

EMMI Workshop: Probing the early stages with jets

Understanding the origin of collective phenomena in jets

Xiaoyu Liu
Rice University

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



U.S. DEPARTMENT OF
ENERGY

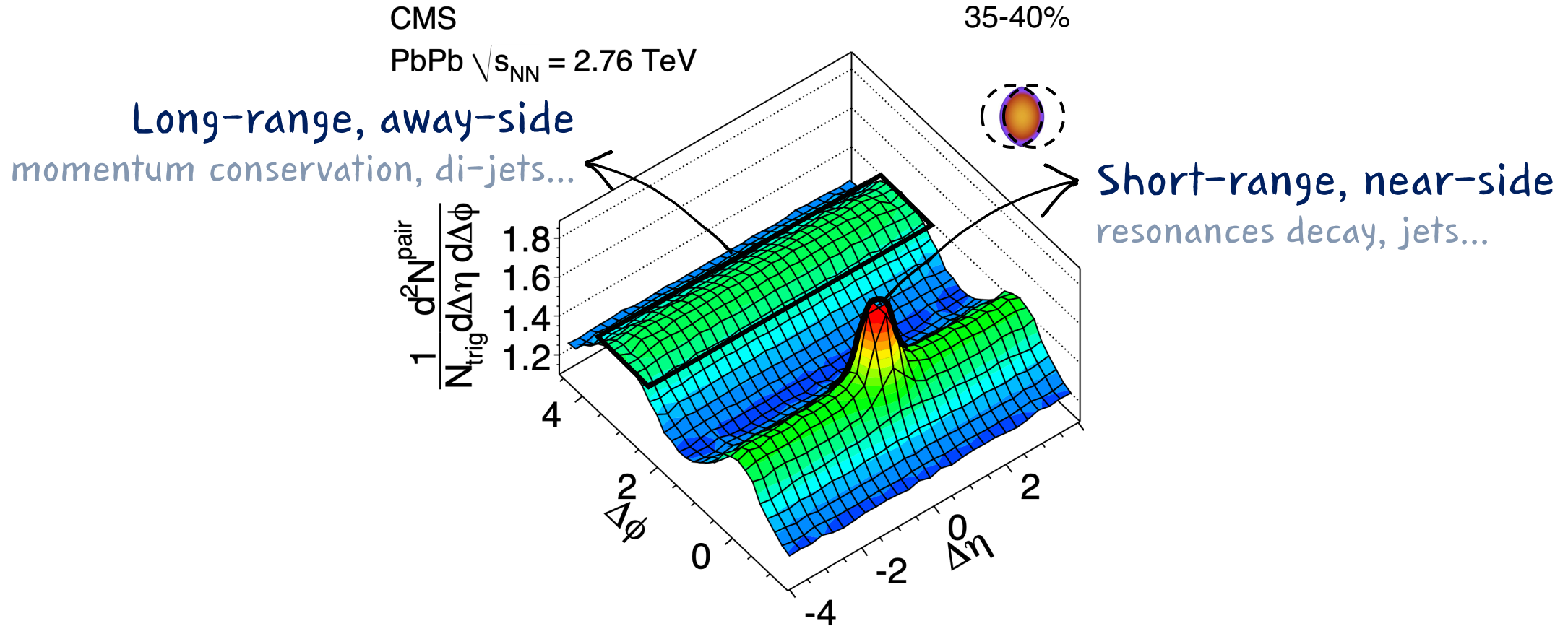
Office of Science



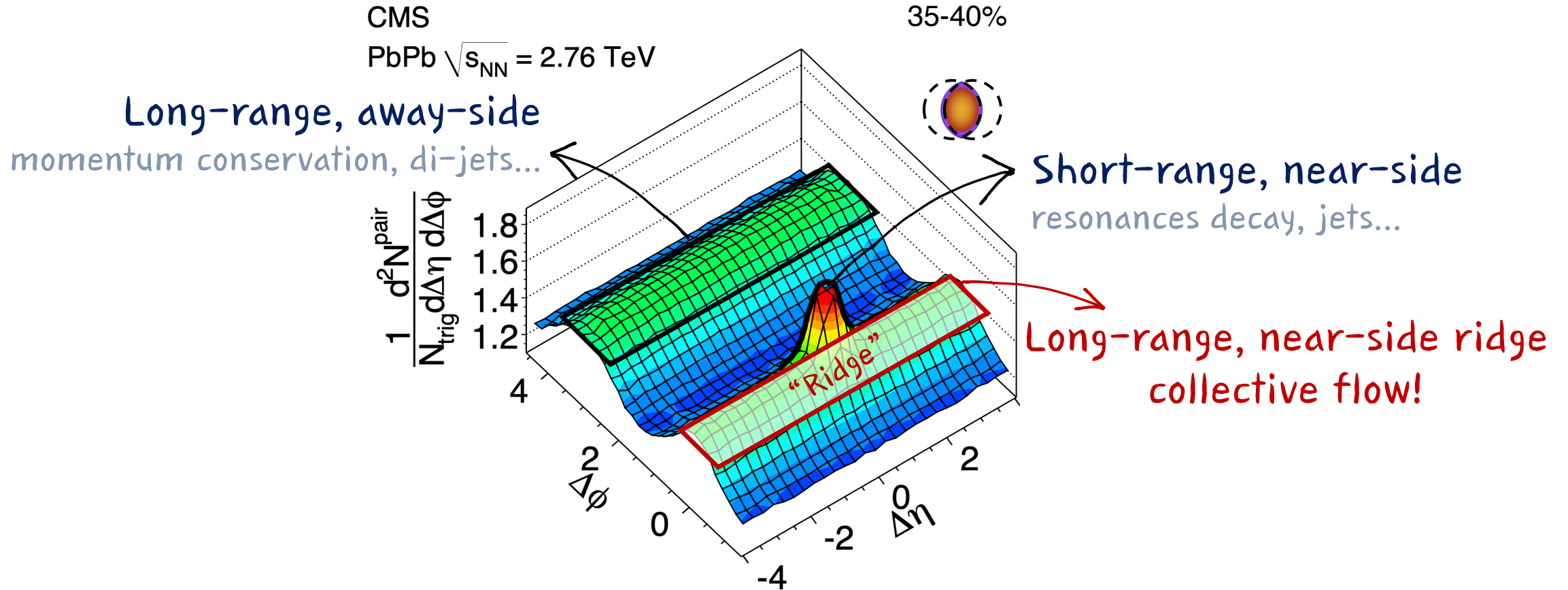
RICE



Collectivity in Heavy Ion



Collectivity in Heavy Ion



Collectivity in Heavy Ion

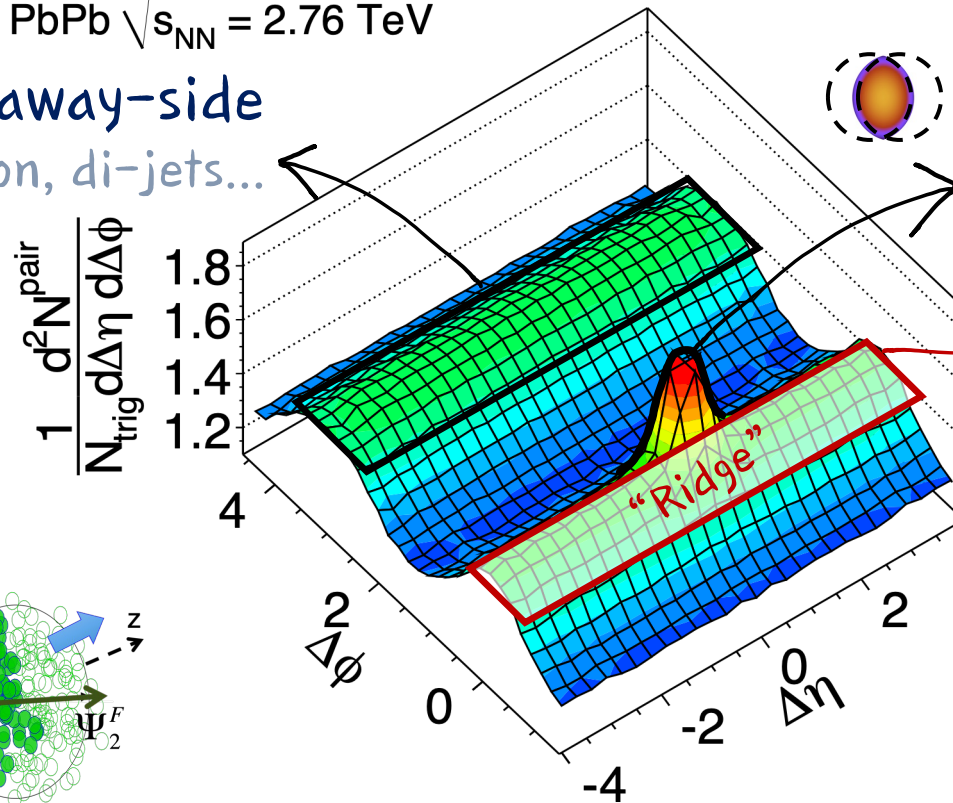
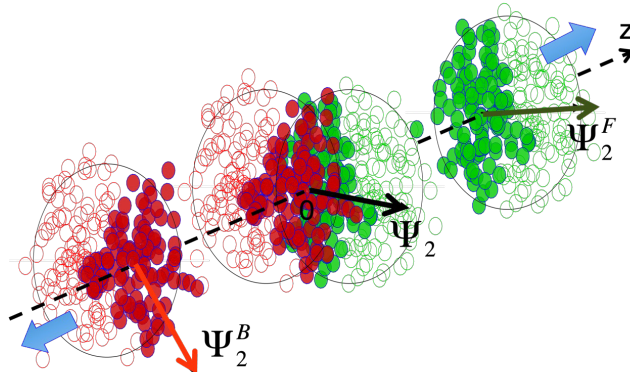
CMS
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

35-40%

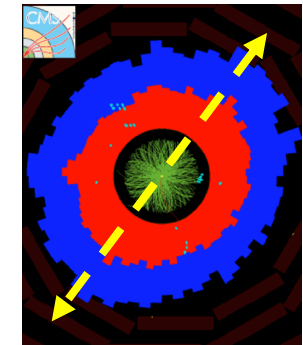
Long-range, away-side
momentum conservation, di-jets...

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

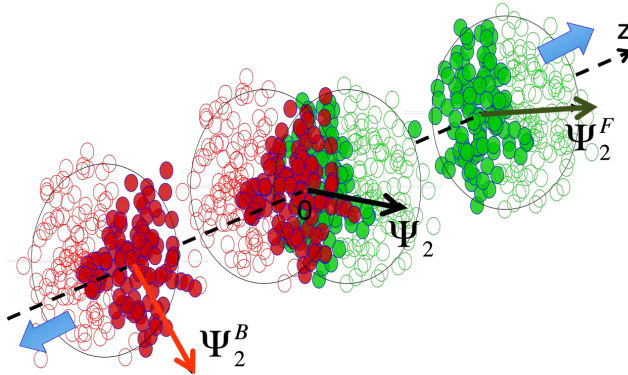
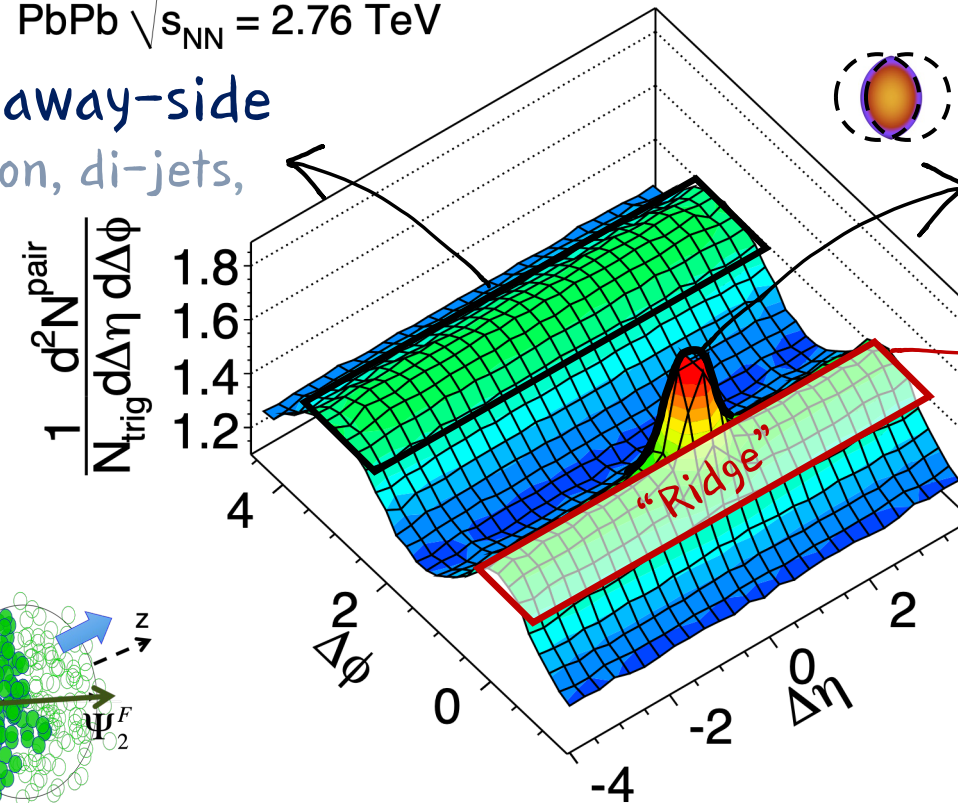
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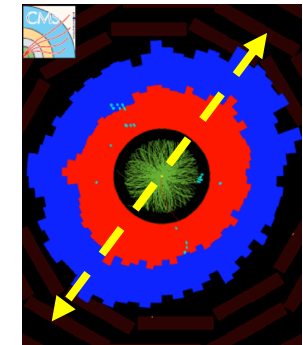
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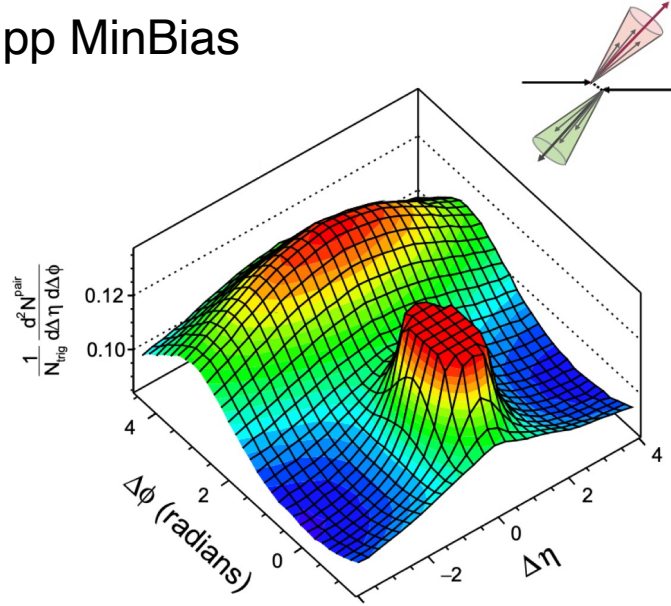
Initial State Geometry

Strong Rescattering

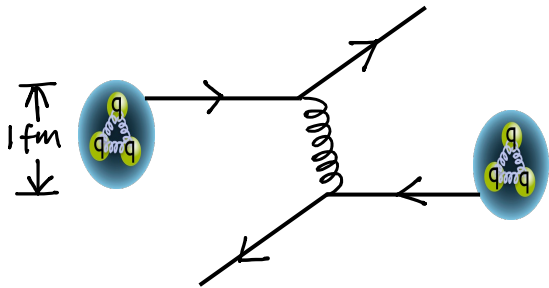
Final State Anisotropy

Collectivity in small systems

pp MinBias

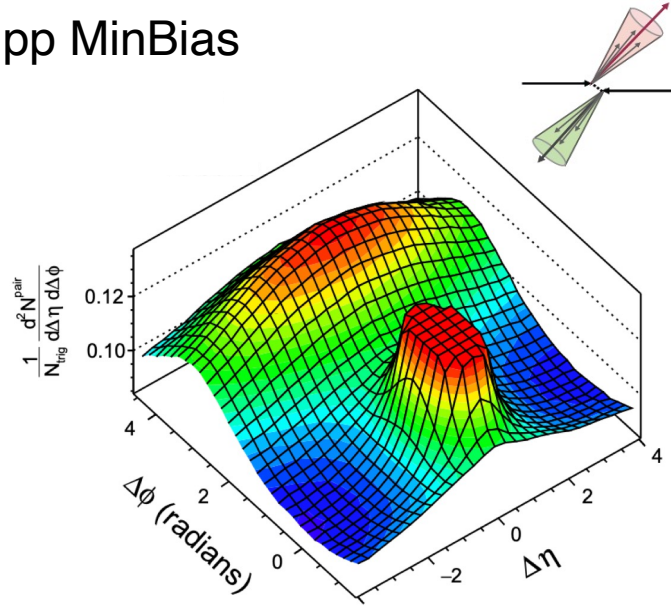


X No near-side ridge in MB pp

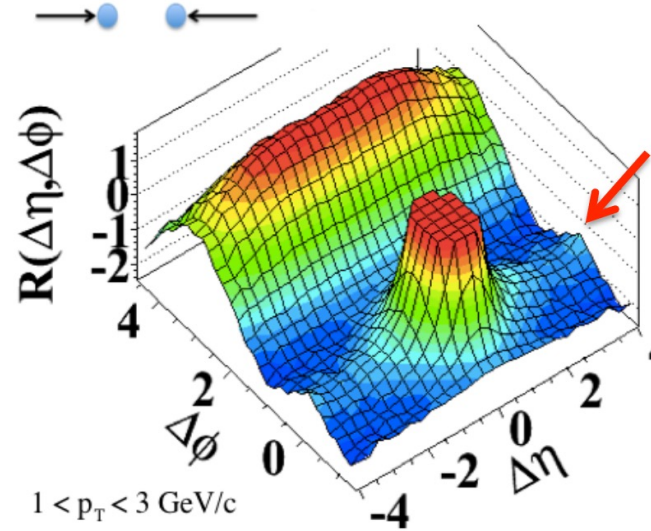


Collectivity in small systems

pp MinBias

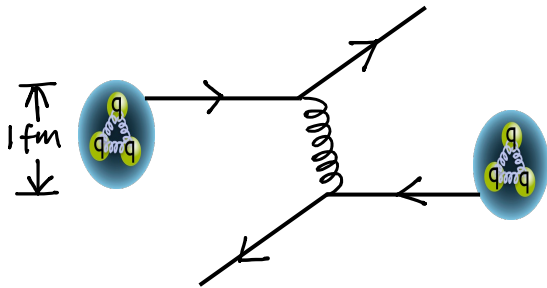


(a) pp $\sqrt{s} = 7$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$



$1 < p_T < 3$ GeV/c
JHEP 09 (2010) 091

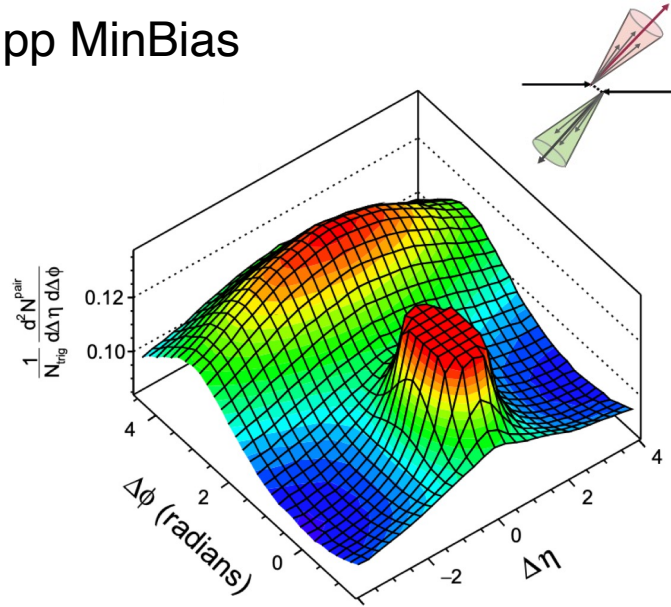
✗ No near-side ridge in MB pp ✓ Near-side ridge in HM pp



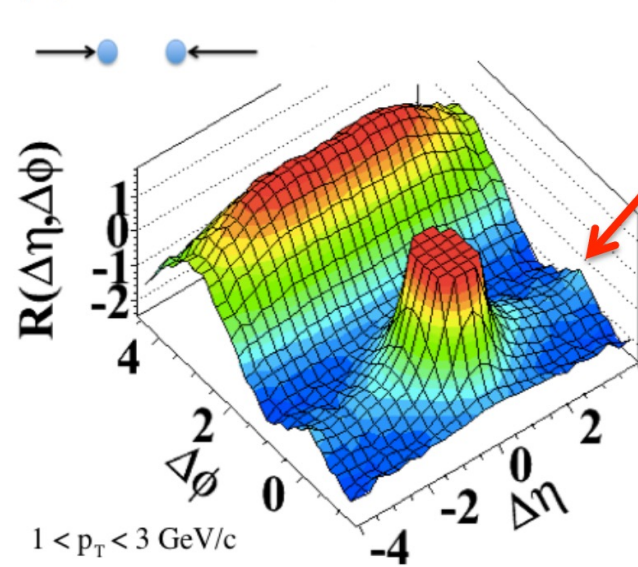
Collectivity in small systems

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

pp MinBias

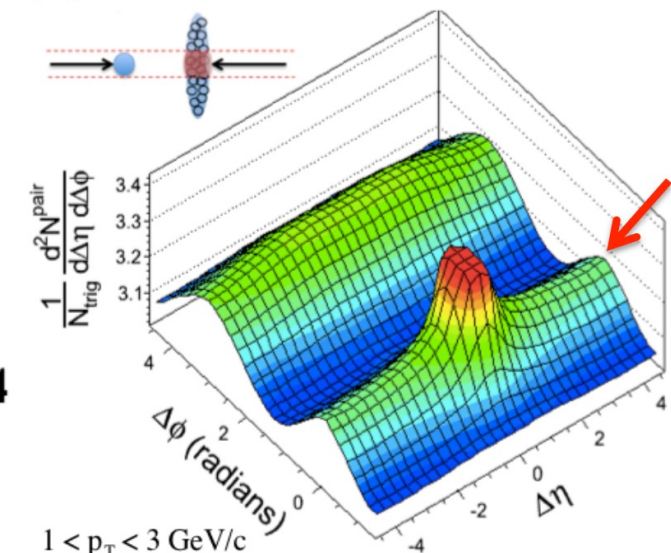


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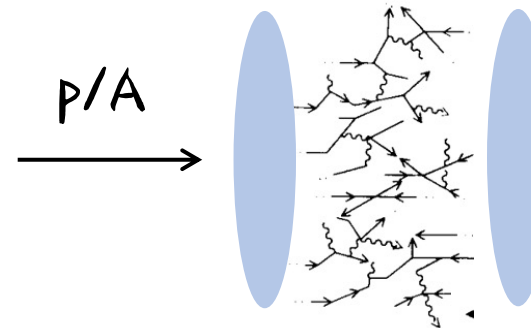
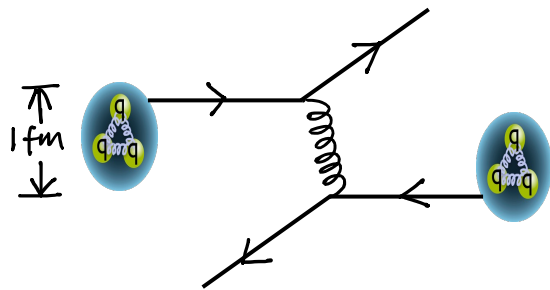
(b) pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 < N_{\text{trk}}^{\text{offline}} \leq 260$



$1 < p_T < 3$ GeV/c
PLB 718 (2013) 795

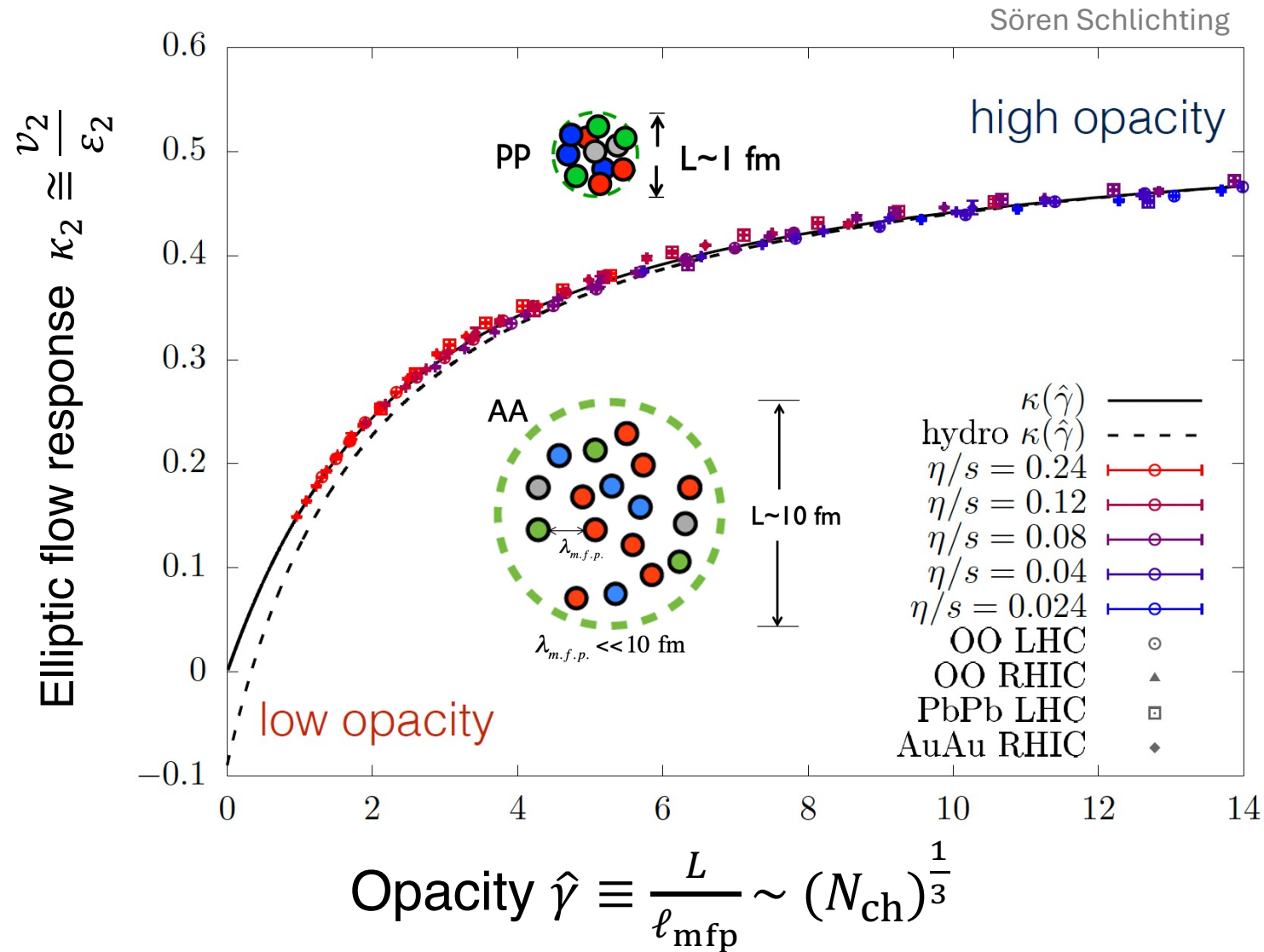
✗ No near-side ridge in MB pp

✓ Near-side ridge in HM pp and pPb

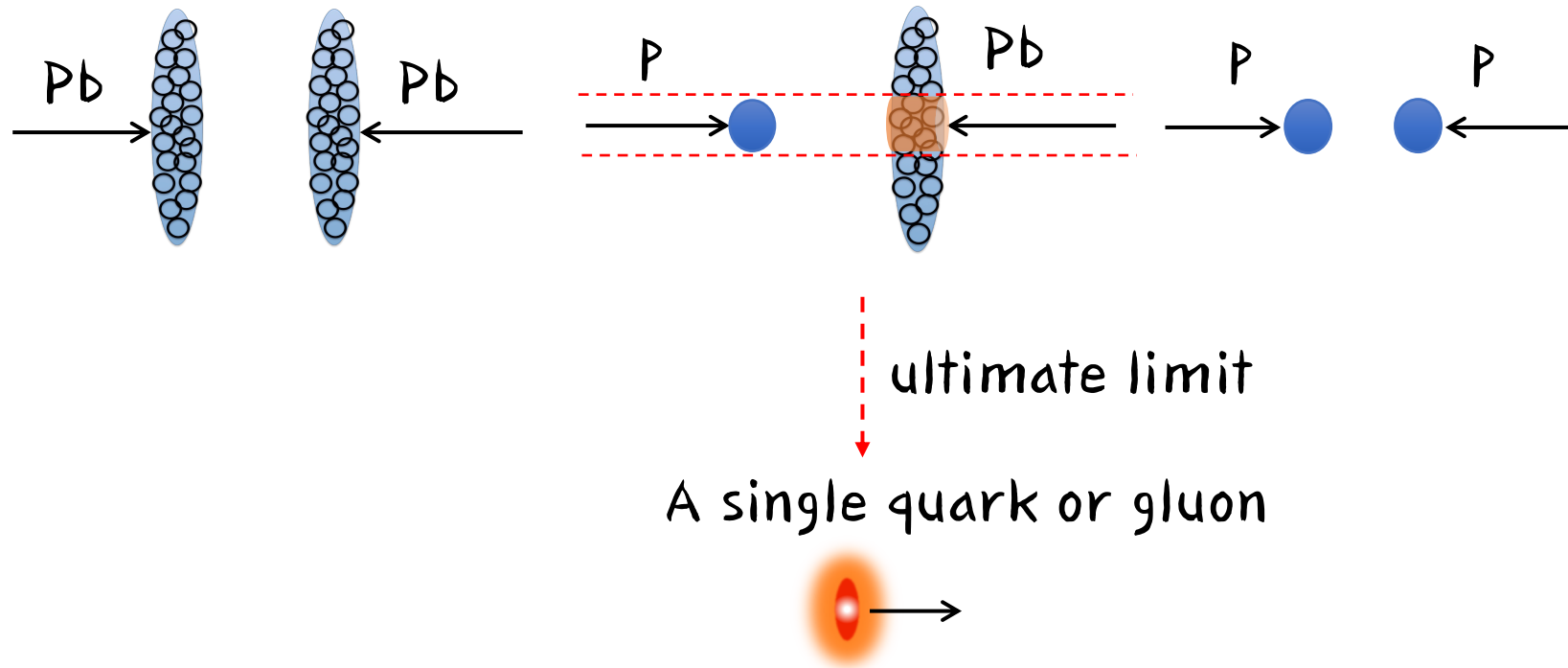


Strong partonic re-scatterings at subfermi scales

A new paradigm - Universal QGP across systems



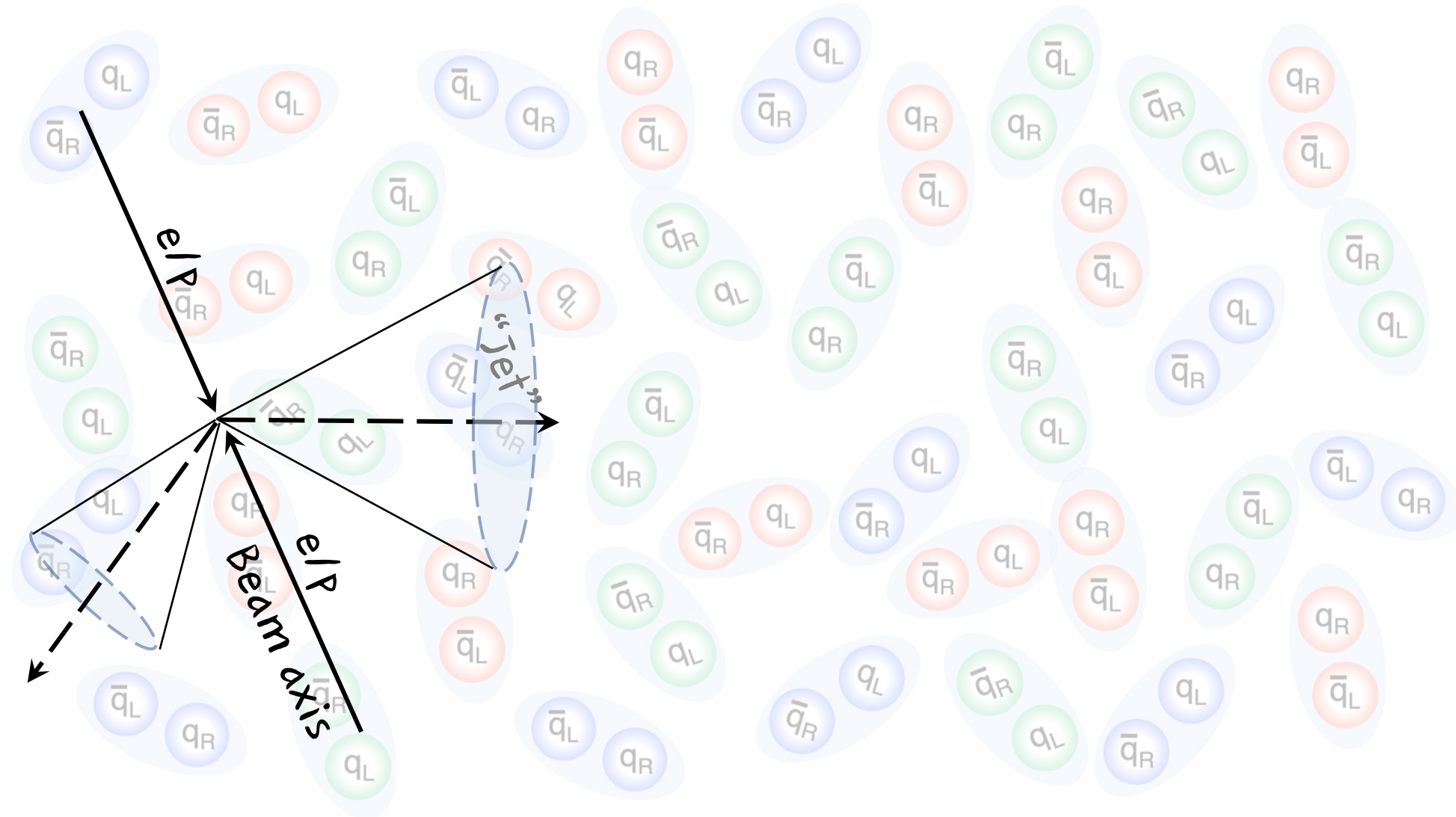
How small a QGP droplet can be ?



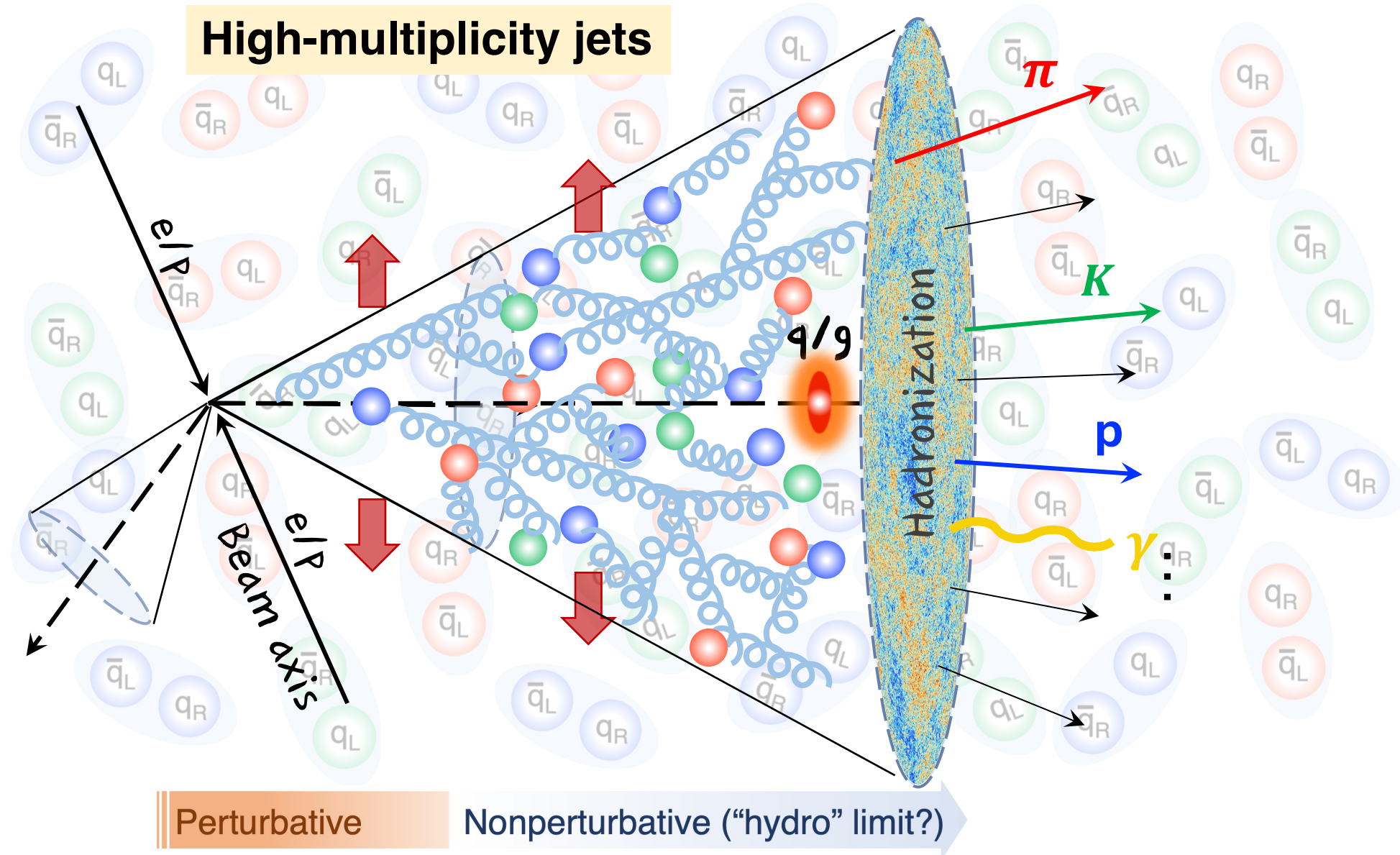
Can a QGP droplet be initiated by a “single parton” in the vacuum?

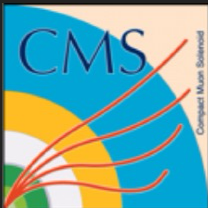
A. Baty, P. Gardner, WL, PRC 107 (2023) 064908

Jet: a proxy for system initiated by a parton



Jet: a proxy for system initiated by a parton



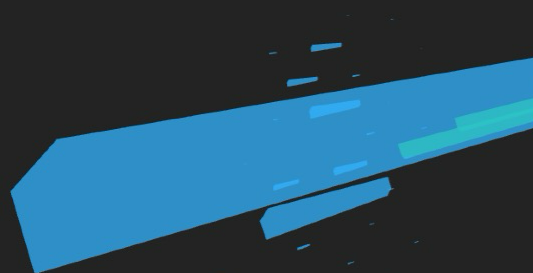


CMS Experiment at the LHC, CERN

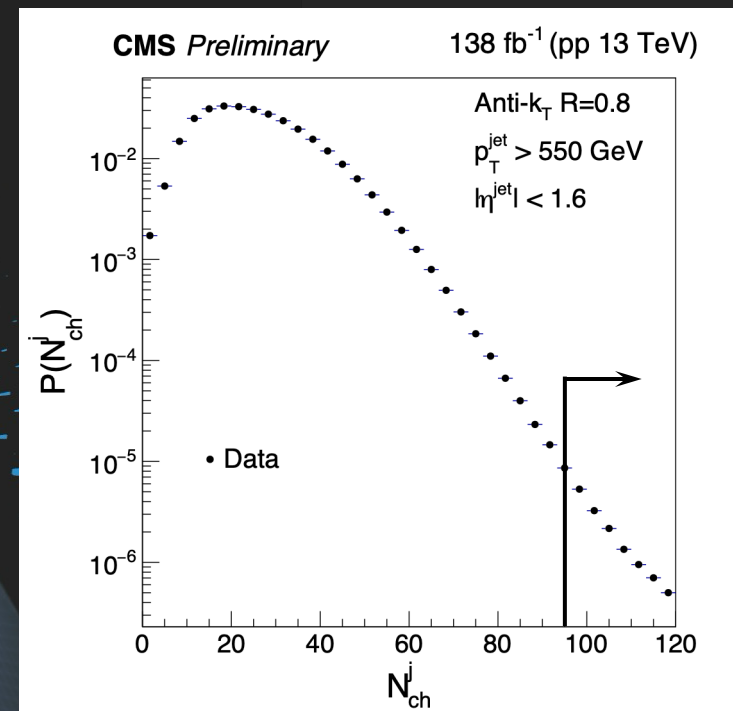
Data recorded: 2018-Aug-03 17:13:35.770304 GMT

Run / Event / LS: 320809 / 369847775 / 233

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

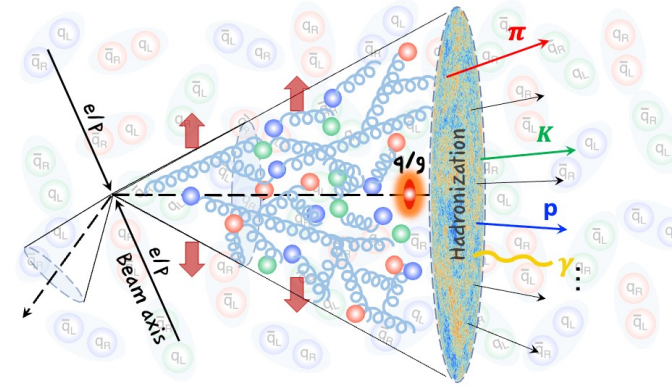
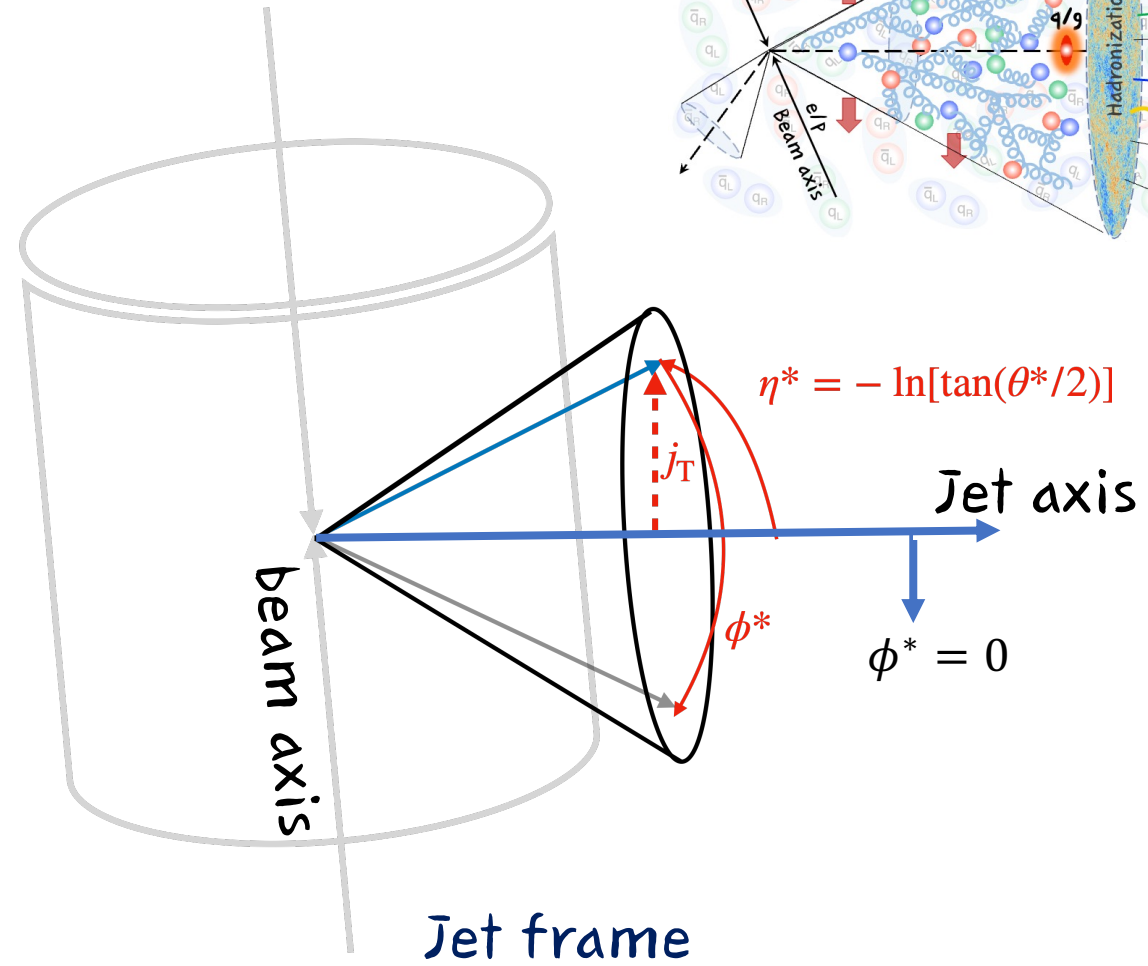
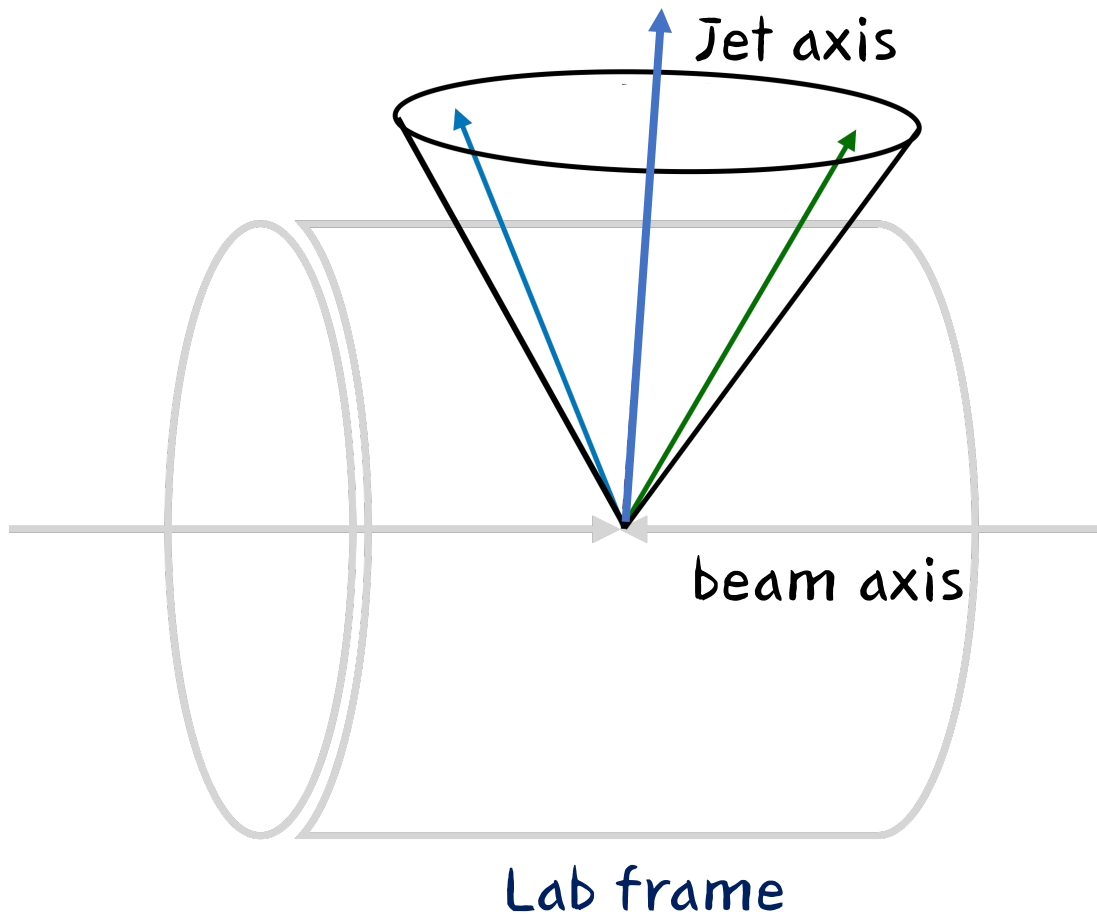


$p_T^{jet} > 550 \text{ GeV}$
 $|\eta_{jet}| < 1.6$
R=0.8 anti- k_T



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

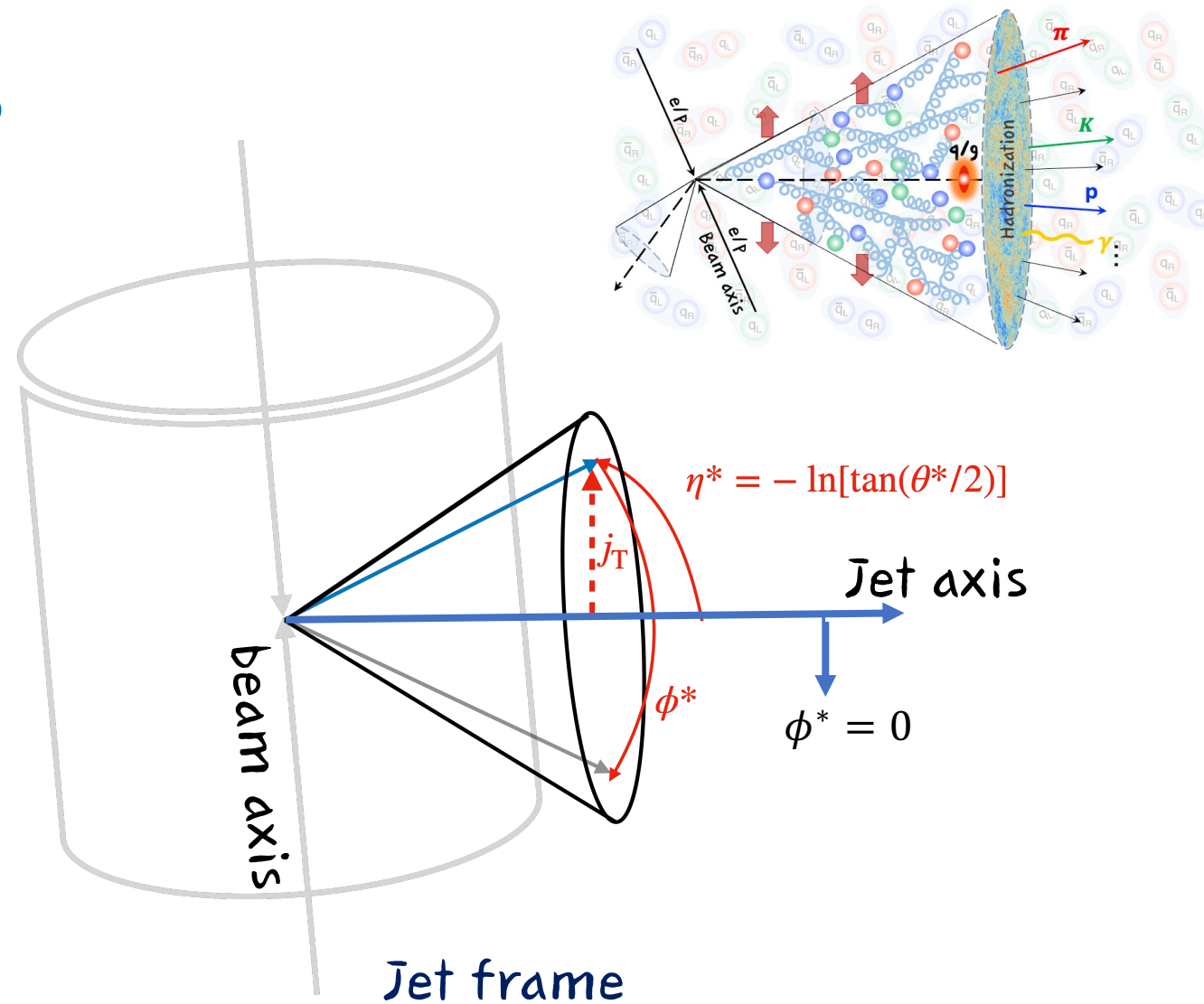
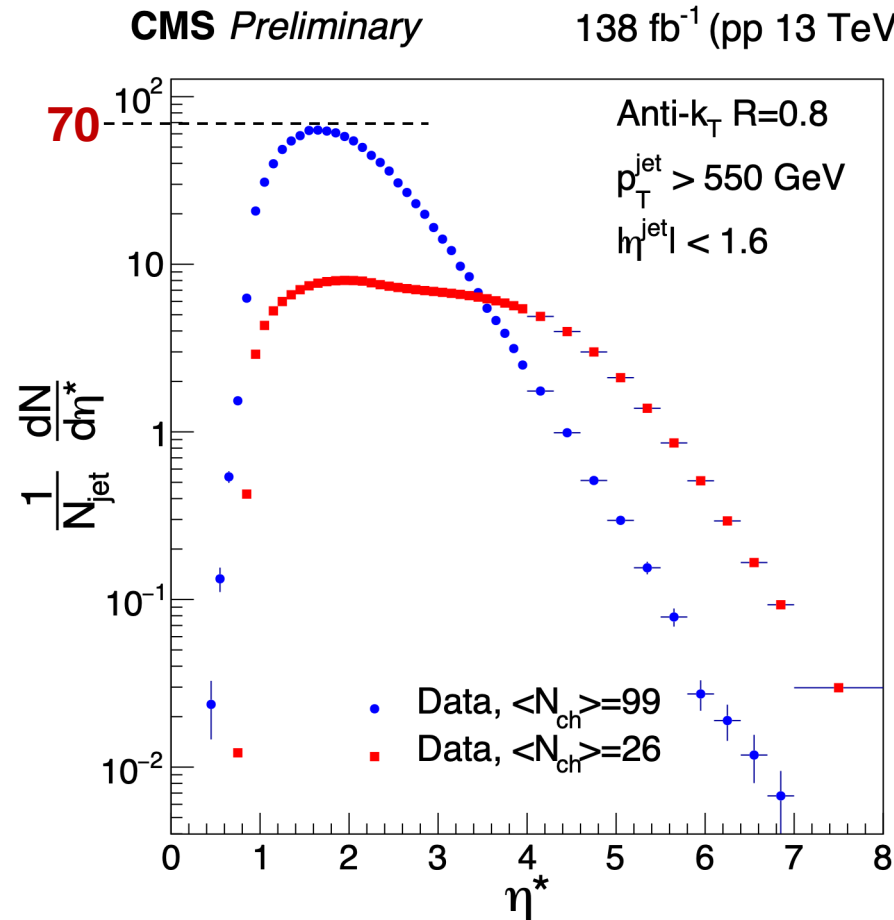
Projection to the jet axis



Projection is done for every jet individually.

$$\mathbf{p} = (p_T, \eta, \phi) \rightarrow \mathbf{p}^* = (j_T, \eta^*, \phi^*)$$

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Two particle correlation within jets

CMS

138 fb⁻¹ (pp 13 TeV)

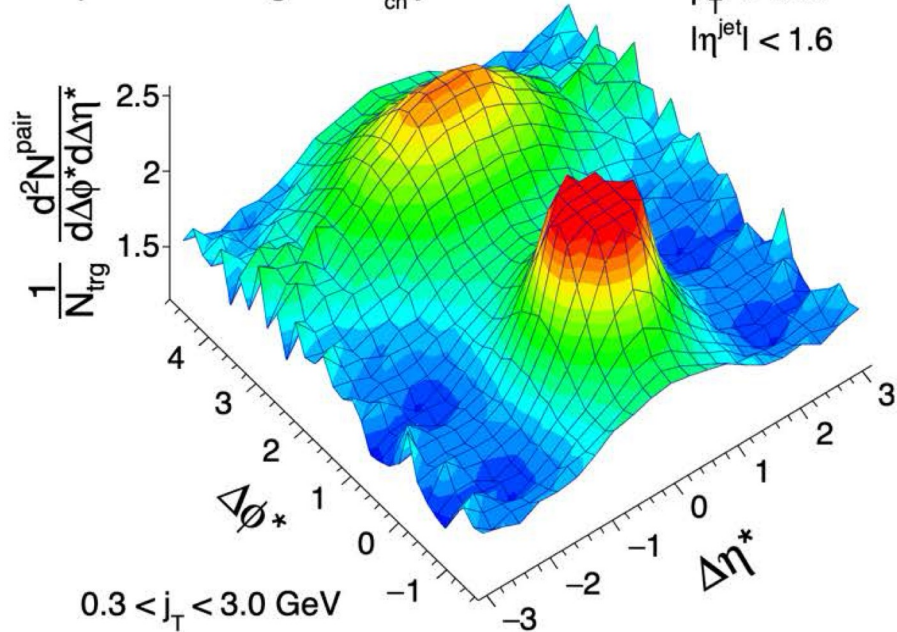
$\langle N_{\text{ch}}^j \rangle = 101$

Top 0.0023% highest- N_{ch}^j jets

Anti k_T R=0.8

$p_T^{\text{jet}} > 550$

$|\eta^{\text{jet}}| < 1.6$



Two particle correlation within jets

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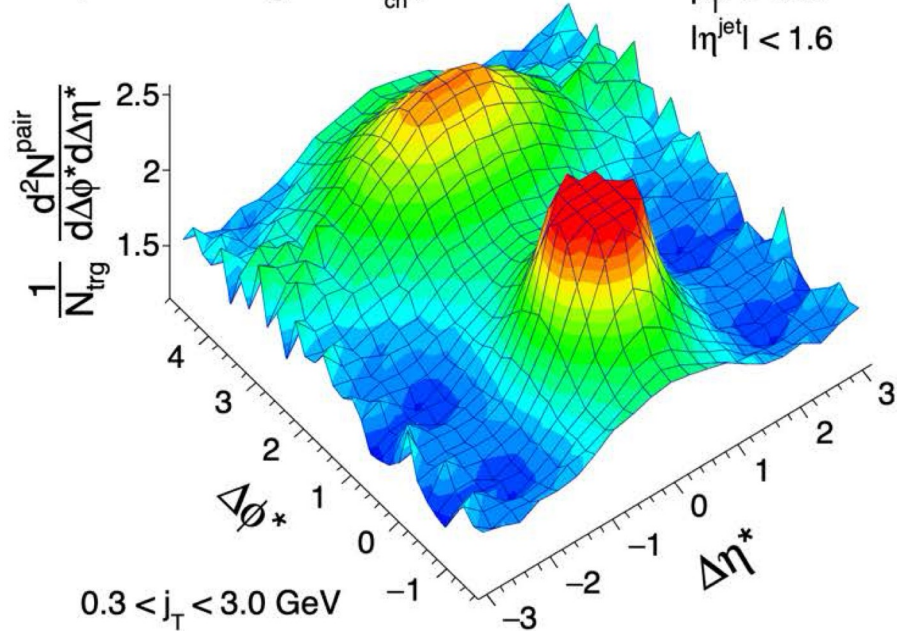
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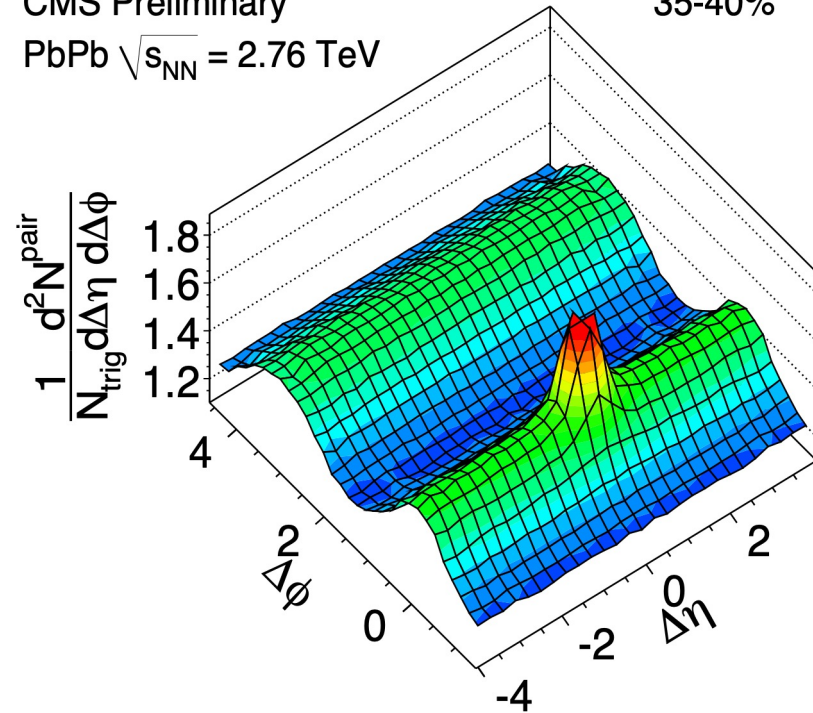


Similar

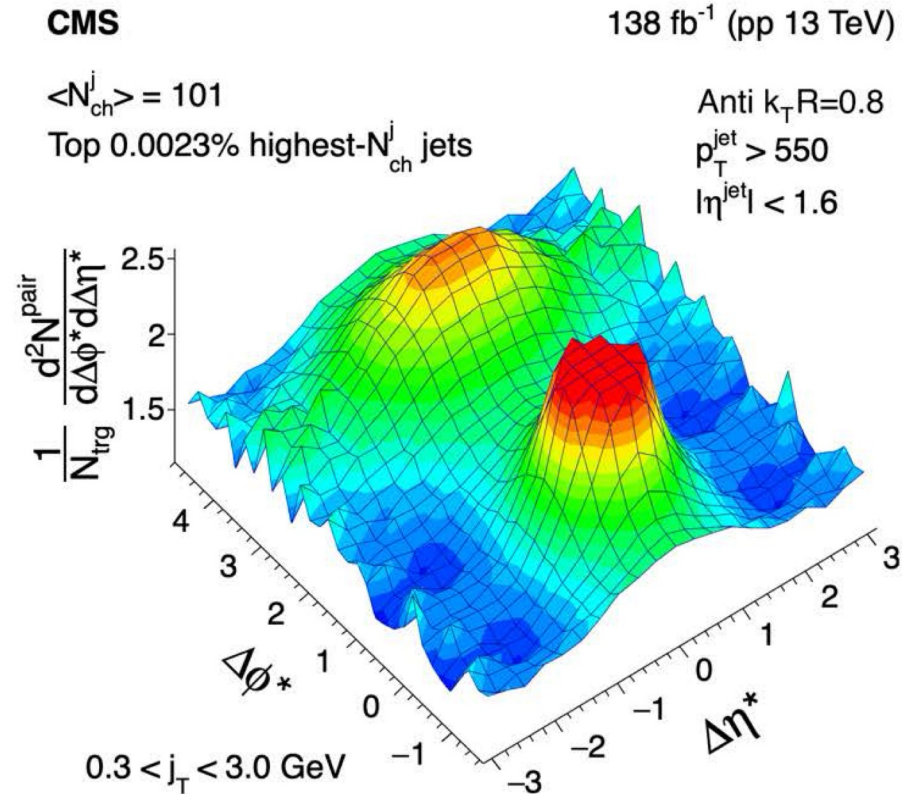
CMS Preliminary

PbPb $\sqrt{s_{NN}} = 2.76$ TeV

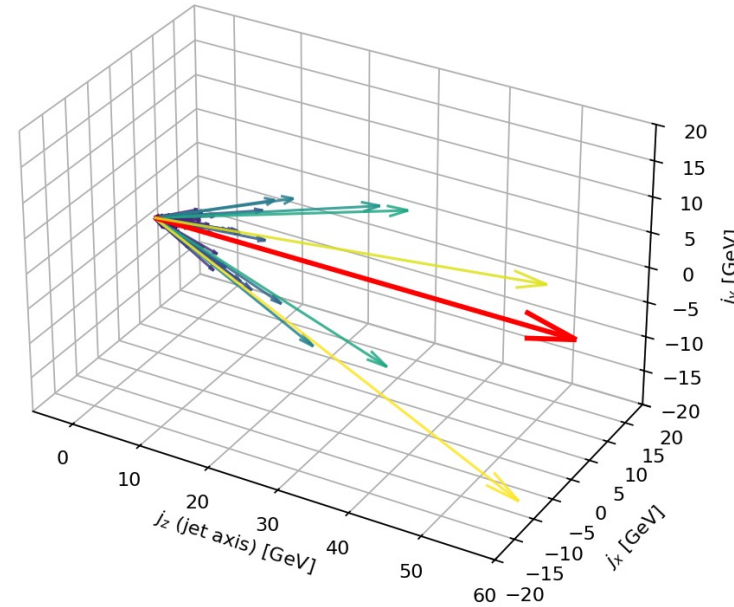
35-40%



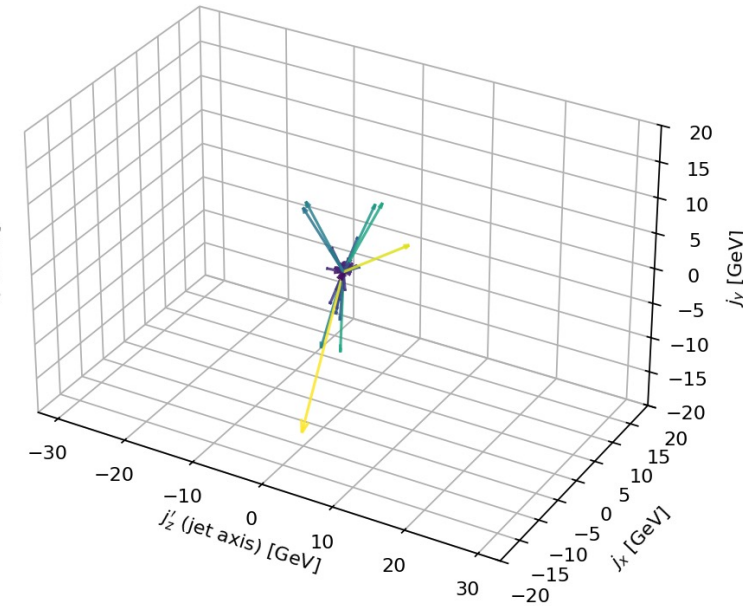
Two particle correlation within jets



Jet frame



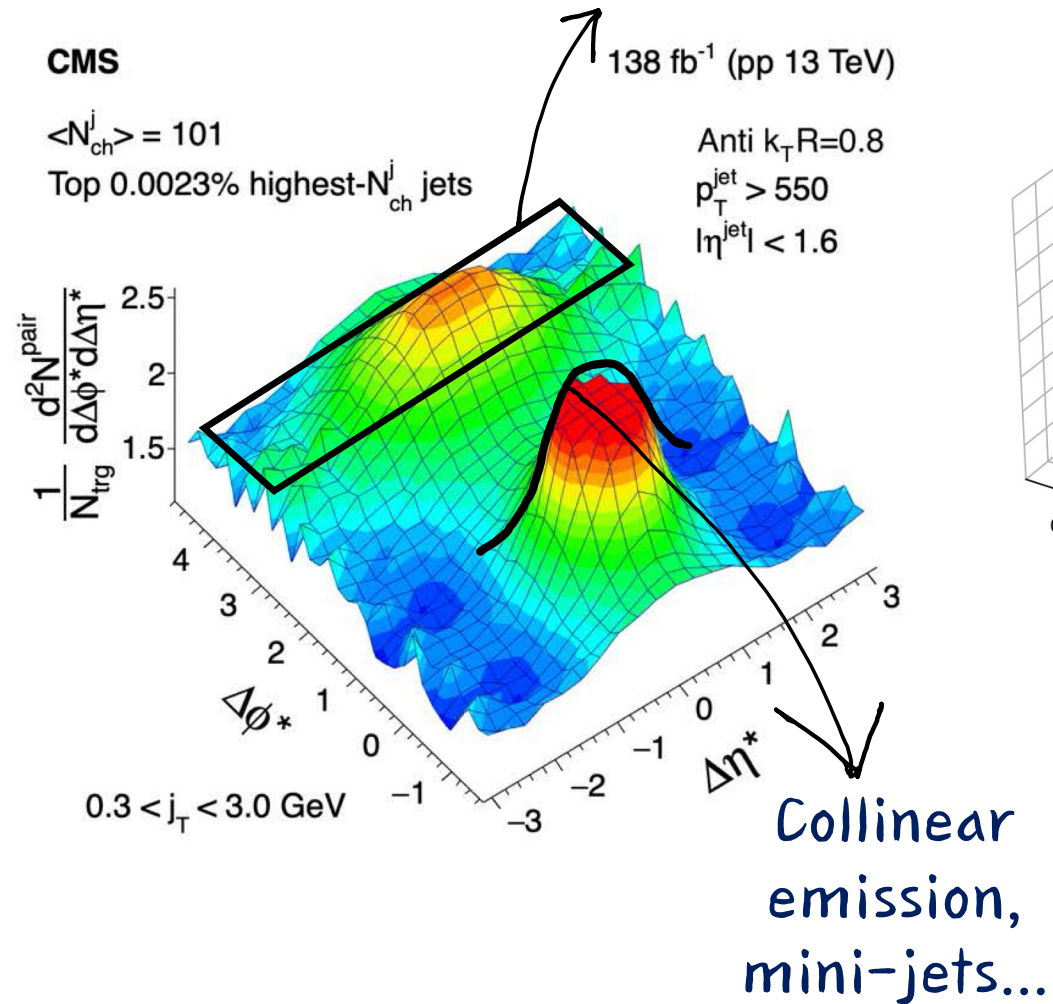
Jet rest frame



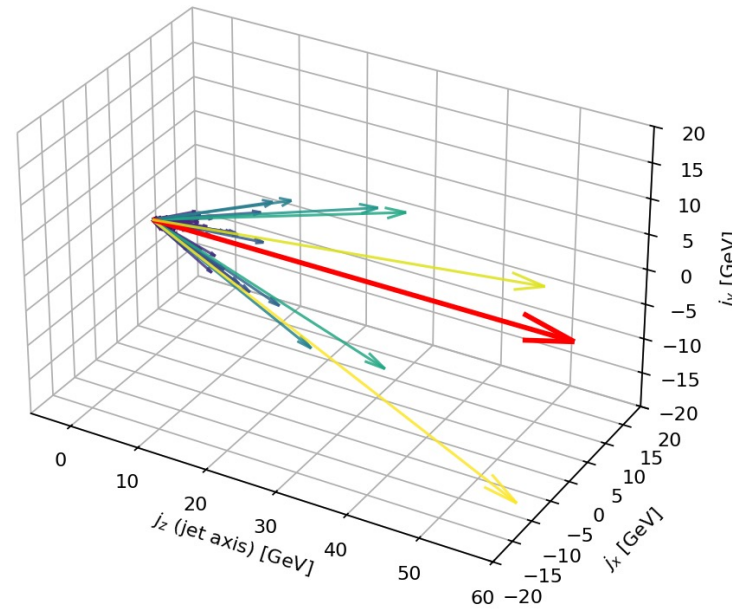
Jets are “boosted collisions”
 $\Delta\phi^* - \Delta\eta^*$ is boost invariant

Two particle correlation within jets

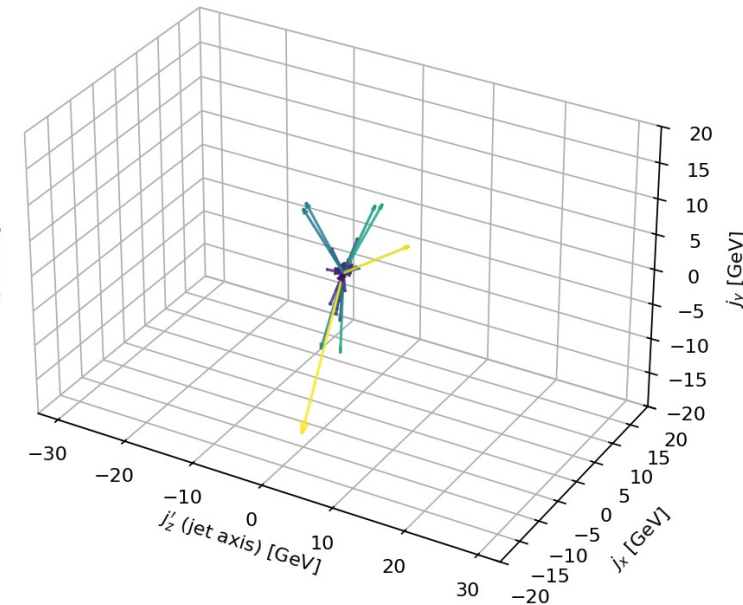
Momentum conservation



Jet frame



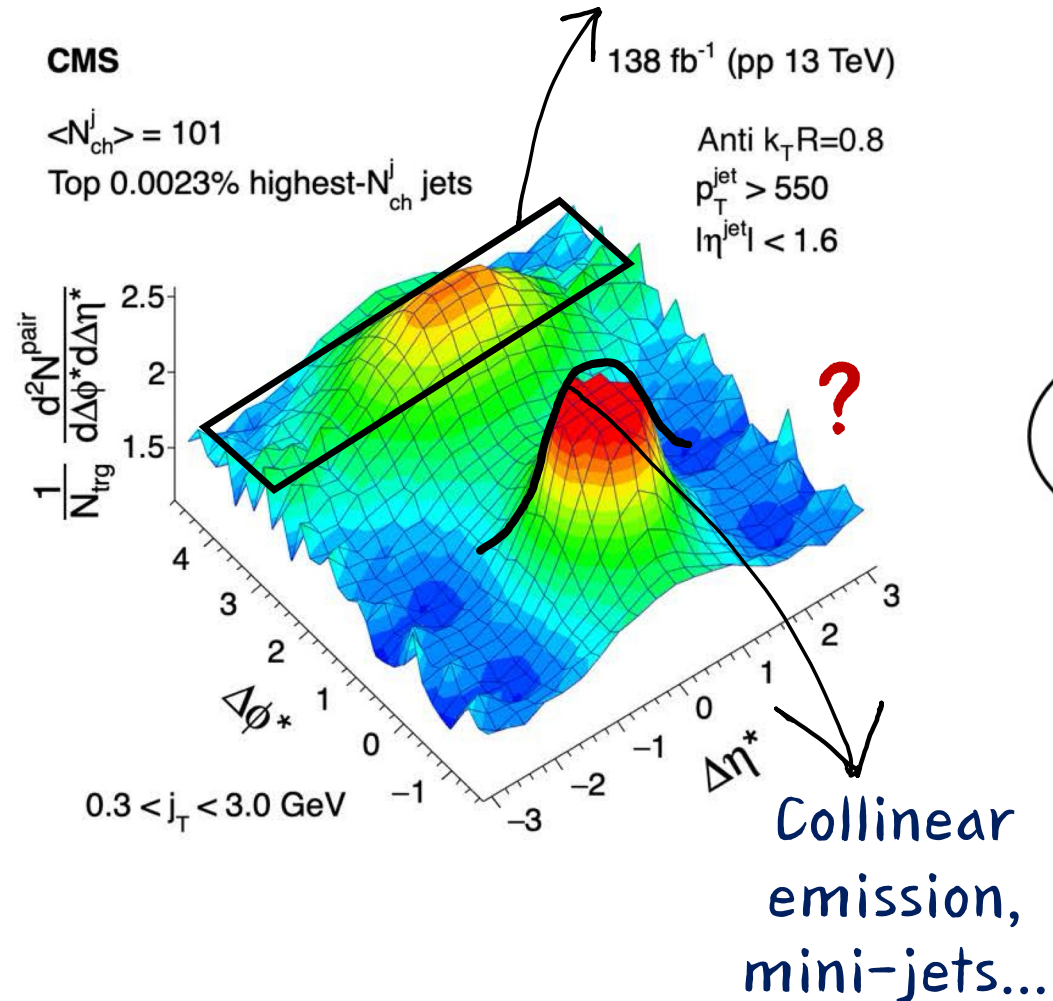
Jet rest frame



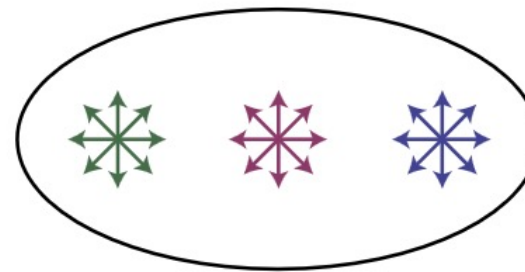
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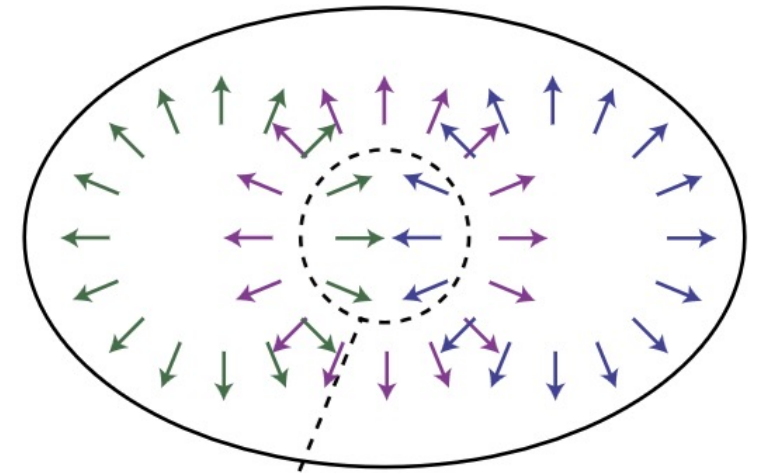
Momentum conservation



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



Initially isotropic momentum distribution

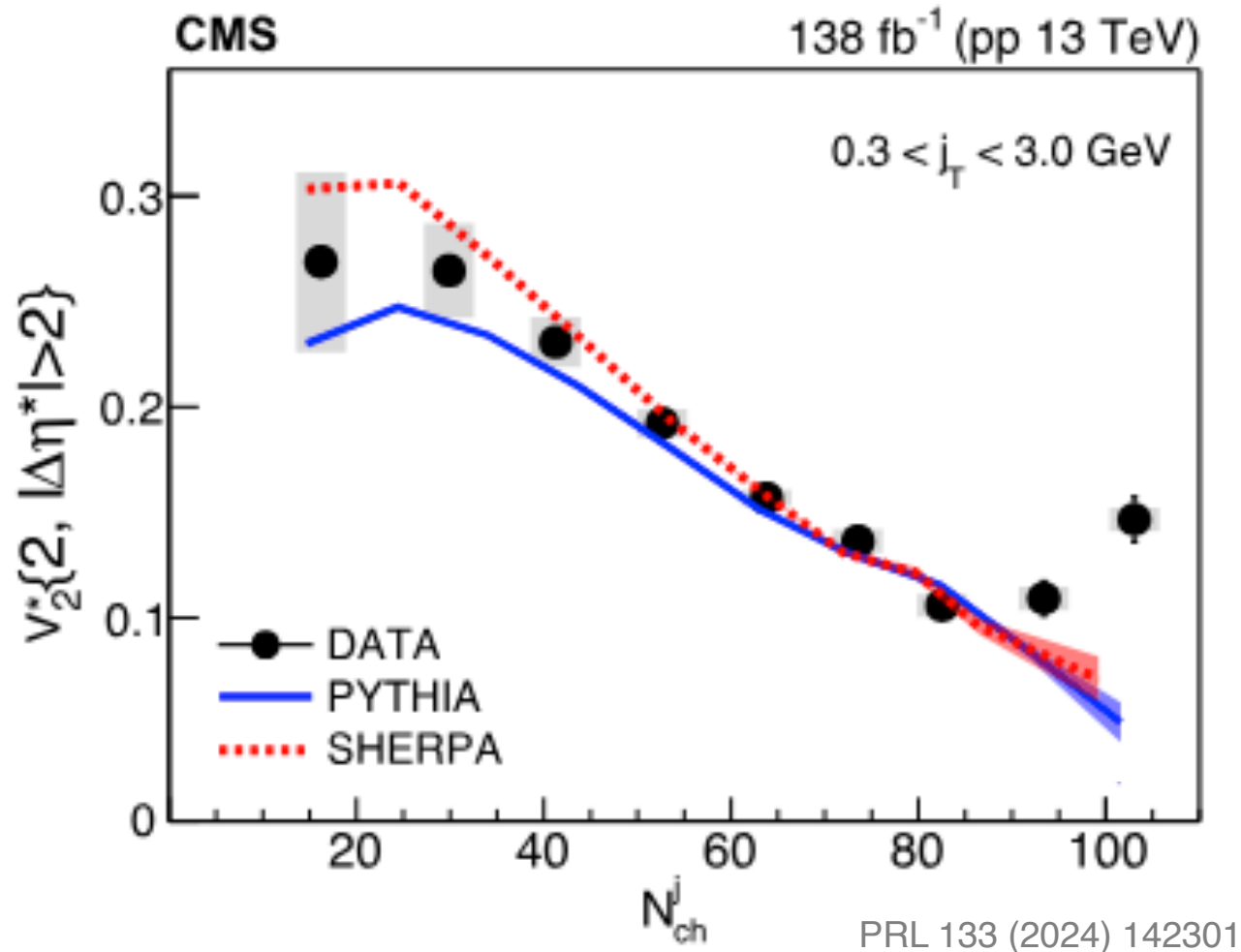


More particles moving in $\pm x$ -direction

Phys.Lett.B 783 (2018)

“Single-hit dynamics”

Elliptic flow v_2^*



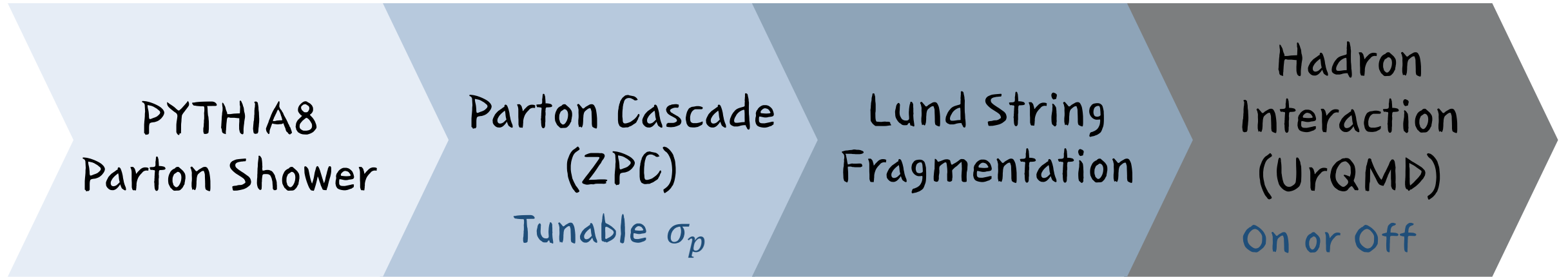
Enhanced elliptic anisotropies
at high multiplicities

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

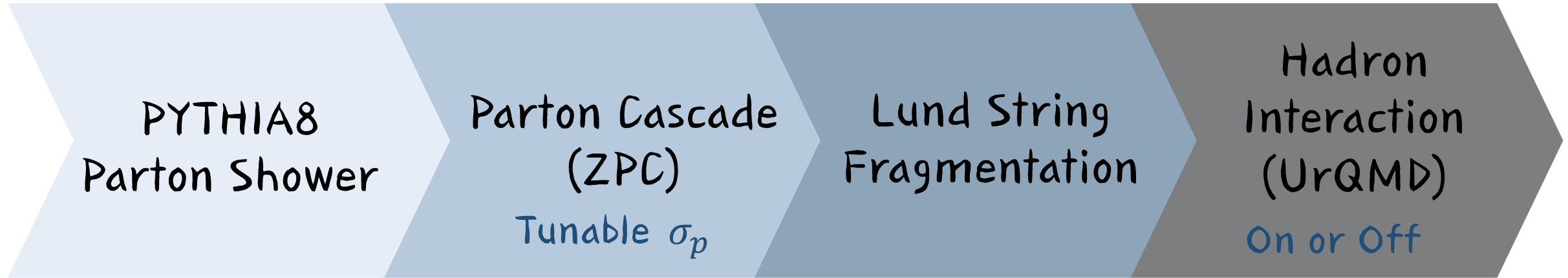


Xiao Huang (RICE), *in collaboration with Wenbin Zhao, Zi-Wei Lin and Xin-Nian Wang.*

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

W. Zhao et. al., arXiv:2401.13137



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.

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Parton shower

Formation time: accumulated from the full PYTHIA splitting history.

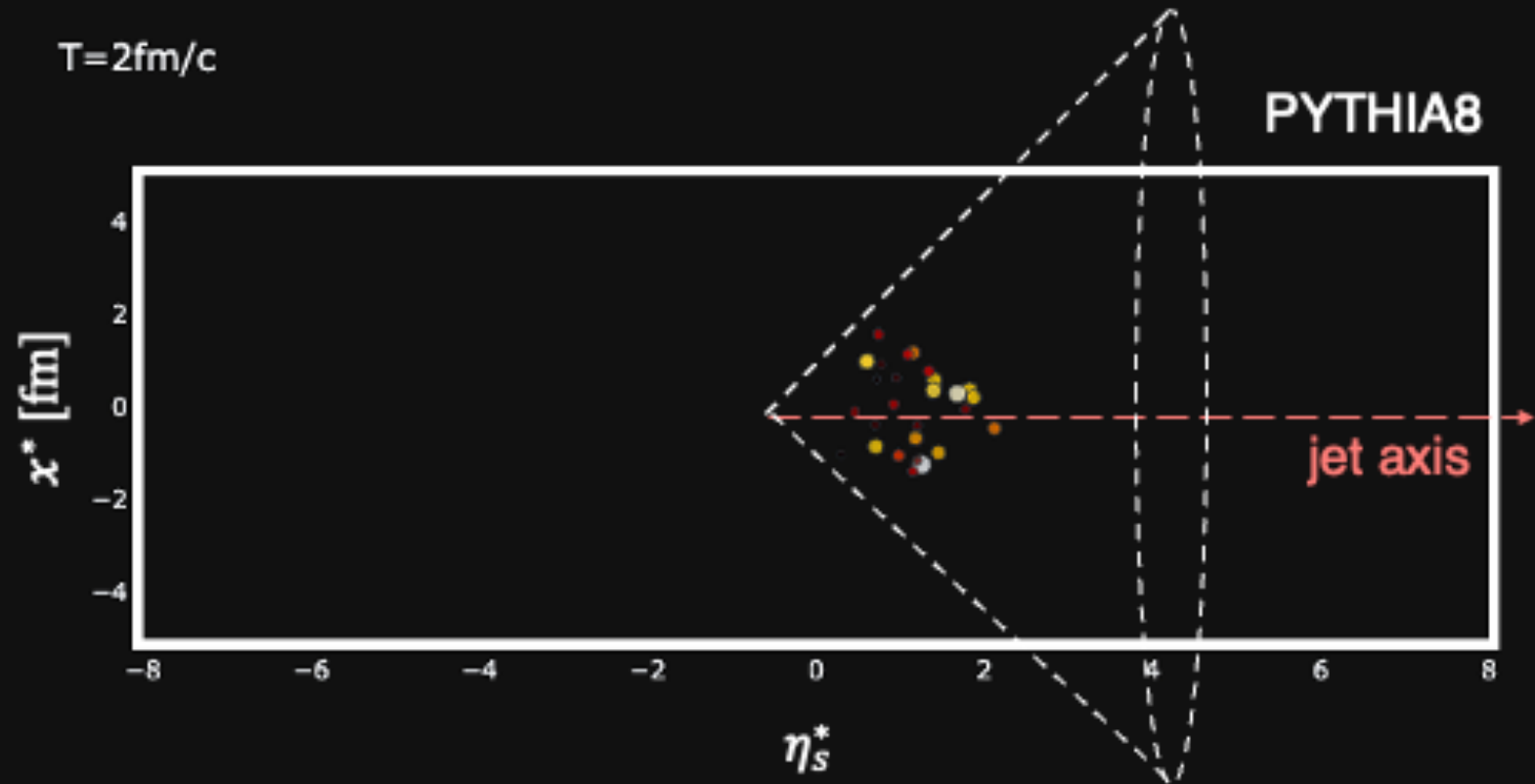
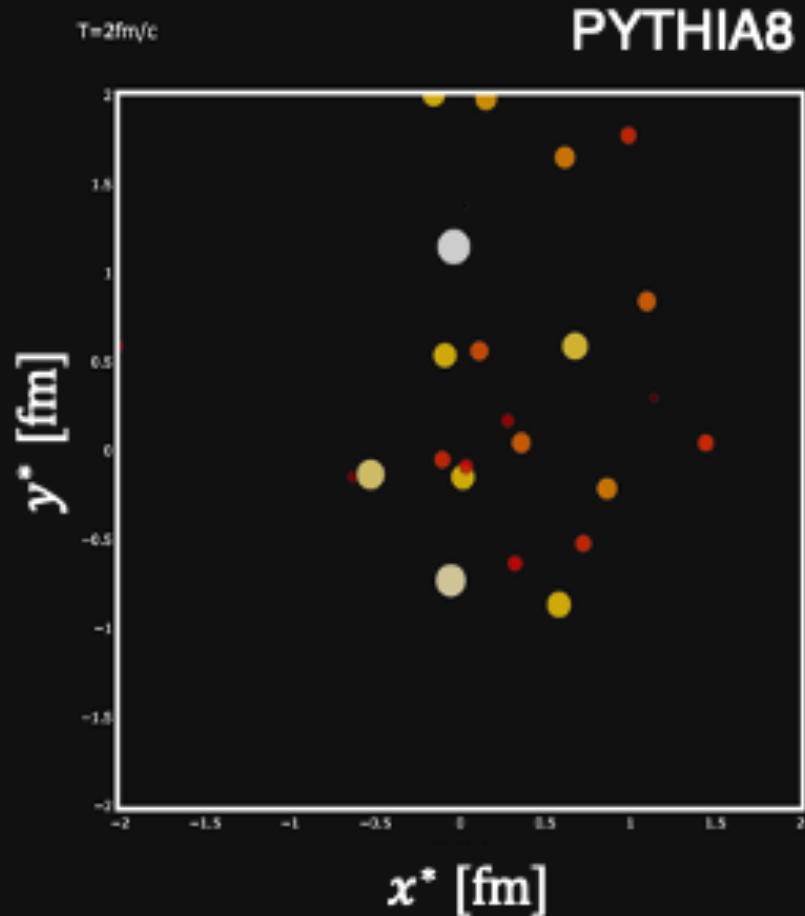
$$\Delta t_i = \begin{cases} \frac{2E_i x_i (1 - x_i)}{k_{T,i}^2}, & x_i < 0.5 \\ \frac{1}{E_i}, & x_i \geq 0.5 \end{cases}$$

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.

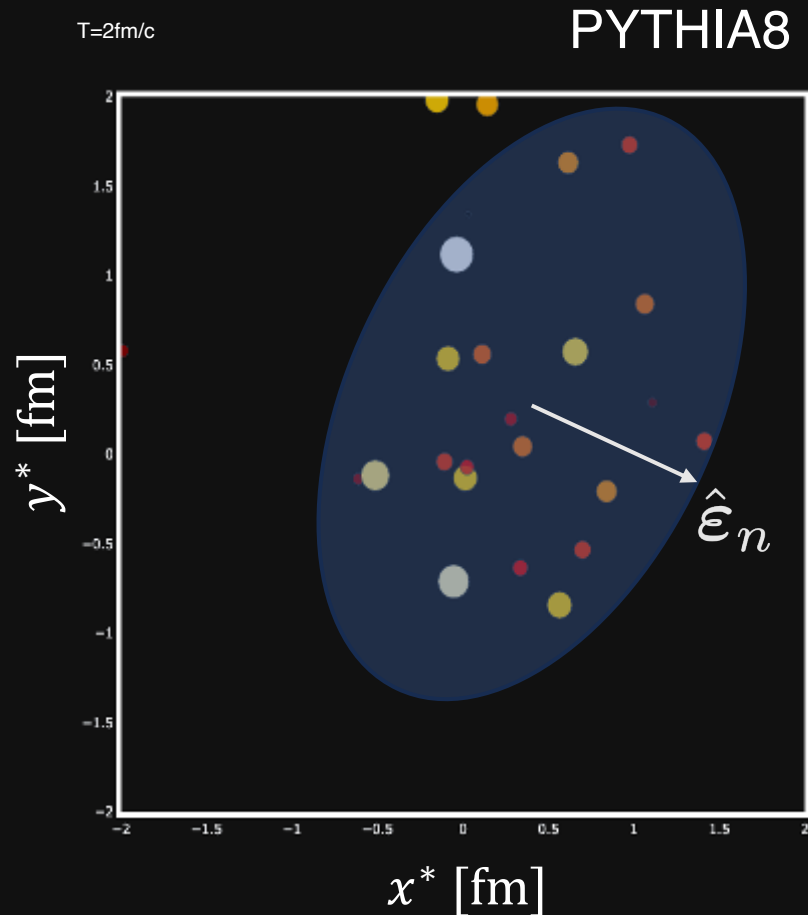
Initial stage of a jet

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



Gif made by Feng Liu (SBU/BNL)

Initial transverse geometry

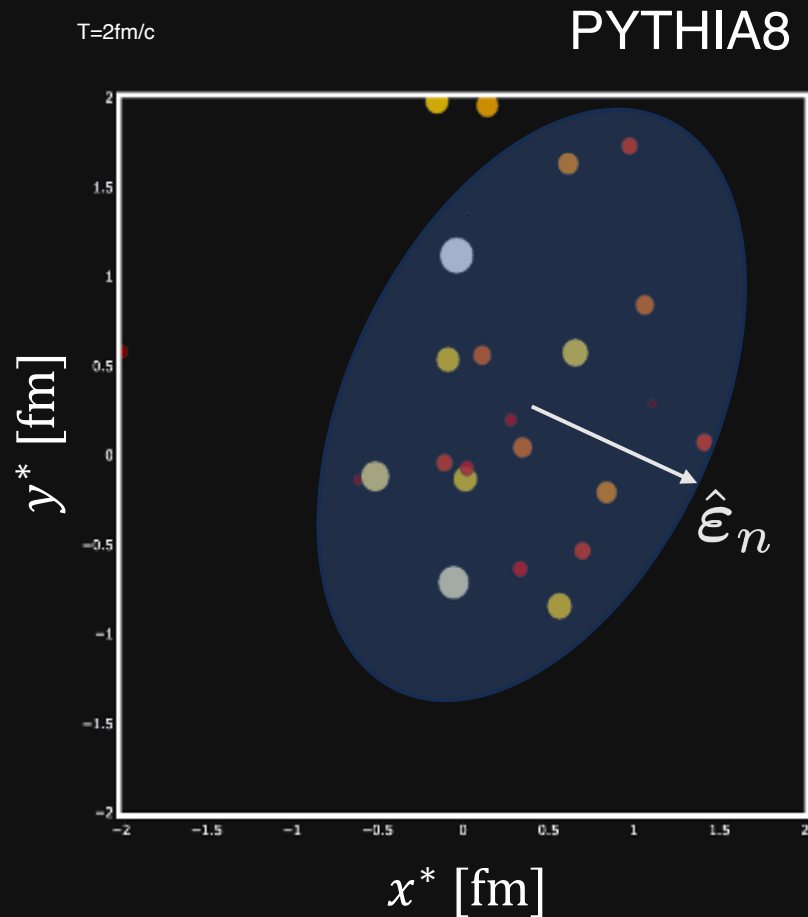


$$\phi_j^{*,\text{coord}} = \arctan \left(\frac{y_j^* - \langle y^* \rangle_p}{x_j^* - \langle x^* \rangle_p} \right) + \frac{\pi}{2}$$

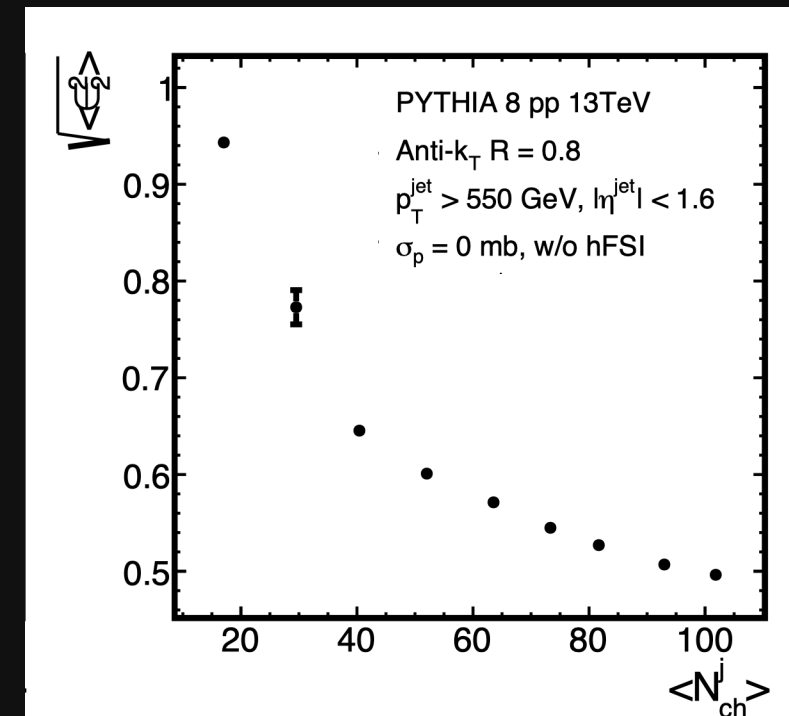
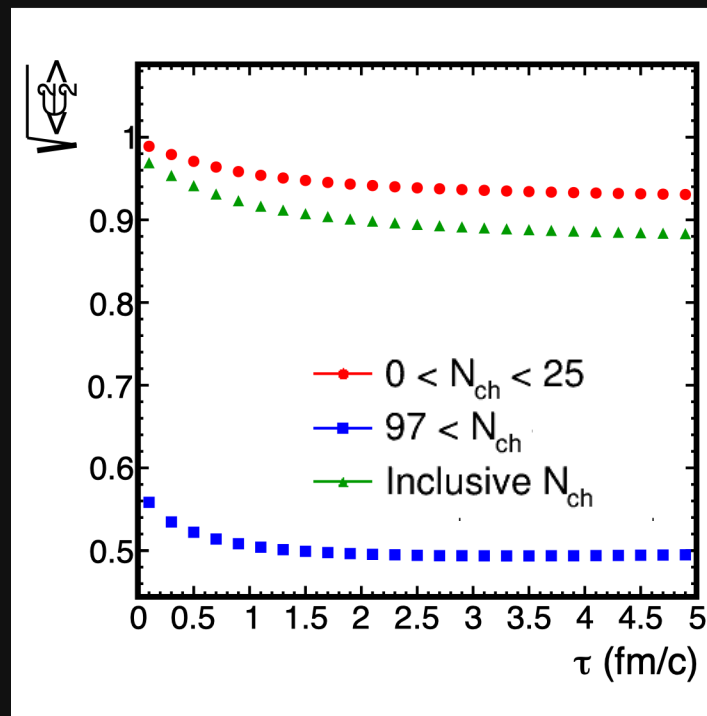
$$\epsilon_n = \epsilon_n e^{in\Phi_n} \equiv \frac{\sum_j w_j e^{in\phi_j^{*,\text{coord}}}}{\sum_j w_j}$$

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

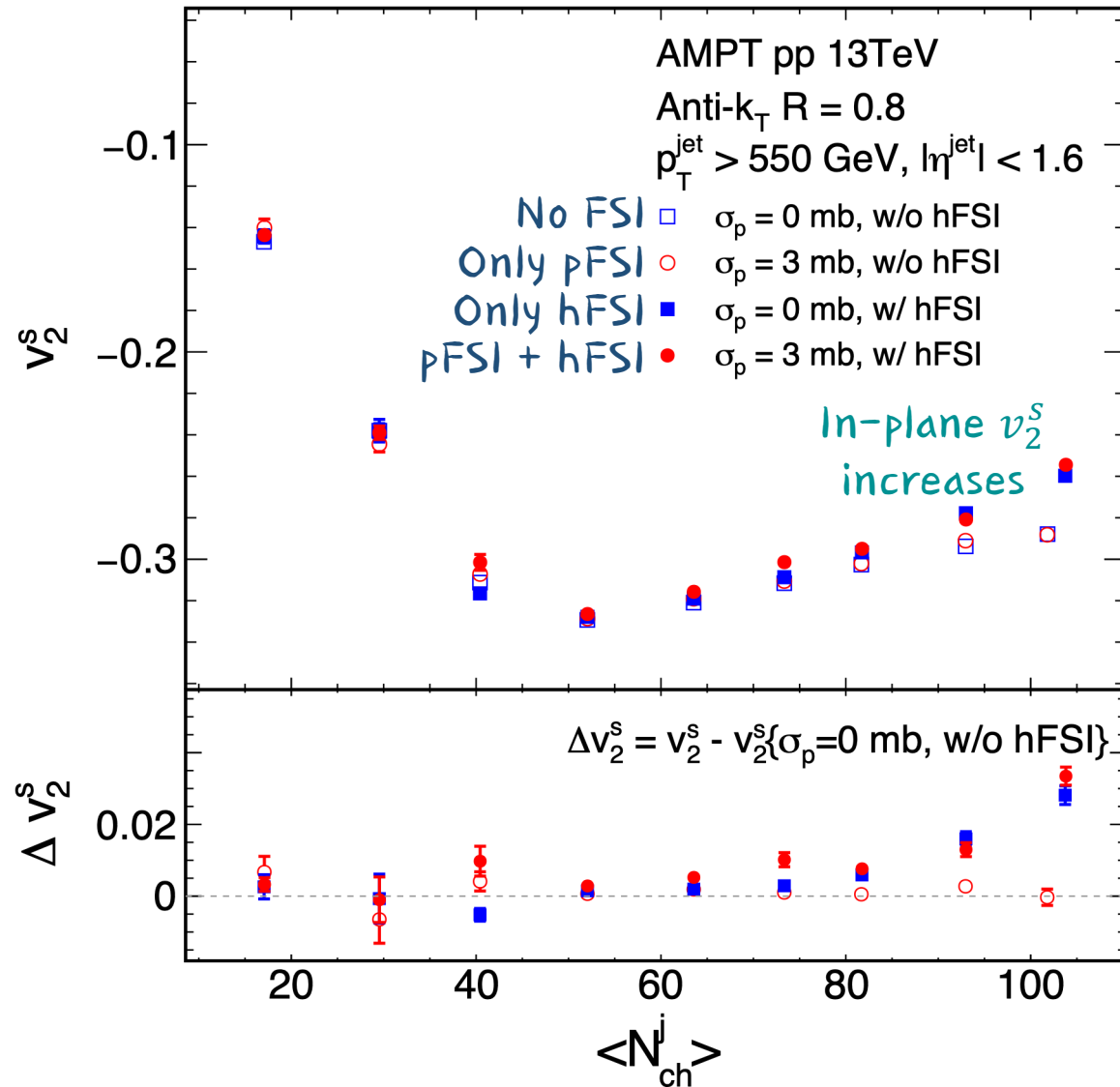
Initial transverse geometry



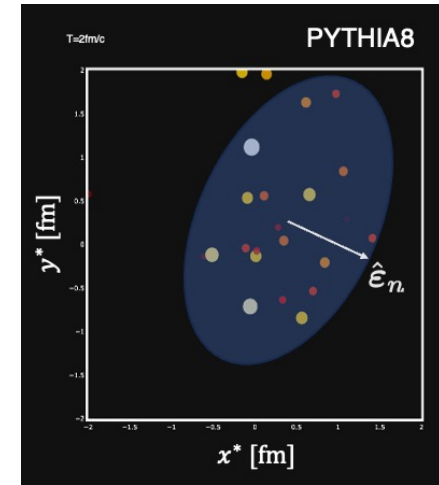
Sizable initial-state eccentricity



Elliptic flow w.r.t “participant plane”



$$v_n^s \equiv \frac{\langle Q_n \epsilon_n^* \rangle}{\sqrt{\langle \epsilon_n \epsilon_n^* \rangle}}$$

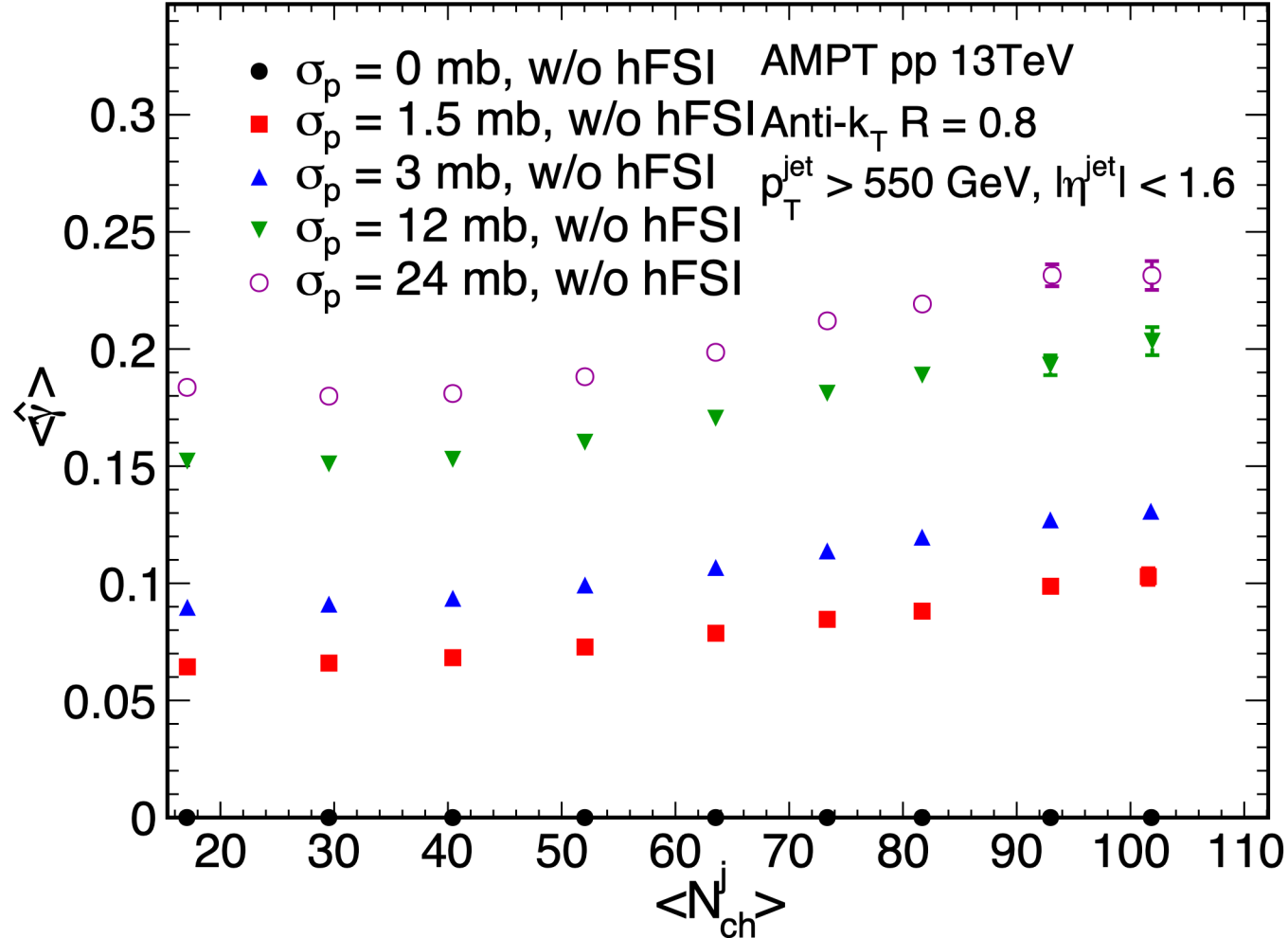


$$Q_n \equiv Q_n e^{in\Psi_n} = \frac{1}{N} \sum_{j=1}^N e^{in\phi_j^*}$$

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

pFSI alone shows no significant effect.

Why is pFSI effect small?



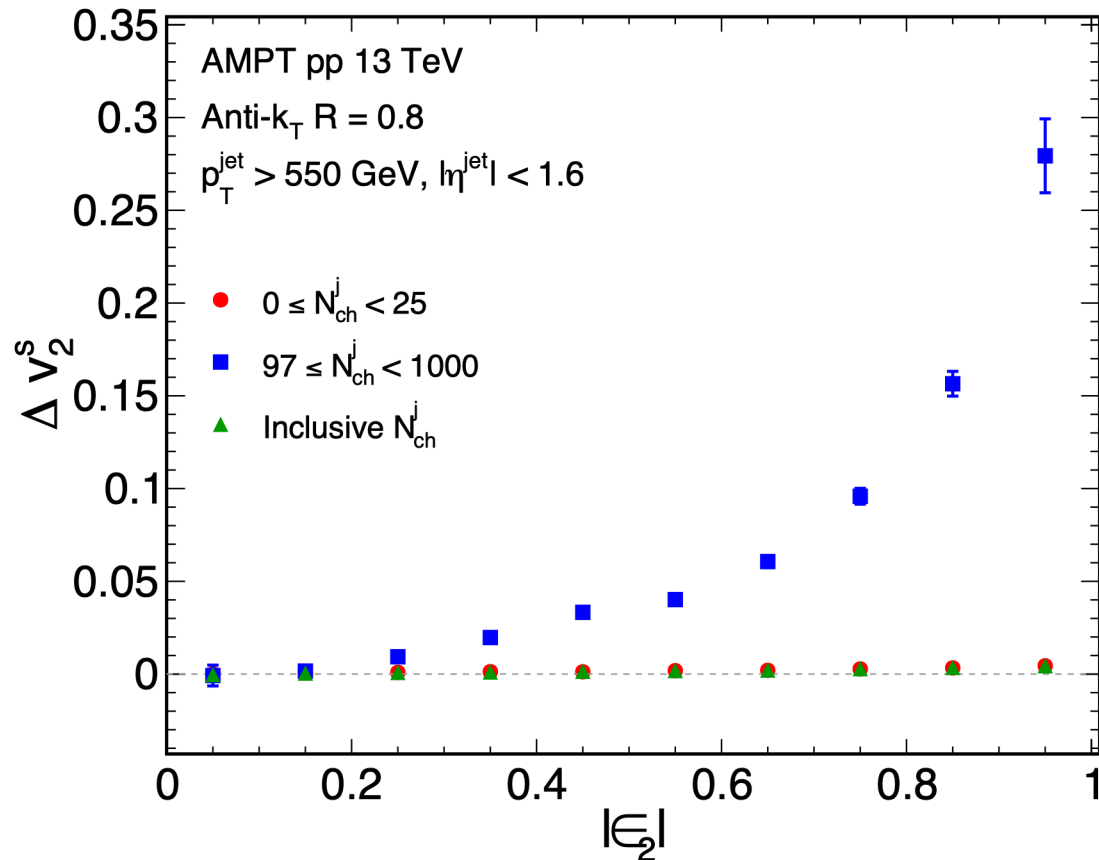
Small partonic opacity?

Forward rescattering angles in ZPC?

More studies underway:

- increase partonic opacity
- isotropic rescattering angles

Flow response to initial geometry

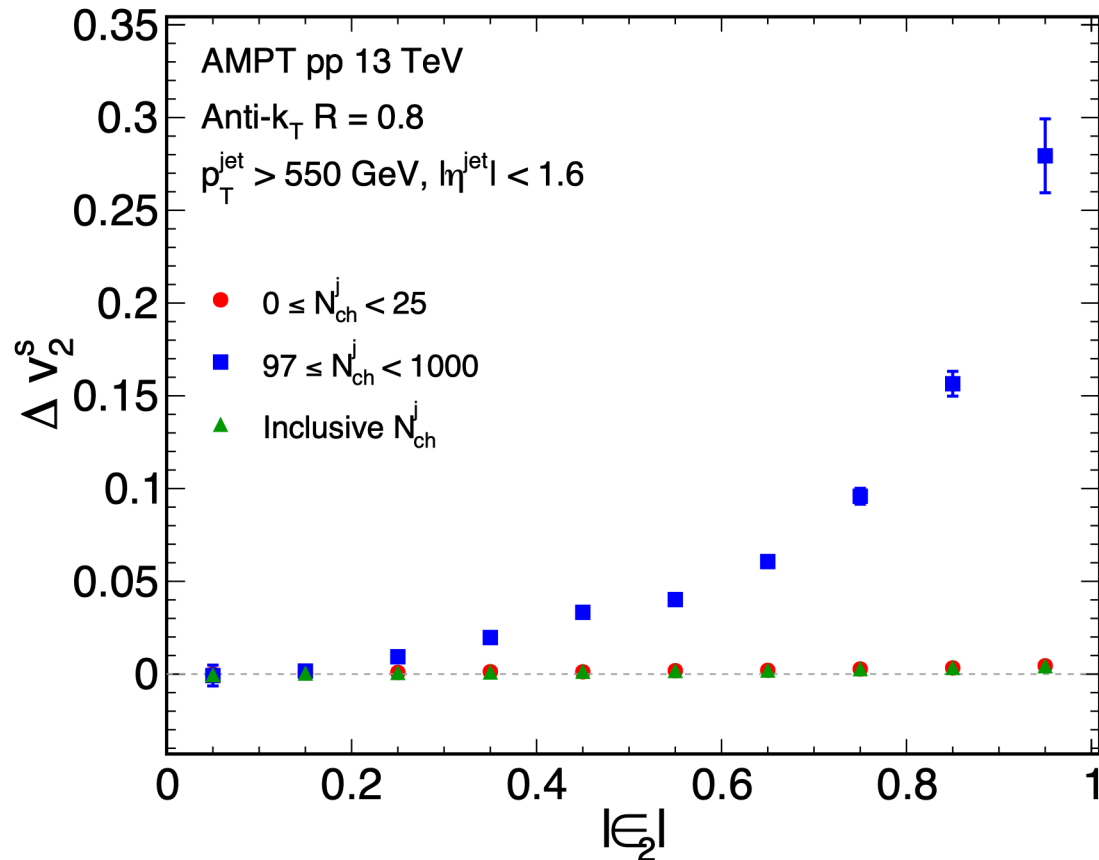


$$\Delta v_2^s = v_2^s (\text{FSI}) - v_2^s (\text{No FSI})$$

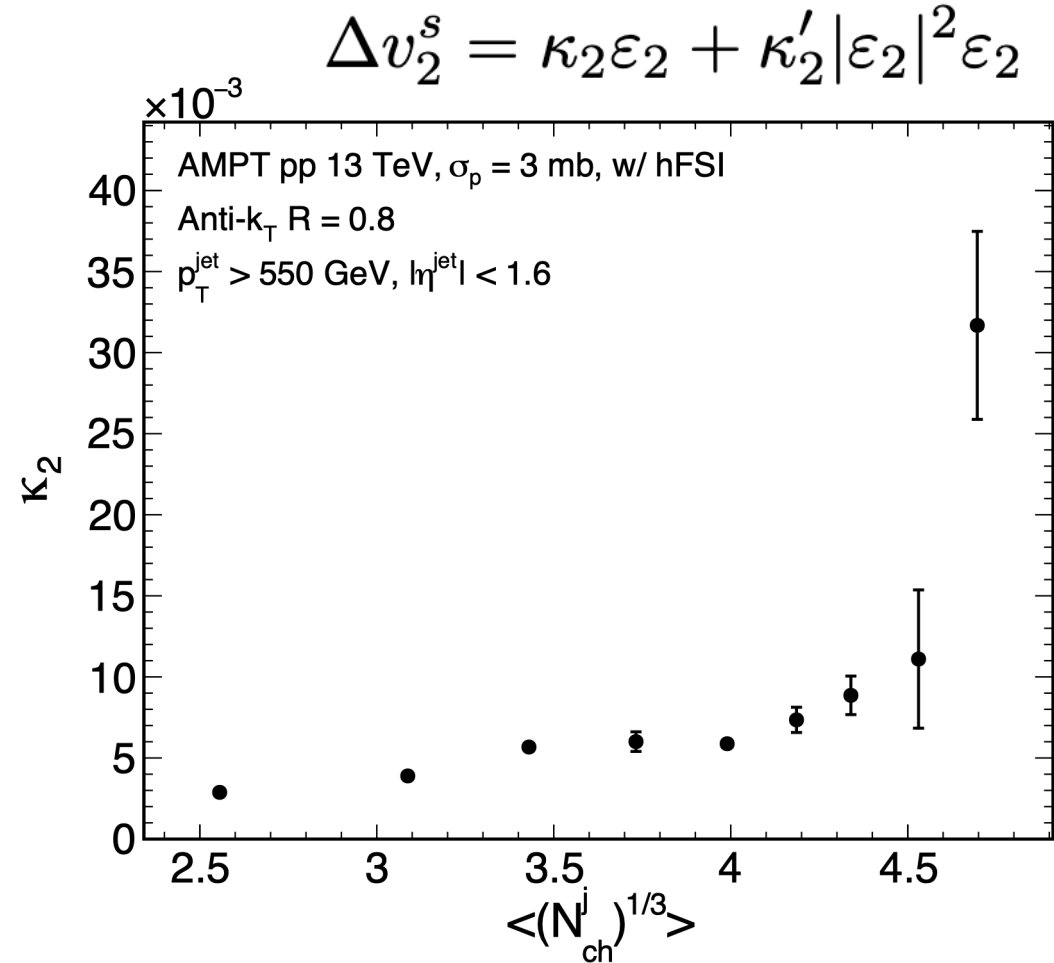
Non-zero Δv_2^s only for **high- N_{ch}^j** jets

Δv_2^s is sensitive to the
initial geometry

Flow response to initial geometry

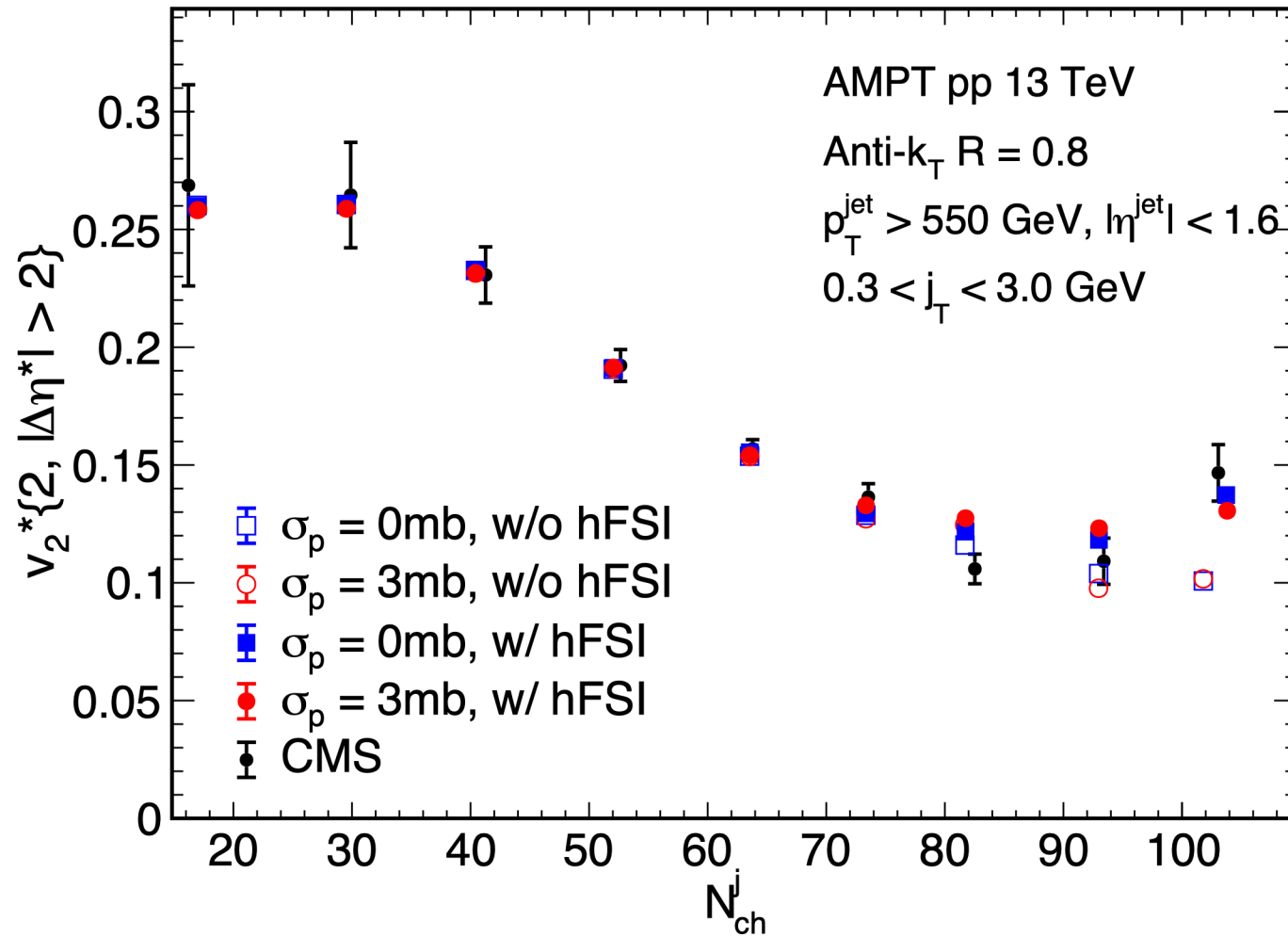


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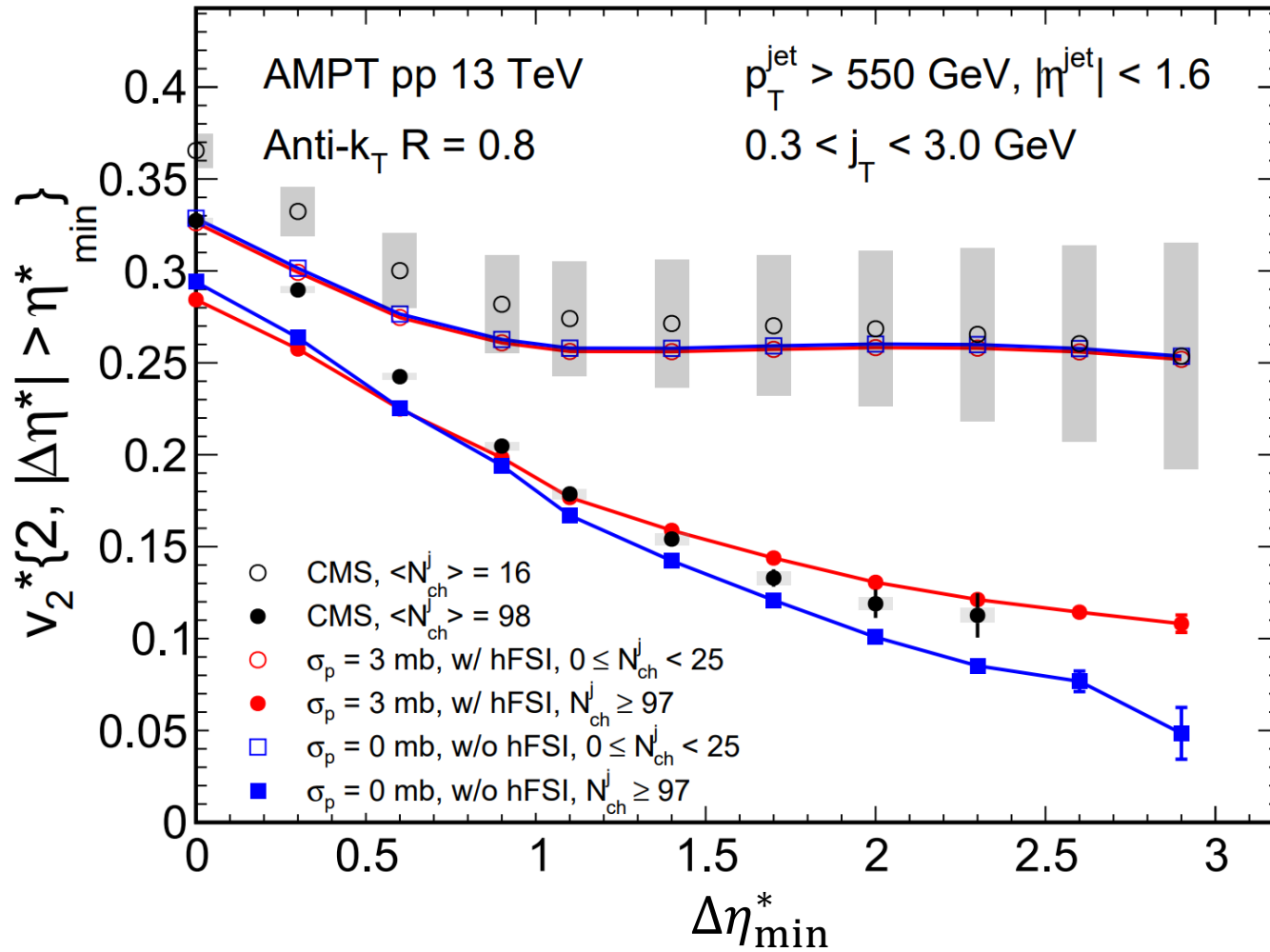
Flow response increases with opacity

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

CMS

138 fb⁻¹ (pp 13 TeV)

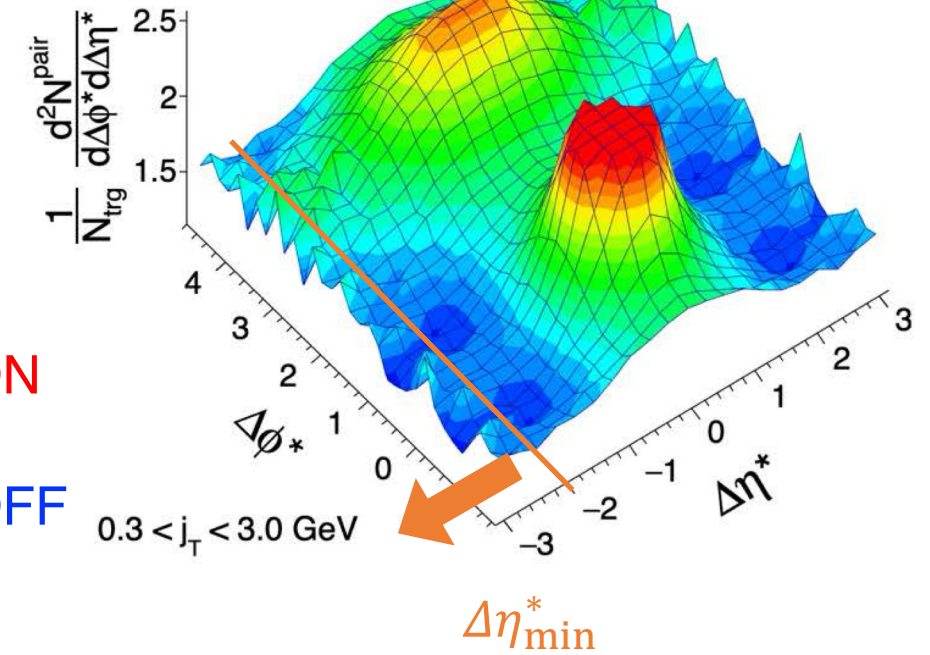
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Top 0.0023% highest- N_{ch}^j jets

Anti k_T R=0.8

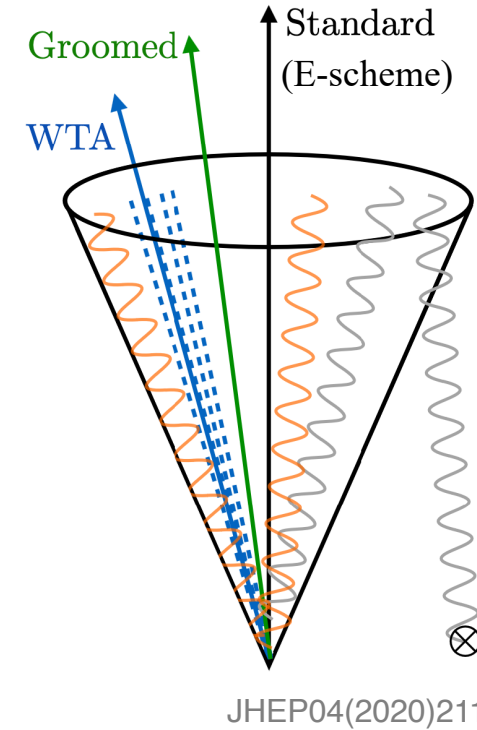
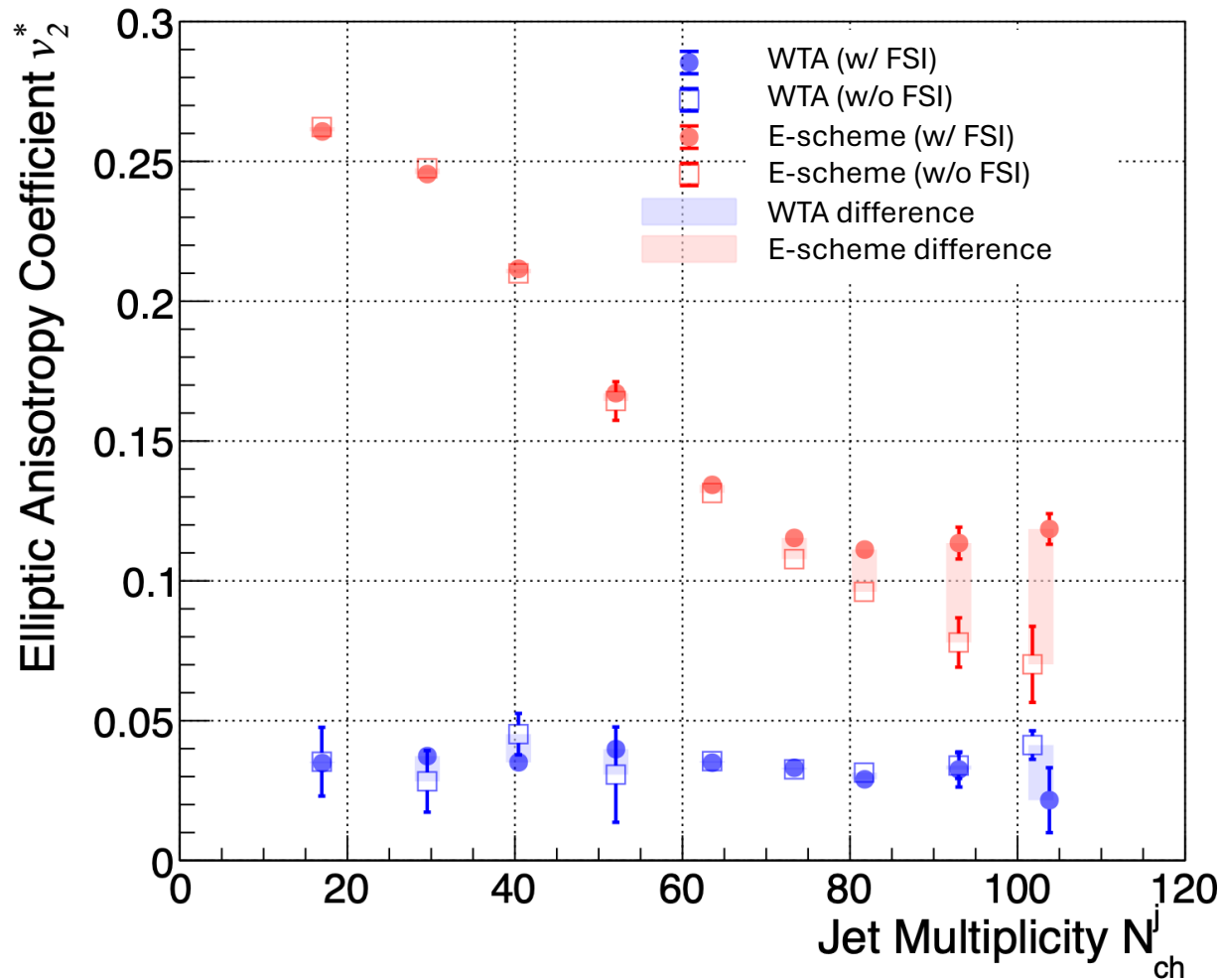
$p_T^{\text{jet}} > 550$

$|\eta^{\text{jet}}| < 1.6$



Winner-take-all (WTA) axis

Model study done by Rohan Jagadeesa (RICE)

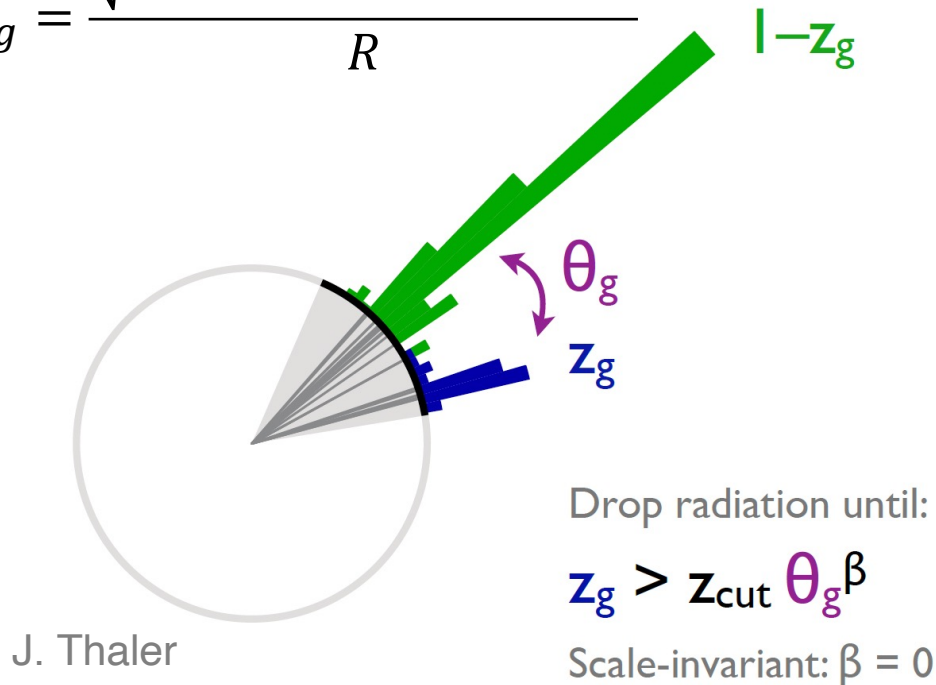


WTA mitigates nonflow from the momentum conservation effect but also suppresses the signal of interest.

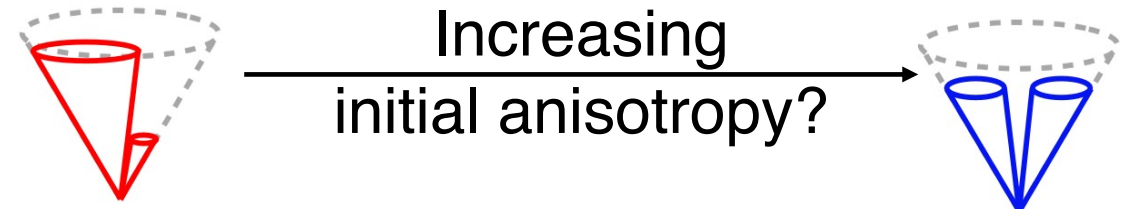
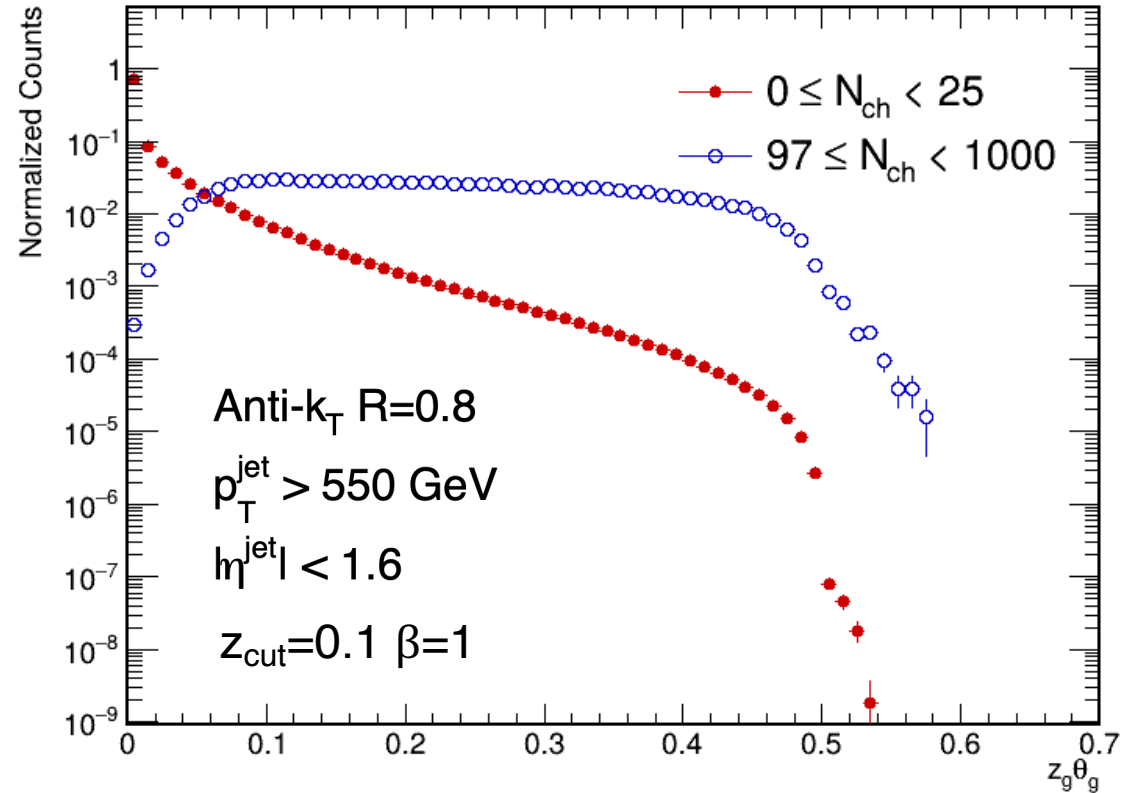
Effect of initial geometry – jet shape engineering

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

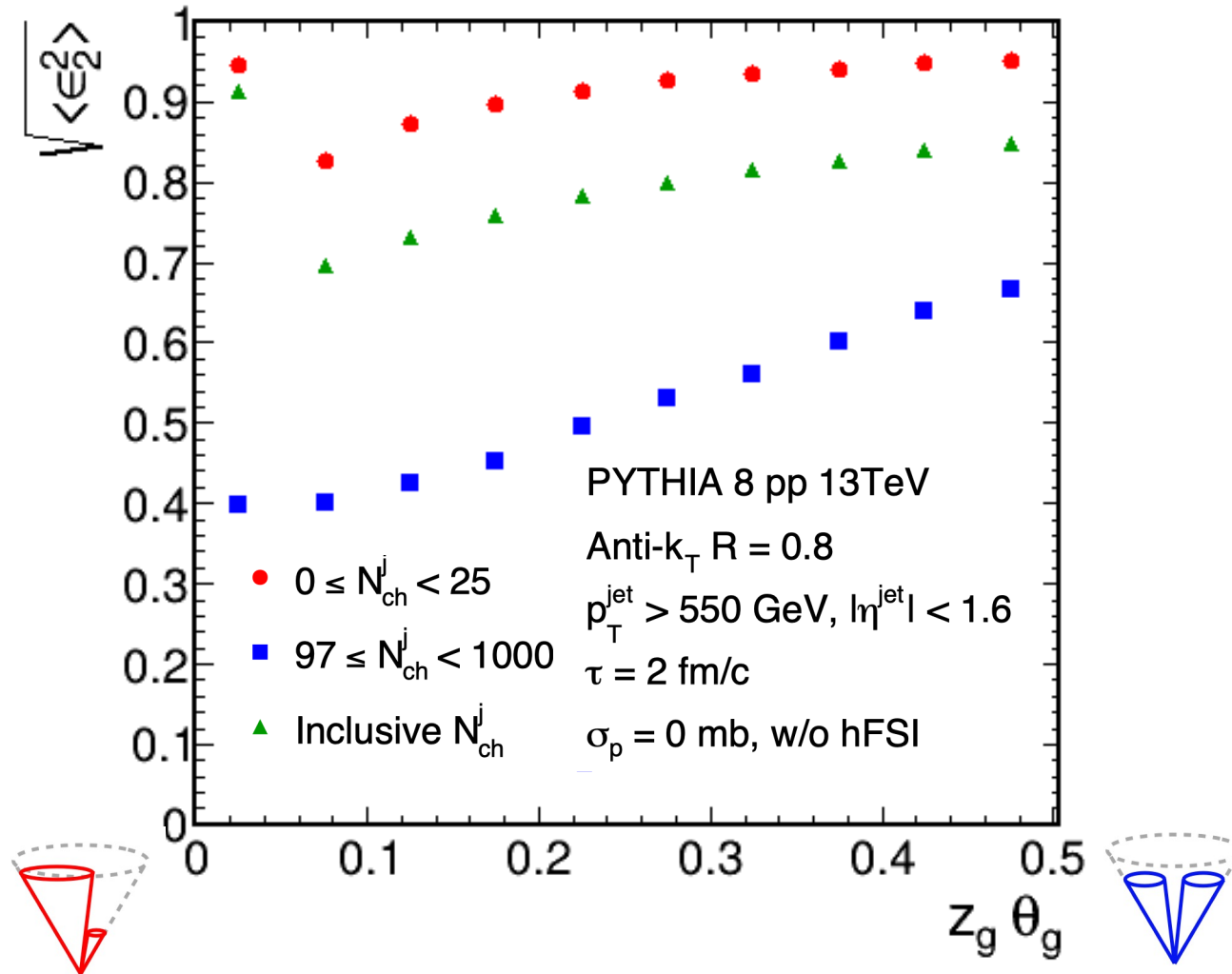
$$\theta_g = \frac{\sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}}{R}$$



PYTHIA 8 pp 13 TeV

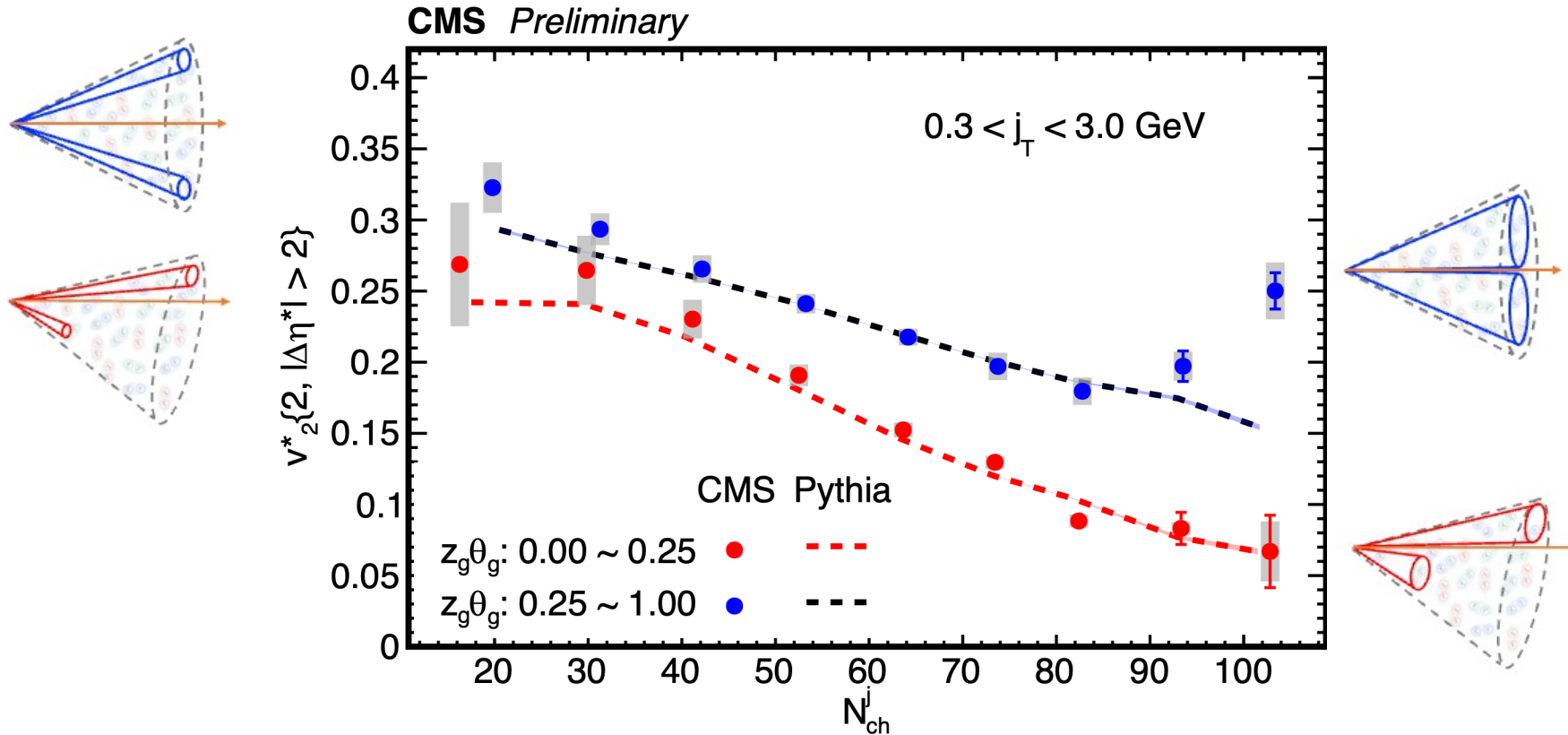


Jet substructure vs. eccentricity



Engineering the substructure does vary the “initial jet geometry”.

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



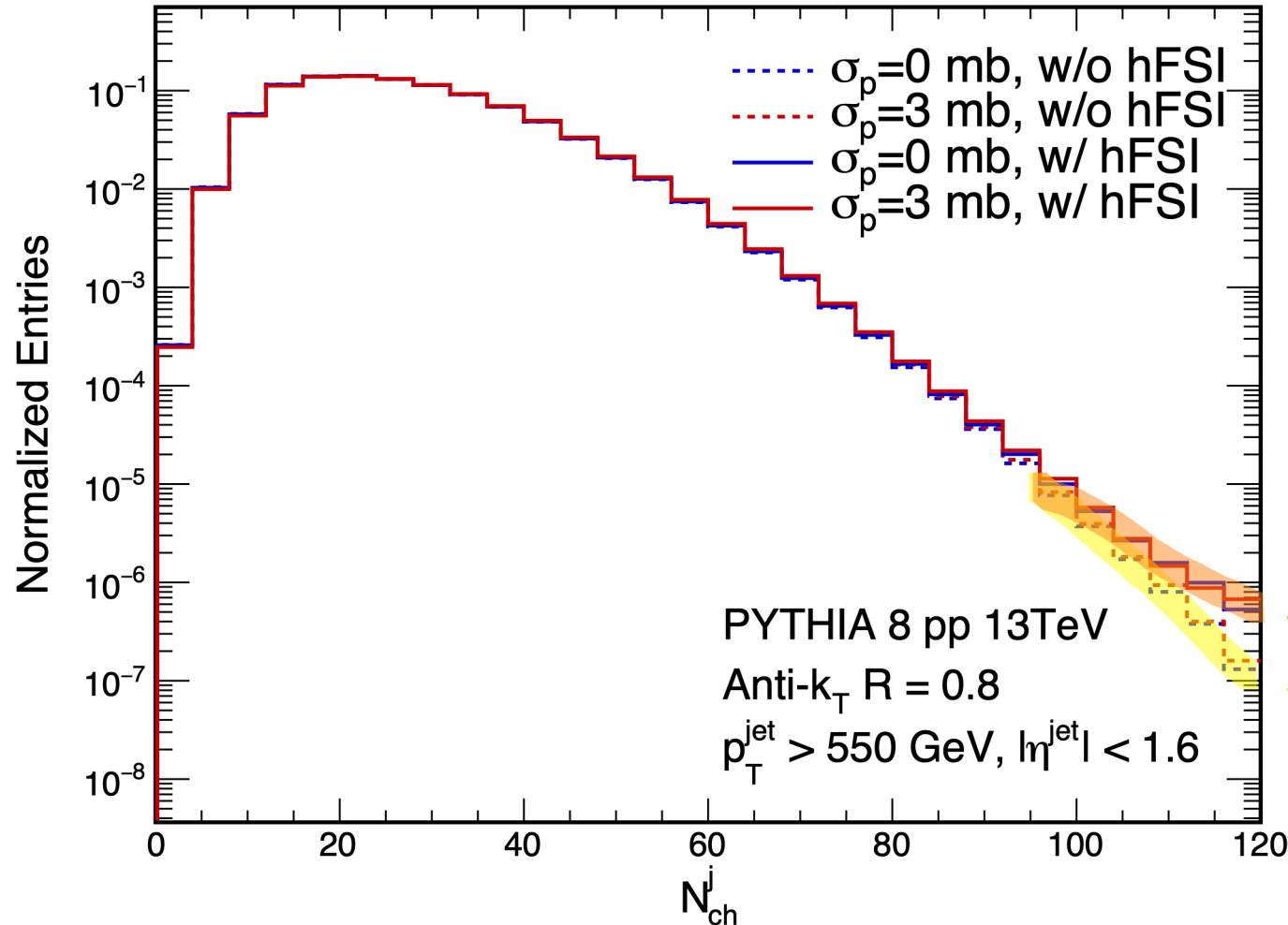
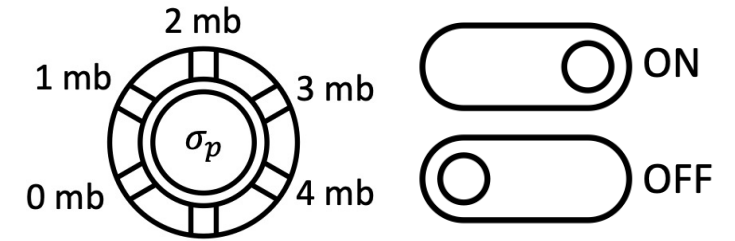
Enhancement of v_2^* relative to MC mainly for two-prone jets.

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

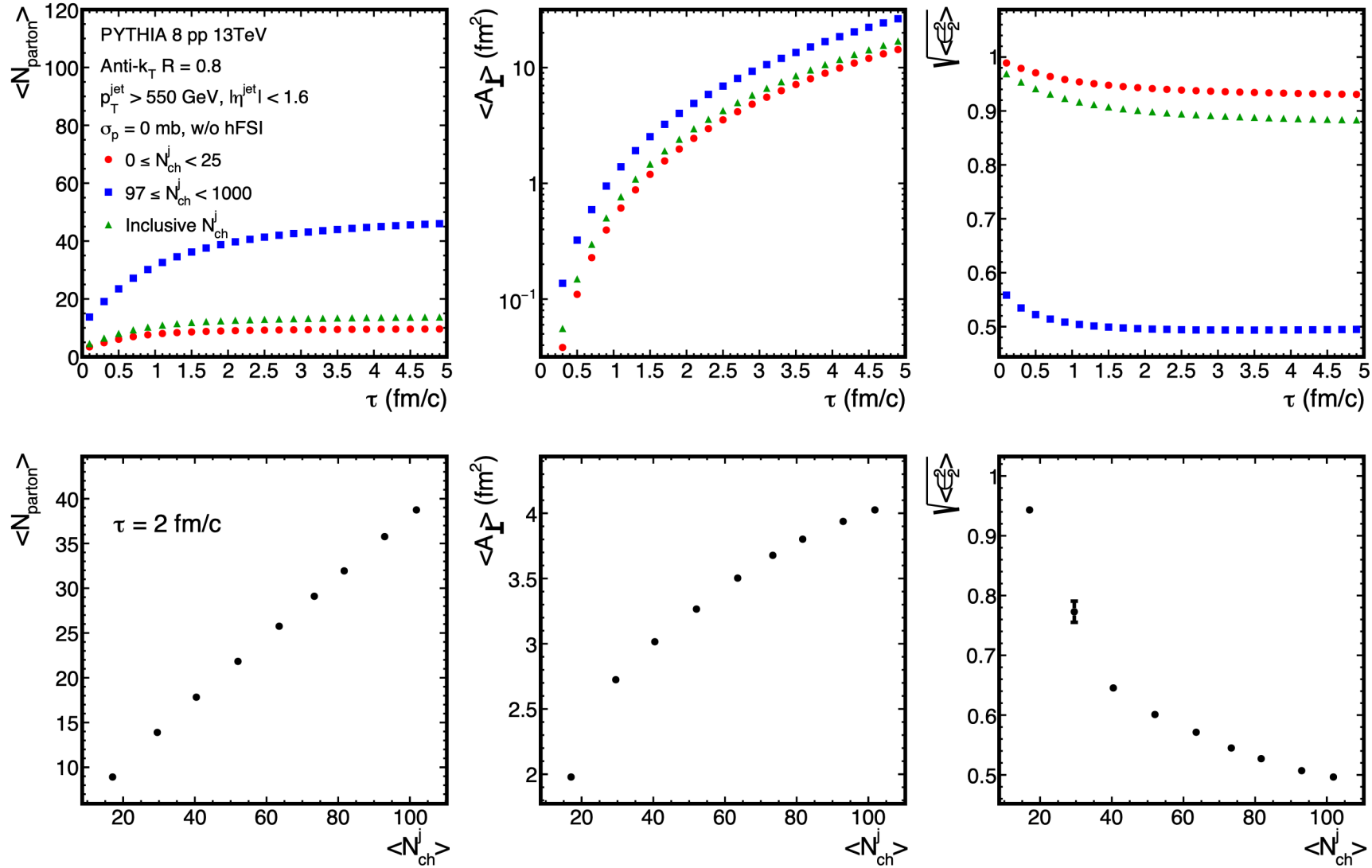
Jet charged multiplicity



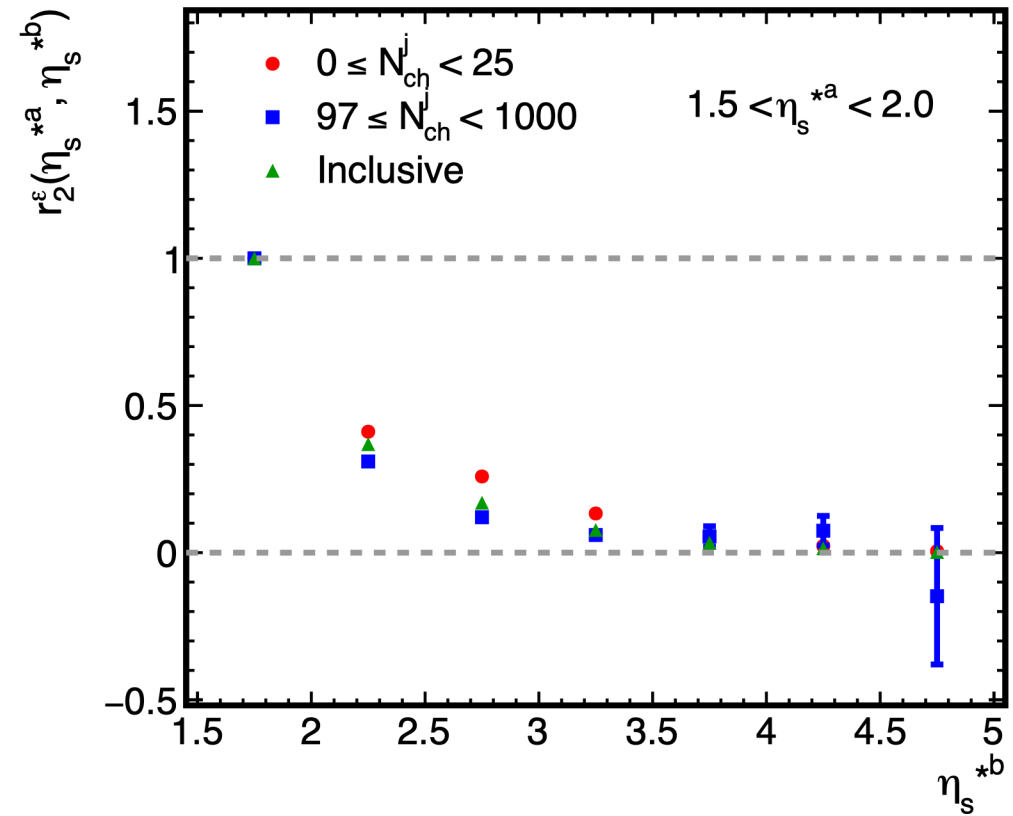
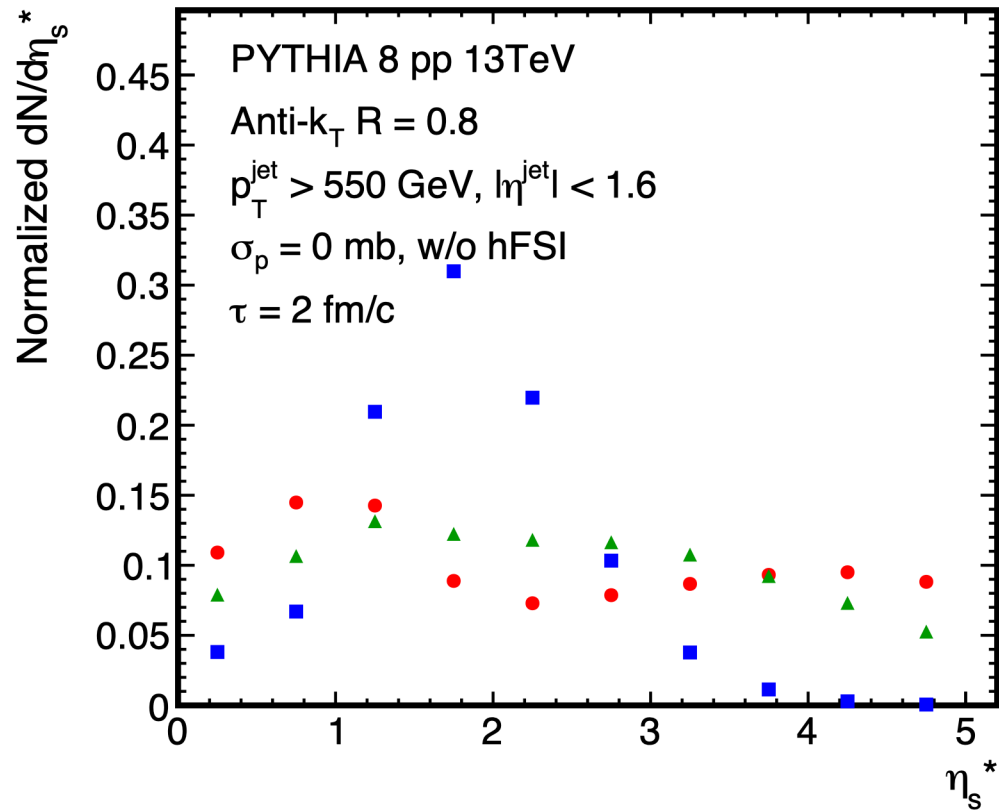
Hadronic rescatterings
broaden the N_{ch}^j distribution.

w/ hadronic FSI
w/o hadronic
FSI

Initial transverse geometry



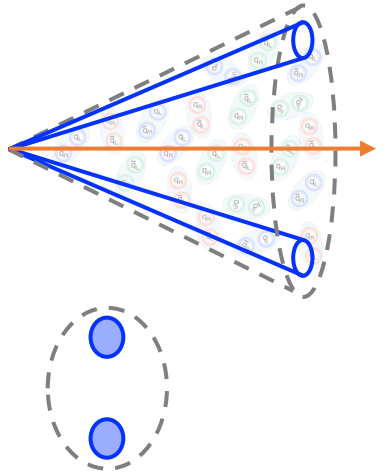
Initial longitudinal structure



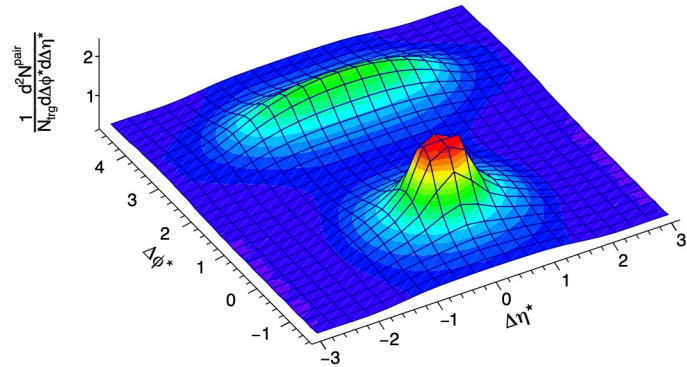
$$r_n^\epsilon(\eta_s^{*a}, \eta_s^{*b}) \equiv \frac{\langle \epsilon_n(\eta_s^{*a}) \epsilon_n^*(\eta_s^{*b}) \rangle}{\sqrt{\langle \epsilon_n(\eta_s^{*a}) \epsilon_n^*(\eta_s^{*a}) \rangle} \sqrt{\langle \epsilon_n(\eta_s^{*b}) \epsilon_n^*(\eta_s^{*b}) \rangle}}$$

Strong decorrelation across η_s

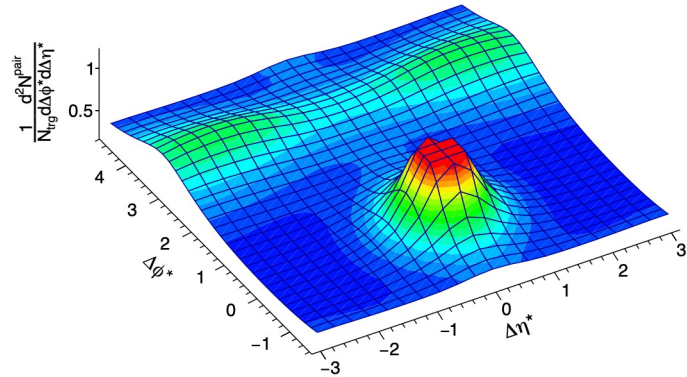
2D correlation within jets



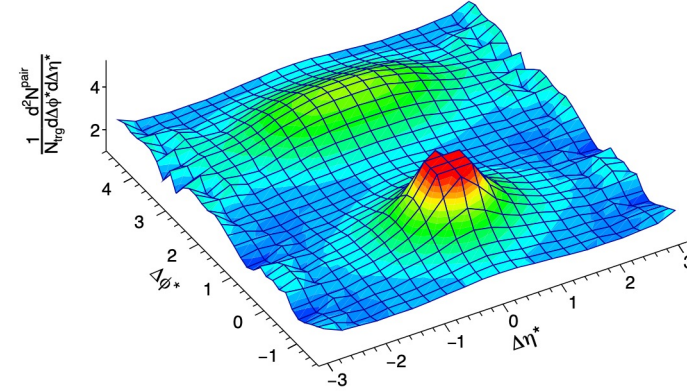
CMS Preliminary 138 fb⁻¹ (pp 13 TeV)
 $\langle N_{ch} \rangle = 31$
 $0.25 < z_g \theta_g < 1.00$ $0.3 < j_T < 3.0$ GeV



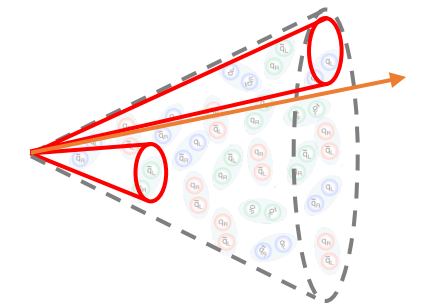
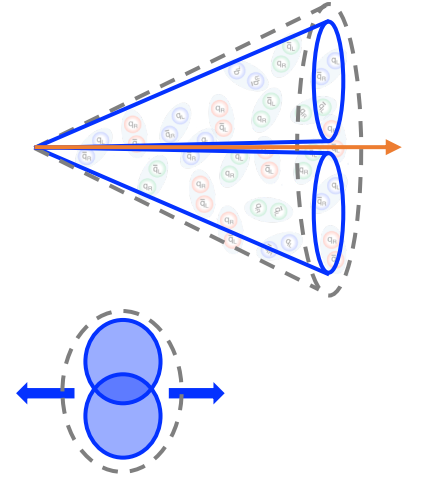
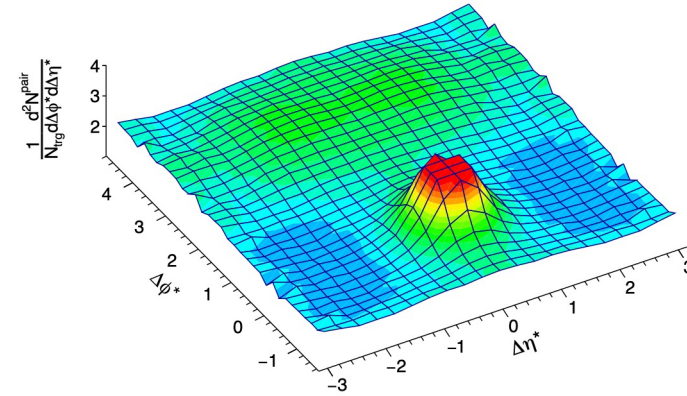
CMS Preliminary 138 fb⁻¹ (pp 13 TeV)
 $\langle N_{ch} \rangle = 29$
 $0.00 < z_g \theta_g < 0.25$ $0.3 < j_T < 3.0$ GeV



CMS Preliminary 138 fb⁻¹ (pp 13 TeV)
 $\langle N_{ch} \rangle = 93$
 $0.25 < z_g \theta_g < 1.00$ $0.3 < j_T < 3.0$ GeV

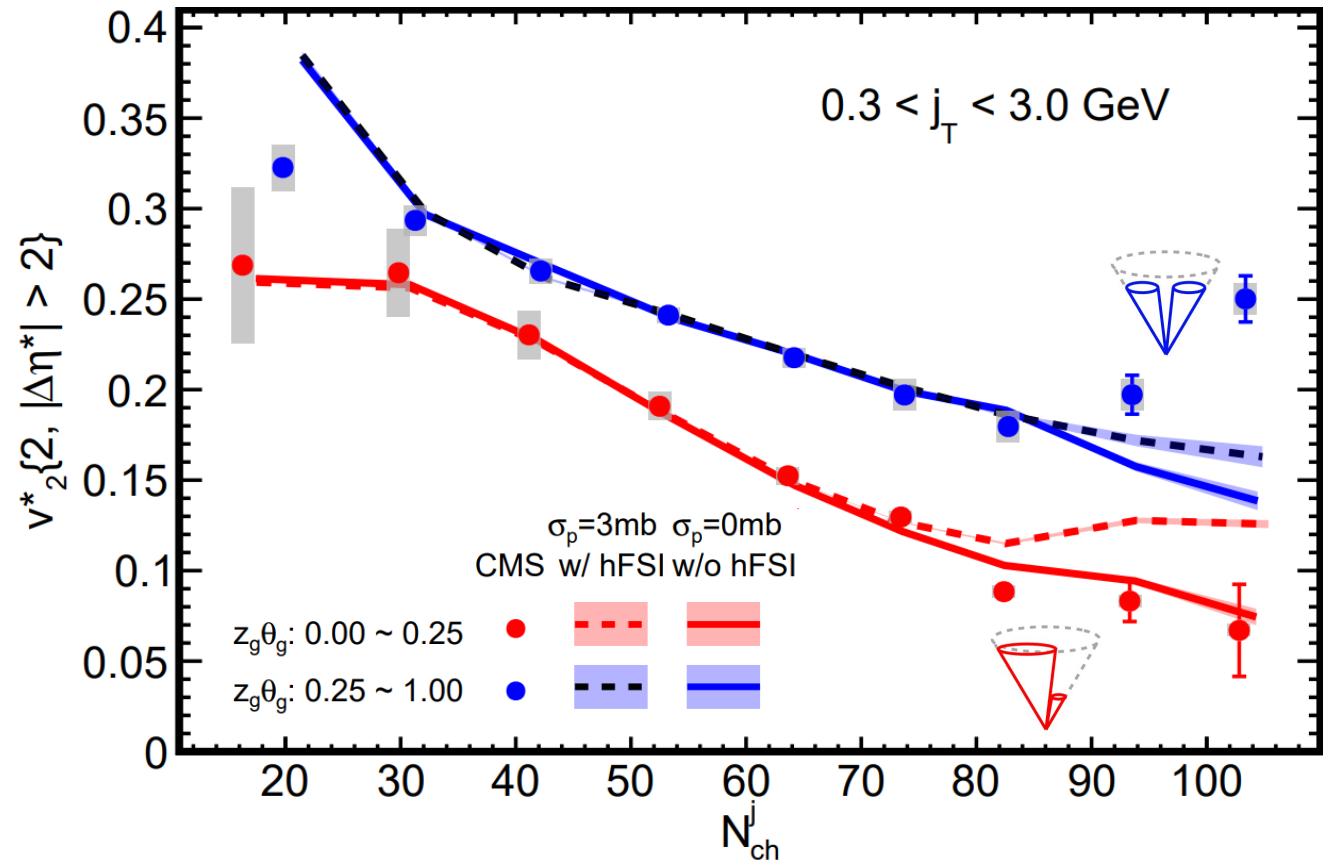
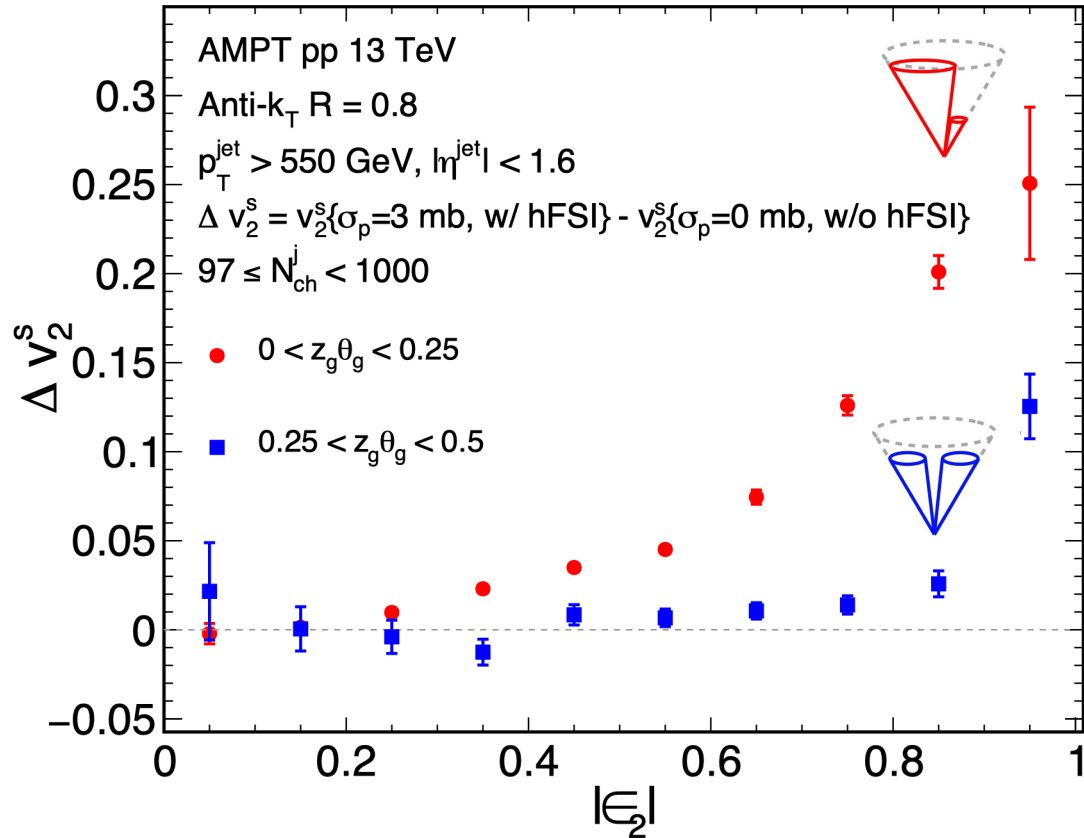


CMS Preliminary 138 fb⁻¹ (pp 13 TeV)
 $\langle N_{ch} \rangle = 93$
 $0.00 < z_g \theta_g < 0.25$ $0.3 < j_T < 3.0$ GeV



Jet substructure – model study

High-multiplicity jets



Larger v_2 enhancement for one prong jet?

Longitudinal Invariant Coordinate

Suggested by Alba and Gavin: [presentation](#) at the small system workshop in Paris

Step 1 **alternative**: transformation based on longitudinally invariant coordinates

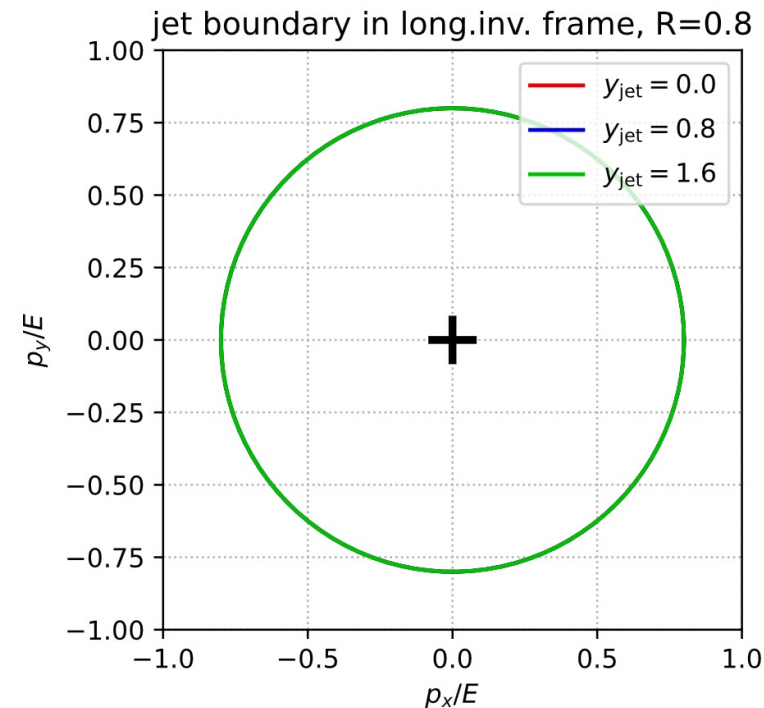
$$\theta_i^2 \equiv \Delta y_{i,\text{jet}}^2 + \Delta \phi_{i,\text{jet}}^2,$$

$$\eta_i^* = -\log \tan \frac{\theta_i}{2},$$

$$\phi_i^* = \tan^{-1} \frac{\Delta y_{i,\text{jet}}}{\Delta \phi_{i,\text{jet}}},$$

$$j_{ti} = p_{ti} \theta_i$$

long. inv. constituents:
use Δy and $\Delta \phi$ of particles wrt
jet axis



forward and central jets both circular
(no intrinsic v_2)