Measurement of azimuthal flow of soft and high-p_T charged particles in 5.02 TeV Pb+Pb collisions with the ATLAS detector

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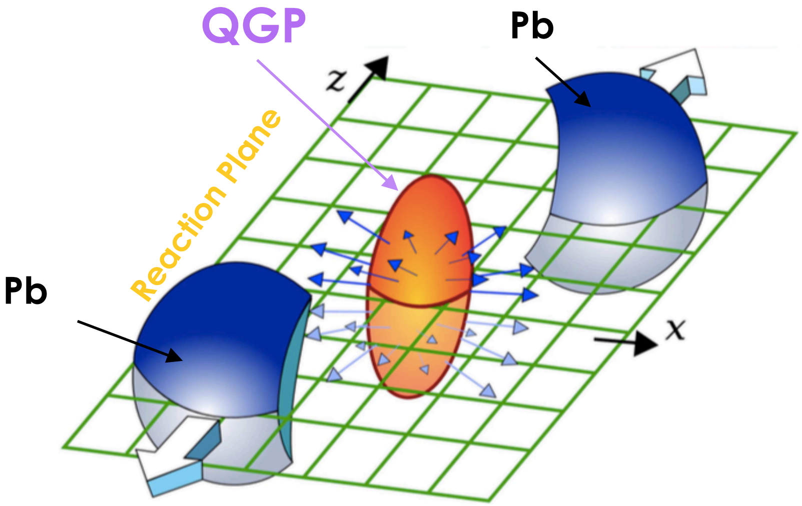
Relativistic Heavy-Ion
Collisions

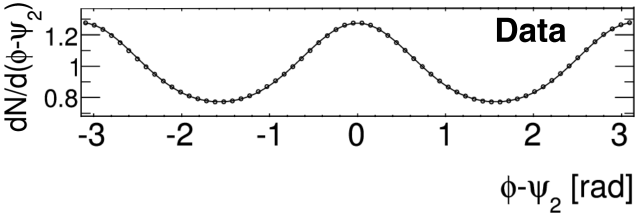
Motivation

Azimuthal anisotropy

- **Quark Gluon Plasma (QGP) produced and probed in heavy ion collisions**
- **Signatures of QGP: collective expansion, jet quenching, etc.**



Anisotropic azimuthal distribution



- **Study QGP properties**
  - **Particle azimuthal distribution**
  - **Two/multi – particle correlations**

Singles:

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[\mathrm{n}(\phi - \Psi_\mathrm{n})]$$

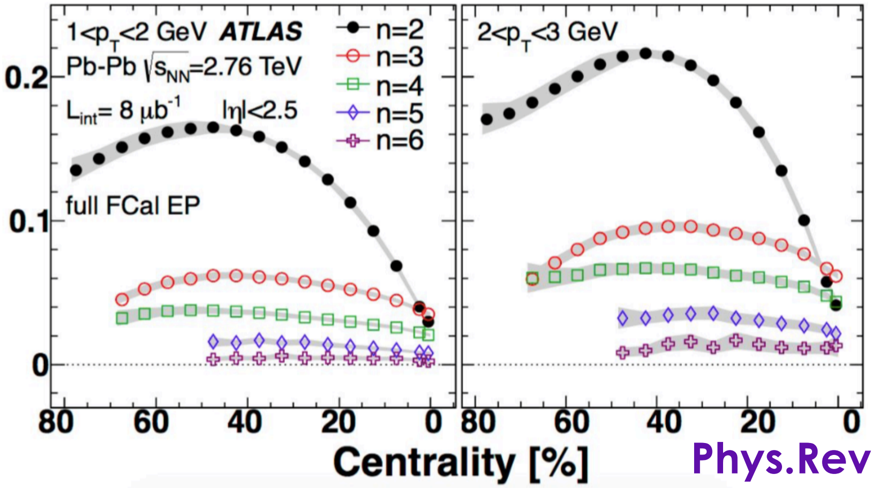
Pairs:

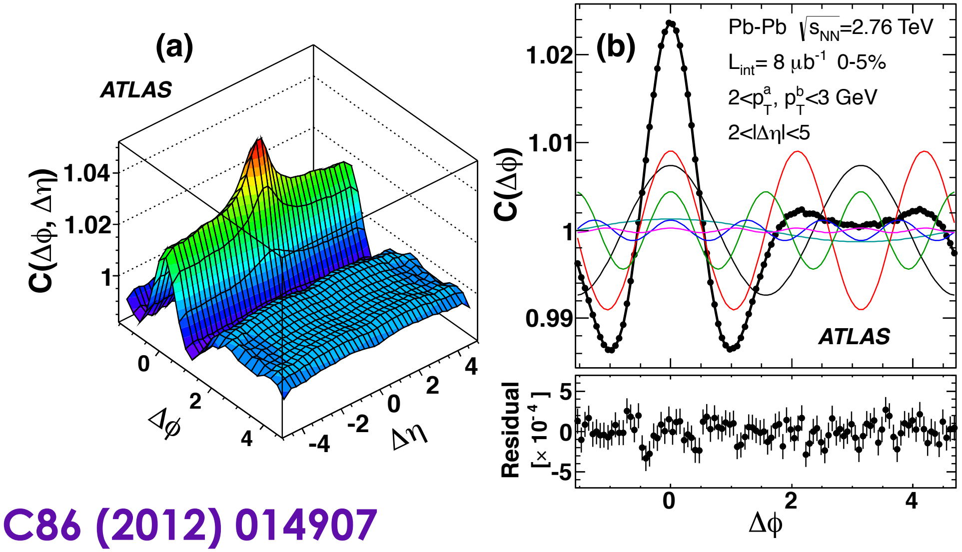
$$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos[n(\Delta\phi)]$$

  - **Azimuthal anisotropy results from different pressure gradients in different spatial directions**

Pb+Pb@2.76 TeV – results from Run-1

- v_n harmonics measured with Event Plane method
  - p_T = 0.5 - 20 GeV
  - $|\eta| < 2.5$
  - centrality 0-80%
- Flow depends on centrality
  - Biggest asymmetry observed in mid-central events (30-50%)
- Non-zero v_n observed up to n=6
  - Very low viscosity of the system
- Two particle η / ϕ correlations revealed ridge and double-hump structures
- $v_{n,n}$ expansion parameters factorize to single particle ones, meaning they come from harmonic flow



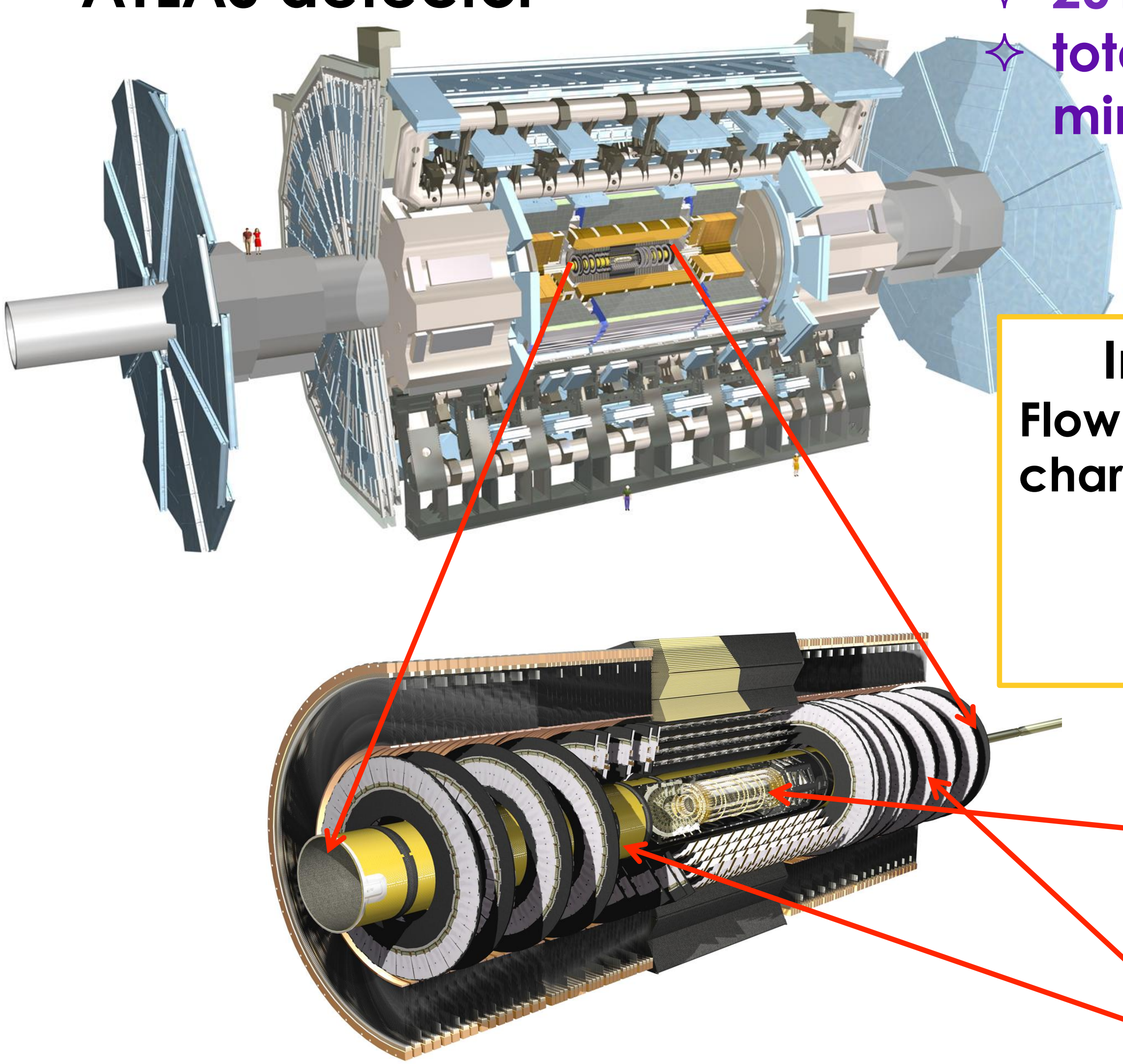


Phys.Rev. C86 (2012) 014907

Datasets

ATLAS detector → v_n measurement

ATLAS detector



- ✧ 2015: Pb+Pb 5.02 TeV, 0.49 nb^{-1}
- ✧ total luminosity sampled by minimum – bias triggers: 22 μb^{-1}

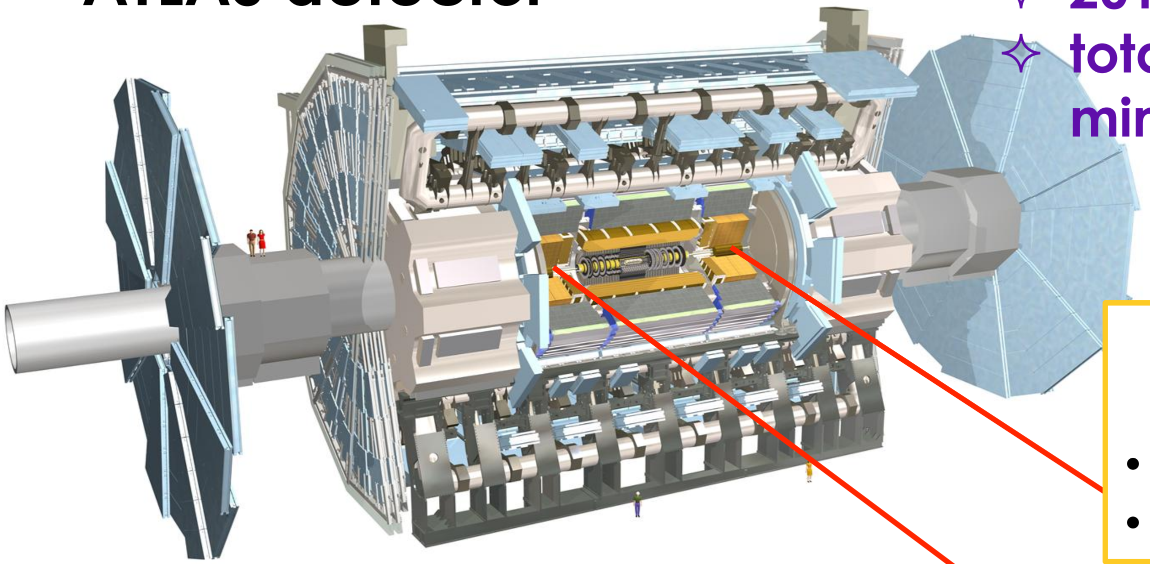
Inner Detector (Pixel+SCT)

Flow measurements is based on charged tracks reconstructed in ID

- $|\eta| < 2.5$
- 2π ϕ acceptance
- $p_T > 0.5$ GeV

ATLAS detector → v_n measurement

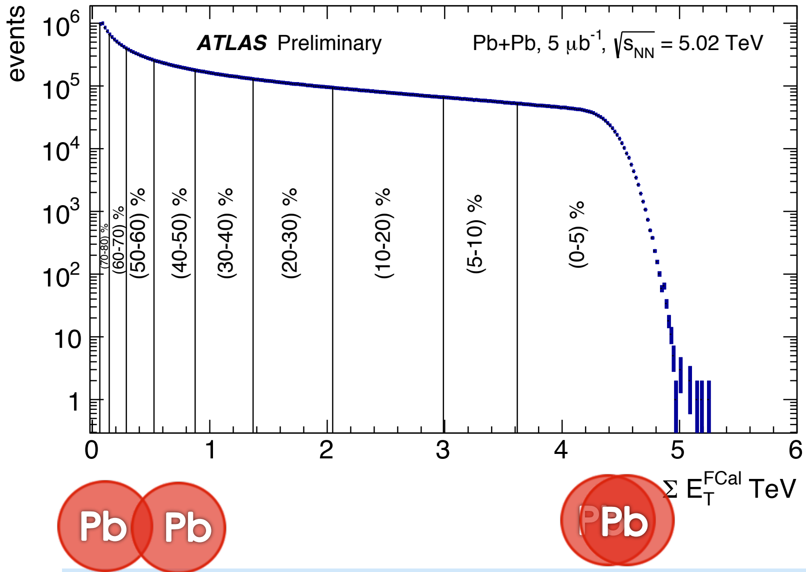
ATLAS detector

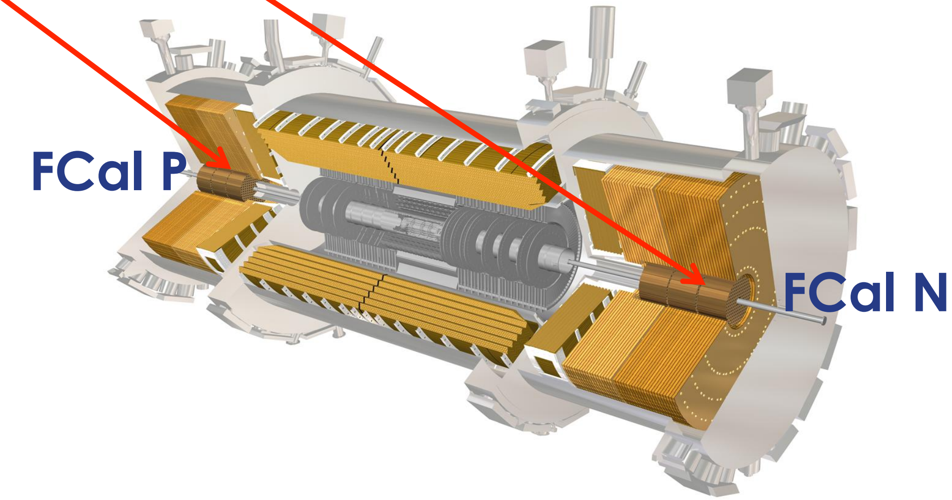


- ✧ **2015: Pb+Pb 5.02 TeV, 0.49 nb^{-1}**
- ✧ **total luminosity sampled by minimum – bias triggers: 22 μb^{-1}**

Forward Calorimeter
($3.2 < |\eta| < 4.9$)

- **Centrality definition**
- **Flow vectors**





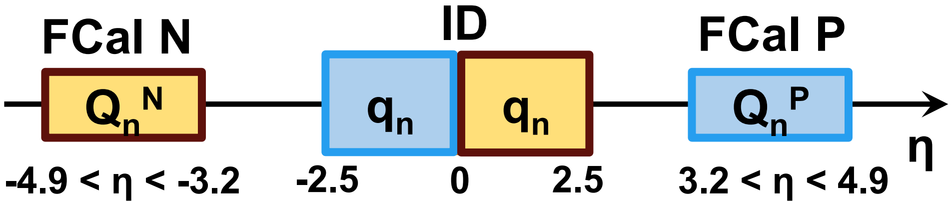
Analysis procedures

Scalar Product (SP)

- Flow vector:

$$Q_n = |Q_n|e^{in\Psi_n} = \frac{1}{S}\sum_j q_{n,j} = \frac{1}{S}\sum_j w_j e^{in\phi_j}$$

- Flow vectors are measured in sub-events
  - FCal N and FCal P → Sum over calorimeter towers
  - ID → sum over charged tracks



FCal N

ID

FCal P

Q_n^N

q_n

q_n

Q_n^P

η

$-4.9 < \eta < -3.2$

-2.5

0

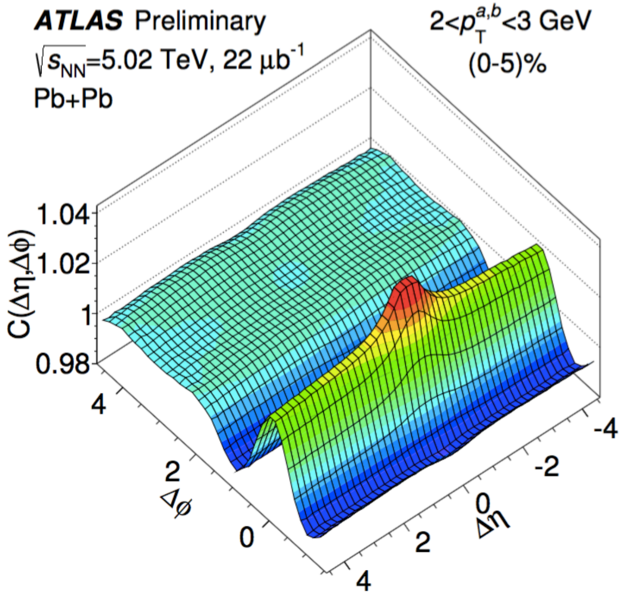
2.5

$3.2 < \eta < 4.9$

$$v_n\{SP\} = \frac{\langle |q_{n,j}||Q_n^{N|P}|cos[n(\phi_j - \Psi_n^{N|P})]\rangle}{\sqrt{\langle |Q_n^N||Q_n^P|cos[n(\Psi_n^N - \Psi_n^P)]\rangle}}$$

- Large eta gap (| η |> 3.2) to suppress short-range correlations
- Scalar Product: unambiguous measurement of v_n → always RMS v_n
- Event Plane: used only to compare to Run-1 results
  - Obtained by Q vectors normalization

Two – particle correlations (2PC)



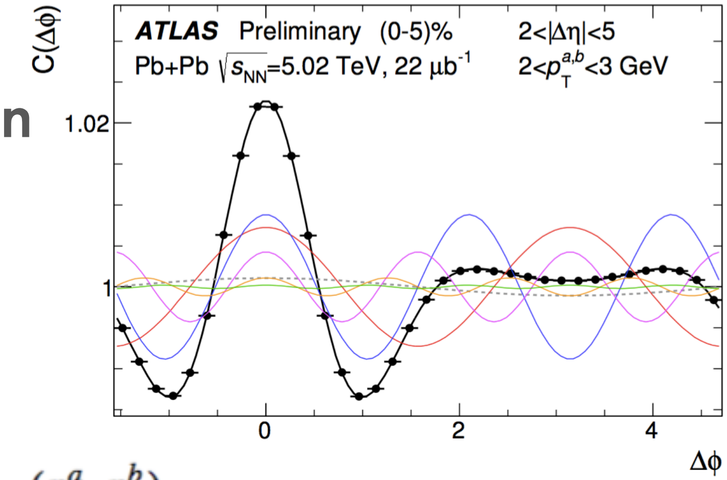
- ✧ **Measure pair distributions in ($\Delta\eta$, $\Delta\phi$)**

$$C(\Delta\eta,\Delta\phi) = \frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)}$$

signal

background

- ✧ **Project S($\Delta\eta$, $\Delta\phi$) and B($\Delta\eta$, $\Delta\phi$) to $\Delta\phi$ axis for $|\Delta\eta| > 2$**
  - **Remove short – range correlations: resonance decays, jet fragmentation etc.**



- ✧ **Divide: S($\Delta\phi$)/B($\Delta\phi$) to obtain correlation function C($\Delta\phi$)**

$$C(\Delta\phi) = C_0\left(1 + \Sigma_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b)\cos(n\Delta\phi)\right)$$

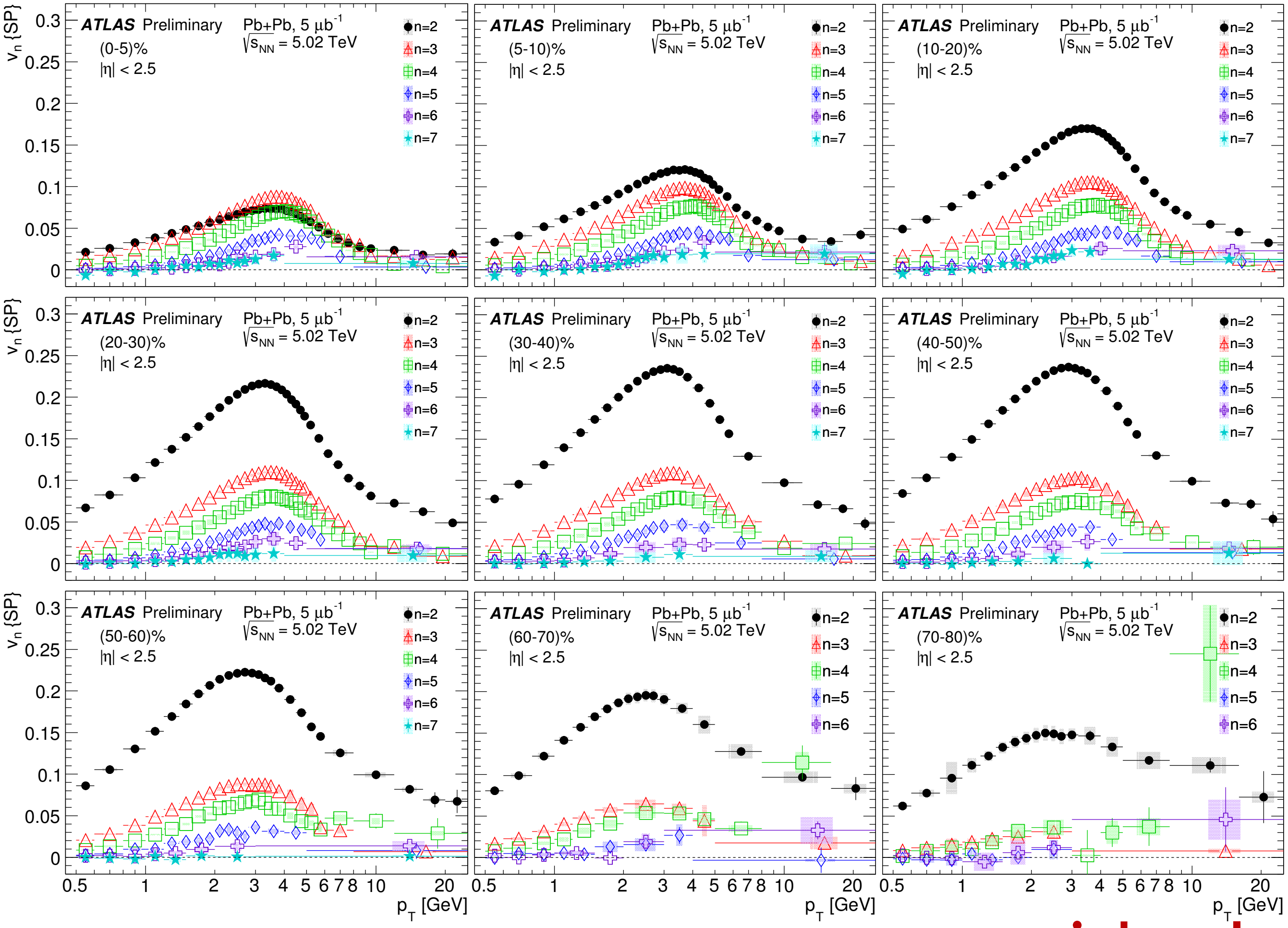
- ✧ **Obtain v_n from $v_{n,n}$ using factorization:**

$$v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b) \qquad v_n(p_T^b) = \frac{v_{n,n}(p_T^a, p_T^b)}{v_n(p_T^a)} = \frac{v_{n,n}(p_T^a, p_T^b)}{\sqrt{v_{n,n}(p_T^a, p_T^a)}}$$

Results

SP Results I: $v_n(p_T)$ dependence

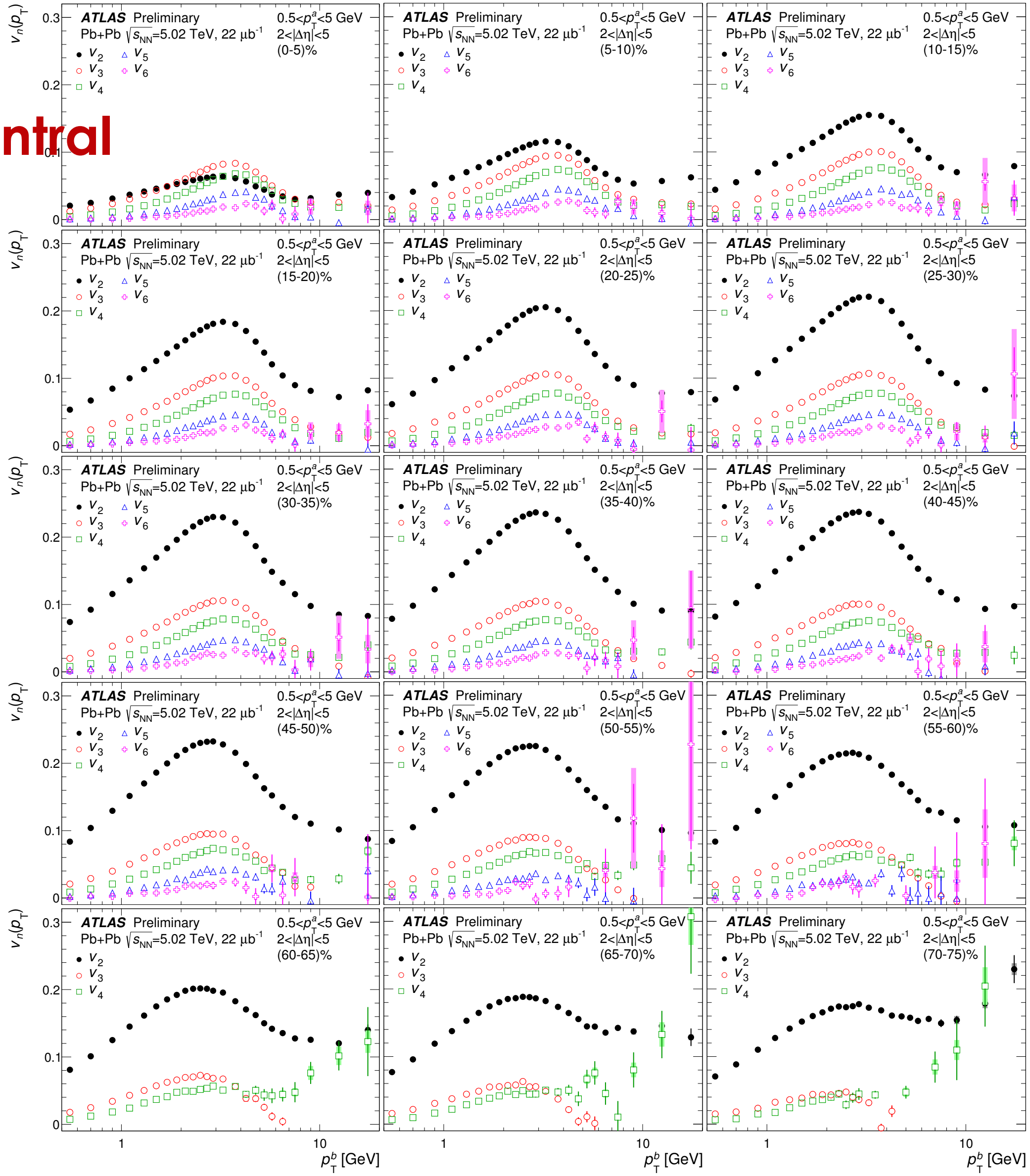
central



peripheral

- ✧ v_n measured up to p_T = 25 GeV
- ✧ v_2 is dominant and remains positive at high p_T
- ✧ Flow harmonics measured for n = 2-7

2PC Results I: v_n (p_T) dependence

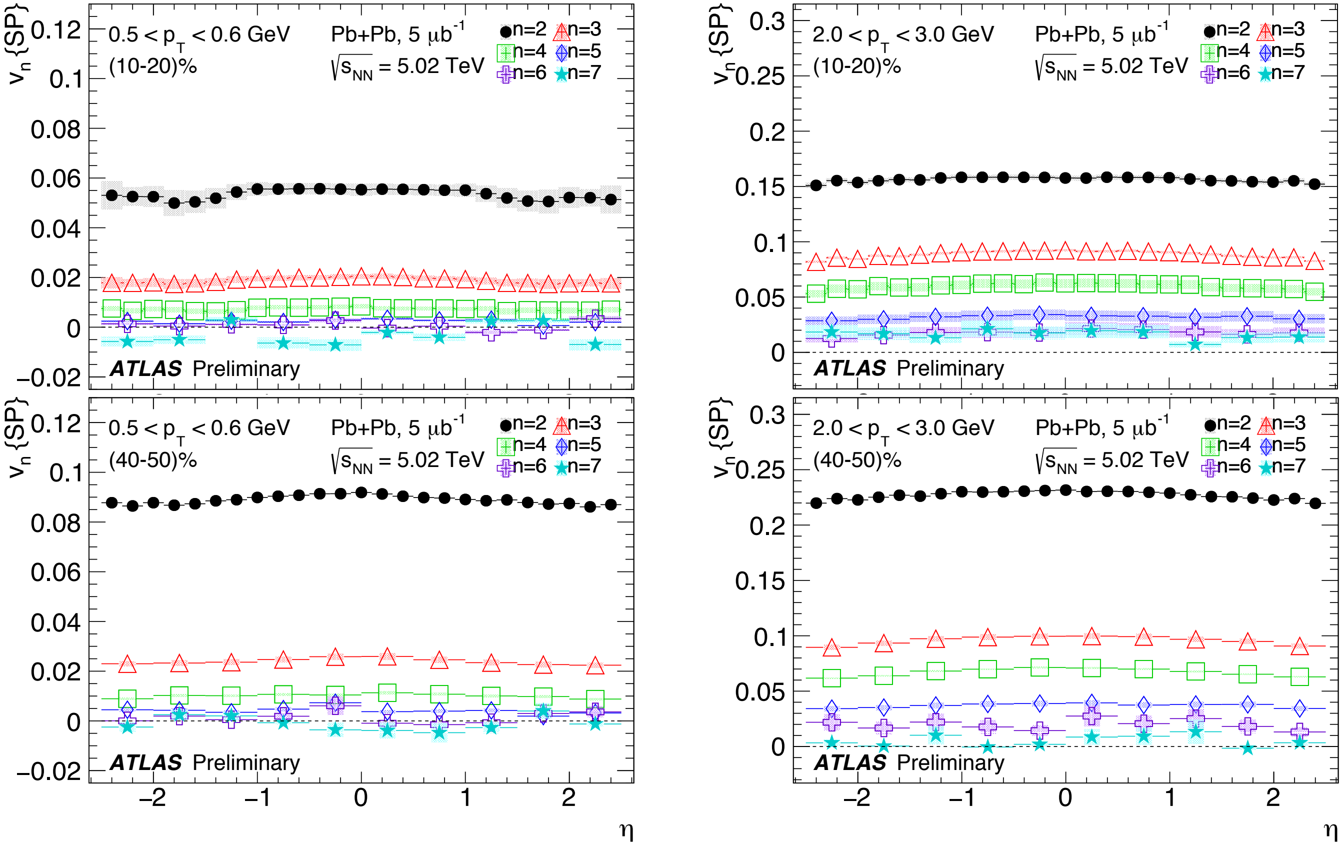


central

peripheral

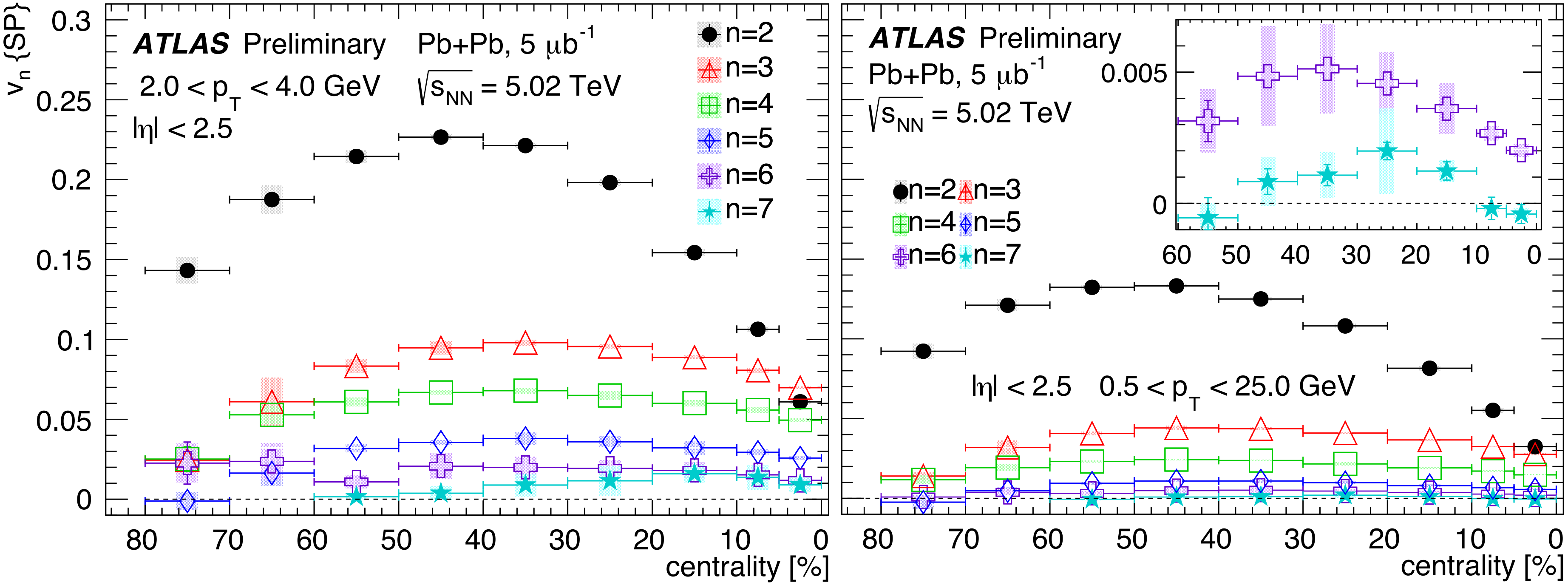
- **v_n measured up to p_T = 25 GeV**
- **v_2 is dominant and remains positive at high p_T**
- **Flow harmonics measured for n = 2-6**

SP Results II: $v_n(\eta)$ dependence



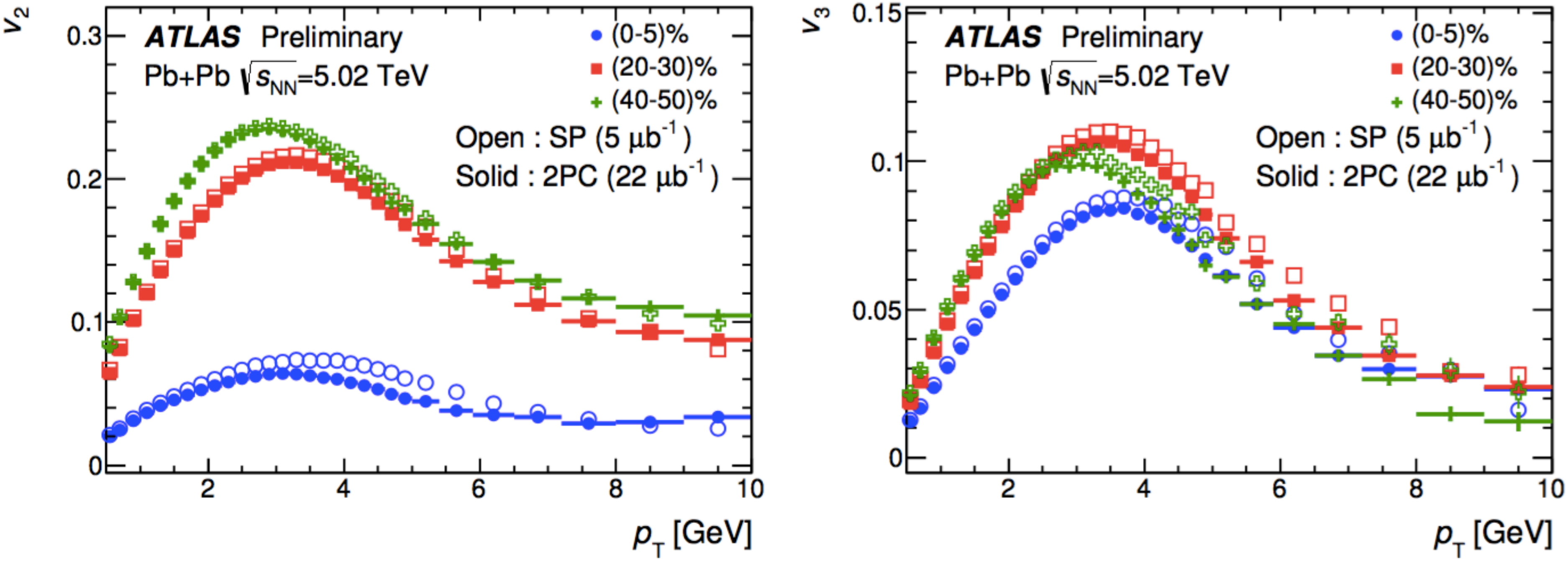
- ✧ **Flow harmonics integrated over narrow p_T intervals:**
  - p_T = 0.5 – 0.6 GeV and p_T = 2 – 3 GeV
- ✧ **All harmonics show very weak η – dependence**
  - In mid-central collisions the integrated v_n over p_T range from 2 to 3 GeV is higher by about 10% in $\eta \approx 0$ compared $\eta \approx \pm 2.5$

SP Results III: v_n centrality dependence



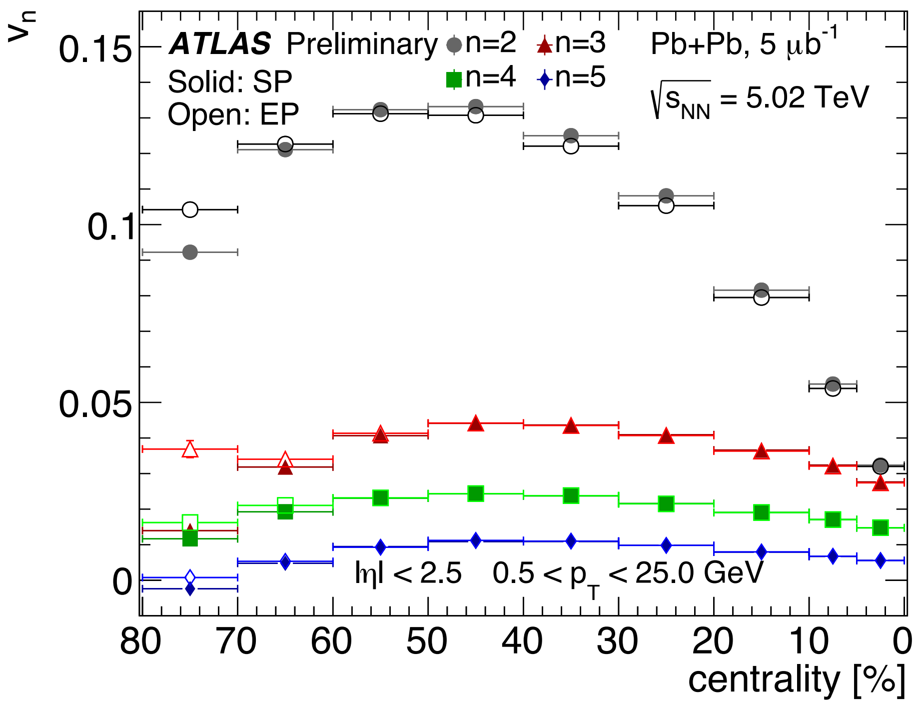
- **v_n dependence on centrality intervals**
  - Integrated over narrow p_T intervals as well as the whole p_T range
- **The biggest asymmetry observed in mid-central collisions (30-50 %)**
  - elliptic flow is dominant asymmetry, except for the most central bin 0-5%
- **Measurement of v_7 for the first time**
  - v_7 is most significant for 10-40% interval

2PC – SP: Methods comparison



- **Both, 2PC and SP, methods are based on two particle correlations**
  - **In 0-5% interval the SP method gives consistently higher values for v_2**
  - **For more peripheral collisions v_2\{SP\} and v_2\{2PC\} match within 2-5%**
  - **Similar trend is observed for n > 2**

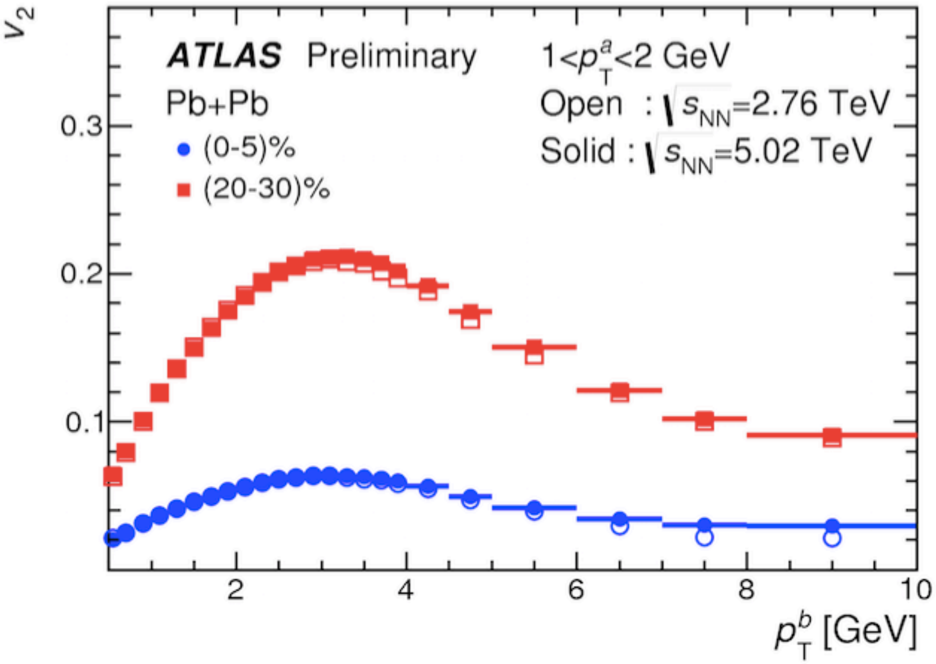
SP vs EP: Methods comparison



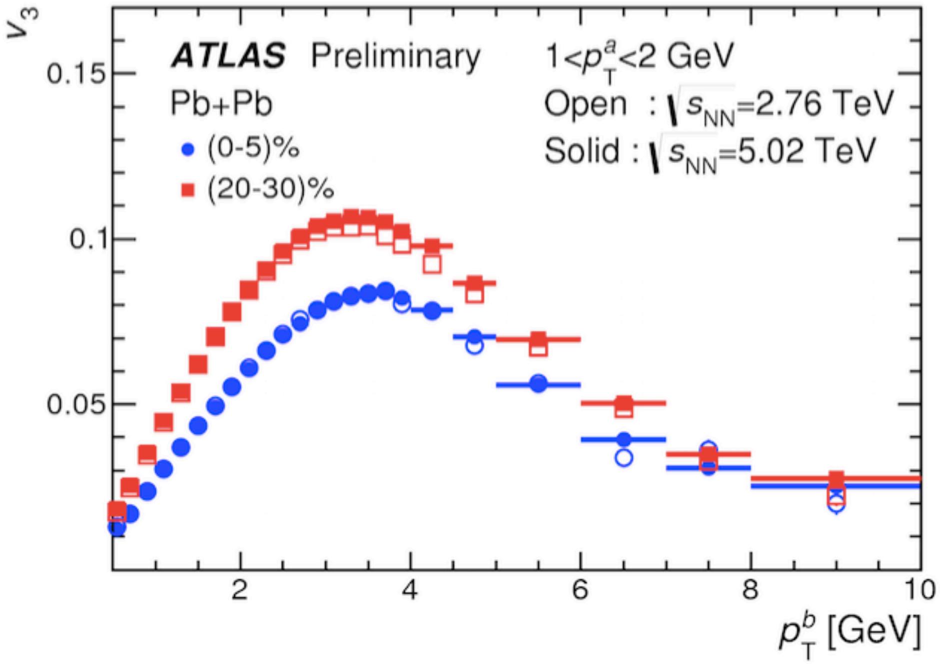
- EP results obtained from SP by Q-vector normalization
  - SP measure always RMS v_n
  - EP measure value between $\langle v_n \rangle$ and RMS v_n
- A small difference is seen for v_2
  - Largest for mid-central 20-50% interval → ~3%
- For n > 2 the EP and SP results are consistent

2PC Results: Run-1 – Run-2 comparison

v_2



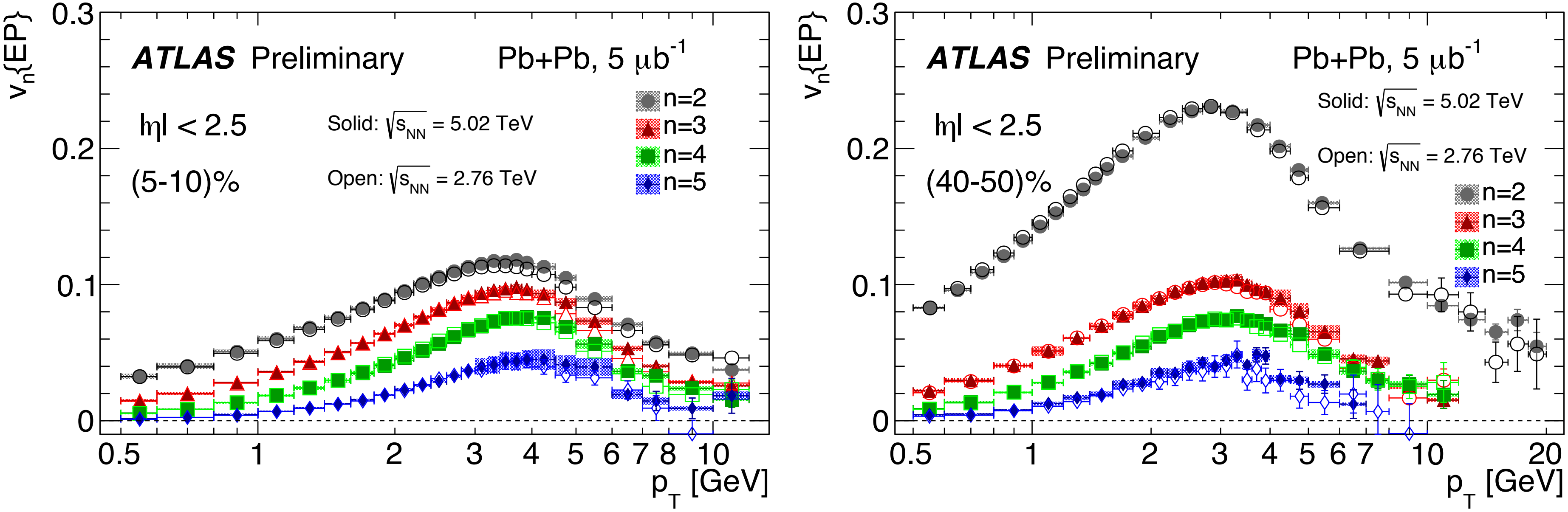
v_3



- **2PC shows overall good agreement between results obtained with different system energies**
  - **Within statistical and systematic uncertainties**

- **Consistent with recent ALICE results (PRL 116 (2016) 132302)**

EP results: Run-1 – Run-2 comparison



- ✧ **EP methods shows overall good agreement between results obtained with different system energies**
  - **Within statistical and systematic uncertainties**
- ✧ **Consistent with recent ALICE results (PRL 116 (2016) 132302)**

Summary

- The first ATLAS measurement of azimuthal anisotropy of charged particles in Pb+Pb collisions at 5.02 TeV using LHC Run-2 data
- The flow harmonics, v_n, are measured using two methods, SP and 2PC:
  - n=2-7
  - wide $p_T = 0.5 – 25$ GeV range
  - $|\eta| < 2.5$
  - centrality 0-80%
- The first measurement of v_7 harmonic
- Significant v_2 even at highest p_T
- The v_n show weak η - dependence
- The $v_n(p_T)$ values do not change from 2.76 TeV to 5.02 TeV

Acknowledgments

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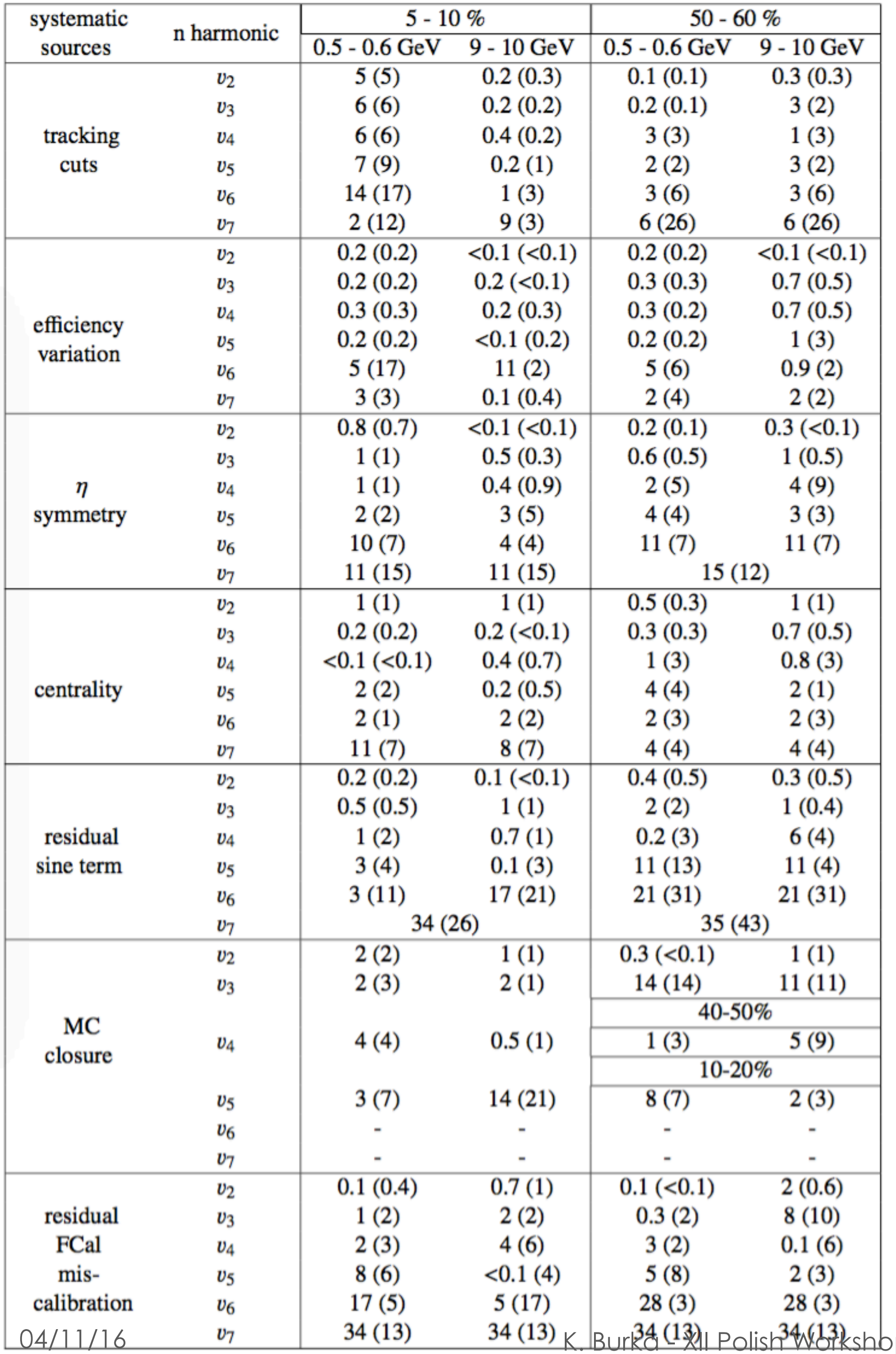
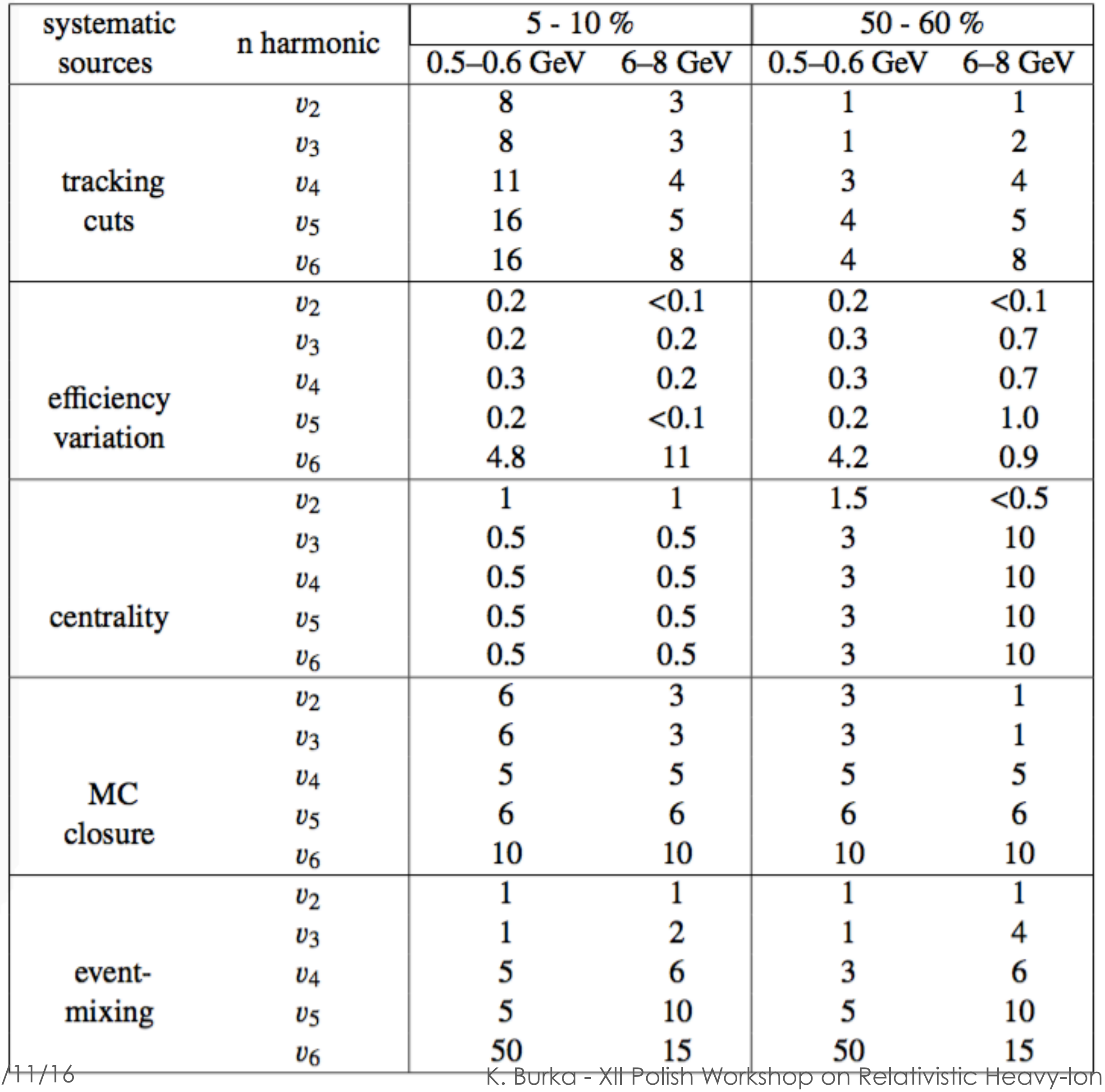
Backup slides

SP/EP systematics summary table



systematic sources	n harmonic	5 - 10 %		50 - 60 %	
		0.5 - 0.6 GeV	9 - 10 GeV	0.5 - 0.6 GeV	9 - 10 GeV
tracking cuts	v_2	5 (5)	0.2 (0.3)	0.1 (0.1)	0.3 (0.3)
	v_3	6 (6)	0.2 (0.2)	0.2 (0.1)	3 (2)
	v_4	6 (6)	0.4 (0.2)	3 (3)	1 (3)
	v_5	7 (9)	0.2 (1)	2 (2)	3 (2)
	v_6	14 (17)	1 (3)	3 (6)	3 (6)
	v_7	2 (12)	9 (3)	6 (26)	6 (26)
efficiency variation	v_2	0.2 (0.2)	<0.1 (<0.1)	0.2 (0.2)	<0.1 (<0.1)
	v_3	0.2 (0.2)	0.2 (<0.1)	0.3 (0.3)	0.7 (0.5)
	v_4	0.3 (0.3)	0.2 (0.3)	0.3 (0.2)	0.7 (0.5)
	v_5	0.2 (0.2)	<0.1 (0.2)	0.2 (0.2)	1 (3)
	v_6	5 (17)	11 (2)	5 (6)	0.9 (2)
	v_7	3 (3)	0.1 (0.4)	2 (4)	2 (2)
η symmetry	v_2	0.8 (0.7)	<0.1 (<0.1)	0.2 (0.1)	0.3 (<0.1)
	v_3	1 (1)	0.5 (0.3)	0.6 (0.5)	1 (0.5)
	v_4	1 (1)	0.4 (0.9)	2 (5)	4 (9)
	v_5	2 (2)	3 (5)	4 (4)	3 (3)
	v_6	10 (7)	4 (4)	11 (7)	11 (7)
	v_7	11 (15)	11 (15)	15 (12)	
centrality	v_2	1 (1)	1 (1)	0.5 (0.3)	1 (1)
	v_3	0.2 (0.2)	0.2 (<0.1)	0.3 (0.3)	0.7 (0.5)
	v_4	<0.1 (<0.1)	0.4 (0.7)	1 (3)	0.8 (3)
	v_5	2 (2)	0.2 (0.5)	4 (4)	2 (1)
	v_6	2 (1)	2 (2)	2 (3)	2 (3)
	v_7	11 (7)	8 (7)	4 (4)	4 (4)
residual sine term	v_2	0.2 (0.2)	0.1 (<0.1)	0.4 (0.5)	0.3 (0.5)
	v_3	0.5 (0.5)	1 (1)	2 (2)	1 (0.4)
	v_4	1 (2)	0.7 (1)	0.2 (3)	6 (4)
	v_5	3 (4)	0.1 (3)	11 (13)	11 (4)
	v_6	3 (11)	17 (21)	21 (31)	21 (31)
	v_7	34 (26)		35 (43)	
MC closure	v_2	2 (2)	1 (1)	0.3 (<0.1)	1 (1)
	v_3	2 (3)	2 (1)	14 (14)	11 (11)
				40-50%	
	v_4	4 (4)	0.5 (1)	1 (3)	5 (9)
				10-20%	
	v_5	3 (7)	14 (21)	8 (7)	2 (3)
	v_6	-	-	-	-
	v_7	-	-	-	-
residual FCal mis-calibration	v_2	0.1 (0.4)	0.7 (1)	0.1 (<0.1)	2 (0.6)
	v_3	1 (2)	2 (2)	0.3 (2)	8 (10)
	v_4	2 (3)	4 (6)	3 (2)	0.1 (6)
	v_5	8 (6)	<0.1 (4)	5 (8)	2 (3)
	v_6	17 (5)	5 (17)	28 (3)	28 (3)
	v_7	34 (13)	34 (13)	34 (13)	34 (13)

2PC systematics summary table



systematic sources	n harmonic	5 - 10 %		50 - 60 %	
		0.5–0.6 GeV	6–8 GeV	0.5–0.6 GeV	6–8 GeV
tracking cuts	v_2	8	3	1	1
	v_3	8	3	1	2
	v_4	11	4	3	4
	v_5	16	5	4	5
	v_6	16	8	4	8
efficiency variation	v_2	0.2	<0.1	0.2	<0.1
	v_3	0.2	0.2	0.3	0.7
	v_4	0.3	0.2	0.3	0.7
	v_5	0.2	<0.1	0.2	1.0
	v_6	4.8	11	4.2	0.9
centrality	v_2	1	1	1.5	<0.5
	v_3	0.5	0.5	3	10
	v_4	0.5	0.5	3	10
	v_5	0.5	0.5	3	10
	v_6	0.5	0.5	3	10
MC closure	v_2	6	3	3	1
	v_3	6	3	3	1
	v_4	5	5	5	5
	v_5	6	6	6	6
	v_6	10	10	10	10
event-mixing	v_2	1	1	1	1
	v_3	1	2	1	4
	v_4	5	6	3	6
	v_5	5	10	5	10
	v_6	50	15	50	15

SP/EP methods

Scalar Product:

$$v_{n,j}\{SP\} = Re\frac{\langle q_{n,j} Q_n^{N|P*}\rangle}{\sqrt{\langle Q_n^N Q_n^{P*}\rangle}} = \frac{\langle |q_{n,j}||Q_n^{N|P}|cos[n(\phi_j - \Psi_n^{N|P})]\rangle}{\sqrt{\langle |Q_n^N||Q_n^P|cos[n(\Psi_n^N - \Psi_n^P)]\rangle}}$$

Event Plane:

$$v_{n,j}\{EP\} = Re\frac{\langle q_{n,j}\frac{Q_n^{N|P*}}{|Q_n^{N|P}|}\rangle}{\sqrt{\langle \frac{Q_n^N}{|Q_n^N|}\frac{Q_n^{P*}}{|Q_n^P|}\rangle}} = \frac{\langle cos[n(\phi_j - \Psi_n^{N|P})]\rangle}{\sqrt{\langle cos[n(\Psi_n^N - \Psi_n^P)]\rangle}}$$