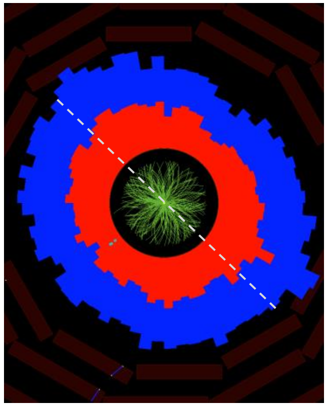
Collective Behavior of the Hottest, Densest Matter in the Universe with CMS

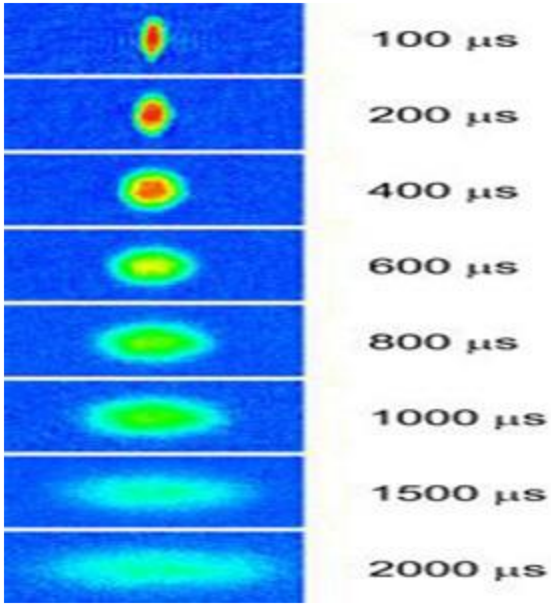
LNS Lunchtime Seminar

Dragos Velicanu

Why make a QGP

- Study the strong force in a system of colored particles
- Study the behavior of a strongly coupled system
- Test predictions from AdS/CFT

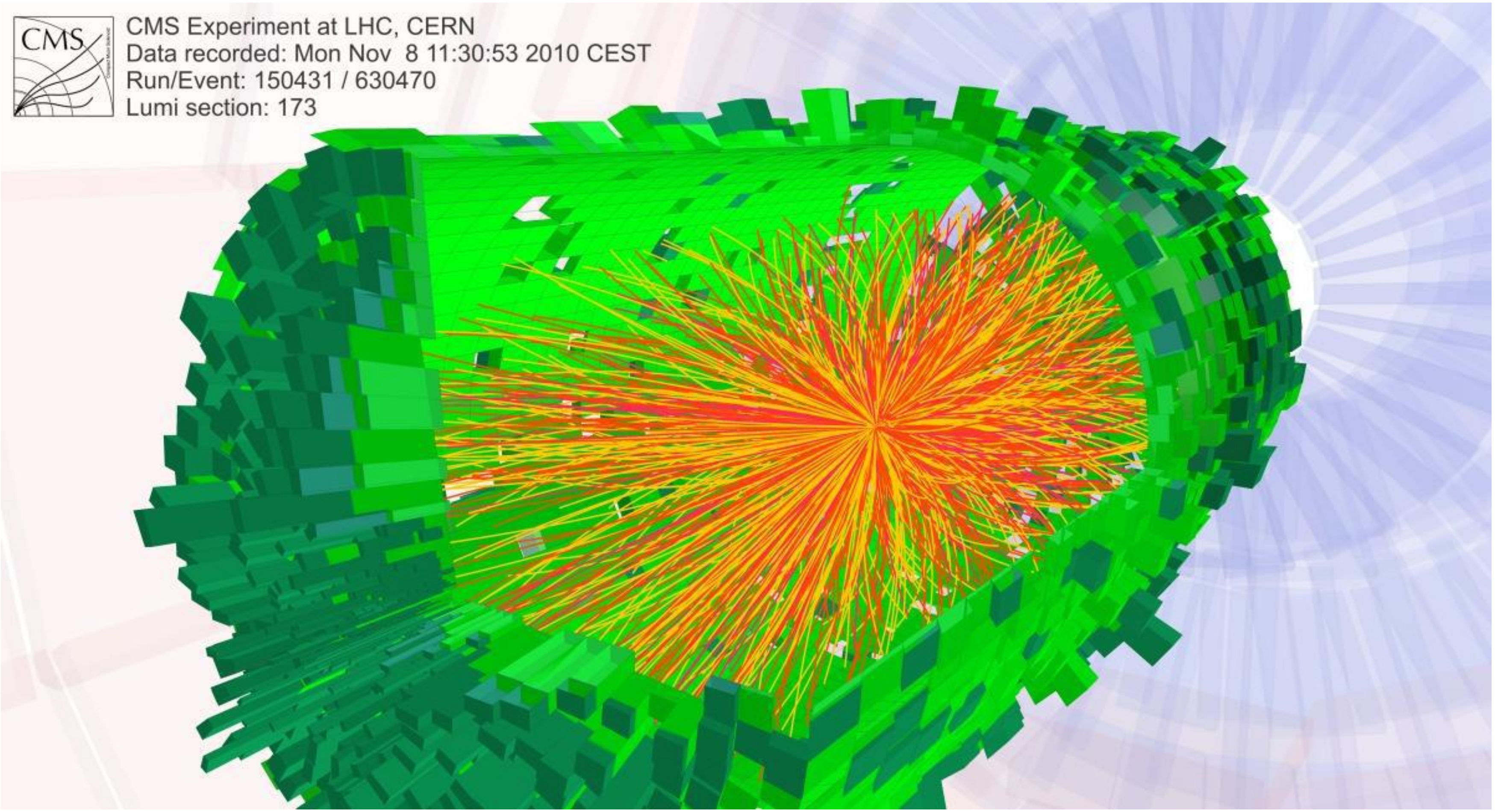




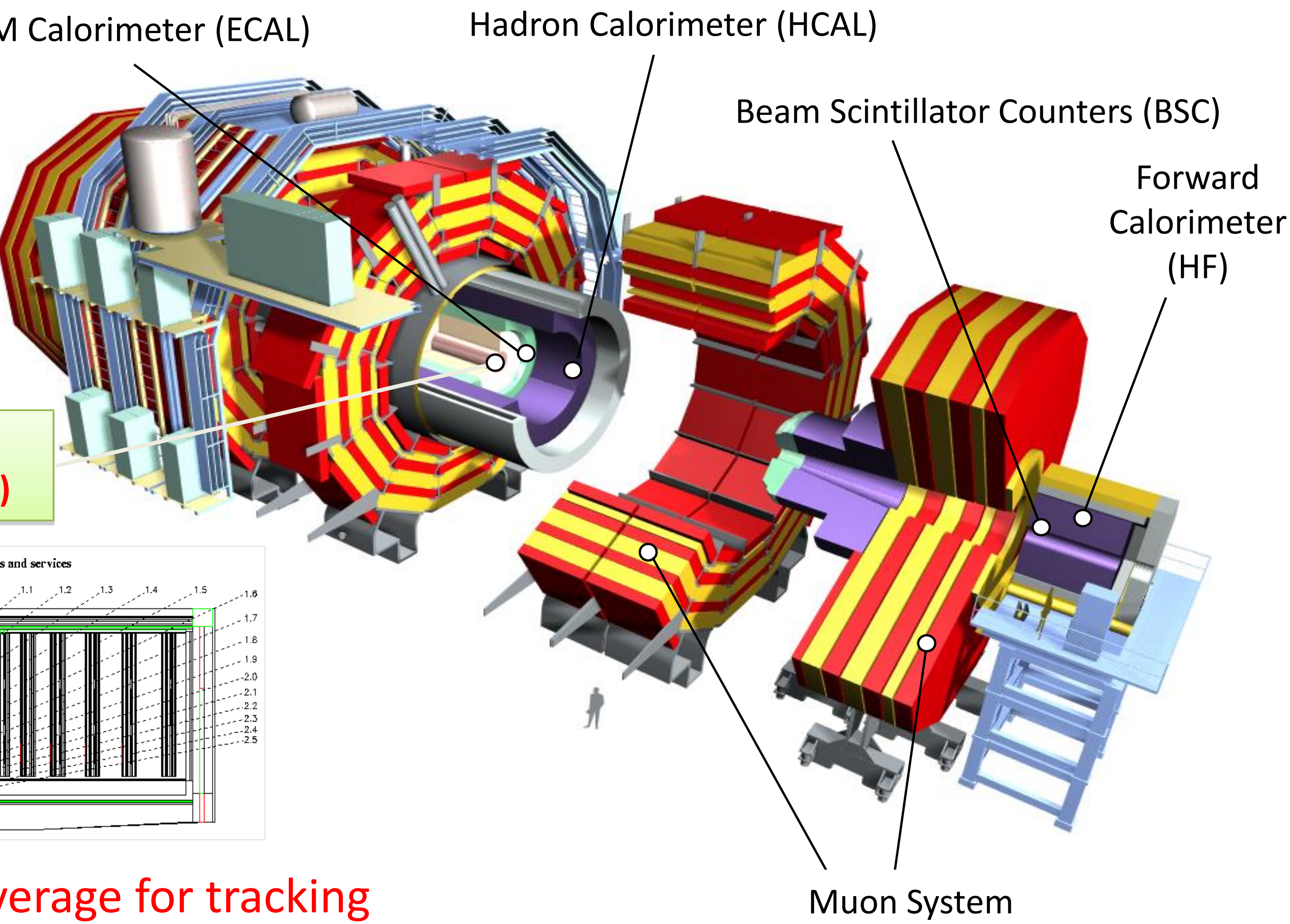
Connection

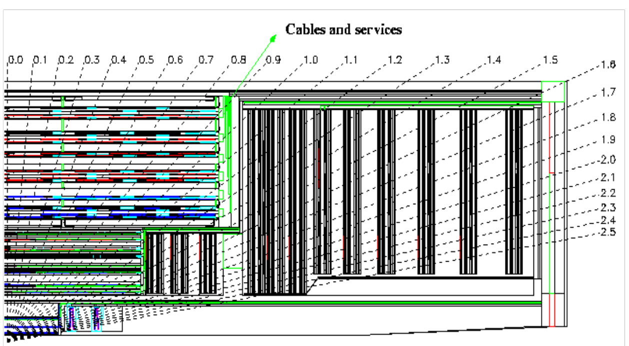
- The QGP is made of quarks and gluons at the microscopic level, but flows like a macroscopic liquid
  - Where can we make the connection between the two
  - Will there be flow in increasingly smaller systems

How to study this?



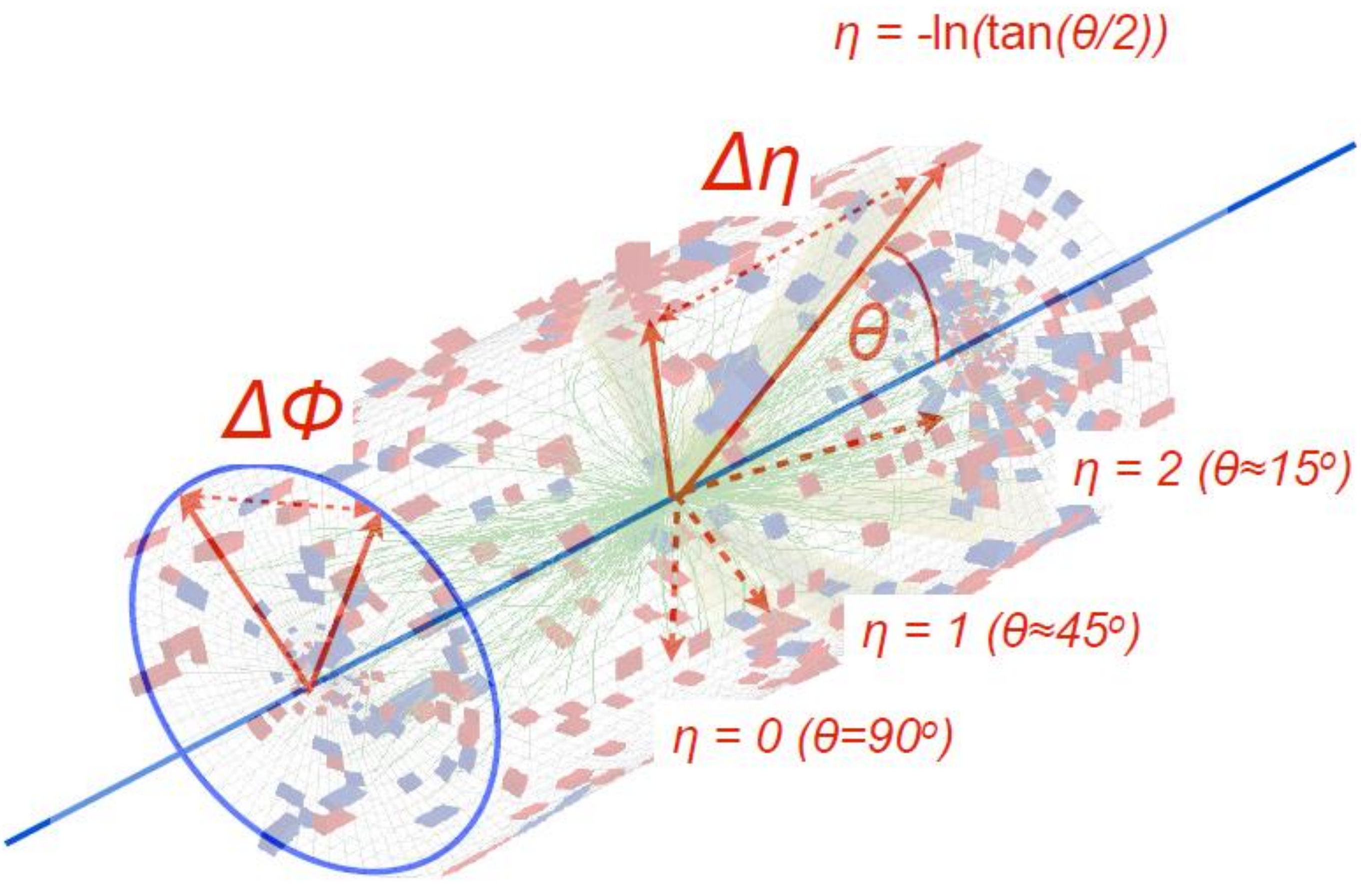
Compact Muon Solenoid



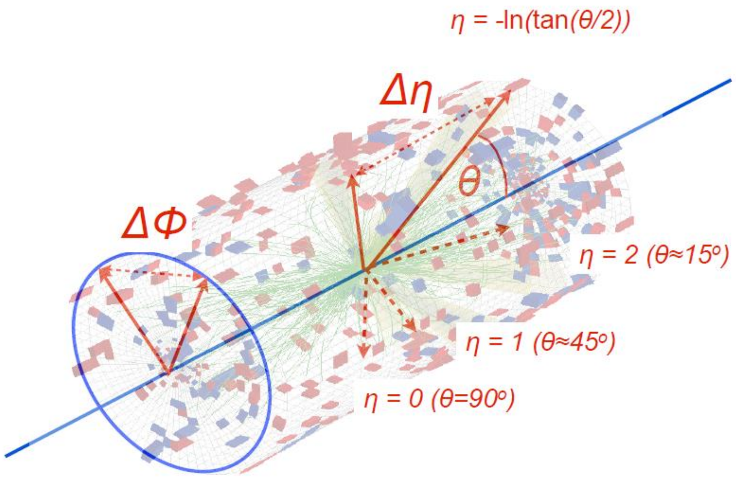


Very large coverage for tracking ($|\Delta\eta|$ up to 5.0)!

Coordinates

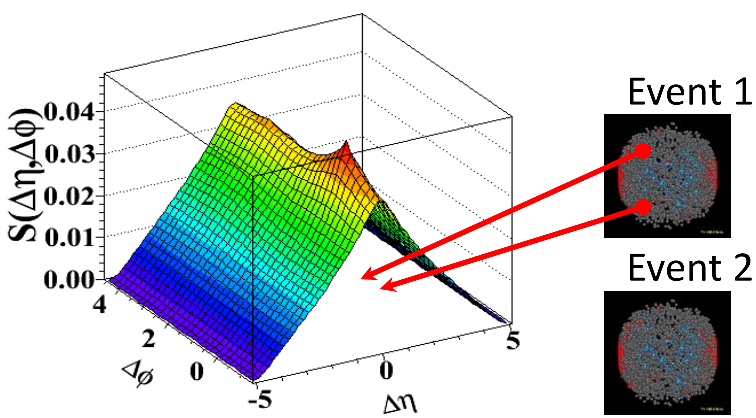


Two-particle correlations



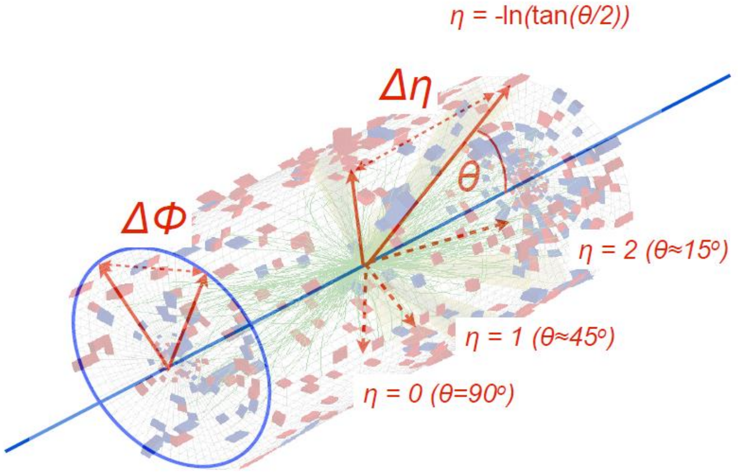
Signal pair distribution:

same
event
pairs



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

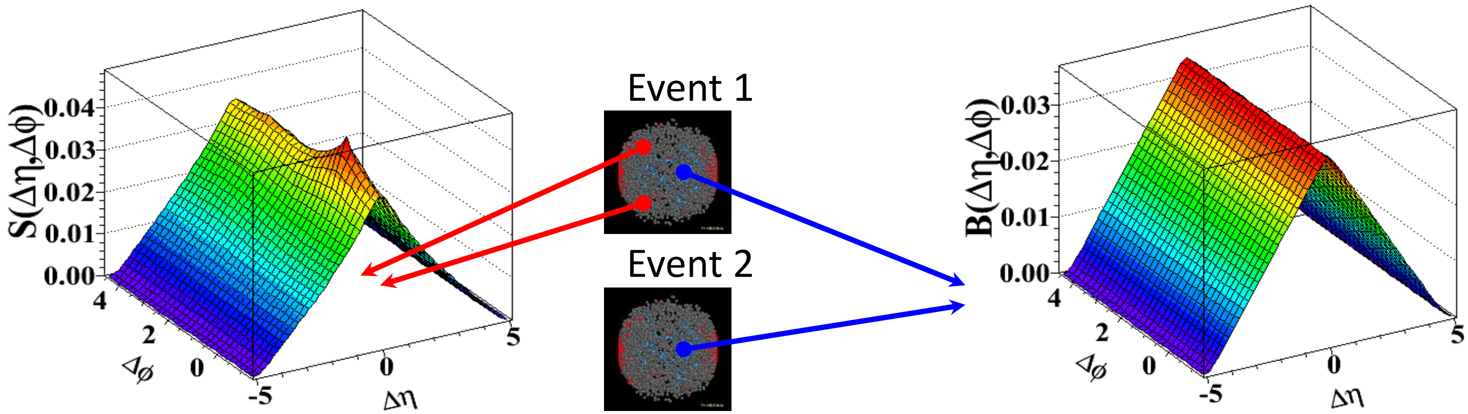
By making two-particle correlations



Signal pair distribution:

Background pair distribution:

same event pairs



mixed event pairs

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

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

By making two-particle correlations

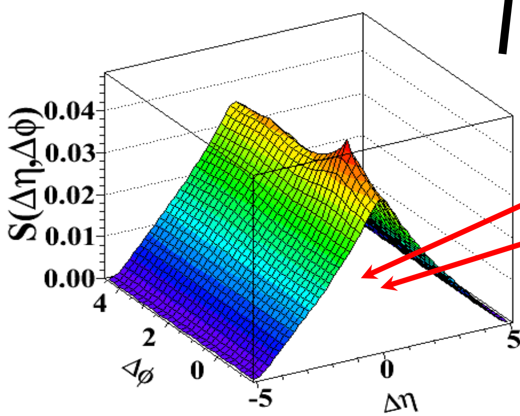
Divide Signal by Background

Associated hadron yield per trigger:

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

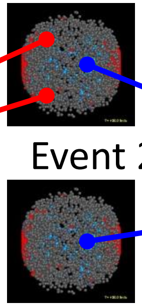
Signal pair distribution:

same event pairs

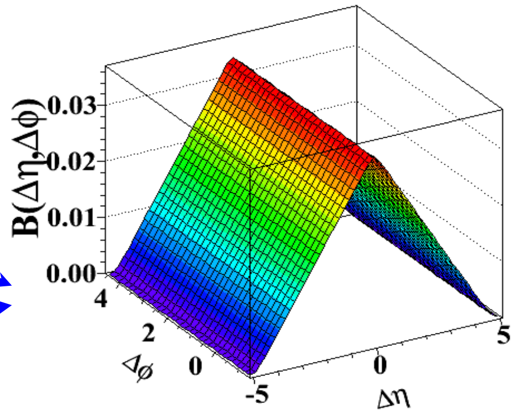


Event 1

Event 2



Background pair distribution:



mixed event pairs

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

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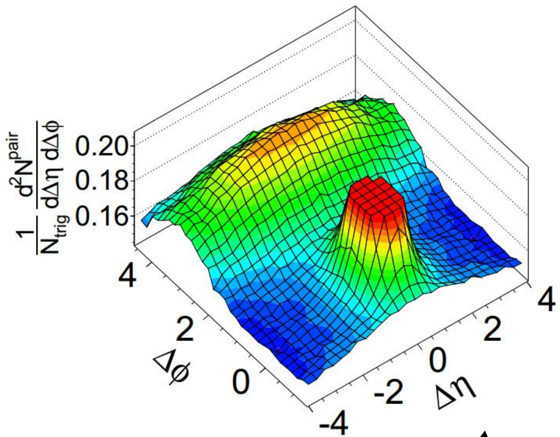
By making two-particle correlations



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Signal pair distribution:

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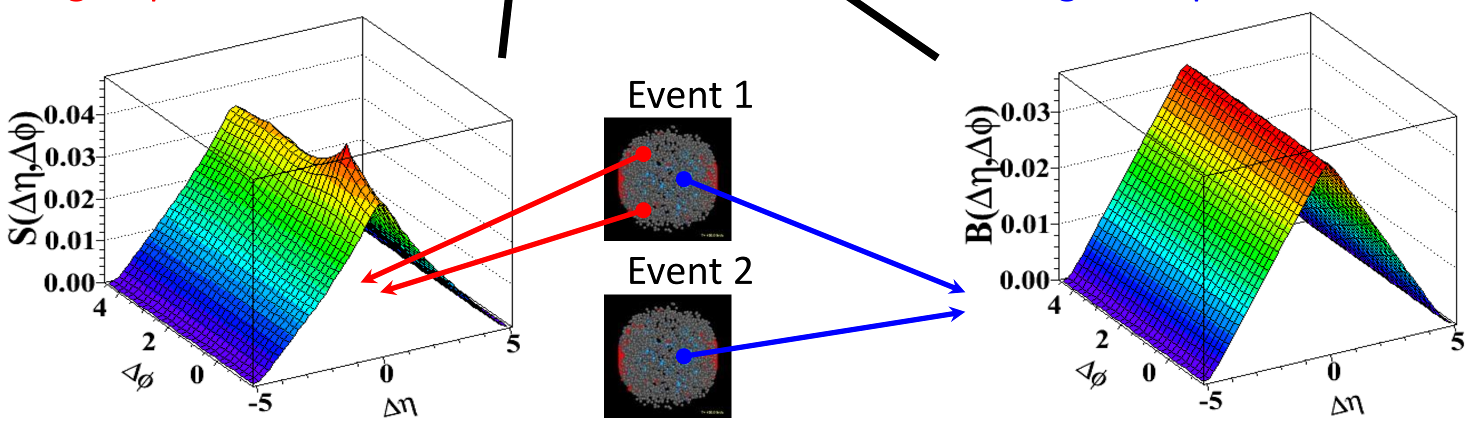

mixed event pairs

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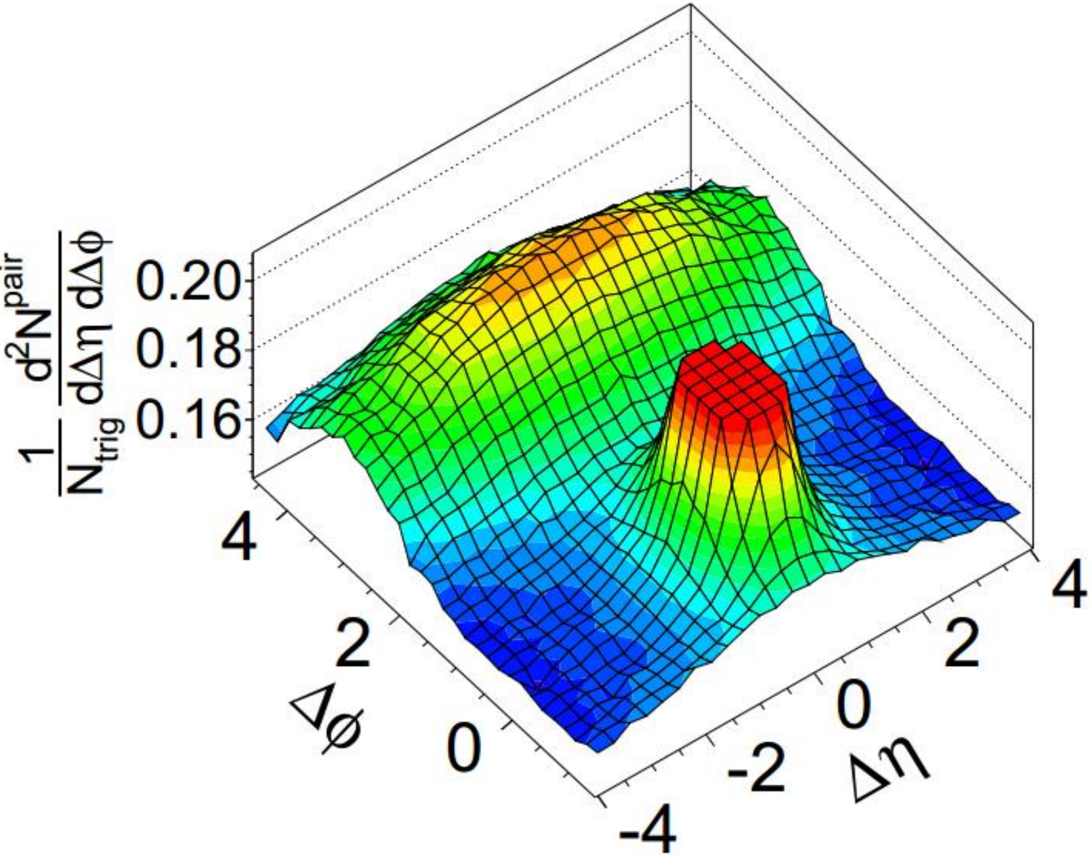
A typical proton proton collision



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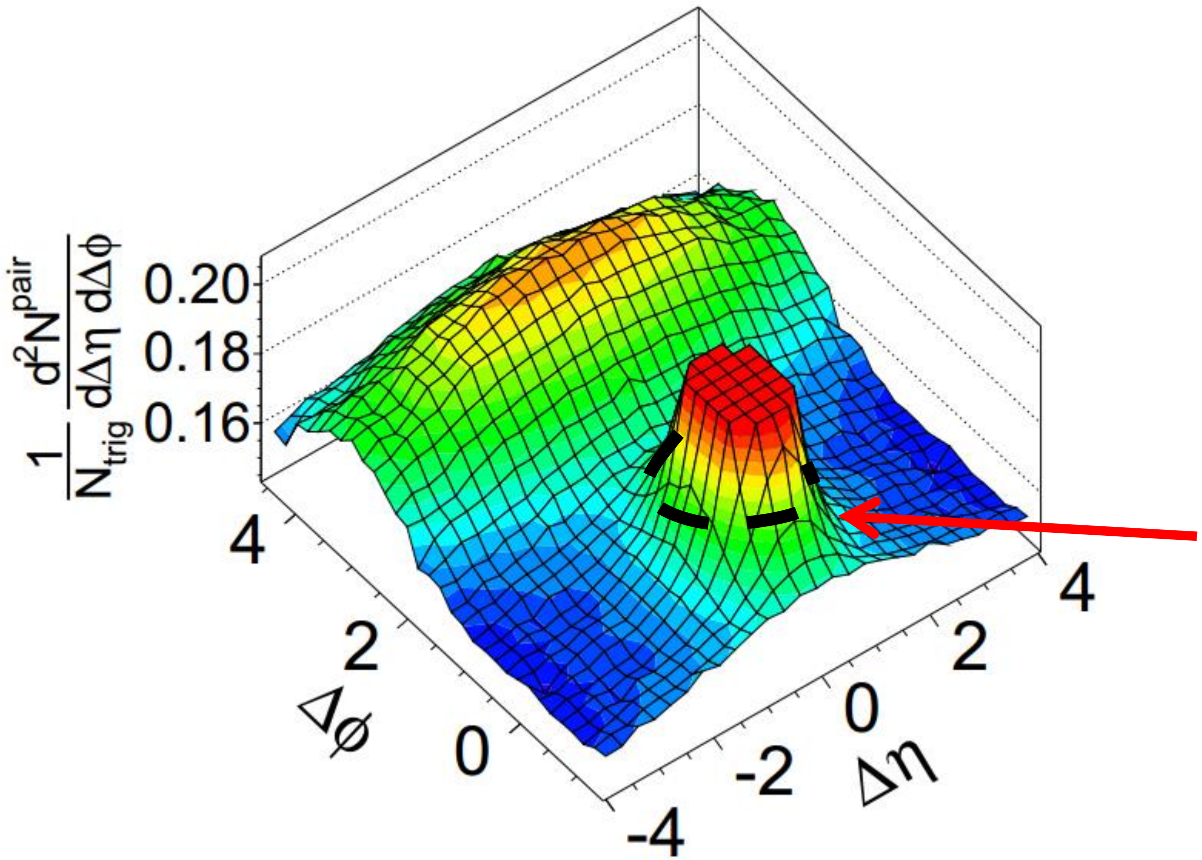
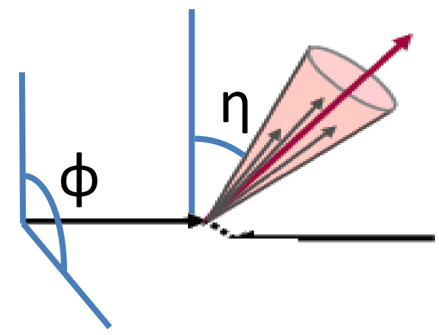
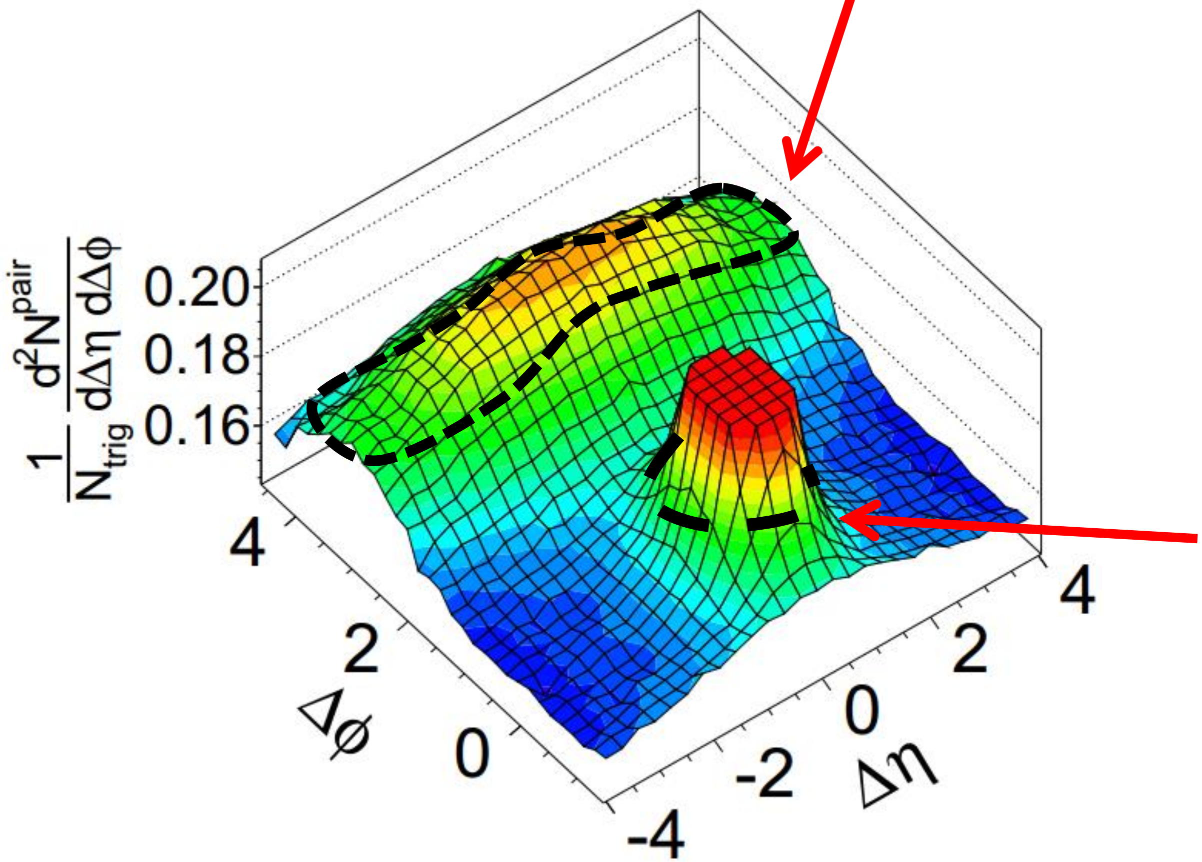


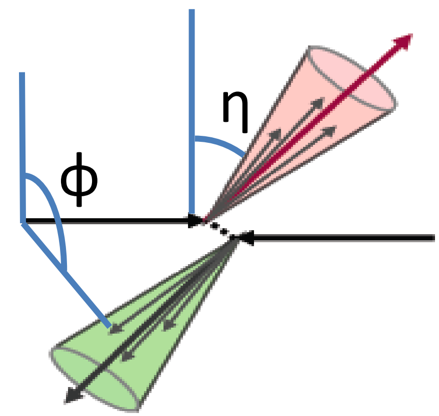


"Near-side" (Δϕ, Δη ~ 0) correlations from single jets

A typical proton proton collision

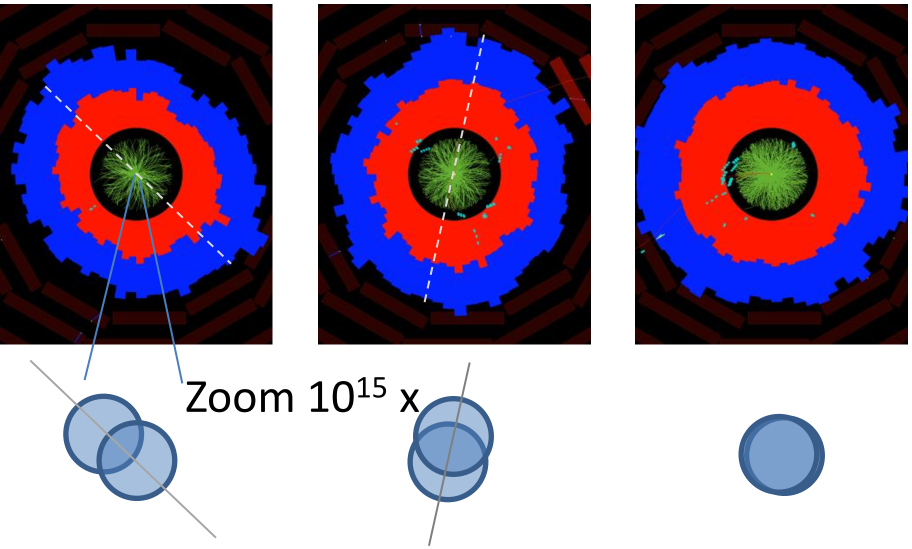
“Away-side” ($\Delta\phi \sim \pi$)
back-to-back jet correlations

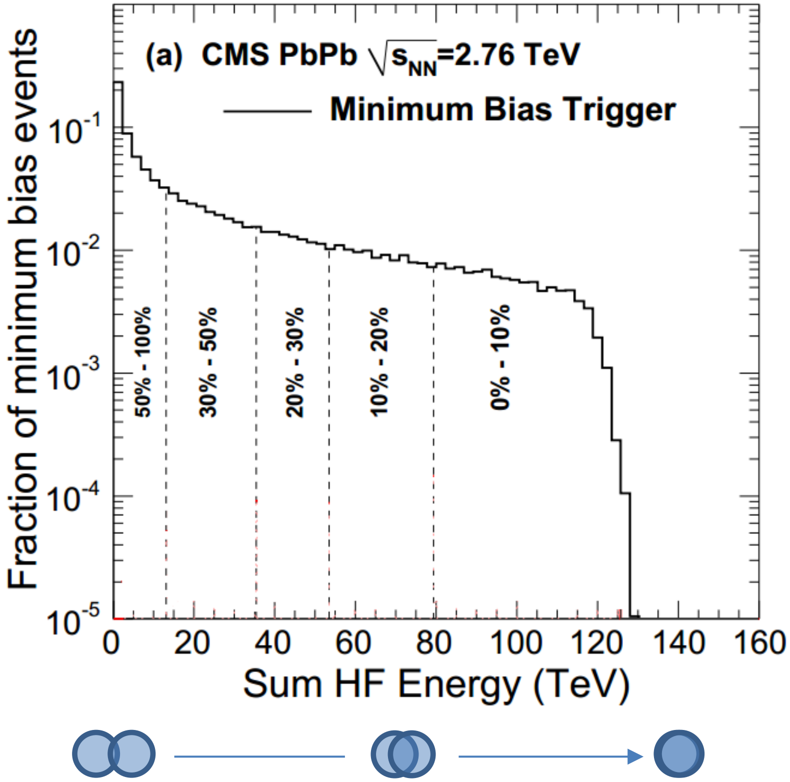




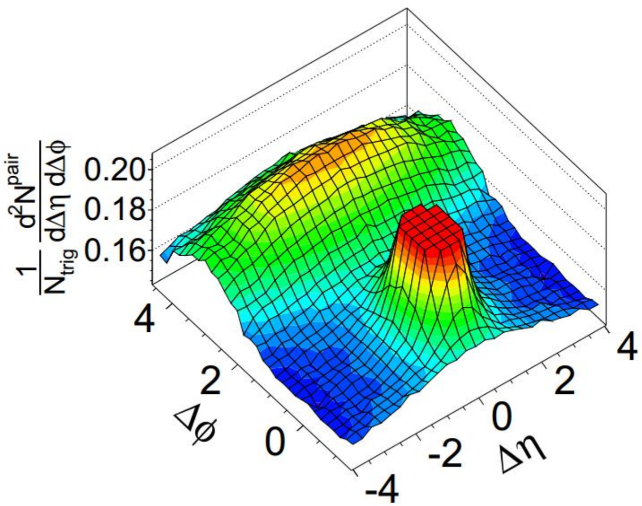
“Near-side” ($\Delta\phi$, $\Delta\eta \sim 0$)
correlations from single jets

Centrality

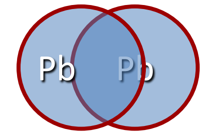

Zoom 10^15 x


(a) CMS PbPb √sNN=2.76 TeV
Minimum Bias Trigger
Fraction of minimum bias events
Sum HF Energy (TeV)
50% - 100%
30% - 50%
20% - 30%
10% - 20%
0% - 10%
0
20
40
60
80
100
120
140
160
10^-1
10^-2
10^-3
10^-4
10^-5

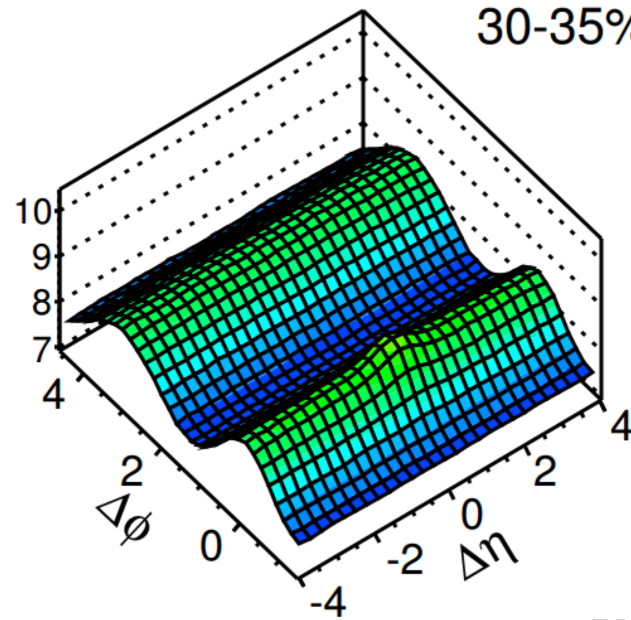
Standard Model of Heavy Ion Collisions



CMS PbPb 2.76 TeV



30-35% centrality



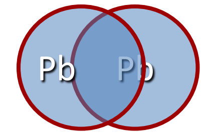
EPJC 72 (2012) 2012

$3.0 < p_T^{trig} < 3.5$ GeV/c

$1.0 < p_T^{assoc} < 1.5$ GeV/c

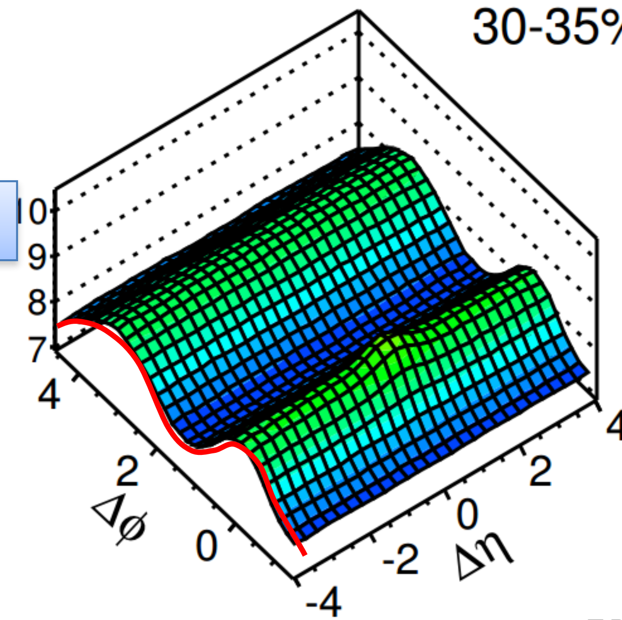
Standard Model of Heavy Ion Collisions

CMS PbPb 2.76 TeV

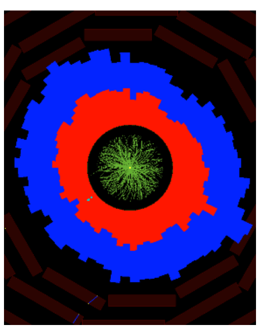


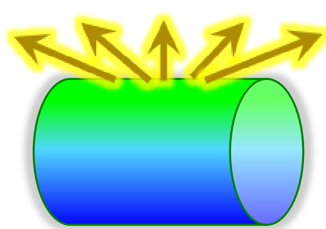
30-35% centrality

$V_{2\Delta} \cos(2\,\Delta\phi)$



EPJC 72 (2012) 2012





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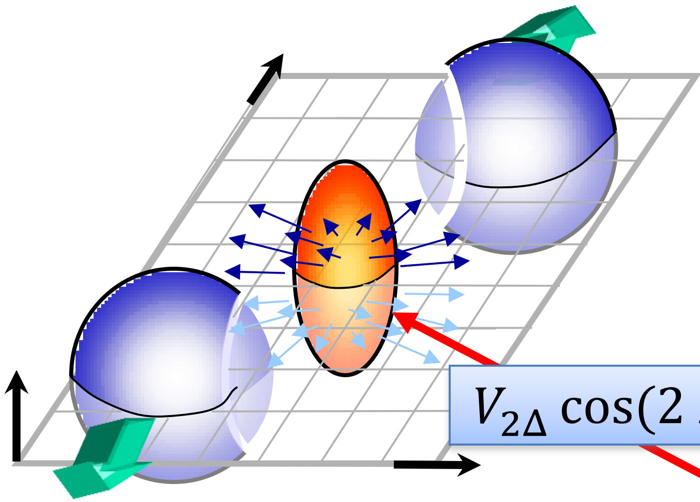
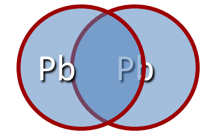


$V_{2\Delta}\cos(2\,\Delta\phi)$

CMS PbPb 2.76 TeV



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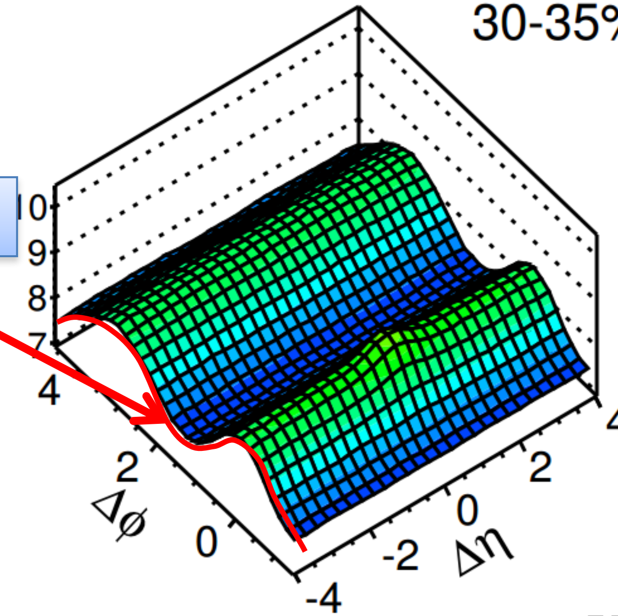

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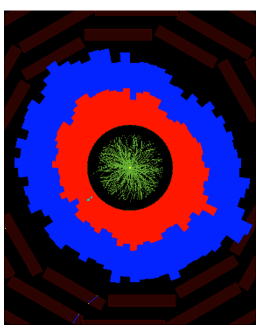

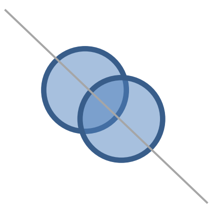

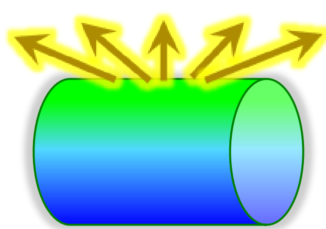

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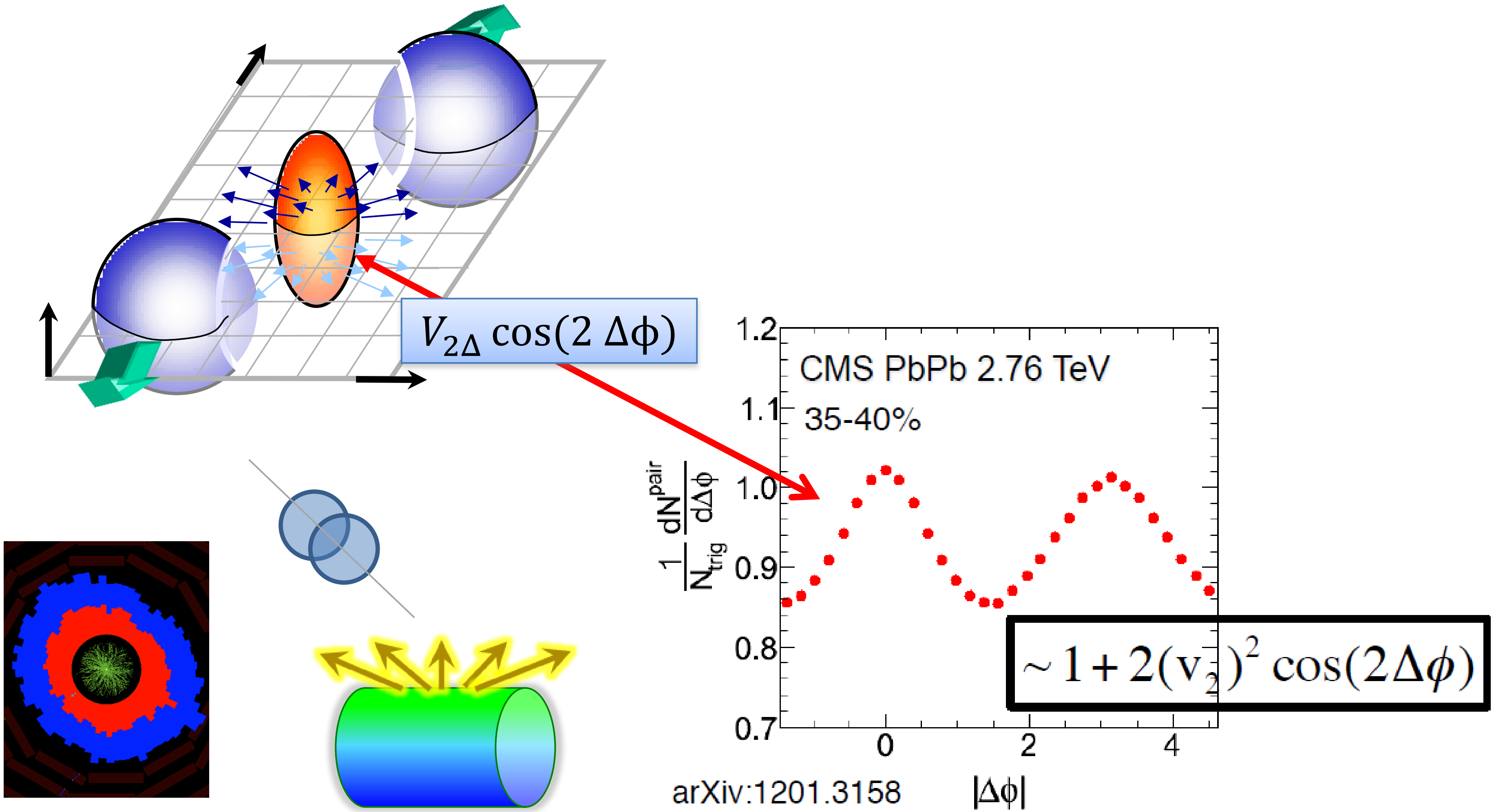
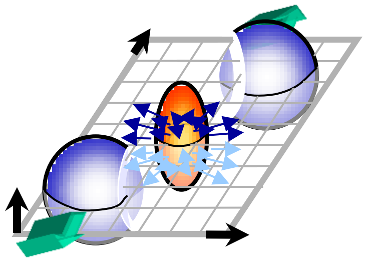
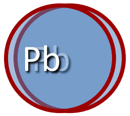


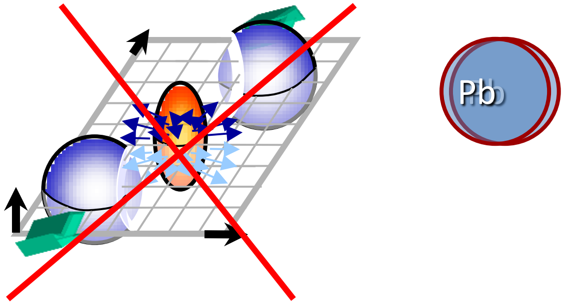
Something interesting happens near 0%

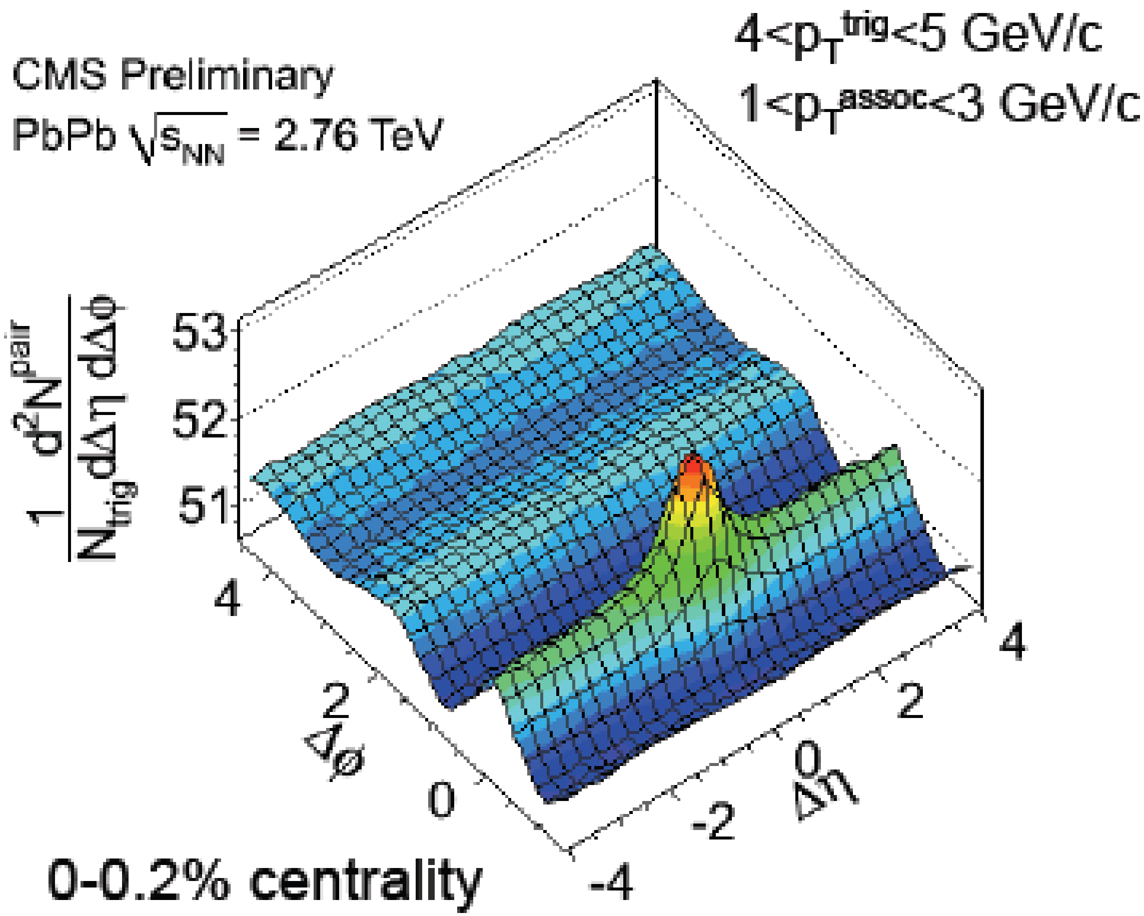




Predicts no anisotropy

Something interesting happens near 0%





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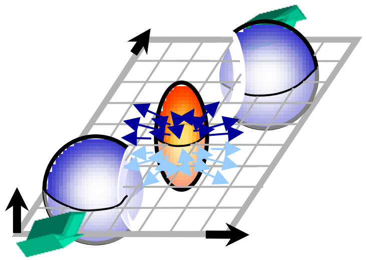
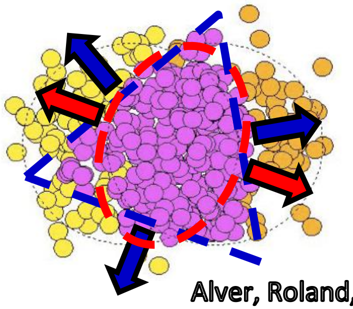
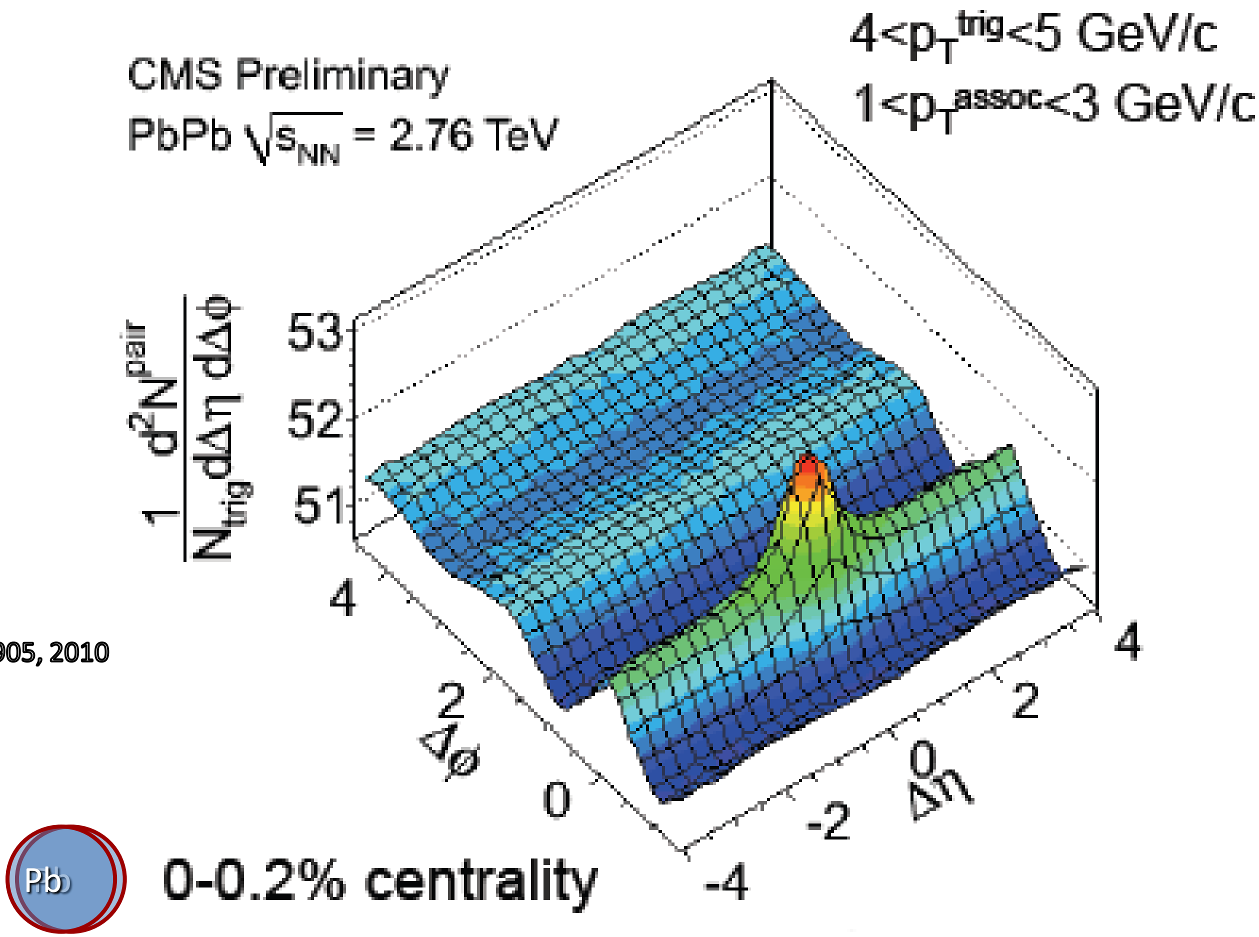


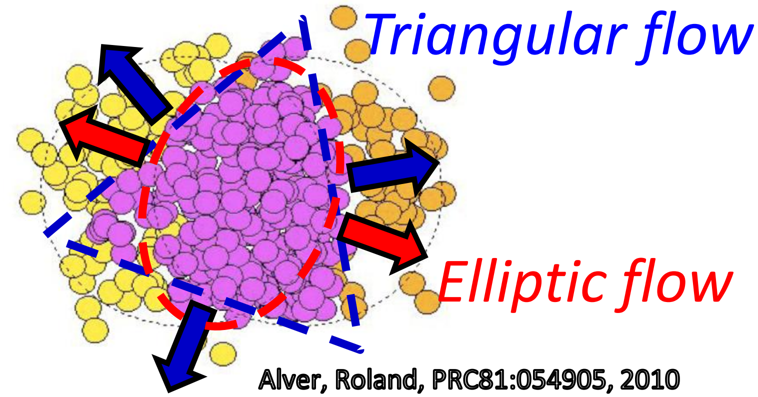
+



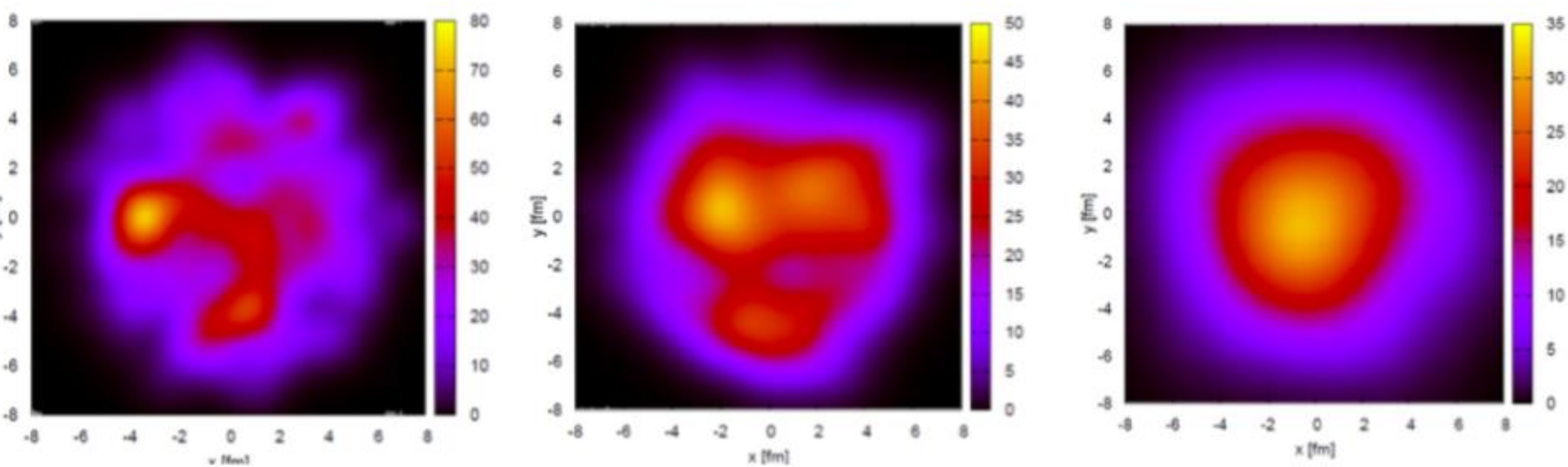
Alver, Roland, PRC81:054905, 2010



Extension to the Standard Model



[H. Petersen, QM2011]



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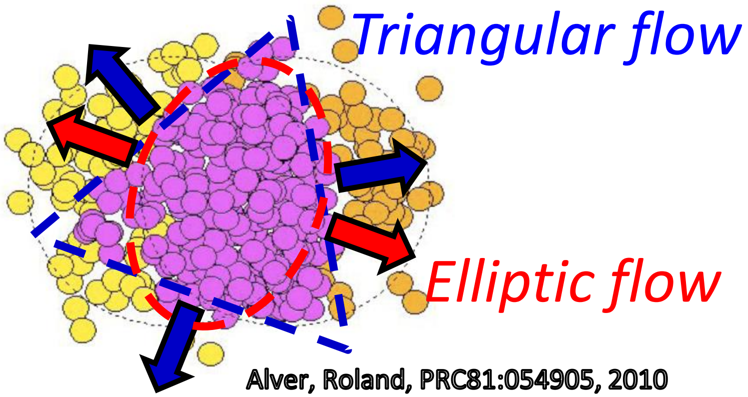
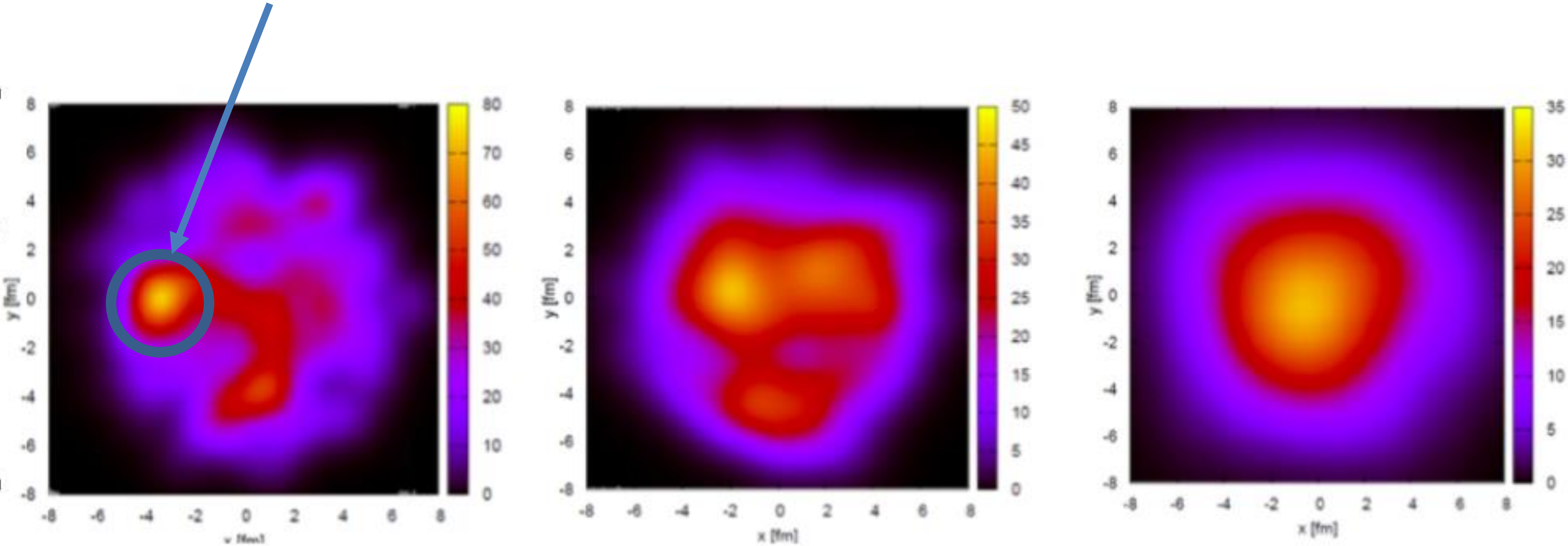


Alver, Roland, PRC81:054905, 2010

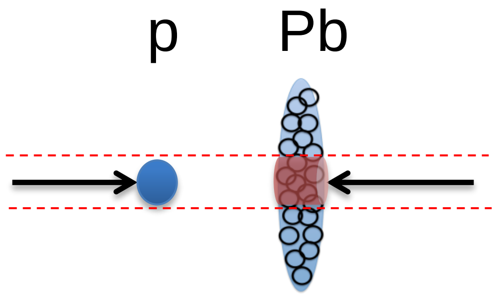
We have a relatively small region of incredible energy density from fluctuations. Can we get flow from this alone?

[H. Petersen, QM2011]



Enter pPb

In late 2012 the LHC ran a test for a few hours to see if it could collide protons on lead…
In that time we recorded 2 million pPb collisions.



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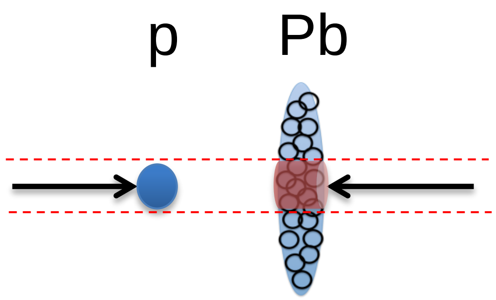
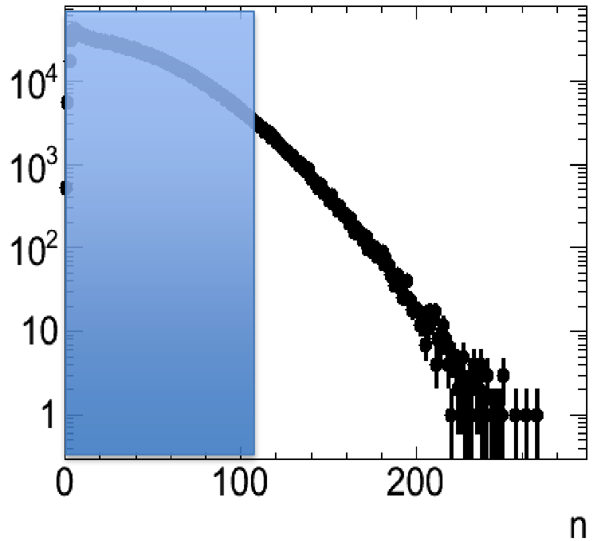


Centrality → Multiplicity , N ≡ number of reconstructed charged particles with p_T>0.4 GeV/c



Top 1% multiplicity events

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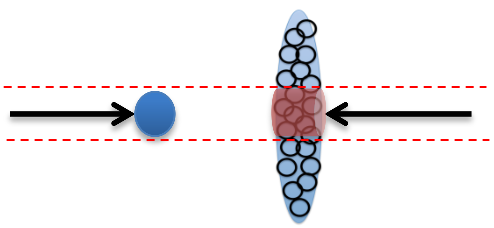
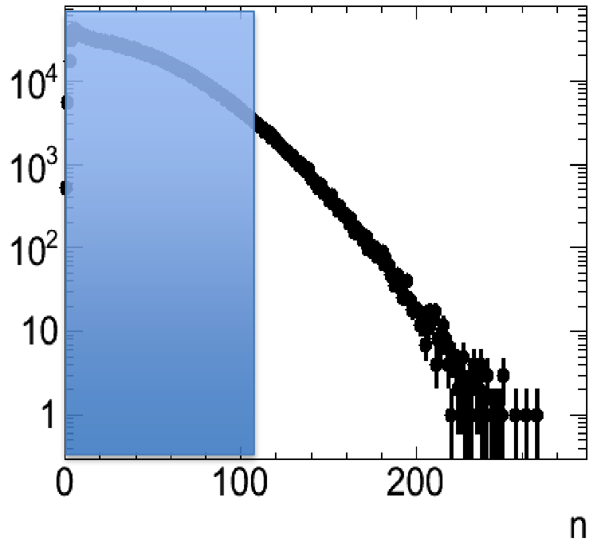
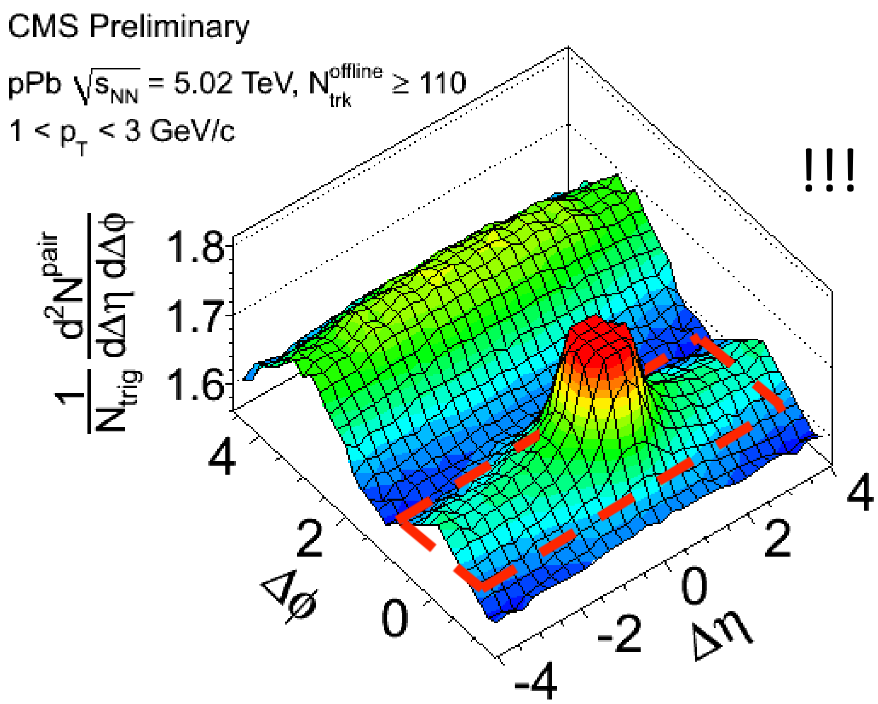
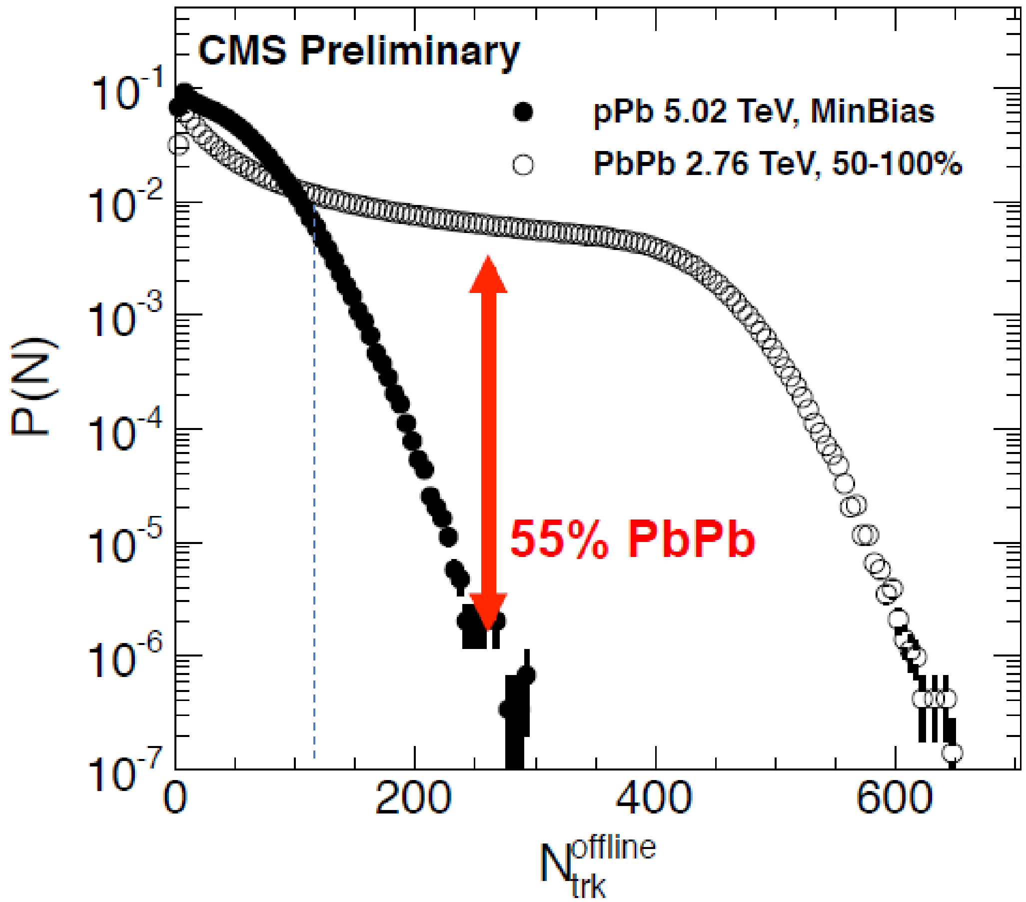




Top 1% multiplicity events

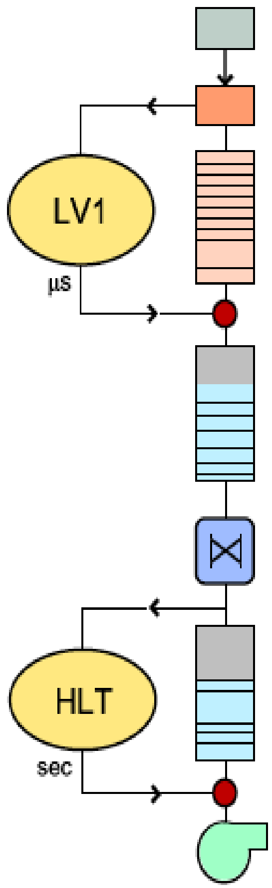


We need a trigger for pPb



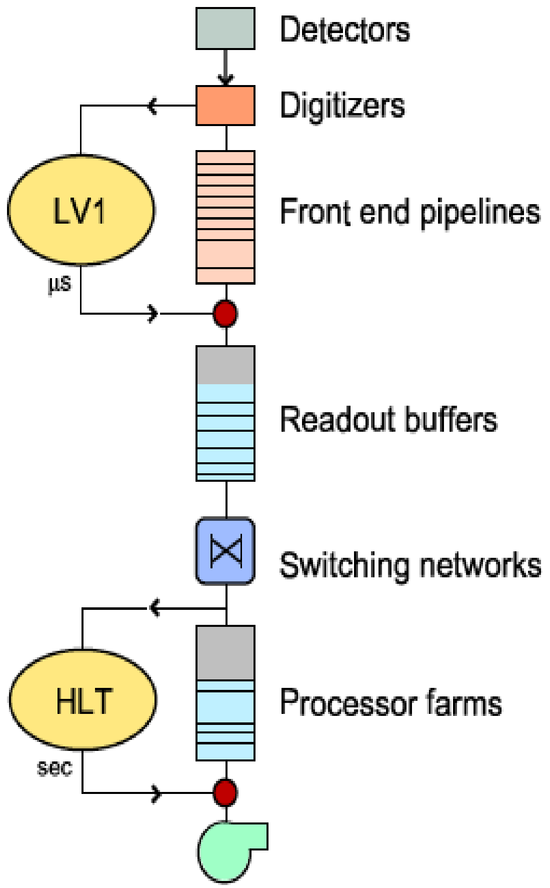
The high multiplicity trigger

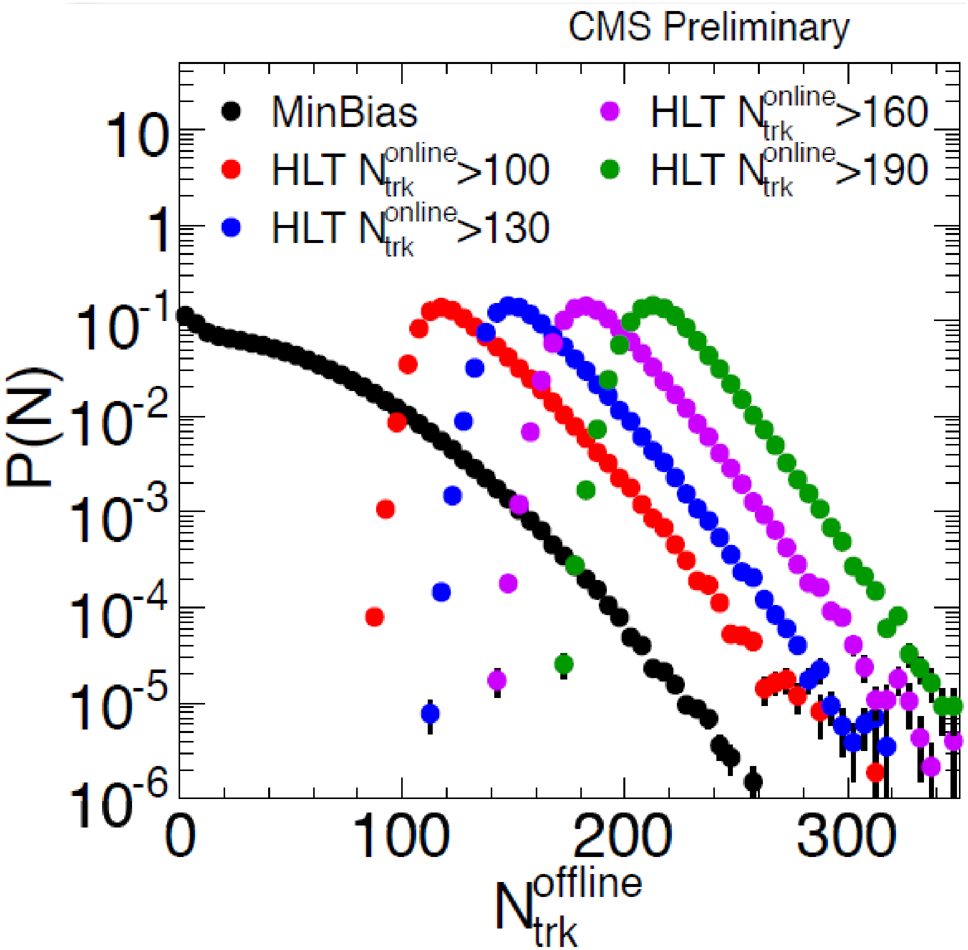
CMS trigger and DAQ



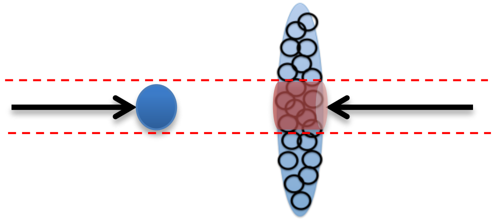
The high multiplicity trigger

CMS trigger and DAQ

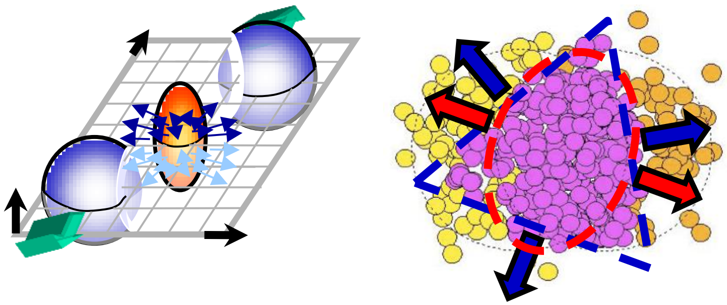


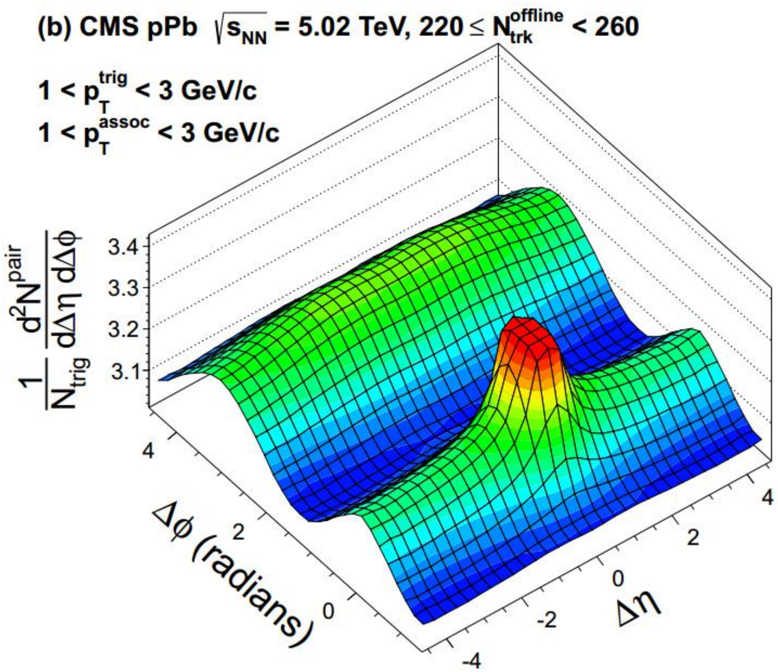


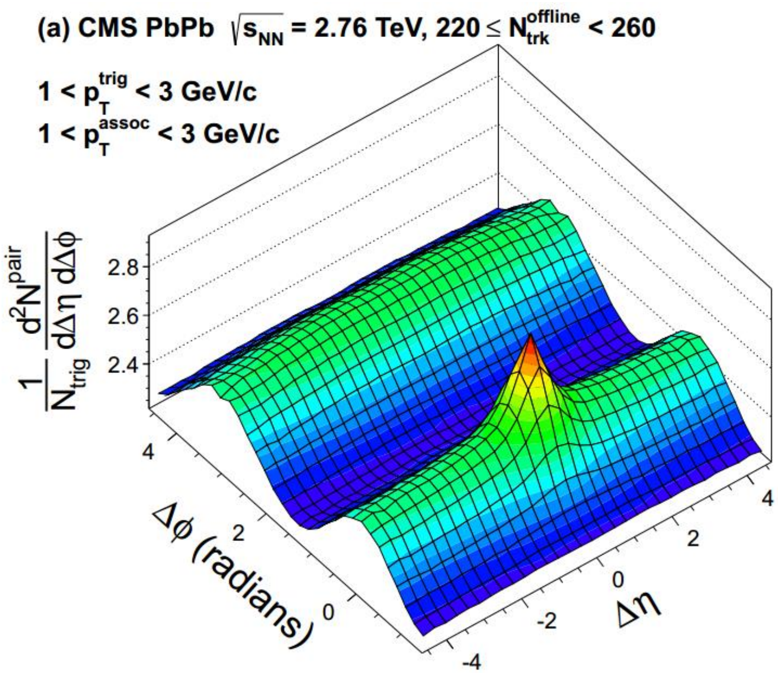
Beautiful Correlations in pPb and PbPb



vs



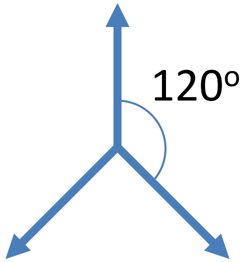




Striking similarity… but is it flow?

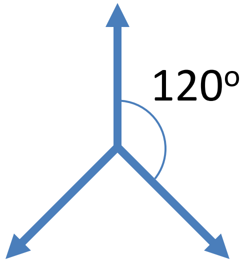
Hint no. 1

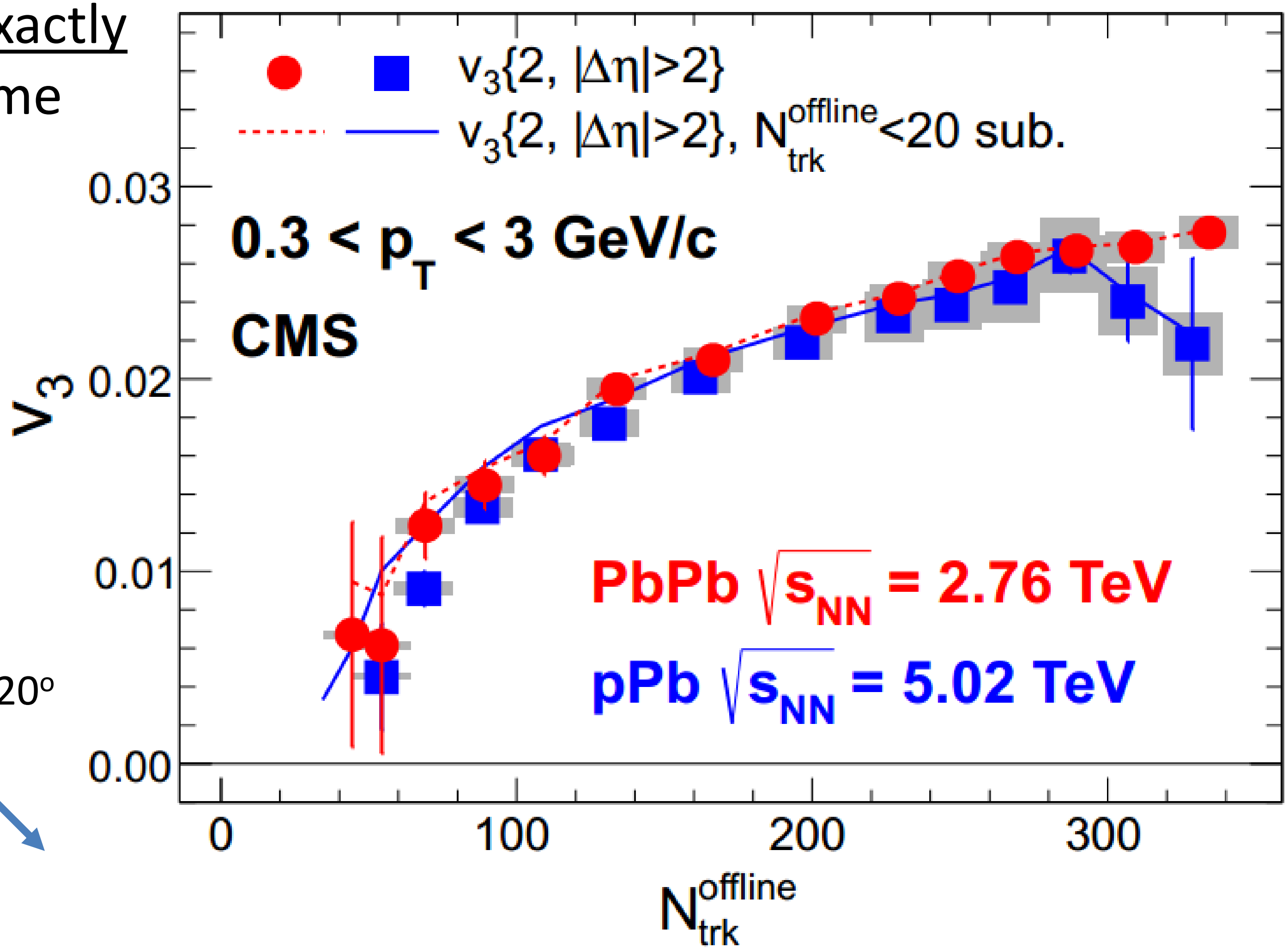
- Look for v_3



Hint no. 1

v3 is <u>exactly</u> the same

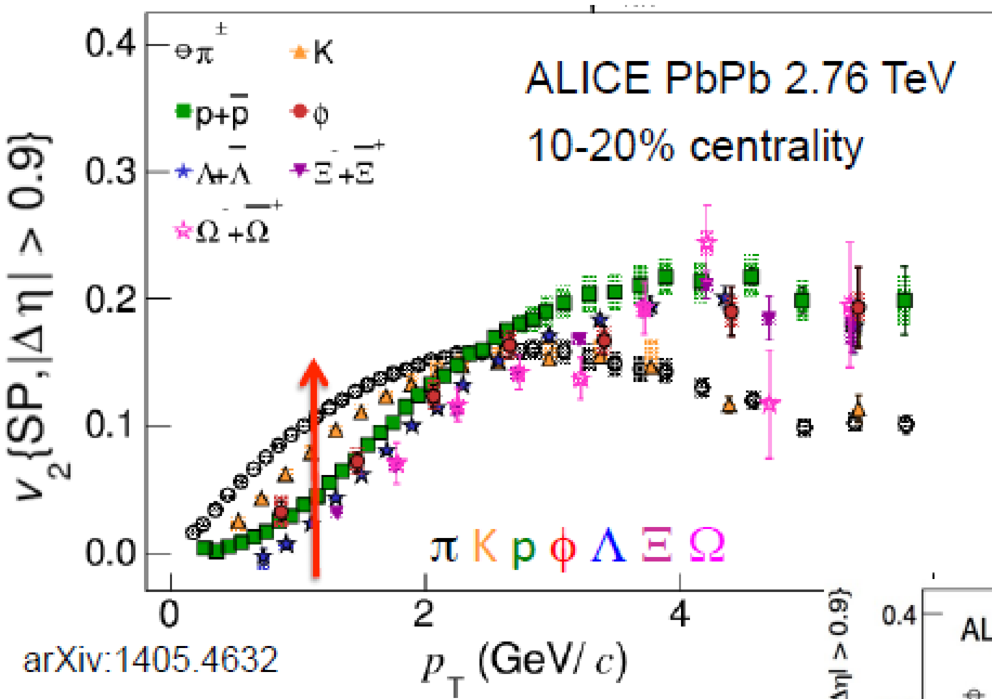




Hint no. 2

- Look for mass ordering of elliptical flow

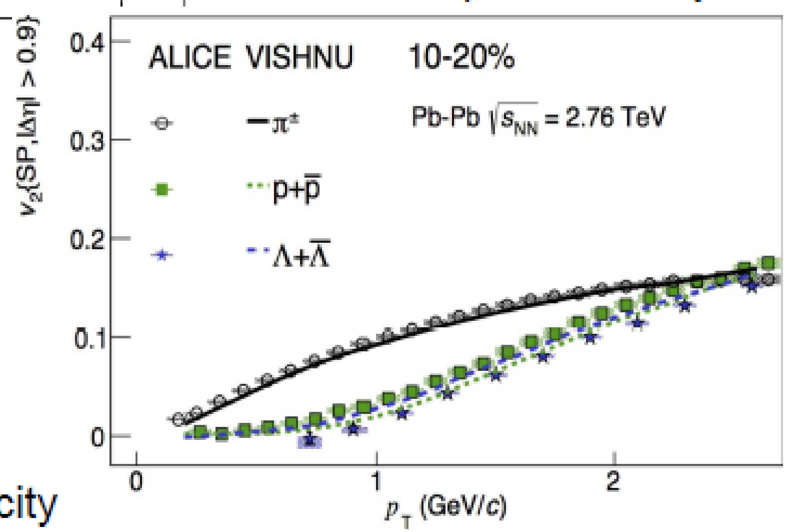
Hint no. 2



arXiv:1405.4632

- Mass ordering at low p_T: Smaller v_2 for heavier particles
- v_2(baryon) > v_2 (meson) at higher p_T

Comparison to hydro



In hydro, radial flow boosts heavier particles to higher p_T

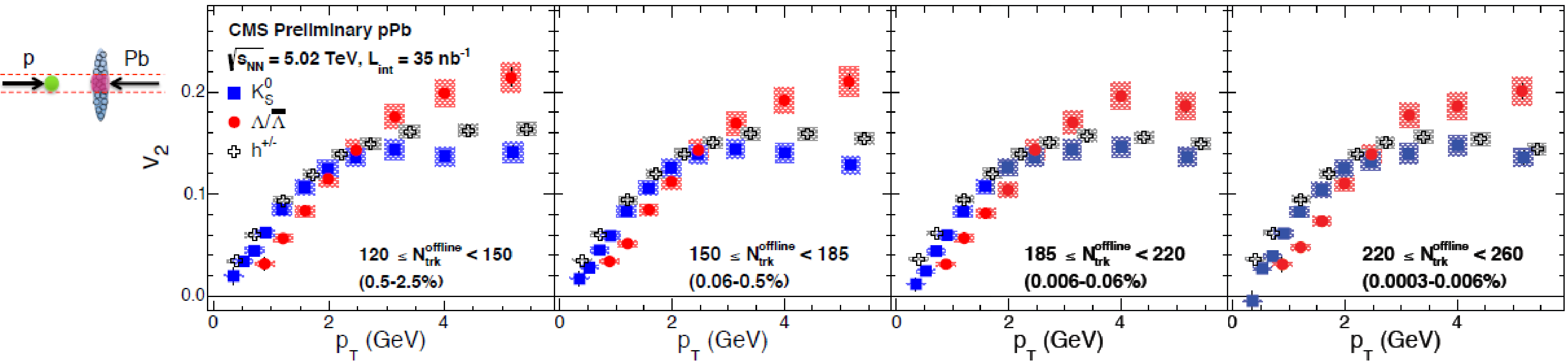
$$\Delta p_T \sim m\,\beta_T$$

radial flow velocity

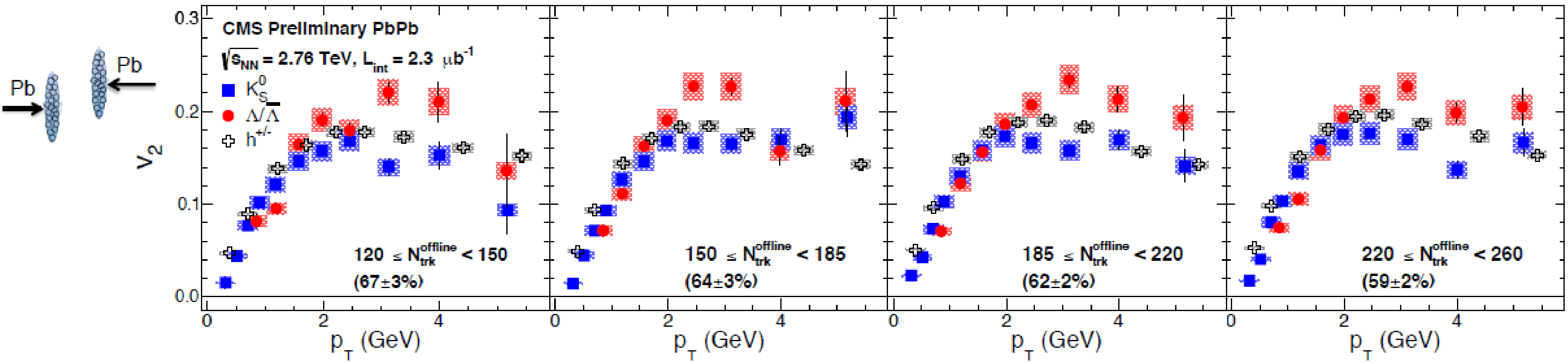
Hint no. 2

High multiplicity pPb

Elliptic flow (v_2)



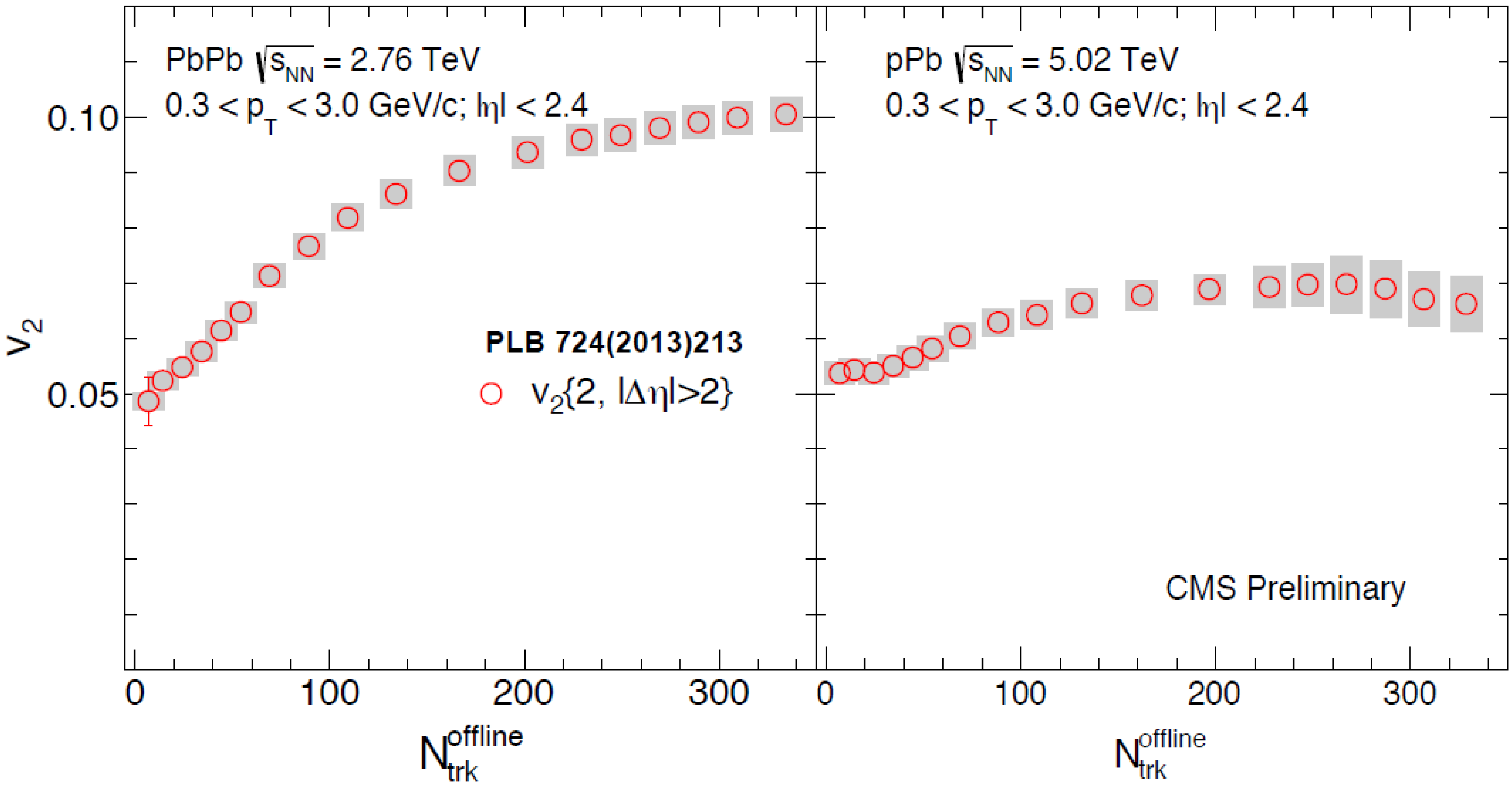
Comparison to PbPb at comparable multiplicities



Hint no. 3

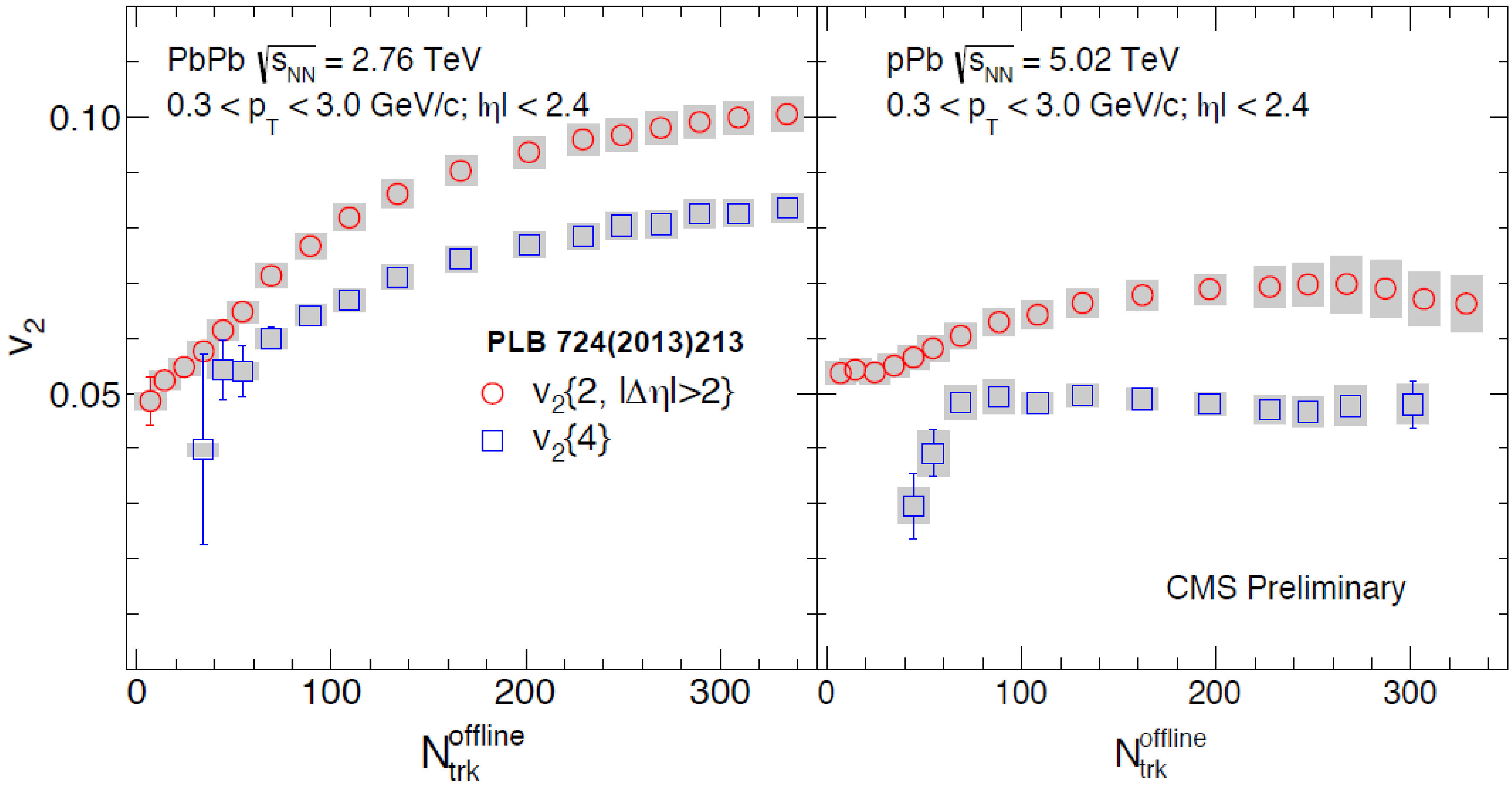
- Look for collective behavior (v2) in multiparticle (n>2) correlations

Hint no. 3

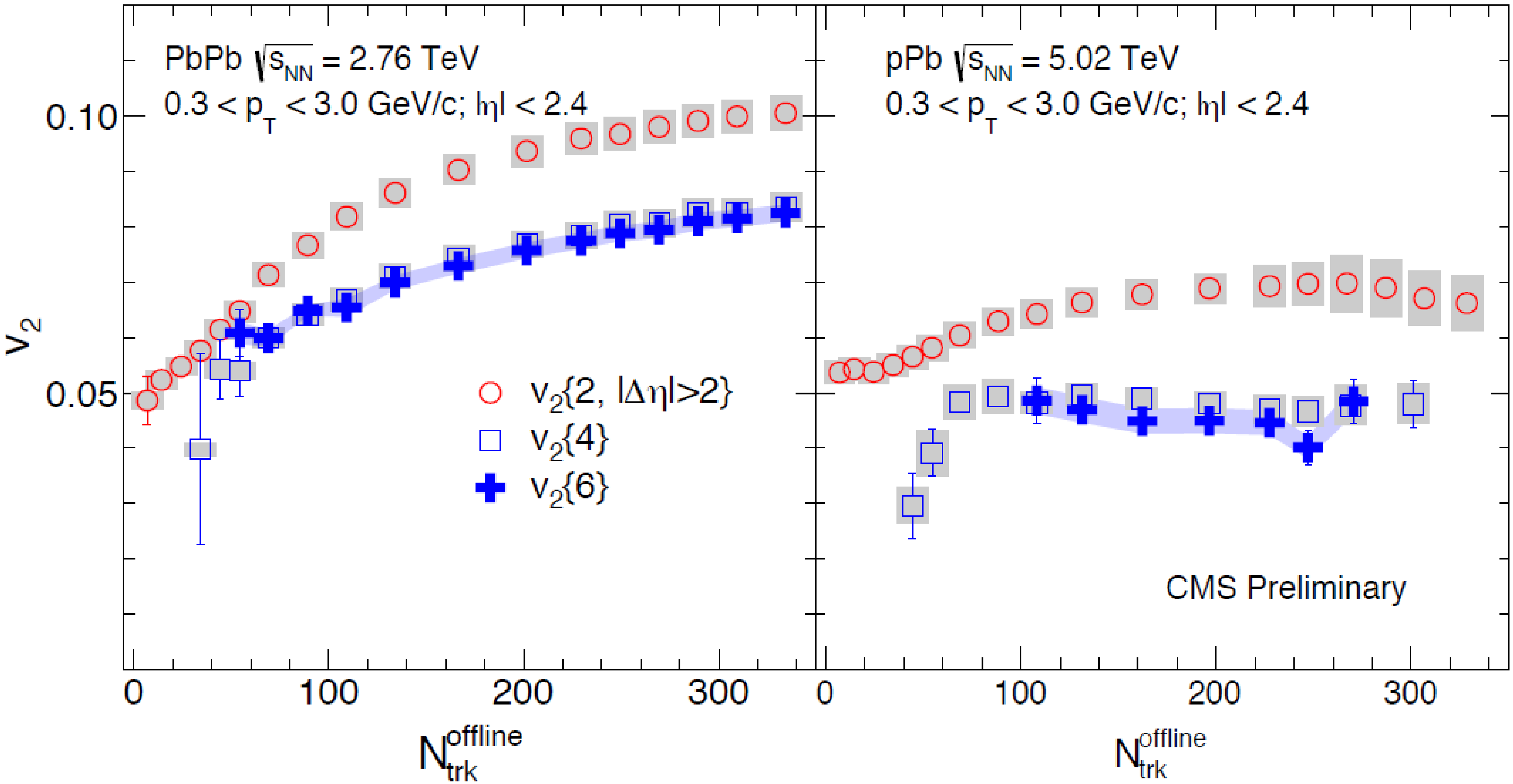


PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
PLB 724(2013)213
$v_2\{2, |\Delta\eta|>2\}$
CMS Preliminary
v_2
0.10
0.05
0
100
200
300
$N_{trk}^{offline}$

Hint no. 3


PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
PLB 724(2013)213
$v_2\{2, |\Delta\eta|>2\}$
$v_2\{4\}$
CMS Preliminary
v_2
0.10
0.05
0
100
200
300
$N_{trk}^{offline}$

Hint no. 3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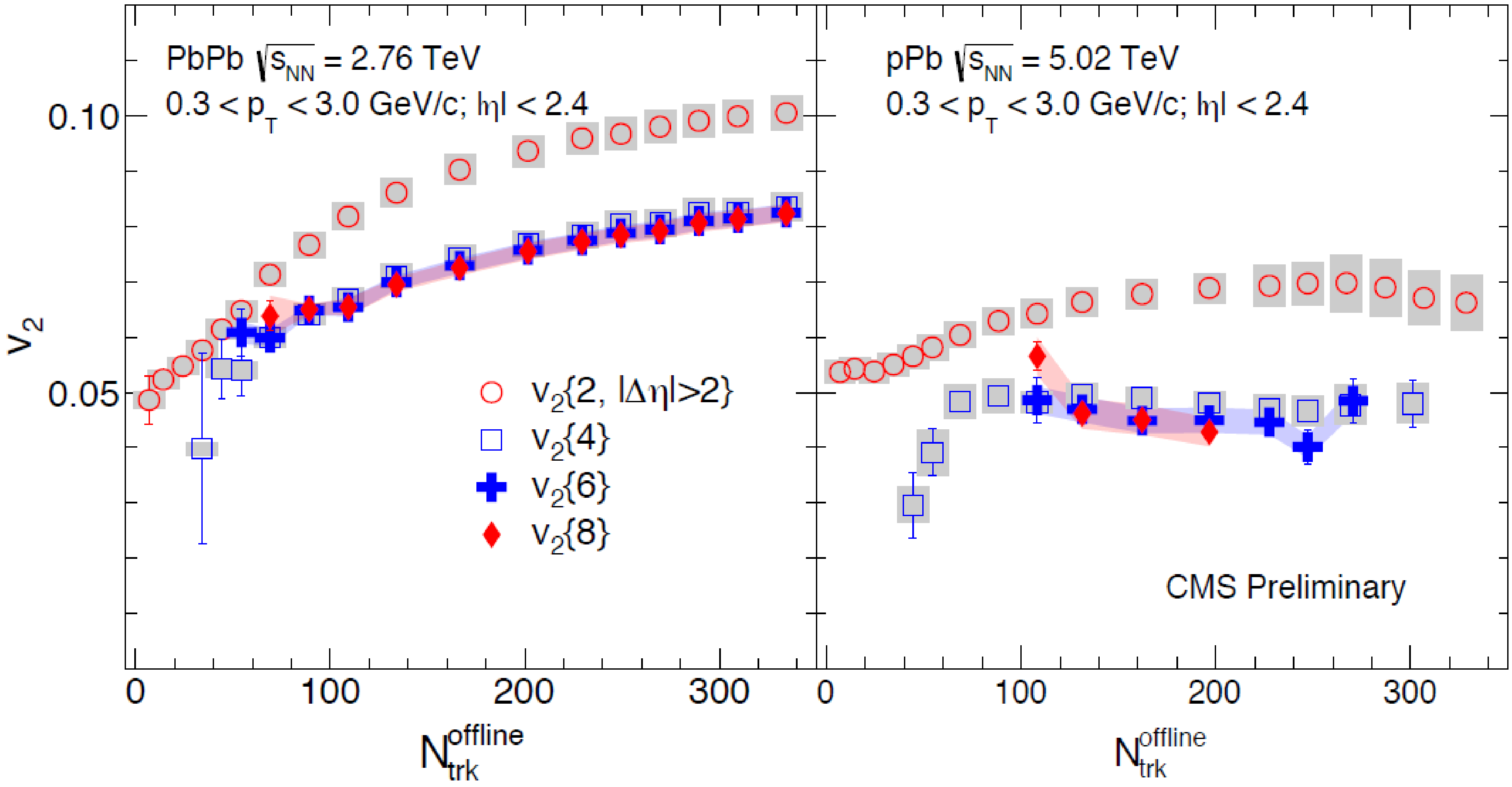
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
$v_2\{2, |\Delta\eta|>2\}$
$v_2\{4\}$
$v_2\{6\}$
CMS Preliminary
v_2
0.10
0.05
0
100
200
300
$N_{trk}^{offline}$

Hint no. 3



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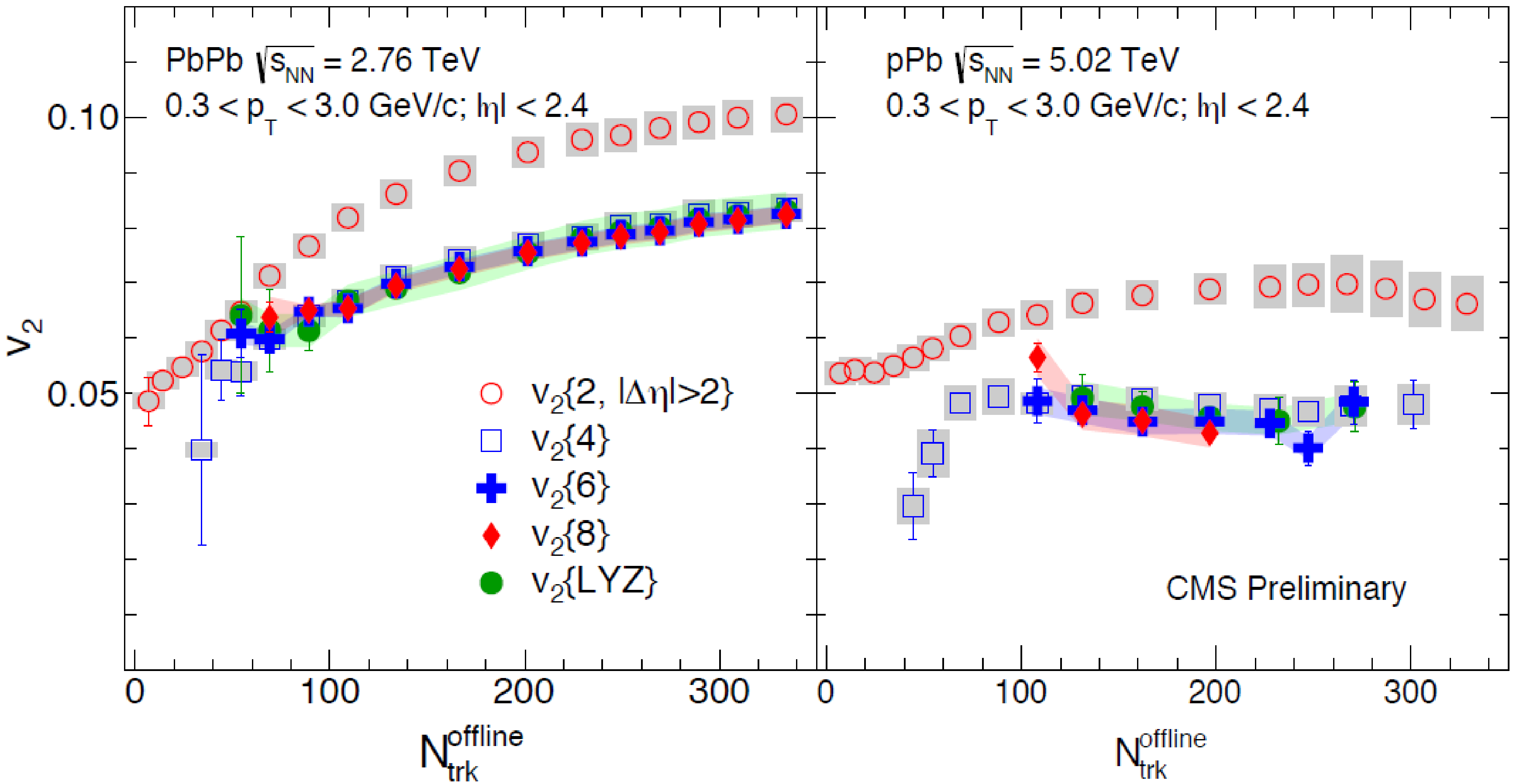
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
v_2
0.10
0.05
$v_2\{2, |\Delta\eta|>2\}$
$v_2\{4\}$
$v_2\{6\}$
$v_2\{8\}$
CMS Preliminary
0
100
200
300
$N_{trk}^{offline}$

Hint no. 3



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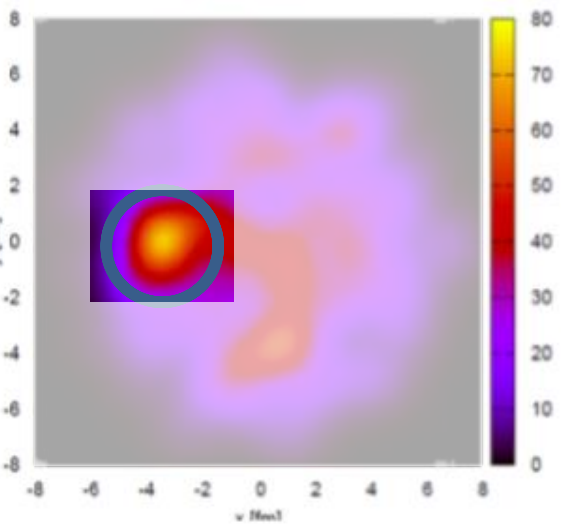
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
v_2
0.10
0.05
v_2{2, |Δη|>2}
v_2{4}
v_2{6}
v_2{8}
v_2{LYZ}
CMS Preliminary
0
100
200
300
$N_{trk}^{offline}$

pPb Flows!

- The long range azimuthal correlations we are seeing in pPb really seems to be flow

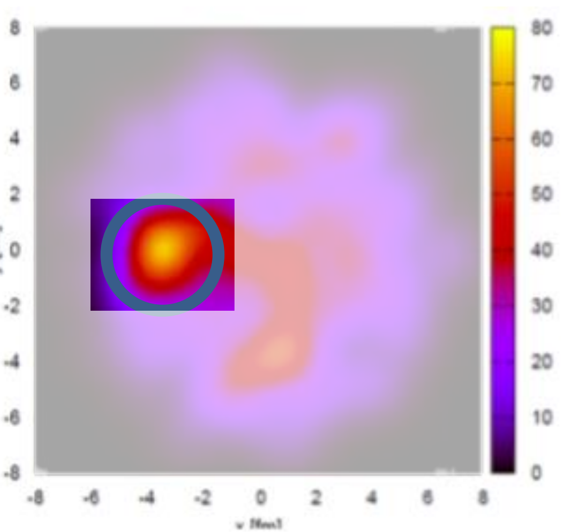
[H. Petersen, QM2011]



pPb Flows!

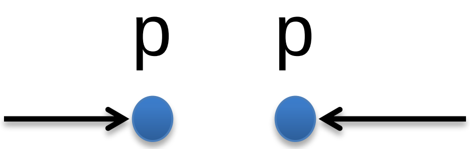
- The long range azimuthal correlations we are seeing in pPb really seems to be flow

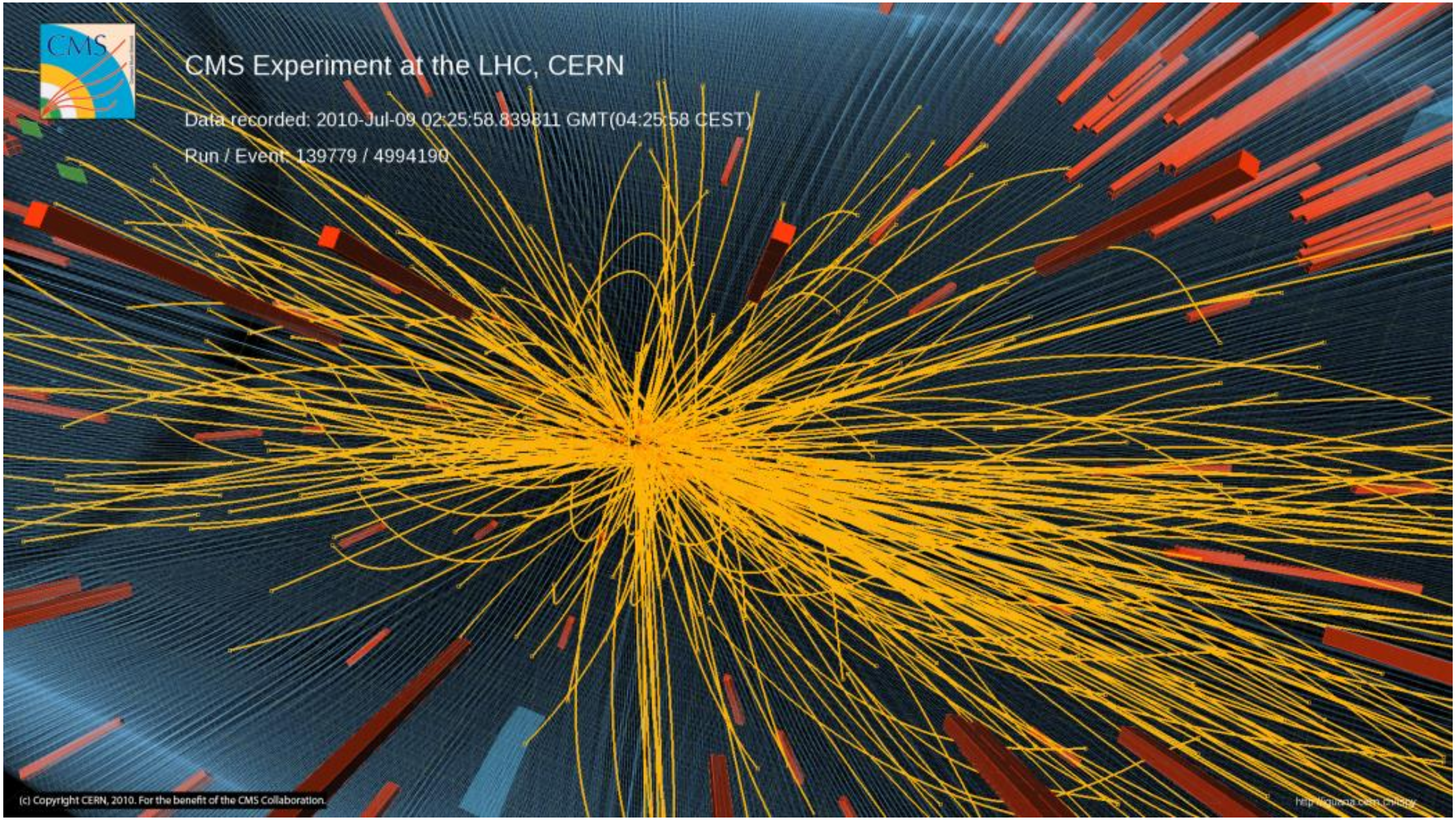
[H. Petersen, QM2011]



How small can we go?
Could there be flow even in pp (at very high multiplicity)?

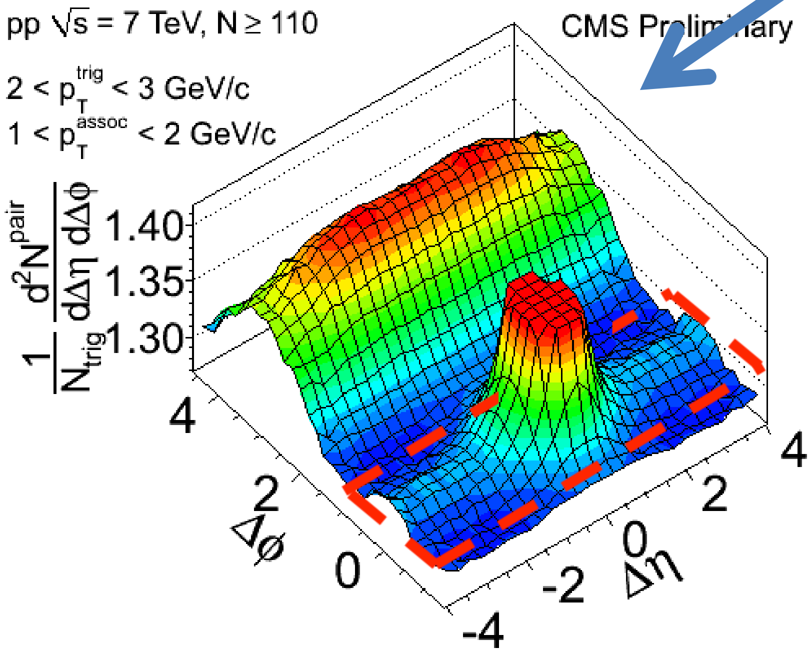
High multiplicity pp

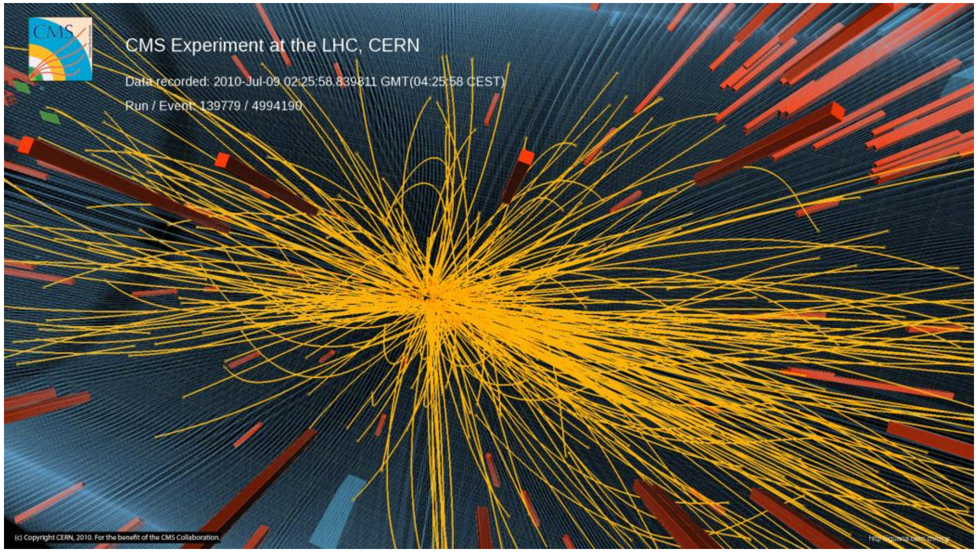




High Energy Density pp Collisions

Ran our trigger…



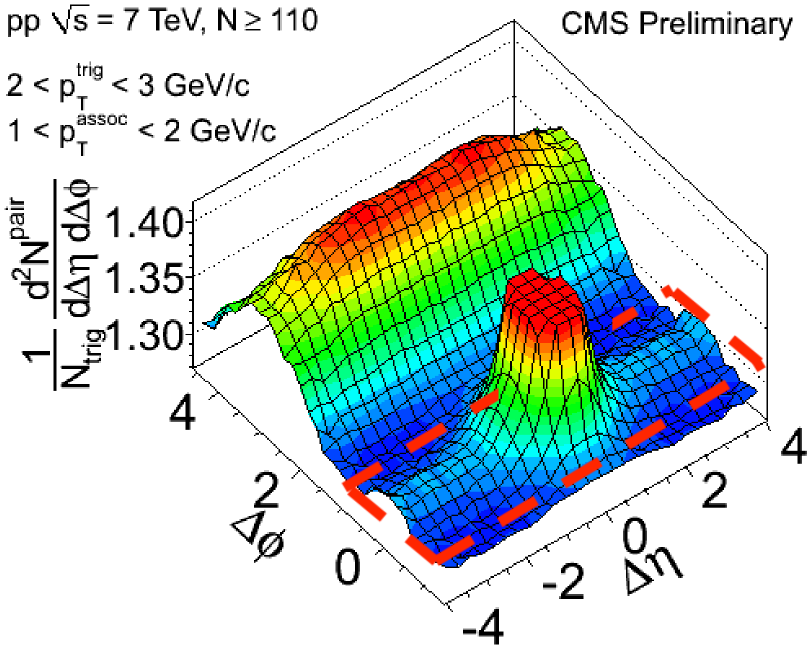


In <u>high-multiplicity</u> , N≥110 where:

N ≡ number of reconstructed charged particles with p_T>0.4 GeV/c

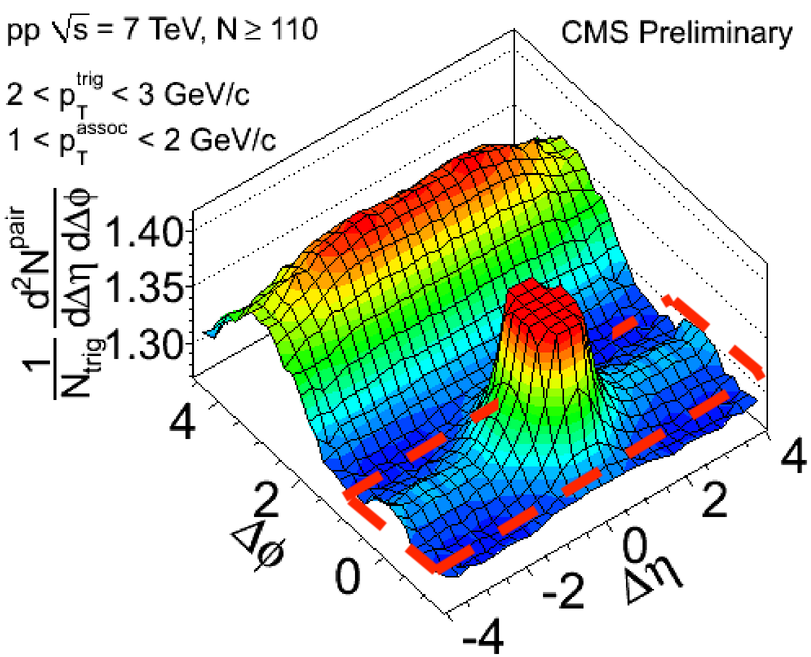
High Energy Density pp Collisions

Is this also flow…



High Energy Density pp Collisions

Is this also flow… or something more exotic?

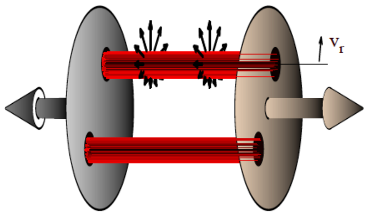


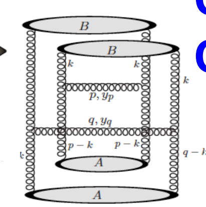
Interpretations:

Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections

Jet

Glasma tube

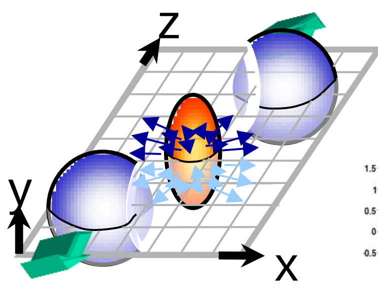




Color Glass Condensate

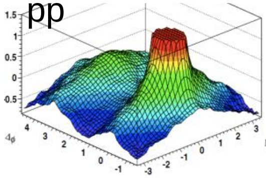
Phys. Lett. B697:21-25, 2011

Hydrodynamic flow



Quark Gluon Plasma

EPOS model: pp



K. Werner, WWND2011

⋮

Stay tuned

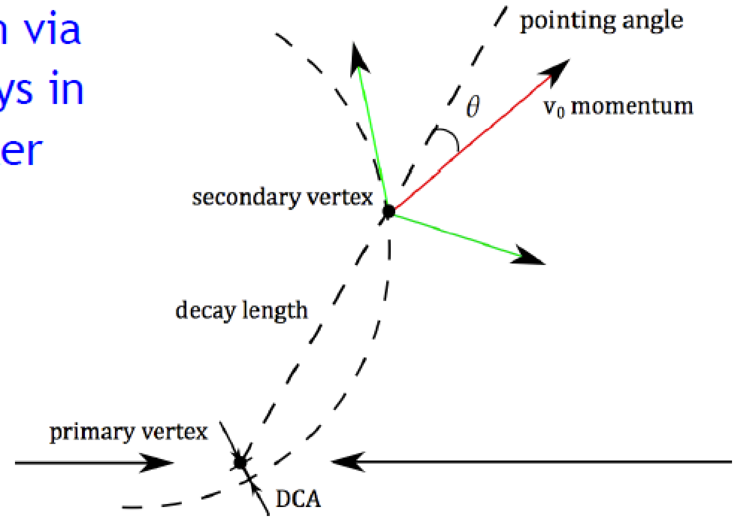
- 2015 run coming up!
  - 13 TeV pp collisions, higher center of mass energy
    - No ridge in pp has ever been observed below 7TeV
  - Much higher multiplicity reach
  - Measure v3 , multi-particle correlations and mass ordering

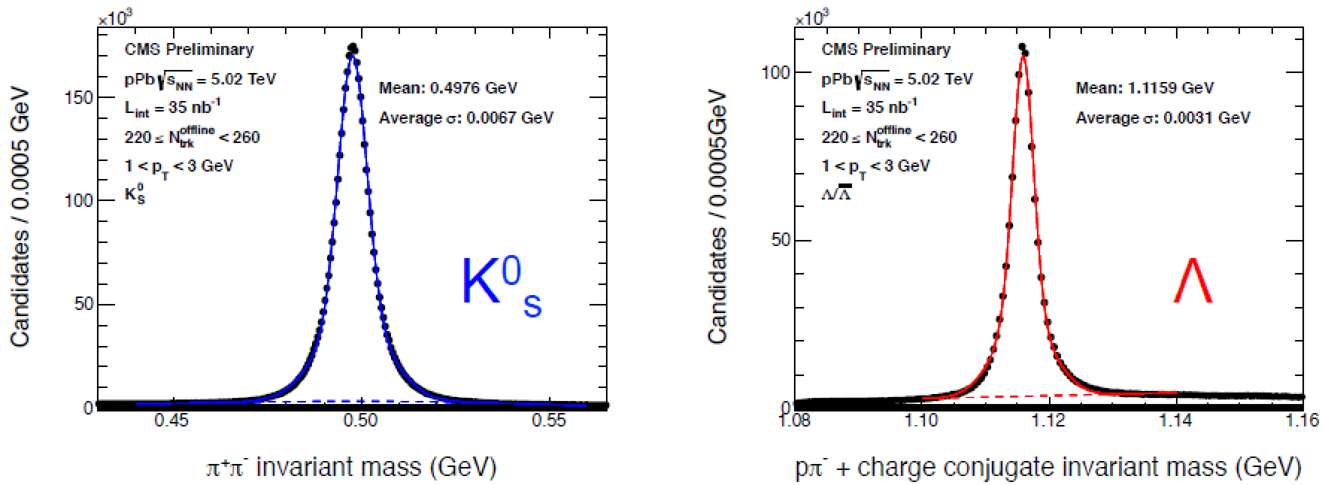
Conclusion

- An super-dense form of matter is created from ultra-relativistic PbPb collisions at the LHC which flows like a perfect liquid
- This same form of matter seems to be created in the highest energy density proton lead collisions which shows all the signs of flow
- pp shows clear long range correlations, whether they are flow is yet to be determined

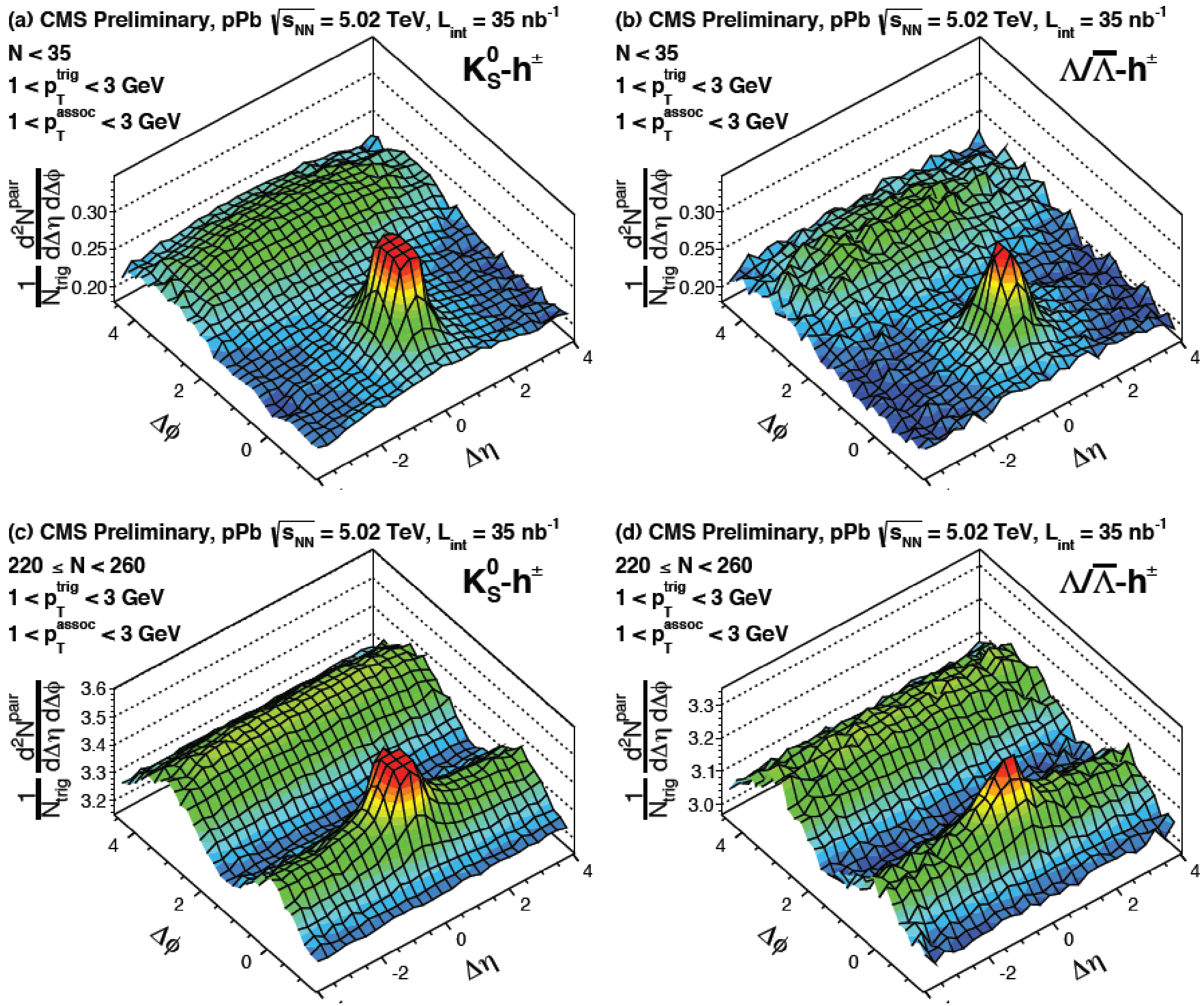
Backup

- V^0 reconstruction via topological decays in CMS silicon tracker

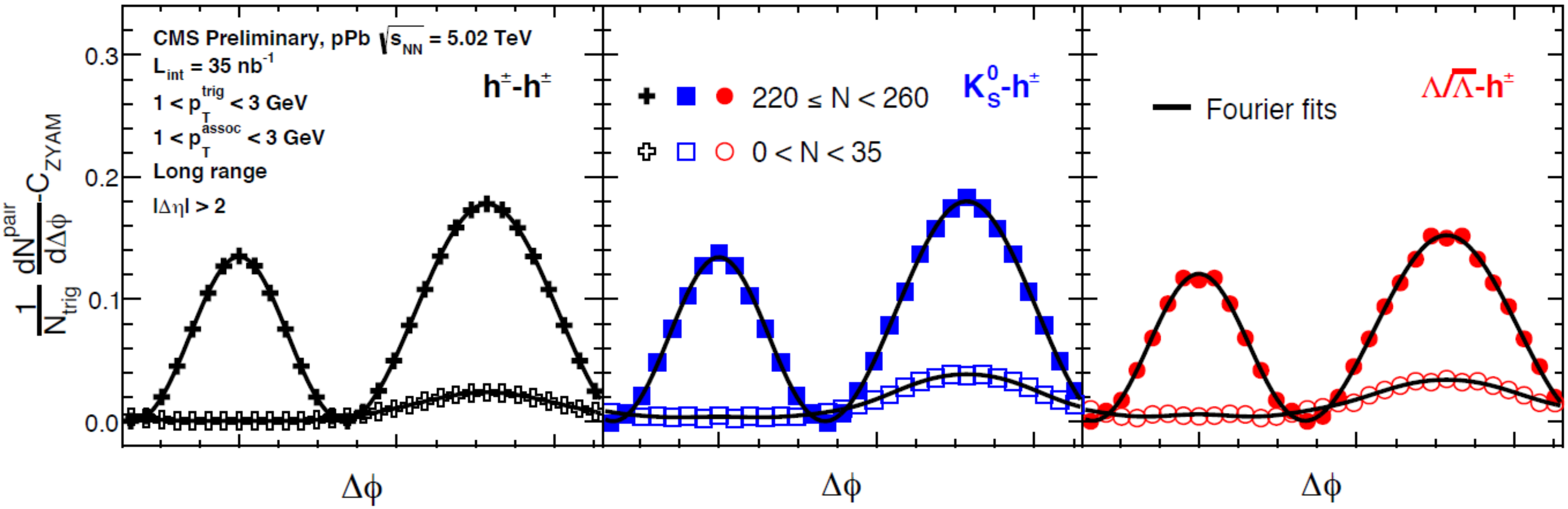




Clean reconstruction of K^0_s and Λ over wide range of p_T and η



(a) CMS Preliminary, pPb $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 35 nb^{-1}
N < 35
1 < p_T^{trig} < 3 GeV
1 < p_T^{assoc} < 3 GeV
K_S^0-$h^{\pm}$
(b) CMS Preliminary, pPb $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 35 nb^{-1}
N < 35
1 < p_T^{trig} < 3 GeV
1 < p_T^{assoc} < 3 GeV
$\Lambda/\bar{\Lambda}$-$h^{\pm}$
(c) CMS Preliminary, pPb $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 35 nb^{-1}
220 ≤ N < 260
1 < p_T^{trig} < 3 GeV
1 < p_T^{assoc} < 3 GeV
K_S^0-$h^{\pm}$
(d) CMS Preliminary, pPb $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 35 nb^{-1}
220 ≤ N < 260
1 < p_T^{trig} < 3 GeV
1 < p_T^{assoc} < 3 GeV
$\Lambda/\bar{\Lambda}$-$h^{\pm}$
$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
$\Delta\phi$
$\Delta\eta$



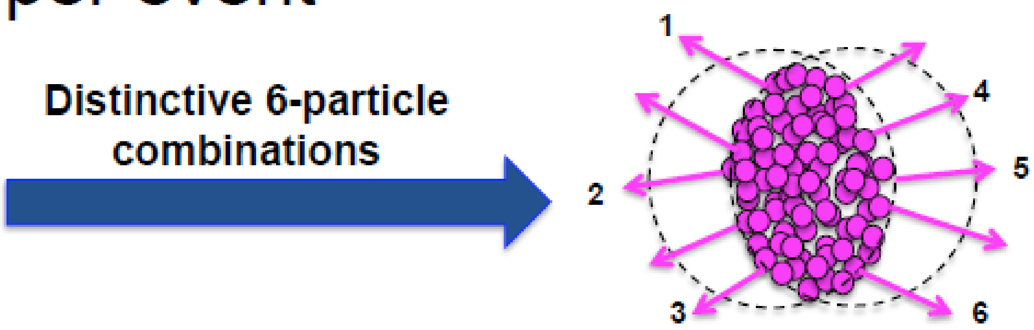
CMS Preliminary, pPb $\sqrt{s_{NN}}$ = 5.02 TeV
L_{int} = 35 nb^{-1}
1 < p_T^{trig} < 3 GeV
1 < p_T^{assoc} < 3 GeV
Long range
|Δη| > 2
$h^{\pm}$-$h^{\pm}$
220 ≤ N < 260
0 < N < 35
K_S^0-$h^{\pm}$
Fourier fits
$\Lambda/\overline{\Lambda}$-$h^{\pm}$
$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi}$-$C_{ZYAM}$
0.3
0.2
0.1
0.0
Δφ
Δφ
Δφ

Multiparticle Cumulant

- 6-particle correlator, per event

$$\langle 6 \rangle \equiv \left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)} \right\rangle$$

$$\equiv \frac{1}{P_{M,6}} \sum_{\substack{i\neq j\neq k \\ \neq l\neq m\neq n}}^{M} e^{in(\phi_i+\phi_j+\phi_k-\phi_l-\phi_m-\phi_n)}$$



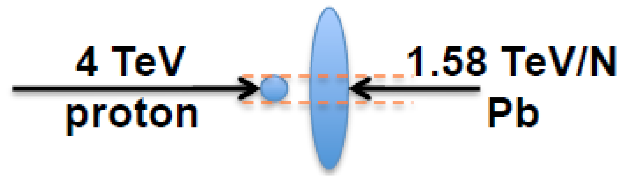
- 6-particle cumulant, all events

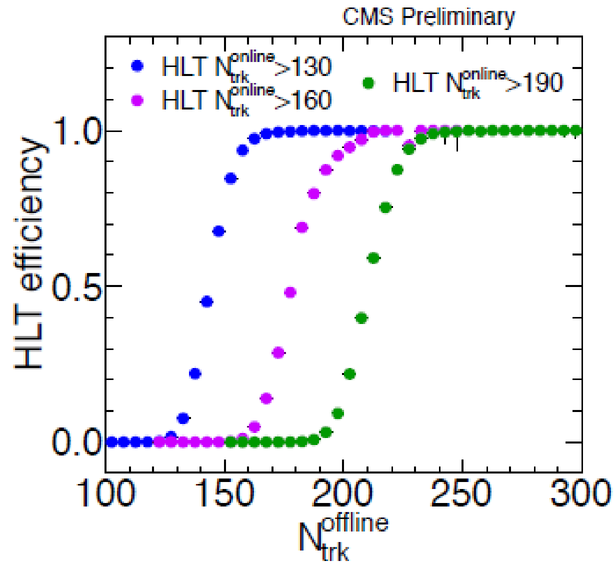
$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9 \cdot \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle + 12 \cdot \langle\langle 2 \rangle\rangle^3$$

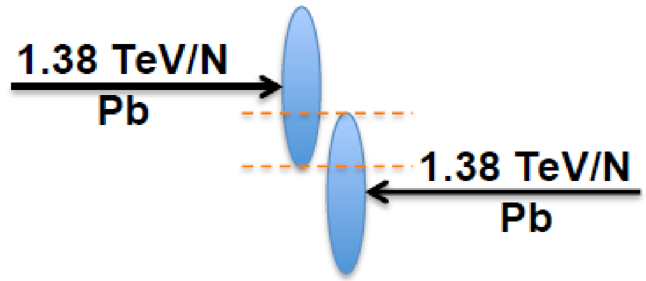
- Q-Cumulant: decompose → flow vector $Q_n \equiv \sum_{i=1}^{M} w_i e^{in\varphi_i}$

- Cumulant v_n →

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}, v_n\{6\} = \sqrt[6]{\frac{1}{4} c_n\{6\}}, v_n\{8\} = \sqrt[8]{-\frac{1}{33} c_n\{8\}}$$


4 TeV
proton
1.58 TeV/N
Pb

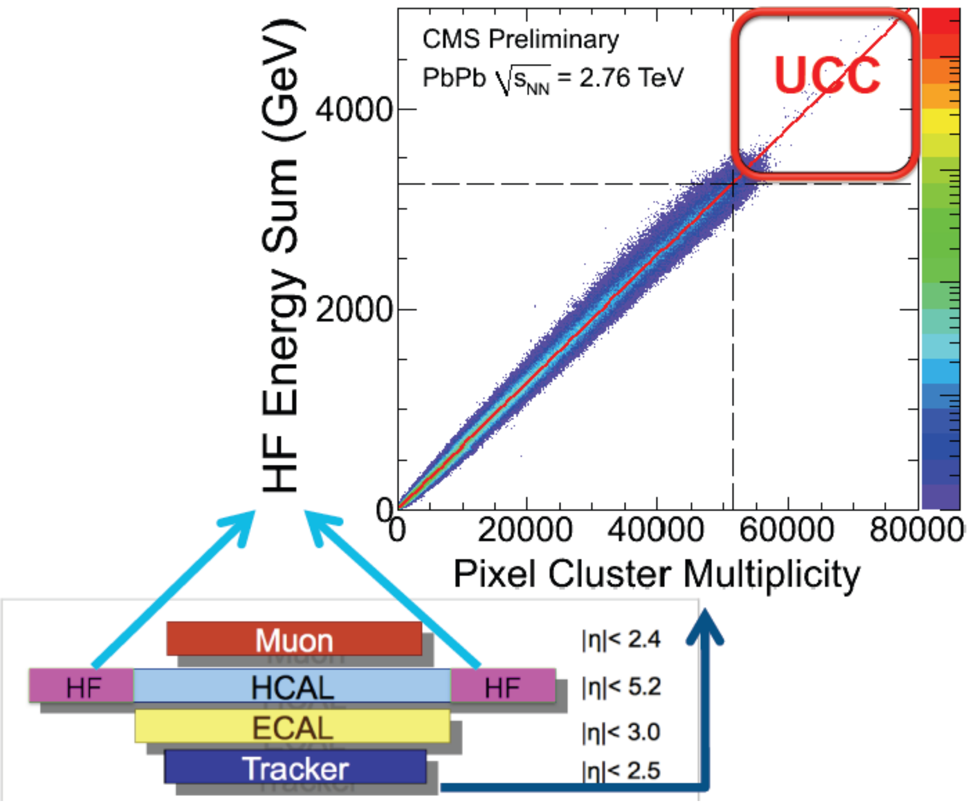

CMS Preliminary
HLT N_{trk}^{online}>130
HLT N_{trk}^{online}>160
HLT N_{trk}^{online}>190
HLT efficiency
1.0
0.5
0.0
100
150
200
250
300
$N_{trk}^{offline}$


1.38 TeV/N
Pb
1.38 TeV/N
Pb

Look at most extreme PbPb collisions

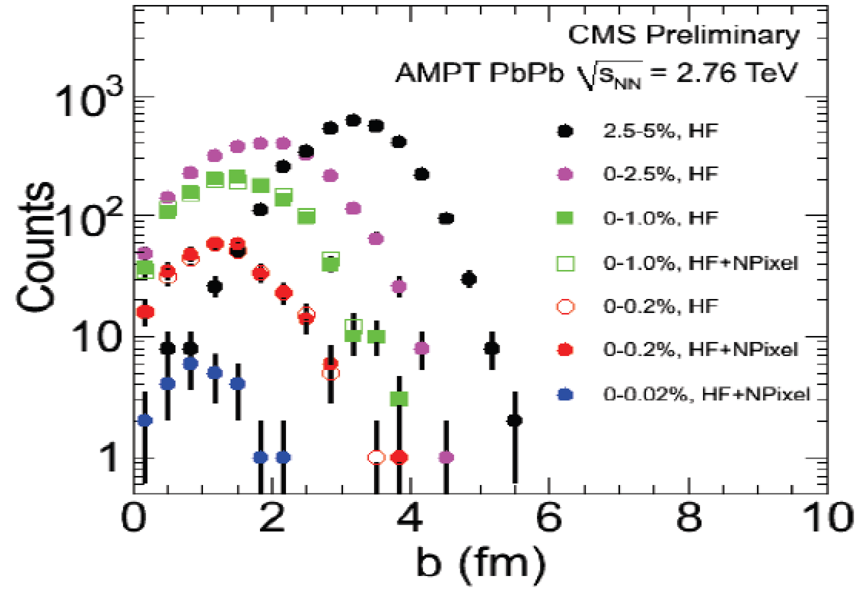
Highest energy density …

- 1.8 M 0-0.2% central events recorded



Fixes the geometry

Centralities from AMPT simulations



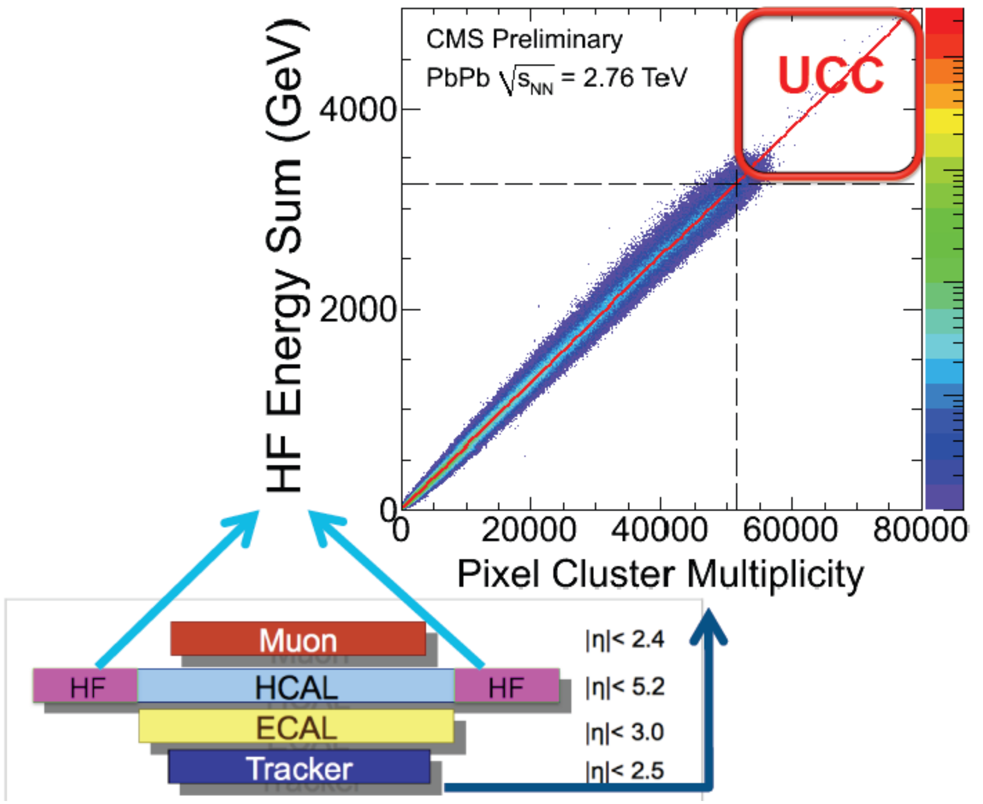
Centrality	<N_{part}>	RMS_{Npart}	<b> (fm)	RMS_b (fm)
0-0.02%	406.2	3.6	0.98	0.49
0-0.2%	404.0	6.9	1.30	0.64
0-1%	401.1	8.3	1.51	0.70
0-2.5%	395.8	11.3	1.86	0.80
2.5-5%	370.0	16.5	3.13	0.73

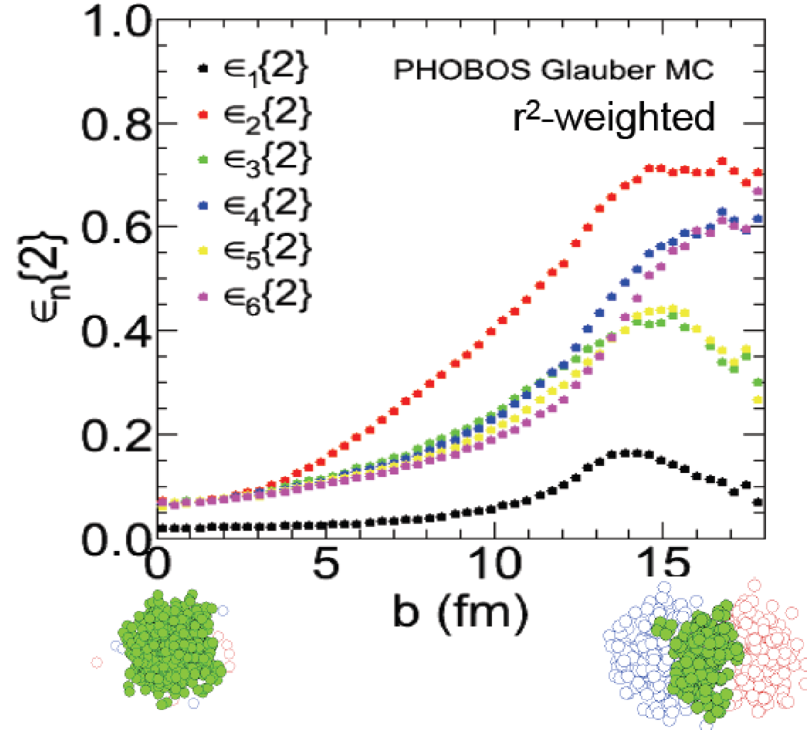
Look at most extreme PbPb collisions

Highest energy density …

Fixes the geometry

- ❑ 1.8 M 0-0.2% central events recorded





- ❑ ε_n tend to converge as b→0 in Glauber
- ❑ ε_n in various models also tend to converge as b→0 (M. Luzum)