Search for collective behavior in very small and in large colliding systems

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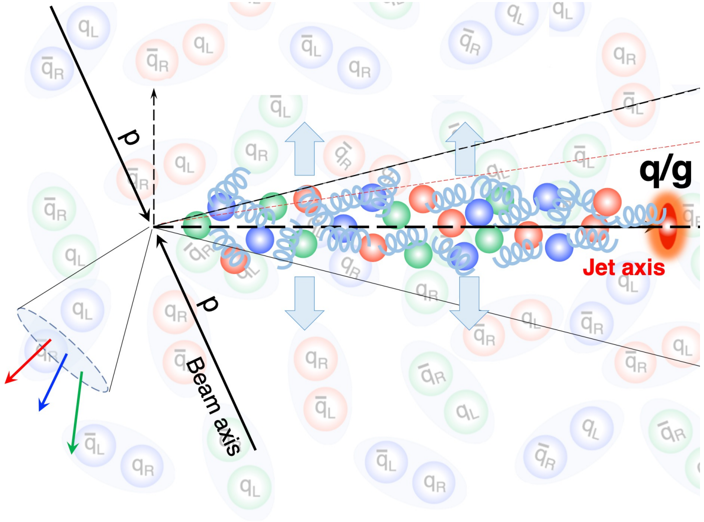
SPRACE - UNESP

Highlights (two complementary measurements)

Search for collectivity in very small system

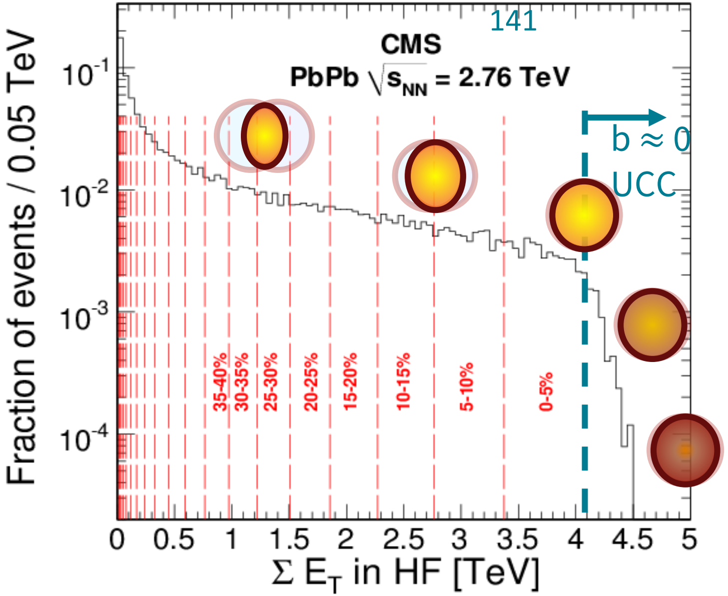
- pushing (ridge) correlation measurements to lowest possible system sizes



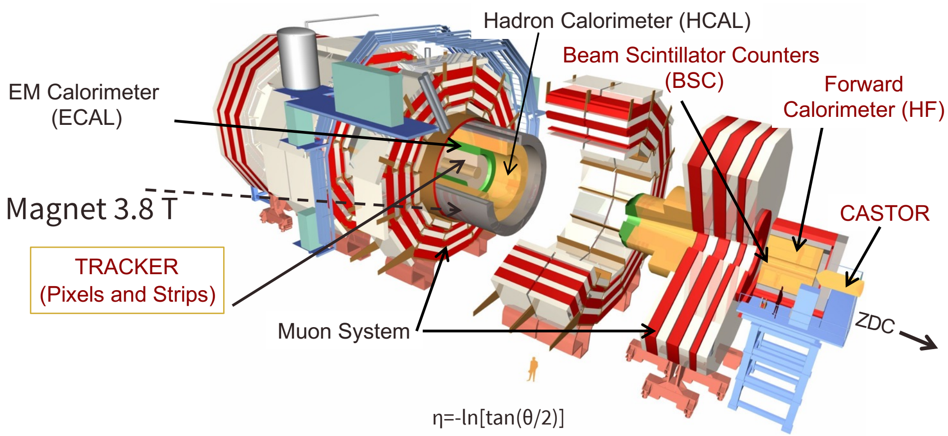
Measure of the thermodynamic properties of the QGP

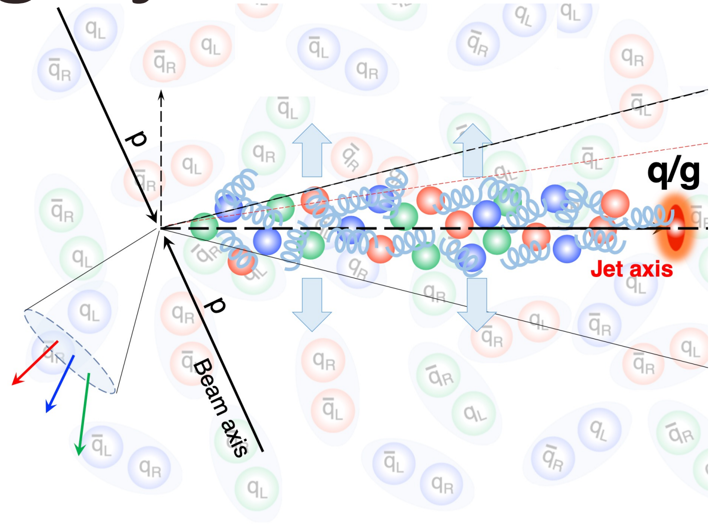
- in ultracentral PbPb collisions

JHEP **08** (2011) 141



Search for collectivity in single jets

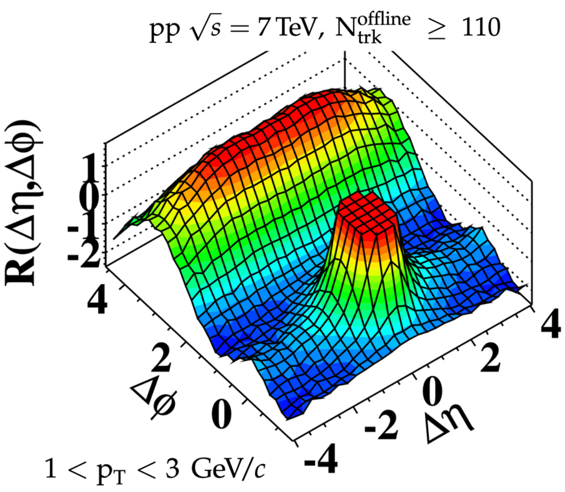




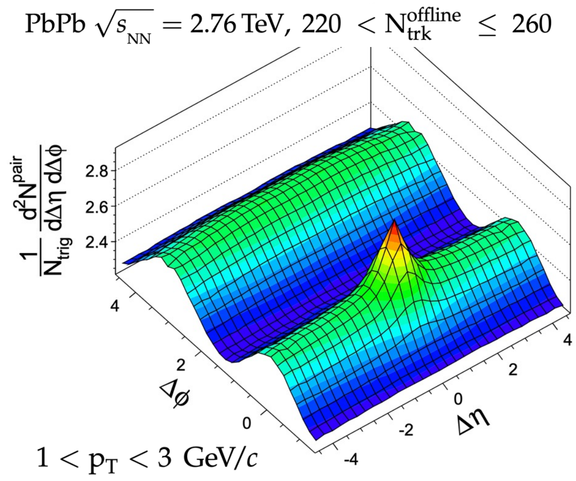
Surprises at the start of LHC era

Starting of LHC era brought intriguing surprises

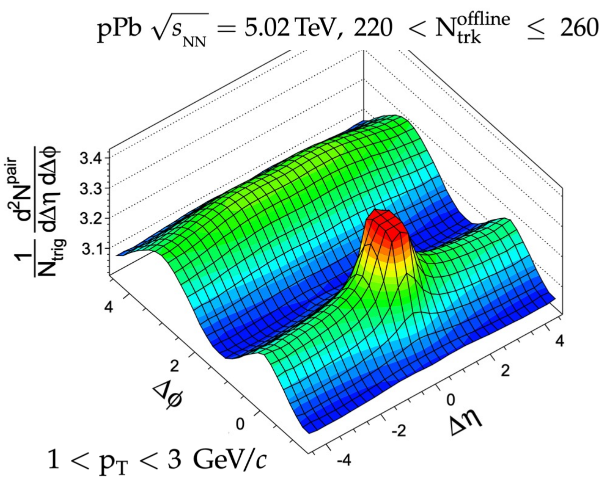
- ❑ Collectiviy in small systems?
  - ridge-like structure in pp
  - confirmed in PbPb
  - new surprise in pPb



JHEP **09** (2010) 091



Eur. Phys J C ***72*** (2012)

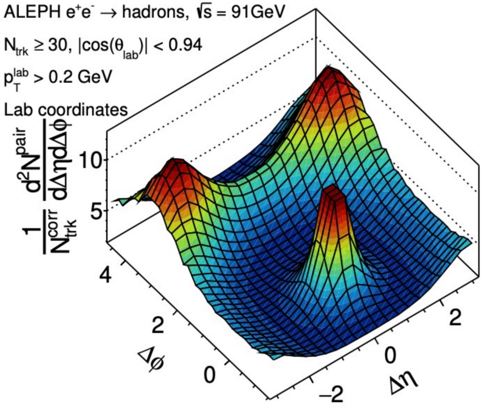


Phys.Lett.B 718 (2013)

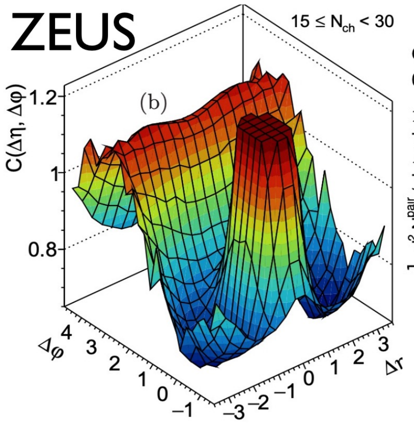
Is there a limit on the system size? And…

- From how small of a system can partonic collectivity emerge?
- True surprise or consequence of strongly coupled nature of QCD?
- Can hydrodynamics be generalized for non perturbative QCD processes?

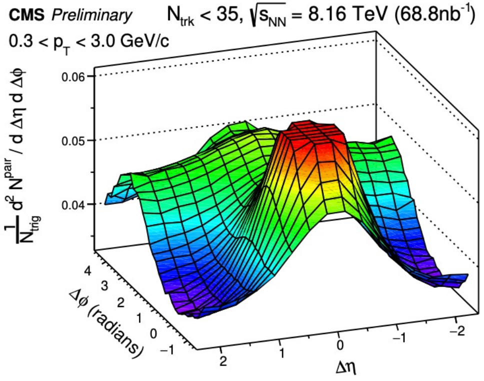
e^+e^- (~30) e^-p (~30) γp (~20) γPb (~40)



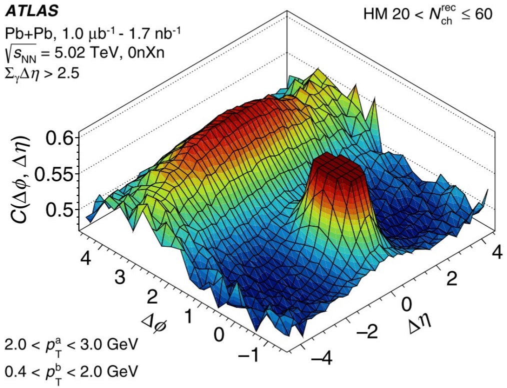
PRL 123, 212002 (2019)



JHEP 04 (2020) 070



arxiv: 2204.13486



PRC 104 014903 (2021)

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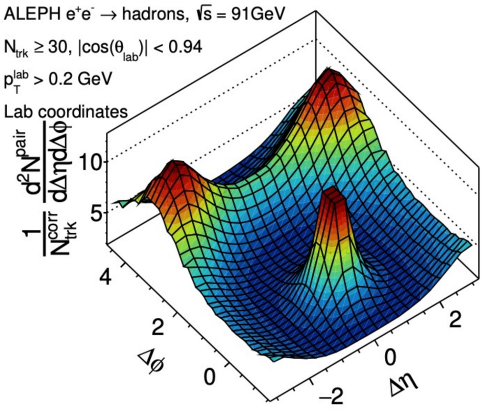

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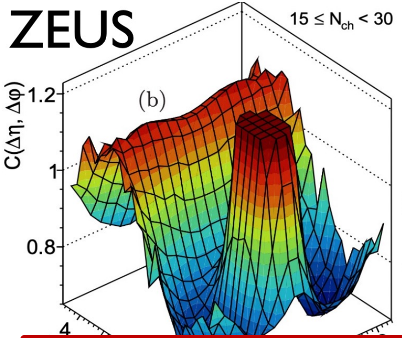

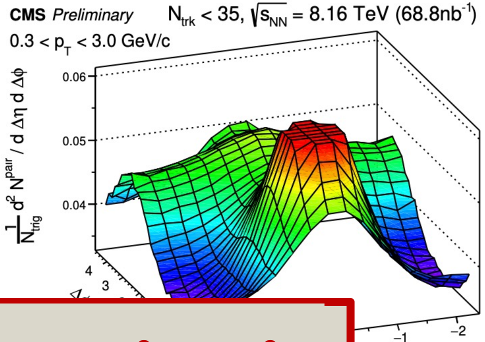

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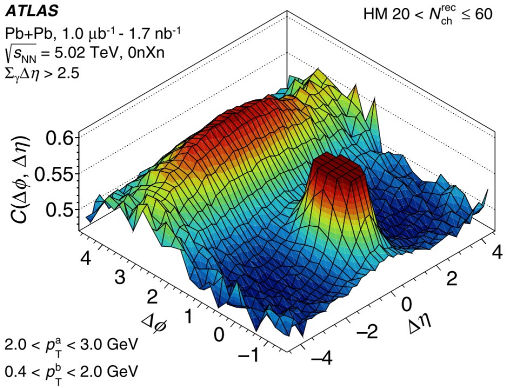
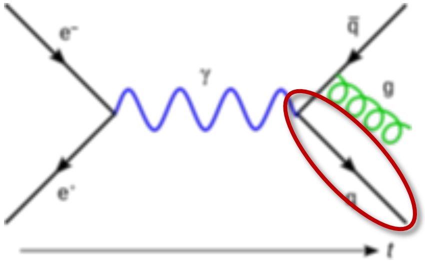


PRC 104 014903 (2021)

Low N_{ch} Limit

Ridge-like studies in even smaller systems

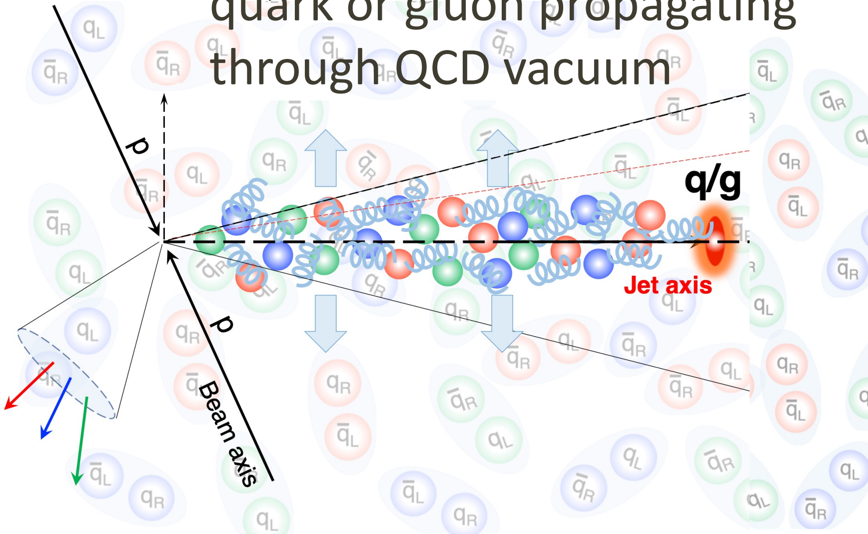
- 2D correlation studies in e^+e^- (PRL 123 212002)



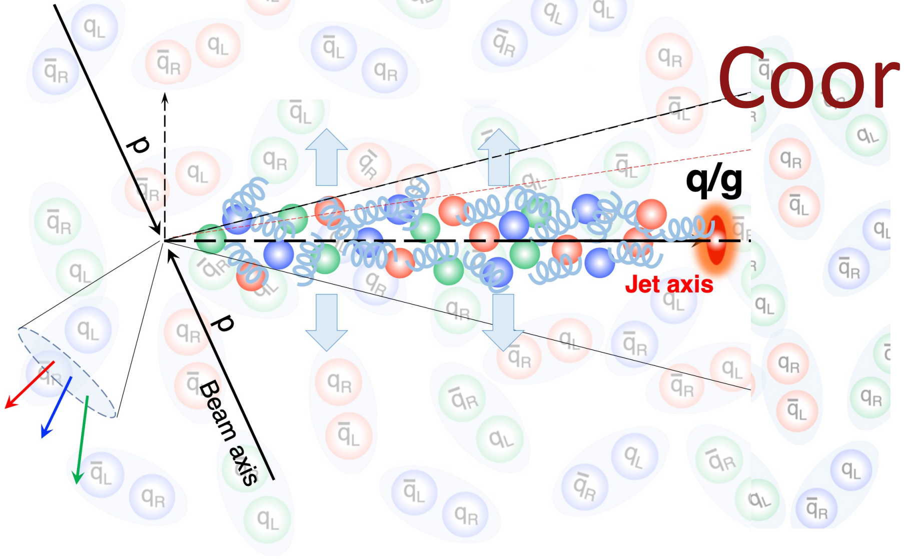
  - final state with N_{ch}~30
    - too few particles?

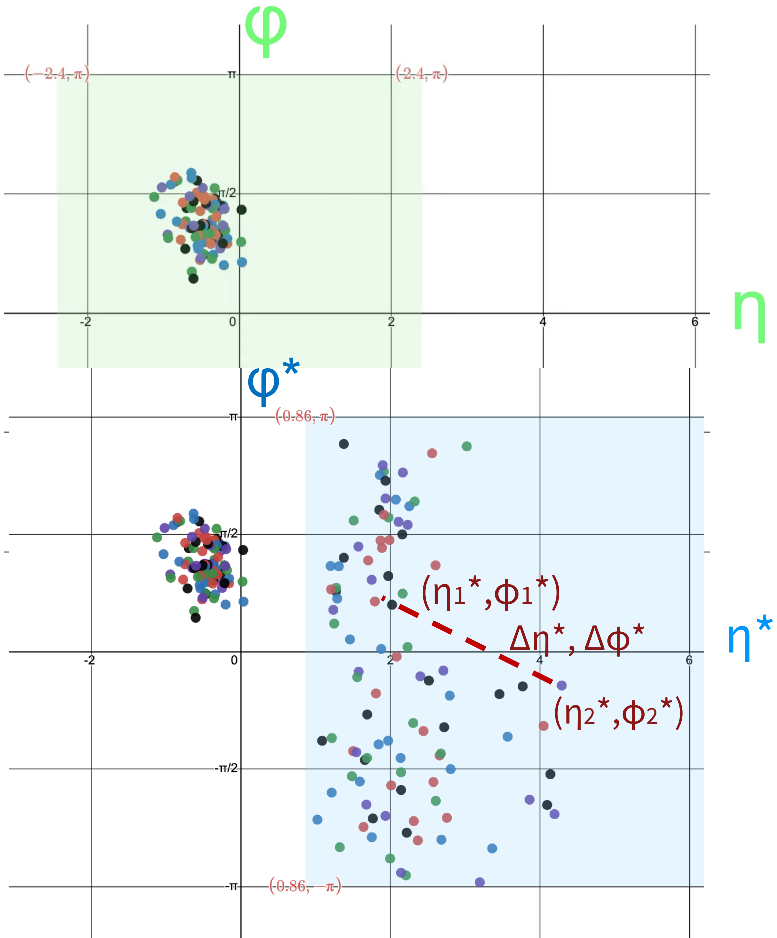
- Even smaller system:
  - study single jets fragmenting into high multiplicity final state!

- Postulate (A. Baty, P. Gardner, W. Li, Phys. Rev. C 107 064908)
  - strongly interacting QGP-like state can be formed by systems initiated by single quark or gluon propagating through QCD vacuum



Coordinate transformation





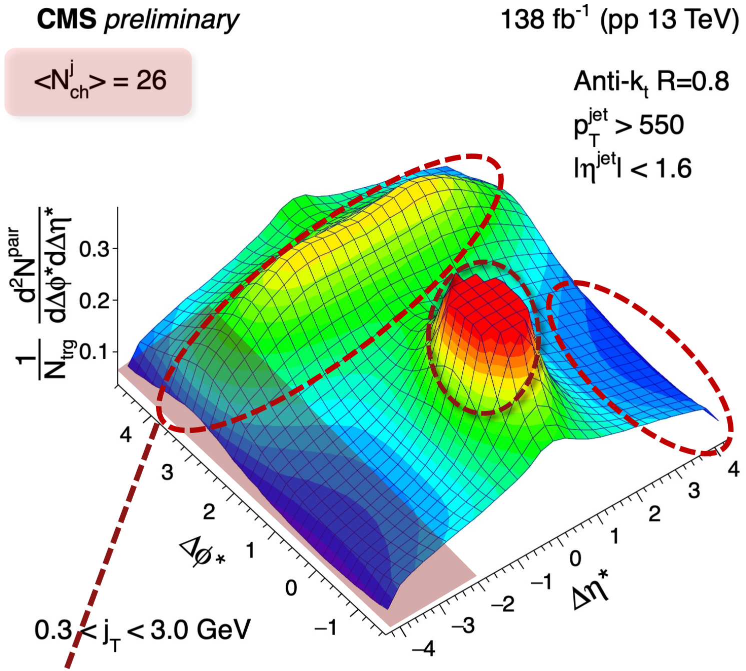
- calculate daughter θ wrt jet axis
- daughter rapidity*

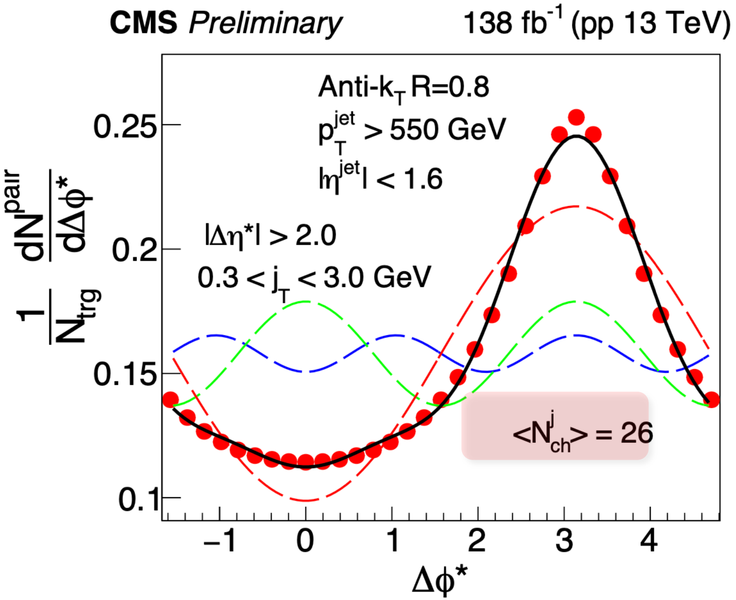
$$\eta^* = -\ln\left(\tan\left(\frac{\theta^*}{2}\right)\right)$$

- j_T → particle transverse momentum wrt the jet axis

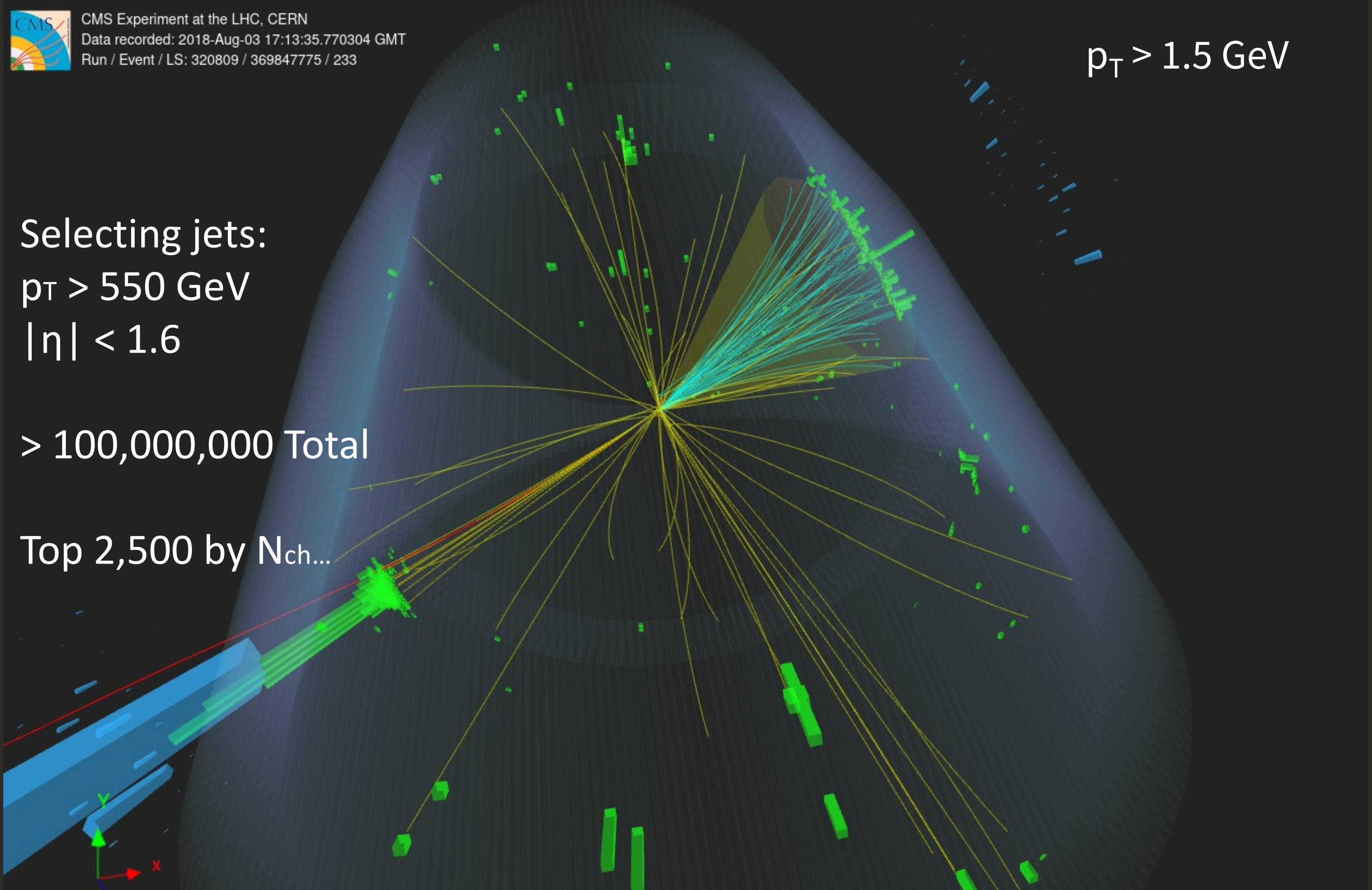
2D (Δη*, Δϕ*) Particle Correlation

$$\frac{1}{N^{j}_{\rm ch}}\frac{\mathrm{d}N^{\rm pair}}{\mathrm{d}\Delta\phi^*} \propto \sum_{n=1}^{\infty} V_{n\Delta}\cos(n\Delta\phi^*)$$





- particle dynamics → similar to Min Bias events in the beam axis:
  - away side: enhancement at $\Delta\varphi^*=\pi$
  - peak at $(\Delta\varphi^*, \Delta\eta^*) = (0,0)$
- highlighted area (left) → study of long range $\Delta\eta^*$ projections in $\Delta\varphi^*$
- no long-range (ridge-like) structure
- behavior in $\Delta\phi^*$ → similar to h^+h^-



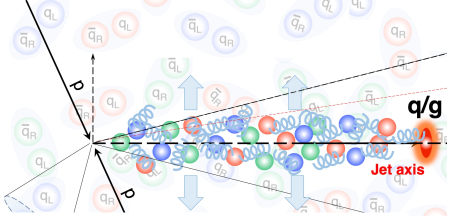
$p_T > 1.5$ GeV

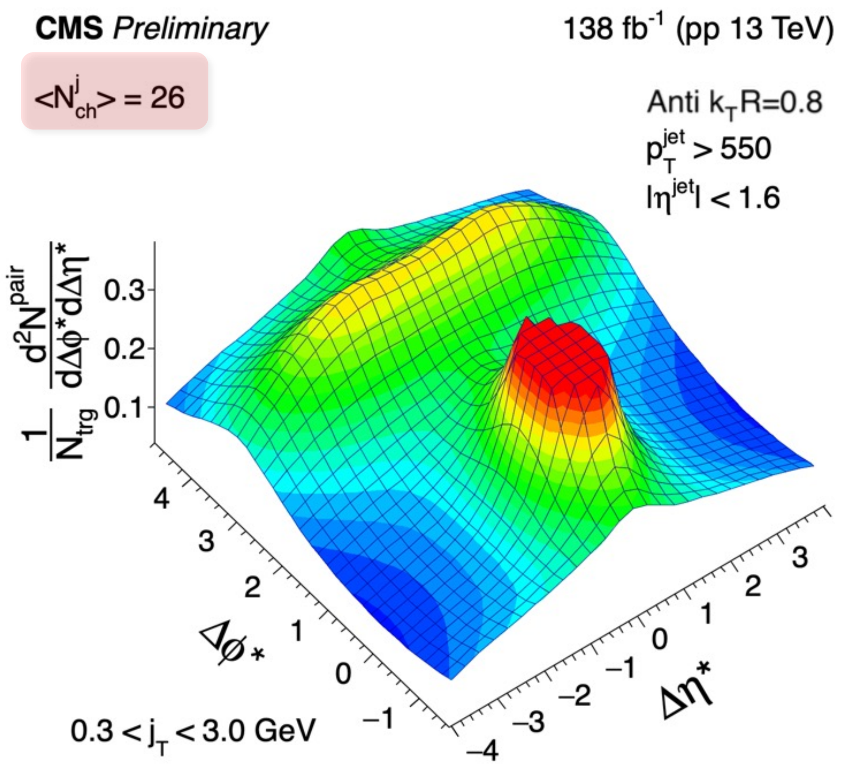
Selecting jets:
$p_T > 550$ GeV
$|\eta| < 1.6$

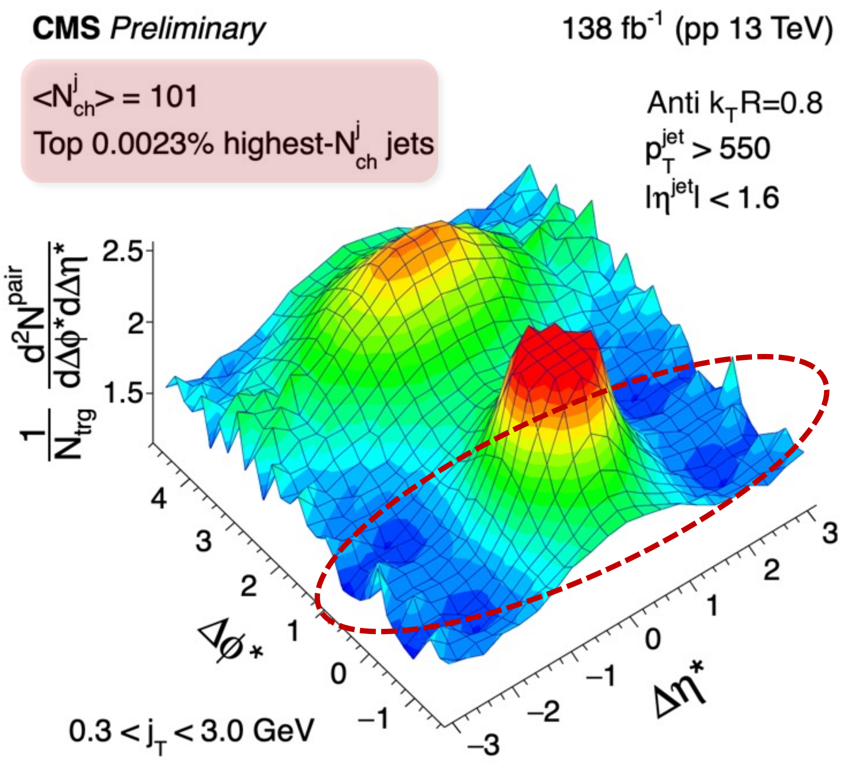
> 100,000,000 Total

Top 2,500 by N_{ch}…

2D correlation for top N_{ch} jets





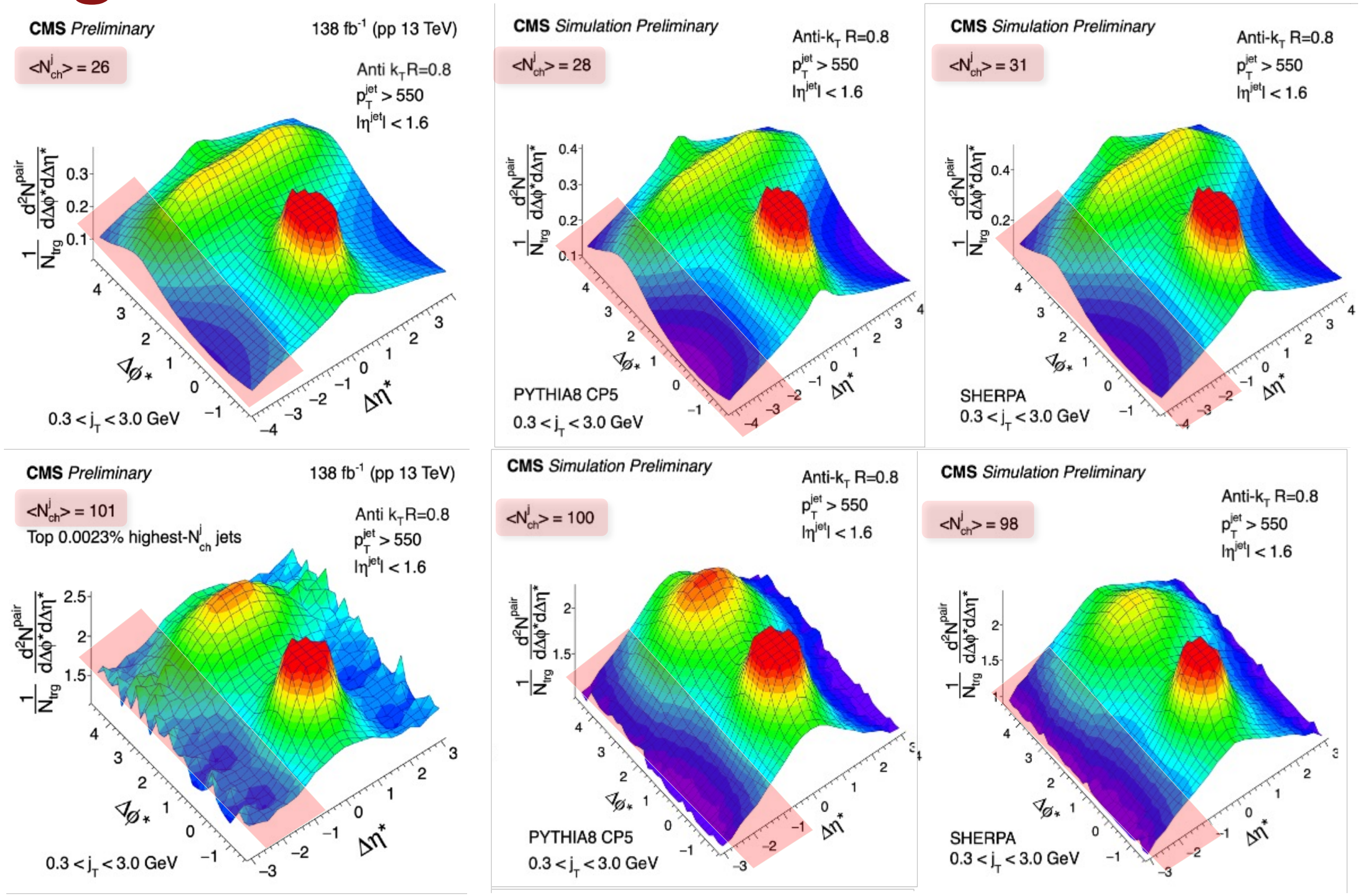


Possible “ridge” with high-multiplicity jets??

Is the “rigde” seen in MC?

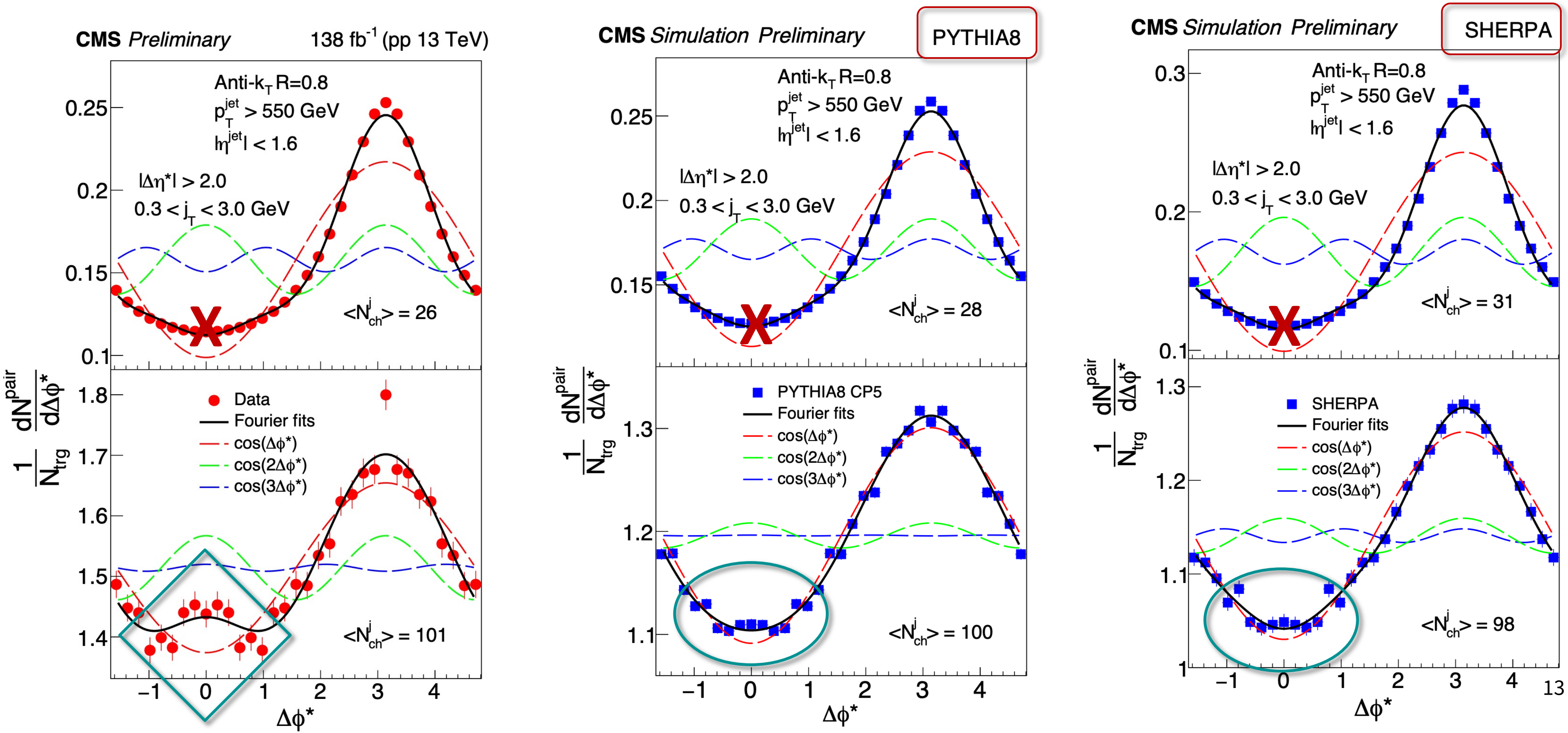
N∼26

N∼100

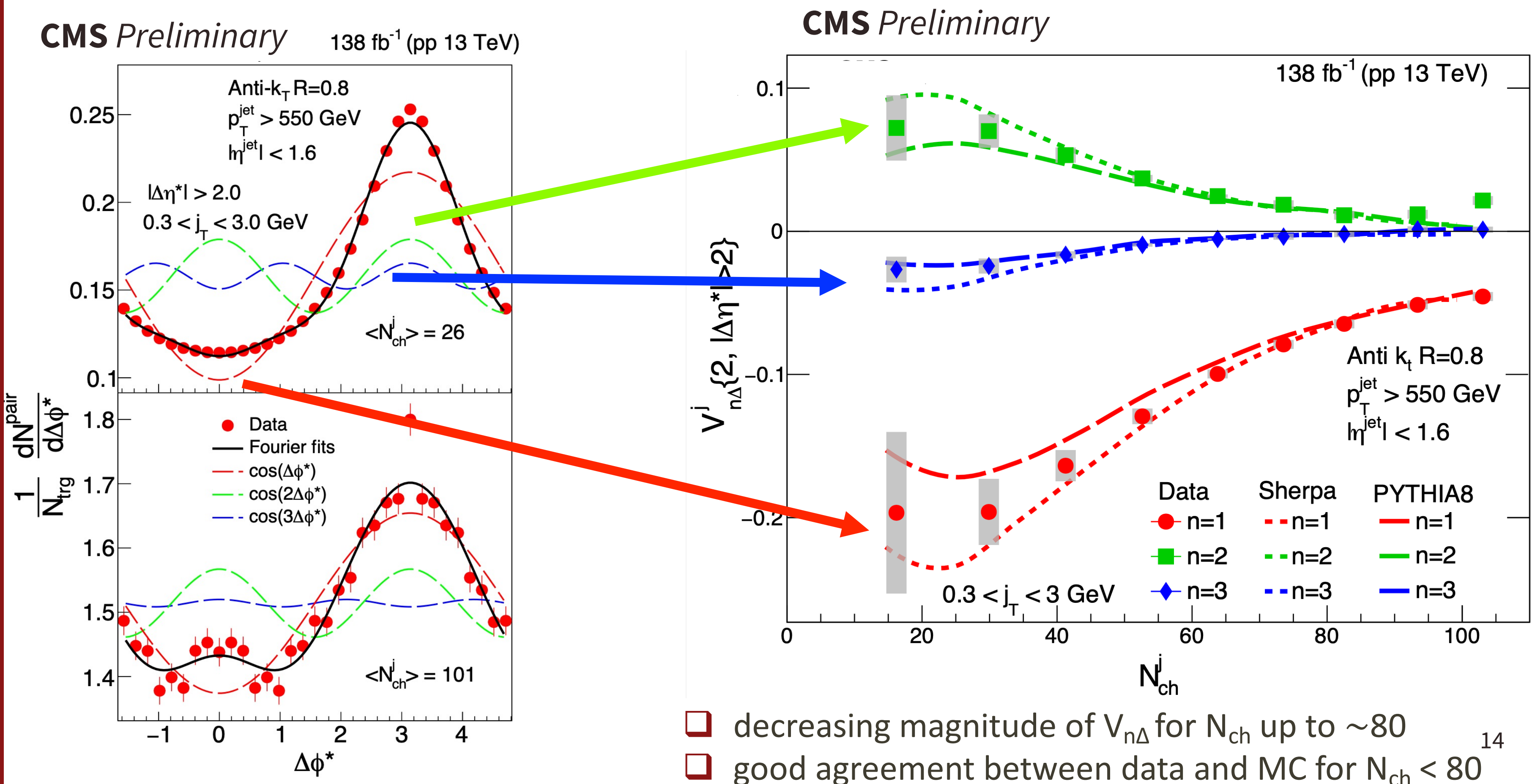


DATA PYTHIA8 SHERPA

(|Δη*| > 2) Correlations: 1D Δϕ* Is the "rigde" seen in MC?

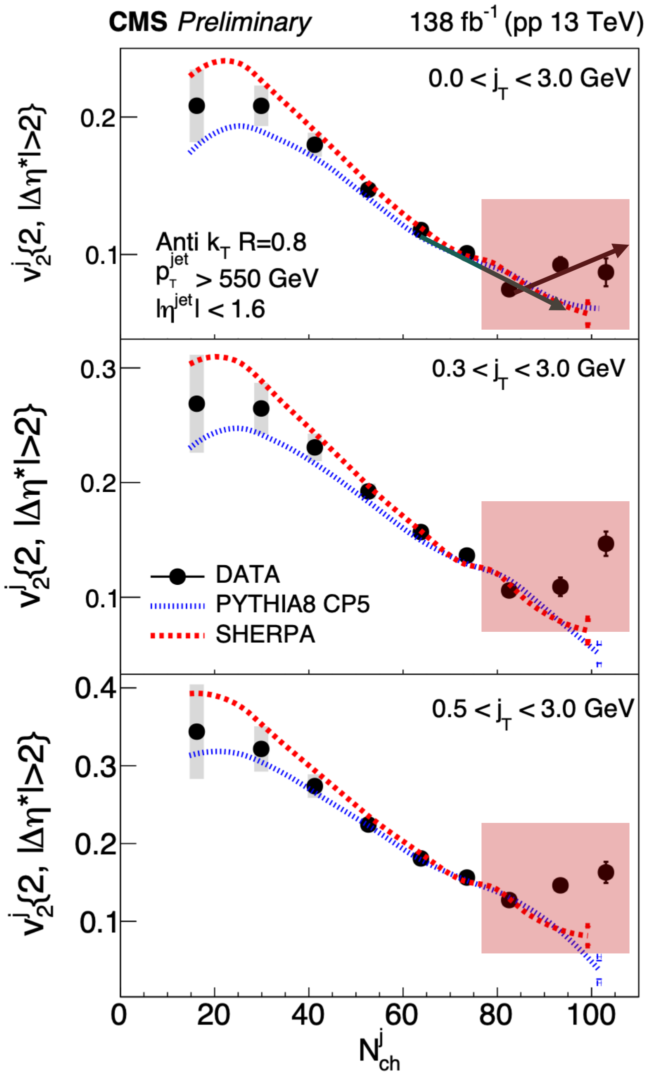


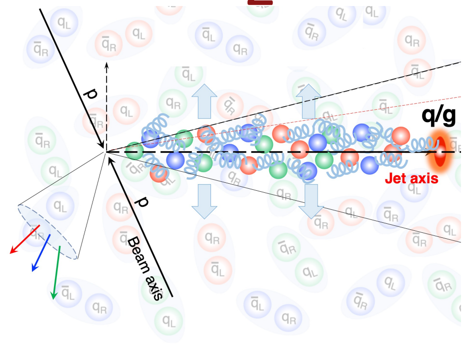
Results: (|Δη*| > 2) Correlations: 1D Δφ*



- ❑ decreasing magnitude of $V_{n\Delta}$ for N_{ch} up to ~80
- ❑ good agreement between data and MC for N_{ch} < 80

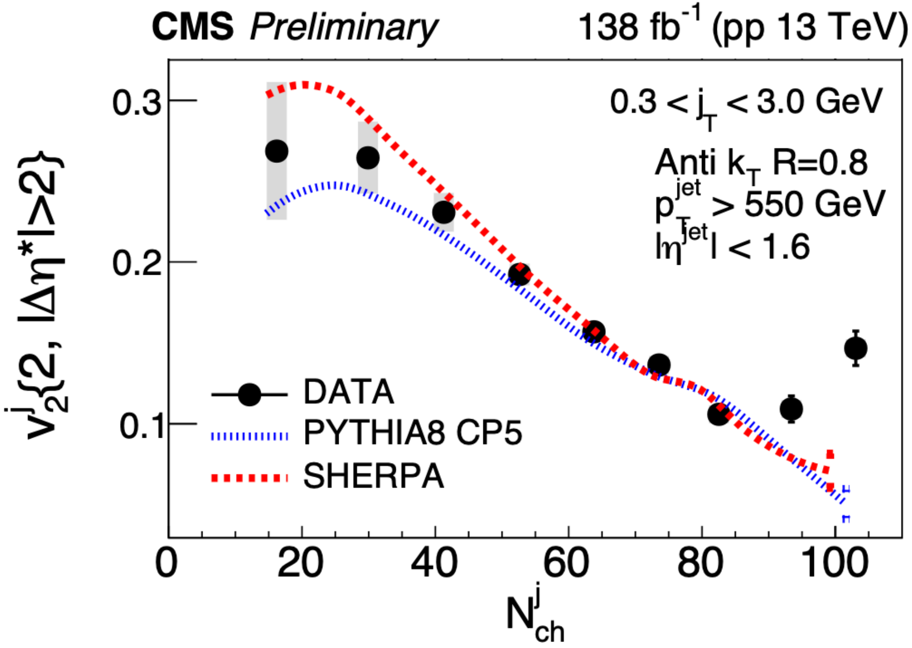
Results: evolution of $v_2\{2\}$





- linear fit for last 3 points in MC and Data → slope extracted
- comparing Data to Sherpa, PYTHIA8 in 0.3-3.0 & 0.5-3.0 GeV j_T →
  - slope deviates from MC: Significance > 5σ
- above N_{jch} ~ 80 → in-jet $v_2\{2\}$ w.r.t to jet axis
  - increases across 3 j_T ranges in Data
  - decreases in Sherpa and PYTHIA8

Summary 1



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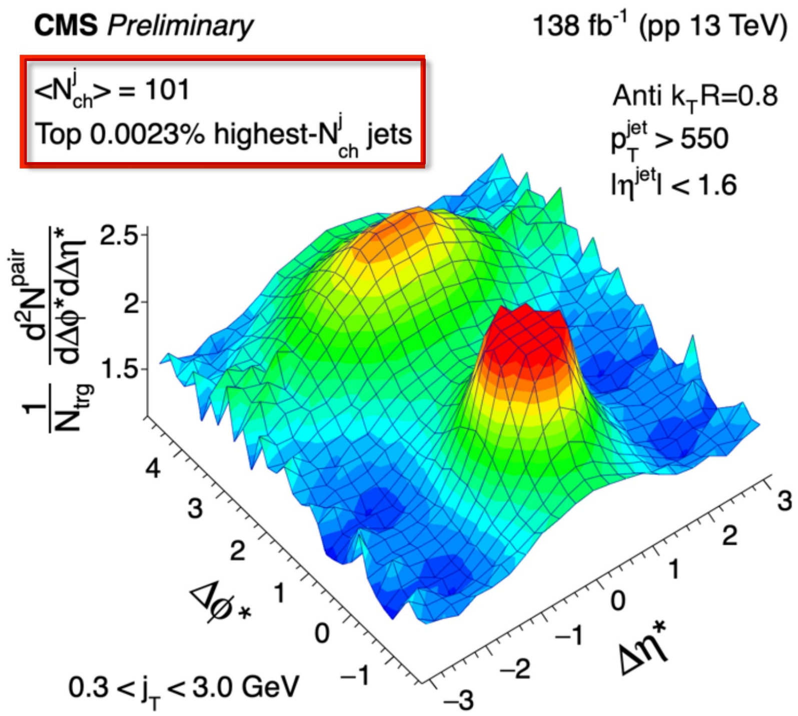
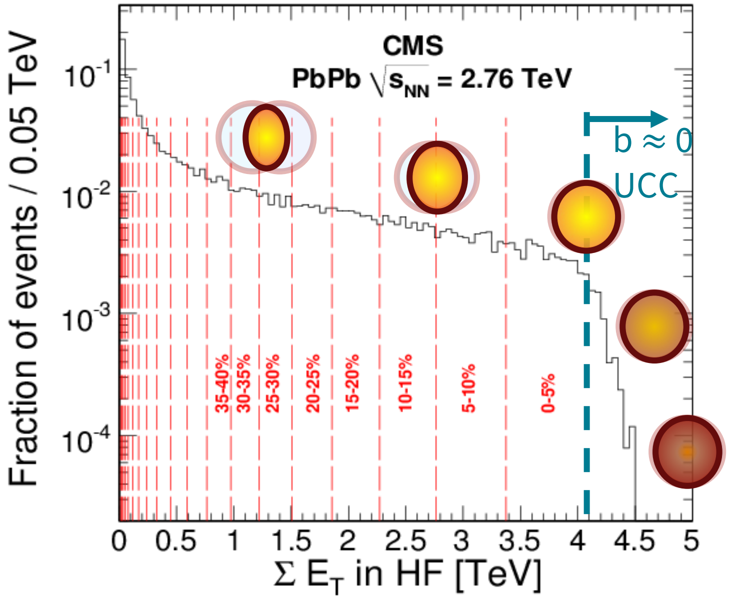
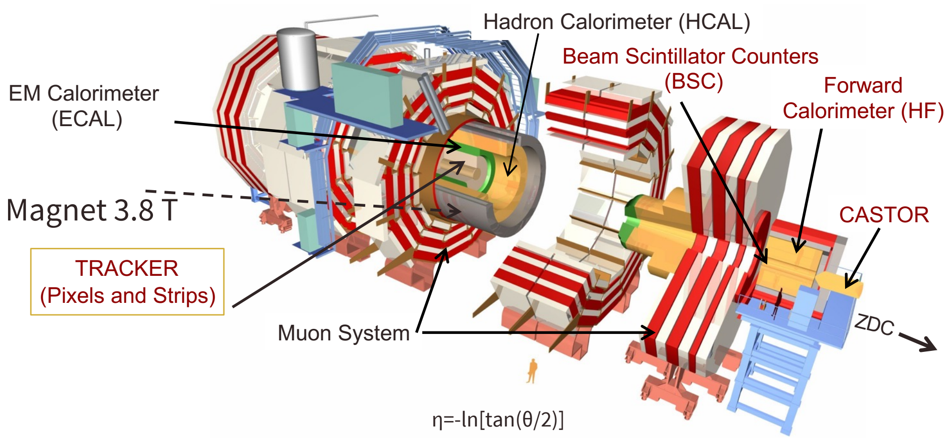


- collectivity in single parton jets during fragmentation?

  - link to [CMS-PAS-HIN-21-013]

Thermodynamic properties in UCC





Measurements of QGP properties

Speed of sound

- ❑ fundamental property of any medium
  - in fluids → velocity of longitudinal compression wave propag. in medium
  - $c_s^2 = dP/d\varepsilon$
- ❑ directly related to the EoS

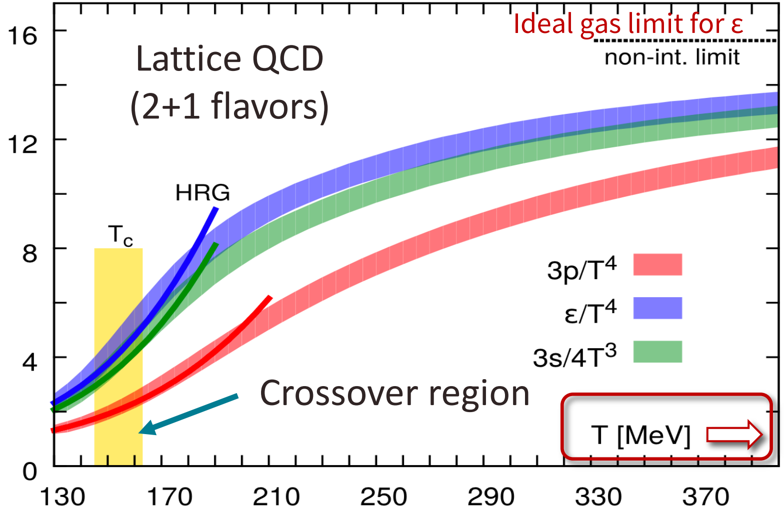
Effective temperature T_{eff}

(F. Gardim et al., Nature Phys. **16** (2020) 615)

- hydrodynamics simulation: $T_{\mathrm{eff}} \approx \langle p_{\mathrm{T}} \rangle / 3$ (ideal gas at rest)
  - Longitudinal expansion ⇒ T_{eff} smaller than the initial T_0

Lattice QCD results

- ❑ Normalized pressure, entropy and energy densities vs. T

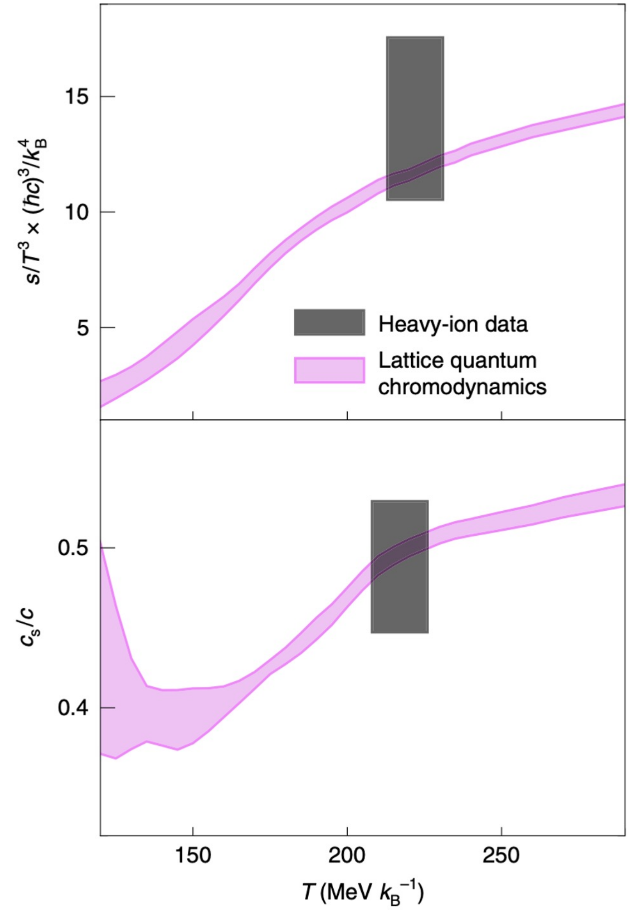


PRD **90** (2014) 094503

Speed of sound: extraction using AA data

F. Gardim et al., Nature Physics **16** (2020) 615:

- ALICE PbPb data at 2.76 and 5.02 TeV (0-5% centrality)
- Varied collision energy at a fixed centrality (constant V)
  - $c_s^2(T_{\text{eff}}) = \frac{dP}{d\varepsilon} = \frac{sdT}{Tds}\Big|_{T_{\text{eff}}} = \frac{dl_n\langle p_T\rangle}{dl_n(dN_{\text{ch}}/d\eta)} = 0.24 \pm 0.04$
- Uncertainties: only two data points



Ultracentral (UCC) events in PbPb collisions

Based on PLB **809** (2020) 135749:

- ❑ $\langle p_\mathrm{T}\rangle$ ($\sim T_\mathrm{eff}$) vs N_ch ($\sim s = S/V$)
  - expected: $\langle p_\mathrm{T}\rangle$ increase at $b \approx 0$
- ❑ fixed volume (similar to previous procedure)
  - But varying $\langle p_\mathrm{T}\rangle$ and N_ch
- ❑ slope: $\propto c_s^2$

Collision centrality

- ❑ experimentally: sum of transversal energy (E_T) in HF
- ❑ related to impact parameter (b), system volume (geometry)
- ❑ For b ≈ 0 (~0-1% centrality)
  - volume V ≈ constant
  - energy density (ε)→can fluctuate

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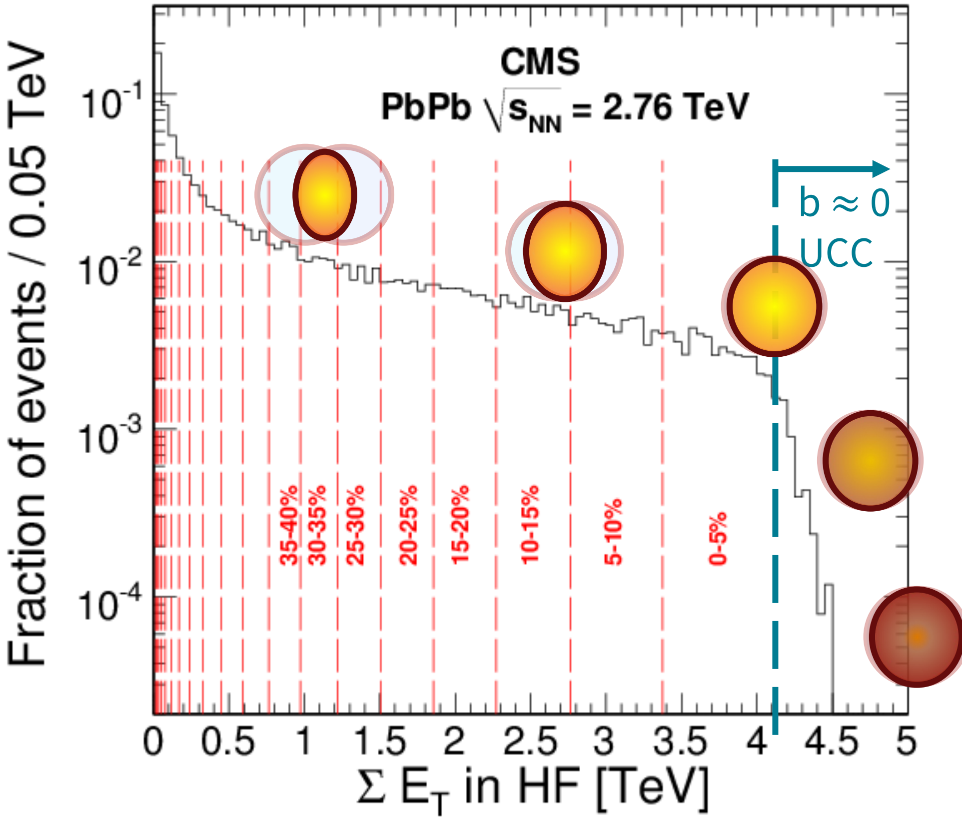


Analysis method - observables

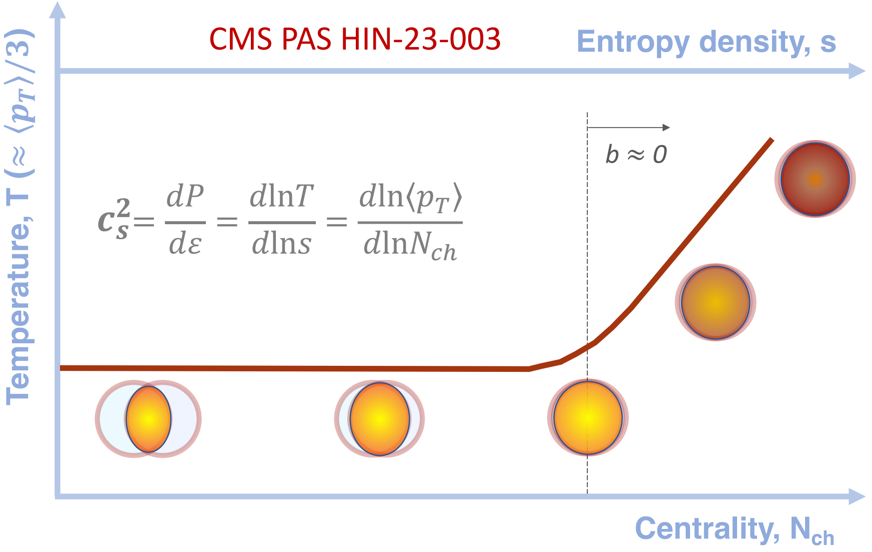
The c_s^2 depends on the relative variation of $\langle p_T \rangle$ vs N_{ch}

- Can be extracted using
  - $\frac{\langle p_T \rangle}{\langle p_T \rangle^0} \sim \left(\frac{N_{ch}}{N_{ch}^0}\right)^{c_s^2}$
    - with $\langle p_T \rangle^0$ and N_{ch}^0 in a reference event class
      - obtained in 0-5% (as for c_s^2)
      - extrapolated to $p_T \approx 0$
    - $T_{eff} \approx \langle p_T \rangle^0/3$ in 0-5%

Analysis observables

$\langle p_T \rangle^{norm} = \frac{\langle p_T \rangle}{\langle p_T \rangle^0}$ vs $N_{ch}^{norm} = \frac{N_{ch}}{N_{ch}^0}$

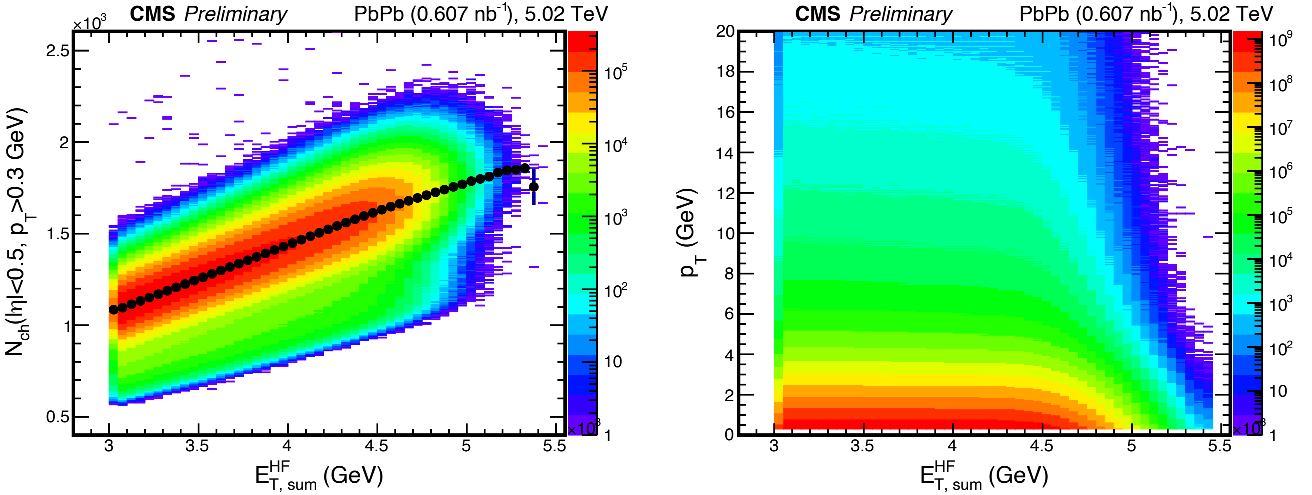
$\langle p_T \rangle^0$ (used to estimate T_{eff})



Analysis method - $\langle p_{\mathrm{T}} \rangle$ and N_{ch}

To avoid other sources of correlations between $\langle p_{\mathrm{T}} \rangle$ and N_{ch}

- Both are measured first in bins of $E_{\mathrm{T,\,sum}}^{\mathrm{HF}}$ (bin width of 50 GeV)



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- $\langle p_{\mathrm{T}} \rangle$ and N_{ch} are corrected for tracking efficiency
- Extrapolation to $p_{\mathrm{T}} \approx 0$ by fitting the spectrum in $p_T > 0.4\ \mathrm{GeV}$
- After corrections, for each bin of $E_{\mathrm{T,\,sum}}^{\mathrm{HF}}$ → $\langle p_{\mathrm{T}} \rangle^{\mathrm{norm}}$ vs $N_{\mathrm{ch}}^{\mathrm{norm}}$

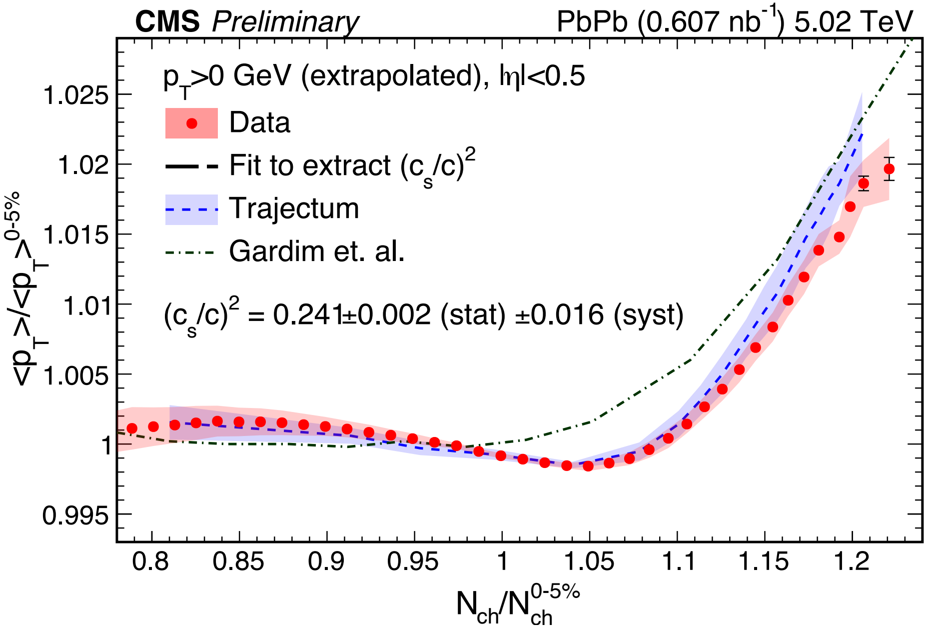
Results

Trajectum: global Bayesian analysis based on many data observables

- Uncertainties within the allowed parameter space (https://arxiv.org/abs/2305.00015)

Gardim et.al.: EoS from 2+1 flavors Lattice QCD (PLB **809** (2020) 135749)

Significant increase of $\langle p_T \rangle$ toward UCC events as predicted by the simulations



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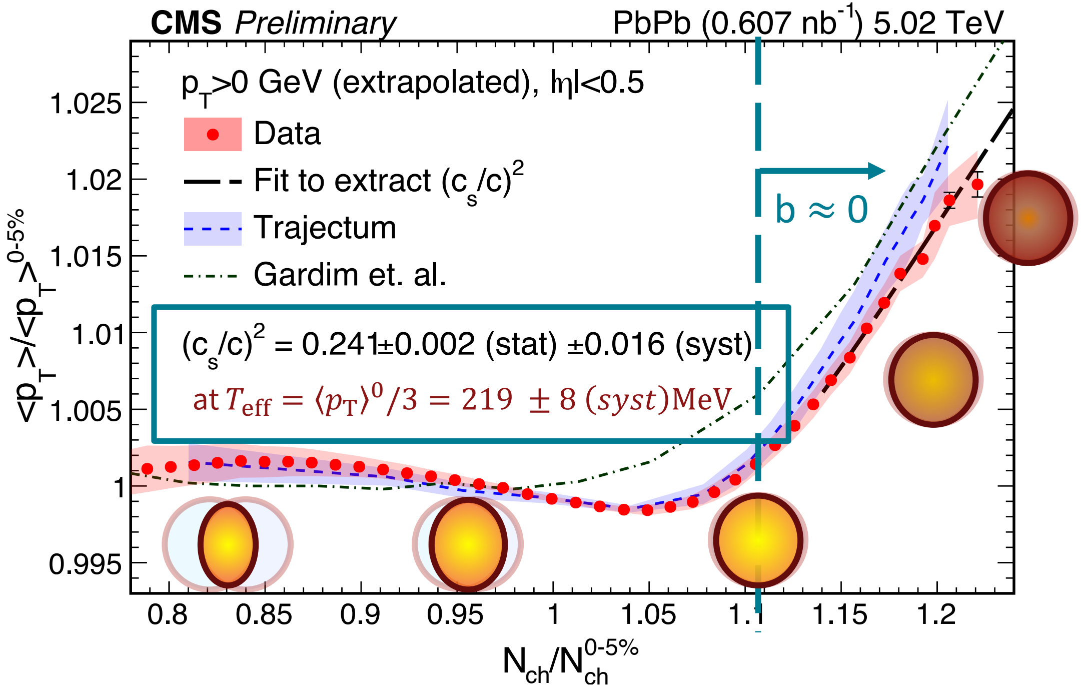
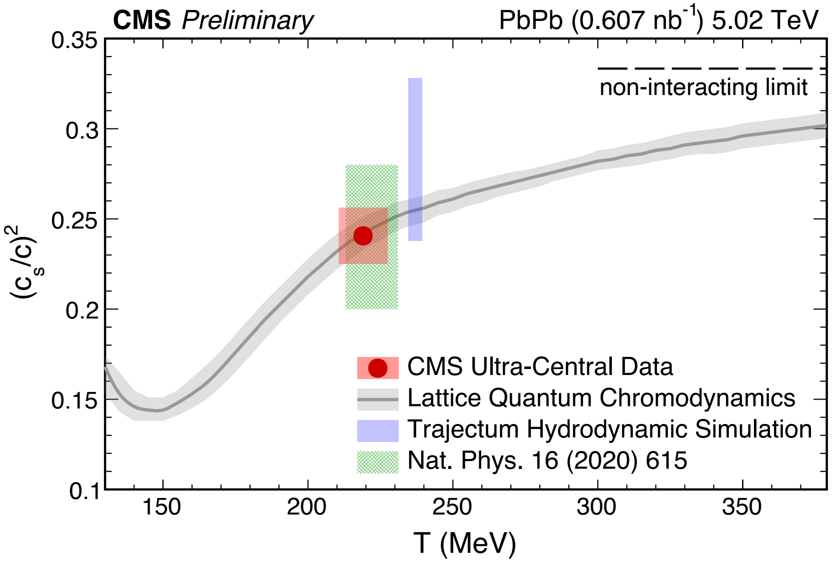


Speed of sound extracted from the fit and T_{eff} from $\langle p_T \rangle^0$

Results

Speed of sound (c_s^2) → determined for 1st time with high precision in AA UCC

- In agreement with Lattice QCD
  - $\mu_B \sim 0$ and 2+1 flavors
  - and with previous measurements
- Compatible with a deconfined phase at high T
- Robust method to extract c_s^2 from UCC events
  - can be used to scan of c_s^2 at various energies



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Summary 2

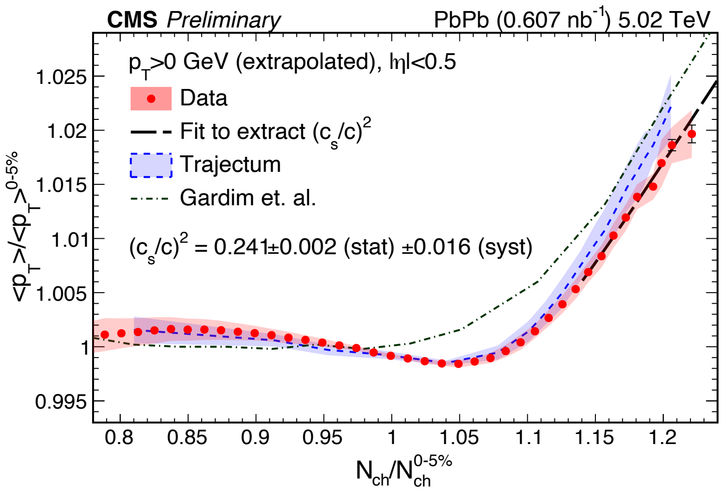
Extracted the speed of sound for the first time using ultracentral AA collisions

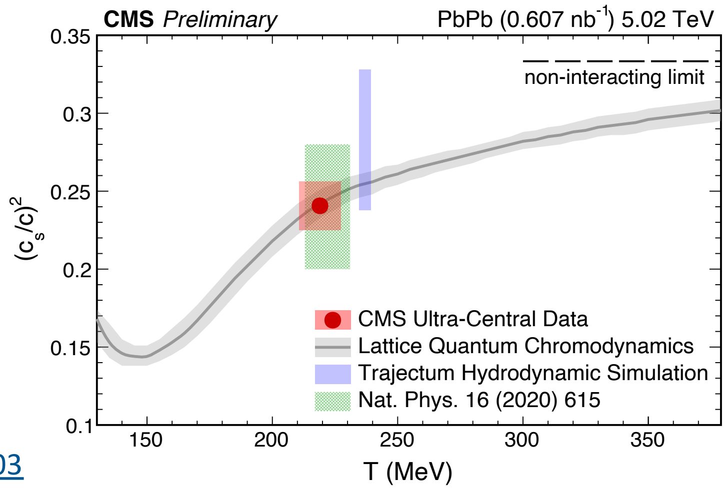
- $c_s^2 = 0.241 \pm 0.002\ (\text{stat}) \pm 0.016\ (\text{syst})$ at $T_{\text{eff}} = 219 \pm 8\ (\text{syst})\ \text{MeV}$

Under assumptions, in agreement with Lattice QCD ($\mu_B \sim 0$ and 2+1 flavors)

- Constraint on the QCD equation of state
- Compatible with a deconfined phase at high temperature

Robust method to extract c_s^2 → can be applied to different energies





CMS PAS HIN-23-003

THANK YOU!

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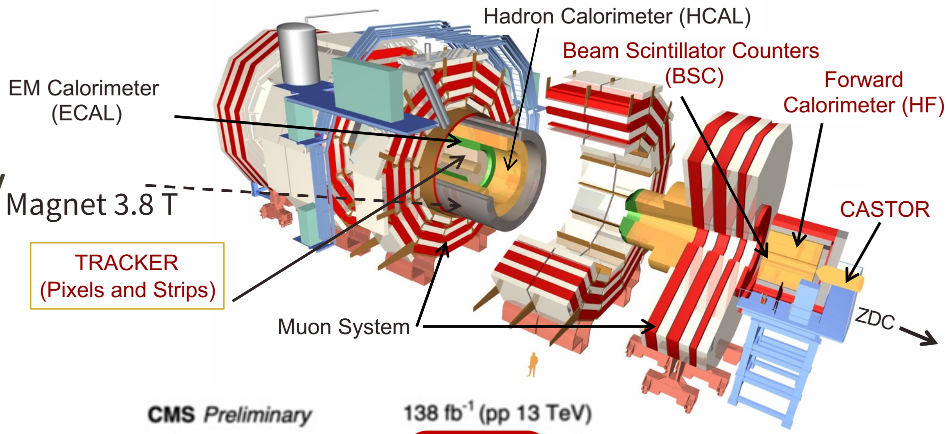
EXTRA SLIDES

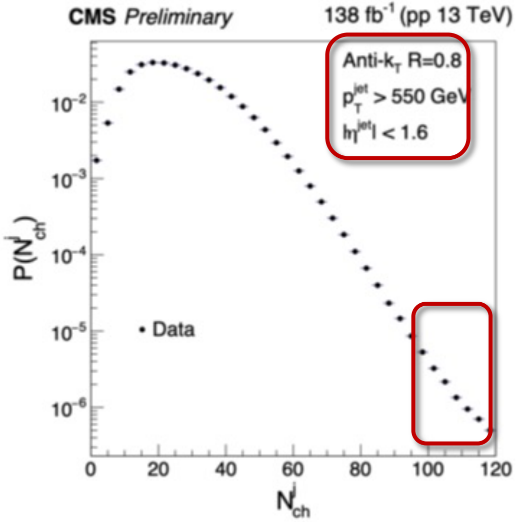
Search at LHC: rare jets with very high N_{ch}

Goal of analysis:

- look for evidence of in-jet collectivity using highest multiplicity parton jets in pp collisions at the CMS



- Full 13 TeV pp dataset (LHC Run II)
- High PU events: PUPPI
- CMS is particularly good in this environment
- >100 million jets analyzed
- A few thousand jets at highest multiplicities

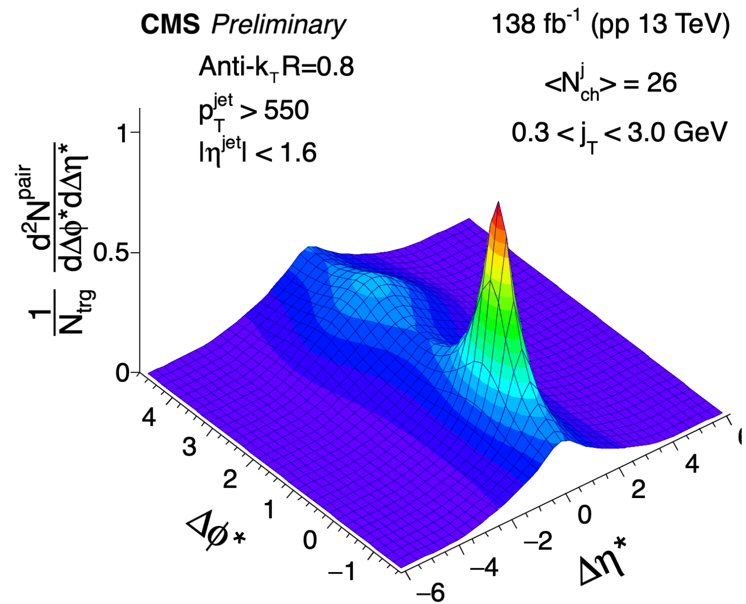


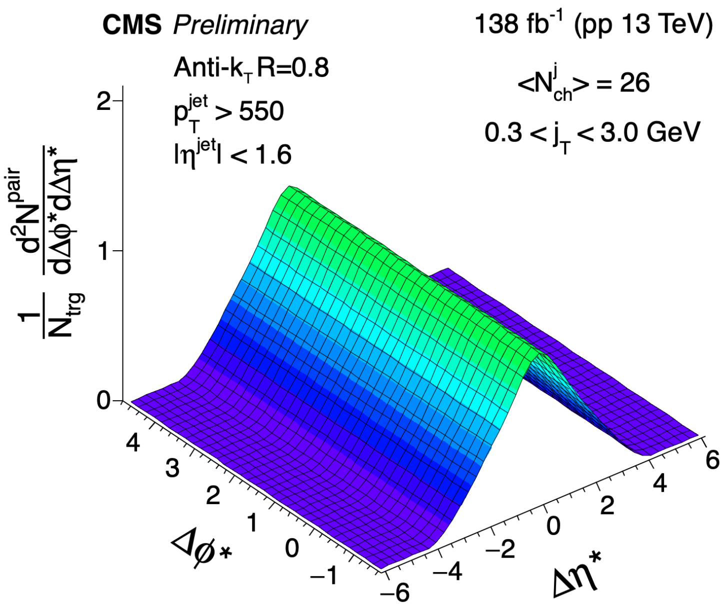
2D (Δη*, Δϕ*) Particle correlations

$$\frac{1}{N_{\mathrm{ch}}^{\mathrm{trg}}}\frac{\mathrm{d}^2 N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta^*\mathrm{d}\Delta\phi^*} = B(0,0)\frac{S(\Delta\eta^*,\Delta\phi^*)}{B(\Delta\eta^*,\Delta\phi^*)}$$

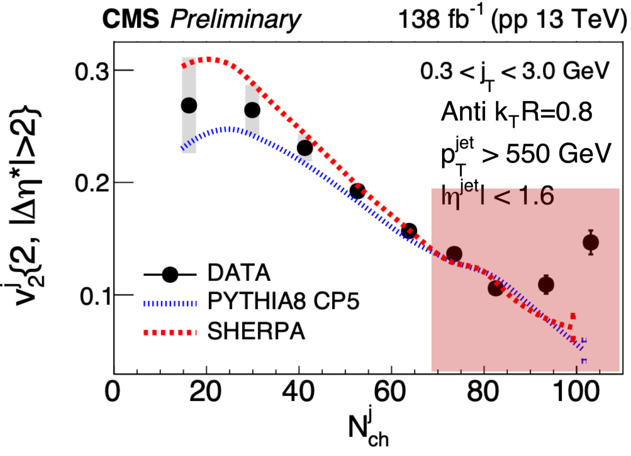
SIGNAL

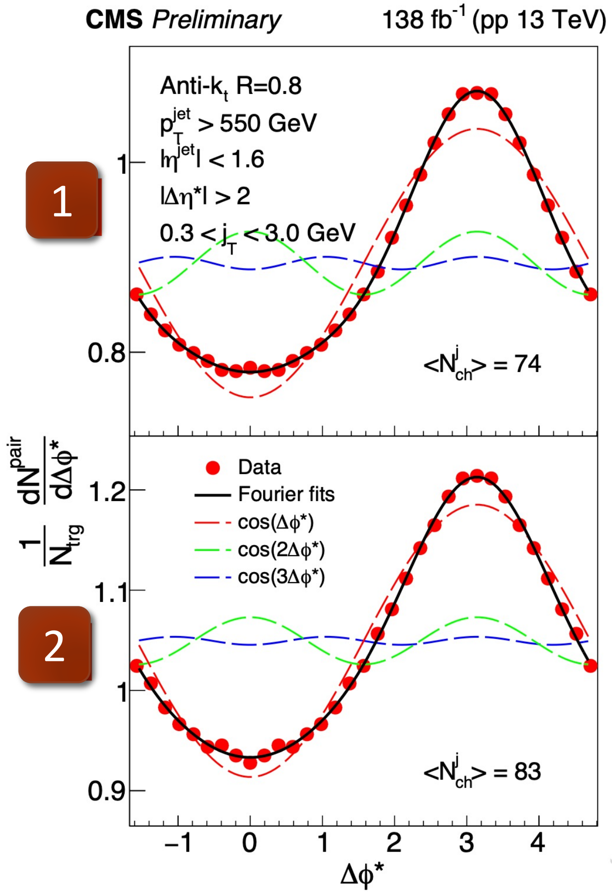
BACKGROUND

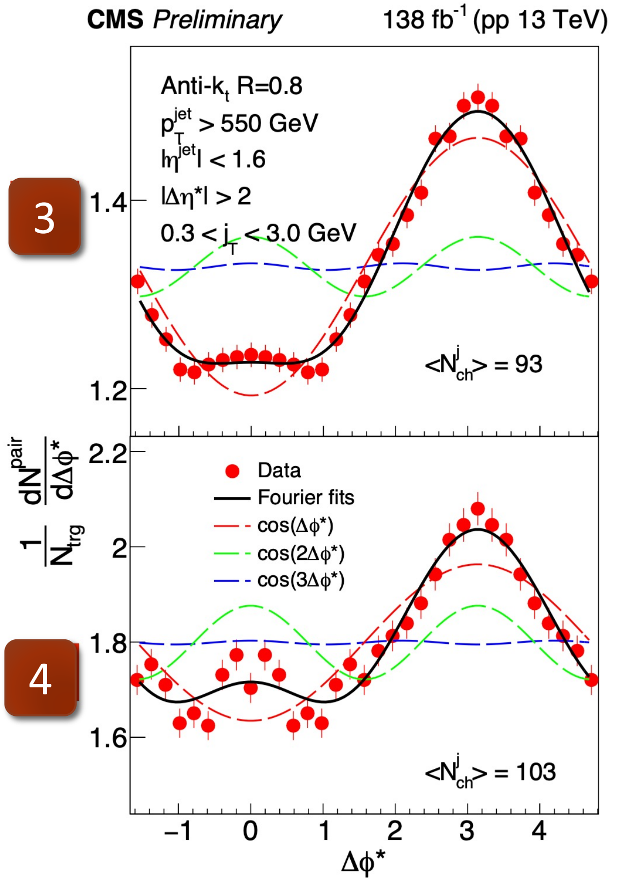




Evolution of $v_2\{2\}$ – 1D fits







Highlighted Point	$\langle N^j_{ch} \rangle$	χ^2 / ndf
1	74	1.09
2	83	0.73
3	93	0.81
4	103	1.41

Analysis method - p_{T} extrapolation to zero

$\langle p_{\mathrm{T}} \rangle$ and N_{ch} are corrected for tracking efficiency

Extrapolation to $p_{\mathrm{T}} \approx 0$ by fitting the spectrum in $p_T > 0.4$ GeV

- Hagedorn function

$$\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}} = p_{\mathrm{T}} \left(1 + \frac{1}{\sqrt{1 - \langle \beta_{\mathrm{T}} \rangle^2}} \frac{\left(\sqrt{p_T^2 + m^2} - \langle \beta_{\mathrm{T}} \rangle p_{\mathrm{T}} \right)}{nT} \right)^{-n}$$

- m is the pion mass and $\langle \beta_{\mathrm{T}} \rangle$, n, T are free parameters

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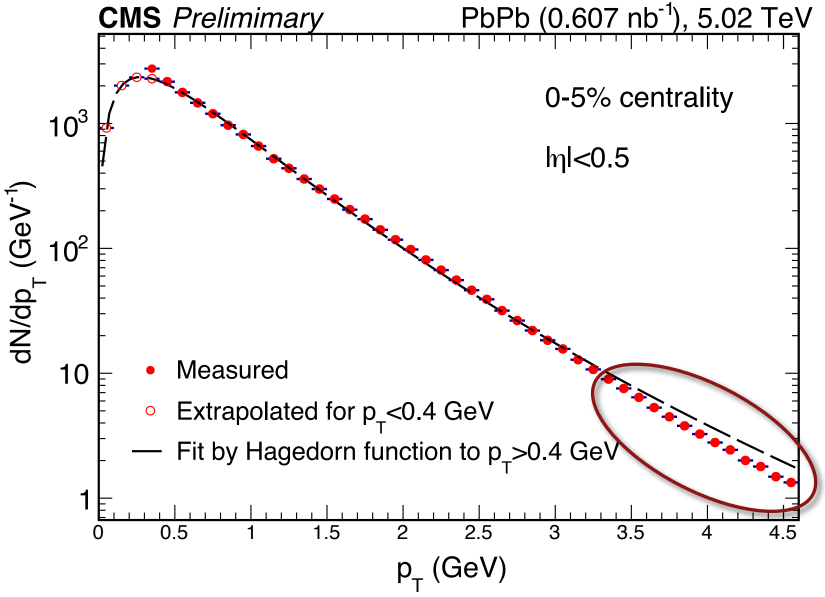

After corrections, for each bin of $E_{\mathrm{T,\,sum}}^{\mathrm{HF}}$ → $\langle p_{\mathrm{T}} \rangle^{\mathrm{norm}}$ vs $N_{\mathrm{ch}}^{\mathrm{norm}}$

Systematic uncertainties and cross-checks

Systematics

- Tracking efficiency corrections
- Extrapolation to $p_{\mathrm{T}} \approx 0$
- Choice of fit range (only for c_s^2)

Main cross-checks

- HF energy resolution
  - Data HF energy smearing
  - Vary bin width
    - 50GeV → 25GeV and 100GeV
- Efficiency correction
  - Dependence on particle species
- Extrapolation to $p_{\mathrm{T}} \approx 0$
  - Use of different fit function
  - Closure using simulations