Stony Brook University | The State University of New York

Forward-backward multiplicity correlations in PbPb, pPb and pp collisions from ATLAS

Jiangyong Jia for the ATLAS collaboration

http://cds.cern.ch/record/2029370, ATLAS-CONF-2015-020

http://cds.cern.ch/record/2055672, ATLAS-CONF-2015-051

QUARK MATTER 2015

Brookhaven National Laboratory

Office of Science | U.S. Department of Energy

9/27-10/3, 2015

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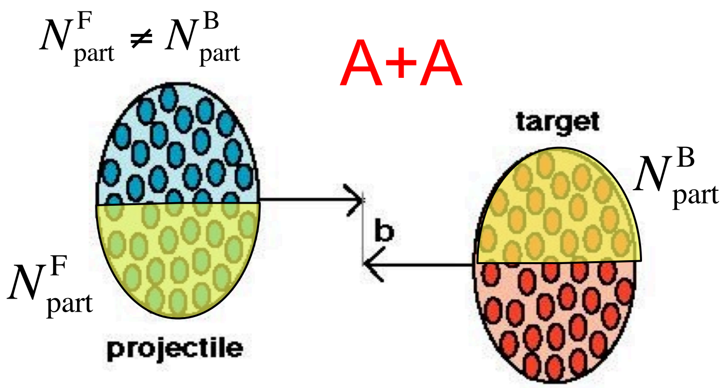
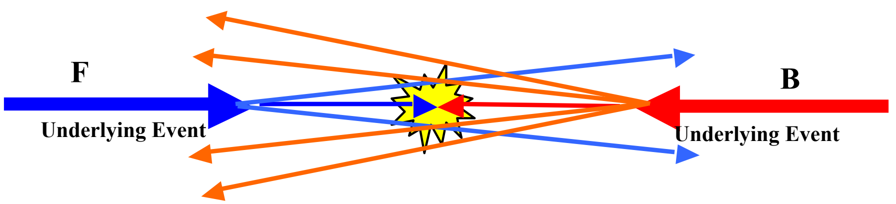
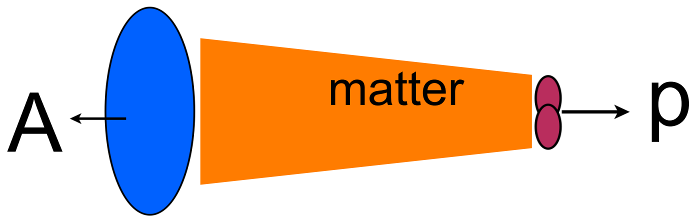
Origin of pseudorapidity correlations

- dN/dη shape reflects asymmetry in num. of forward/backward sources
  - Sources can be wounded nucleons, or partons in nucleons (MPI)

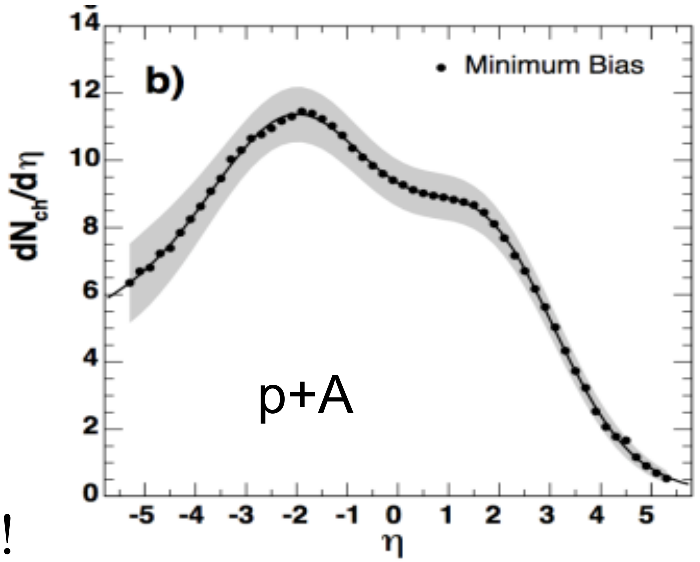




- Asymmetry seen directly in p+A collisions



$$dN/d\eta \propto f^{F}(\eta)N_{part}^{F} + f^{B}(\eta)N_{part}^{B}$$



  - Naturally exists in A+A collisions on EbyE bases!

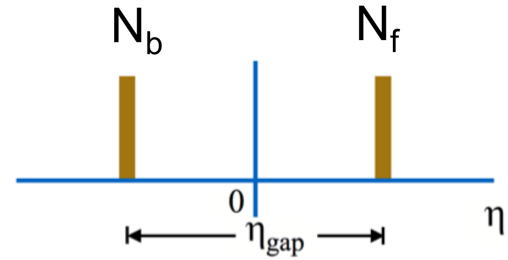
- Goal: understand event-by-event fluctuation of dN/dη

1. Probes early time dynamics, longitudinal flow, final state effects.
2. Inputs for 3+1D hydrodynamic models **W/O** boost invariance

Observables

- Traditional observables:

Lots of people worked on this



$$b = \frac{\langle N_f N_b \rangle - \langle N_f \rangle \langle N_b \rangle}{\sigma_{N_f} \sigma_{N_b}}$$

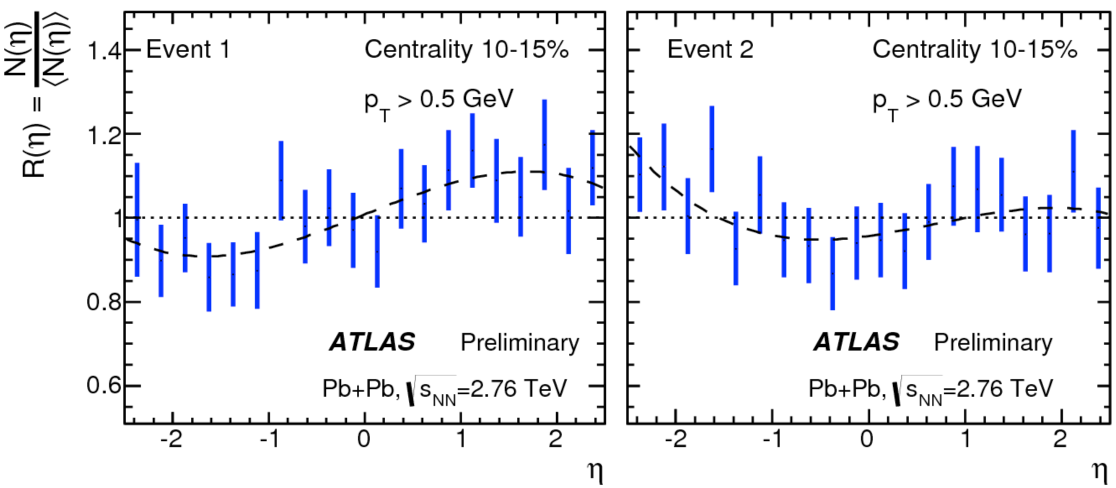
- Alternative observables: 2D correlation function

E. L. Berger, NPB 85 (1975) 61

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

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

Single particle distribution



Correlation function disentangles dynamical fluctuation from statistical fluctuation

Observables

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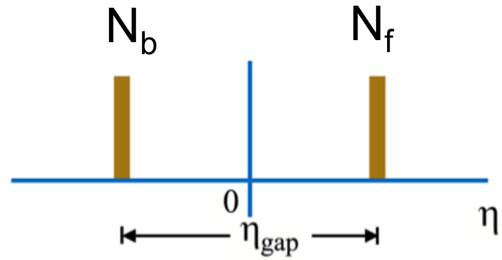

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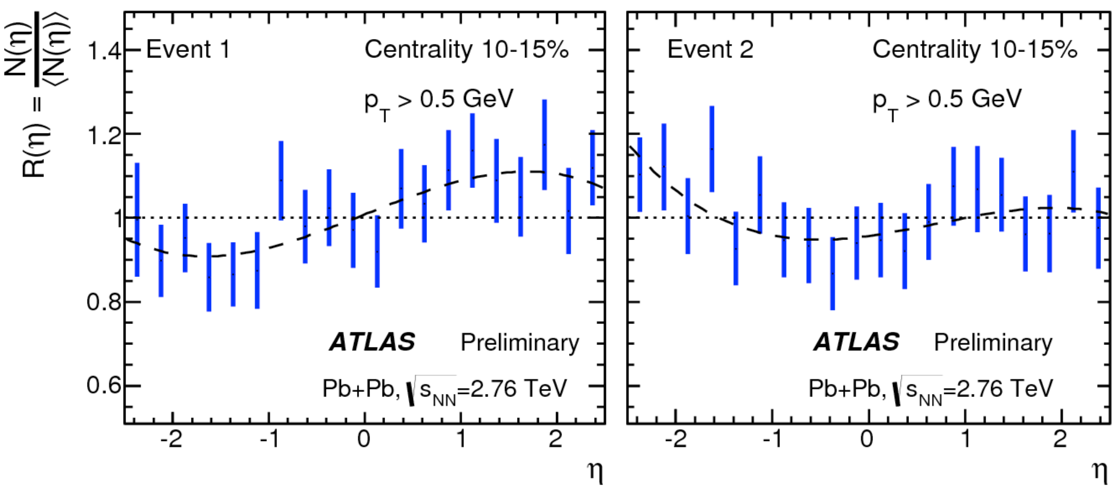
Single particle distribution

Mixed events may not match perfectly



Remove residual centrality dependence

$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1) C_p(\eta_2)}$$

$$C_p(\eta_1) = \frac{\int C(\eta_1, \eta_2) d\eta_2}{2Y}, C_p(\eta_2) = \frac{\int C(\eta_1, \eta_2) d\eta_1}{2Y}$$

See 1506.03496 and talk by Peng Huo

Correlation function disentangles dynamical fluctuation from statistical fluctuation

Quantifying the shape fluctuations

- EbyE fluct. expanded in Legendre polynomials

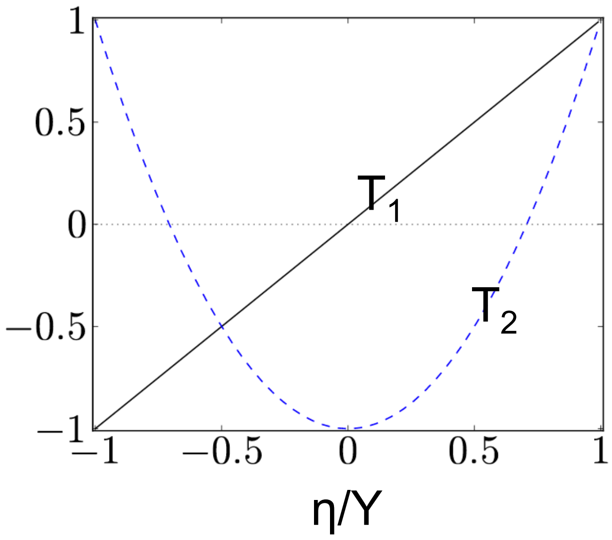
$$R_S(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle} = 1 + \sum_n a_n T_n(\eta) \quad T_n(\eta) \equiv \sqrt{\frac{2n+1}{3}}\, Y\, P_n\!\left(\frac{\eta}{Y}\right)$$

$$P_0(x) = 1, \quad P_1(x) = x, \quad P_2(x) = \frac{1}{2}(3x^2 - 1), \cdots$$

$$\eta \in [-Y, Y], \quad Y = 2.4$$

  - a_1 → fluctuation in the FB asymmetry of N(η),
  - a_2 → fluctuation in the width of N(η)

See Bzdak, Teaney 1210.1965



- Legendre expansion of two-particle correlations

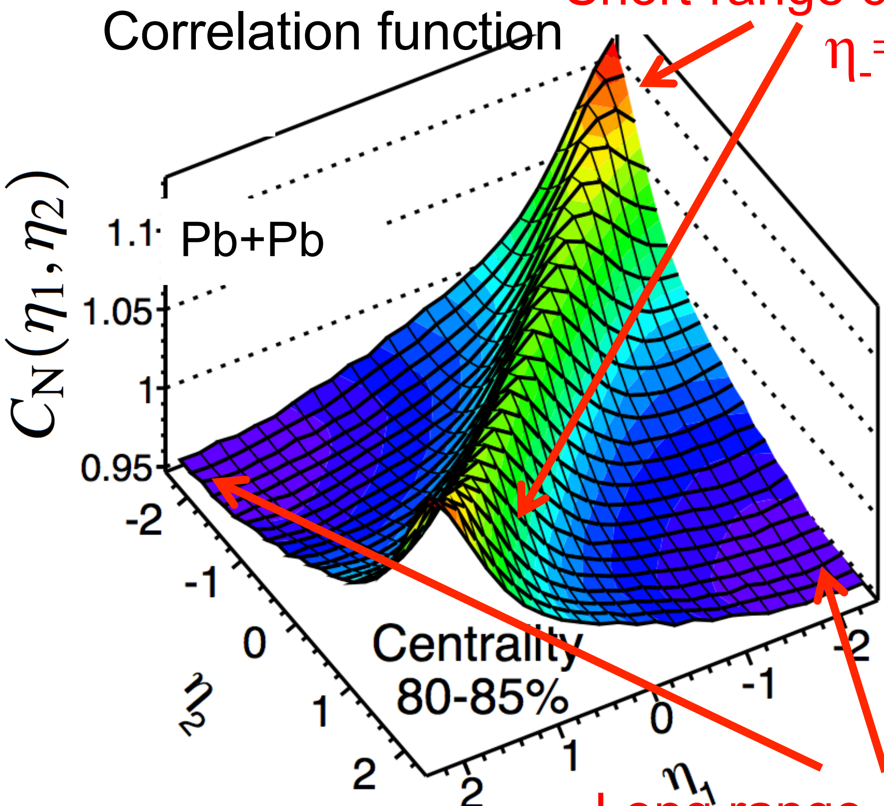
$$C_{\mathrm{N}}(\eta_1, \eta_2) = 1 + \sum_{n,m=1}^{\infty} \langle a_n a_m \rangle \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2}$$

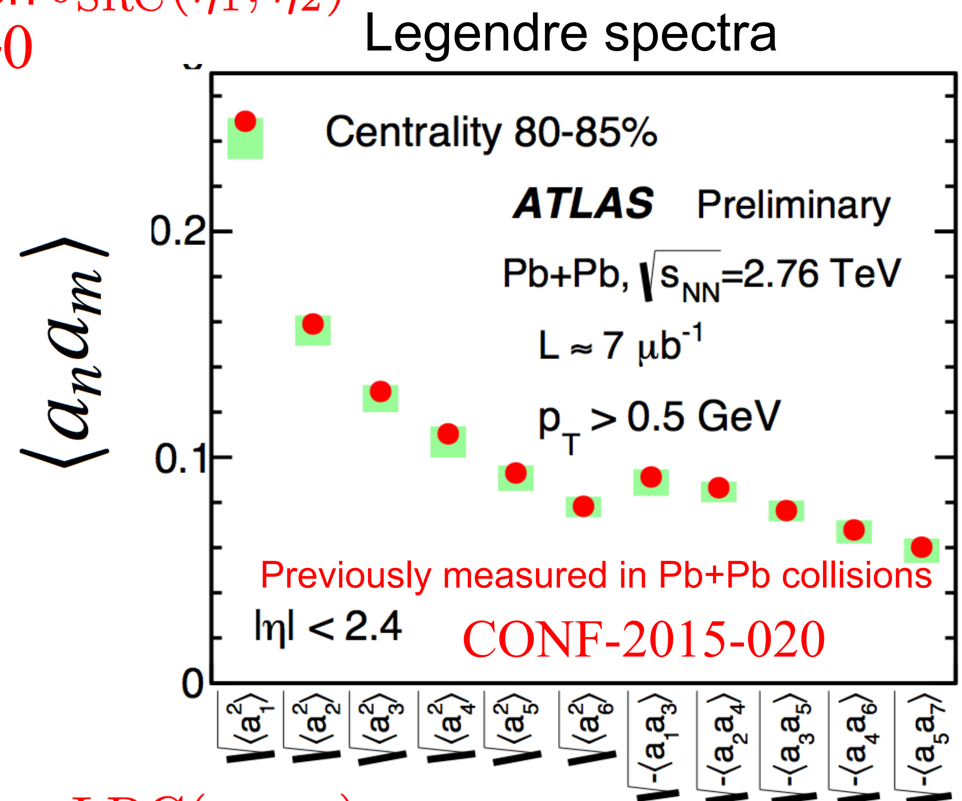
$$= 1 + \langle a_1^2 \rangle \eta_1\eta_2 + \langle a_2^2 \rangle \frac{5}{12Y^2}(3\eta_1^2 - Y^2)(3\eta_2^2 - Y^2) + \ldots$$

Features of $C_N(\eta_1,\eta_2)$

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

$\eta_-=\eta_1-\eta_2\sim0$





Long range correlation $\mathrm{LRC}(\eta_1,\eta_2)$

$\eta_+=\eta_1+\eta_2\sim0$ & large $|\eta_-|$

- Corr. Func.=short-range corr. (SRC) + long-range corr. (LRC)

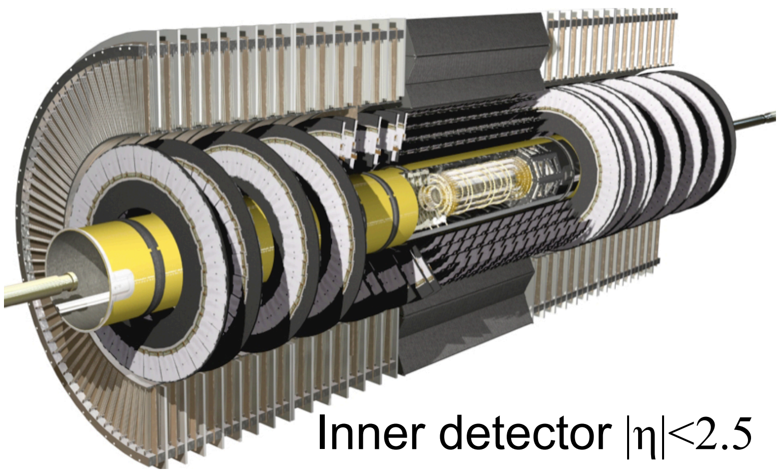
Goal of this measurement:

$$C(\eta_1,\eta_2)=1+\delta_{\mathrm{SRC}}(\eta_1,\eta_2)+\mathrm{LRC}(\eta_1,\eta_2)$$

1. Data-driven method to separate SRC from LRC
2. Compare SRC or LRC in three collision systems, pp,pPb,PbPb at similar N_{ch}

Pb+Pb, p+Pb and pp datasets

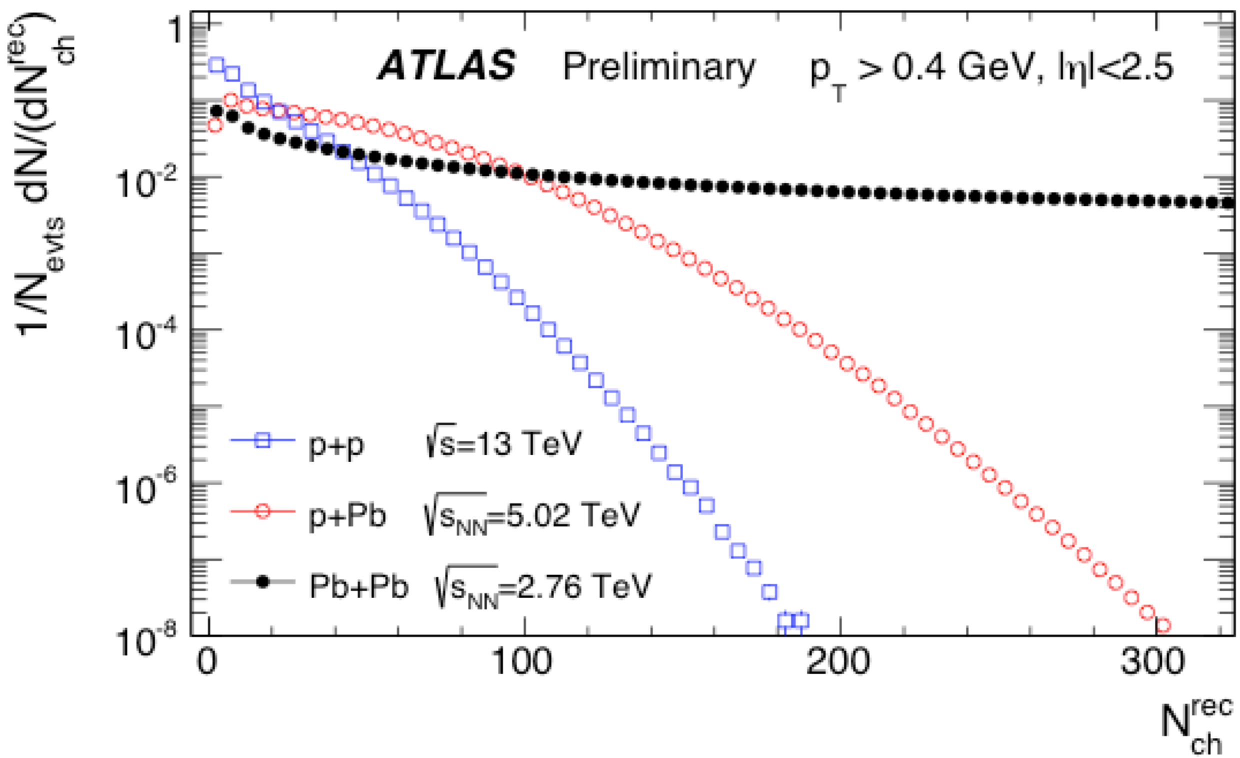
- $C_N(\eta_1,\eta_2)$ calculated using charged particles $p_T > 0.2$ GeV.
- High-multiplicity track (HMT) trigger used to increase statistics



Pb+Pb 2.76 TeV, 2010, MB

p+Pb 5.02 TeV, 2013, MB+HMT

p+p 13 TeV, 2015, MB+HMT

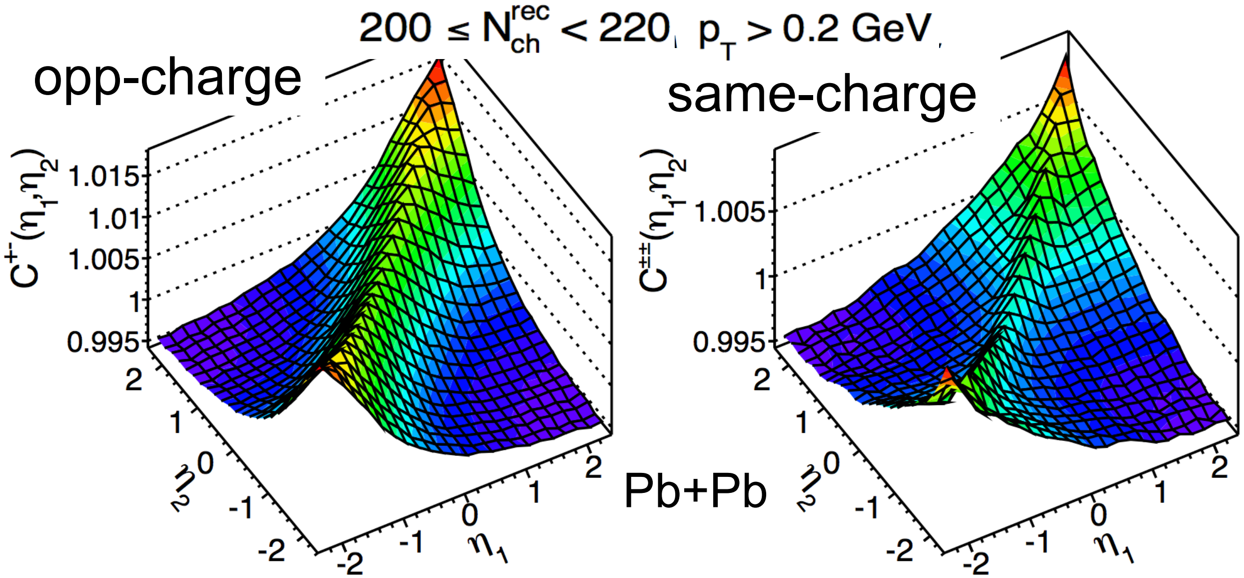


- Analysis carried out in many bins over $10 \leq N_{ch}^{rec} < 300$
- Results presented as a function efficiency-corrected values $N_{ch} = bN_{ch}^{rec}$
  - b~1.19 for pp and ~1.29 for pPb and PbPb

How signals in three systems compare at same N_{ch}?

Properties of short-range correlations

- CF for +- and ++,-- pairs separately.
  - different SRC, similar LRC (based on ratio)



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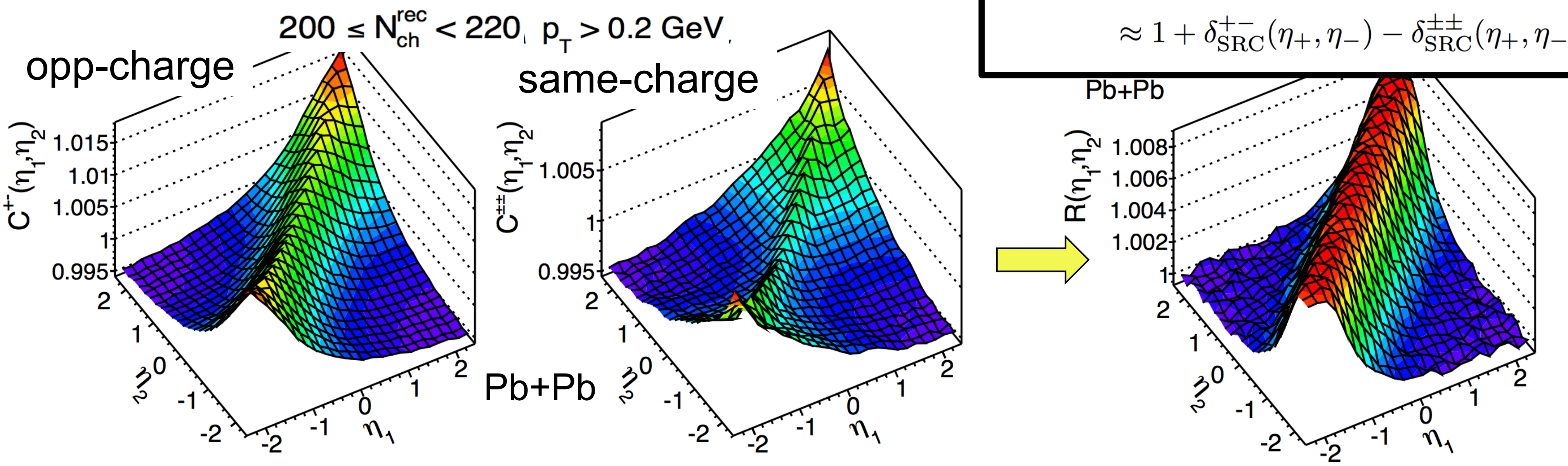
LRC drops out of the ratio

$$R(\eta_+,\eta_-) = \frac{C^{+-}(\eta_+,\eta_-)}{C^{\pm\pm}(\eta_+,\eta_-)} \qquad \eta_+ = \eta_1 + \eta_2 \quad \eta_- = \eta_1 - \eta_2$$

$$\approx 1 + \delta^{+-}_{\mathrm{SRC}}(\eta_+,\eta_-) - \delta^{\pm\pm}_{\mathrm{SRC}}(\eta_+,\eta_-)$$



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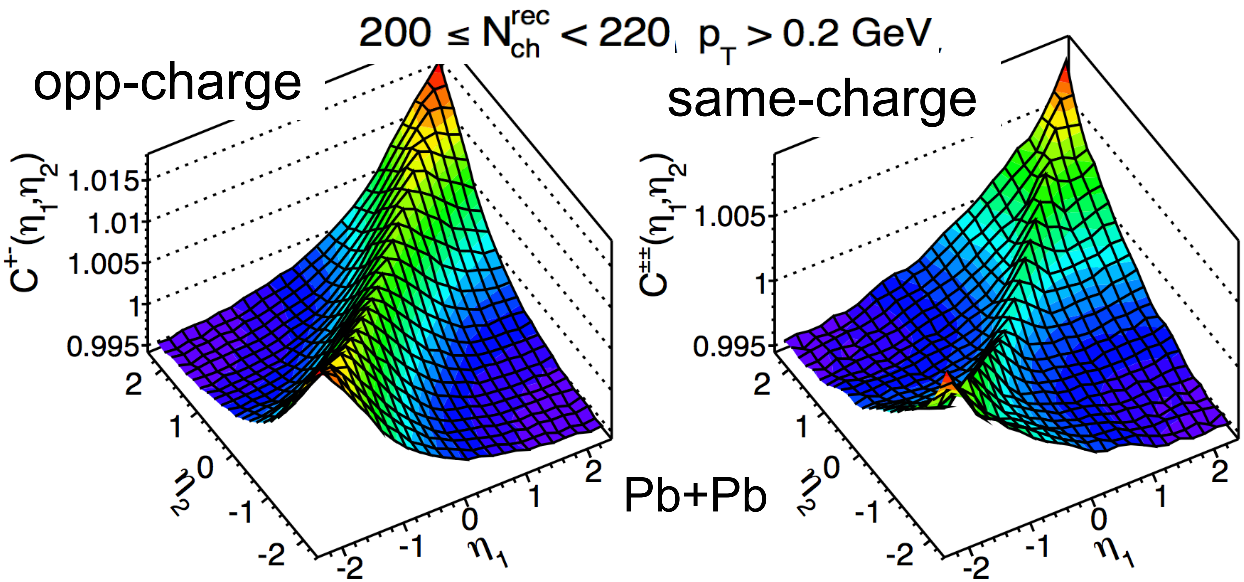
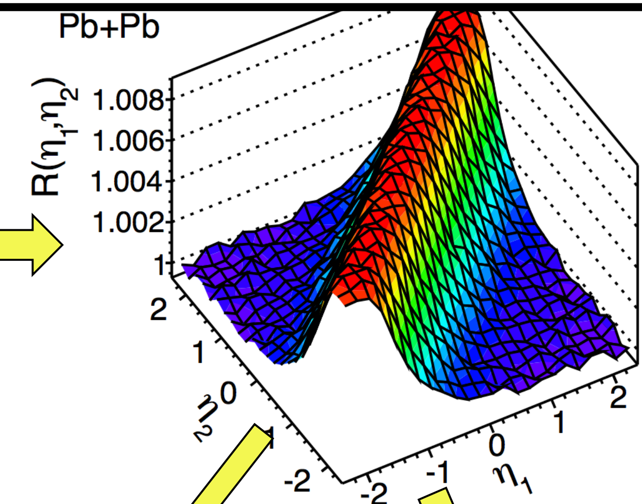




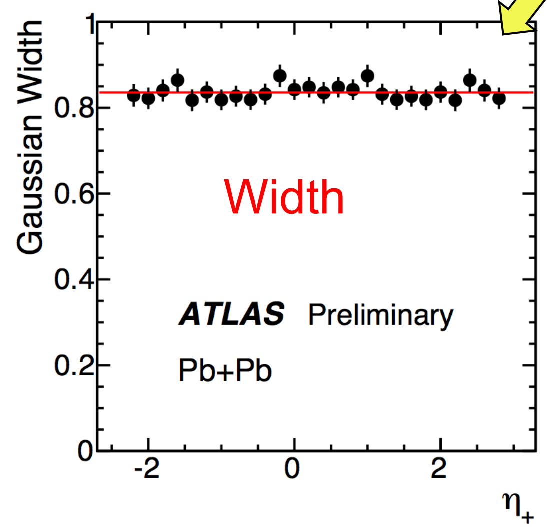
- Amplitude quantified via

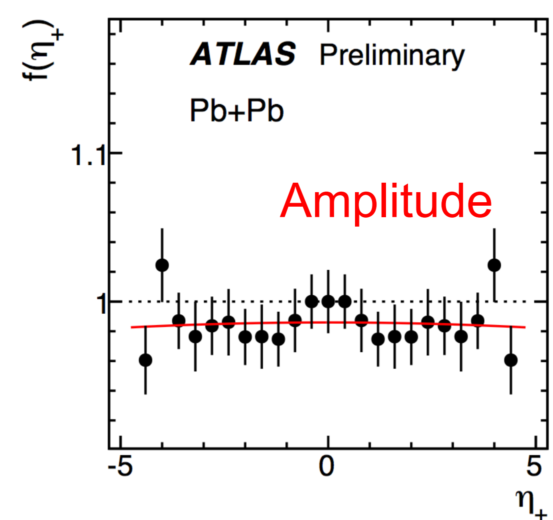
$$f(\eta_+) = \frac{\int_{-0.4}^{0.4} R(\eta_+,\eta_-)/0.8\, d\eta_- - 1}{\int_{-0.4}^{0.4} R(0,\eta_-)/0.8\, d\eta_- - 1}$$

Shape along η_+

- η_- peak width is constant in η_+

Shape of $\delta^{+-}_{\mathrm{SRC}} - \delta^{\pm\pm}_{\mathrm{SRC}}$ factorize in η_+ and η_-





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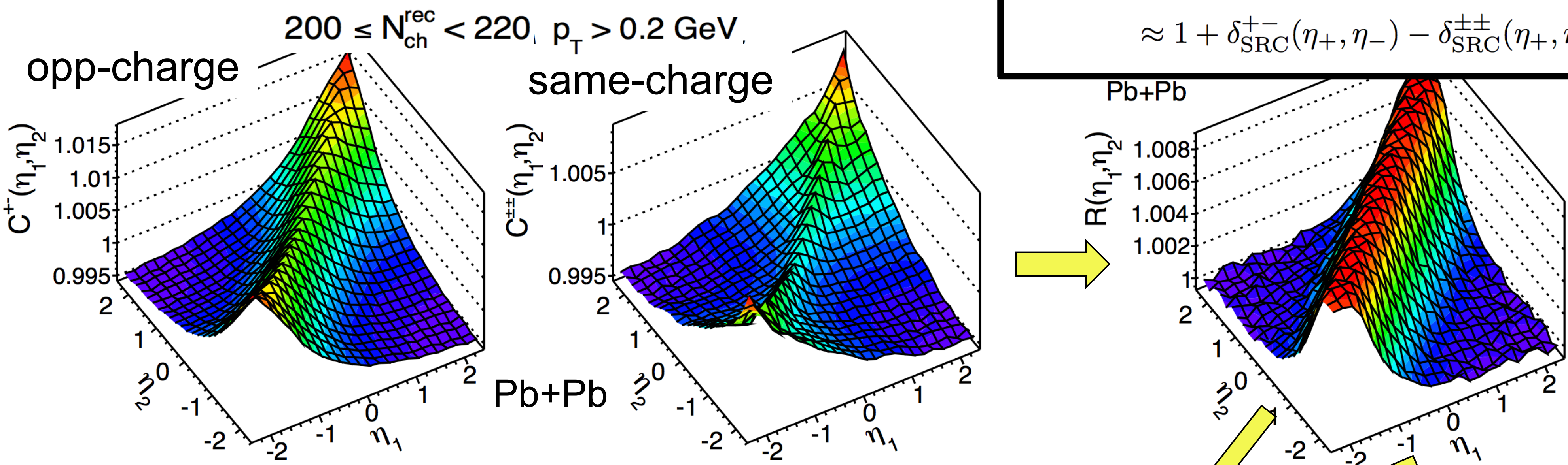


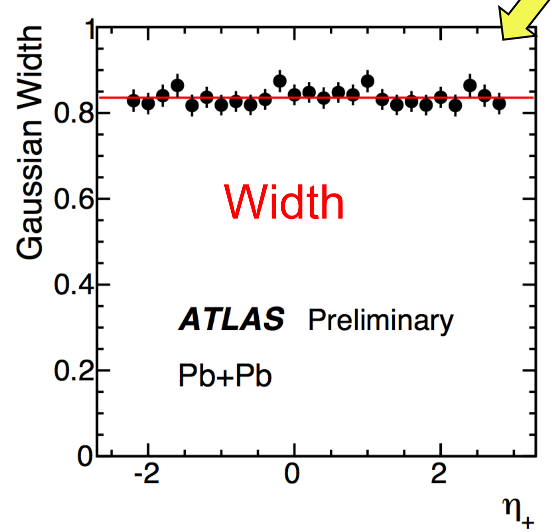
Hence, $\delta_{\mathrm{SRC}}(\eta_+,\eta_-)$ assumed to factorize in η_+,η_-.

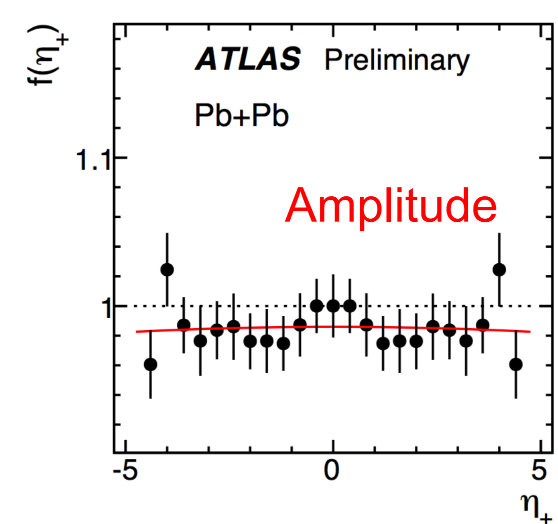
$$\delta^{+-}_{\mathrm{SRC}} = f(\eta_+)g^{+-}(\eta_-)$$

$$\delta^{\pm\pm}_{\mathrm{SRC}} = f(\eta_+)g^{\pm\pm}(\eta_-)$$

$$R(\eta_+,\eta_-) \approx 1 + f(\eta_+)\left[g^{+-}(\eta_-) - g^{\pm\pm}(\eta_-)\right]$$

Key is to determine $g(\eta_-)$!

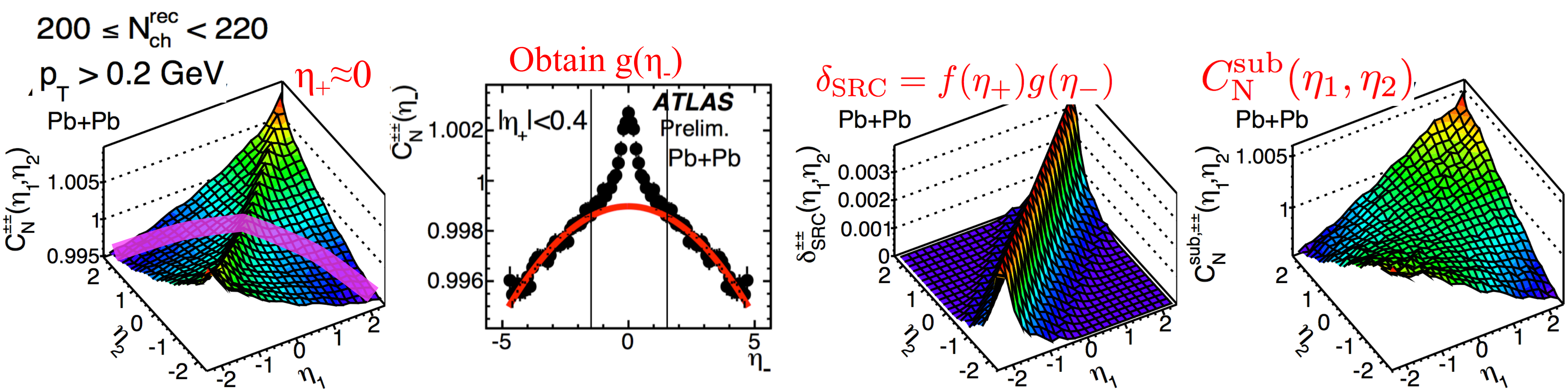




Estimate short-range correlations

- Take $C_N(\eta_-)$ in $|\eta_+|<0.4$, fit a quadratic function in $|\eta_-|>\eta_0=1.5$, difference between data and fit in $|\eta_-|<2$ is the $g(\eta_-)$ for SRC
  - Vary η_0 and the range of η_+ slices to check systematics.

$$\delta_{SRC}^{+-} = f(\eta_+)g^{+-}(\eta_-)$$
$$\delta_{SRC}^{\pm\pm} = f(\eta_+)g^{\pm\pm}(\eta_-)$$



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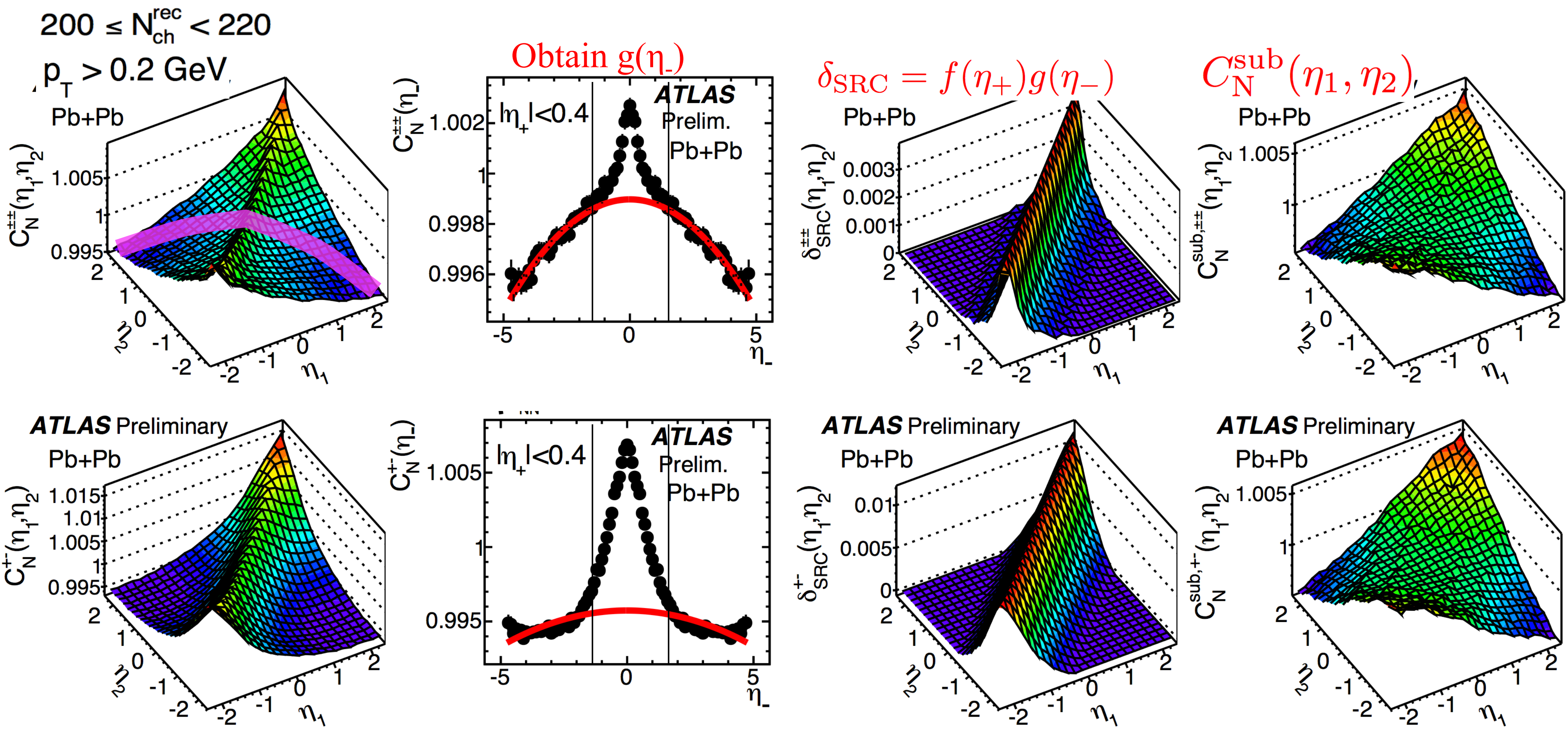
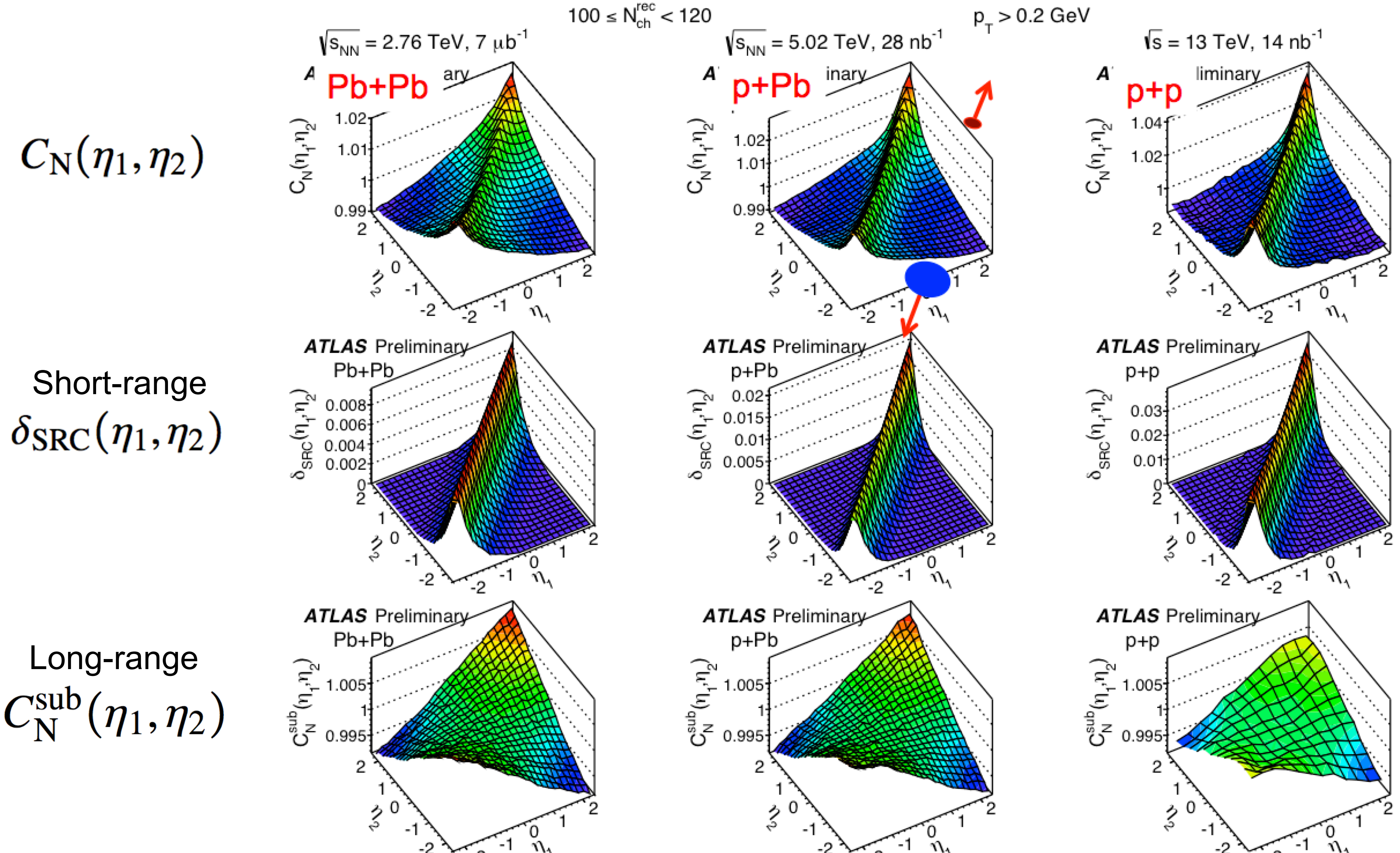


The LRC, $C_N^{\mathrm{sub}}(\eta_+,\eta_-)$, has similar magnitudes between ++,-- and +-

Results

Correlation functions in three systems



After SRC subtraction, similar LRC in all three systems

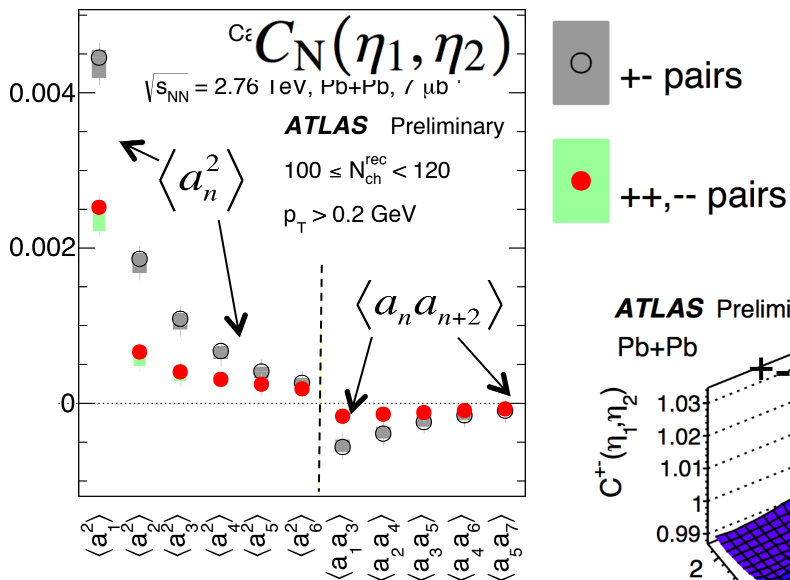
Most FB asymmetry in pPb collisions is due to the SRC.

Legendre spectra in Pb+Pb

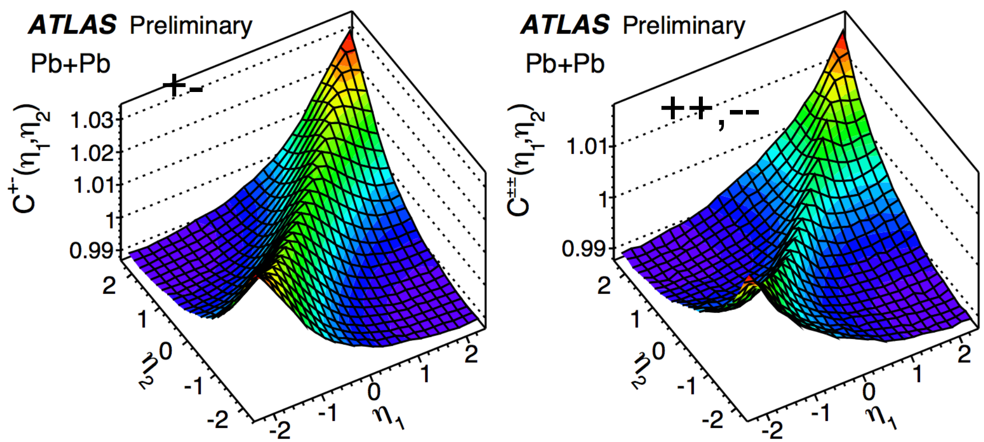
$$C_N(\eta_1,\eta_2) \text{ or } C_N^{sub}(\eta_1,\eta_2) = 1 + \sum_{n,m=1}^{\infty} \langle a_n a_m \rangle \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2}$$

Before subtraction

Pb+Pb



Before SRC subtraction



- The strong charge dependence → SRC contributes to all coefficients

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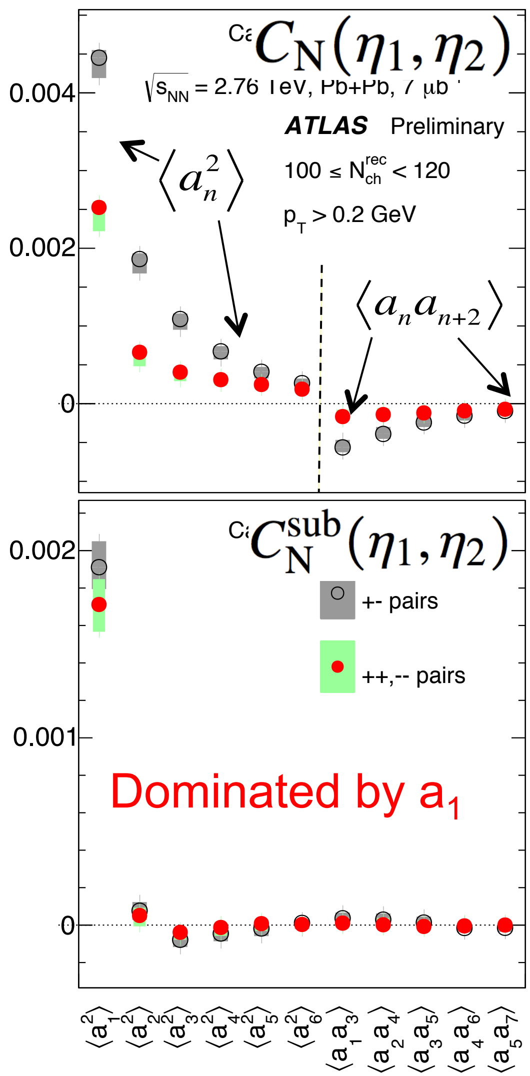
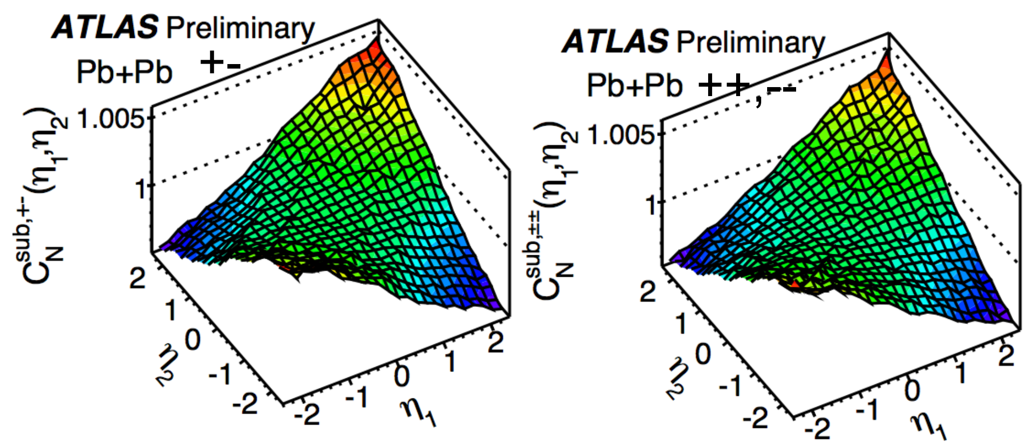
Pb+Pb

Before subtraction

After subtraction



After SRC subtraction



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After SRC removal, results are independent of charge combinations!

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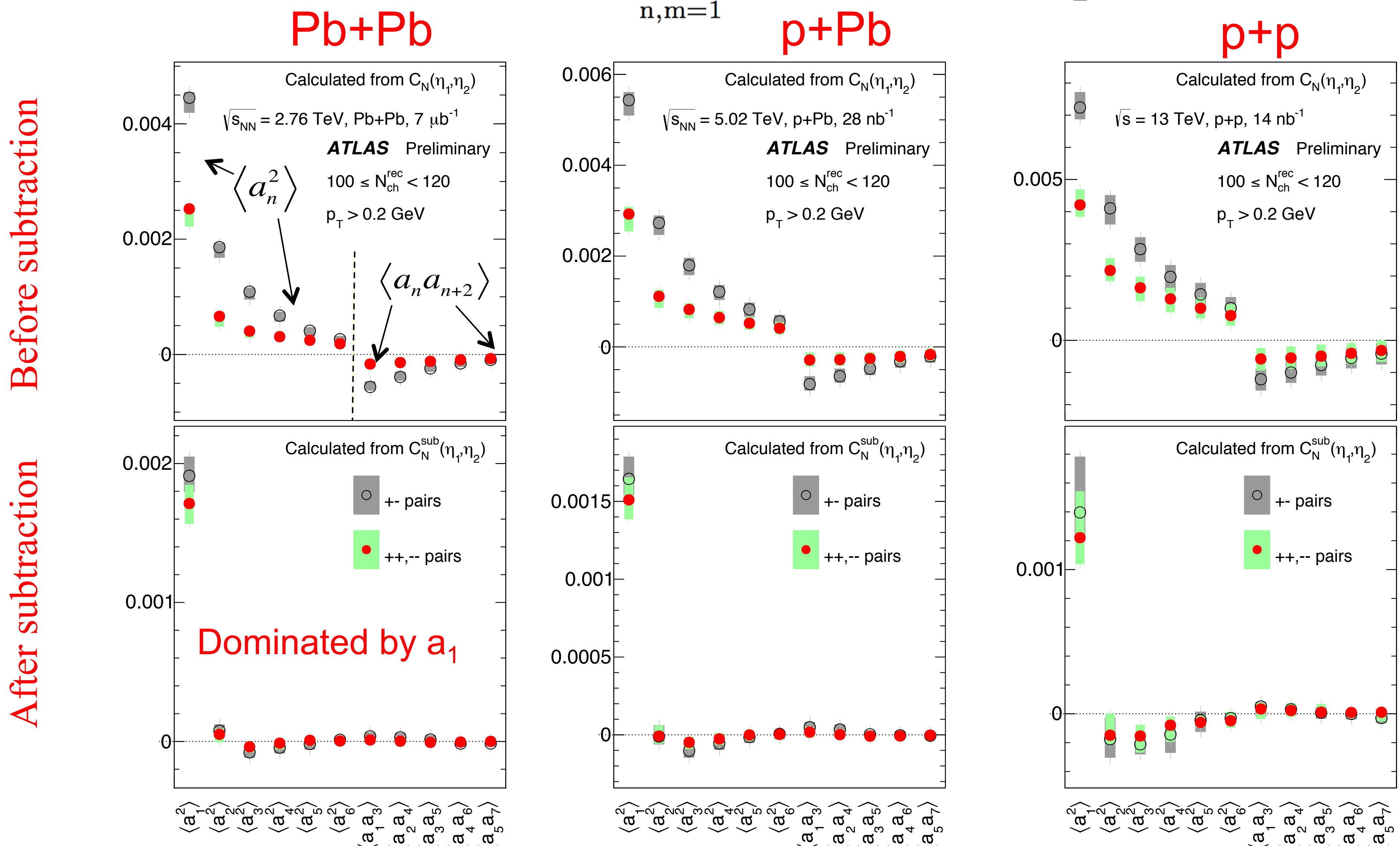

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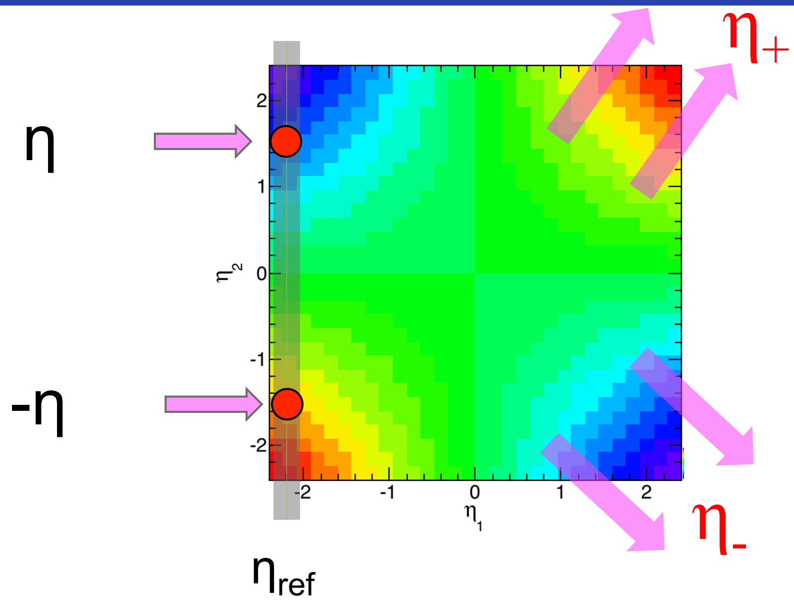
Projections of correlation function



CF dominated by a_1, thus:

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

2. Quadratic fit of $C_N^{sub}(\eta_-)$ in narrow slice of η_+, this gives a_1 as a function of η_+.
3. Quadratic fit of $C_N^{sub}(\eta_+)$ in narrow slice of η_-, this gives a_1 as a function of η_-.
4. Linear fit of the η dependence of $r_N^{sub}(\eta,\eta_{ref})$ in narrow slice of η_{ref}.

$$r_N^{sub}(\eta,\eta_{ref}) = C_N^{sub}(-\eta,\eta_{ref})/C_N^{sub}(\eta,\eta_{ref}) = 1 - 2\langle a_1^2 \rangle \eta\eta_{ref}$$

similar to the CMS correlator for flow decorrelation 1503.01692

Compare to a_1 obtained from Legendre expansion method

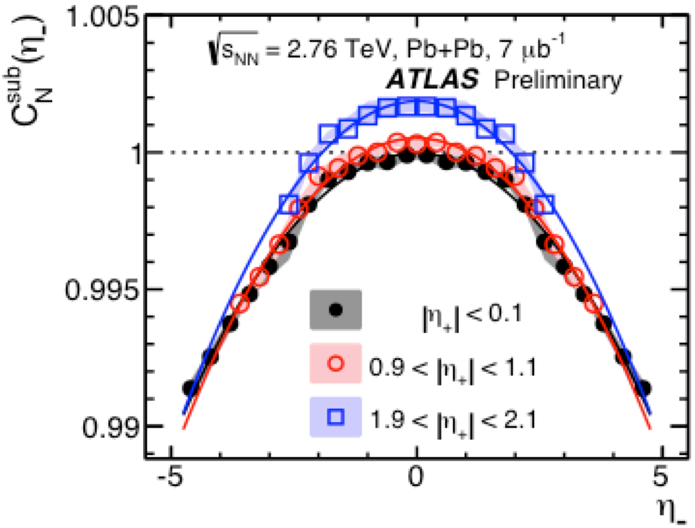
Fit in limited η_1 and η_2 space, the systematics largely independent!

Projections of CF in p+Pb

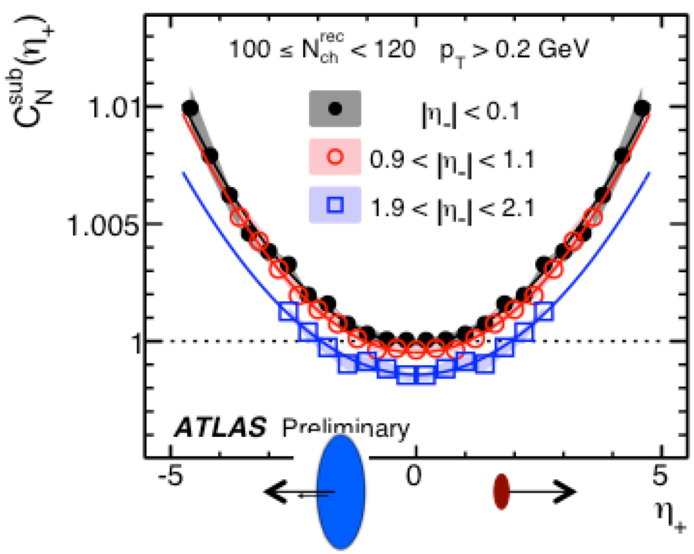
$$C_N^{sub}(\eta_1,\eta_2) \approx 1 + \langle a_1^2 \rangle \eta_1\eta_2 = 1 + \frac{\langle a_1^2 \rangle}{4}(\eta_+^2 - \eta_-^2)$$

$$r_N^{sub}(\eta,\eta_{ref}) = 1 - 2\langle a_1^2 \rangle |\eta_{ref}|\, \eta$$

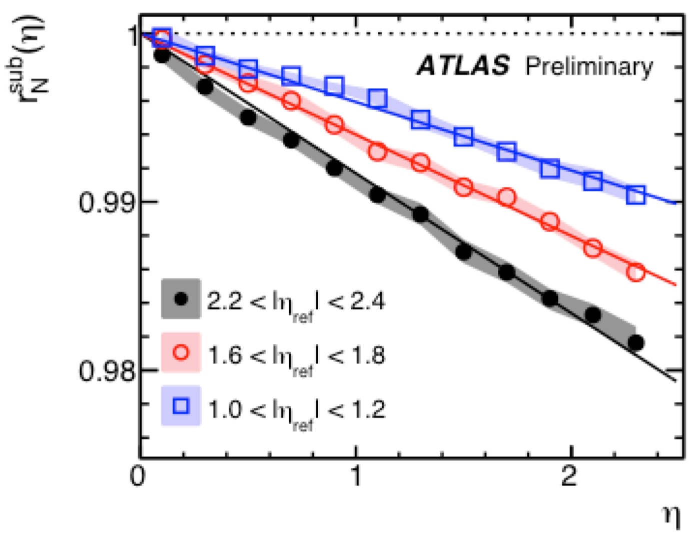
Fit η_- dependence



Fit η_+ dependence



Fit η dependence



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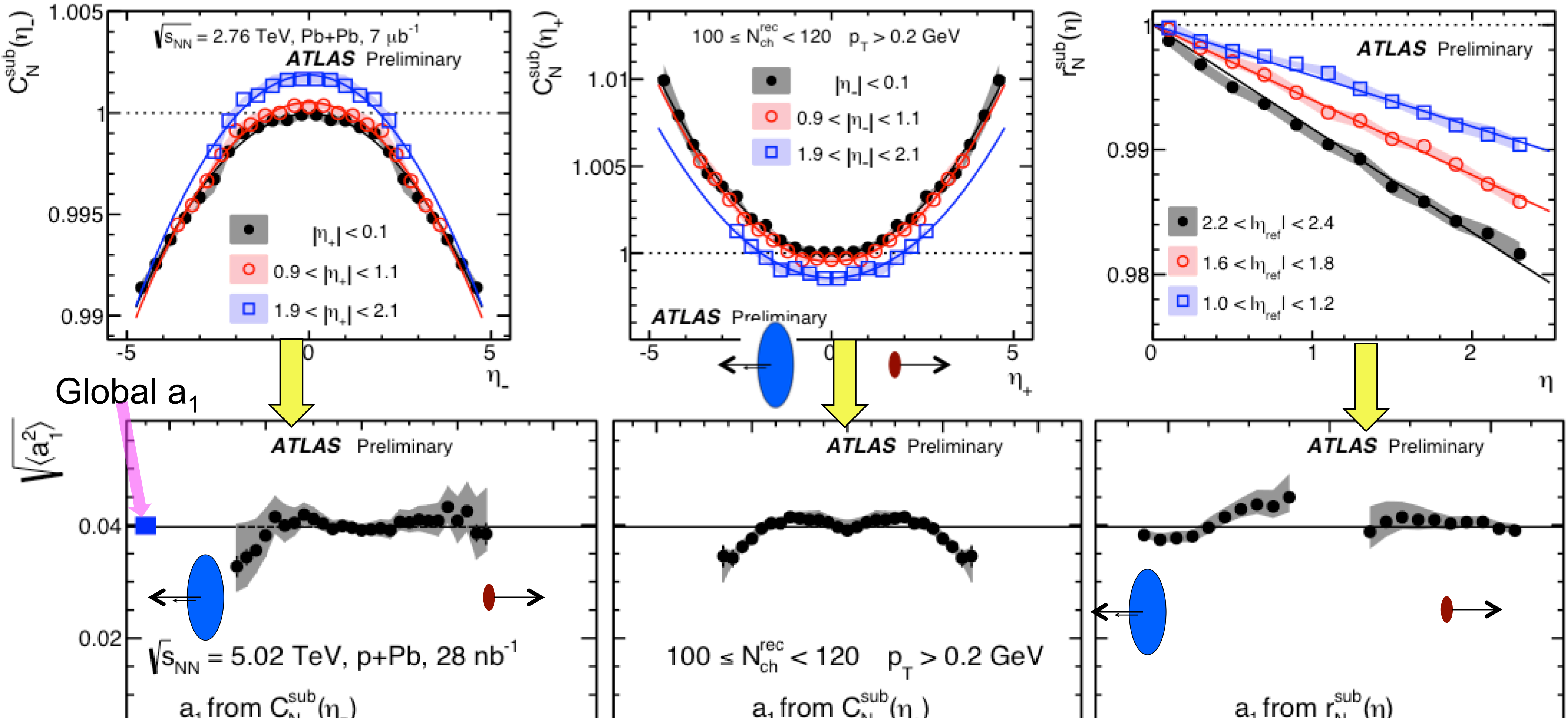
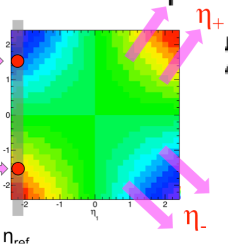
Fit η_- dependence — Fit η_+ dependence — Fit η dependence



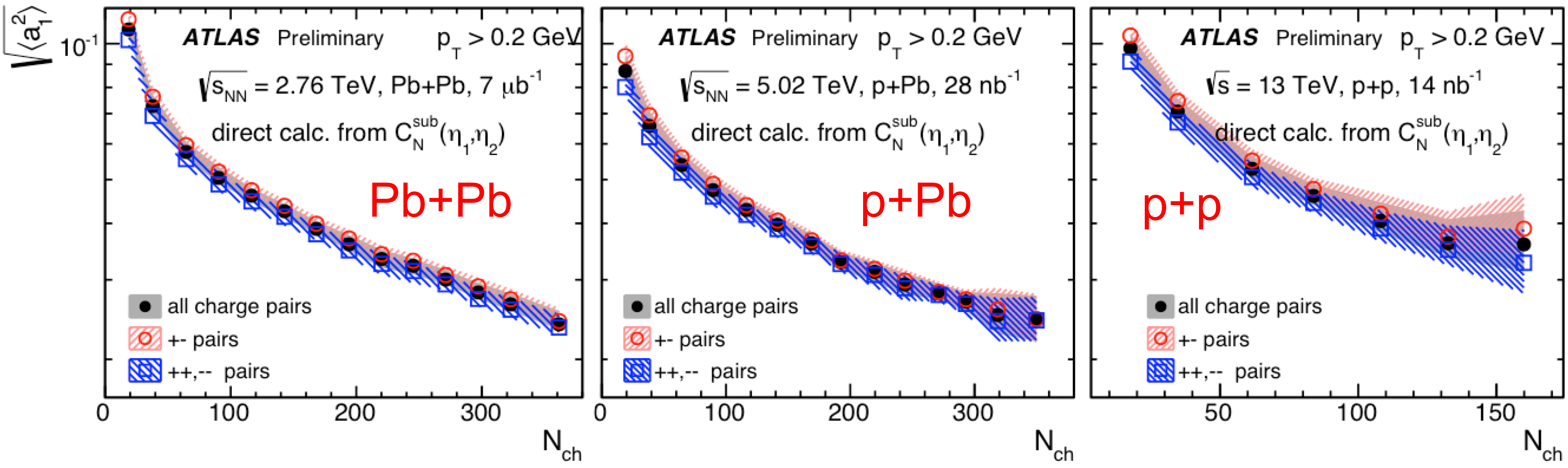


LRC is ~symmetric between proton- and lead-going side!

N_{ch} dependence of LRC (in terms of a_1)

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

- Calculated from Legendre expansion method for all-charge, opposite-charge and all-charge pairs

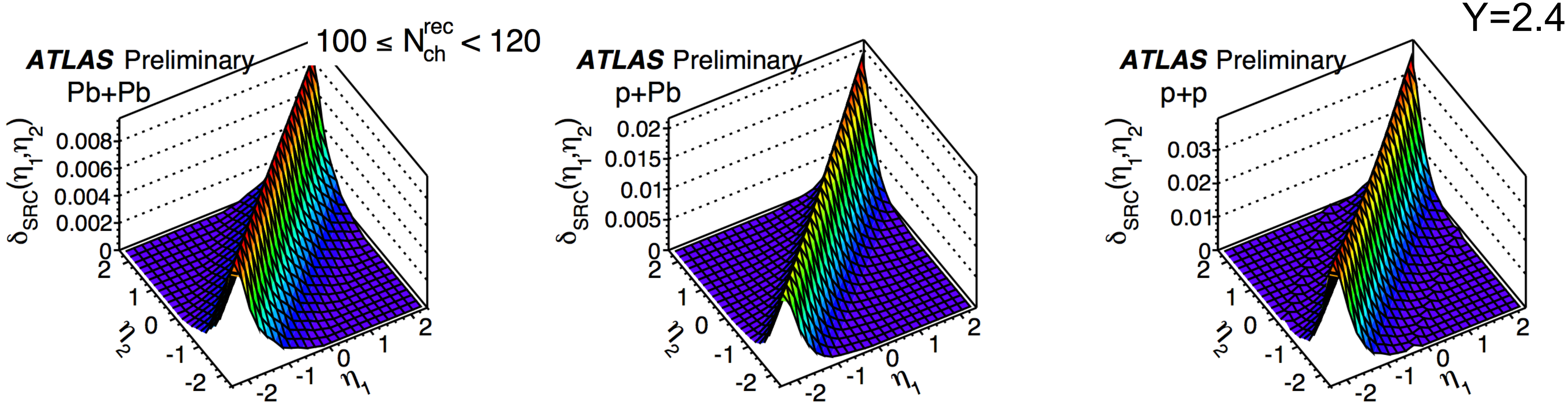


No dependence on charge combinations

N_{ch} dependence of SRC

- Quantify SRC using its average amplitude $\Delta_{SRC} = \frac{\int \delta_{SRC}(\eta_1,\eta_2)d\eta_1 d\eta_2}{4Y^2}$

Y=2.4



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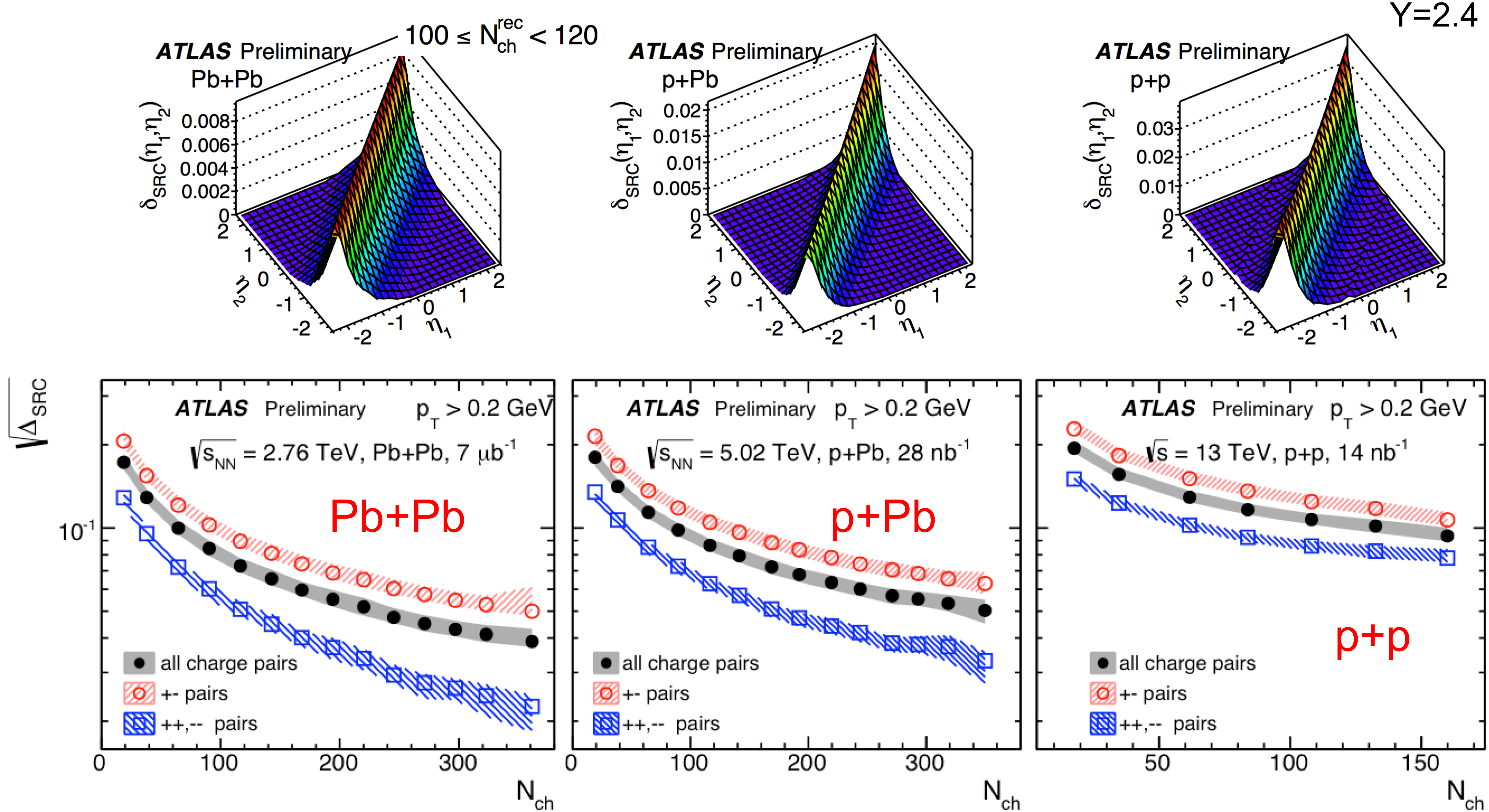
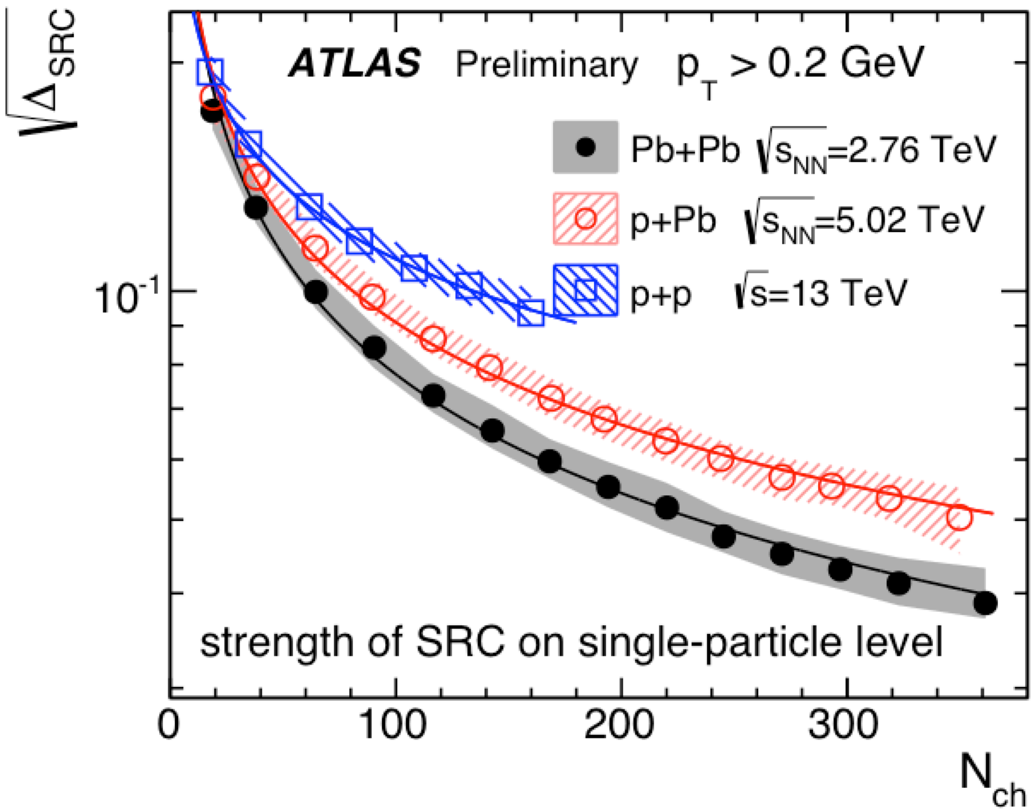


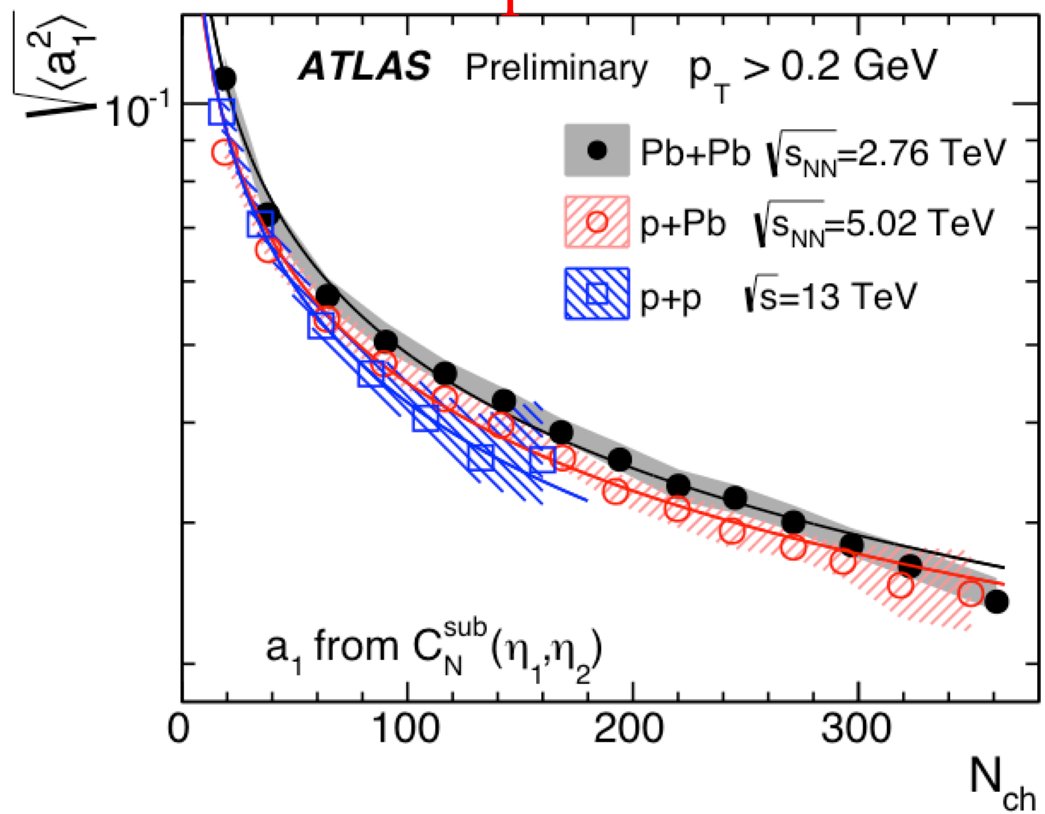
Strong dependence on charge and system size

N_{ch} dep. of SRC and a_1 in three systems

SRC



a_1 for LRC



- They follow power-law function

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

Expected scaling behavior?

- SRC can be related to the number of sources n contributing to N_{ch}

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

- LRC expected to be related to the asymmetry between n_f and n_b

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

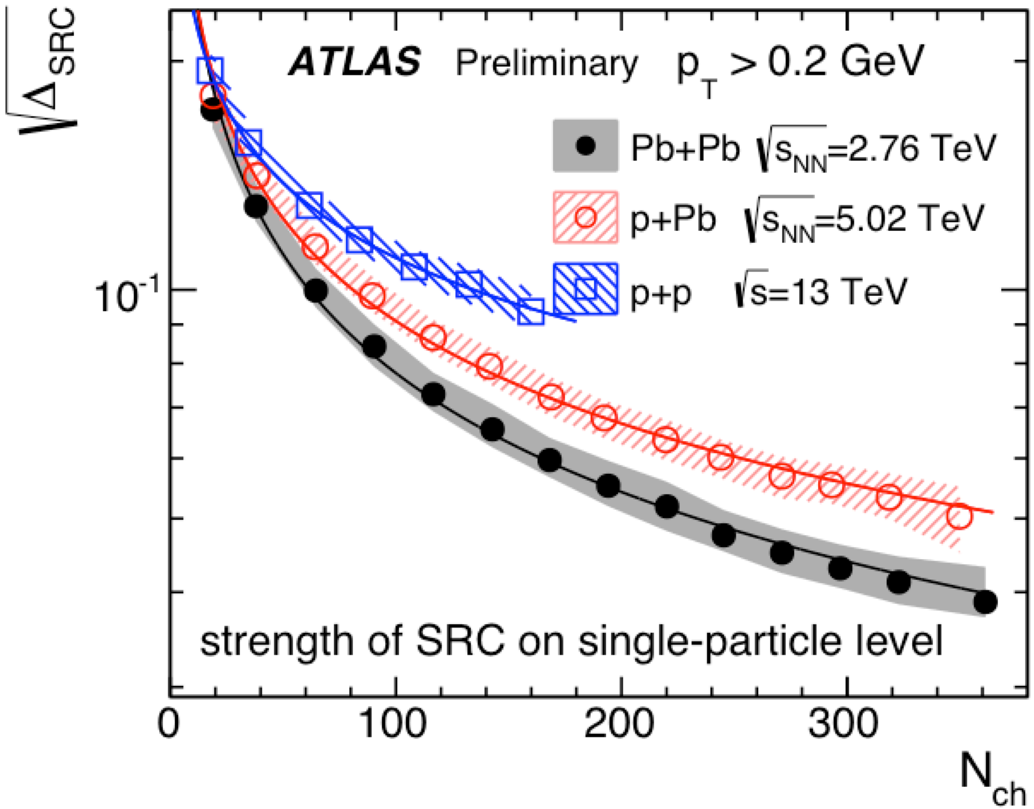
- Assume independent cluster picture NPB85 (1975)61: each source emits the same number of pairs and the number of sources follows Poisson fluctuations, then

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

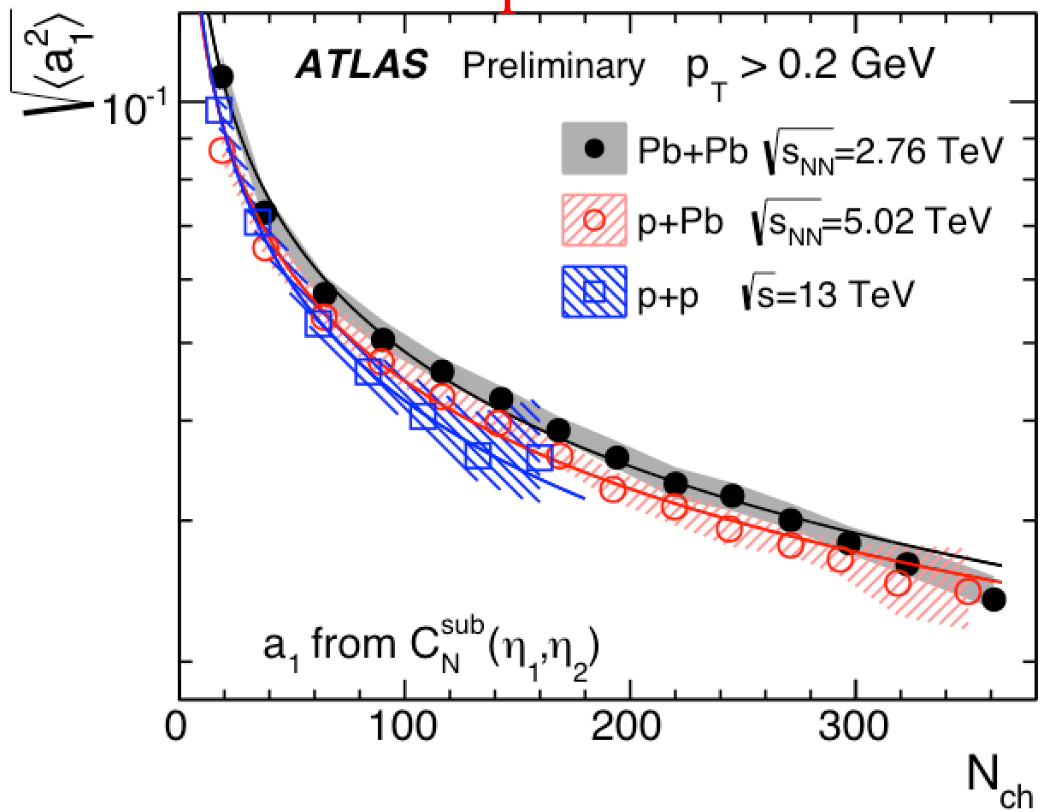
Sources could be:
wounded nucleons, or partons (via frag.), flux tubes, or final state resonance decays

N_{ch} dep. of SRC and a_1 in three systems

SRC



a_1 for LRC



- They follow power-law function   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

α smaller in pp→ num. of cluster is smaller or cluster size is larger at same N_{ch}?

Summary

- Two-particle correlation $C_N(\eta_1,\eta_2)$ measured in PbPb, pPb and pp collisions for p_T>0.2 GeV and $|\eta|<2.4$ at similar event multiplicity N_{ch}.
  - Sum of a short-range component (SRC) + a long-range component (LRC).

- Data-driven method to separate SRC and LRC based on the fact that SRC differs between +- and ±± pairs, but not for LRC
  - LRC is symmetric in all systems, but in pPb SRC is asymmetric for η and $-\eta$.
  - LRC consistent with $1+\langle a^2{}_1\rangle\eta_1\eta_2$, $\langle a^2{}_1\rangle$ is extracted via Legendre expansion as well as from the projections of the LRC in limited η_1,η_2 phase space

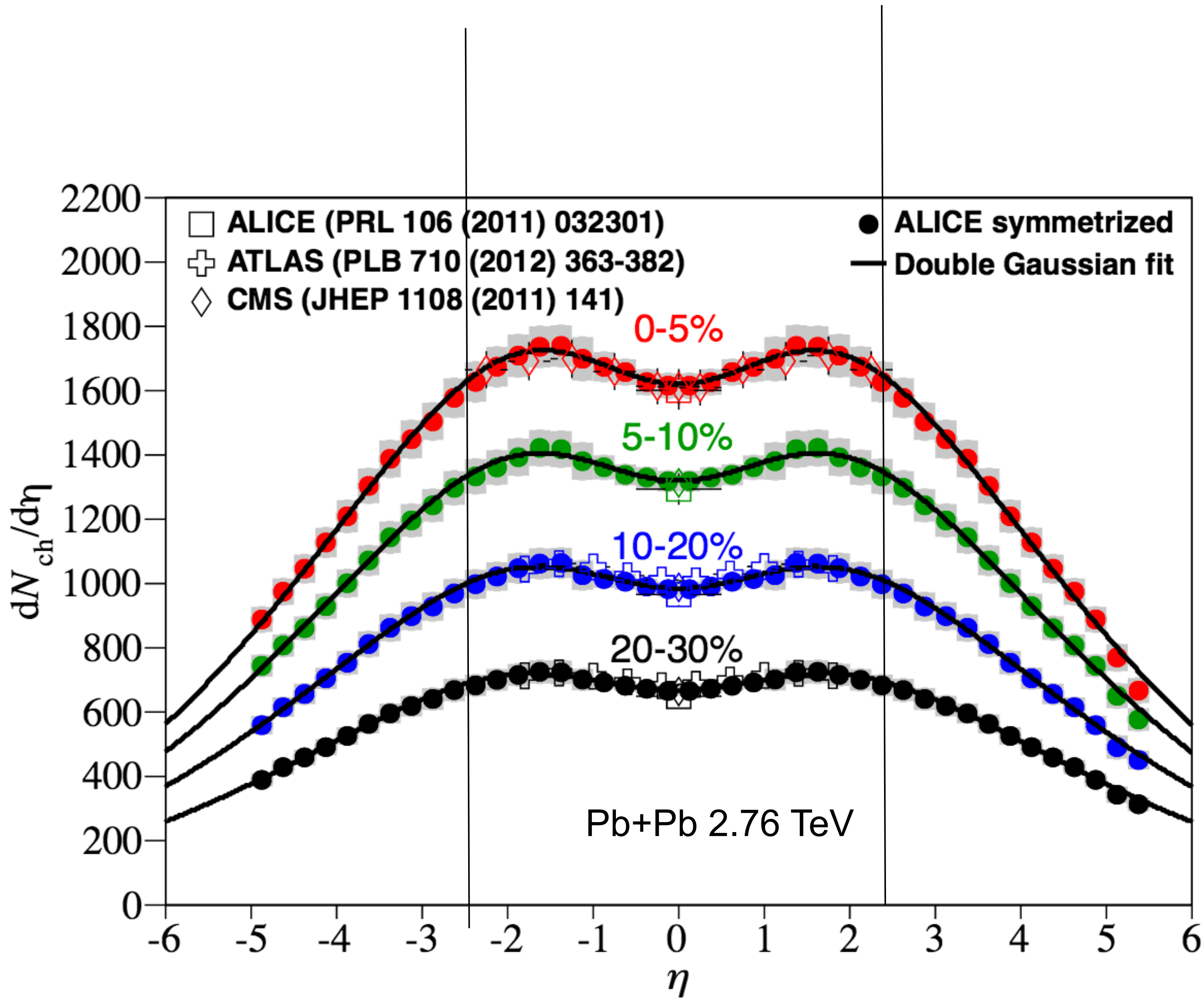
- N_{ch}-scaling of LRC (via a_1) and SRC are studied
  - LRC (via a_1) controlled by N_{ch}, not by collision systems or charge combination
  - SRC depends strongly on collision system and charge combination
  - N_{ch} dependence of LRC and SRC follows power-law with an index close to 0.5 → relation to the number of sources for particle production?

Important inputs for 3+1D hydrodynamic models **W/O** boost invariance
Insights on particle production, longitudinal transport, final-state effects

See works by Bzdak, Bozek, Broniowski1509.02967,1509.04124; , Akihiko, Schenke 1509.04103

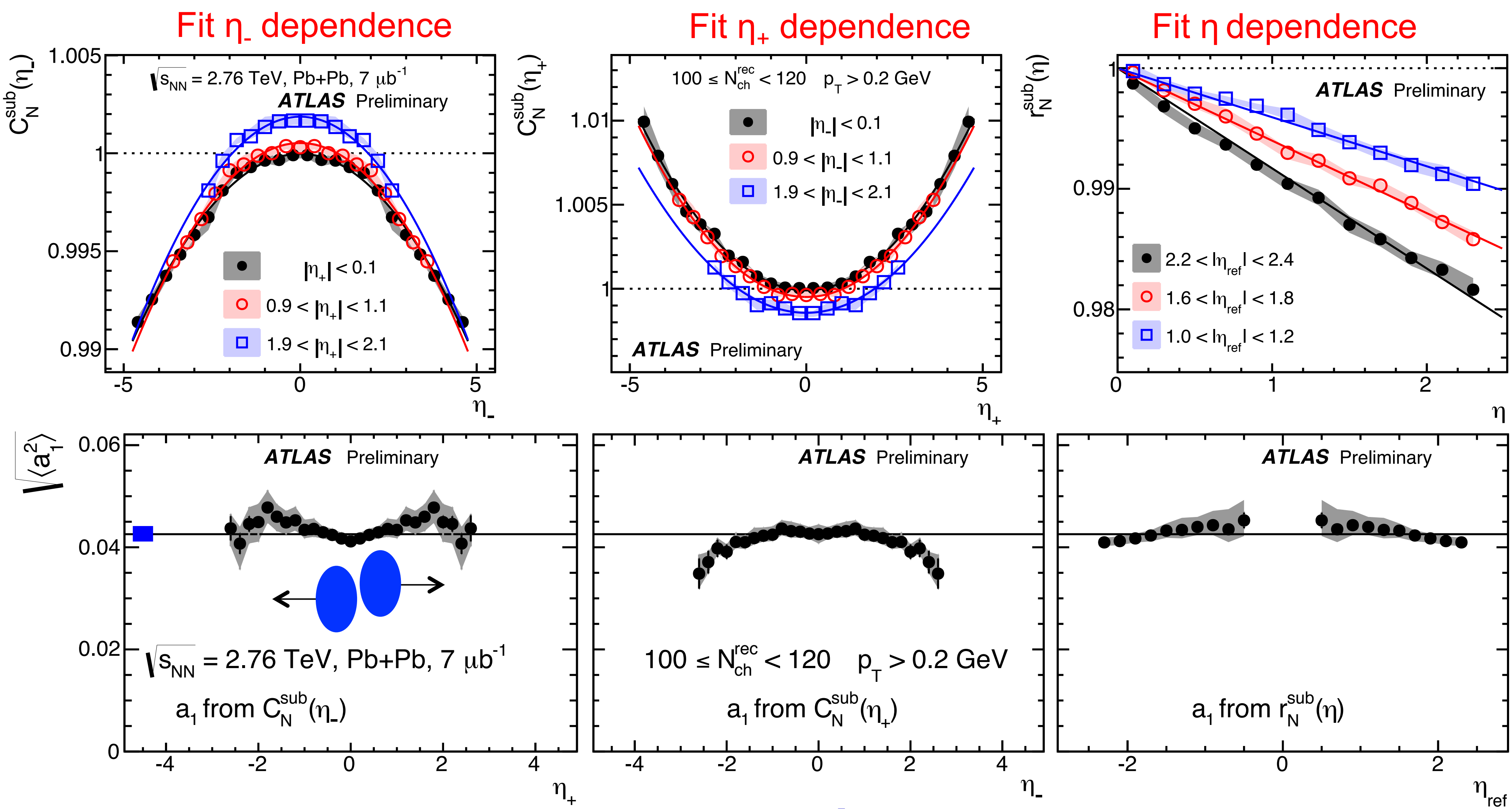
END

ALICE dN/dη distribution



Projections of CF in Pb+Pb

$$C_N^{sub}(\eta_1,\eta_2) \approx 1 + \langle a_1^2\rangle \eta_1\eta_2 = 1 + \frac{\langle a_1^2\rangle}{4}(\eta_+^2 - \eta_-^2) \qquad r_N^{sub}(\eta,\eta_{ref}) = 1 - 2\langle a_1^2\rangle |\eta_{ref}|\,\eta$$

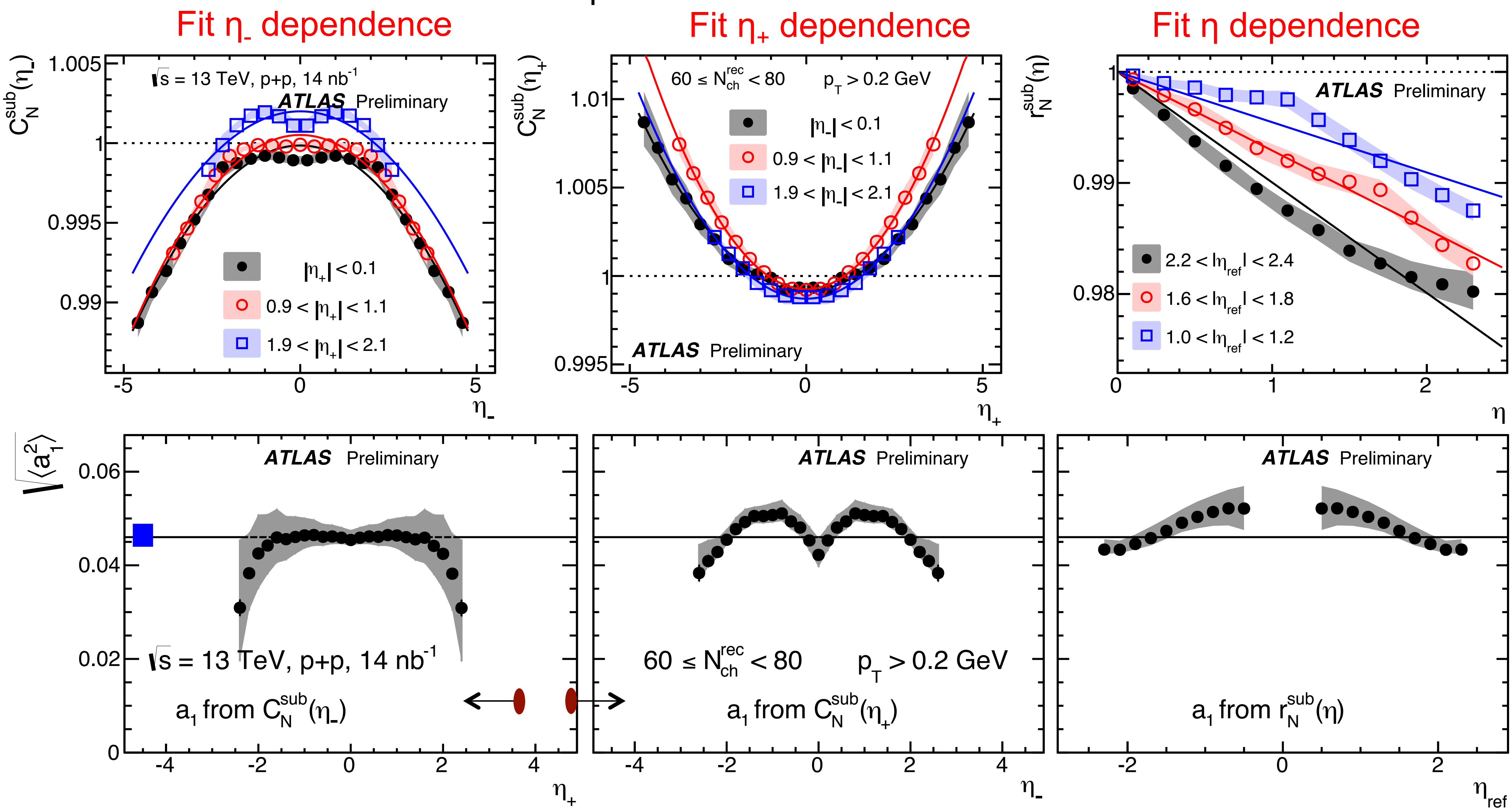


- Consistent a_1 at different slices → LRC dominated by a_1.

Consistent between four methods

Projections of CF in p+p

$$C_N^{sub}(\eta_1,\eta_2) \approx 1 + \langle a_1^2\rangle \eta_1\eta_2 = 1 + \frac{\langle a_1^2\rangle}{4}(\eta_+^2 - \eta_-^2) \qquad r_N^{sub}(\eta,\eta_{ref}) = 1 - 2\langle a_1^2\rangle |\eta_{ref}|\,\eta$$

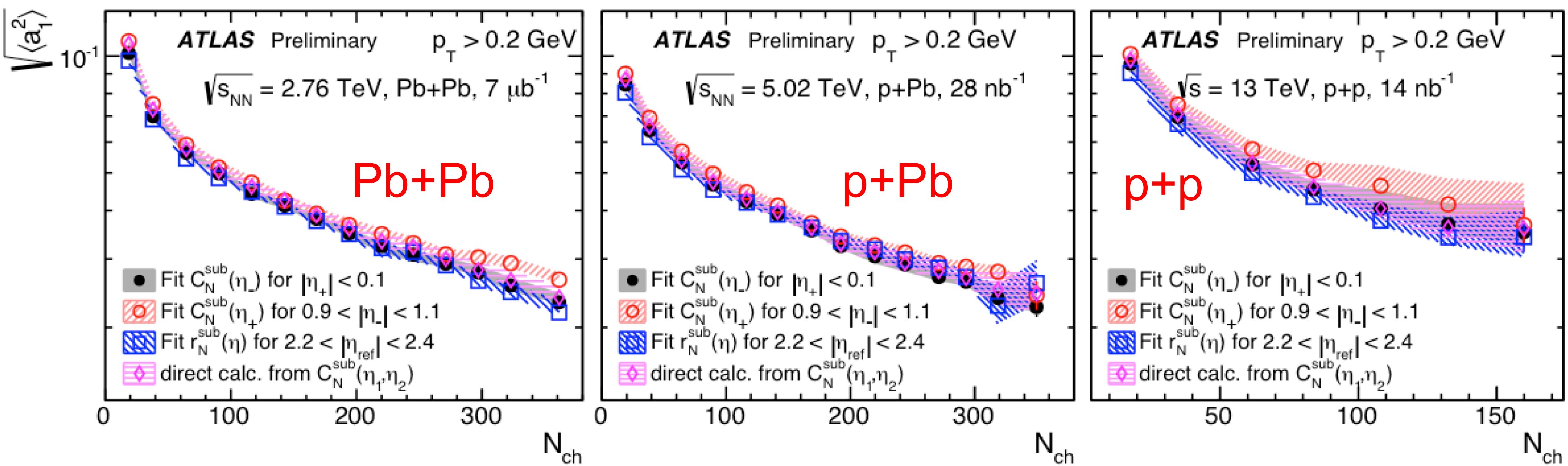


- Consistent a_1 at different slices → LRC dominated by a_1.

Consistent between four methods

a_1 from four methods

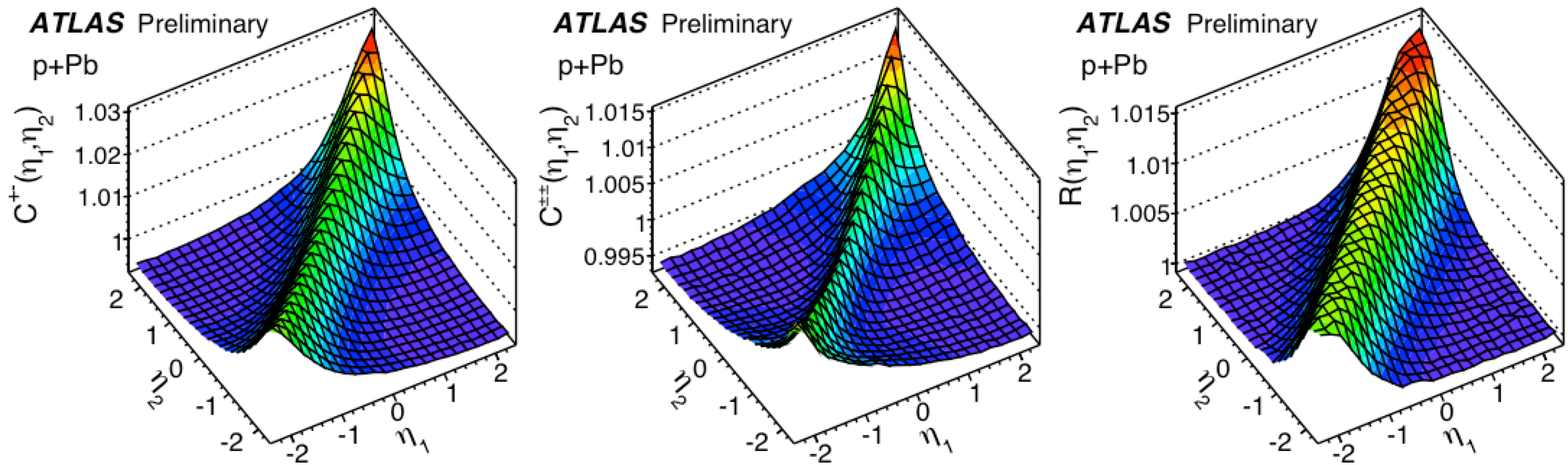
- (i) Quadratic fit to η- direction, $C_N^{sub}(\eta_-)|_{|\eta_+|<0.1}$
- (ii) Quadratic fit to η+ direction, $C_N^{sub}(\eta_+)|_{0.9<|\eta_-|<1.1}$
- (iii) Linear fit to r correlator, $r_N^{sub}(\eta)|_{2.2<|\eta_{ref}|<2.4}$
- (iv) Legendre expansion



4 methods consistent with each other in all three collision systems

Properties of SRC in p+Pb

- Most of the FB asymmetry is in the magnitude of the SRC.
- η_--width of SRC is constant as a function of η_+.

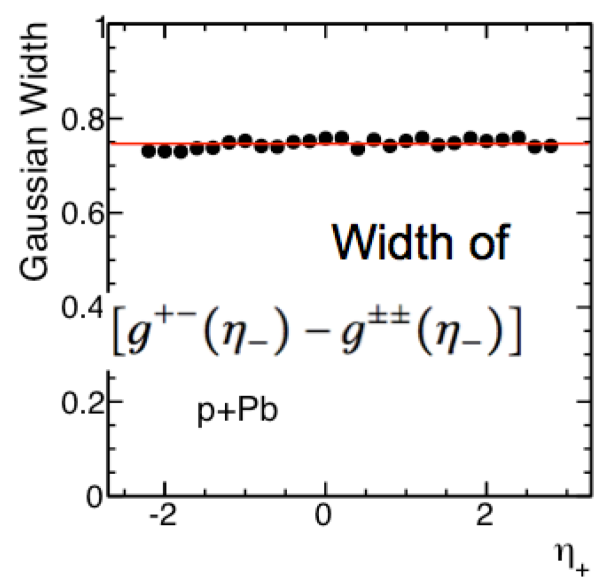


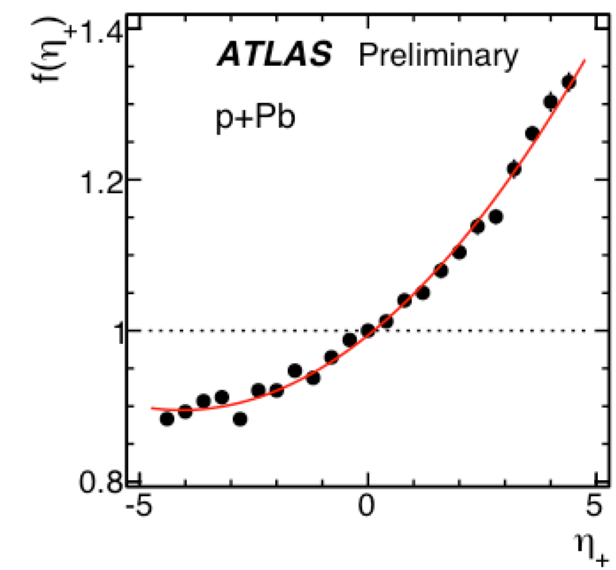
ATLAS Preliminary

$200 \le N_{ch}^{rec} < 220$

$\sqrt{s_{NN}}$ = 5.02 TeV, p+Pb, 28 nb^{-1}

$p_T > 0.2$ GeV

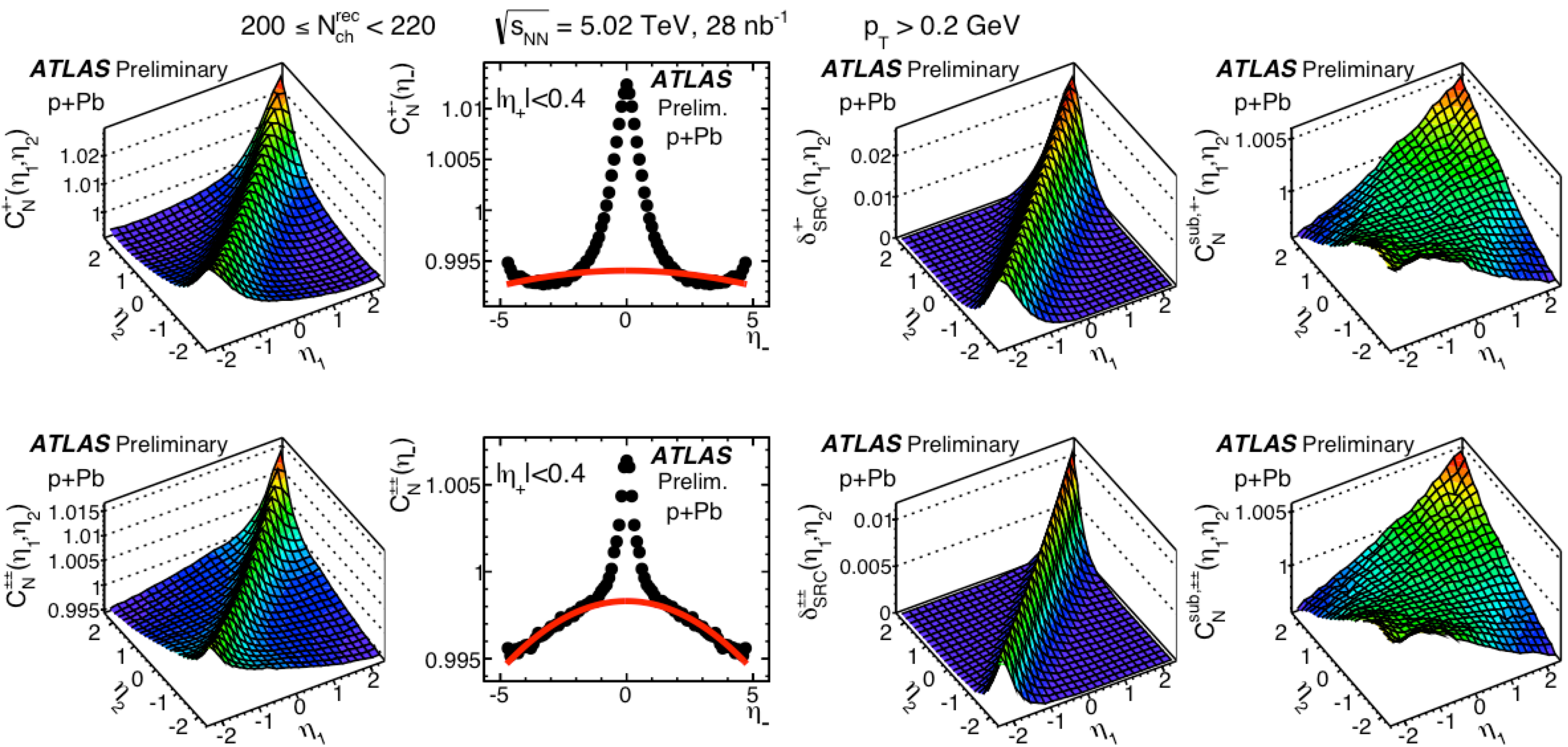




Estimation of the SRC in pPb

$$R(\eta_+,\eta_-) \approx 1 + f(\eta_+)\left[g^{+-}(\eta_-) - g^{\pm\pm}(\eta_-)\right]\ ,\ \ \delta_{\rm SRC}^{+-} = f(\eta_+)g^{+-}(\eta_-),\ \ \delta_{\rm SRC}^{\pm\pm} = f(\eta_+)g^{\pm\pm}(\eta_-)$$

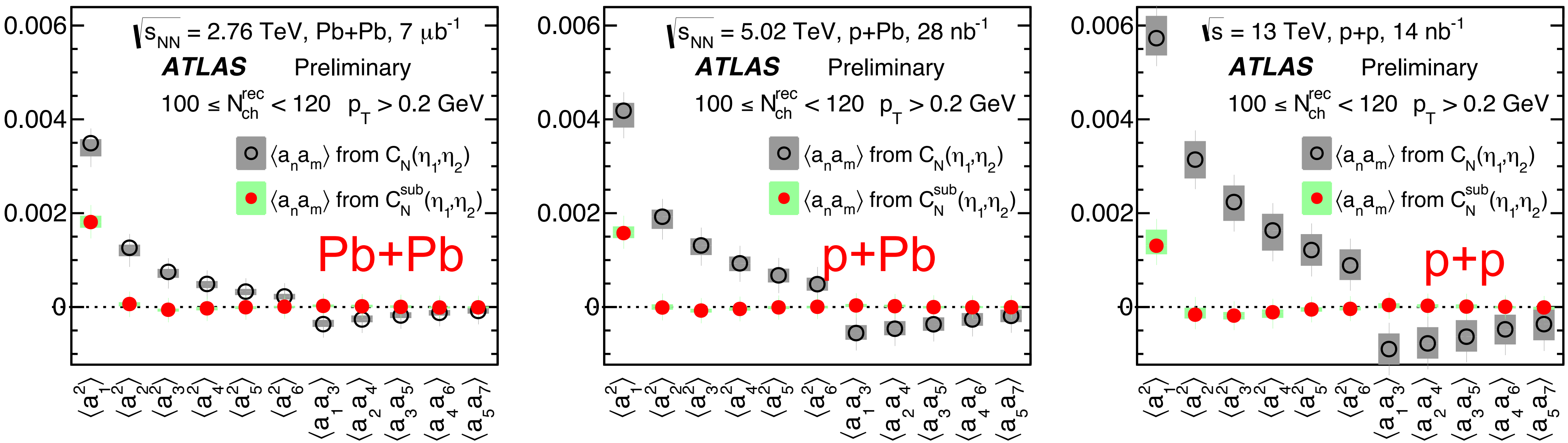
- Asymmetry between proton-going and lead-going direc is due to SRC
- LRC is very symmetric



- The LRC, $C_N^{sub}(\eta_+,\eta_-)$, has similar magnitude between charge combinations.

Legendre spectra before and after subtraction

$$C_N(\eta_1,\eta_2) \text{ or } C_N^{sub}(\eta_1,\eta_2) = 1 + \sum_{n,m=1}^{\infty} \langle a_n a_m \rangle \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2}$$



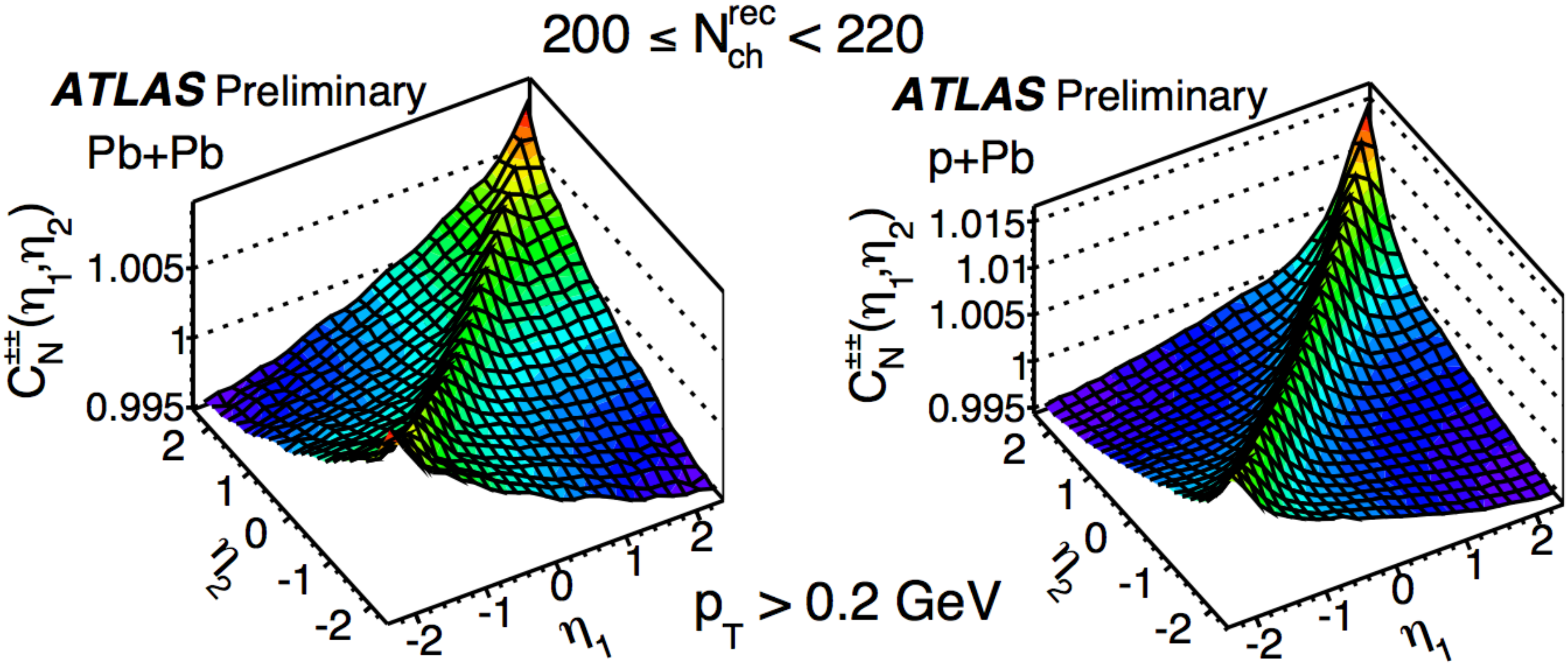
- a_n values significantly reduced after SRC subtraction
  - Dominated by a_1.

Constructing correlation function

- Signal and Background distributions
  - Tracks from events with similar N_{ch} and z_{vtx}

$$C = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} = \frac{S(\eta_1,\eta_2)}{B(\eta_1,\eta_2)}$$

- Due to symmetry in PbPb or pp, only one quadrant is independent.
  - $\eta_-=\eta_1-\eta_2>0$, $\eta_+=\eta_1+\eta_2>0$ $\quad C_N(\eta_1,\eta_2) = C_N(\eta_2,\eta_1)$ $\quad C_N(\eta_1,\eta_2) = C_N(-\eta_1,-\eta_2)$
- In pPb collision, only one half is independent
  - $\eta_-=\eta_1-\eta_2>0$ $\quad C_N(\eta_1,\eta_2) = C_N(\eta_2,\eta_1)$
  - But distribution can be symmetrized in any case to compare PbPb and pp



Summary of systematics

- Evaluate based on ratios of correlation function

$$d(\eta_1,\eta_2)=\frac{C(\eta_1,\eta_2)_{\mathrm{check}}}{C(\eta_1,\eta_2)_{\mathrm{default}}} \quad \delta_{sys}C=\sqrt{\sum_k (d_k-1)^2} \quad \delta_{sys}a_n=\sqrt{\sum_k ((a_n)_k-1)^2}$$

  - Separately for $C_{\mathrm{N}}(\eta_1,\eta_2)$ & $C_{\mathrm{N}}^{\mathrm{sub}}(\eta_1,\eta_2)$

- Uncertainty propagate to the a_1 calculated from four methods

Correlation function

Collision system	Pb+Pb	*p*+Pb	*pp*
Event-mixing [%]	0.4–0.7	0.4–2.2	0.2–1.4
Run-by-run stability [%]	0.3–0.5	0.3–1.5	0.2–1.5
z_{vtx} variation [%]	0.3–0.6	0.3–1.5	0.2–1.6
Track selection & efficiency [%]	0.6–1.2	0.2–1.3	0.3–0.7
MC consistency [%]	0.2–1.6	0.5–2.5	0.7–3.3
Charge dependence [%]	1.0–1.8	0.8–3.8	1.5–2.5
SRC subtraction [%]	1.1–2.1	1.0–5.9	1.2–5.0
Total [%]	1.7–3.2	2.1–7.6	2.5–6.9

a_1 from the four methods

	quadratic fit to the $C_{\mathrm{N}}^{\mathrm{sub}}(\eta_-)\|_{\|\eta_+\|<0.1}$			quadratic fit to the $C_{\mathrm{N}}^{\mathrm{sub}}(\eta_+)\|_{0.9<\|\eta_-\|<1.1}$		
Collision system	Pb+Pb	*p*+Pb	*pp*	Pb+Pb	*p*+Pb	*pp*
Event-mixing [%]	0.5–2.2	0.3–1.8	0.2–2.8	0.2–1.7	0.2–1.6	0.2–2.7
Run-by-run stability [%]	0.2–1.3	0.2–1.7	0.2–2.8	0.2–1.5	0.2–1.1	0.2–1.6
z_{vtx} variation [%]	0.3–1.9	0.1–2.2	0.1–1.6	0.1–1.8	0.2–0.7	0.1–0.9
Track selec.& efficiency[%]	0.4–2.1	0.3–0.9	0.8–2.2	0.8–3.7	1.0	0.9–1.2
MC consistency [%]	0.2–3.6	0.4–3.9	0.2–10.0	0.2–4.3	0.2–2.4	0.2–4.7
Charge dependence [%]	0.9–4.2	1.0–10.2	2.8–4.6	0.4–3.8	0.6–3.1	1.2–6.2
SRC subtraction [%]	0.9–2.5	1.2–6.3	1.3–4.8	1.4–2.5	1.2–3.7	1.2–4.6
Total [%]	2.1–5.2	2.7–10.3	10–12	2.4–5.5	2.5–6.8	3.5–11.2

	linear fit to the $r_{\mathrm{N}}^{\mathrm{sub}}(\eta)\|_{2.2<\|\eta_{\mathrm{ref}}\|<2.4}$			Global Legendre expansion of $C_{\mathrm{N}}^{\mathrm{sub}}$		
Collision system	Pb+Pb	*p*+Pb	*pp*	Pb+Pb	*p*+Pb	*pp*
Event-mixing [%]	0.3–2.3	0.3–1.4	0.1–1.5	0.2–1.8	0.1–1.7	0.1–0.9
Run-by-run stability [%]	0.1–1.2	0.1–1.7	0.2–2.8	0.2–0.7	0.1–1.3	0.1–2.1
z_{vtx} variation [%]	0.2–1.2	0.2–2.1	0.2–2.6	0.1–1.3	0.2–2.5	0.2–1.7
Track selec.& efficiency[%]	0.4–1.3	0.6–0.9	0.7–1.7	0.3–0.9	0.4–0.7	0.8–2.4
MC consistency [%]	0.2–2.6	0.2–3.7	0.8–7.6	0.2–2.5	0.4–3.2	0.1–6.7
Charge dependence [%]	0.4–4.9	0.1–8.8	1.6–5.3	2.3–5.3	1.0–12.7	3.4–8.1
SRC subtraction [%]	1.4–3.2	2.2–3.4	1.7–5.0	1.7–4.3	2.0–8.9	2.7–9.6
Total [%]	2.4–6.2	2.9–8.9	4.4–9.8	3.4–6.4	4.1–12.9	6.2–12.5