# Two-Particle Correlations in pp Collisions at 13 TeV Measured with CMS

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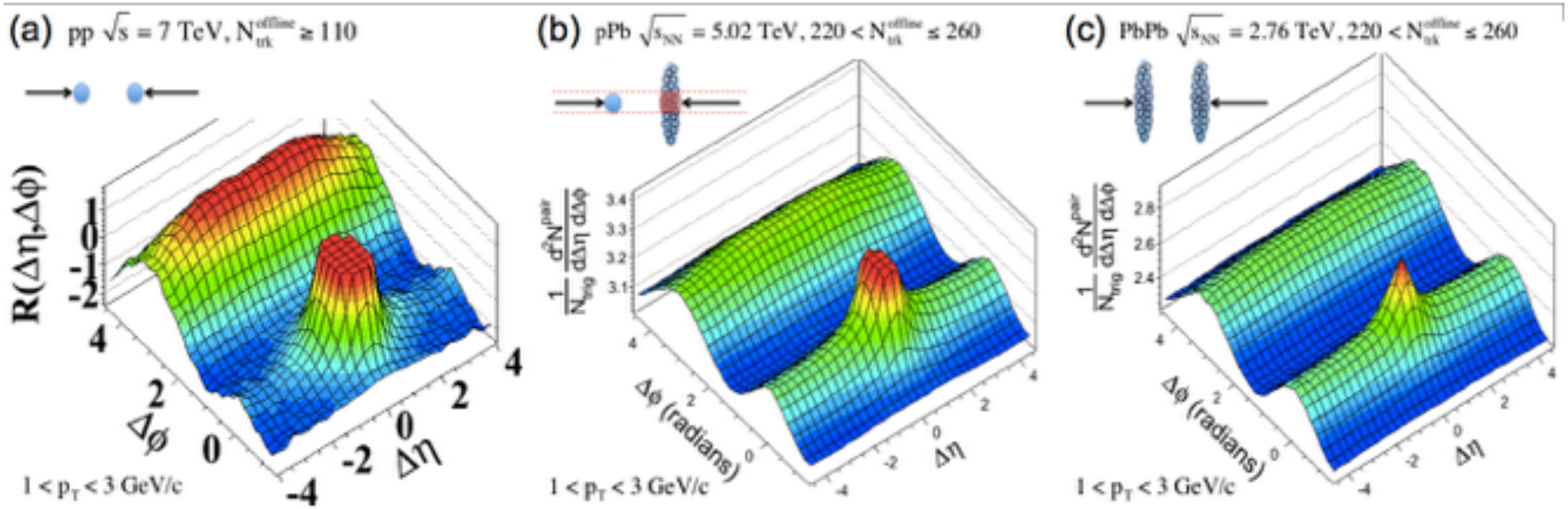
# Outline

- Two particle correlations in p+p, p+Pb and Pb+Pb
- First results in p+p collisions at 13 TeV
  - Two particle correlation results
  - Associated yields
    - $p_T$ and multiplicity dependence
- Anisotropy Fourier Harmonics from 7 TeV
  - Long-range correlations for charged hadrons, $K_s^0$ and Λ particles
  - Jet contributions studied and subtracted multi-particle azimuthal correlations
  - $p_T$ and event multiplicity dependence
- Summary

# Two particle correlations in p+p, p+Pb and Pb+Pb




JHEP 09 (2010) 091

PLB 724 (2013) 213

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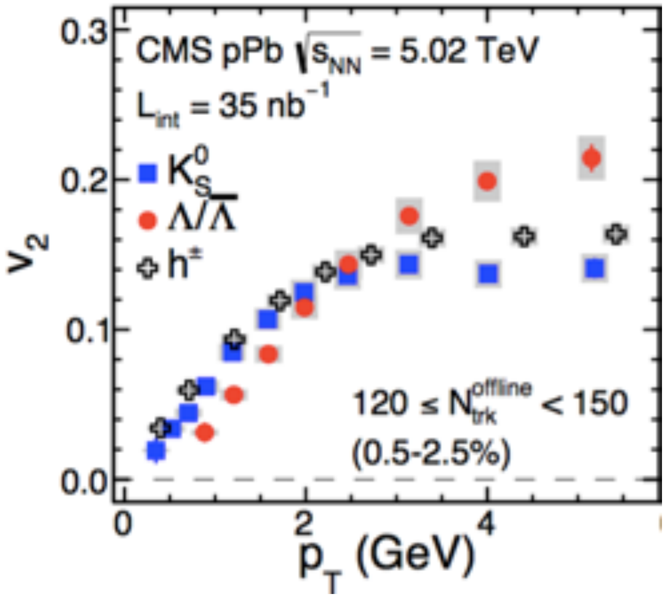
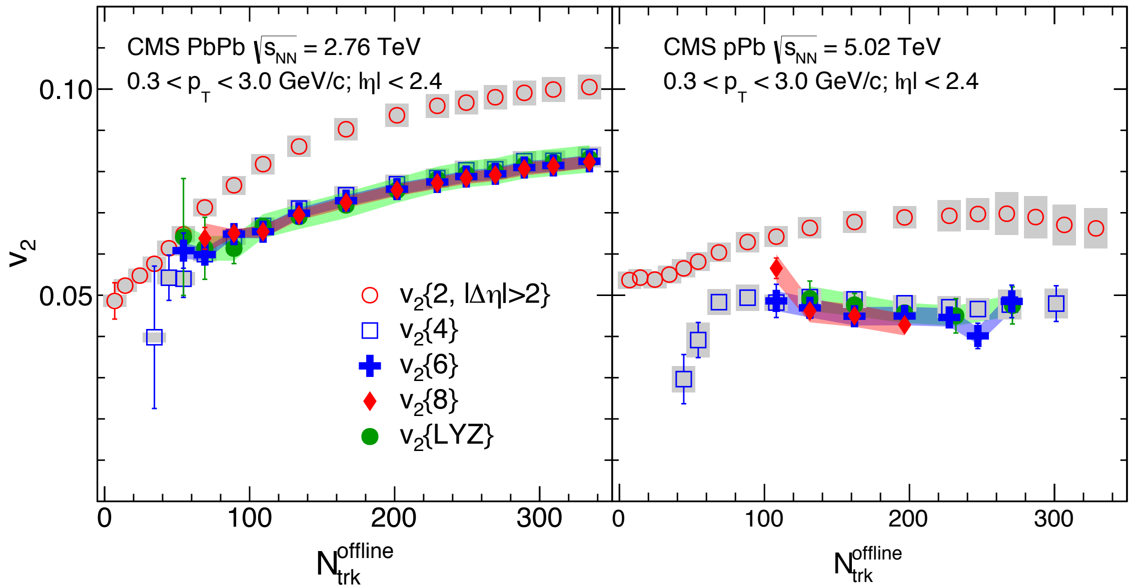
- The long-range same-side correlations seen in all systems at the LHC
- Interpretation:
  - Heavy ions: hydrodynamic flow
  - Small systems: ??

# Extensive studies in pPb and PbPb collisions

PLB 742, 200 (2015)



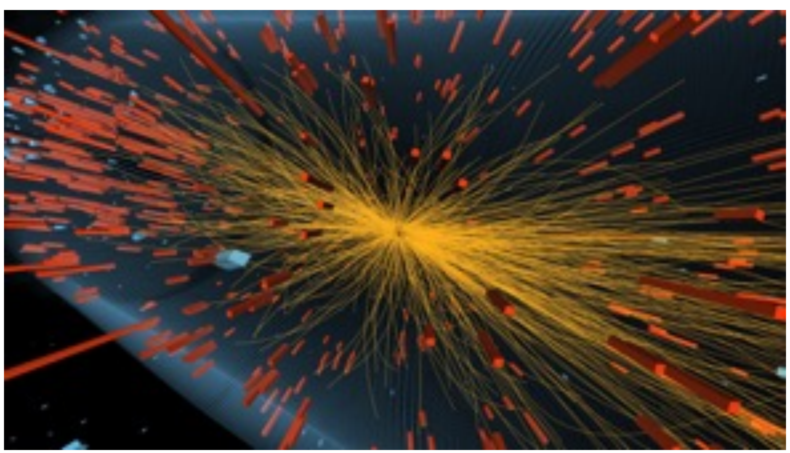

PRL 115, 012301 (2015)




- Results supporting collectivity:
  - $v_n$ with particle identification
  - Mass ordering
  - Similar picture in AA Collisions
- Multiparticle correlations:
  - Even 8-particle and many-particle correlations give the same $v_2$ (jet correlations suppressed)

# Small Systems —> Pushing the limits

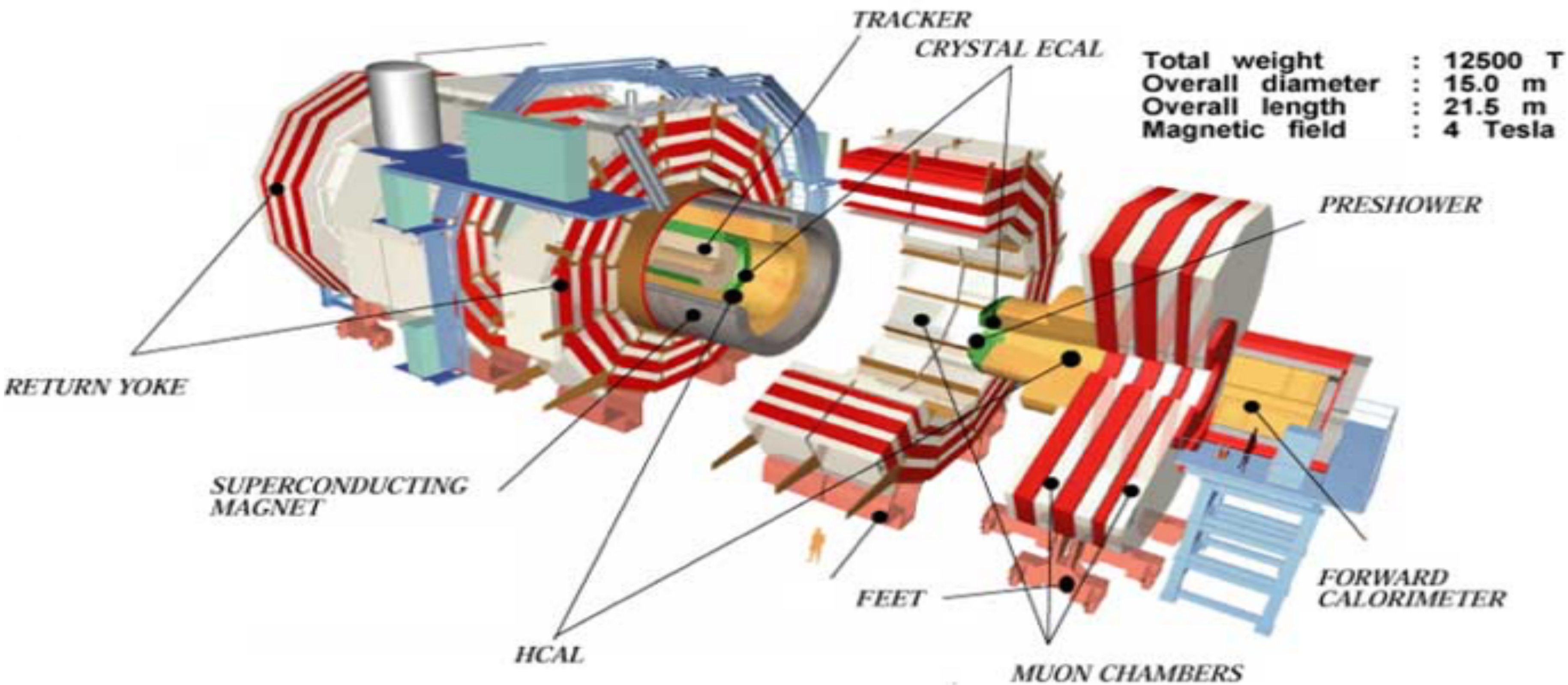
- Small fraction of **p+p** and **p+Pb** collisions produce a high number of charged particles same as mid-central heavy ions
- The initial geometry and its fluctuations is very different from heavy ions
- What does the final state (azimuthal asymmetries) tell us?

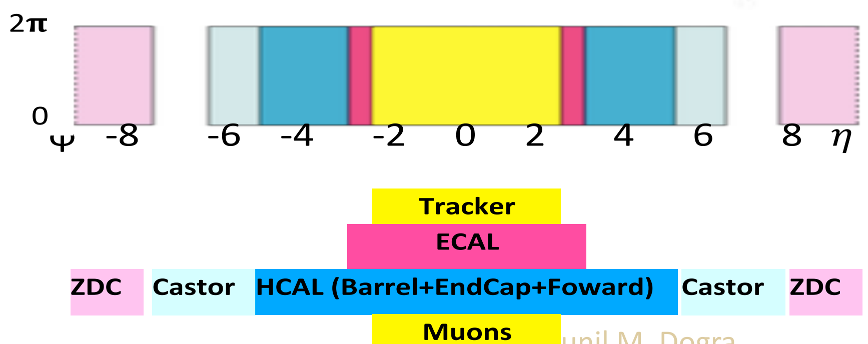


More than 420 charged particles in pPb collisions at 5.02 TeV


More than 200 charged particles in pp collisions at 7 TeV

# Compact Muon Solenoid Experiment



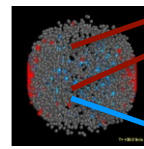



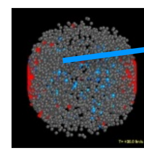
# Defining Two Particle Correlations

- Trigger particle: a hadron in a certain $p_T$ bin
- Same- and mixed-event pair distributions

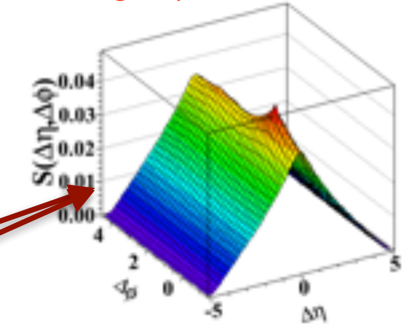
$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\phi}$$

$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\phi}$$

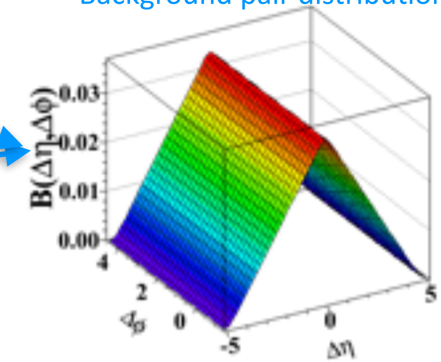




Signal pair distribution




Background pair distribution

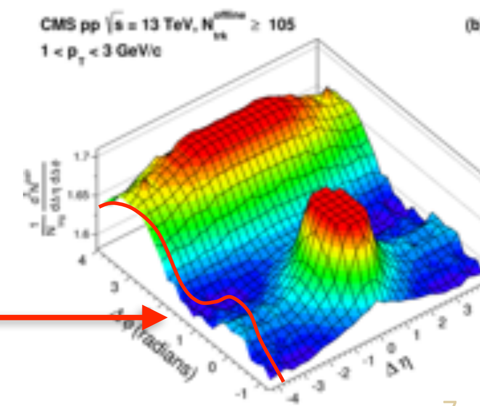



- Associated Yield per trigger

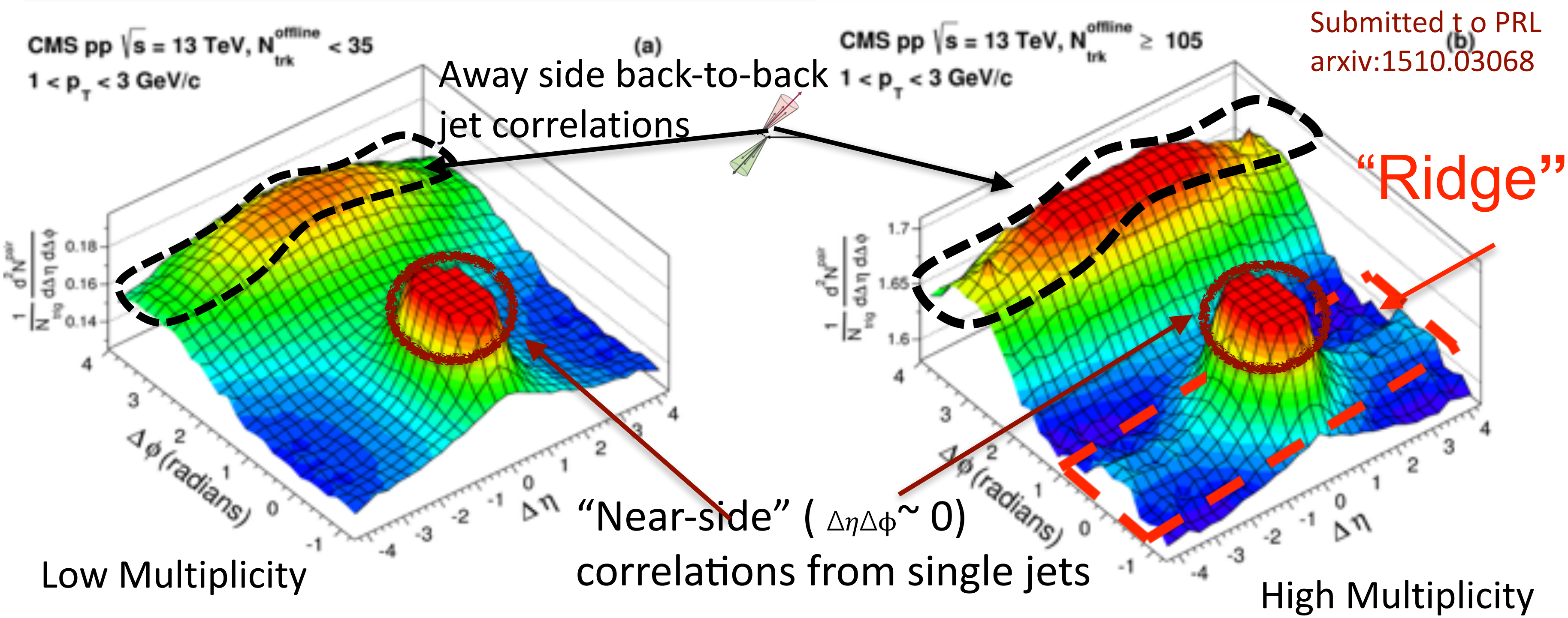
$$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

- Fourier-coefficients $V_{n\Delta}$ from $|\Delta\eta|>2$:

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1+\sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

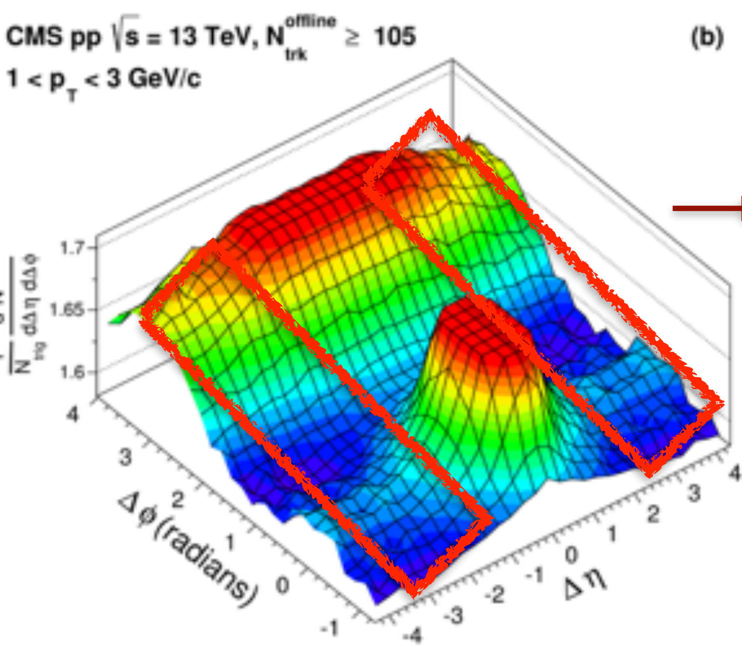


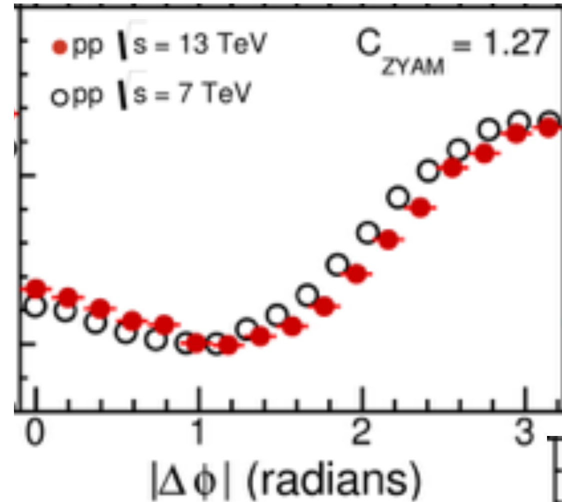
# 2D Correlation in pp collisions at 13 TeV




- Features
  - Jet peak (truncated)
  - Away Side back-to-back Jet correlations
  - Long range near side correlation "ridge"

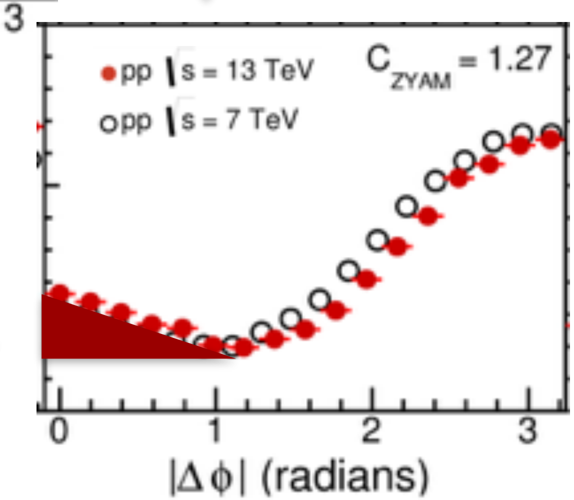
# 1Dimension Projection and Yield Extraction



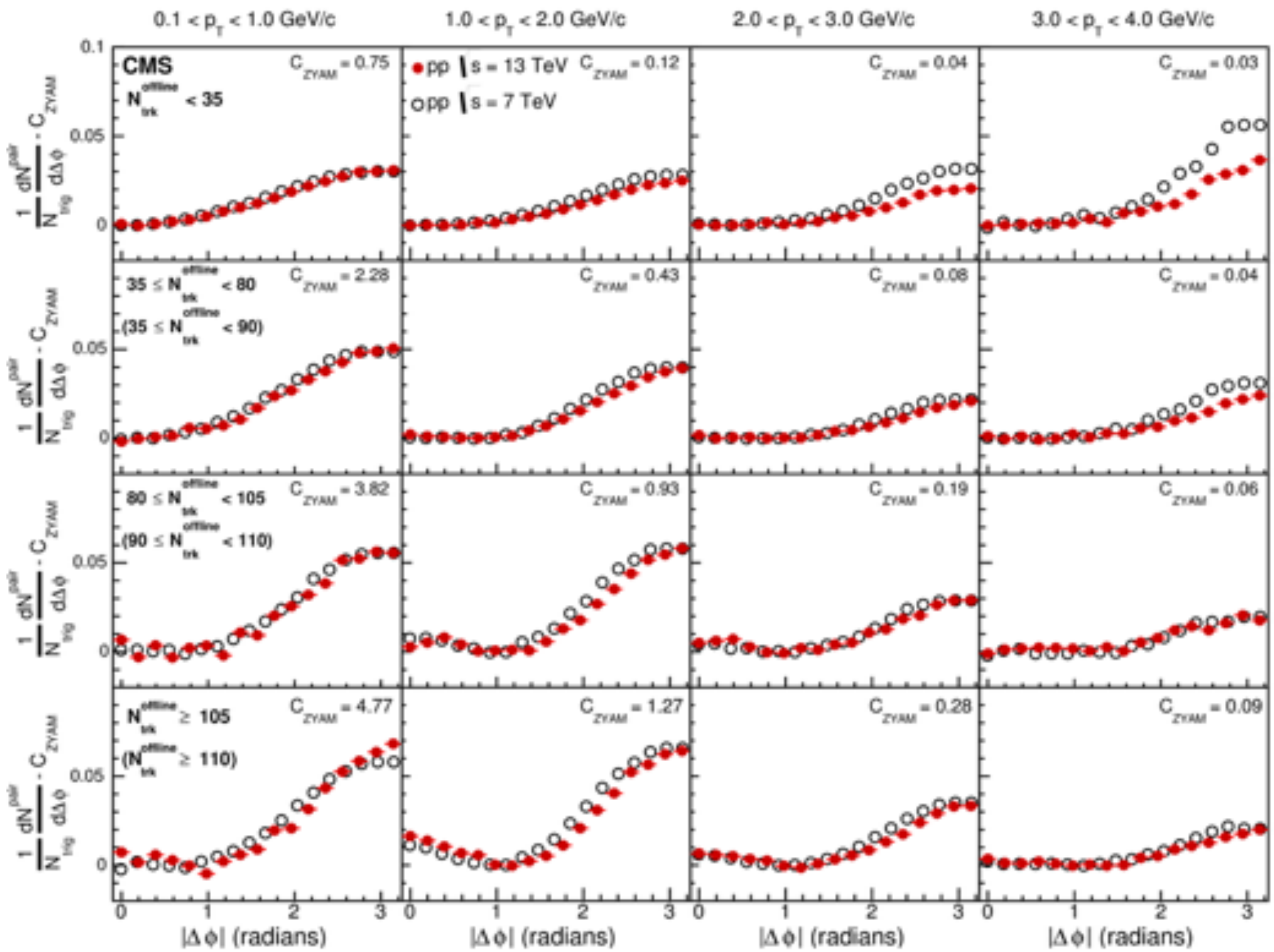

Submitted to PRL
arxiv:1510.03068

Associated Yield




- ZYAM procedure: **Z**ero **Y**ield **A**t **M**inimum (constant subtracted) in order to comparisons

# Projection in 1Dimension




Submitted to PRL
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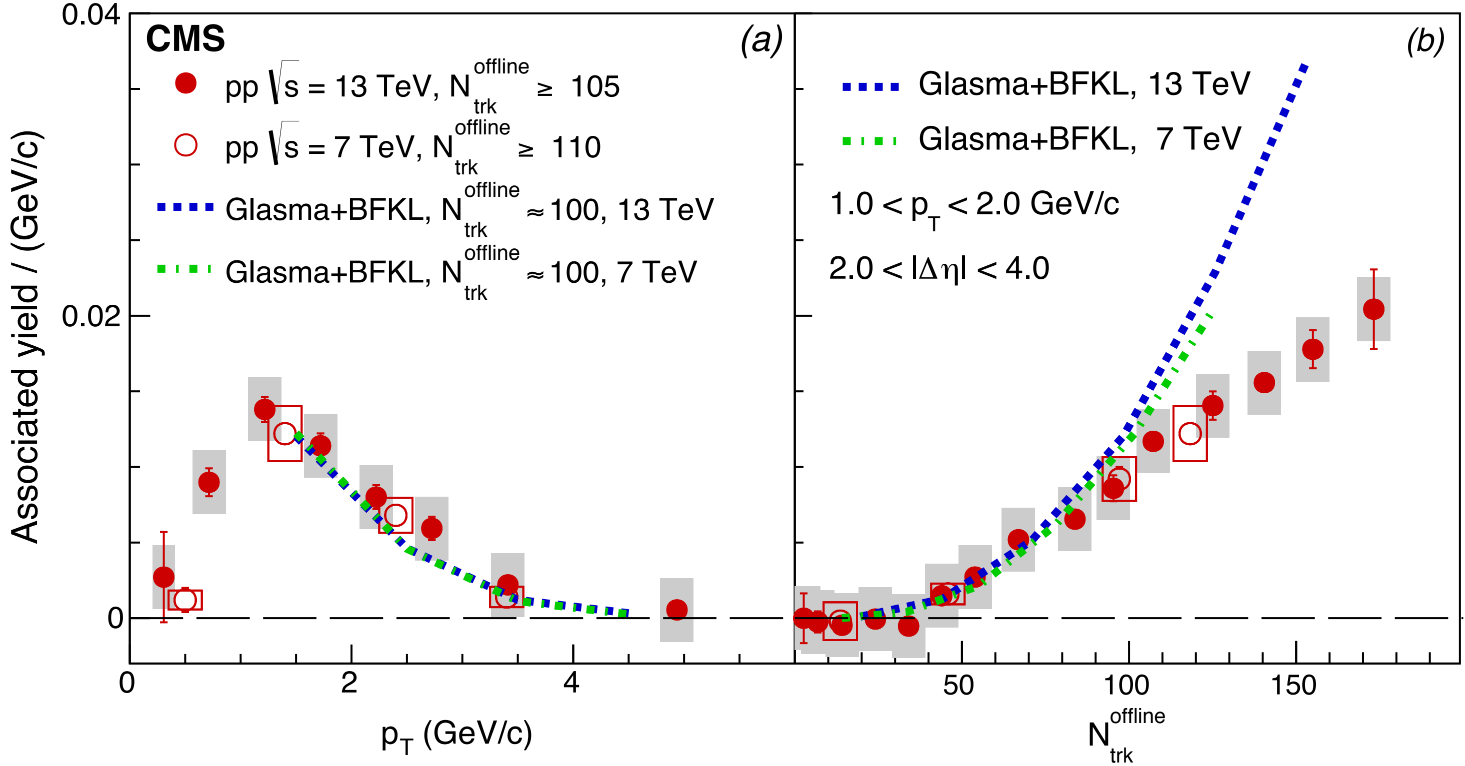
- Near-side long range correlated yield increases with multiplicity

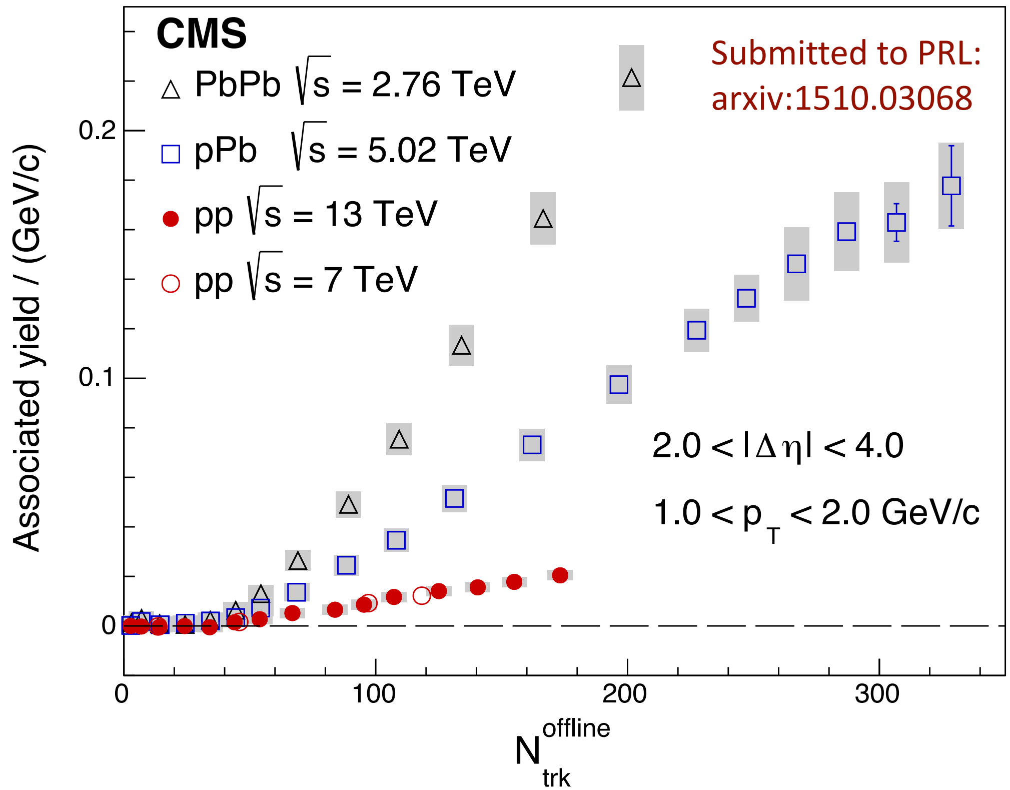
# Associated Yield vs. $p_T$ and multiplicity

Submitted to PRL:  arxiv:1510.03068




- No dependence on collision energy
- Peak between 1 and 2 GeV/c
- Caution: ZYAM can flatten out the $N_{trk}$-dependence at low $N_{trk}$

# Comparison pp, Pb and PbPb




- Strong system size dependence
- At the same multiplicity,
  - Pb+Pb: ~10 times larger yield
  - p+Pb: ~4 times larger yield

# Lessons

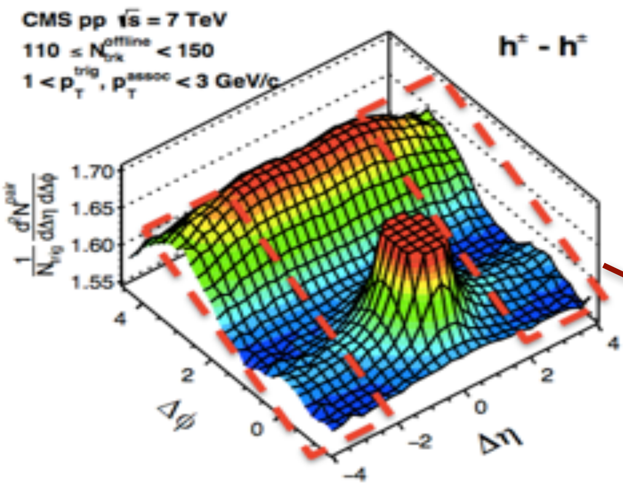
- So far what we learnt in pp collisions
  - There is no collision energy dependence of the associated yields
  - There is a rise and fall as a function of pT

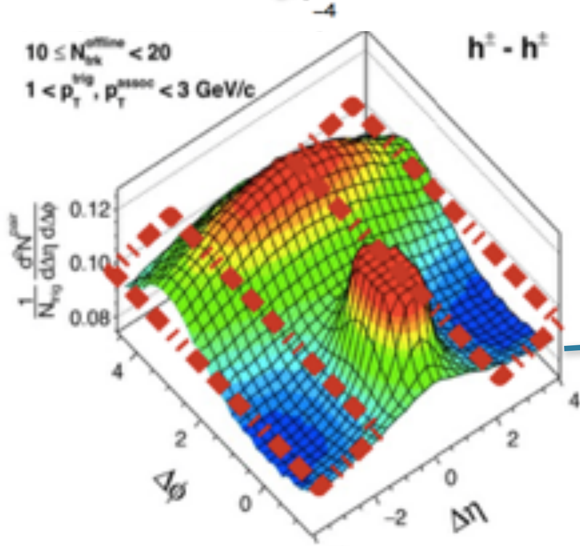
- Can we go more deeply into the question of what is the mechanism creating the “ridge” in p+p collisions, experimentally?
- For that, much more data is needed, we have to go back to our high-statistics 7 TeV p+p sample...

# Projection to 1D and Fourier fit

- Two particle correlation functions projected in ridge range ($|\Delta\eta|>2$), fit by Fourier decomposition to get $V_{n\Delta}$

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left\{1+\sum_{n} 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

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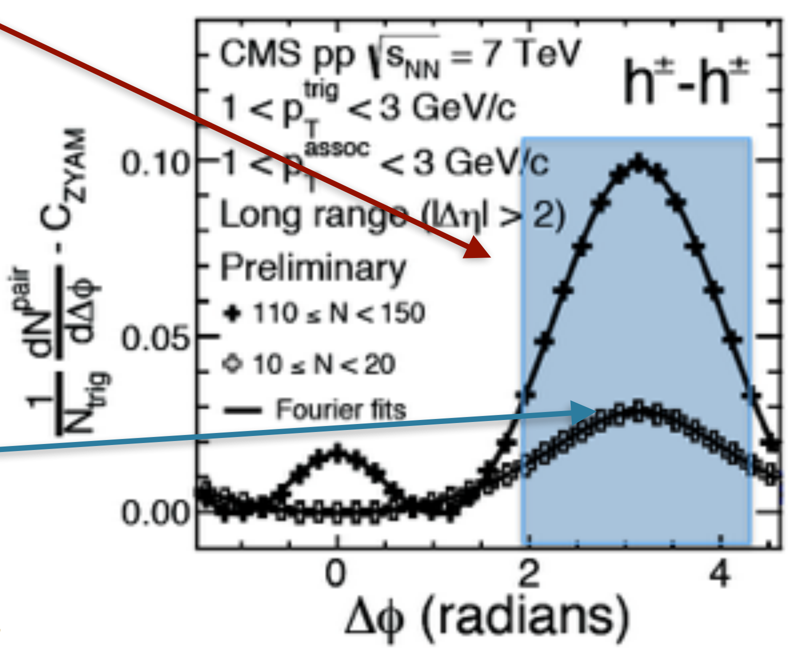
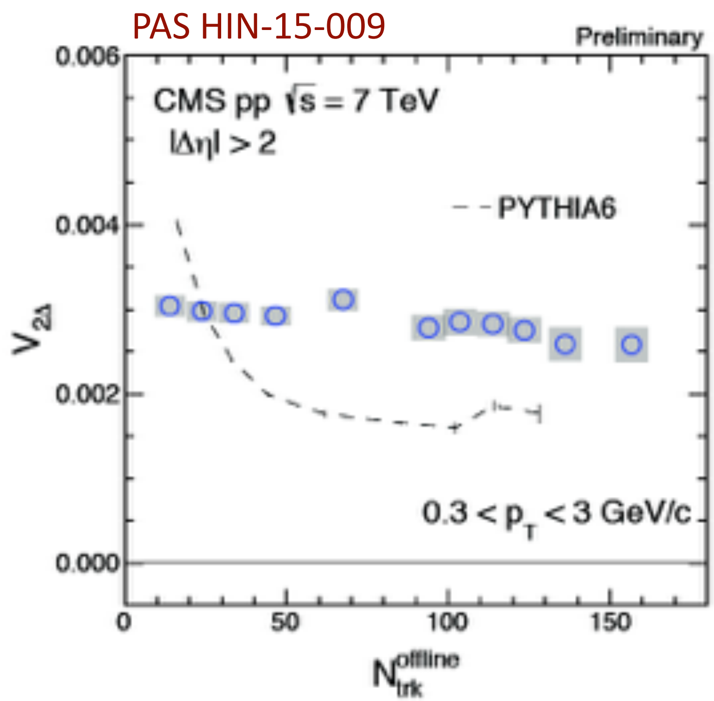
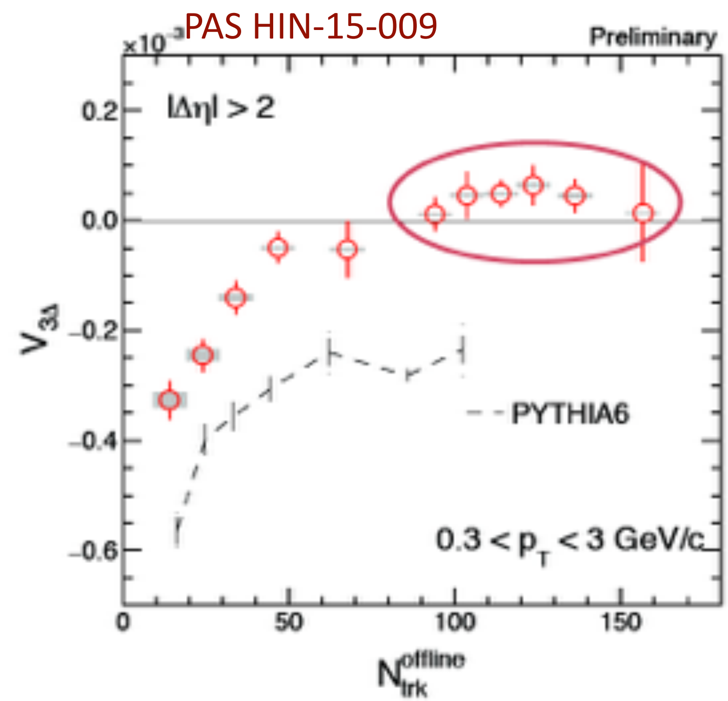


# $v_{2\Delta}$ and $v_{3\Delta}$ vs. Multiplicity




- $v_{2\Delta}$
  - MC: Only jet correlations.
  - Data: Very different trend.
- $v_{3\Delta}$
  - MC: does not predict positive $v_{3\Delta}$
  - Positive $v_{3\Delta}$ —> new phenomena!

# Jet contributions

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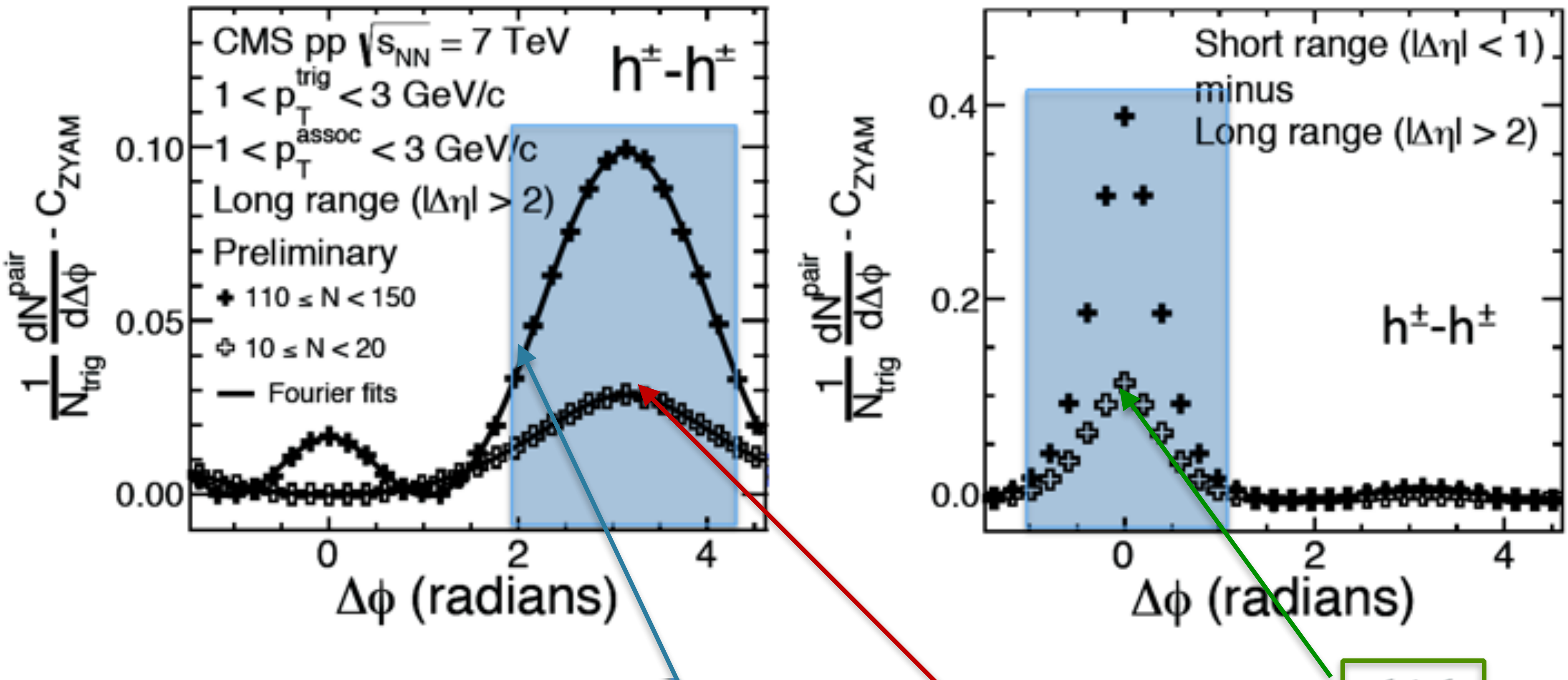


$$V_{n\Delta}^{\mathrm{sub}} \times N_{\mathrm{assoc}}^{\mathrm{high}} = V_{n\Delta}^{\mathrm{high}} \times N_{\mathrm{assoc}}^{\mathrm{high}} - V_{n\Delta}^{\mathrm{low}} \times N_{\mathrm{assoc}}^{\mathrm{low}} \times \frac{Y_{\mathrm{jet}}^{\mathrm{high}}}{Y_{\mathrm{jet}}^{\mathrm{low}}}$$

# After Jet Contribution Corrections

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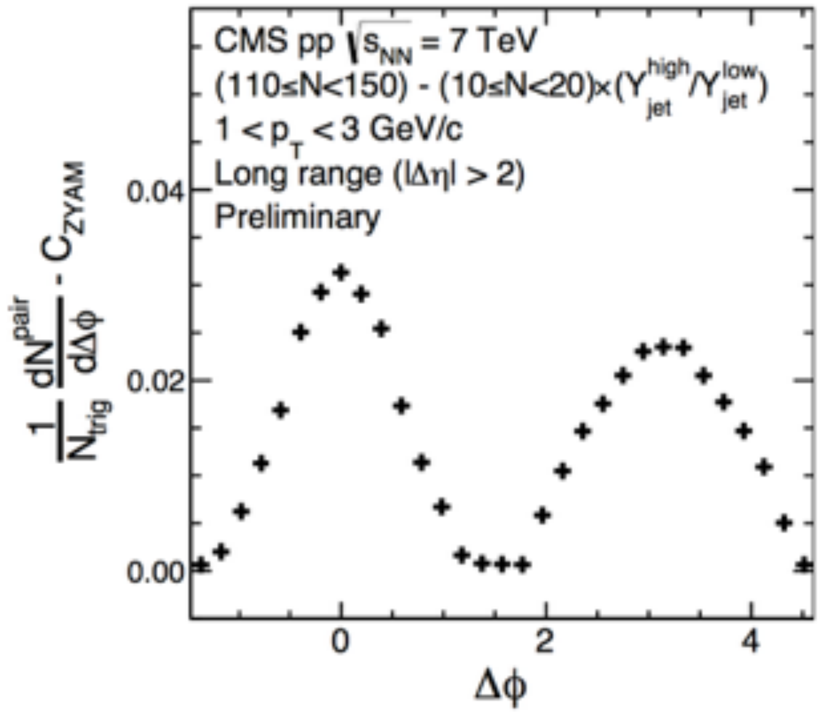
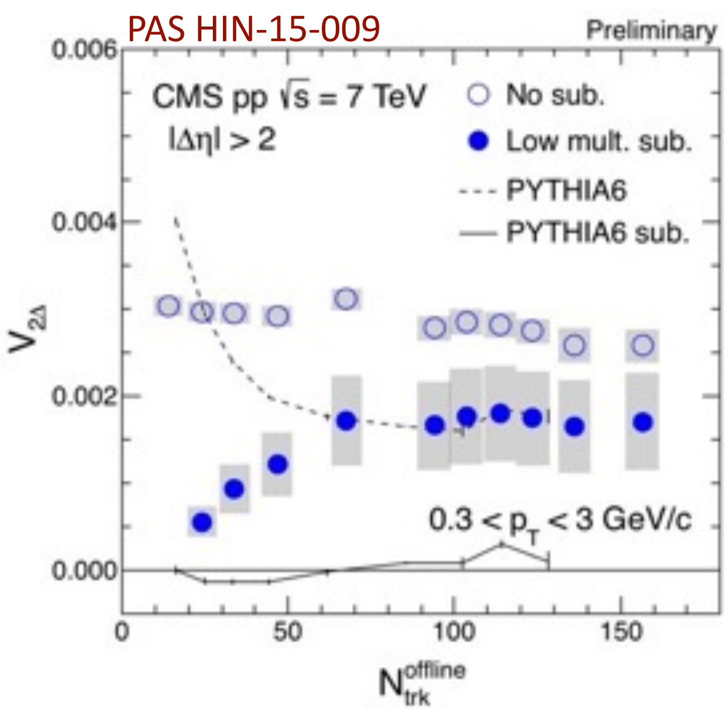
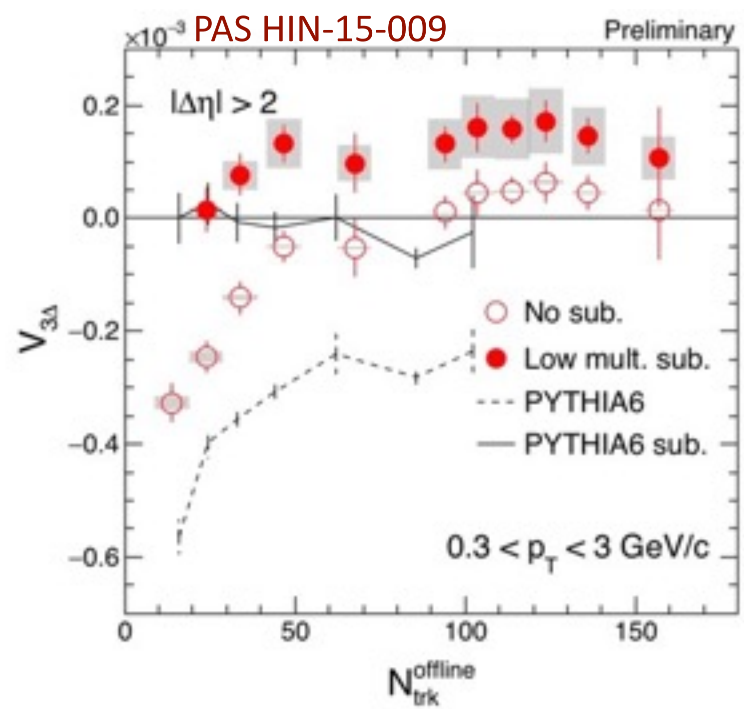



$V_{n\Delta}$ after subtraction:
$V_{1\Delta}^{sub} \approx 0.0003$
$V_{2\Delta}^{sub} \approx 0.0042$
$V_{3\Delta}^{sub} \approx 0.0008$

- Assumptions in this procedure:
  - at very low multiplicity $V_n$ is dominated by jets
  - jet-like correlation is not modified from low to high multiplicity
  - no decorrelation between near and away side jets
- "Double ridge" structure similar to pPb and PbPb

# After Jet Subtraction: $v_{n\Delta}$




- $V_{2\Delta}$ shows an increasing trend after subtraction
- $V_{3\Delta}$ is always positive
- Subtraction also brings PYTHIA model curves to zero

# Results: $v_2$ vs. Multiplicity

- Using the factorization:

$$v_n(p_T^{trig}) = \frac{V_{n\Delta}(p_T^{trig}, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}$$

$0.3<p_T<3$ GeV

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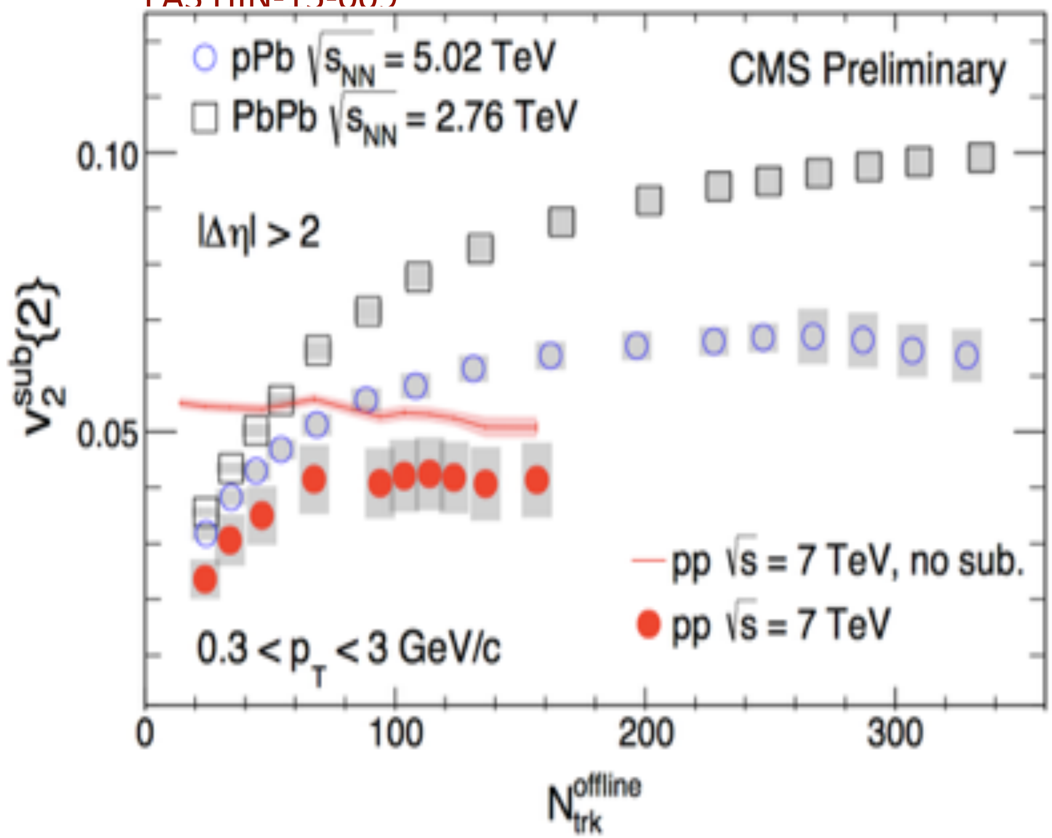


- $v_2$ (pp) is around 0.04 at high multiplicity
- Hierarchy: $v_2$(pp) < $v_2$(pPb) < $v_2$(PbPb)
- In a hydro picture: due to very different initial geometry

# Results: $v_3$ vs. Multiplicity

- Using the factorization:

$$v_n(p_T^{trig}) = \frac{V_{n\Delta}(p_T^{trig}, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}$$

0.3<$p_T$<3 GeV

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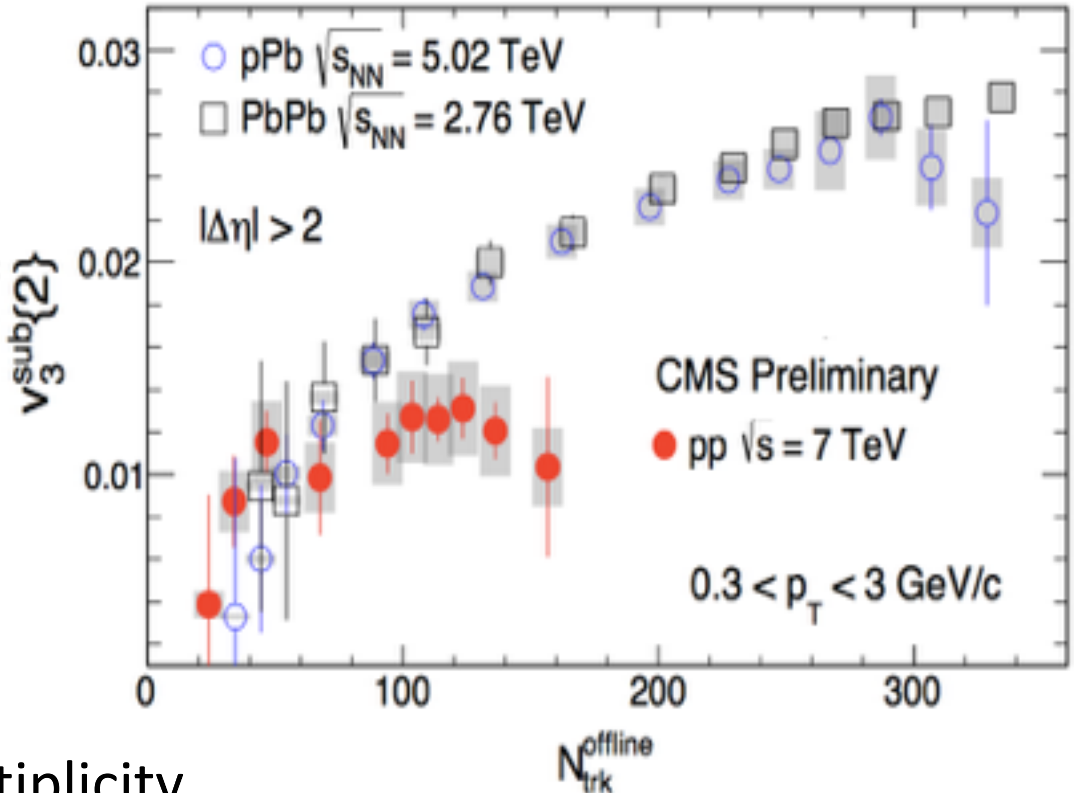


- $v_3$(pp) ≈ 1.2% at high multiplicity
- In a hydro picture: due to different fluctuations of the initial geometry
- Constraining the shape (fluctuations) of the proton

# $V_0$ Reconstruction and Correlations

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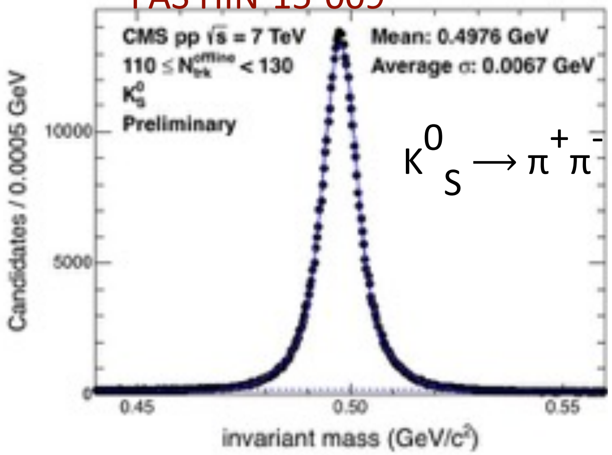


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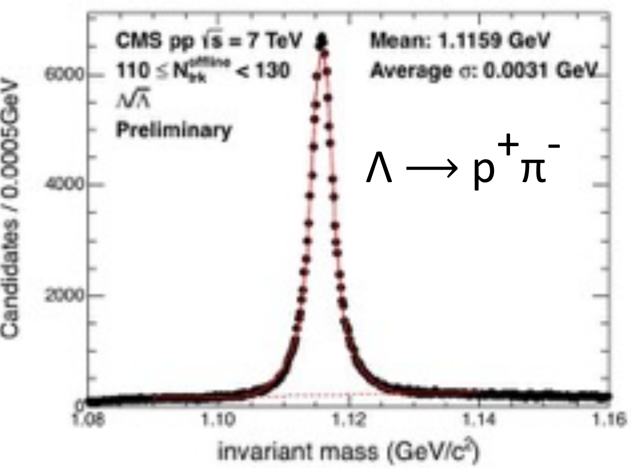


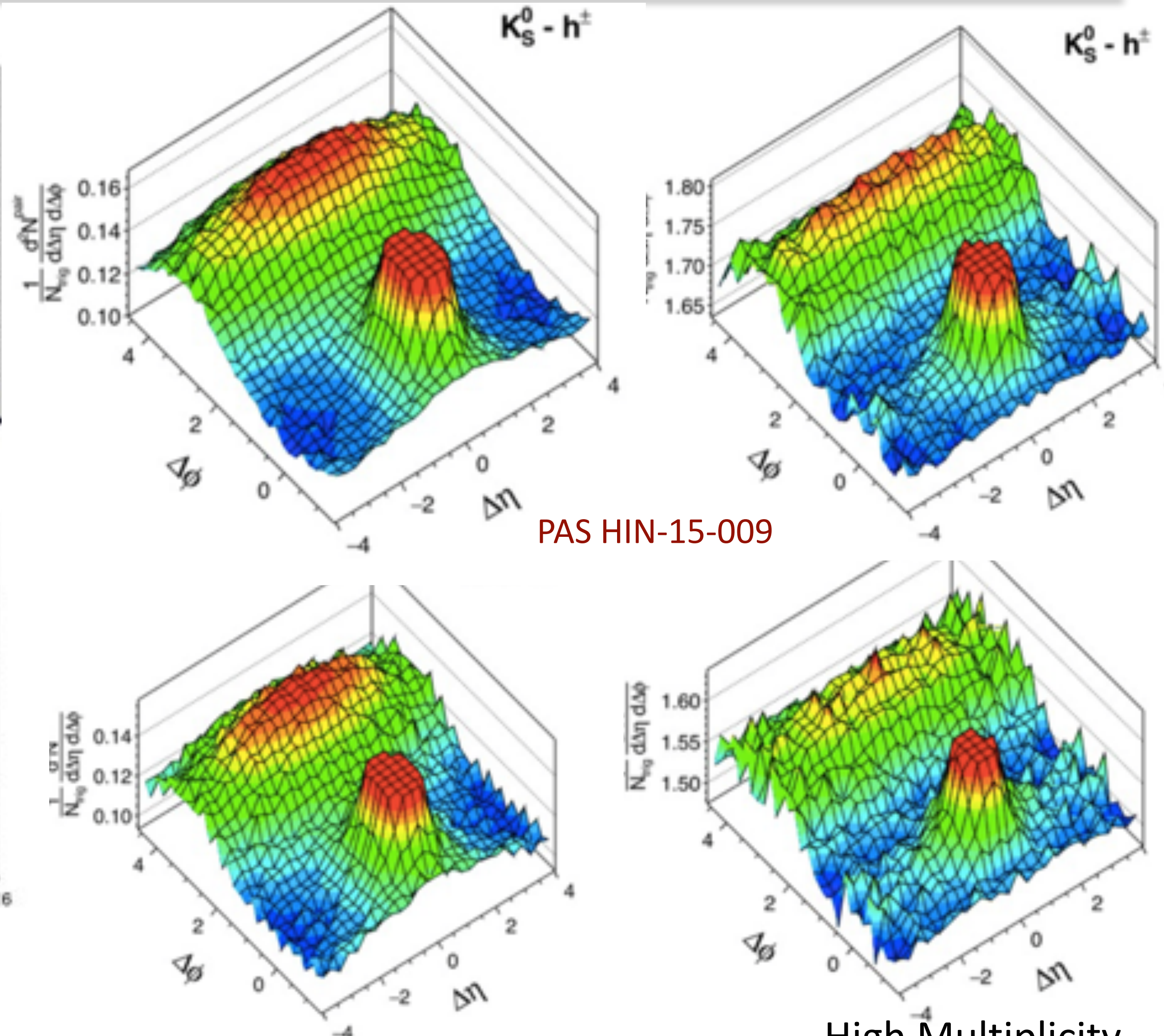


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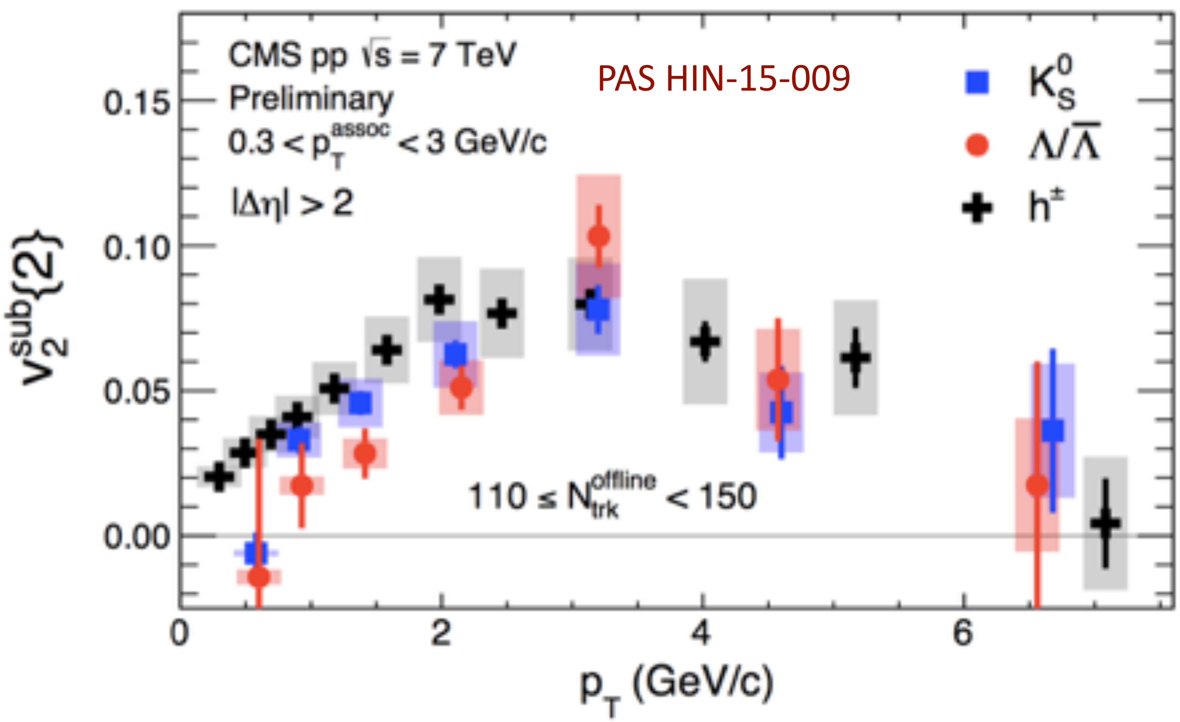
High Multiplicity

Low Multiplicity

# Results: pid $v_2$ vs. $p_T$




- No mass dependence of $v_2$ from jet correlation at low multiplicity
  - Dominated by back-to-back jets
- Mass ordering in low $p_T$ region at high multiplicity
- Similar to A+A and p+A collisions!

# Results: 4-Particle Correlations

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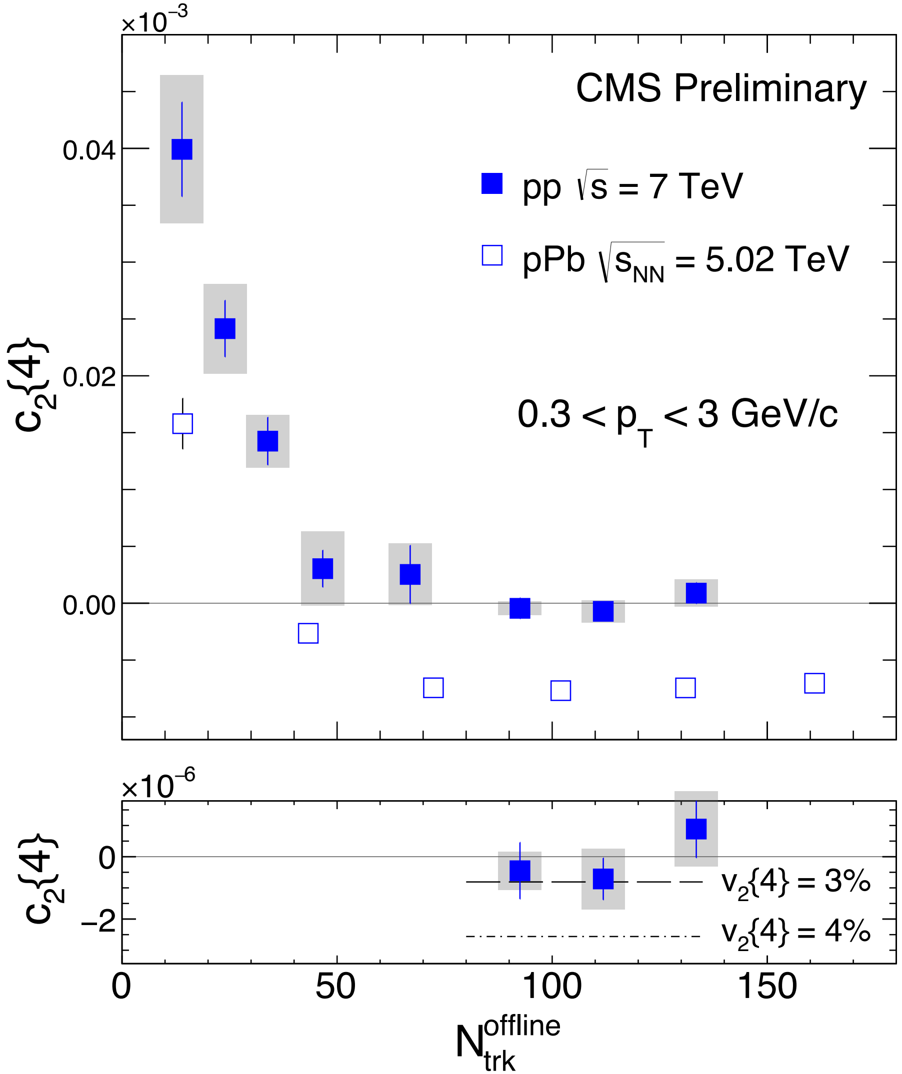



- **4-particle** correlations studied with the cumulant method

$$c_2\{4\} = \langle\langle e^{-2i(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\times\langle\langle e^{-2i(\phi_1-\phi_2)}\rangle\rangle^2$$

$$v_2\{4\}^4 = -c_2\{4\}$$

- $c_2\{4\}$ decreases with multiplicity, similarly to pPb
- Not (yet) significant negative signal (which would mean a $v_2\{4\}$ signal, collectivity...)

# Summary

- First measurements of two particle correlation at 13 TeV in pp collisions
- Second/order ($v_2$) and third/order ($v_3$) anisotropy of charge hadron, $K^0_S$ and Λ for high multiplicity pp collisions
- Multiplicity dependent (charge hadron)
  - overall $v_2(pp) < v_2(pPb) < v_2(PbPb)$
  - $v_3(pp)$ deviates from $v_3$(pPb & PbPb) at high multiplicity
- Transverse momentum dependent (PID)
  - Mass ordering clearly observed in low $p_T$ region

# CMS Results on Two Particle Correlation

- Other CMS results on correlations and more:

  ✓https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

  ✓https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

**Thank you**

# Back Up

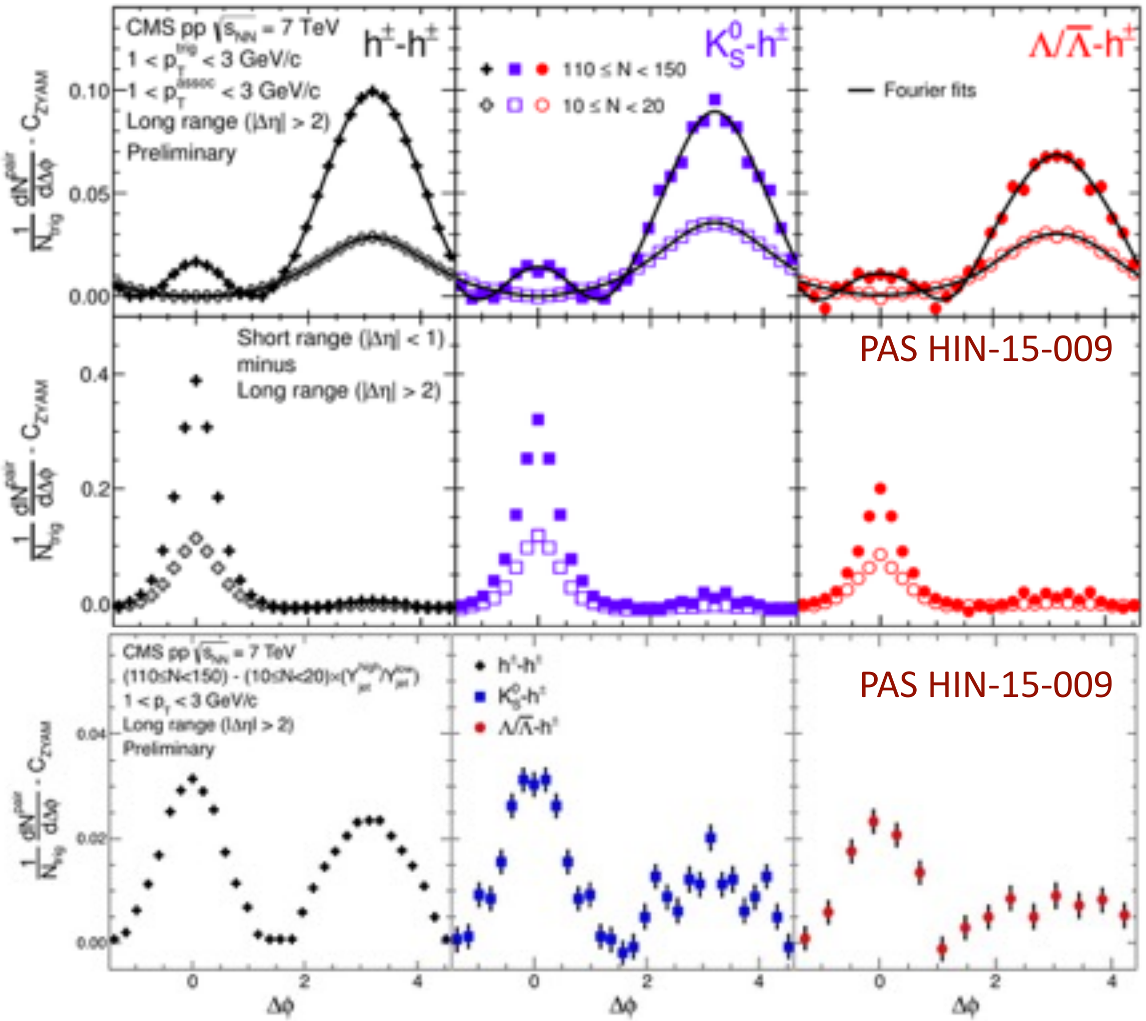
# Systematics

| Systematic uncertainty sources | Abs. uncertainty ($\times 10^{-3}$) |
|---|---|
| Track quality requirements | 0.6 |
| Trigger efficiency | 1.5 |
| Correction for tracking efficiency | $<0.08$ |
| Effect of pile-up events | 0.6 |
| Vertex selection | 1.0 |
| ZYAM procedure | 0.7 |
| Total | 2.1 |

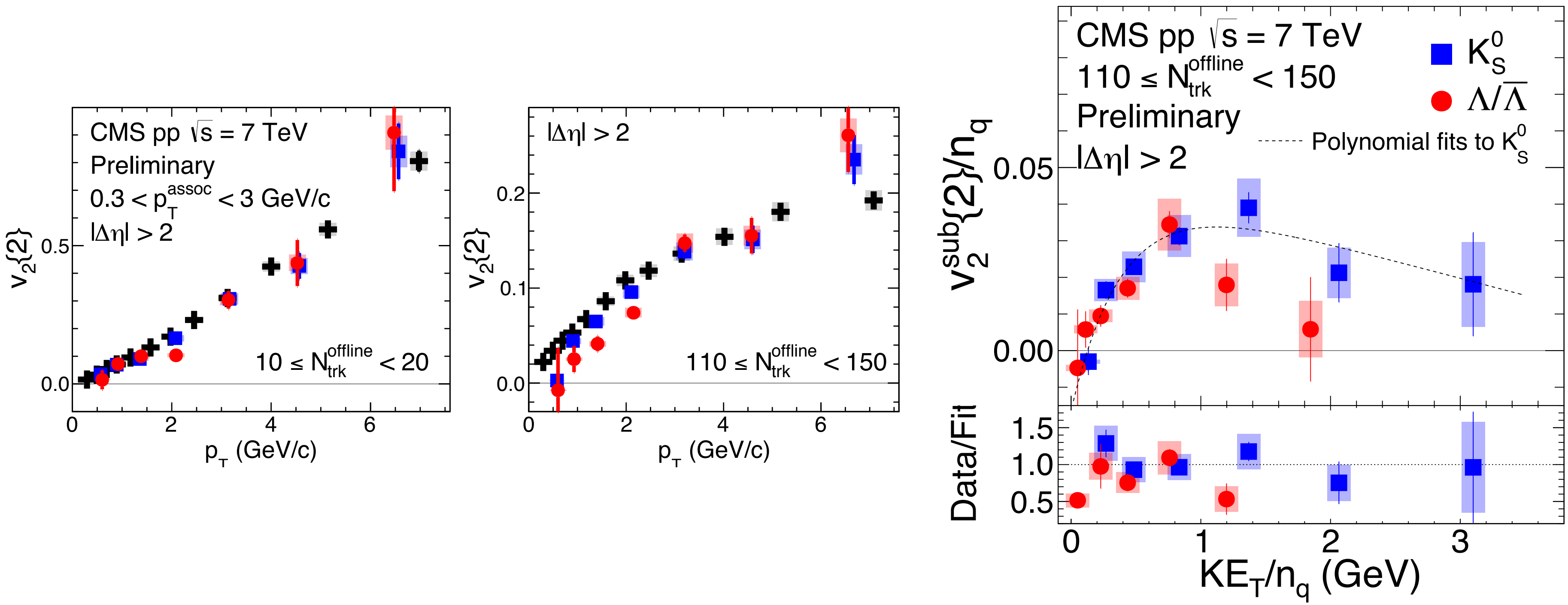
# 1D Projections and Jet Subtraction

- The procedure can be repeated, pairing a **$V^0$ and a hadron**

- **Jet Subtraction:** same way as it was done for charged hadrons



# Results: pid v2 and NCQ Scaling

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