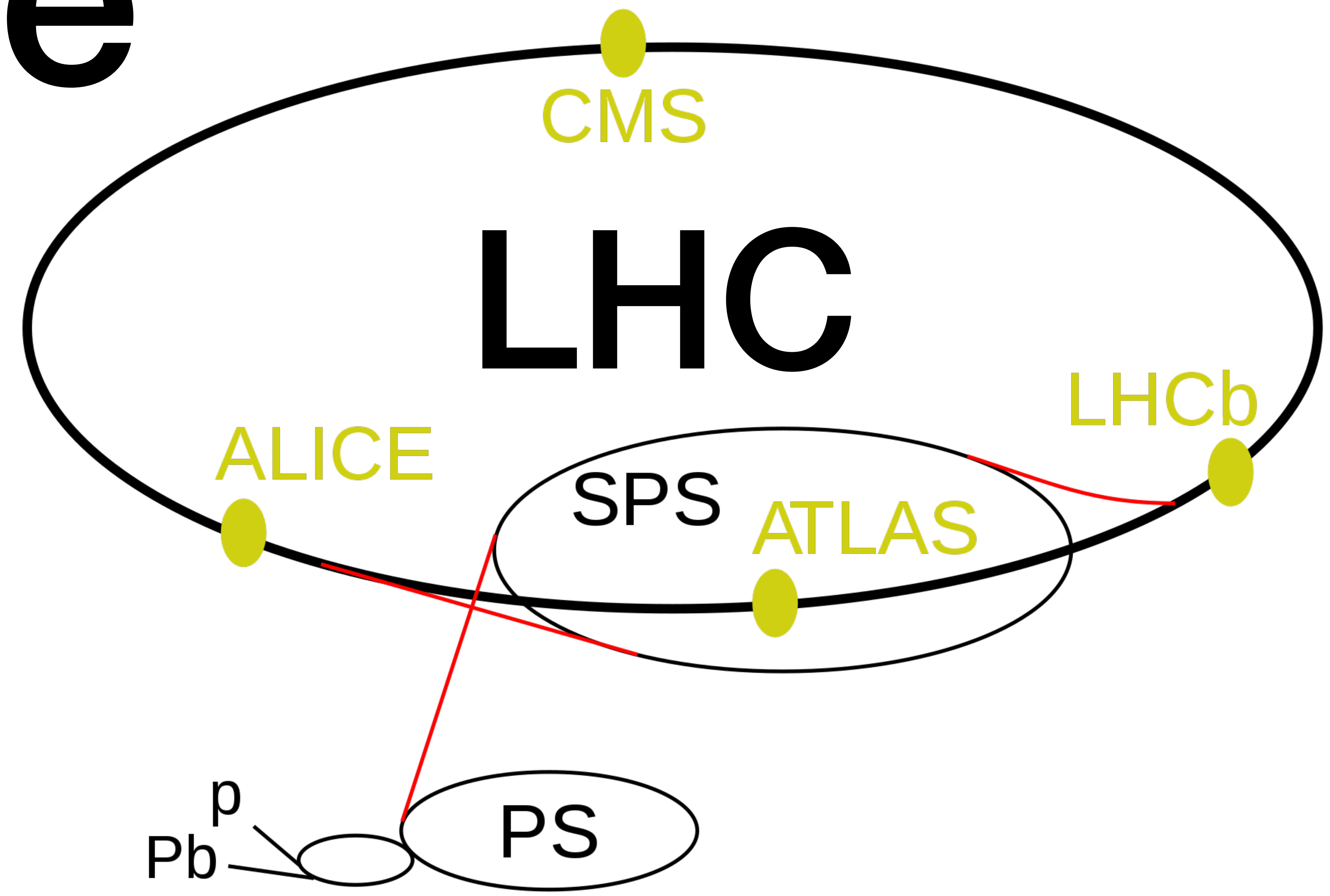
Future LHC program

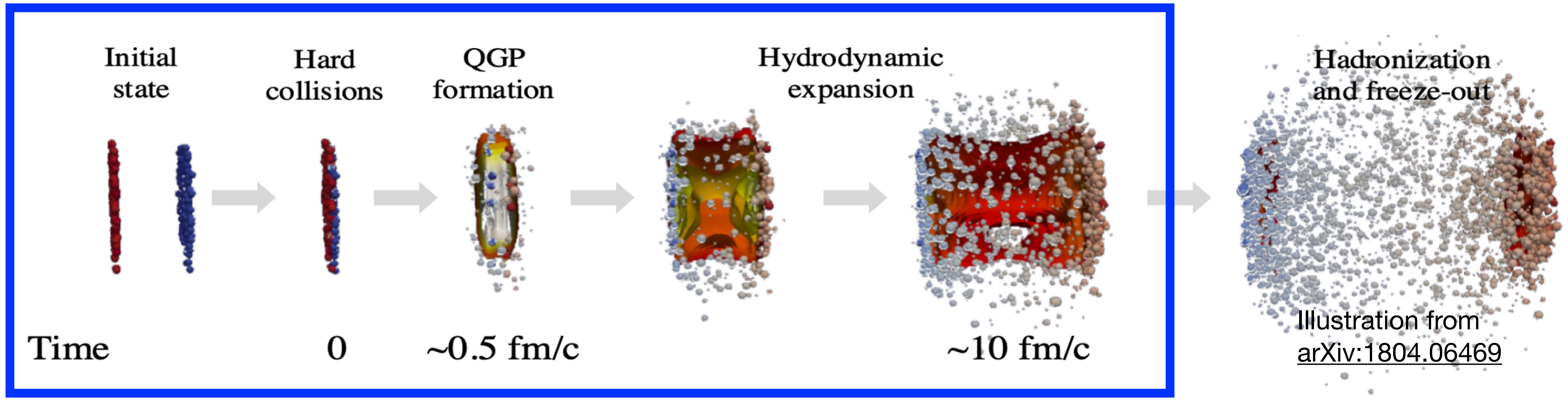


Constantin Loizides
(ORNL)

23.06.2023

Future instrumentation related to initial stages of high-energy nuclear collisions

Initial Stages



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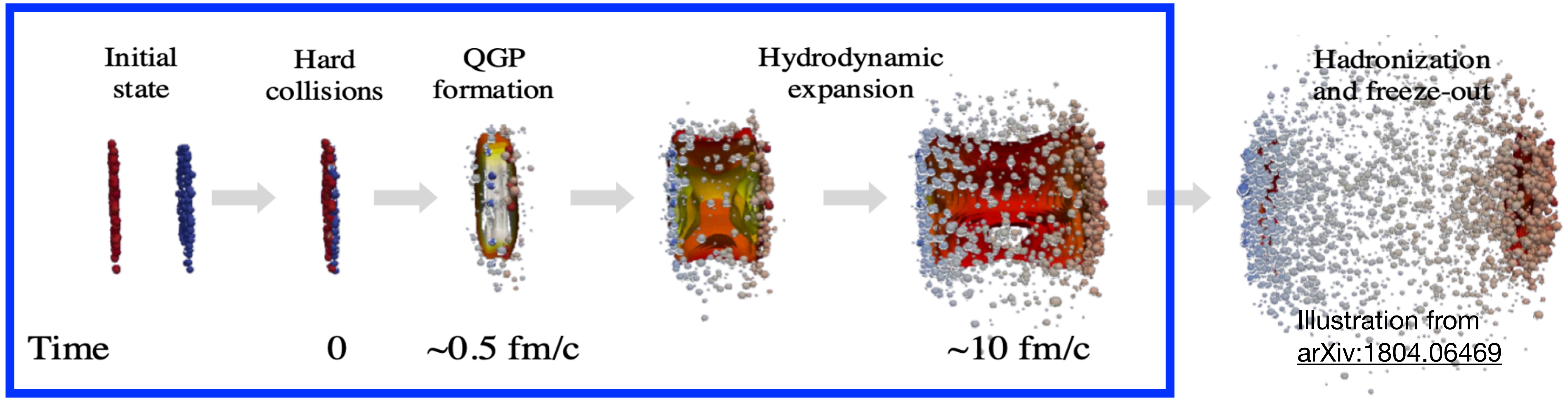
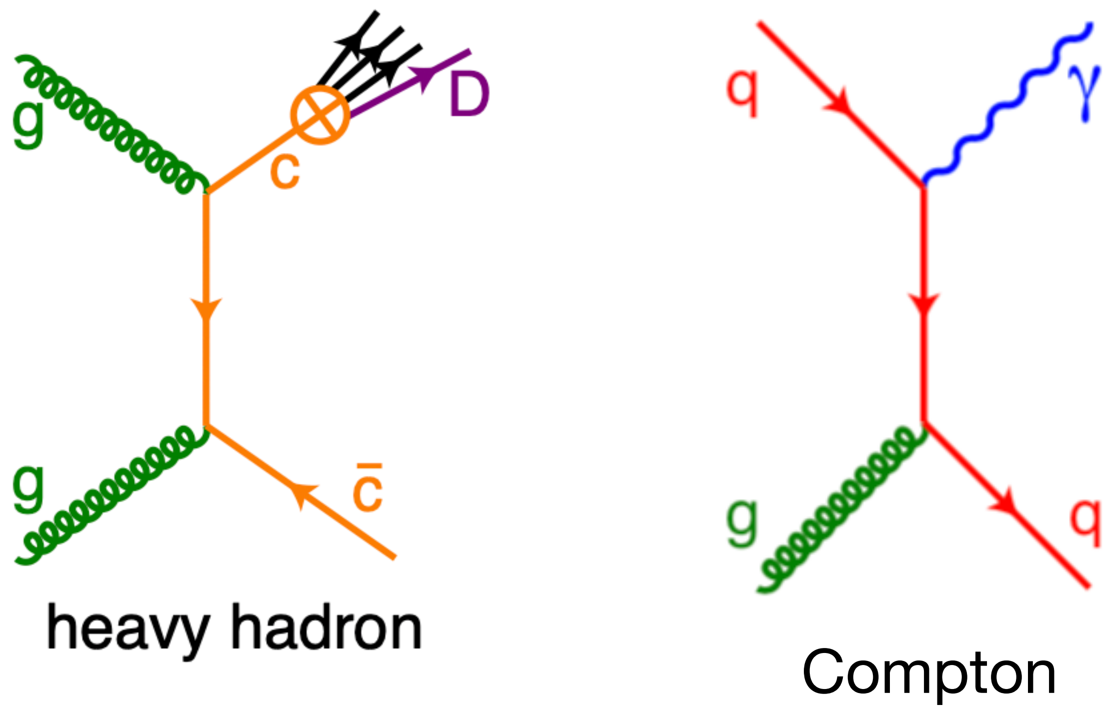


Experimental tools informing about or affecting the initial stages

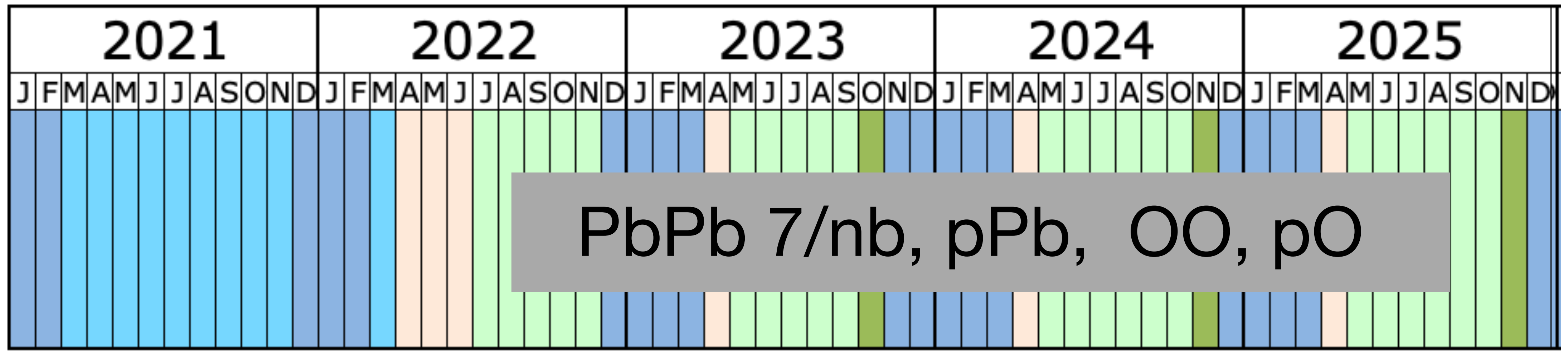
- Correlations over large range in rapidity ($\tau_{\mathrm{corr}} \sim \tau_{\mathrm{f.o.}}\, e^{-\frac{1}{2}|\Delta y|}$)
  - i.e. $\tau_{\mathrm{corr}} \sim 0.5\mathrm{fm}/c$ for $|\Delta y| \sim 7$
  - need large acceptance (tracking) detectors
- Use probes related to gluons as HF or direct photons, also dileptons
  - need precision vertexing, PID, muon detectors, EM calorimeters
- Change initial state by variation of collision species, including
  - ultra-peripheral collisions
  - ee and ep or eA collisions



FUTURE: improvement or new instrumentation, increase precision and accuracy

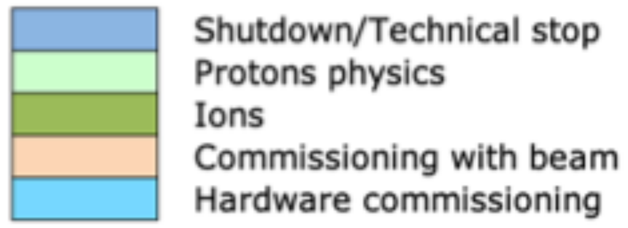
Ongoing LHC program

Run-3



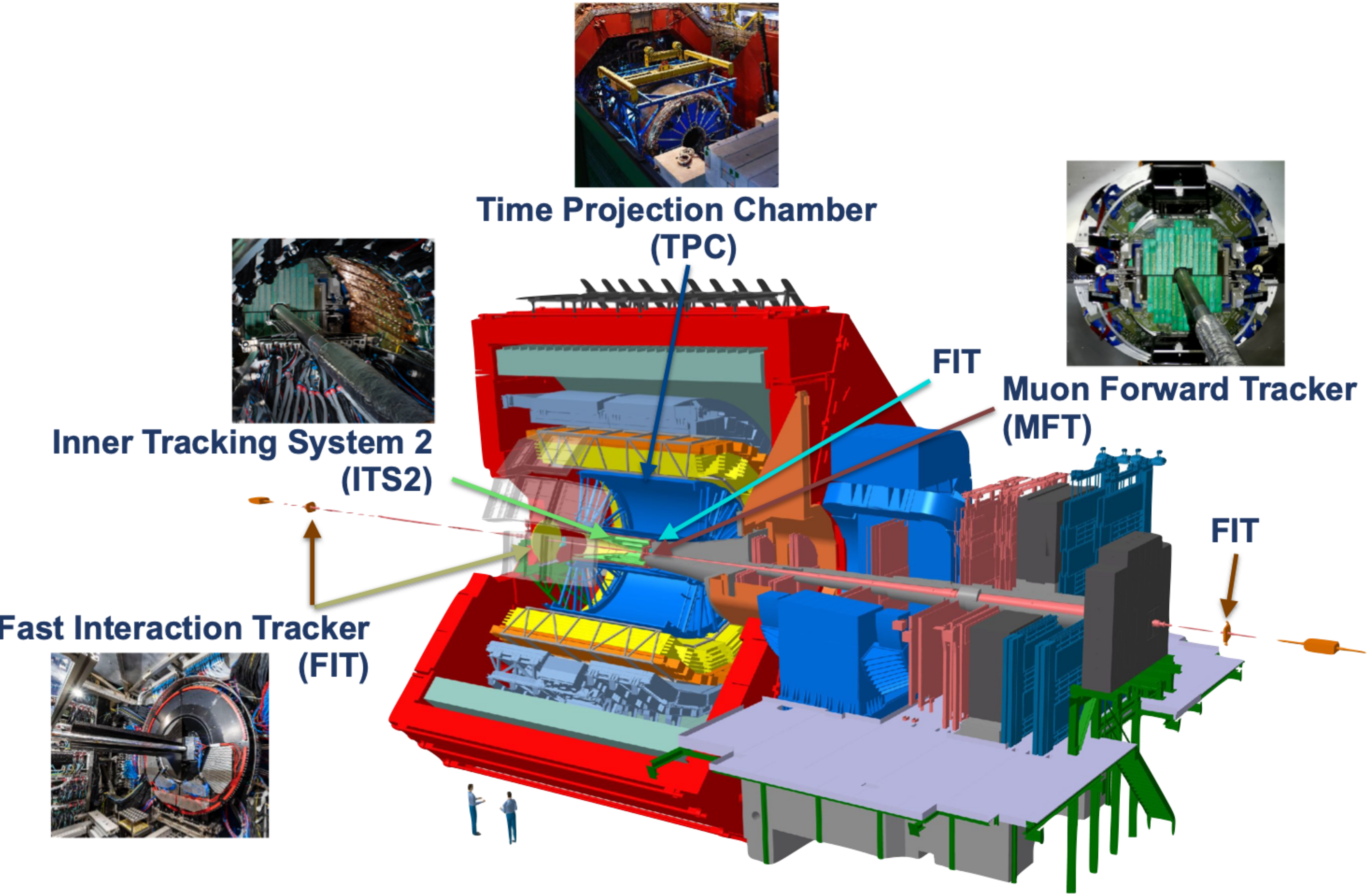
ALICE 2.0

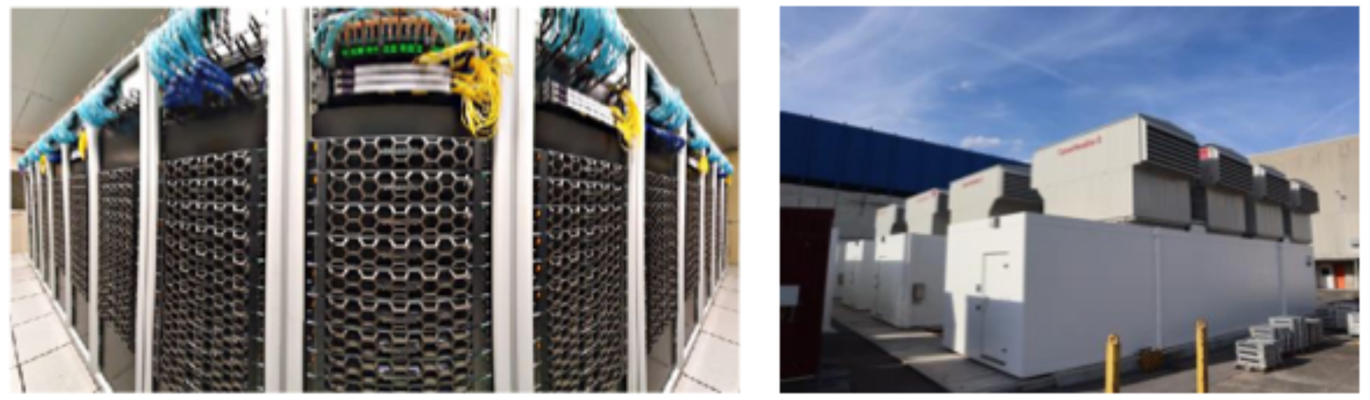
LHCb Phase I



ALICE2.0 - essentially a new detector for Run 3/4

ALICE upgrades during the LHC Long Shutdown 2, arXiv:2302.01238





Integrated Online-Offline system (O^2)

Readout upgrade

-TOF, TRD, MUON, ZDC, Calorimeters

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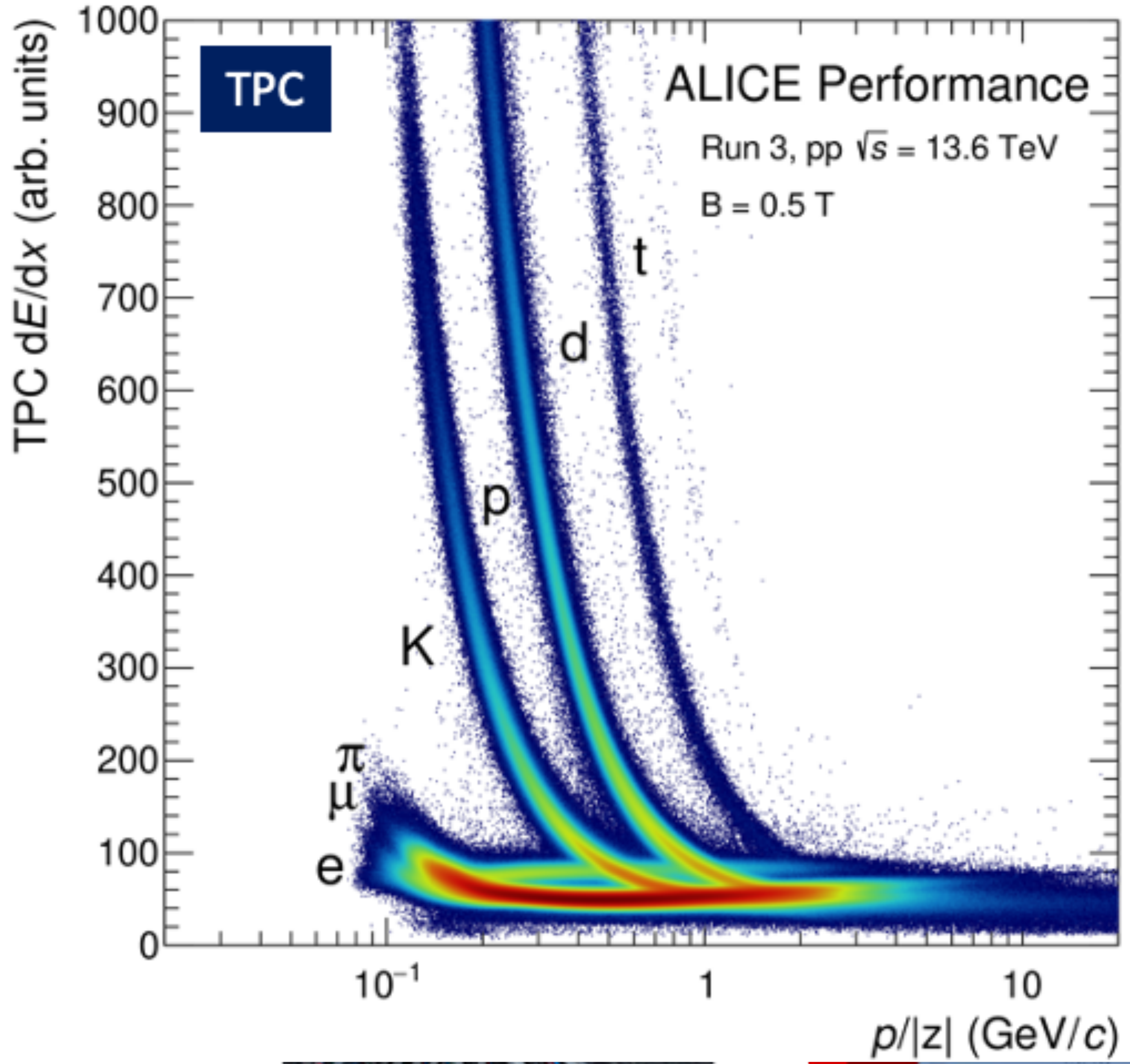

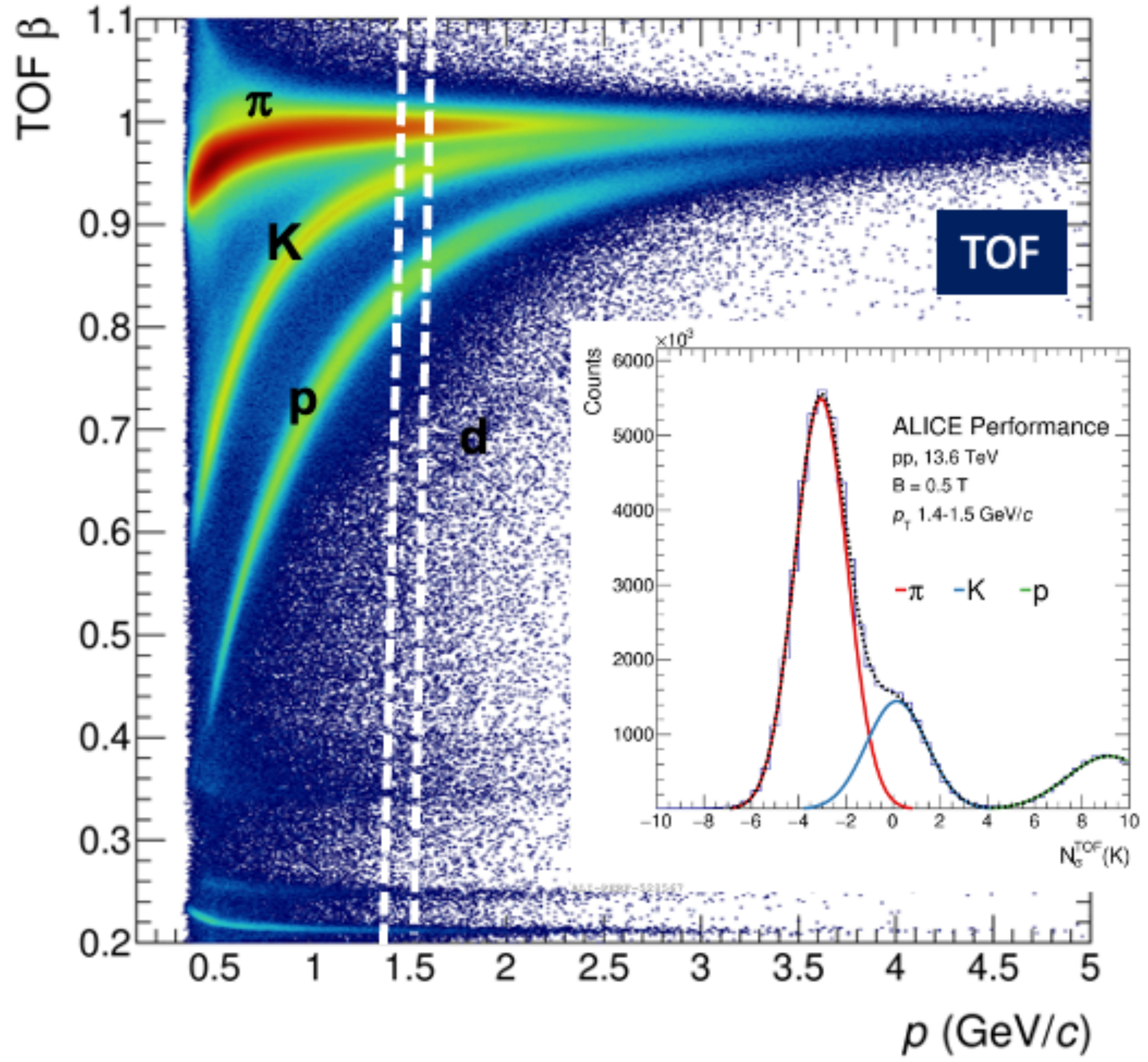

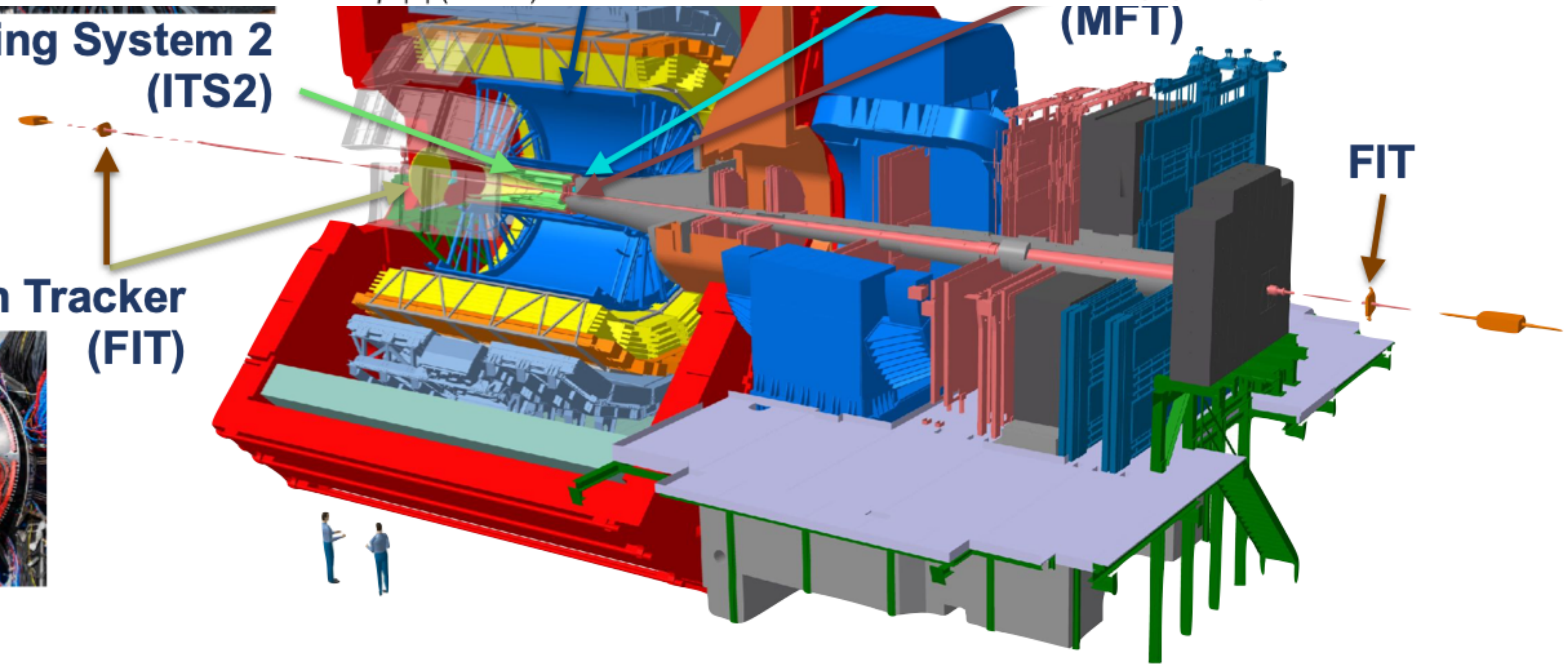

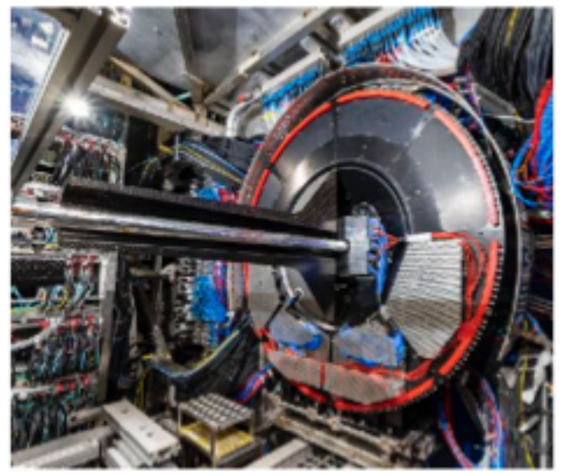

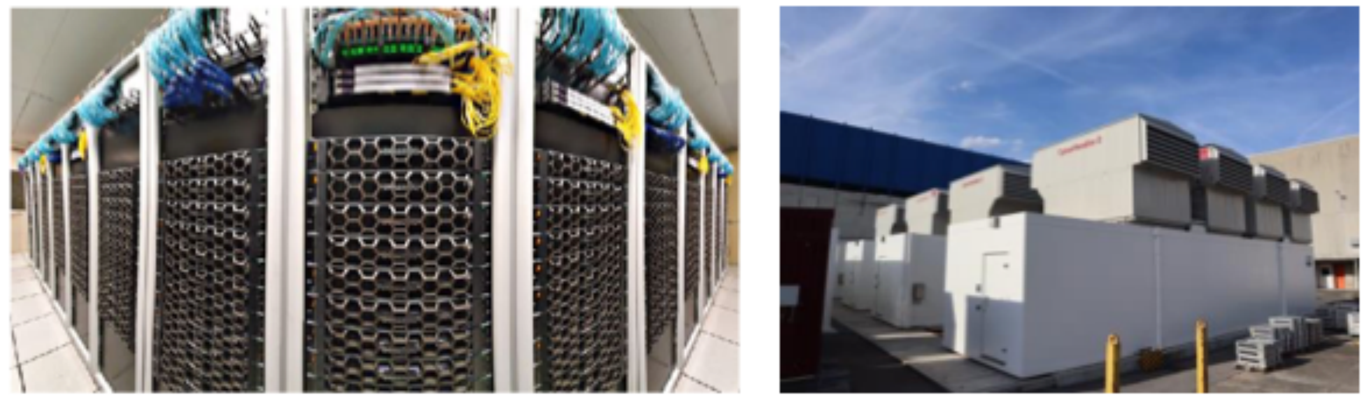

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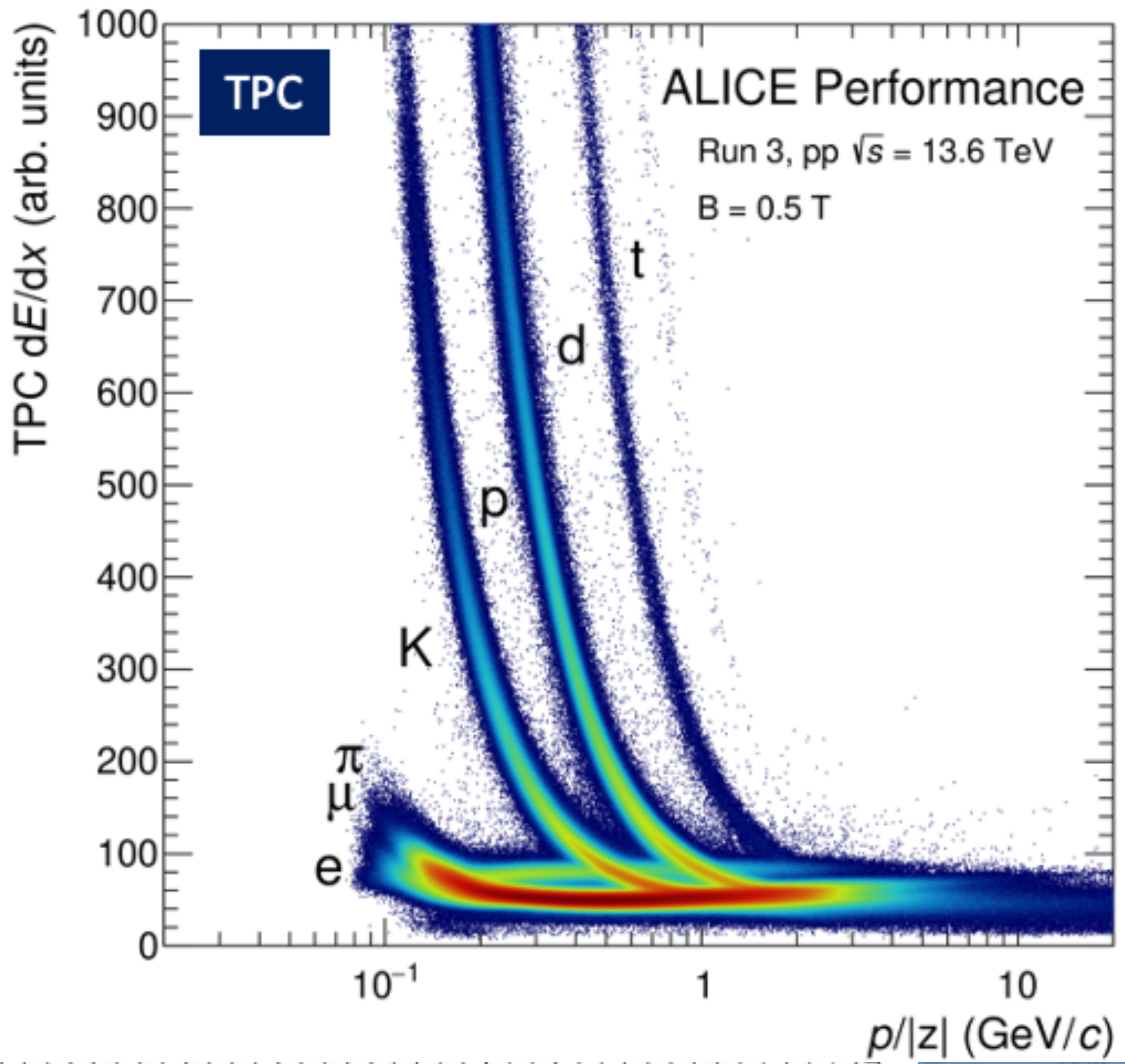

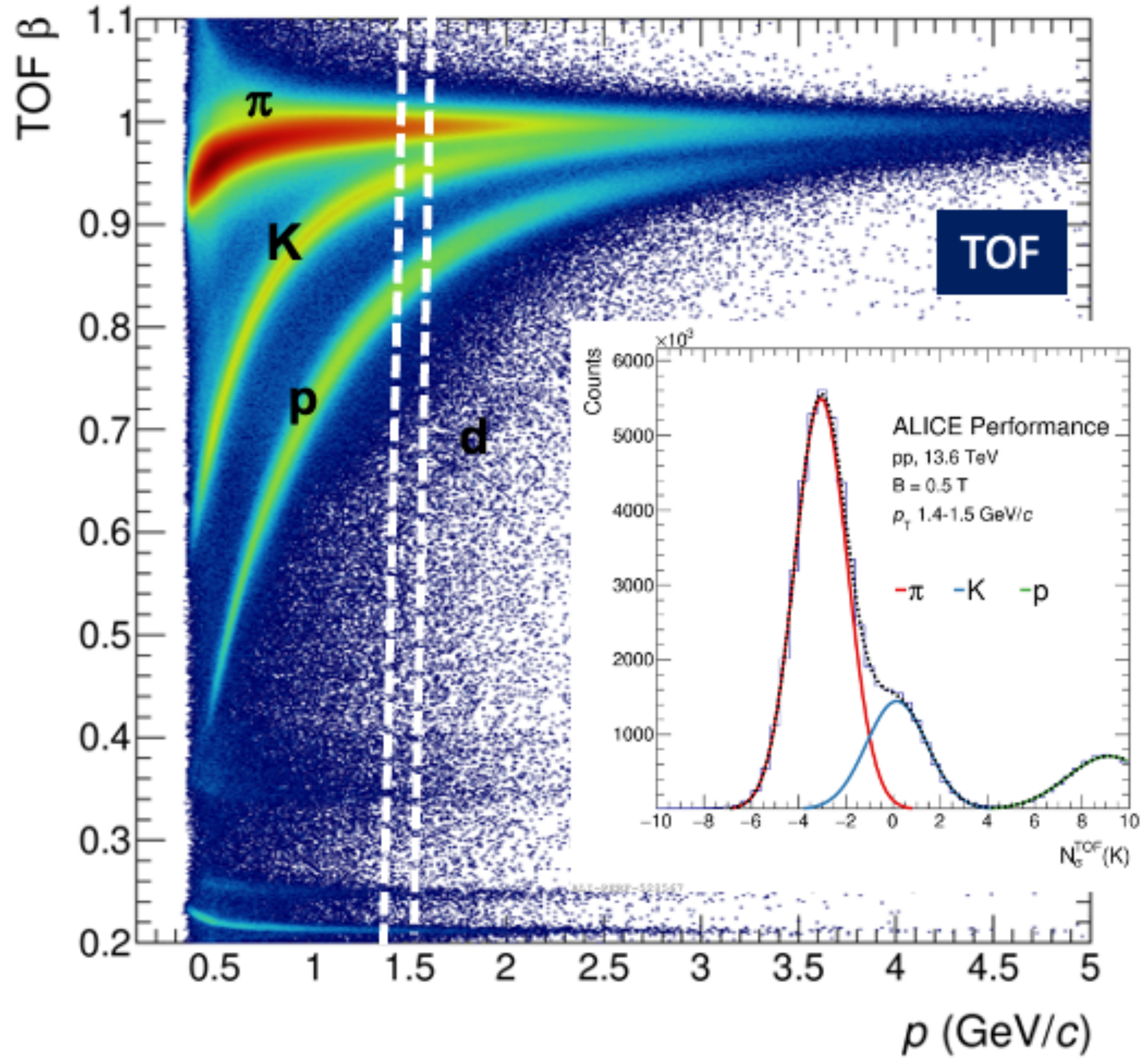

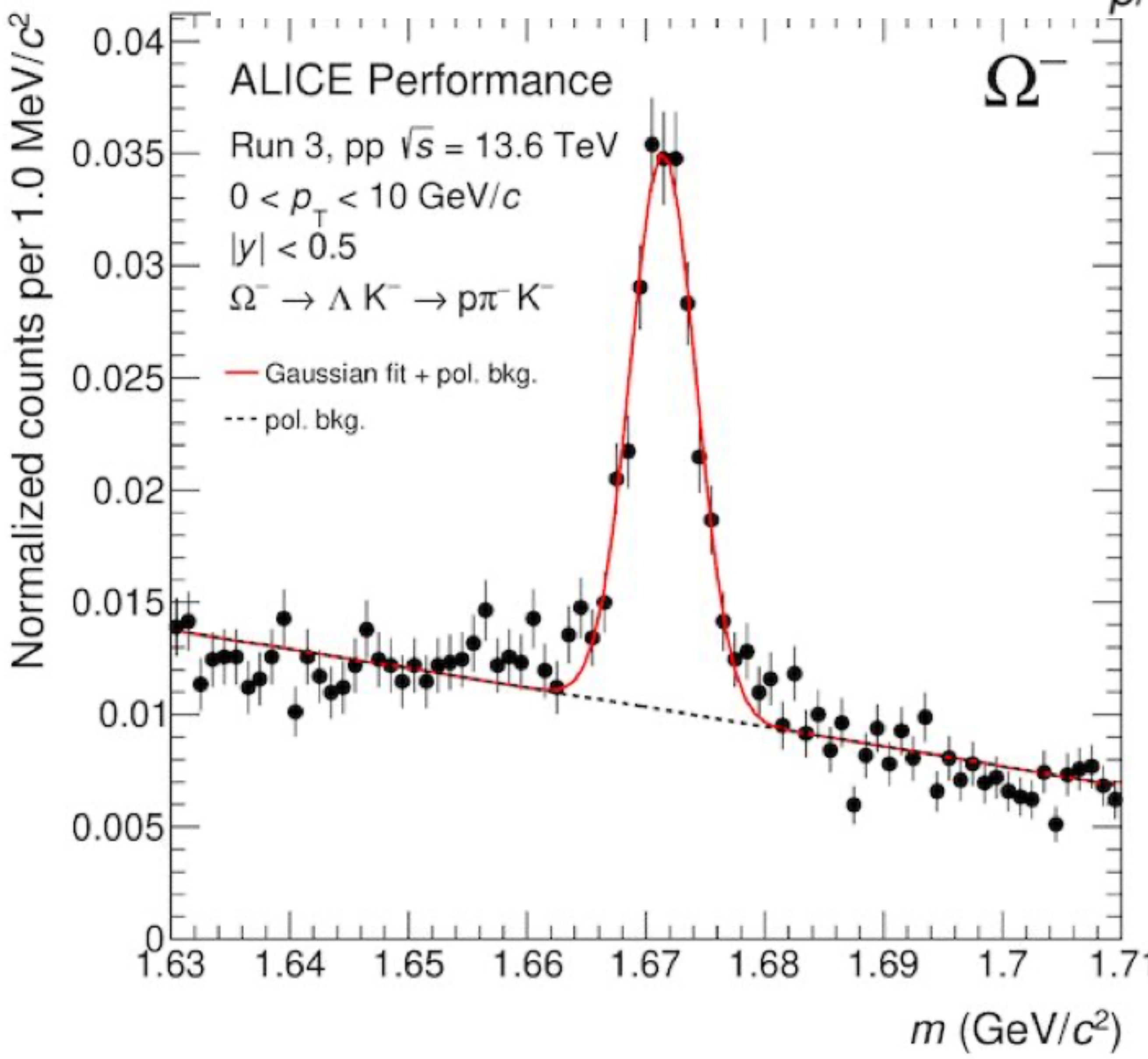

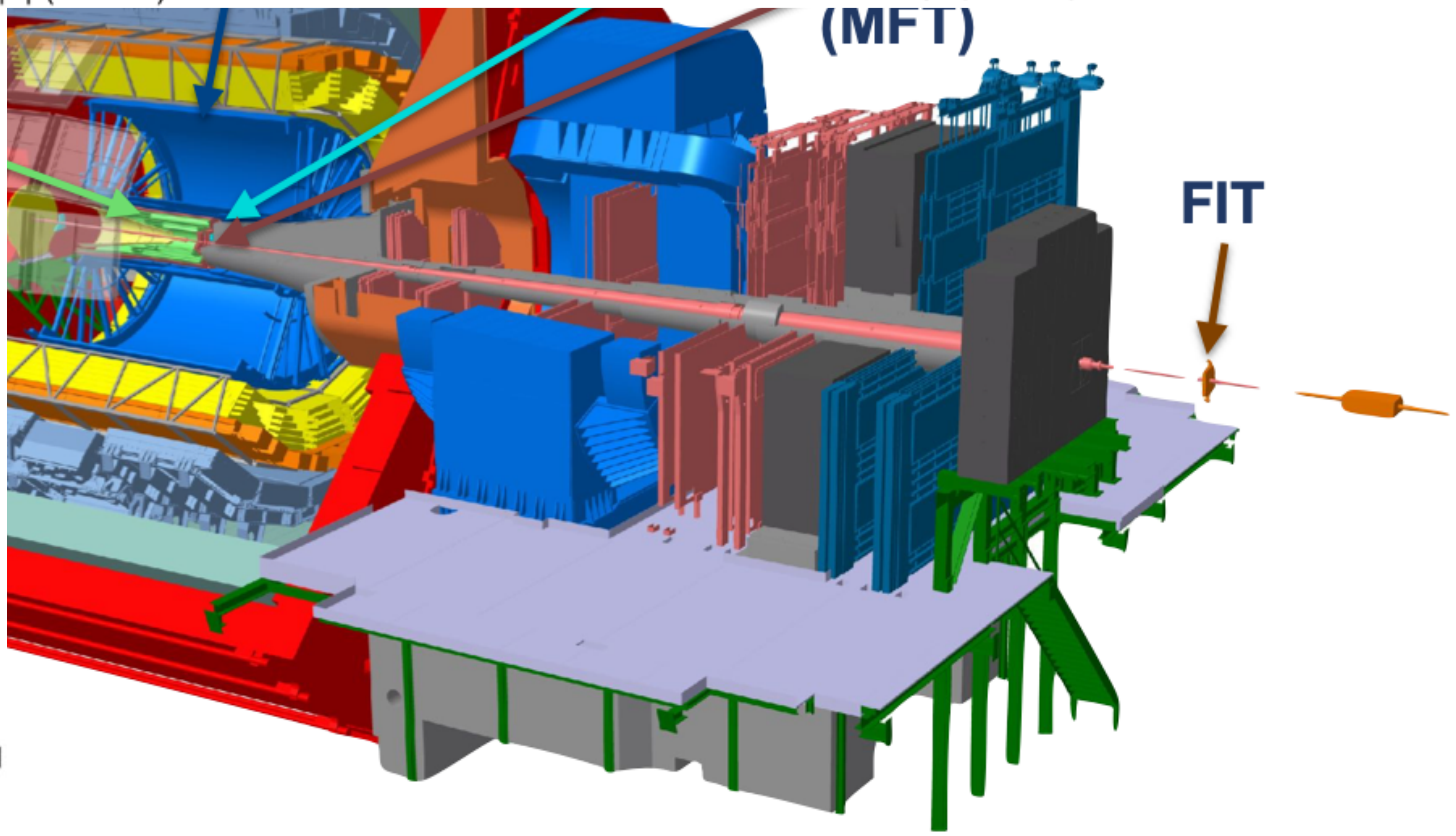

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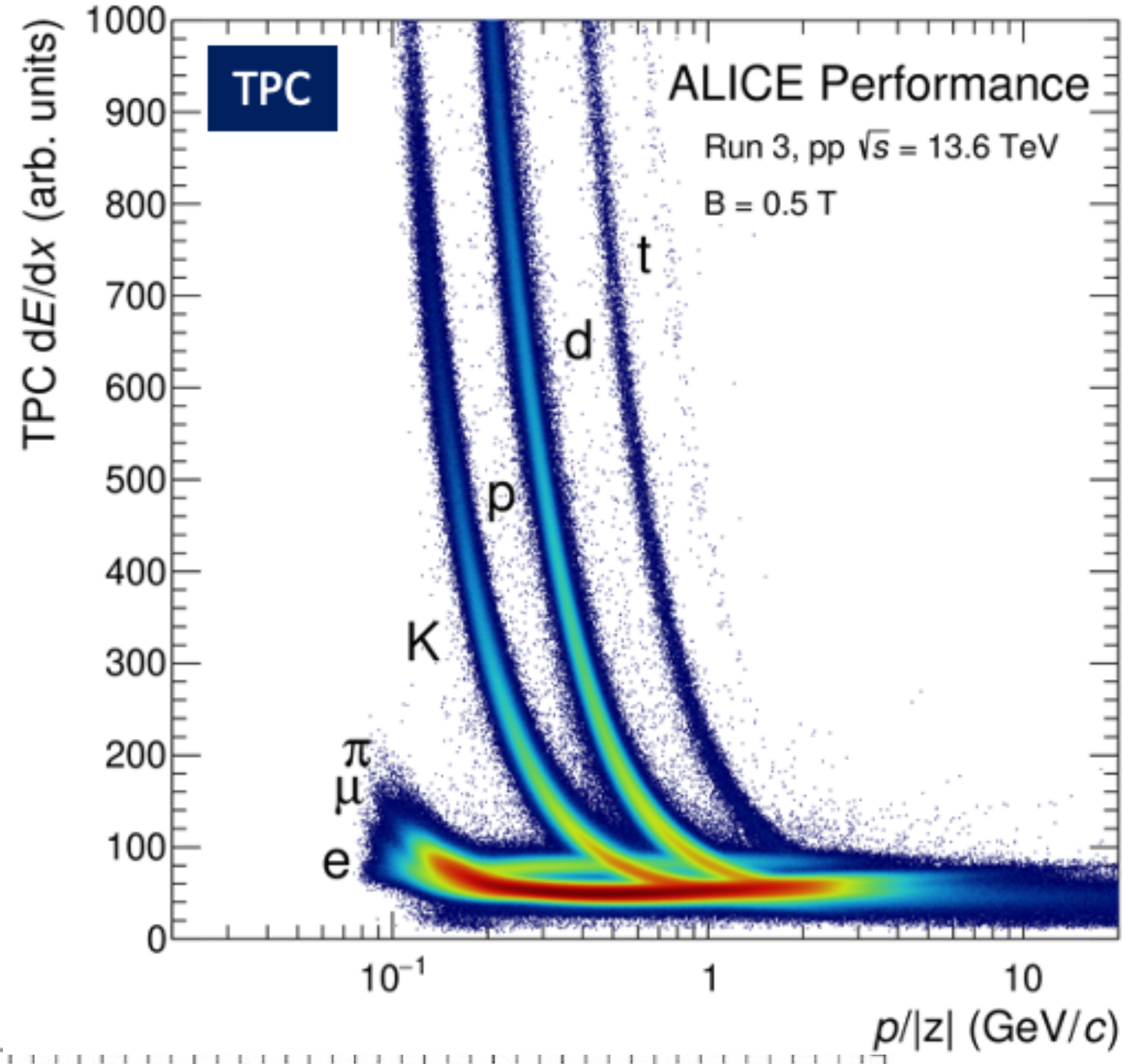

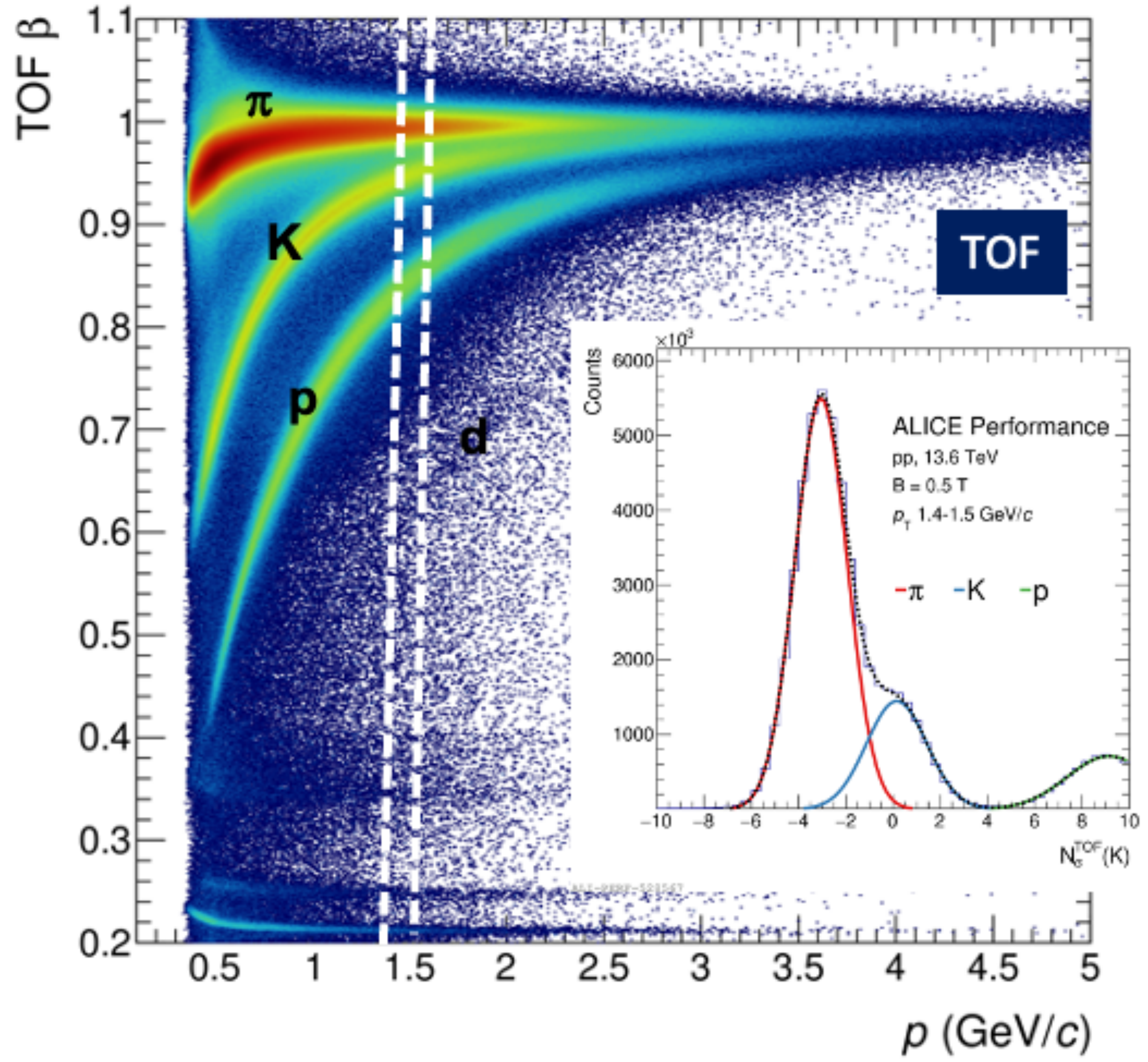

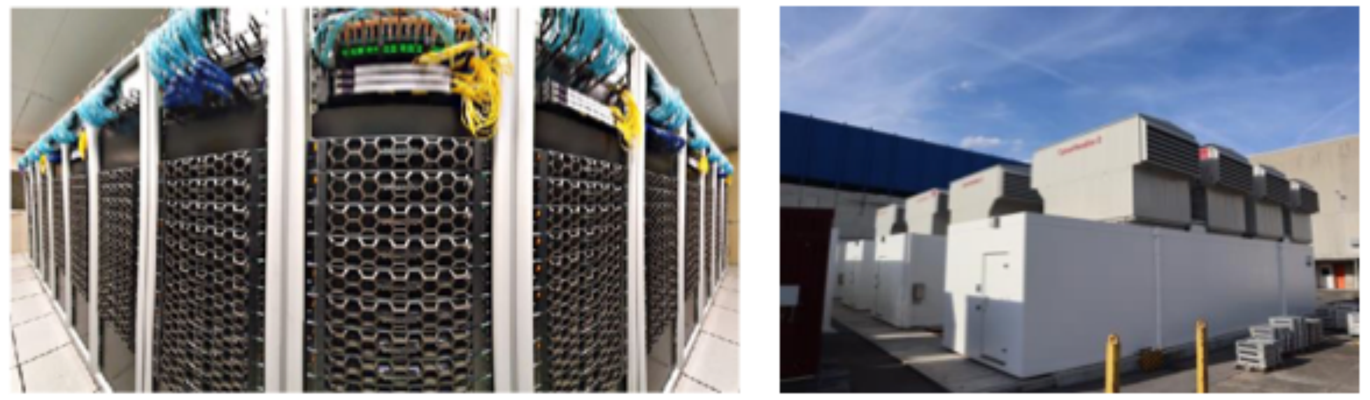

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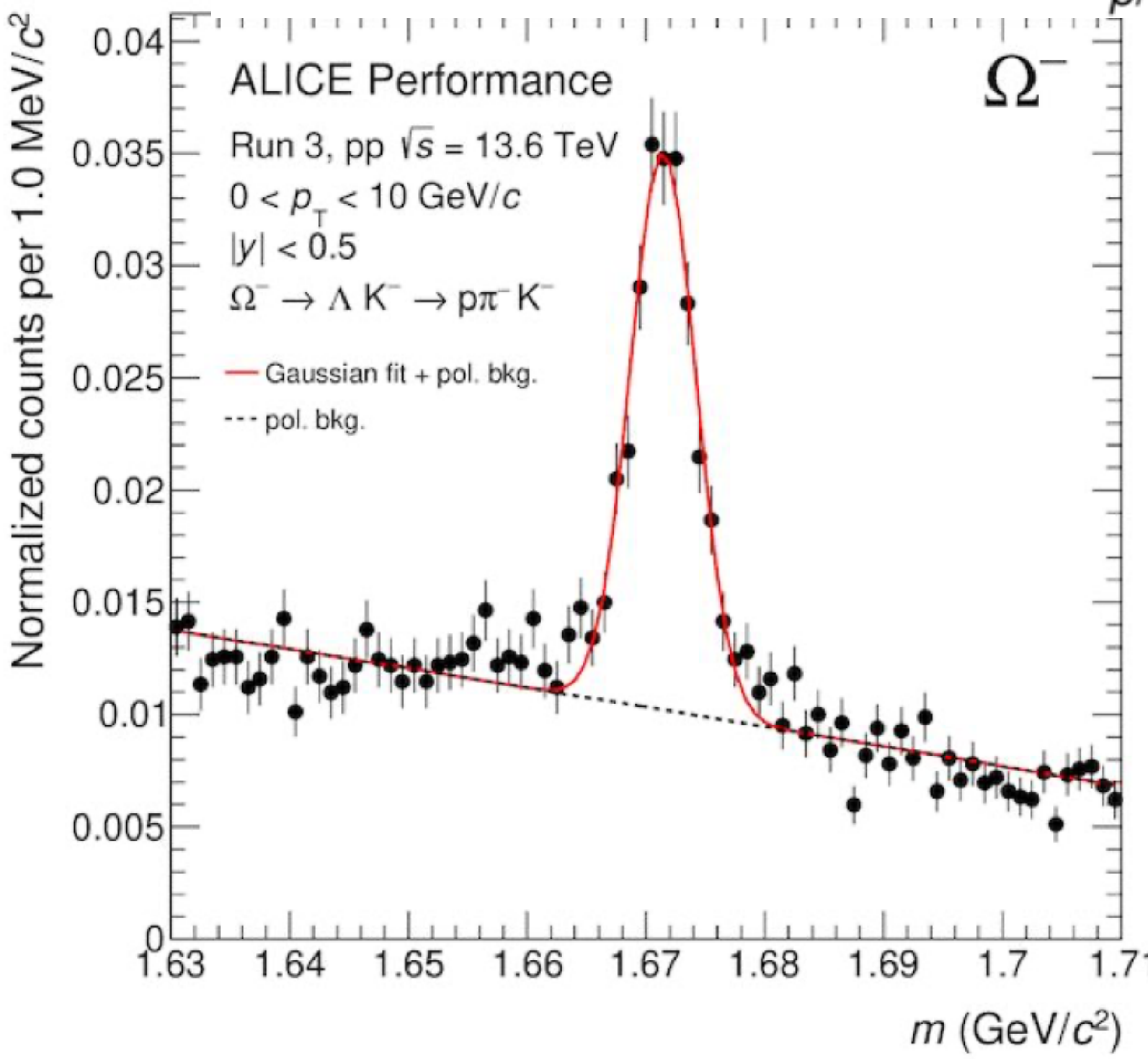
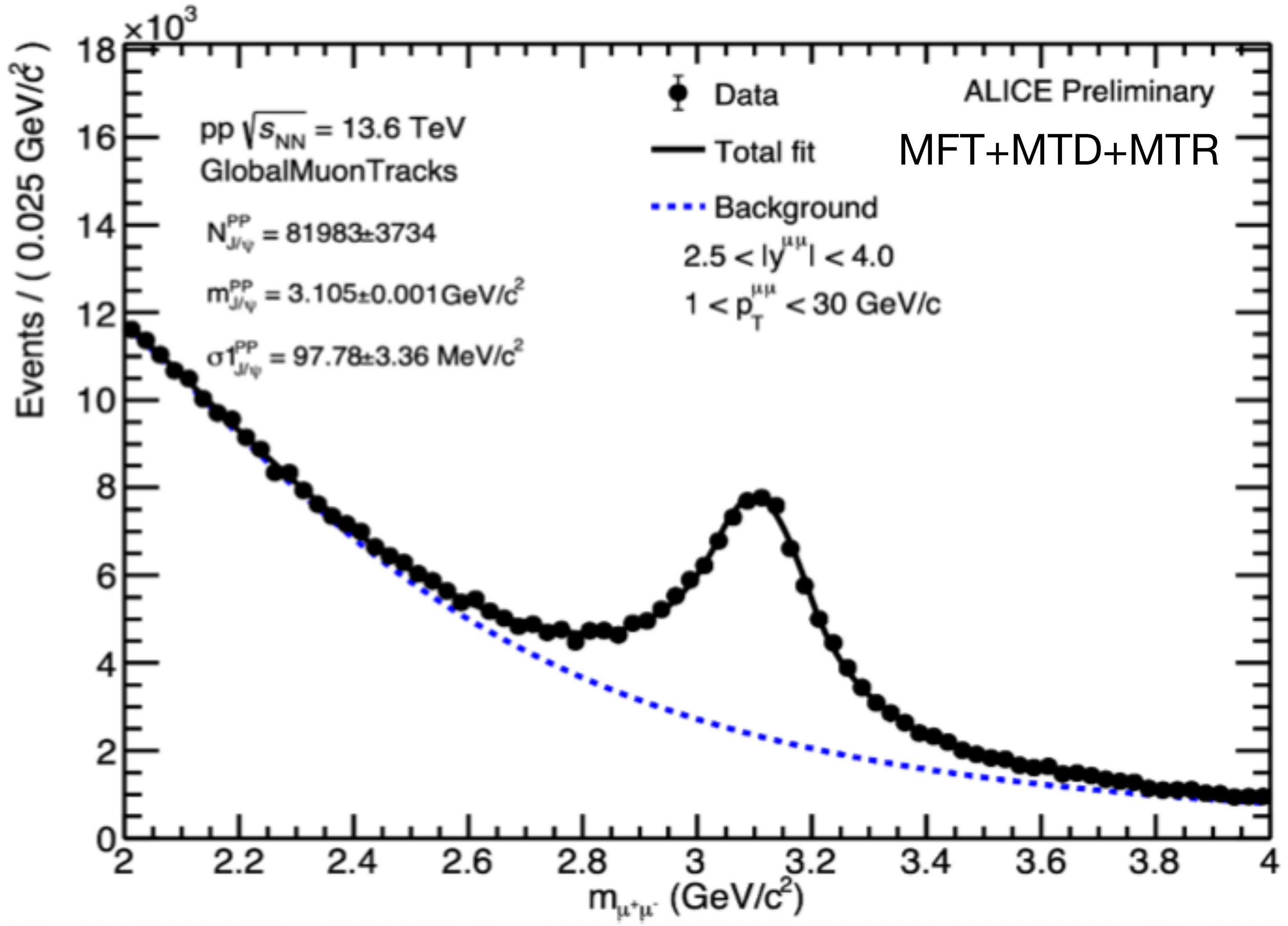
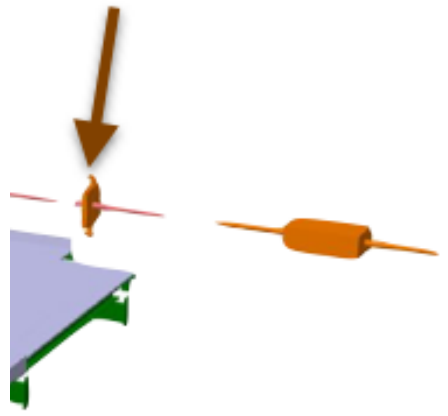




FIT



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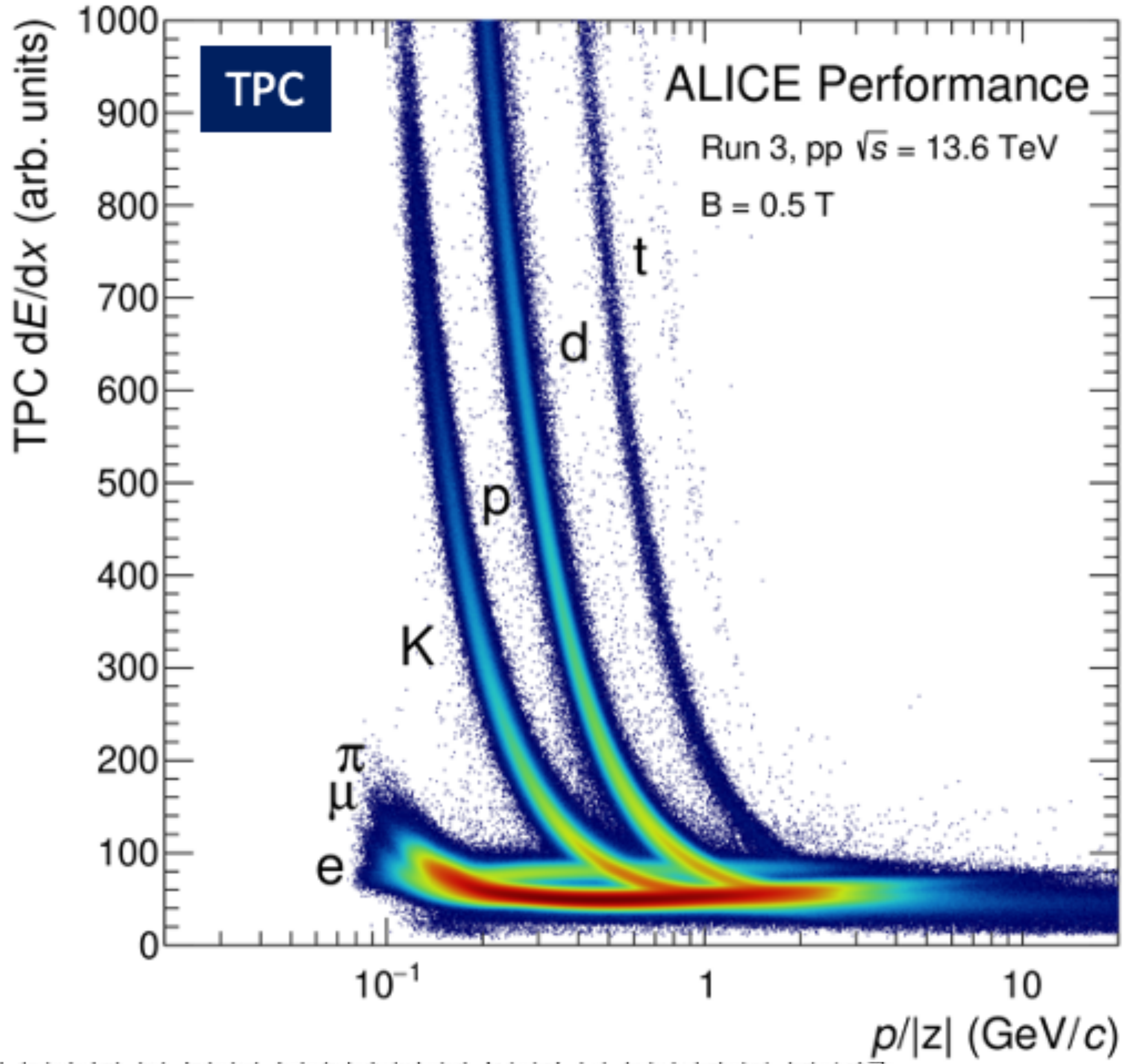

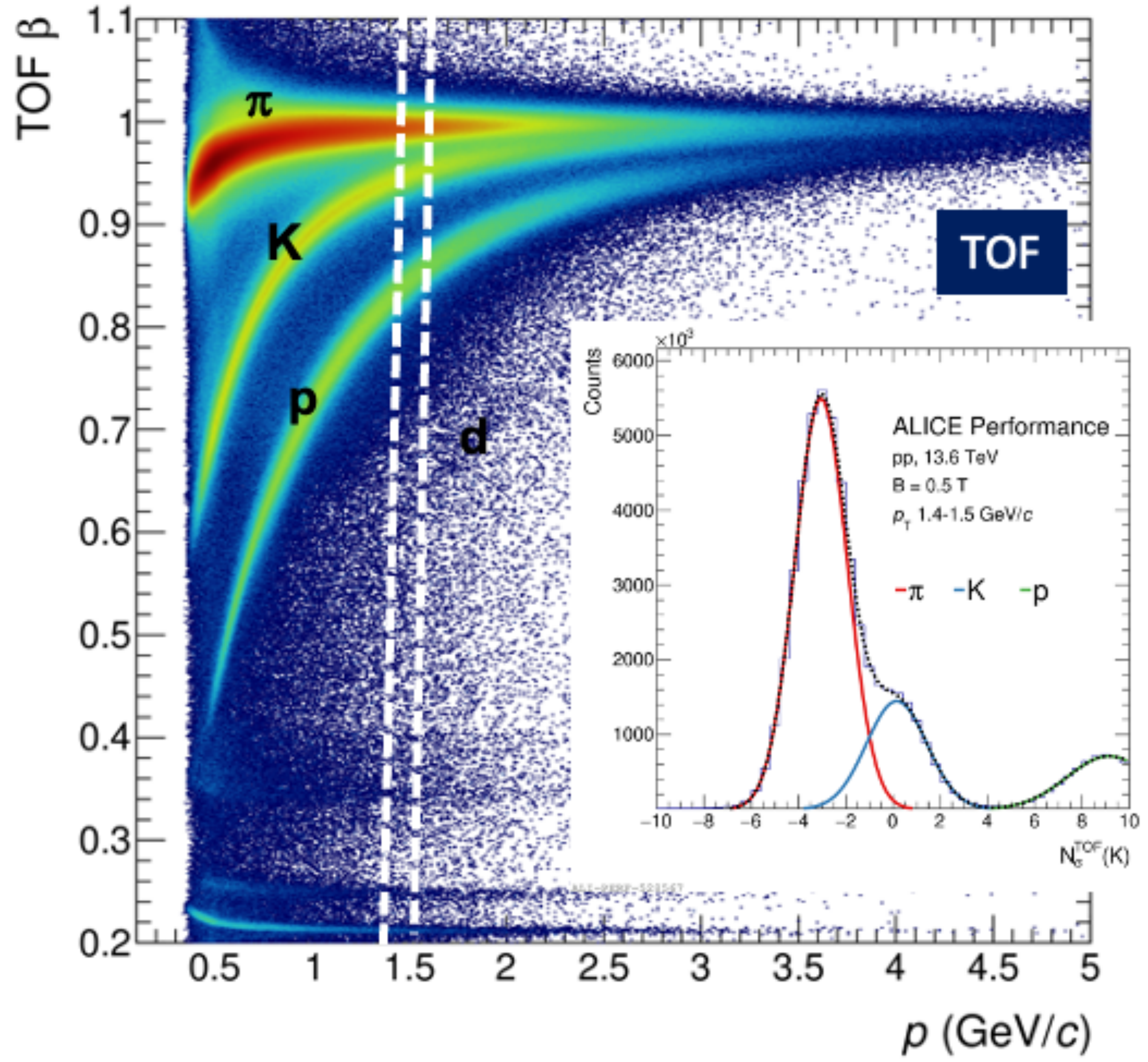

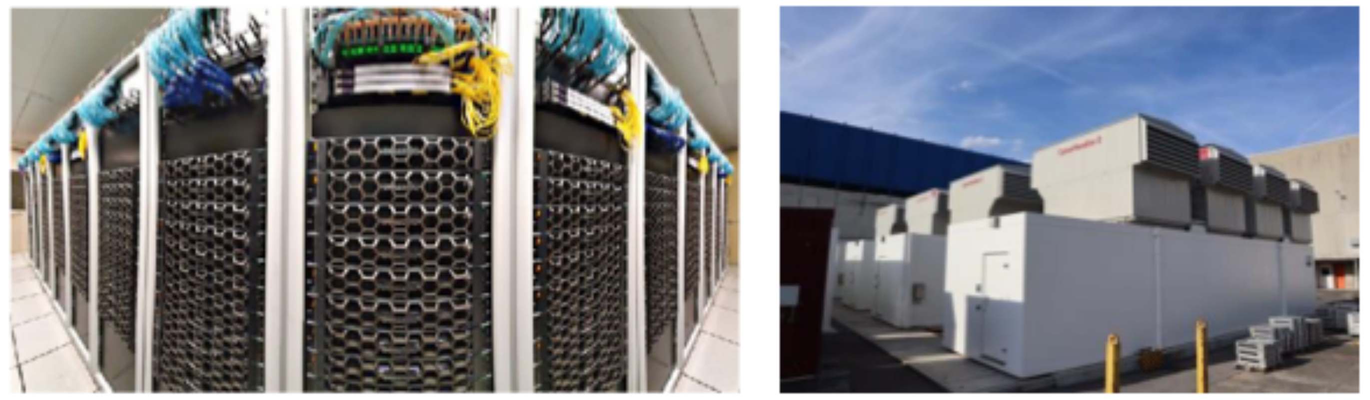

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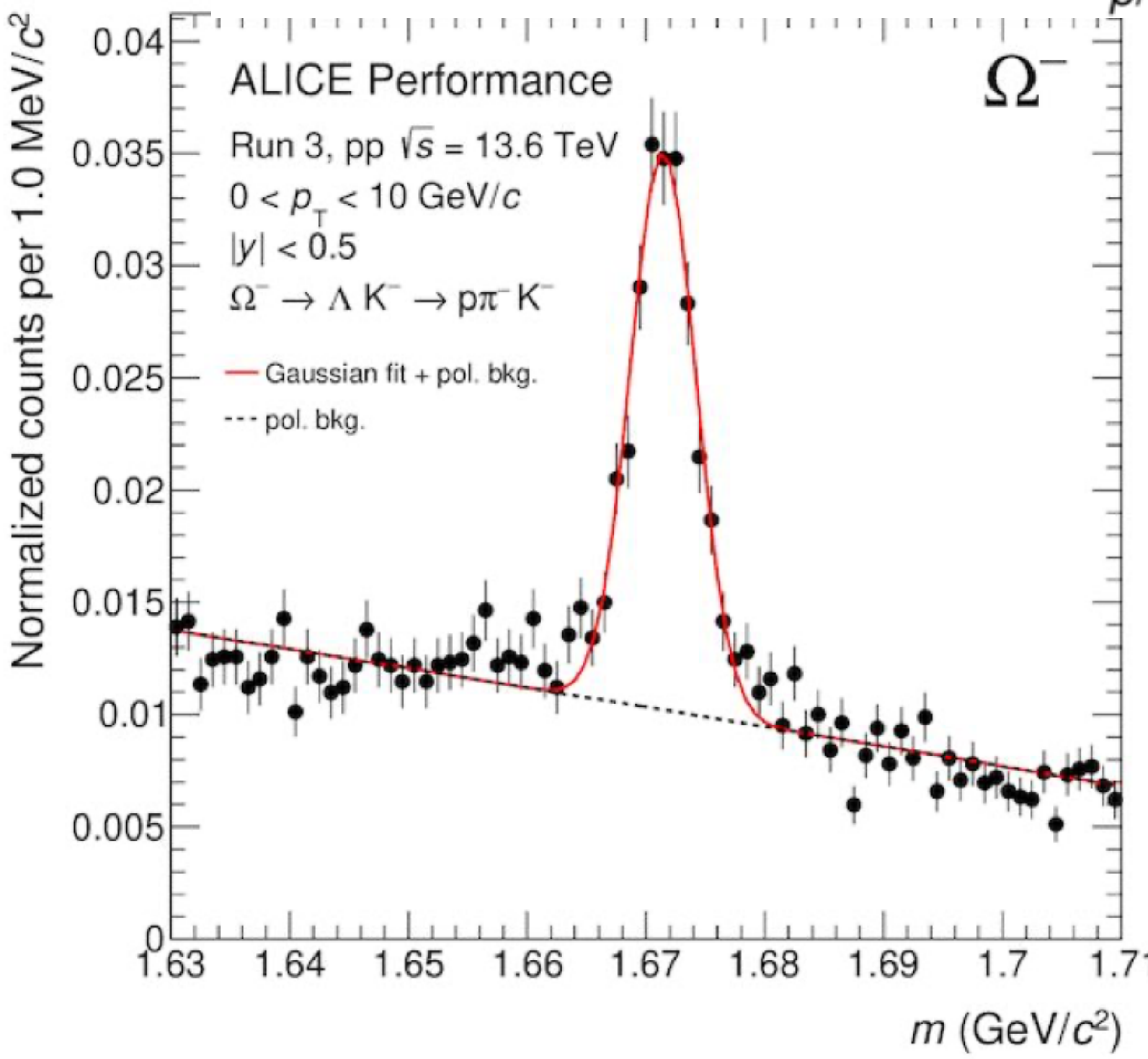
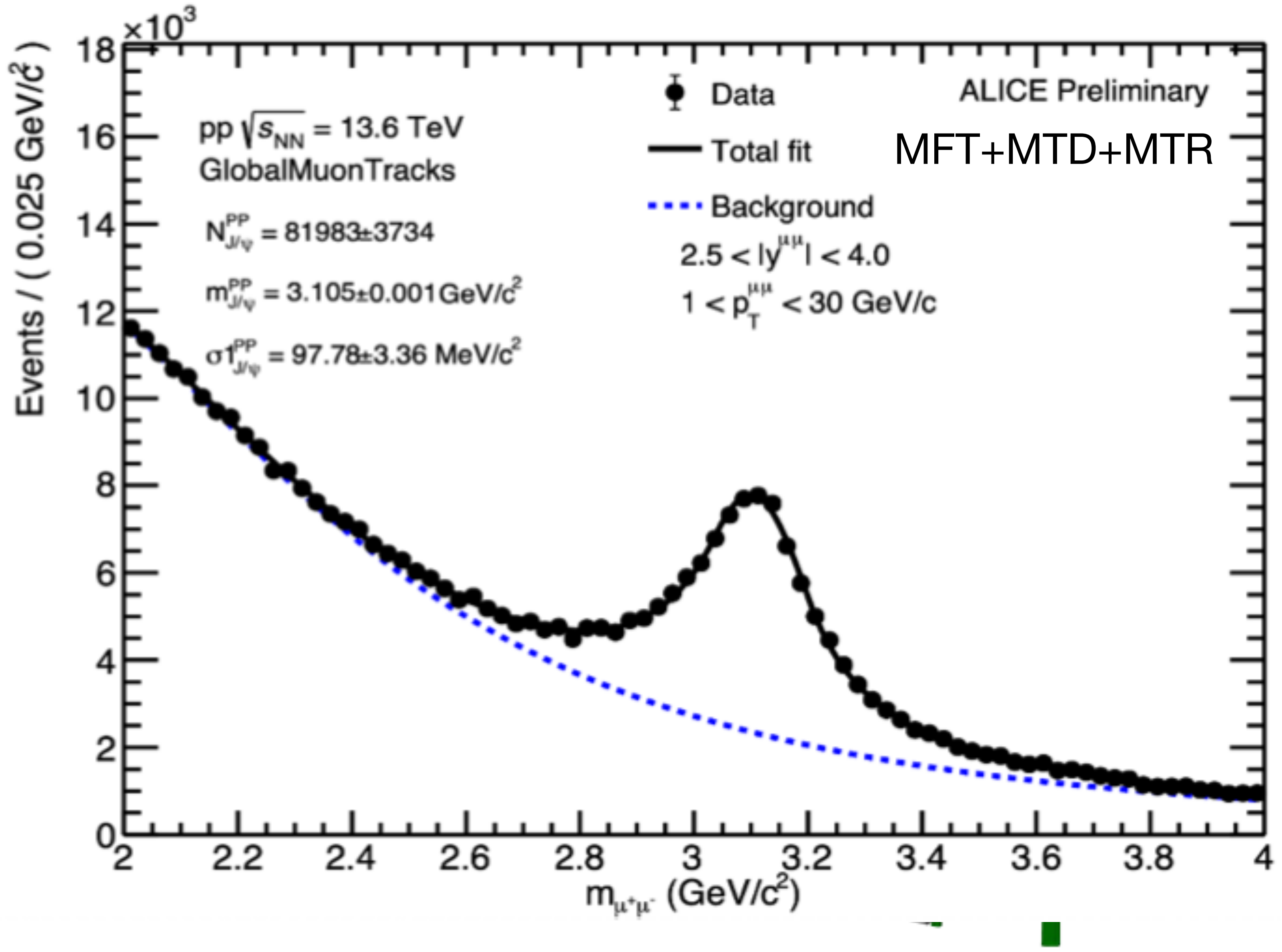
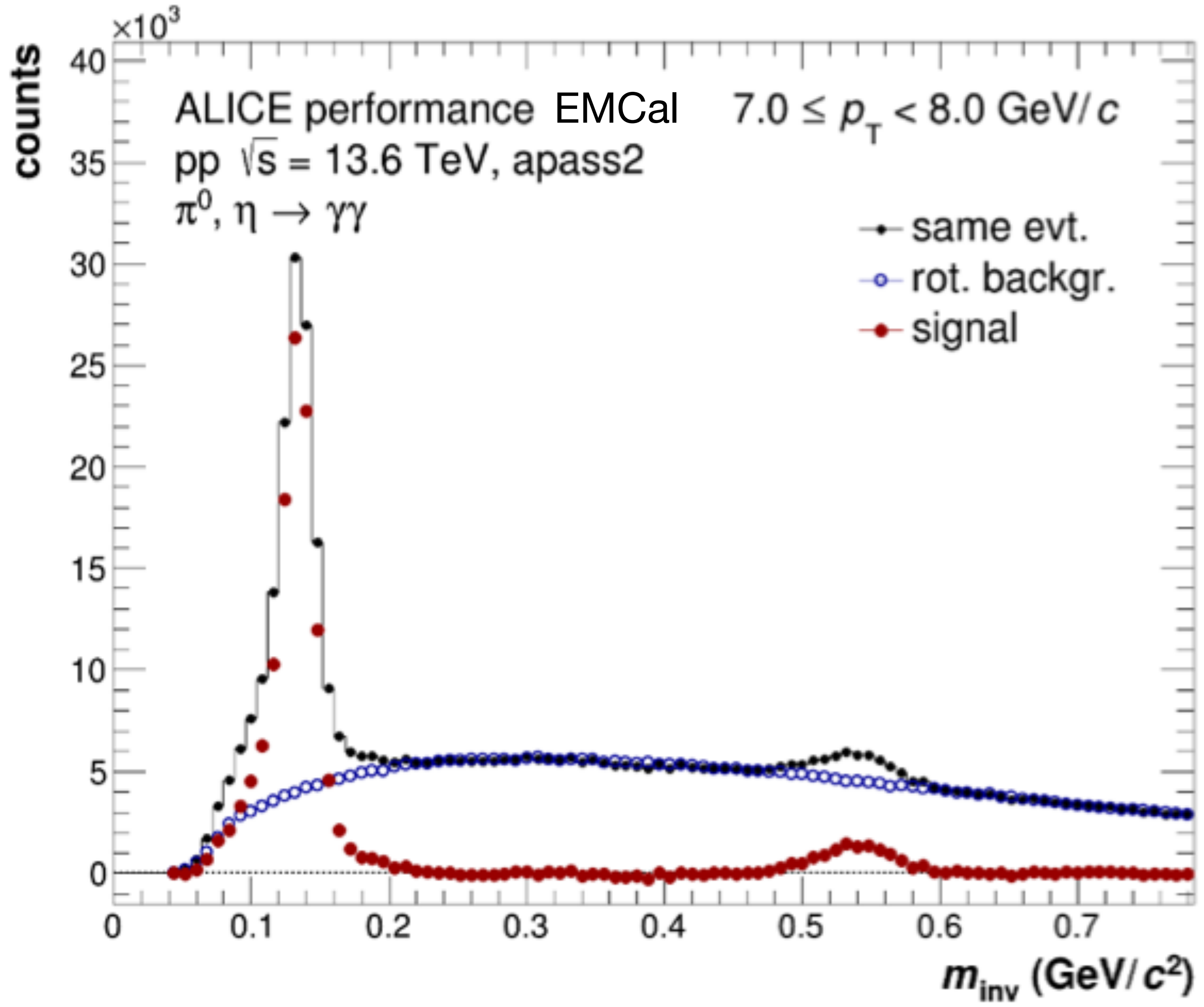
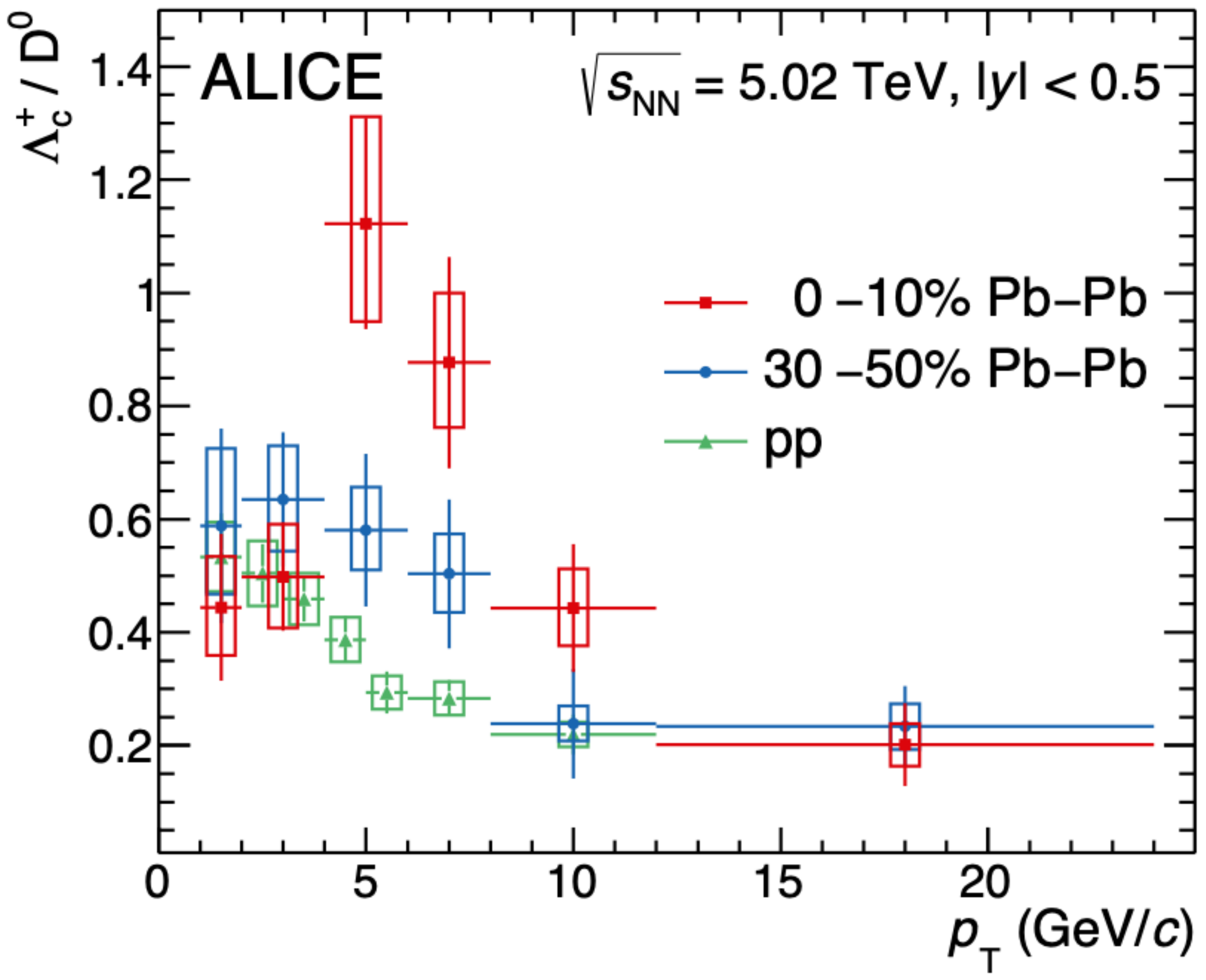




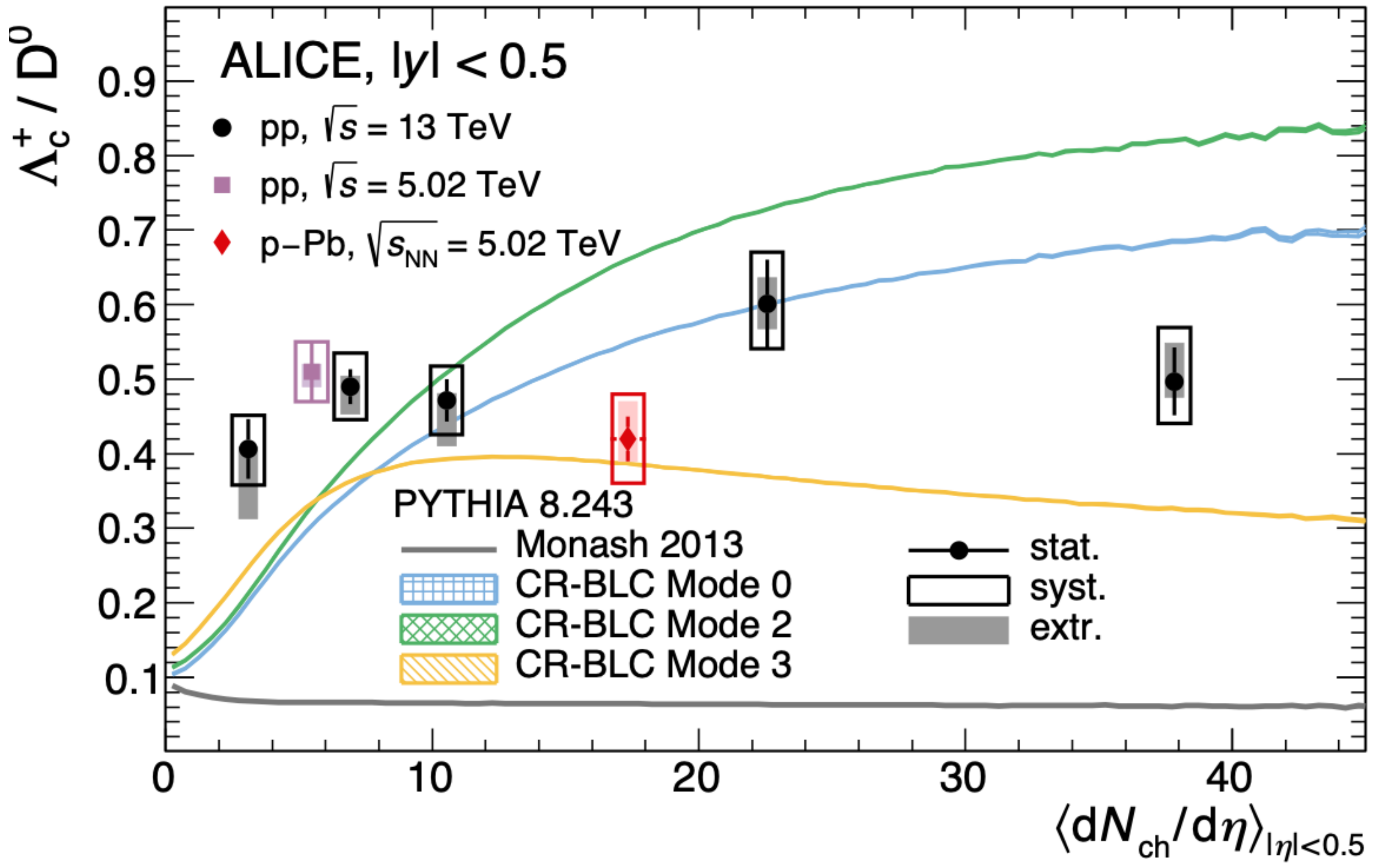


ALICE2.0 - example current and future measurements

Phys.Lett.B 839 (2023) 137796



Phys.Lett.B 829 (2022) 137065



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- Unique high-multiplicity pp program (200/pb)

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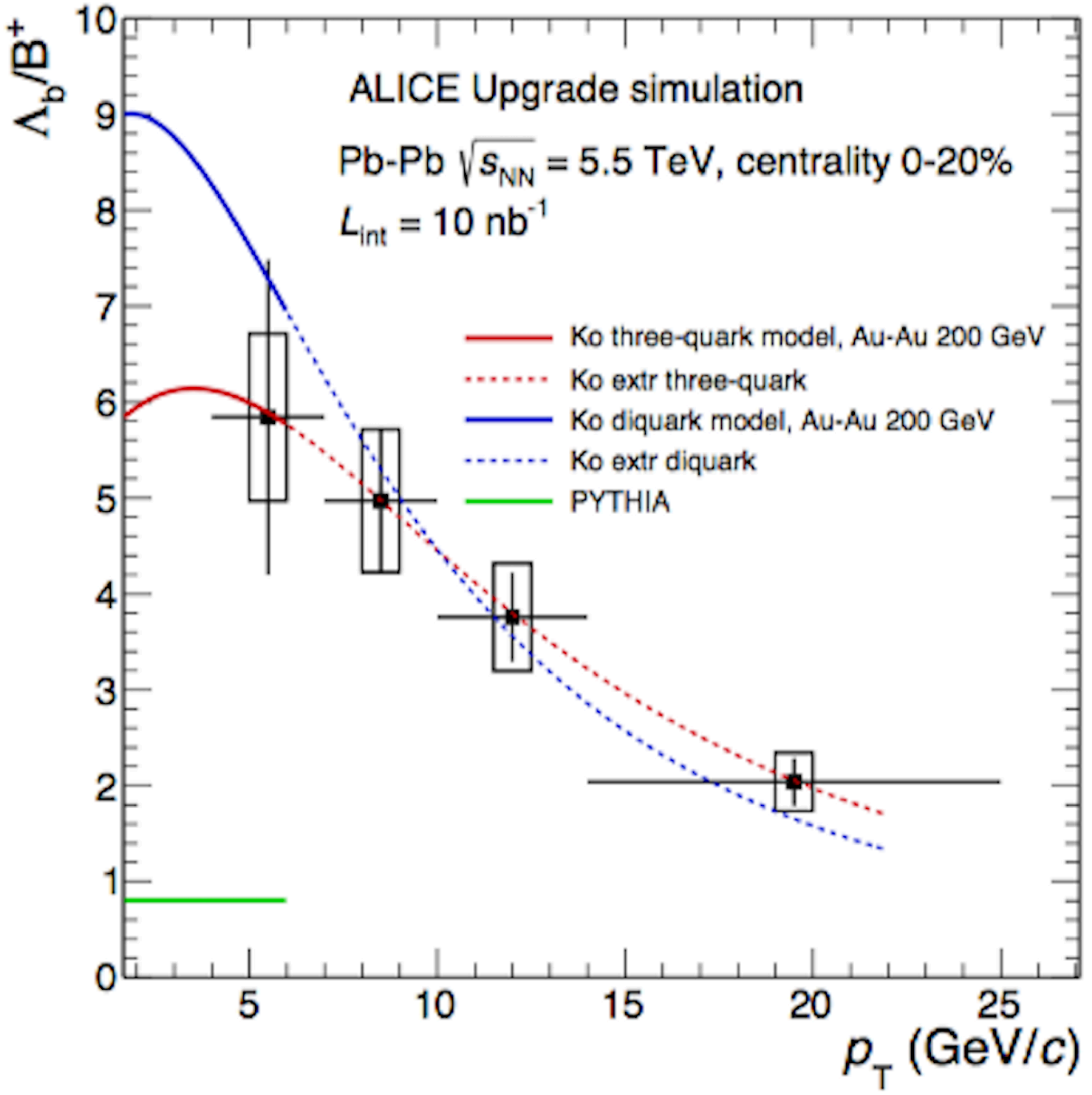

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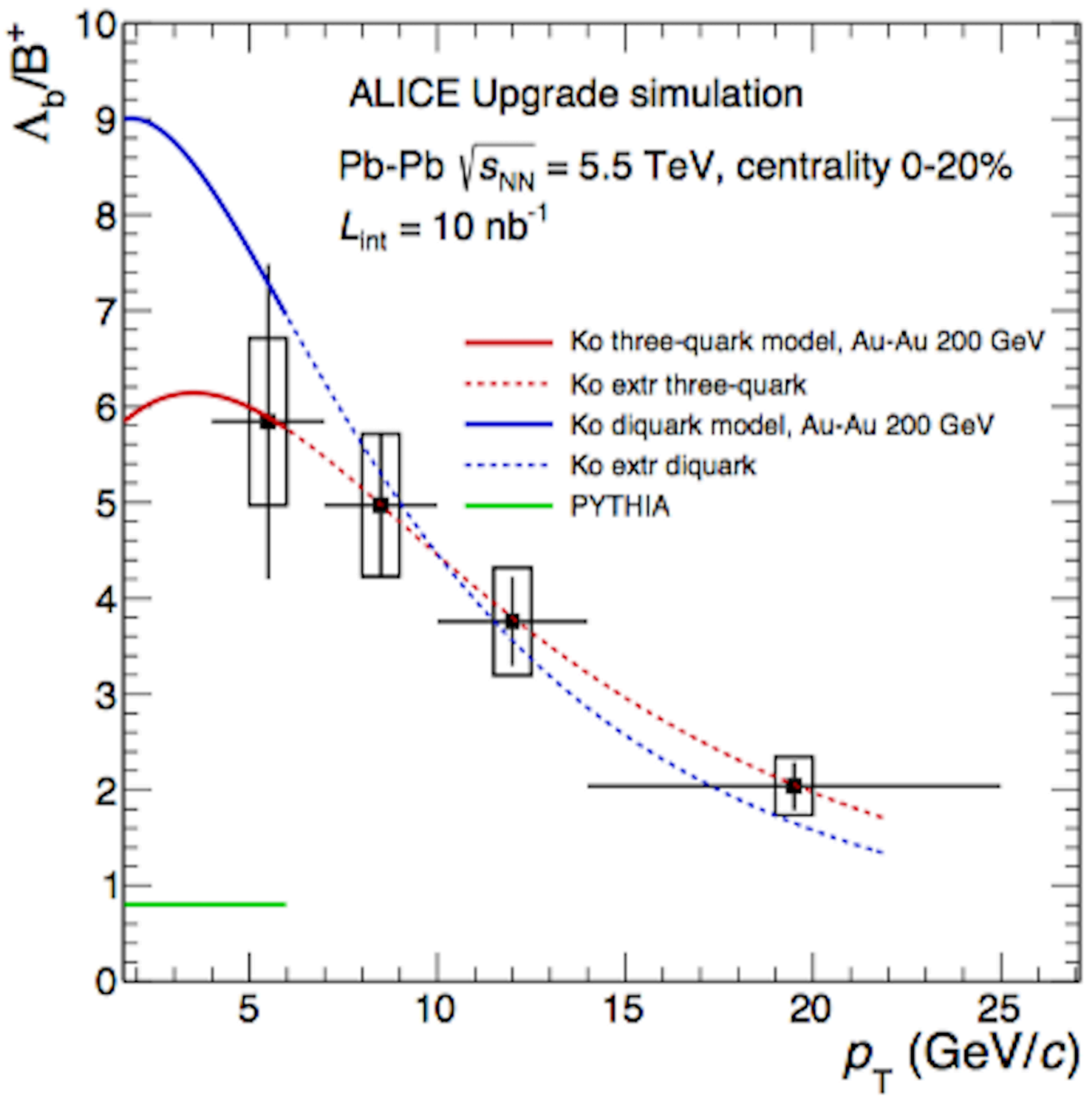
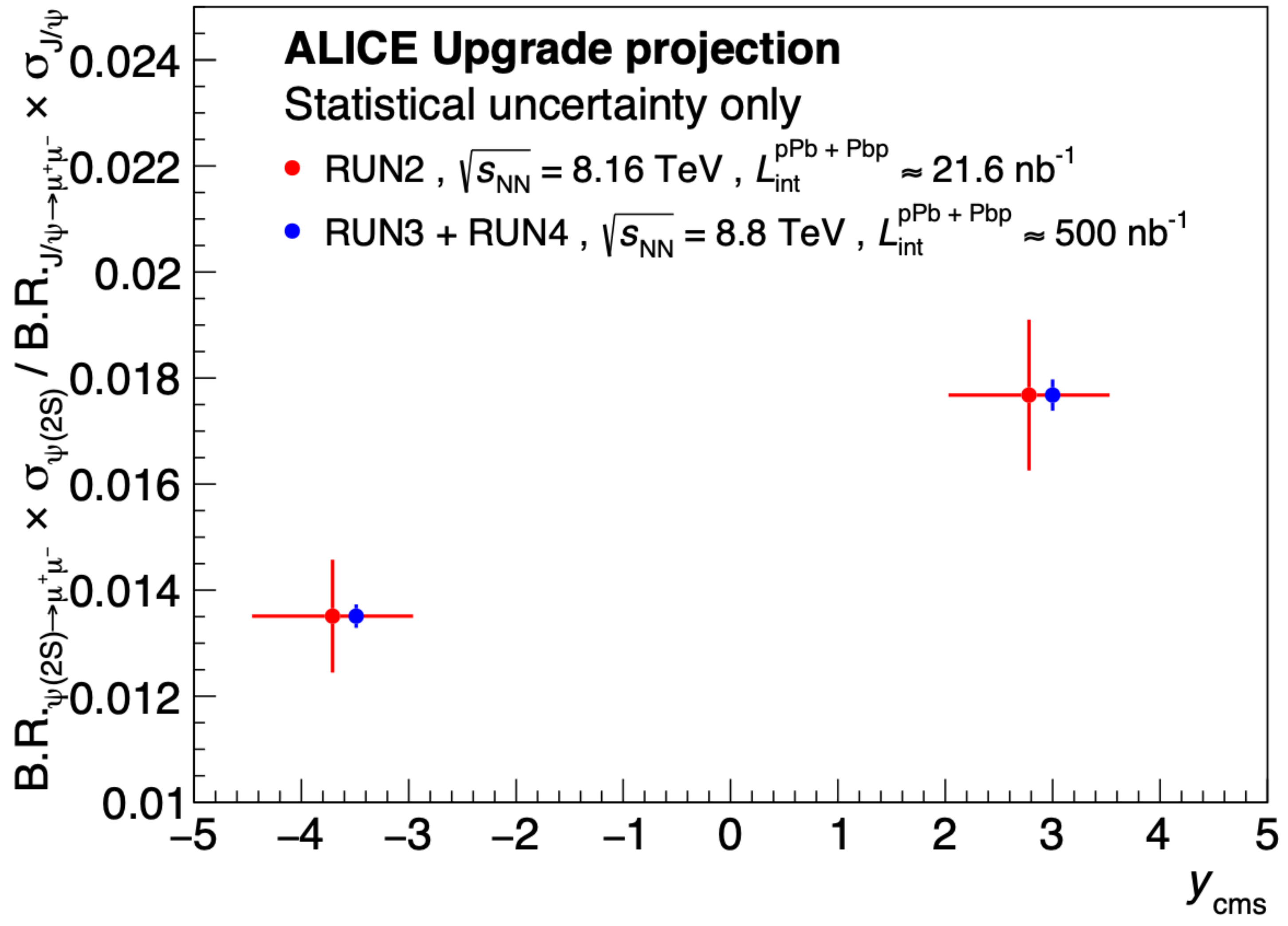


$\psi(2S)$ to J/ψ ratio ALICE-PUBLIC-2020-008



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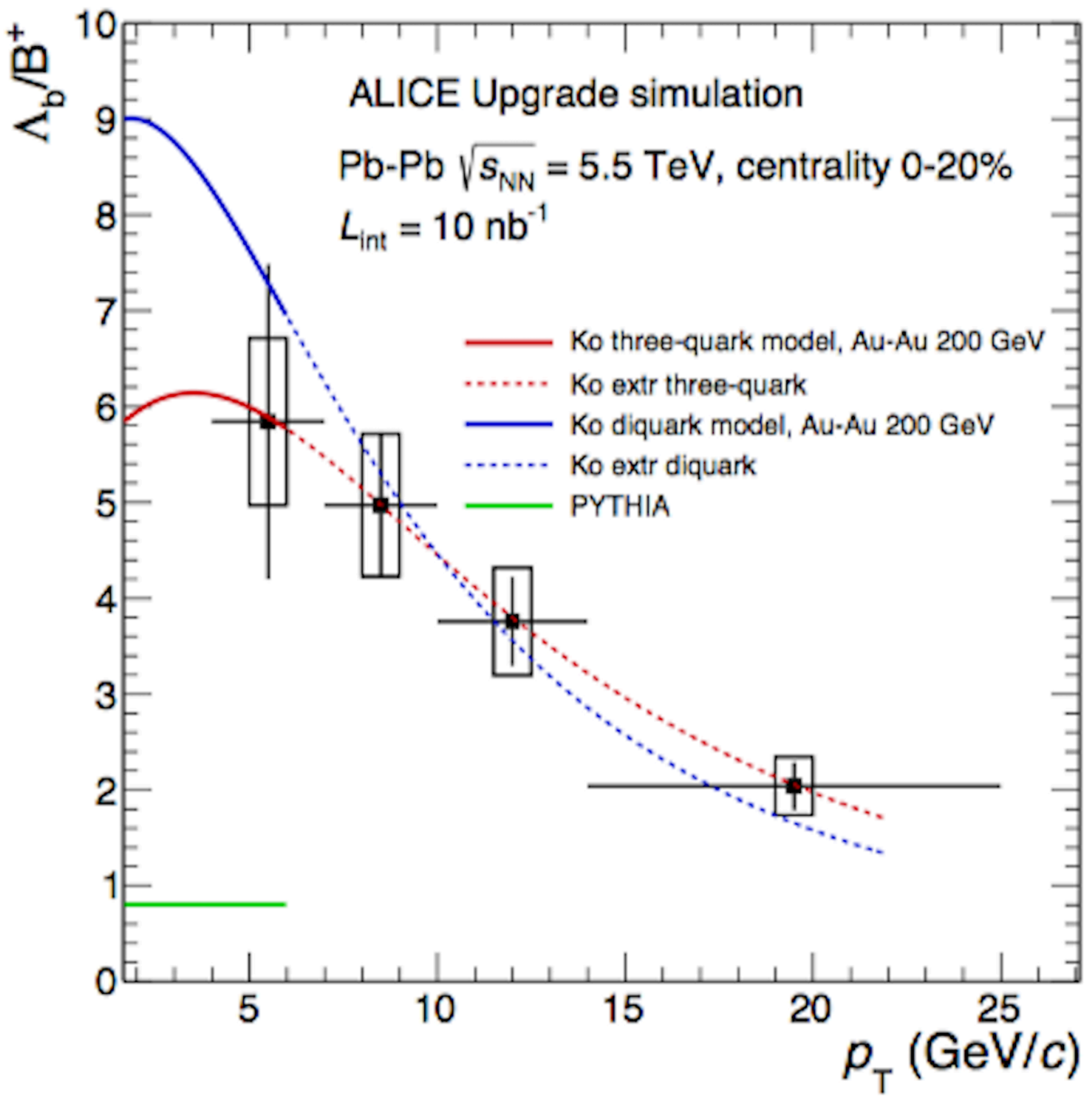

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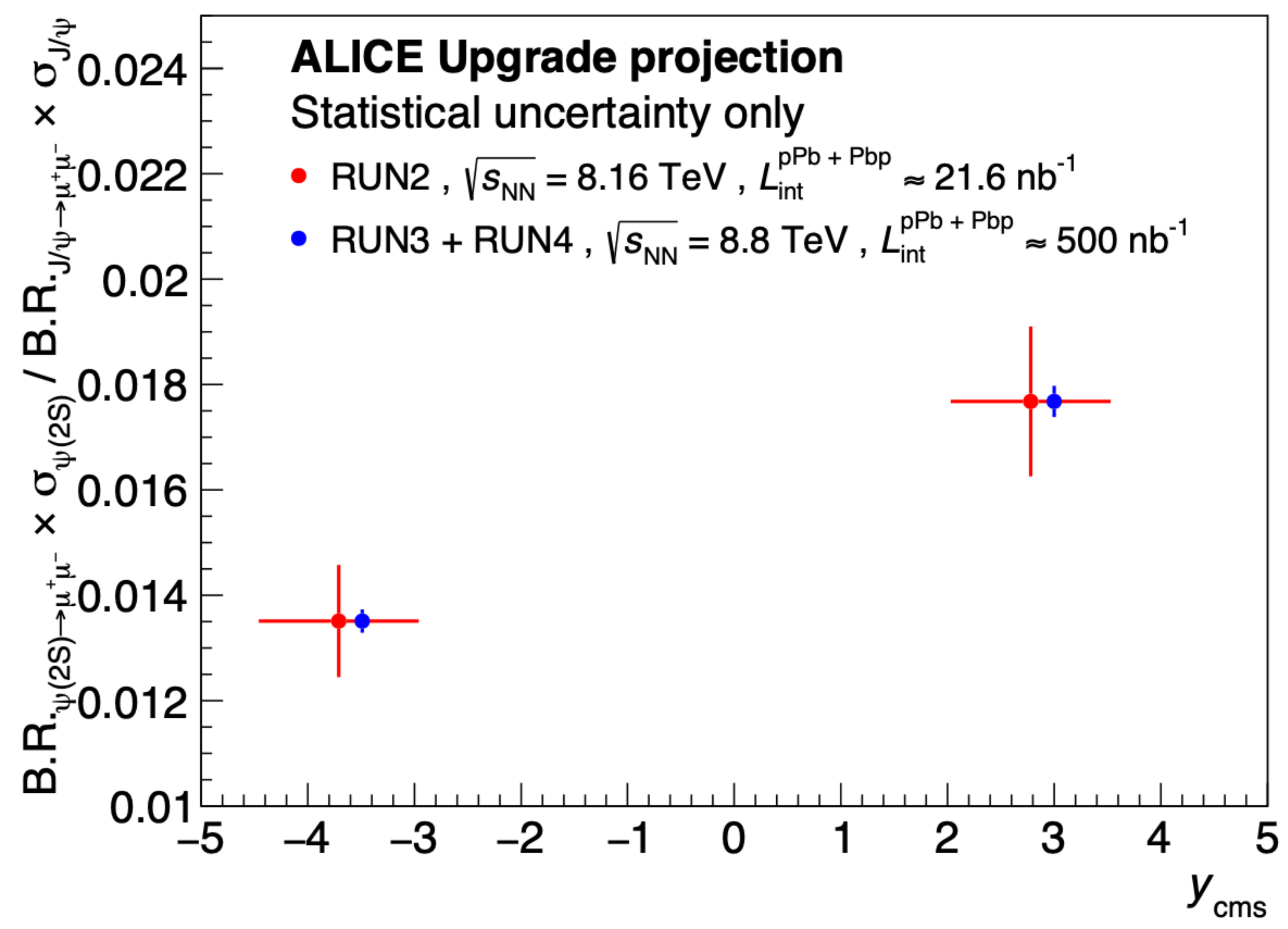

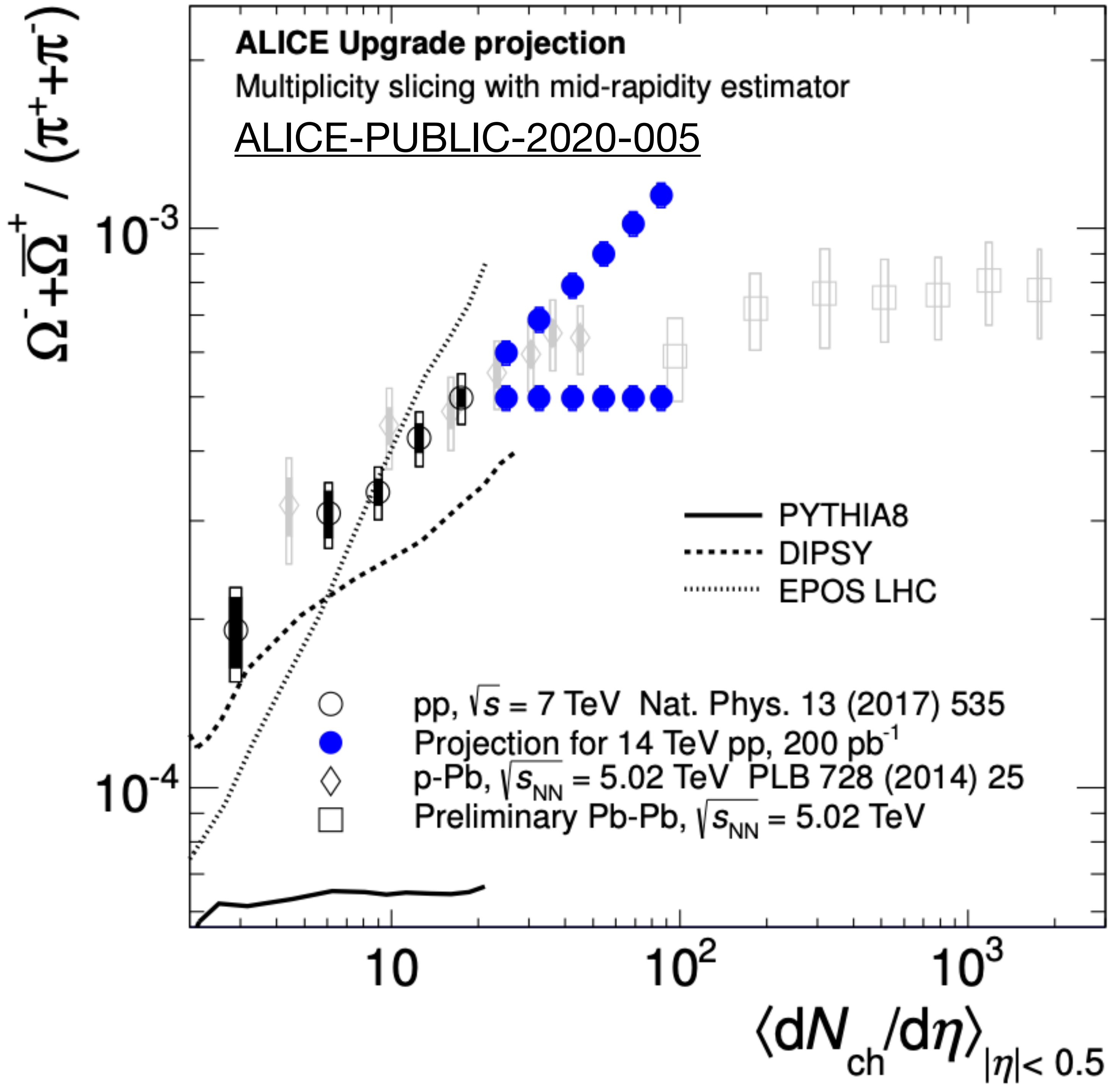

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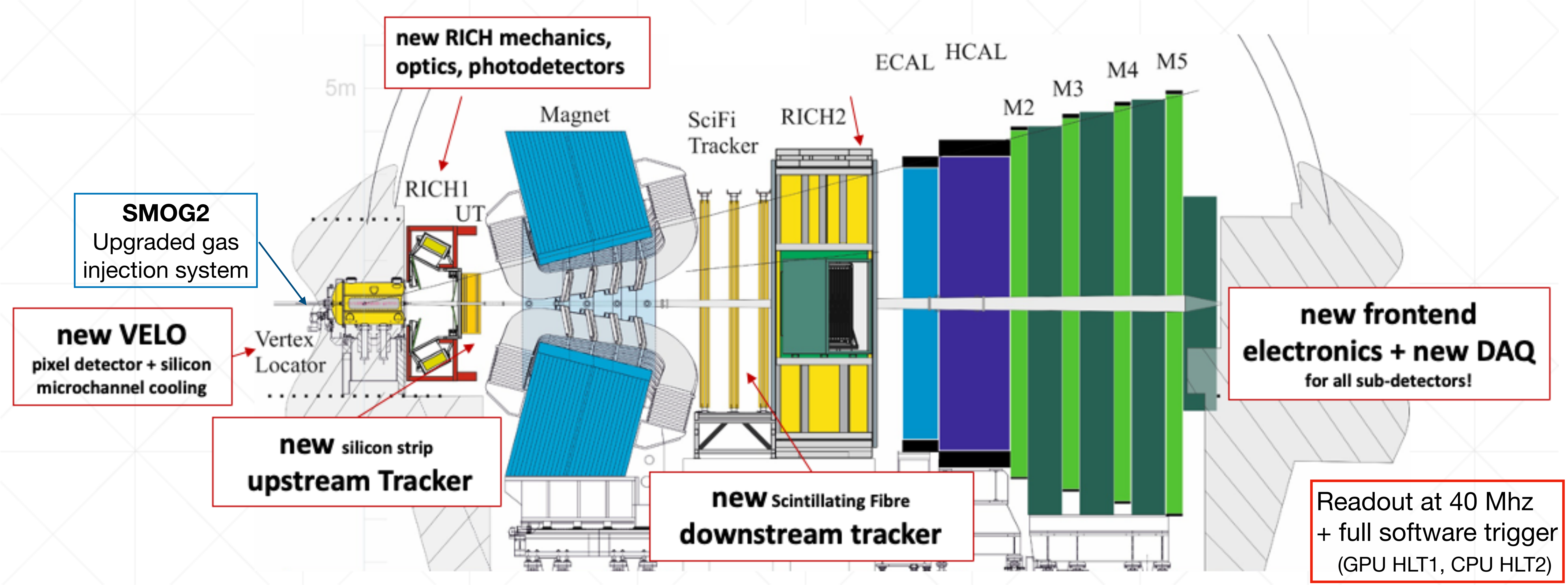
$2 \lesssim \eta \lesssim 5$

LHCb phase I upgrade

The LHCb upgrade I, arXiv:2305.10515

- Significantly improved tracking (pixel, silicon strip, scintillating fibre) + PID
- New tracking can reconstruct even PbPb up to 30% most central
- LHCb with full streaming readout at 40 Mhz
- Upgraded SMOG2 in front of VELO with increased fixed target rates



Readout at 40 Mhz
+ full software trigger
(GPU HLT1, CPU HLT2)

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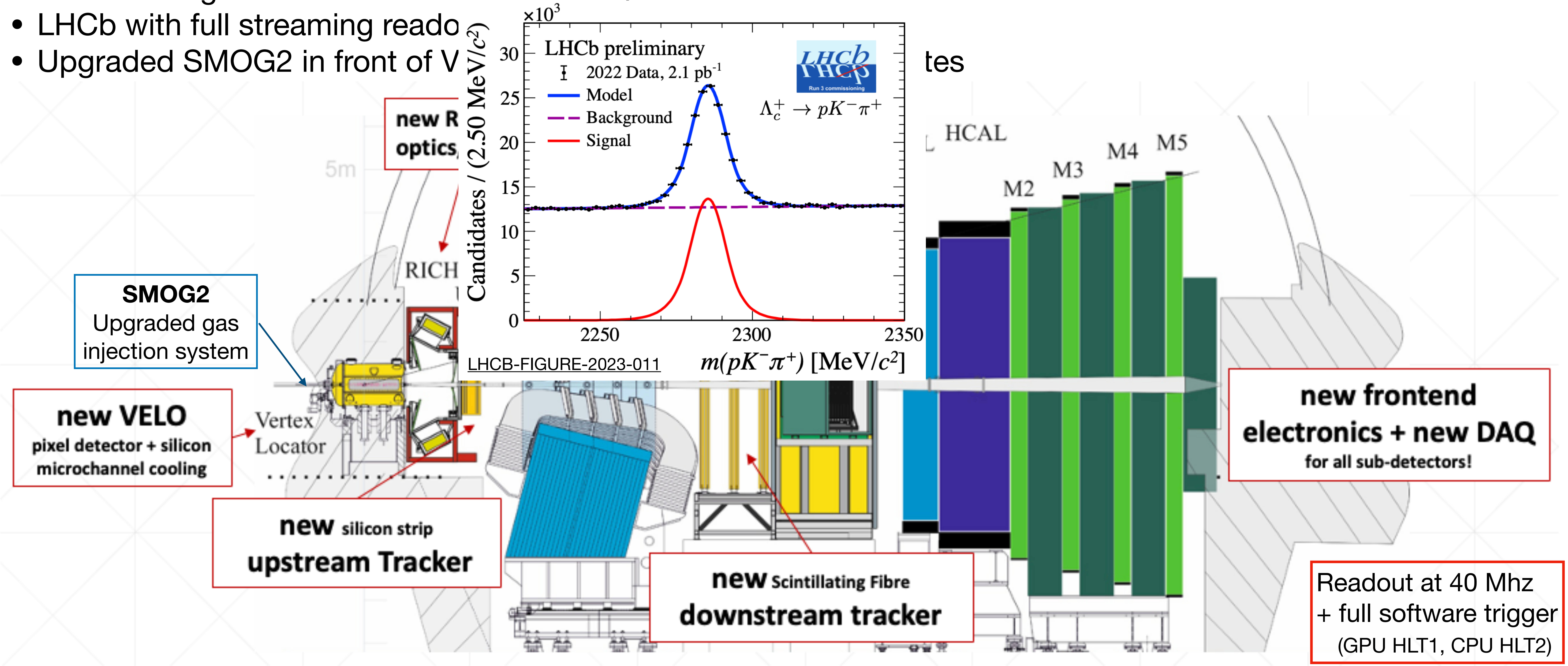

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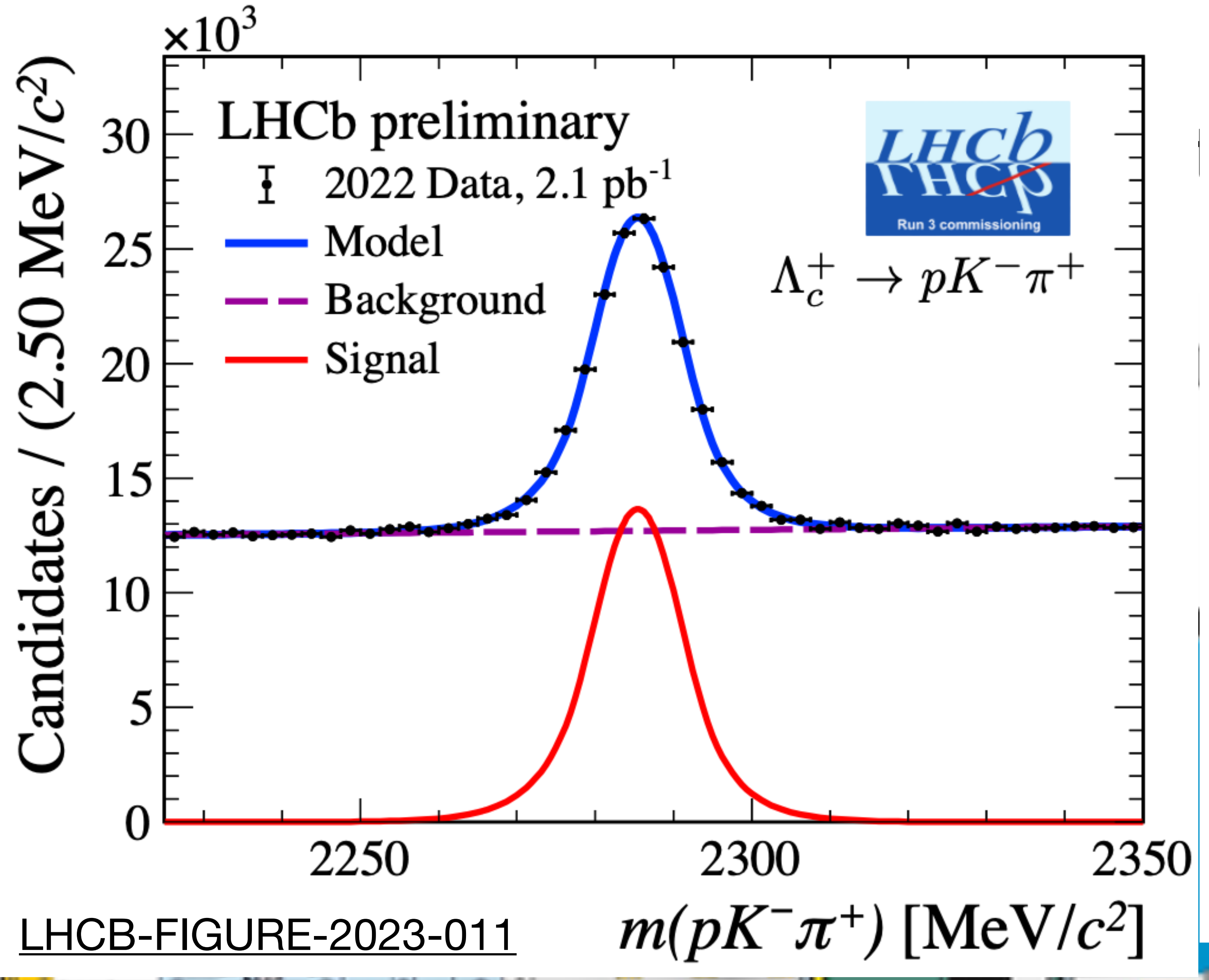
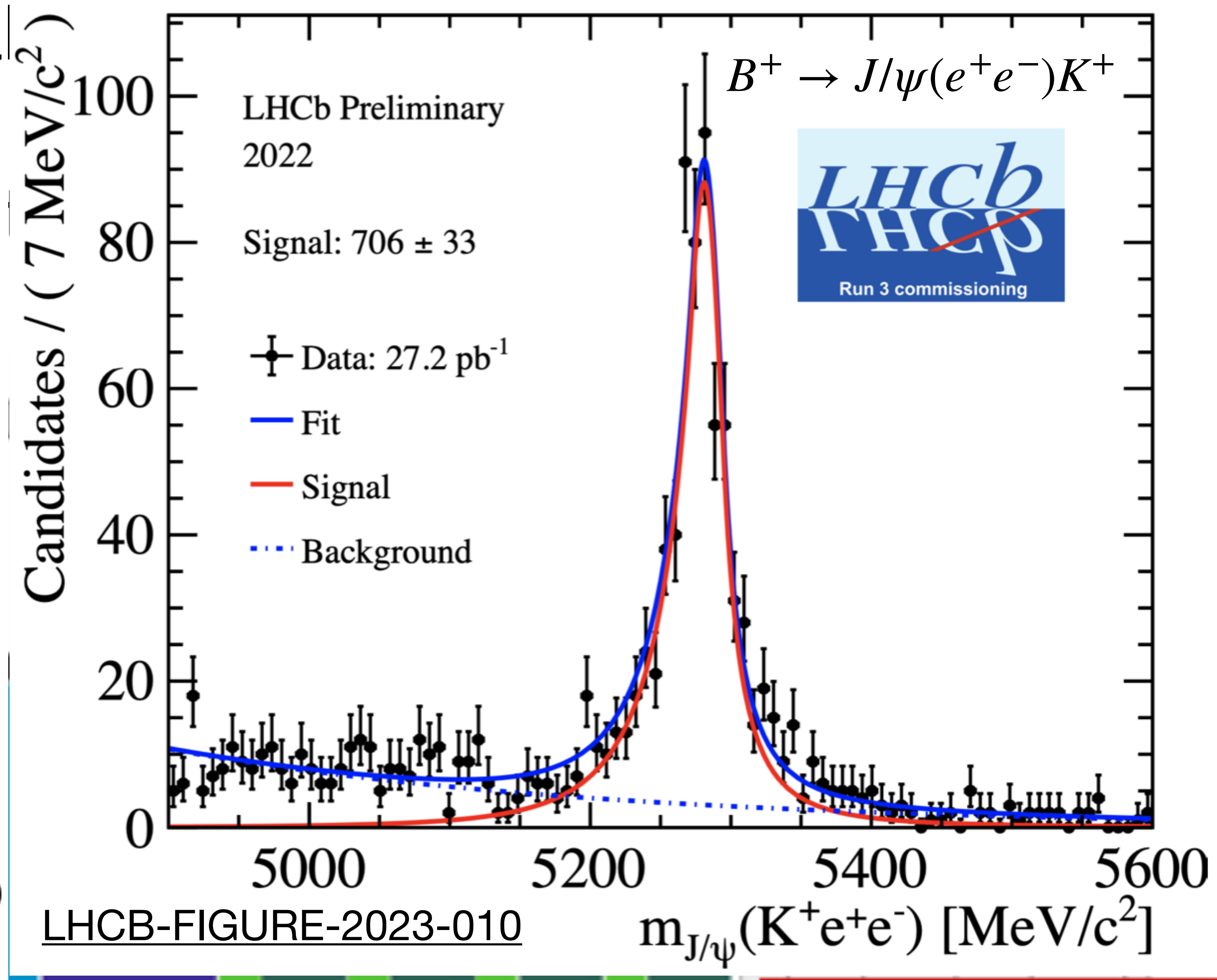
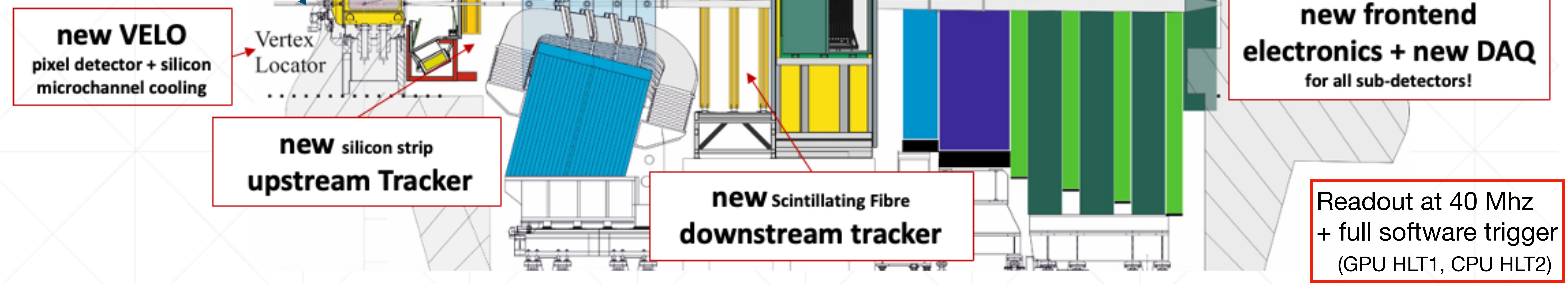


LHCB-FIGURE-2023-011



LHCB-FIGURE-2023-010



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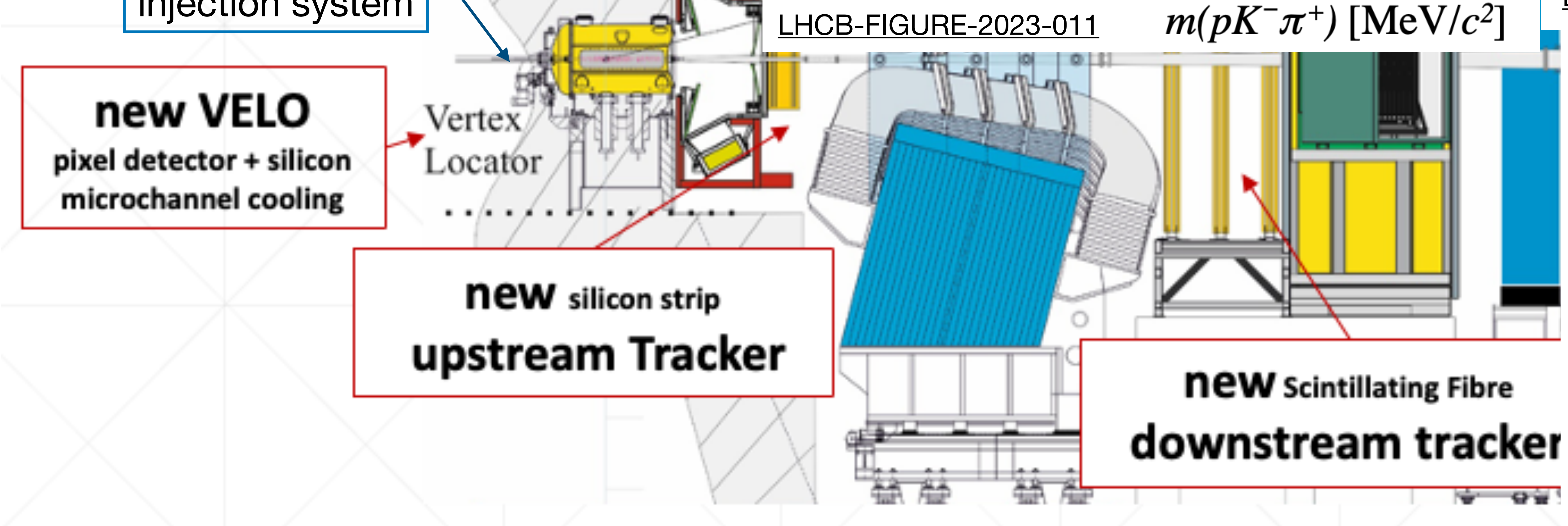
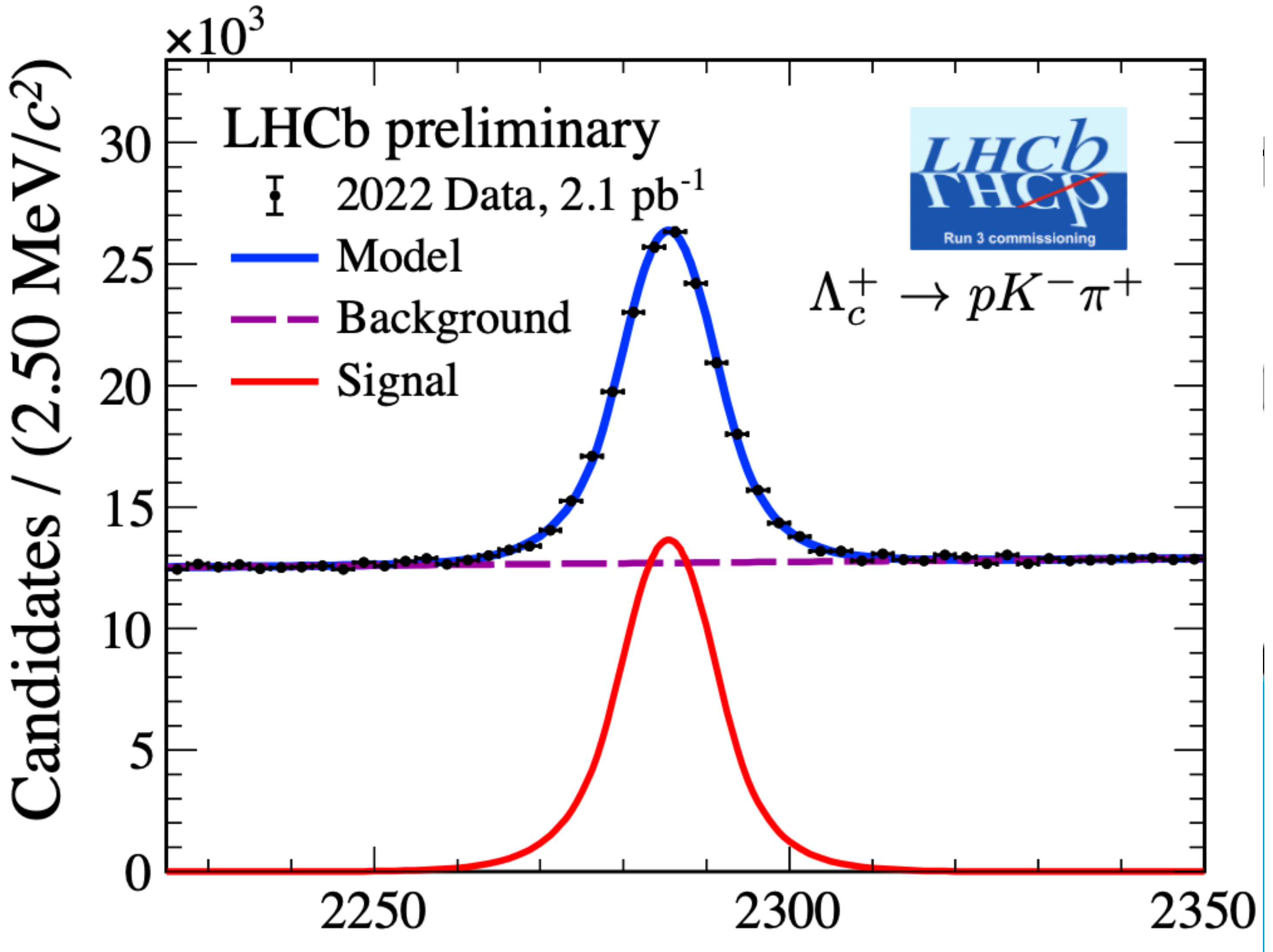
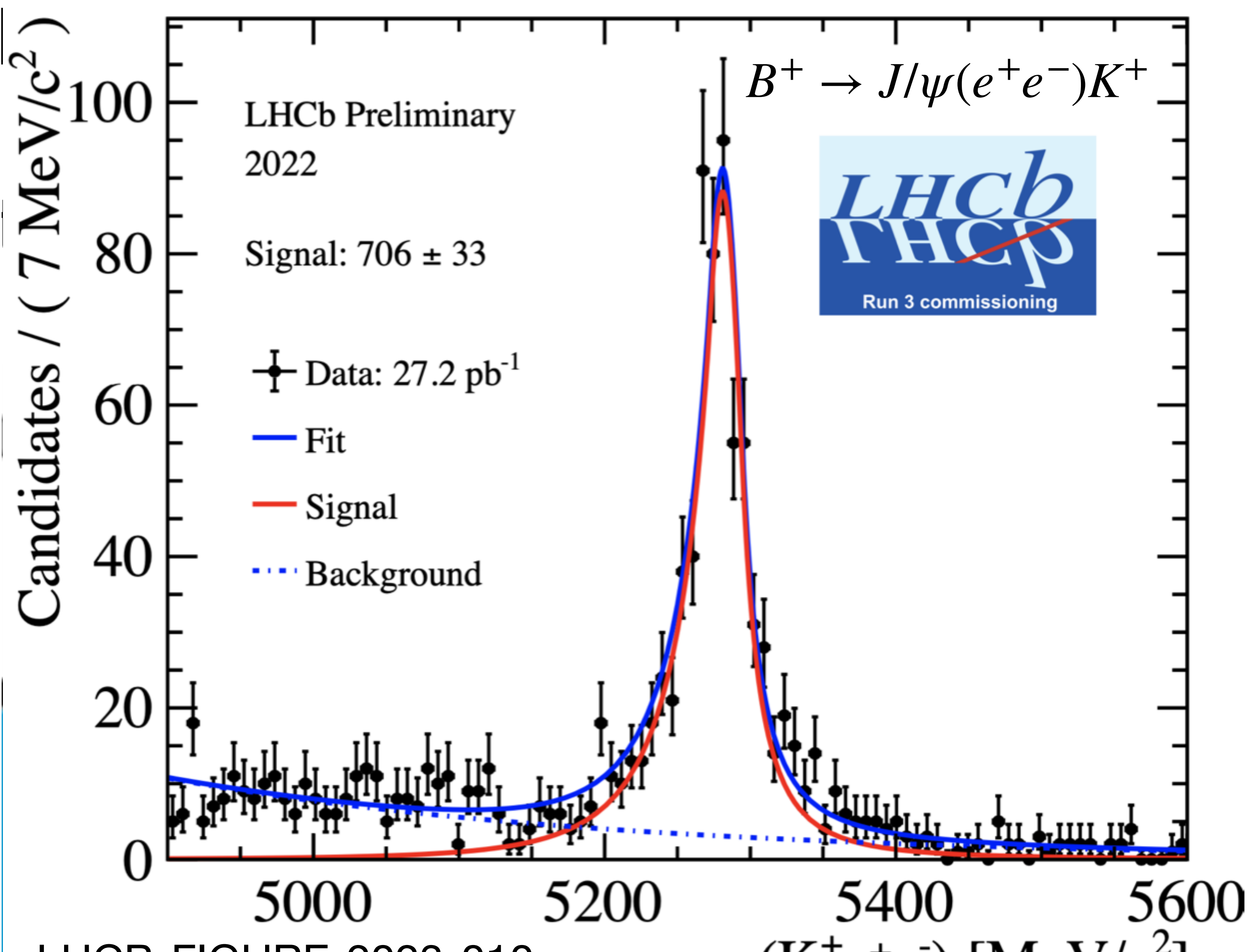
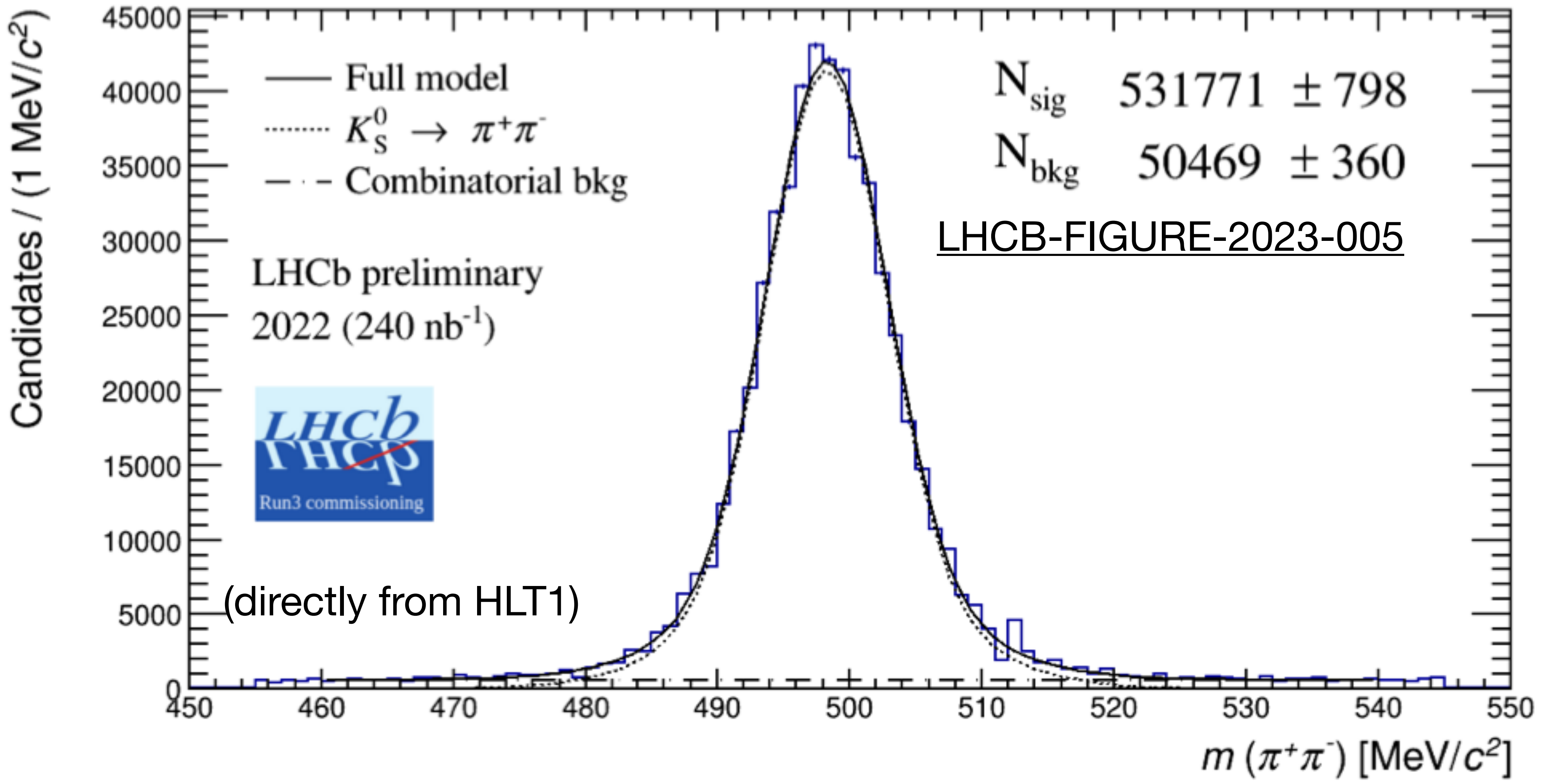




LHCB-FIGURE-2023-011



LHCB-FIGURE-2023-010



LHCB-FIGURE-2023-005

$2 \lesssim \eta \lesssim 5$

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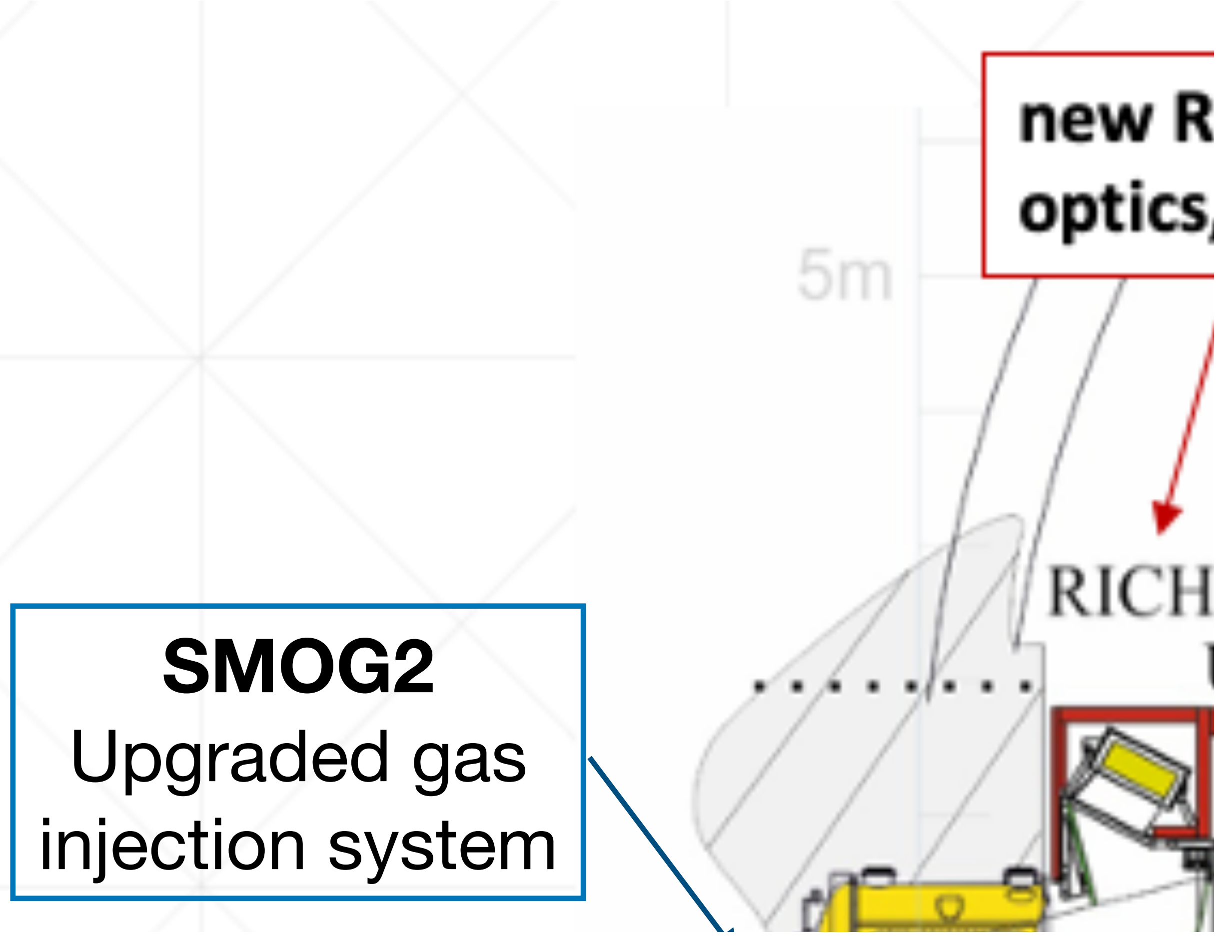
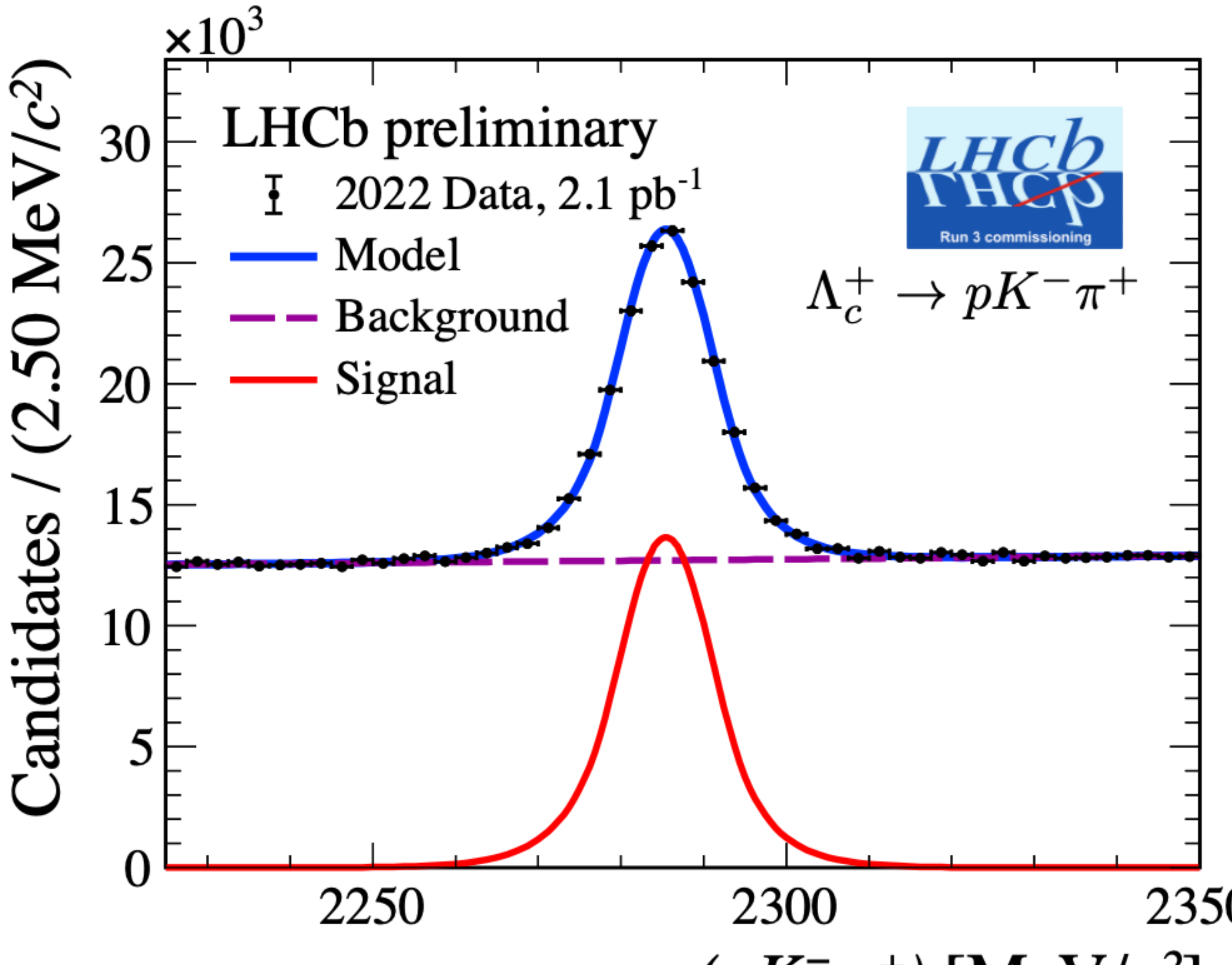
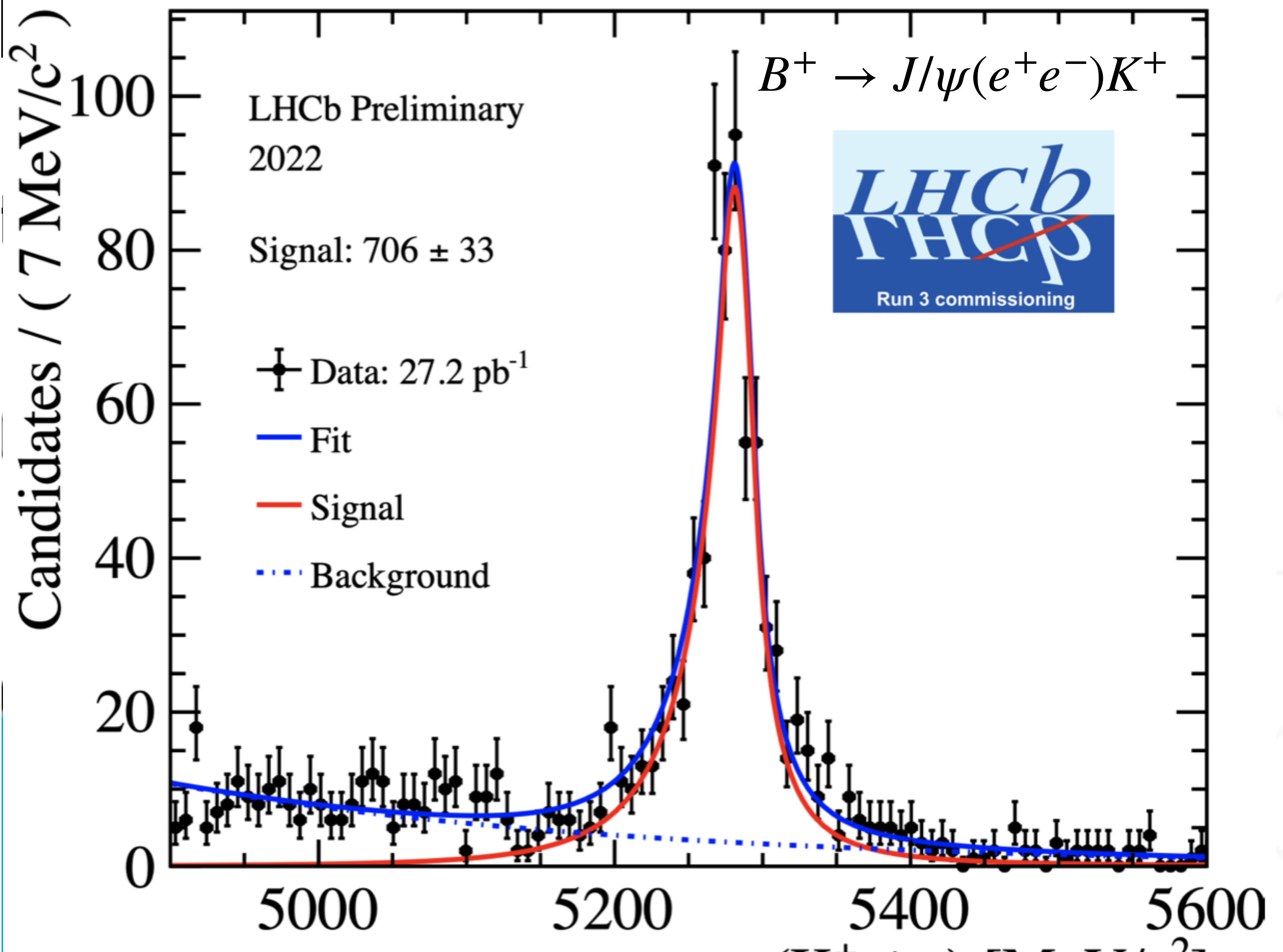
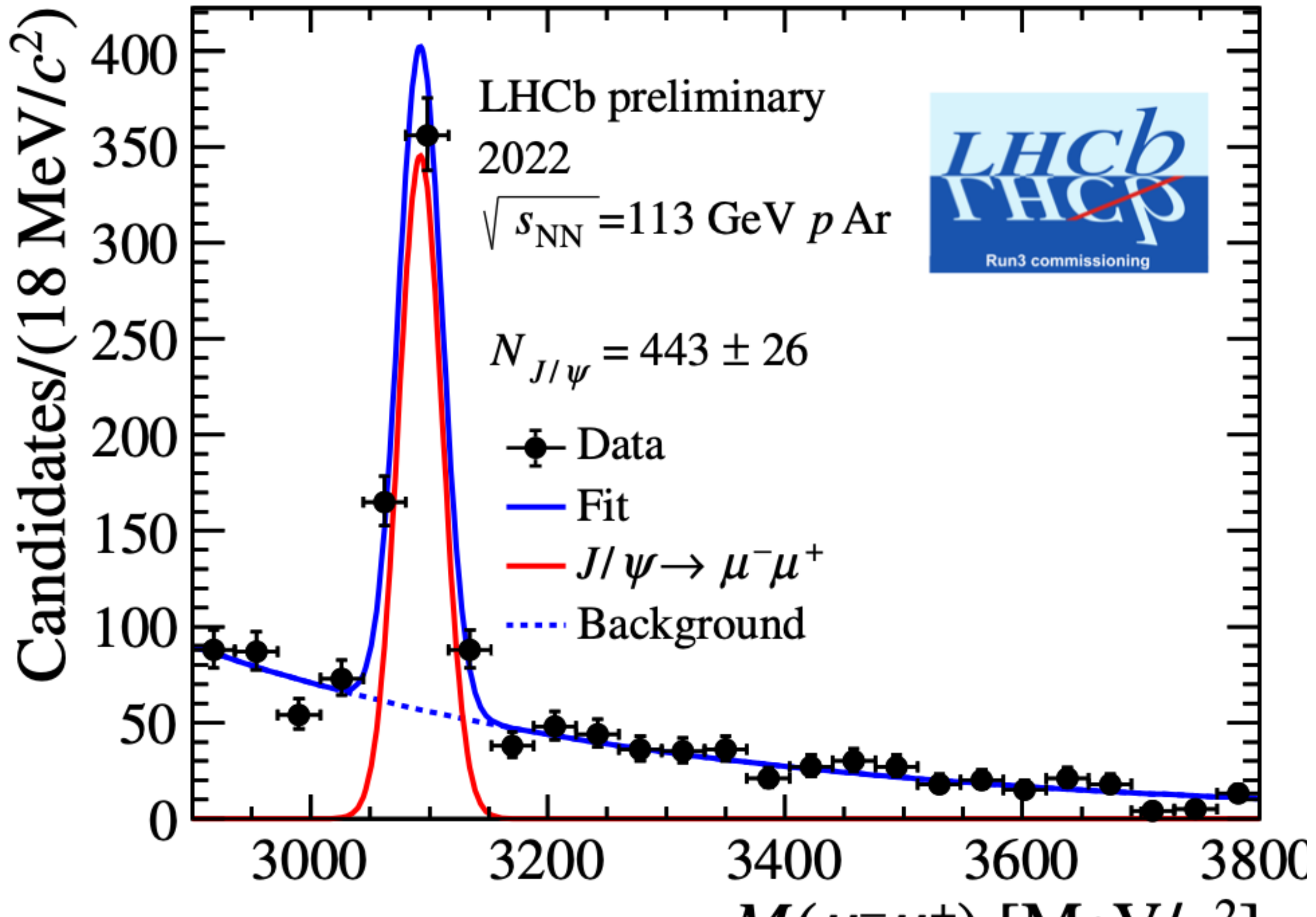




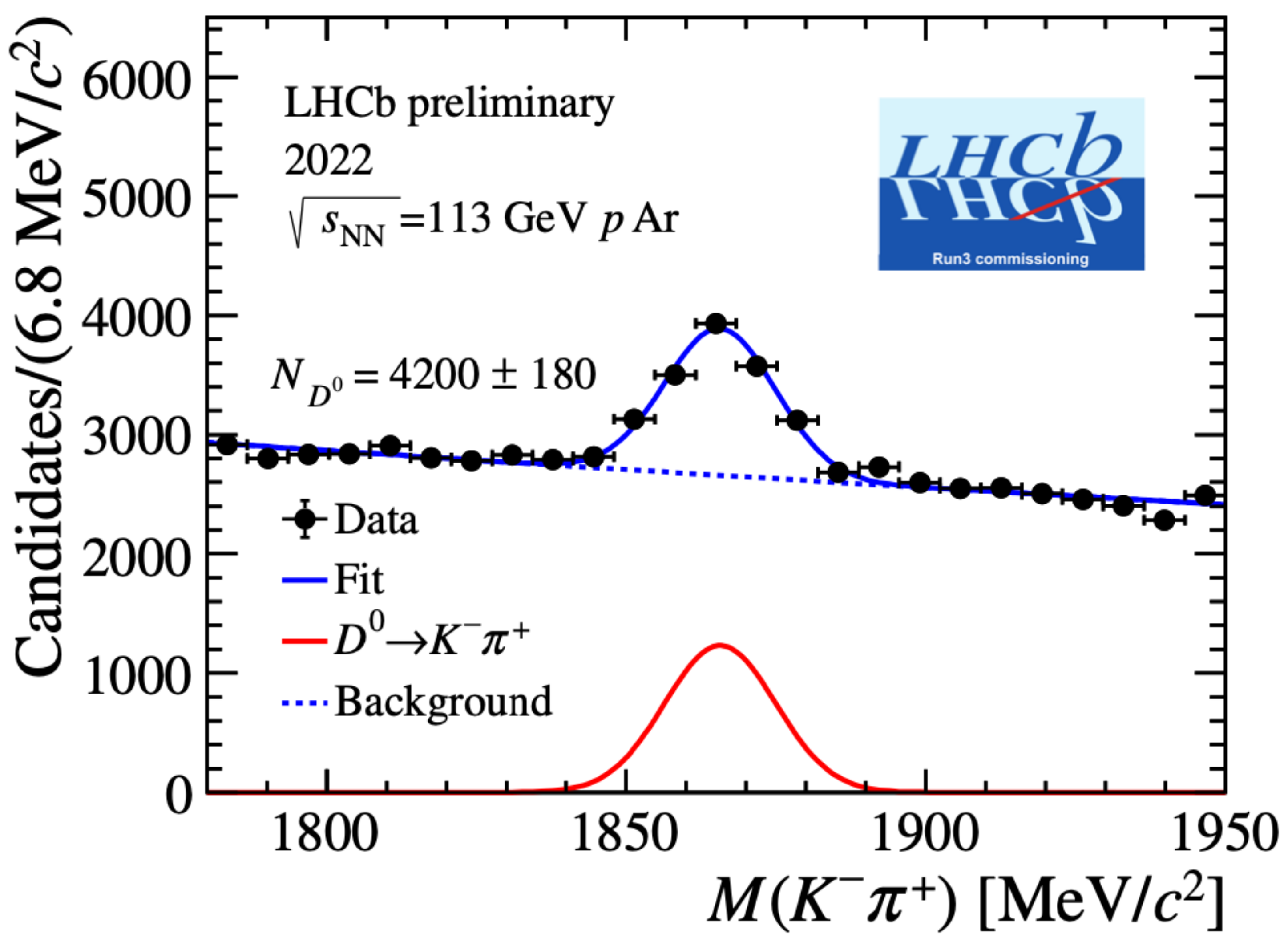
LHCB-FIGURE-2023-011

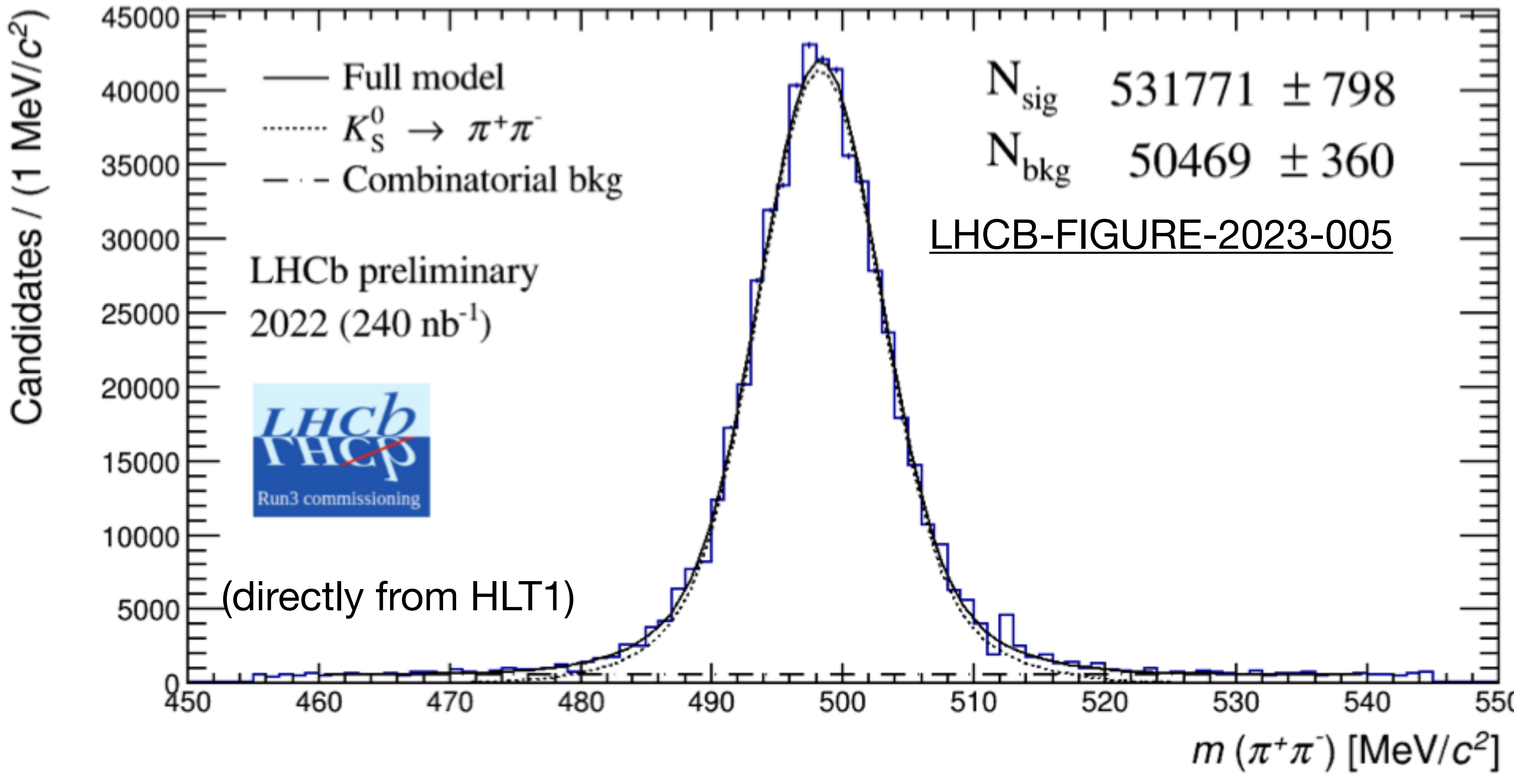


LHCB-FIGURE-2023-010



LHCB-FIGURE-2023-008

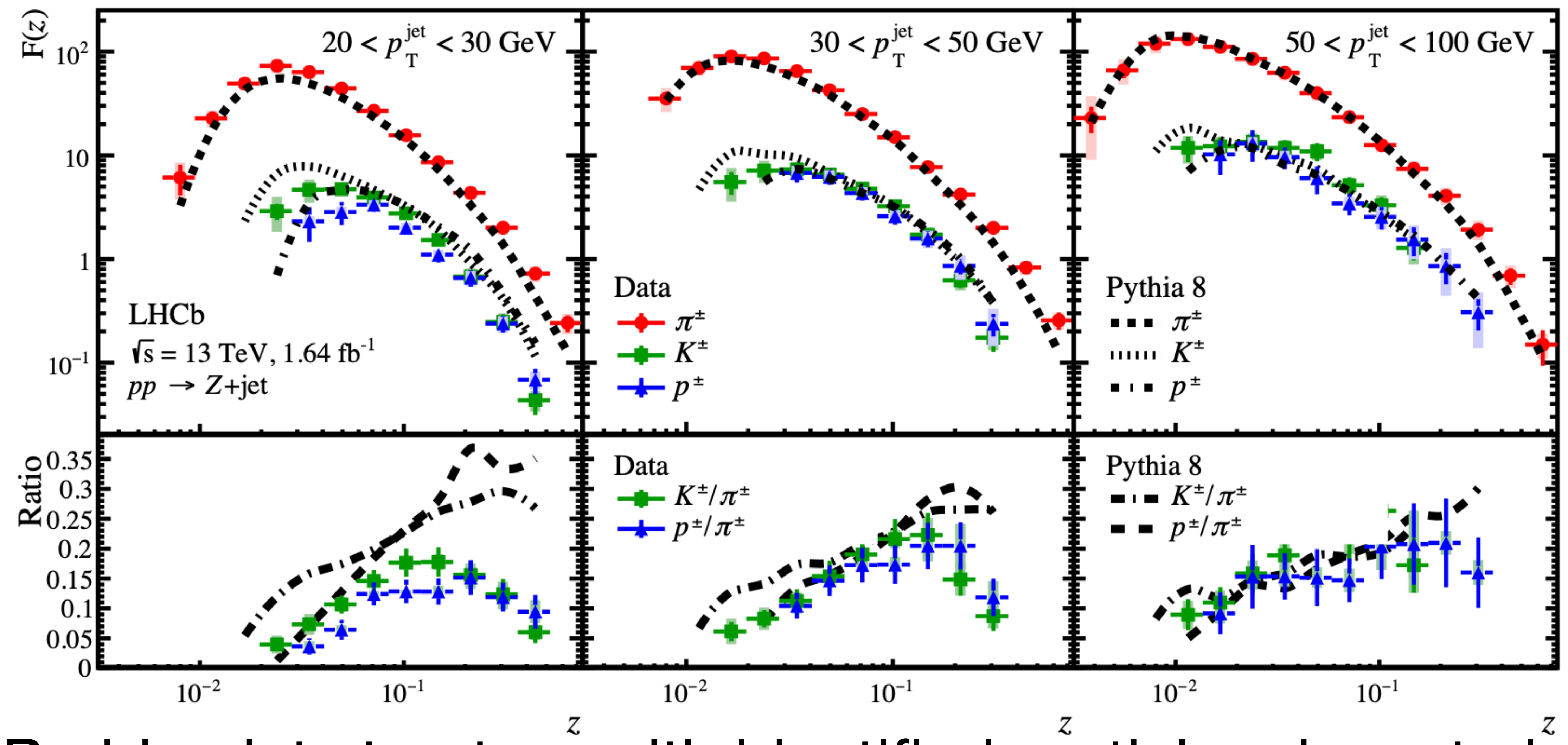




LHCB-FIGURE-2023-005

LHCb phase I - example current and future measurements

LHCb, arXiv:2208.11691



Probing jet structure with identified particles down to low p_T

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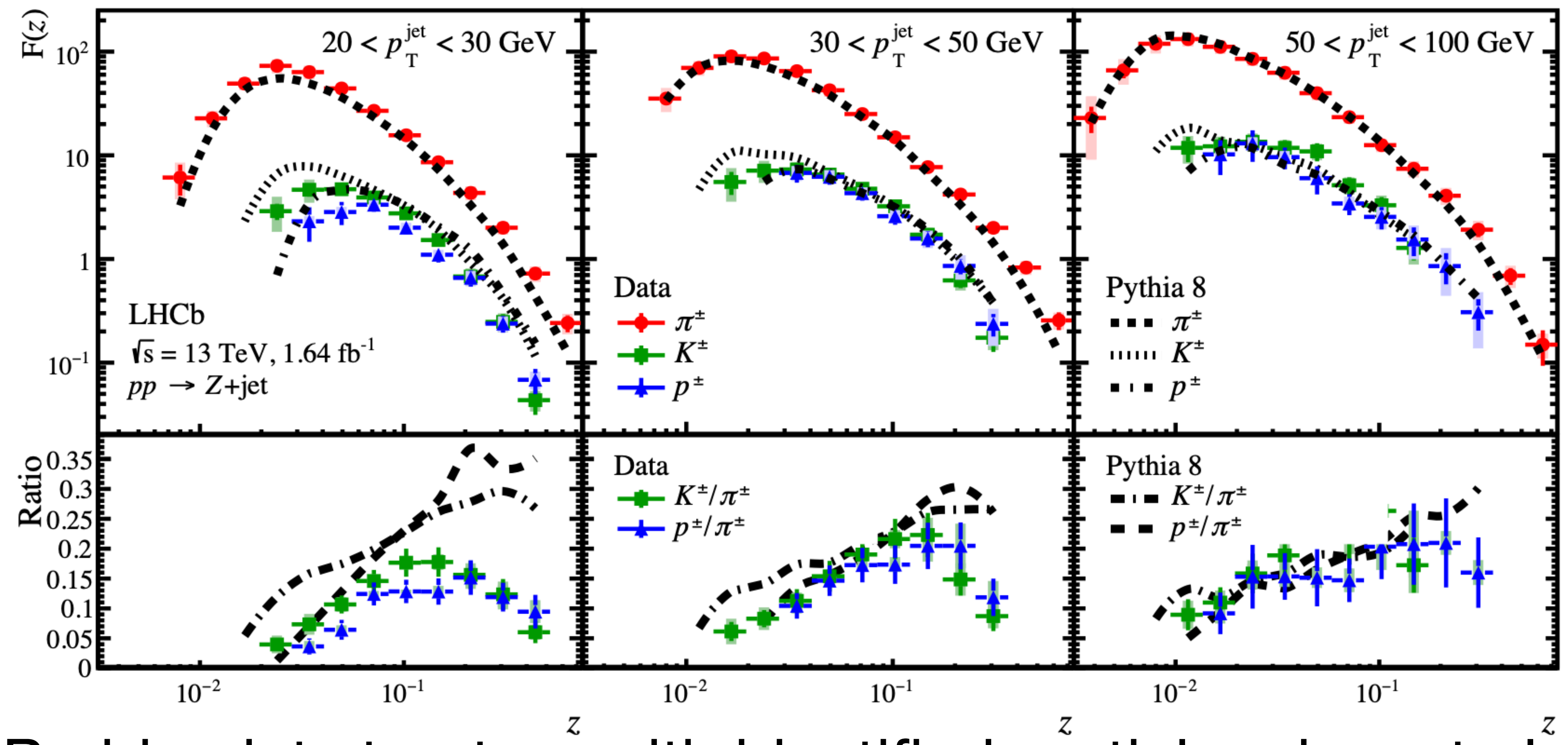

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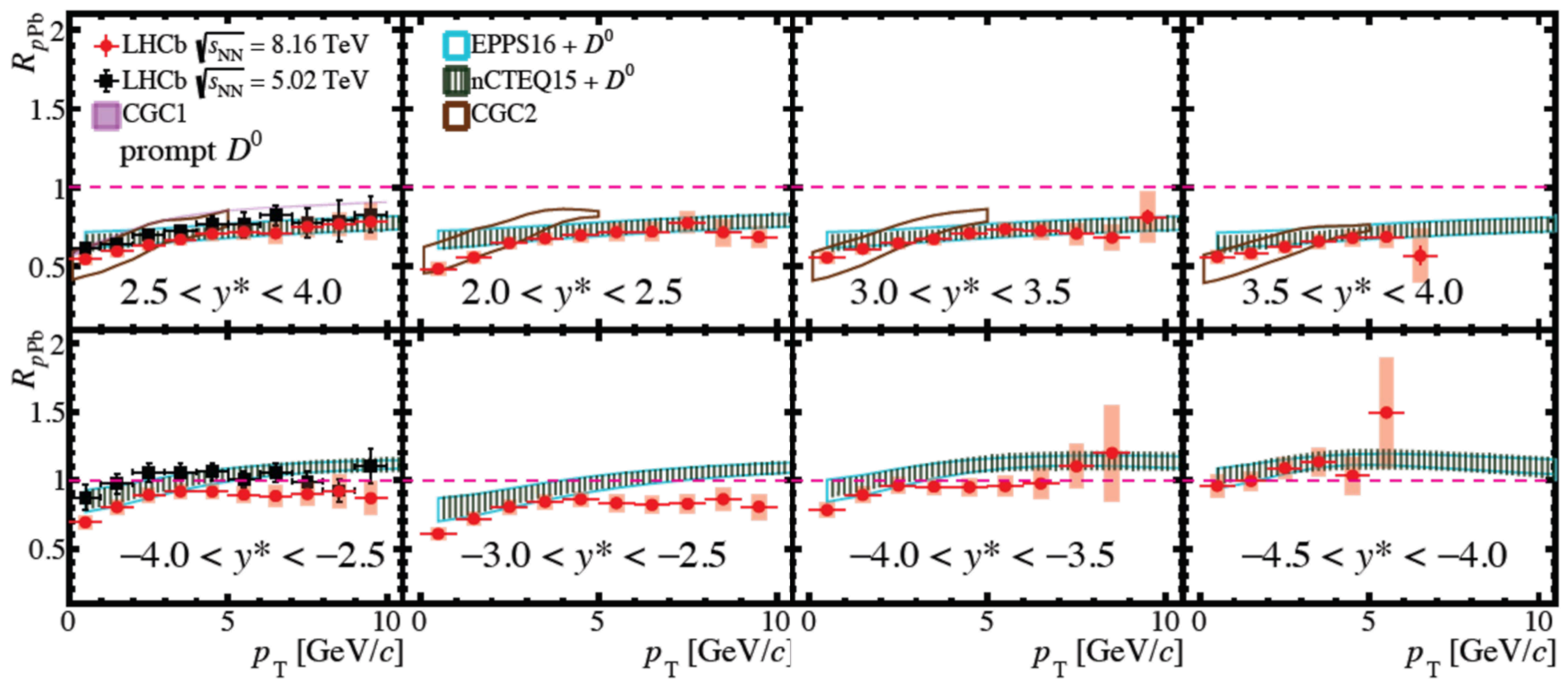
arXiv:2205.03936



World's most precise D^0 meson data in pPb at 8.16 TeV

LHCb phase I - example current and future measurements

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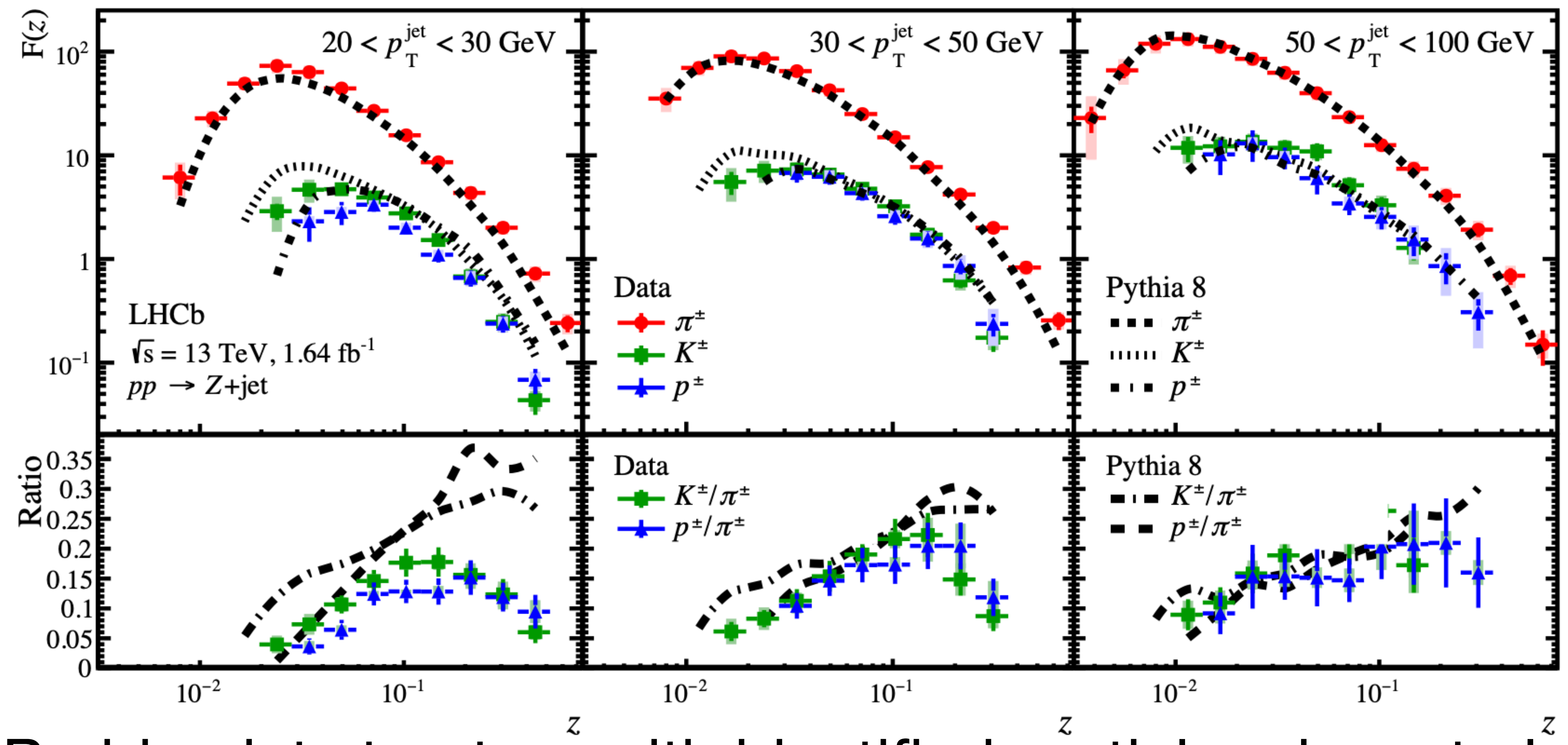

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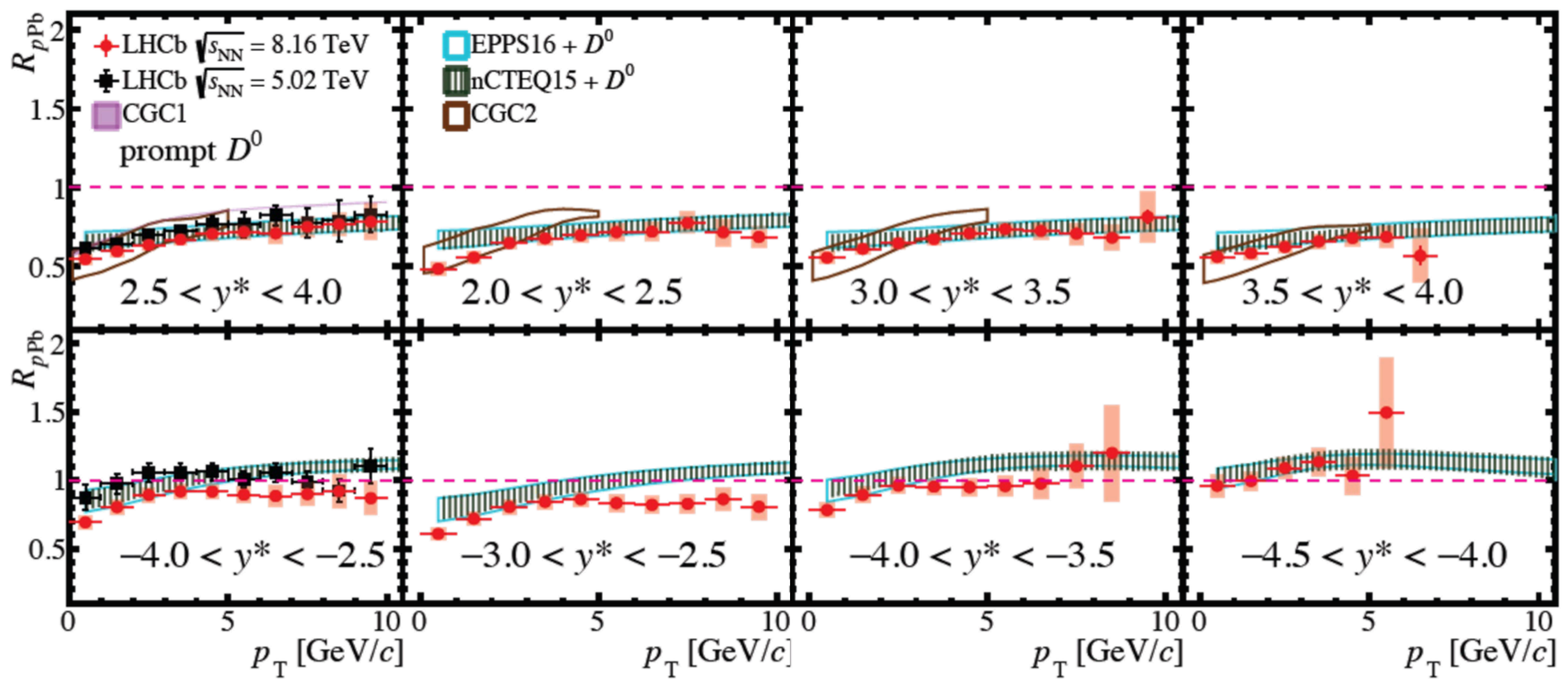

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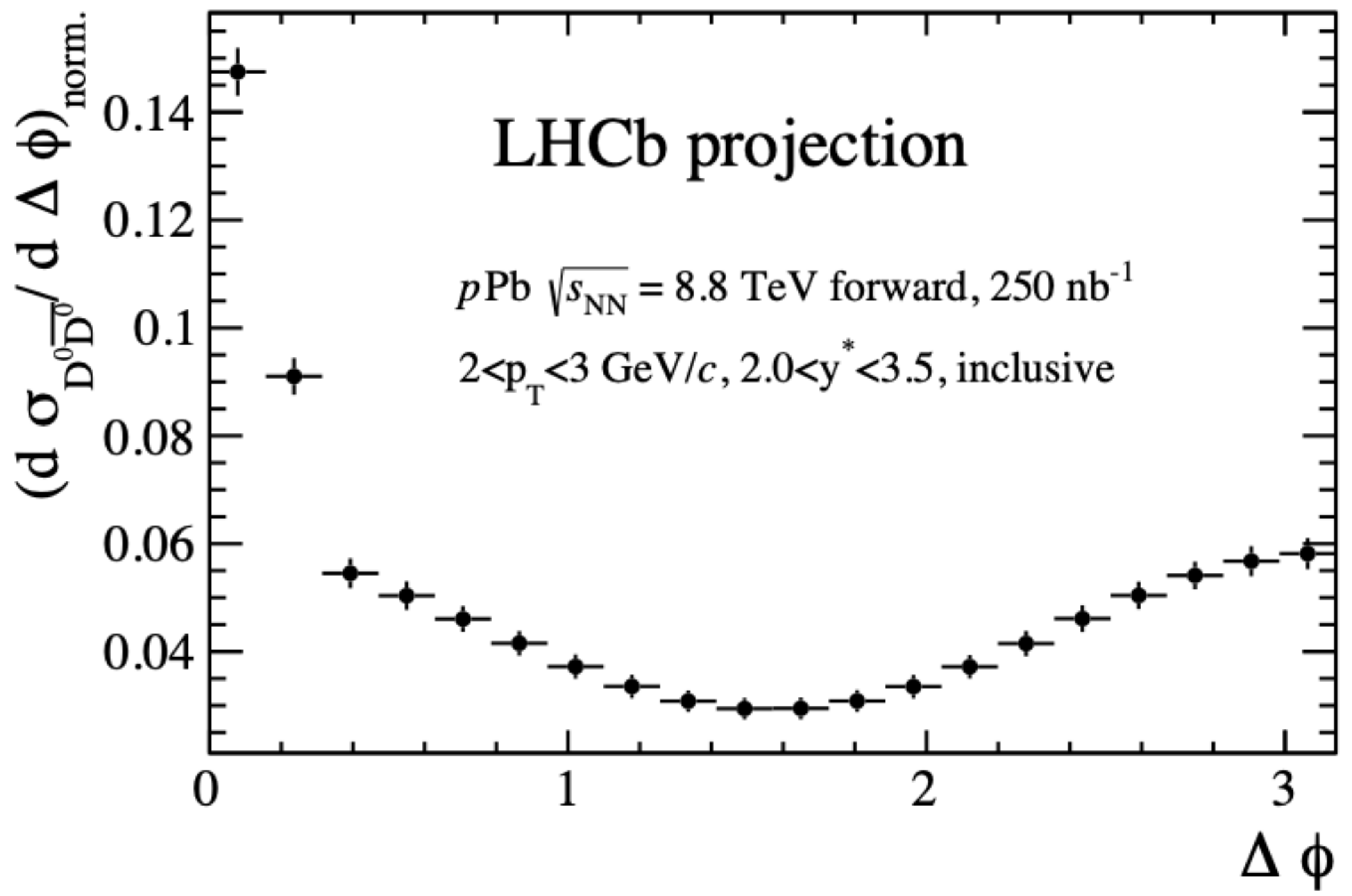
LHCb-CONF-2018-005



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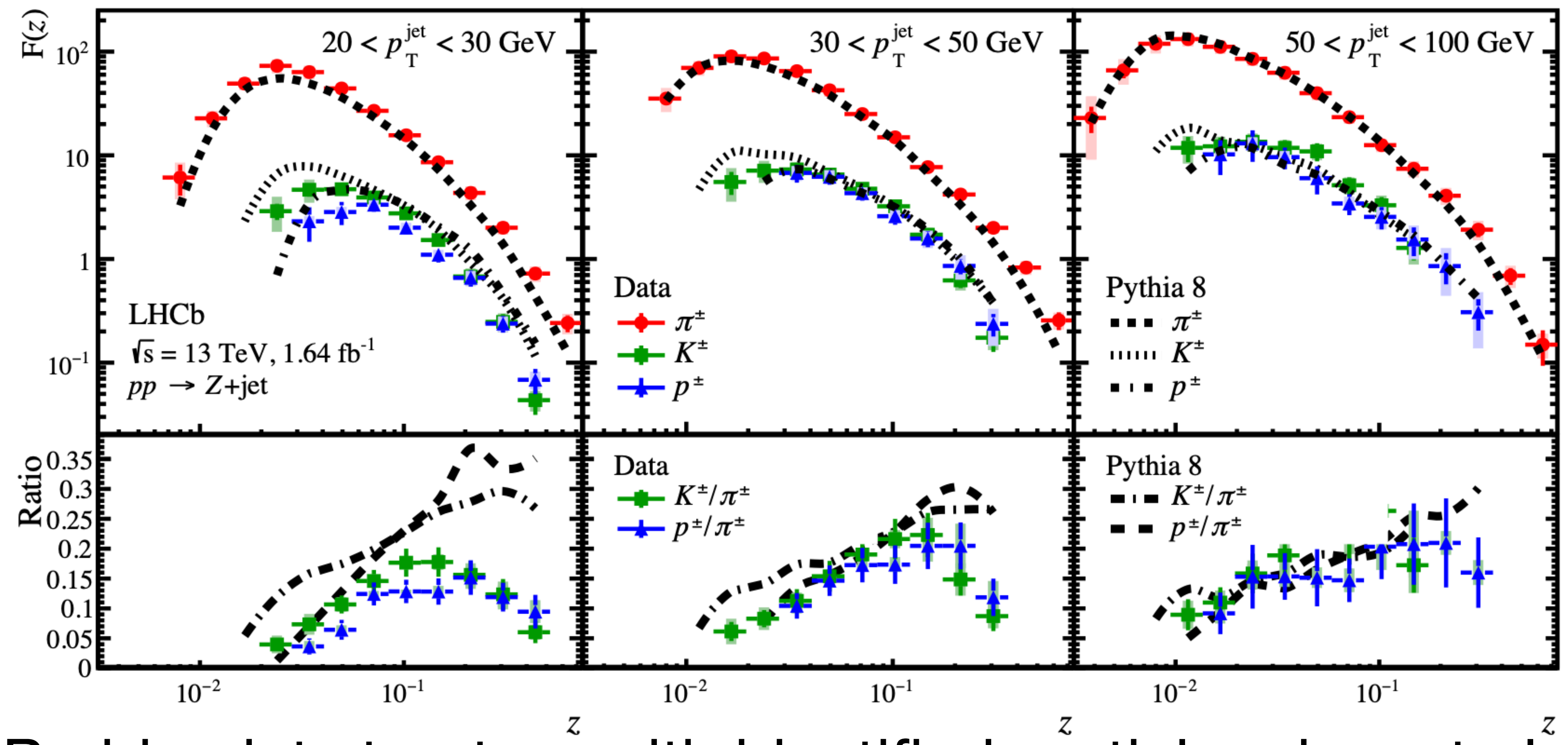
LHCb, arXiv:2208.11691



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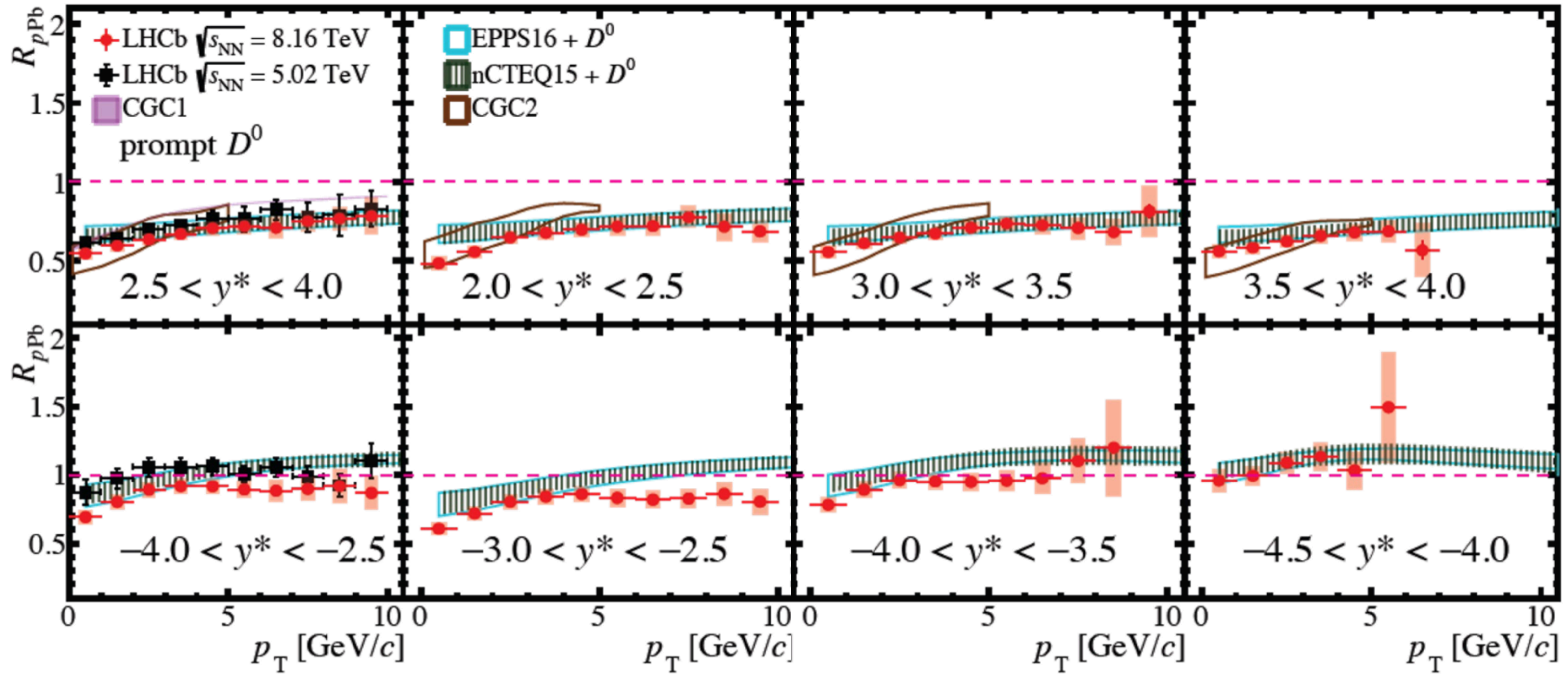
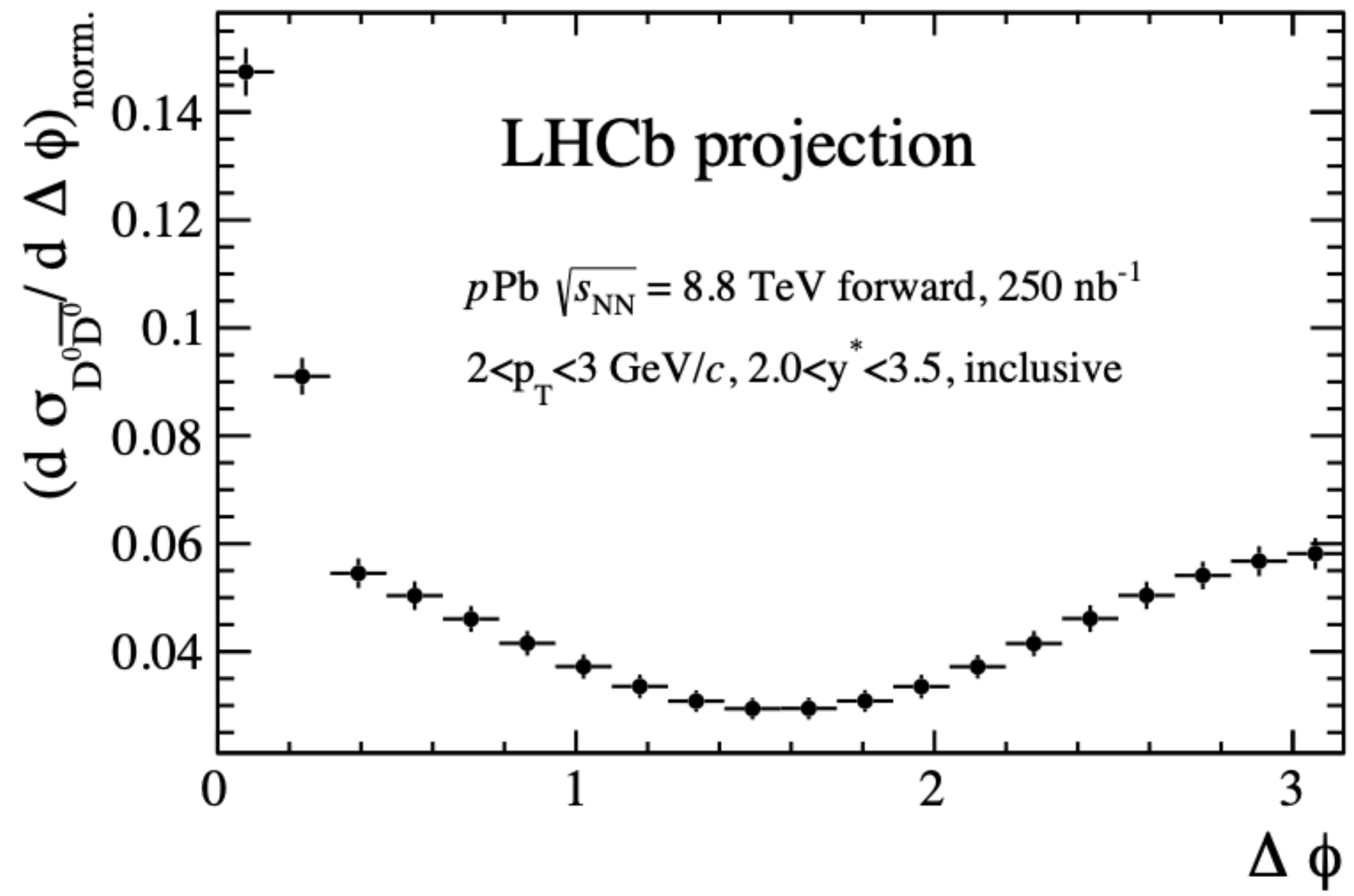
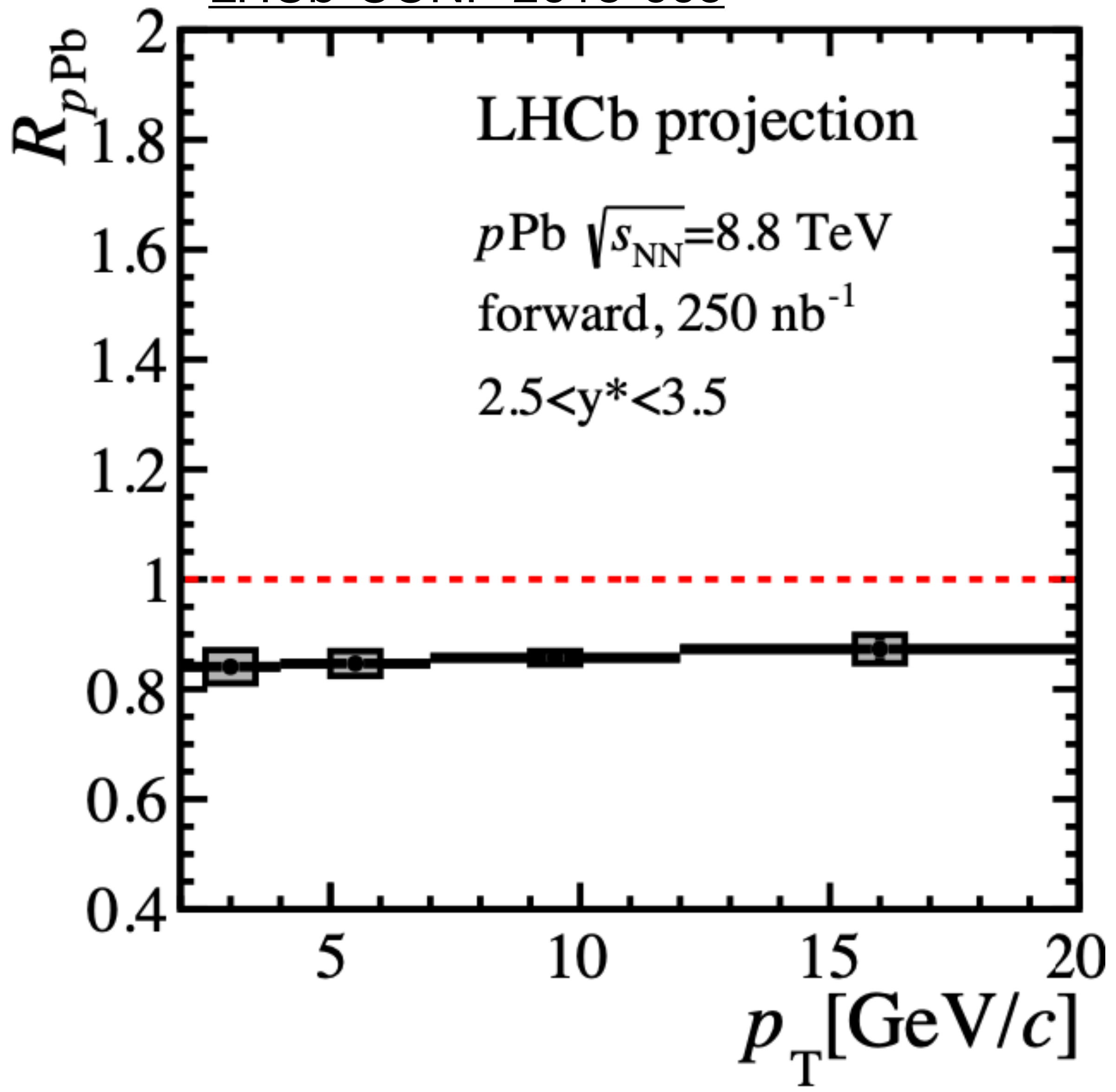


World's most precise D^0 meson data in pPb at 8.16 TeV

LHCb-CONF-2018-005

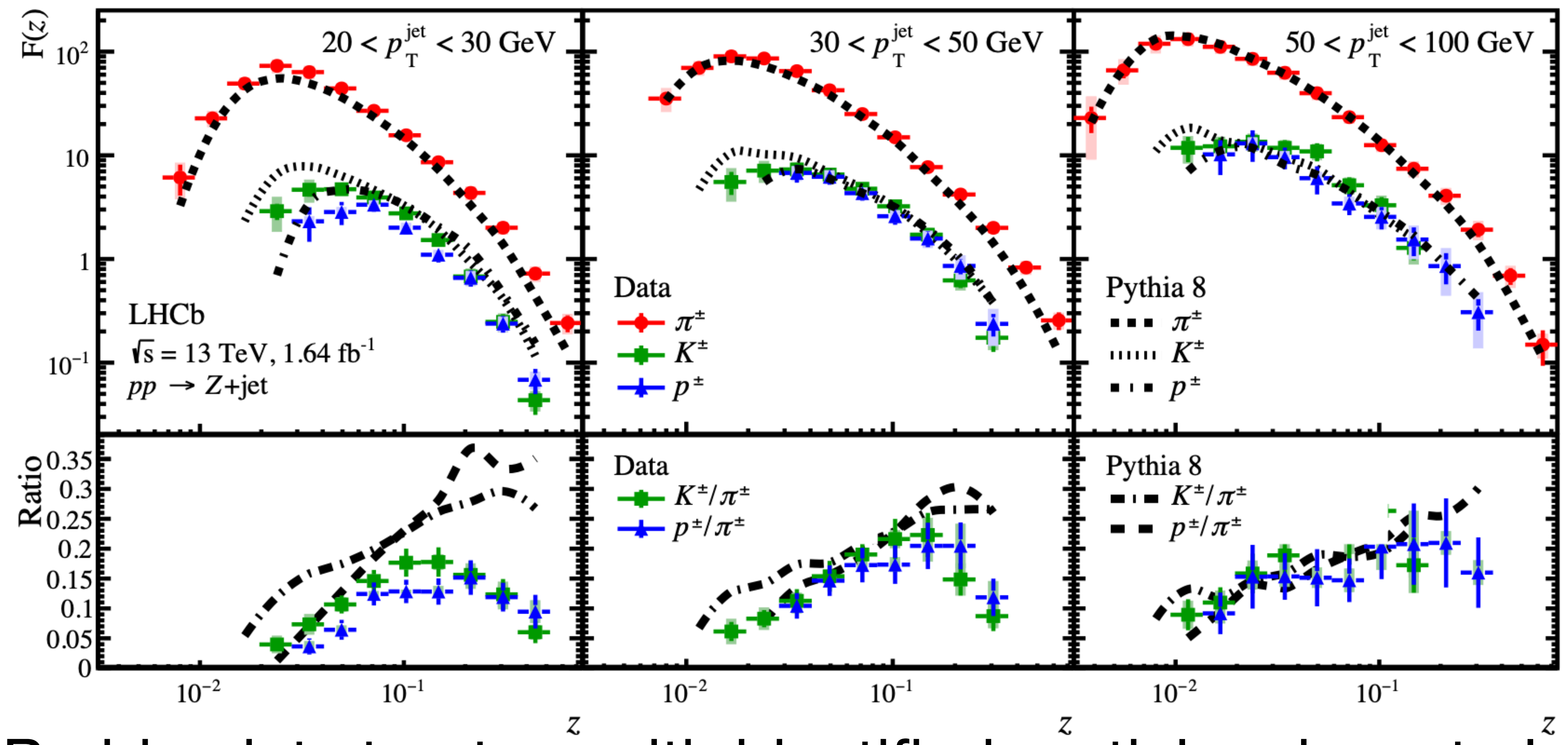


LHCb-CONF-2018-005



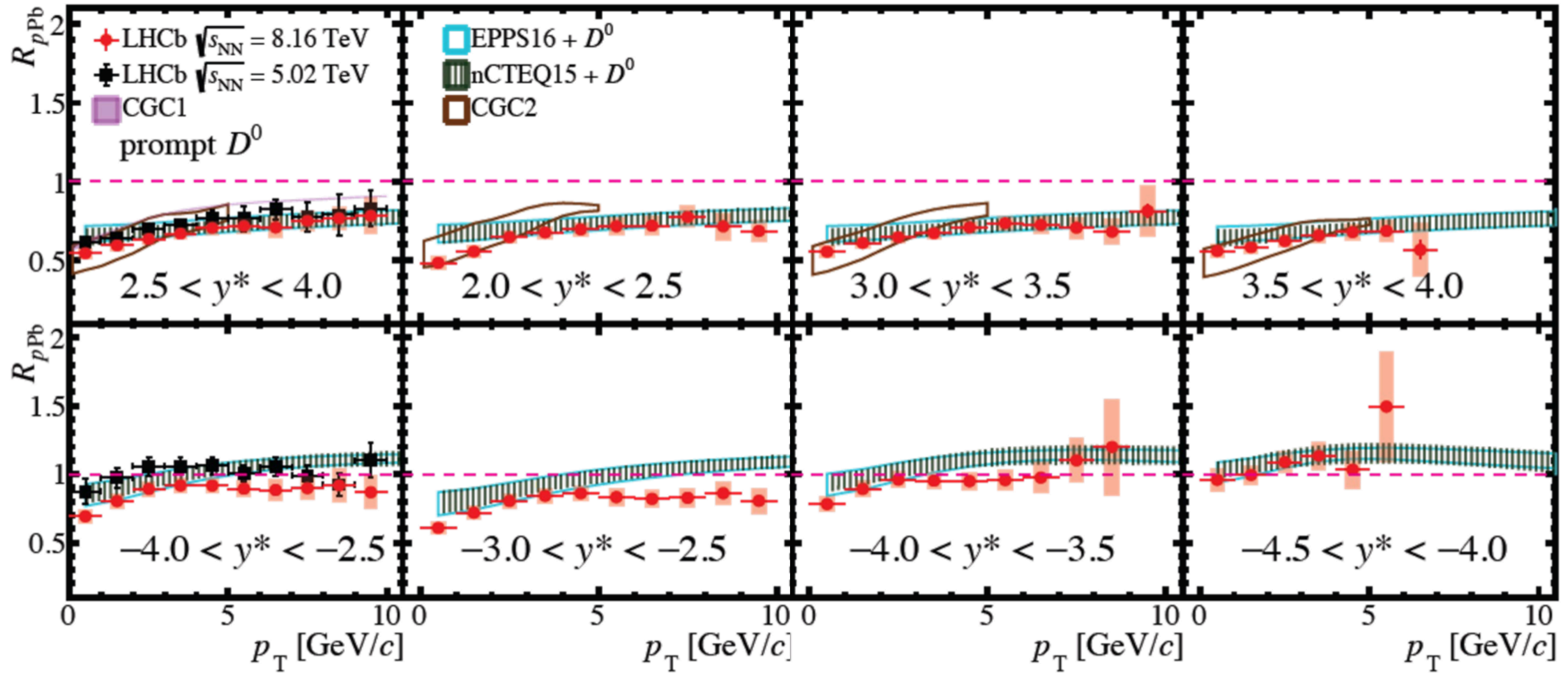
LHCb phase I - example current and future measurements

LHCb, arXiv:2208.11691



Probing jet structure with identified particles down to low p_T

arXiv:2205.03936



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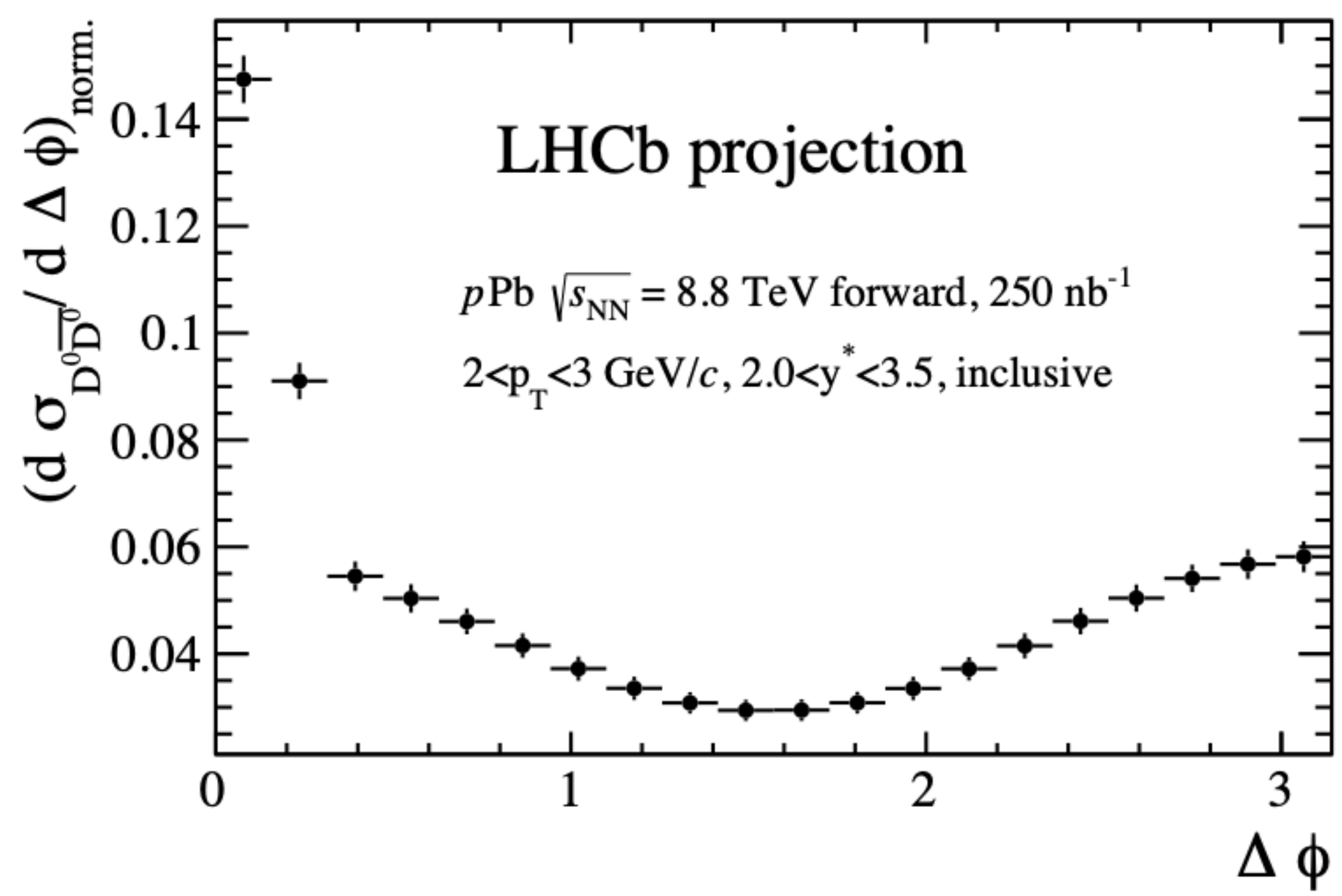

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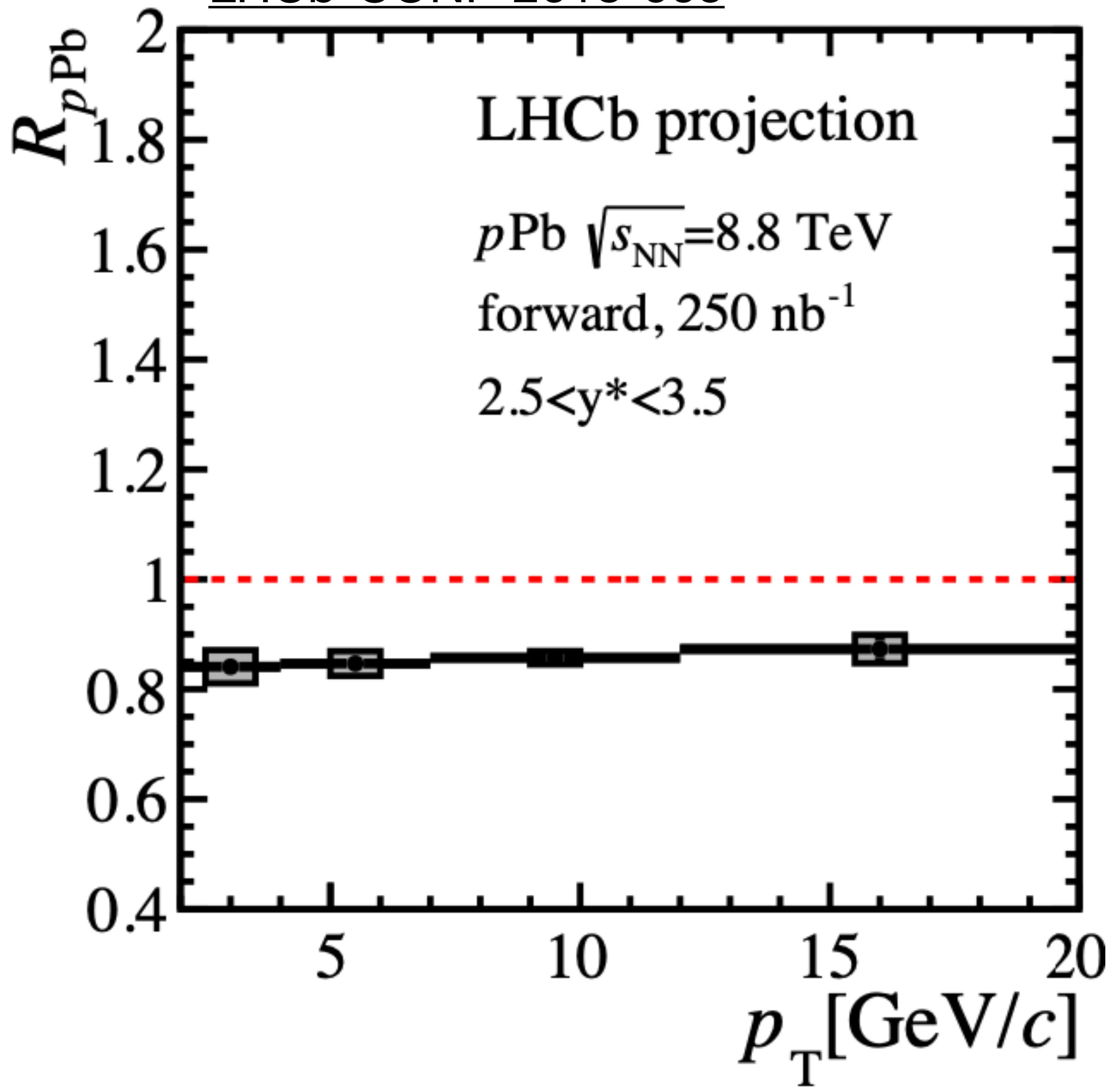

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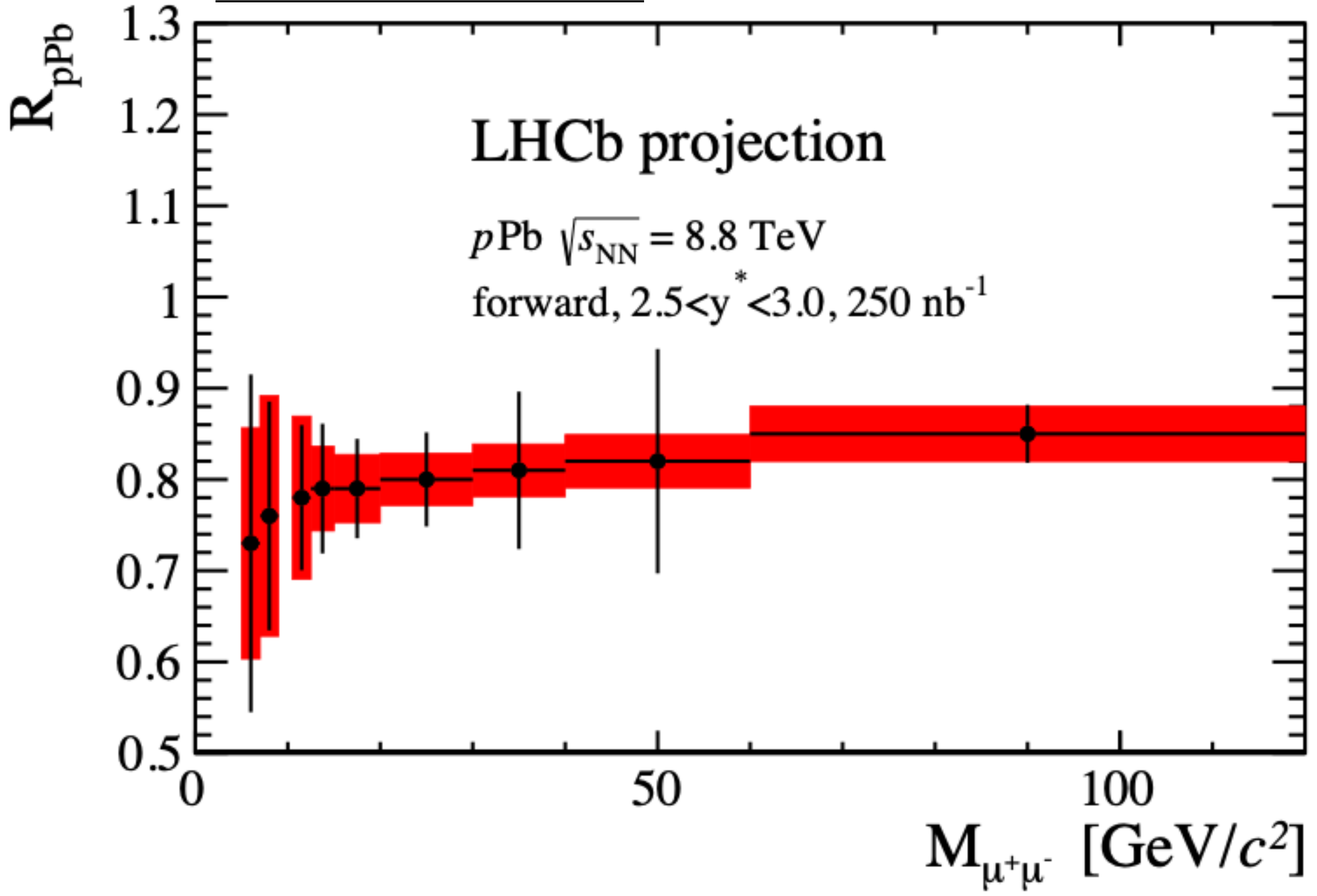
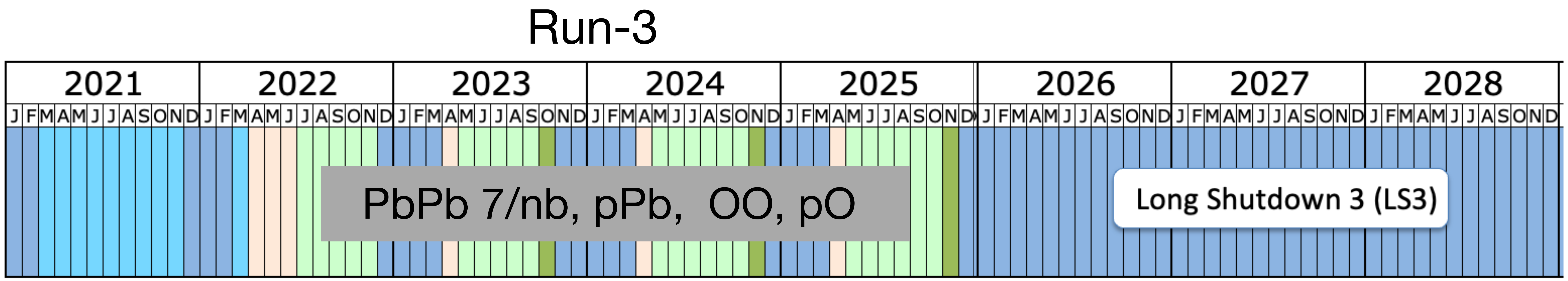
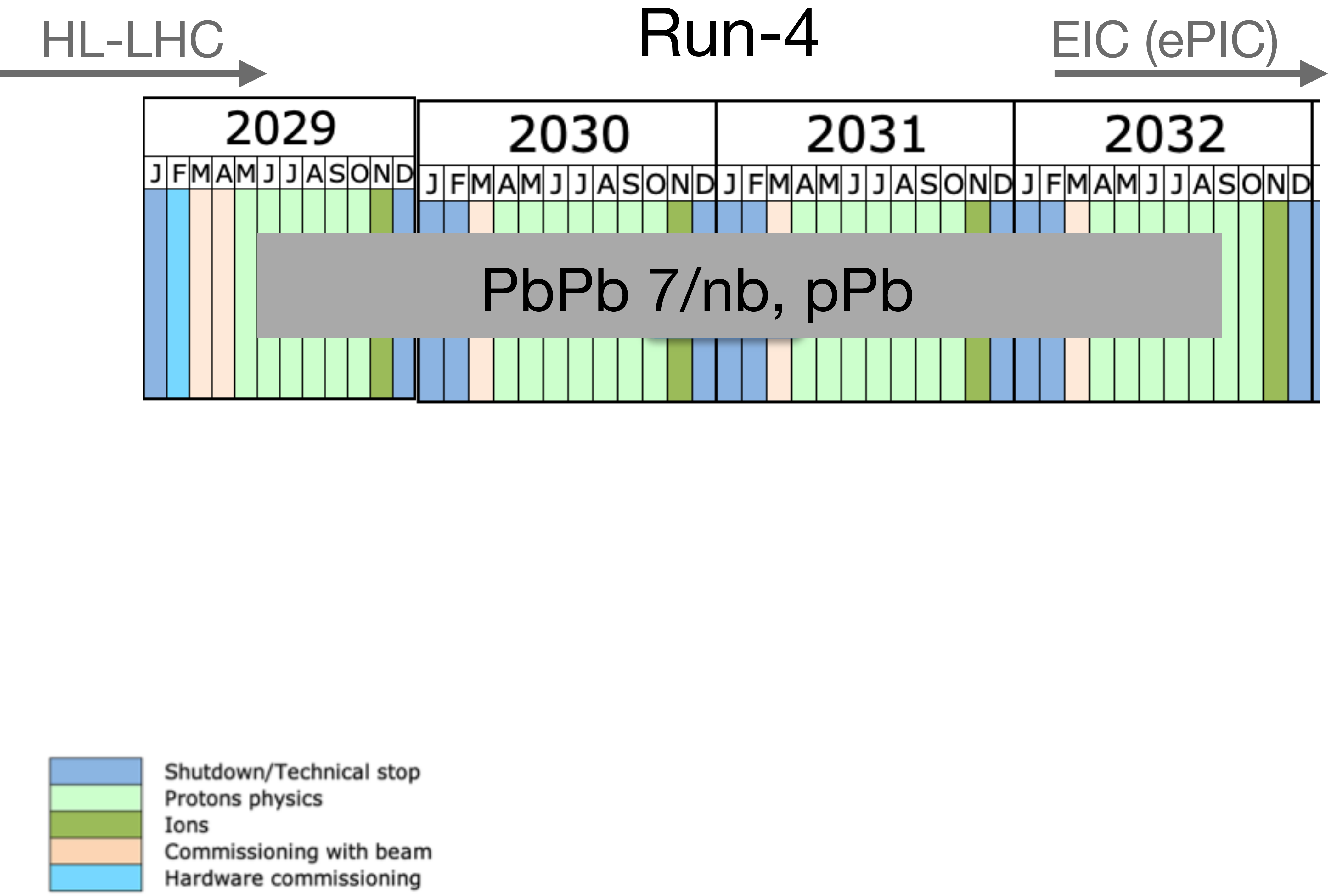


Ongoing and future LHC program



ALICE 2.0
LHCb Phase I

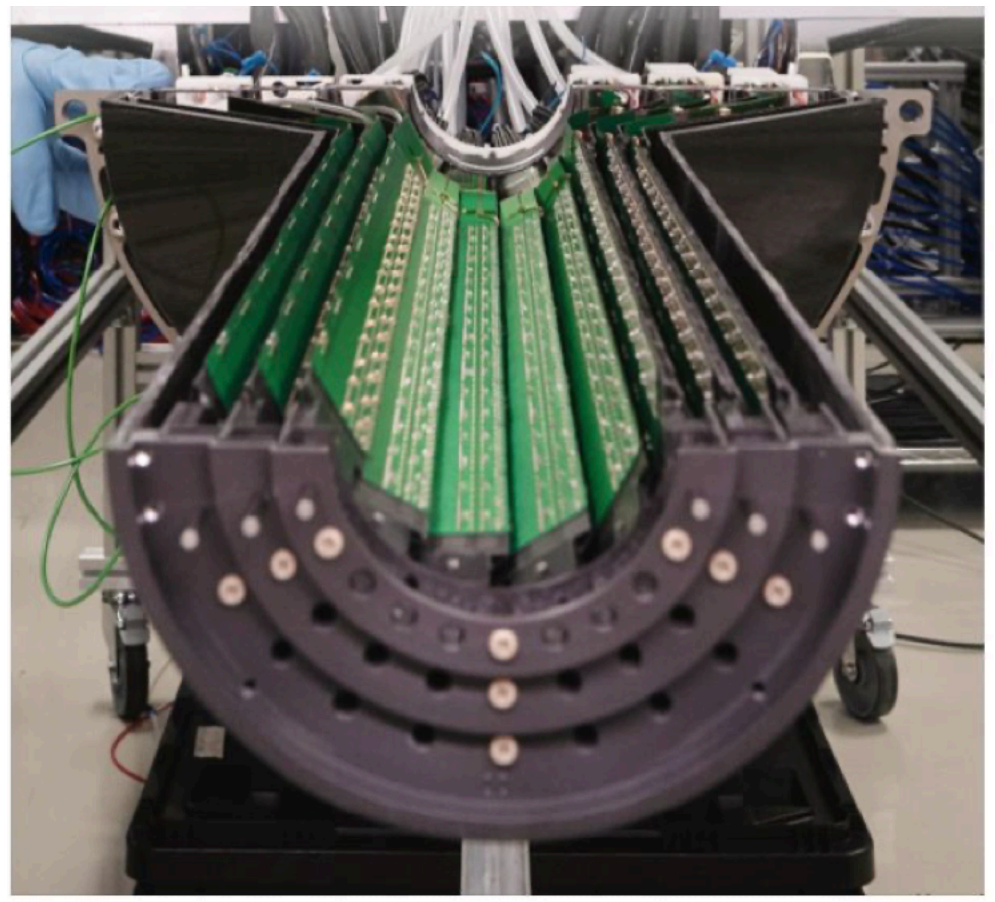
ALICE 2.1 (ITS3, FoCal)
CMS/ATLAS Phase II



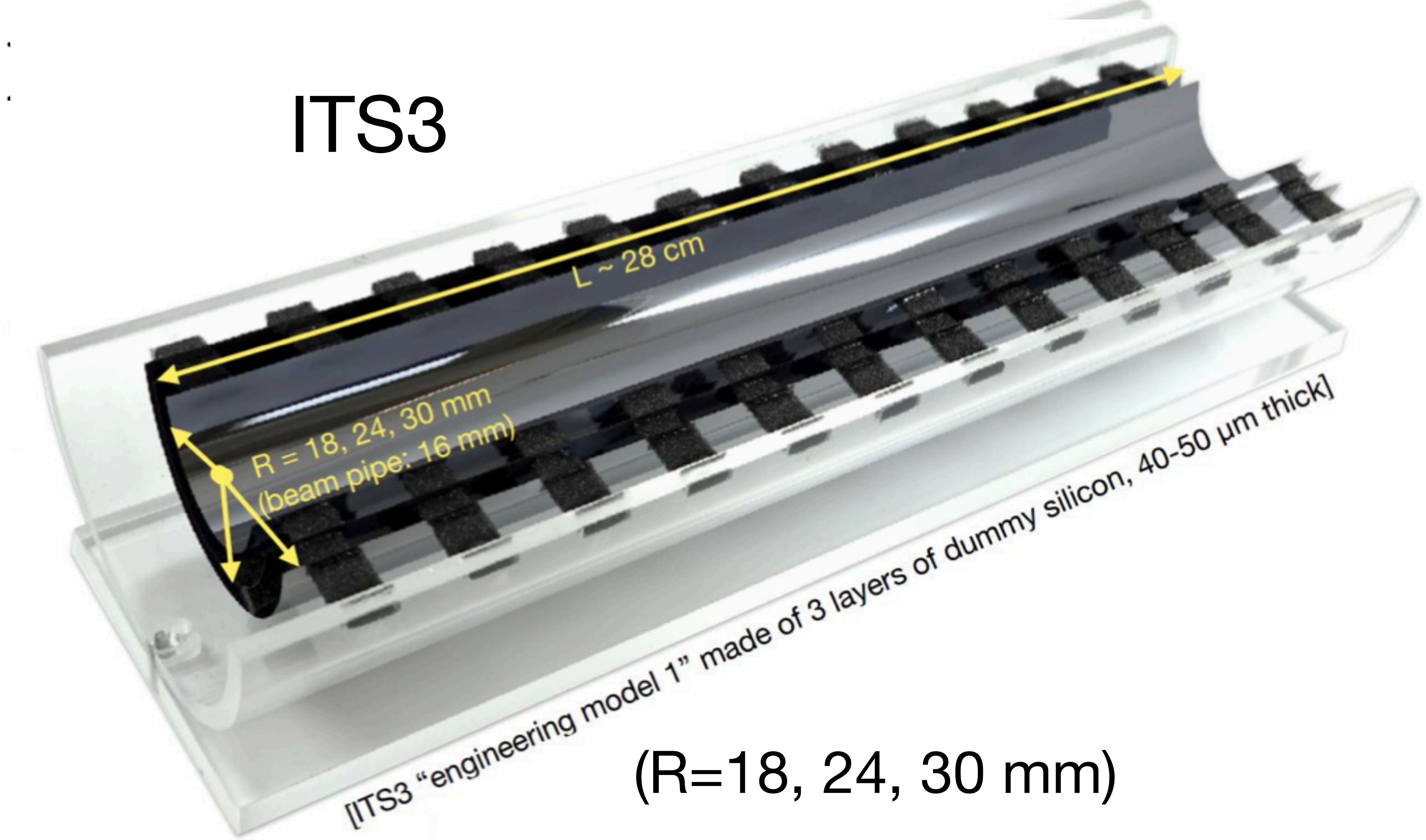
ALICE 2.1: ITS3

CERN-LHCC-2019-018

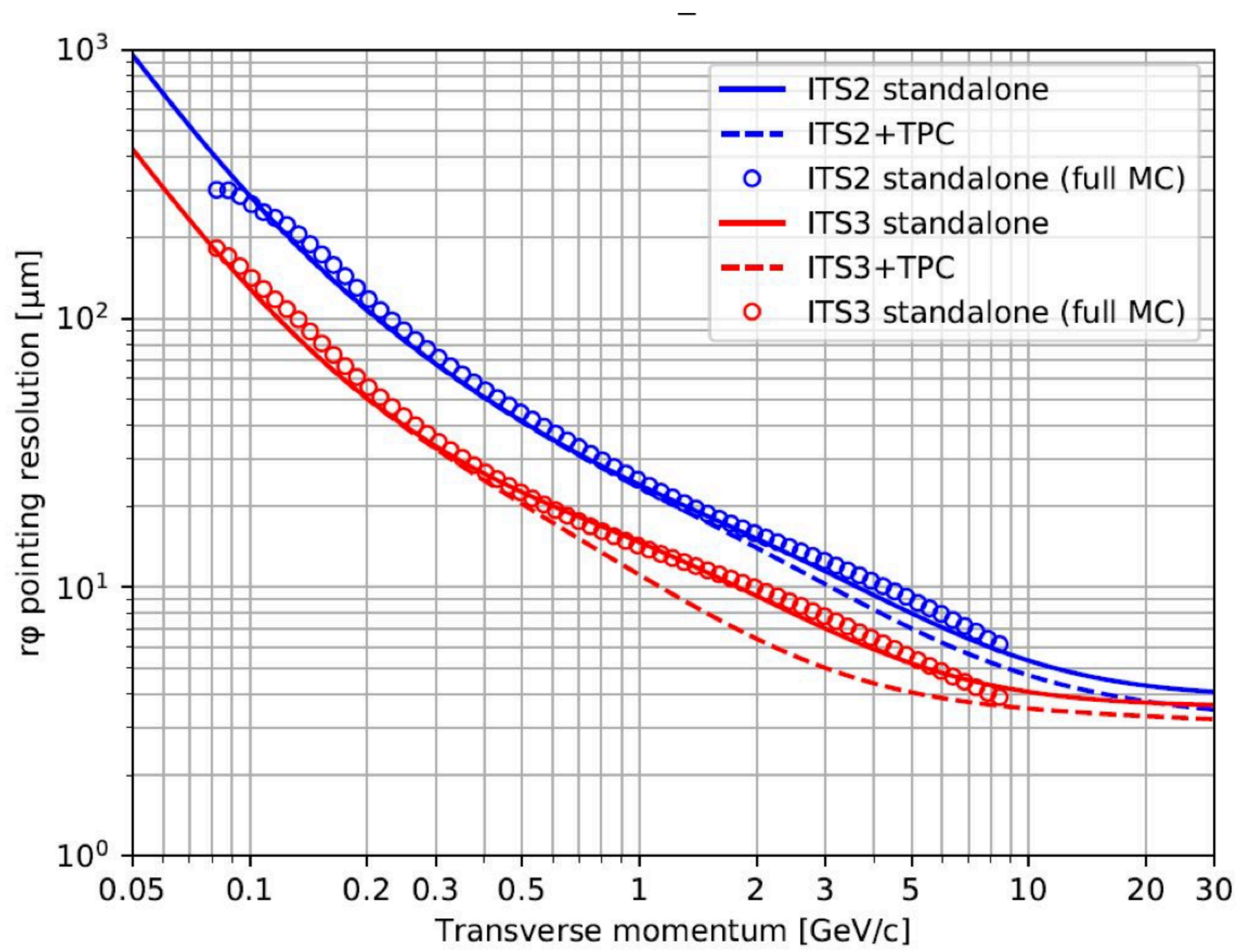
ITS2 (inner barrel)



ITS3



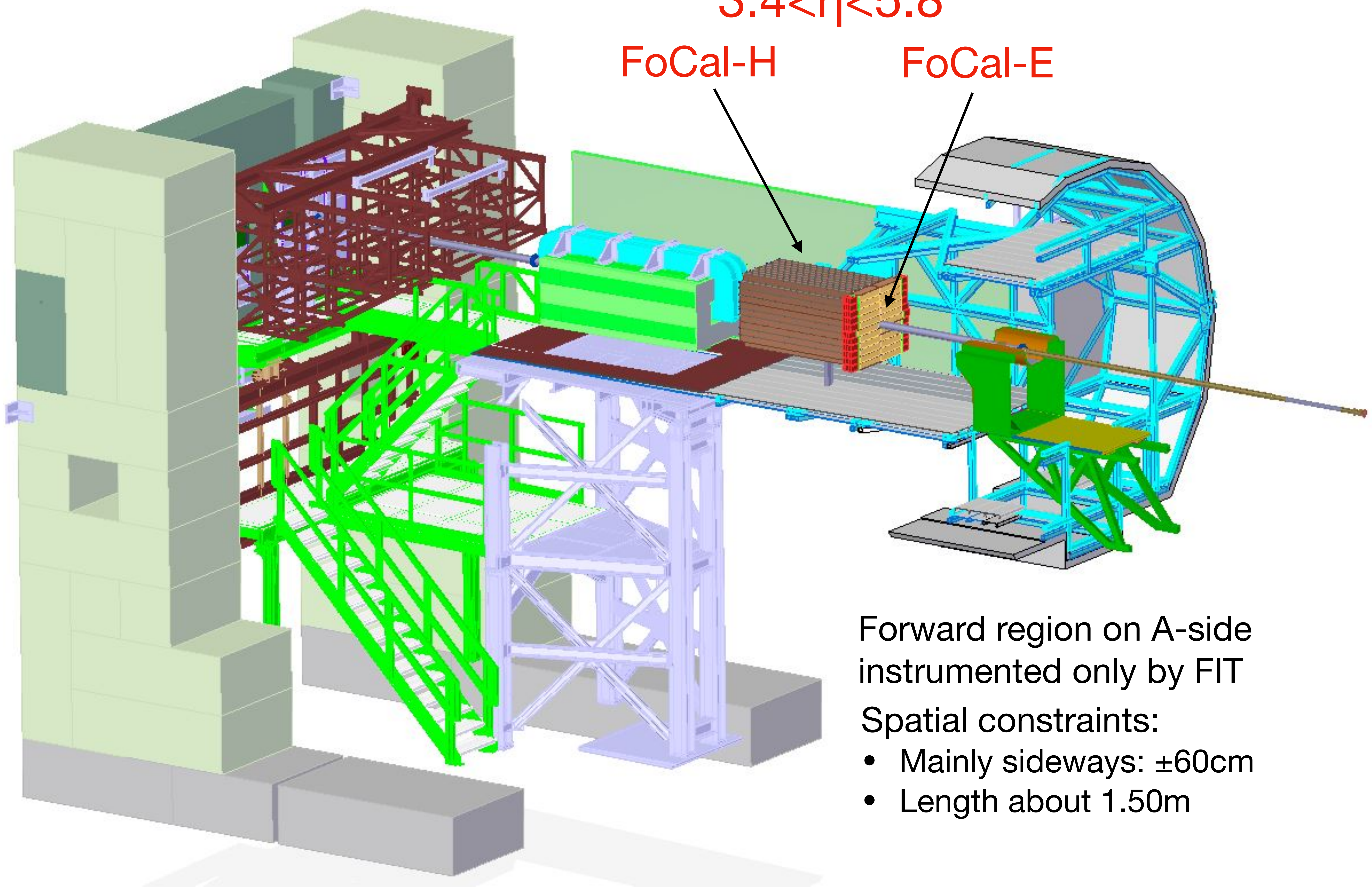
(R=18, 24, 30 mm)



factor ~2 improvement in pointing resolution

- Replace the 3 innermost layers by real half-cylinders of bent, thin silicon
- Use wafer-scale sensors (1 sensor per half-layer) in 65 nm technology
- Minimised material budget and distance to interaction point
    - requires also smaller + thinner beam pipe
- ~2x better pointing precision and substantially improved physics performance
- Many spin-offs, in particular important also for the EIC (ePIC)

ALICE 2.1: FoCal



Forward region on A-side instrumented only by FIT

Spatial constraints:

- Mainly sideways: ±60cm
- Length about 1.50m

FoCal-E: high-granularity Si-W sampling sandwich calorimeter for photons and π^0

FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets

Main physics goal:

Universal structure of matter at small-x

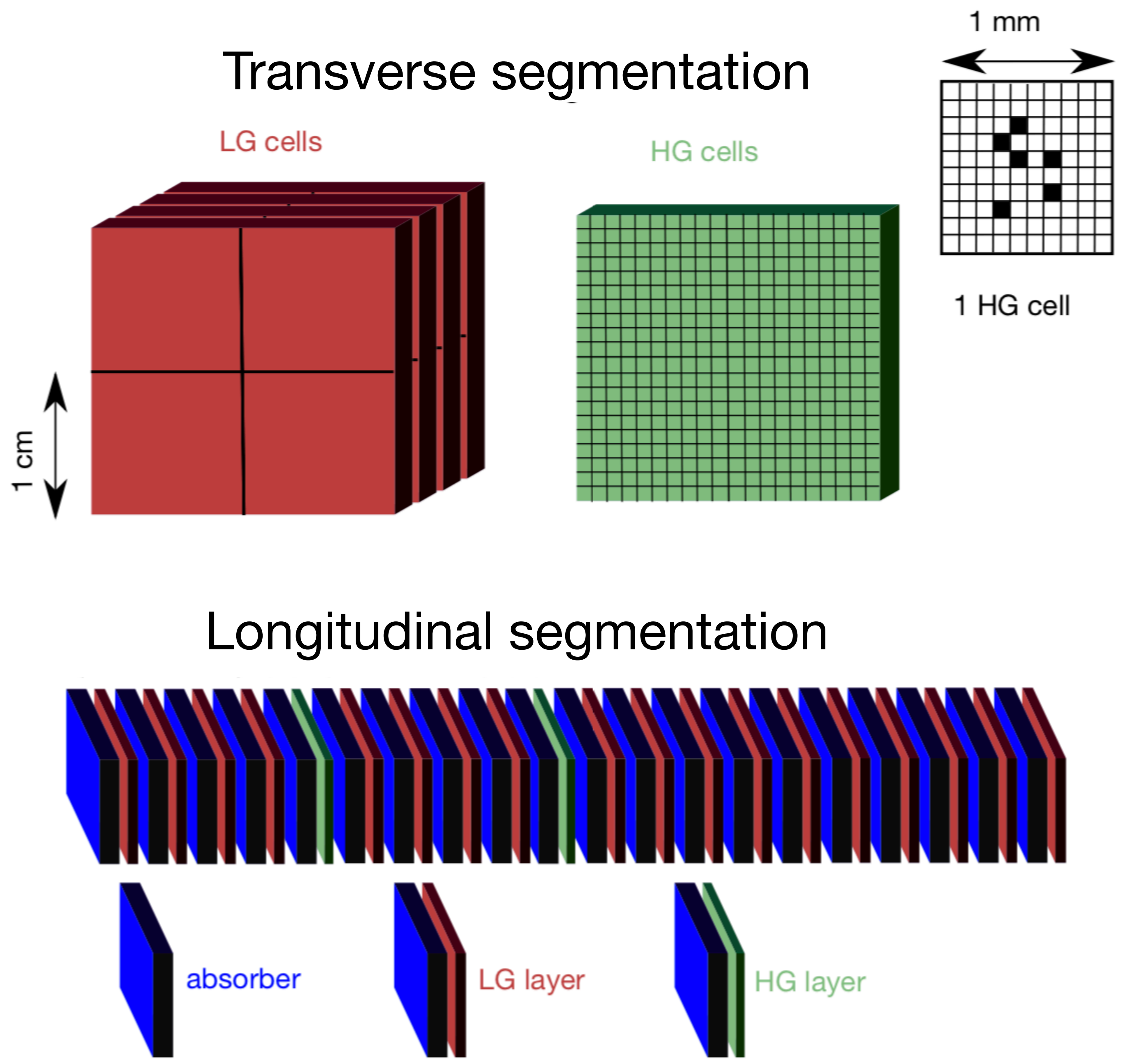
Observables

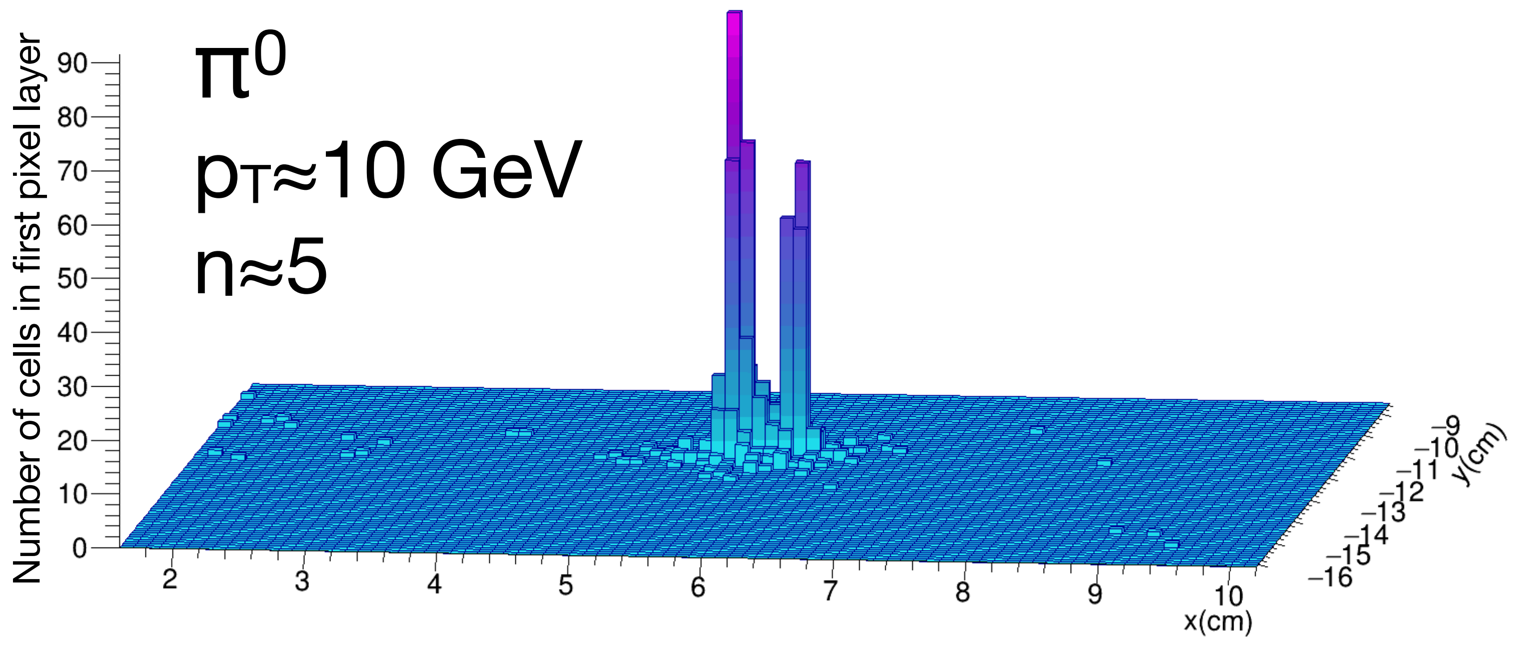
- π^0 and other neutral mesons
- Isolated (direct) photons
- Jets
- J/ψ, Υ (in UPC)
- Z, W
- Correlations

Letter-of-Intent: CERN-LHCC-2020-009

(see talks by P.Jacobs, M.Rauch, Tue afternoon)

FoCal-E and FoCal-H design





FoCal-E long. segmentation with 20 layers:
W(3.5 mm ≈ $1X_0$) + silicon sensors
Two types: Pads (LG) and Pixels (HG)

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

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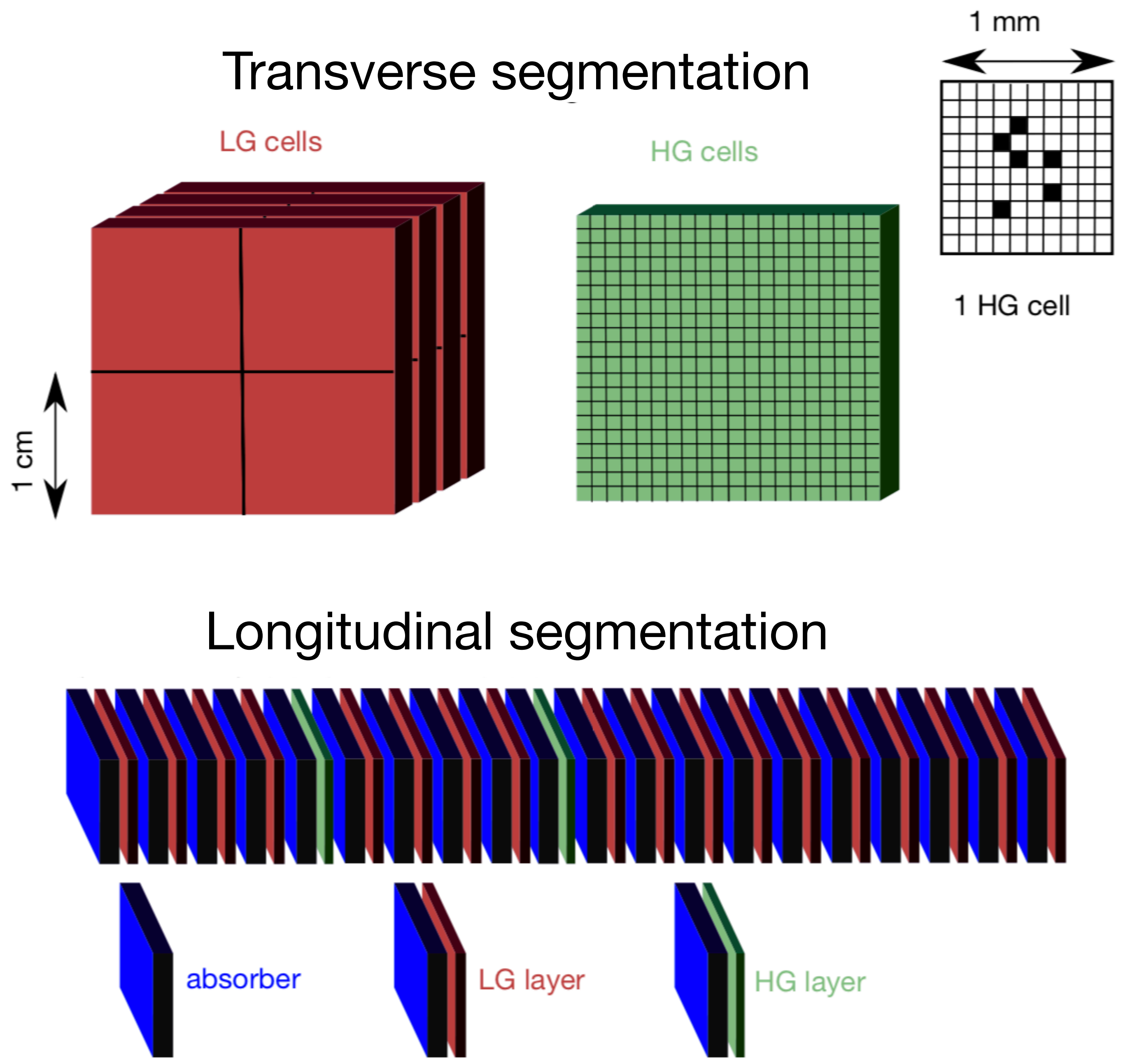

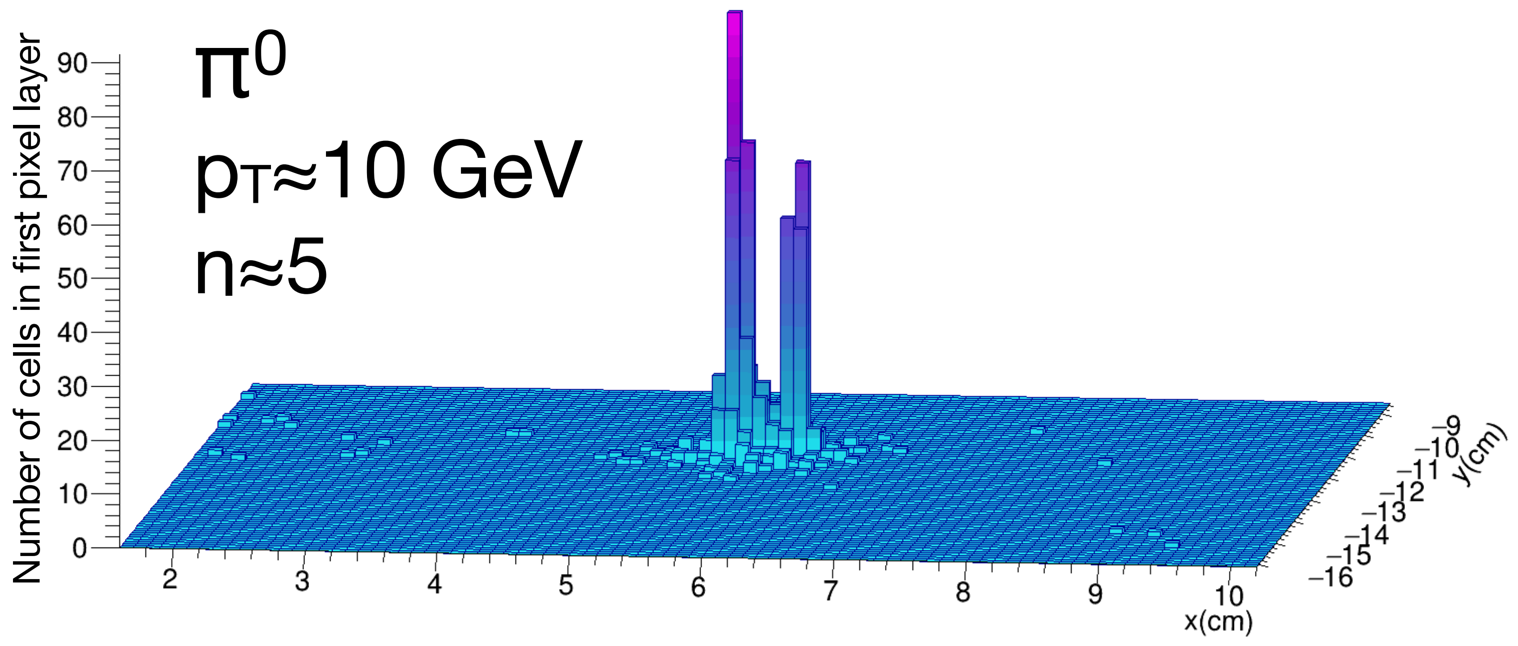

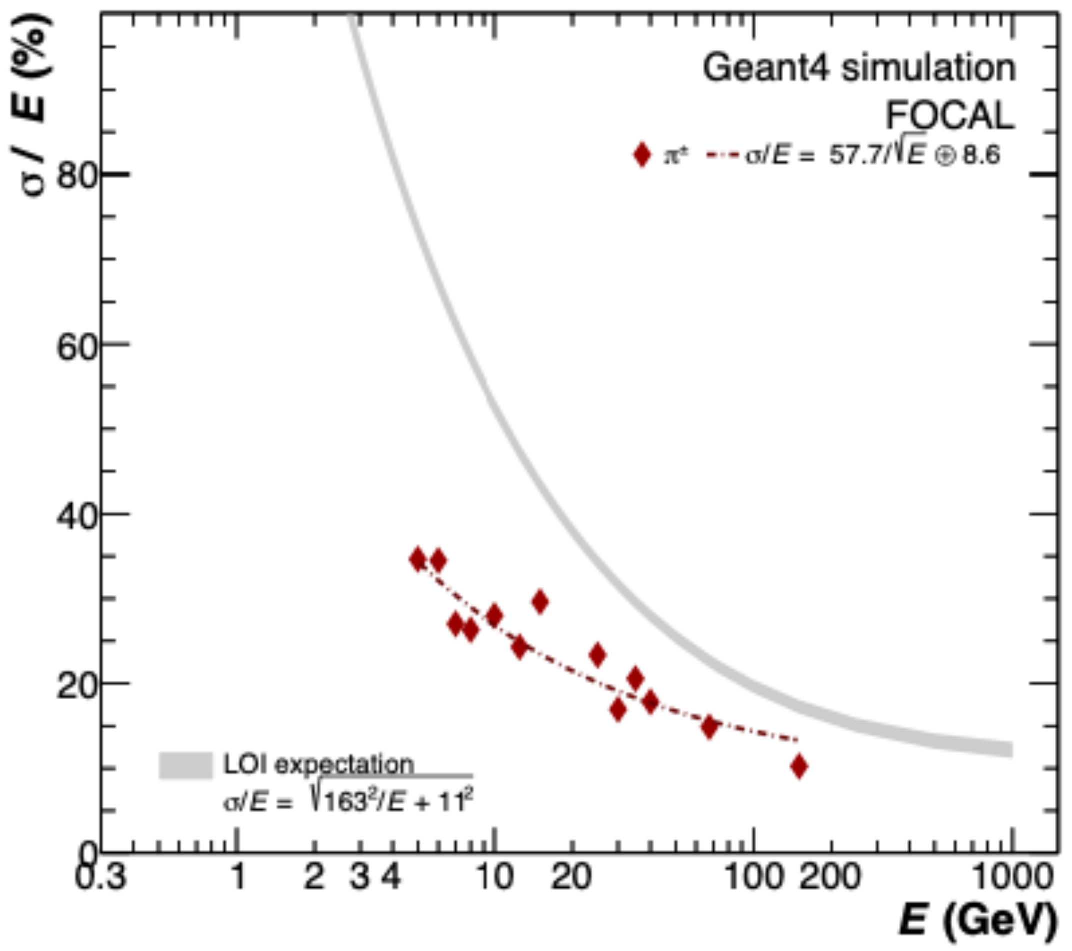

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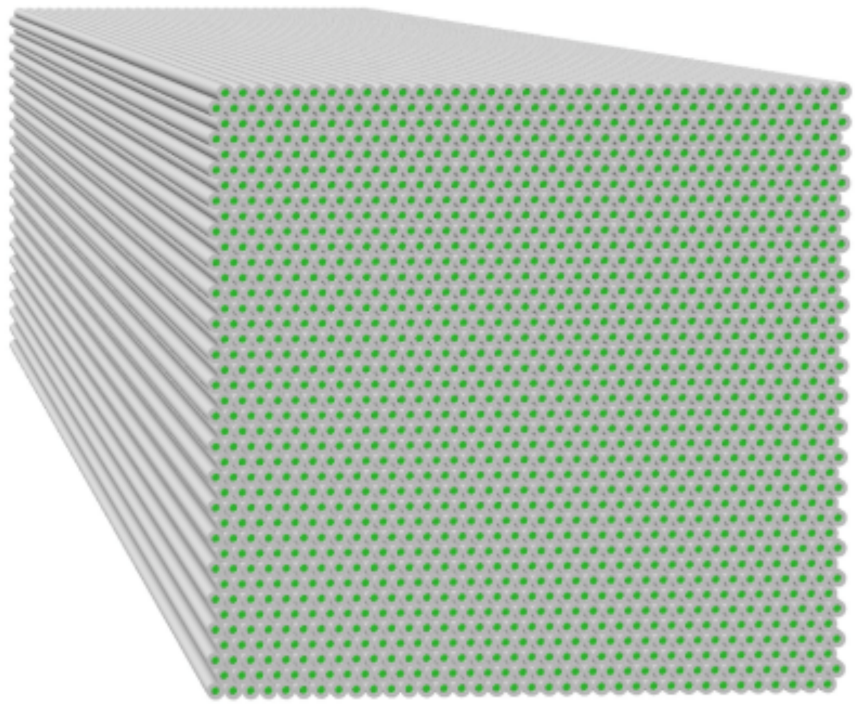
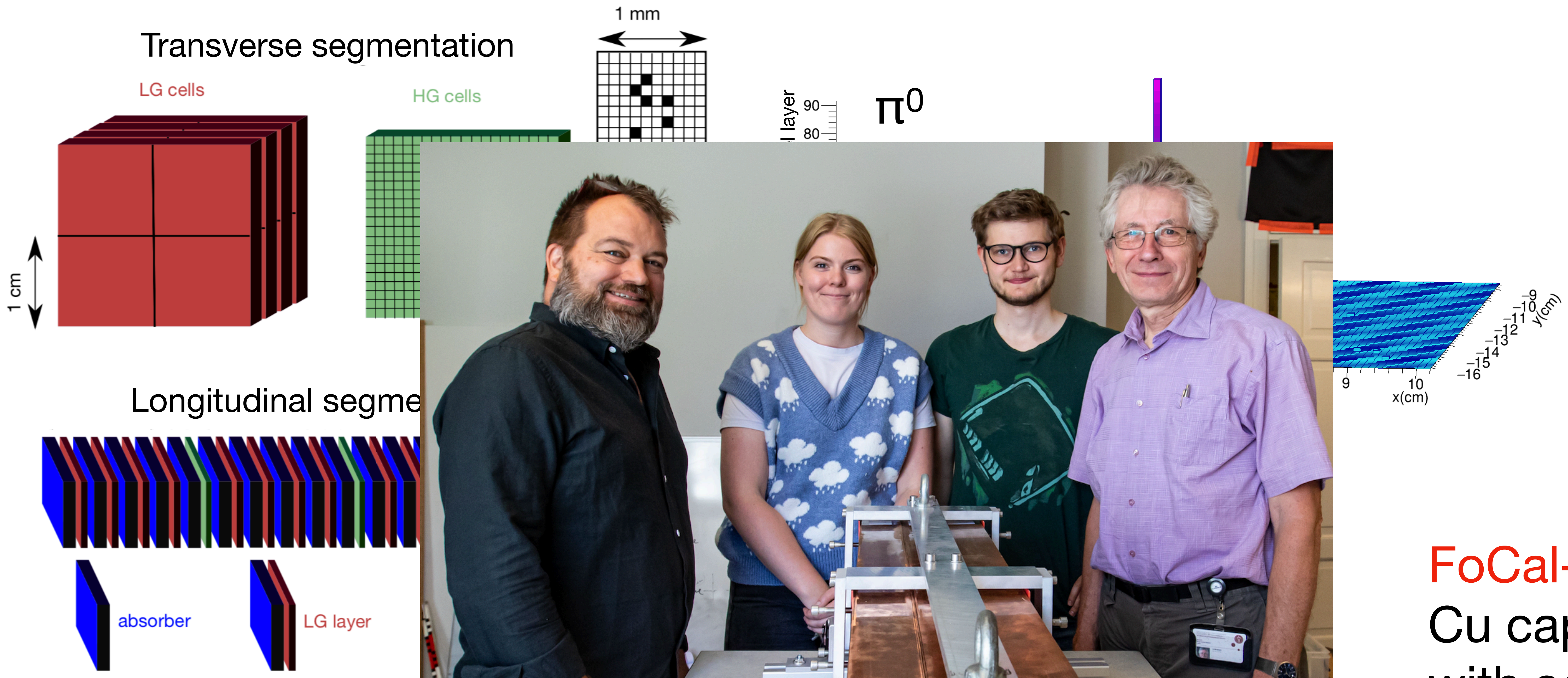
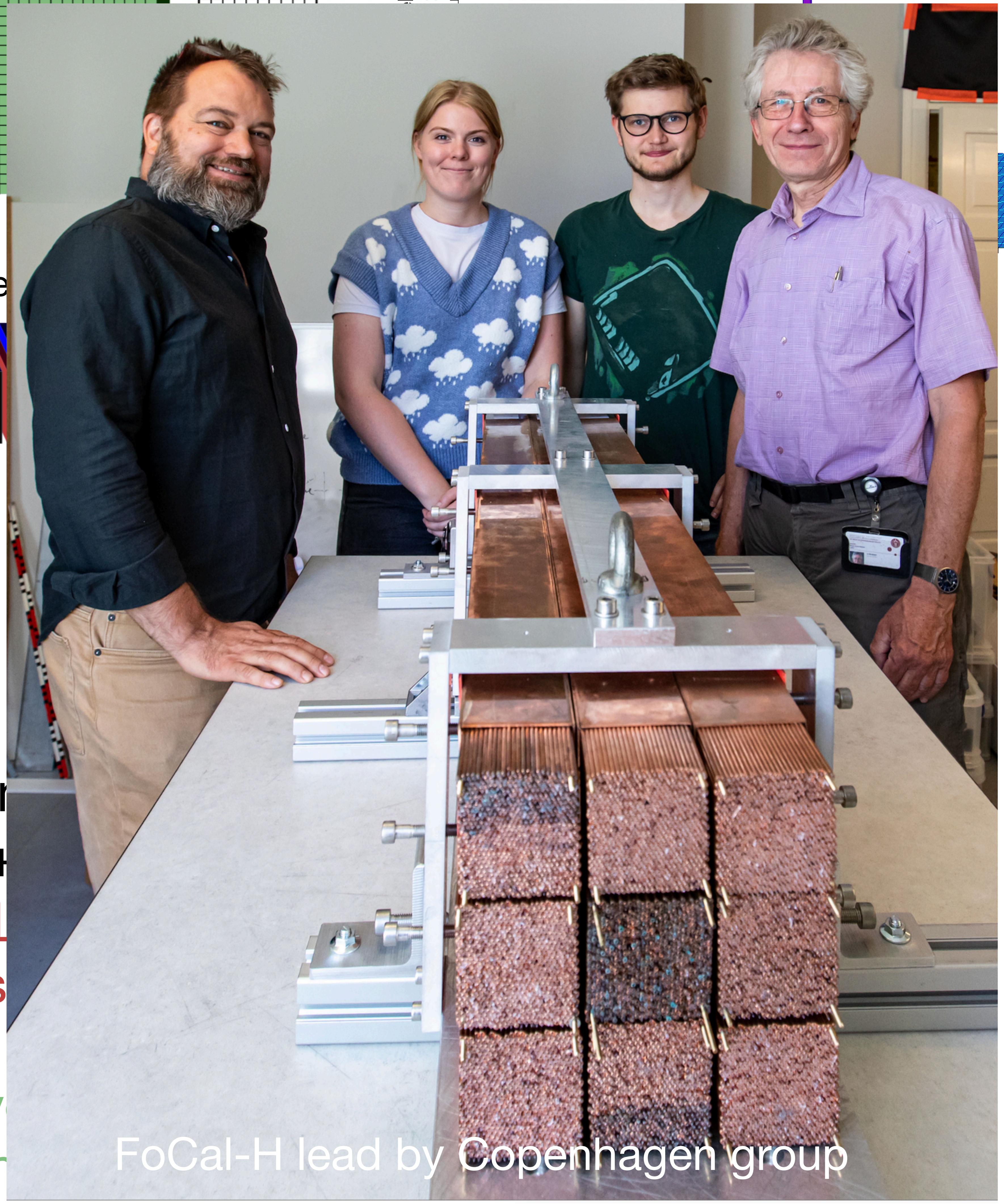
FoCal-H:
Cu capillary-tubes filled with scintillating fibers

- 90cm x 90cm x110cm (~6 λ)
- Tubes OD 2.5mm, ID1.1mm
- Fiber-bundles into SiPMs
- ~5000 towers of ~1.25x1.25cm^2
- Final readout with H2GCROC



FoCal-E and FoCal-H design





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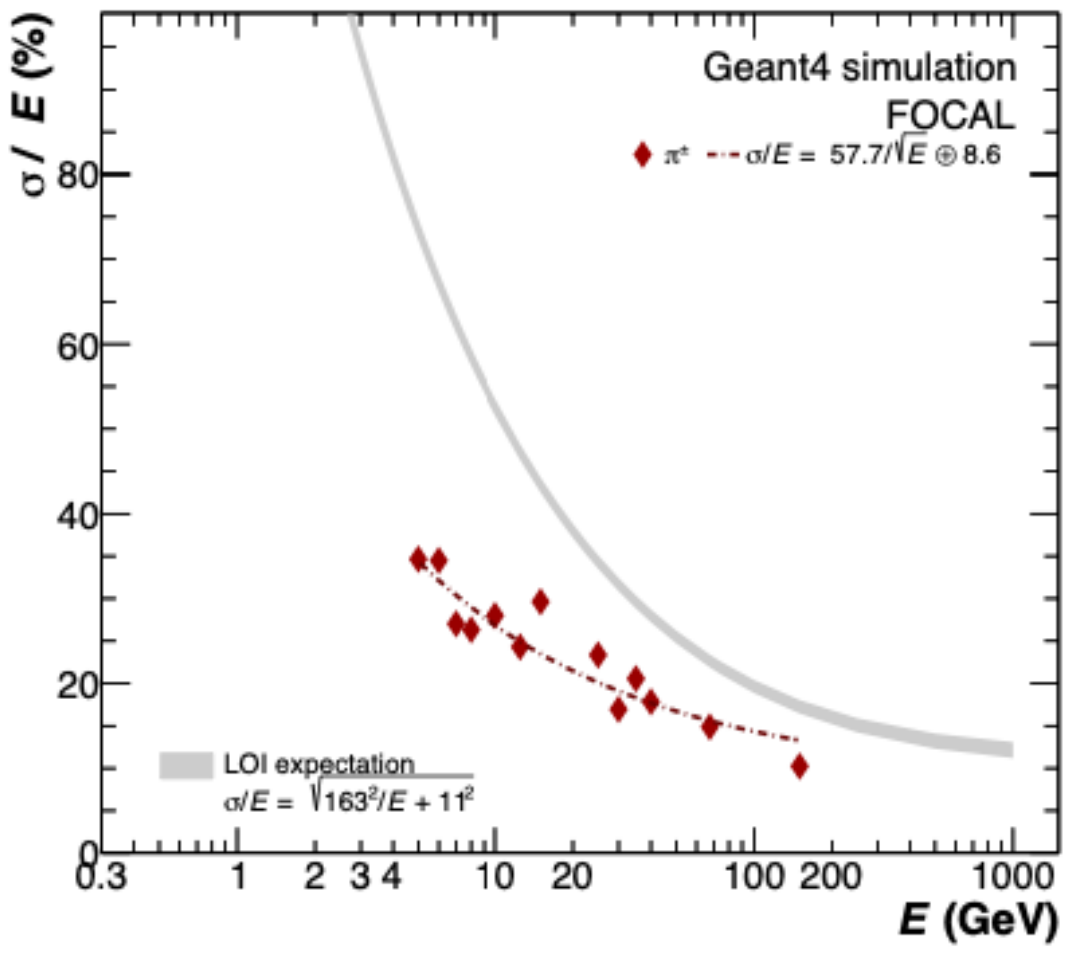

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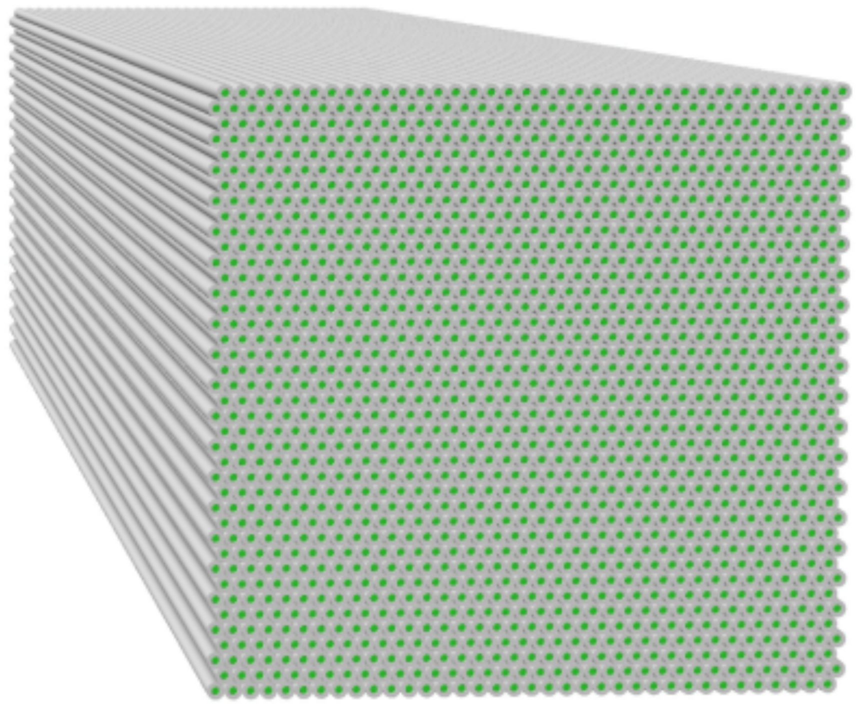
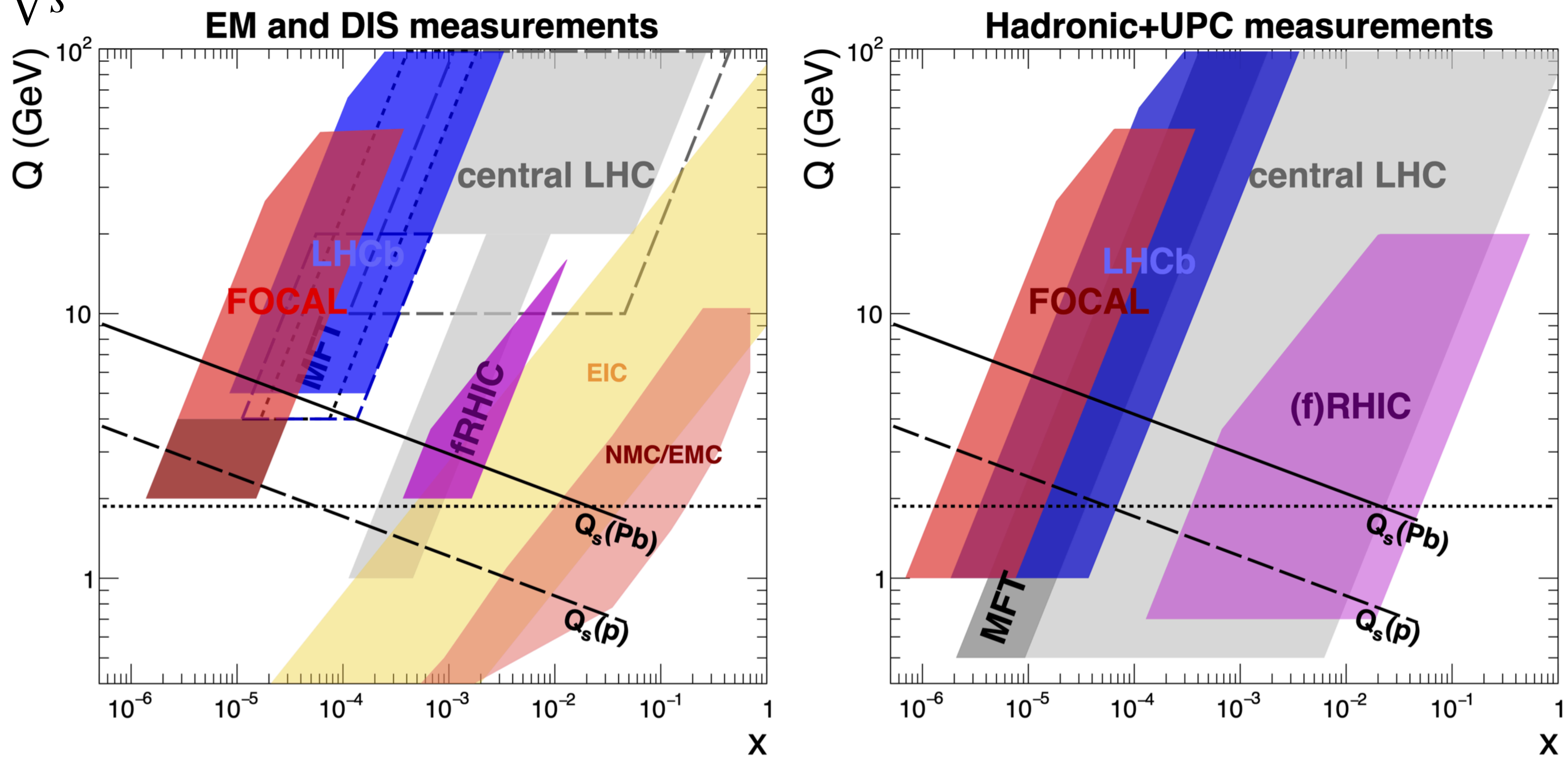


$$x \approx \frac{Q}{\sqrt{s}} \exp(-y)$$

Current and future measurements



- Study of saturation requires to study evolution of observables over large range in x at low Q^2
- Forward LHC (+RHIC) and EIC are complementary: together they provide a huge lever arm in x
  - EIC: Precision control of kinematics + polarisation
  - Forward LHC: Significantly lower x
    - Observables: isolated γ, jets, open charm, DY, W/Z, hadrons, UPC

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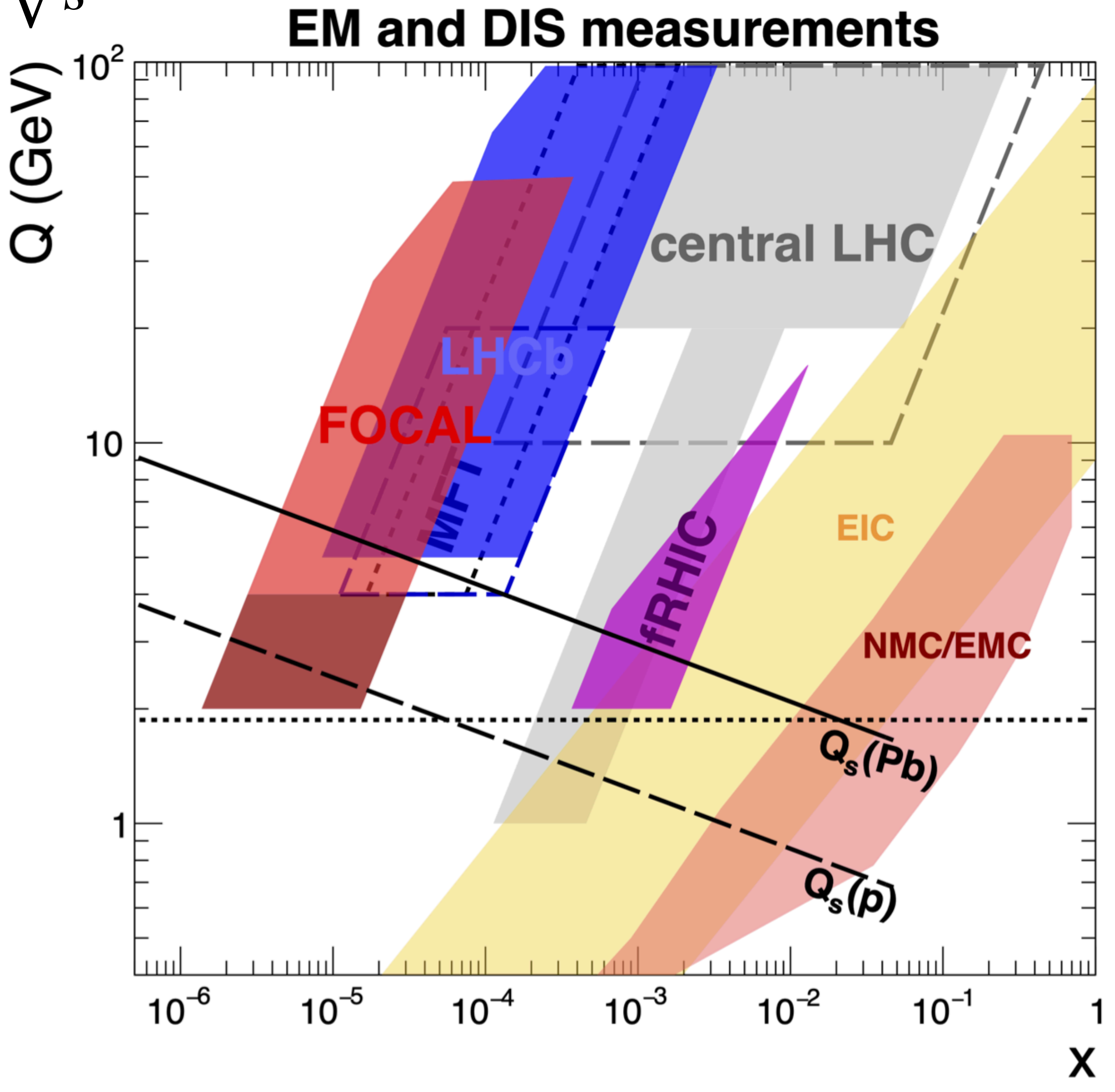
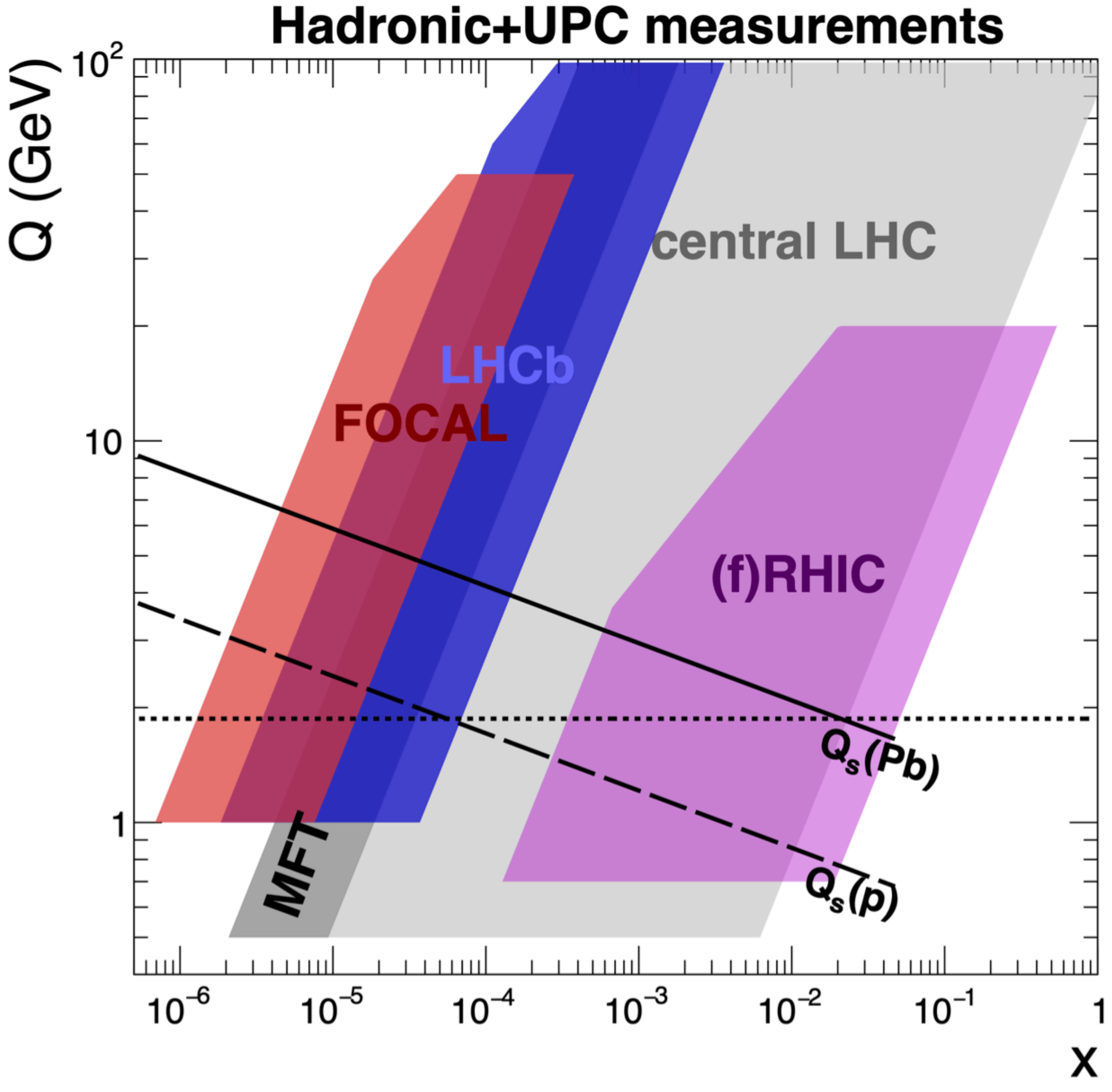
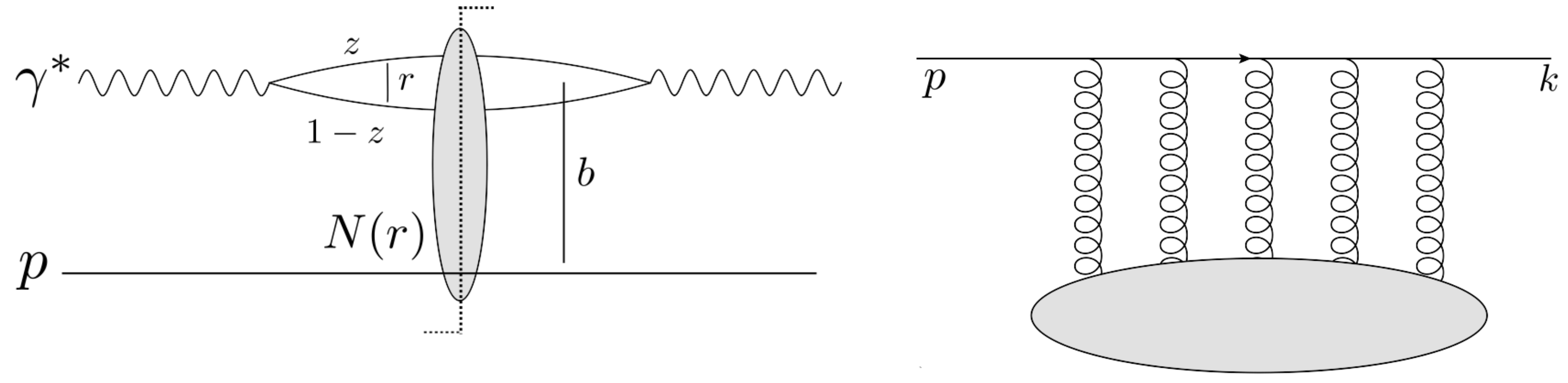




DIS (EIC)

Forward pA at high energies



$$\text{Dipole } N = 1 - \frac{1}{N_C} \mathrm{tr} V(x) V^{\dagger}(y)$$

Multiple processes in eA and forward pA are described by the same dipole-operator (ideally calculated at higher orders)

also see p232ff in the EIC YR

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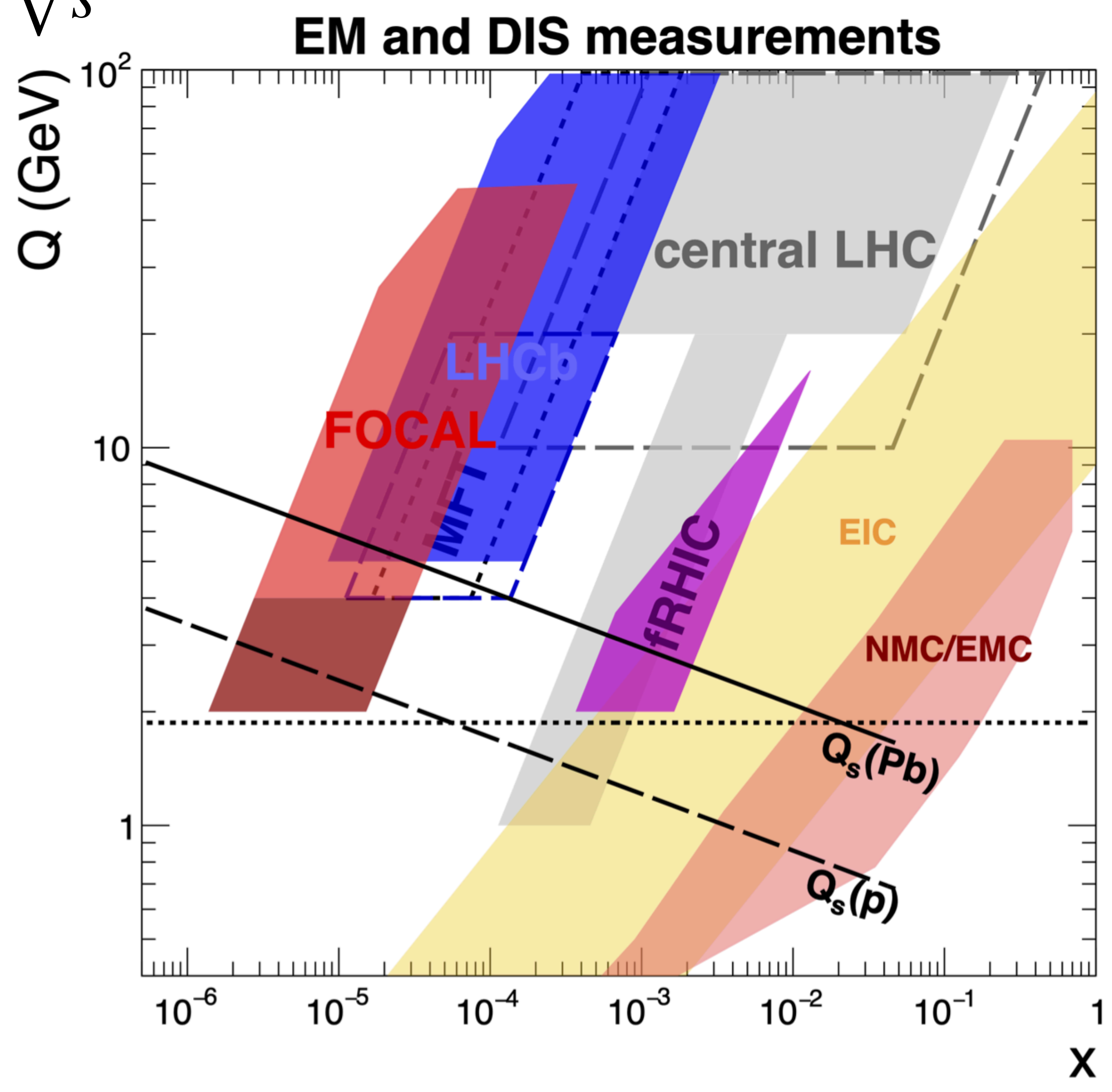

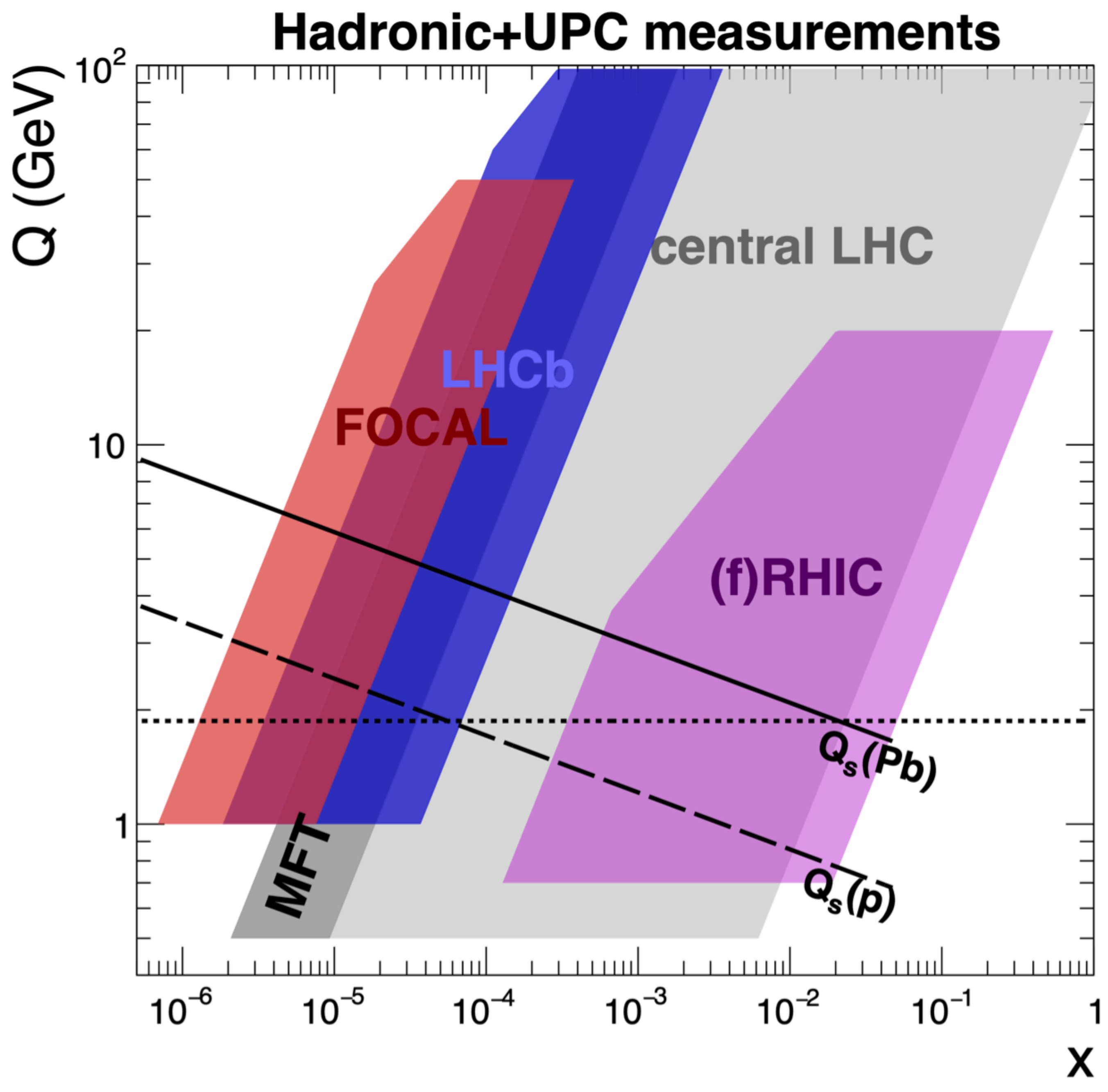

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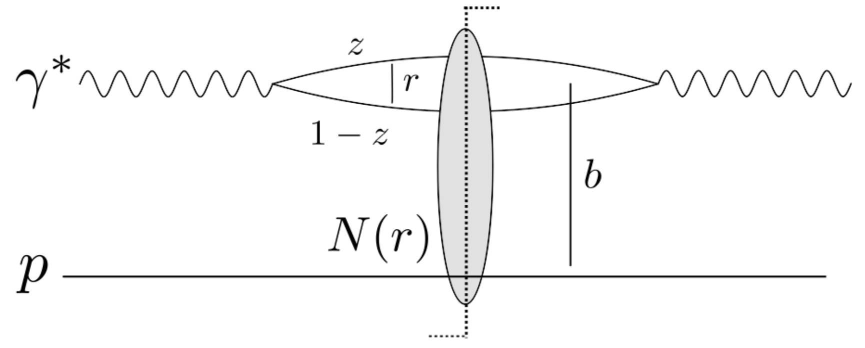
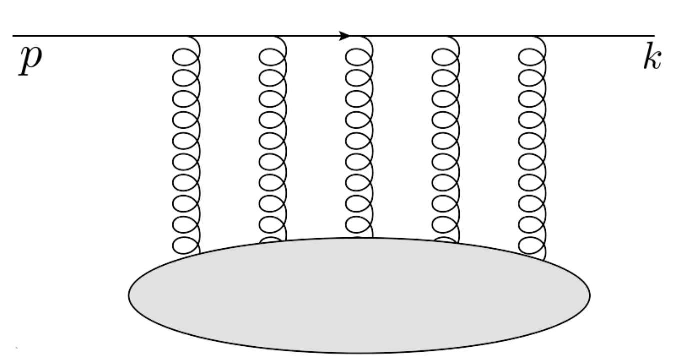


Forward pA
at high energies



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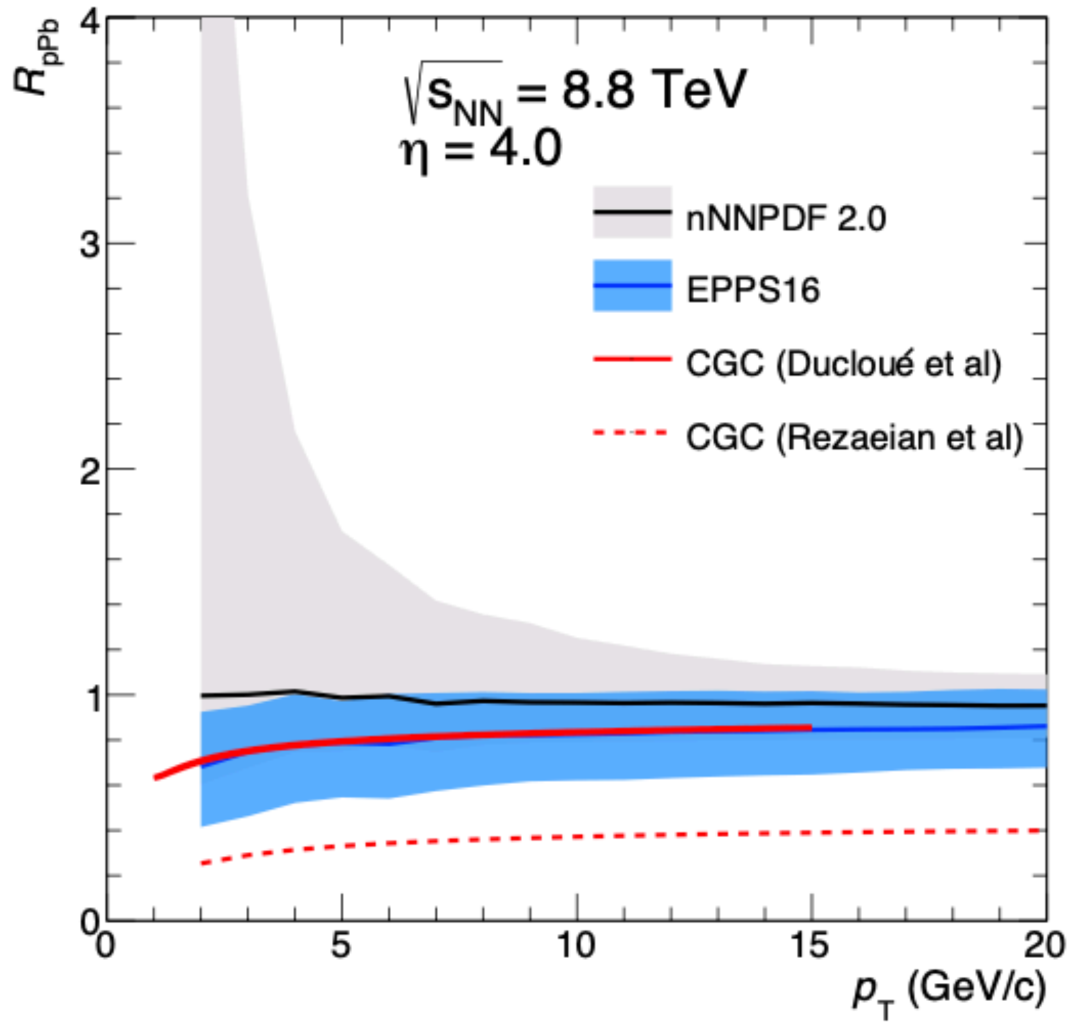
  - Observables in **DIS and forward LHC are fundamentally connected via same underlying dipole operator**
- Multi-messenger program to test **QCD universality**: does saturation provide a coherent description of all observables, and is therefore a **universal** description of the high gluon density regime?

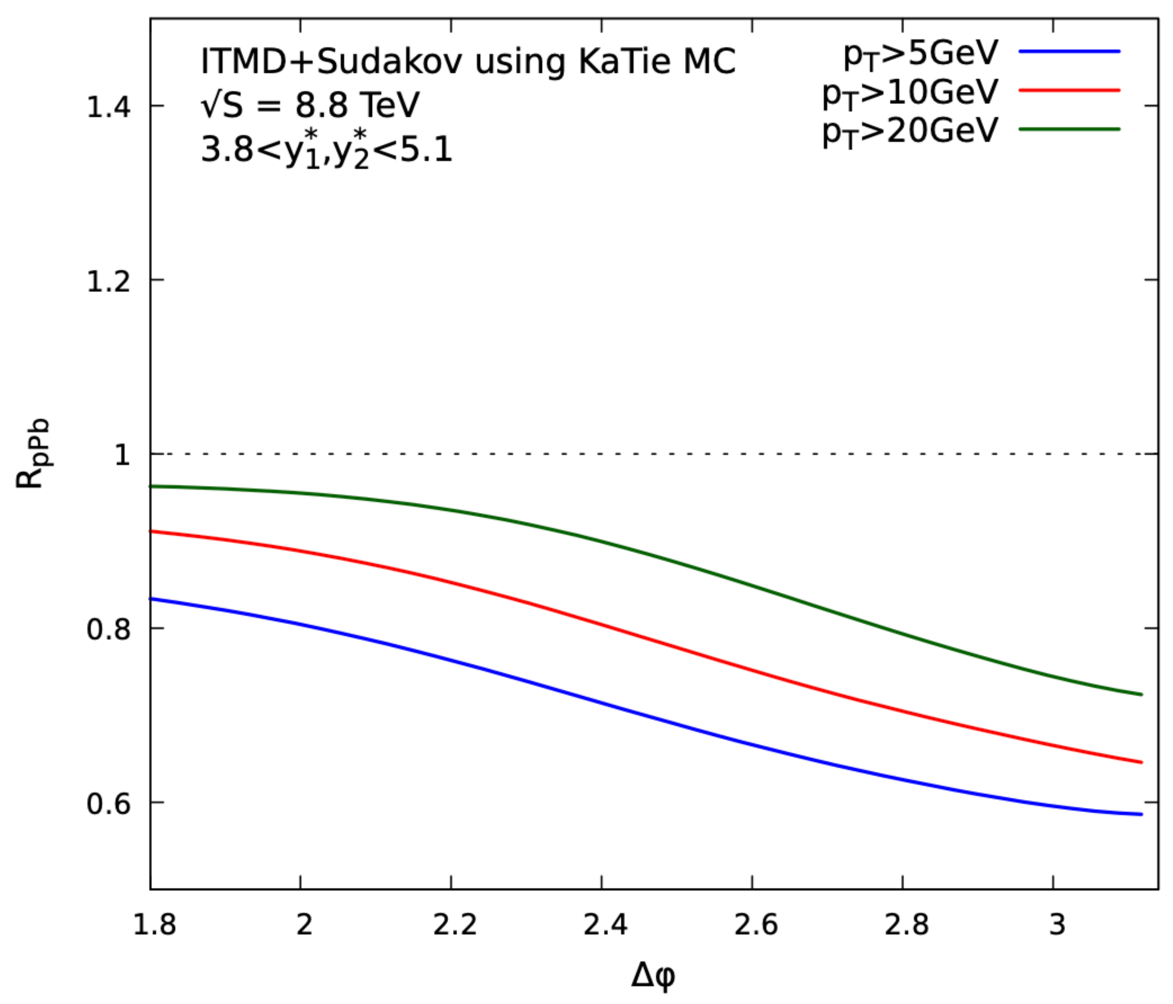
The FoCal physics program ALICE-PUBLIC-2023-001

1. Study of gluon saturation and non-linear QCD evolution
   - Needs rigorous comparison between theory calculation and data sets
   - FoCal observables:
     - Isolated photons
     - Mesons and jets
     - Correlations (π^0-π^0, π^0-jet, jet-jet, γ-π^0, γ-jet)
     - Quarkonia (and dijet) photo-production at in UPC

Isolated photon RpPb



Isolated photon-jet correlations



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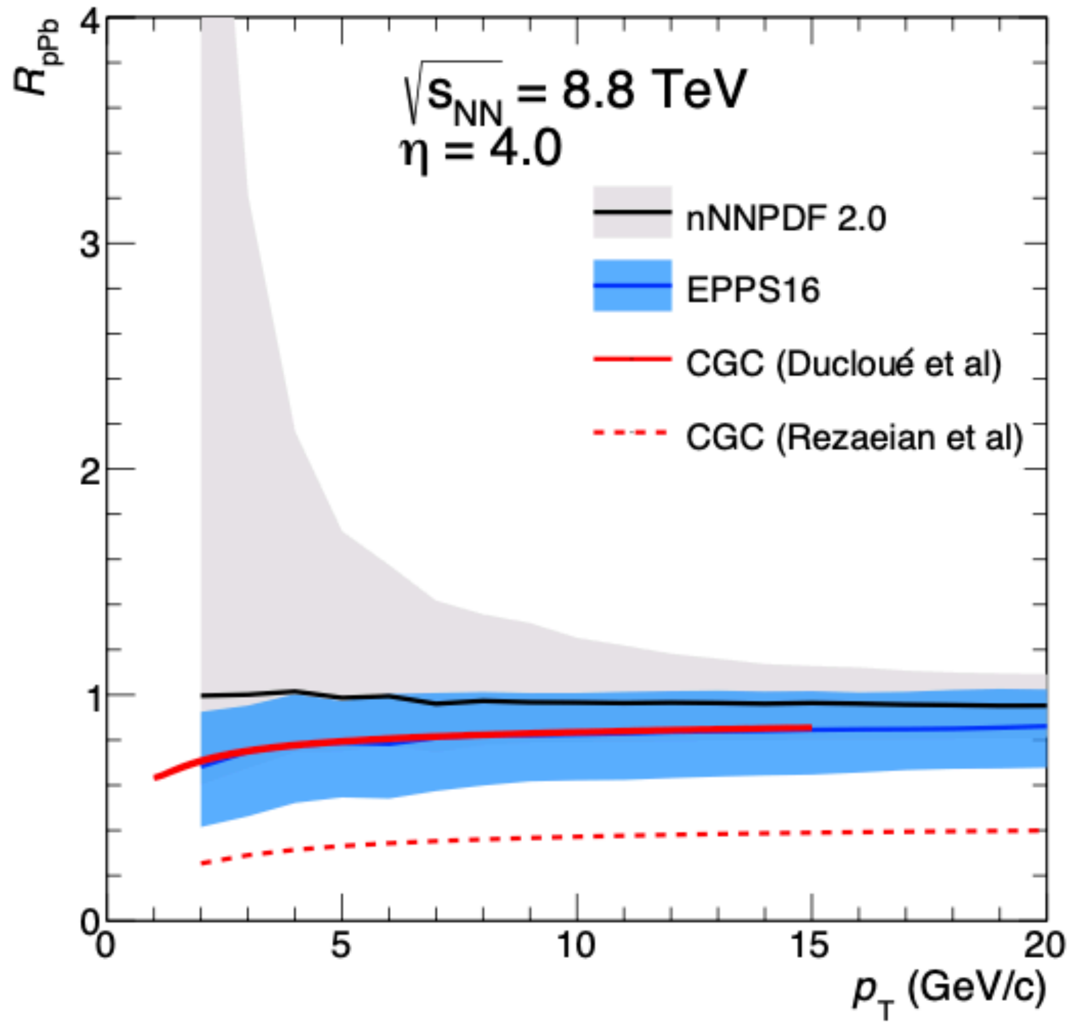

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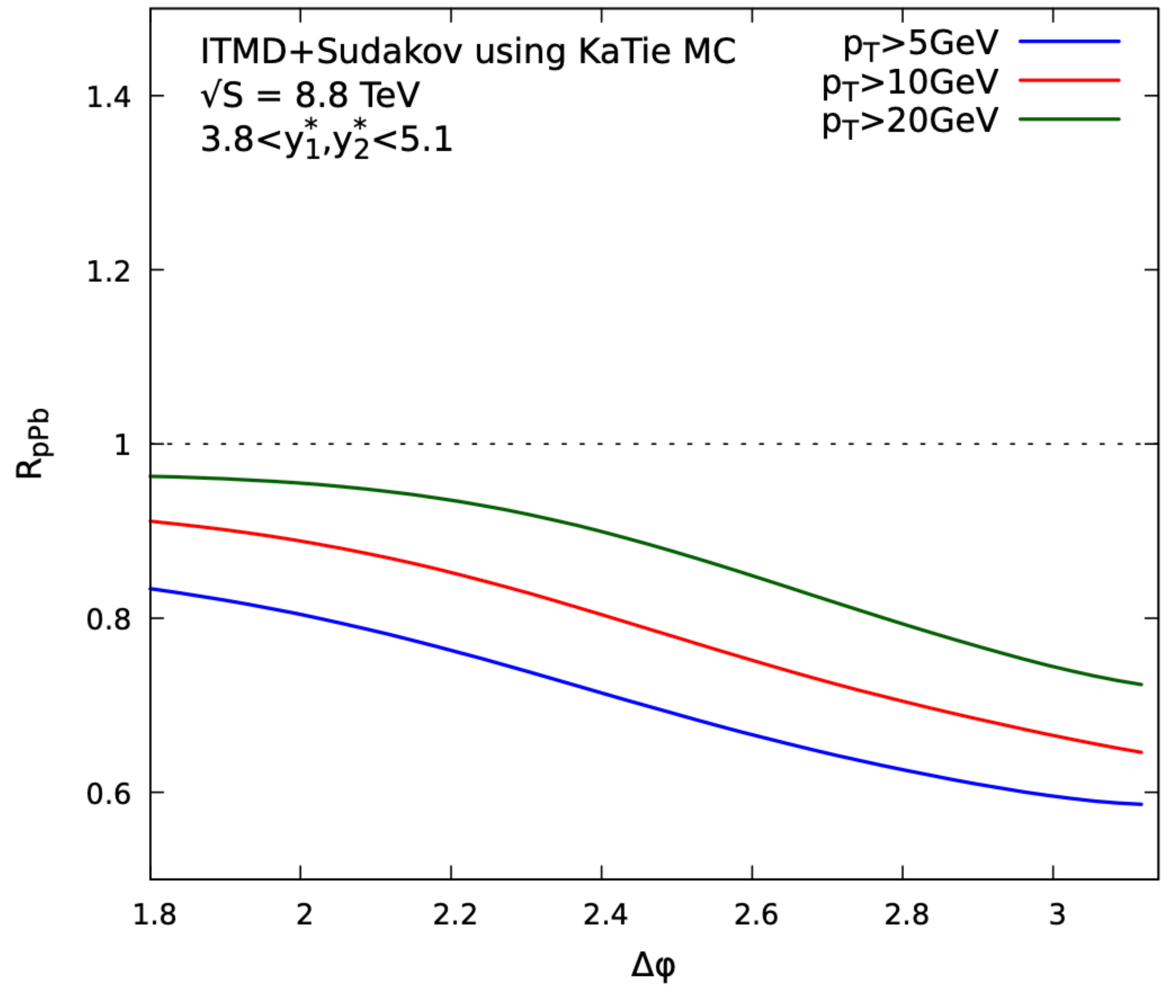

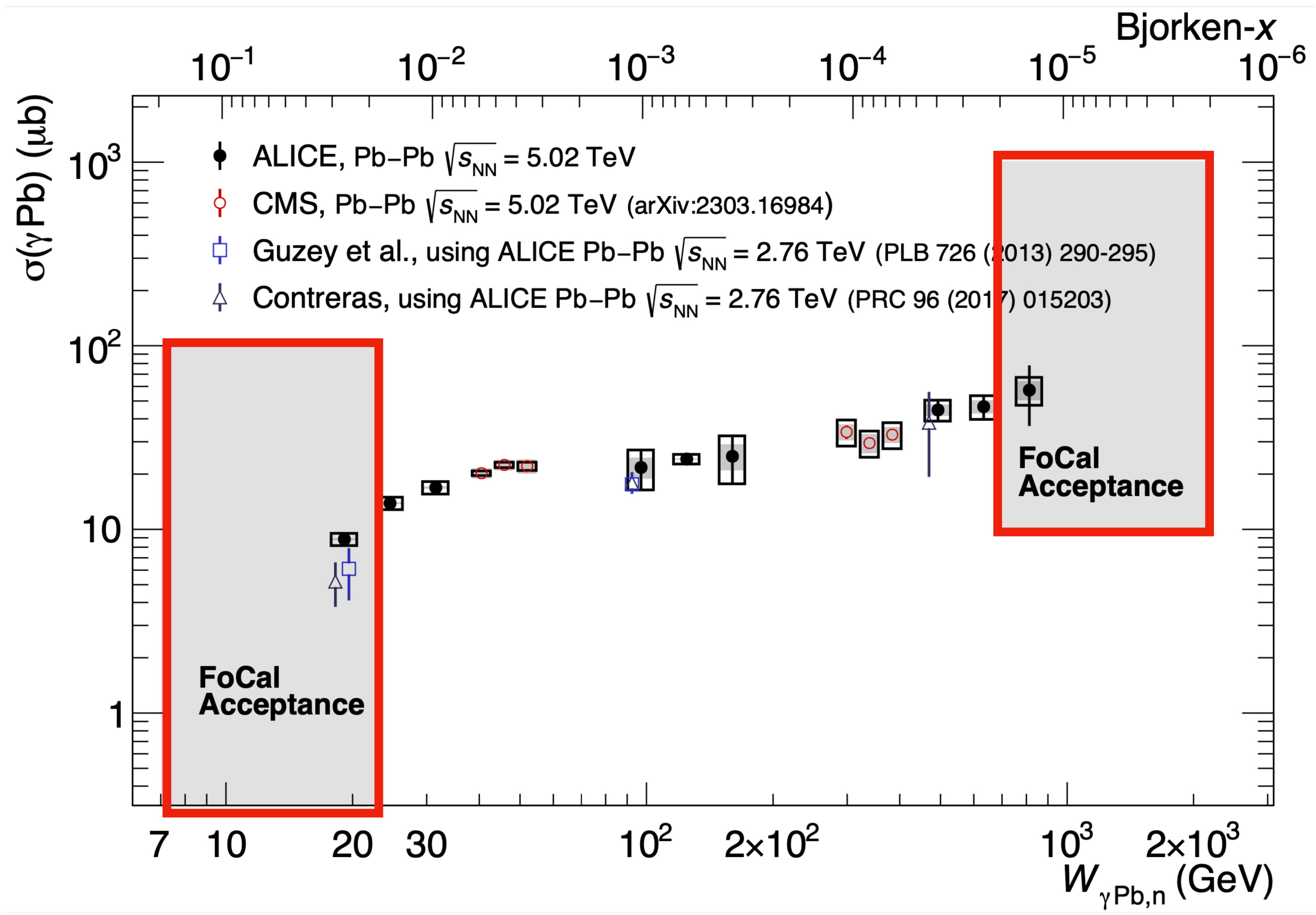

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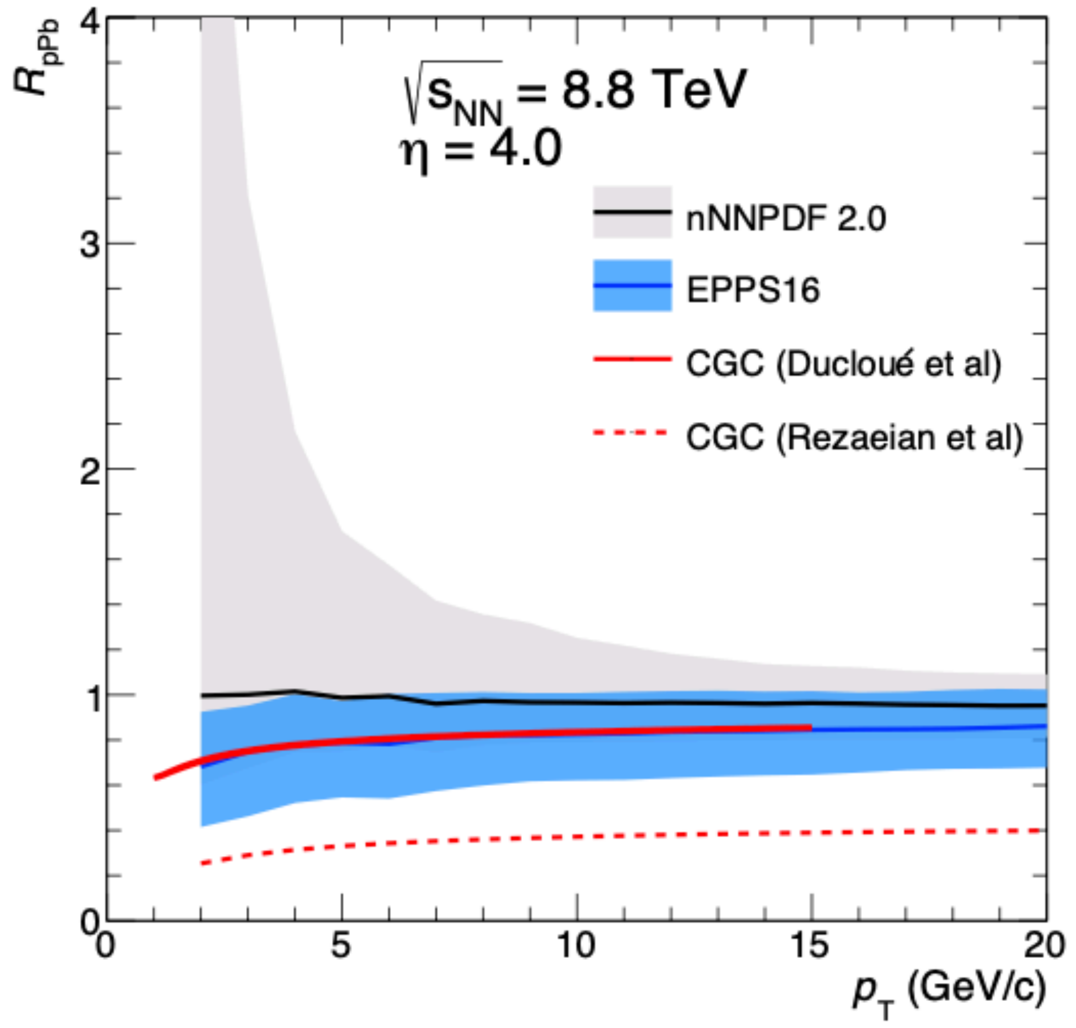

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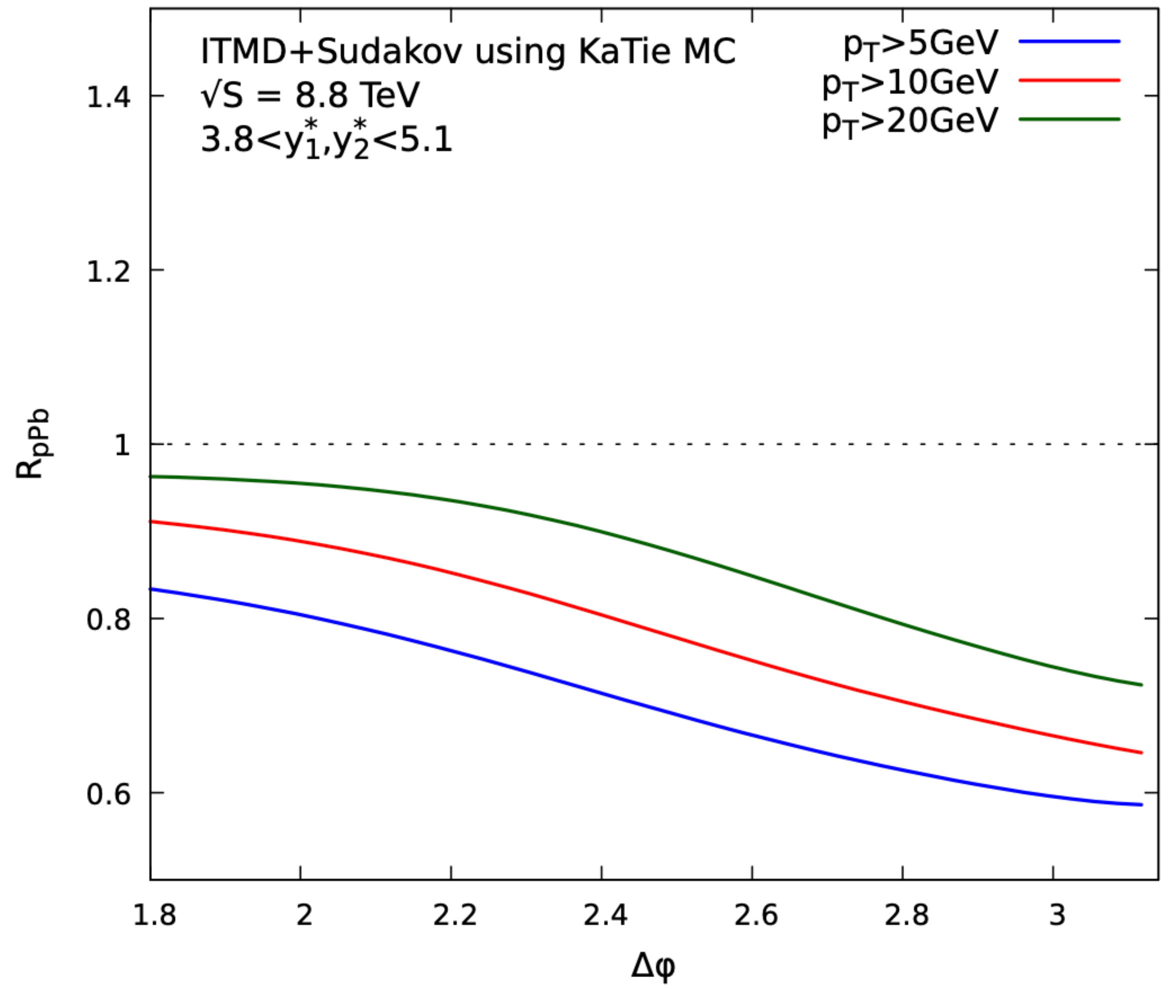
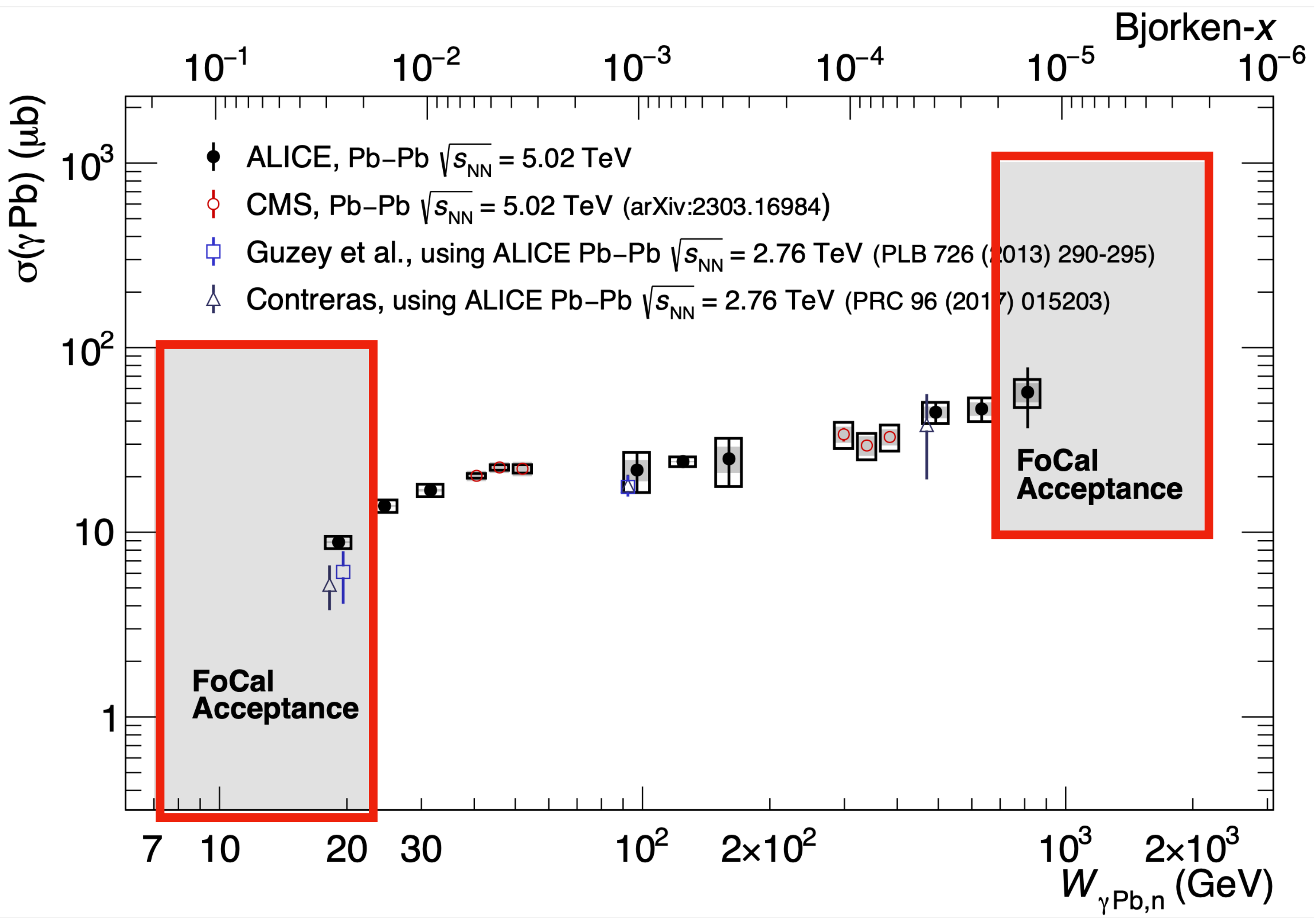
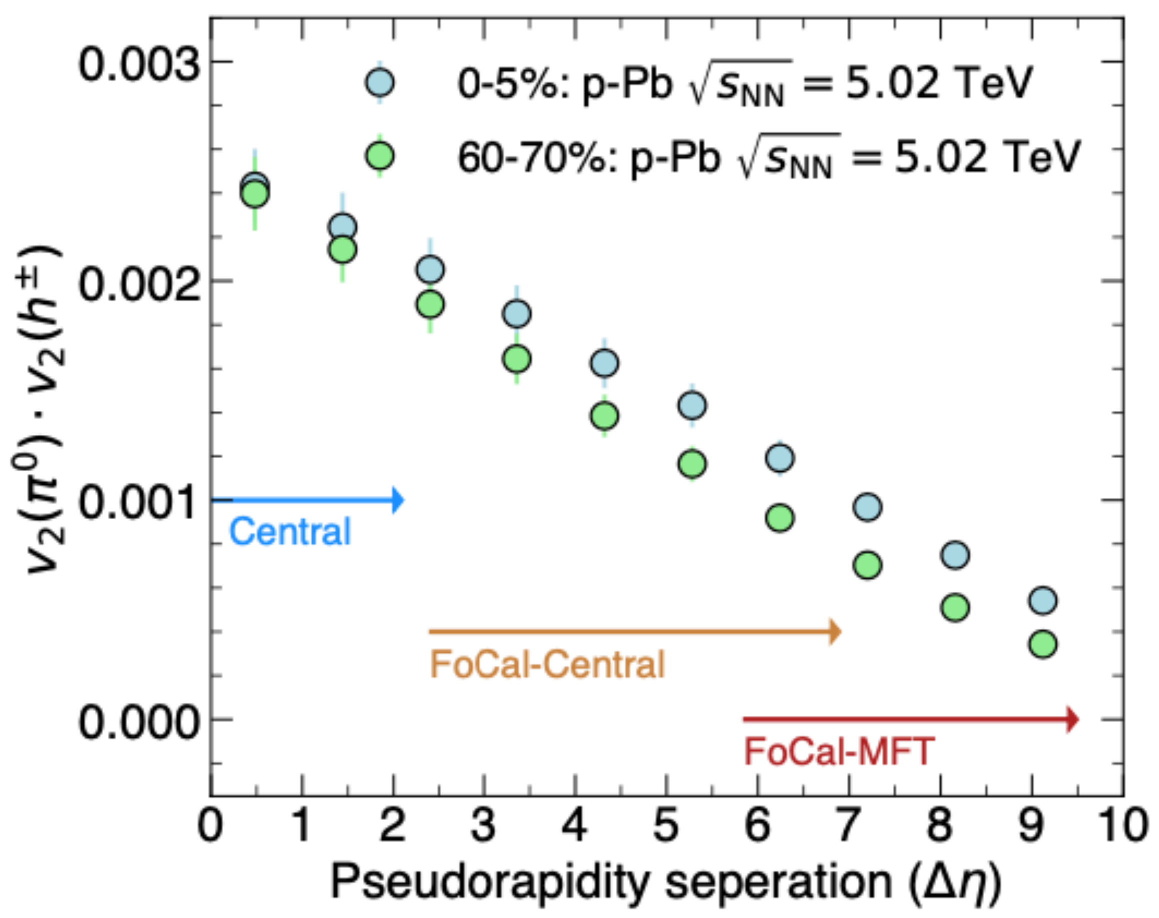




Long-range correlations



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2. Investigate the origin of long range correlations

- Azimuthal π^0-h correlations using FoCal and central ALICE (and muon arm) in pp and pPb collisions

3. Explore jet quenching at forward rapidity

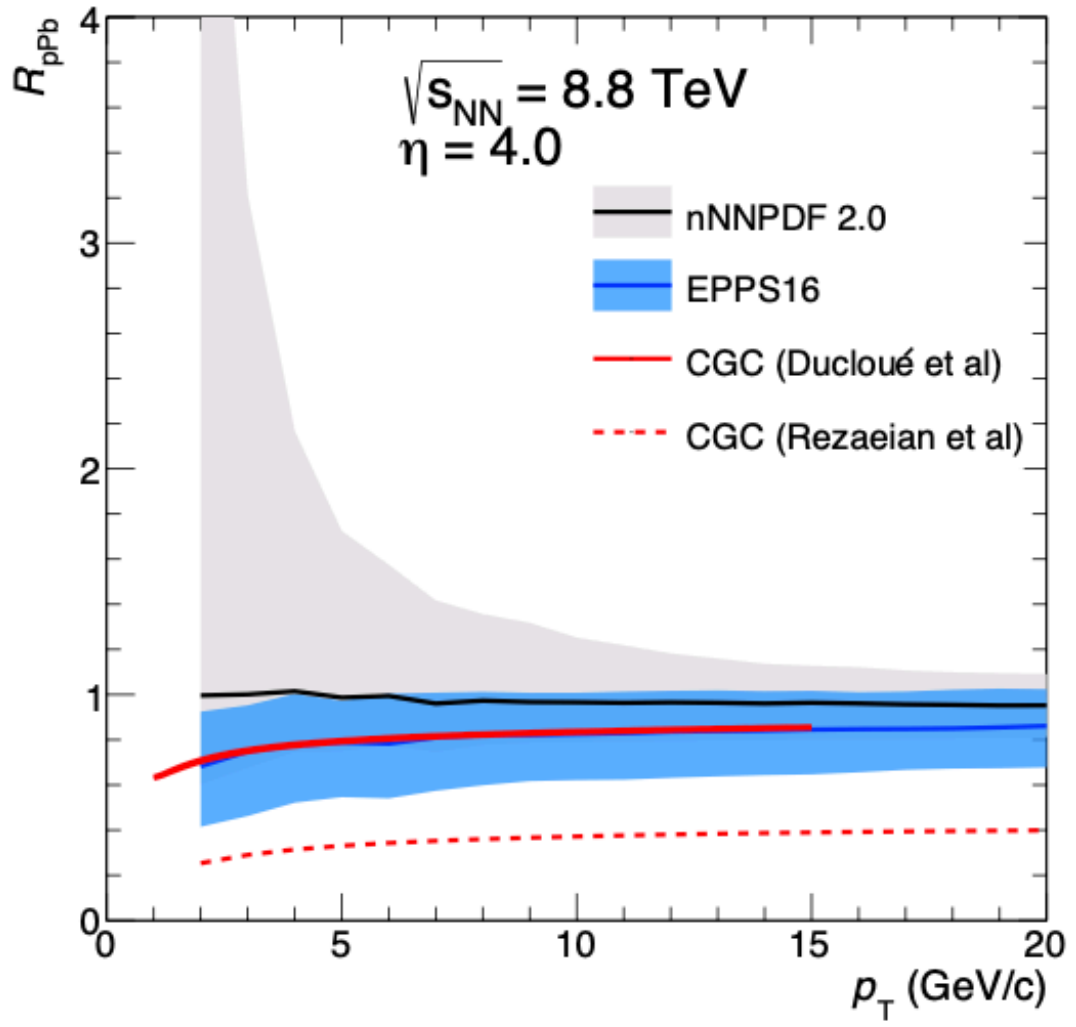
- Measure high-p_T neutral pions and jets in PbPb

4. Other observables or measurements

- Quarkonia in hadronic collisions
- Photon and pion HBT (*)
- Z (W) in pp/pPb
- Isolated photons in PbPb (*)
- Reaction plane and centrality determination in PbPb

(*=feasibility not yet explored)

Isolated photon RpPb



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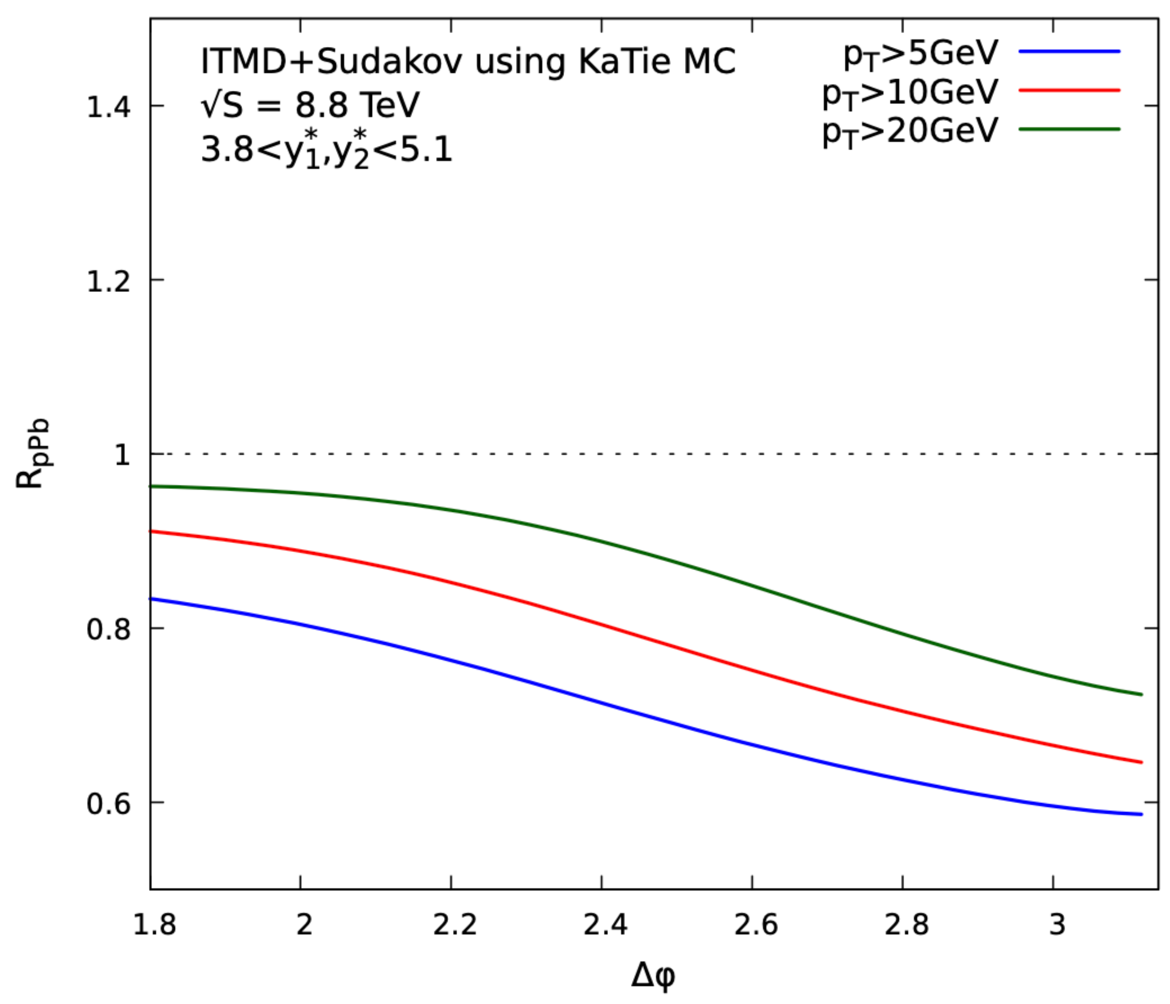

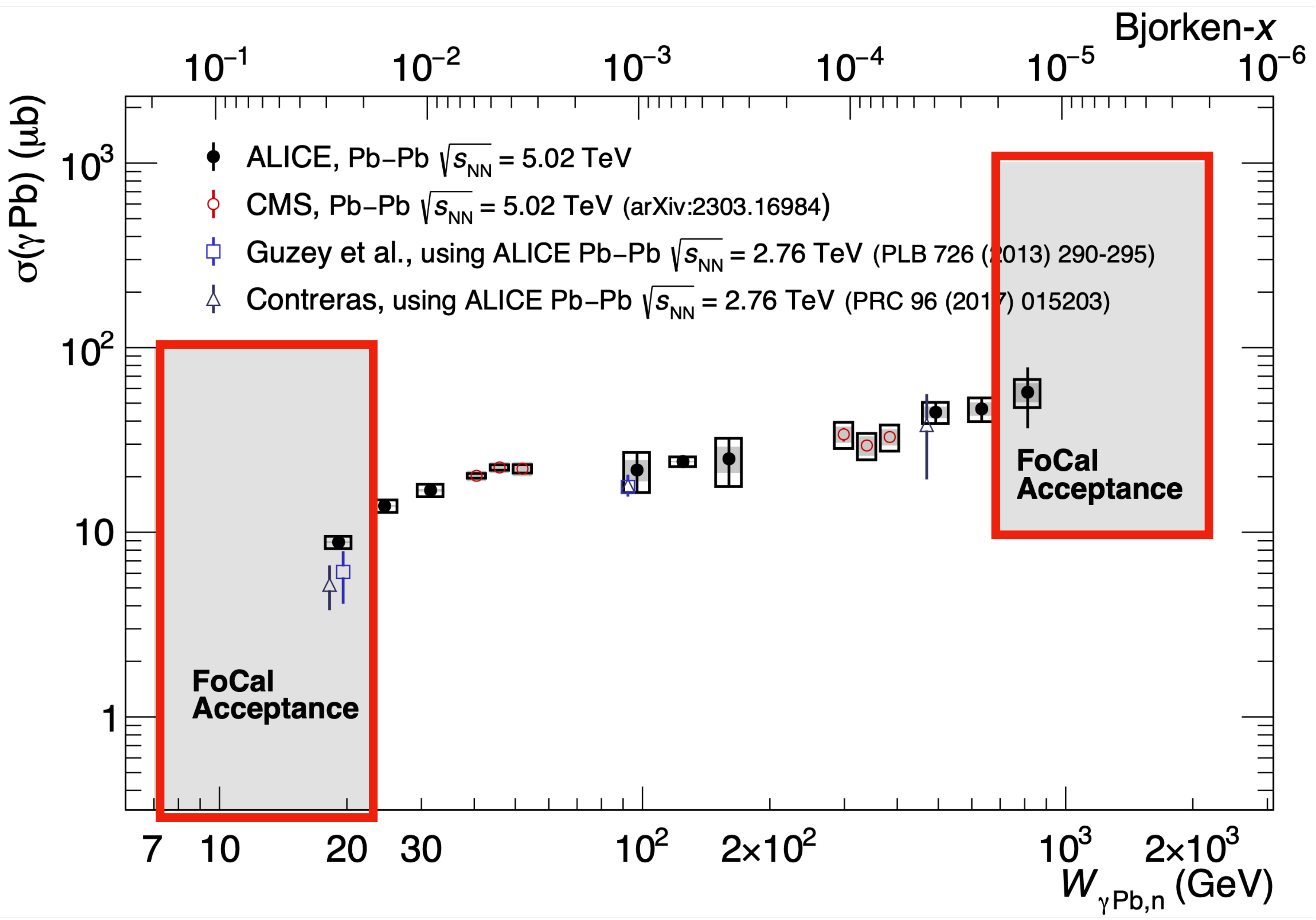

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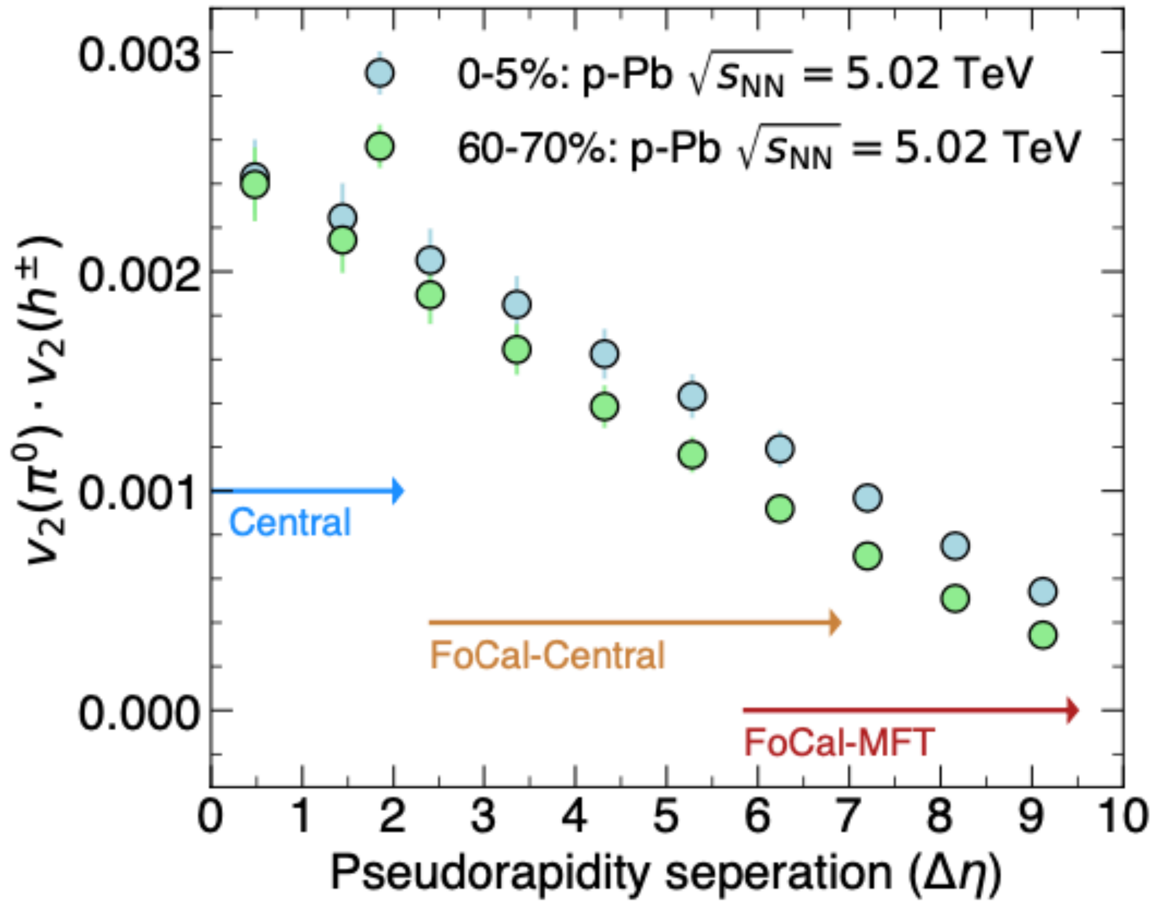
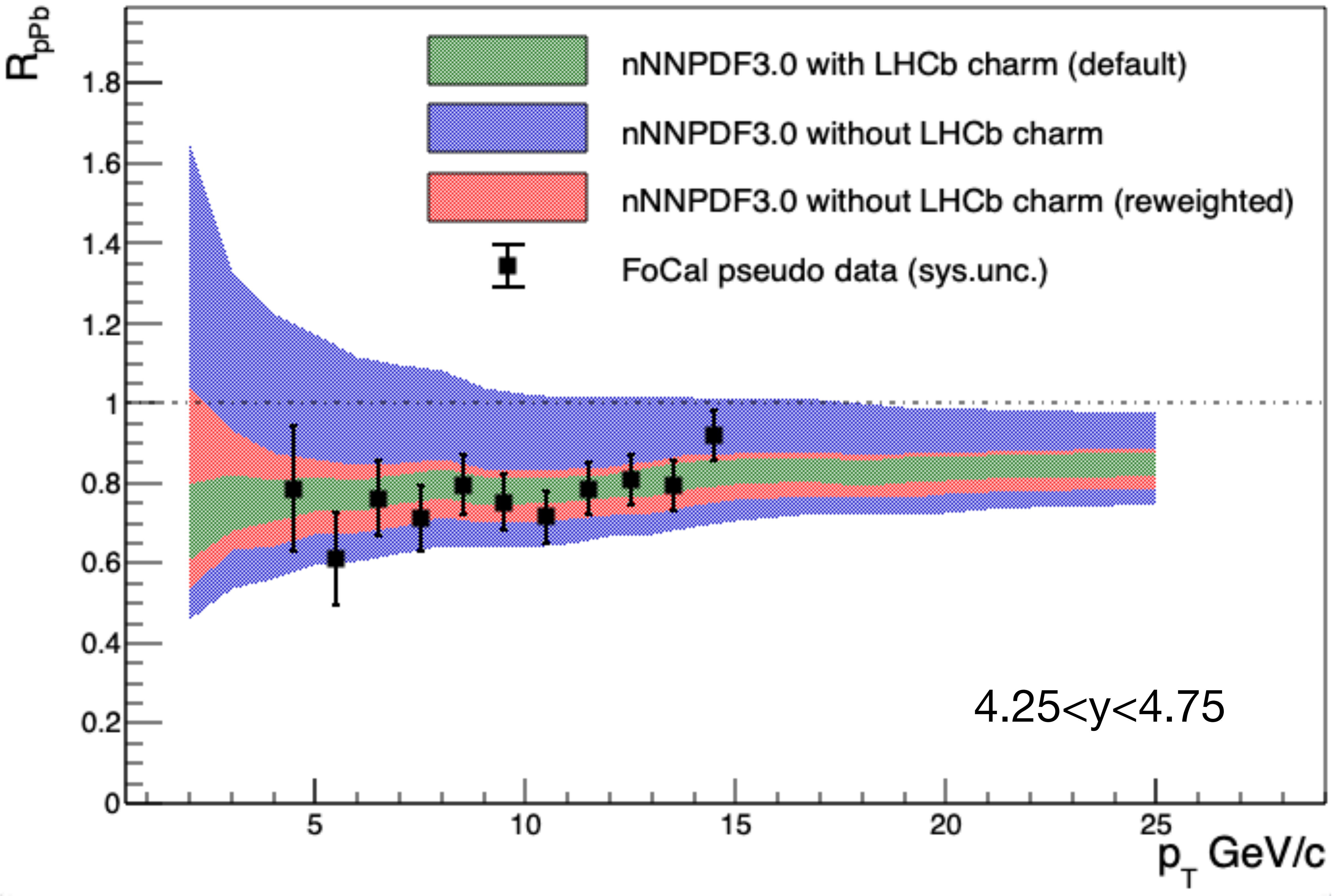


Example of global analysis using nNNPDF3.0

arXiv:2201.12363v2

Reweighting follows approach
in arXiv:1909.05338, 90% CL shown

Suppressed photon yield (toy-model)



Validate or invalidate factorization/universality

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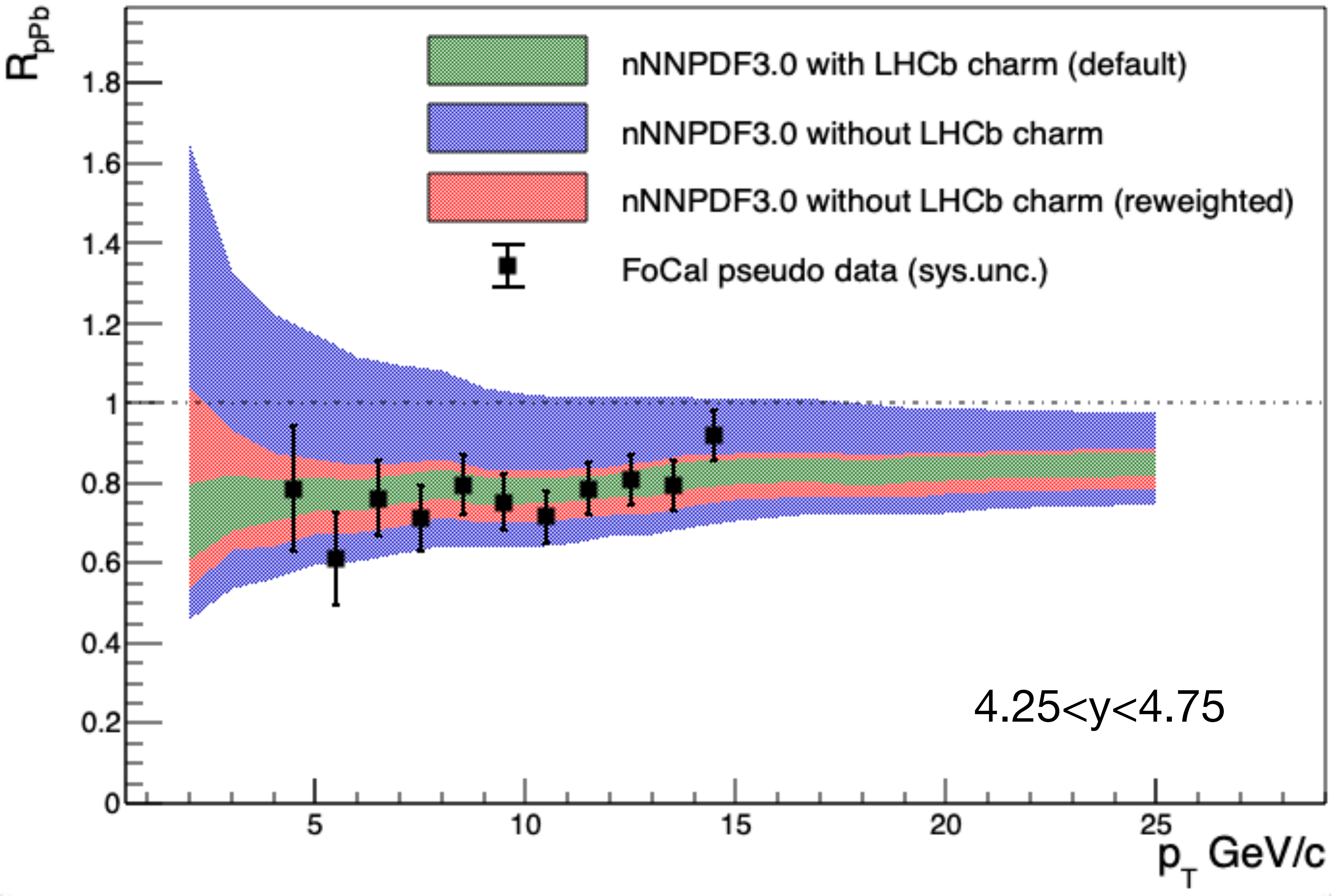
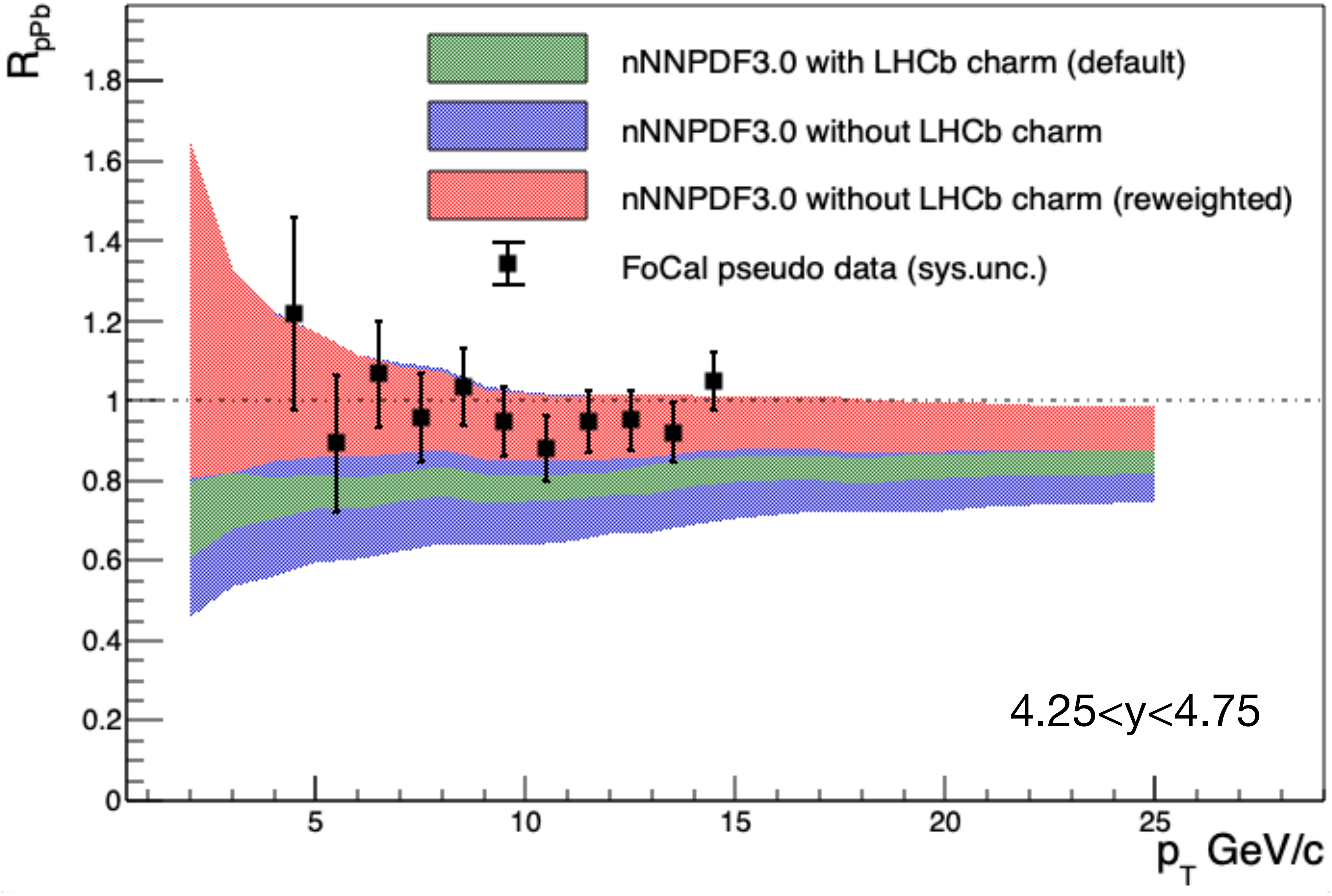


Un-Suppressed photon yield (from nNNPDF2.0)



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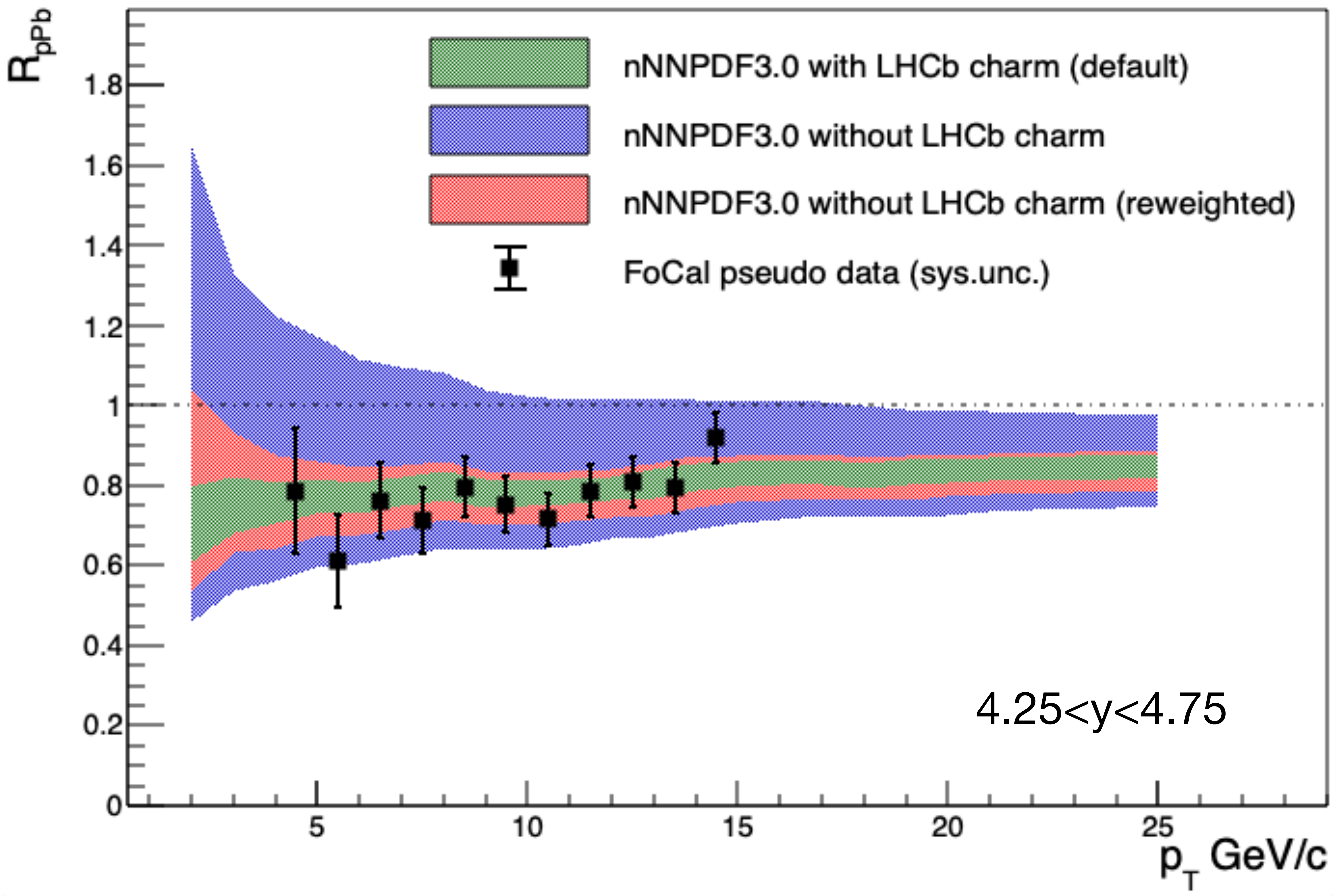

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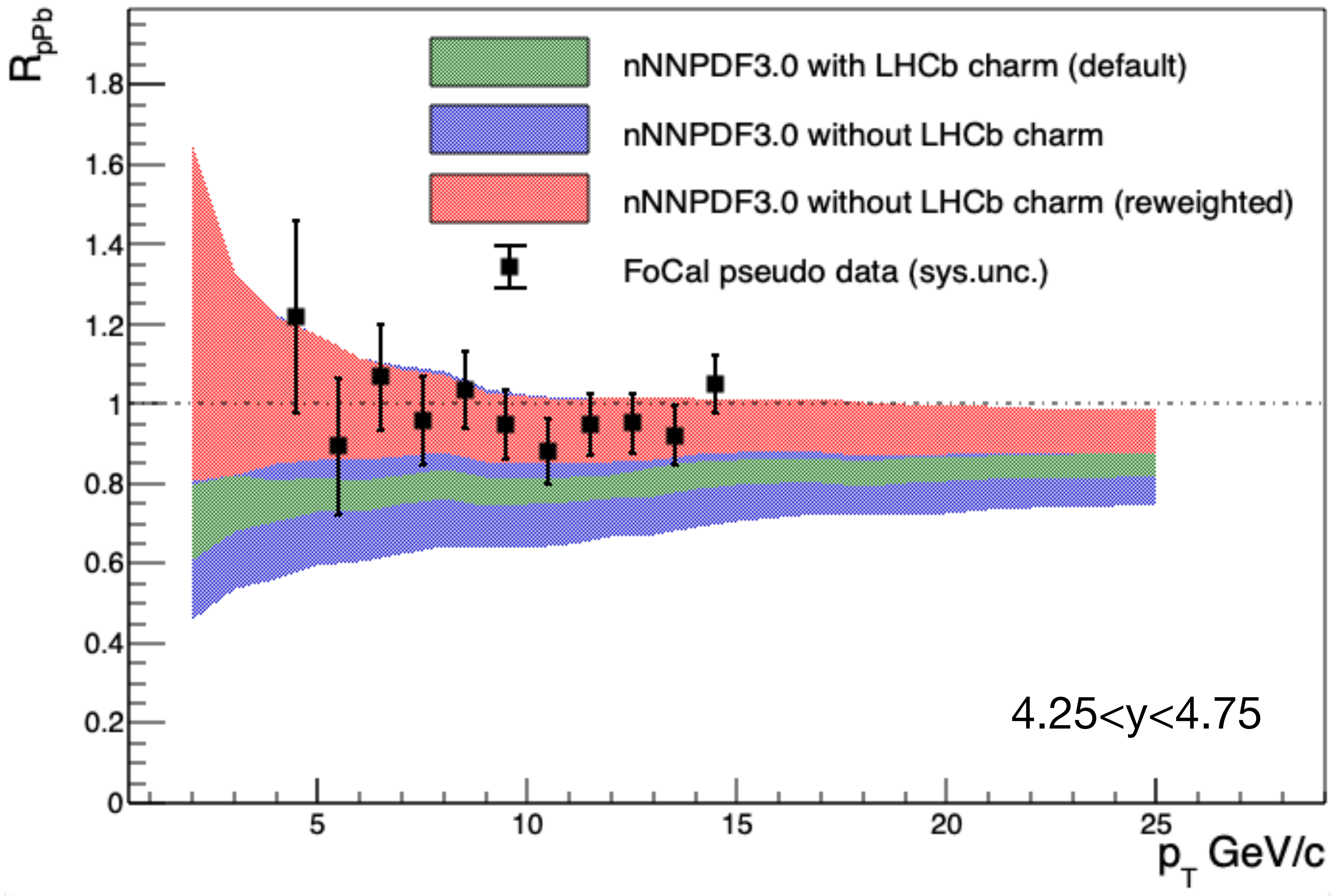
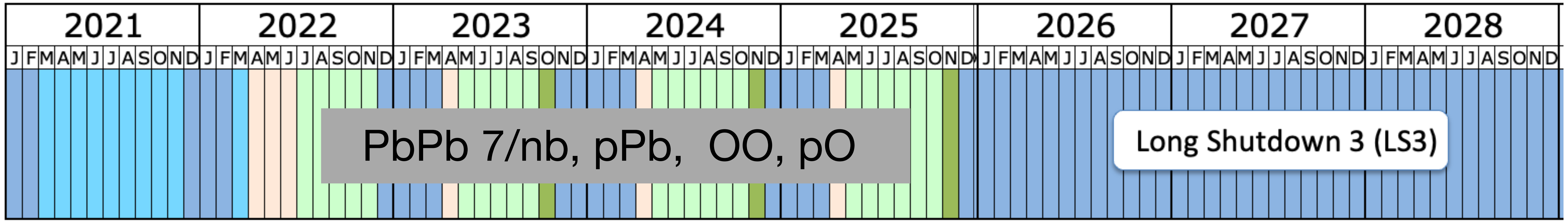


Validate or invalidate factorization/universality

- Non-linear dynamics, if present, could be reabsorbed in the nuclear PDF fit
- To discriminate linear from non-linear evolution may likely need to go beyond nPDF fits in collinear approximation
- Develop common framework for many eA and pA observables to allow for consistent predictions and/or Bayesian-based parameter extraction (e.g. see SURGE collaboration)

Ongoing and future LHC program

Run-3



ALICE 2.0

LHCb Phase I

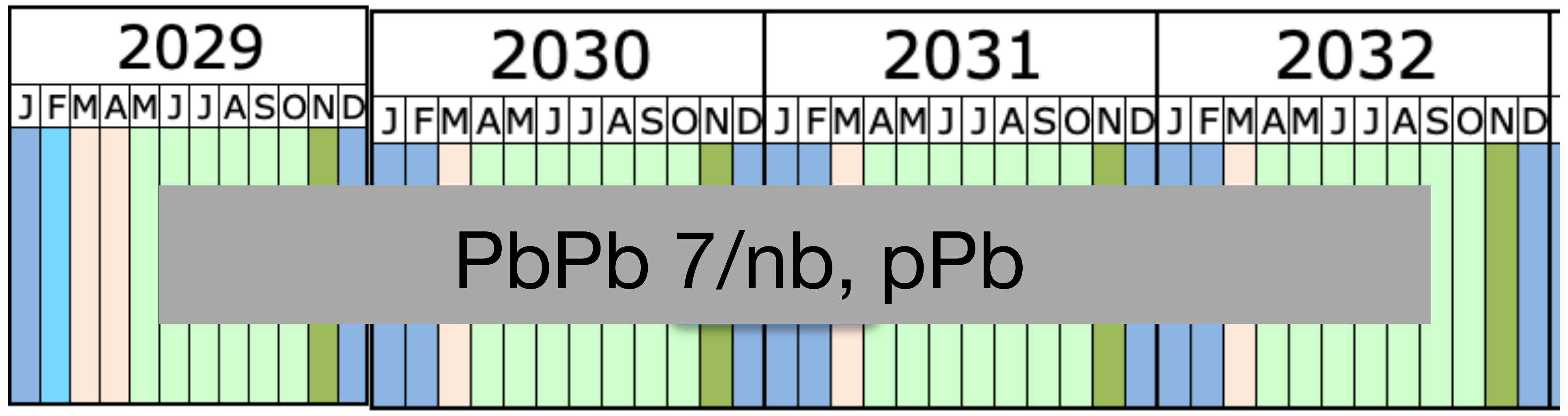
ALICE 2.1 (ITS3, FoCal)

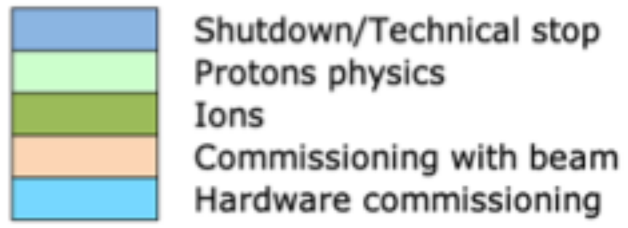
CMS/ATLAS Phase II

HL-LHC

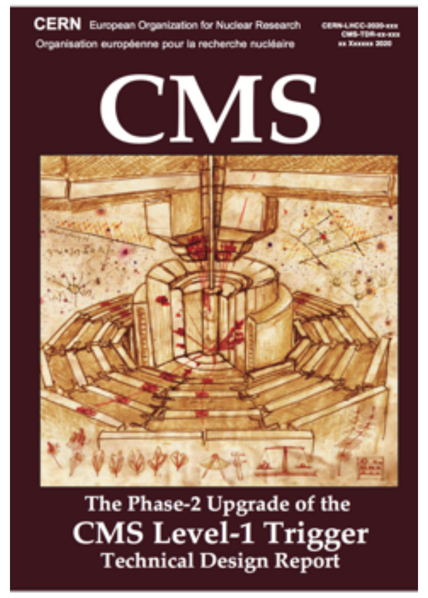
Run-4

EIC (ePIC)





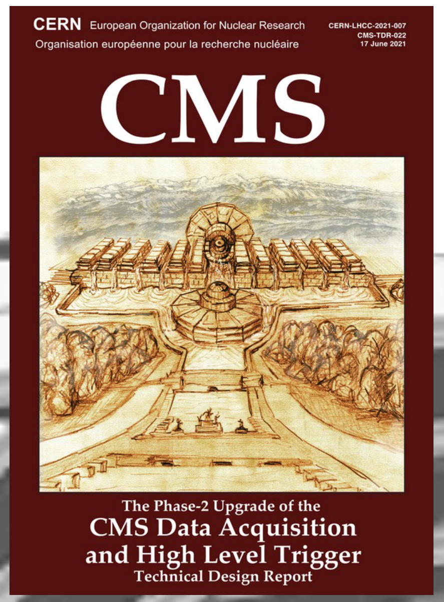
CMS phase II upgrade: A new detector for HL era



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

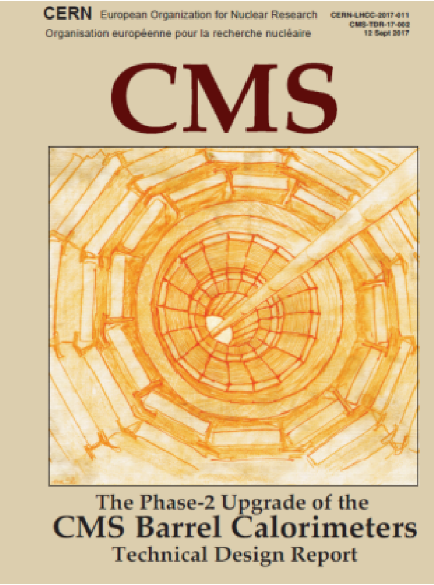
https://cds.cern.ch/record/2759072

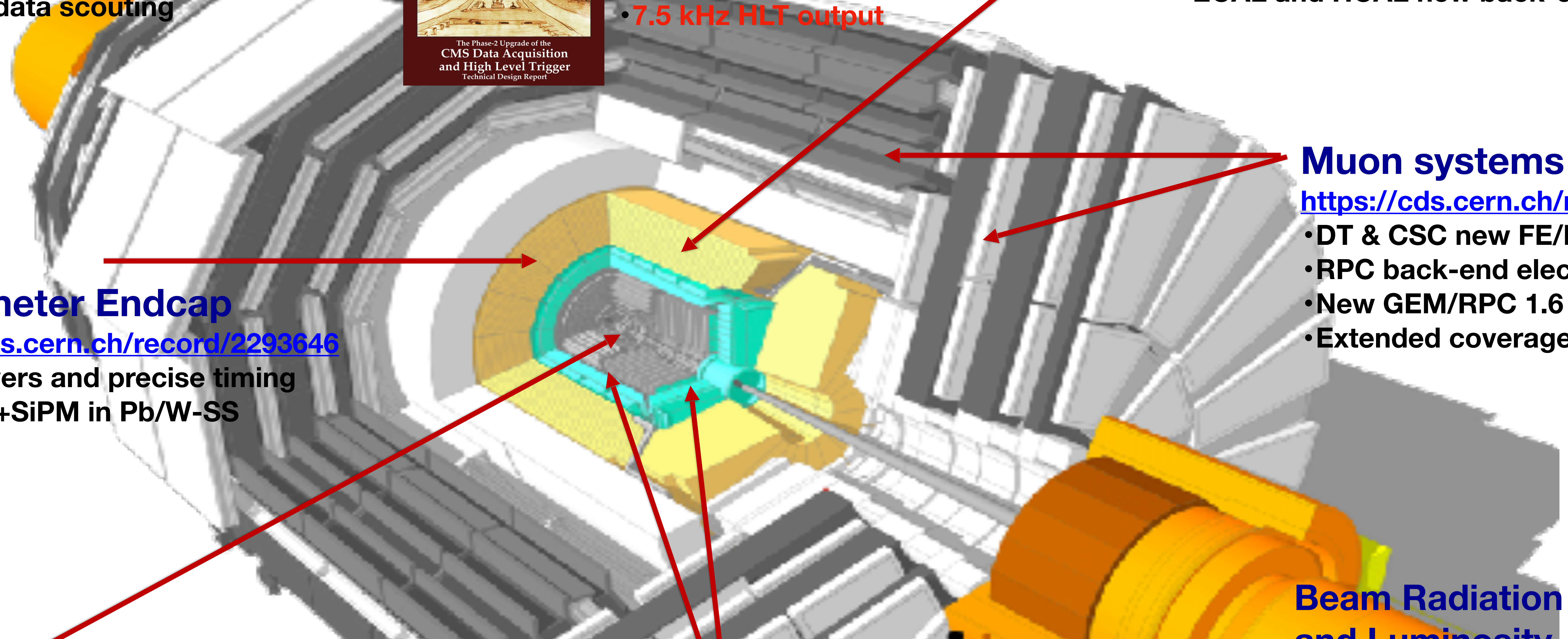
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

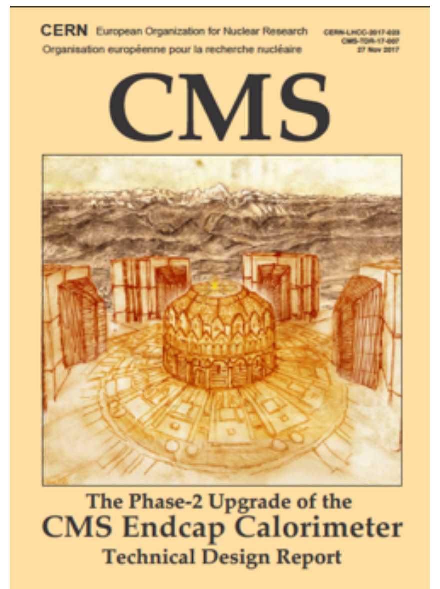
Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end boards







Calorimeter Endcap

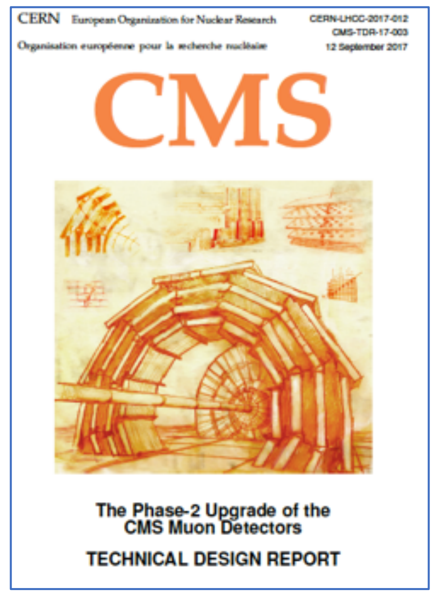
https://cds.cern.ch/record/2293646

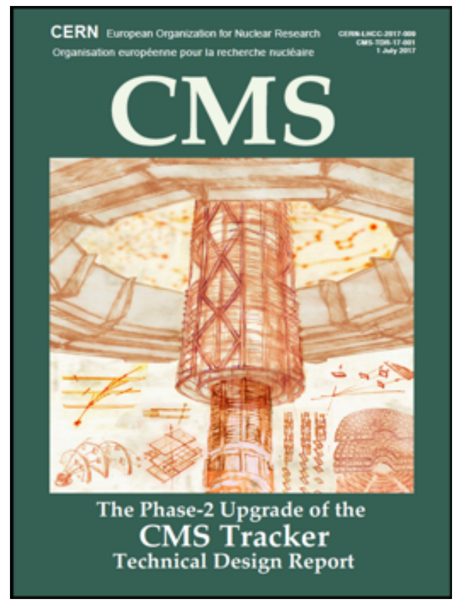
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3

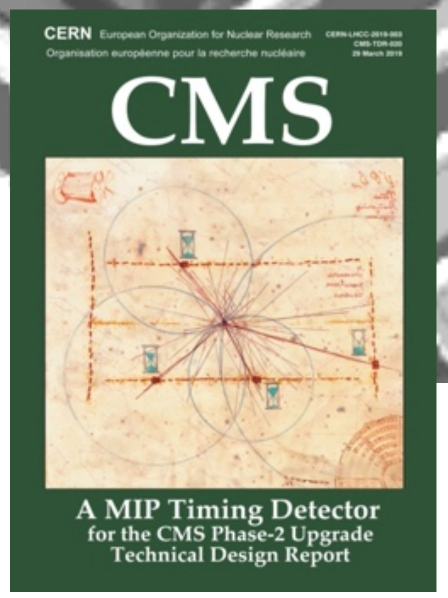




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 4.0



MIP Timing Detector

https://cds.cern.ch/record/2667167

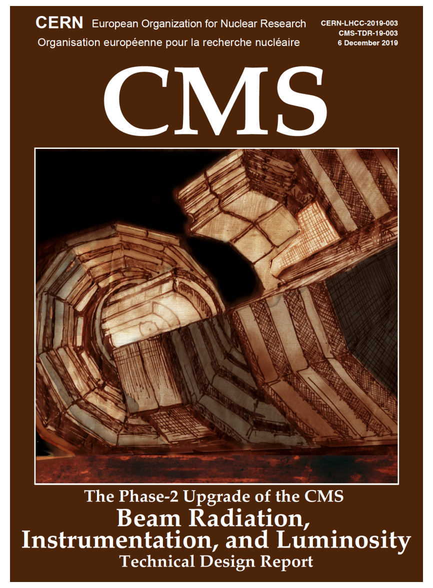
Precision timing with:

- Barrel layer: LYSO Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

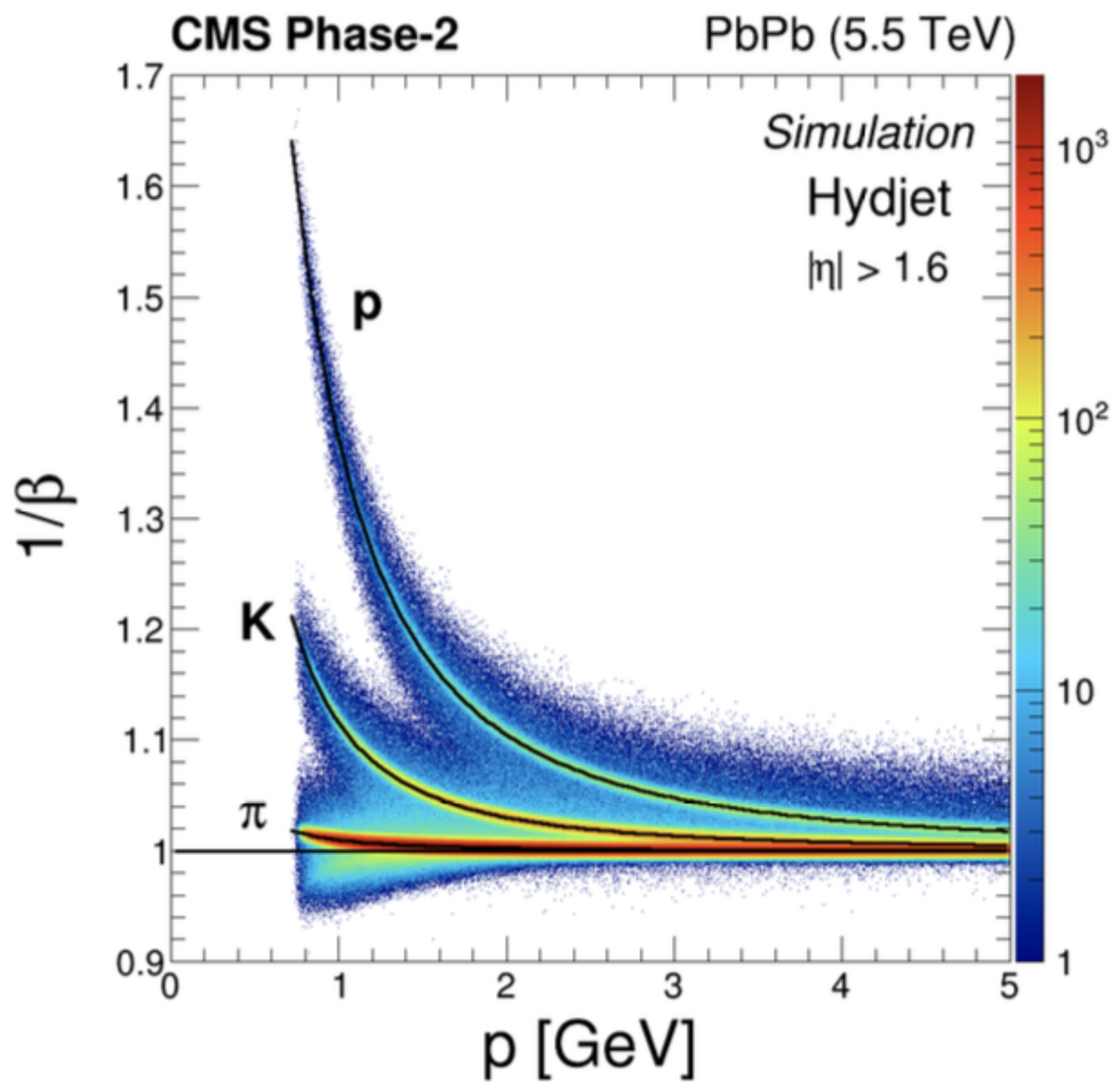
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors
- Proposed ZDC-HL (joint project with ATLAS)



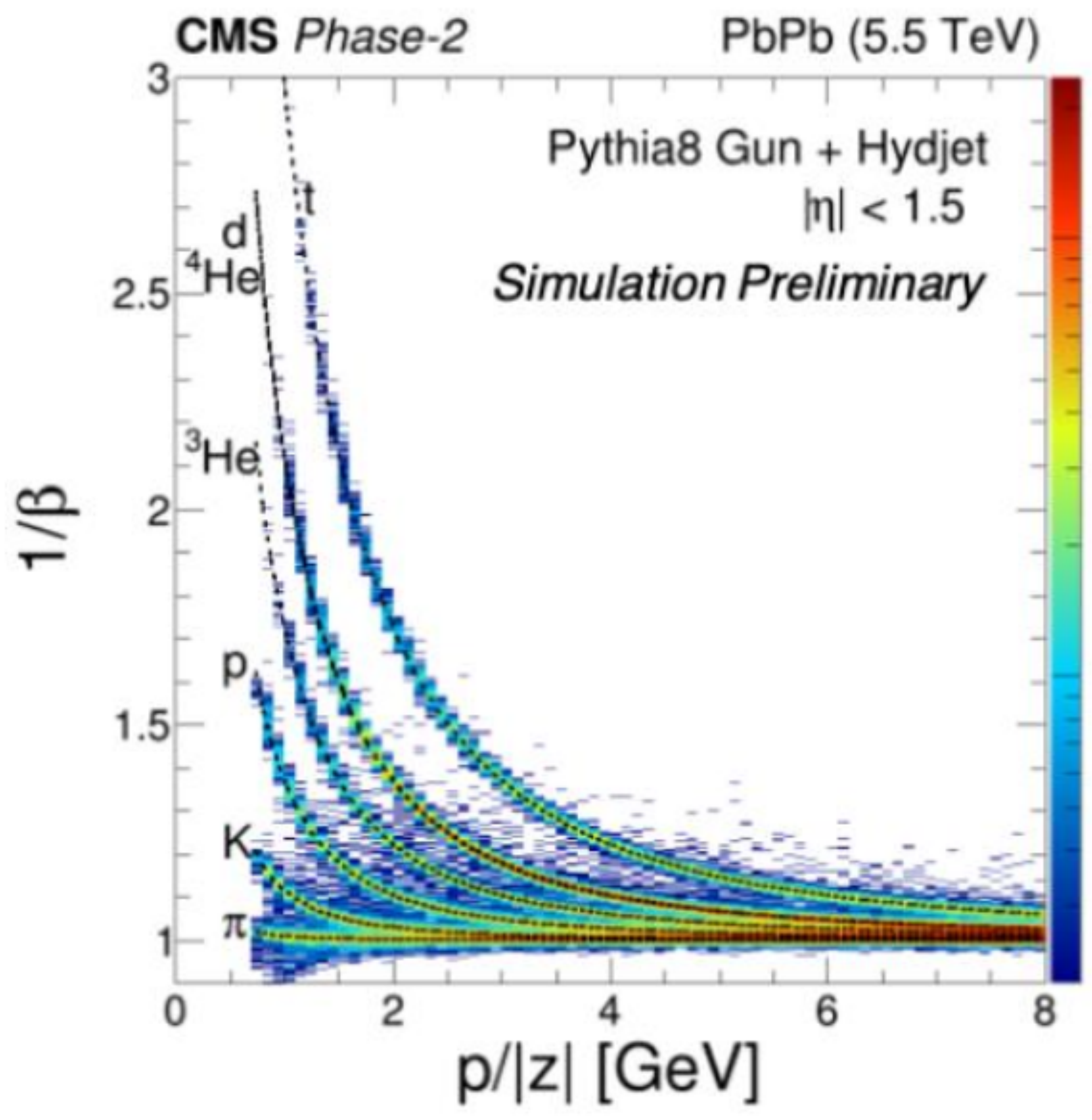
CMS MIP timing detector

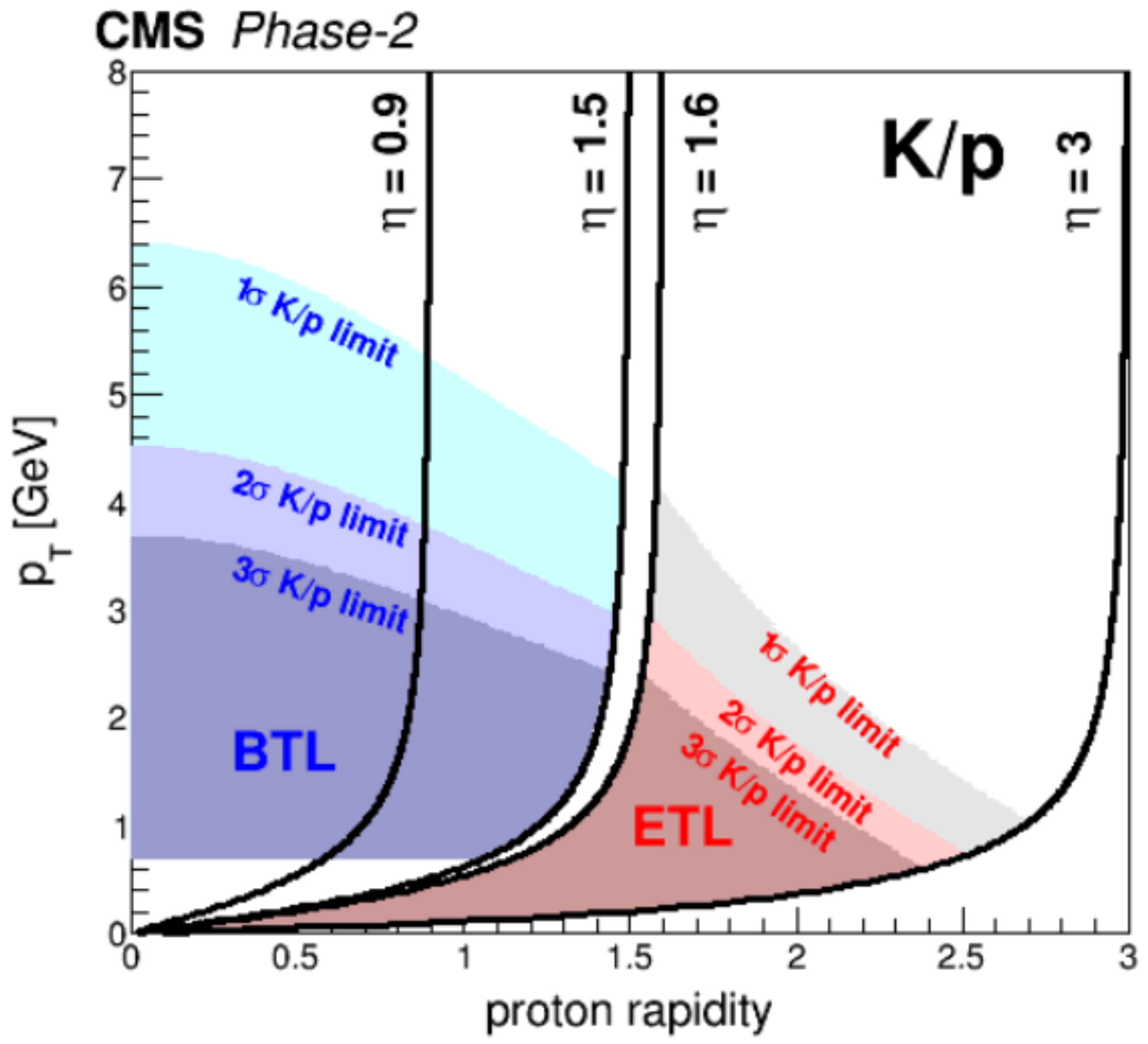
CMS-DP-2021-037

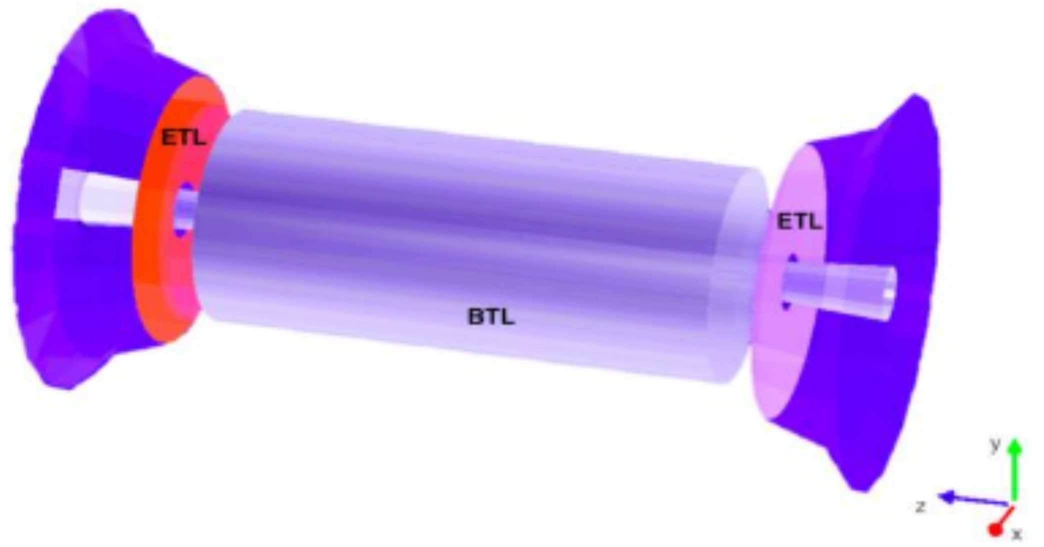
p / K / π separation



Light ion identification



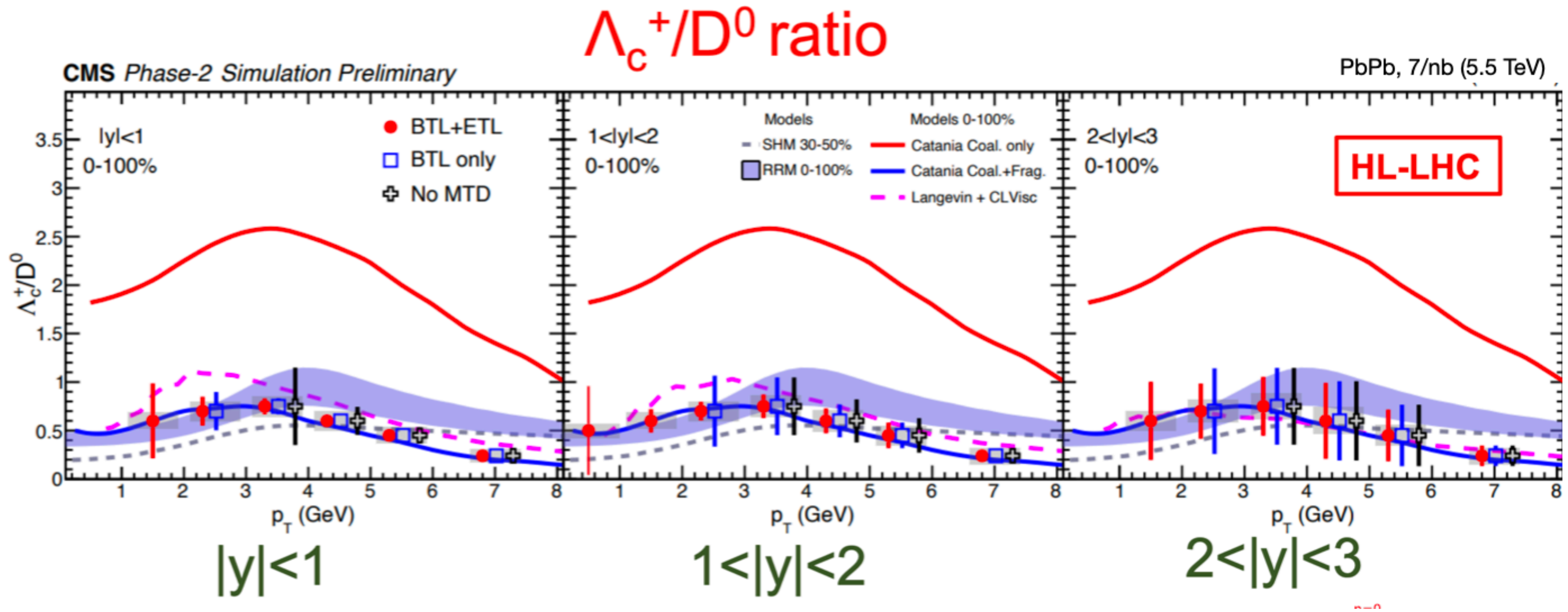


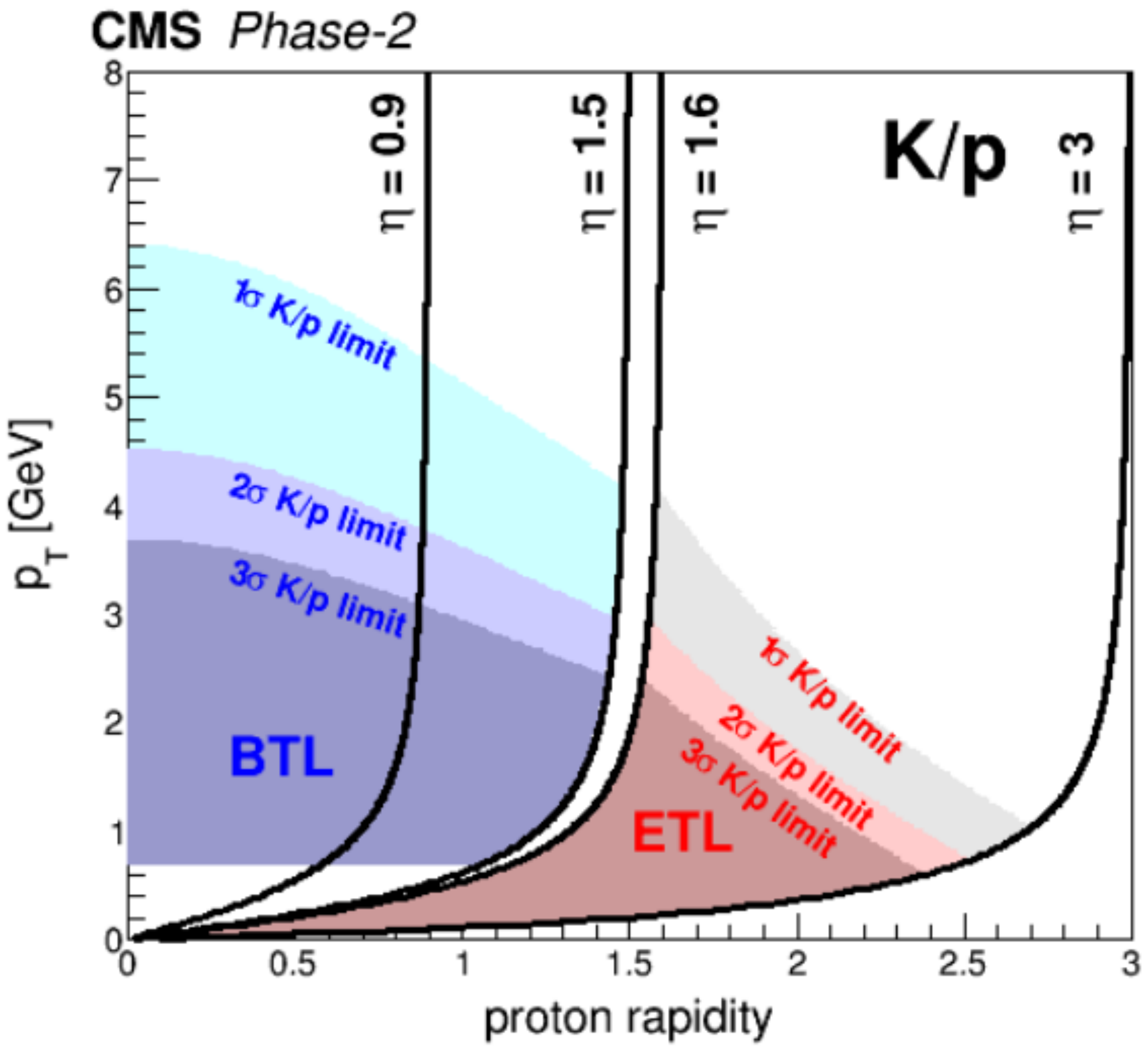


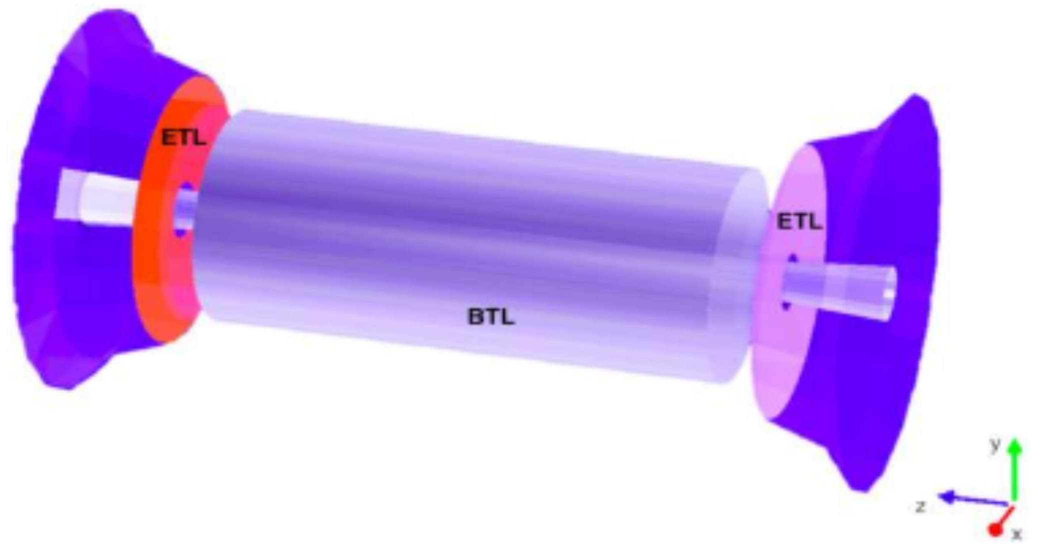
- Unique hermetic particle identification coverage by CMS MTD
- Crucial to measure eg. Λ_c^+/D^0 ratio over large pseudorapidty and down close to zero p_T

CMS MIP timing detector

CMS-DP-2021-037







- **Unique hermetic particle identification coverage by CMS MTD**
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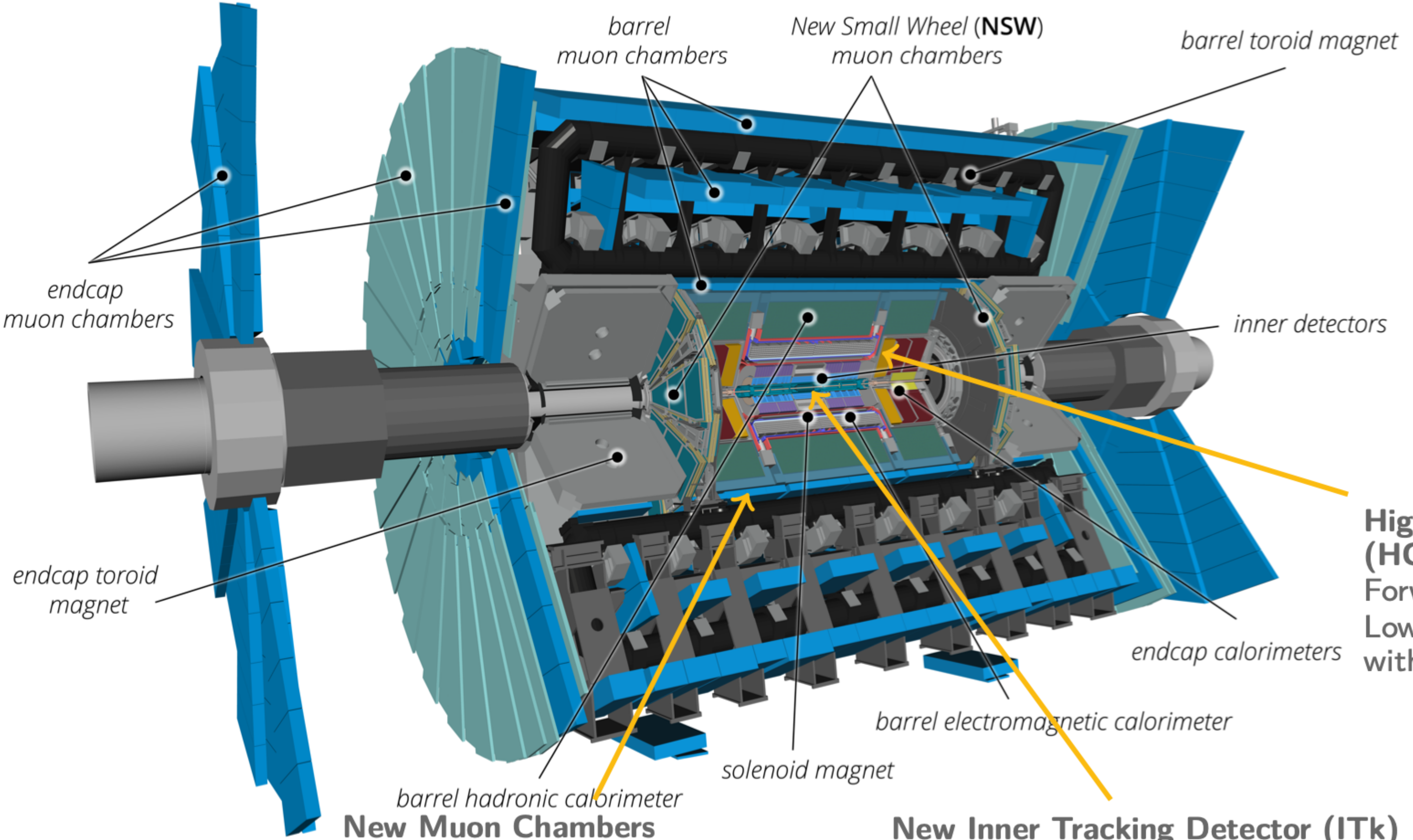
ATLAS phase-II upgrade (for TDR references, see here)



Upgraded Trigger and Data Acquisition system
Level-0 Trigger at 1 MHz,
Improved High-Level Trigger
(150 kHz full-scan tracking)

Electronics Upgrades
LAr Calorimeter
Tile Calorimeter
Muon System

High Granularity Timing Detector (HGTD)
Forward region ($2.4 < |\eta| < 4.0$)
Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

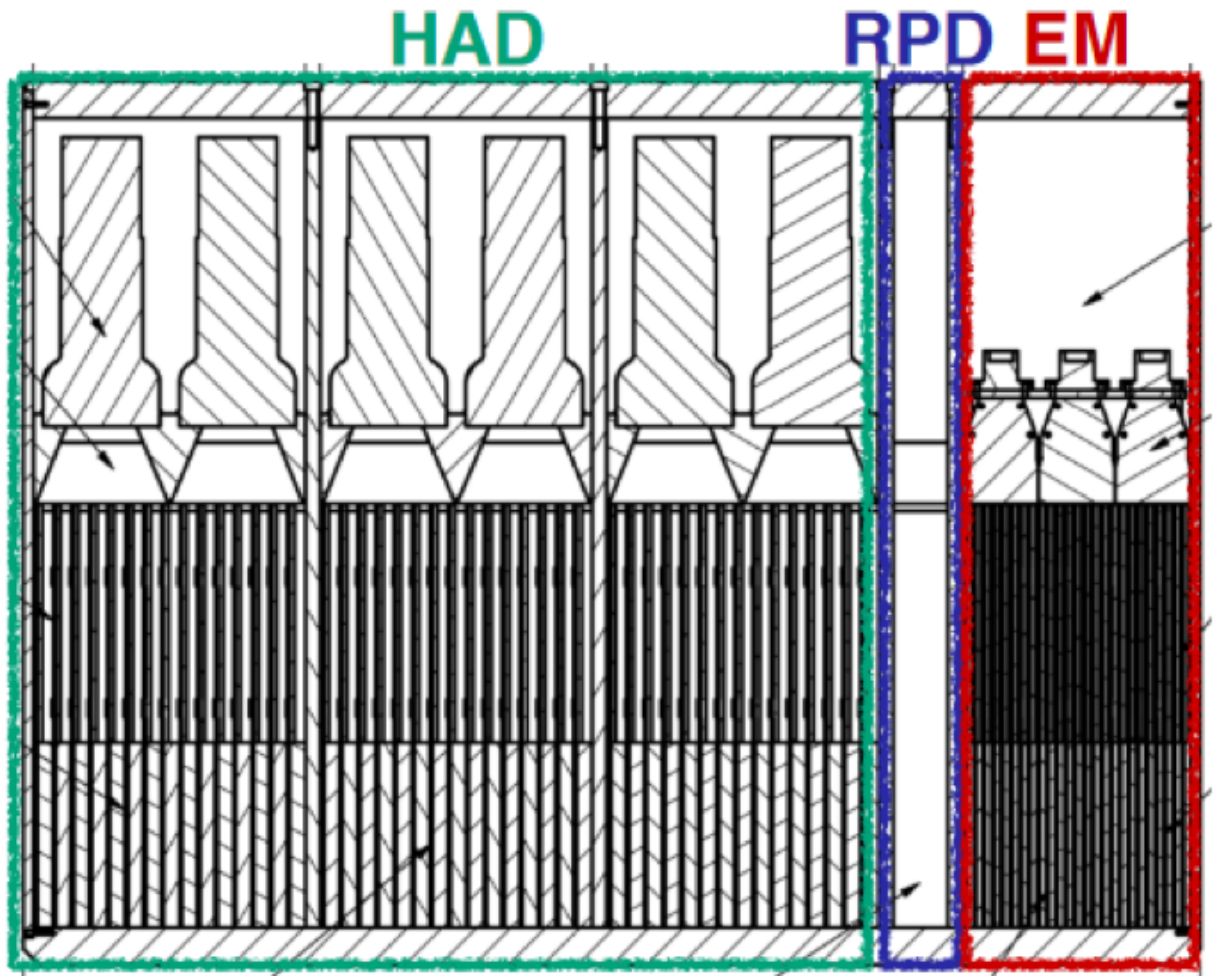
New Muon Chambers
Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)
All silicon up to $|\eta| = 4$

Additional small upgrades
Luminosity detectors (1% precision goal), HL-ZDC

High Luminosity Zero Degree Calorimeters

CERN-LHCC-2021-018



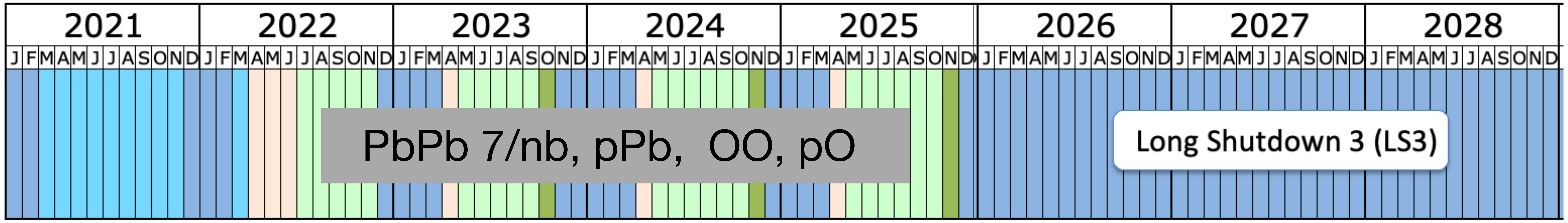
Thinner and finer segmented absorber for neutrons and protons

- Ambitious due to limited space in the TANX region
- Joint project between ATLAS and CMS (HI) groups
- Centrality in PbPb and pPb
- Separations of number of neutron for UPC
- Reaction plan determination (in particular 1st-order)
- Potential MB trigger

- Detection of Cherenkov light emission in high-purity, ultra-radiation-hard fused silica rods
- EM and HAD sections are calorimeters with different sampling ratios
- RPD consists of an array of fused-silica fibers of different lengths to map the transverse profile of the shower produced within the EM module.

Ongoing and future LHC program

Run-3



ALICE 2.0

LHCb Phase I

ALICE 2.1 (ITS3, FoCal)

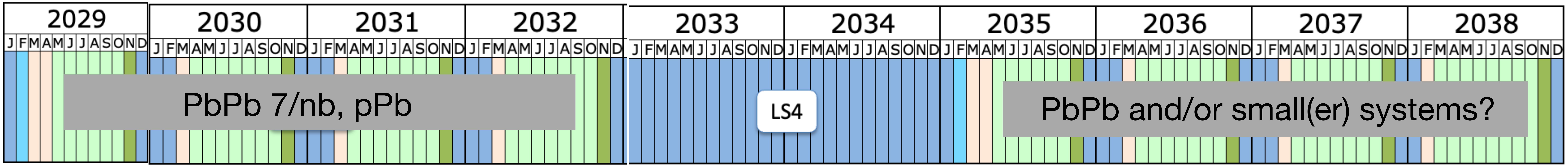
CMS/ATLAS Phase II

HL-LHC

Run-4

EIC (ePIC)

Run-5

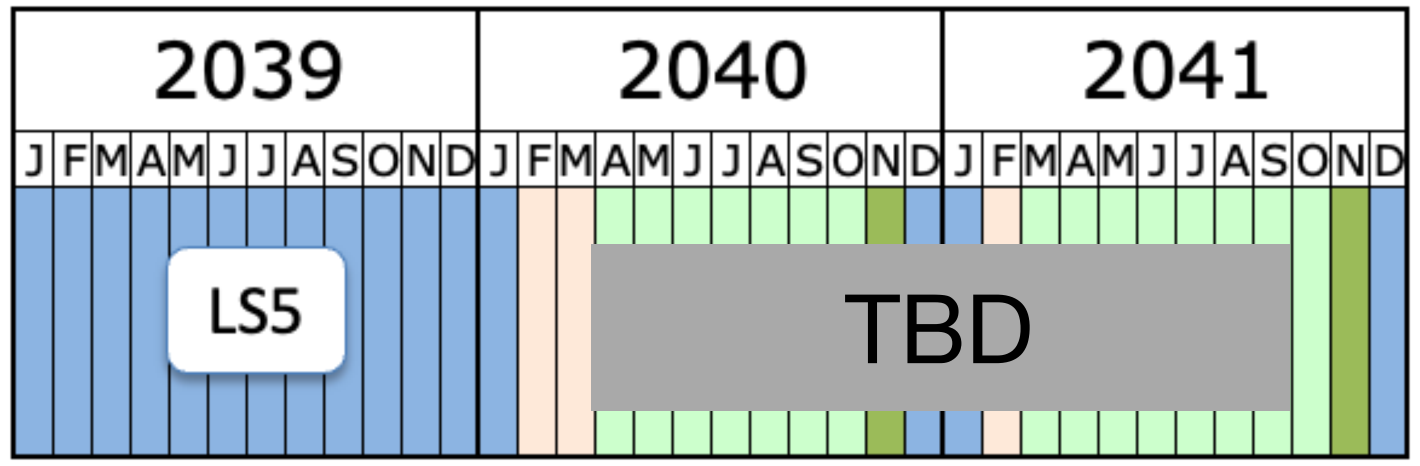


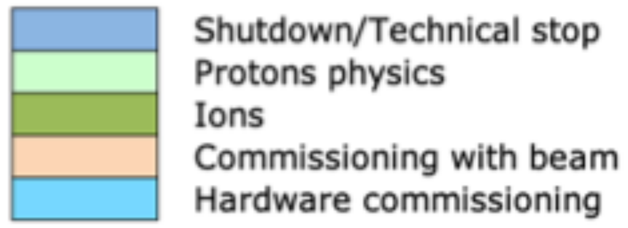
Run-6

FCC

ALICE 3.0

LHCb Phase II



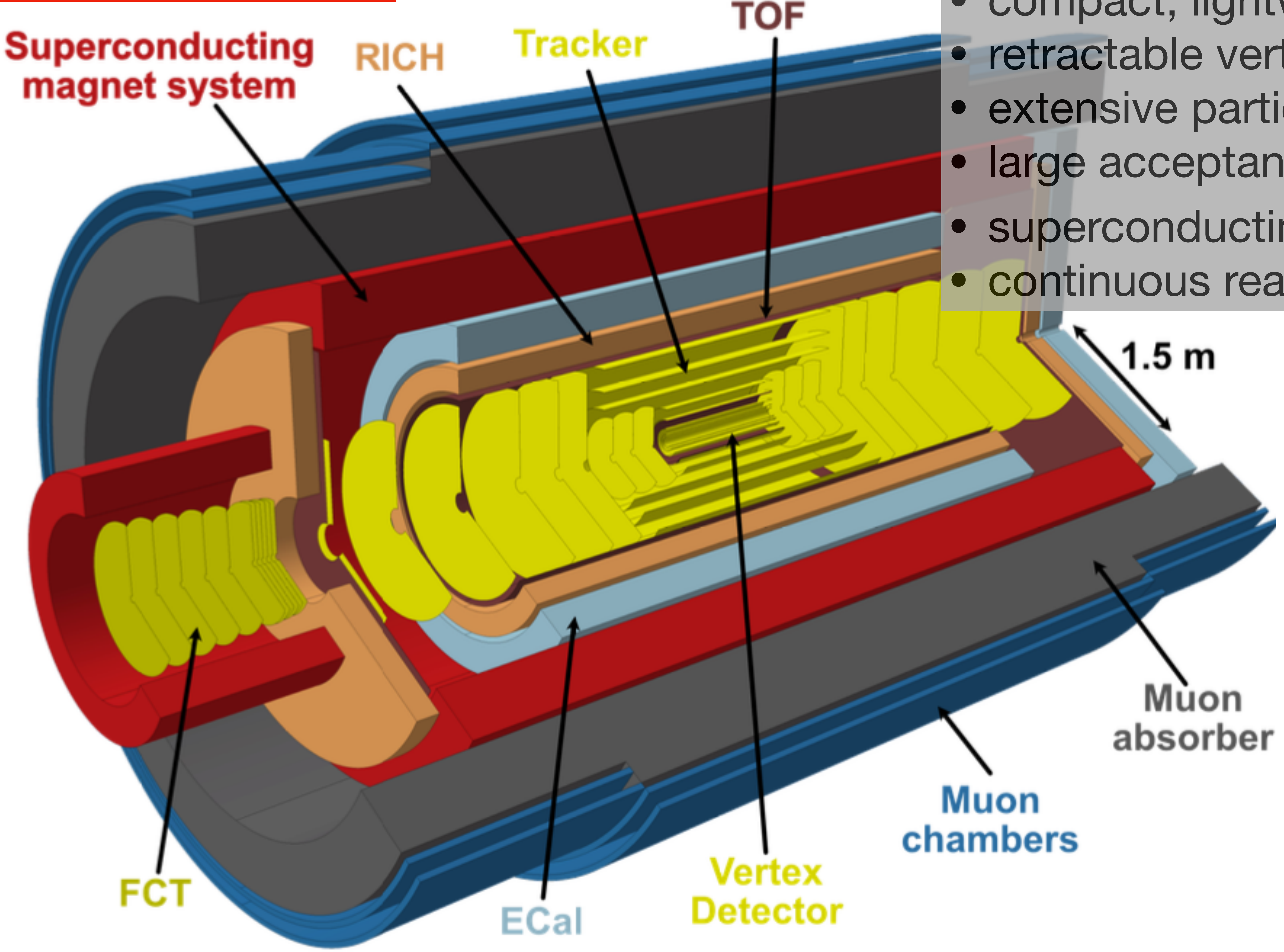


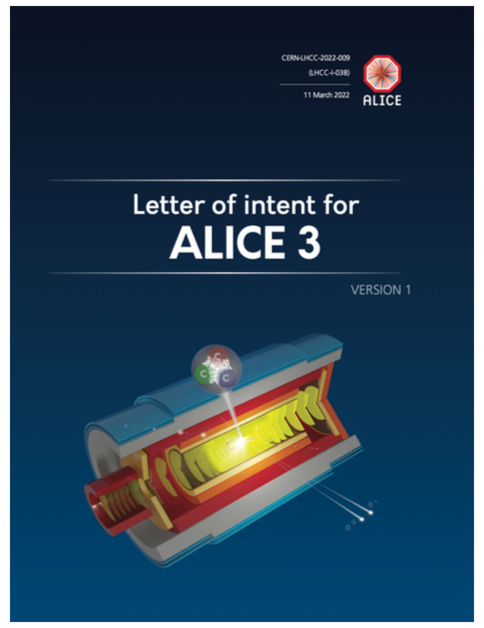
ALICE 3: A next-generation heavy-ion experiment

- Tracking precision × 3: PR<10 μm at p_T > 200 MeV
- Acceptance × 4.5: $|\eta| < 4$ (with particle ID)
- AA rate × 5 (pp × 25)

LOI, arXiv:2211.02491

Novel and innovative detector concept
- compact, lightweight all-silicon tracker
- retractable vertex detector
- extensive particle identification
- large acceptance ($|\eta|<4|$ with PID)
- superconducting magnet system
- continuous readout and data processing





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Tracker (60 m² silicon pixel detector)

- large coverage: 8 pseudorapidity units
- compact: R_{out} ≈ 80cm, z_{out} ≈ ±400cm
- pixel size ~ 50x50 μm²
- high-spatial resolution: σ_{pos} ≈ 10 μm
- low material budget: x/X_0 ~ 1% per layer
- low power density: ≈ 20 mW/cm²

Barrel RICH (|η| < 1.75)

- radius= 0.9m, length= 5.6m
- photon detection area = 39 m²
- readout cell size = 3x3 mm²

Forward RICH (1.75 < |η| < 4)

- photon detection area = 14 m²
- Monolithic photon sensors (digital SIPM) (baseline); hybrid photon sensors (fallback)

Superconducting magnet system

- free bore r=1.5m, length ~8m
- 1-2 T (field to be opt.)

Barrel TOF (|η| < 1.75)

- Outer TOF radius = 85cm
  surface: 30m², pitch: 5mm
- Inner TOF, radius = 19cm
  surface: 1.5m², pitch: 1mm

Forward TOF (1.75 < |η| < 4)

- Inner radius = 15cm, Outer radius = 150cm
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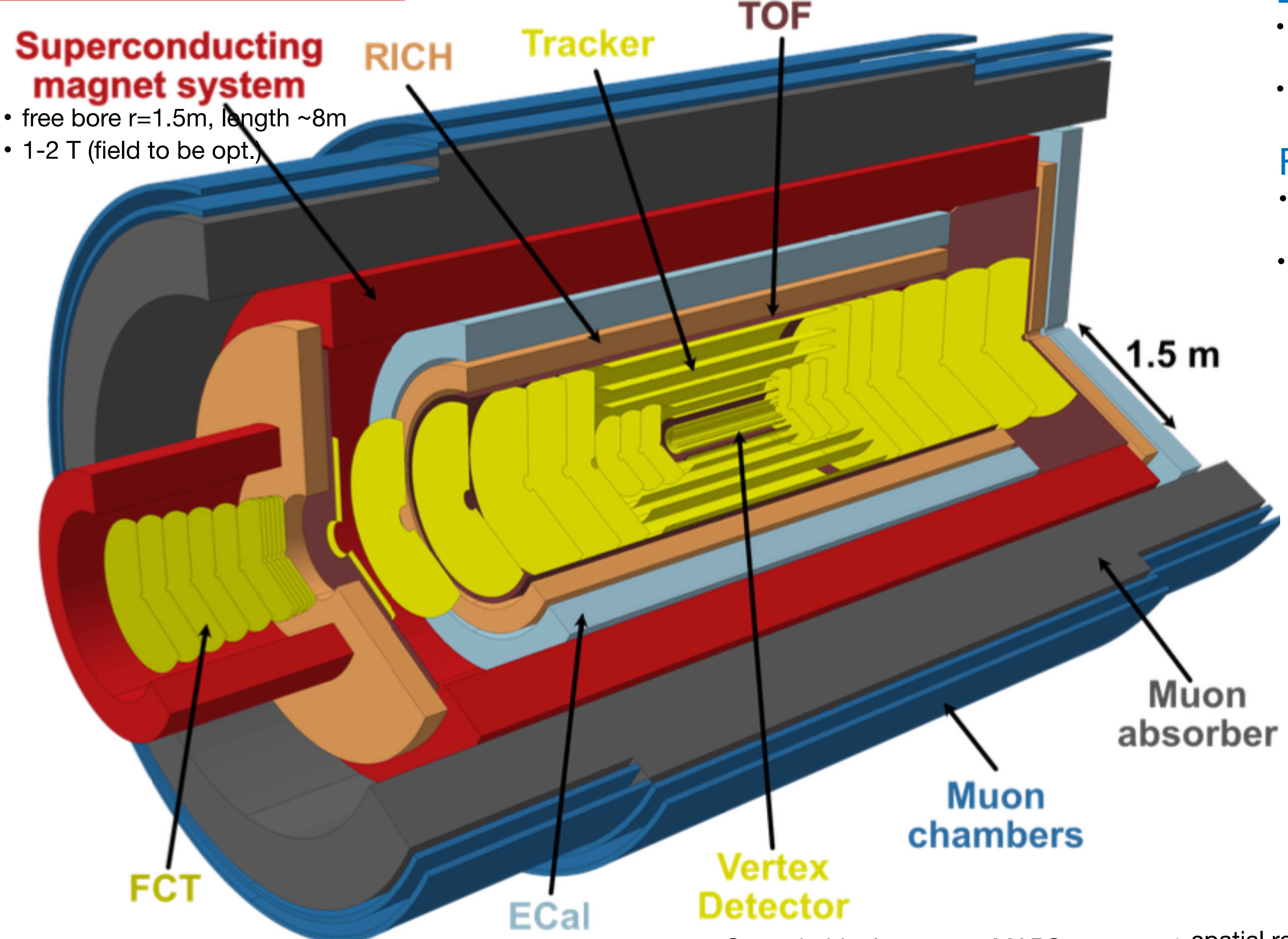

Muon chambers

- search spot for muons ~0.1x0.1 ($\eta x\varphi$)
  → ~5x5cm² cell size
- matching demonstrated with 2 layers of muon chambers
  - scintillator bars with SiPM read-out
  - resistive plate chambers

Forward Conversion Tracker

- Detect ultras-oft photons (p_T > 10 MeV/c)
- Thin tracking disks to cover 3<η< 5
  - few ‰ of a radiation length per layer
  - position resolution < 10 μm
- R&D
  - Large area, thin disks
  - Minimisation of material in front of FCT
  - Operational conditions

Vertex Detector

- Curved, thin, large-area MAPS
- 5 mm from the beam center, retractable
- pixel size about 10x10μm²
- spatial resolution: σ_{pos} ≈ 2.5μm
- material budget ≈ 0.1% of X_0 per layer

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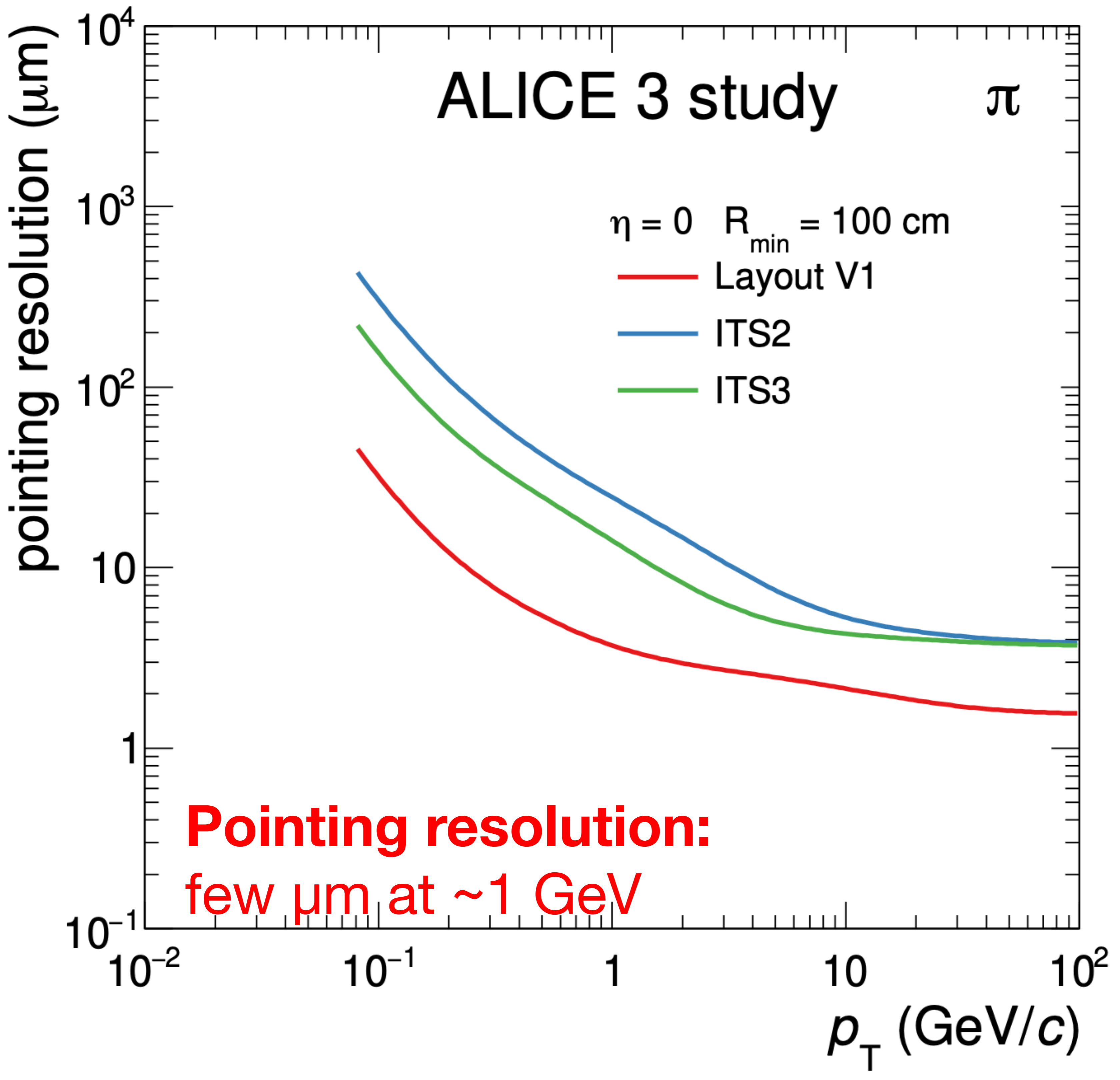

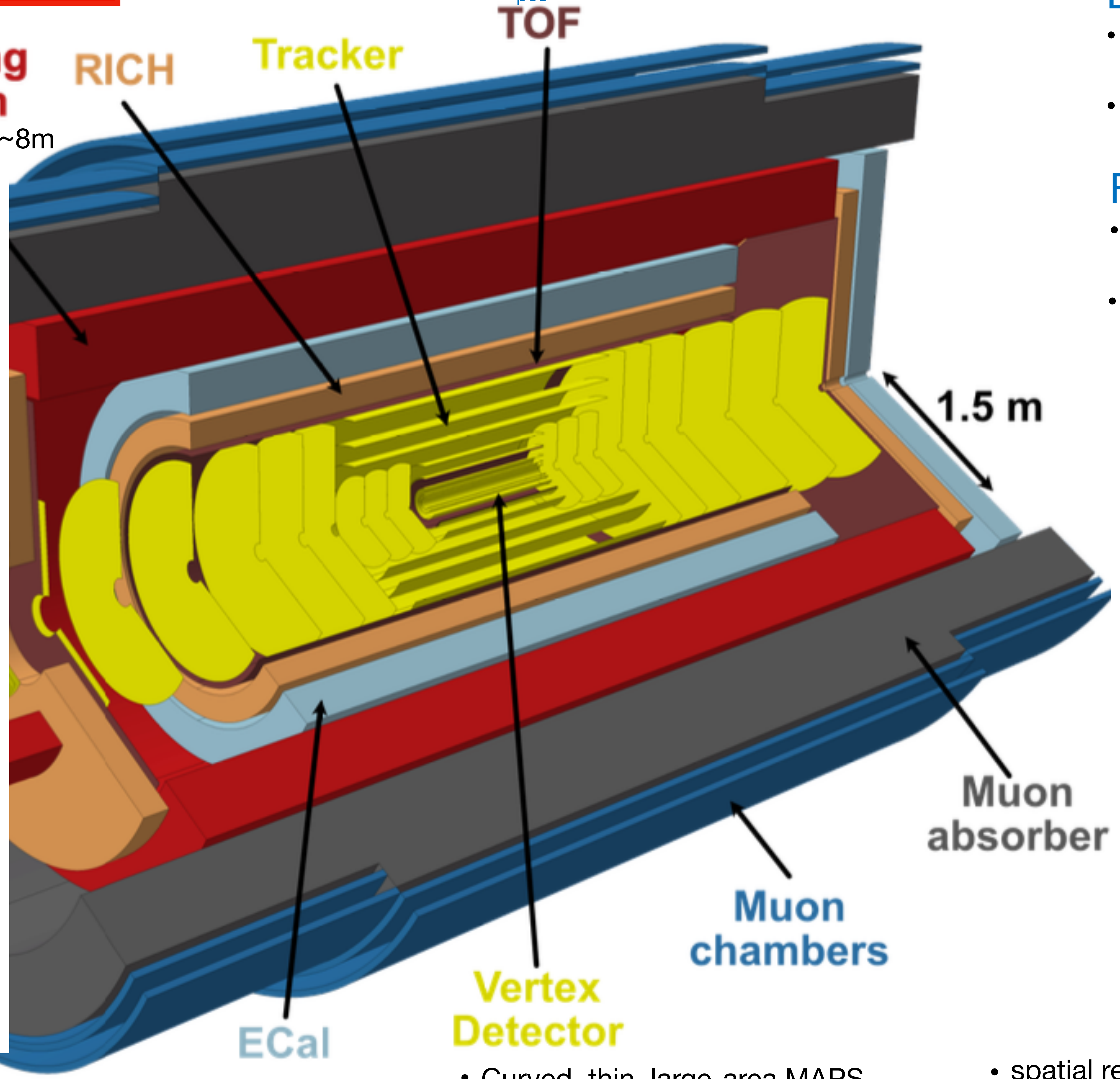

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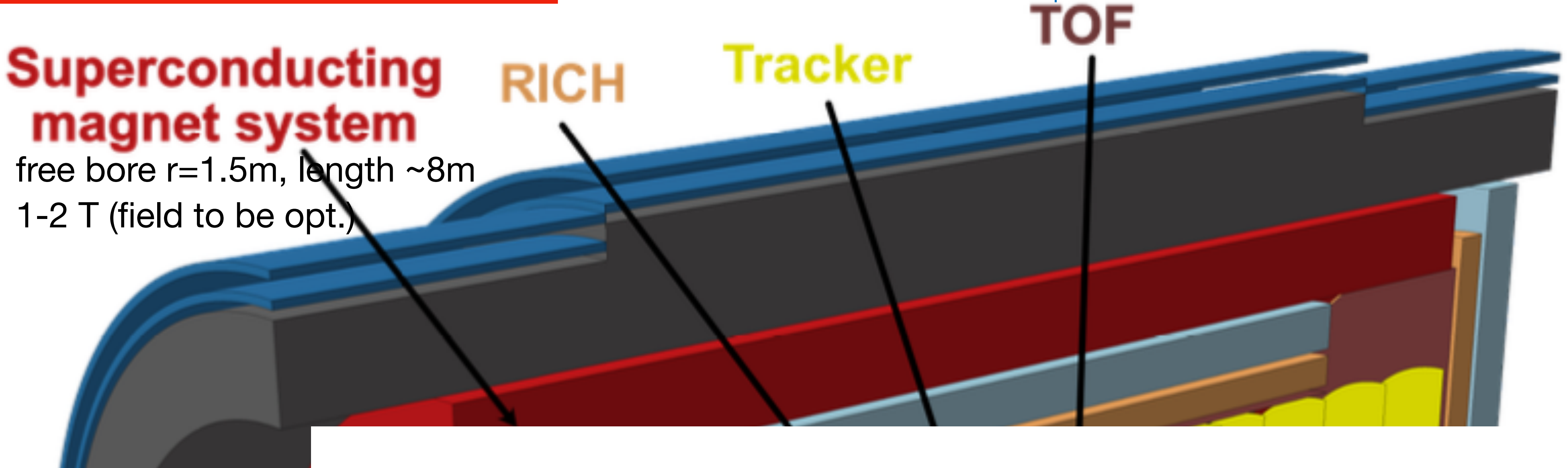

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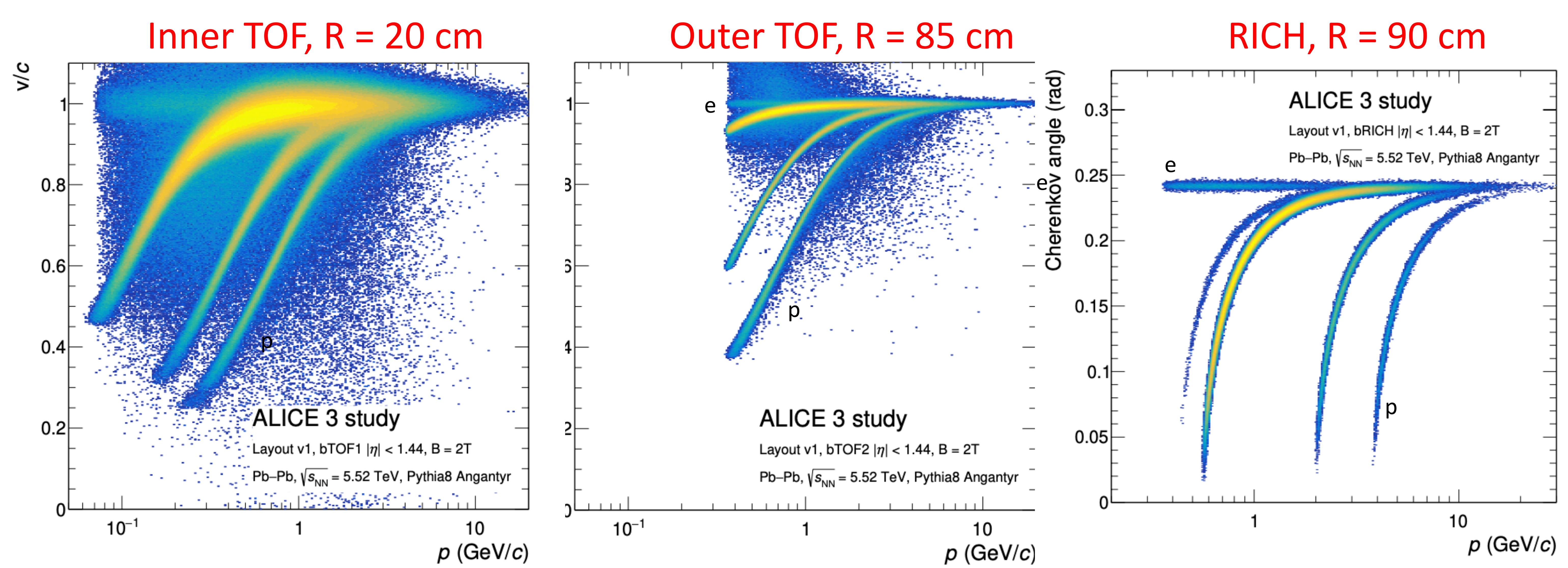
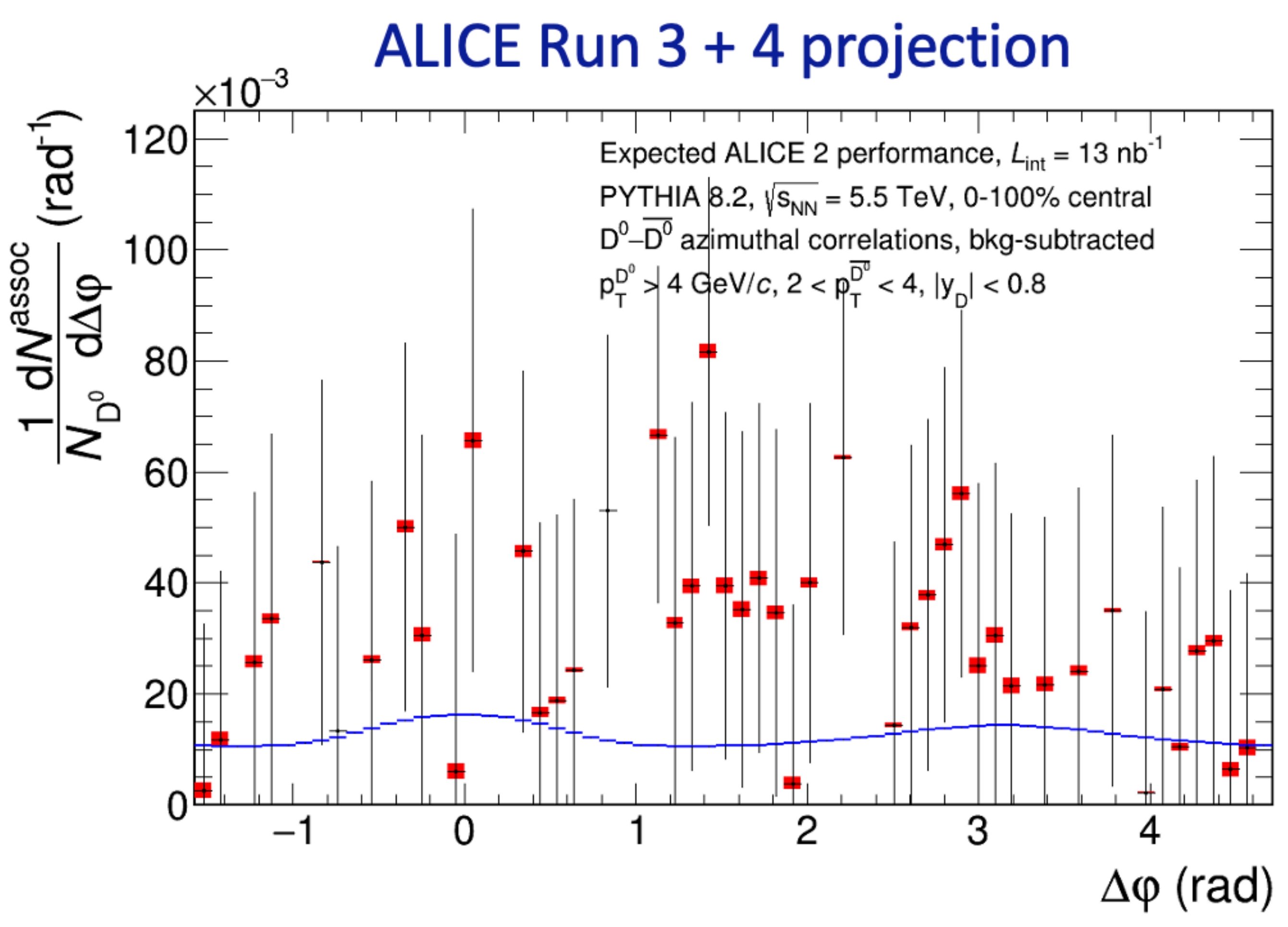
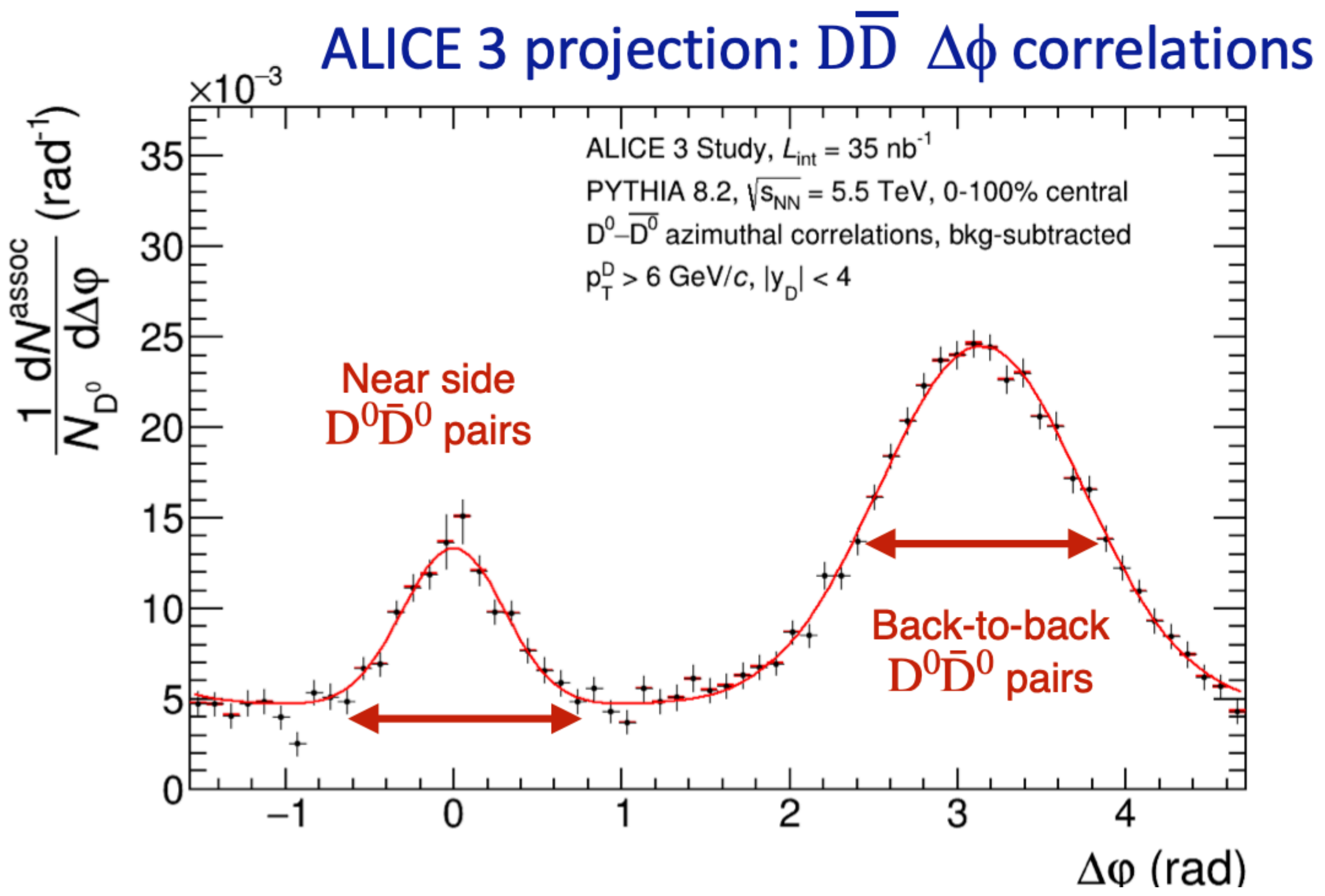


e, π, K, p separation with **TOF + RICH** detectors, with specifications σ_t = 20 ps, σ_θ = 1.5 mrad

Projected performances for key observables

LOI, arXiv:2211.02491

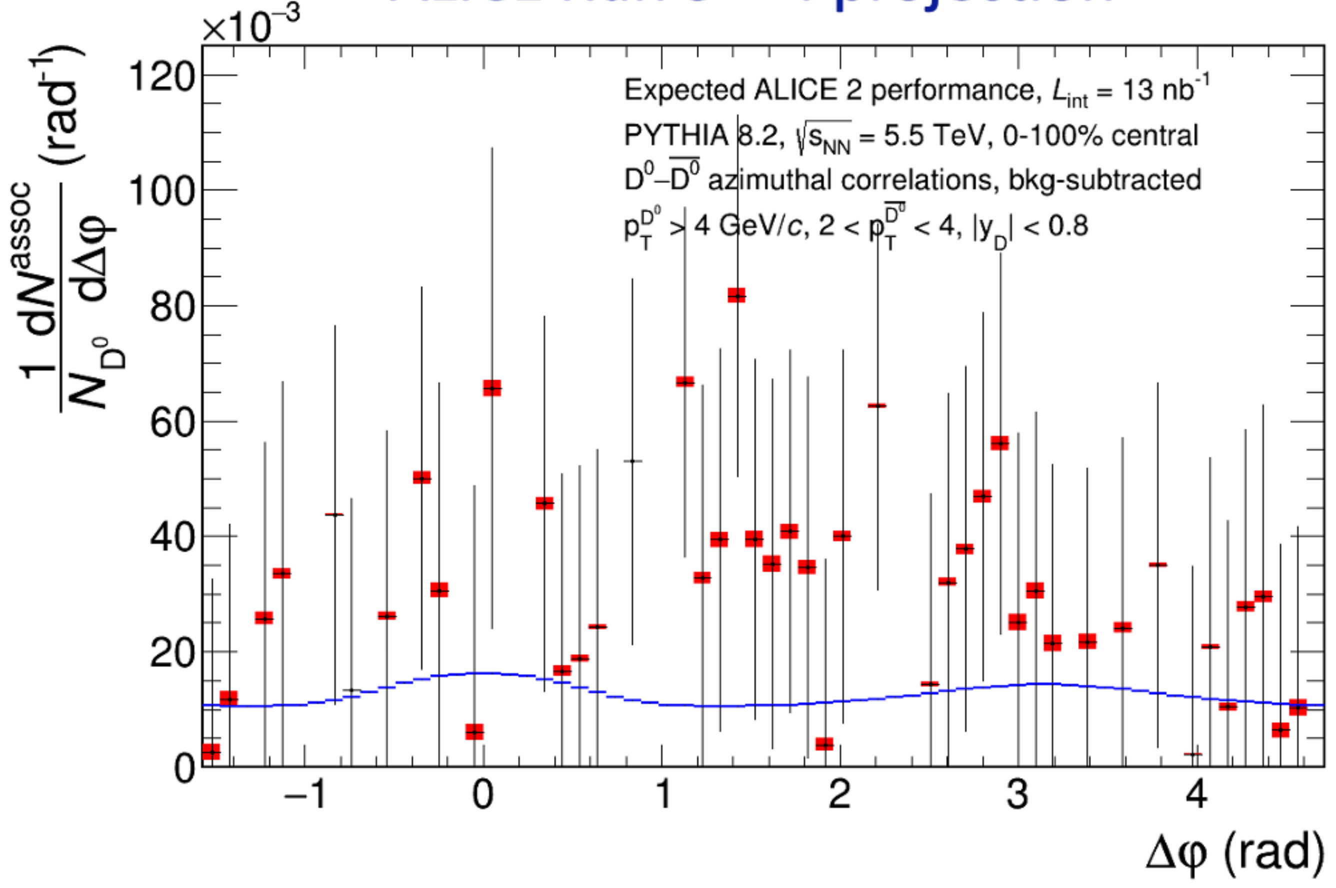




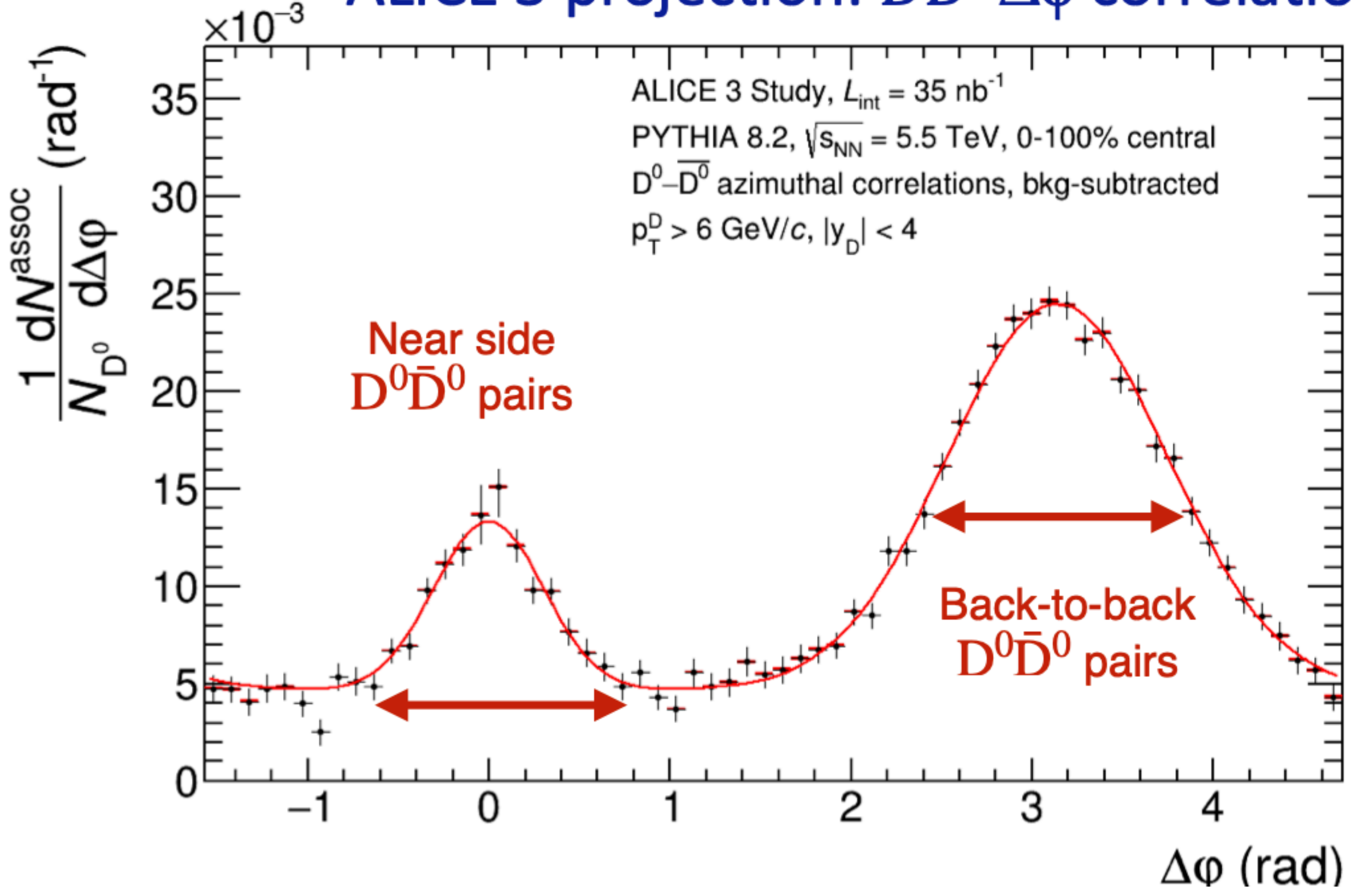
Projected performances for key observables

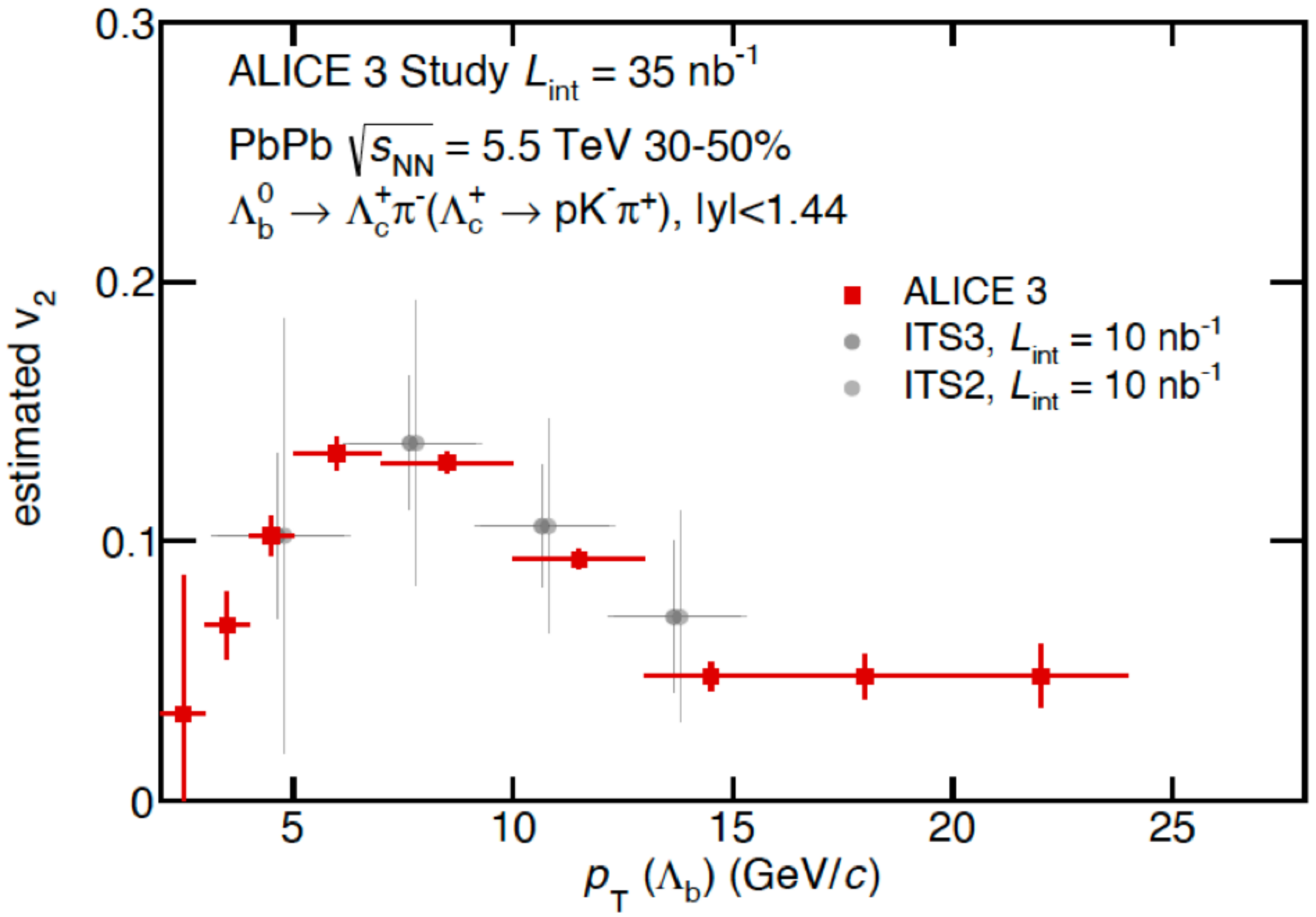
LOI, arXiv:2211.02491

ALICE Run 3 + 4 projection



ALICE 3 projection: $D\overline{D}$ $\Delta\phi$ correlations





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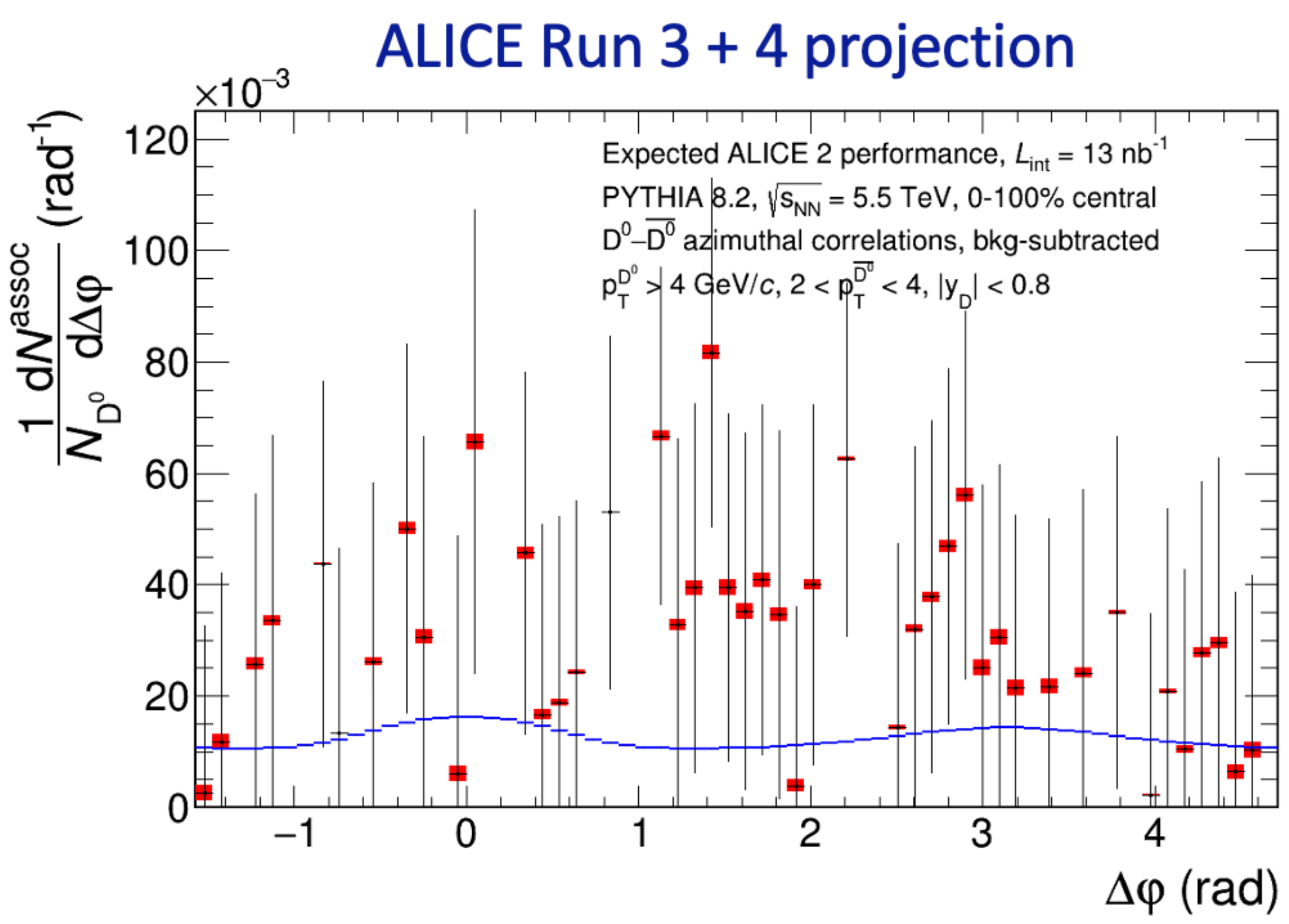
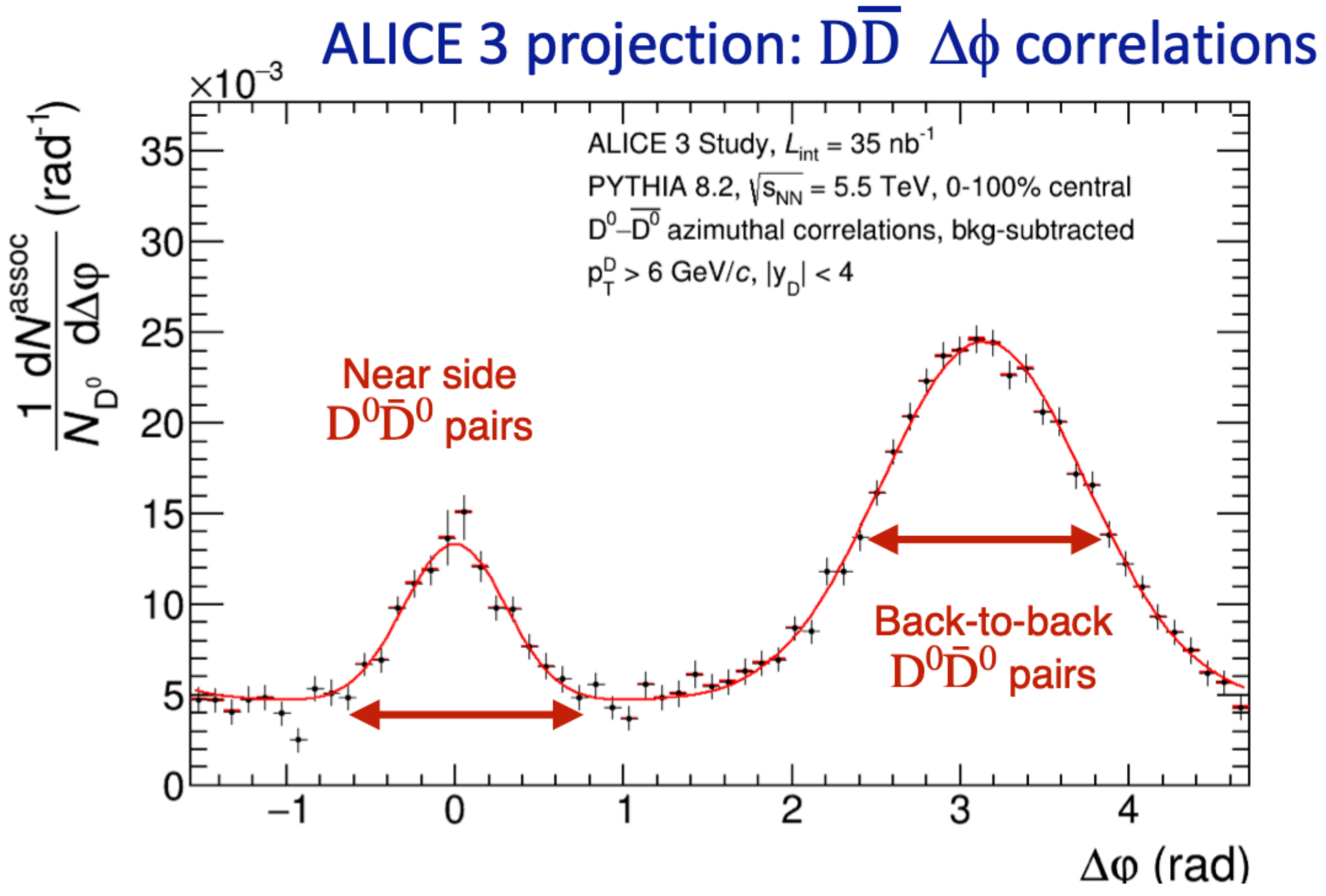
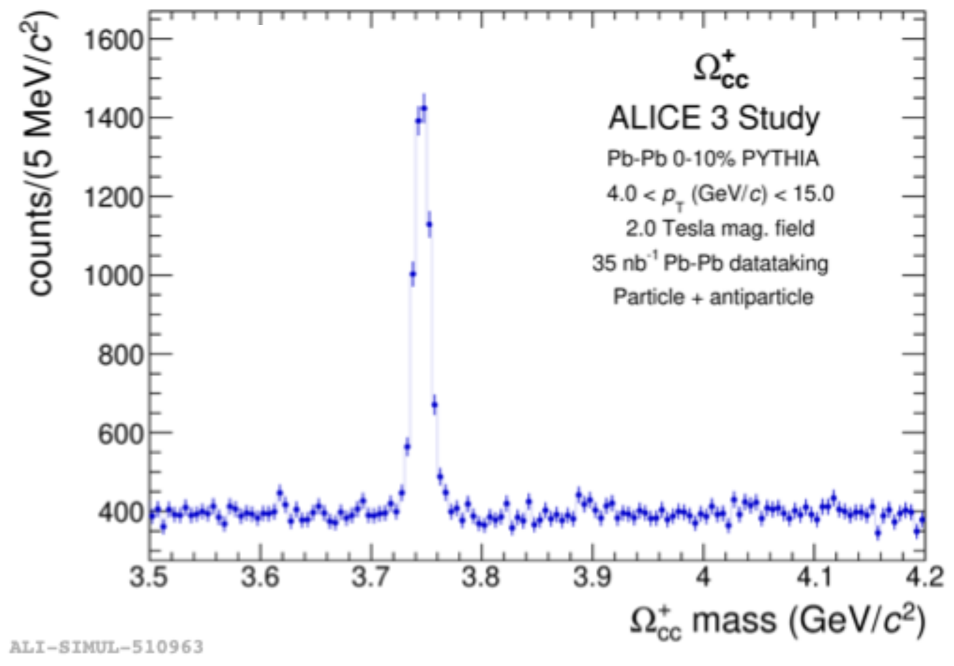
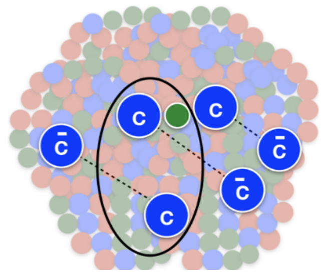
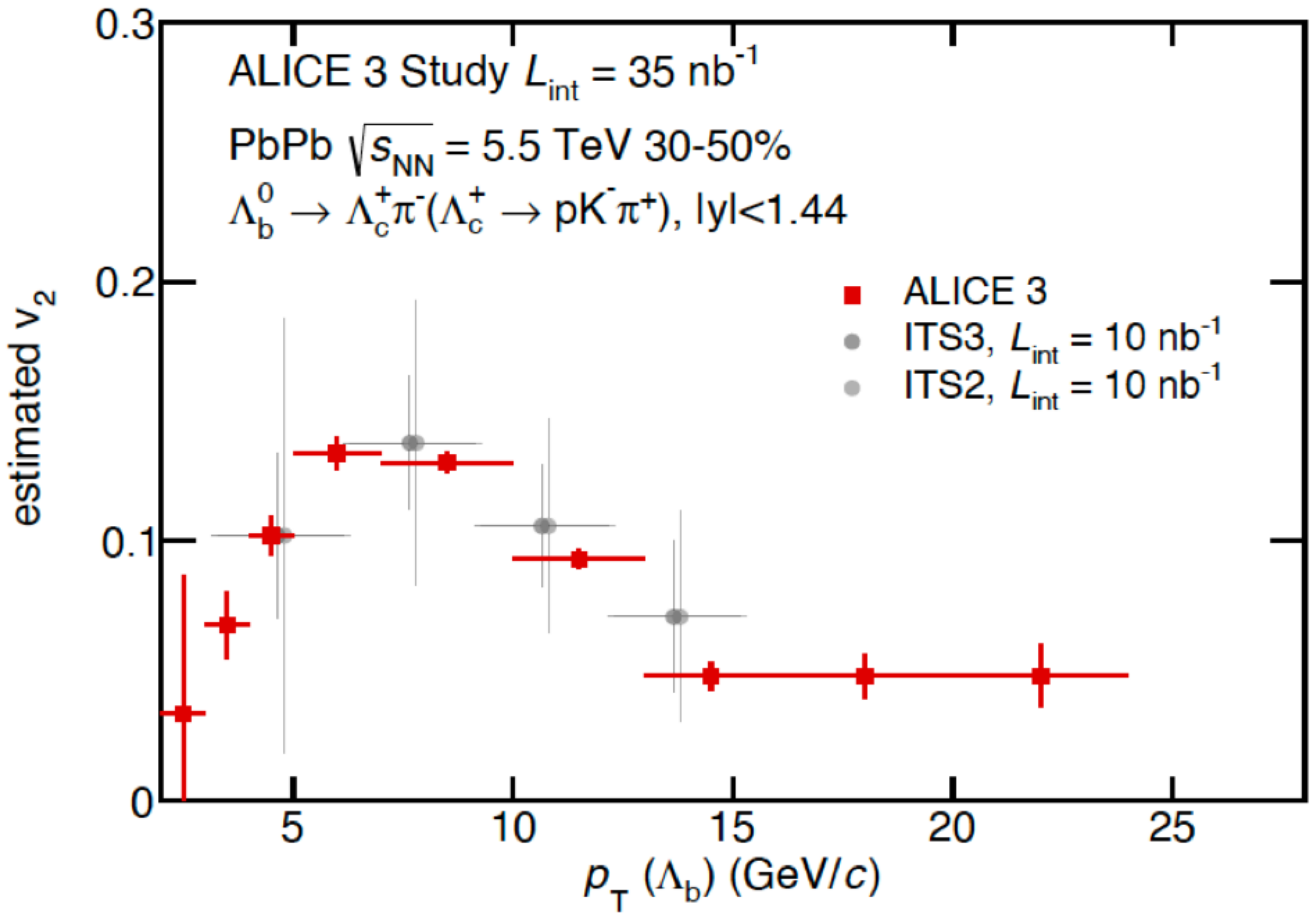
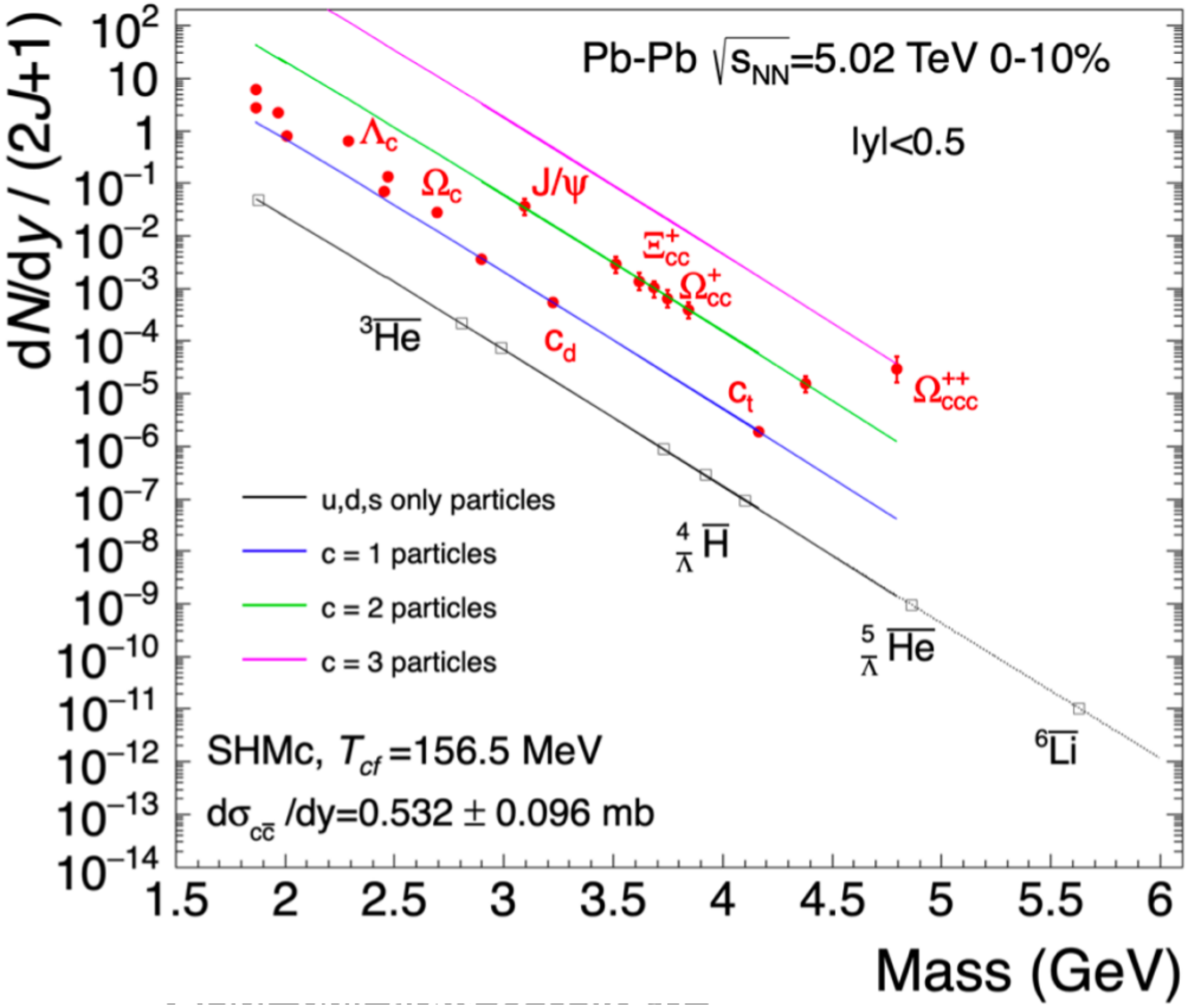












LHCb phase II

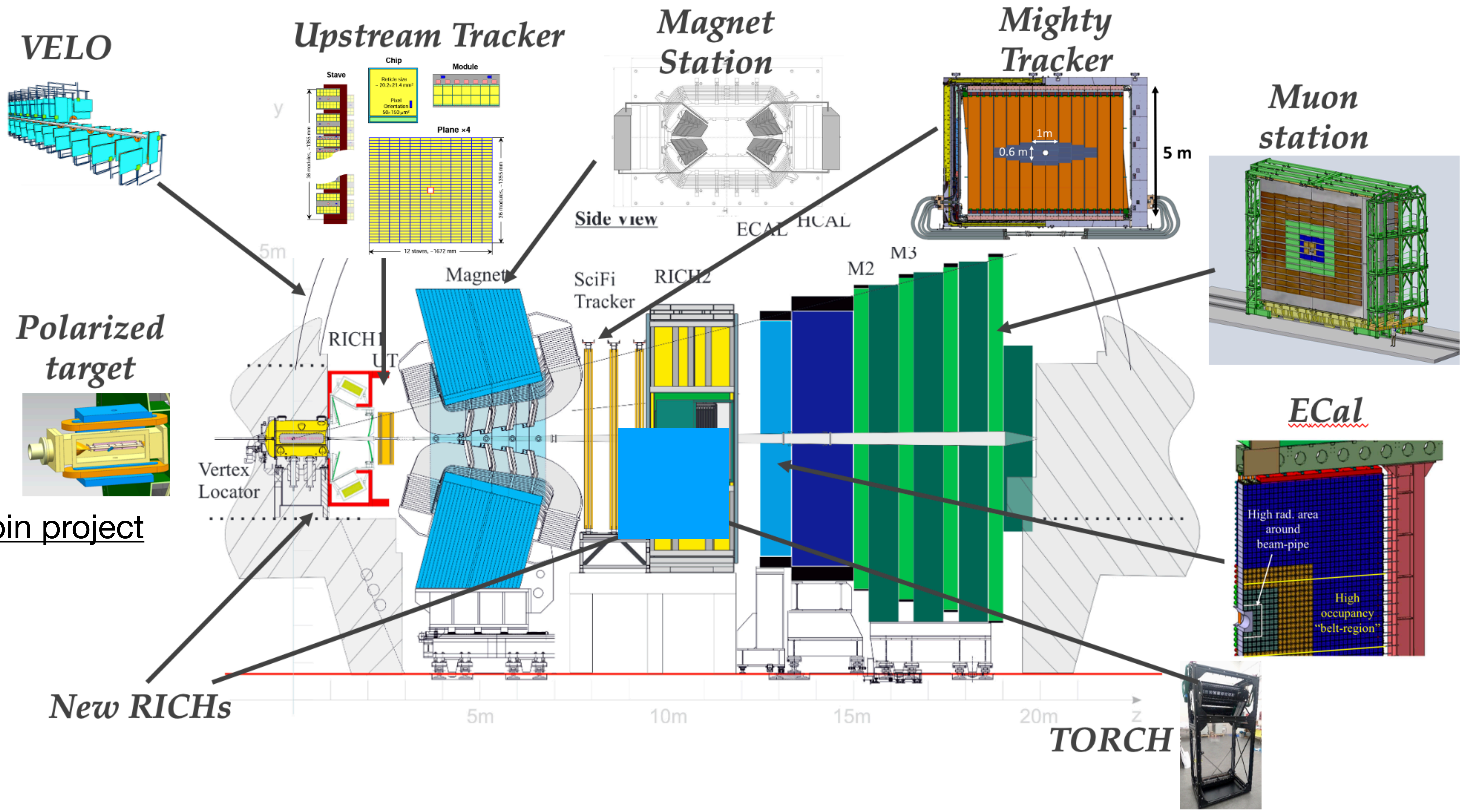
CERN-LHCC-2021-012

Goal is same performance as in Run 3/4, but with pileup of about 40

(consequence for HI, LHCb will be able to access even the most central PbPb events)

Same spectrometer footprint, however with innovative technology for detector and data processing

- granularity
- fast timing (few tens of ps)
- radiation hardness



LHCspin project

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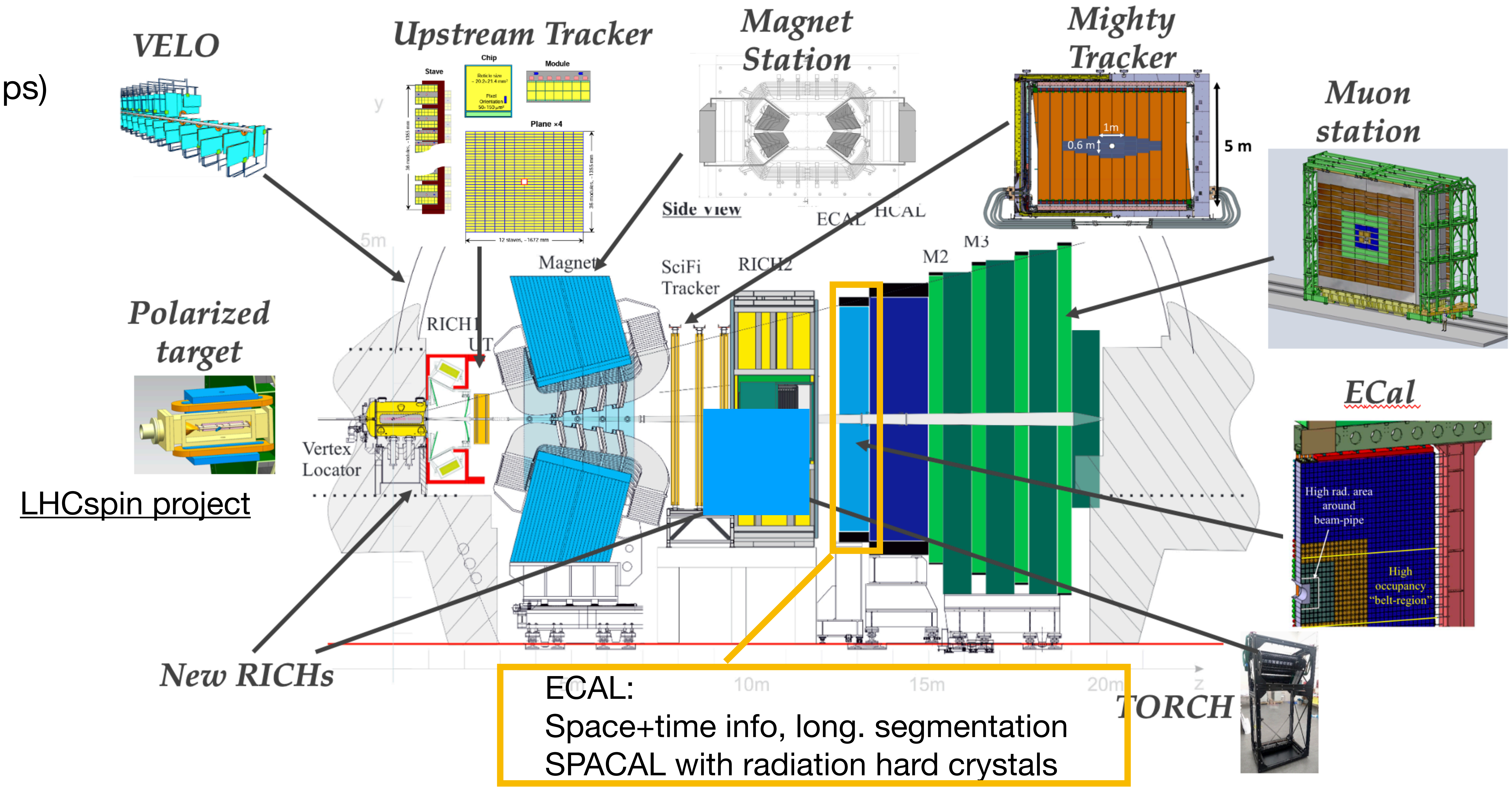

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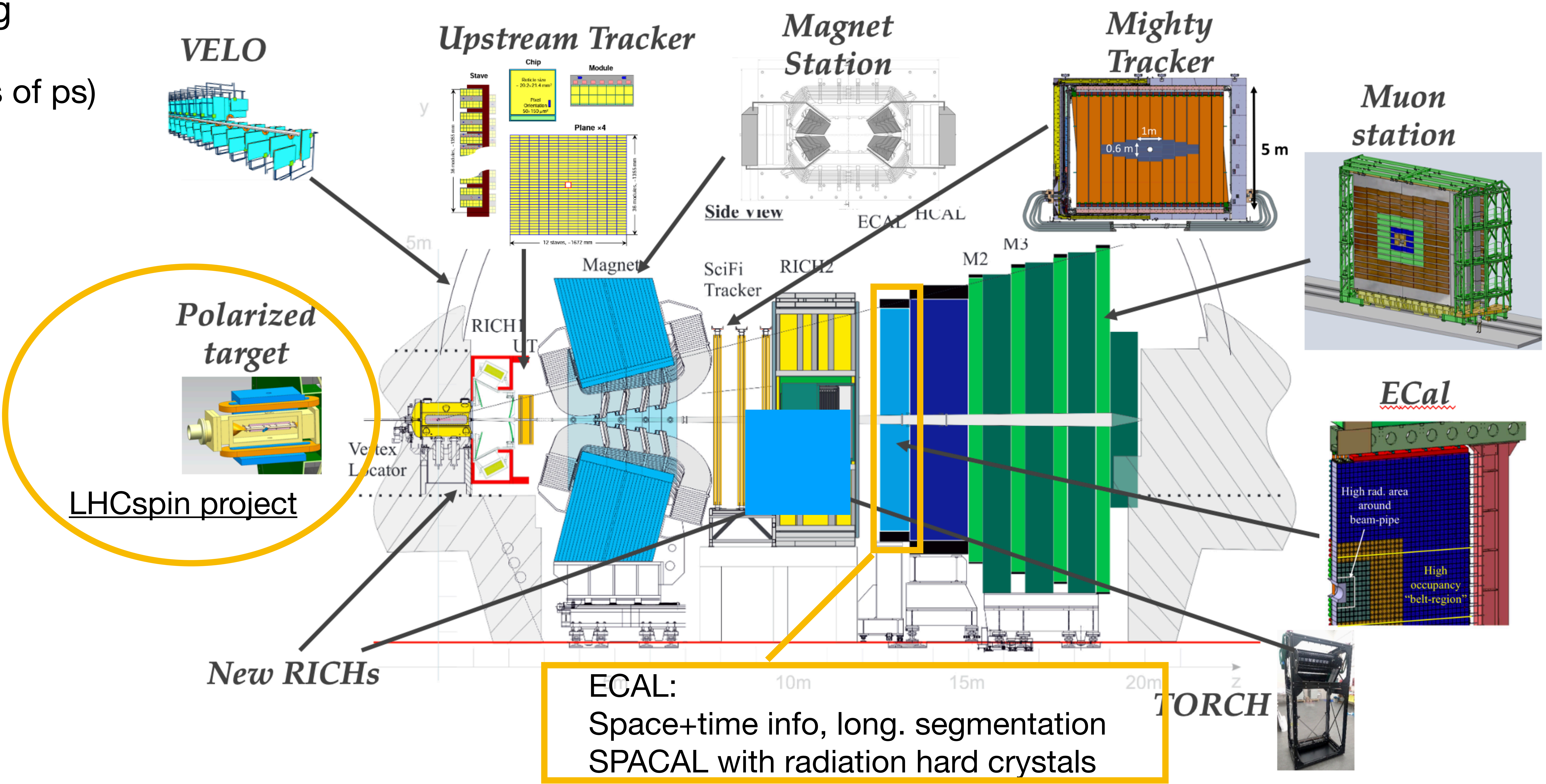
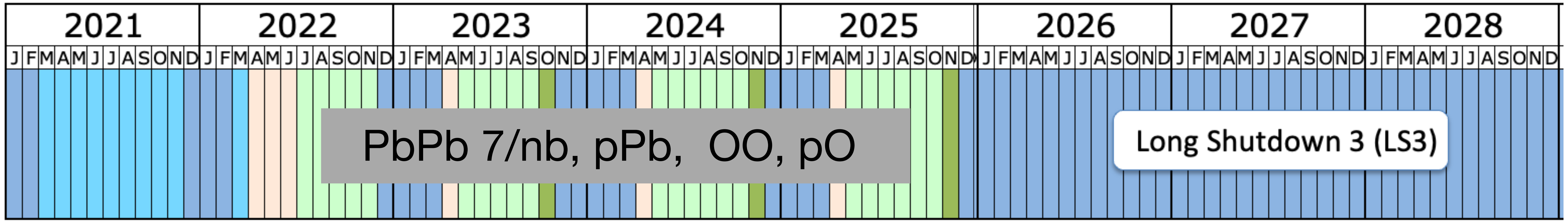


ECAL:
Space+time info, long. segmentation
SPACAL with radiation hard crystals

Ongoing and future LHC program

Run-3



ALICE 2.0

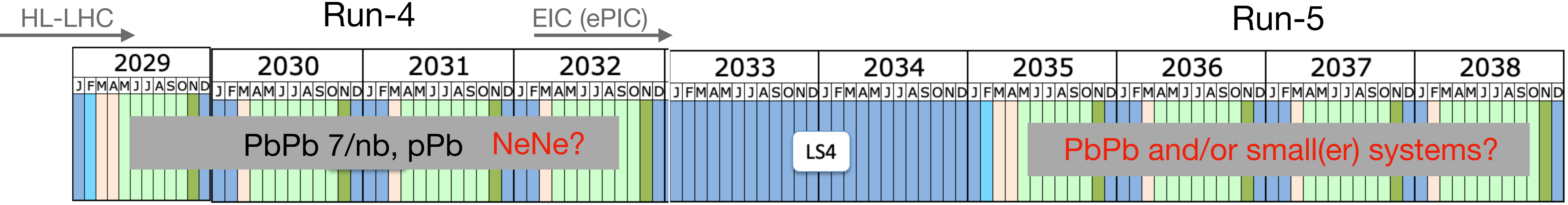
LHCb Phase I

ALICE 2.1 (ITS3, FoCal)

CMS/ATLAS Phase II

Run-4

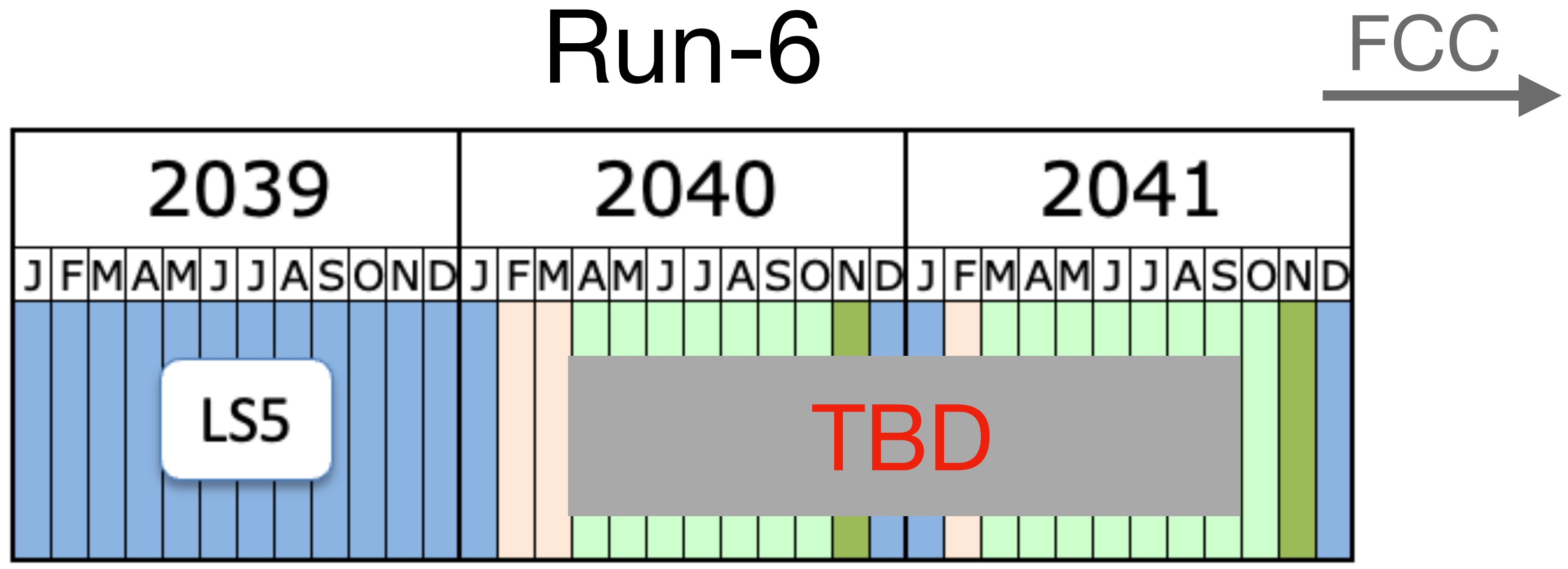
Run-5

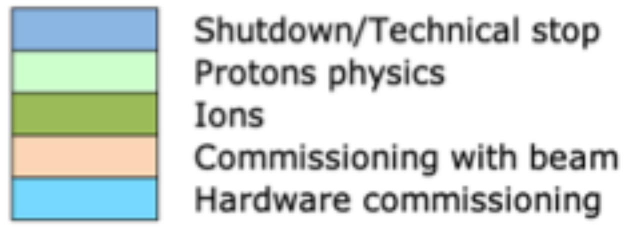


ALICE 3.0

LHCb Phase II

Run-6





Running scenario (Run 5+6)

optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
⟨L_{AA}⟩ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
⟨L_{NN}⟩ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathcal{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathcal{L}_{NN}$ (pb^{-1} / month)	409	550	500	510	512	434	242

$\mathscr{L}_{NN} = A^2 \mathscr{L}_{AA}$

Strength of expected QGP effects
(e.g. charm abundance, jet quenching but also background)

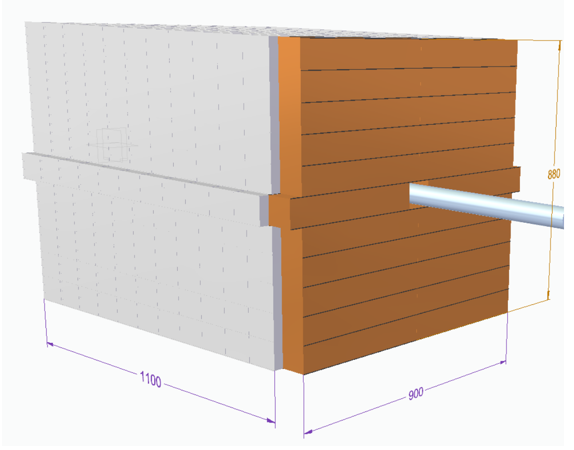
- Baseline approach for HI programme (ALICE-3 perspective)
- Maximise stats for rare probes; identify species best suited for physics program
- 6 running years with 1 month / year with that species
  - For PbPb, in total ~35/nb
- Consider special runs (low B, pp ref, small(er) systems based on insights from Run 3+4

CERN BE (beams department) working group setup to define future ion operation needs based on requests by LHC and North Area experiments and their implications on the ION injector complex

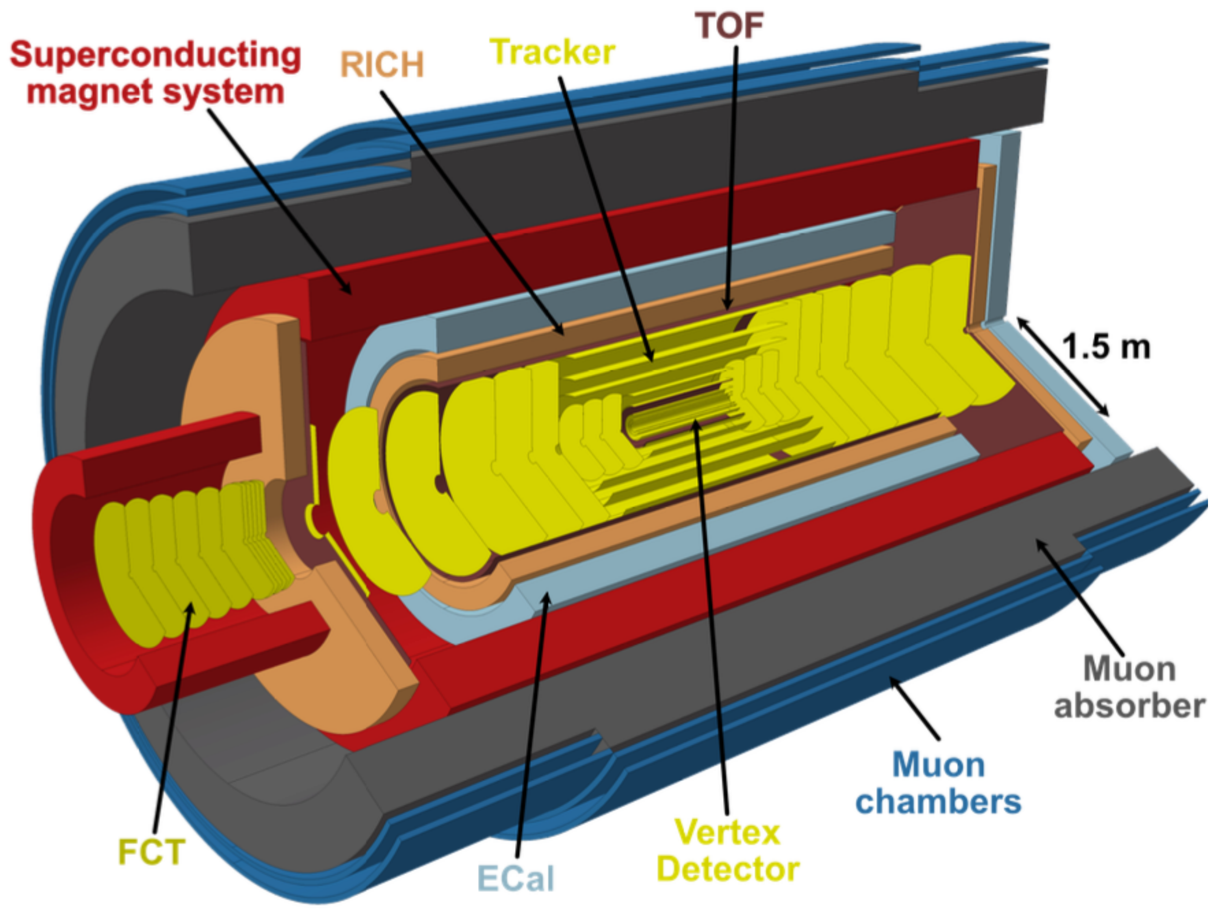
- Consider requesting Ne for Run 4?

(see here for recent talk)

Running scenario (Run 5+6)



Upgraded FoCal
in-front of FCT ?



Would also need various light AA and/or pA runs

Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$1.9\cdot10^{29}$	$5.0\cdot10^{28}$	$2.3\cdot10^{28}$	$1.6\cdot10^{28}$	$3.3\cdot10^{27}$
$3.0\cdot10^{32}$	$3.0\cdot10^{32}$	$3.0\cdot10^{32}$	$2.6\cdot10^{32}$	$1.4\cdot10^{32}$
$3.1\cdot10^{2}$	$8.4\cdot10^{1}$	$3.9\cdot10^{1}$	$2.6\cdot10^{1}$	$5.6\cdot10^{0}$
500	510	512	434	242

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g. charm abundance, jet quenching but also background)

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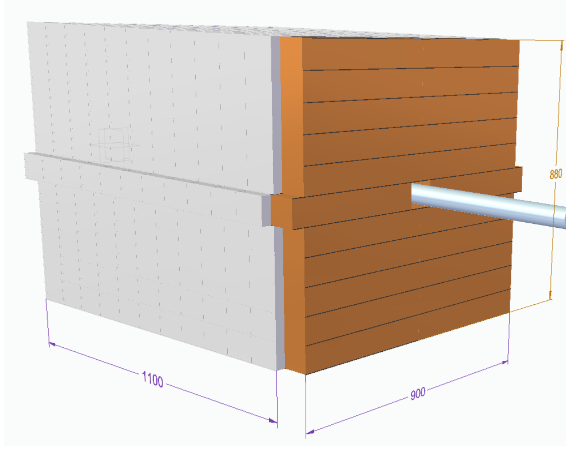

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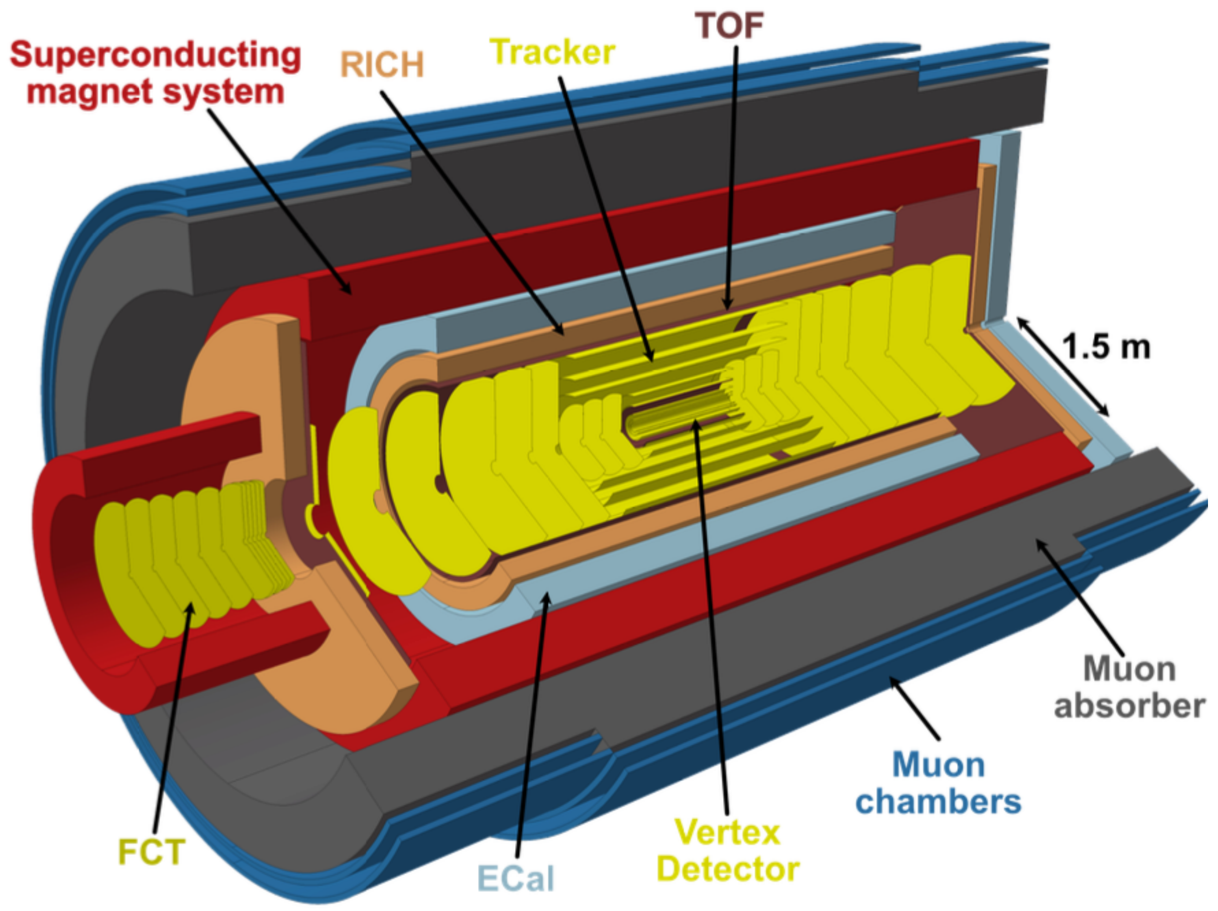
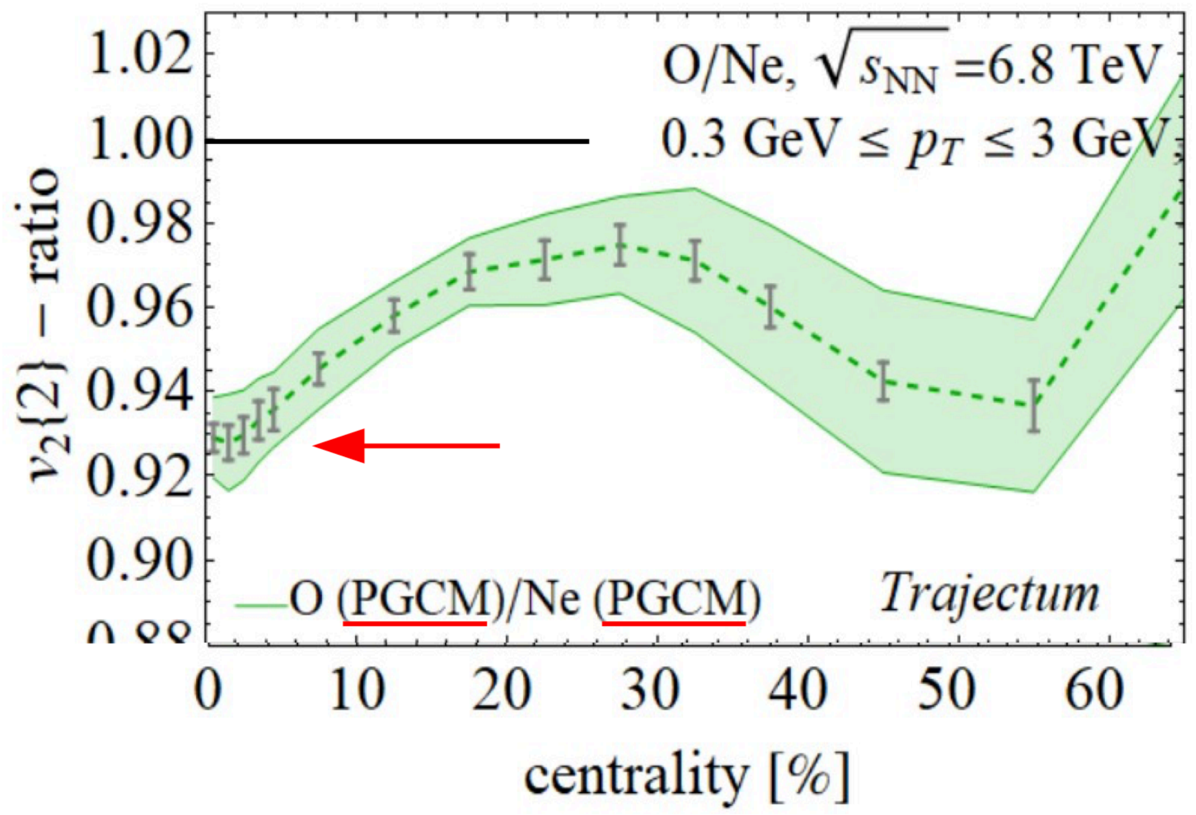


Would also need various light AA and/or pA runs

A quantitative prediction. (G.Giacalone, Wed morning)



dN / dy ~ 100

$$\frac{v_2\,[\mathrm{O+O}]}{v_2\,[\mathrm{Ne+Ne}]} = 0.93 \pm 0.01$$

[Bally *et al*. in preparation]

Giuliano Giacalone's talk

→ **Uncertainty contains large systematic scan of hydro model parameters.**

→ **Nuclear shapes consistently taken from *ab initio* theory.**

- Baseline approach for HI programme (ALICE-3 perspective)
- Maximise stats for rare probes; identify species best suited for physics program
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  - For PbPb, in total ~35/nb
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- Consider requesting Ne for Run 4?

(see here for recent talk)

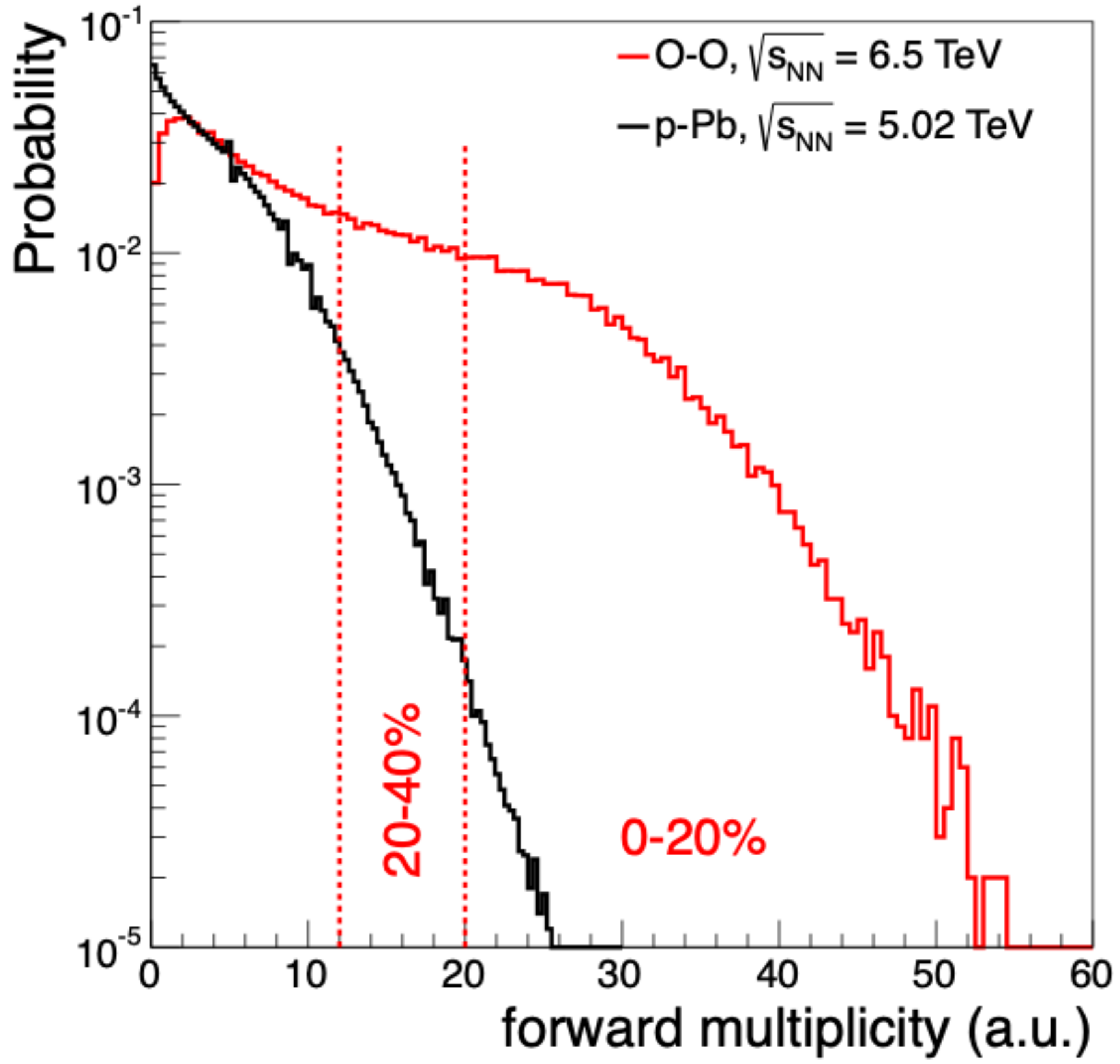
Summary

- We are still only at the beginning of the LHC
- Multiple, ambitious upgrade projects still ahead
- All detectors have and will significantly improve in terms of acceptance, rate and PID capabilities
  - Most-often focus on HF and dileptons
  - For direct photons at forward rapidity, FoCal in Run 4, LHCb ECAL in Run 5
- LHCb specialises on forward rapidity
  - SMOG2 system since Run 3: fixed target at roughly RHIC energies
  - LHCspin: Polarized gas target in Run 5
- Nuclear community needs to engage to define the run plan for Run 5 and 6
  - Depending on how Run 3 progresses, even room to influence Run 4 schedule (Ne?)
  - Make use of LHCb SMOG2 as much as possible
  - Increase “lobbying” to extend yearly HI beam budget by 1 or 2 weeks ?

Additional

Oxygen run in 2024

CERN Yellow Rep.Monogr. 7 (2019) 1159-1410

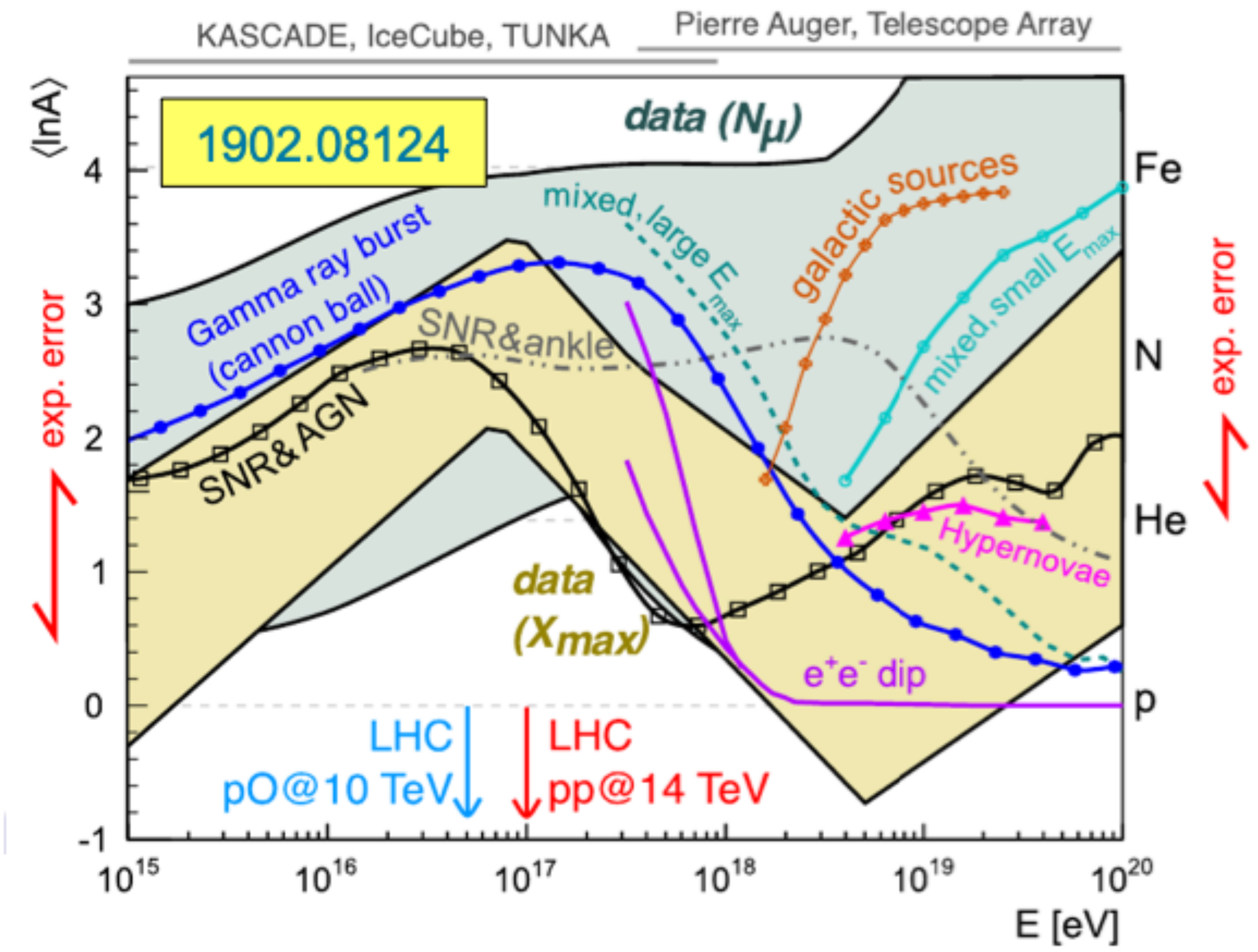


O-O run

- to study emergence of collective effects in small systems
- Luminosity goal: 0.5 nb^{-1} in ALICE/CMS/ATLAS,
- OO energy: same energy per charge as PbPb run to minimize setup time
- No time for dedicated pp reference run, need to extrapolate from existing pp reference runs
- Duration: ~1 day + setup

p-O run

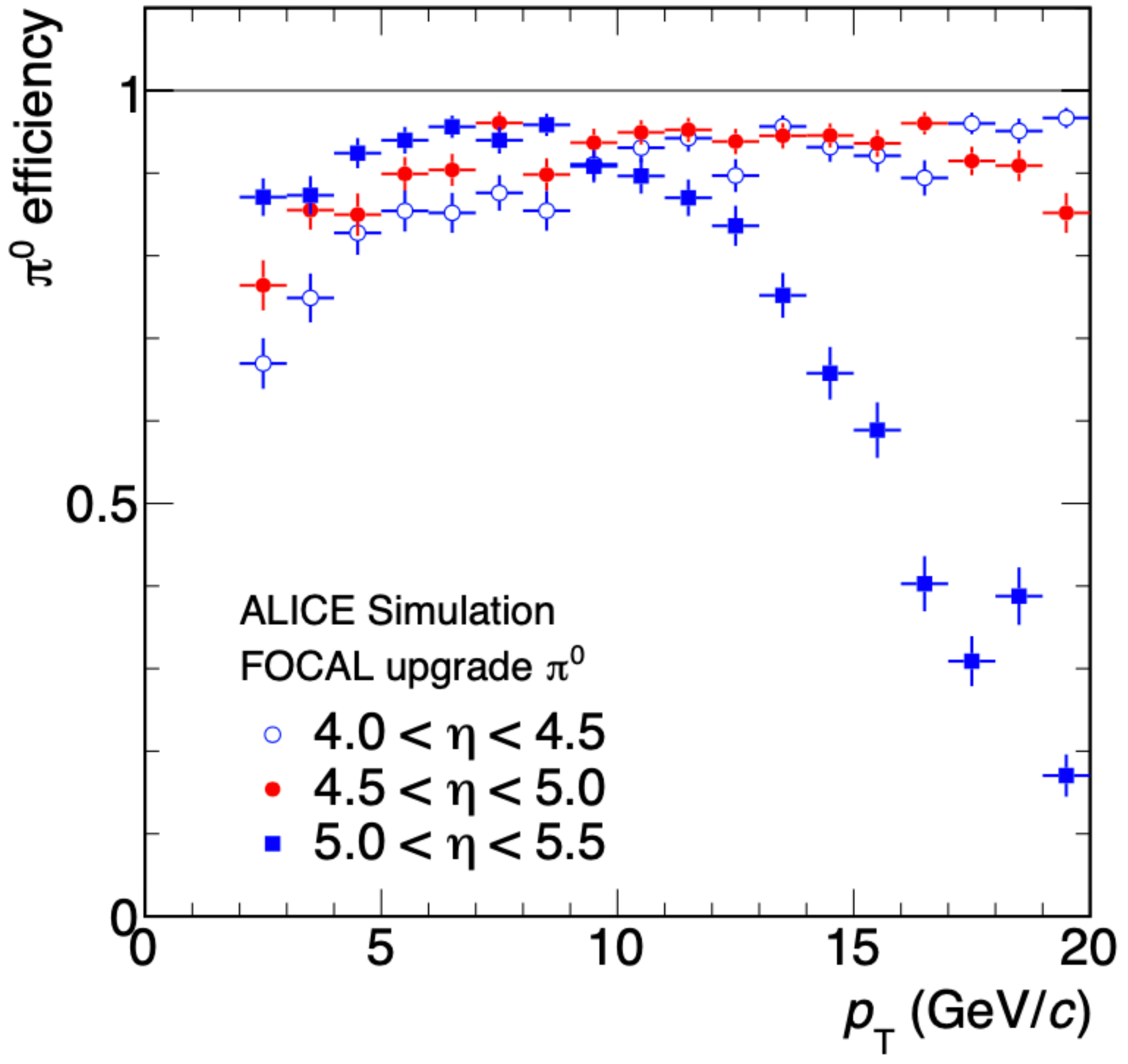
- Long-standing request from cosmic ray community, to improve modeling of high energy air showers
- Luminosity goals: 2 nb^{-1} in LHCb, 1.5 nb^{-1} in LHCf
- pO energy: 6.8 TeV/charge if possible, protons need to be in beam 1
- Duration: few days + setup



Full oxygen run should take ~1 week,
foreseen for either July or September 2024

FoCal: Key ingredients for isolated photon measurement

π^0 reconstruction efficiency



Main ingredients for direct photon identification

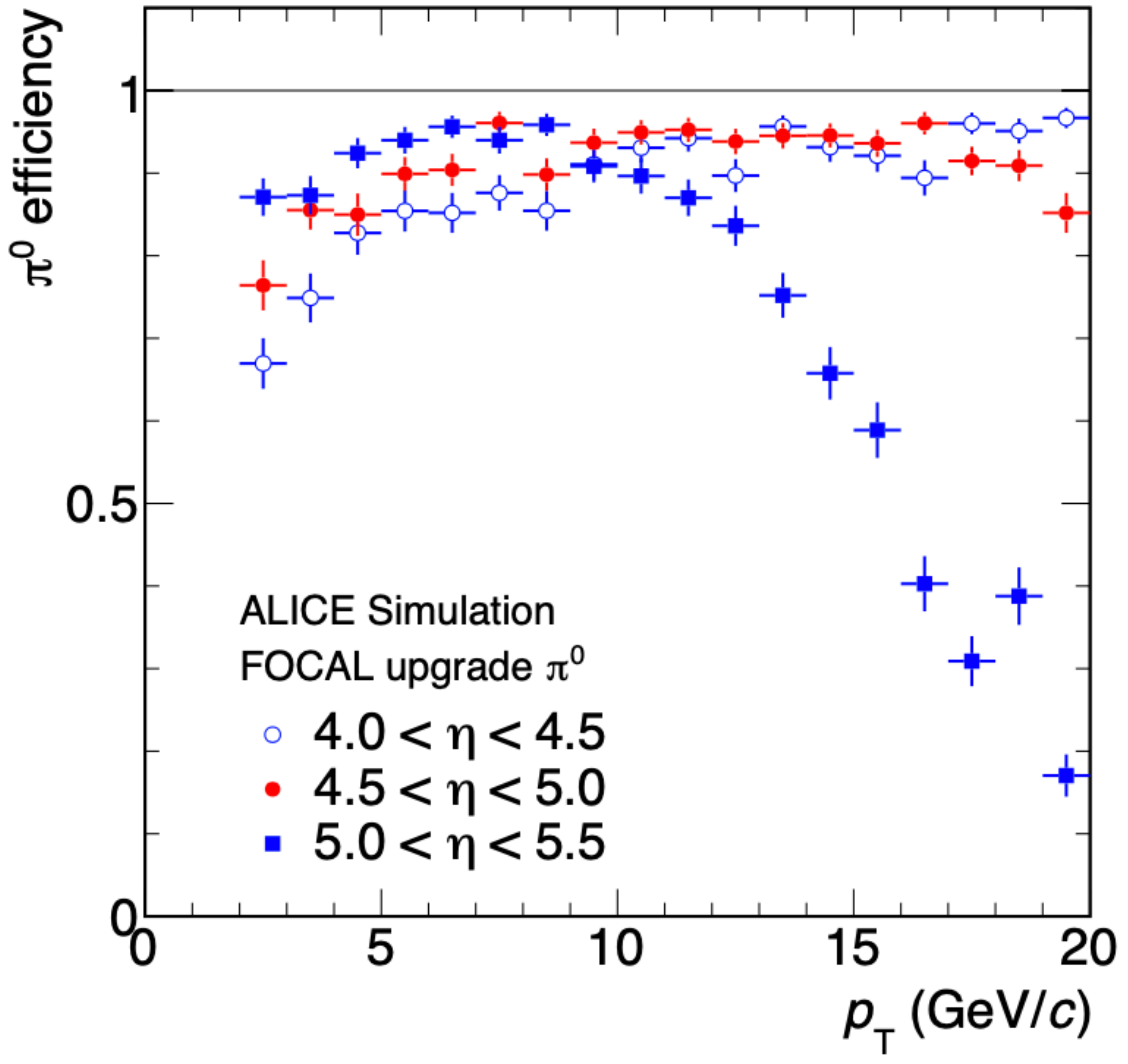
- π^0 reconstruction efficiency: measure background
- Isolation cut (EmCal + HCal)
- Rejection of decays by invariant mass reconstruction

CERN-LHCC-2020-009

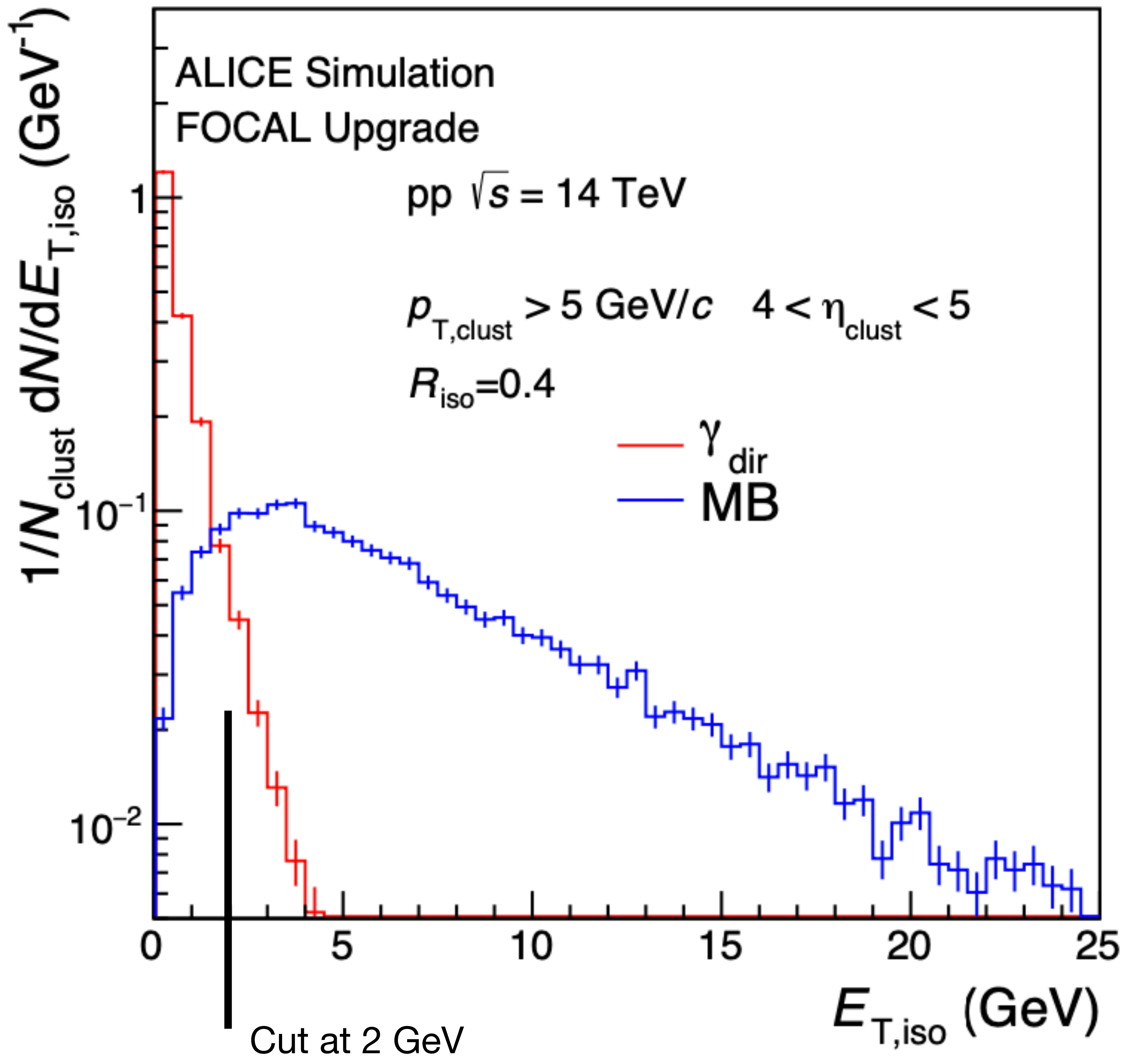
Improvement in signal fraction by factor ~10 to ~0.1-0.6

FoCal: Key ingredients for isolated photon measurement

π^0 reconstruction efficiency



Isolation energy distribution



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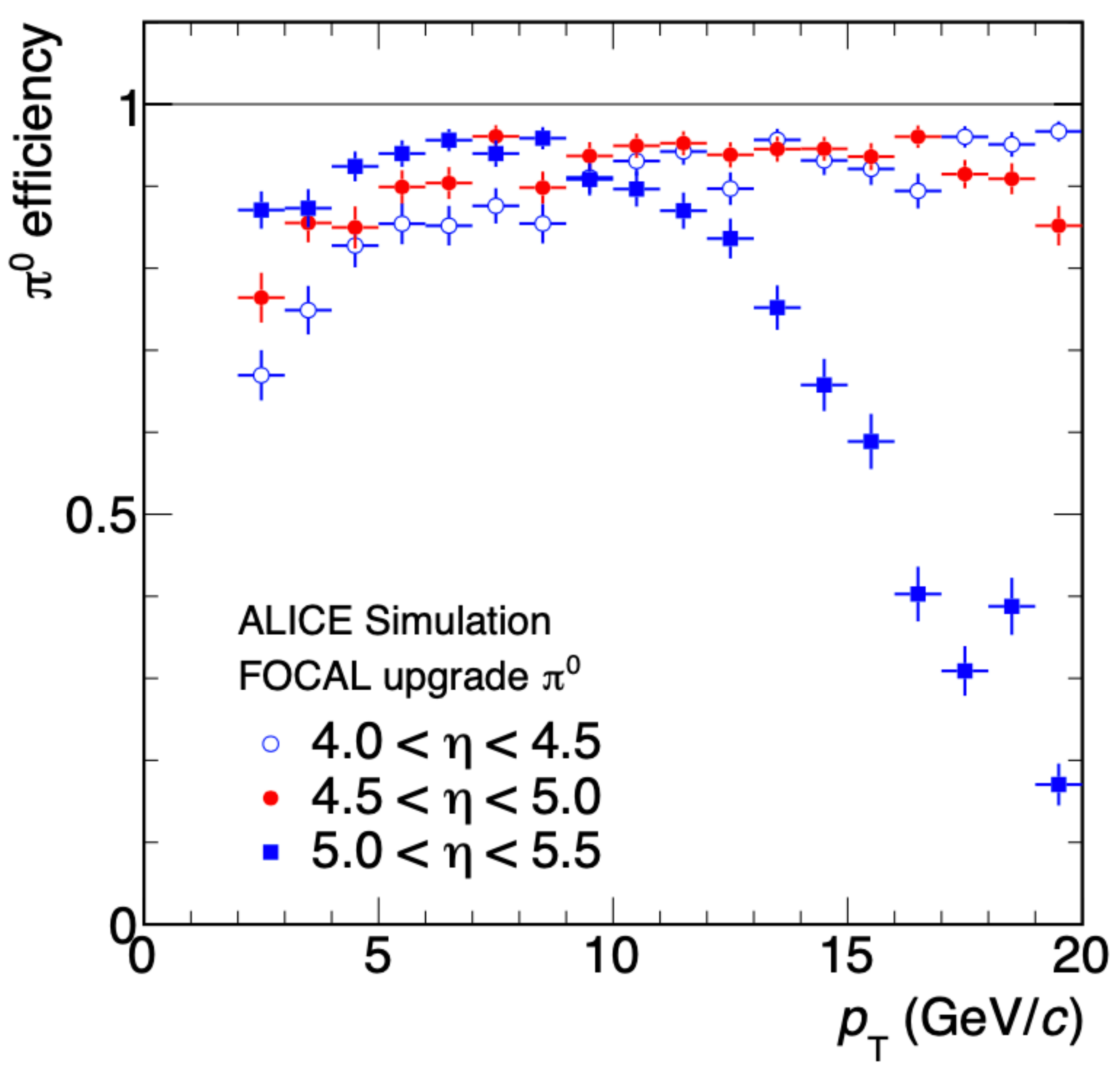
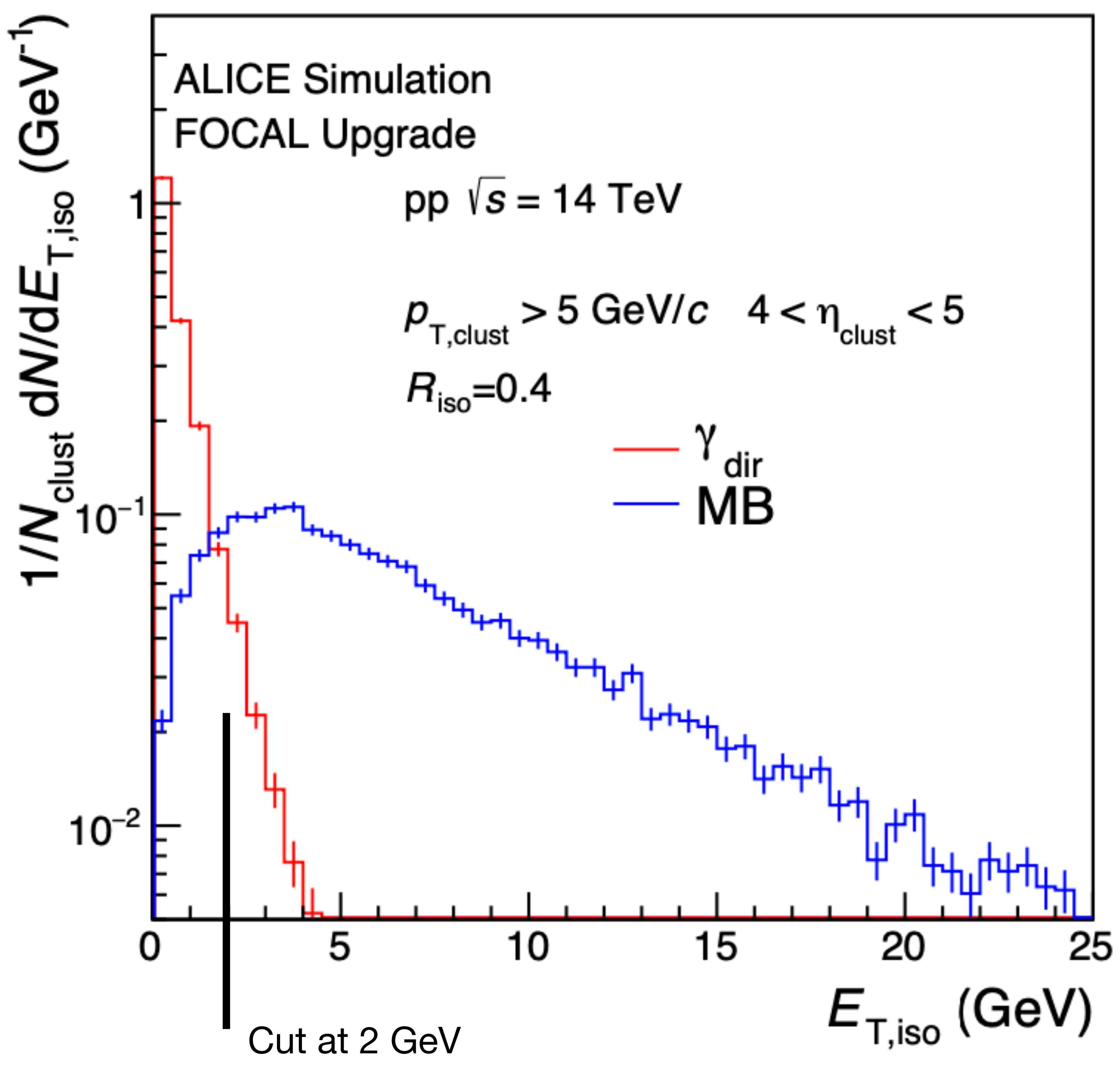
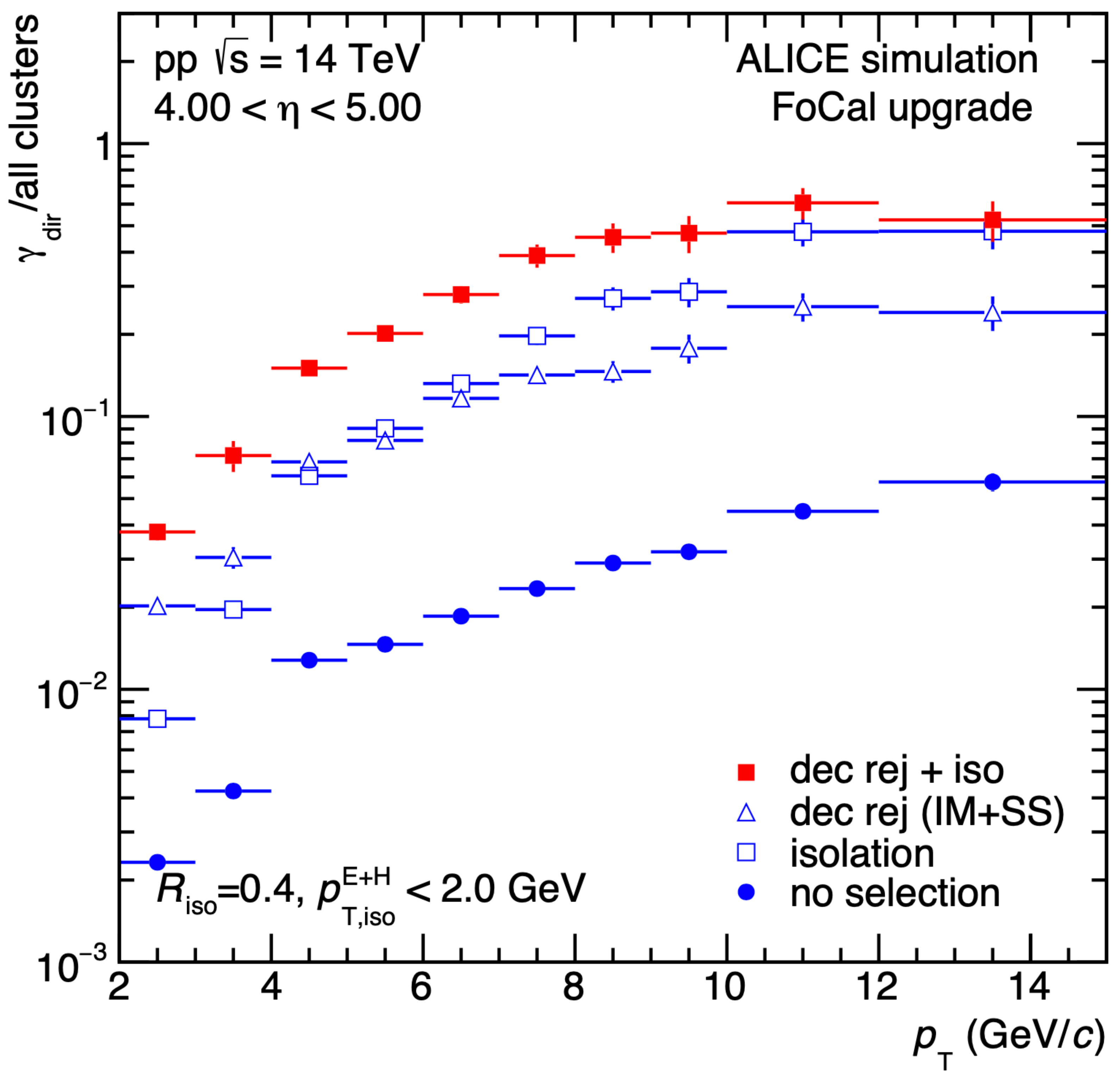


Isolation energy distribution



Direct γ/all cluster ratio



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CERN-LHCC-2020-009

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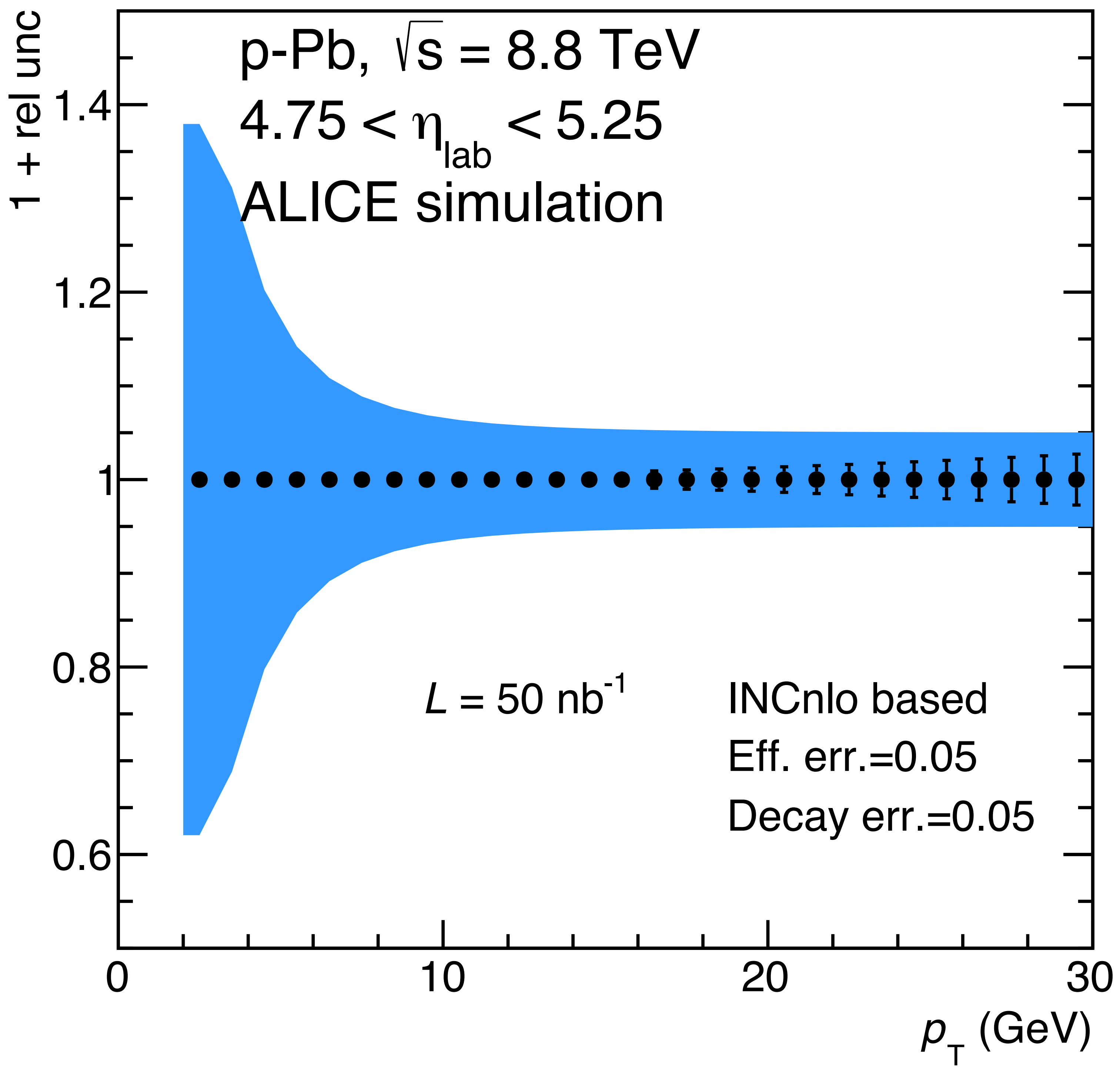
FoCal: Expected performance and impact on nPDF

Relative uncertainties in pPb



- Systematic uncertainty <10% at high p_T
- Below ~10 GeV, uncertainty rises due to remaining background

CERN-LHCC-2020-009

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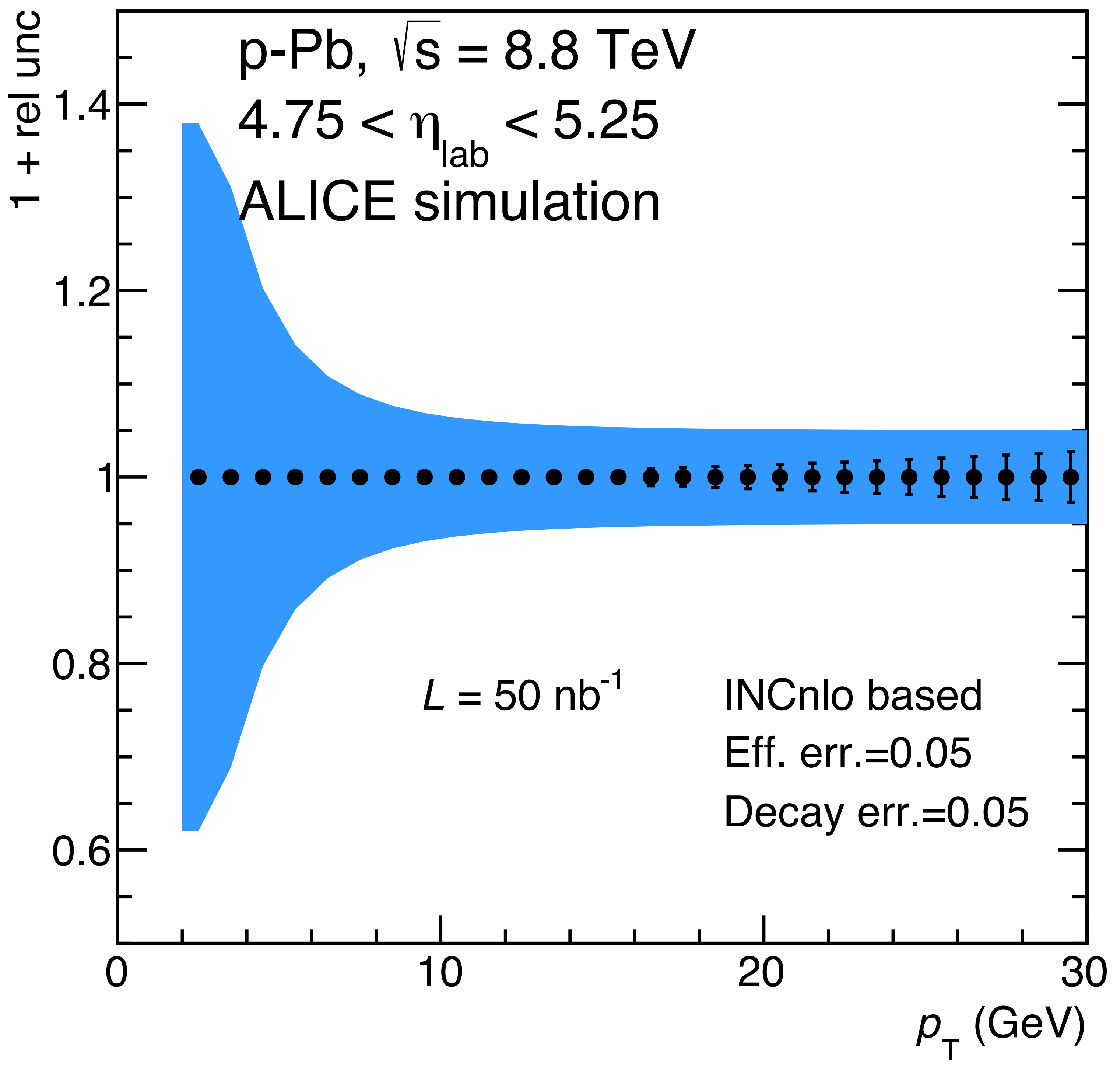

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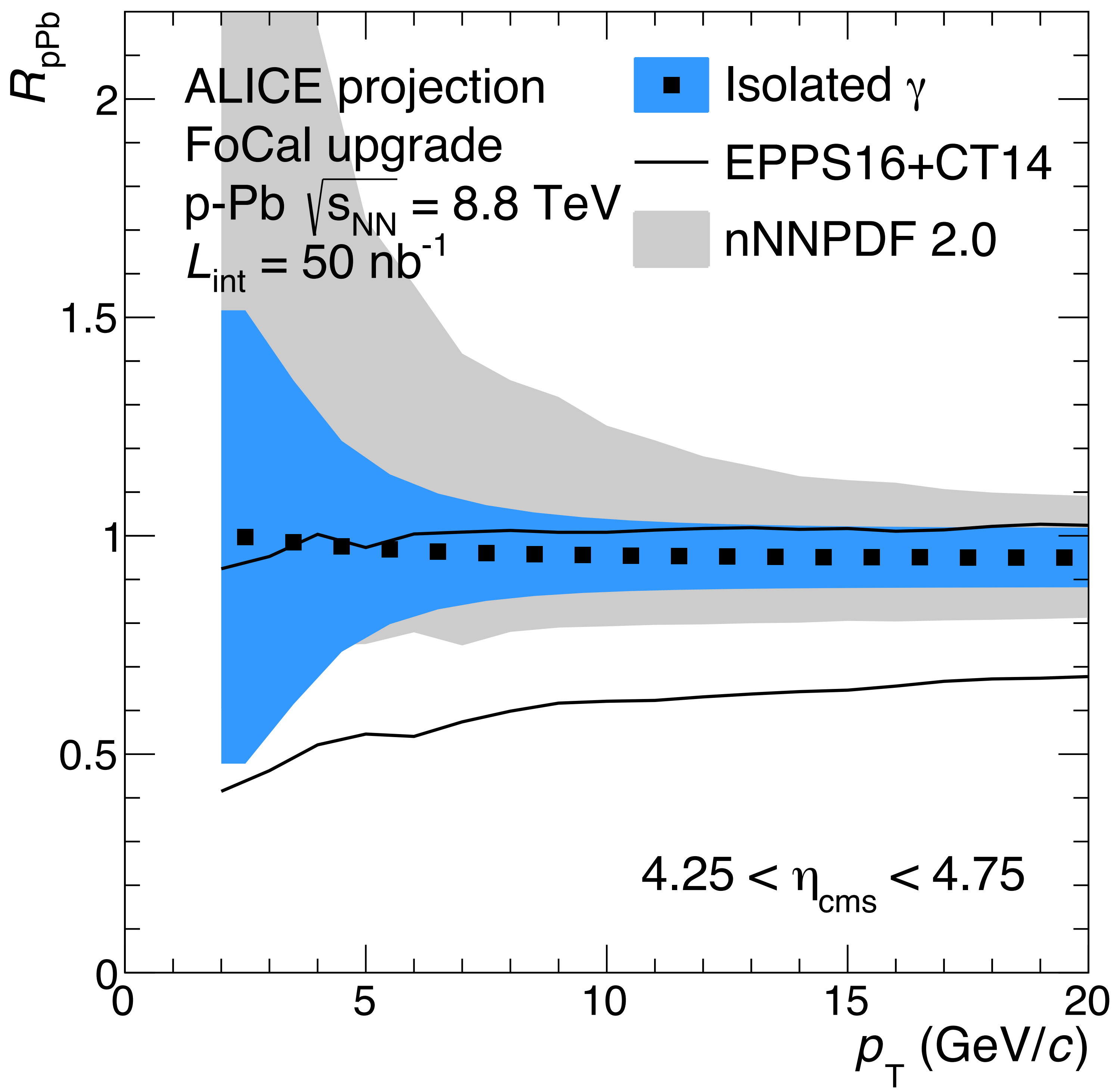
Nuclear modification factor



- Significant improvement (up to factor 2) on EPPS16, nNNDF 2.0 uncertainties
- Compare to e.g. open charm: test factorization/universality

CERN-LHCC-2020-009

FoCal: Expected performance and impact on nPDF

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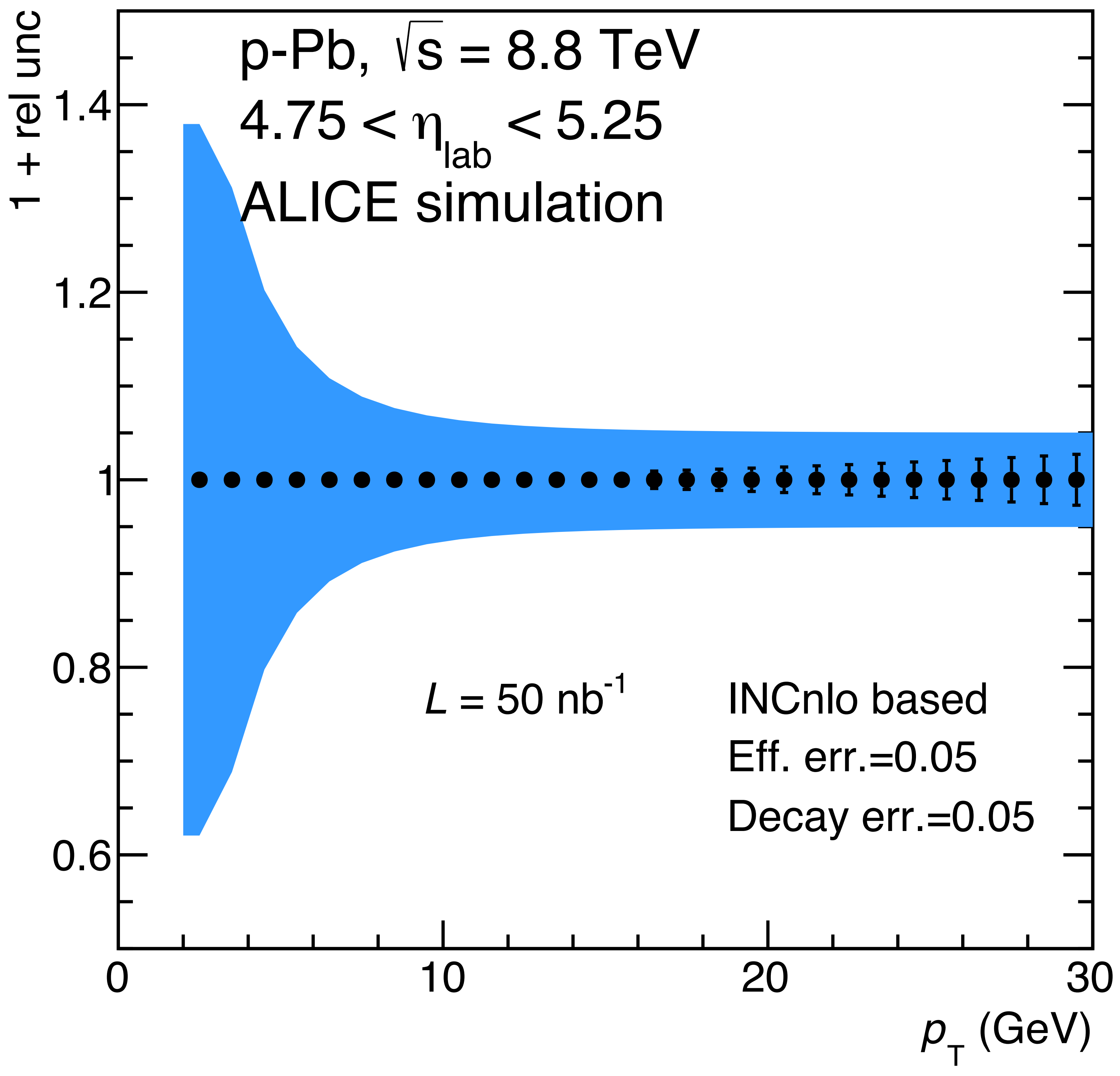

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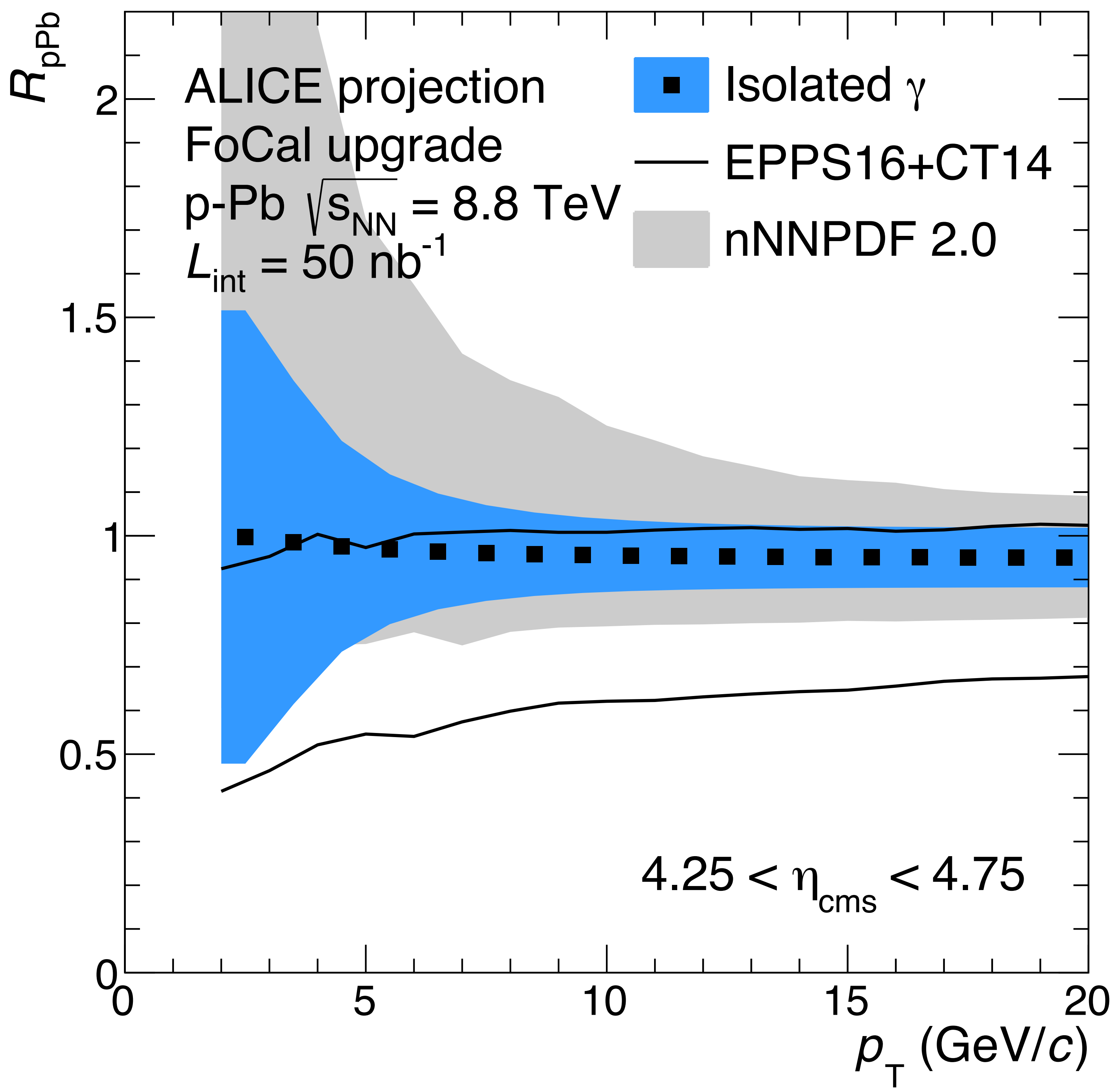

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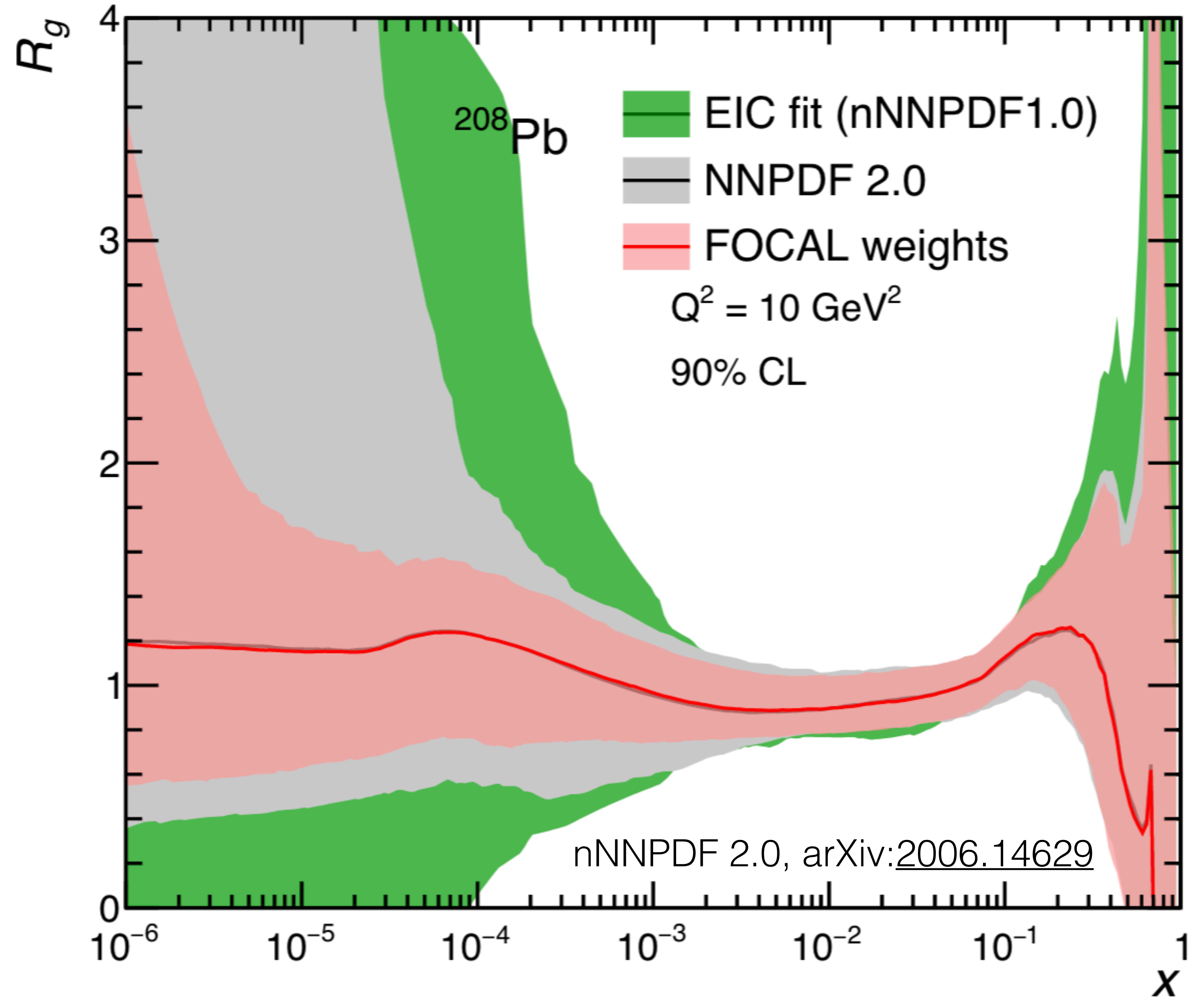
Constraints on Rg



nNNPDF 2.0 from DIS + LHC

- No constraints for $x < 10^{-2}$ from DIS
- LHC: high-Q^2 constraints down to 10^{-4}
- FOCAL significant constraints over a broad range: ~10^{-5} - 10^{-2} at small Q^2
  - No additional constraints from EIC expected

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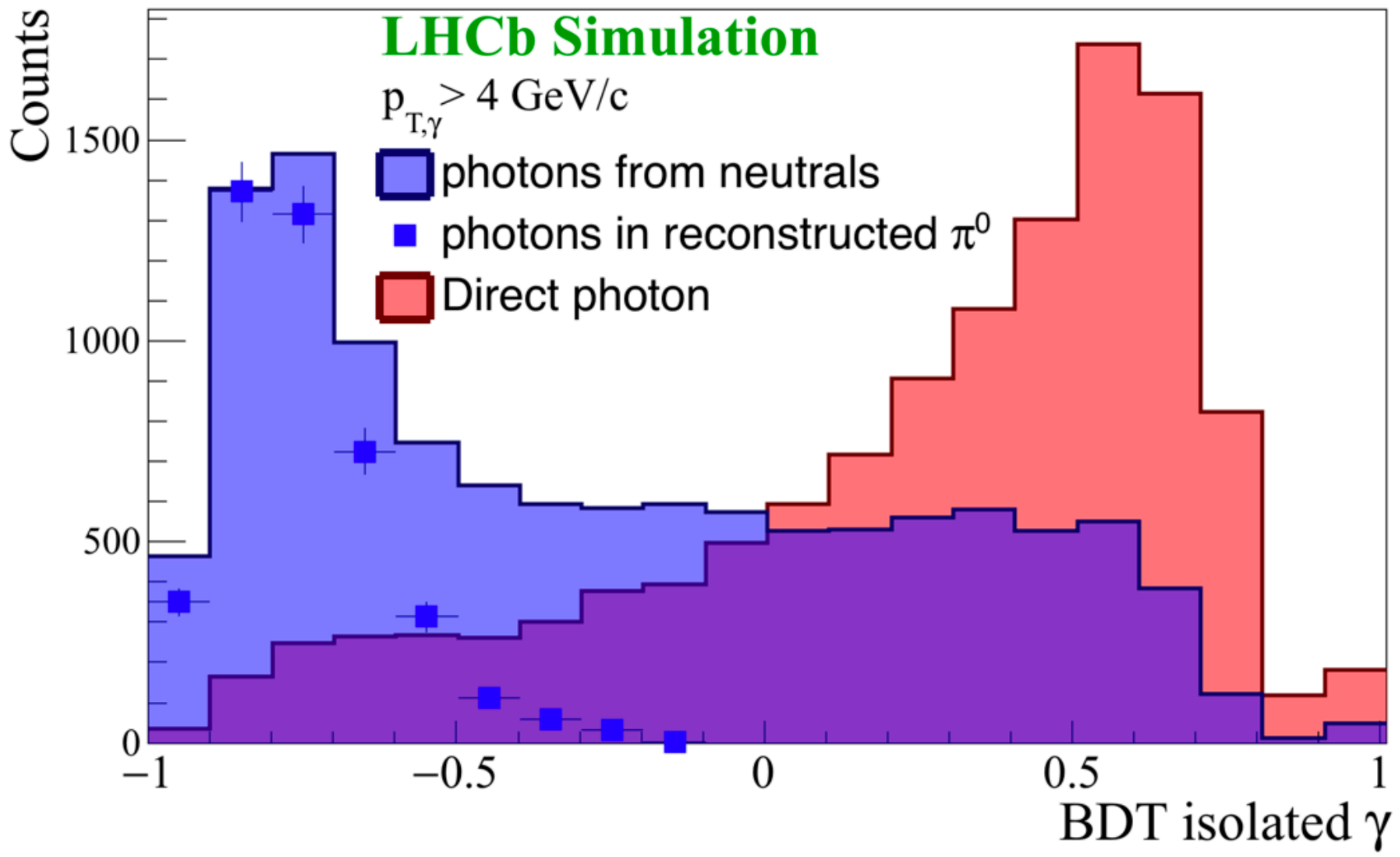
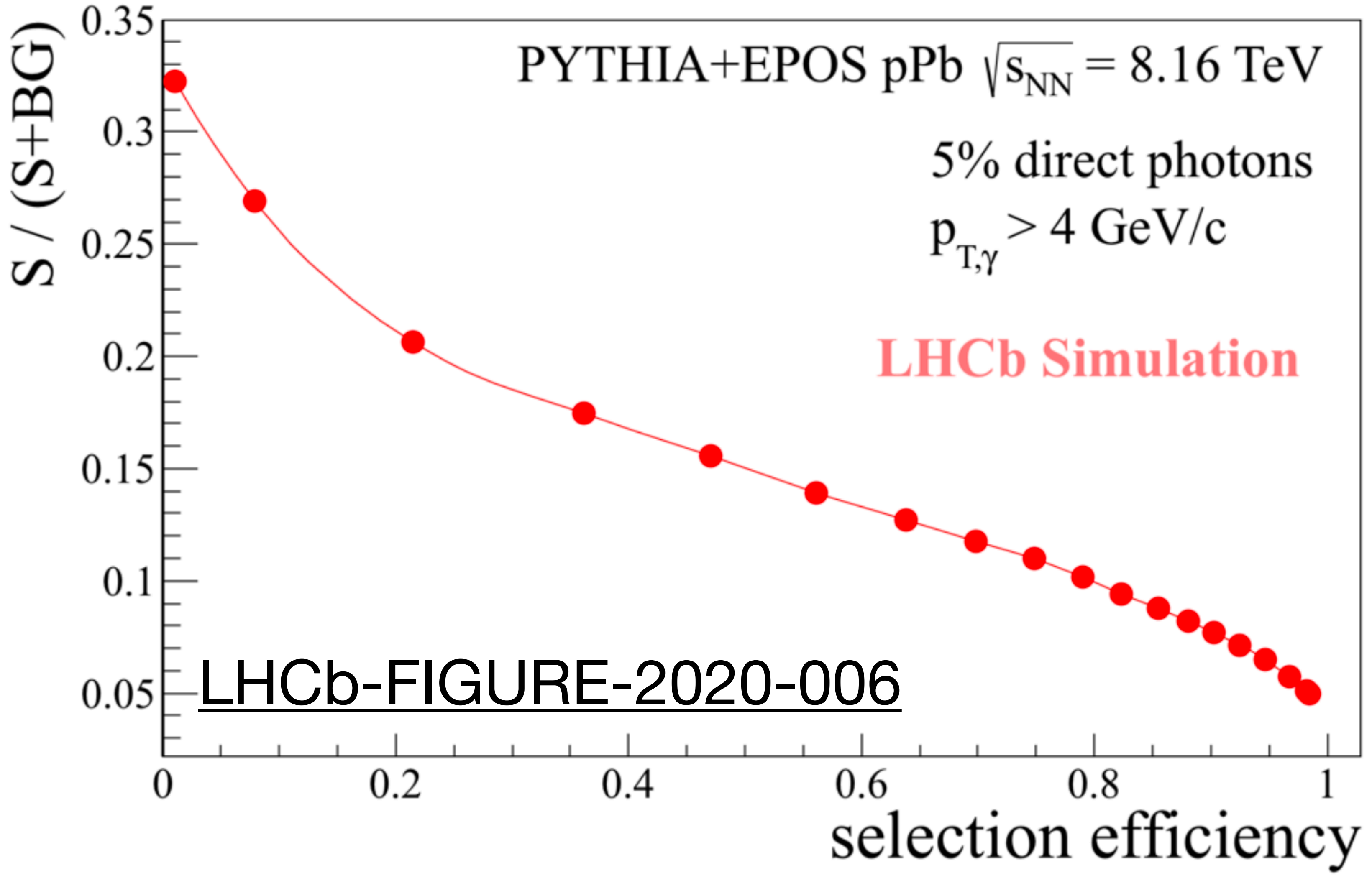
FoCal: Comparison of isolated performance with LHCb projection

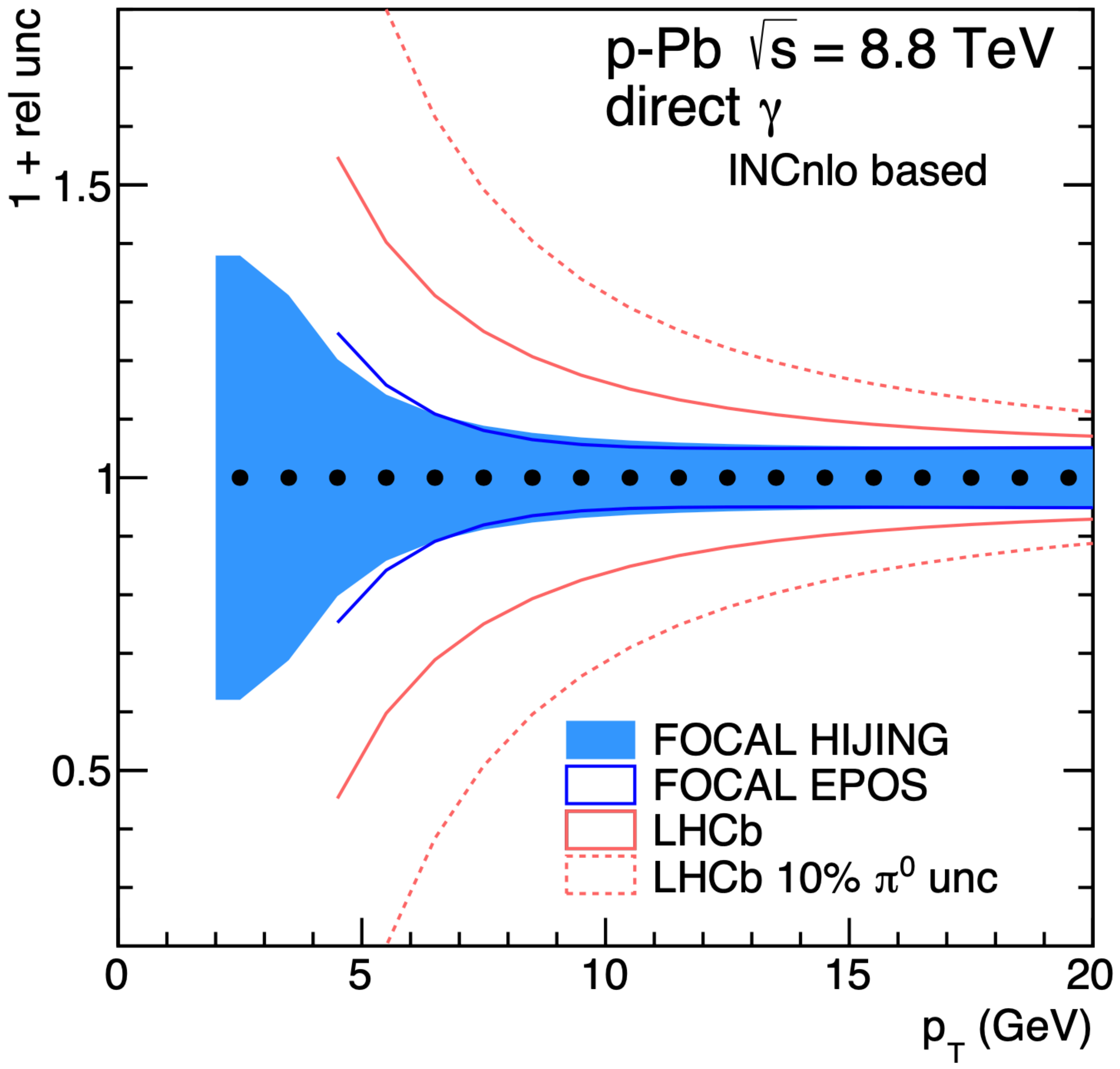
BDT response



Purity vs efficiency of BDT cut



CERN-LHCC-2020-009



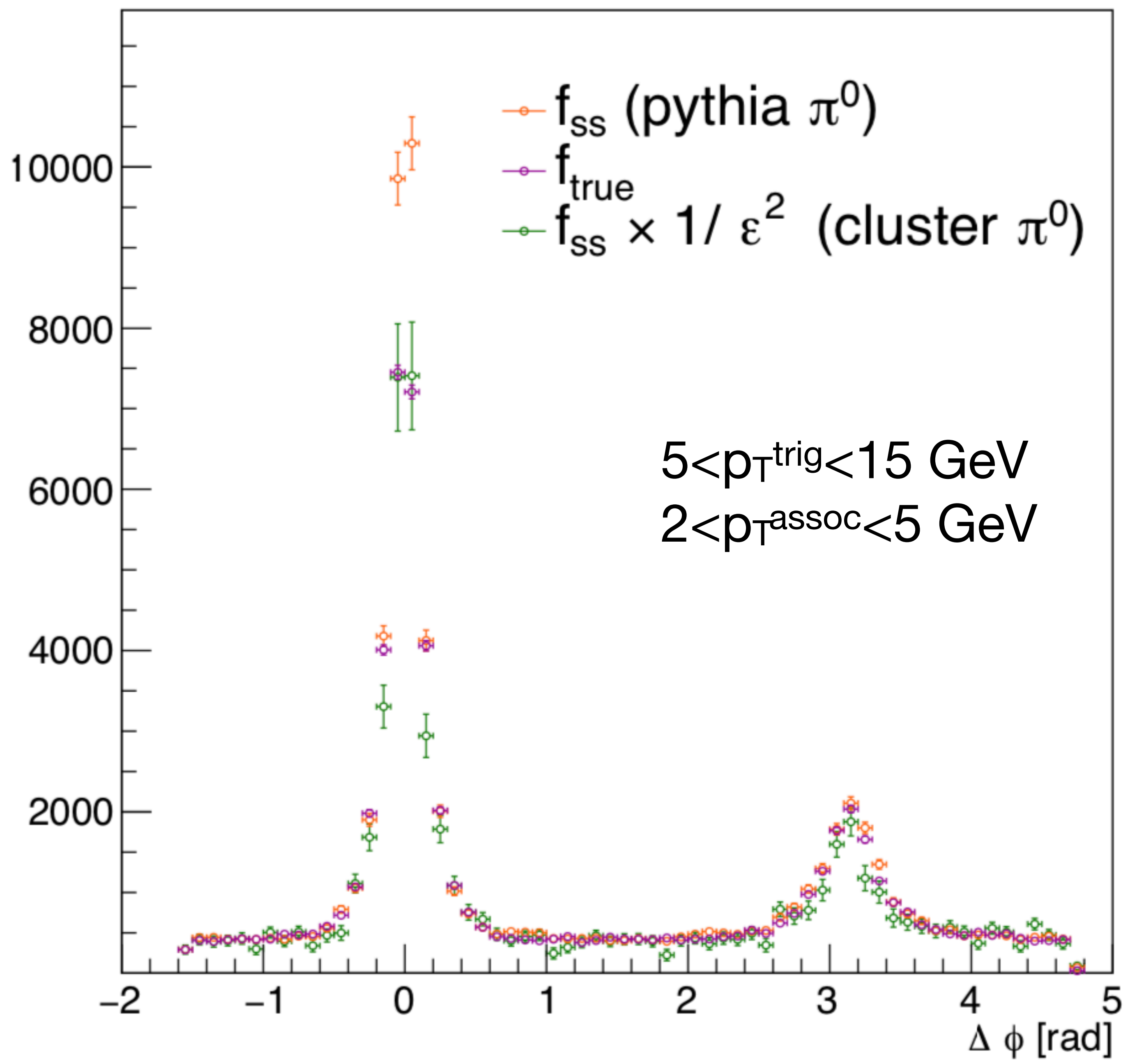
FoCal performance ($4<\eta<5$) outperforms LHCb ($3<\eta<4$) by a factor of 2 or more in uncertainty

(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)

FoCal: Performance for various observables

π^0-π^0 correlations in pp



Large program beyond photons and π^0

- Excellent two-particle correlation performance
- Good J/psi, Y, Z reconstruction capabilities
- Excellent jet resolution thanks to good FoCal-E/H perf.
    - pushing performance to very low pt

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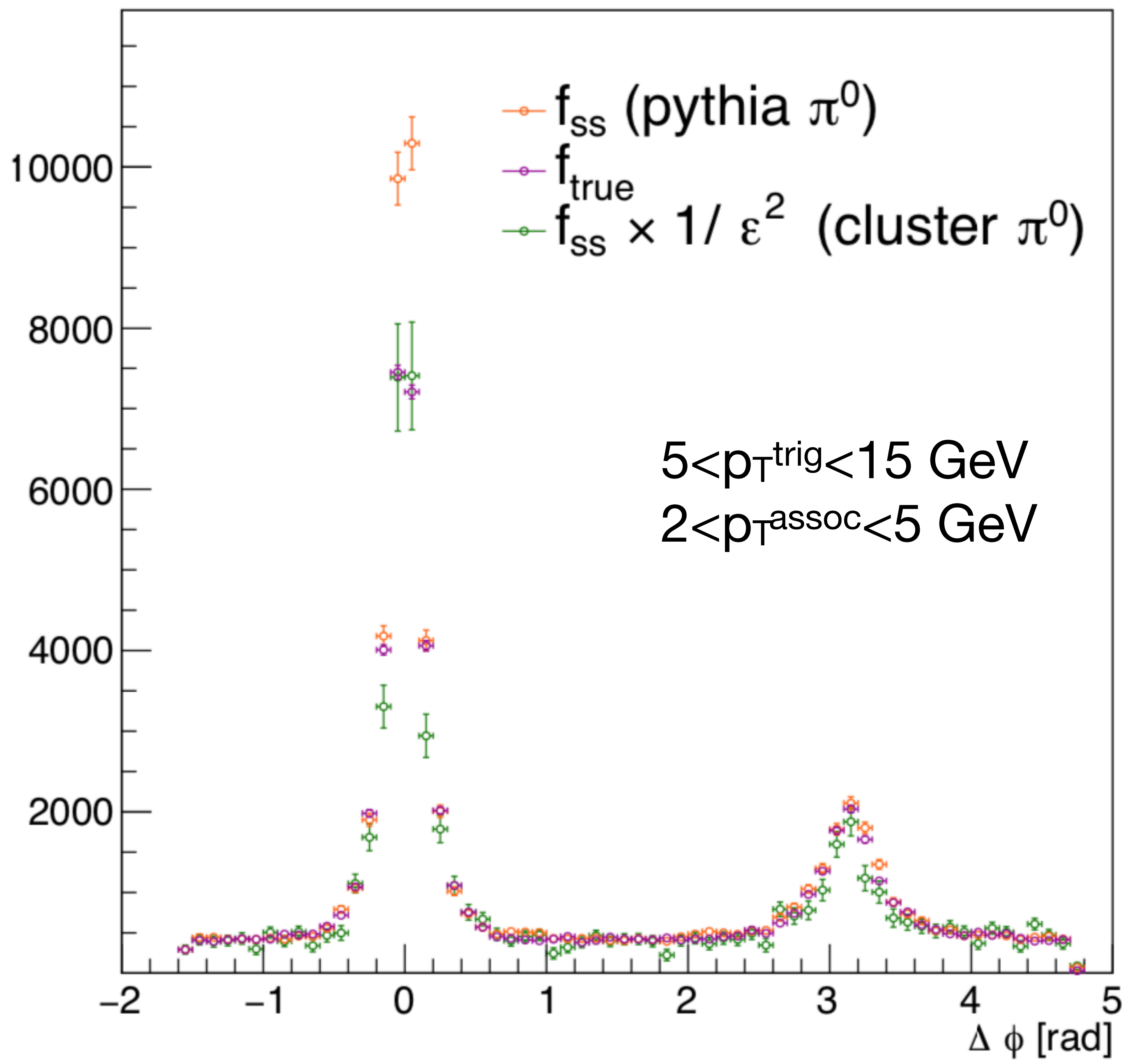
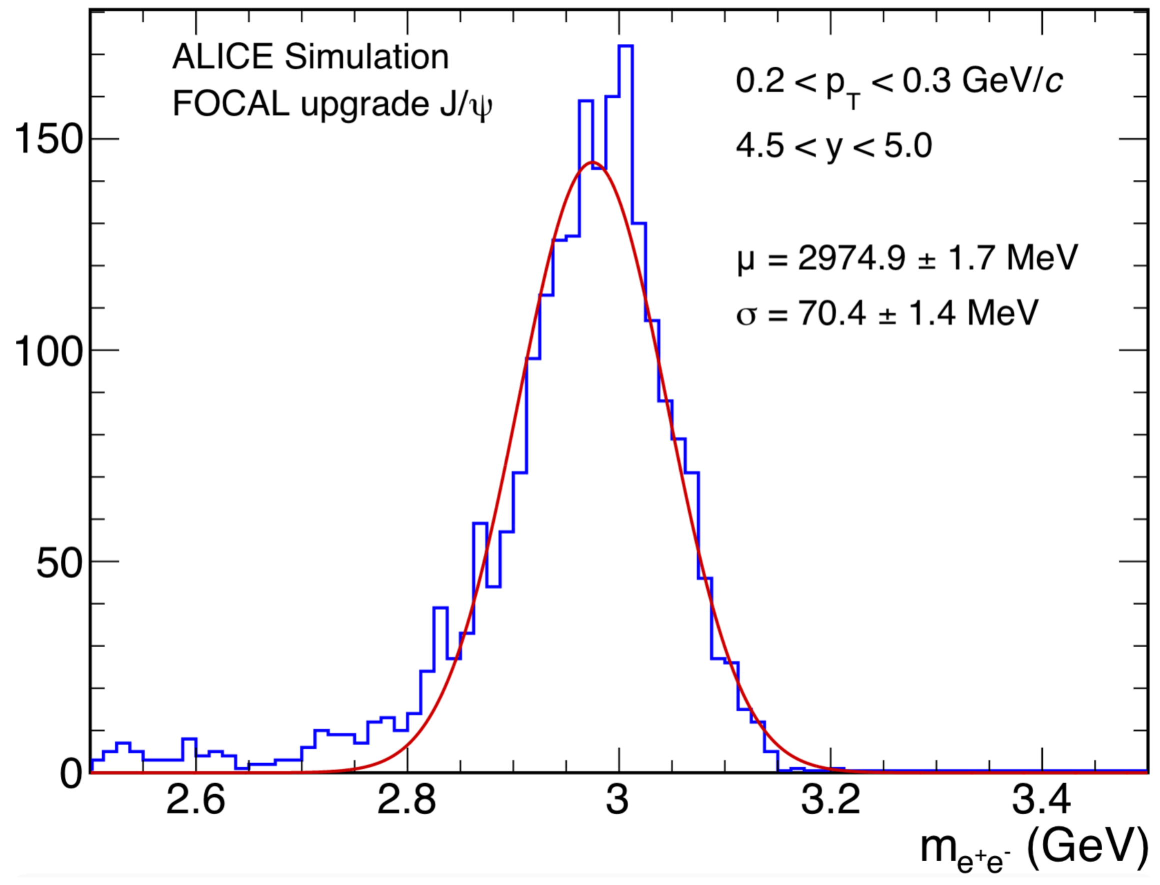
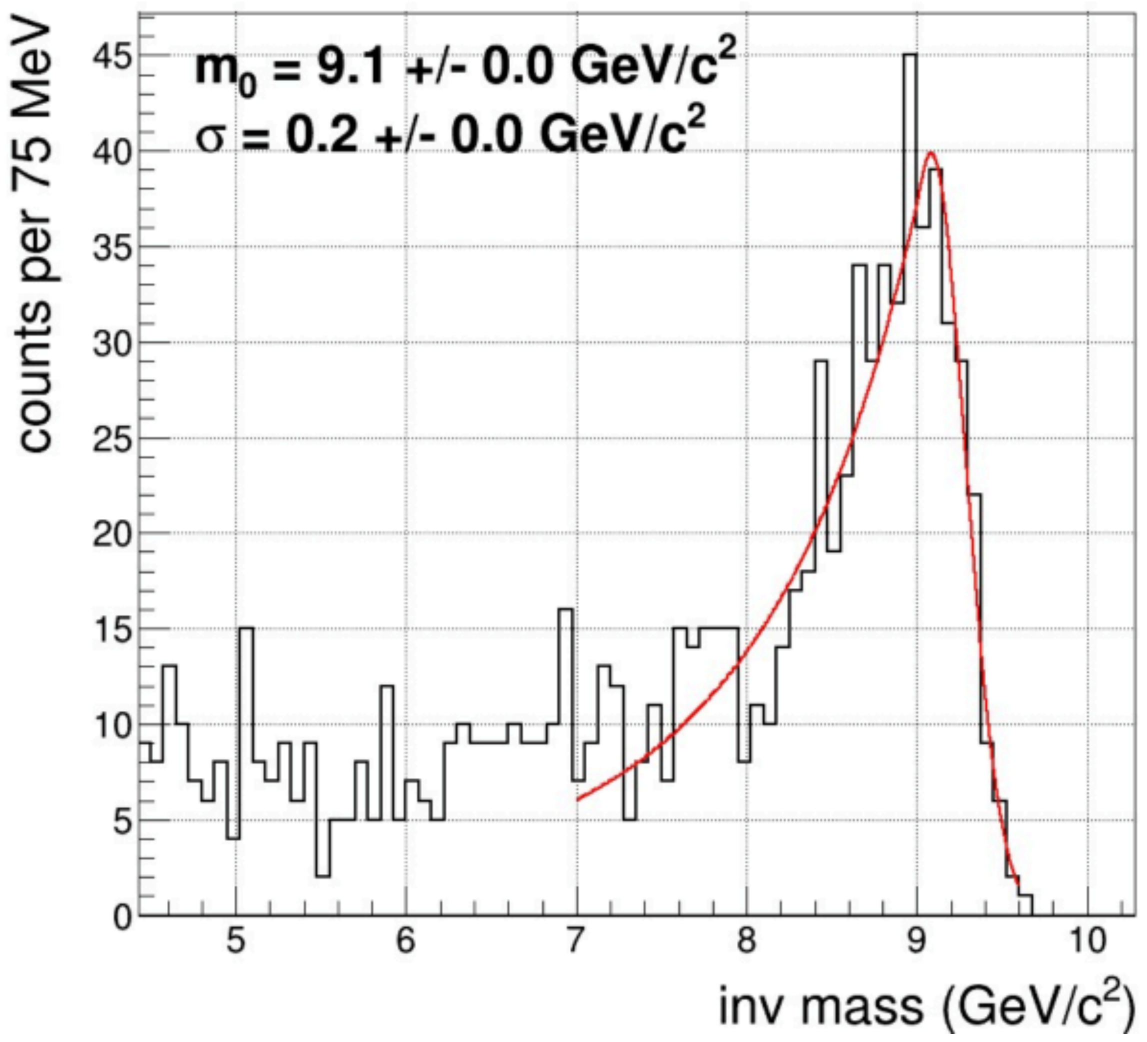


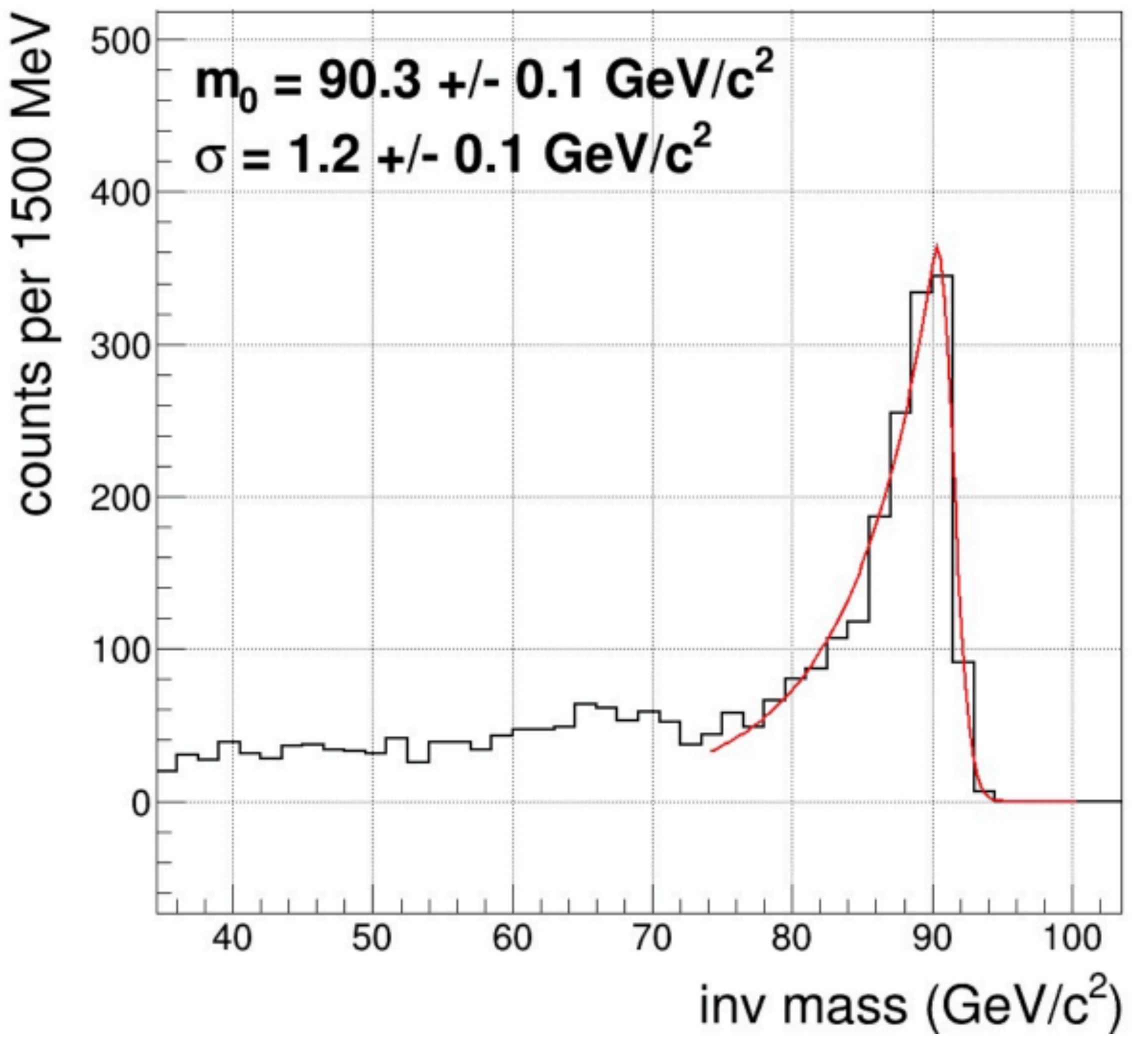
J/ψ reconstruction



Y reconstruction



Z reconstruction



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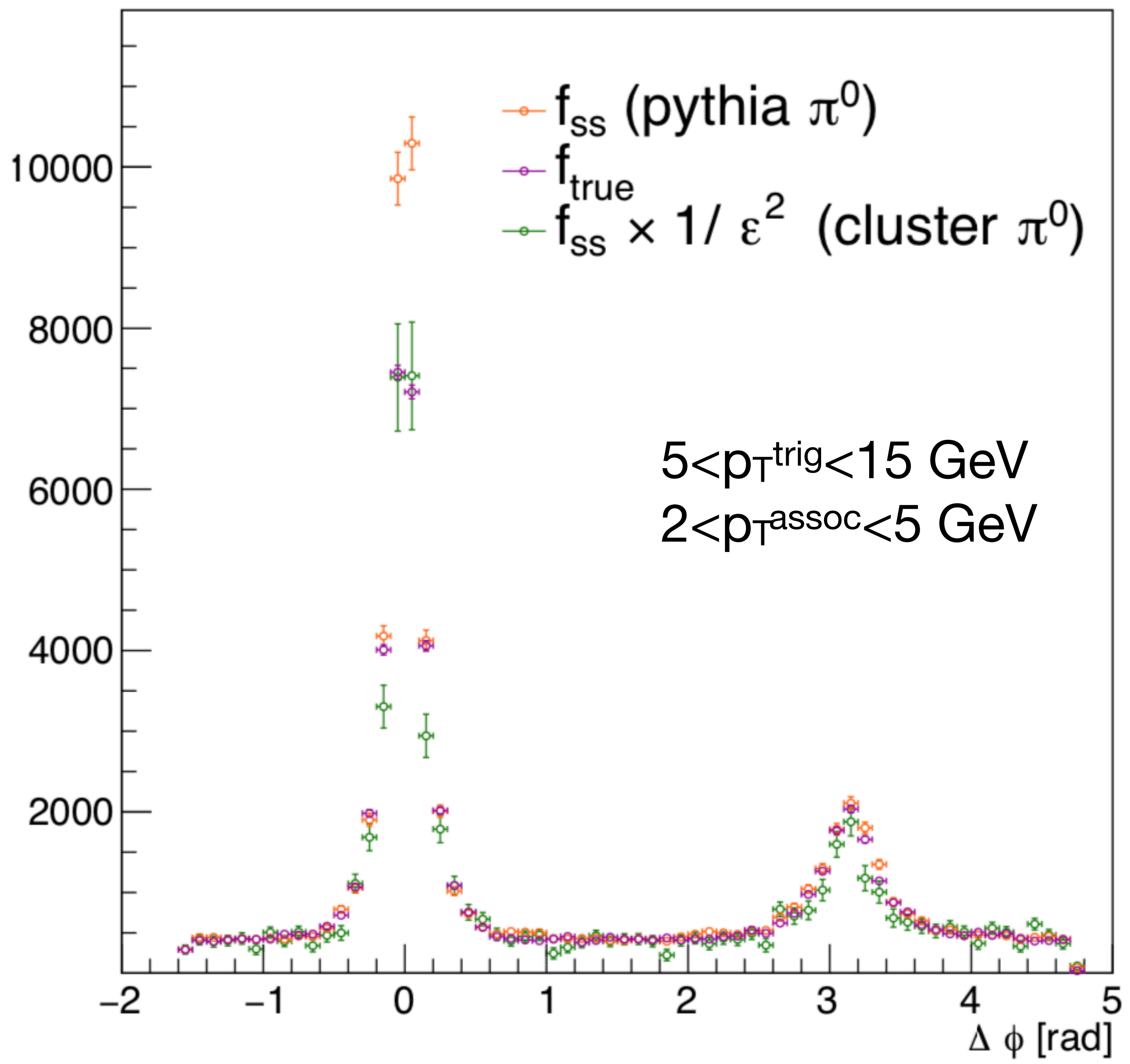
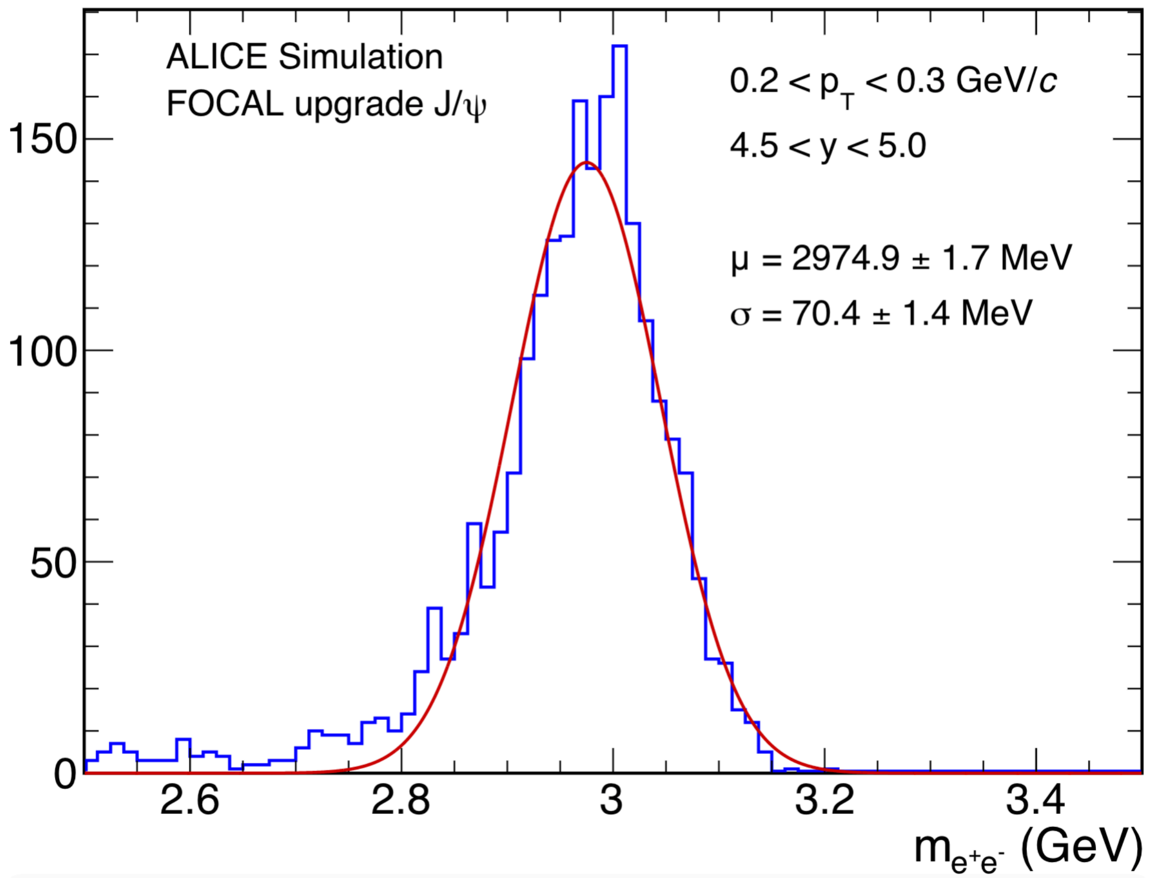
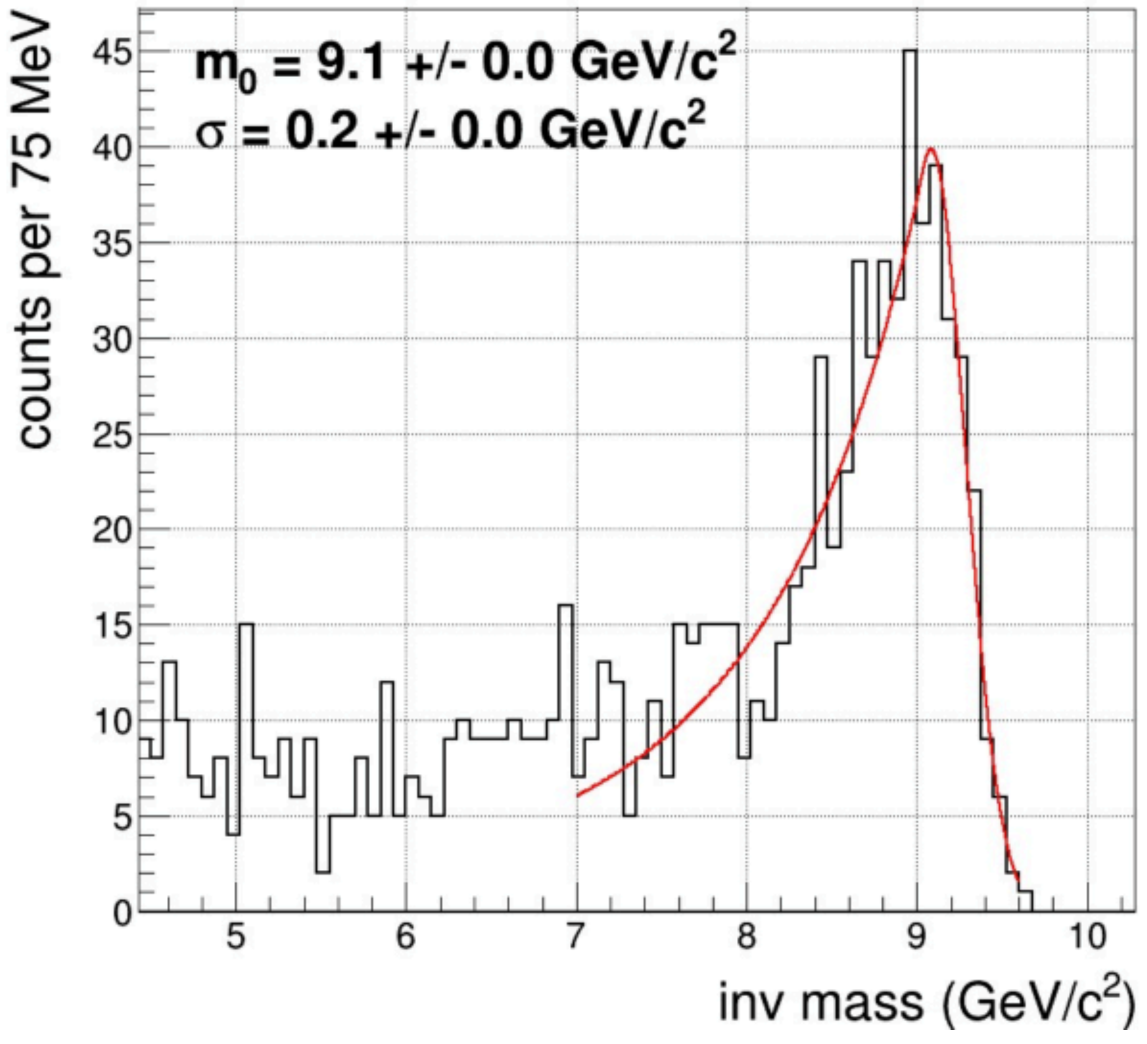


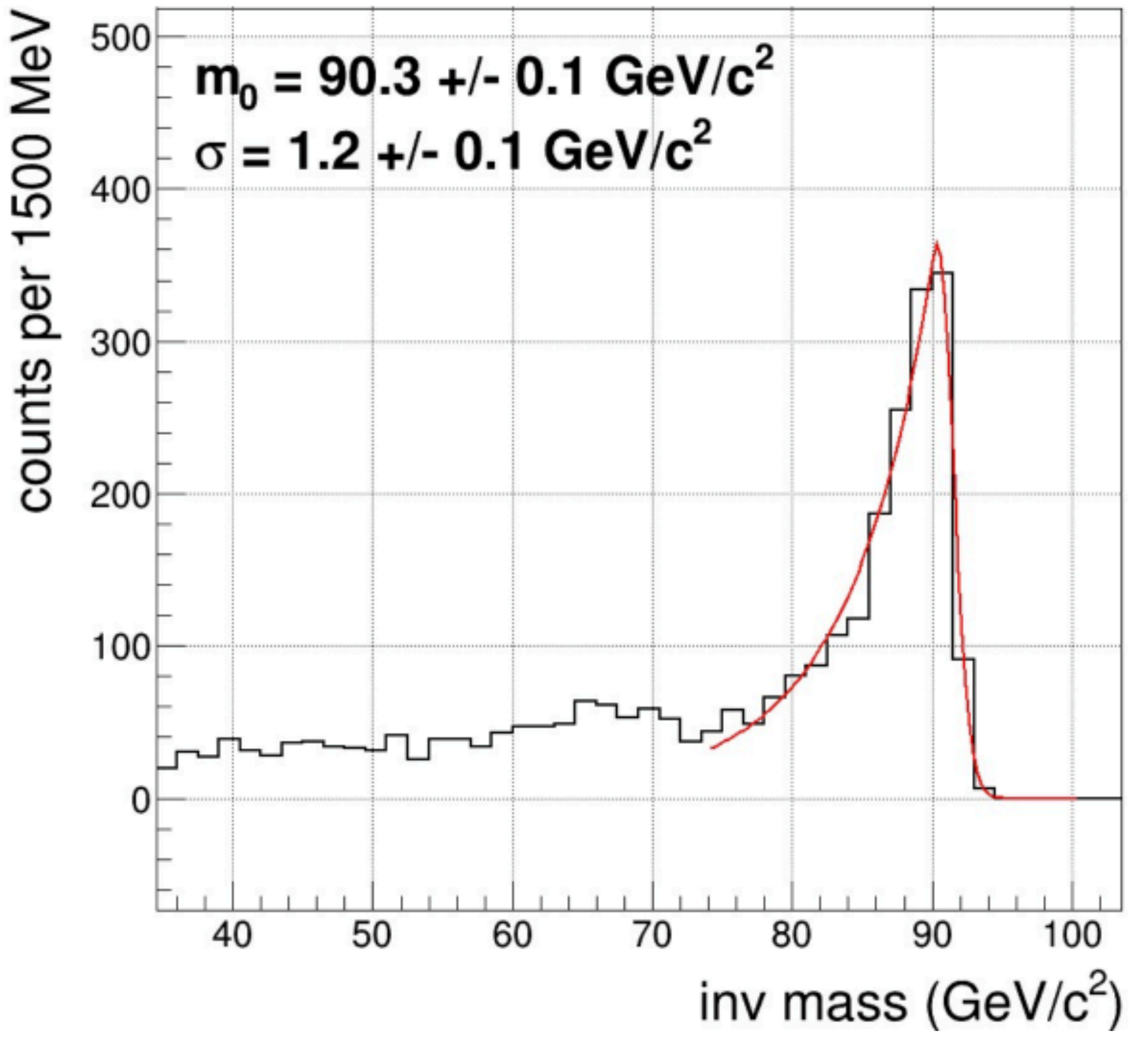
J/ψ reconstruction



Y reconstruction



Z reconstruction



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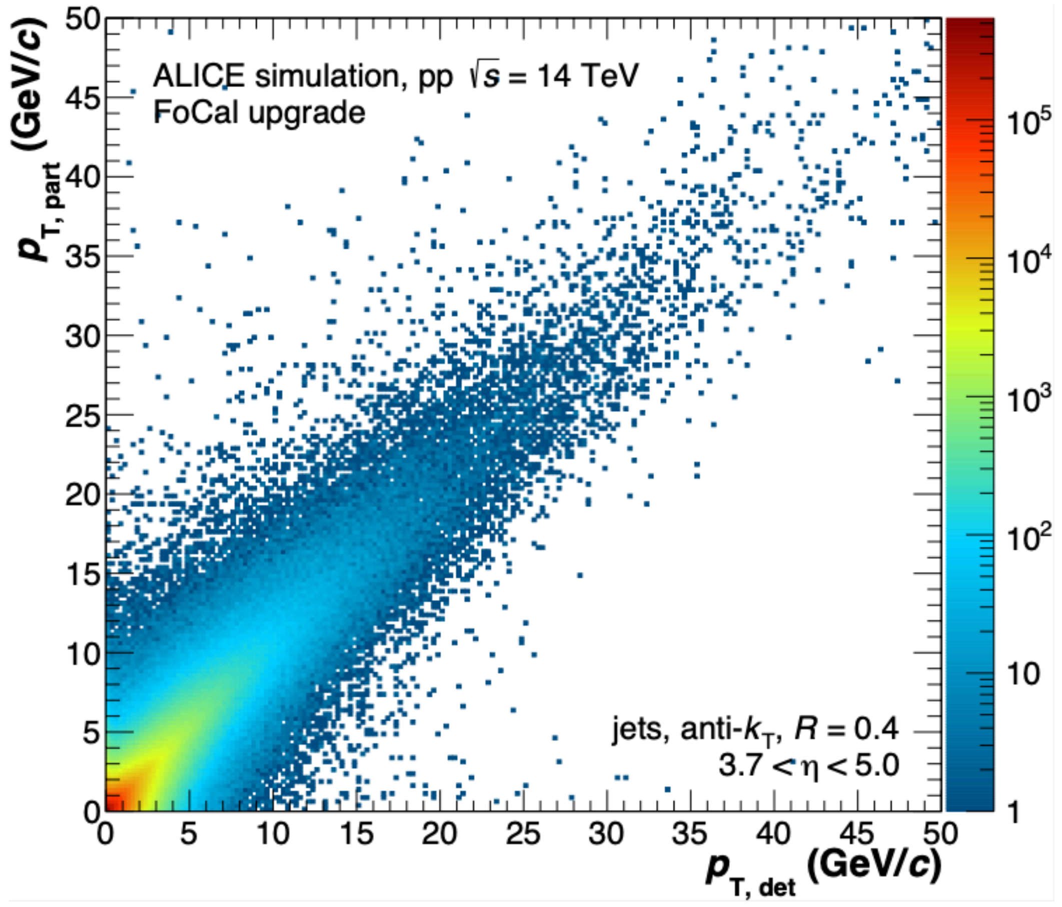
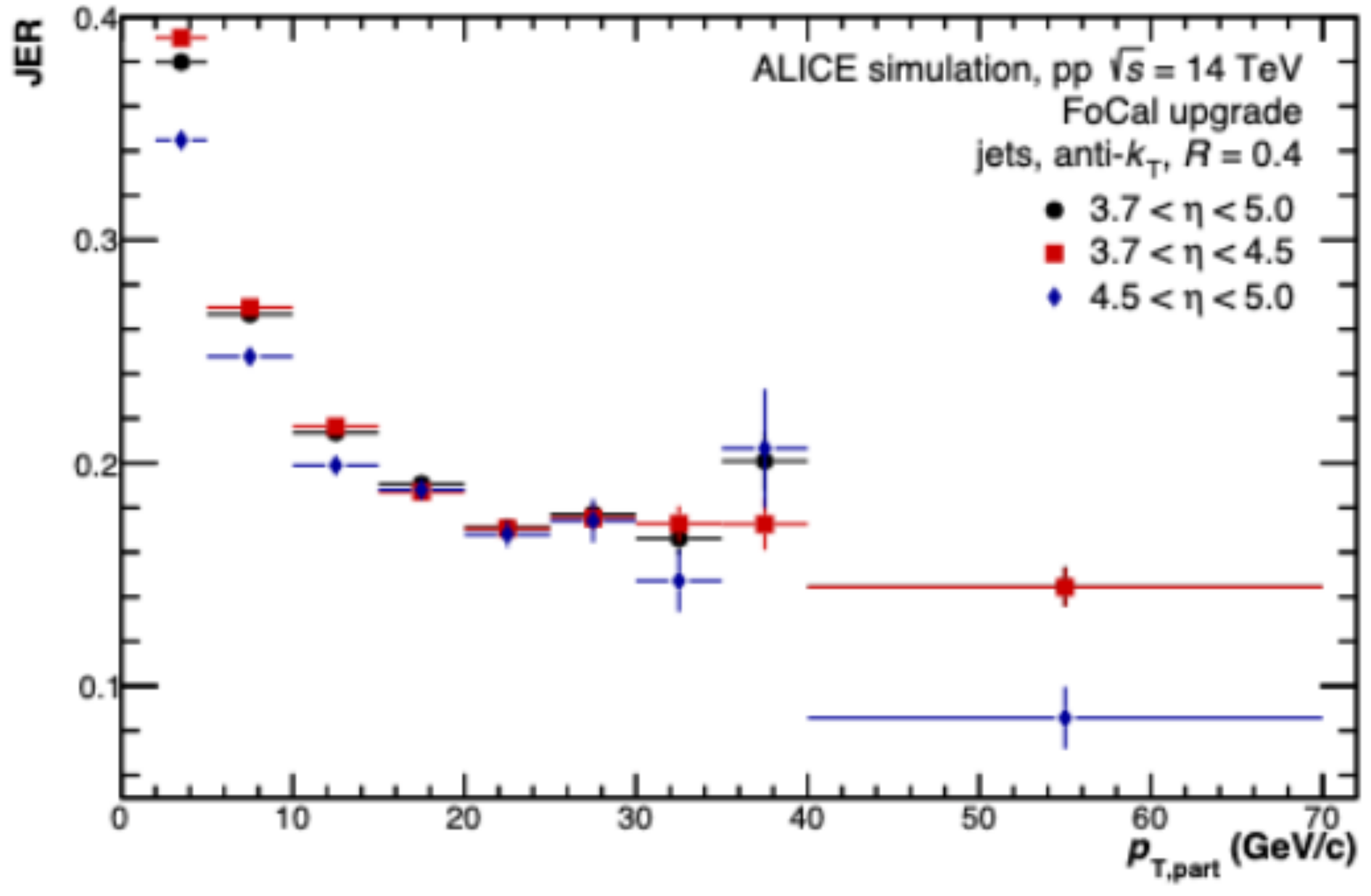
Jet reco: performance at low jet p_T under study

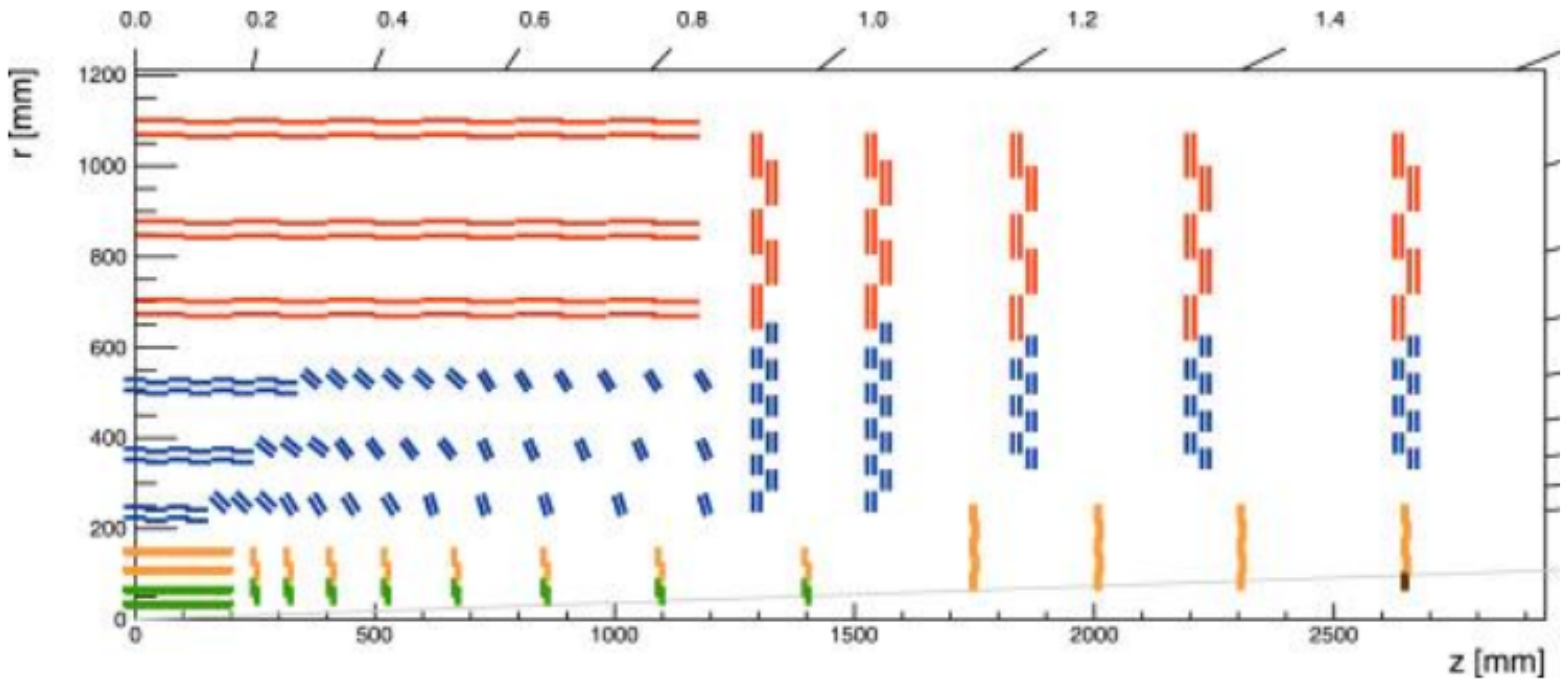


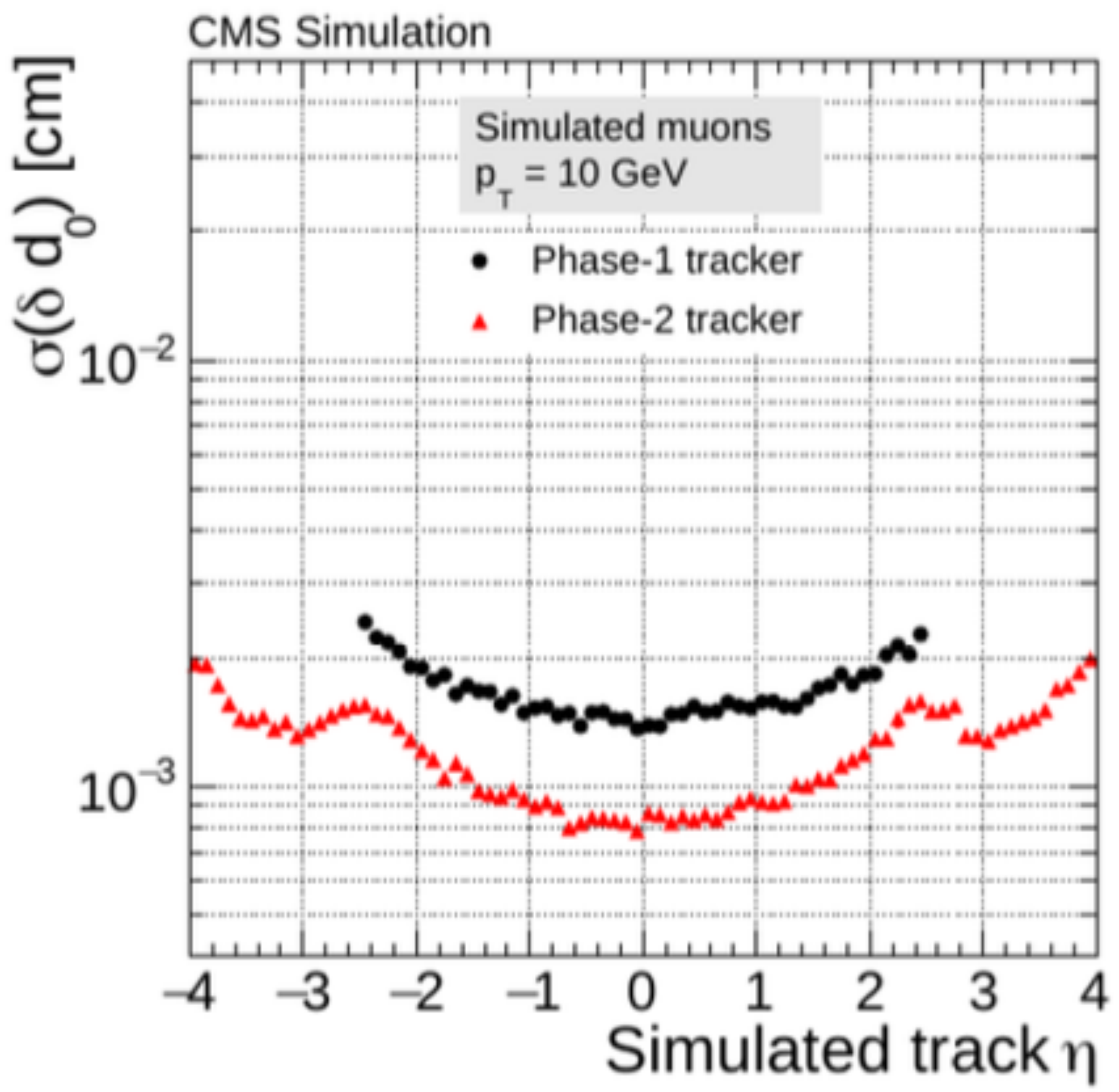


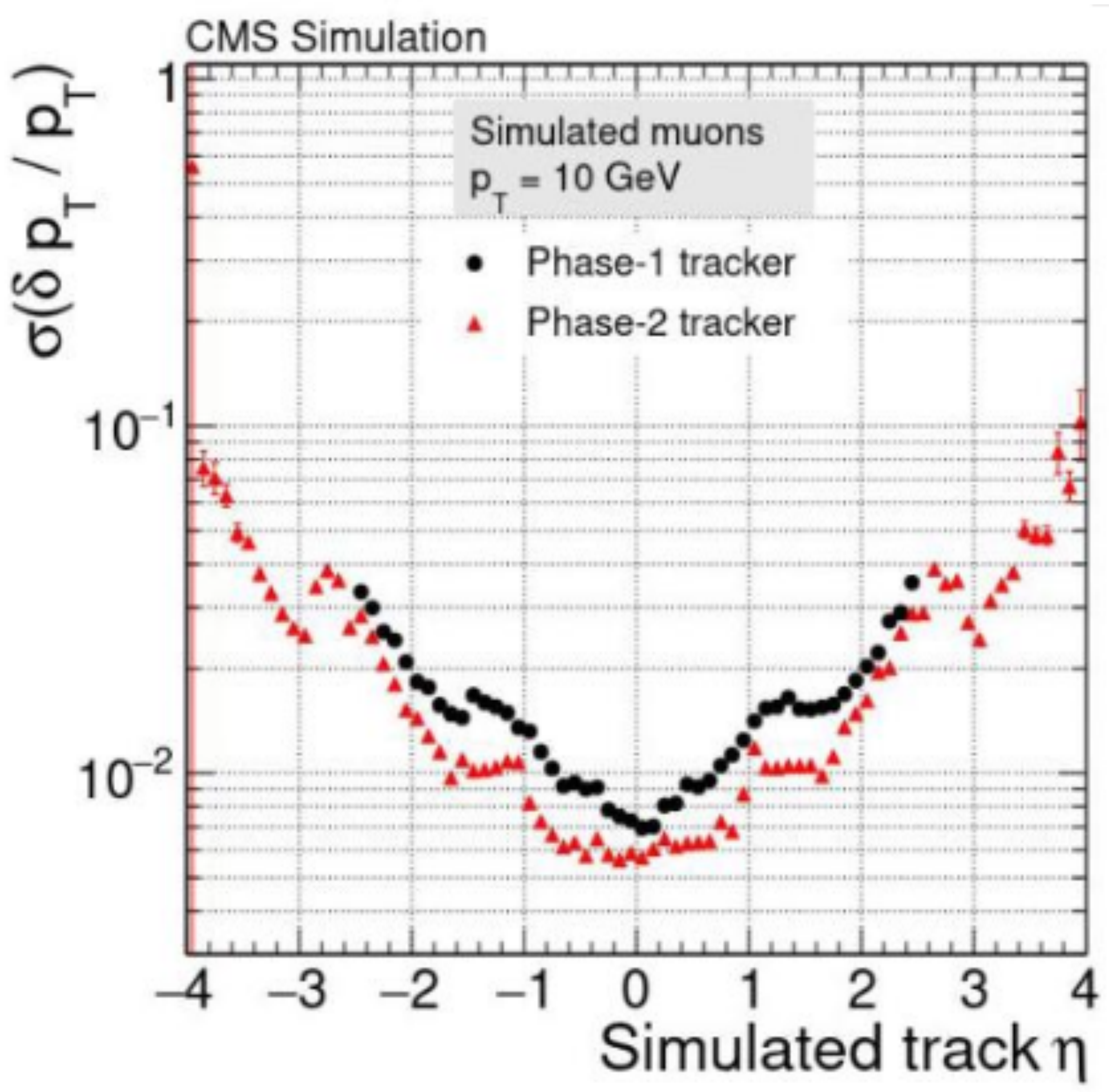
CMS phase 2 tracking

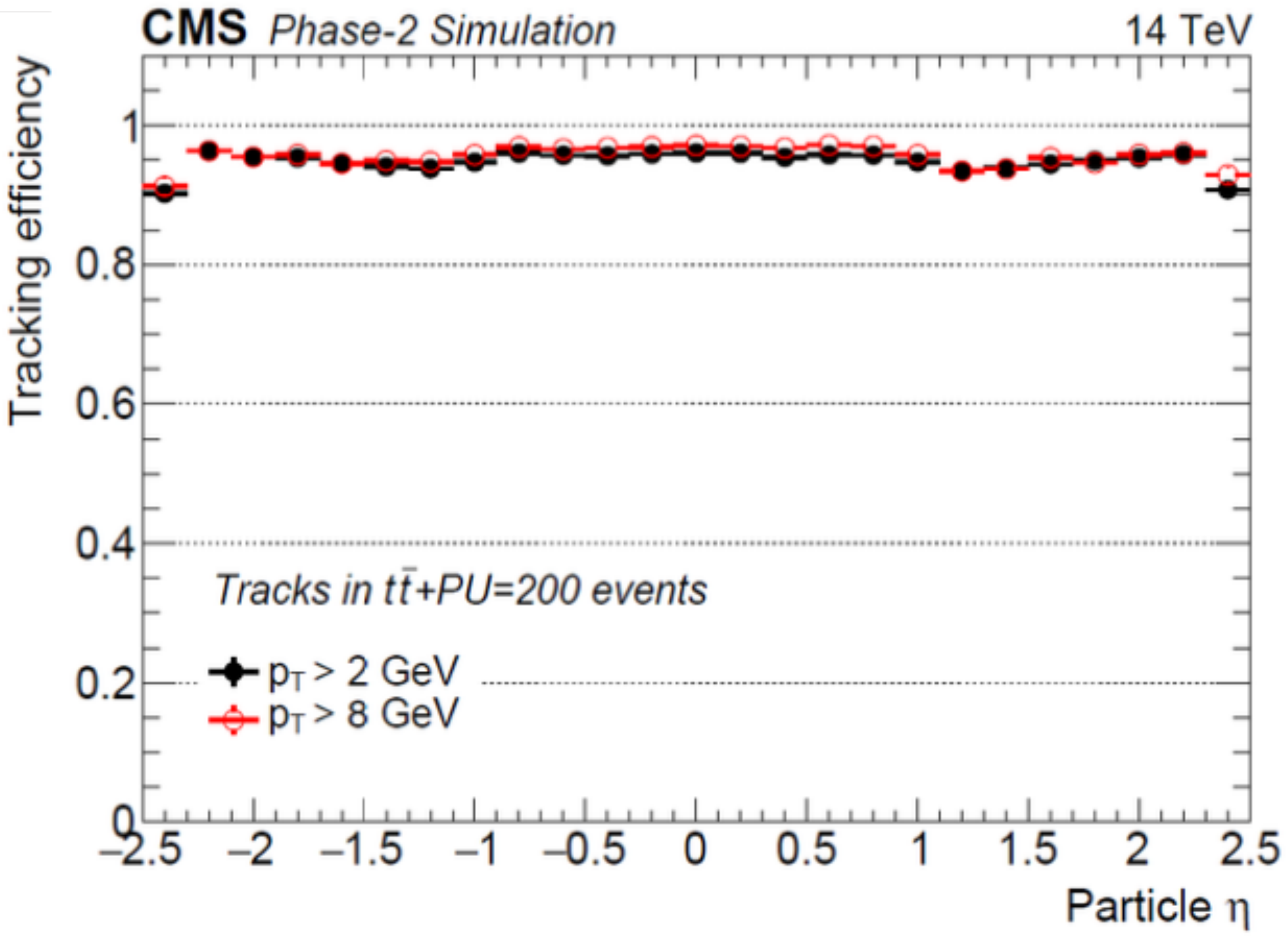
CMS-TDR-014

- Installation before Run 4
- Charged particle reconstruction up to **|η|<4**
- At <Pile-Up>=200 (heavy-ion like):
  - Efficiency > 90%, fake rate < 3%
- Significantly better p_T and d_0 resolution
  - Improvement on HF hadron and b/c-jet tagging
  - Level-1 track trigger









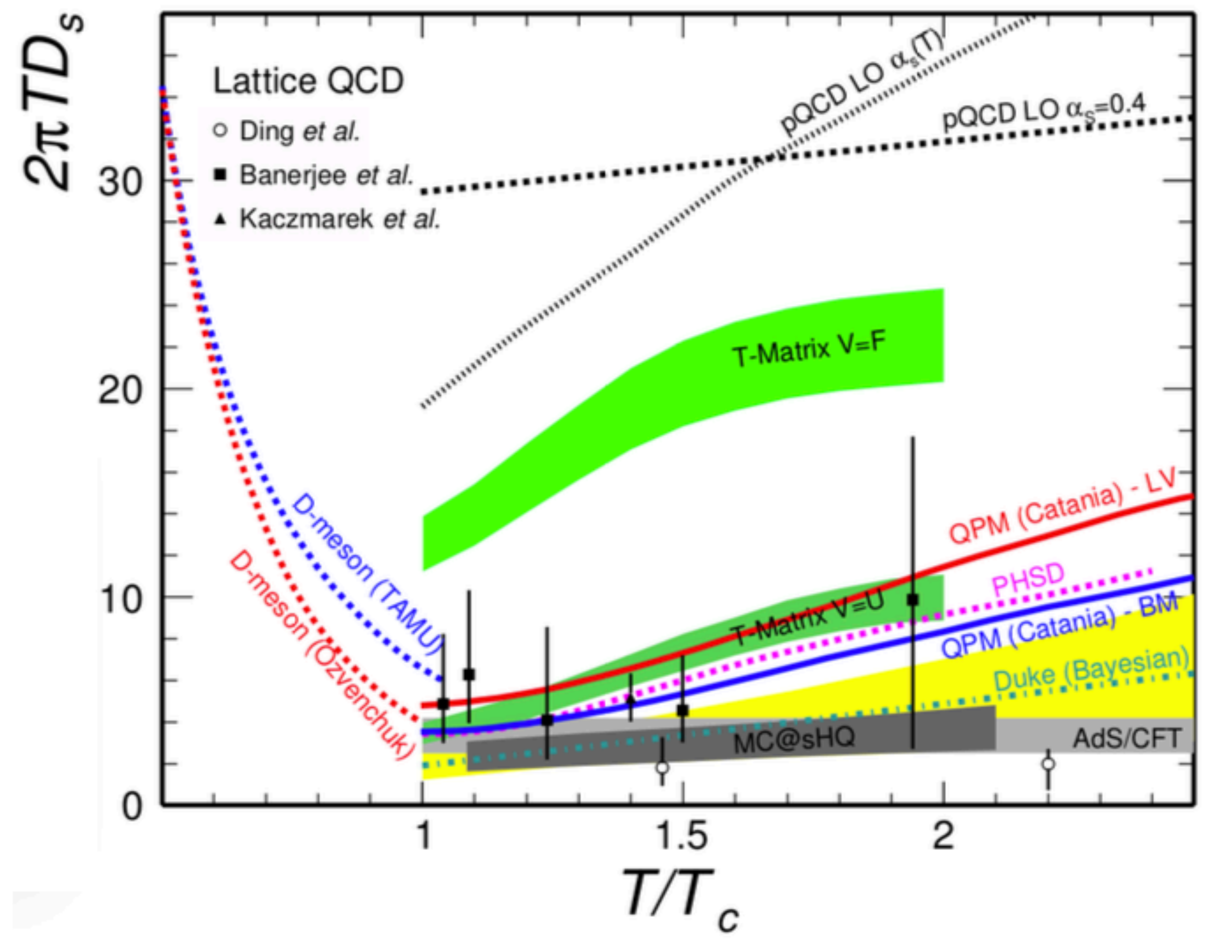
ALICE 3 - physics program

- **Early stages**: temperature of QGP before hadronisation
  - Di-lepton and photon production, elliptic flow
  - Electric conductivity of the QGP
- **Chiral symmetry** restoration: $\rho - a_1$ mixing
- **Heavy flavour diffusion and thermalisation in the QGP**
  - Beauty and charm flow
  - Charm hadron correlations
- **Hadronisation**, final state interactions in heavy-ion collisions
  - Multi-charm baryon production: thermal processes/quark recombination
  - Quarkonia and exotic mesons: dissociation and regeneration
- Structure of **exotic hadrons**
  - Momentum correlations (femtoscopy)
  - Production yields — dissociation in final state scattering
  - Decay studies in ultra-peripheral collisions
- New **nuclear states**: charm nuclei
- **Susceptibilities**
- **Ultra-soft photons**: experimental test of Low's theorem
- **BSM searches**: ALPs, dark photons

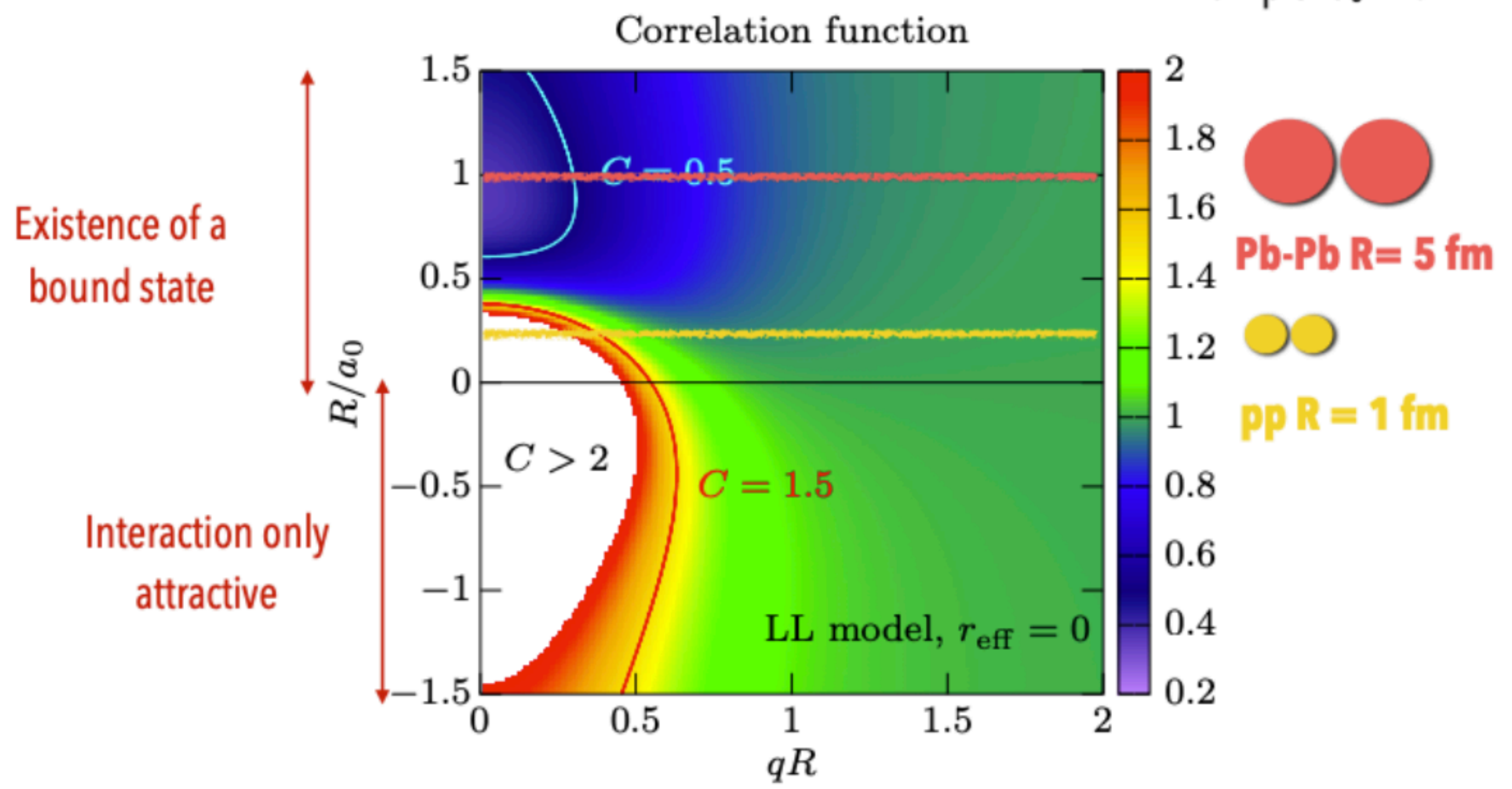
D$_s$: heavy quark diffusion coefficient

$$\langle r^2 \rangle = 6\, D_s\, t$$

$$\tau_Q = (m_Q/T)\, D_s$$



Example: a_0 = 5 fm



Y. Kamiya et al. arXiv:2108.09644v1

LOI, arXiv:2211.02491