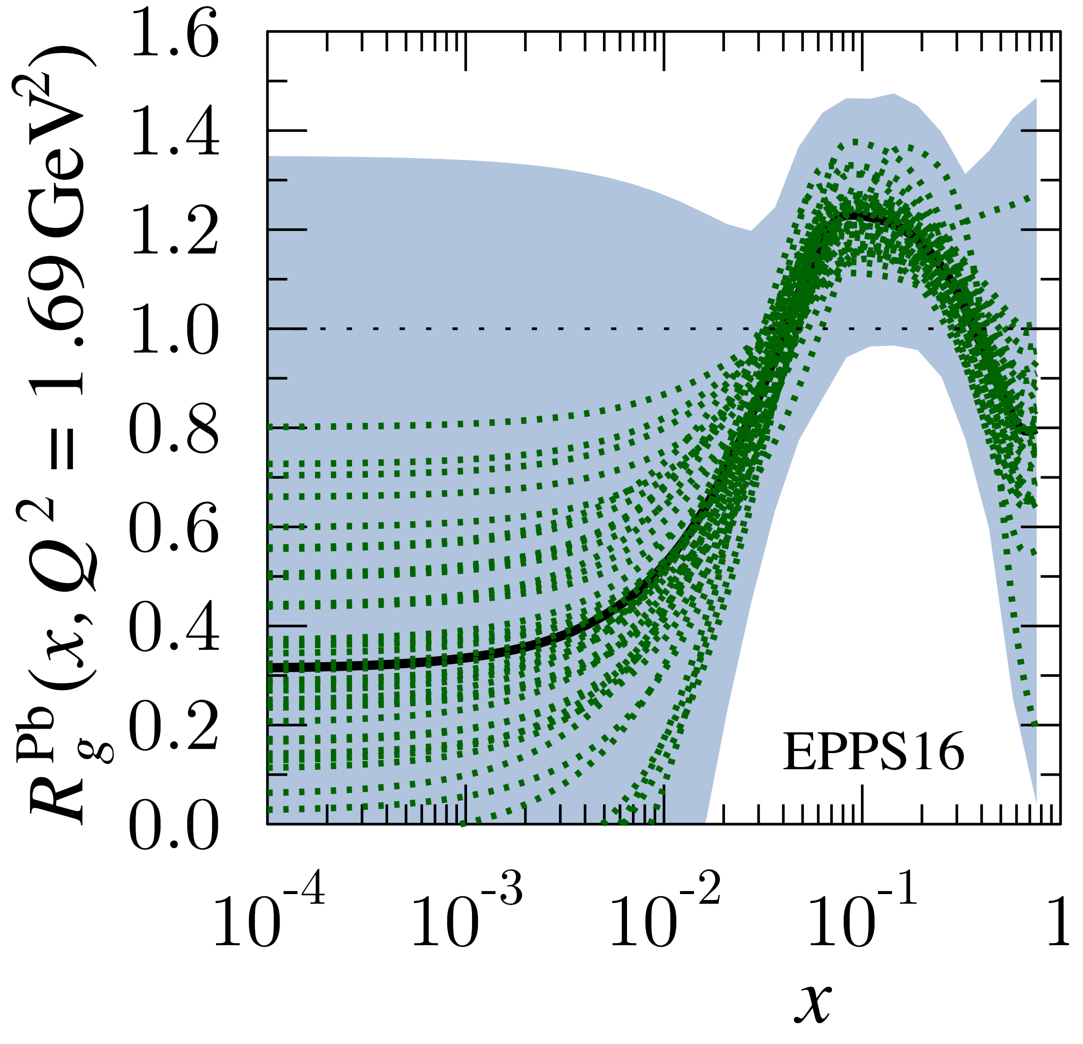
3. Investigate the origin of long range flow-like correlations
   - Azimuthal π^0-h correlations using FoCal and central ALICE (and muon arm) in pp and pPb collisions

4. Explore jet quenching at forward rapidity
   - Measure high p_T neutral pion production in PbPb

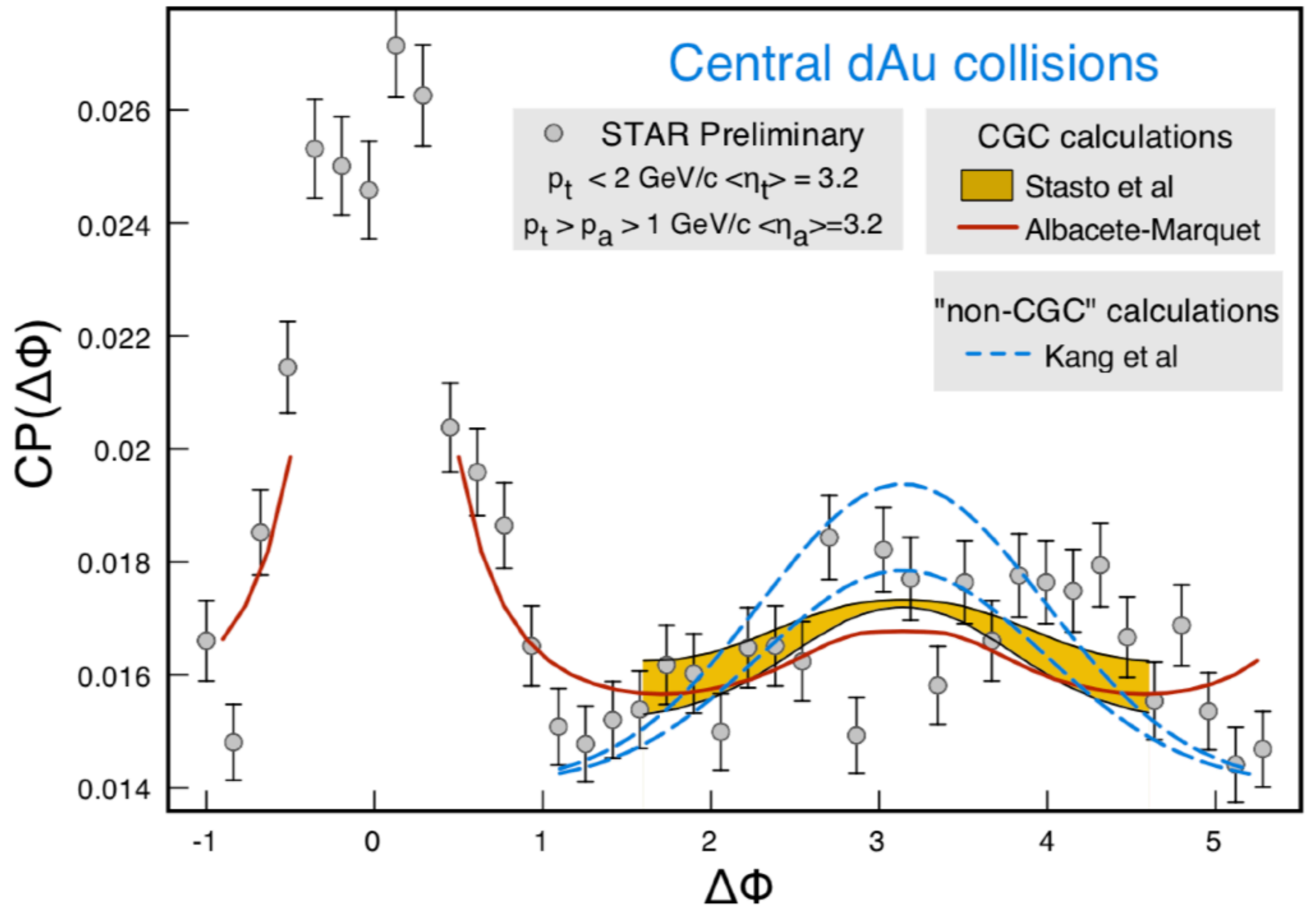
5. Other measurements
   - Jets and dijets in pp/pPb and UPC
   - Quarkonia in UPC (and pp*)
   - Photon and pion HBT (*)
   - W,Z in pp/pPb?
   - Isolated photons in PbPb (*)
   - Measurements at 14 TeV
     - Universality at small-x
     - Saturation in pp
     - High-x (>0.1) gluon constraints (*)

(*=feasibility not yet explored)

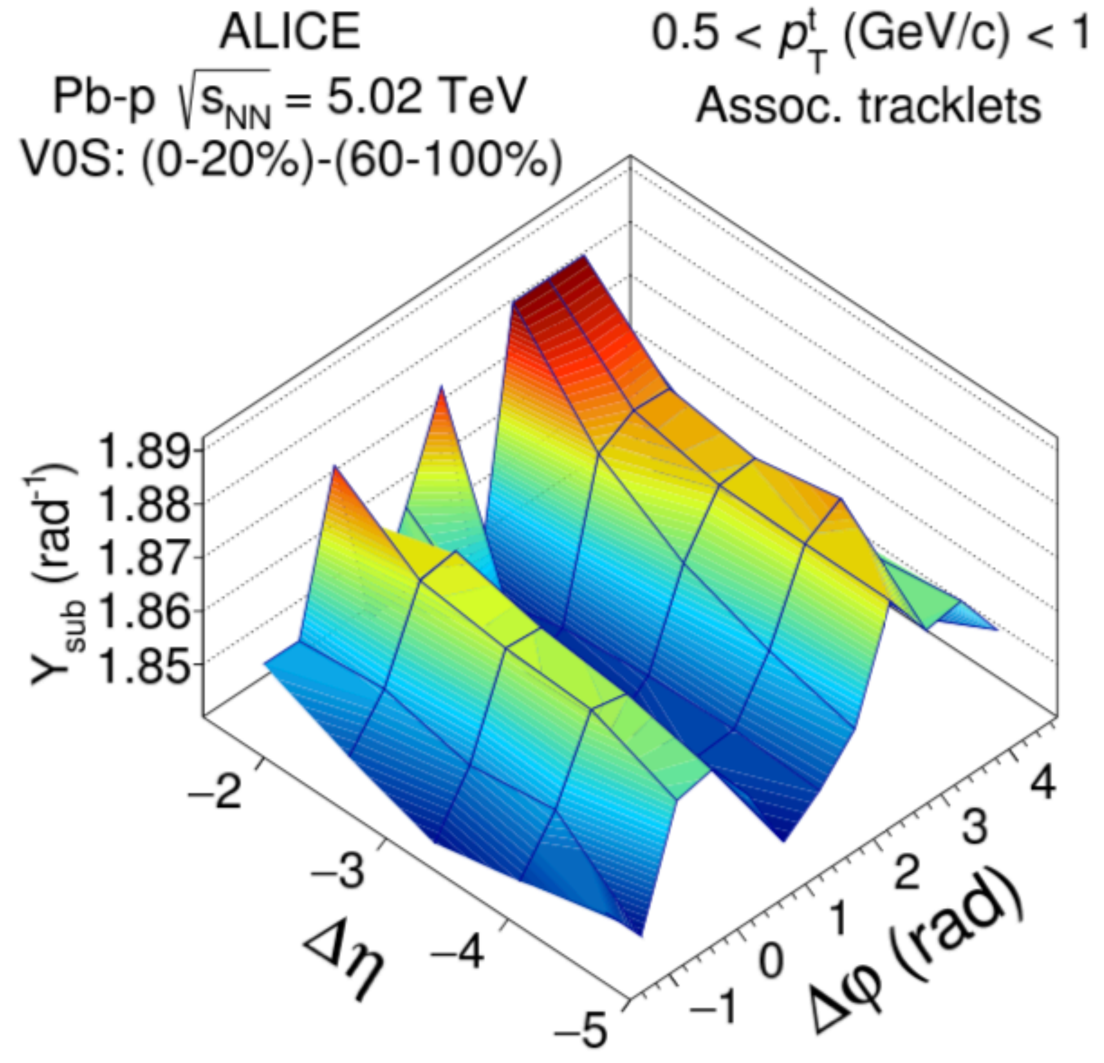
1. Nuclear PDFs



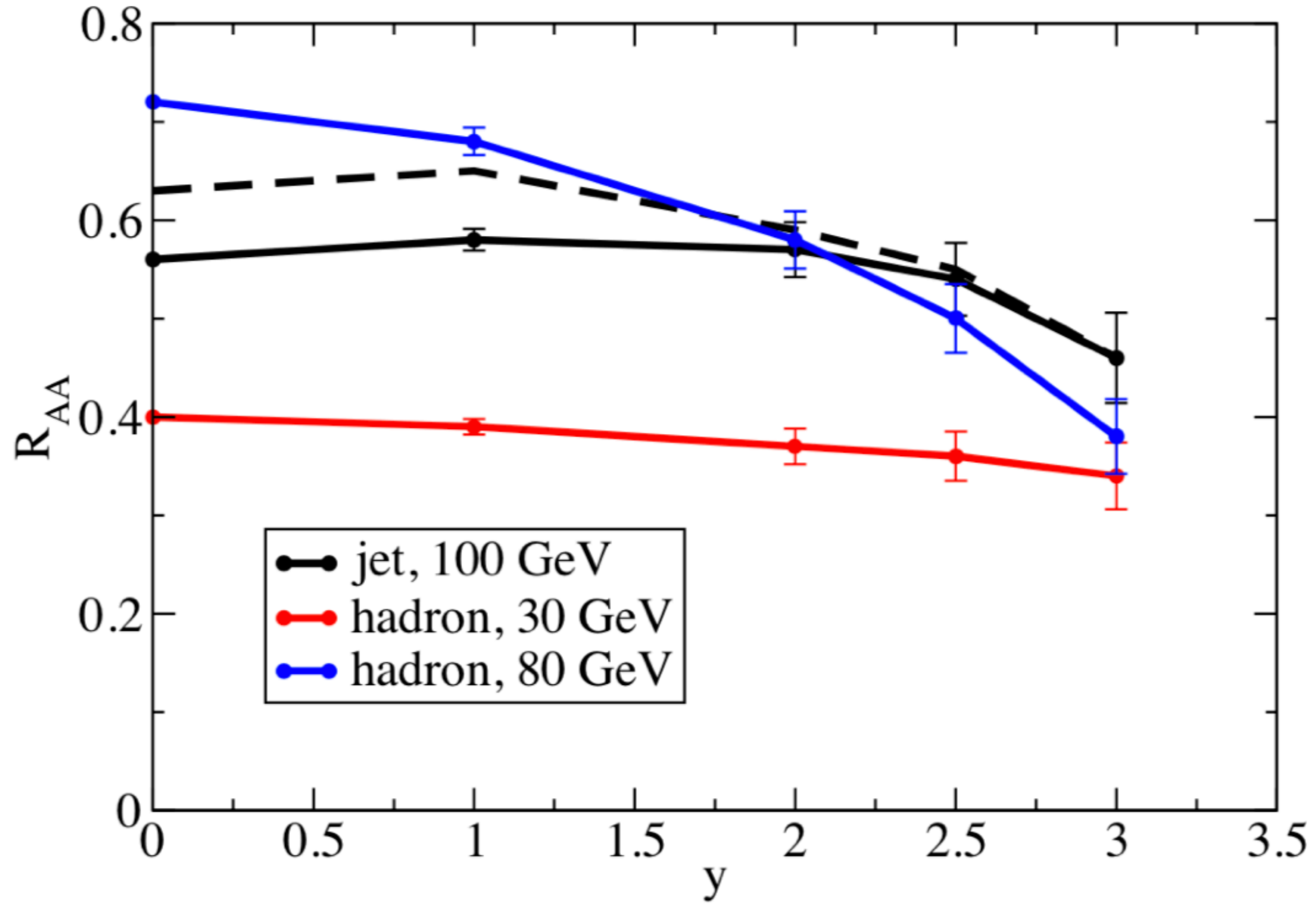
2. Non-linear evolution



3. Long-range correlations

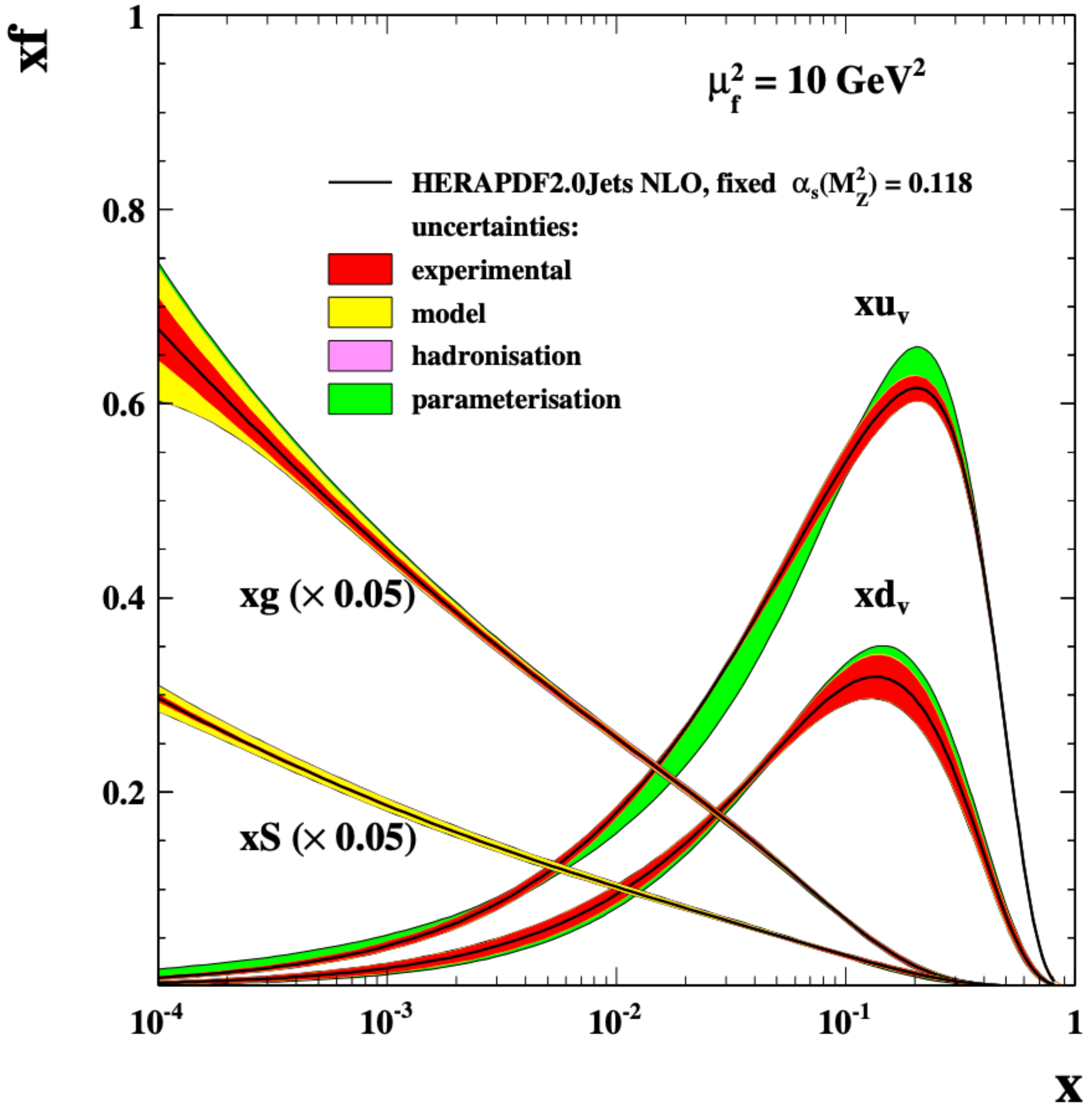


4. Jet quenching

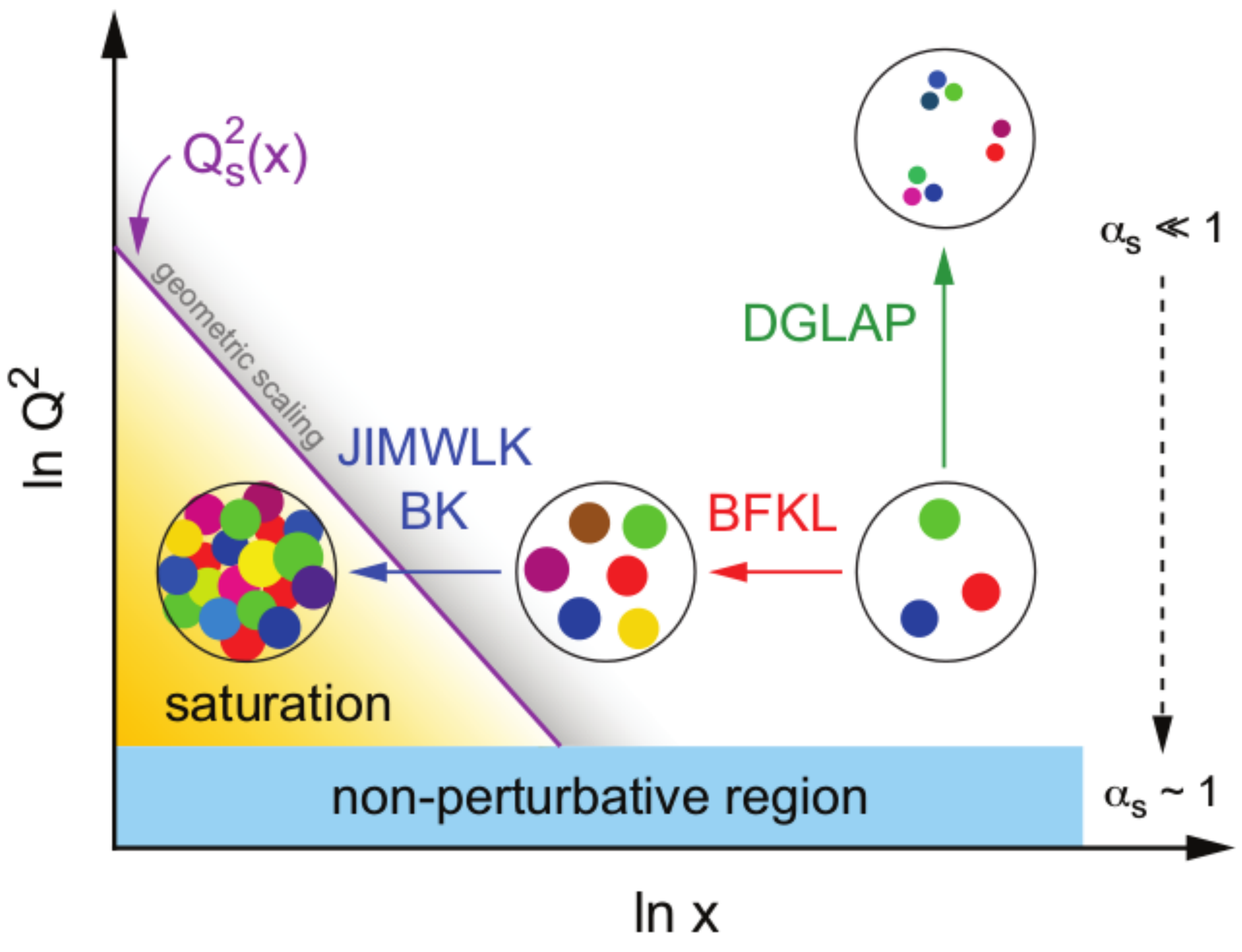


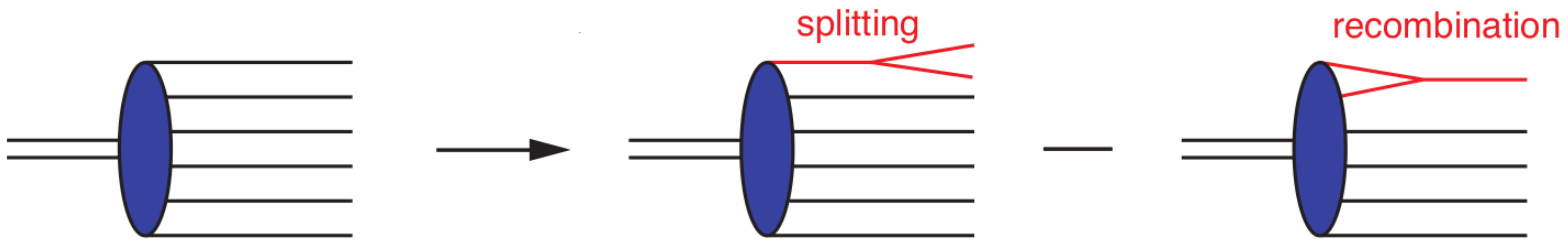
Linear and non-linear QCD evolution

Proton PDF from DIS data



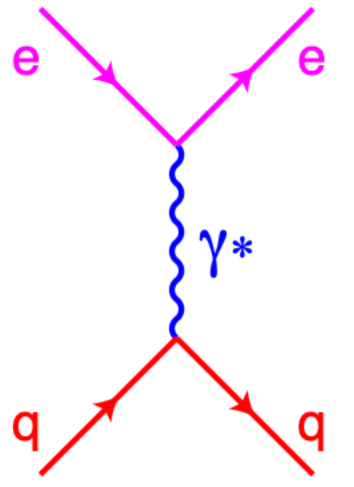
$$Q_s^2 \approx \frac{xG_A(x,Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda}$$



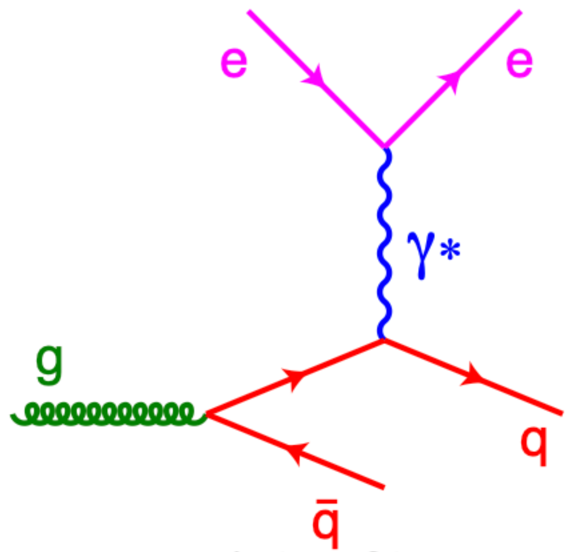


- Rise of gluon density natural for linear QCD evolution describing parton splitting
- Expected to be tamed by non-linear QCD evolution functions describing parton recombination, perhaps leading to saturation at the saturation scale Q_s

DIS vs direct photons

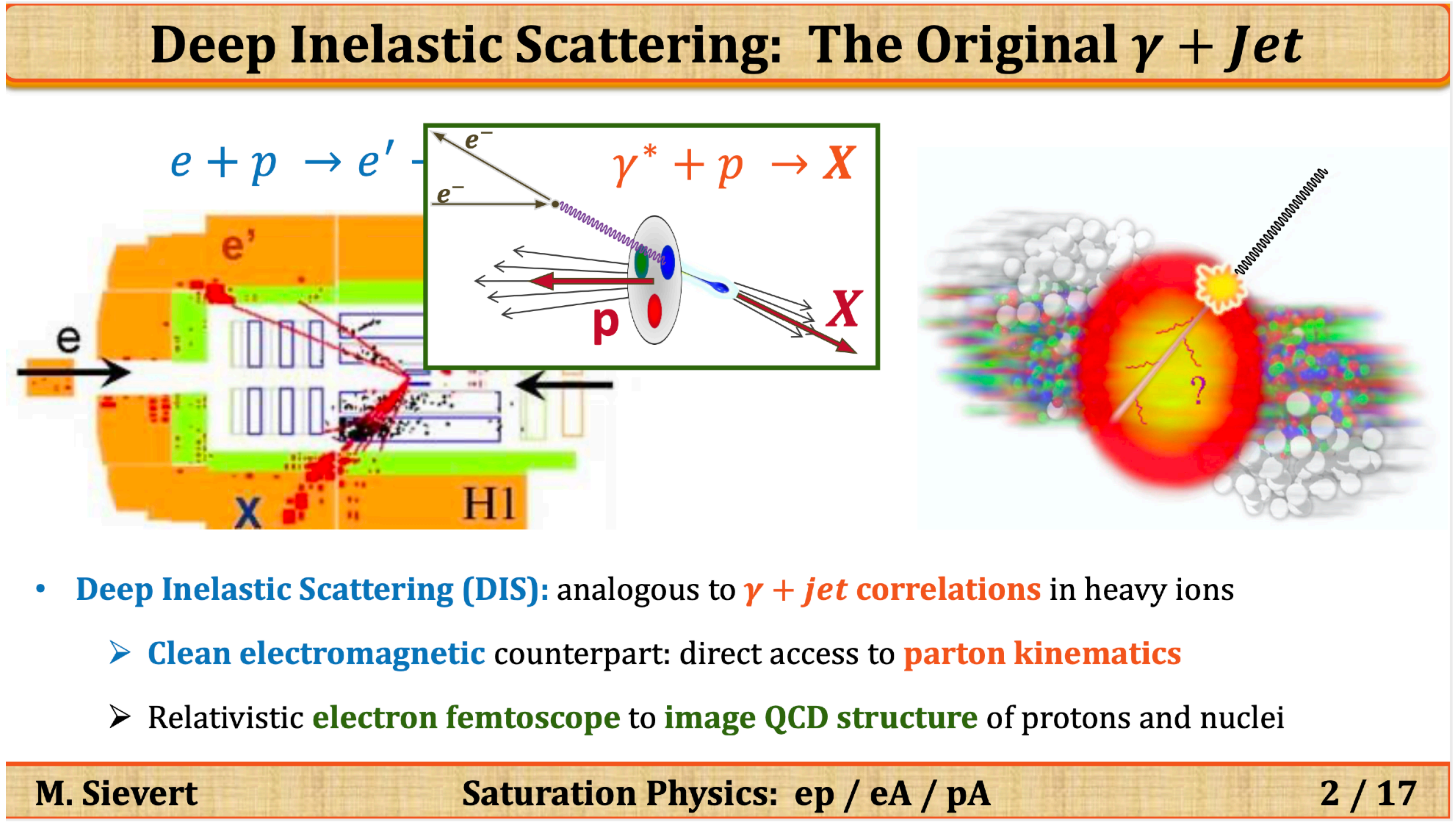


DIS (LO)



DIS (NLO)

M.Sievert, Hard Probes 2020



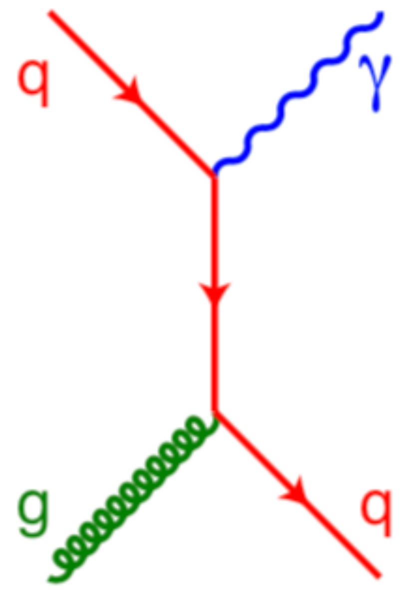
Deep Inelastic Scattering: The Original $\gamma + Jet$

$e + p \to e' +$

$\gamma^* + p \to X$

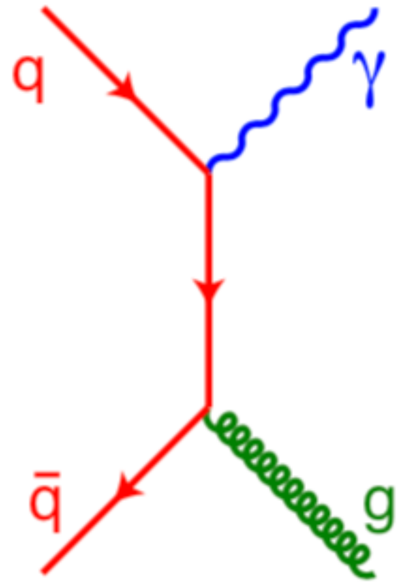
- **Deep Inelastic Scattering (DIS):** analogous to **$\gamma + jet$ correlations** in heavy ions
  - **Clean electromagnetic** counterpart: direct access to **parton kinematics**
  - Relativistic **electron femtoscope** to **image QCD structure** of protons and nuclei

M. Sievert **Saturation Physics: ep / eA / pA** **2 / 17**



Sensitive at LO to gluon PDF

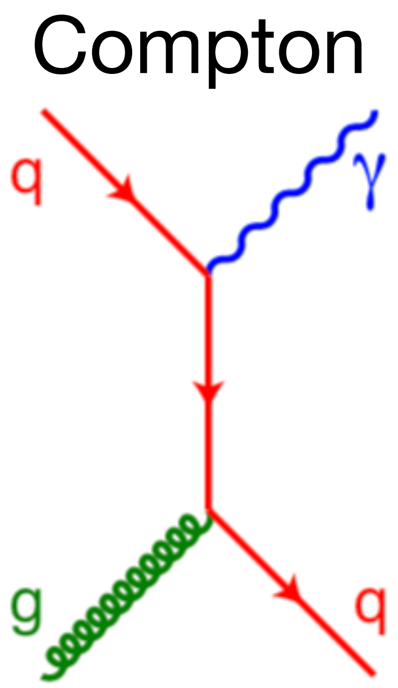
Compton

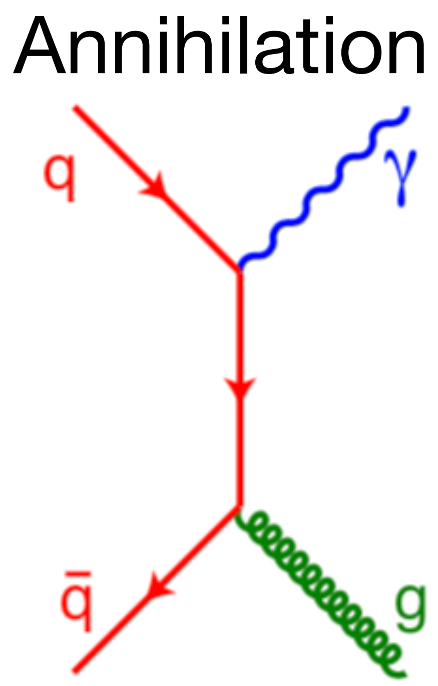


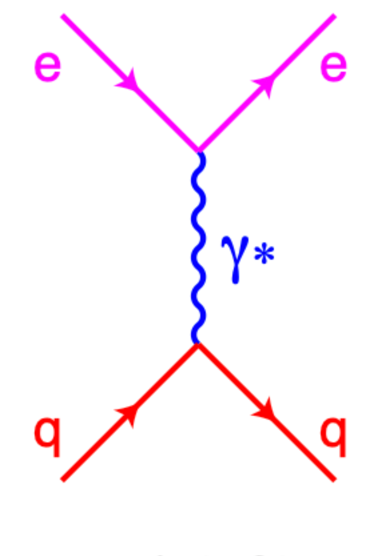
Annihilation

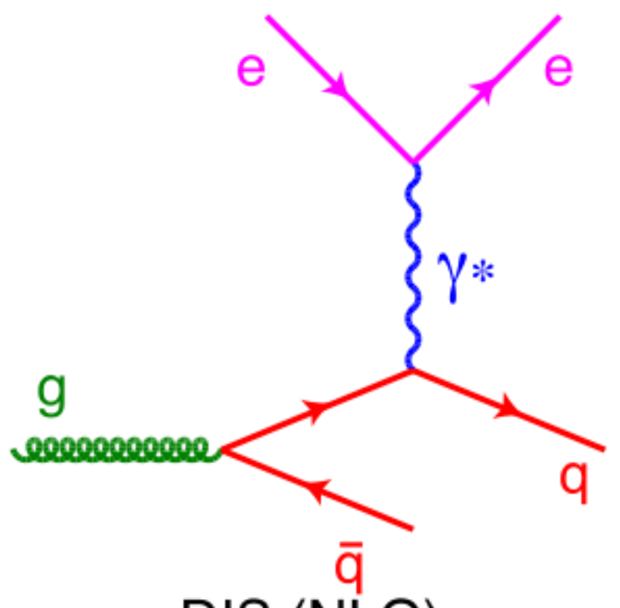
In pp or pA collisions, direct photons provide "direct" access to gluon density

Forward isolated photons and the LHC small-x program


Compton

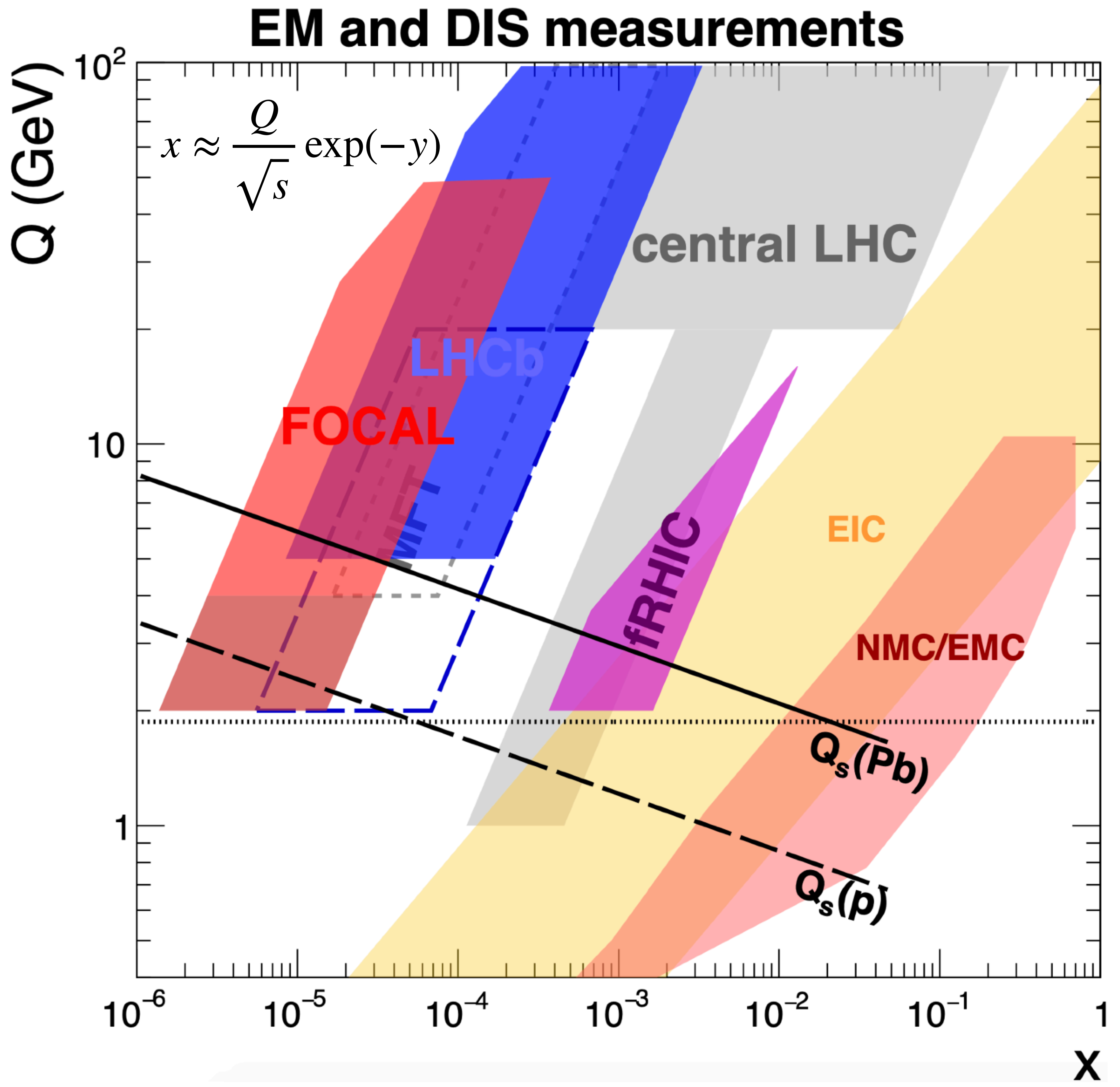

Annihilation


DIS (LO)


DIS (NLO)

- Measure isolated photons forward
  - At LO more than 70% from Compton with direct sensitivity to gluon density
  - Not affected by final state effects nor hadronization
  - Uniquely low-x coverage at LHC (similar to LHeC)

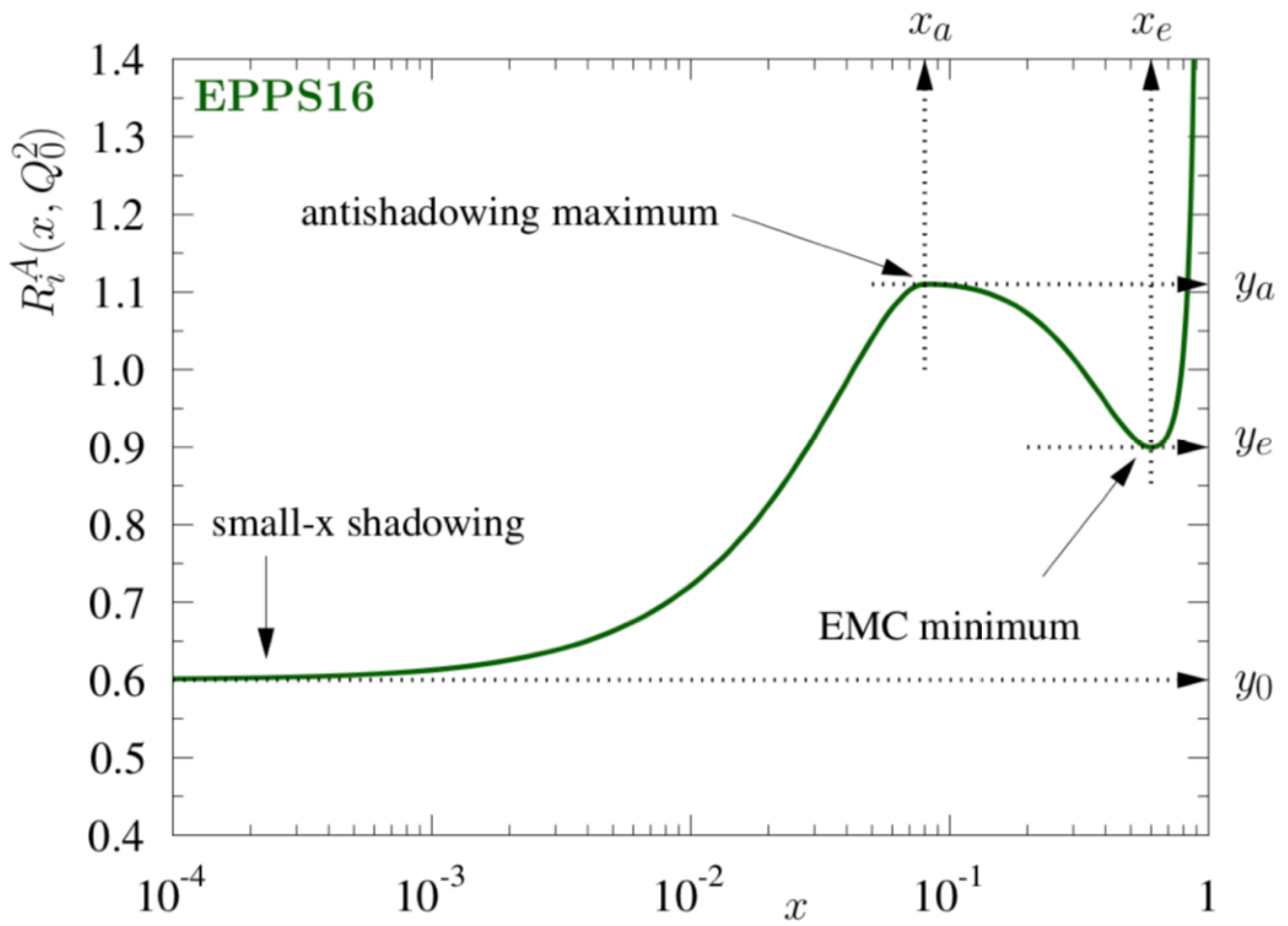
- Goal
  - Explore non-linear QCD evolution at small x
    - Constrain nuclear PDFs at small x
  - Logarithmic dep. of QCD evolution on Q and x, requires several measurements over largest possible range



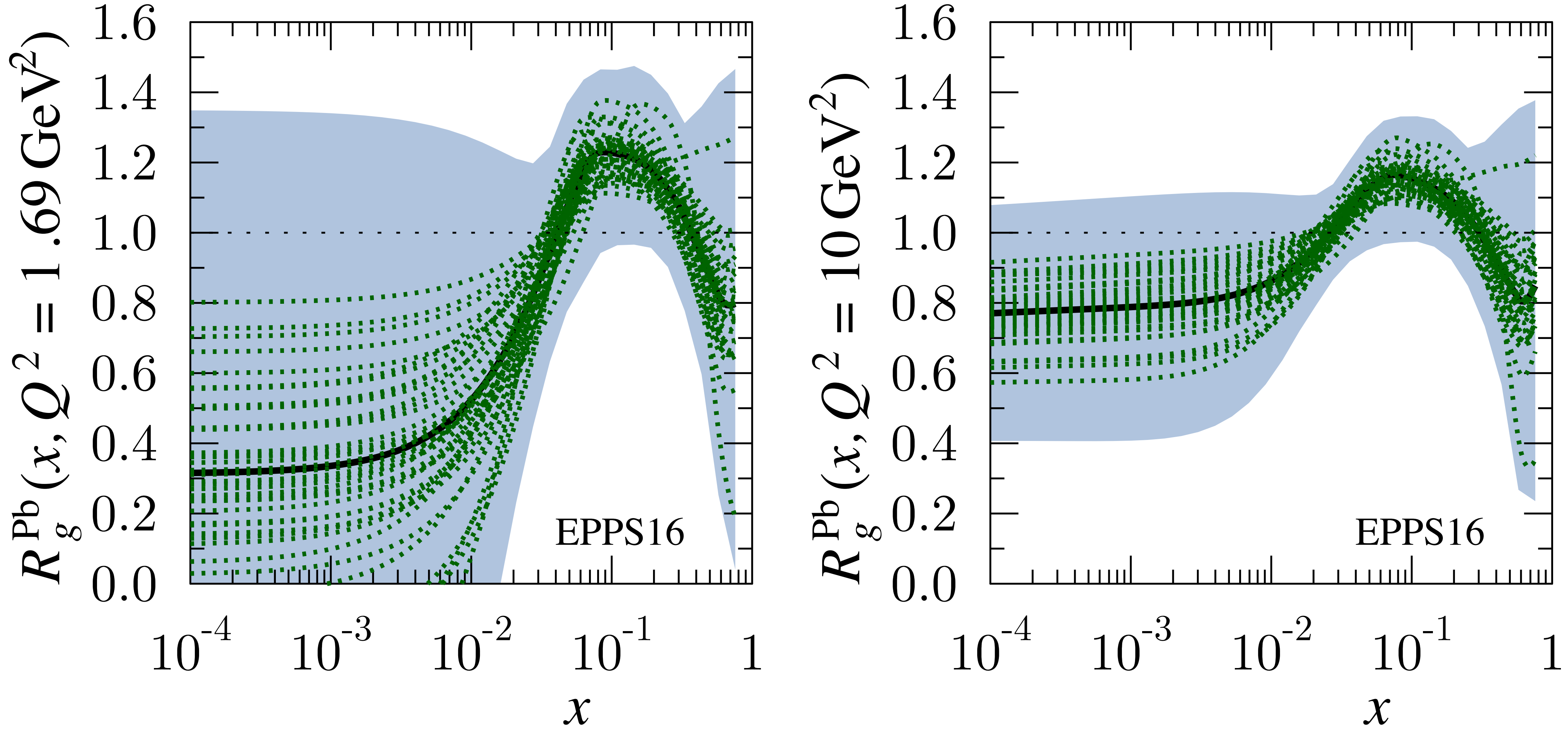
Strong small-x program at LHC

- Various experiments/measurements: isolated γ, DY, open charm (+UPC)
- Test factorization/universality
- Complementary to fRHIC + EIC

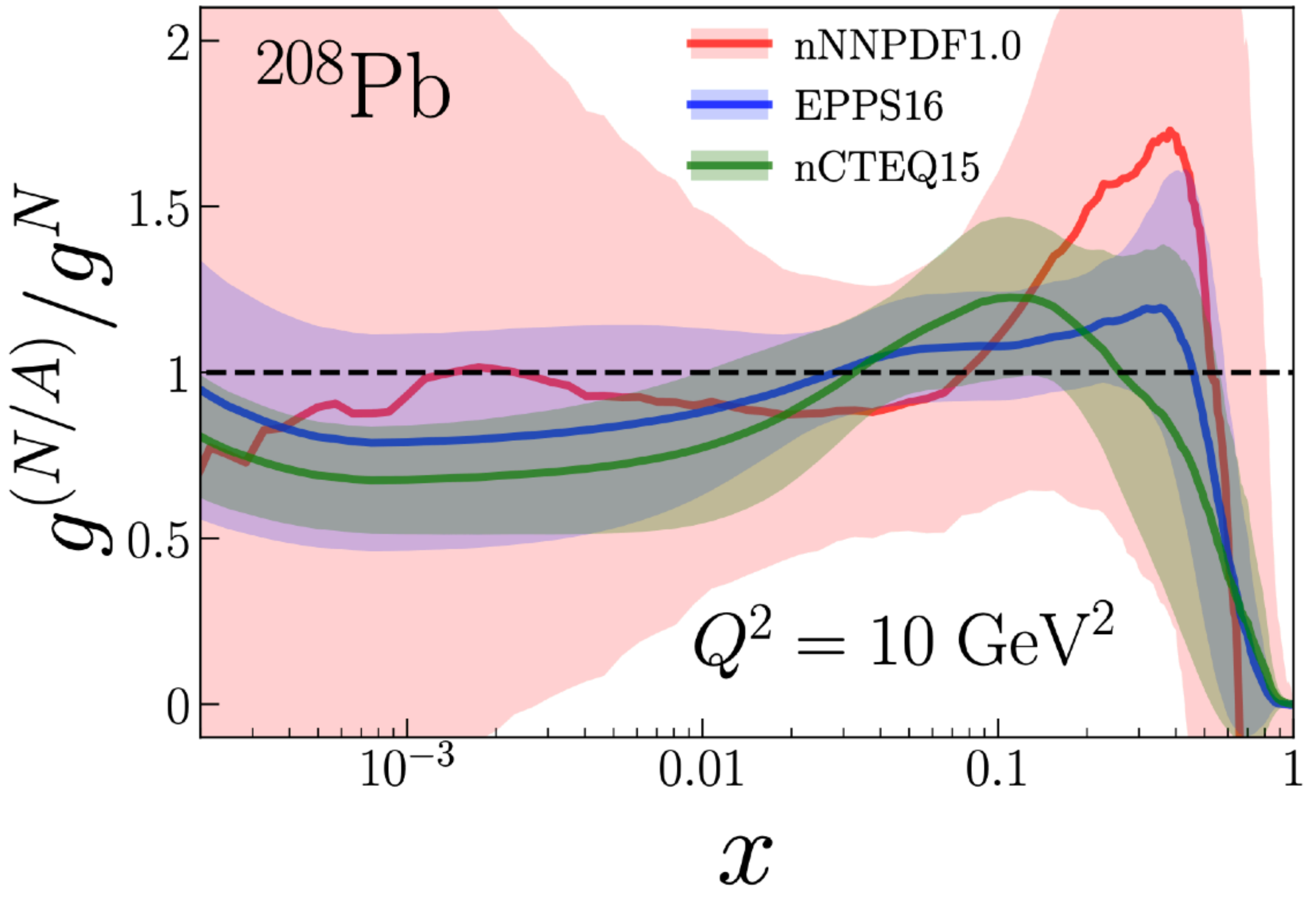
Nuclear parton distribution functions

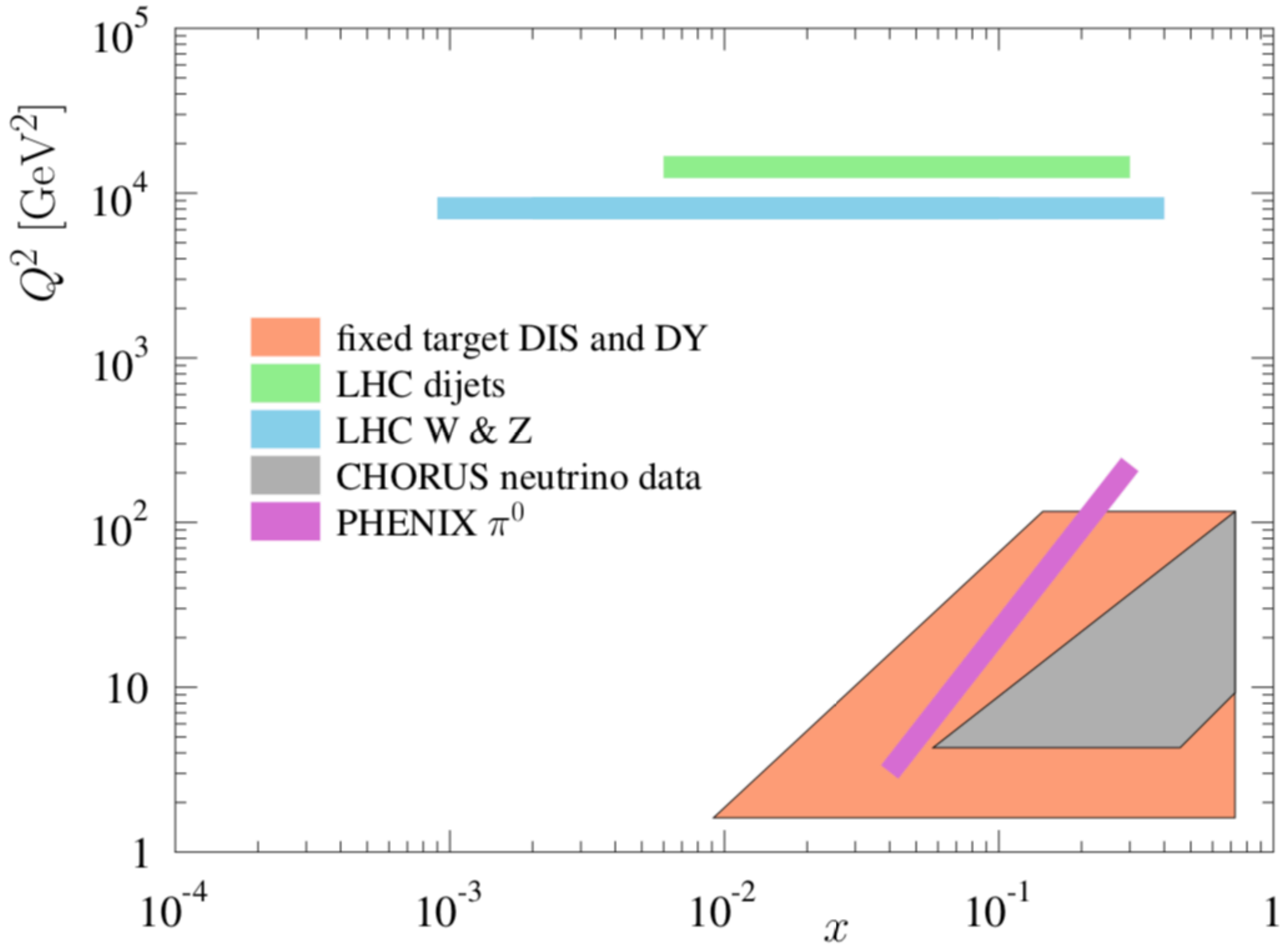


Eskola et al., EPJC 77 (2016) 163



R. Khalek et al.,
arXiv:1904.00018



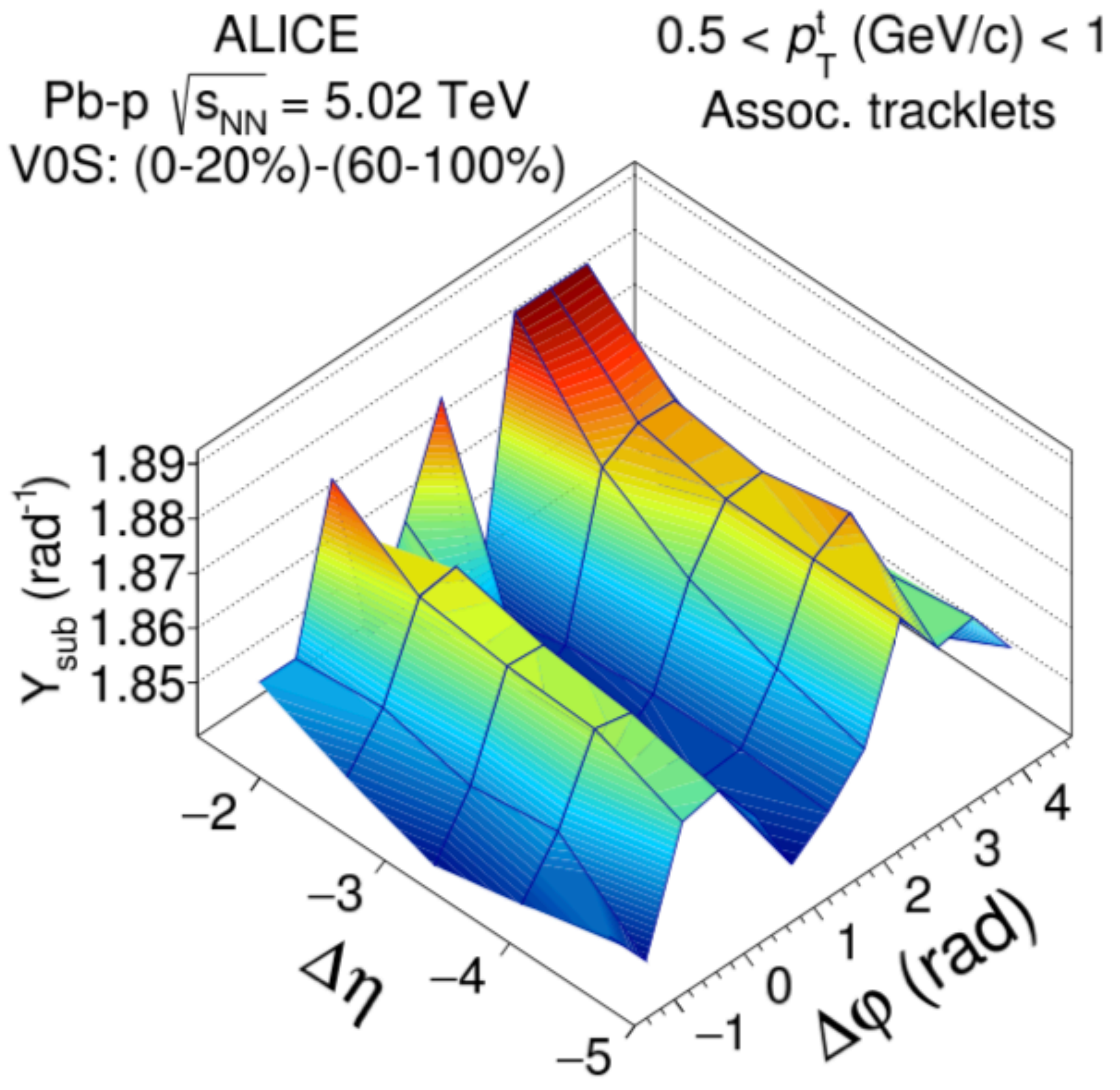


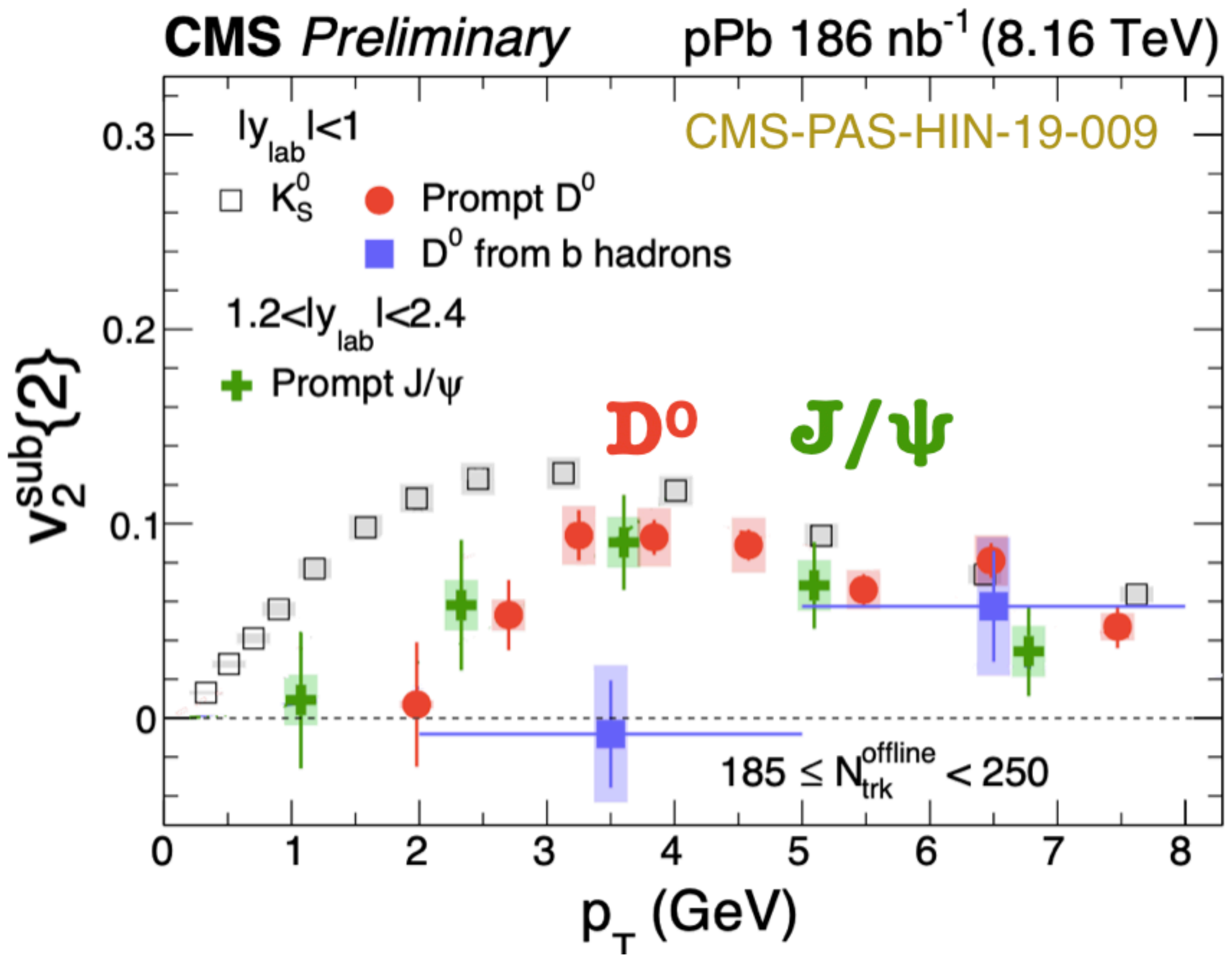
- Large uncertainties on the gluon content of the nucleus at small x
- Very few (DIS) measurements available
  - They only probe the gluon density via the (DGLAP) evolution

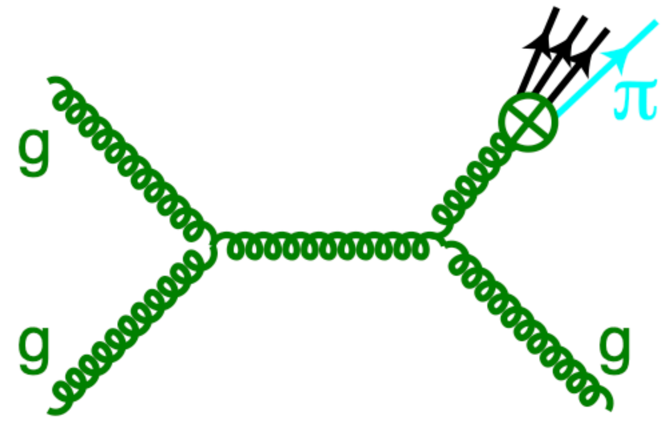
- EPPS16 (and nCTEQ) nuclear PDFs
  - Use hadron data and functional form at small-x parameterized "adhoc"
    - Possible final-state effects (next slide)

- nNNPDF from DIS data only and minimal theoretical assumptions

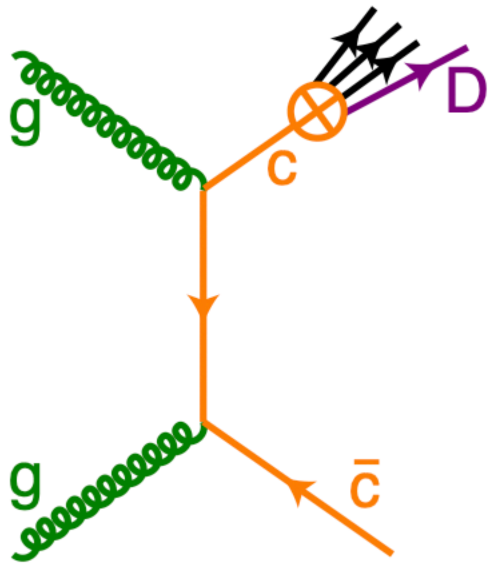
Light and heavy-flavor results





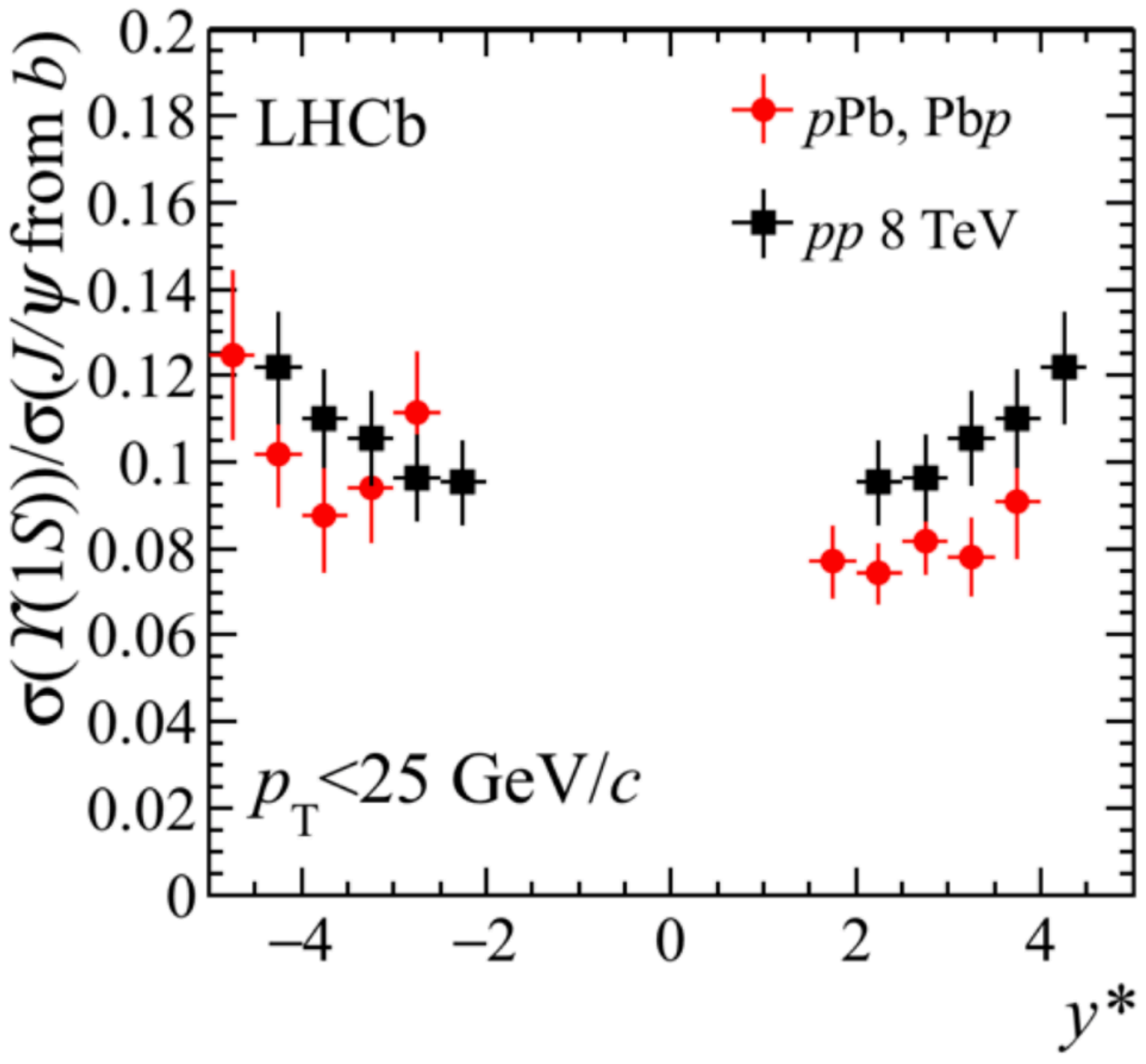


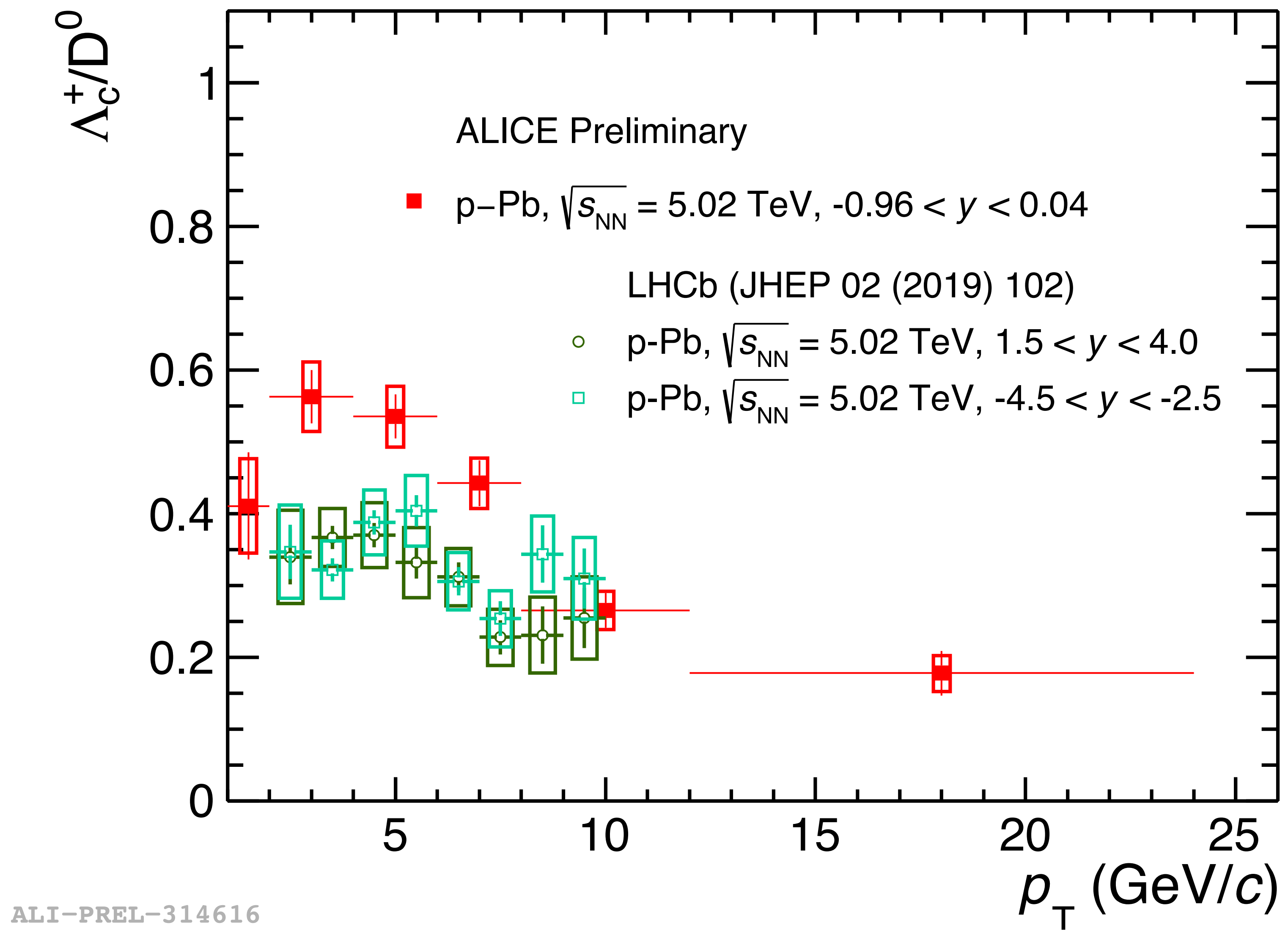
light hadron



heavy hadron

Sensitive to gluon PDF at NLO but also suspect to final state and hadronization effects

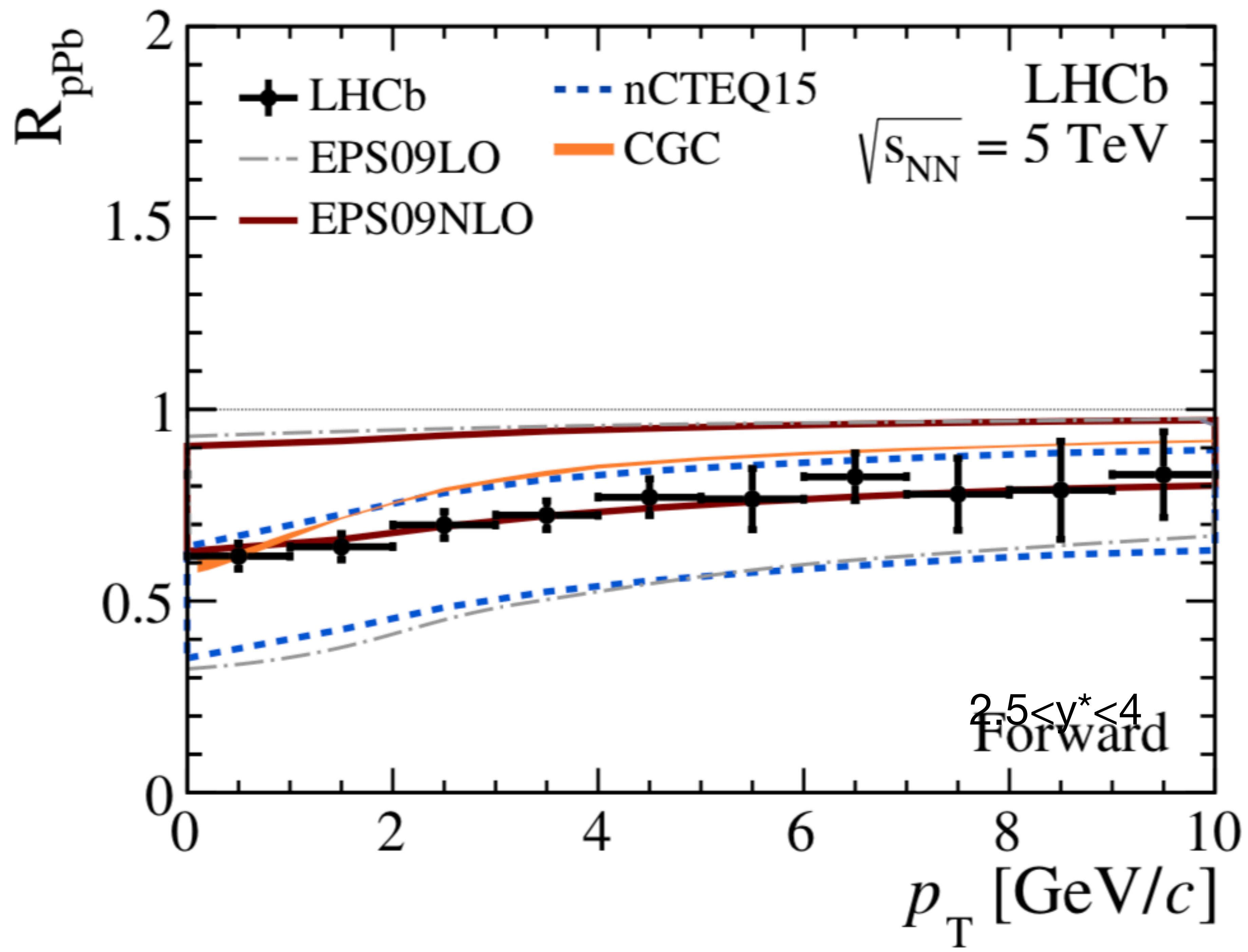




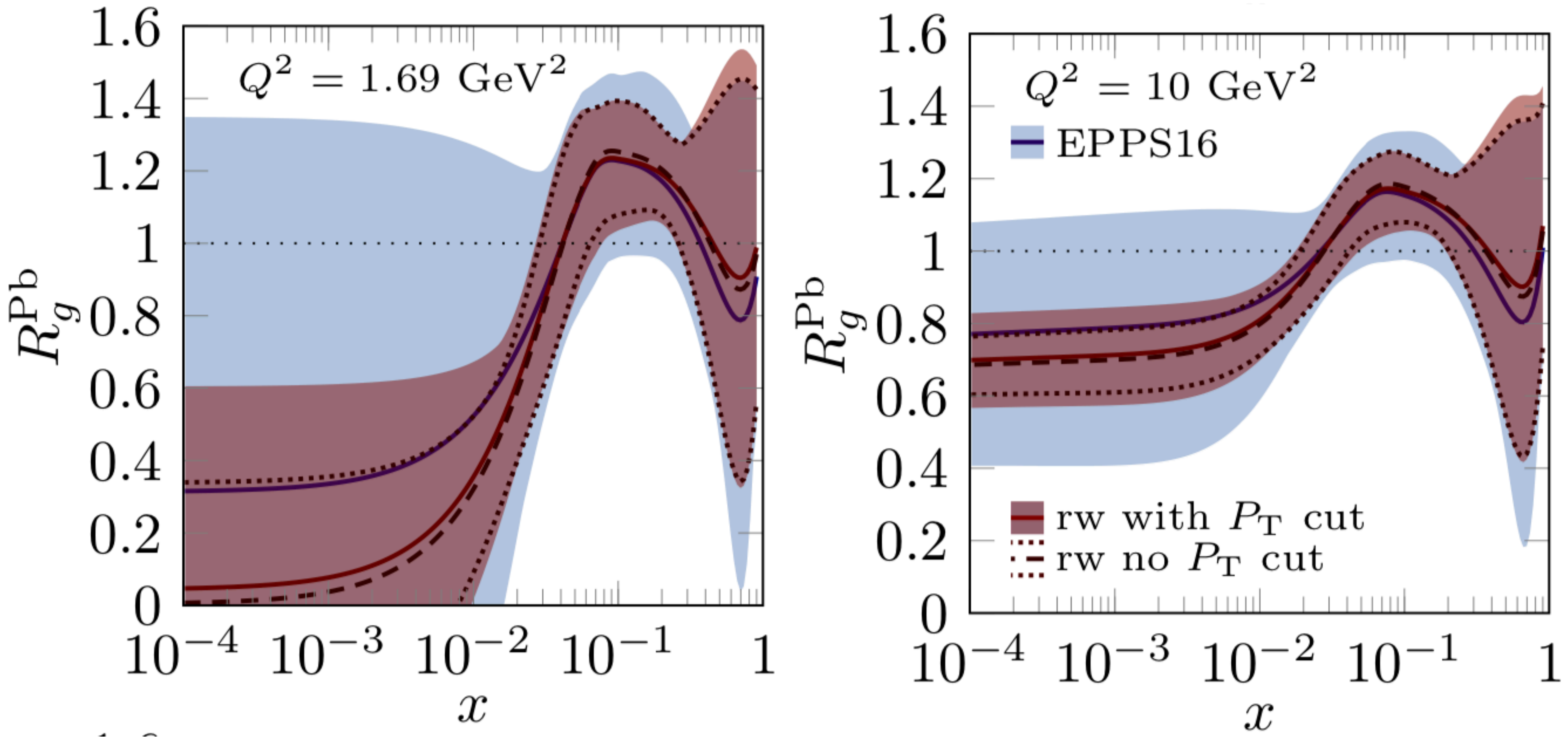
Measurements exhibit features that are difficult to disentangle between initial or final state effects

Forward open charm by LHCb

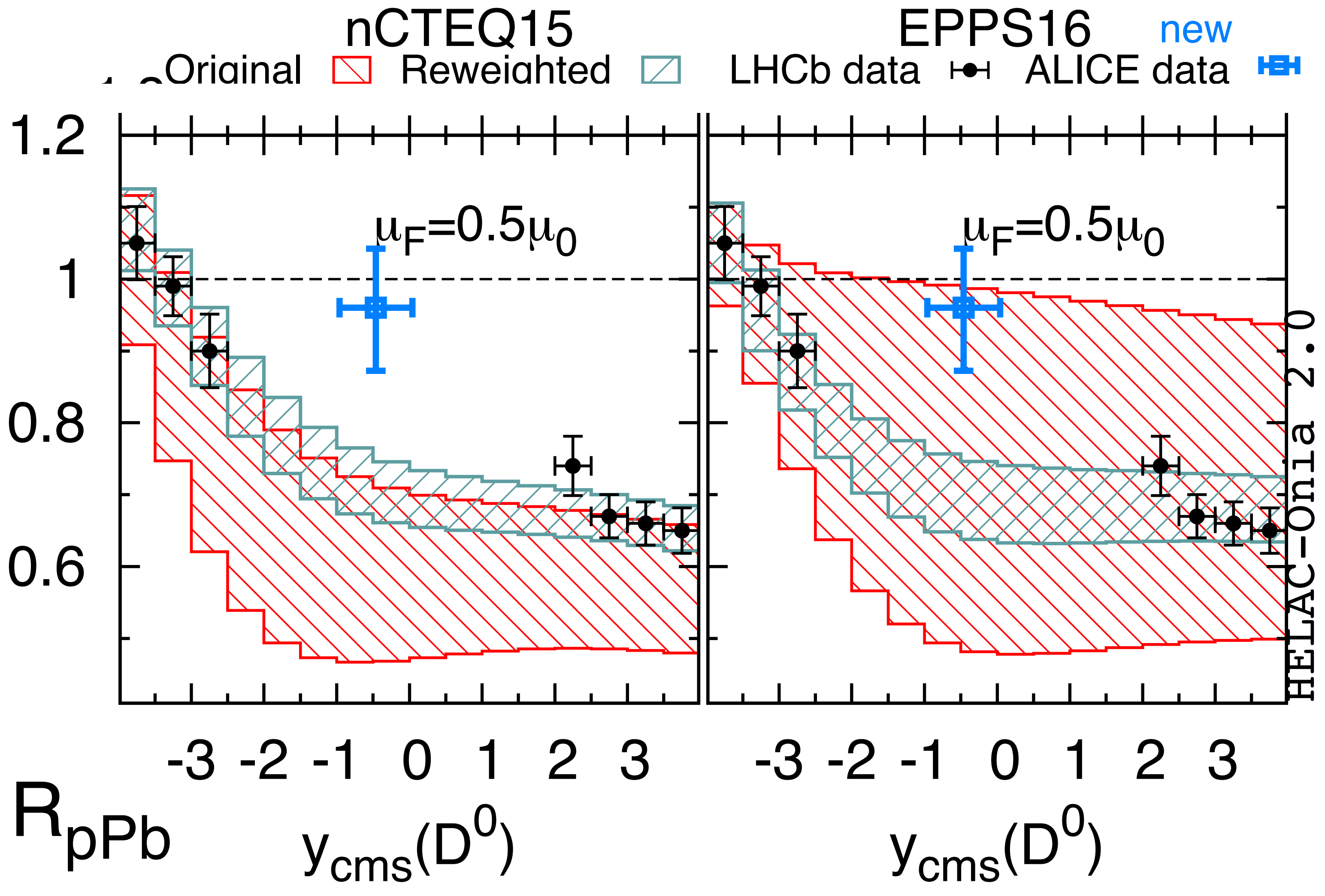
LHCb, arXiv:1707.02750



Eskola et al., arXiv:1906.02512

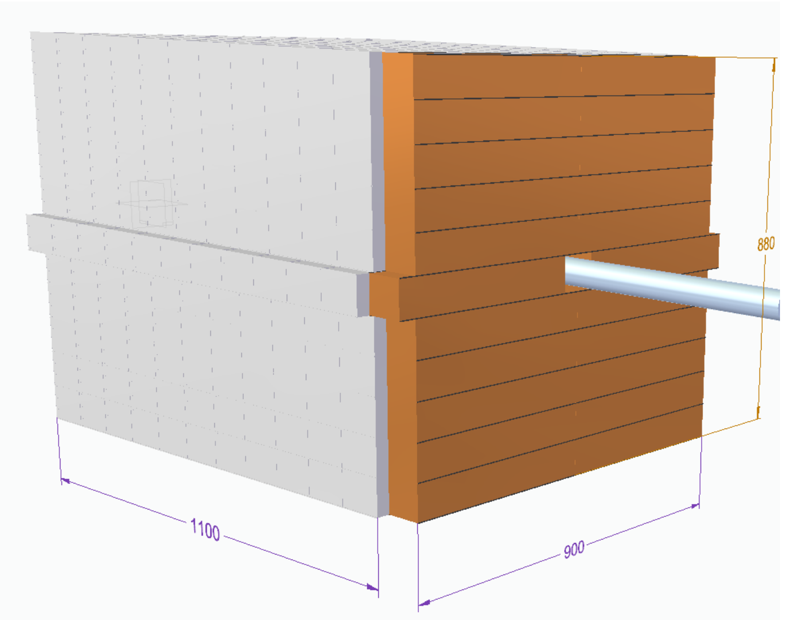


- Forward D^0 suppression observed by LHCb
- Consistent description with nuclear PDFs, with a large contribution from high x from fragmentation
  - Data constrain nPDF uncertainties by ~factor 2
  - Potential final state effects ignored
    - Small tension with ALICE mid-rap data
- Measurements with photons will verify factorization and universality



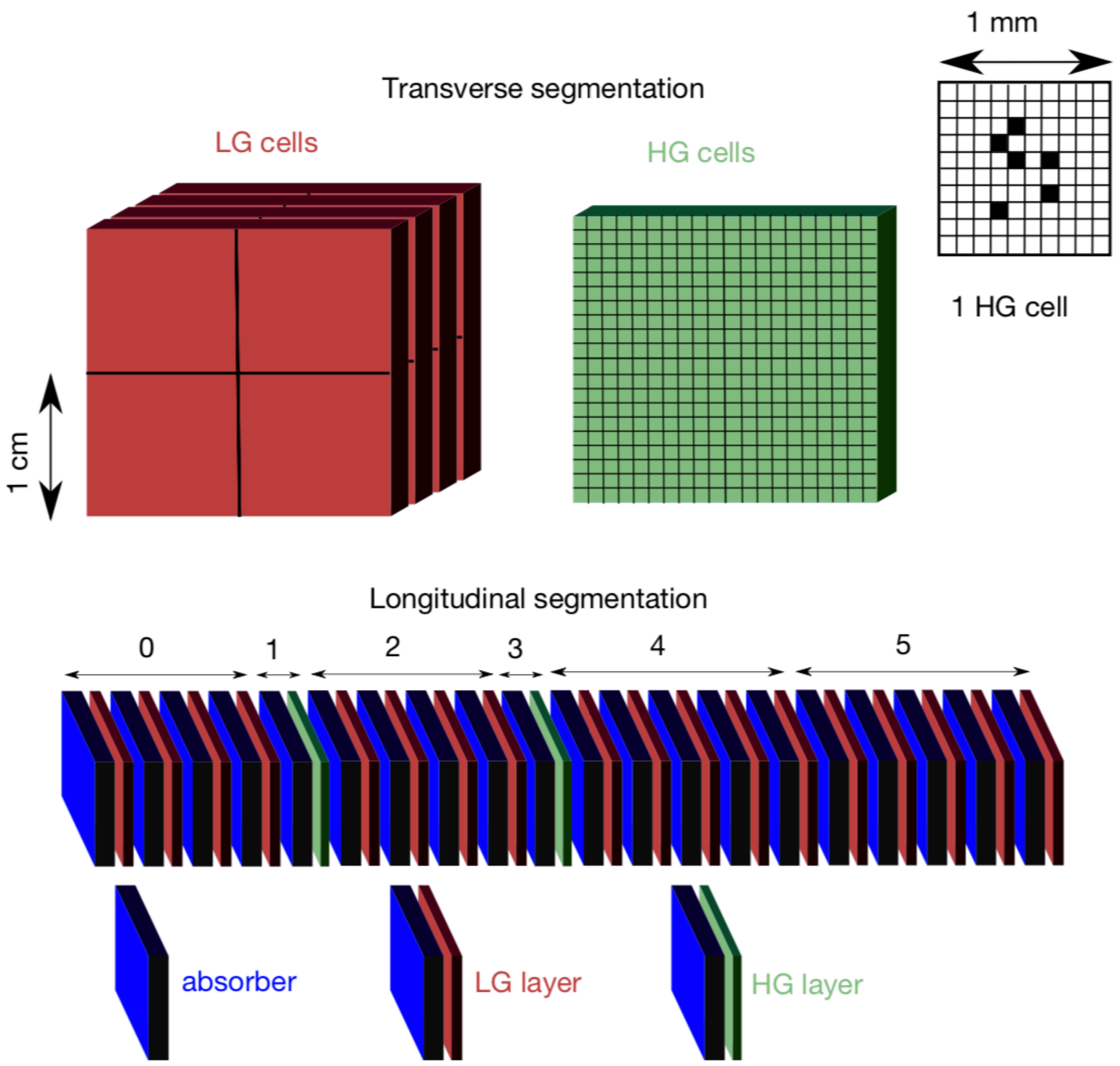
Kusina et al., PRL121 (2018) 052004   ALICE, arXiv:1906.03425

2. FoCal concept and physics performance



FoCal-E conceptual design

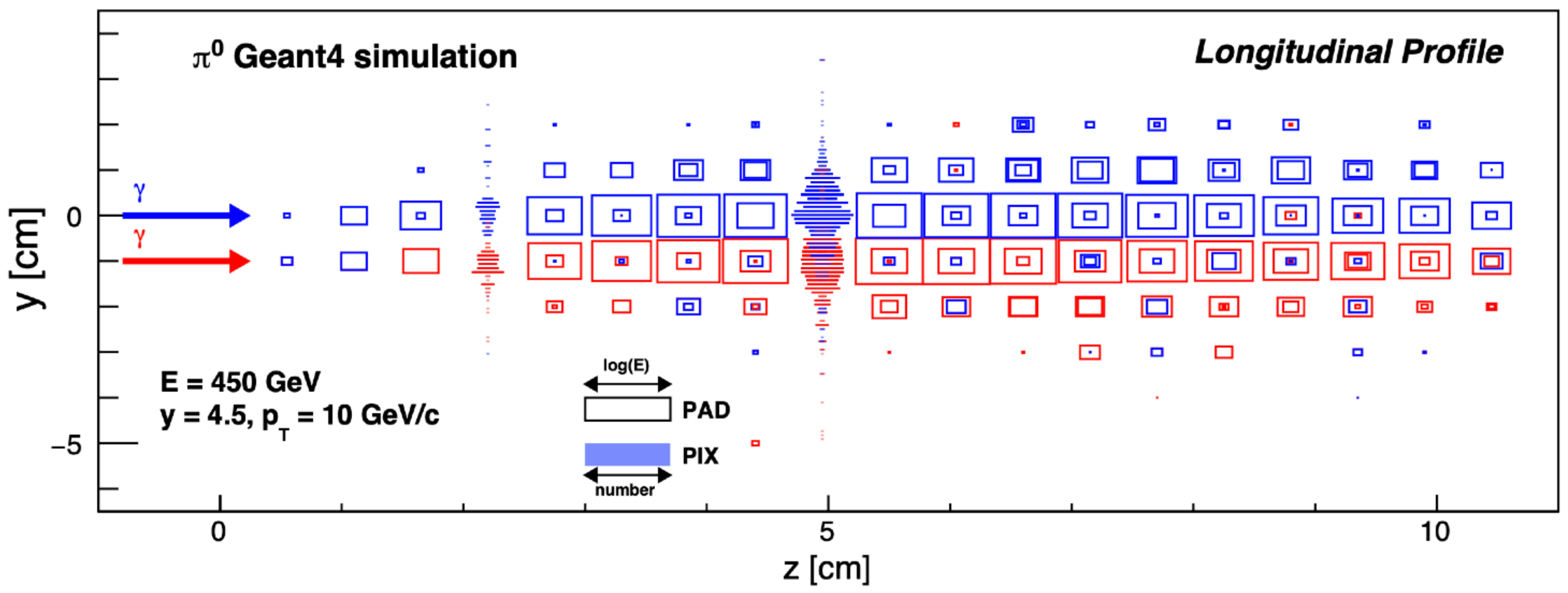
- Main challenge: Separate γ/π^0 at high energy
  - Two photon separation from π^0 decay (p_T=10 GeV, η=4.5) ~5mm
  - Requires small Molière radius and high granularity readout
  - Si-W calorimeter with effective granularity ≈ 1mm^2



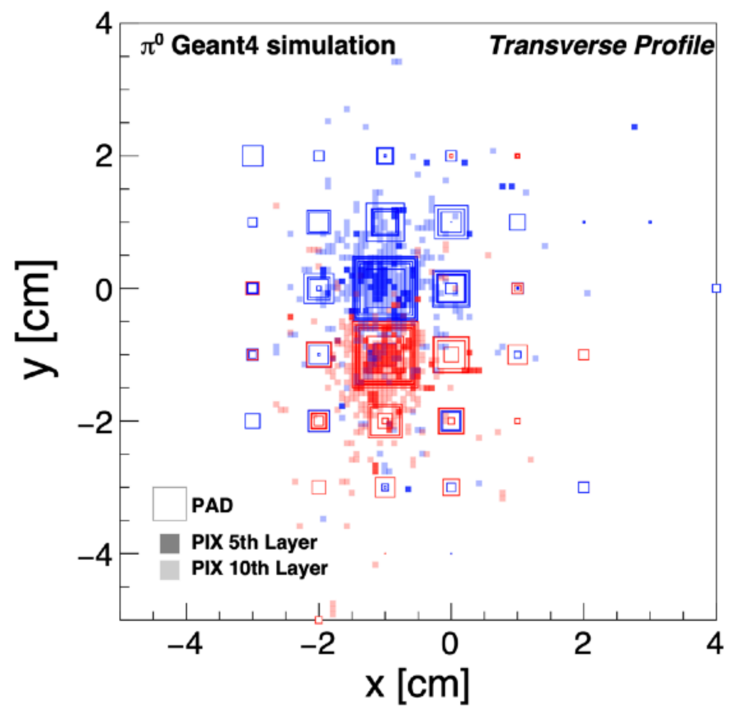
Studied in simulations 20 layers:
W(3.5 mm ≈ 1X_0) + silicon sensors
Two types: Pads (LG) and Pixels (HG)

- Pad layers provide shower profile and total energy
- Pixel layers (ALPIDE) provide position resolution to resolve overlapping showers

Longitudinal profile (2γ showers)



Trans. profile



Further optimization left for TDR:

- Location of pixel layers
- Number of pad layers
- Sensitive area at front for CPV/eID

Rapidity coverage and π^0 efficiency

position z = 7m
beam pipe radius 3.5cm

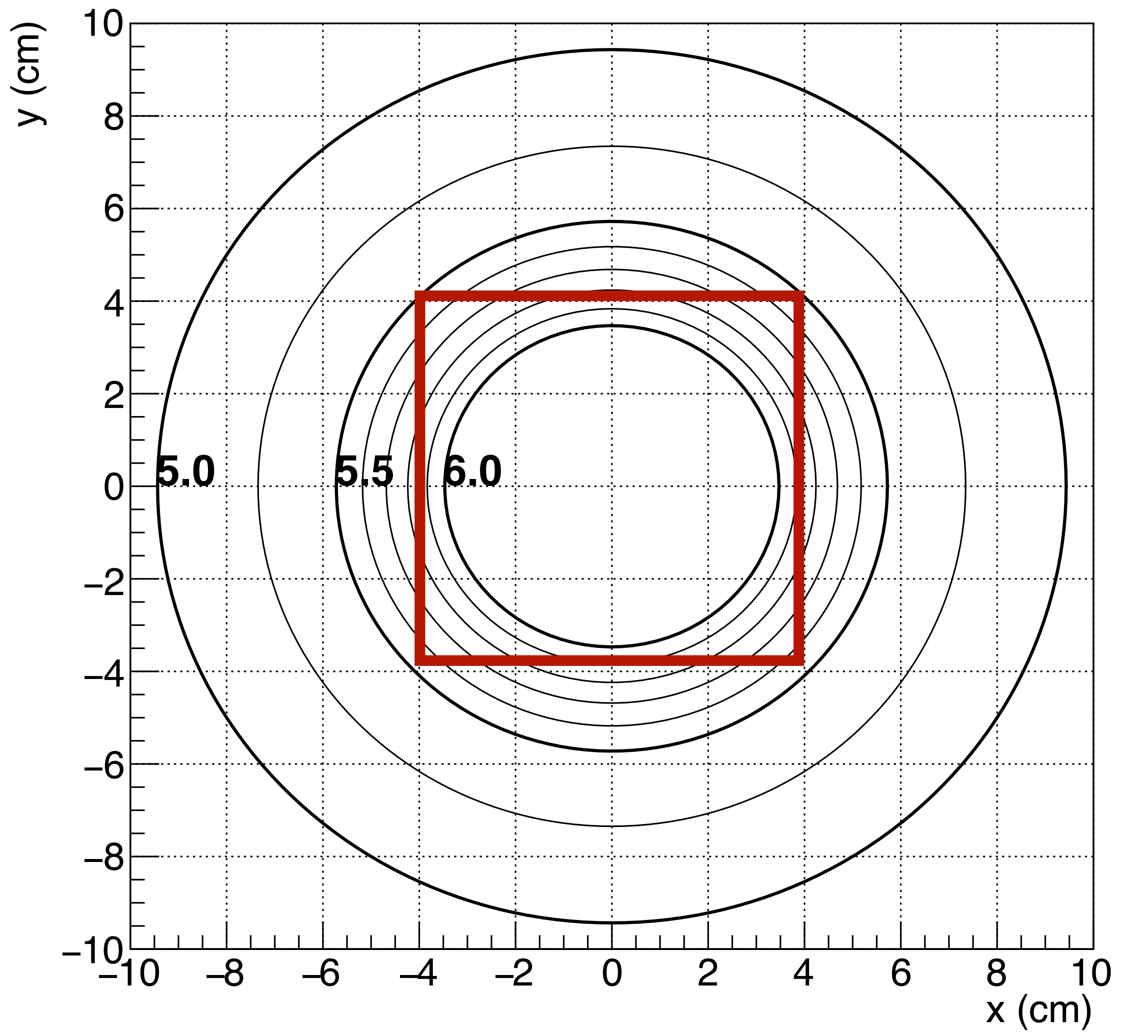
8x8cm square around beam:
maximum rapidity 5.5-5.8

2-gamma distance gets small beyond η=5.5:
→ sharp drop at R_{min} plus effect of circle vs square

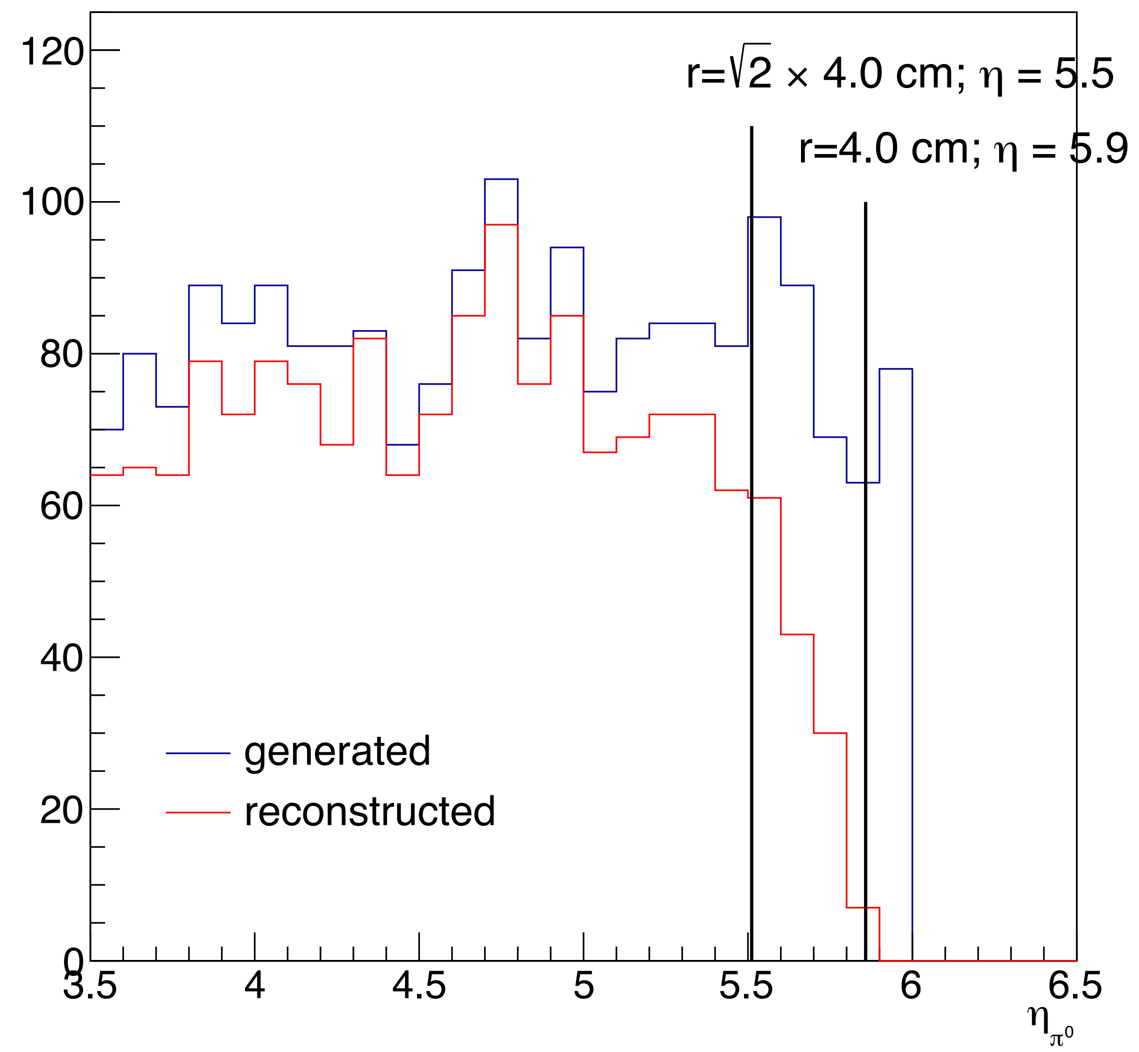
Very high π^0 efficiency
up to η = 5.5
(falls off above p_T = 10 GeV
due to 2-gamma distance)

80-90% π^0 efficiency above p_T=2GeV

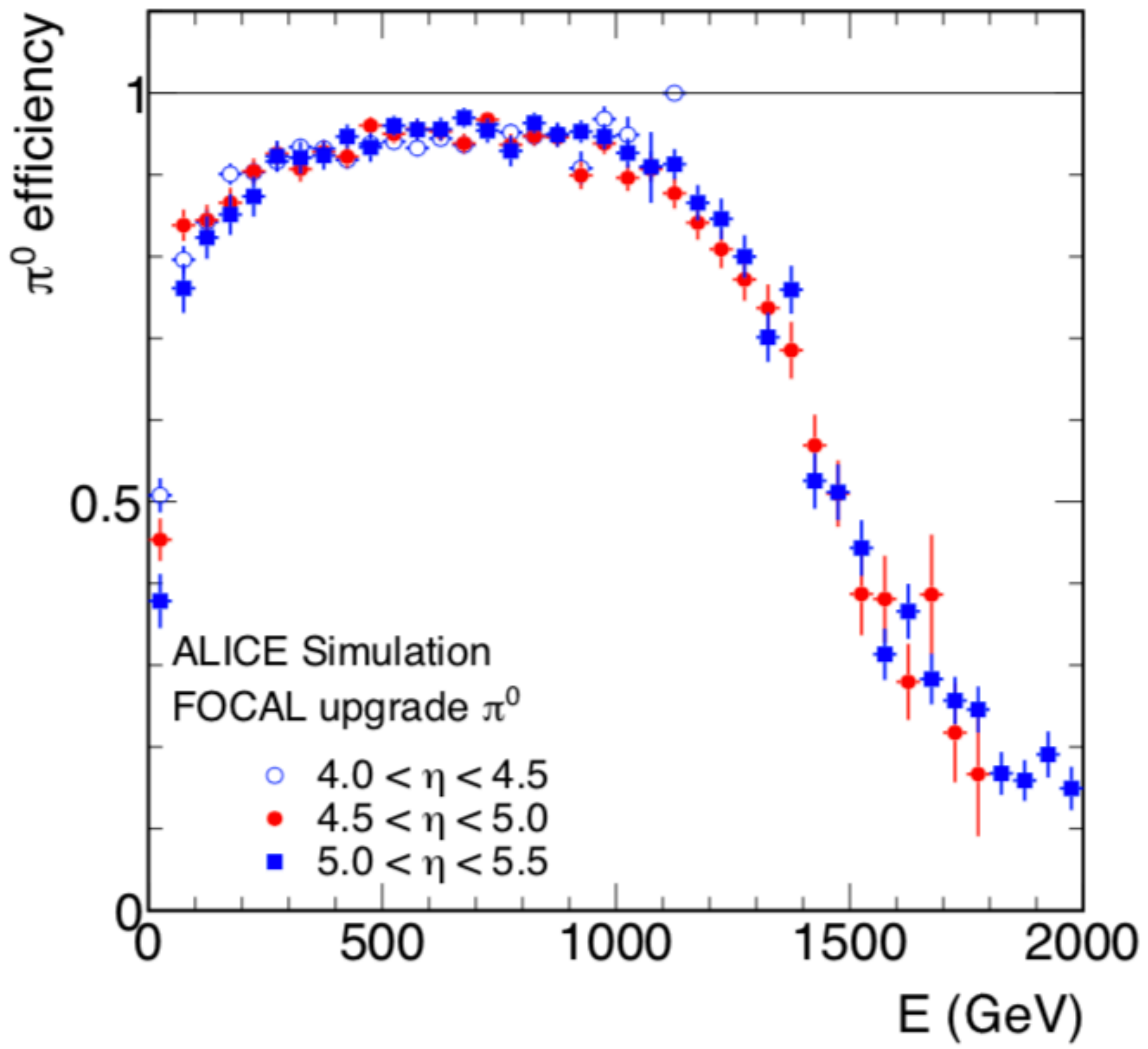
z = 700 cm



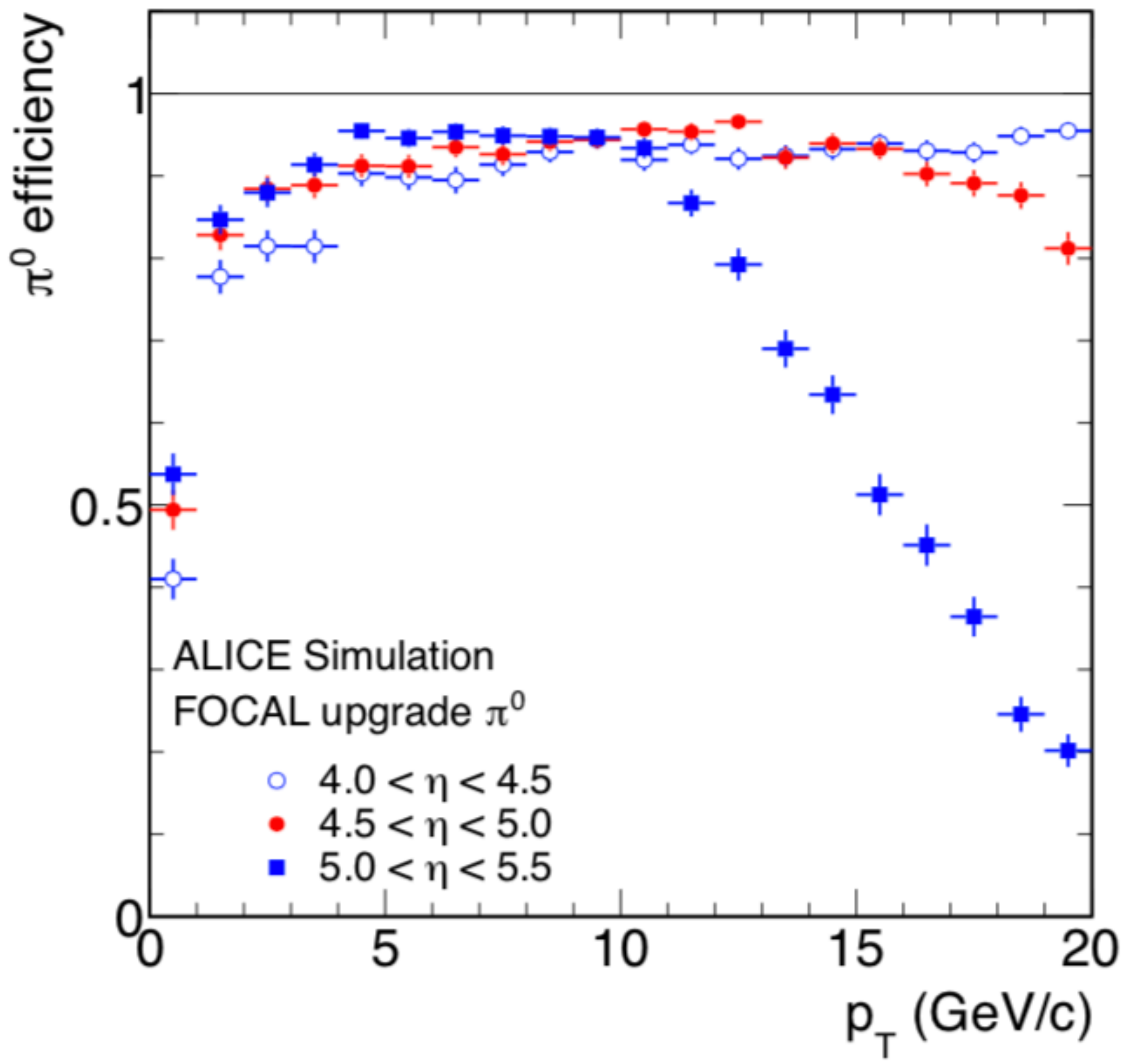
π^0 rapidity distribution



Single π^0 efficiency vs E



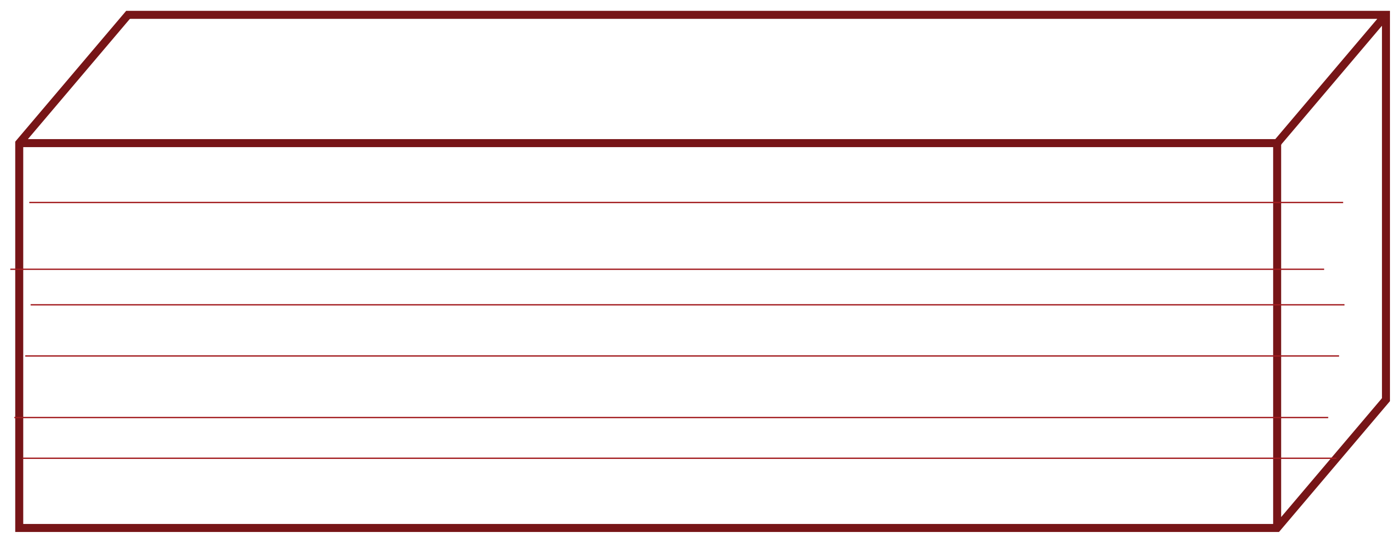
Single π^0 efficiency vs p_T

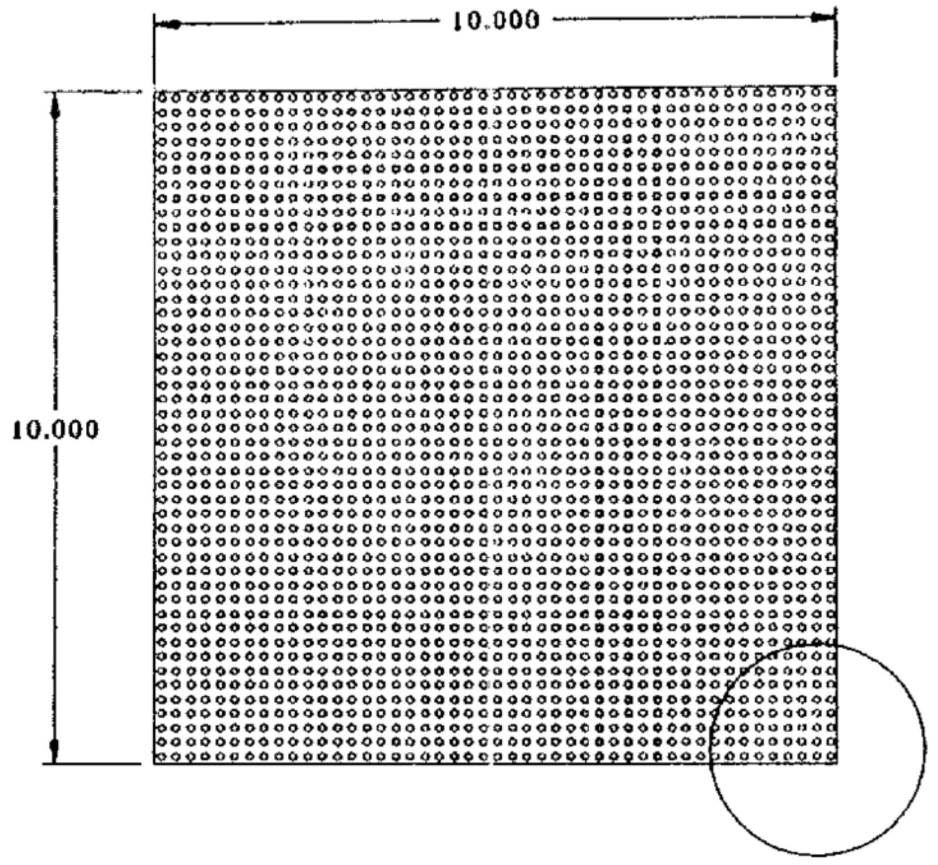


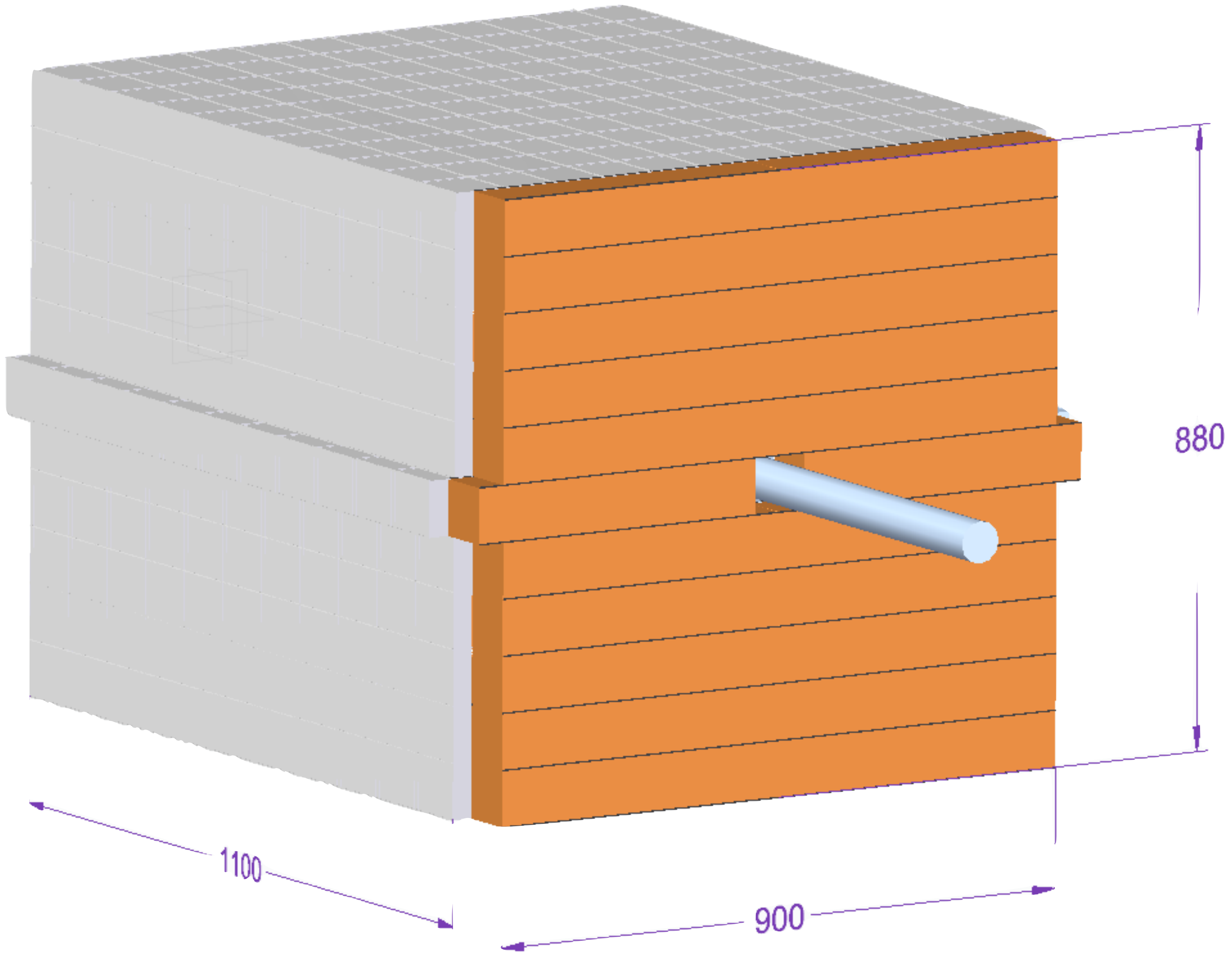
FoCal-H conceptual design

Geometry can be based on
SPACAL design: spaghetti calorimeter

Nuclear Instruments and Methods in Physics Research A 406 (1998) 227–258





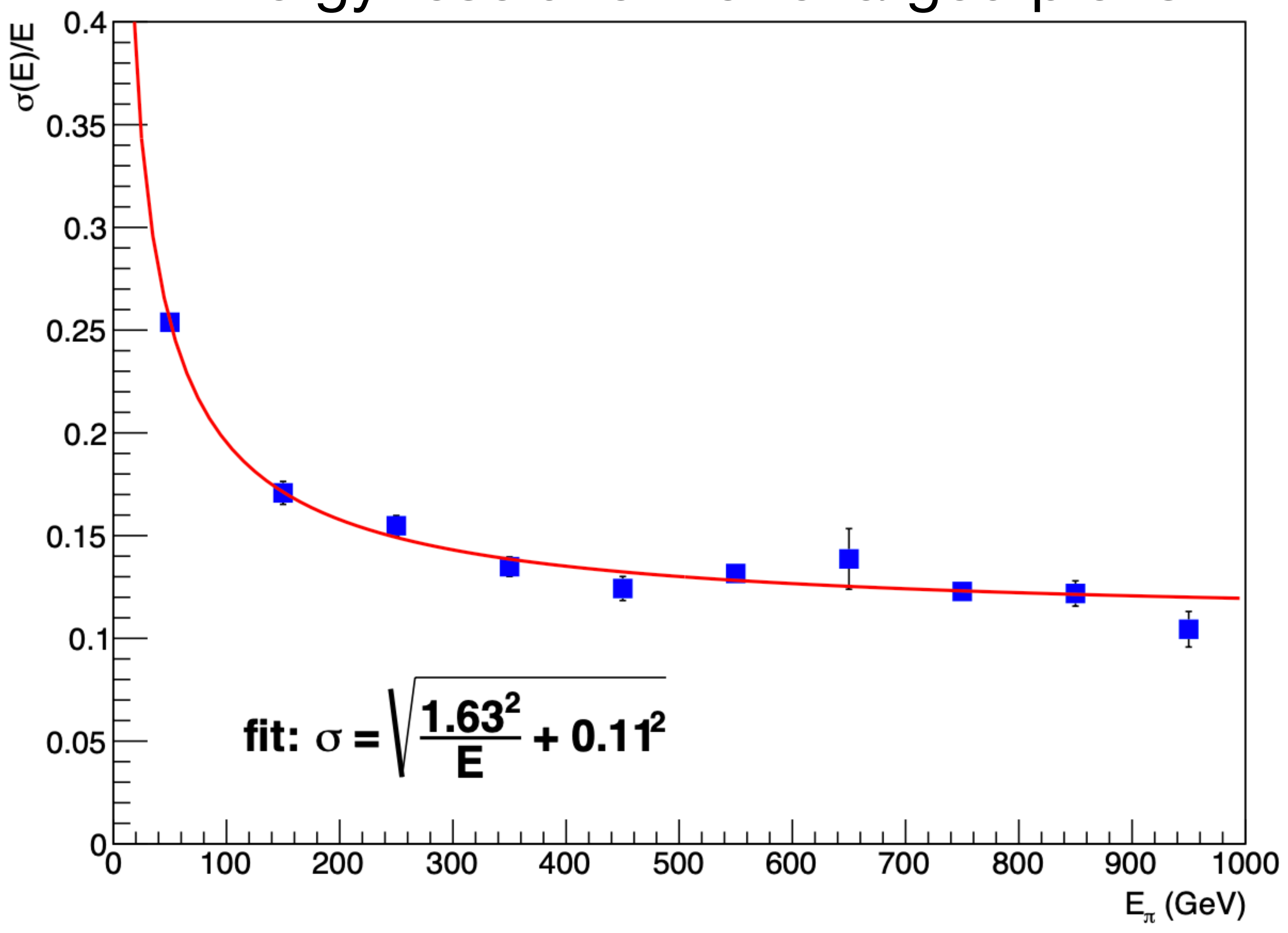


1.1 m long: ~6 λ_I

Tower size: 2-5 cm

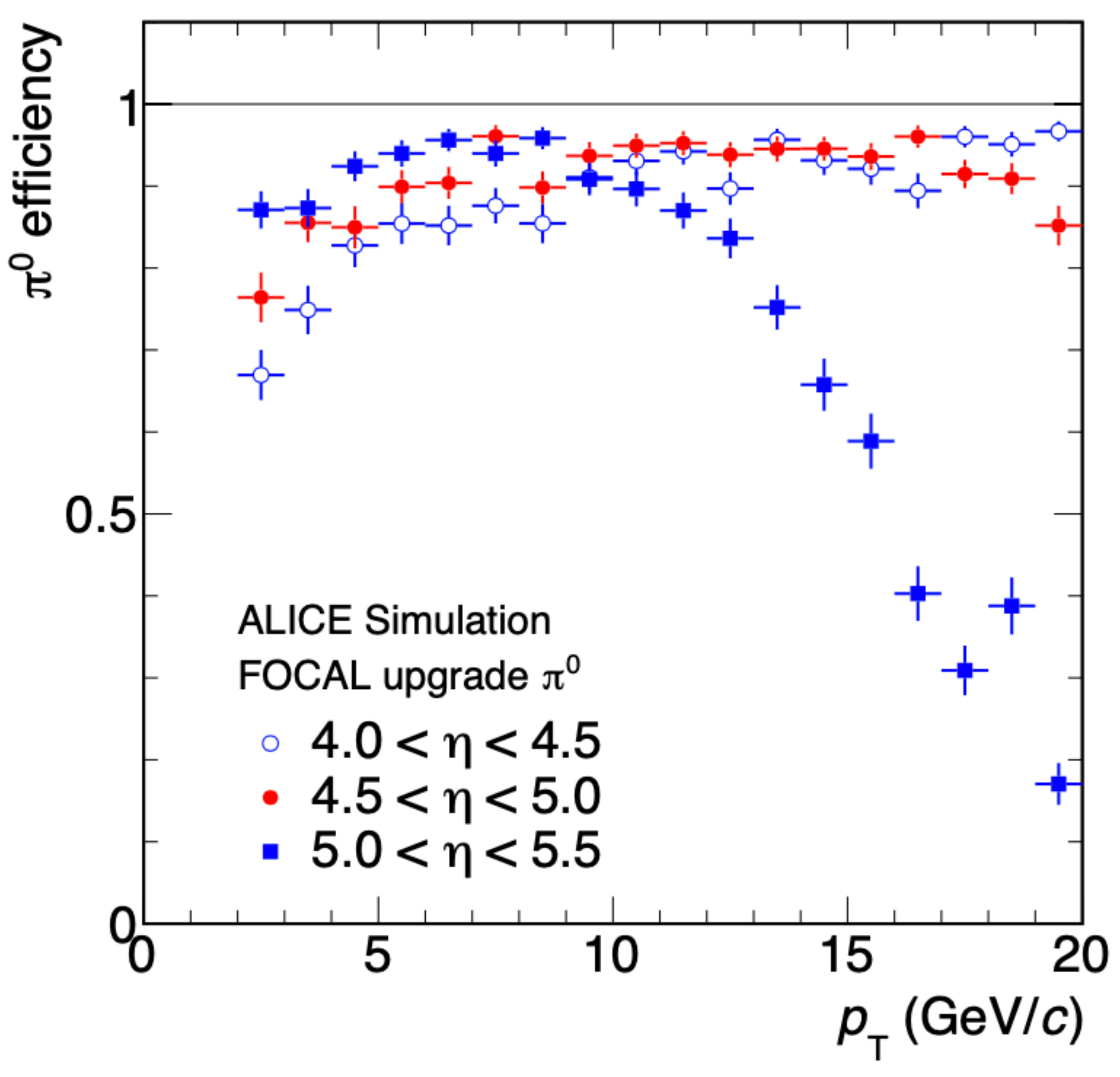
~1k towers

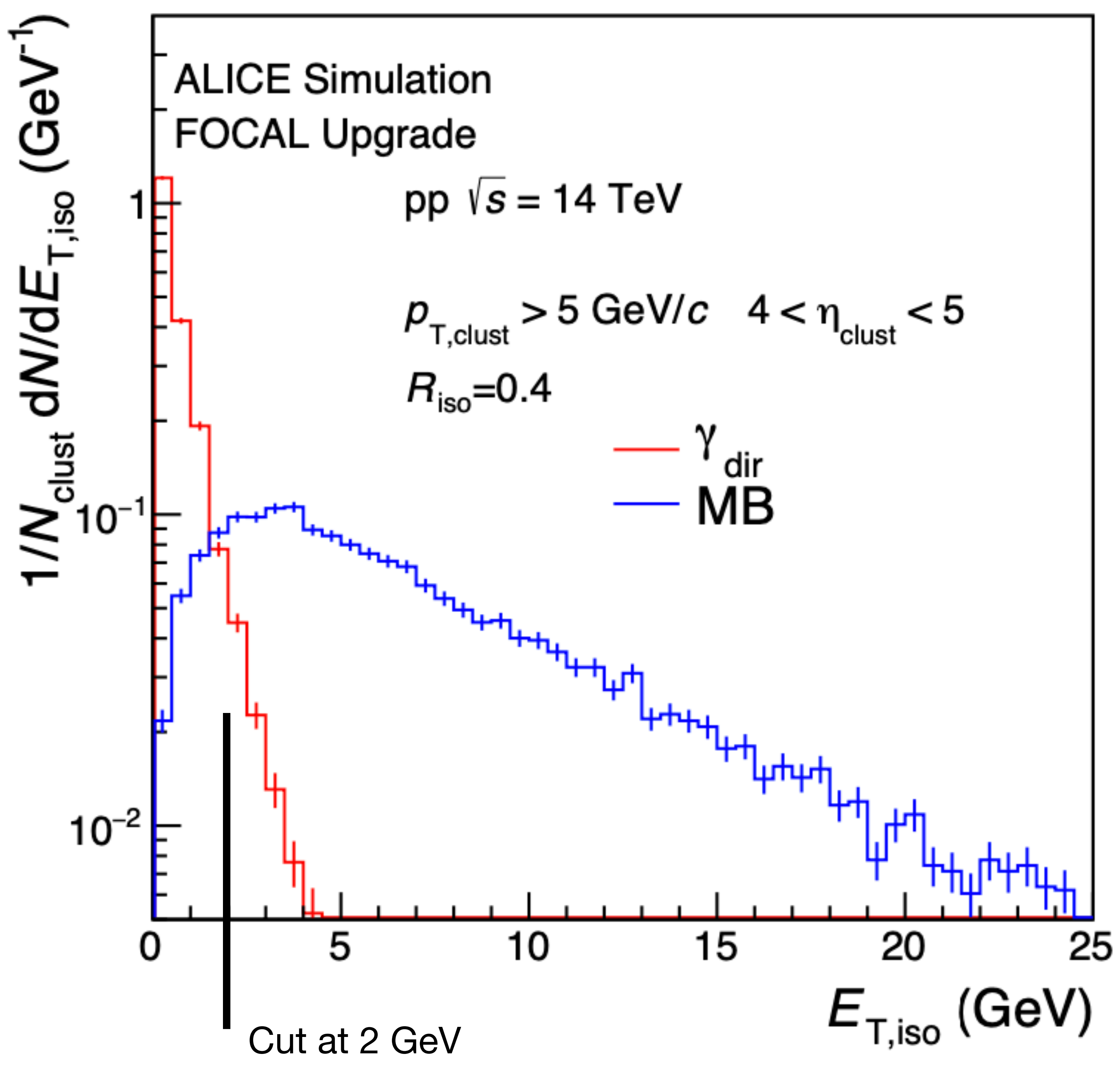
Energy resolution for charged pions

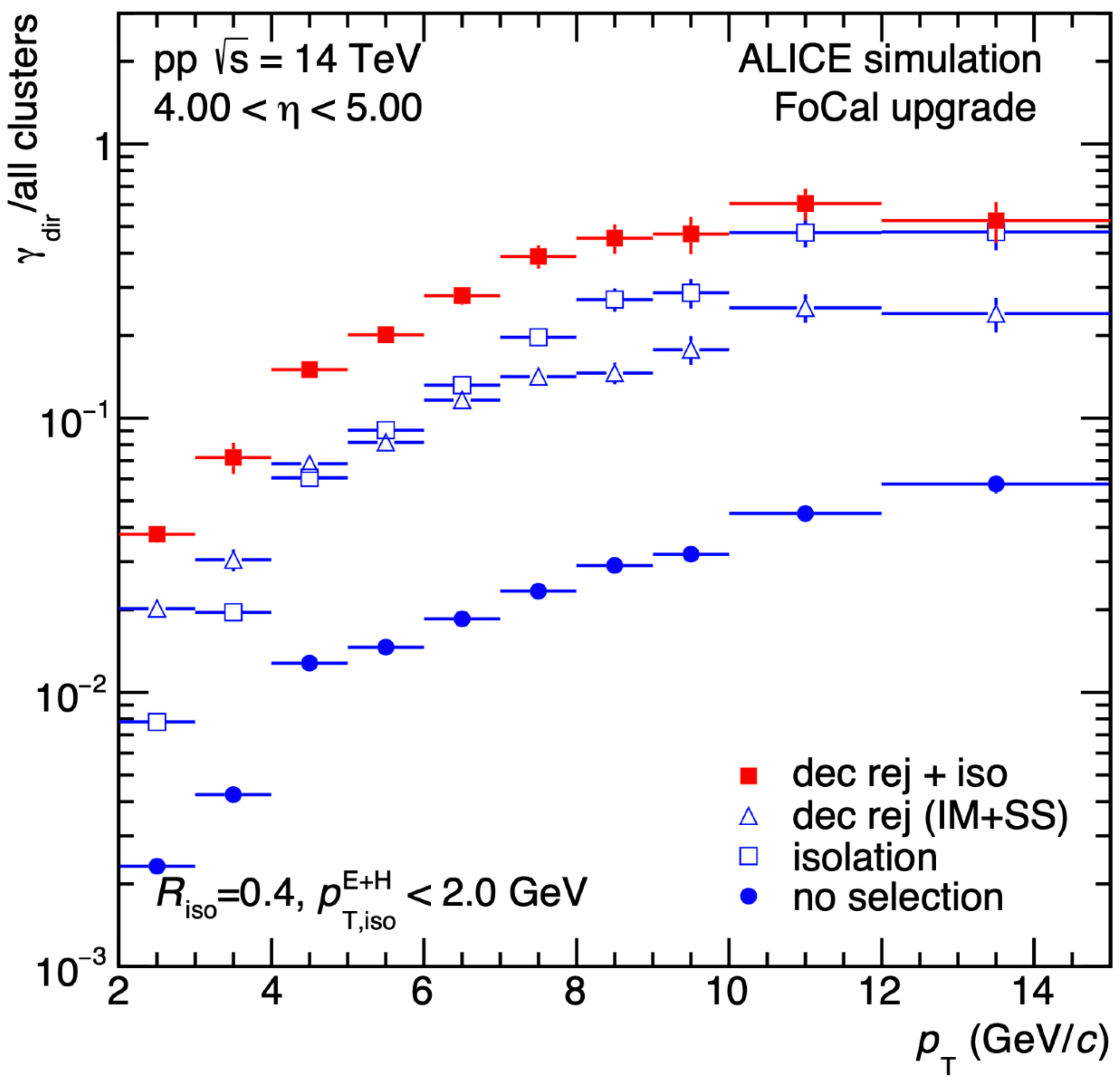


- Conventional metal-scintillator design
  - Sampling / tower structure not yet defined
  - No longitudinal readout required
- Simulation uses sandwich-structure:
  - 34 layers of 3cm absorber and 0.2cm scintillator
- Good performance for isolation and jets
  - Single hadron energy resolution of 10-25%
  - E_T = 2 GeV for isolation about E = 100 GeV at $\eta = 4.5$
  - Constant term (e/h compensation) more, sampling-fraction less important

Key ingredients for isolated photon measurement


π^0 reconstruction efficiency


Isolation energy distribution

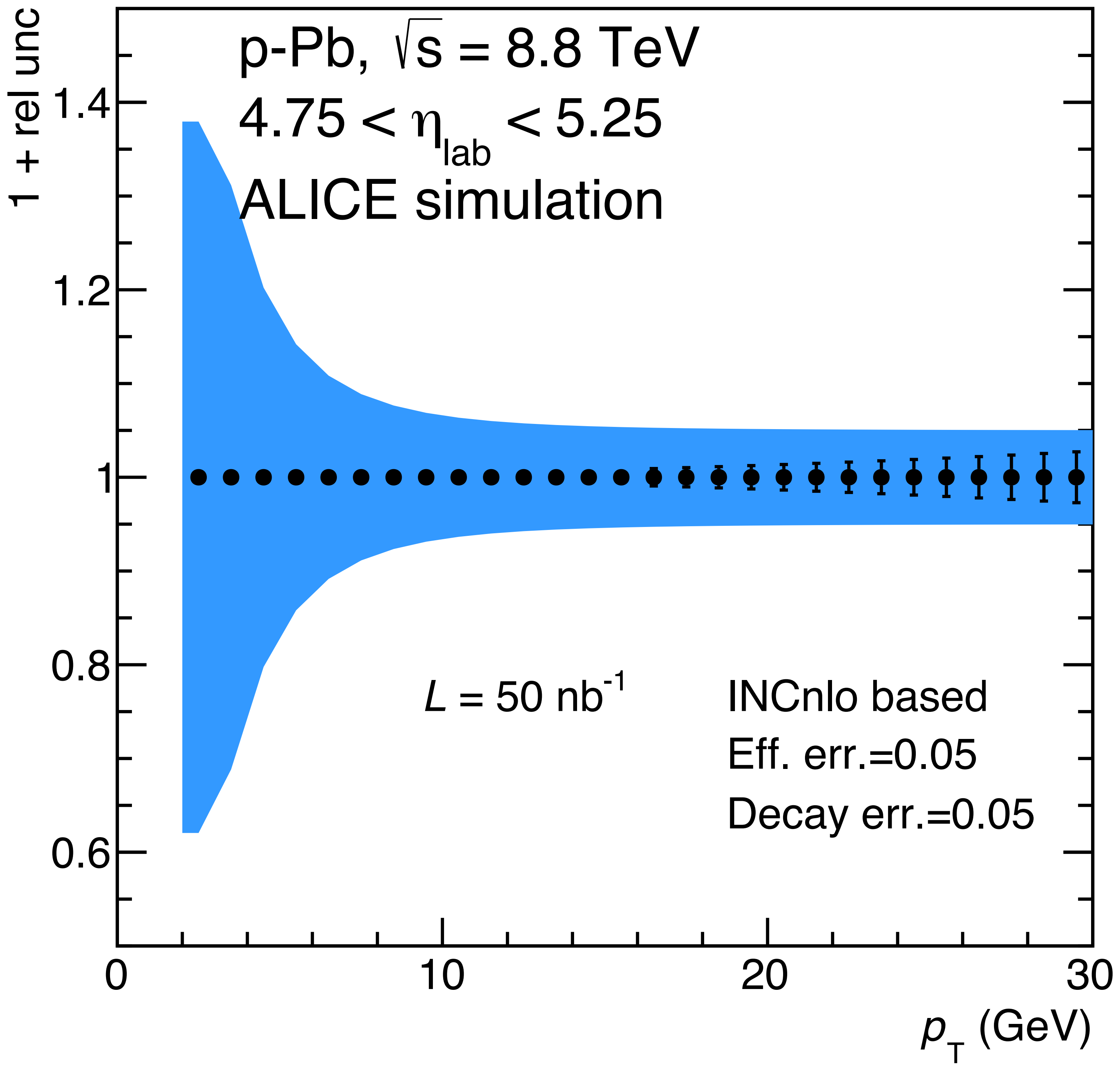

Direct γ/all cluster ratio

Main ingredients for direct photon identification

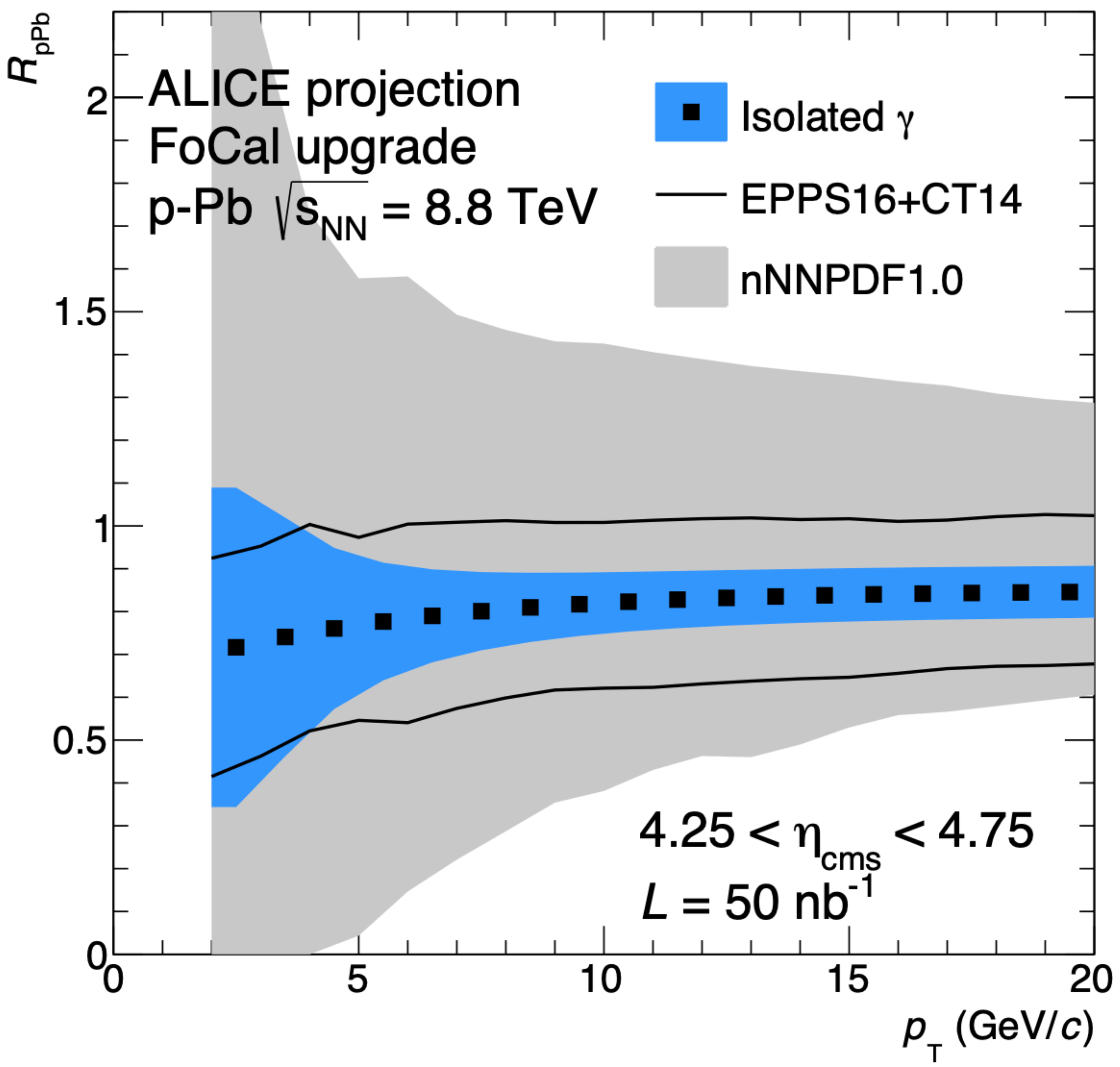
- π^0 reconstruction efficiency: measure background
- Isolation cut (EmCal + HCal)
- Rejection of decays by invariant mass reconstruction

Improvement in signal fraction by factor ~10 to ~0.1-0.6

Expected performance and impact on nPDF

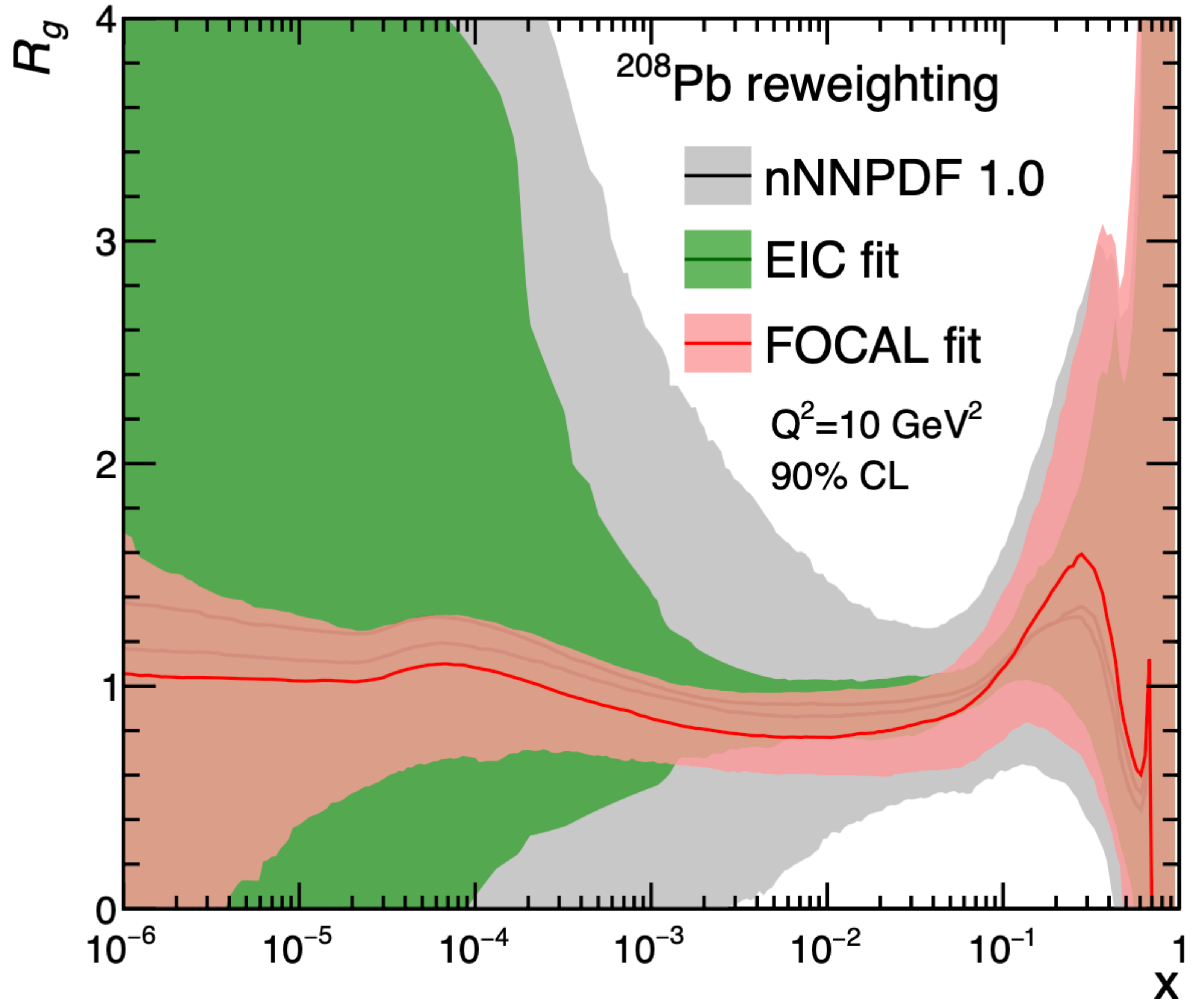


- Systematic uncertainty ~20% at ~4 GeV
- Below ~6 GeV, uncertainty rises due to remaining background



- Significant improvement (up to factor 2) on EPPS16 gluon PDF
- Similar improvement as from open charm
  - Test factorization/universality
- Below 4 GeV: challenging regime
  - Also measure direct photons by statistical subtraction

R. Khalek et al.,
arXiv:1904.00018

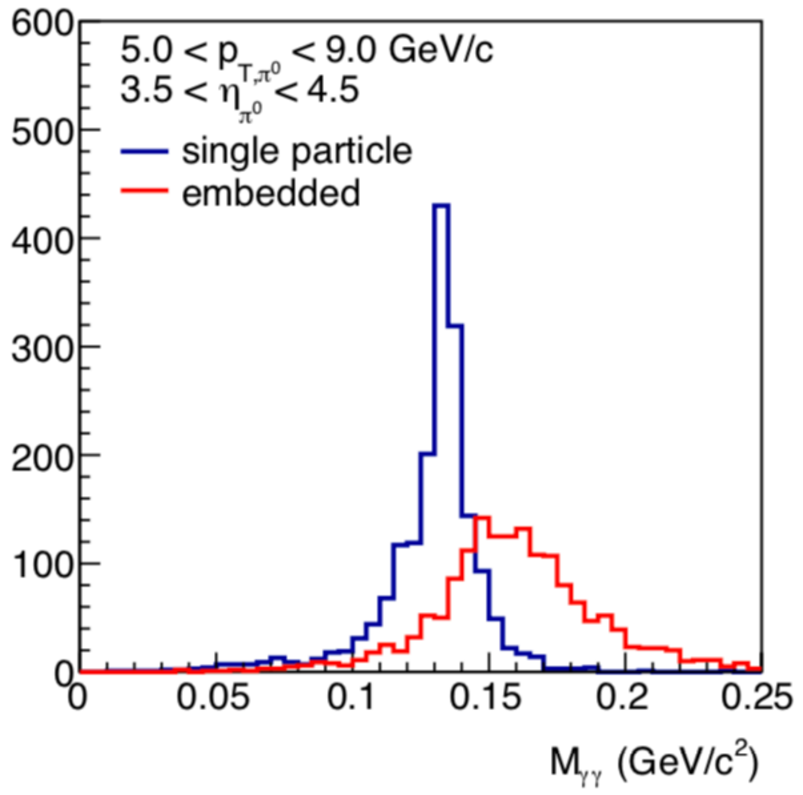


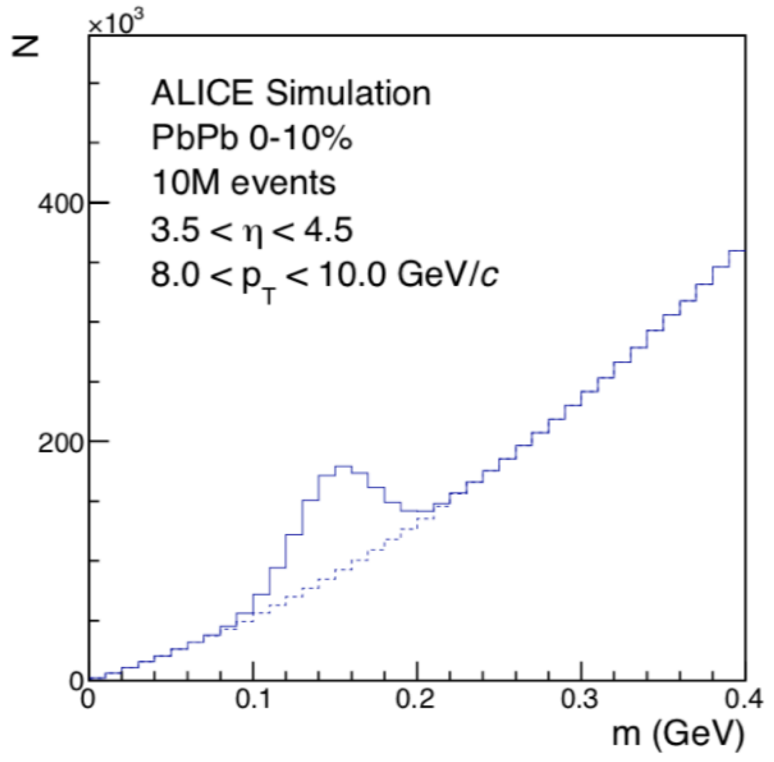
Recent nuclear PDFs: nNNPDF from DIS and minimal theoretical assumptions

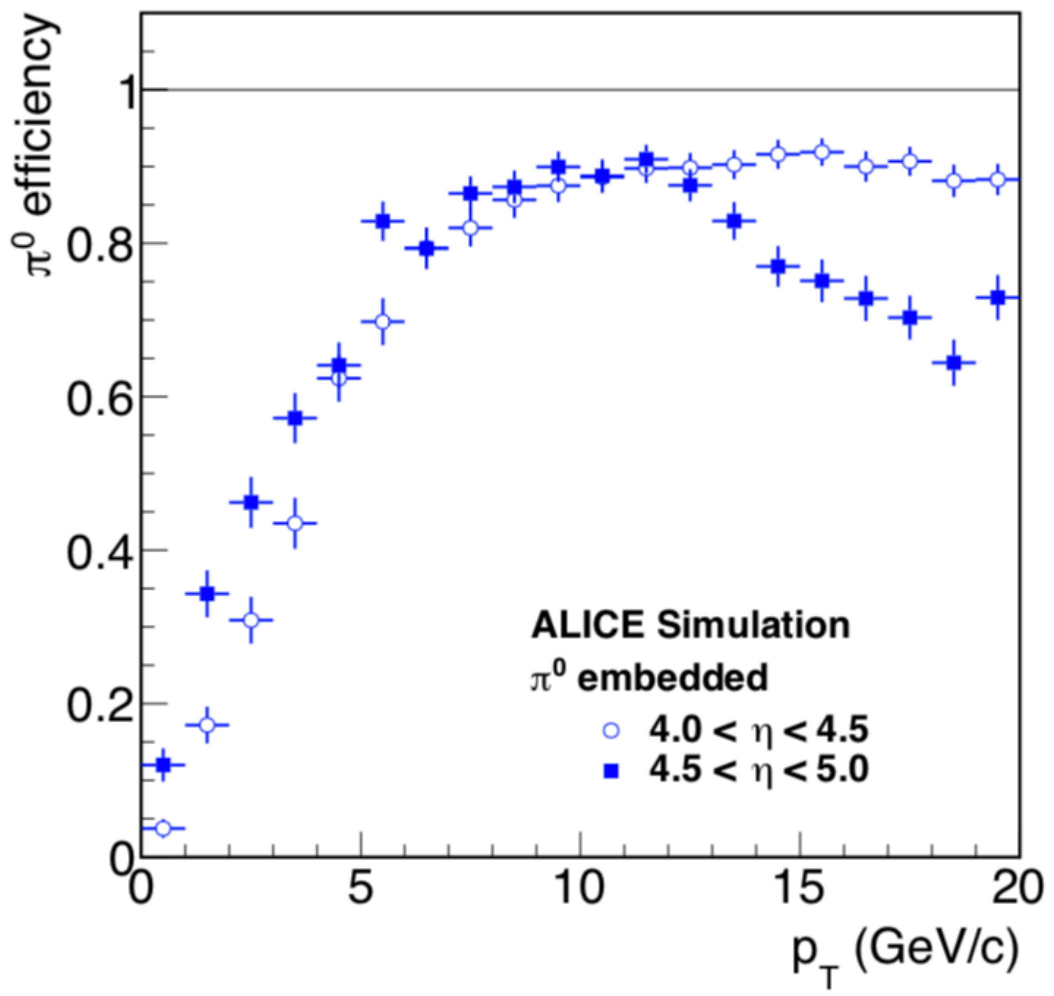
- No constraints for x < 10^{-2} from DIS
- FOCAL provides significant constraints over a broad range: ~10^{-5} - 10^{-2}
- Outperforming the EIC for x < 10^{-3}

Performance in PbPb and other observables

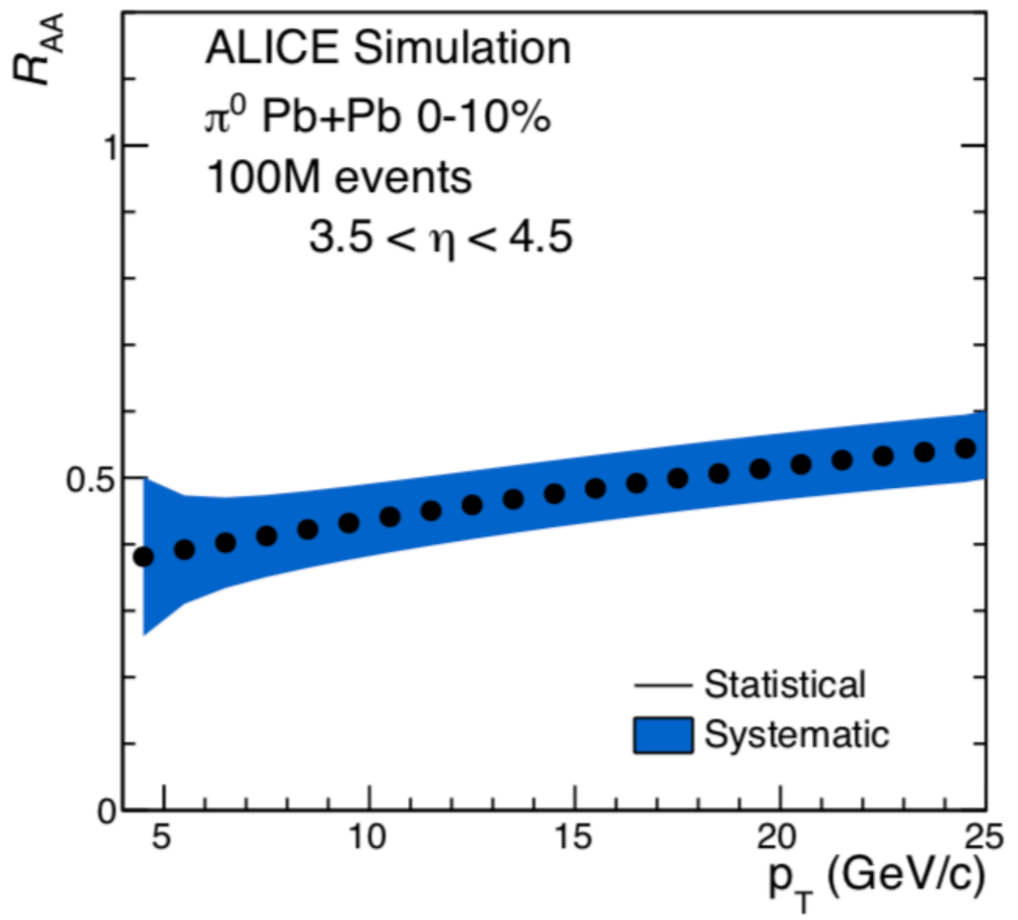
Performance in PbPb







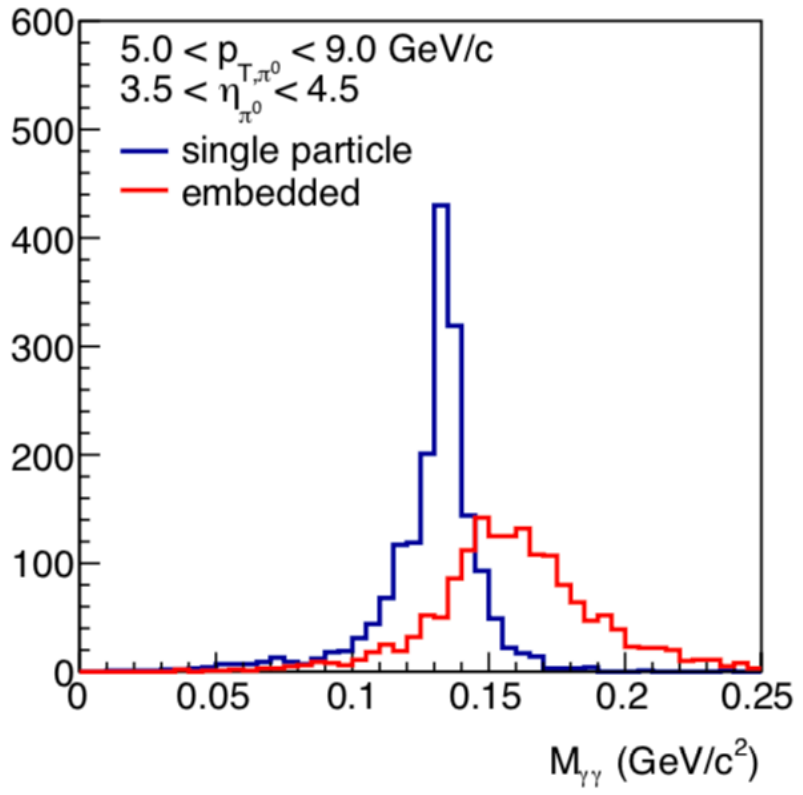
- Performance in PbPb affected by shower overlaps and combinatorial background
- Efficiency for high energy neutral pions nevertheless quite good
- Combinatorial background may prohibit very low p_T reconstruction, but above 5 GeV expect a precise R_{AA} measurement

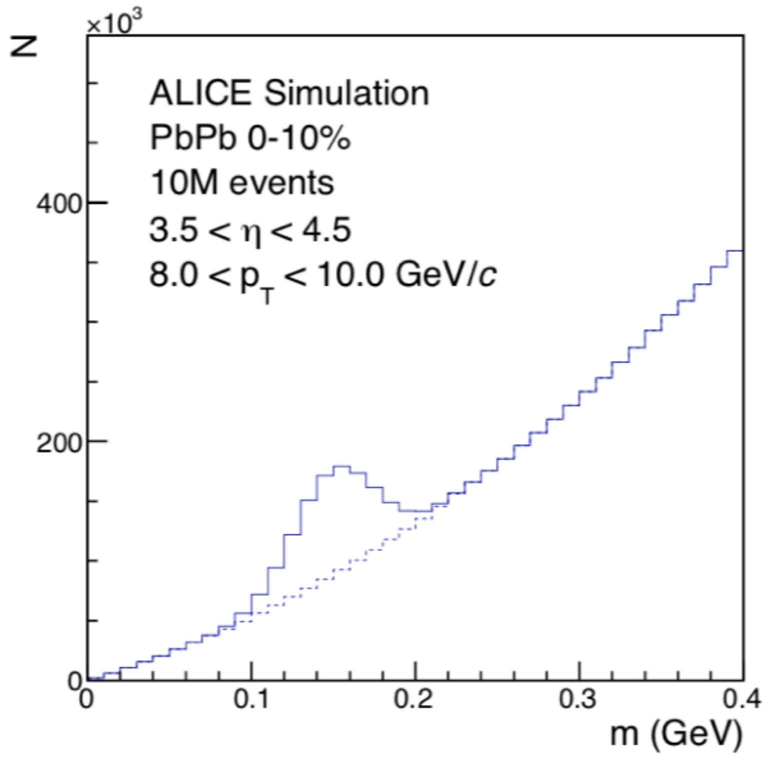


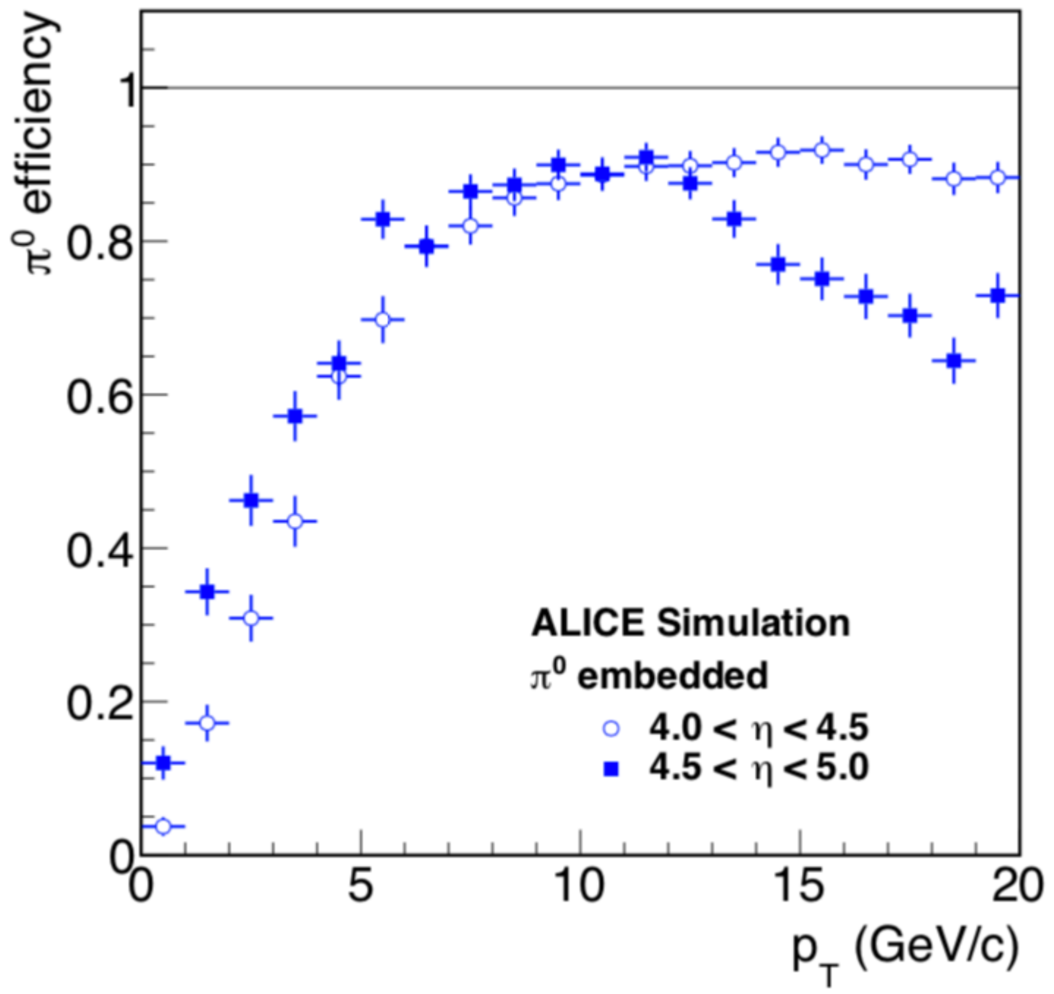
Letter-of-Intent focused on isolated direct photon measurement as the core of the program;
Broader program to be studied for TDR: correlation measurements; UPC; PbPb

Performance in PbPb and other observables

Performance in PbPb







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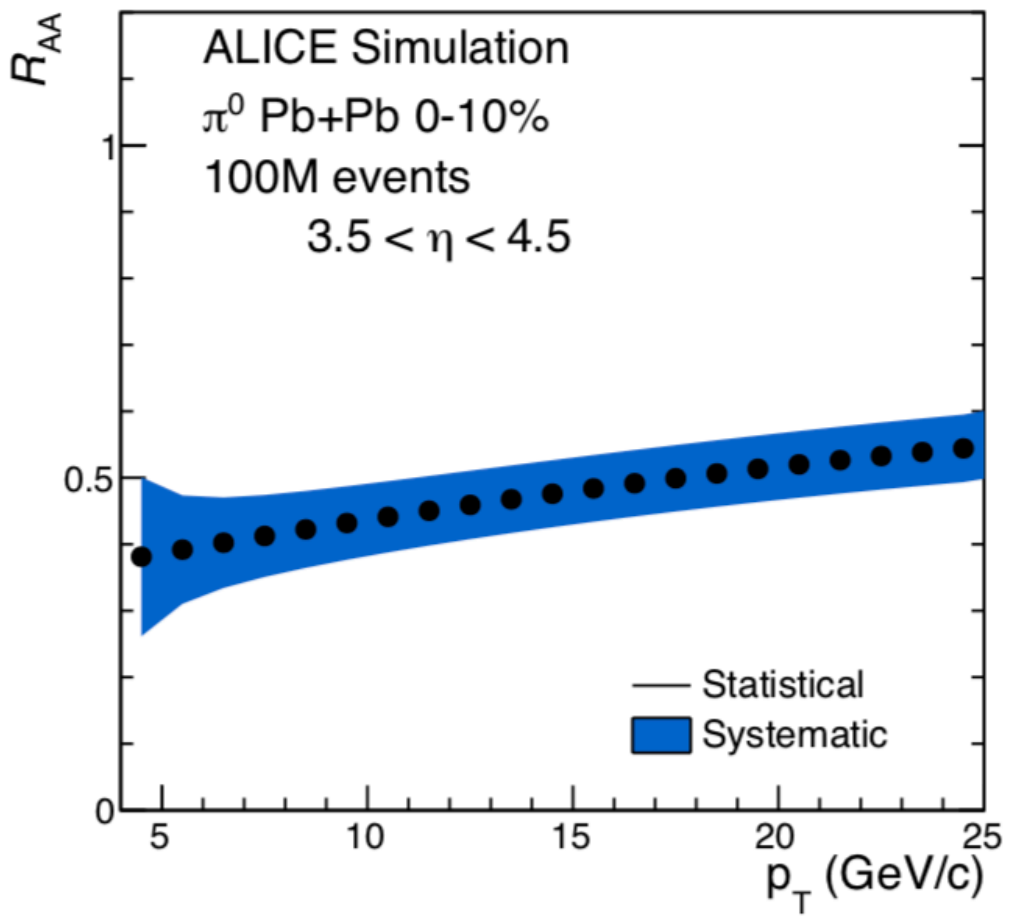
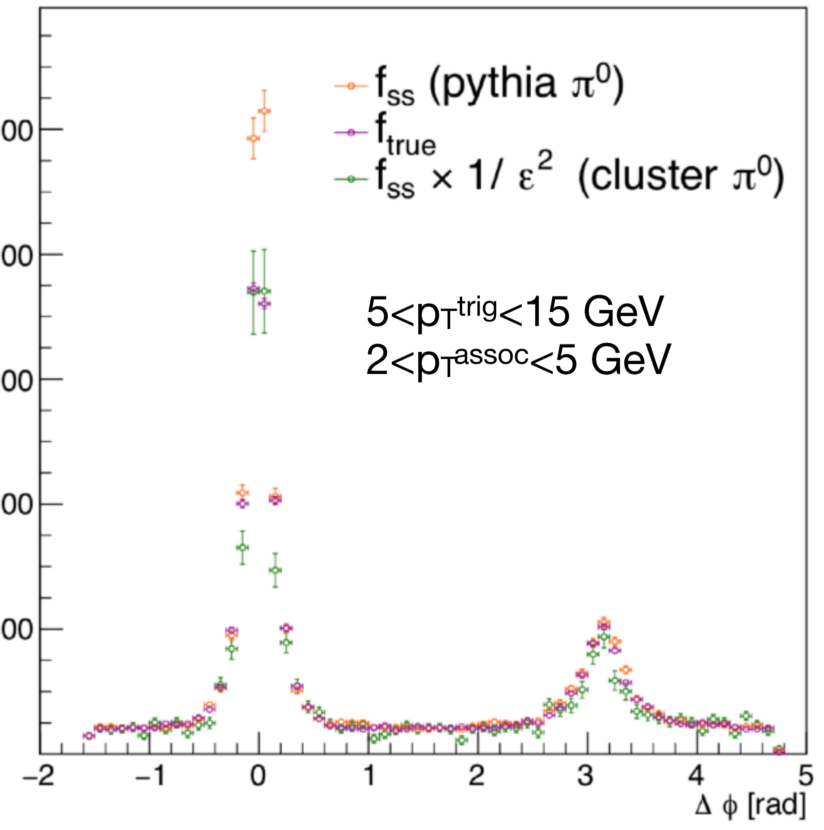
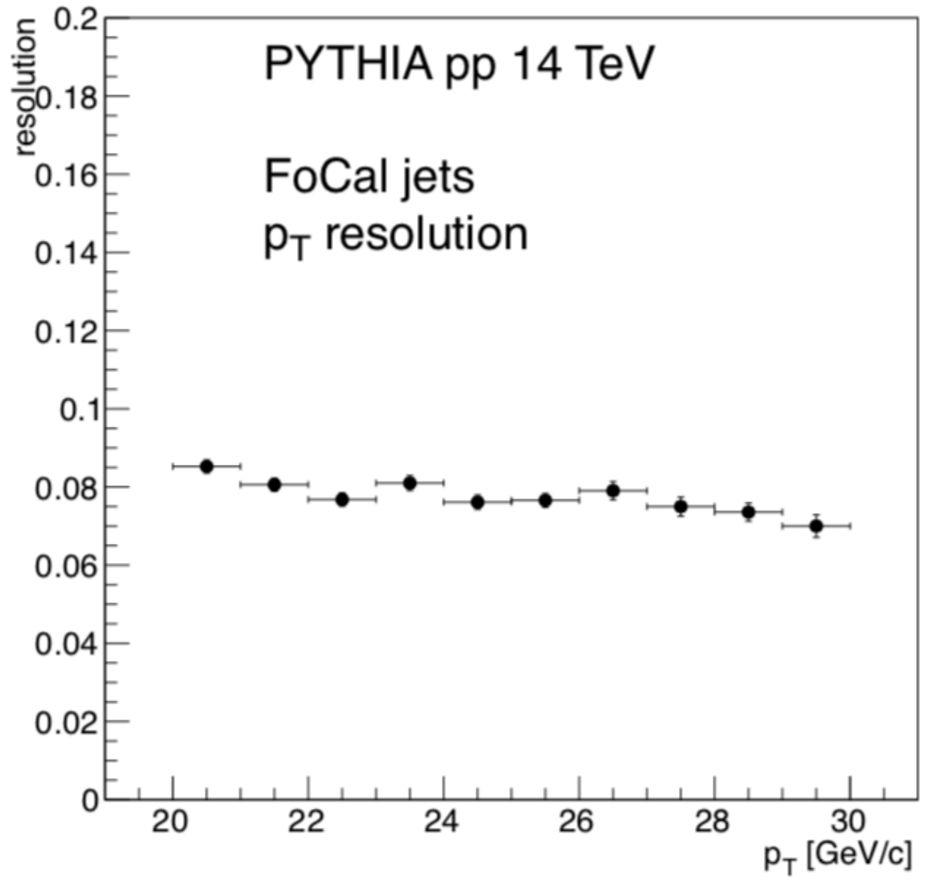


Other observables

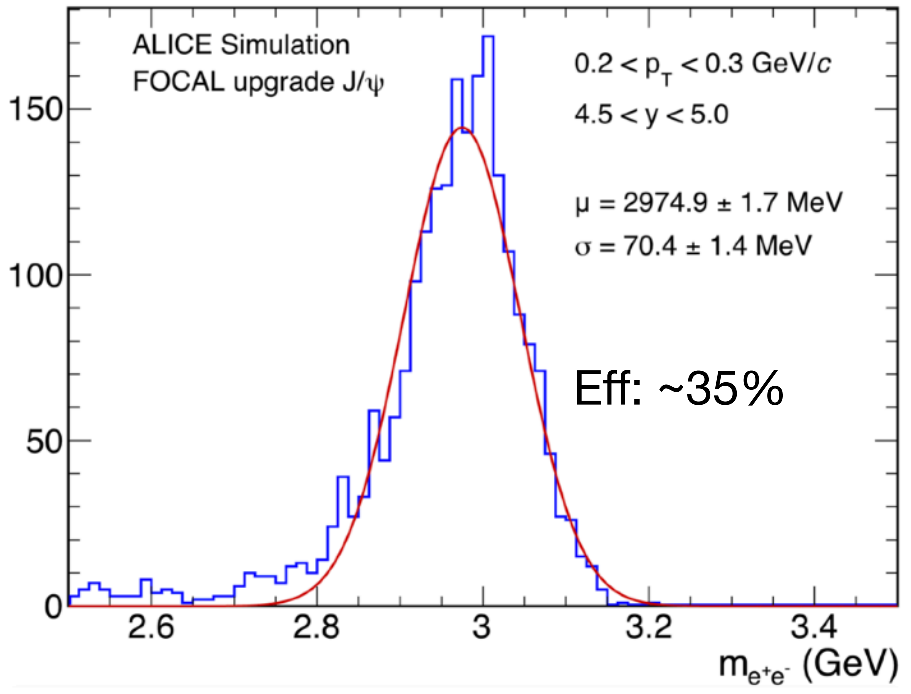


π^0-π^0 correlations in pp
(for decorrelation studies)



Jet resolution
(jet/dijets in pp/pPb/UPC)

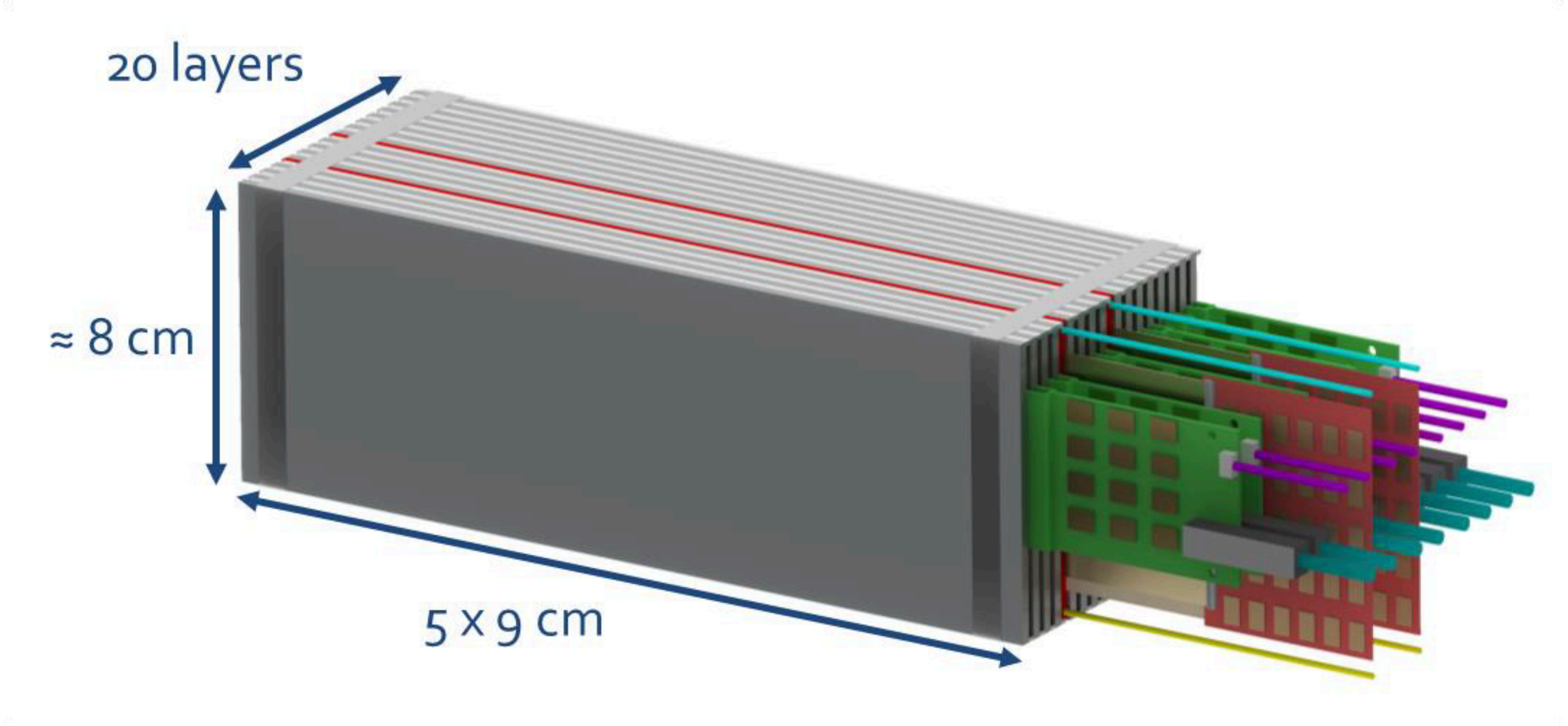
- Promising performance for other key observables
- To be studied in more detail for TDR



J/ψ reconstruction
(in UPC)

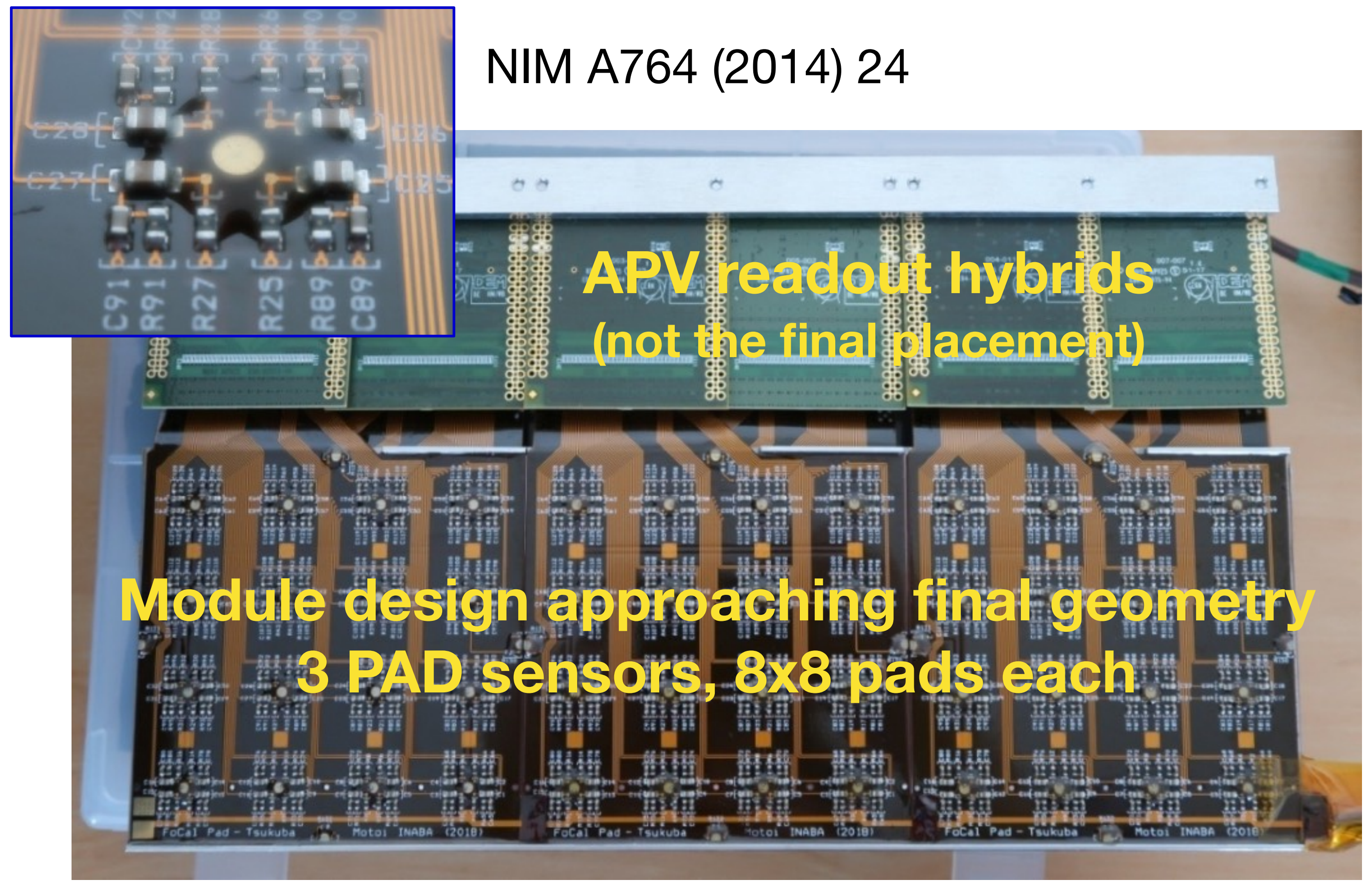
Letter-of-Intent focused on isolated direct photon measurement as the core of the program;
Broader program to be studied for TDR: correlation measurements; UPC; PbPb

3. R&D and test beam results



Prototypes (since ~2014)

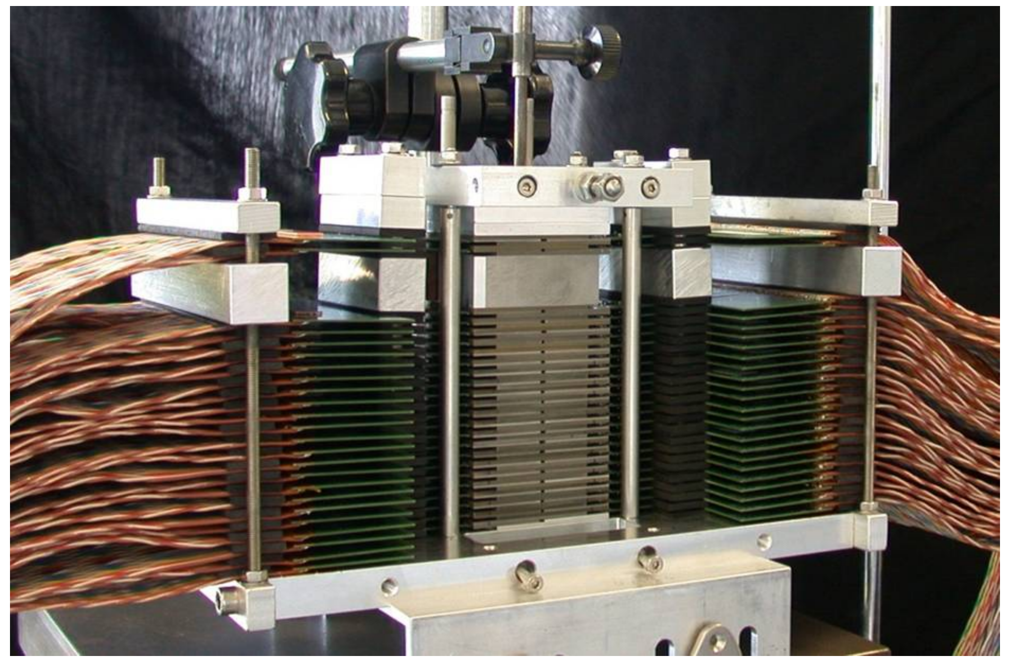
Pads connected to flex PCB



NIM A764 (2014) 24

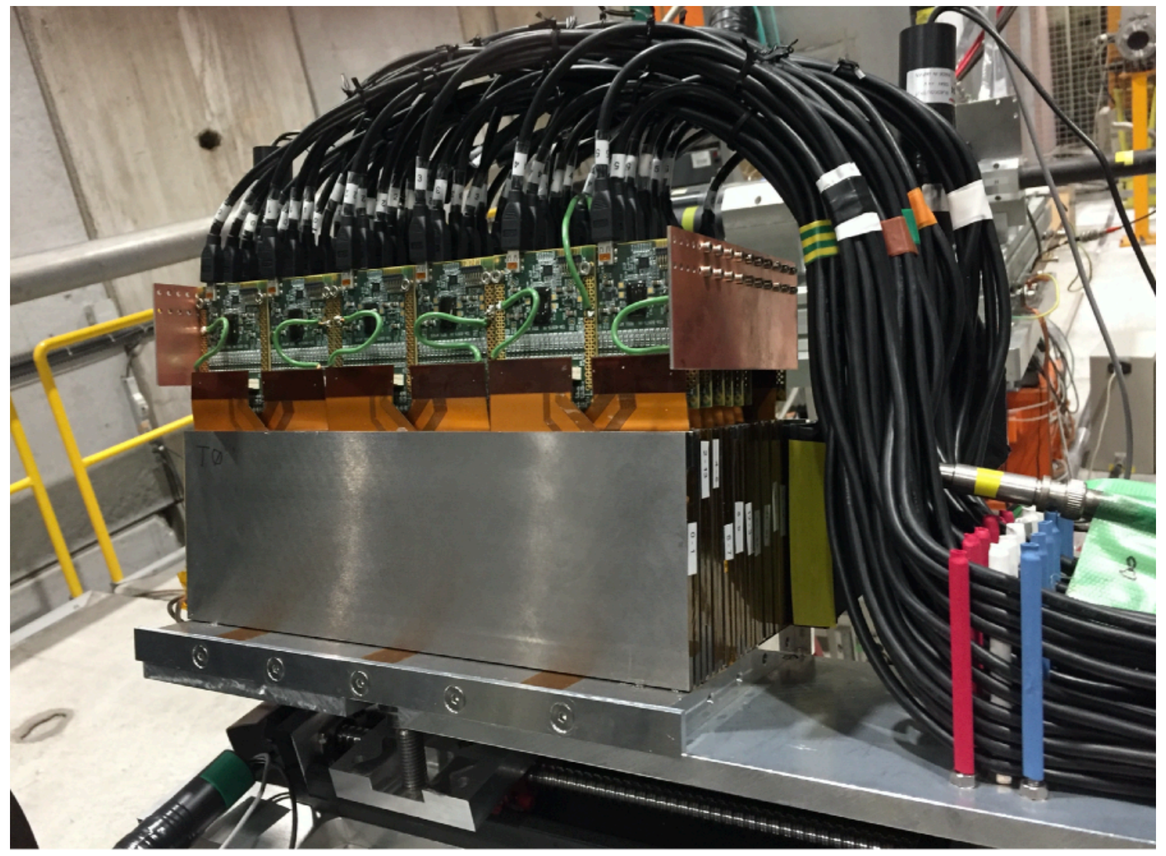
JINST 15 (2020) 03, P03015

Full pixel - MIMOSA tower
39M pixels



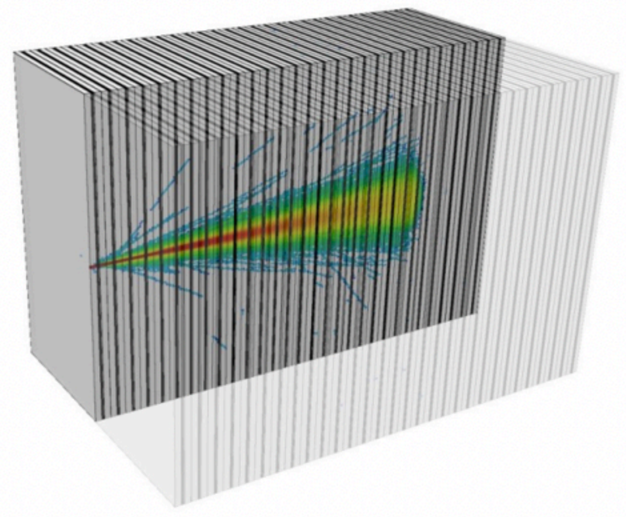
JINST 13 (2018) P01014

Mini-FoCal (PADs only) in beam at P2



Experience with prototypes since ~2014

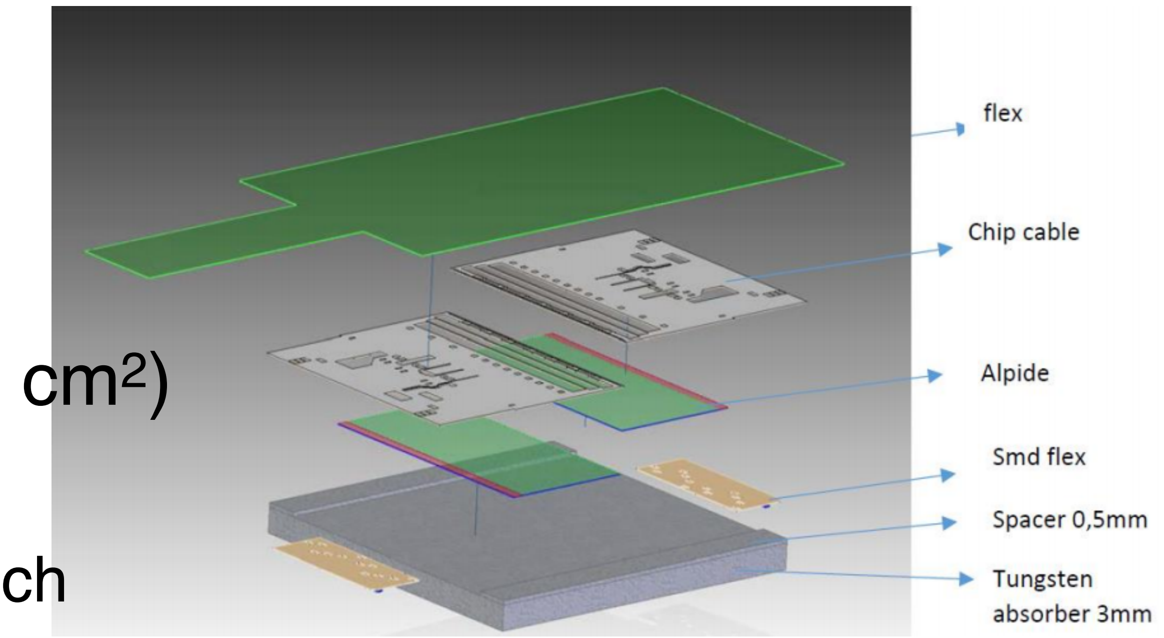
- Pad layers: Several more-and-more refined prototypes
- Pixel layers: Full (22 layers) pixel prototype and proton CT prototype
- Mini-FoCal in 13 TeV beam at P2:
  - Measure/verify backgrounds in situ
- Proton CT project (Bergen et al.)



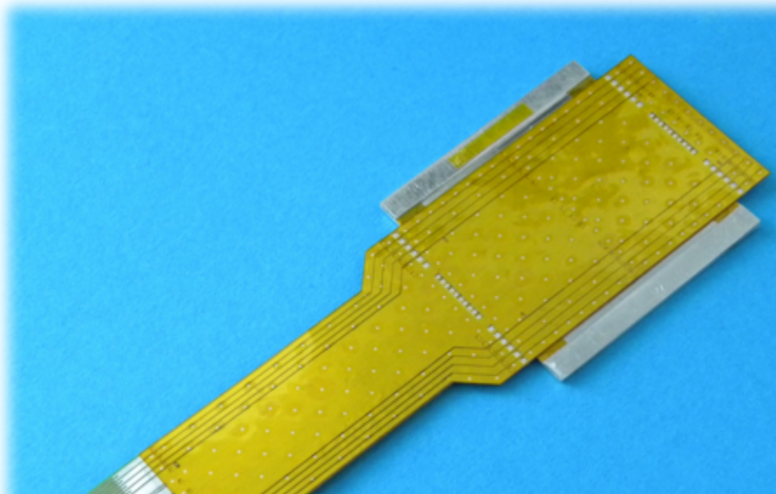
See recent detector seminar at CERN:
https://indico.cern.ch/event/856365/

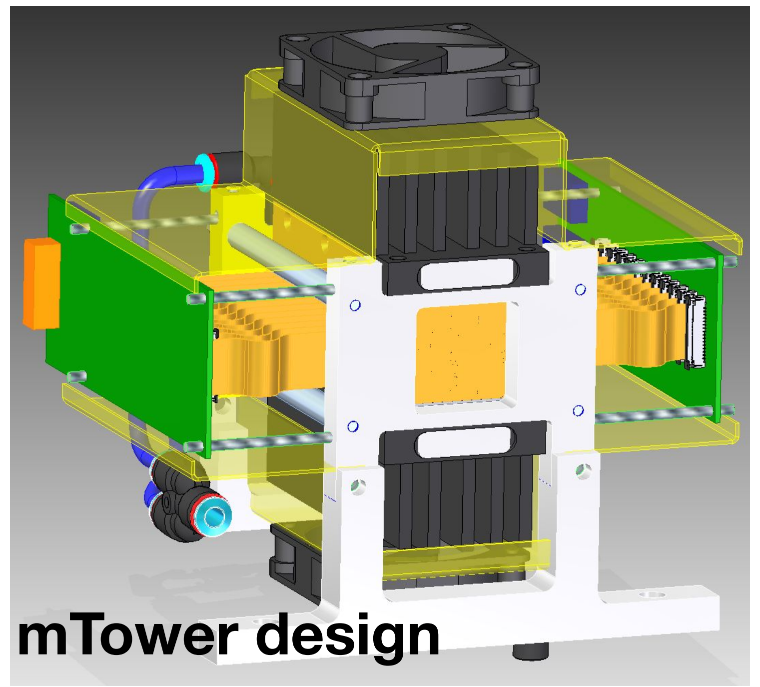
References to all publications in LOI

ALPIDE
Prototype: mTower

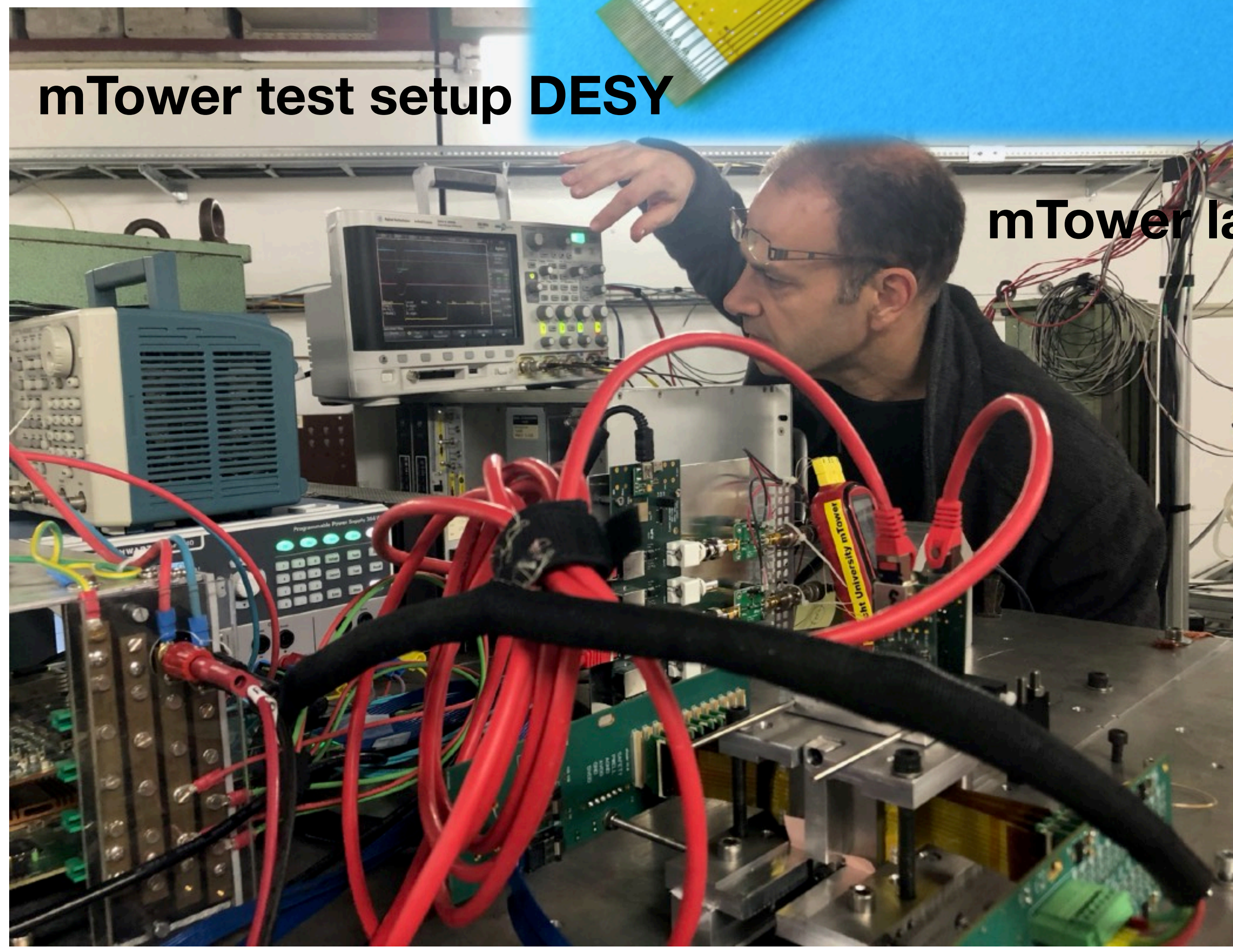


- Small digital calorimeter (3x3 cm^2)
- 24 layers
  - 2 ALPIDE sensors/3 mm W each
- first measurement with 1-5 GeV electron beams @ Desy
- main goal: ALPIDE/system performance with high occupancy
  - also collect shower data, measure resolution, …





mTower design



mTower test setup DESY

Data just taken at DESY - being analyzed

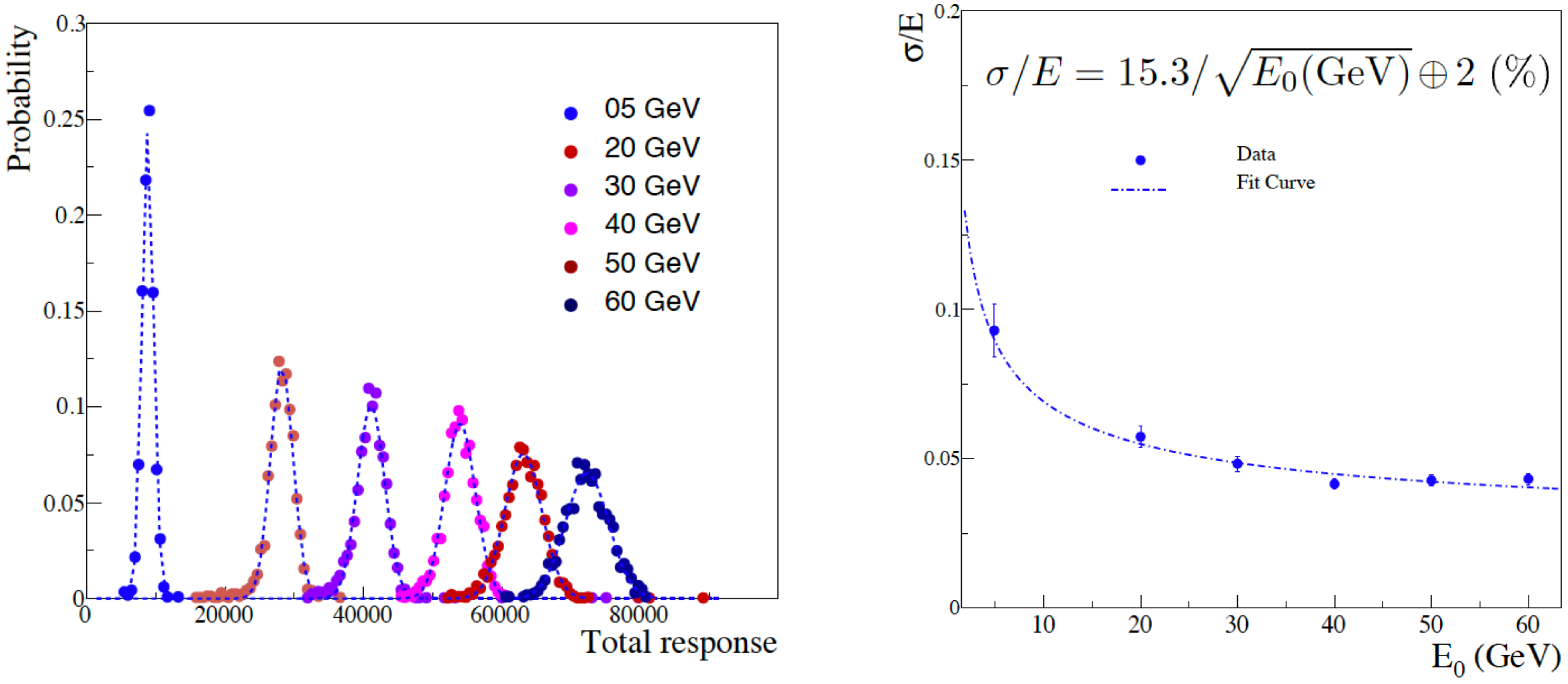
Pad prototypes and results

Experience gained over past years

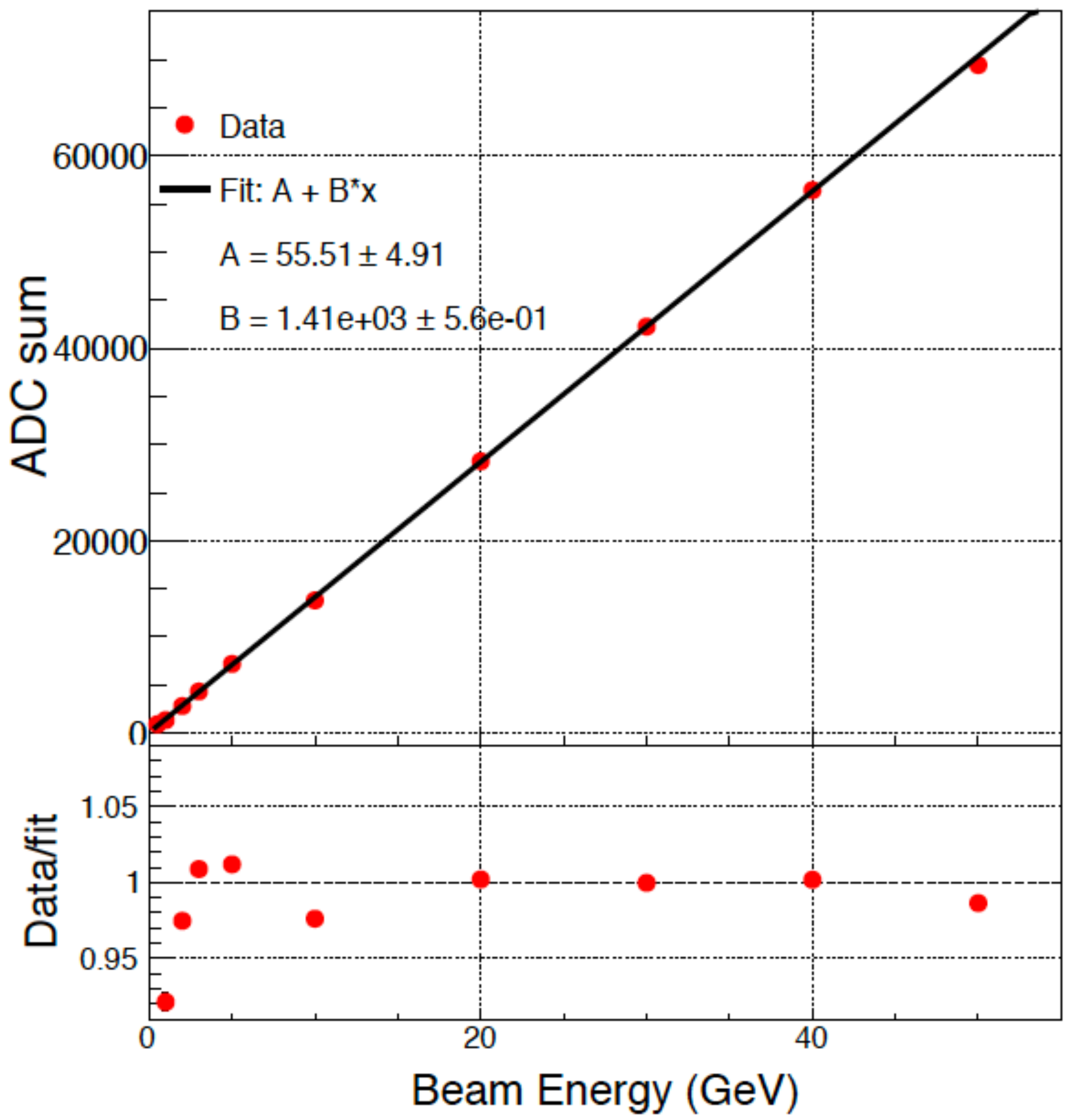
- Series of beam tests (PS, SPS): 2012-2018
- Beam times shared pad + pixel technology

Large activity in Japan (Tsukuba, Tsukuba Tech, Nara W, Hiroshima), India (VECC, BARC), US (ORNL)

- Indian prototypes:
  - NIM A 764 (2014) 24
  - JINST 15 (2020) 03, P03015
- ORNL / Japan prototype:
  - https://arxiv.org/abs/1912.11115

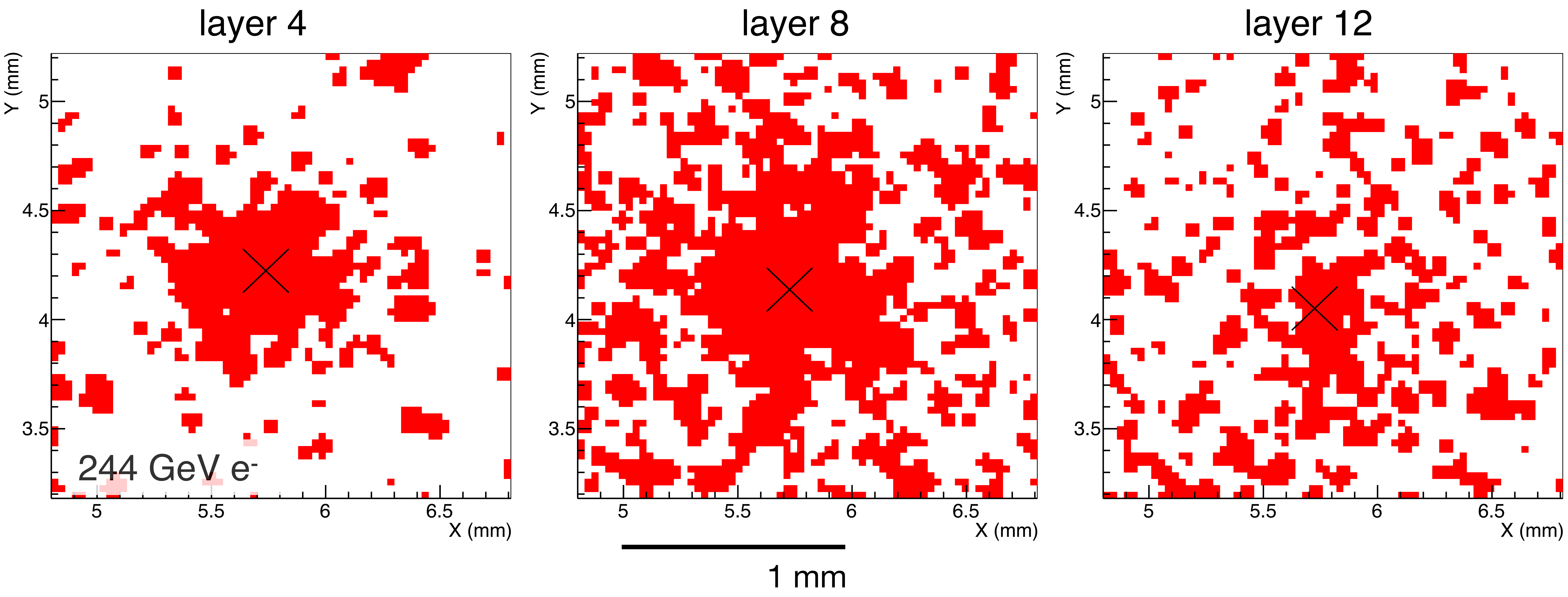


Indian prototypes : MANAS readout



ORNL / Japan prototypes : APV25 hybrid readout

Single Event Hit Distribution - FoCal Pixel Prototype



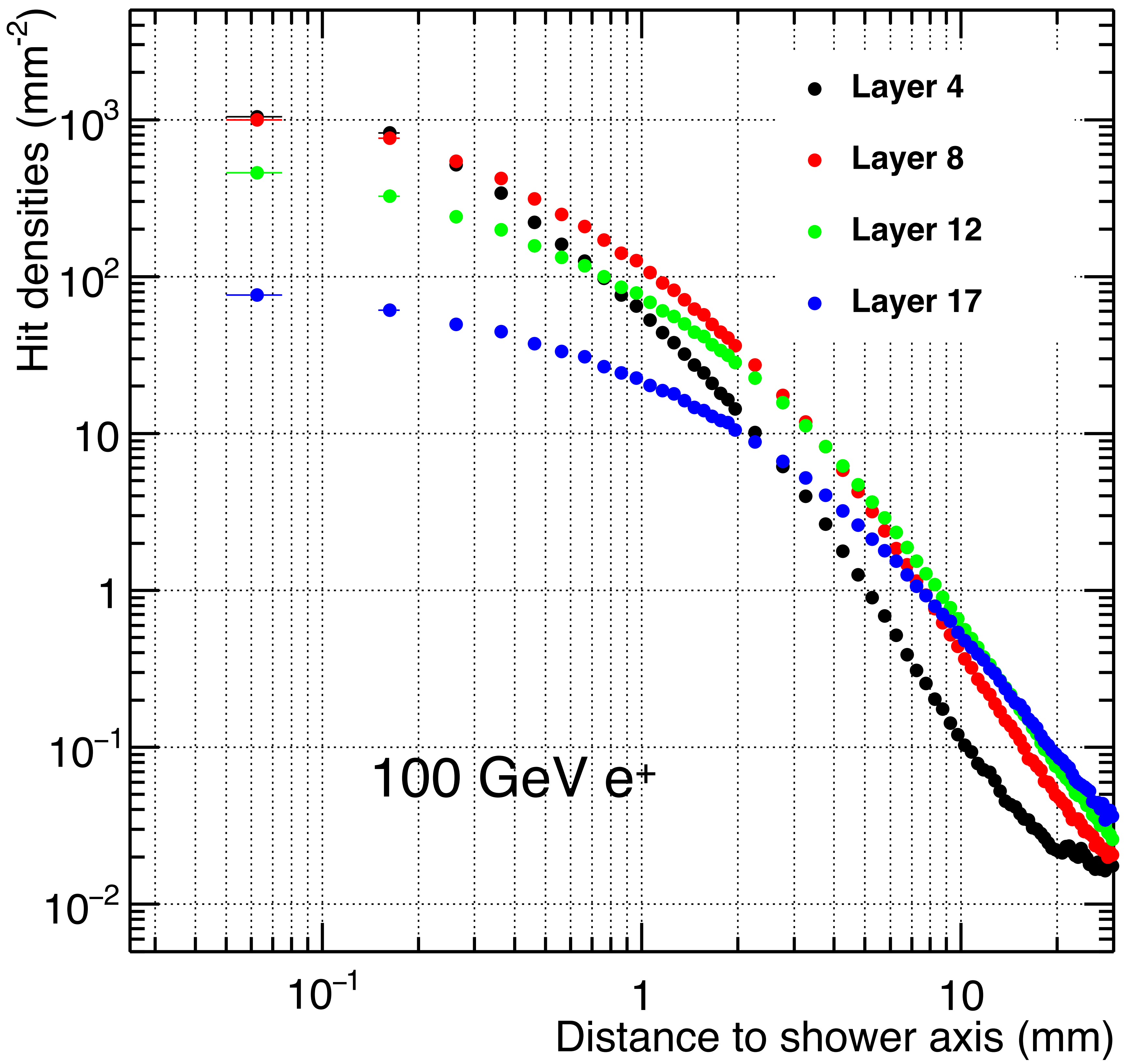
Pixel layers: very detailed view of shower

2-shower separation at mm scale

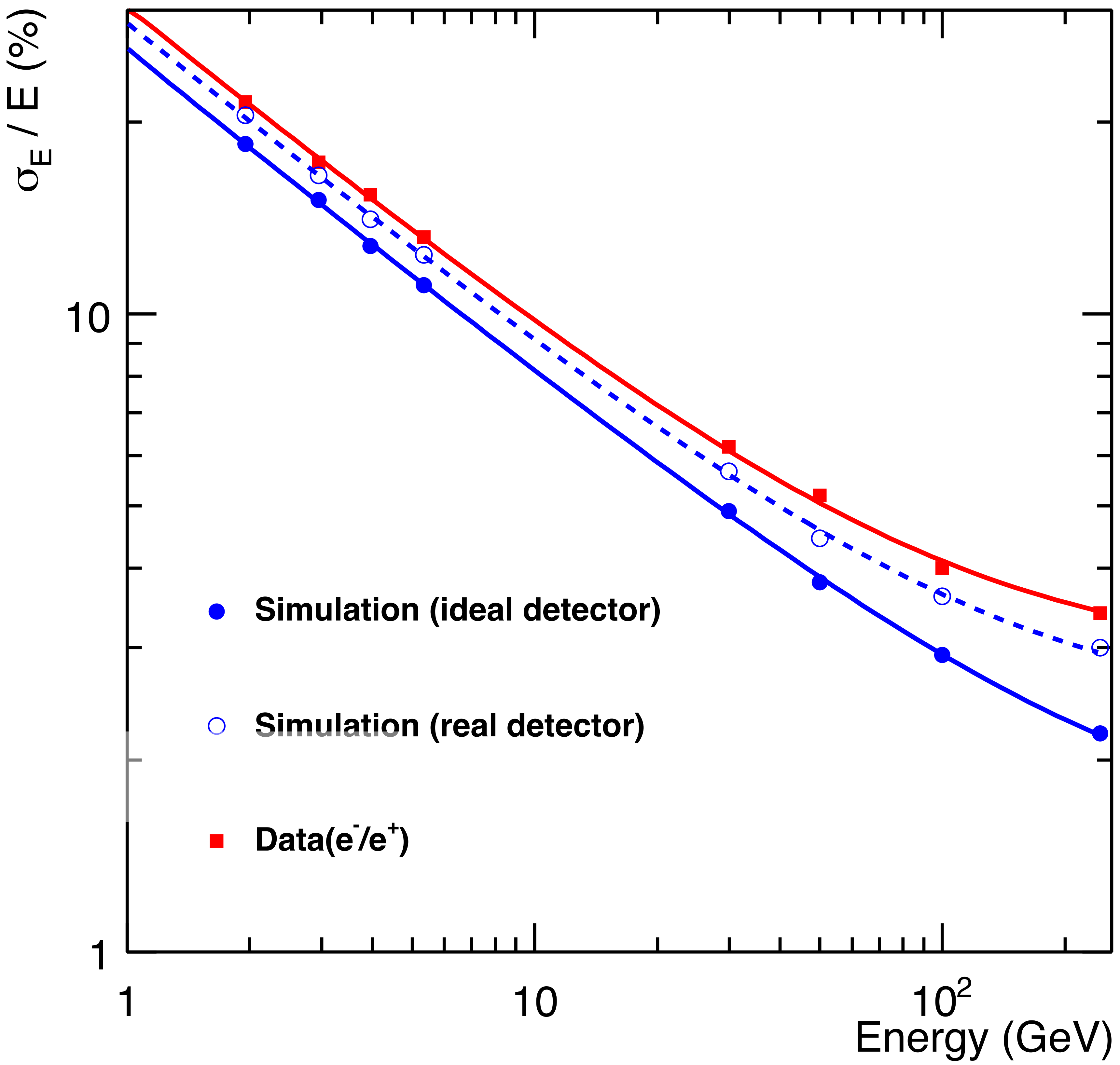
Use hit count as amplitude

Pixel test beam results

Lateral profile: hit densities as a function of radius



Energy resolution



$$\frac{\sigma_E}{E} = \frac{(28.5 \pm 3.8)\,\%}{\sqrt{E/\mathrm{GeV}}} + \frac{(6.3)\,\%}{E/\mathrm{GeV}} + (2.95 \pm 1.65)\,\%$$

Unique detailed measurements of shower shapes

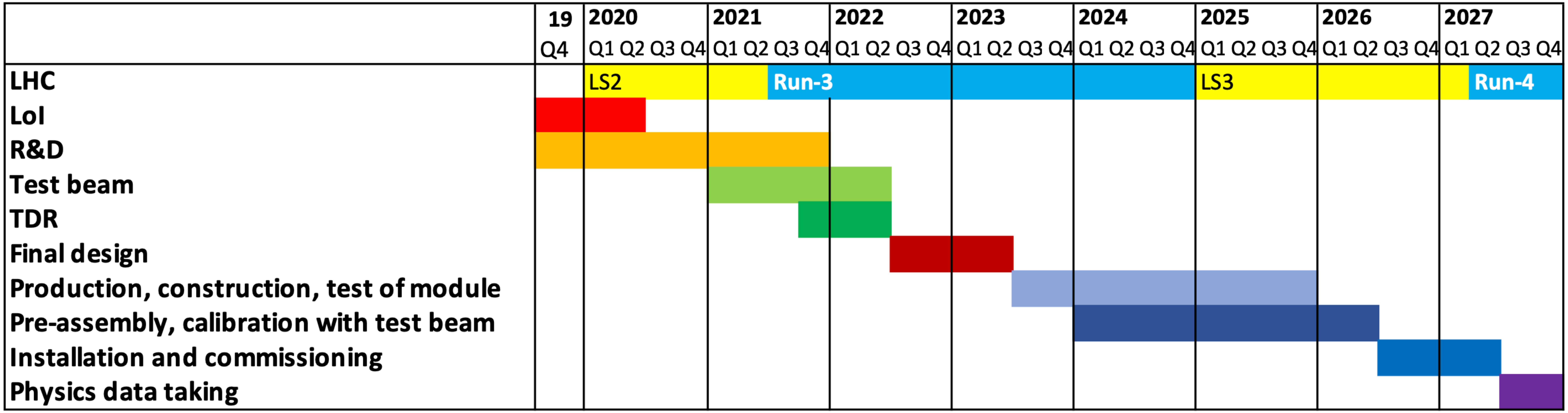
Large fraction of hits in first few mm around shower axis
Profile broadens in later layers

Energy resolution slightly worse than expected
Sufficient for FoCal physics program

First results published in
JINST 13 (2018) P01014

4. Timeline and next steps

Timeline



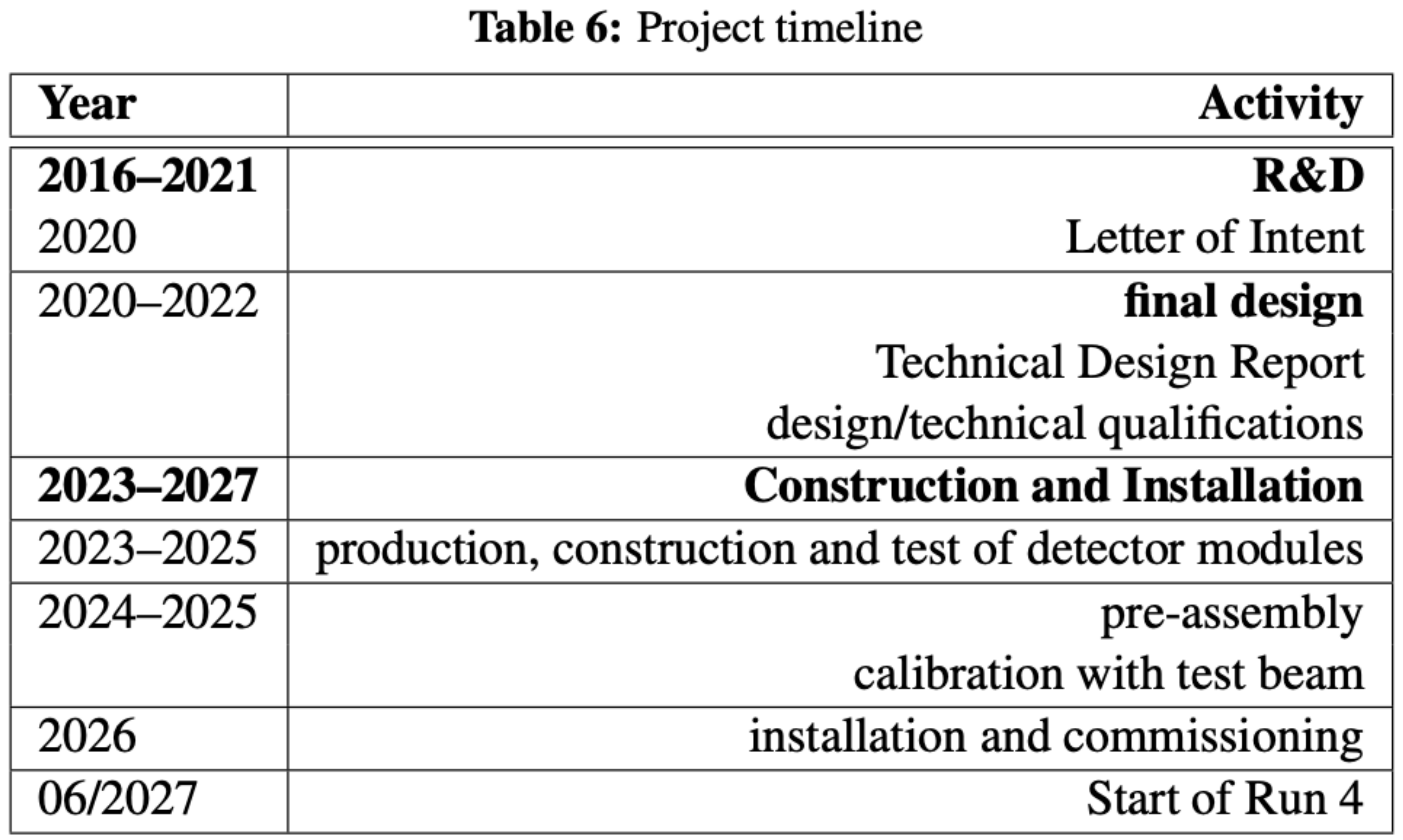


Table 6: Project timeline

Year	Activity
2016–2021	**R&D**
2020	Letter of Intent
2020–2022	**final design** Technical Design Report design/technical qualifications
2023–2027	**Construction and Installation**
2023–2025	production, construction and test of detector modules
2024–2025	pre-assembly calibration with test beam
2026	installation and commissioning
06/2027	Start of Run 4

- Next important step:
  Entering the engineering phase towards testbeam(s) 2021/22 and TDR
  - Produce a close-to-final prototype module
    - Pad and pixel layers
    - Hcal prototype
- Production estimated to fit well into 24 months
  - Plus half a year of "learning curve"

(not adjusted for Covid-19 changes)

Towards TDR: test module with close-to-final design

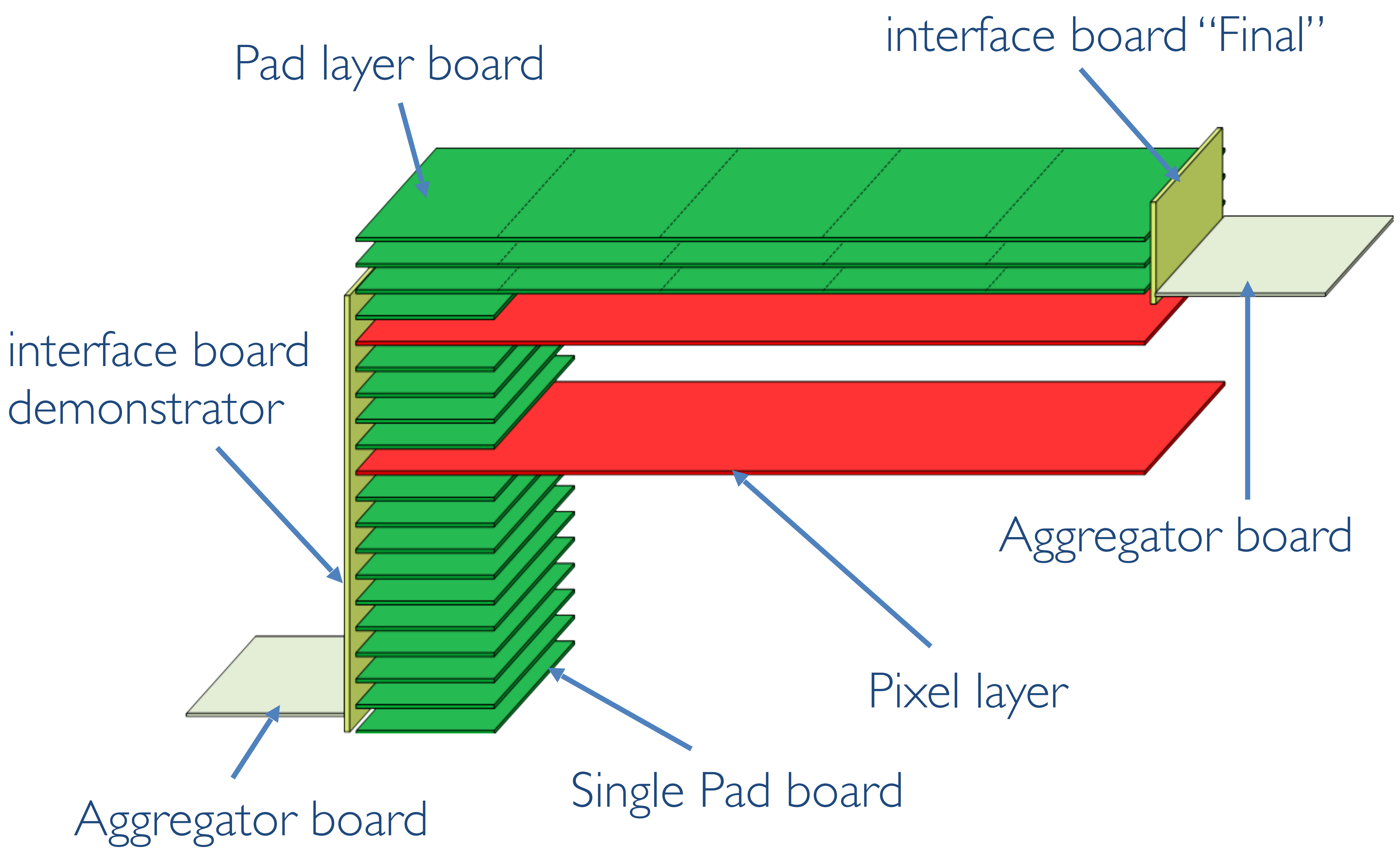
Produce and test prototype module:

- Use final electronics configuration
- HGCROC + sensor modules + readout
- Pixel modules + readout
- Develop cooling solution
- HCAL module

Goals:

- Test/verify performance
- Gain experience with production/assembly
- Optimise processes
- Specification for TDR

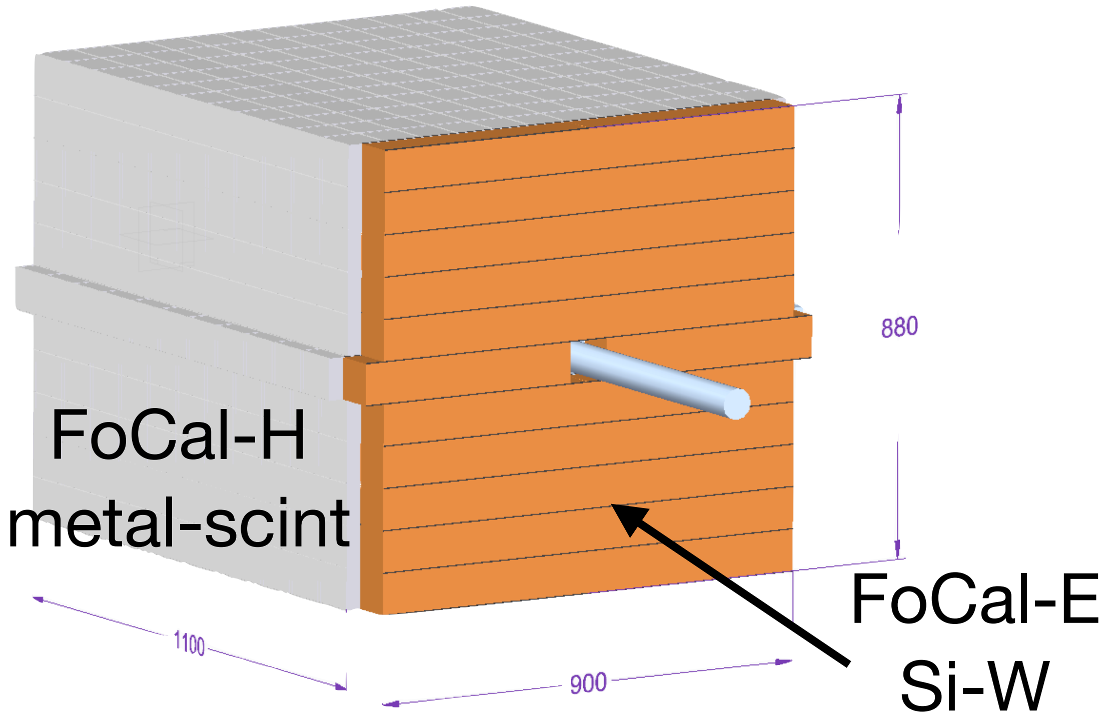
Test module concept: full depth, reduced area



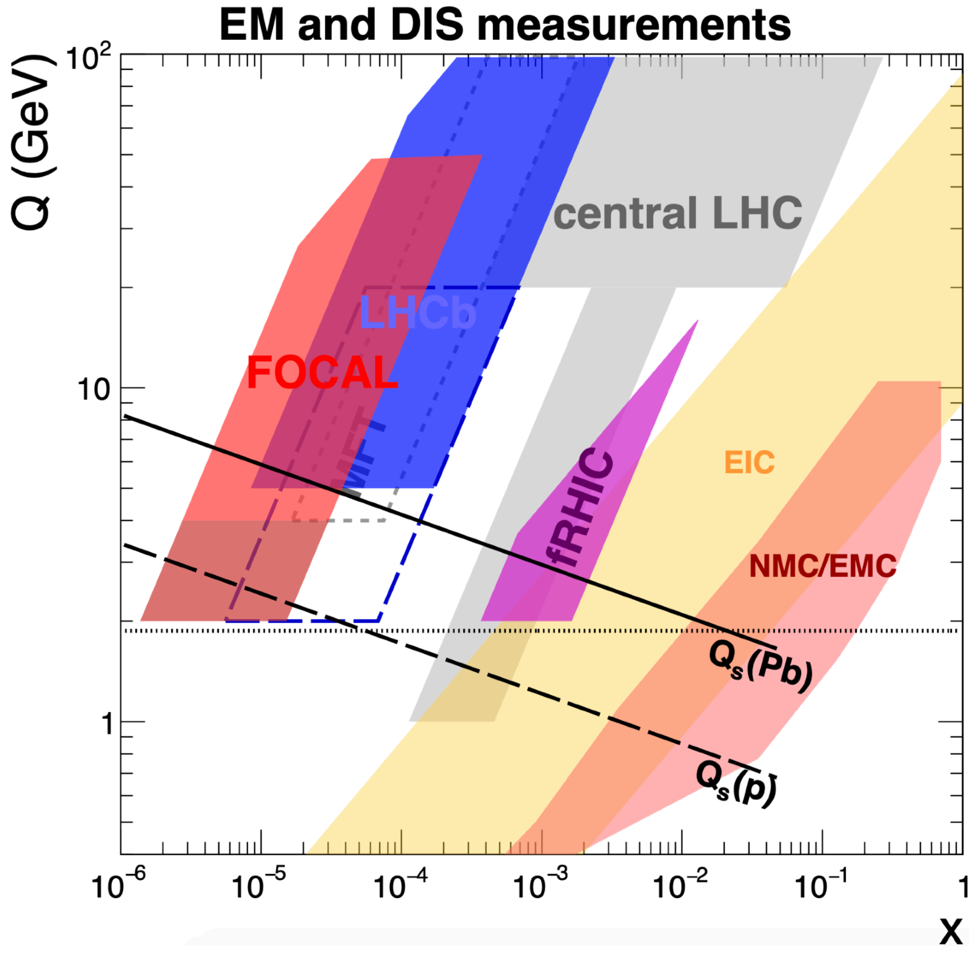
Summary

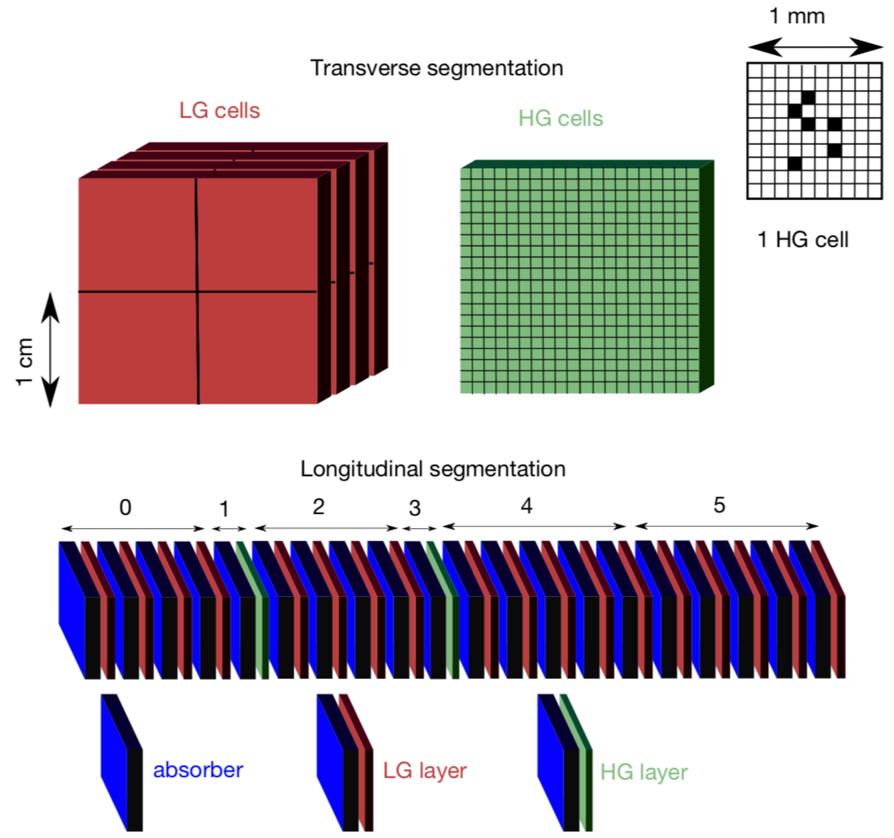
CERN-LHCC-2020-009

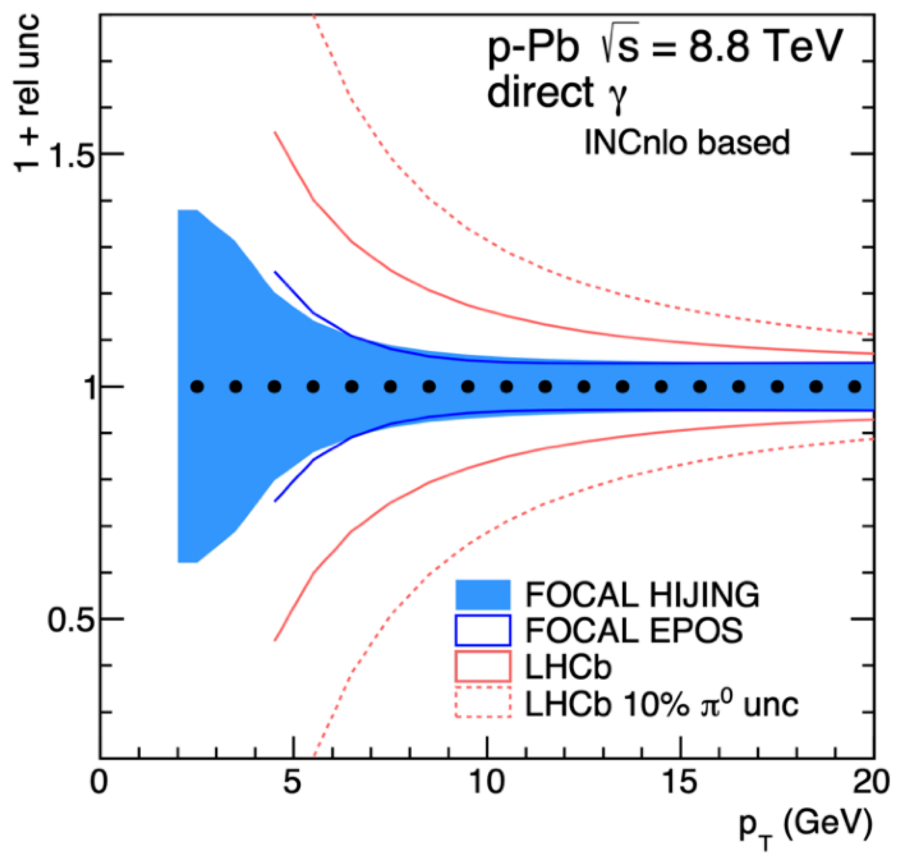
$3.4 < \eta < 5.8$

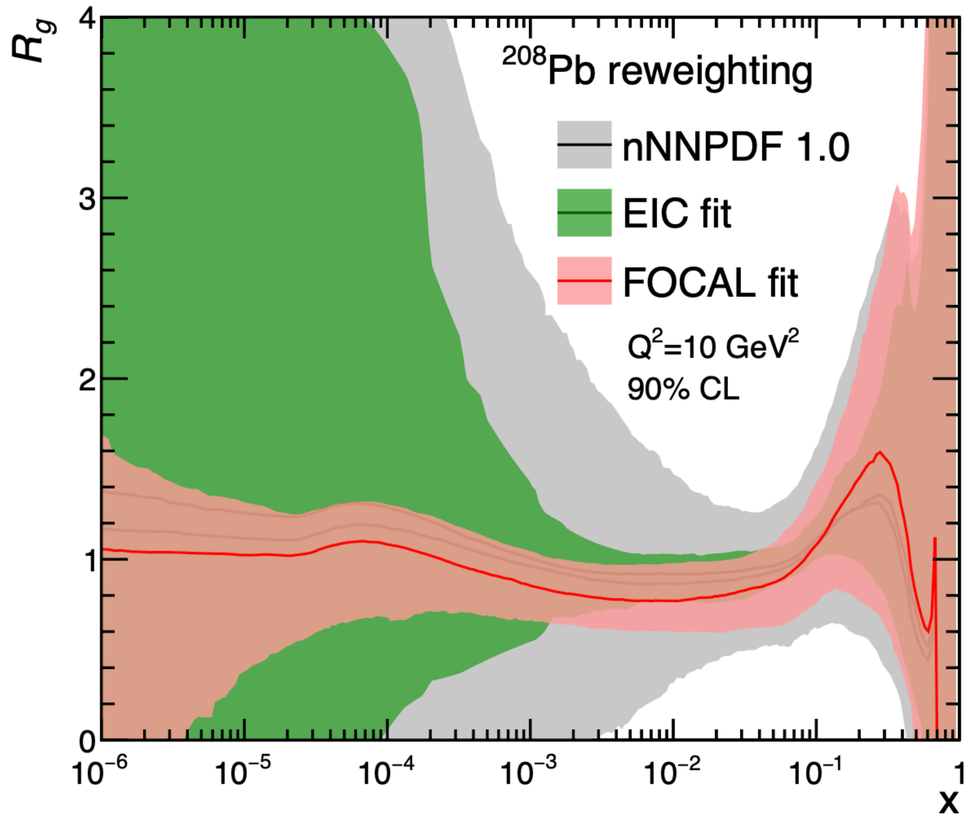


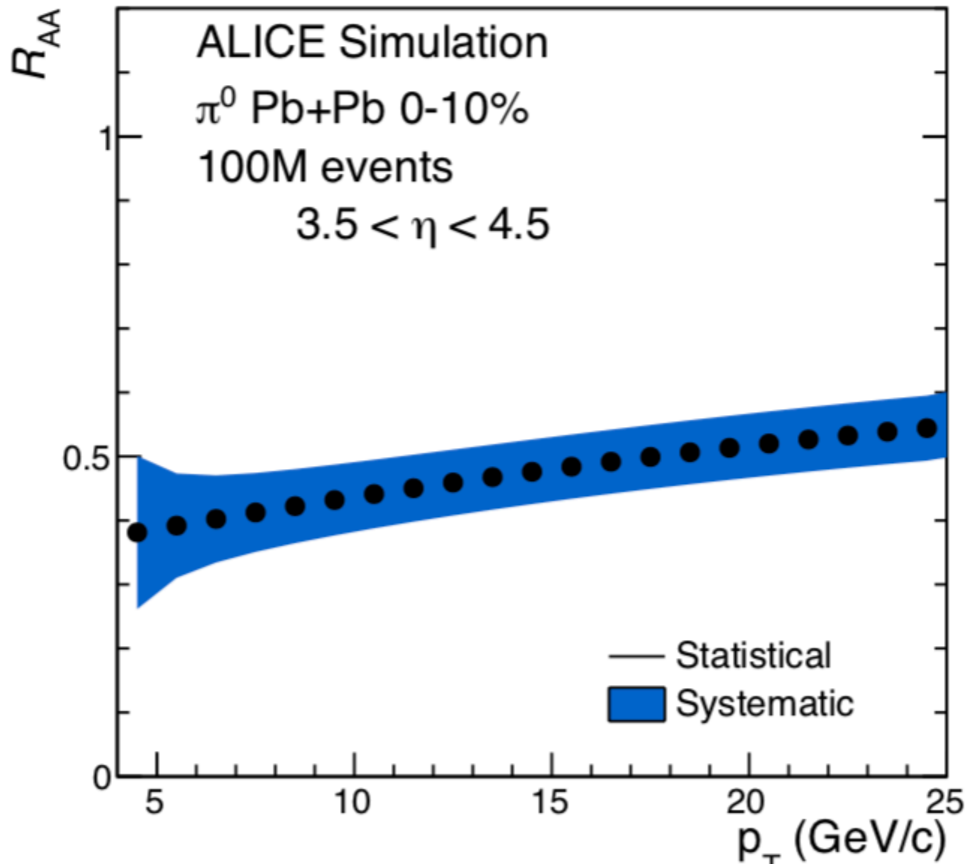
- FoCaL very forward, highly-granular Si+W "shower tracking" ECal with HCal
  - Rich physics programme in pp, pPb, PbPb and UPC
  - Main physics goal to explore non-linear QCD evolution
    - Isolated photons, UPC, correlations
    - Excellent performance over large η down to low p_T with small uncertainties as necessary to constrain nPDFs and to observe deviations from linear evolution
    - Strong small-x program at LHC together with LHCb; smaller x-region than at fRHIC and EIC
- Exciting calorimeter concept and technology
  - Large experience with prototypes
  - Technology synergy (ALPIDE, HGCROC)
  - Feasibility (choice of technology, integration, adequate resources) established
- Challenging and interesting times ahead towards the TDR
  - Individuals and institutions are very welcome to join the effort



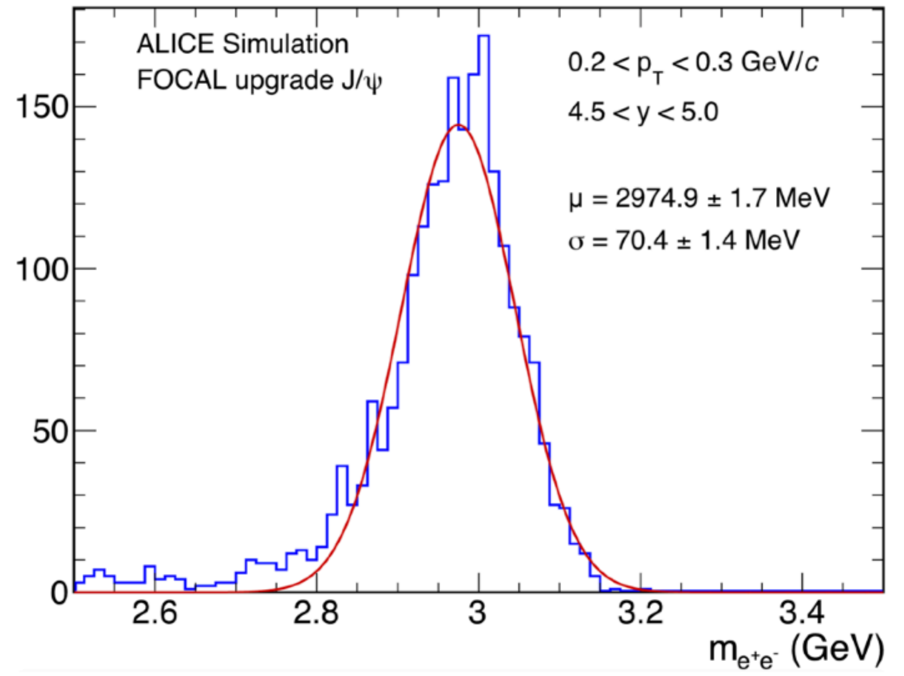








+ UPC, correlations, jets



Extra

Comparison to LHCb

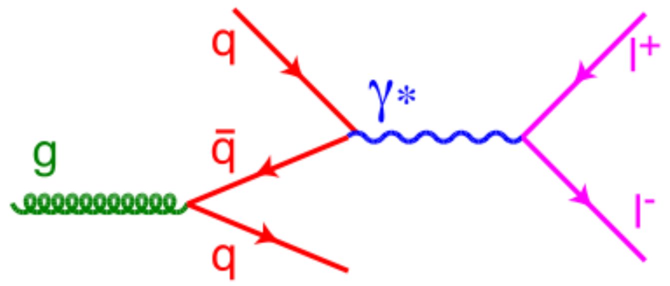
LHCb-CONF-2018-005

Forward measurements enabled by LHC

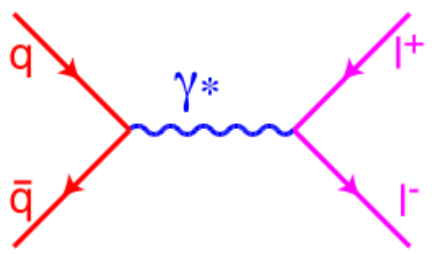
- Open heavy flavor:
  - D^0 production and D^0-D^0 correlations
  - Measurements of B^+ production
    - Advantage higher scale for calculation (but also larger x)
  - Drawback: Final state + hadronization effects

- Drell-Yan with muons
  - Small cross section
  - Sensitive to gluons only at NLO

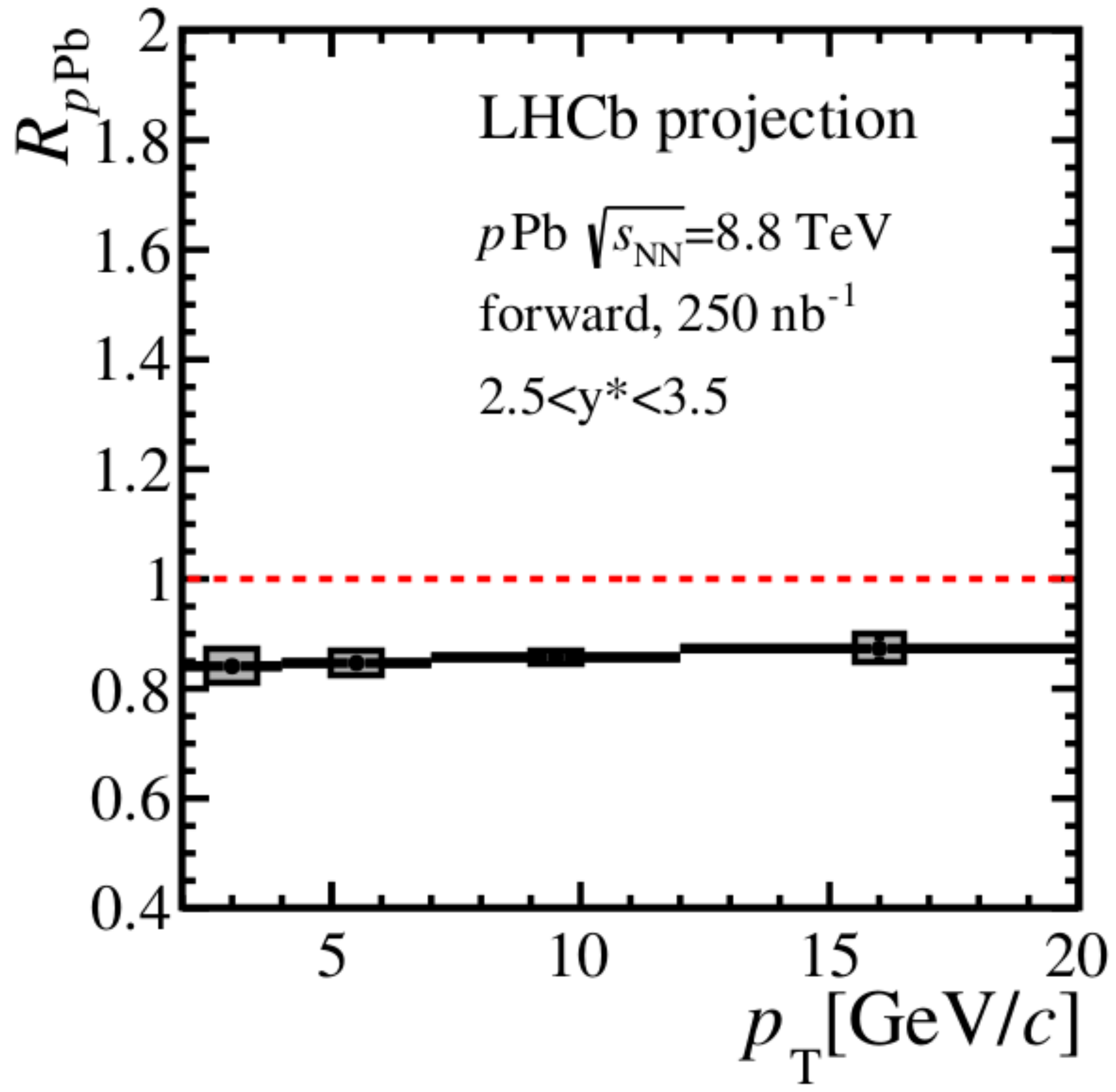
- Isolated photon production and correlations with hadrons / jets
  - Ongoing effort by LANL group with Run-2 data
  - Preparation for Run-3 with HLT (and maybe prototype of new tracking stations in magnet)

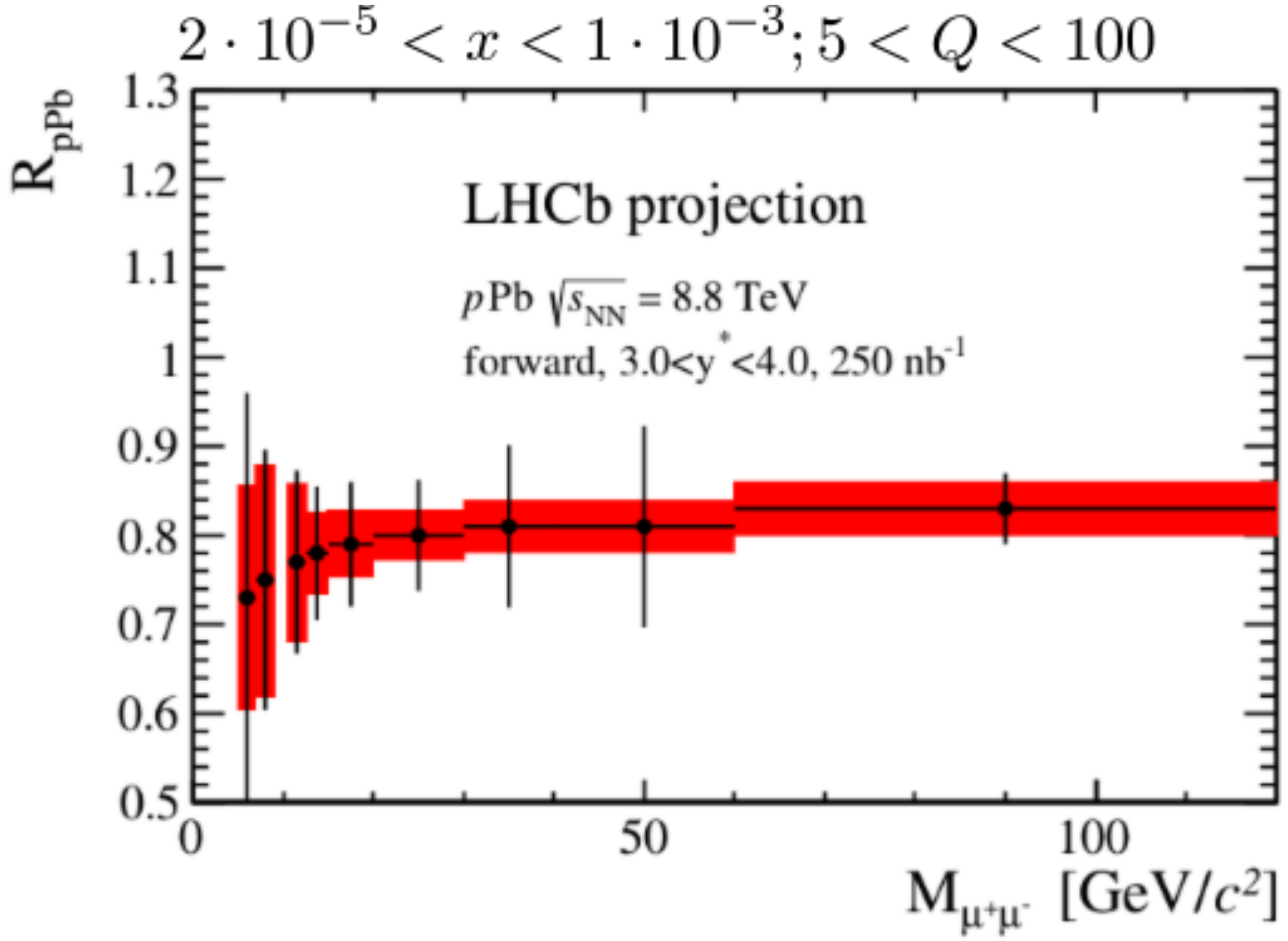


DY, virtual Compton (NLO)



DY (LO)





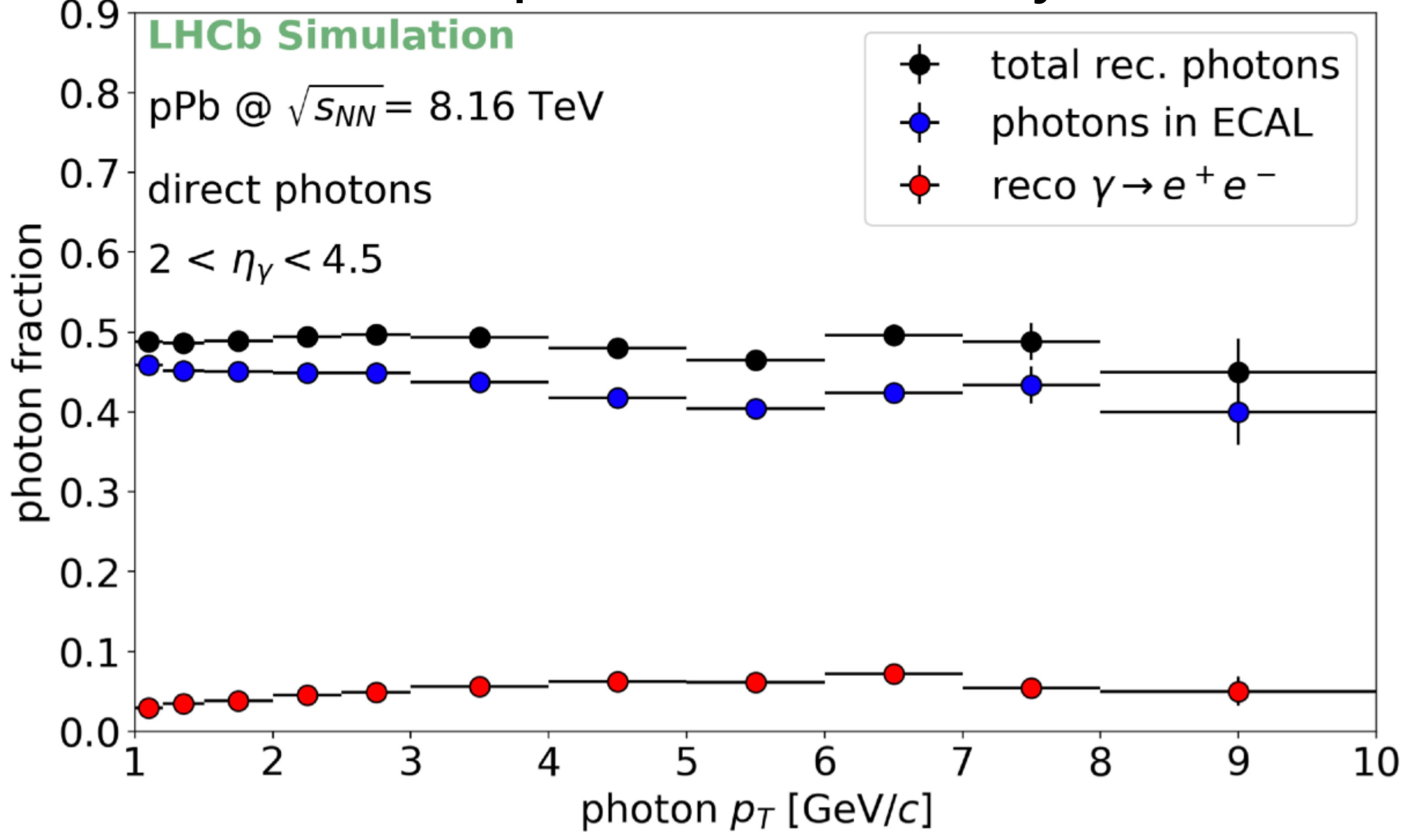
Isolated photons with LHCb

LHCb-FIGURE-2020-006

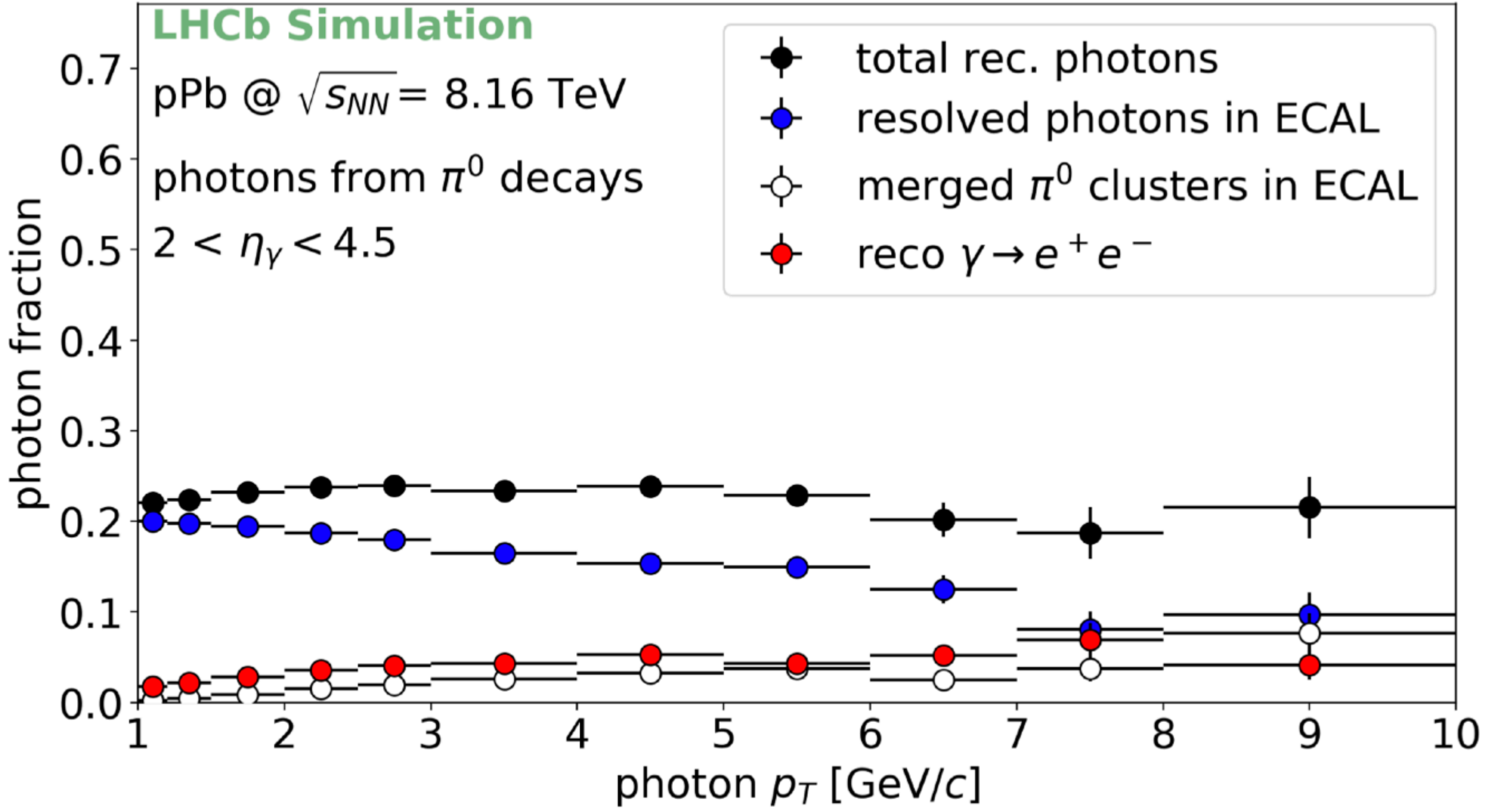
New analysis being pursued in LHCb (LANL group)

- Signal: (early) photon conversions
  - Clean identification
  - About ~0.25 X_0 with 6% uncertainty
  - Limited efficiency ~10%
    HLT trigger in Run 3
- Decay rejection by isolation
  - Accceptance limited to η<4
    (isolation up to Ecal edge η=4.4)
- Final selection:
  cuts combined with BDT

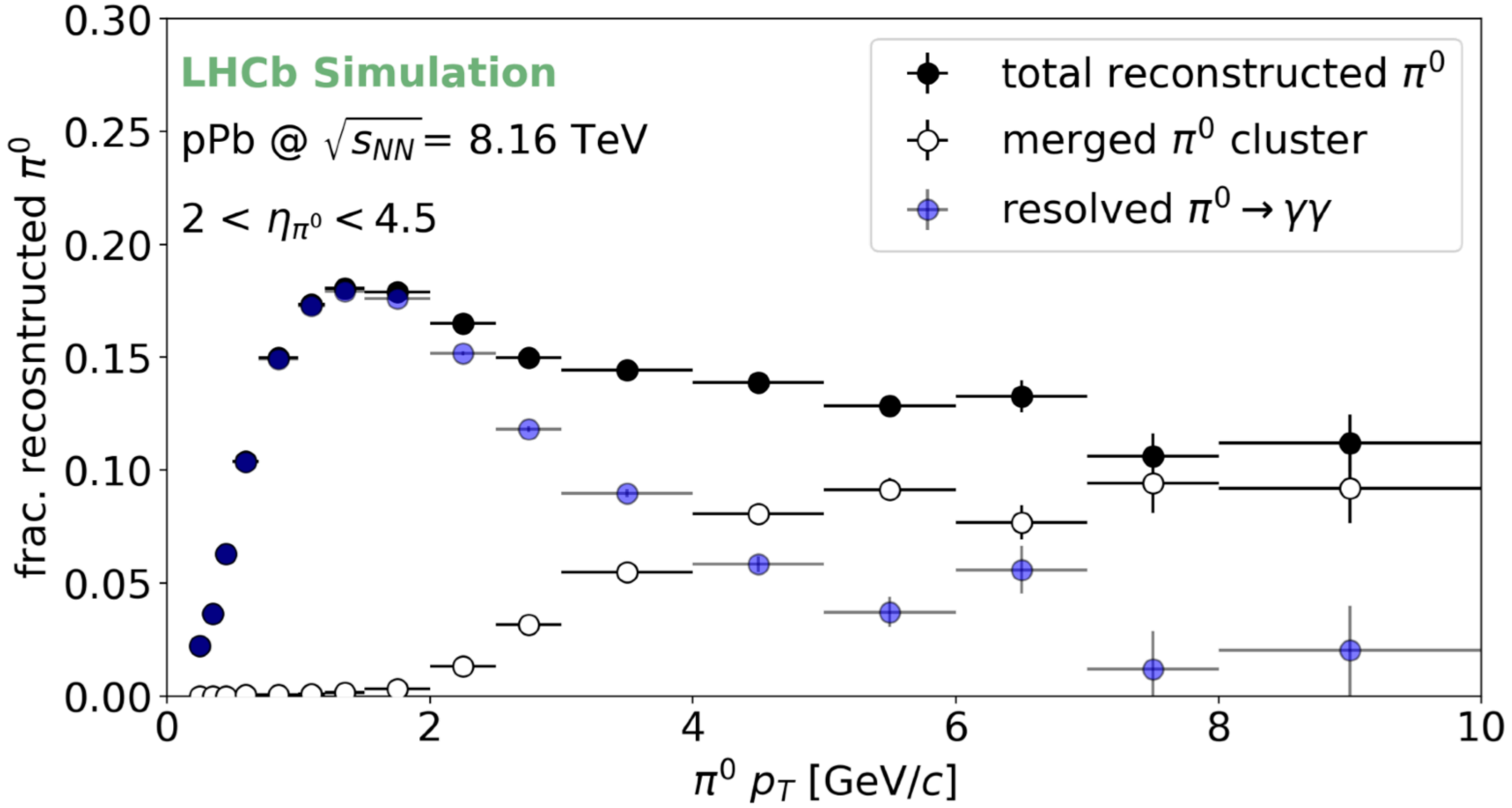
Direct photon efficiency



Decay photon efficiency



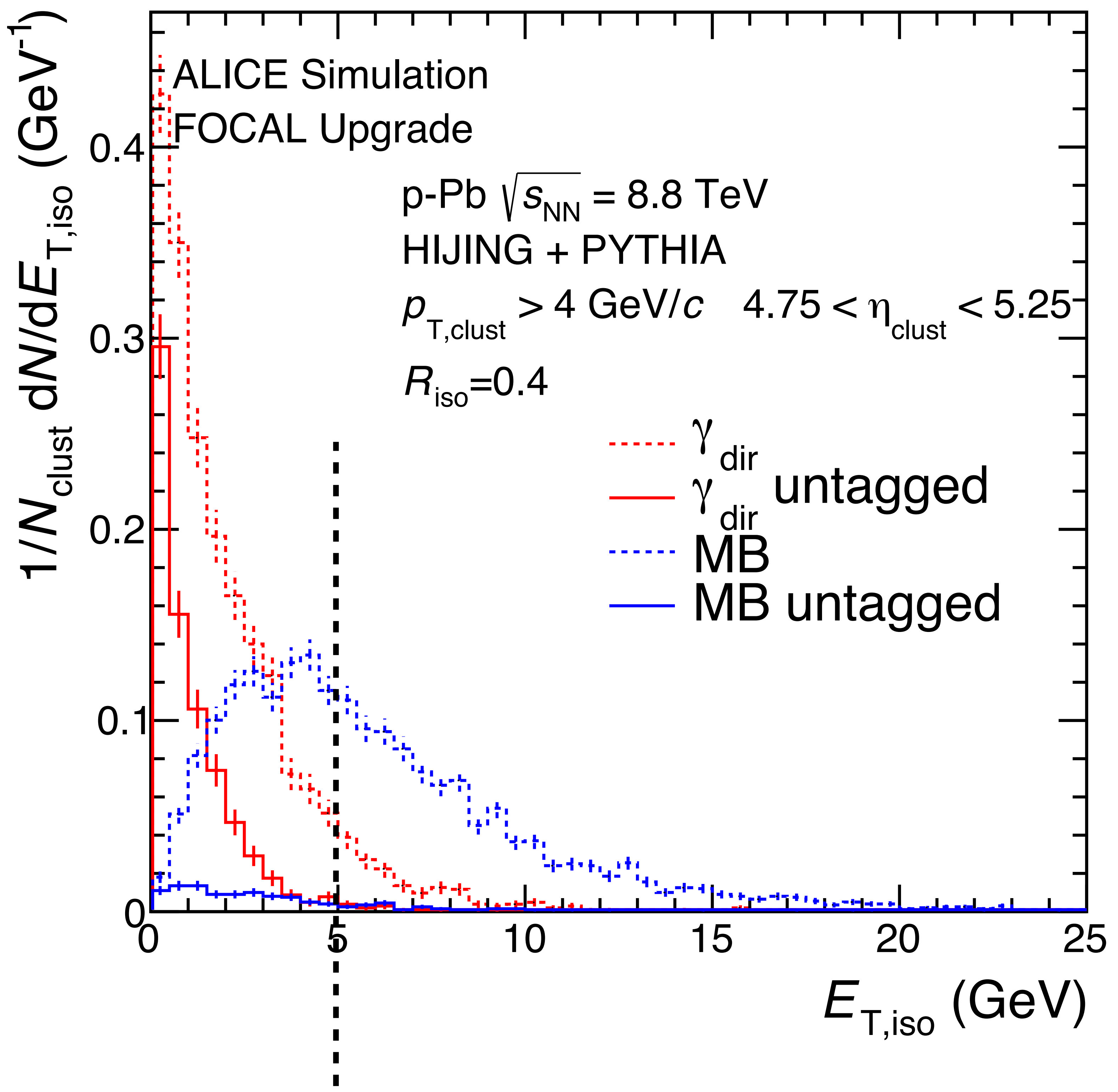
π^0 efficiency



- Photon efficiency between 25-45% (depending on activity)
- Reconstruction efficiency of π^0 only ~15% above 2 GeV
  - Compare with FoCal ~85%
- Direct tagging of decay photons very limited

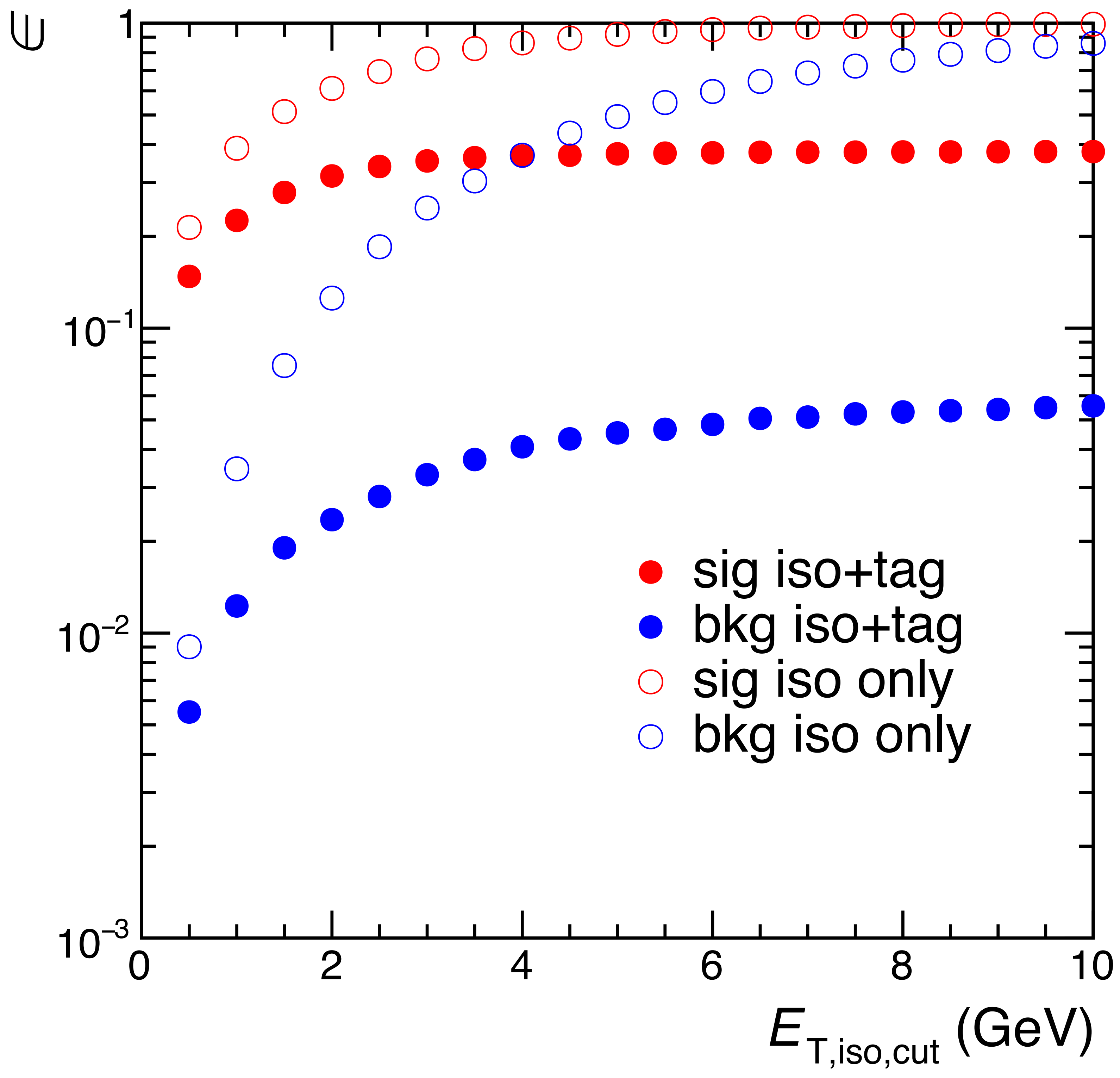
Focal performance (pPb)

($\eta_{lab} = 5$)

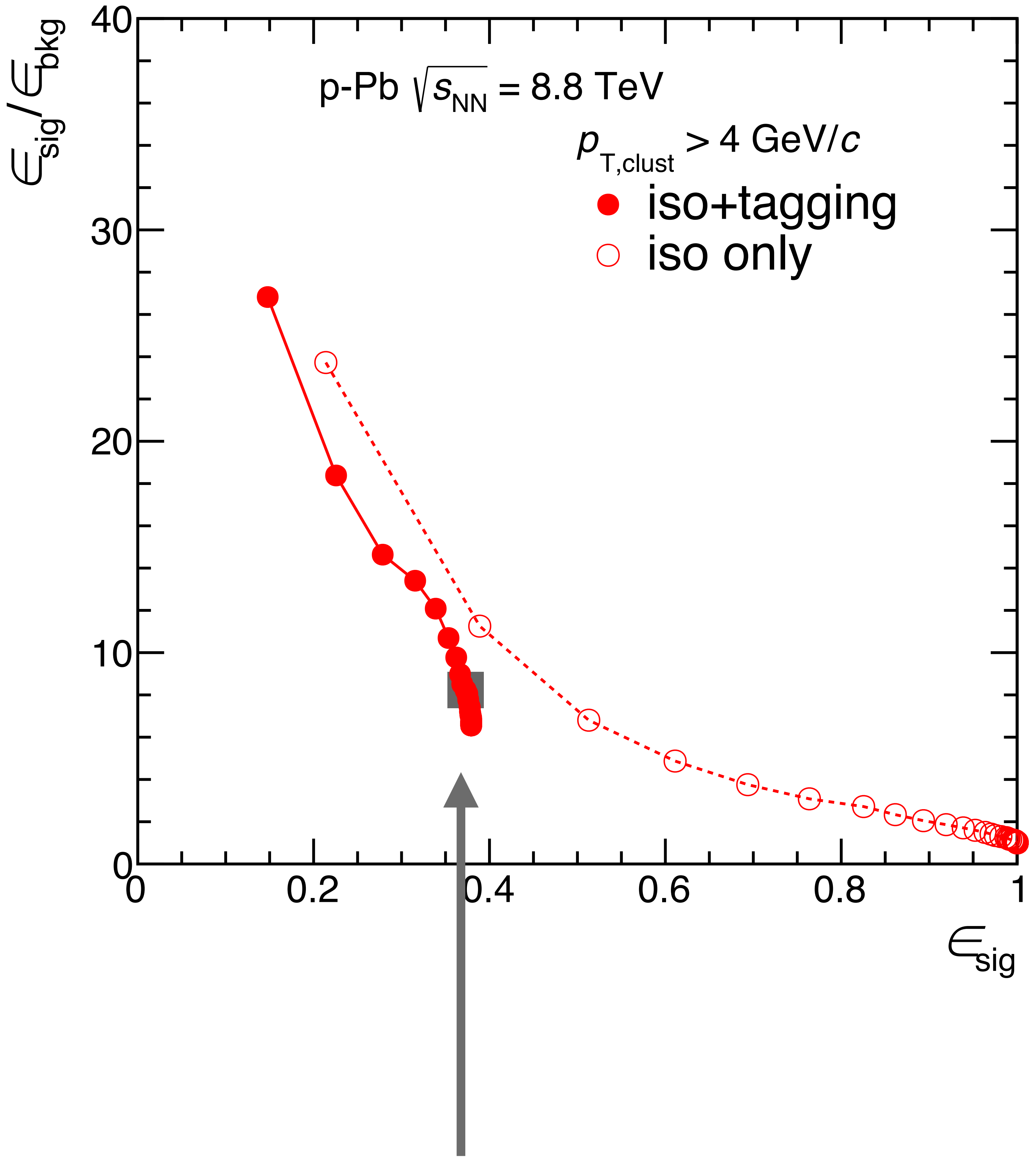


Default cut
$E_{T,iso} < 5$ GeV

Efficiencies sig, bkg



Improvement (eff sig/eff bkg)



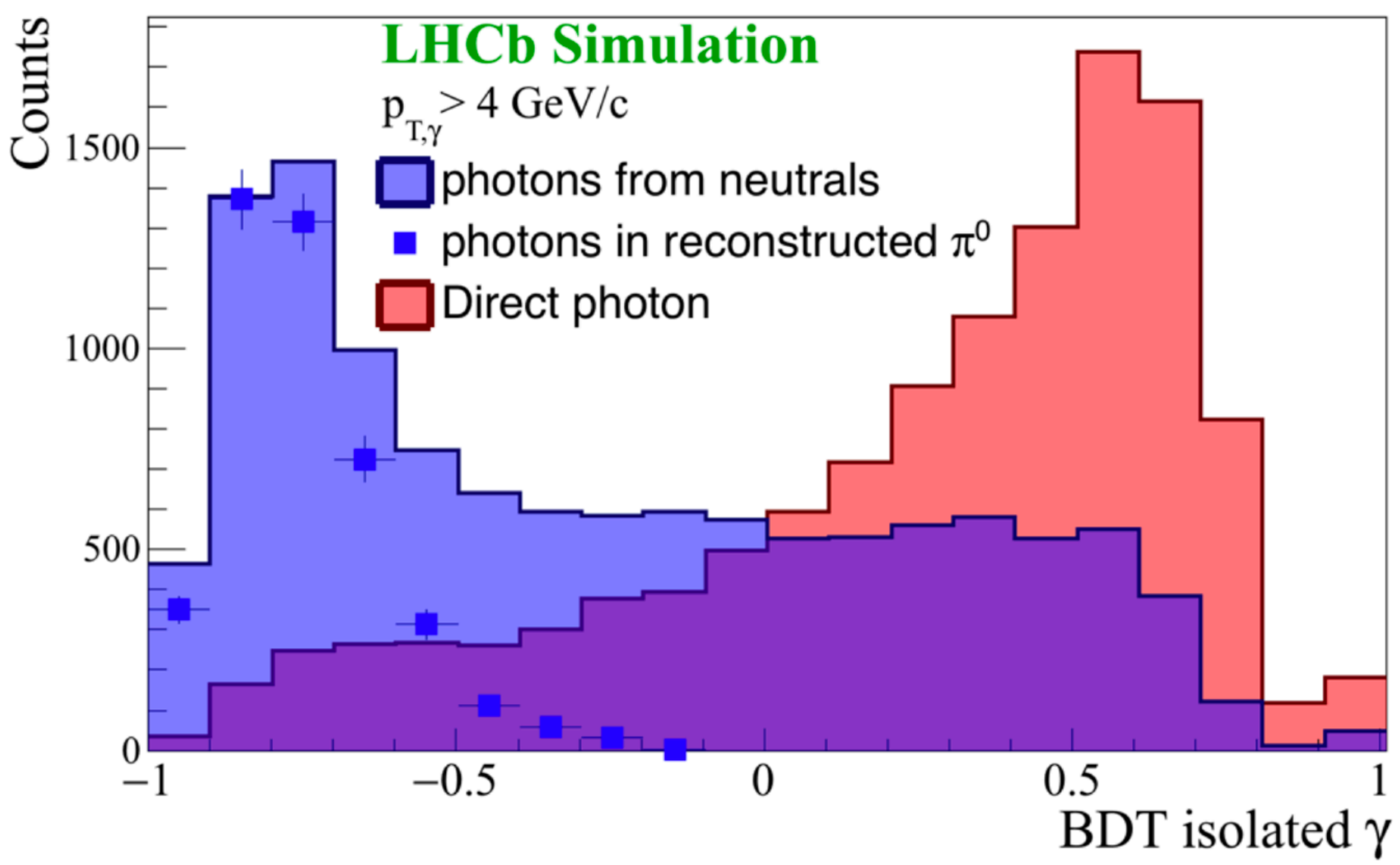
FoCal operating point in LOI

N.B.: "untagged" means "decay photon rejected"

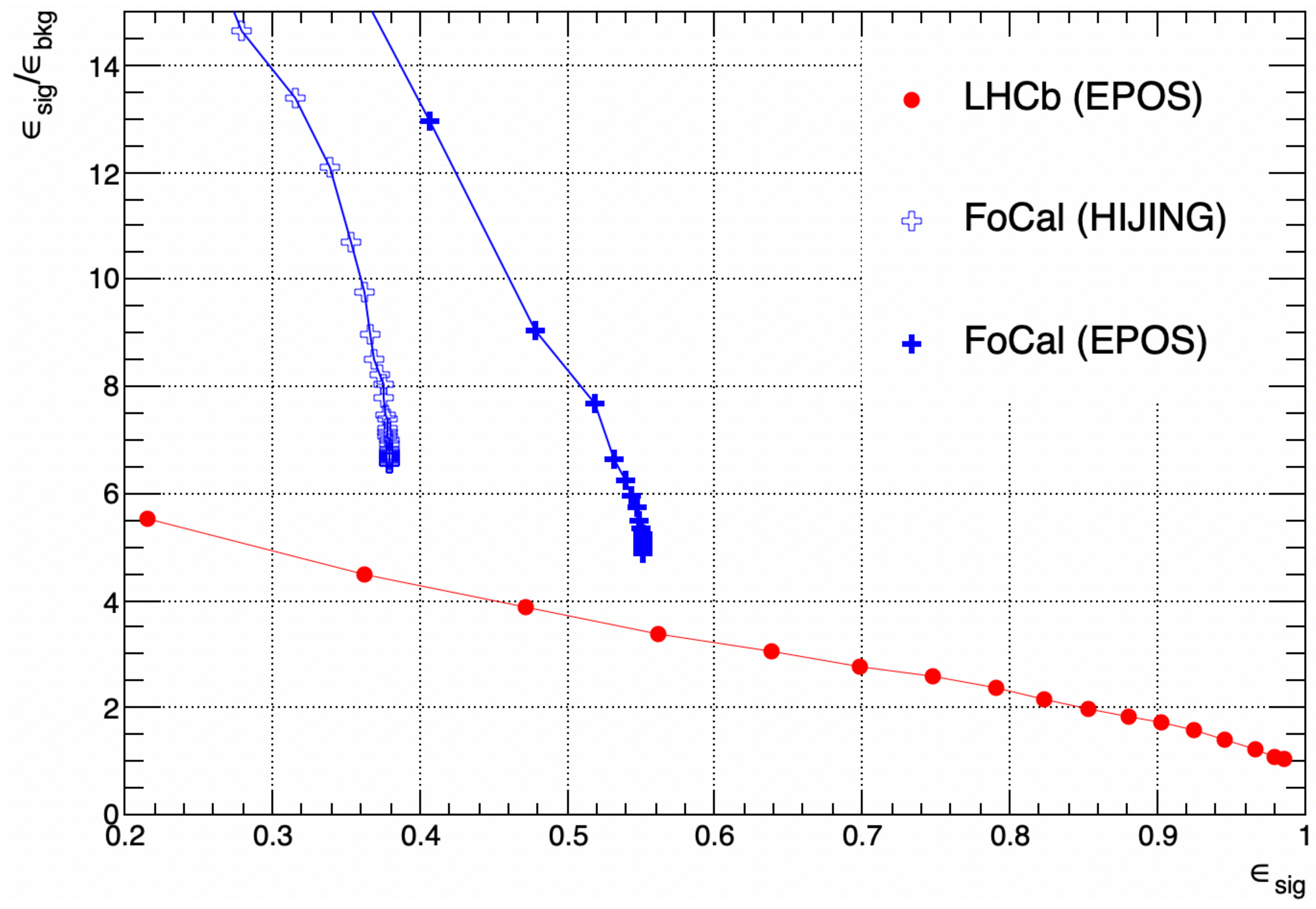
LHCb-FIGURE-2020-006

Comparison with LHCb

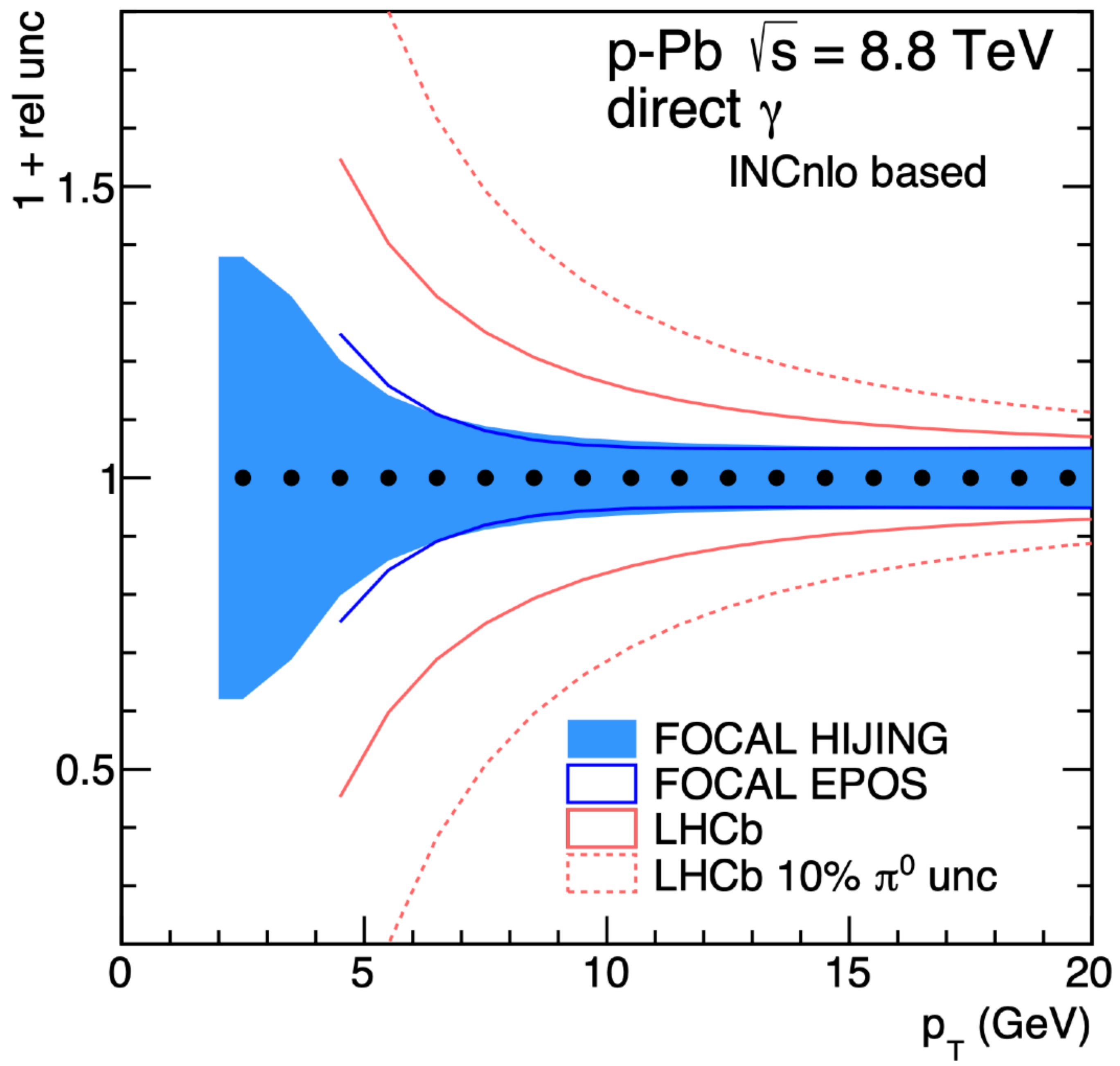
BDT response



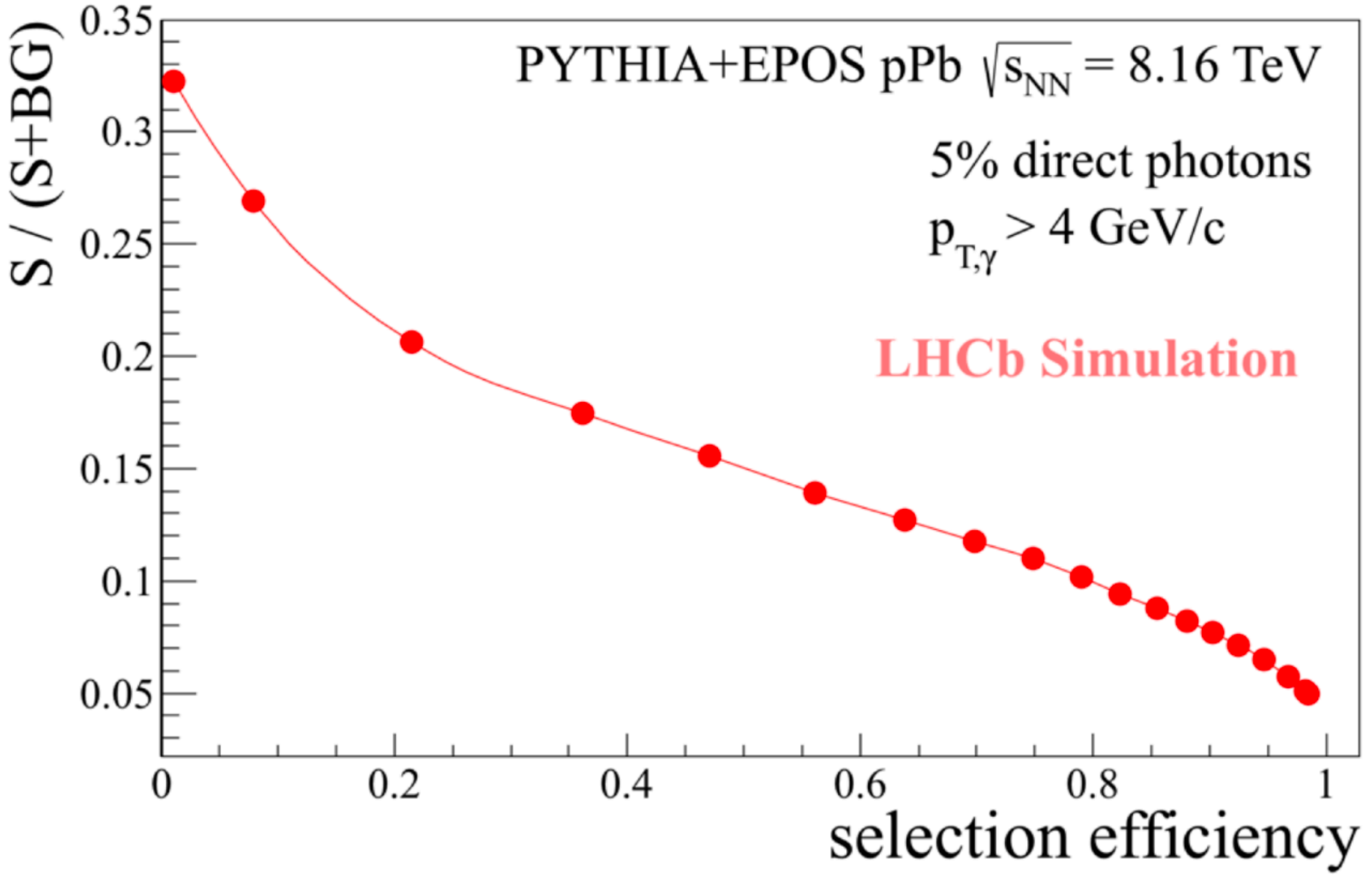
Improvement in S/B



Performance in pPb



Purity vs efficiency of BDT cut



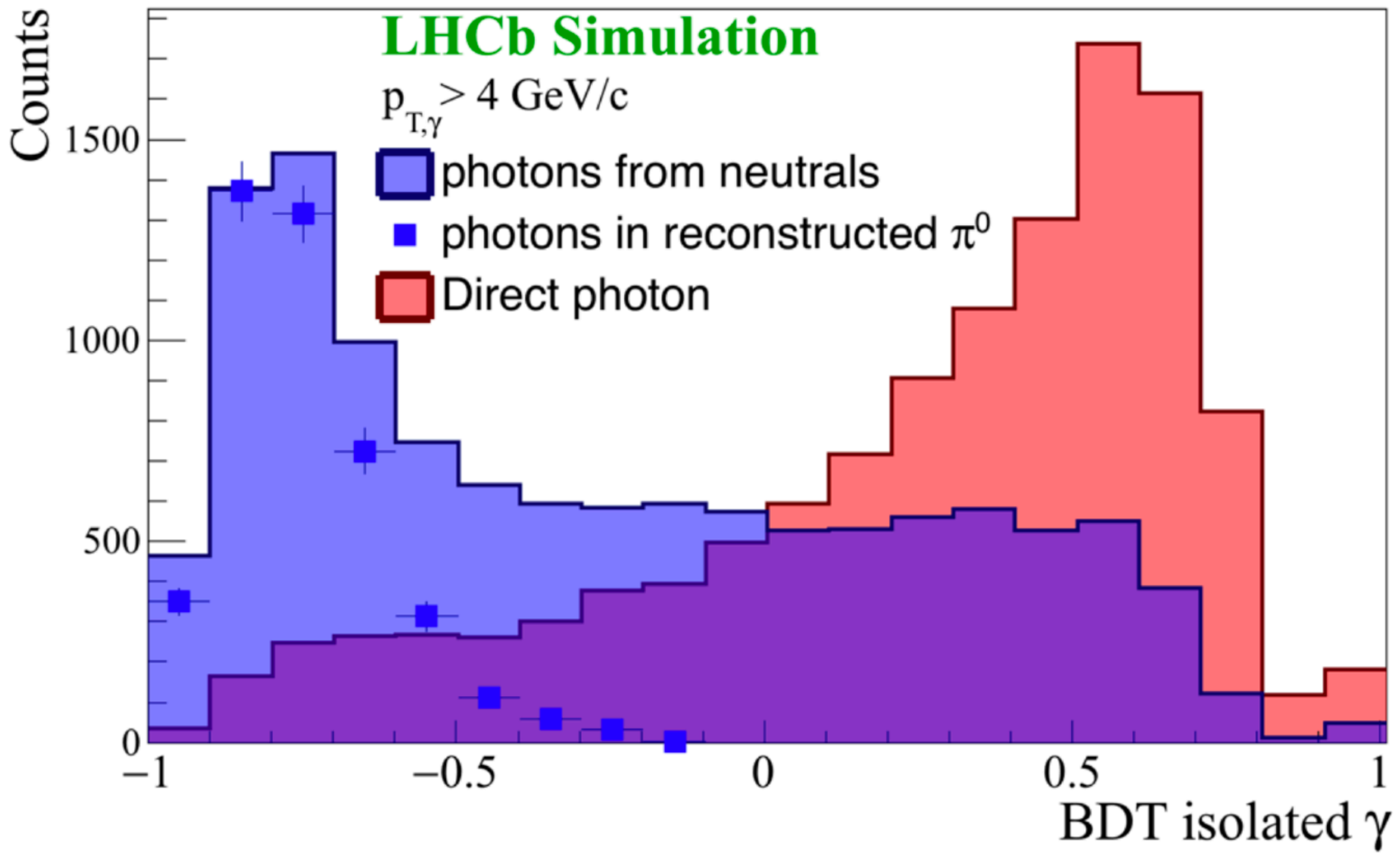
- LHCb analysis approach: identify signal by BDT based on a combination of variables, e.g. isolation energy
- Improvement in S/B significantly smaller than of FoCal
- Leads to factor 2 or larger systematic uncertainty compared to FoCal
  - Expected performance depends on uncertainty on remaining background

(WP at ε_{sig}=0.2 for LHCb,
at ε_{sig}~0.4 for FoCal)

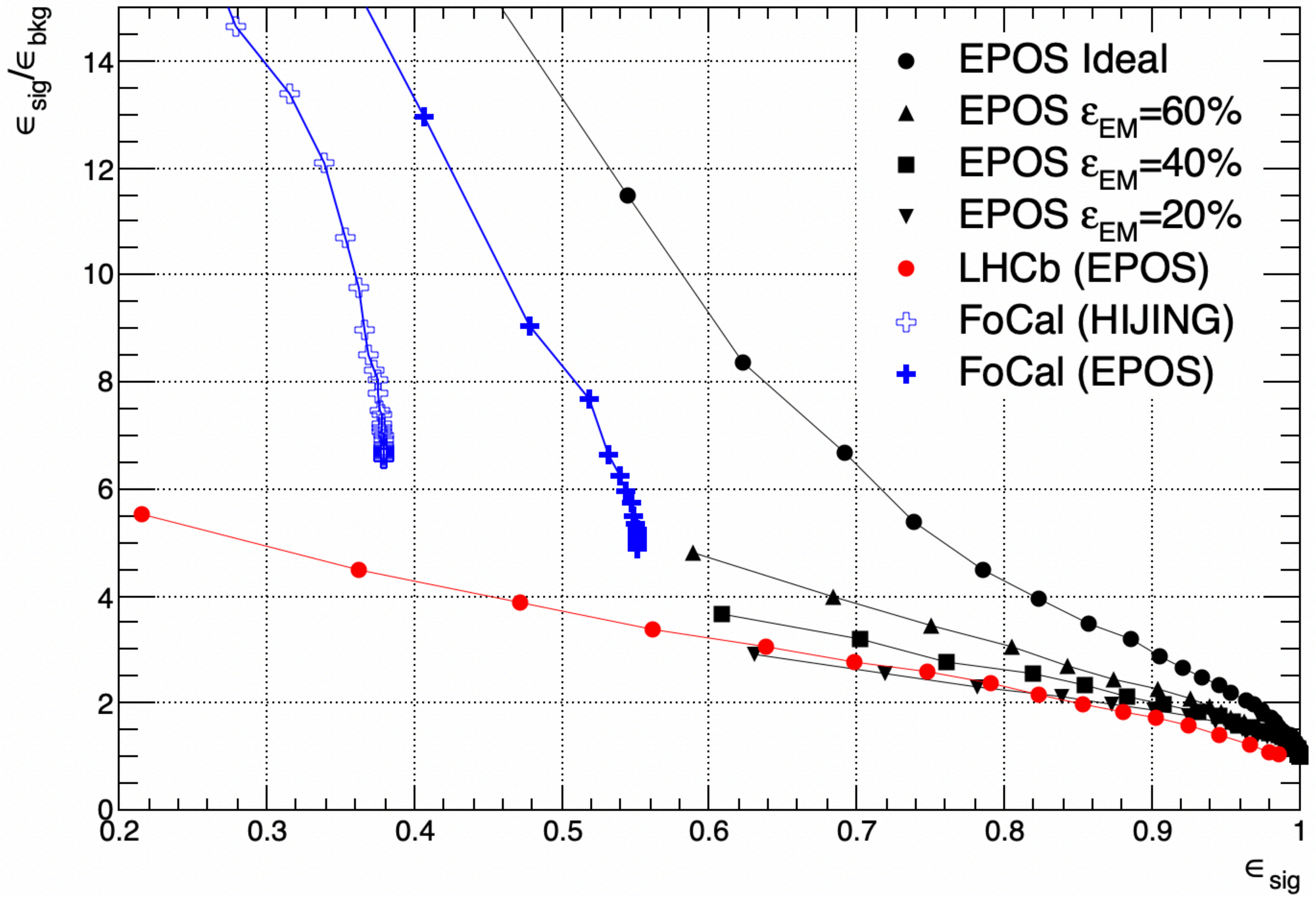
LHCb-FIGURE-2020-006

Comparison with LHCb

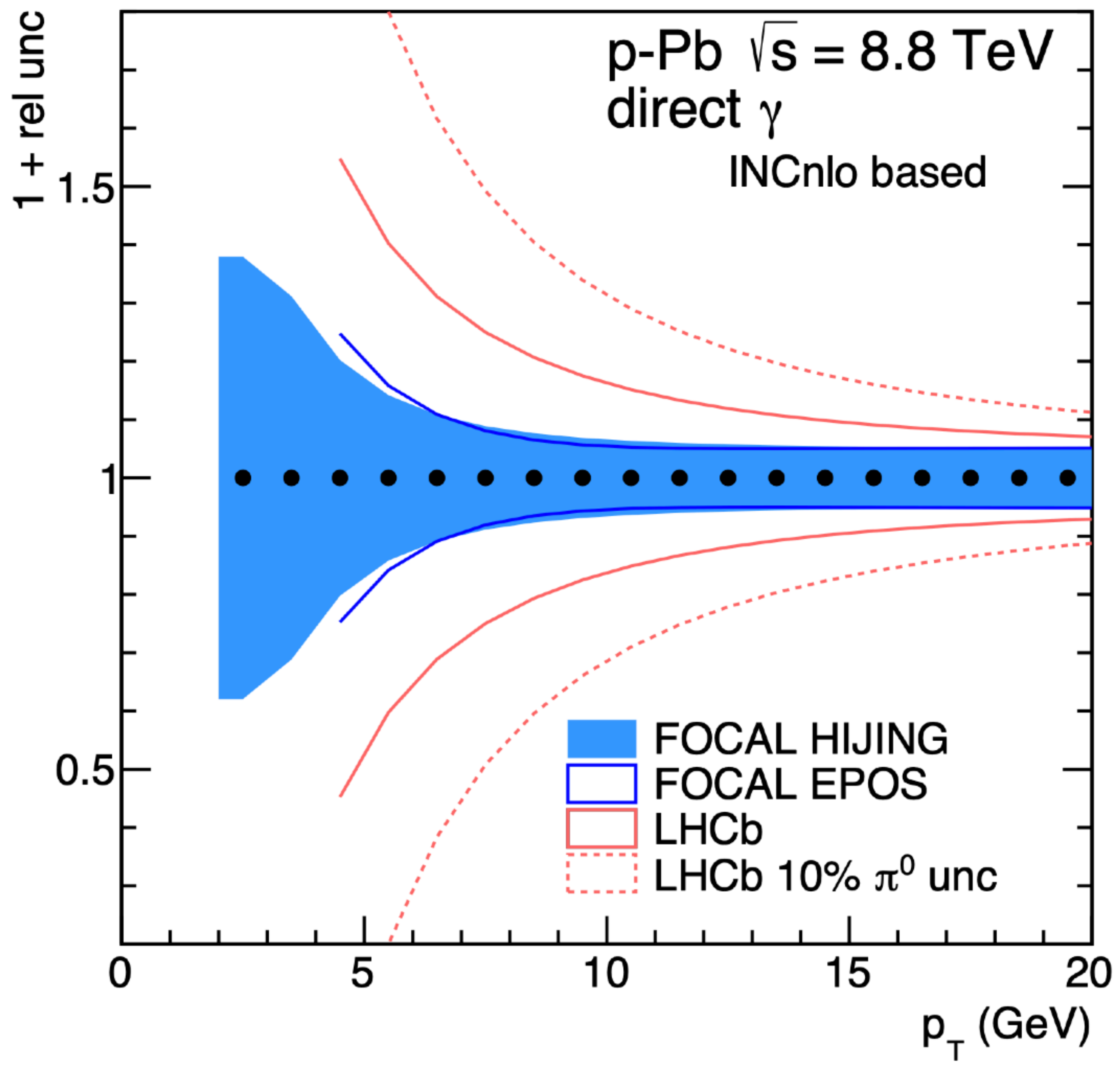
BDT response



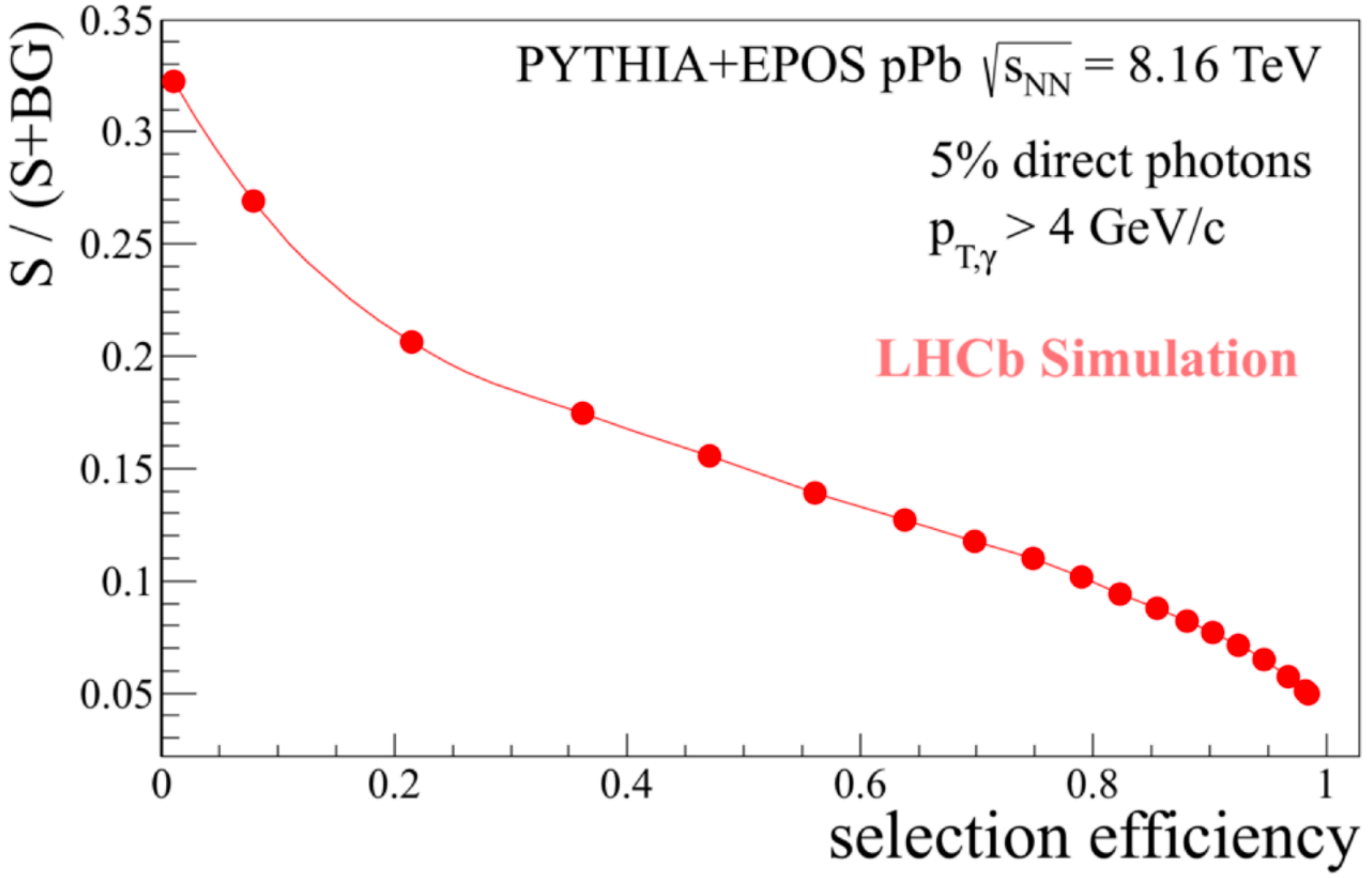
Improvement in S/B



Performance in pPb



Purity vs efficiency of BDT cut



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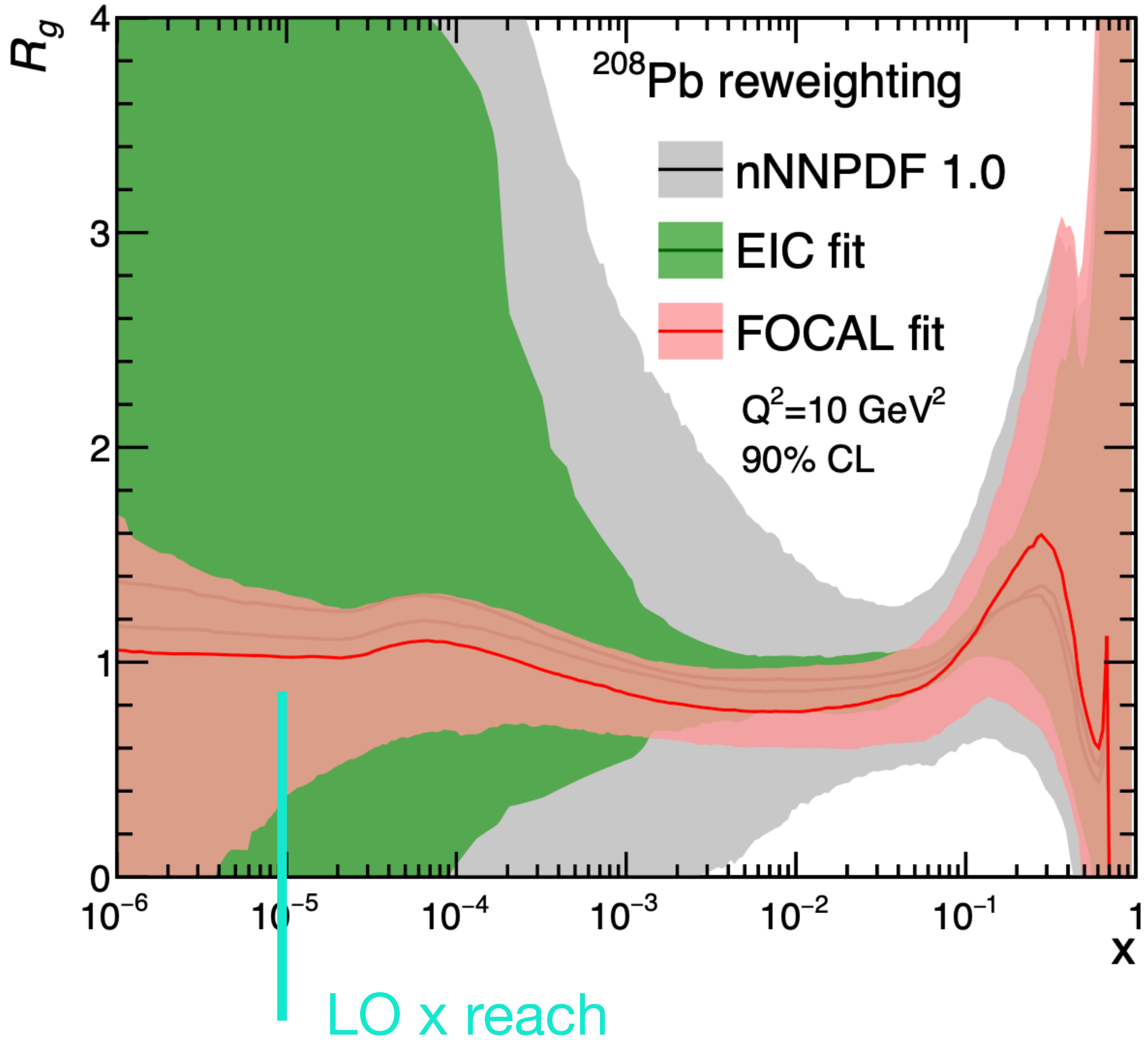
- Improvement in S/B significantly smaller than of FoCal
- Leads to factor 2 or larger systematic uncertainty compared to FoCal
  - Expected performance depends on uncertainty on remaining background

(WP at ε_{sig}=0.2 for LHCb,
at ε_{sig}~0.4 for FoCal)

FoCal vs LHCb: sensitivity to nPDF

η=4.5 (FoCal)

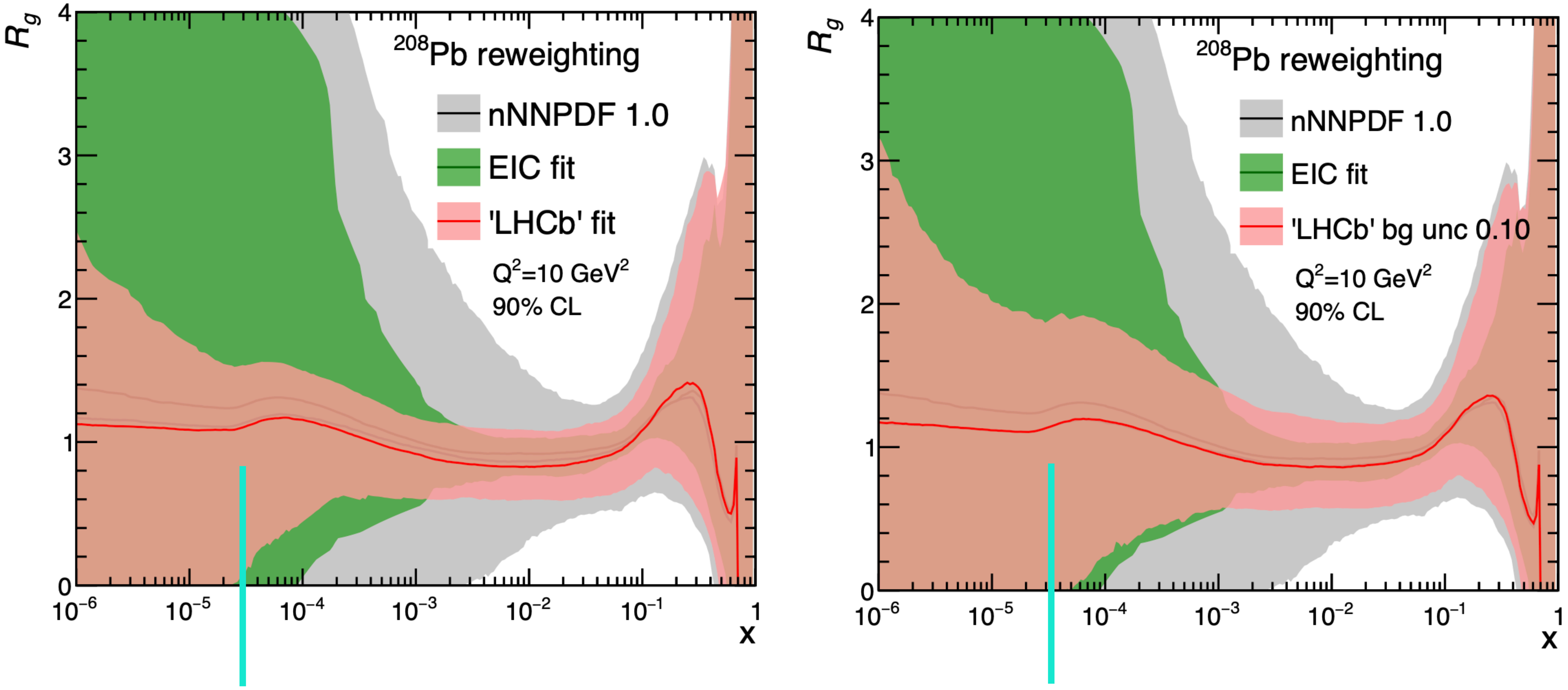


LO x reach

$$x \approx \frac{Q}{\sqrt{s}} \exp(-y)$$

FoCal uncertainties

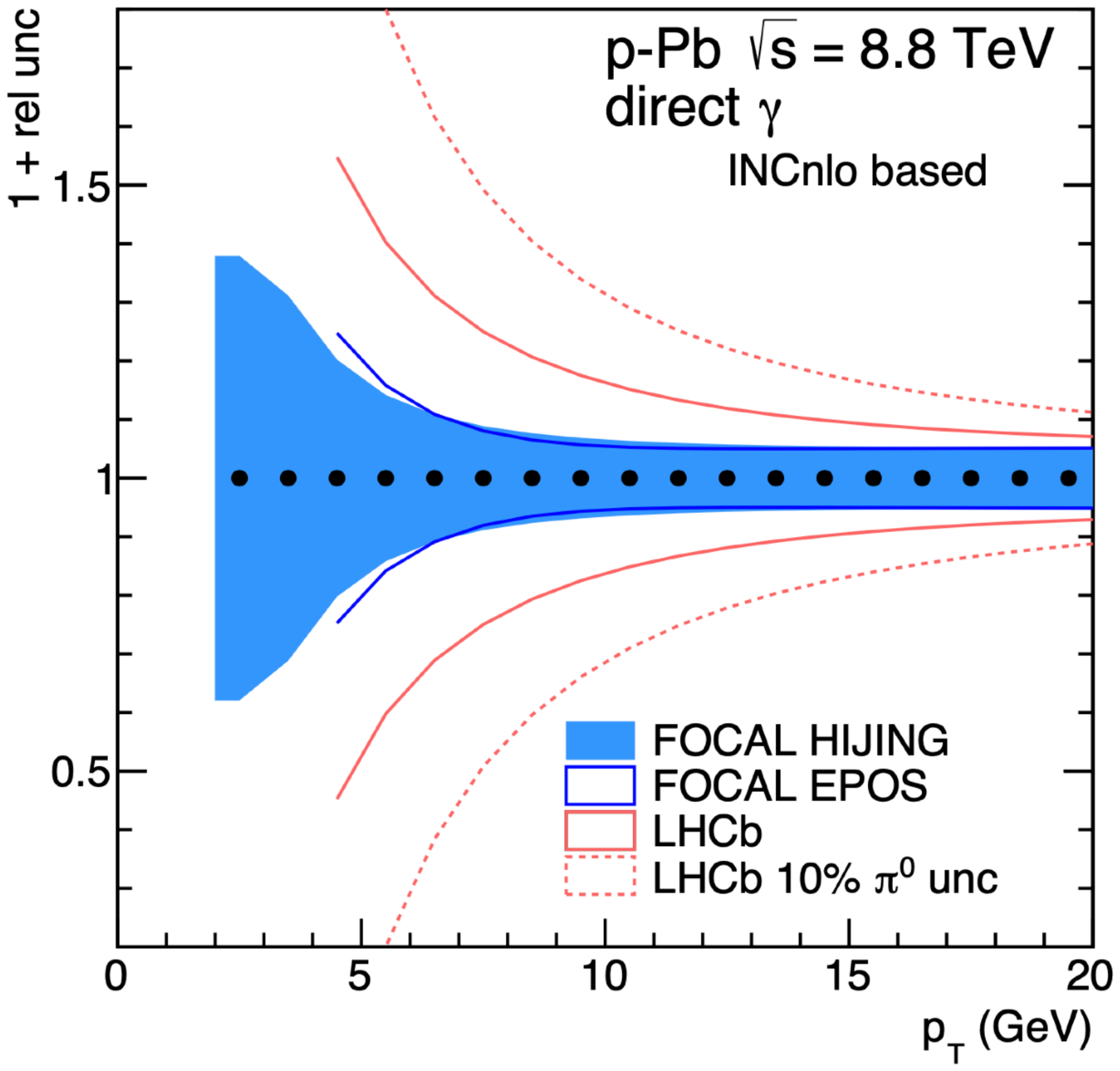
η=3.5 (LHCb)

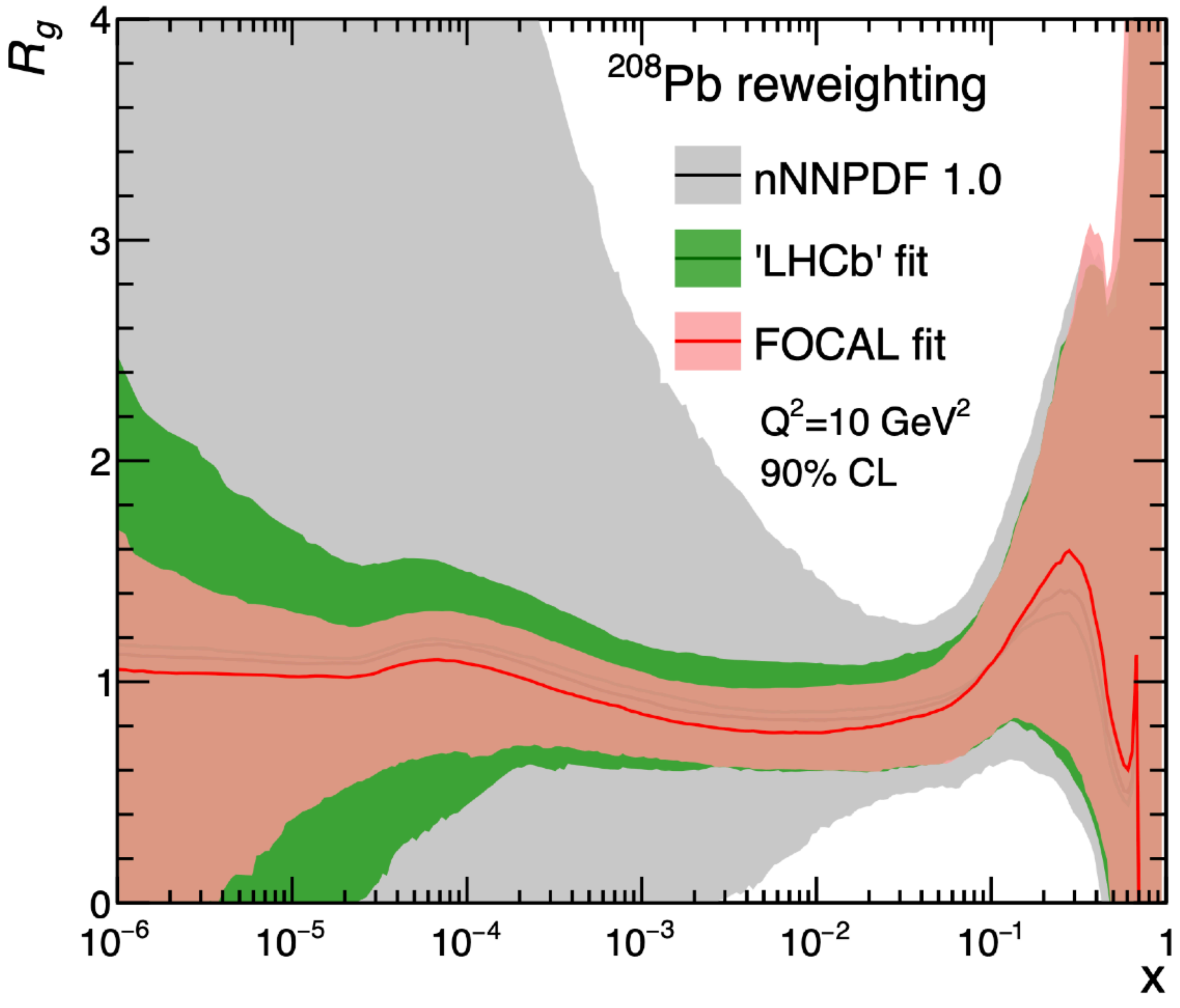


LHCb projected uncertainties
(5% vs 10% uncertainty on the background)

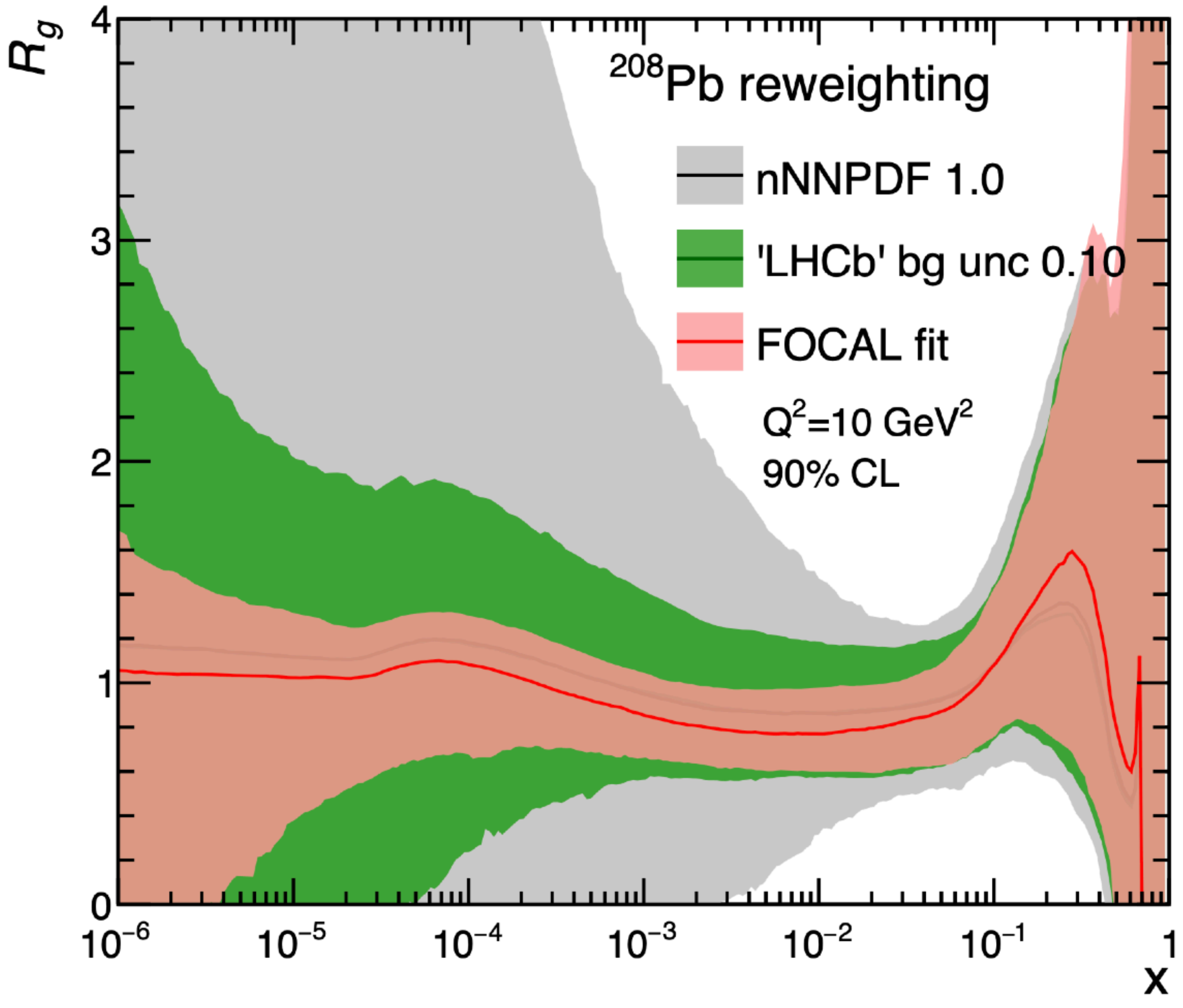
Significantly better performance on nuclear PDF expected by FoCal measurement
(in addition one unit higher reach in pseudorapidity, i.e. factor 3 smaller x reachable)

Comparison of isolated performance with LHCb projection





bgk unc=5%



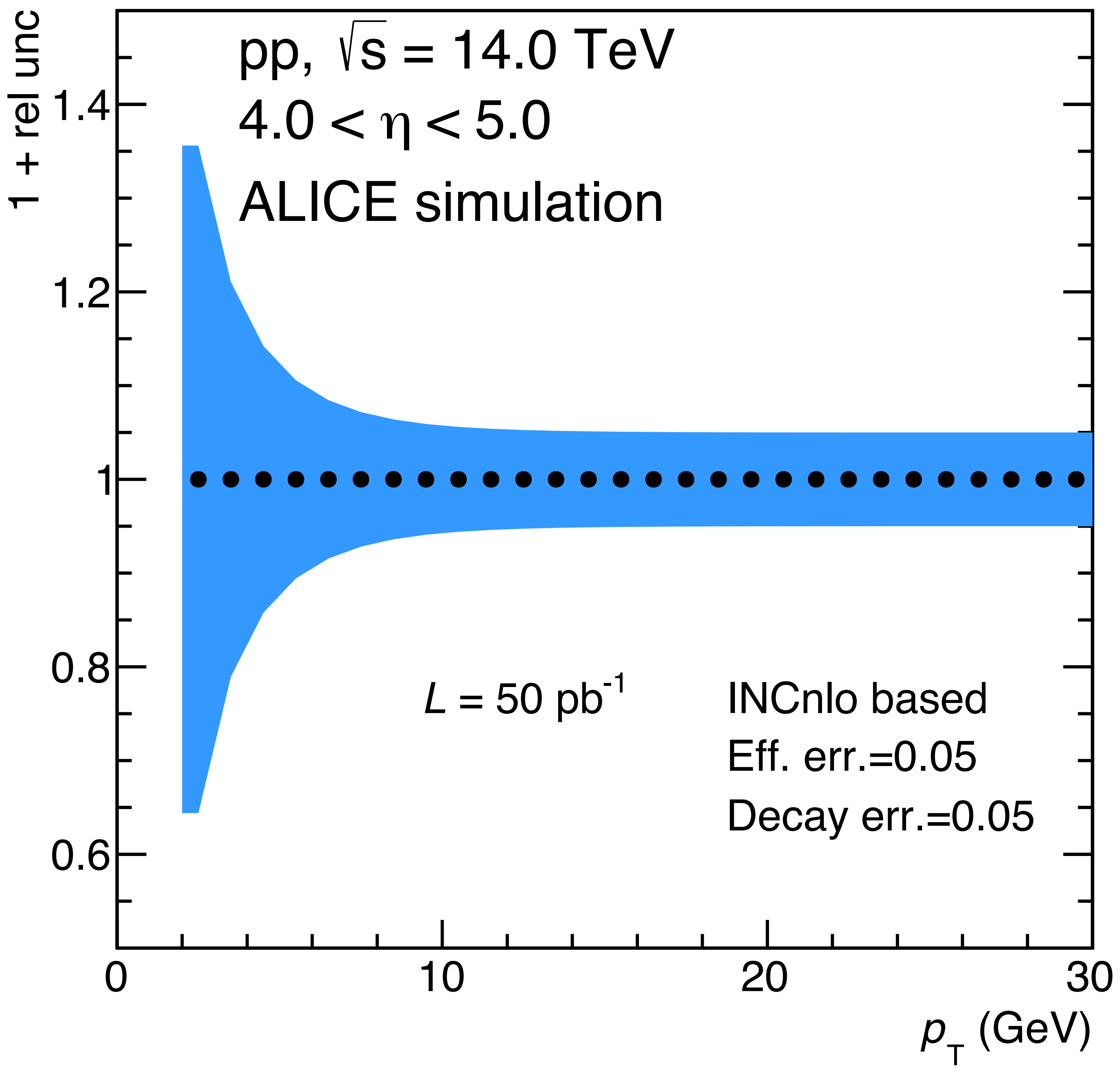
bgk unc=10%

FoCal performance (4<η<5) outperforms LHCb (3<η<4) by a factor of 2 or more in uncertainty
(LHCb measures only about 25-40% of the photons from π^0)

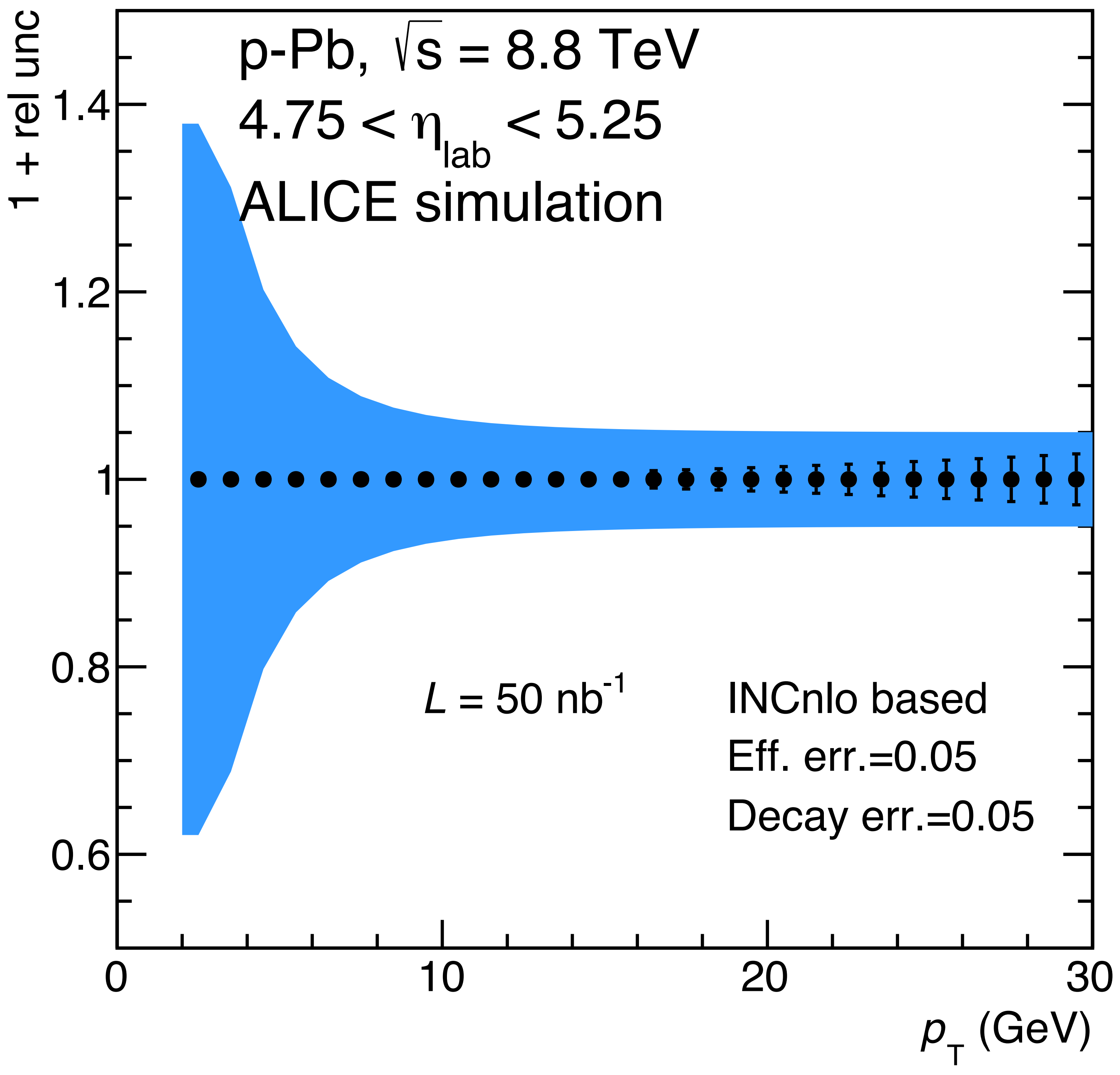
(WP at ε_{sig}=0.2 for LHCb,
at ε_{sig}~0.4 for FoCal)

Direct photon uncertainties

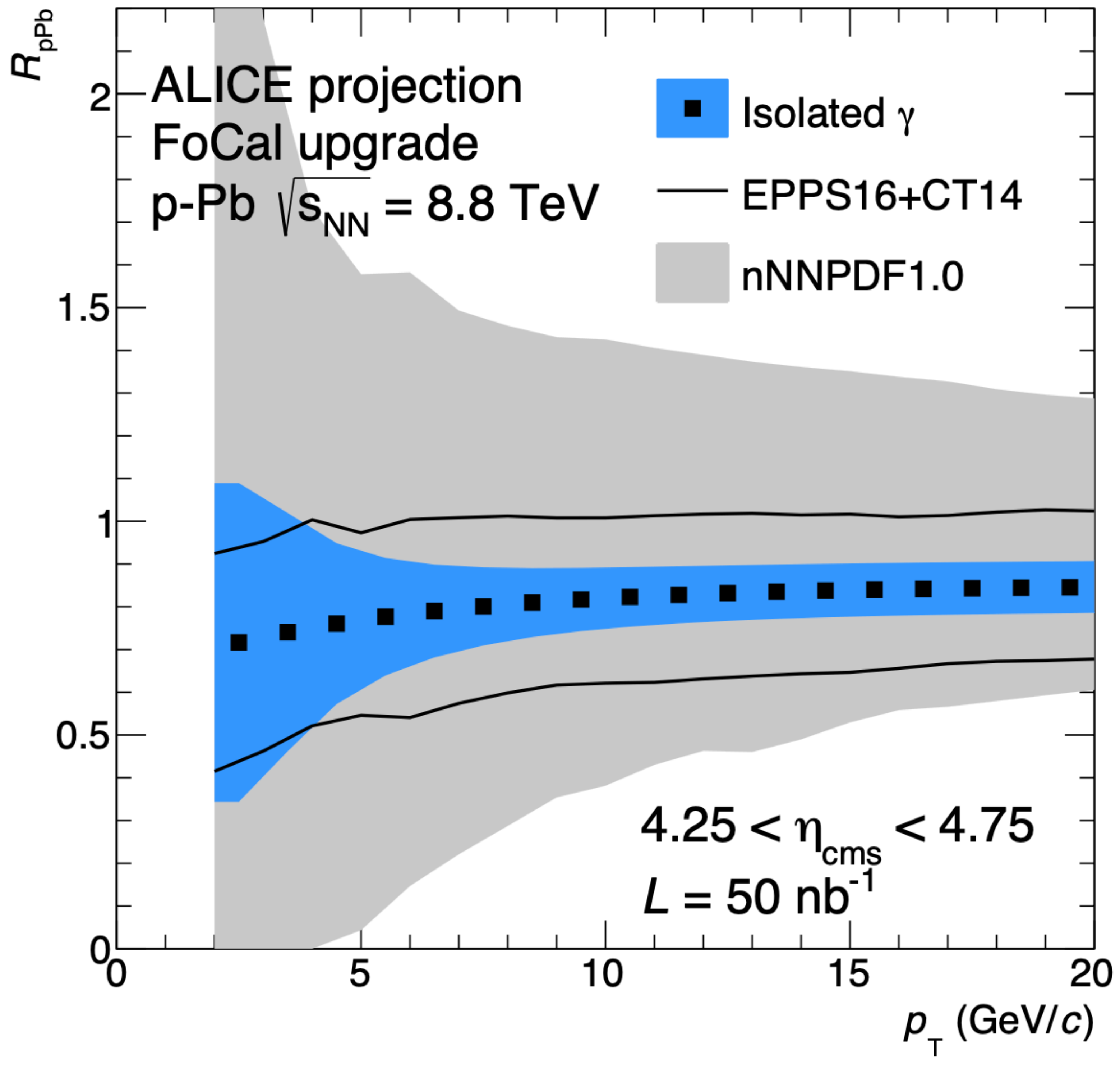
pp uncertainties



p-Pb uncertainties



R_{pPb} projection



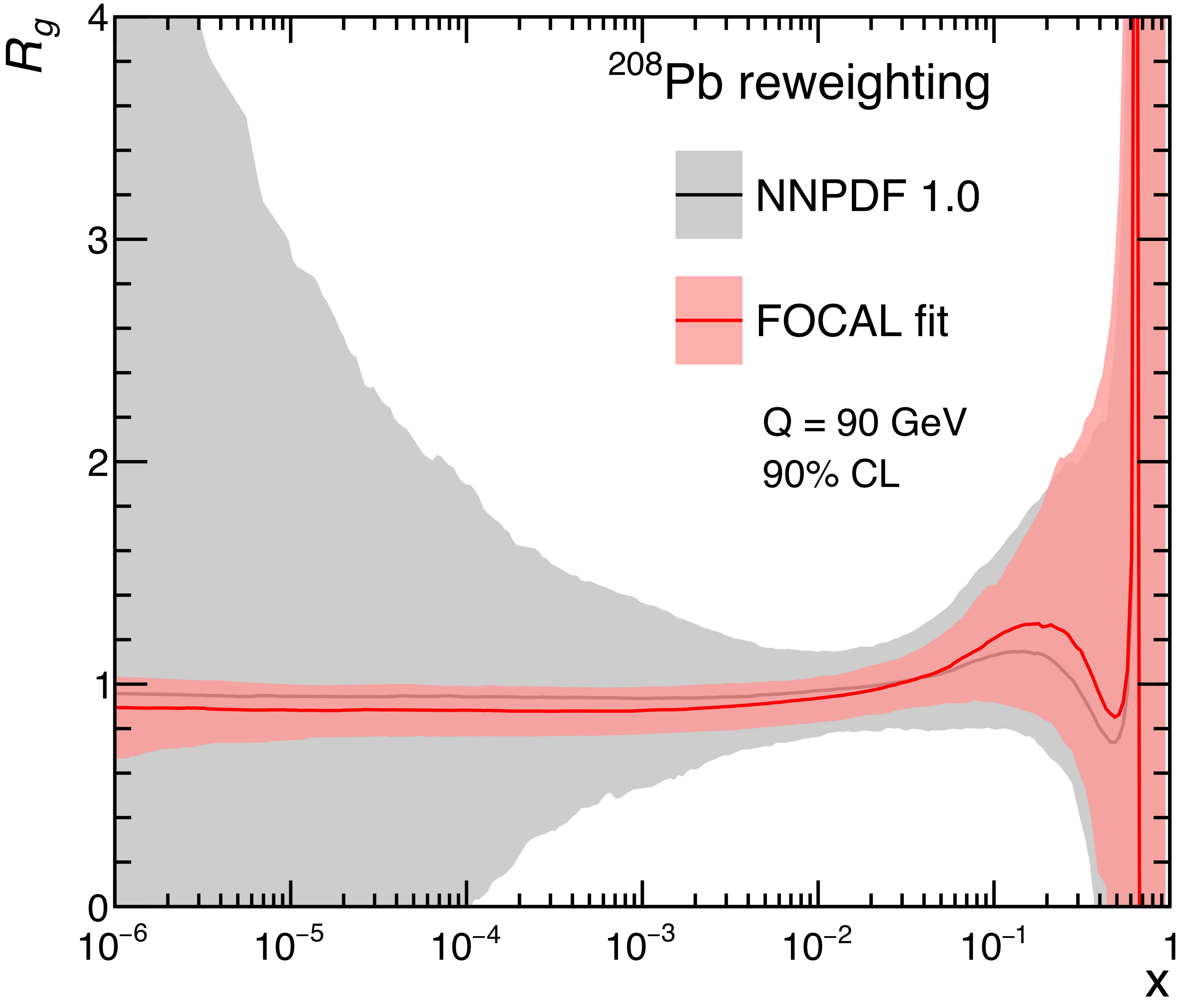
$\eta_{cms} = \eta_{lab} \sim 4.5$ for pp

$\eta_{cms} \sim 4.5$: $\eta_{lab} \sim 5.0$ for p-Pb

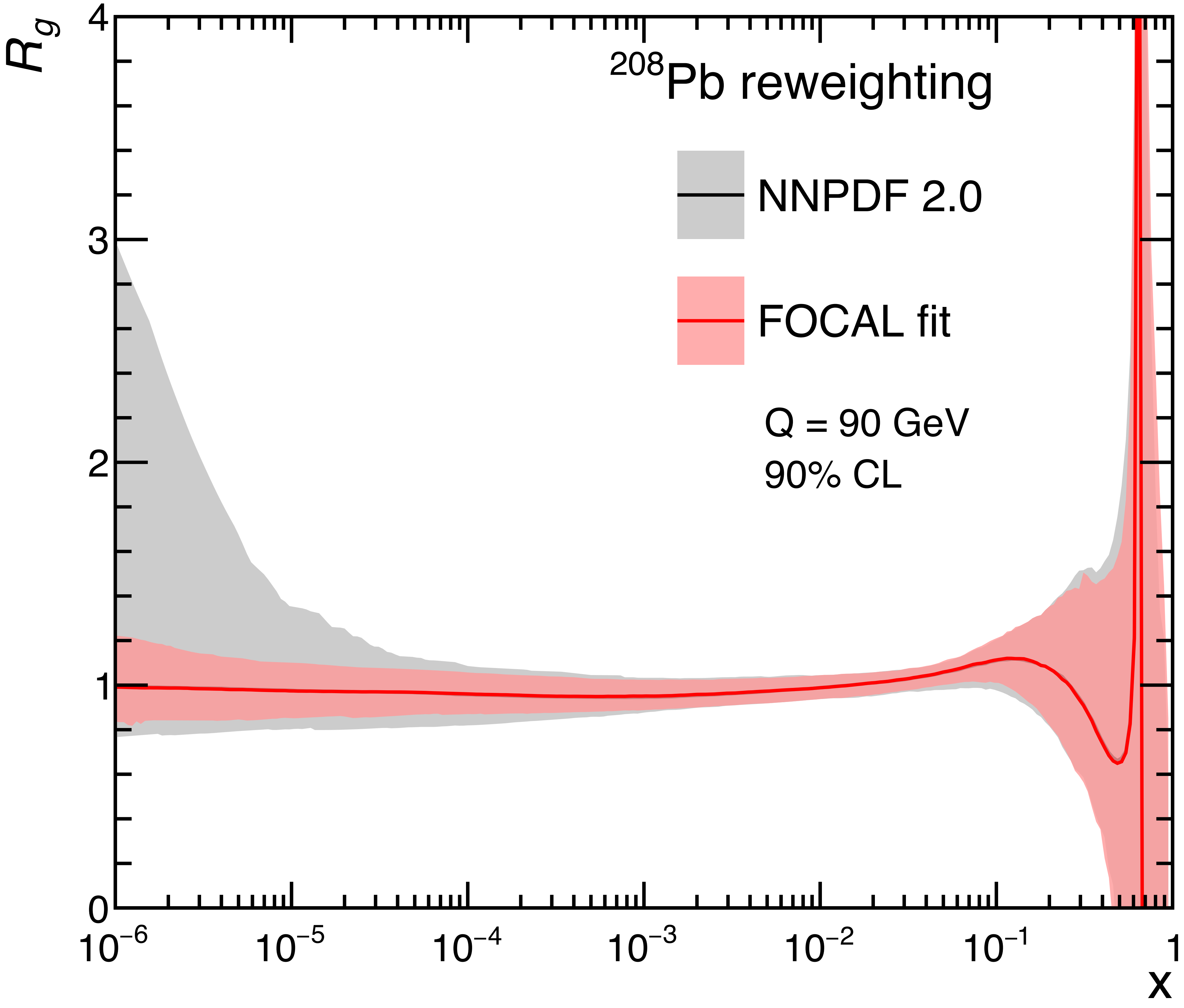
nNNPDF 1.0 vs 2.0 at M_Z

- Include (some) LHC W/Z data
- Include DIS charged current data: flavor separation
- Include 'positivity constraint' : F_L (long structure function) has to be positive

nNNPDF 1.0



nNNPDF 2.0

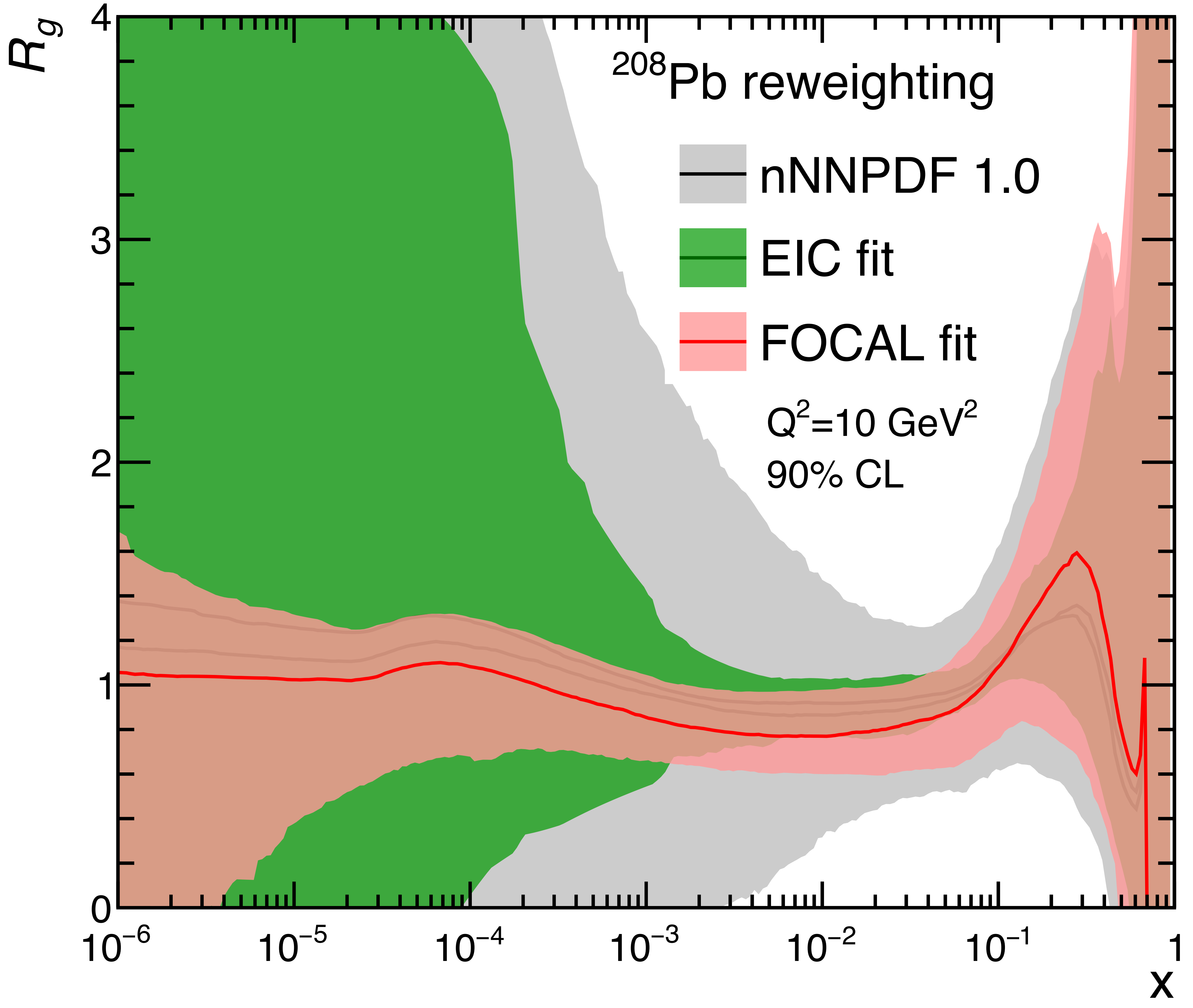


Clear impact of W/Z LHC data

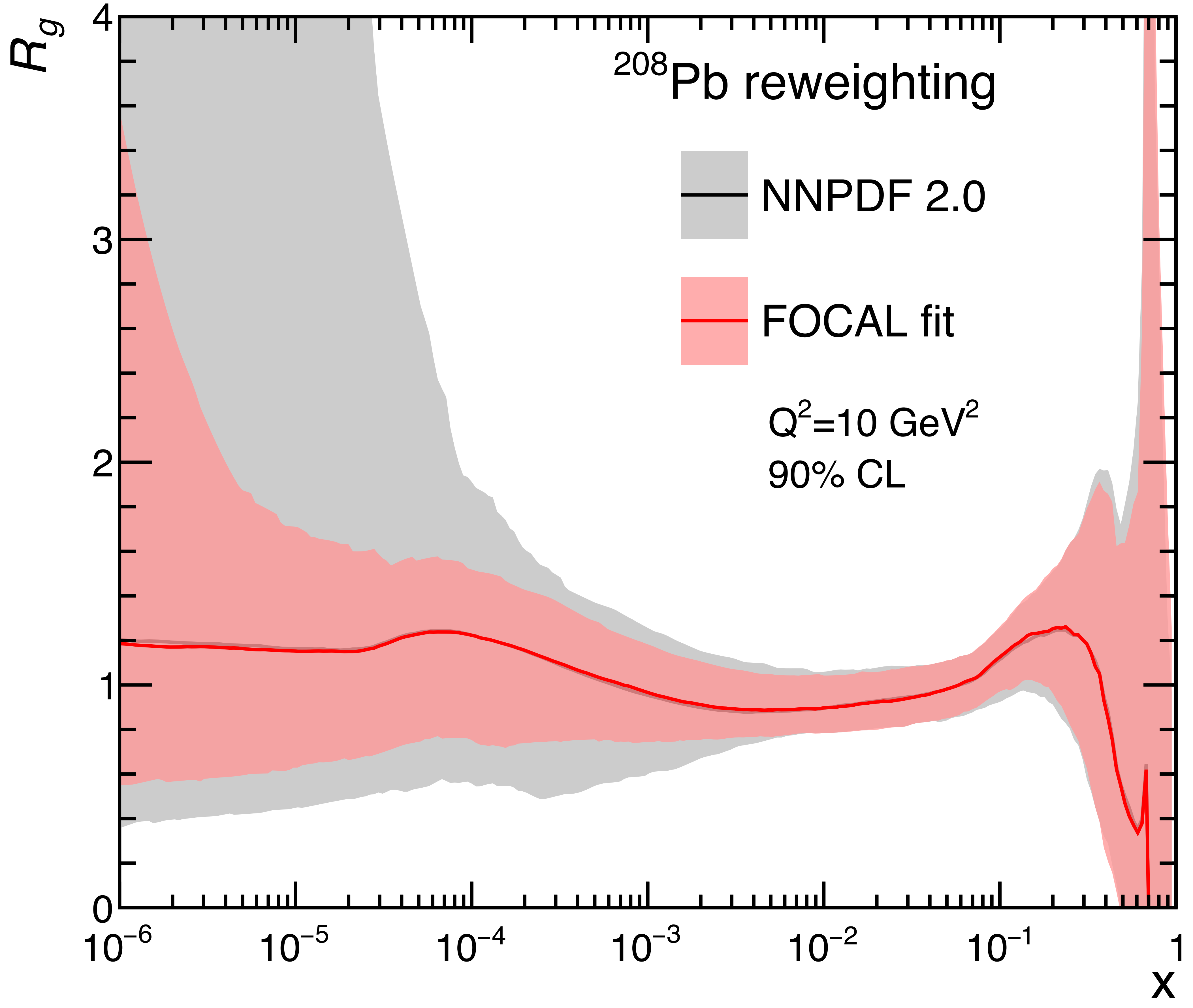
NNPDF2.0

- Include (some) LHC W/Z data
- Include DIS charged current data: flavor separation
- Include ‘positivity constraint’ : F_L (long structure function) has to be positive

nNNPDF 1.0



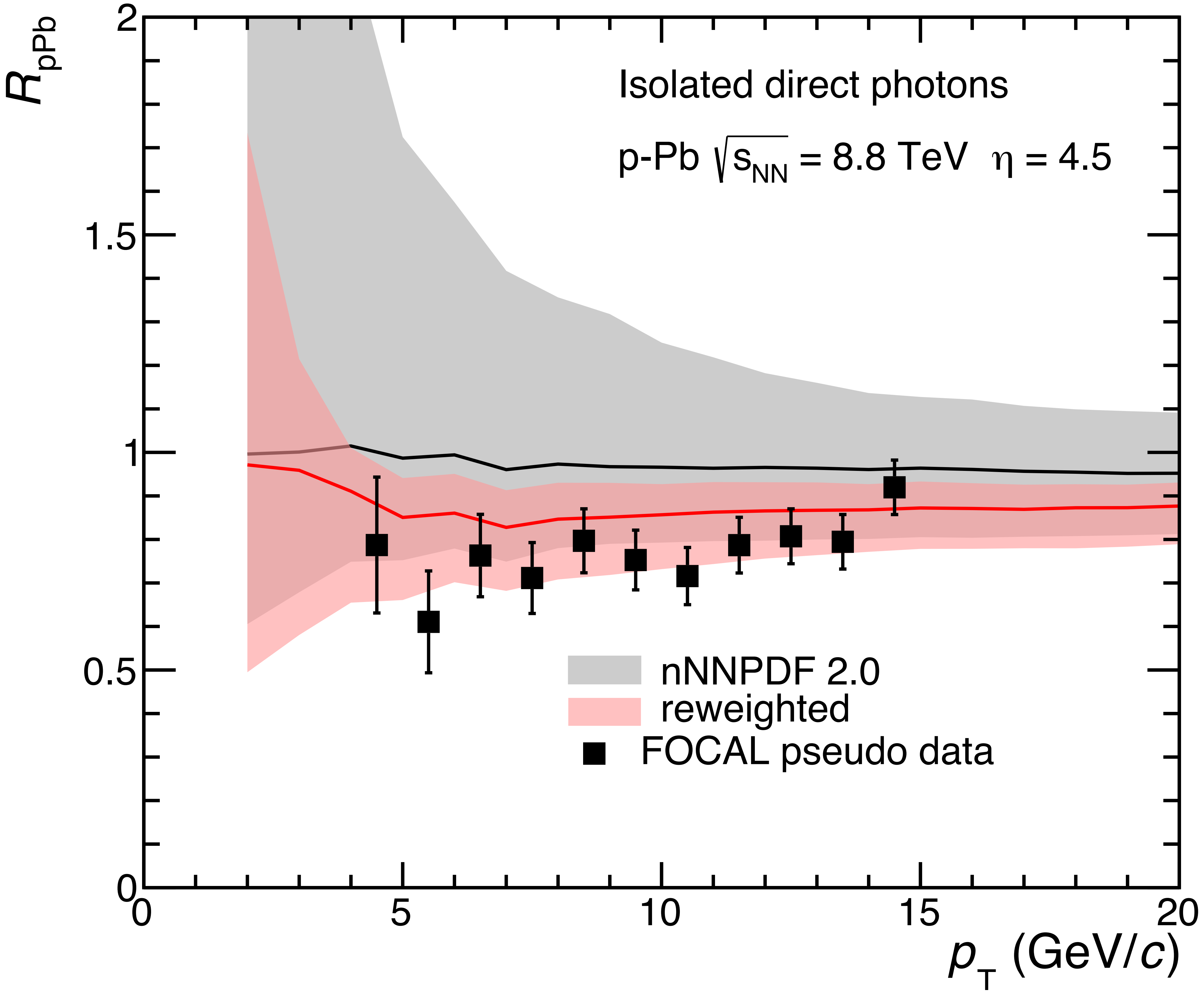
nNNPDF 2.0



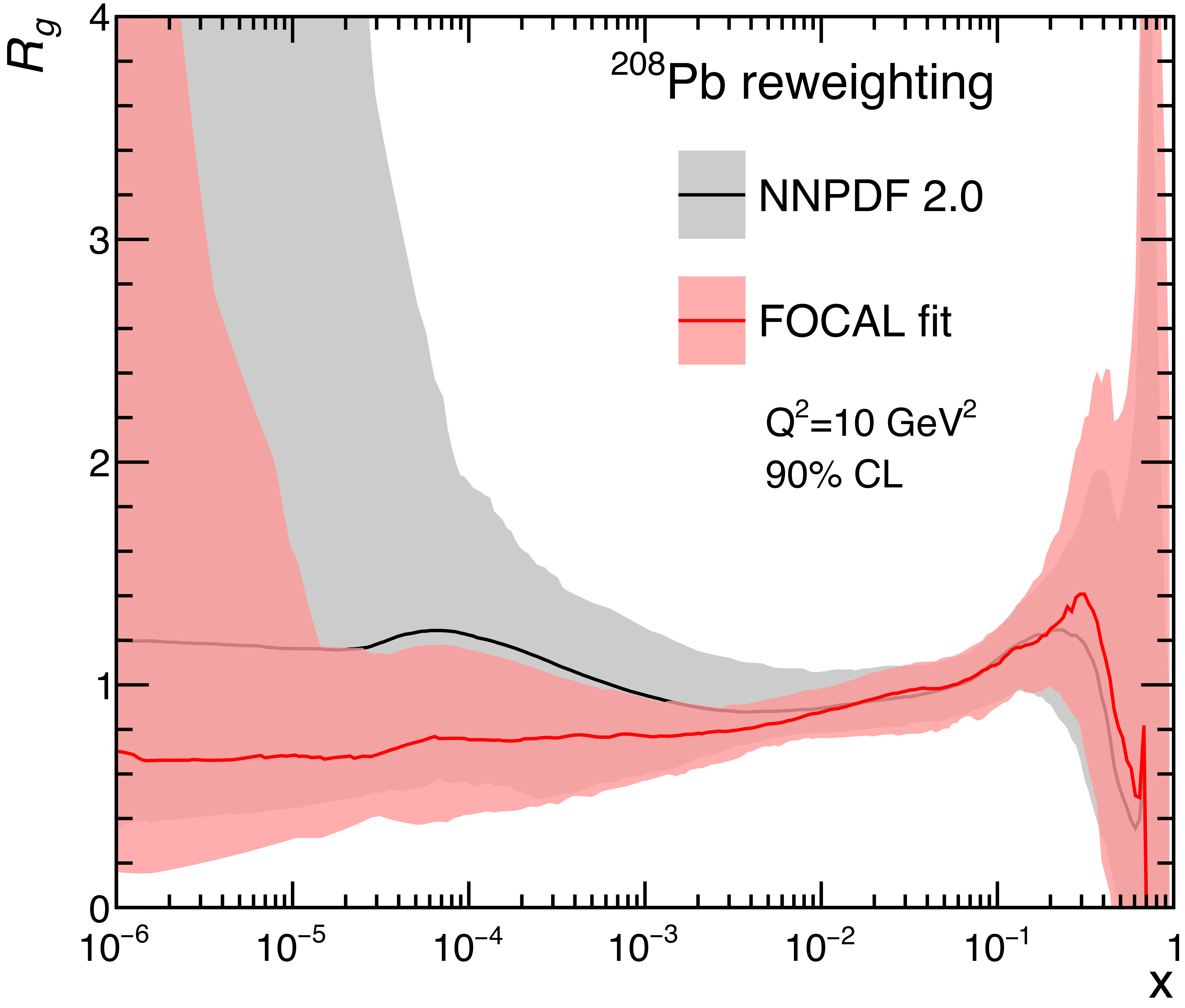
FOCAL places significant constraints in $10^{-5} < x < 10^{-3}$

Sensitivity to non-linear evolution: What if we see suppression?

Use smaller central values for pseudo-data



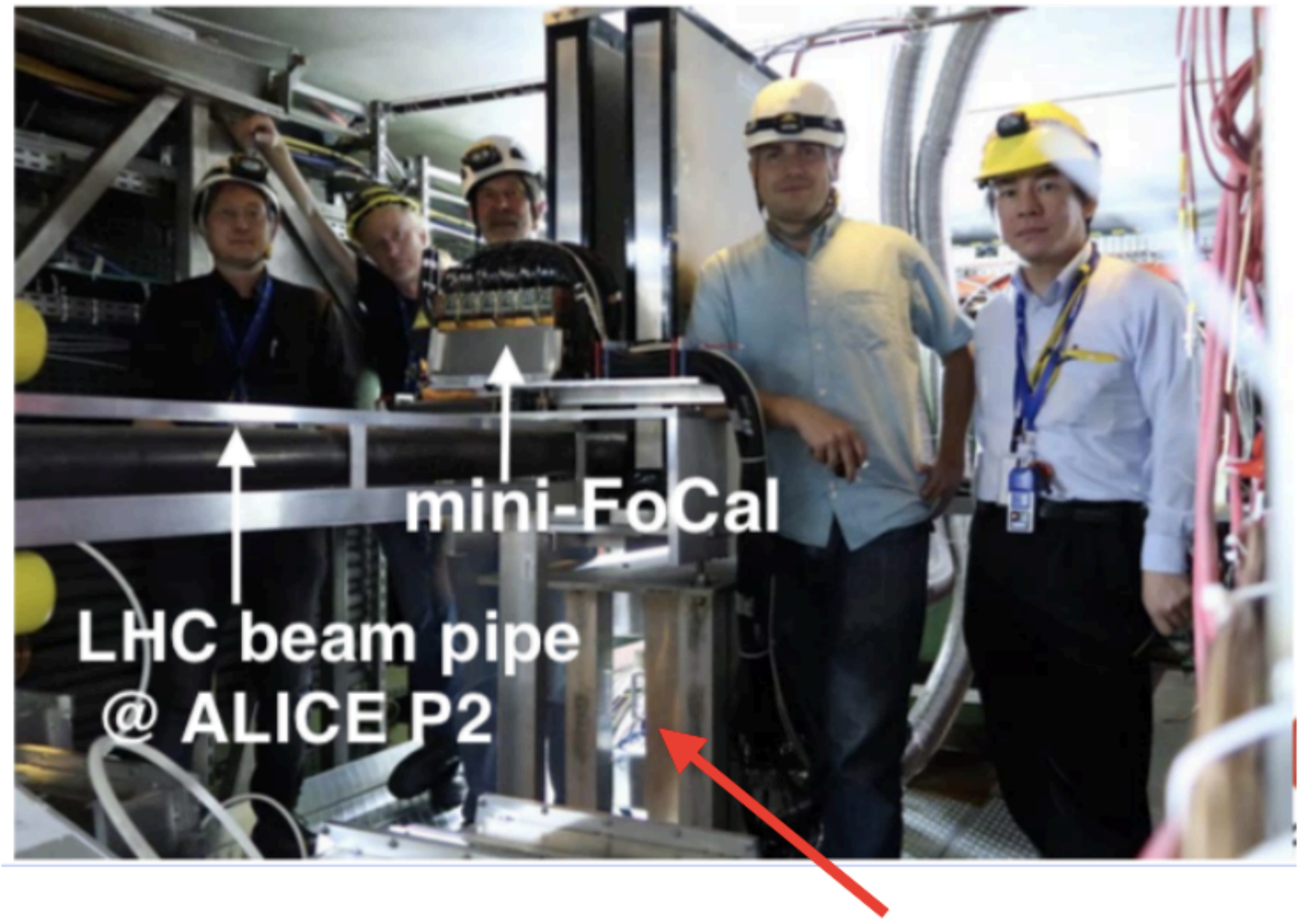
Clear tension between nNPDF2.0 and pseudo data: Red band/line above the data points



Fit 'pulls down' both central value and lower edge of band at small x as expected

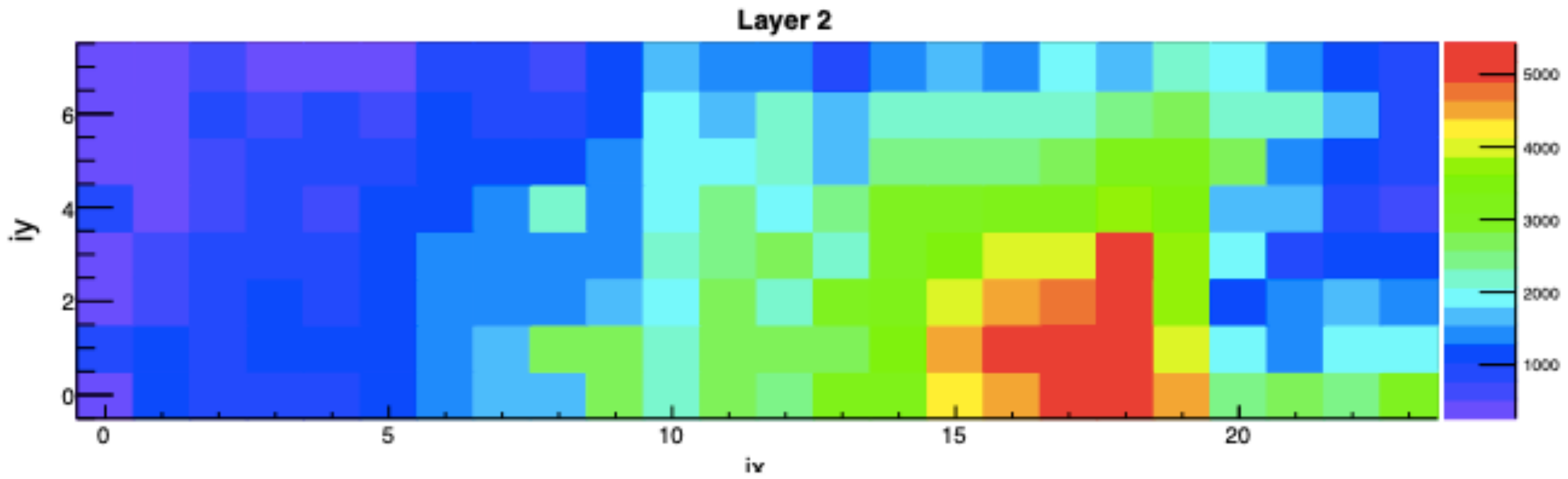
Conclusion: a suppression at LHC would result in a tension: sign of non-linear evolution?

mini-FoCal in ALICE (2018)

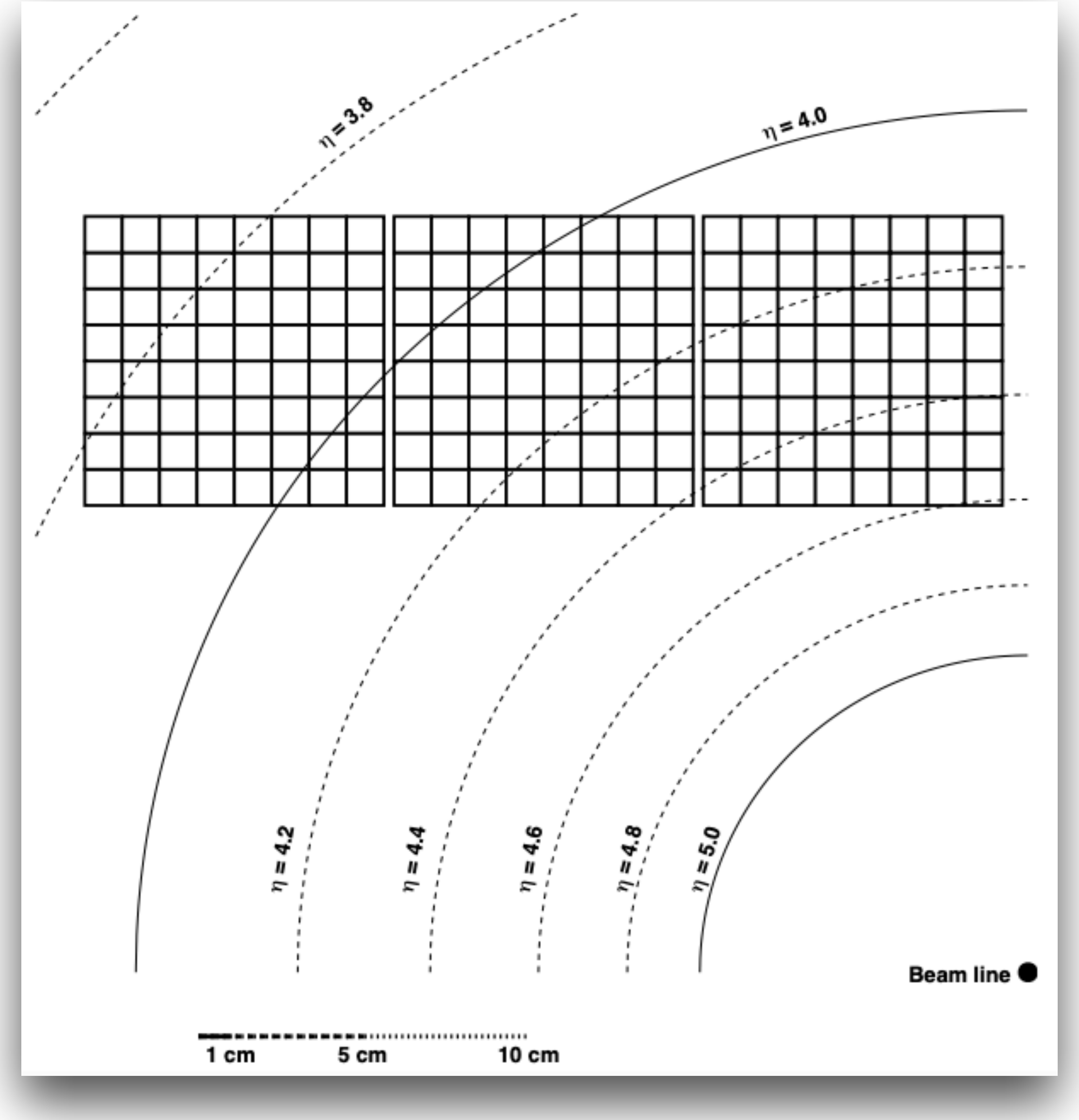


SRS system under the table

Hit Map of mini-FoCal in ALICE



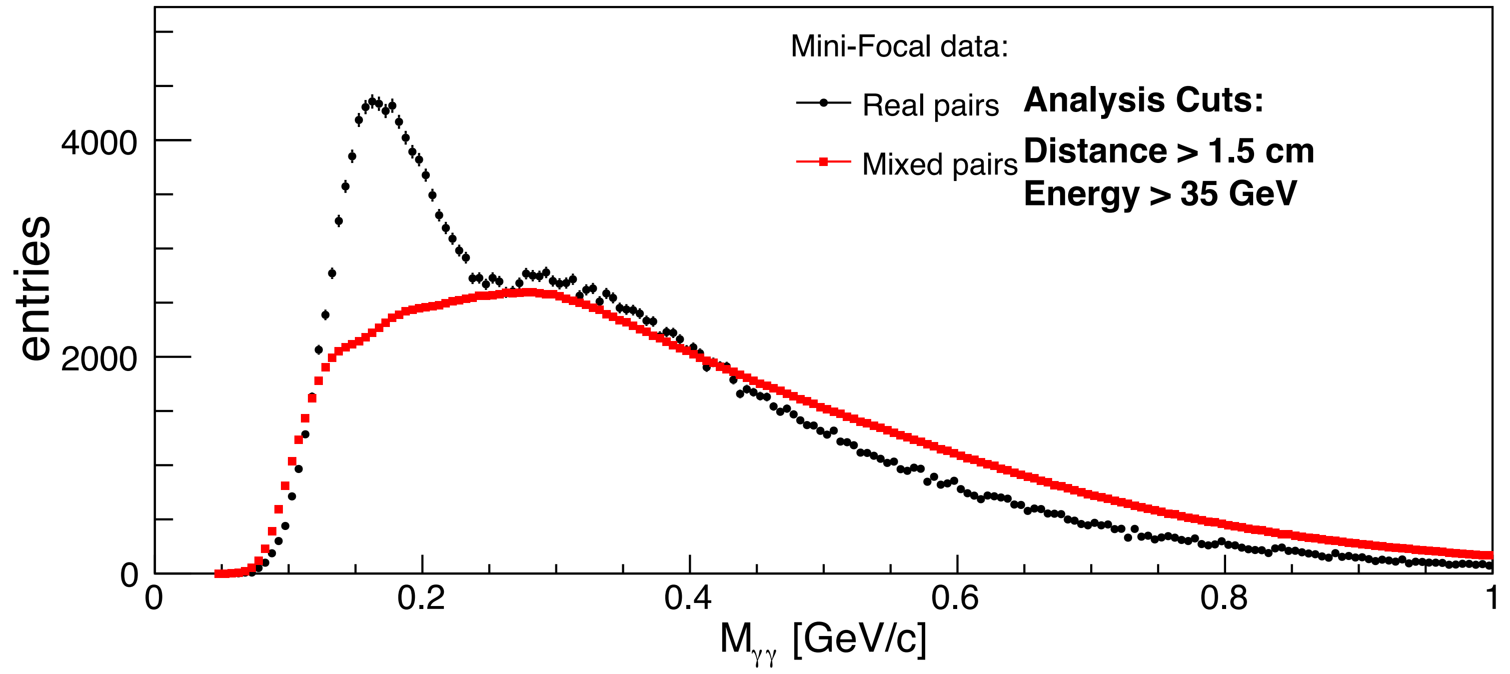
Acceptance



Goal: measure/verify backgrounds in situ with p+p @ √s = 13 TeV collisions in ALICE

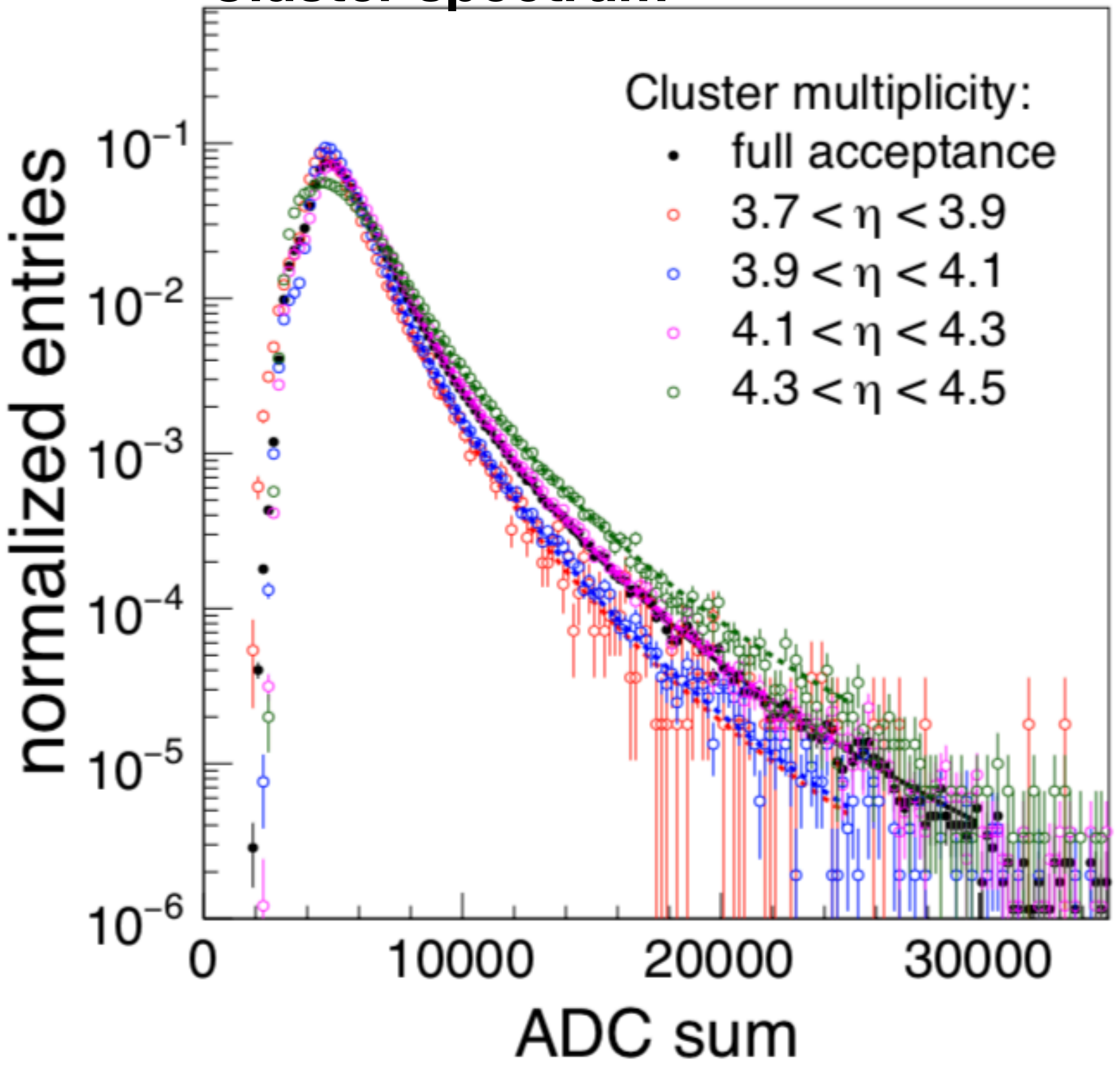
- Calibration based on test beam
- Comparison to MC (cluster spectrum, slid lines)

π^0 peak

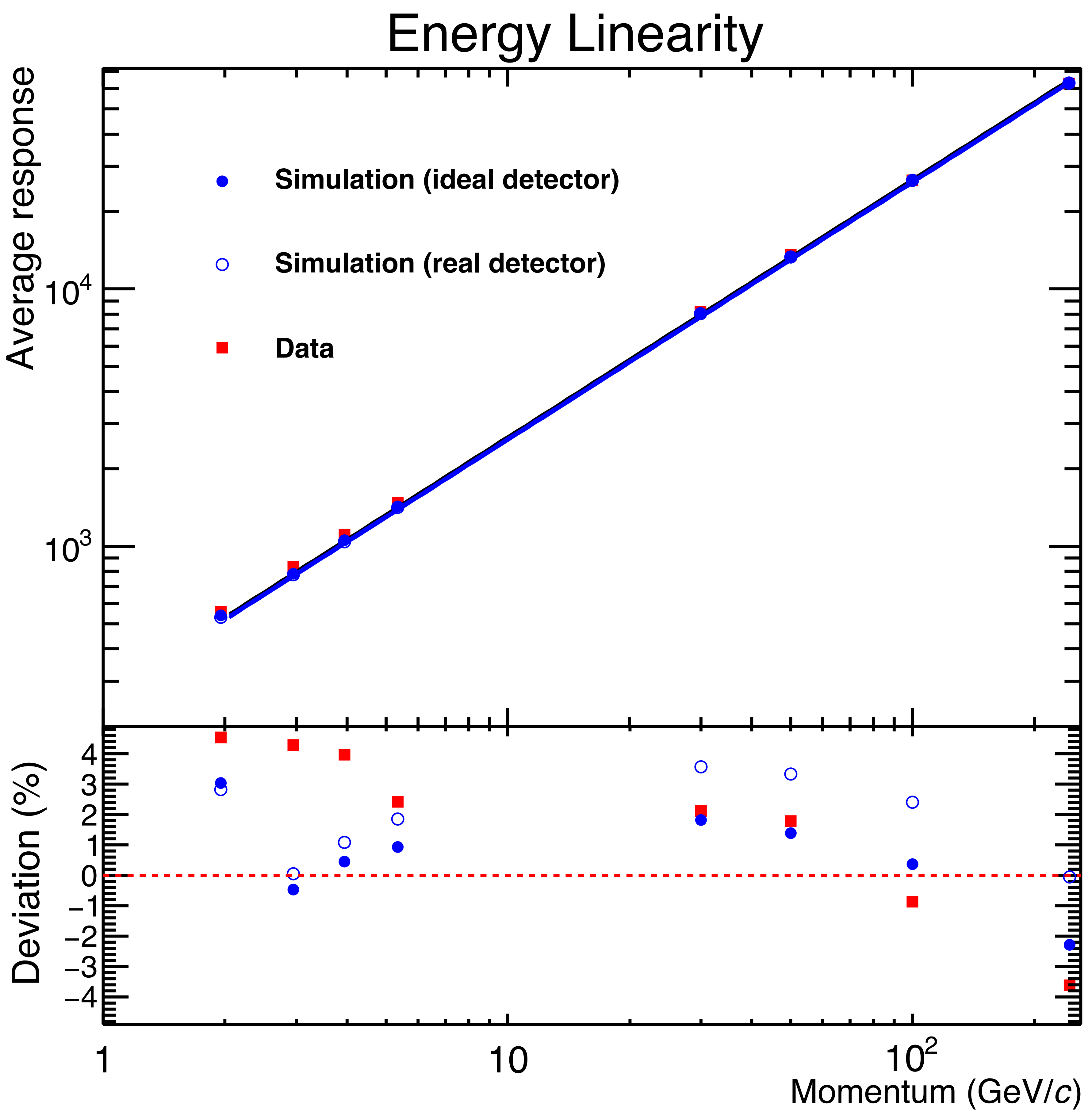


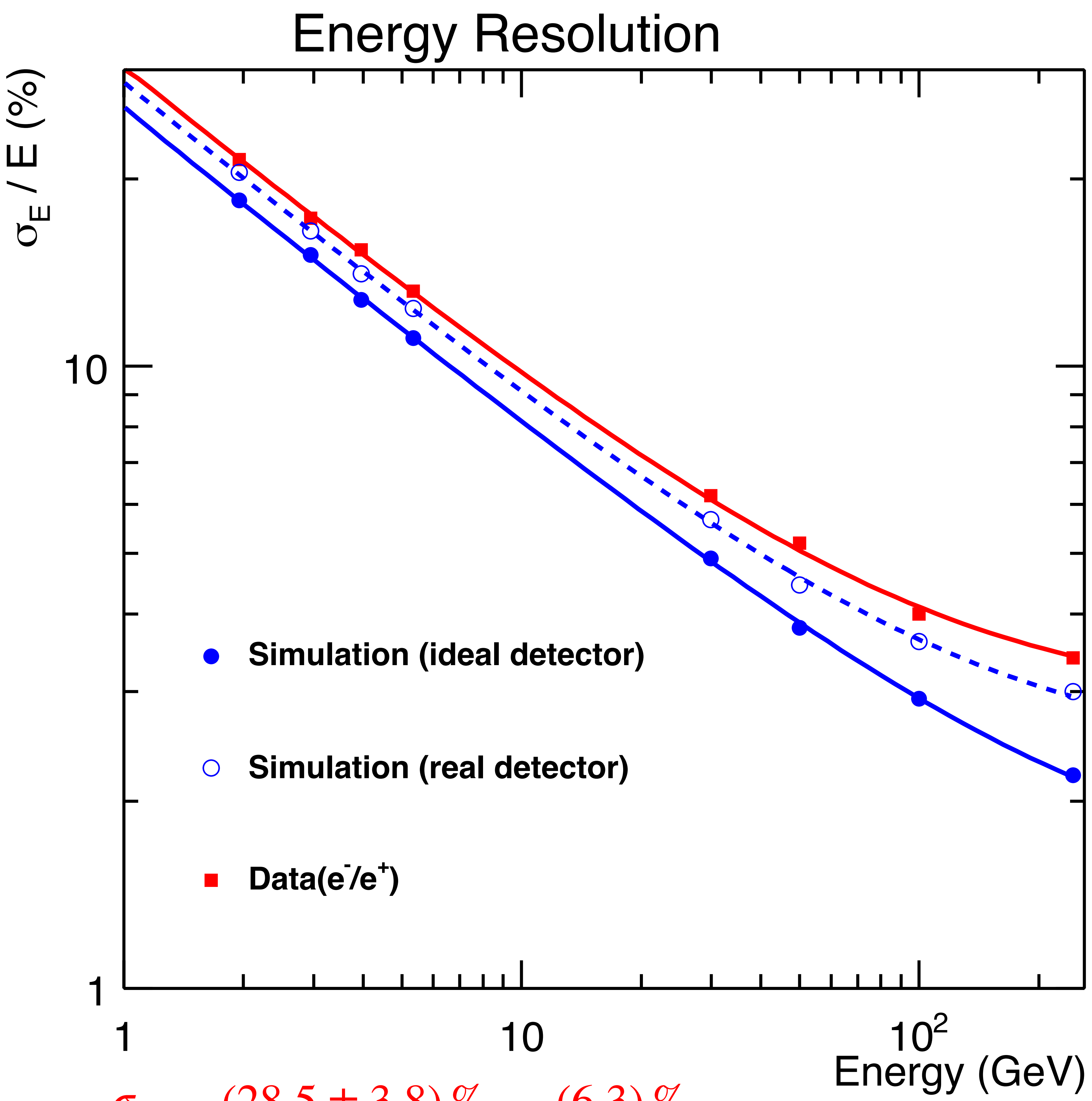
N. Novitzky

Cluster spectrum



MIMOSA: Energy Linearity and Resolution





$$\frac{\sigma_E}{E} = \frac{(28.5 \pm 3.8)\,\%}{\sqrt{E/\mathrm{GeV}}} + \frac{(6.3)\,\%}{E/\mathrm{GeV}} + (2.95 \pm 1.65)\,\%$$

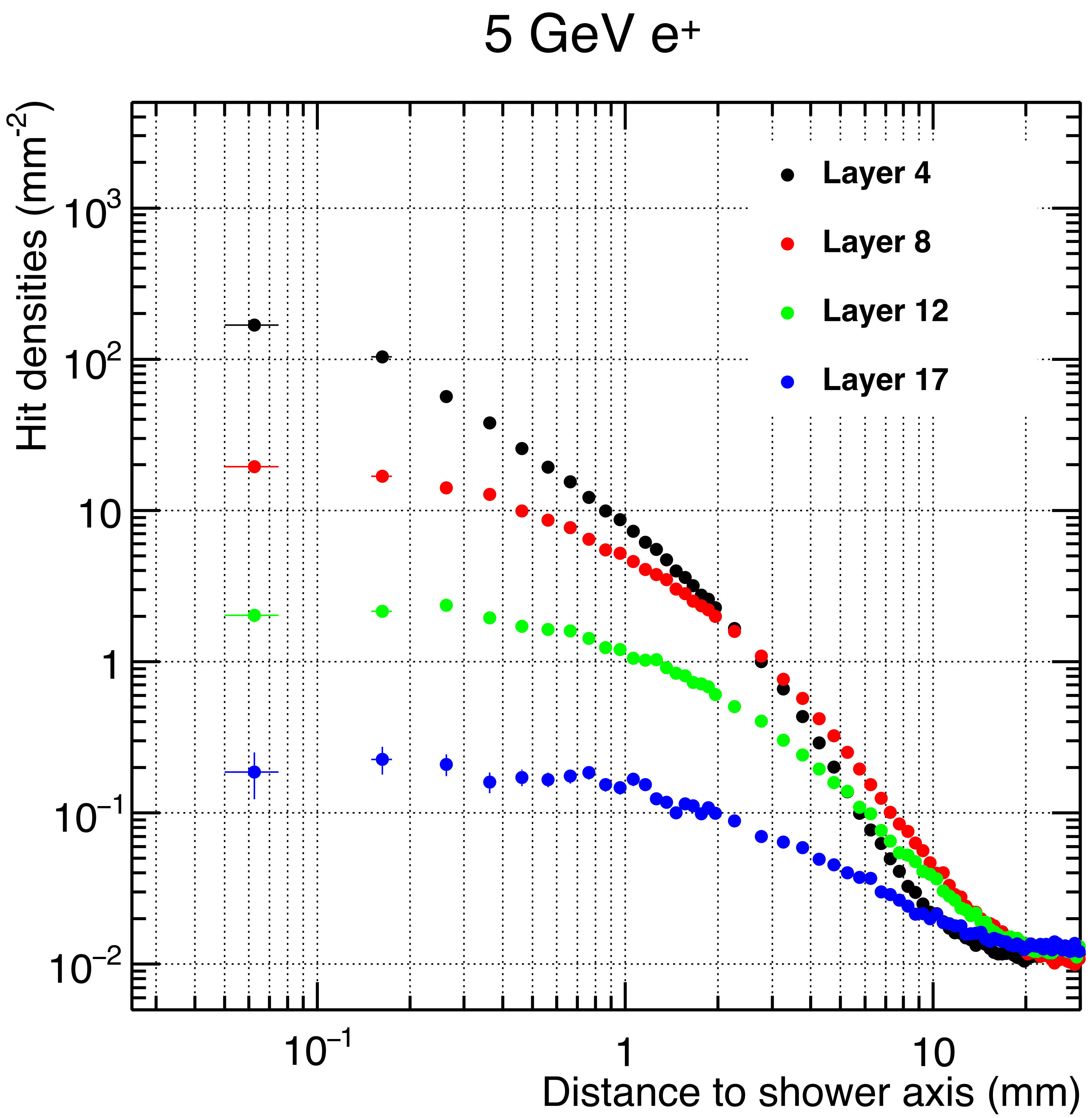
good linearity and energy resolution

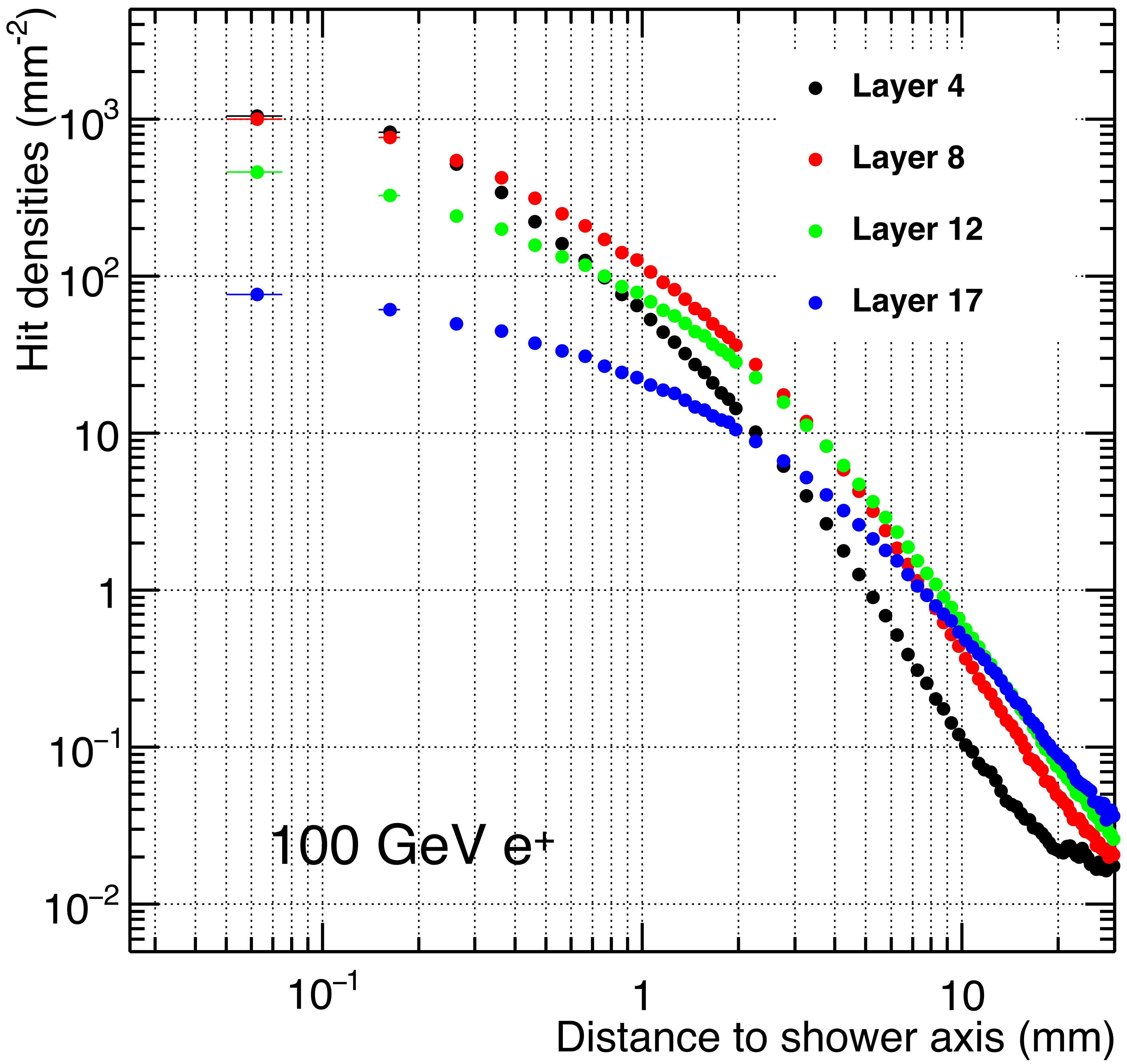
- note: different calibration for low and high energy
- possibly still improve calibration
- effects of saturation seen at 244 GeV – to be corrected

proof of principle of digital calorimetry

First results published in
JINST 13 (2018) P01014

R&D - Lateral Profiles





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

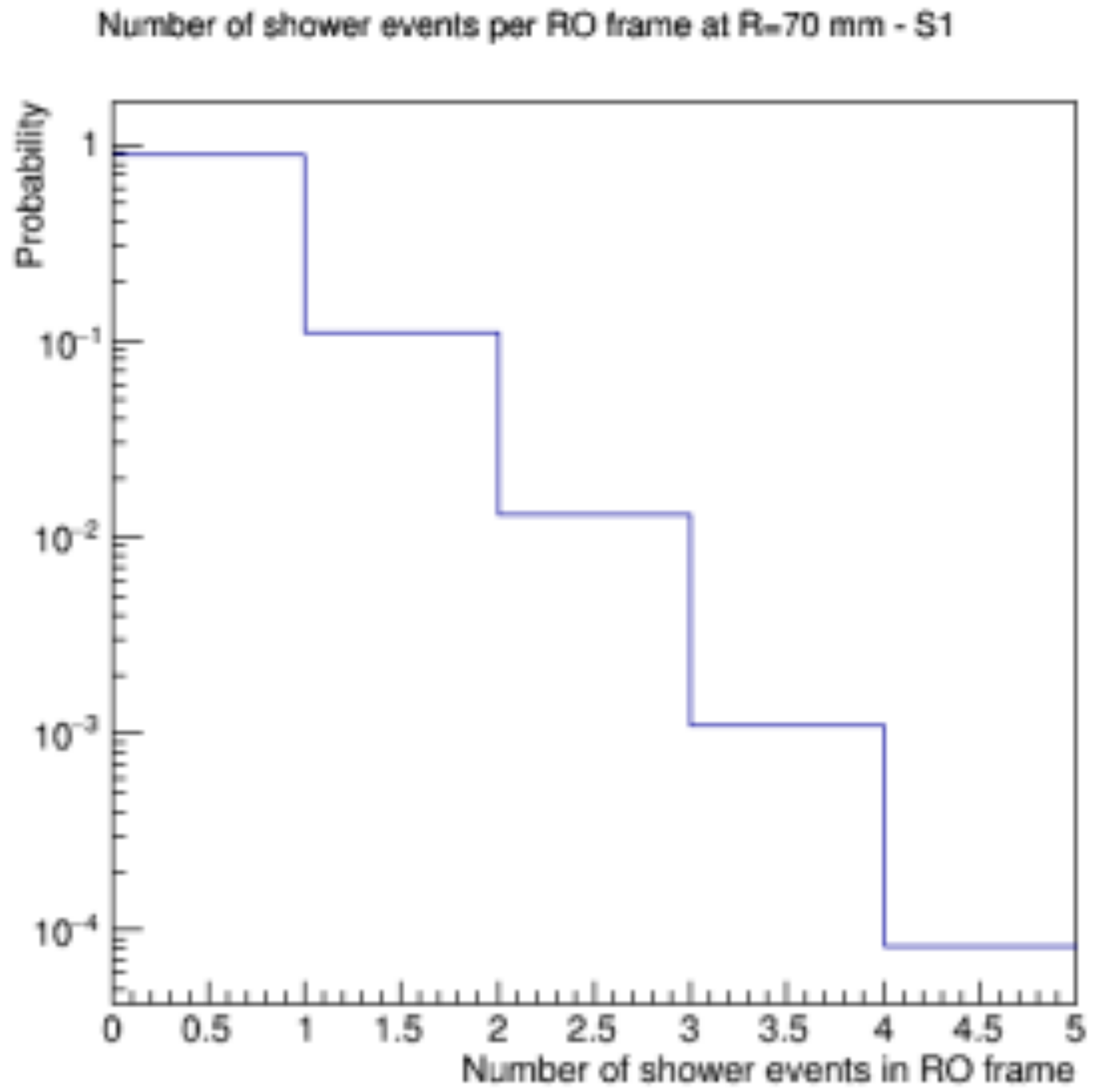
- low energy: early shower maximum, profiles broaden and decay with depth
- high energy: profiles broaden with depth, increase up to shower maximum

shower measurements with unprecedented detail!

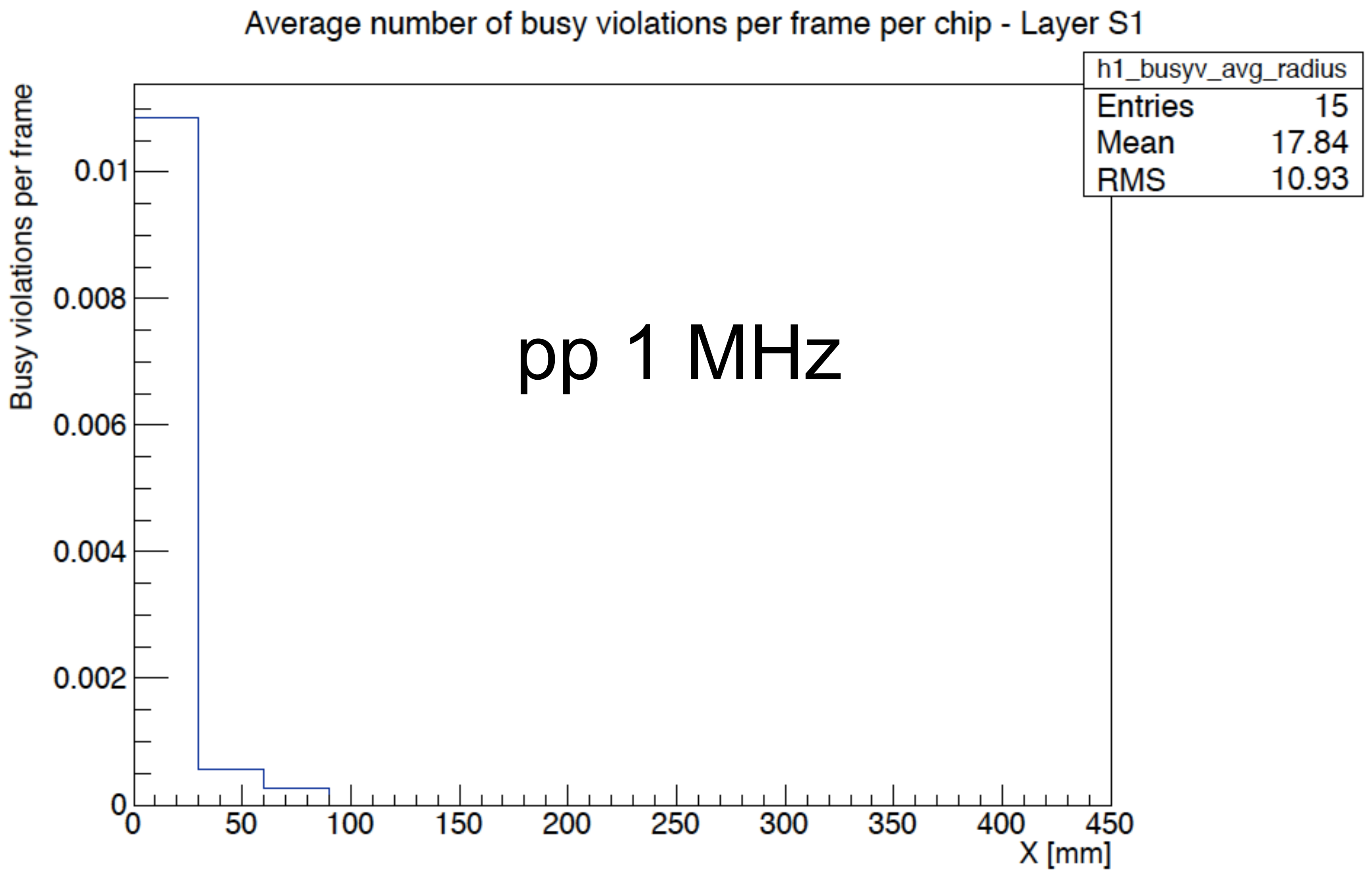
Pile up in pixel layers

Baseline design - use ITS2 ALPIDEs for the pixel layers

- **pile-up**
  - **min. bias pp, 1 MHz interaction rate**
  - **10μs readout frame**
  - **shower event: more than 50 hits per sensor**

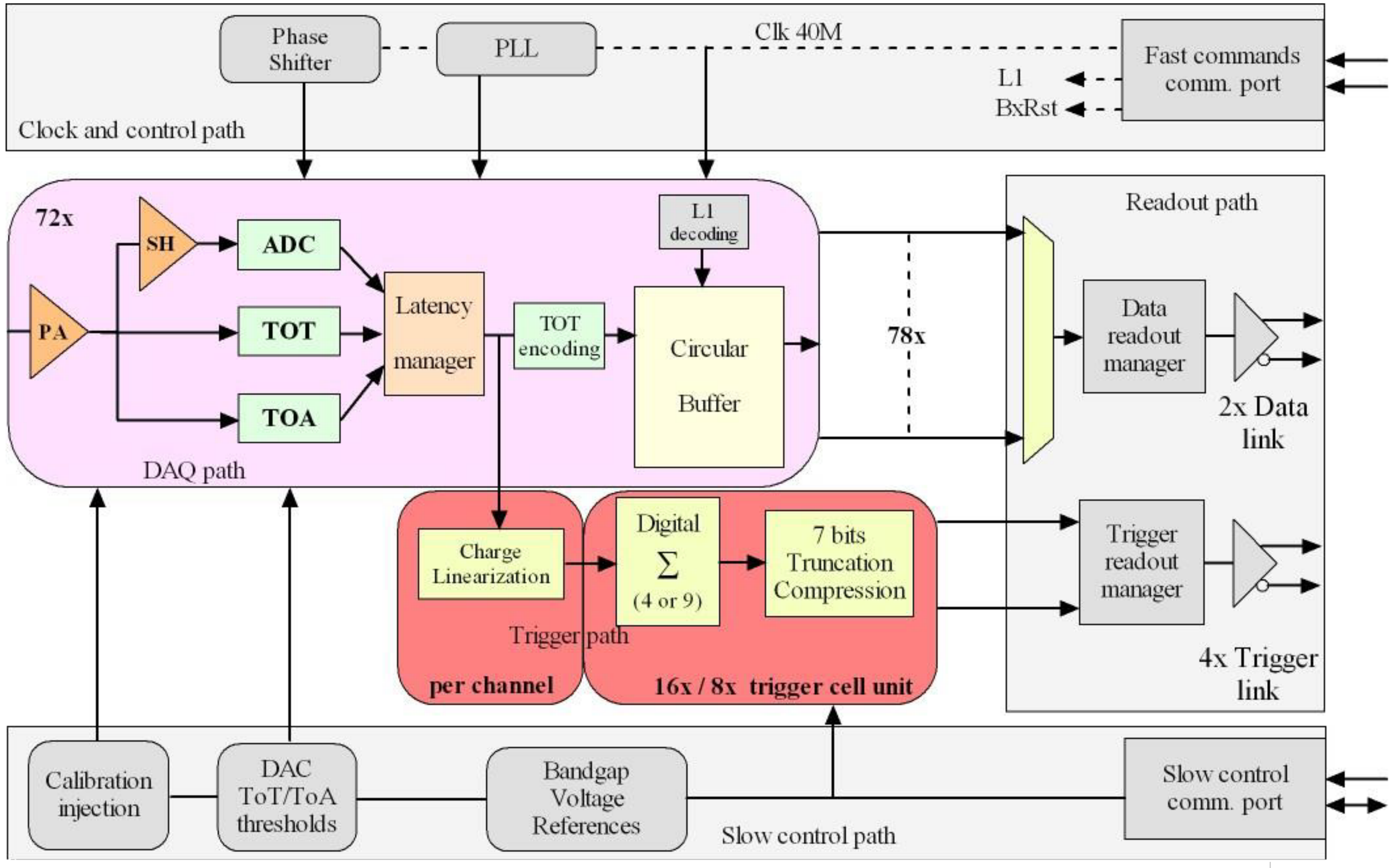


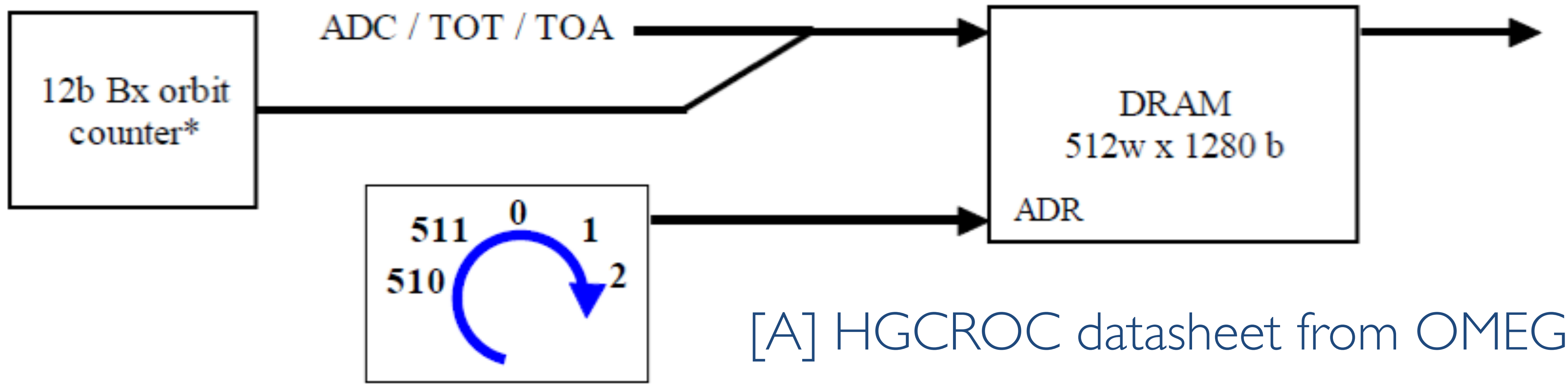
- **busy violations**
  - **only relevant for few innermost ALPIDEs**



HGCROC description

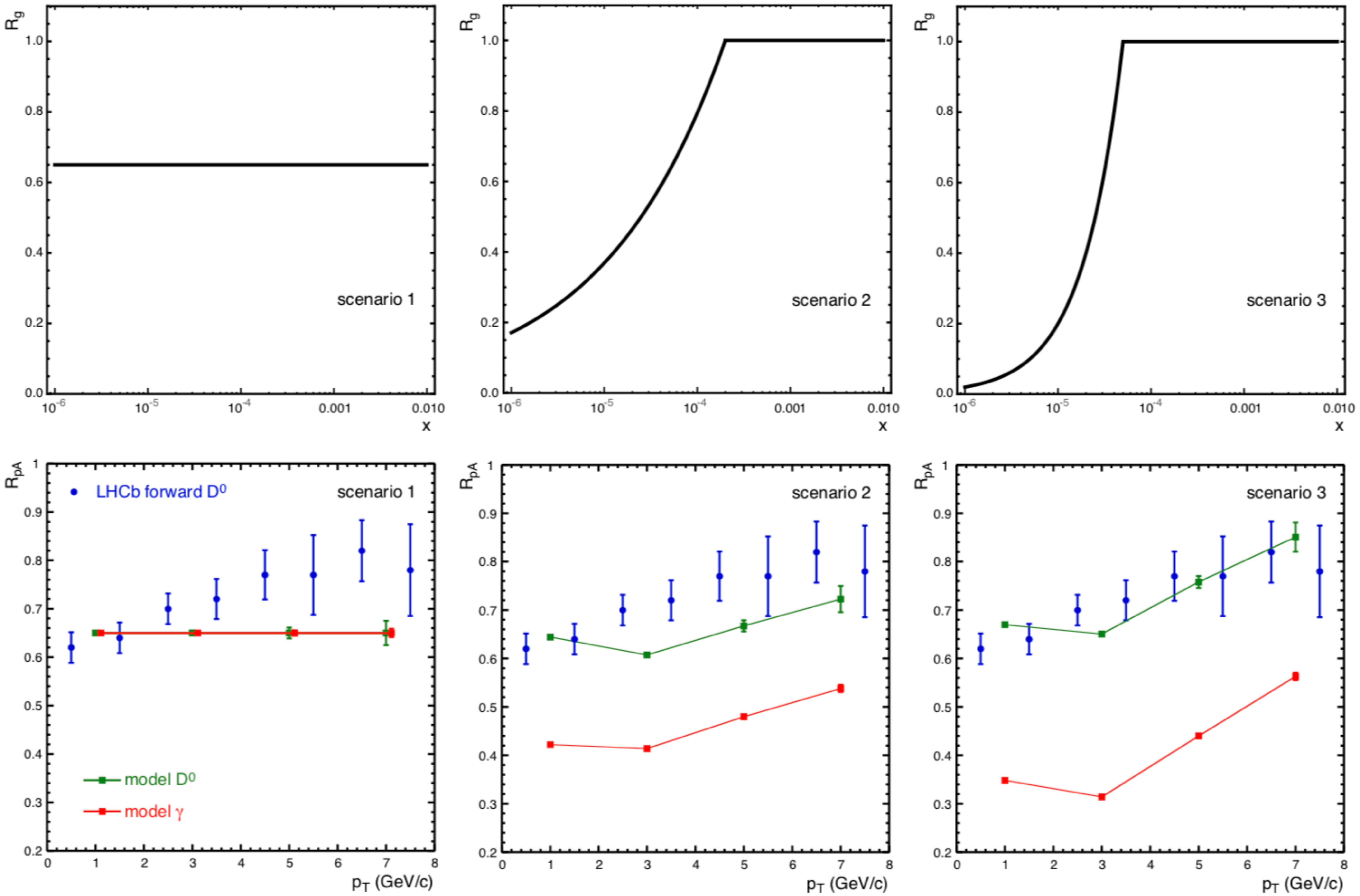
- 72 channels + 4 channels for common mode subtraction + 2 special calibration channels
- 32b Digital Data continuously stored in 512 length DRAM @40MHz
  - 72 ch. x 32b x 40MHz: **huge data volume**
  - ➔ Only **Local-L1-triggered** data are read out
- Idle packet is continuously sent out when no L1-trigger is activated
- The data processing for the trigger “information” path
  - 32b: 4b header + 7b x 4
  - Sum of 4 or **9 channels** depending on the sensor





[A] HGCROC datasheet from OMEGA group

Charm vs photon sensitivity



Toy study: Photons are more sensitive to shape of Rg than charm

Distribution in x from Pythia

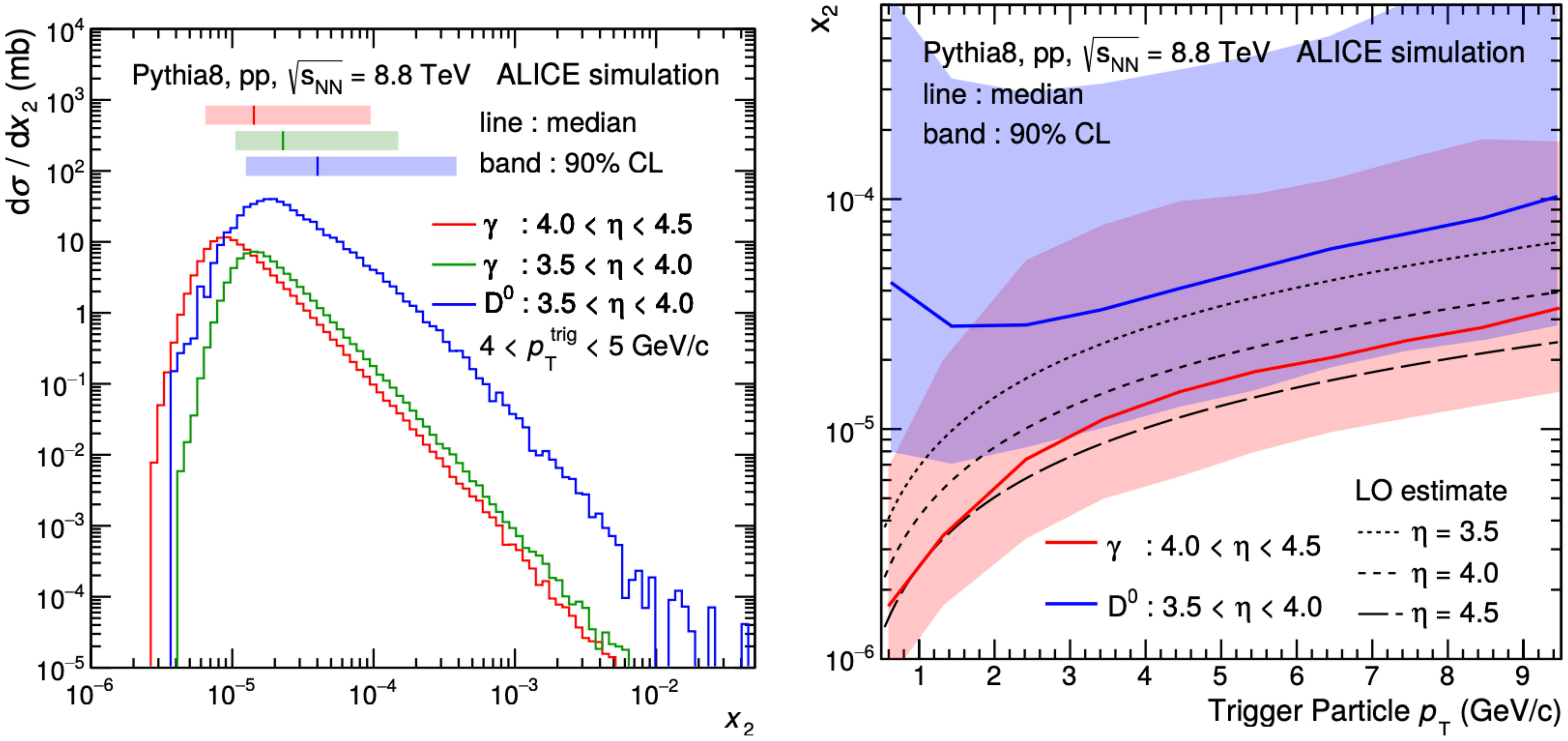
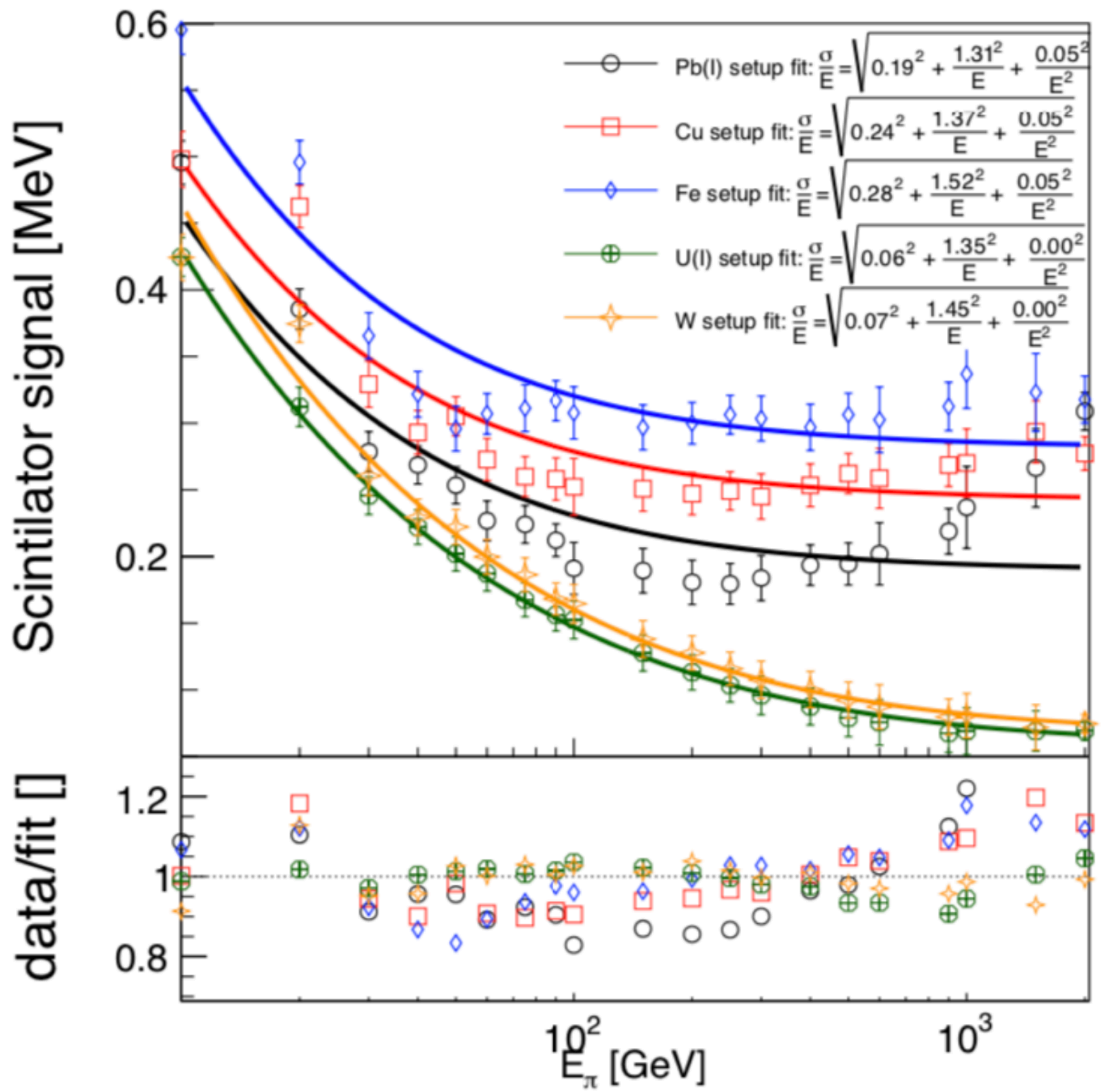


Fig. 8: (Left) Distribution of the momentum fraction of the gluons (x_2) contributing to production of
mesons and prompt photons in the PYTHIA event generator (v8.235) for $4 < p_T < 5$ GeV/c. The ba
above the distribution indicate the median and the interval that contains 90% of the distribution. The rig
panel shows the median and 90% spread of the gluon-x (x_2) distribution as a function of the transvers
momentum.

(similar conclusion from NLO calculations)

Absorber material in HCal

Thesis
Mark Waterlaa (Tsukuba)

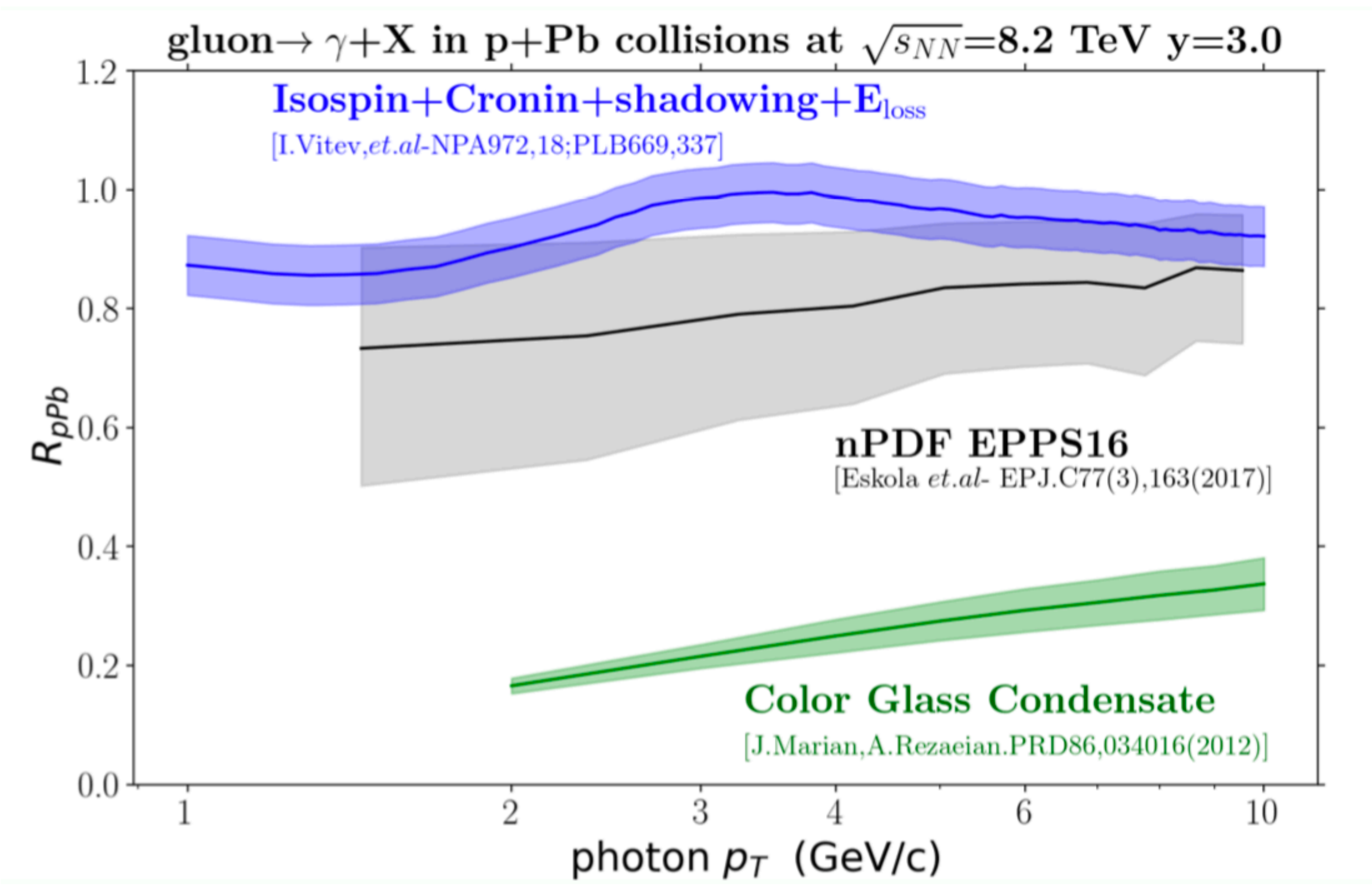


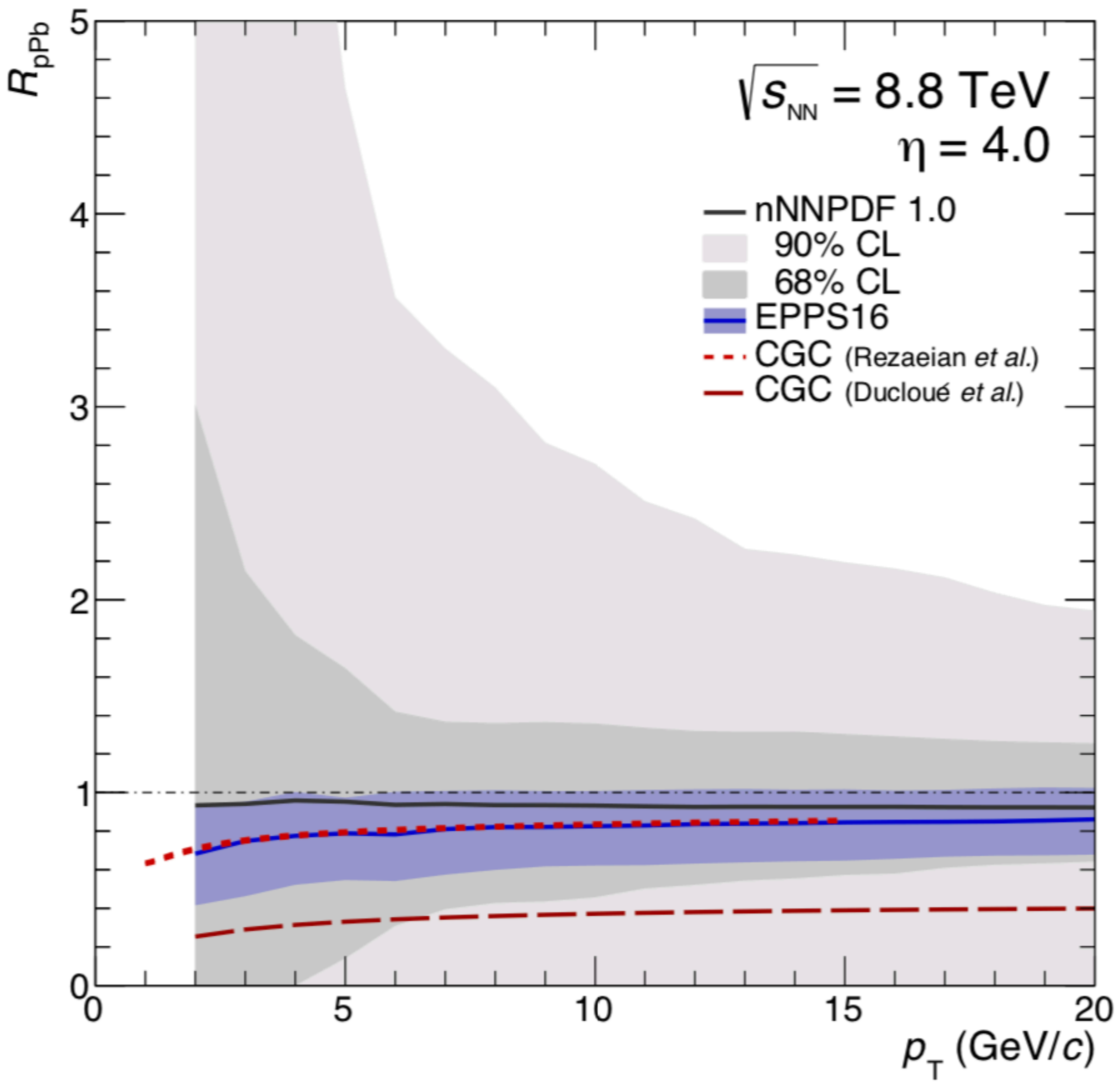
Stand-alone HCal simulation ongoing to study choice of passive material

Predictions for nuclear modification of forward isolated photons

https://arxiv.org/abs/1204.1319

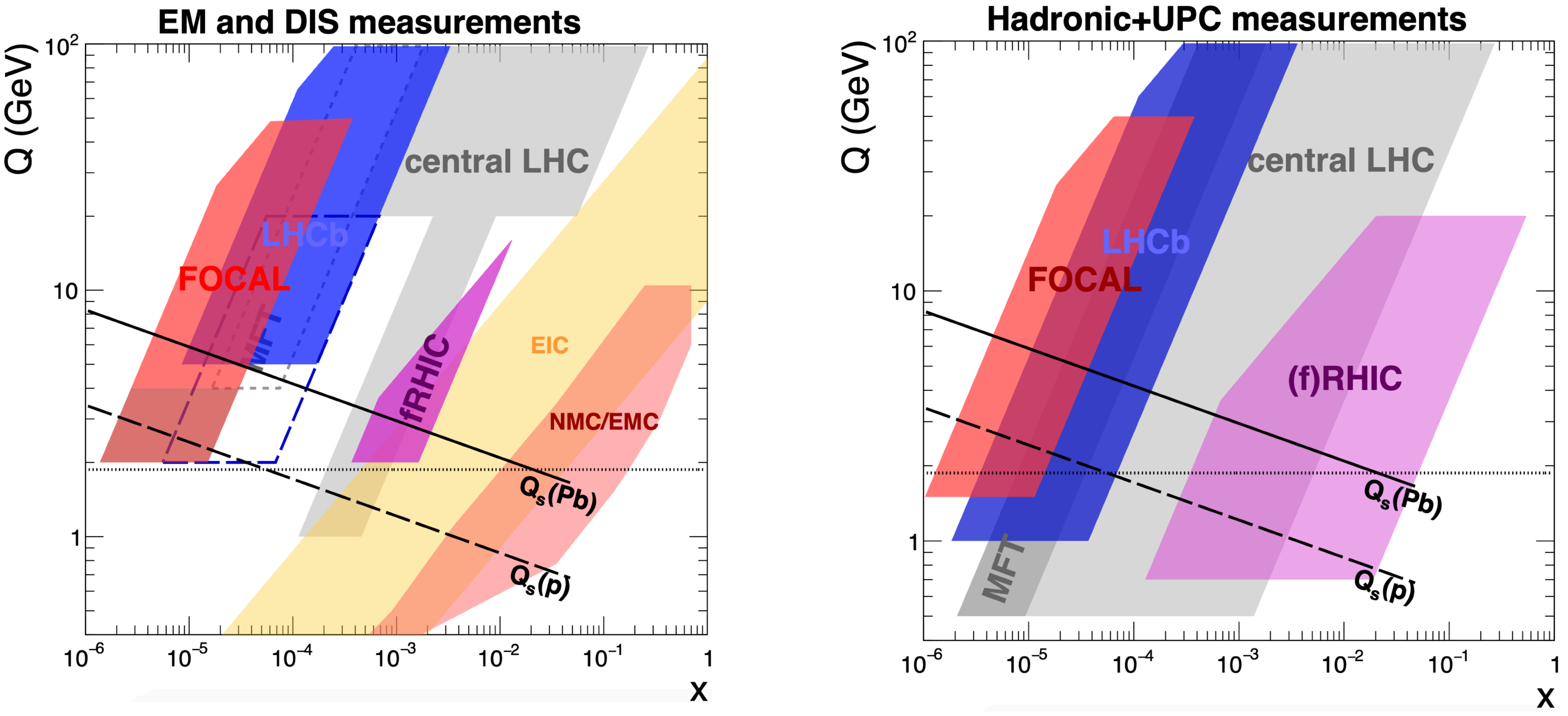
https://arxiv.org/abs/1710.02206



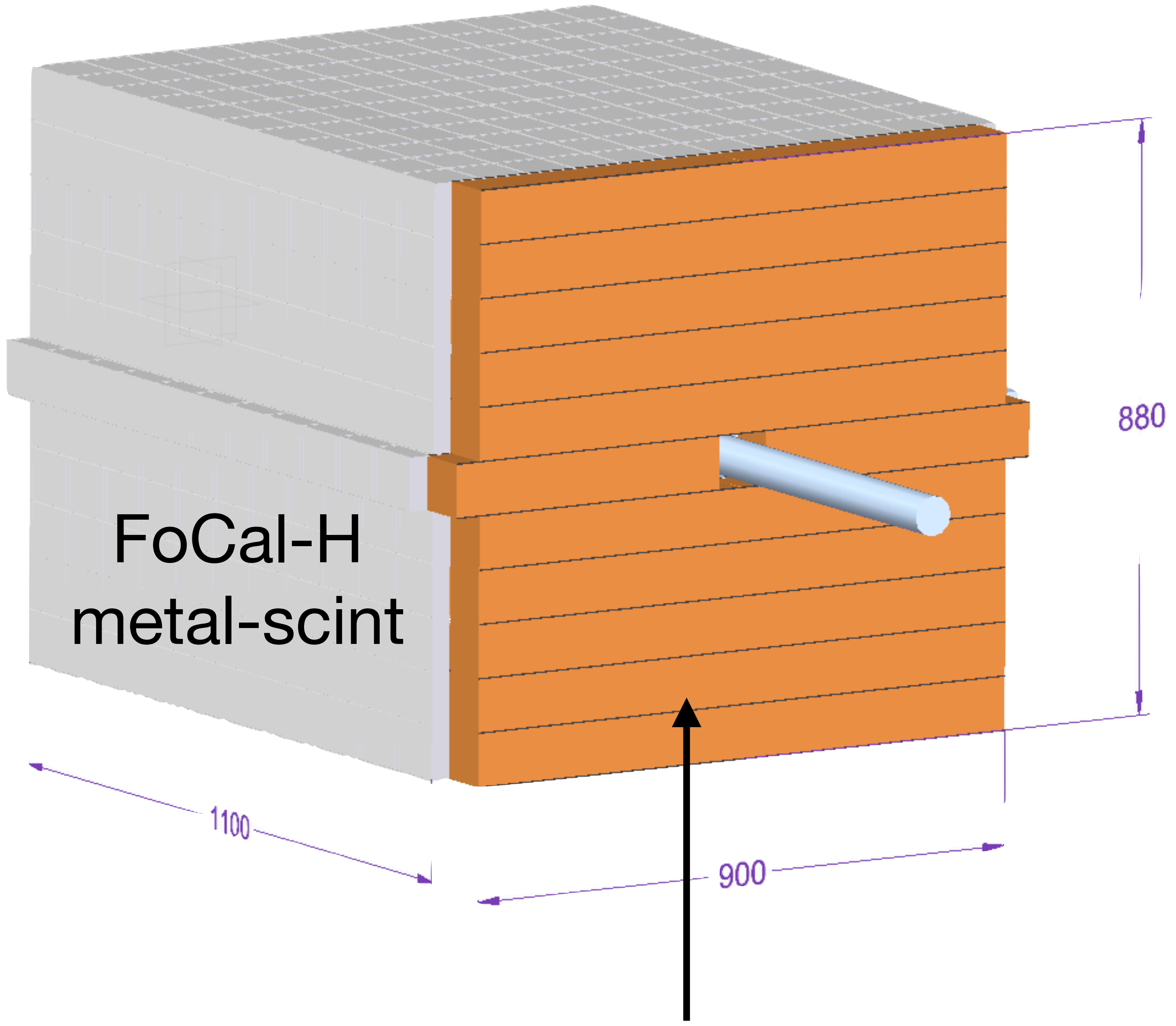


- Predictions have changed over time.
- Now, CGC and central value of EPPS16 prediction numerically the same
  - Large uncertainties
  - Is this a coincidence, by construction or does it have a deeper meaning?

Kinematic coverage



Costs (material only)



Total sensitive area:

$20 \times 0.9 \times 0.9 m^2 = 16 m^2$

FoCal Pad layers

1 module = 5 x silicon sensor (8x9 cells a 1cm^2)

1) **Total number of modules: 11 x 2 = 22 modules**
2) **Total number of Pad layers: 22 x 18 = 396 layers**
3) **Total number of towers : 22 x 5 = 110 towers**
4) **Total number of silicon sensors: 396 x 5 = 1,980 sensors**
5) **Total number of readout ch.: (8 x 9) x 1,980 = 142,560 ch**

+ 396 FEE PCB (5 HGCROC each),
180 aggregator boards, 8 CRU

FoCal HG layer

- **1980 ALPIDEs**
- **132 staves**
- **612 links (324 IB/OB + 288 OB)**
- **6 IB/OB modules (6 * 6 = 36 IB/OB staves) -> 36 RUs**
- **16 OB modules (16 * 6 = 96 staves) -> 16 RUs**

+132 Flex PCB, 52 RU, 22 TB, 6 CRU
x2 for two pixel layers

ECal

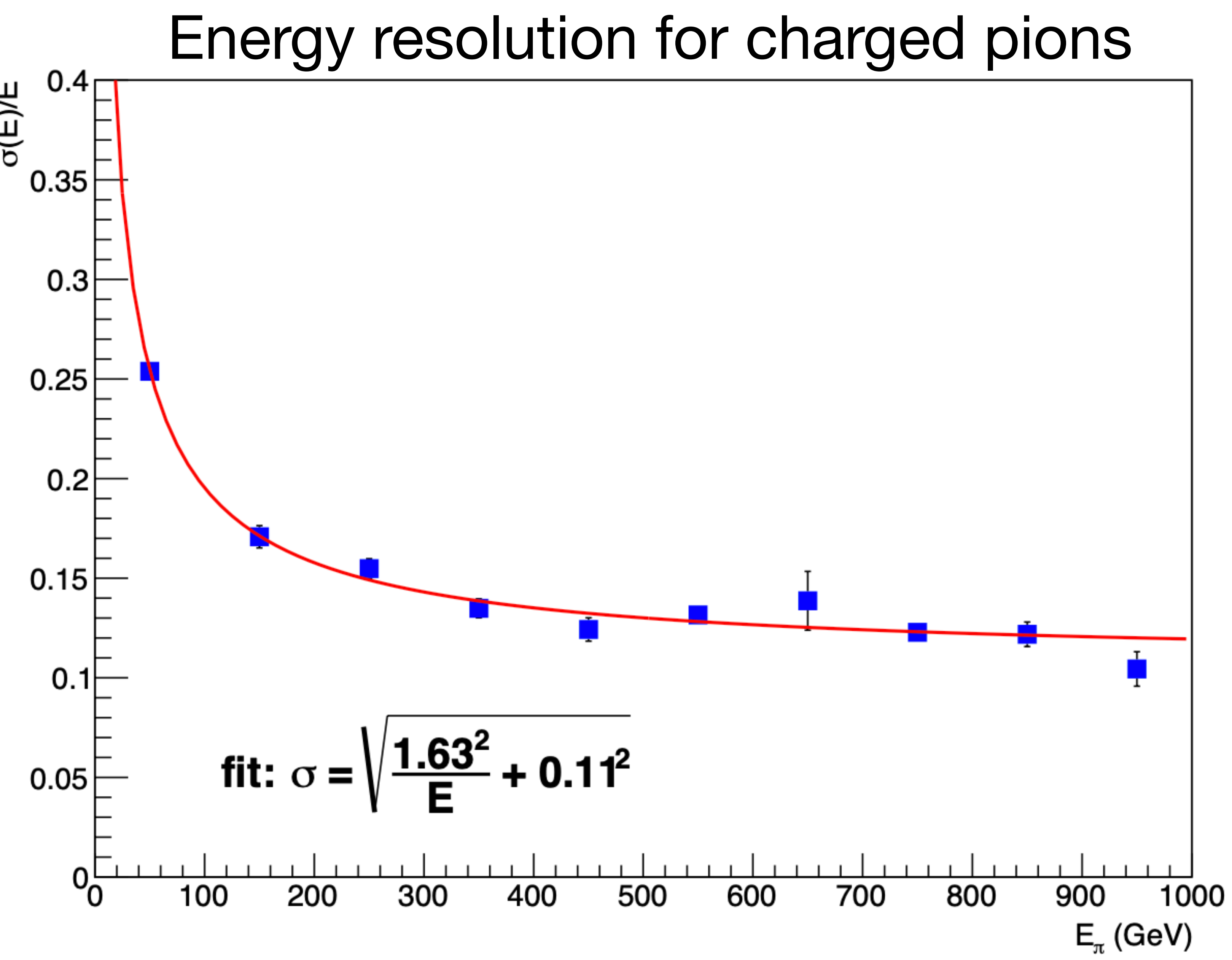
Table 3	Cost (kCHF)
tungsten	500
mechanics	500
silicon sensors (pads)	2000
pad power and readout	800
ALPIDE+PCB/flex	750
ALPIDE power and readout	1150
infrastructure	200
cooling	1000
support + integration	1200
beampipe	800
total detector cost	8900

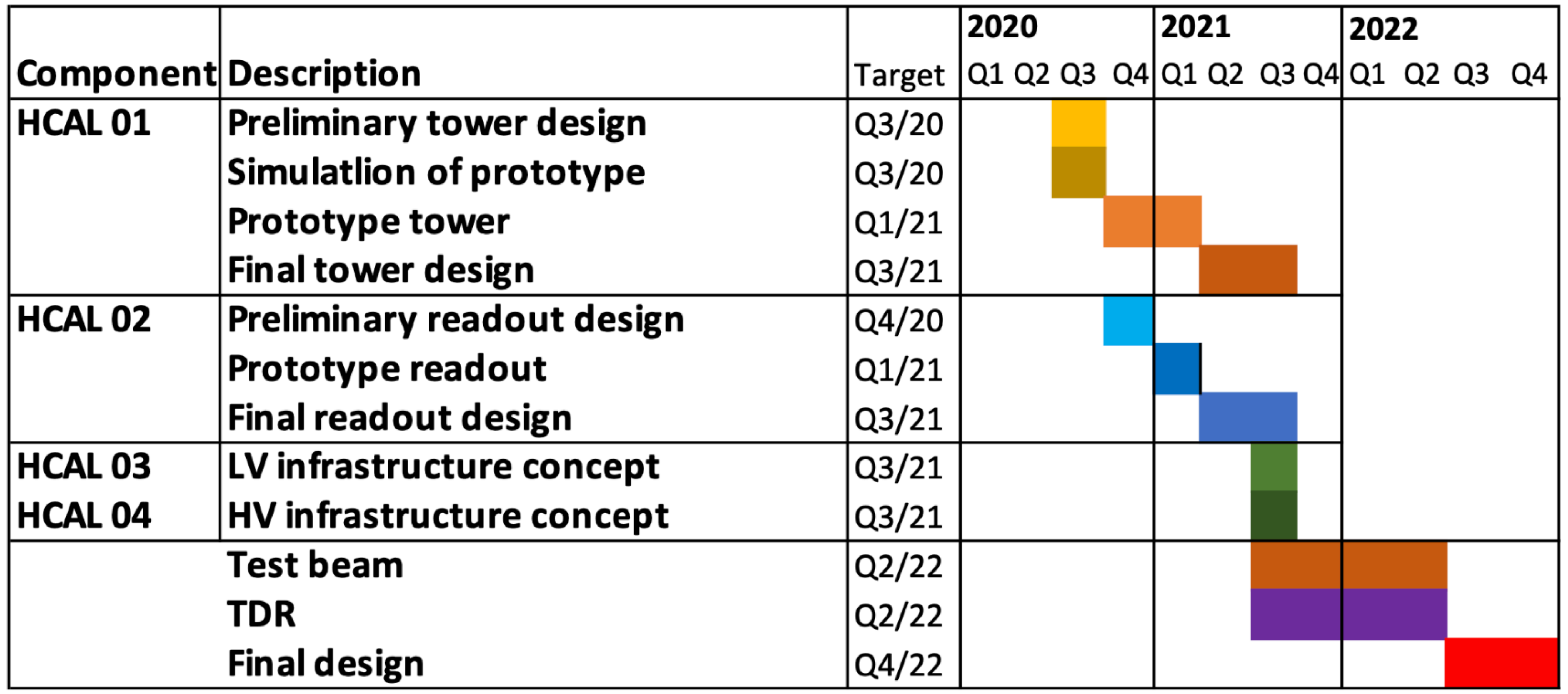
HCal (based on E864)

Table 4	Cost (kCHF)
absorber material (Pb plates)	700
scint. fibers + diffuser	280
tools	140
photo sensors (APD/SiPM) + accessories	130
LED system + CR calibration	130
misc. electronics	100
packing/shipping	120
Integration	350
total detector cost	1950

Total cost estimate: 11 MCHF

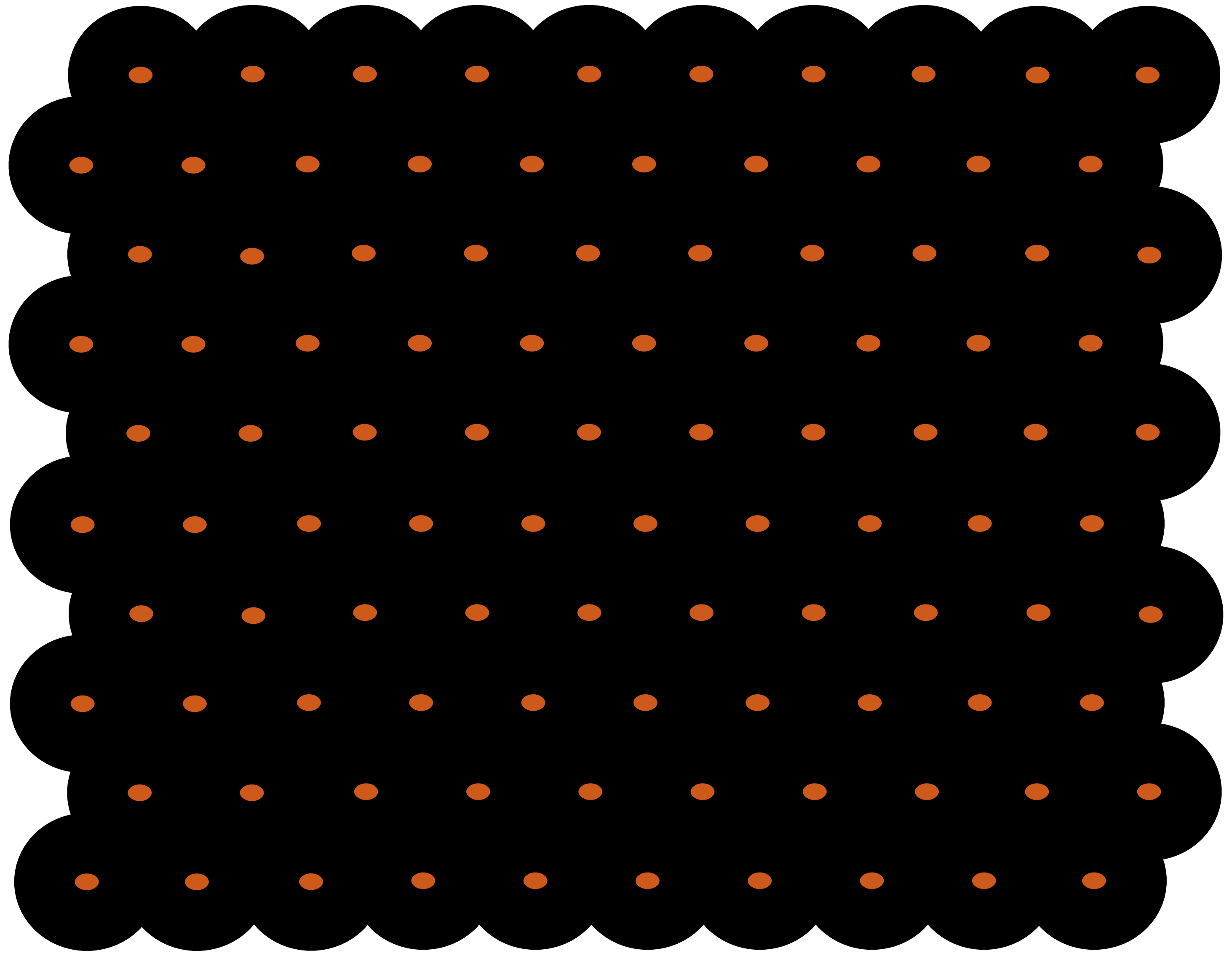
HCal - next steps





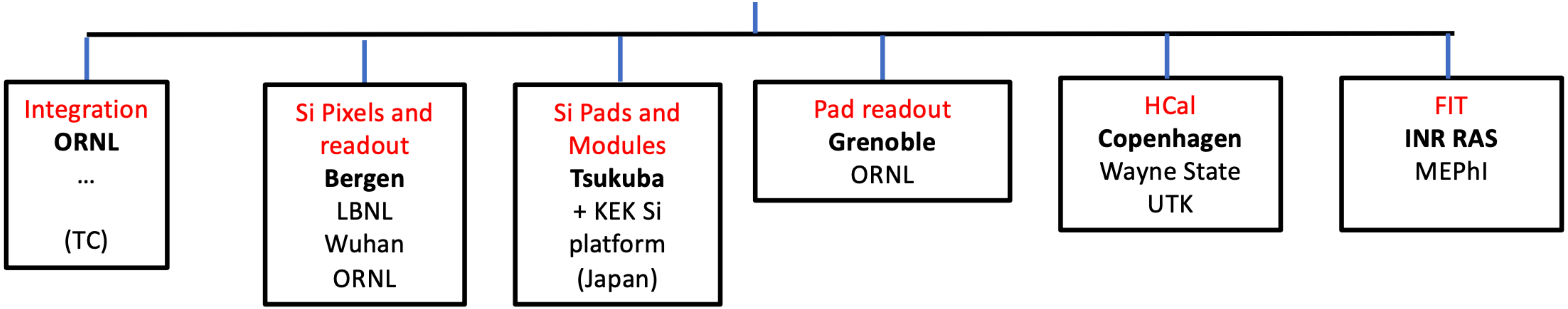
			2020				2021				2022			
Component	**Description**	Target	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
HCAL 01	**Preliminary tower design**	Q3/20			■									
	Simulatlion of prototype	Q3/20			■									
	Prototype tower	Q1/21				■	■							
	Final tower design	Q3/21						■	■					
HCAL 02	**Preliminary readout design**	Q4/20				■								
	Prototype readout	Q1/21					■							
	Final readout design	Q3/21						■	■					
HCAL 03	**LV infrastructure concept**	Q3/21							■					
HCAL 04	**HV infrastructure concept**	Q3/21							■					
	Test beam	Q2/22							■	■	■	■		
	TDR	Q2/22							■	■	■	■		
	Final design	Q4/22											■	■

- Performance from simulations sufficient for photon isolation and jets
  - Constant term (e/h compensation) more, sampling fraction less important
  - Requirements on resolution to be defined in more detail
- Plan: test FoCal-H prototype together with FoCal-E in test beam in 2021
  - Ongoing effort to construct a prototype based on Cu capillary tubes by 2020
  - In parallel perform detailed simulations to further optimise performance (e.g. optimal ratio of active-passive material)
  - Study granularity requirements (does it make sense and is it possible to go finer than ~0.1)?
- Choice of readout (SiPM/APD) rather independent of sampling structure
  - SiPM likely more cost-effective and HGCROC compatible version exists



(Similar approach suggested and being tested by IDEA collaboration in Oct 2020, eg. see talk)

Key institutions and responsibilities



Integration
ORNL
…
(TC)

Si Pixels and readout
Bergen
LBNL
Wuhan
ORNL

Si Pads and Modules
Tsukuba
+ KEK Si platform (Japan)

Pad readout
Grenoble
ORNL

HCal
Copenhagen
Wayne State
UTK

FIT
INR RAS
MEPhI

We would welcome individuals or institutions to join, please just contact me for more info