Collectivity of (non-) strange hadrons in high-multiplicity pp with CMS

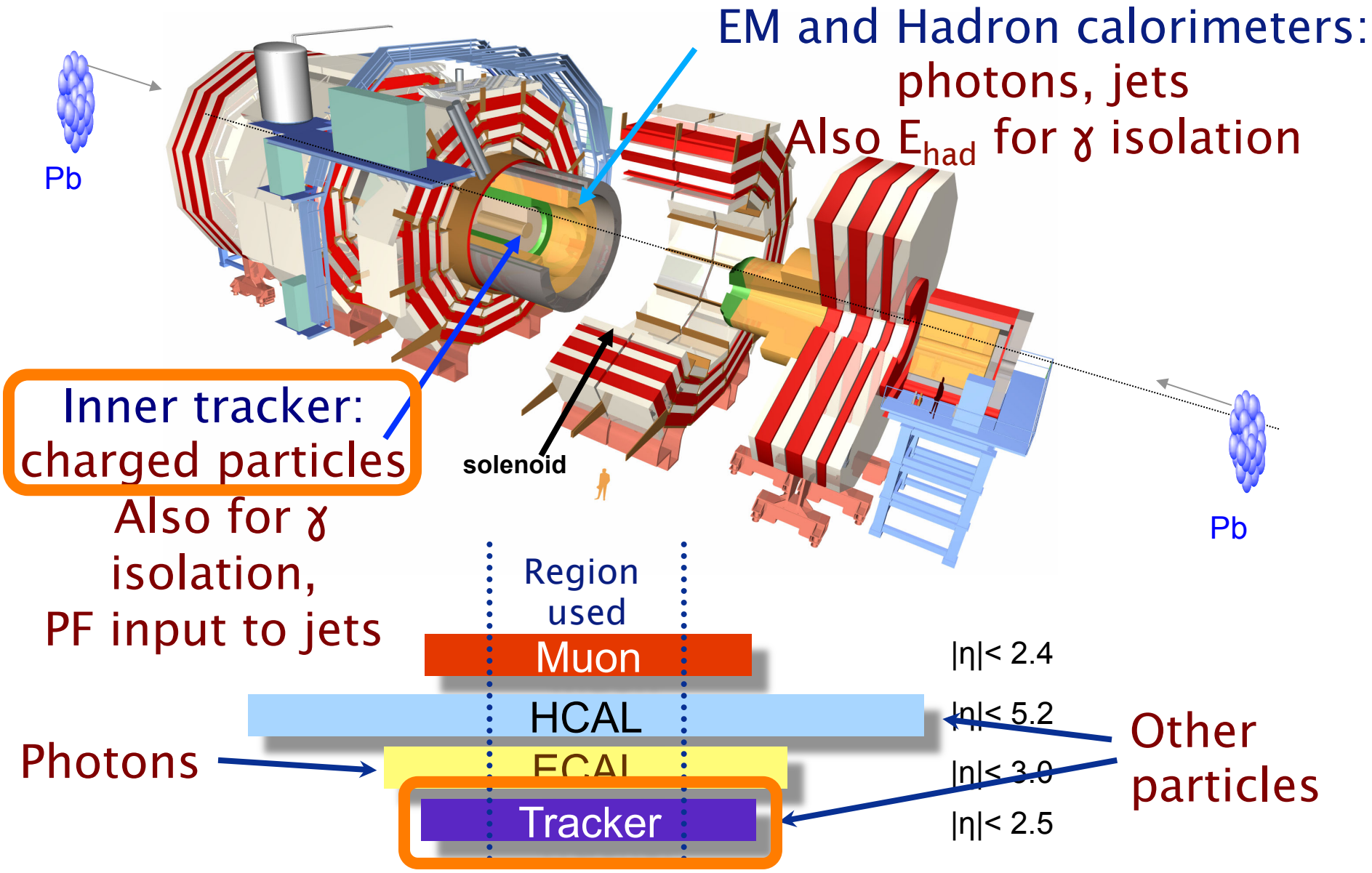
George Stephans
For the CMS Collaboration

Newer CMS data to be discussed

- HIN-16-010: pp
  - > v_2 and v_3 of charged particles vs event multiplicity
  - > v_2 of K_S^0 and $\Lambda/\overline{\Lambda}$ vs event multiplicity and p_T
  - > Multiparticle cumulant analysis for charged particles vs event multiplicity
  - > arXiv: 1606.06198, submitted to Phys Lett B
- HIN-15-006: pp/pPb/PbPb
  - > Spectra of K_S^0 and $\Lambda/\overline{\Lambda}$
  - > arXiv: 1605.06699, Submitted to Phys Lett B

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

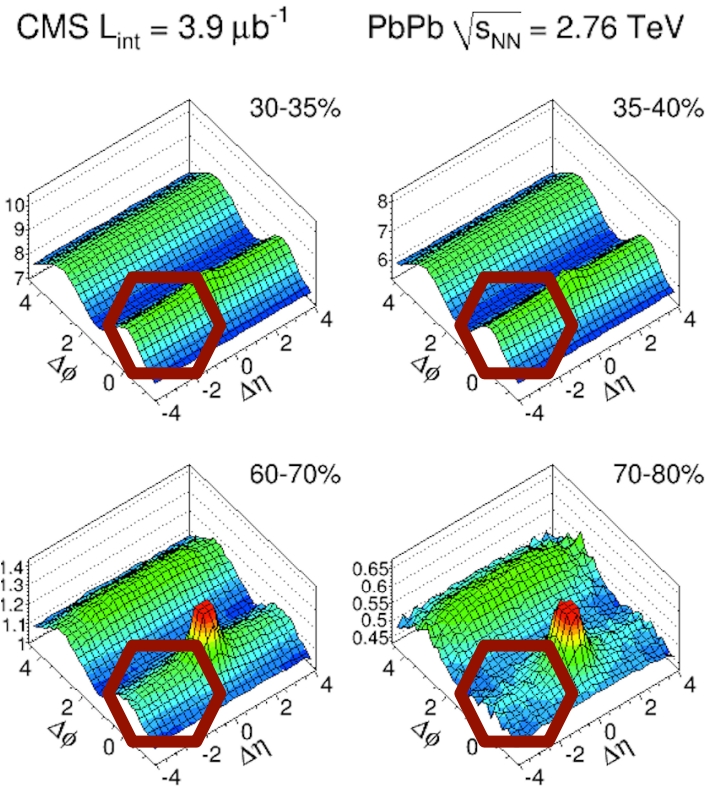
CMS detector



s quark mass: Nature's gift to Heavy Ion physics

- s quark mass
  - > Largely responsible for the kaon mass falling between π and proton => PID with TOF or dE/dx.
  - > Big enough that kaon decays in a "short" time
  - > Small enough that it decays in a macroscopic distance (unlike, for example, B mesons)
  - > It's just right for particles like K^0_S and $\Lambda/\bar{\Lambda}$ to decay in a "reasonable" distance and be "identified" because of their V^0 topology
- This last feature is exploited in the analysis shown in this talk

Where we started…



EPJC 72 (2012) 2012

- Correlations of pairs of charged particles emitted in heavy ion collisions were observed to show a very clear "ridge", a significant near-side (small ΔΦ) long-range (large Δη) enhancement.

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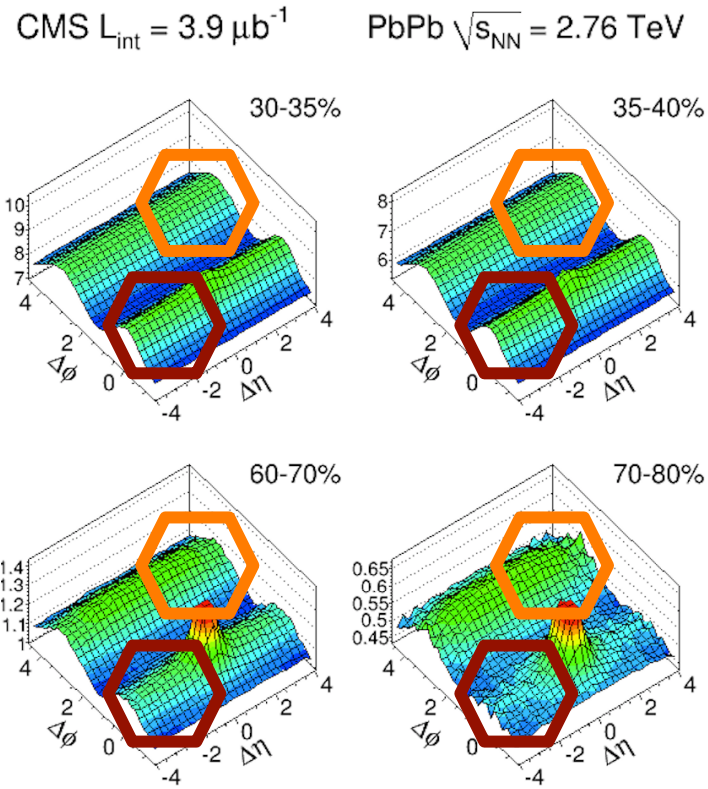
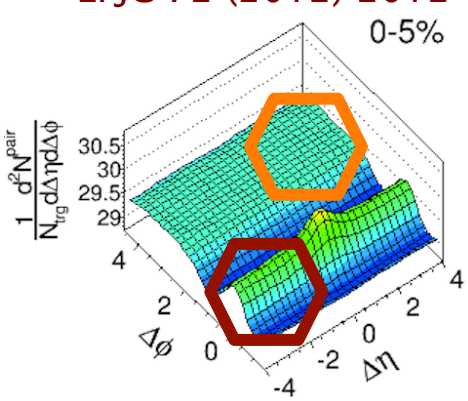
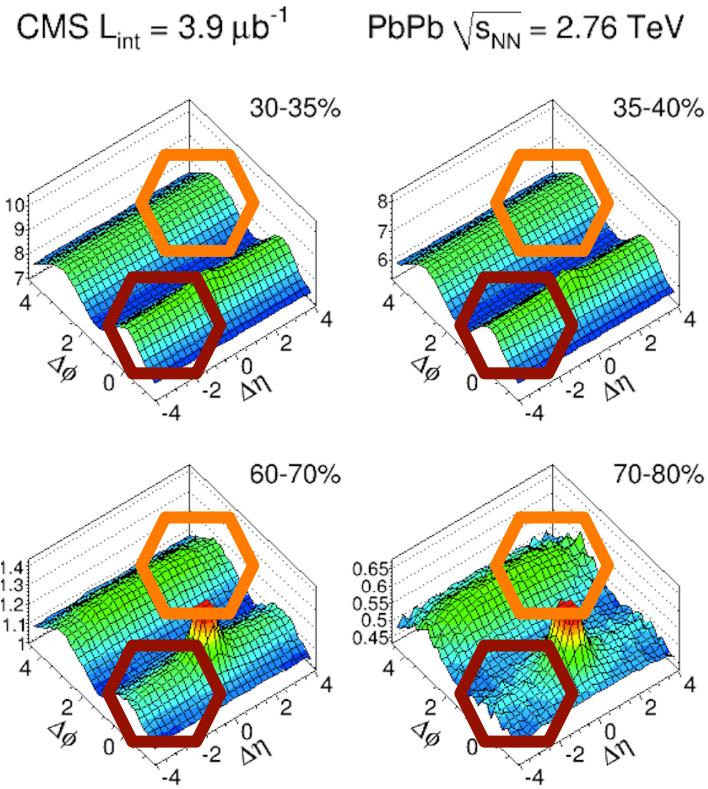


EPJC 72 (2012) 2012



- Correlations of pairs of charged particles emitted in heavy ion collisions were observed to show a very clear "ridge", a significant near-side (small ΔΦ) long-range (large Δη) enhancement.
- As well as a broad away-side (large ΔΦ) structure.

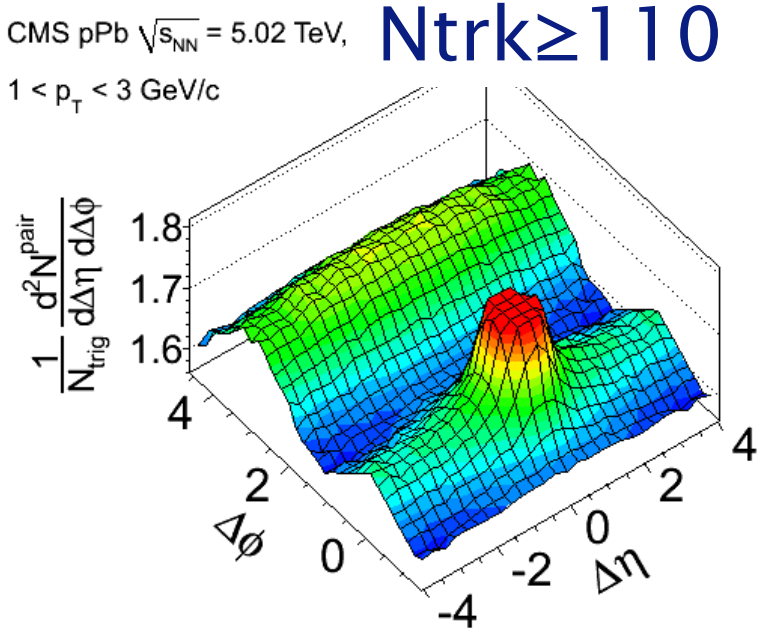
Where we started…



EPJC 72 (2012) 2012

- Recognizing the importance of fluctuations and triangular flow killed off the "Mach cone" and other distractions.
- The "ridge" (and most of the away-side) result from hydrodynamic flow of a dense asymmetric medium.
- Now being extensively studied to understand the detailed properties of the medium.

Then something strange (not the quark) happened!



PLB 718 (2013) 795

- Ridge in pPb collisions!
- But only in events with a very high multiplicity.
- Who ordered that???

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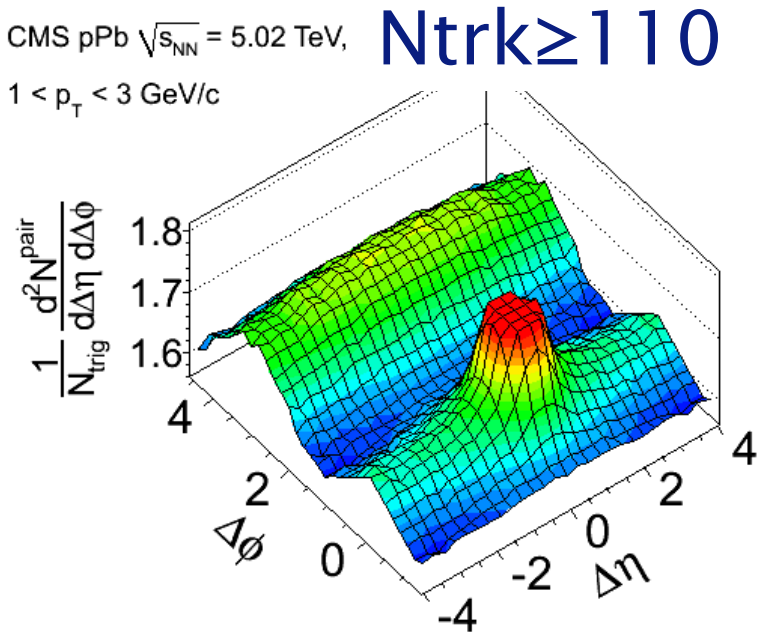
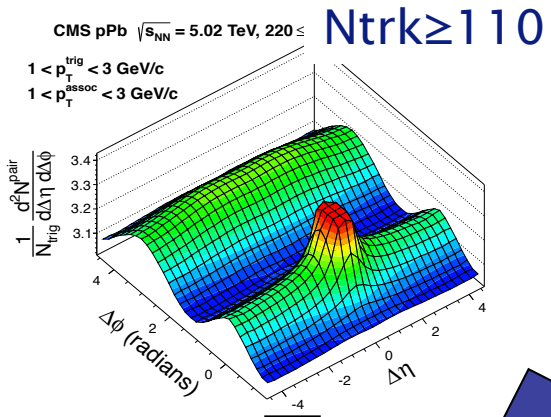


PLB 718 (2013) 795

- Ridge in pPb collisions!
- But only in events with a very high multiplicity.
- Who ordered that???

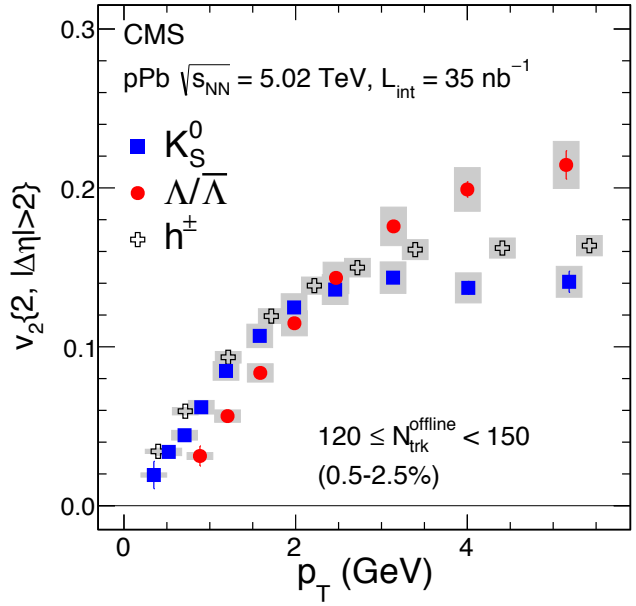
- Many detailed studies followed to try to understand the nature and origin of these near-side (small $\Delta\Phi$) long-range (large $\Delta\eta$) correlations in "small" systems.

Ridge studies in pPb (now with strangeness)



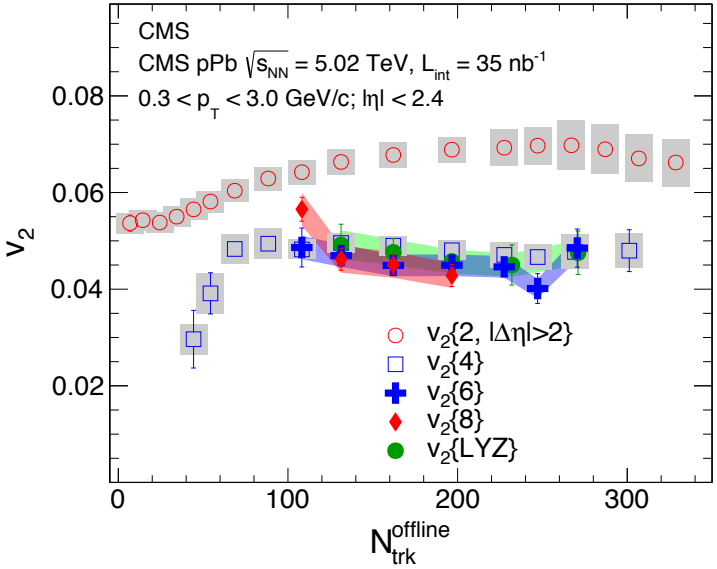
Ntrk≥110

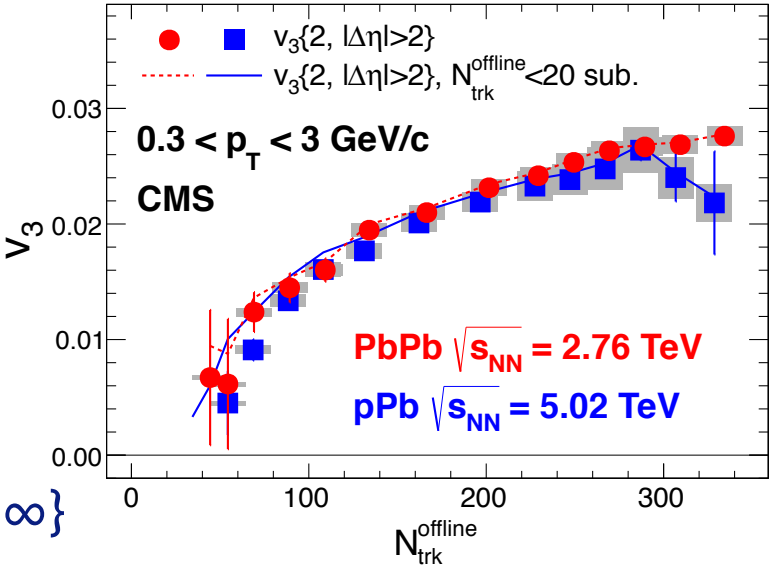
PRL 115 (2015) 012301



PLB 742 (2015) 200

Mass ordering (using strangeness)





v_3 Similar to Pb-Pb

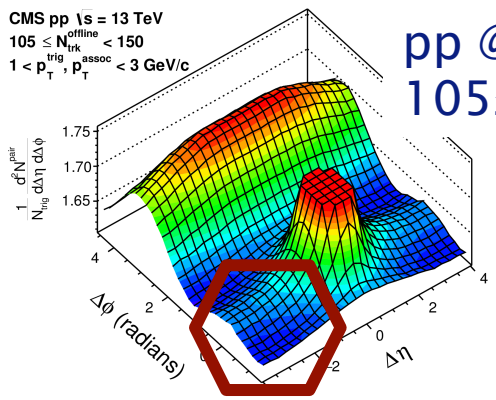
PLB 724 (2013) 213

$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$

What we learned for pPb ridge

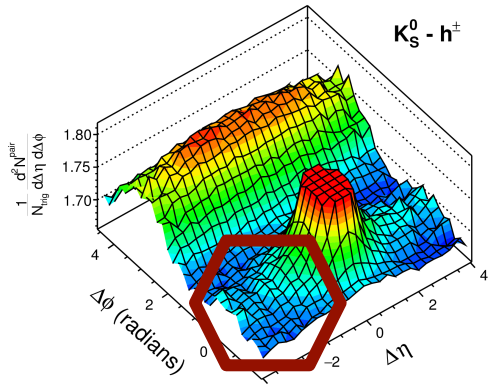
- It is a collective effect
  - > v_2 from multi-particle correlations all about equal
- Importance of fluctuations
  - > v_3 about the same for pPb and PbPb
- Suggestion of hydrodynamic flow
  - > Mass ordering of elliptic flow versus p_T (but other models might also explain this feature)

But the strangest thing of all!

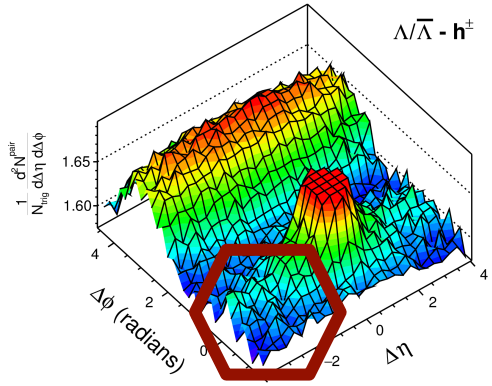


pp @ 13 TeV
105≤Ntrk≤150

charged particles



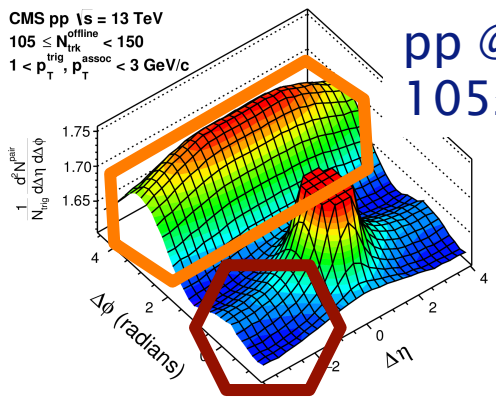
K^0_S-$h^{\pm}$



$\Lambda/\bar{\Lambda}$-$h^{\pm}$

- Ridge in high mult pp!!
- First with charged particles in pp @ 7 TeV in 2010 (JHEP 09 (2010) 091).
- Now found for both charged and strange particles in pp @ 13 TeV (CMS-HIN-16-010).

But the strangest thing of all!



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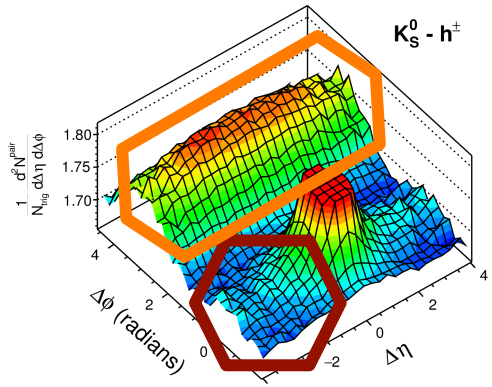

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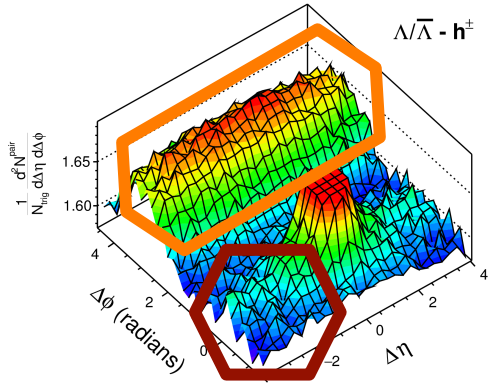
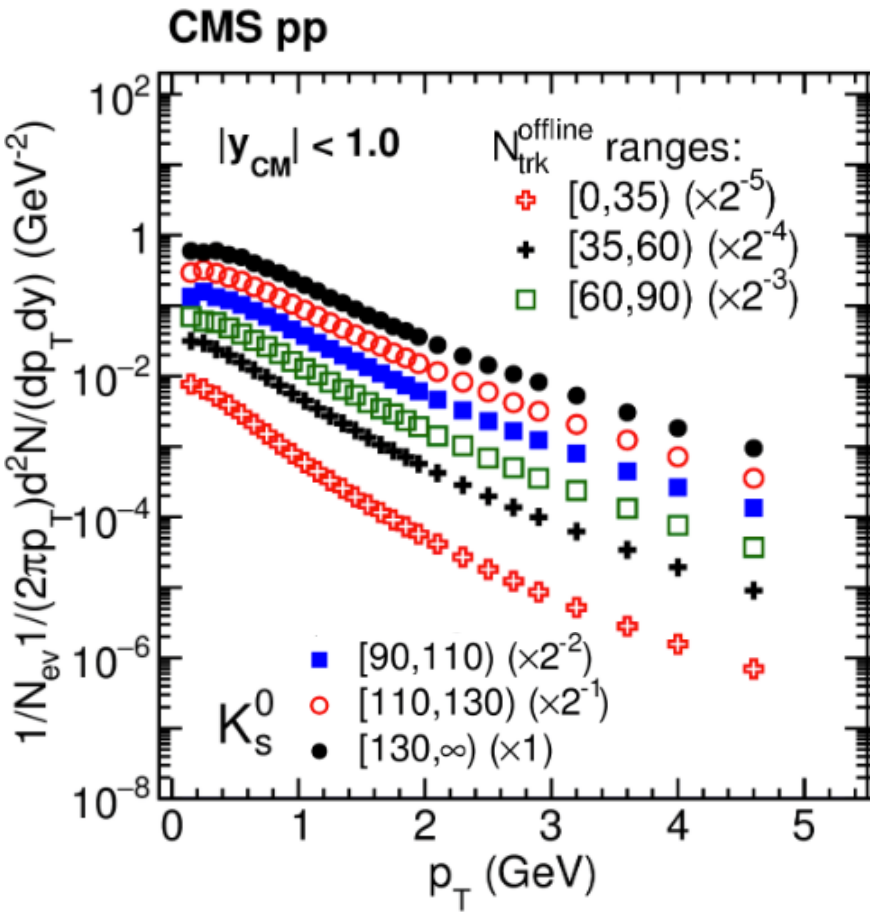


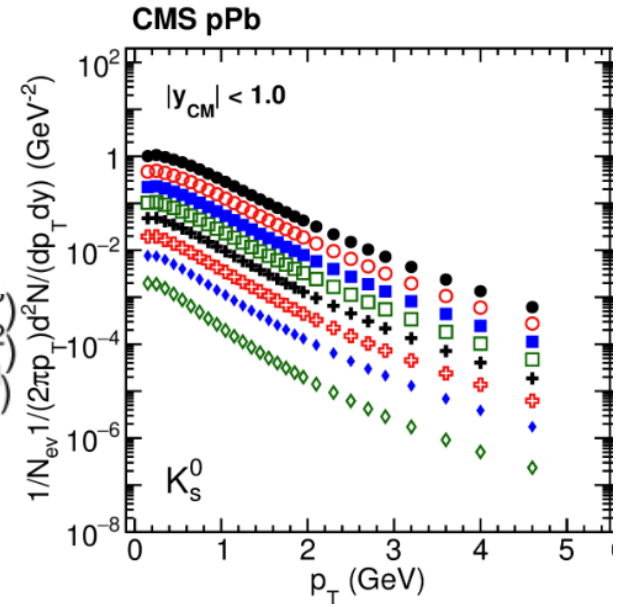
$\Lambda/\bar{\Lambda}$-$h^{\pm}$

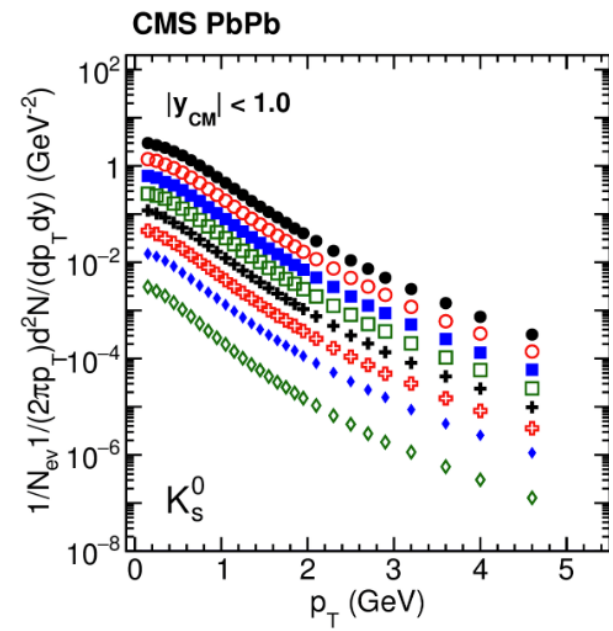
- Ridge in high mult pp!!
- First with charged particles in pp @ 7 TeV in 2010 (JHEP 09 (2010) 091).
- Now found for both charged and strange particles in pp @ 13 TeV (CMS-HIN-16-010).
- However, they are harder to study because here the away-side is dominated by the effects of jets

Spectra of particles in high-mult pp



$N_{trk}^{offline}$ ranges:
- [0,35) (×2^-7)
- [35,60) (×2^-6)
- [60,90) (×2^-5)
- [90,120) (×2^-4)
- [120,150) (×2^-3)
- [150,185) (×2^-2)
- [185,220) (×2^-1)
- [220,260) (×1)

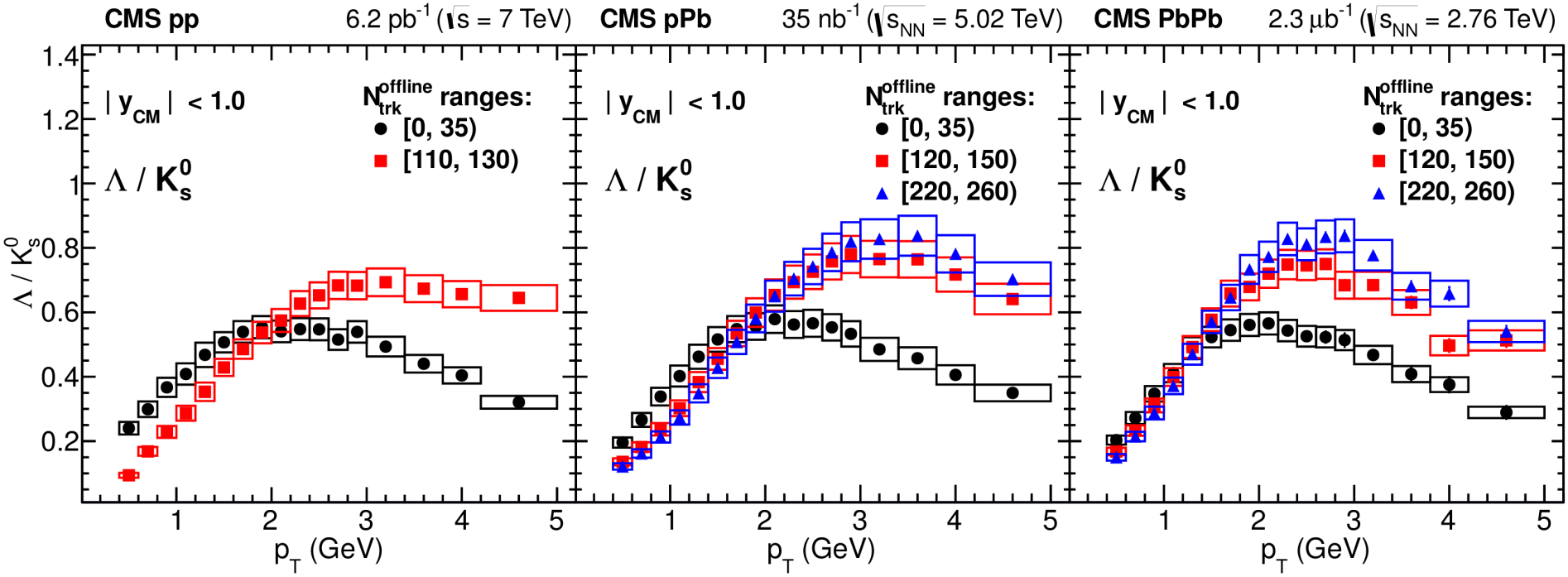




Spectra qualitatively similar

CMS HIN-15-006

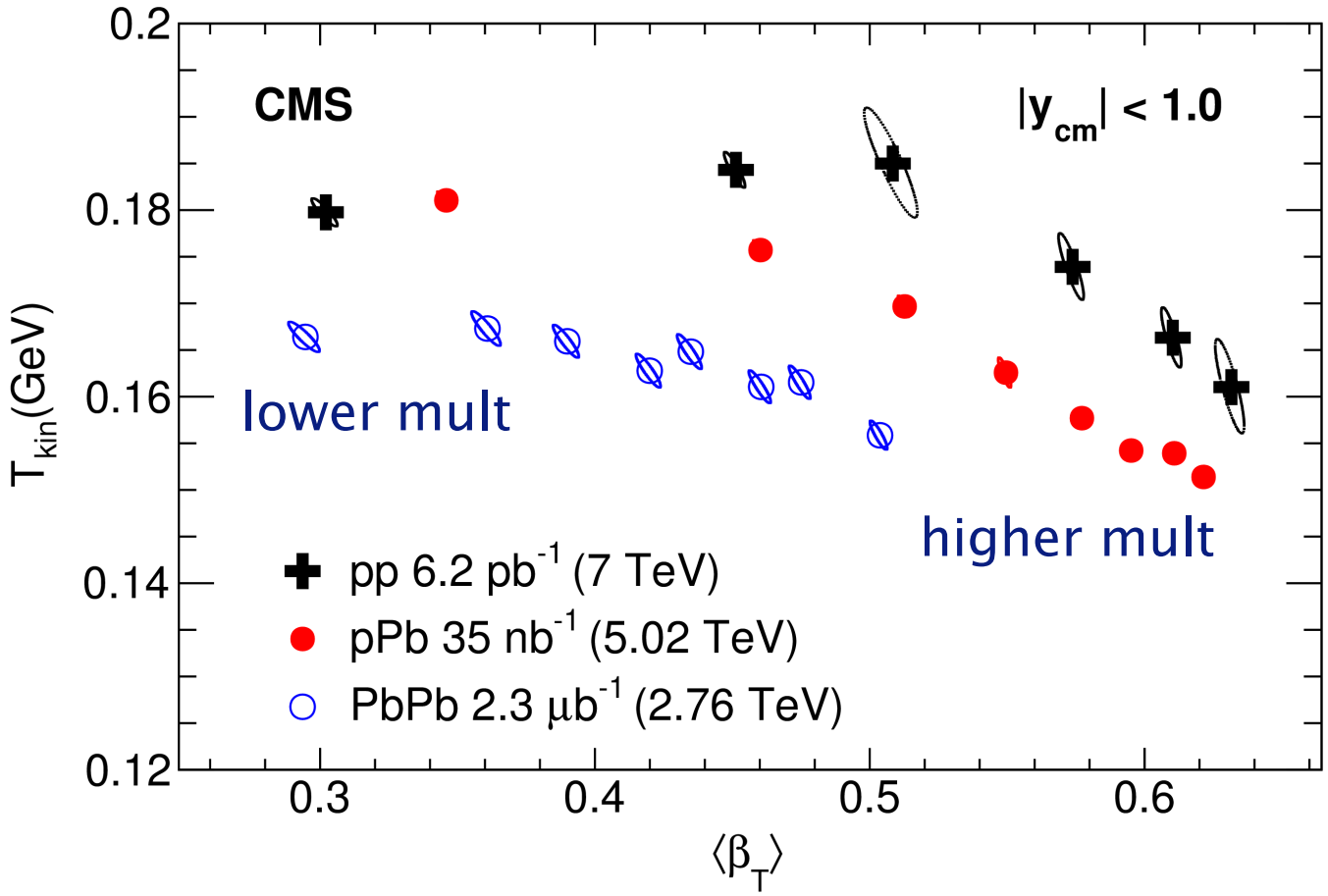
Spectra of particles in high-mult pp



Especially particle ratios

CMS HIN-15-006

Spectra of particles in high-mult pp



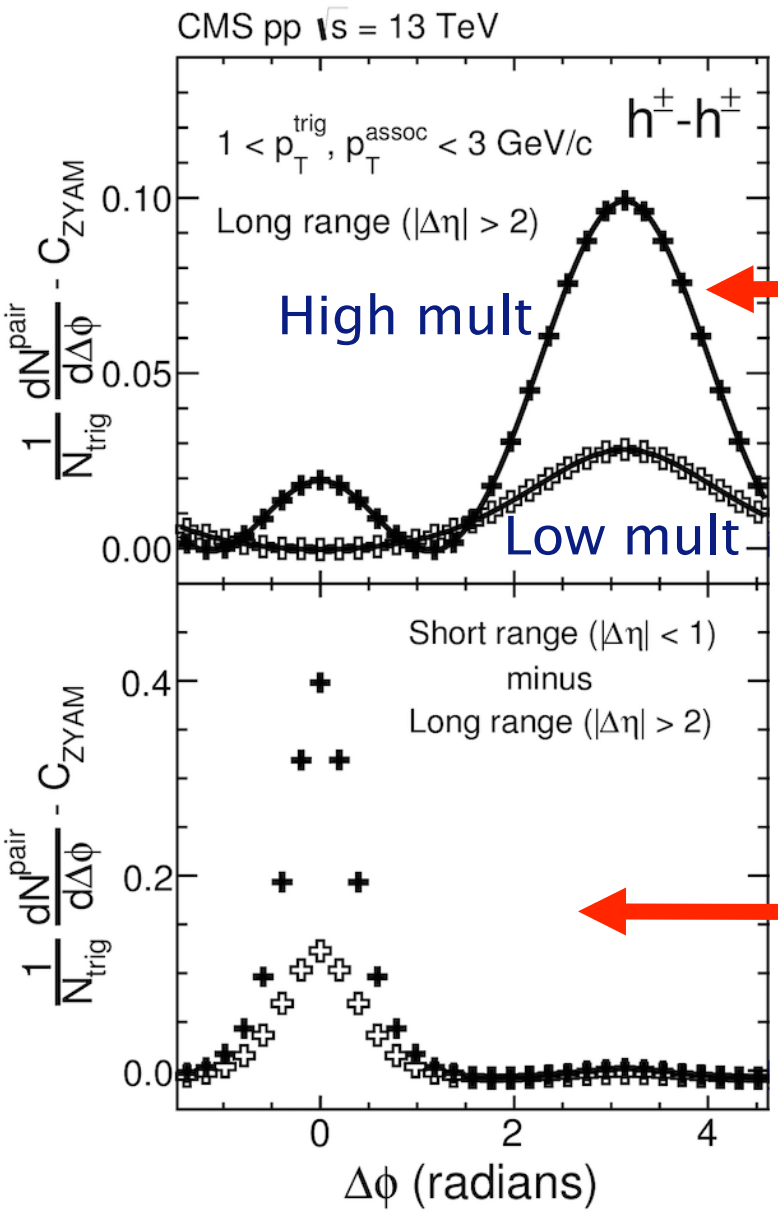
But small differences in the details (Blast Wave fits shown)

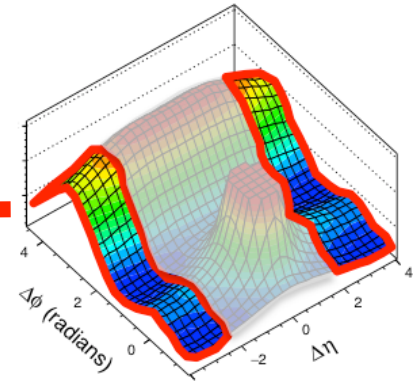
CMS HIN-15-006

Correlations in high-mult pp collisons?

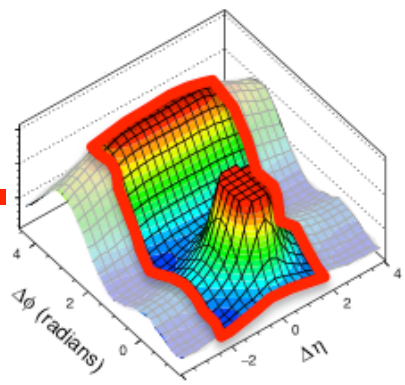
Need a robust procedure for removing the effect of jets on the away-side correlations!

Jet removal technique

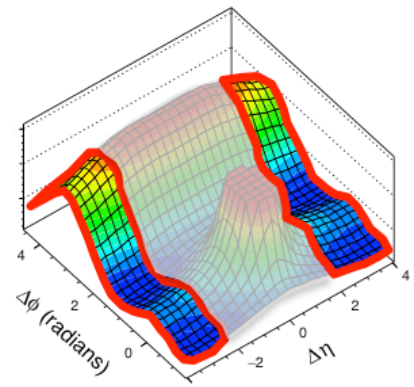




Project long range (above) and short minus long range (below)



minus



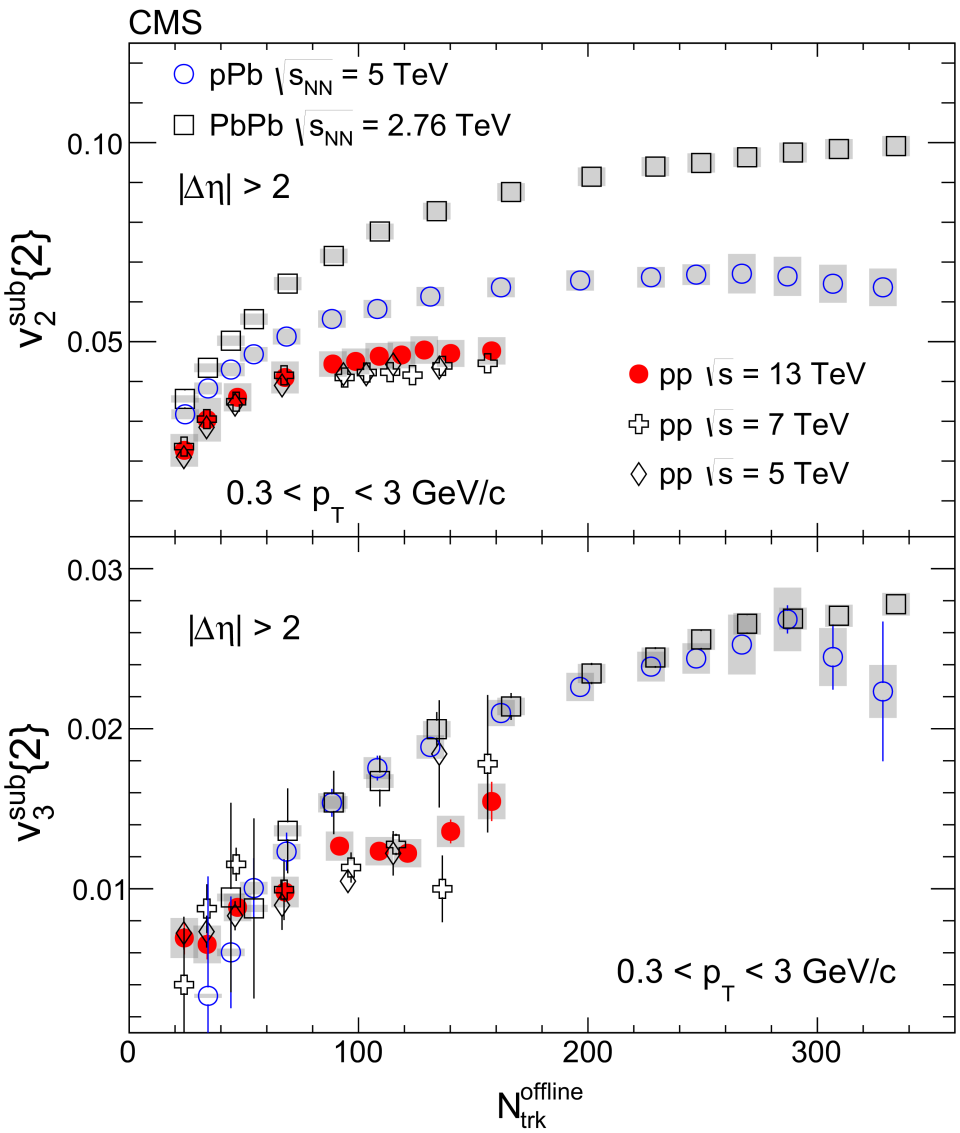
CMS HIN-16-010

Jet removal technique

- Jet shape taken from low multiplicity data
  - > Assume it doesn't depend on multiplicity
- Shape is scaled by the yield in the jet peak
- Correction is applied to the V_n after fitting
  - > The only option for multi-particle cumulants
- Need to also scale by associated total multiplicity

$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}(10 \leq N_{trk}^{offline} < 20) \times \frac{N_{\mathrm{assoc}}(10 \leq N_{trk}^{offline} < 20)}{N_{\mathrm{assoc}}} \times \frac{Y_{\mathrm{jet}}}{Y_{\mathrm{jet}}(10 \leq N_{trk}^{offline} < 20)}$$

Results: v_2 and v_3 in pp @ 5, 7, 13

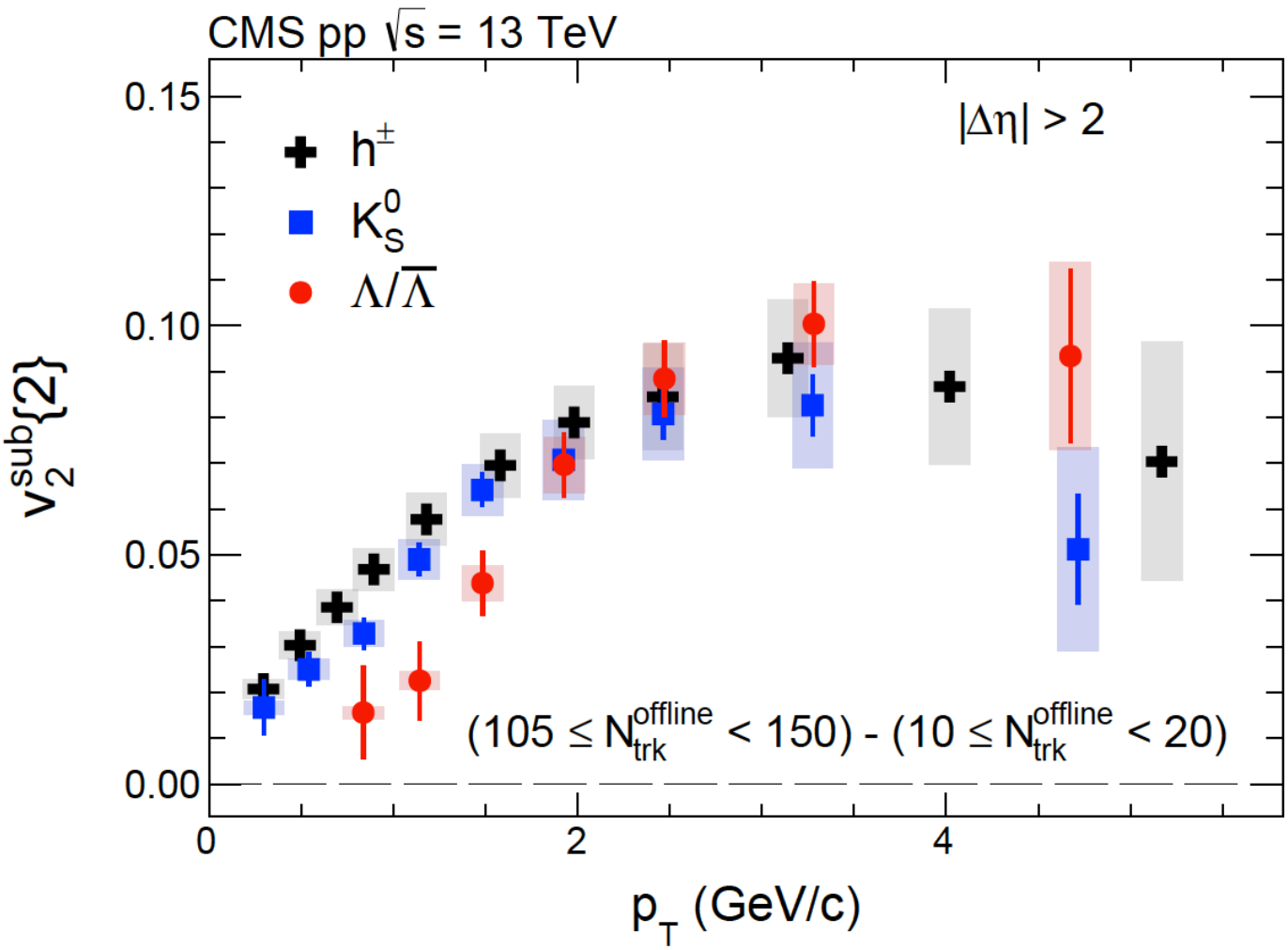


- v_2:
  - > No energy dependence
  - > Qualitatively similar shape for pp, p-Pb, and Pb-Pb
- v_3:
  - > No energy dependence
  - > Slightly different from p-Pb and Pb-Pb at higher mult

Difference in initial state fluctuations?

CMS HIN-16-010

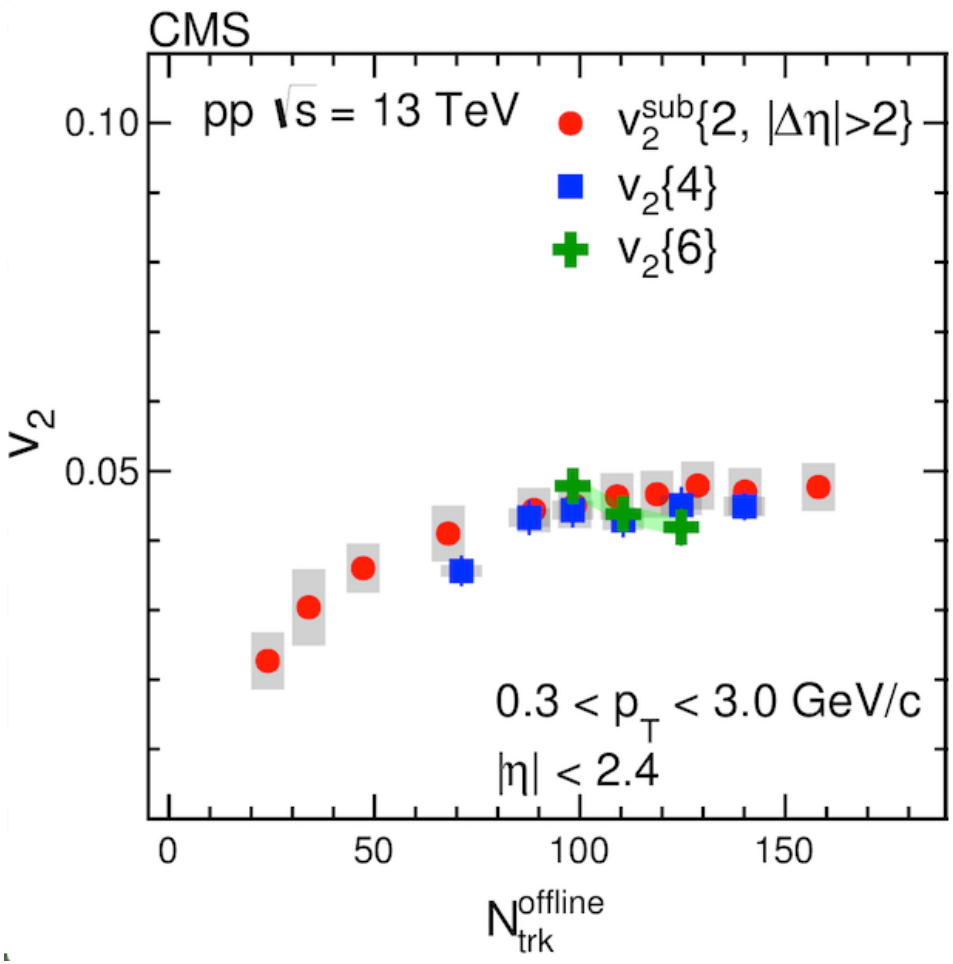
Results: v_2 versus p_T for K^0_S and Λ



Clear mass splitting observed up to about 2 GeV/c

CMS HIN-16-010

Results: Multi-particle correlations in pp



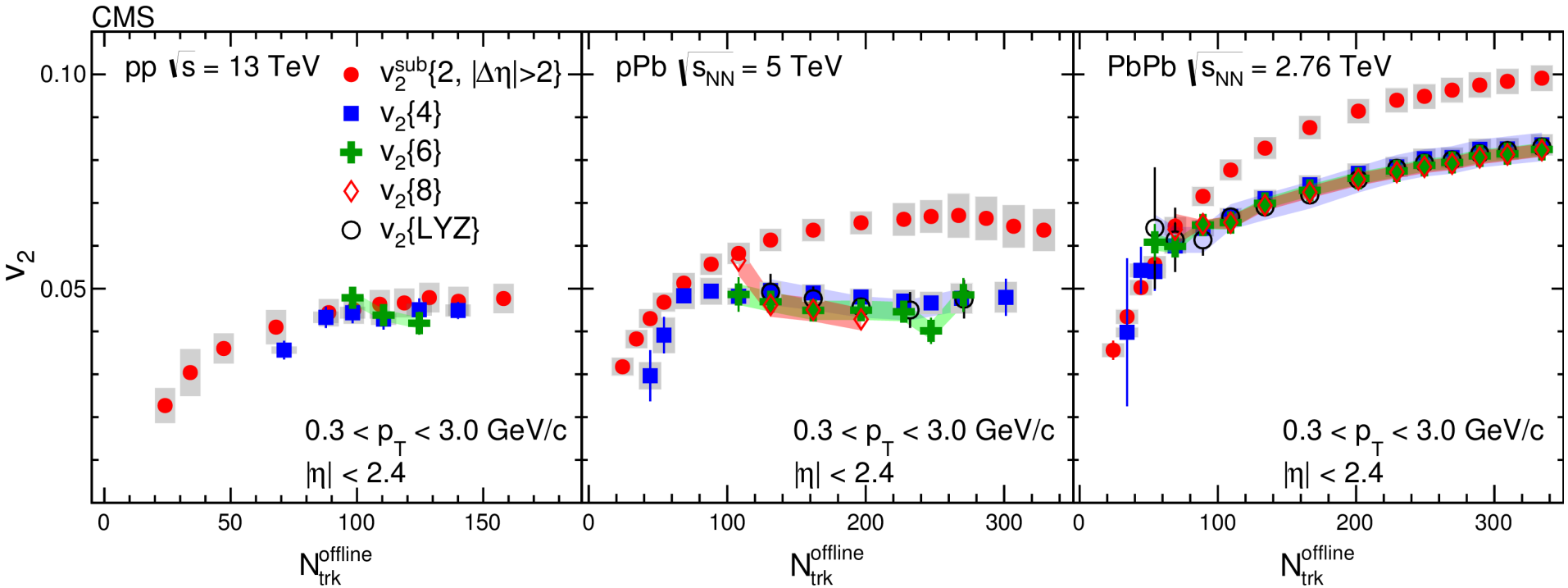
- Cumulant method for multi-particle correlations
- Find that:

  $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$

- Collectivity!

CMS HIN-16-010

Multi-particle/multi-system comparison



Qualitatively similar results seen in high-mult pp and pPb, as well as peripheral PbPb

CMS HIN-16-010

Conclusions

Can you tell the difference between a very high mult pp, a high mult pPb, and a peripheral PbPb, all at same multiplicity?

Conclusions

Can you tell the difference between a very high mult pp, a high mult pPb, and a peripheral PbPb, all at same multiplicity?

The answer so far is:

No (qualitatively)

but also

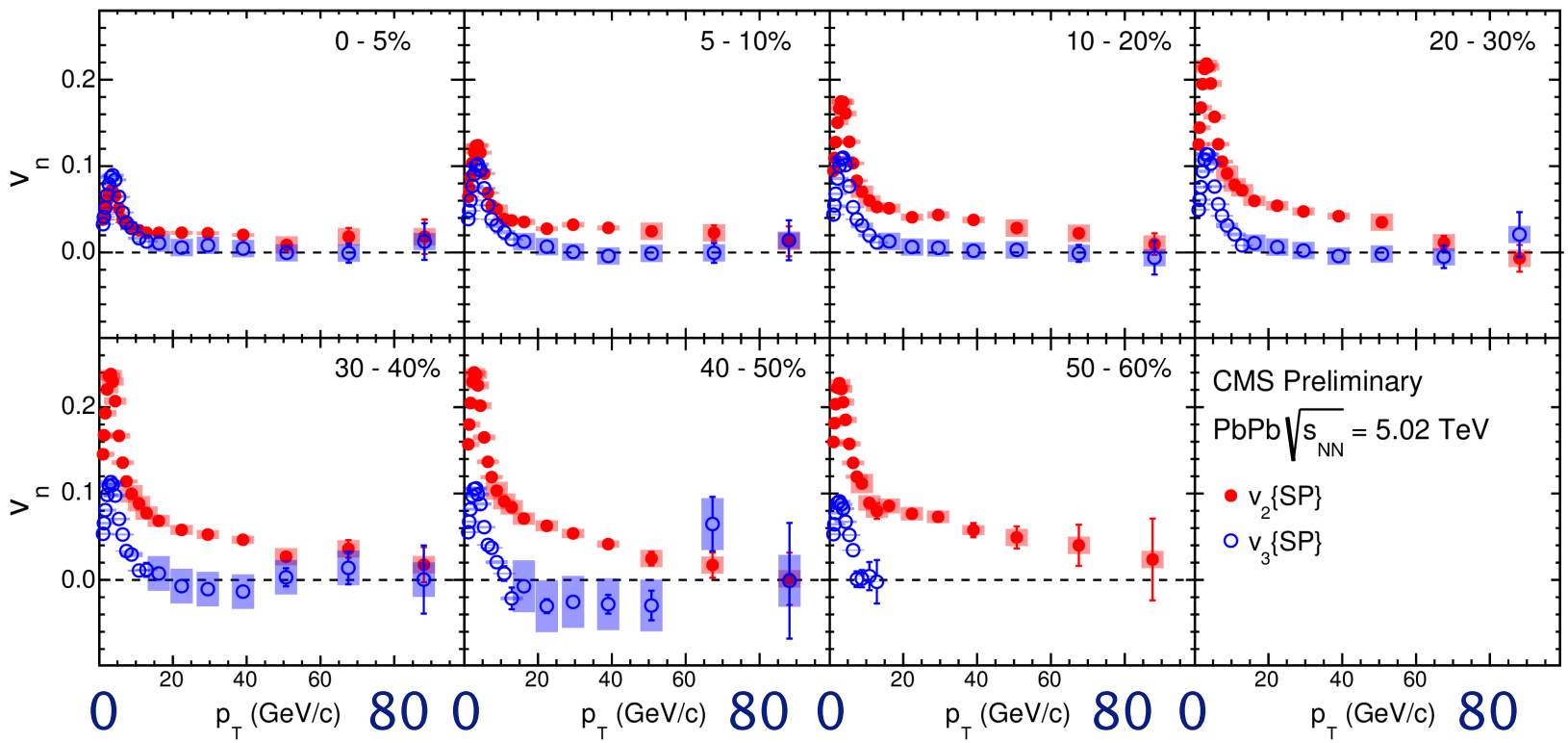
Yes (quantitatively in details)

Results relevant to many interesting questions

- Fluctuations in the initial state of the proton
- Onset of collectivity in small systems

CMS has many other recent flow results…

Flow at very high p_T (>80 GeV/c) in PbPb



0 80 0 80 0 80 0 80

p_T

CMS HIN-15-014

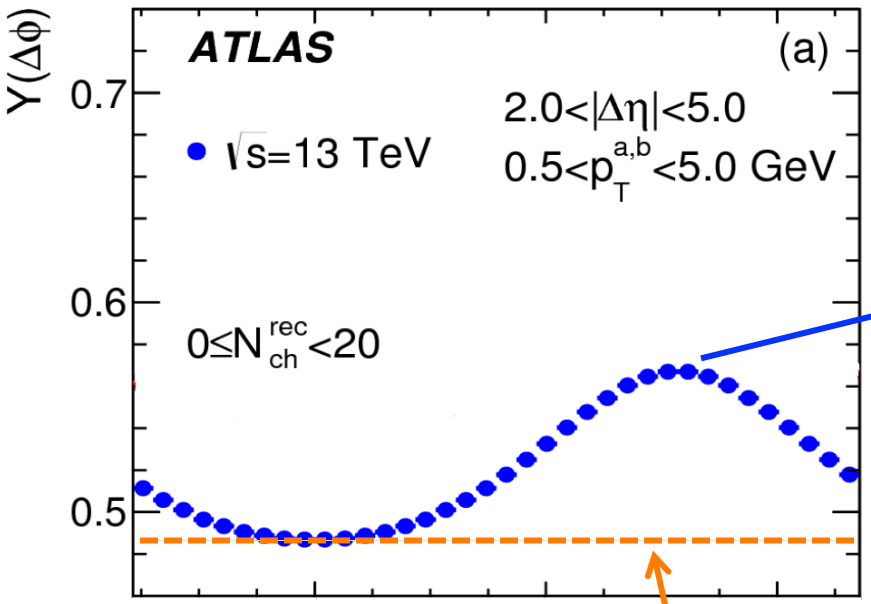
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

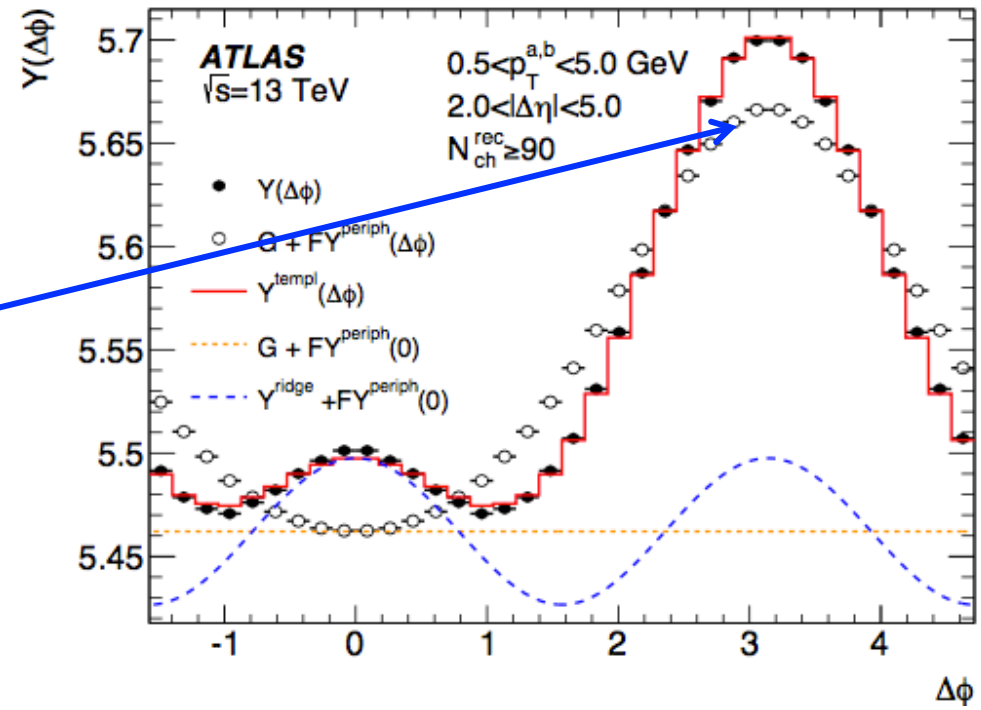
Conclusions

- Detailed properties of spectra and correlations in high-multiplicity p-p collisions at several energies
  - > Spectra and yield ratios of particles similar to pPb and PbPb, but small differences in Blast Wave fits
  - > Significant v_2 and v_3 at 5, 7, and 13 TeV
  - > Qualitatively similar shape for v_2 in high-mult pp and p-Pb, as well as peripheral PbPb
  - > v_3 values are even more similar for the three systems, especially at lower (but still high for pp) multiplicity
  - > Mass ordering observed using strange particles
  - > Evidence of collectivity: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$
- Provide insight to many different interesting questions
  - > Fluctuations in the initial state of the proton
  - > Onset of collectivity in small systems

BACKUP

Effect of ATLAS templates on v_2

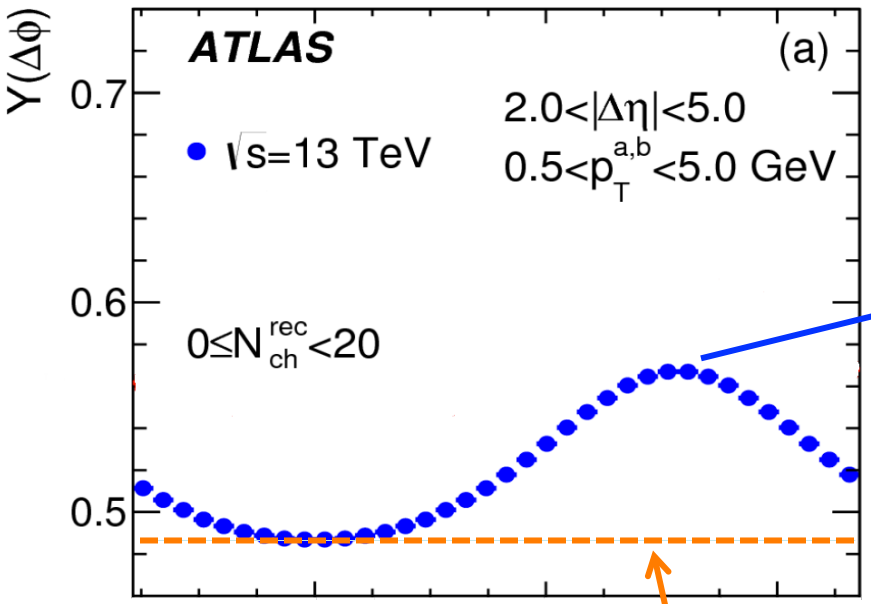


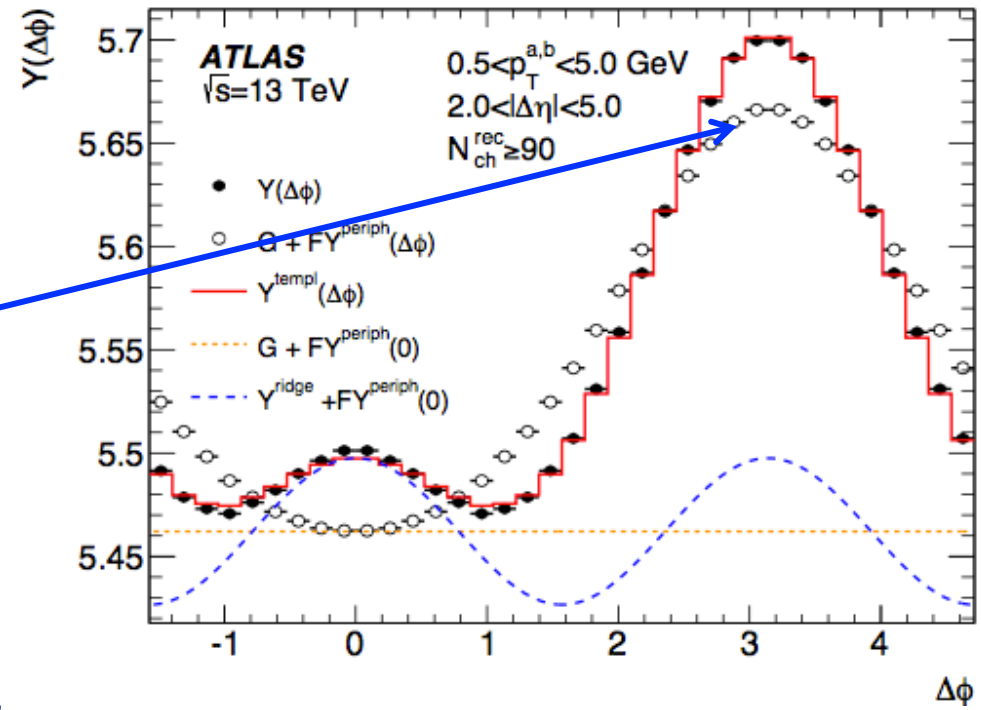


F scales up **baseline** in addition to jet peak

$$Y^{\mathrm{templ}}(\Delta\phi) = \boxed{F\, Y^{\mathrm{periph}}(\Delta\phi)} + Y^{\mathrm{ridge}}(\Delta\phi)$$

Effect of ATLAS templates on v_2





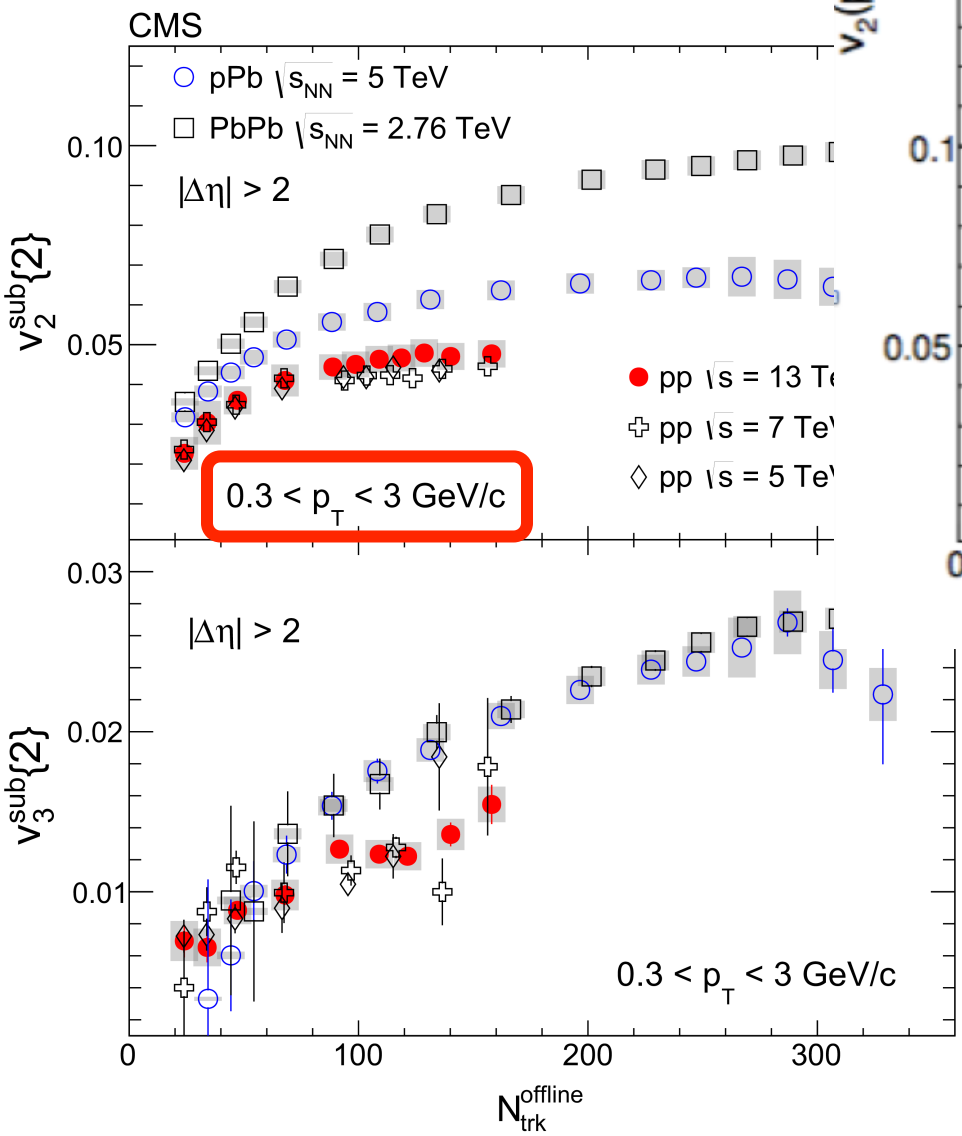
F times this number of particles are not allowed to "flow"
So, extracted v_n are **larger**
In this case, ~(1.2/5.5)=22%

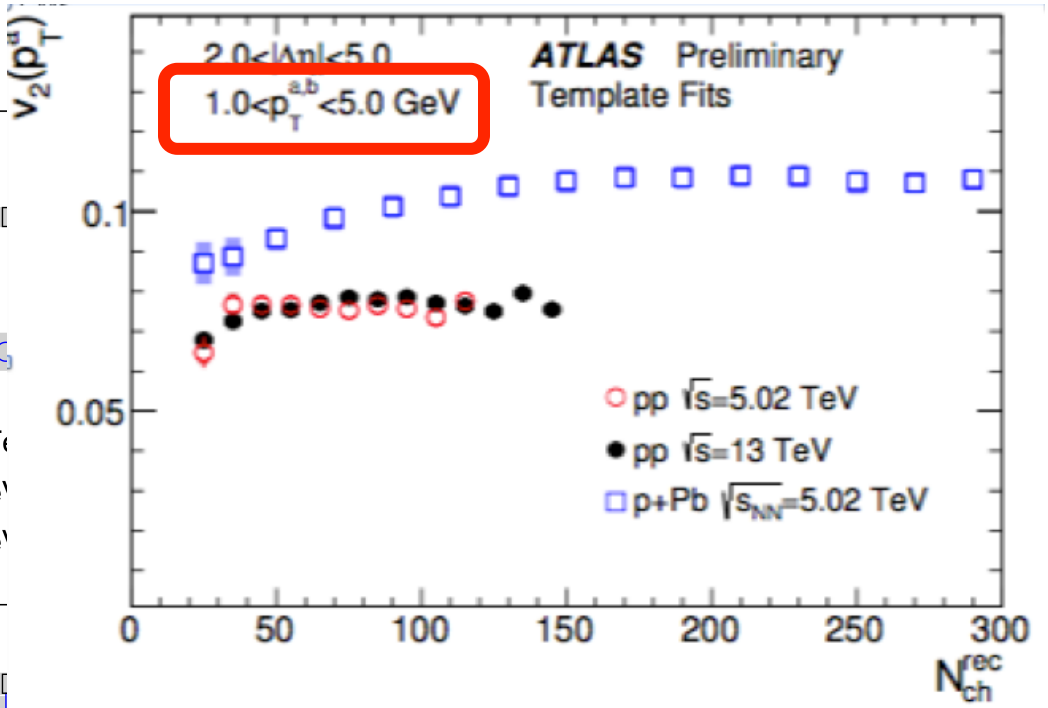
Much bigger effect at low mult

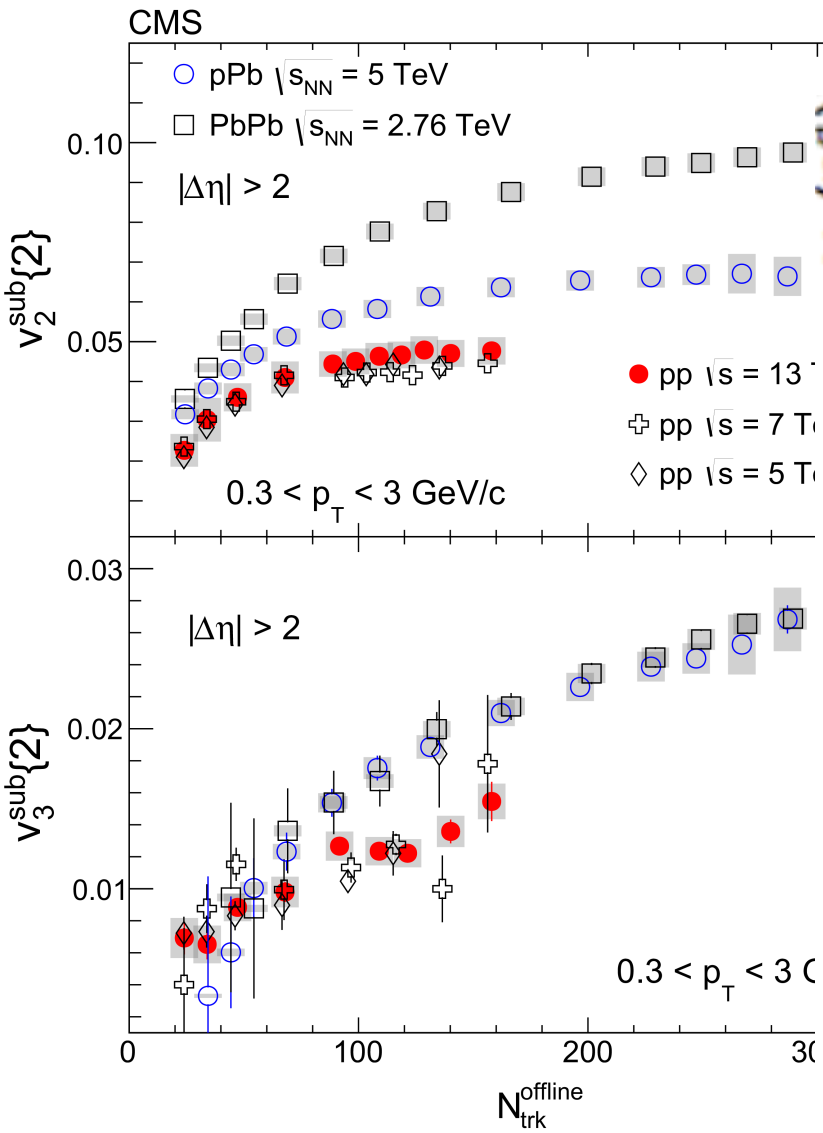
$$Y^{\text{templ}}(\Delta\phi) = \boxed{F\, Y^{\text{periph}}(\Delta\phi)} + Y^{\text{ridge}}(\Delta\phi)$$

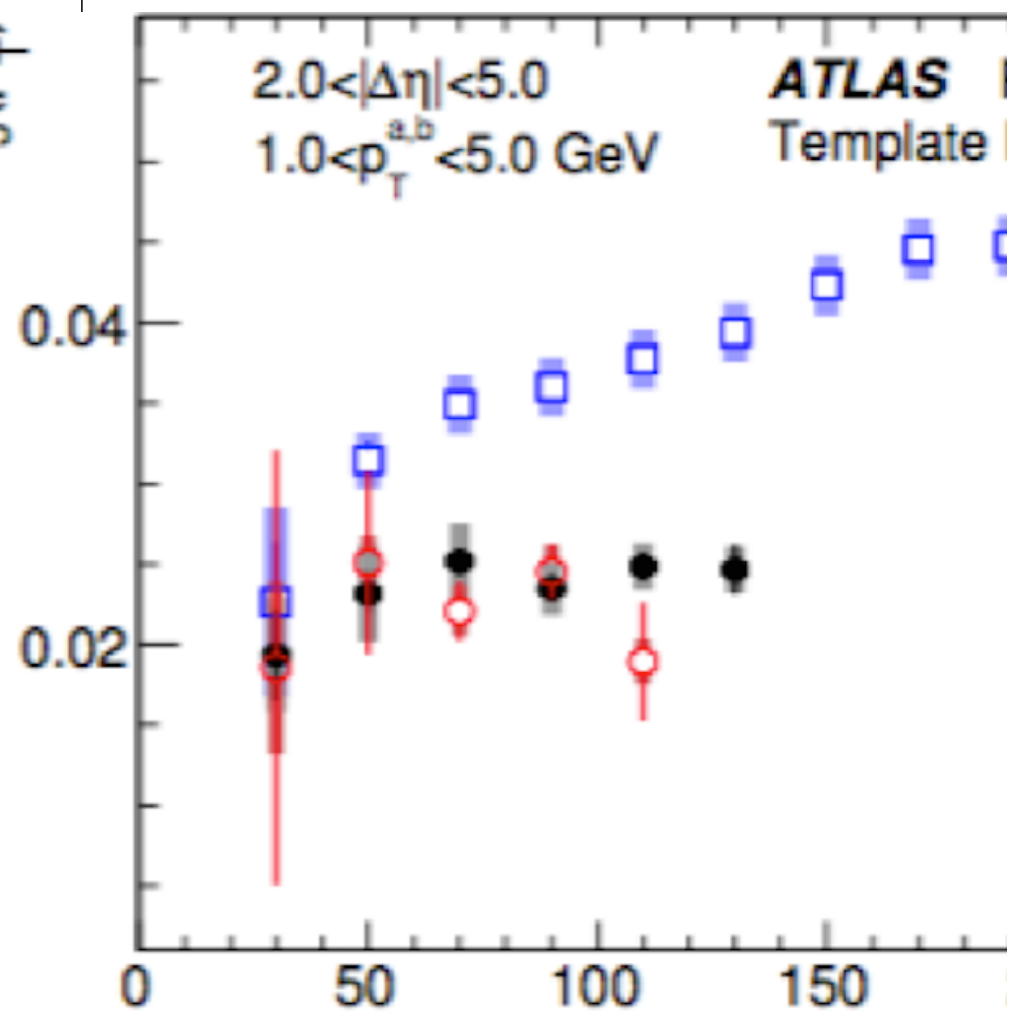
F scales up **baseline** in addition to jet peak

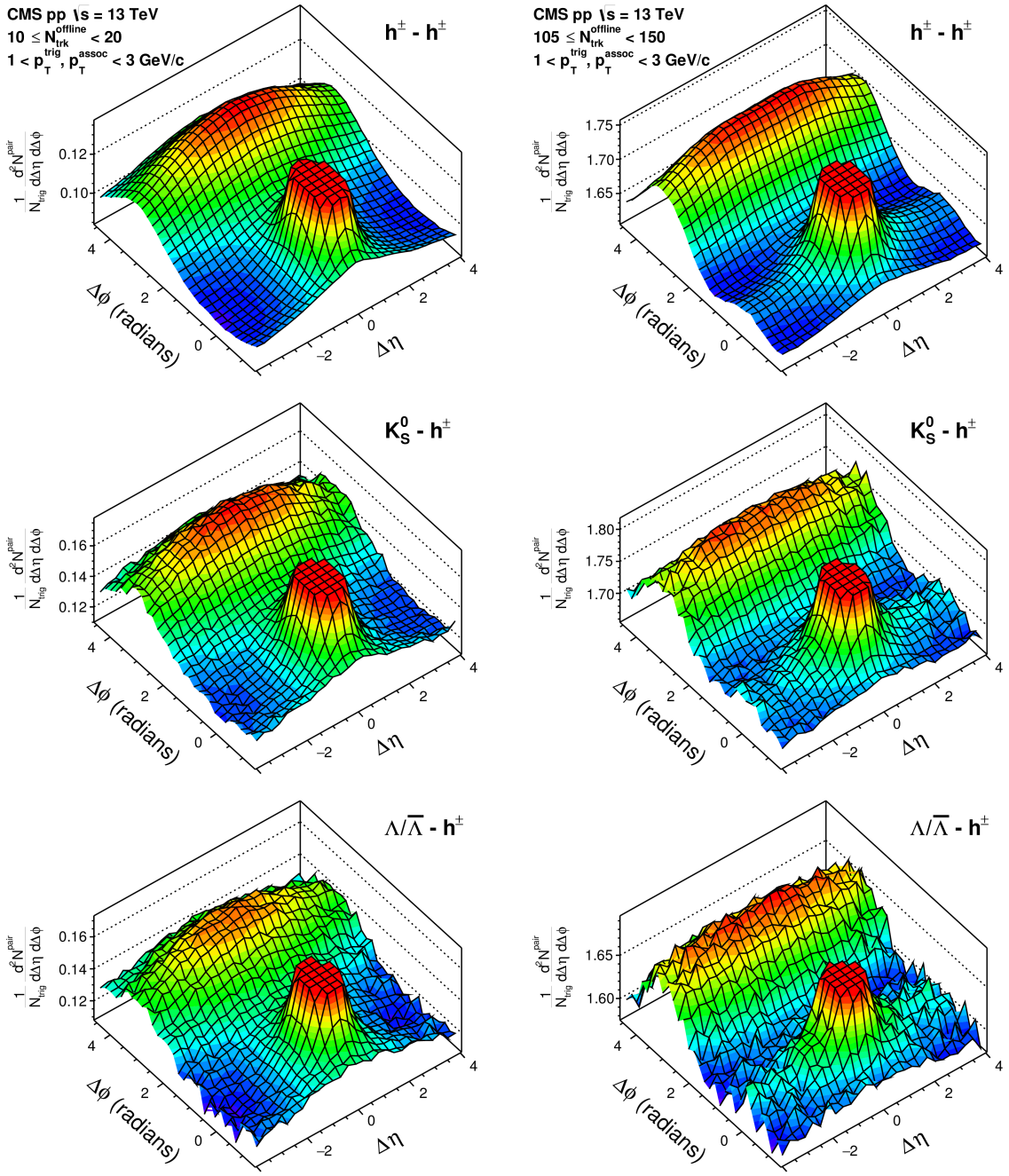
$$Y^{\text{ridge}}(\Delta\phi) = G\left(1 + 2v_{2,2}\cos\left(2\Delta\phi\right)\right)$$


CMS
pPb √sNN = 5 TeV
PbPb √sNN = 2.76 TeV
|Δη| > 2
pp √s = 13 Te
pp √s = 7 Te
pp √s = 5 Te
0.3 < pT < 3 GeV/c
v2sub{2}
0.10
0.05
|Δη| > 2
0.03
0.02
0.01
v3sub{2}
0.3 < pT < 3 GeV/c
0
100
200
300
Nchtrkoffline


2.0<|Δη|<5.0
1.0<pTa,b<5.0 GeV
ATLAS Preliminary
Template Fits
v2(pTa)
0.1
0.05
pp √s=5.02 TeV
pp √s=13 TeV
p+Pb √sNN=5.02 TeV
0
50
100
150
200
250
300
Nchrec


CMS
pPb √sNN = 5 TeV
PbPb √sNN = 2.76 TeV
|Δη| > 2
0.3 < pT < 3 GeV/c
pp √s = 13
pp √s = 7 T
pp √s = 5 T
v2sub{2}
v3sub{2}
0.10
0.05
0.03
0.02
0.01
0
100
200
Ntrkoffline


2.0<|Δη|<5.0
1.0<pT a,b<5.0 GeV
ATLAS
Template
v3(pTa)
0.04
0.02
0
50
100
150


CMS pp √s = 13 TeV
10 ≤ N_trk^offline < 20
1 < p_T^trig, p_T^assoc < 3 GeV/c
h± - h±
CMS pp √s = 13 TeV
105 ≤ N_trk^offline < 150
1 < p_T^trig, p_T^assoc < 3 GeV/c
h± - h±
K0S - h±
K0S - h±
Λ/Λ̄ - h±
Λ/Λ̄ - h±
1/N_trig d²N^pair/dΔη dΔφ
Δφ (radians)
Δη

- Vn Δ coefficients extracted using a Fourier fit

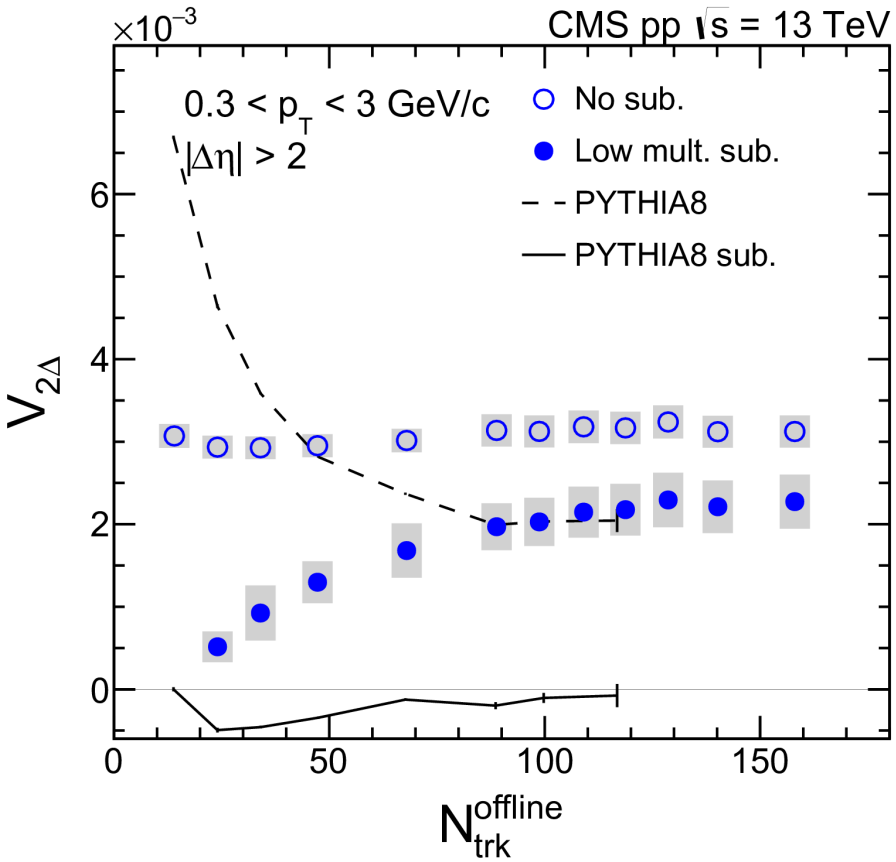
$$\frac{1}{N_{\rm trig}}\frac{{\rm d}N^{\rm pair}}{{\rm d}\Delta\phi} = \frac{N_{\rm assoc}}{2\pi}\left[1+\sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

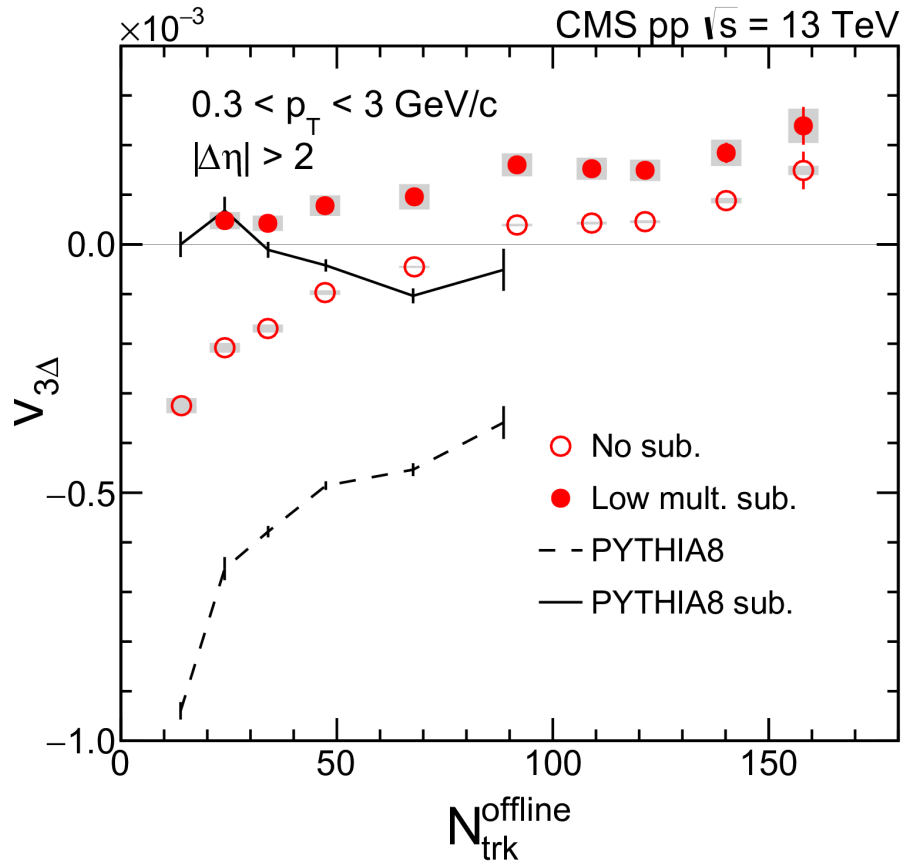
- Single vn coefficients are computed with:

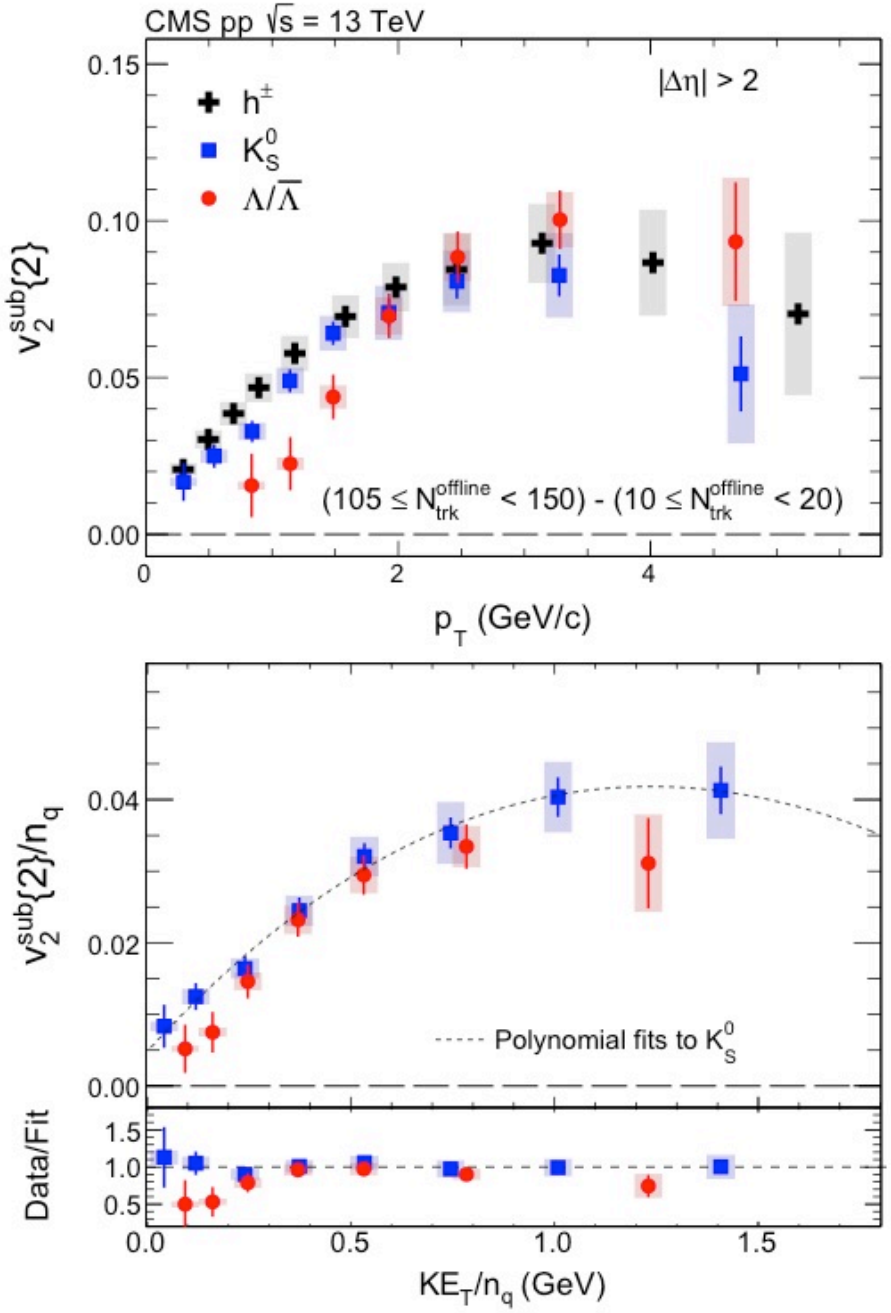
$$v_n(p_T^{trg}) = \frac{V_{n\Delta}(p_T^{trg}, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}, \qquad n = 2, 3.$$

$$\langle\langle 2\rangle\rangle \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle,$$
$$\langle\langle 4\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle,$$
$$\langle\langle 6\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\rangle\rangle.$$

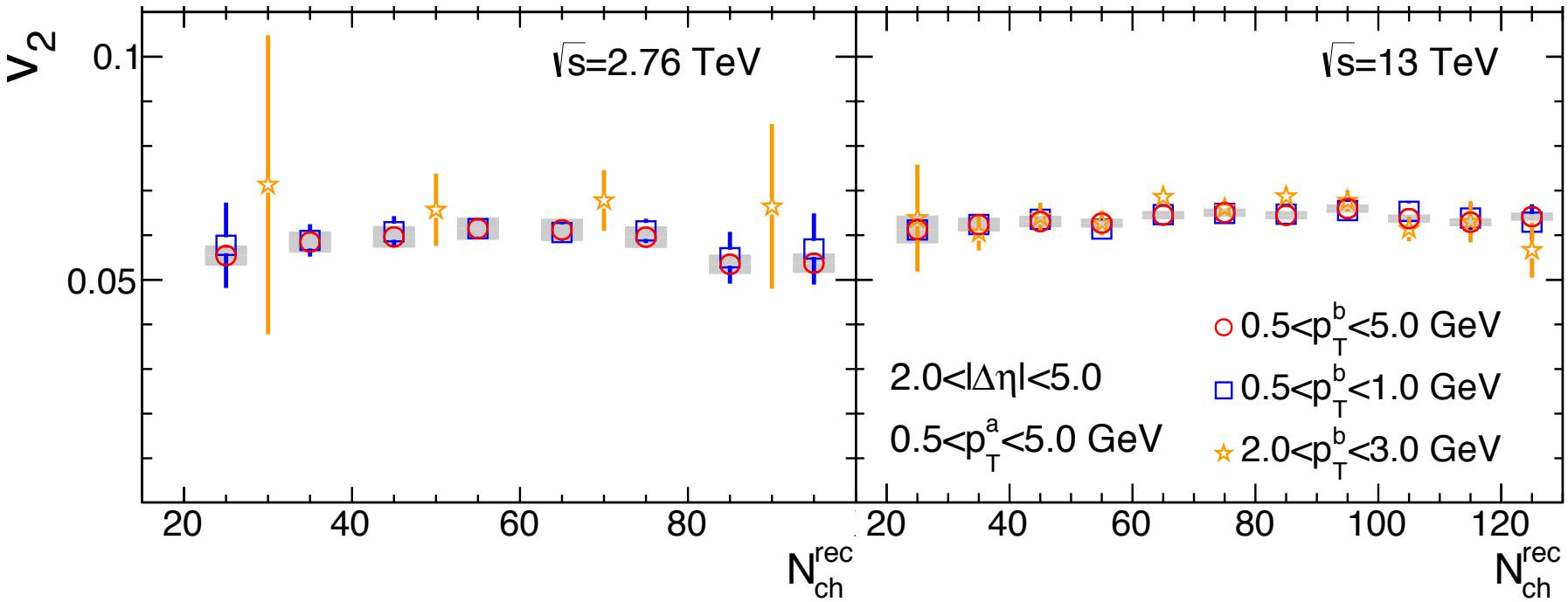
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\times\langle\langle 2\rangle\rangle^2, \qquad v_2\{4\} = \sqrt[4]{-c_n\{4\}},$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\times\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\times\langle\langle 2\rangle\rangle^3 \qquad v_2\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}},$$


CMS pp √s = 13 TeV
×10⁻³
0.3 < p_T < 3 GeV/c
|Δη| > 2
No sub.
Low mult. sub.
PYTHIA8
PYTHIA8 sub.
V_2Δ
N_trk^offline


CMS pp √s = 13 TeV
×10⁻³
0.3 < p_T < 3 GeV/c
|Δη| > 2
No sub.
Low mult. sub.
PYTHIA8
PYTHIA8 sub.
V_3Δ
N_trk^offline


CMS pp √s = 13 TeV
|Δη| > 2
h±
K0S
Λ/Λ̄
(105 ≤ Ntrkoffline < 150) - (10 ≤ Ntrkoffline < 20)
v2sub{2}
pT (GeV/c)
v2sub{2}/nq
Polynomial fits to K0S
Data/Fit
KET/nq (GeV)

v_2 results on from ATLAS



➔A new method is used (template fit)
➔First measurement of v_2 in p-p

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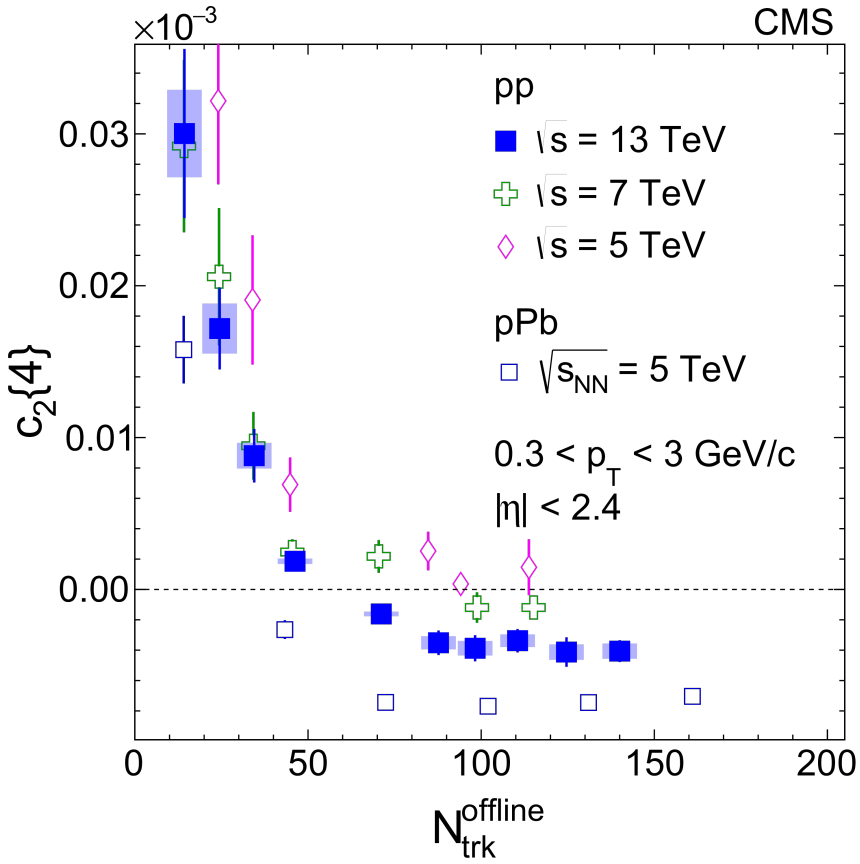
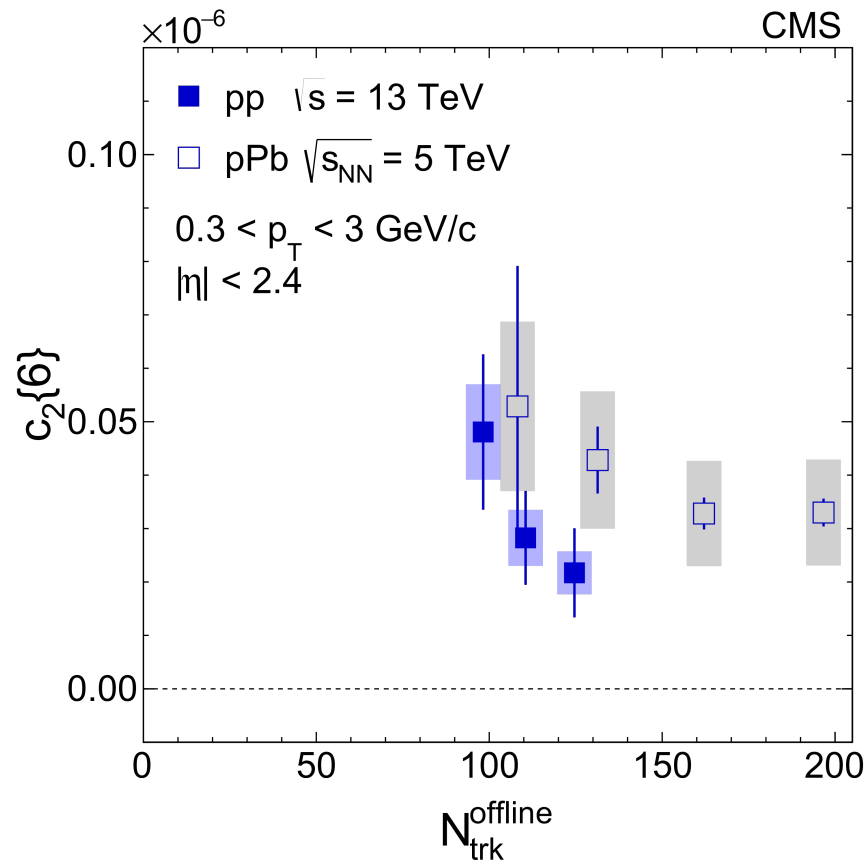

×10^−3
CMS
pp
√s = 13 TeV
√s = 7 TeV
√s = 5 TeV
pPb
√s_NN = 5 TeV
0.3 < p_T < 3 GeV/c
|η| < 2.4
c_2{4}
0.03
0.02
0.01
0.00
0
50
100
150
200
N_trk^offline


×10^−6
CMS
pp √s = 13 TeV
pPb √s_NN = 5 TeV
0.3 < p_T < 3 GeV/c
|η| < 2.4
c_2{6}
0.10
0.05
0.00
0
50
100
150
200
N_trk^offline