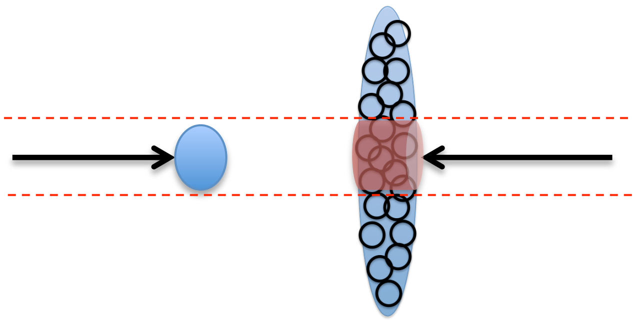

Exploring the high-density QCD medium via particle correlations in pA collisions at the LHC

Wei Li (Rice University)
for the CMS collaboration

Workshop on pA physics, MIT, May 2013

“Ridge” in pp collisions

Opportunity of studying novel QCD phenomena opened up by the LHC

September, 2010

JHEP

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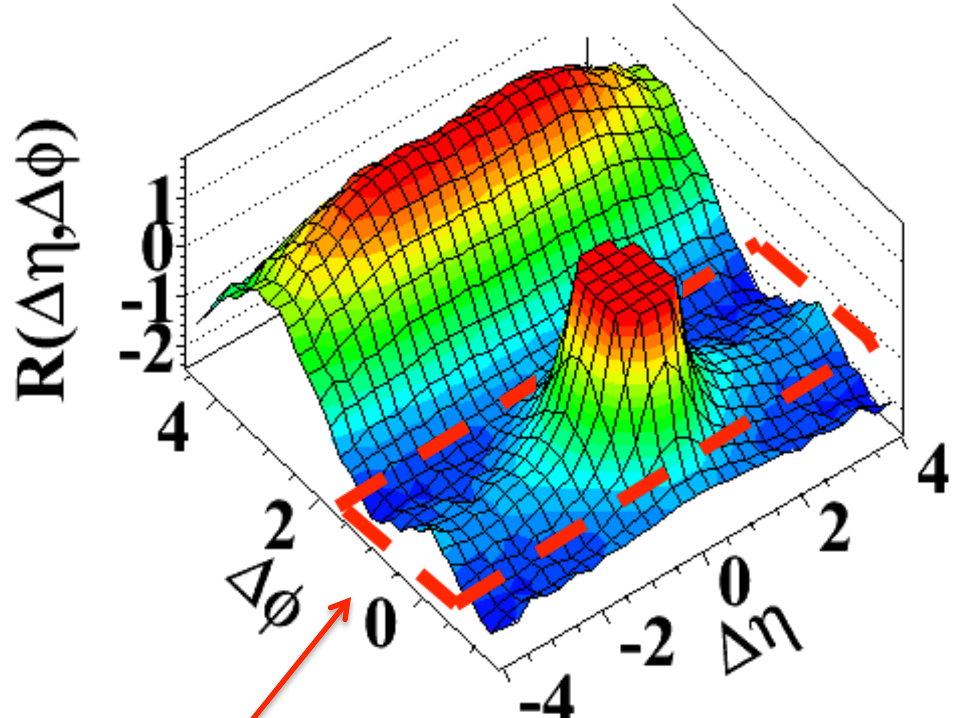
Observation of long-range, near-side angular correlations in proton-proton collisions at the LHC

The CMS collaboration

ABSTRACT: Results on two-particle angular correlations for charged particles emitted in proton-proton collisions at center-of-mass energies of 0.9, 2.36, and 7 TeV are presented, using data collected with the CMS detector over a broad range of pseudorapidity (η) and azimuthal angle (ϕ). Short-range correlations in $\Delta\eta$, which are studied in minimum bias

Two-particle Δη-Δϕ correlation

pp N>110, 1<p_T<3 GeV/c

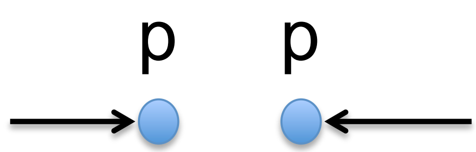


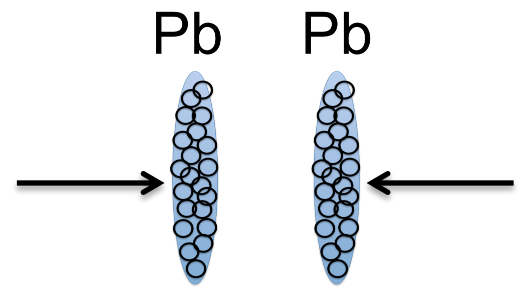
Planar particle emission

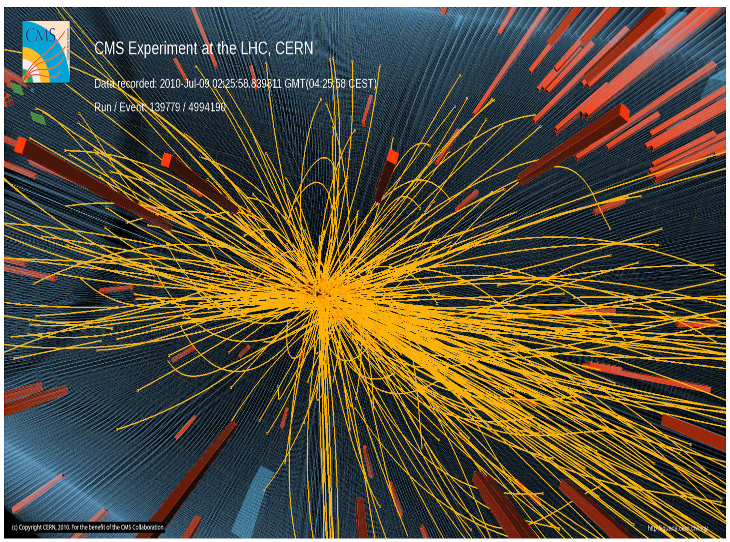
Unexpected ridge-like correlations in high multiplicity pp!

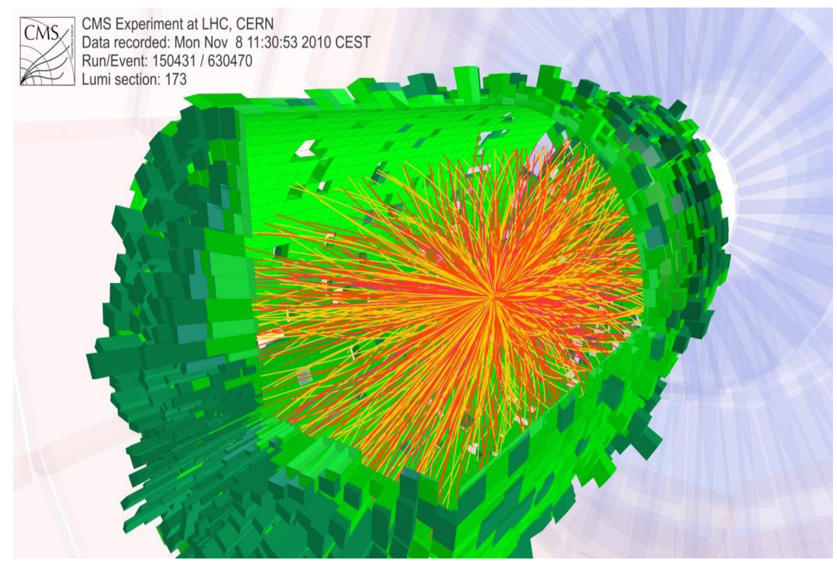
Not in minimum bias pp or pp MC models

High multiplicity in pp and AA







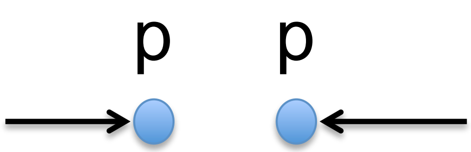


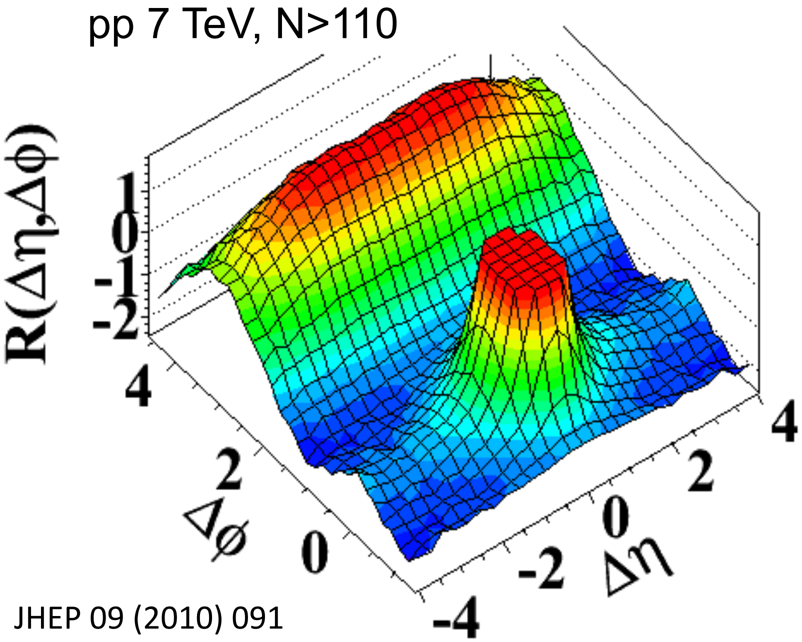
Quark Gluon Plasma (QGP)

High particle density achieved in both pp and PbPb

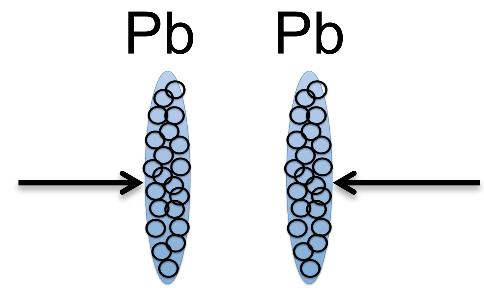
Is there any similarity between them?

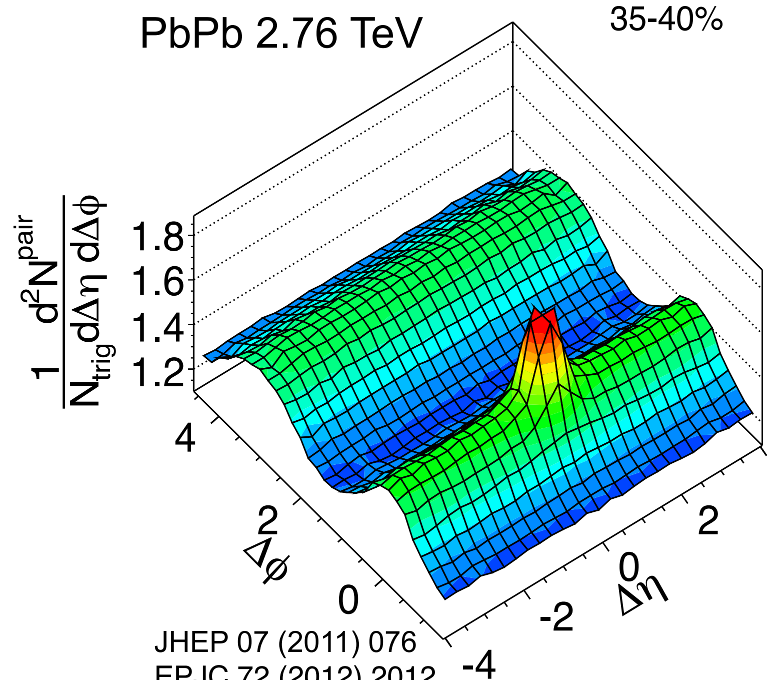
“Ridge” in pp and AA collisions





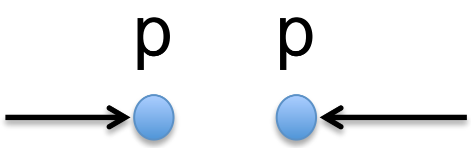
JHEP 09 (2010) 091



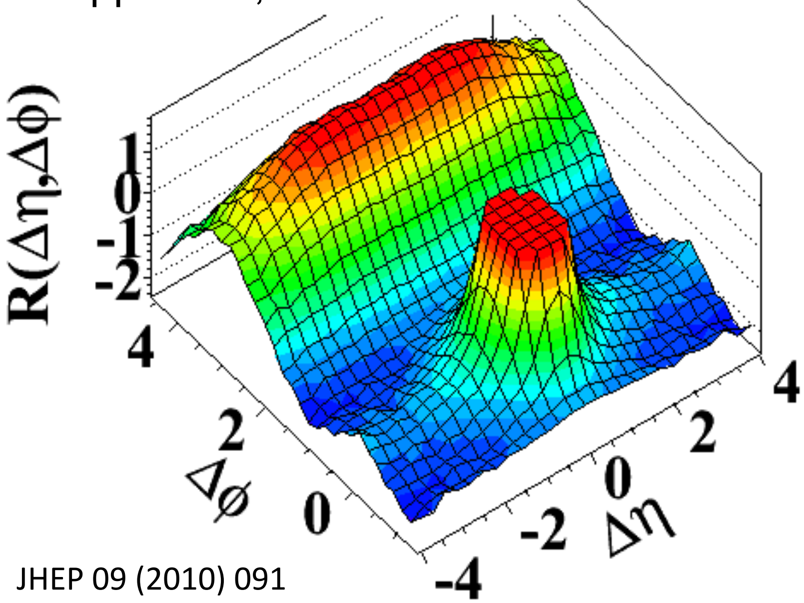


JHEP 07 (2011) 076
EPJC 72 (2012) 2012

“Ridge” in pp and AA collisions

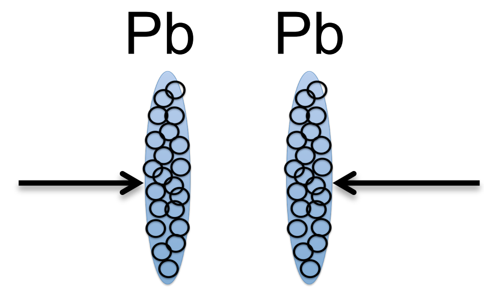


pp 7 TeV, N>110



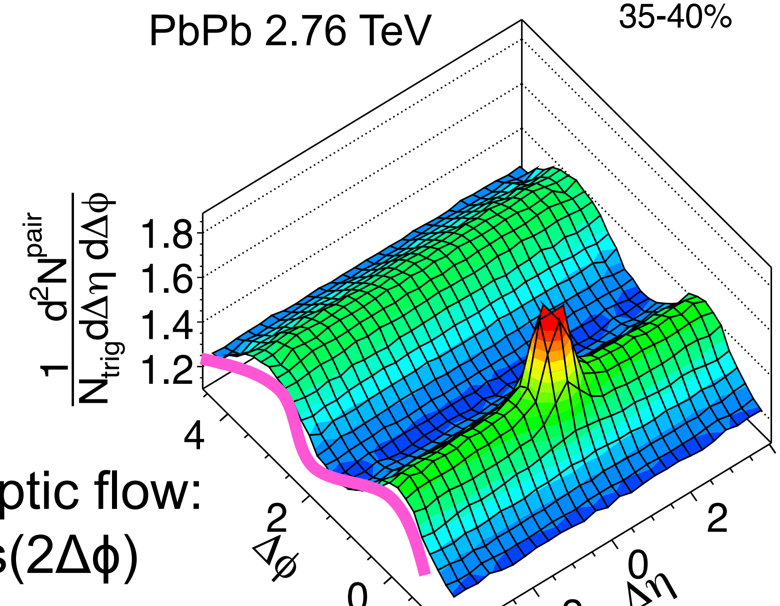
JHEP 09 (2010) 091

Physical origin of pp ridge is not completely clear



PbPb 2.76 TeV

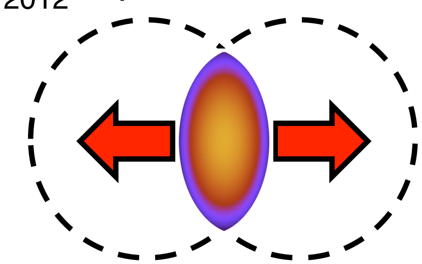
35-40%



Elliptic flow: cos(2Δϕ)

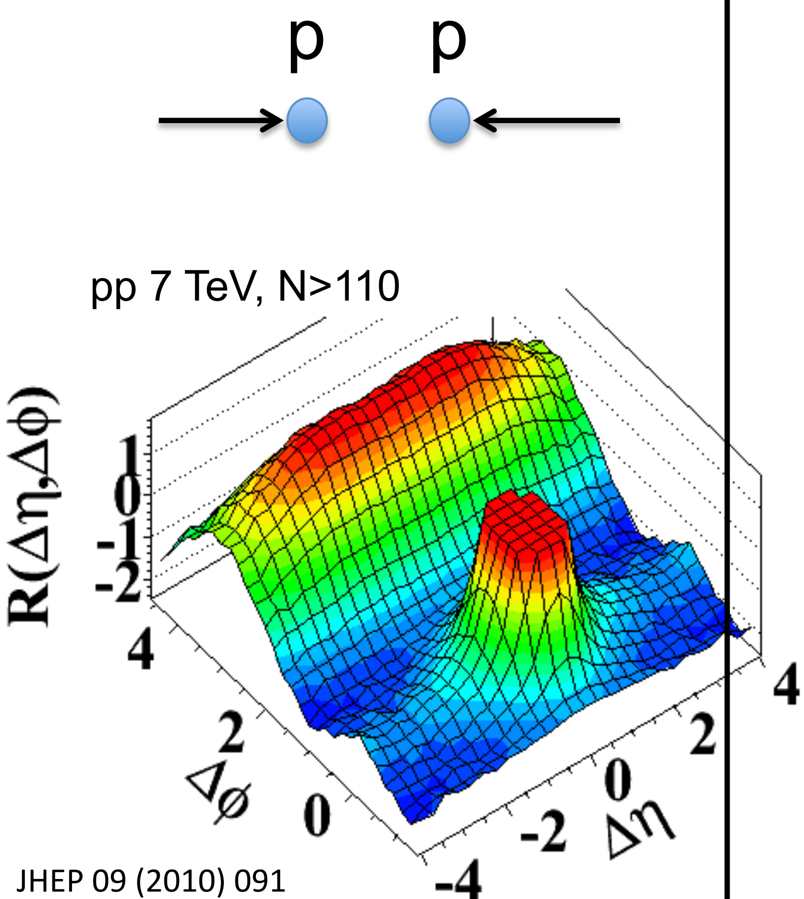
JHEP 07 (2011) 076
EPJC 72 (2012) 2012

Initial-state geometry
+
collective expansion

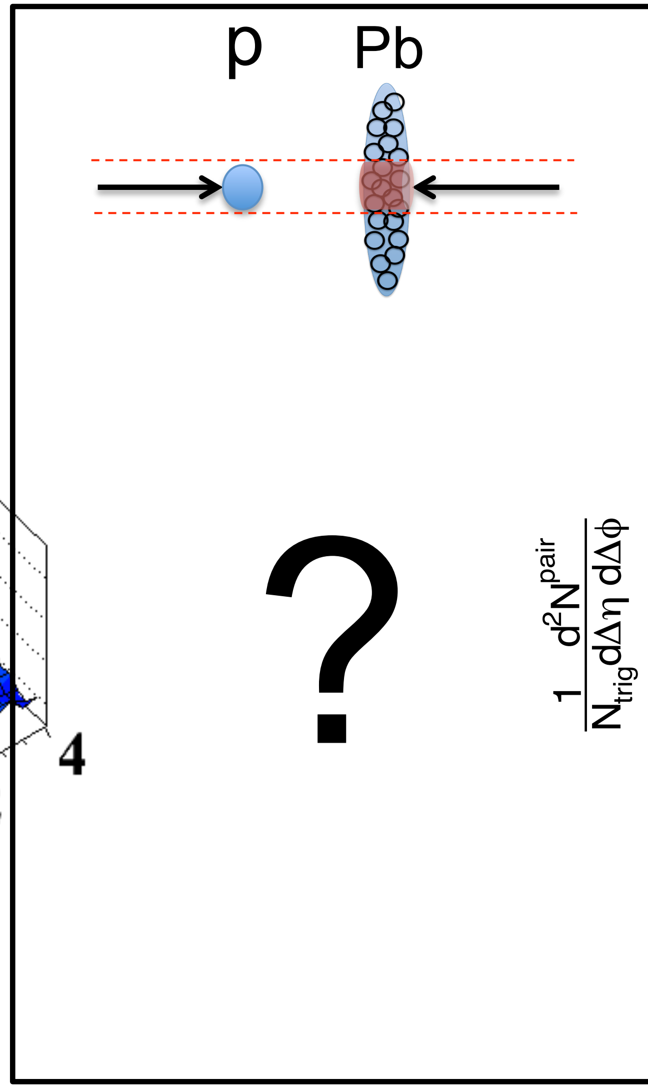


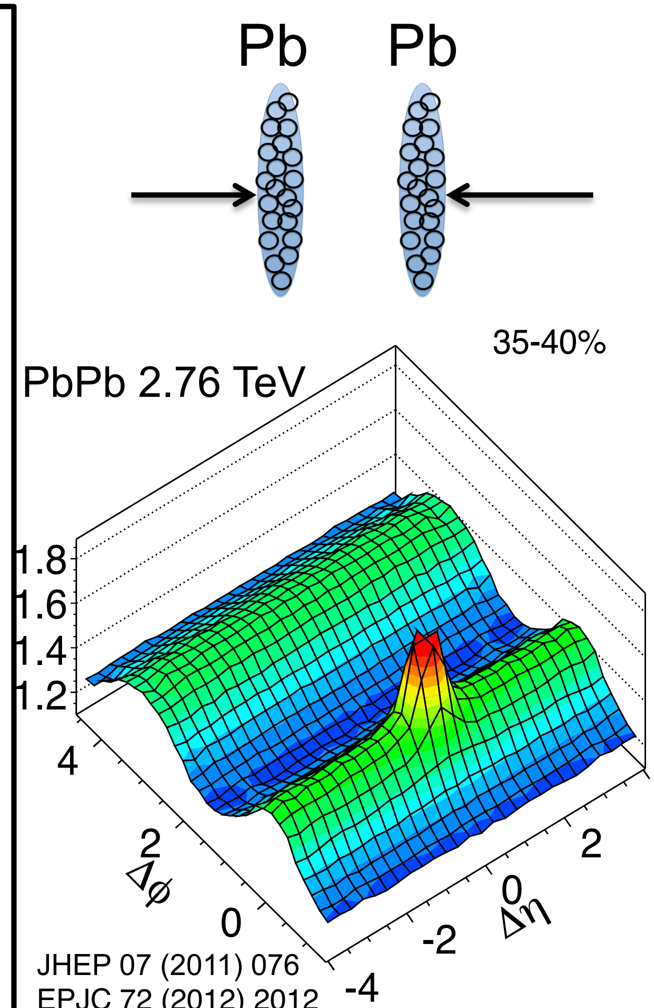
“Smoking gun” of a strongly interacting QGP liquid!

“Ridge” in pA collisions?



JHEP 09 (2010) 091

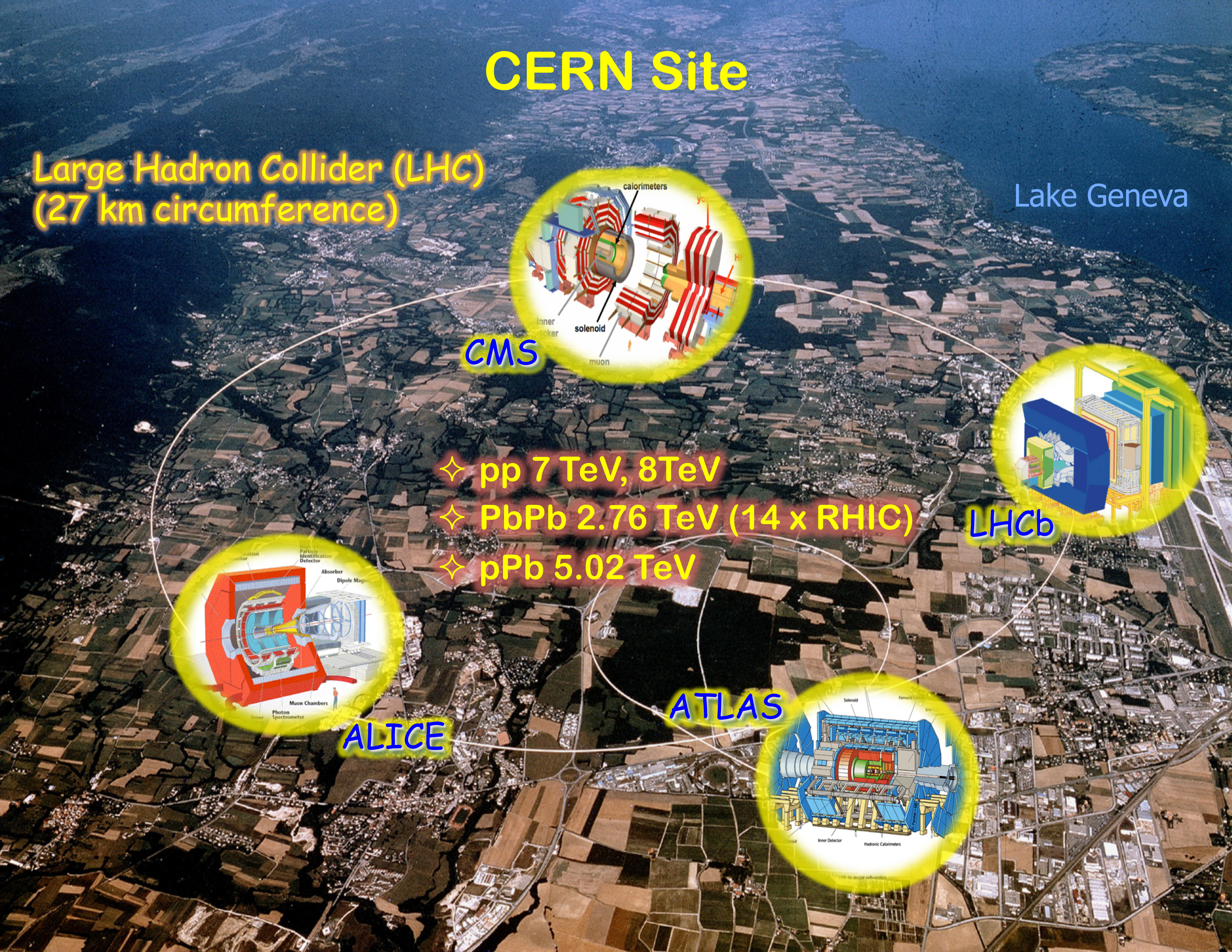




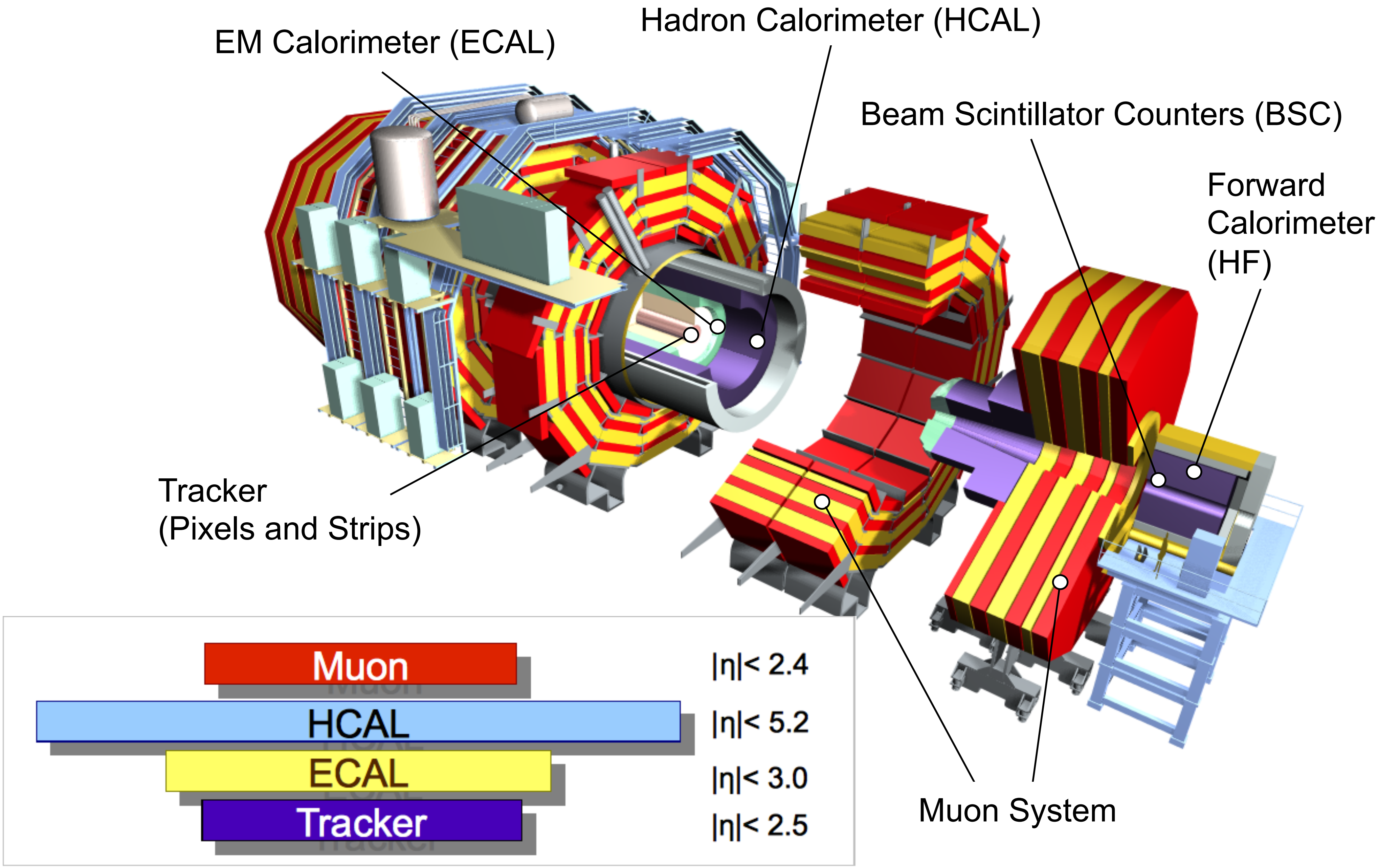
JHEP 07 (2011) 076
EPJC 72 (2012) 2012

What if colliding a proton and a nucleus?

Is there a ridge? how big is it and what makes it?

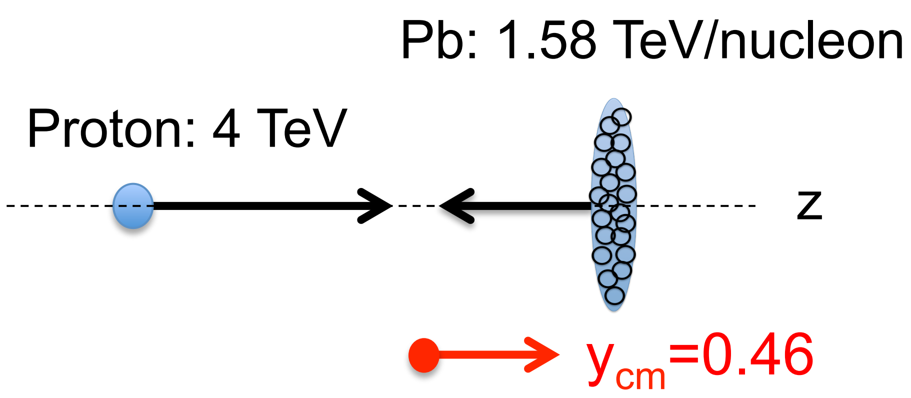

CERN Site
Large Hadron Collider (LHC)
(27 km circumference)
Lake Geneva
CMS
calorimeters
solenoid
muon
LHCb
✧ pp 7 TeV, 8TeV
✧ PbPb 2.76 TeV (14 x RHIC)
✧ pPb 5.02 TeV
Absorber
Muon Chambers
ALICE
ATLAS
Inner Detector
Hadronic Calorimeters

CMS experiment at the LHC



Unprecedented kinematic range and acceptance

Proton-nucleus collisions at the LHC

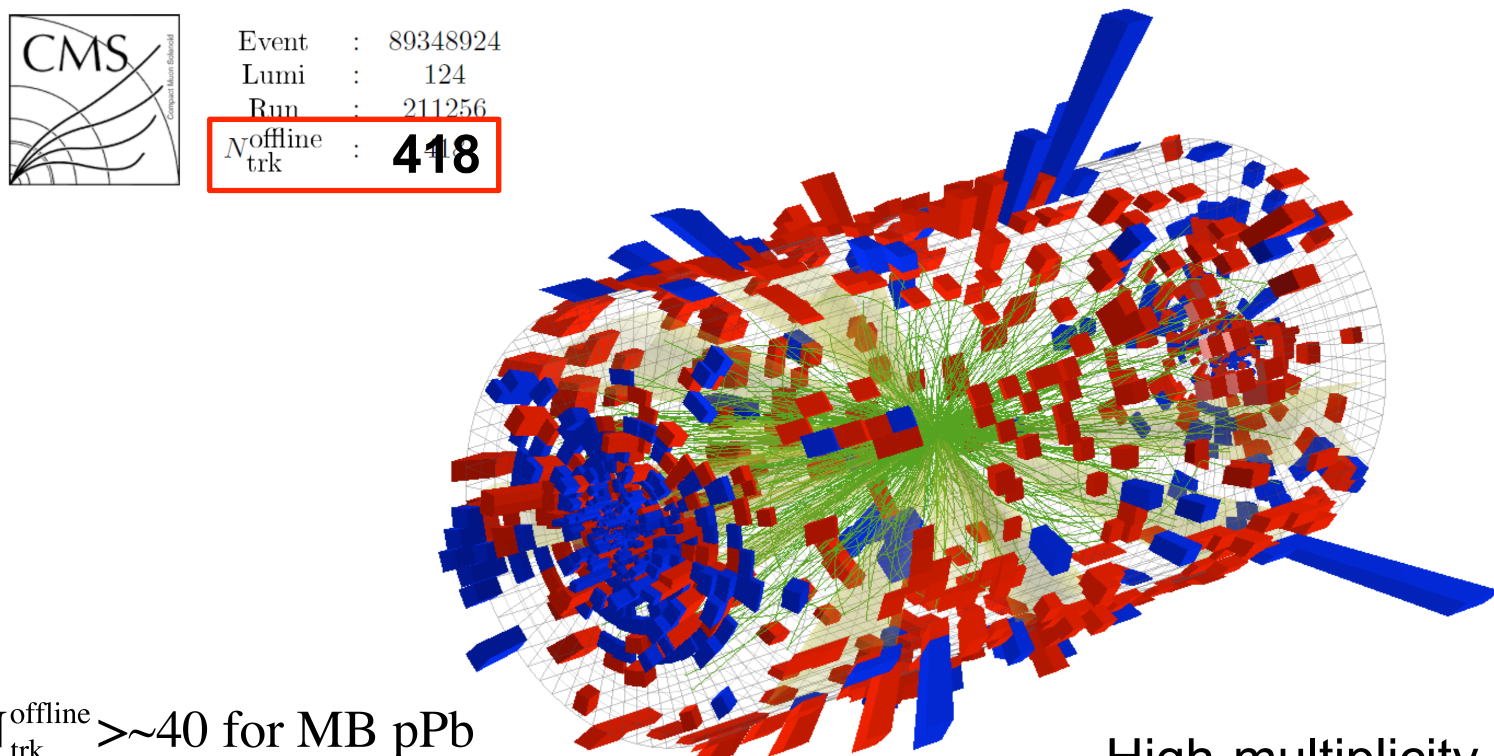


Center-of-mass energy: $\sqrt{s_{NN}}$ = 5.02 TeV

2012 pilot run (8 hours): 1 μb^{-1}

2013 nominal run (3 weeks): 31 nb^{-1}
(18 nb^{-1} for pPb and 13 nb^{-1} for Pbp)

60 billion collisions

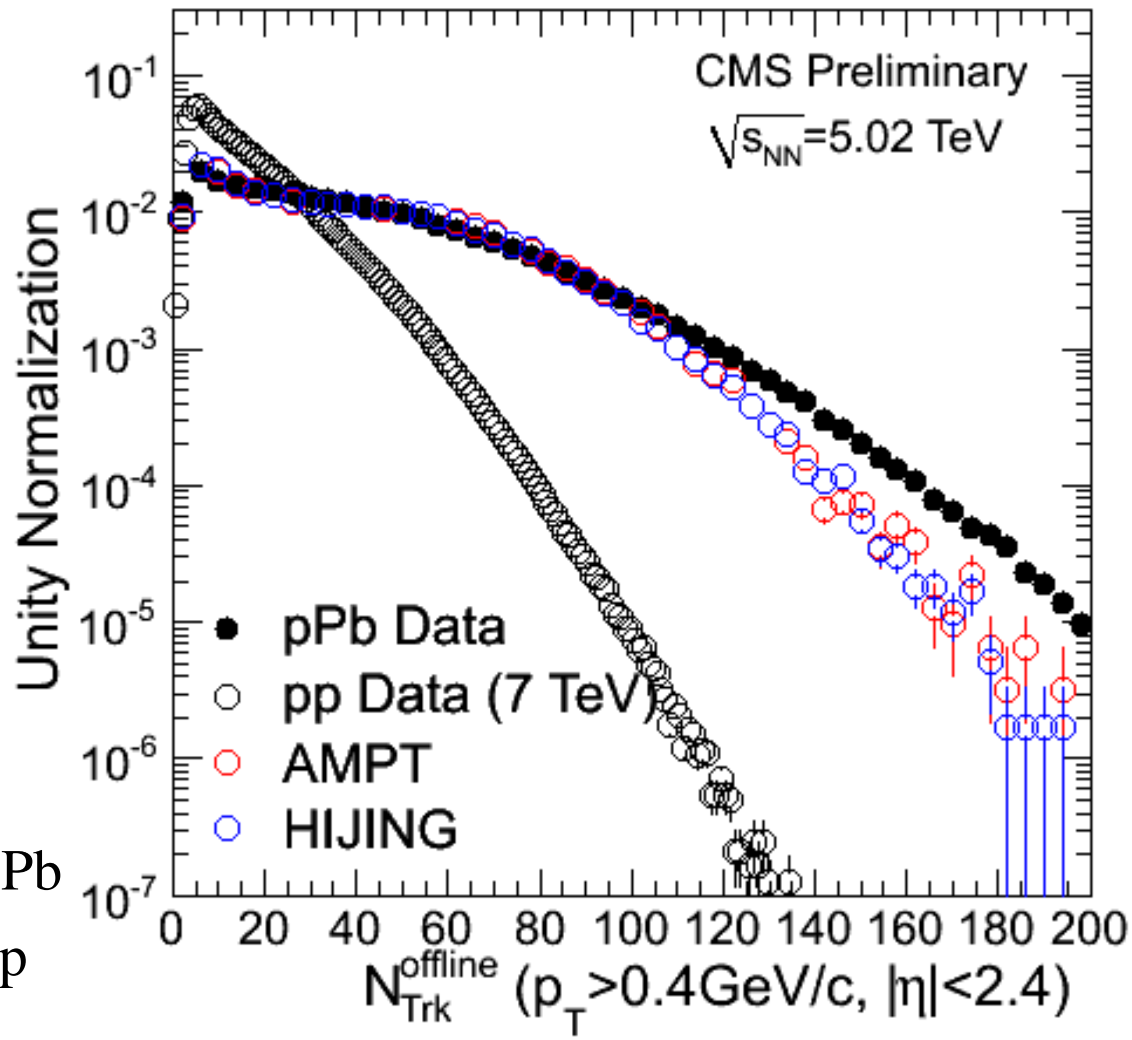


$\langle N_{trk}^{offline} \rangle$~40 for MB pPb

High-multiplicity pPb event

2012 pPb pilot run at the LHC

Interaction rate of 200 Hz, all two million MB pPb events collected

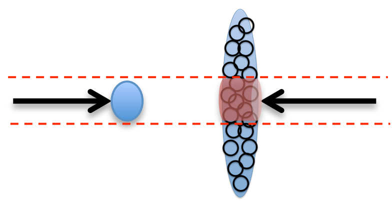


$\langle N_{trk}^{offline} \rangle$~40 for MB pPb

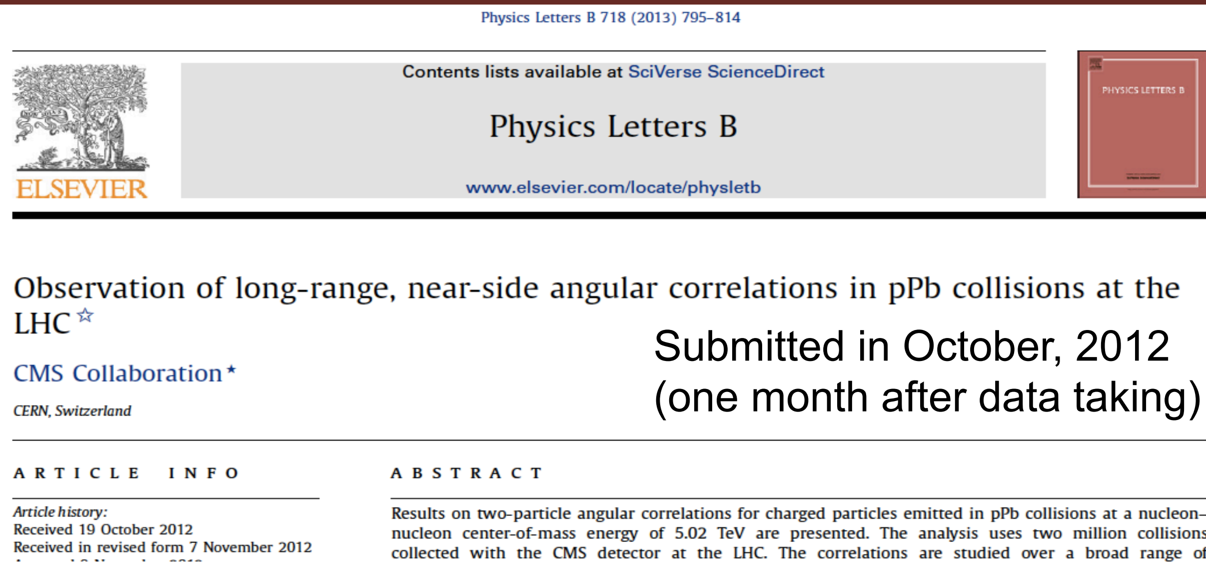
$\langle N_{trk}^{offline} \rangle$~15 for MB pp

Much easier to reach high multiplicity in pPb, as expected

2012 pPb pilot run at the LHC



2 million MB events total


Physics Letters B 718 (2013) 795–814

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Observation of long-range, near-side angular correlations in pPb collisions at the LHC ☆

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

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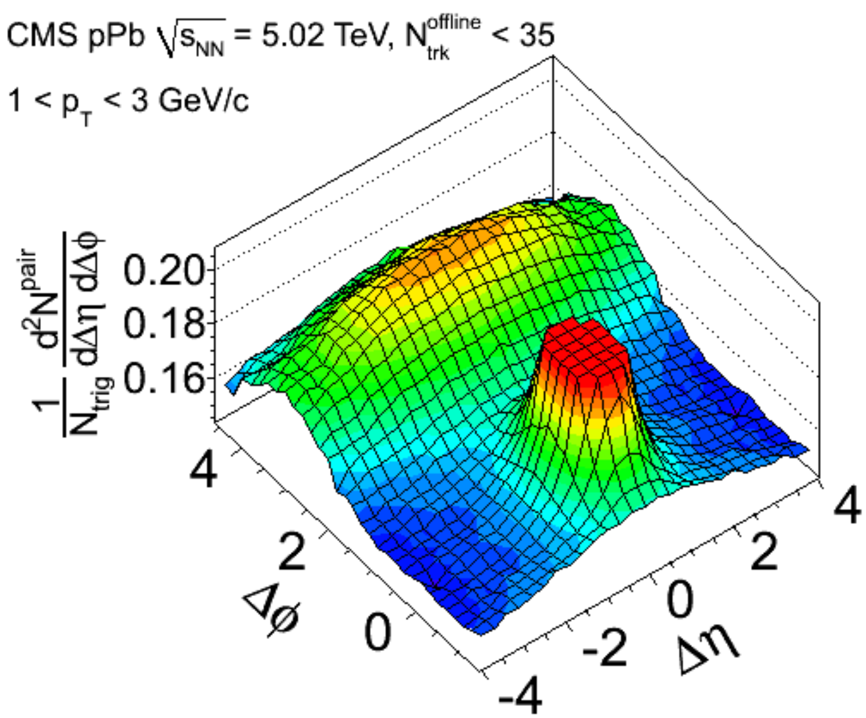
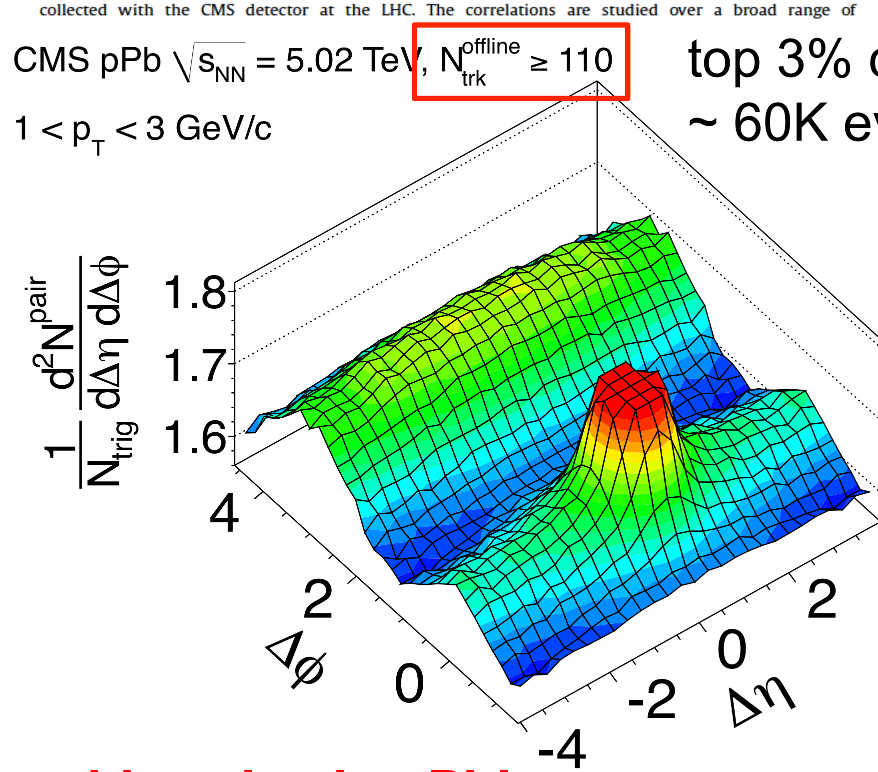
ABSTRACT

Results on two-particle angular correlations for charged particles emitted in pPb collisions at a nucleon–nucleon center-of-mass energy of 5.02 TeV are presented. The analysis uses two million collisions collected with the CMS detector at the LHC. The correlations are studied over a broad range of

Submitted in October, 2012
(one month after data taking)

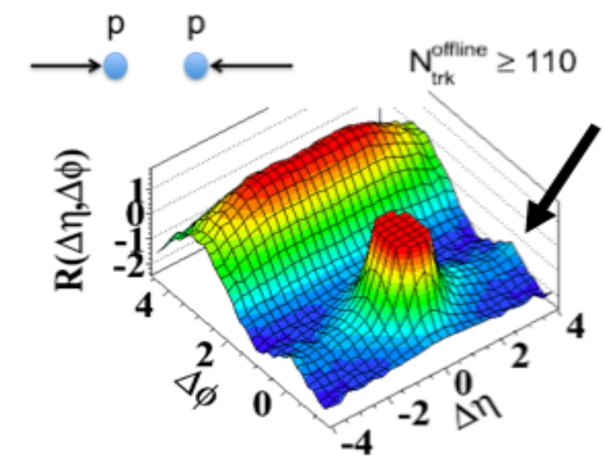


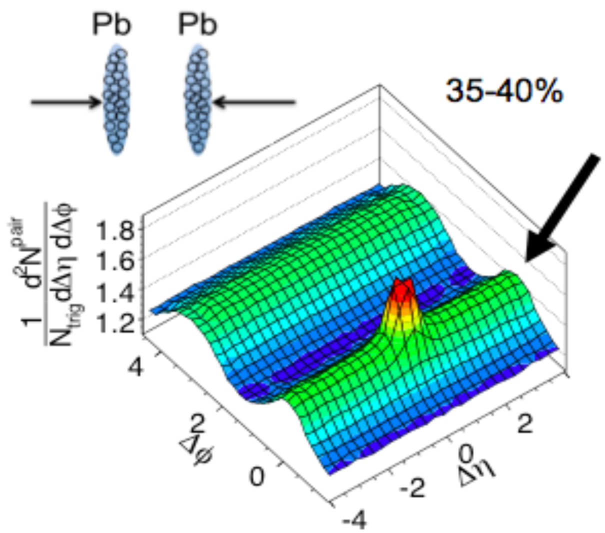


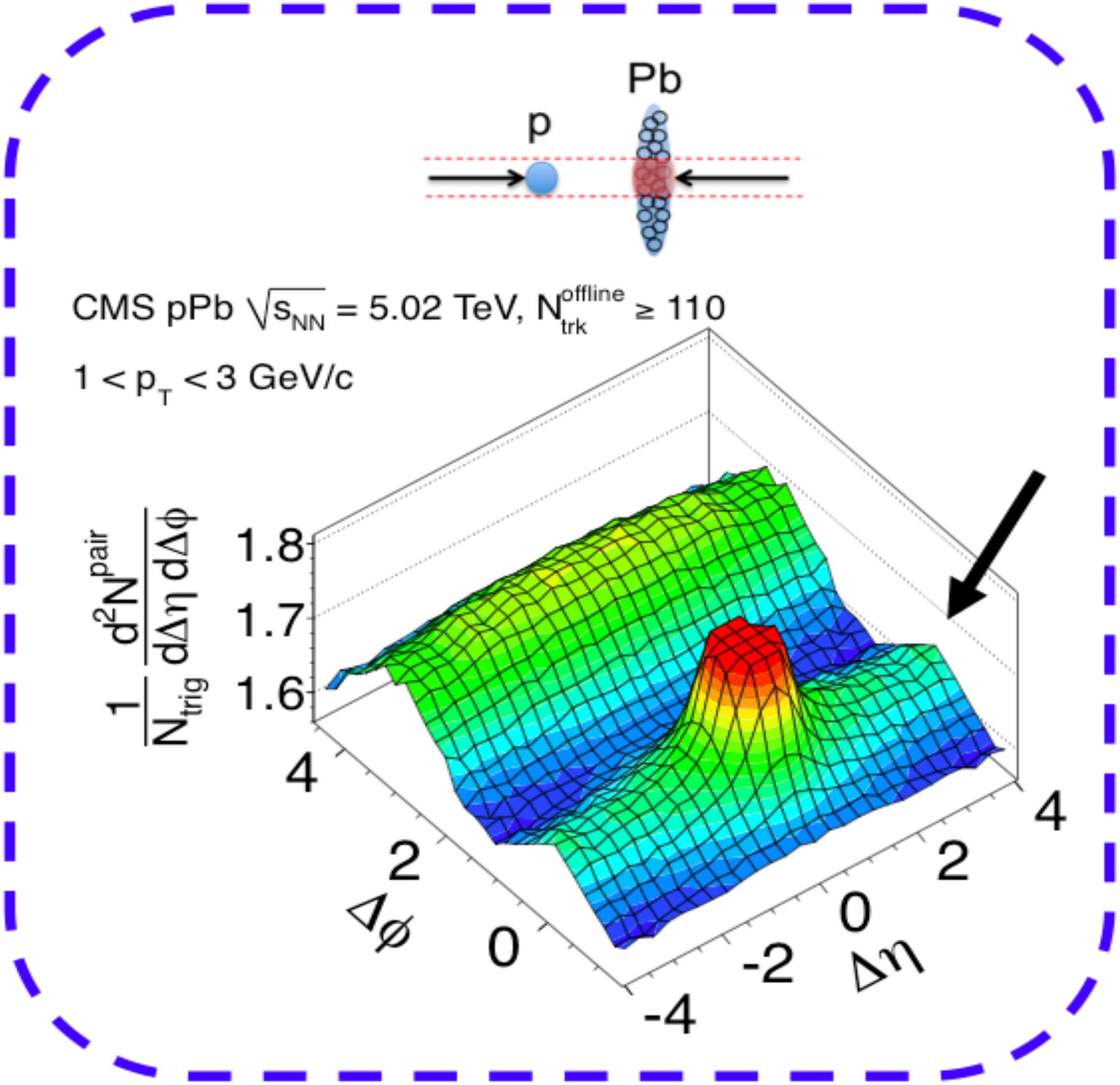
top 3% central
~ 60K events

"Expectedly", a ridge also in pPb!
But somewhat surprisingly strong!

A complete picture of ridge correlations





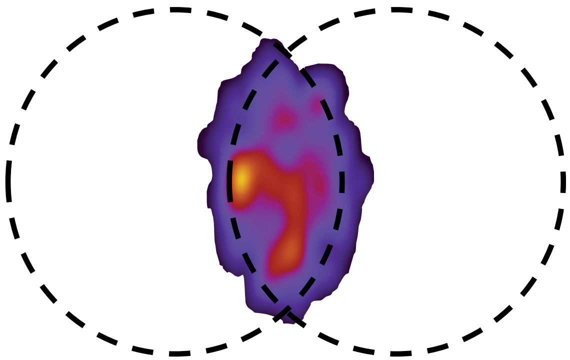


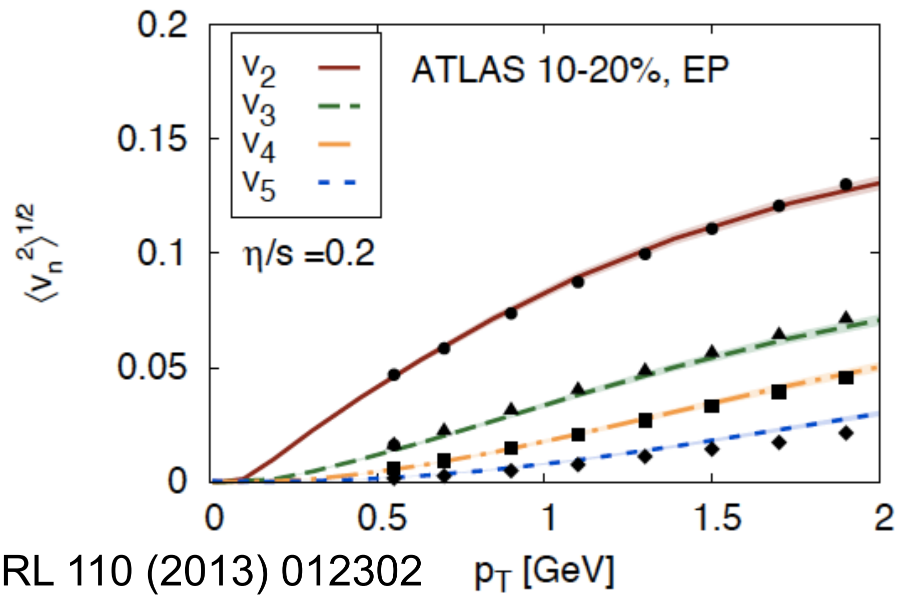
Is there a common origin of the ridge in all systems?

"Perfect Liquid" or Gluon Condensate?

Hydrodynamics

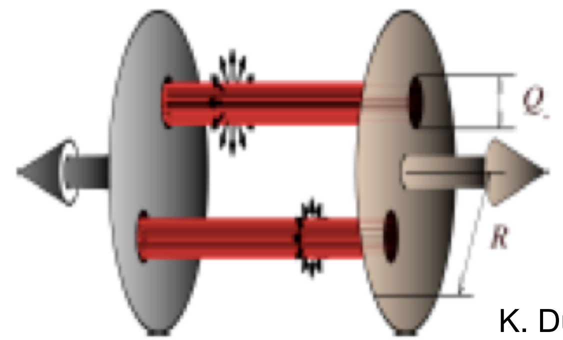
Initial-state asymmetry



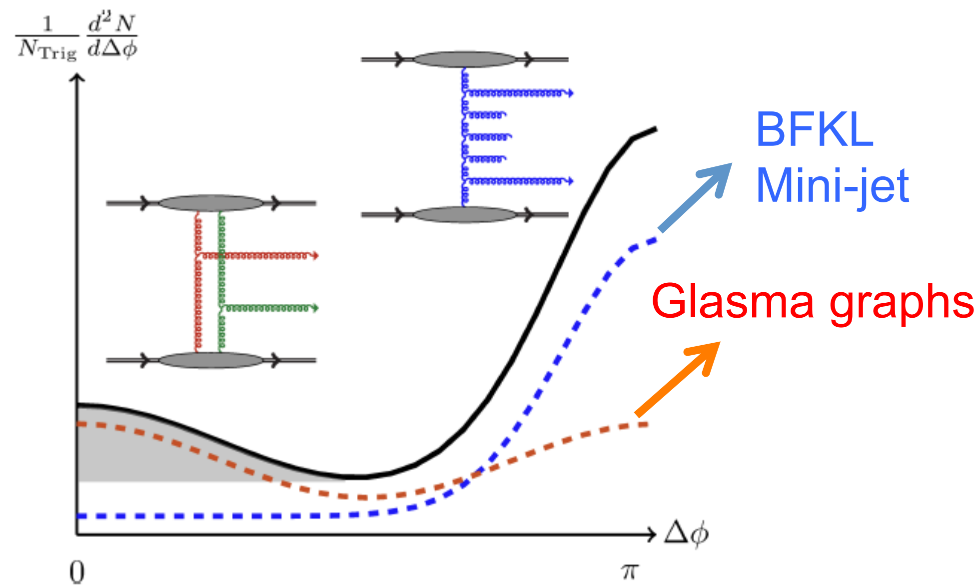


PRL 110 (2013) 012302

Intrinsic gluon collimation from glasma diagram (CGC)



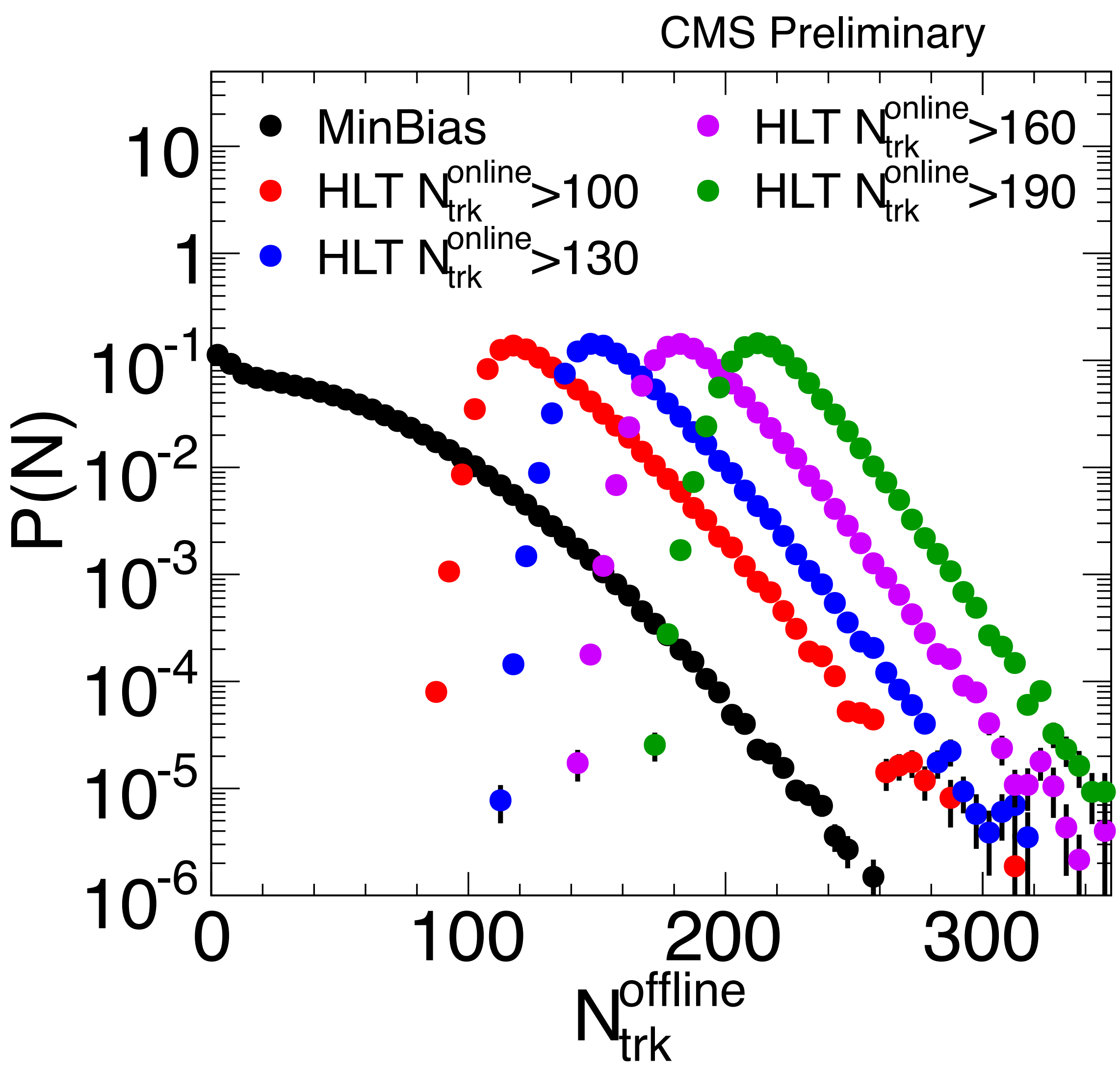
K. Dusling, R. Venugopalan: arXiv:1210.3890



- **Initial-state geometry related or not?**
- **Final-state interaction or quantum interference?**

2013 pPb nominal run at the LHC

High-multiplicity trigger in pPb at CMS



Interaction rate of 200 kHz

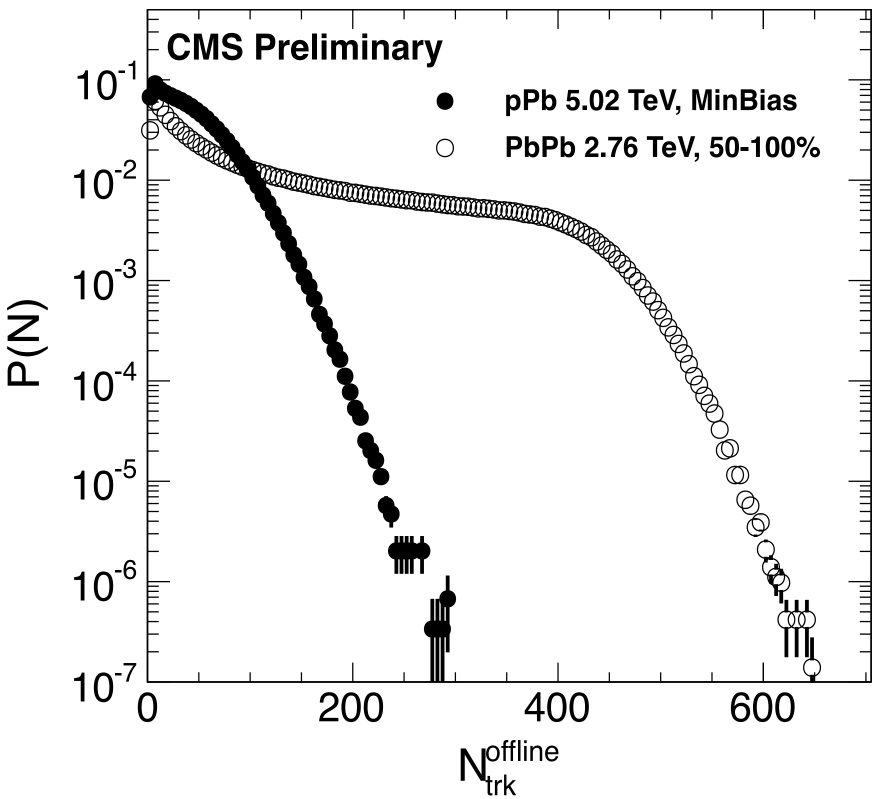
4 different trigger thresholds, each collecting ~20 million events

- Powerful high-level trigger farm: 16K CPU cores
- Online tracking and vertexing to avoid pileup

Sampled full 31 nb^{-1} luminosity (60 billion collisions)

First direct comparison of PbPb and pPb

Multiplicity distribution in pPb and PbPb



same reconstruction in pPb and PbPb

Overall tracking efficiency:
~ 83% ($N_{trk}^{offline}/N_{trk}^{corrected}$)

	PbPb data			pPb data		
$N_{trk}^{offline}$ bin	<Centrality> ± RMS (%)	$\langle N_{trk}^{offline}\rangle$	$\langle N_{trk}^{corrected}\rangle$	Fraction	$\langle N_{trk}^{offline}\rangle$	$\langle N_{trk}^{corrected}\rangle$
$[0, \infty)$				1.00	40	50±2
[0, 20)	92±4	10	13±1	0.31	10	12±1
[20, 30)	86±4	24	30±1	0.14	25	30±1
[30, 40)	83±4	34	43±2	0.12	35	42±2
[40, 50)	80±4	44	55±2	0.10	45	54±2
[50, 60)	78±3	54	68±3	0.09	54	66±3
[60, 80)	75±3	69	87±4	0.12	69	84±4
[80, 100)	72±3	89	112±5	0.07	89	108±5
[100, 120)	70±3	109	137±6	0.03	109	132±6
[120, 150)	67±3	134	168±7	0.02	132	159±7
[150, 185)	64±3	167	210±9	4×10^{-3}	162	195±9
[185, 220)	62±2	202	253±11	5×10^{-4}	196	236±10
[220, 260)	59±2	239	299±13	6×10^{-5}	232	280±12
[260, 300)	57±2	279	350±15	3×10^{-6}	271	328±14
[300, 350)	55±2	324	405±18	1×10^{-7}	311	374±16

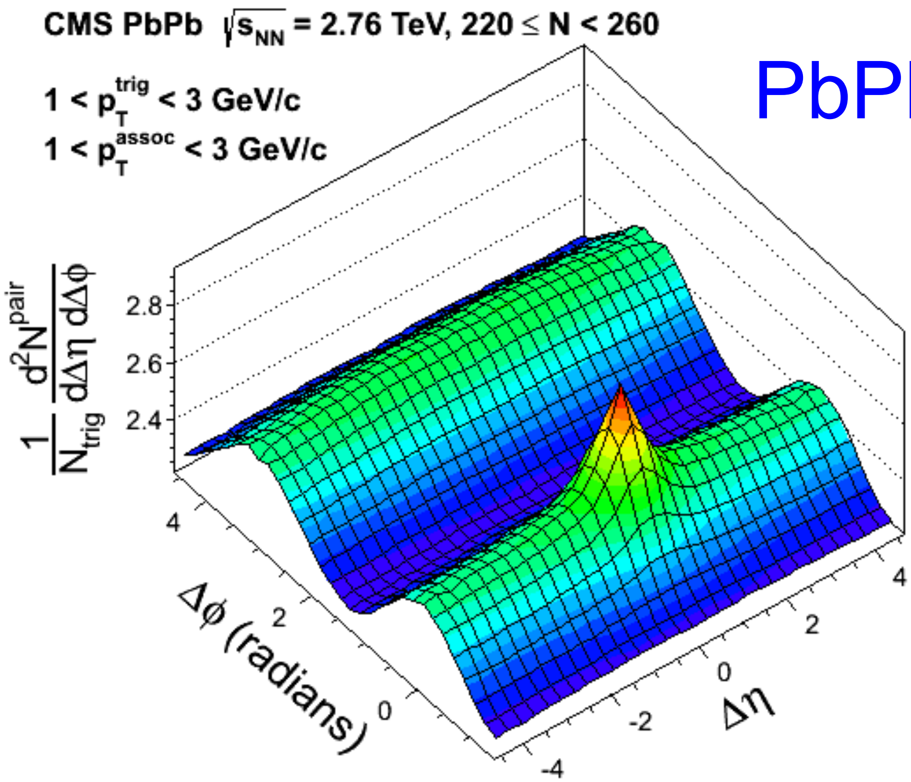
- Highest multiplicity of **~ 370** explored in pPb
- Occurs once in **every 10 million** events (~ 6000 events recorded)
- Comparable up to **55% mid-central PbPb**

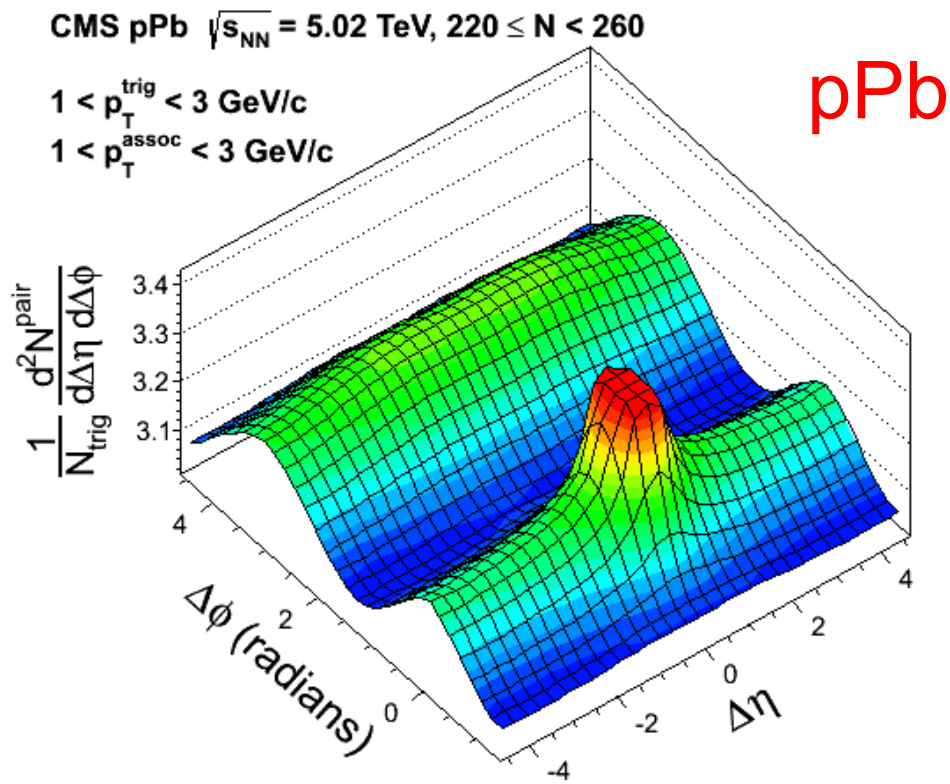
2D correlation structures in PbPb vs pPb

arXiv:1305.0609, submitted to PLB

~ 60% centrality

220 ≤ N < 260





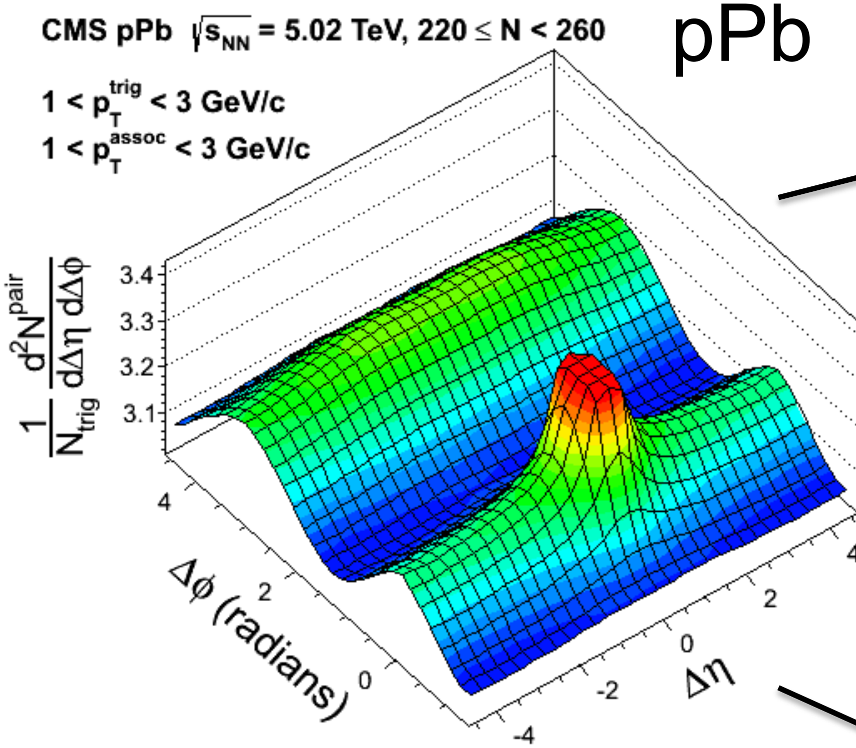
Remarkably similar, who is who's reference?

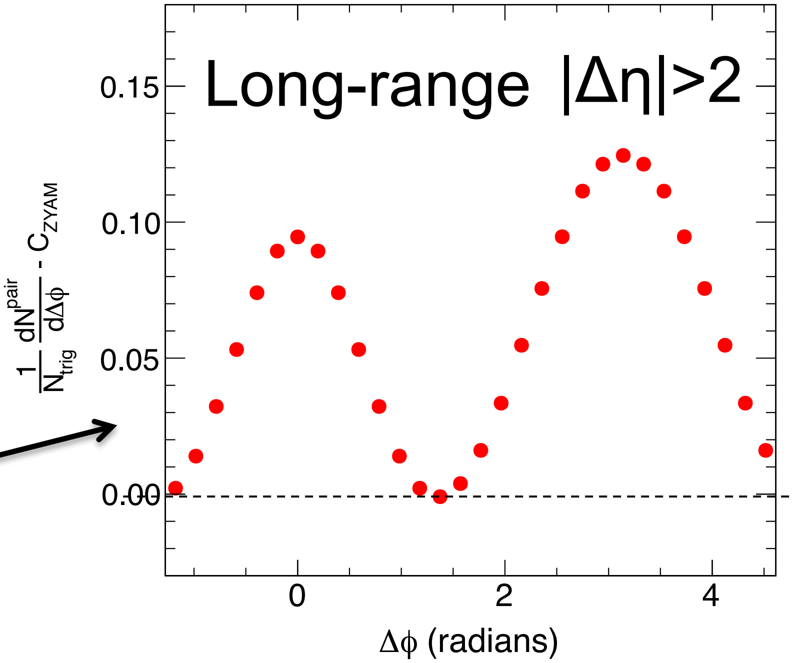
Quantify the short- and long-range correlations

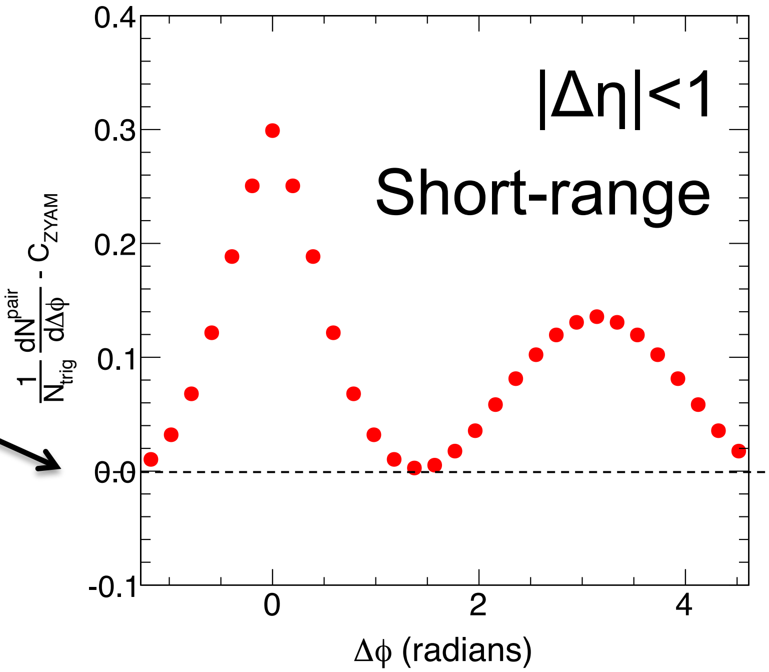
Projection to 1D Δϕ-axis

$220 \leq N < 260$

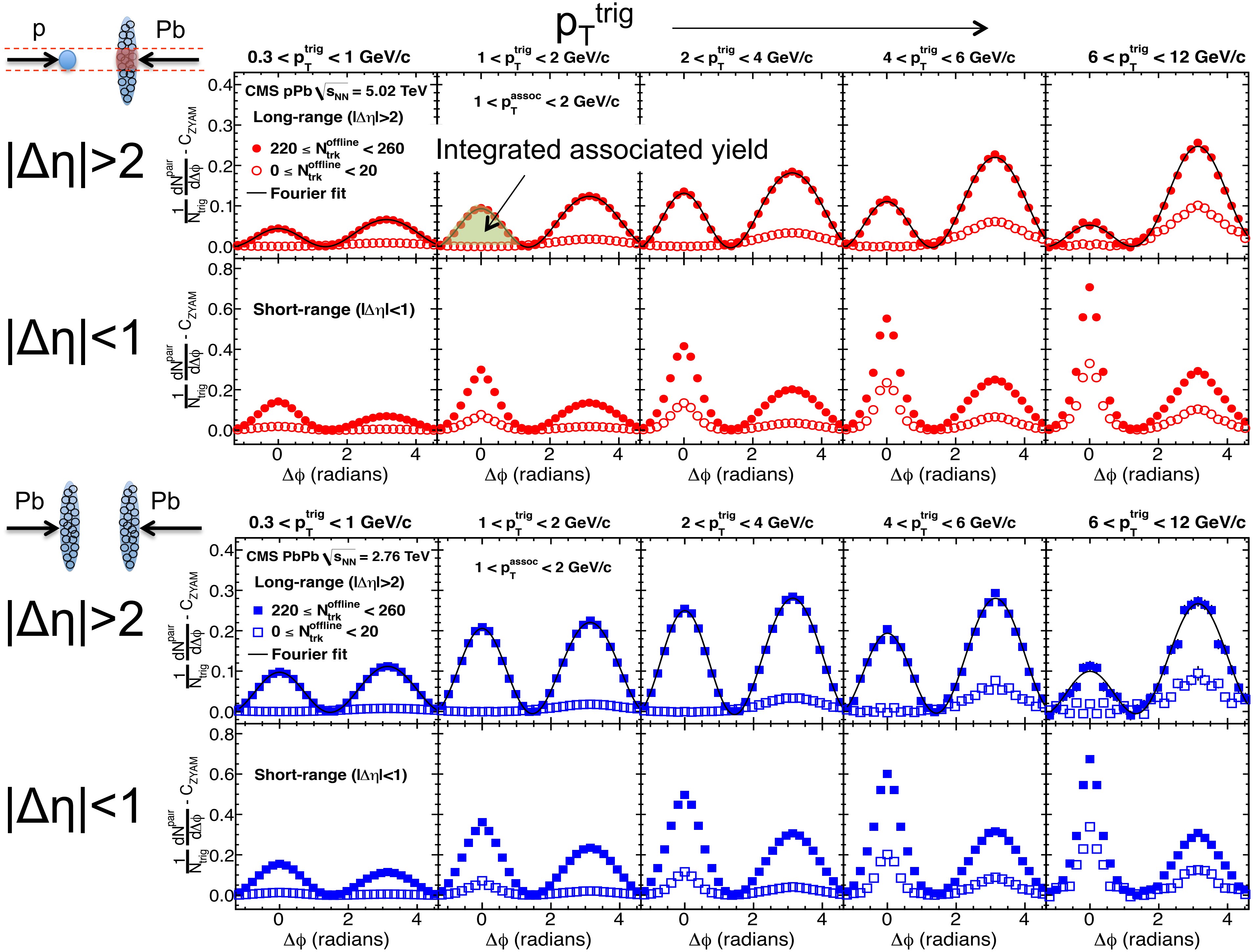
pPb





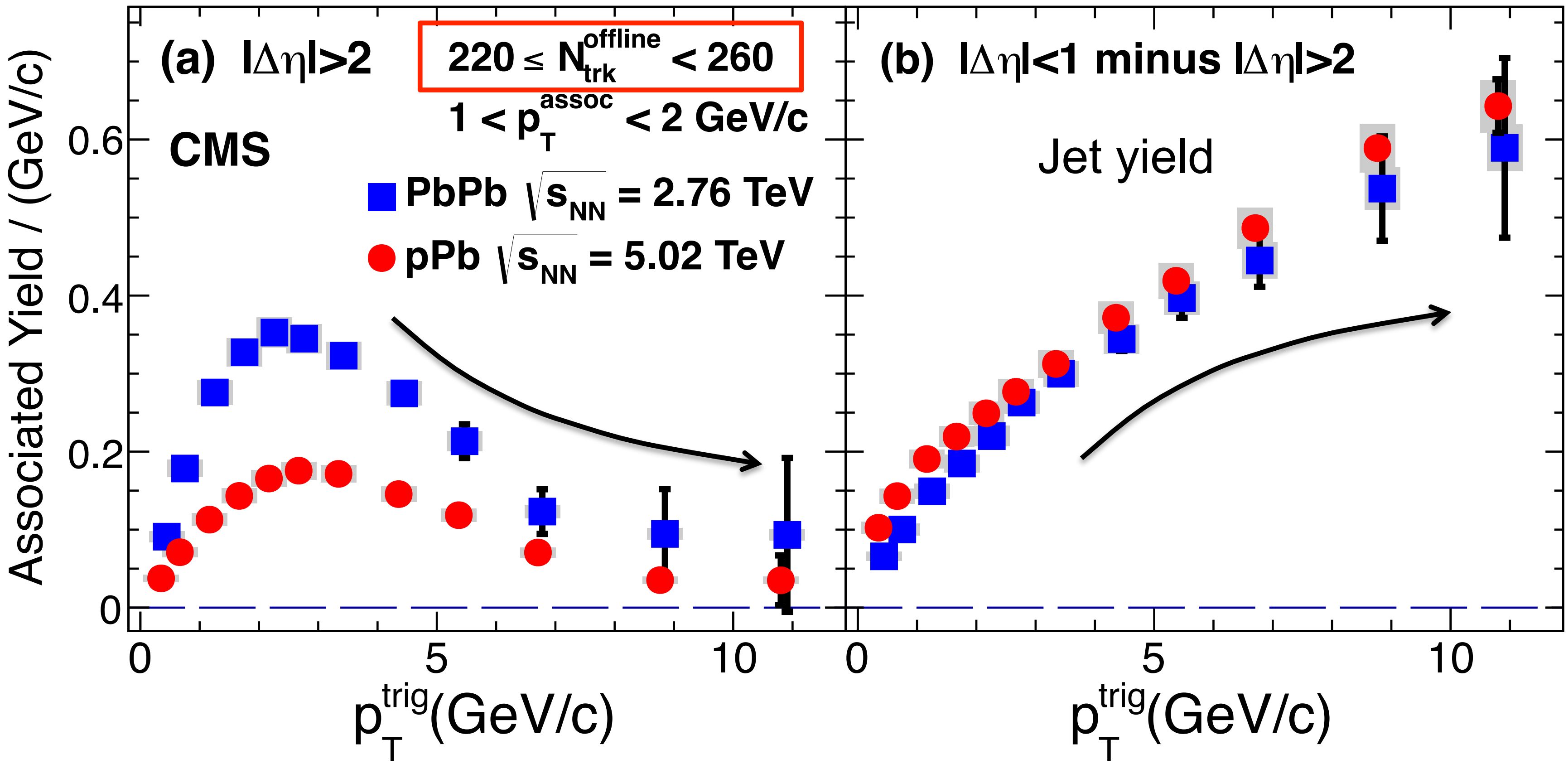


1D Δϕ correlation functions



p_T dependence of associated yield

Long-range region ($|\Delta\eta|>2$)   Short-range region ($|\Delta\eta|<1$)

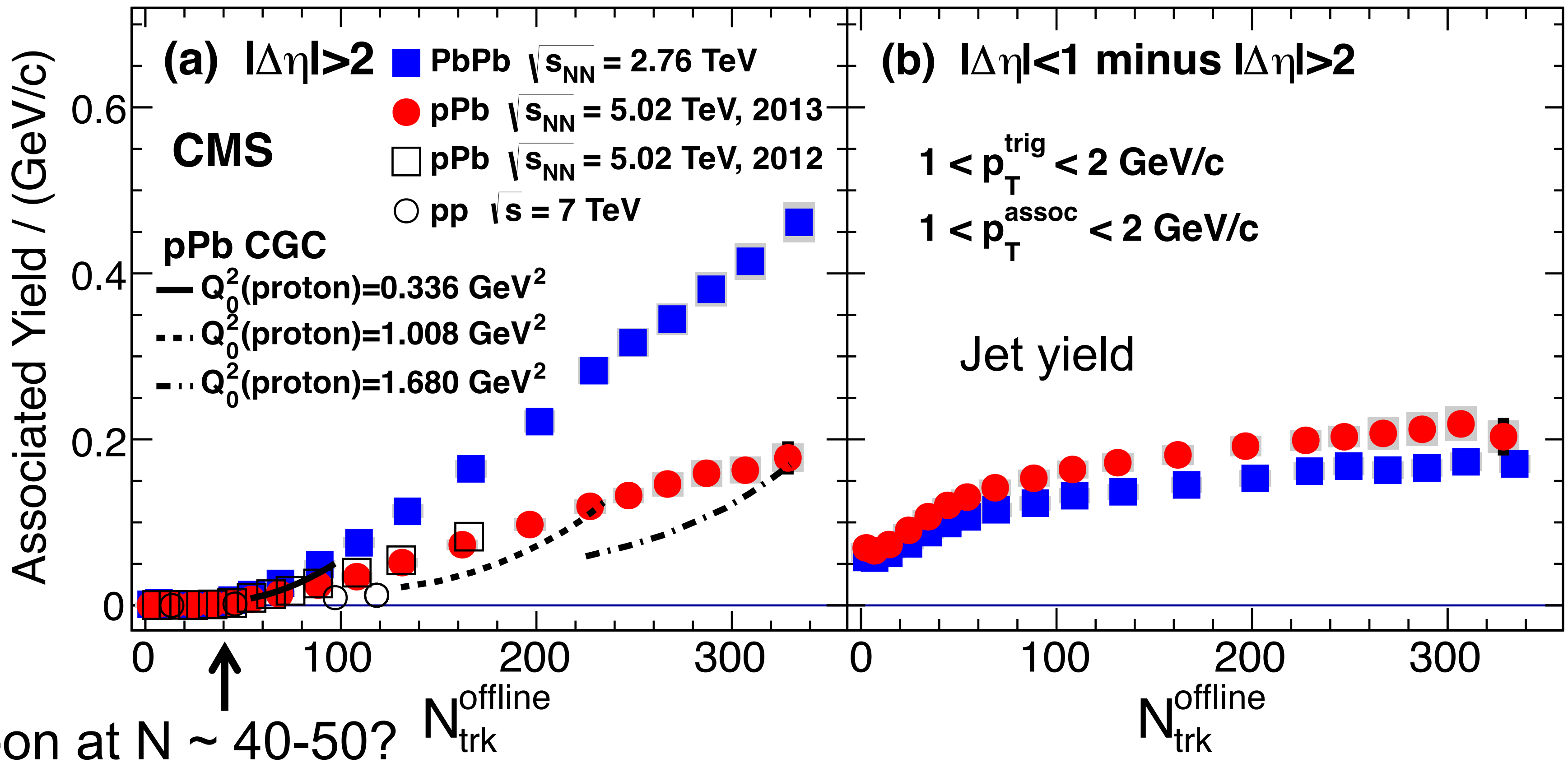


Long-range yield goes in the opposite direction as the jet yield at high p_T, not related to hard processes

Very similar trend for pPb and PbPb

Multiplicity dependence of associated yield

Long-range region (|Δη|>2)   Short-range region (|Δη|<1)



turn-on at N ~ 40-50?

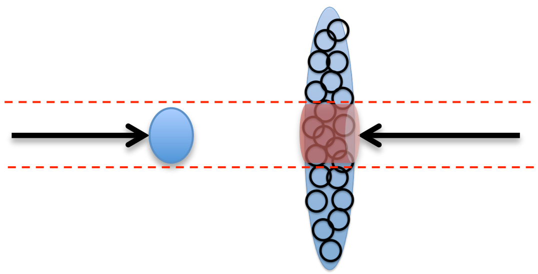
PbPb : pPb : pp ≈ 8 : 4 : 1

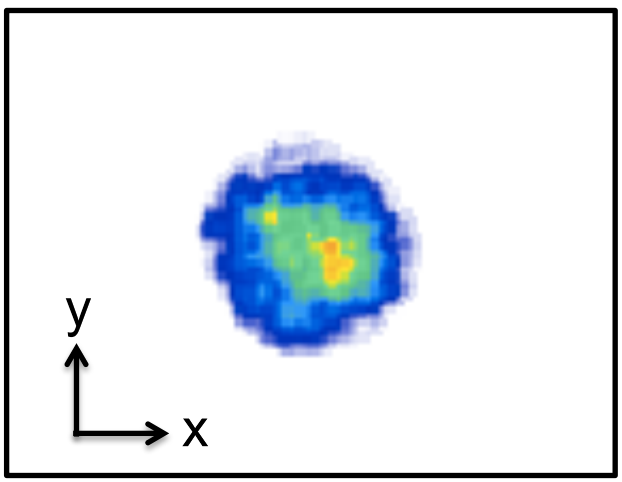
Long-range yield is strongly correlated with global multiplicity, behaving differently from the jet yield. Collective phenomena?

Very similar trend for pPb and PbPb!

Hydrodynamics in pp and pA?

With sufficient initial energy density and fluctuating geometry, anisotropic flow in pp and pA could be possible

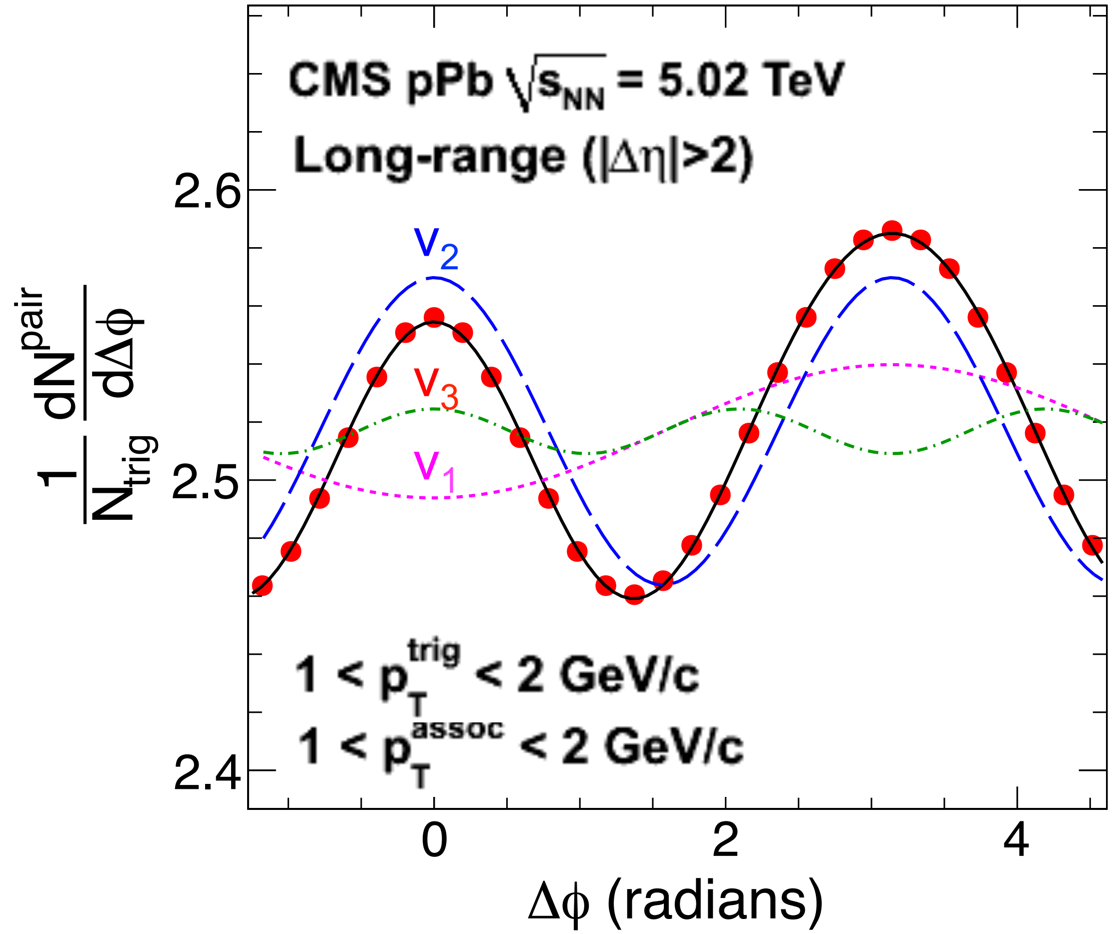




P. Bozek, PRC85 (2012) 014911, arXiv: 1304.3044

A. Bzdak. et al., arXiv: 1304.3403

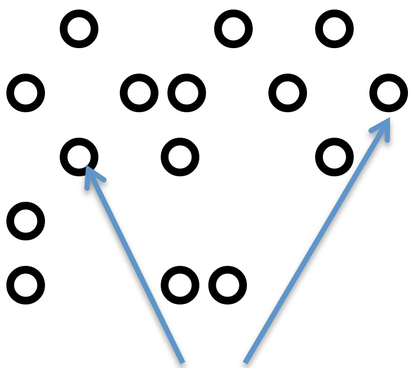
Data described by just v_1, v_2 and v_3!

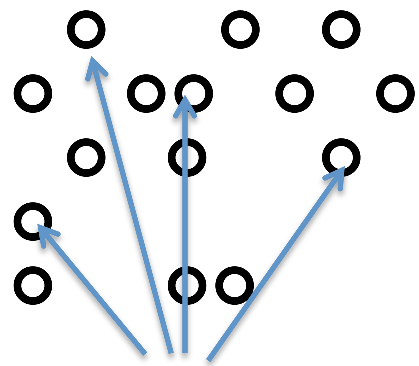


Of course, Fourier is designed to do this …

Multi-particle correlations (cumulant)

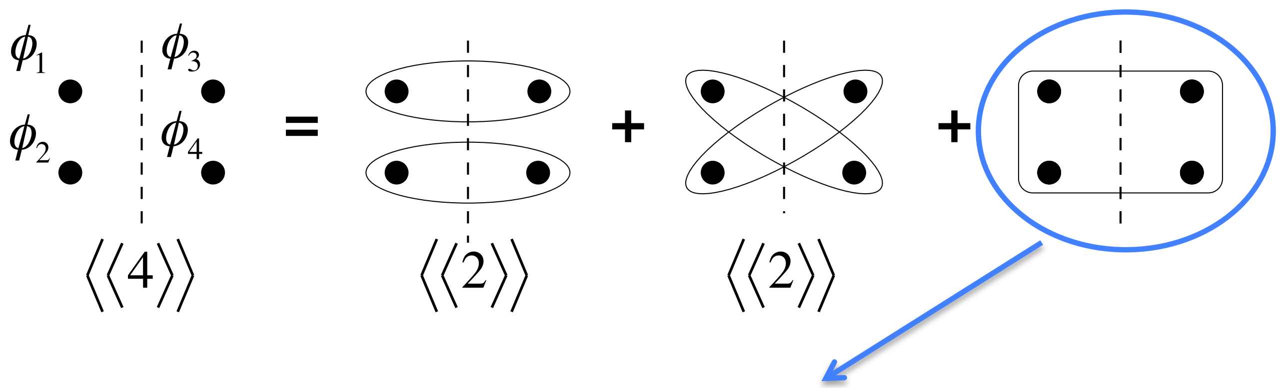
Is the Ridge just a two-particle effect, or it involves more particles?





$$\langle\langle 2 \rangle\rangle = \langle \cos 2(\phi_1 - \phi_2) \rangle \quad (v_2\{2\})$$

$$\langle\langle 4 \rangle\rangle = \langle \cos 2(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle$$

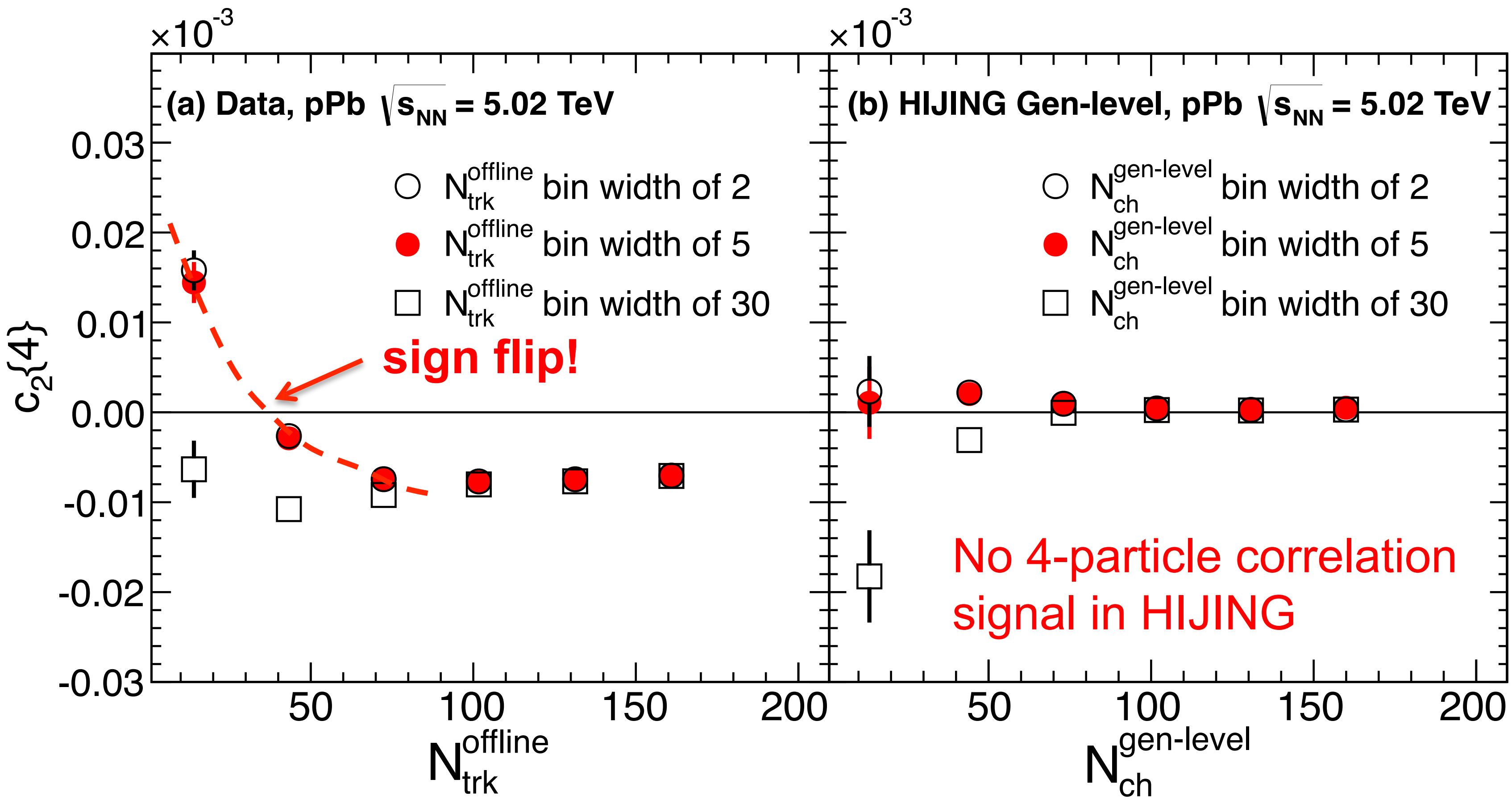


4th-order cumulant: $c_2\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

average over particles and events

Multi-particle correlations (cumulant)

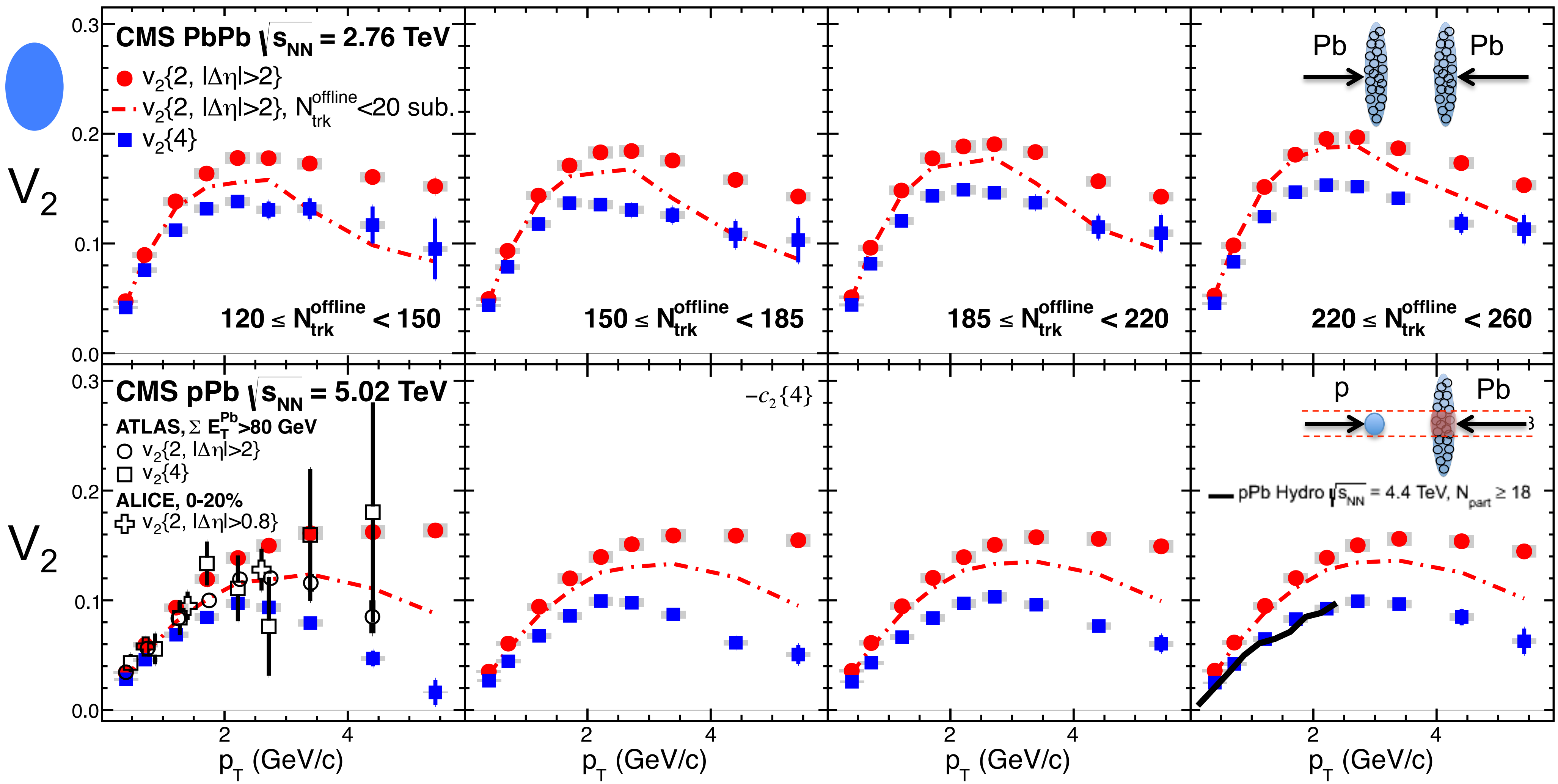


Analysis should be done in small N bins first to avoid multiplicity fluctuations

p_T dependence of elliptic flow (v_2)

Dash-dotted curves: peripheral 70-100% subtracted

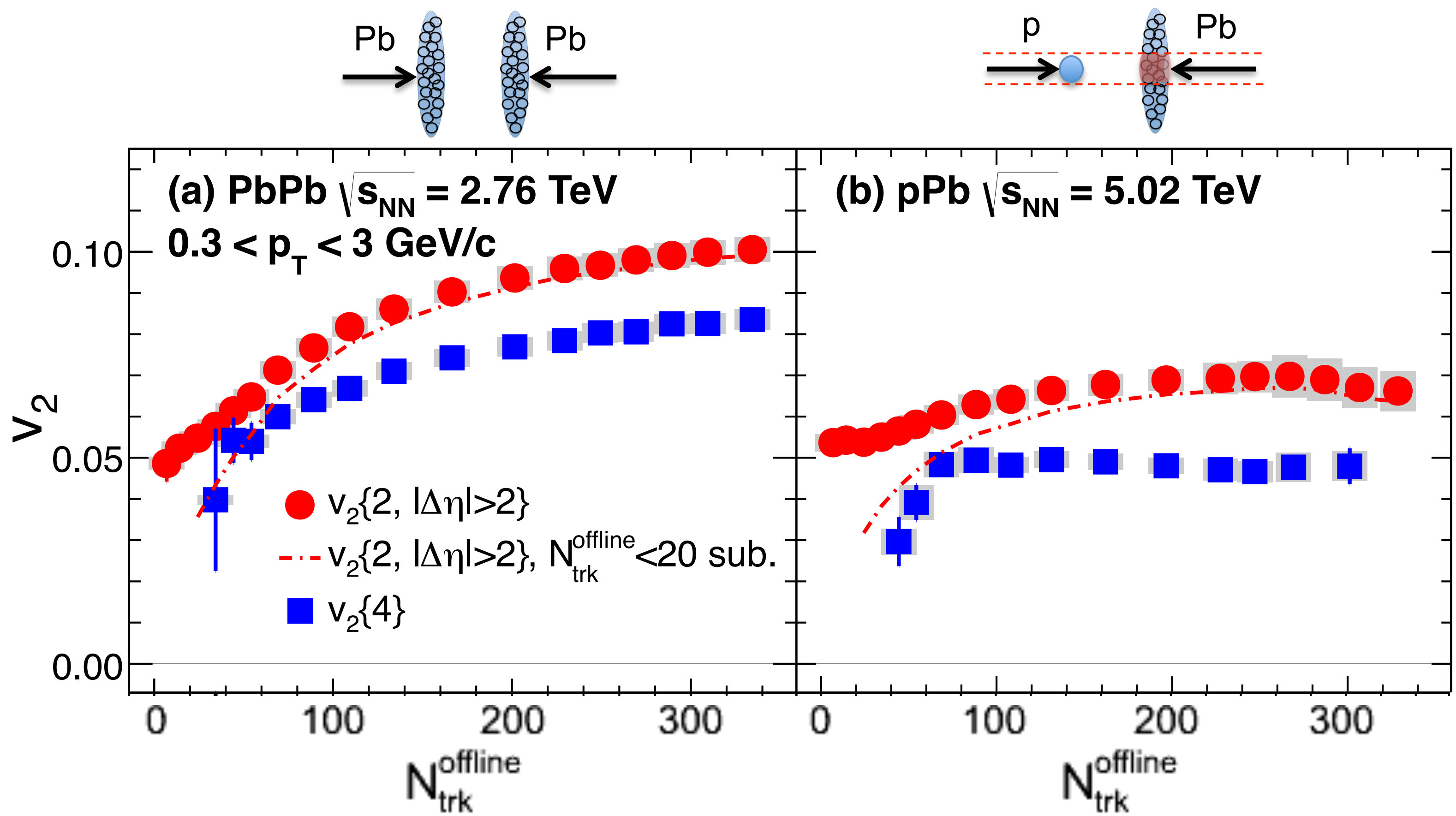
Multiplicity →



$v_2\{PP\}$ from hydro

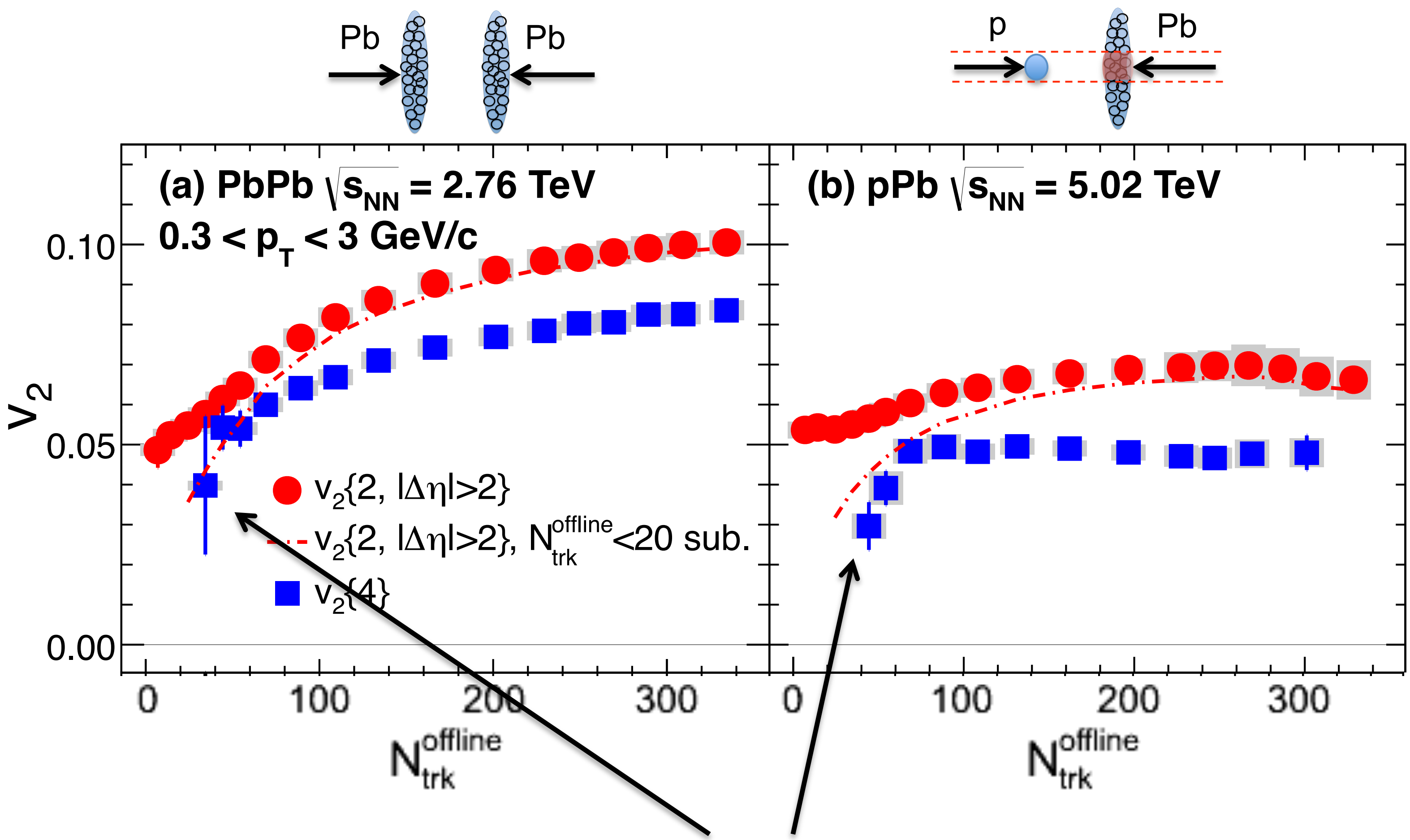
PRC85 (2012) 014911

Multiplicity dependence of elliptic flow (v_2)



Peripheral subtraction makes no difference at high multiplicity!

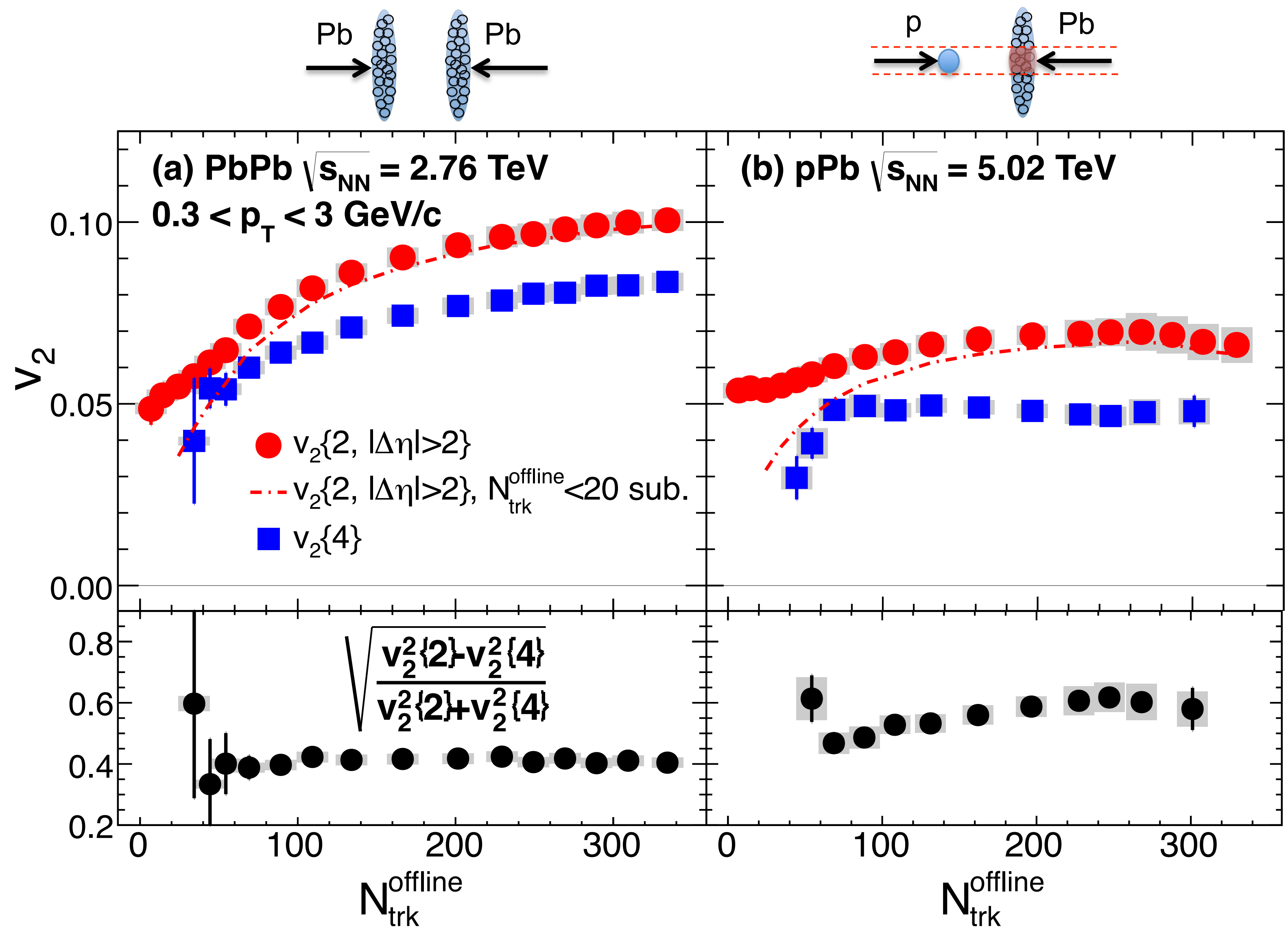
Multiplicity dependence of elliptic flow (v_2)



$v_2\{4\}$ turns on at N ~ 40: onset of collective phenomena?

Peripheral subtraction makes no difference at high multiplicity!

Multiplicity dependence of elliptic flow (v_2)



Extract "v_2 fluctuations"

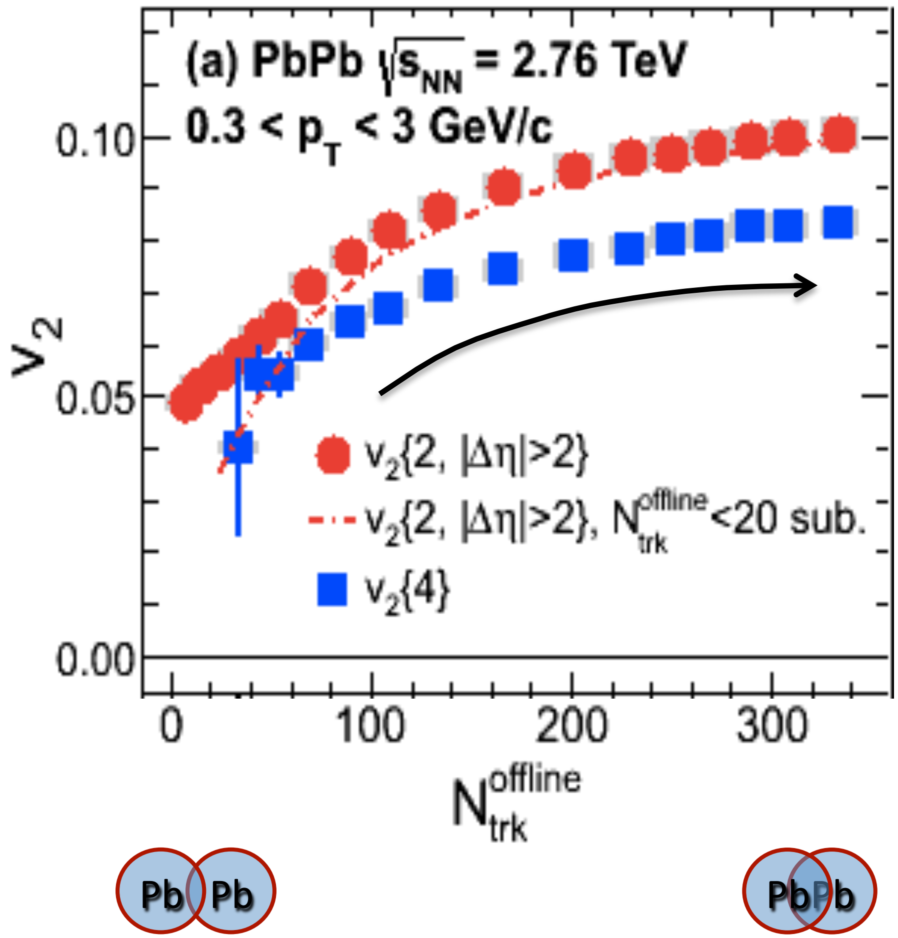
$$v_2\{2\} = \sqrt{< v_2 >^2 + \sigma_{v_2}^2}$$
$$v_2\{4\} = \sqrt{< v_2 >^2 - \sigma_{v_2}^2},$$

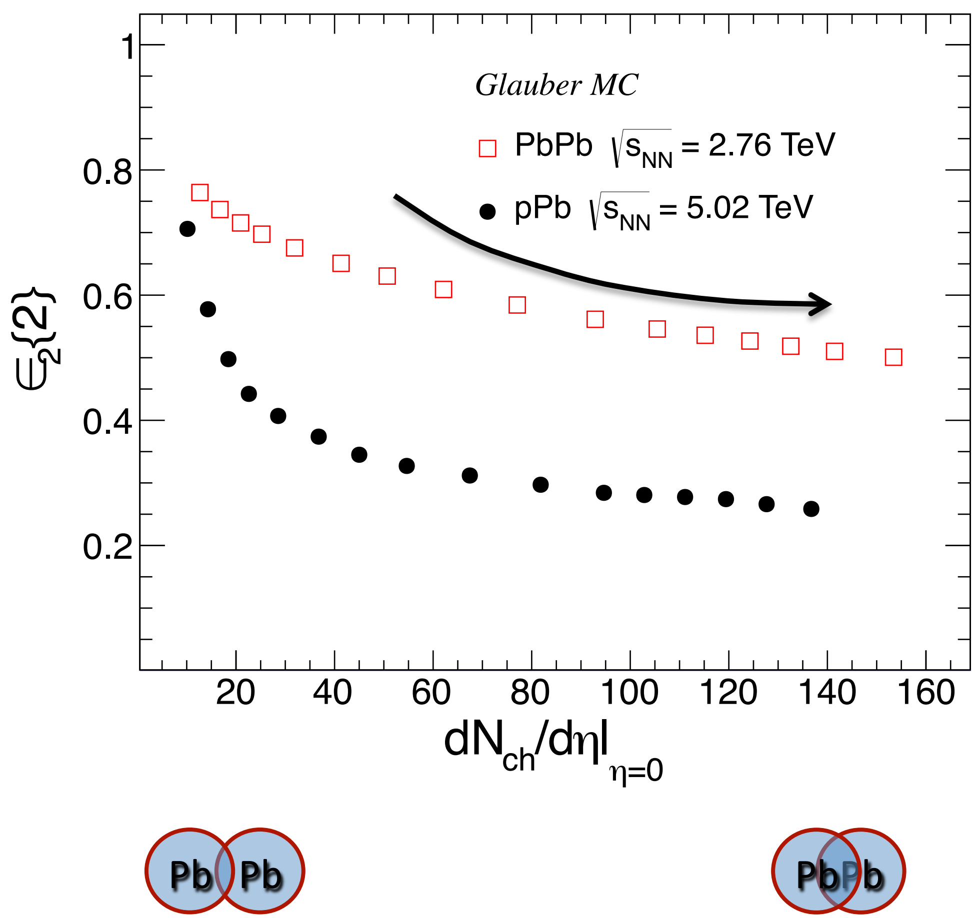
$$\frac{\sigma_{v_2}}{v_2} = \sqrt{\frac{v_2^2\{2\} - v_2^2\{4\}}{v_2^2\{2\} + v_2^2\{4\}}}.$$

Larger in pPb with moderate multiplicity dependence

Multiplicity dependence of elliptic flow (v_2)

v_2 in PbPb increases as eccentricity decreases?



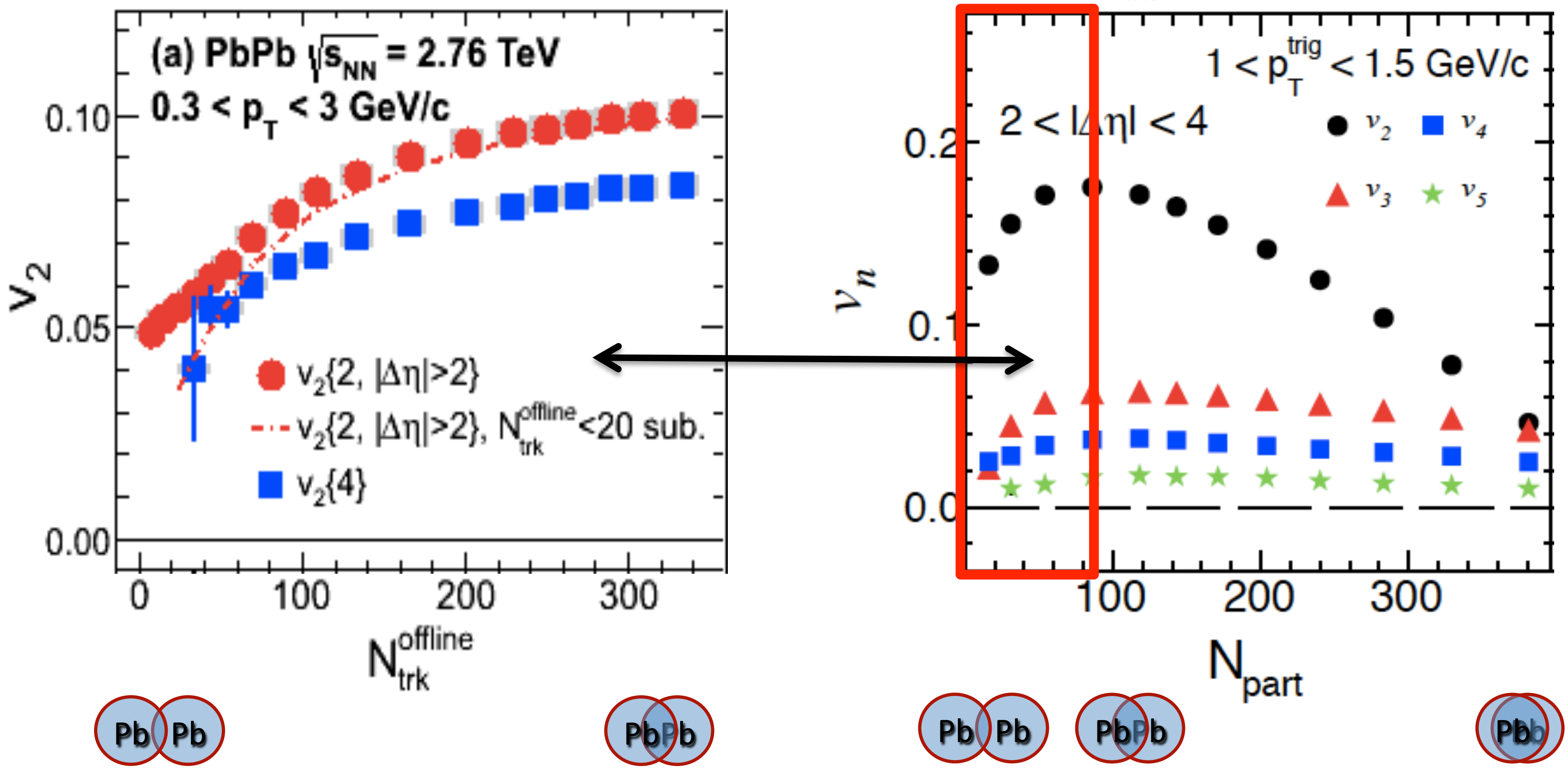


Multiplicity dependence of elliptic flow (v_2)

PbPb 2.76 TeV, 50-100%

PbPb 2.76 TeV

CMS L_{int} = 3.9 μb^{-1} EPJC 72 (2012) 2012



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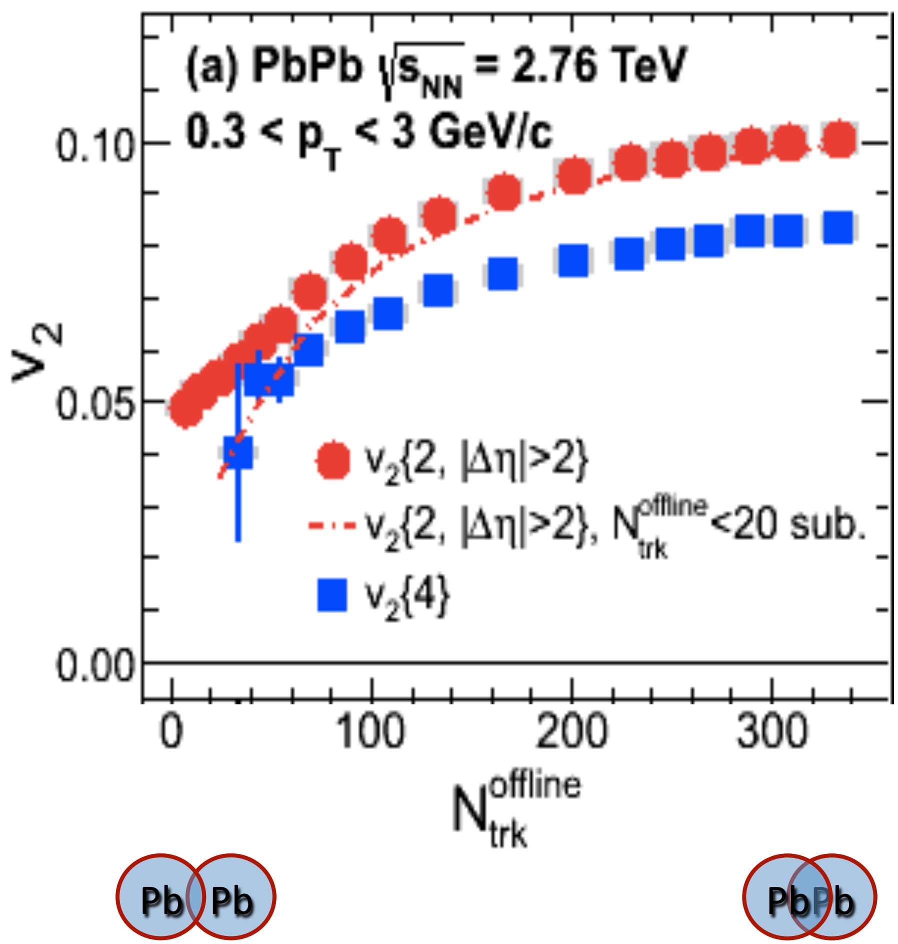

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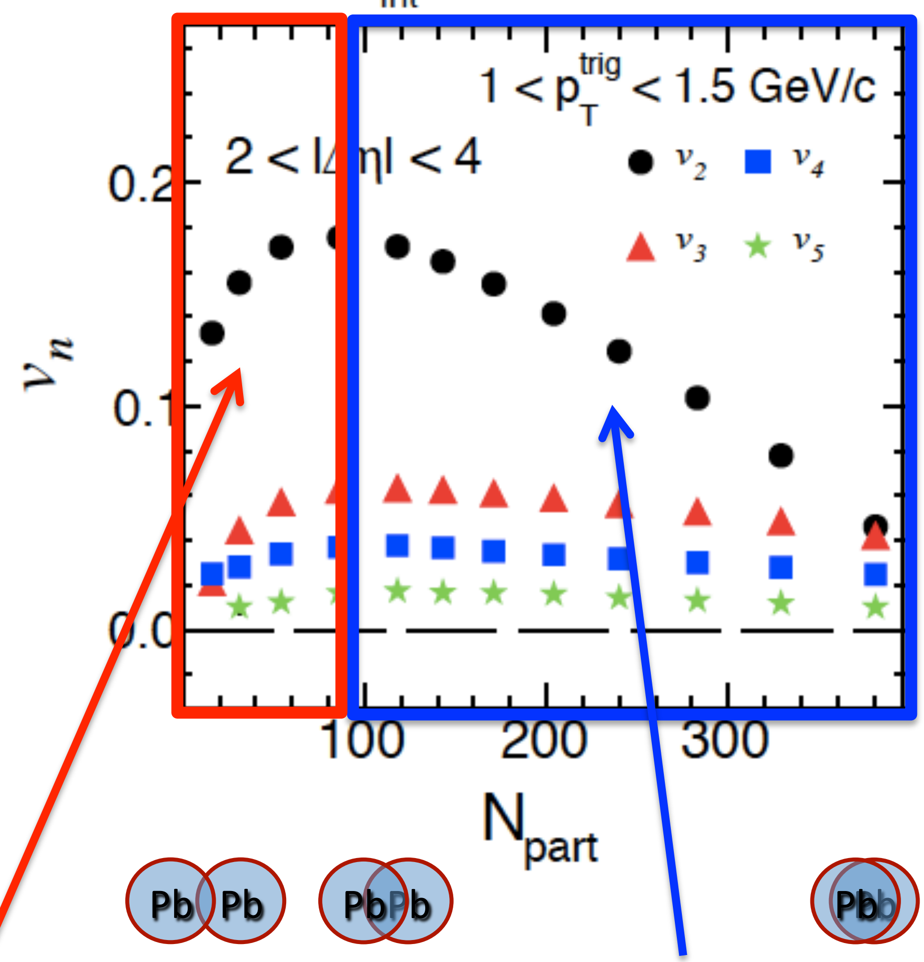


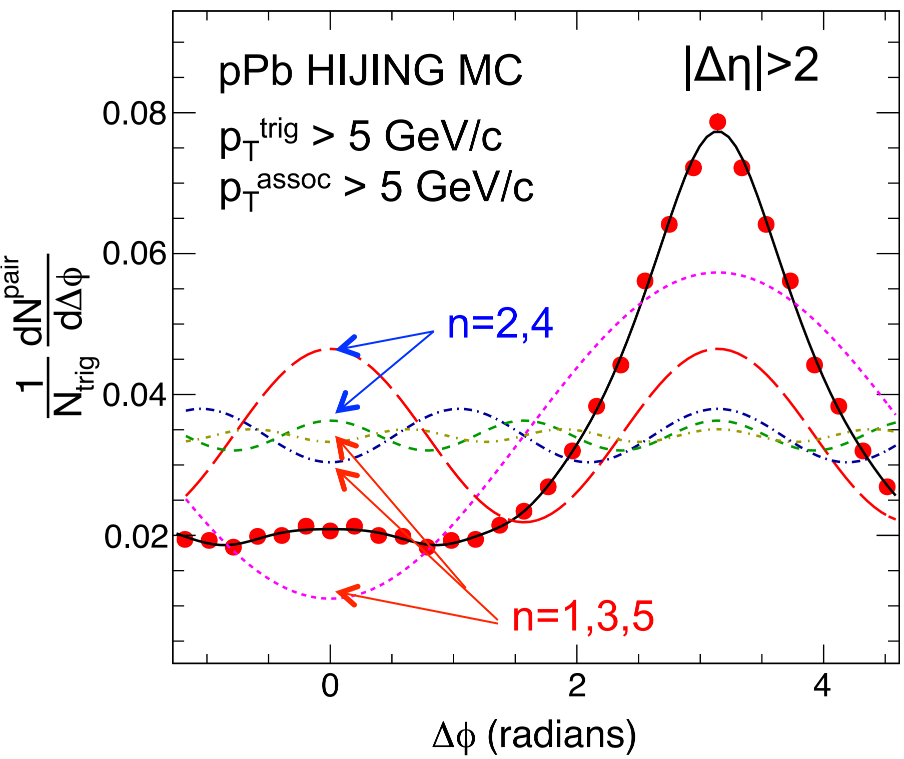
Smaller system size (L ~ λ)
➔ larger viscous correction

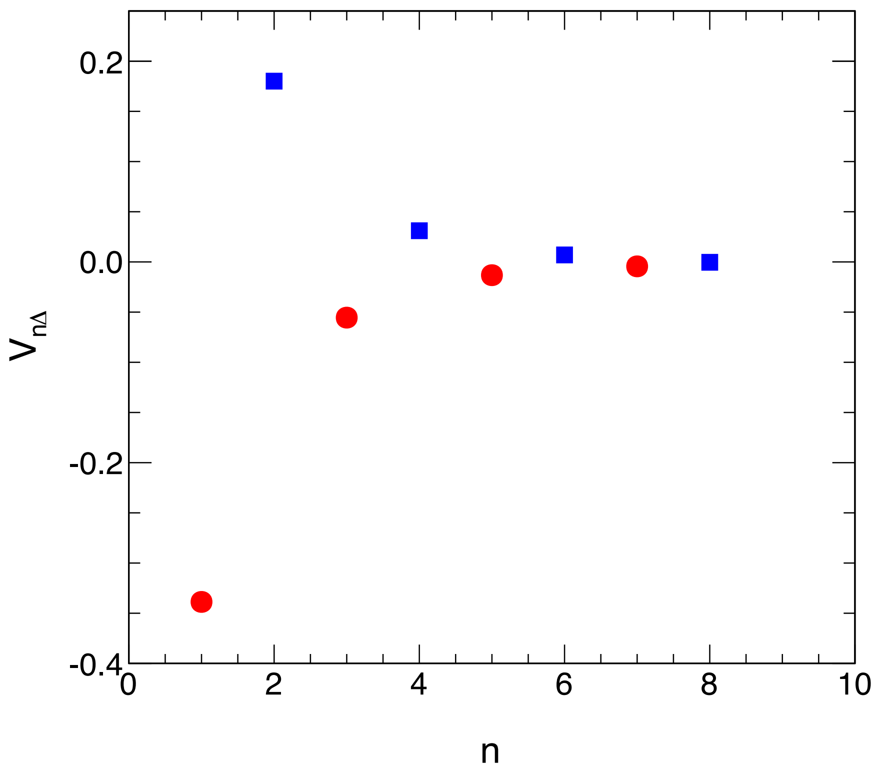
Nearly ideal hydro, geometry driven

Crucial to understand the full centrality range!

Triangular flow (v_3)

v_3 is special as "nonflow" dijets on the away side can only give rise to negative $V_{3\Delta}$ component





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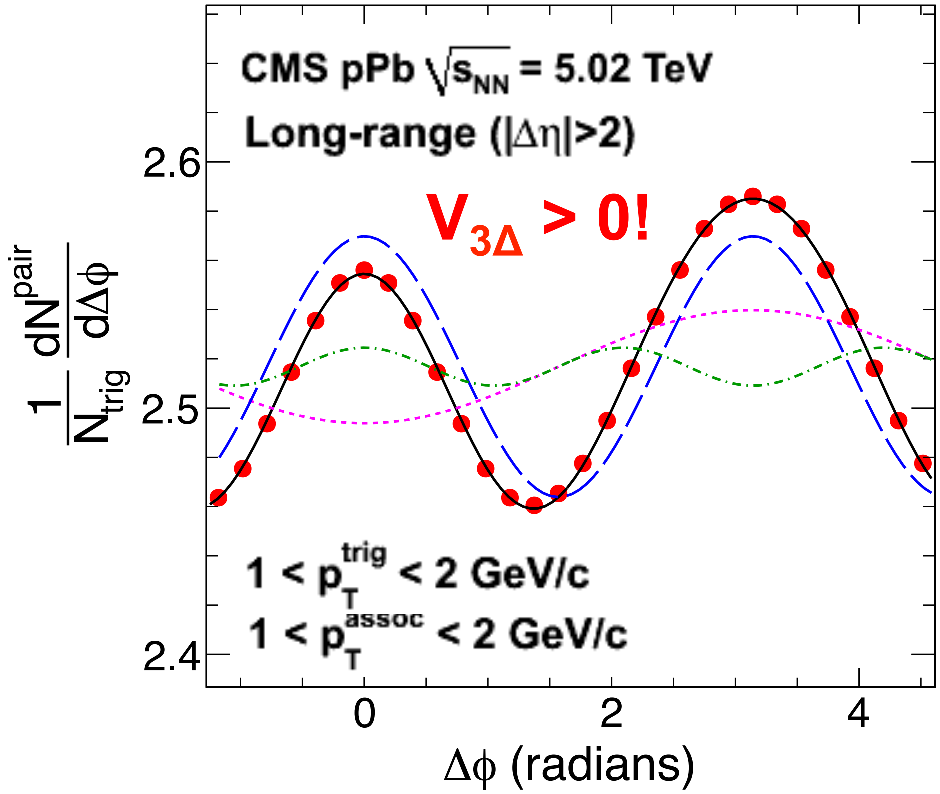
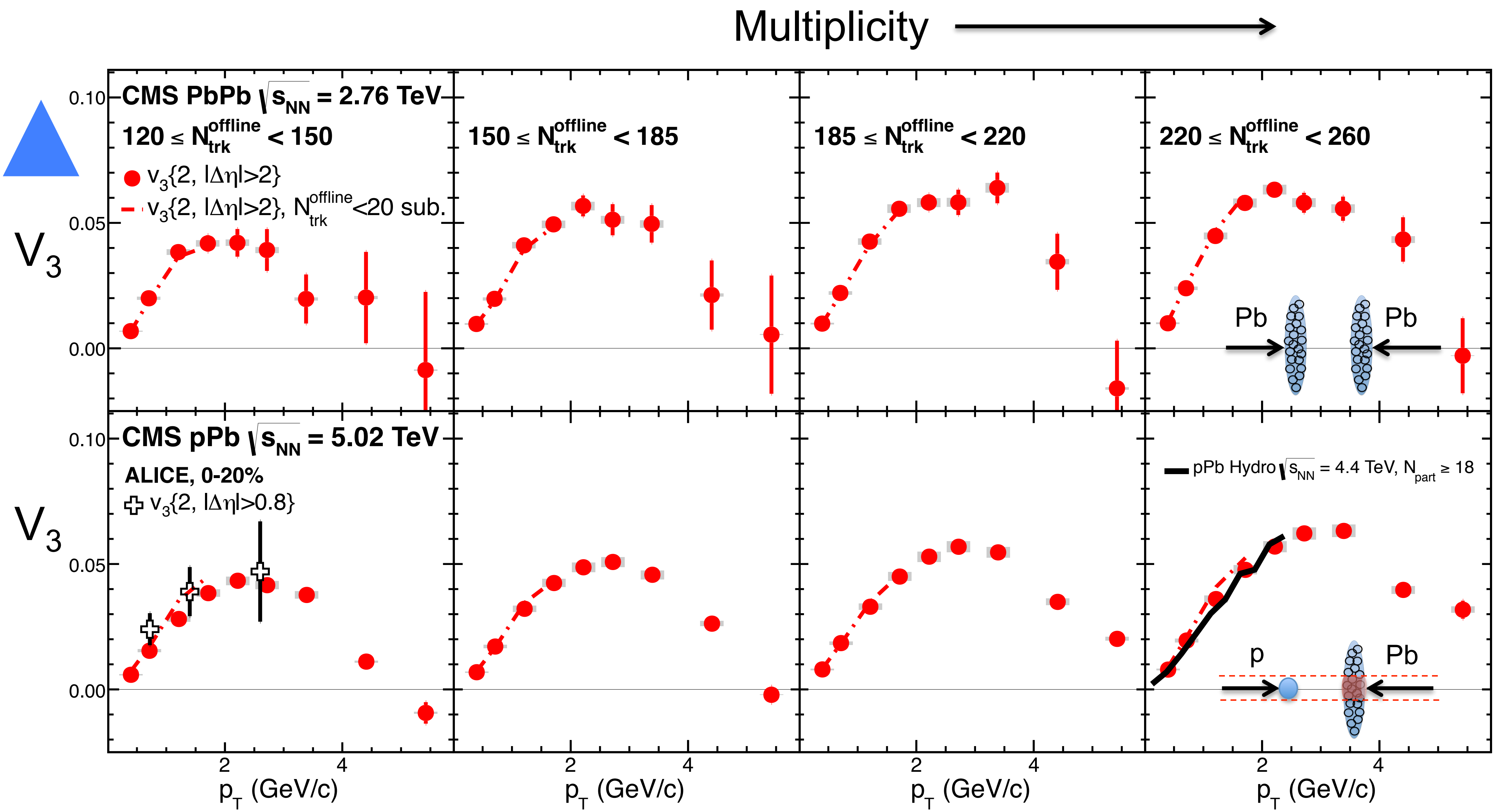


Positive long-range $V_{3\Delta}$ must indicate "new physics"

p_T dependence of triangular flow (v_3)

Dash-dotted curves: peripheral 70-100% subtracted



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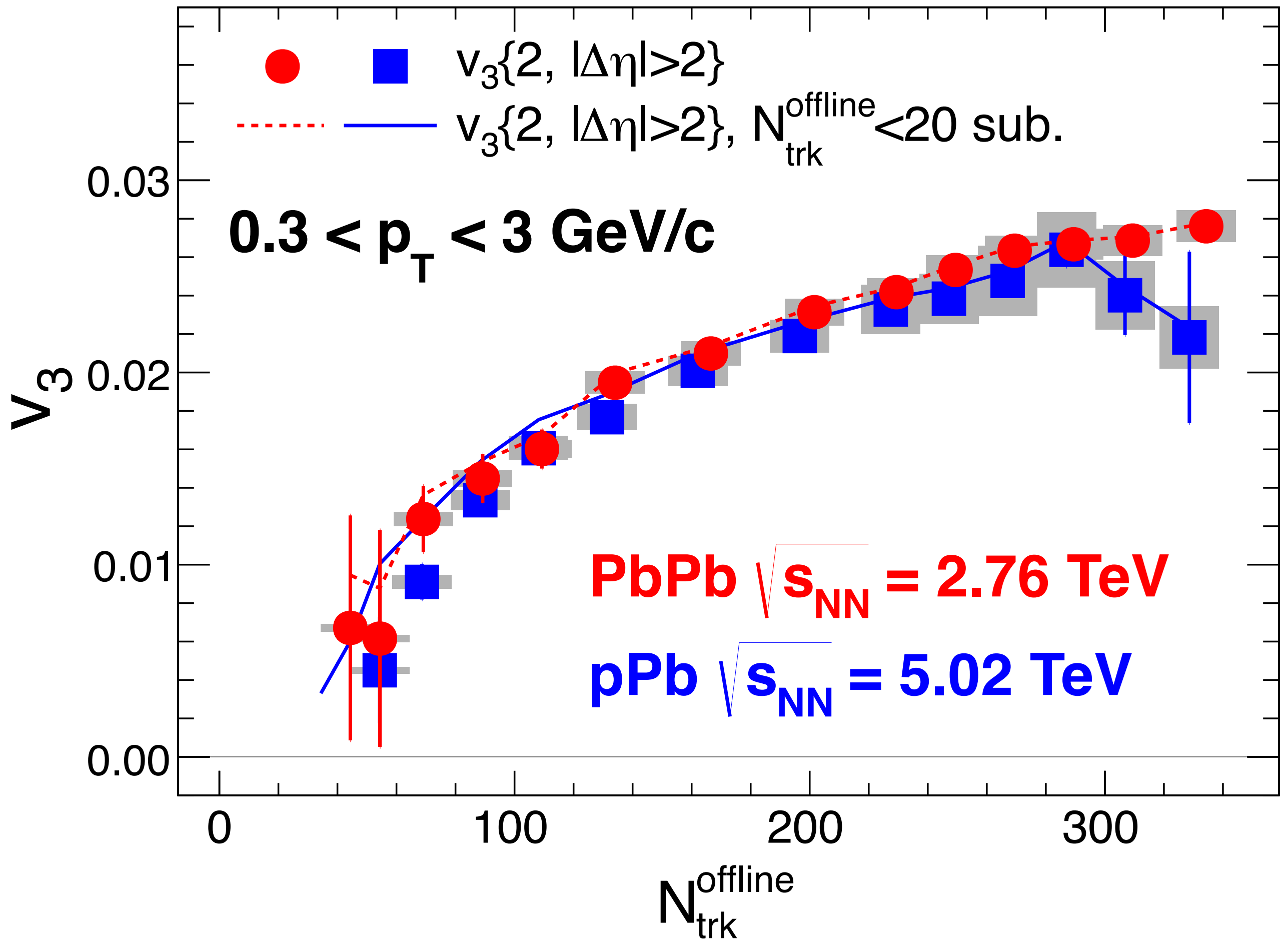
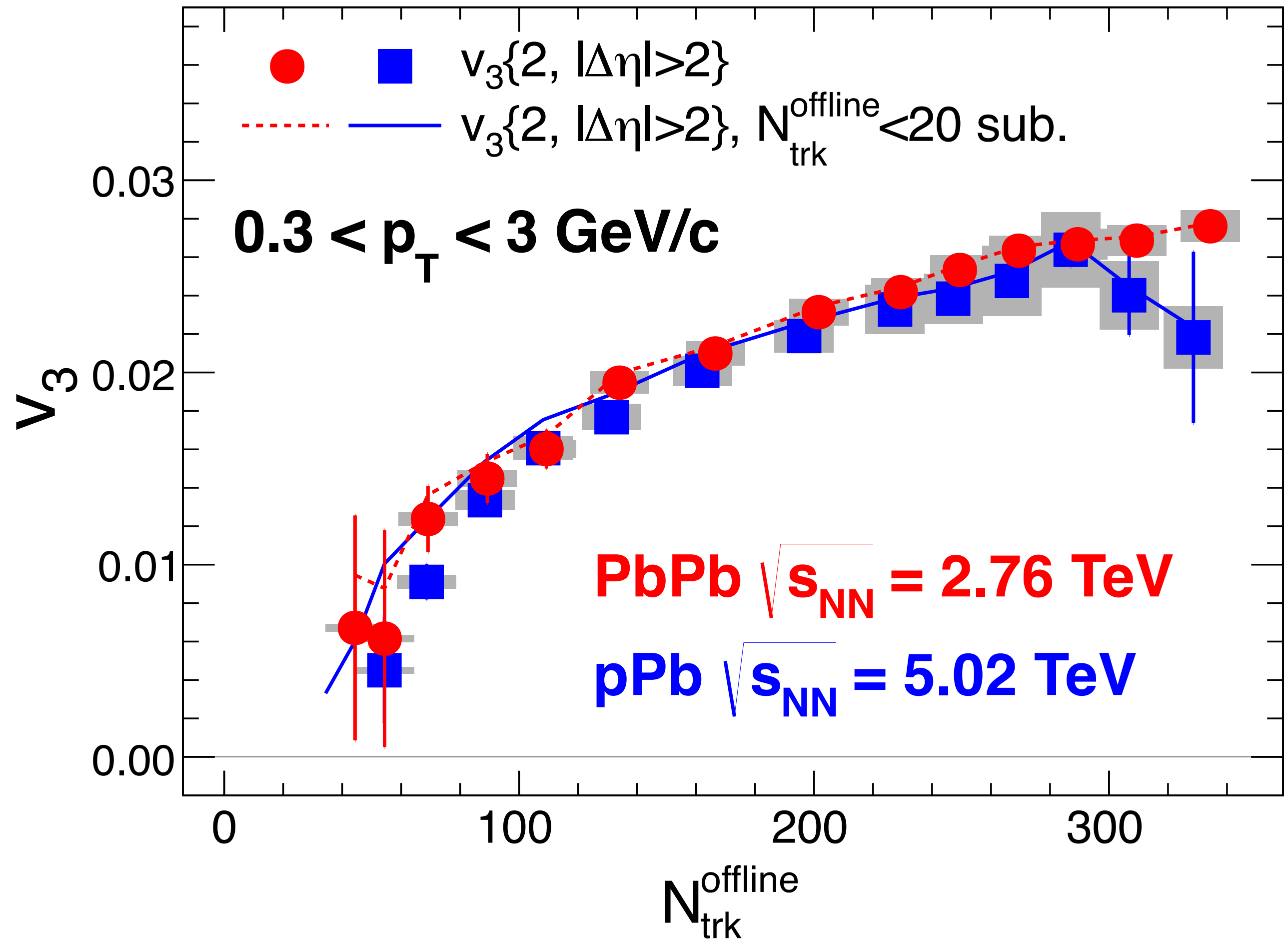


Striking similarity of v_3 for PbPb and pPb systems with drastically different collision geometry and its fluctuations

Can this be understood in hydrodynamics?

(uncertainties are much larger for smaller systems)

Multiplicity dependence of triangular flow (v_3)



✧ $\varepsilon_3\{PbPb\}>\varepsilon_3\{pPb\}$
✧ viscous correction smaller in PbPb
➔ $v_3\{PbPb\}>v_3\{pPb\}$?

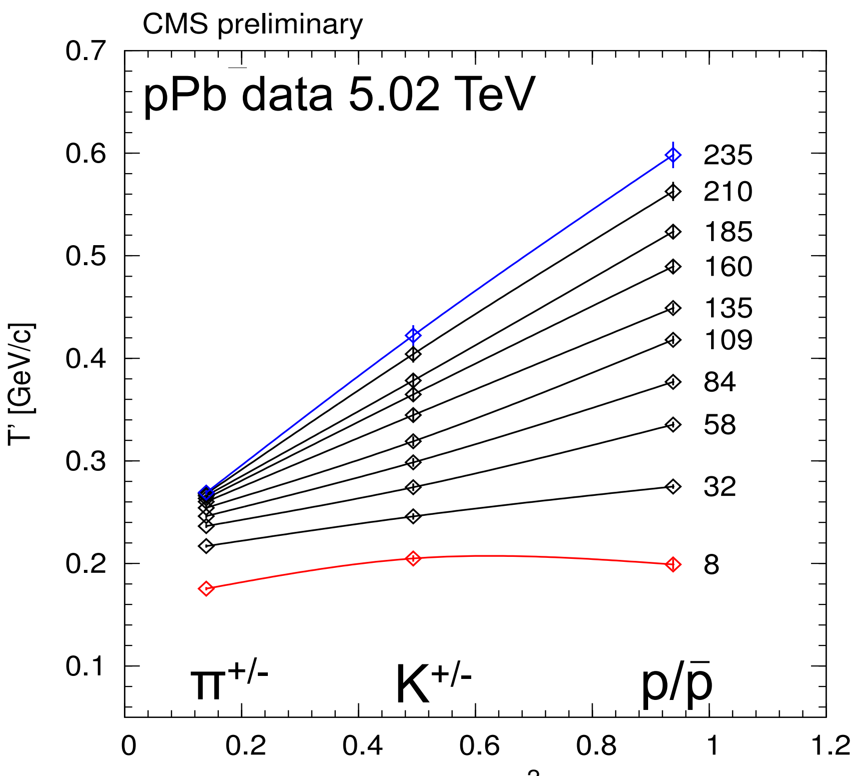
Striking similarity of v_3 for PbPb and pPb systems with drastically different collision geometry and its fluctuations

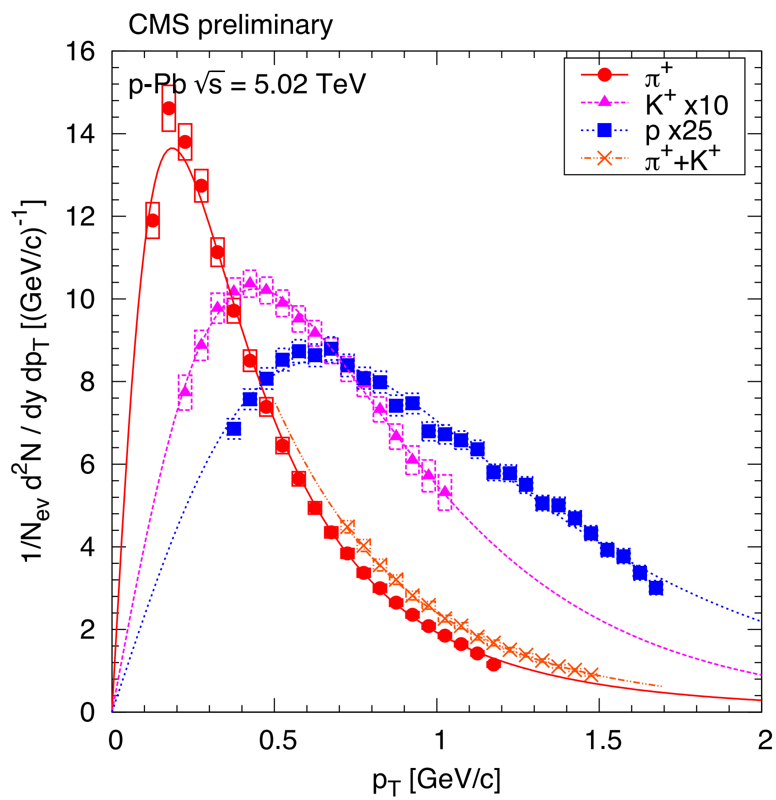
Can this be understood in hydrodynamics?
(uncertainties are much larger for smaller systems)

Any other evidence of hydro flow?

Inverse slope of m_T distributions, T_{slope}: $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp(-\frac{m_T}{T_{slope}})$

"Nu Xu's plot" in pPb





CMS PAS HIN-12-016

➢ T_{slope} linear with particle mass; proportionality increasing with N

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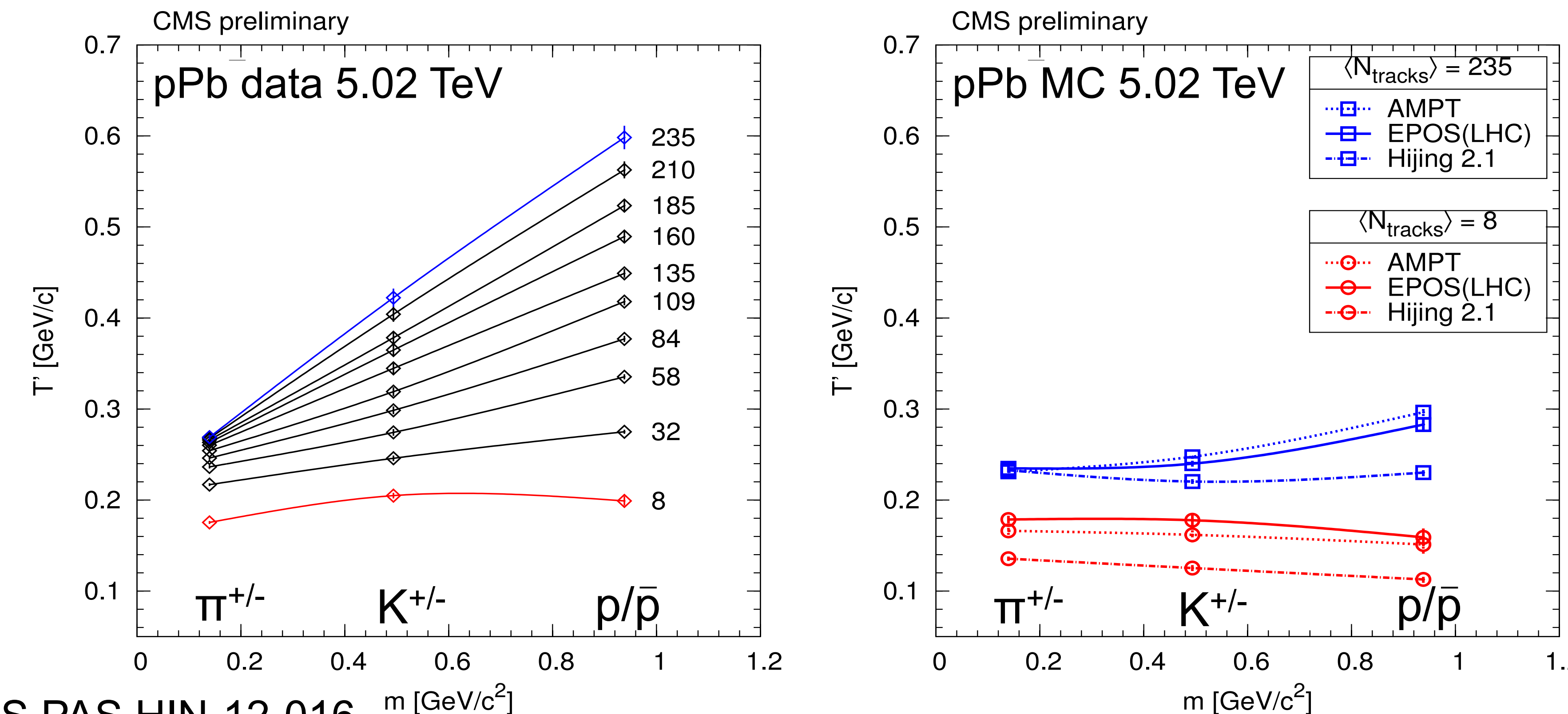

CMS PAS HIN-12-016

- T_{slope} linear with particle mass; proportionality increasing with N
- No such trend observed in MC models (AMPT, HIJING)

Any other evidence of hydro flow?

Inverse slope of m_T distributions, T_{slope}: $$\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp(-\frac{m_T}{T_{slope}})$$

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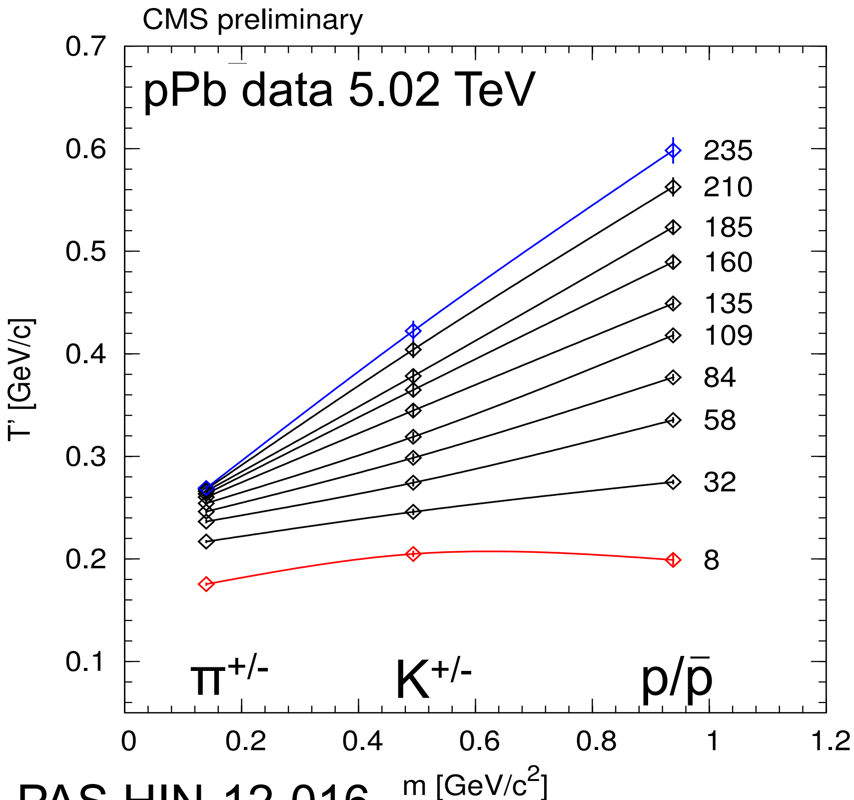
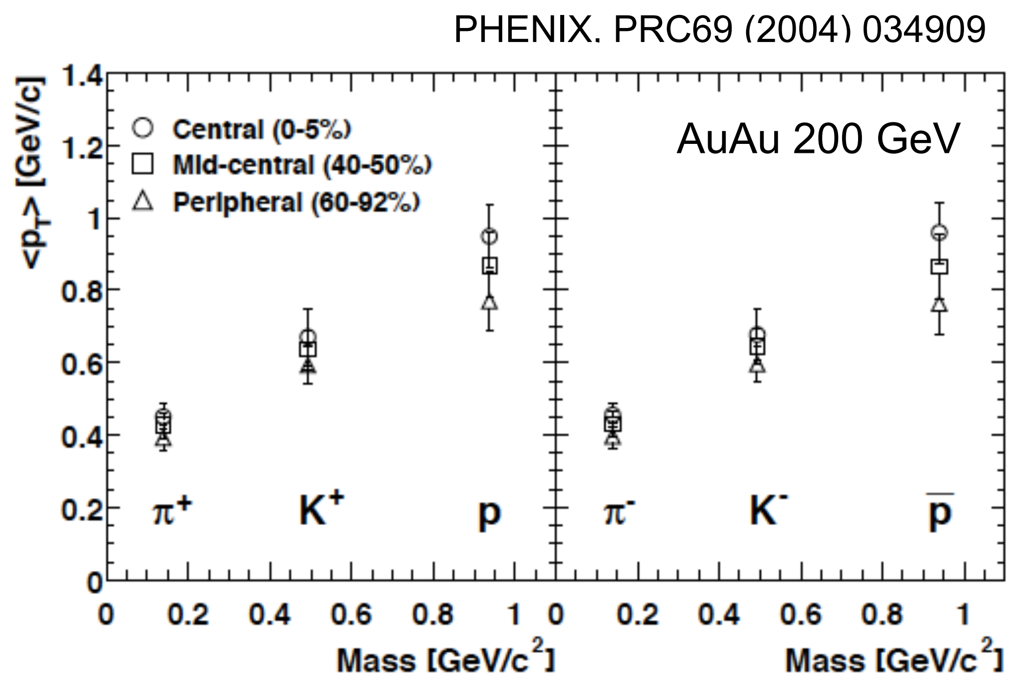


CMS PAS HIN-12-016

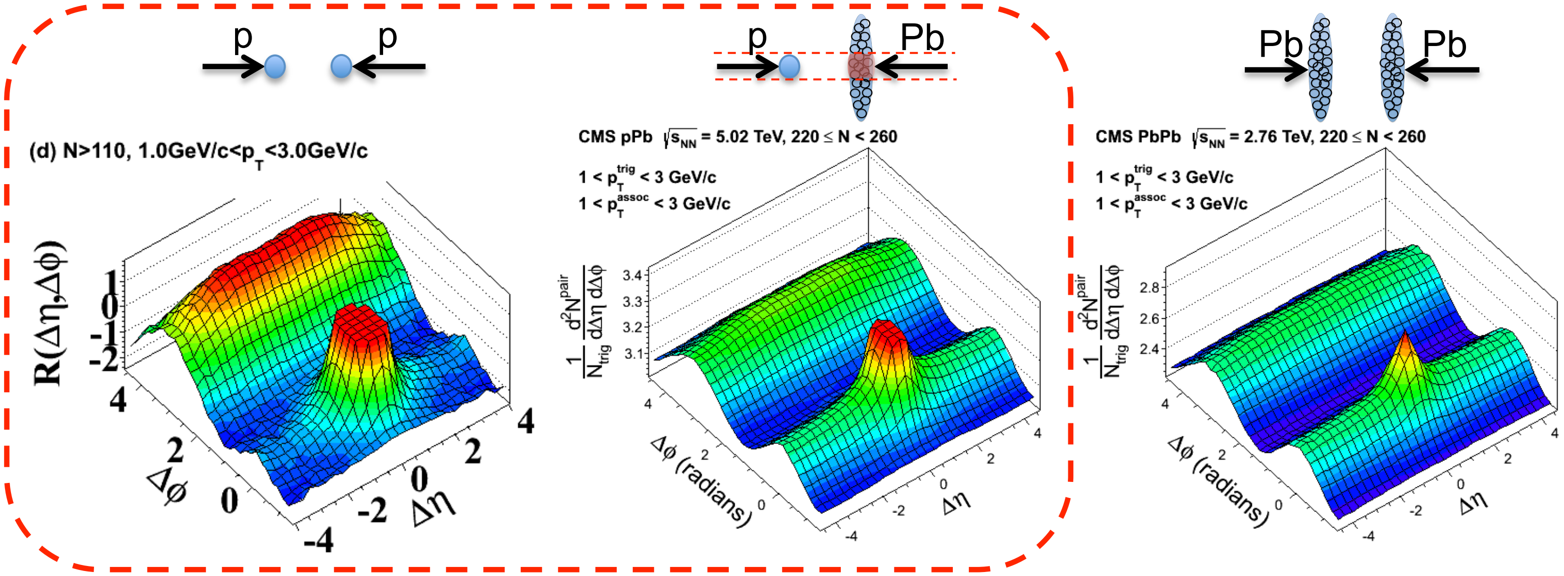


- Similar trend as observed in AA collisions
- Onset of radial flow effect: $T_{slope} \approx T_{freeze\text{-}out} + m\langle u \rangle^2$?

radial flow velocity

Outlook and Summary

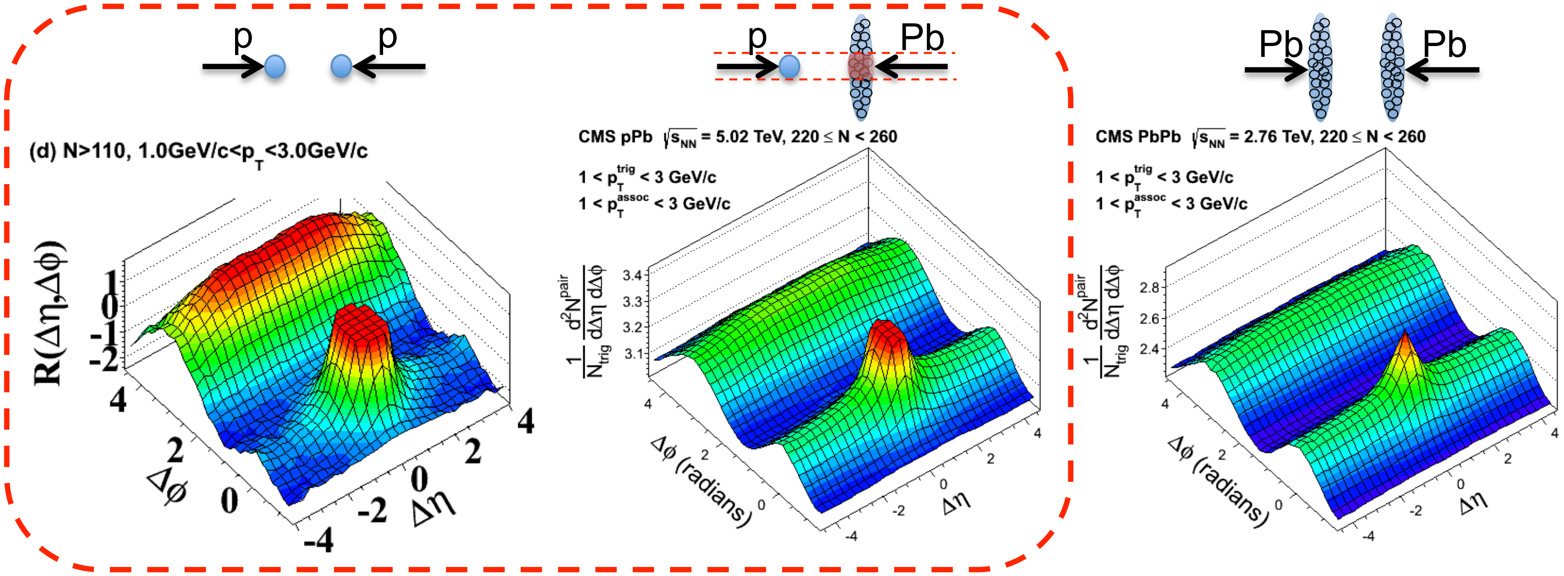
New dimension of probing high-density QCD medium



Common origin or coincidence? We are closing in to the answer

Outlook and Summary

New dimension of probing high-density QCD medium



Common origin or coincidence? We are closing in to the answer

A comprehensive investigation of AA observables in pA will provide us the definitive answer in the next few years:

- HBT radii, as big as in AA?
- Identified particles spectra and correlations, hadron chemistry
- Jet-medium interaction (where does v_2 p_T ~ 6 GeV/c come from?)
- Quarkonia melting

None of these could be imagined a couple of years ago

Outlook and Summary

Future pA program at the LHC beyond 2015:

- Higher energy
- Higher luminosity

→ *Higher multiplicity reach!*

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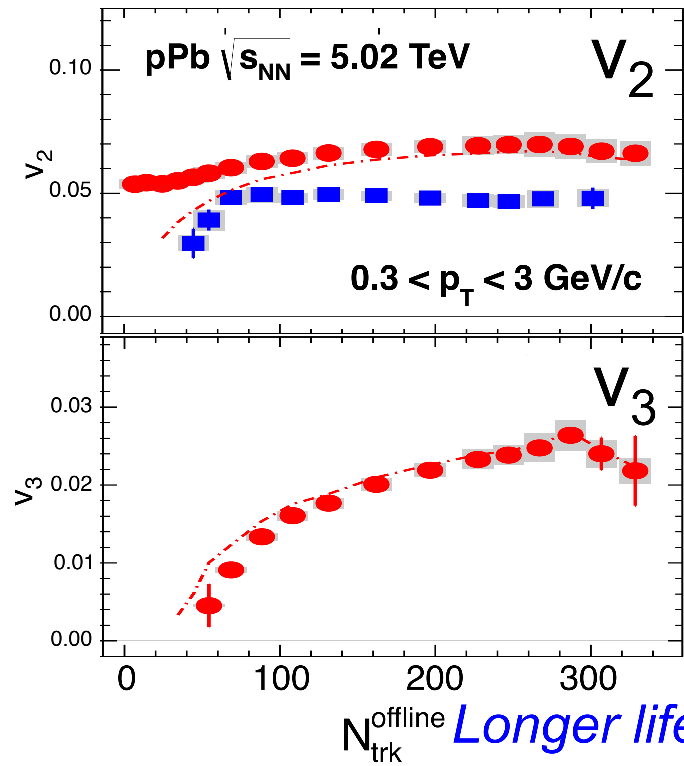

?

?

Longer lifetime,
smaller viscous correction
finally more sensitive to ε_n?

Outlook and Summary

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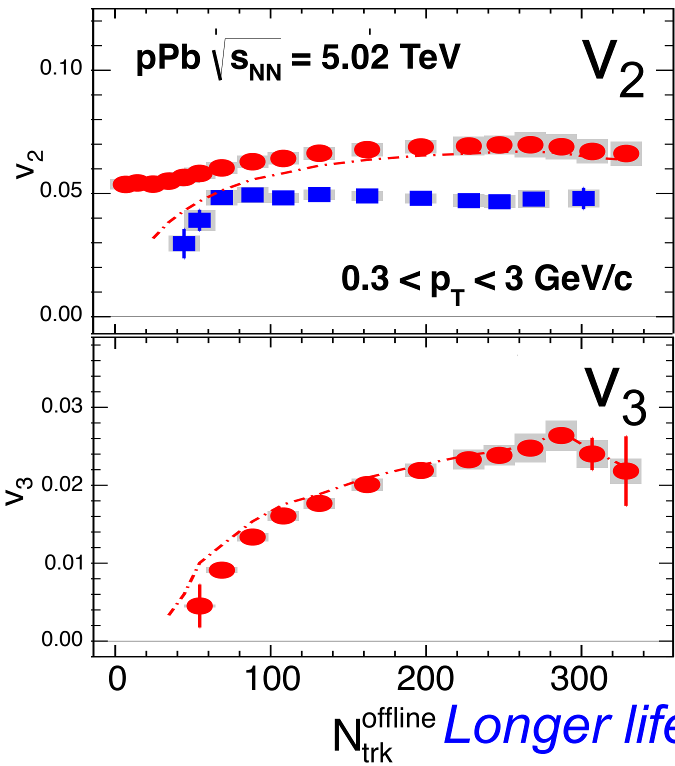

? →

? →

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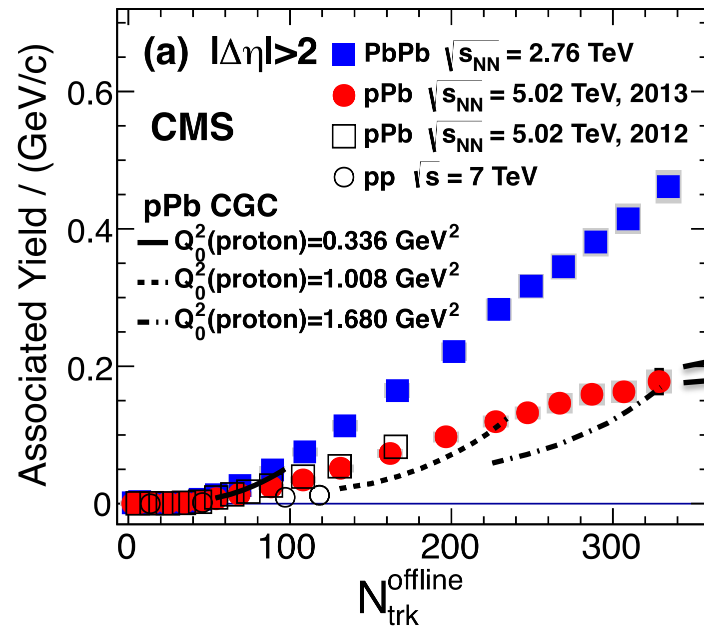

or

Turnover of the yield is possible for hydro but not CGC?

pp needs to catch up.

Outlook and Summary

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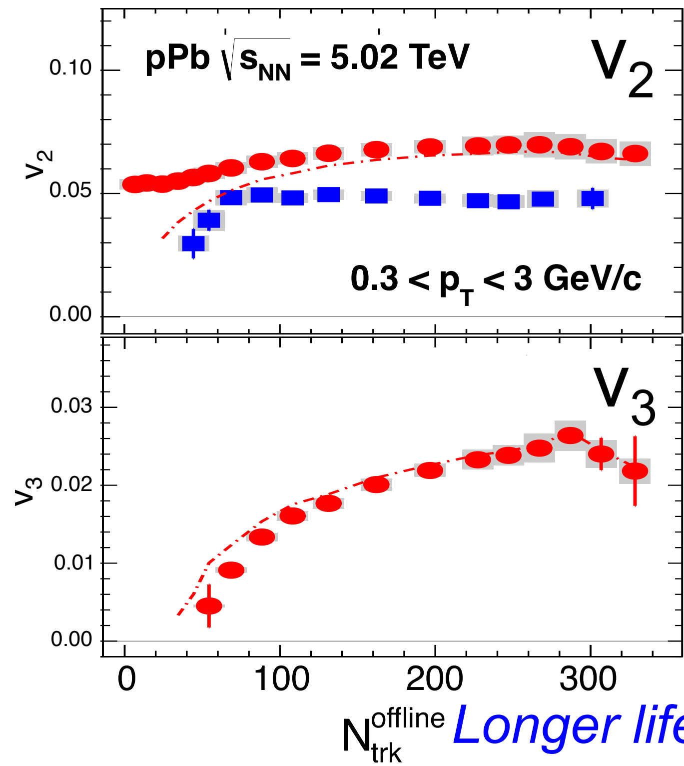
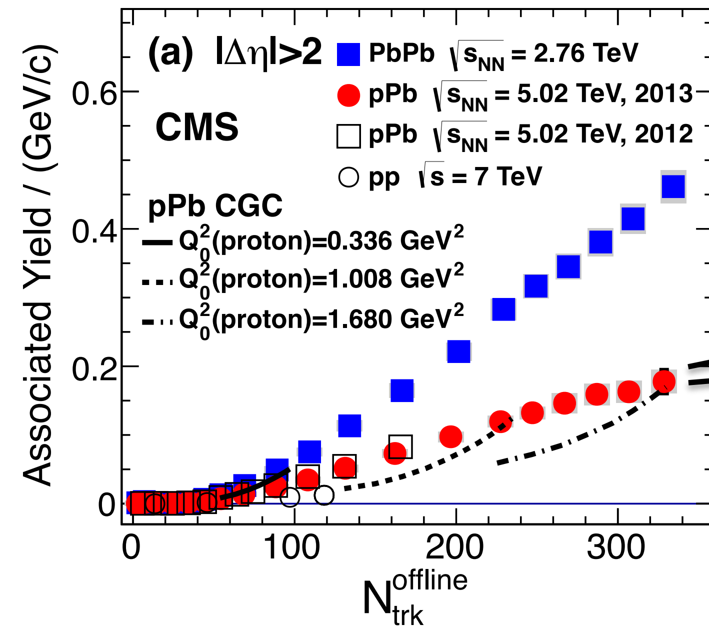


? →

? →



or

Longer lifetime,
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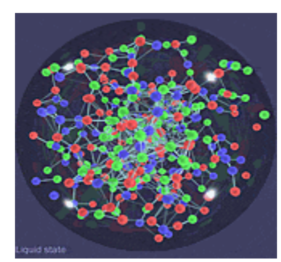
finally more sensitive to ε_n?

Turnover of the yield is possible for hydro but not CGC?

pp needs to catch up.

If many features of high multiplicity pp and pA appear to be consistent with AA,

QGP liquid also in pp and pA?!

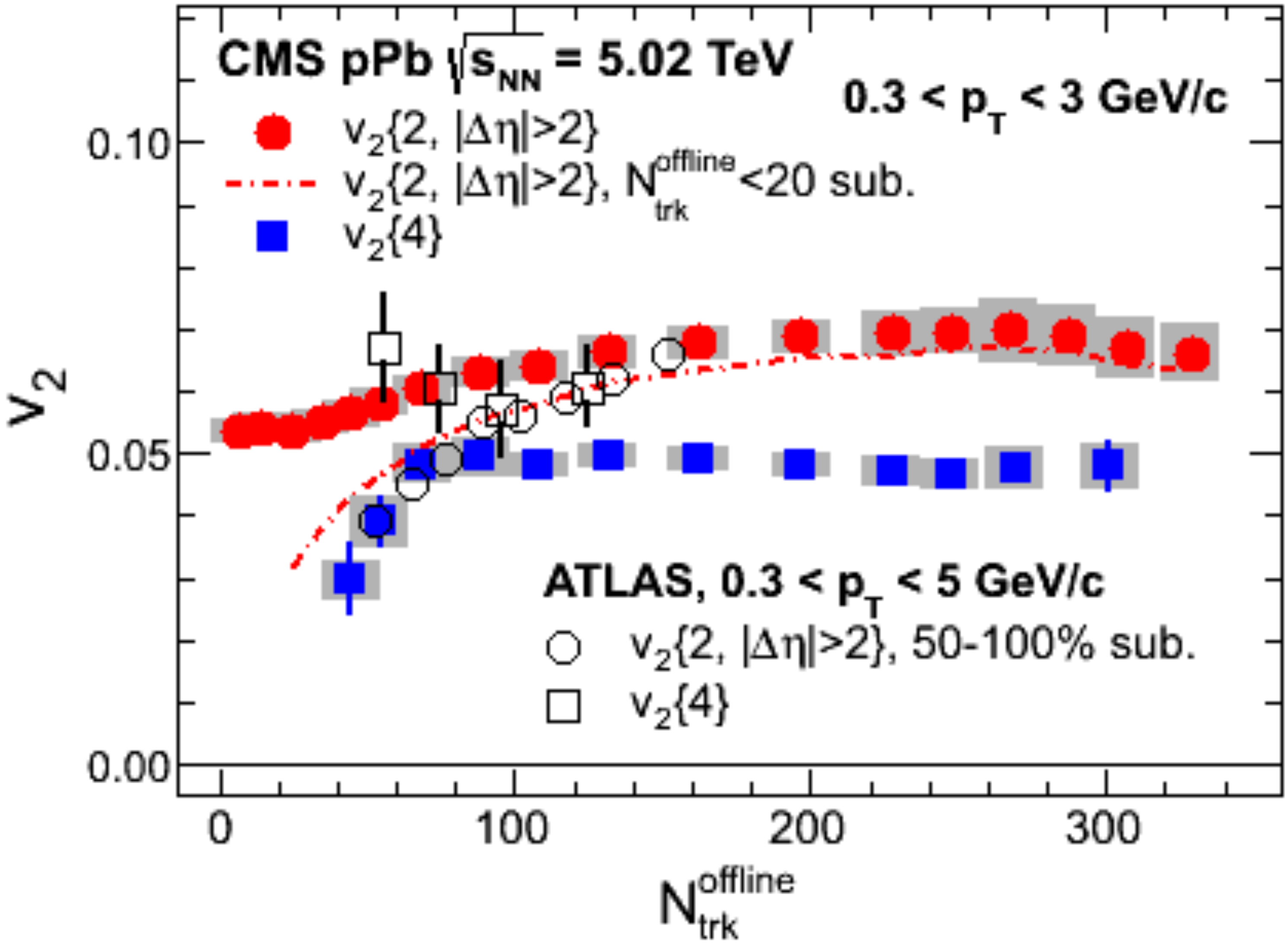


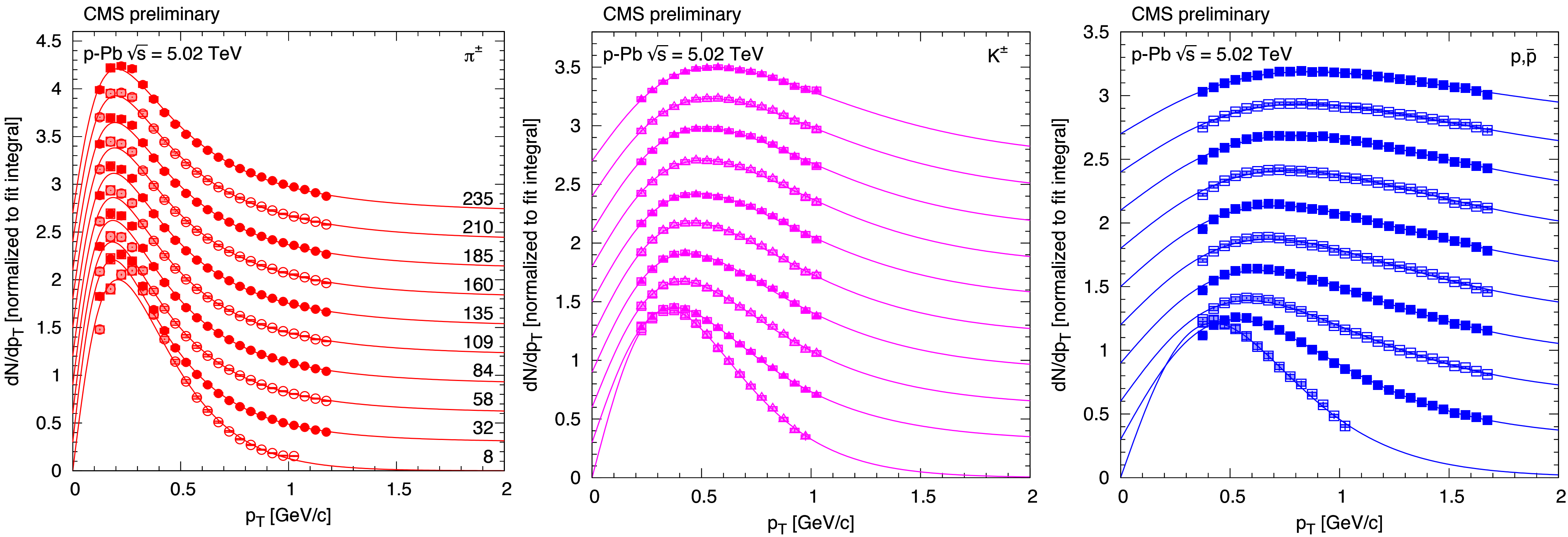
"pA is like a litmus test. Until we understand pA from our understanding of pp and AA, we cannot claim to have a deep understanding of pp and AA."

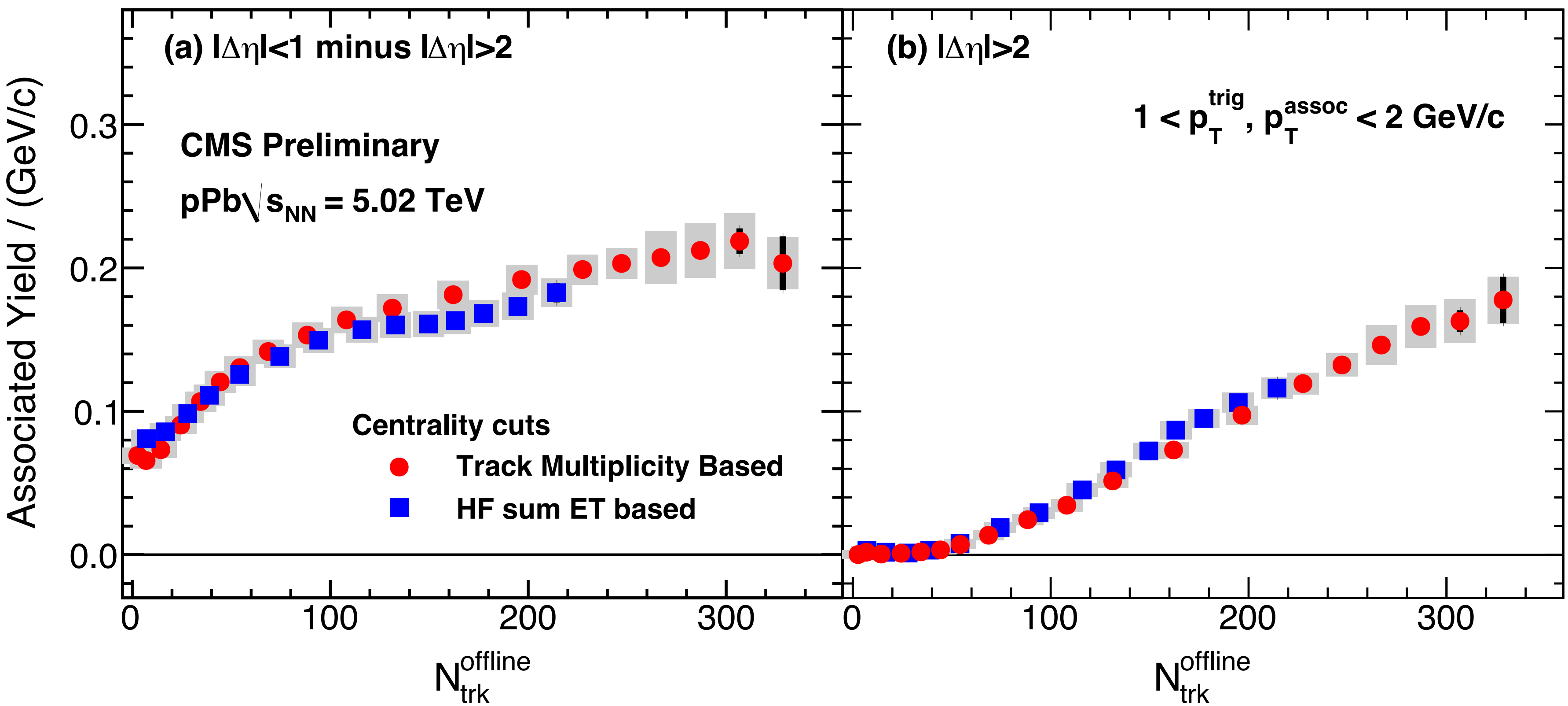
— Wit Busza

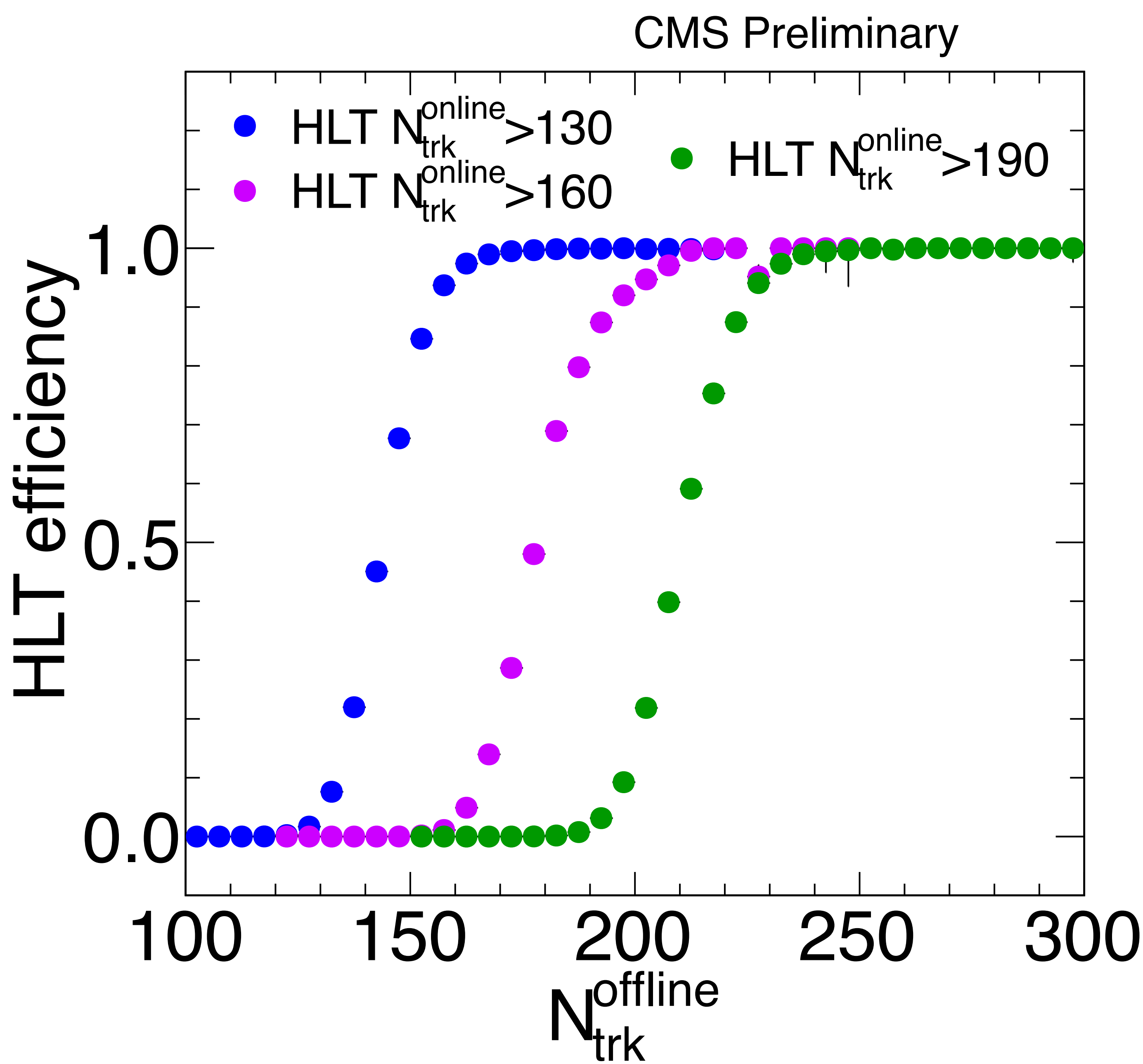
Stay tuned!

Backups


CMS pPb √s_NN = 5.02 TeV
0.3 < p_T < 3 GeV/c
v_2{2, |Δη|>2}
v_2{2, |Δη|>2}, N_trk^offline<20 sub.
v_2{4}
ATLAS, 0.3 < p_T < 5 GeV/c
v_2{2, |Δη|>2}, 50-100% sub.
v_2{4}
0.10
0.05
0.00
v_2
0
100
200
300
N_trk^offline


CMS preliminary
p-Pb √s = 5.02 TeV
π±
dN/dp_T [normalized to fit integral]
p_T [GeV/c]
235
210
185
160
135
109
84
58
32
8
CMS preliminary
p-Pb √s = 5.02 TeV
K±
dN/dp_T [normalized to fit integral]
p_T [GeV/c]
CMS preliminary
p-Pb √s = 5.02 TeV
p,p̄
dN/dp_T [normalized to fit integral]
p_T [GeV/c]

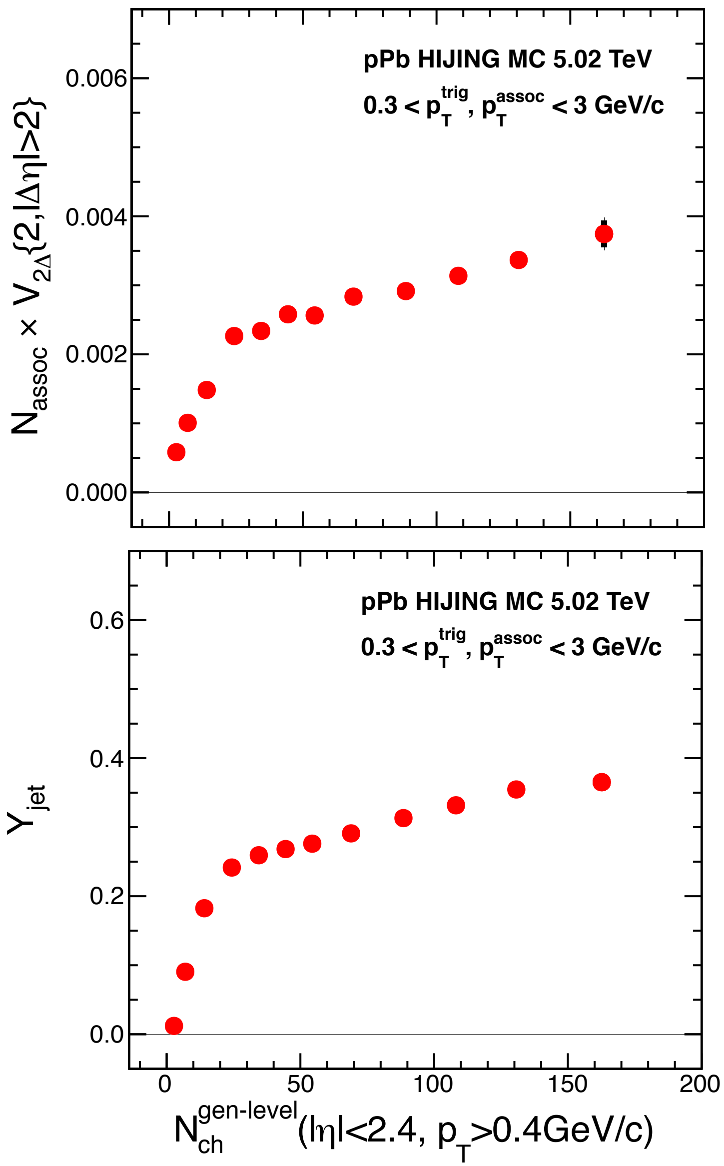

(a) |Δη|<1 minus |Δη|>2
CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
Centrality cuts
Track Multiplicity Based
HF sum ET based
(b) |Δη|>2
$1 < p_T^{trig}, p_T^{assoc} < 2$ GeV/c
Associated Yield / (GeV/c)
0.0
0.1
0.2
0.3
0
100
200
300
$N_{trk}^{offline}$

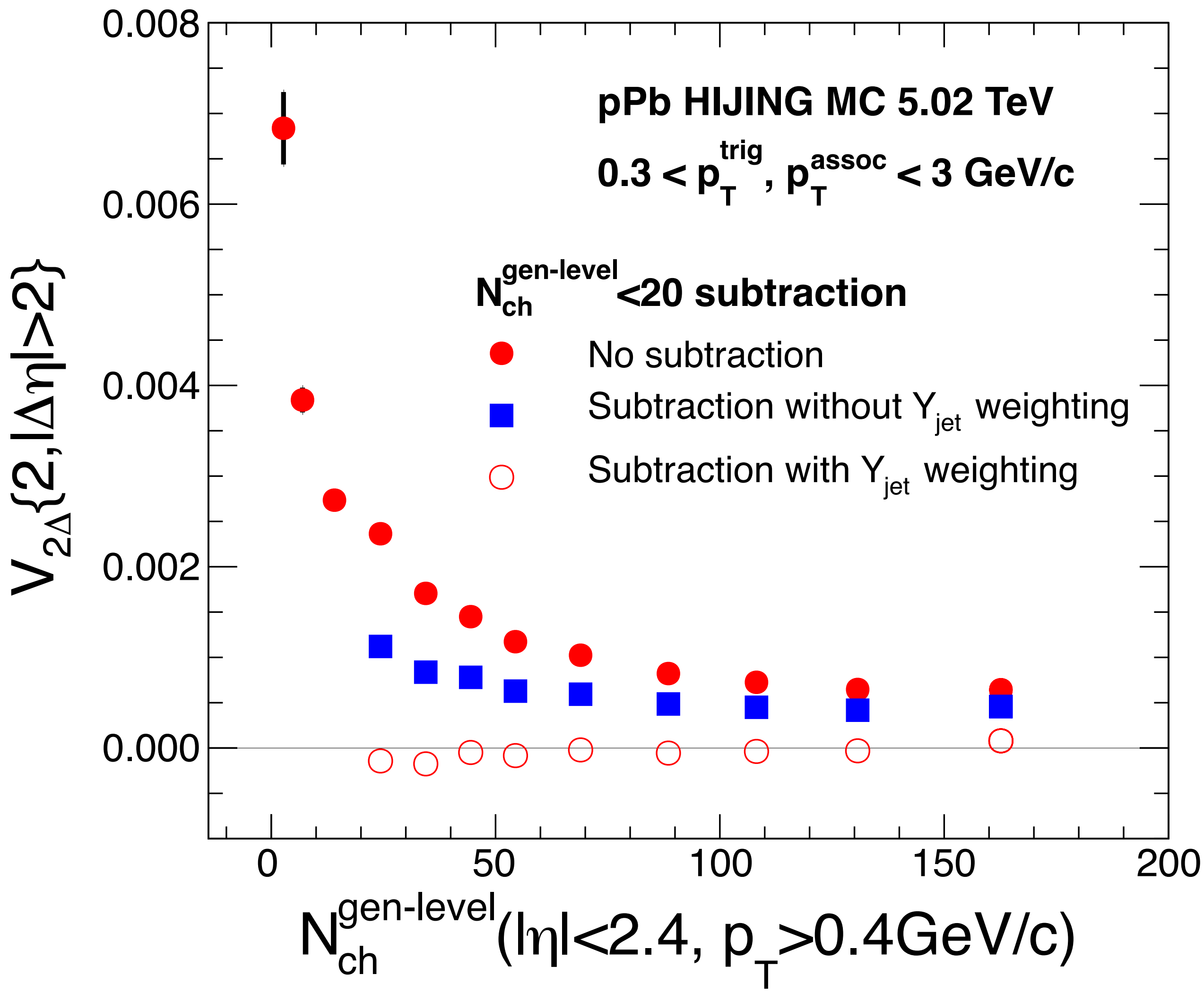

CMS Preliminary
HLT N_{trk}^{online}>130
HLT N_{trk}^{online}>160
HLT N_{trk}^{online}>190
HLT efficiency
1.0
0.5
0.0
100
150
200
250
300
$N_{trk}^{offline}$

Peripheral subtraction

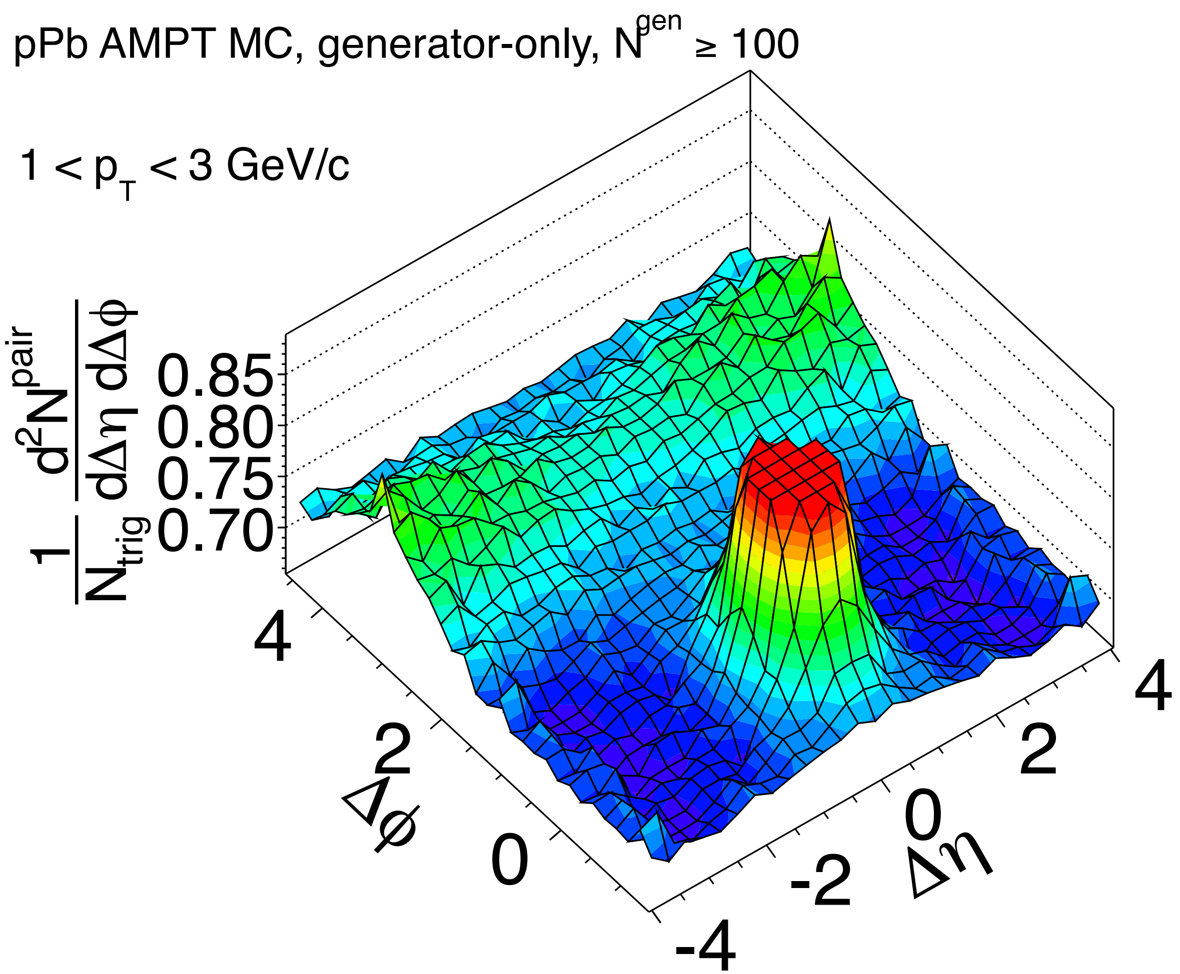
$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}(N_{\mathrm{trk}}^{\mathrm{offline}} < 20) \times \frac{N_{\mathrm{assoc}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 20)}{N_{\mathrm{assoc}}} \times \frac{Y_{\mathrm{jet}}}{Y_{\mathrm{jet}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 20)}$$

correct for multiplicity bias of jet yield





Correlations from AMPT pPb



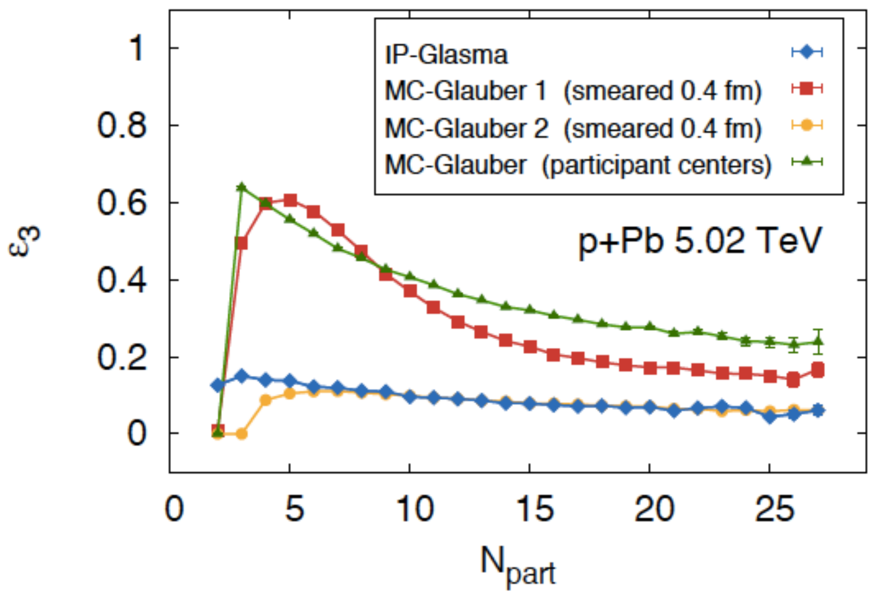
No ridge in high multiplicity AMPT pPb

Reason to be understood as AMPT can describe the ridge in AA:

- *Transport model not applicable for small system?*
- *Process turned off?*
- *Not enough high multiplicity?*

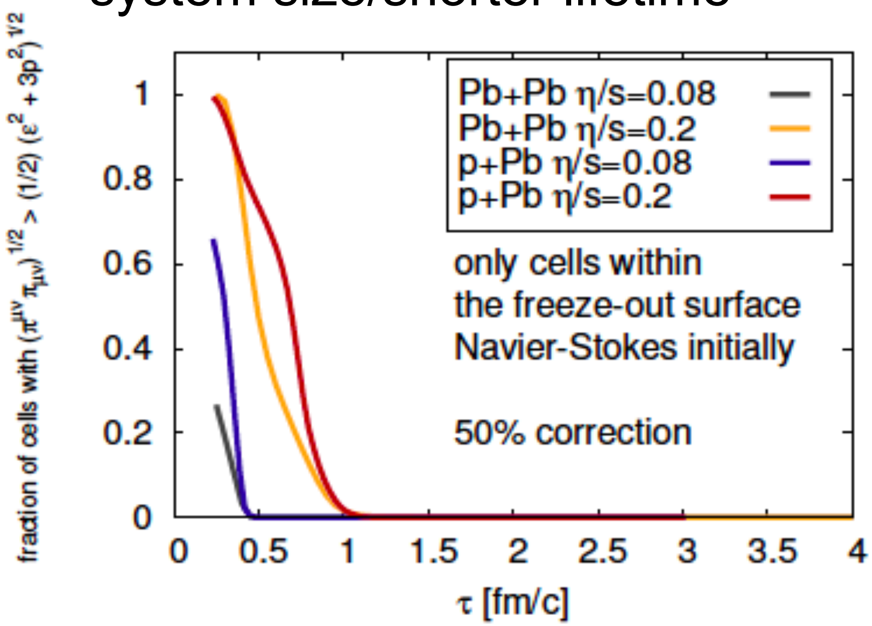
Hydrodynamics in small systems

Large uncertainty of initial condition



only 20% difference for AA

Larger corrections due to smaller system size/shorter lifetime



A. Bzdak. et al., arXiv: 1304.3403

ε_n is not the only predictor of v_n

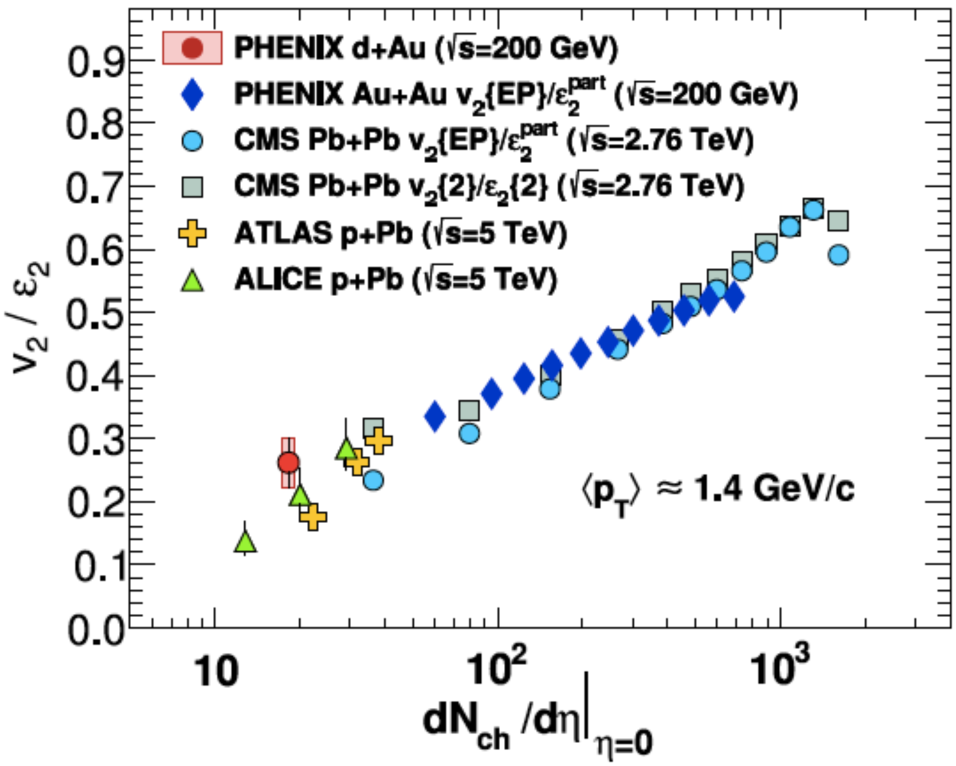
If we are confident with hydro + viscosity for central AA, we must test it in the regime where viscous correction is more significant

If IP-glasma model is the right description of initial condition, pp/pA provides an ideal testing ground of it

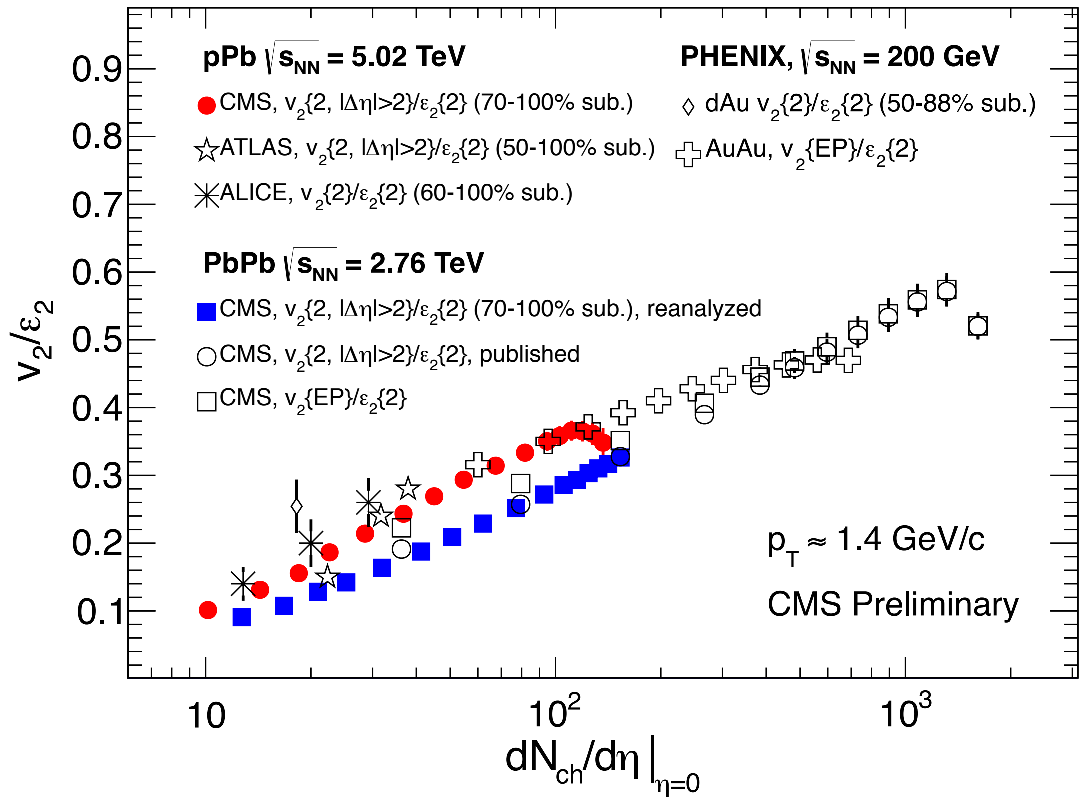
The Ridge in dA at RHIC

ε_n from MC Glauber

Eccentricity scaling!?



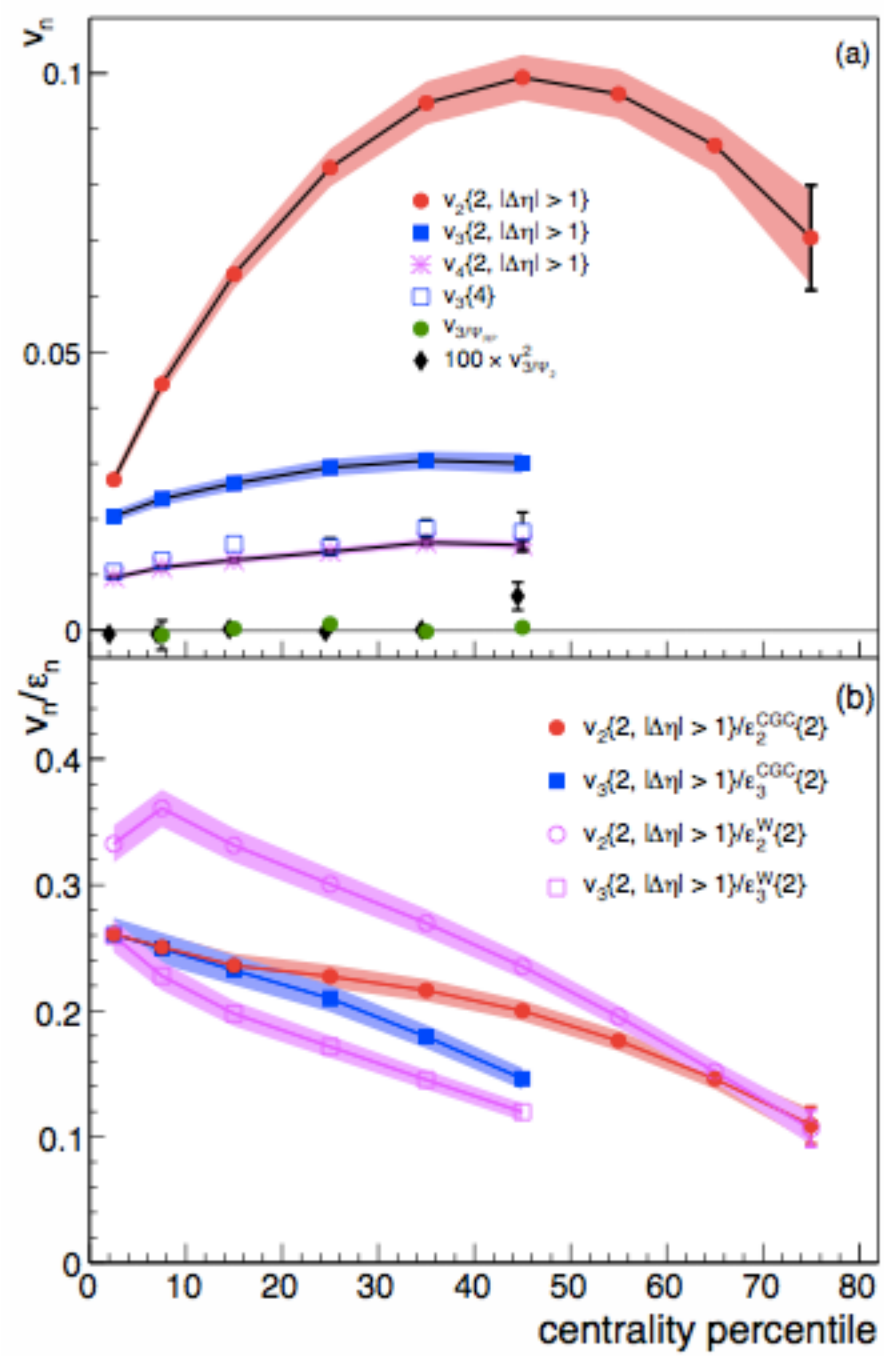
CMS version



CMS does not seem to see the scaling between pPb and peripheral PbPb …

Given the large uncertainty, we should be careful when dividing by ε_n!

Peripheral subtraction



Two-particle correlations at CMS

Pair of two primary reconstructed tracks within |η|<2.4

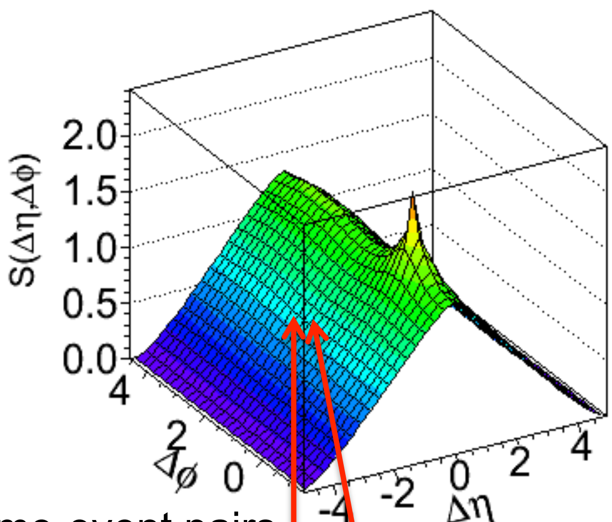
- Trigger particle from a p_T^{trig} interval
- Associated particle from a p_T^{assoc} interval

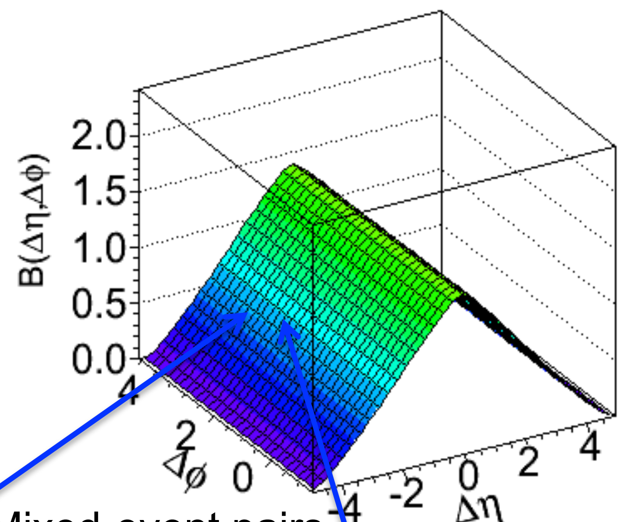
Signal-pair distribution

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

Background-pair distribution

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

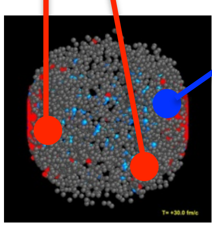




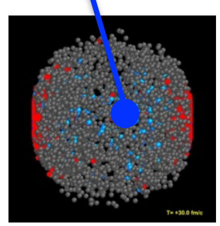
Same-event pairs

Mixed-event pairs (similar z_{vtx})

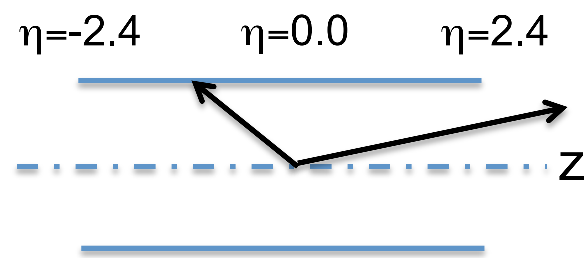
Event 1:



Event 2:



Triangular shape in Δη due to limited acceptance



$\Delta\eta = \eta^{assoc} - \eta^{trig}$
$\Delta\phi = \phi^{assoc} - \phi^{trig}$

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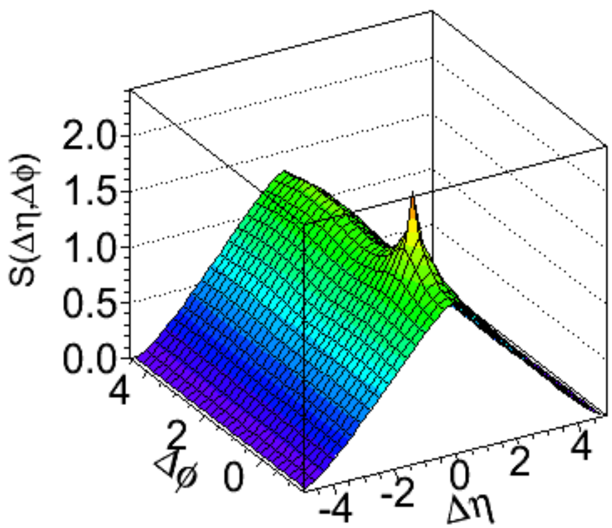

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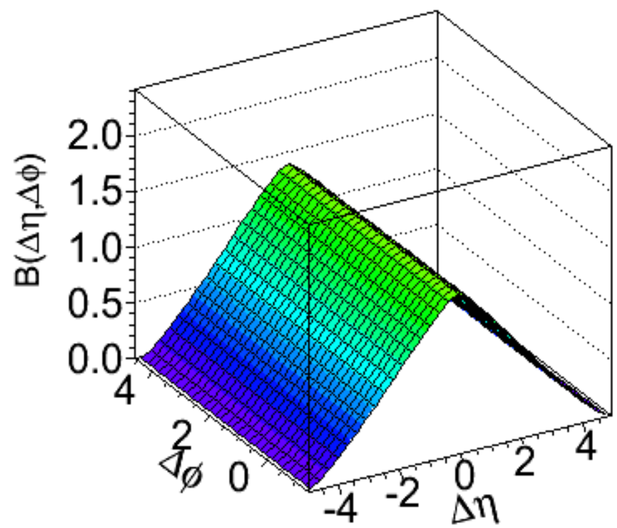
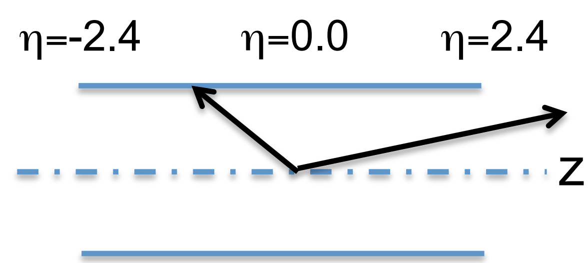


Triangular shape in $\Delta\eta$ due to limited acceptance



Pair yield per trigger particle:

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

$$\Delta\eta = \eta^{assoc} - \eta^{trig}$$
$$\Delta\phi = \phi^{assoc} - \phi^{trig}$$