ALICE studies and plans in hadronic proton-nucleus collisions at the LHC

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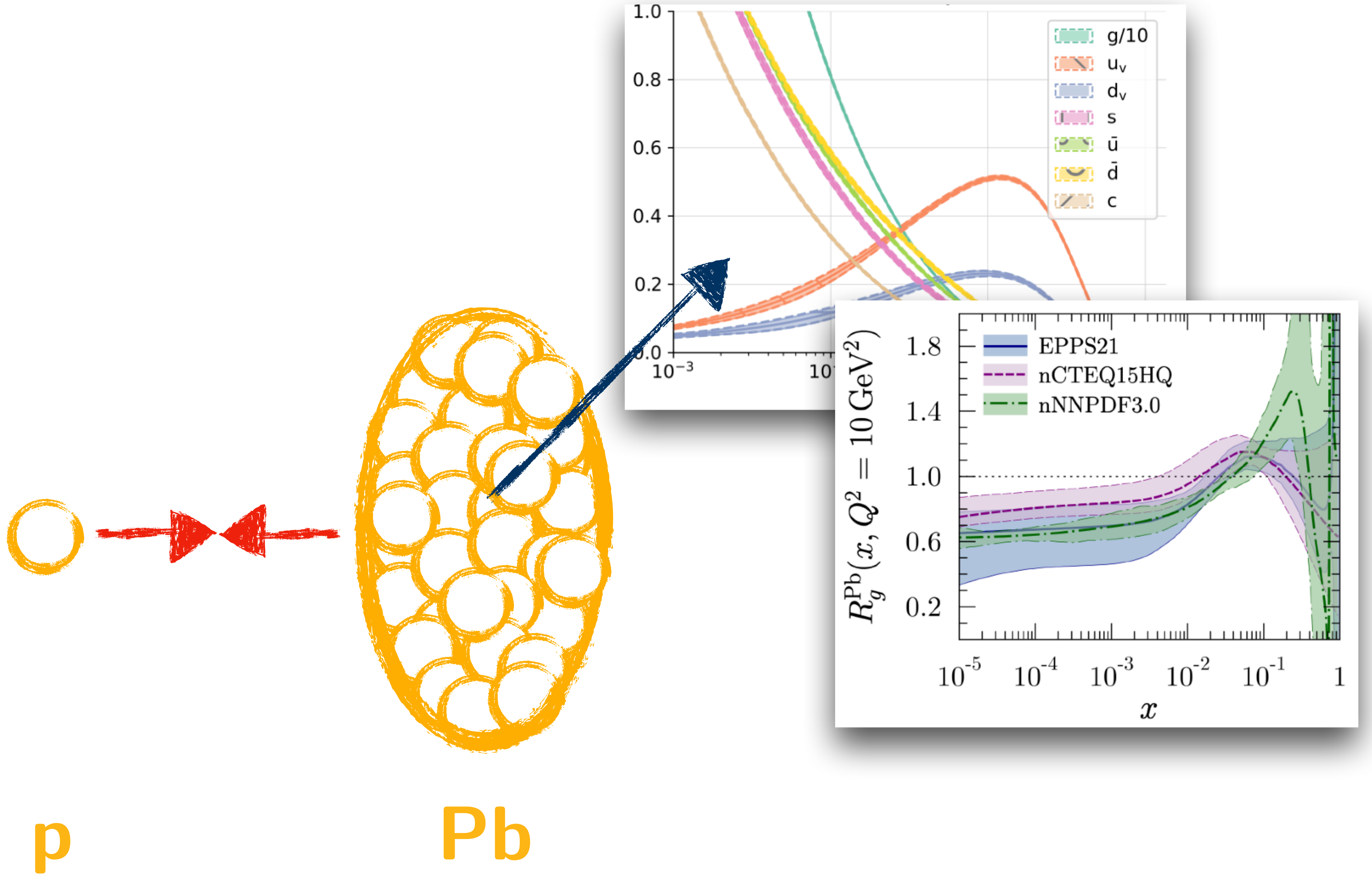
ALICE

Outline: An overview of experimental results & plans in three parts

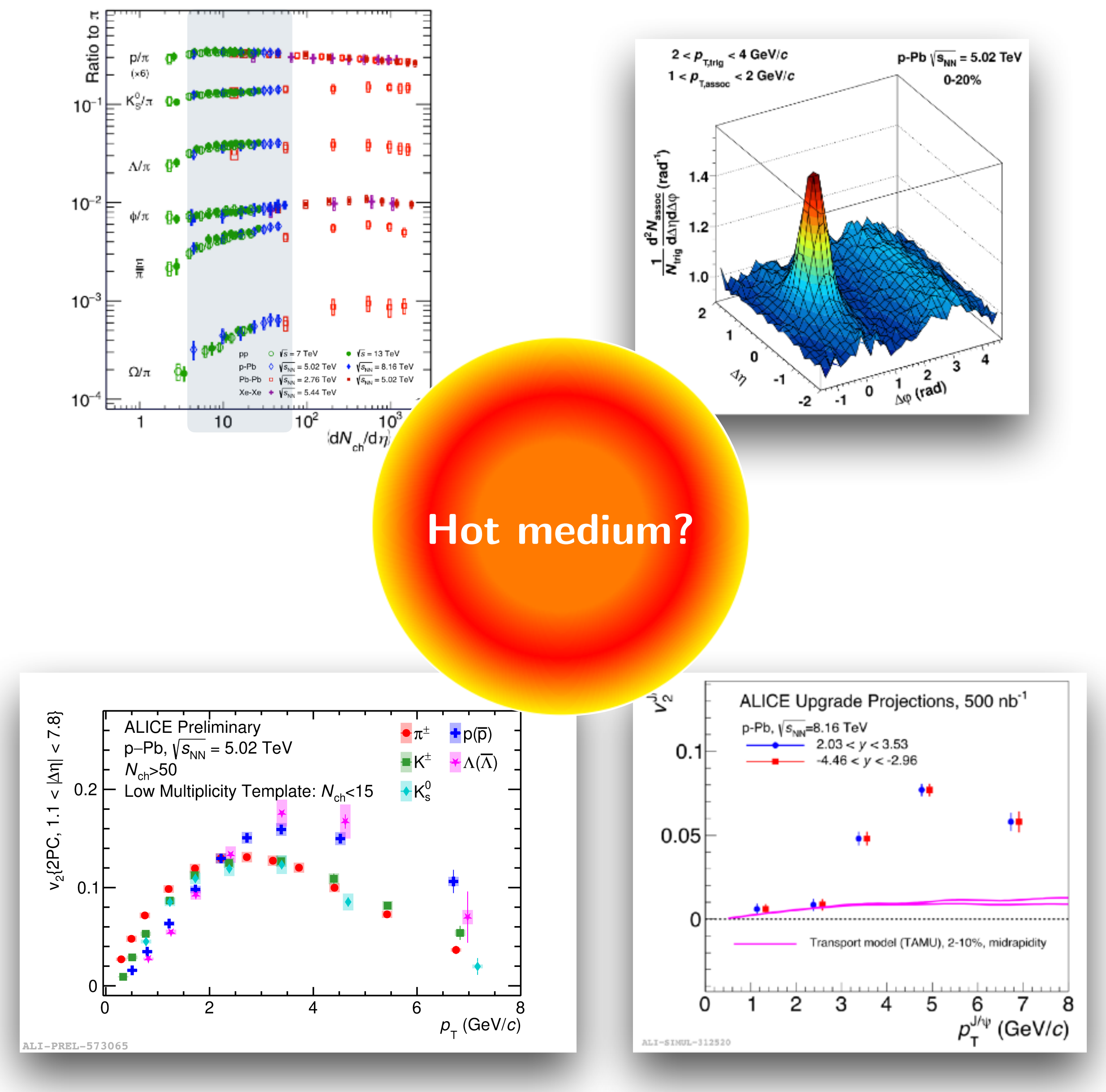
Part 1
Cold nuclear matter effects

Constraining parton densities and quantifying cold nuclear matter effects with ALICE data



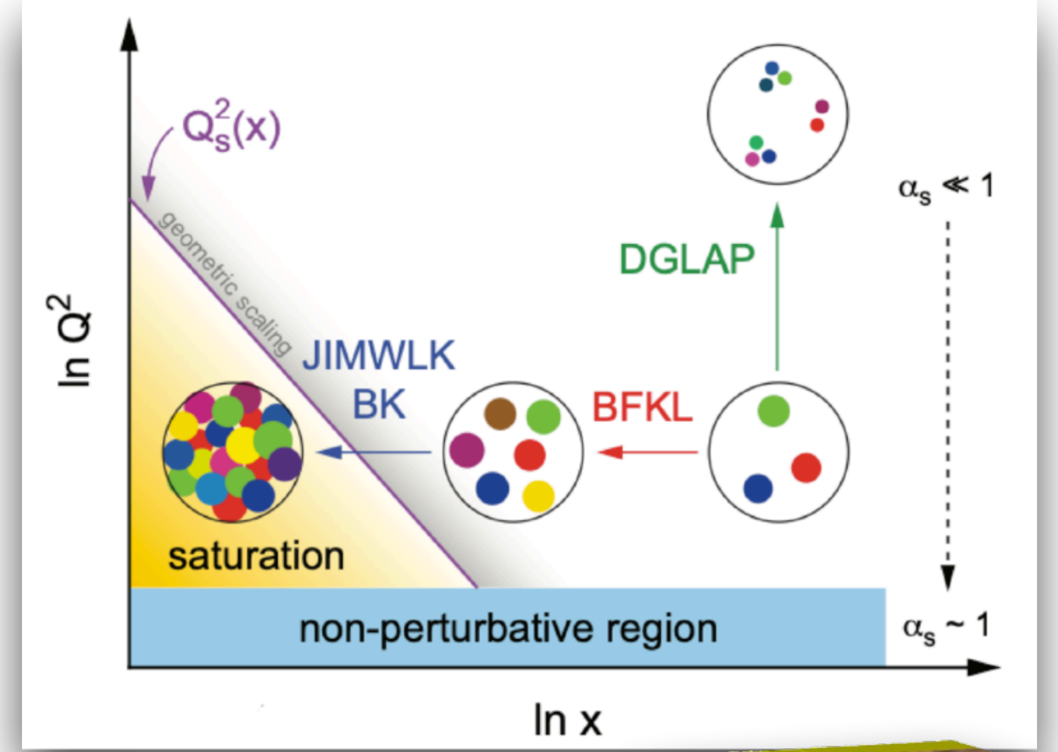
Part 2
Hot nuclear matter?

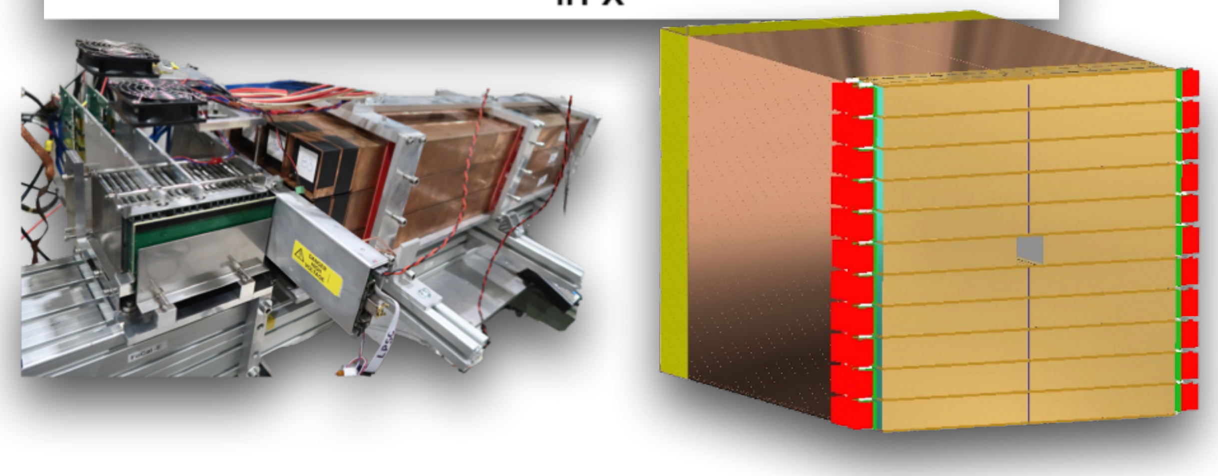
Do we only see cold nuclear matter effects in p-Pb collisions? QGP in p-Pb?



Part 3
Non-linear QCD

Searching for gluon saturation with the ALICE FoCal





All figure references given on respective slide of appearance

Introduction: LHC heavy-ion schedule

	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041
Run 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Runs 5&6
	Pb-Pb p-Pb		Pb-Pb O-O p-O		Pb-Pb p-Pb		Pb-Pb

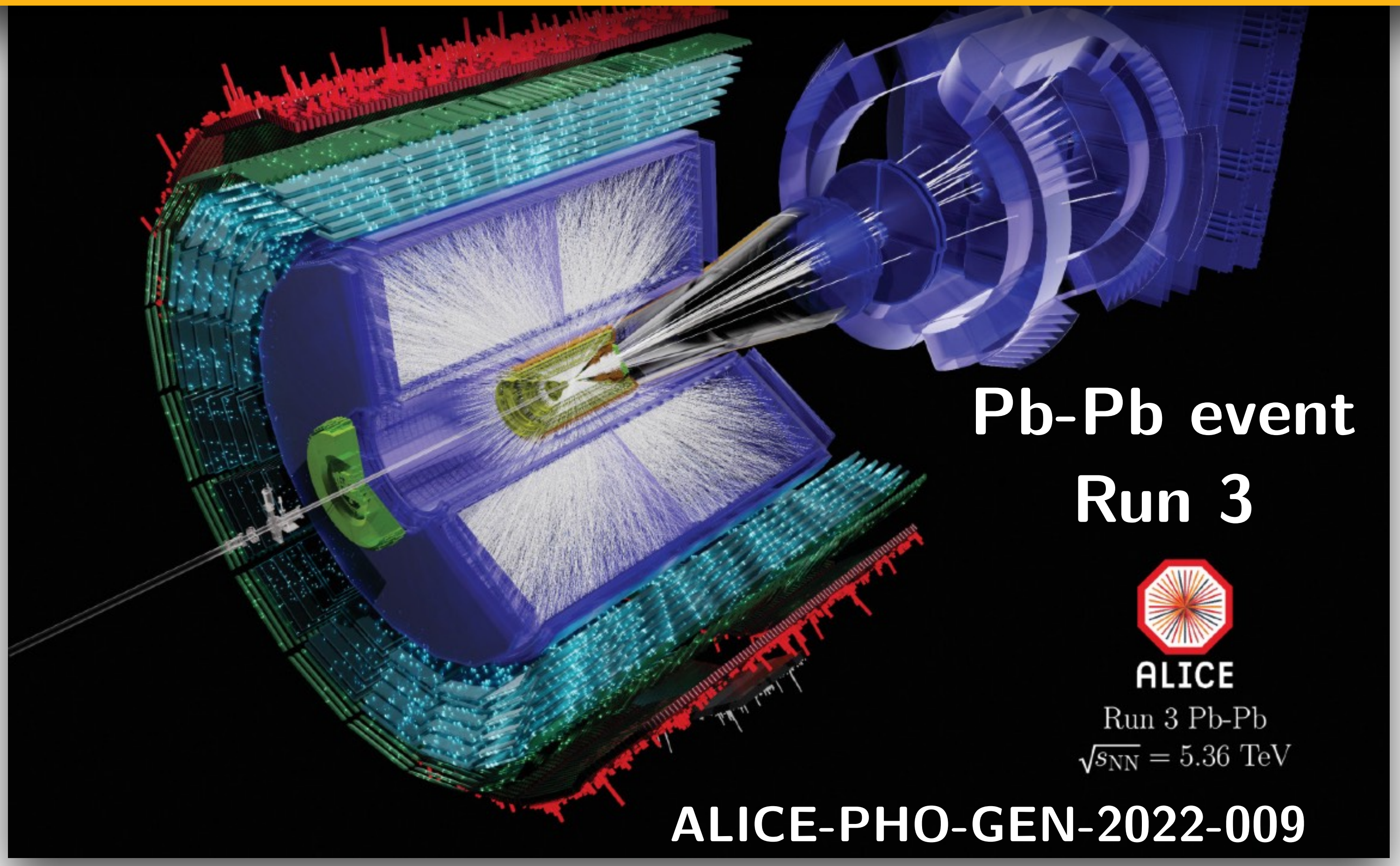
High-Luminosity LHC

CERN-2020-010

Prospects for proton-nucleus collisions in ALICE:

- ALICE: increase of MB (triggered) p-Pb **x1000 (x50-100)** **compared to Run 2**
- **instantaneous luminosity at P2 is levelled** and for p-Pb at HL-LHC expected to be $\mathscr{L} = 5 \times 10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ Eur.Phys.J.Plus 136 (2021) 7, 745
- A brief run with oxygen nuclei provides opportunity to study system with similar number of participation nucleons (w.r.t p-Pb) but larger geometrical transverse overlap ALICE-PUBLIC-2021-004
- Prospects for Ultra-peripheral collisions (UPCs) in dedicated talk by Daniel Tapia Takaki tomorrow at 12:05

HL for heavy-ions is already ongoing ...



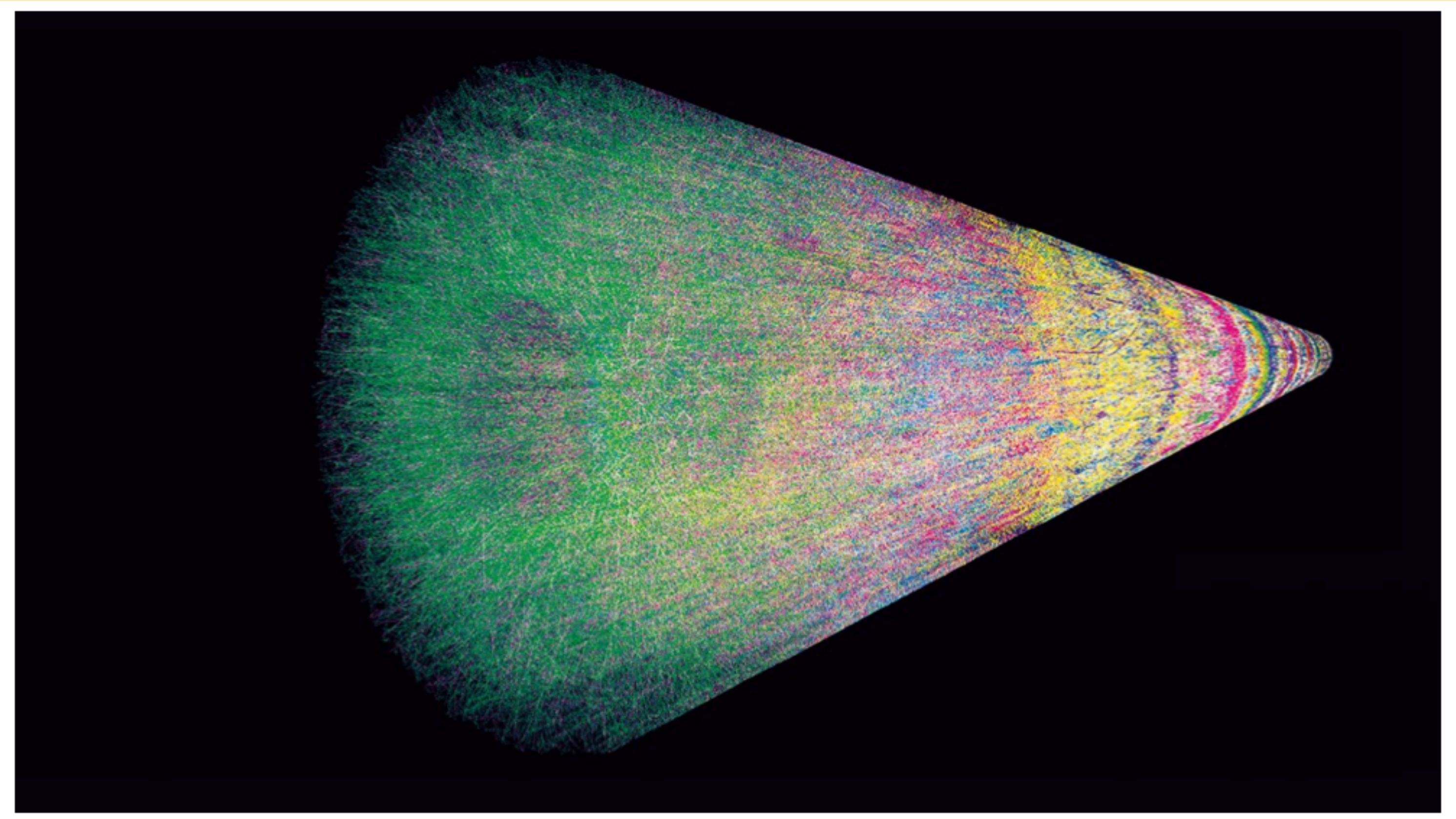
Introduction: ALICE Upgrades

Run 1	2015-2018 Run 2	2019-2021 LS 2	2022-2025 Run 3	2026-2028 LS 3	2029-2032 Run 4	2033-2034 LS 4	2035-2041 Runs 5&6

LS 2

ALICE2

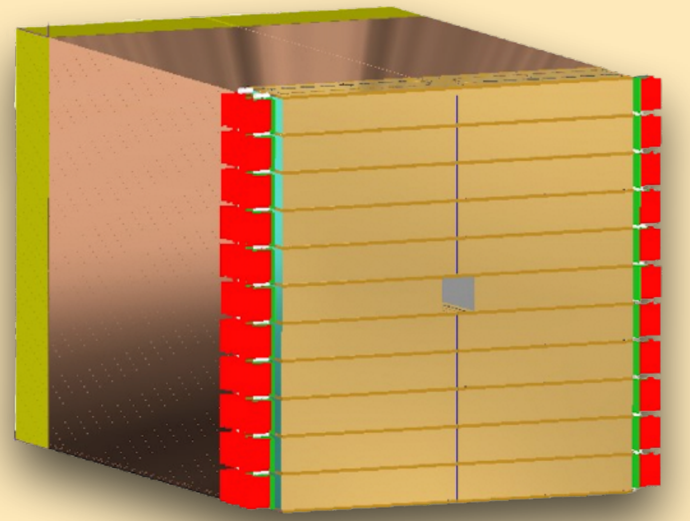
- New Inner Tracking System (ITS2)
- New Muon Forward Tracker (MFT)
- TPC upgrade & continuous readout



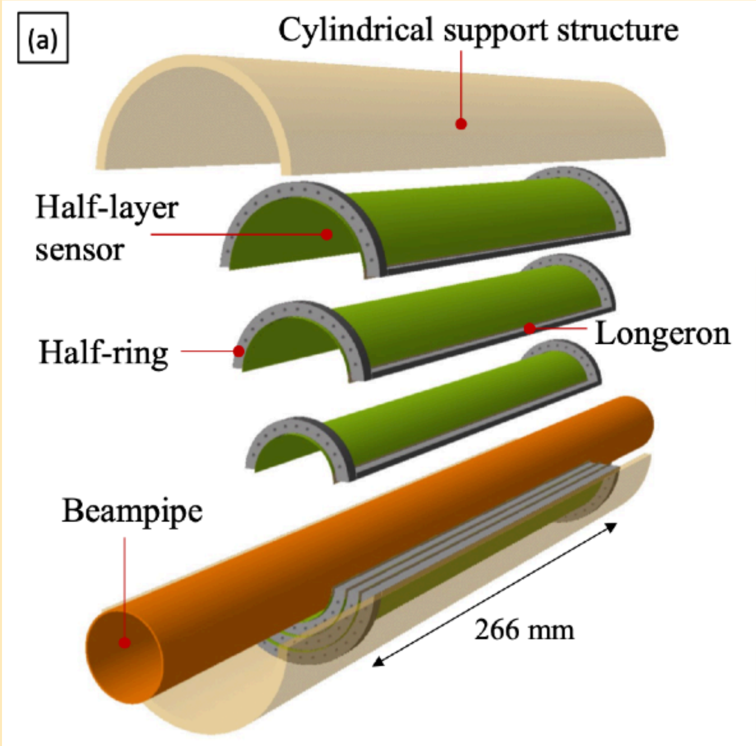
2 msec timeframe of Pb-Pb collisions at 50kHz IR in the TPC

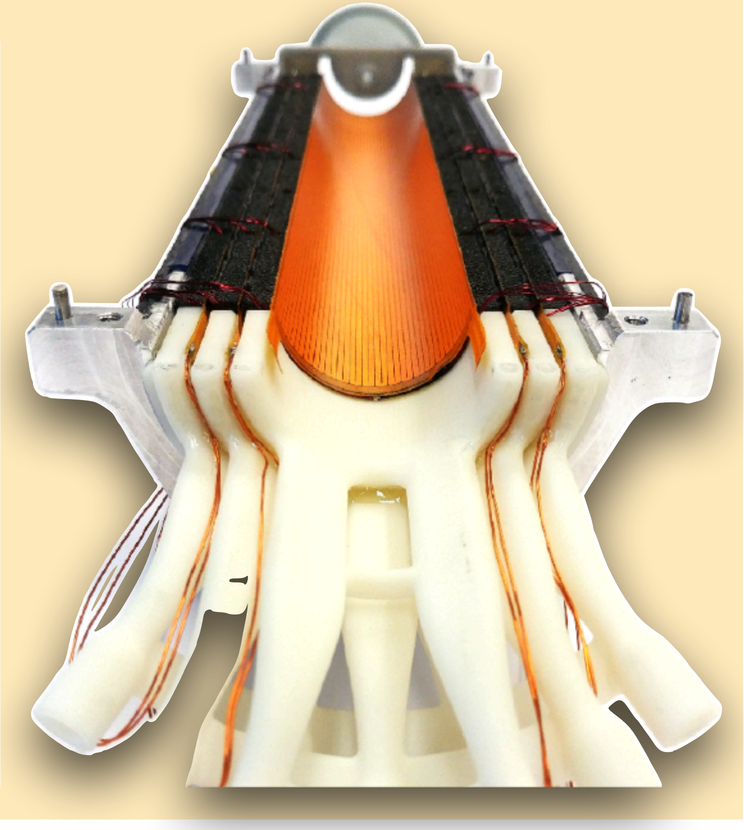
LS 3

Forward Calorimeter (FoCal)



Inner Tracking System 3

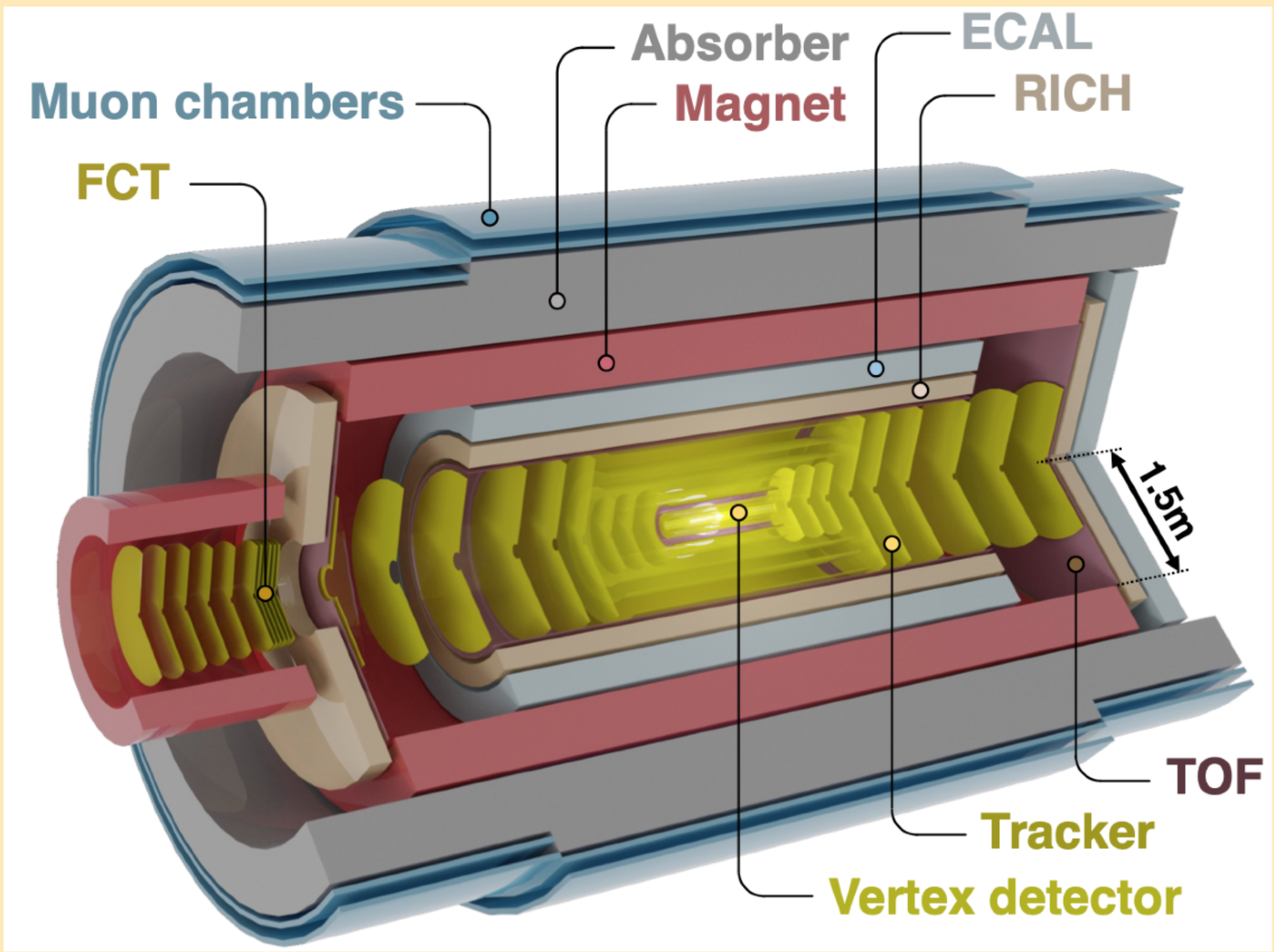




LS 4

All new experiment!

ALICE3



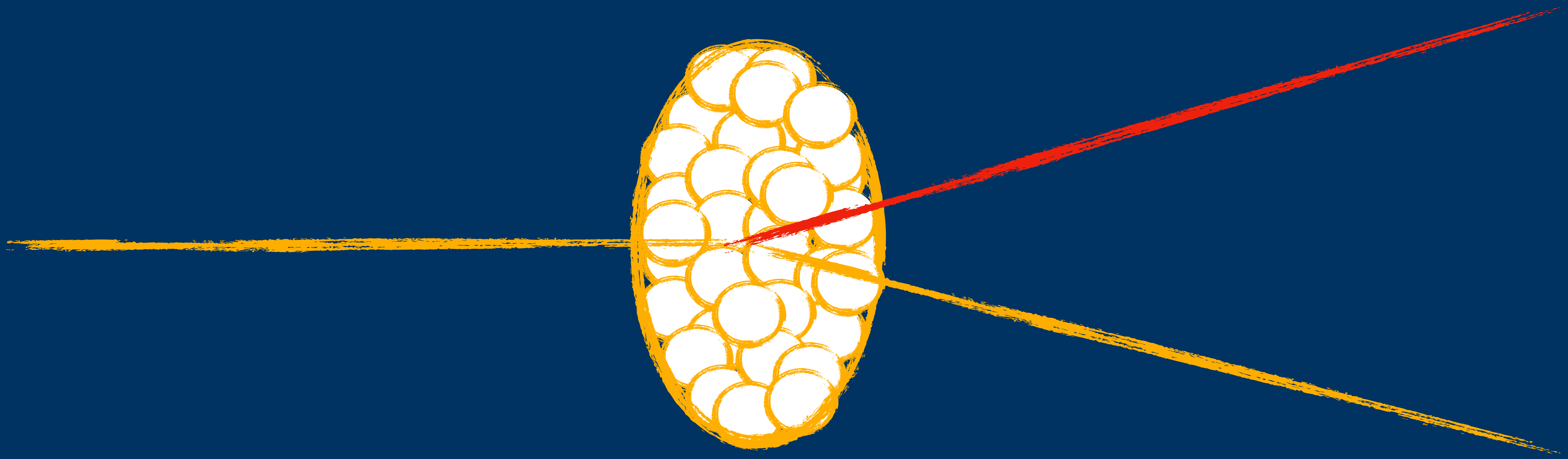
- Compact all-silicon tracker
- Retractable vertex detector

JINST 16 (2021) P03022; ALICE-TDR- 015, 2013

FoCal TDR: CERN-LHCC-2024-004 ITS3 TDR: CERN-LHCC-2024-003

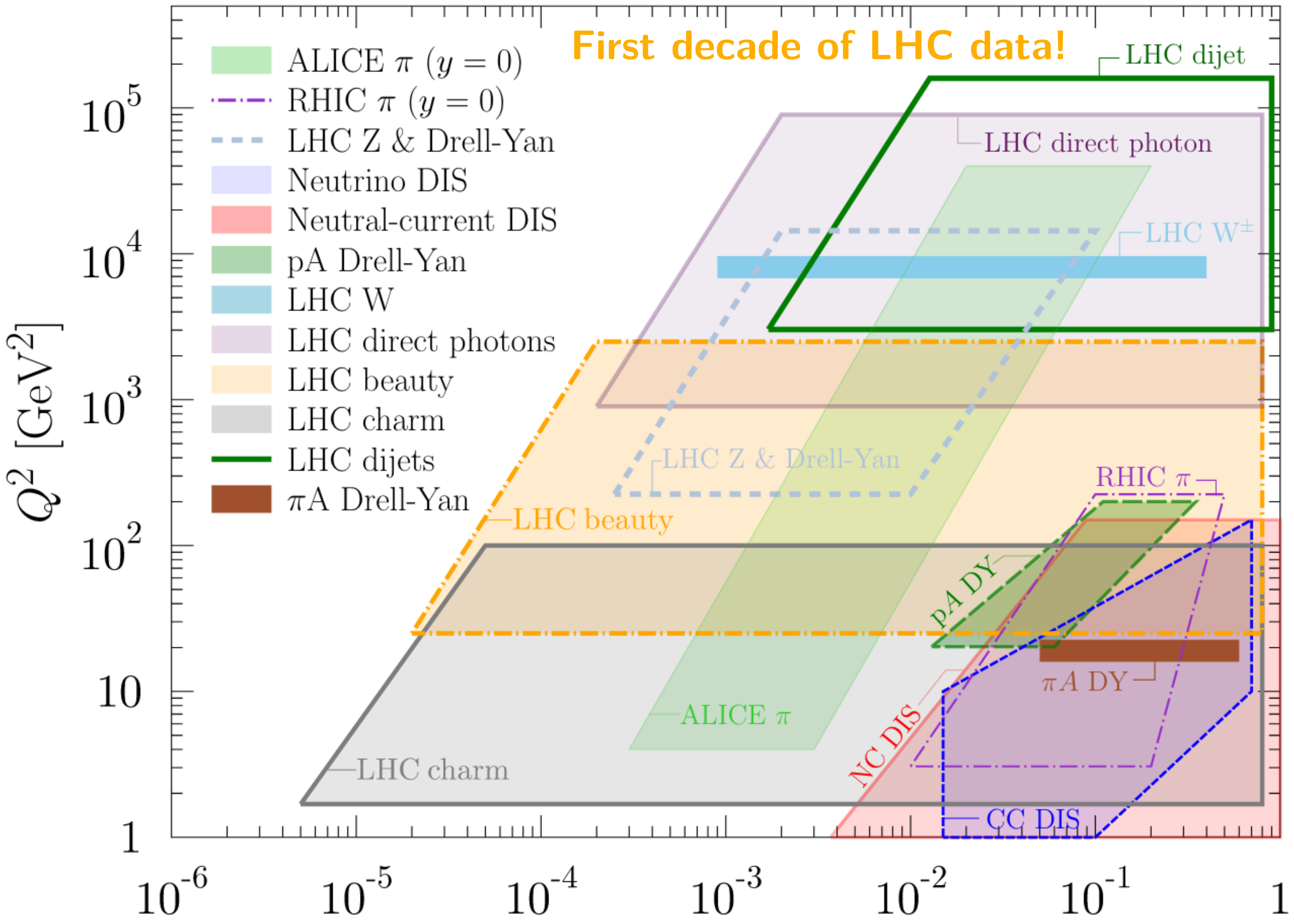
ALICE3 LOI: CERN-LHCC-2022-009

Probing the initial state of heavy-ion collisions

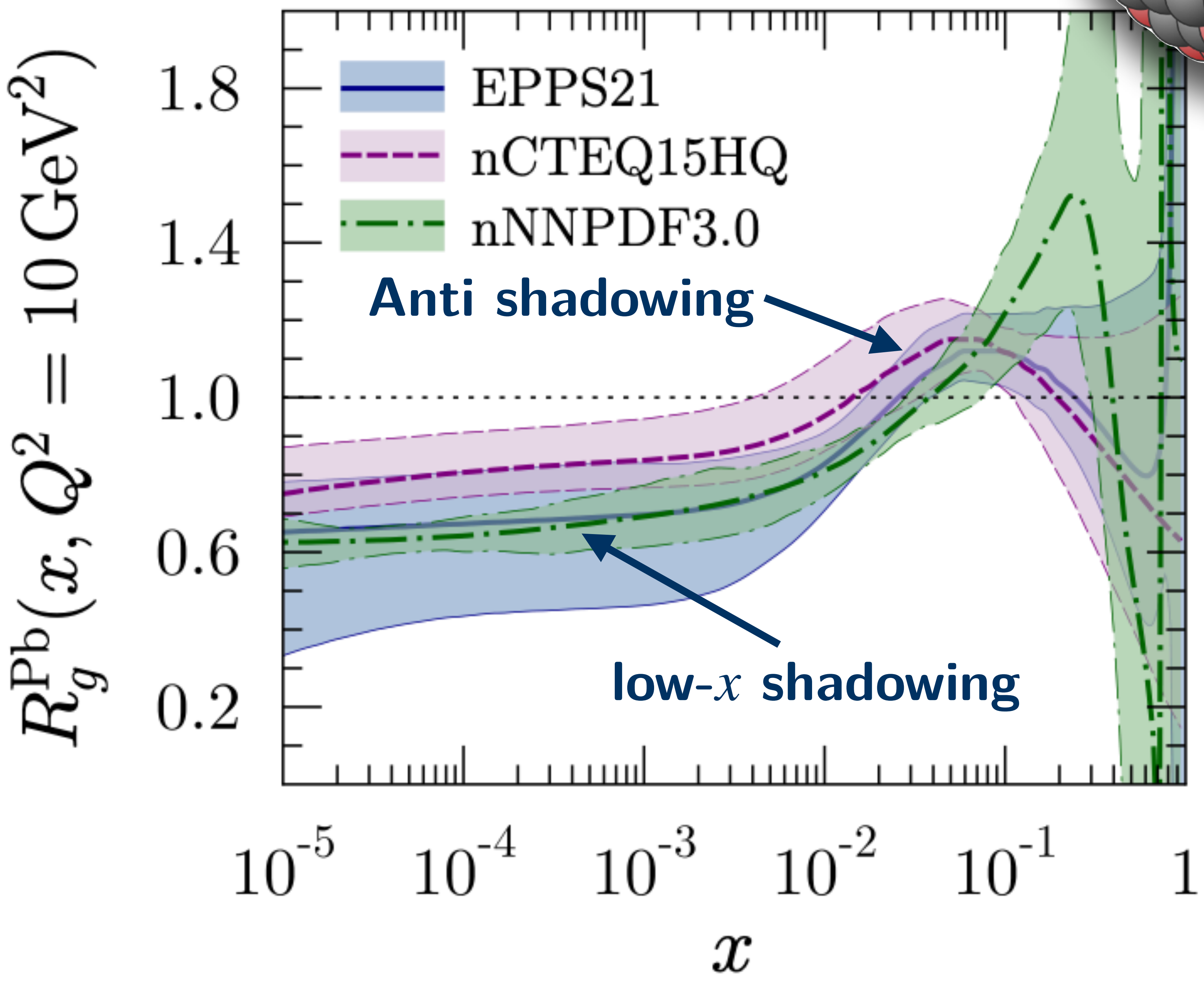


Constraining the initial-state: nPDFs

Coverage of lepton-A, pion-A and proton-A data in nPDFs

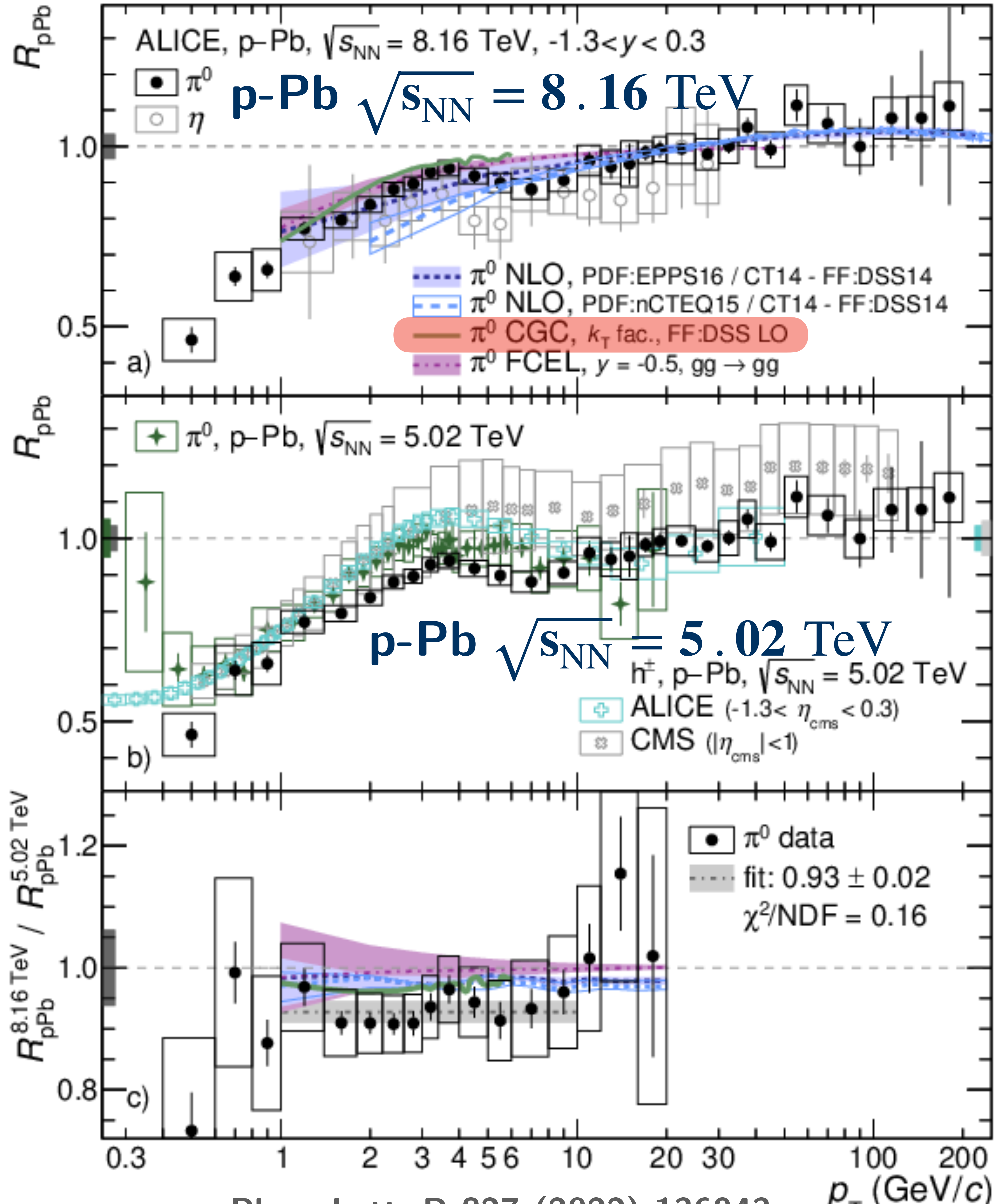


"Nuclear PDFs After the First Decade of LHC Data"
M. Klasen & H. Paukkunen (arXiv:2311.00450)



- A decade of LHC data provided significant constraints for nPDF in novel phase space
- Increase of exp. data included in global fits: EPPS09 ($N_{\mathrm{dat}} = 929$) → EPPS21 ($N_{\mathrm{dat}} = 2077$)
- Sizeable gluon shadowing at low-x, but slight tension between different global fits

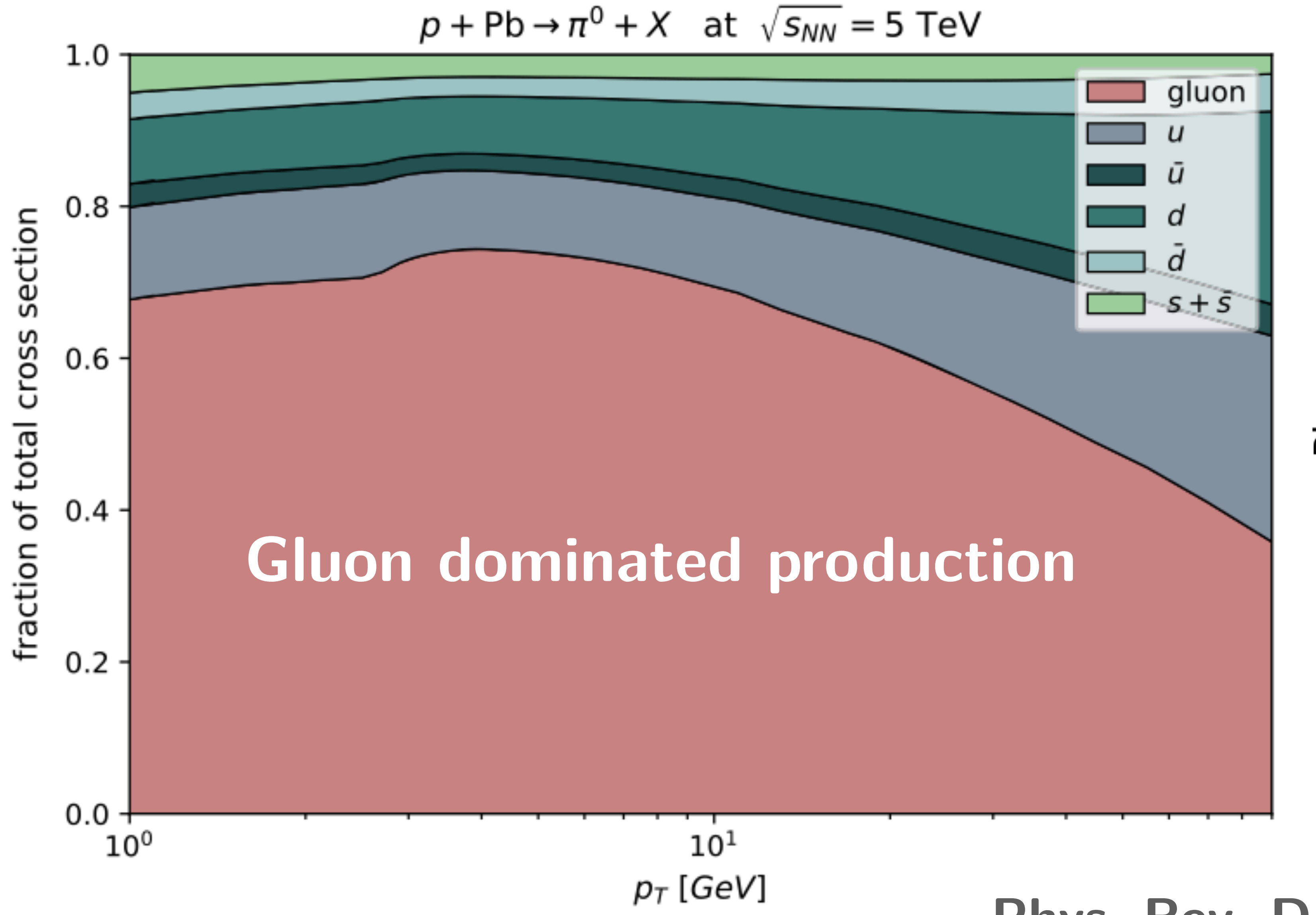
Neutral meson production in p-Pb collisions



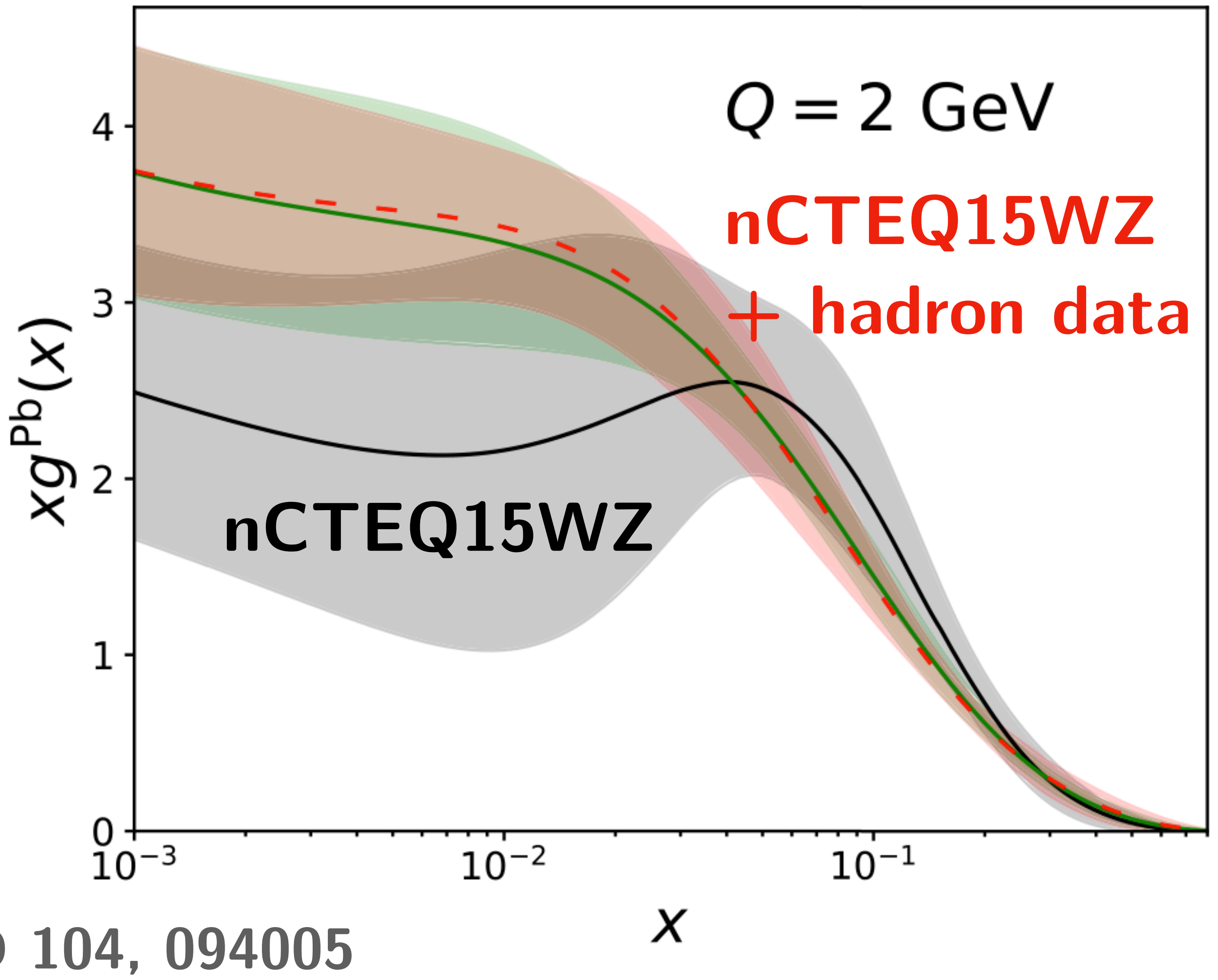
Phys. Lett. B 827 (2022) 136943

- π^0 and η mesons measured over unprecedented p_T range
- For $p_T > 10$ GeV/c: R_{pA} consistent with unity
- For $p_T < 10$ GeV/c: significant suppression in agreement with gluon shadowing, saturation effects or parton energy loss in CNM
- Measurement provide constrains for nPDF and fragmentation functions
- Publication for heavier $\omega(782)$ meson in preparation, stay tuned!

Large gluon contribution to π^0 cross section



Constrains of gluon n(PDF)



Phys. Rev. D 104, 094005

Electroweak boson production in p-Pb collisions

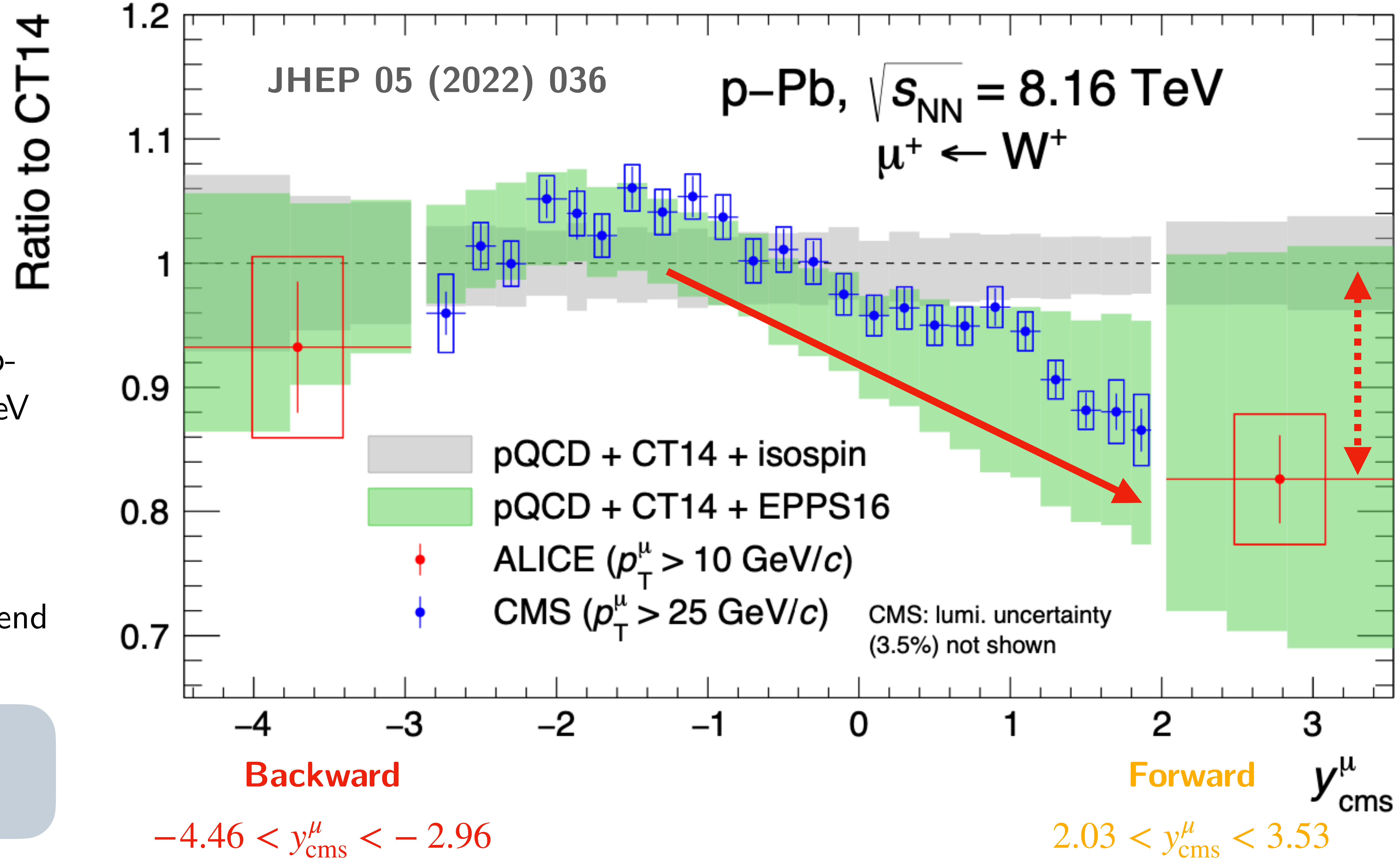
$W^{\pm}$ boson production:

- Only participates in electroweak interaction
- Sensitive to light quark content of nucleus

ALICE measurement

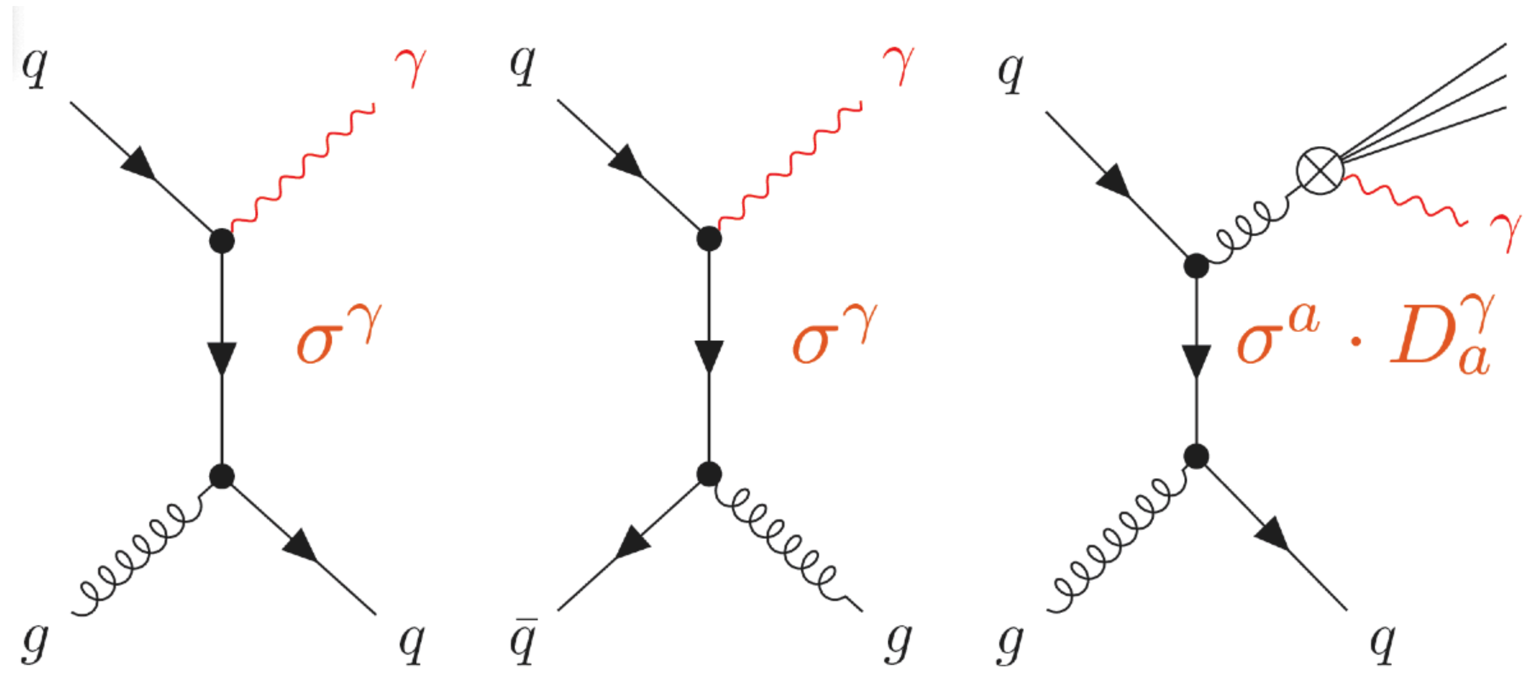
- Measurement of $W^{\pm} \rightarrow \mu^{\pm}$ in p-Pb collisions at $\sqrt{s_{\rm nn}} = 8.16$ TeV at **forward** and **backward** rapidities
- Indication of nuclear effects at forward rapidities, extending trend observed by CMS

Constrains on nPDFs at $x \sim 10^{-4}$

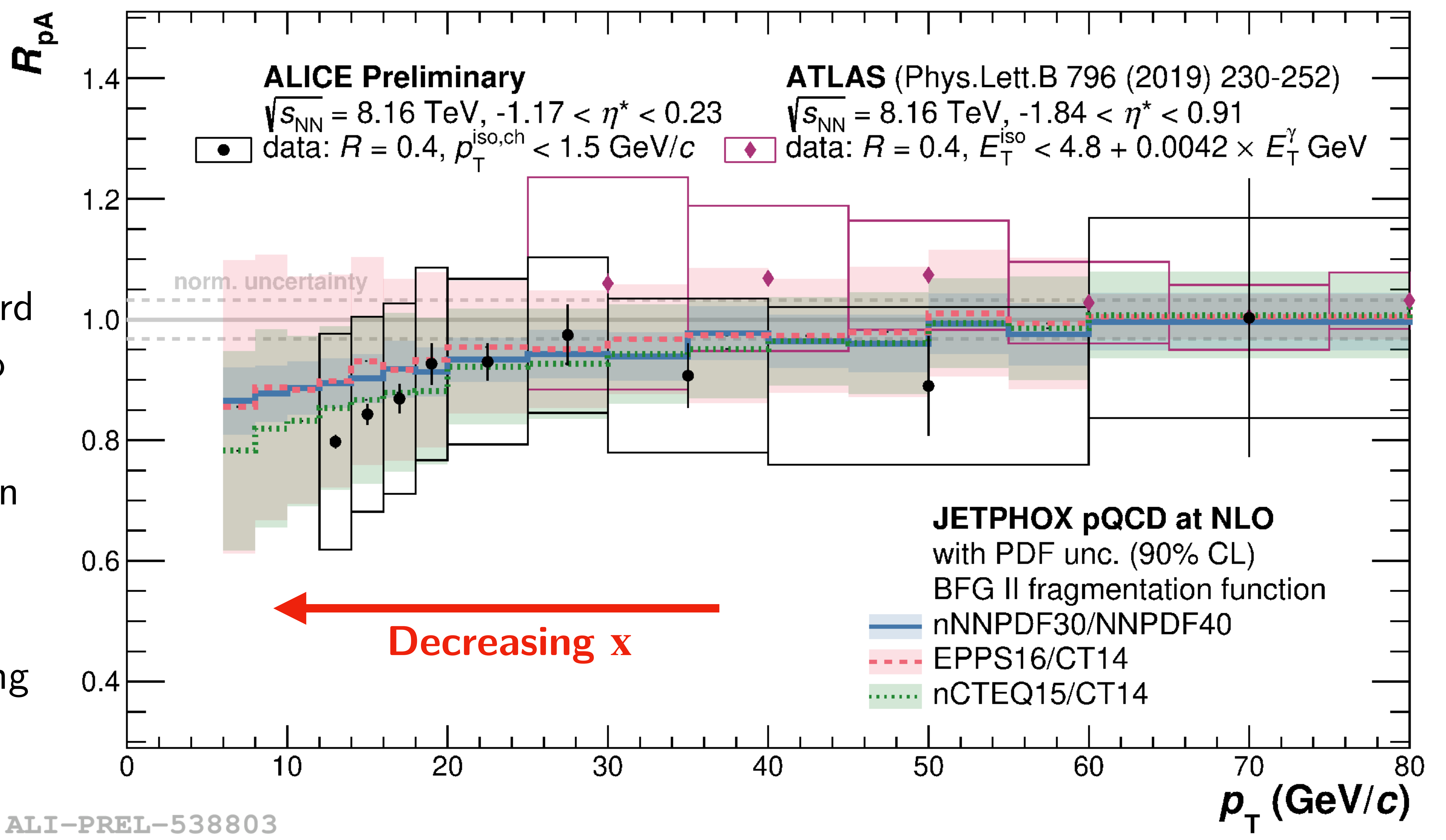


Isolated prompt photon production in pp and p-Pb collisions

Compton **Annihilation** **Fragmentation**



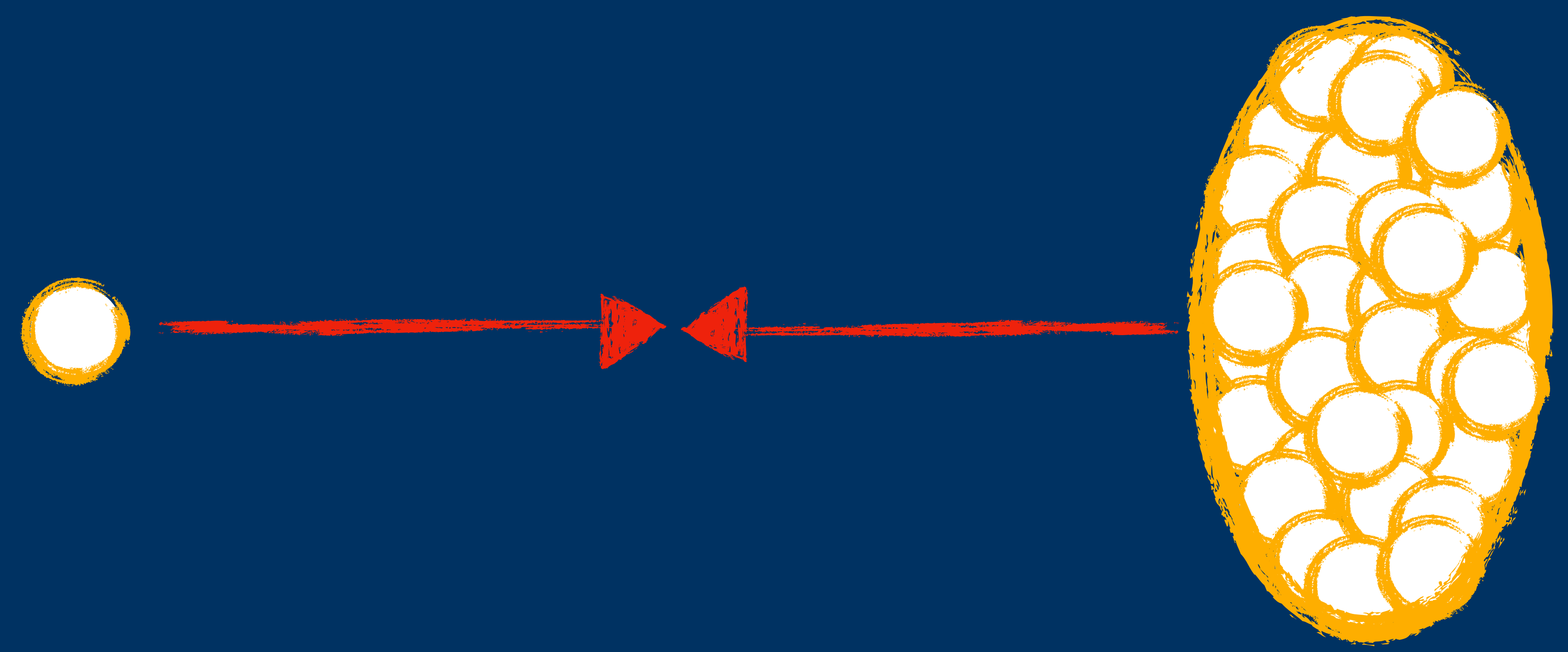
- Prompt photons are produced directly in hard scattering → sensitivity to initial state + no strong interaction in final state!
- **First hint of suppression** of prompt photon cross section due to nuclear effects in p-Pb collisions for $p_T < 20$ GeV/c
- In agreement with pQCD@NLO incorporating gluon shadowing at low-x in nPDFs
- Extending low-x reach of previous measurements in p-Pb collisions by **factor 2**



Publication in preparation, stay tuned!

Are p-Pb collisions a "clean" laboratory for initial-state effects?
Is there QGP droplet in p-Pb collisions?

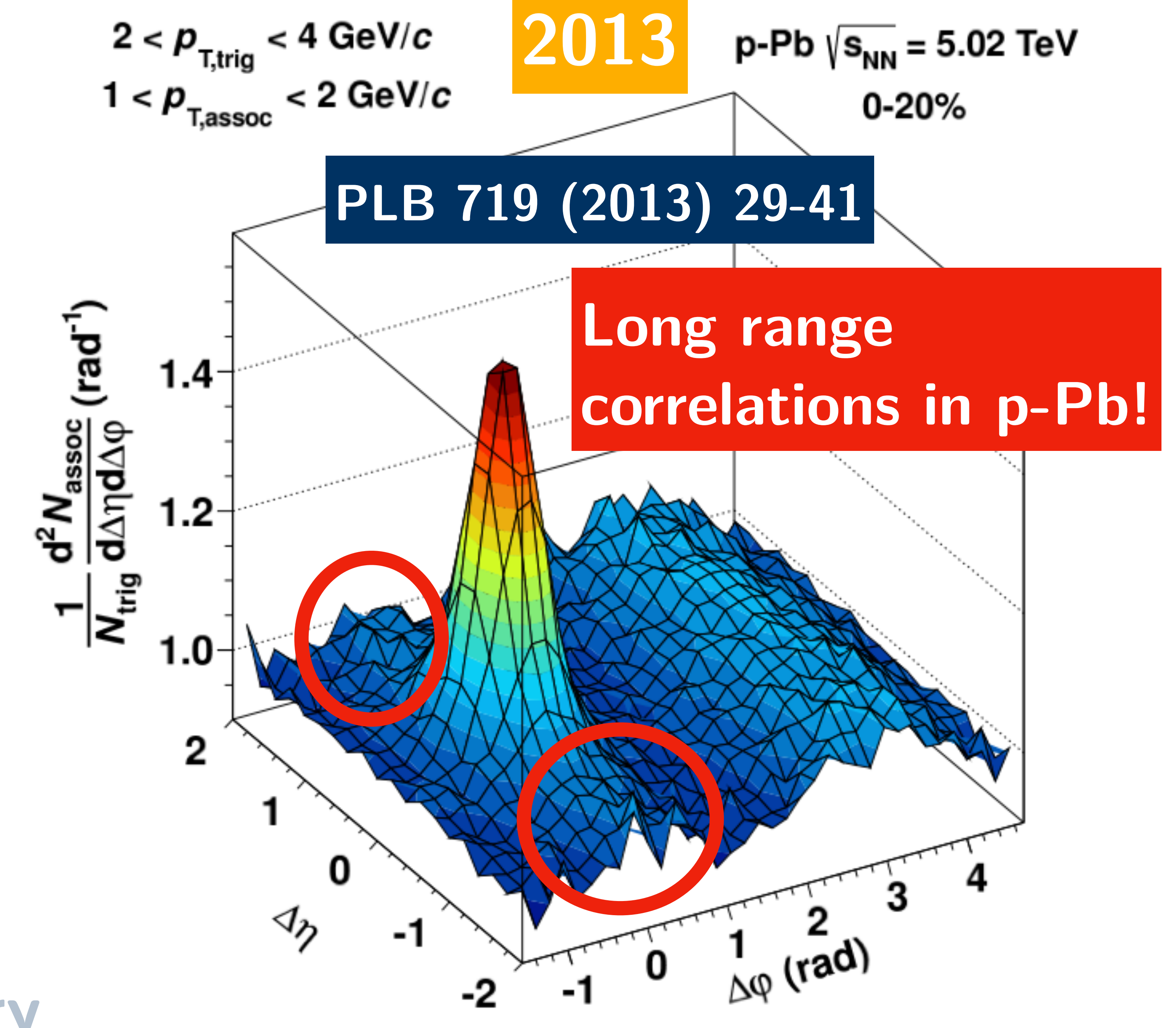
Measuring QGP observables in small systems



"The ridge" and (multi) anisotropic flow in p-Pb collisions

2013

PLB 719 (2013) 29-41

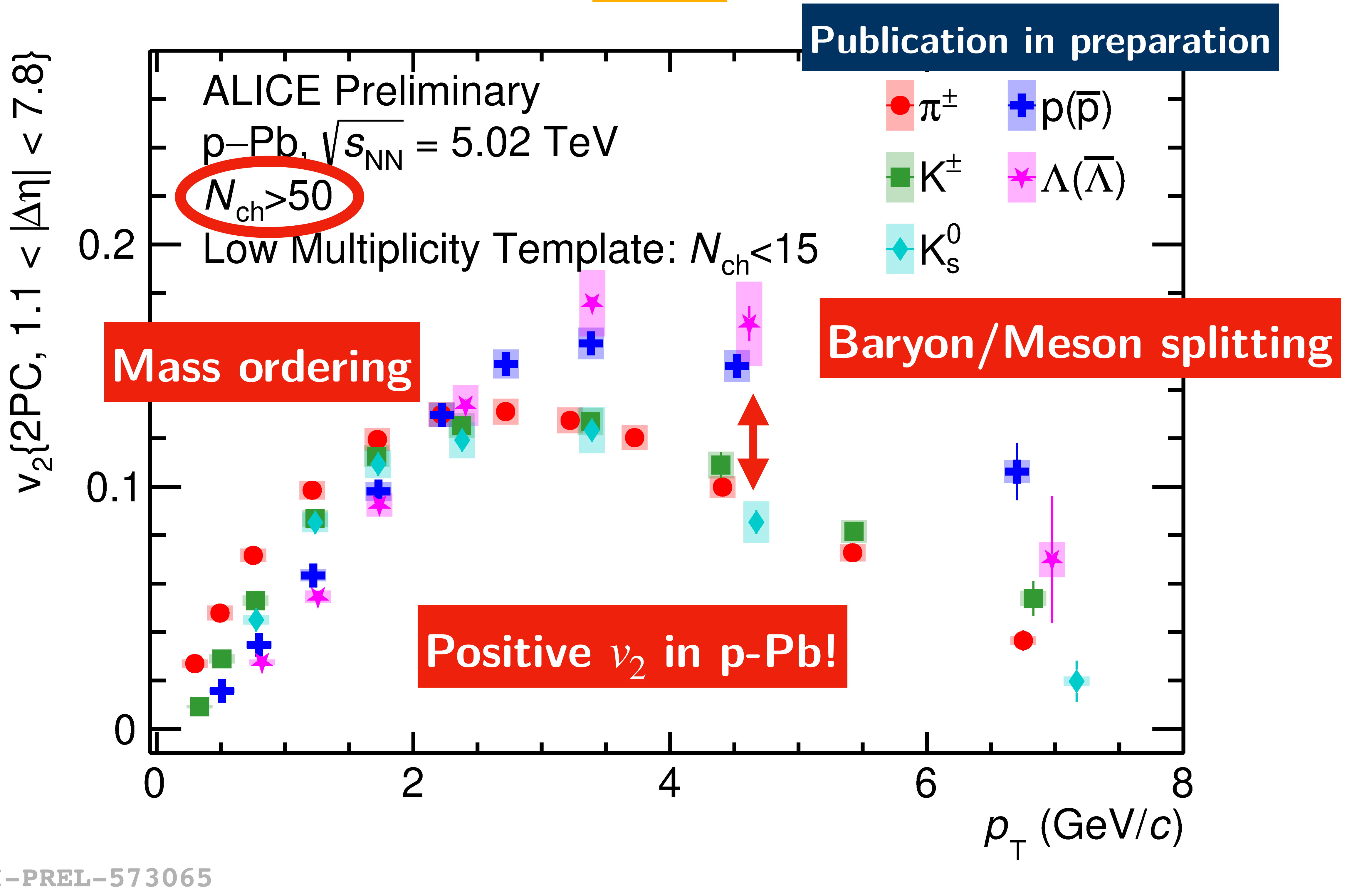


Long range correlations in p-Pb!

~10 years

2024

Publication in preparation



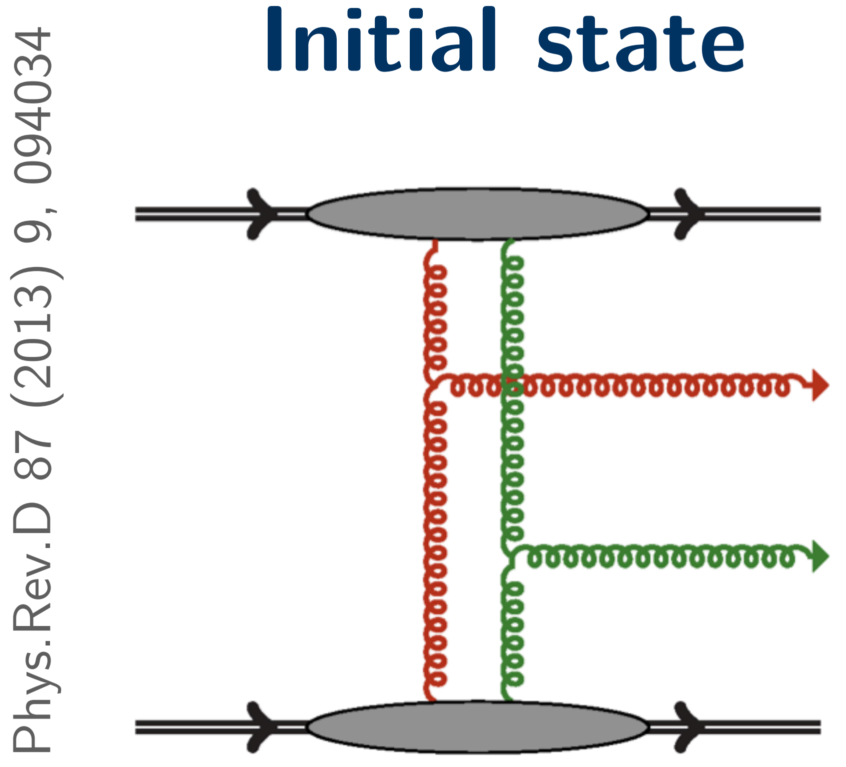
Mass ordering

Baryon/Meson splitting

Positive v_2 in p-Pb!

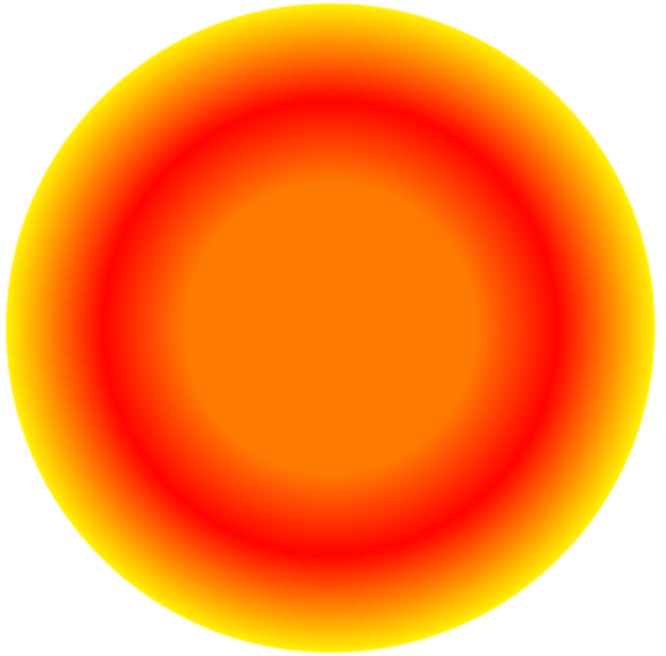
Theory

Initial state



?

Hydrodynamics

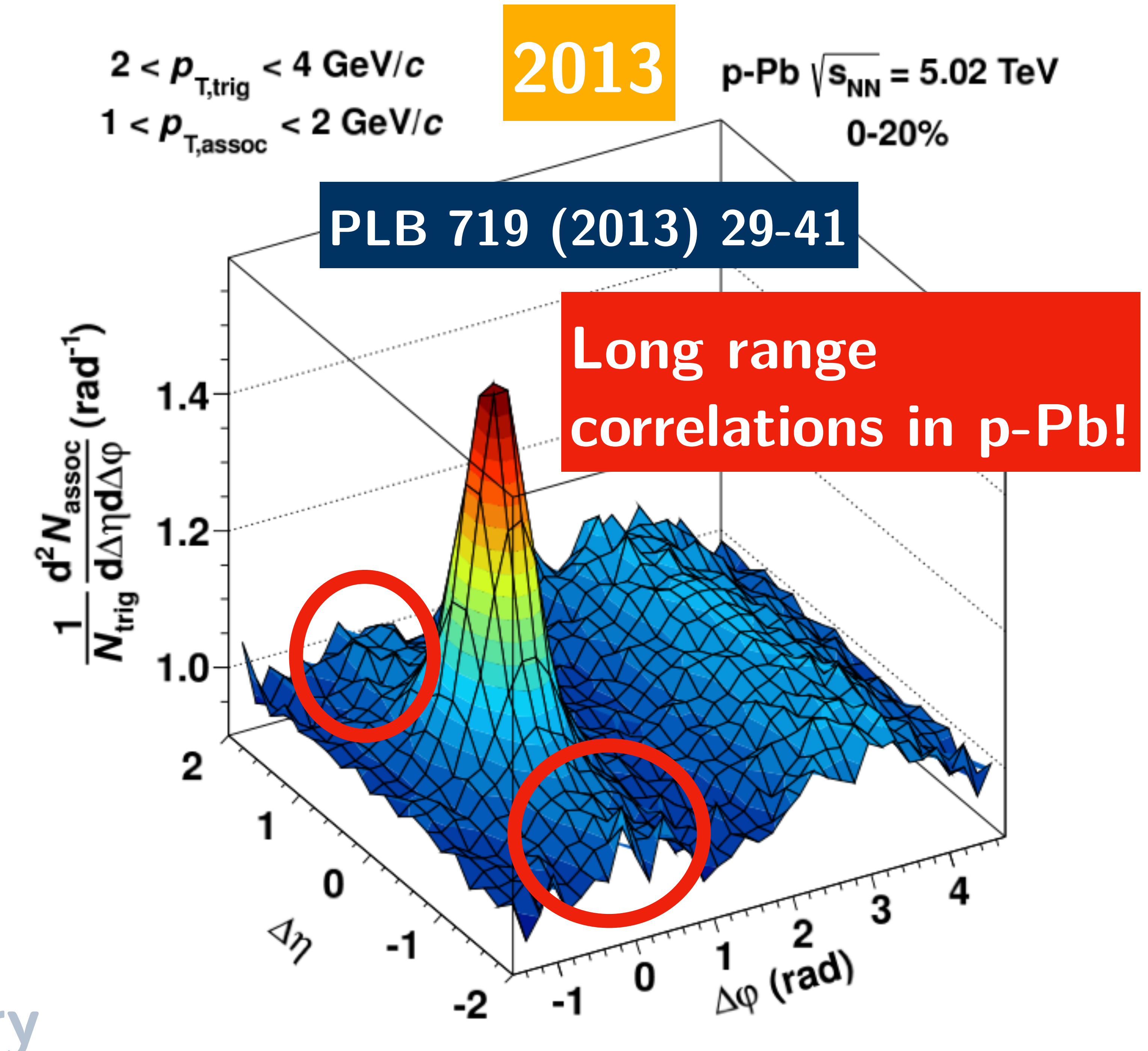


Initial-momentum correlations

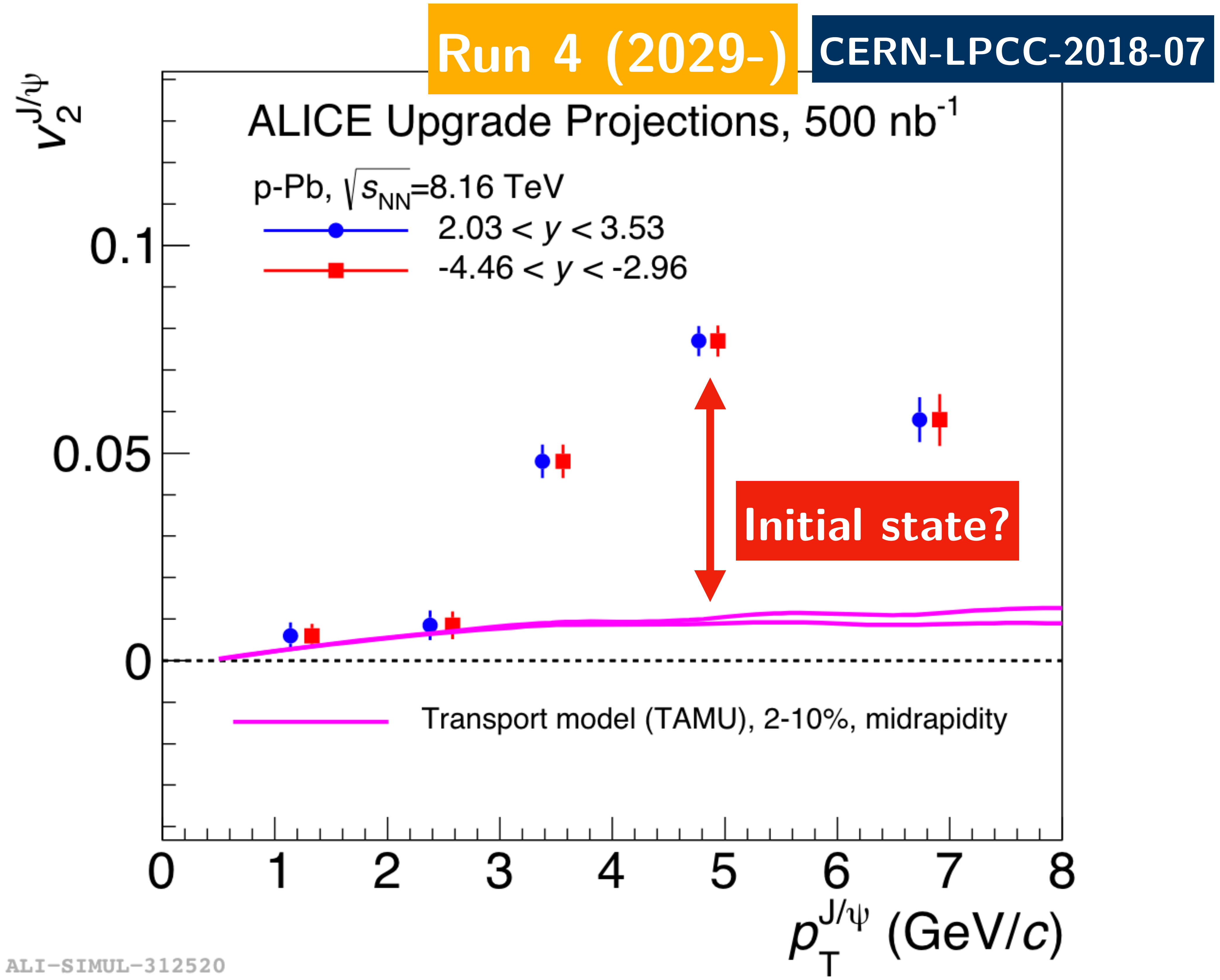
Many scatterings

- Significant progress in precision measurement of identified charged particle v_2 since first observation of "the ridge" in p-Pb collisions (also multi-particle correlations)
- Theory has room from **momentum correlations in initial state** to **multiple scatterings in a QGP droplet**

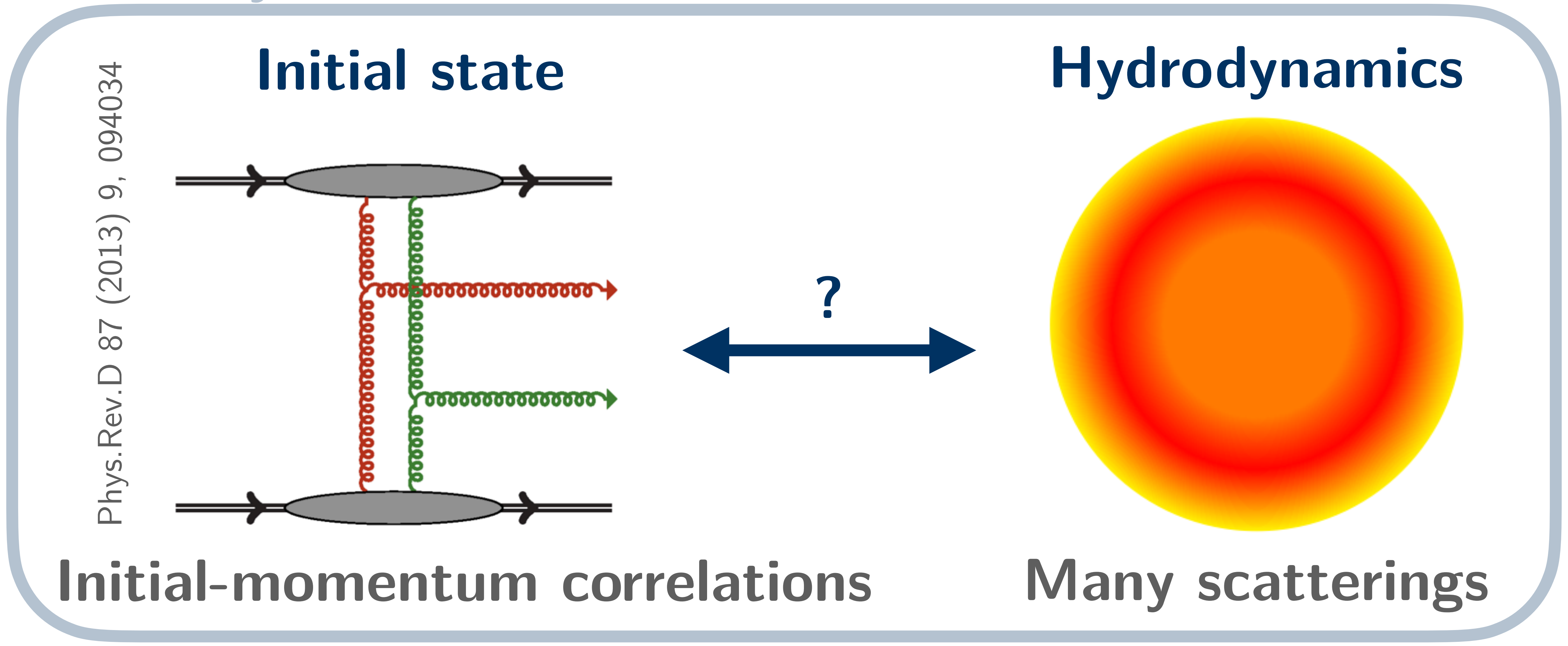
"The ridge" and (multi) anisotropic flow in p-Pb collisions



HL-LHC



Theory



- Significant progress in precision measurement of identified charged particle v_2 since first observation of "the ridge" in p-Pb collisions (also multi-particle correlations)
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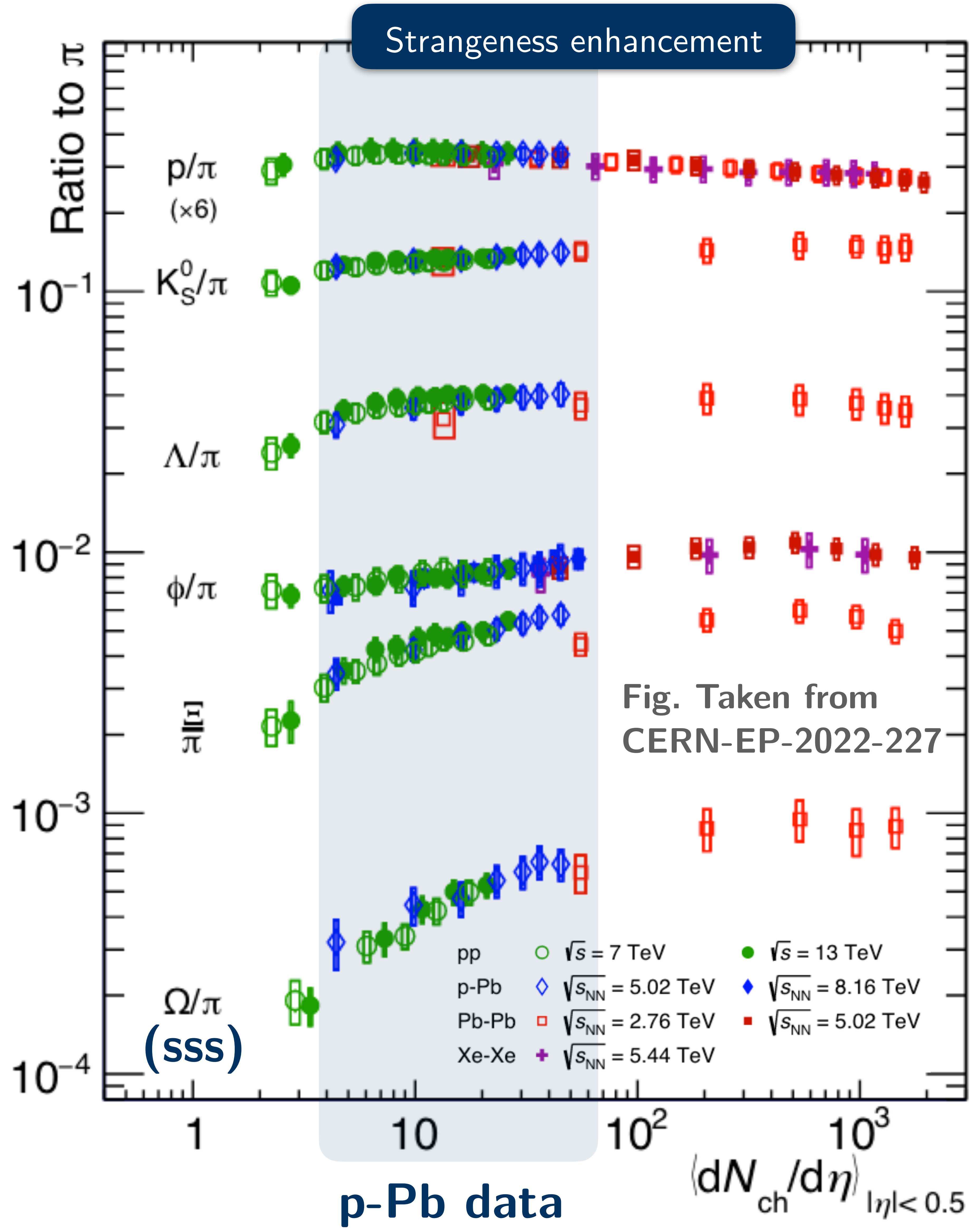
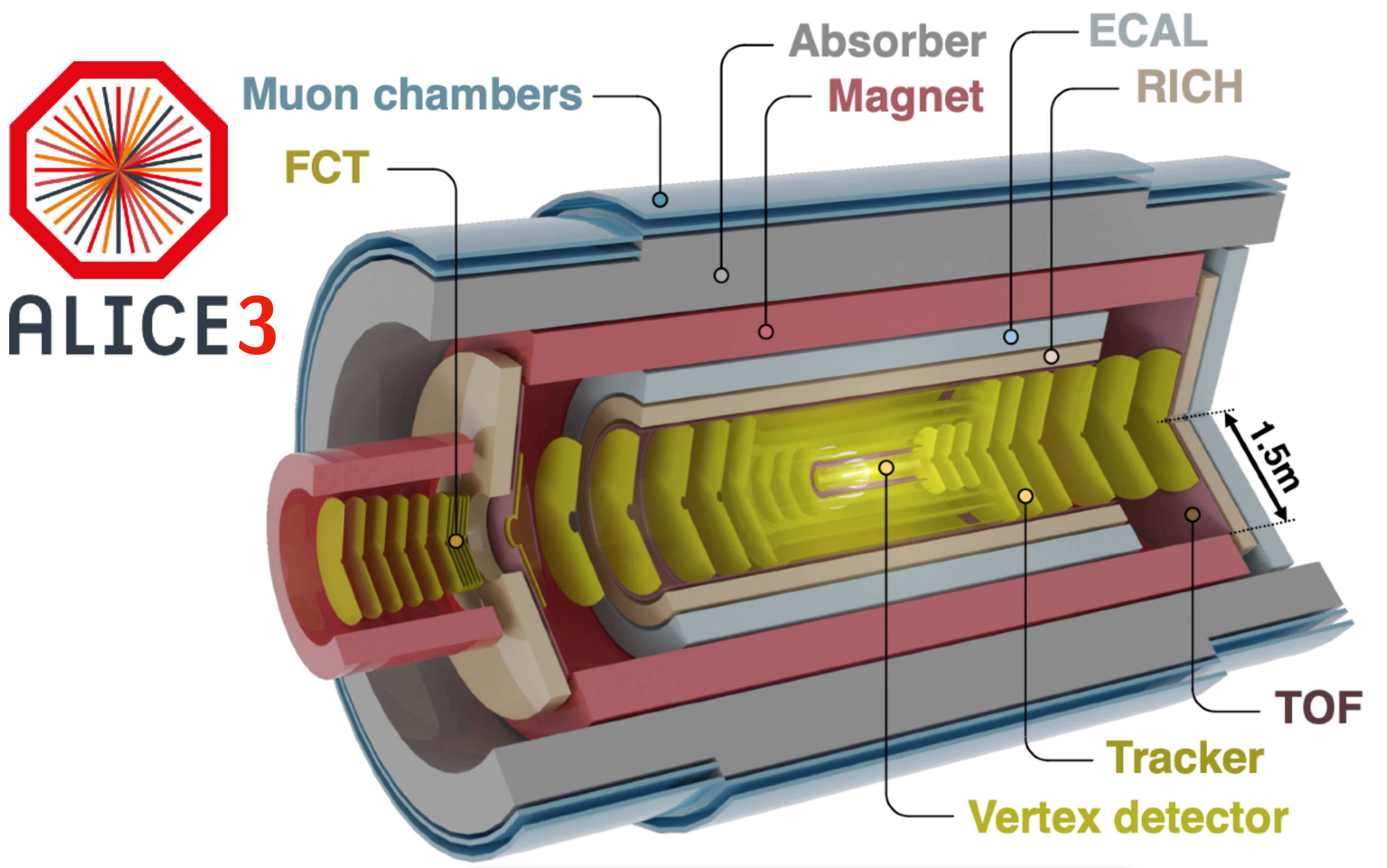
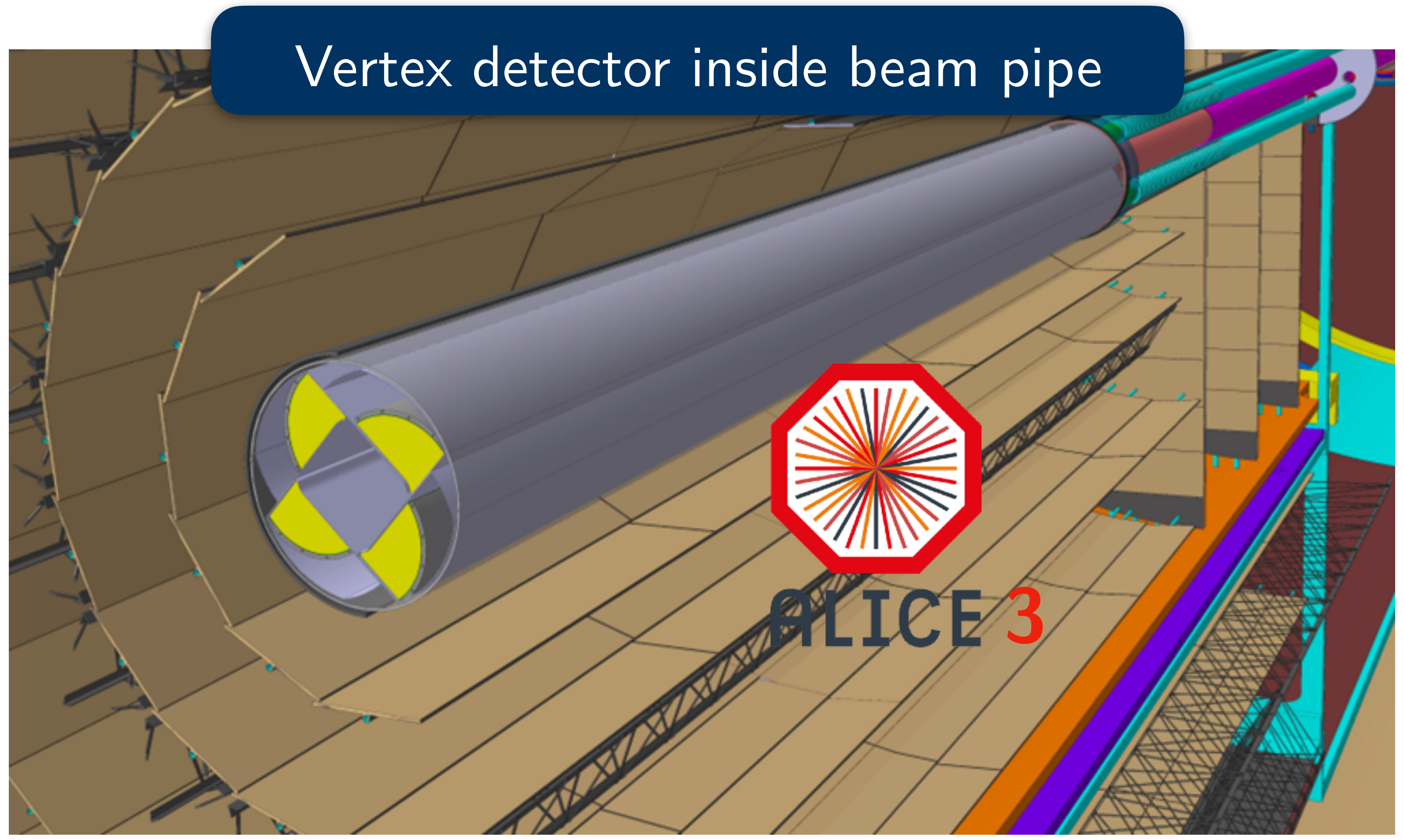
Strangeness enhancement & multi-charm production



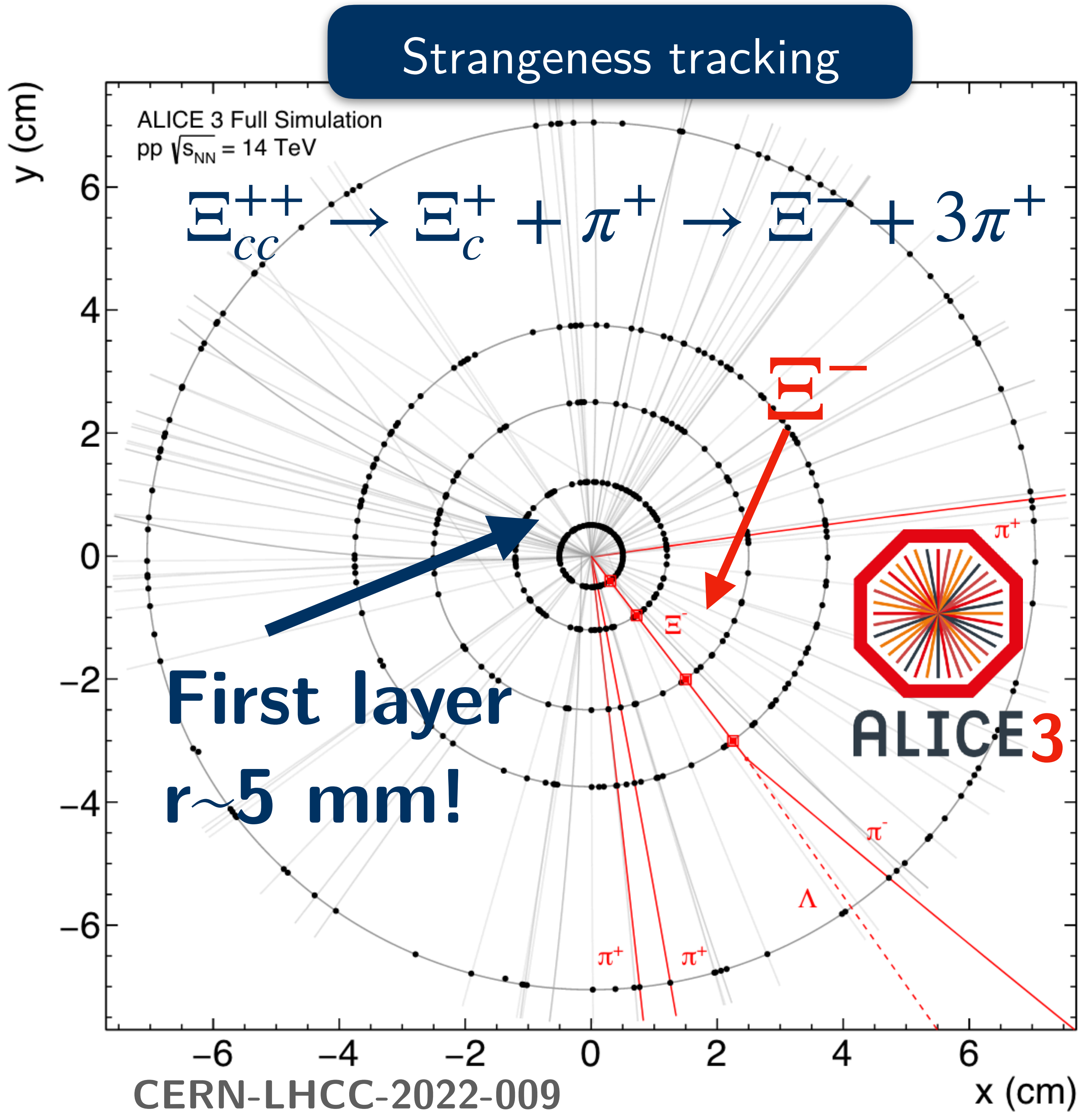
- Strangeness enhancement observed in pp and p-Pb collisions → smooth as a function of multiplicity

ALICE3 (and ITS3) will offer novel insights in the multi-charm sector!





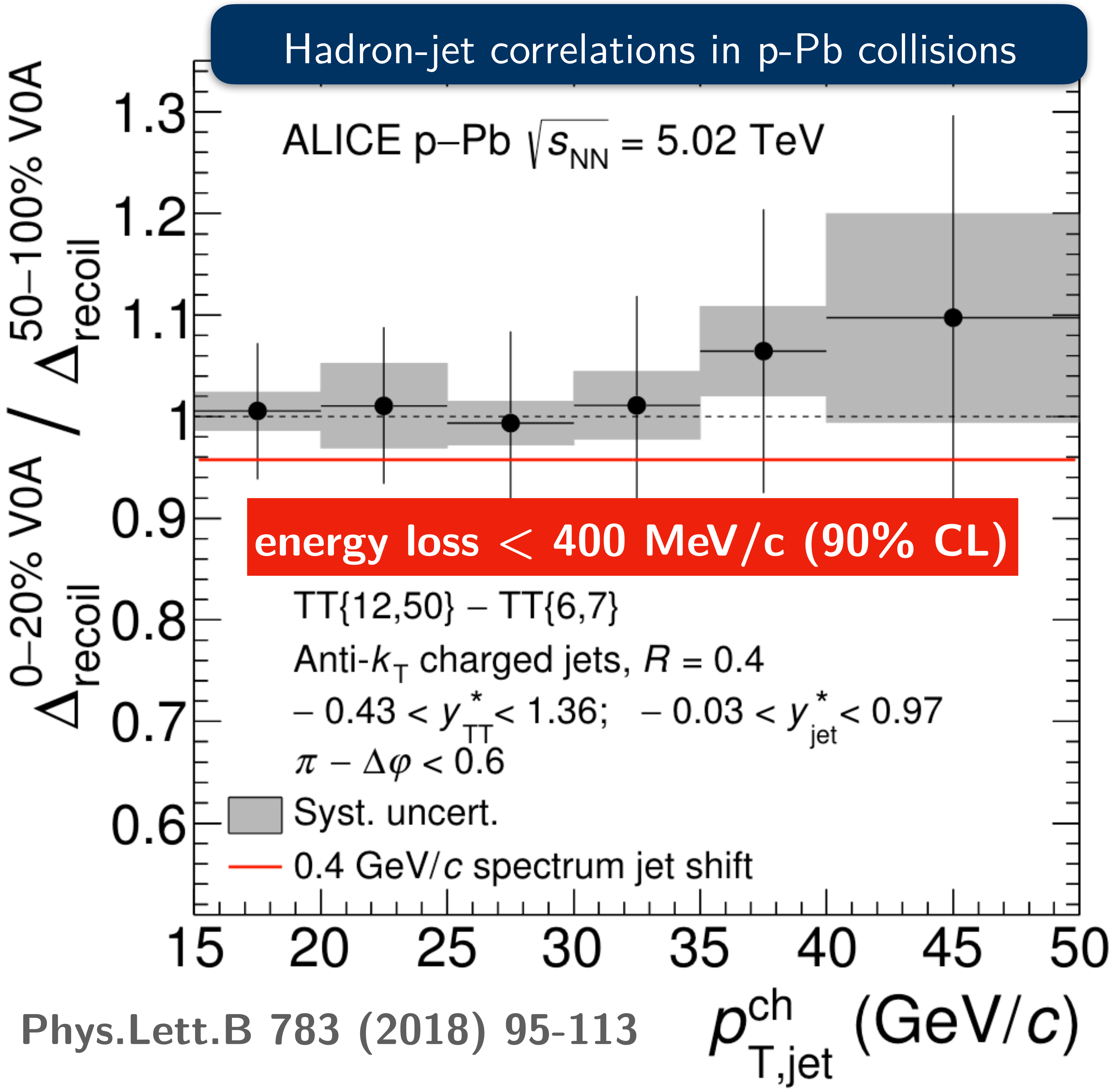
unique opportunities thanks to "strangeness tracking" in silicon pixel tracking layers



Jet quenching in p-Pb collisions?

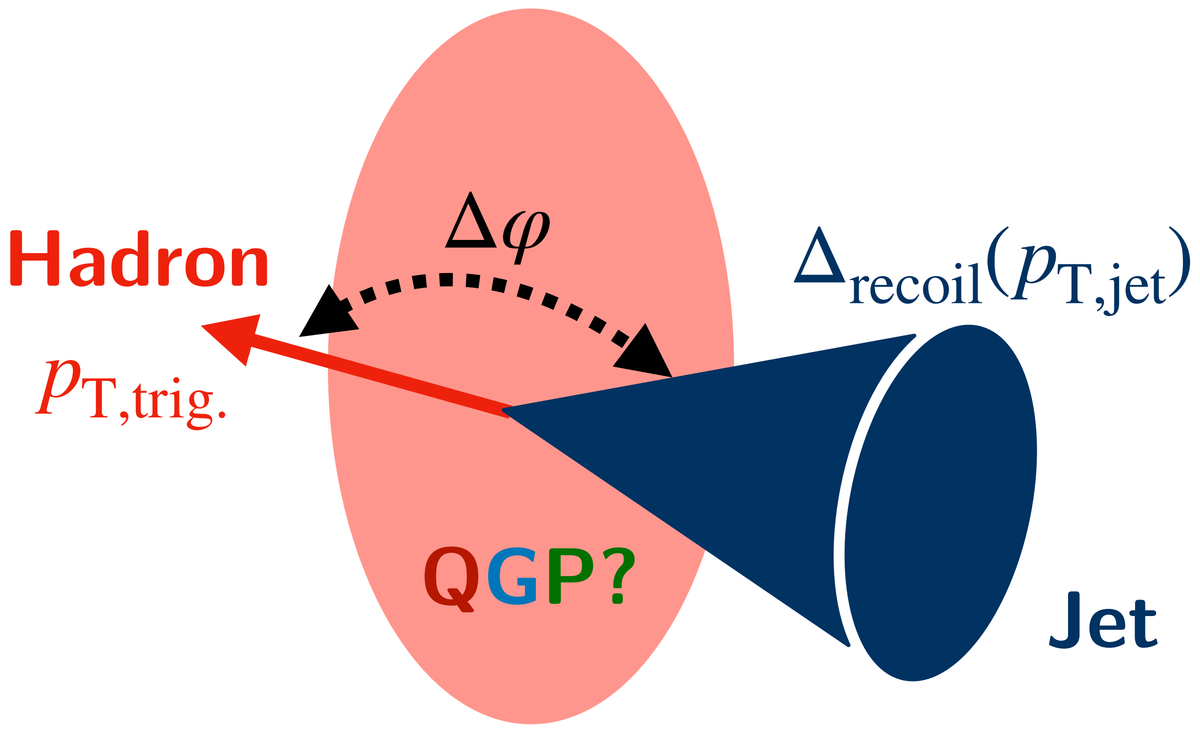
- **Jets are a key observable in heavy-ion collision**; significant jet quenching observed in Pb-Pb collisions
- BUT: so far no jet quenching observed in p-Pb collisions within experimental uncertainties
- Significant increase in p-Pb statistics at HL-LHC → higher sensitivity to energy loss in p-Pb

ALICE Run 1/2



Phys.Lett.B 783 (2018) 95-113

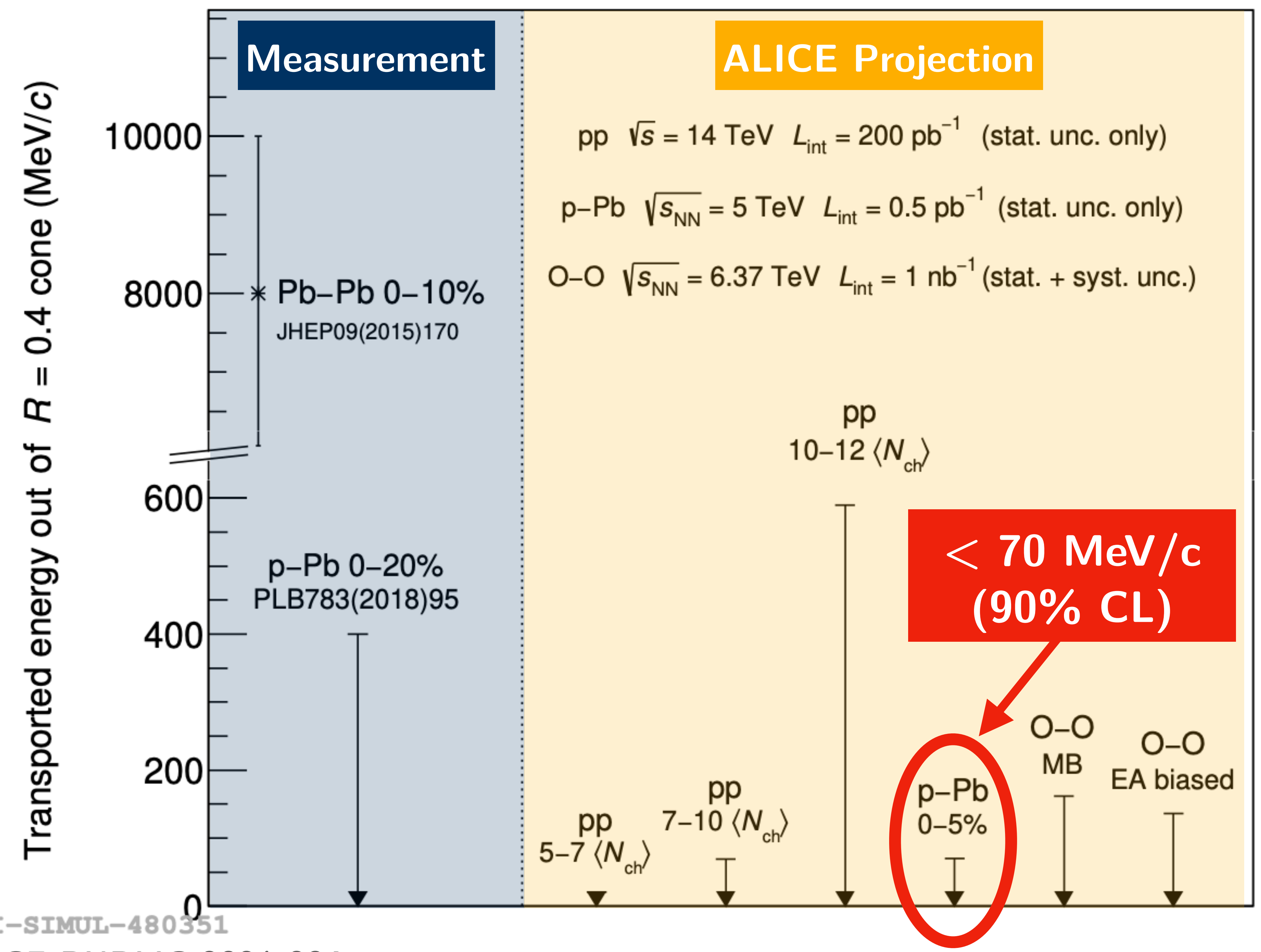
HL-LHC →



$$\Delta_{recoil}\left(p^{ch}_{T,jet}\right) = \frac{1}{N_{trig}} \frac{d^2 N_{jets}}{dp^{ch}_{T,jet}}\bigg|_{p_{T,trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jets}}{dp^{ch}_{T,jet}}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

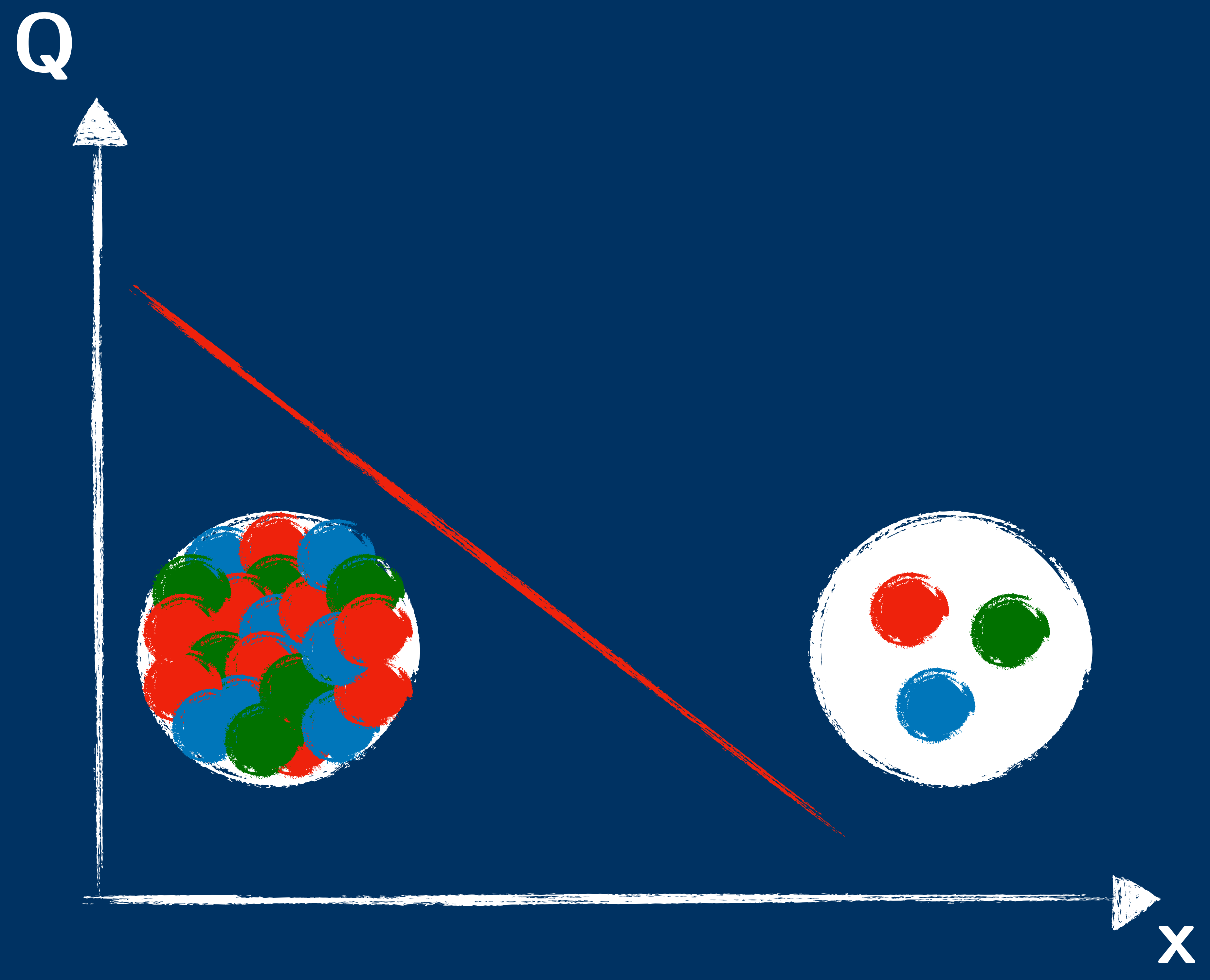
Projection Run 3 & 4

Semi-inclusive hadron-jet correlations

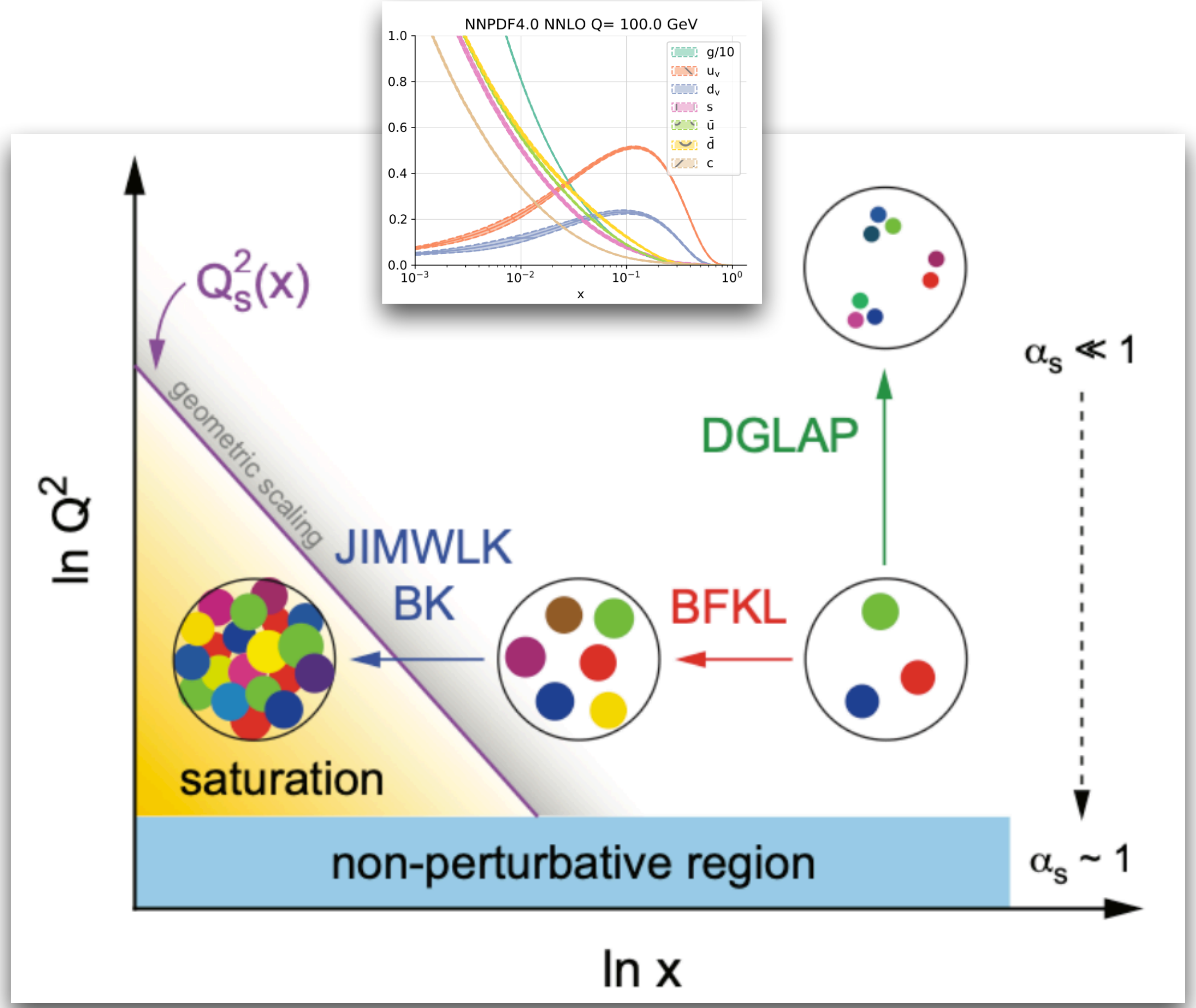


ALICE-PUBLIC-2021-004

Pushing to lower Bjorken-x:
Gluon saturation & the ALICE FoCal



Non-linear QCD at low-x



ALICE-PUBLIC-2023-001
Eur.Phys.J.C 82 (2022) 5, 428

How can we probe gluon saturation experimentally in a meaningful way?

QCD phenomena evolve logarithmically in x and Q^2

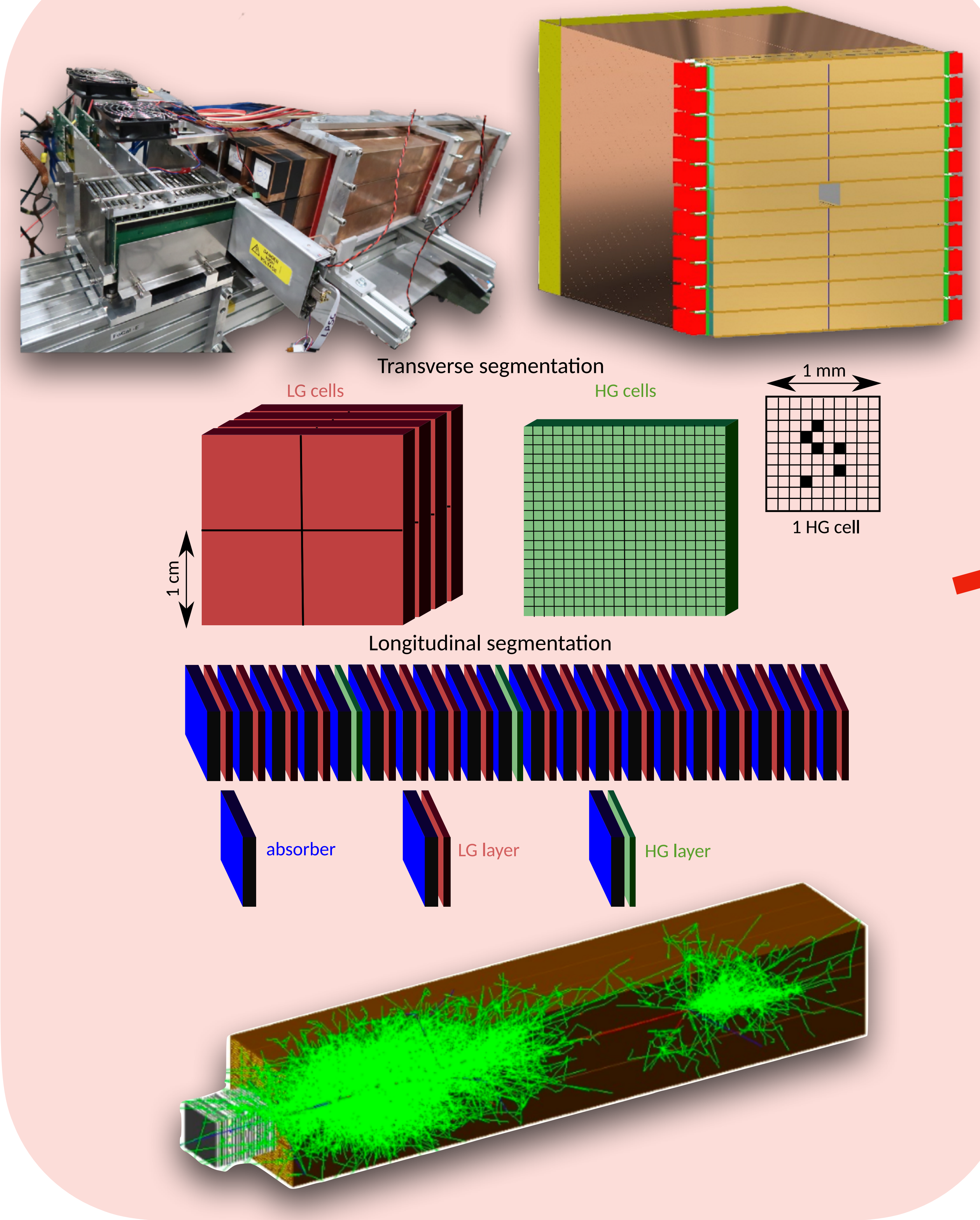
→ **logarithmically large experimental coverage in x and Q^2 desirable**

Universality: theoretical description should be able to self consistently describe multiple observables in multiple collision systems

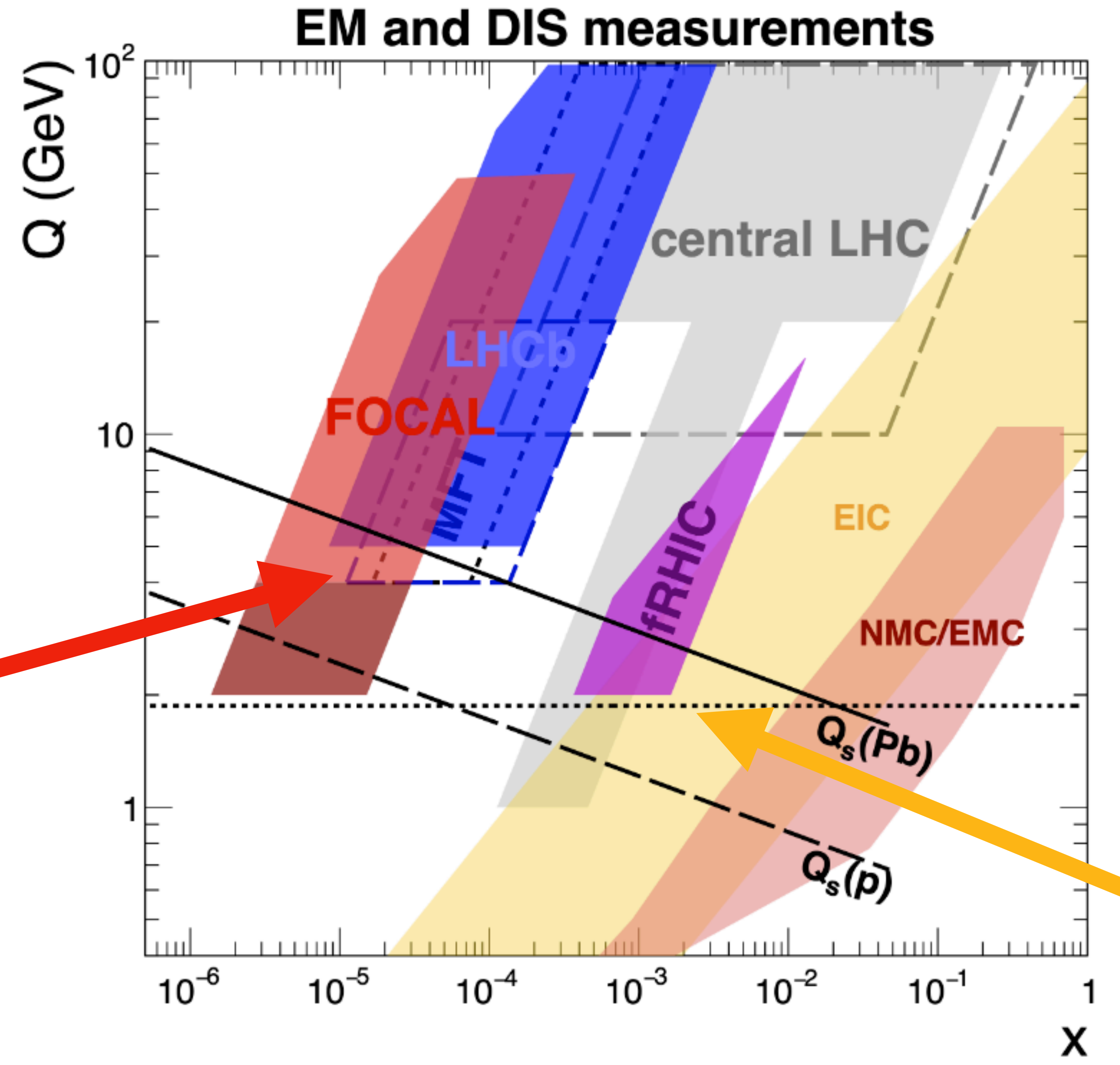
→ **multi-messenger approach: measure multiple probes at various experimental facilities**

Phasespace coverage for "saturation searches"

Forward p-A collisions:
The ALICE FoCal



CERN-LHCC-2020-009, ALICE-PUBLIC-2023-001, CERN-LHCC-2024-004



Logarithmically large coverage in x and Q

Deep theoretical connection

DIS in e-A collisions:
The Electron-Ion Collider (EIC)

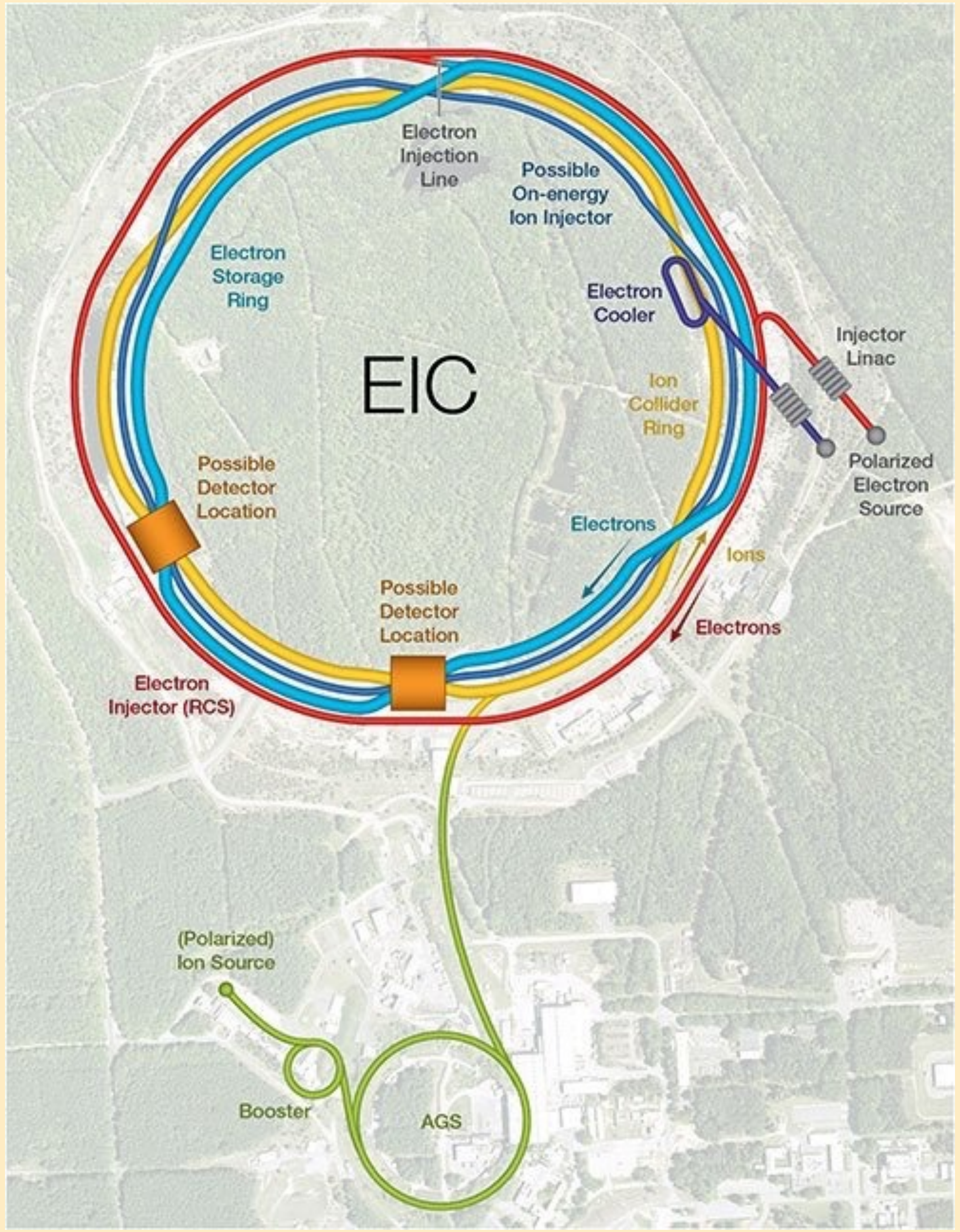
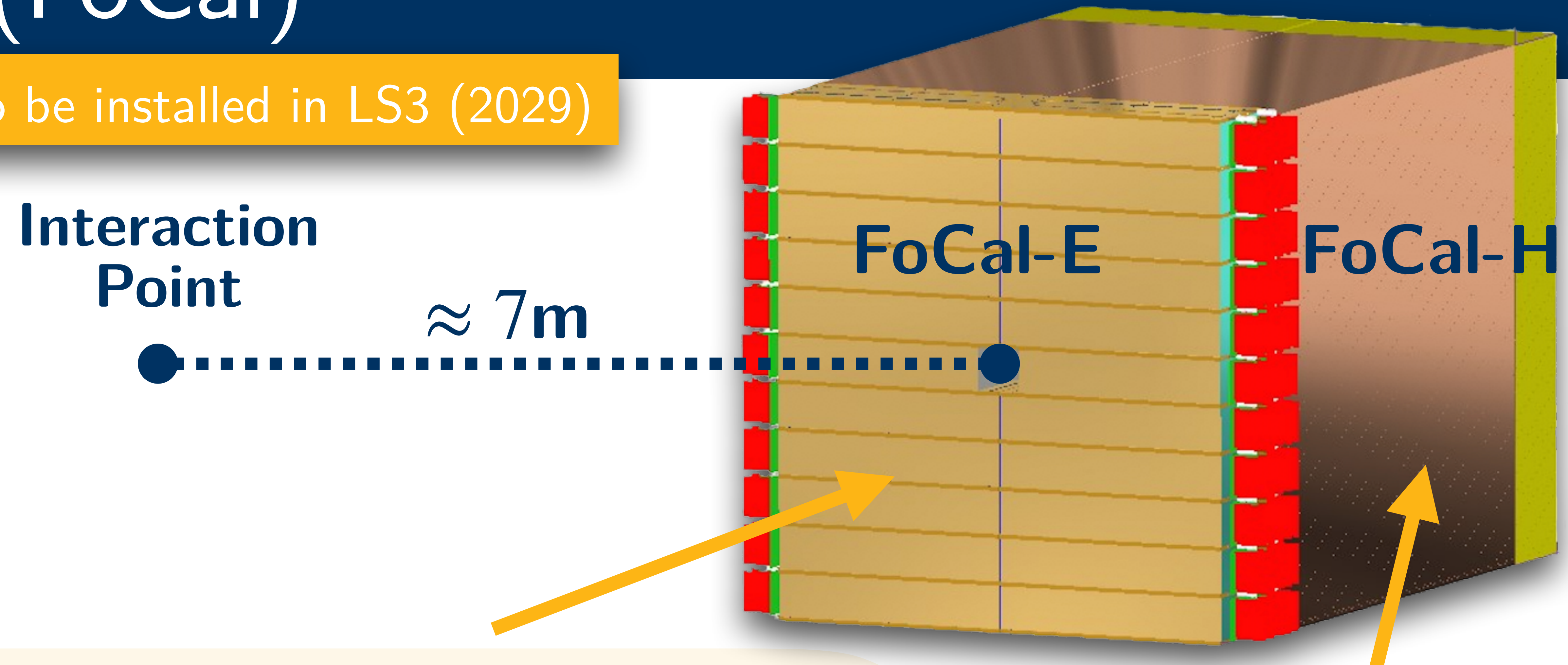


Image Credit: DOE

The ALICE Forward Calorimeter (FoCal)

To be installed in LS3 (2029)

- upgrade to the ALICE detector covering very forward rapidities $3.2 < \eta < 5.8 \rightarrow x \sim 10^{-6}$
- **FoCal-E** is a highly granular Si-W calorimeter combining two sensor technologies: 18 silicon pad layers ($1\text{x}1\text{cm}^2$); two pixel layers ($30\text{x}30\mu\text{m}^2$)
- **FoCal-H** uses scint. fibres embedded into Cu tubes



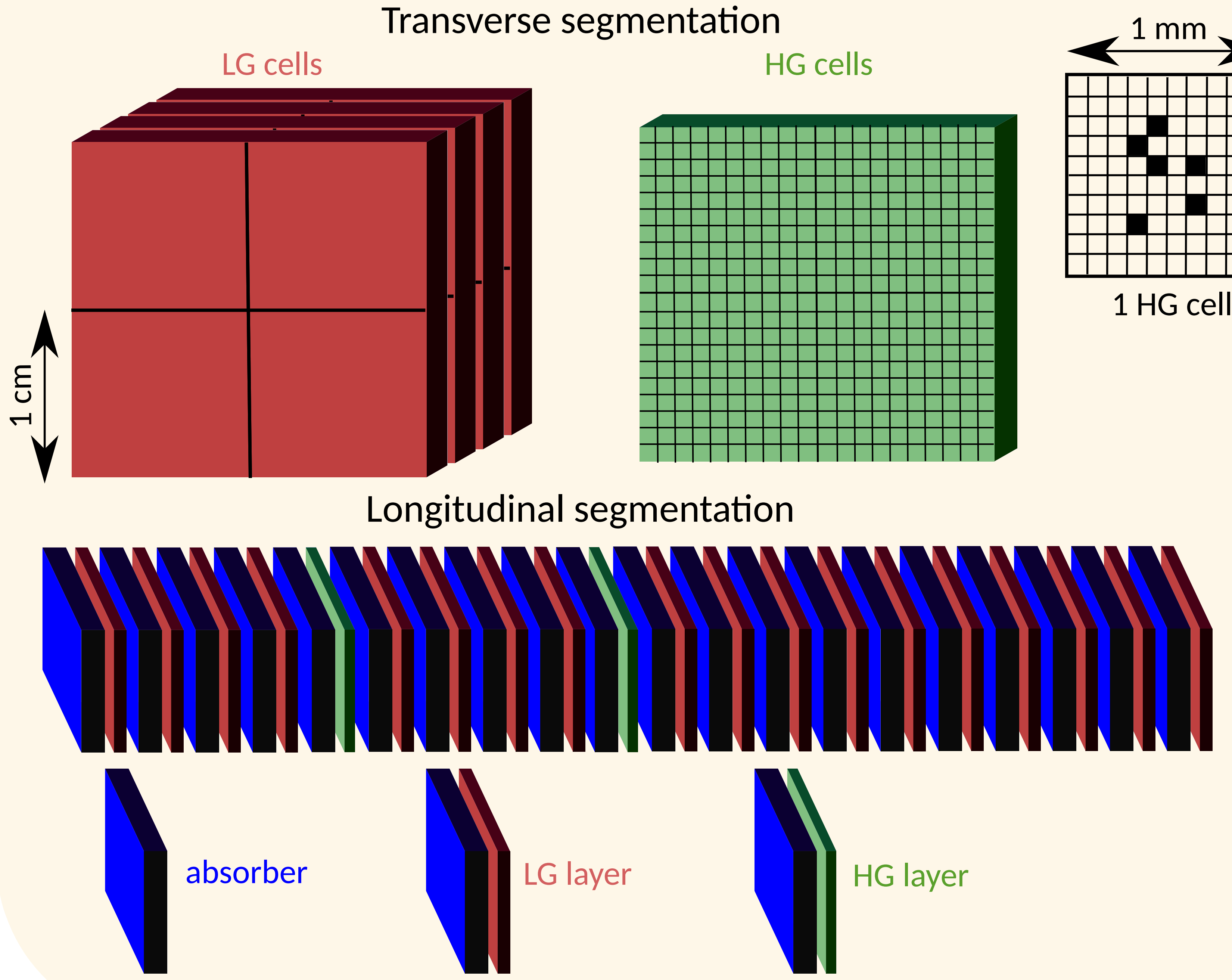
The FoCal physics program

FoCal capabilities allow explorations of gluon saturation using a **multi-messenger approach**:

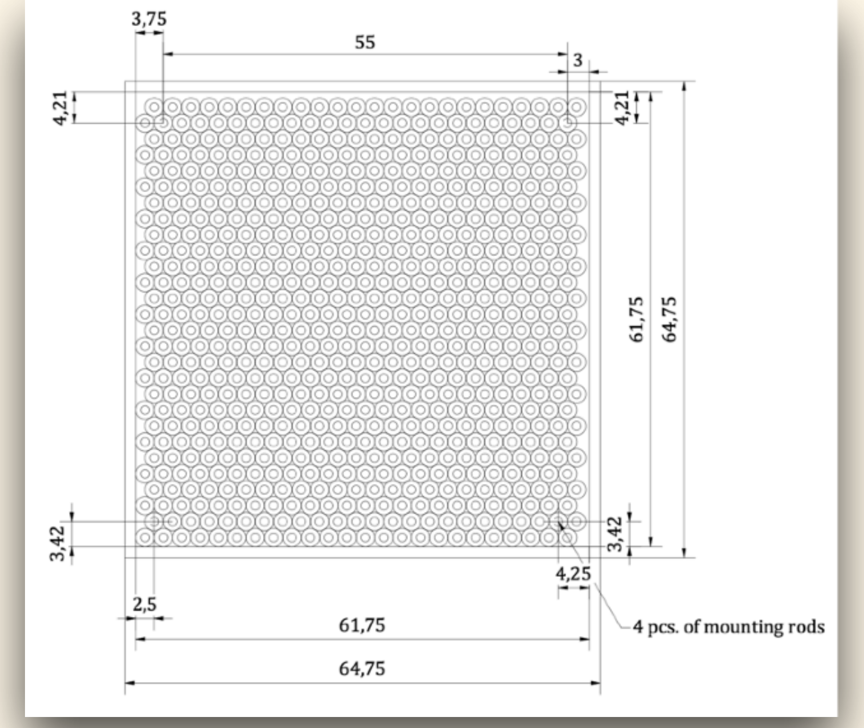
- Prompt photon production
- $\gamma-$hadron correlations
- Production of π^0, η and vector mesons
- Jet measurements (e.g. dijet production)
- Vector meson photoproduction in UPCs

In this talk

FoCal-E detector

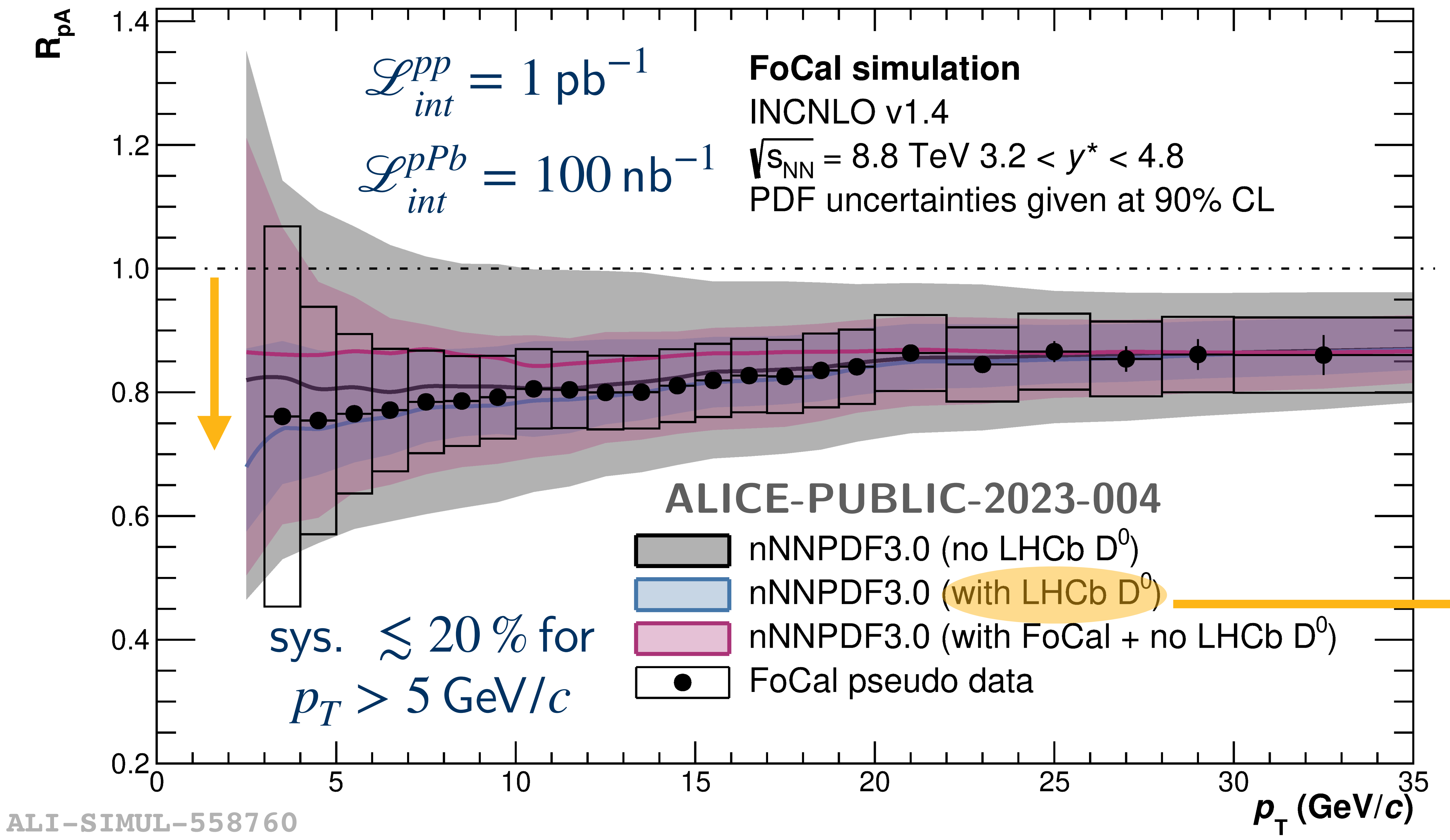


FoCal-H detector

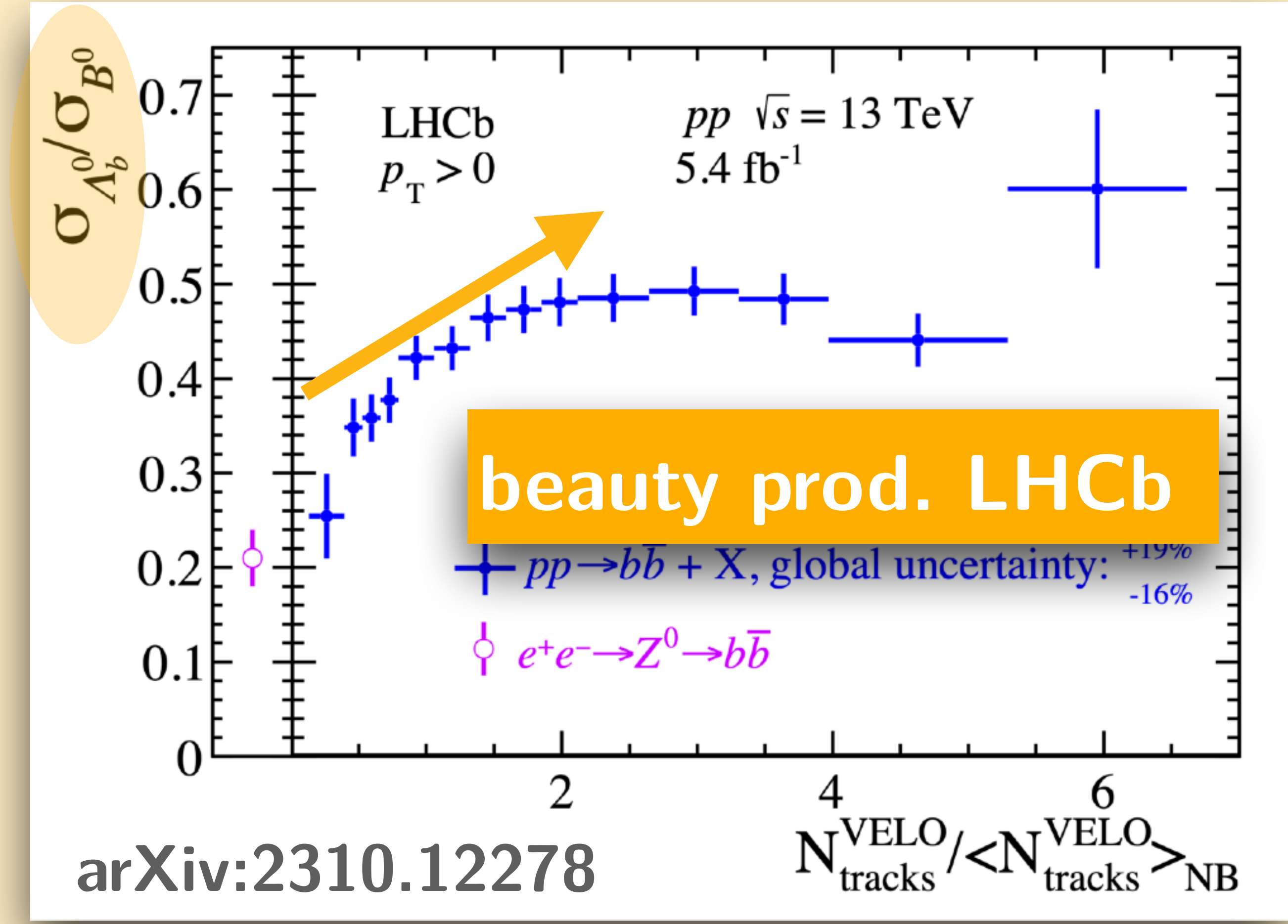


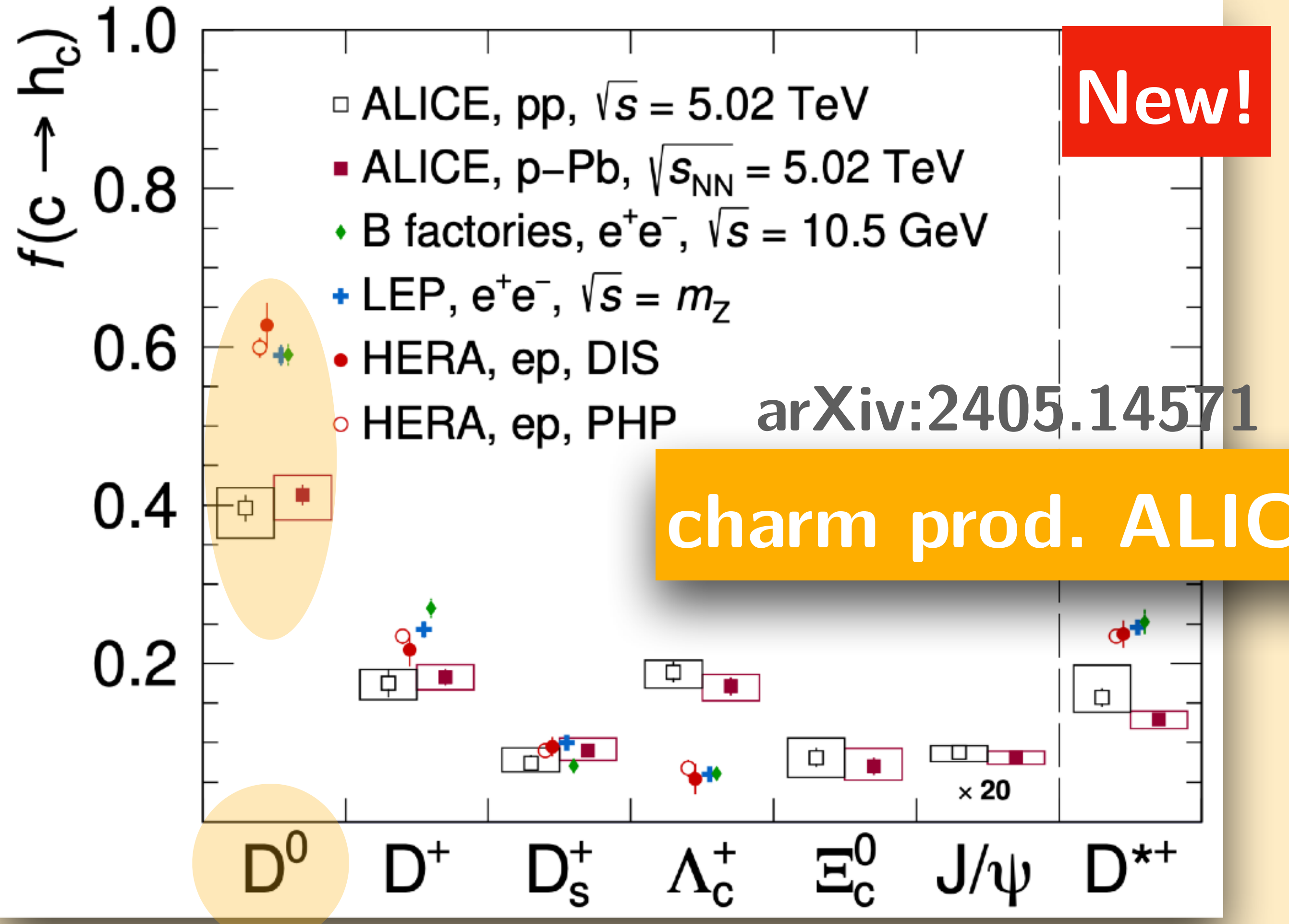
CERN-LHCC-2020-009,
ALICE-PUBLIC-2023-001
ALICE-TDR-022

Prompt photon production at forward rapidities



Are fragmentation functions universal?

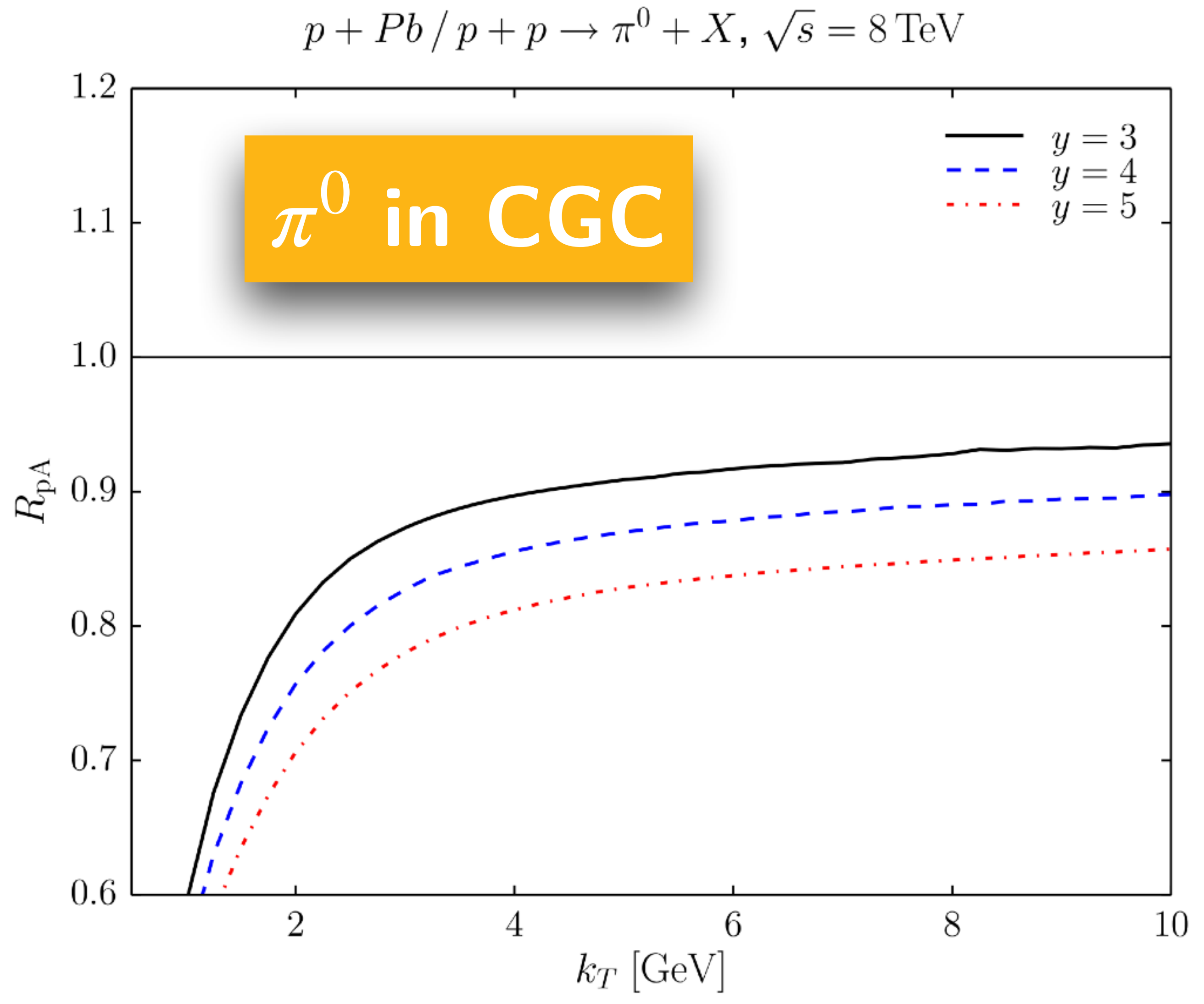




- **FoCal pseudo-data** of nuclear modification factor R_{pA} constructed using input from NLO+nPDF and assumptions on stat. and sys. uncertainties from perf. studies
- **Bayesian re-weighting of nNNPDF30** prediction showcases **significant reduction of nPDF uncertainties** when including FoCal data; comparable to D meson measurement by LHCb

Prompt photons → no final state and hadronisation effects → universality test of low-x formalism

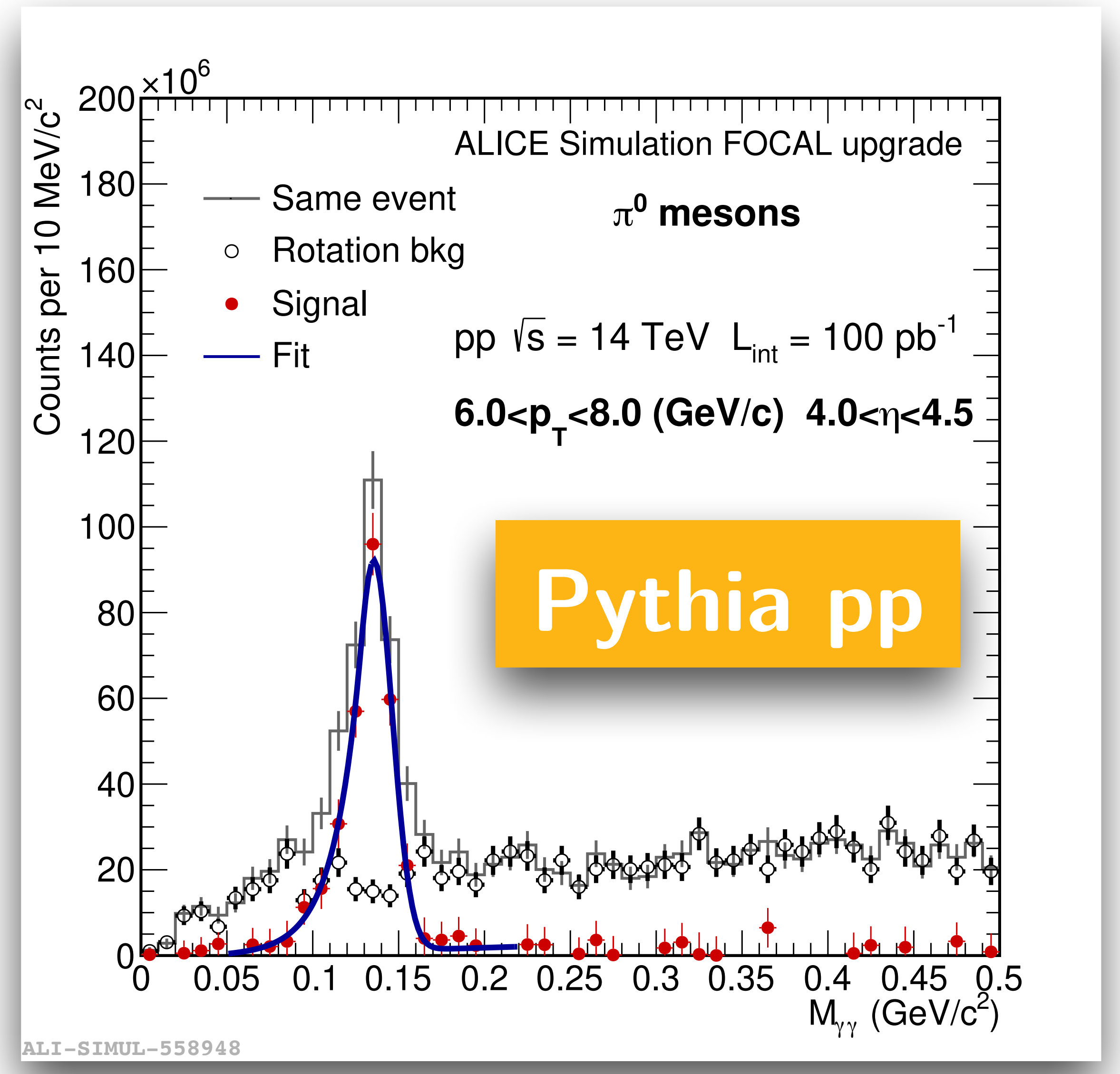
Neutral meson production at forward rapidities



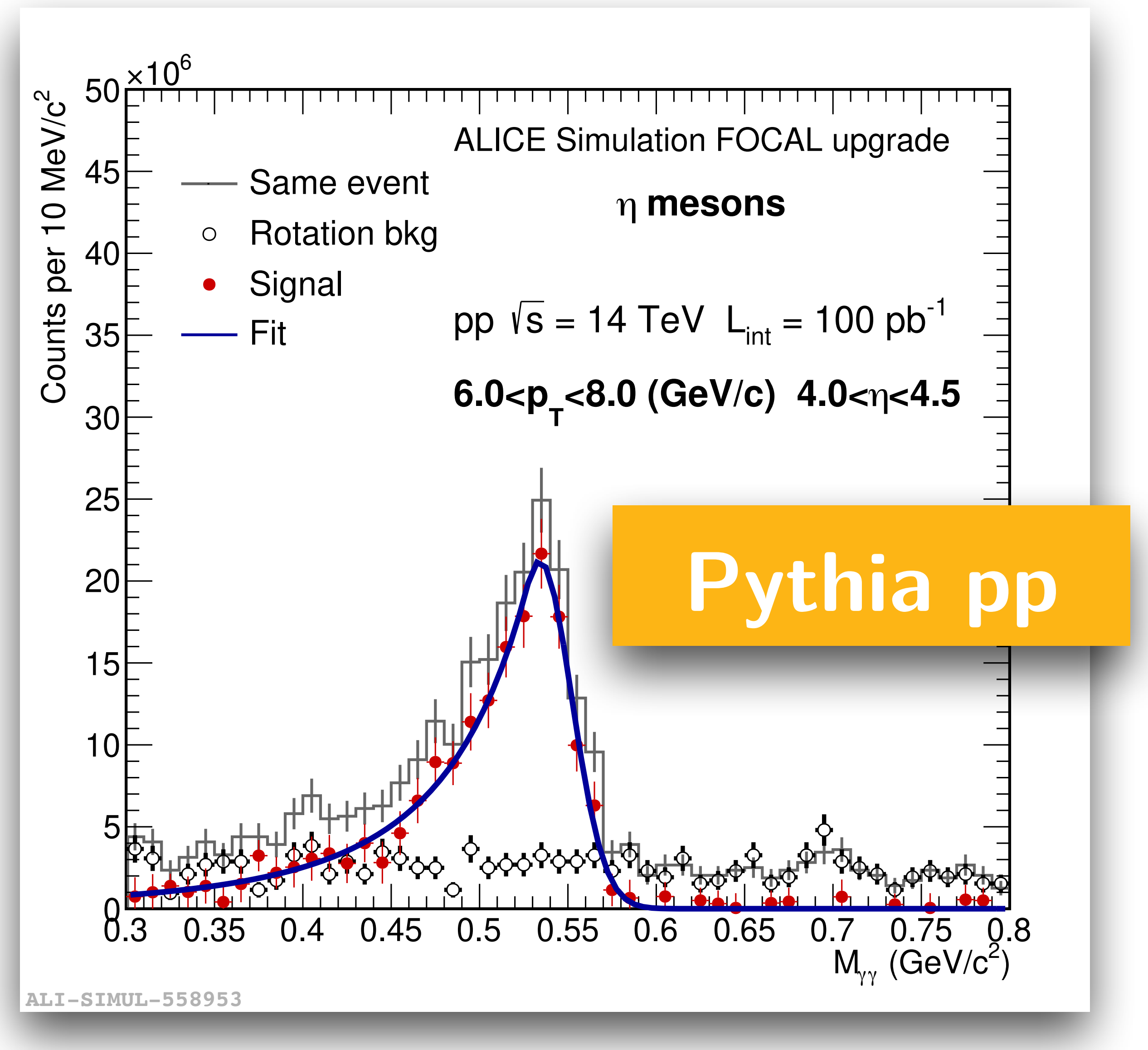
- simulated data + FoCal geometry in GEANT demonstrate FoCal capabilities to measure e.g. π^0, η and ω mesons
- expected luminosities in Run 4 sufficient to measure over large energy range **of up to 2 TeV**, also differentially in rapidity
- highly granular **pixel layers** allow for efficiencies of up to $80\,\%$, even for **photon separation of $<$ 5mm**!

ALICE-PUBLIC-2023-004

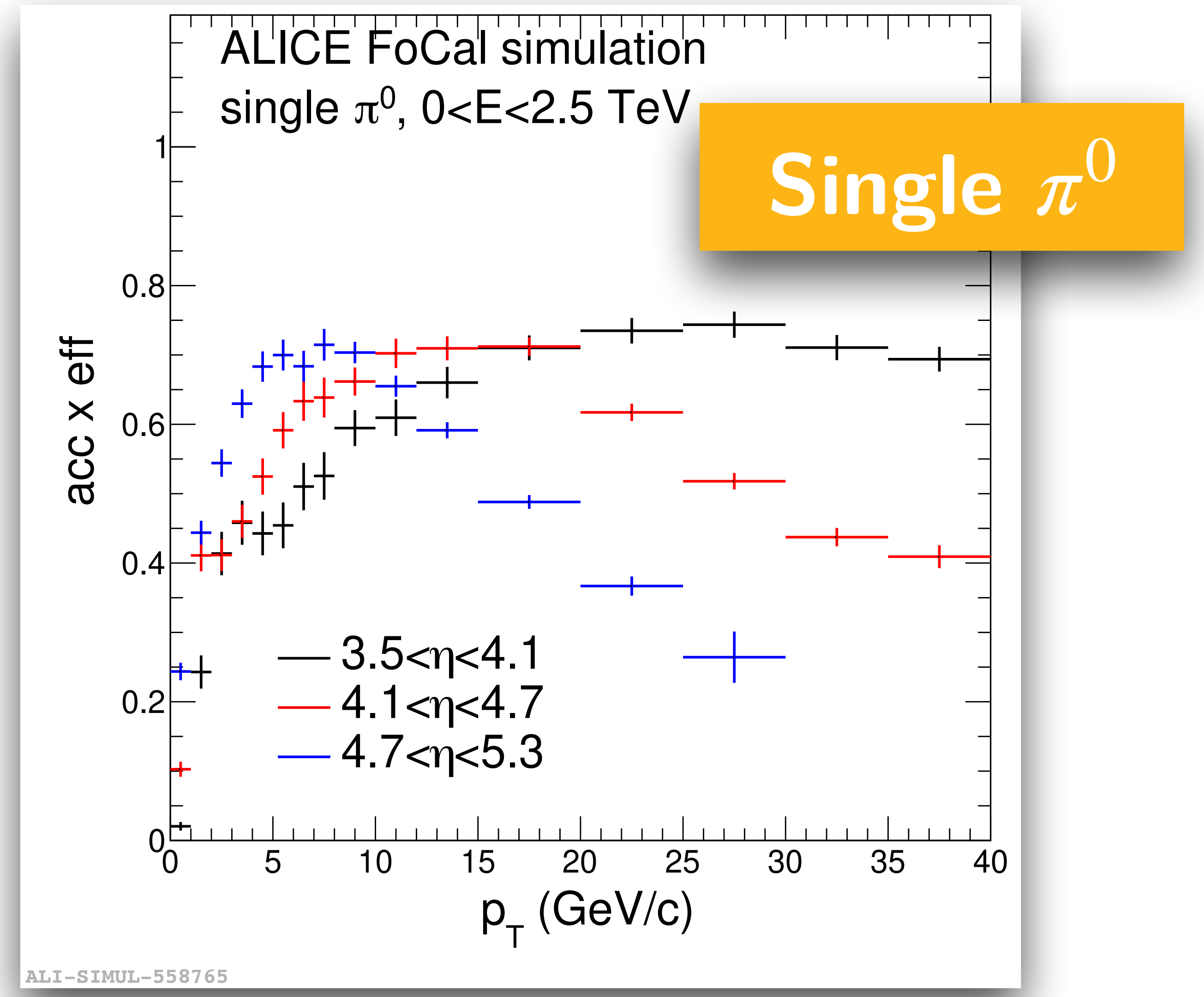
$\pi^0 \rightarrow \gamma\gamma$ reconstruction



$\eta \rightarrow \gamma\gamma$ reconstruction



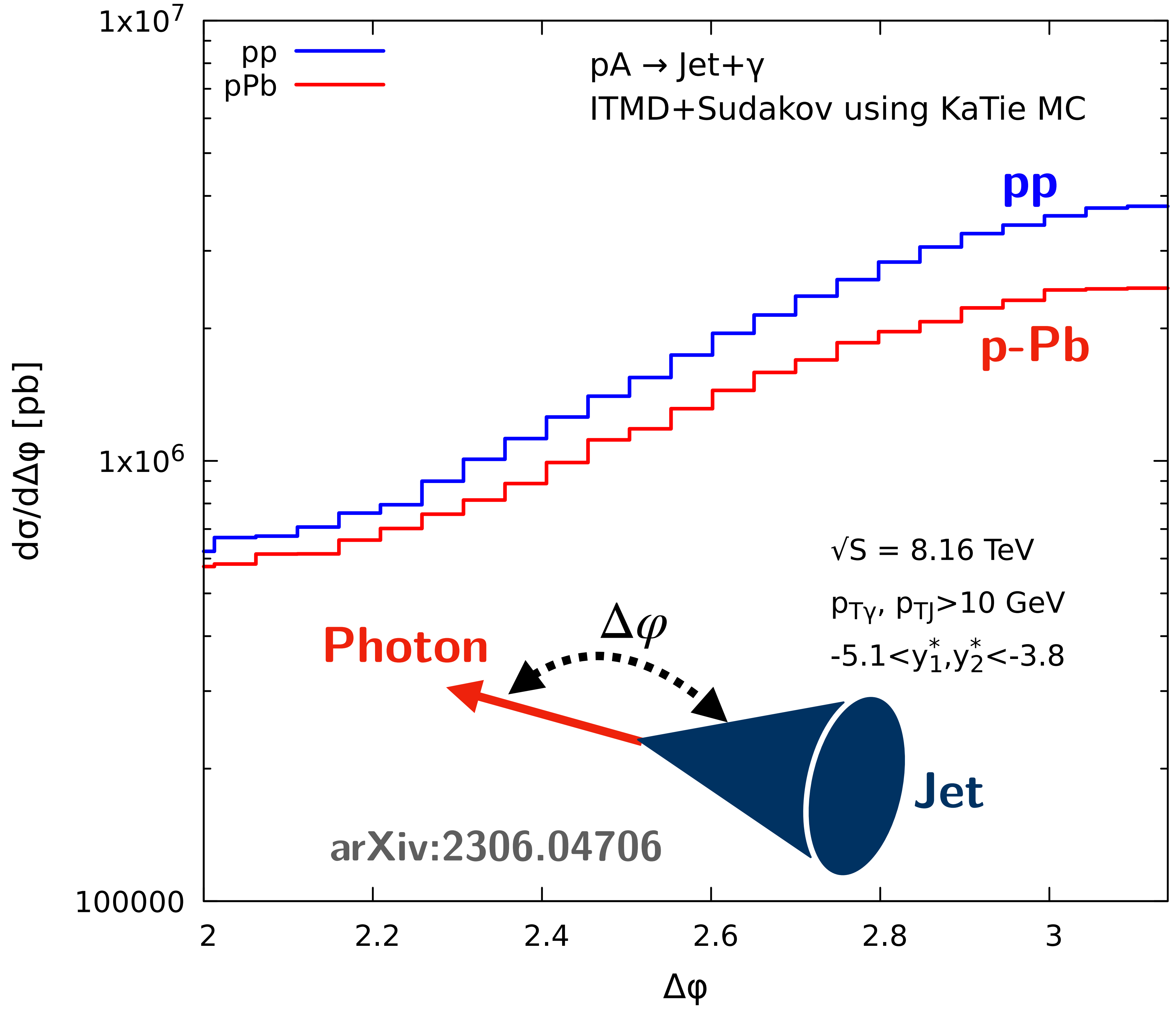
π^0 reconstruction efficiency



γ-hadron and γ—jet correlations

Theory:

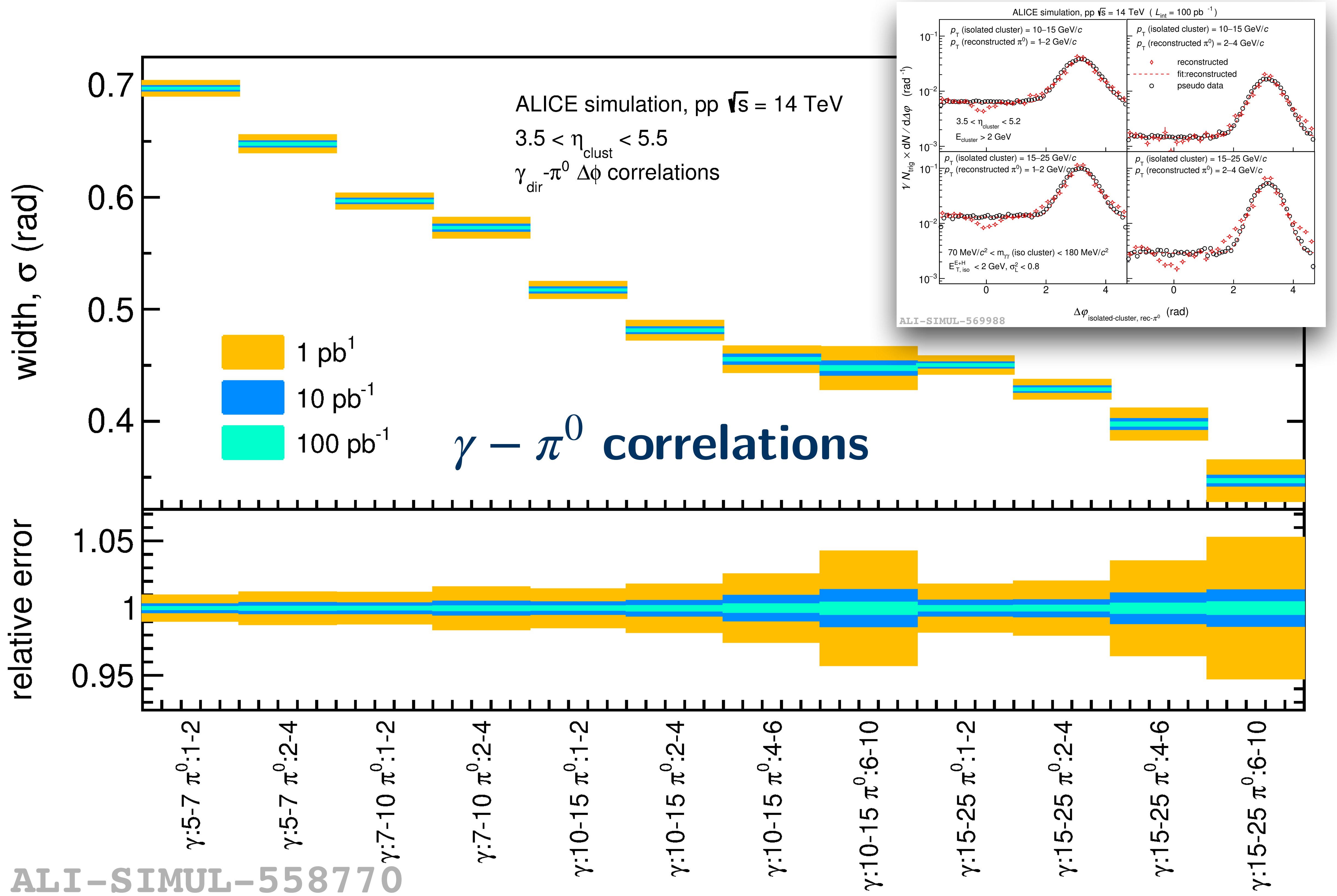
- Study of γ-hadron correlations offers additional sensitivity to low-x gluon dynamics
- Expectation of **yield suppression** and **de-correlation** due to saturation effects



FoCal performance:

ALICE-PUBLIC-2023-004

- Analysis of γ-π^0 corr. in simulated pp collision events + detector smearing
- correlation peak can be measured precisely: stat. unc. of peak width $\sim$ 0.001 rad for expected Run 4 luminosities

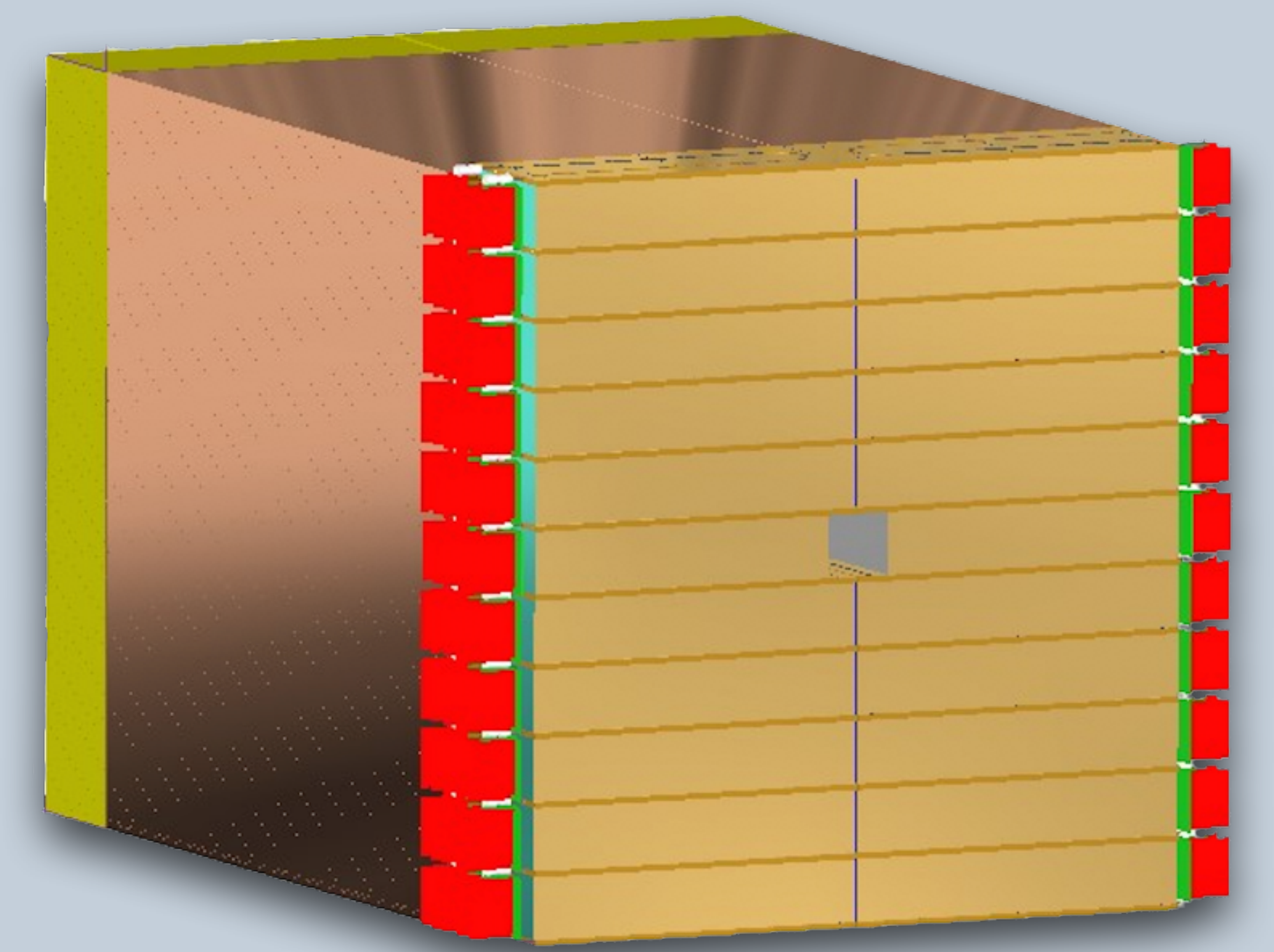


Possibilities for ALICE3 + FoCal?

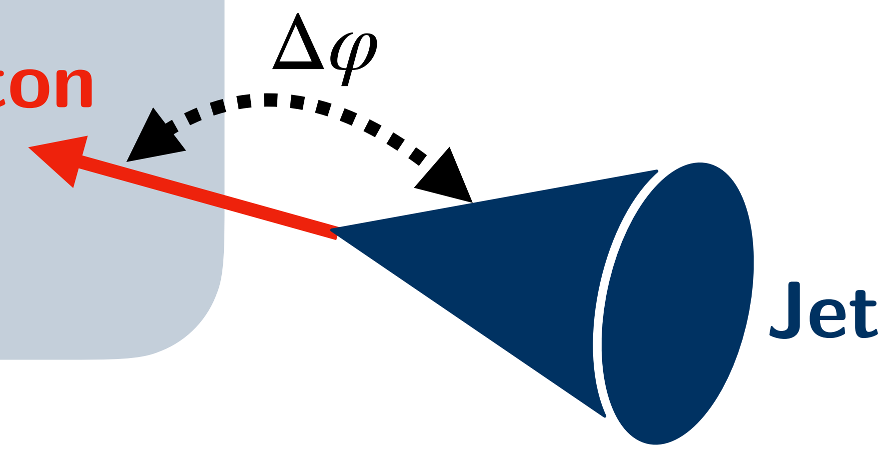
Simulation physics studies in progress!

FoCal detector

FoCal TDR: CERN-LHCC-2024-004

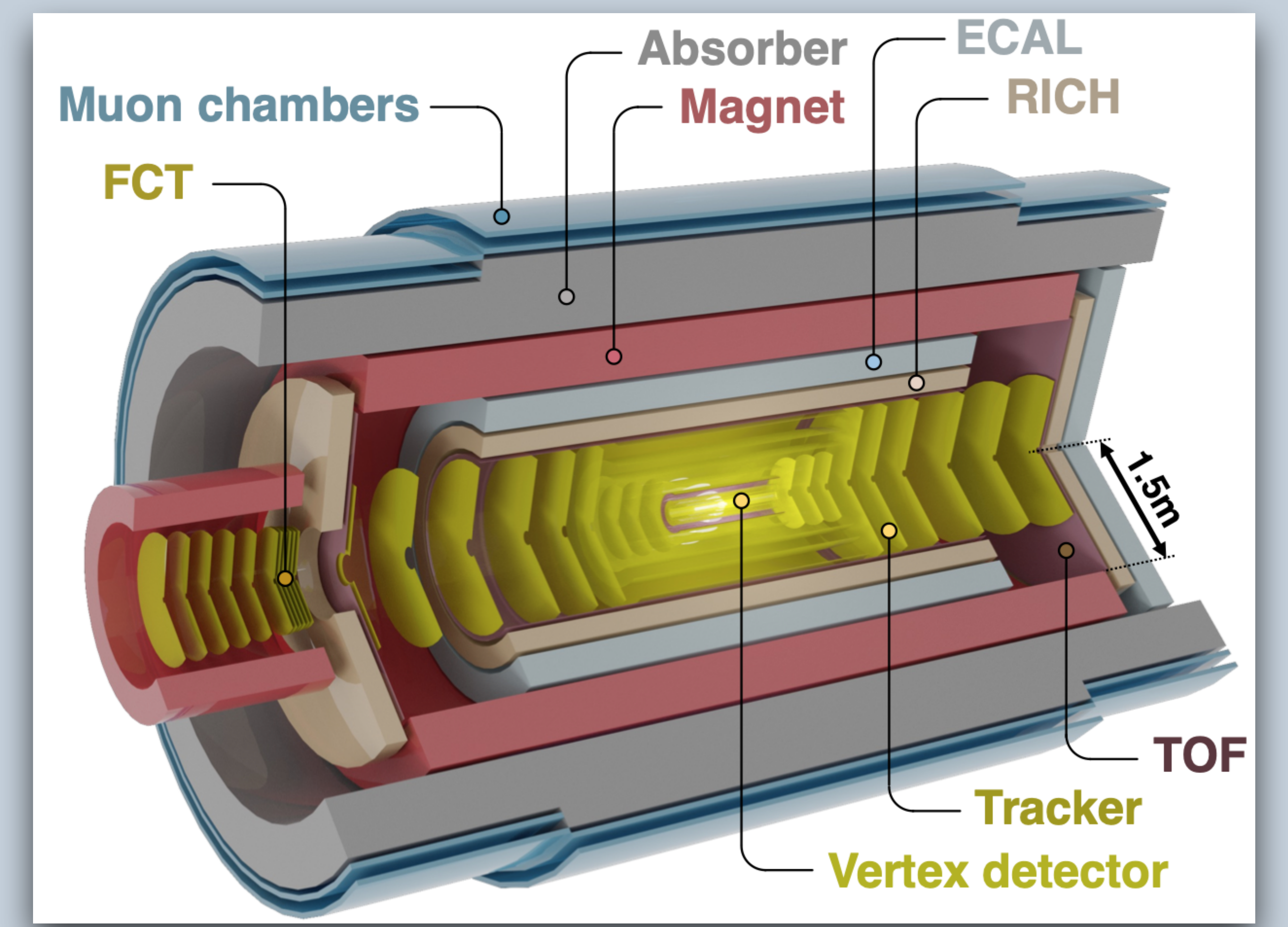


$3.2 < \eta < 5.8$



ALICE3

ALICE3 LOI: CERN-LHCC-2022-009



Tracking: $|\eta| < 4$; **ECAL:** $-1.6 < \eta < 4$

Unprecedented coverage $\Delta\eta \sim 10$!

Unique possibilities for forward dijet production, γ-jet production and UPCs

Connections between EIC and LHC

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in p+A	γ+jet in p+A	dijet in p+A
xG_{WW}	$-$	$-$	$+$	$-$	$-$	$+$
xG_{DP}	$+$	$+$	$-$	$+$	$+$	$+$

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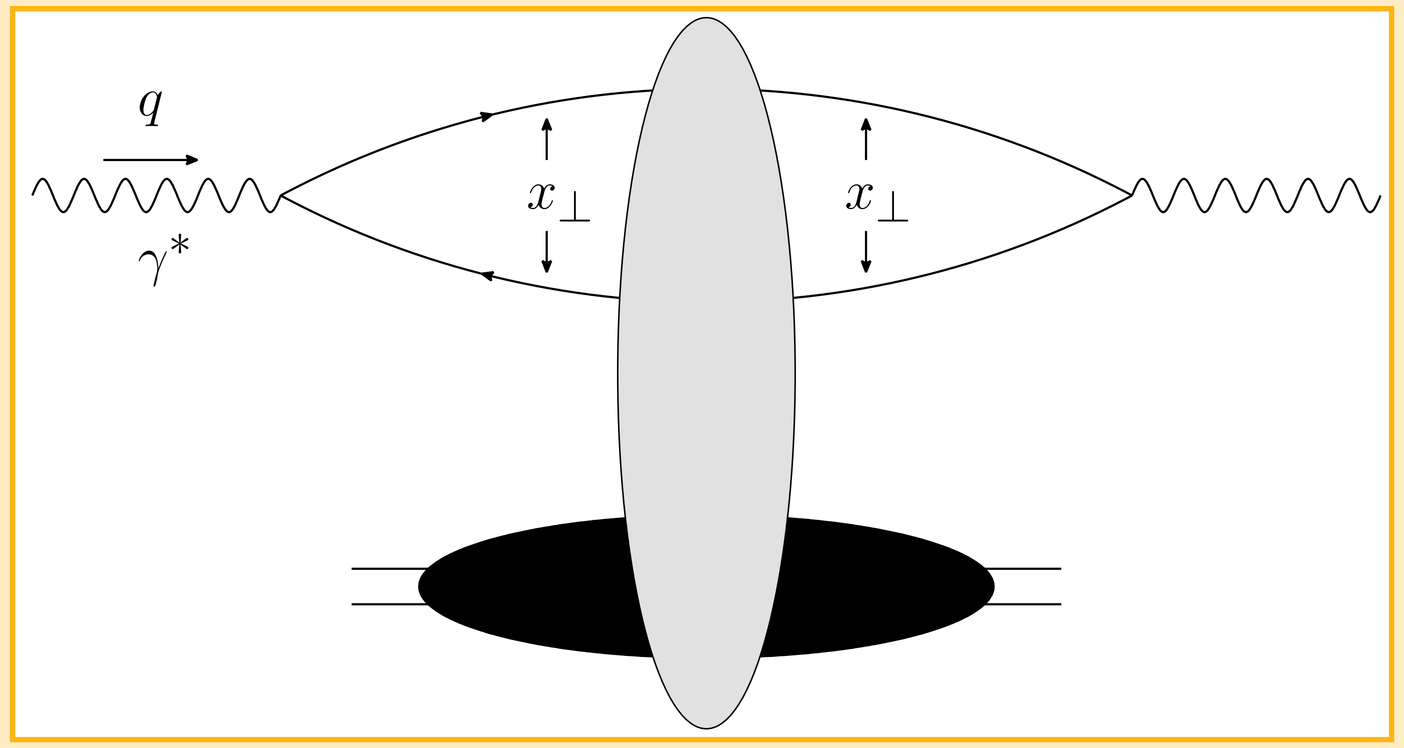
Multiple processes in **e-A DIS** and **forward p-A** collisions are theoretically described using the **same dipole/quadrupole scattering amplitudes!**

measurements in e-A DIS and forward p-A collisions
→ **test universal description of gluon saturated matter**

Bayesian inference already used successfully as a powerful tool study QGP → let's use it **in the saturation regime!**

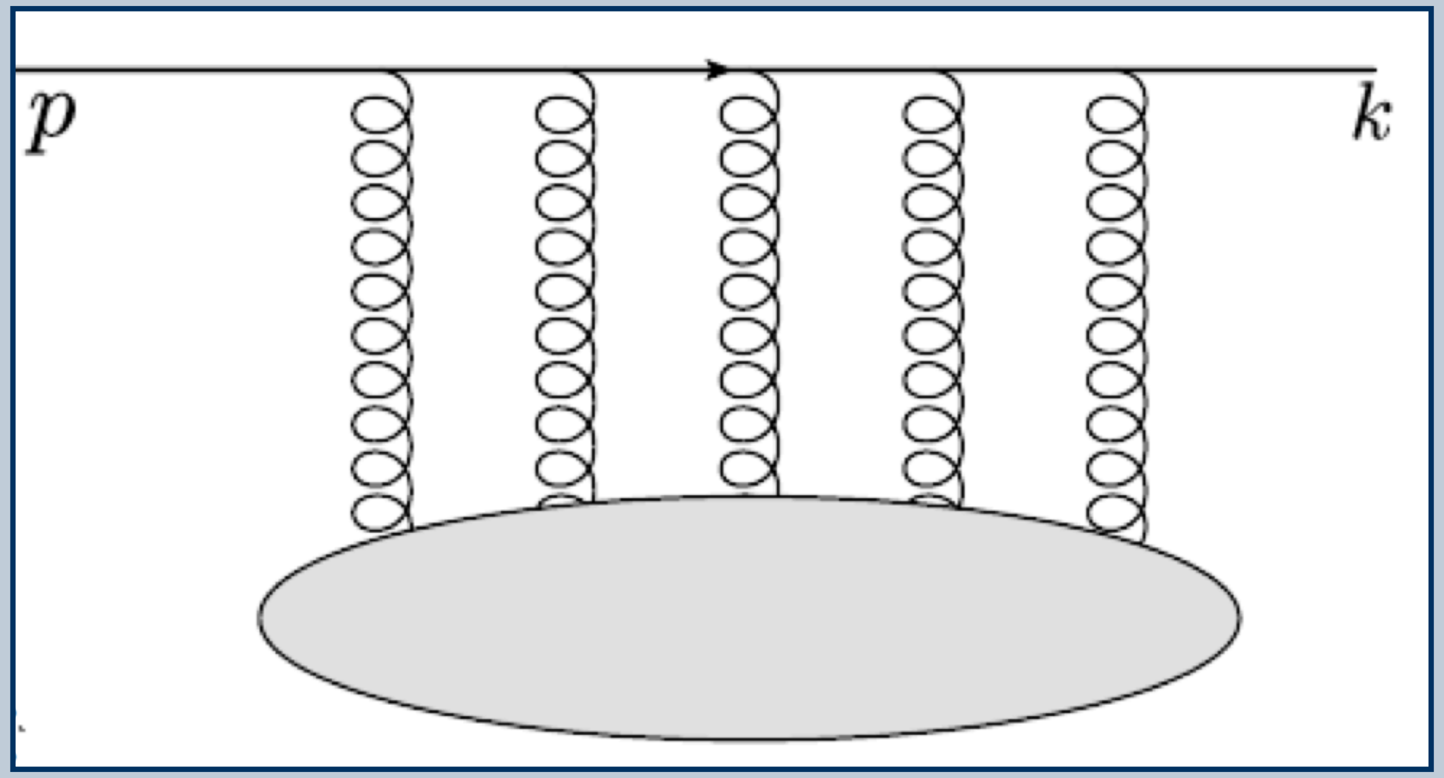
The whole picture (EIC + forward LHC/RHIC) will be more than the sum of its parts!

e+A Deep Inelastic Scattering (DIS)



JETP 30 (1970) 709-717, Phys. Rev. D 8 (1973) 1341, Nucl. Phys. B 335 (1990) 115

Forward p+A collisions



Phys. Rev. C 59 (1999) 1609, Phys. Rev. D66 (2002) 014021, Phys. Lett. B 503 (2001) 91

Summary

LHC data allowed for significantly improved constrains of nuclear PDFs in the last decade

ALICE is part of this effort with a rich p-Pb physics program & variety of observables at low p_T

Studies in small systems continue to surprise us with QGP like “signatures"

Distinction of p-Pb (cold nuclear matter) vs. Pb-Pb (hot nuclear matter) is no longer so clear!

ALICE will build a Forward Calorimeter (FoCal) for Run 4 with coverage $3.2 < \eta < 5.8$ $(x \sim 10^{-6})$

Exploration of gluon saturation with a multi-messenger program for p-Pb collisions

Deep theoretical connections between forward physics at LHC & RHIC and EIC

Additional detector synergies between FoCal and ALICE3 for Run 5 & 6

Thank you for your attention!

Not shown today: UPCs (see talk by Daniel tomorrow); p-O and O-O (see e.g. ALICE-PUBLIC-2021-004), many other interesting ALICE results not shown

Backup