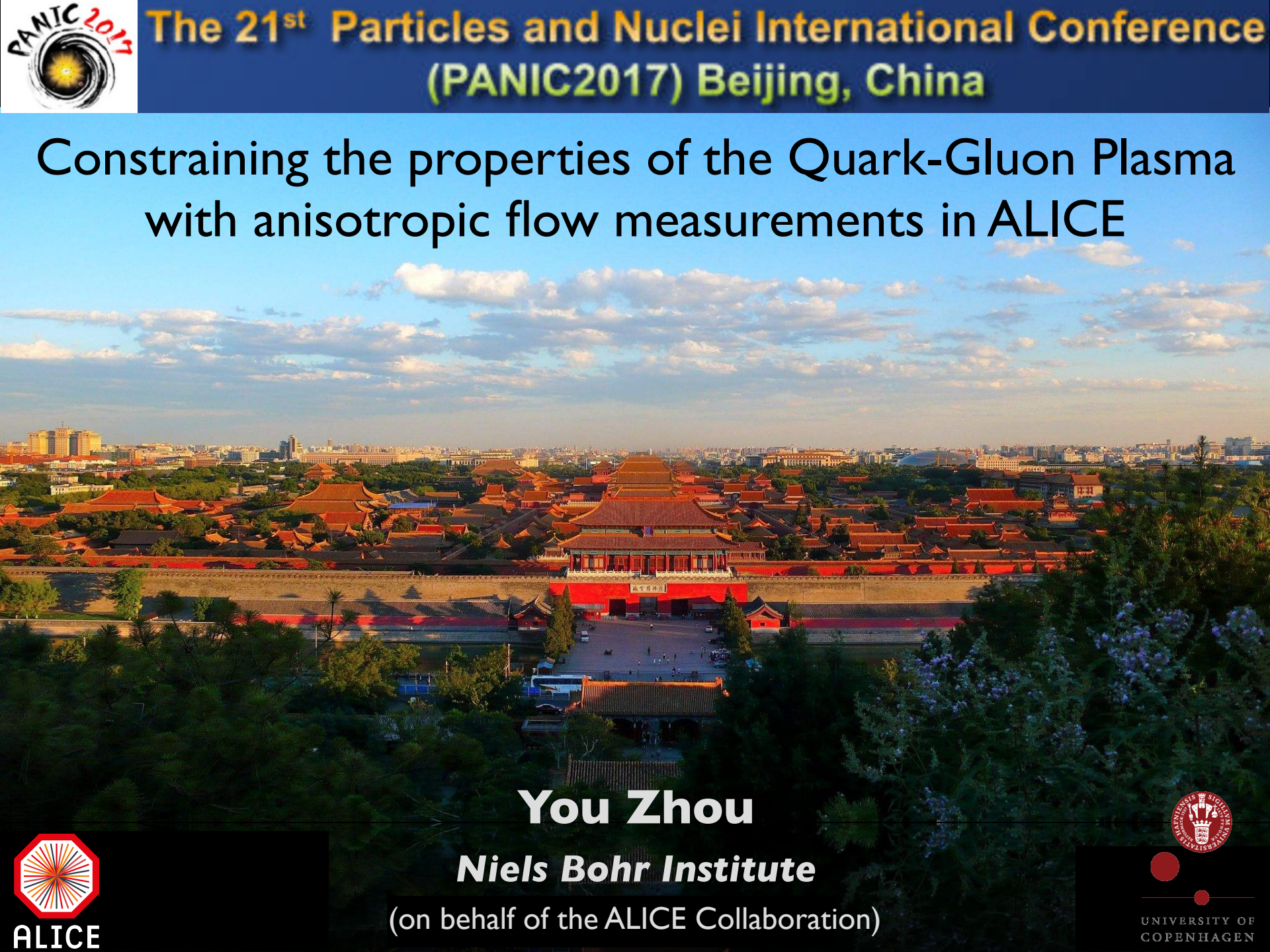
The 21st Particles and Nuclei International Conference
(PANIC2017) Beijing, China

Constraining the properties of the Quark-Gluon Plasma with anisotropic flow measurements in ALICE



You Zhou

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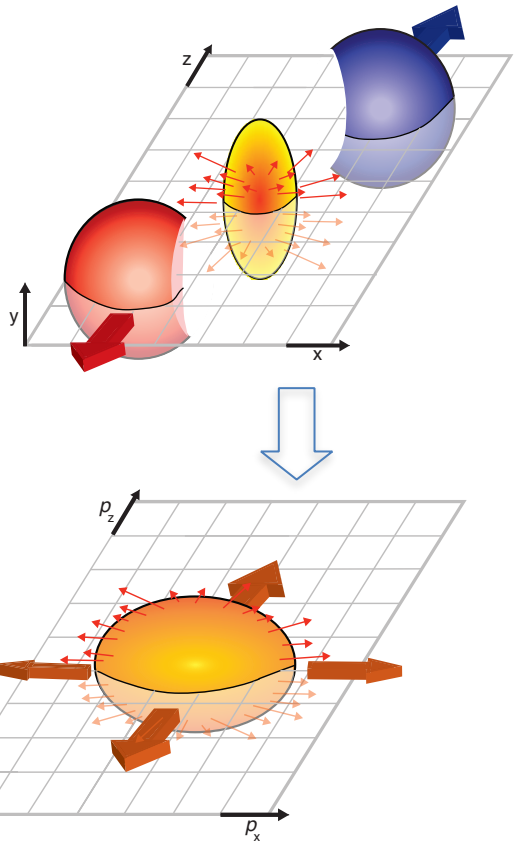
(on behalf of the ALICE Collaboration)

Elliptic Flow

- "Elliptic flow, described by the Fourier coefficients of the azimuthal particle distributions *w.r.t.* the reaction plane, could be used to probe the Quark-Gluon Plasma."

J.Y. Olltriault, PRD 46, 229 (1992)



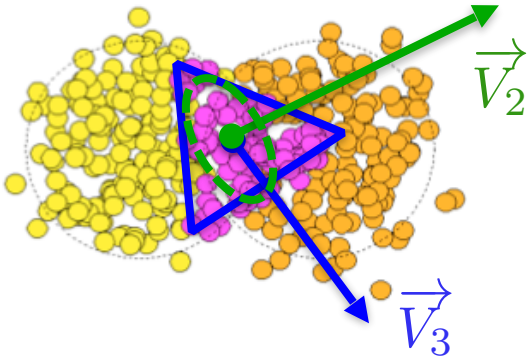
$$\varepsilon_2 = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

coordinate space Eccentricity

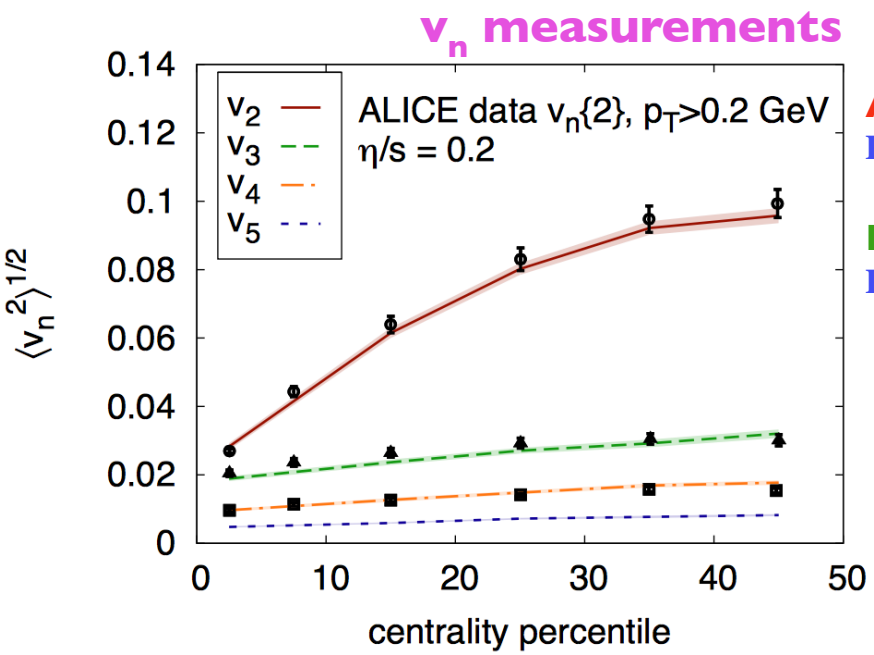
$$v_2 = \langle \cos 2(\varphi - \Psi_{\mathrm{RP}}) \rangle$$

momentum space Elliptic Flow

Flow vector $\vec{V}_m$ and $\vec{V}_n$



$$\vec{V}_m = v_m e^{-im\Psi_m}$$
$$\vec{V}_n = v_n\, e^{-in\Psi_n}$$



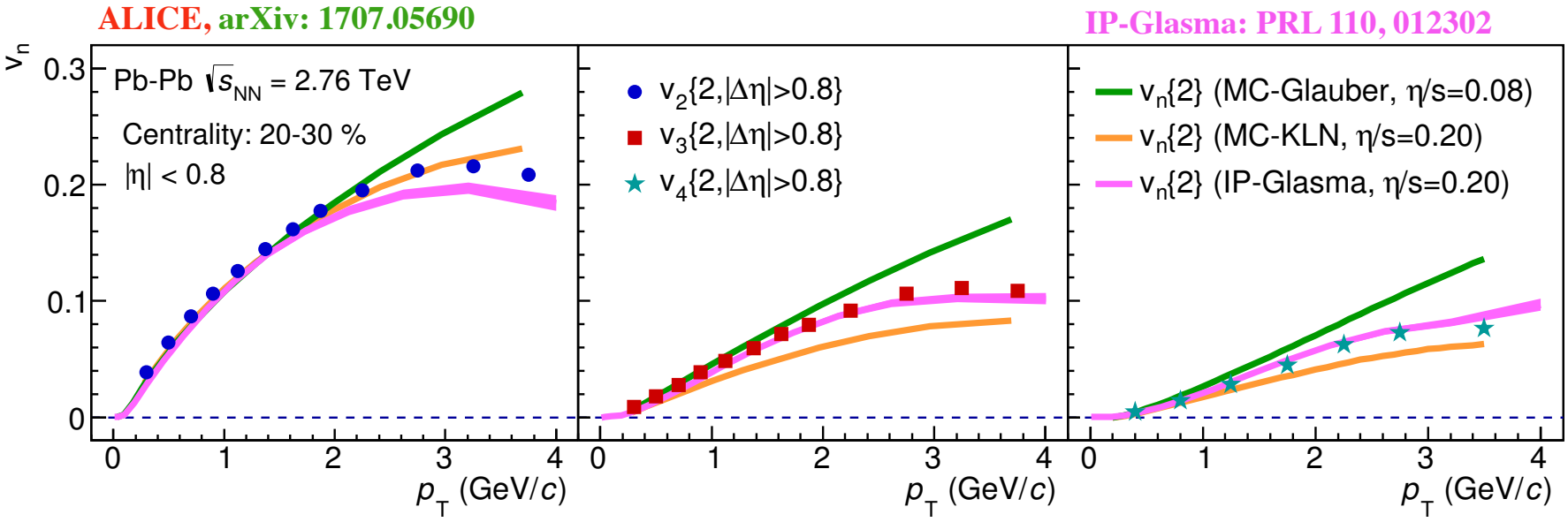
ALICE:
PRL107, 032301 (2011)

IP-Glasma:
PRL110, 012302 (2013)

- The anisotropic flow coefficients v_n (magnitude of the n^{th}-harmonic flow vector) have been measured in great detail (centrality, p_T, η, PID)
  —> constraints on the initial conditions, η/s, EoS, freeze-out conditions …
- The fluctuations of each individual flow harmonics have been investigated.

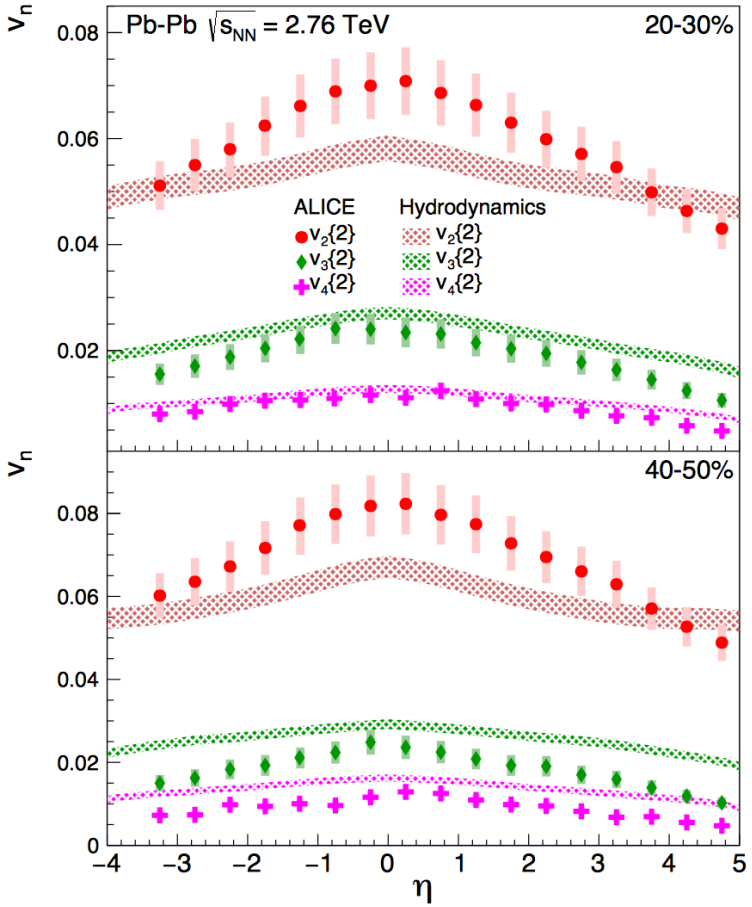
Transverse momentum dependence of v_n

- More detailed information is carried by transverse momentum or pseudorapidity dependence of anisotropic flow v_n



- comparisons of data and hydrodynamic calculations show:
  - calculations with IP-Glasma initial conditions and η/s =0.20 give the best description of data
  - calculation with MC-Glauber initial conditions using the same eta/s gives poorer description.
  - strong constraints on the initial state and η/s of QGP.

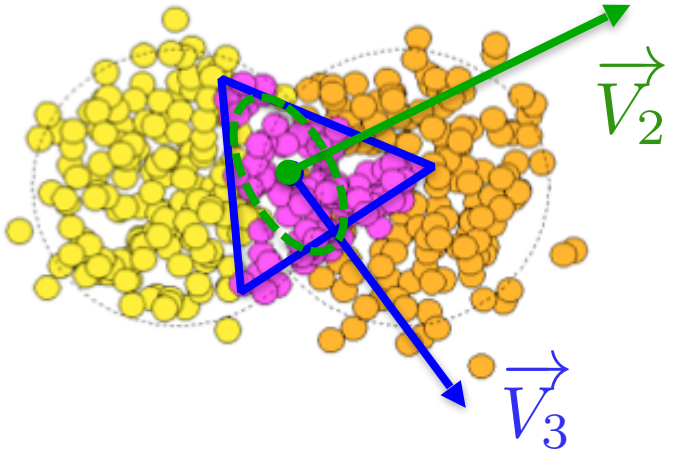
Pseudorapidity dependence of v_n



ALICE Collaboration, PLB 762 (2016) 376
Hydrodynamics: PRL 116, 212301 (2016)

- We find that the shape of $v_n(\eta)$ is largely independent of centrality for the flow harmonics n = 2, 3 and 4,
- hydrodynamic calculations:
  - tuned $\eta/s(T)$ to fit $v_n(\eta)$ at RHIC
  - do not reproduce the data well, new challenge to the theory community

V_n and V_m



$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n\, e^{-in\Psi_n}$$

- General questions:
  - what are the correlations between v_n and v_m ?
  - what are the correlations between Ψ_n and Ψ_m ?
  - will these correlations provide new information ?

SC(m,n)

- Novel observable:
  Symmetric 2-harmonic 4-particle **C**umulants, ***SC(m,n)***, measures the correlations of v_n and v_m

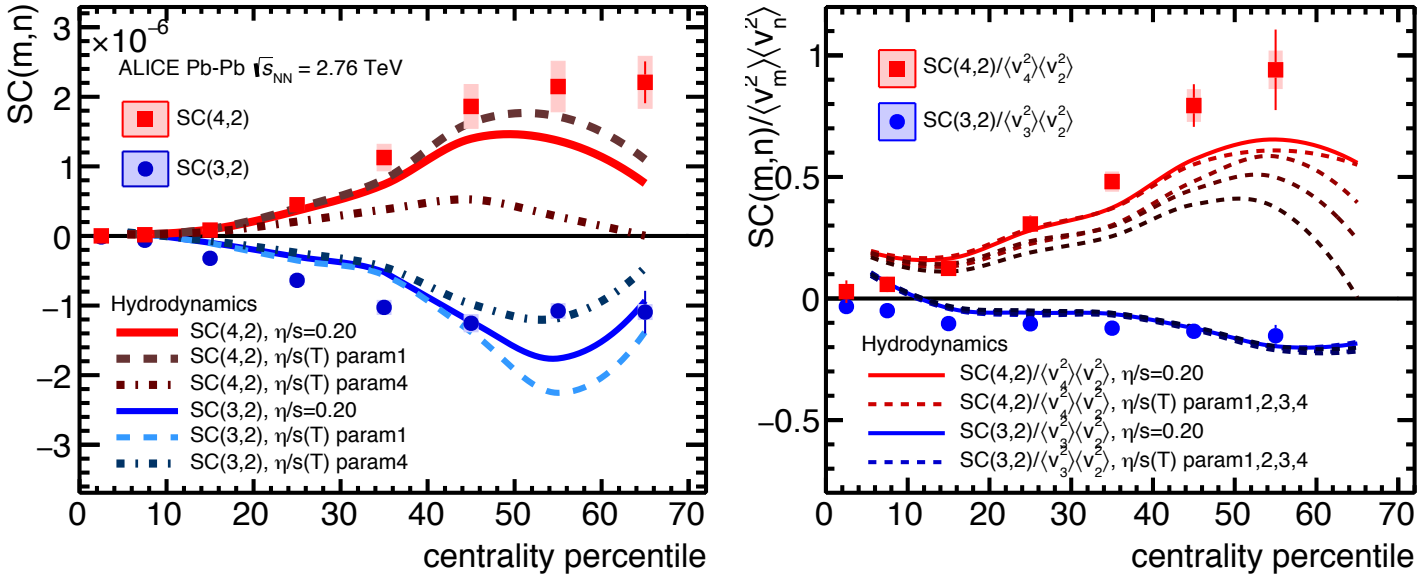
A. Bilandzic etc, PRC 89, 064904 (2014)

$$\begin{aligned}
&\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c \\
&= \langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle - \langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle \\
&= \langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle\,.
\end{aligned}$$

- By construction not sensitive to:
  - non-flow effects, due to usage of 4-particle cumulant
  - inter-correlations of various symmetry planes (Ψ_n and Ψ_m correlations)
- It is non-zero if v_n and v_m are (anti-)correlated.

Correlations between v_m and v_n

ALICE Collaboration, PRL117, 182301 (2016)



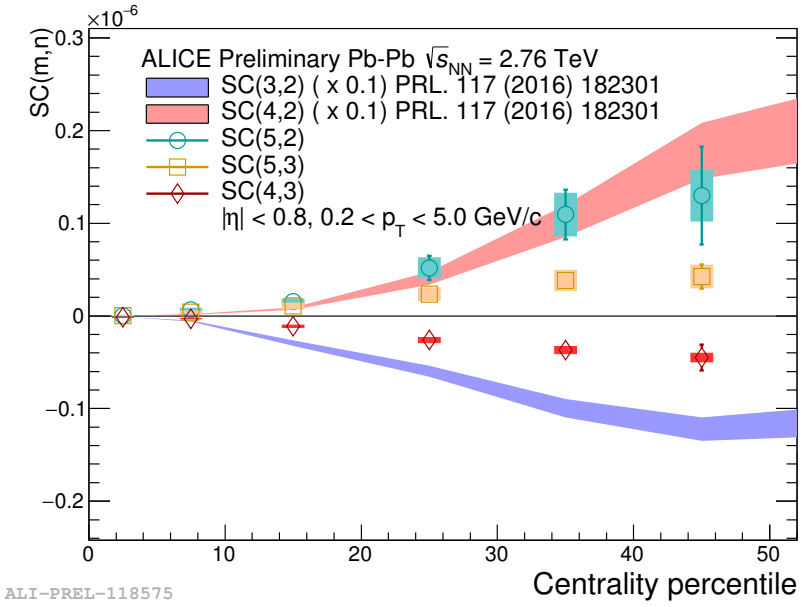
- Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations
  - Although hydro describes v_n fairly well, there is not a single centrality for which a given η/s parameterization describes simultaneously SC and NSC.
  - NSC(3,2) is insensitive to parameterization of η/s(T)

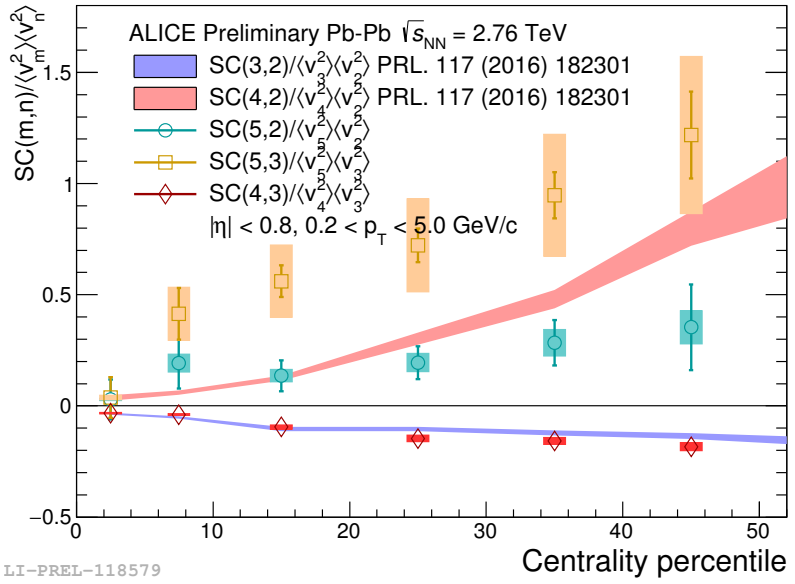
    -> direct constraints on initial conditions.
  - SC and NSC measurements provide stronger constraints on the η/s in hydro than standard v_n measurements alone.

SC and NSC with other harmonics

$$SC(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

$$NSC(m,n) = \frac{SC(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$



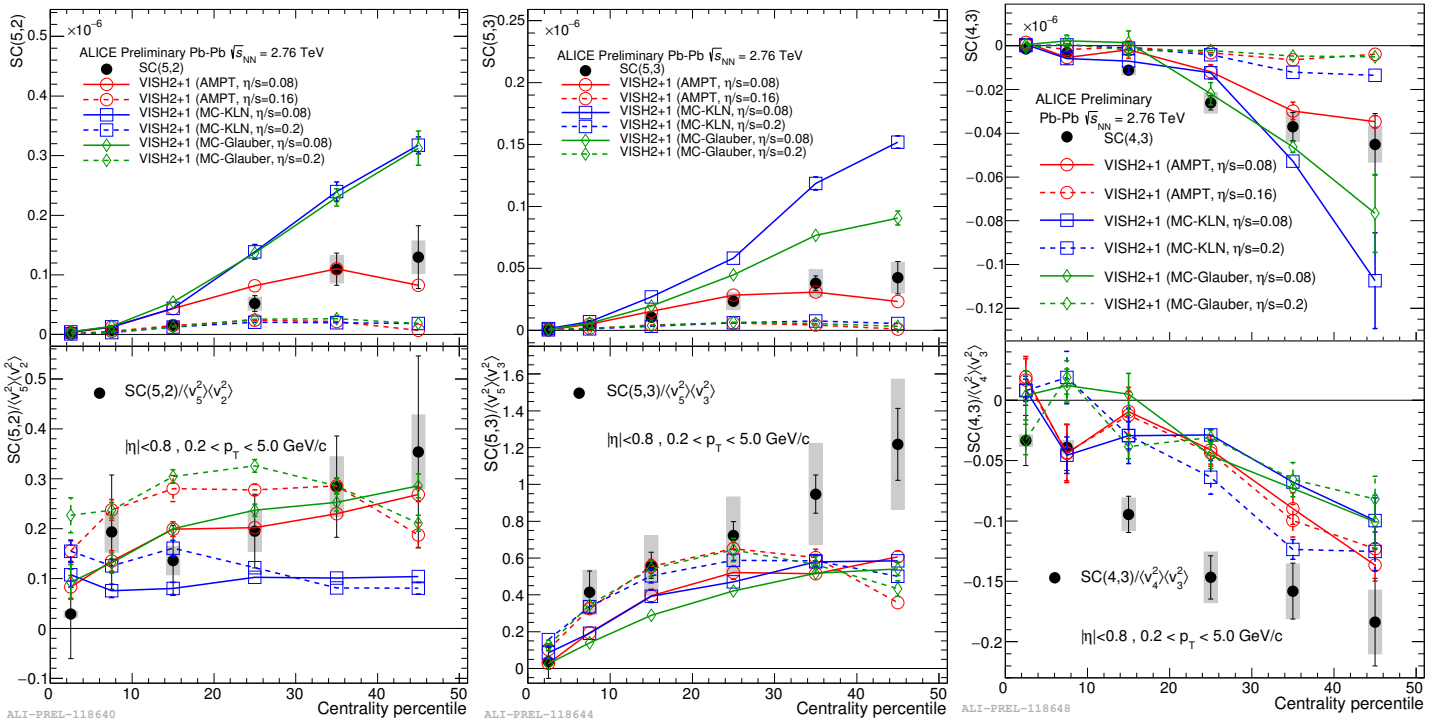


- SC(m,n) and NSC(m,n) with other harmonics:
  - correlations between (v_2, v_5) and (v_3,v_5) observed
  - anti-correlations between (v_3, v_4) observed
  - |NSC(5,3)| > |NSC(5,2)| > |NSC(4,3)| as predicted by hydrodynamic calculations

VISH2+1, X. Zhu et al., arXiv: 1608.05305

SC and NSC with other harmonics

(v_2, v_5) (v_3, v_5) (v_3, v_4)



ALICE
AMPT,η/s=0.08
AMPT,η/s=0.16
MC-KLN,η/s=0.08
MC-KLN,η/s=0.2
MC-Glb,η/s=0.08
MC-Glb,η/s=0.2

VISH2+1, X. Zhu et al., arXiv: 1608.05305

- Comparison to VISH2+1 hydrodynamic calculations
  - hydrodynamic calculation ***can not*** describe all data with one combination of initial condition and η/s
  - ***tight constraints on initial conditions and η/s of QGP,*** in addition to SC(3,2) and SC(4,2).

Symmetry plane correlations

IP-Glasma, PRC 95, 064913 (2017)

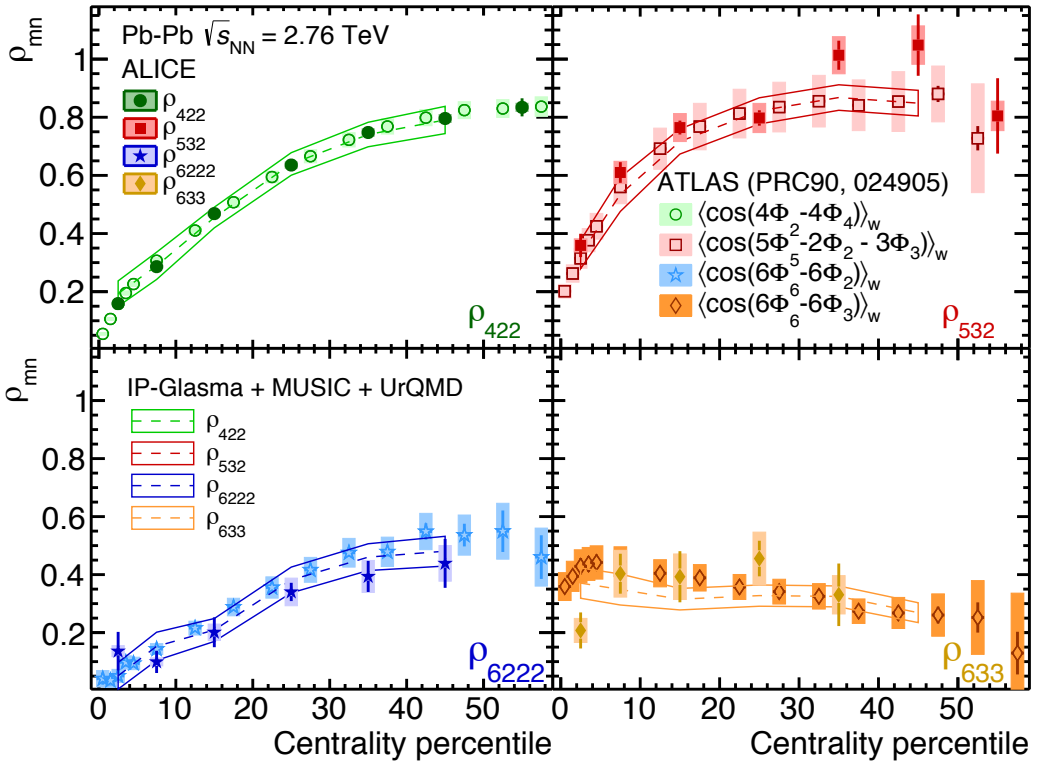
ALICE
arXiv:1705.04377 (accepted by PLB)

$$\rho_{4,22} = \langle \cos(4\Psi_4 - 4\Psi_2) \rangle,$$

$$\rho_{5,32} = \langle \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2) \rangle,$$

$$\rho_{6,222} = \langle \cos(6\Psi_6 - 6\Psi_2) \rangle,$$

$$\rho_{6,33} = \langle \cos(6\Psi_6 - 6\Psi_3) \rangle.$$



- ρ_{mn}
  - Agreement between ALICE and ATLAS (different eta coverage)
  - ***Results are compatible with hydrodynamic calculations using IP-Glasma & η/s=0.095,***
  - calculations using EKRT, MC-Glauber, MC-KLN initial conditions have difficulties to quantitatively describe the data.

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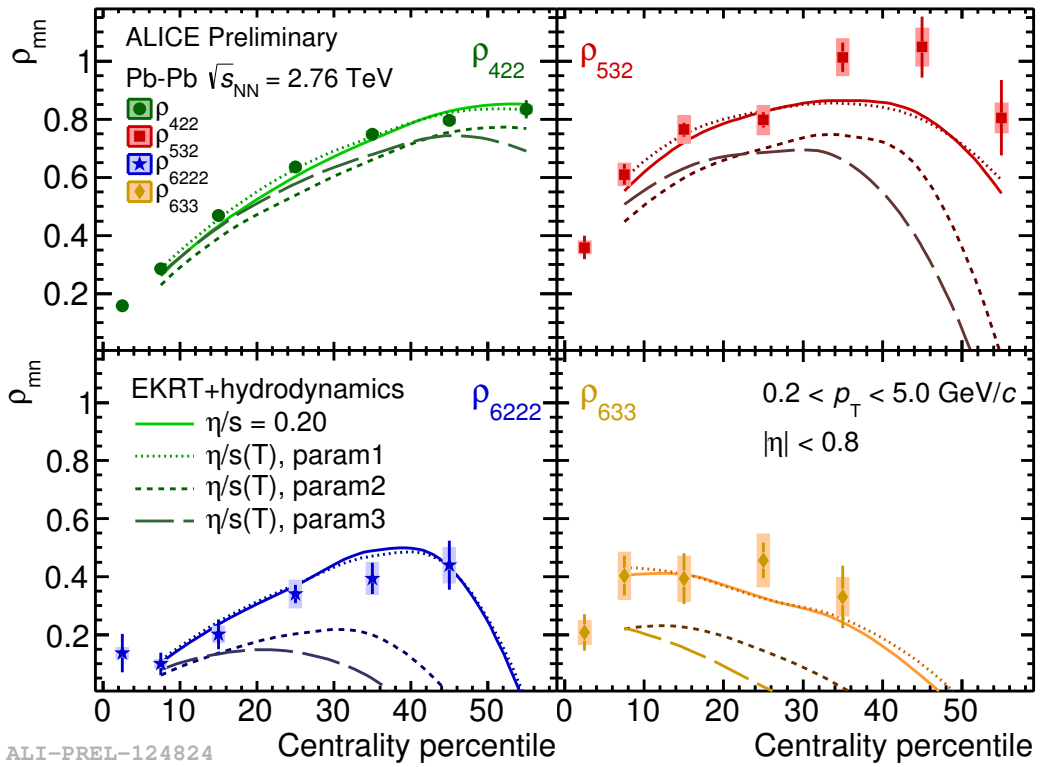

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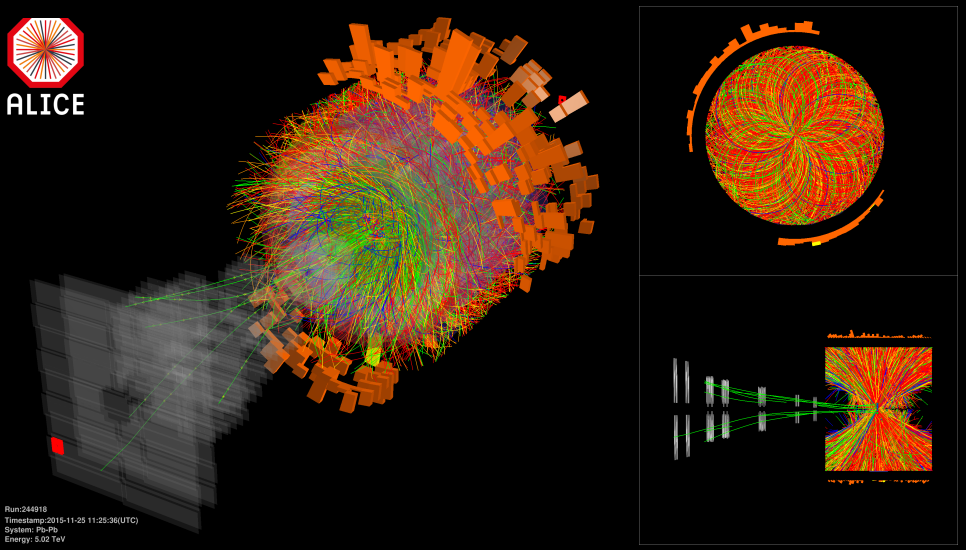
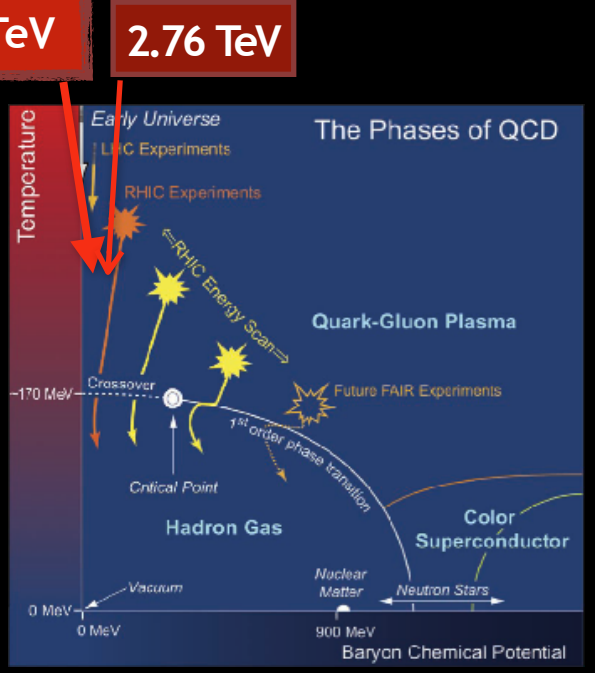
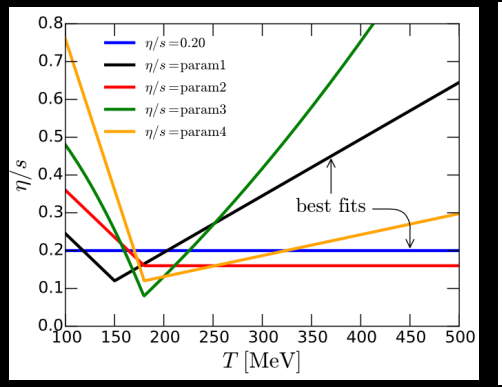
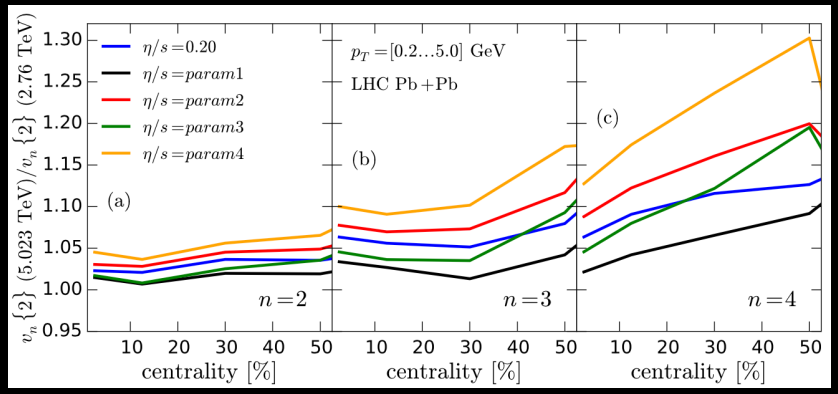
5.02 TeV Pb-Pb collisions





- **Pb-Pb 2.76 TeV: 2010, 2011**
- **Pb-Pb 5.02 TeV: 2015**



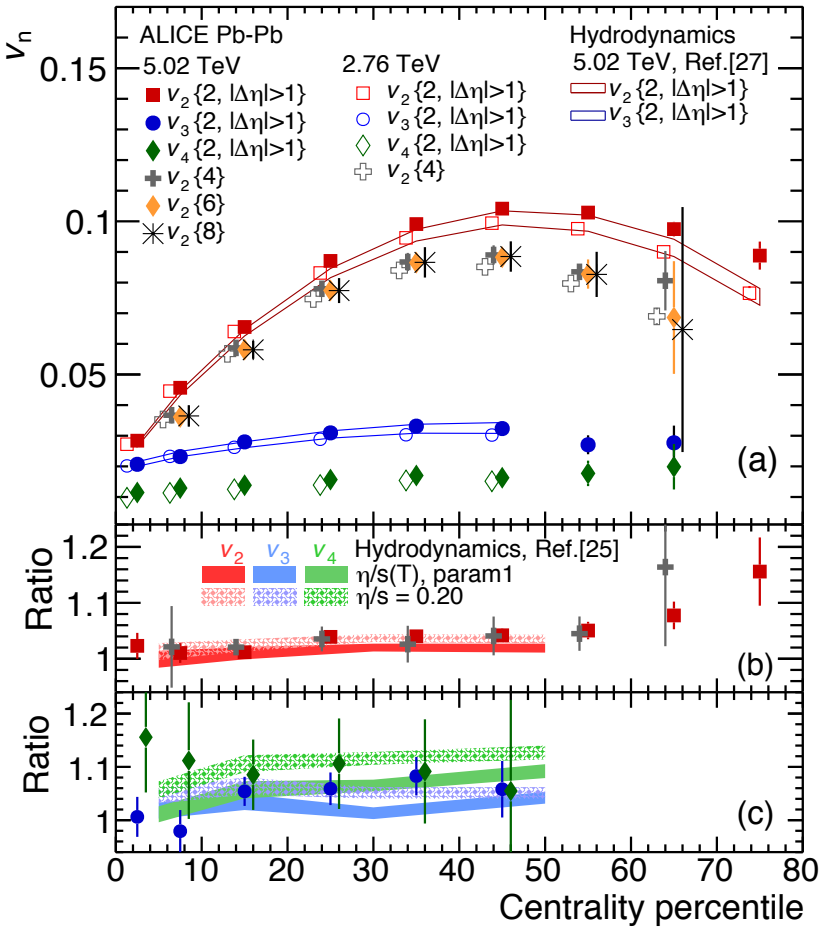


The increase of v_n from 2.76 TeV to 5.02 TeV are sensitive to the detailed setting of η/s(T)

v_n from 2.76 to 5.02 TeV

ALICE Collaboration
PRL 116, 132302 (2016)

Ref [27]: J. Noronha-Hostler et al., PRC93 (2016) 034912
Ref [25]: H. Niemi et al, PRC 93, 014912 (2016)



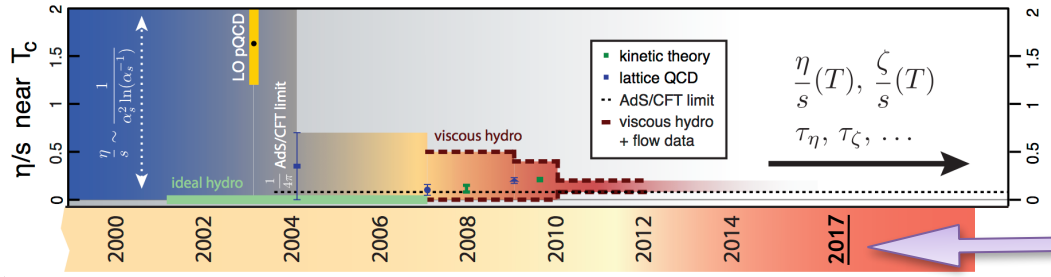
- The anisotropic flow coefficients v_2, v_3 and v_4 are found to increase by (3.0±0.6)%, (4.3±1.4)% and (10.2±3.8)%, respectively, in the centrality range 0-50%.
- None of the ratios 5.02 TeV/2.76 TeV of flow harmonics exhibit a significant centrality dependence in the centrality range 0–50%,
- Changes of anisotropic flow are compatible with theoretical predictions.

Summary

- We present the different order anisotropic flow as well as their correlations.
- These measurements open new possibilities for investigation of the initial conditions and the η/s, especially the freeze-out conditions which were not very well constrained by previous flow data.

Observable \ IC	MC-Glauber	MC-KLN	AMPT	IP-Glasma	EKRT
v_2	✓	✓	✓	✓	✓
v_n	✗	✗	✓	✓	✓
(v_n, v_m)	✗	✗	✗	N/A	✗
(ψ_n, ψ_m)	✗	✗	N/A	✓	✓

✗/✓ : this talk
N/A: not available



a small η/s

this talk