What do recent ATLAS measurements tell us about the dynamics and properties of quark-gluon plasma?

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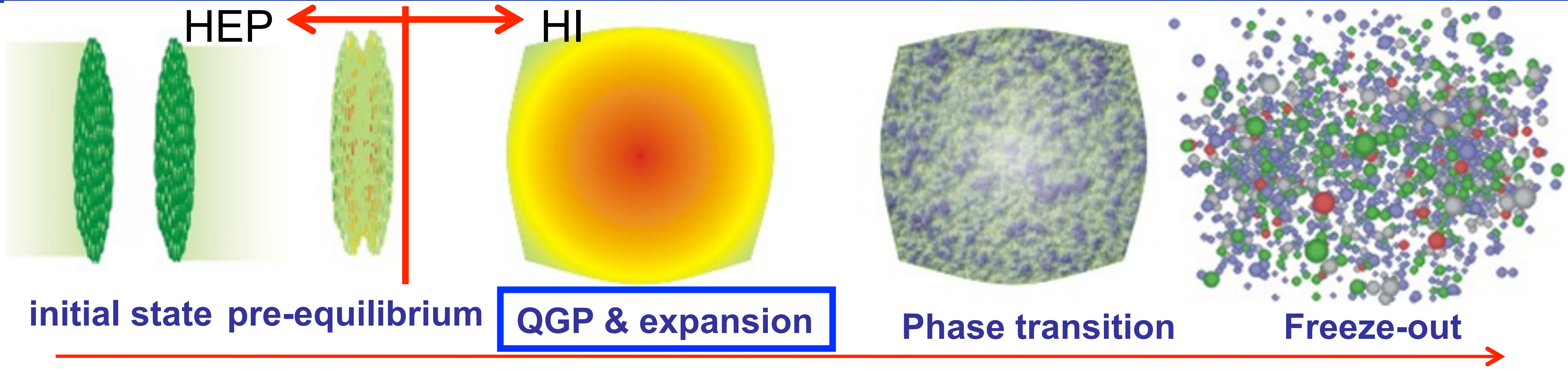
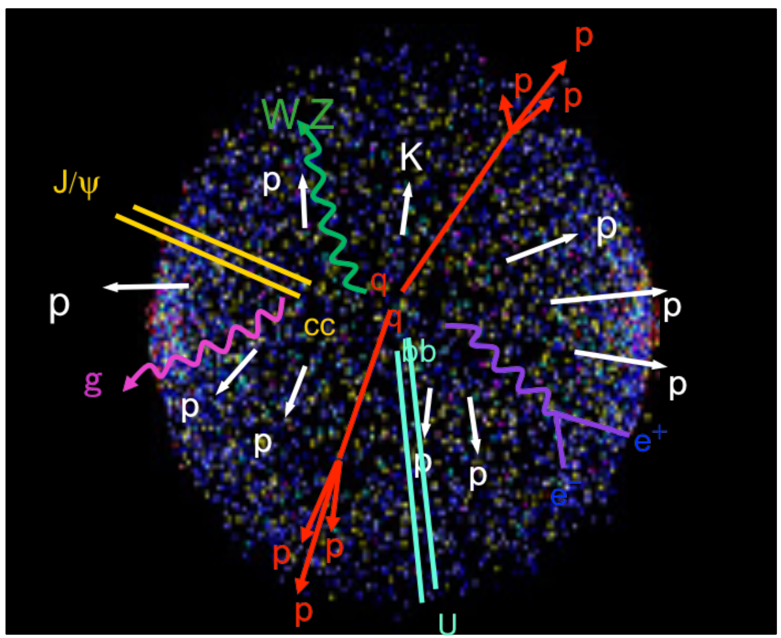
Space-time history of Pb+Pb collisions

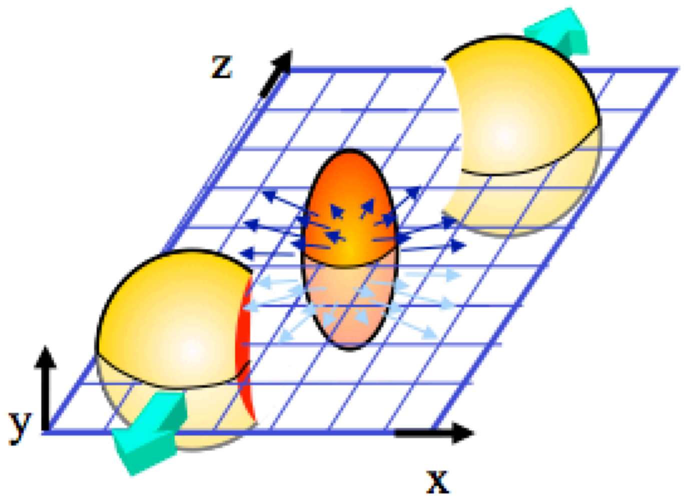


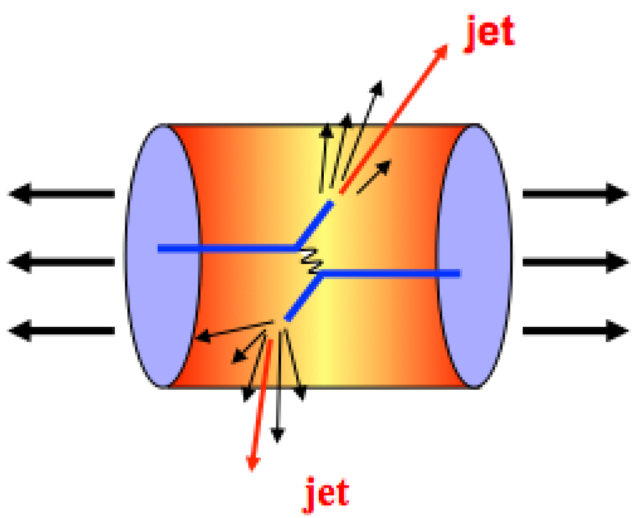
Space-time dynamics ⟷ QGP properties



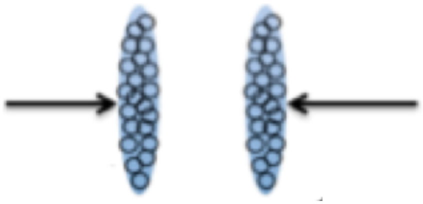
Properties of the QGP medium

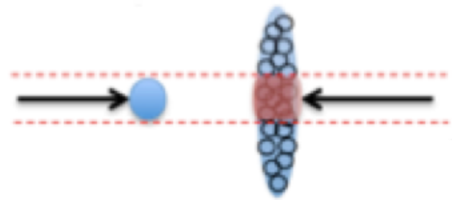
- Long-wavelength properties with bulk, soft particles
  - Space-time picture, thermalization mechanism, collective flow, hadronization
- Short-wavelength properties with hard probes
  - QGP structure and effective degrees-of-freedom at different length-scales

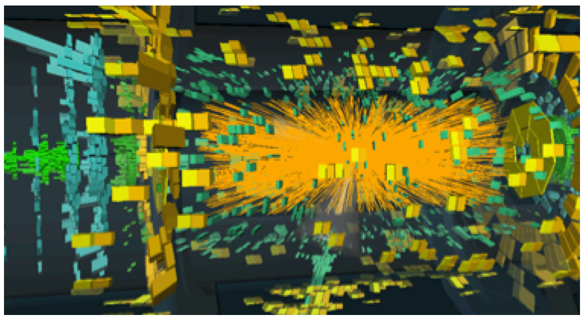


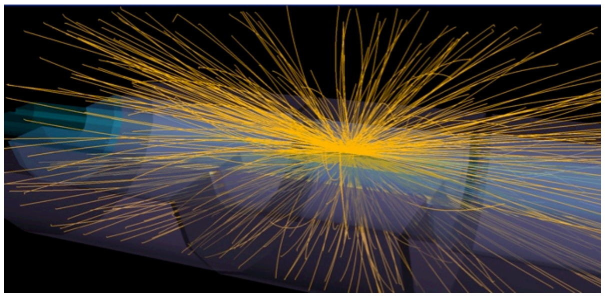


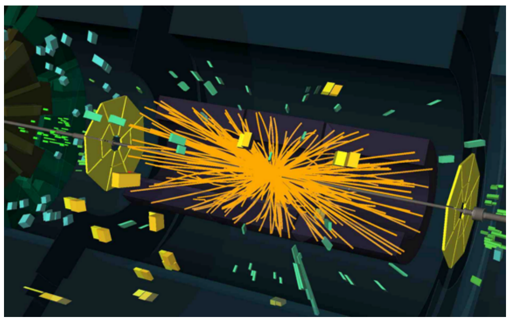
Importance of small collision systems











~30000 particles*

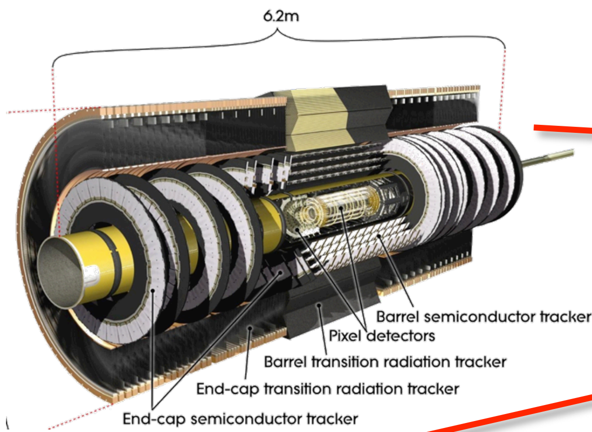
~1000 particles*

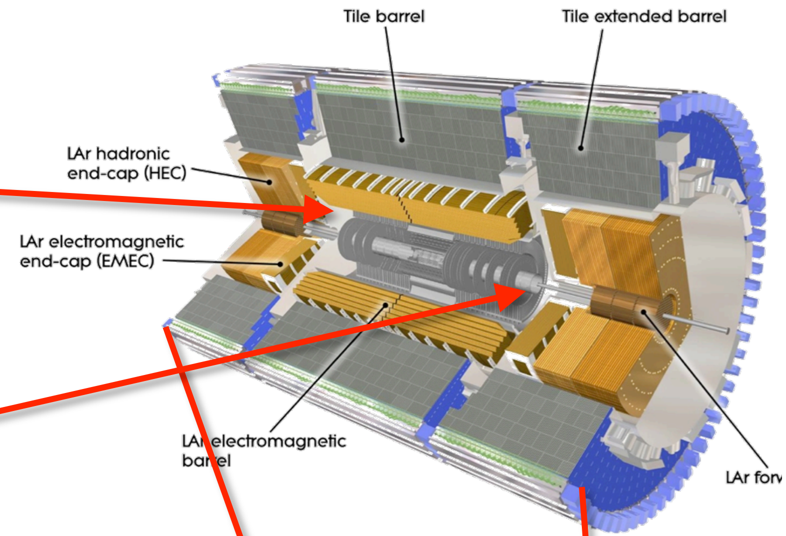
~few 100 particles*

- Switching off the QGP effects.
- Calibrate the initial conditions and rates of hard-probes

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

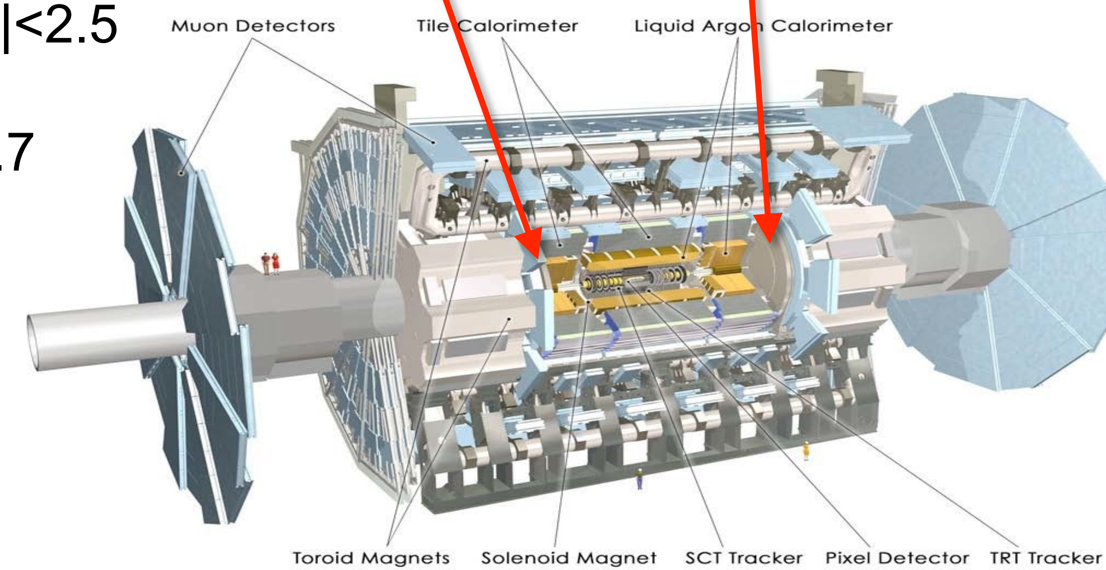
ATLAS detector





Three main subsystems

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

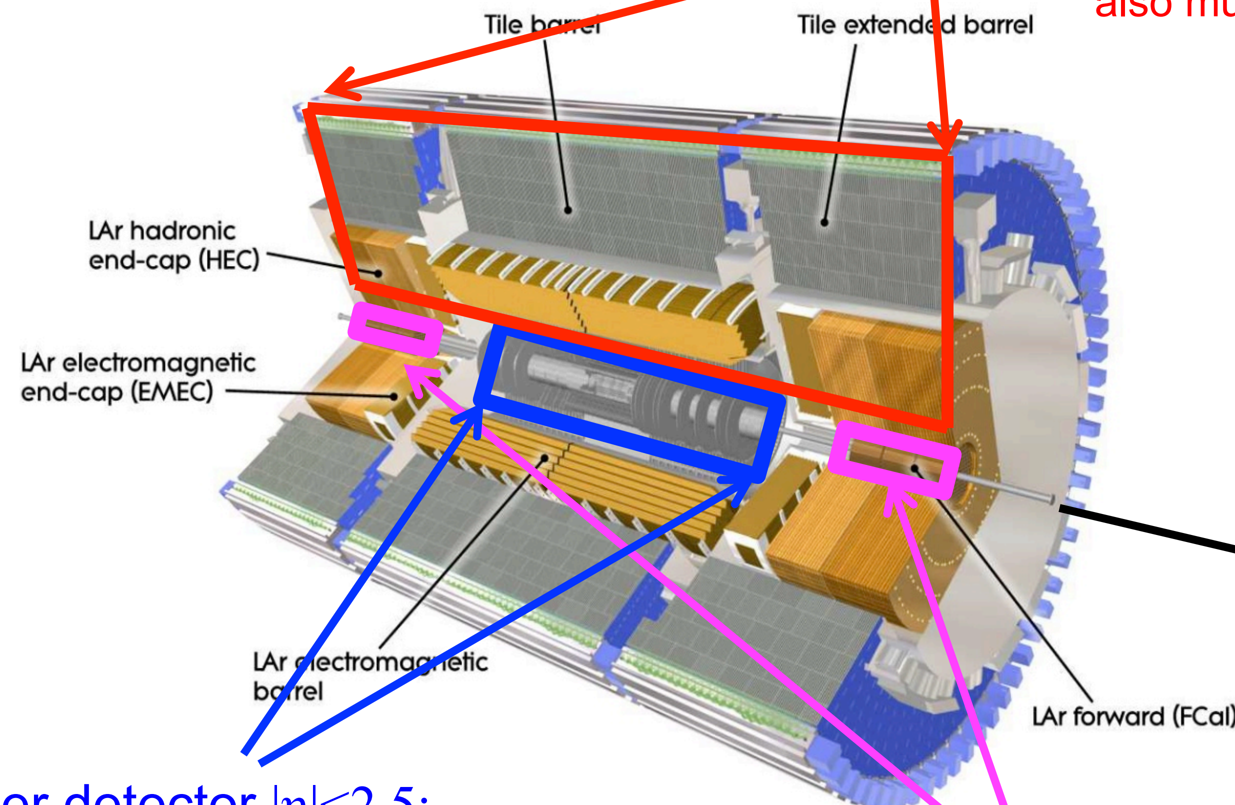


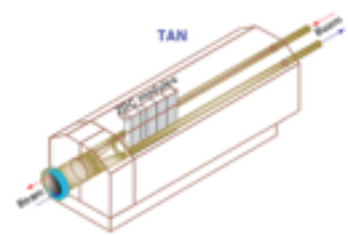
ATLAS detector

EM&HCal $|\eta|<3.2$:

<u>**Jets, photons, electrons→ jet quenching**</u>

also muons from MS





ZDC $|\eta|>8.3$

<u>**HI triggering**</u>

Inner detector $|\eta|<2.5$:

<u>**charged hadrons→ spectra, correlations**</u>

FCal $3.1<|\eta|<4.9$:

<u>**Event centrality & event shape**</u>

Datasets & presentation outline

Datasets collected in 2010-2015

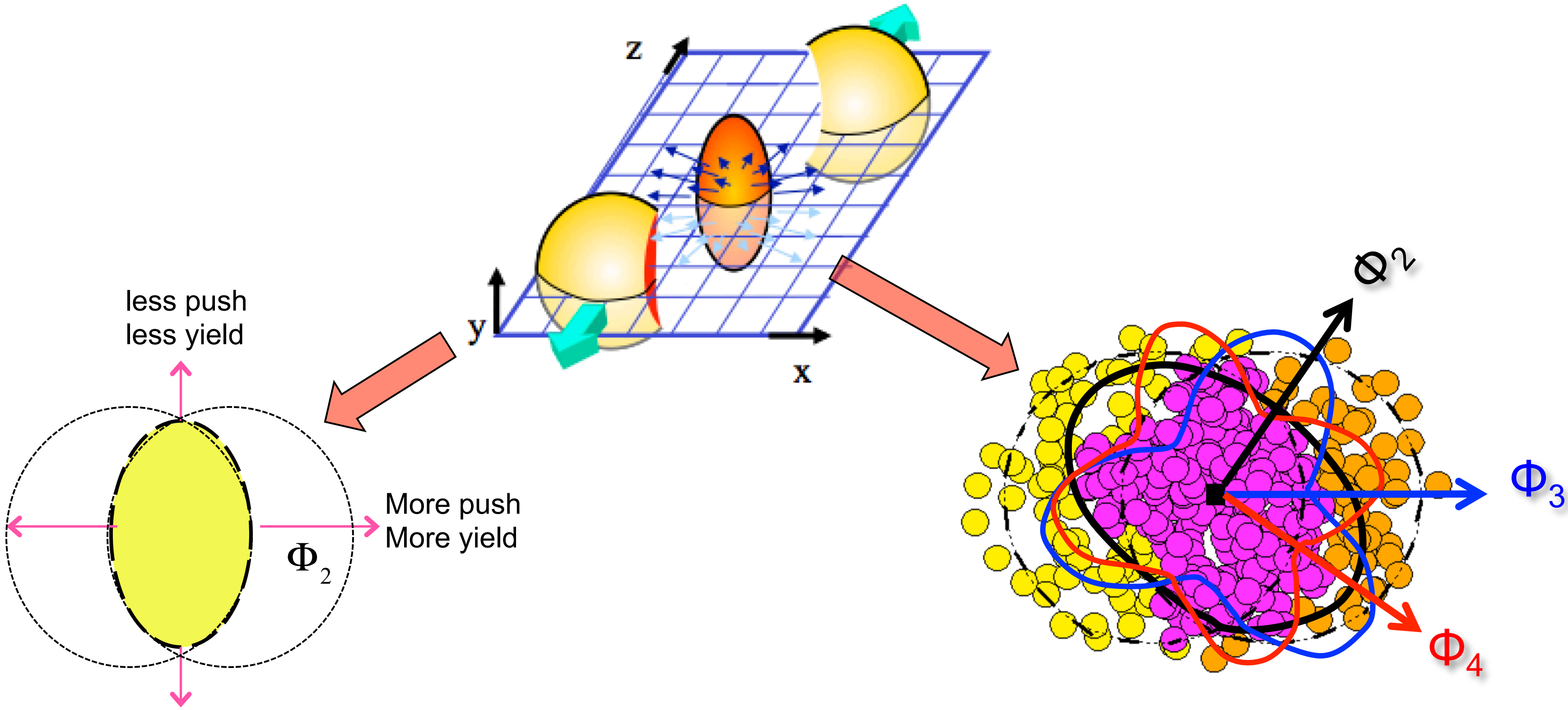
Pb+Pb	@	2.76	TeV, 2010 & 2011	160ub^{-1}
p+Pb	@	5.02	TeV, 2013	28 nb^{-1}
p+p	@	2.76,13	TeV, 2011,2013,2015	

Heavy-ion physics productivity: 27 papers & 44 conference notes

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

- What are the long-wavelength behaviors/properties of QGP?
- What are the short-wavelength behaviors/properties of QGP?
- Do we understand the initial conditions and rates of hard-probes prior to the formation of QGP?
- What is the smallest droplet of QGP created?

Long wave-length behavior: Collective flow



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

Elliptic flow

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

+directed flow, triangular flow+..

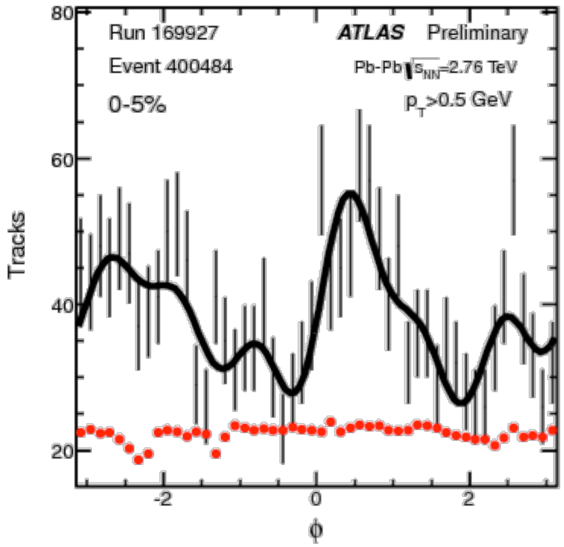
also measure via two-particle correlation.

$$\frac{dN}{d\Delta\phi} = \left[\frac{dN}{d\phi_1} * \frac{dN}{d\phi_2}\right] \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n}^\mathrm{a}\mathrm{v}_\mathrm{n}^\mathrm{b} \cos(n\Delta\phi)$$

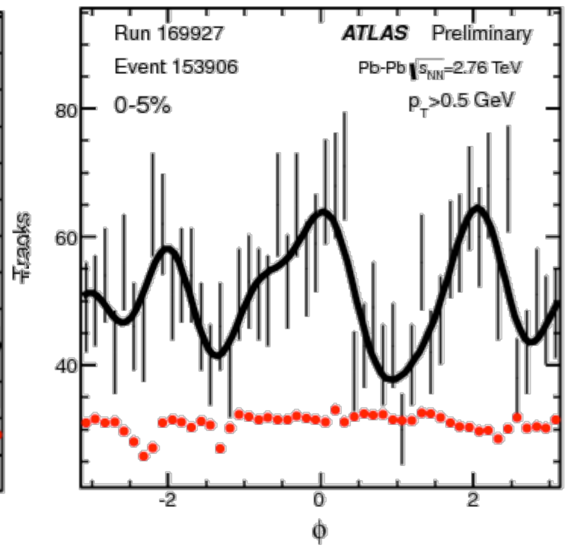
Hydrodynamic fluid behavior

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

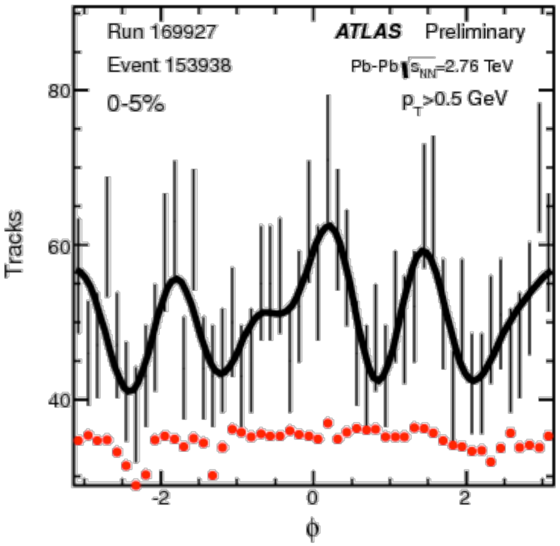
Event 1



Event 2



Event 3

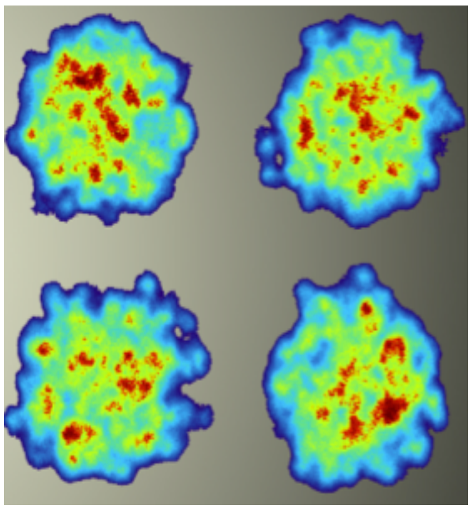


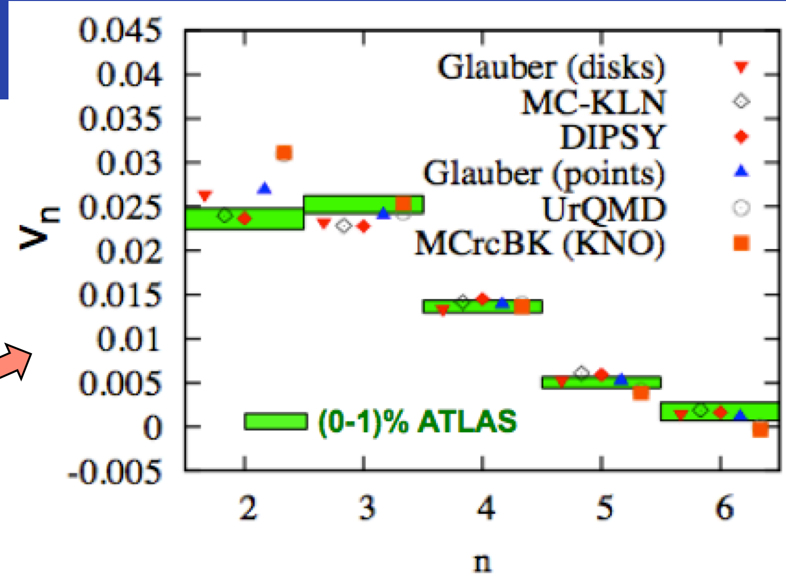
- v_n sensitive to initial perturbation and viscosity.
  - Bigger initial fluctuation lead to bigger v_n
  - Small viscosity ensure efficient transfer of initial fluctuation to final state flow.

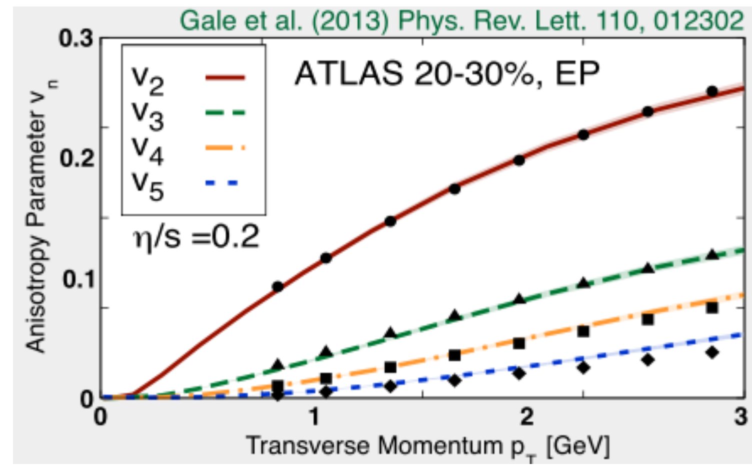
Collective flow fluctuations

Event-averaged quantities (2010-2013)

ATLAS data:
PRC86,014907(2012), PLB707(2012)330







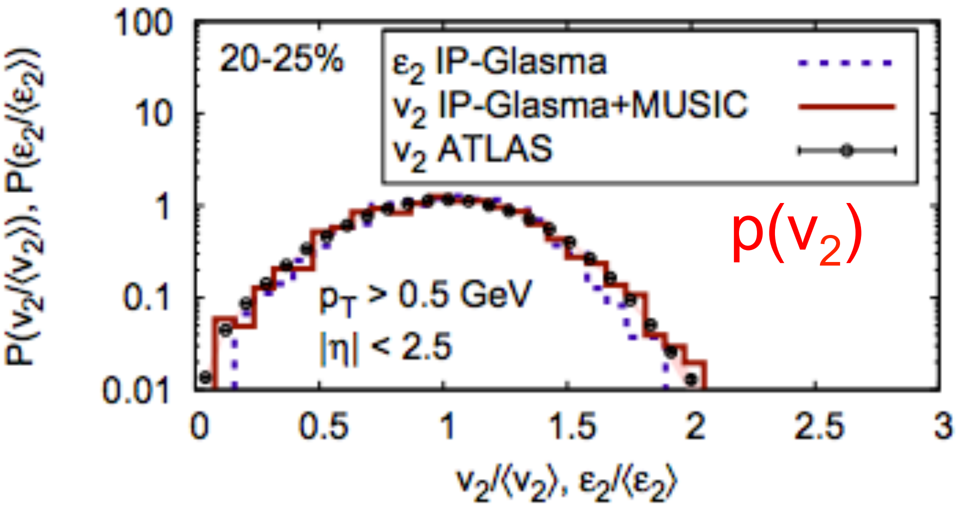
New observables (2013-2015):

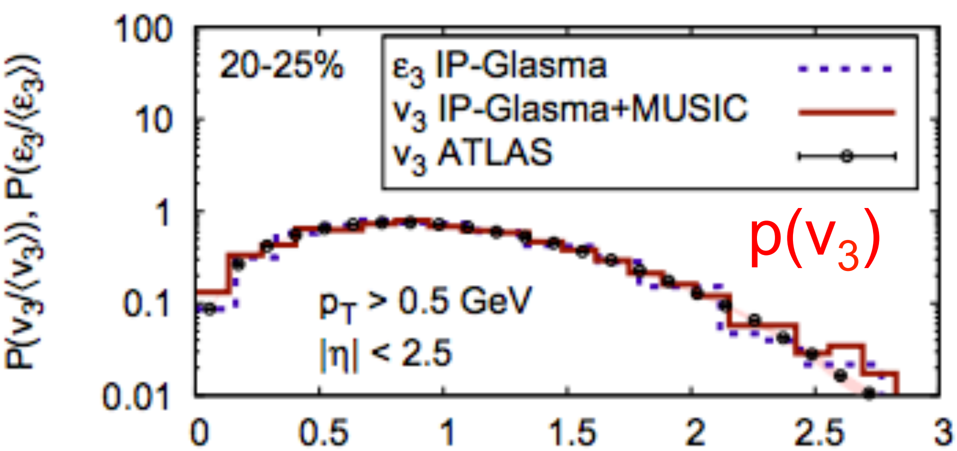
Event by event distribution of flow amplitudes, v_n, and phases, Φ_n.

$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\rm evts}} \frac{dN_{\rm evts}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

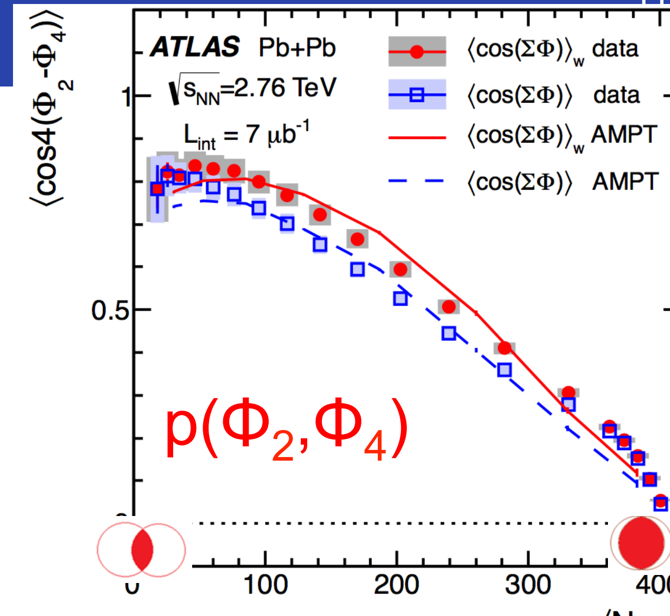
Examples of EbyE distributions

Data: JHEP11(2013)183

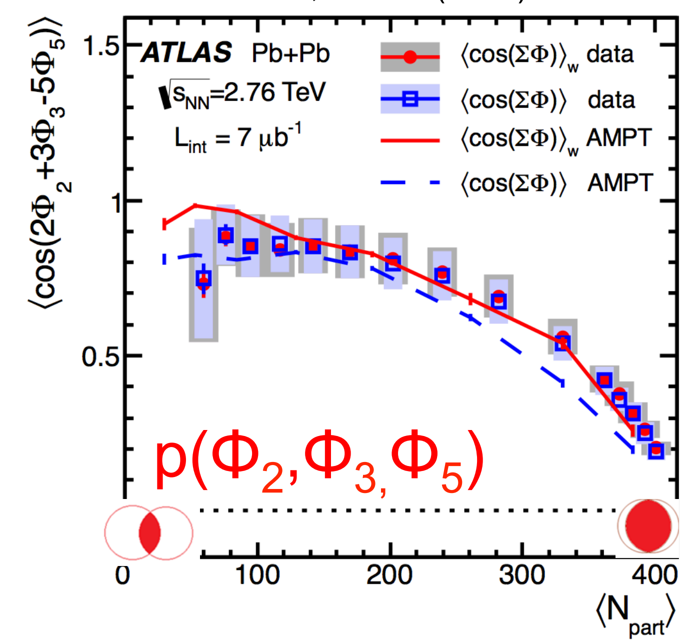




Credit: Bjorn Schenke



PRC90,024905 (2014)



Measured distributions used to tune hydrodynamic models.

$p(v_n, v_2)$ via event-shape engineering technique

Fourier expansion of FCal E_T distribution <u>in each event</u>

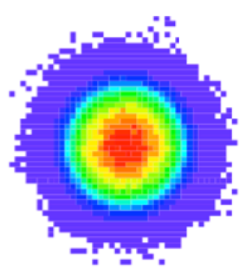
$$\frac{dE_T}{d\phi} = \Sigma E_T \left[1 + 2v_2^{\mathrm{obs}} \cos 2\left(\phi - \Phi_2^{\mathrm{obs}}\right) + 2v_3^{\mathrm{obs}} \cos 3\left(\phi - \Phi_3^{\mathrm{obs}}\right) + \ldots \right]$$

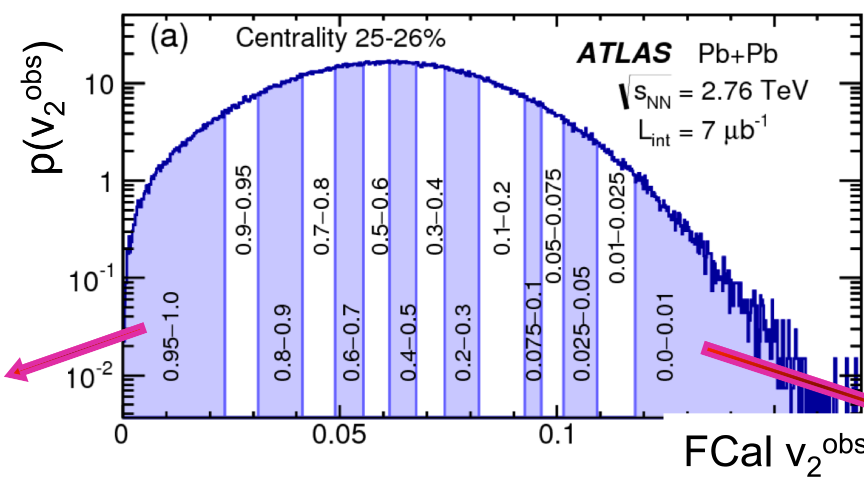
- 1st order event-shape selection: Centrality by ΣE_T (system size)
- 2nd order event-shape selection: ellipticity by v_2^{obs} (system shape)
- 3nd order event-shape selection: triangularity by v_3^{obs} (system shape)

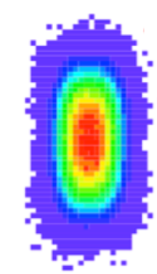
- Select events with same geometric size but different ellipticity

arXiv:1208.4563

arxiv:1311.7091



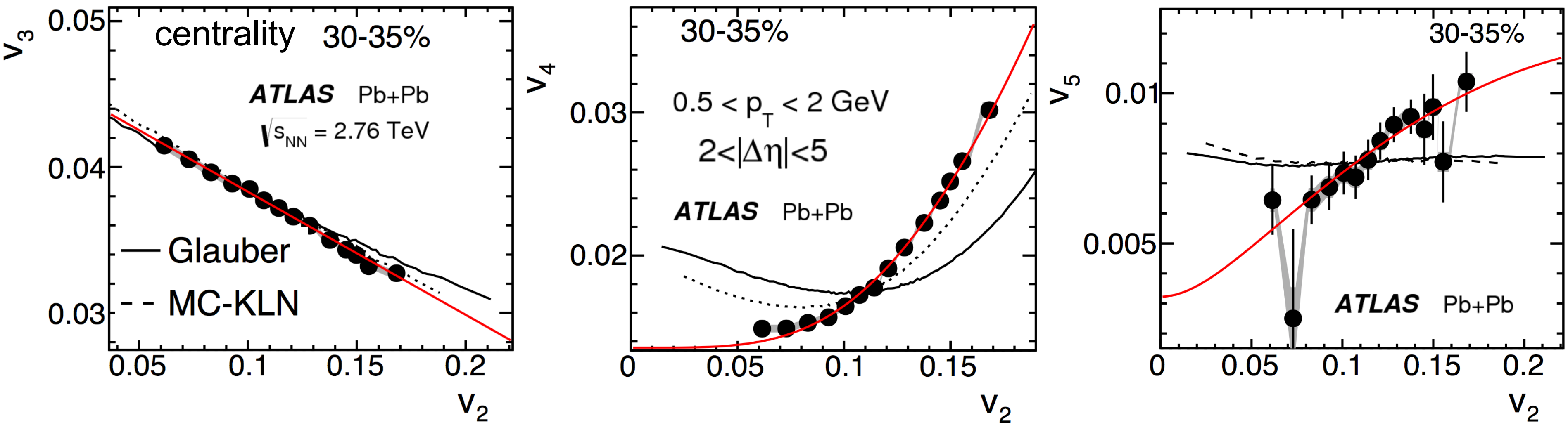




PRC92,034903(2015)

$p(v_n,v_2)$ via event-shape engineering tech.

- Study the correlation between v_2 and higher-harmonics.
  - New insights on initial state fluctuations and fluid non-linear dynamics



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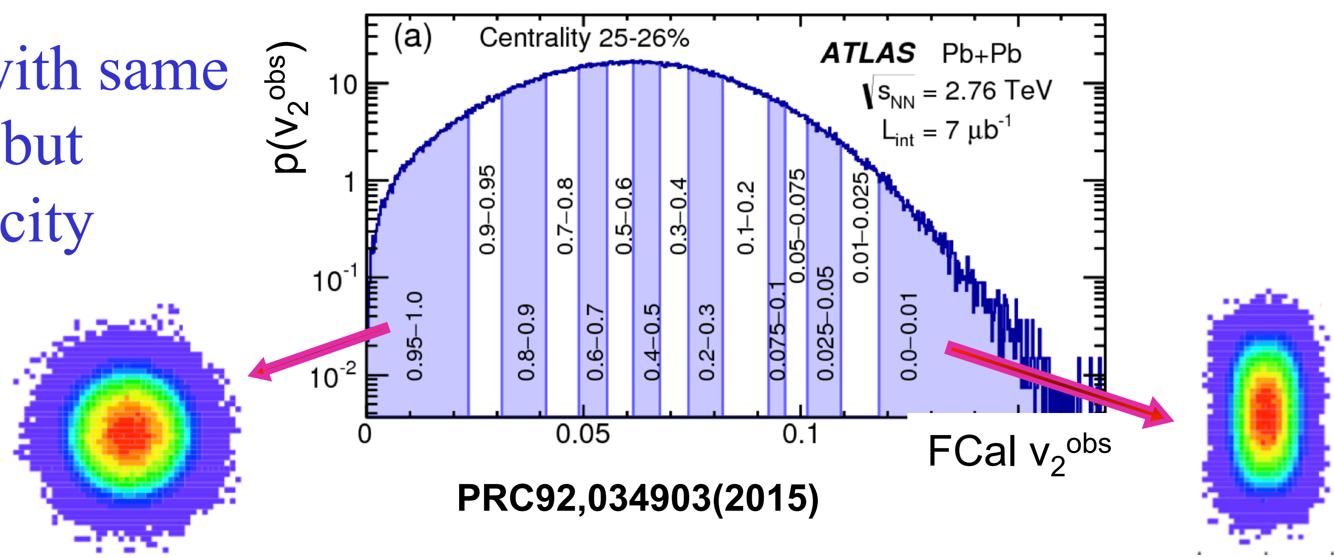
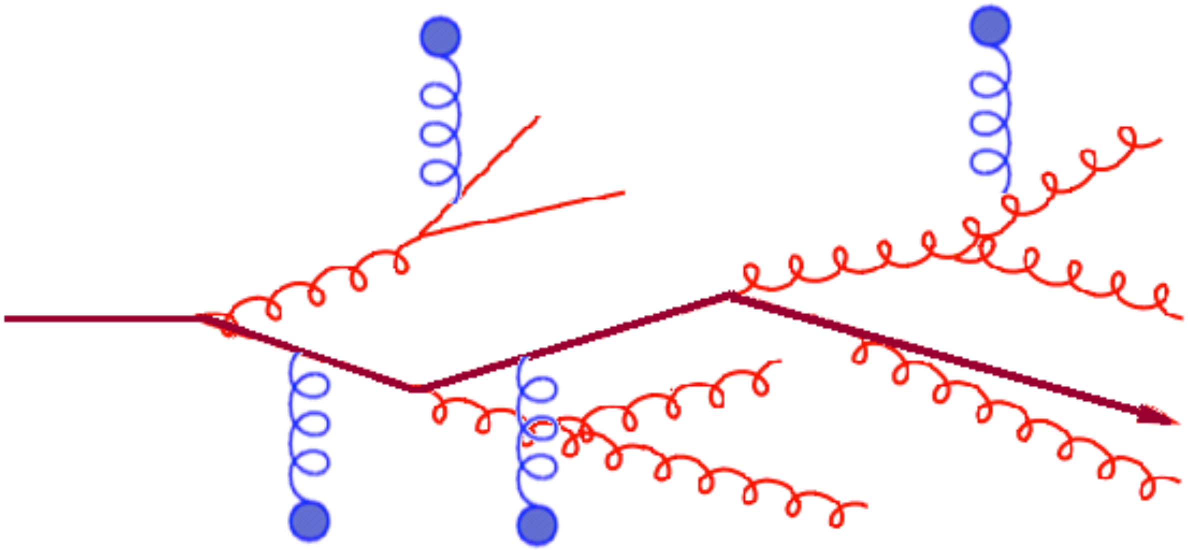


PRC92,034903(2015)

Short wave-length behavior: Jet-medium interaction



- Need to measure
  - Leading parton energy loss distributions: P(ΔE)
  - + Modified parton shower and medium response: $\dfrac{dN^g}{d\omega d^2\mathbf{k}_\perp}$
- Learn about energy loss mechanism
  - Probe the effective DOF and transport properties of medium

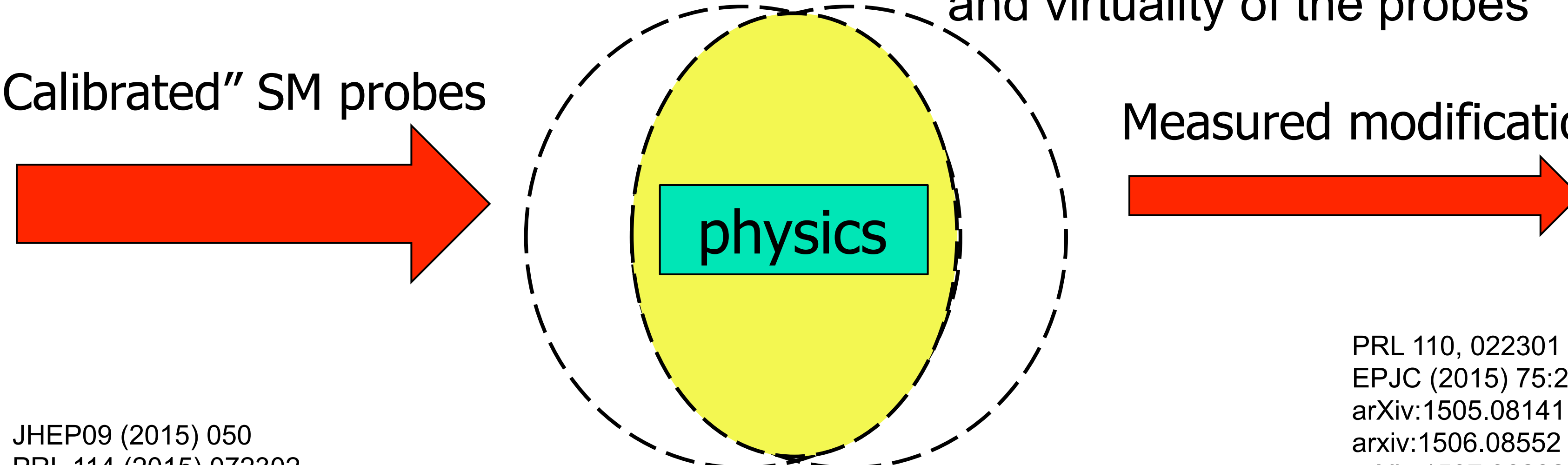
How to study the QGP with hard probes?

throw everything at it !

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

"Calibrated" SM probes

Measured modifications

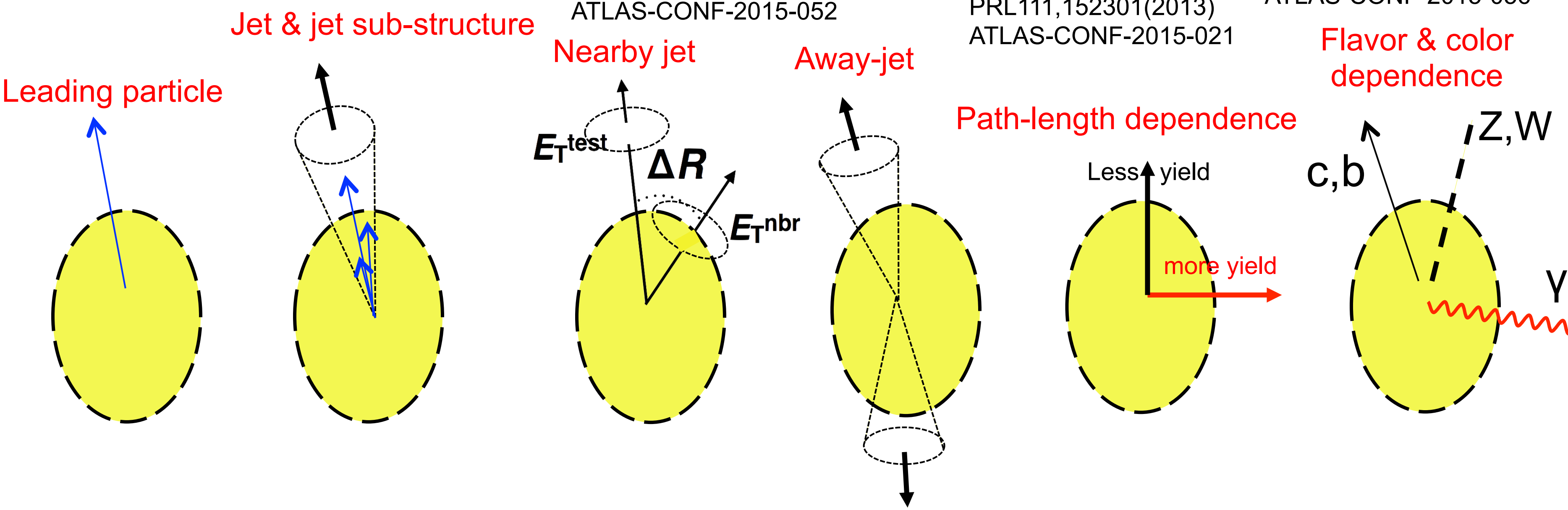


JHEP09 (2015) 050
PRL 114 (2015) 072302
PLB739(2014)320
ATLAS-CONF-2015-055

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

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

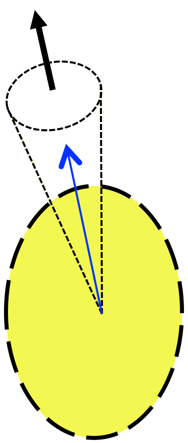
PRL 110, 022301 (2013)
EPJC (2015) 75:23
arXiv:1505.08141
arxiv:1506.08552
arXiv:1507.06232
ATLAS-CONF-2015-053
ATLAS-CONF-2015-056

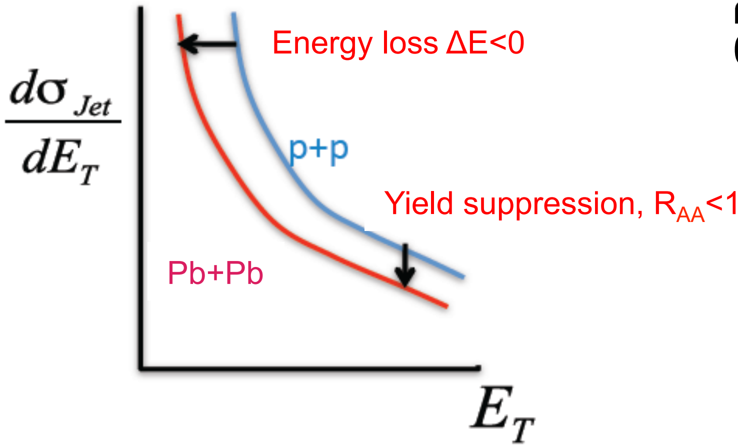


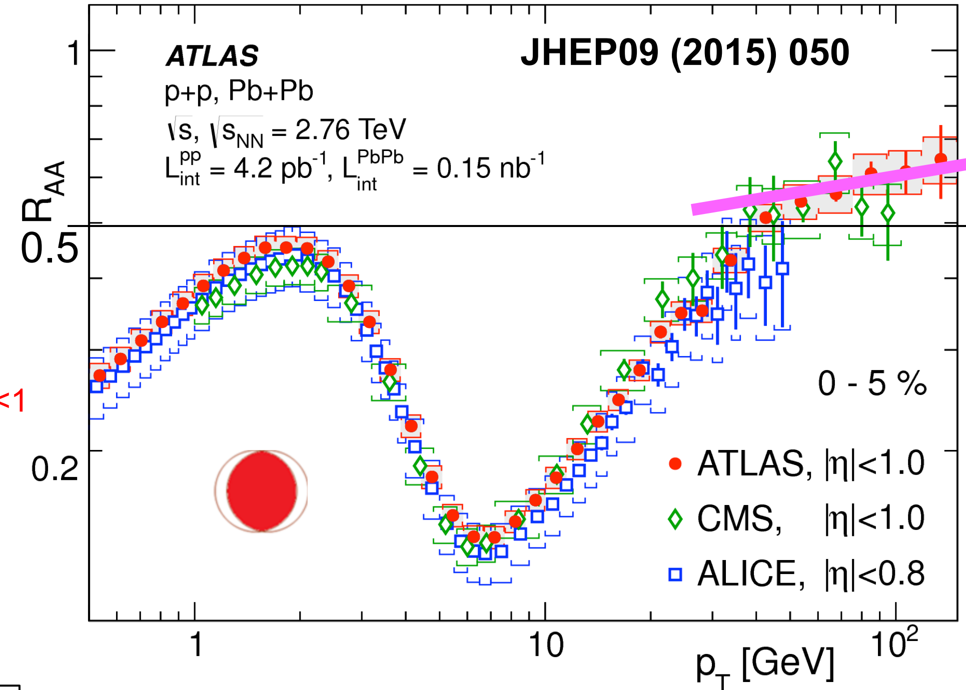
Jet quenching via high-p_T hadrons & jets

- In-medium energy loss leads to suppression in leading-particle and jet yield

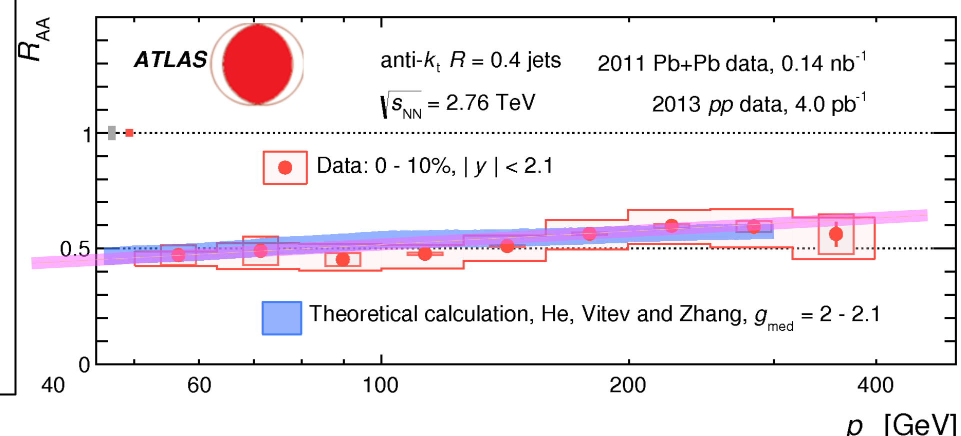
$$R_{AA} = \frac{\text{Yield in Pb+Pb}}{\text{Scaled Yield in pp}}$$







- RUN1 legacy measurements: highest p_T and smallest uncertainty
- $R_{AA}(p_T)$ reflects input-spectra shape & $\Delta E(p_T)$
- Suppression of yield is ~2 in central Pb+Pb 40-400 GeV
- For first time see a slight increase of R_{AA} with p_T: 0.4-0.6 (consistent with theory)



PRL 114 (2015) 072302

Modification of jet sub-structure

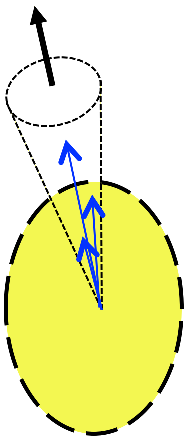
PLB739(2014)320

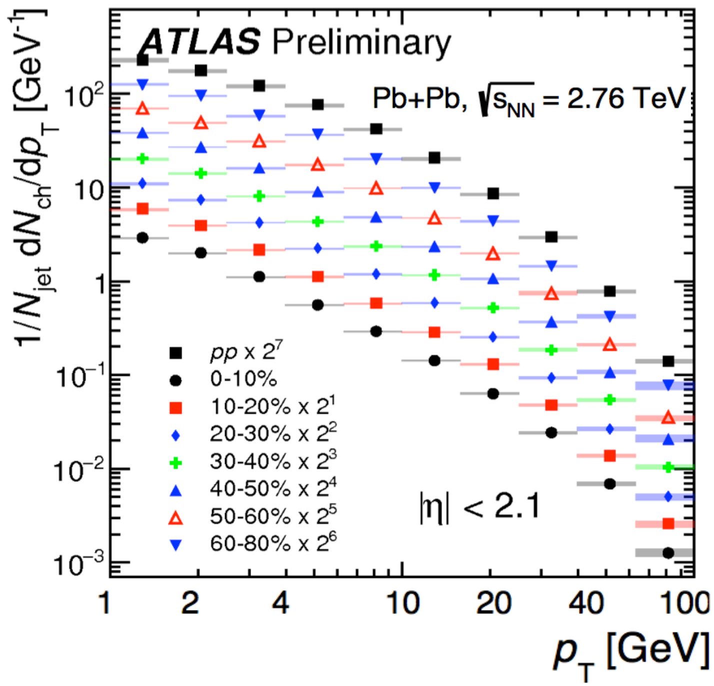
Update: ATLAS-CONF-2015-055

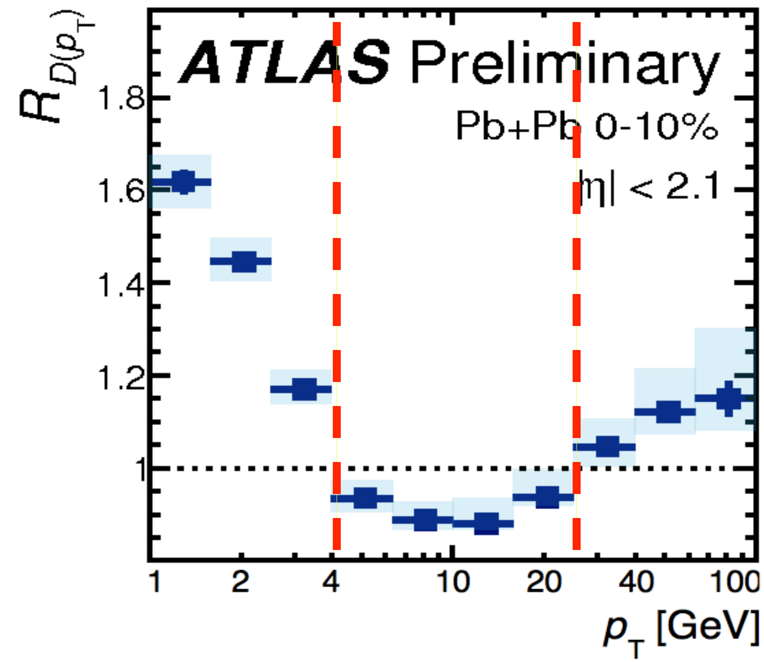
$$D(p_{\mathrm{T}}) = \frac{1}{N_{\mathrm{jet}}}\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{ch}}}$$

Jet p_T>100 GeV

R_D= D(cent)/D(peri.)







- Results extended to lower p_T frag, new pp ref, and details in jet p_T and η
- Characteristic modification of fragmentation yield:
  - Low p_T enhanced (1-4 GeV)
  - Moderate p_T suppressed (4-25 GeV)
  - High pT enhanced (>25 GeV)

Modification of jet sub-structure

PLB739(2014)320

Update: ATLAS-CONF-2015-055

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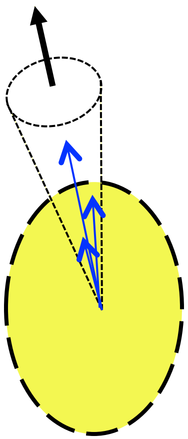
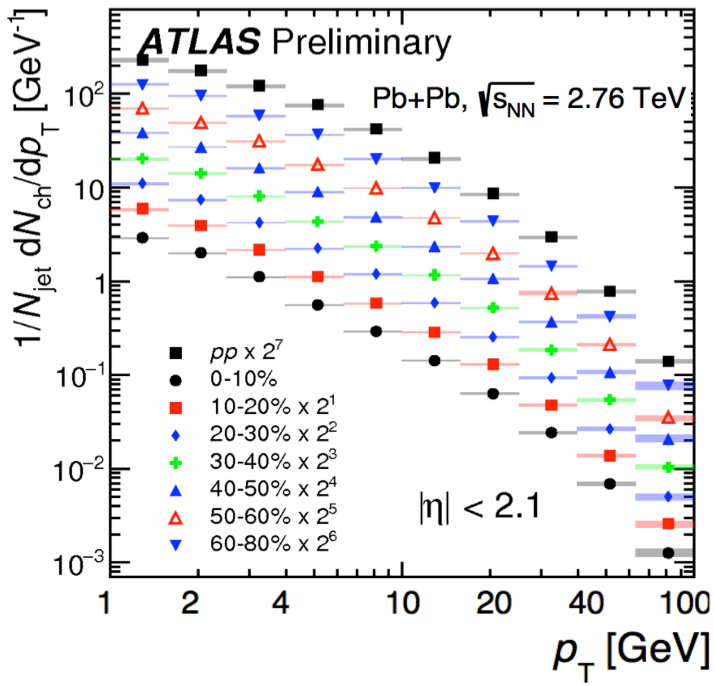
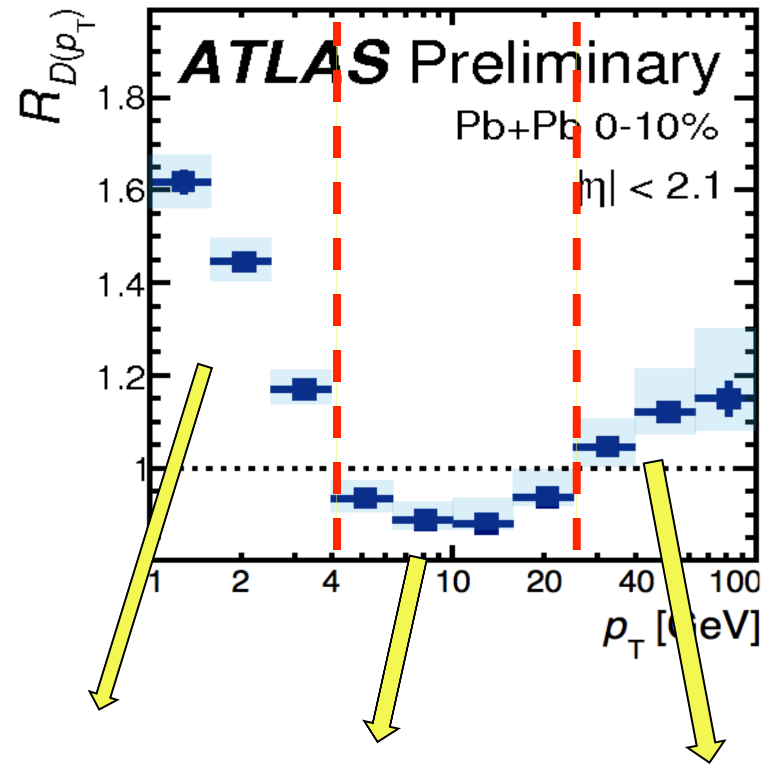






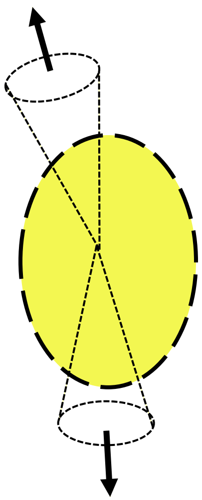
~2.7 GeV ~ −3.9 GeV ~1.8 GeV

Quantify p_T flow via:

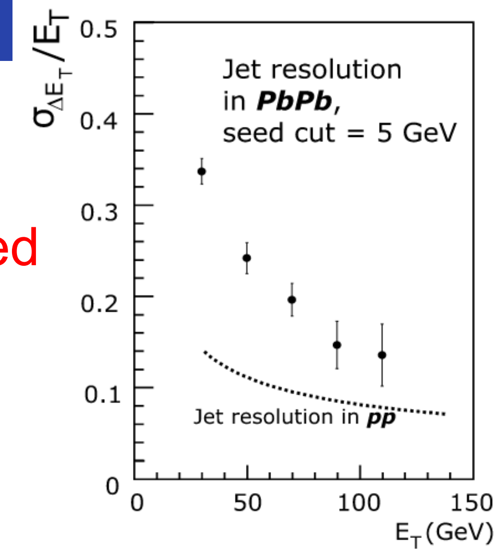
$$P_\mathrm{T}^\mathrm{ch} \equiv \int_{p_\mathrm{T,min}}^{p_\mathrm{T,max}} \left(D(p_\mathrm{T})|_\mathrm{cent} - D(p_\mathrm{T})|_\mathrm{pp} \right) p_\mathrm{T}\, \mathrm{d}p_\mathrm{T}$$

sum: 0.8±0.7 GeV, p_T flow is balanced!

Dijet energy imbalance



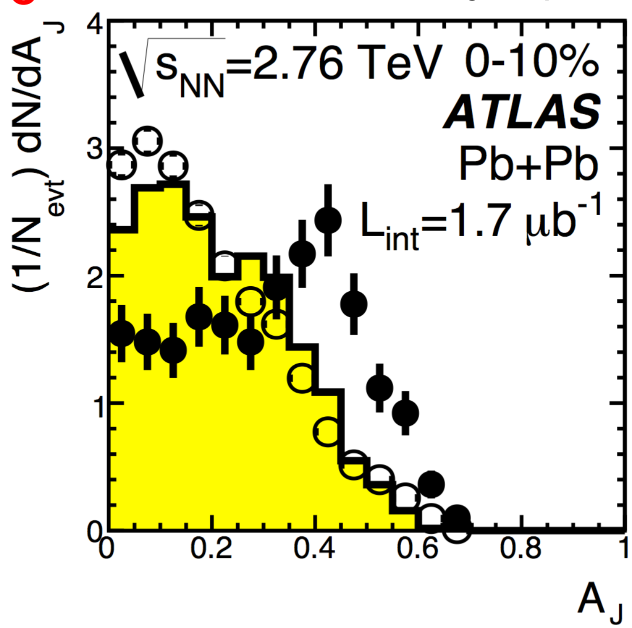
A_J or x_J distributions are smeared by detector and UE fluctuation



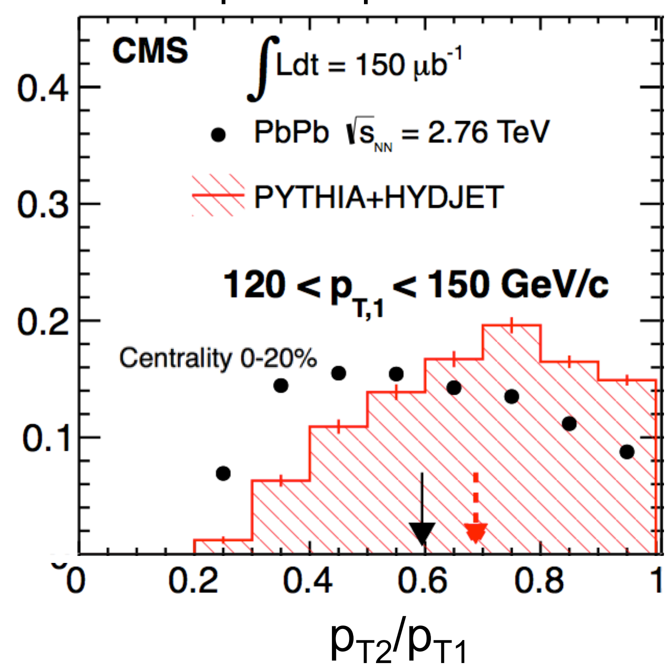
$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

$$x_J = p_{T2}/p_{T1}$$

2010 direct observation of jet quenching



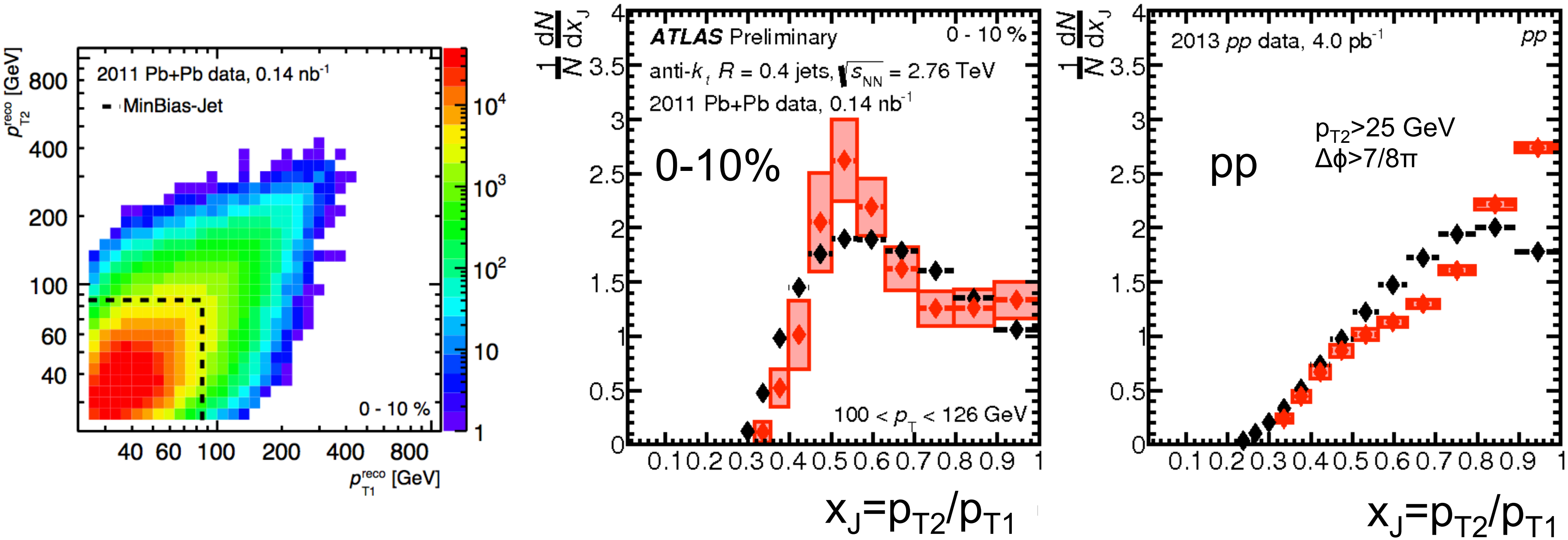
2012 Improved precision



Unfolded dijet imbalance distribution

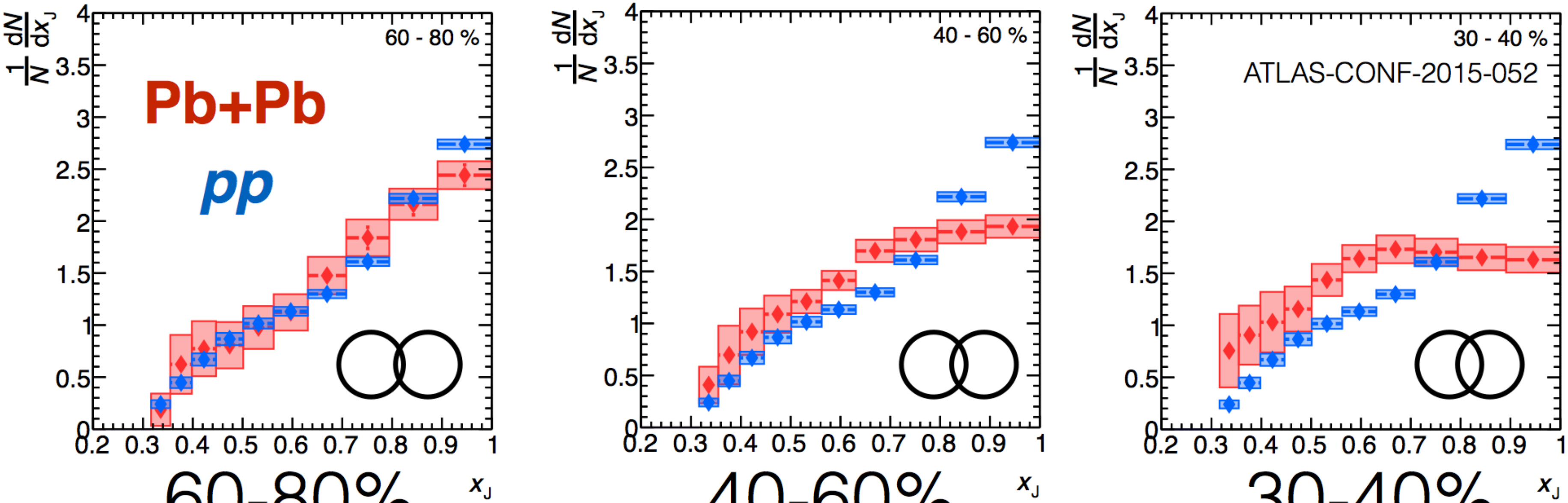
ATLAS-CONF-2015-052

- 2D-Unfolding of di-jet (p_{T1}, p_{T2}) spectra
  - Accounts for p_T migration and switch between p_{T1}& p_{T2}
  - Flow and combinatorial background subtraction
- Unfolded (p_{T1}, p_{T2}) distribution projected to x_J.



Unfolding changes the shape and mean of x_J distribution

x_J distribution vs centrality



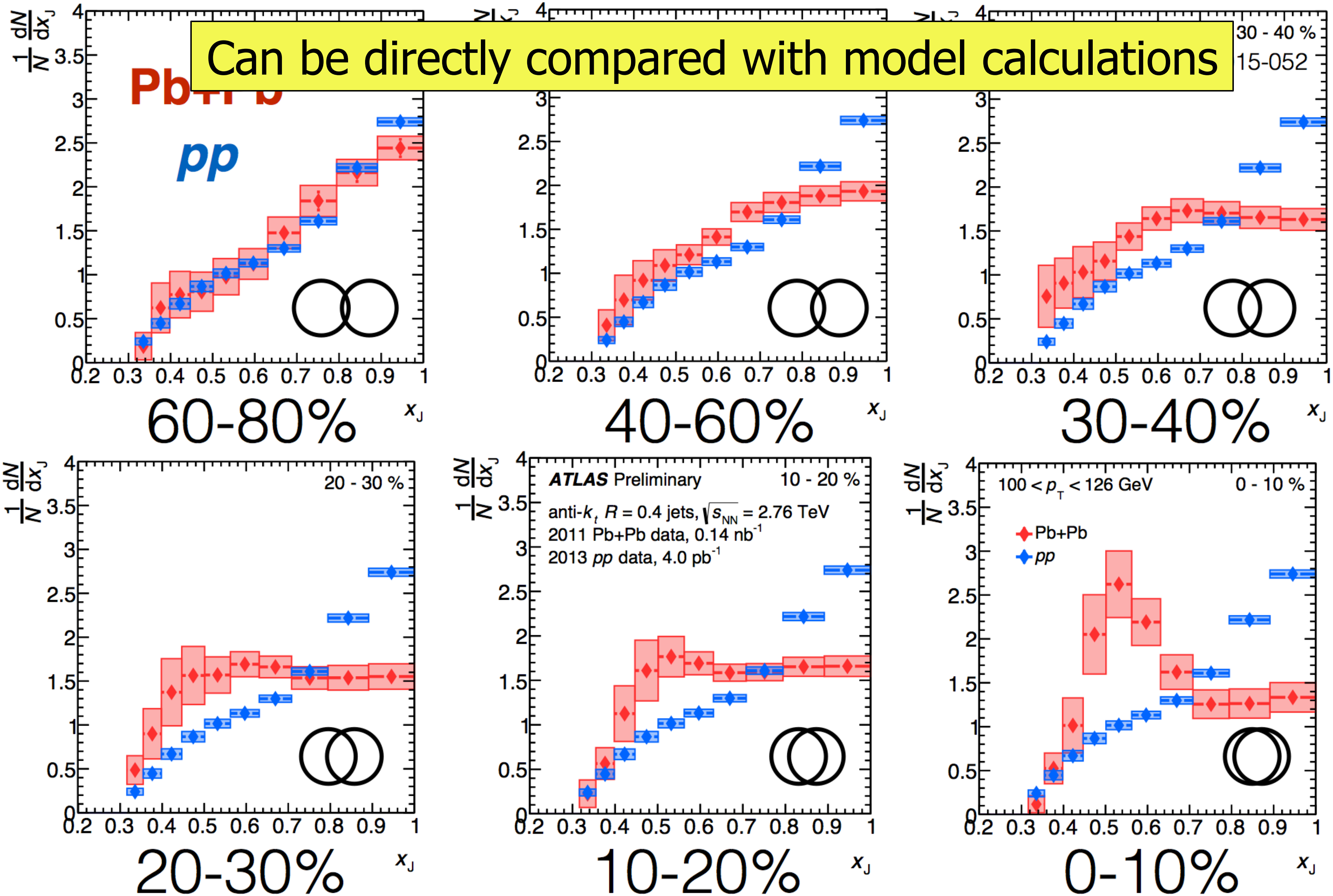
60-80%

40-60%

30-40%

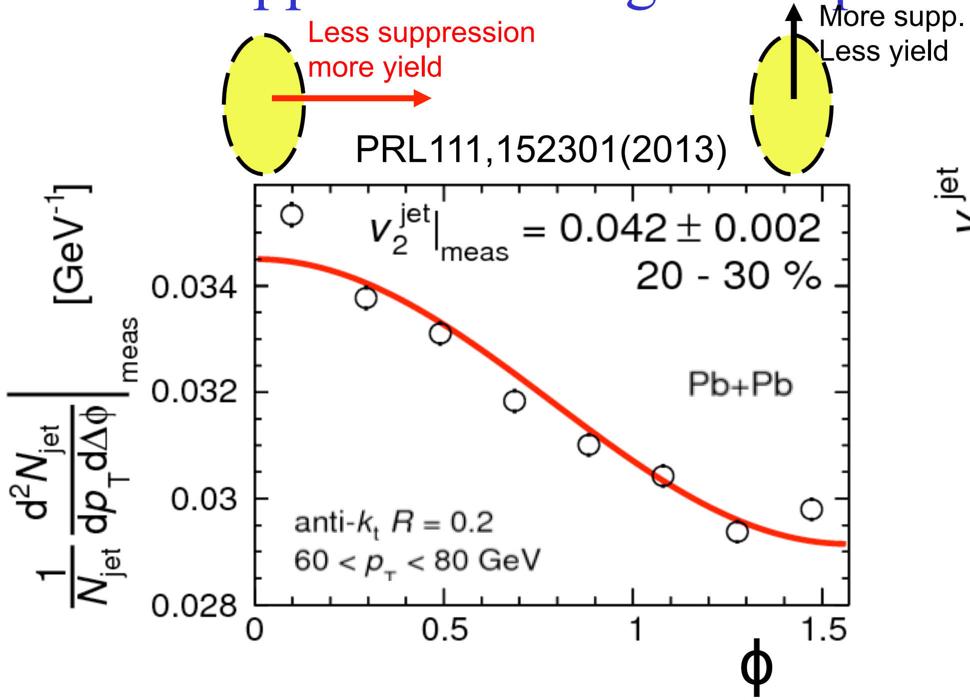
x_J distribution vs centrality

Can be directly compared with model calculations

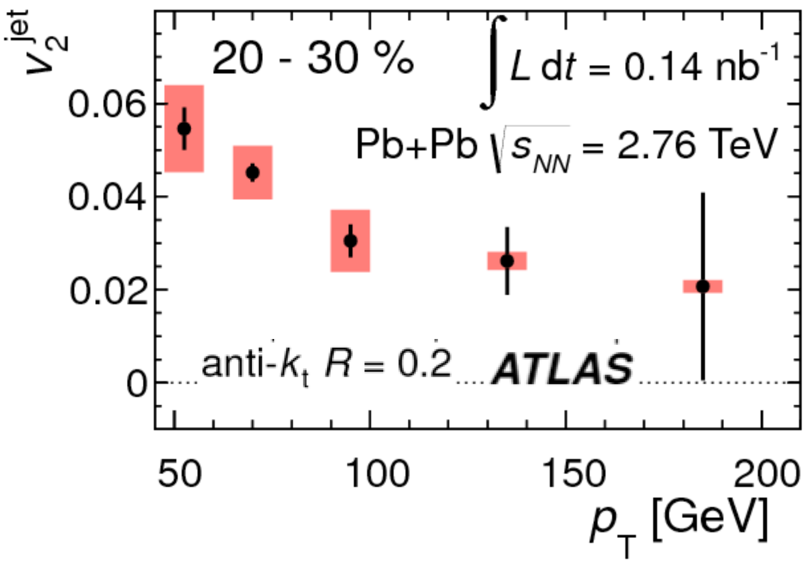


Detailed jet path-length dependence

- More suppression along event-plane direction $R_{AA}(\phi) = R_{AA}\left[1 + 2\, v_2 \cos 2\phi\right]$



high p_T: decrease of v_2 consistent with smaller quenching (larger R_{AA})



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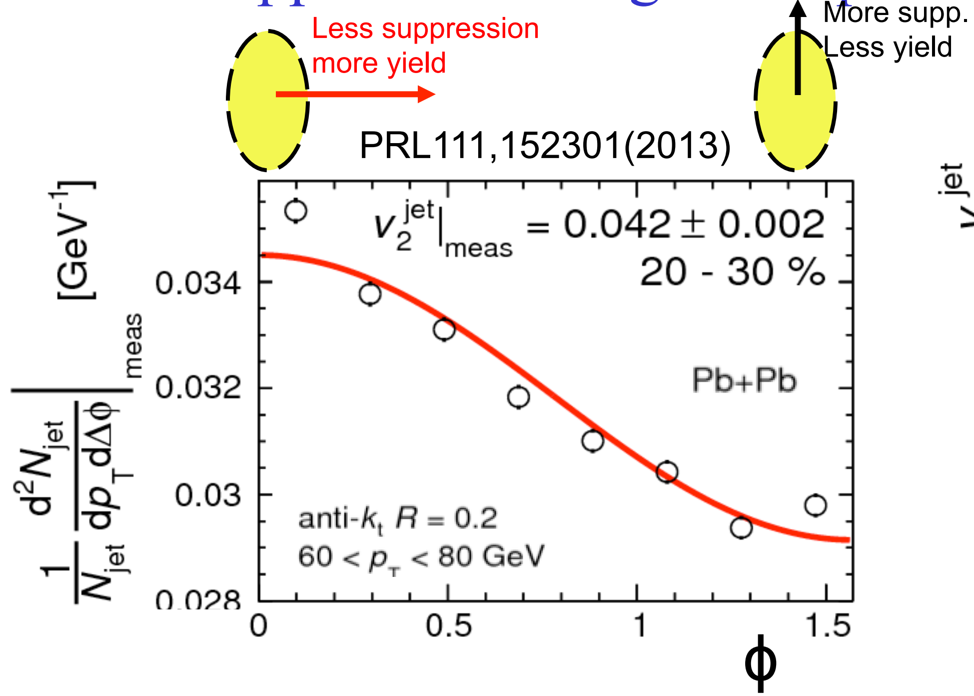
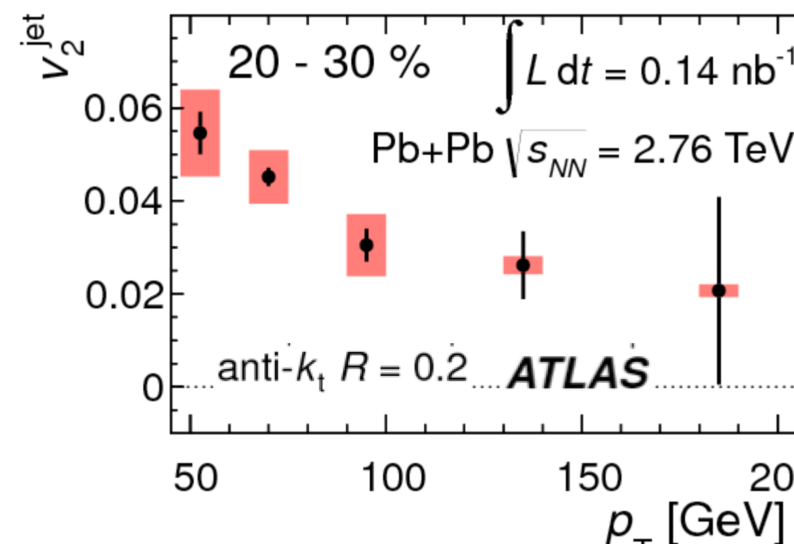
- More suppression along event-plane direction $R_{AA}(\phi) = R_{AA}\left[1 + 2\, v_2 \cos 2\phi\right]$



high p_T: decrease of v_2 consistent with smaller quenching (larger R_{AA})

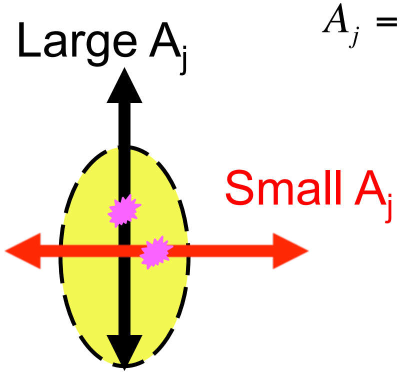


- Dijet asymmetry vs angle wrt event-plane:

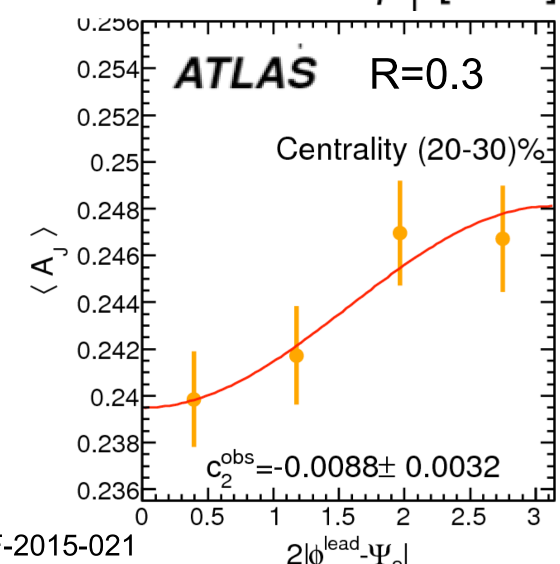
$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

E_{T1}>100 GeV

E_{T2}>25 GeV

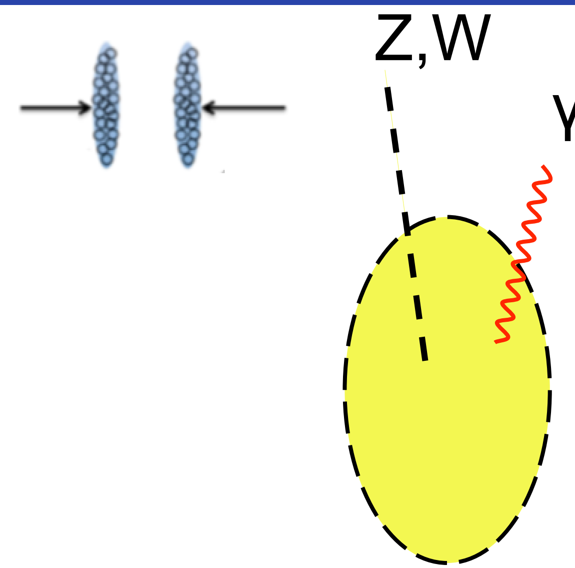


A_J is smaller along event-plane direction!



ATLAS-CONF-2015-021

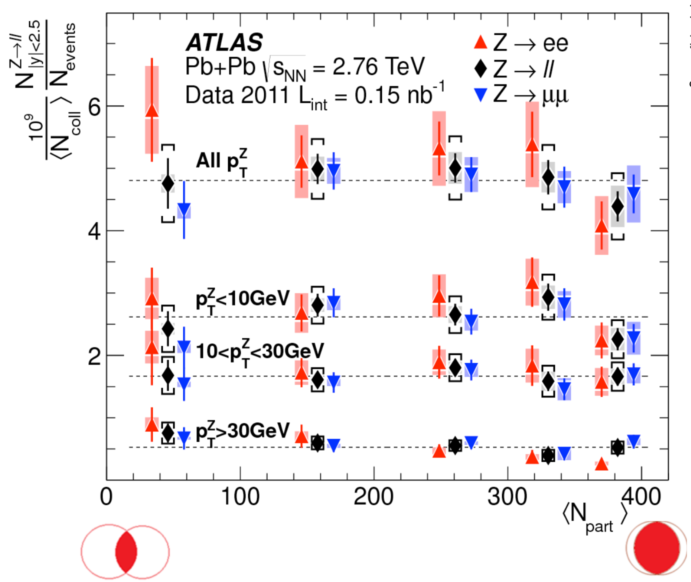
Calibration of initial state: EW probes in Pb+Pb



Can we calibrate initial condition & hard-probe rates prior to QGP formation?

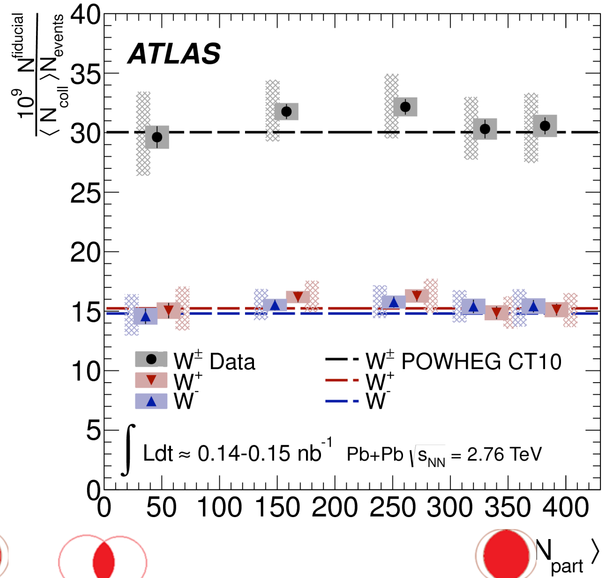
- Good calibration of geometry (N_{coll}, N_{part}).
  - $AA_{Rate} \approx N_{coll}$ x pp_{rate}.

N_{coll} scaling of Z



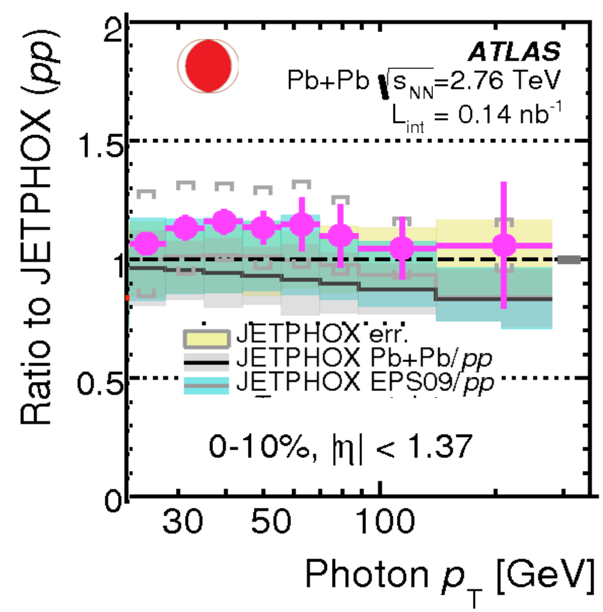
PRL 110, 022301 (2013)

N_{coll} scaling of W



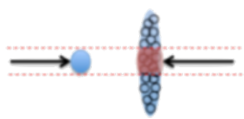
EPJC (2015) 75:23

γ rate agree with pQCD



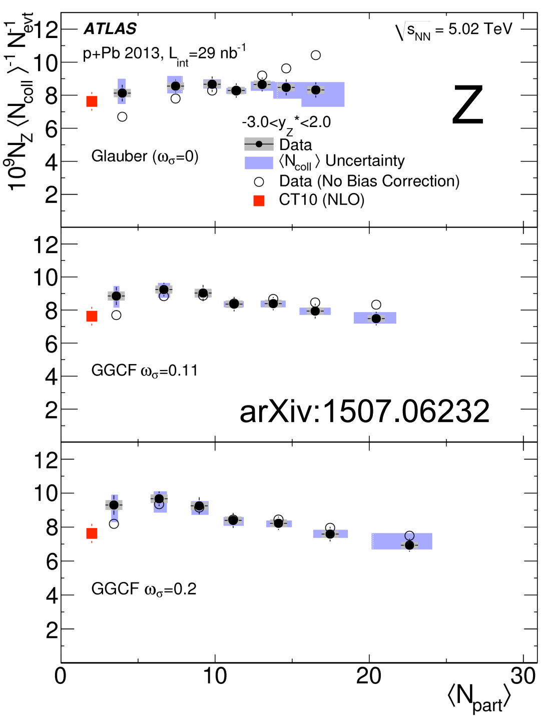
arxiv:1506.08552

Calibration of initial state: EW probes in p+Pb

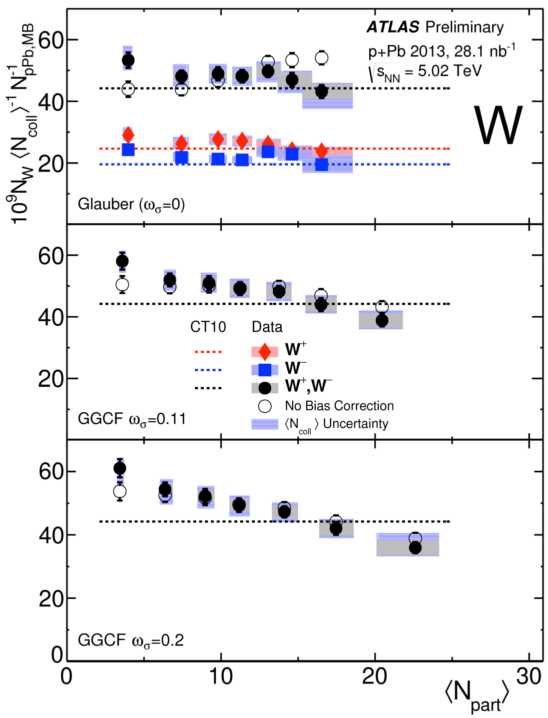


ATLAS-CONF-2015-056

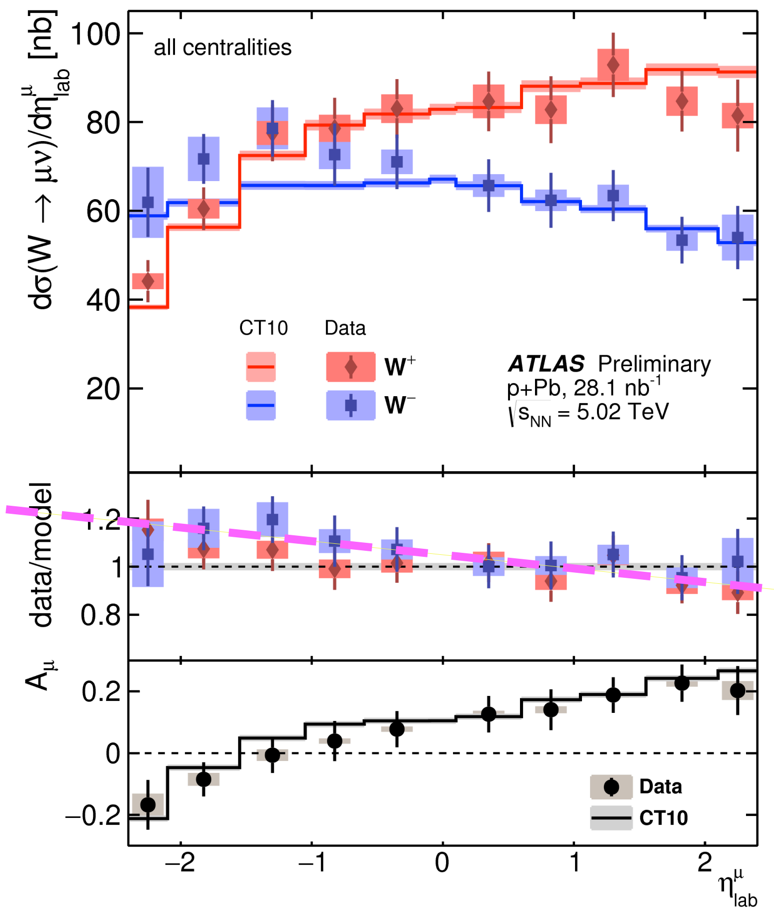
Yield ≈ N_{coll}-scaling

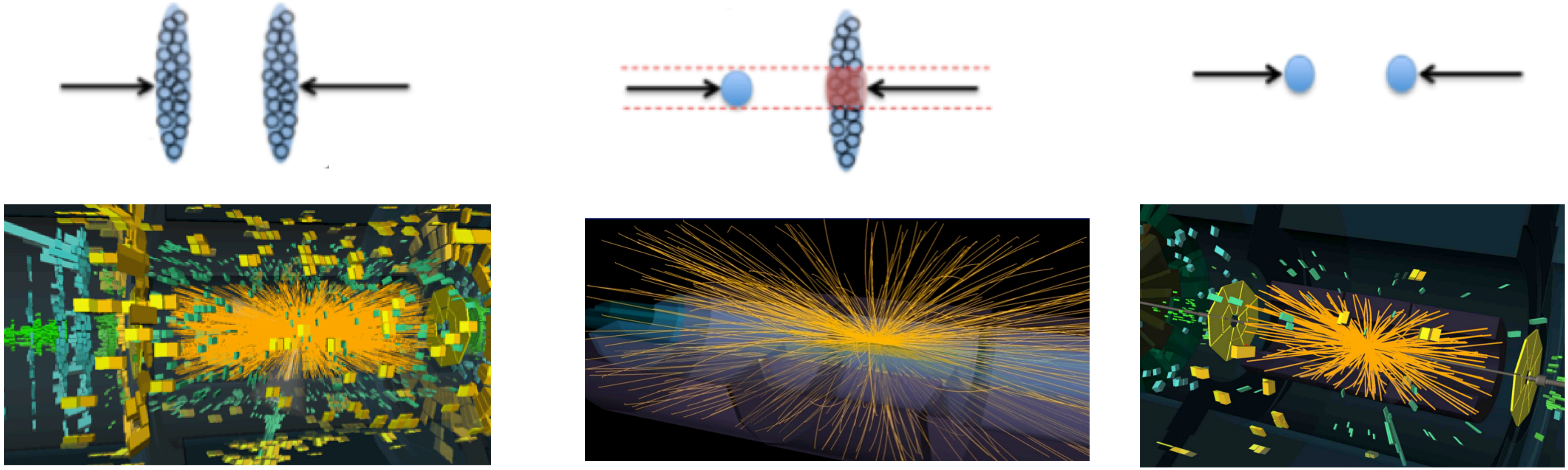


arXiv:1507.06232



dN/dη indicates effects of isospin & nPDF





~30000 particles* ~1000 particles* ~few 100 particles*

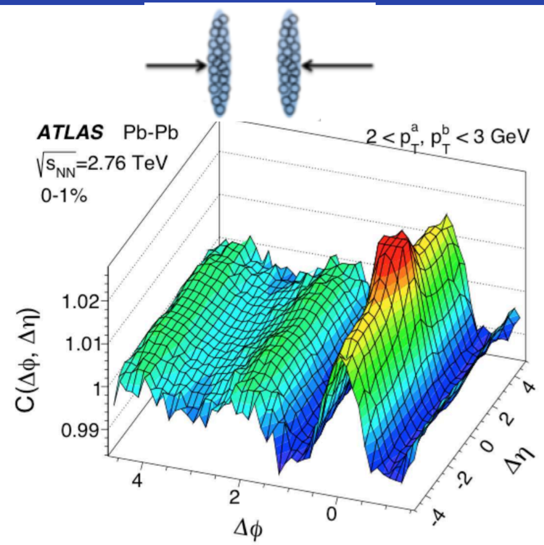
What is the smallest droplet of QGP created in these collisions?

Reveal possible collective/flow like behavior via
the two-particle correlation method

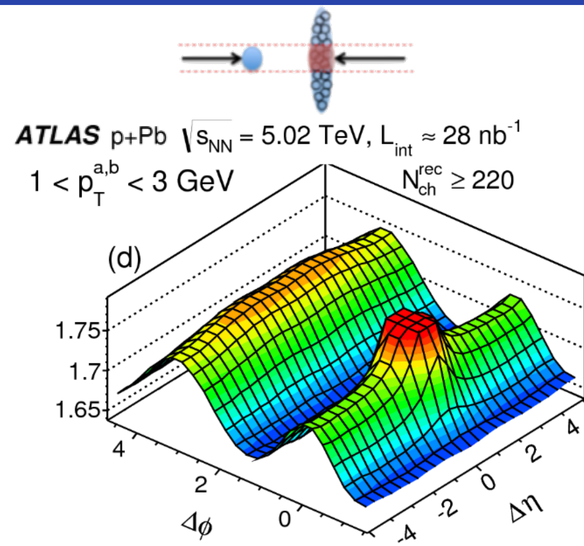
$$\frac{dN}{d\Delta\phi} = \left[\frac{dN}{d\phi_1} * \frac{dN}{d\phi_2}\right] \propto 1 + \sum_n 2 \mathrm{v}_n^a \mathrm{v}_n^b \cos(n\Delta\phi)$$

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

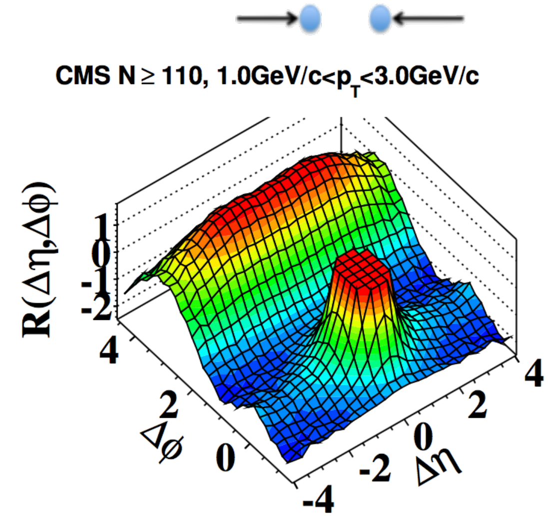
The tale of the three ridges



The ridge in A+A attributed to collective flow

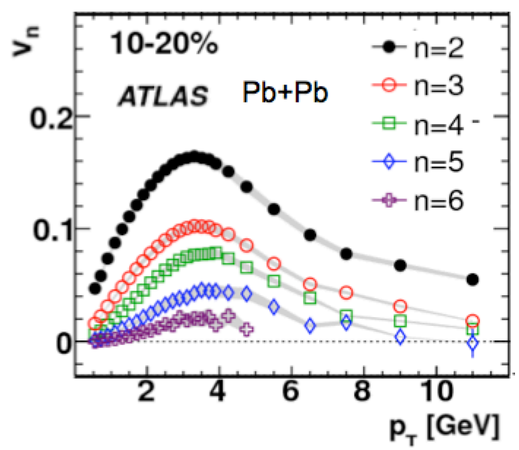


pPb ridge observed in 2012

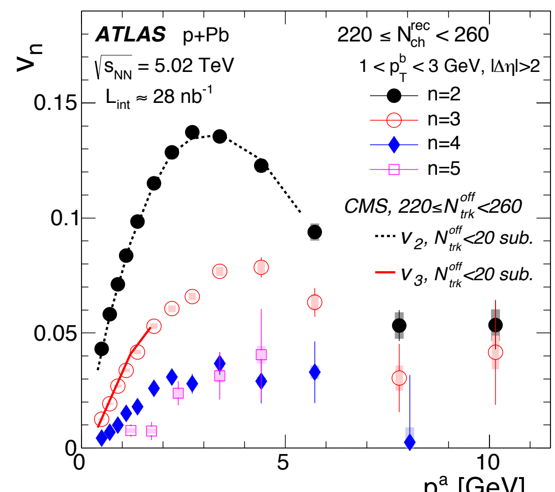


pp ridge observed in 2010

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



Single-particle v_n was measured



PRC90,044906 (2014)

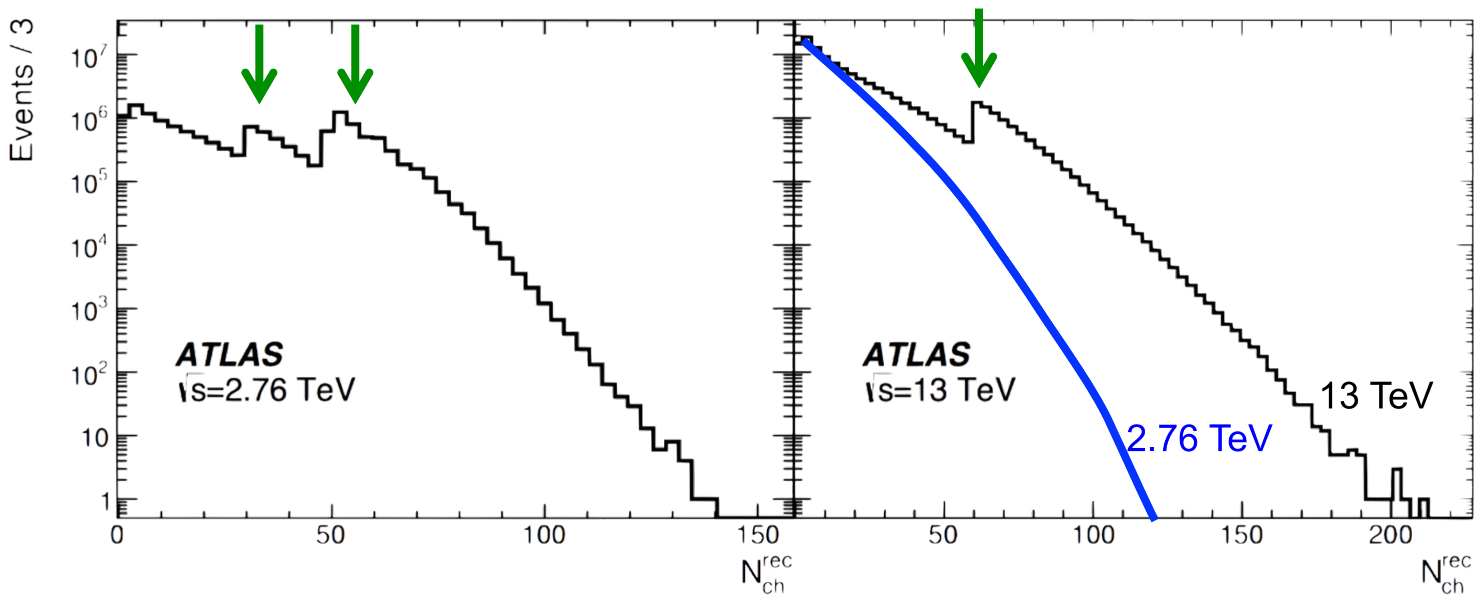
v_n was soon measured

- Single-particle v_n?
- Energy-dependence?
- Is it collective?
- Initial or final-state effects?

pp datasets for ridge studies

- 2.76 TeV and 13 TeV pp data
- High-Multiplicity Track triggers used to increase statistics.
  - HMT triggers also used in pPb ridge studies

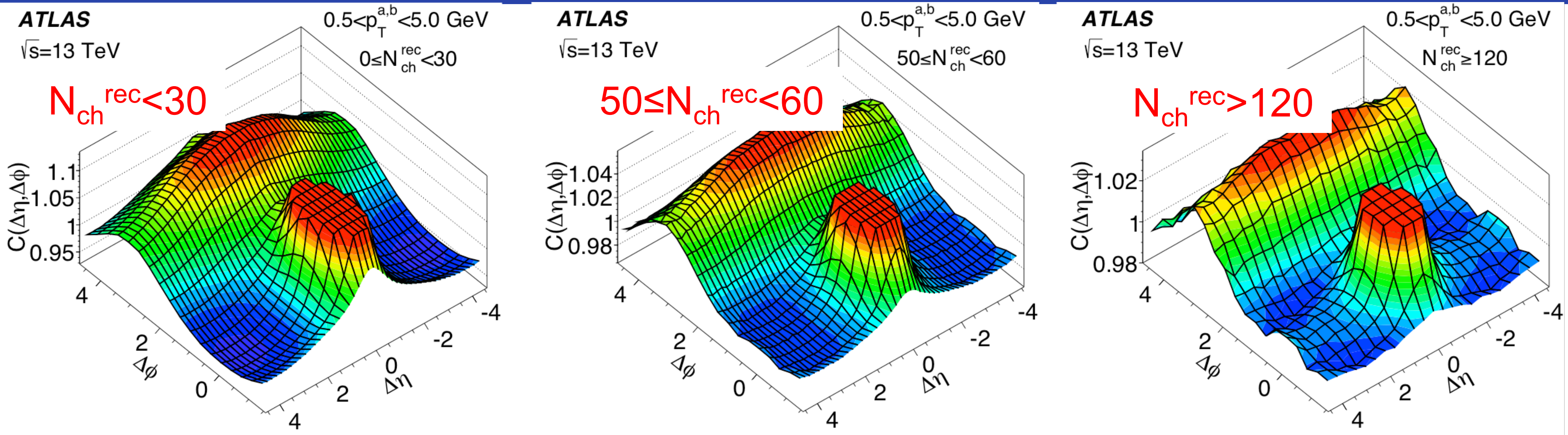
ATLAS-CONF-2013-104



What controls the ridge: N_{ch} or $\sqrt{s}$ or $p(N_{ch})$?

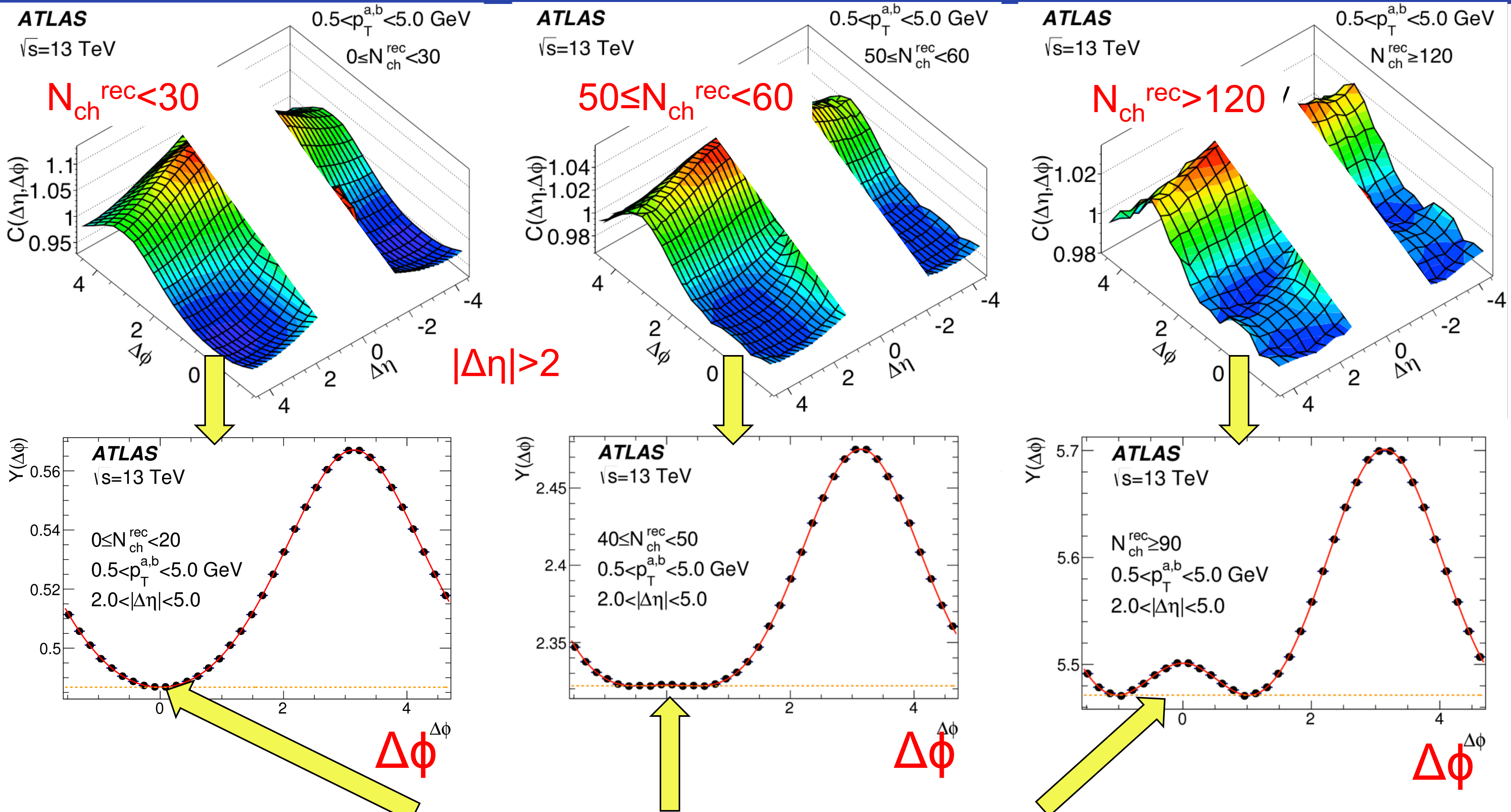
The “hidden” pp ridge

arxiv:1509.04776



The "hidden" pp ridge

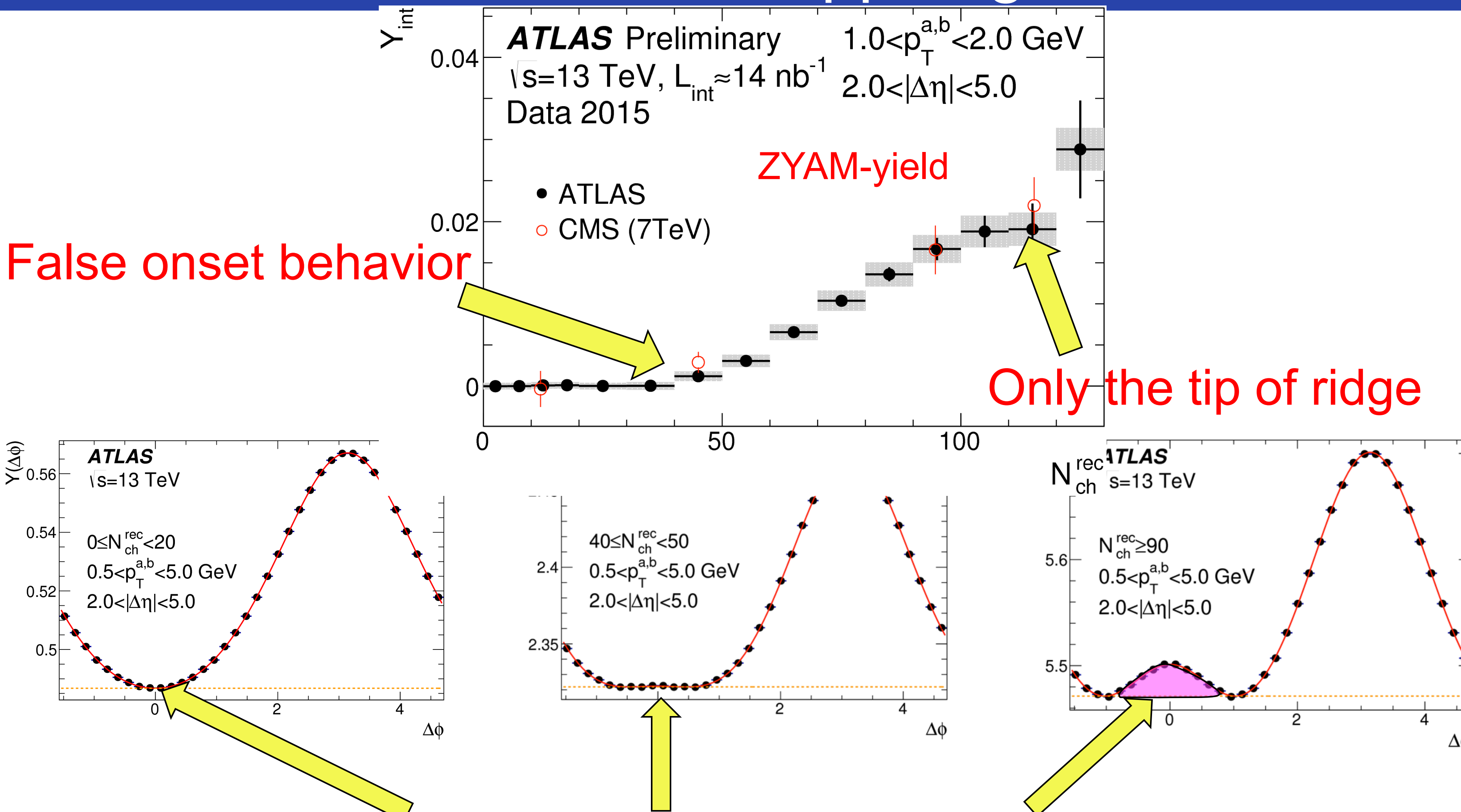
arxiv:1509.04776



Ridge could be masked by away-side tails

The “hidden” pp ridge

arxiv:1509.04776



Ridge could be masked by away-side tails

ZYAM (zero-yield-at-minimum) procedure often used

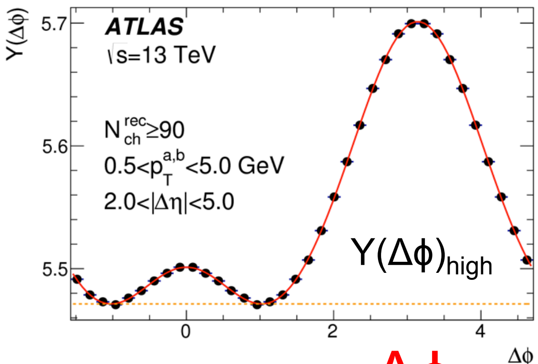
How to expose the “entire” ridge (if we know how to define it)?

The "hidden" pp ridge

arxiv:1509.04776

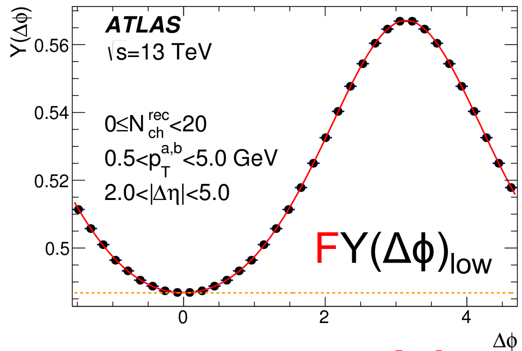
Observation: $Y(\Delta\phi)_{\text{high-mult}} \cong FY(\Delta\phi)_{\text{low-mult}} + A\cos 2\Delta\phi + C$

Other harmonics much smaller



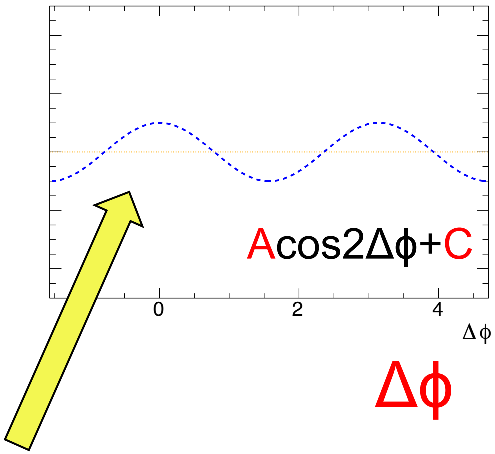
Δφ

=



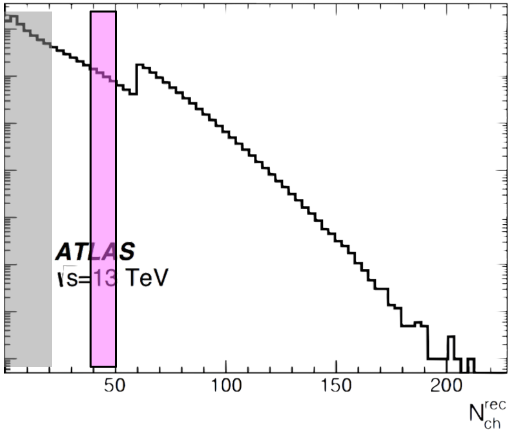
Δφ

+



Δφ

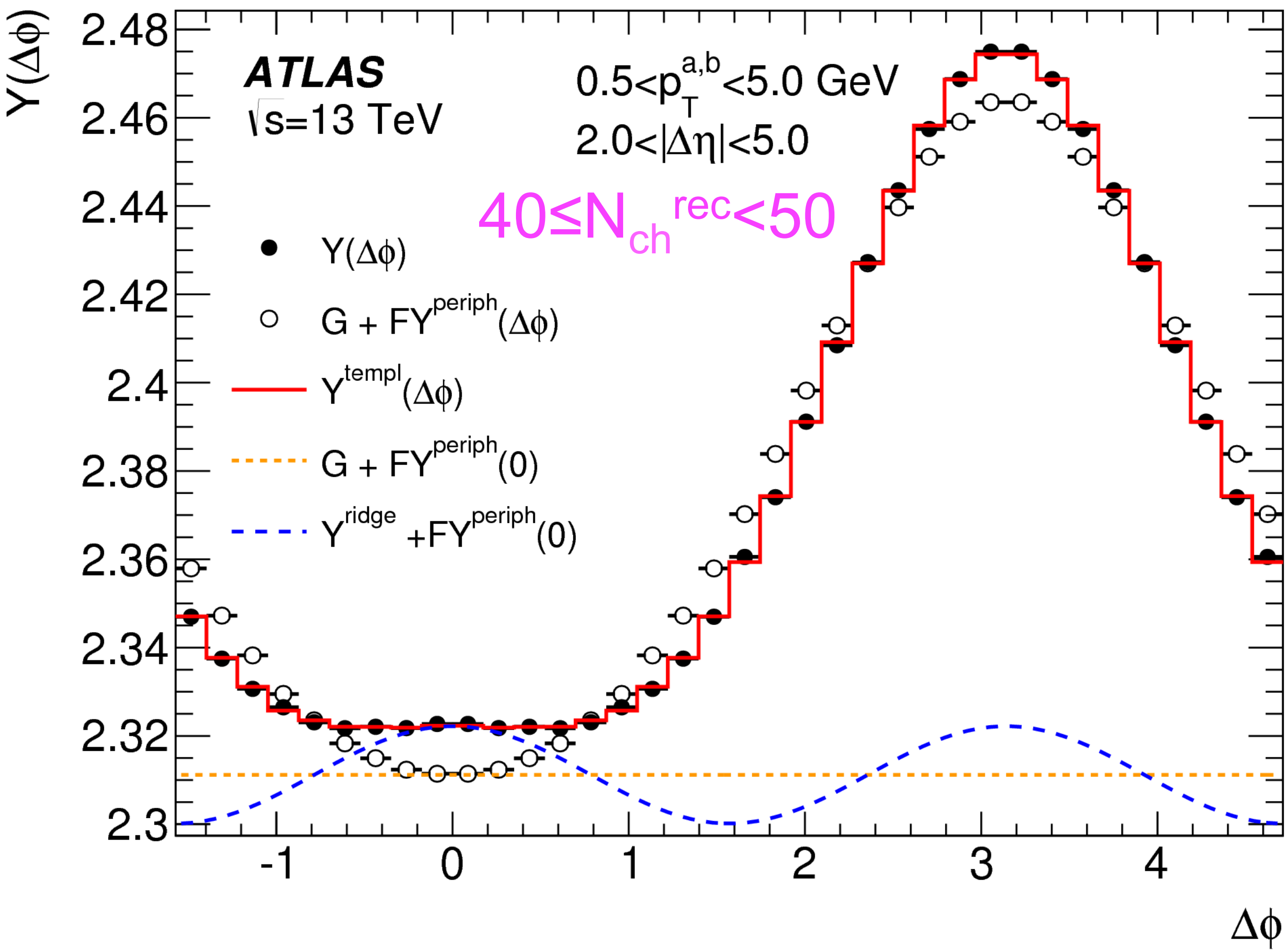
Operational definition of ridge



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

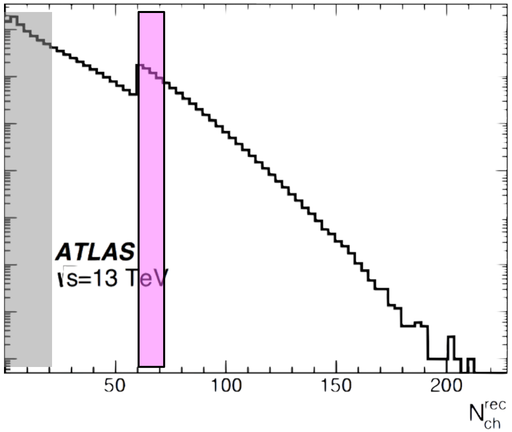
arxiv:1509.04776

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

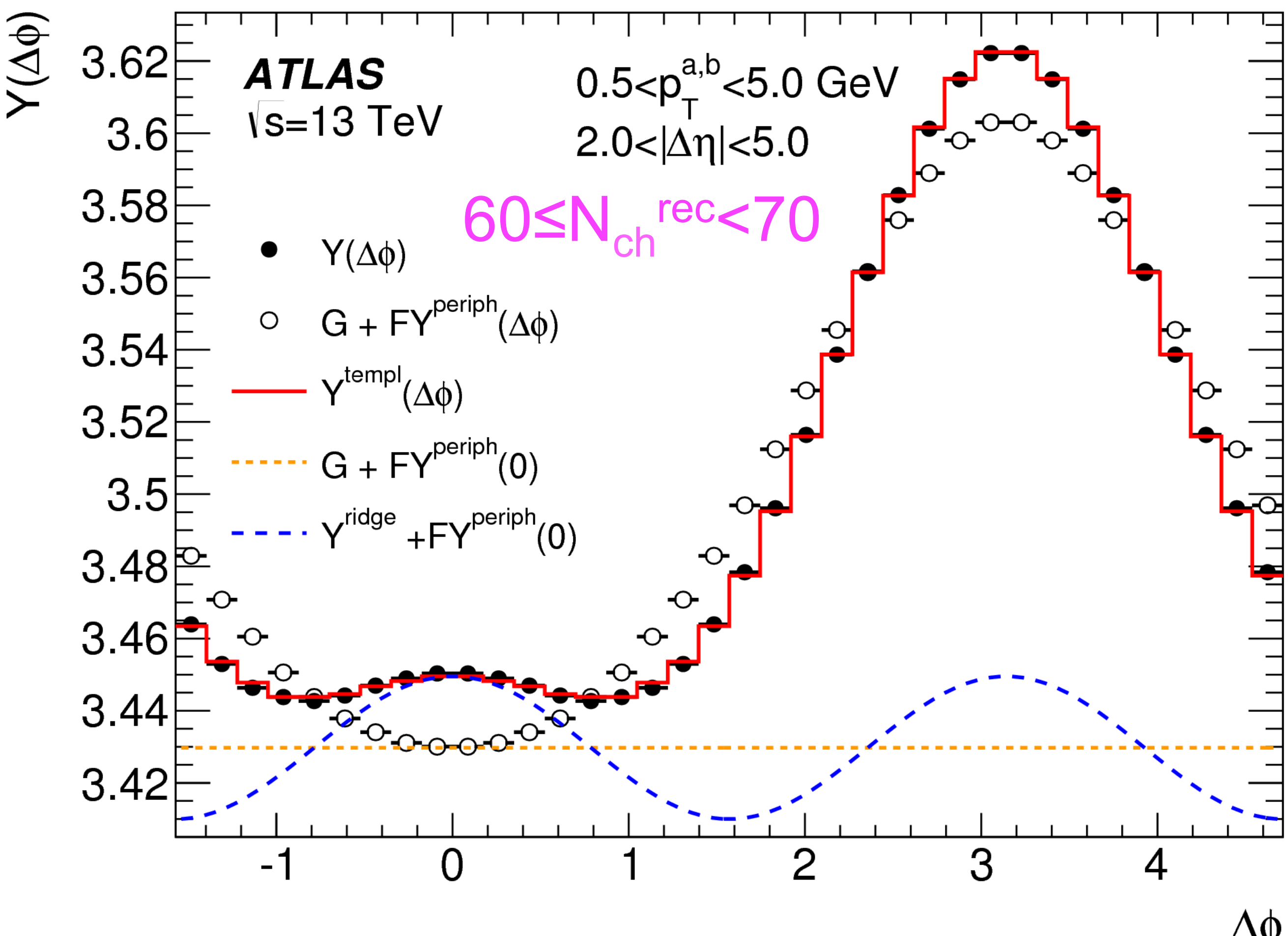


Low multiplicity bin: N_{ch}^{rec}<20

arxiv:1509.04776

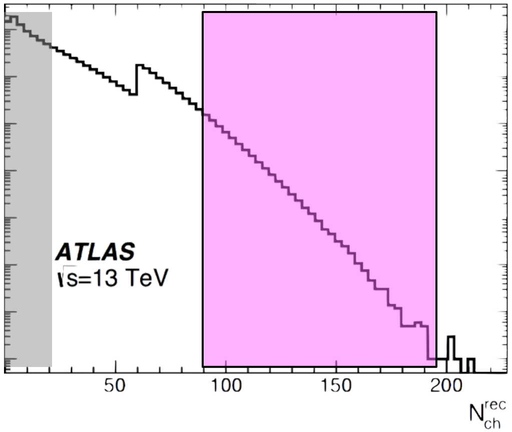


$Y(\Delta\phi)_{Fit} \cong FY(\Delta\phi)_{low\text{-}mult} + A\cos 2\Delta\phi + C$

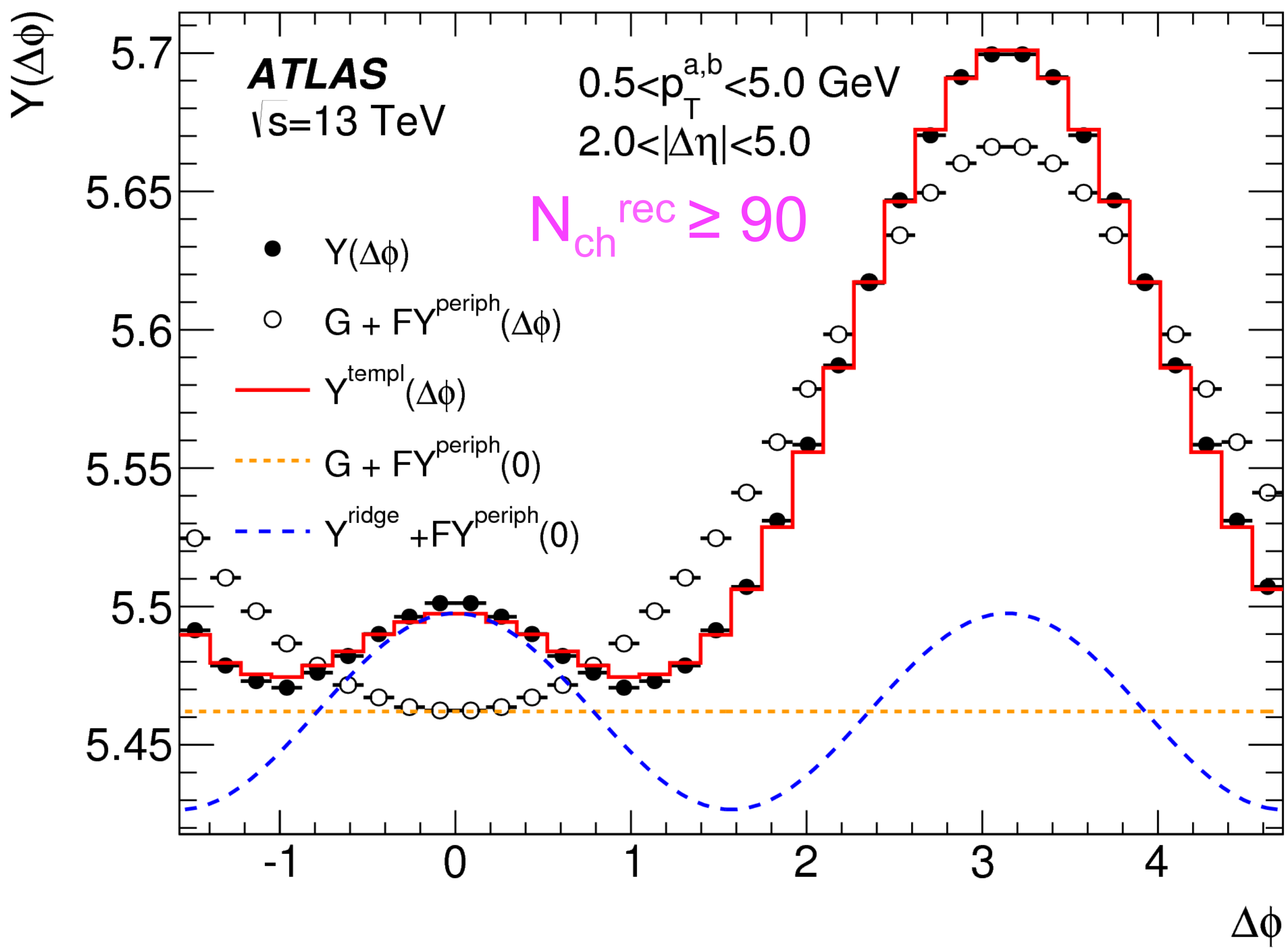


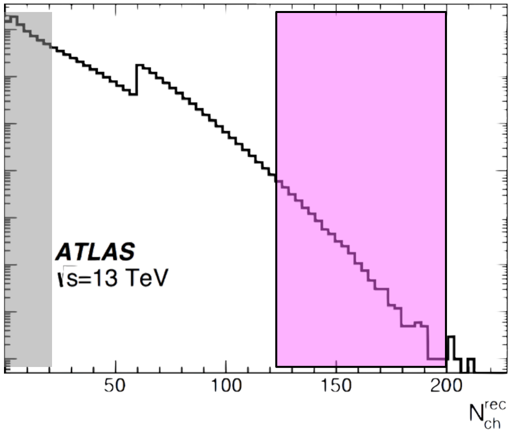
Low multiplicity bin: $N_{ch}^{rec}<20$

arxiv:1509.04776



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





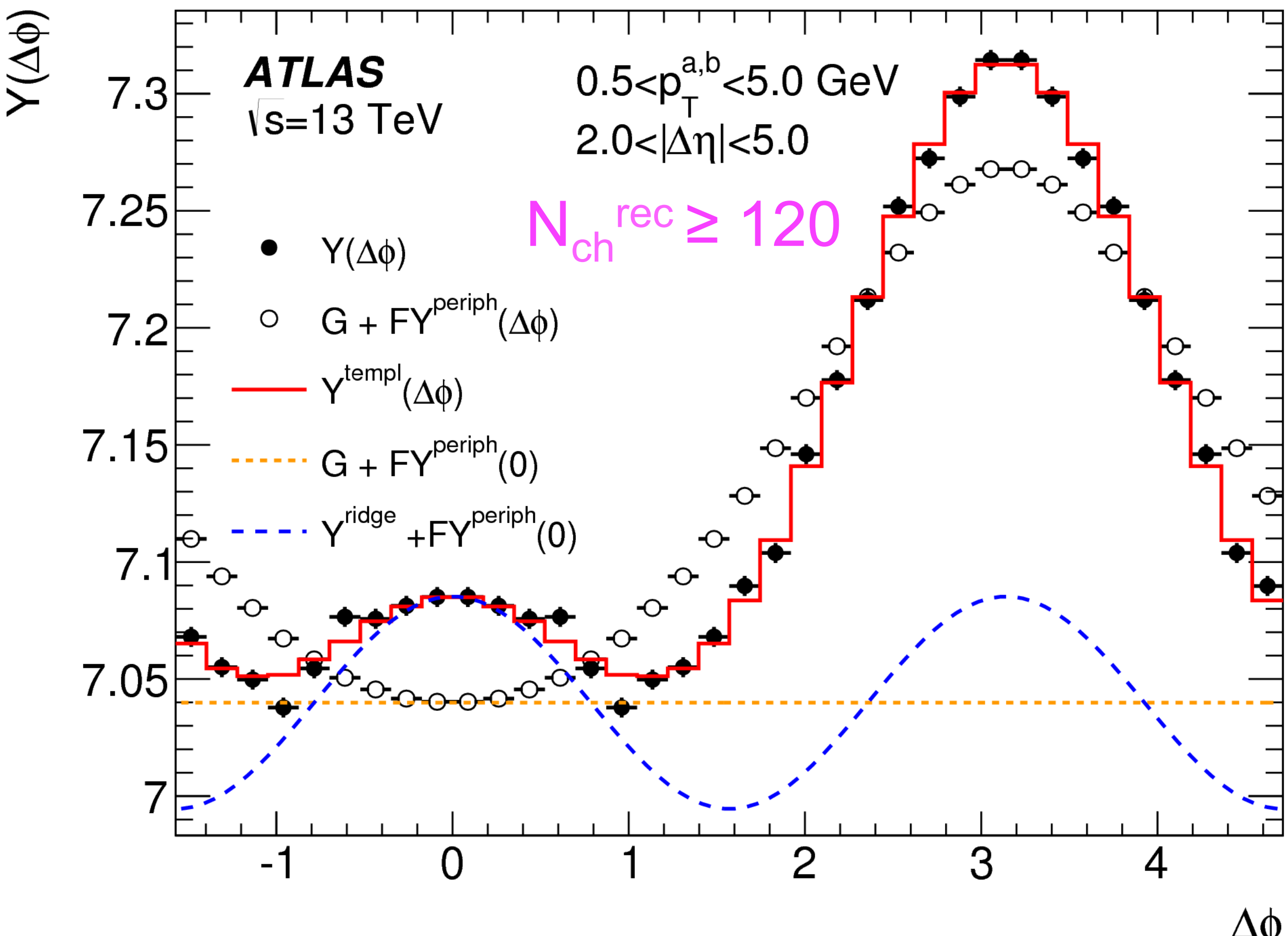
Low multiplicity bin: $N_{ch}^{rec}<20$

arxiv:1509.04776

Narrowing of Y(Δϕ) distribution ➔

- ➢ presence of a cos2Δϕ component
- ➢ other harmonics much smaller.

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

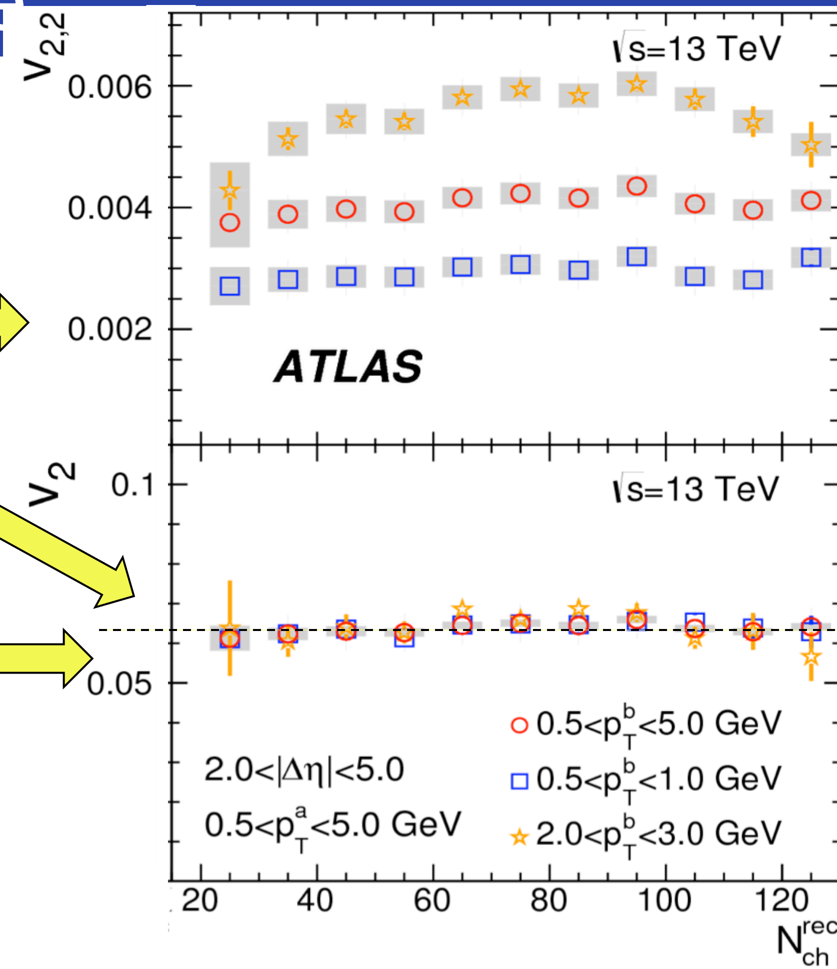


Properties of the quadrupole

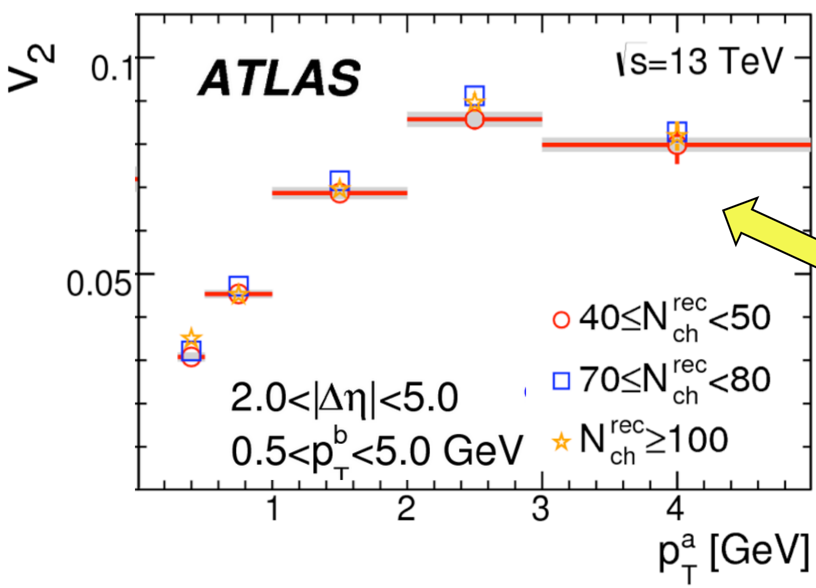
Two-particle quadrupole factorize into single particle quadrupole:

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

$$v_{2,2}(p_T^a, p_T^b) = v_2(p_T^a)v_2(p_T^b)$$

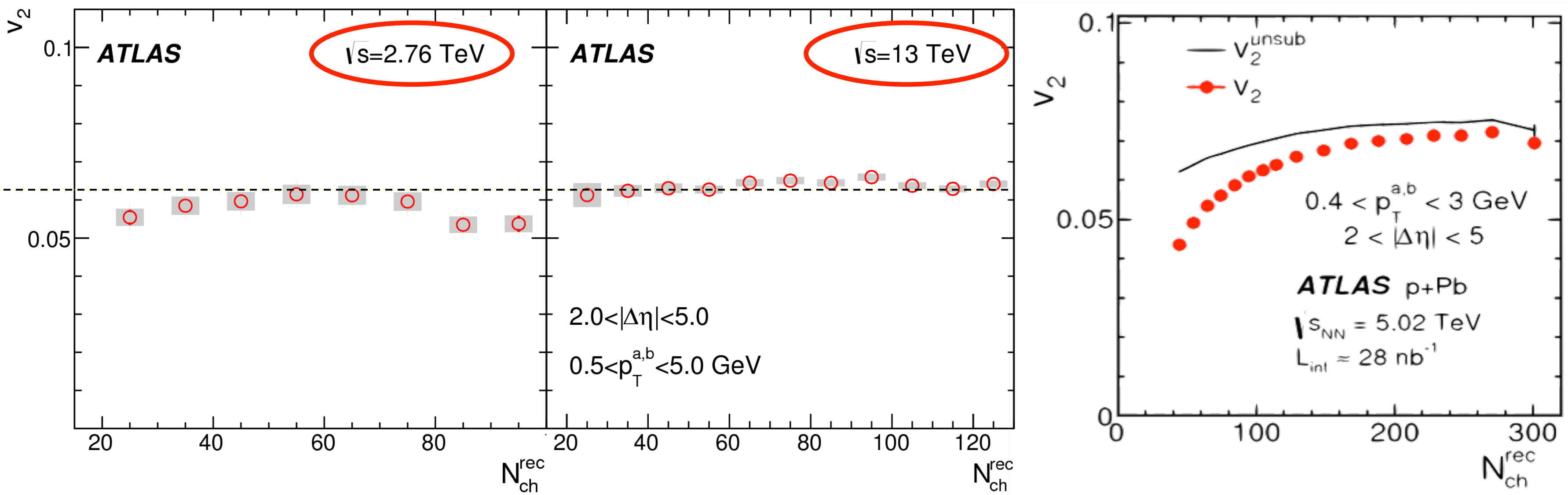


Very weak multiplicity dependence



$v_2(p_T)$ shows a rise & fall shape characteristic of behavior seen in pPb and PbPb

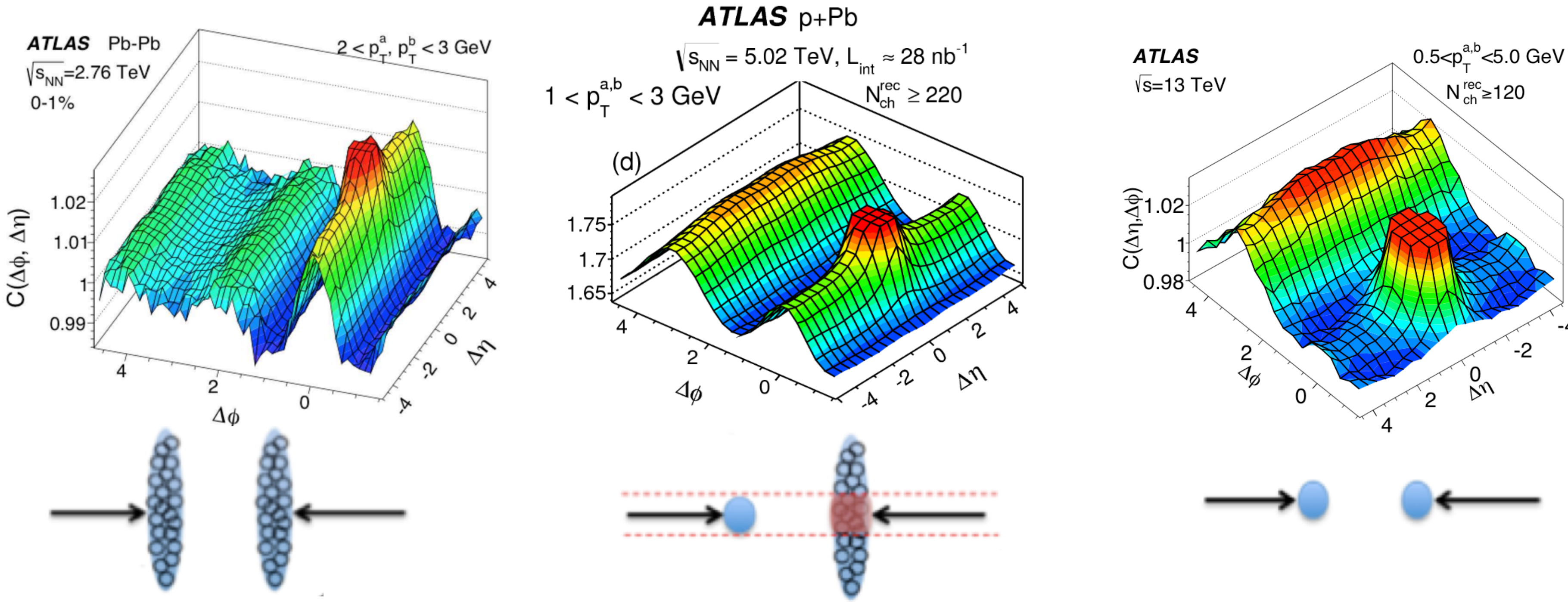
Energy and system size dependence



- Very weak energy dependence
- Somewhat different trend from pPb
  - In pPb, v_2 drops with N_{ch} even w/o subtraction.
- v_2 (pp)<v_2(pPb)<v_2(Pb+Pb)

What do these results mean?

- Initial or final-state effect? does this distinction even make sense in pp system?
- Why significant cos2Δϕ down to Nch ≈ 20 (close to multi. for minbias pp events)?
- How much v_2 in pA, AA collisions is non-hydrodynamic origin?

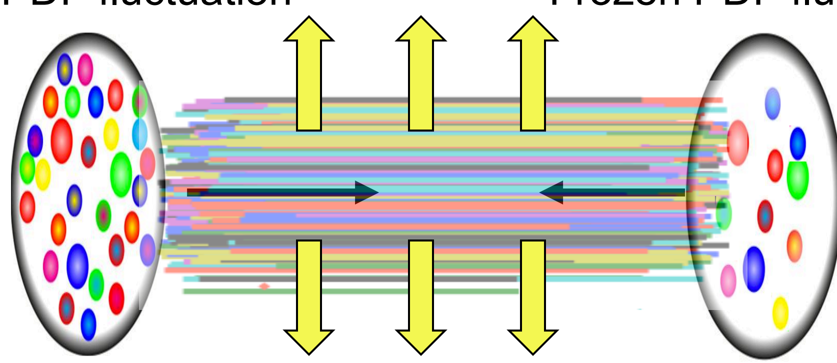


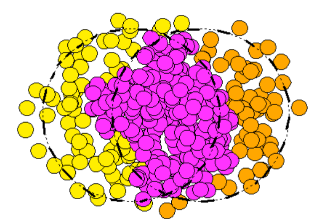
What sources seed these long-range ridges?

Particles (entropy) are produced very early in collision

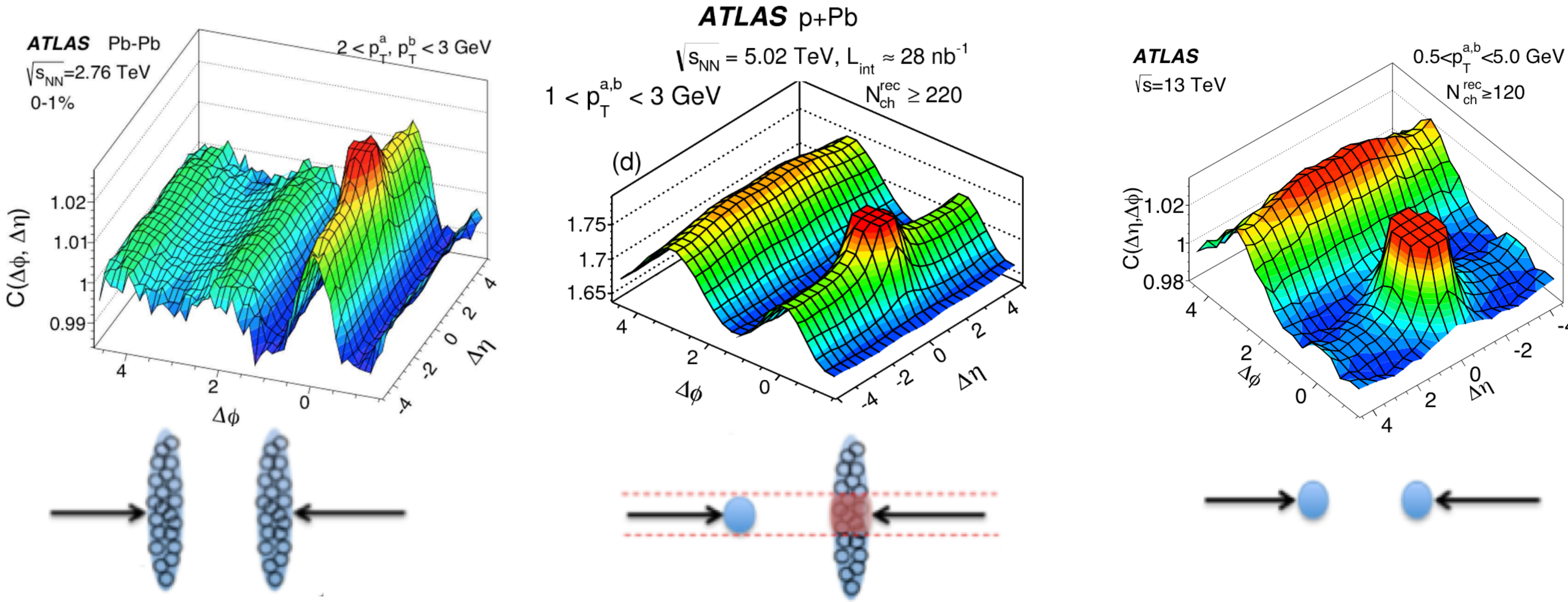
Frozen PDF fluctuation

Frozen PDF fluctuation





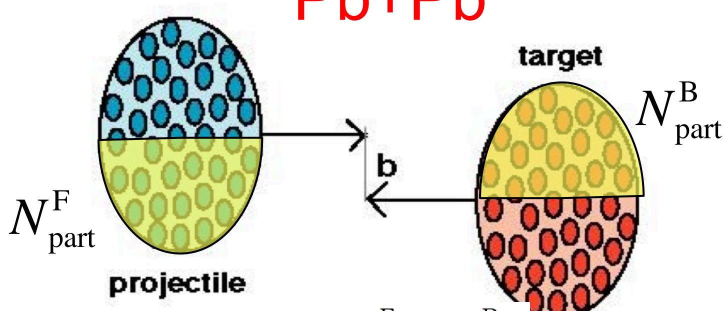
How many such sources and what are their sizes?



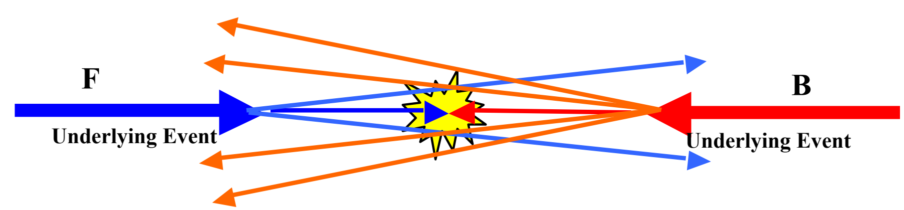
What sources seed these long-range ridges?

Particles (entropy) are produced very early in collision

Pb+Pb



p+p



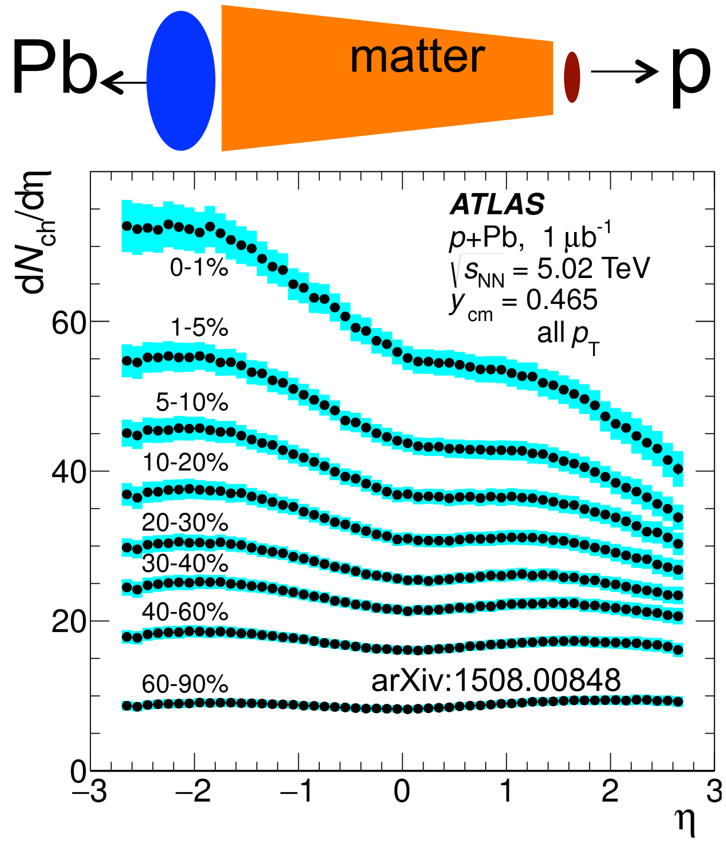
$N_{part}^F \neq N_{part}^B$ $\quad A_{part} = \frac{N_{part}^F - N_{part}^B}{N_{part}^F + N_{part}^B}$

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

forward/backward multiplicity correlations provide a handle

Forward/backward multiplicity correlation

- dN/dη shape reflects asymmetry in num. of forward/backward sources
  - Seen directly in p+Pb collisions.



FB asymmetry is expected in Pb+Pb or pp collisions on event-by-event bases!

Observable

- 2-D pseudorapidity correlation function

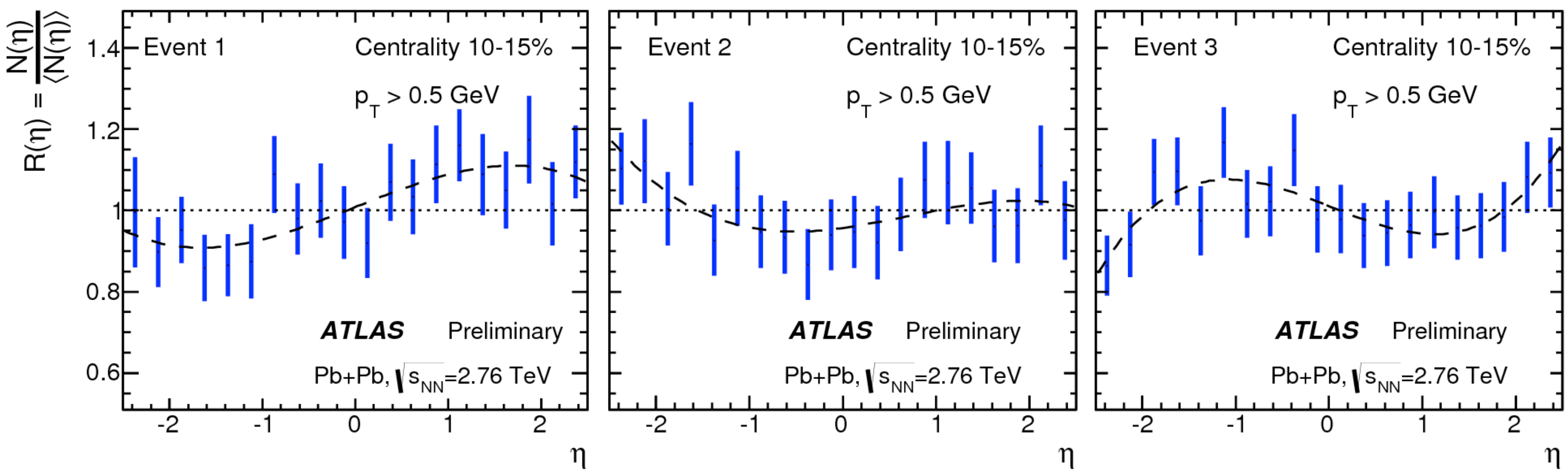
$$C = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} = \langle R_S(\eta_1) R_S(\eta_2) \rangle_{events}$$

|η|<Y=2.4

Mixed events

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

Single particle distribution

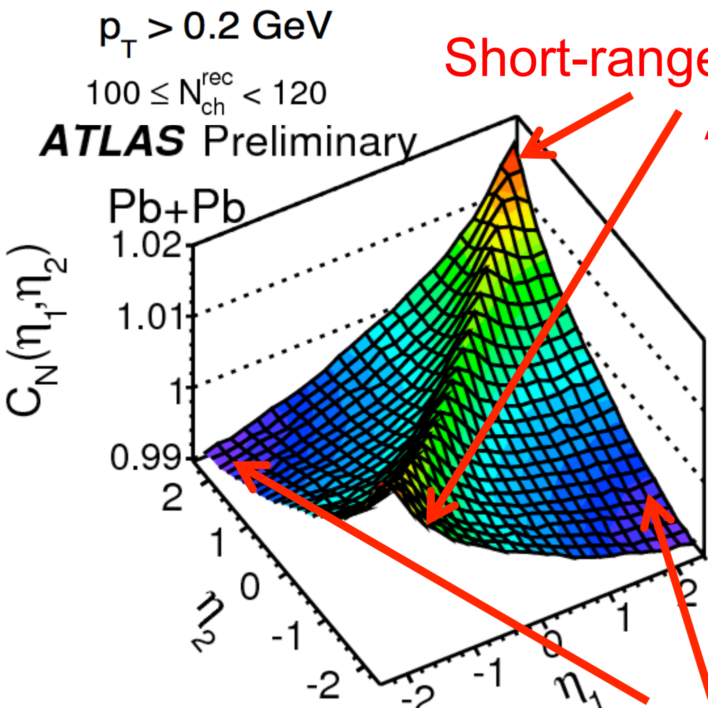


CF disentangles statistical fluctuation from dynamical fluctuation

Property of the correlation function

Short-range correlation $\delta_{\mathrm{SRC}}(\eta_1, \eta_2)$

$\Delta\eta=\eta_1-\eta_2\sim 0$



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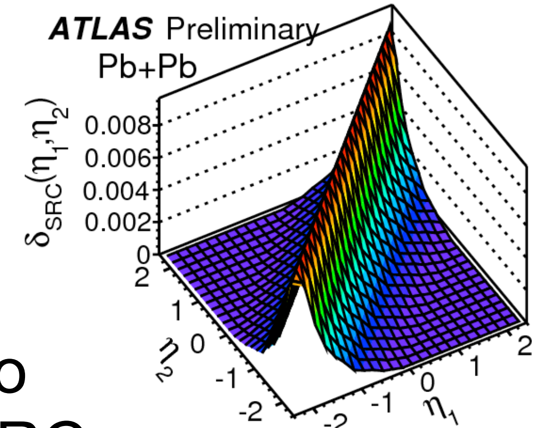
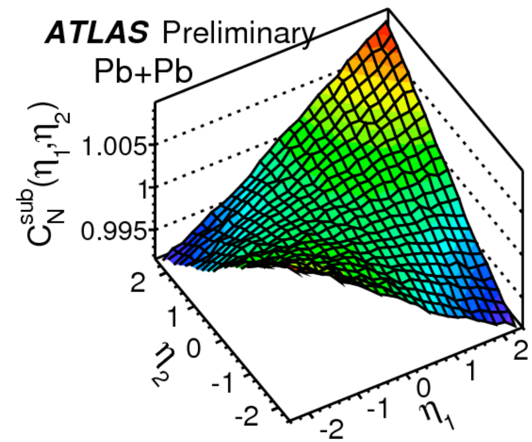


Data-driven method to separate SRC from LRC

Long range correlation $\mathrm{LRC}(\eta_1, \eta_2)$
large $|\Delta\eta|$

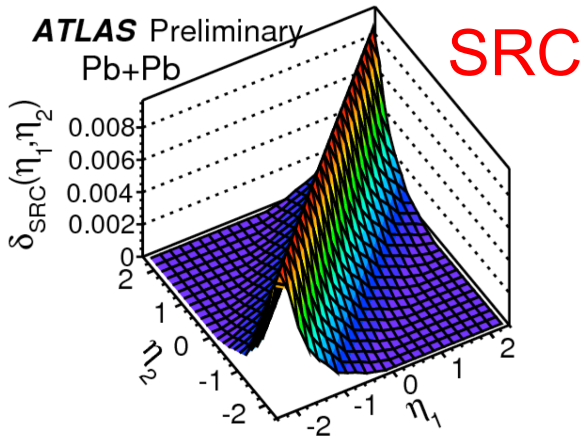
=



ATLAS-CONF-2015-051

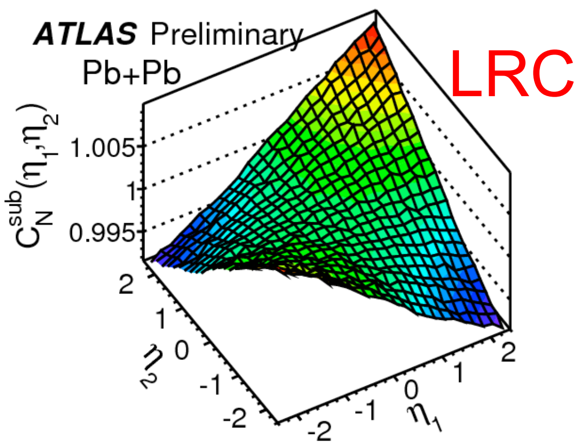
- SRC reflects correlations within the same source
- LRC reflects FB-asymmetry of number of sources, e.g. $A_{\mathrm{part}} = \frac{N_{\mathrm{part}}^{\mathrm{F}} - N_{\mathrm{part}}^{\mathrm{B}}}{N_{\mathrm{part}}^{\mathrm{F}} + N_{\mathrm{part}}^{\mathrm{B}}}$

Quantifying the SRC and LRC



$p_T > 0.2$ GeV

$100 \leq N_{ch}^{rec} < 120$



Quantify by average amplitude:

$$\Delta_{\mathrm{SRC}} = \frac{\int \delta_{\mathrm{SRC}}(\eta_1,\eta_2)d\eta_1 d\eta_2}{4Y^2}$$

$|\eta|<Y=2.4$

$$\eta_+ = \eta_1 + \eta_2$$
$$\eta_- = \eta_1 - \eta_2$$

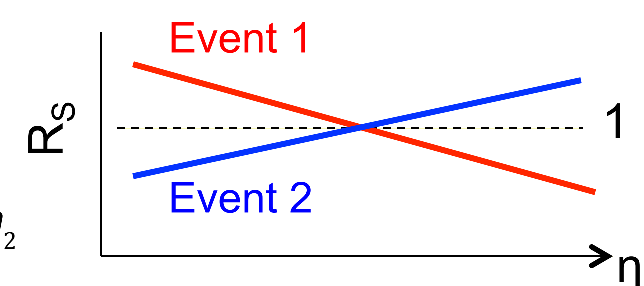
Shape approximate by:

$$C_{\mathrm{N}}^{\mathrm{sub}}(\eta_1,\eta_2) \approx 1 + \langle a_1^2 \rangle \eta_1\eta_2 = 1 + \frac{\langle a_1^2 \rangle}{4}(\eta_+^2 - \eta_-^2)$$

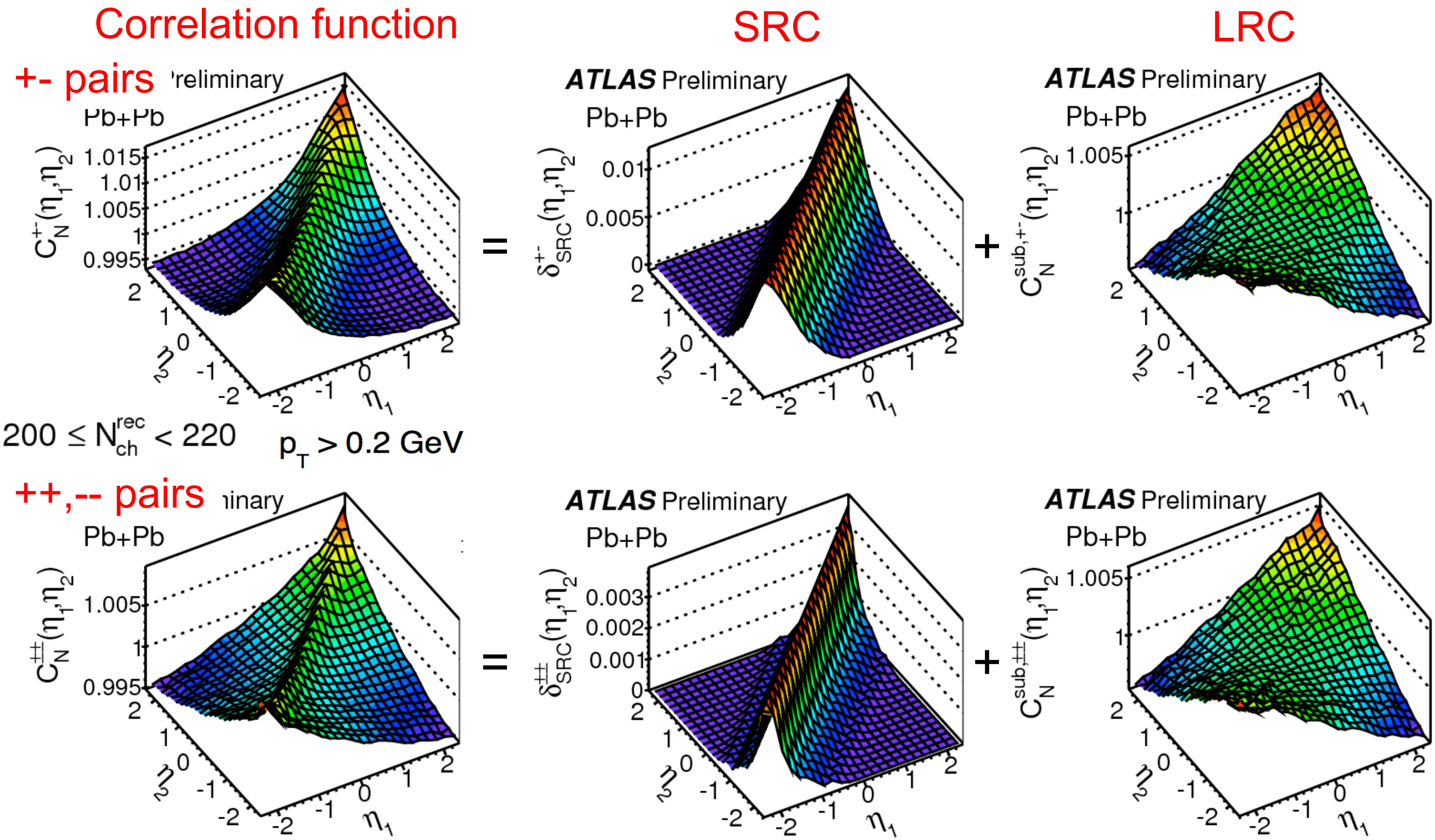
Implication: deviation from average is linear in η

$$R_s(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle} \approx 1 + a_1\eta$$

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



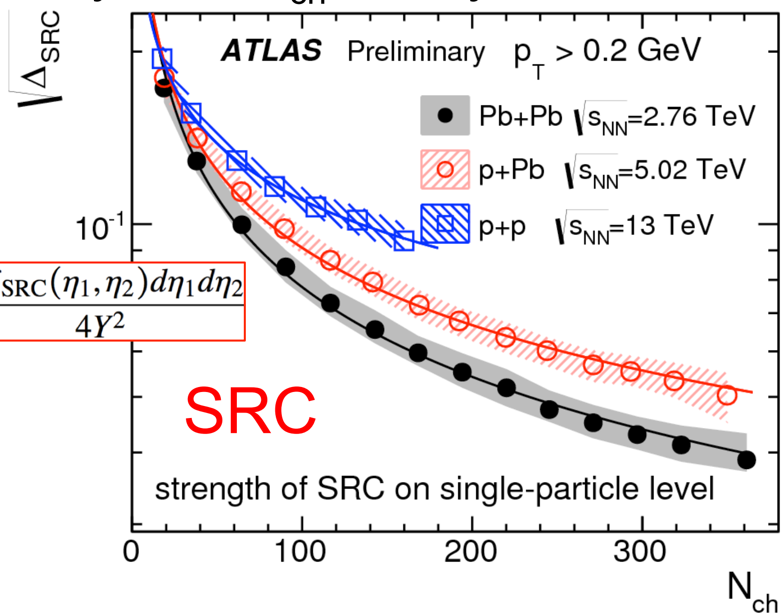
Dependence on charge combination



- SRC: more +- pairs than ±± pairs in each source
- LRC: no charge dependence → reflect global event property

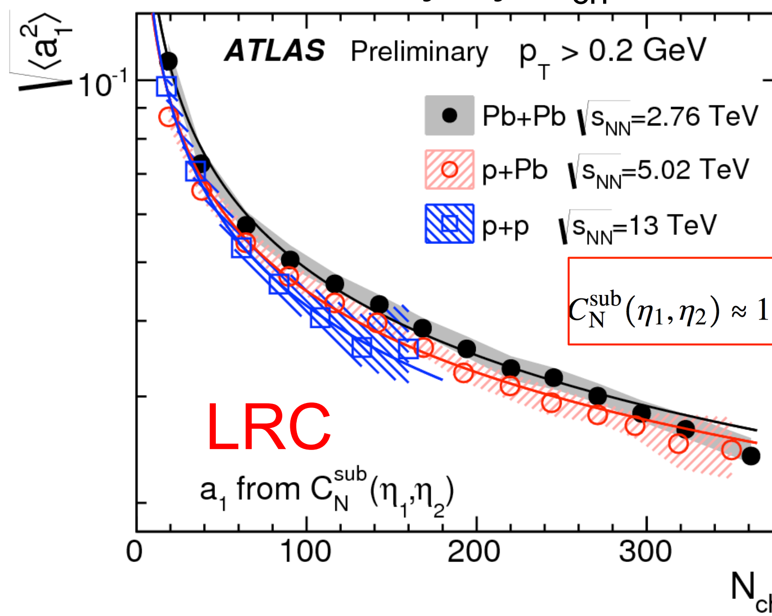
Dependence on N_{ch} and collision systems

By both N_{ch} and system size



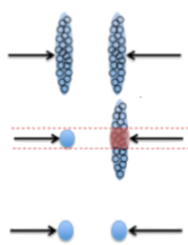
$$\Delta_{\mathrm{SRC}} = \frac{\int \delta_{\mathrm{SRC}}(\eta_1,\eta_2)d\eta_1 d\eta_2}{4Y^2}$$

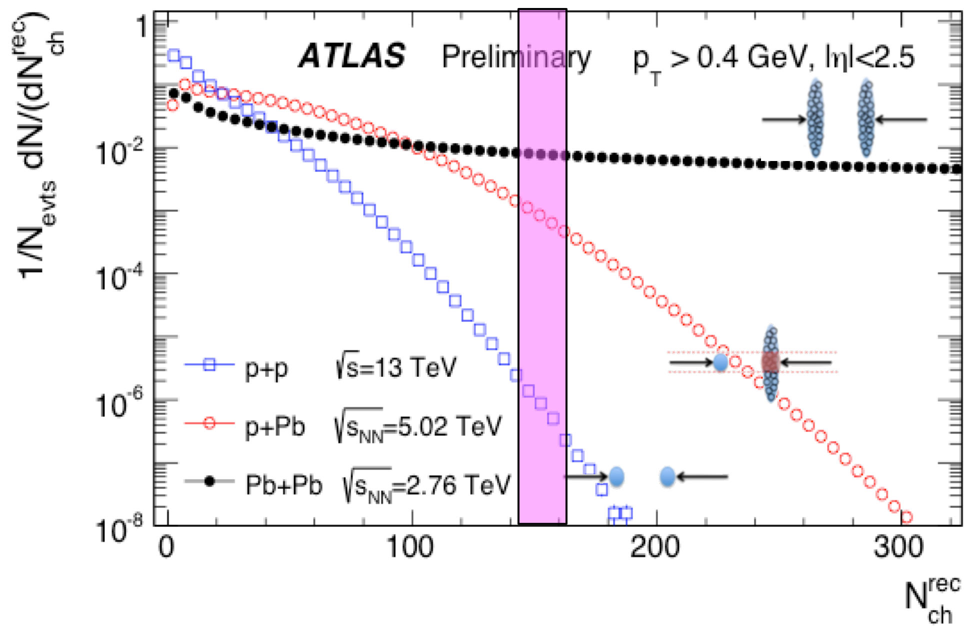
only by N_{ch}



$$C_N^{\mathrm{sub}}(\eta_1,\eta_2) \approx 1 + \langle a_1^2 \rangle \eta_1\eta_2$$

Compare between



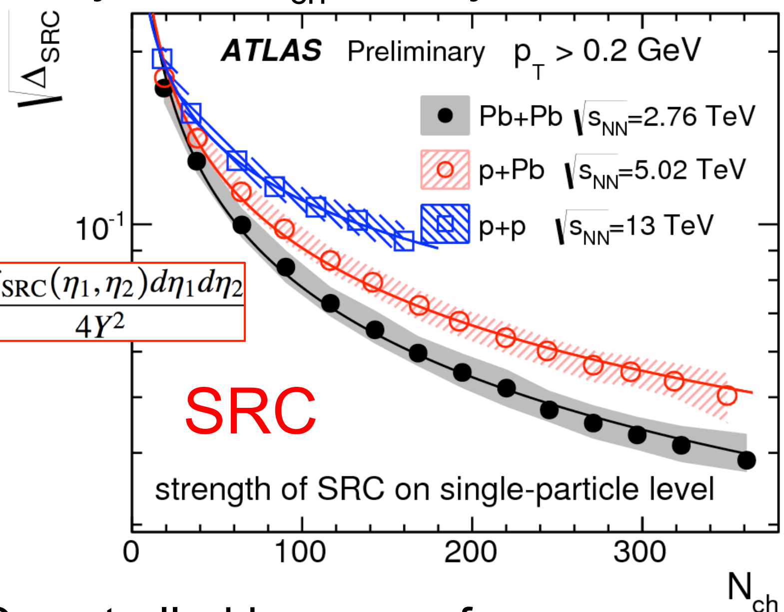


SRC/LRC control by

N_{ch} or transverse geom. size?

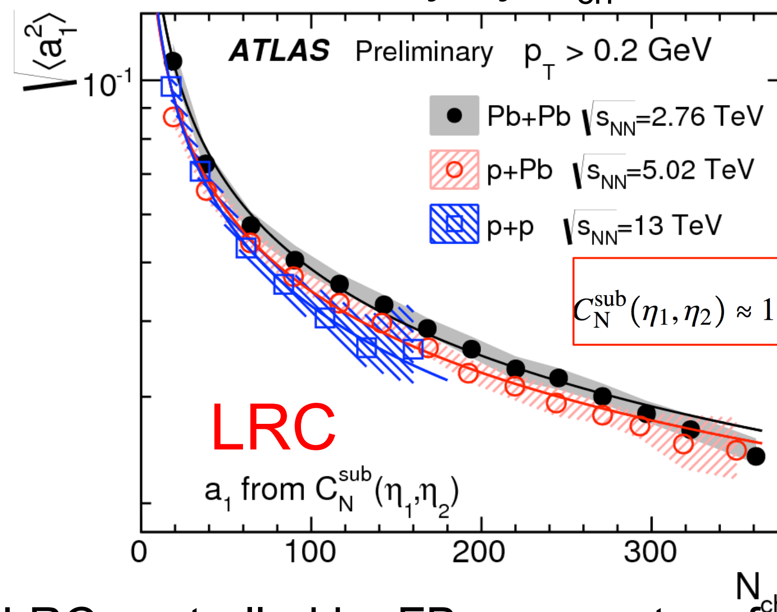
Dependence on N_{ch} and collision systems

By both N_{ch} and system size



$$\Delta_{SRC} = \frac{\int \delta_{SRC}(\eta_1,\eta_2)d\eta_1 d\eta_2}{4Y^2}$$

only by N_{ch}



$$C_N^{sub}(\eta_1,\eta_2) \approx 1 + \langle a_1^2 \rangle \eta_1\eta_2$$

SRC controlled by num. of sources

LRC controlled by FB asymmetry of sources

$$n = n_f + n_b \propto N_{ch}$$

$$\langle a_1^2 \rangle \propto \langle A_n^2 \rangle \qquad A_n = \frac{n_f - n_b}{n_f + n_b}$$

Assume "independent source picture":

$$\sqrt{\Delta_{SRC}} \sim \sqrt{\langle a_1^2 \rangle} \sim \frac{1}{n^{\alpha}} \sim \frac{1}{N_{ch}^{\alpha}}, \alpha \sim 0.5$$

- Fit with c/N_{ch}^{α}

	Pb+Pb	p+Pb	pp
α for $\sqrt{\Delta_{SRC}}$	0.502 ± 0.022	0.451 ± 0.020	0.342 ± 0.030
α for $\sqrt{\langle a_1^2 \rangle}$	0.467 ± 0.011	0.448 ± 0.019	0.489 ± 0.032

- LRC: num. of sources, n, controlled by N_{ch}, think in terms of partons !
- SRC: pp vs PbPb at same N_{ch} → n is similar but pairs/source is larger?

Summary

- What are the long-wavelength behaviors/properties of QGP?
  - Many observables to study hydrodynamic response to EbyE fluctuating initial conditions
  - Improved understanding of space-time dynamics & QGP properties via model comparison.

- What are the short-wavelength behaviors/properties of QGP?
  - Study by varying the energy, color, mass of hard-probes and their in-medium path-length.
  - Detailed control of energy loss and its fluctuations for fine-tuning quenching models

- Can we calibrate initial condition & hard-probe rates prior to QGP formation?
  - Hard-probe rates follow N_{coll} scaling, hints of nPDF effects observed for W/Z.

- Have we created a small droplet of QGP in pp, pPb collisions?
  - Strong collectivity observed in high-multiplicity pPb maybe even HM pp collisions
  - pp ridge described by $\cos 2\Delta\phi$, has(surprisingly) weak dependence on event activity and $\sqrt{s}$.
  - Is the $\cos 2\Delta\phi$ component in low-multiplicity pp due to collectivity?

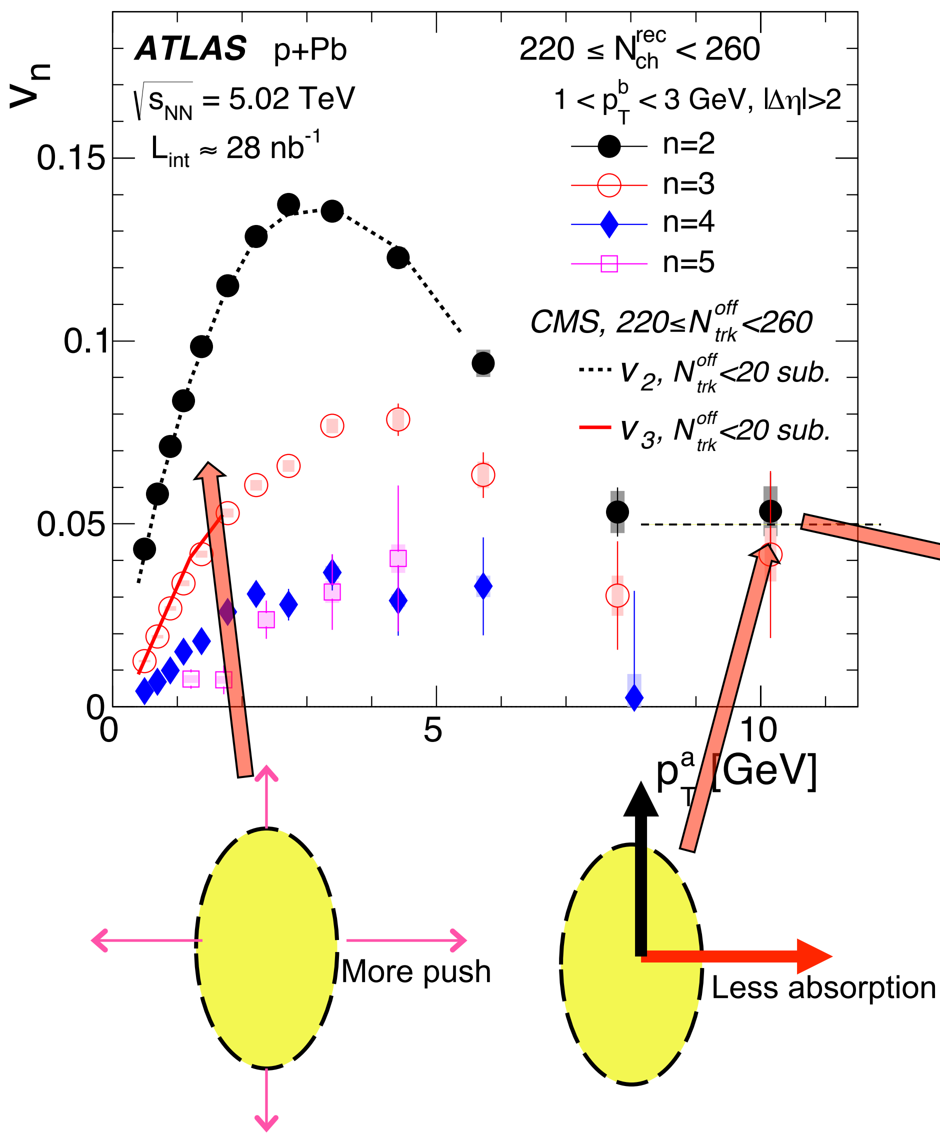
- Studied the nature of the sources that seed the long-range correlations via forward/backward multiplicity correlation.
  - Number-of-sources scales with event activity (N_{ch}) independent of the collision systems and hence the transverse geometry?

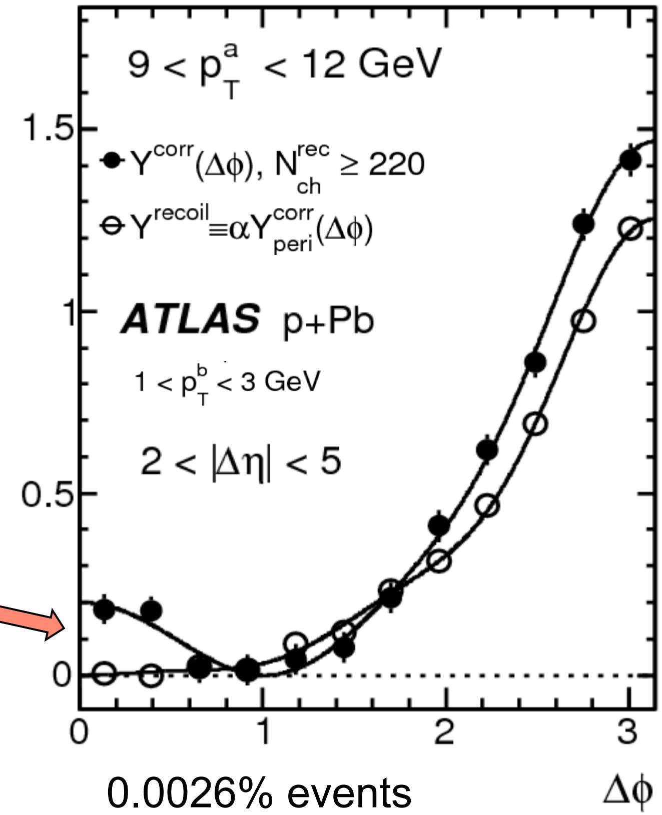
Back up

Evidence of final-state effects in p+Pb?

- If soft particle v_2 arises from final-state, do we expect energy loss?

PRC90,044906 (2014)





0.0026% events

Near-side ridge seen directly at 10GeV
Corresponds to 5% v_2

Evidence of jet quenching in HM pPb?