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Study of strongly-coupled QCD matter with ATLAS detector at the LHC

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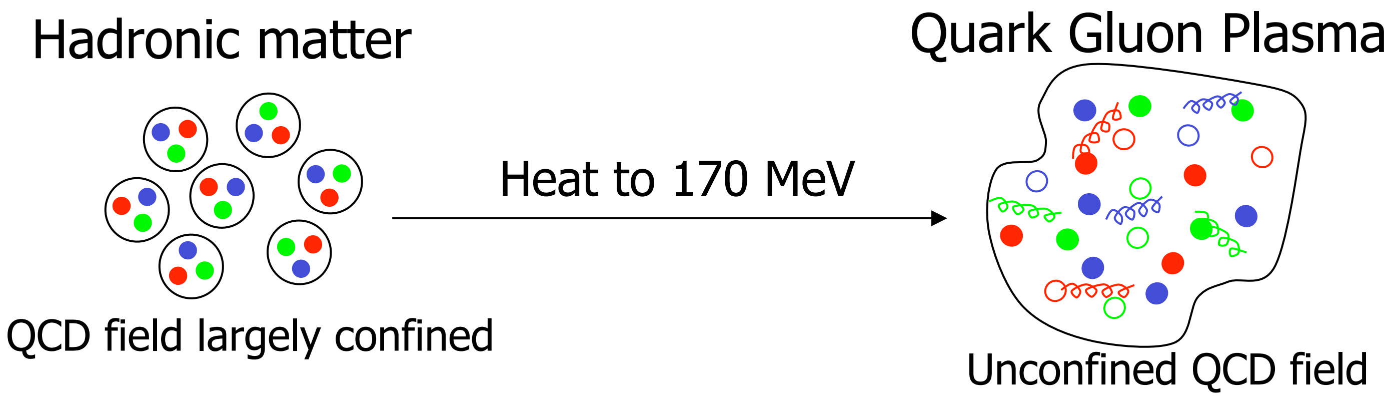
Heavy-ion physics

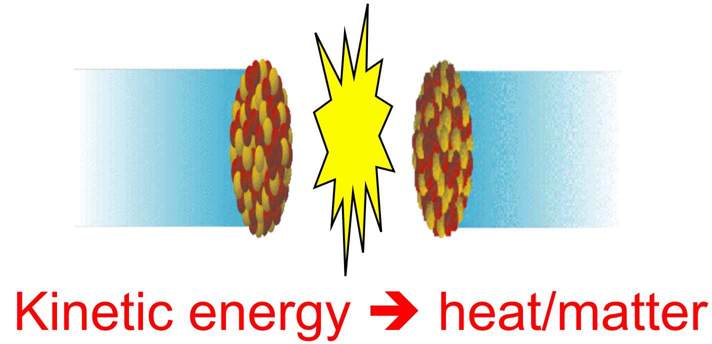
- Study of non-Abelian QCD matter
  - Consists of nucleons, hadrons, quarks or gluons
  - Occupy extended volume, has finite lifetime



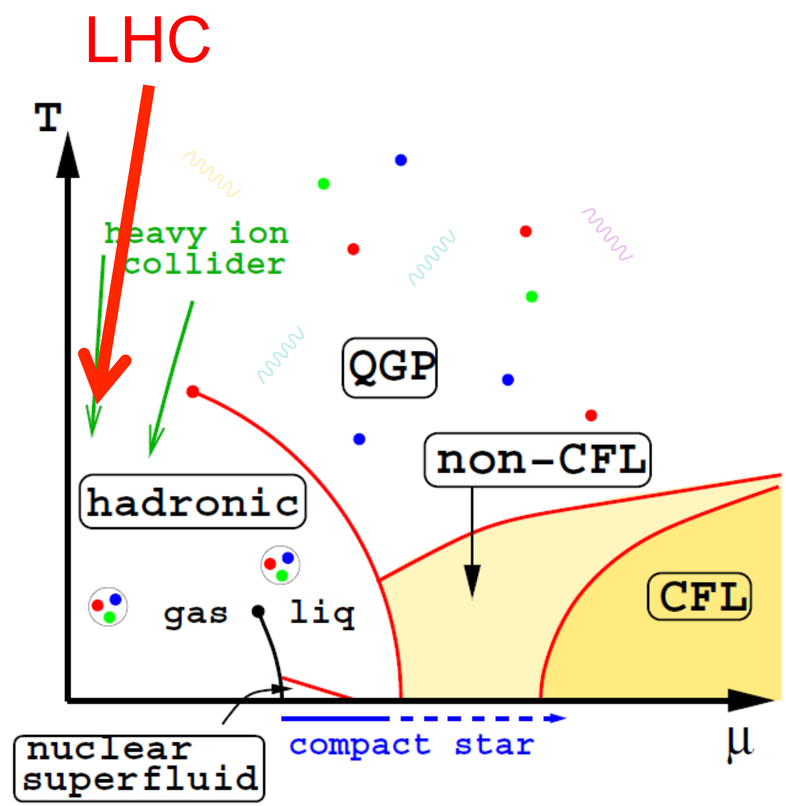
Solid state physics, but with QCD force instead of QED

Phases of QCD Matter

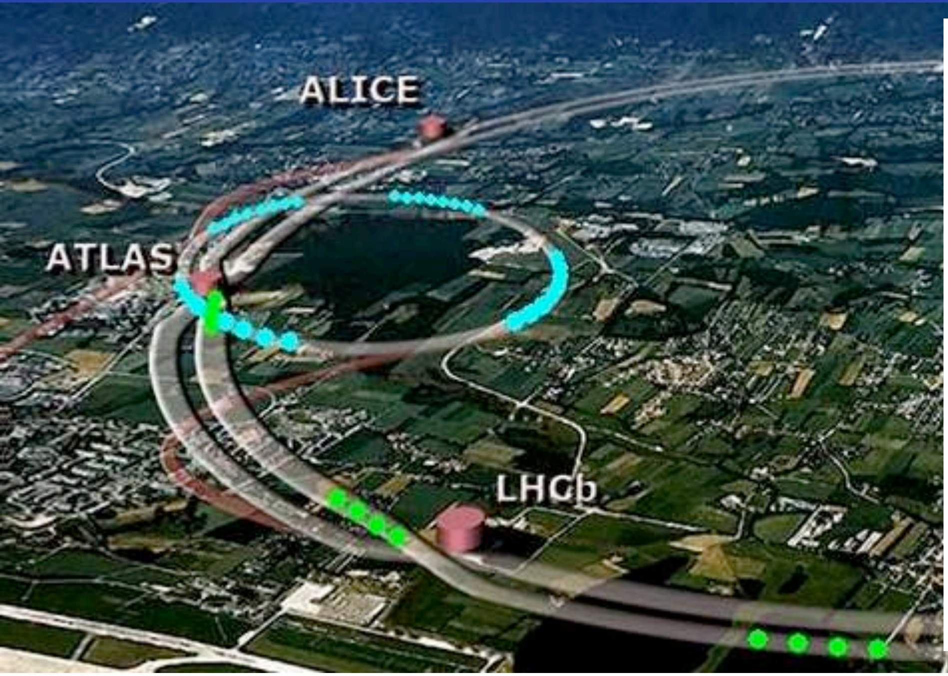
- Regions reached by varying √s
  - Matter at LHC has high T (~0.4 GeV) and low chemical potential.

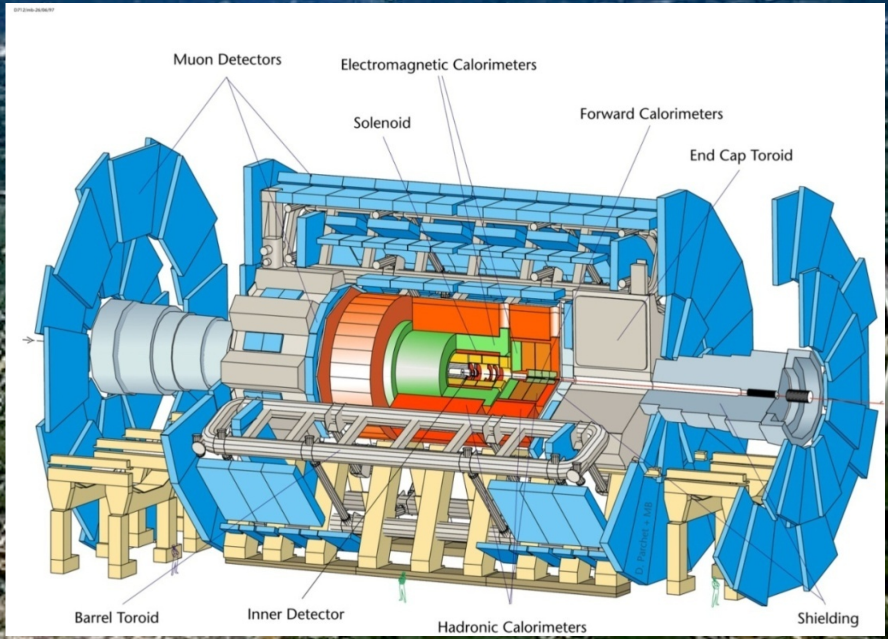


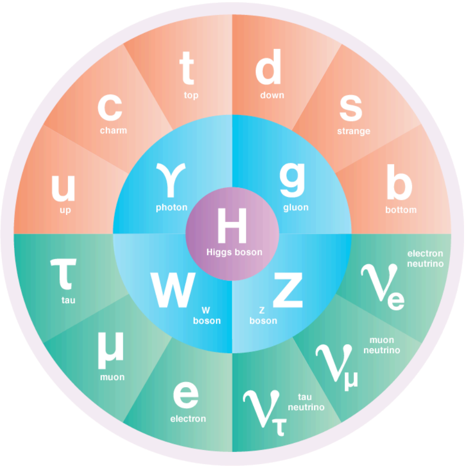
- Some big questions:
  - Confinement and Chiral symmetry restoration.
  - Phase boundaries & Phase transitions.
  - QGP equation of state & various transport properties.
  - QCD at finite T: local parity violation and polarization.
  - …



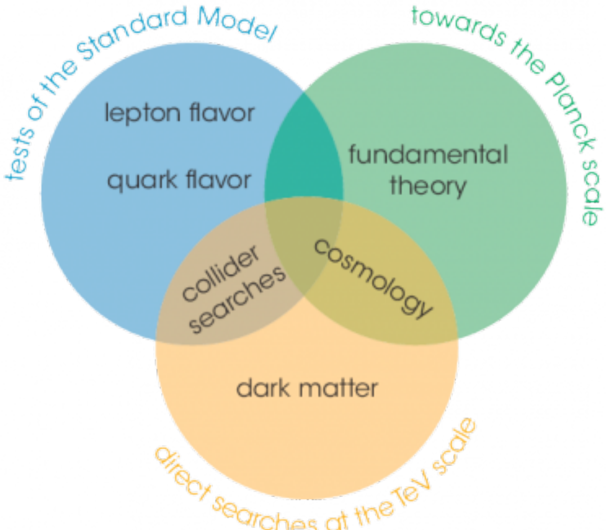
ATLAS and Large Hadron Collider





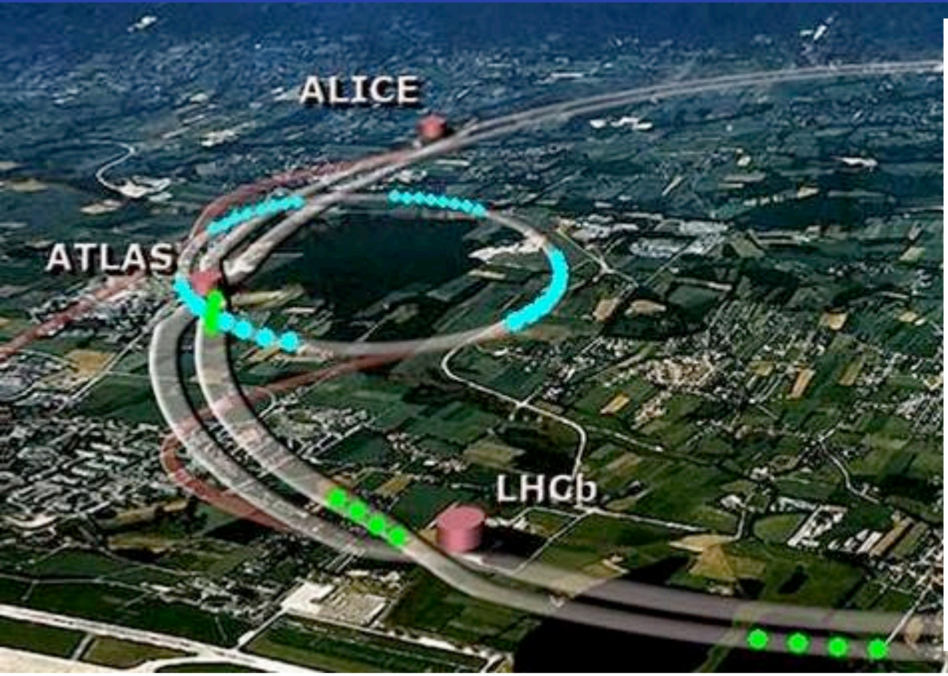


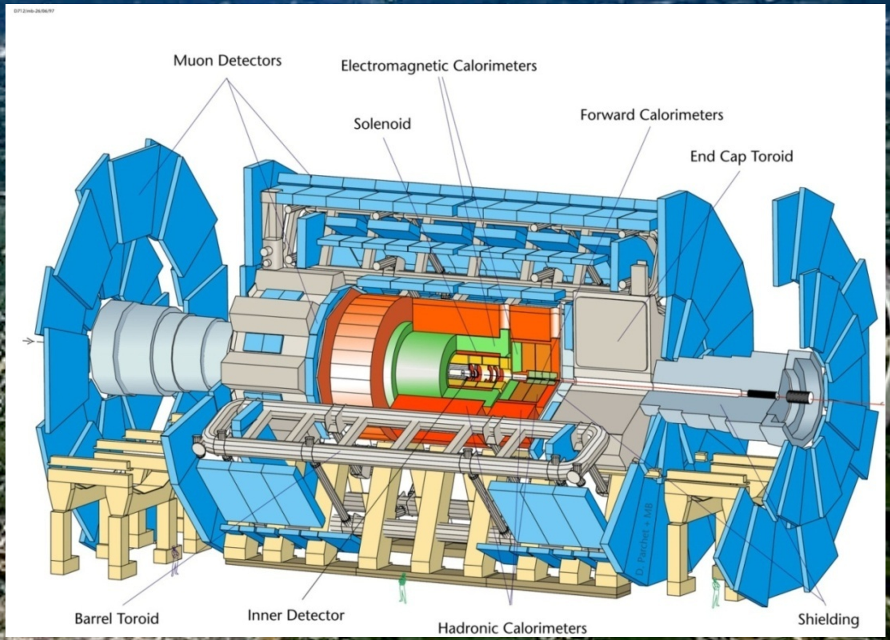
Precision standard model physics



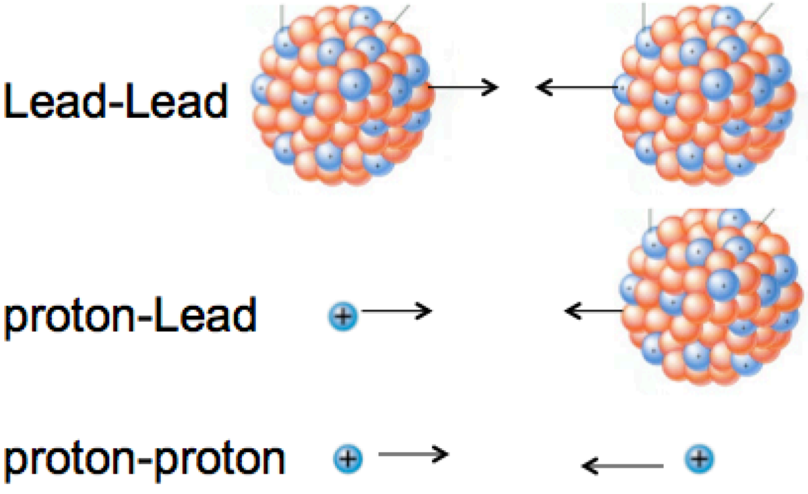
Beyond standard model physics

ATLAS and Large Hadron Collider

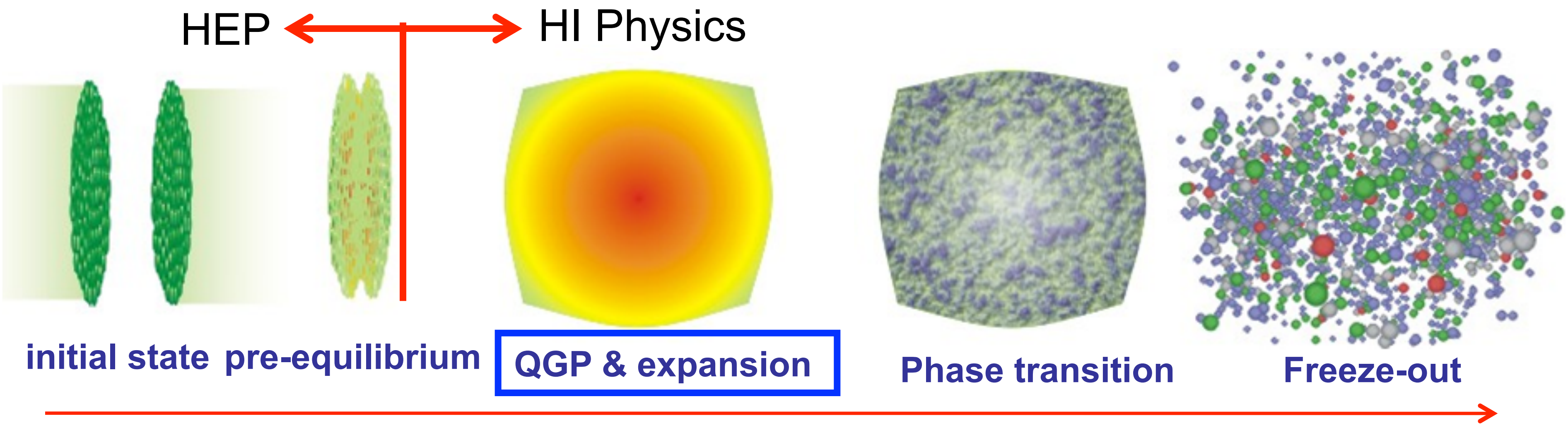


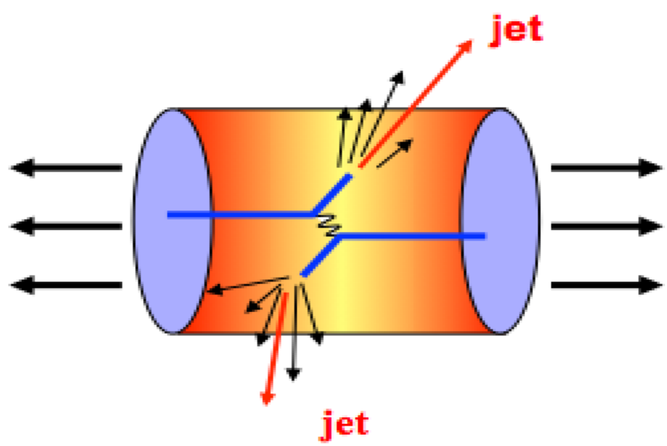


- Collide heavy-ions 1 month/year
  - Produce extended dense partonic matter, Quark-Gluon Plasma (QGP)
- Mostly lead-lead, but also proton-lead, and special proton-proton runs
  - Switching off the QGP effects.



How to study the QCD matter?

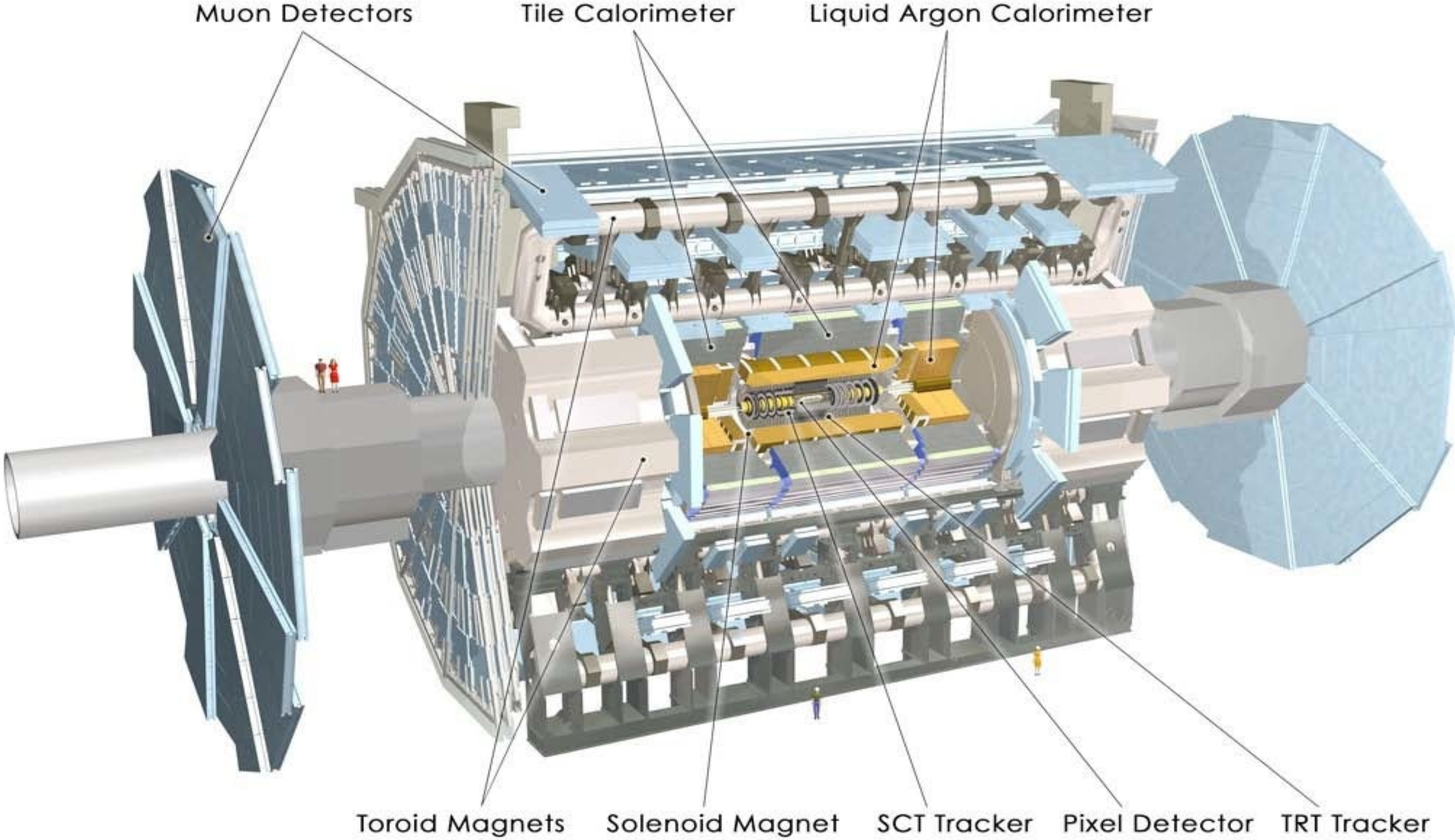




Standard model particles as hard probes of the matter

Bulk, soft particles to probe the space-time dynamics

ATLAS detector



Three main subsystems with large coverage

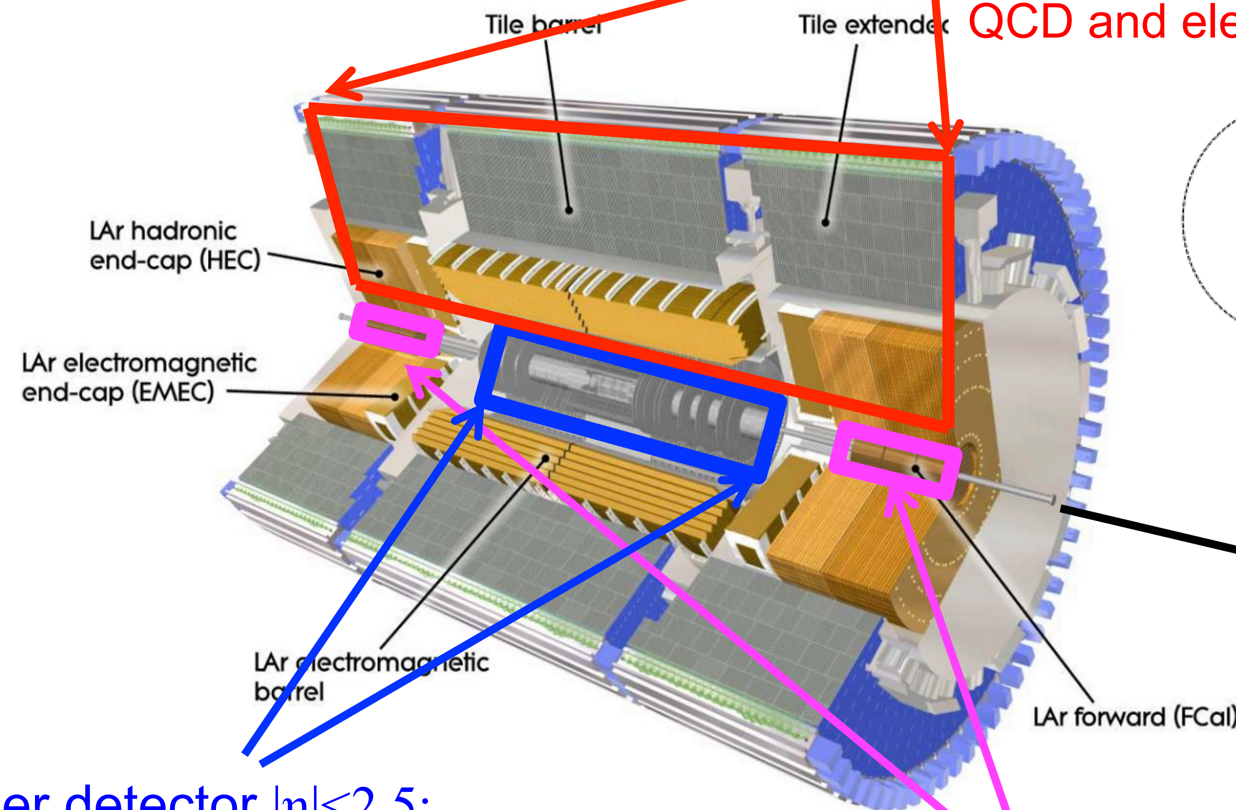
- Inner Detector – tracking $|\eta|<2.5$
- Calorimetry – $|\eta|<4.9$
- Muon Spectrometer - $|\eta|<2.7$

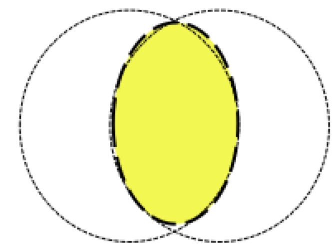
ATLAS detector

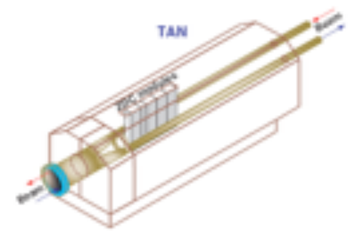
EM&HCal |η|<3.2, also MS |η|<2.7

Jets, photons, electrons + muons

QCD and electro-weak hard probes







ZDC |η|>8.3

Event shape

Inner detector |η|<2.5:

charged hadrons

bulk property the QCD matter

FCal 3.1<|η|<4.9:

Event centrality & event shape

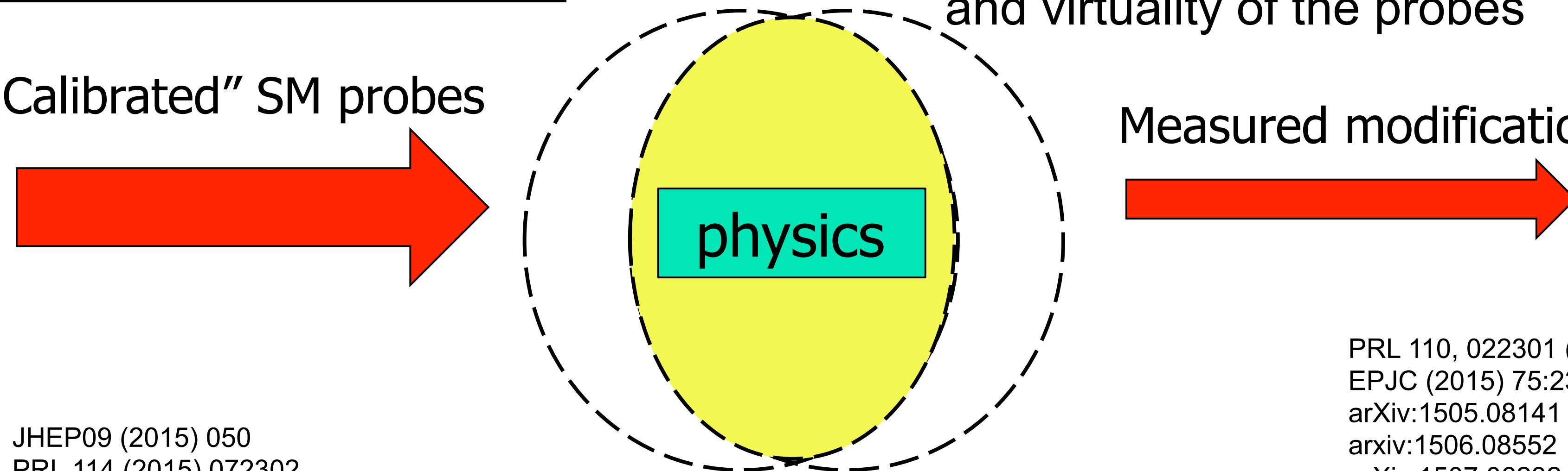
How to study the QGP with hard probes?

throw everything at it !

Varying the energy, color, mass and virtuality of the probes

"Calibrated" SM probes

Measured modifications



JHEP09 (2015) 050
PRL 114 (2015) 072302
PLB739(2014)320
ATLAS-CONF-2015-055

PRL105(2010) 252303
arxiv:1506.08656
ATLAS-CONF-2015-052

PRL111,152301(2013)
ATLAS-CONF-2015-021

PRL 110, 022301 (2013)
EPJC (2015) 75:23
arXiv:1505.08141
arxiv:1506.08552
arXiv:1507.06232
ATLAS-CONF-2015-053
ATLAS-CONF-2015-056

Leading particle

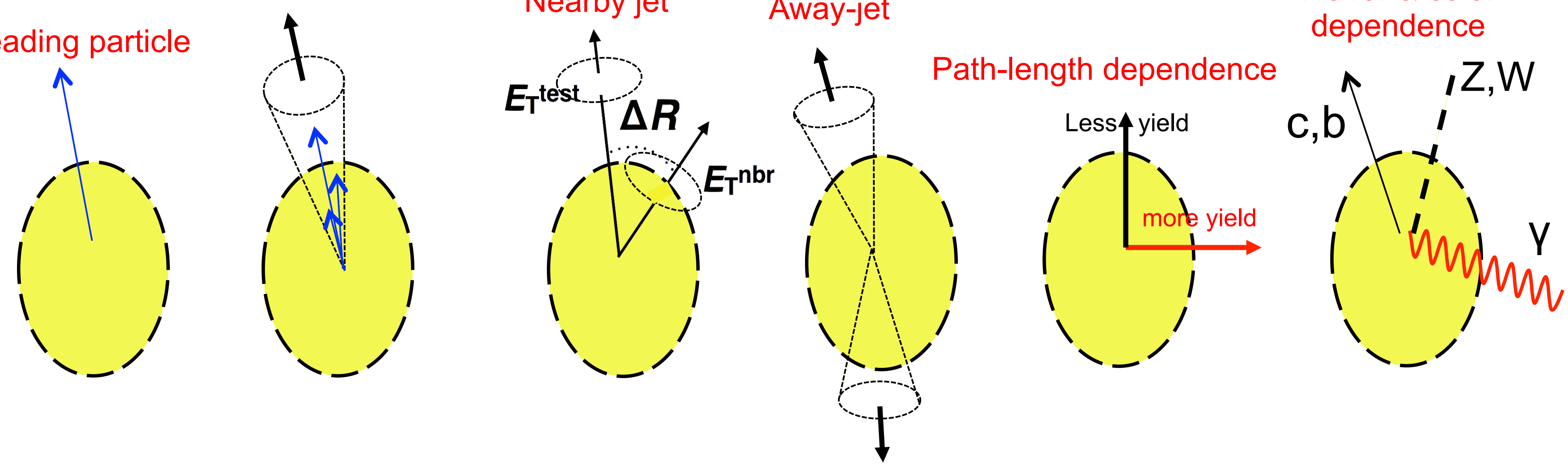
Jet & jet sub-structure

Nearby jet

Away-jet

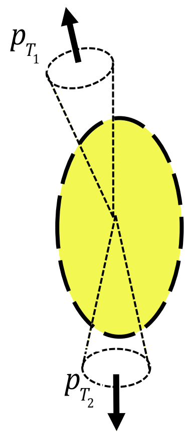
Path-length dependence

Flavor & color dependence

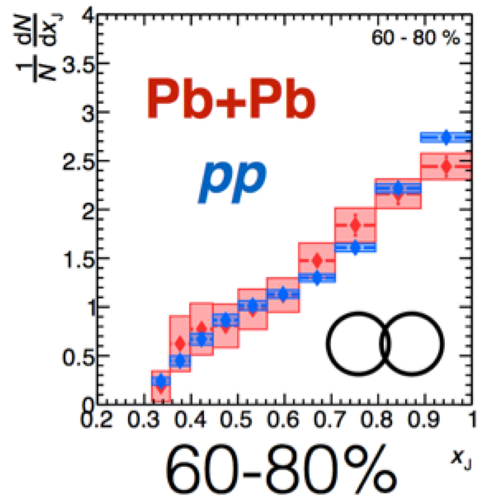


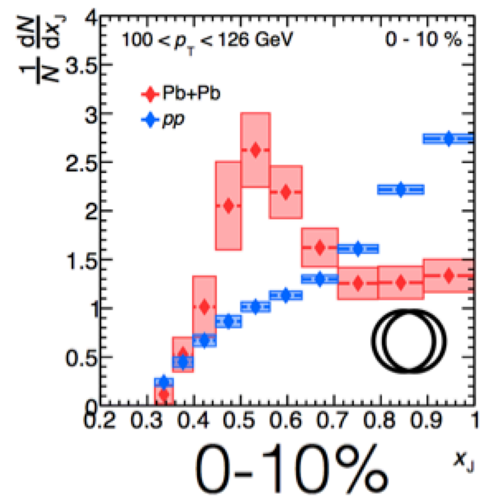
Highlight: Jet quenching

- Strong energy imbalance observed for the back-to-back dijets
  - Quarks, gluons suffer significant energy loss traversing medium



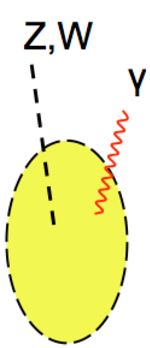
$$x_j = \frac{p_{T_2}}{p_{T_1}}$$

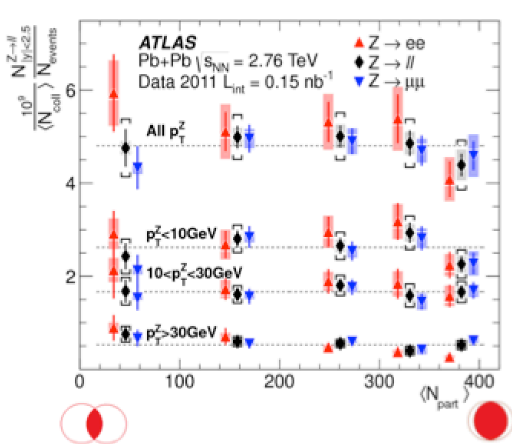




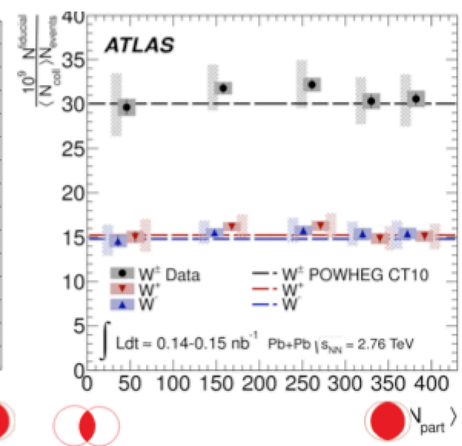
- No modification observed for electro-weak probes

Rates agree with geometry-scaled pp data or pQCD calculation

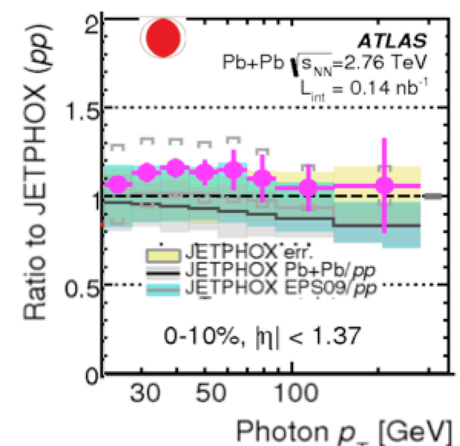




PRL 110, 022301 (2013)



EPJC (2015) 75:23



arxiv:1506.08552

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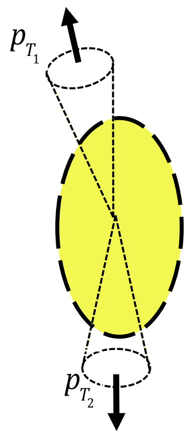

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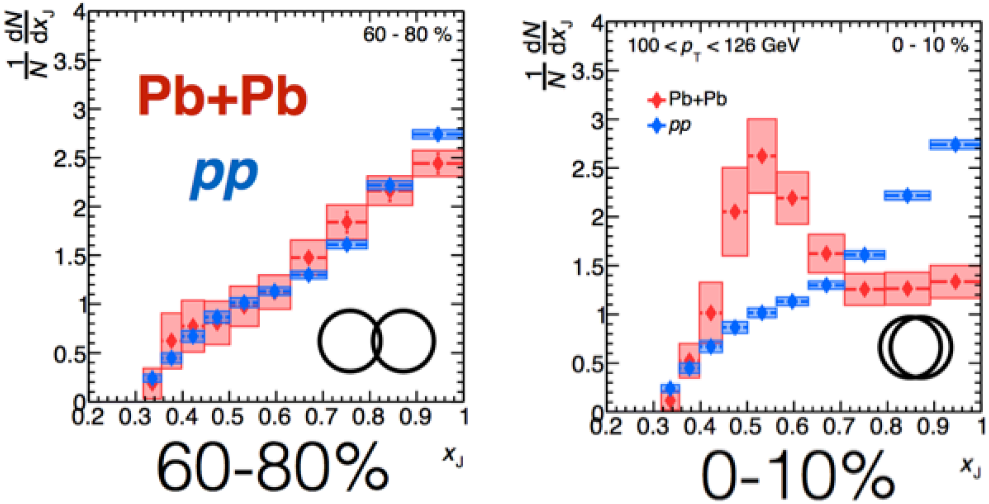
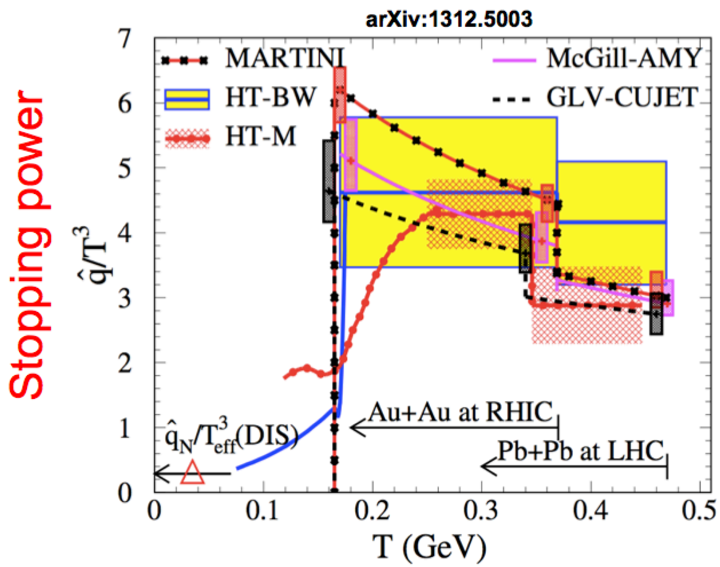


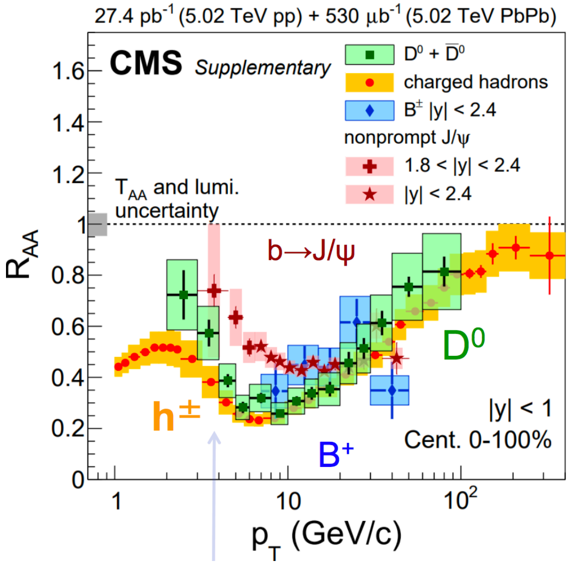
- Constrain QGP stopping power via theory/data comparison



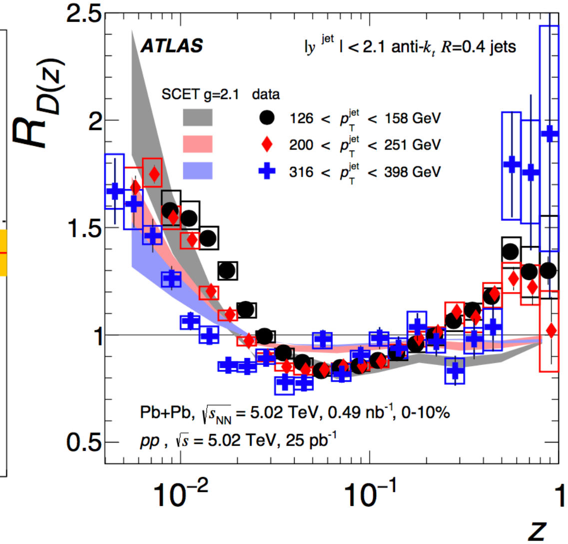
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \text{ at } \begin{matrix} T = 370 \text{ MeV, RHIC} \\ T = 470 \text{ MeV, LHC} \end{matrix}$$

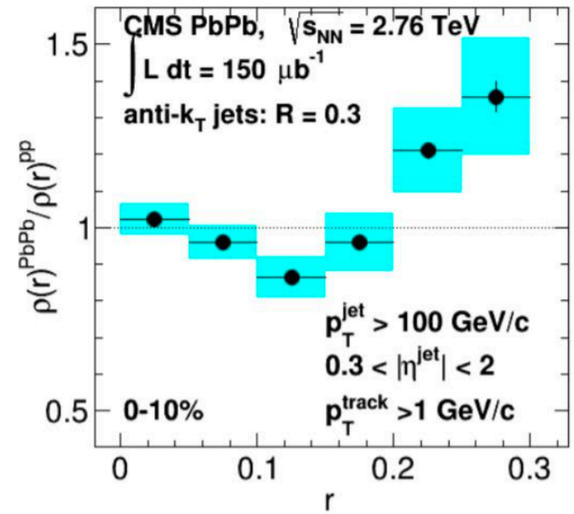
Very rich jet quenching physics

Flavor dependence



Modification of jet fragmentations

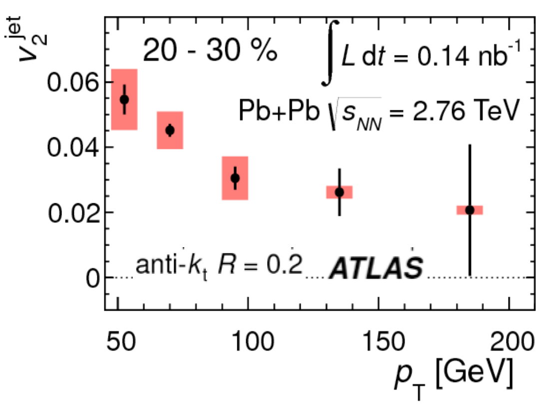


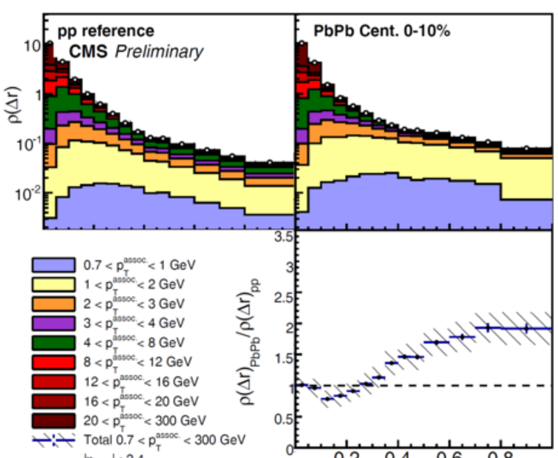


Jet sub-structure & grooming

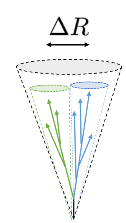
Away-side momentum balance

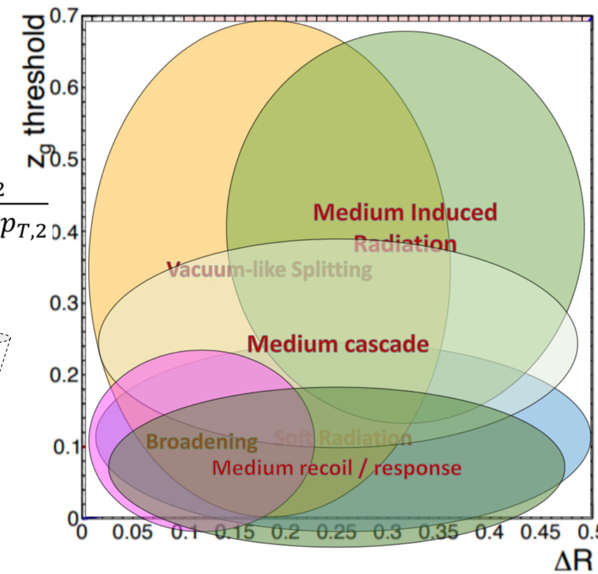
path-length dependence





$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

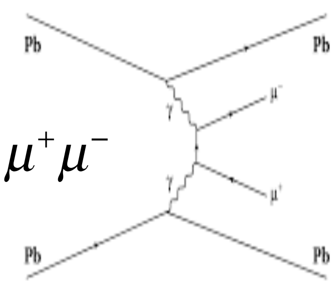


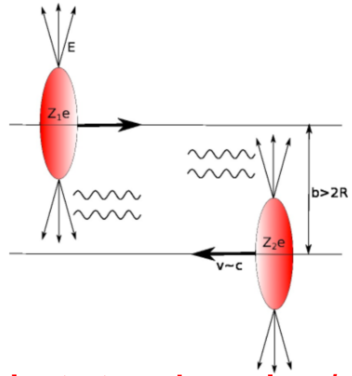


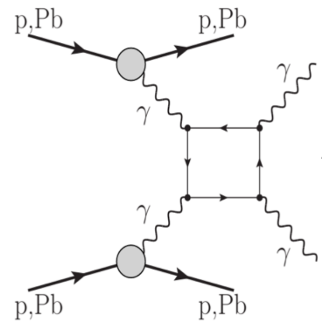
Highlight: PbPb collisions as γ+γ factory

- Coherent production σ enhanced by $Z^4 \sim 4.5\times10^7$ relative to pp

$\gamma\gamma \rightarrow \mu^+\mu^-$



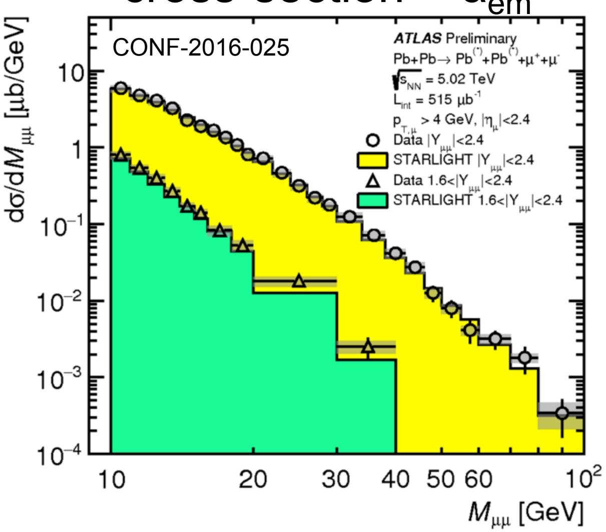




$\gamma\gamma \rightarrow \gamma\gamma$

Require simple final state signal w/o any other event activity

cross-section ~ α_{em}^2



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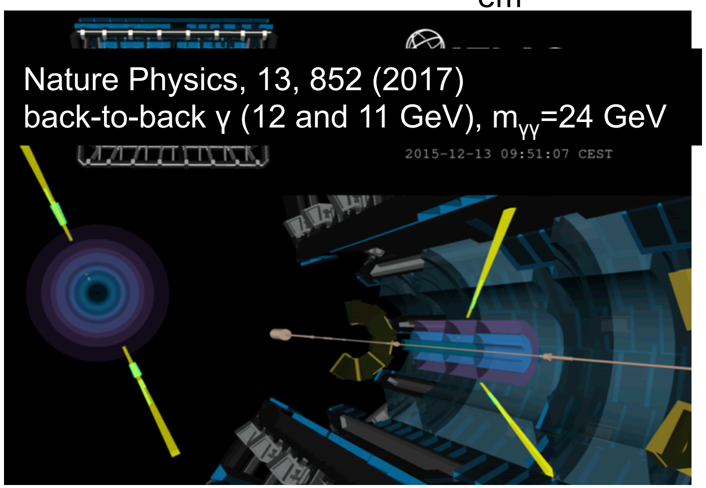


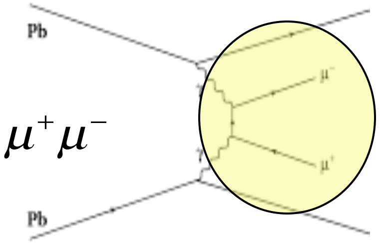
Well described by LO QED (StarLight)
Photon flux well calibrated

13 events observed, significance: **4.4σ** (3.8σ expected)

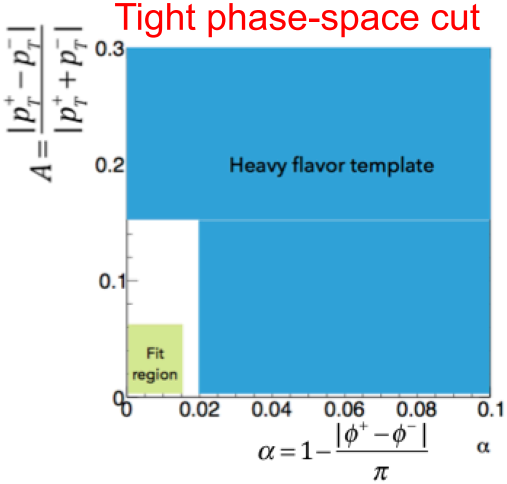
Highlight: γγ→μμ as probe of QGP?

- Tight alignment of γγ→μμ pairs allow detection in inelastic AA collisions.
  - Small heavy flavor bg subtracted statistically
  - Other bg flat over measured range.

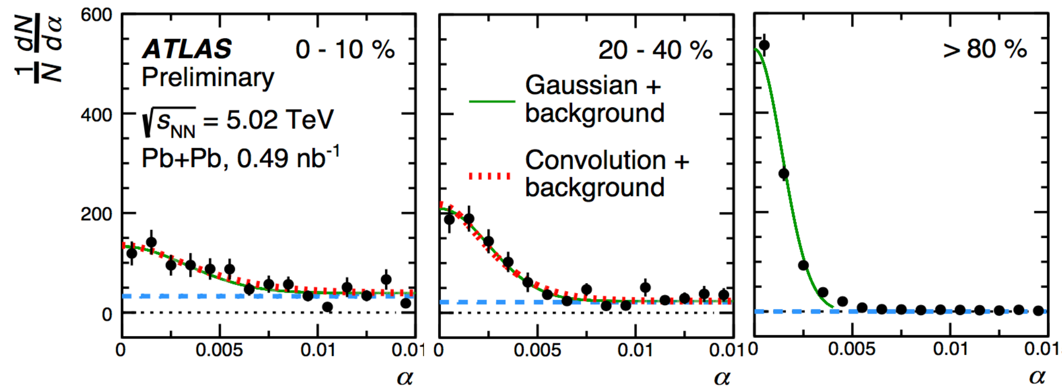
$\gamma\gamma \to \mu^+\mu^-$



Tight phase-space cut

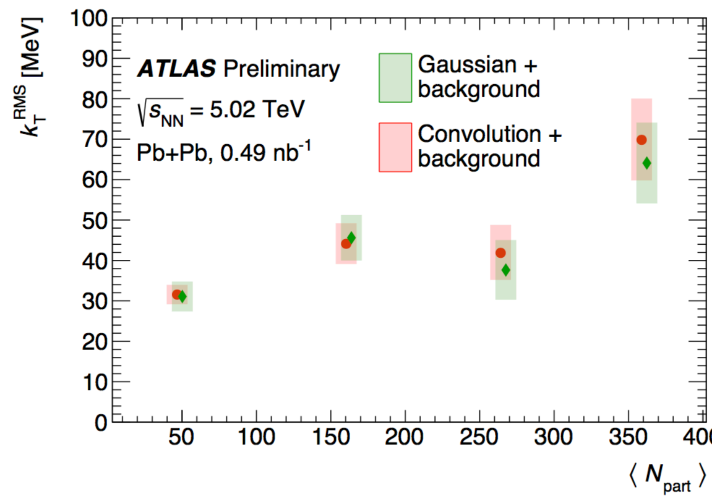


Significant centrality dependent broadening observed



- Gaussian fits to extract k_T broadening
  - From 30-70MeV

$$\langle\alpha^2\rangle = \langle\alpha^2\rangle_0 + \frac{1}{\pi^2}\frac{\left\langle \vec{k}_T^2 \right\rangle}{\left\langle p_{T\,avg}^2 \right\rangle}$$



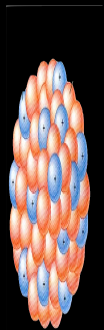
Are we probing the QGP with muons?

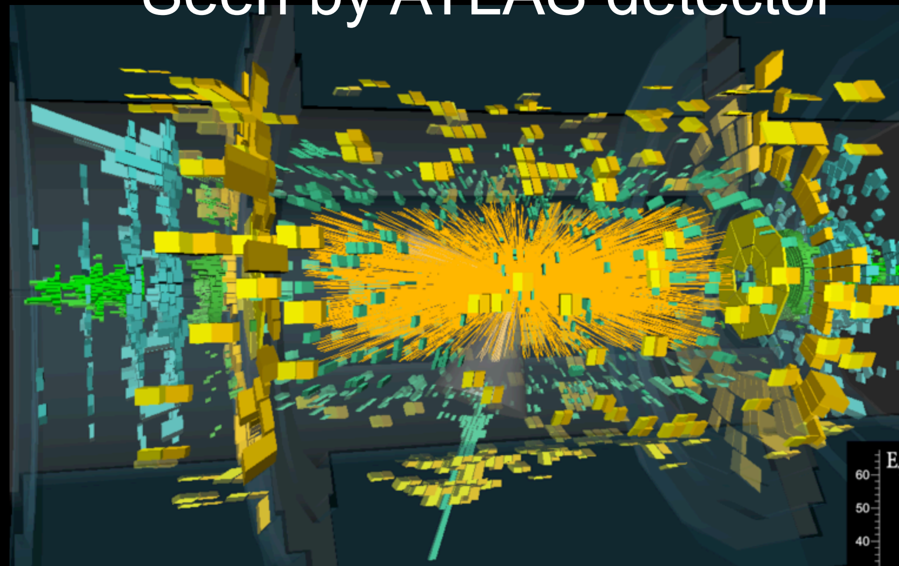
Study the QGP with bulk, soft particles

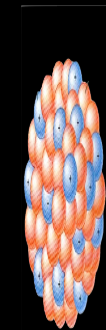
focus of our efforts since 2010

Seen by ATLAS detector

$t \sim 10^{-8}$ s

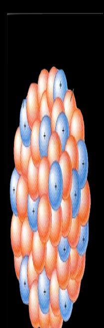


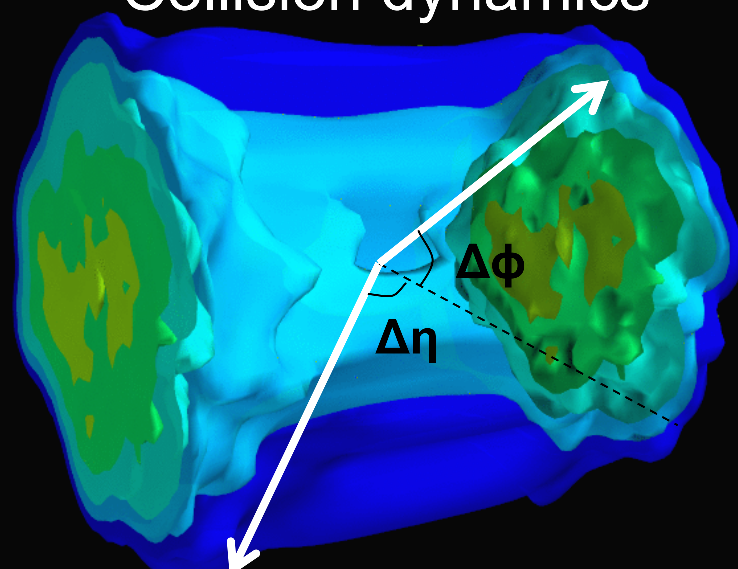


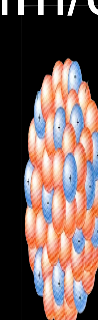


Collision dynamics

$t \sim 10 fm/c = 10^{-22}$ s



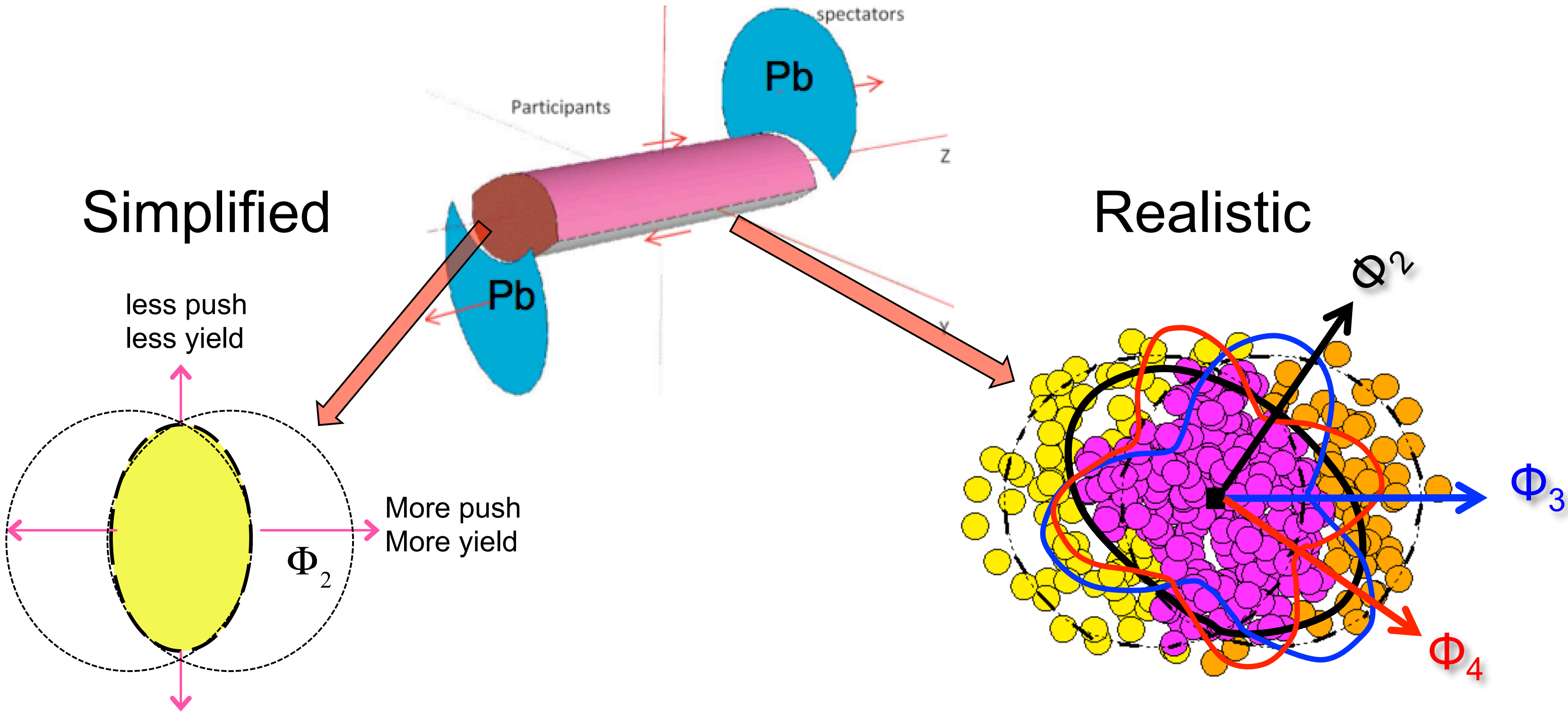




Model by 3D relativistic viscous hydrodynamics

Credit: Bjoern Schenke

Transverse collective flow



$$\frac{dN}{d\phi} \propto 1 + 2\mathrm{v}_2 \cos 2(\phi - \Phi_2)$$

Elliptic flow

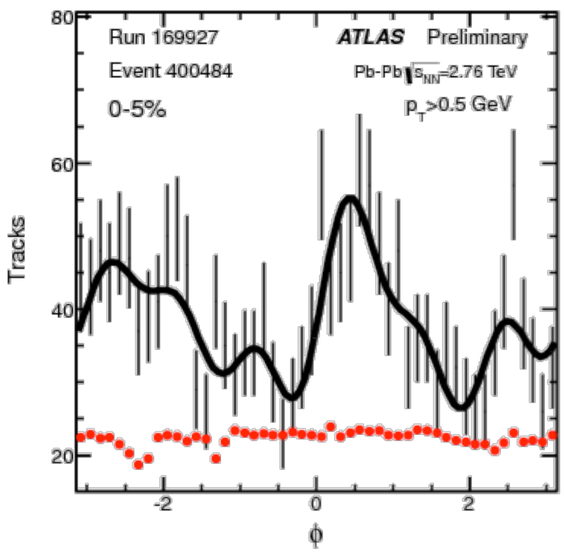
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n \mathrm{v}_n \cos n(\phi - \Phi_n)$$

+directed flow, triangular flow+..

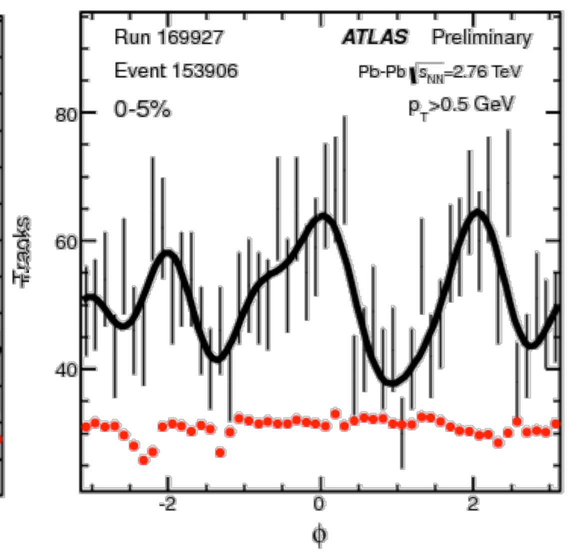
Hydrodynamic fluid behavior

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n \mathrm{v}_n \cos n\left(\phi - \Phi_n\right)$$

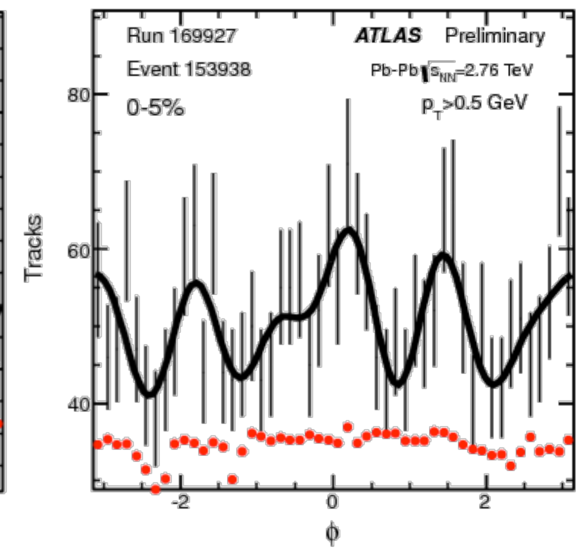
Event 1



Event 2



Event 3

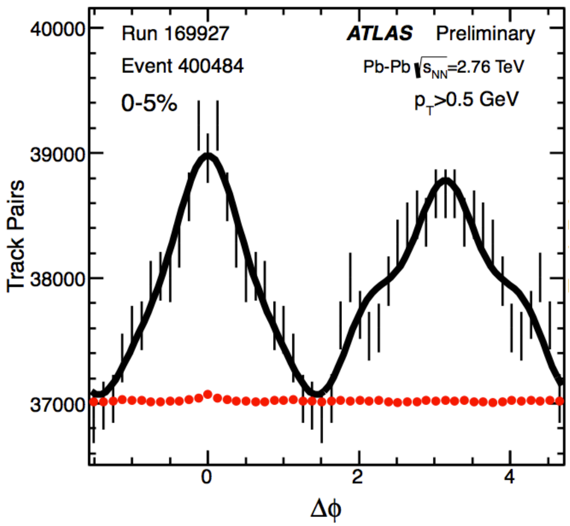


- v_n sensitive to initial perturbation and viscosity (η/s).
  - Bigger initial fluctuation lead to bigger v_n
  - Small viscosity ensure efficient transfer of initial fluctuation to final state flow.

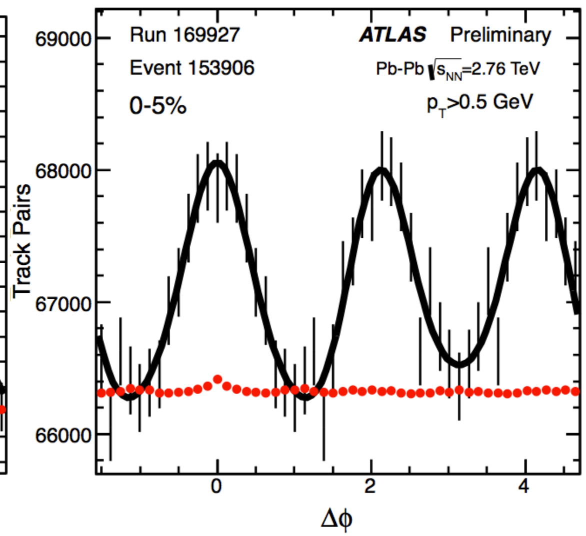
Pair distributions in same events

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n} v_n^a v_n^b \cos(n\Delta\phi)$$

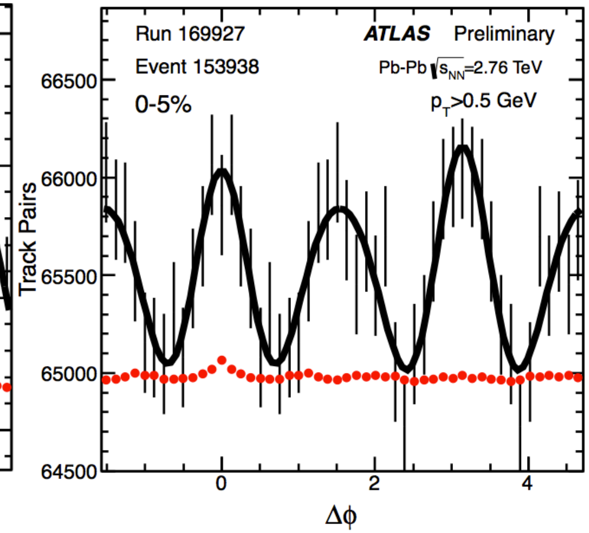
Event 1



Event 2



Event 3



- v_n sensitive to initial perturbation and viscosity (η).
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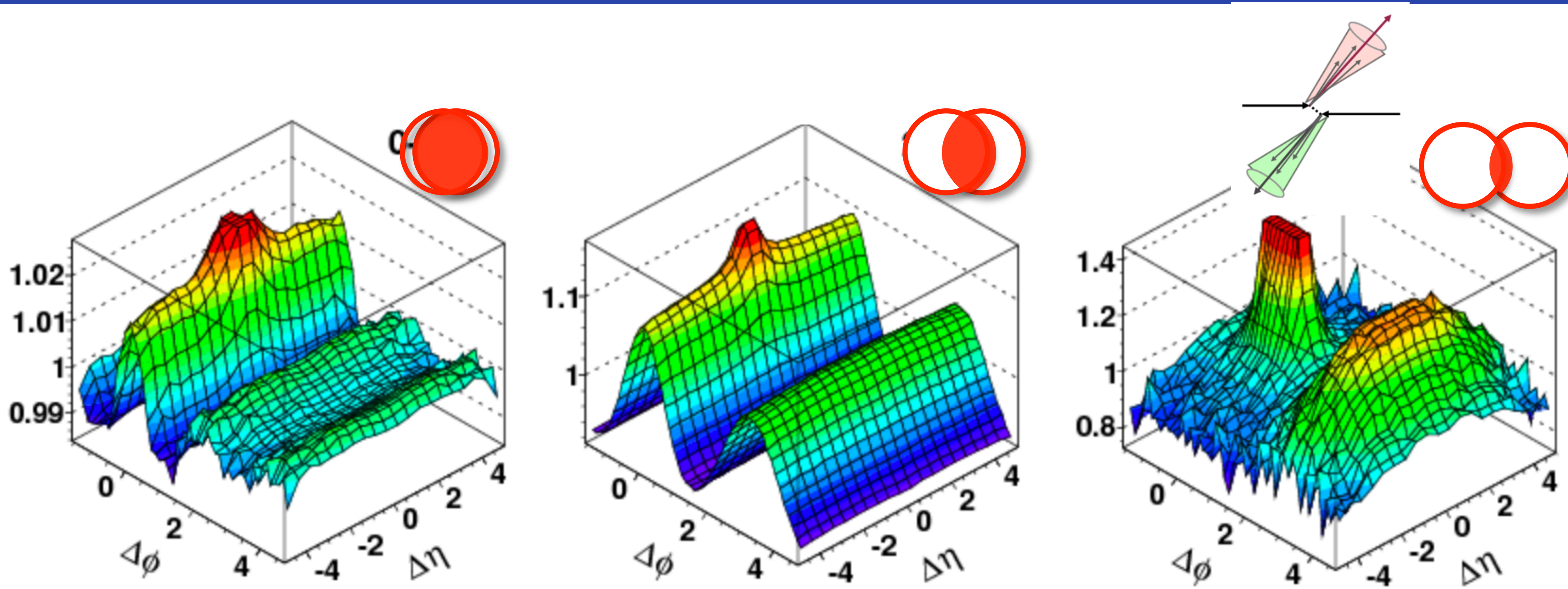
Pair distributions in Δϕ and Δη

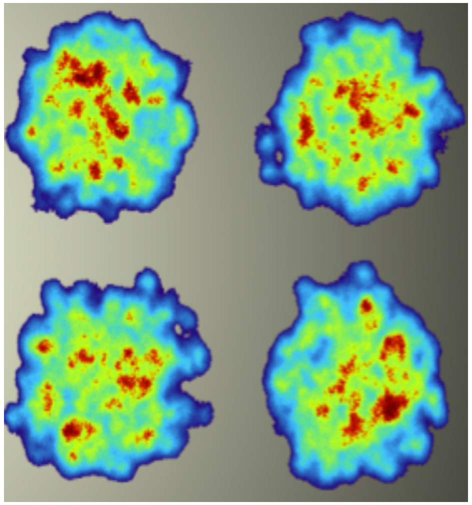


Peripheral results dominated by pairs from dijets fragmentation

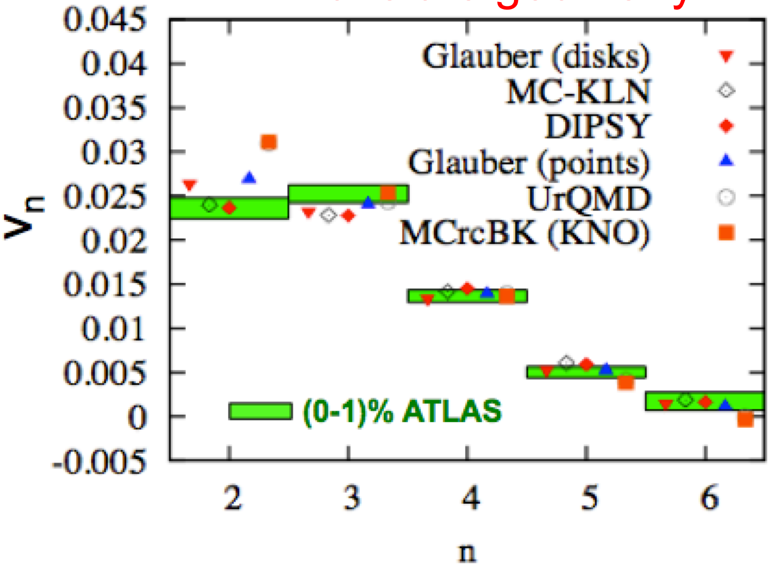
- Δϕ shape extended over wide Δη, the so-called "ridge"
  - Δη=5 means the particles from 10° and 170°, must arise from early time

Collective flow fluctuations

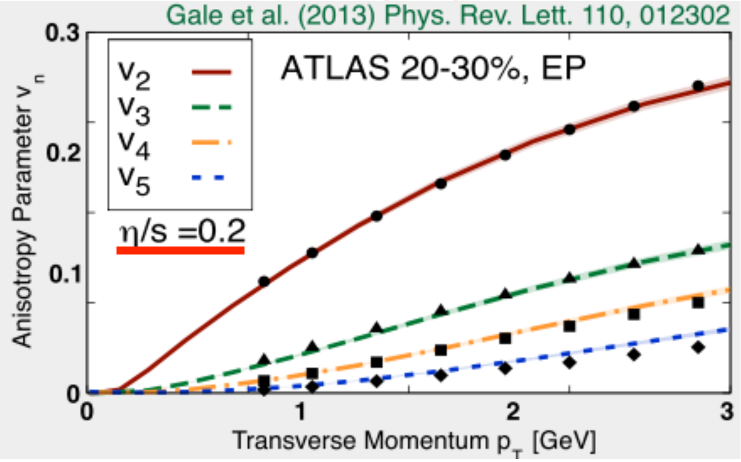
Event-averaged quantities (2010-2013)



Initial state geometry



Matter properties

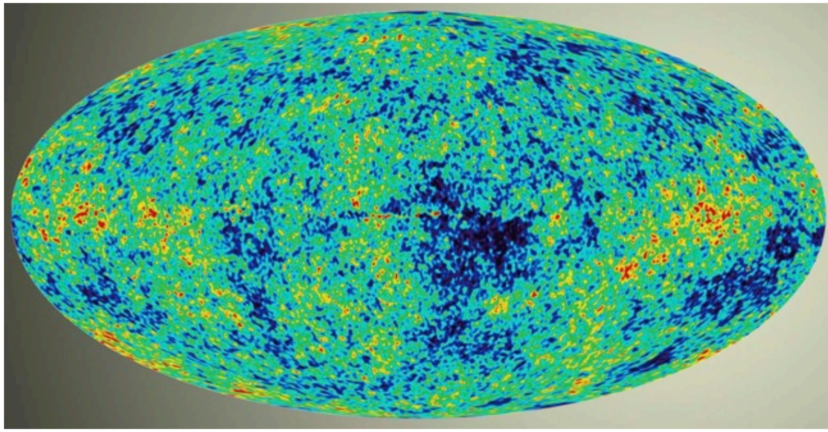


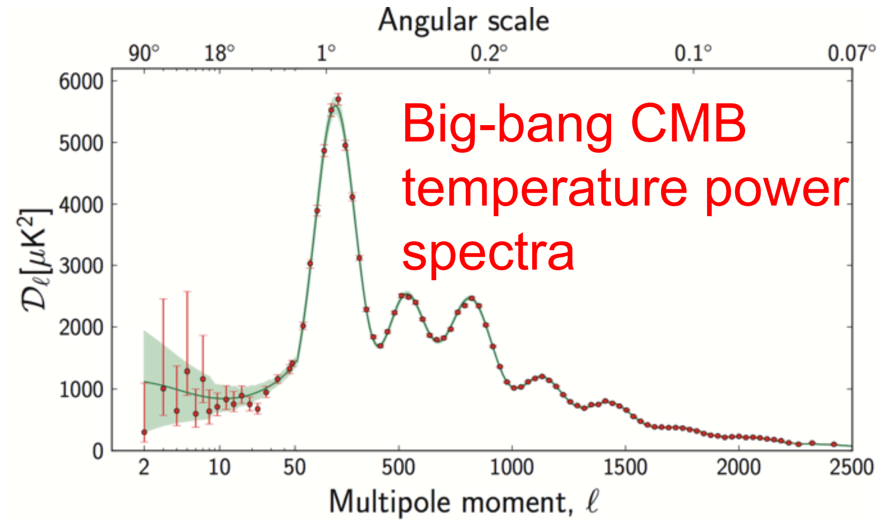
ATLAS data: PRC86,014907(2012)

Constrain initial geometry and shear viscosity via hydrodynamic model

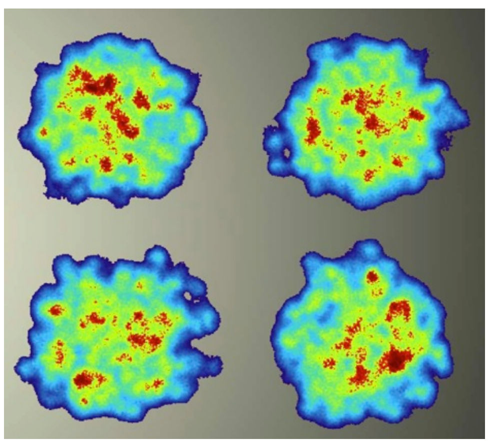
Analogy to the big-bang

One big-bang event

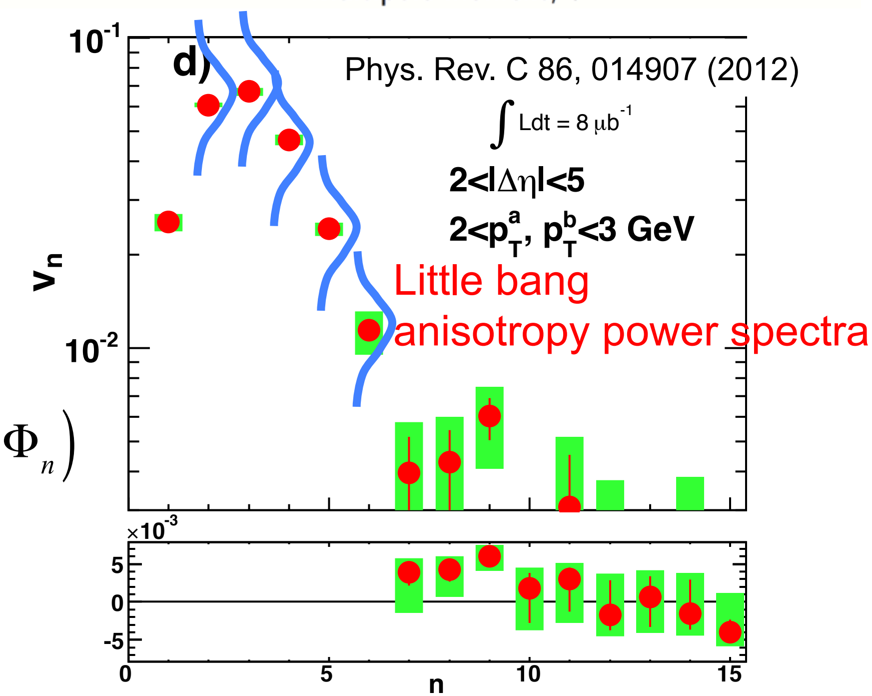




Many little-bang events



$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

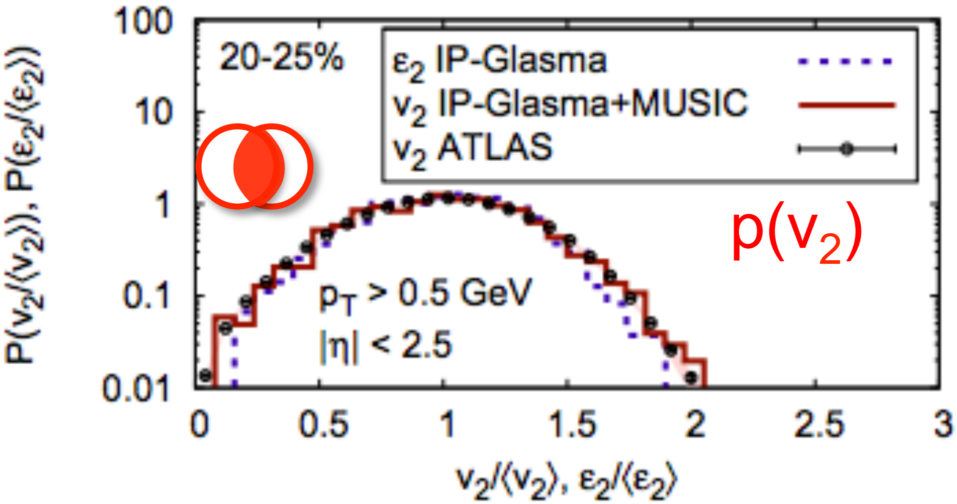


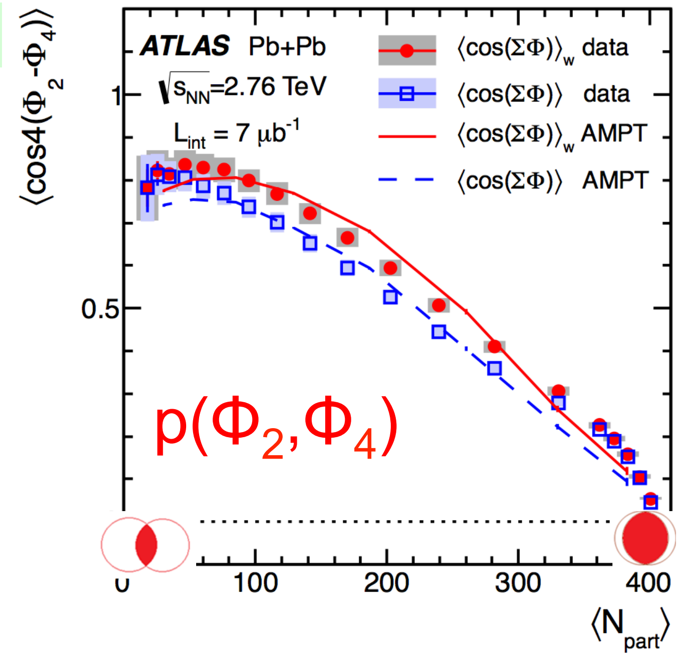
New observables (2013-2015):

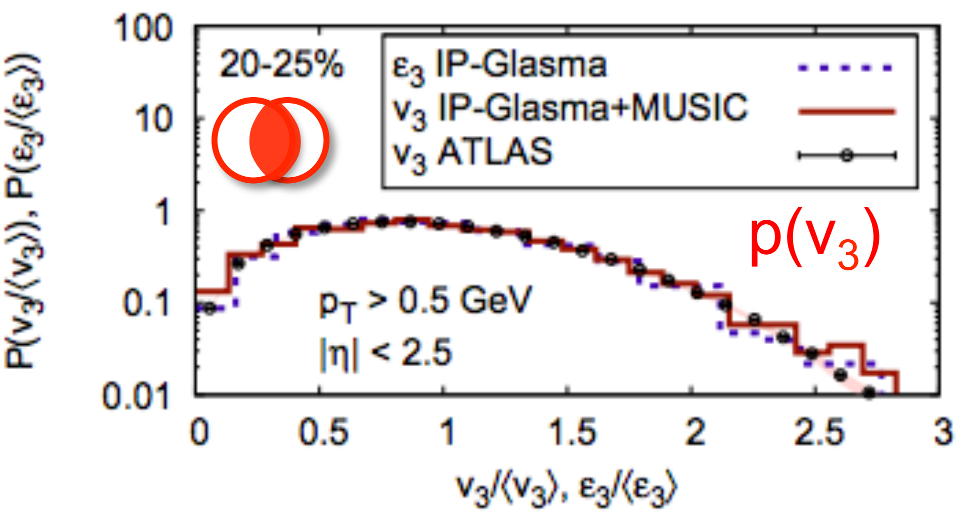
Probability distribution: $p(v_n, v_m, \ldots, \Phi_n, \Phi_m \ldots)$

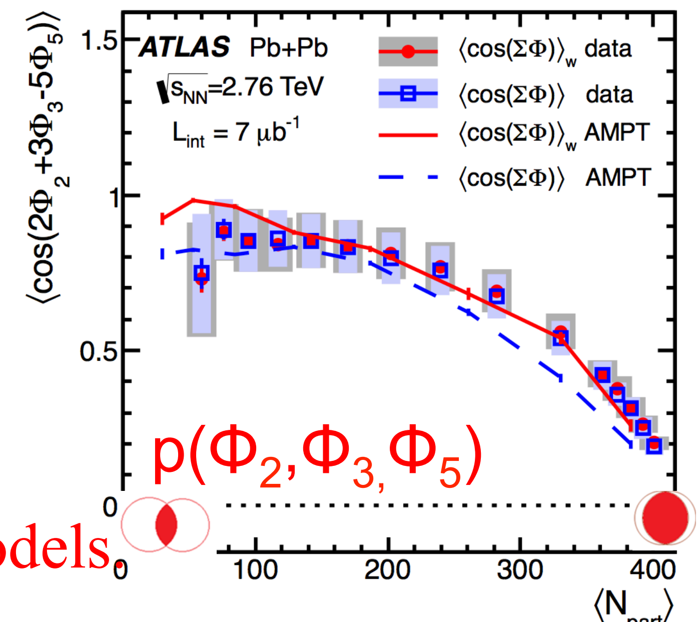
Results on event-by-event fluctuations

JHEP11(2013)183, PRC90,024905 (2014), PRC92,034903(2015)



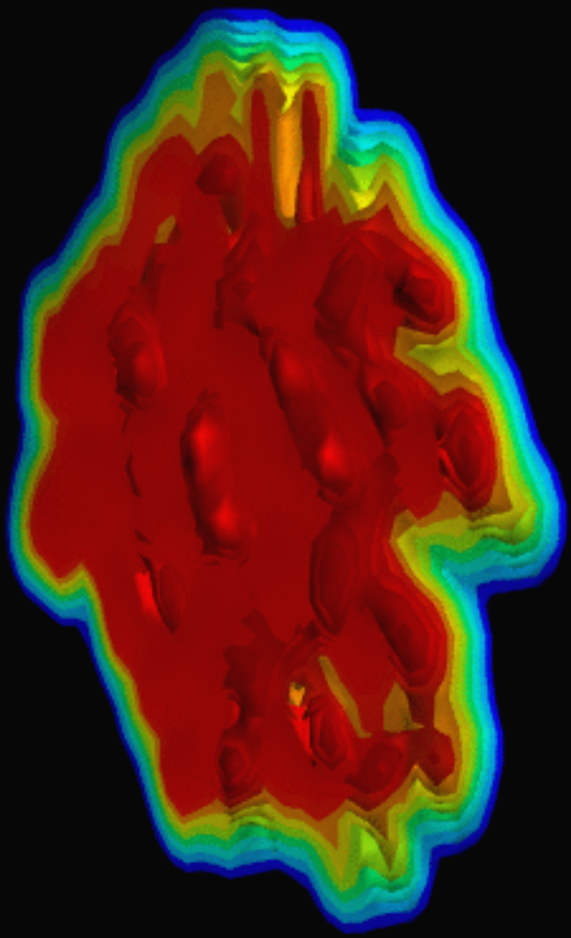






Measurements improve hydrodynamic models.

Dynamics in longitudinal direction

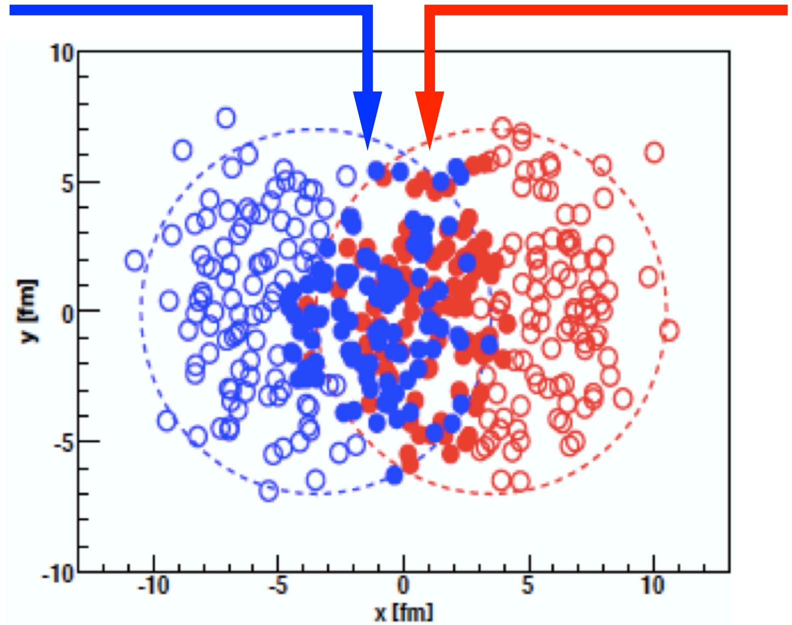


Credit: Bjoern Schenke

Dynamics in longitudinal direction

Fluctuation of sources in two nuclei → fluc. of size and transverse-shape

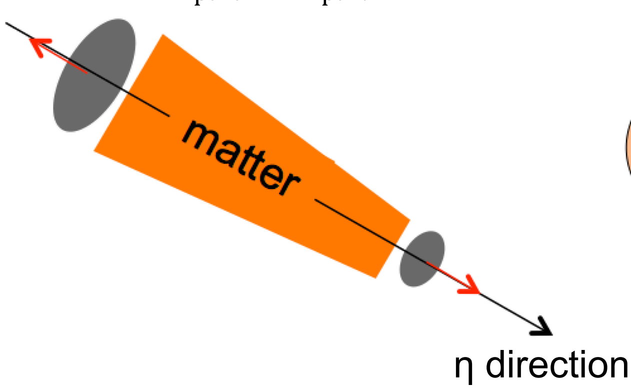
$N^{\mathrm{F}}_{\mathrm{part}}$ v^{F}_{n}, Ψ^{F}_{n}



$N^{\mathrm{B}}_{\mathrm{part}}$ v^{B}_{n}, Ψ^{B}_{n}

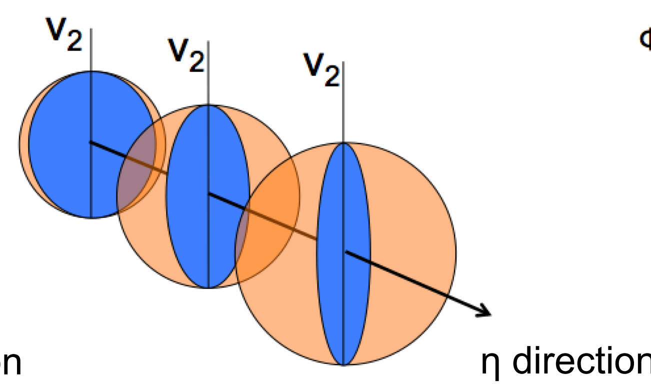
$$\boldsymbol{v}_n = v_n e^{in\Psi_n}$$

(a) $N^{\mathrm{F}}_{\mathrm{part}} \neq N^{\mathrm{B}}_{\mathrm{part}}$



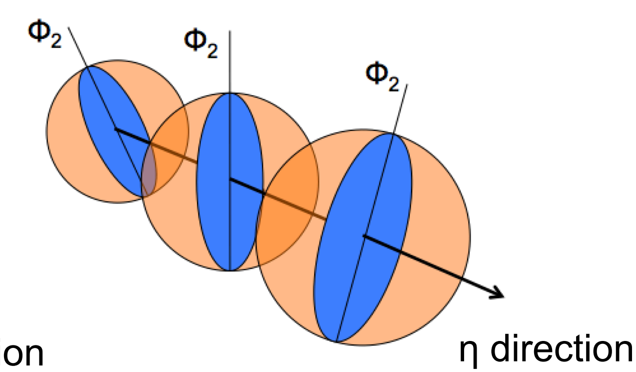
Asymmetry in multiplicity

(b) $v^{\mathrm{F}}_{2} \neq v^{\mathrm{B}}_{2}$



Asymmetry in flow magnitude

(c) $\Psi^{\mathrm{F}}_{2} \neq \Psi^{\mathrm{B}}_{2}$



Twist of flow plane

Flow fluctuation along rapidity direction

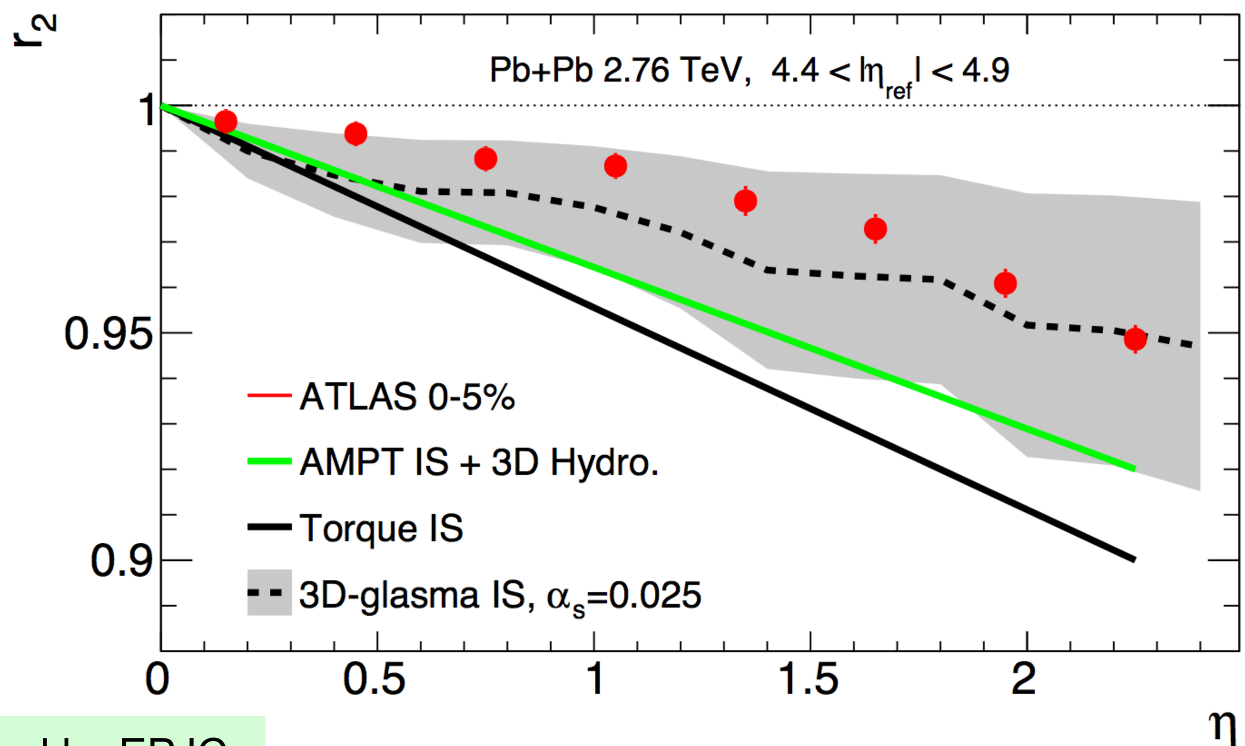
Observables:

Assume small fluct: $v_n(\eta) \approx v_n(0)(1+\alpha_n\eta)e^{i\beta_n\eta}$

$$r_2(\eta) = \frac{\langle v_2(-\eta) v_2^*(\eta_{\rm ref})\rangle}{\langle v_2(\eta) v_2^*(\eta_{\rm ref})\rangle} \approx 1 - F_2^{\rm asy}\eta - F_2^{\rm twi}\eta$$

$$R_2(\eta) = \frac{\langle v_2(-\eta_{\rm ref}) v_2(-\eta) v_2^*(\eta) v_2^*(\eta_{\rm ref})\rangle}{\langle v_2(-\eta_{\rm ref}) v_2(\eta) v_2^*(-\eta) v_2^*(\eta_{\rm ref})\rangle} \approx 1 - 2F_2^{\rm twi}\eta$$

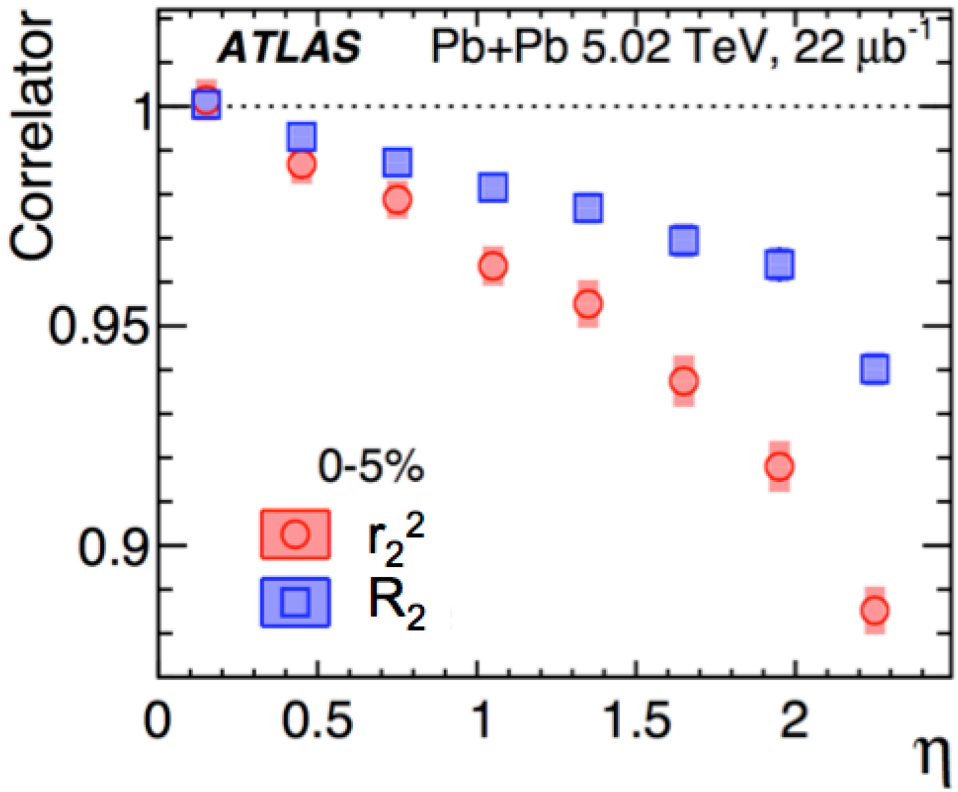
Significant de-correlation, not described by models:



1709.02301 accepted by EPJC

Flow fluctuation along rapidity

$$r_2^2(\eta) \approx 1 - 2F_2^{\mathrm{asy}}\eta - 2F_2^{\mathrm{twi}}\eta \qquad R_2(\eta) \approx 1 - 2F_2^{\mathrm{twi}}\eta$$



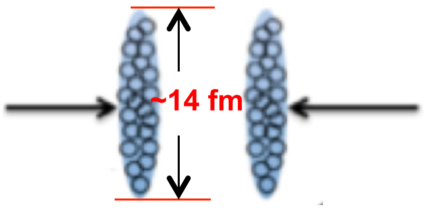
- R_2 signal is about half of r_2^2

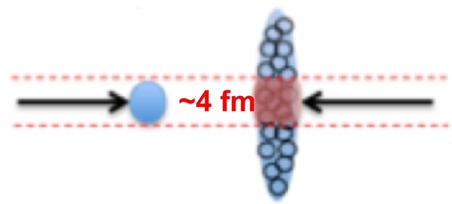
  ➔ approximately equal contribution from asymmetry and twist

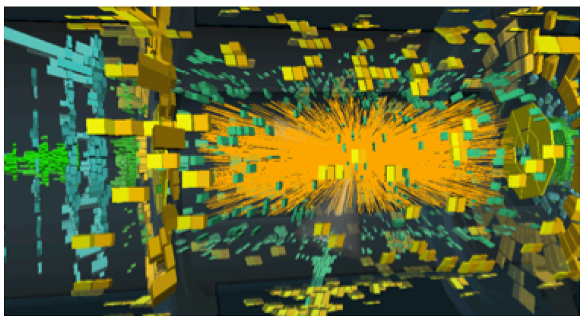
Important new info on initial condition in 3D & stopping mechanism

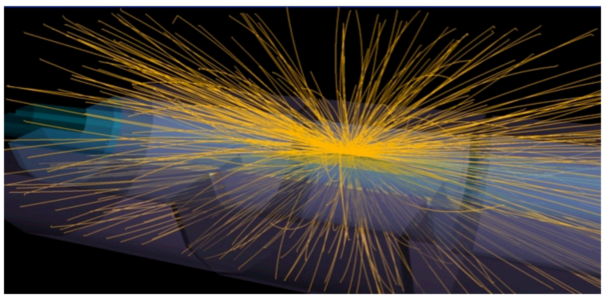
1709.02301 accepted by EPJC

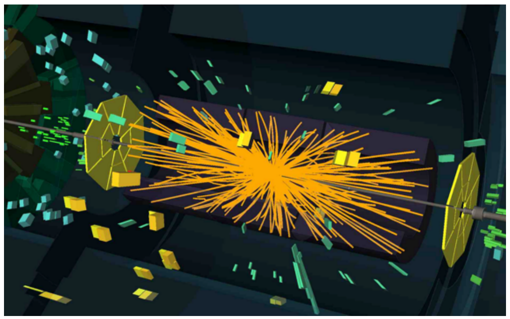
Importance of small collision systems











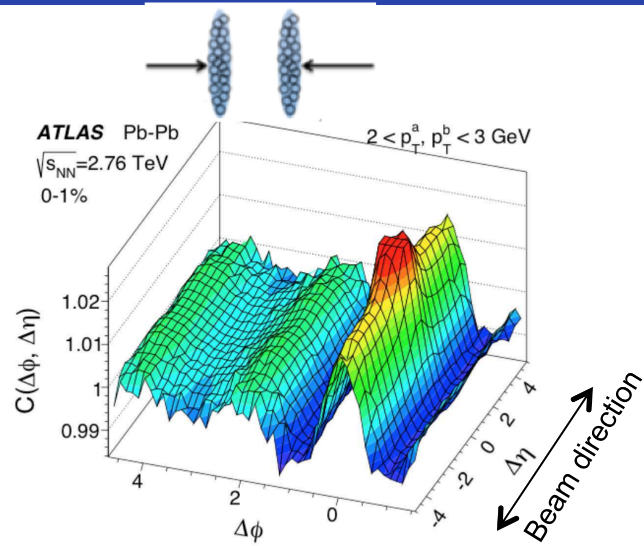
~30000 particles*   ~2000 particles*   ~ 600 particles*

What is the smallest droplet of QGP created in these collisions?

→ Change matter size, life-time and space-time dynamics

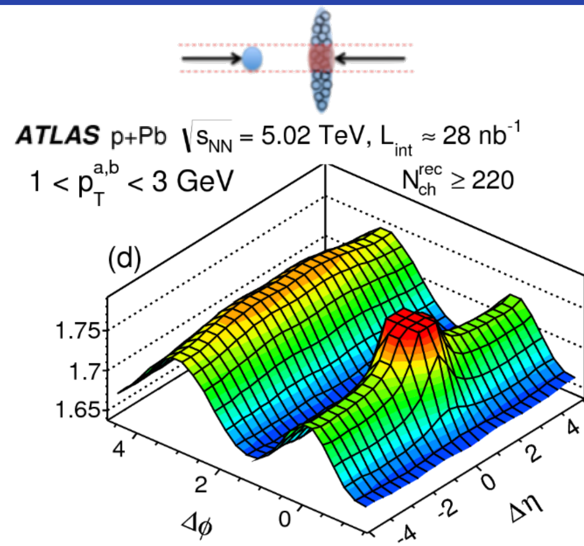
* Rough number in very high-multiplicity events, integrated over full phase space

Big surprise:collective feature seen in small systems!



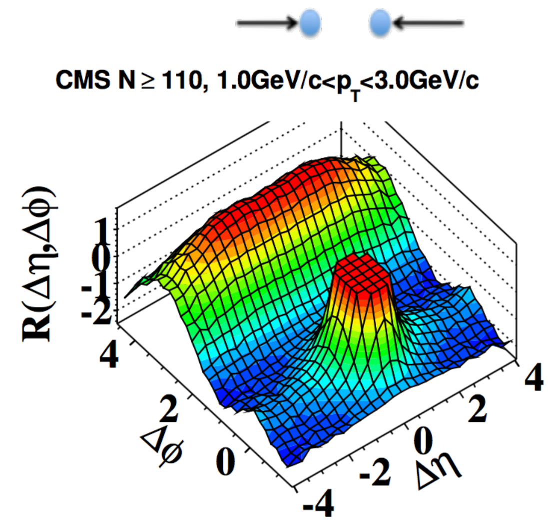
The ridge in Pb+Pb attributed to collective flow

$$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2 v_n^a v_n^b \cos n\Delta\phi$$



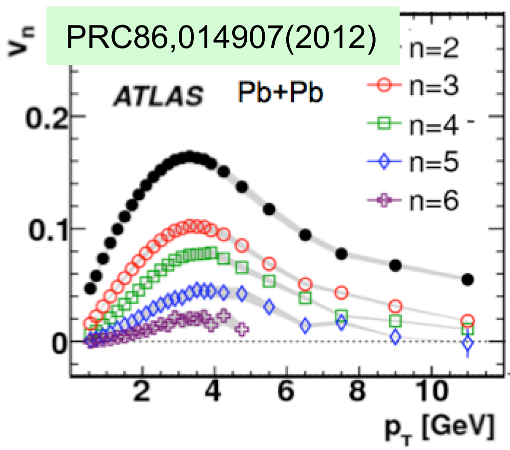
p+Pb ridge observed in 2012

PRL110,182302 (2013)

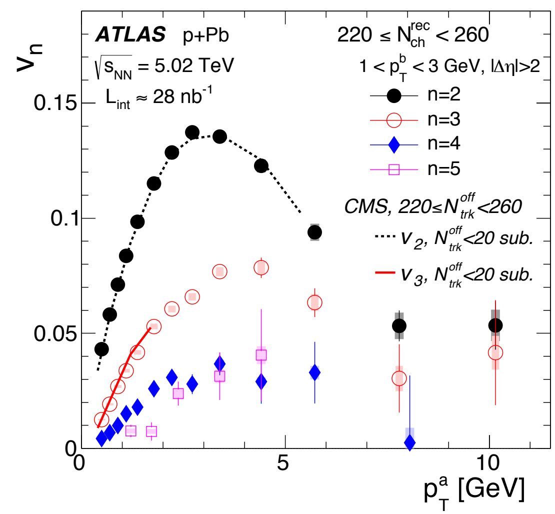


p+p ridge observed in 2010

PRC86,014907(2012)

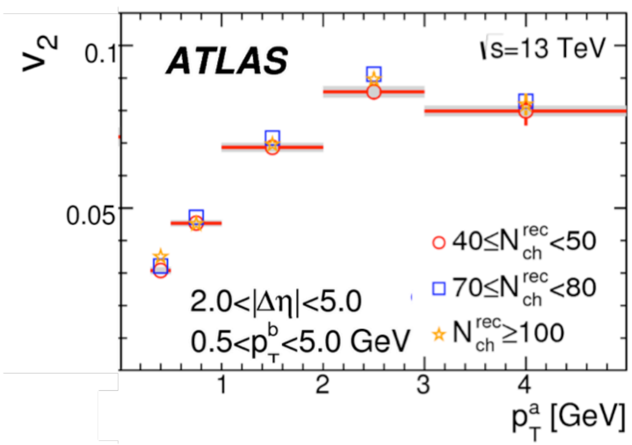


Single-particle v_n was measured



PRC90,044906 (2014)

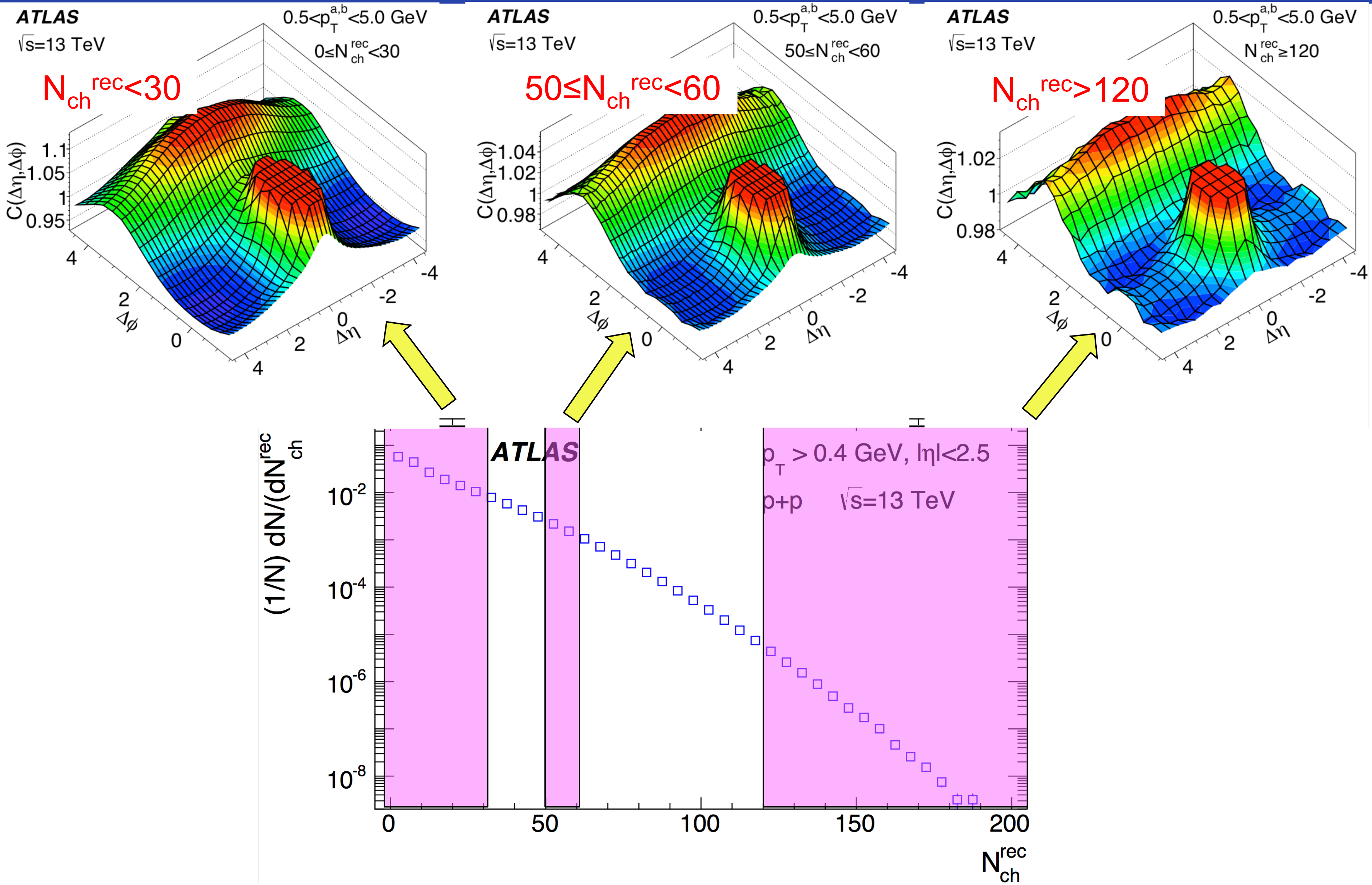
v_n was soon measured



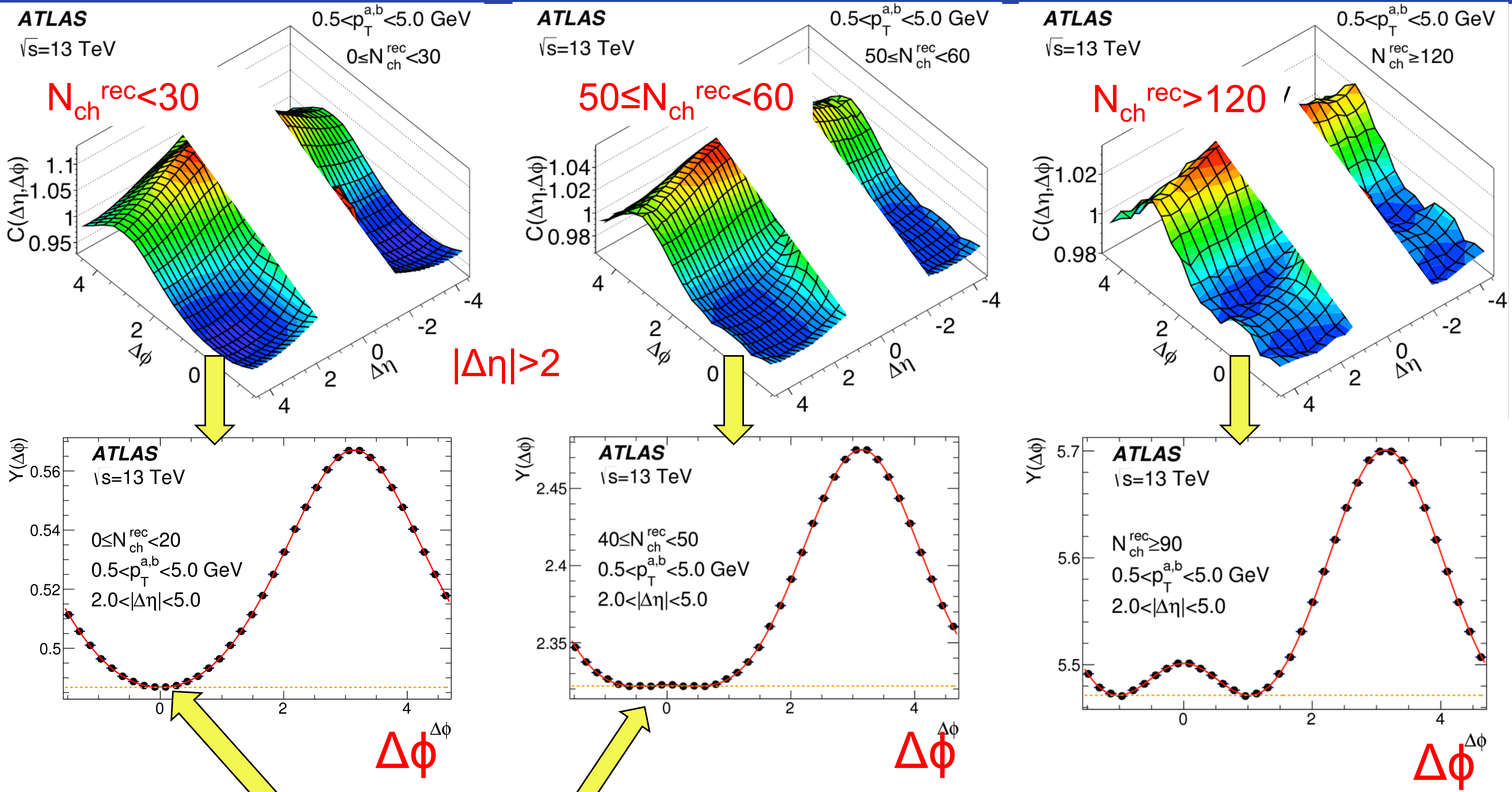
Finite v_2 recently obtained, but how?

PRL116, 172301 (2016)

The “hidden” pp ridge



The “hidden” pp ridge

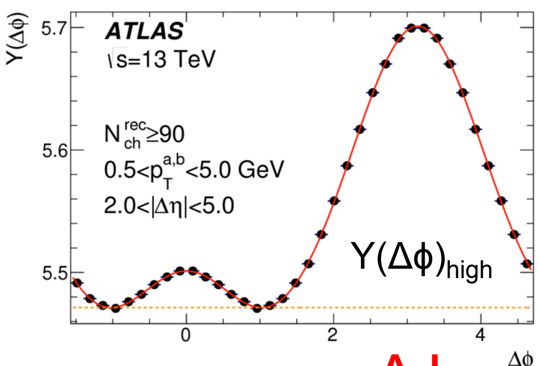


Ridge could be masked by away-side

The "hidden" pp ridge

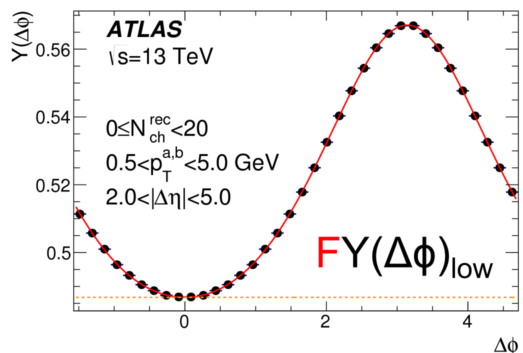
Observation: $Y(\Delta\phi)_{\text{high-mult}} \cong F\,Y(\Delta\phi)_{\text{low-mult}} + A\cos 2\Delta\phi + C$

Other harmonics much smaller



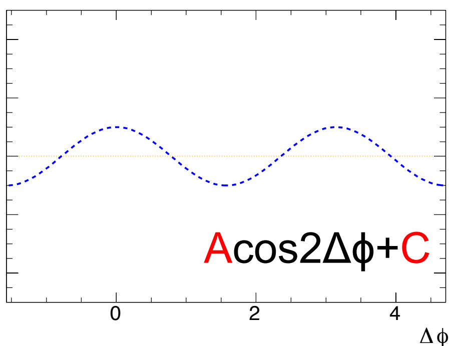
$\Delta\phi$

=



$\Delta\phi$

+

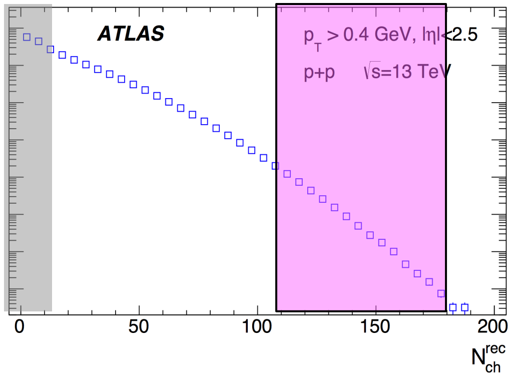


$\Delta\phi$

Assume: di-jet correlation unmodified.

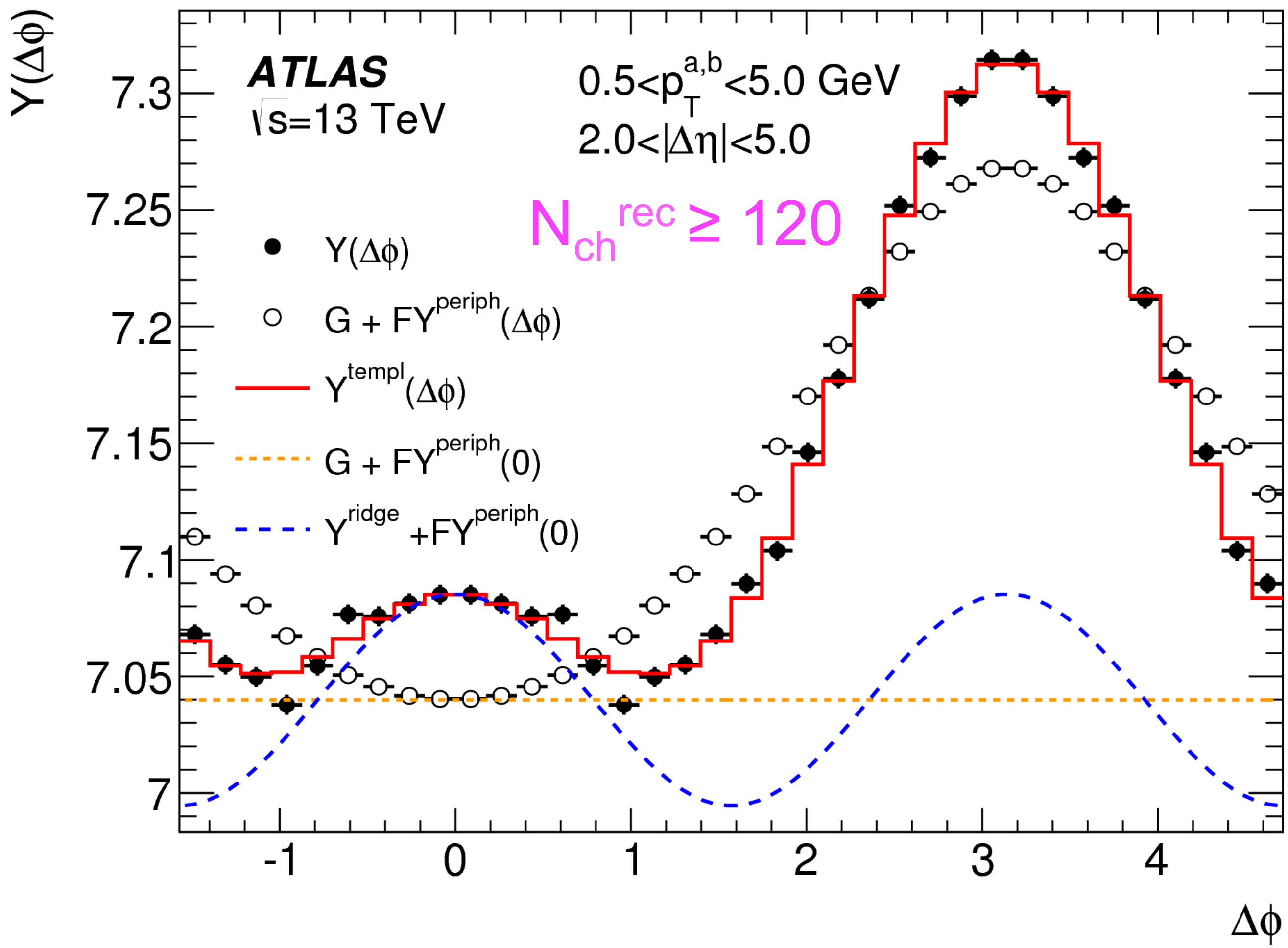
Low multiplicity bin: N_{ch}^{rec}<20

Assume away-side jet correlation unmodified



Narrowing of away Y(Δϕ) due to cos2Δϕ component

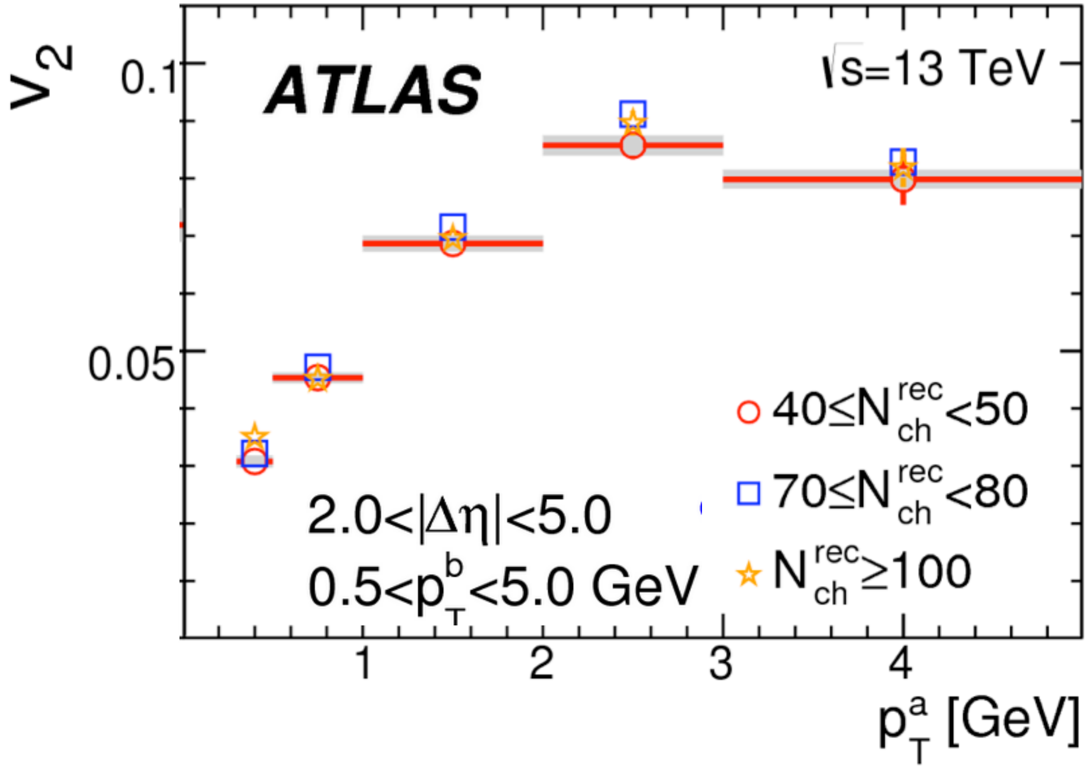
$$Y(\Delta\phi)_{Fit} \cong FY(\Delta\phi)_{low\text{-}mult} + A\cos 2\Delta\phi + C$$



Properties of the quadrupole

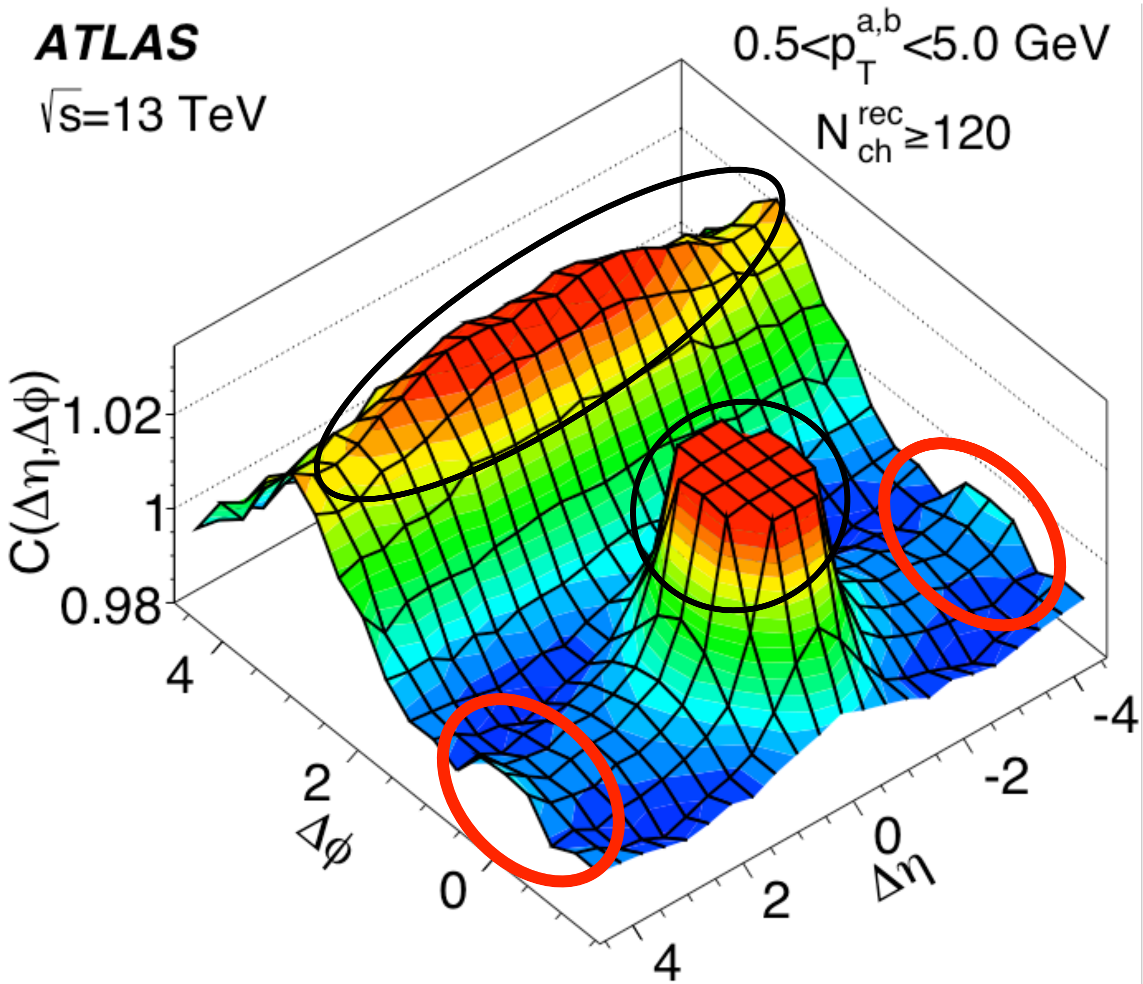
Two-particle quadrupole factorize into single particle quadrupole:

$$\frac{dN}{d\Delta\phi} \propto 1 + 2 v_2(p_T^a) v_2(p_T^b) \cos 2\Delta\phi$$



Rise & fall pattern similar to pPb and PbPb

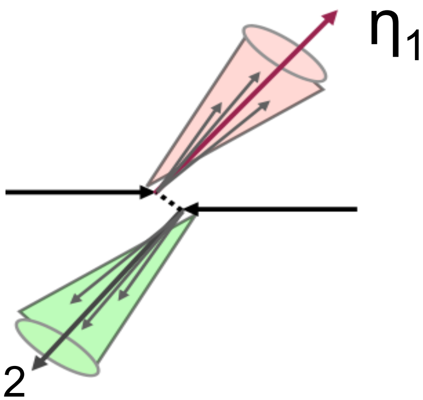
Is “ridge” really collective?



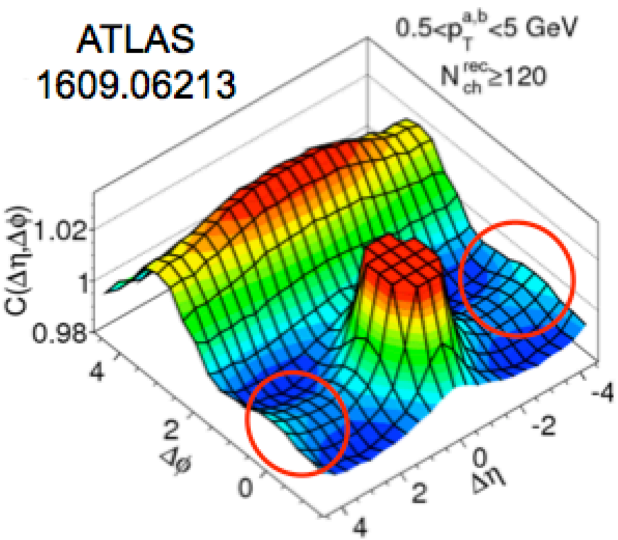
How to beat the large dijet background?

Non-flow vs long-range collectivity

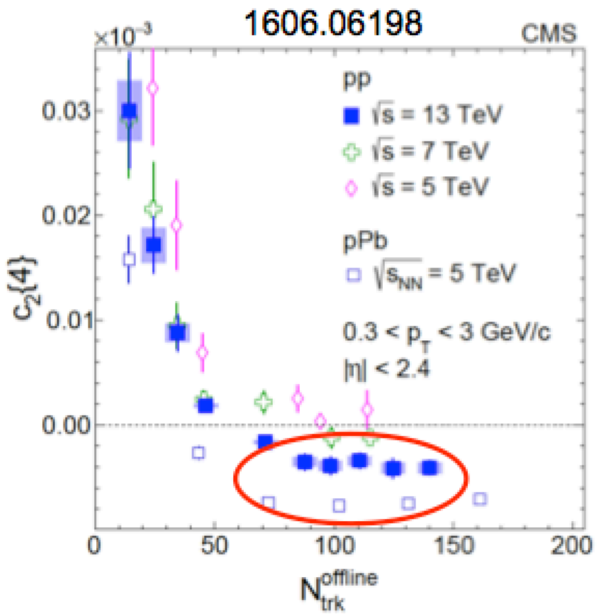
Dominating non-flow is jets and dijets, which are confined in **one or two η regions**



Features of long-range ridge:



Long-range in η



Multi-particle (3,4,5..) signal

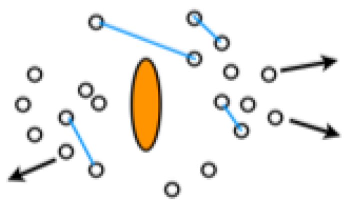
Simultaneous correlations between multiple η ranges

Is "ridge" really collective?

- Need to suppress correlation involving only a few particles.
  - ➔ Multi-particle correlations.

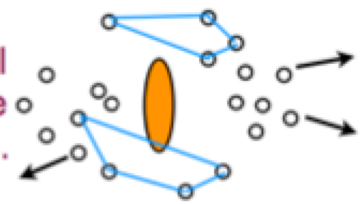
Two-particle Cumulant

Consider all two-particle correlations.



Four-particle Cumulant

Consider all four-particle correlations.



- Four-particle cumulant removes all two-particle correlations

$$c_n\{4\} = \left\langle e^{in(\phi_i+\phi_j-\phi_k-\phi_l)}\right\rangle - \left\langle e^{in(\phi_i-\phi_k)}\right\rangle\left\langle e^{in(\phi_j-\phi_l)}\right\rangle - \left\langle e^{in(\phi_i-\phi_k)}\right\rangle\left\langle e^{in(\phi_j-\phi_k)}\right\rangle$$

$$= \left\langle\!\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\!\right\rangle - 2\left\langle\!\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\!\right\rangle^2 = \left\langle v_n^4\right\rangle - 2\left\langle v_n^2\right\rangle^2$$

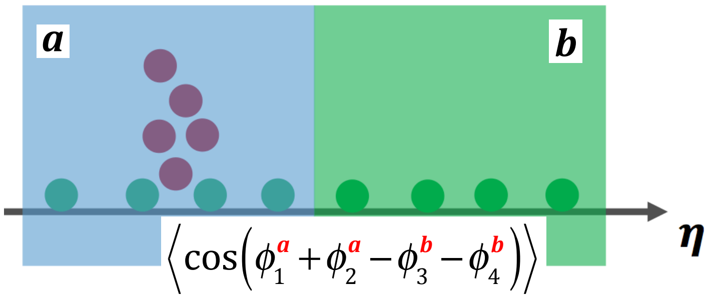
If flow is constant, $c_n\{4\} = -v_n^4 < 0$

- Can generalize to six-particle, eight-particle ⋯ correlations.

Long-range collectivity via subevent correlations

arXiv:1701.03830

Event with jet

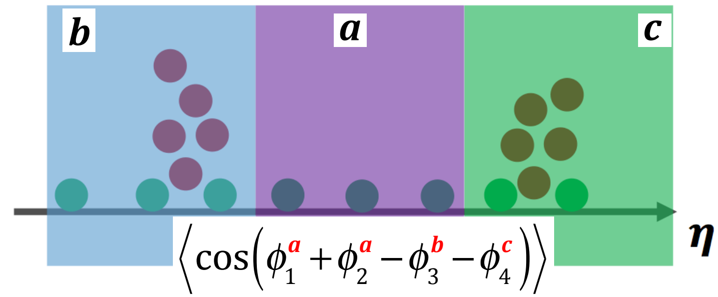


$$\left\langle \cos\left(\phi_1^{a}+\phi_2^{a}-\phi_3^{b}-\phi_4^{b}\right)\right\rangle$$

2 sub-event

removes intra-jet correlations

Event with dijet



$$\left\langle \cos\left(\phi_1^{a}+\phi_2^{a}-\phi_3^{b}-\phi_4^{c}\right)\right\rangle$$

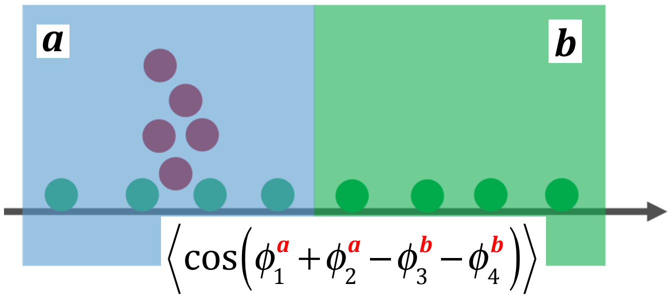
3 sub-event

removes inter-jet correlations

Long-range collectivity via subevent correlations

arXiv:1701.03830

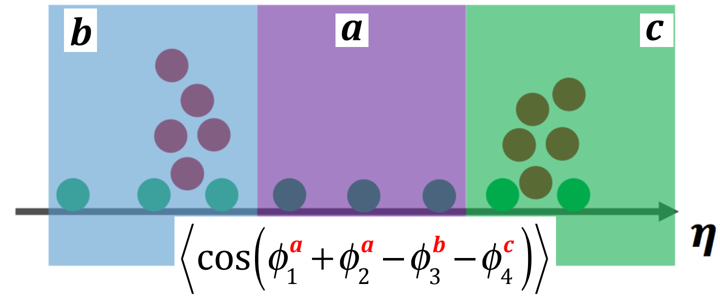
Event with jet



2 sub-event

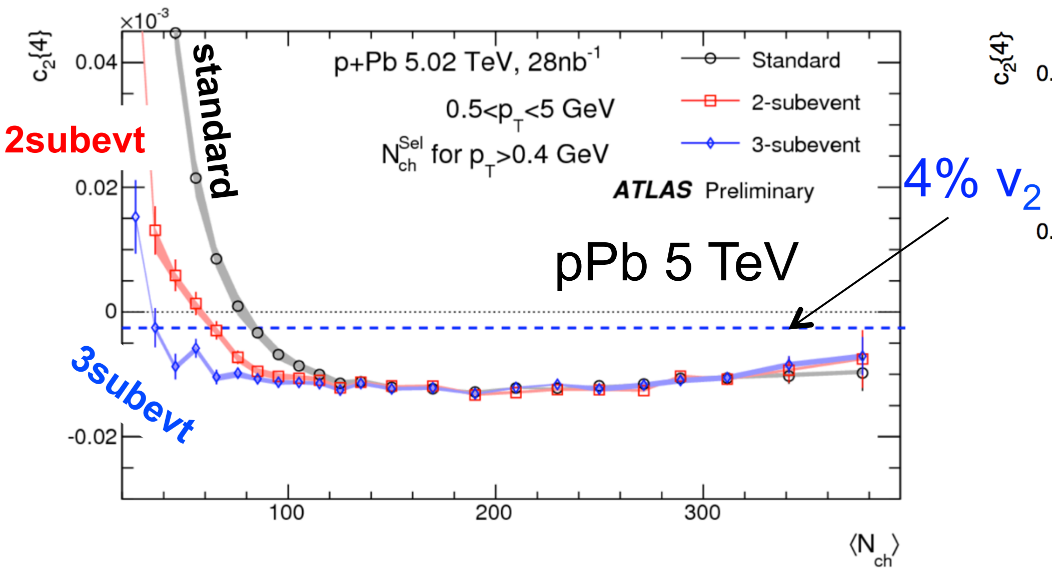
removes intra-jet correlations

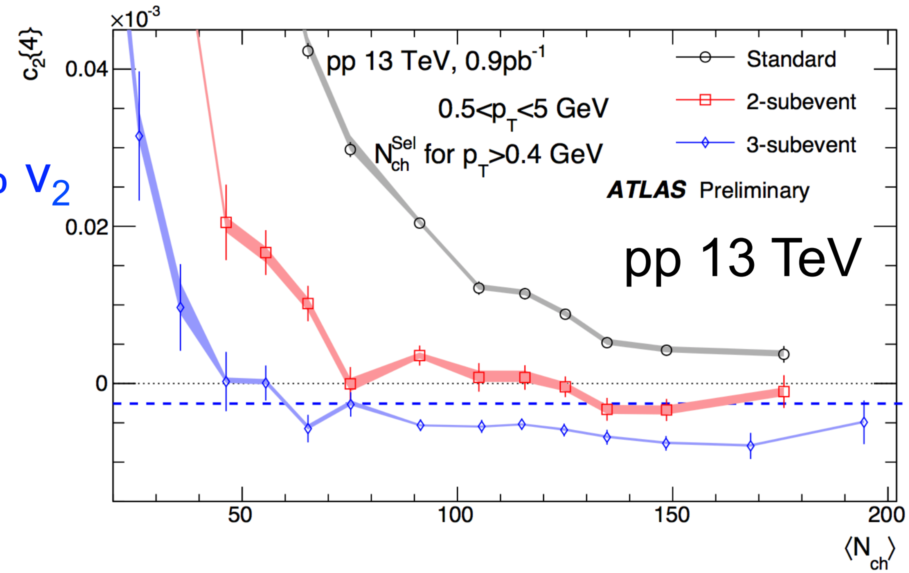
Event with dijet



3 sub-event

removes inter-jet correlations





pPb: methods consistent for N_{ch}>100, but split below that

Only subevent method gives negative $c_2\{4\}$ in broad range of N_{ch}

arXiv:1708.03559, accepted by PRC

What about its event-by-event fluctuation?

- In Pb+Pb we measured directly $p(v_2)$.
- In pPb and pp, probe $p(v_2)$ from higher moments

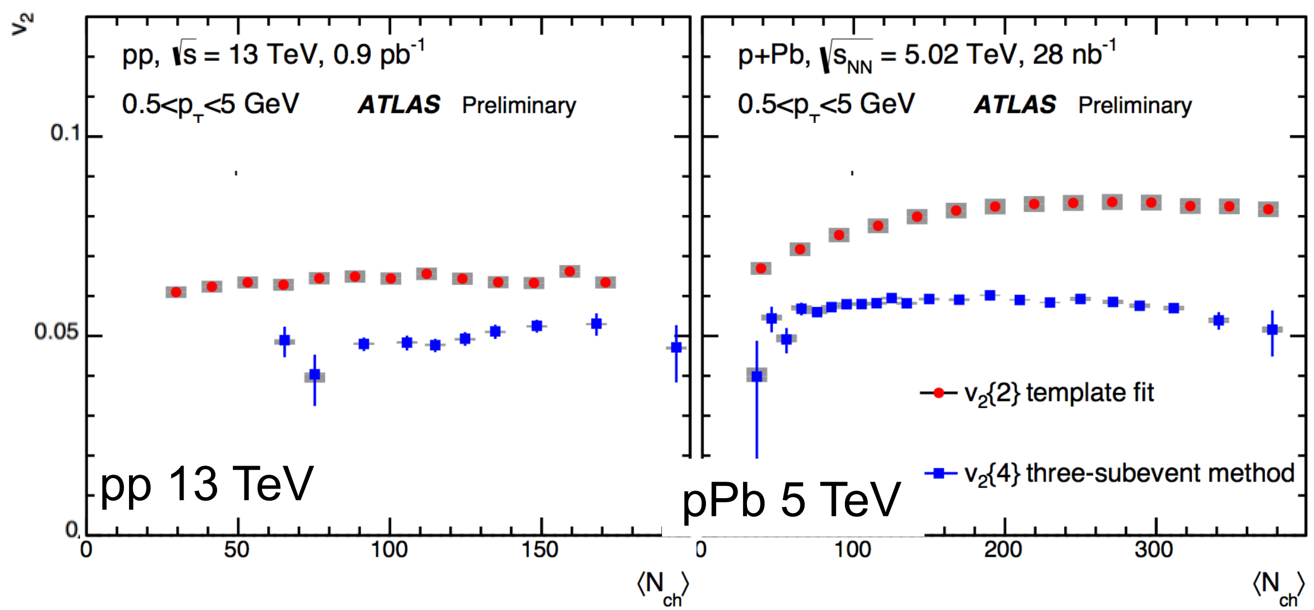
$$c_2\{2\} = \left\langle v_2^2 \right\rangle \equiv v_2\{2\}^2$$

Two-particle corr

$$c_2\{4\} = \left\langle v_2^4 \right\rangle - 2\left\langle v_2^2 \right\rangle^2 \equiv -v_2\{4\}^4$$

Four-particle corr

- If $p(v_2)$ is Gaussian, if no average geometry, $c_2\{4\}=0$

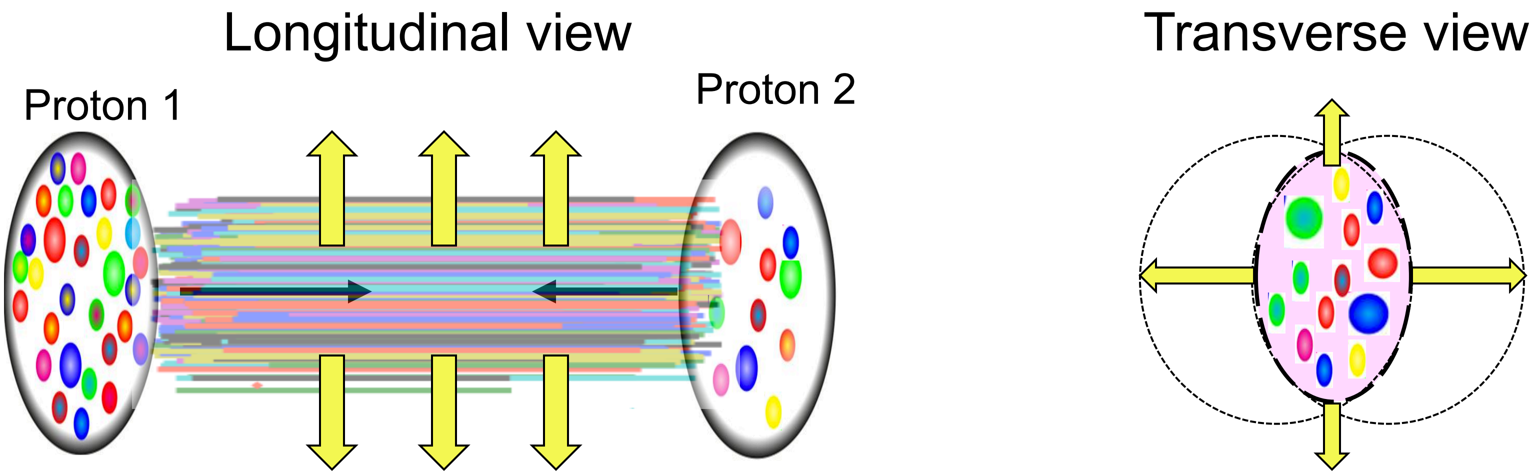


0<$v_2\{4\}$<$v_2\{2\}$: Significant non-Gaussian EbyE fluctuations

What do we learn from this?

PRL112,082301(2014)

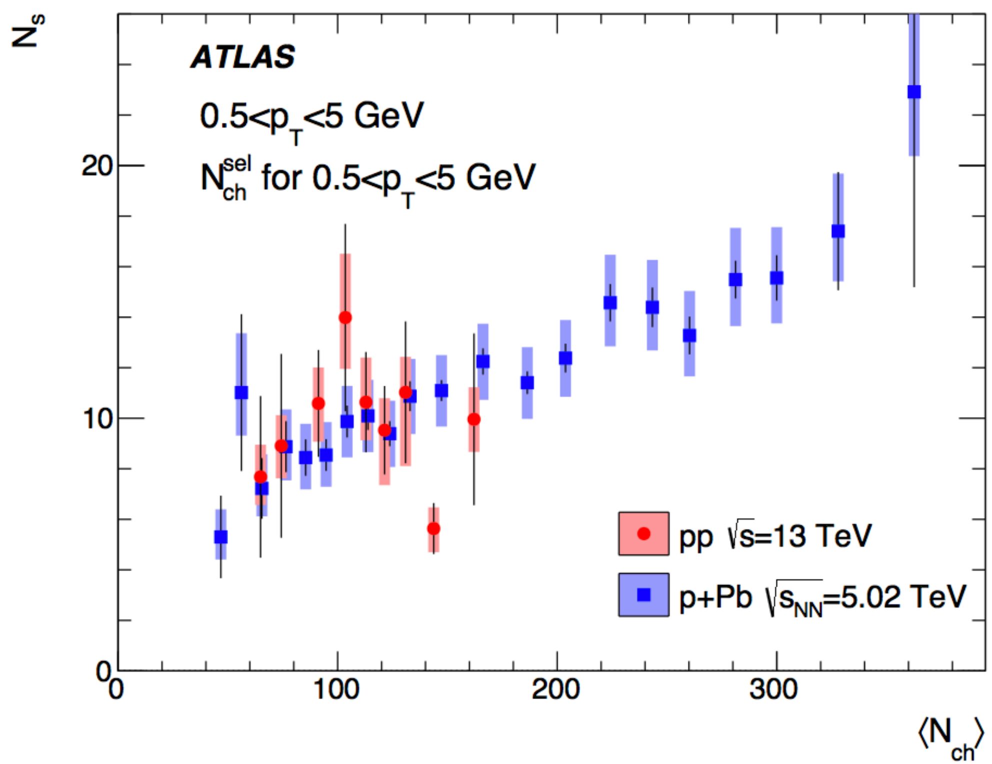
- $p(v_2)$ driven by fluc. of independent sources: multi-parton interactions (MPI)



What do we learn from this?

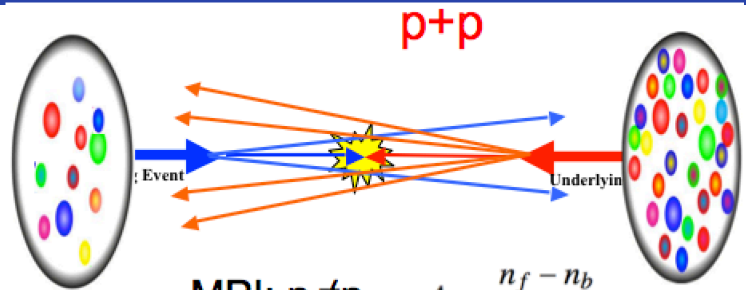
PRL112,082301(2014)

- $p(v_2)$ driven by fluc. of independent sources: multi-parton interactions (MPI)
- Number of sources N_s can be estimate from $v_2\{4\}/v_2\{2\}$ $\frac{v_2\{4\}}{v_2\{2\}} = \left[\frac{4}{(3+N_s)}\right]^{1/4}$



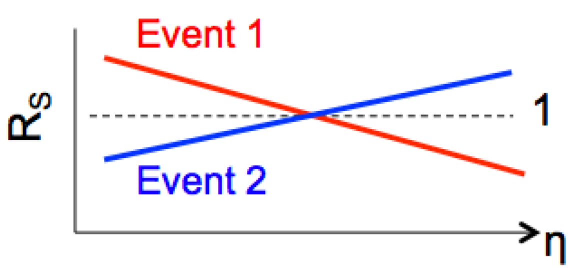
N_s similar for pp and pPb at similar multiplicity.

N_s from forward-backward multiplicity fluc.



MPI: $n_f \neq n_b$ $\quad A_n = \frac{n_f - n_b}{n_f + n_b}$

- Rapidity correlation:



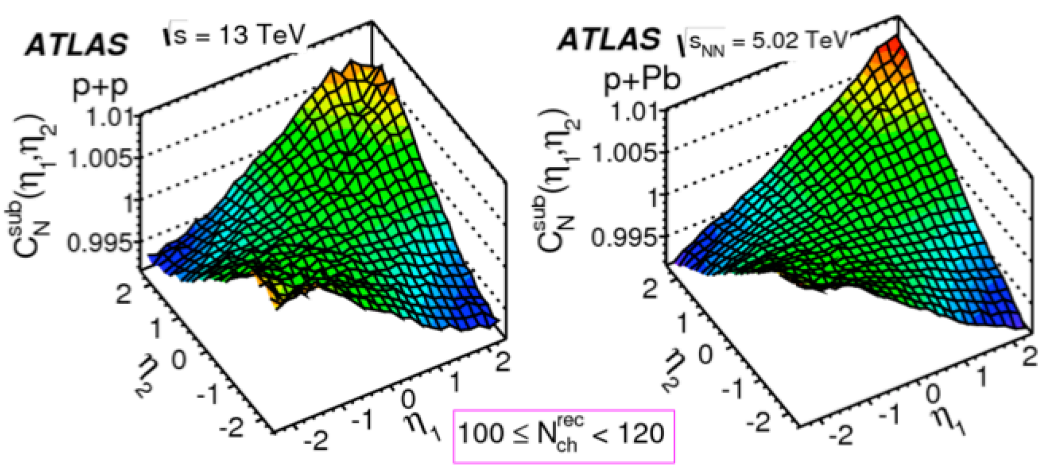
$$R_S(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle}$$

$$C = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} = \langle R_S(\eta_1) R_S(\eta_2) \rangle_{events}$$

$$R_S(\eta) \approx 1 + a_1 \eta$$

$$C = \langle R_S(\eta_1) R_S(\eta_2) \rangle \approx 1 + \langle a_1^2 \rangle \eta_1 \eta_2$$

- Confirmed by data:



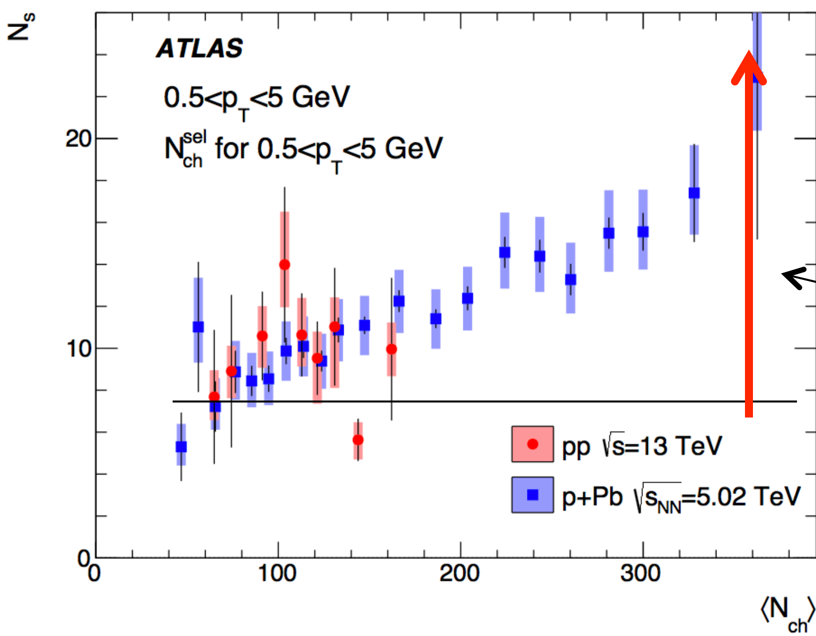
PRC 95, 064914 (2017)

Relate to the initial geometry

arXiv:1708.03559

Sources driving the transverse flow

$$\frac{v_2\{4\}}{v_2\{2\}} = \left[\frac{4}{(3+N_s)}\right]^{1/4}$$

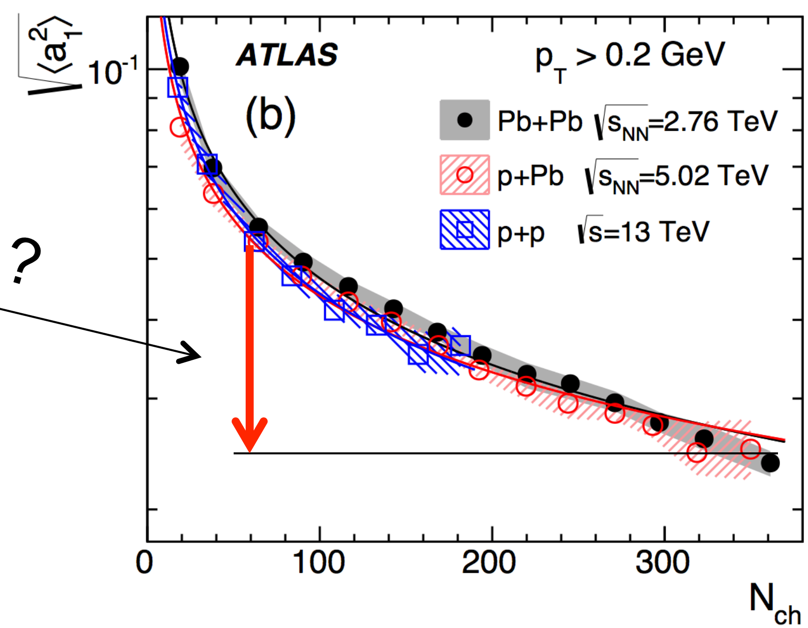


PRC 95, 064914 (2017)

Source for particle production which drives FB multiplicity fluc.

$$\frac{N(\eta)}{\langle N(\eta)\rangle} \approx 1 + a_1\eta \qquad a_1 \propto 1 \Big/ \sqrt{N_s}$$

N_S?



Same sources responsible for particle production and flow?

Summary

- Study phenomena emerging from strongly-coupled, extended, hot &dense QCD systems created in pp, pA and AA collisions.
  - Understand phase diagram, confinement, transport properties…
- Use both short wavelength (jets, EW particles) & long wavelength soft particles
  - Multiple experiments on different observables simultaneously (even for just 1 month/year).

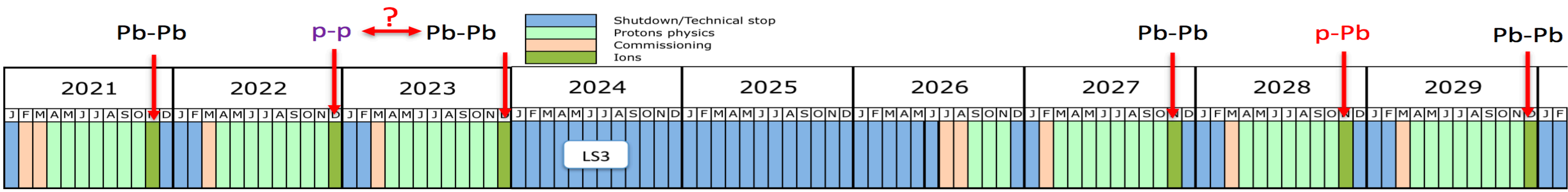
- Talk focused on the long-wavelength behaviors/properties of QCD matter
  - Many observables to study hydrodynamic response to EbyE fluctuating initial conditions
  - Understand space-time dynamics & QGP properties via model comparison.

  Explore new observables, further constrain medium properties
- Collective behavior of QCD matter in pp and pPb collisions
  - Strong collectivity observed in high-multiplicity pPb and pp collisions
  - Multi-particle long-range signal suggests similar collective behavior as AA.
  - Support soft multi-parton interaction picture, which drive both flow and FB fluctuation.

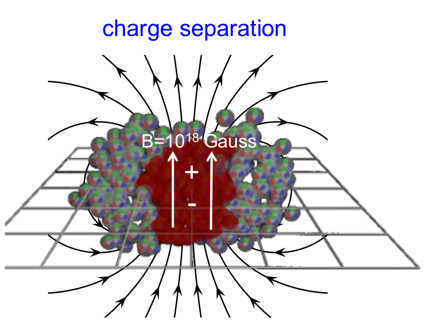
  Have we created a small droplet of QGP in pp, pPb collisions?

Outlook

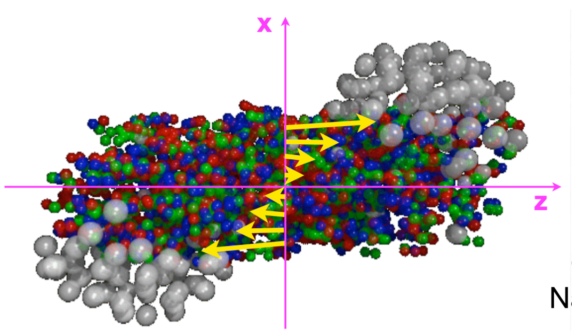
- Just took x100 more low pileup data for ridge physics in 2017
  - 200pb^{-1} @ 5 TeV and 100 pb^{-1} at 13 TeV, comparing to 0.19pb^{-1} and 0.9pb^{-1}
- Robust HI program planned out for next 10 years
  - >x30 L_{int} for Pb+Pb and p+Pb with tracking extended to $|\eta|<4$
  - Light ions: Xe+Xe, Ar+Ar,O+O? bridge between small & large system



- Other ideas: chiral magnetic effect, global/local polarization+others



B-field + chirality=current



Observed at RHIC
Nature 548, 62 (2017)

Fluid vorticity ➔ polarization of hadrons