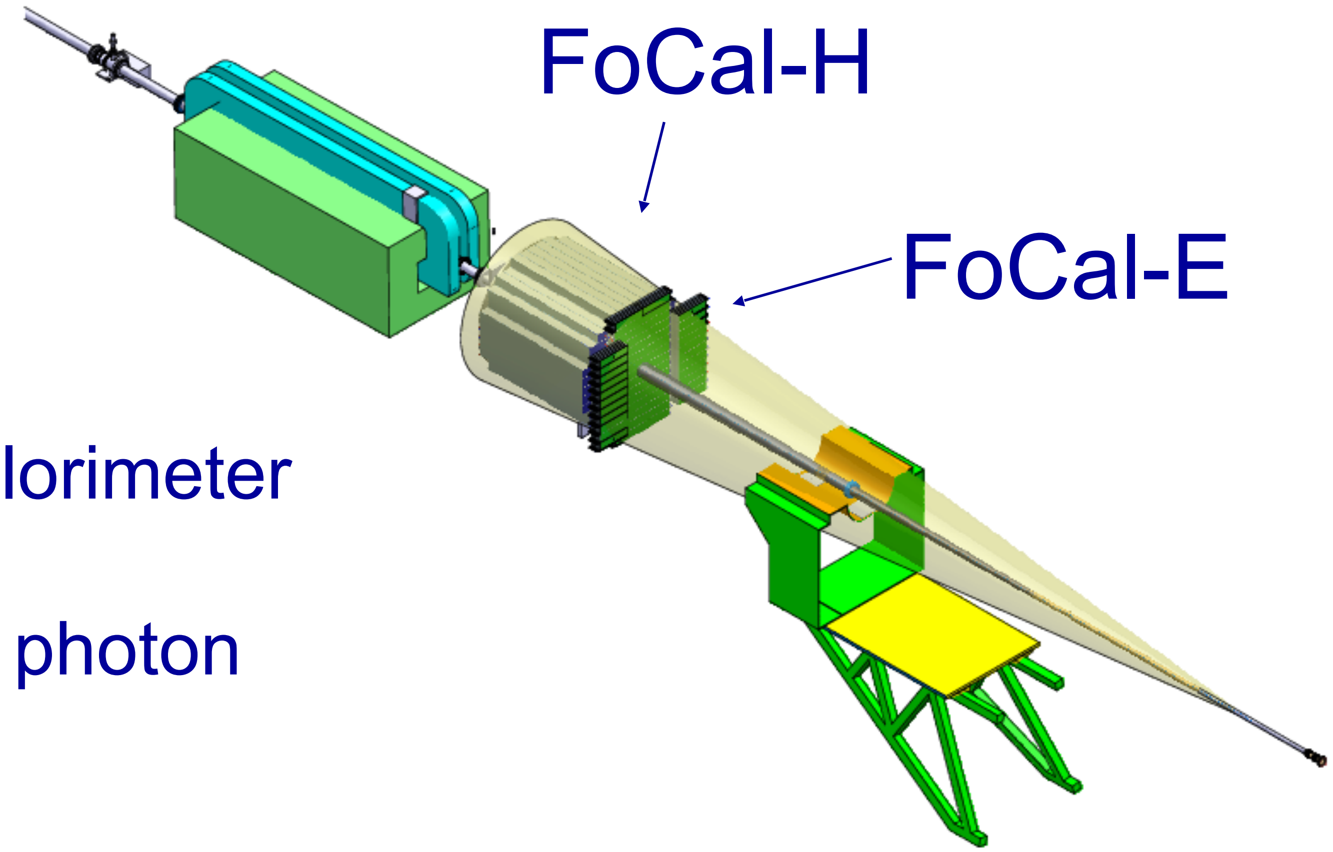
# FOCAL project and physics overview

*Marco van Leeuwen, Nikhef*

# The FOCAL proposal

Under discussion within ALICE

$3.2 < \eta < 5.3$



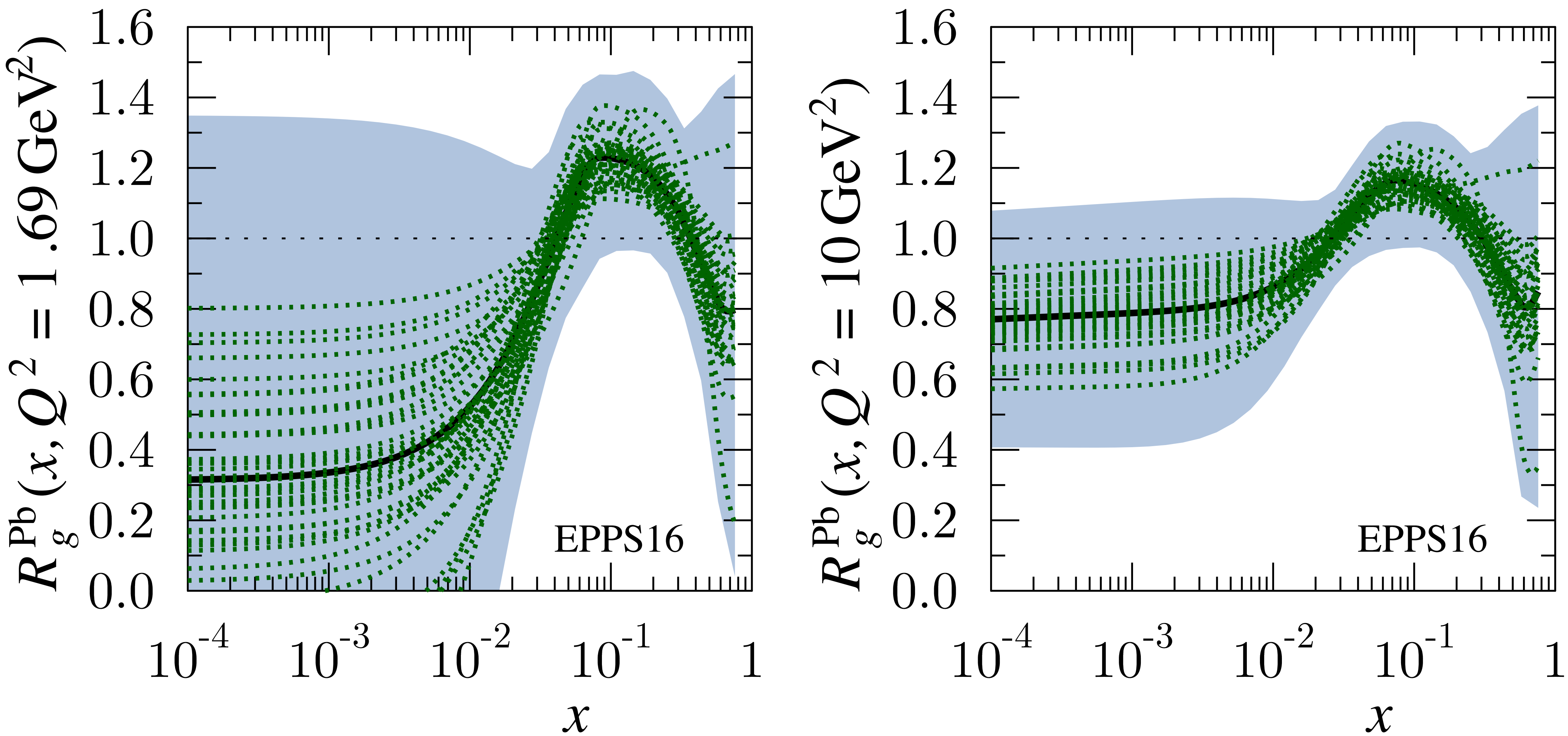

**FoCal-E**: high-granularity Si-W calorimeter for photons and $\pi^0$
**FoCal-H**: hadronic calorimeter for photon isolation and jets

Observables:
- $\pi^0$
- Direct (isolated) photons
- Jets

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

# Uncertainties in Nuclear PDFs

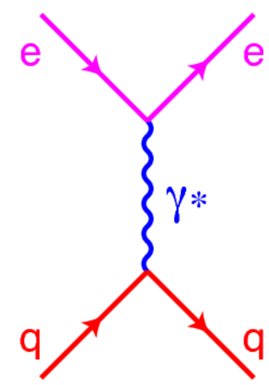
EPPS16, EPJC 77, 163



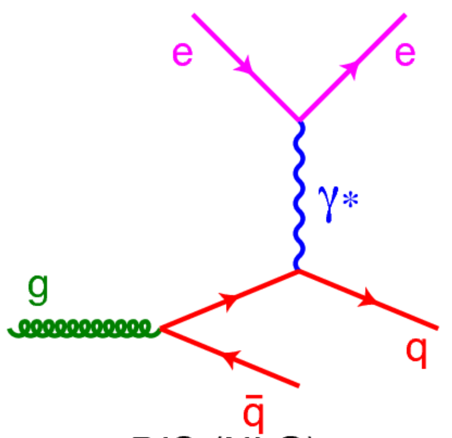

- large uncertainties of nPDFs
  - parameterised nuclear modification
  - recently updated to allow more freedom (e.g. flavour dependence)
- x-dependence?
  - very little dependence for $x < 10^{-2}$

# How to probe the gluon density

**Deep-Inelastic Scattering** (DIS)
Classical PDF method
Not sensitive to gluons at LO



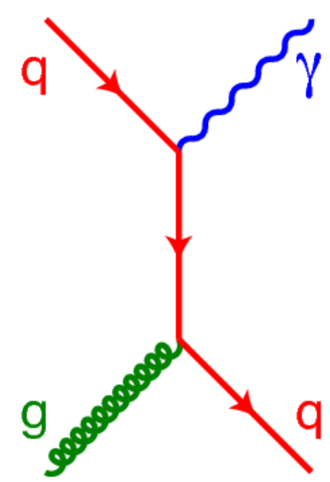
DIS (LO)



DIS (NLO)

**Gluons from NLO**/evolution
and/or $F_L$

**Photon production**
in hadronic collisions:
Sensitive to **gluons at LO**



direct-γ, Compton (LO)

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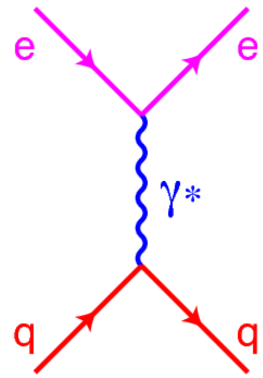


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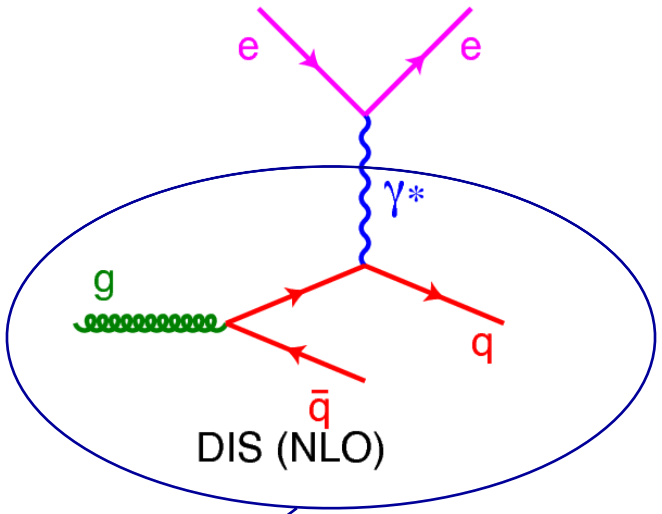


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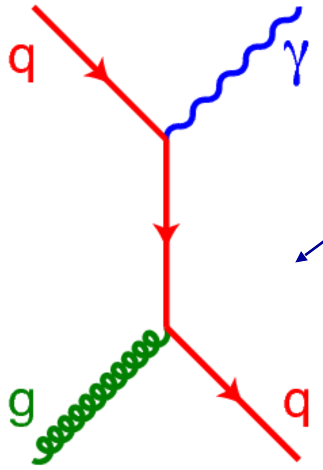
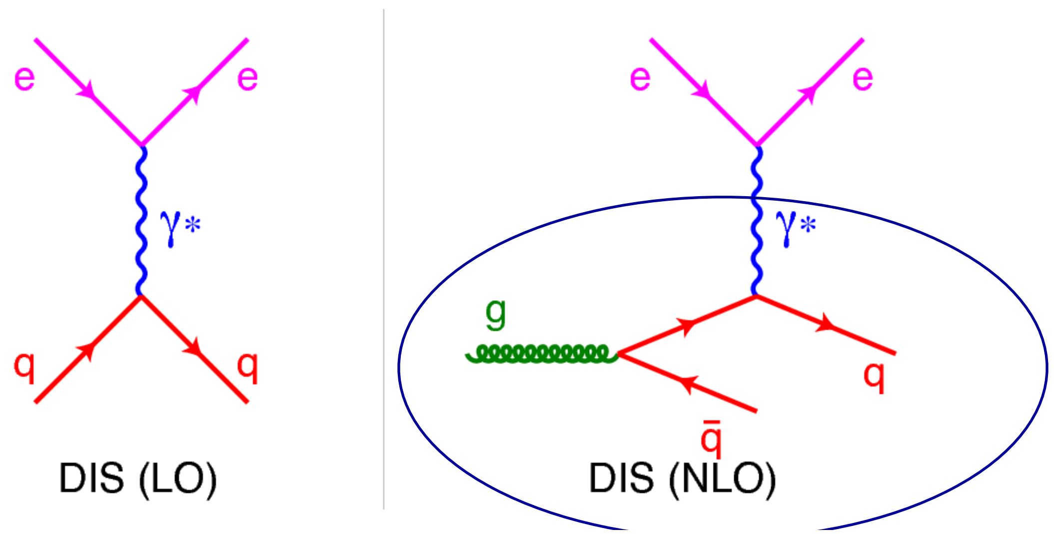



direct-γ, Compton (LO)

Directly related to DIS:
real instead of virtual photon

# How to probe the gluon density

**Deep-Inelastic Scattering** (DIS)
Classical PDF method
Not sensitive to gluons at LO

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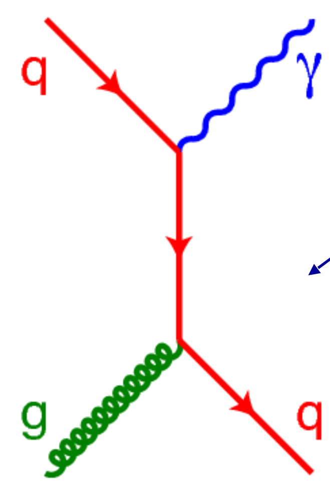
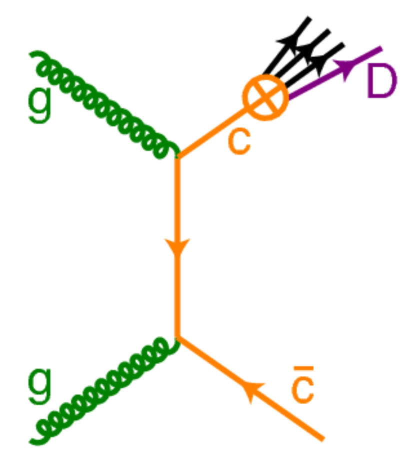
**Photon production**
in hadronic collisions:
Sensitive to **gluons at LO**




direct-γ, Compton (LO)

re




Heavy hadron:
tag hard scattering,
but includes fragmentation

# Accessing small x – Kinematics

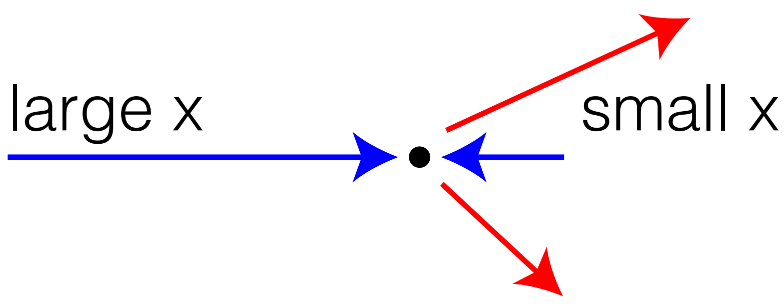
- for 2 → 2 process (LO on parton level):

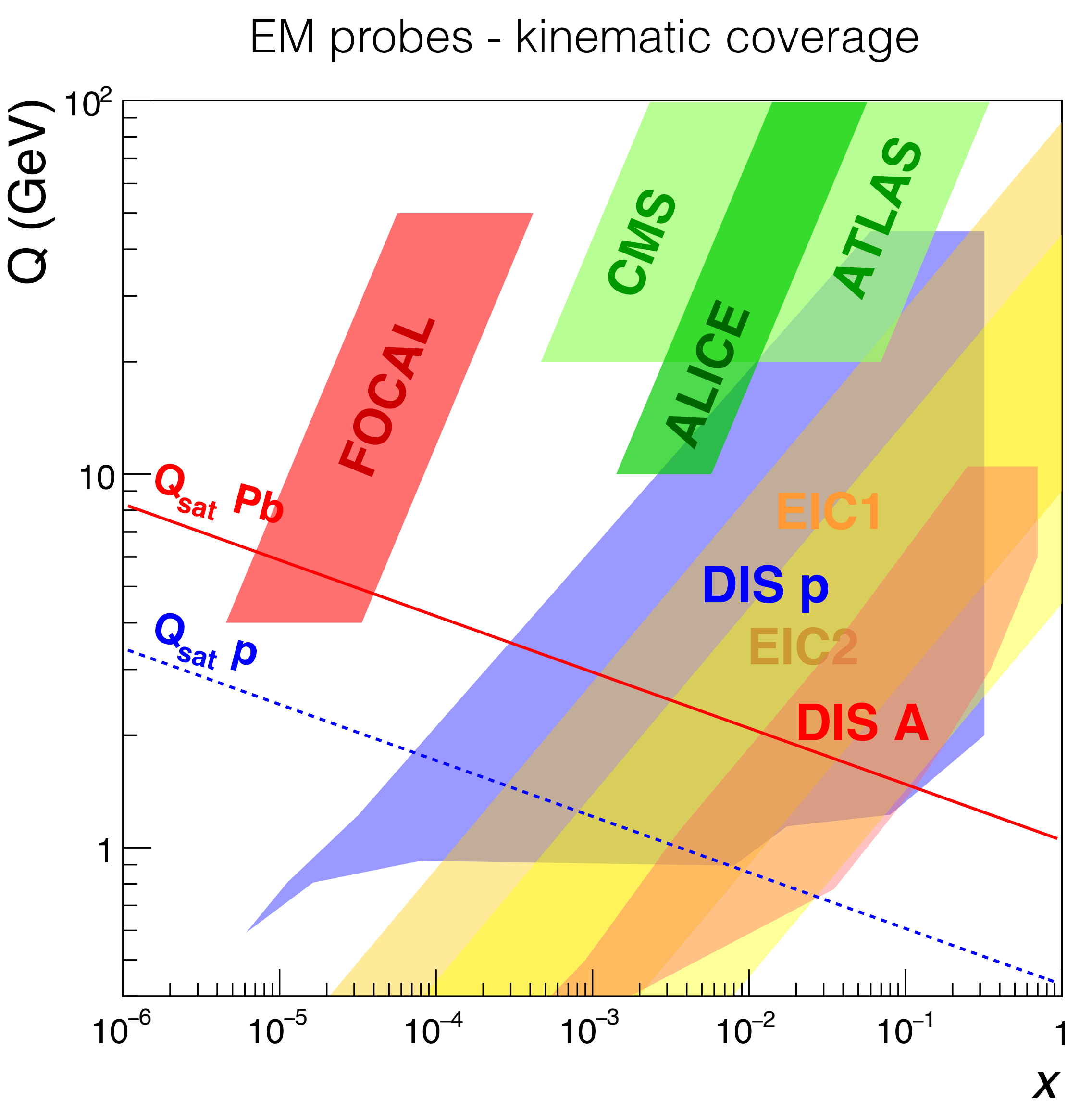
$$x_{1,2} = \frac{M}{\sqrt{s}} \exp\left(\pm\frac{y_3 + y_4}{2}\right)$$

  - forward rapidity selects small x
  - advantage for exclusive measurement
- for singles assume:

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

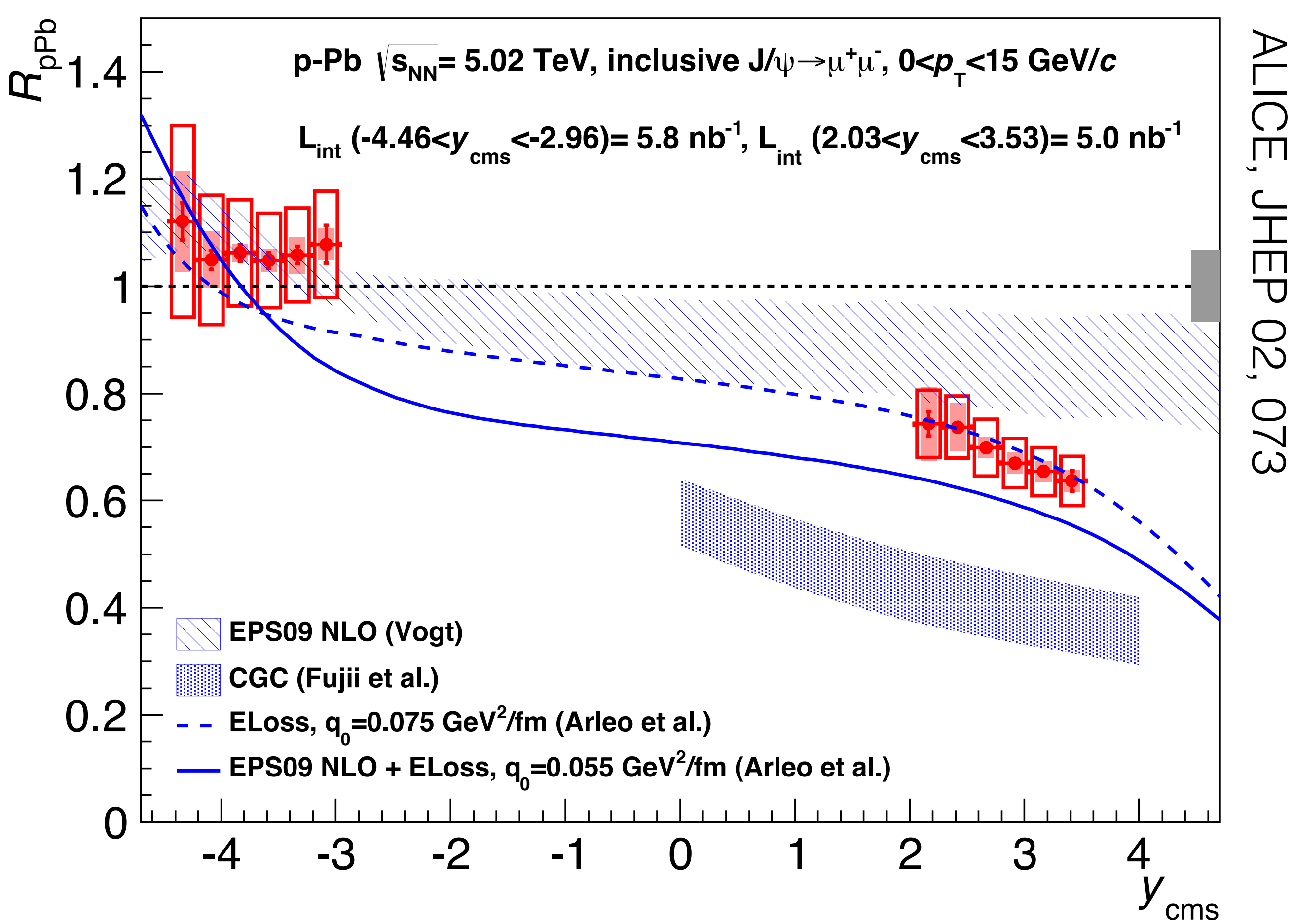
  - valid for jets (large $m_T$) and photons
  - for hadrons take fragmentation into account!
- further modification via higher order contributions
  - significant at LHC
- limited data so far!



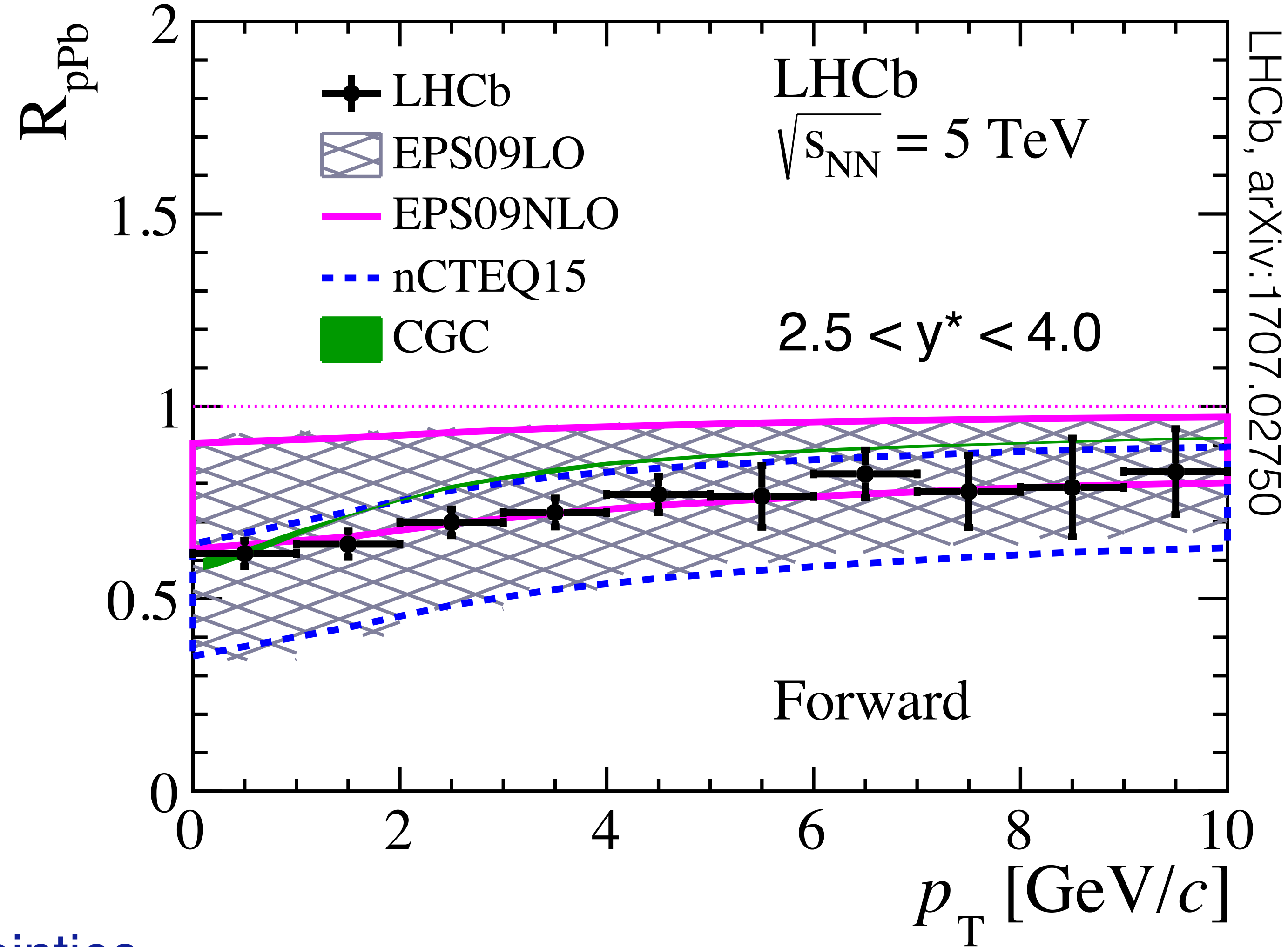



# Charm production at forward rapidity

## J/Ψ production




## Forward open charm production



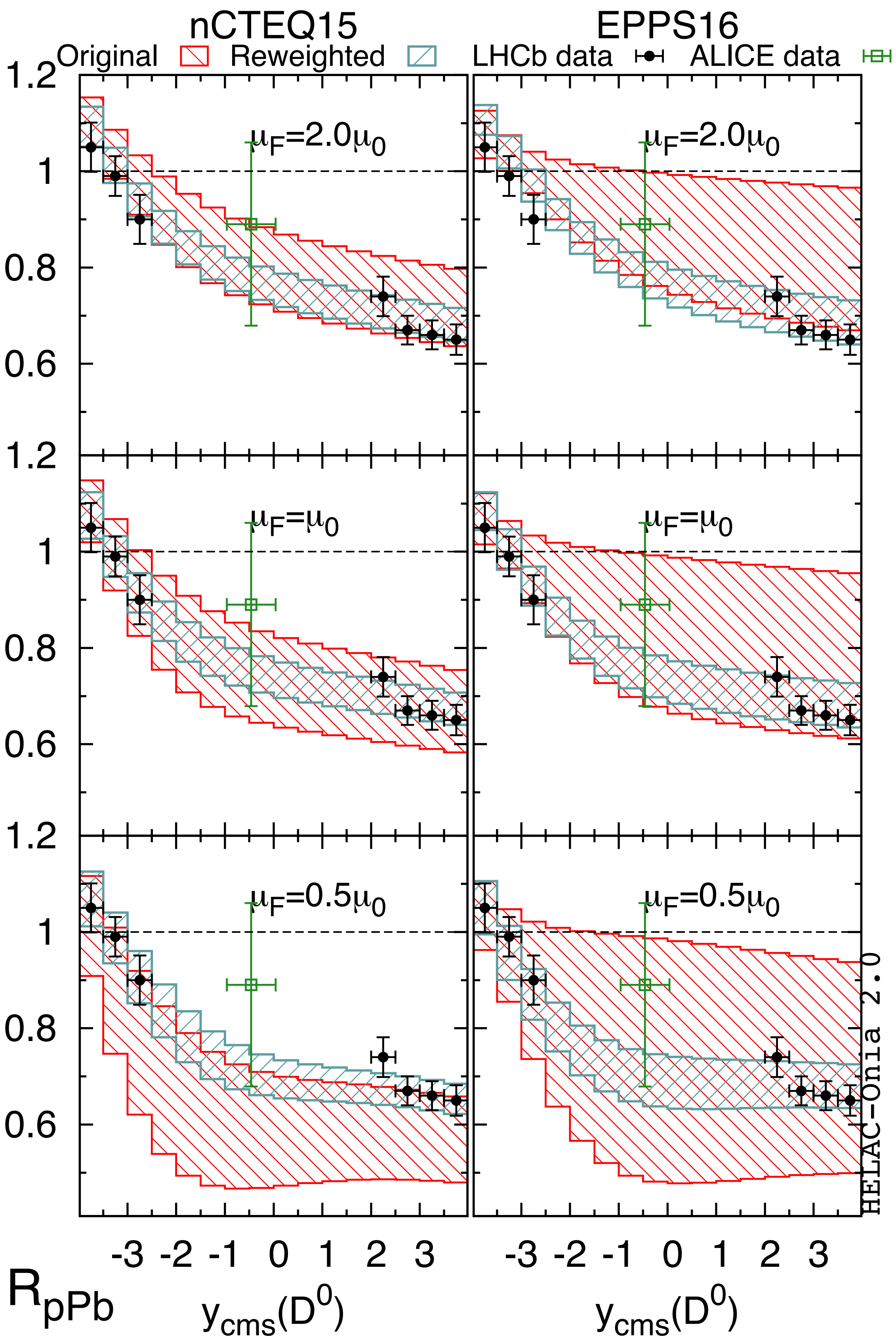

NB: J/Ψ has sizeable hadronisation+CNM uncertainties

Large suppression: $R_{pPb}$ 0.6-0.8 observed at forward rapidity

Consistent with 'shadowing' implemented in nPDFs; first data to constrain this?

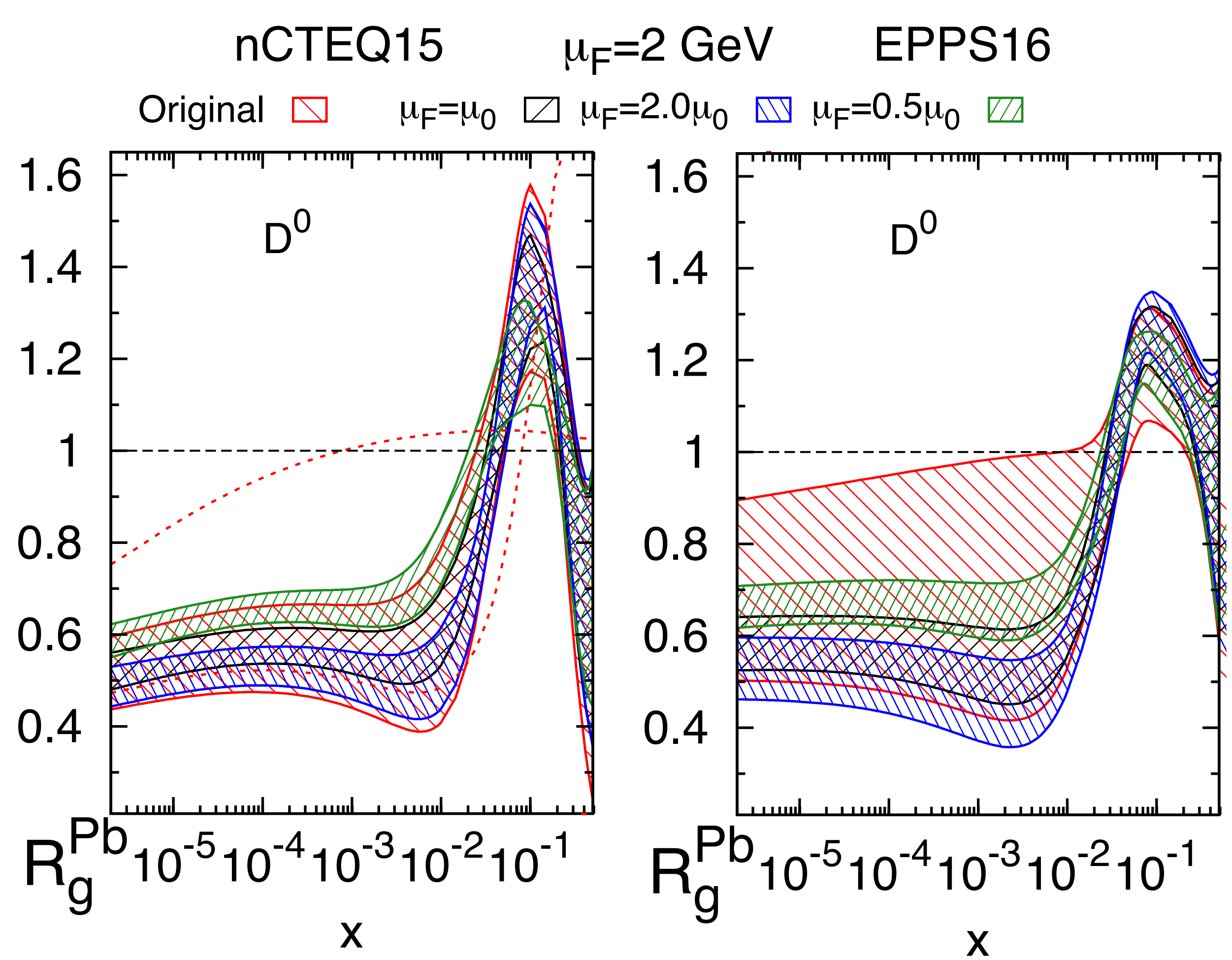
Kusina et al., arXiv:1712.07024

# Recent: 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)

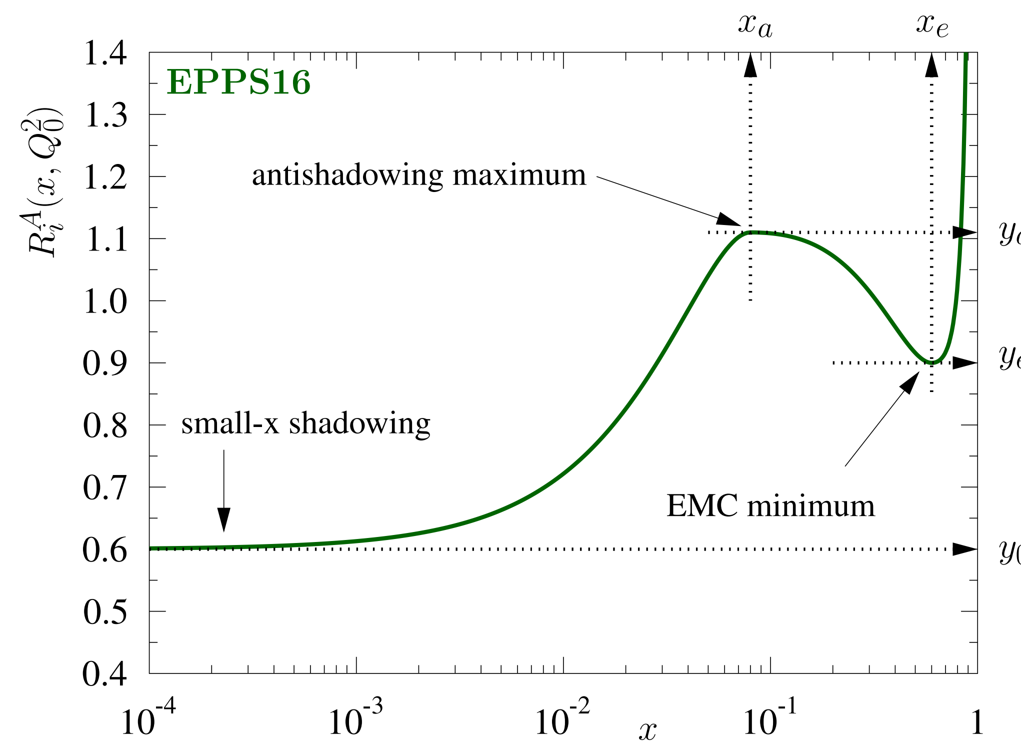
Fit predicts suppression at mid-rapidity; not observed



# x-Dependence of PDF modification

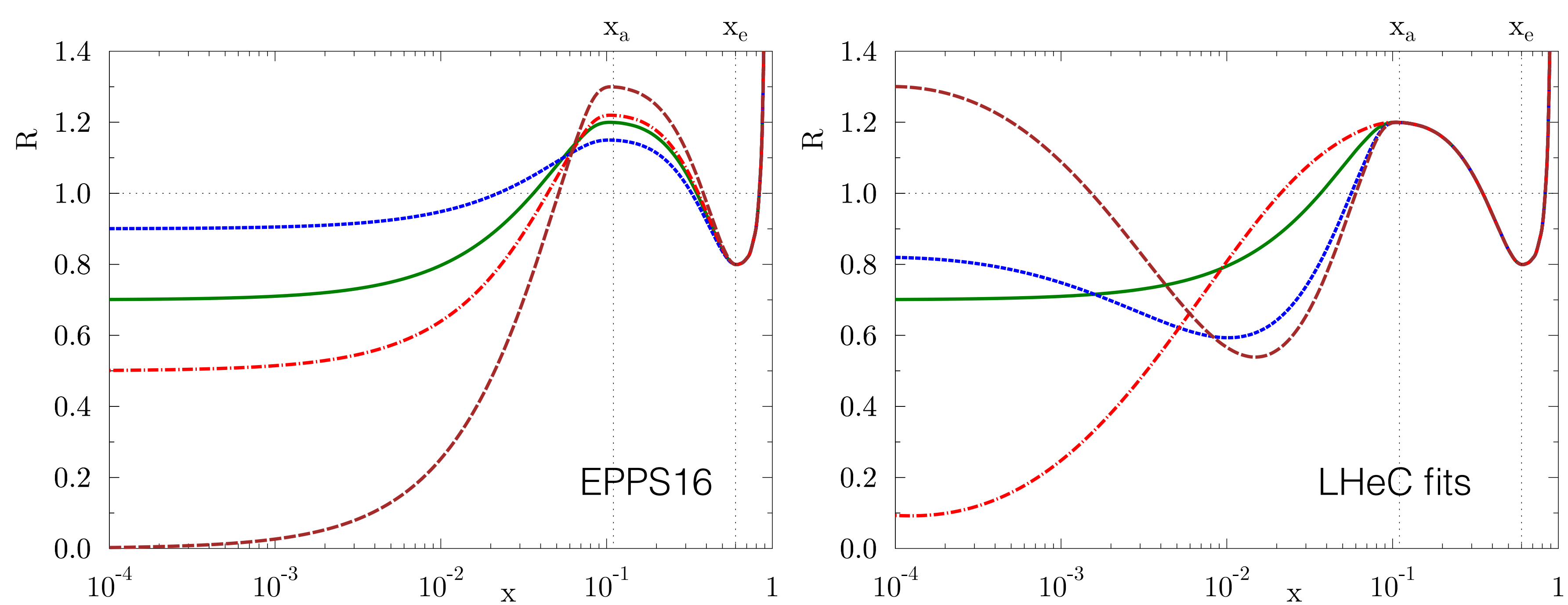
EPPS16, EPJC 77, 163

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



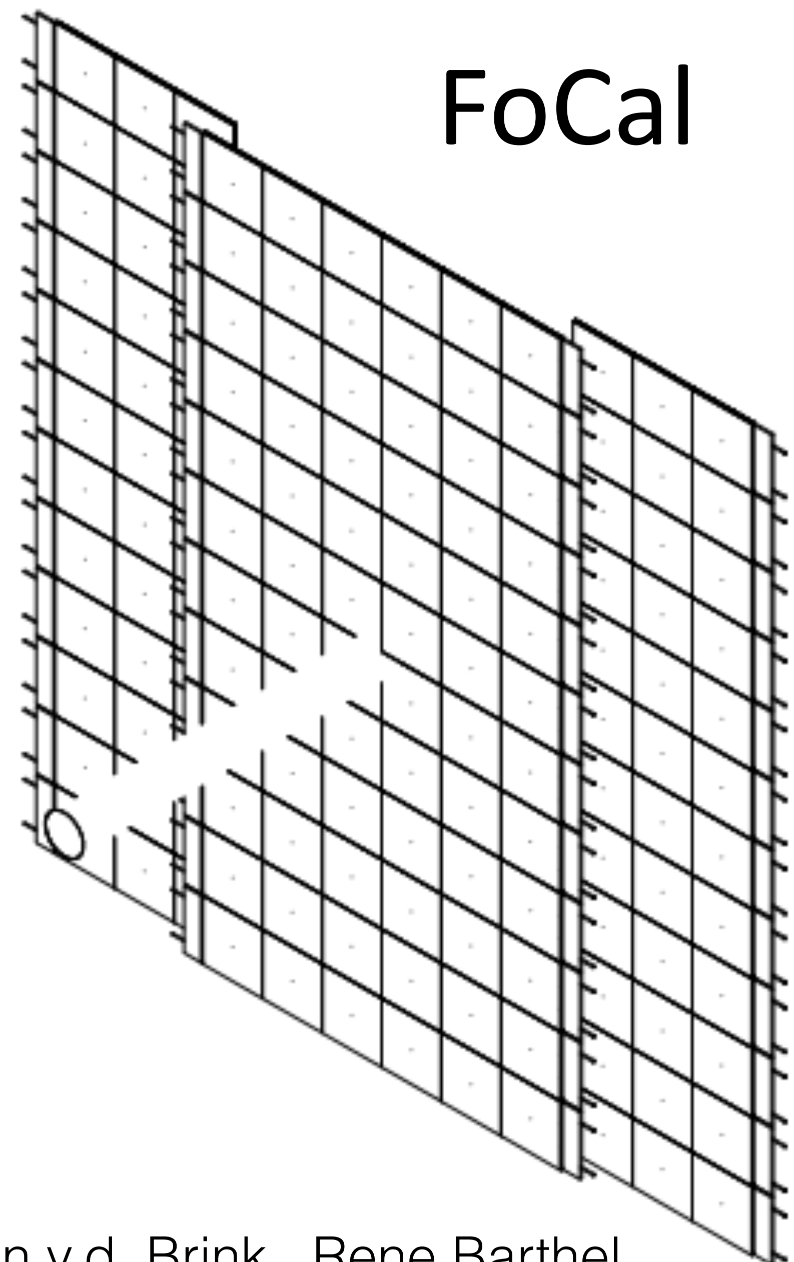

- parameterisation of $R_A$
  - shape similar to EPS09
  - at low $x$ leads to "plateau" in log($x$)

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



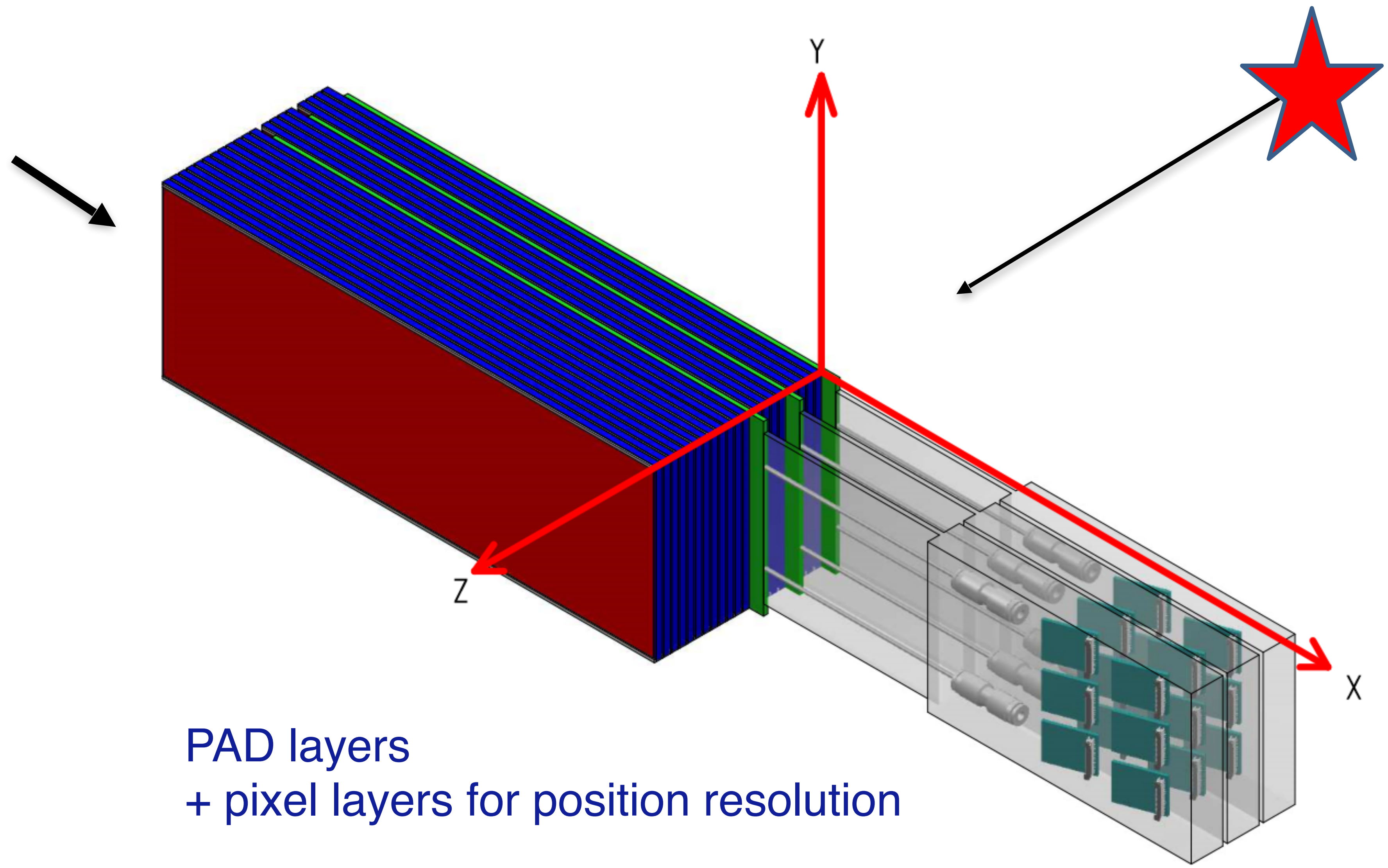

Helenius, Paukkunen, Armesto, arXiv:1606.09003

# FOCAL-E design concept




Ton v.d. Brink, Rene Barthel

FoCal module: ~24x8 cm




PAD layers
+ pixel layers for position resolution

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

Main open design question:
What is the minimal distance between layers?
Affects Moliere radius, position resolution

# Performance study: $\pi^0$ detection efficiency

Use $\pi^0$ reconstruction
to reject decay photons

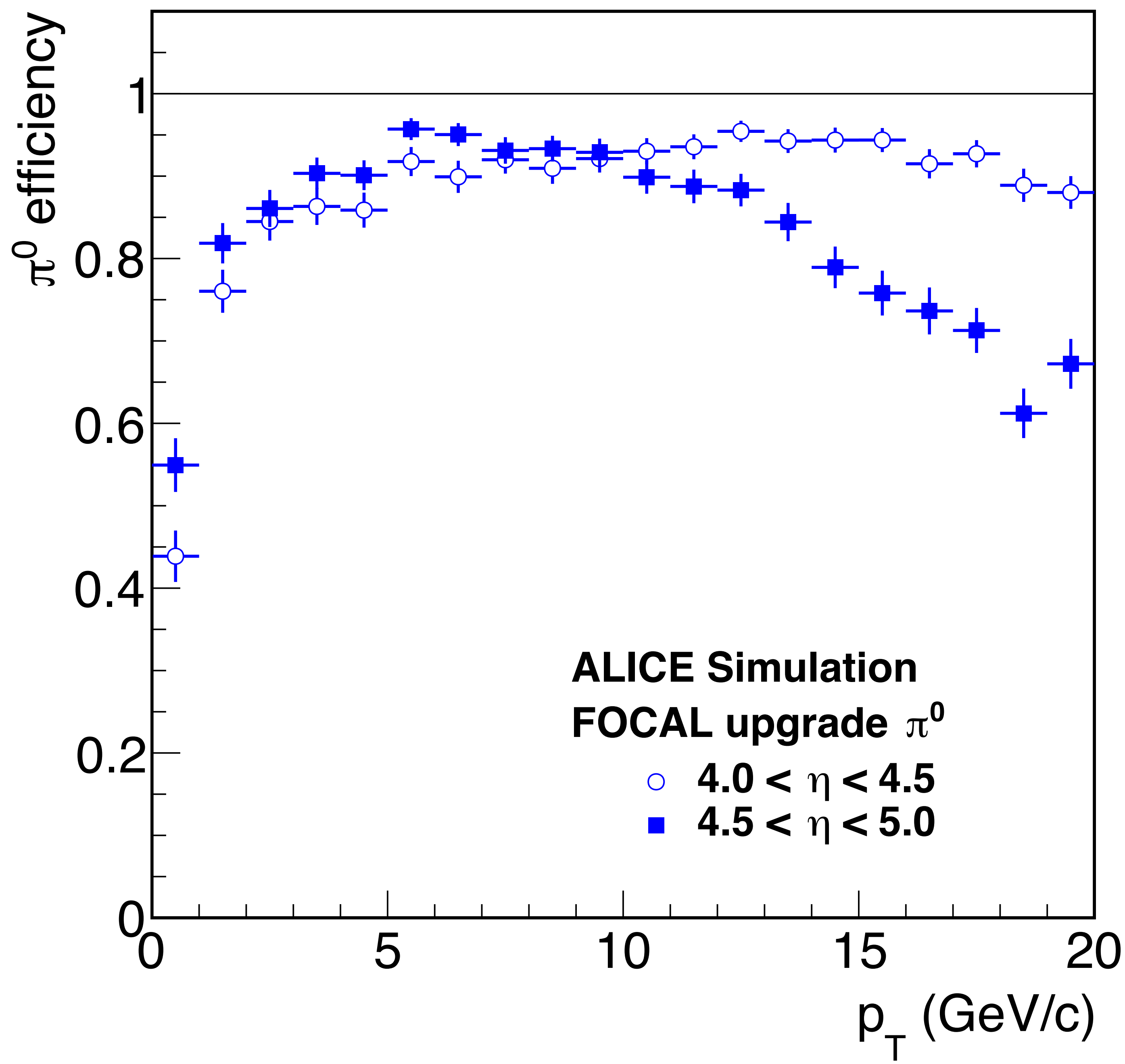
Relies on **two-shower separation with pixel layers**

**Very good efficiency > 90%**

$p_T$ ~ 2-18 GeV at $\eta$ = 4.0-4.5

NB: $\eta$ = 5, $p_T$ = 12 GeV ⇒ E = 900 GeV

Single $\pi^0$ with GEANT



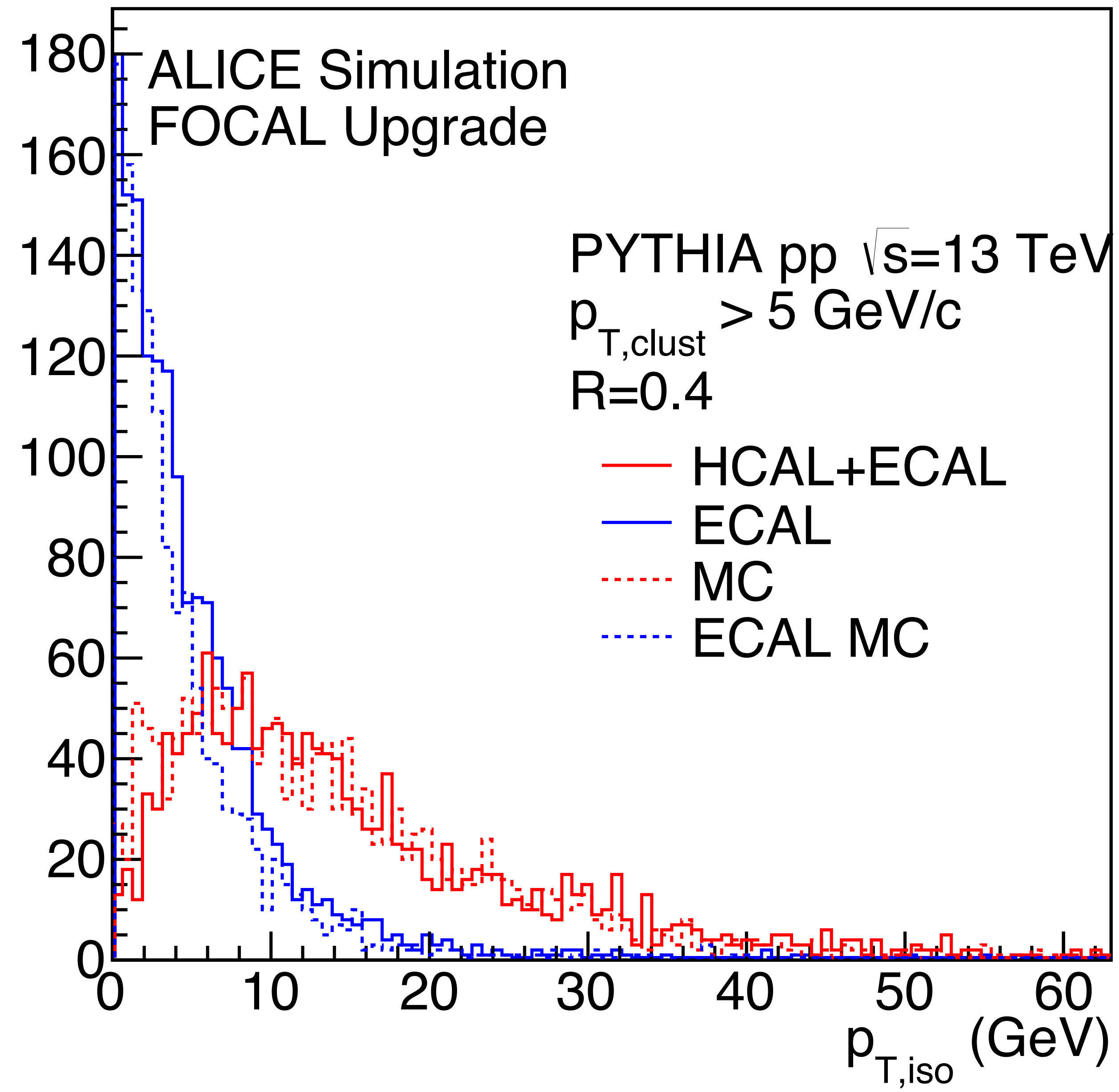

Covers the intended range for CGC measurements: low-intermediate $Q^2$

# $\gamma$ isolation: HCAL contribution

$\gamma$ isolation is an important handle for $\gamma$ identification

HCAL helps with isolation:
HCAL+ECAL energy peaks at 6 GeV instead of 0 GeV

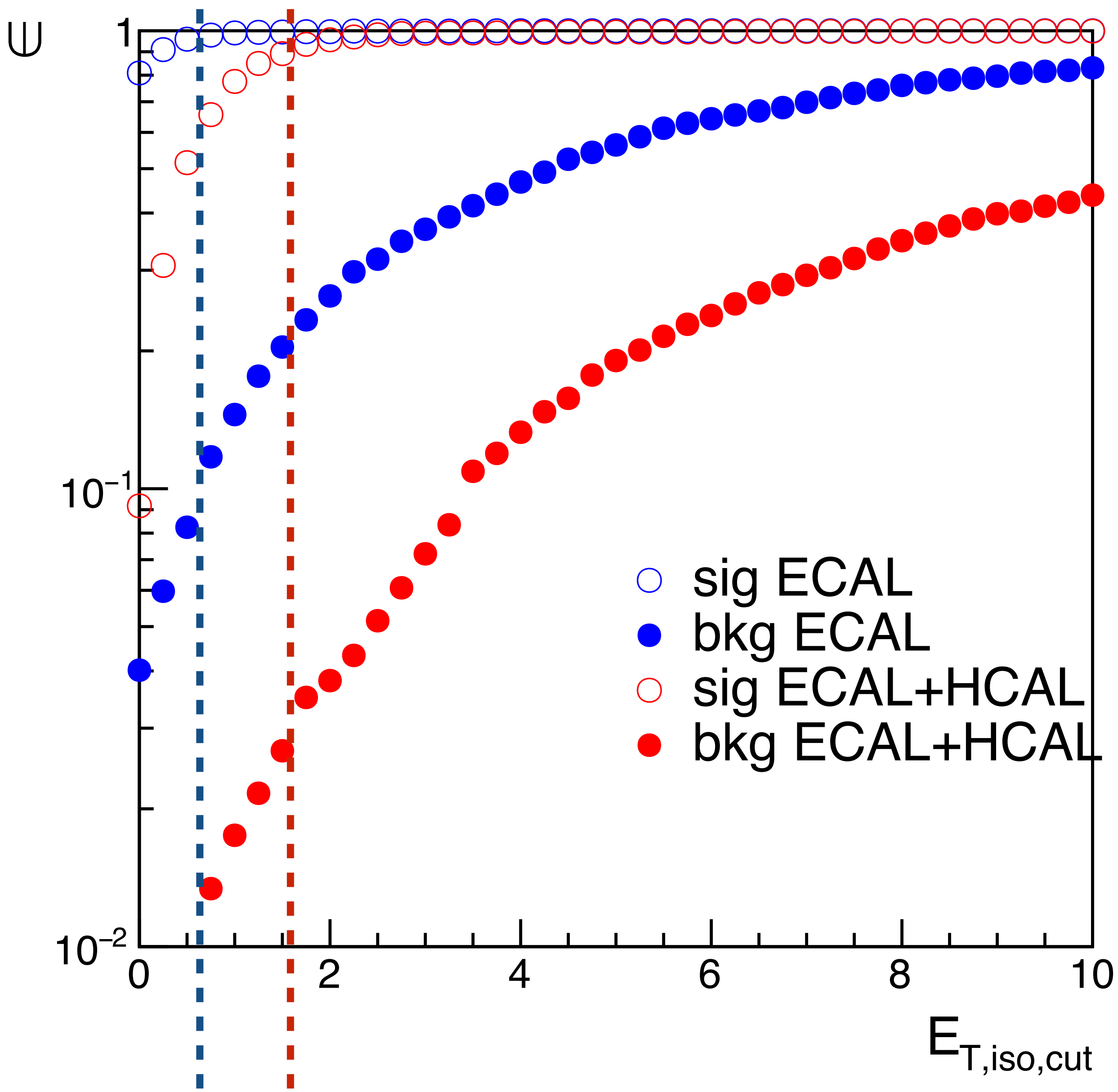
Isolation energy distribution




Full Pythia + GEANT
MC: particle level (dashed curves)

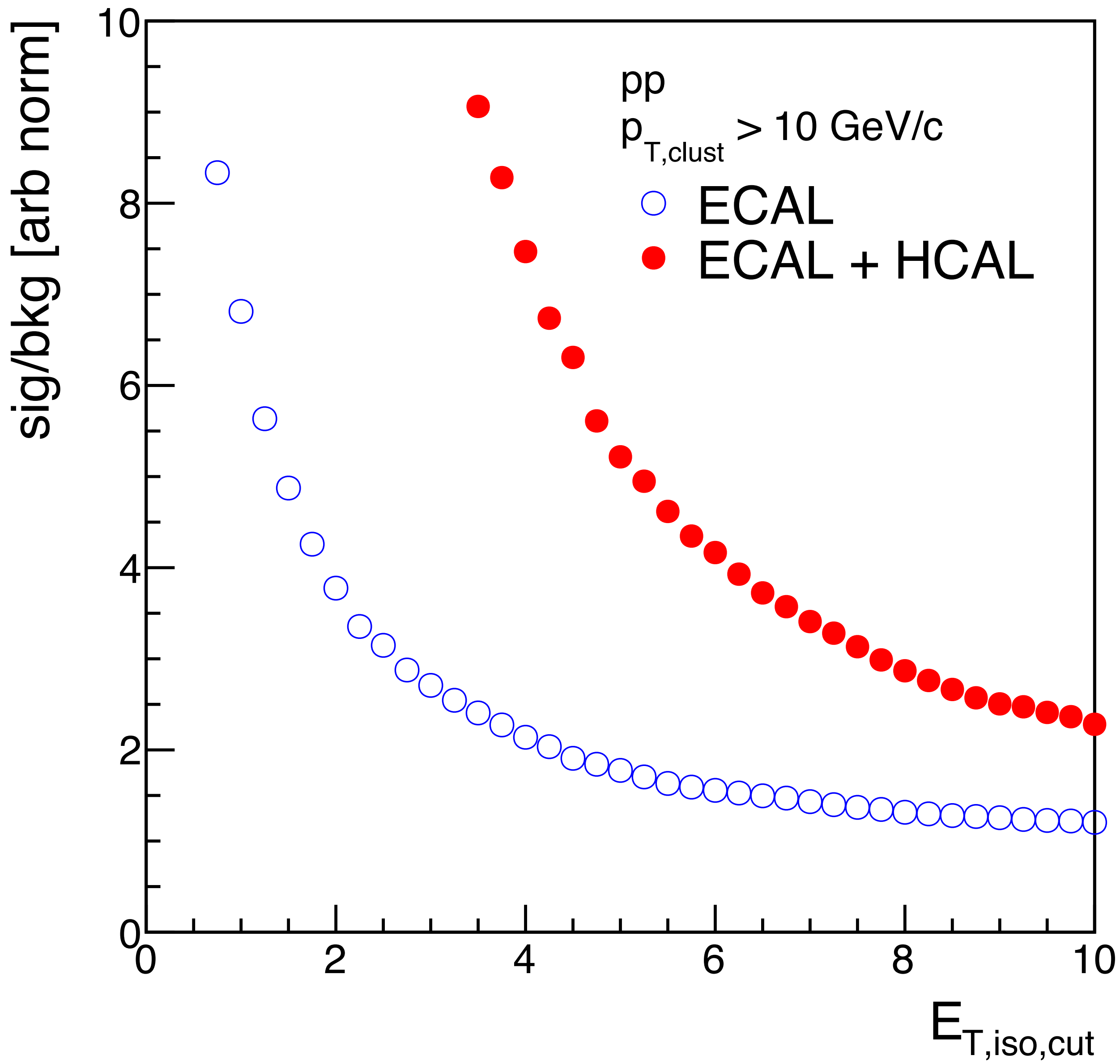
# $\gamma$ isolation: HCAL contribution

## Signal, background efficiency




HCAL: more signal; larger $E_{T,cut}$ for same efficiency

## Signal/background ratio



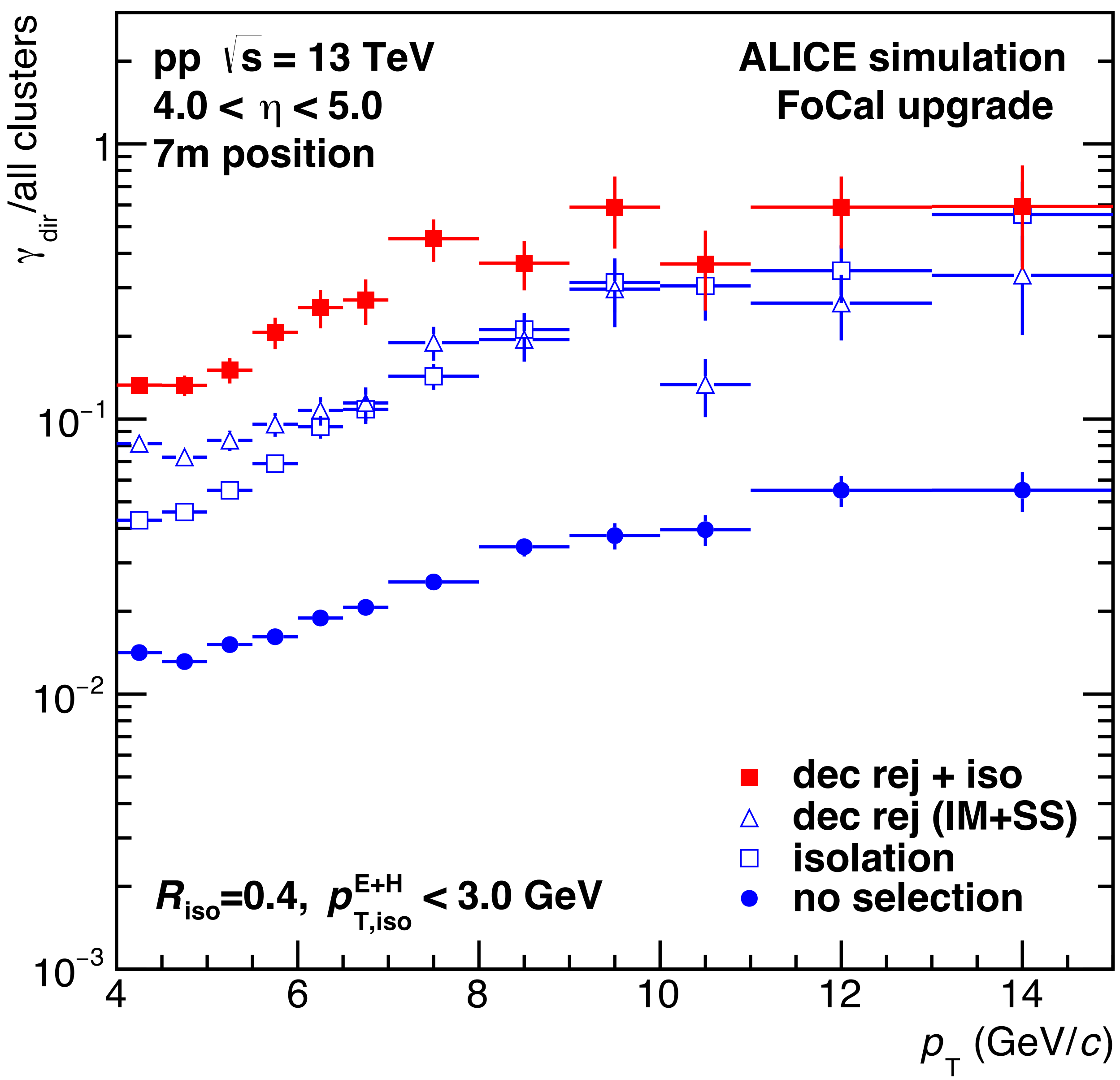

HCAL: signal/background improves by factor 5-10

# Direct/decay separation

Two main handles for direct gamma identification:

- Reject decays by invariant mass reconstruction
- Isolation cuts (EMCal + HCal)

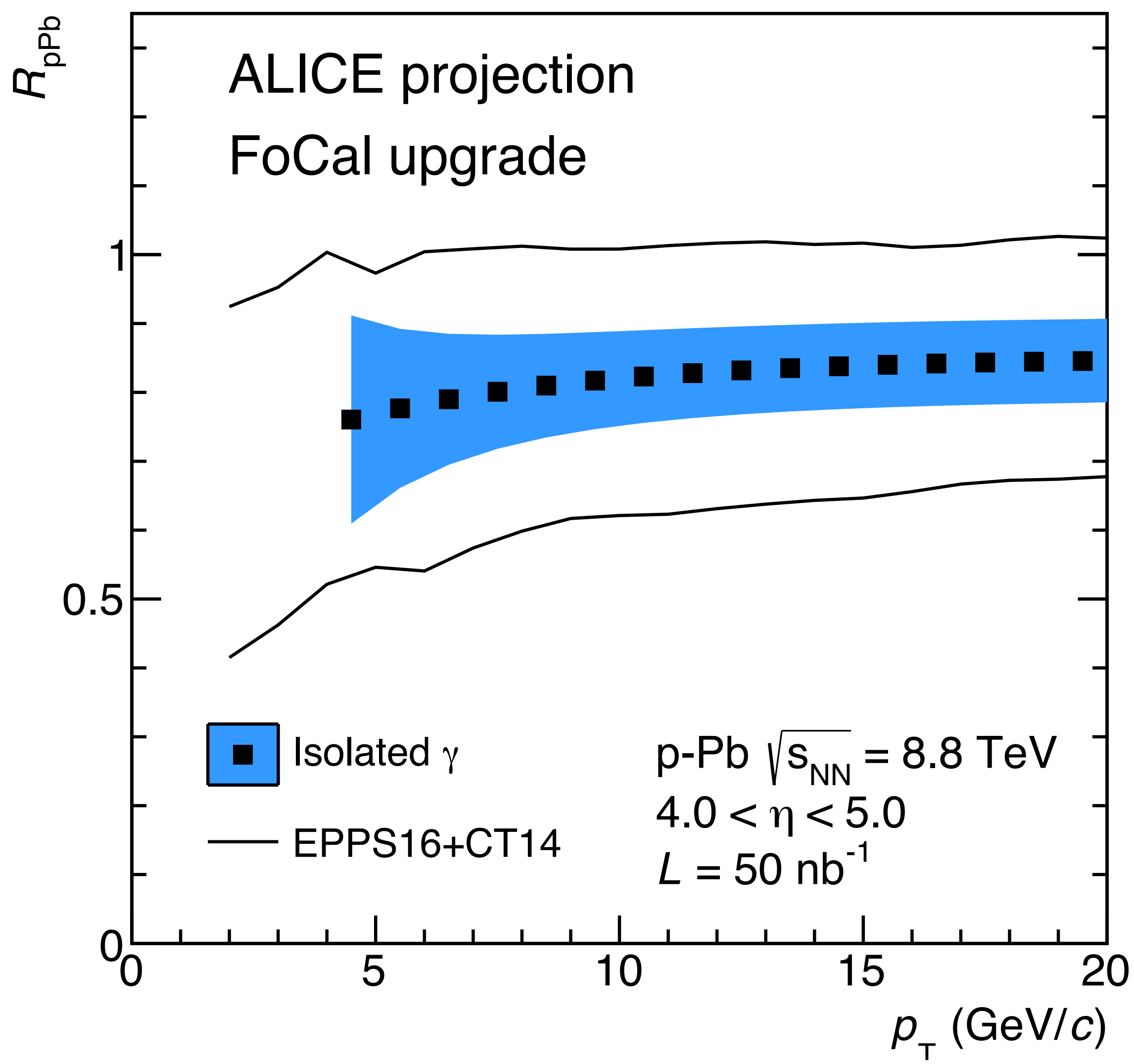
Direct $\gamma$/all cluster ratio

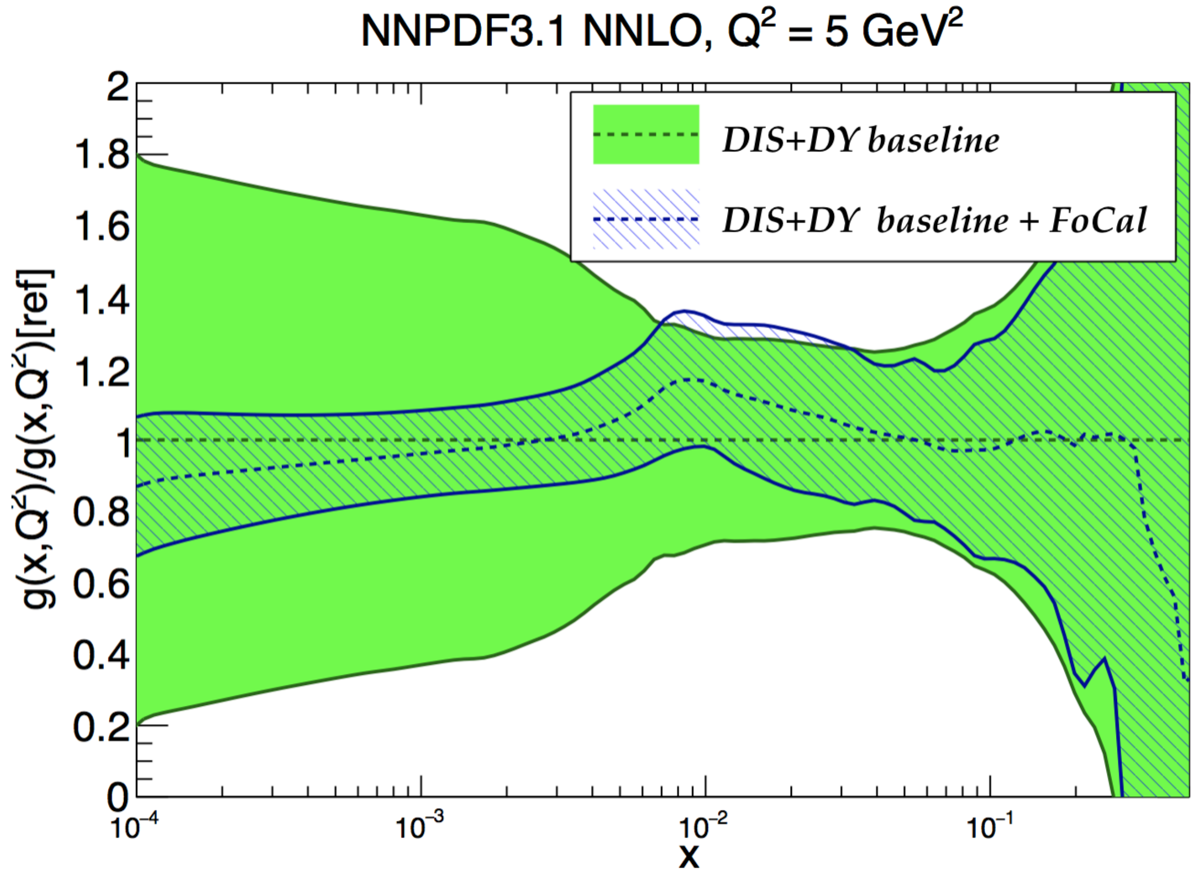



Improve signal fraction by factor ~10, from 0.01-0.06 to 0.1-0.6

# Impact of Forward Photons on nPDFs

Projection for $R_{pPb}$ of photons




uncertainty of nPDFs without/with FoCal

J. Rojo et al, arXiv 1610.09373,1706.00428,1802.03021

See also: I. Helenius, H. Paukkunen, arXiv 1406.1689

Uncertainties improve significantly

Still some discussion about quantifying the improvements:
choice of $\Delta\chi^2$, effect of DGLAP evolution, shape of parameterisation

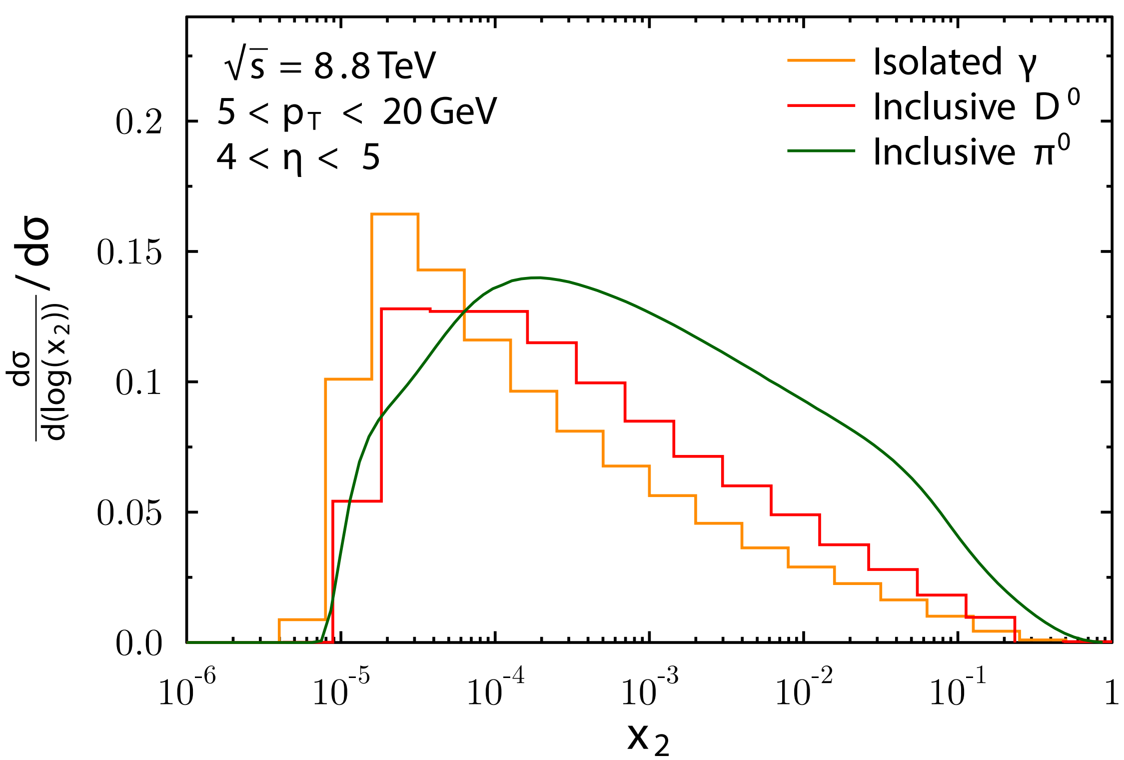
# x ranges sampled by different processes

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

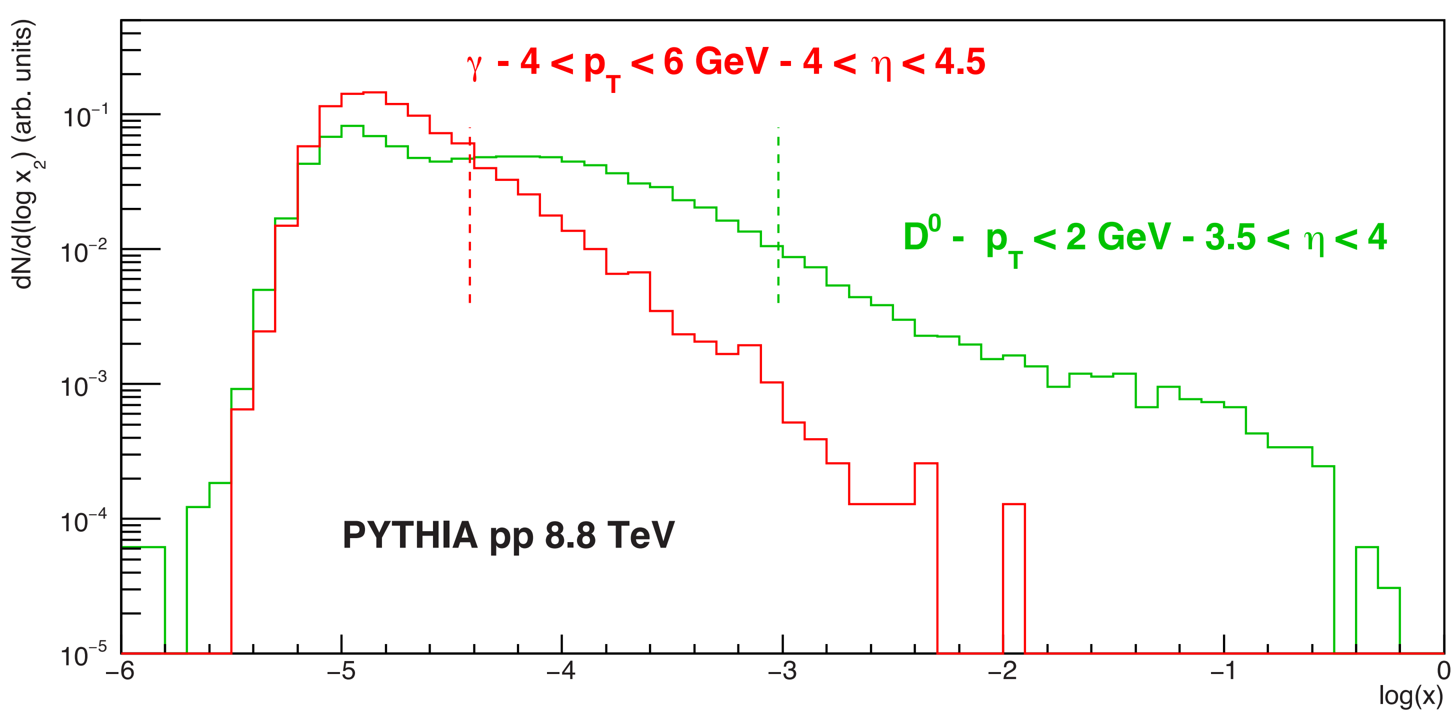
- LO kinematics estimates provide rather lower limit for $x_2$
- but: higher orders contribute significant tail towards large $x_2$

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

- *x*-distributions from NLO pQCD

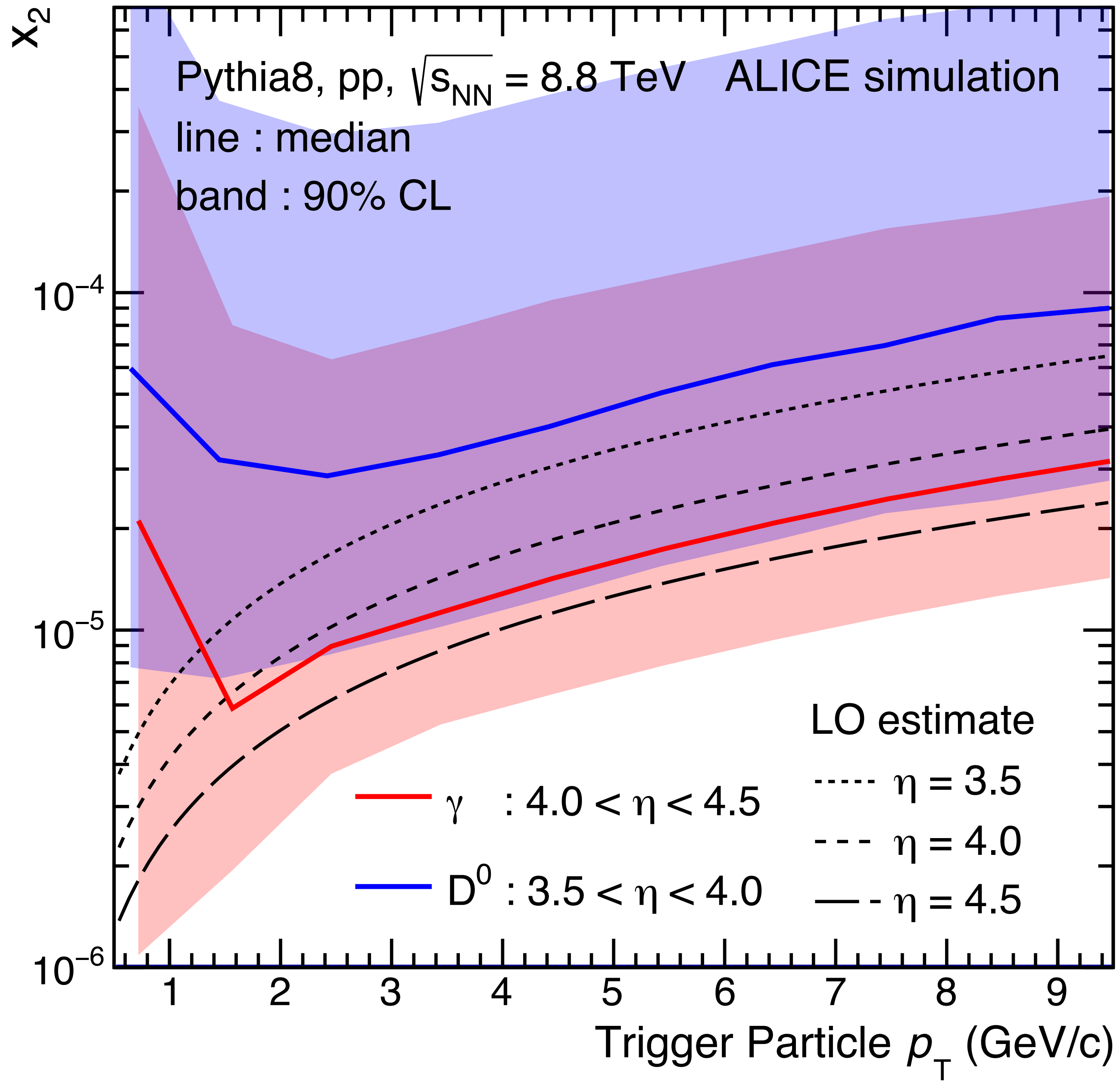



- *x*-distributions from PYTHIA




no analytical approximation, taking into account η of recoil parton

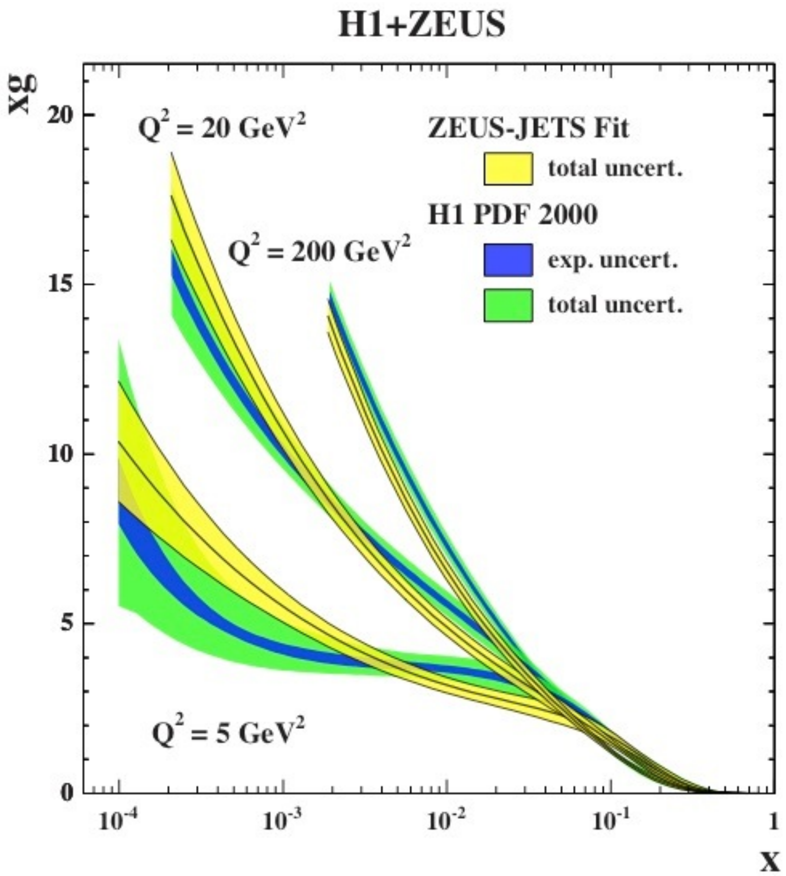
# Comparing x-reach for charm and photons




Median $x_2$, spread lower for direct gamma in FOCAL acceptance than for D in LHCb

- No final state effects expected for photons
- Measurements are complementary; test universality

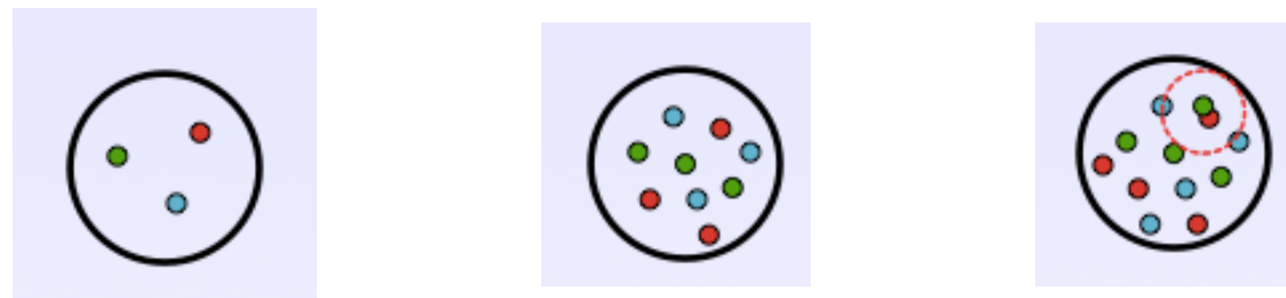
# Gluon saturation at low x: non-linear evolution




From DIS, HERA:
Gluon density increases rapidly at low *x*

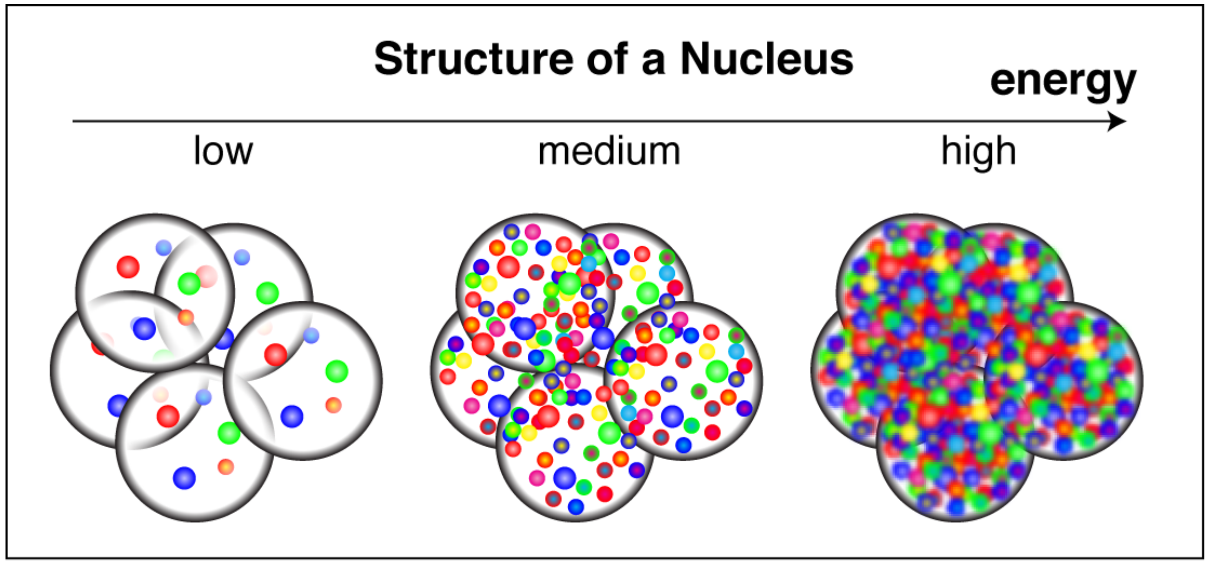
**Something must 'tame' the gluons at low *x***

## Saturation: gluons start to overlap/recombine



high x: valence

low x: many gluons



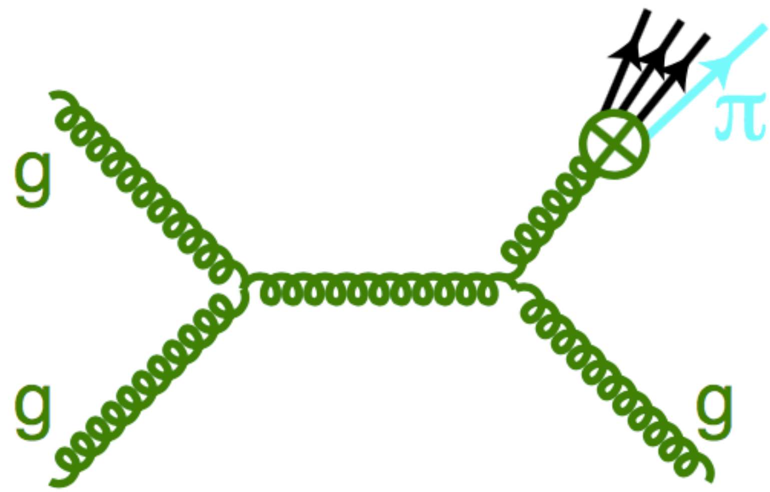

**Saturation criterion** **[Gribov, Levin, Ryskin (1983)]**

$$\underbrace{\alpha_s Q^{-2}}_{\sigma_{gg\to g}} \times \underbrace{A^{-2/3} xG(x,Q^2)}_{\text{surface density}} \geq 1$$

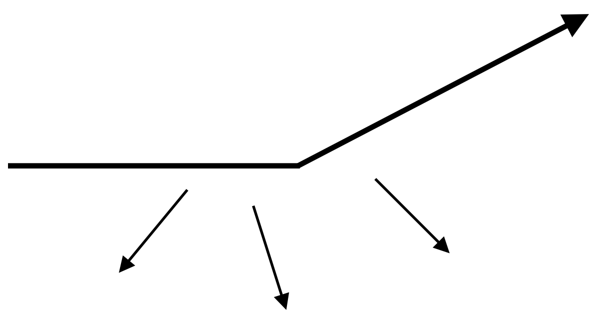
$$Q^2 \leq \underbrace{Q_s^2 \equiv \frac{\alpha_s xG(x,Q_s^2)}{A^{2/3}}}_{\text{saturation momentum}} \sim A^{1/3} x^{-0.3}$$

# Two-particle correlations

QCD 2 → 2 scattering




CGC: recoil taken by multiple gluons

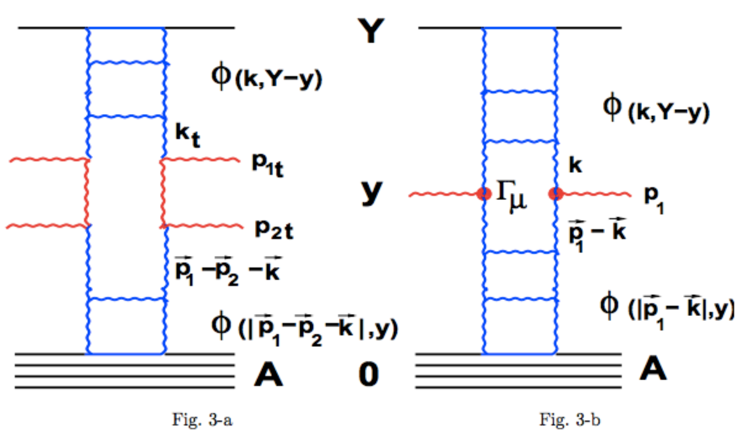



Produces a back-to-back jet

Measure rapidity of the away-side jet
to constrain $x$ further

$\gamma$-hadron correlations?

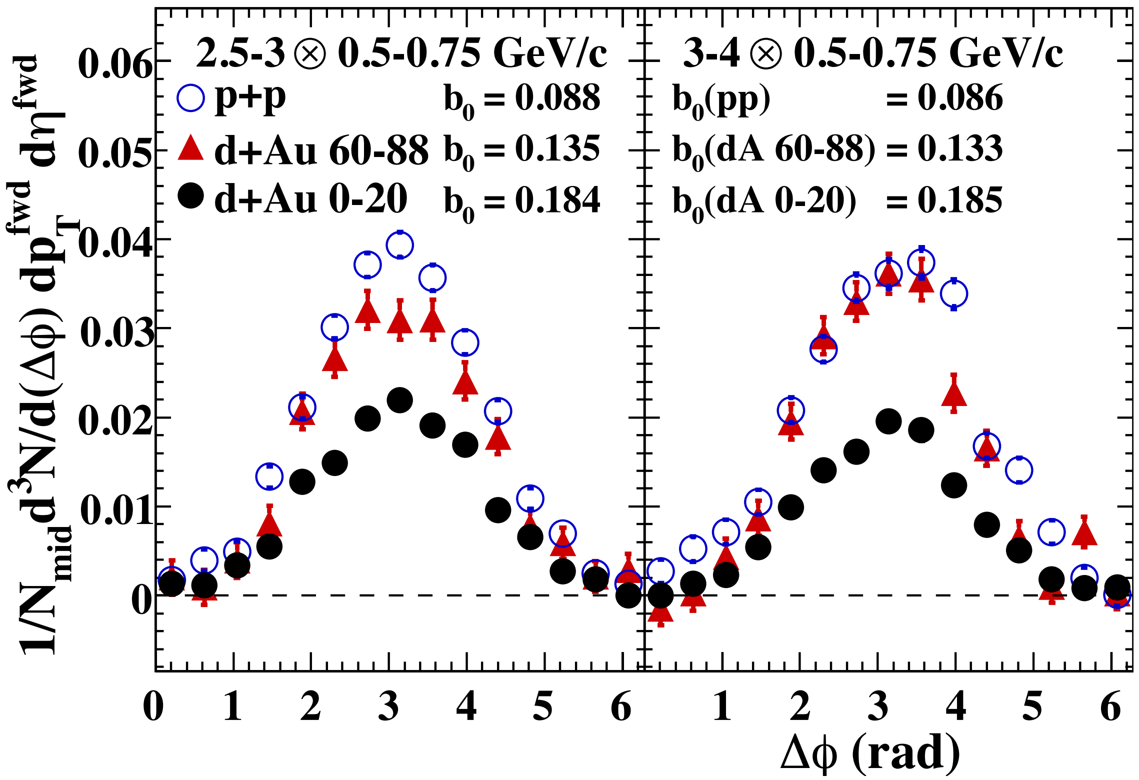
Recoil jet broadened/disappears



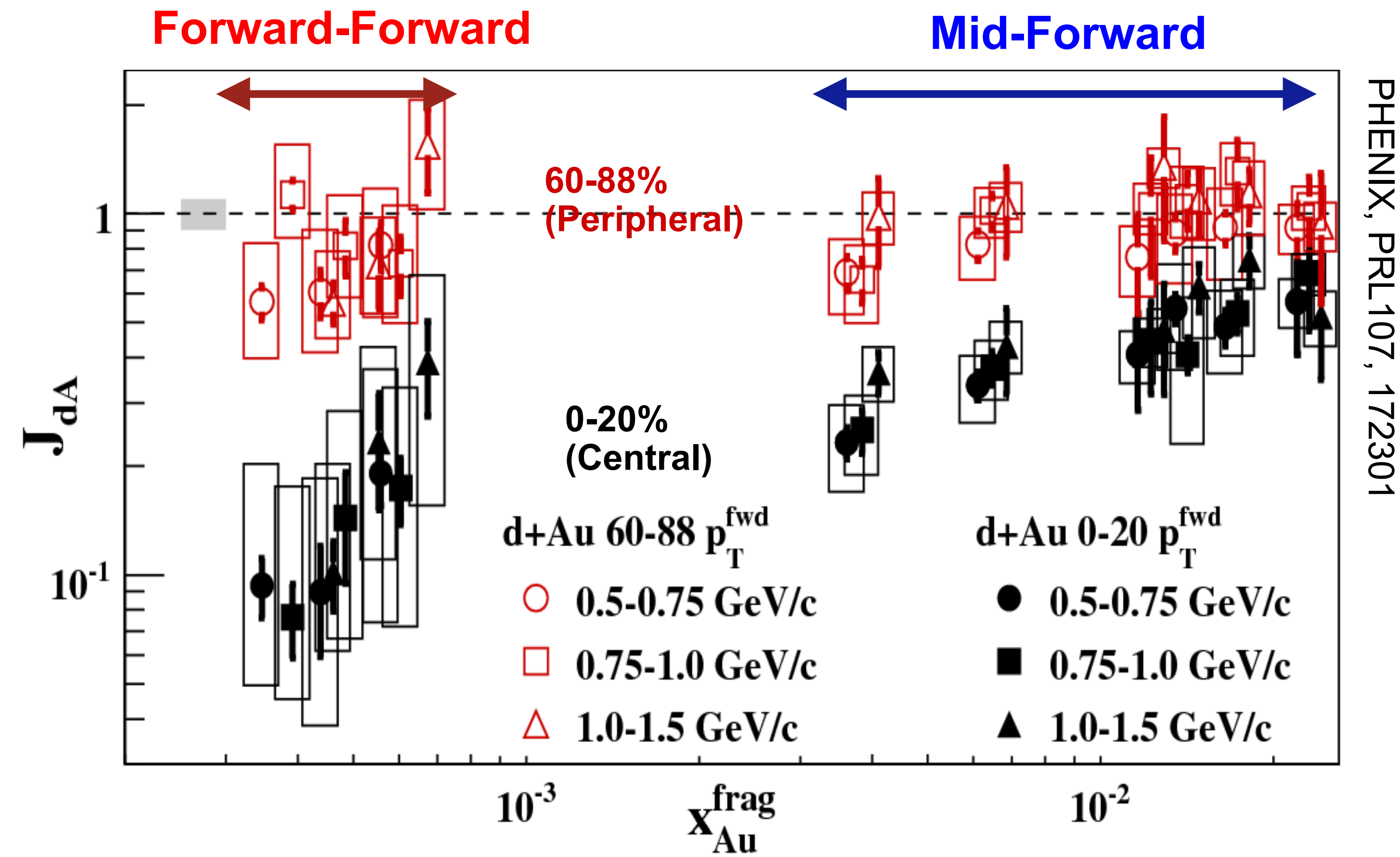

Kharzeev et al, hep-ph/0403271

# Di-hadron correlations at RHIC II

$\pi^0$-$\pi^0$ mid - forward




$|\eta| < 0.35$ and $3.0 < \eta < 3.8$




Scan '*x*' with $p_{T1}$ and forward, mid rapidity

More systematic study shows similar effects, trends as a function of *x*

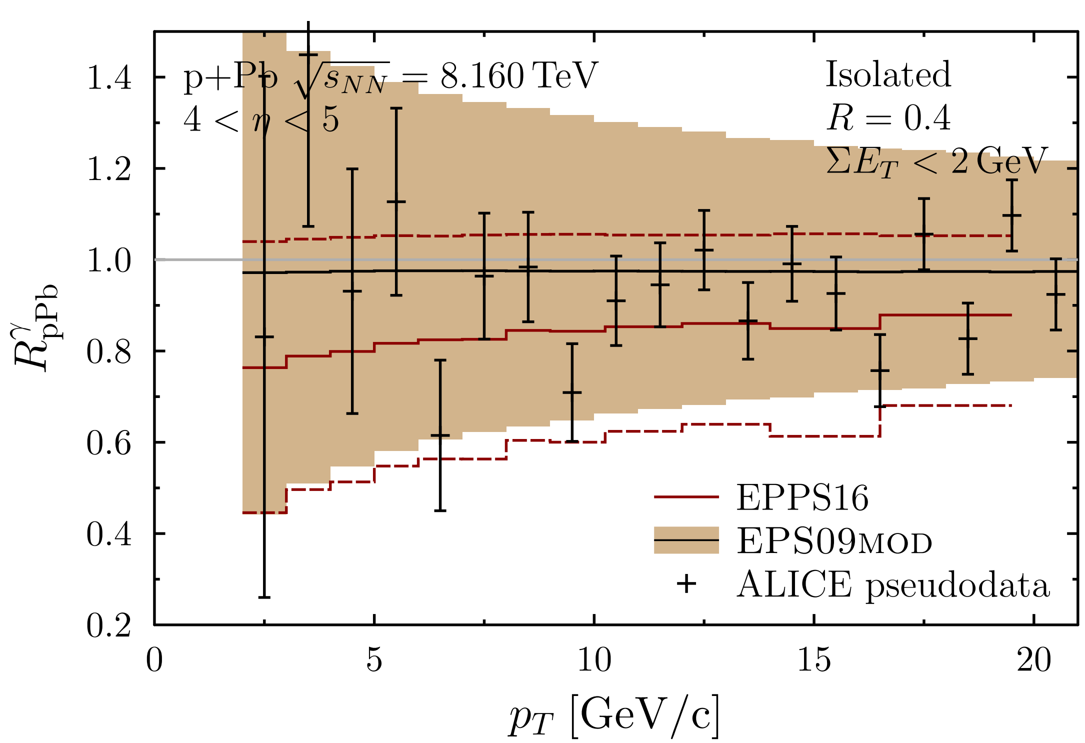
Large suppression at '*x*' < $10^{-3}$ in central events

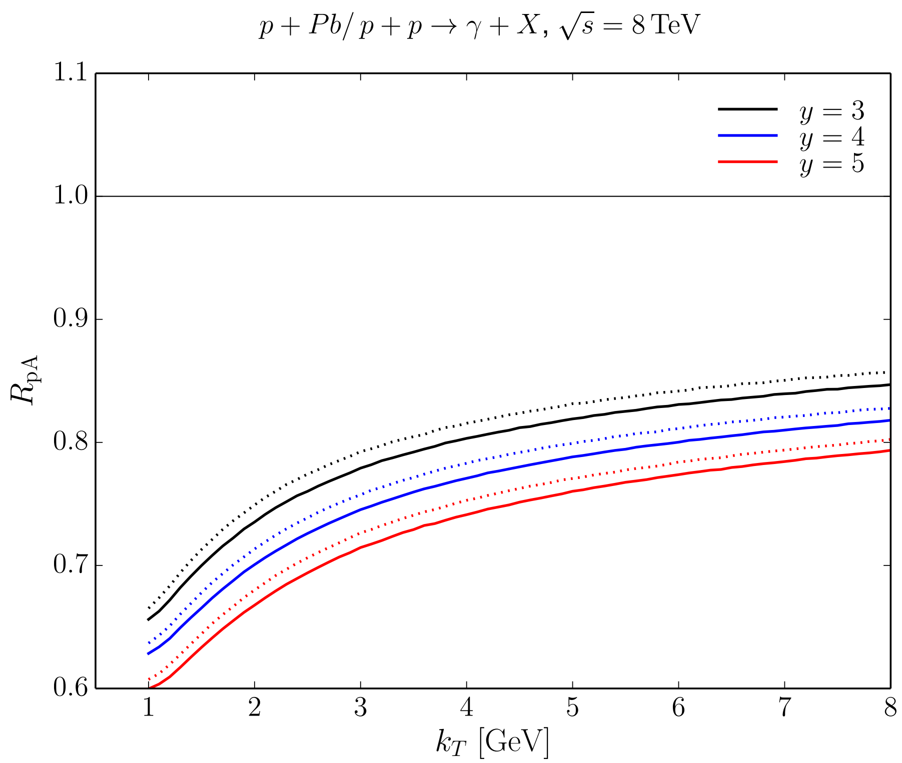
Similar measurements foreseen with FOCAL at LHC: larger dynamic range

# 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?)

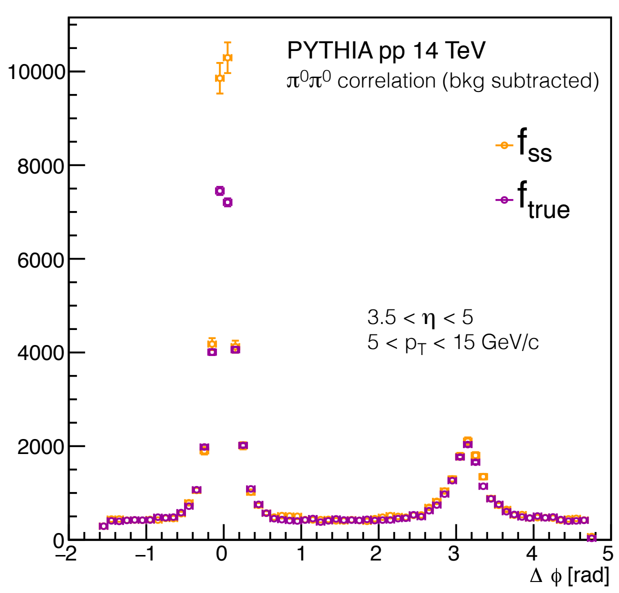


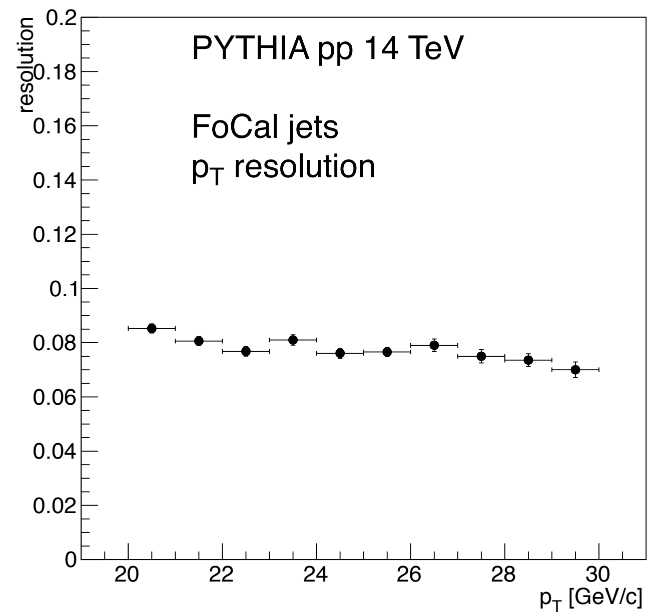




**CGC Calculation:** Ducloué, Lappi, Mäntysaari, arXiv:1210.02206

# Other FOCAL Physics Topics: Overview

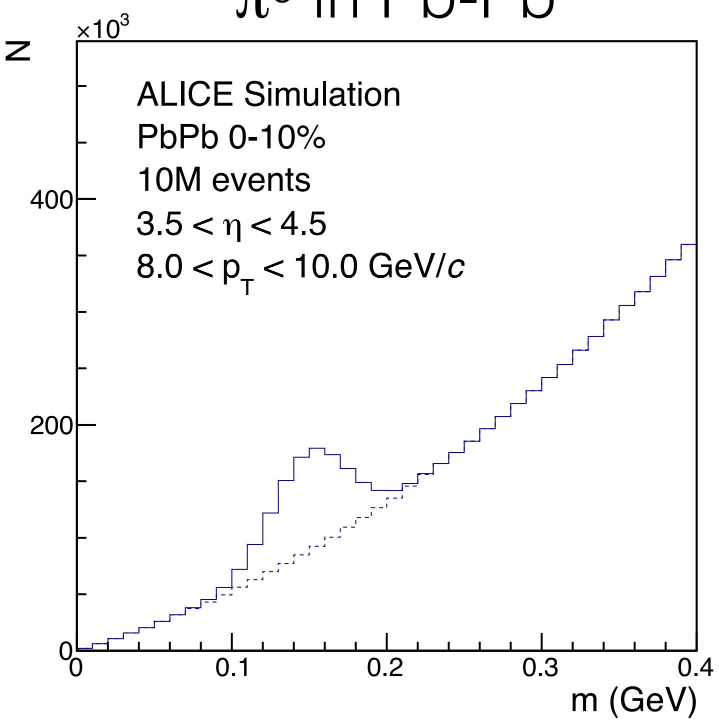
Tomoko Sakamoto, Toma Suzuki




- low-x gluons (n)PDFs, saturation
  - pion and 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

$\pi^0$ in Pb-Pb



# A tentative schedule

| 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Work out conceptual design | Finalise design | | Production | Calibration in test beam | Installation |
| LoI | TDR | | | | |

Need to make concrete steps/decisions this year to have a final design by end of 2020

In parallel: understand needed/available resources

First draft of TDR by end of 2019?

Thank you for listening!

# Topics under discussion

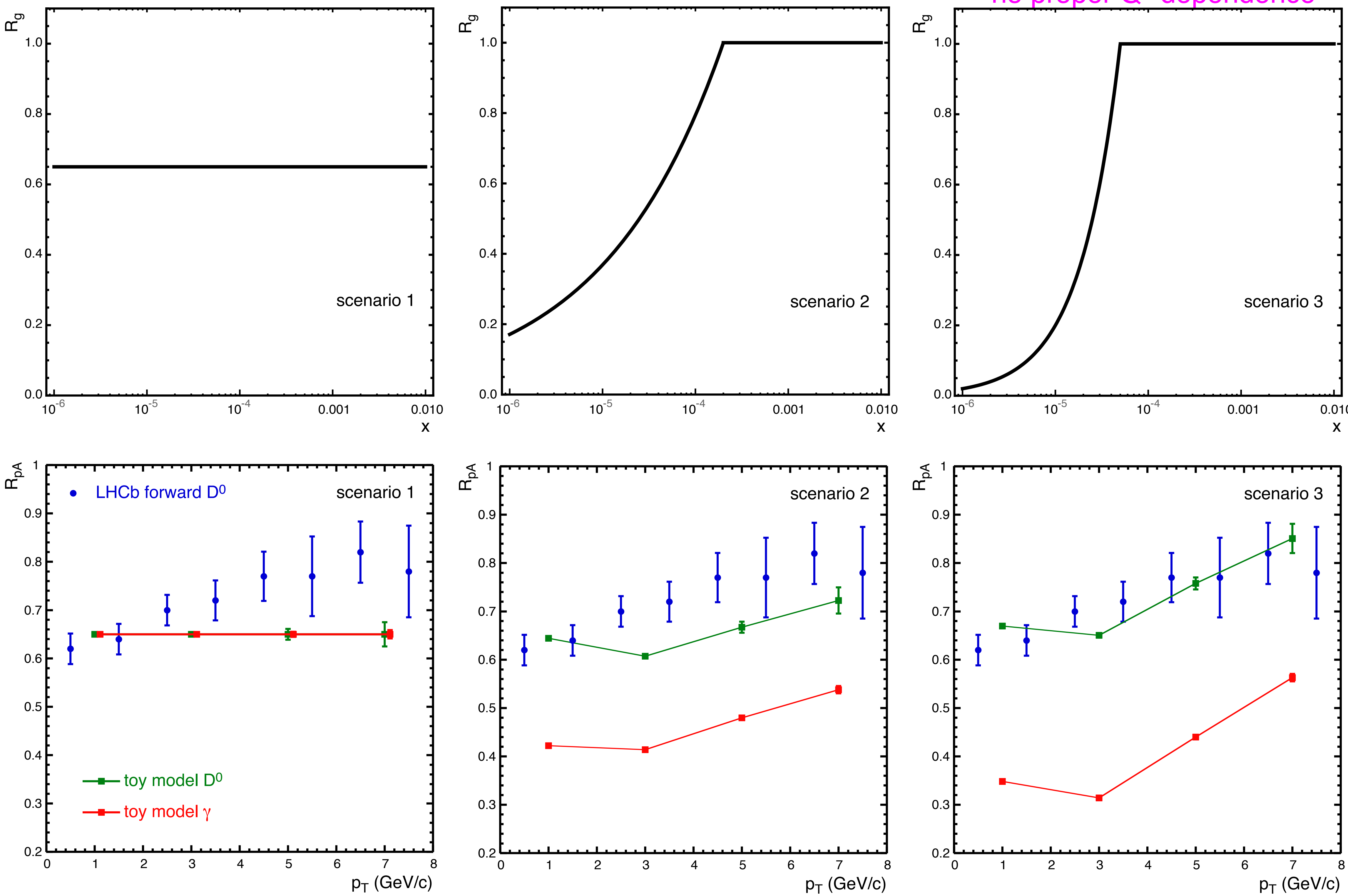
See also recent meeting at CERN: https://indico.cern.ch/event/782776/

- PAD layers
  - Key point: selection of digitisation ASIC
    - Long lead time, in particular if we need/want a development step
  - Implications for cooling, layout, etc
- PIXEL layers
  - ALPIDE is the main technology; verify high-occupancy use
- Integration/mechanical design
  - Key point: distance between W layers; Molière radius
  - Electronics in layer or outside sensitive volume
- Trigger/readout
  - Synchronisation between PAD and PIXEL
  - Data rates/readout infrastructure
- HCAL
  - Start exploring options — make conceptual design
- Integration in ALICE
  - FIT and FOCAL: clear overlap in phase space; integrate functionality?

# Influence of x Dependence

parameterise nuclear modification of gluon PDFs

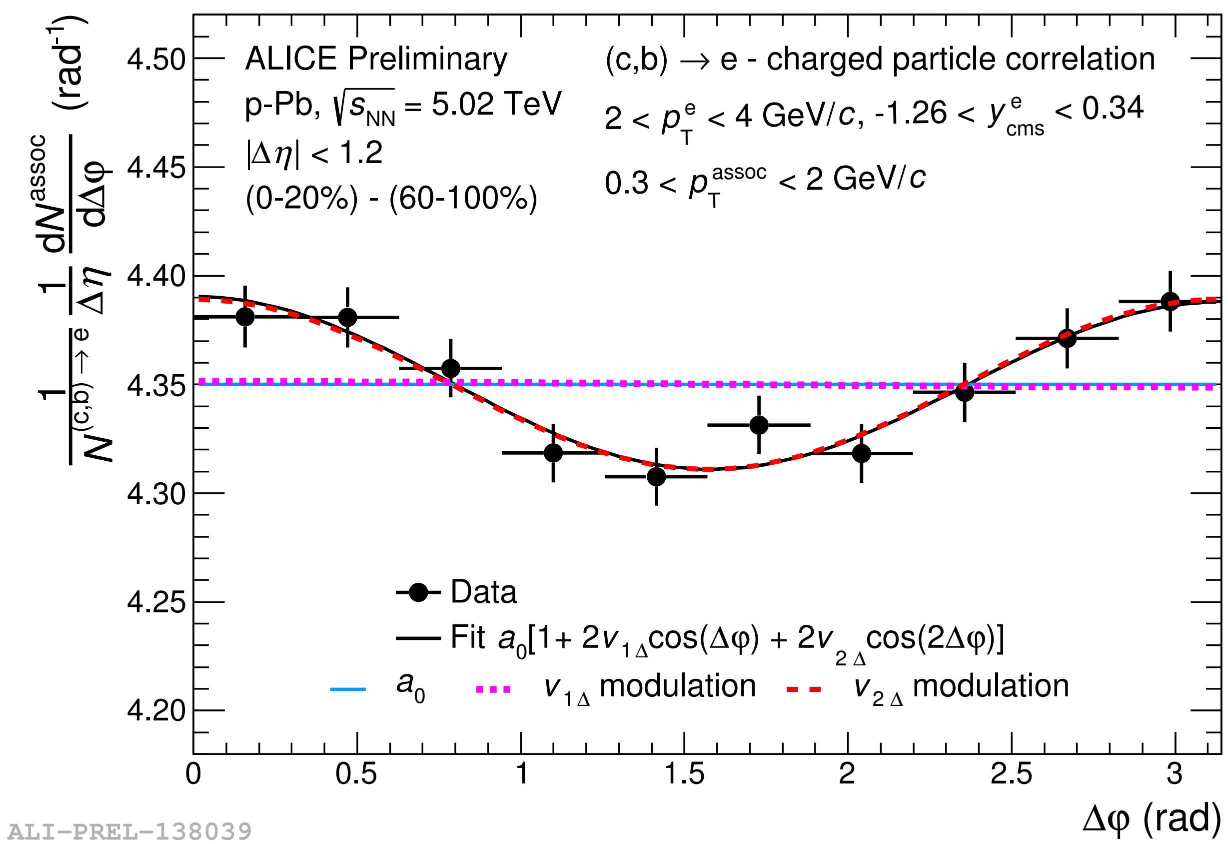
Simple Model based on PYTHIA – no proper $Q^2$ dependence




different x-sensitivity of probes reflected in nuclear modification factor

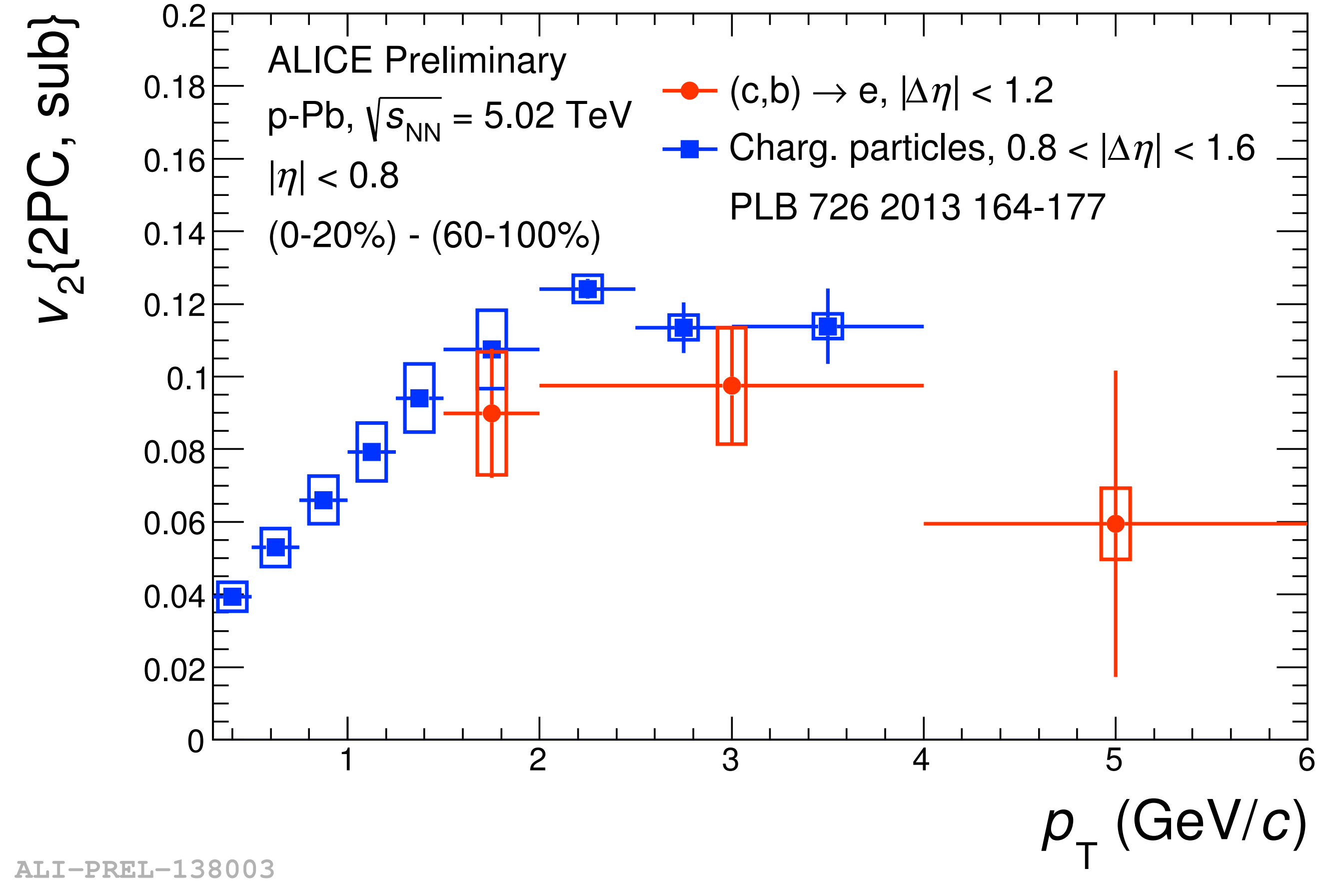
# Final State Modification of Open Charm?

## Azimuthal distributions of HFE-h




Difference central-peripheral (high-low multiplicity) double-peaked structure: $v_2$-like signal

## $v_2$ for heavy flavour electrons




$v_2$ modulations similar for HFE and charged particles in p-Pb

- Flow-like correlation in heavy flavour electrons
  - mechanism still unclear, possibly final-state interaction!
  - relation between initial and final state kinematics may be lost
  - introduces additional systematic uncertainty