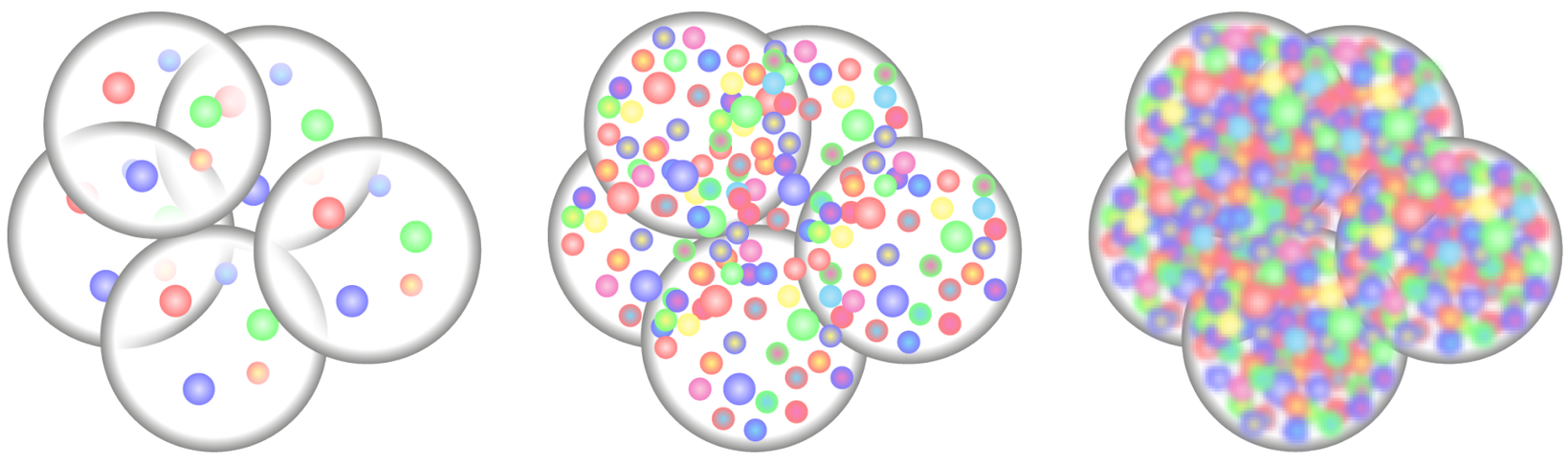
FoCal Physics Case and Basic Design



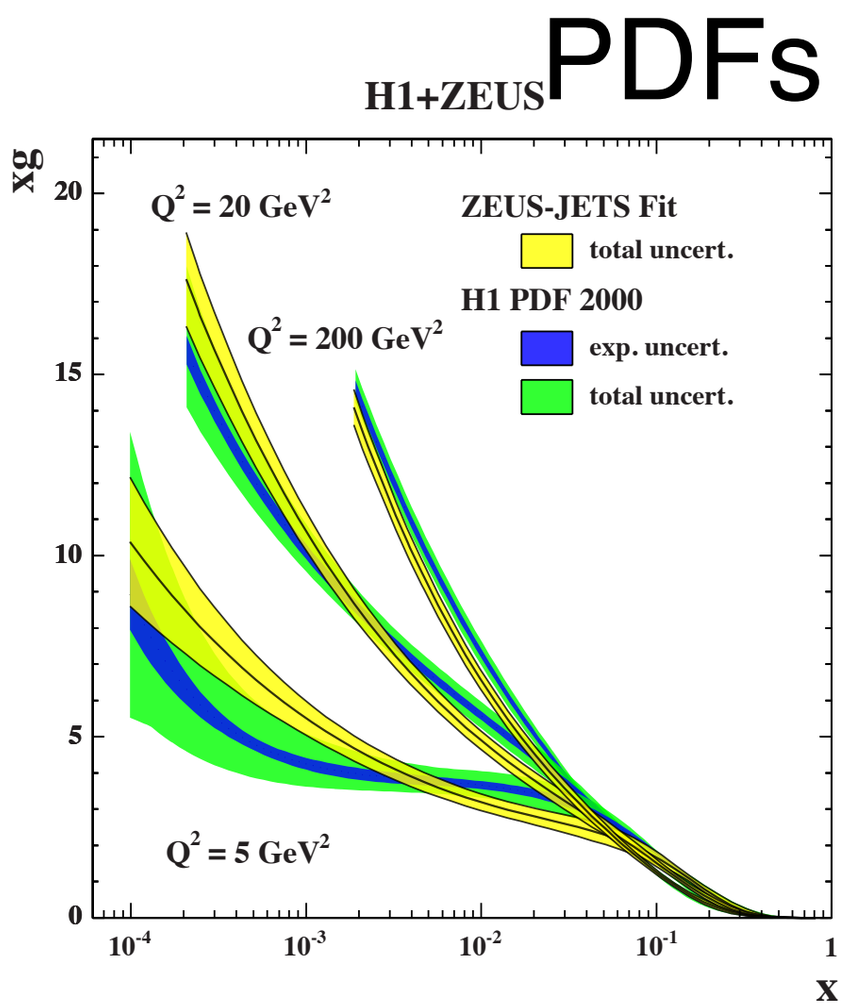
T. Peitzmann (Utrecht University/Nikhef)

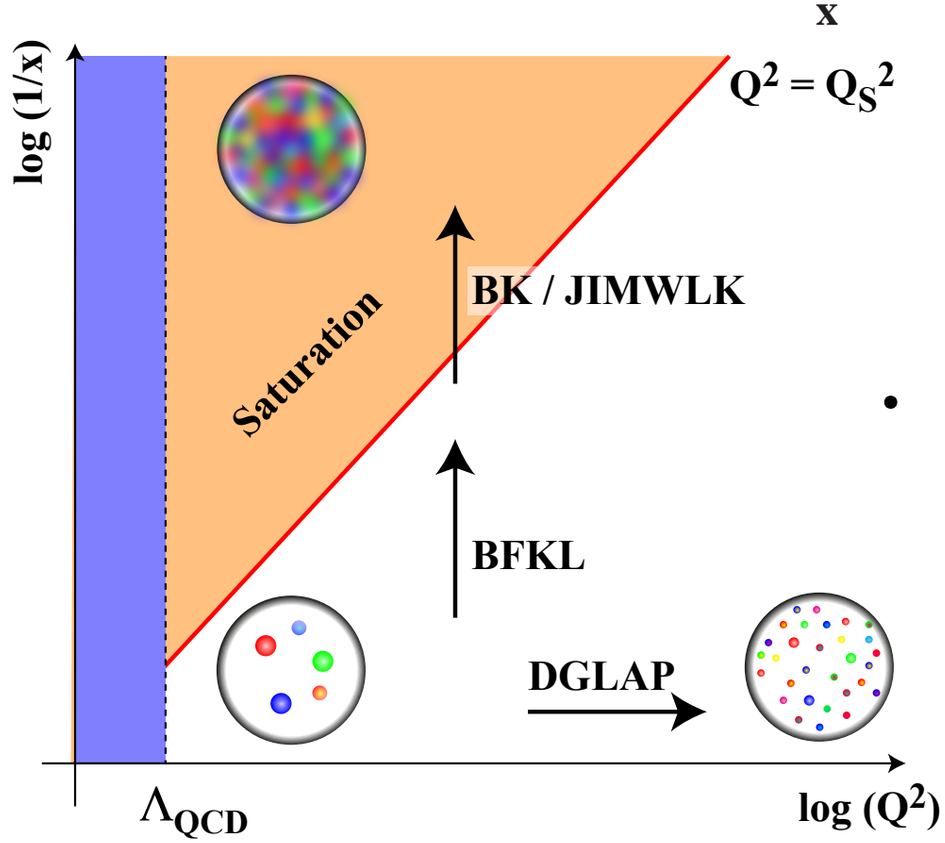
CALICE Collaboration Meeting, Utrecht, 10.04.2019

Outline

- Introduction: low-*x* PDFs and gluon saturation
- PDF studies in pA with photons
- The FoCal Proposal

PDFs and Gluon Saturation





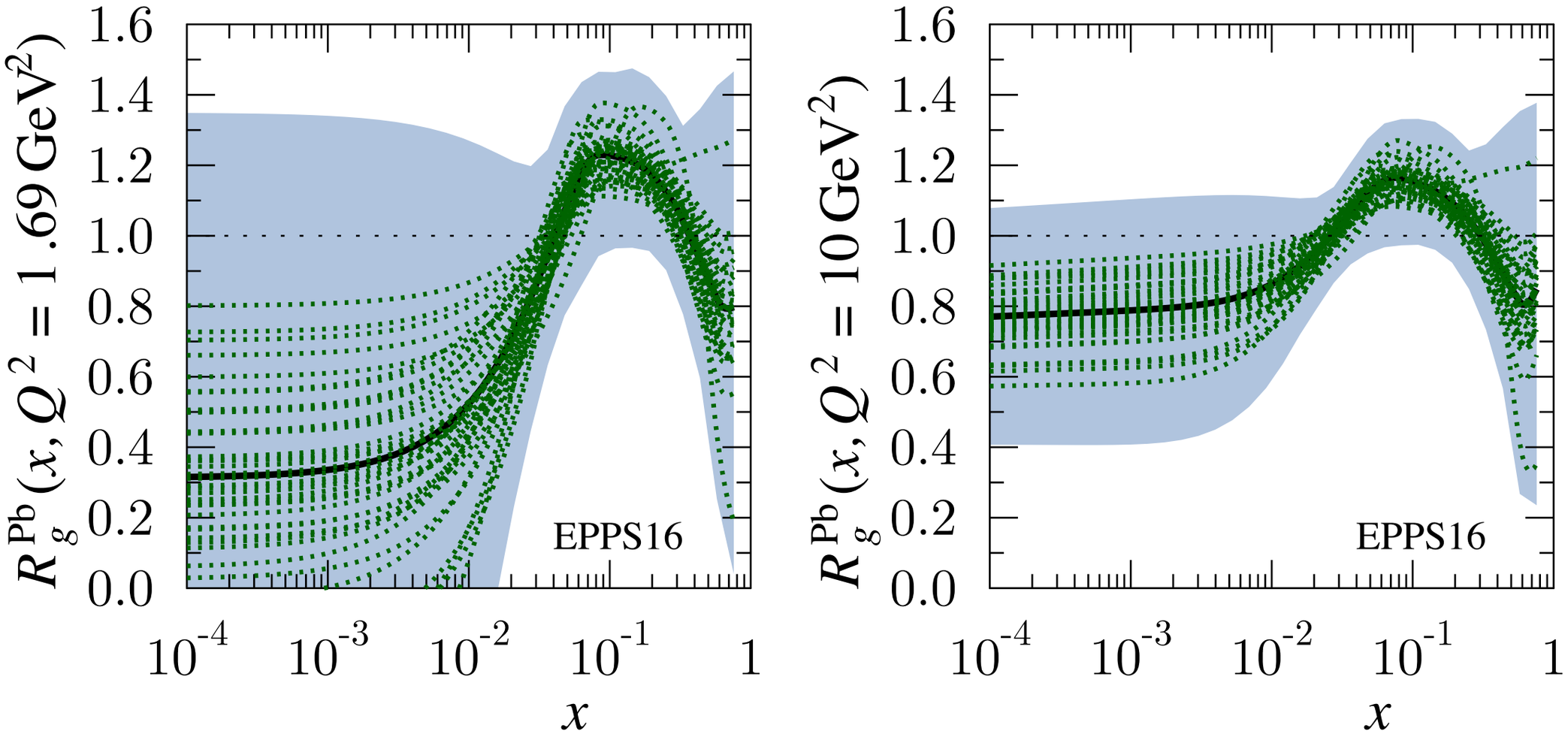
- from evolution equations (DGLAP, BFKL):
  - gluon density increases with Q^2 and 1/x
    - leads to very high gluon density
    - problems with unitarity
- for high density non-linear processes become important
- gluon saturation below saturation scale
  - enhanced in nuclei

$$Q_S^2(x) \approx \frac{\alpha_s}{\pi R^2} x\, G\left(x, Q^2\right) \propto A^{1/3} \cdot x^{-\lambda}$$

- signatures in hadronic collisions:
  - suppression of particle yields
  - dijet suppression

Uncertainties in Nuclear PDFs

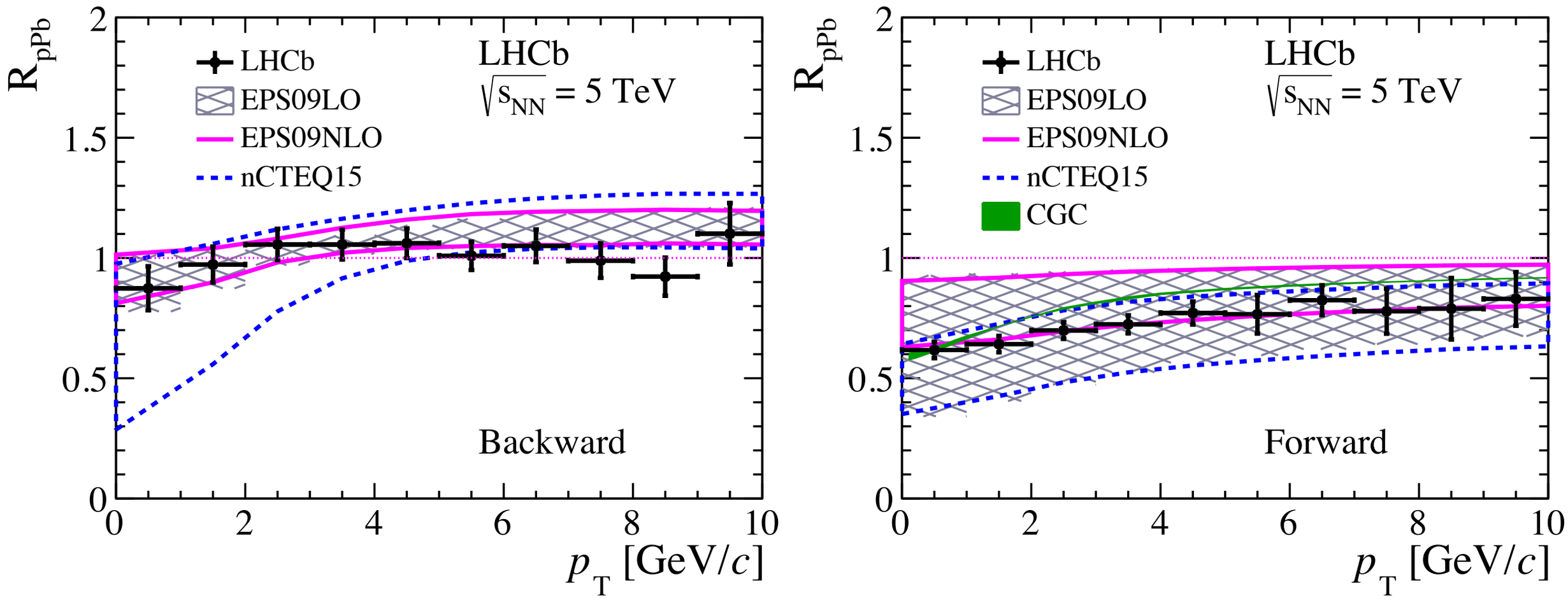
EPPS16, EPJC 77, 163



- large uncertainties of nPDFs
  - parameterised nuclear modification
  - recently updated to allow more freedom (e.g. flavour dependence)
- x-dependence?
  - very little dependence for $x < 10^{-2}$

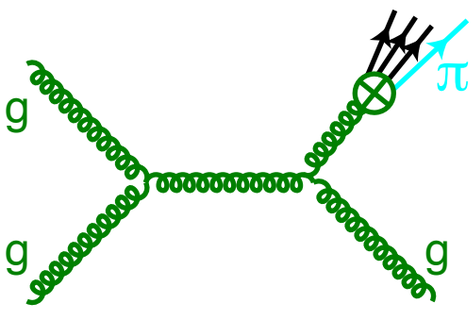
LHCB, JHEP 10 (2017) 090

Results from p-Pb at LHC (2)

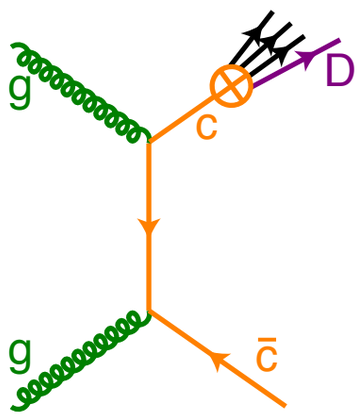


- prompt D^0 suppressed at forward rapidity
  - consistent with pQCD + shadowing (EPS09)
  - also consistent with CGC calculation

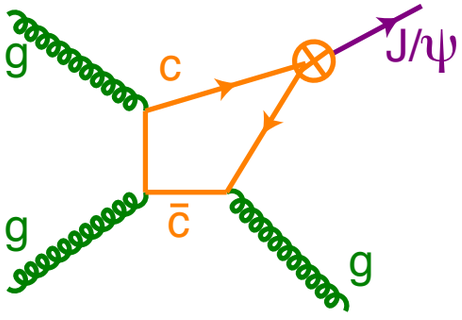
Hadronic Processes



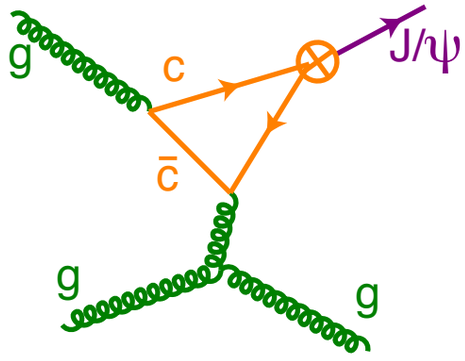
light hadron



heavy hadron



J/ψ

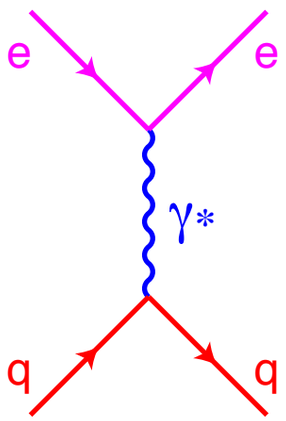


J/ψ (COM)

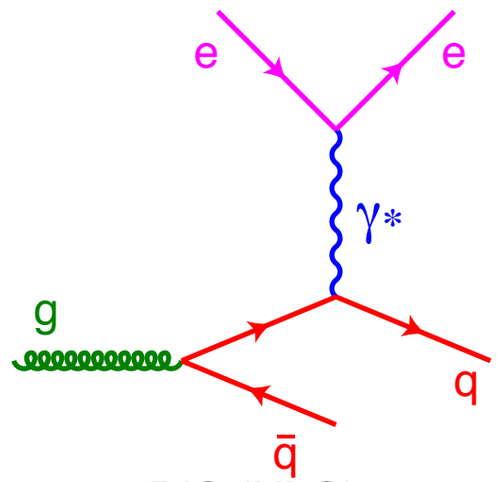
- hadron production needs fragmentation
  - other hadronisation mechanisms (coalescence)?
  - strong disadvantage for light hadrons
- heavy flavour
  - J/ψ not fully understood
  - open charm?

- possible other final-state modifications: energy loss, collective flow

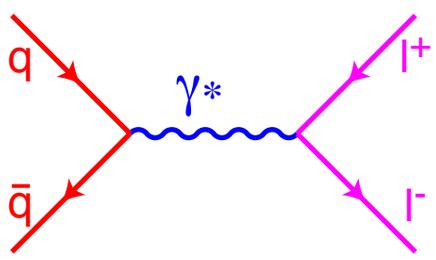
Electromagnetic Processes



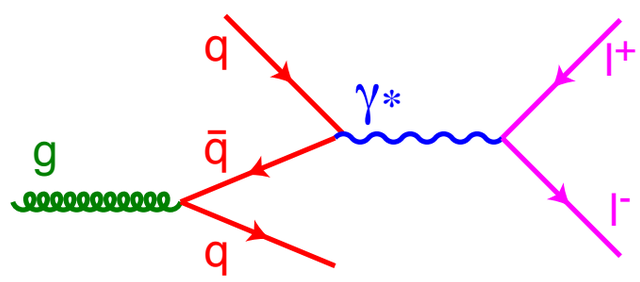
DIS (LO)



DIS (NLO)

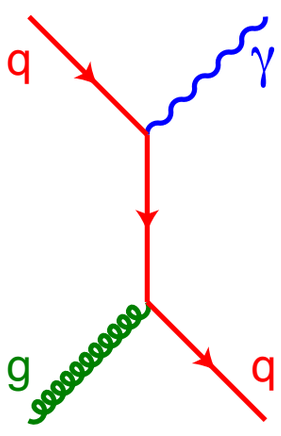


DY (LO)



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)

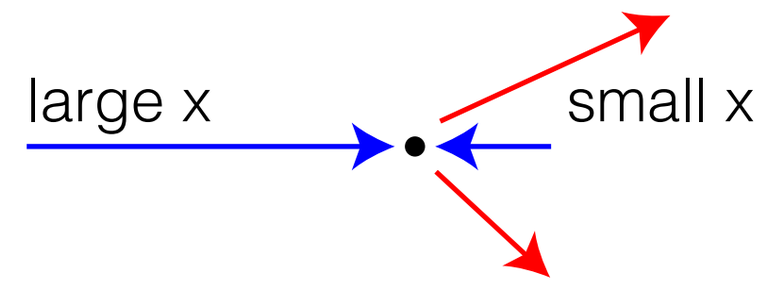
- real photons: sensitivity to gluons at LO, clear kinematic relation
  - higher order corrections?

Accessing small x – Kinematics

- for 2 → 2 process (LO on parton level):

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp\left(\pm \frac{y_3 + y_4}{2}\right)$$

  - forward rapidity selects small x
  - advantage for exclusive measurement

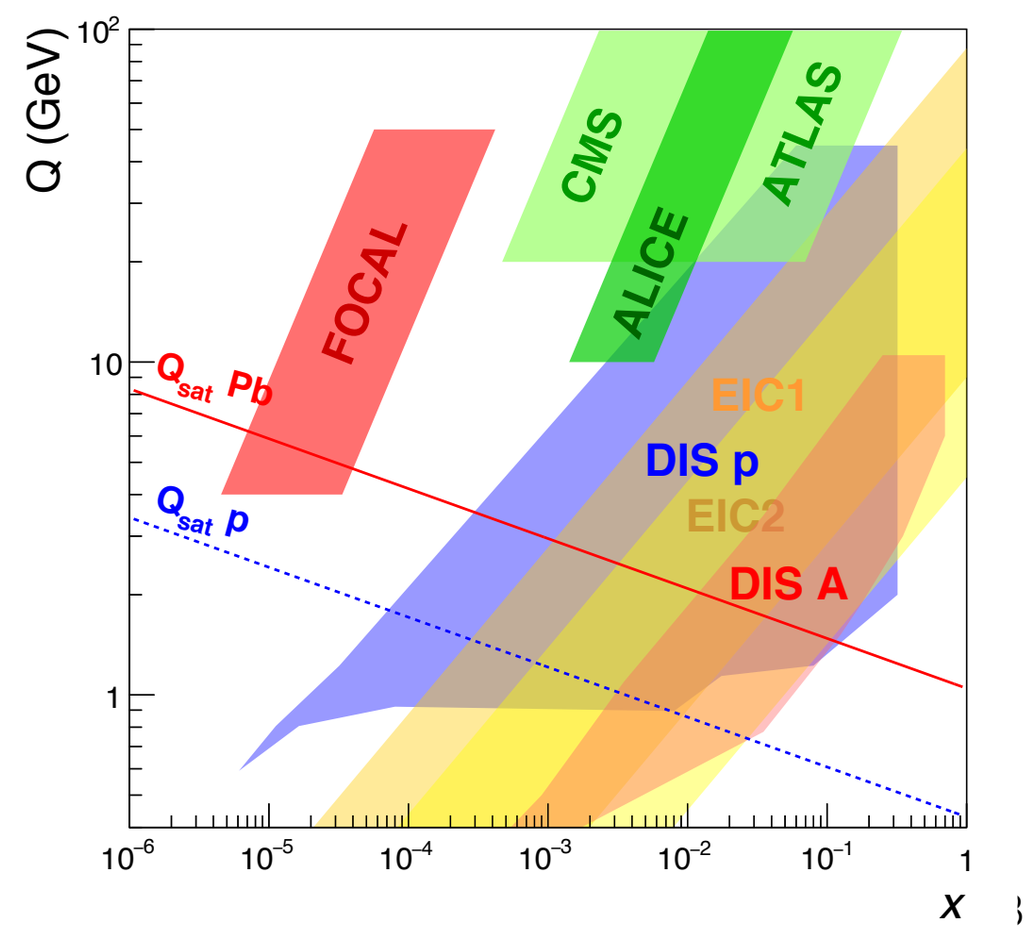


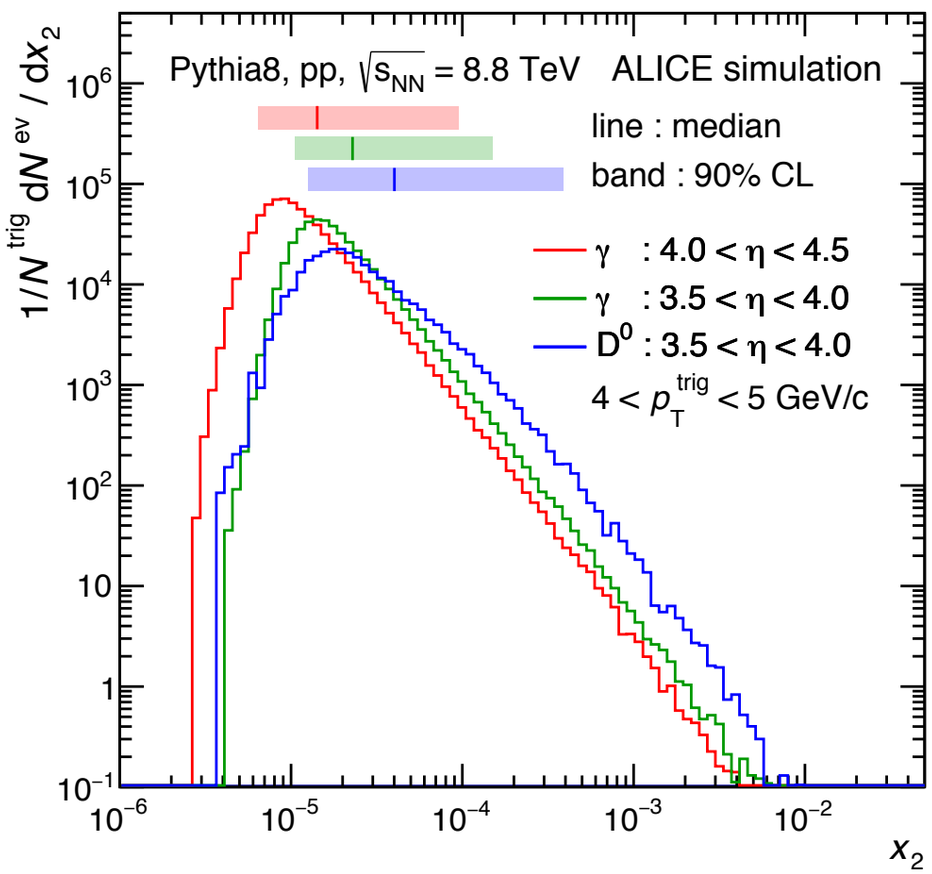
- for singles assume:

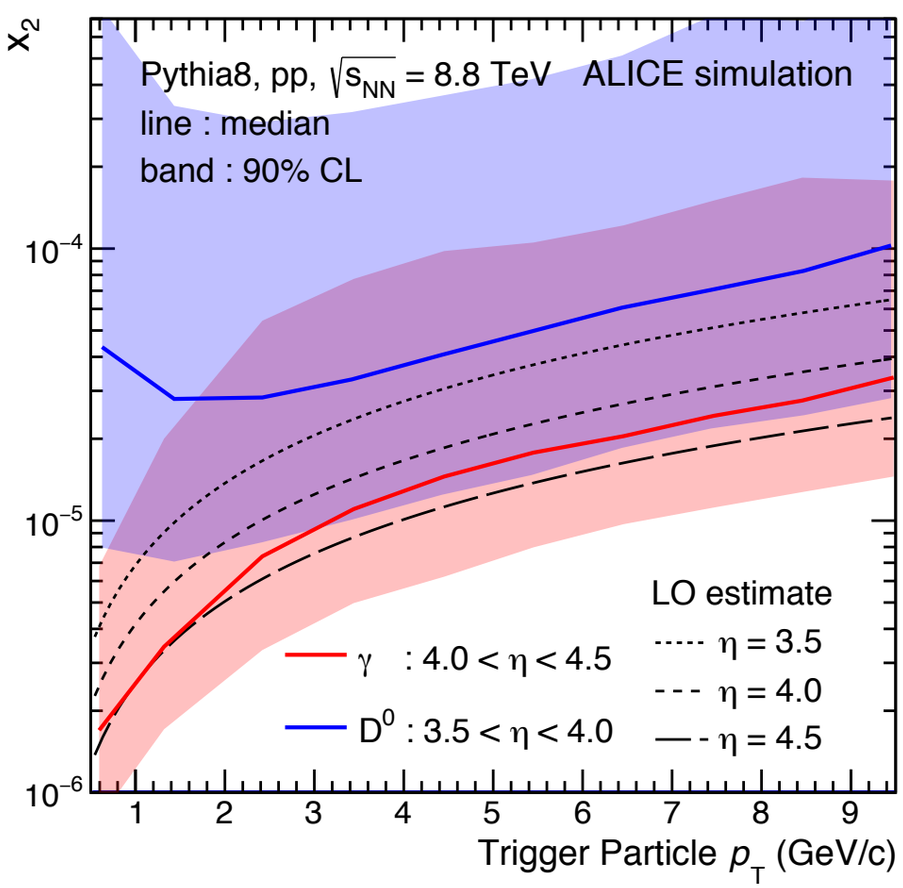
$$x_{1,2} \approx \frac{2m_T}{\sqrt{s}} \exp(\pm y)$$

  - valid for jets (large m_T) and photons
  - for hadrons take fragmentation into account!
- further modification via higher order contributions
  - significant at LHC
- limited data so far!

EM probes - kinematic coverage







x-Q^2-Sensitivity

PYTHIA pp 8.8TeV
forward measurements

LHCb D0 vs FoCal photons

study median of distribution and 90% confidence level limits

better sensitivity for photons

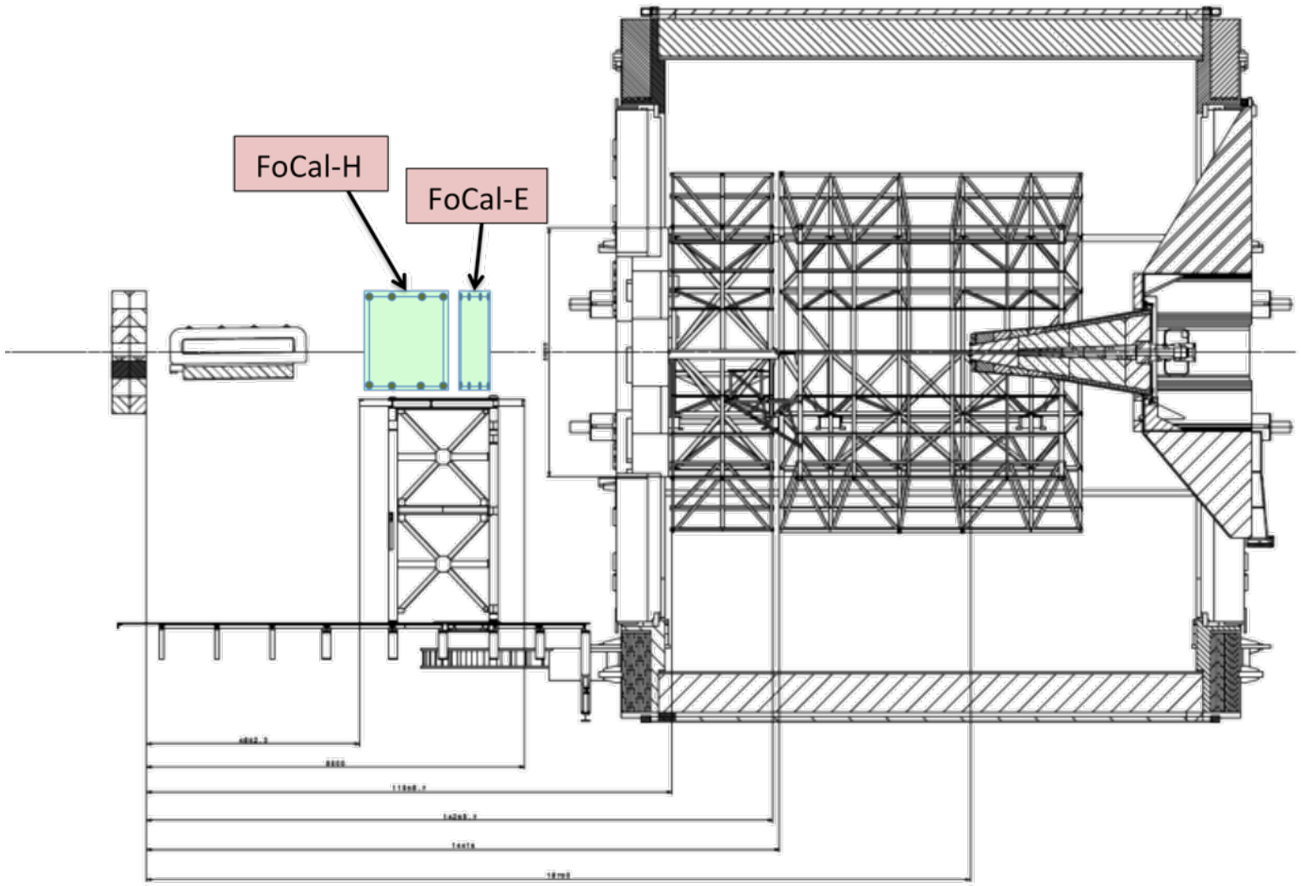
uncertainties of theoretical description at very low p_T

Low-x Probes

- Open charm and photons apparently most sensitive probes
- Some advantages for photons
- Charm measurements possible with existing LHCb apparatus
- Photons provide complementary measurement

- Not possible with existing experiments
  - need new detector!

FoCal in ALICE



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

preferred scenario:

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

under internal discussion
possible installation in LS3

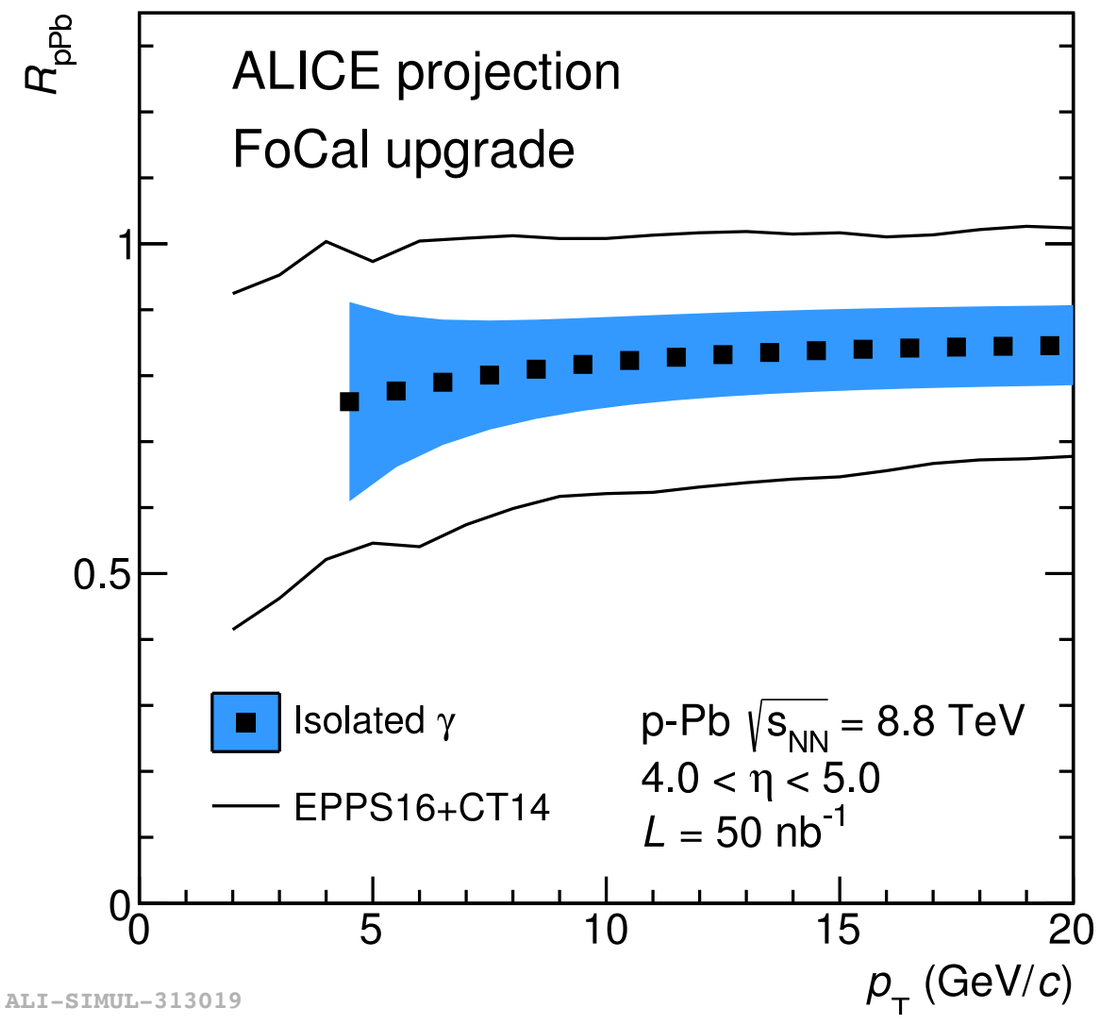
advantage in ALICE: forward region not instrumented, “unobstructed view”

- main challenge: separate γ/π^0 at high energy
- need small Molière radius, high-granularity read-out
  - Si-W calorimeter, effective granularity ≈ 1mm²

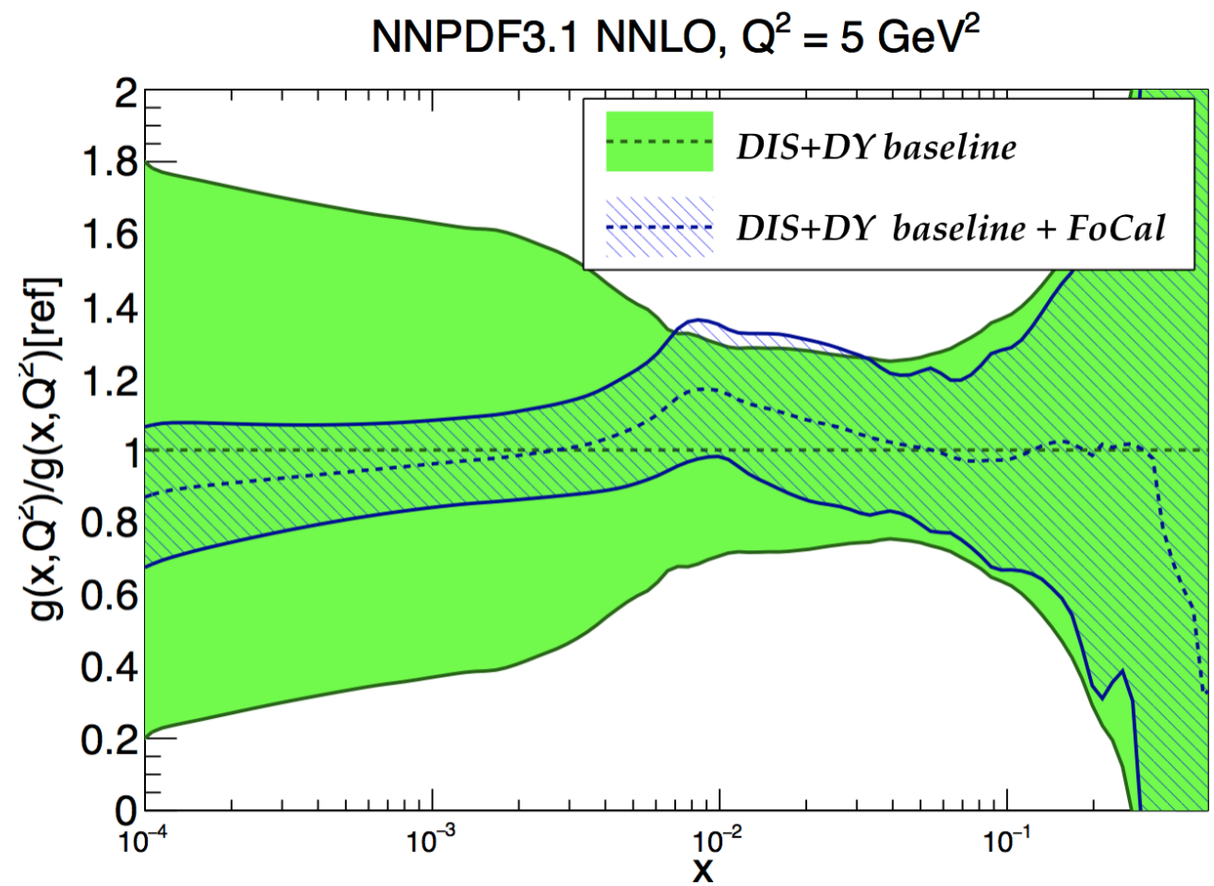
note: two-photon separation from π^0 decay (p_T = 10 GeV/c, y = 4.5, α = 0.5) is d = 2 mm!

Impact of Forward Photons on nPDFs

Performance estimate of FoCal measurement



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

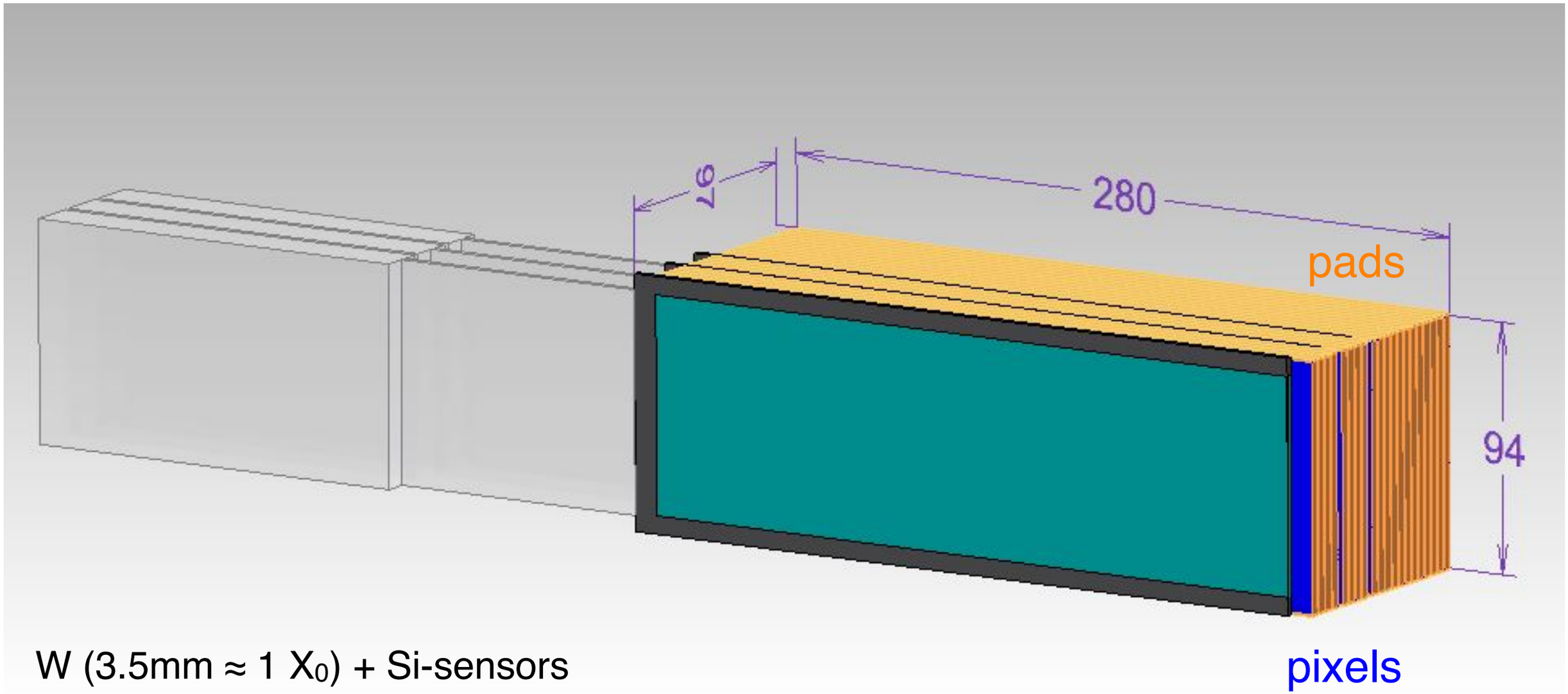


Uncertainties can be improved significantly

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

Work in progress!

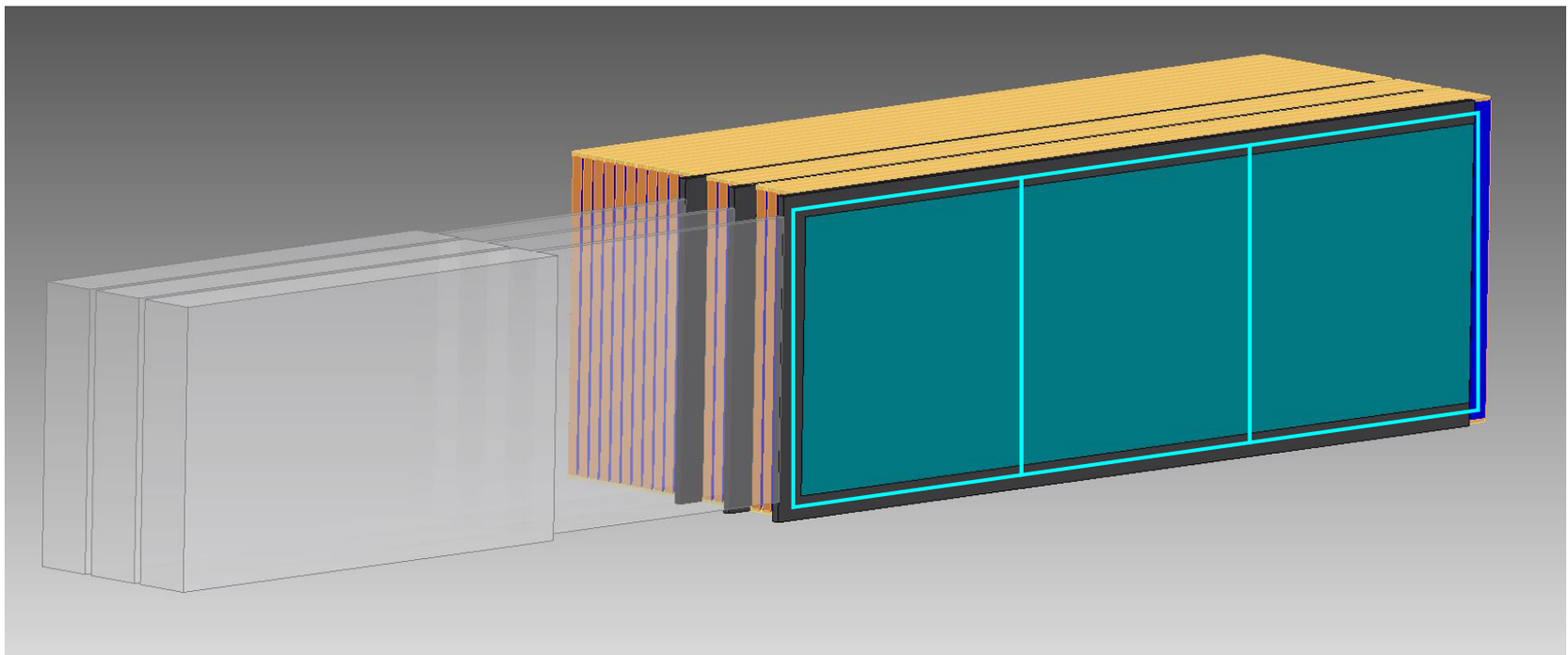
FoCal-E – Detector Module

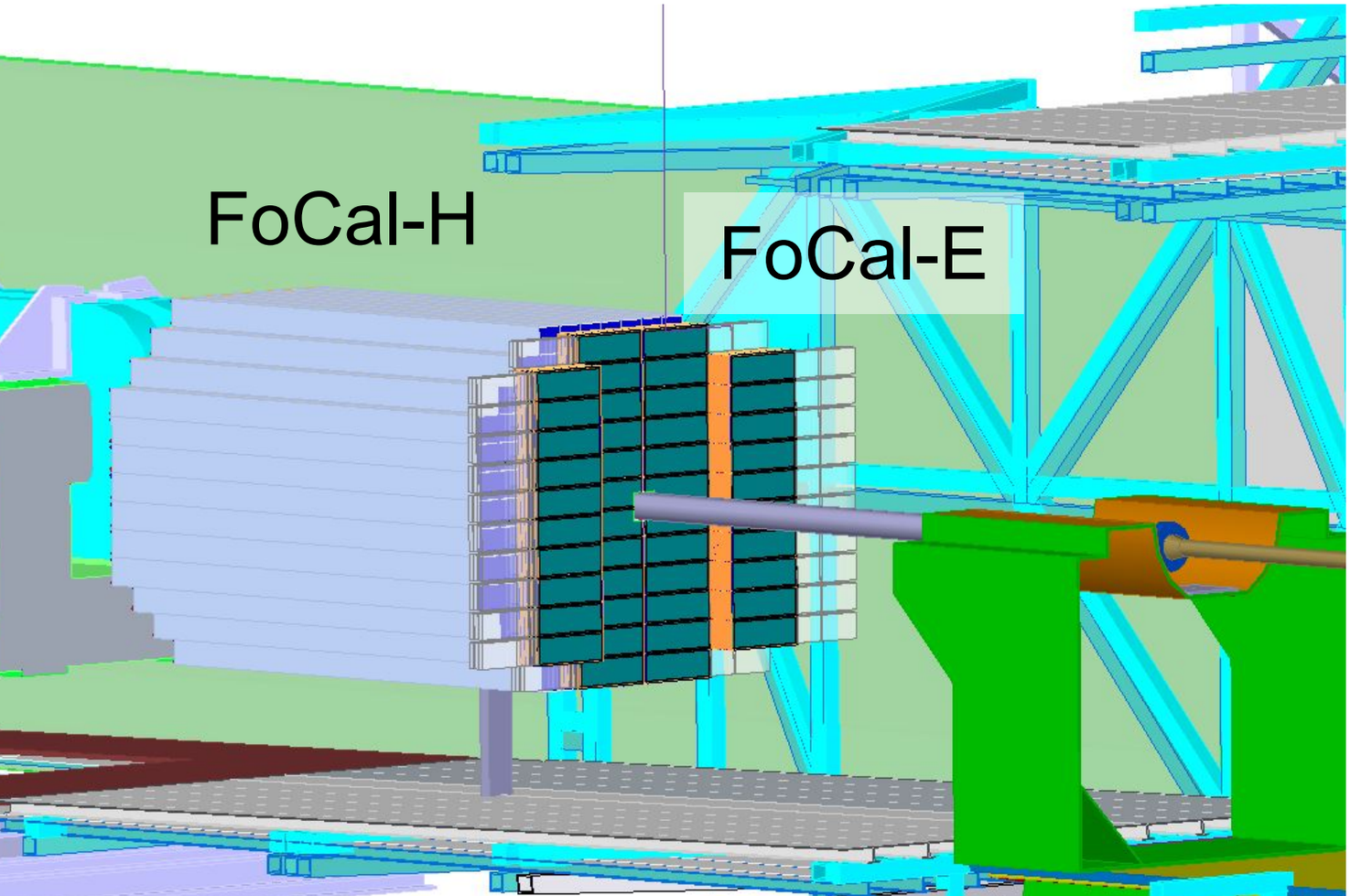


hybrid design (2 types of sensors)

- **Si-pads** (≈ 1 cm²):
  energy measurement, timing(?)
- **CMOS pixels** (≈ 30x30 μm²):
  two-shower separation, position resolution

FoCal-E Design Concept



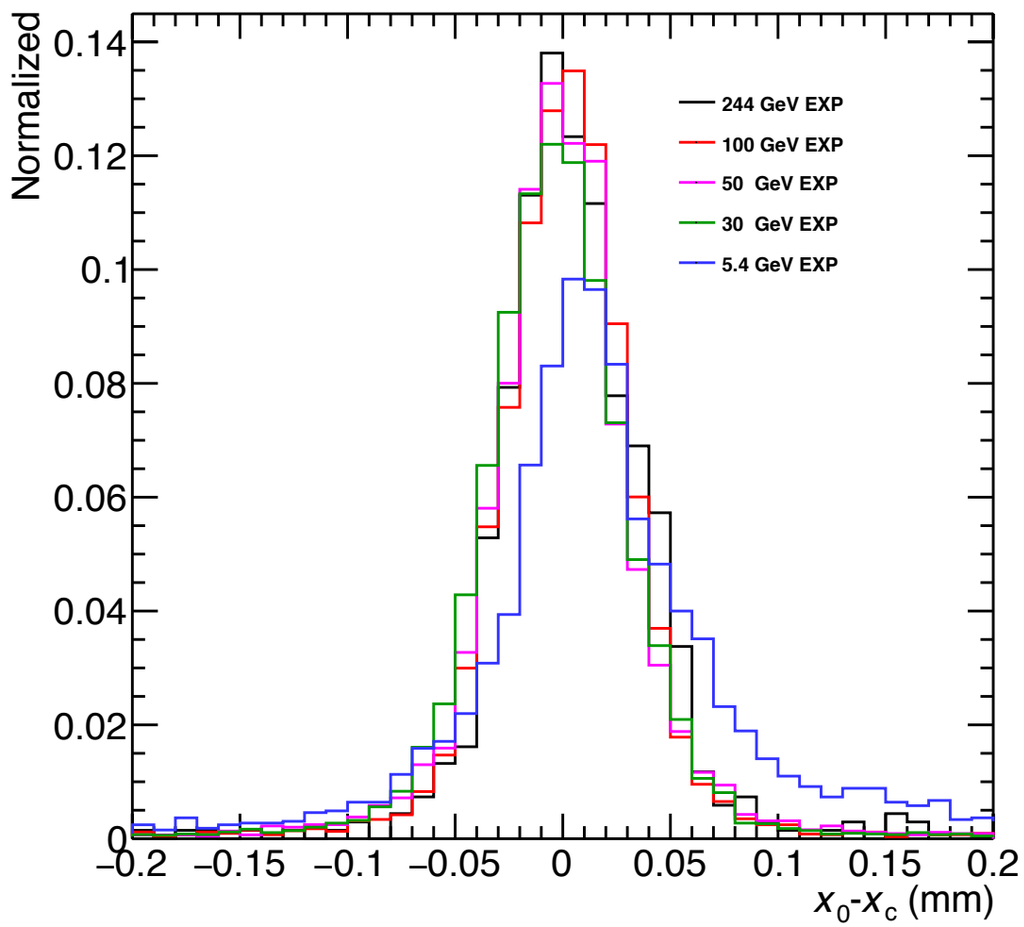


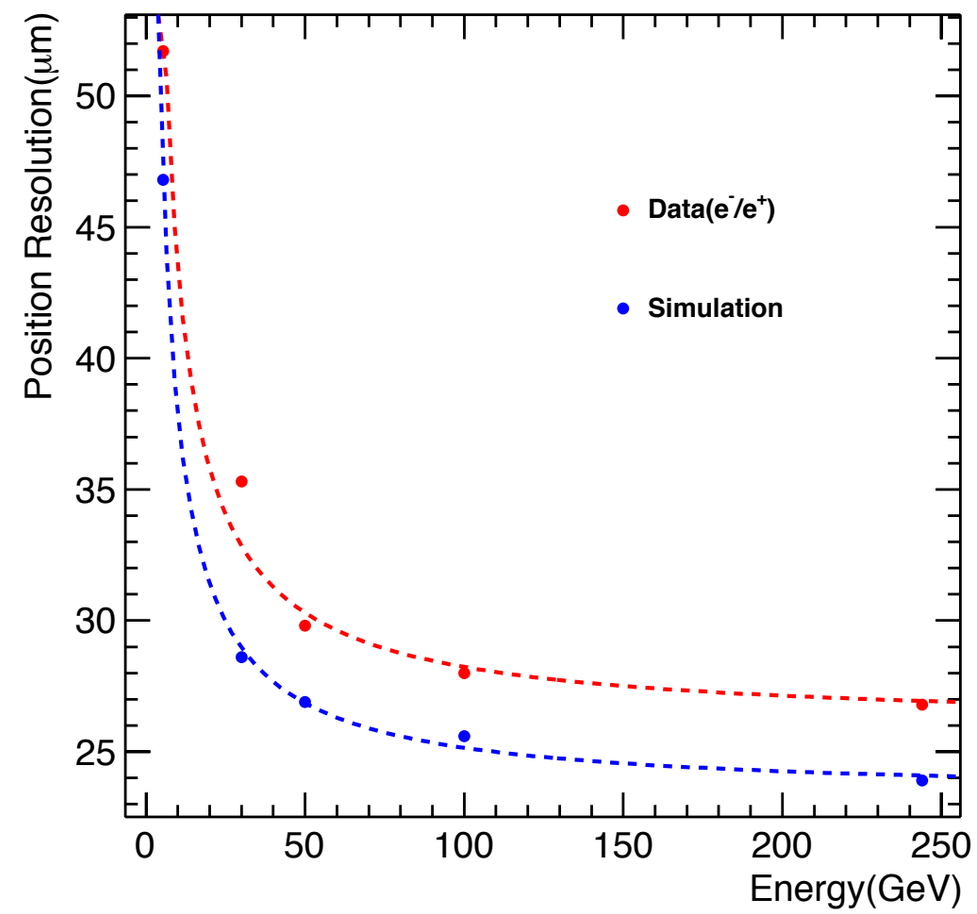
goal/idea:
build modules with 3 towers

minimize gaps between towers

stacked vertically into slabs

Pixel R&D - Example





calculate difference of position from

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

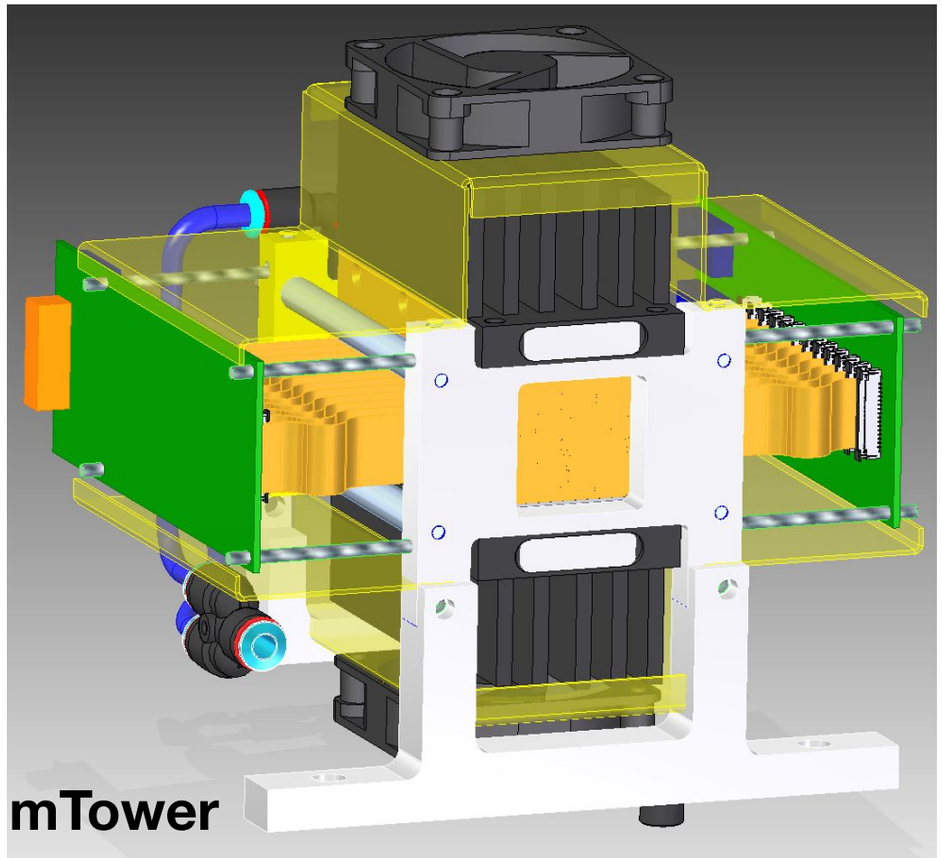
single shower position resolution obtained from width of residuals

can also provide excellent two-shower separation

first results published in JINST 13 (2018) P01014

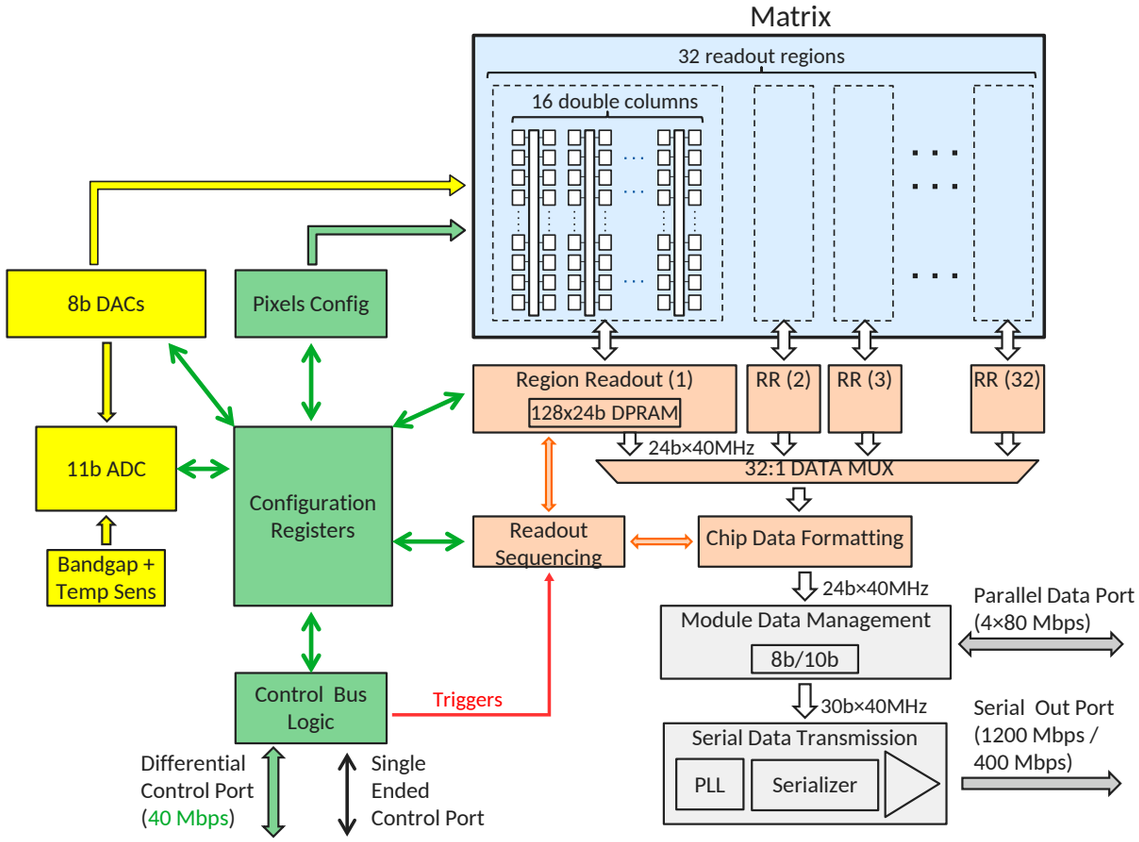
New Prototype: mTower

- Currently building new prototypes based on the **ALPIDE MAPS sensor** that is developed for the new ALICE Inner Tracking System
- New prototype **mTower**
  - Small digital calorimeter (3x3 cm^2) with 24 layers of 2 ALPIDE sensors and 3 mm W
  - Allows to test the performance of the ALPIDE in a calorimeter
  - Provides input into the FoCal design parameters
  - Allows to study particle showers in detail

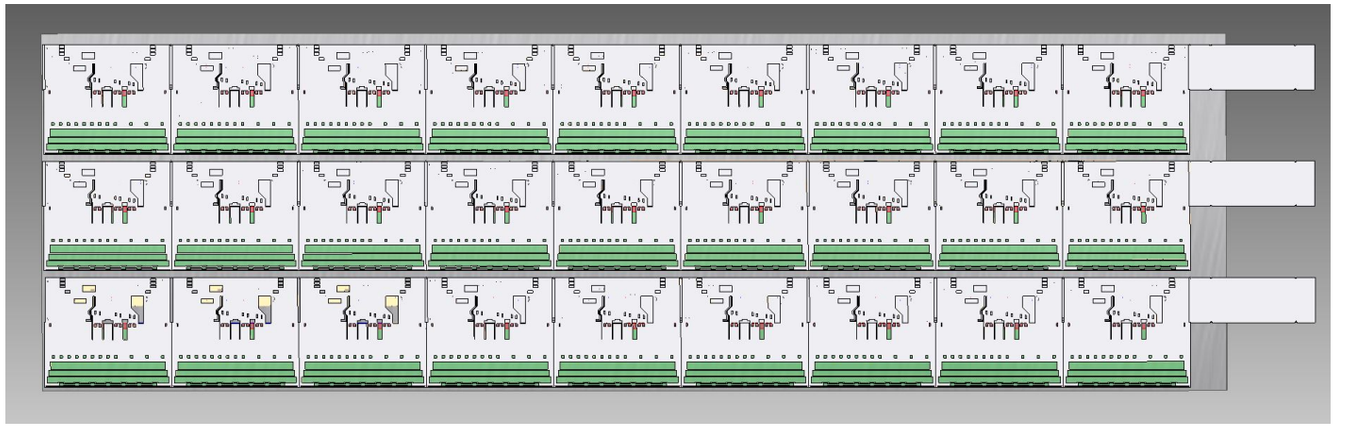


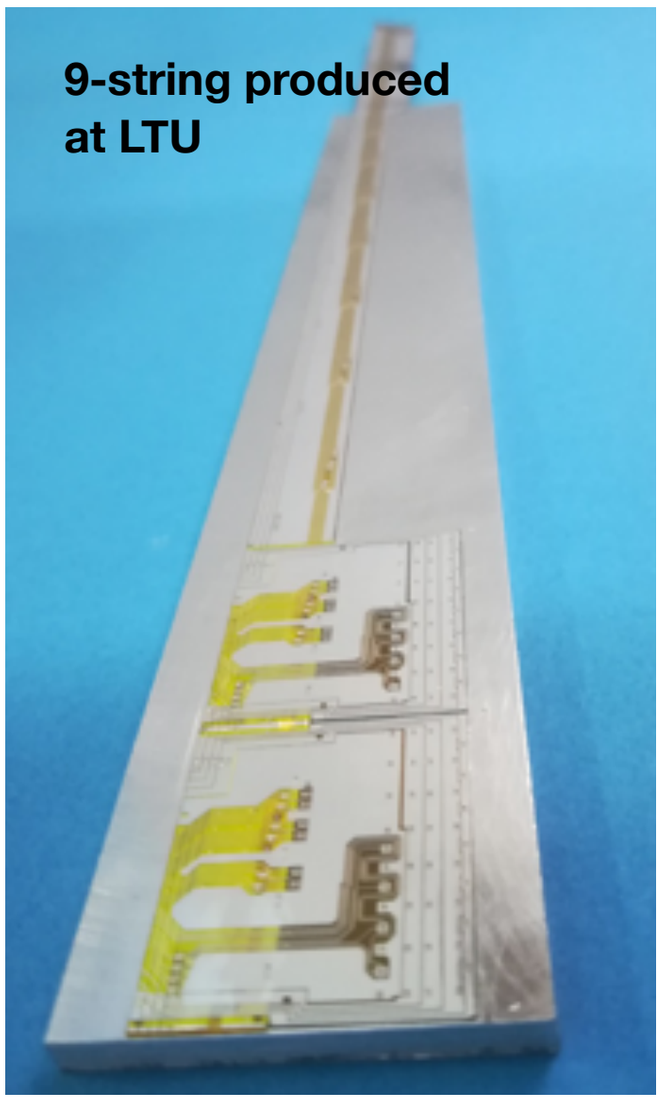
ALPIDE

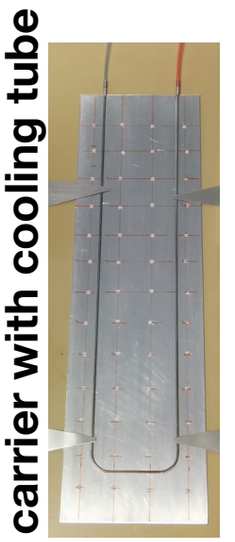
- Monolithic Active Pixel Sensor
- Chip size: 30.00 mm x 15.00 mm
- Pixel matrix: 1024 x 512 (=524288 pixels / chip)
- Active area: 29.94 mm x 13.76 mm
- Pixel size: 29.24 µm x 26.88 µm
- Hit driven readout
- Readout speed: 400 Mb/s - 1.2 Gb/s
- Power consumption proportional to the occupancy.



MiniFoCal – FoCal Module Prototype







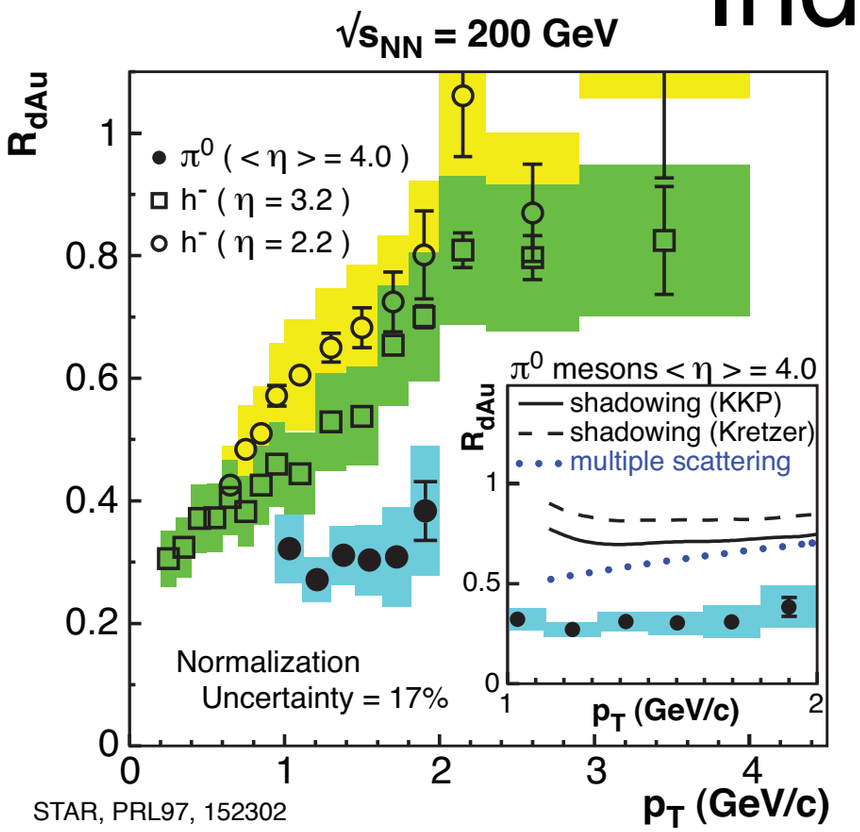
- MAPS layers design ready
- Mechanical tests ongoing (gluing, cooling, etc.)
- First functional 9-string (2 chips mounted) tested, some performance issues, revision of chip cable design ongoing
- PADS have been tested in ALICE cavern

Summary

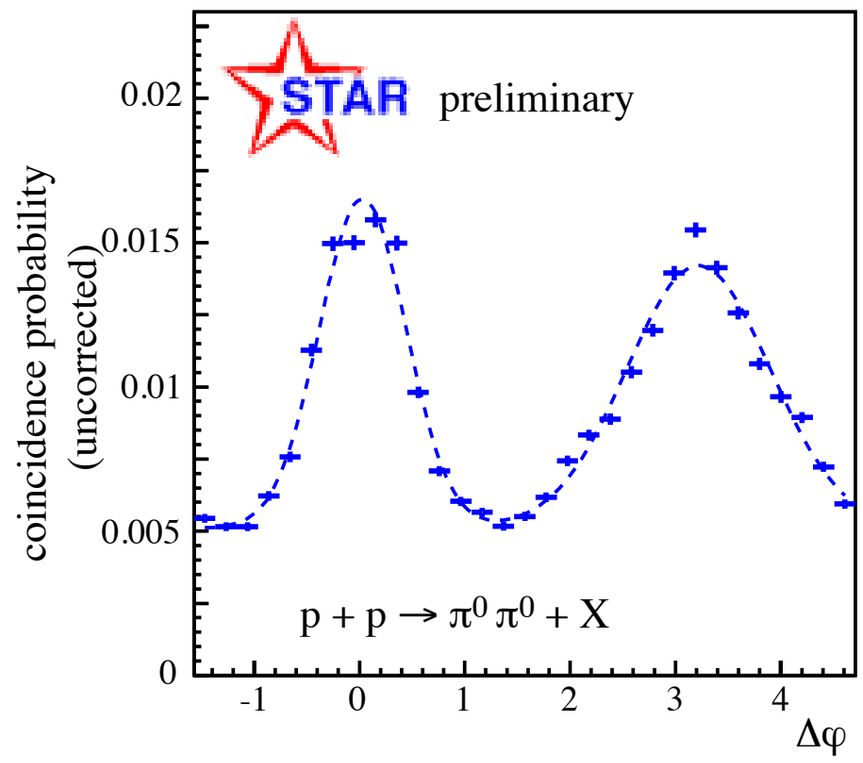
- Large uncertainties in low-x parton density
  - hints for gluon saturation, no proof!
- Opportunity for forward photon measurement
  - complementary information to open charm
  - possibly cleaner signal
  - main observable: direct photon R_{pA}
  - study also correlations (needs more theory work)
- FoCal proposal in ALICE
  - unique information from forward photons in pp and pA
  - needs extremely high-granularity EM calorimeter
  - ongoing R&D on SiW with pixel and pad sensors

Backup Slides

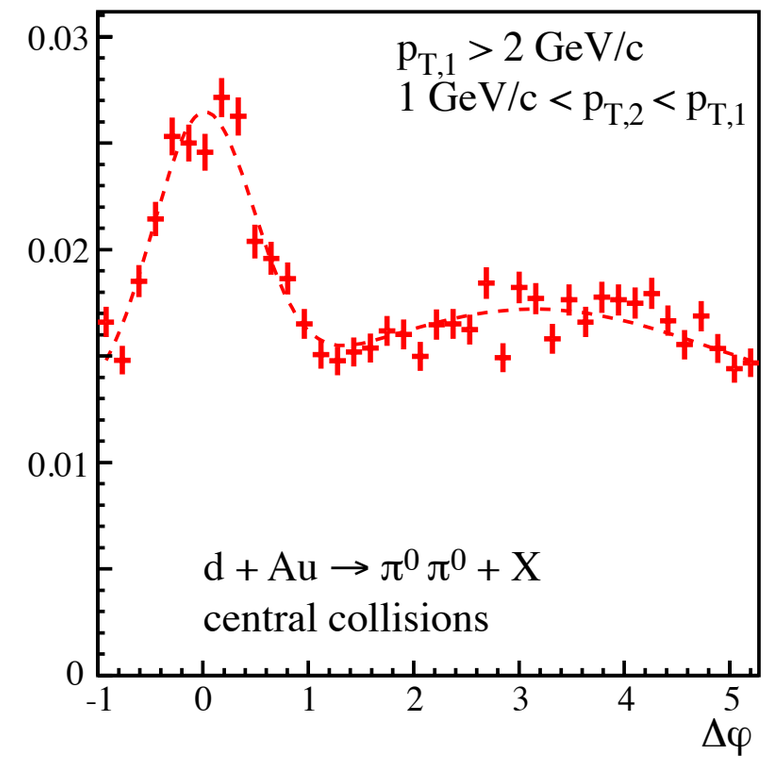
Indications from RHIC



STAR, PRL97, 152302



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

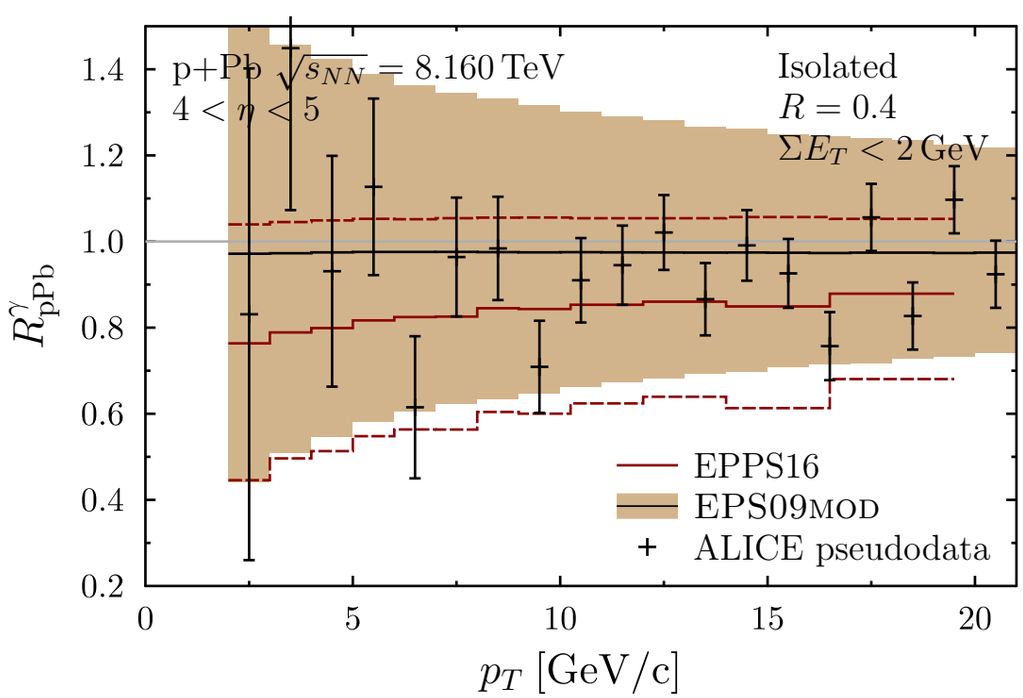
$$R_{\mathrm{dA}} = \frac{dN/dp_{\mathrm{T}}(dA)}{\langle N_{\mathrm{coll}}(dA)\rangle \, dN/dp_{\mathrm{T}}(pp)}$$

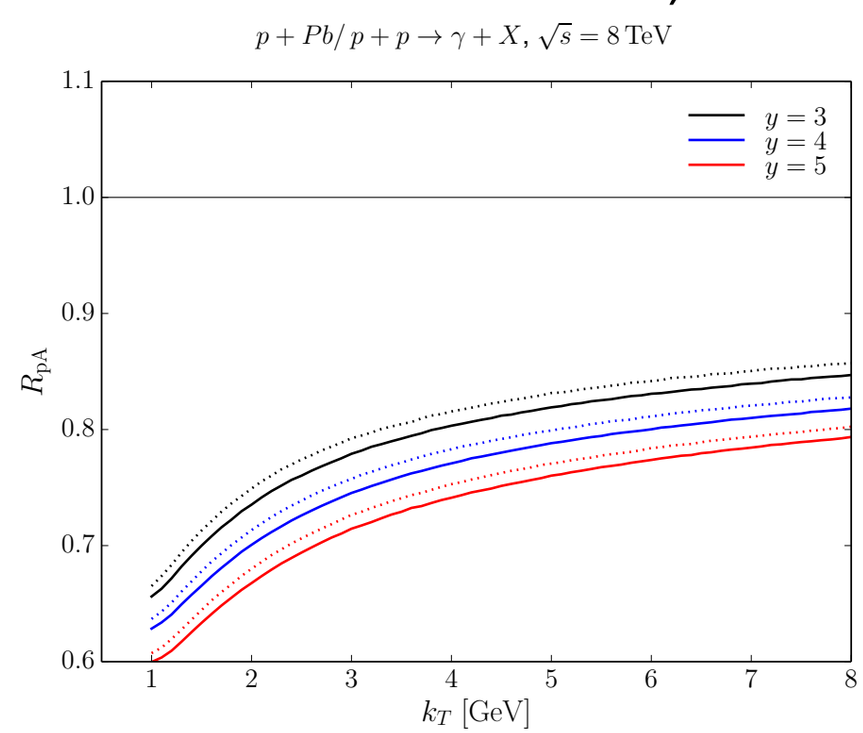
- qualitatively consistent with CGC, but ...
  - very low p_T, close to kinematic limit, hadron observable (final state interactions)!
- extend p_T and y range (not possible at RHIC)

Main Physics Motivation for FoCal (A Hierarchy)

1. prove or refute gluon saturation
   - compare saturation models with linear QCD
   - depends on saturation model implementation and flexibility of PDF analytical shape
2. show invalidity of linear QCD at low *x*
   - can all potential measurement outcomes be absorbed in a modified PDF?
3. constrain the PDFs at low x
   - nuclei, also protons

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

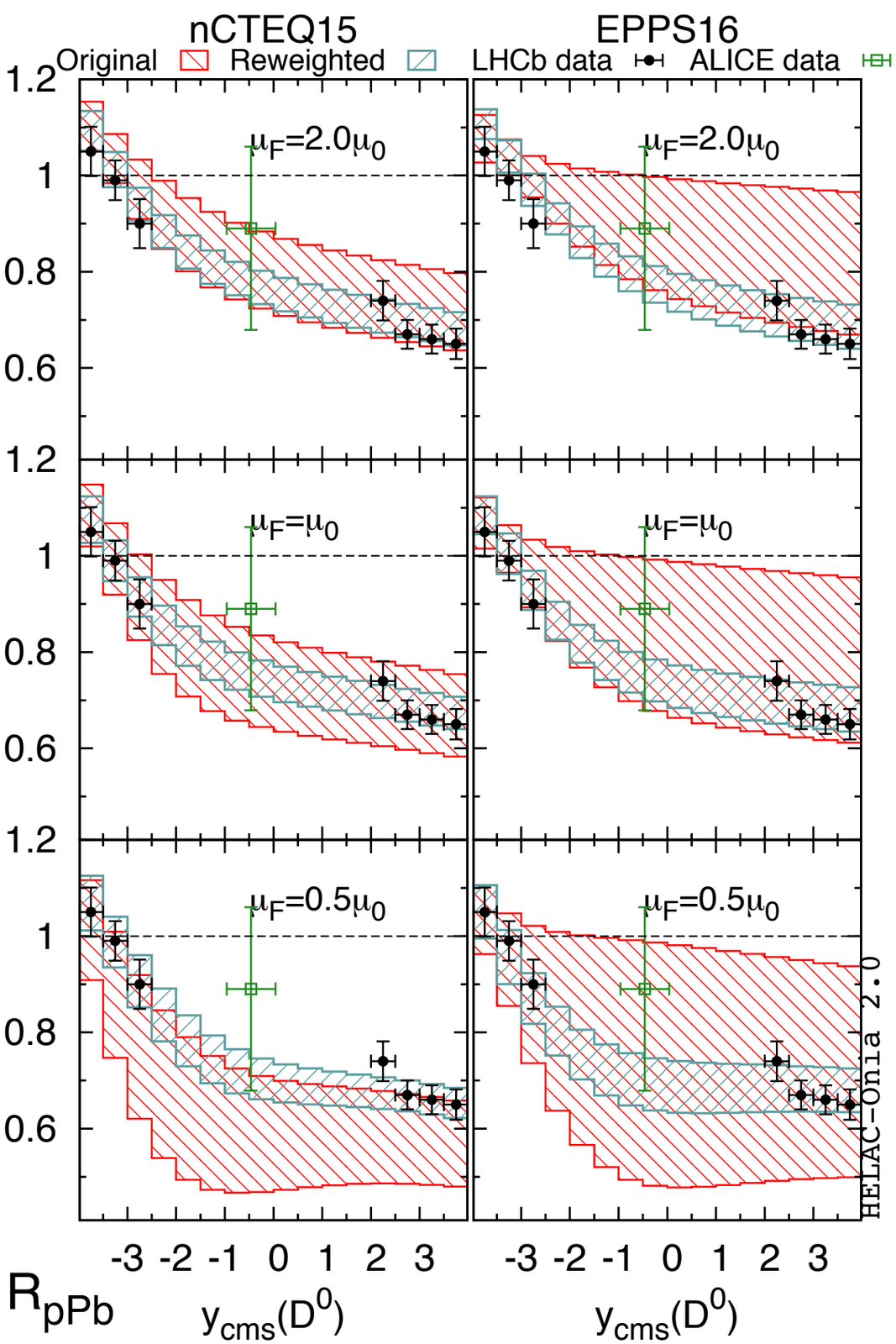




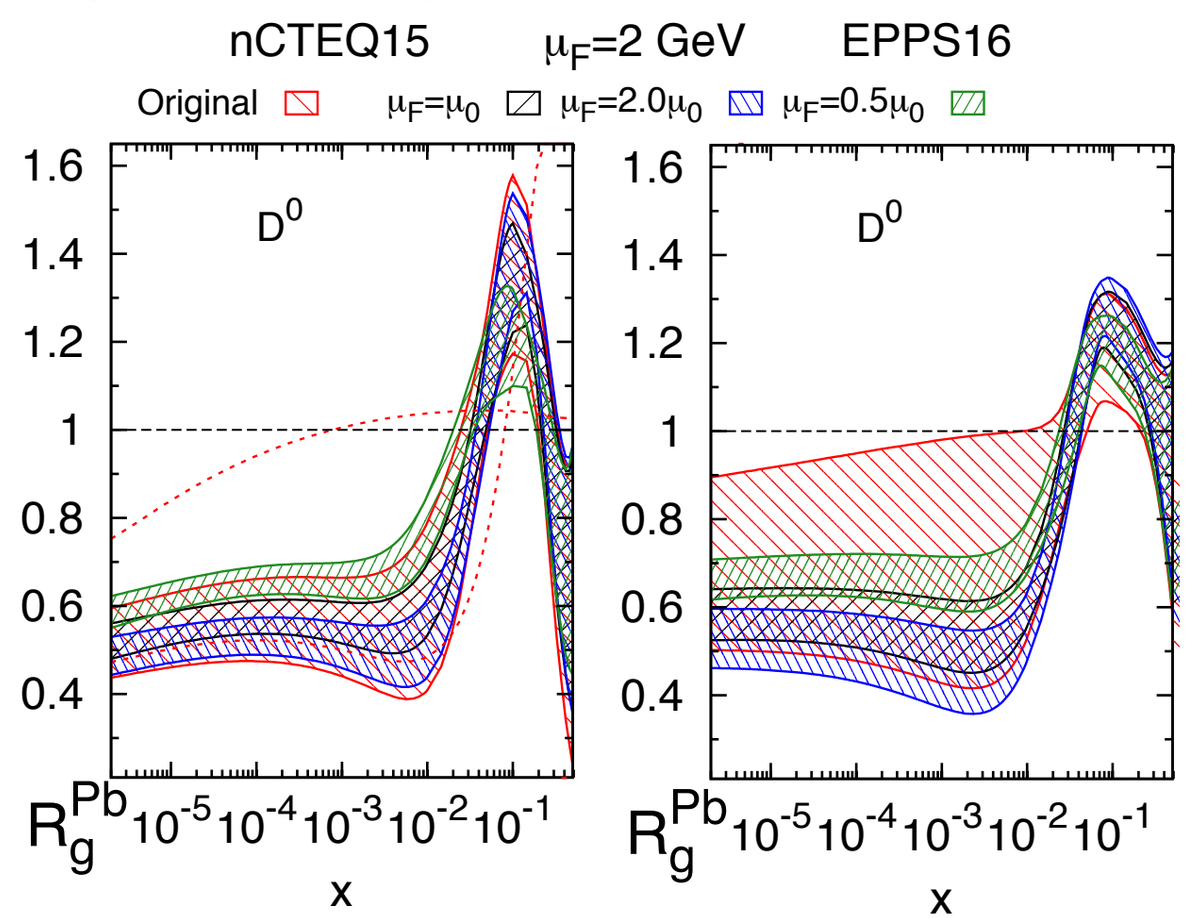
CGC Calculation: Ducloué, Lappi, Mäntysaari, arXiv:1210.02206

Recent: PDF Fits Using Charm

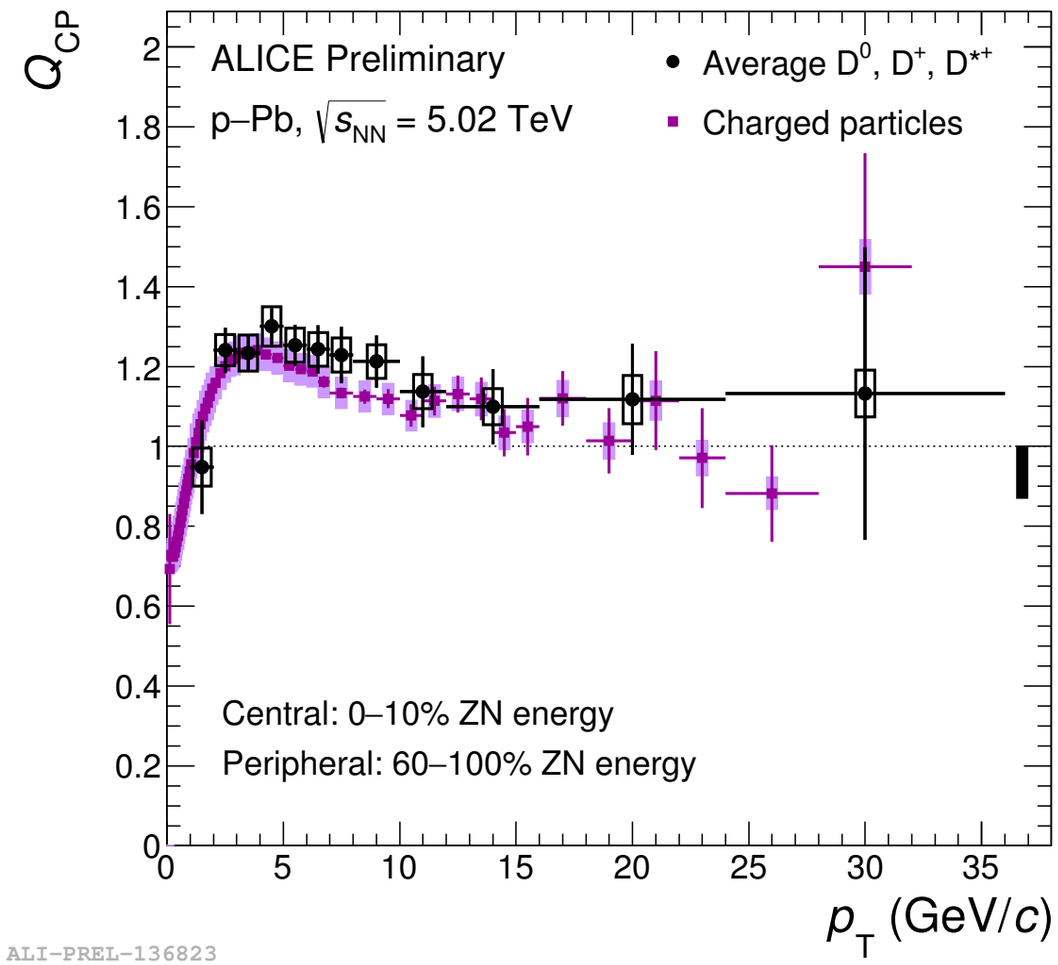
Kusina et al., arXiv:1712.07024



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

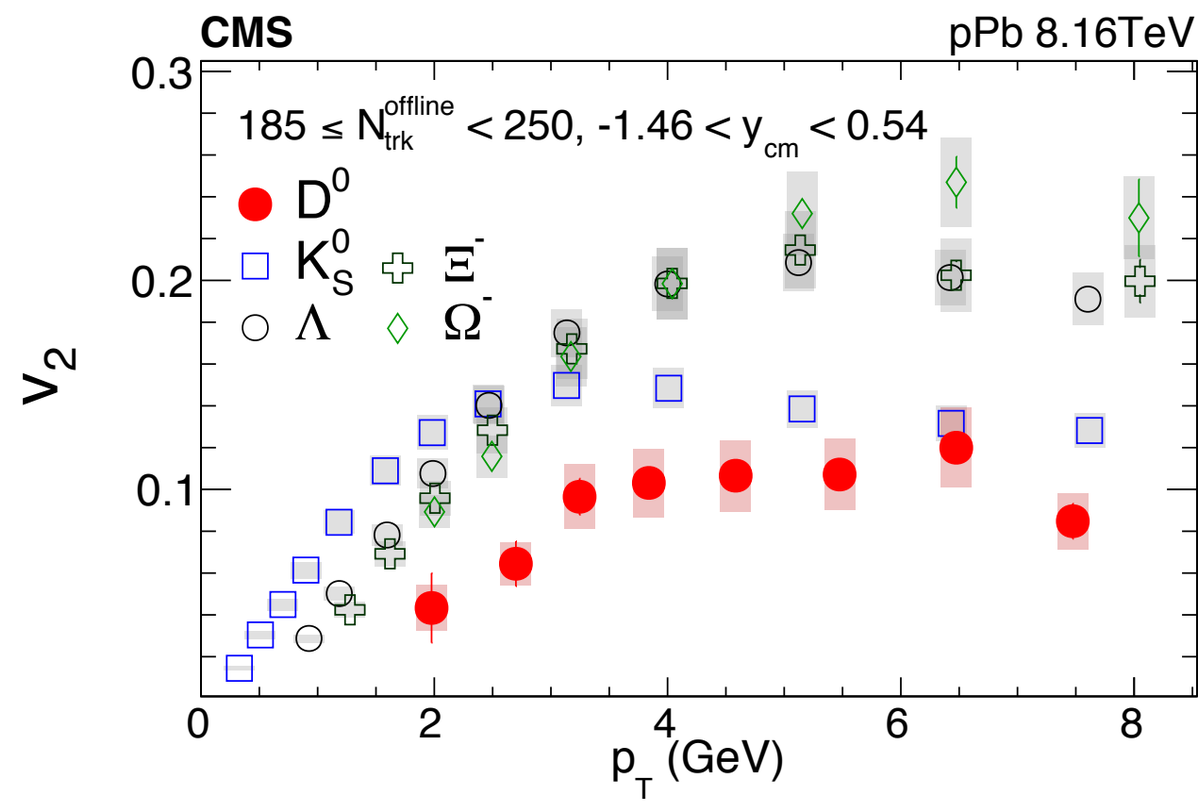


Final-State Modification of Open Charm in p–A?



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

CMS Collaboration, CERN-EP-2018-076

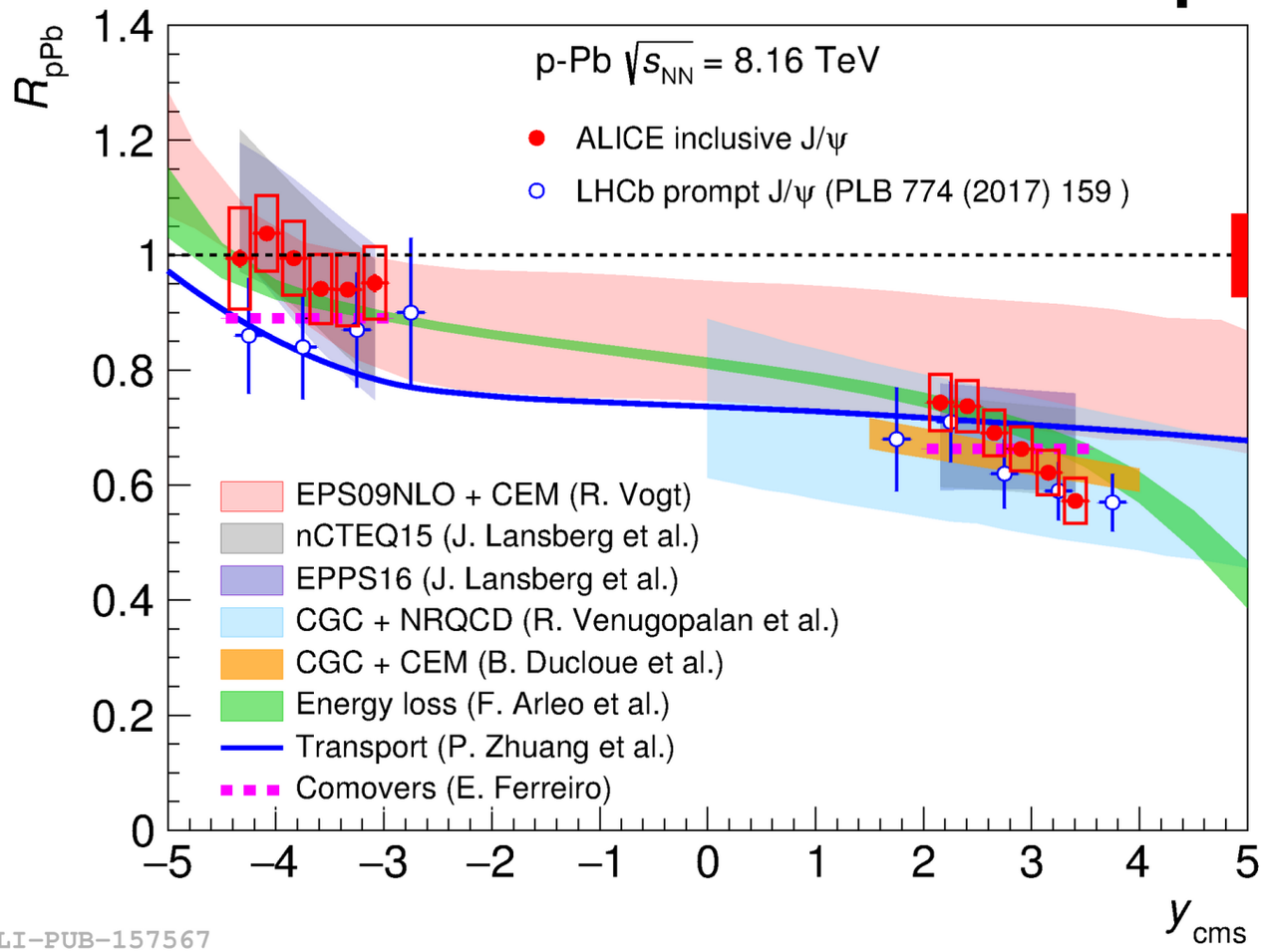


significant v_2 for D mesons,
similar results for HF-decay leptons

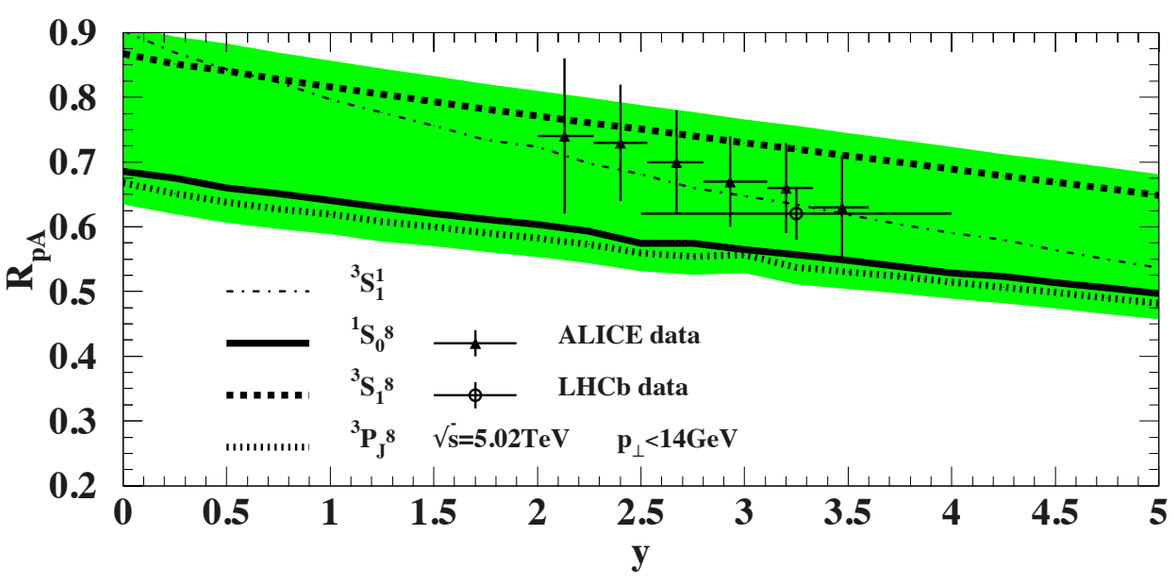
- mechanism for modifications still unclear, possibly final-state interaction!
- relation between initial- and final-state kinematics may be obscured
- introduces additional systematic uncertainty

ALICE, JHEP 07 (2018) 160

Results from p-Pb at LHC (1)



Ma, Venugopalan, Zhang, arXiv:1503.07772



- nuclear modification factor RpPb for charmonium
- J/ψ suppressed at forward rapidity
  - can be described by very different theoretical calculations
- additional uncertainties from hadronisation?
  - e.g. uncertainties in CGC model due to population of different quantum states
- not conclusive

True x-Sensitivity?

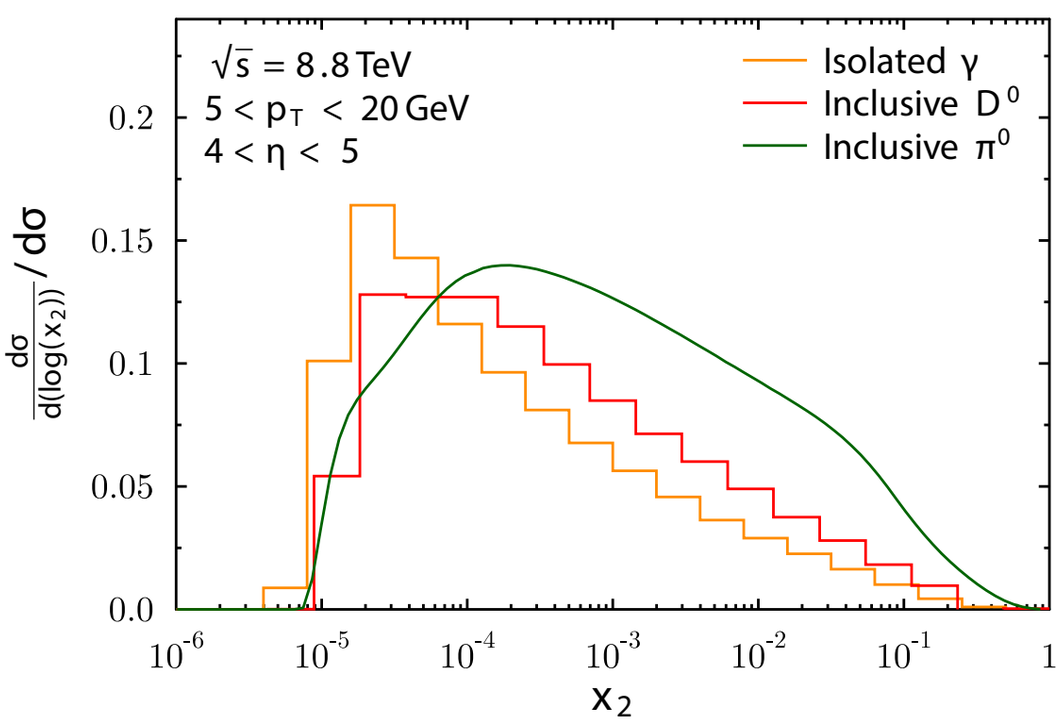
	$\sqrt{s}$ (TeV)	y	p_T (GeV/c)	z	x_2
π	0.2	4	2	0.3	$1.2 \cdot 10^{-3}$
π	8.8	0	2	0.3	$1.5 \cdot 10^{-3}$
jet	8.8	4	20	1	$8.3 \cdot 10^{-5}$
π	8.8	4	2	0.3	$2.8 \cdot 10^{-5}$
D	8.8	4	0	0.5	$1.5 \cdot 10^{-5}$
γ	8.8	4	4	1	$1.7 \cdot 10^{-5}$
γ	8.8	4.5	4	1	$1.0 \cdot 10^{-5}$

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

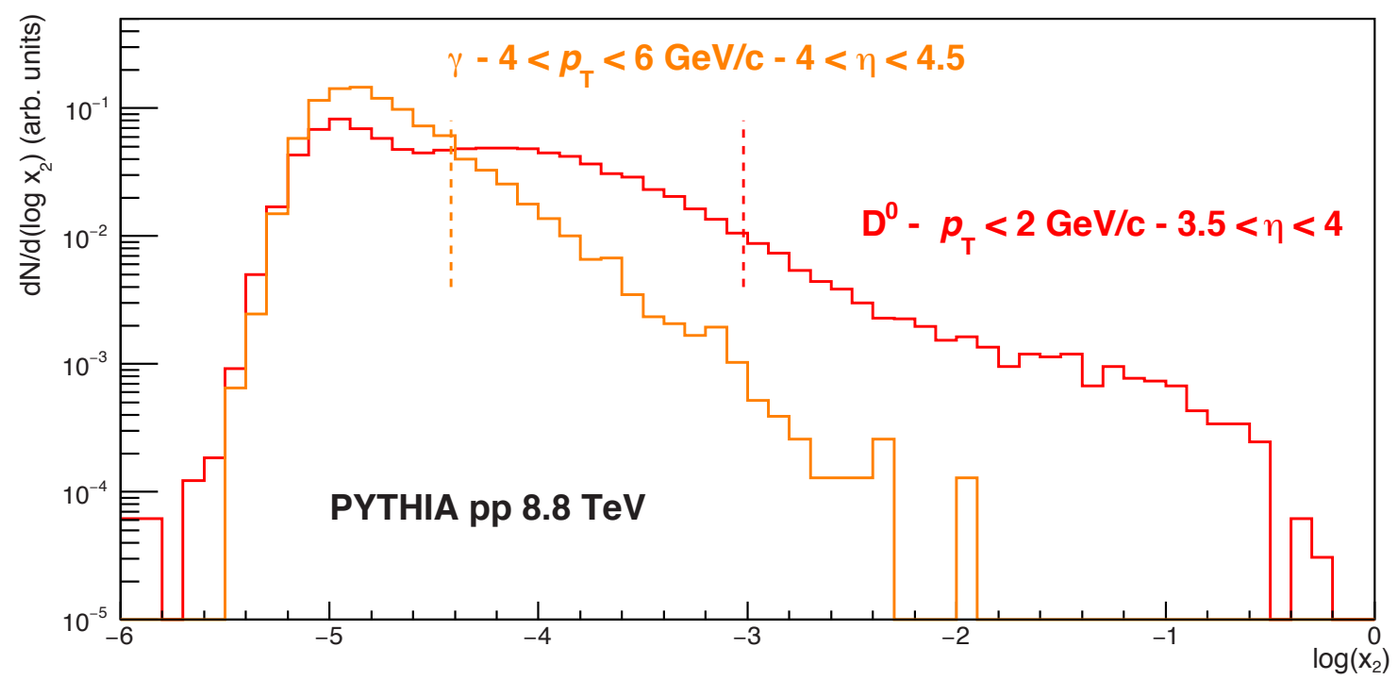
- LO kinematics estimates provide rather lower limit for x_2
- but: higher orders contribute significant tail towards large x_2

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

- *x*-distributions from NLO pQCD



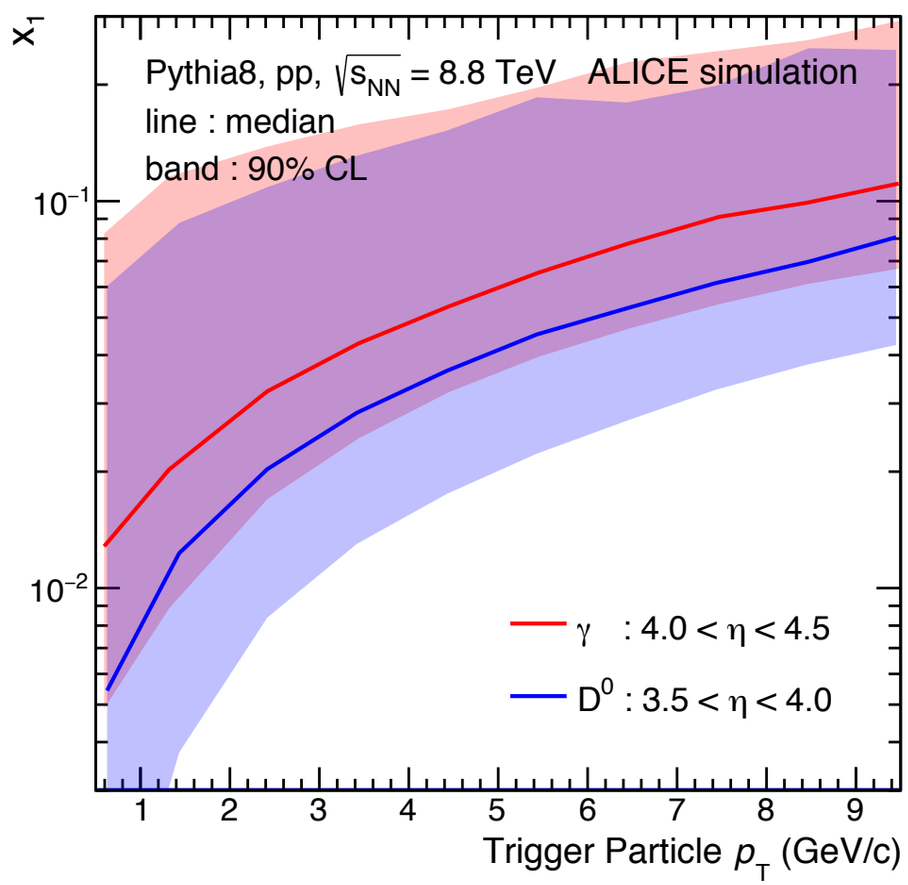
- *x*-distributions from PYTHIA



no analytical approximation, taking into account η of recoil parton

Hiroki Yokoyama

x-Q^2-Sensitivity

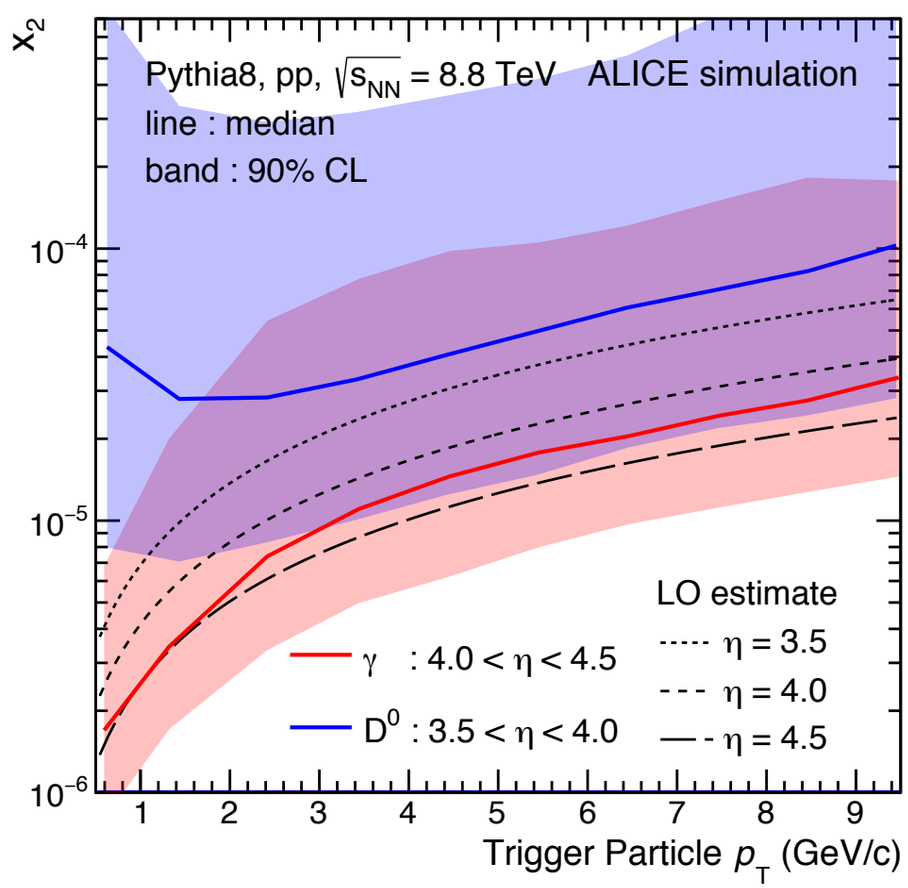


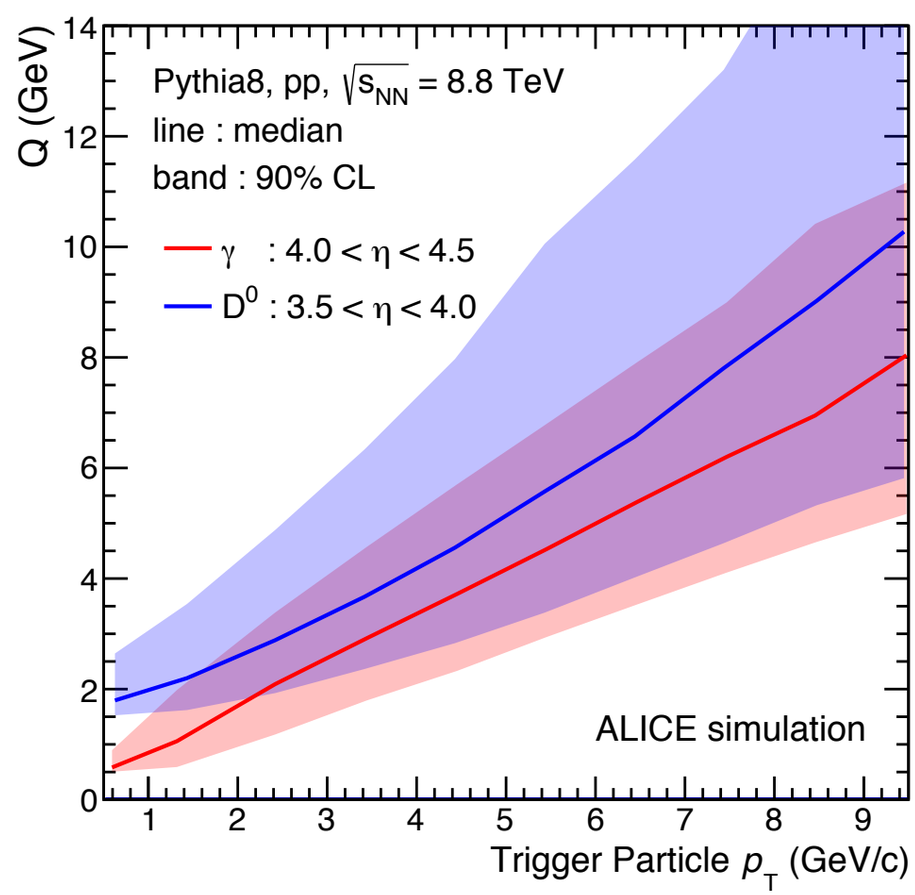
PYTHIA pp 8.8TeV
forward measurements

LHCb D0 vs FoCal photons

study median of distribution and 90% confidence level limits

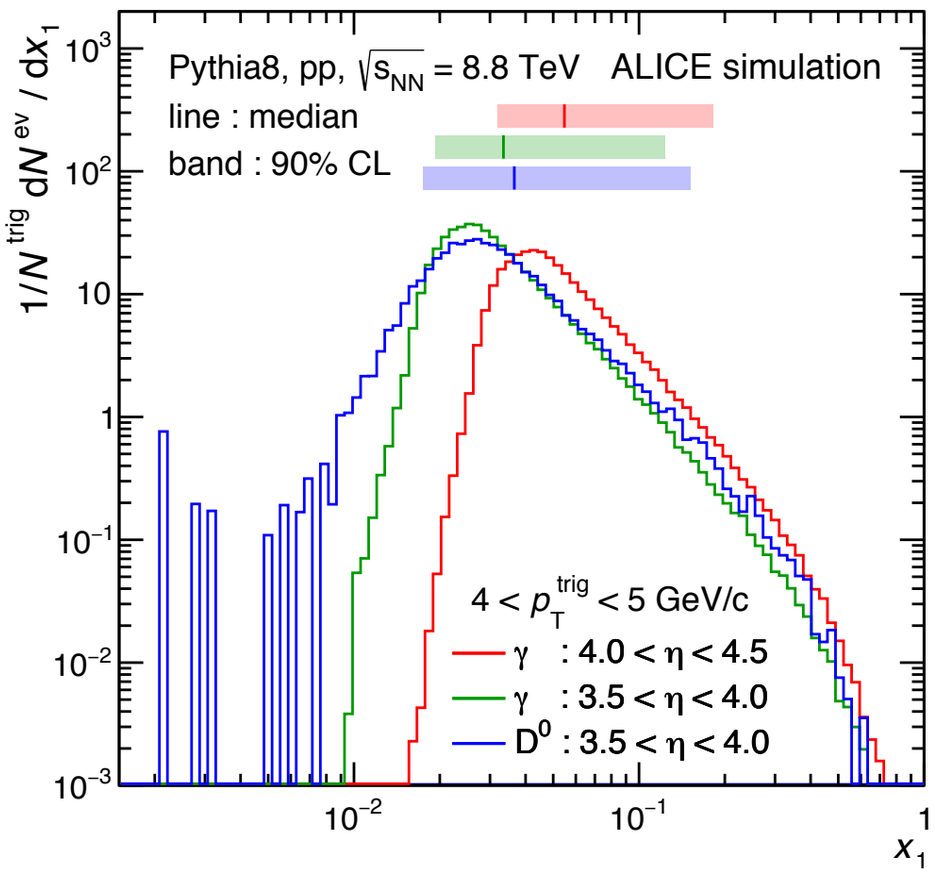
better sensitivity for photons





Hiroki Yokoyama

x-Q^2-Sensitivity



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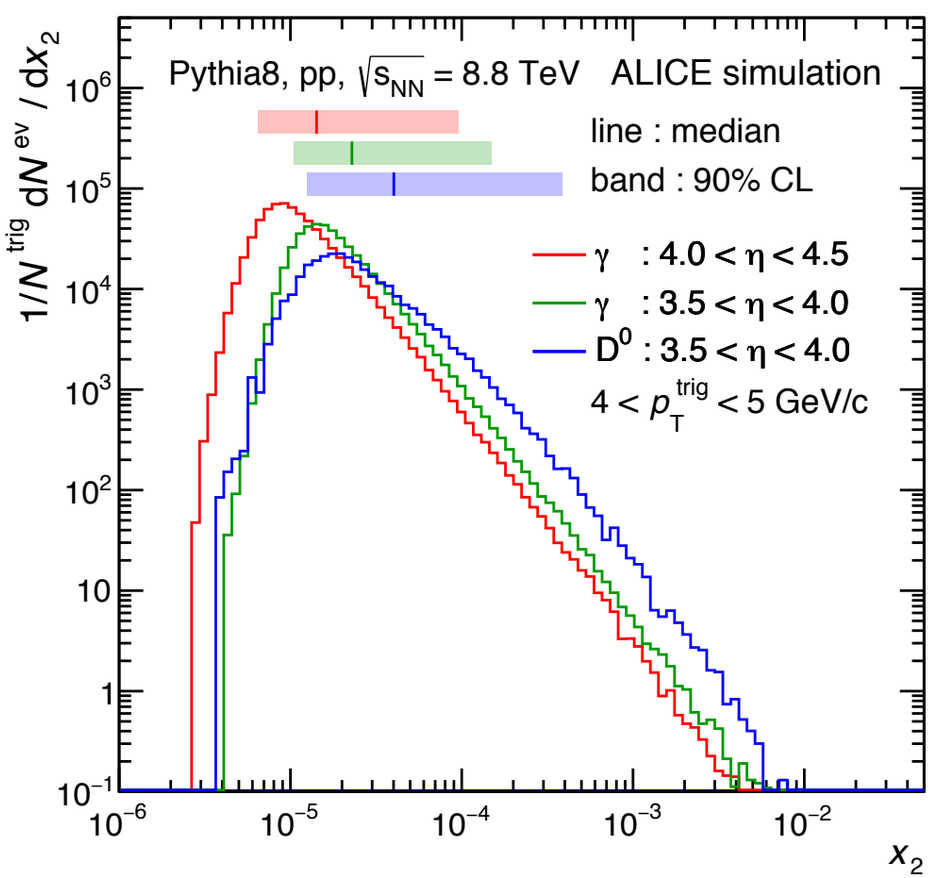
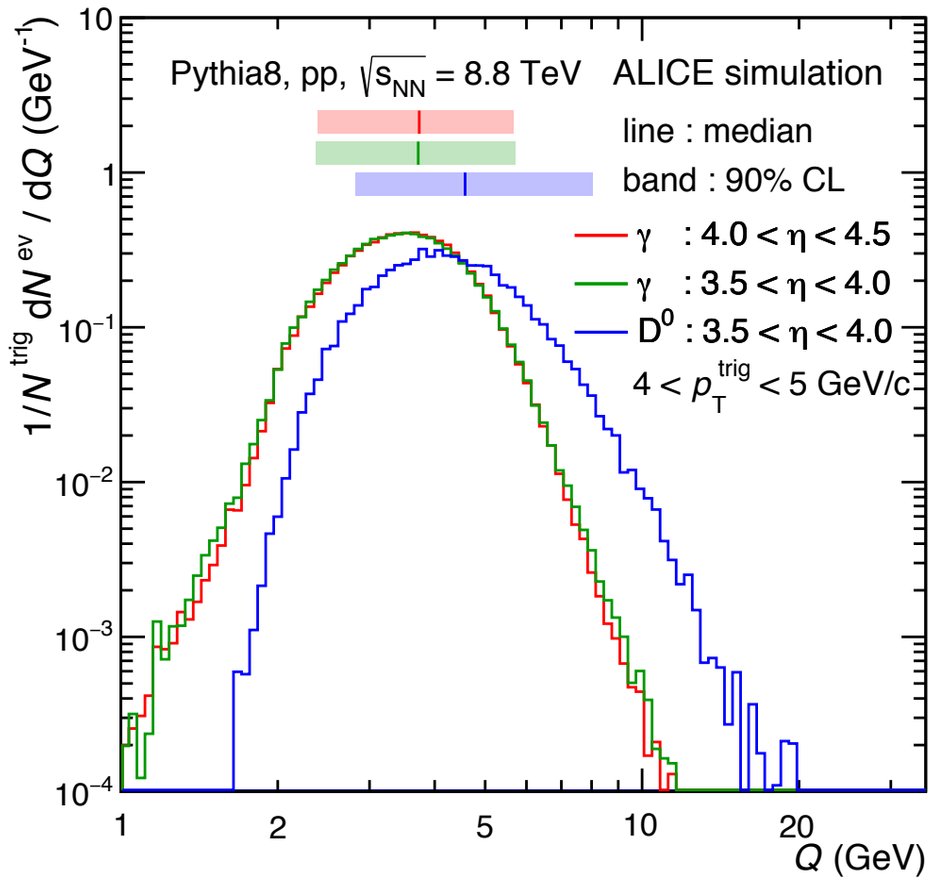
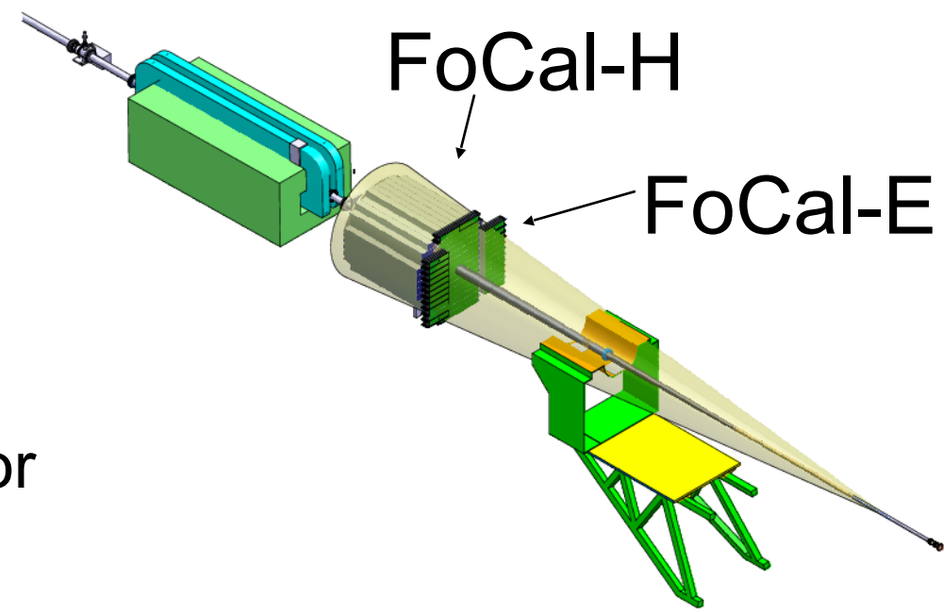




The FoCal Proposal

$3.2 < \eta < 5.3$
(baseline design @ 7m)

FoCal-E: high-granularity Si-W calorimeter for photons and π^0
FoCal-H: hadronic calorimeter for photon isolation and jets

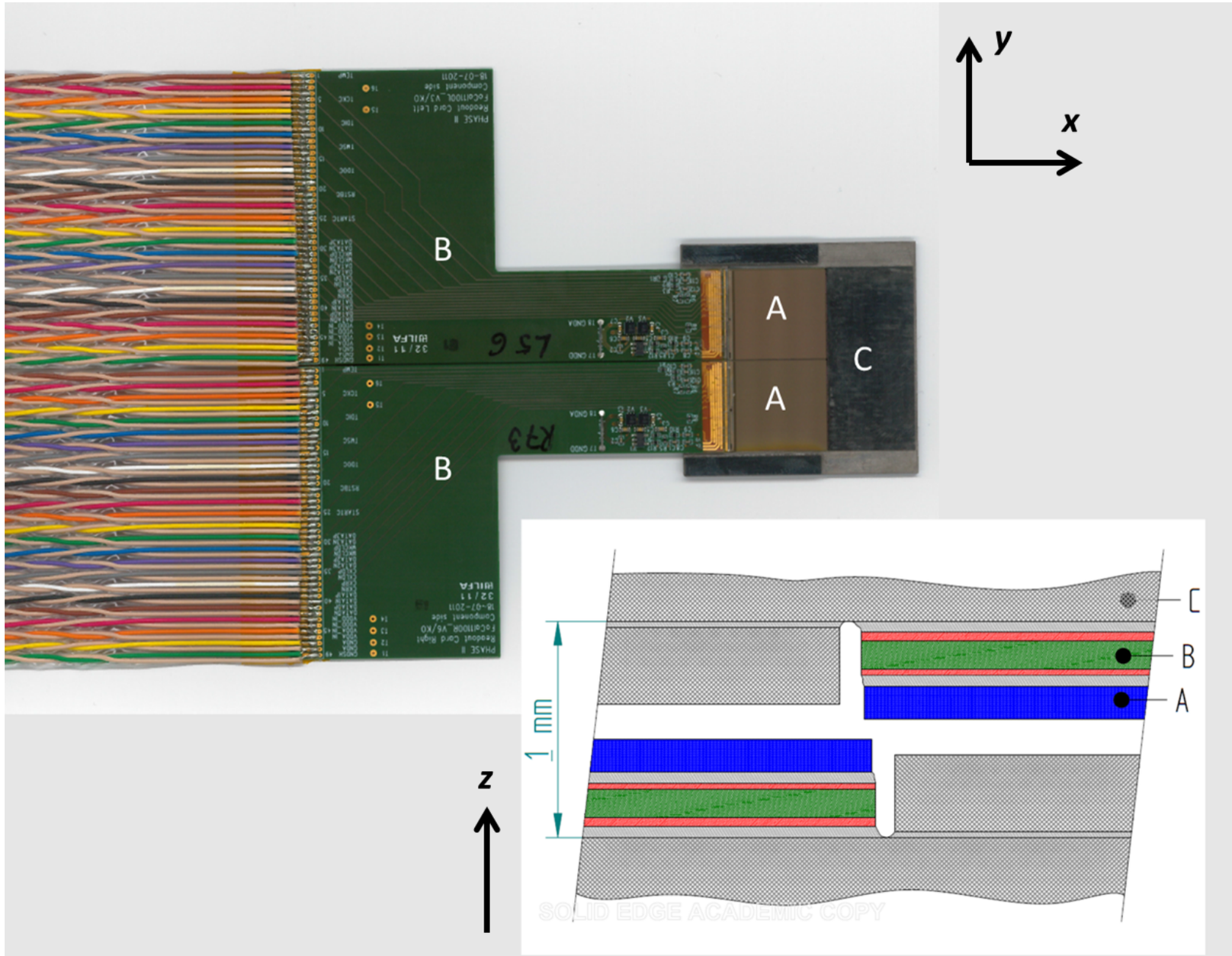


Observables:

- π^0
- Direct (isolated) photons
- Jets

Advantage in ALICE:
forward region not instrumented;
'unobstructed' view of interaction point

MIMOSA Prototype



calorimeter stack of 24x2 half layers equipped with MIMOSA CMOS pixel sensors

half layer with two sensors and 1.5mm W

two half layers mounted together with opposite orientation to minimise dead areas

total layer thickness ≈ 1 X_0

full active layer with readout boards within 1mm

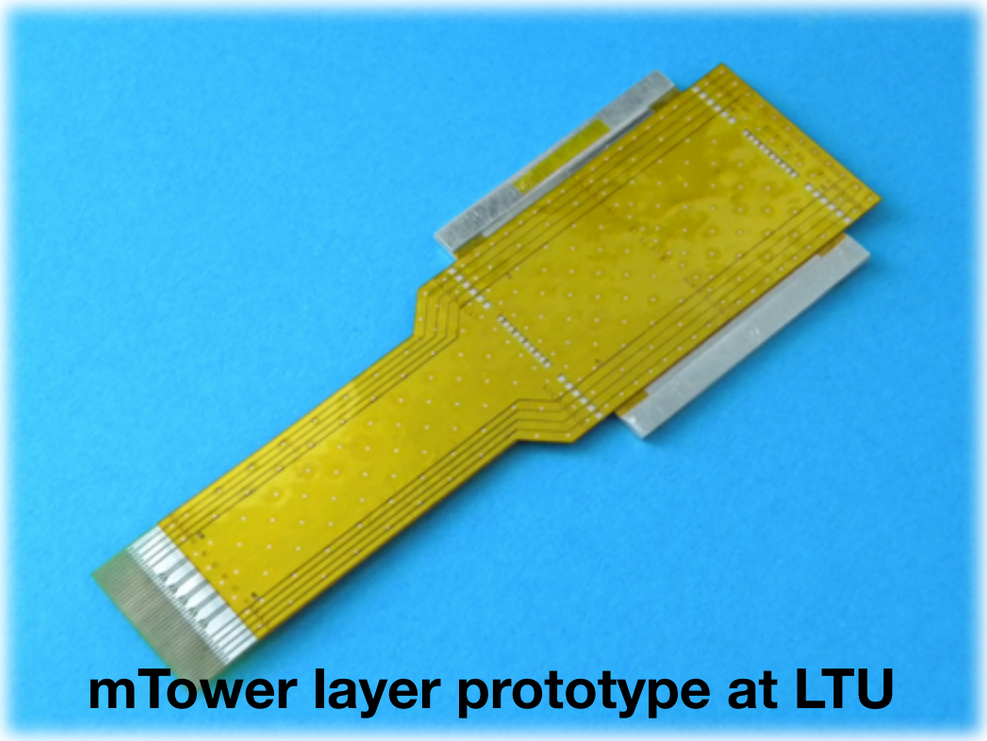
A: MIMOSA sensor
B: PCB
C: tungsten

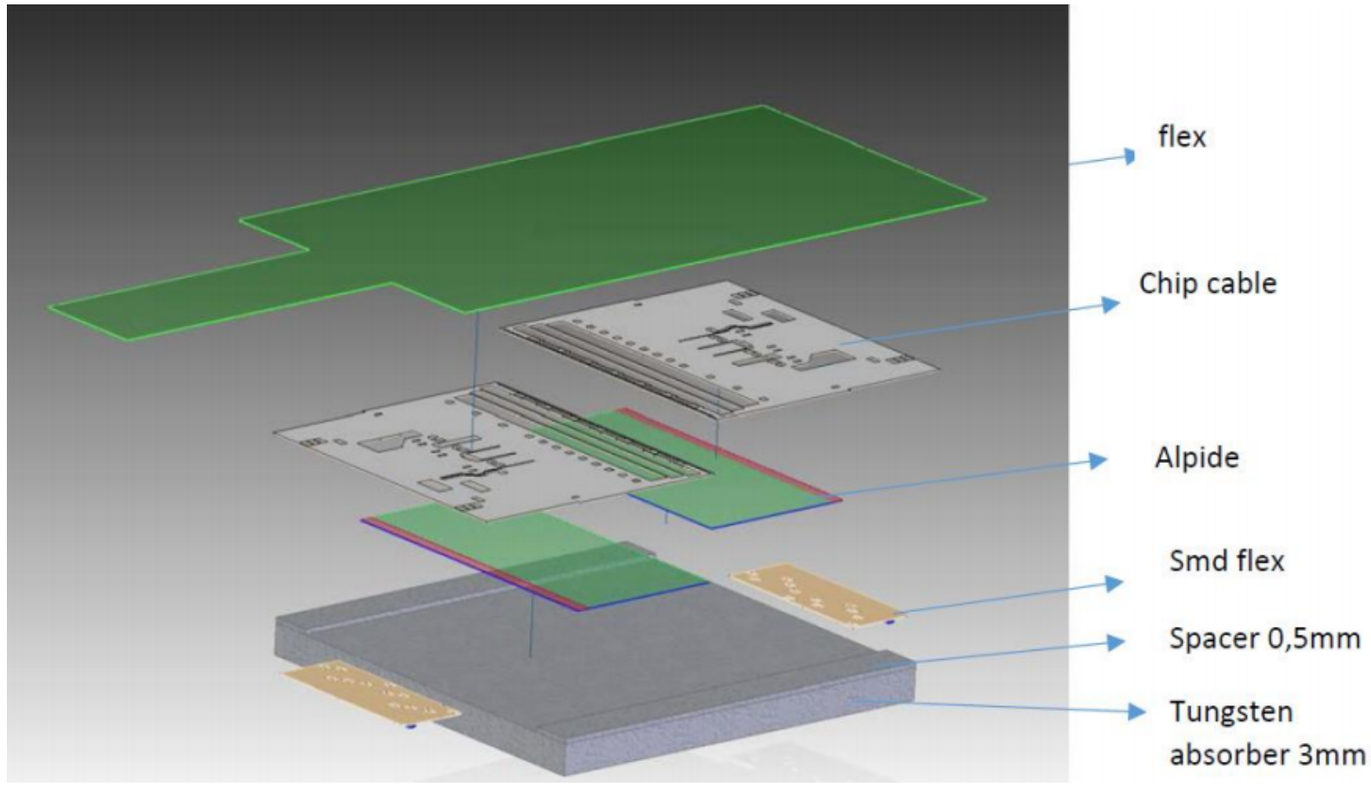
extremely compact design

- allows for high pixel density and small Moliere radius

mTower Layers

- Layer: W absorber and two ALPIDE chips
- Thin, compact cabling to keep small Molière radius
  - Chip-cable and multilayered flex for connection (LTU Charkov)

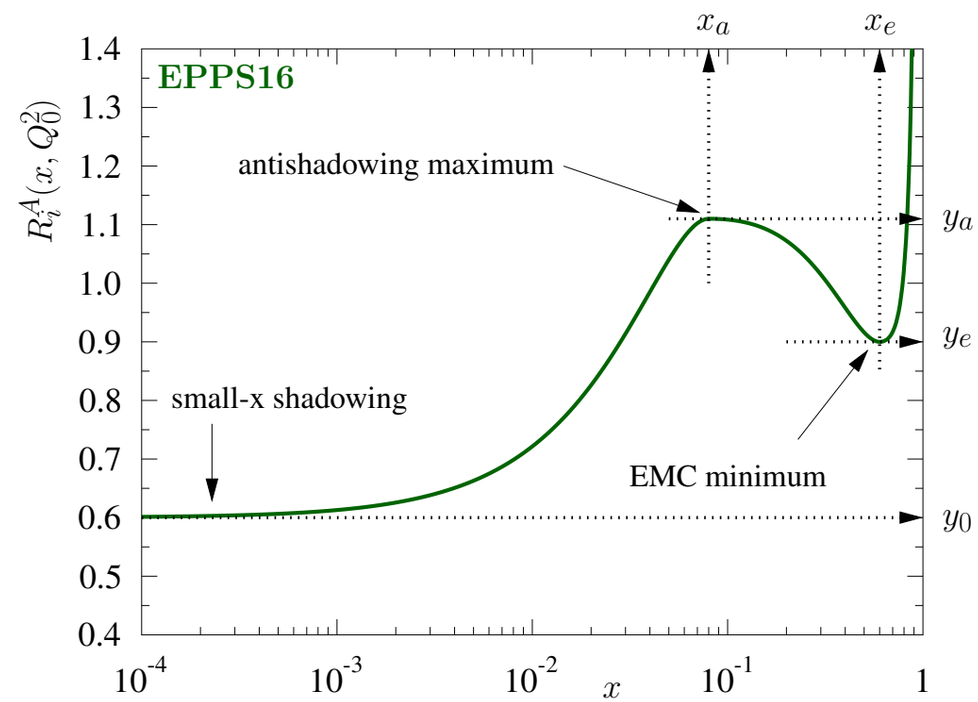




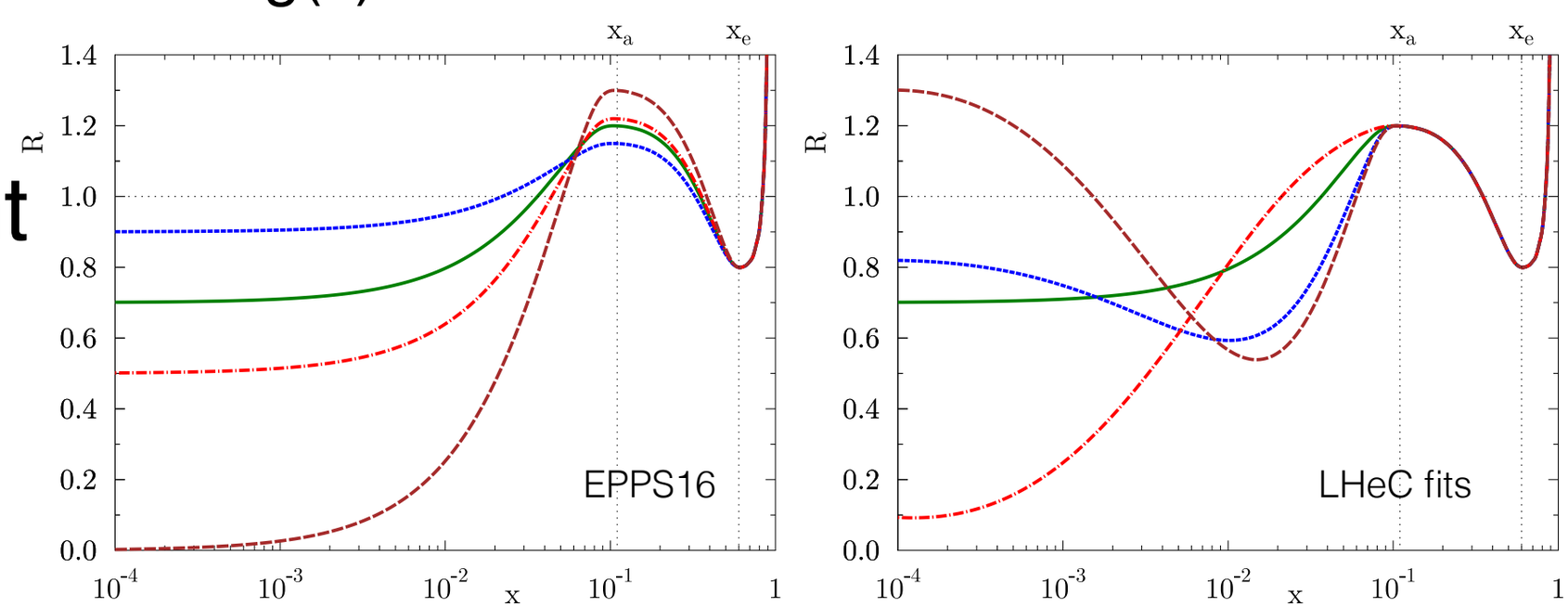
x-Dependence of PDF modification

EPPS16, EPJC 77, 163

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



- parameterisation of R_A
  - shape similar to EPS09
  - at low x leads to "plateau" in log(x)
- likely not sufficient
  - more flexible PDF used for LHeC estimates



Helenius, Paukkunen, Armesto, arXiv:1606.09003