Non-Perturbative & Topological QCD Final States at ePIC

Instanton-induced processes: signal vs. background with InstGen + Pythia 8 — and the baryon junction

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about me: background and research Interest

- background in theoretical physics since 1993; active in experimental physics since 2005
- experience in forward physics, diffraction, and exclusive processes, with work spanning VFPS, ALFA, AFP, and X17
- expertise across the full chain: analysis, detector software and simulation, hardware development, and accelerator optics
- main interests: non-perturbative QCD, forward physics, tracking and time-of-flight detectors, MC and detector simulations, deep learning

recent activities include AFP ToF, ATLAS Forward Detectors Institutional Board, ATLAS exclusive pion-pair analysis, QCD instanton studies, the GAČR X17 project, DRD5, and **EPIC**.

EPIC 2025+: primary areas: hardware – backward calorimeter (simulations, performance), analyses: non-perturbative physics; ...

in general, my **professional and research interests:**

- theory: particle physics and cosmology, standard model of particle interactions and beyond, forward physics – diffraction mathematical physics
- hardware: tracking & time of flight detectors,
- simulations: detector simulations, MC simulations, simulations of accelerator optics, deep learning

abstract

ePIC's luminosity, 4π hermeticity (near-complete angular coverage), and particle identification (PID: π/K/p separation) give direct access to **non-perturbative** and **topological** QCD final states (i.e. states produced due to topologically non-trivial configurations — instantons) in deep-inelastic scattering (DIS: $ep \to e'X$ via a virtual photon).

We develop one case with dedicated simulation and outline a second as motivation.

Primary — instanton-induced DIS. With InstGen [adapted to ePIC's 9 GeV (e) × 275 GeV (hadron) asymmetric beams] + Pythia 8, we compare instanton events to real neutral-current DIS background at parton and hadron level. Accessible events are low-mass; the high-mass fireball is rate-suppressed. Surviving discriminators: strangeness, multiplicity, isotropy — a two-cut selection keeps ~50% of signal at ~6% background. PID is the key handle.

Second — the baryon junction. Proposed gluonic carrier of baryon number; observables matched to ePIC. To my best knowledge no generator implements it (yet) — motivation + required development.

OK… but

WHY?

two words we owe you: non-perturbative and topological

Perturbative: expand observables in powers of the coupling $\alpha_s(\mu)$ — Feynman diagrams. Works when α_s is small (hard scales). Example: jet cross sections.

Non-perturbative: effects invisible at **EVERY** order of that expansion — typically $\propto \exp(-c/\alpha_s)$, which has no Taylor series in α_s. Everyday example: quantum tunnelling through a barrier.
QCD examples: vacuum condensates, hadron formation.

Topological: a property of a field configuration that cannot change under any smooth deformation — an integer. Everyday example: how many times a loop winds around a circle.
QCD: gauge fields carry an integer winding ($\pi_3(SU(3)) = \mathbb{Z}$),

$$Q_{top} = (1/16\pi^2) \int F \tilde{F}\, d^4x \;\in\; \mathbb{Z},$$

and the **instanton** is the minimal-action field with $Q_{top} = \pm 1$: a tunnelling event between vacua of different winding — manifestly both topological and non-perturbative ($\sim e^{-2\pi/\alpha_s}$).

why this is not exotica: mass and spin

Where does the proton mass come from? m_p = 938 MeV, but the Higgs-generated quark masses contribute only $2m_u+m_d \approx 9$ MeV — about 1%.
No order of perturbation theory generates the rest ⇒ **~99% of visible mass is non-perturbative QCD.**

Mechanism: chiral symmetry breaking — the vacuum condensate $\langle\bar{q}q\rangle \neq 0$ turns nearly massless quarks into constituent quarks of ~350 MeV.
In the **instanton-liquid** picture (Shuryak; Diakonov–Petrov; Schäfer–Shuryak), quark zero modes of instantons generate exactly this condensate — quantitatively successful for light-hadron masses (and $m_{\eta'}$ via the anomaly).

The proton spin puzzle: quark spins carry only ~30% of the proton spin [EMC (1988) found the quark spin contribution consistent with zero; today's value is ~30%]. The quark-spin sum is tied to gluon topology by the axial anomaly, $\partial J_5 = 2n_f\,(g^2/32\pi^2)\,F\tilde{F}$: topological fluctuations screen the singlet axial charge; instanton mechanisms produce the observed suppression (Shore–Veneziano; Kochelev) — **very likely no resolution without topology.**

what instantons do NOT explain — confinement

Confinement = the quark–antiquark potential rises linearly, $V(r) = \sigma r$; σ is the string tension.
Equivalently the Wilson loop obeys an AREA law, $\langle W \rangle \sim e^{-\sigma \cdot \text{area}}$.

Instantons do not produce it, for a clean reason:

- they are localized lumps of size $\rho \approx 1/3$ fm with power-law tails — field correlations are short-range;
- a dilute ensemble of such lumps disorders a large Wilson loop only near its boundary ⇒ PERIMETER law, not area law ⇒ $\sigma \approx 0$ (the Callan–Dashen–Gross hope failed here);
- the instanton liquid gets $\langle \bar{q}q \rangle$ and $m_{\eta'}$ right while giving $\sigma \simeq 0$ — its own diagnostic.

What lattice QCD points to instead: center vortices — surface-like defects (line-like in a time slice) defects carrying the center flux of $\pi_1(SU(3)/\mathbb{Z}_3) = \mathbb{Z}_3$: removing them destroys the string tension (and the chiral condensate!) — de Forcrand–D'Elia, PRL 82, 4582; Greensite EPJ Web of Conferences, 01009 (2017). Abelian monopoles give ~90% of σ.

Different topology for different jobs: π_3 ***(instantons)*** $\leftrightarrow$ **mass/spin/chirality**
π_1 ***(vortices)*** $\leftrightarrow$ **confinement**

three messages

1 InstGen brings instanton DIS to real ePIC kinematics

asymmetric beams, hadron level via Pythia 8, compared against genuine NC DIS background with identical selection.

2 The accessible regime is low-mass (M_{inst} ~ 3–12 GeV) [one of the key messages from discussions so far]

M_{inst} = invariant mass of the instanton subprocess; the high-mass fireball (a high-multiplicity final state) is exponentially rate-suppressed at $\sqrt{s} \approx 100$ GeV.

target: precision characterization, not high-mass discovery.

3 Discrimination is PID- and hermeticity-driven

strange-hadron yield is the strongest single observable; single cuts overlap, so a combined (multivariate) selection is the strategy — where ePIC's PID and 4π coverage pay off.

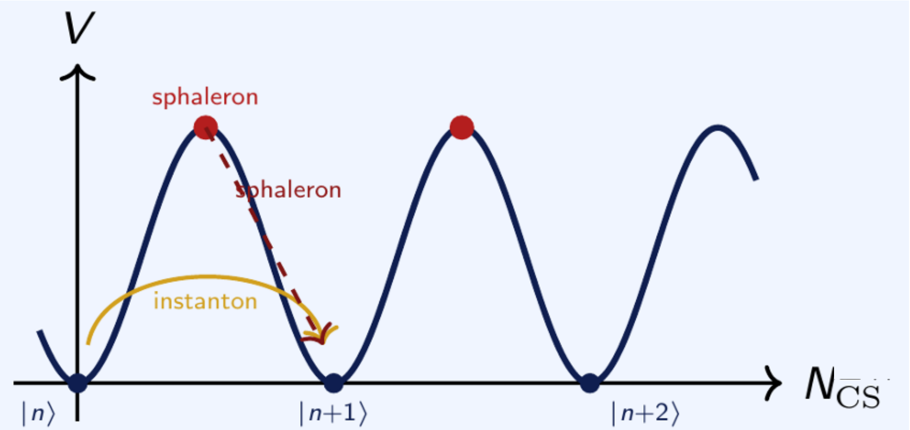
PRIMARY CASE

Instanton-Induced DIS

signal vs. background with InstGen + Pythia 8

what is a QCD instanton?

- Classical tunnelling solution connecting vacua of different winding number; carries Q_{top} = ±1; sources the axial anomaly.
- **Chirality** = handedness of a (nearly) massless quark: spin along (R) or against (L) its momentum. The instanton **flips chirality** — by exactly $2n_f$ units per event — absent at any order of perturbation theory.
- In DIS the hard scale Q' (virtuality of the quark entering the instanton subprocess) caps the size ρ ≲ O(1/Q') ⇒ calculable rate (Ringwald–Schrempp).



Framework (HERA, EIC)
Ringwald–Schrempp

Generators
QCDINS (RS) → InstGen

Established
BPST (1975)
't Hooft (1976)
Schäfer–Shuryak (1998)

BPST $Q = 1$ solution (regular gauge)

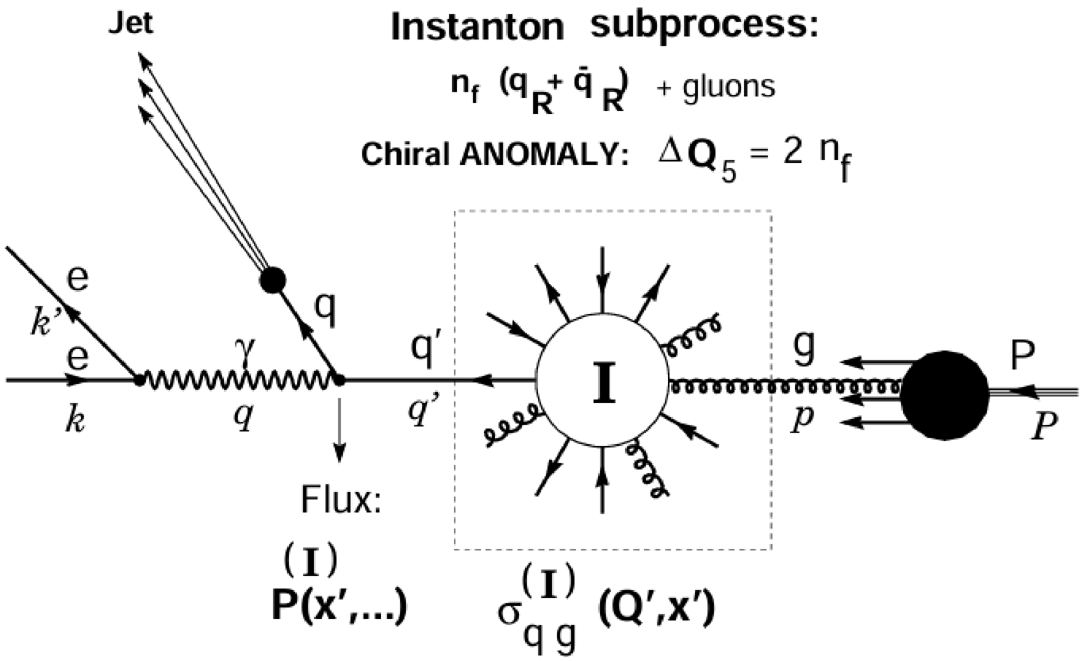
$$A^a_\mu(x) = \frac{2}{g} \frac{\eta^a_{\mu\nu}(x-z)_\nu}{(x-z)^2 + \rho^2}$$

$\eta^a_{\mu\nu}$: 't Hooft symbol

Field strength:

$$F^a_{\mu\nu}(x) = \frac{-8\rho^2\, \eta^a_{\mu\nu}}{g\left[(x-z)^2+\rho^2\right]^2}$$

The signature (concept)



$$\sigma_{ep}(\mathrm{I}) = f_{\gamma^*/e}(y,Q^2) \otimes g(x,\mu) \otimes \hat{\sigma}(I)_{\gamma^* g}(Q',x'),$$

$$\hat{\sigma}(\mathrm{I}) \propto \int d\rho\, D(\rho)\, e\hat{}(-4\pi/\alpha_s(1/\rho)) \cdots$$

A. Ringwald and F. Schrempp arXiv:hep-ph/9805492v1 28 May 1998

Current jet: the collimated spray from the struck quark (perturbative).

Fireball: the isotropic, flavour-democratic hadron system from the instanton vertex — one $q\bar{q}$ pair of every kinematically open flavour, plus gluons. Multiplicity and transverse energy E_T grow with the fireball mass M_{inst}; at ePIC the typical object is a low-mass, O(5–10)-charged-hadron system.

how InstGen works

$$\sigma_{ep}(I) \;=\; f_{\gamma^*/e}(y,Q^2) \;\otimes\; g(x,\mu) \;\otimes\; \hat{\sigma}(I)_{\gamma^* g}(Q',x'), \qquad \hat{\sigma}(I) \propto \int d\rho\, D(\rho)\, e\hat{}(-4\pi/\alpha_s(1/\rho)) \cdots$$

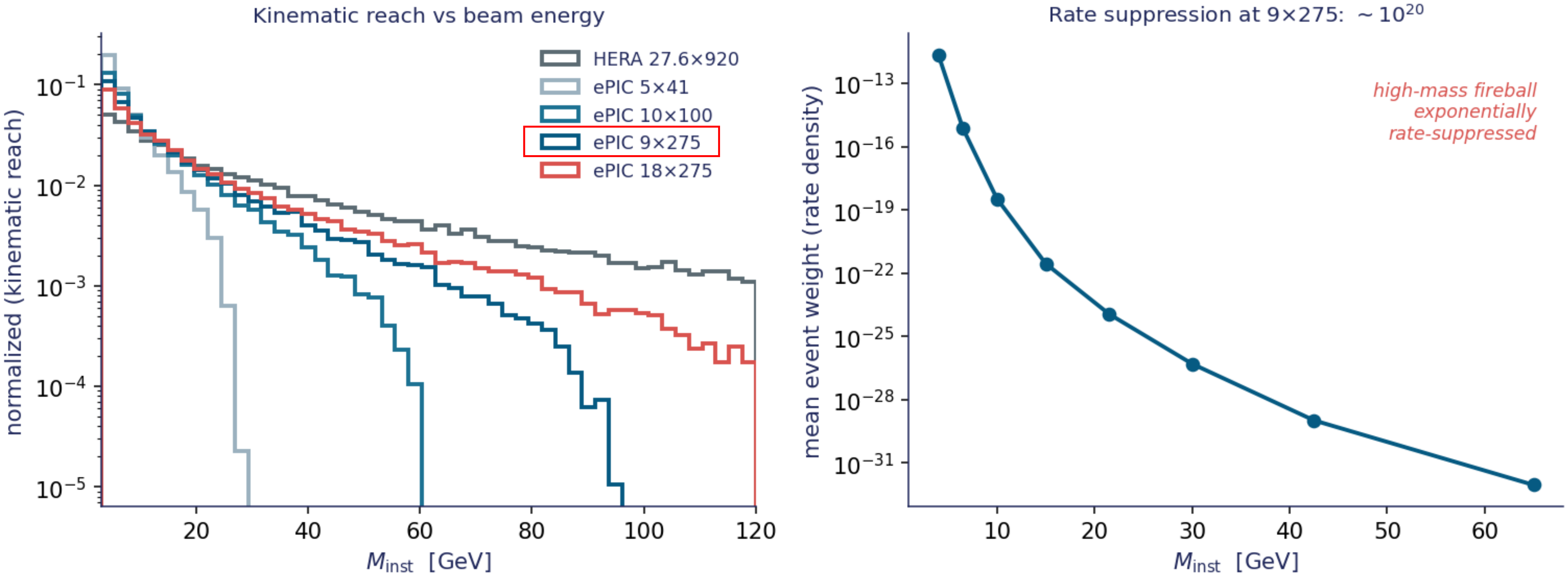
- Photon flux × gluon density × instanton cross section; the **size integral over ρ** is regularized because the hard scale pins the size, $\rho \sim 1/Q'$ (photon form factor).
- **Final state = the 't Hooft vertex:** one $\bar{q}q$ pair per open flavour ($2n_f$ quarks, all with the SAME helicity, sign = Q_{top} — the anomaly) + $O(1/\alpha_s)$ gluons.
- Pipeline: sample (y,Q^2,x,ρ) with the weight → build vertex partons → RA(NDOM) MO(MENTA) B(EAUTIFULLY) O(RGANIZED) — RAMBO (flat relativistic phase space at mass M_{inst}) → planar colour flow → **Pythia 8 string hadronization**.
- Validated: 5-part selftest; HERA-shape cross-checks; asymmetric ep beams added and verified in this work.

InstGen, adapted to ePIC

- One validated physics core ('t Hooft vertex, ρ integration, RAMBO, colour flow); thin lines: pp, **ep**, γγ.
- **Asymmetric-beam adaptation** (9×275): invariants unchanged — the fireball lands **forward** (hadron-going), $\eta \sim +2.5$ in ePIC convention (proton beam = +z).
- Chain: InstGen partons → Pythia 8 strings.
  Background: genuine Pythia 8 NC DIS, same $Q^2 \in [1,100]$ GeV², same selection.

Caveat All following results are luminosity-independent shapes/ratios. Absolute rates carry a factor-of-several size uncertainty; yields need $\sigma_{abs} \times L_{int}$ × acceptance from official sim.
Signal record = fireball subsystem (no remnant/scattered e); no FSR on the semiclassical state;
K_0^S, Λ are considered as stable.

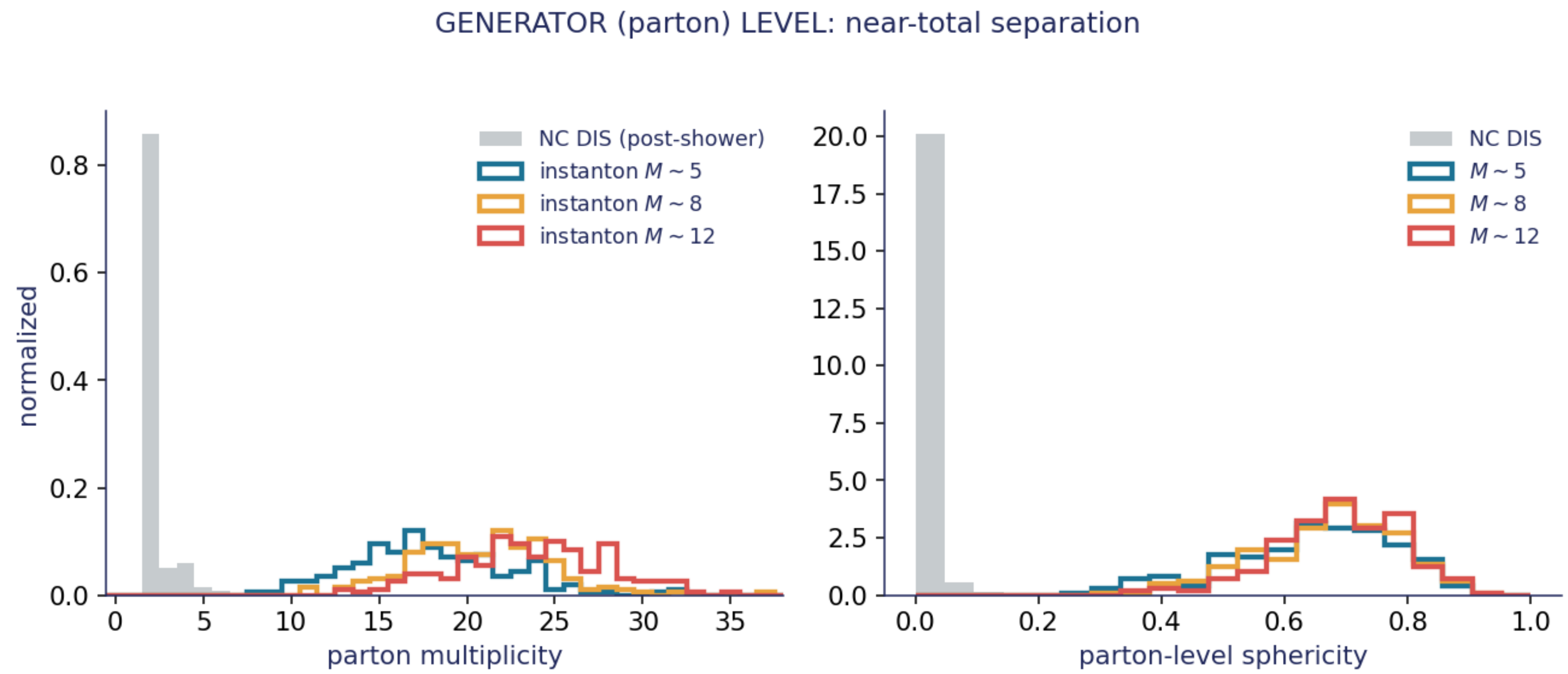
the low-mass reality at ePIC



Variables: M_{inst} = invariant mass of the instanton subprocess (as before); left = normalized counts (kinematic reach only); right = mean event weight ∝ dσ (arb. units).

Conclusions: (i) beam energy sets reach — 5×41 stops at M~27 GeV, 18×275 reaches M~130 GeV; (ii) the rate density falls ~10^{20} from threshold to M~50 GeV: *higher energy extends reach but does not recover the high-mass fireball rate — the target must live at M ~ 3–12 GeV.*

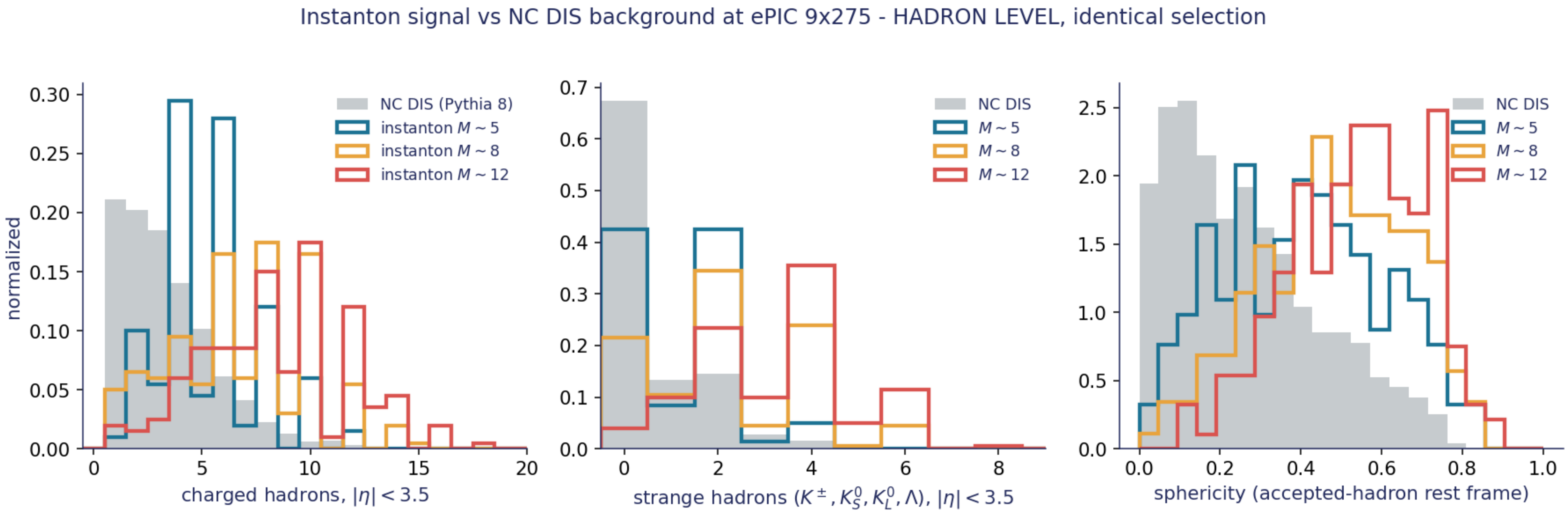
Signal vs. background — generator (parton) level



Variables: parton multiplicity = number of quarks+gluons; sphericity S = (3/2)(λ_2+λ_3) from the eigenvalues of the momentum tensor Σ $p^a p^b/\Sigma|p|^2$ in the system rest frame: S = 1 isotropic, S → 0 back-to-back.

Conclusions: the vertex gives 18–28 partons at S ≈ 0.65; post-shower DIS gives few partons at S ≈ 0 — near-total separation before hadronization dilutes it.

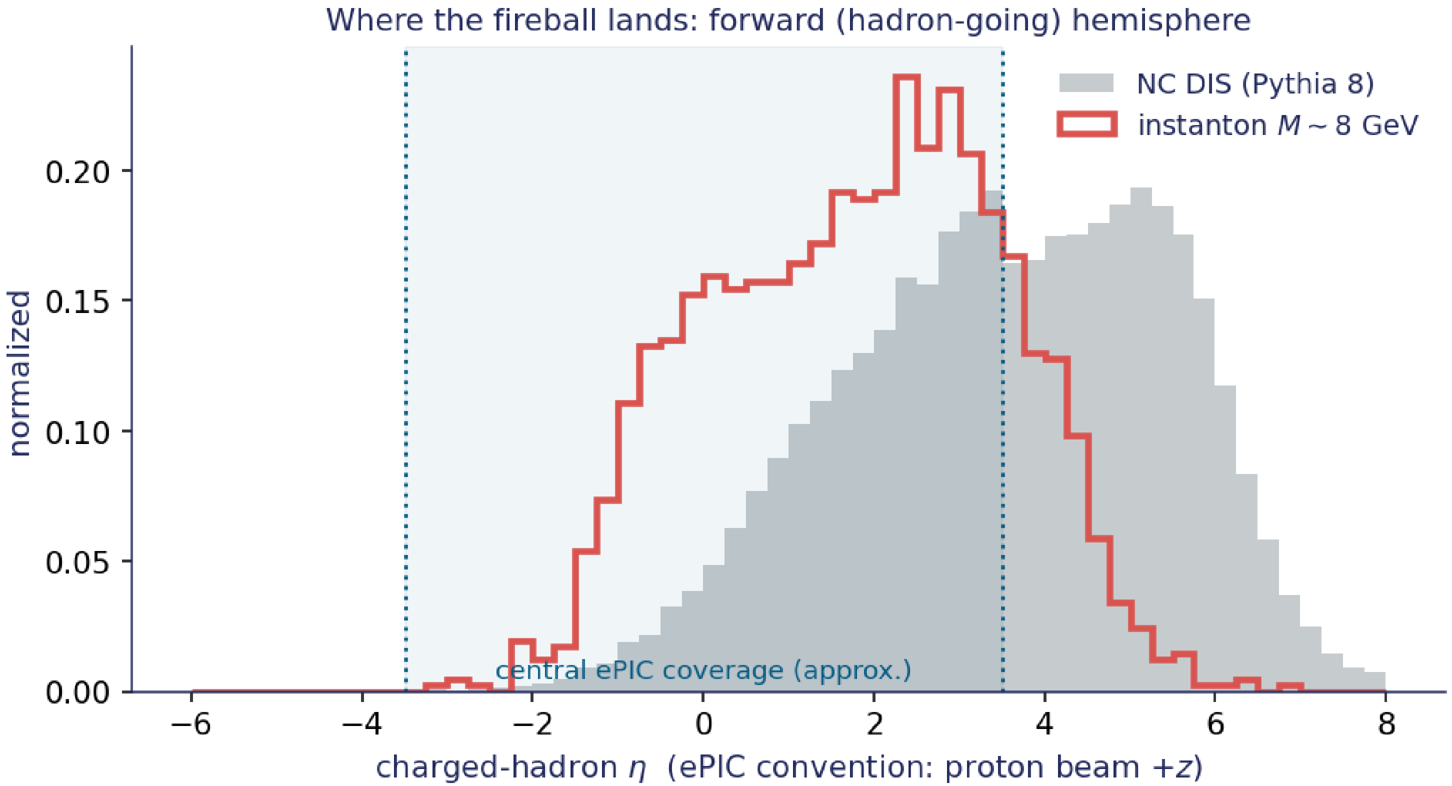
Signal vs. background — hadron level



Variables: n_{ch} = charged hadrons, $|\eta|<3.5$; strange hadrons = $K_{\pm}$, K^0_S, K^0_L, Λ (all reconstructable at ePIC); sphericity as defined, from accepted hadrons.

Conclusions: distributions overlap — no single cut suffices. Strangeness is the strongest handle: $\langle n_{str} \rangle = 0.6$ (DIS) vs 1.2–3.3 (signal); K/π = 0.10 vs 0.14–0.22. **Two cuts ($n_{ch} \geq 6$, $n_{str} \geq 2$): 54% of M~8 signal at 6% background** — a multivariate combination does better (the H1 lesson).

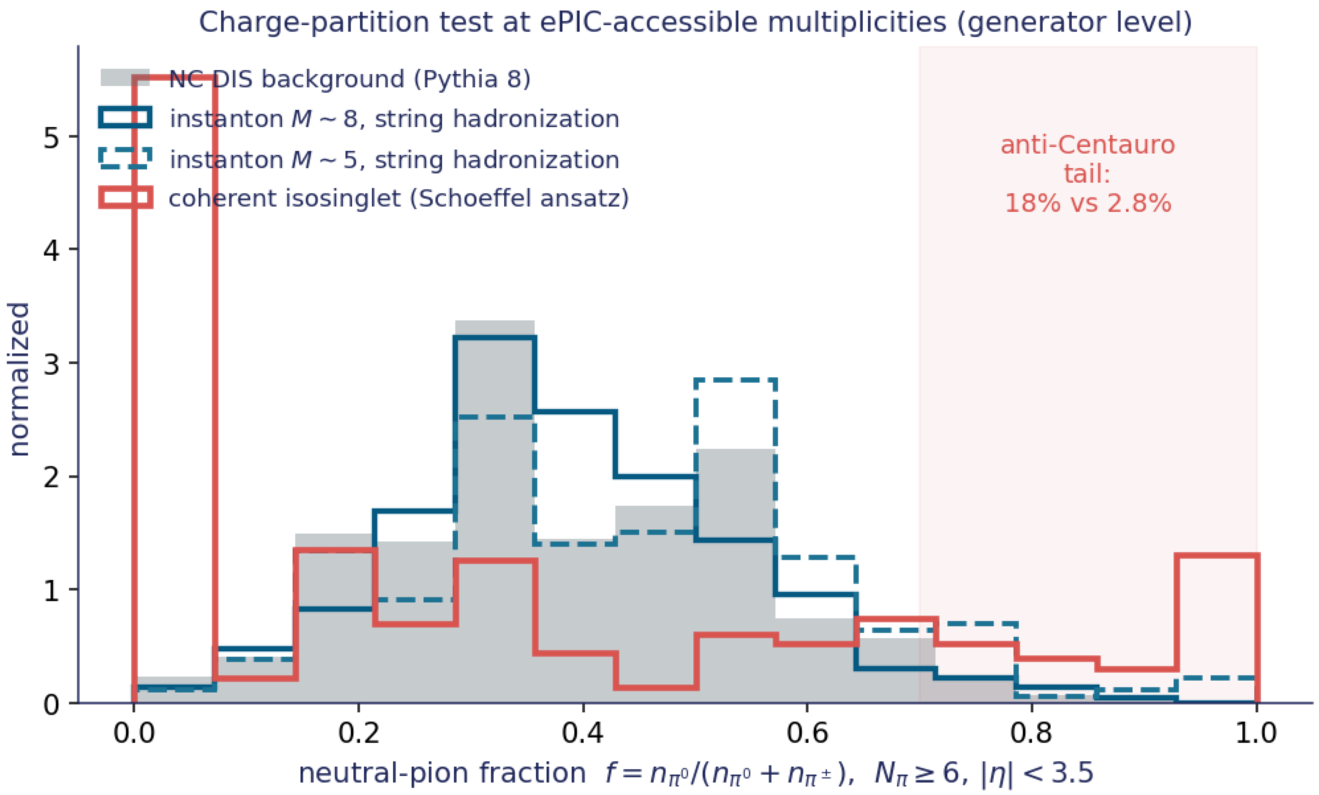
where the fireball lands in ePIC



Variable: pseudorapidity η [= −ln tan(θ/2)], ePIC convention (proton beam = +z ⇒ forward = hadron-going).

Conclusions: signal hadrons sit at η ~ 0–4, peaked near +2.5 — barrel + forward PID and the hadron endcap carry this measurement; backward instrumentation sees little signal. Background peaks further forward (remnant), partly outside acceptance.

a coherence test: the charge partition of the fireball



- **Coherent state**: all pions share one quantum state (like a laser), here an isospin singlet — motivated by the small source $\rho \sim 1/Q'$ (Schoeffel, H1-12/99-579; DCC / anti-Centauro physics).
- **Variable:** f = n_{π^0}/ N_π, the neutral-pion fraction; coherence predicts P(f) ~ 1/(2√f) vs near-multinomial for incoherent (string) hadronization.
- Orthogonal to all other observables: tests *how* the fireball hadronizes; lives in the low-mass regime (⟨N_π⟩ ≈ 9–10); no PID.

- **Conclusion**: tail lever arm P(f≥0.7) = **18%** coherent vs **2.8%** strings/DIS; two-sided. Needs Bose–Einstein correlations-aware baseline + imaging-EMCal π^0.

Why ePIC — the realistic case

- **PID is the decisive capability**: strangeness enhancement is the best single discriminator; flavour democracy the qualitative smoking gun — both need K/π/p separation over the forward hemisphere.
- **Hermeticity** enables event-shape reconstruction of low-multiplicity systems where every track counts.
- **Luminosity $\gg$ HERA** turns overlapping distributions into a statistically decisive multivariate analysis (the H1 lesson).
- Forward tagging secondary here (a diffractive instanton–Pomeron channel would be uniquely ePIC; see glossary).

Caveat Background here = NC DIS only (no photoproduction/diffraction); no detector effects.
A sensitivity projection needs the official simulation — this defines the PWG-level study we propose.

Outlook: spin as the direct probe of chirality violation

- The instanton vertex **flips quark chirality** — the defining property, invisible to multiplicity/shape observables.
- Spin-dependent hadronization could carry it: Λ polarization (*self-analyzing*: $\Lambda \rightarrow p\pi^-$ reveals the spin direction) and hadron-spin correlations.
- **StringSpinner** (string+$^3P_0$: string breaks emit $q\bar{q}$ pairs with vacuum quantum numbers, transmitting spin; Kerbizi–Lönnblad, CPC 272, 108234) — today SIDIS & LO e^+e^-, **mesons only**; baryon-spin model (Kerbizi–Artru 2026) not yet in the code. [$^3P_0$: spin triplet (S=1), P-wave orbital angular momentum (L=1), and total J=0.]
- Required development: string+$^3P_0$ for the multi-string fireball topology, with InstGen helicity input.

Caveat Whether chirality imbalance survives instanton/anti-instanton averaging into net spin observables is an open theory question — flagged, not assumed.

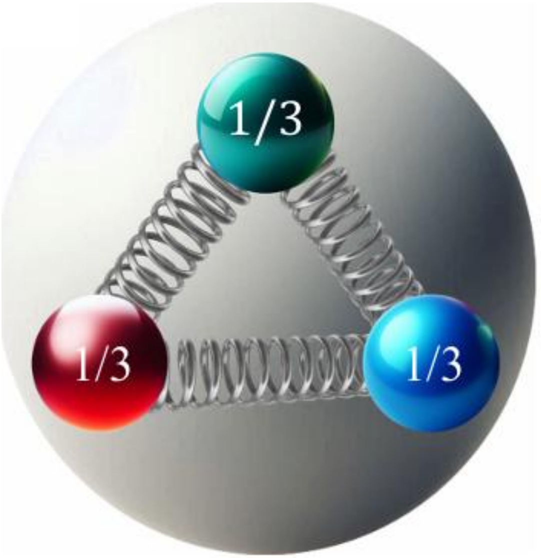
SECOND CASE (MOTIVATION)

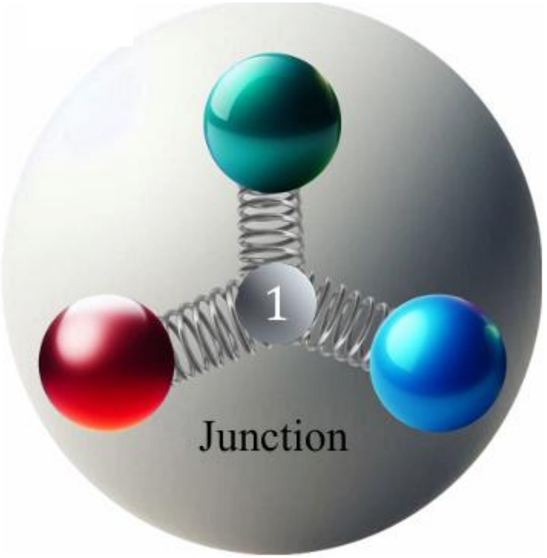
The Gluonic Baryon Junction

no generator yet

what carries a proton's baryon number?

- **Baryon number B**: the conserved charge that makes a proton a baryon (B=1) and cannot disappear. Textbook: the three valence quarks carry B (1/3 each).
- **Proposed** (Rossi–Veneziano; Kharzeev): the three colour strings meet at a soft gluonic **junction** carrying momentum fraction $x_J \ll x_{valence}$, and IT traces B — so baryon number can be **stopped** near midrapidity while the valence quarks fly on.

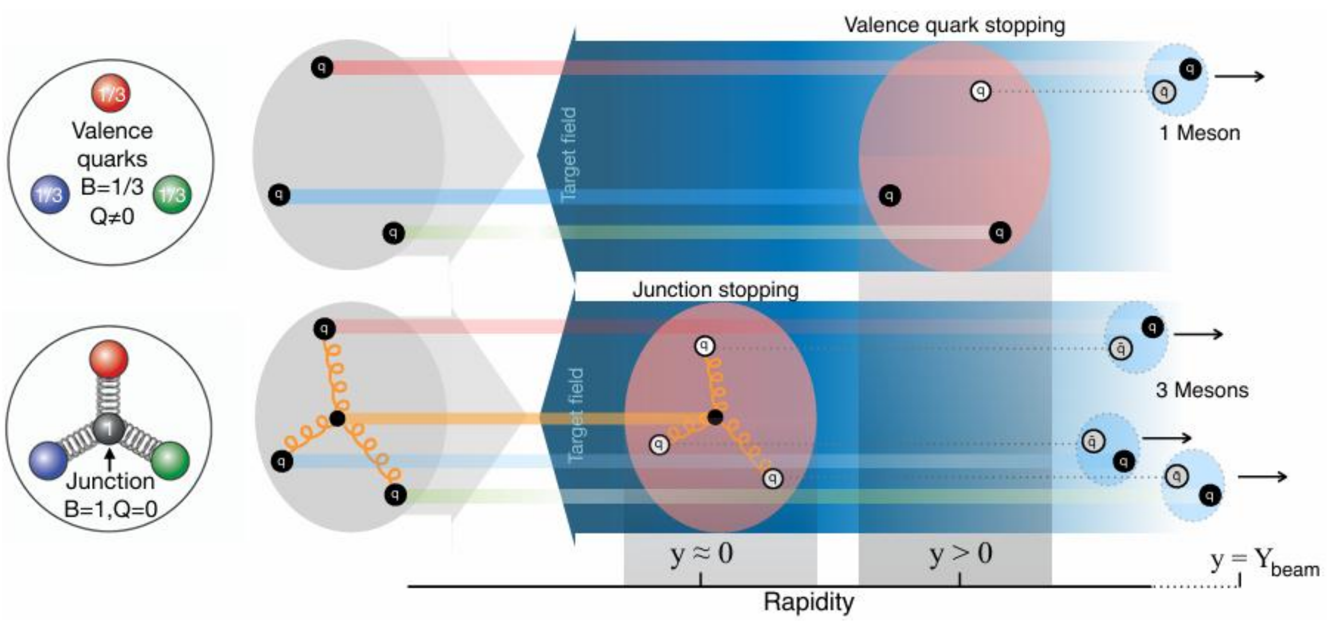




[2408.07131] Search for baryon junctions in e+A collisions at the Electron Ion Collider

2408.15441 STAR: Tracking the baryon number with nuclear collisions

observable & status



- **Variables:** rapidity y = ½ ln[(E+pz)/(E−pz)]; rapidity loss y_beam − y; net baryon = N_B − N_B̄. Slope α in dN/d(y_loss) ∝ e^(−α y_loss): α ≈ 2.5 (valence carry B) vs α_J ≈ 0.5 (junction carries B).

  Plus: net-baryon vs net-charge **decoupling** (charge follows quarks, B follows the junction); A-dependence (nuclear-size scaling in e+Au).

  STAR isobar consistent with junctions; HERA small-x baryon asymmetry; heavy-ion data confounded by MPI — **DIS is clean**.

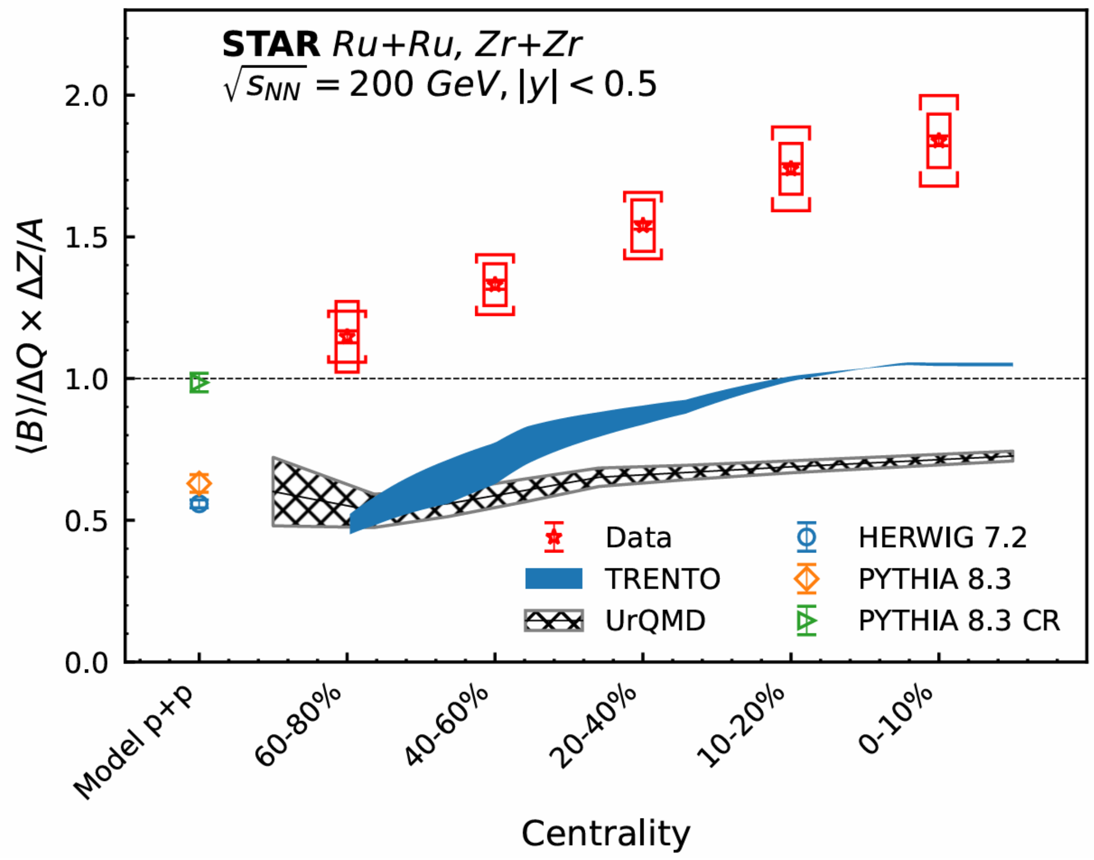
  Hardware: forward tagging **primary** — Roman Pots/B0 (proton taggers), ZDC (forward neutrons); low-p p/p̄ via ToF. e+p, e+Au early.

Caveat A proposal, not established physics — and no generator implements it. A junction MC is the required development.

observable & status II

$$Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}})$$

$$B = (N_p + N_n) - (N_{\bar{p}} + N_{\bar{n}})$$



$$\Delta Q = Q_{\mathrm{Ru+Ru}} - Q_{\mathrm{Zr+Zr}} \approx N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p(R2_p - 1)$$

$$R2_\pi = (N_{\pi^+}/N_{\pi^-})_{\mathrm{Ru+Ru}}/(N_{\pi^+}/N_{\pi^-})_{\mathrm{Zr+Zr}}$$

Two cases, different maturity

	Instantons	Baryon junction
Status	**Generator + S/B at hadron level**	Physics motivation
Generator	InstGen (ep, ePIC beams) + Pythia 8	**none yet**
Key result	54% sig / 6% bkg with two cuts	Observable + hardware case
Decisive capability	PID (strangeness), hermeticity	Forward tagging, ToF
What to trust	Shapes, flavour ratios	Slope, decoupling, A-dep.

The instanton case is ready for a PWG-level study now; the junction case defines the next generator development.

what I would like to learn and what I need to learn

- are there more people interested in non-perturbative effects, particularly instantons and junctions?
  - about which parts/details you would like to hear more?
- should I ask/talk to other people/groups?
- I did not use ePIC software yet – what is the best way to start?
- is there another analysis/es where my contribution may be useful?

I got no reply to my one/two sentences about non-perturbative physics in the document in preparation – anything new?

1: Beyond its precision parton-structure program, ePIC can make genuinely non-perturbative and topological QCD processes a direct measurement target — from instanton-induced final states to the gluonic transport of baryon number — using its high inclusive statistics, 4π hermeticity, and particle identification.

2: While much of the ePIC program targets the (perturbatively calculable) parton structure of nucleons and nuclei, the same high-statistics inclusive data, 4π hermeticity, and particle identification also give direct access to non-perturbative and topological QCD processes in the final state. These include instanton-induced events and the gluonic origin and transport of baryon number — observables that complement, rather than duplicate, the structure-function and TMD program.

thank you