

Postdoctoral seminar · CFNS, Stony Brook

Precision QCD with ALICE Run 3: From jet cross sections to future jet measurements

Joonsuk BAE

Sungkyunkwan University

Peter Paul Seminar Room (C-120) | July 2, 2026



Who I am

*“I started my PhD together with **LHC Run 3** in 2022,
and became primary analyzer of ALICE’s **first Run 3 jet measurement.**”*



Stage

- ▶ PhD candidate, SKKU (advisor: Beomkyu KIM).
- ▶ Defense Nov—Dec 2026; conferral Feb 2027.
- ▶ **Available early 2027.**

Lead analyses

- ▶ ALICE’s first Run 3 jet measurement
 - R -dependence of charged-particle jet spectra, pp $\sqrt{s} = 13.6$ TeV.
- ▶ ALICE O+O charged-particle jet R_{AA}
 - Primary analyzer (one of), Paper Committee member
 - Owns signal-loss · cross-section normalization · mentoring lead analyzer · POWHEG pp reference

Collaborations

- ▶ ALICE (since 2022.10)
- ▶ ePIC (since 2024.02)



Selected presentations:

6 International conferences · 16 invited/contributed talks

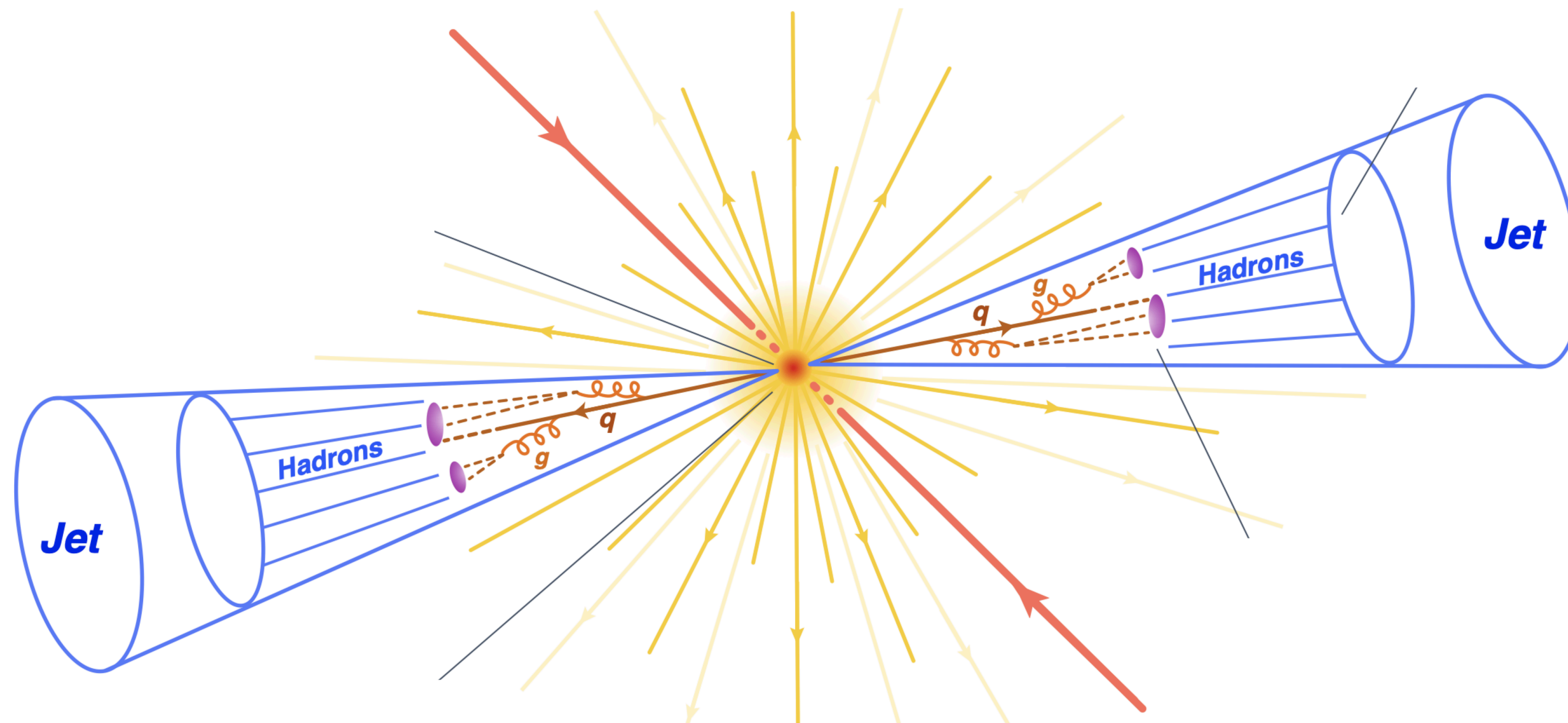
- ▶ HP 2024 (poster) · QM 2025 (poster)
 - EPS-HEP 2025 (merge talk) · HP 2026 (talk, poster)

Hardware

- ▶ ePIC-BIC Pb/SciFi prototype.
- ▶ Lead analyzer @ CERN PS T10 (2025.07).
- ▶ Prompt analysis + on-site DAQ shifter @ KEK AF-AR (2025.03)

Hard probes & jets

“Hard probes are pQCD-calculable partons from initial scattering; jets are how we reconstruct them”

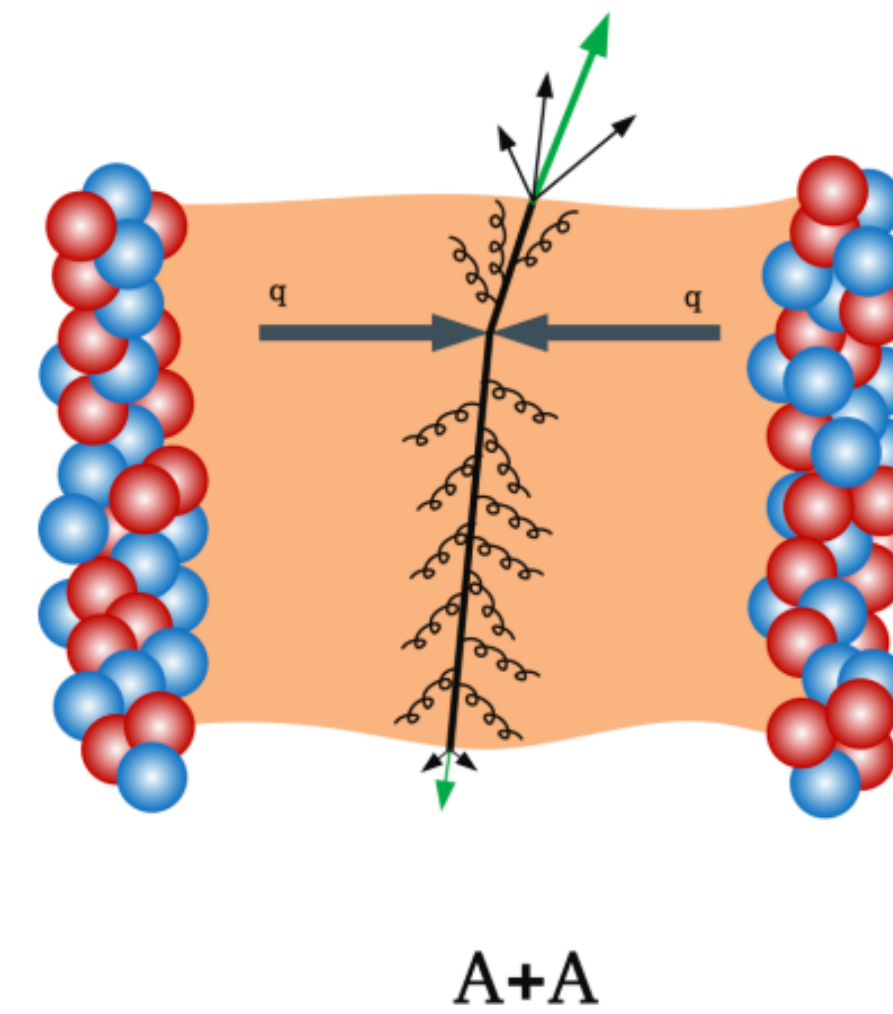
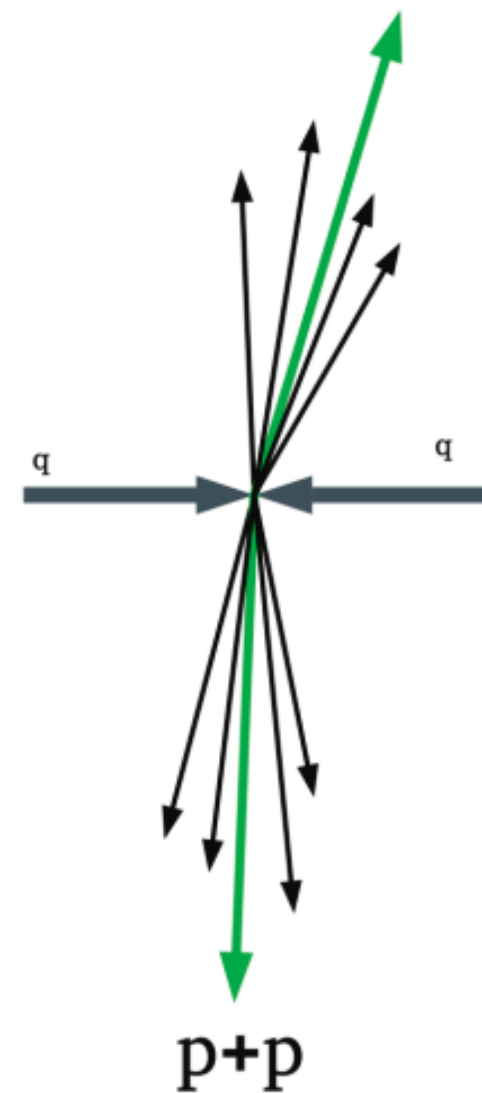


What

- ▶ **Hard probe** — a high- p_T parton from **initial hard scattering**; production rate **calculable in pQCD**.
- ▶ **Jet** — **collimated spray** it fragments into; **experimental proxy** for parton.

Hard probes & jets

“Hard probes are pQCD-calculable partons from initial scattering; jets are how we reconstruct them — measured against known pp baseline, how we probe QGP.”



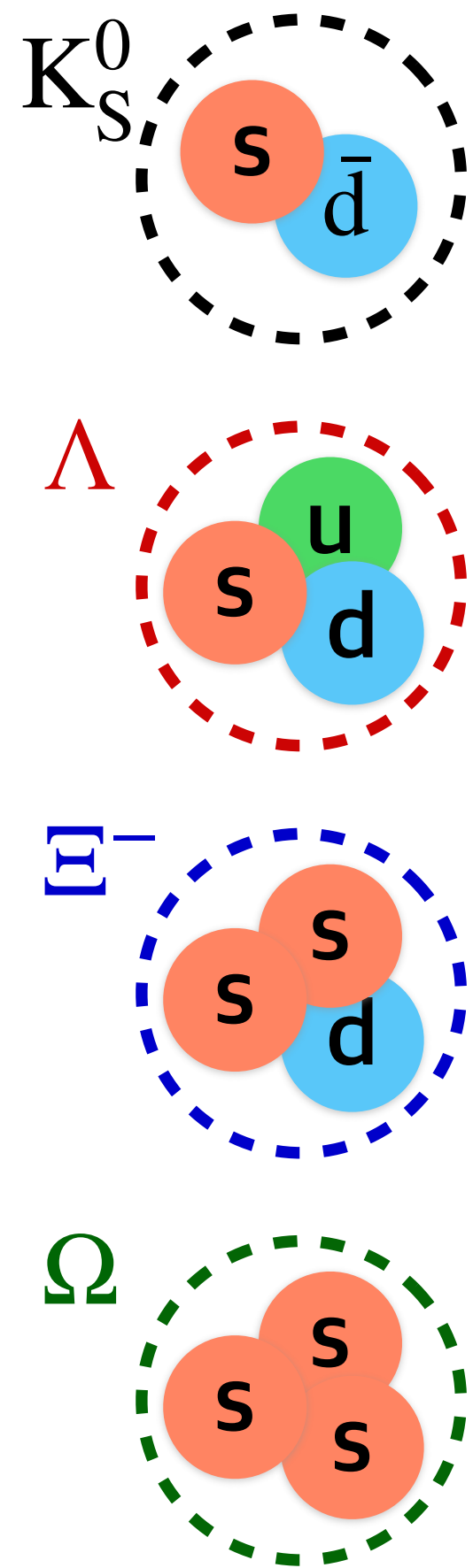
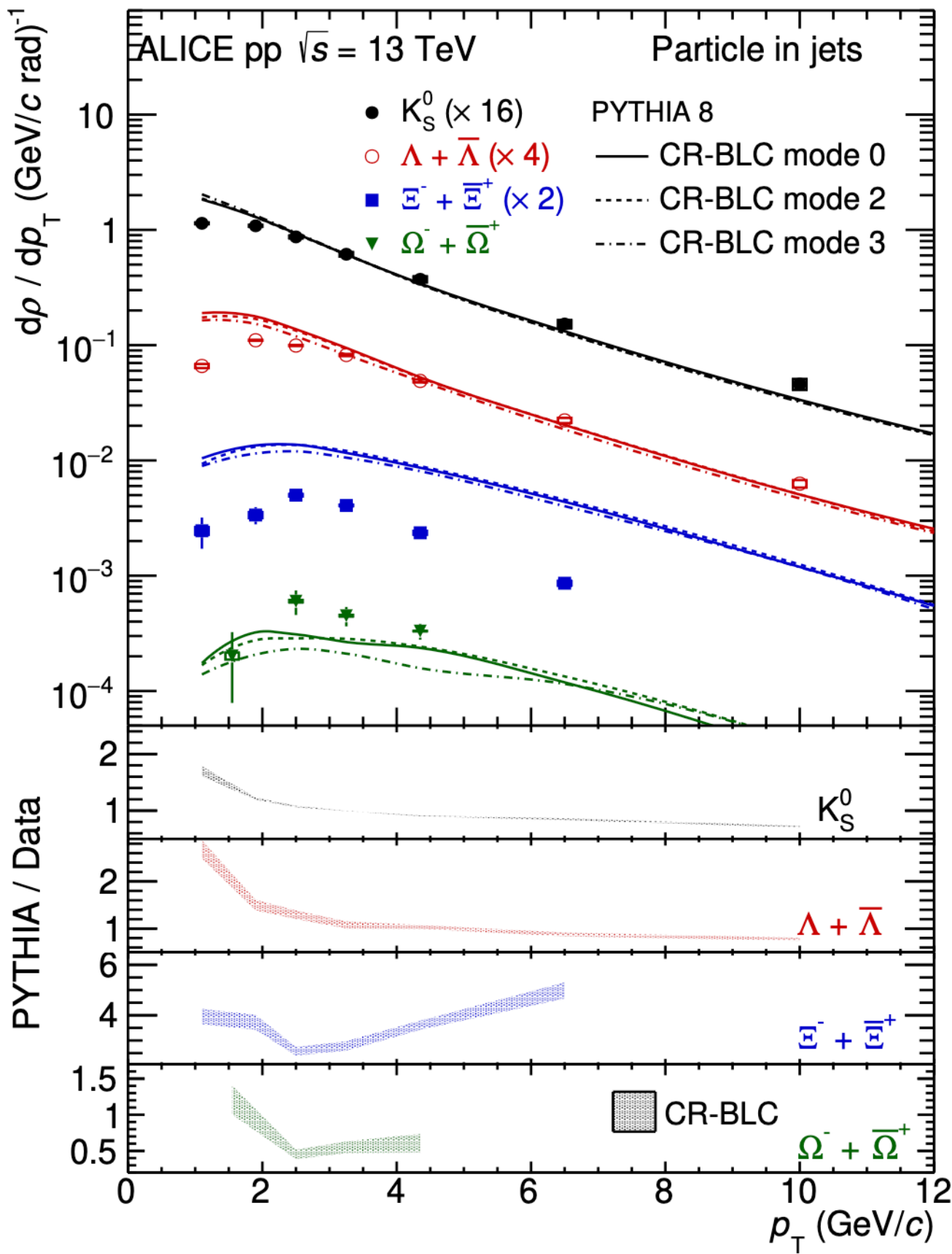
Why jets / why good for Quark-Gluon Plasma (QGP)

- ▶ Jet produced **before QGP forms**, parton traverses medium.
- ▶ **Energy loss** and **shape modification** — **jet quenching** — probes medium.
- ▶ **pp baseline is well understood, modification in AA** due to **medium's effect**.

This talk: **vacuum precision (pp) → quenching (O+O) → substructure tomography**

Modern hard probes — three frontiers

- (1) **Non-perturbative QCD**
 - hadronization, UE, soft radiation
- (2) **Small-system jet-quenching** signatures
 - pp, p—Pb, OO, Ne—Ne
- (3) **Jet-substructure**
 - energy correlators (EEC)



- ▶ (Figure) **Strangeness/baryon enhancement in pp** is **npQCD effect** that no model reproduces (up to ~6× off)
 - soft QCD is not under control, even in baseline system.
- ▶ **Proton is not clean vacuum** — pp hadronizes collectively.

Frontier 1 → my work: charged-particle jet R-ratio

(1) Non-perturbative QCD

— hadronization, UE, soft radiation

My work 1 (lead)

ALICE Run 3 pp, R-dependence of ch-jet cross section

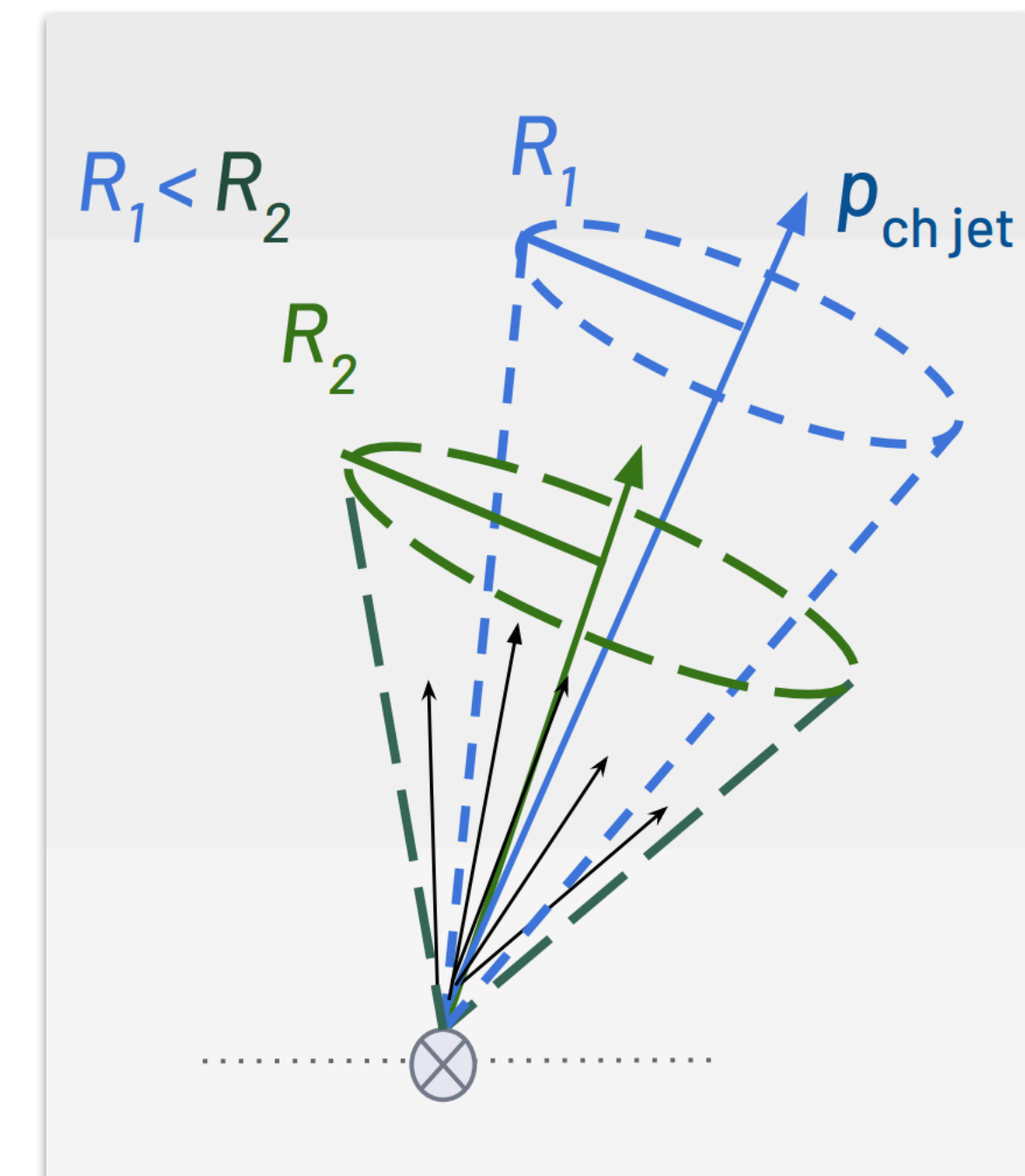
(2) Small-system jet-quenching signatures

— pp, p—Pb, OO, Ne—Ne

(3) Jet-substructure

— energy correlators (EEC)

$$\sigma(R = 0.2)/\sigma(R = X)$$



ALICE detector in Run 3

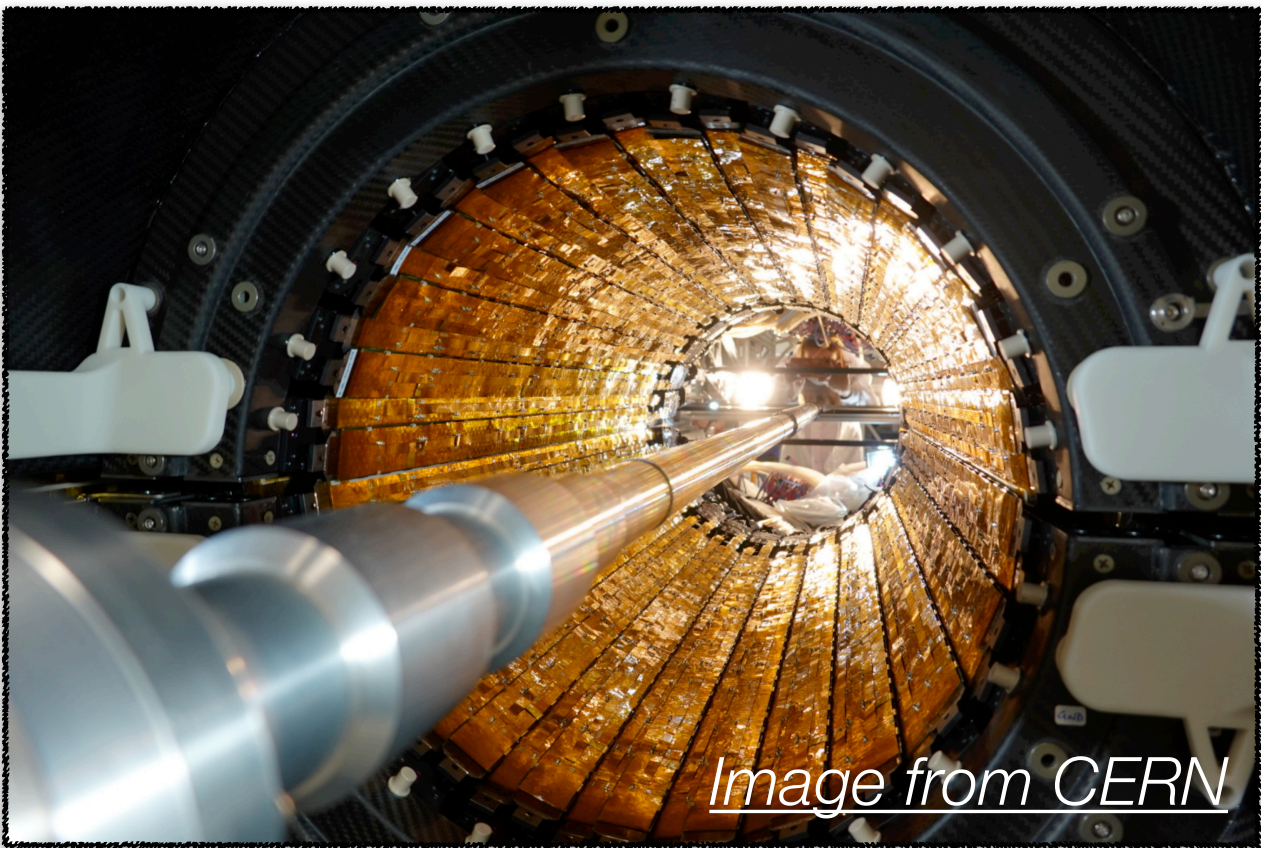


Time Projection Chamber

- ▶ **Continuous readout** based on GEM stacks

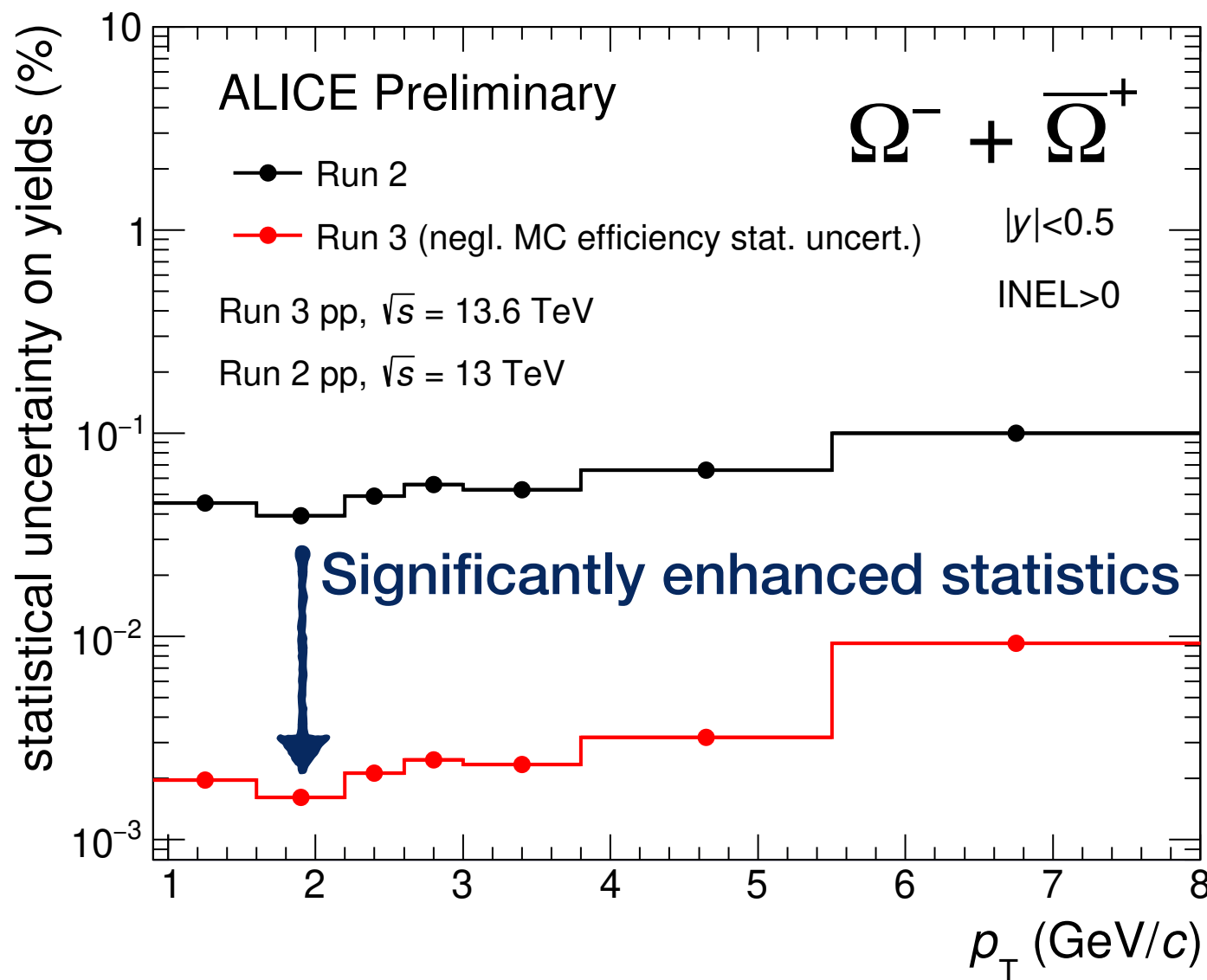
▶ ALICE upgrades:

- ▶ ~100x statistics compared to Run 2.
- ▶ With ~2–3x pointing resolution.

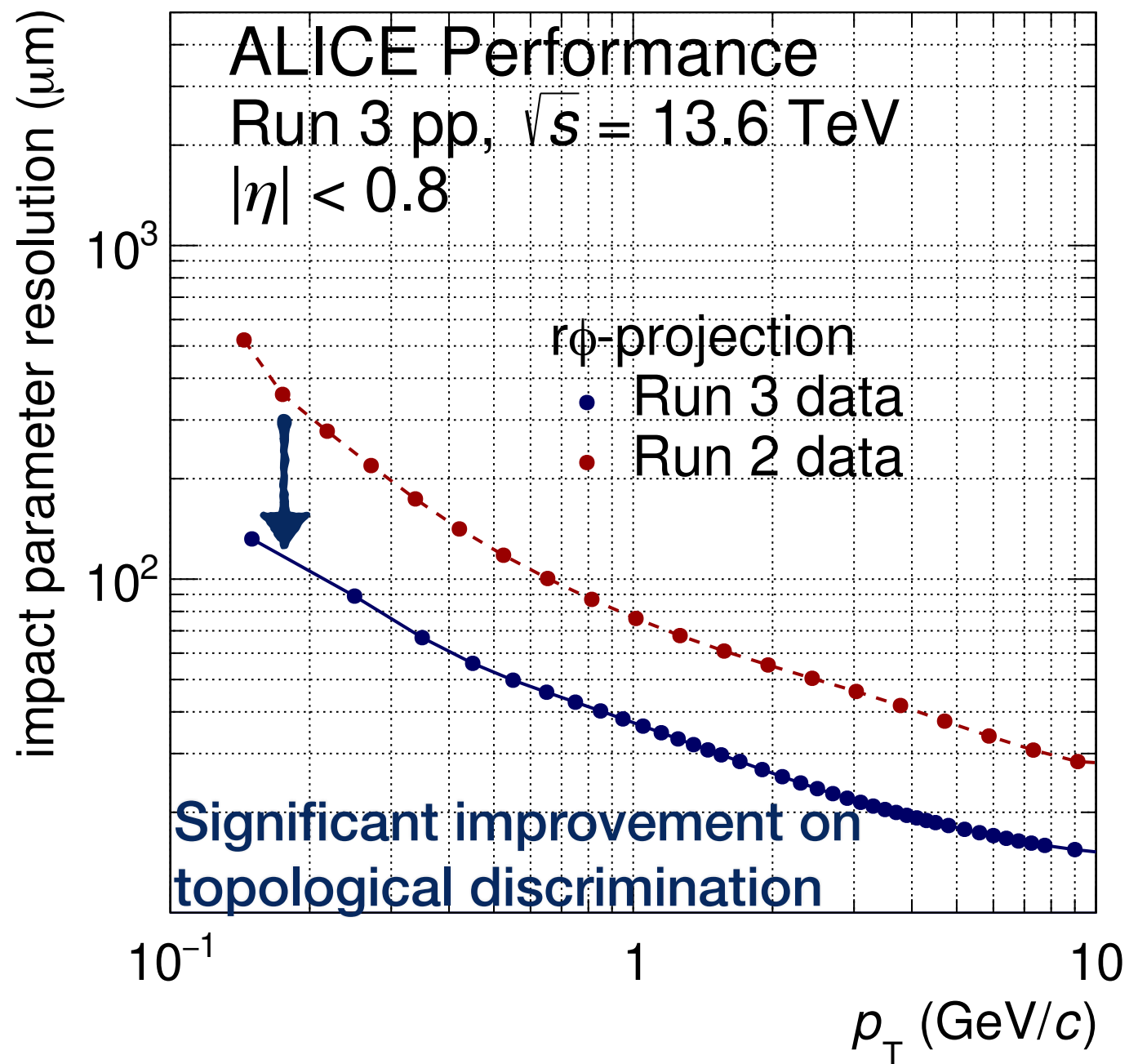


Inner Tracking System 2

- ▶ 7 layer ALPIDE silicon pixels.



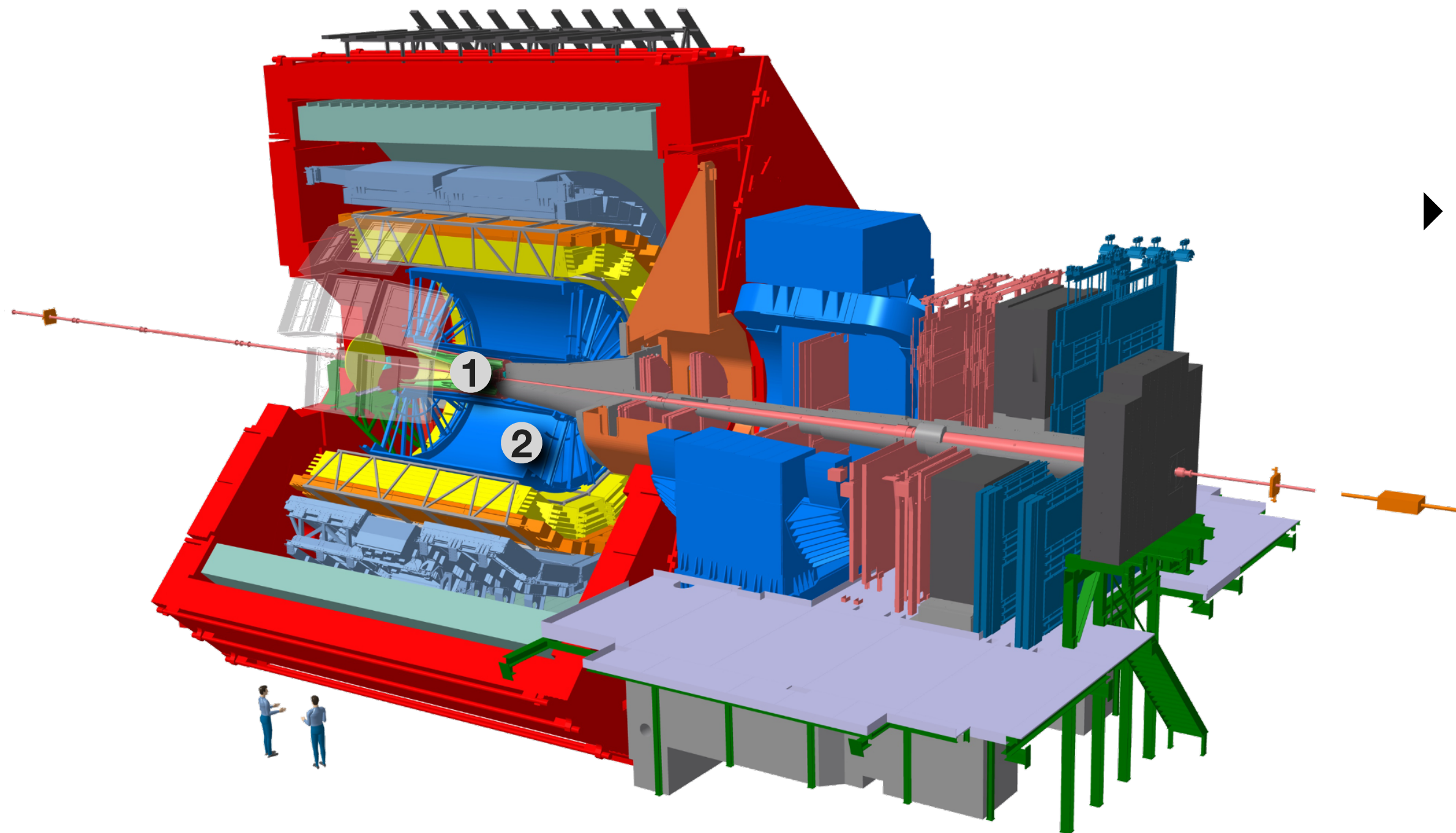
ALI-PREL-571877



ALI-PERF-558822

Data samples

- ▶ 2023 pp collisions at $\sqrt{s} = 13.6$ TeV (4.4 pb^{-1})



[ALICE detector](#)

Selections

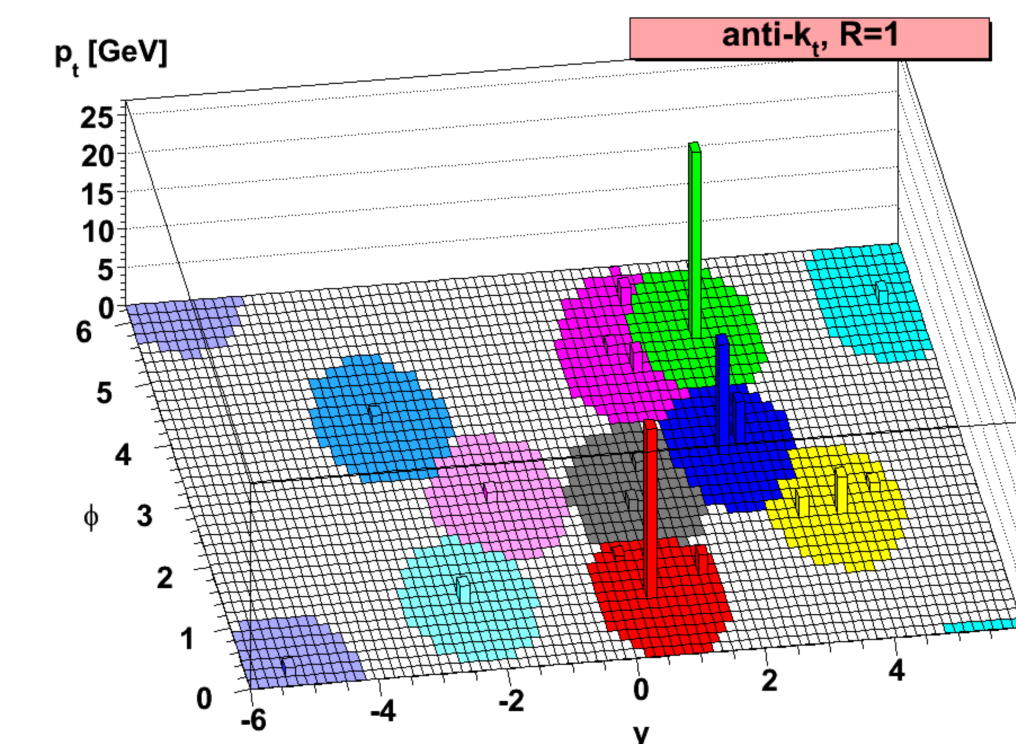
- ▶ **Minimum bias events** with $|z_{\text{vtx}}| \leq 10 \text{ cm}$

1 2

- ▶ **ITS+TPC** charged tracks

with $|\eta| \leq 0.9$ and $0.15 \text{ GeV}/c \leq p_T \leq 100 \text{ GeV}/c$

- ▶ **Jets** reconstructed using anti- k_T algorithm,
with jet resolution parameters $R = 0.2 - 0.6$,
 $|\eta_{\text{jet}}| \leq 0.9 - R$, and $10 \text{ GeV}/c \leq p_{T,\text{jet}}^{\text{ch}} \leq 140 \text{ GeV}/c$.



[Matteo Cacciari et al JHEP04\(2008\)063](#)

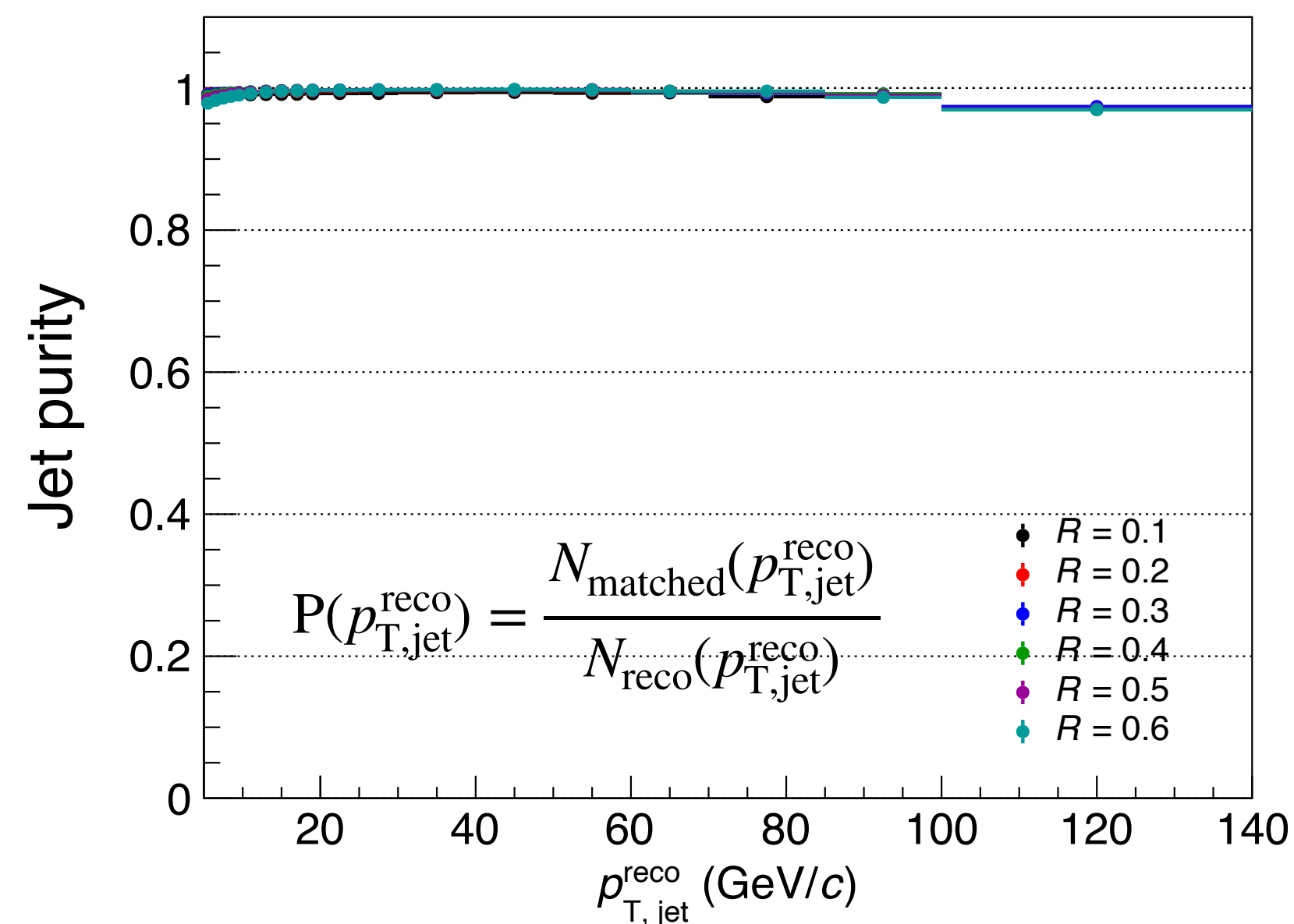
Detector corrections

► Jet matching (geometrical)

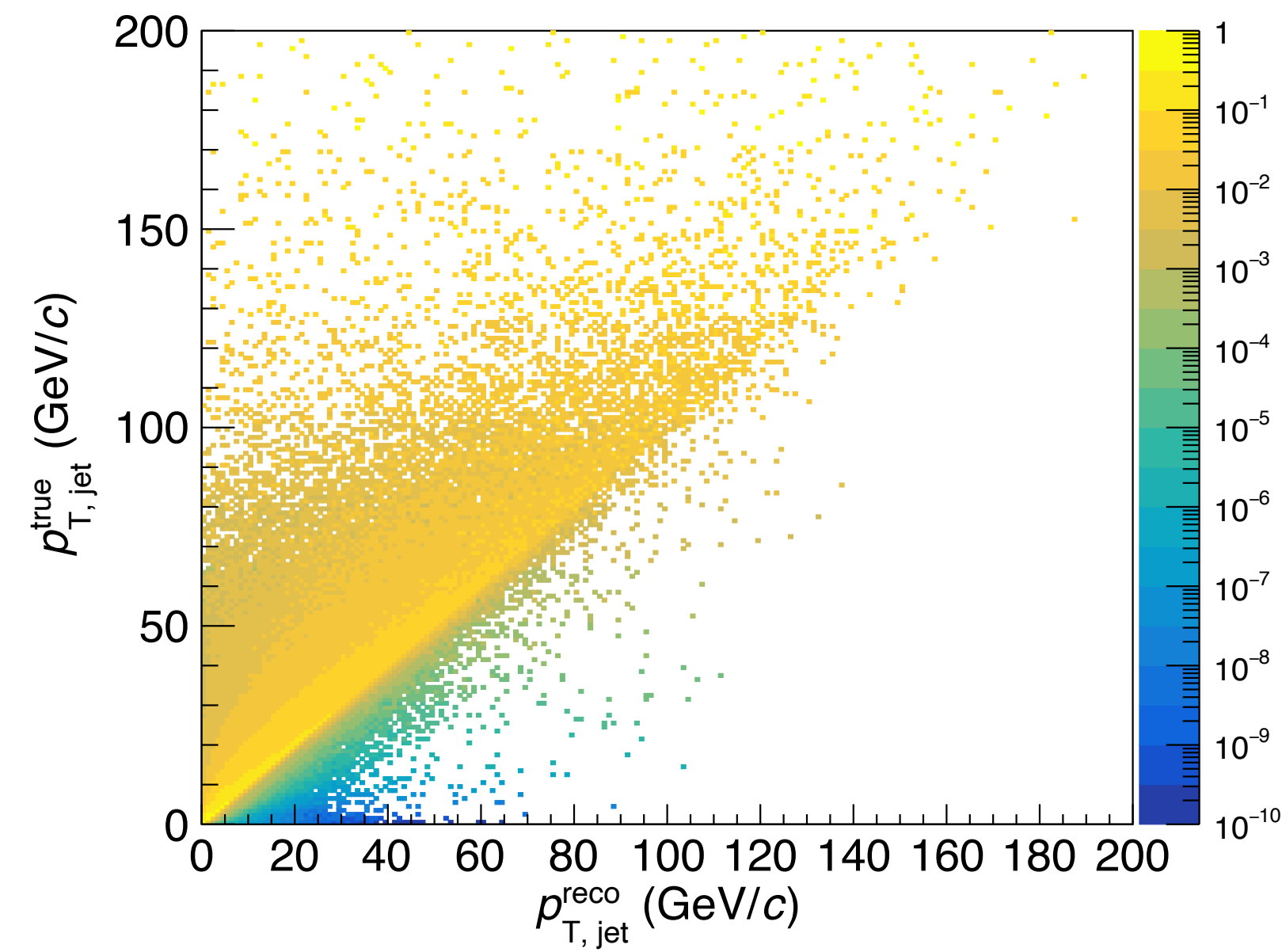
- $\Delta R_{\text{jet axis}} \leq 0.6R$
- $0.5 \leq p_{\text{T, jet}}^{\text{true}} / p_{\text{T, jet}}^{\text{reco}} \leq 2$

► Raw data → **purity correction** → **SVD unfolding** → **efficiency correction** → unfolded results

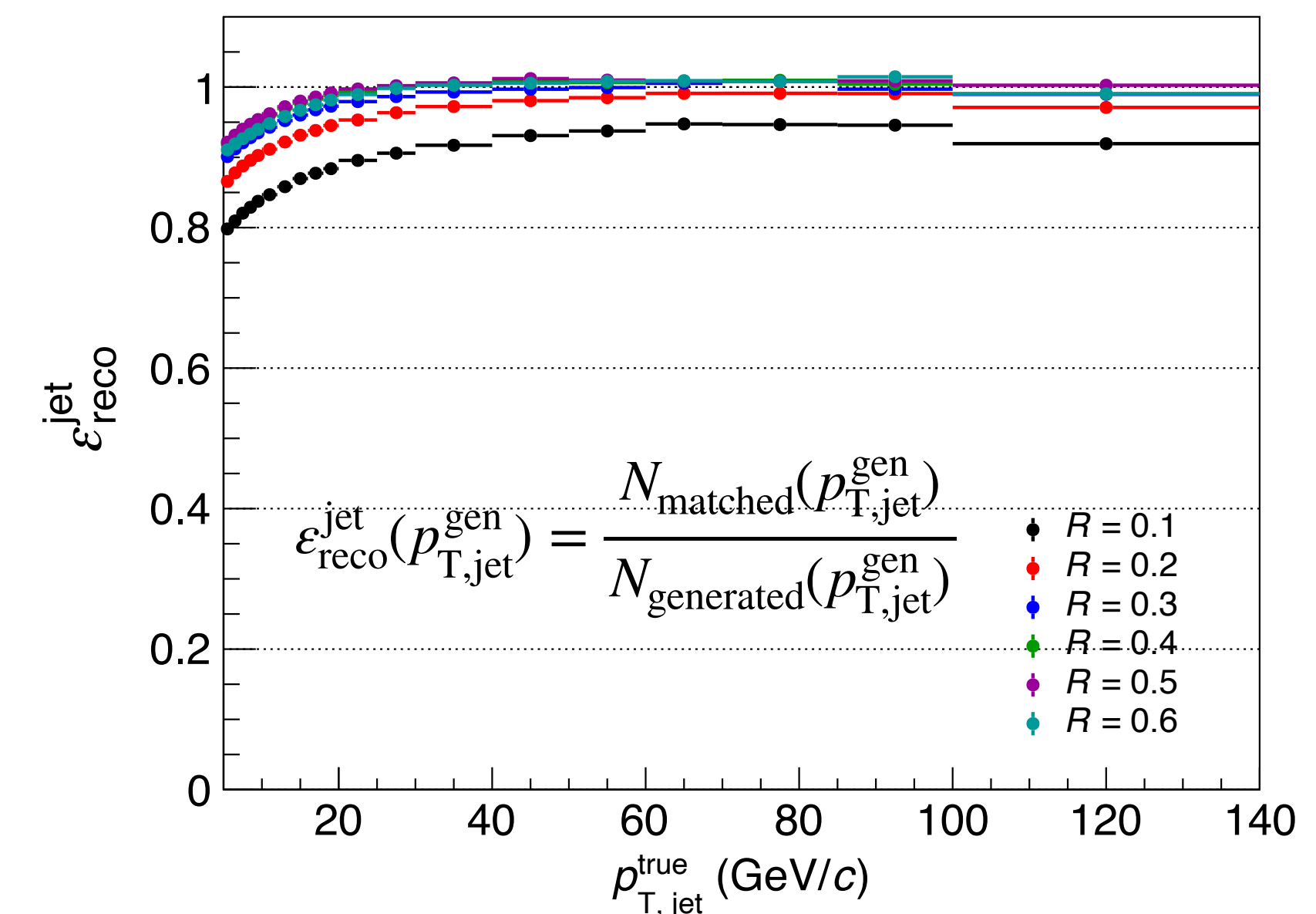
Jet purity



Response matrix (R=0.4)

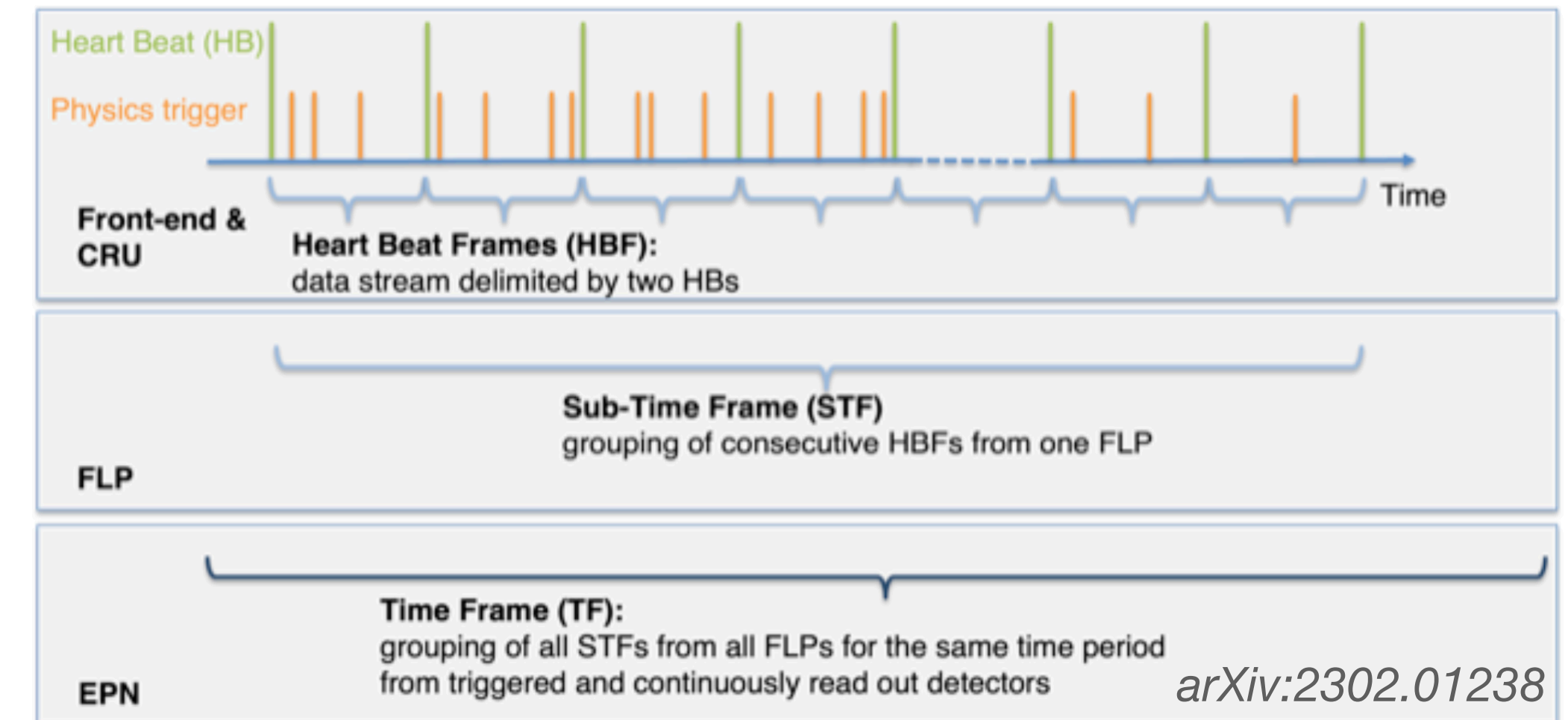


Jet efficiency



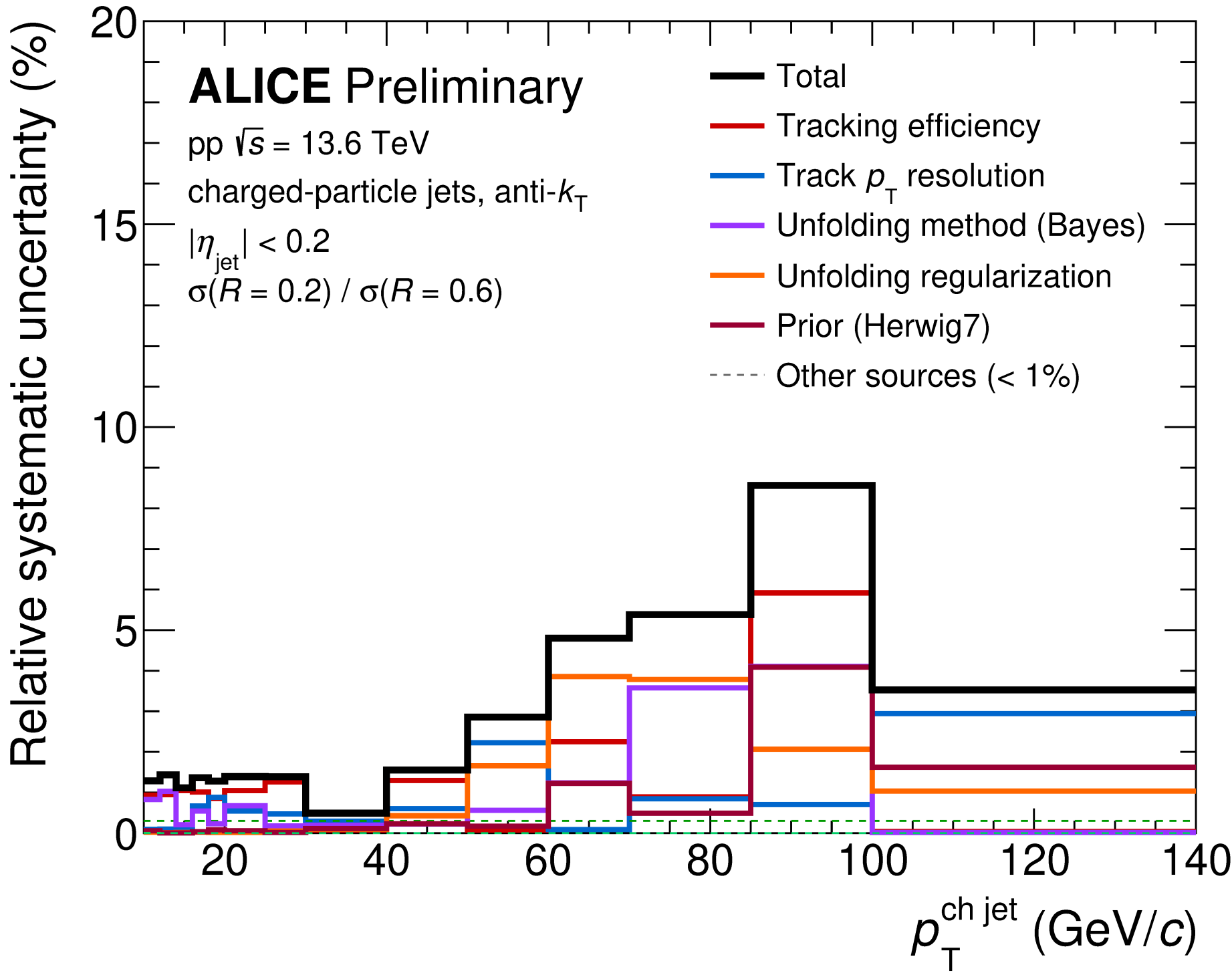
Systematic root: continuous readout

“Run 3's continuous readout delivers the 100× statistics — and is the source of every new systematic.”



- ▶ **Continuous readout** (~500 kHz, offline trigger): **raw data stored first**; tracks & collisions reconstructed offline.
- ▶ **Tracks decoupled from collision** → Run-3-specific effects, hard to model in MC → **no standard reference**.
 - ▶ **Signal loss** (collision-reconstruction efficiency, ~3.5%) → enters normalization.
 - I designed the correction — now in the PWG-JE shared Run-3 chain.
 - ▶ **Track-to-collision association** — ambiguous tracks across pile-up (~5%) → track-level data/MC mismatch.
 - ▶ **Tracking efficiency & p_T resolution**
 - Lead role in WG — data/MC differences (Kalman-covariance & V0-mass cross-checks).
- ▶ All are event-level or R -independent → canceled in $\sigma(R=0.2)/\sigma(R)$.

Systematic uncertainty

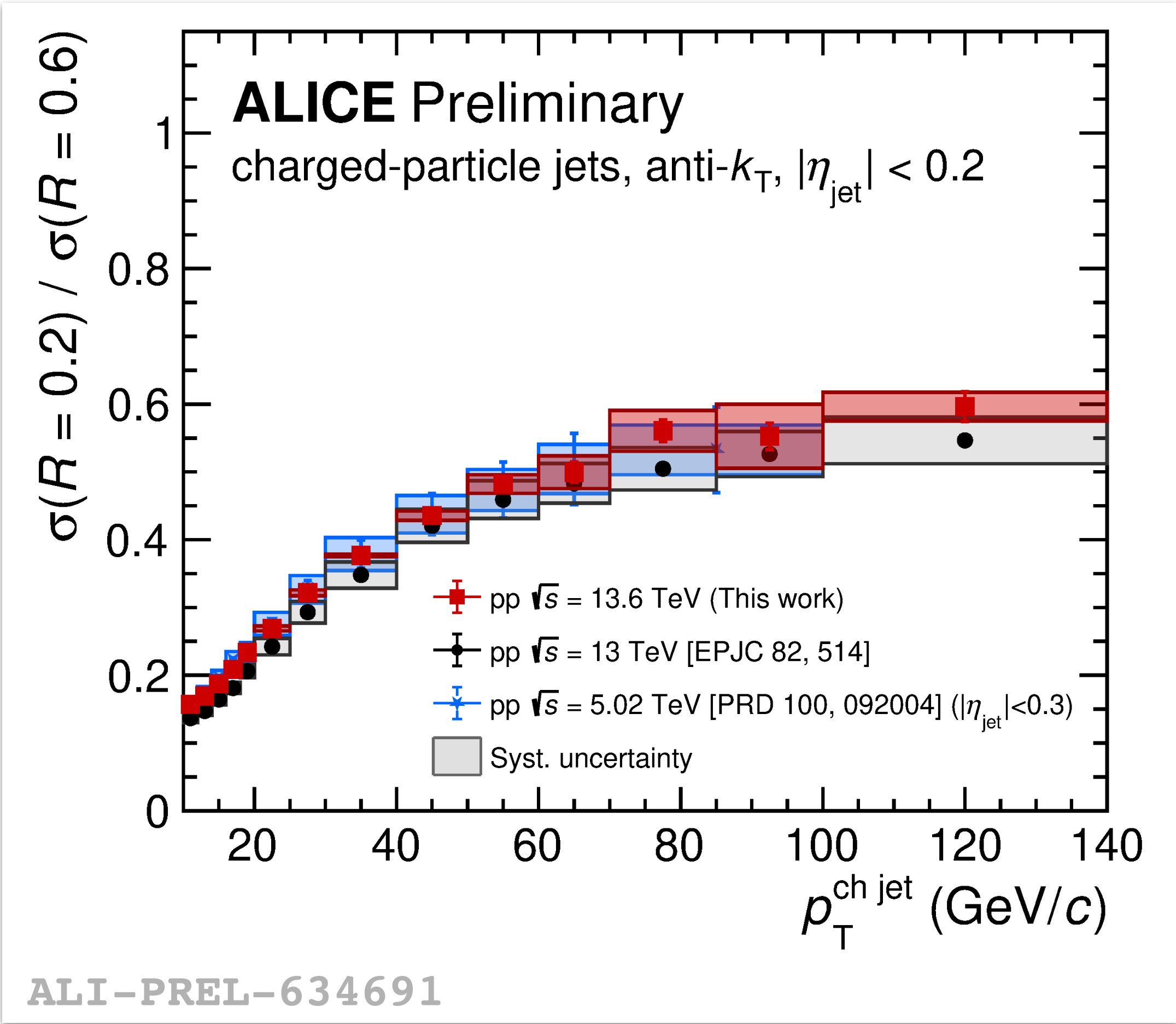


ALI-PREL-634711

- ▶ Full systematic sources are all handled.
- ▶ Most detector and luminosity uncertainties cancel in $\sigma(R = 0.2)/\sigma(R = X)$.
- ▶ Residual uncertainties at 85–100 GeV/c are dominated by low-stat MC unfolding.

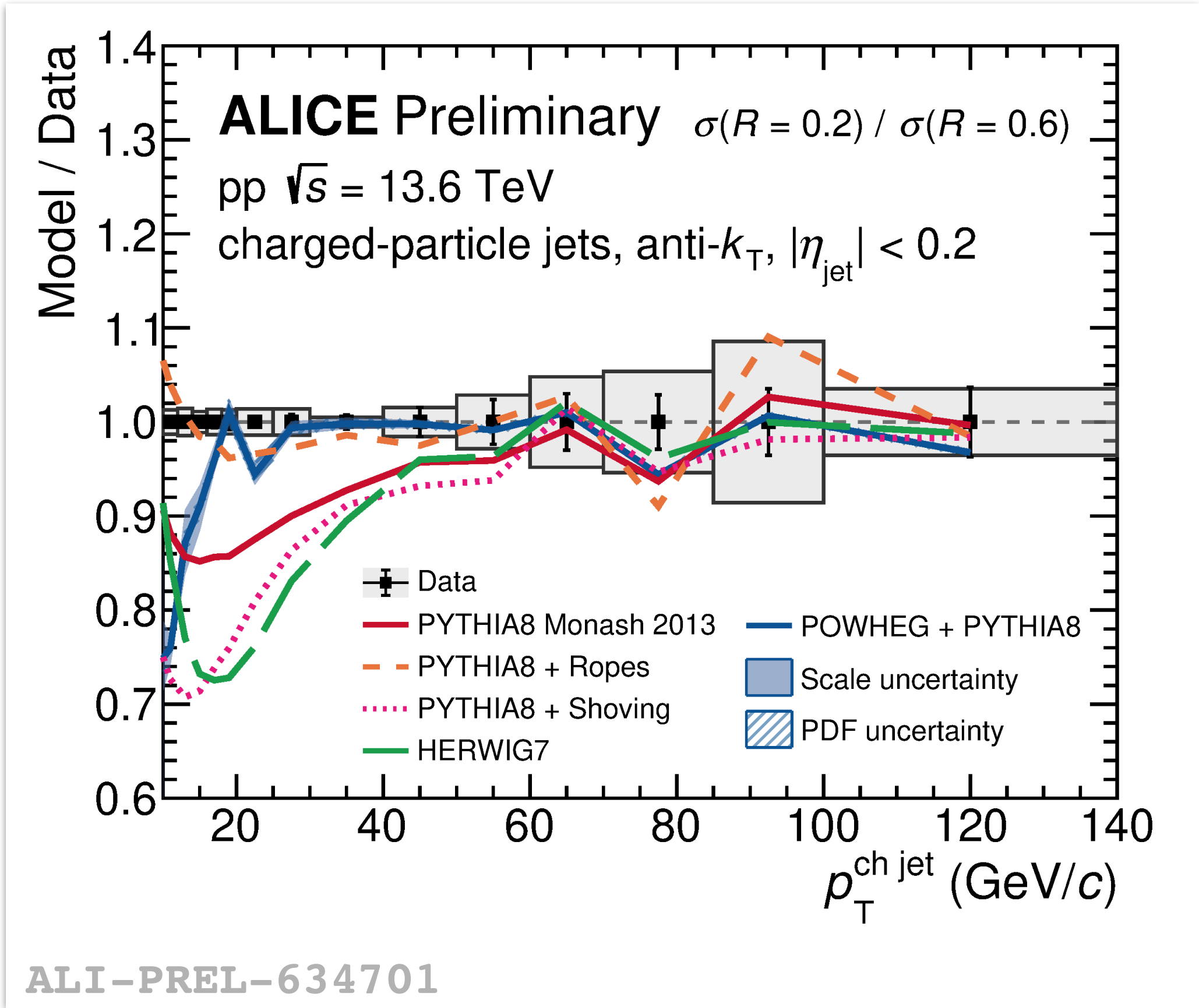
Source	$10 < p_T < 12 \text{ GeV/c}$	$85 < p_T < 100 \text{ GeV/c}$
Tracking efficiency	0.1–0.9 %	4.9–5.9 %
Unfolding method	< 0.8 %	2.9–5.1 %
Unfolding regularization	< 0.1 %	0.4–3.4 %
Prior dependence	< 0.1 %	3.5–5.1 %
Others (track p_T resolution, track-collision association, secondaries, MC closure, jet p_T binning)	< 1 %	< 1 %
Normalization	-	-
Total	0.7–1.3 %	7.0–9.9 %

R-dependent cross section ratios vs. Run 2



- ▶ **First** R-dependent charged-jet cross-section ratios at 13.6 TeV (ALICE Run 3).
- ▶ Detector & luminosity effects largely cancel
→ **discriminator-grade** (ratio syst. 0.7–1.3% at low- p_T)
- ▶ No significant $\sqrt{s}$ dependence (5.02/13/13.6)
→ universal perturbative baseline.
- ▶ **Physics is at low- p_T** — where generators diverge (→ next)

Model comparison (double ratios)



(Model R -ratio) / (Data R -ratio), $R = 0.2/R = 0.3, 0.4, 0.5, 0.6$

- ▶ $\sigma(R = 0.2)/\sigma(R = X)$ vs. pQCD calculations.
- ▶ Overall agreement with models at high- p_T (> 40 GeV/c).
- ▶ Strong **discrimination among soft-QCD predictions at low- p_T** .
- ▶ **Rope** matches best; **Monash** & **Shoving** deviate; **HERWIG** (cluster) deviates, like shoving; **POWHEG NLO** describes well.

PYTHIA8 (Monash 2013)	LO shower + Lund-string fragmentation +MPI
Rope	PYTHIA + density-dependent string overlap (strangeness enhancement in high-mult pp)
Shoving	PYTHIA + string repulsion (Rope family)
HERWIG7	Cluster hadronization + angular-ordered shower (independent generator)
POWHEG + PYTHIA8	NLO matrix element + PYTHIA shower + scale & PDF band

Interpretation

► The tension is non-perturbative

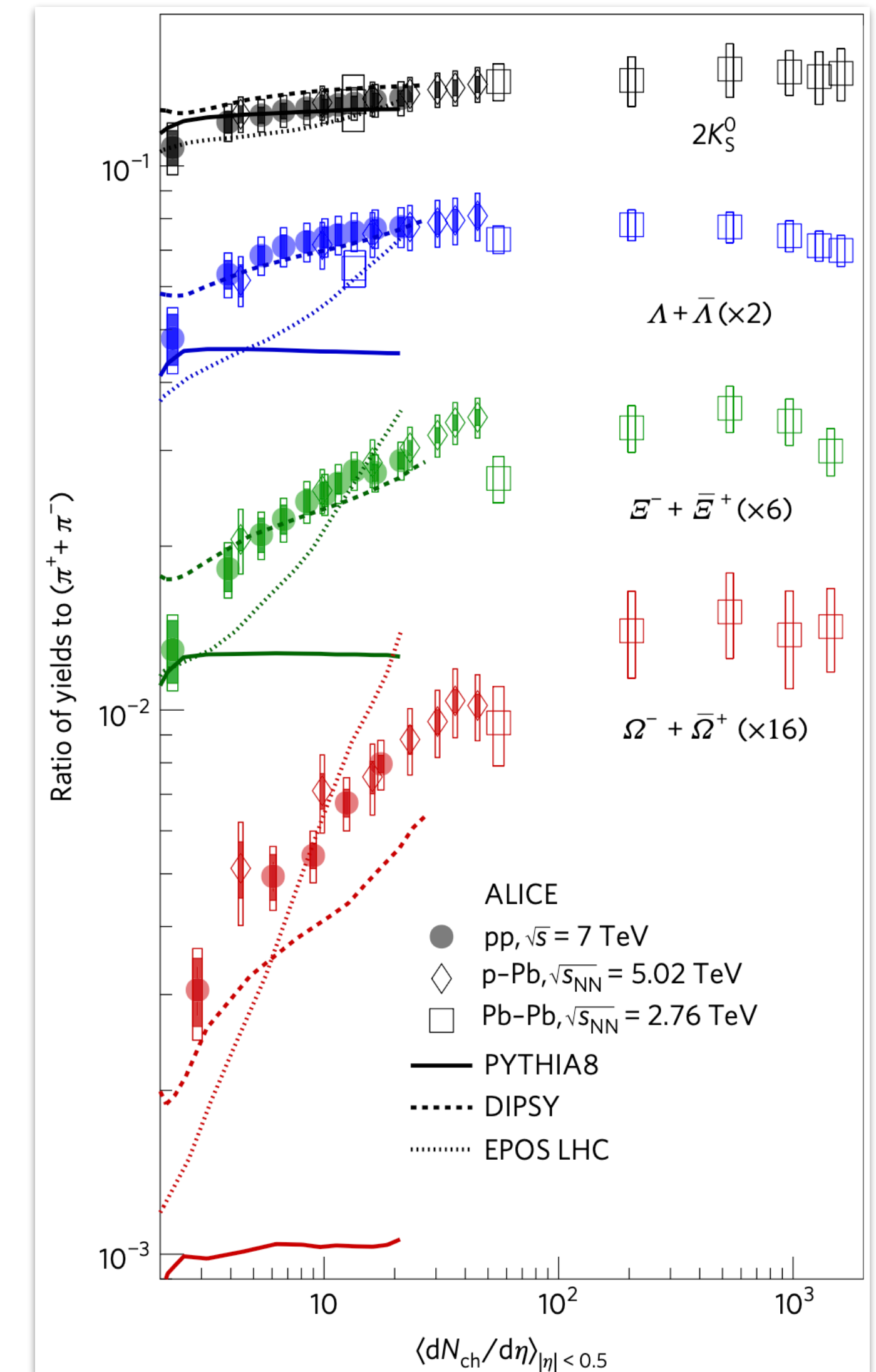
- Above ~ 40 GeV/c, perturbative chain is under control
- Low- p_T / large- R spread is physics
- R -dependence = perturbative + hadronization + UE

► Hadronization drives spread

- **POWHEG NLO** remains stable vs. PYTHIA tune/PDF
- **PYTHIA** tunes share same hard matrix element; spread dominated by hadronization
- **Rope** gives closest description; **Monash**, **Shoving**, and **HERWIG7** all deviate at low- p_T .

► Independent cross-check of density-driven picture

- Rope originally developed for pp strangeness enhancement (Λ/π , Ξ/π , Ω/π) ➡
- A new, flavor-blind test — energy-flow observable (R -ratio).
- Qualitatively consistent with same density-driven hadronization picture.

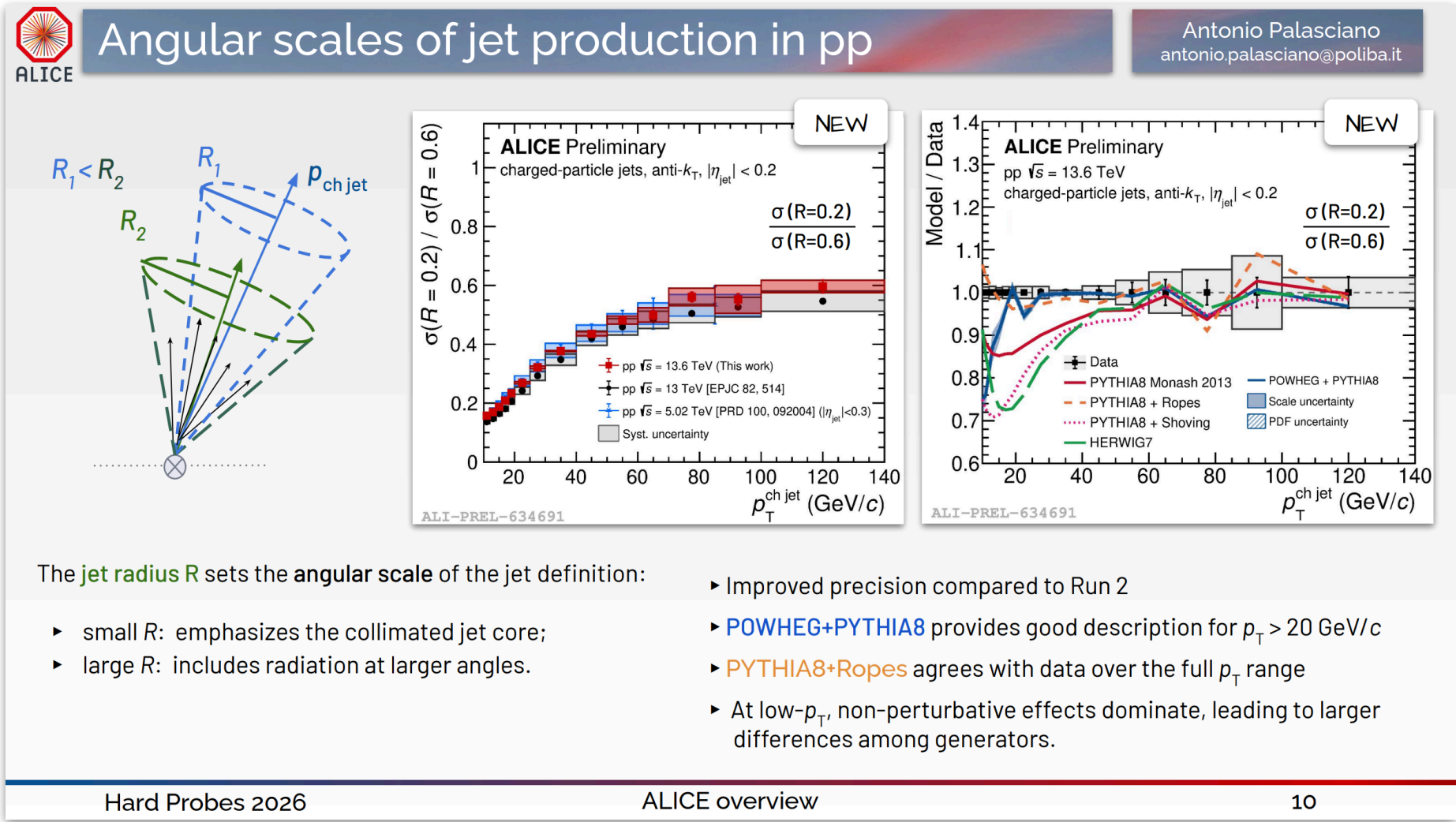


Nature Phys. 13 (2017) 535

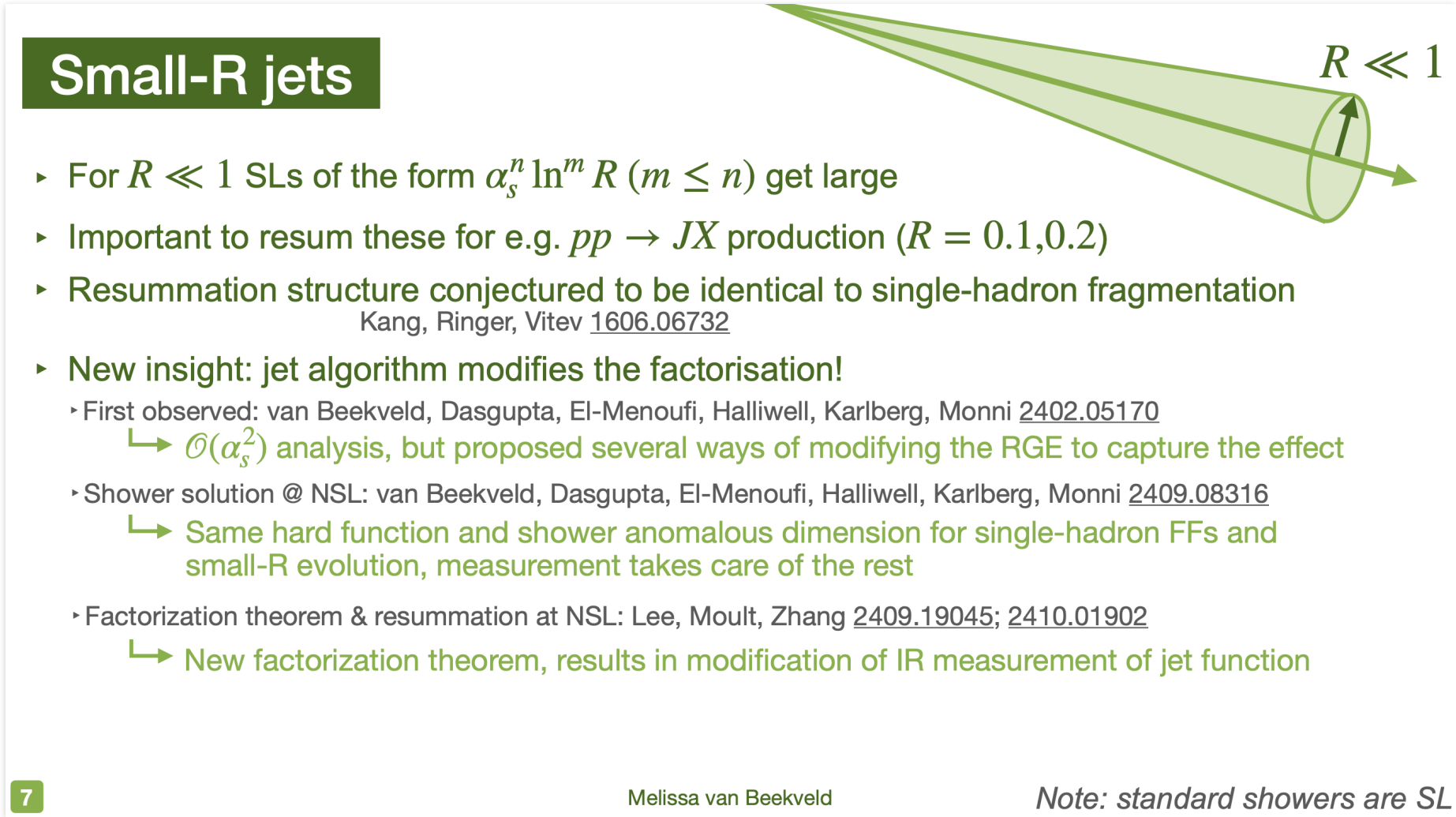
DIPSY (rope) captures rising strangeness.

Recent community impact

- ▶ **EPS-HEP 2025**
 - ▶ Presented on behalf of ALICE (PWG-JE jet merge talk)
- ▶ **HP 2026** — echoed in two experimental & theory plenaries
 - ▶ **ALICE Overview** — $\sigma(R=0.2)/\sigma(R=0.6)$ shown as a new Run-3 result and a hadronization-tune discriminator (Ropes tracks full p_T ; generators diverge at low- p_T)
 - ▶ **pQCD foundations** — same ratio used to motivate small- R resummation ($R=0.1-0.2$) flagged as target.



HP2026 — ALICE overview



HP2026 — pQCD foundations

Summary and outlook

- ▶ **First charged-jet R -ratio** measurement in pp at 13.6 TeV (ALICE Run 3)
 - **discriminator-grade** (syst. cancels in the ratio).
- ▶ **Low- p_T favors density-driven (Rope) hadronization**; NLO POWHEG also describes it.
- ▶ Paper proposal in 2–3 months.
- ▶ Same Run-3 chain now in **O+O jet suppression** (→ next).

Intermediate systems: what does the jet sector say?

(1) Non-perturbative QCD

— hadronization, UE, soft radiation

(2) Small-system jet-quenching signatures

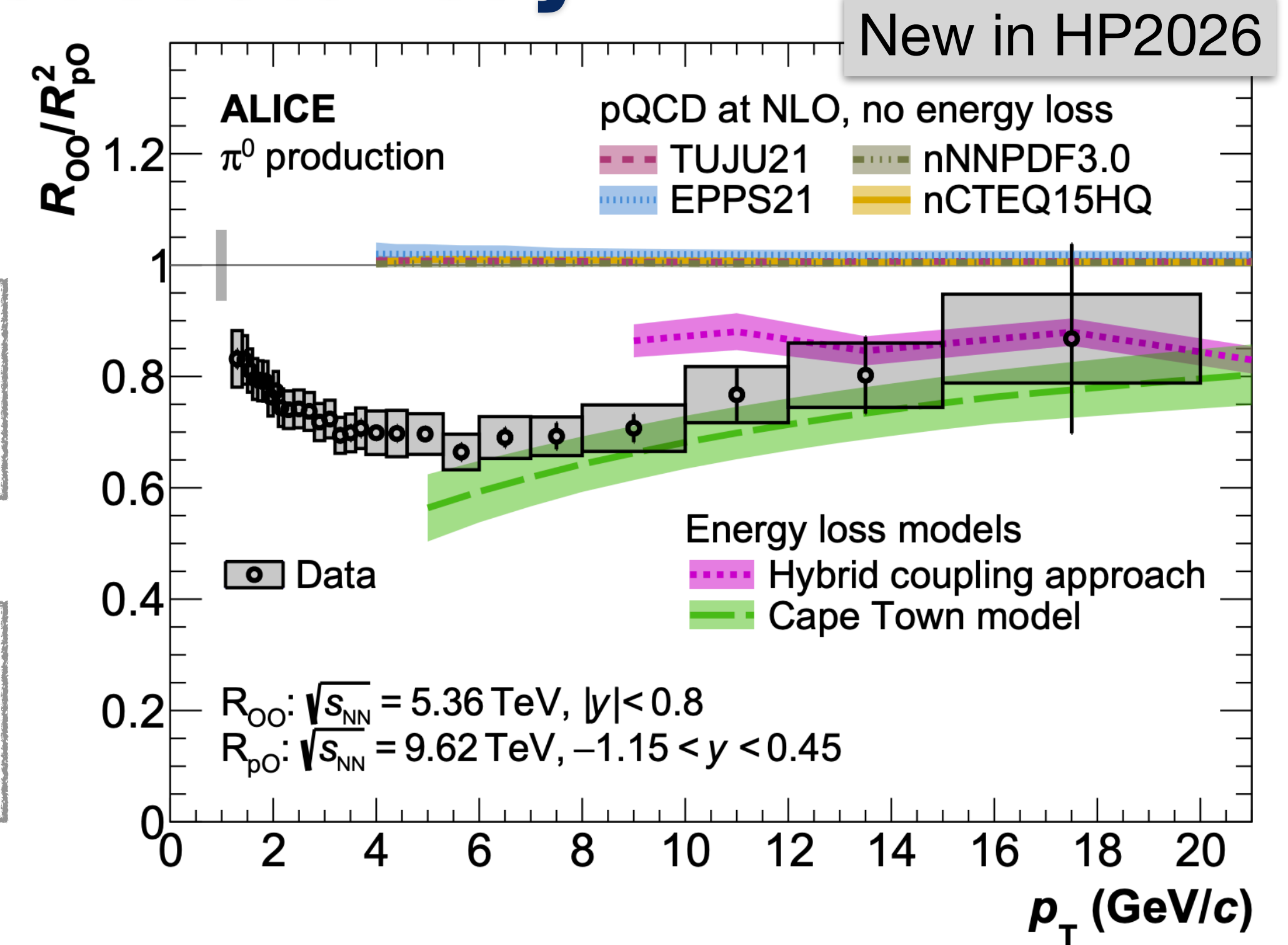
— pp, p—Pb, OO, Ne—Ne

(3) Jet-substructure

— energy correlators (EEC)

$$R_{OO} = \frac{1}{A^2} \frac{\sigma_{OO}}{\sigma_{pp}}$$

$$R_{pO} = \frac{1}{A} \frac{\sigma_{pO}}{\sigma_{pp}}$$

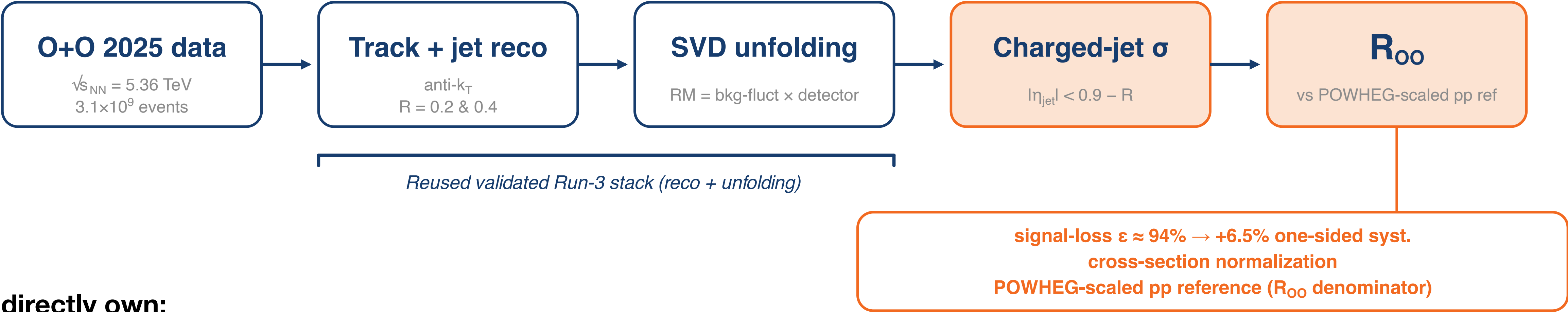


arXiv:2606.19967

- ▶ Hadrons already show it — π^0 R_{OO} : 4.9σ energy-loss evidence (CNM-cancelling double ratio).
- ▶ Jet sector is open gap — only STAR semi-inclusive so far; inclusive R_{OO} not conclusive.
- ▶ **My work 2 (one of primary): ALICE O+O charged-jet R_{OO}** — bridging our pp baseline to Pb+Pb tomography.

Analysis chain & my role

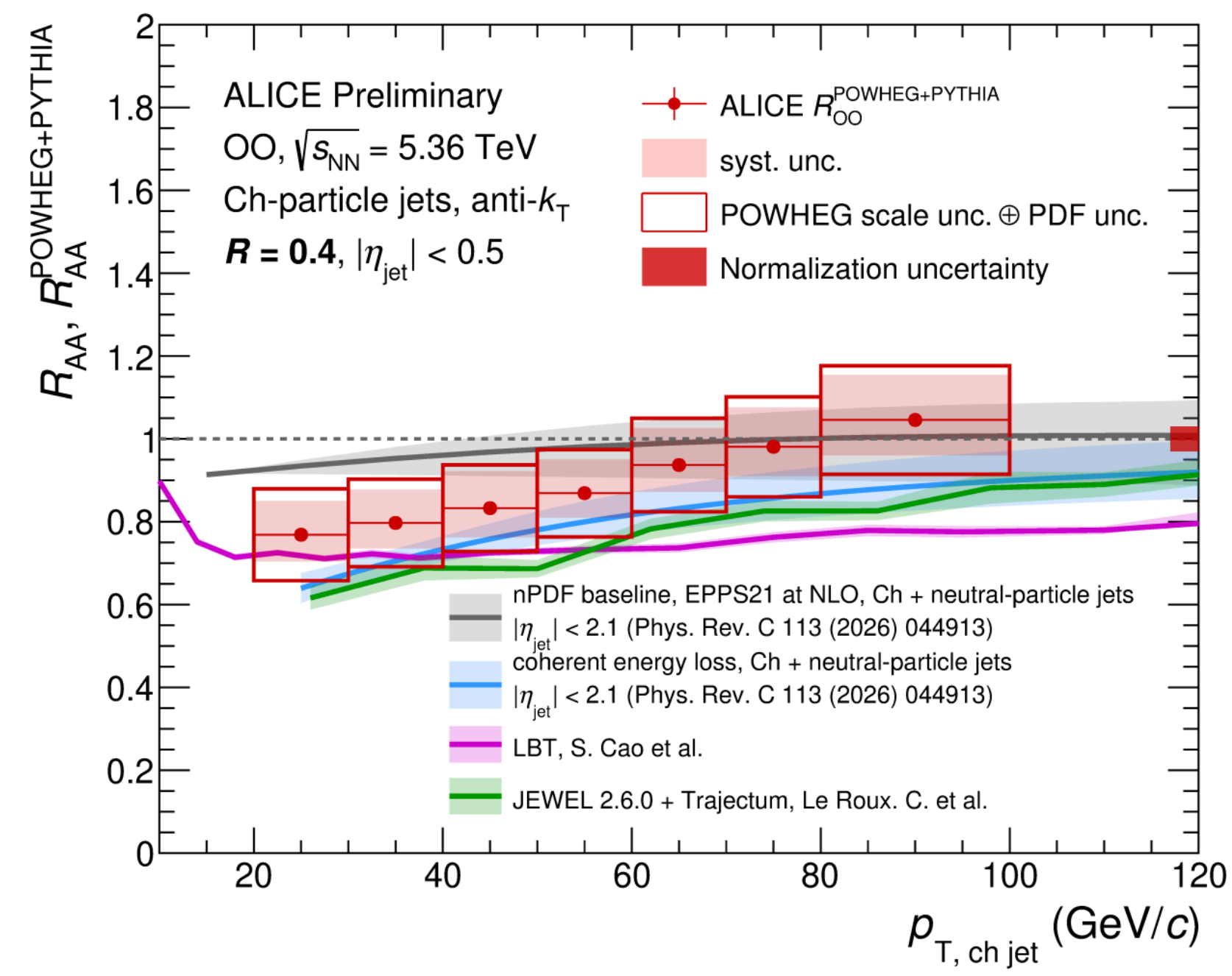
= my ownership



- **I directly own:**
- Share workflow and macros I use in pp measurements.
 - Signal-loss correction — **naive $\epsilon \approx 82\%$ (~18% loss) double-counted event selection; I re-derived it cleanly to $\epsilon \approx 94\%$ (~6%), carried as a +6.5% one-sided systematic (not a correction)**
 - Senior analysis role — mentored MSc lead analyzer (W.Ham) through the full chain; PC + AN member
 - POWHEG pp reference (R_{OO} dominator)

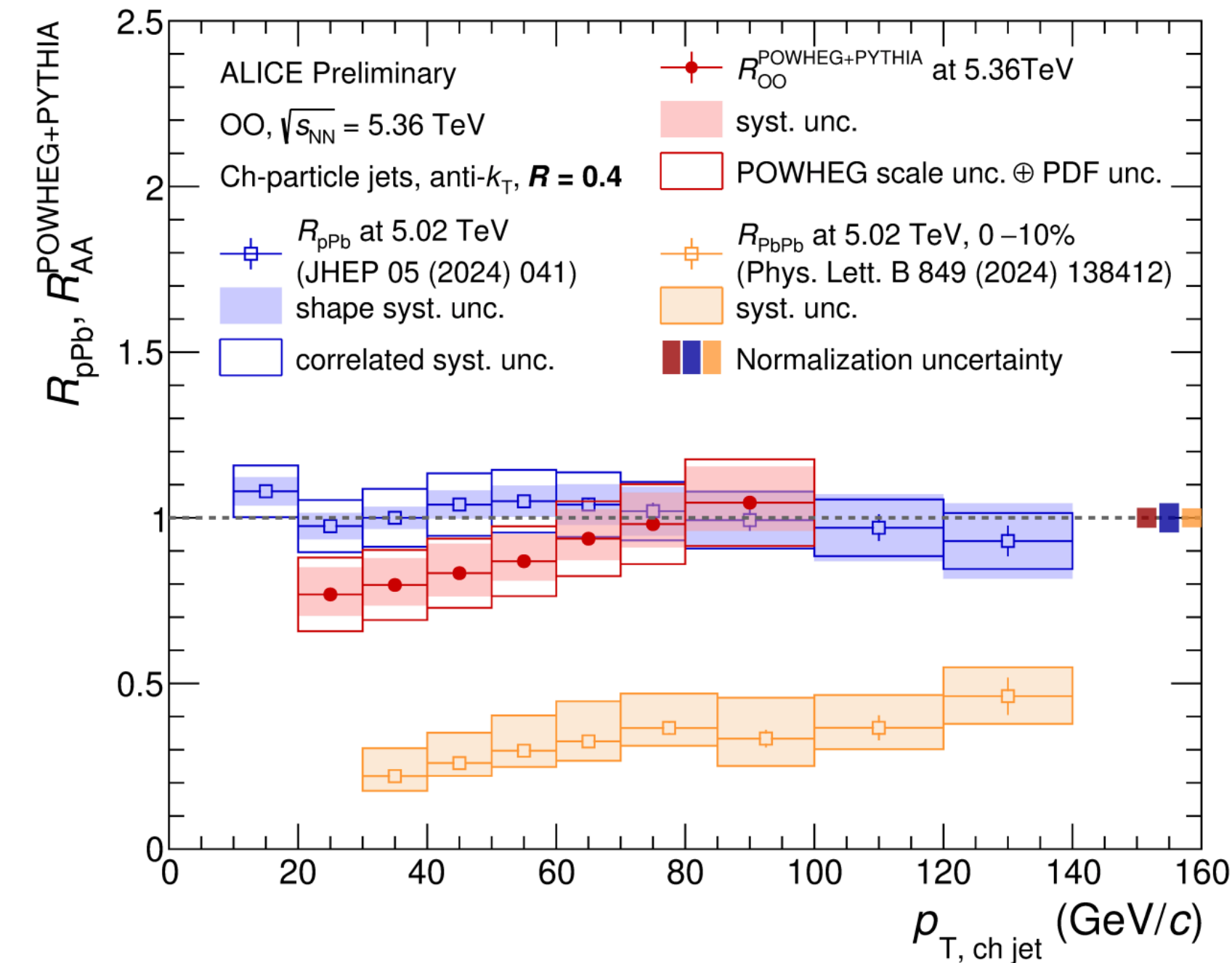
HP 2026 result

Comparison with model predictions ($R=0.4$)



ALI-PREL-635348

System-size comparison ($R=0.4$)



ALI-PREL-635358

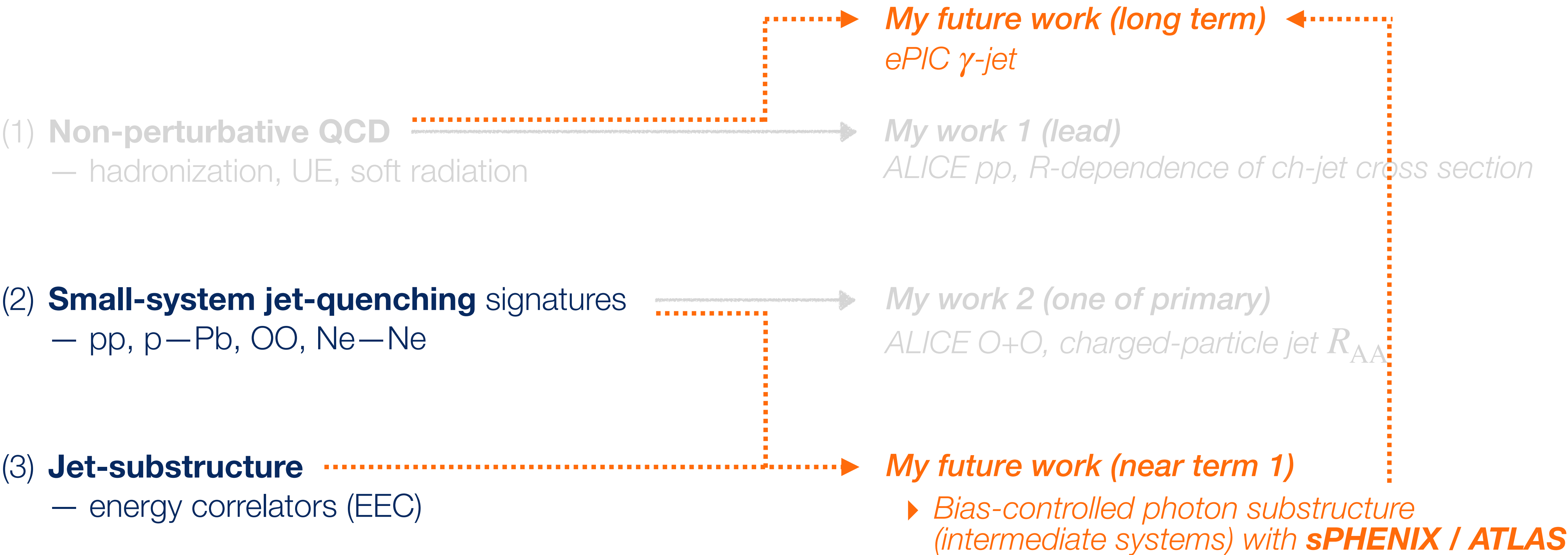
- ▶ **Charged-jet R_{AA} : not yet separable** from the with/without quenching models.
- ▶ **Consistent with the field** — our inclusive jet R_{OO} + ATLAS not conclusive; only **STAR** semi-inclusive shows a clear jet-sector signal [arXiv:2604.13935].
- ▶ Reference is POWHEG+PYTHIA for now; my signal-loss enters as a +6% one-sided systematic, not a correction.

Outlook

- ▶ Finalize the pp 5.36 TeV reference (I am contributing this analysis as well)
 - **data-driven** R_{OO} , replacing the POWHEG-scaled denominator
- ▶ Cross-check with **Ne+Ne** (2025 data) — system-size dependence
- ▶ Differential next — **jet substructure** (→ next section)

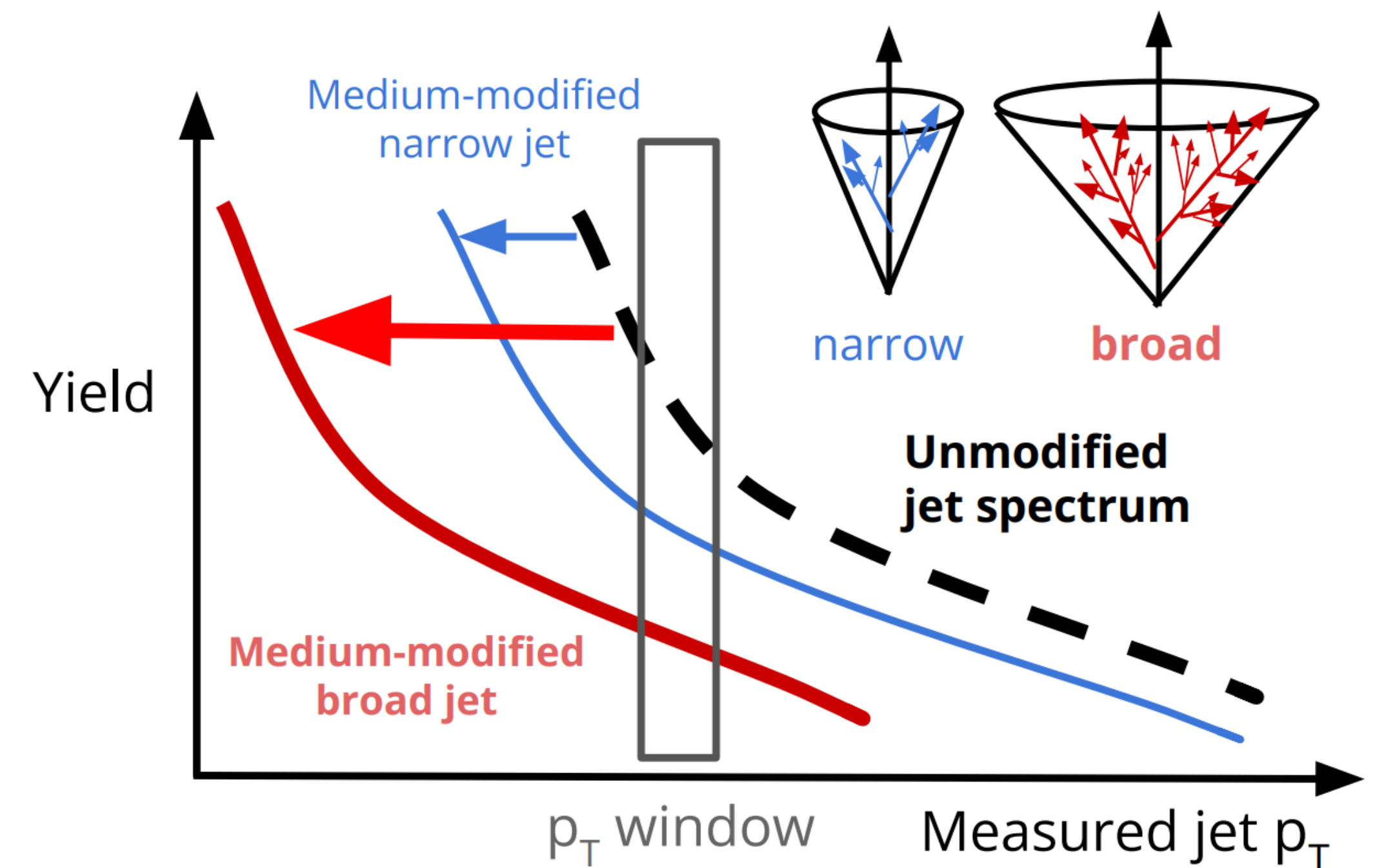
Three frontiers → future map

“Where classical methods plateau — soft QCD, bias, observable complexity — is where my next work, and this group's tools, are aimed.”



Sharpest probe — and biases its own community maps

- (1) **Non-perturbative QCD**
— hadronization, UE, soft radiation
- (2) **Small-system jet-quenching** signatures
— pp, p—Pb, OO, Ne—Ne
- (3) **Jet-substructure**
— energy correlators (EEC)



arXiv:2405.02737

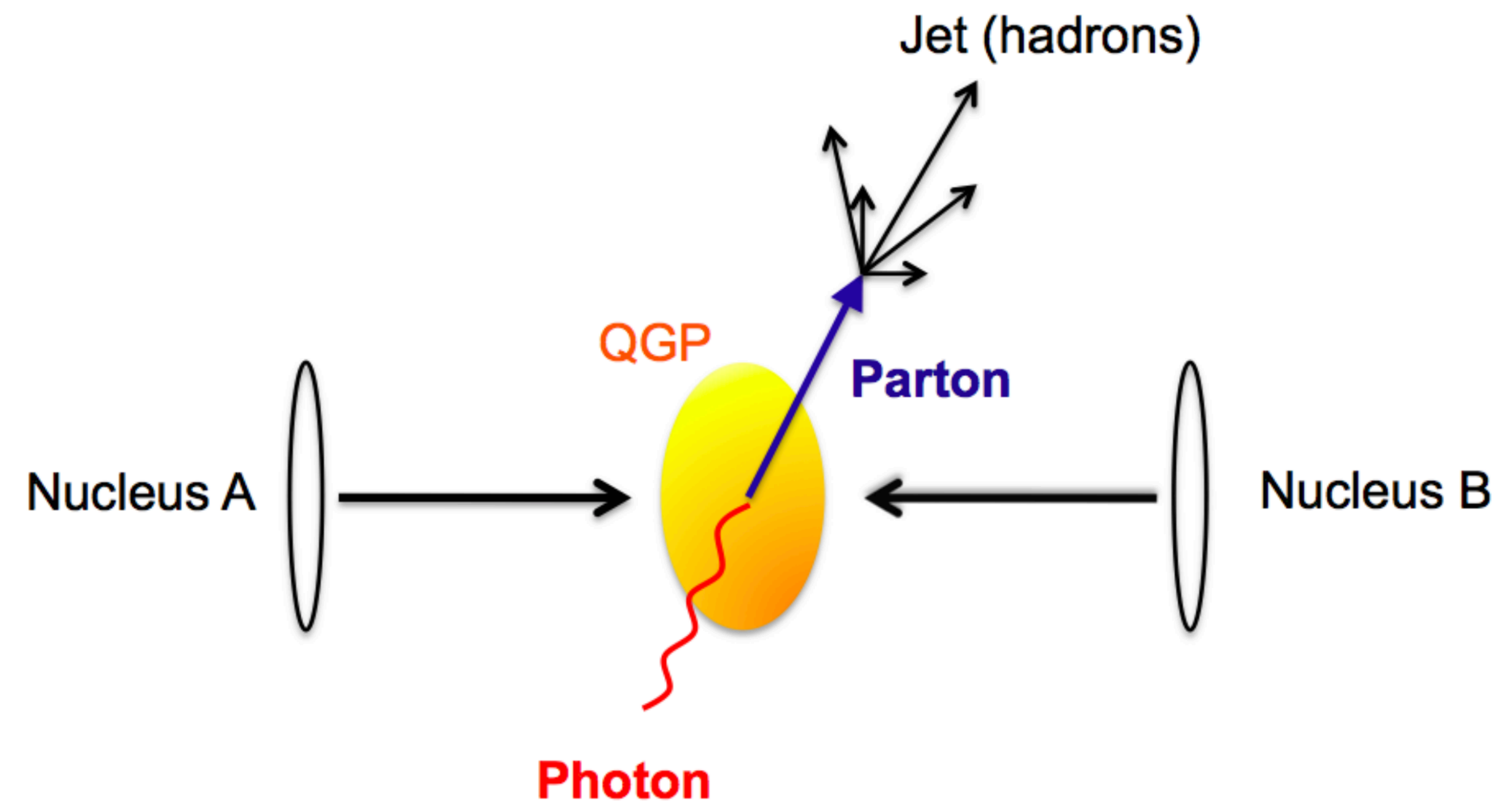
- ▶ **Sharpest probe** — EEC resolves the jet angle-by-angle.
- ▶ **Selection/survivor bias** — we keep less-quenched, narrower survivors; the "narrowing" is partly selection, not per-jet modification. [Madureira PRD 112 054018]
- ▶ **Large-angle ambiguity** — medium radiation vs. background populate same wide angles. [Havener HP2026]
- ▶ **Sharper resolution ≠ more control** — wall is bias, not statistics. → **AI/ML: *My future work (near term 2)***

Near term 1: Jet substructure in intermediate system

— γ +tagged, jet shape $\rho(r)$, with sPHENIX / ATLAS

► Why photon-tag (γ -jet)?

- Prompt γ escape medium unmodified
→ tags initial parton kinematics
- Hard scale is fixed independently of recoil jet
→ **suppresses survivor and selection biases**
- γ +jet shape
→ bias-controlled probe of jet modification

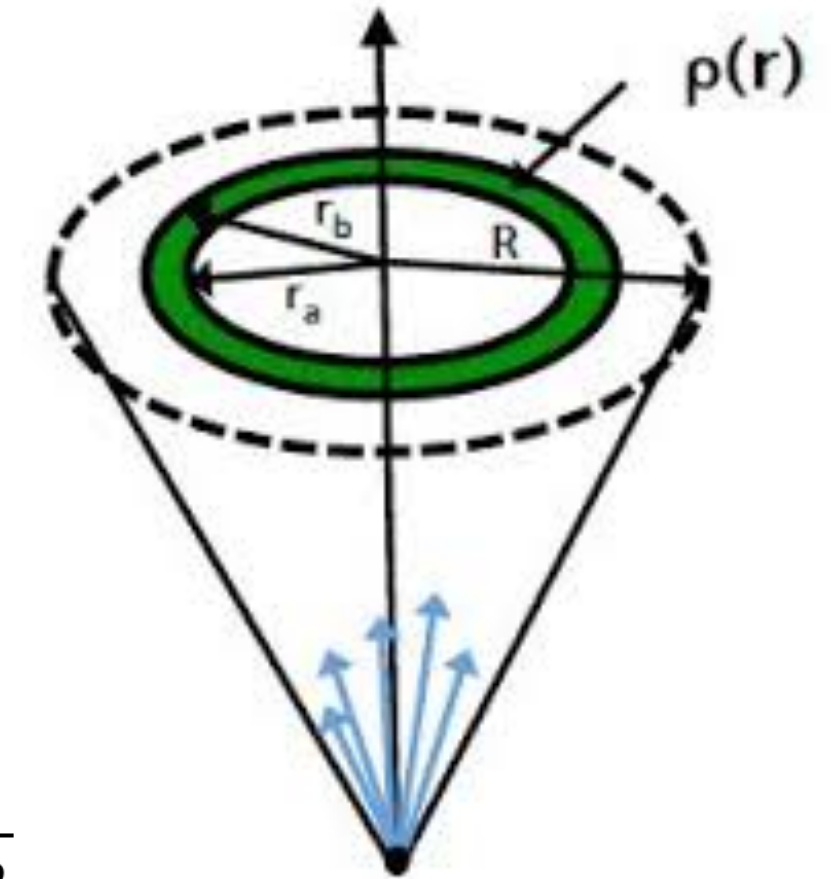


Near term 1: Jet substructure in intermediate system

— γ +tagged, **jet shape** $\rho(r)$, with sPHENIX / ATLAS

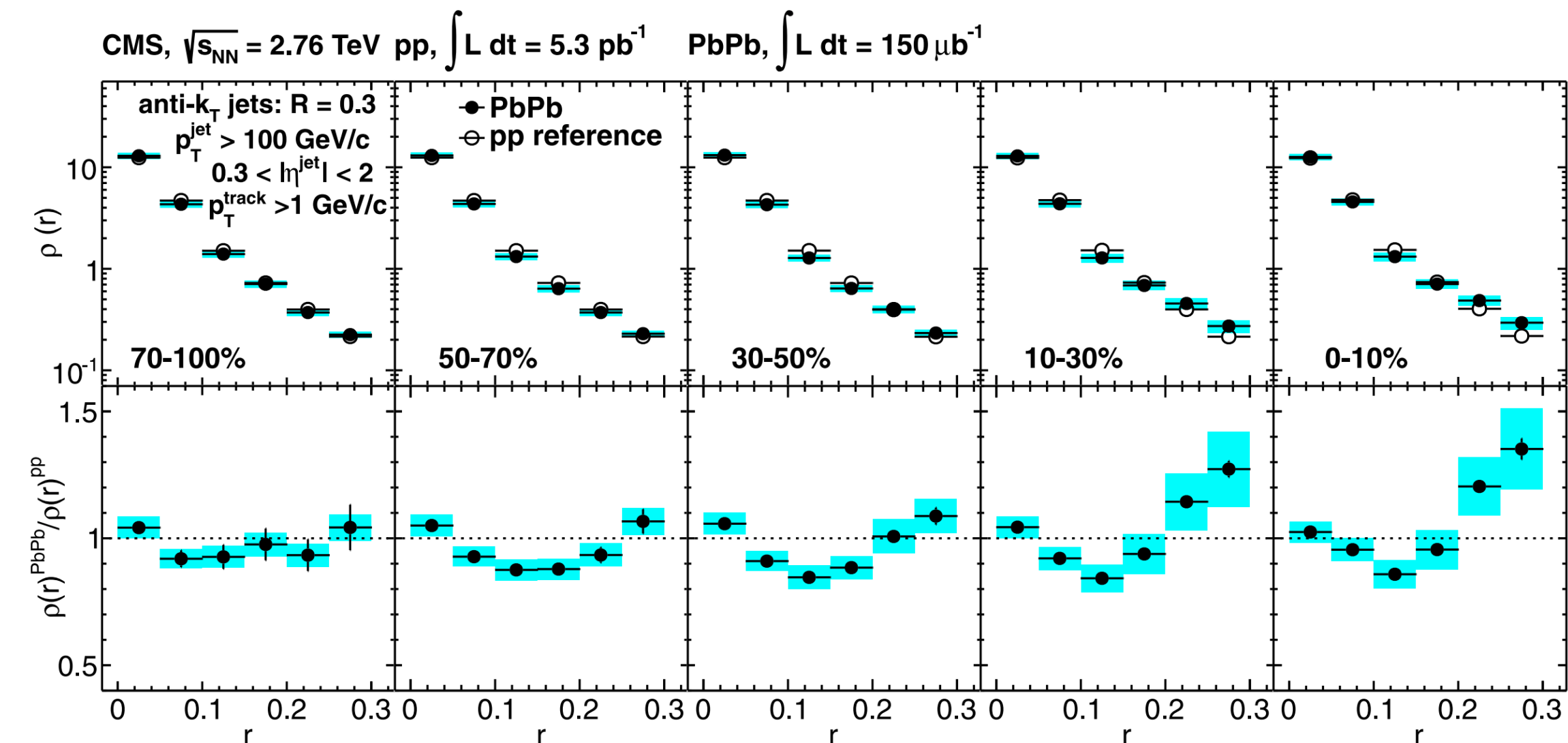
► Why Jet-shape $\rho(r)$?

- **Radial energy profile** — p_T vs. distance r from the axis ($r=0$ core $\rightarrow r=R$ edge); quenching depletes the core, fills the periphery.
- **Interpretation-robust** — a plain "where is the energy" profile; no correlator small-/large-angle ambiguity like the EEC.
- **Bias-controlled by design**
 - two residual biases are handled by the other pieces: selection bias $\rightarrow \gamma$ -tag;
 - large- r underlying event $\rightarrow$ **ML subtraction**.



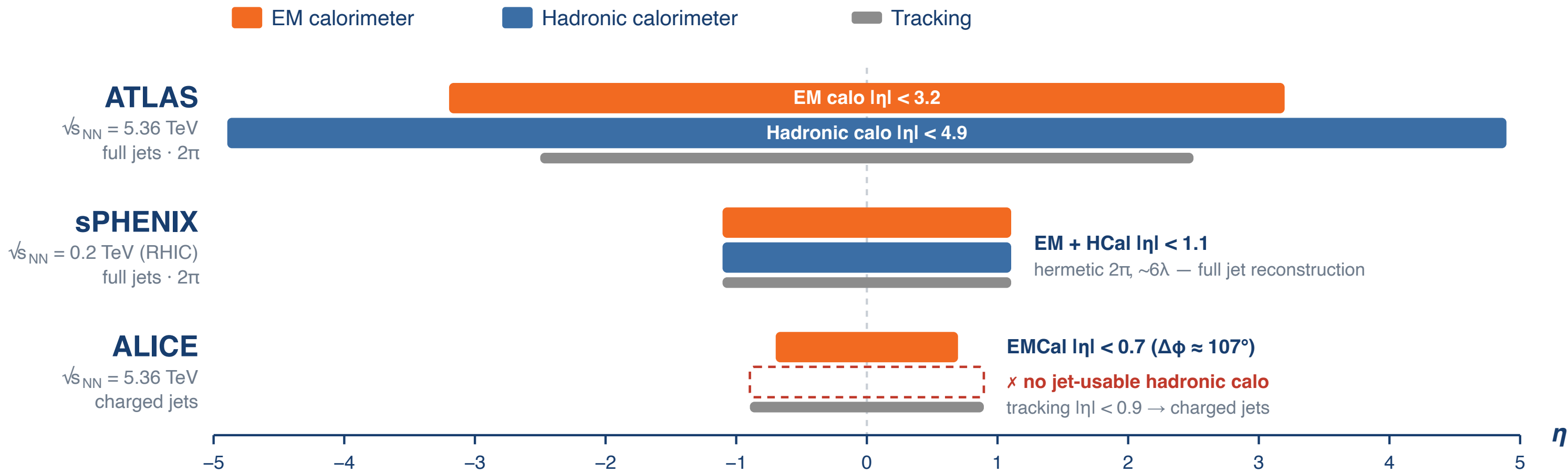
$$\rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in [r_a, r_b]} p_T^{\text{track}}}{p_T^{\text{jet}}}$$

$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$



PLB 730 (2014) 243-263

Near term 1: Jet substructure in intermediate system — γ +tagged, jet shape $\rho(r)$, with **sPHENIX / ATLAS**



Photon-tagged **calorimetric** jets need hermetic calorimetry — sPHENIX & ATLAS, not ALICE's charged jets.

RHIC (sPHENIX) $\times$ LHC (ATLAS) = a $\sqrt{s}$ lever arm across system size.

► Why sPHENIX/ATLAS?

- Photon-tagged jets require **large-acceptance calorimetry** and **full jet** reconstruction.
- **ALICE** is optimized for tracking and charged jets, while **sPHENIX** and **ATLAS** were built for exactly this program.
- Recent O+O γ -hadron in **ATLAS** already open door to cross-experiment comparisons [ATLAS-CONF-2026-007].
- **RHIC** $\times$ **LHC** provides a unique system and energy lever arm for jet-quenching & energy-loss studies.

Longer term: EIC, anchored by KoBIC hardware



Pb/Sci module (30 mm x 30 mm x 320 mm, 4x8 units)

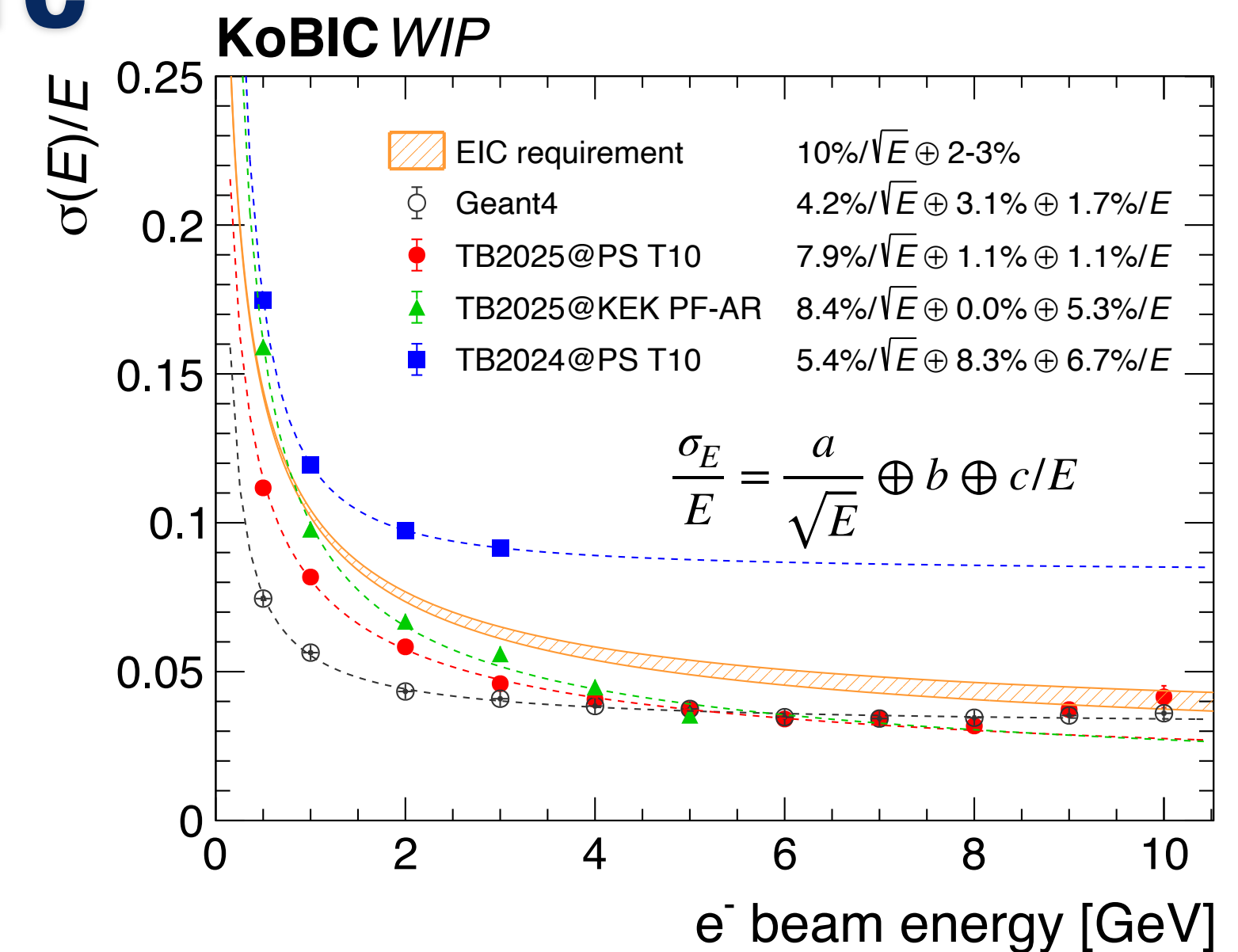
► Why **ep**

- Proton is not fully under control; ep DIS is the cleanest, model-light probe of same proton.
- photon detector (EMCal)

► What I did

- Module assembly + PMT-QA lead; DAQ shifter & prompt analysis (KEK) + lead offline analyst (CERN PS T10)
- Meets the ePIC barrel spec ($\sigma(E)/E \approx 7-8\%/\sqrt{E}$); first test-beam paper submitted (arXiv:2604.22647)
- Two following papers ongoing

Deposited energy resolution



Test-beam @ CERN PS T10 (July 2025)

Why this group

- ▶ Natural intersection
 - ▶ **Small-system jet substructure** — extends my R_{OO} .
 - ▶ **Photon-tagged observables** — fit to **sPHENIX / ATLAS**.
 - ▶ **ePIC R&D + BNL geography** — extends my **KoBIC hardware work**.
- ▶ **Enabling: AI/ML — attacking bias at every layer — *My future work (near term 2)***
 - ▶ **Background** → label-free UE subtraction — cycle-GAN (2510.23717); wins where area-based plateaus (large-r, central)
 - ▶ **Observable** → beyond hand-engineered observables (each partial, each biased): task-agnostic, transferable, data-efficient representations — FM4NPP. Its edge is largest in the low-label regime — exactly intermediate-system (O+O/Ne+Ne) data I work with. This is prof. Go's flagship program and where I'd primarily contribute.
 - ▶ **My contribution** — identifying relevant physics biases and validating result as a robust measurement.

Summary

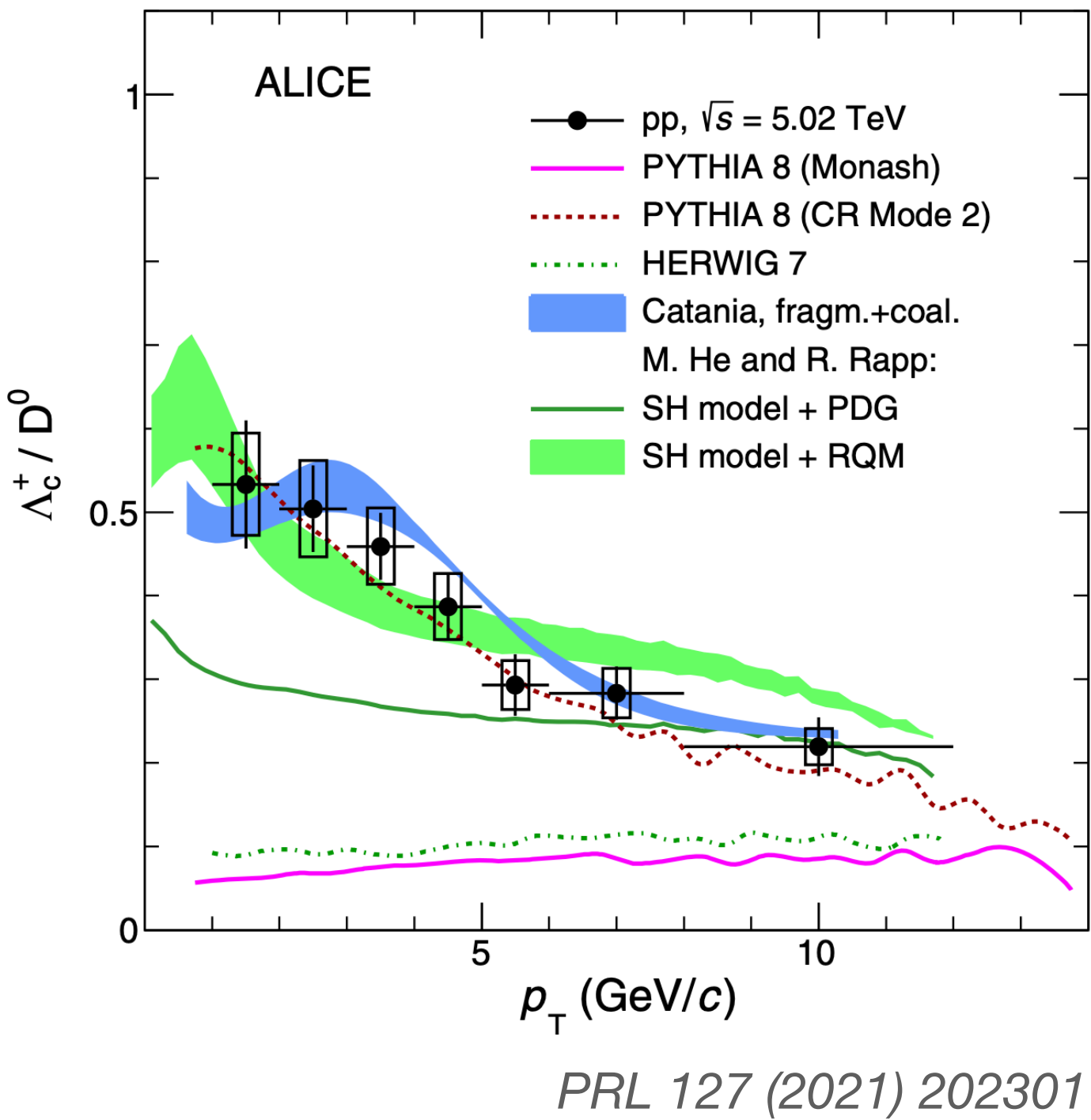
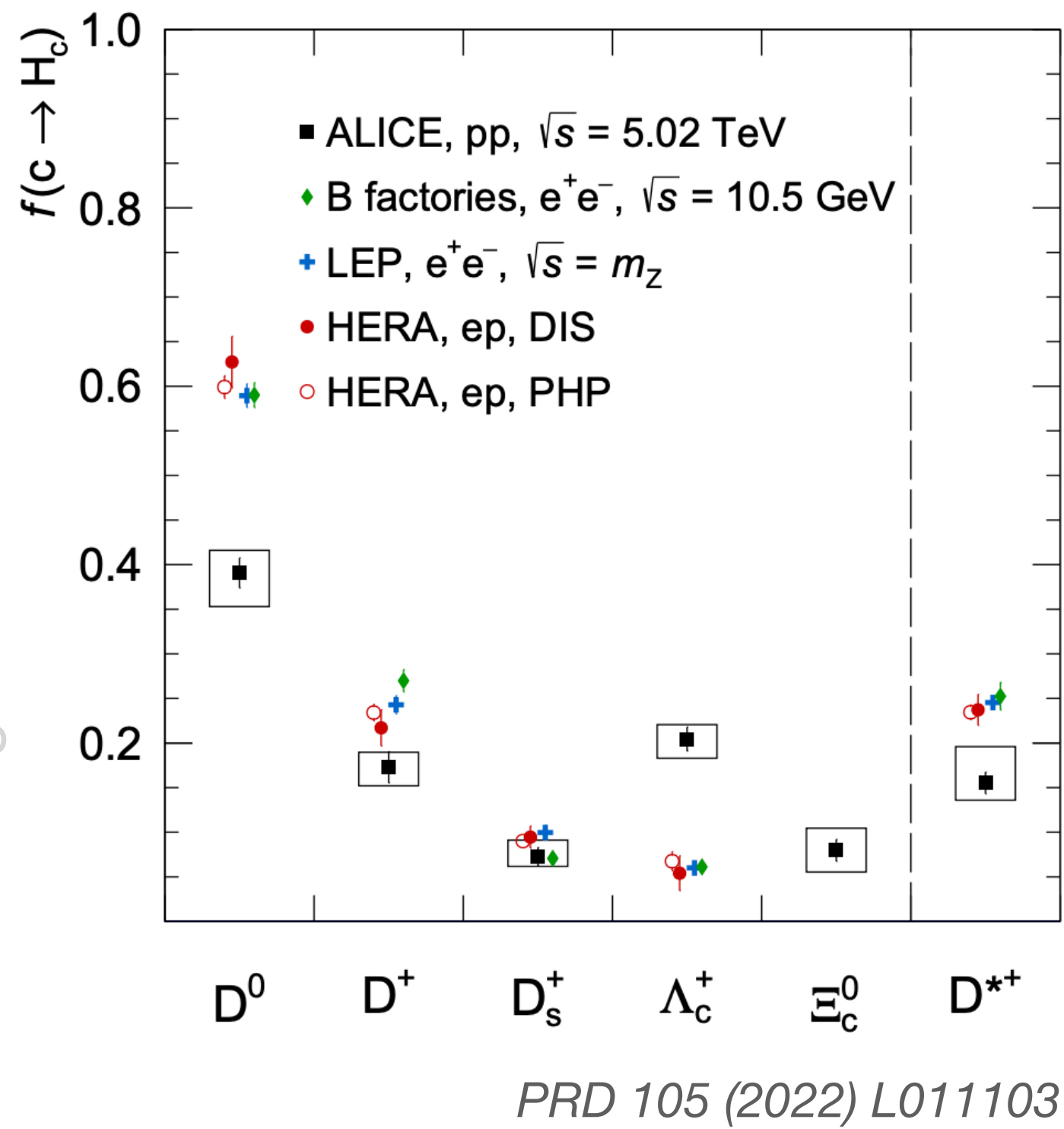
- ▶ Aligned with the three **frontiers of modern hard probes**
- ▶ **Run-3 ALICE's first jet measurement** — pp R -dependence; paper submission fall 2026
- ▶ ~30% tension in the soft, large- R regime — **modern LO tunes break structurally**; NLO POWHEG holds
- ▶ Primary analyzer (one of) on **O+O charged-jet R_{AA}** — owns signal-loss, normalization, POWHEG pp reference
- ▶ Next: intermediate-system substructure · γ -jet (sPHENIX/ATLAS) · AI/ML-assisted analysis · EIC R&D

Look forward to work with you!



Modern hard probes — three frontiers

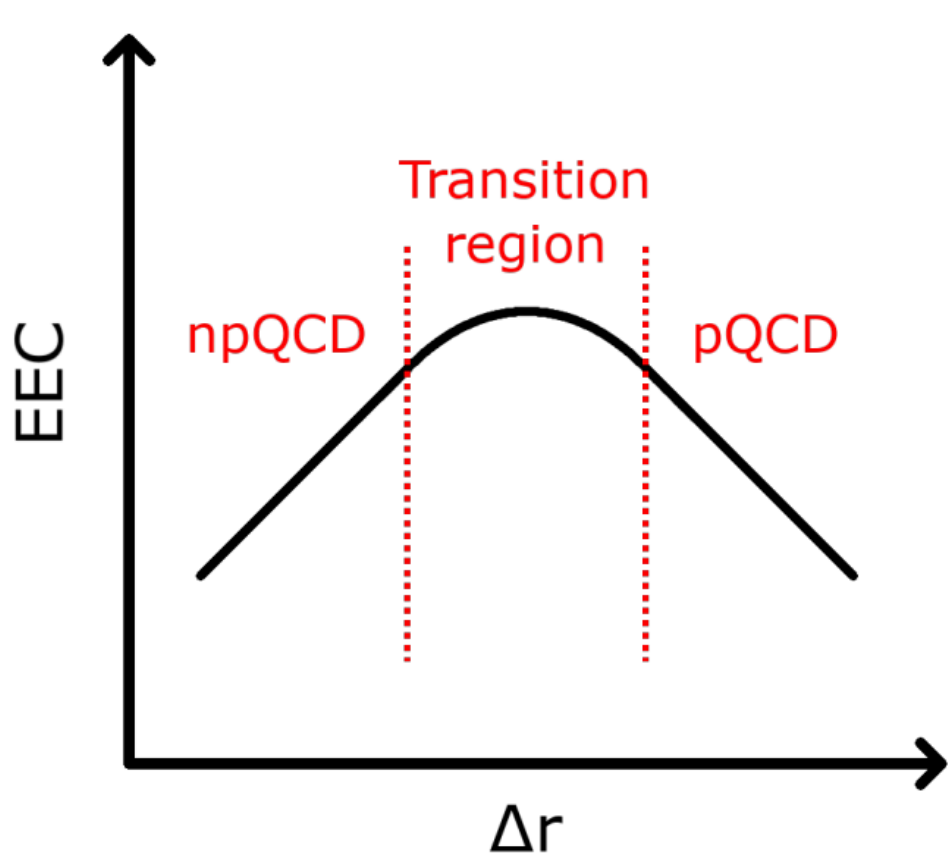
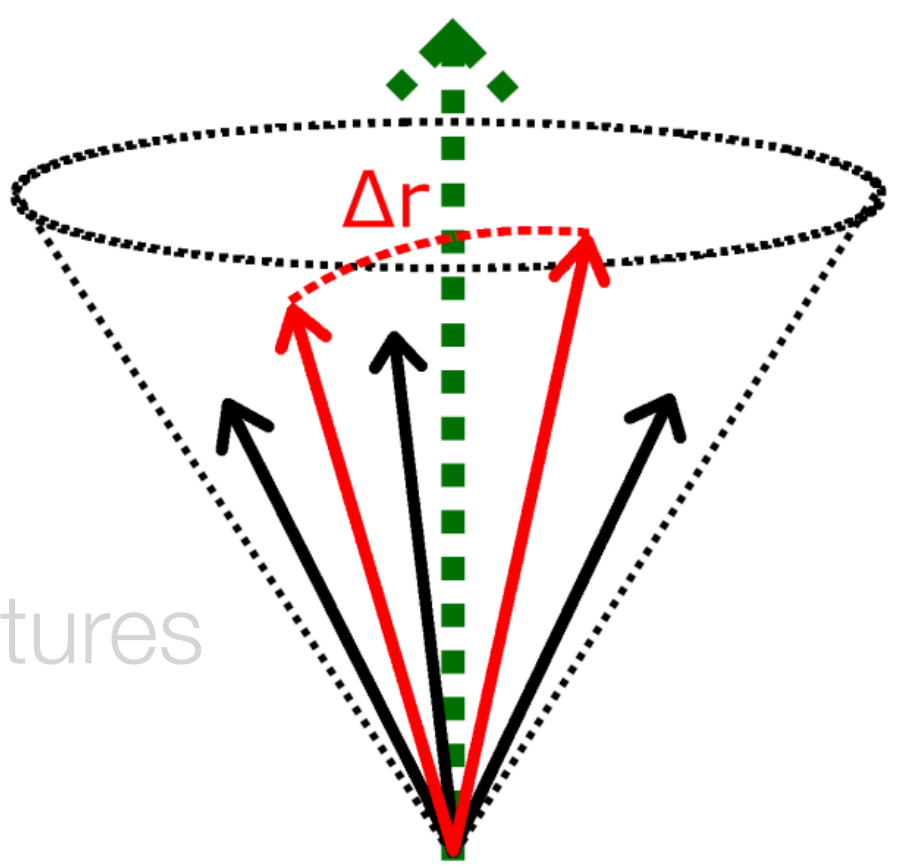
- (1) **Non-perturbative QCD**
— hadronization, UE, soft radiation
- (2) **Small-system jet-quenching** signatures
— pp, p—Pb, OO, Ne—Ne
- (3) **Jet-substructure tomography** of the QGP
— energy correlators, grooming, wake



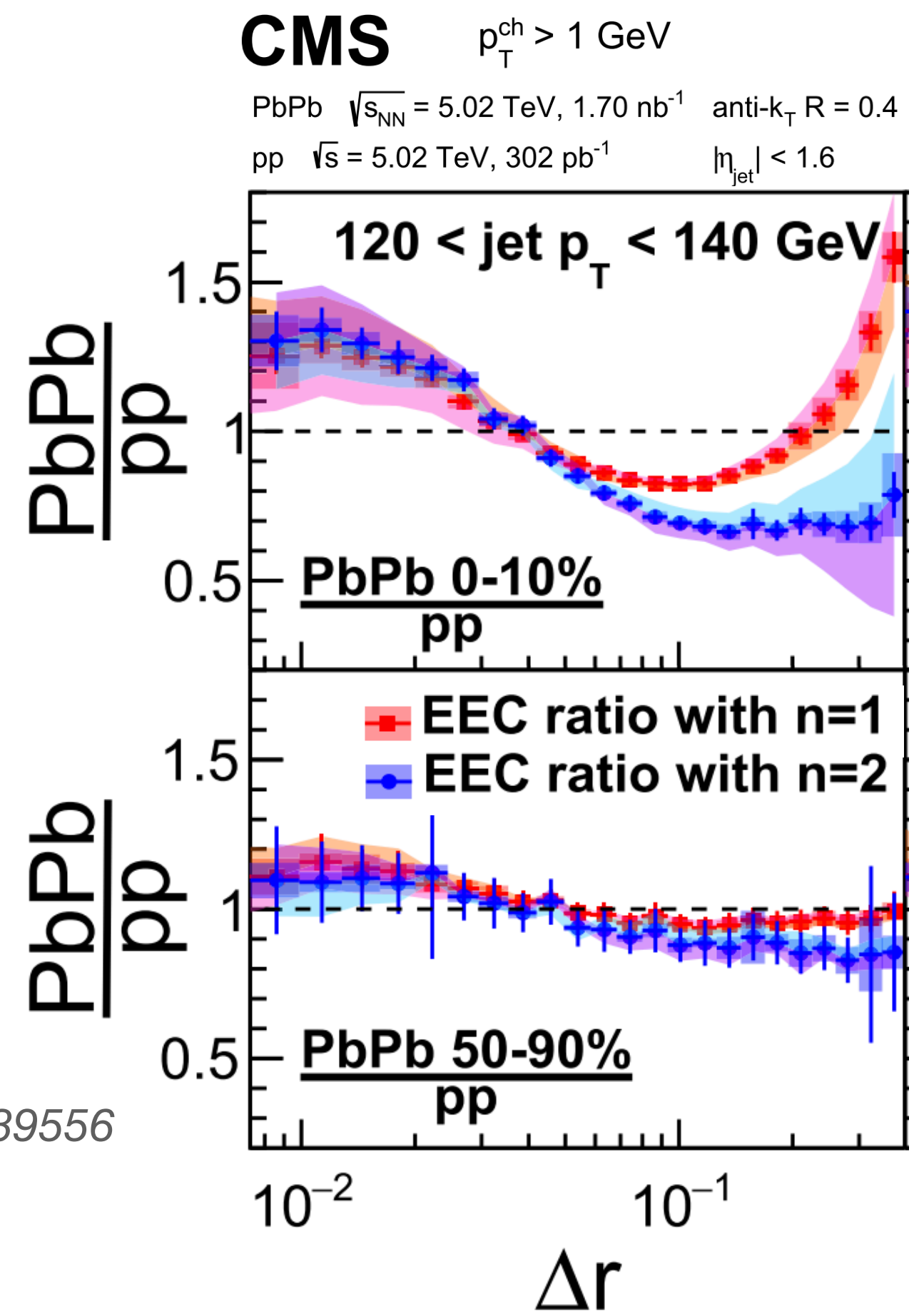
- ▶ (Left) Charm fragmentation fractions: e^+e^-/ep vs. pp.
- ▶ (Right) Charm-baryon enhancement — density-dependent (CR / coalescence) hadronization.
- ▶ **The proton is not “small” enough** — pp hadronizes collectively.

Modern hard probes — three frontiers

- (1) **Non-perturbative QCD**
— hadronization, UE, soft radiation
- (2) **Small-system jet-quenching** signatures
— pp, p—Pb, OO, Ne—Ne
- (3) **Jet-substructure tomography** of QGP
— energy correlators, grooming, wake



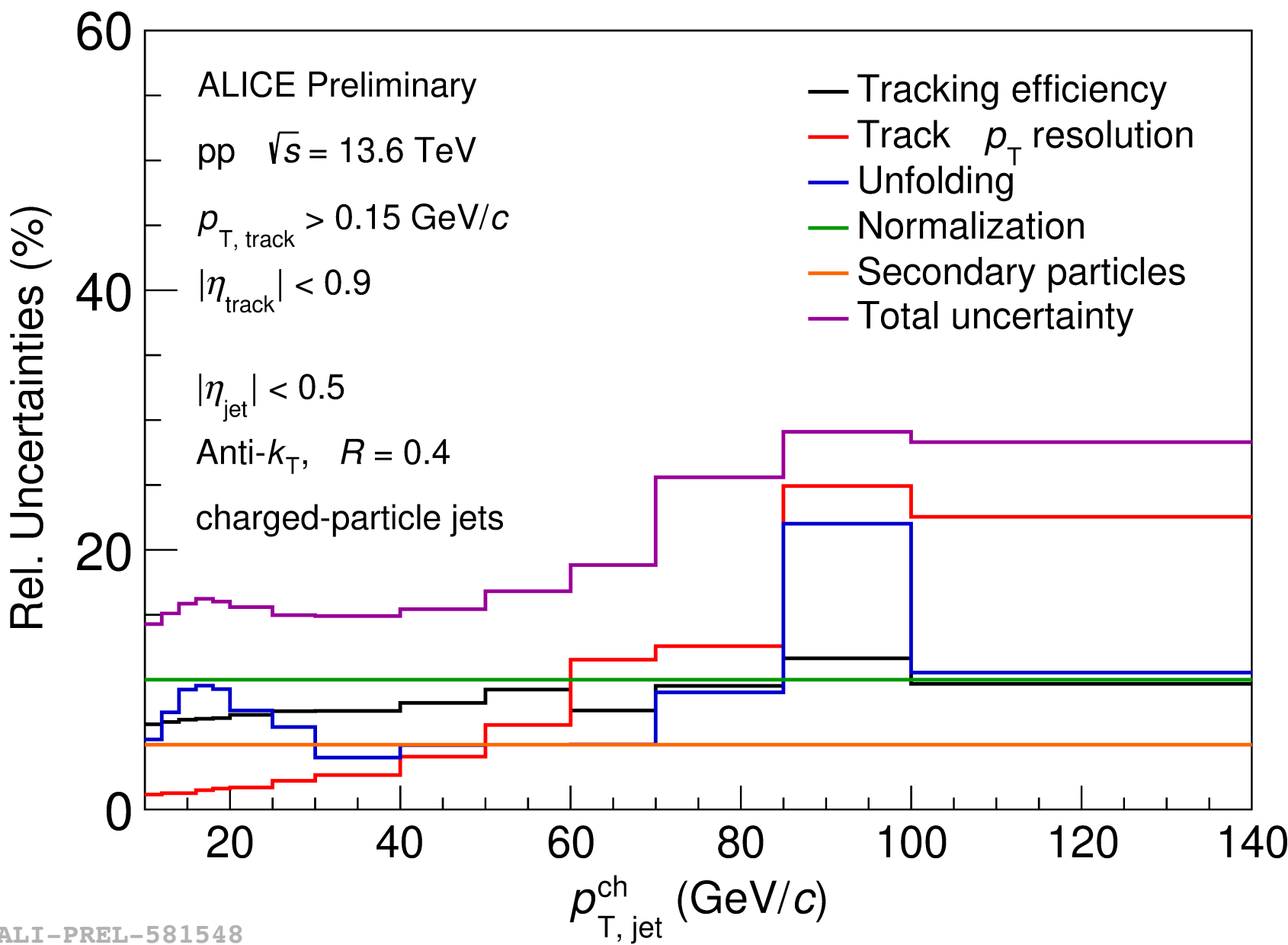
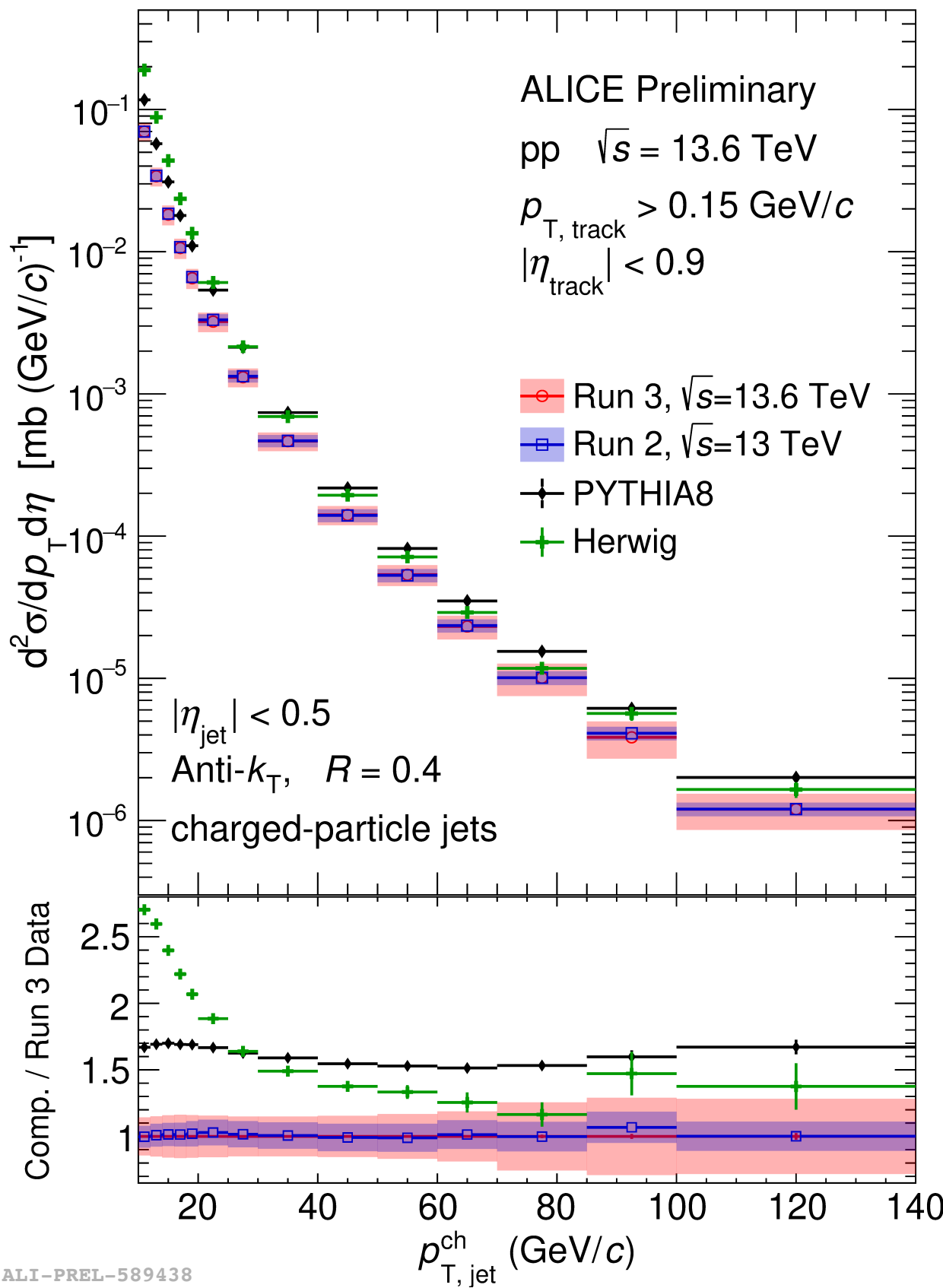
PLB 866 (2025) 139556



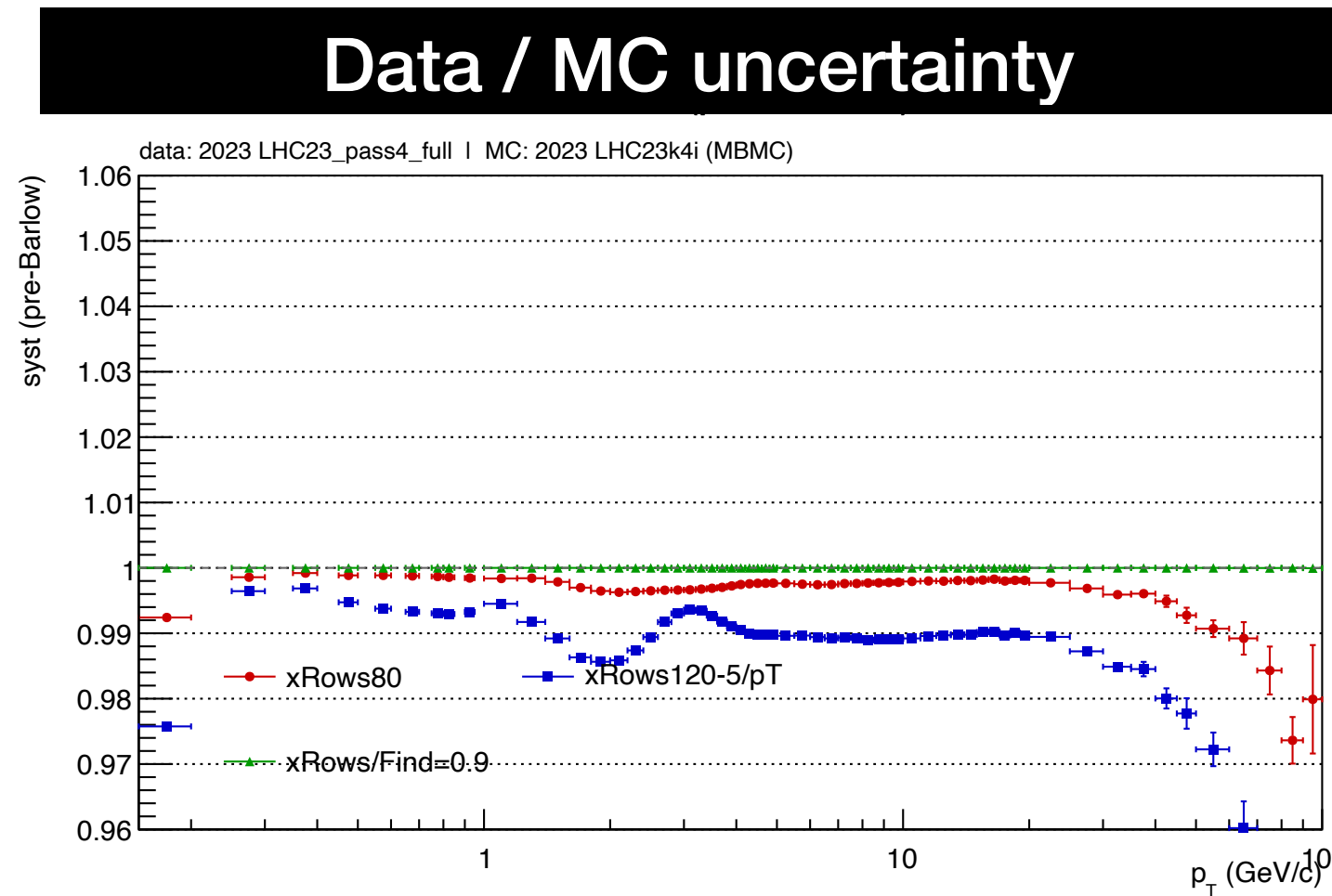
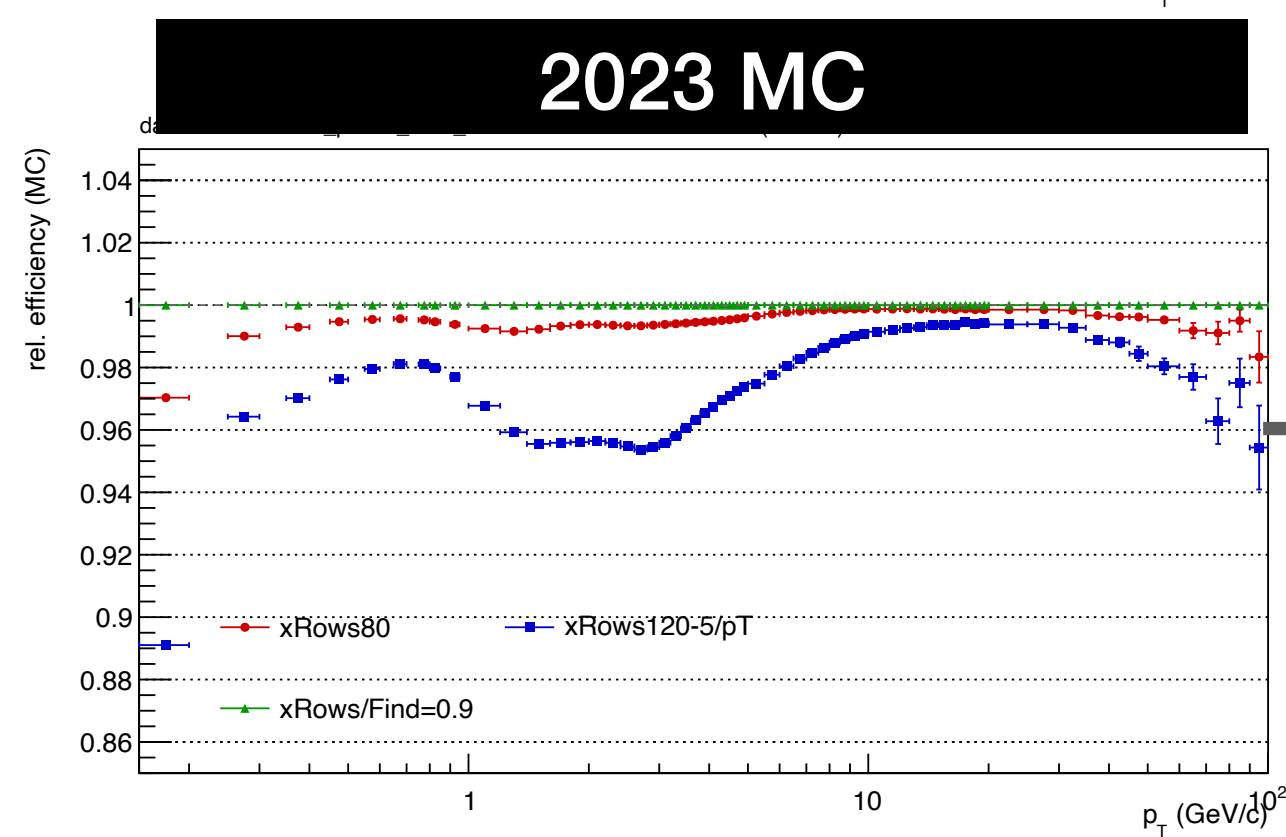
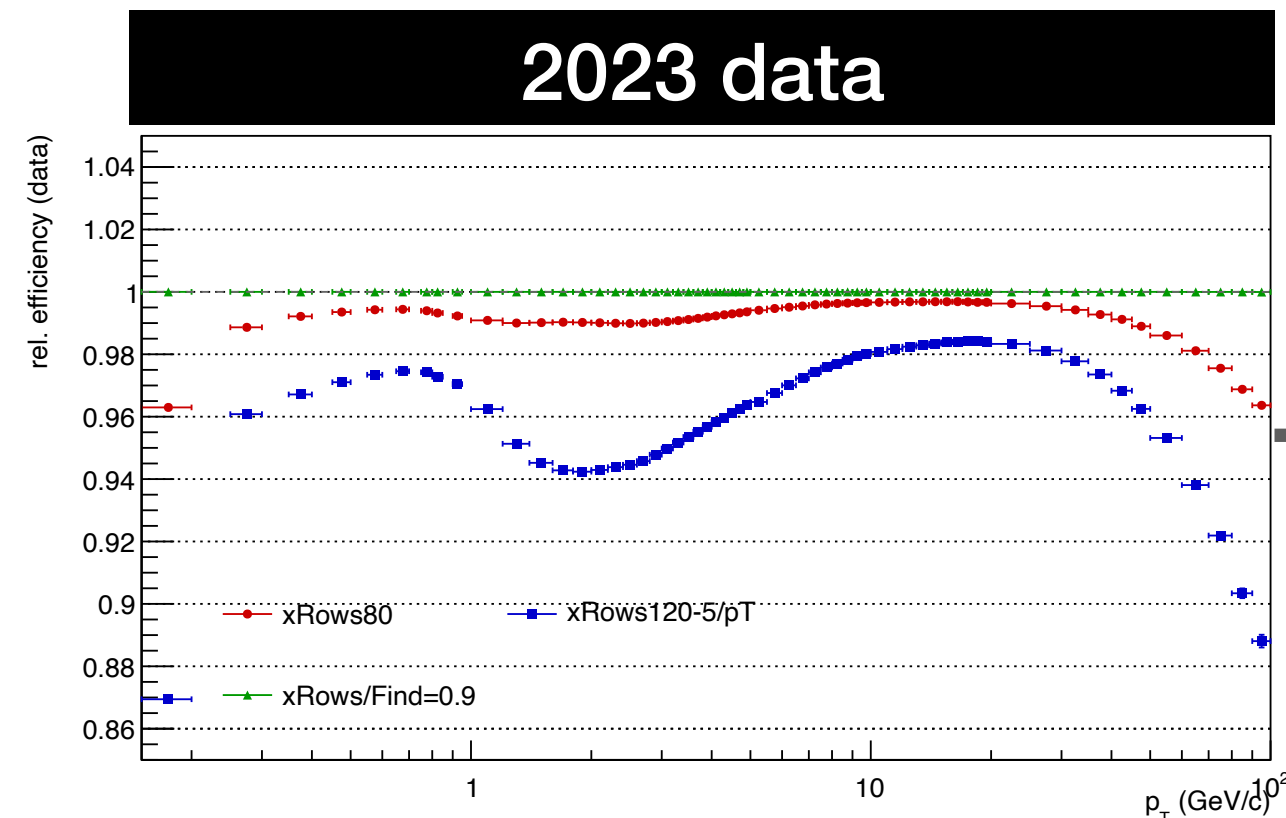
- **The sharpest QGP tomography** — energy correlators quantify medium interaction angle-by-angle (CMS PbPb: small-angle vacuum-like, large-angle medium-enhanced).
- **Bias remains** — selection bias survives and large-angle signal stays interpretation-degenerate; limit is control, not statistics.

Previous preliminary (Sep 2024)

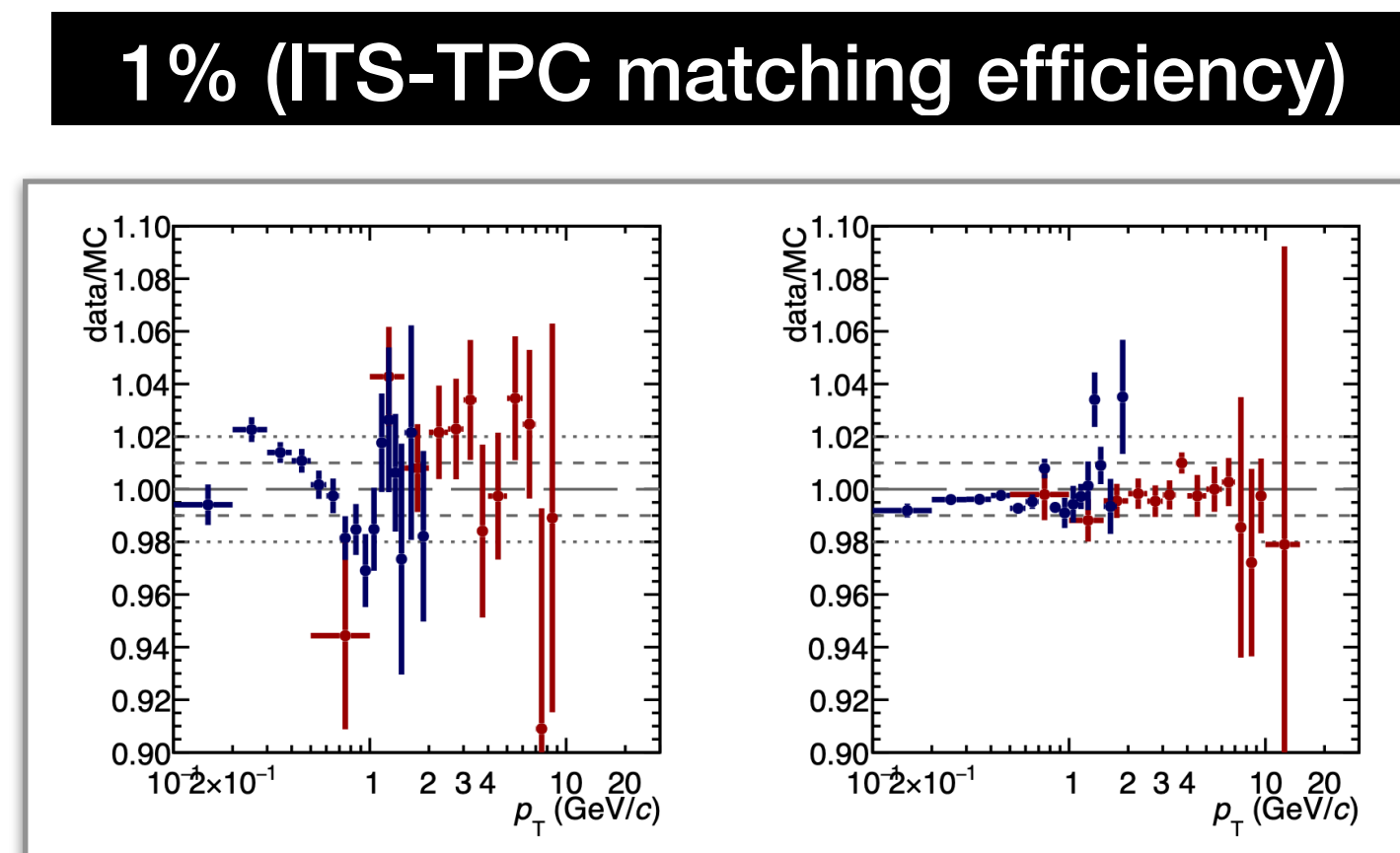
- Updates
 - Period migration from 2022 to 2023, mainly due to precise luminosity estimation (6% $\rightarrow$ 3%).
 - Luminosity (1 pb⁻¹ $\rightarrow$ 5 pb⁻¹)
 - R-dependence & cross section ratios
 - Selections modifications.
 - Unfolding (Bayesian $\rightarrow$ SVD)
 - Normalization
 - Systematics



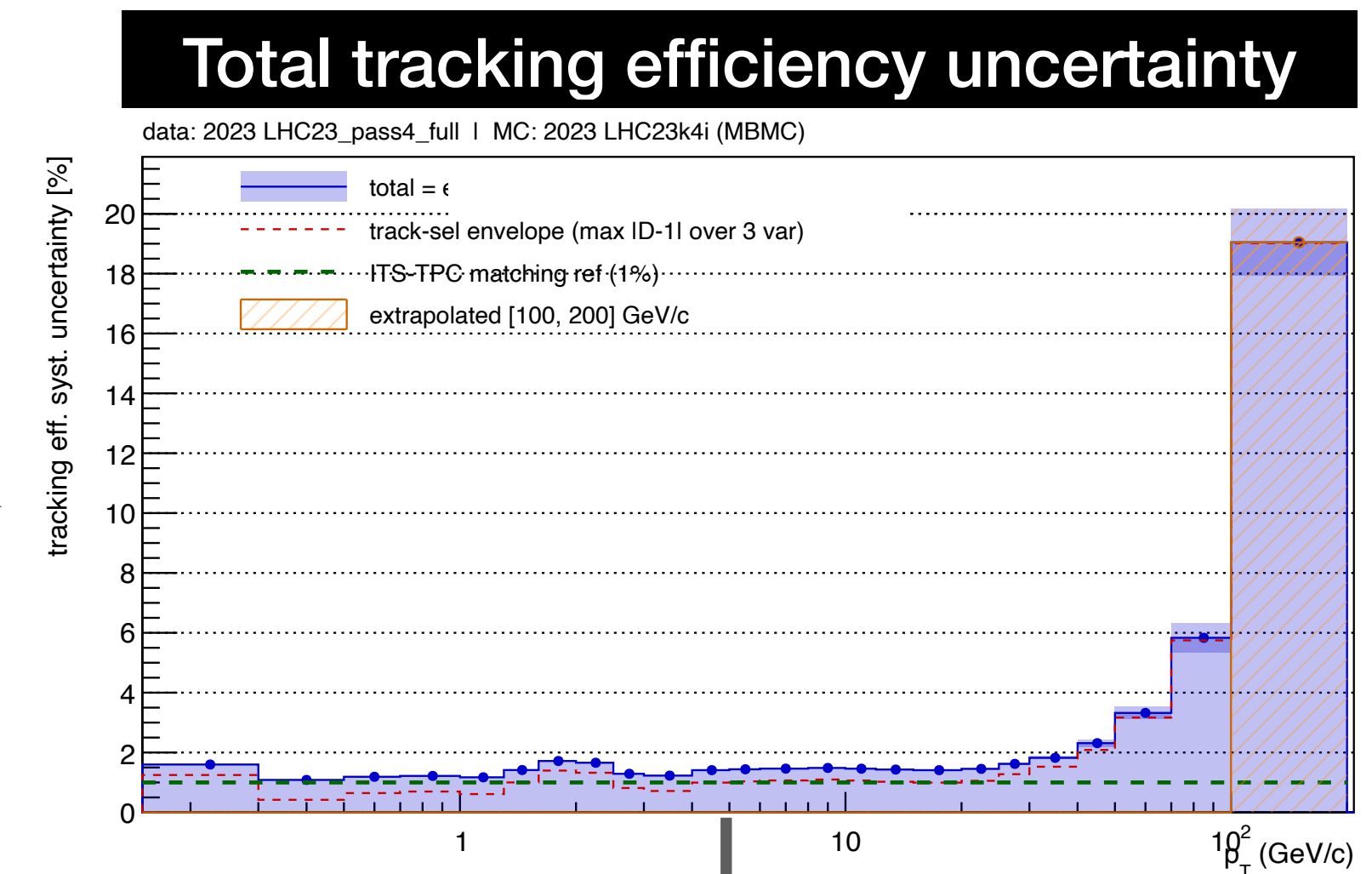
Systematics — tracking efficiency



⊕

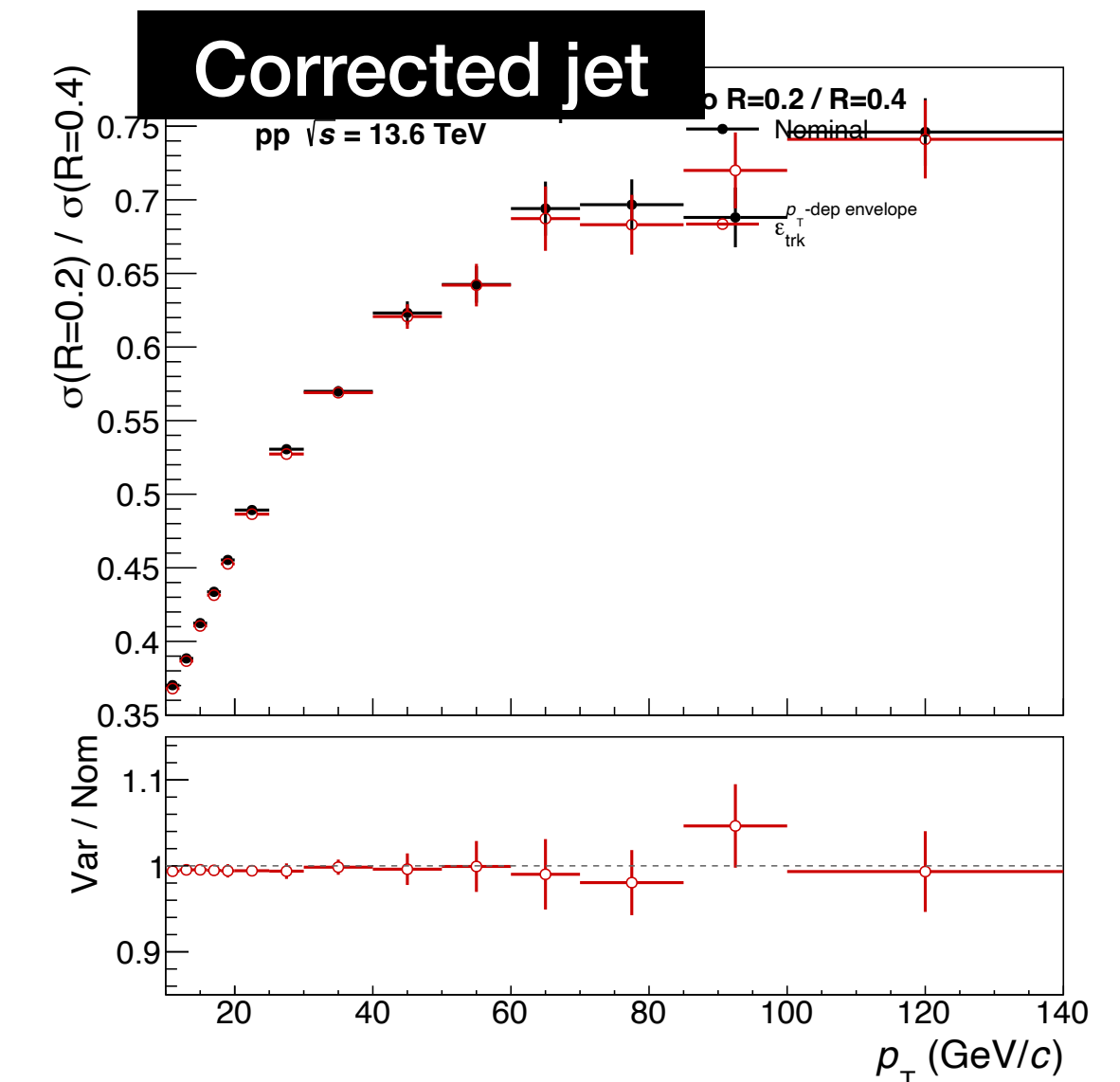


2024 D-meson 1% track uncertainty

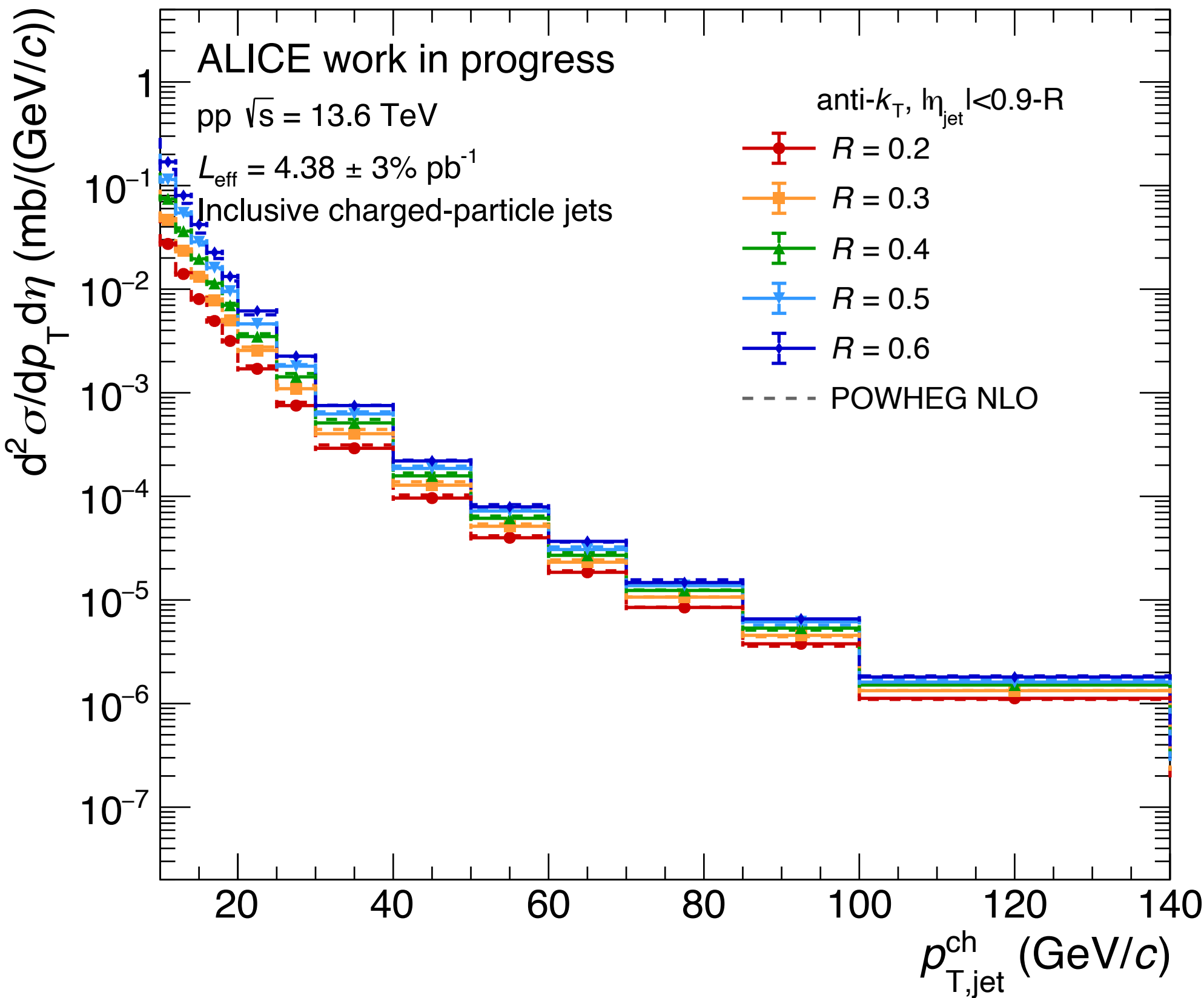


modify

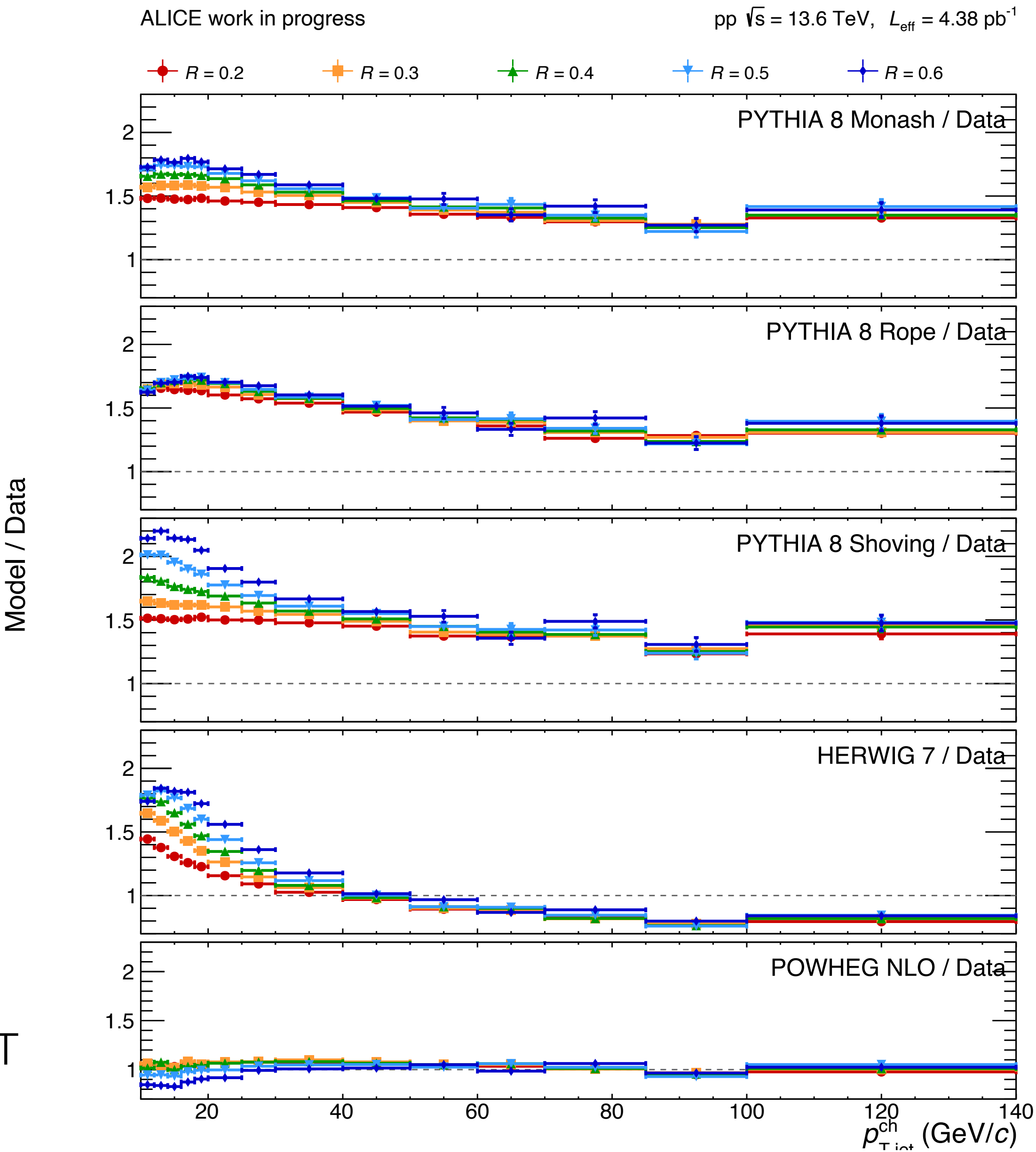
Cross section ratio uncertainty
($R = 0.2/R = 0.4$)



Inclusive jet cross section at 13.6 TeV



- ▶ Not approved due to the conflict with previous preliminary.
- ▶ But included in upcoming paper after finalize normalization track pT smearing.



Used event-generators / models

- **PYTHIA8 Monash 2013**

- LO hard scattering + parton shower
- Lund string fragmentation
- MPI + MPI-based color reconnection

- **PYTHIA8 + Rope hadronization**

- Monash baseline + modified string tension from string overlap
- Modified hadronization stage

- **PYTHIA8 + Shoving**

- Repulsive interaction between overlapping strings
- Additional final-state interaction
- Related to ridge/ v_2 -like collective behavior

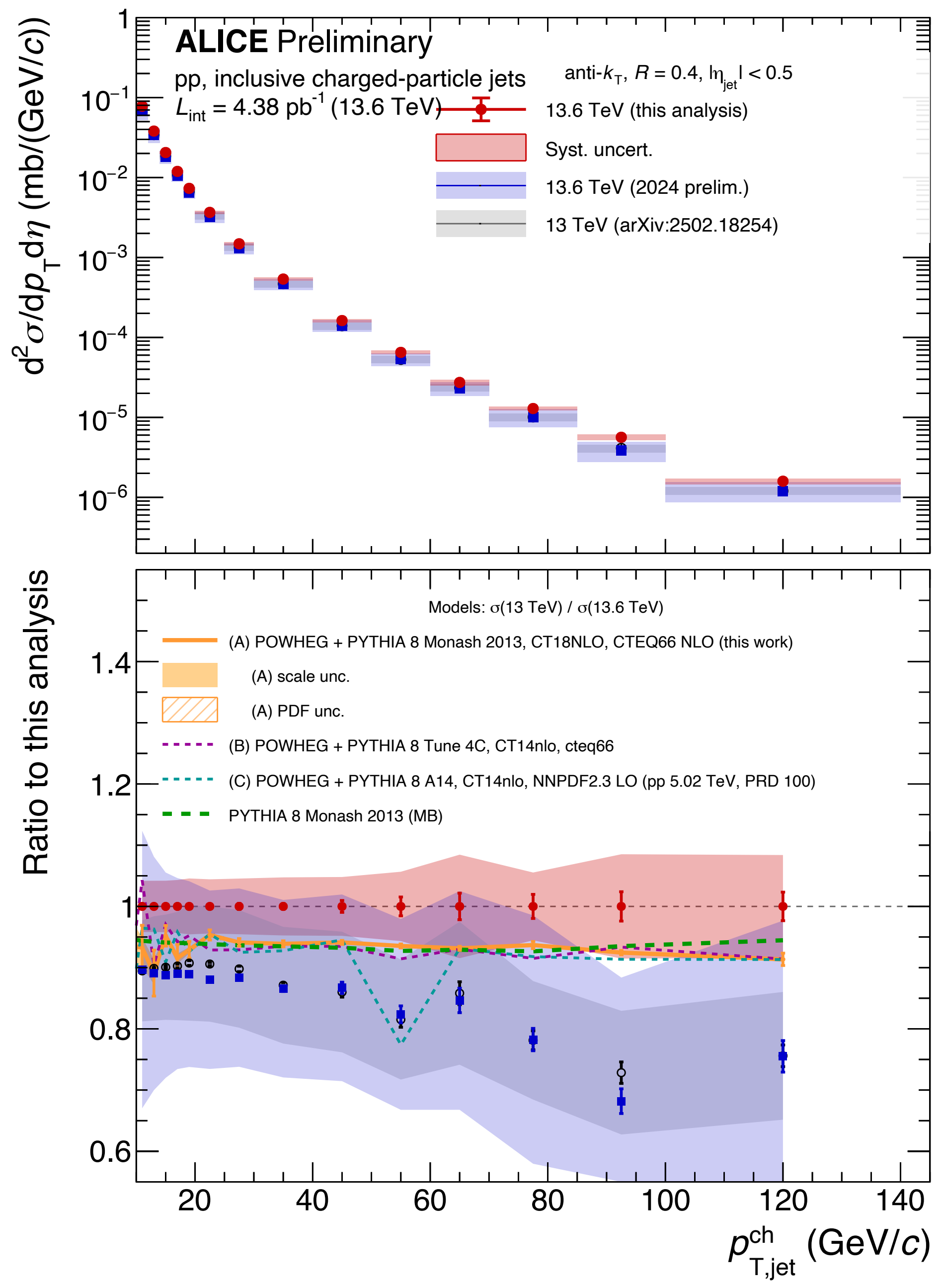
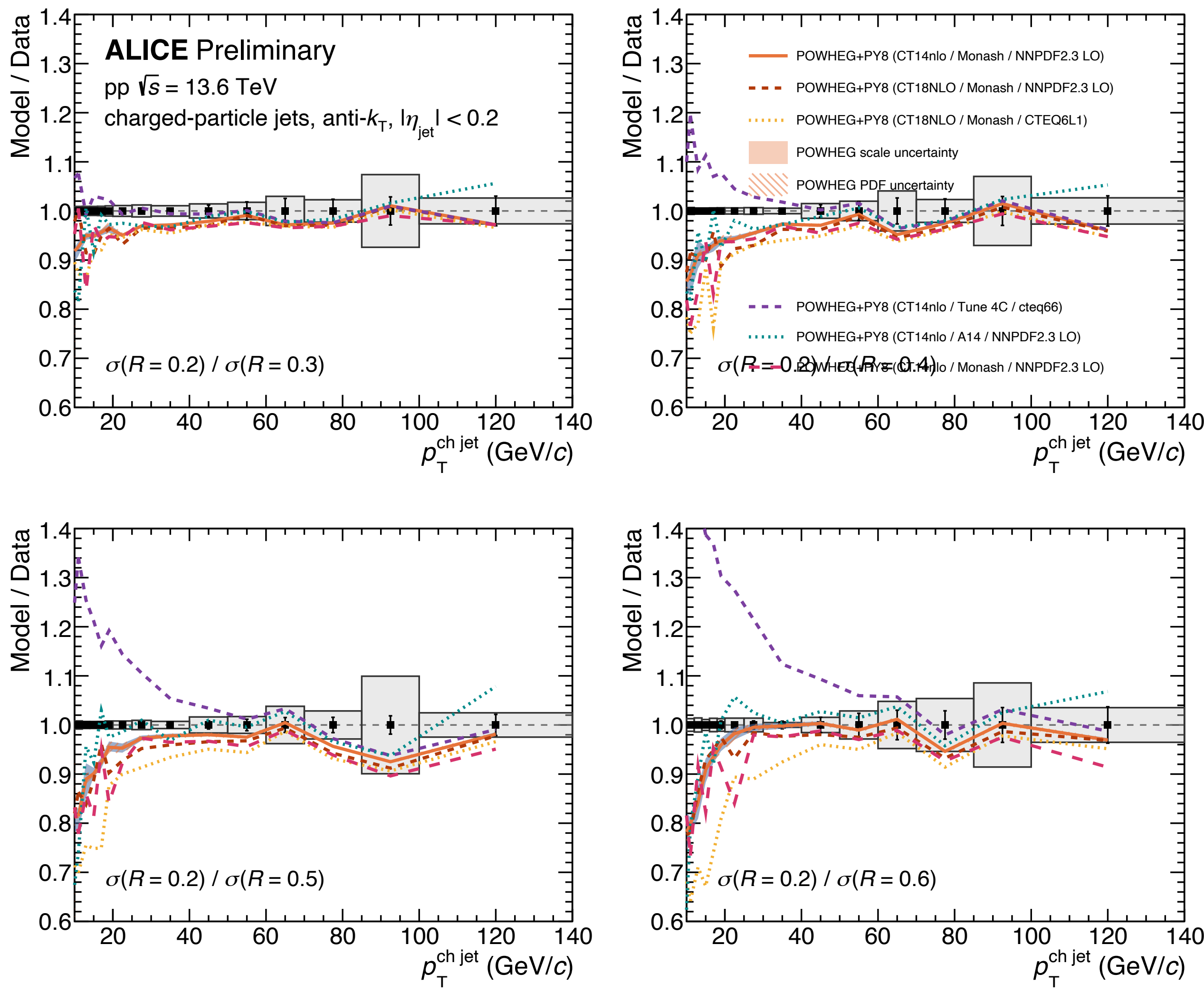
- **HERWIG7**

- Angular-ordered shower
- Cluster hadronization
- Independent MPI model
- Fundamentally different hadronization mechanism

- **POWHEG + PYTHIA8**

- NLO hard scattering + parton shower matching
- Same hadronization model as PYTHIA8
- Designed to improve perturbative accuracy

POWHEG study



Jet signal loss in OO

Cross section normalization

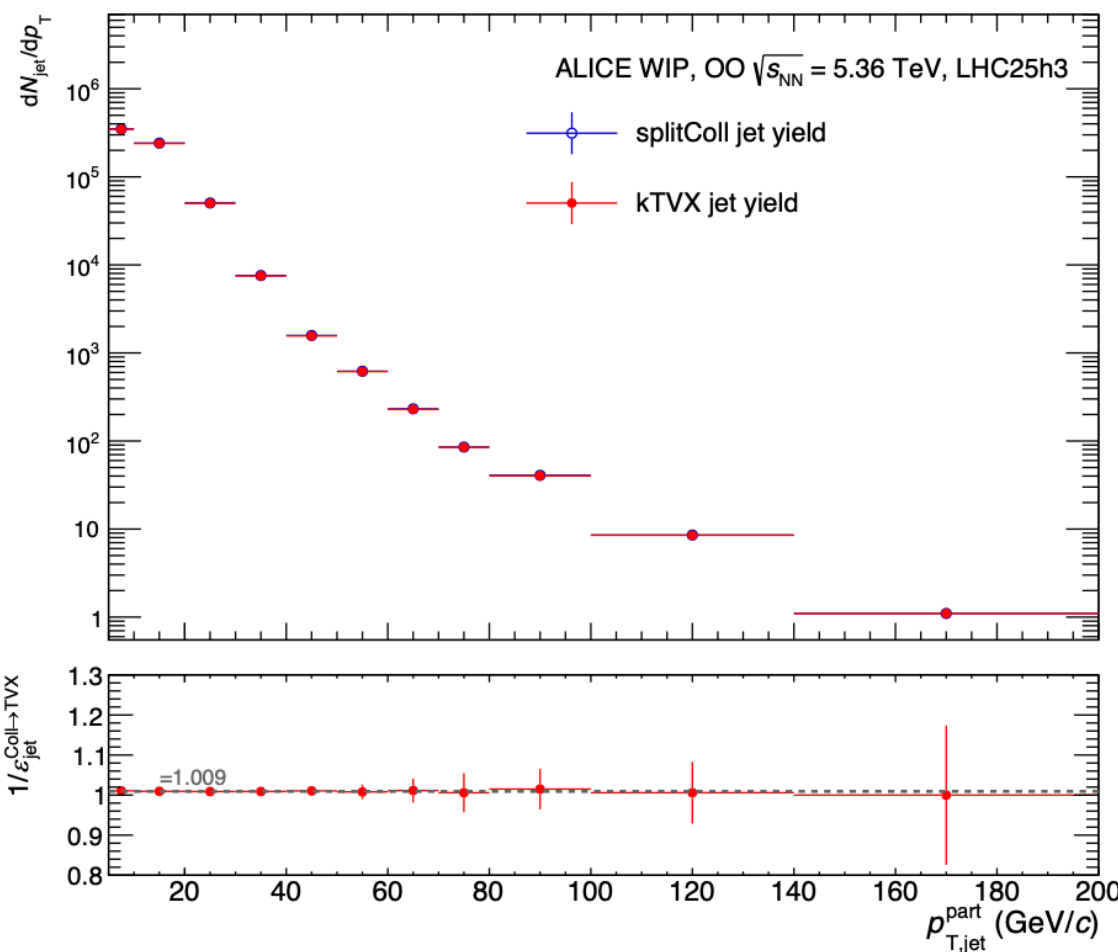
- Jet cross section is written by:

$$\frac{d^2\sigma_{jet}}{dp_T d\eta} = \frac{1}{\mathcal{L}_{int}^{TFB+ITSROFB}} \frac{d^2N_{jet}^{sel8Full+zTVX}}{dp_T d\eta} \times \frac{1}{\epsilon^{zVTX}} \times \frac{1}{\epsilon^{SBP}} \times \frac{1}{\epsilon_{jet}^{coll \rightarrow TVX}} \times \frac{1}{\epsilon_{jet}^{coll}}$$

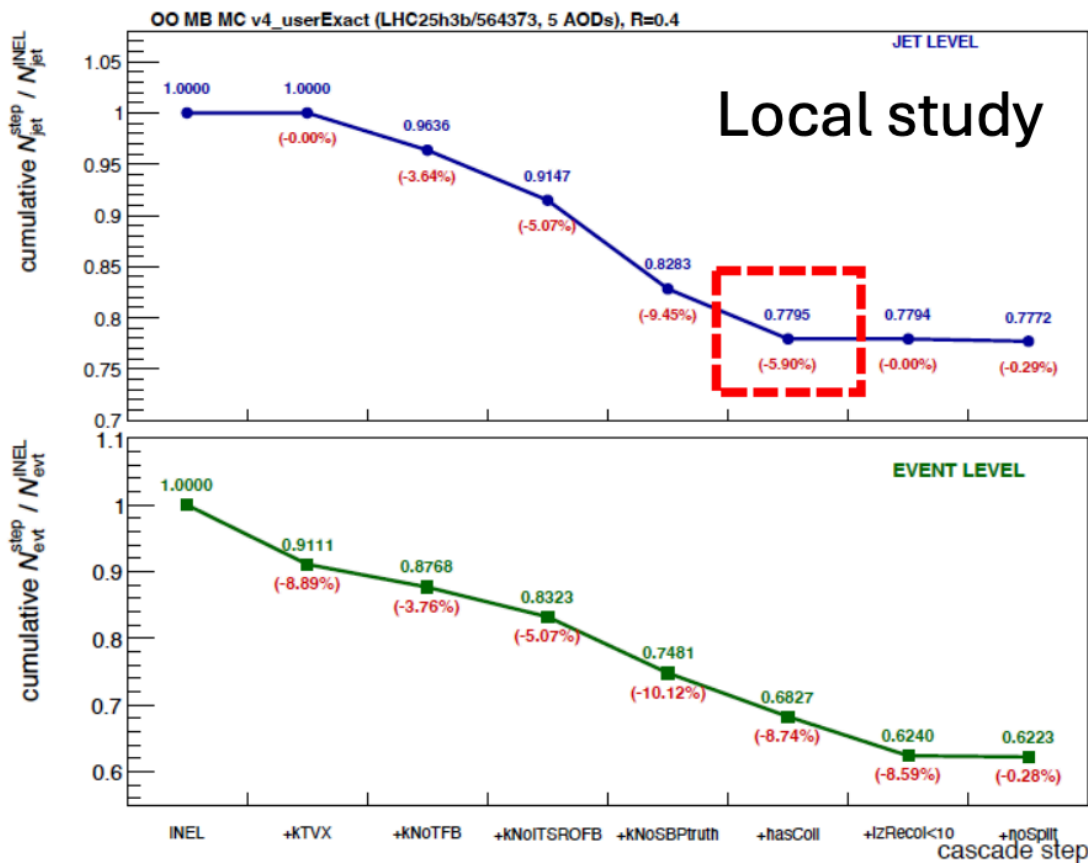
- Signal loss efficiency $\epsilon_{jet}^{coll \rightarrow TVX}$ is calculated from MC

$$\epsilon_{jet}^{INEL \rightarrow coll \rightarrow TVX} = \frac{N_{jet}^{coll+TVX}}{N_{jet}^{INEL}} \sim 81.4\% \rightarrow \left[\begin{array}{l} \epsilon_{jet}^{INEL \rightarrow coll} \approx 82.17\% \\ \epsilon_{jet}^{coll \rightarrow TVX} \approx 99\% \end{array} \right.$$

Double counting!



Thanks to Joonsuk!



- In local study, after TVX, TFB, ITSROFB, SBP cuts,

$$\epsilon_{jet}^{Coll} \approx 94.1\%$$

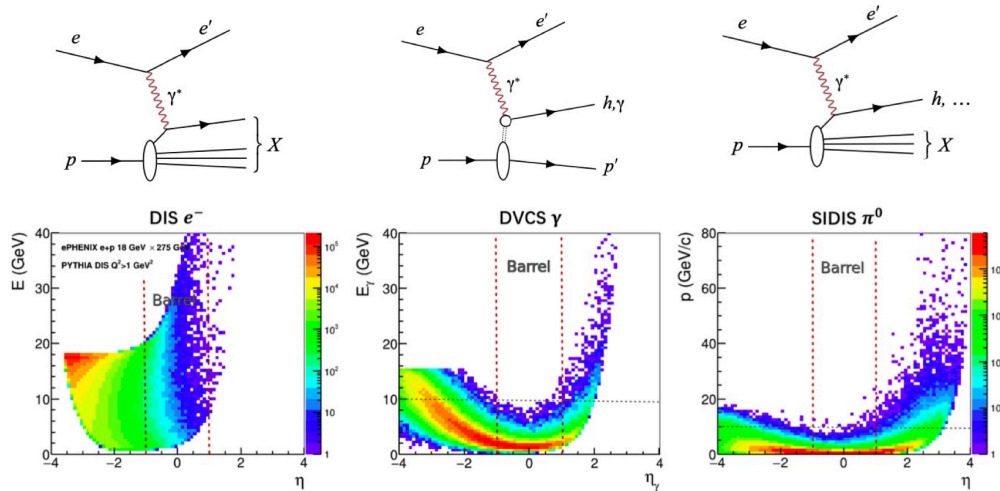
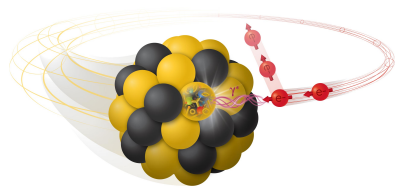
→ Since this is a MC driven method, we also add $|1 - \epsilon_{jet}^{Coll}| \approx 6\%$ as an uncertainty to the negative side

- In pp ref, add 4% as uncertainty to the positive side in R_{OO}

ePIC-BIC

Motivation

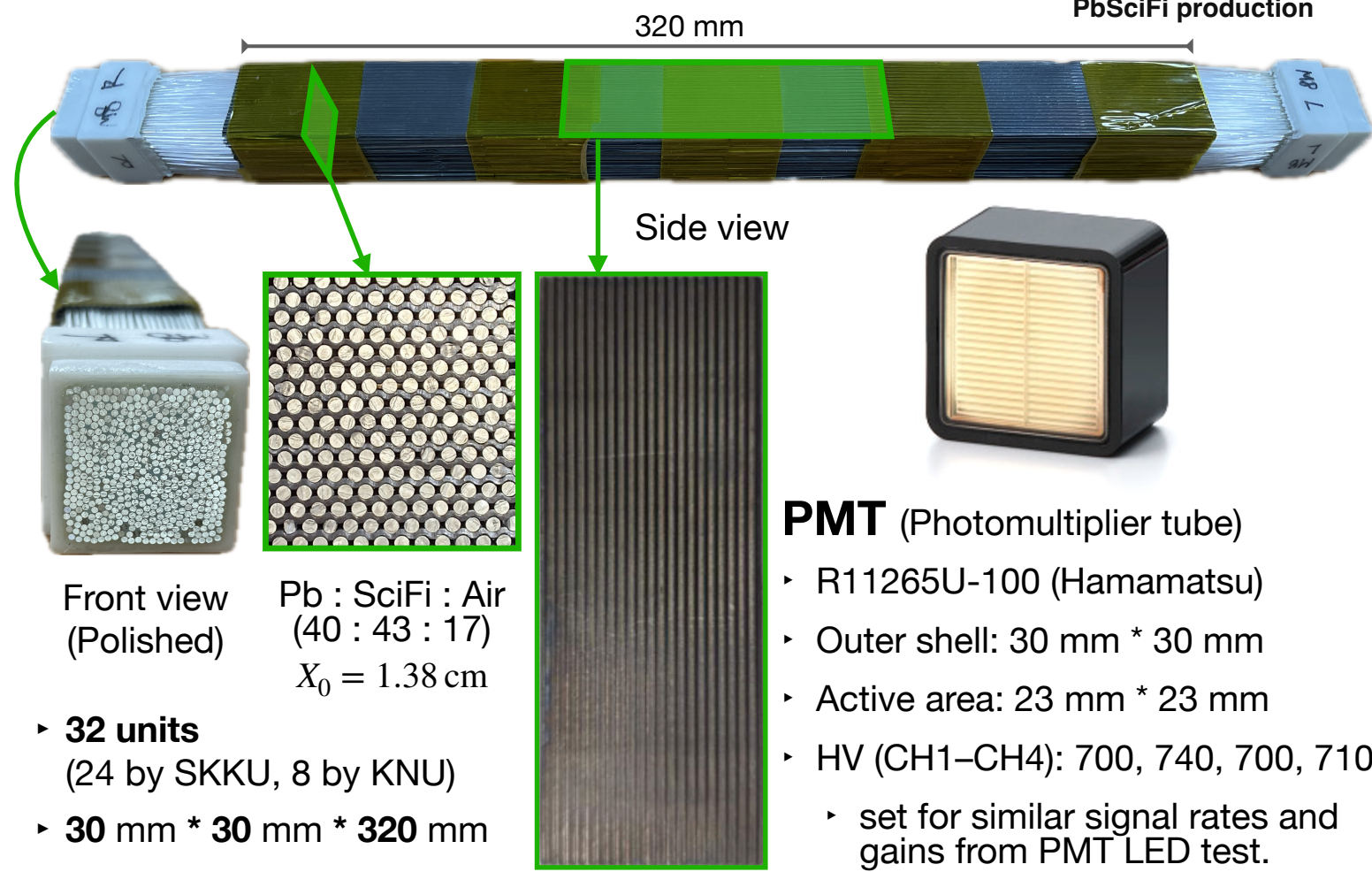
- Electron-proton collision experiments are essential for exploring the structure inside the proton via DIS, DVCS, and SIDIS.



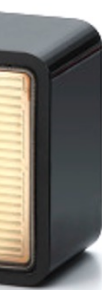
Experimental set-up

Prototype Pb/SciFi module

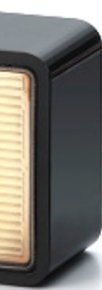
- See production details in Hyungjun's talk on 14:00, 24 Apr



PbSciFi production



- PMT** (Photomultiplier tube)
- R11265U-100 (Hamamatsu)
 - Outer shell: 30 mm * 30 mm
 - Active area: 23 mm * 23 mm
 - HV (CH1-CH4): 700, 740, 700, 710 V
 - set for similar signal rates and gains from PMT LED test.



Side view

Front view (Polished)

Pb : SciFi : Air (40 : 43 : 17)

$X_0 = 1.38$ cm

32 units (24 by SKKU, 8 by KNU)

30 mm * 30 mm * 320 mm

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