5th International Workshop on Emergent QCD Collectivity Across Scales: From Small System Collisions to Jets

Understanding the origin of collective phenomena in jets

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Rice University

Based on: PRL 133 (2024) 142301, CMS-PAS-HIN-24-024, and recent model studies (to be submitted soon)

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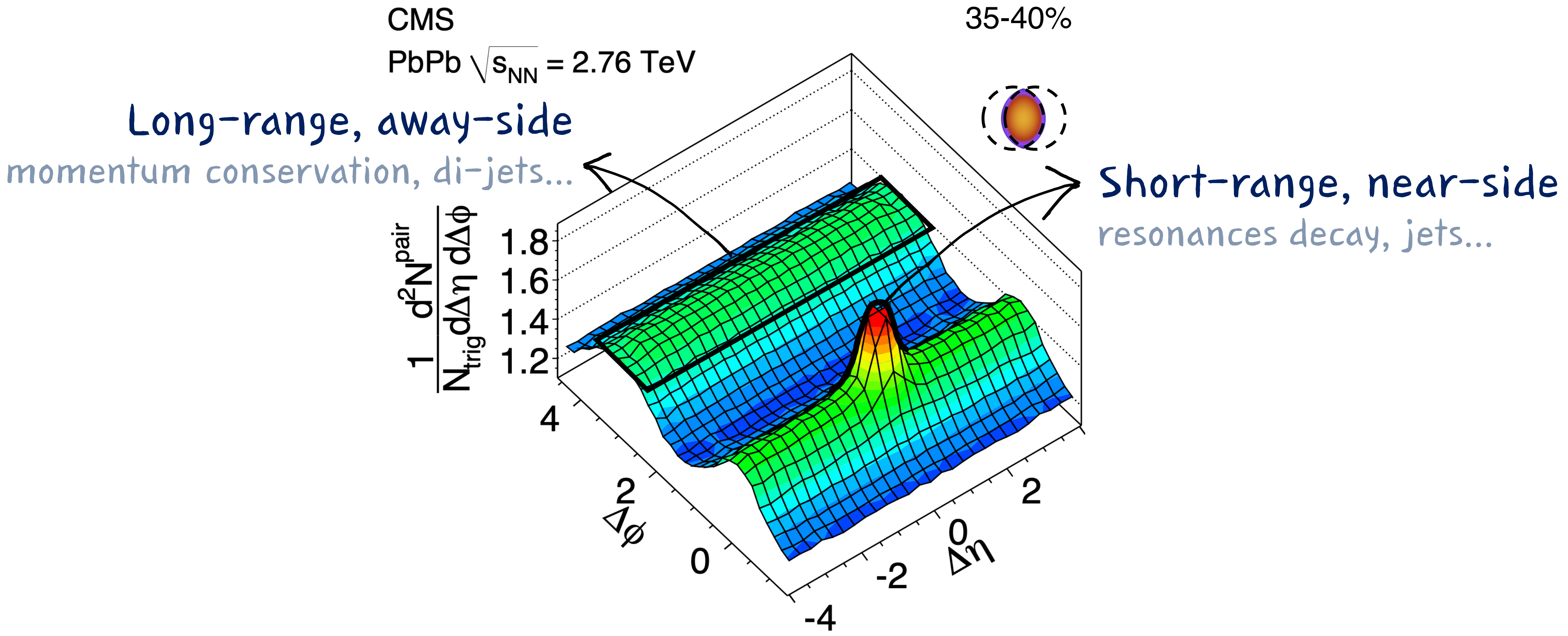
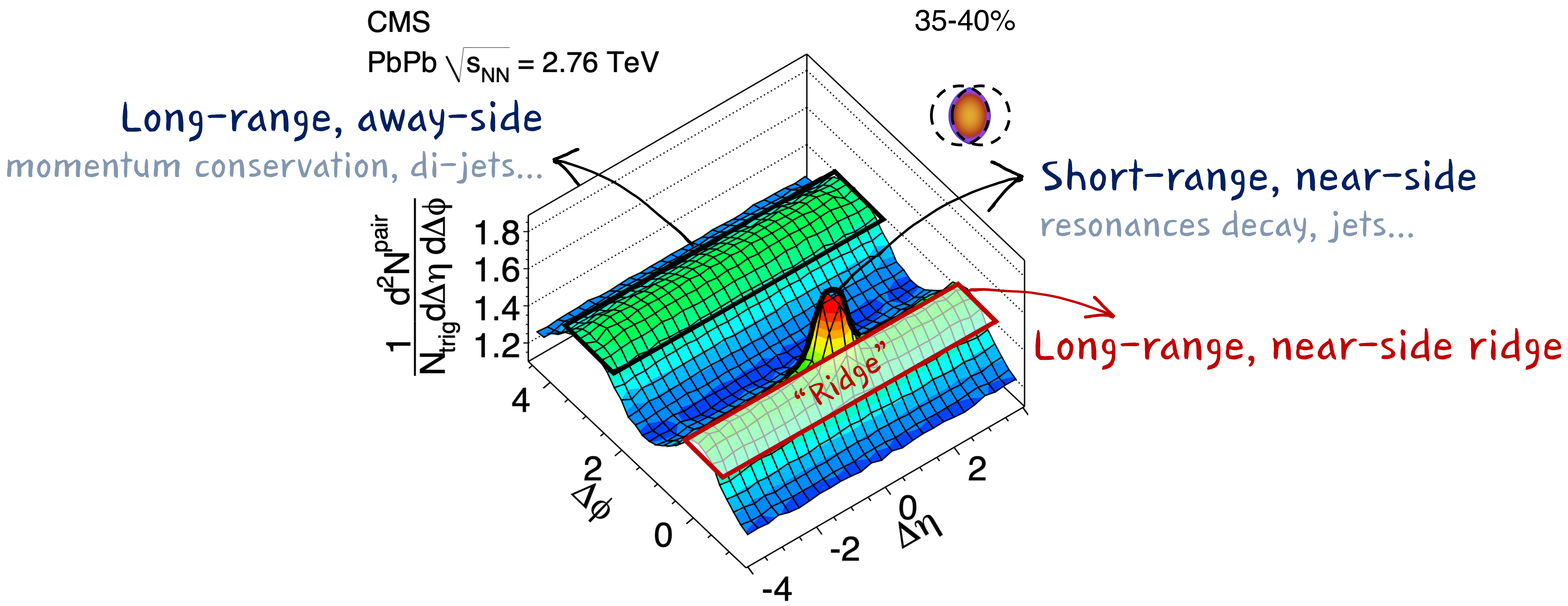
Compact Muon Solenoid

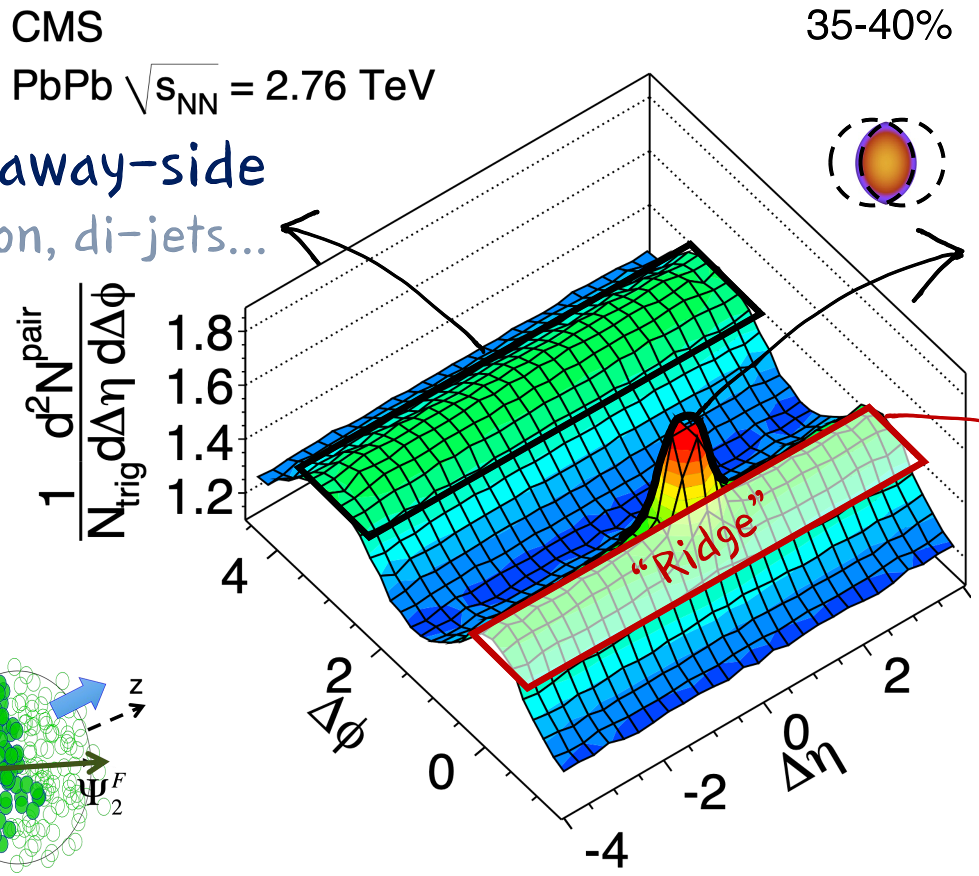
Collectivity in Heavy Ion



Collectivity in Heavy Ion



Collectivity in Heavy Ion



Long-range, away-side

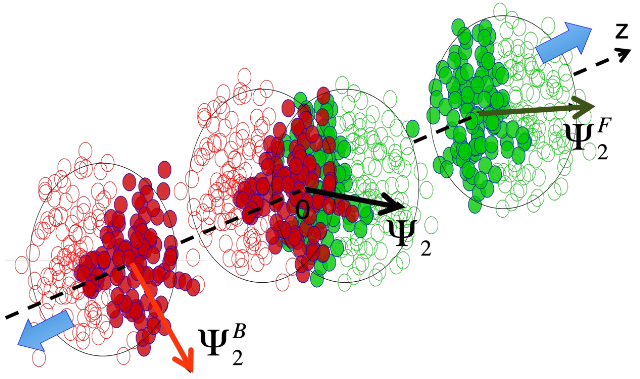
momentum conservation, di-jets...

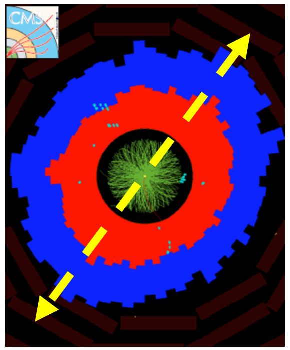
Short-range, near-side

resonances decay, jets...

Long-range, near-side ridge

collective flow!





QGP is a strongly coupled, nearly perfect fluid!

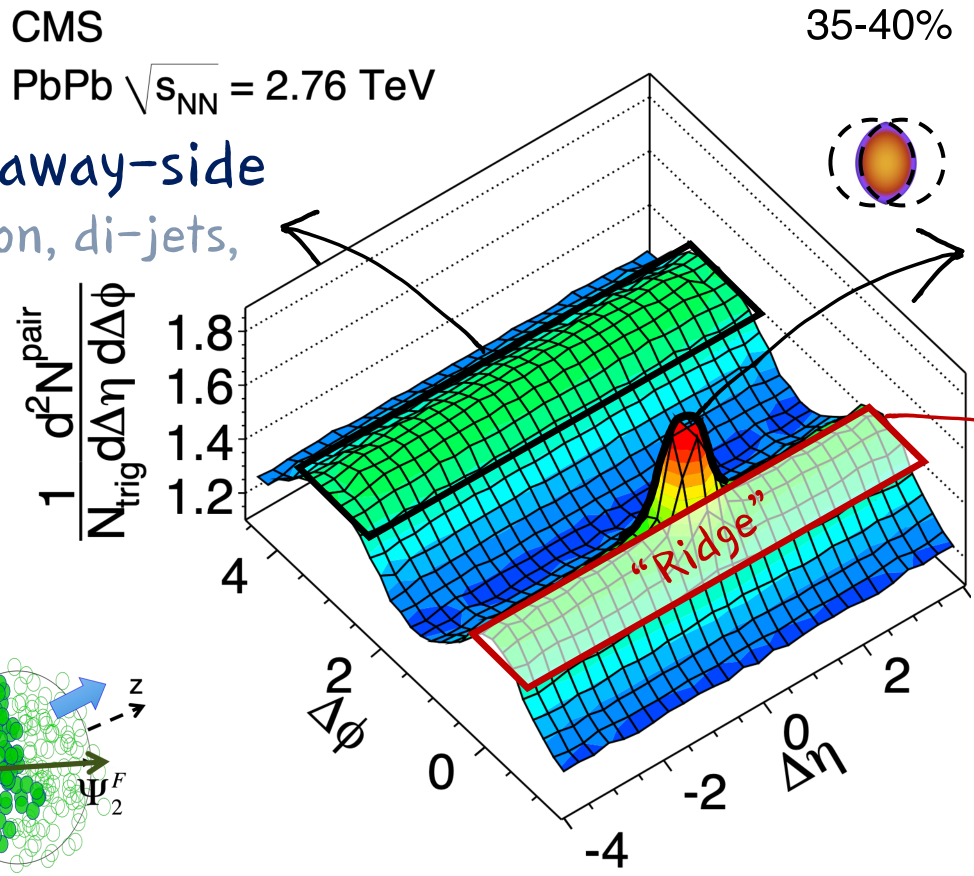
Initial State Geometry → Strong Rescattering → Final State Anisotropy

Collectivity in Heavy Ion

Long-range, away-side

momentum conservation, di-jets,

collective flow…

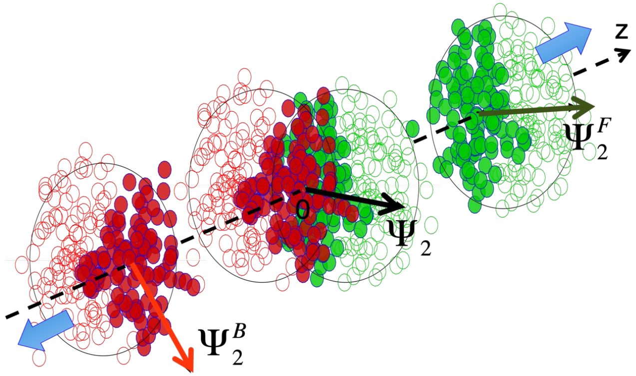


Short-range, near-side

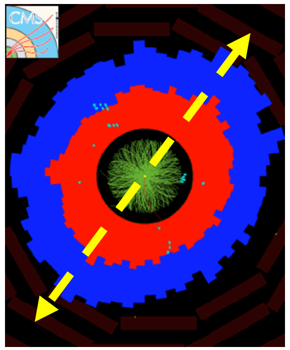
resonances decay, jets…

Long-range, near-side ridge

collective flow!



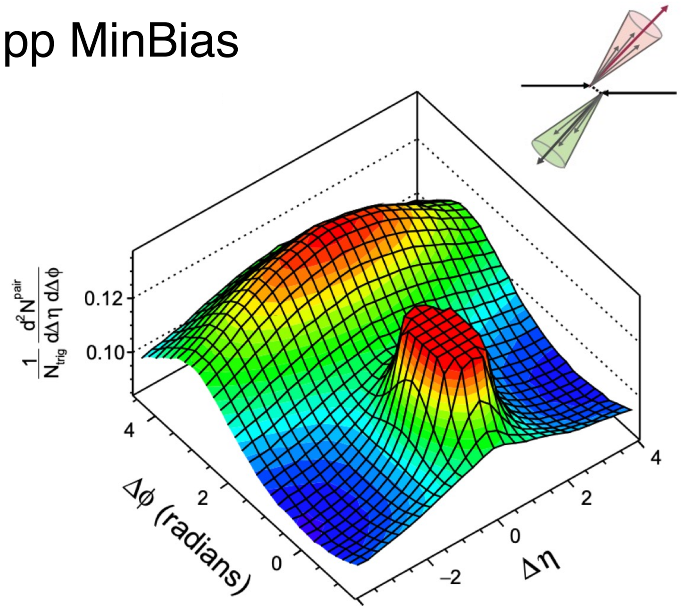
QGP is a strongly coupled, nearly perfect fluid!



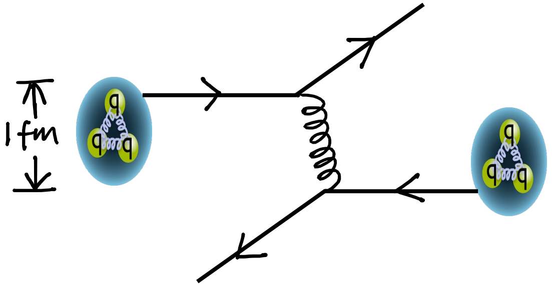
Initial State Geometry → Strong Rescattering → Final State Anisotropy

Collectivity in small systems

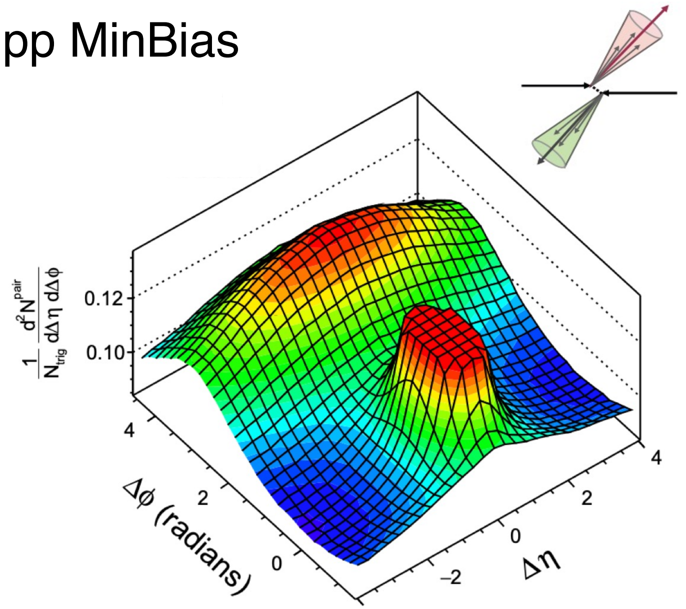
pp MinBias

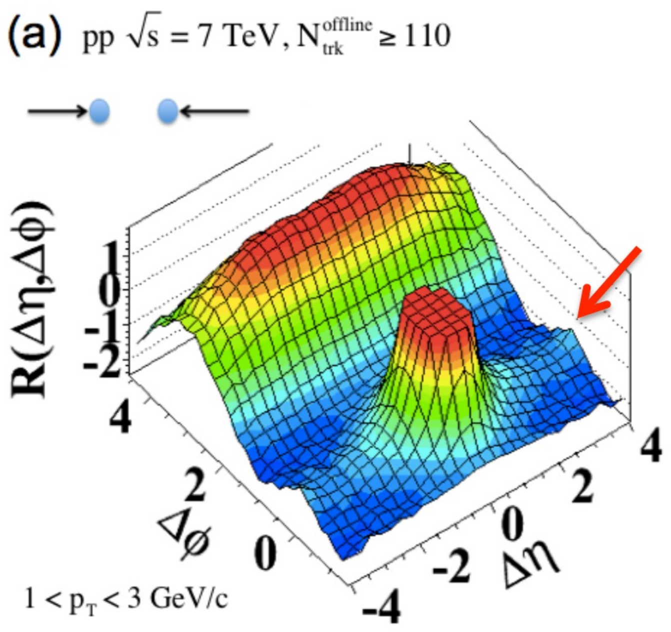


✗ No near-side ridge in MB pp



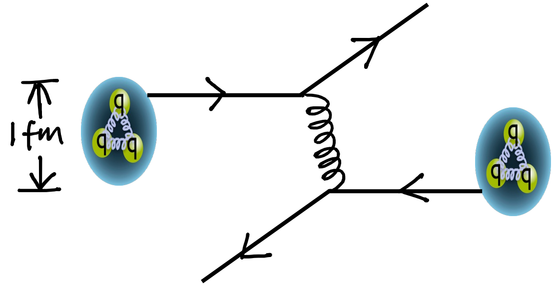
Collectivity in small systems





JHEP 09 (2010) 091

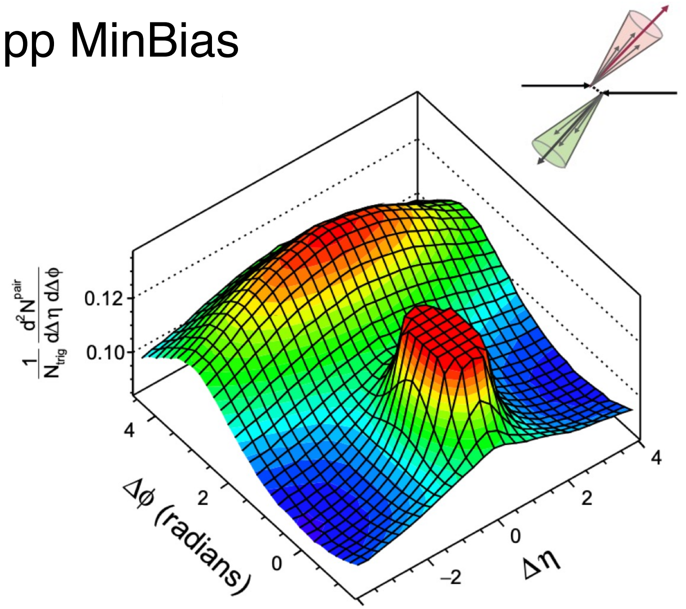
✗ No near-side ridge in MB pp ✓ Near-side ridge in HM pp

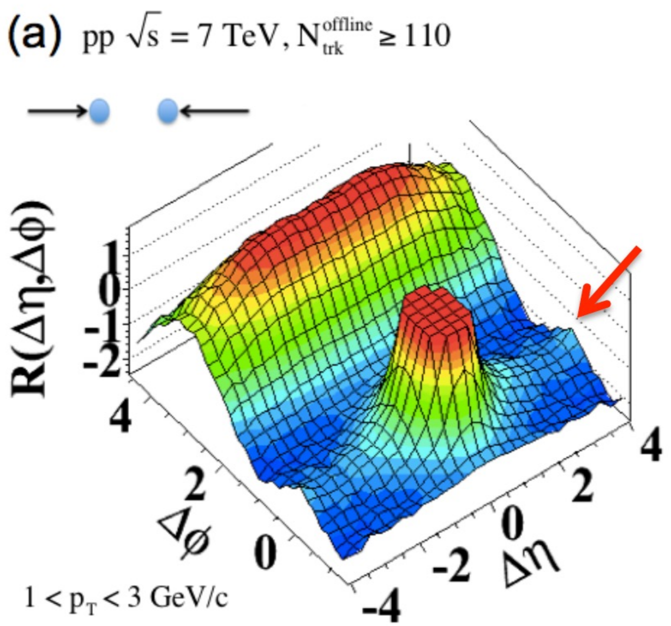


Collectivity in small systems

Also see a review: K. Dusling, WL, B. Schenke, Int.J.Mod.Phys. E25 (2016) 01, 1630002

pp MinBias





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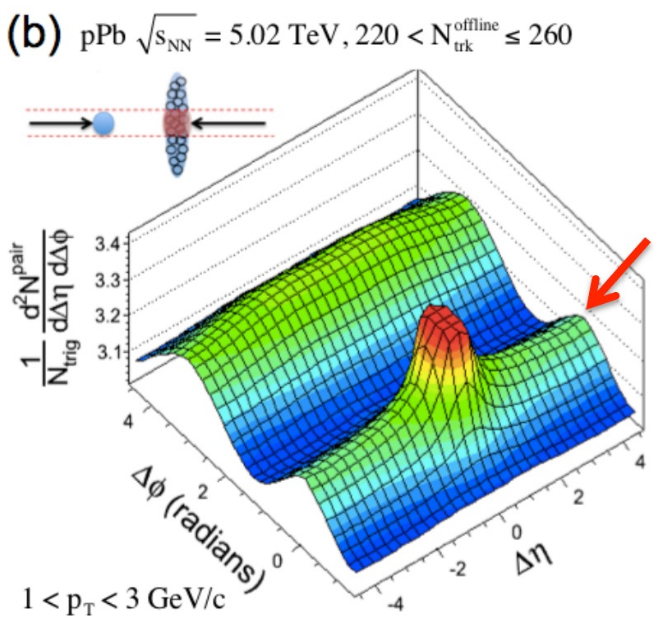
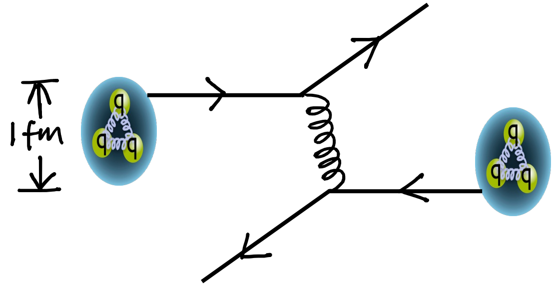
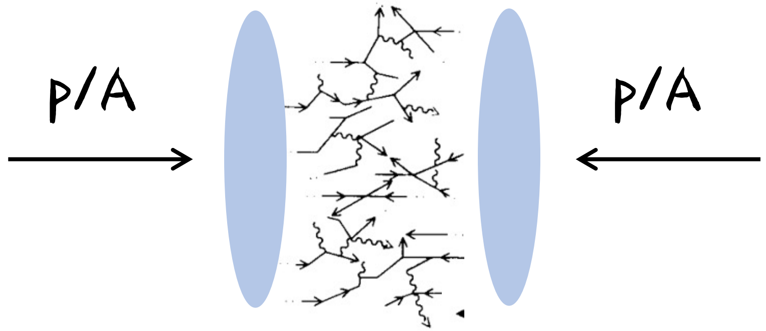


PLB 718 (2013) 795

✗ No near-side ridge in MB pp ✓ Near-side ridge in HM pp and pPb

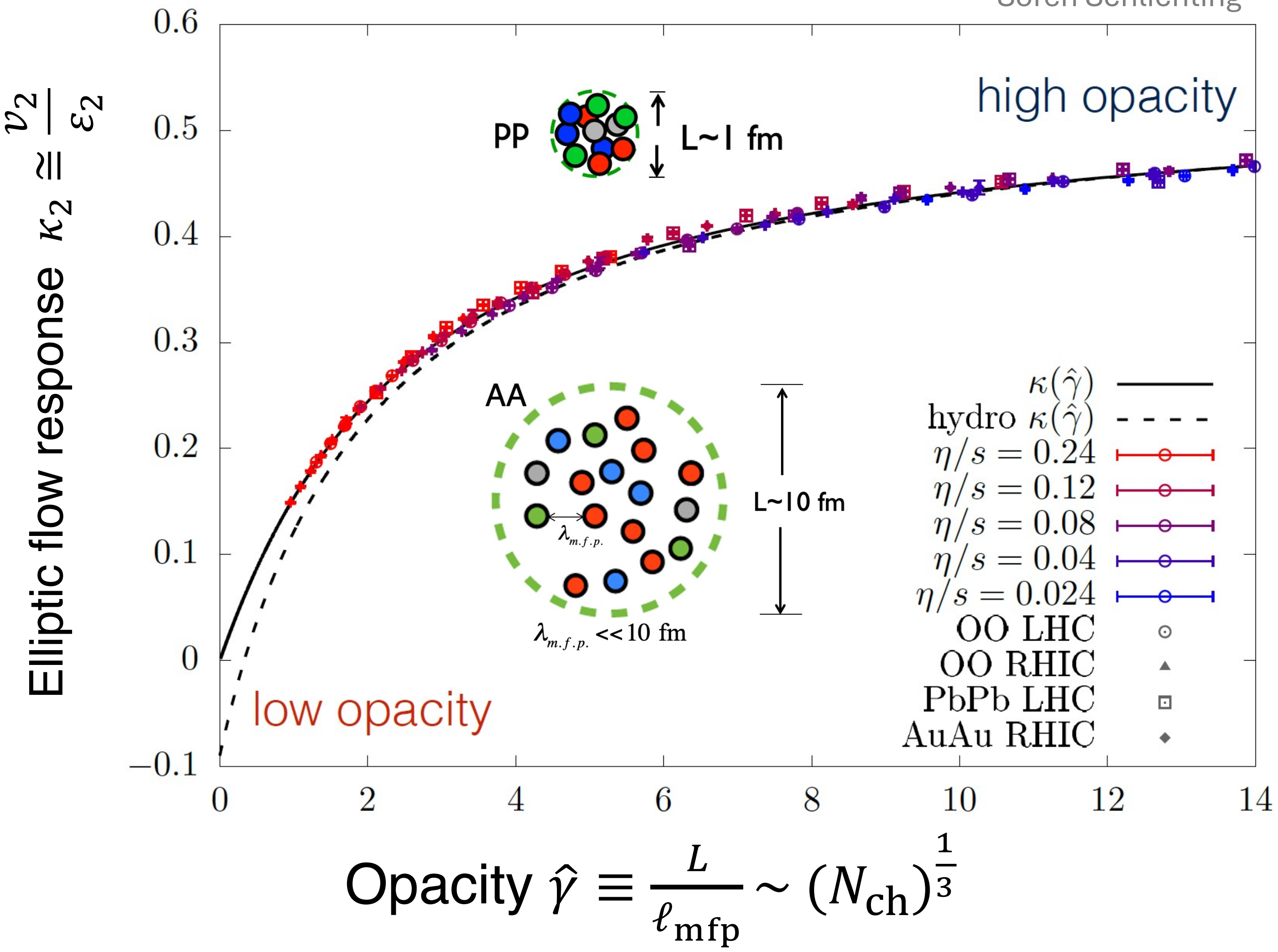




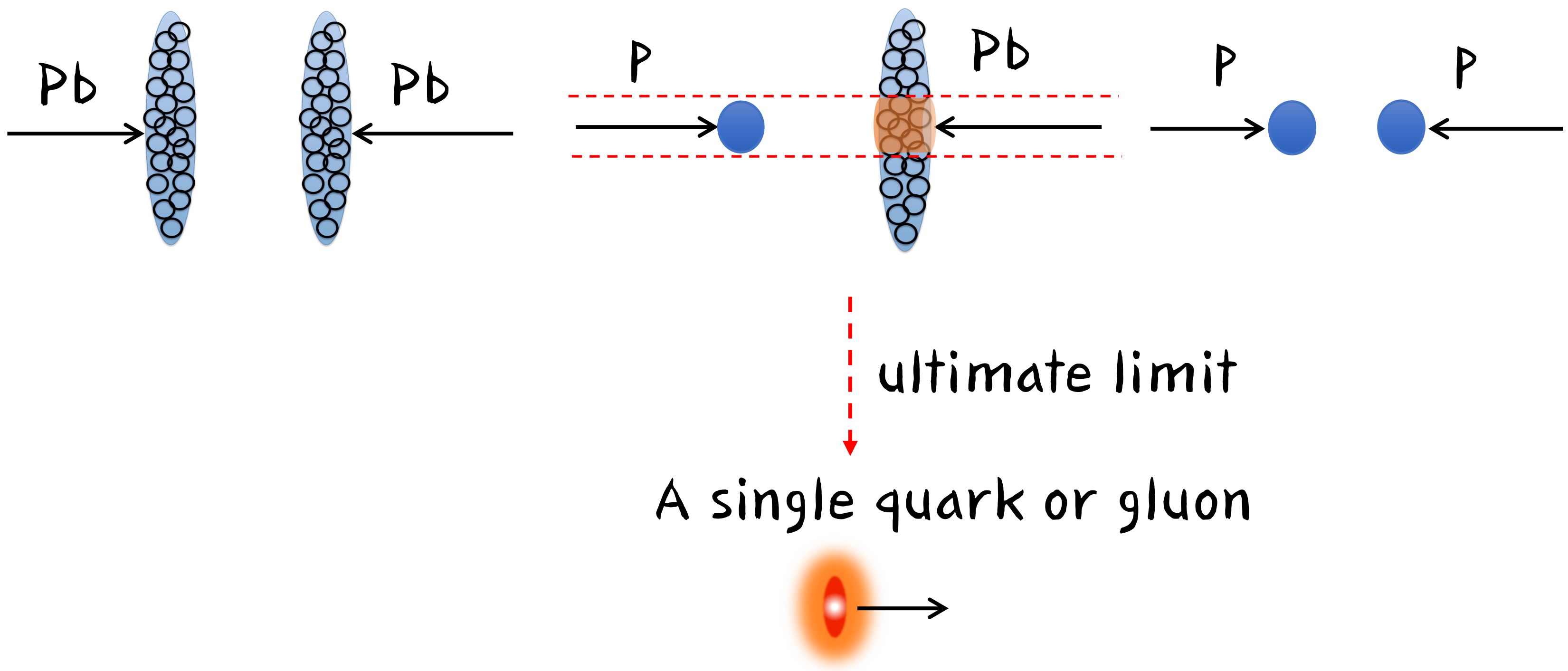
Strong partonic re-scatterings at subfermi scales

A new paradigm - Universal QGP across systems

Sören Schlichting



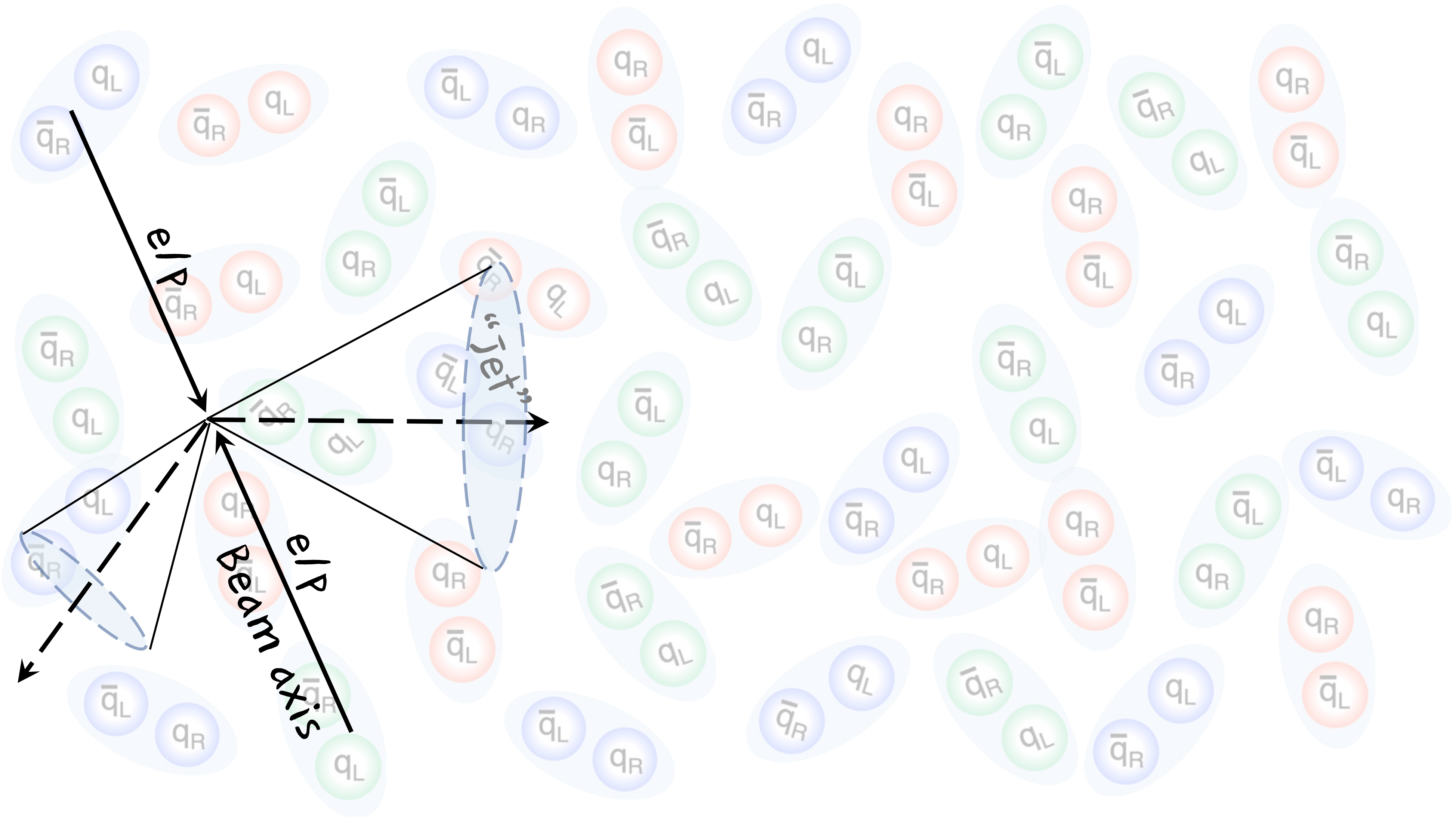
How small a QGP droplet can be ?



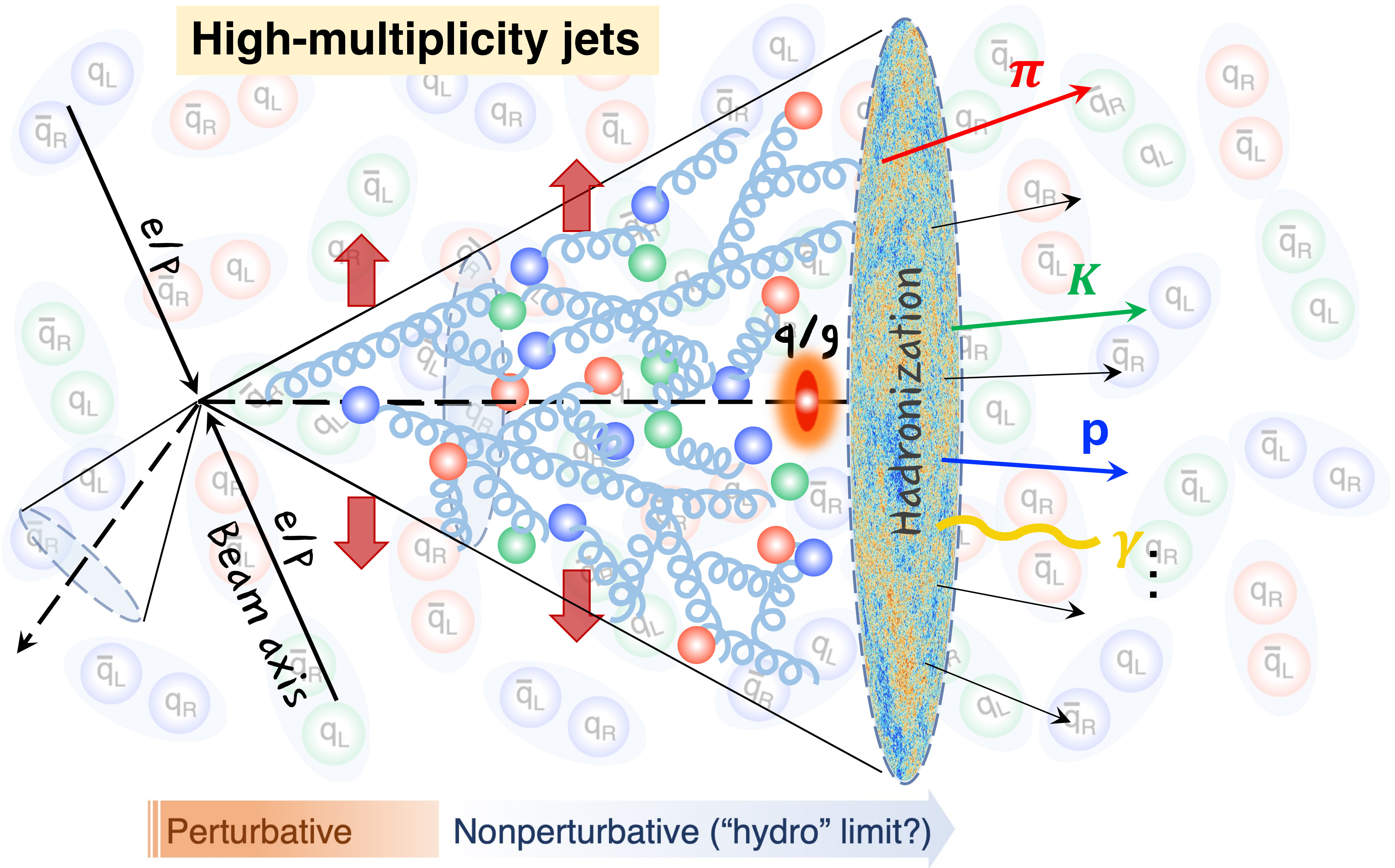
Can a QGP droplet be initiated by a “single parton” in the vacuum?

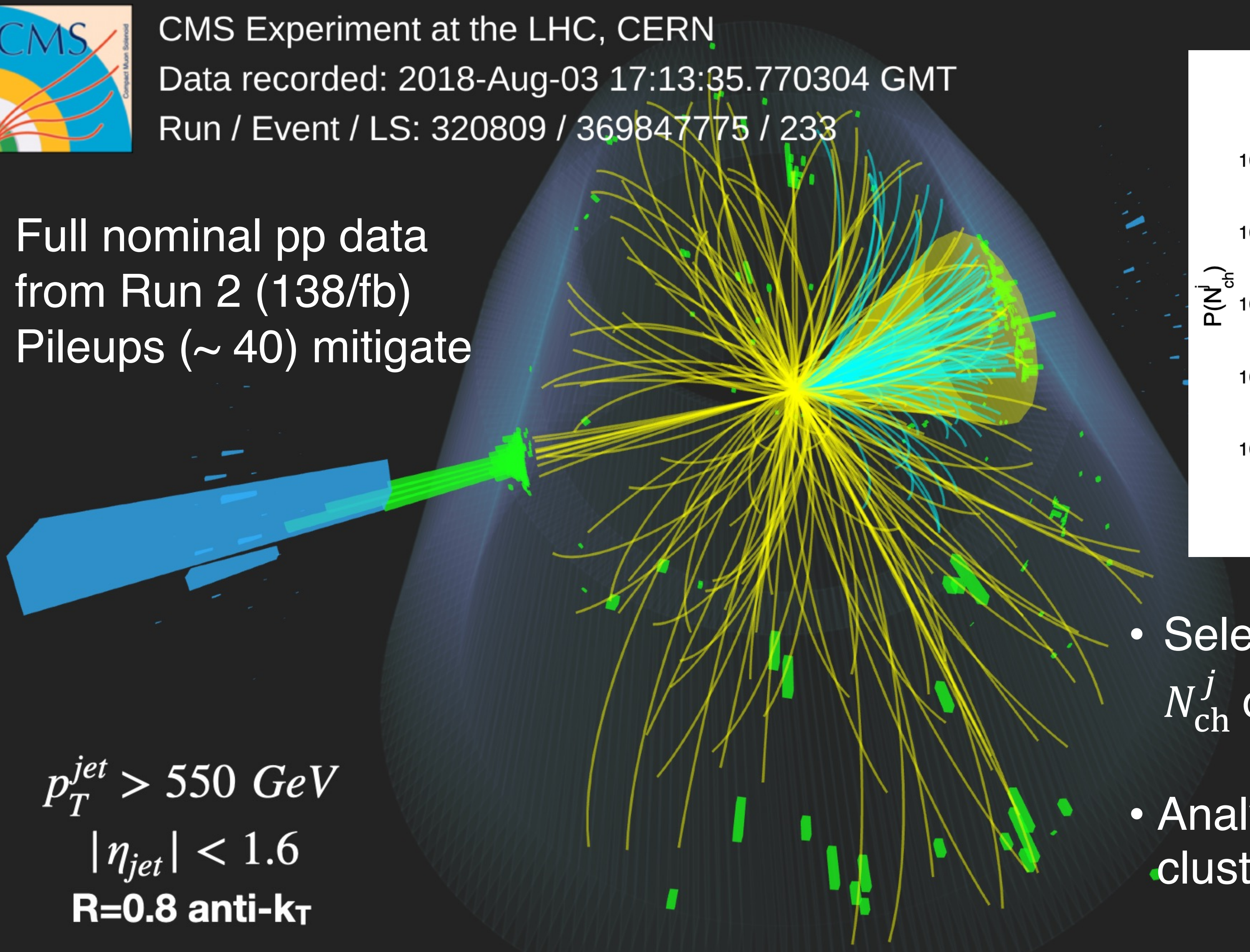
A. Baty, P. Gardner, WL, PRC 107 (2023) 064908

Jet: a proxy for system initiated by a parton



Jet: a proxy for system initiated by a parton

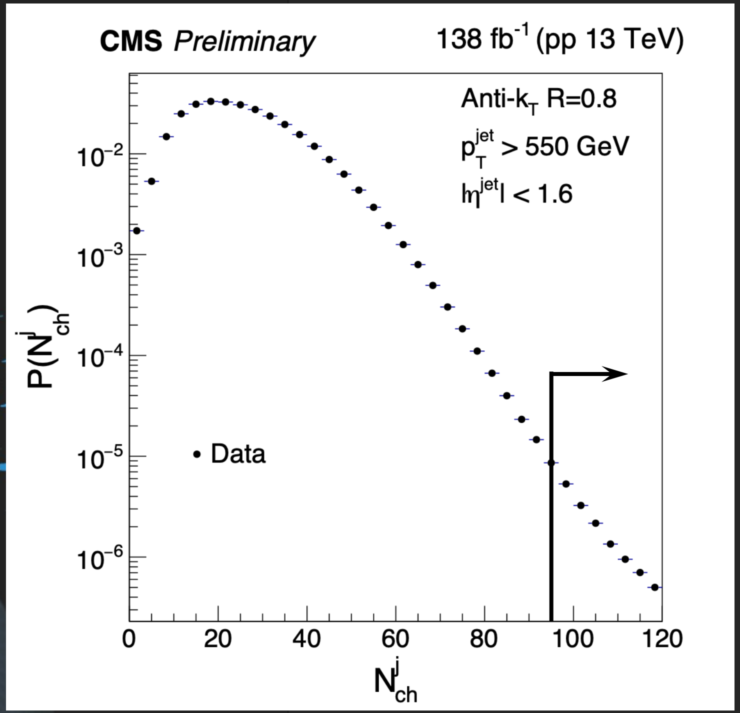




Full nominal pp data from Run 2 (138/fb)
Pileups (~ 40) mitigate

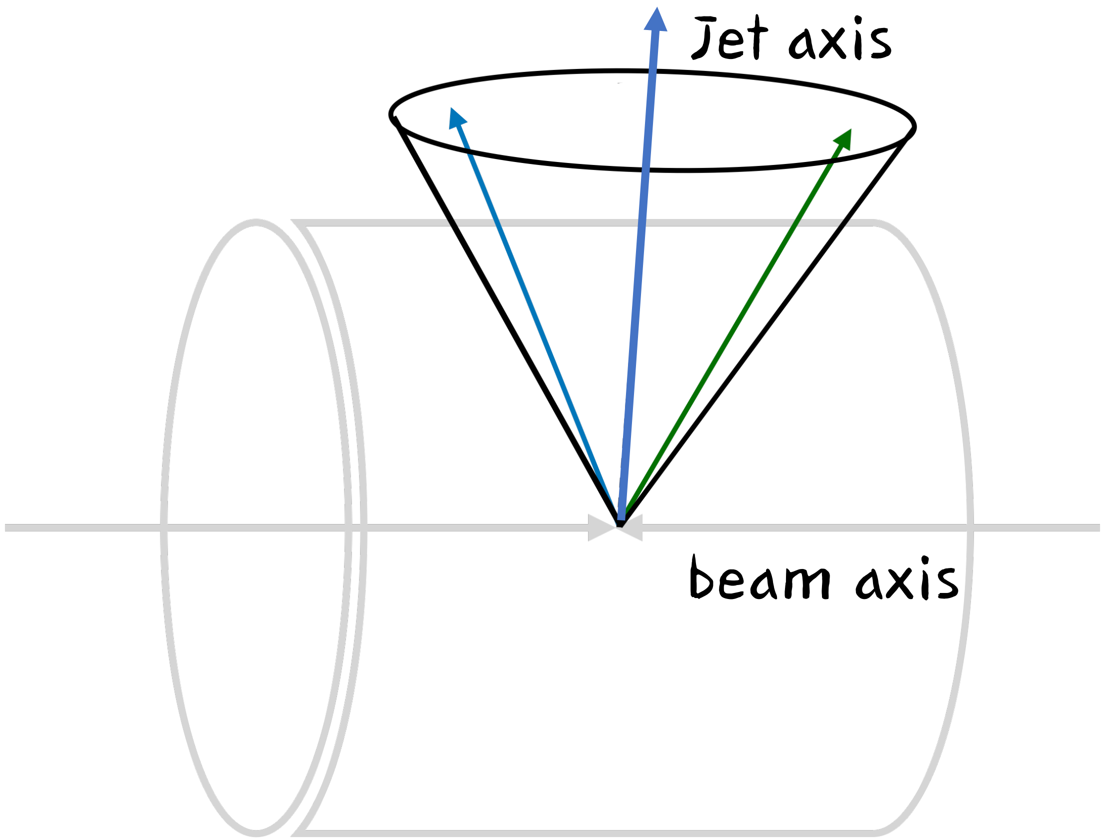
$$p_T^{jet} > 550\ GeV$$
$$|\eta_{jet}| < 1.6$$

R=0.8 anti-k$_T$

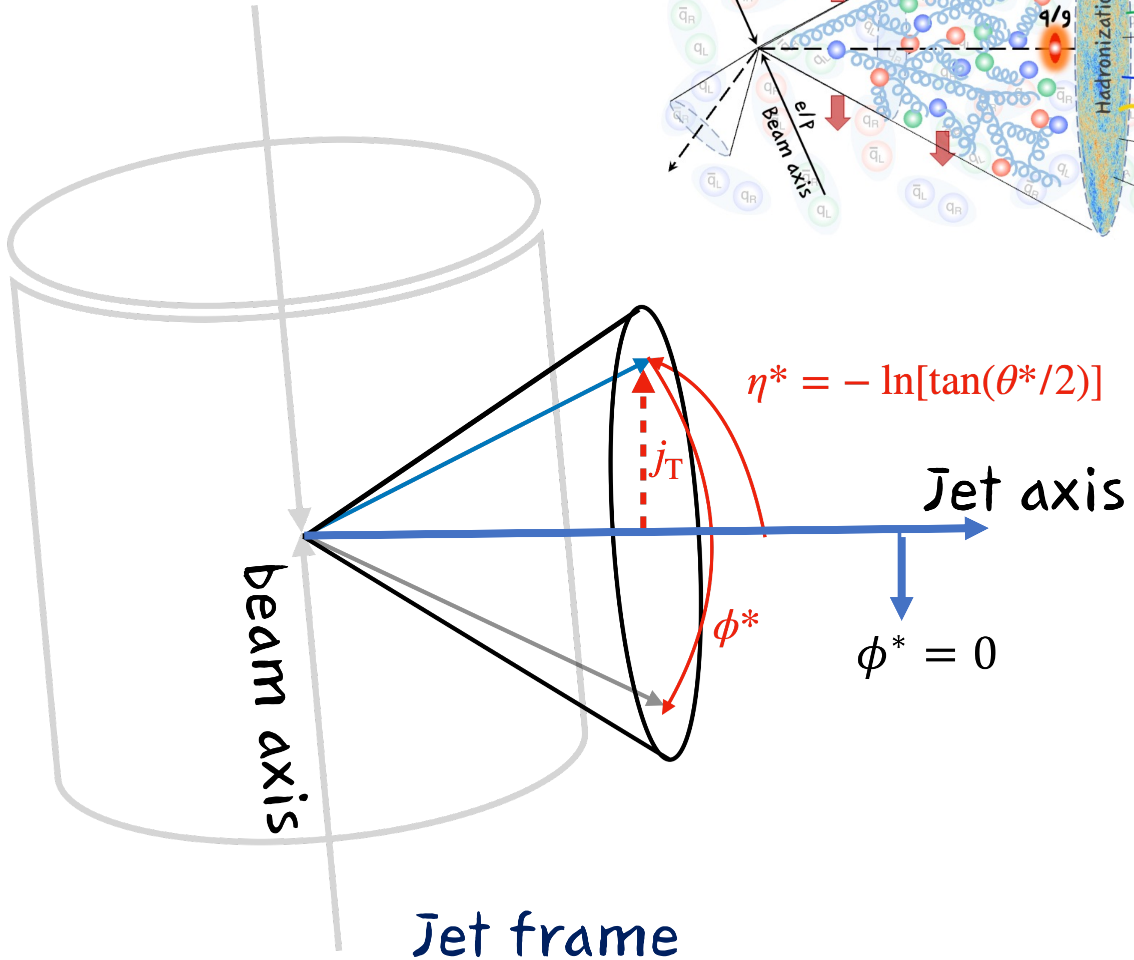


- Select top ~2,500 jets in N_{ch}^{j} out of 10^8 jets analyzed
- Analyzing only particles clustered into a jet

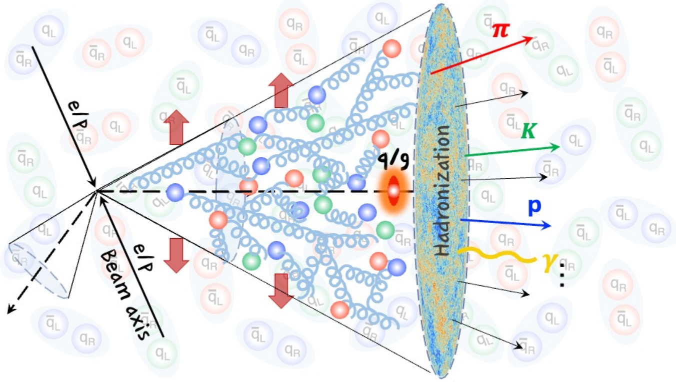
Projection to the jet axis



Lab frame



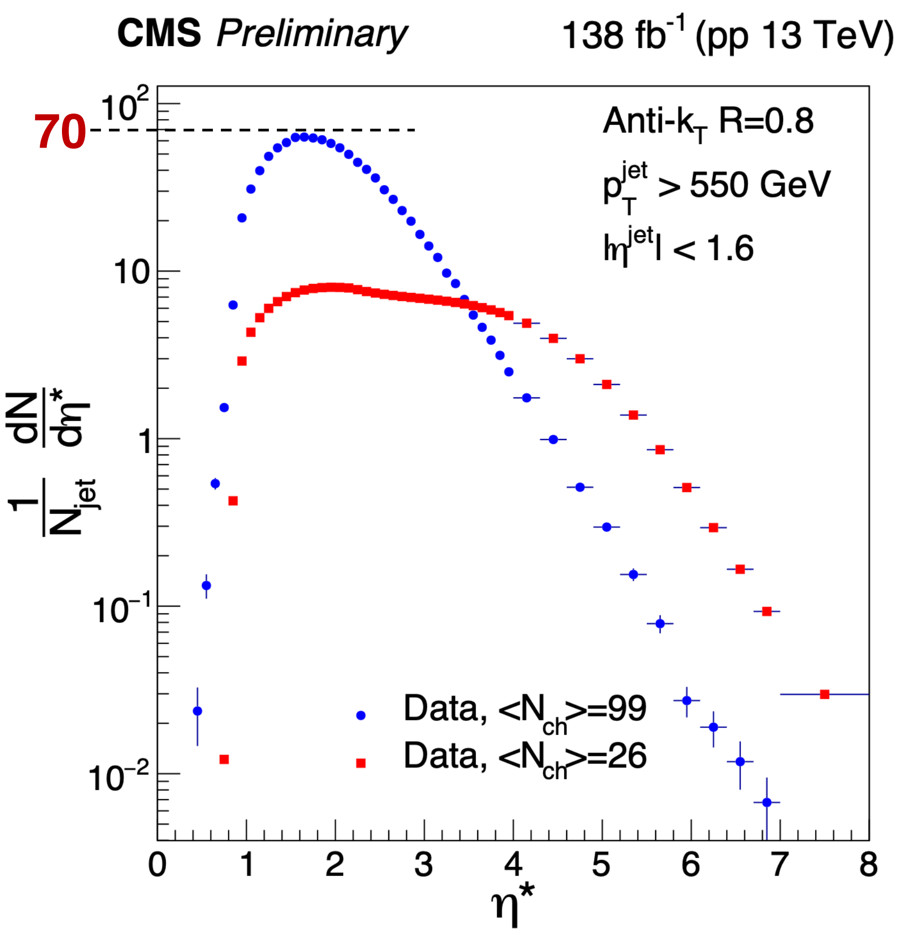
Jet frame

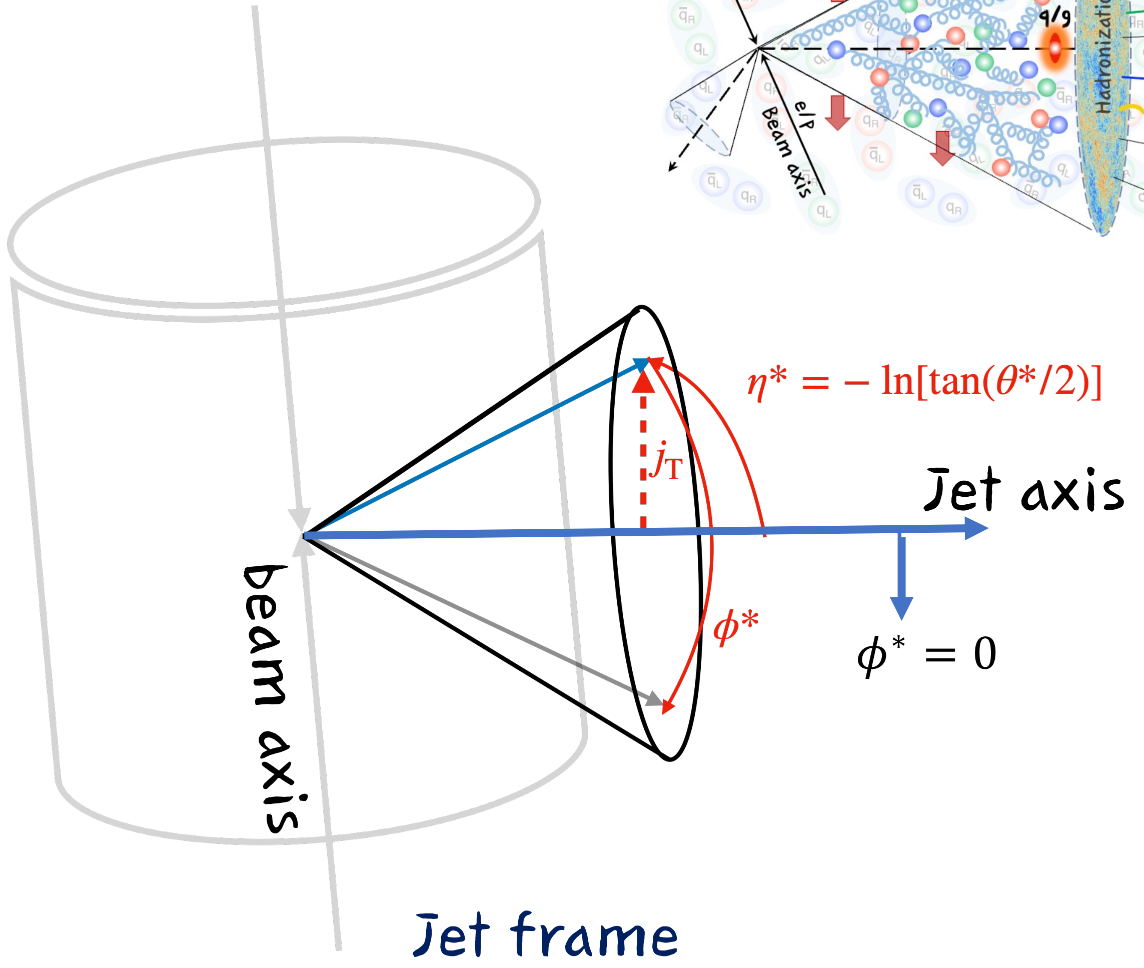


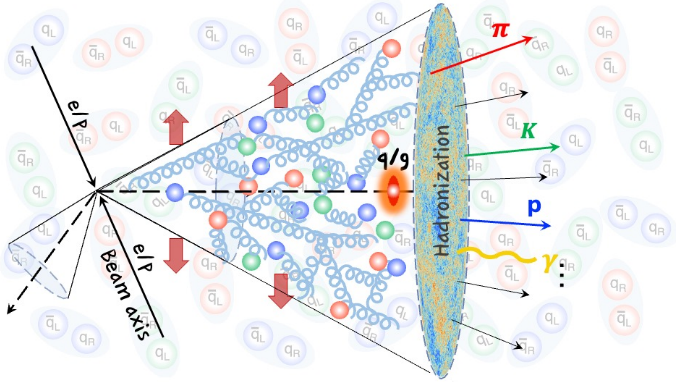
Projection is done for every jet individually.

$$\boldsymbol{p} = (p_\mathrm{T}, \eta, \phi) \rightarrow \boldsymbol{p}^* = (j_\mathrm{T}, \eta^*, \phi^*)$$

Projection to the jet axis







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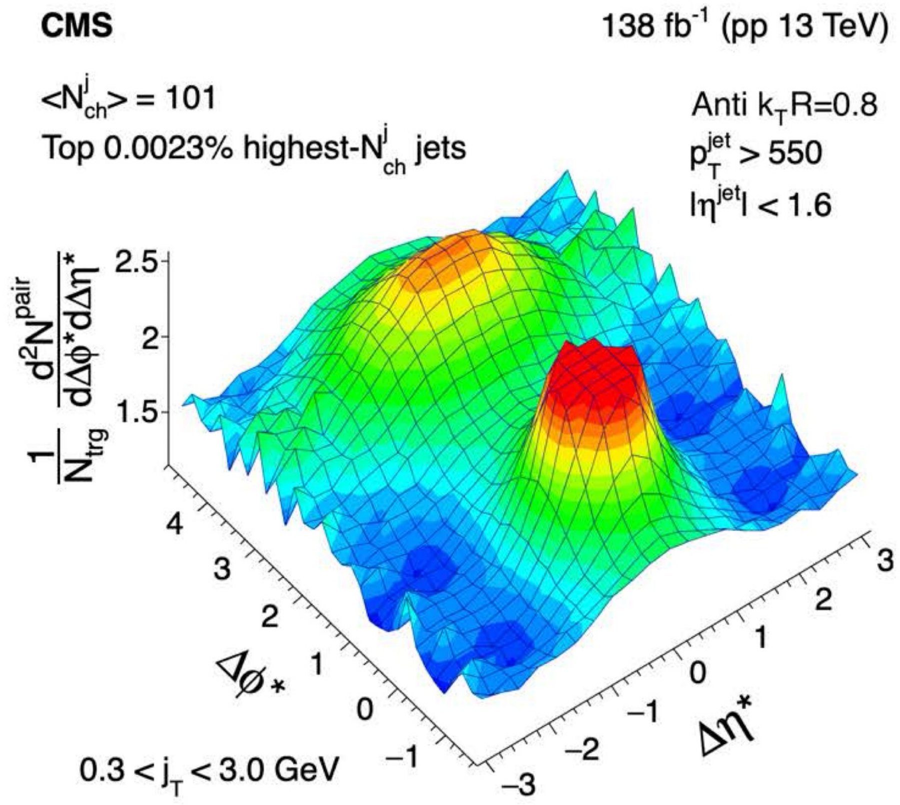
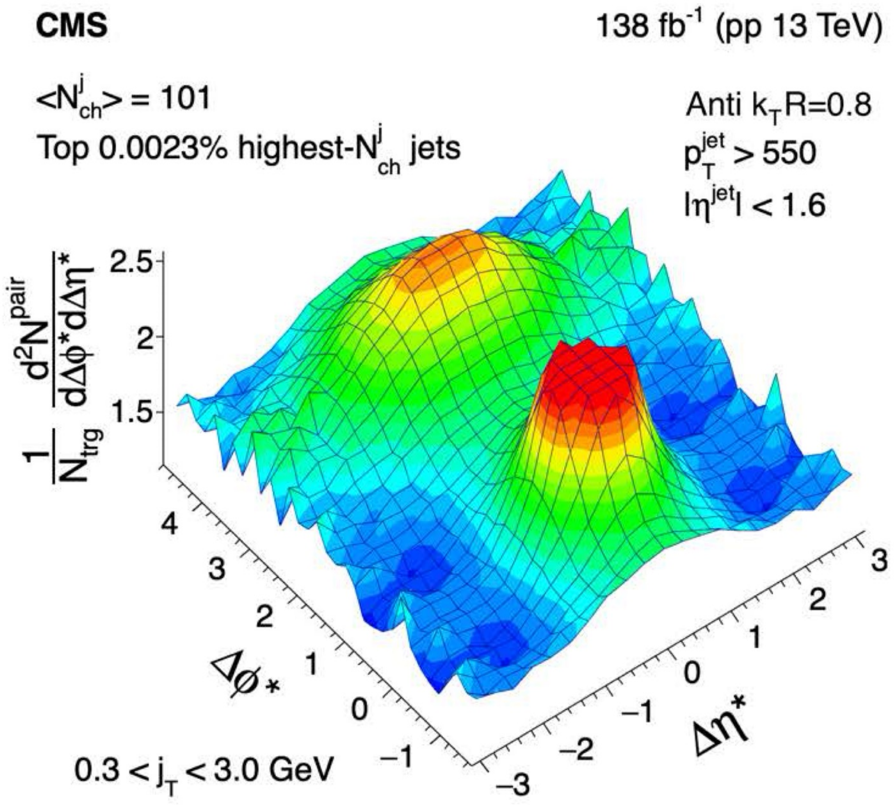
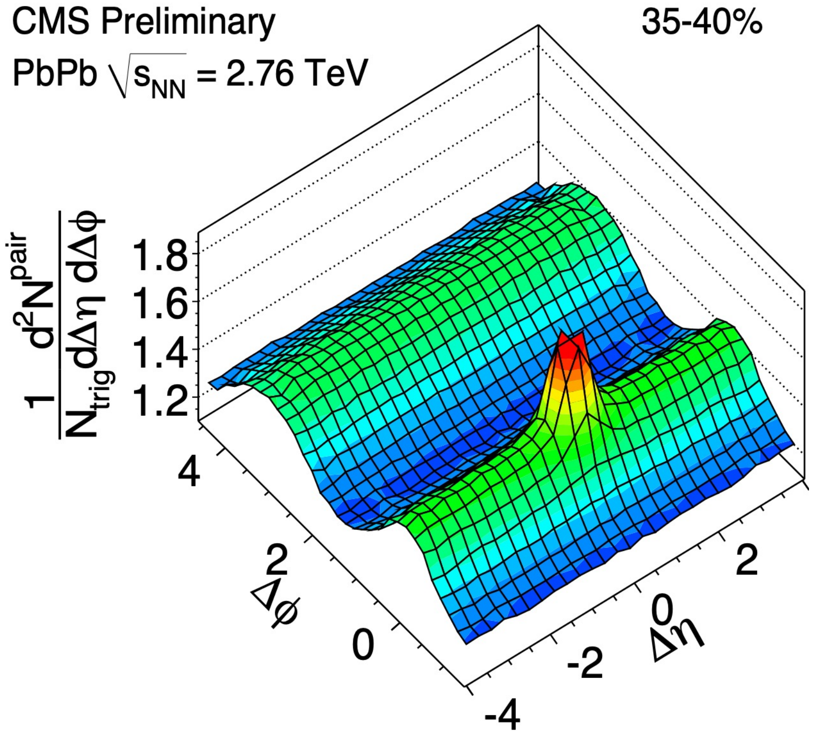
Two particle correlation within jets



Two particle correlation within jets



Similar



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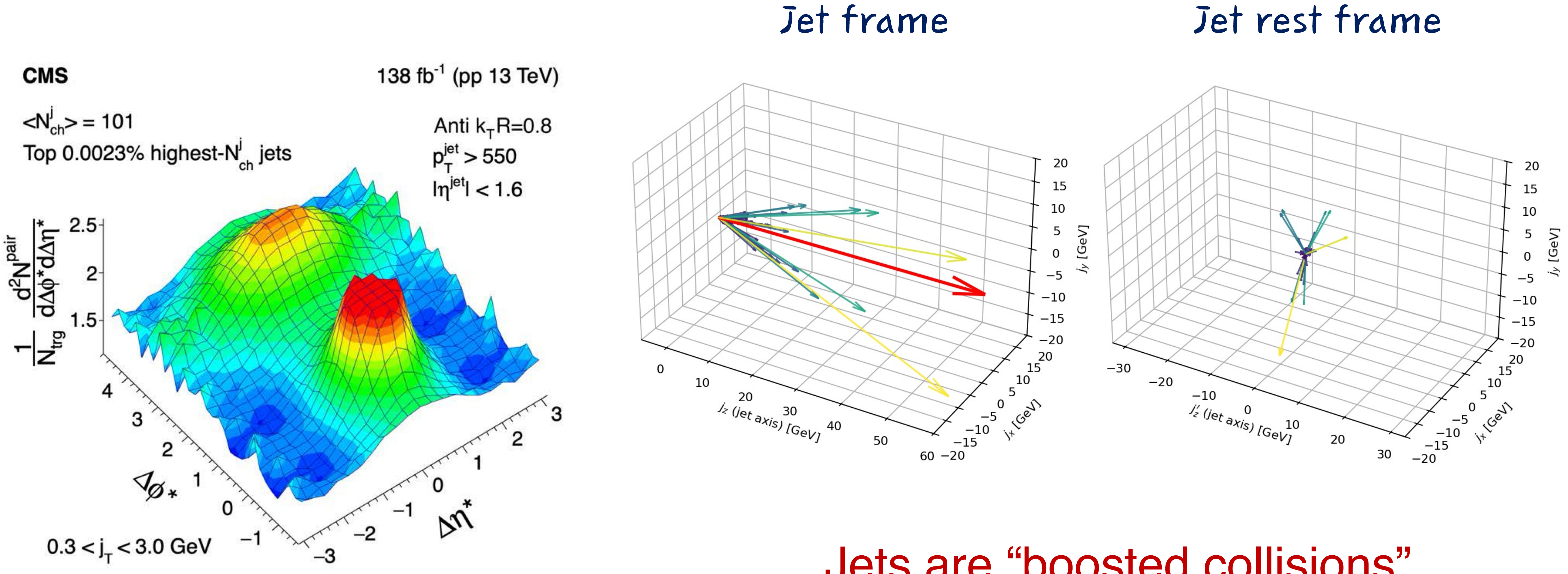
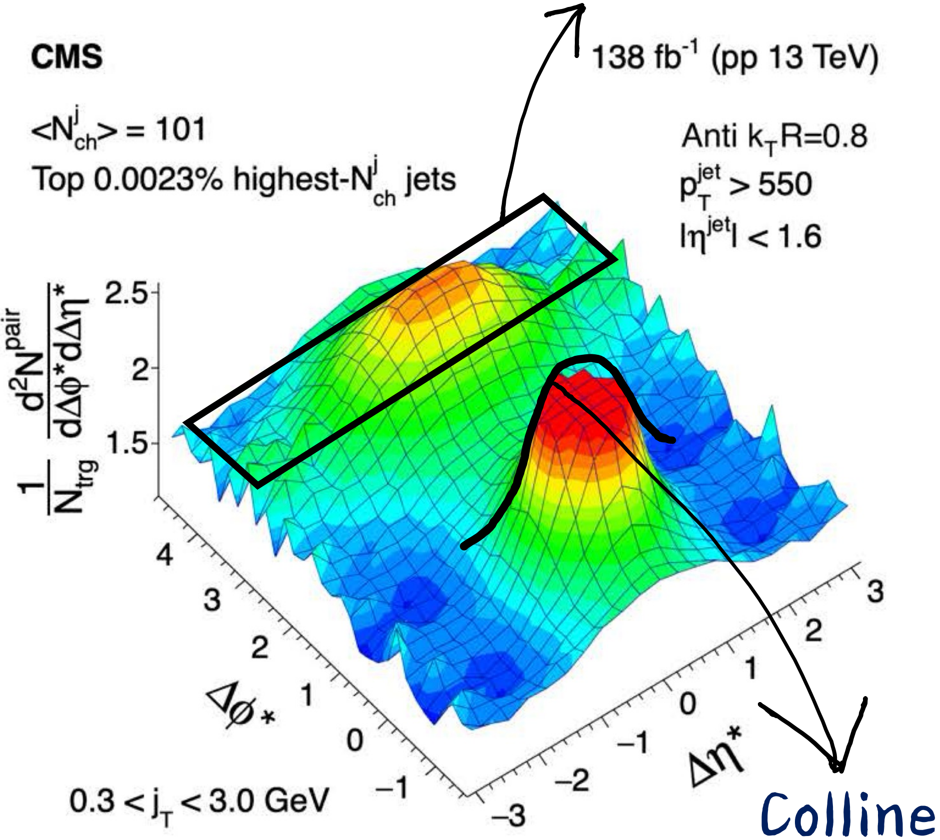


Jets are "boosted collisions"

$\Delta\phi^* - \Delta\eta^*$ is boost invariant

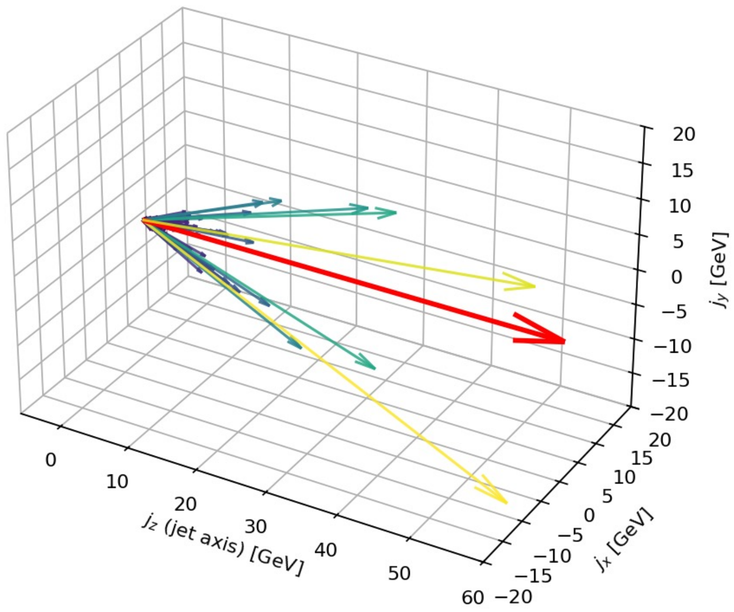
Two particle correlation within jets

Momentum conservation

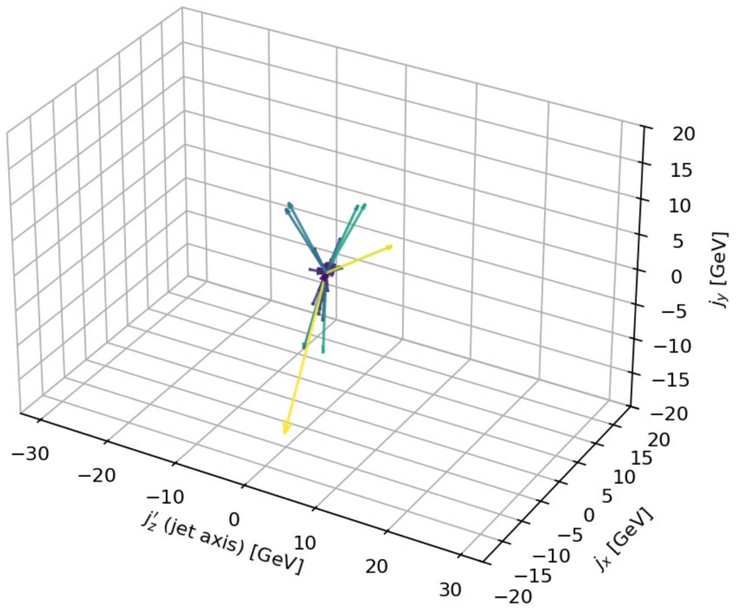


Collinear emission, mini-jets...

Jet frame



Jet rest frame



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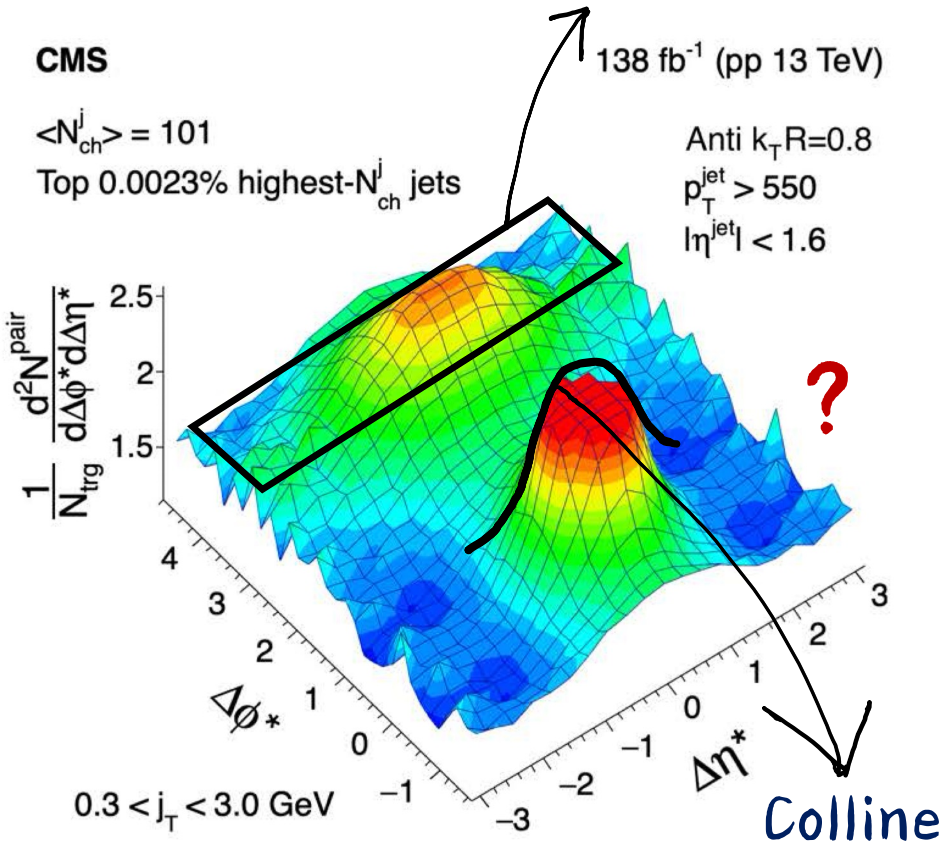
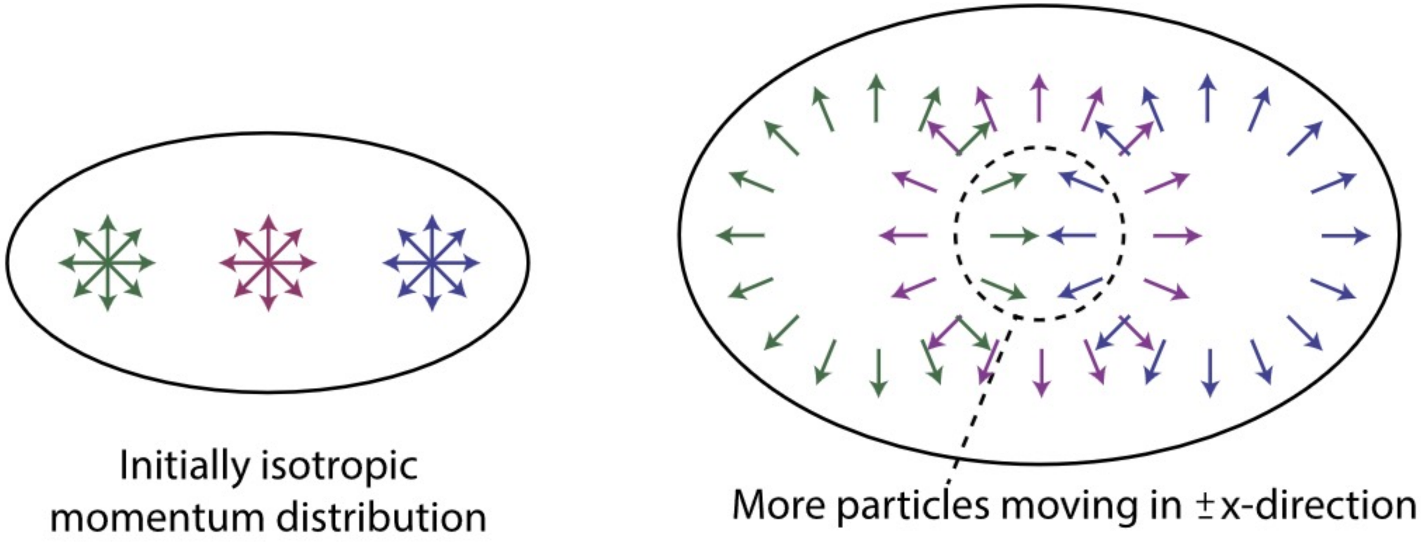


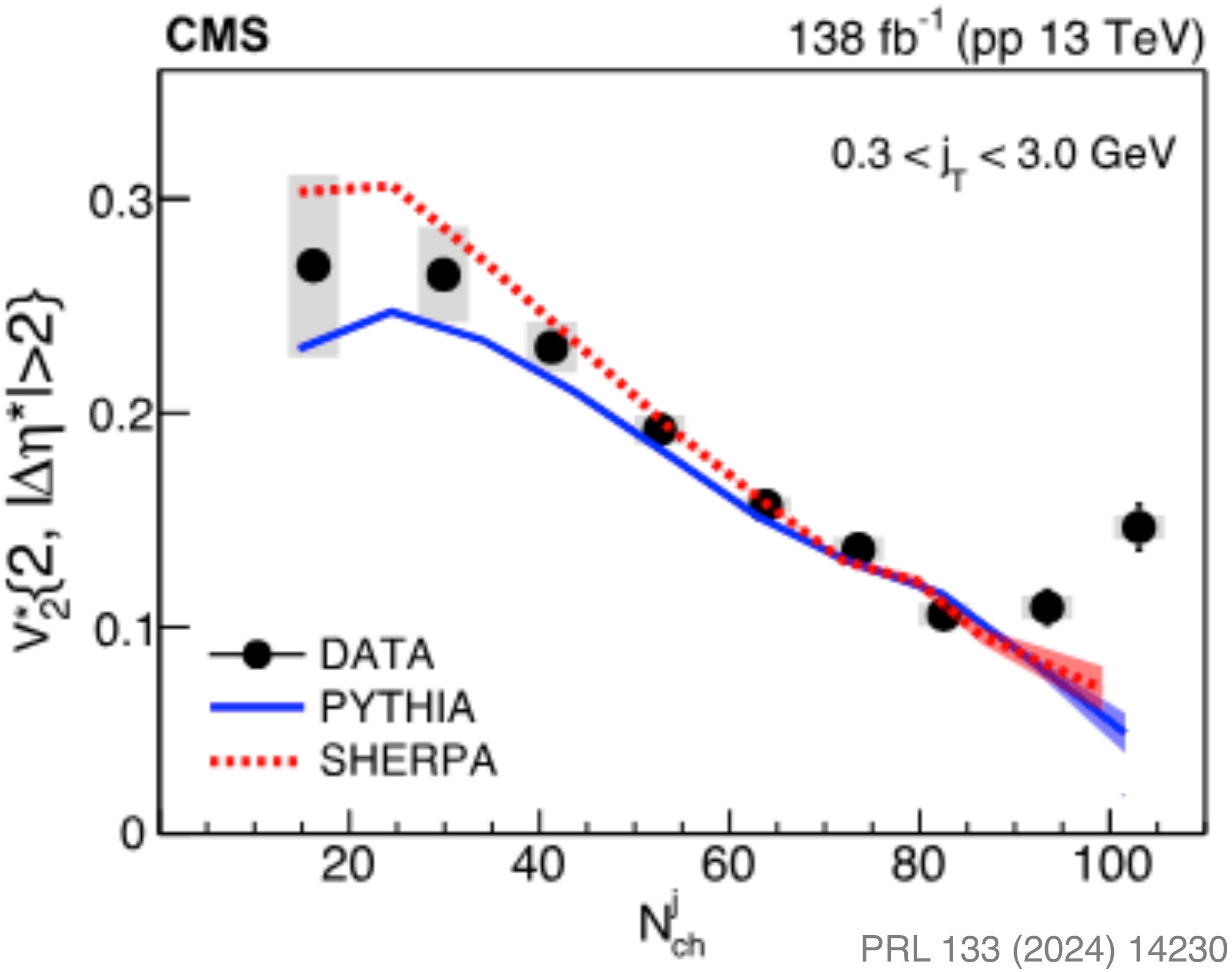
Collinear emission, mini-jets...

What leads to a possible long-range, near-side ridge?



“Single-hit dynamics”

Elliptic flow v_2^*



PRL 133 (2024) 142301

Enhanced elliptic anisotropies at high multiplicities

Onset of collectivity?
Where does it come from?
Final state interaction?
Initial-state geometry?

On the origin of long-range correlations in high multiplicity jets – a model study

W. Zhao et. al.,arXiv:2401.13137

PYTHIA8 Parton Shower → Parton Cascade (ZPC) Tunable σ_p → Lund String Fragmentation → Hadron Interaction (UrQMD) On or Off

Xiao Huang (RICE), *in collaboration with Wenbin Zhao, Zi-Wei Lin and Xin-Nian Wang.*

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PYTHIA8 Parton Shower → Parton Cascade (ZPC) Tunable σ_p → Lund String Fragmentation → Hadron Interaction (UrQMD) On or Off

Initial anisotropy within a jet

Final state interaction:
partonic (pFSI)
hadronic (hFSI)

Collective flow?

Xiao Huang (RICE), *in collaboration with Wenbin Zhao, Zi-Wei Lin and Xin-Nian Wang.*

Parton shower

Formation time: accumulated from the full PYTHIA splitting history.

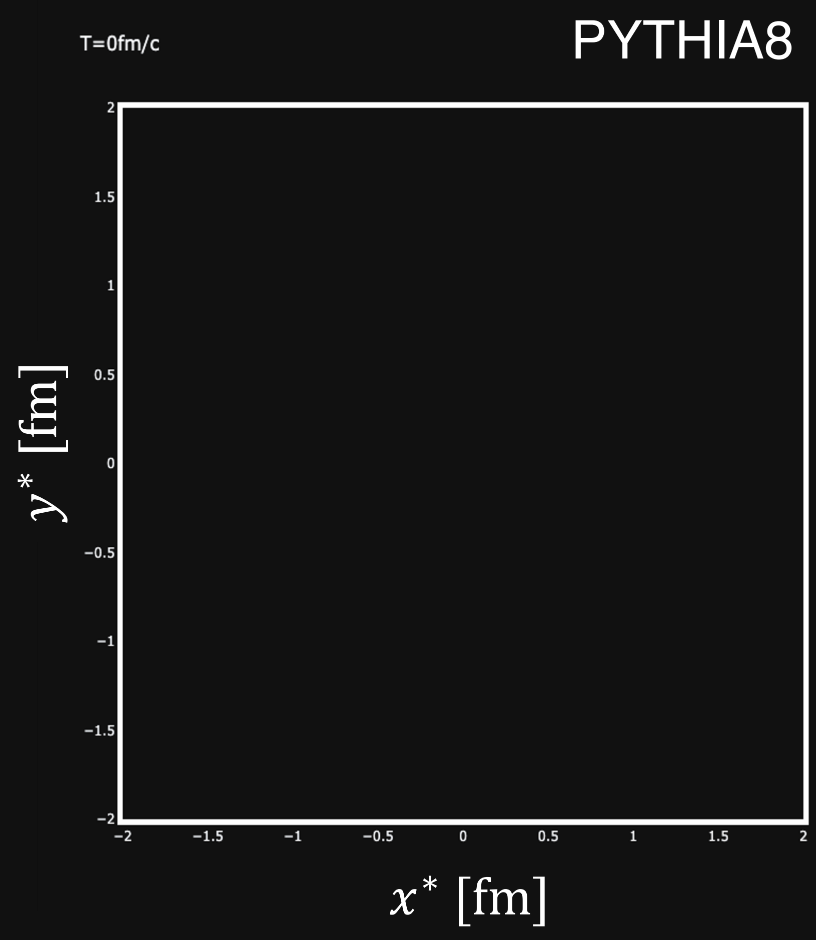
$$\Delta t_i = \begin{cases} \dfrac{2E_i x_i(1-x_i)}{k_{T,i}^2}, & x_i < 0.5 \\ \dfrac{1}{E_i}, & x_i \geq 0.5 \end{cases}$$

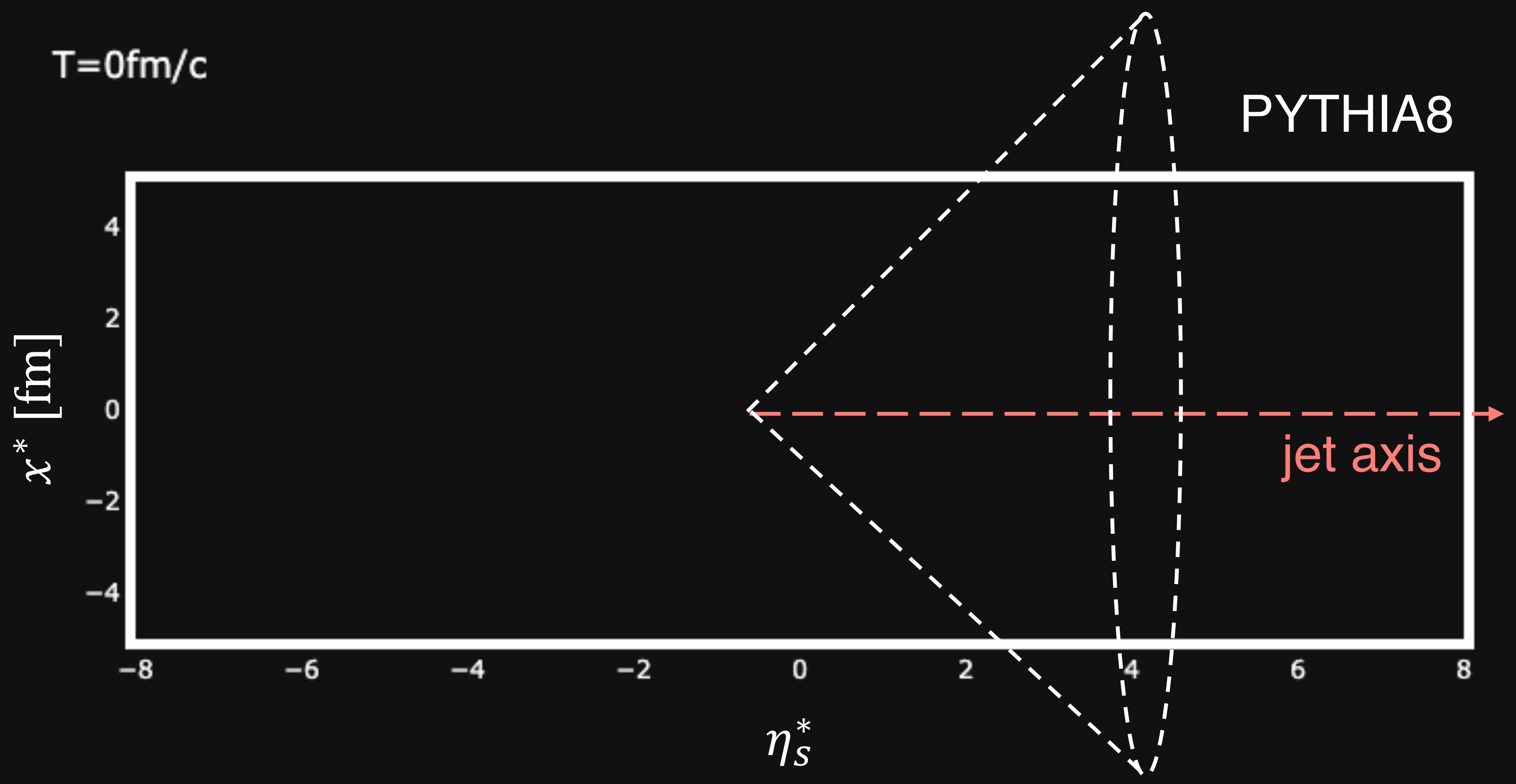
E_i: energy of mother parton
x_i: fractional energy of daughter
k_T: daughter p_T relative to the mother parton direction

Formation position: accumulated from the straight-line propagation of all ancestor partons before each splitting.

Initial stage of a jet

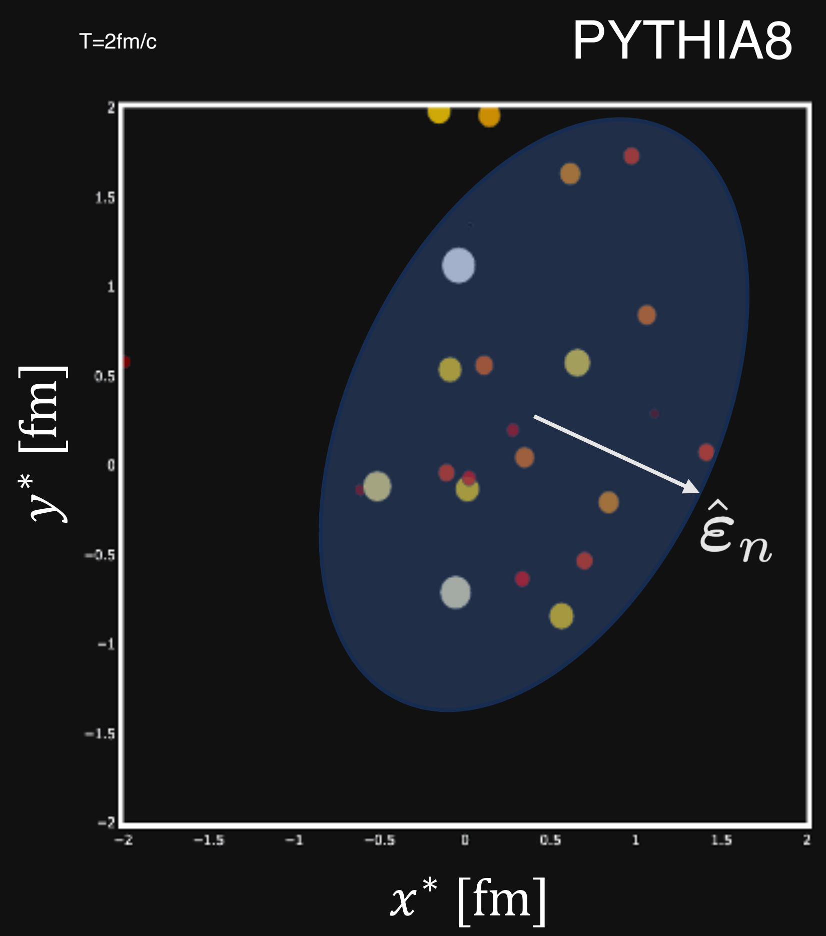
Space-time evolution of parton showers for a jet with $N_{\mathrm{ch}}^{j} > 100$





Gif made by Feng Liu (SBU/BNL)

Initial transverse geometry



$$\phi_j^{*,\mathrm{coord}} = \arctan\left(\frac{y_j^* - \langle y^* \rangle_p}{x_j^* - \langle x^* \rangle_p}\right) + \frac{\pi}{2}$$

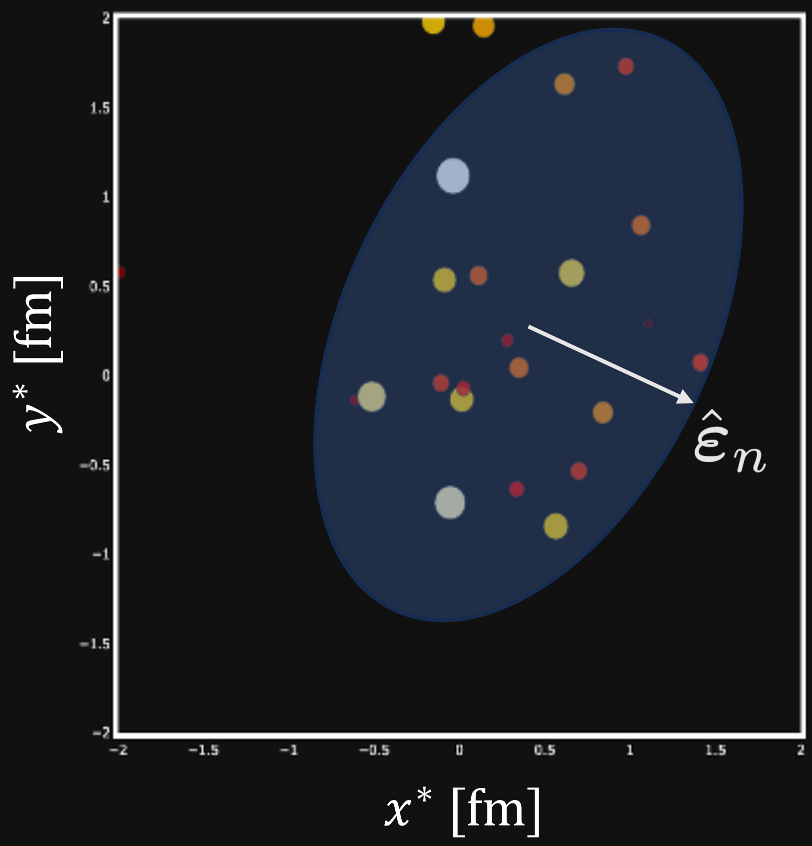
$$\boldsymbol{\varepsilon}_n = \varepsilon_n e^{in\Phi_n} \equiv \frac{\sum_j w_j e^{in\phi_j^{*,\mathrm{coord}}}}{\sum_j w_j}$$

$$w_j = E_j r_j^{*2}$$

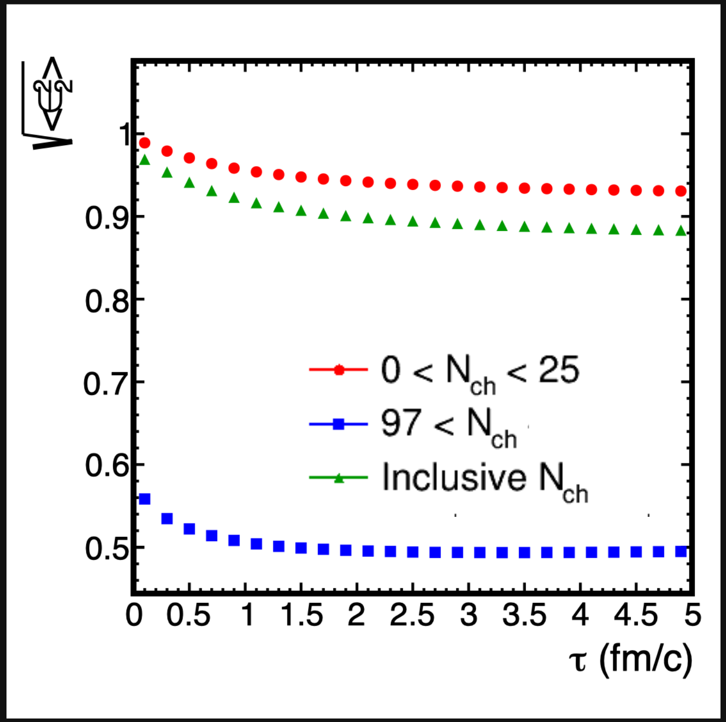
Initial transverse geometry

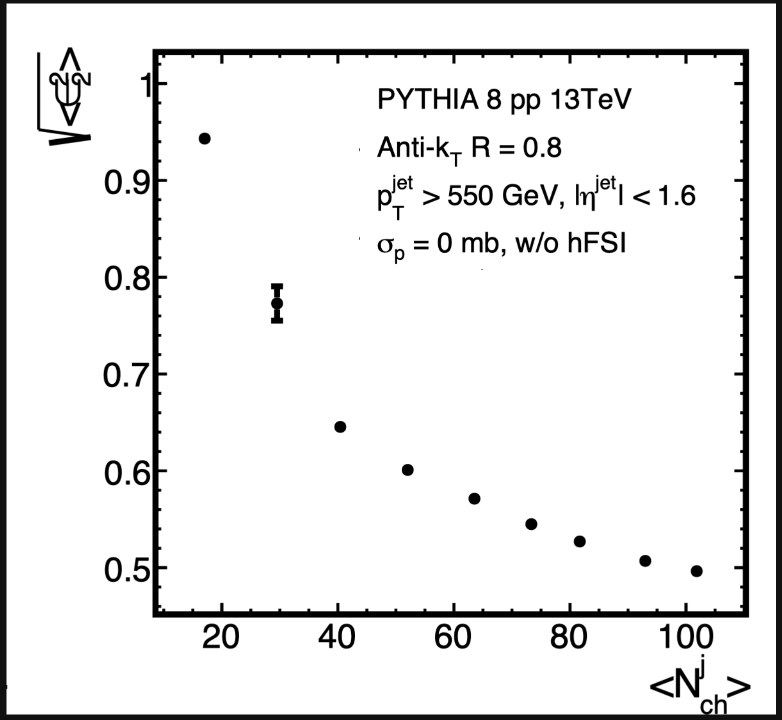
T=2fm/c

PYTHIA8

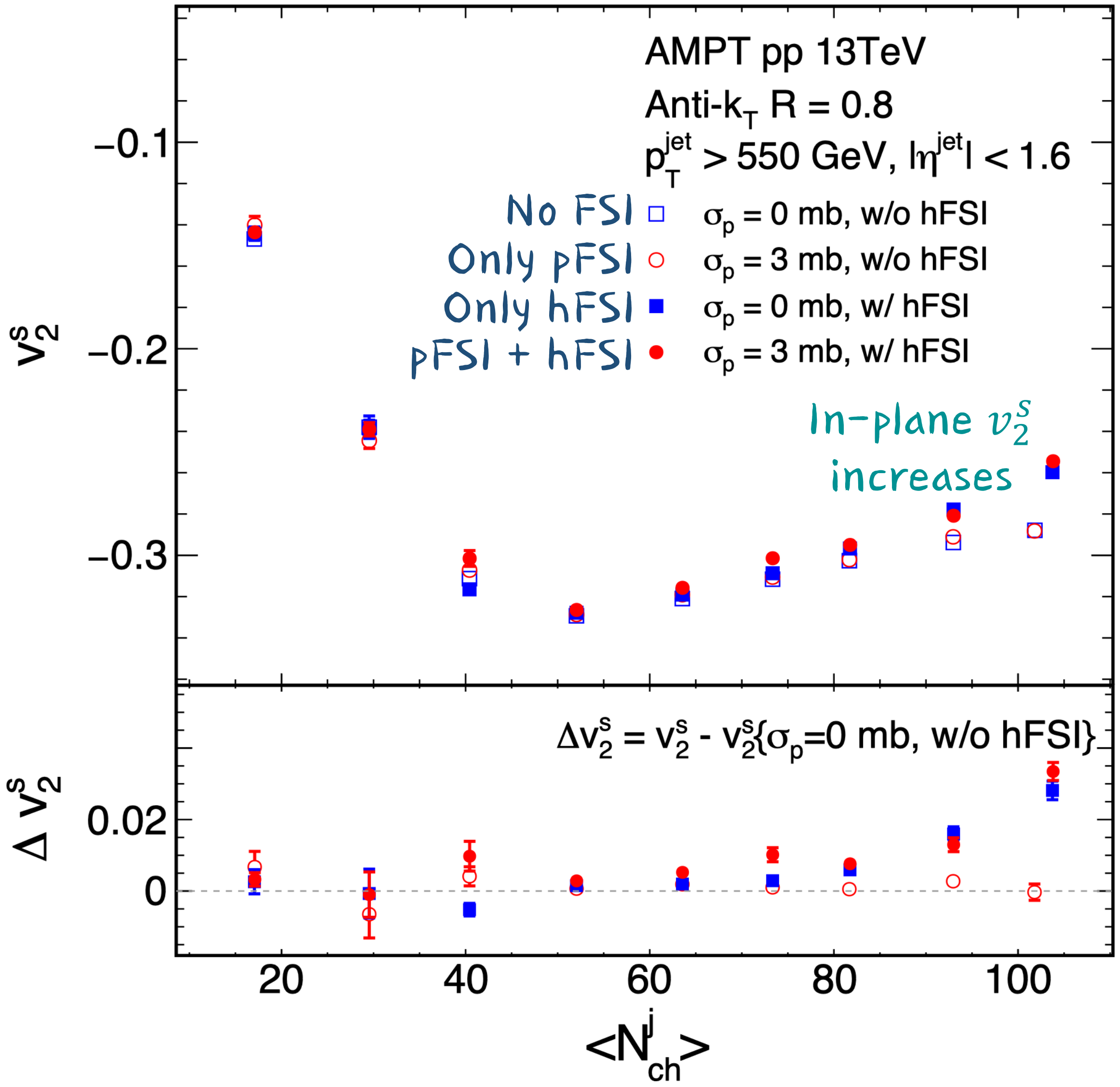


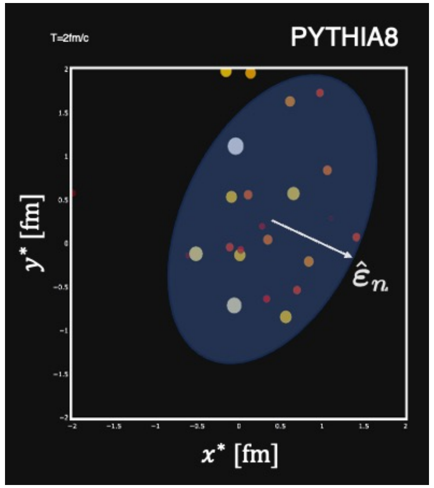
Sizable initial-state eccentricity





Elliptic flow w.r.t "participant plane"





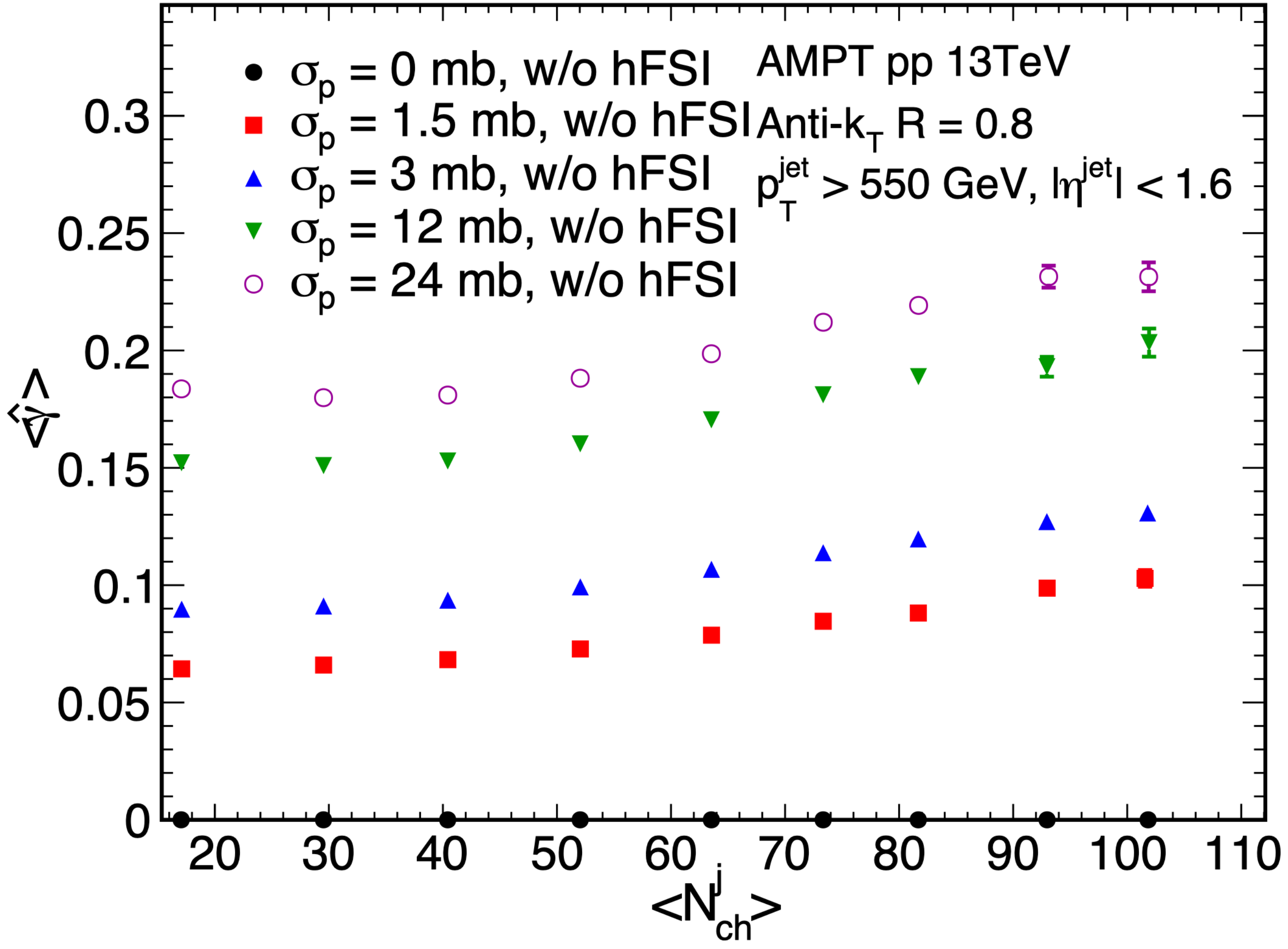
$$v_n^s \equiv \frac{\langle \mathbf{Q}_n \varepsilon_n^* \rangle}{\sqrt{\langle \varepsilon_n \varepsilon_n^* \rangle}}$$

$$\mathbf{Q}_n \equiv Q_n e^{in\Psi_n} = \frac{1}{N} \sum_{j=1}^{N} e^{in\phi_j^*}$$

hFSI leads to enhanced Δv_2^s at high N_{ch}^j.

pFSI alone shows no significant effect.

Why is pFSI effect small?



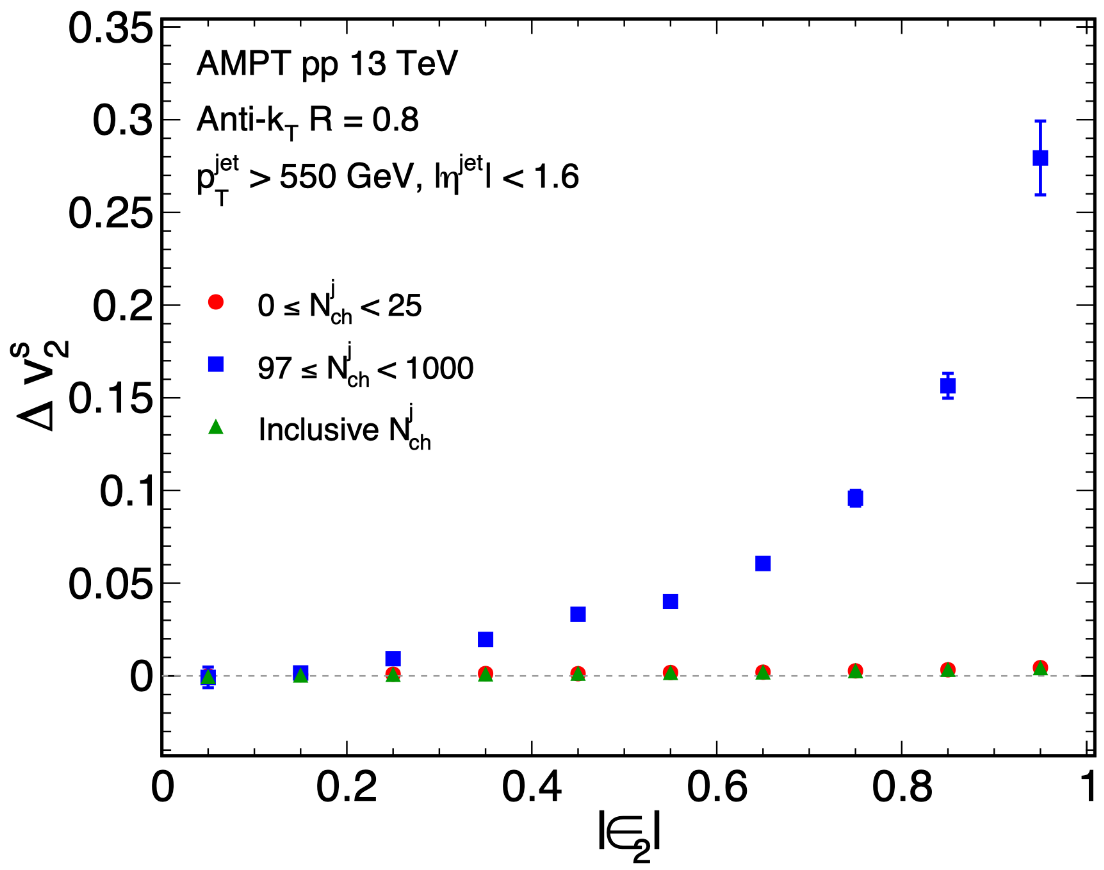
Small partonic opacity?

Forward rescattering angles in ZPC?

More studies underway:

- increase partonic opacity
- isotropic rescattering angles

Flow response to initial geometry

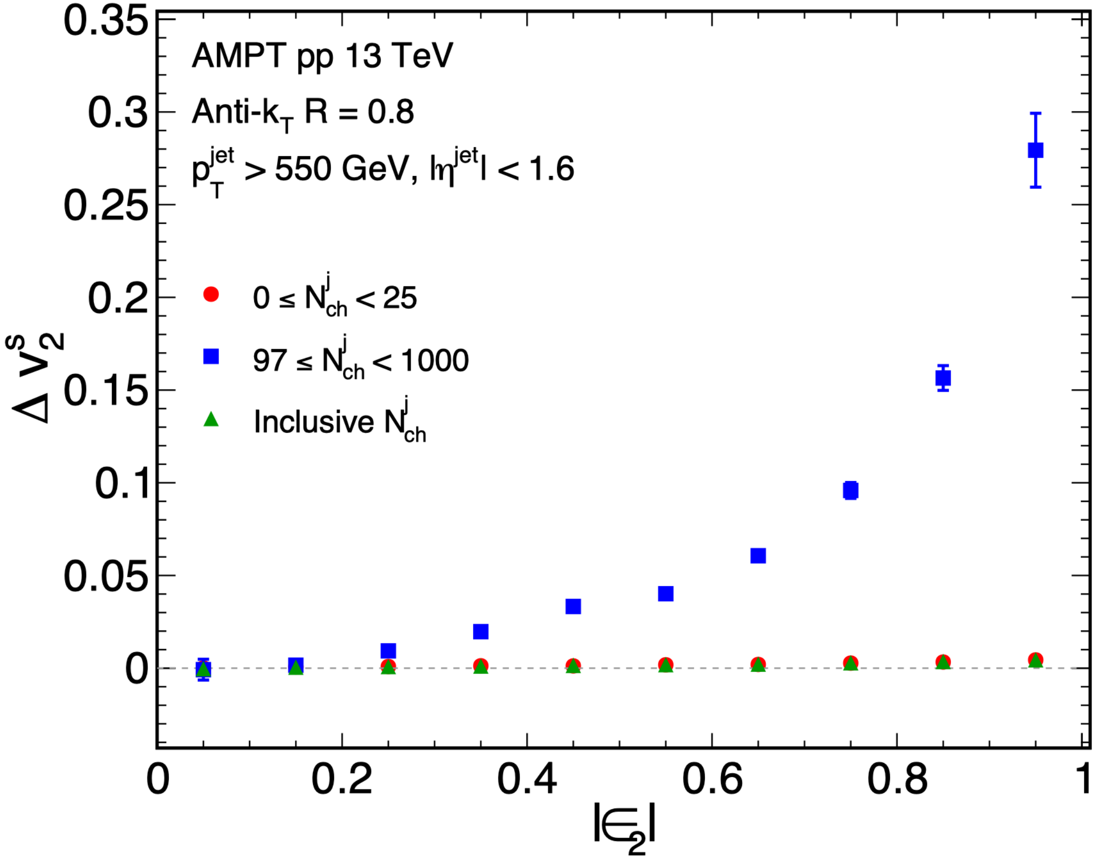


Δv_2^s is sensitive to the initial geometry

$$\Delta v_2^s = \Delta v_2^s\,(\text{FSI}) - \Delta v_2^s\,(\text{No FSI})$$

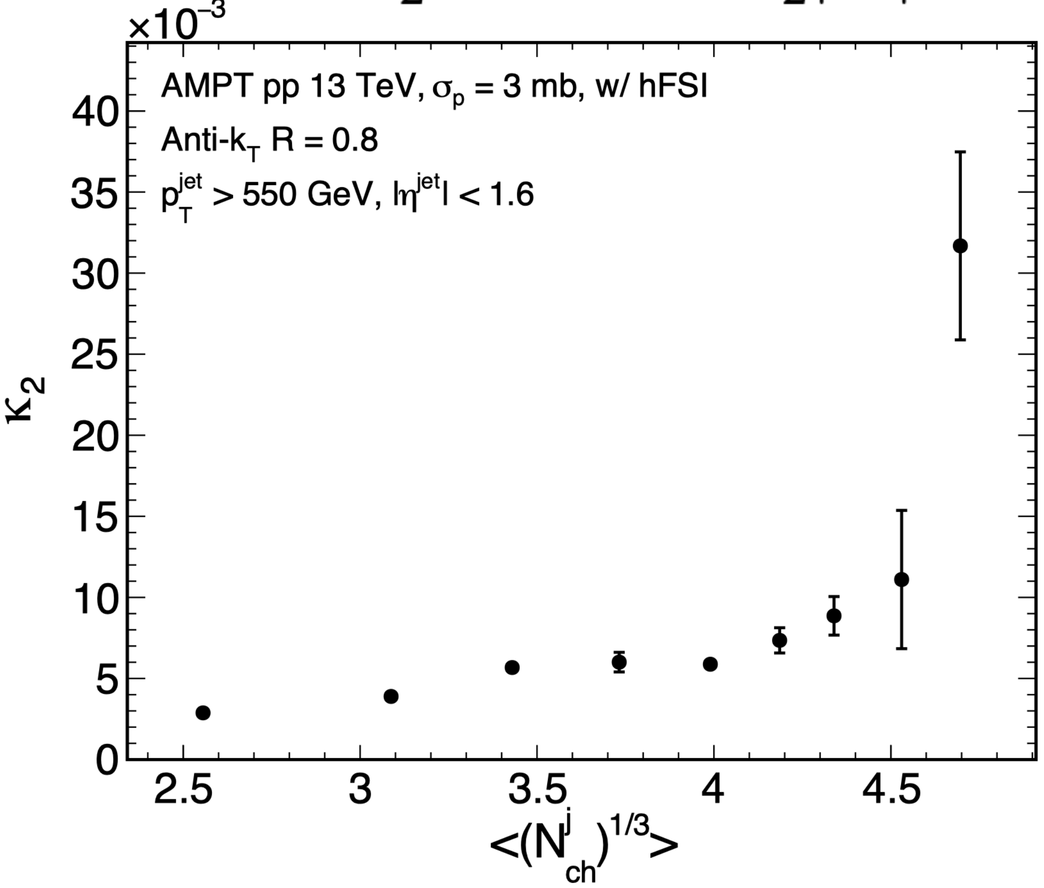
Non-zero Δv_2^s only for high$-N_{ch}^{j}$ jets

Flow response to initial geometry



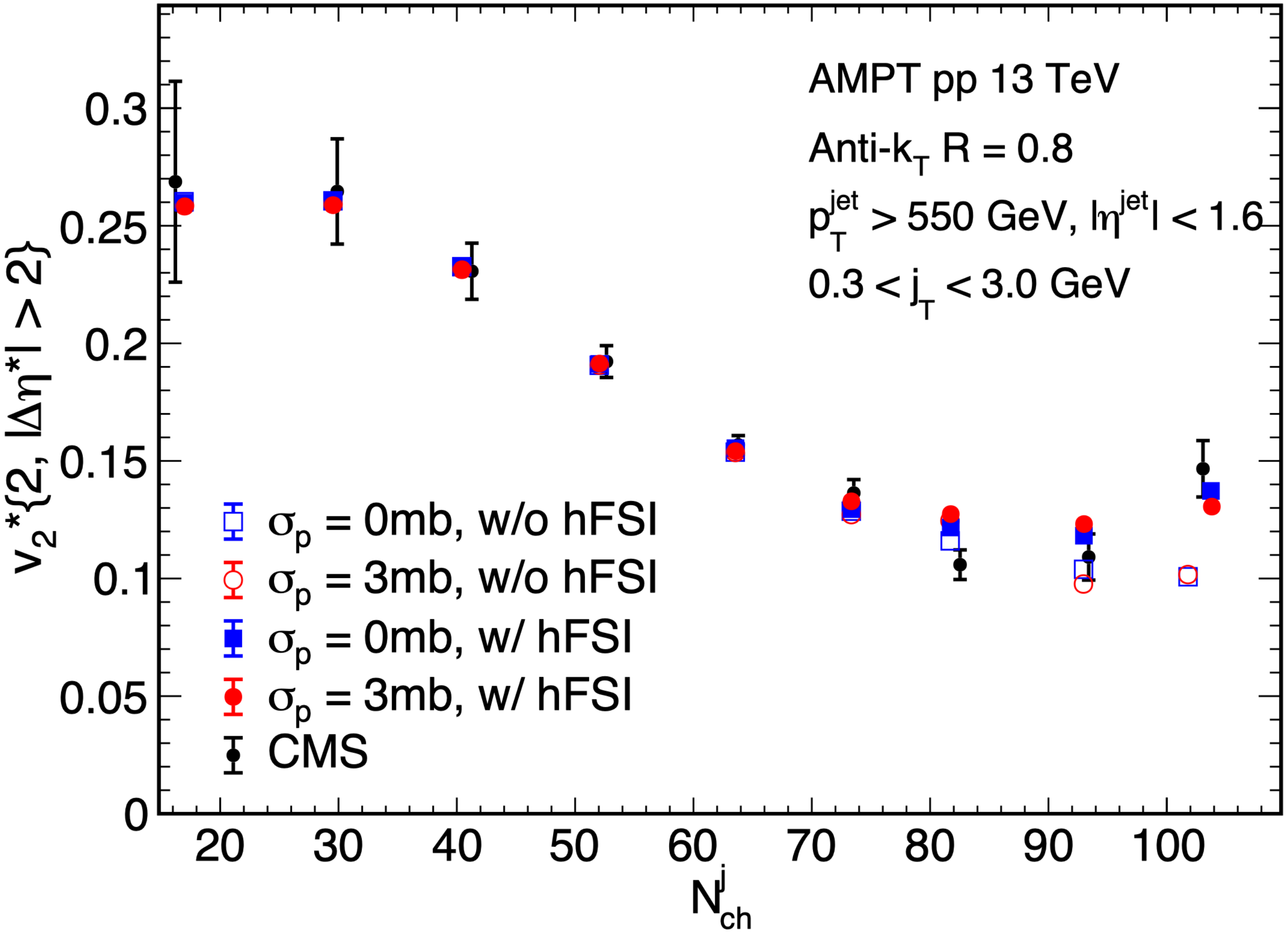
Δv_2^s is sensitive to the initial geometry

$$\Delta v_2^s = \kappa_2 \varepsilon_2 + \kappa_2' |\varepsilon_2|^2 \varepsilon_2$$



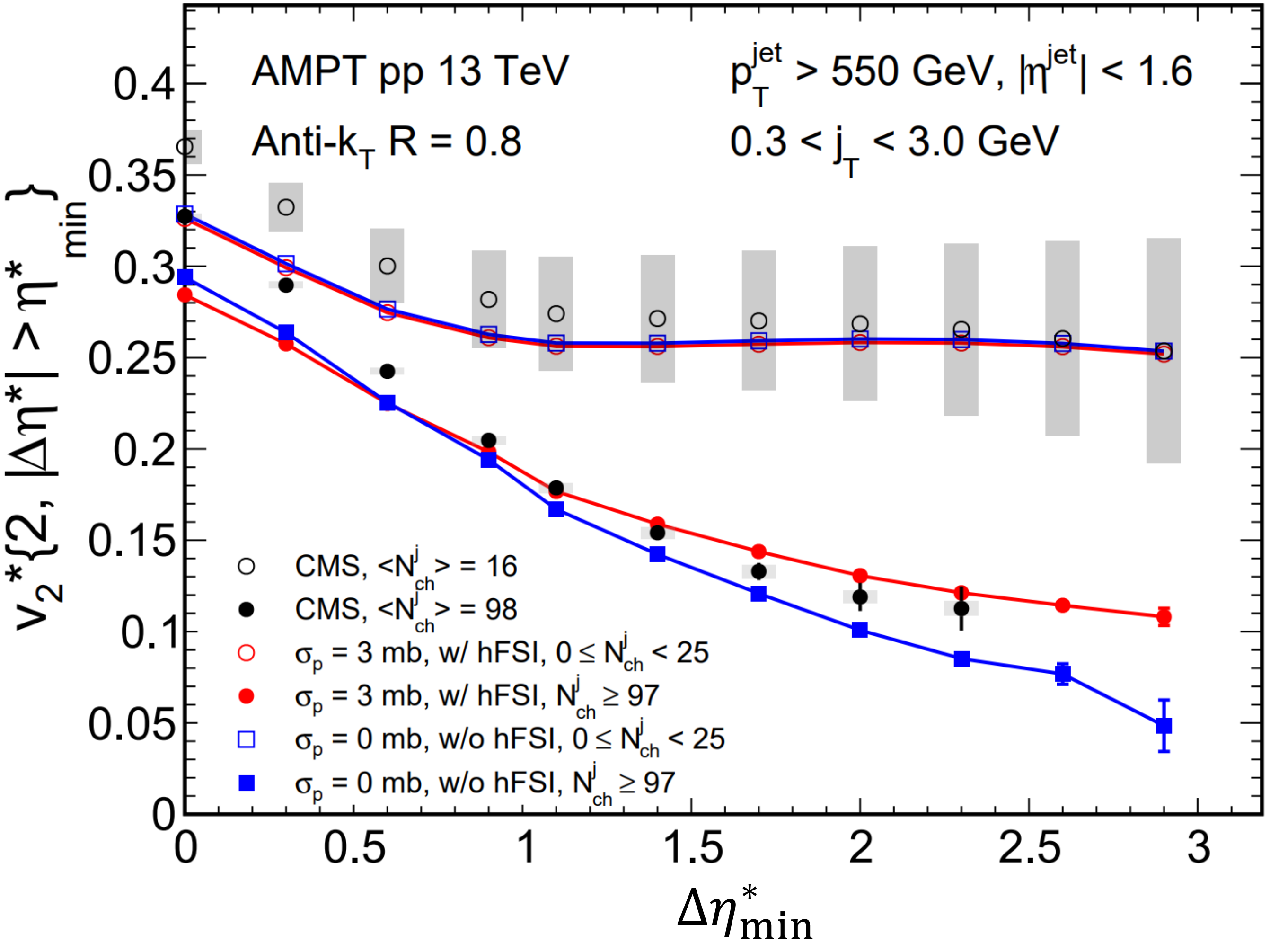
Flow response increases with opacity

Two-particle correlation



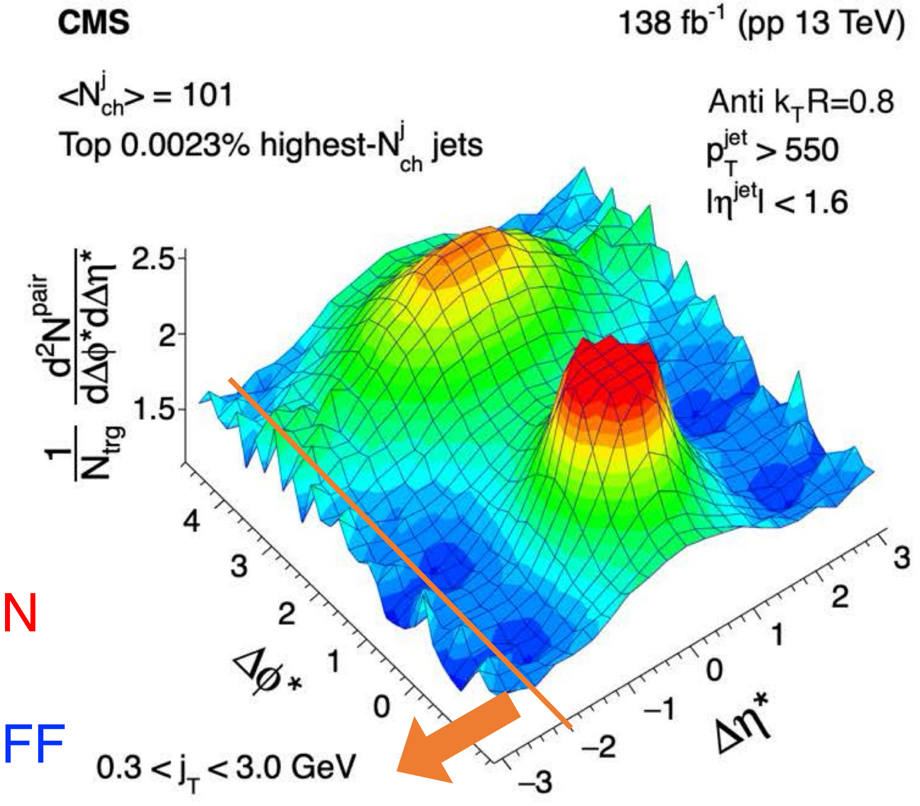
Final state interactions lead to v_2^* enhancement at high N_{ch}^{j}.

Pseudorapidity gap dependent v_2^*



FSI ON

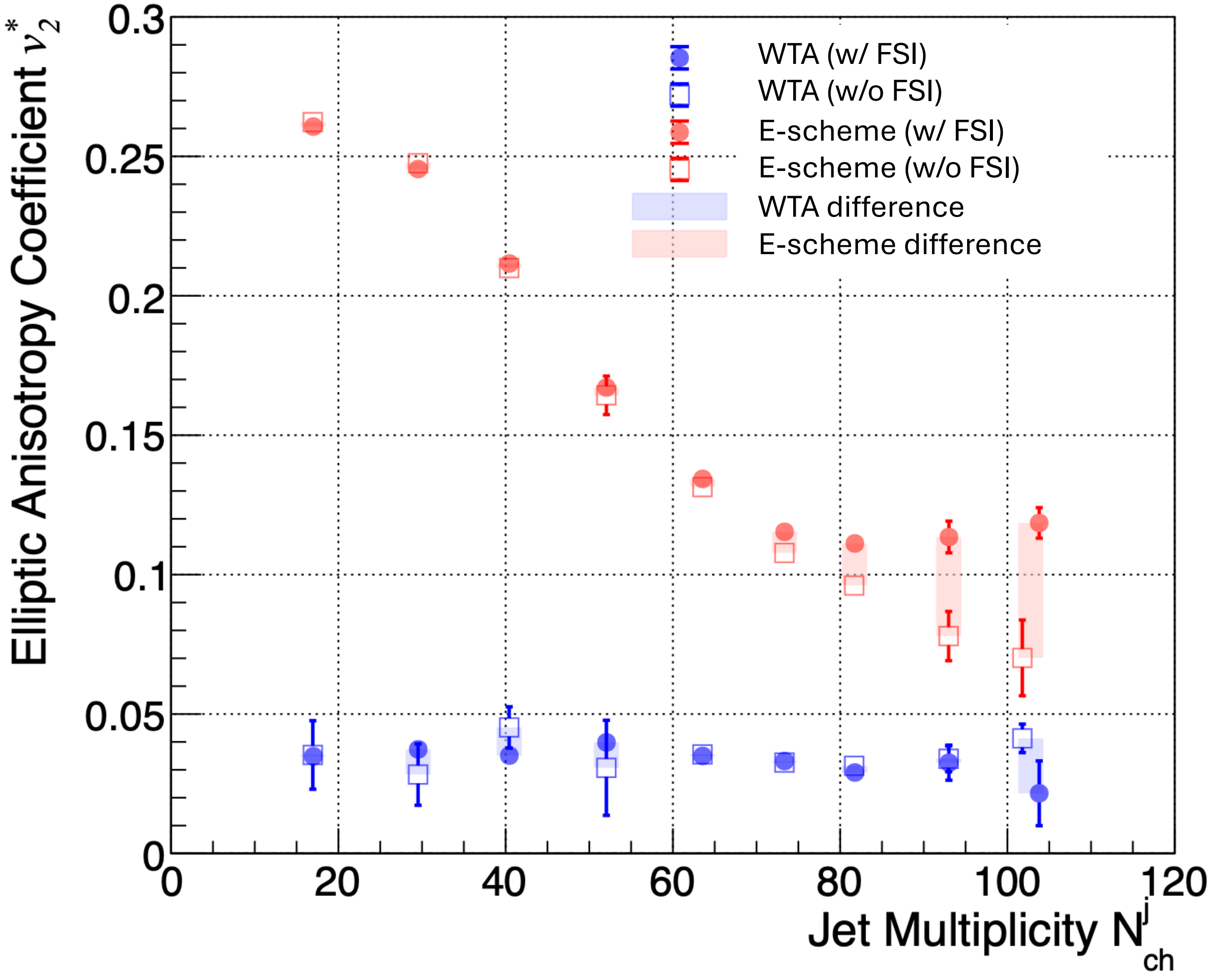
FSI OFF

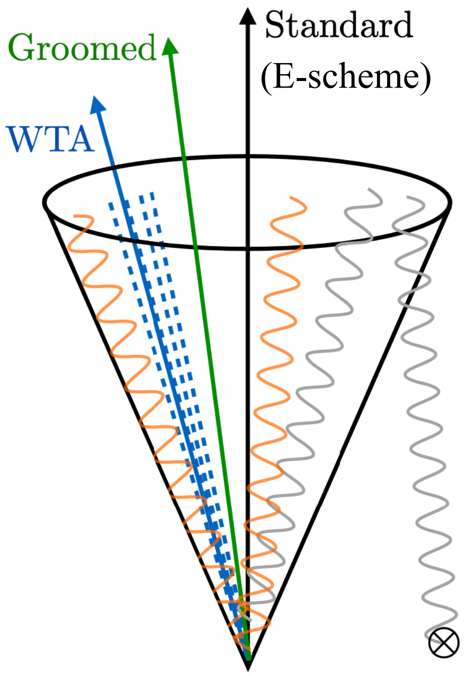


$\Delta\eta^*_{min}$

Winner-take-all (WTA) axis

Model study done by Rohan Jagadeesa (RICE)





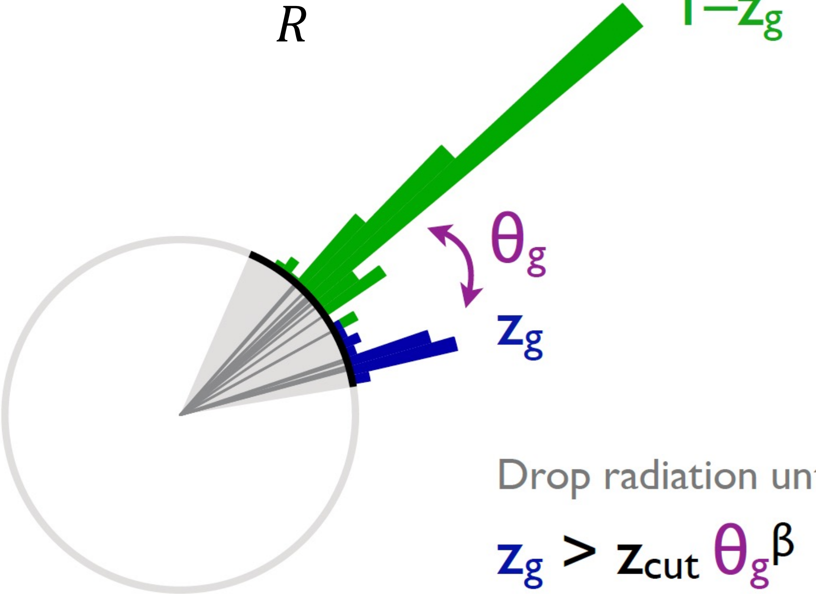
JHEP04(2020)211

WTA mitigates nonflow from the momentum conservation effect but also suppresses the signal of interest.

Effect of initial geometry – jet shape engineering

$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}}$$

$$\theta_g = \frac{\sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}}{R}$$



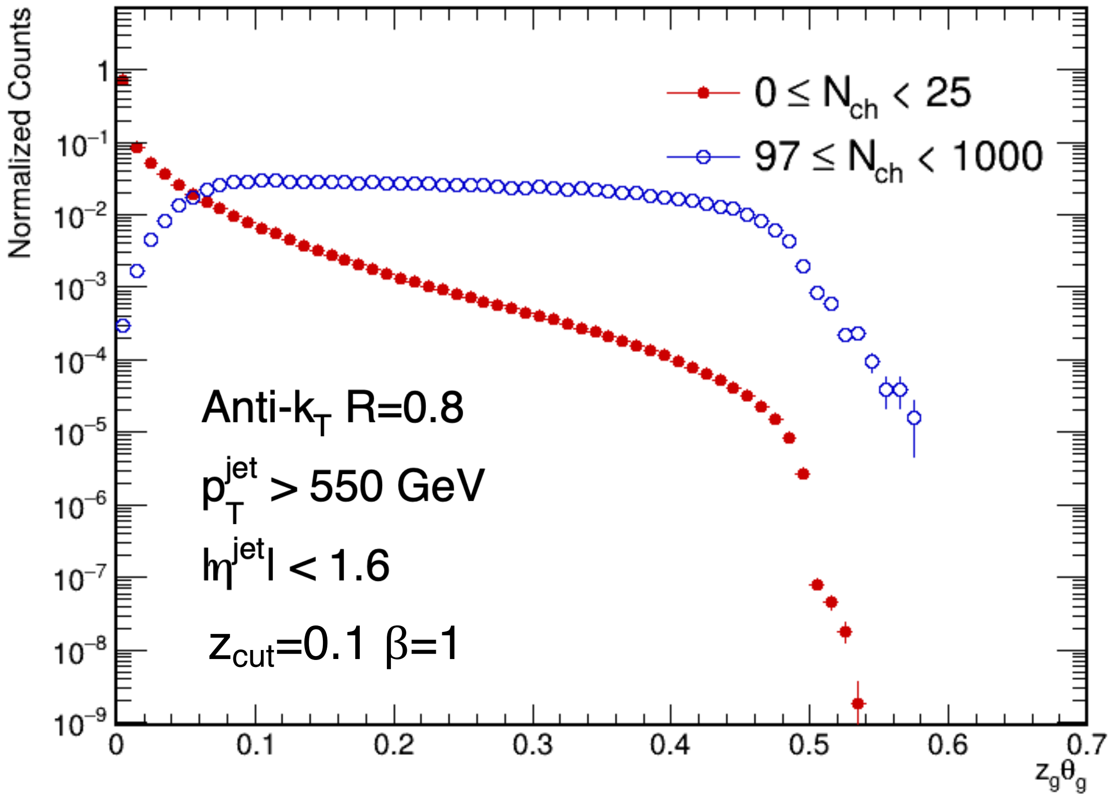
J. Thaler

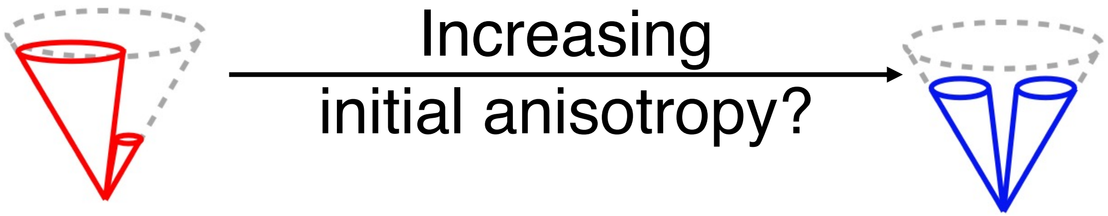
Drop radiation until:

$z_g > z_{cut}\,\theta_g^{\beta}$

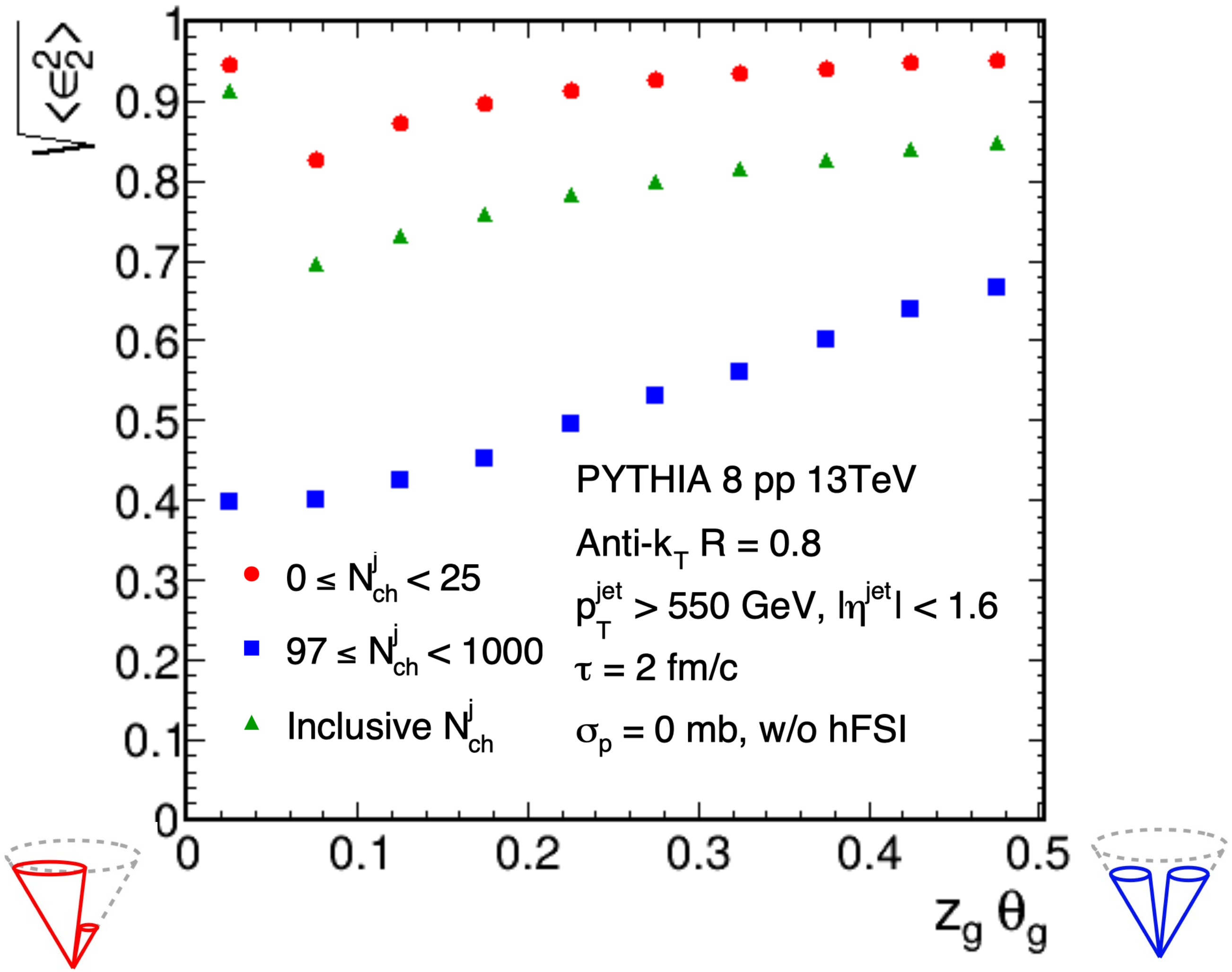
Scale-invariant: β = 0

PYTHIA 8 pp 13 TeV



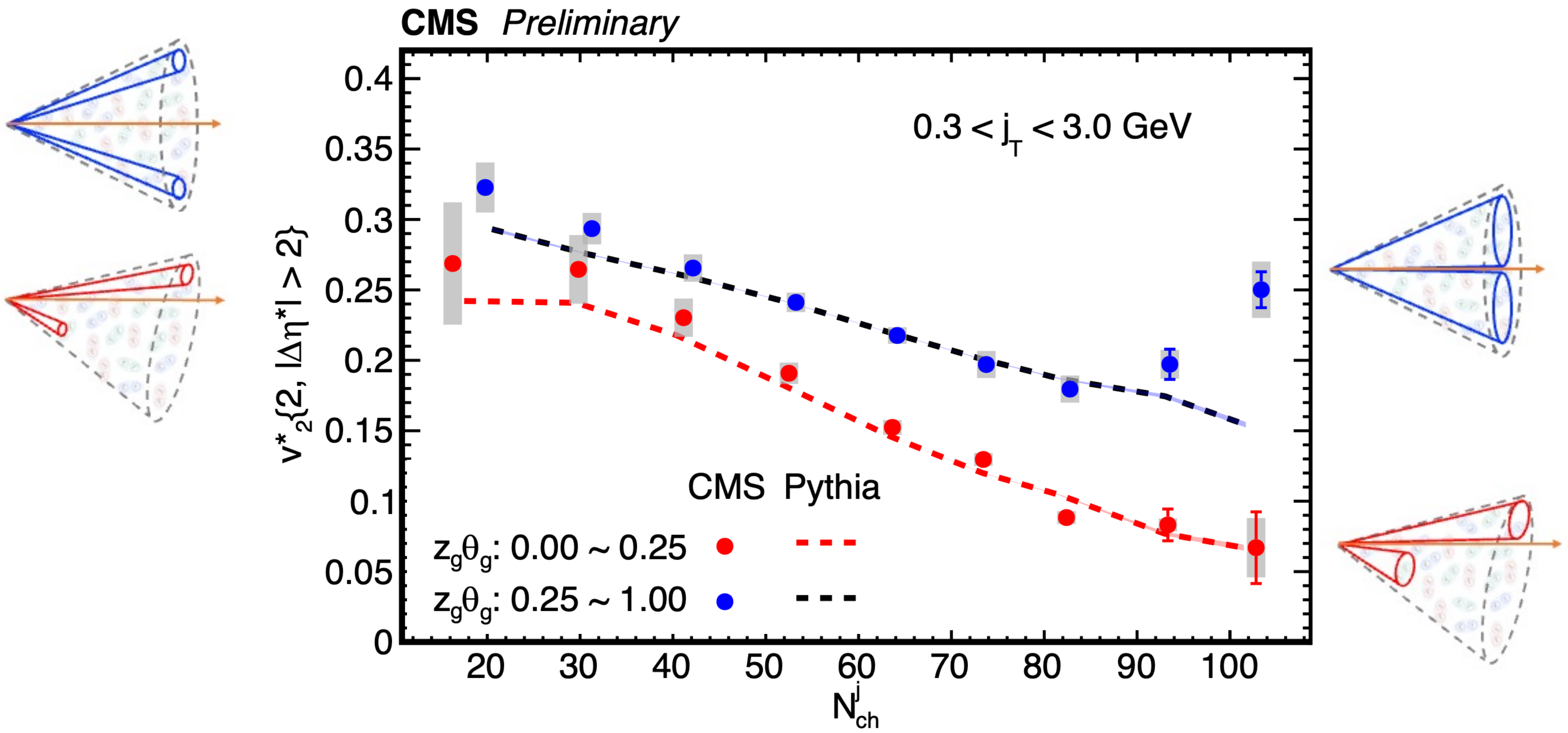


Jet substructure vs. eccentricity



Engineering the substructure does vary the "initial jet geometry".

Jet substructure classified $v_2^*(N_{ch}^j)$



Enhancement of v_2^* relative to MC mainly for two-prone jets.

Summary and outlook

- CMS observed a v_2^* enhancement in high-N_{ch}^{j} jets, with a stronger effect for two-prong jets.

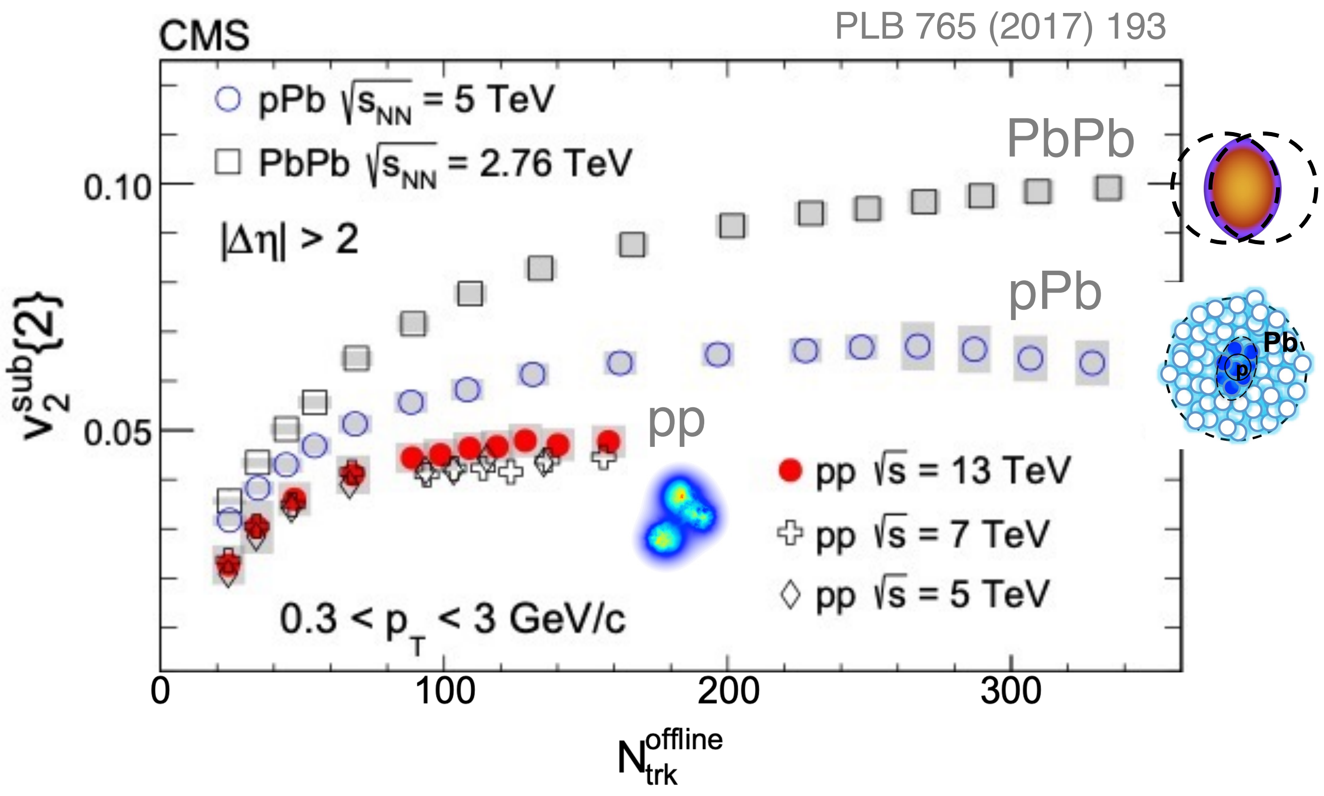
- A transport model study suggests v_2^* enhancement can arise from final-state interactions with "initial eccentricity" of a jet.

- More ideas in high multiplicity jets:
  - EEC
  - HBT
  - hydrodynamic models
  - new substructure observables
  - ...

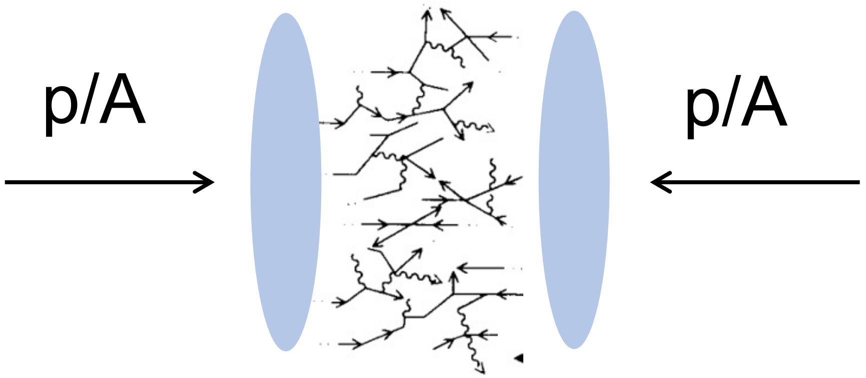
backup

QGP signatures in small systems

Universal QCD collectivity across AA, pA to pp



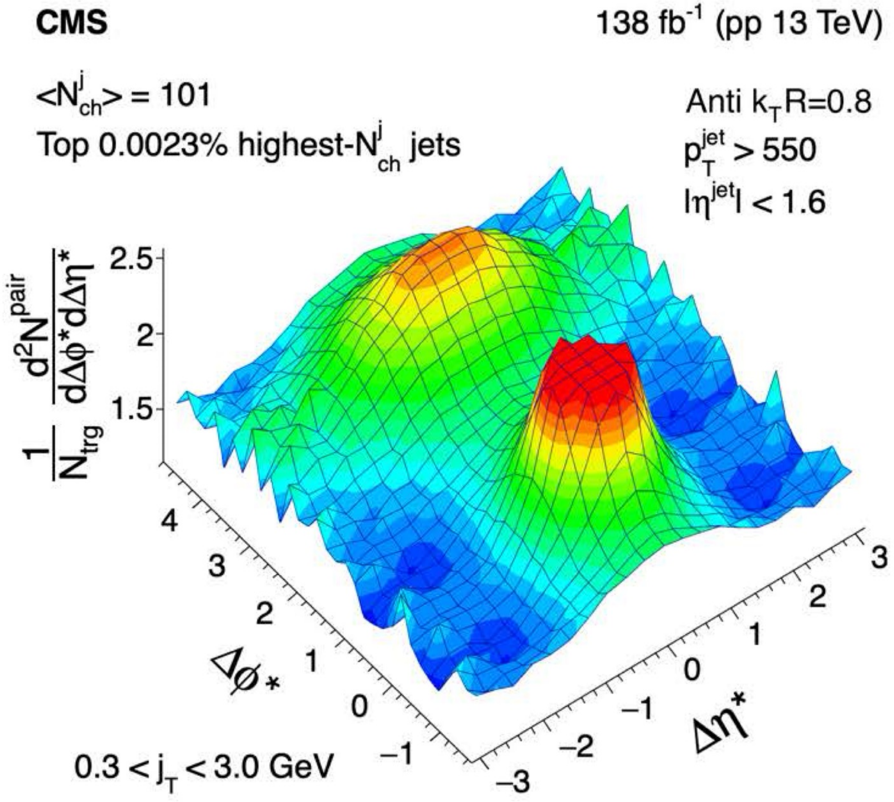
→ Strong partonic re-scatterings at subfermi scales



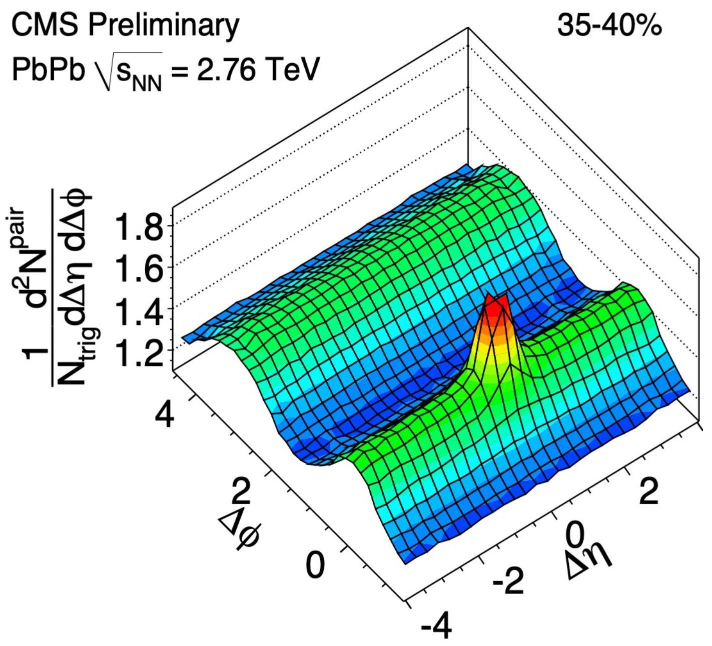
"QGP" everywhere?!

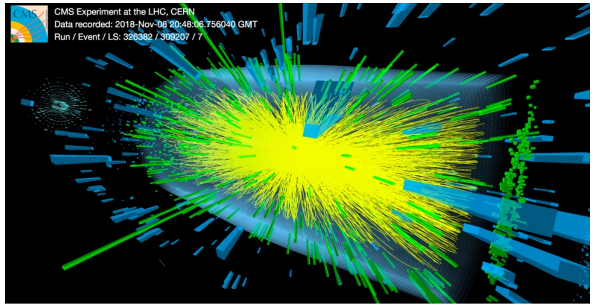
- Ordered roughly by expected initial geometry
- Diminishing toward low multiplicity

Two particle correlation within jets



Similar

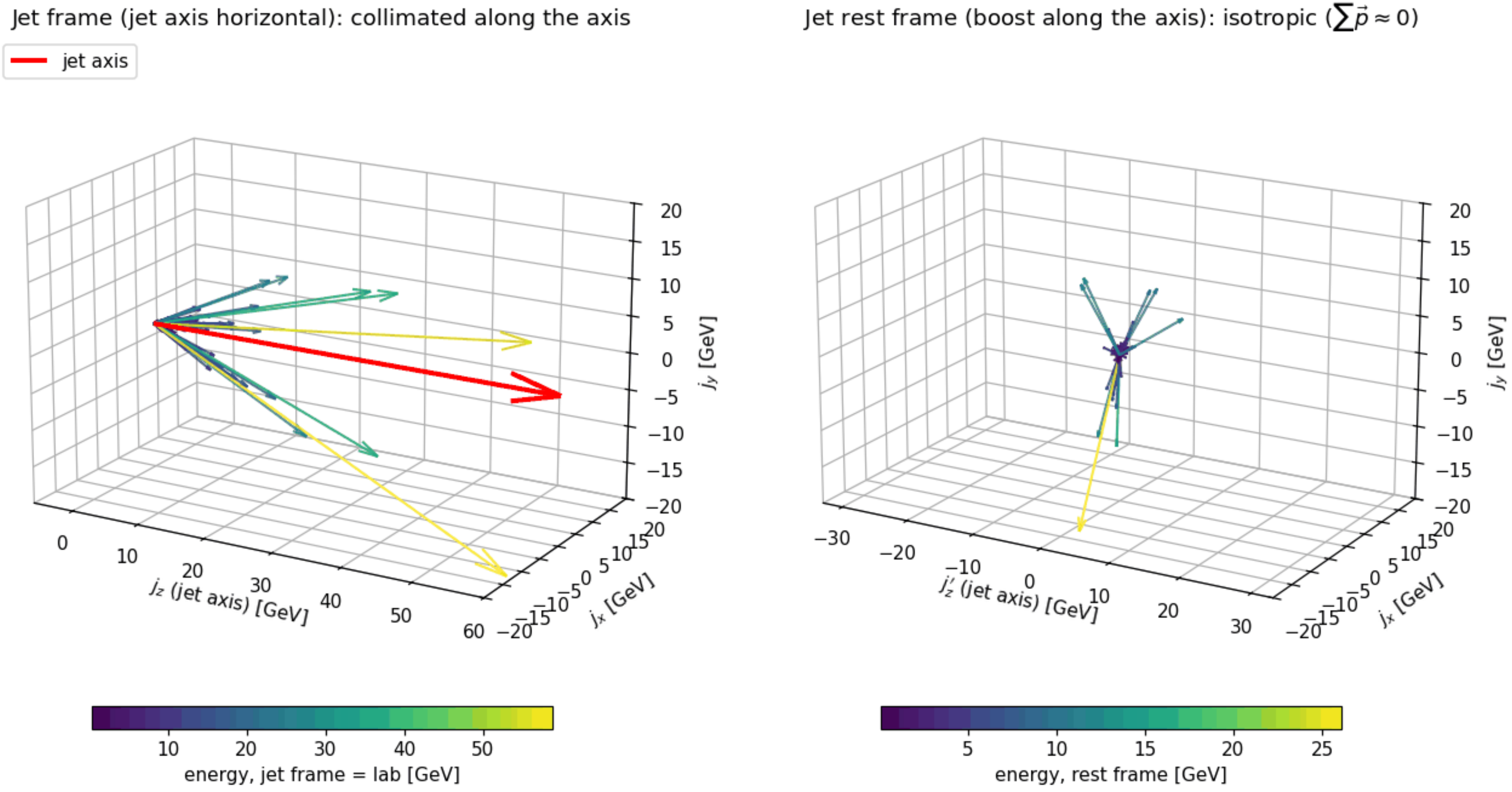




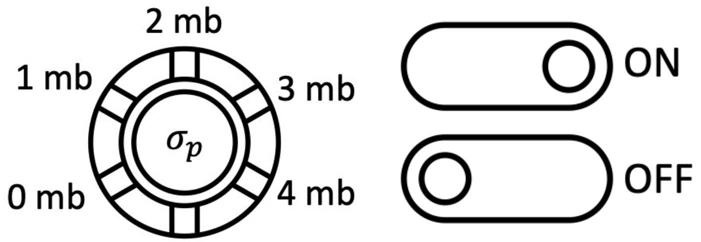
large boost

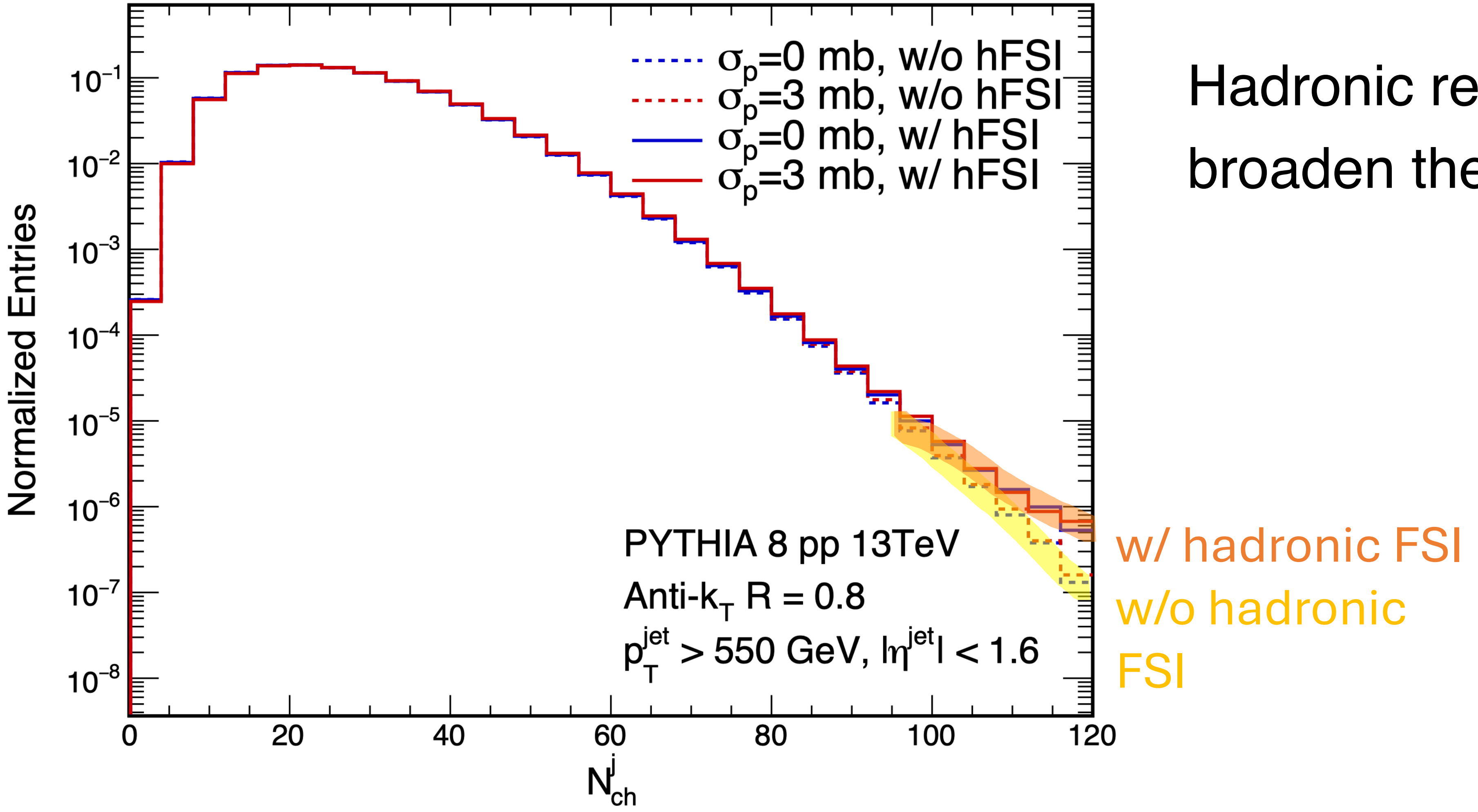
Jets are "boosted collisions"

Jet frame vs. jet rest frame



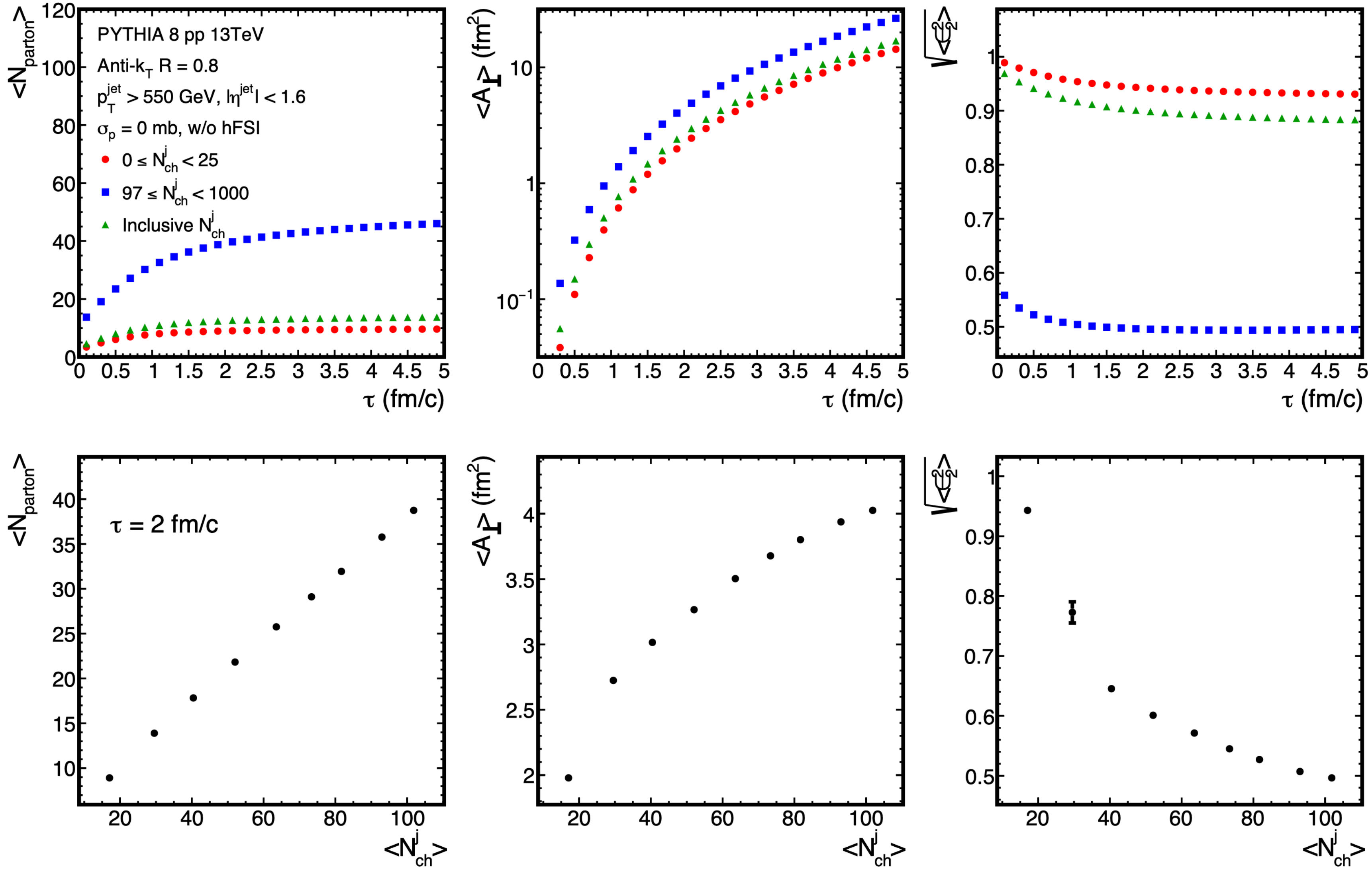
Jet charged multiplicity



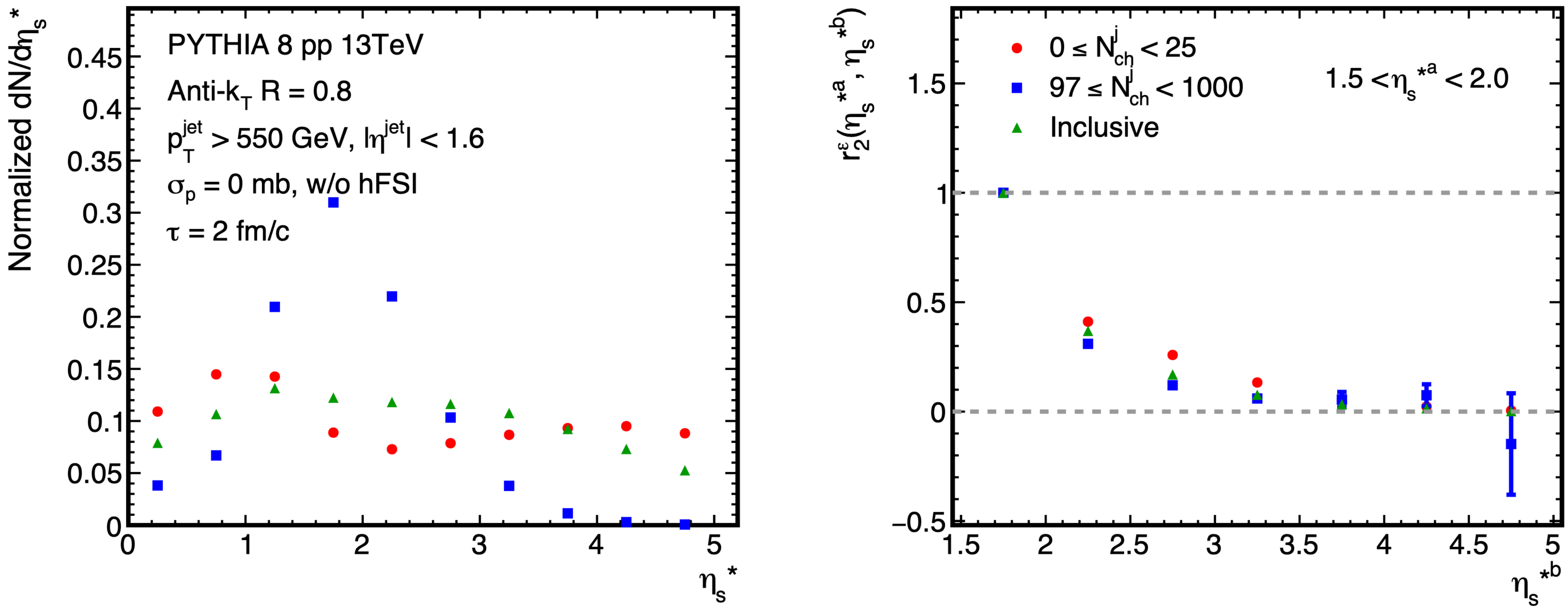


Hadronic rescatterings broaden the N_{ch}^{j} distribution.

Initial transverse geometry



Initial longitudinal structure

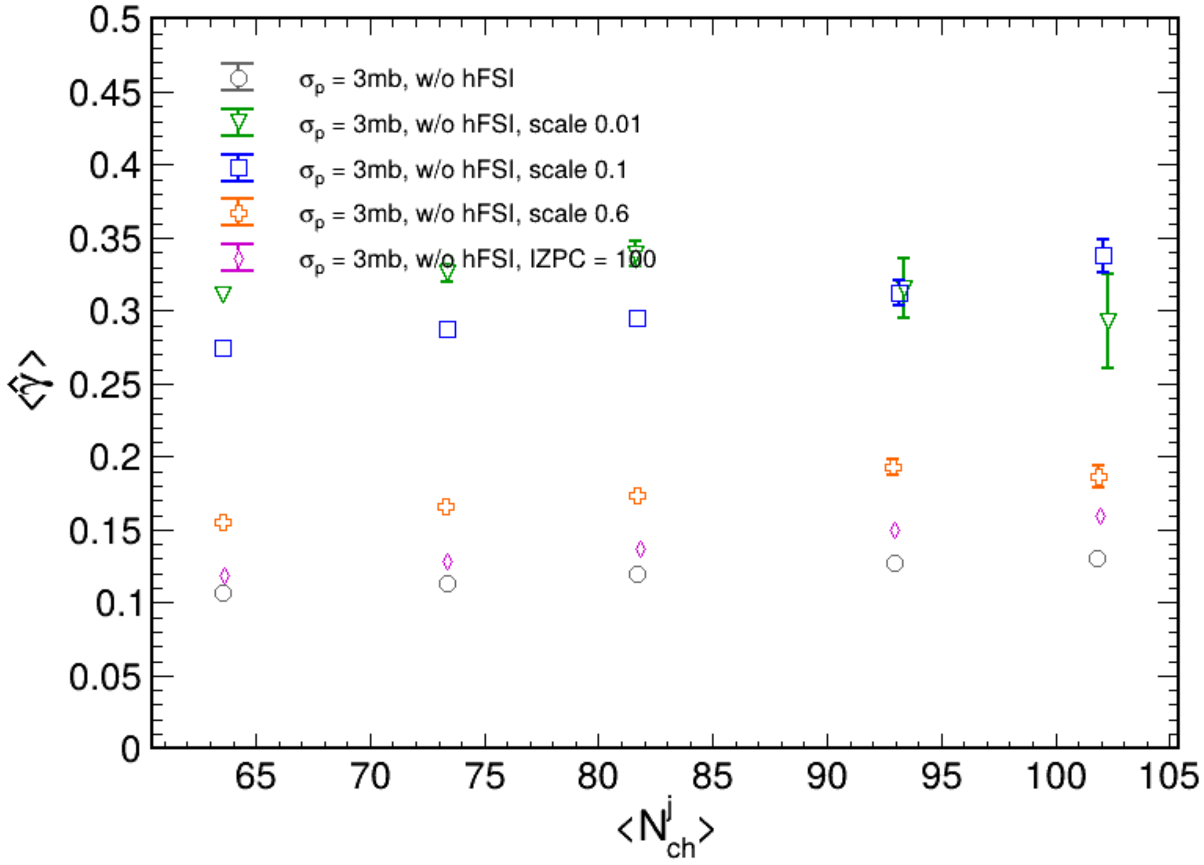


$$r_n^{\varepsilon}(\eta_s^{*a},\eta_s^{*b}) \equiv \frac{\langle \boldsymbol{\varepsilon_n}(\eta_s^{*a})\boldsymbol{\varepsilon_n^*}(\eta_s^{*b})\rangle}{\sqrt{\langle \boldsymbol{\varepsilon_n}(\eta_s^{*a})\boldsymbol{\varepsilon_n^*}(\eta_s^{*a})\rangle}\sqrt{\langle \boldsymbol{\varepsilon_n}(\eta_s^{*b})\boldsymbol{\varepsilon_n^*}(\eta_s^{*b})\rangle}}$$

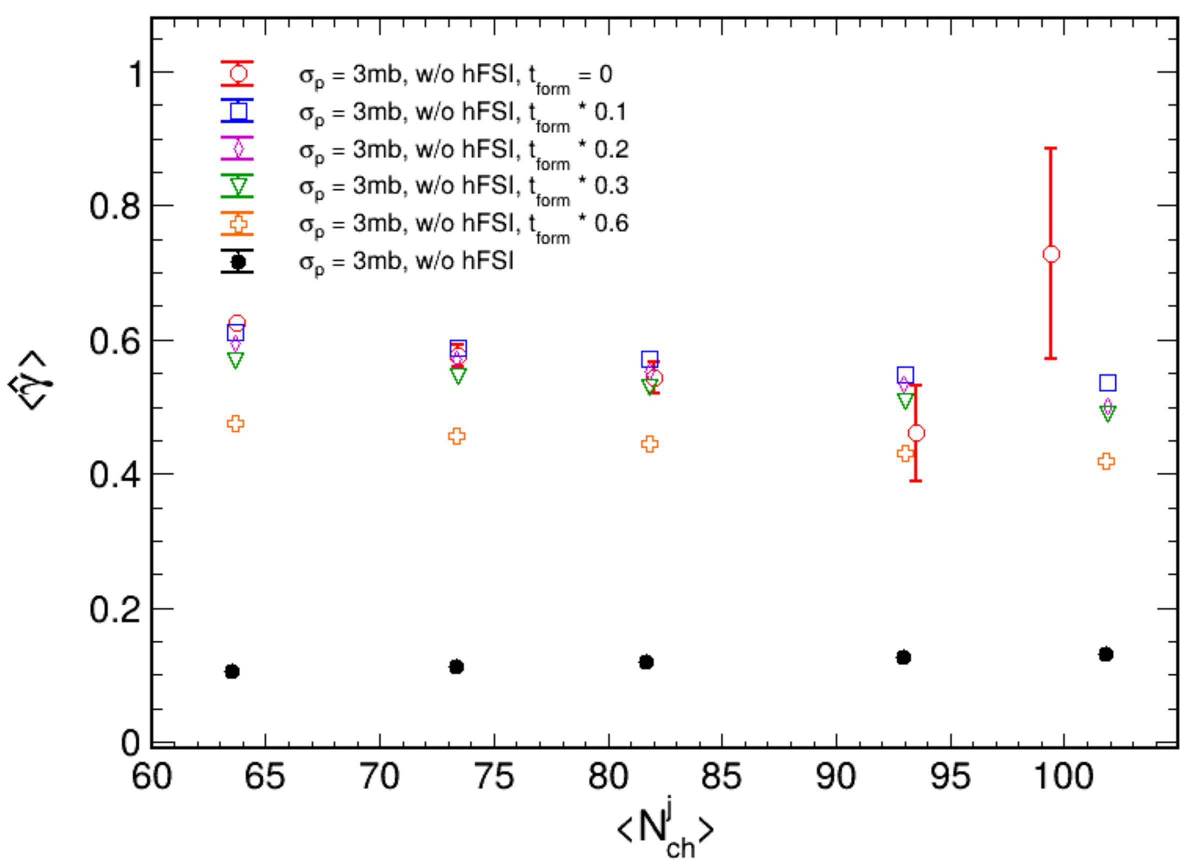
Strong decorrelation across η_s

Partonic opacity

Scale both formation time and position



Only scale formation time

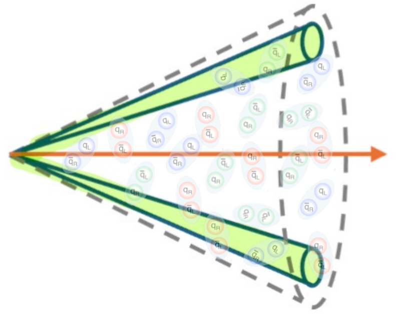


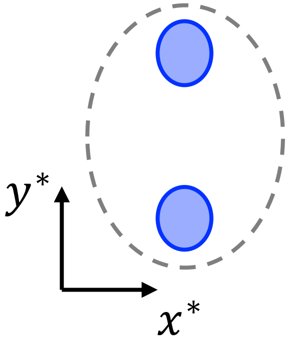
2D correlation function within jets

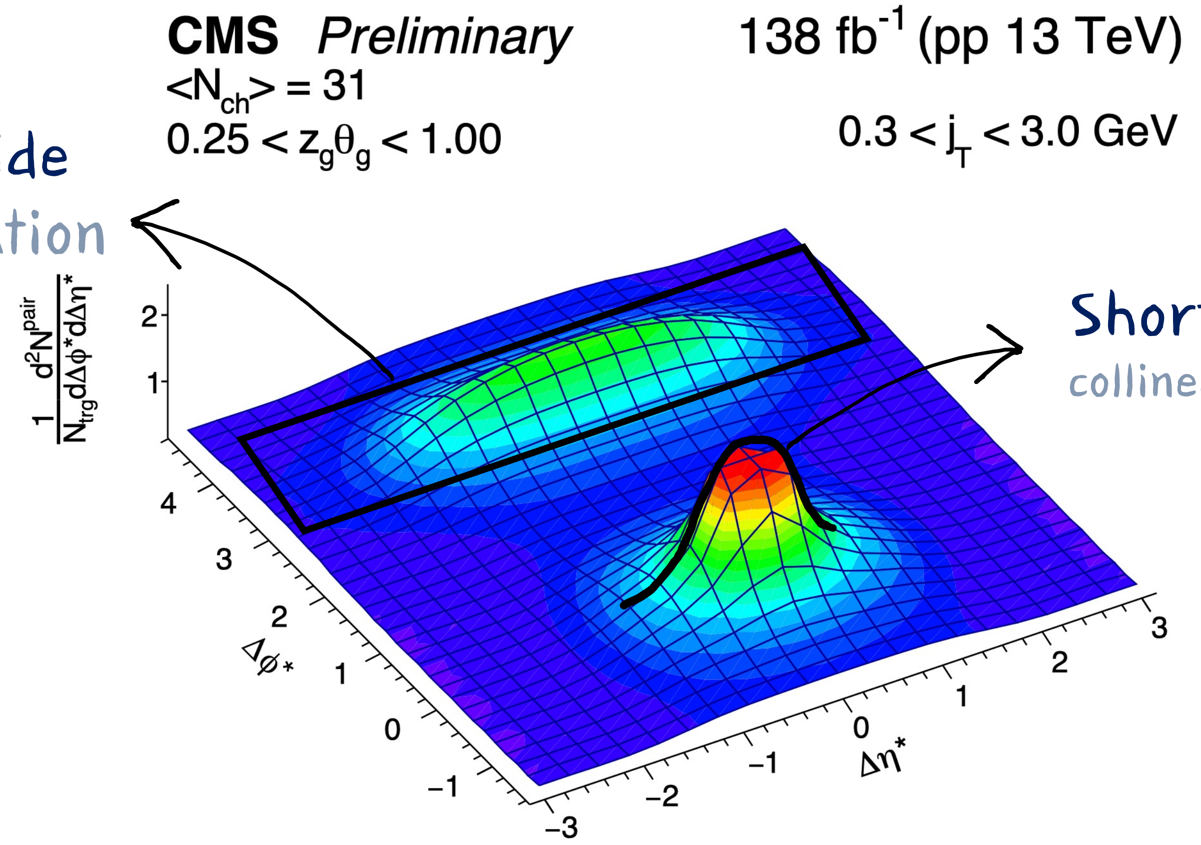
Low-multiplicity jets

long-range, away-side

momentum conservation

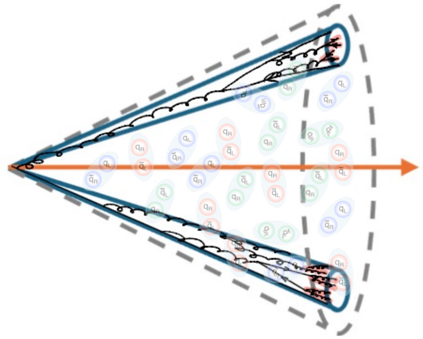






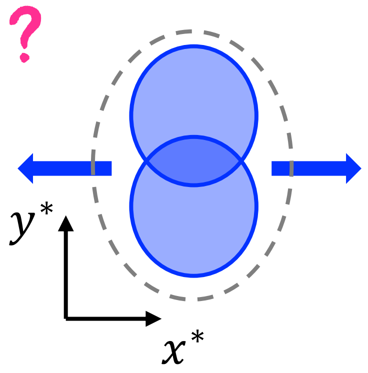
Short-range, near-side

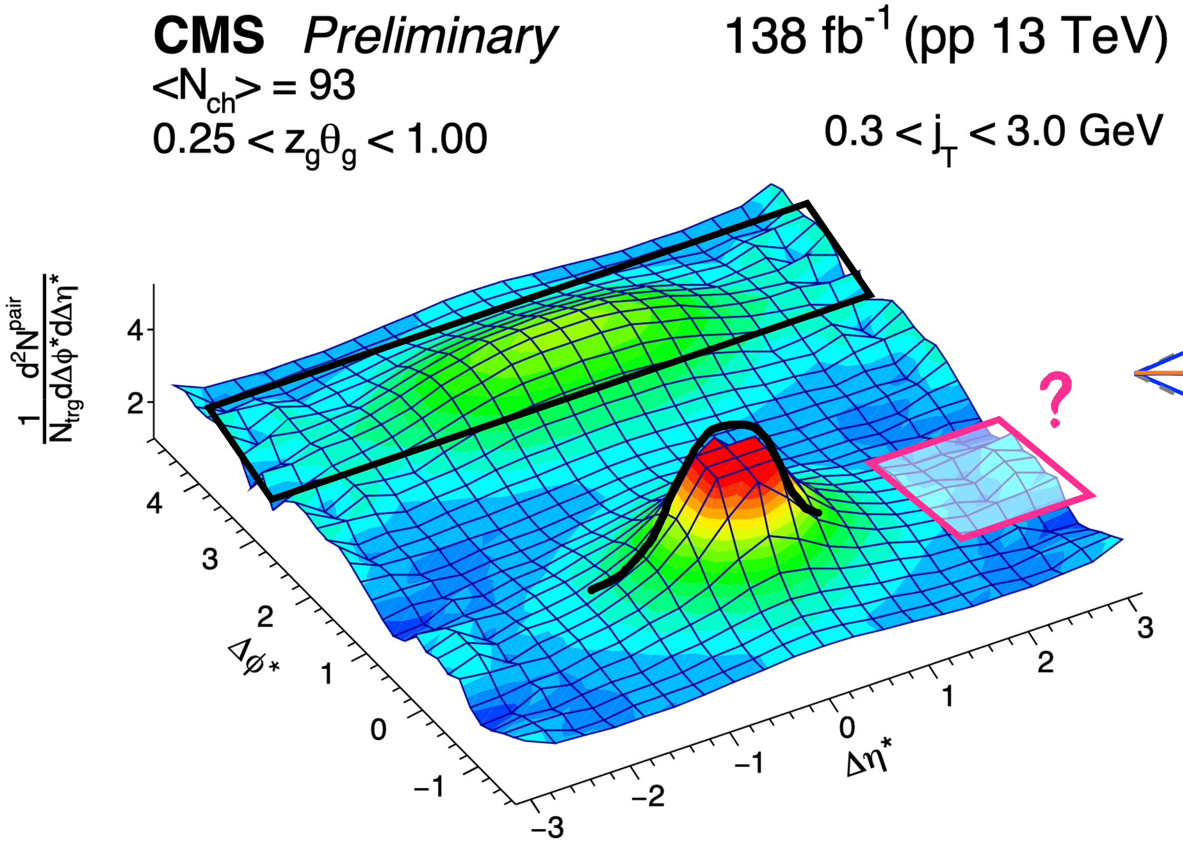
collinear emission, mini-jets

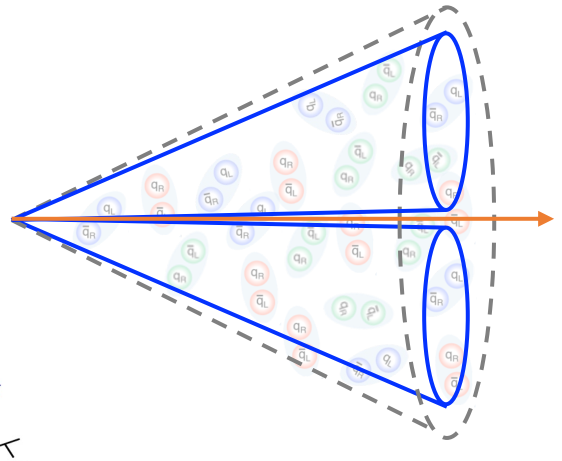


2D correlation function within jets

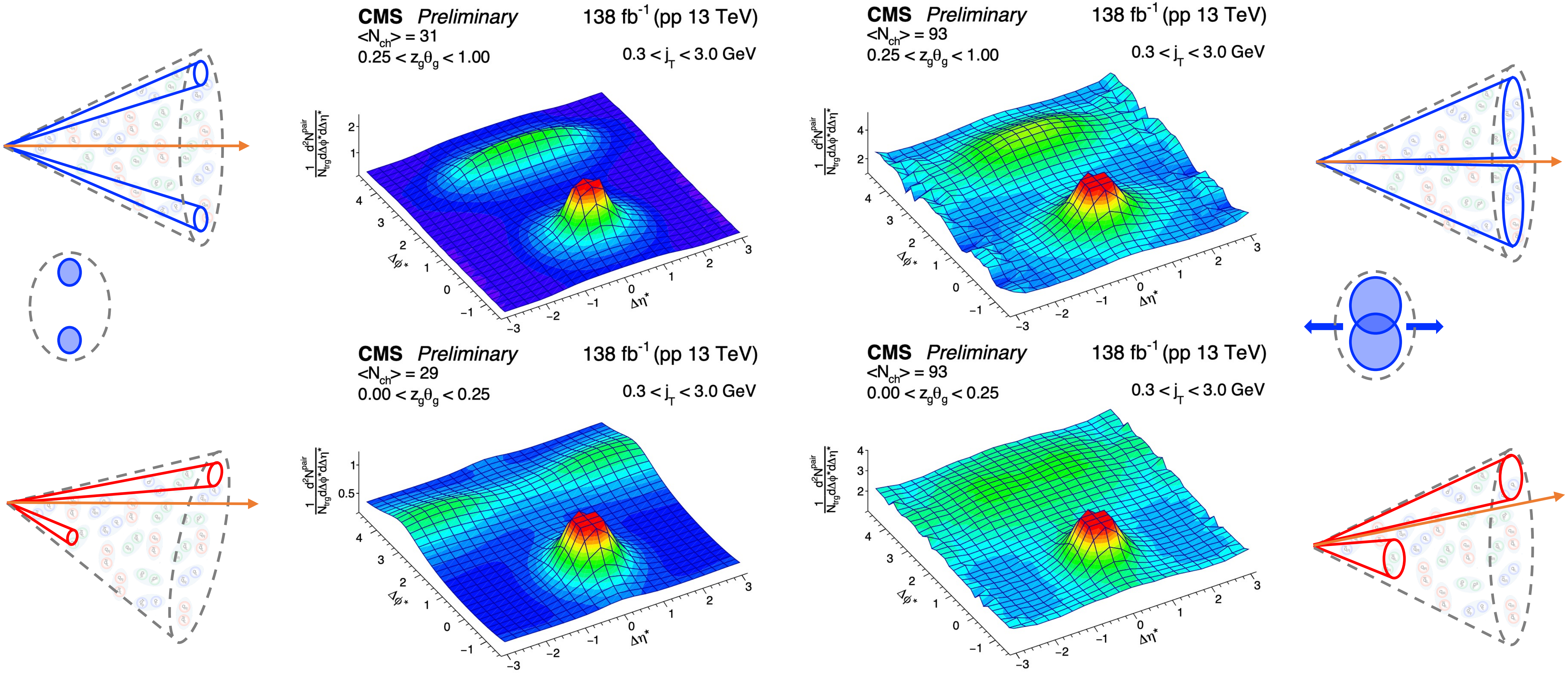
High-multiplicity jets





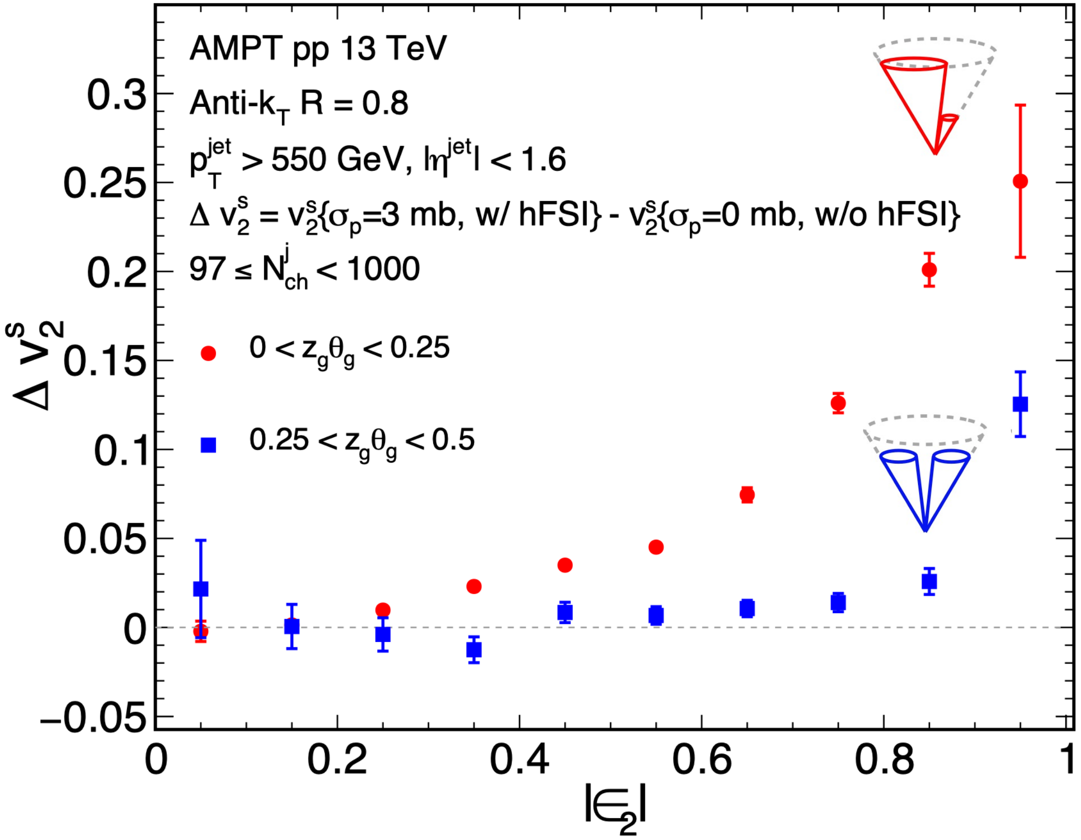


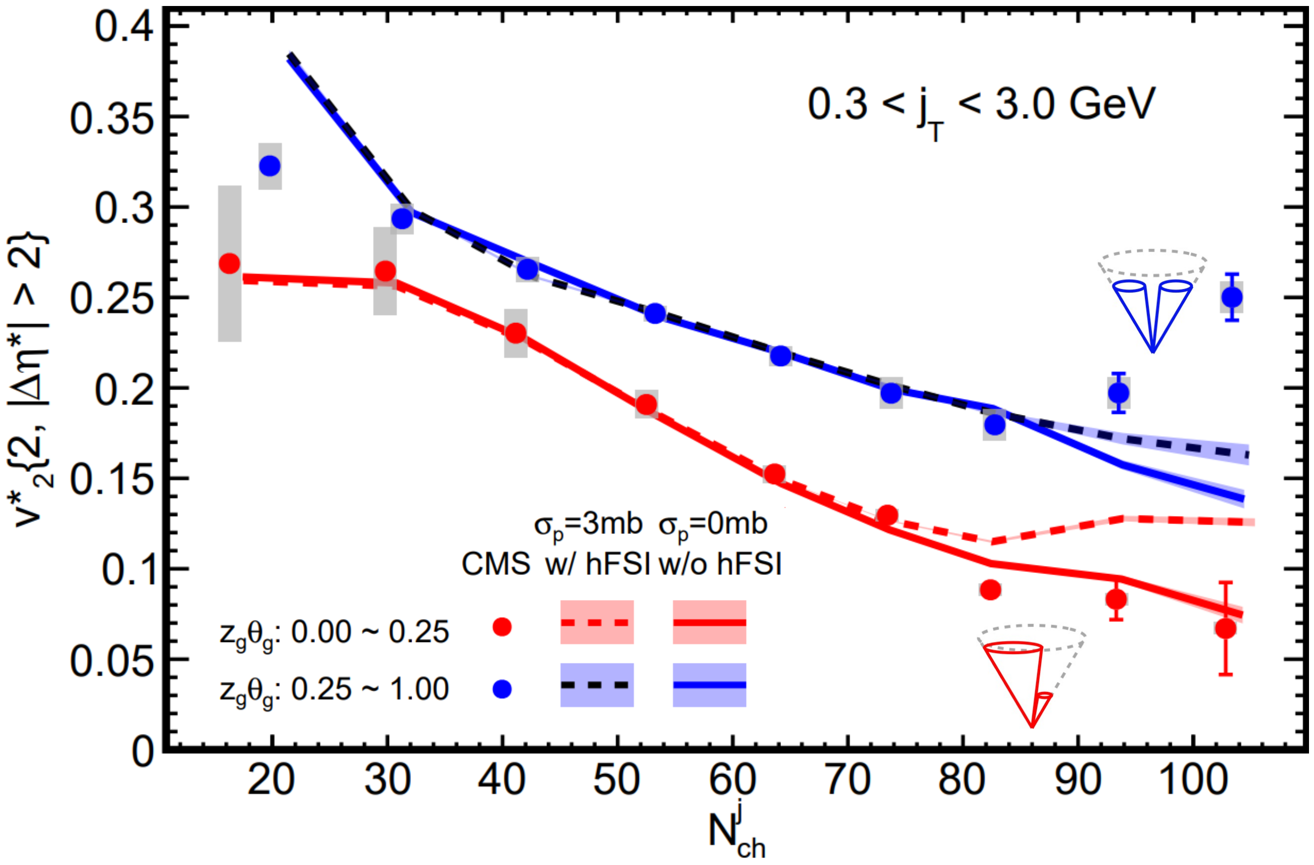
2D correlation within jets



Jet substructure – model study

High-multiplicity jets





Larger v_2 enhancement for one prong jet?