SQM Strasbourg 2024

Supported in part by: U.S. DEPARTMENT OF ENERGY Office of Science

Flow/Correlation in Light Ion Collisions

p/d/^{3}He+Au/Pb, O+O

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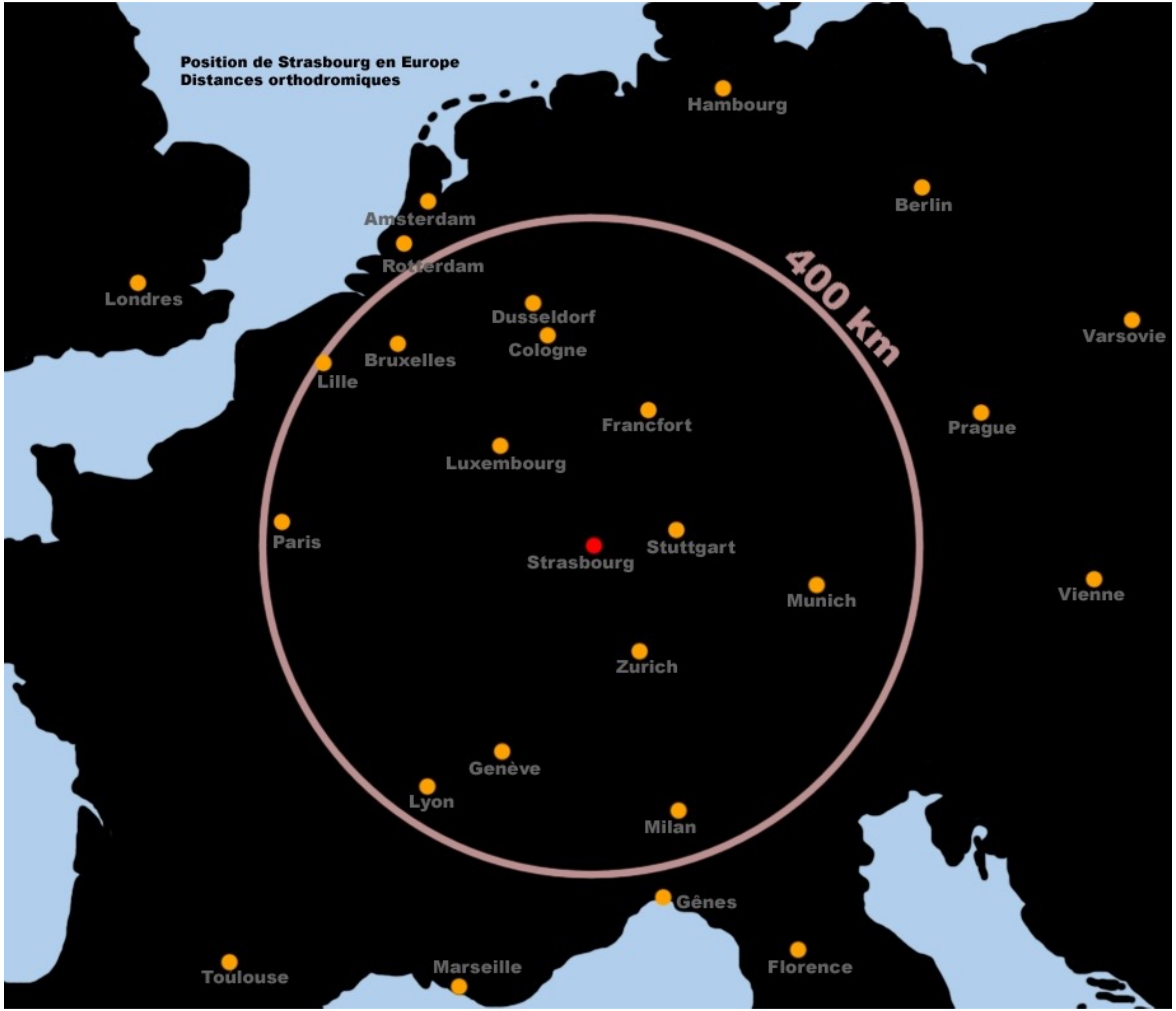
Stony Brook University

Strasbourg

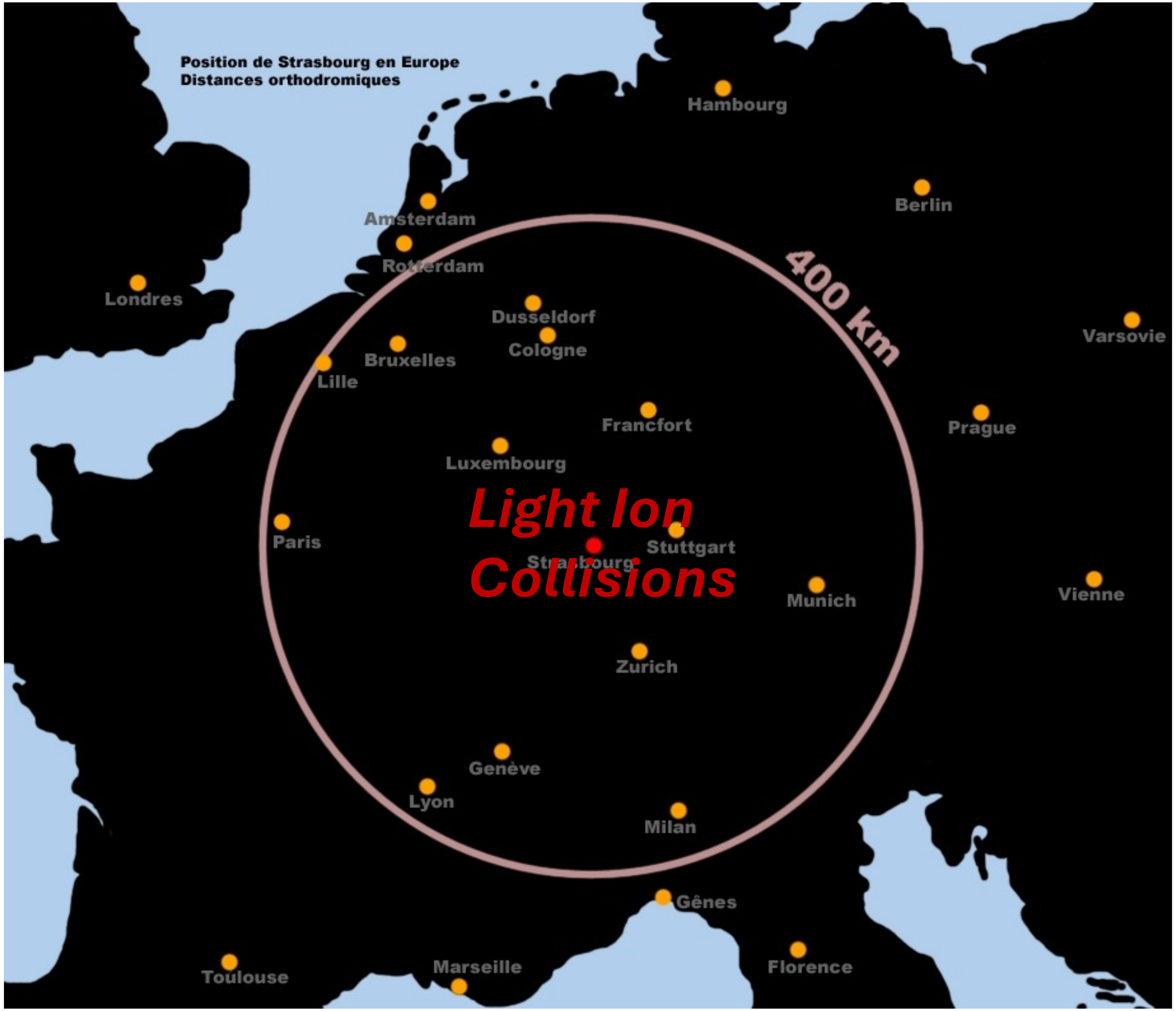
One of the European "capitals"

Different cultures meet here



Light Ion Collisions

Various types of physics come together



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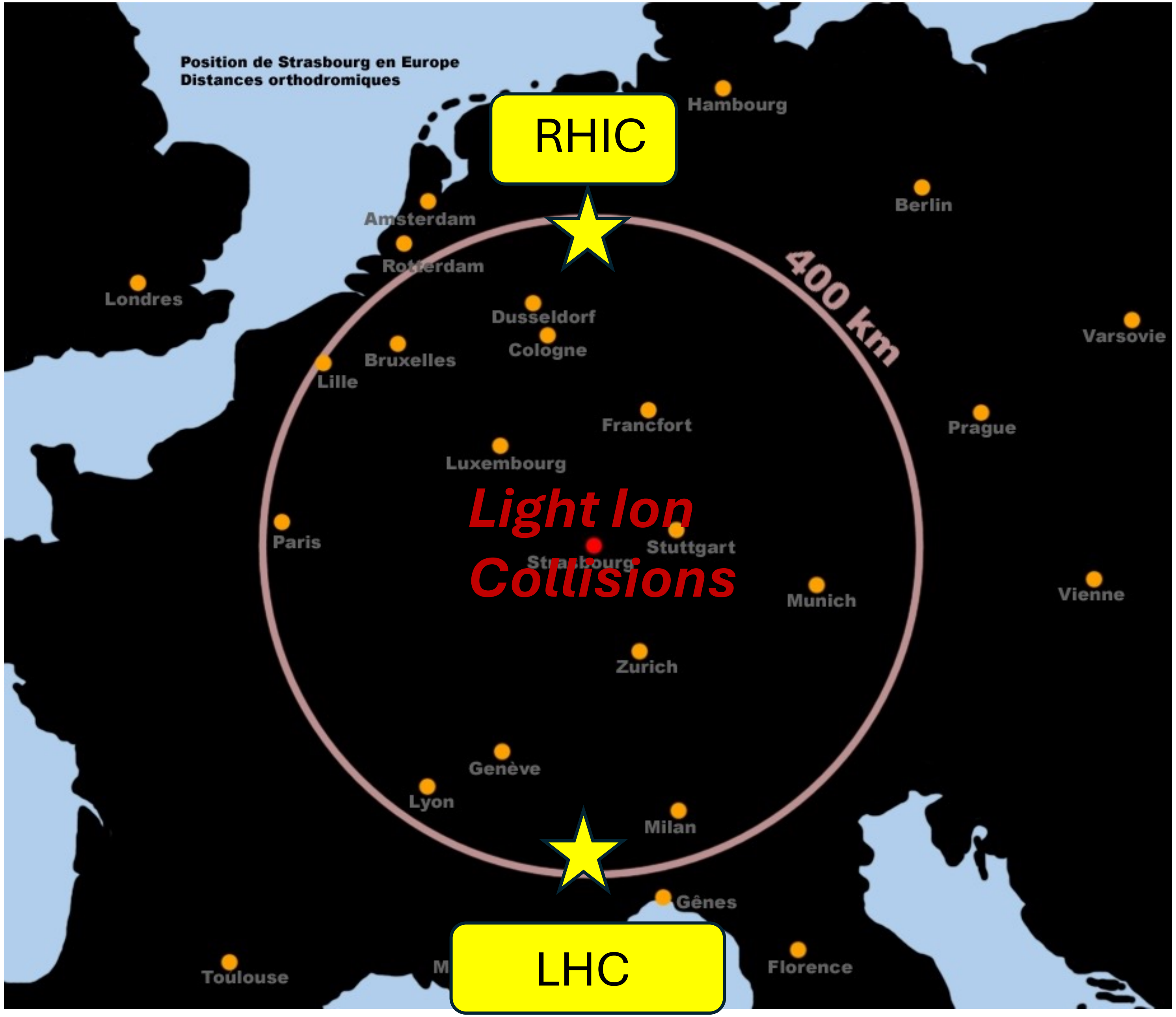

Light Ion Collisions

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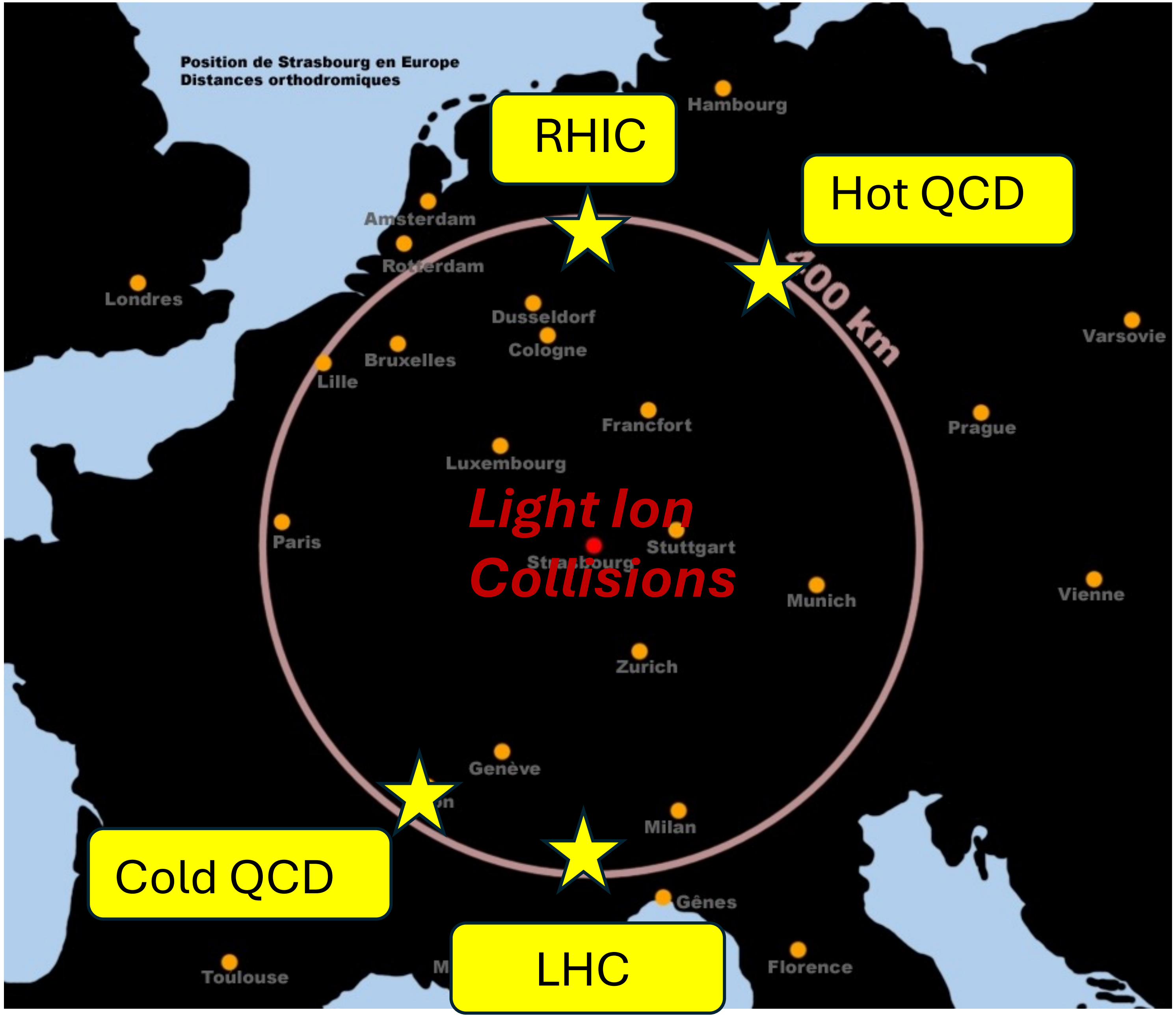

Light Ion Collisions

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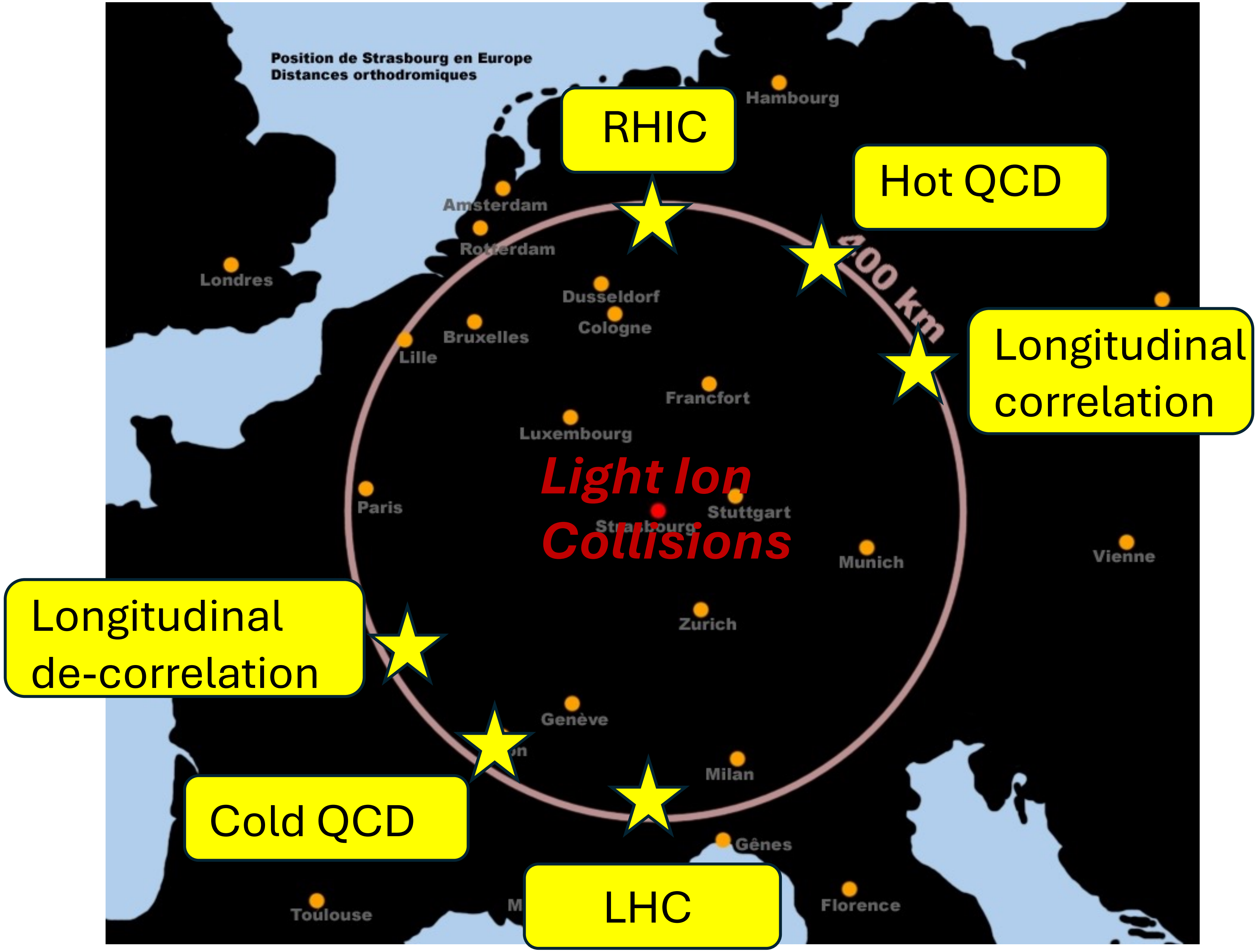

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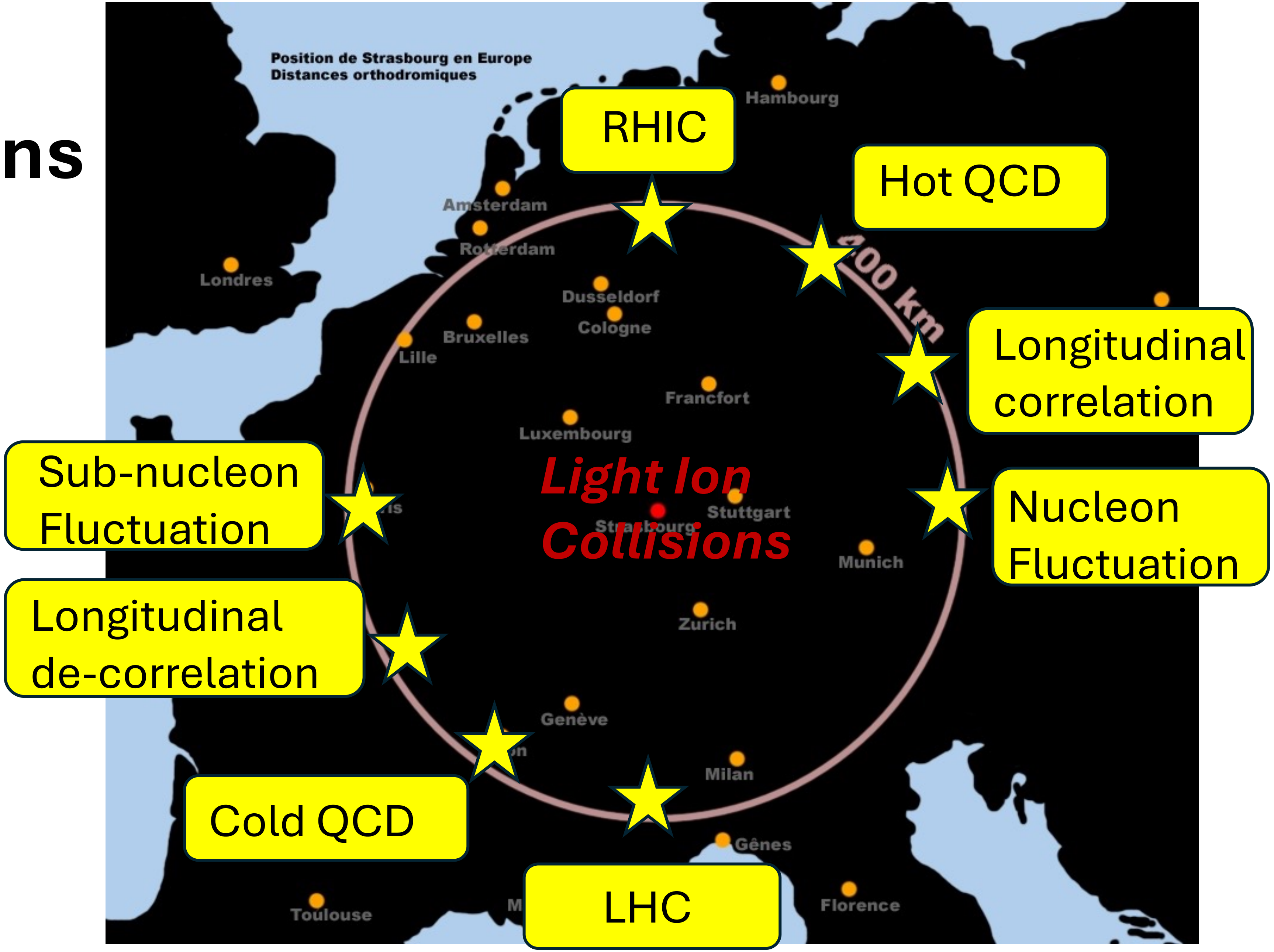
Light Ion Collisions

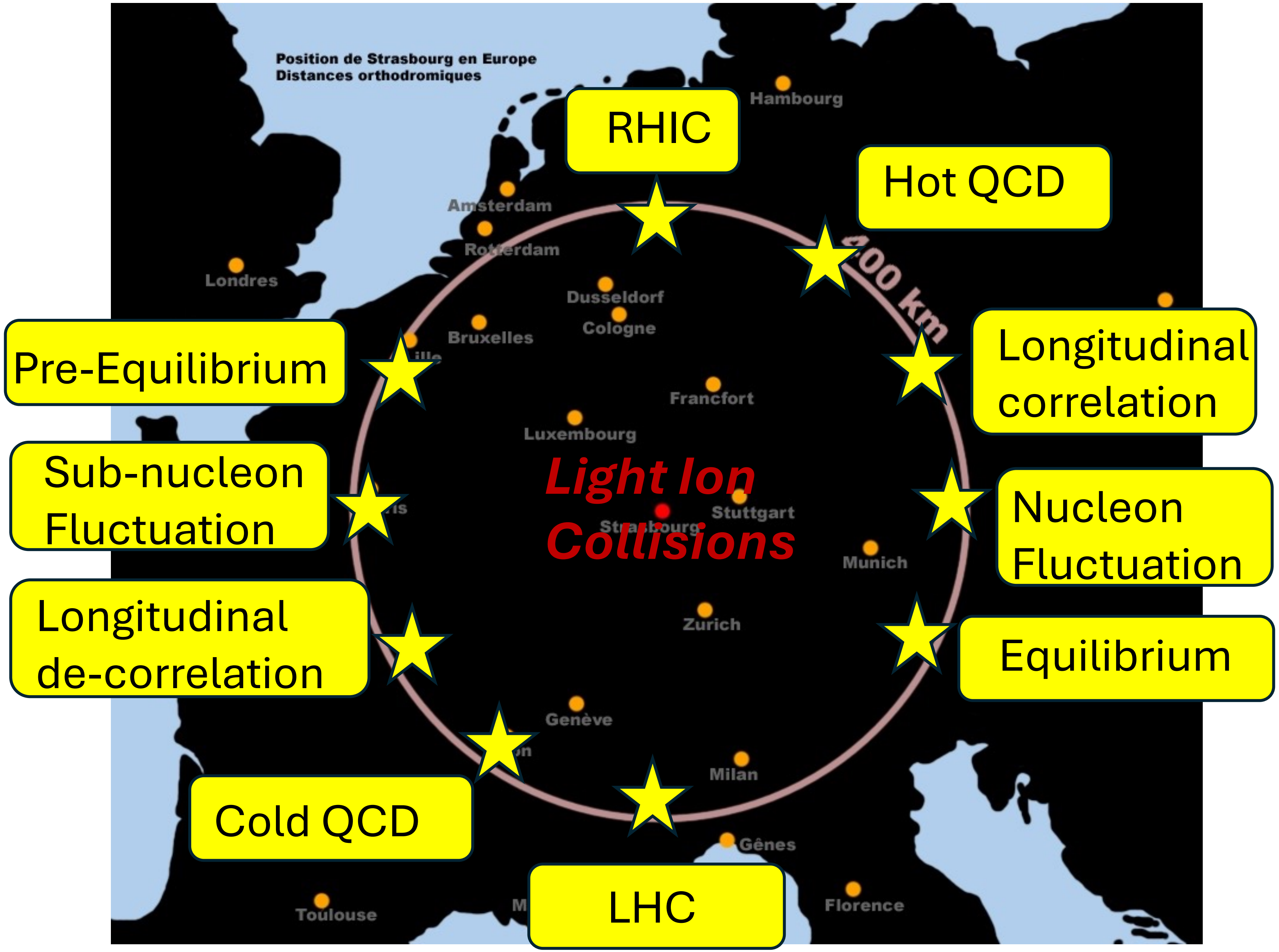
p/d/^{3}He+A, O+O, Ne+Ne…

Various types of physics come together



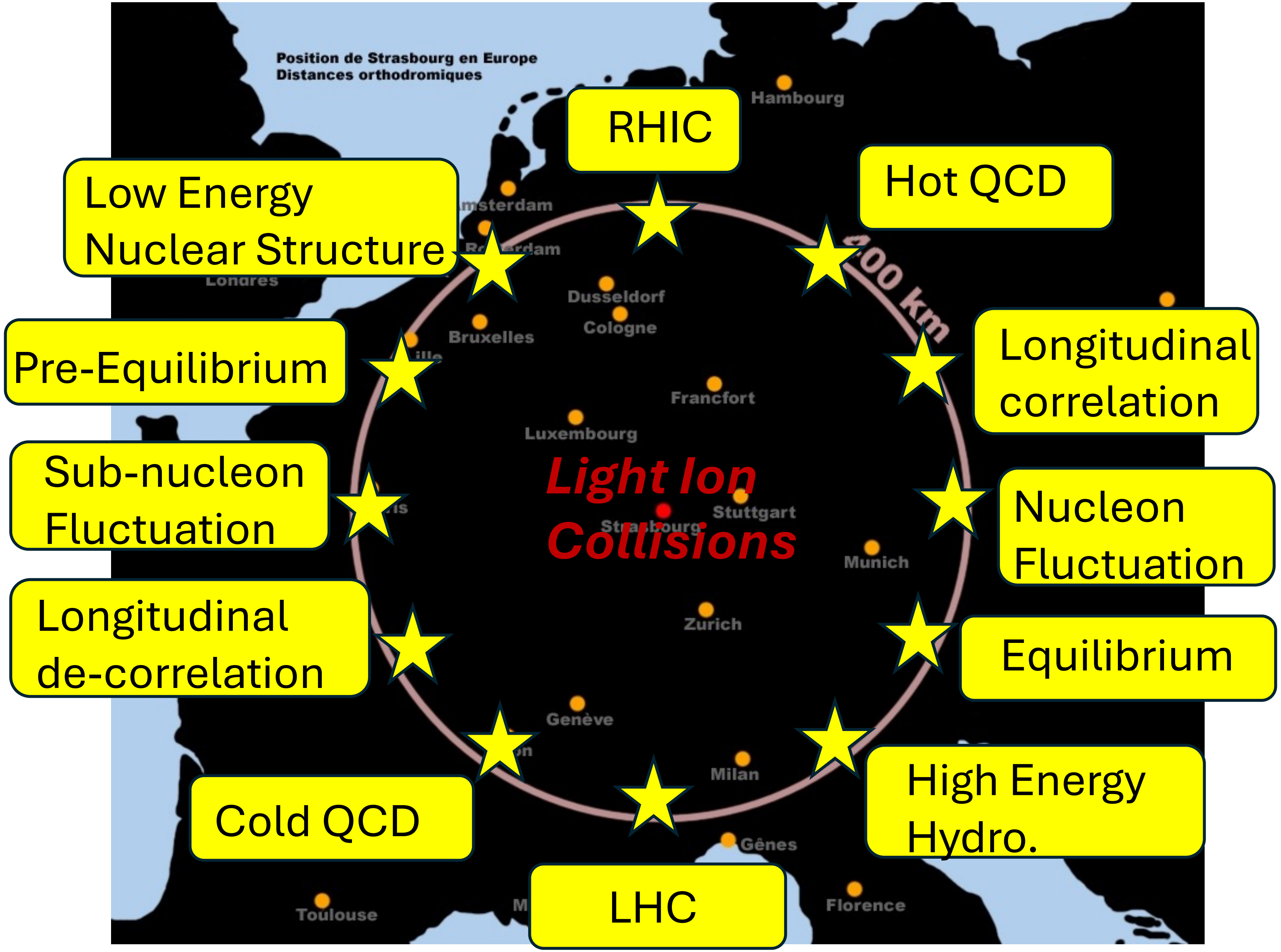
Light Ion Collisions

Various types of physics come together



Light Ion Collisions

Various types of physics come together



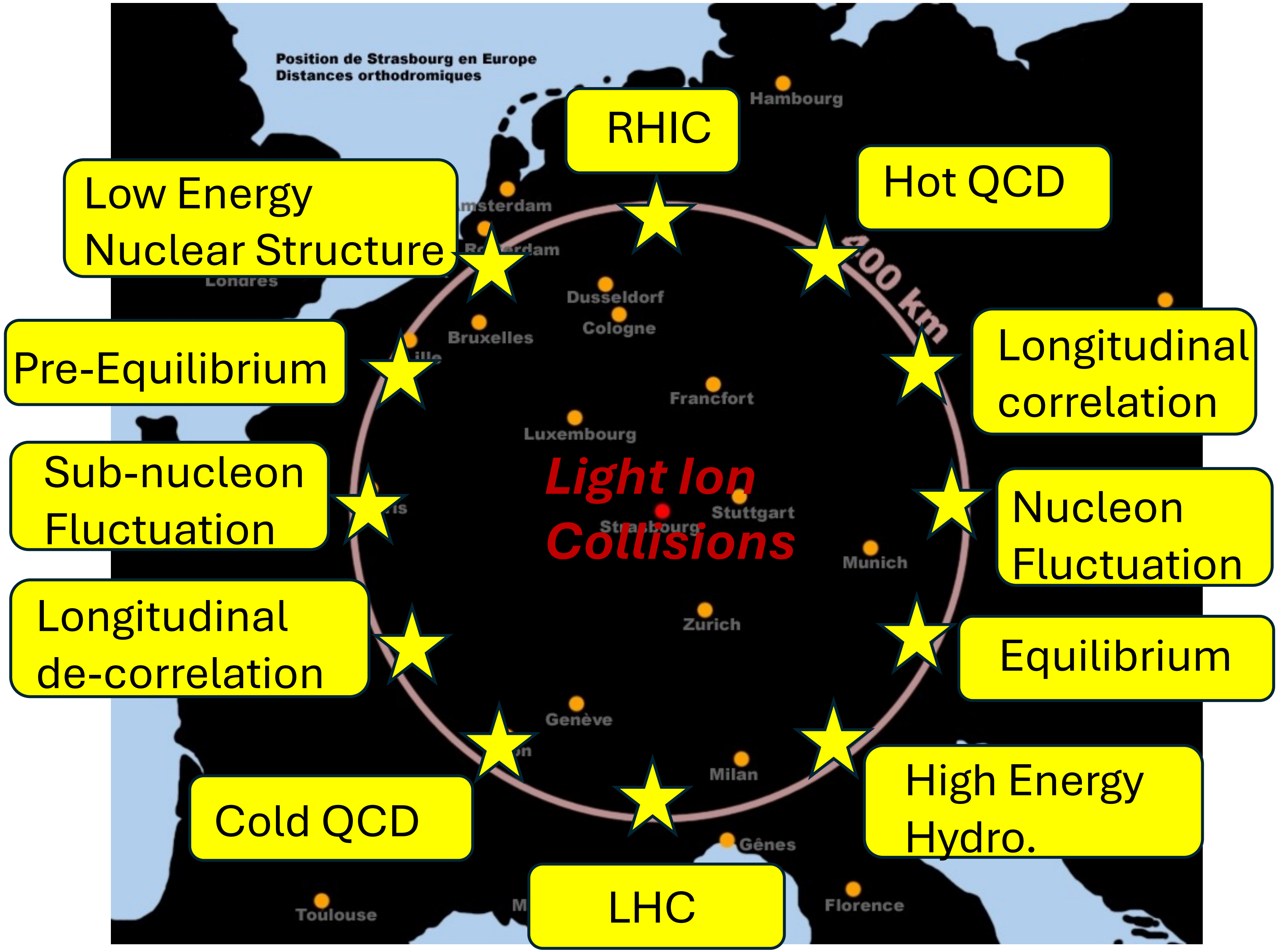
Light Ion Collisions

Various types of physics come together

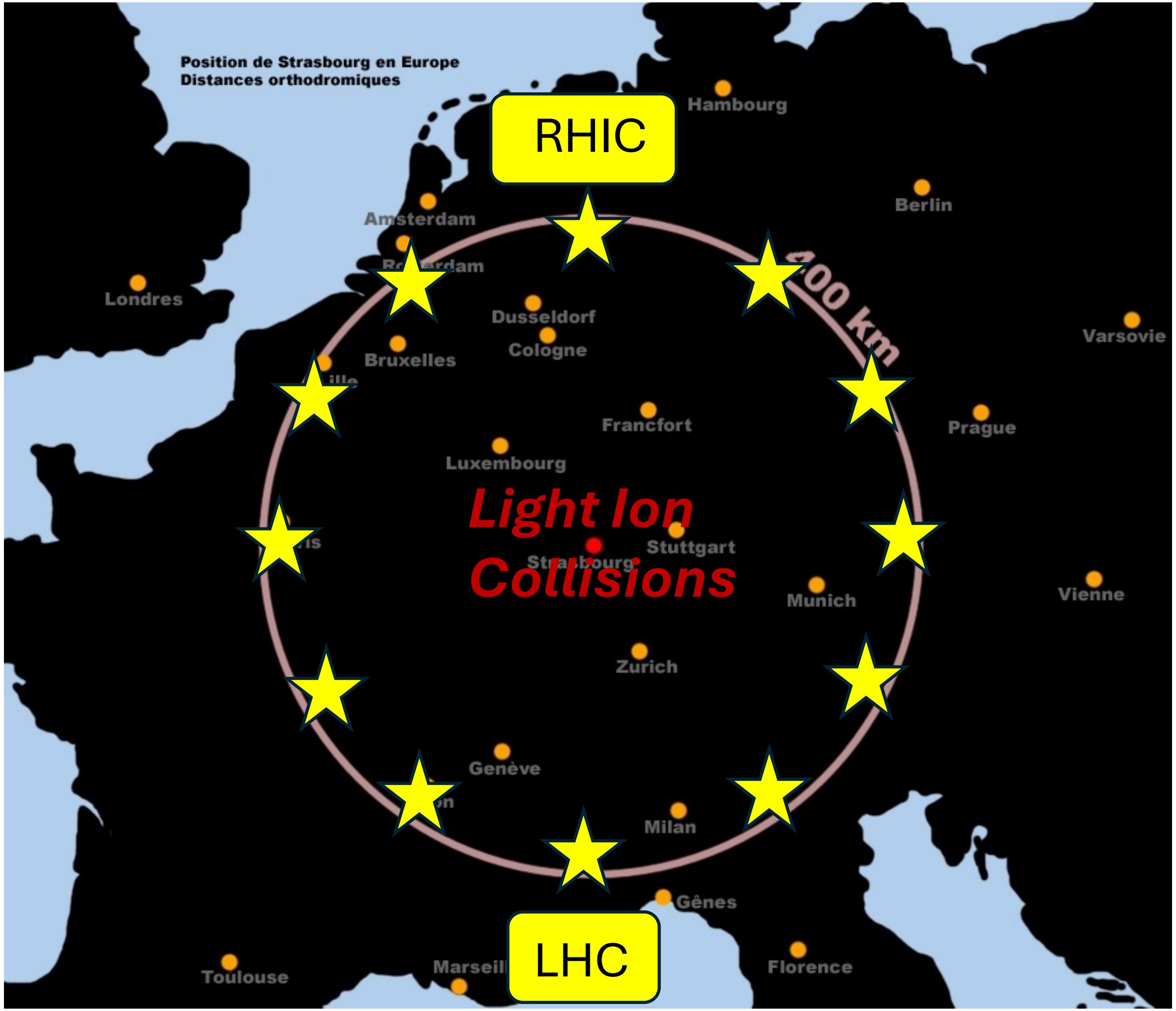
A unique diversity help us study:

1)Initial stage

2)Thermalization

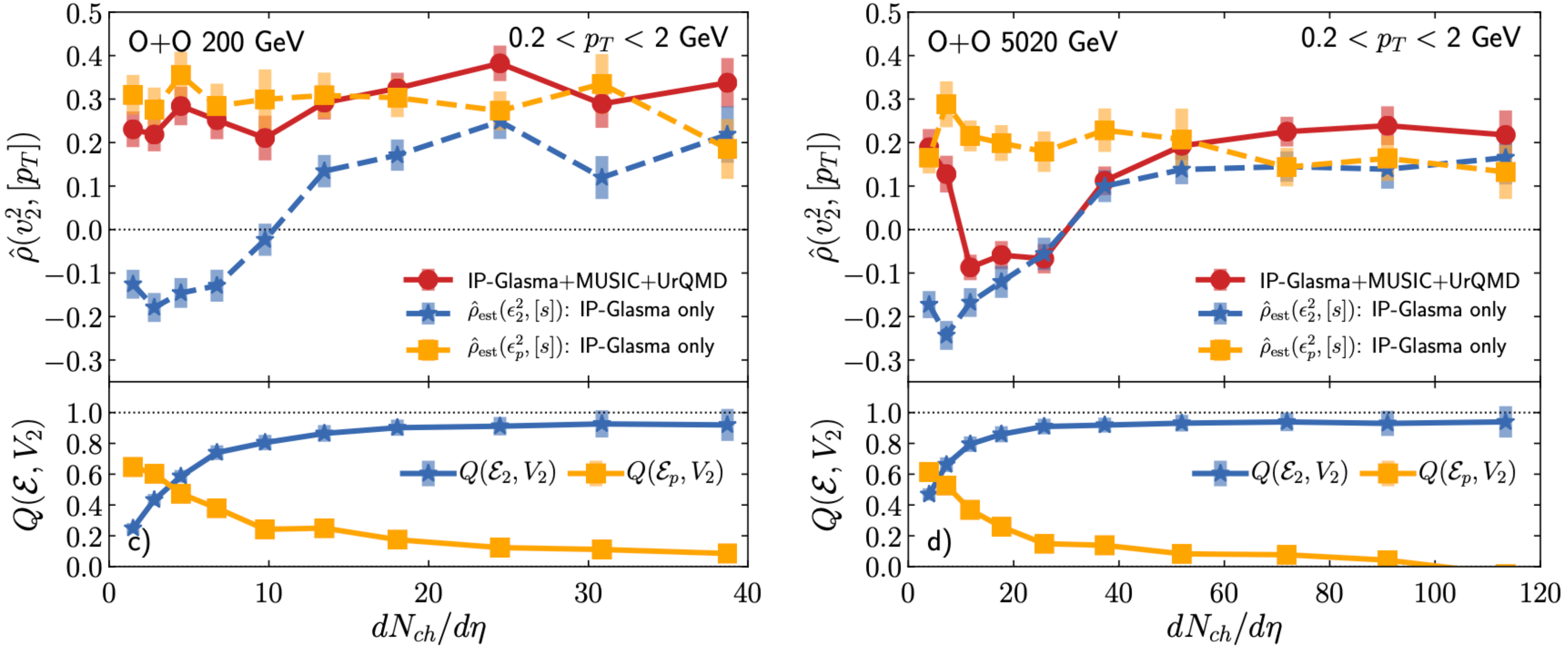


Light Ion Collisions



RHIC vs LHC: Correlation from initial stage

Giuliano Giacalone, Bjoern Schenke, Chun Shen

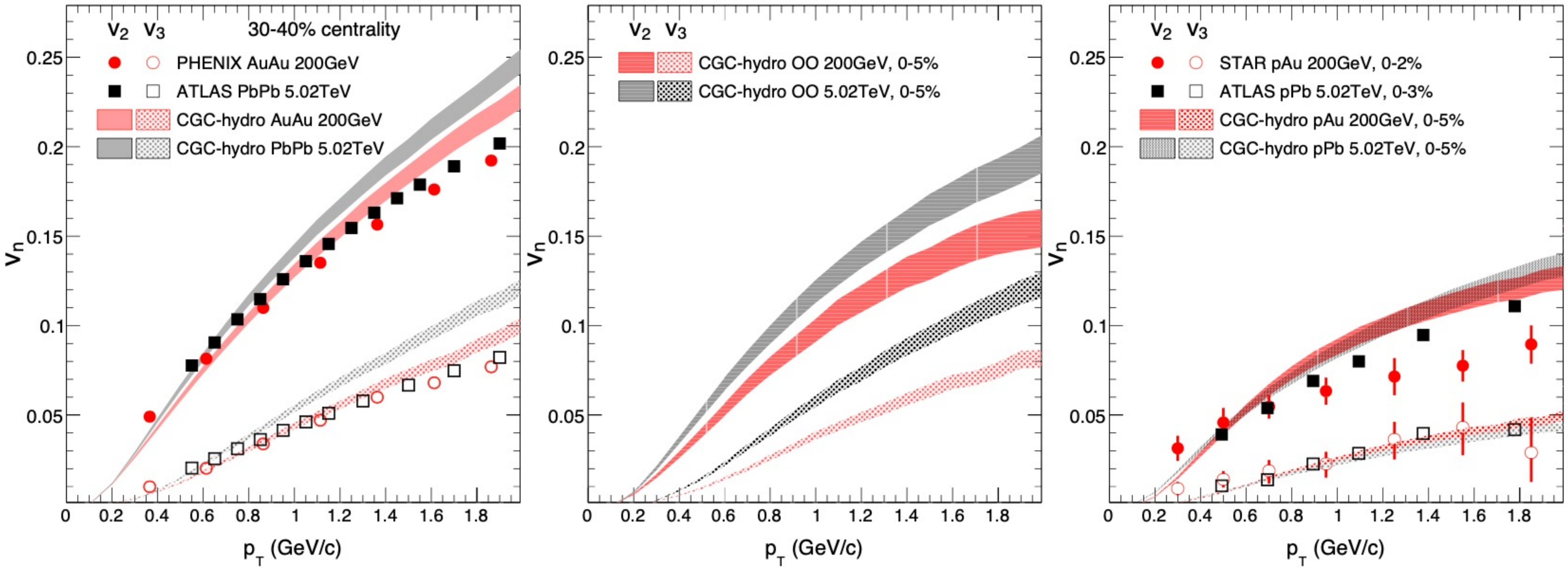


v_2-p_T correlation at low p_T:

The initial momentum-driven correlation is positive, while the geometry-driven correlation is negative. The geometry-driven correlation is larger at the LHC than at RHIC.

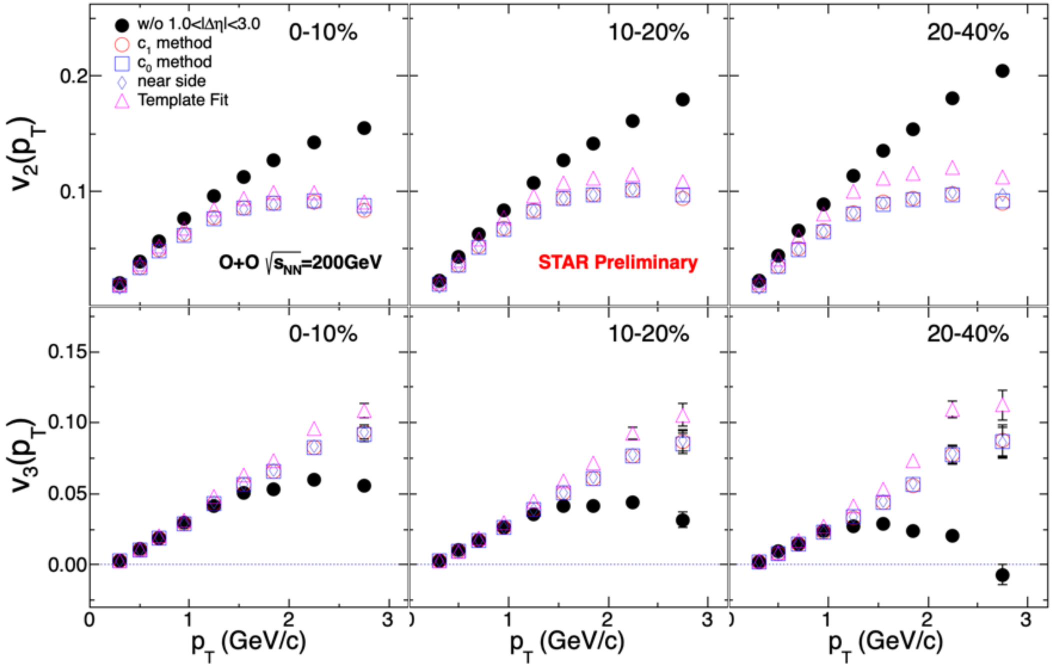
A sign change is predicted at the LHC, but not at RHIC, when combining these two effects

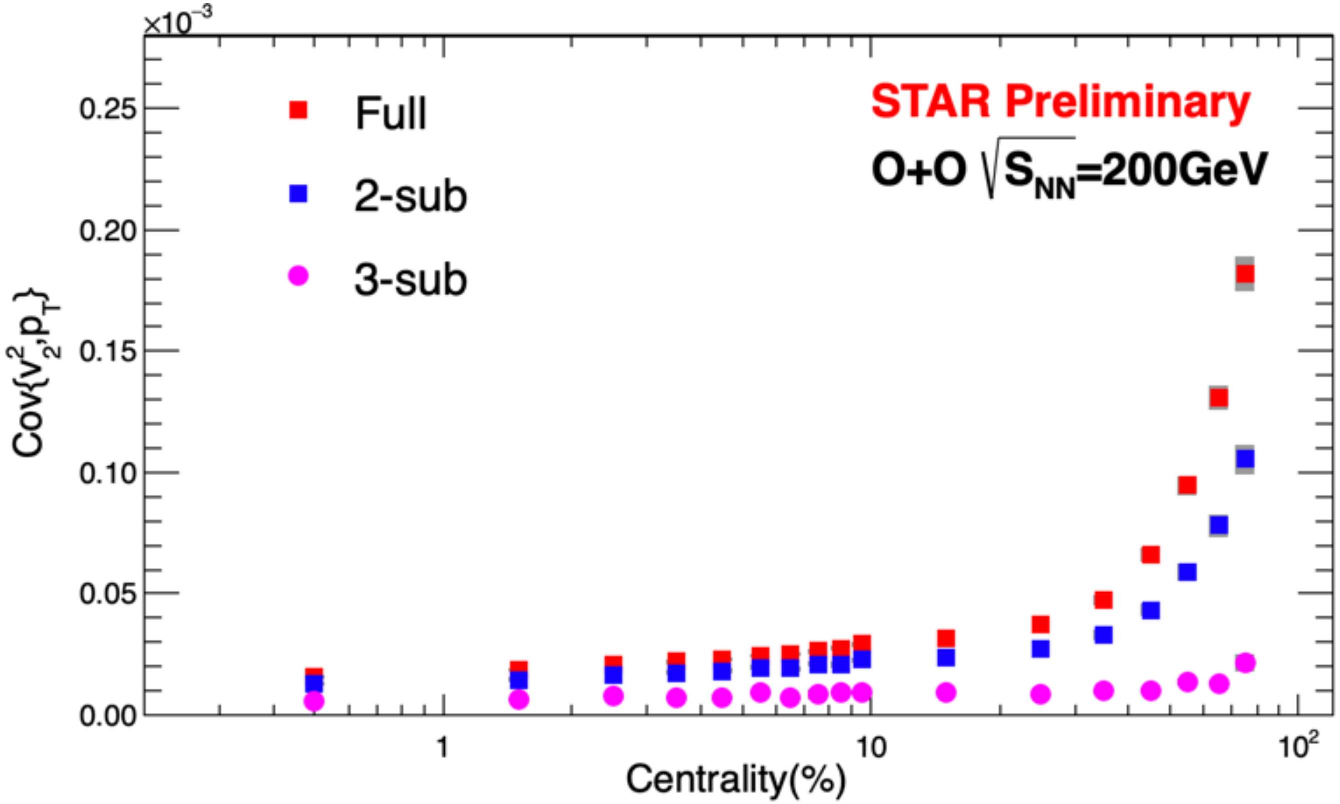
RHIC vs LHC: v_2, v_3



In O+O collisions, a larger v_2 and v_3 values are predicted at LHC energy compared to RHIC energy from CGC-Hydro

v_n and v_2-p_T correlation in O+O at RHIC

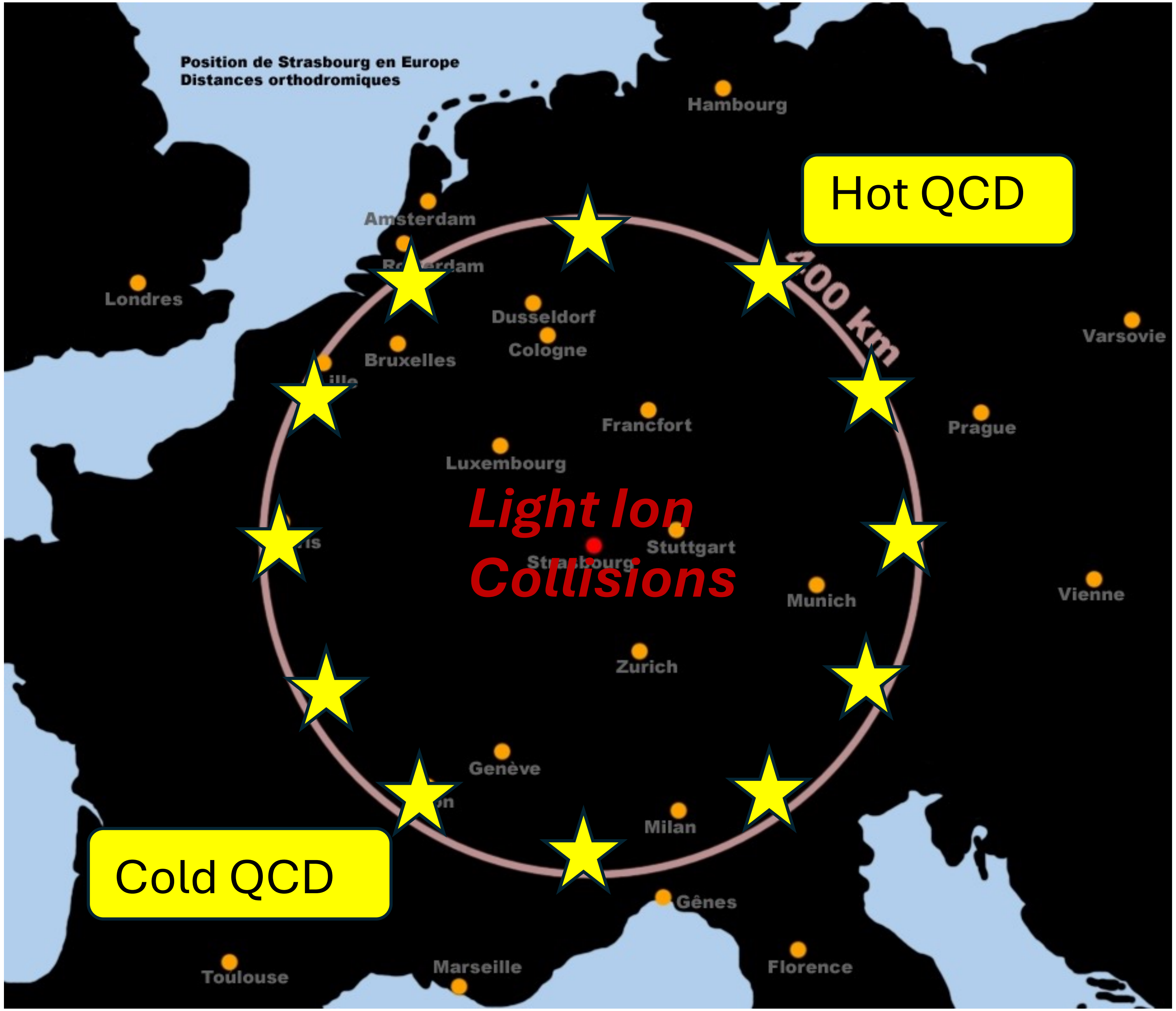




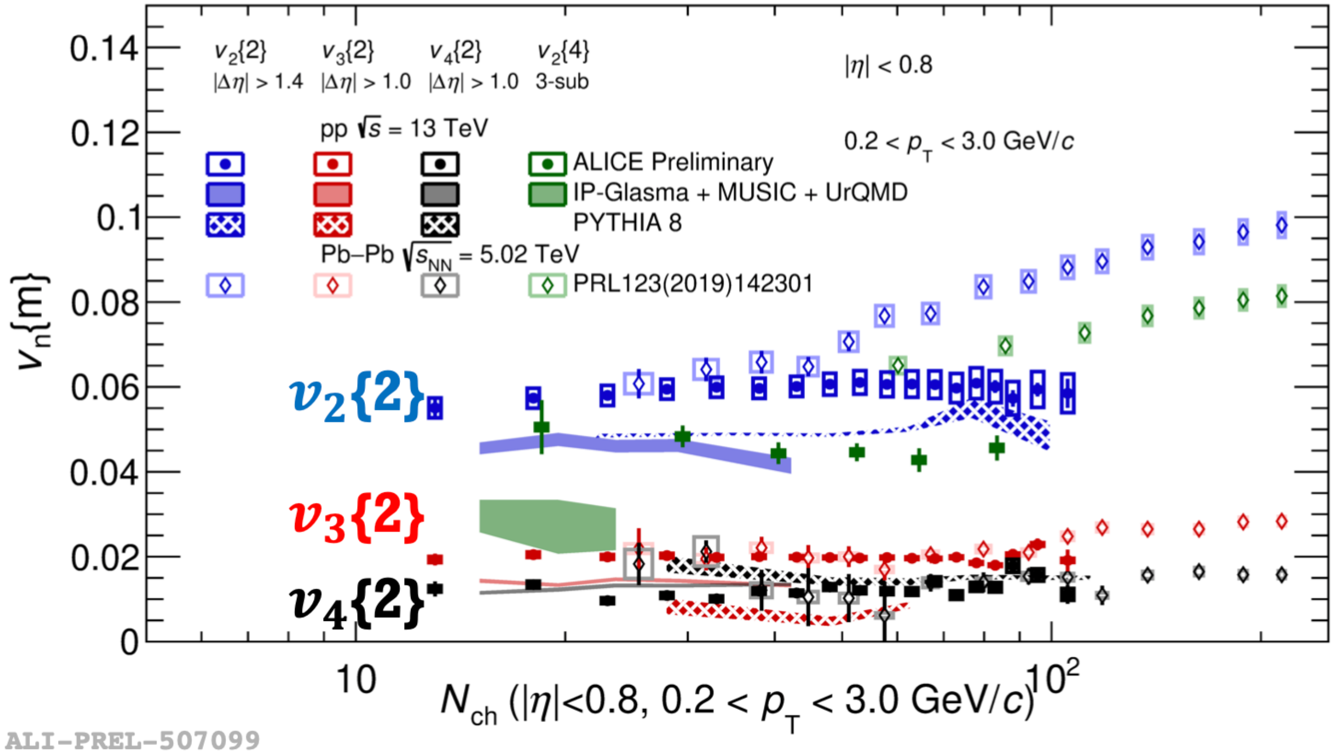
- ✓ Non-flow subtracted v_2 and v_3 show minimal method dependence.
- ✓ A positive v_2-p_T correlation is observed. A non-flow subtraction for peripheral collisions is under study

Waiting results from LHC for comparison.

Light Ion Collisions

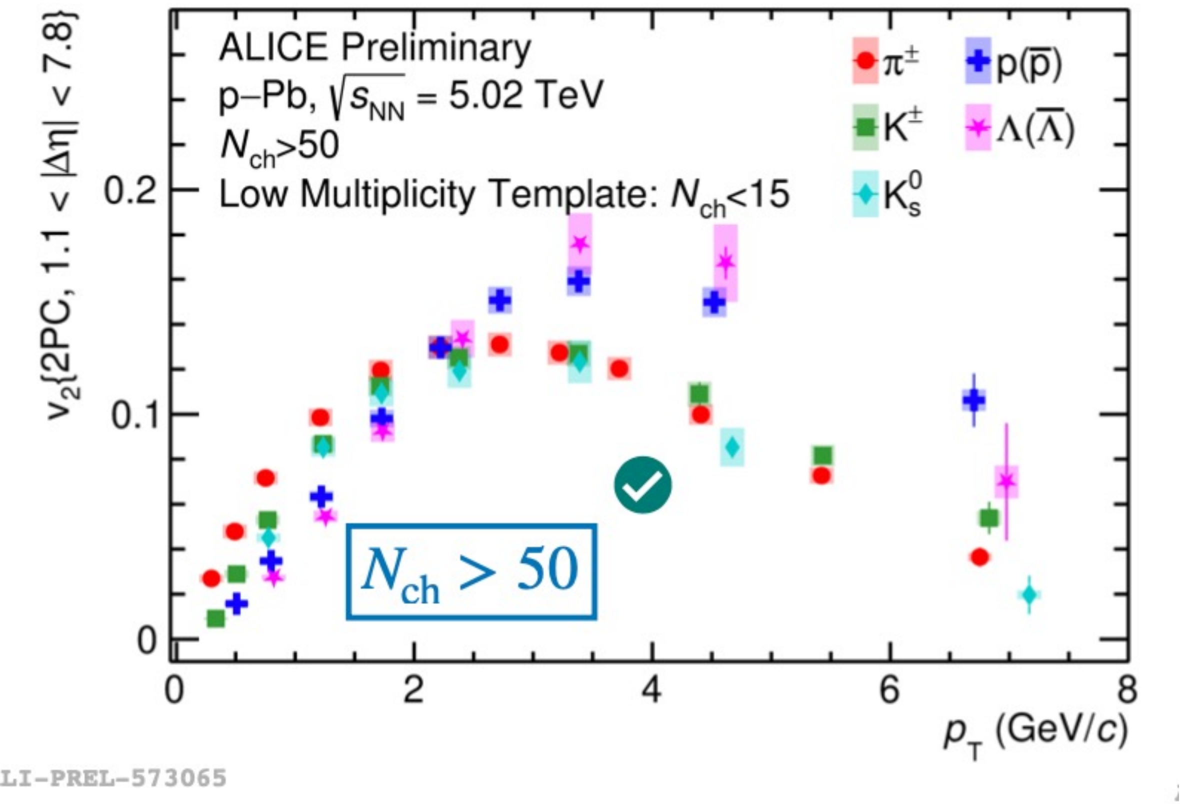


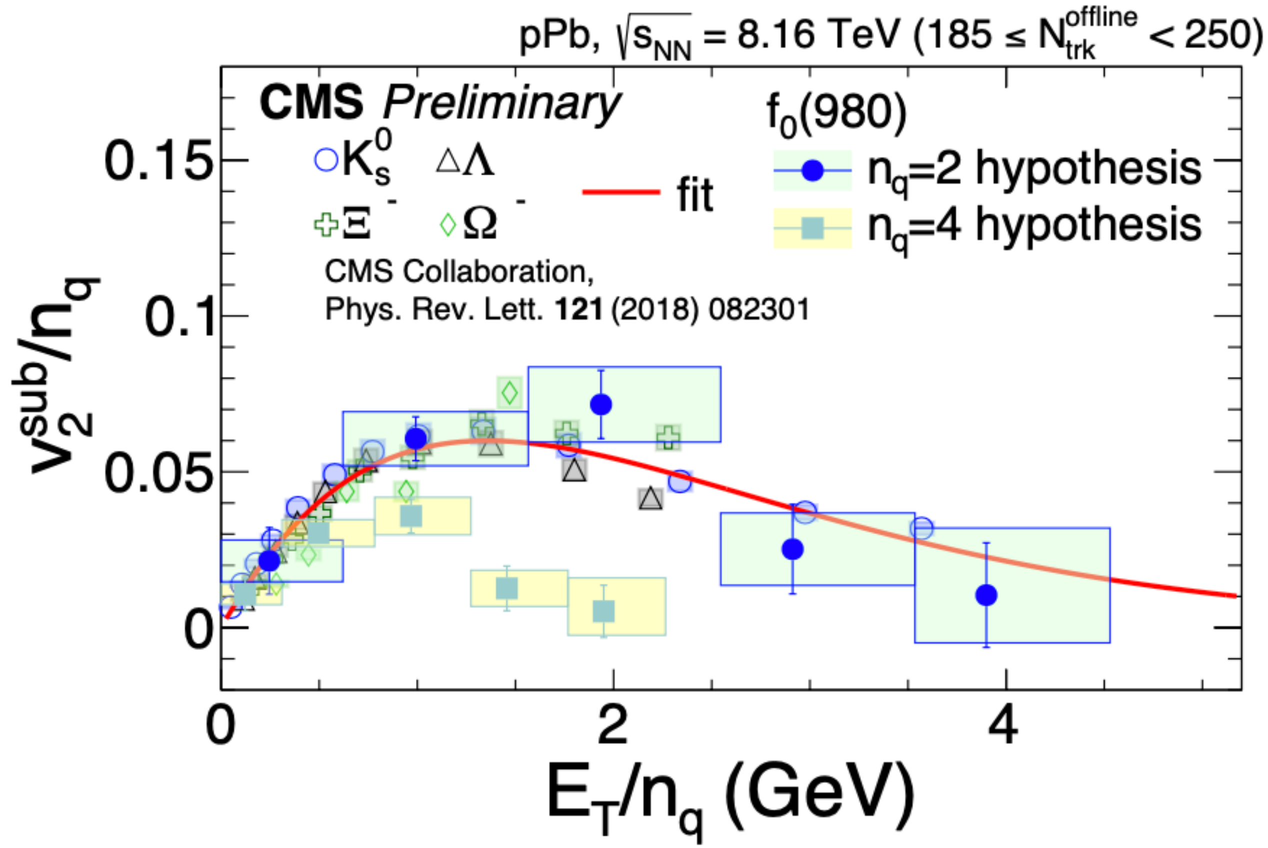
Signature of QGP in Small System: Collectivity from multi-particle cumulant



The four-particle cumulant has been measured in p+p, p+Pb, and peripheral Pb+Pb collisions to investigate collectivity in small systems.

Signatures of QGP in Small System: Species dependent flow

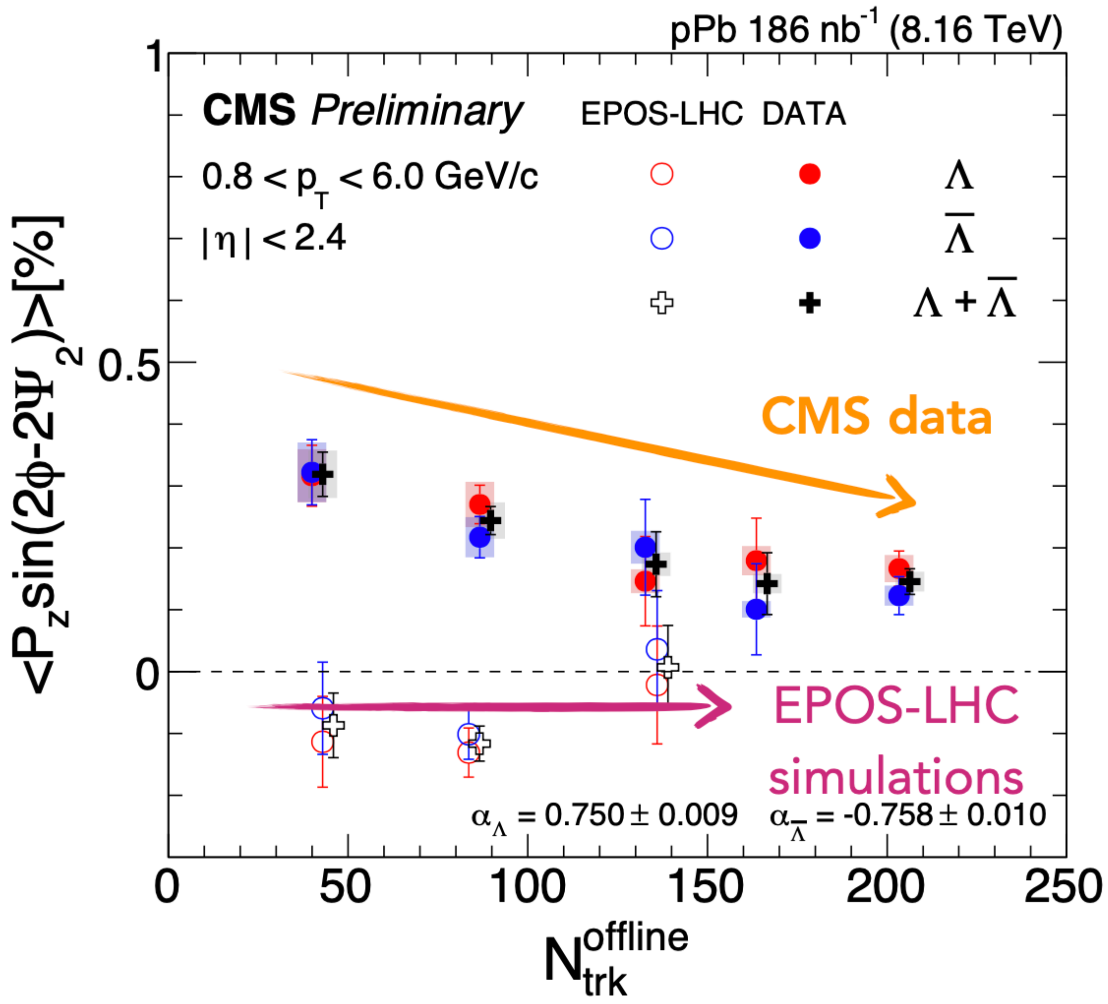




Mass ordering is observed at low p_T for identified particle flow. Radial flow?
NCQ scaling is also found to roughly hold for strangeness particles
f0 flow prefers to two-quark hadron structure

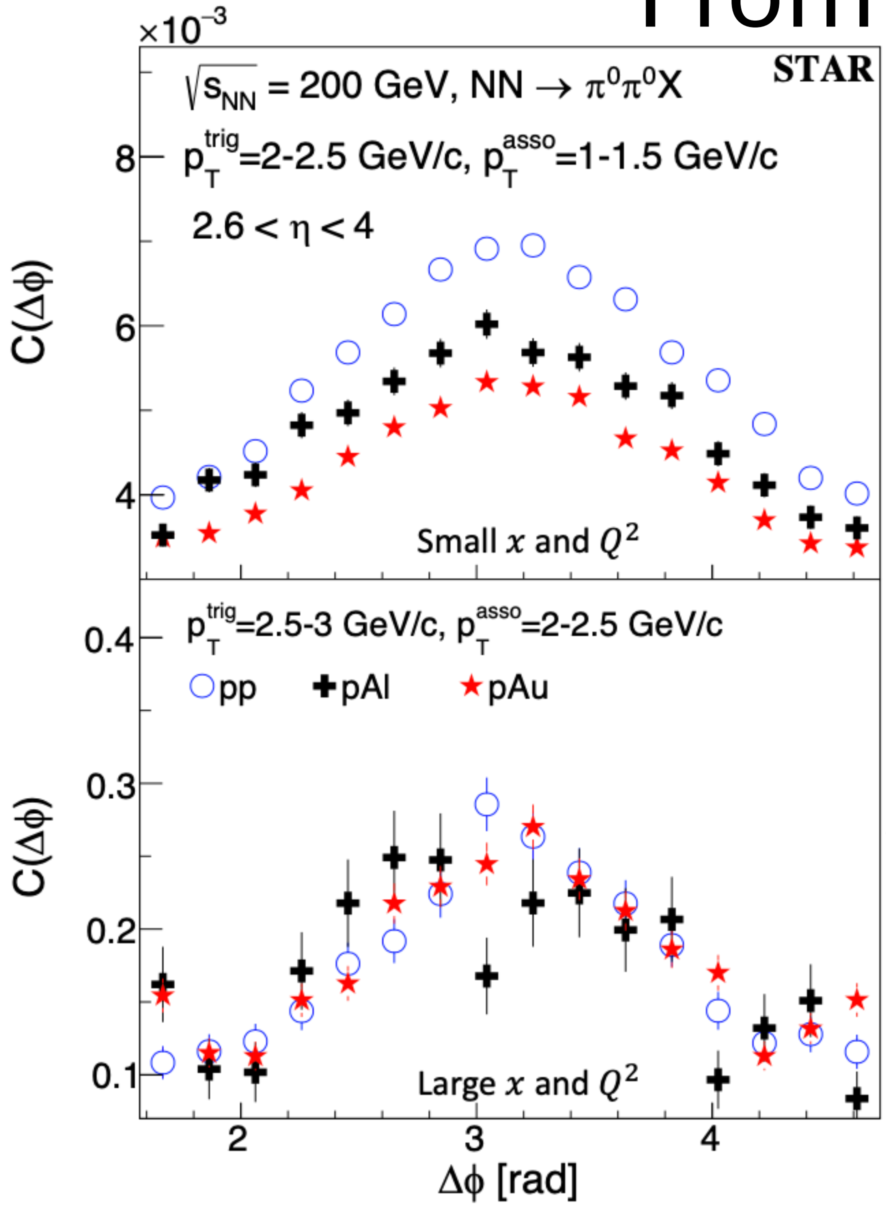
Signatures of QGP in Small System: Local polarization of hyperons

PAS HIN-24-002



Lambda local polarization is also observed in p+Pb collisions

Di-hadron correlation at small x: From equator to north pole



Di-hadron suppression is observed at small x but not at large x.

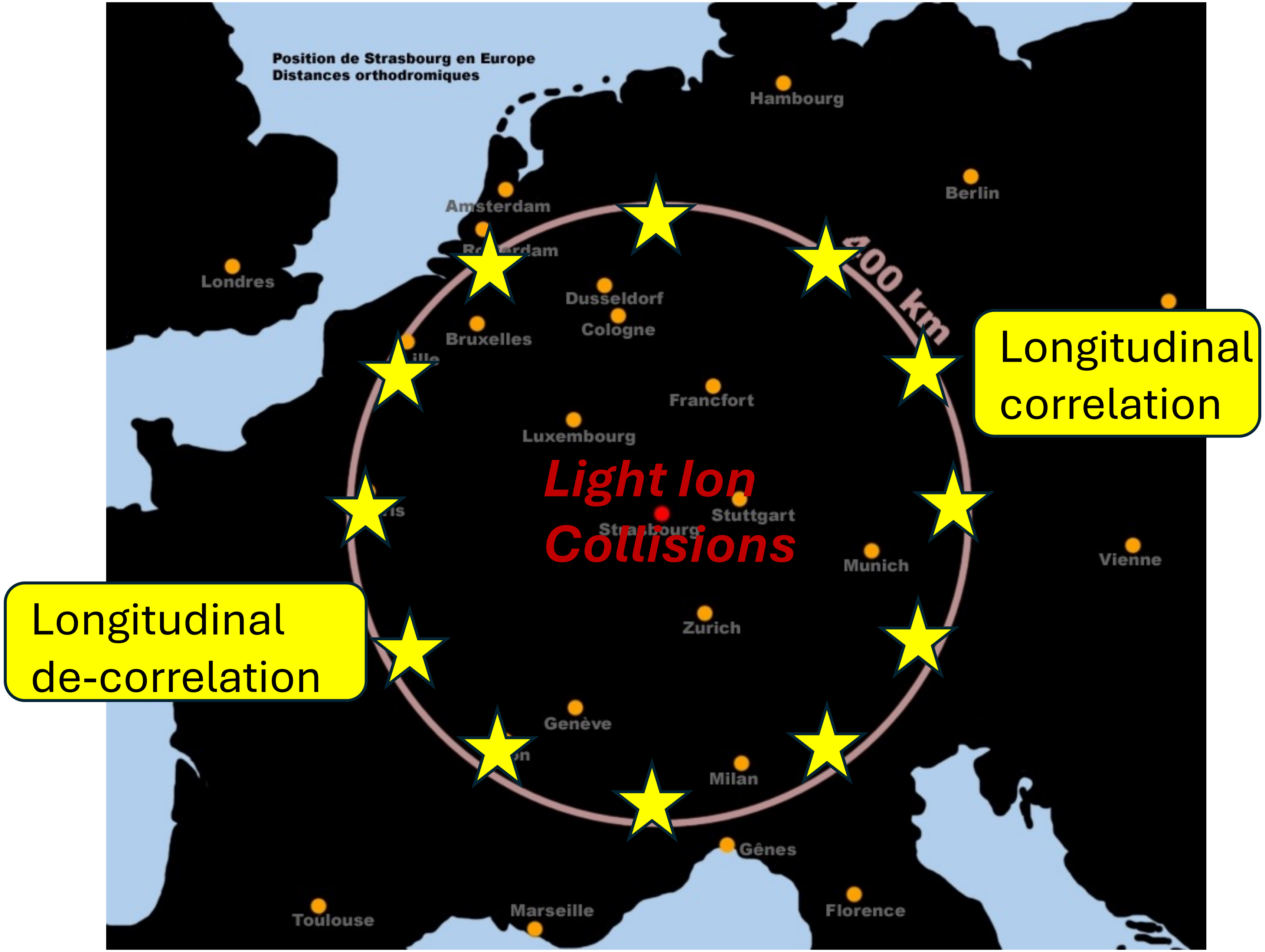
It indicates gluon saturate at small x(CGC)

How can we isolate the final-state effects?

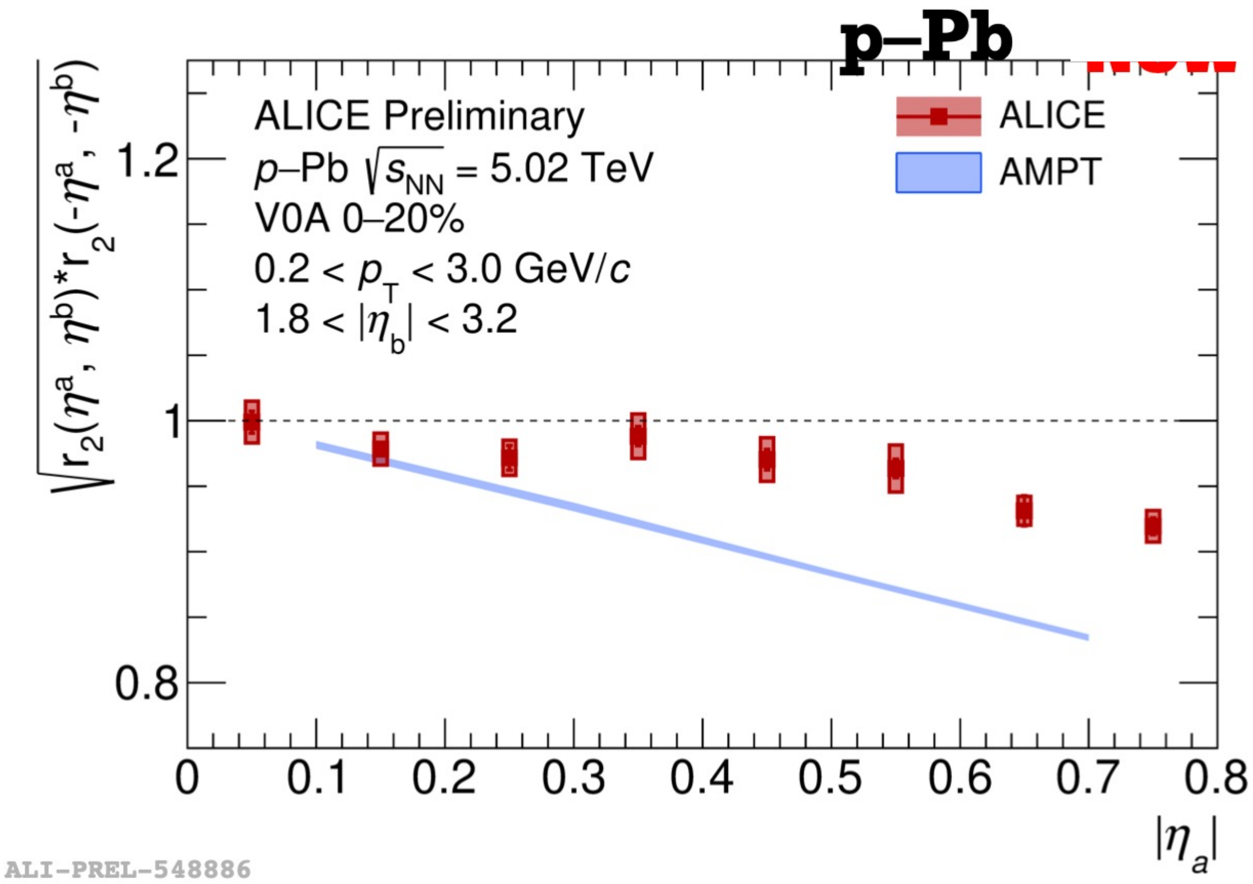
Would collisions such as O+O or p+p with similar multiplicities as central p+Au provide a baseline?

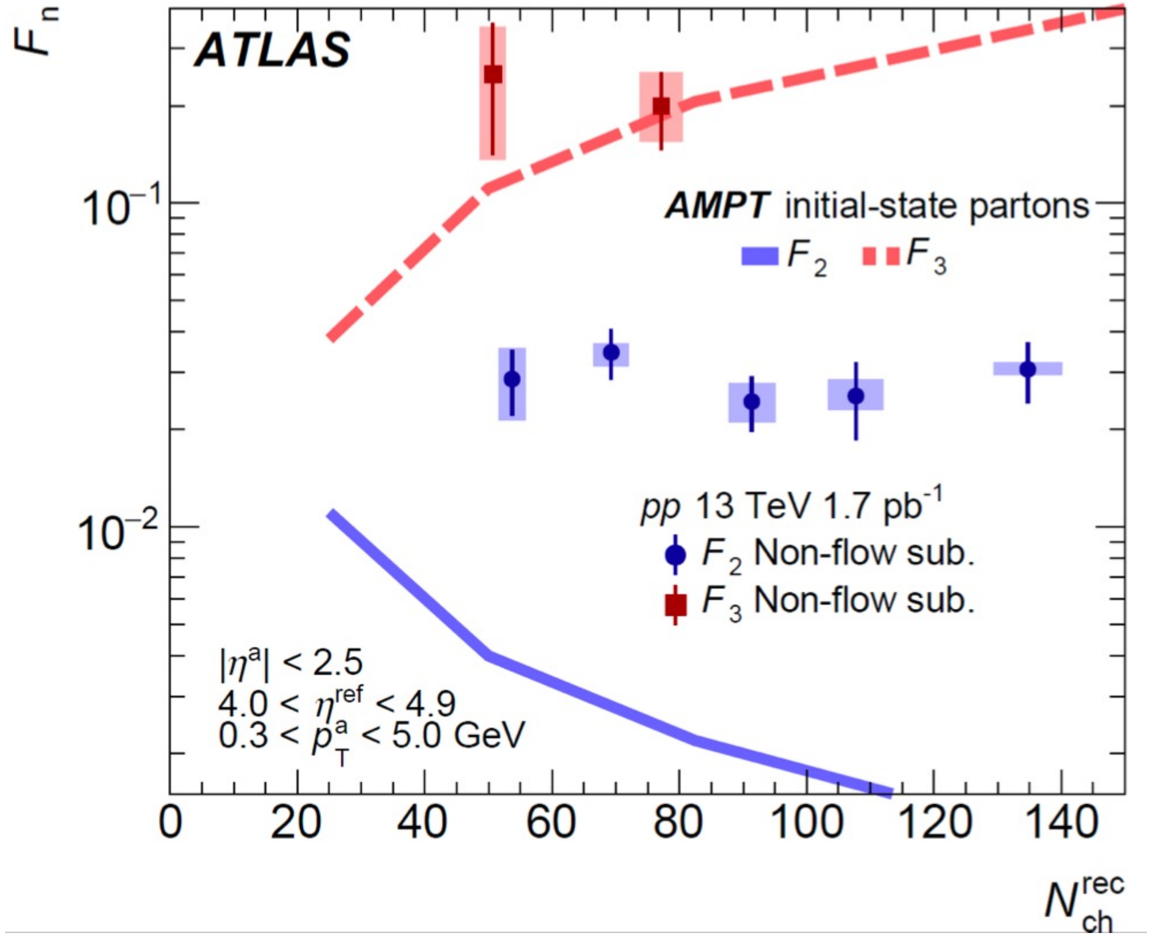
1.5 billion MB and 1.5 billion HM p+p events with tiny pile-up were recorded last month at RHIC.

Light Ion Collisions



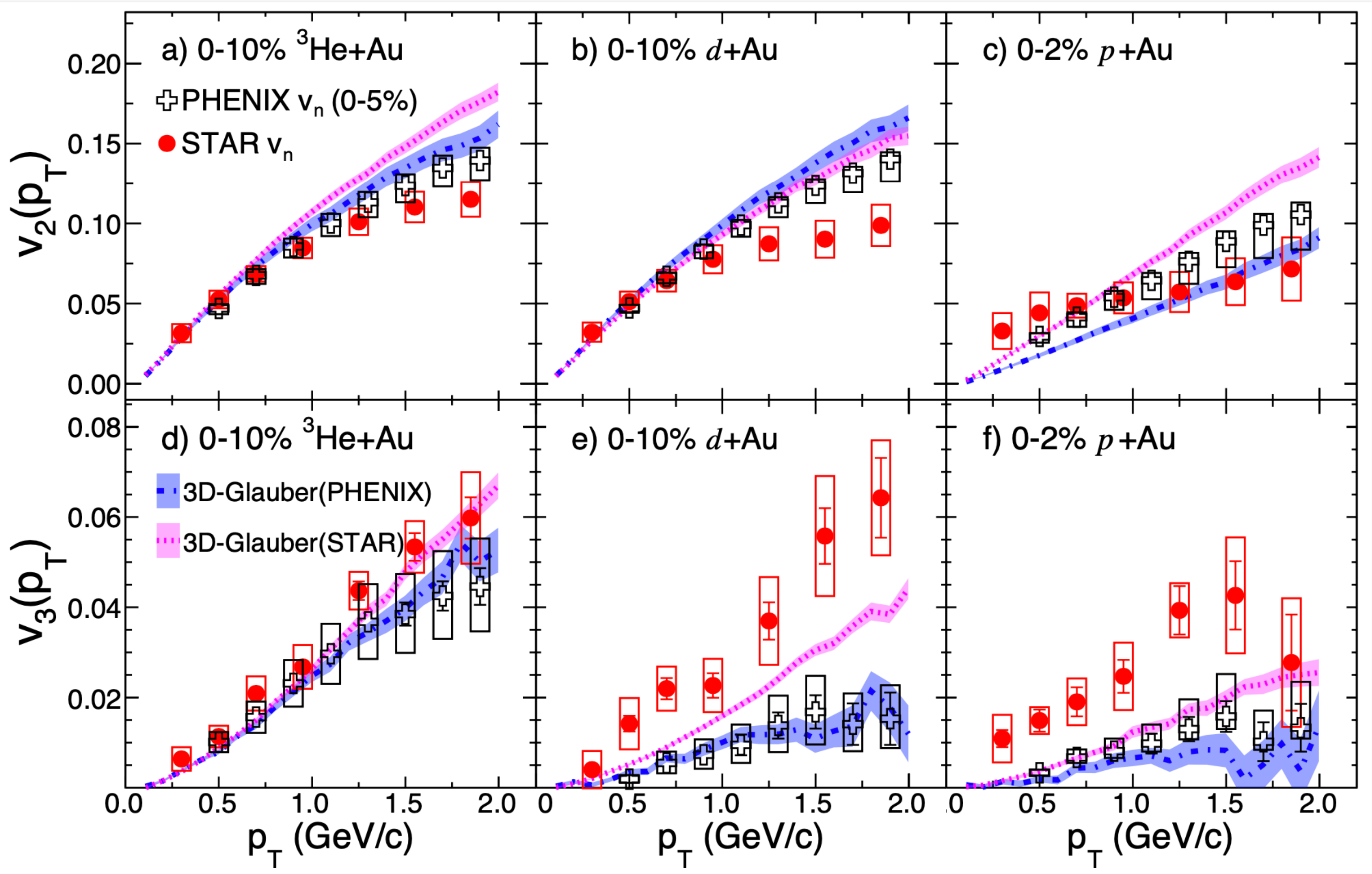
Longitudinal De-Correlation @ LHC





Larger longitudinal flow de-correlation is observed in p+Pb and p+p collisions.
The third-order flow shows greater de-correlation than the second-order flow
AMPT captures the de-correlation for F_3 but underestimates F_2.

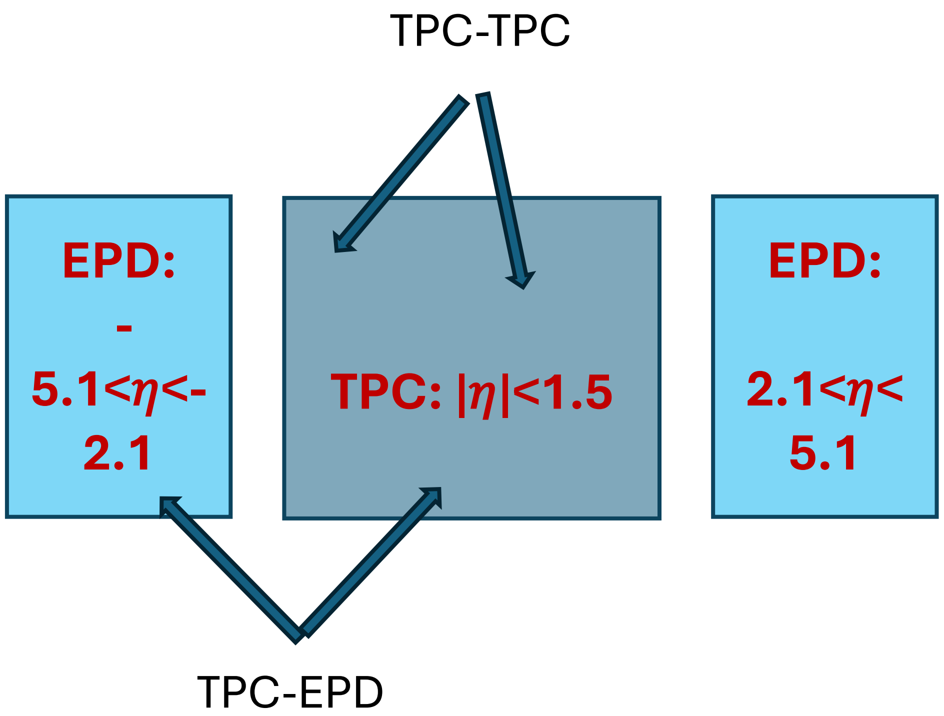
Longitudinal De-Correlation @ RHIC

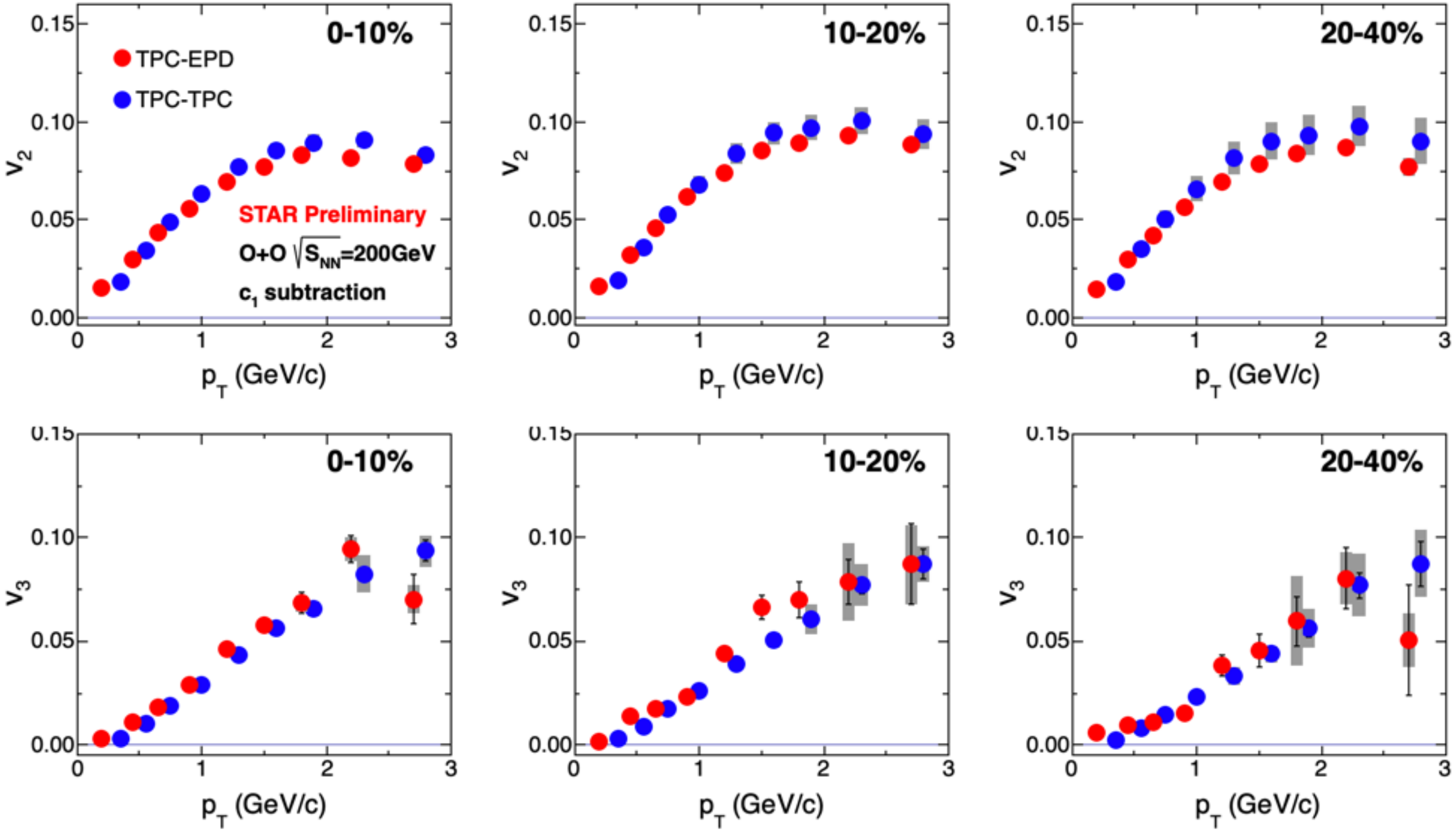


In p/d+Au collisions, $v_3(p_T)$ between measurements obtained from mid-mid rapidity di-hadron correlation(STAR) and those from mid-forward rapidity(PHENIX) differ by a factor of 3

This discrepancy may arise from longitudinal fluctuations (flow de-correlation), a phenomenon partially accounted for by the 3D-Glauber model.

Mid-Mid vs Mid-Forward correlation in O+O



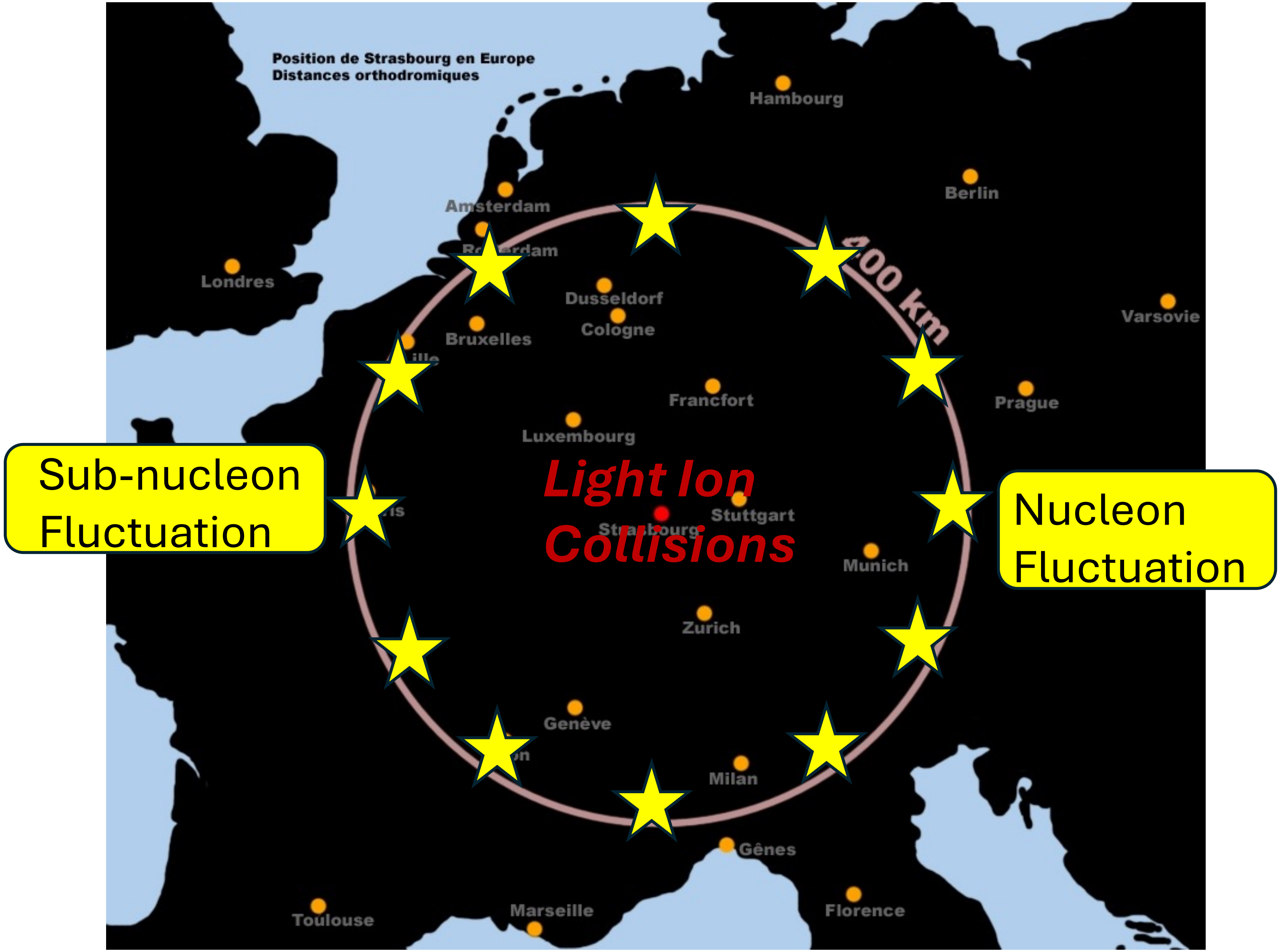


✓ V_n measured from mid-mid(TPC-TPC) and mid–forward(EPD-TPC) correlations are similar

Flow decorrelation is weak in symmetric Ion collision with larger sizes

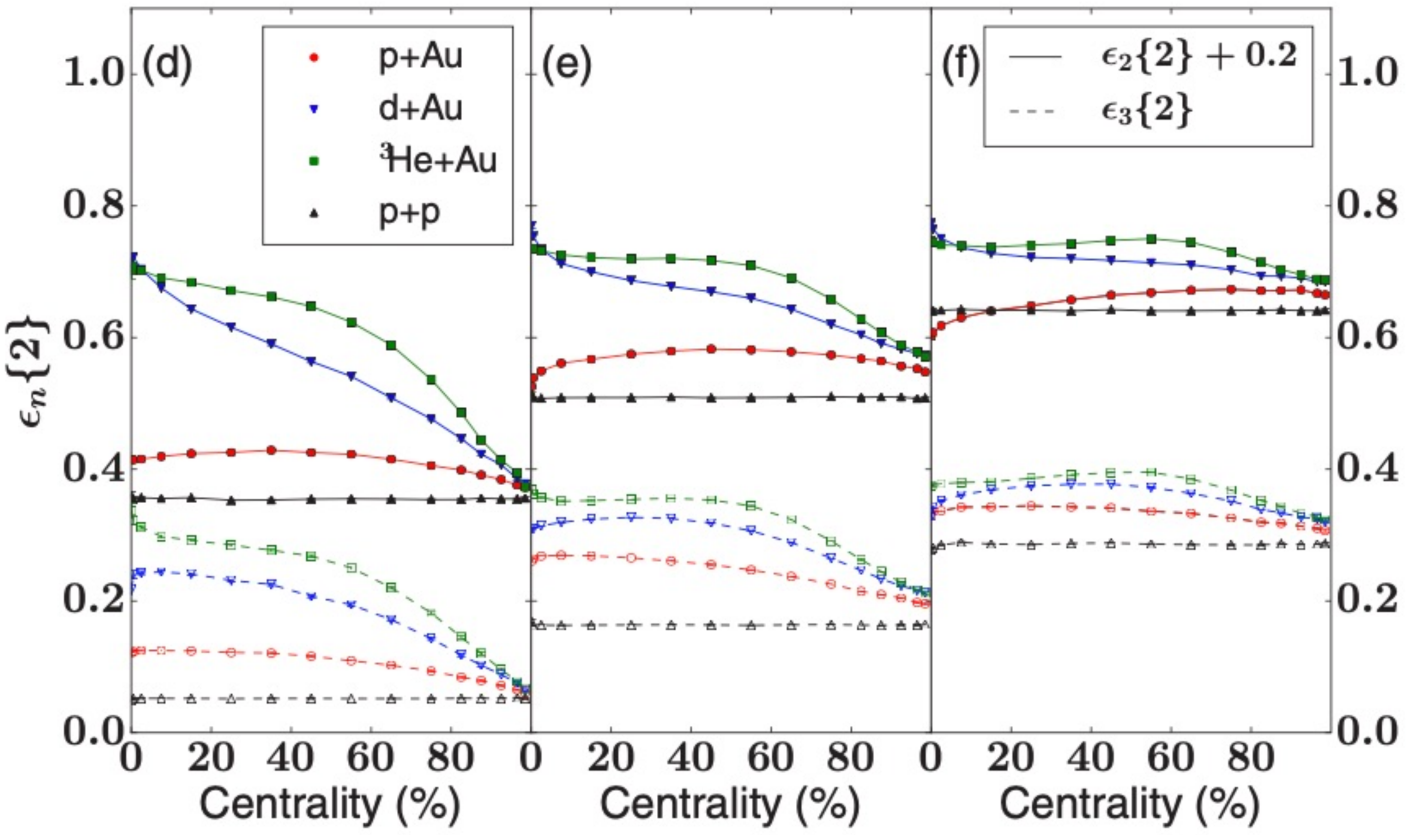
✓ Results from the new STAR d+Au dataset will shed more light on flow decorrelation

Light Ion Collisions



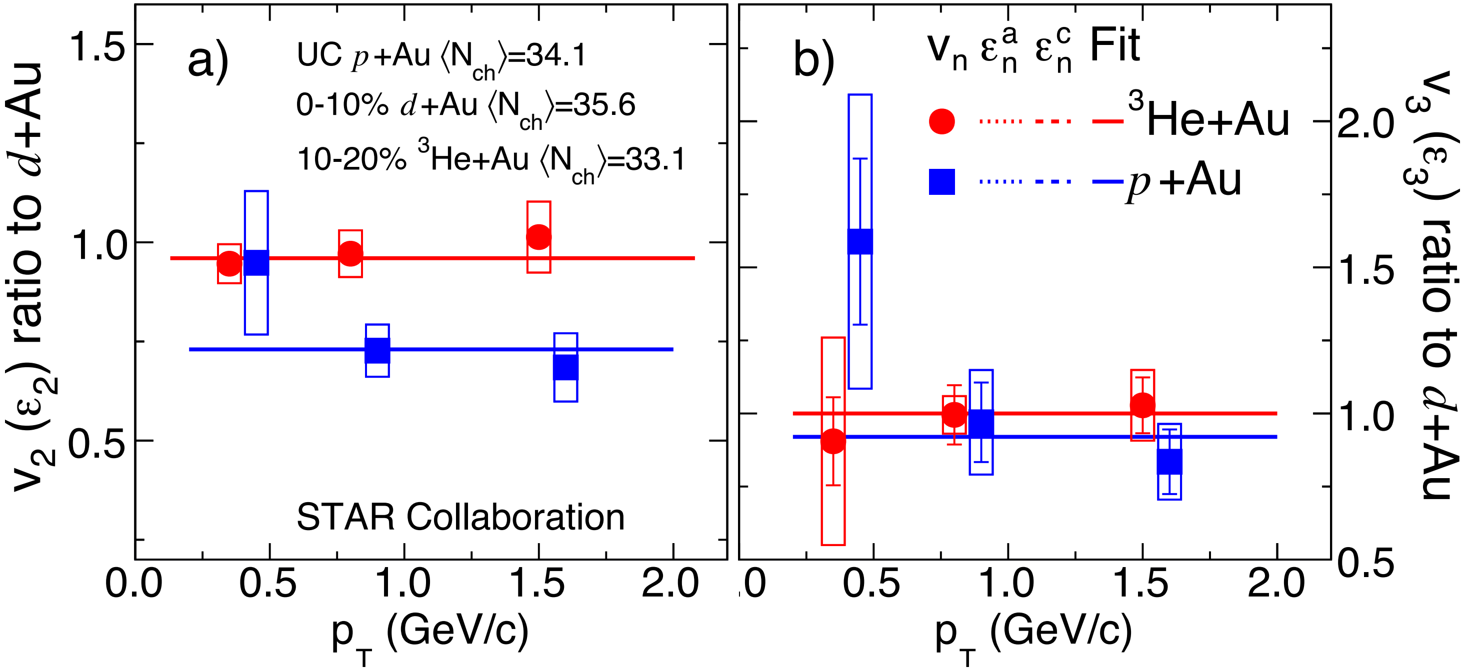
Sub-Nucleon Fluctuation in small system

Disk-like Gaussion-like Quark-like *PRC 94, 024919 (2016)*



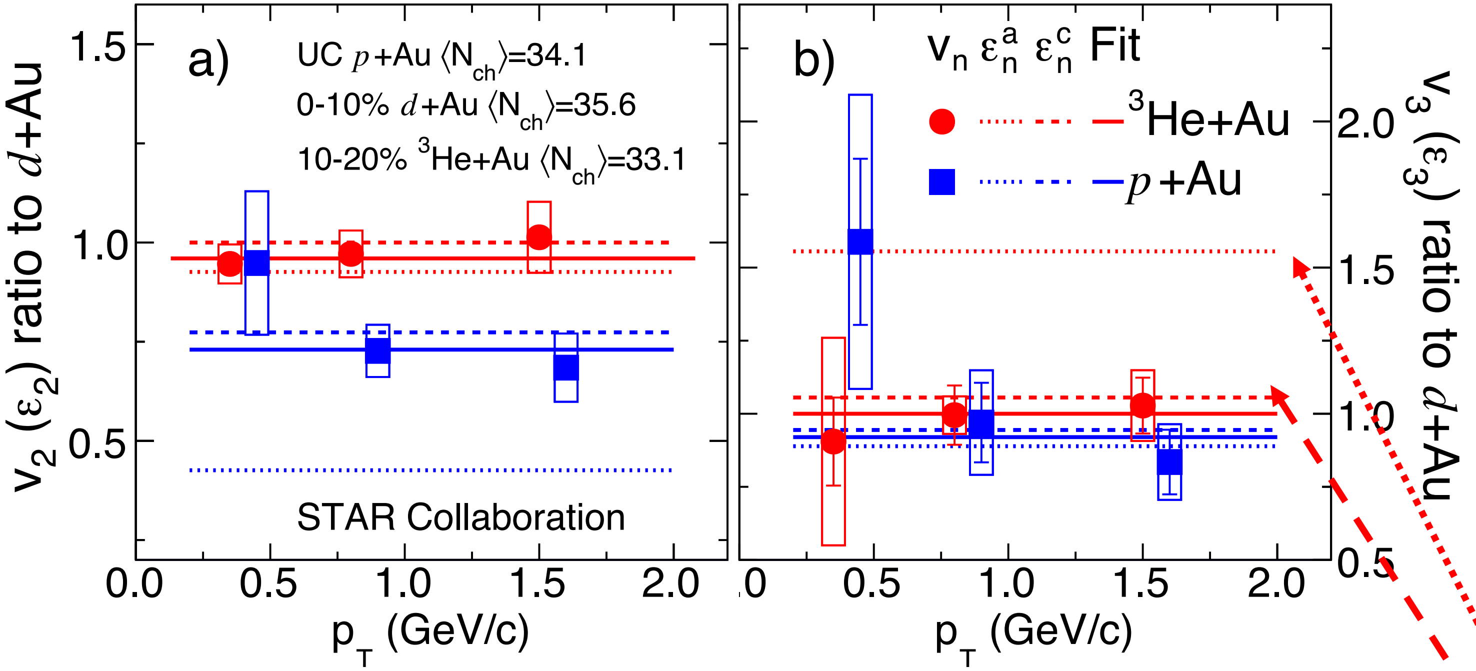
Eccentricity difference between p+p, p+Au, d+Au and ^{3}He+Au is substantially mitigated by the sub-nucleon fluctuation

The system dependence for v_n



The final state contribution is expected to largely cancel out in the v_n ratio due to similar multiplicity.

The system dependence for v_n

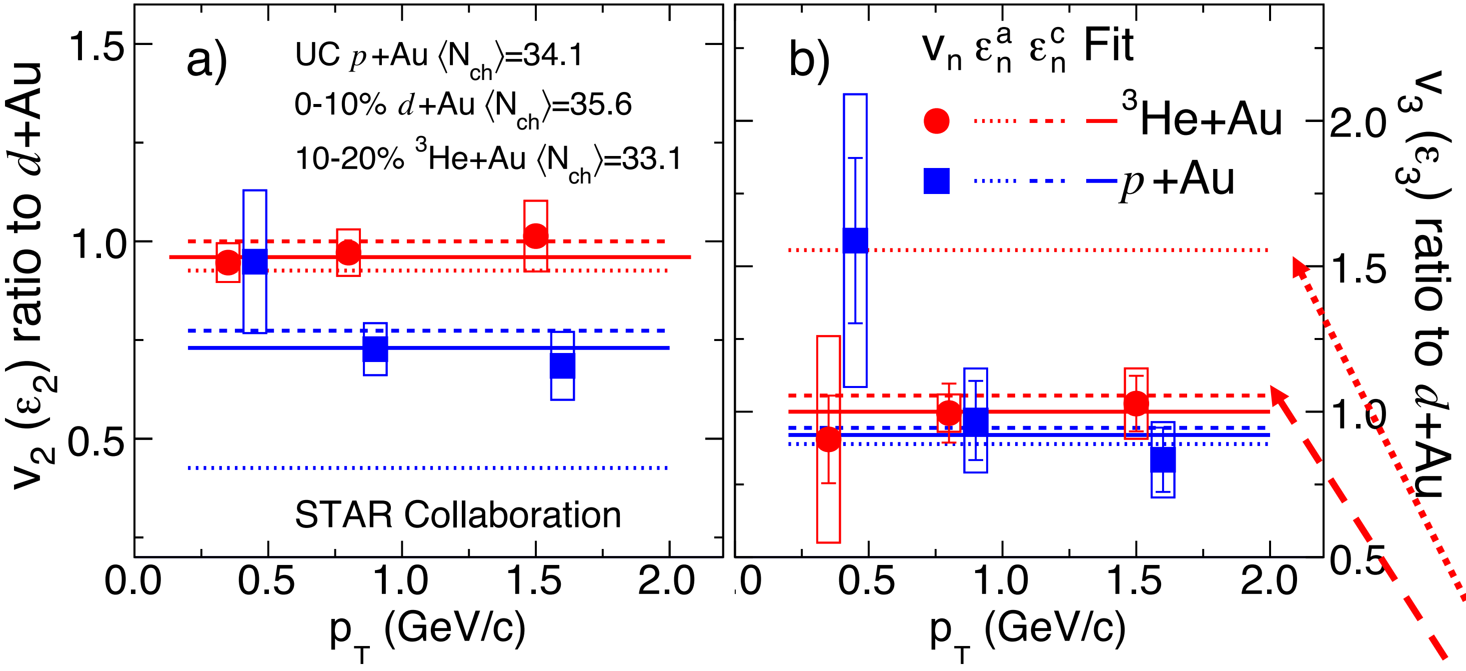


The final state contribution is expected to largely cancel out in the v_n ratio due to similar multiplicity.

$V_2(^3HeAu) \approx v_2(dAu) > v_2(pAu)$
$V_3(^3HeAu) \approx v_3(dAu) \approx v_3(pAu)$

Two Base Lines:
Nucleon spatial Geometry
Sub-nucleon spatial Geometry

The system dependence for v_n



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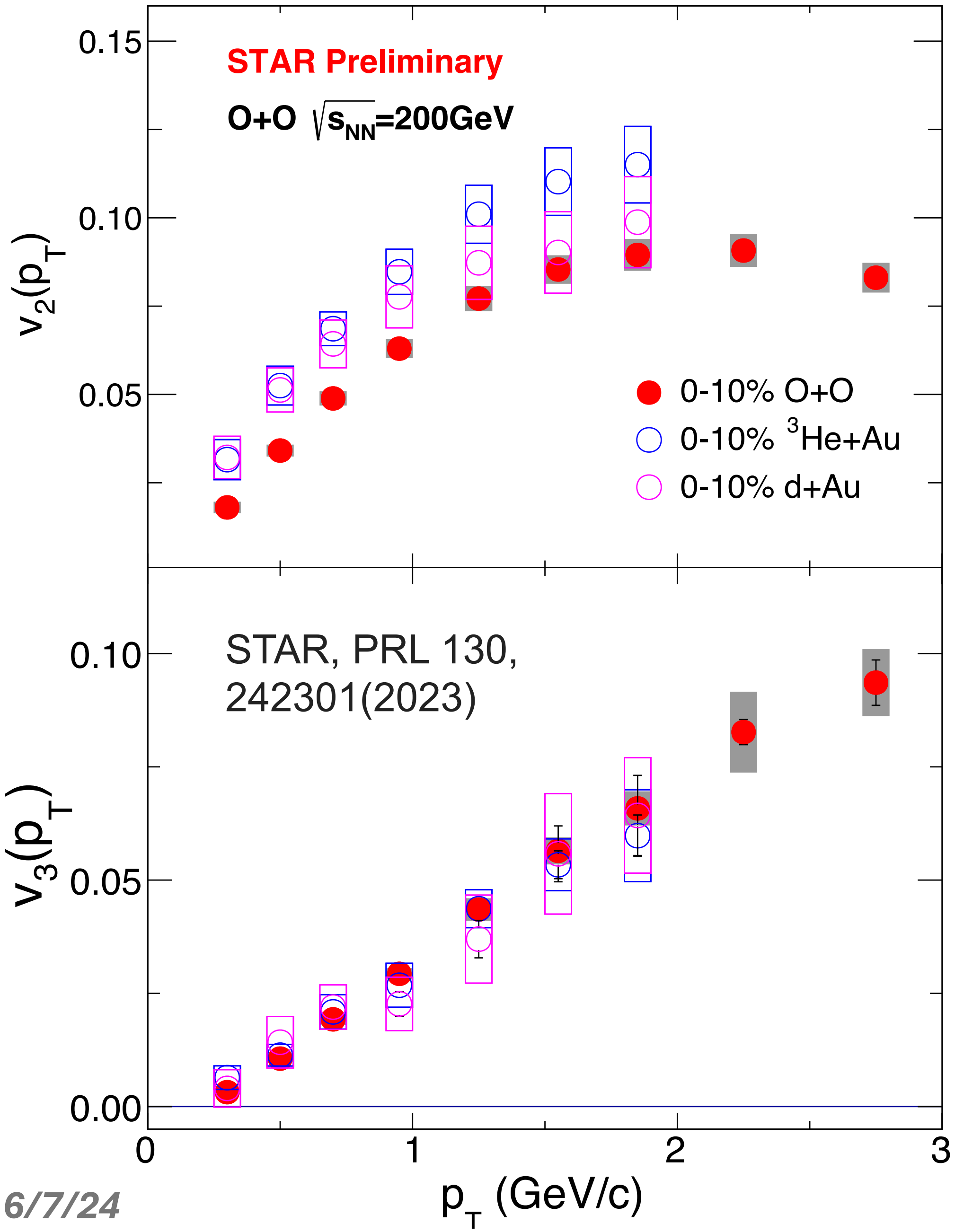
Two Base Lines:

Nucleon spatial Geometry

Sub-nucleon spatial Geometry

STAR measurements prefer to the sub-nucleon fluctuation

Symmetric and asymmetric collisions



Model	point-like quark $\varepsilon_2^c\{2\}(\varepsilon_3^c\{2\})$	fluctuated gluon field $\varepsilon_2^d\{2\}(\varepsilon_3^d\{2\})$
0-10% ^{3}He+Au	0.61(0.47)	0.53(0.38)
0-10% d+Au	0.71(0.45)	0.53(0.36)
0-10% $^{16}O+^{16}O(NLEFT)$	0.44(0.43)	

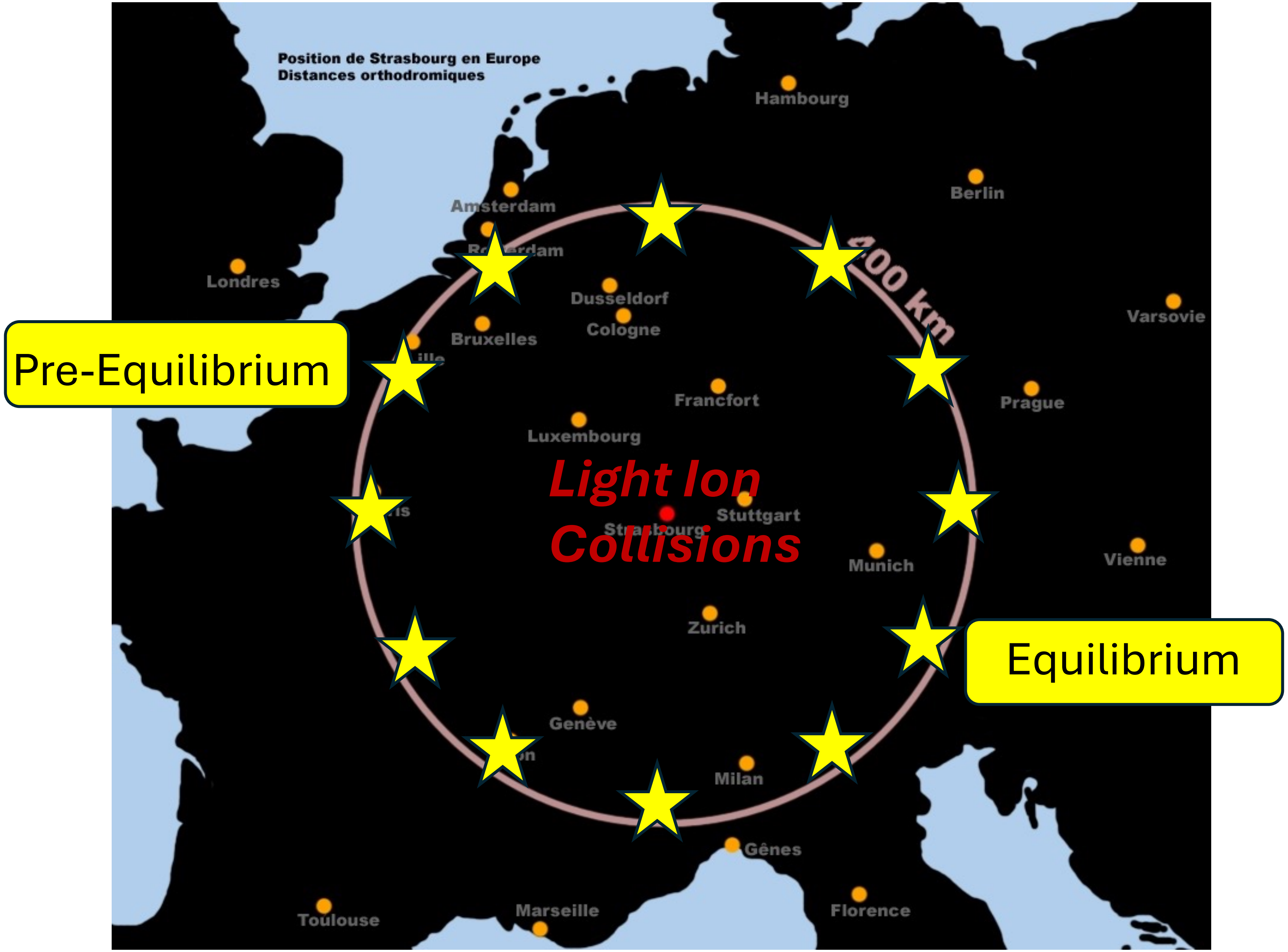
Quark Glauber:
PRC **94**, 024914(2016)
Gluon field:
PRC **94**, 024919(2016)

$v_2(O+O) < v_2(d+Au) \approx v_2(^3He+Au)$

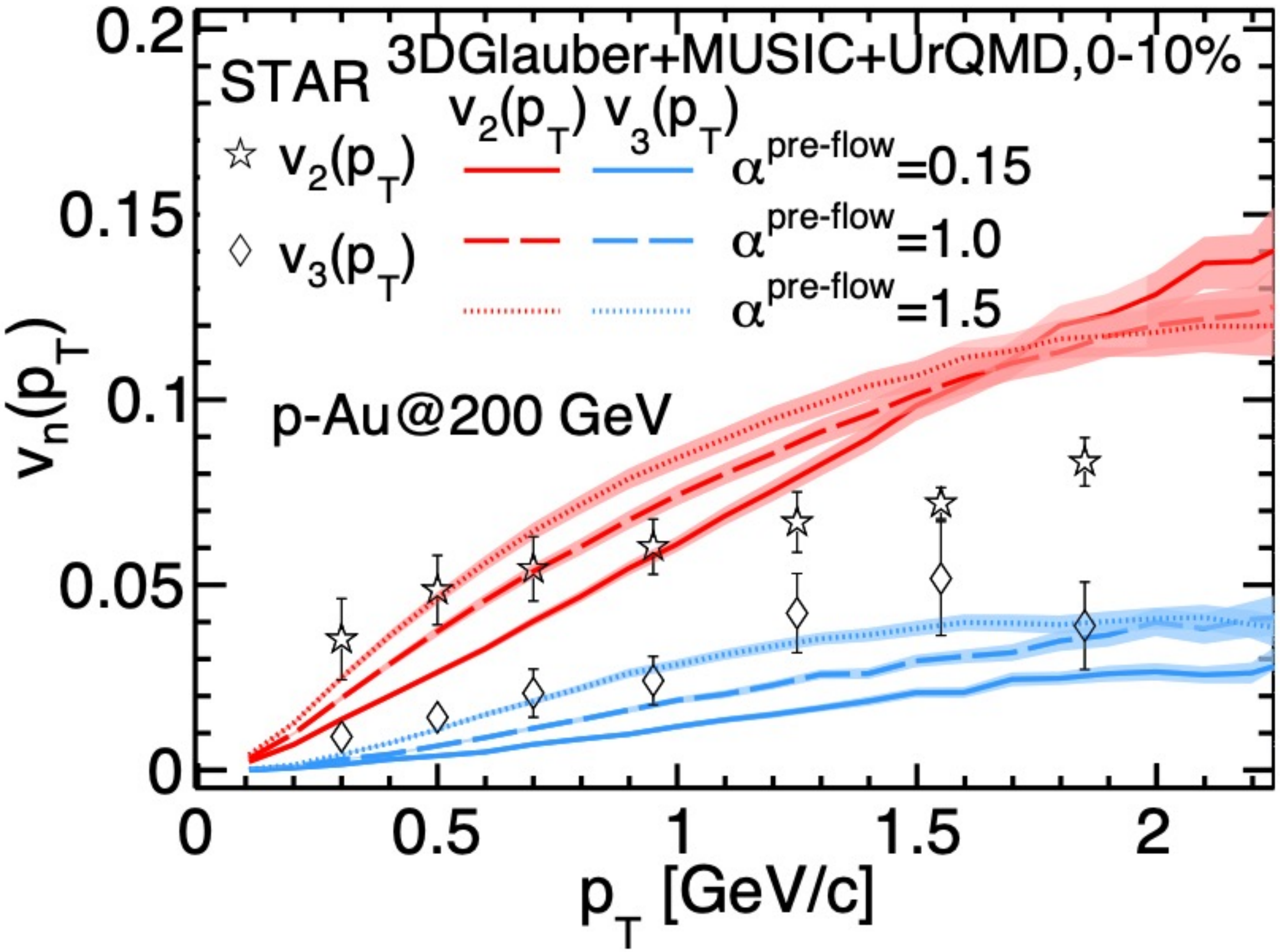
$v_3(O+O) \approx v_3(d+Au) \approx v_3(^3He+Au)$

Consistent with expectation of sub-nucleon fluctuation

Light Ion Collisions

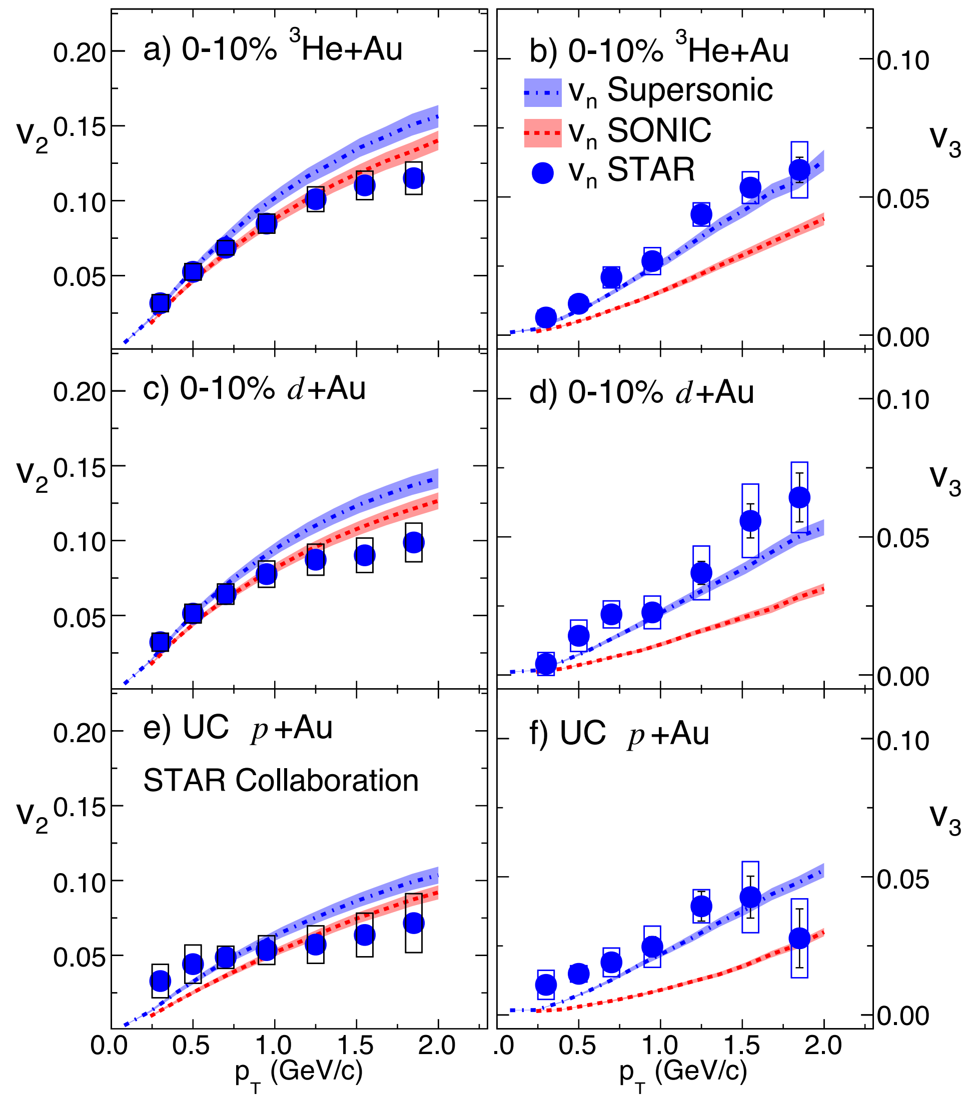


Pre-flow in 3D-Glauber



Pre-flow will boost the v_2 and v_3 in 3DGlauber+Hydro model

Sonic and superSONIC Model

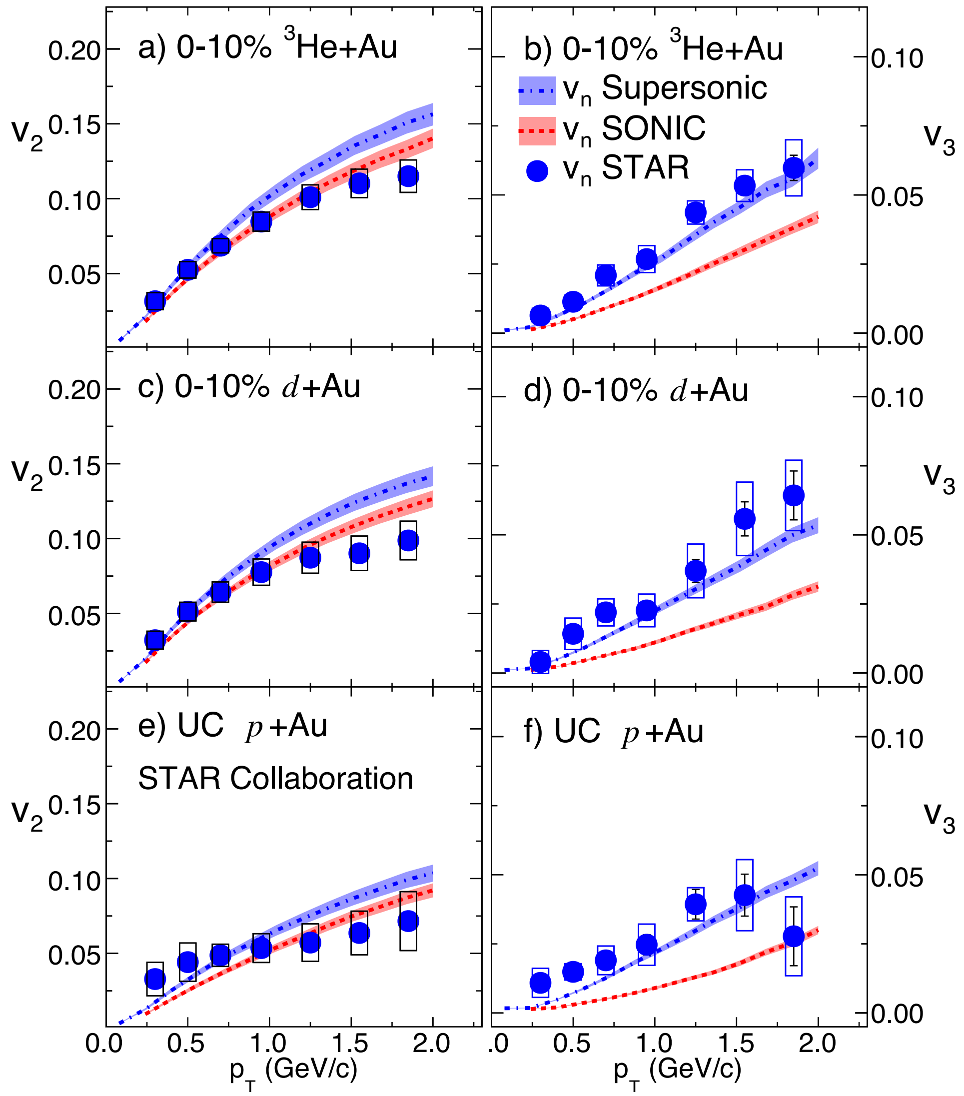


- ***SONIC model*** with initial geometry eccentricity without sub-nuclear fluctuations under-predicts v_3 in all systems

- ***superSONIC model*** with pre-equilibrium flow can reproduce the v_3 even without sub-nucleon fluctuations

SONIC: P. Romatschke *Eur. Phys.J.C* **75**, 305 (2015)

SONIC and superSONIC Model



- ***SONIC model*** with initial geometry eccentricity without sub-nuclear fluctuations under-predicts v_3 in all systems

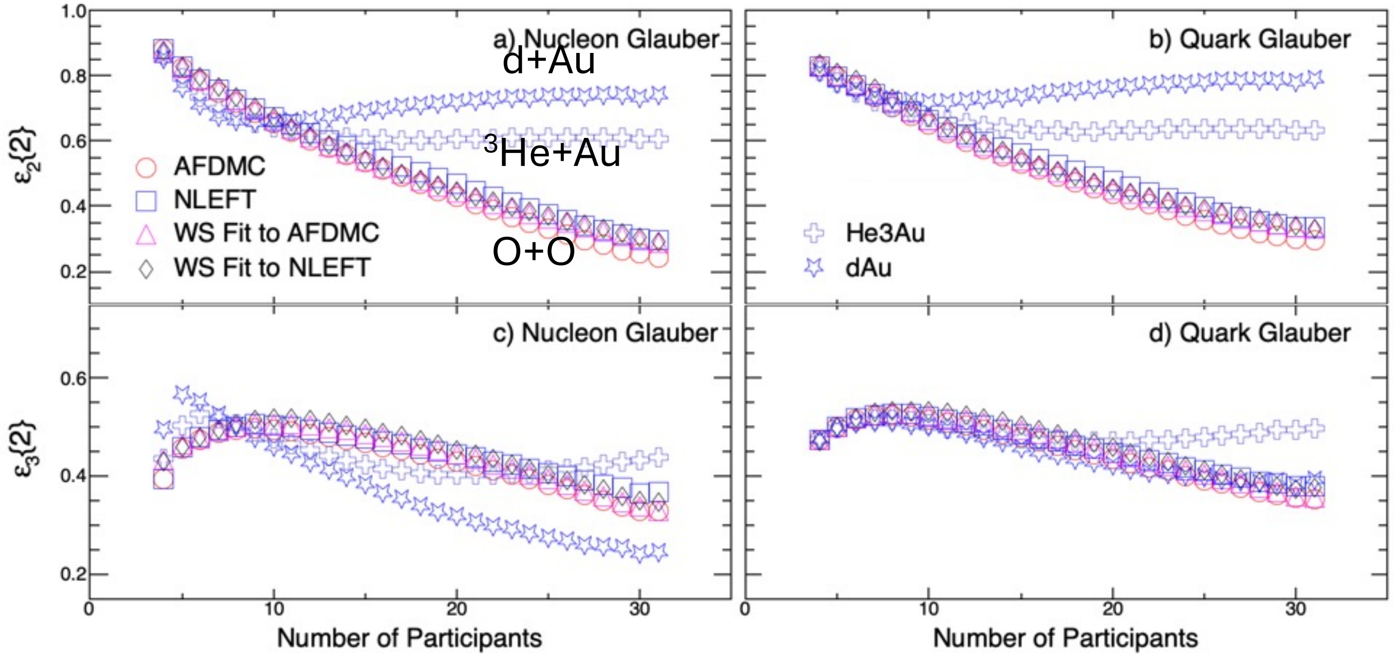
- ***superSONIC model*** with pre-equilibrium flow can reproduce the v_3 even without sub-nucleon fluctuations

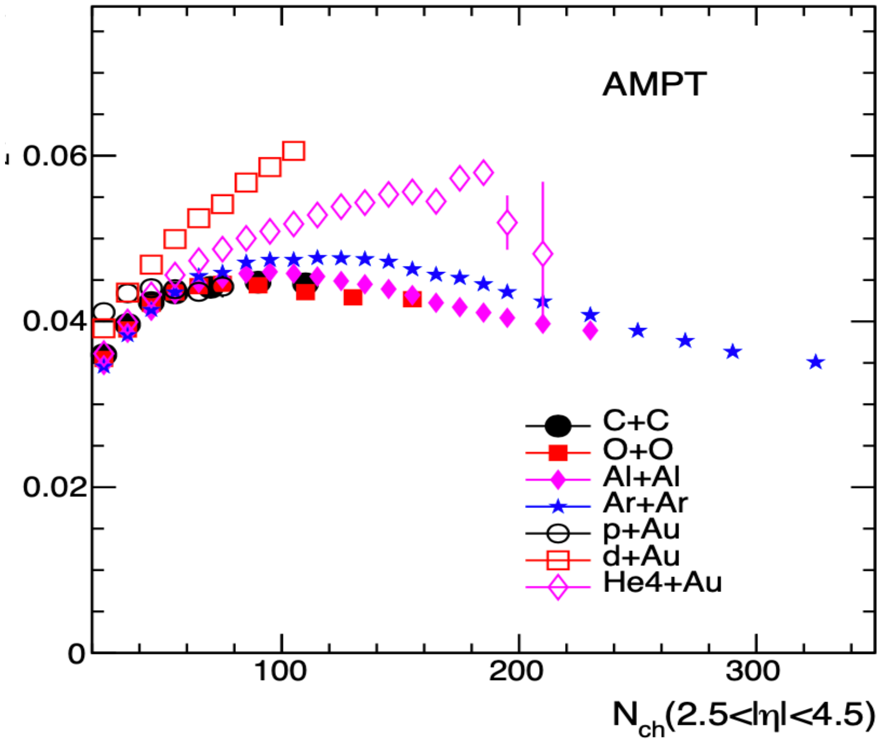
Sub-nucleon fluctuation or pre-flow?

Can we do the geometry scan in small system?

Symmetric and Asymmetric Systems: A True Geometry Scan

S.Huang , Z. Chen, J. Jia, W. Li: PhysRevC.101.021901x





Different multiplicity dependent $\boldsymbol{\varepsilon}_n$

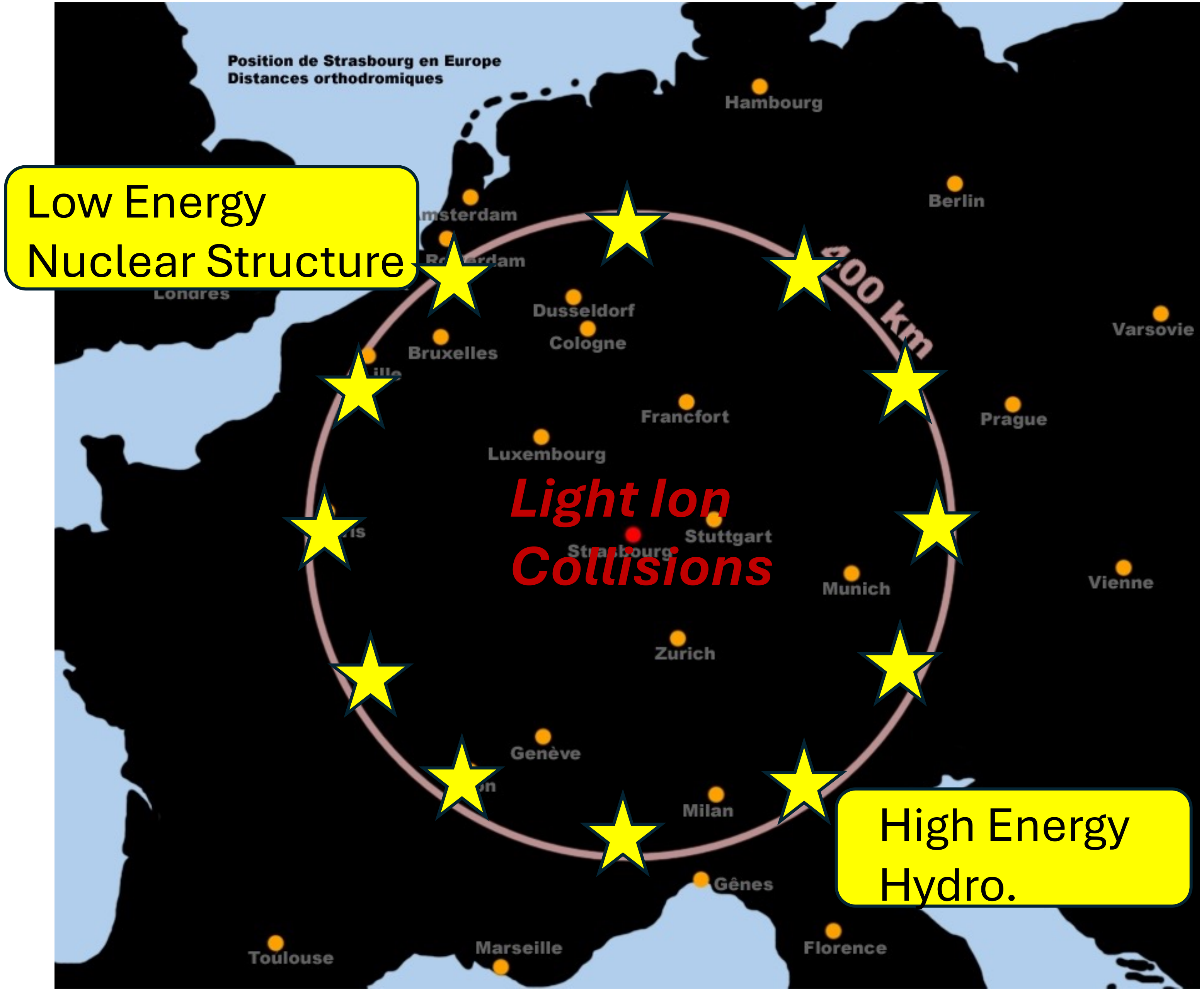
O+O: nuclei shape + (sub-)nucleon fluctuation

^{3}He/d+Au: (sub-)nucleon fluctuation

AMPT: Different flow behaviors between symmetric and asymmetric systems

Comparison v_2 between symmetric and asymmetric systems will provide direct information to study final state contribution

Light Ion Collisions



Effective Field Theory of low energy QCD

AFDMC(VMC) model: Auxiliary Field Diffusion MC

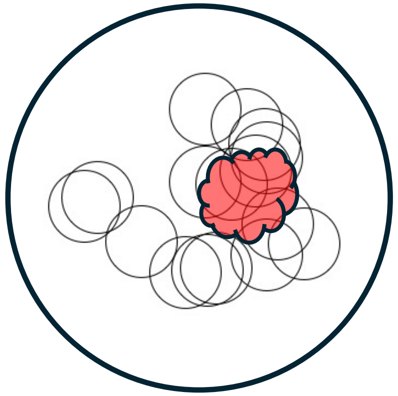
NLEFT model: Nuclear Lattice Effective Field Theory

Two types of *ab initio* EFT models with different choice of the nuclear Hamiltonian and a numerical method to solve the Schrödinger equation

Two types of 3PF fitting to the one body distribution from VMC and NLEFT

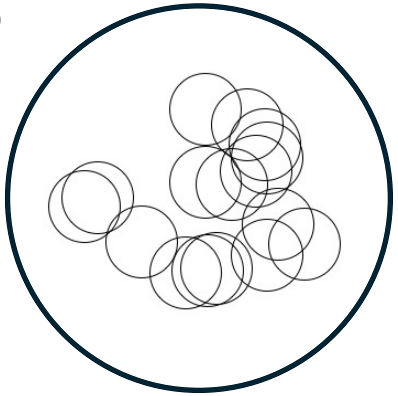
AFDMC/NLEFT:with many-body correlation

^{16}O

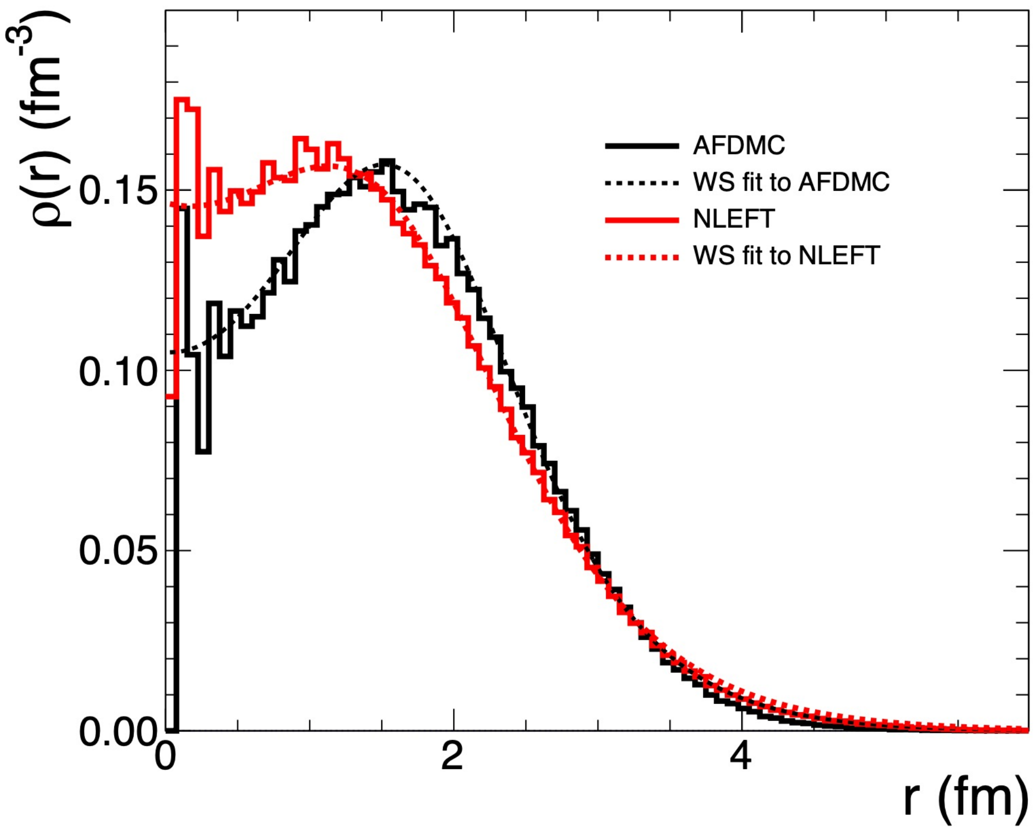


3PF fit: without many-body correlation

^{16}O



One-body distribution



NLEFT: Lu *et al.*, PLB **797** (2019) 134863

AFDMC:Lonardoni et al., PRC **97** (2018) 4, 044318

Eccentricity Fluctuation in $^{16}O+^{16}O$

Eccentricity Fluctuation: $\sigma^2 = <\varepsilon_n^2> - <\varepsilon_n>^2$

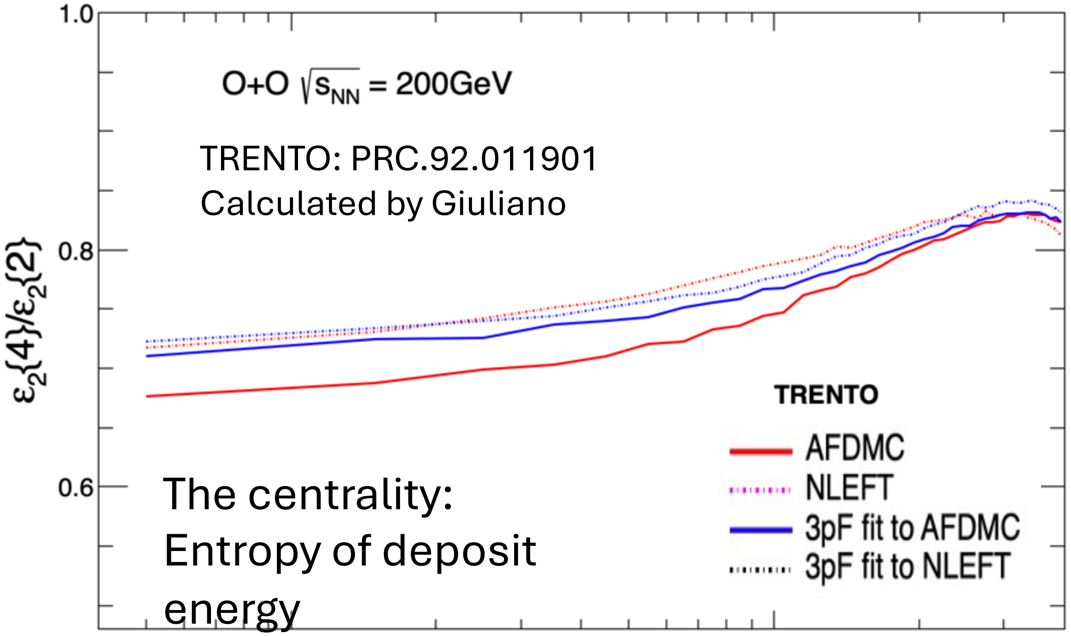
$$(\varepsilon_n\{2\})^2 = <\varepsilon_n^2> = <\varepsilon_n>^2 + \sigma^2$$

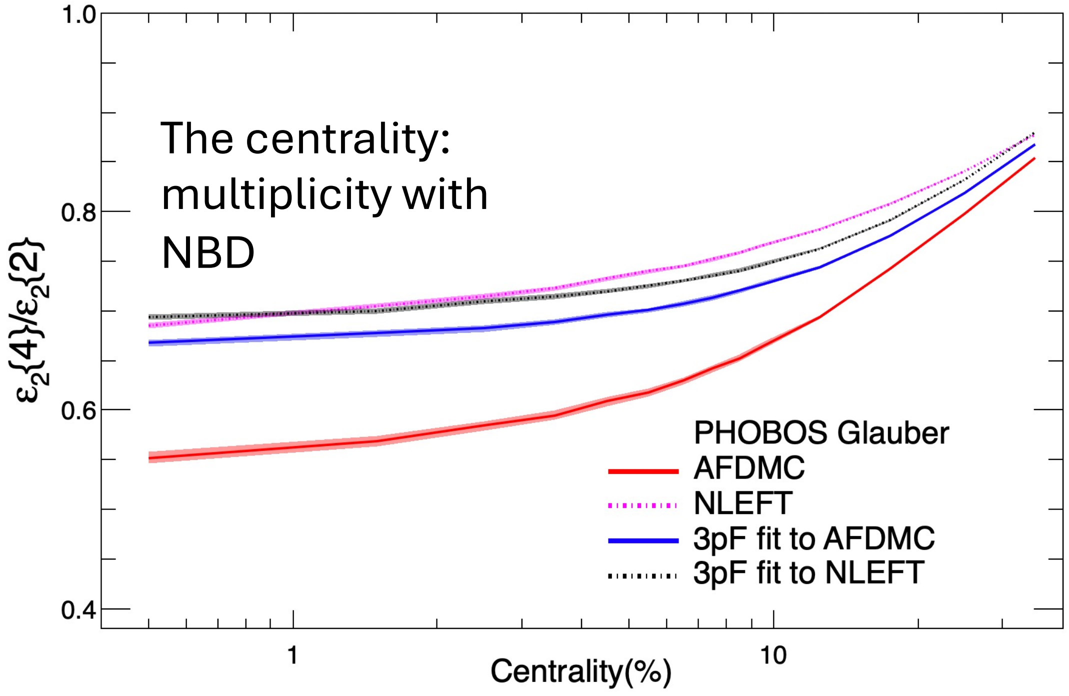
$$(\varepsilon_n\{4\})^2 = \sqrt{2<\varepsilon_n^2>^2 - <\varepsilon_n^4>} \approx <\varepsilon_n>^2 - \sigma^2$$

nucl-th/0607009

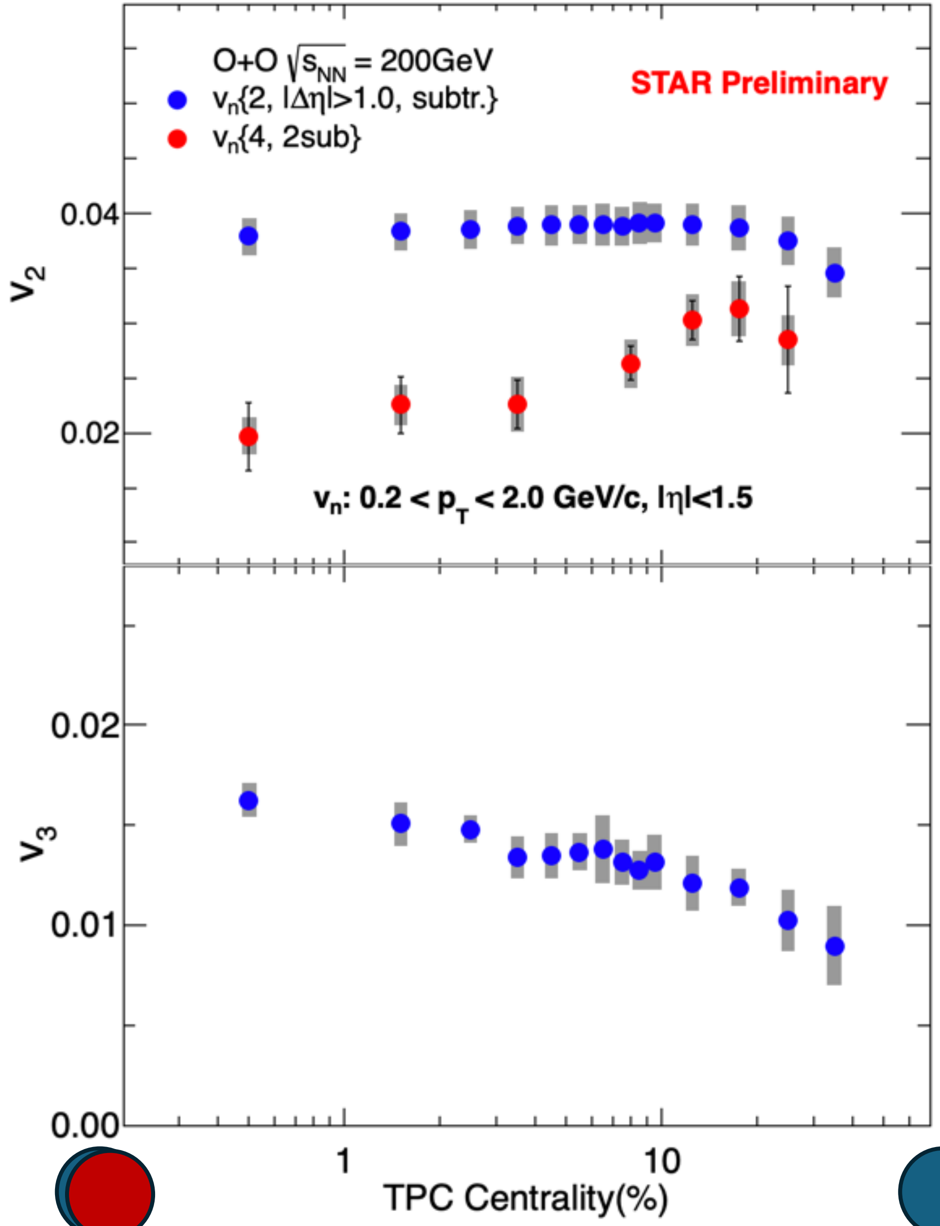
Eccentricity fluctuation from two types of 3PF are similar in both TRENTO and PHOBOS Glauber

Stronger eccentricity fluctuations from NLEFT than that of AFDMC in PHOBOS Glauber





Four-particle cumulant in O+O



In central collisions:

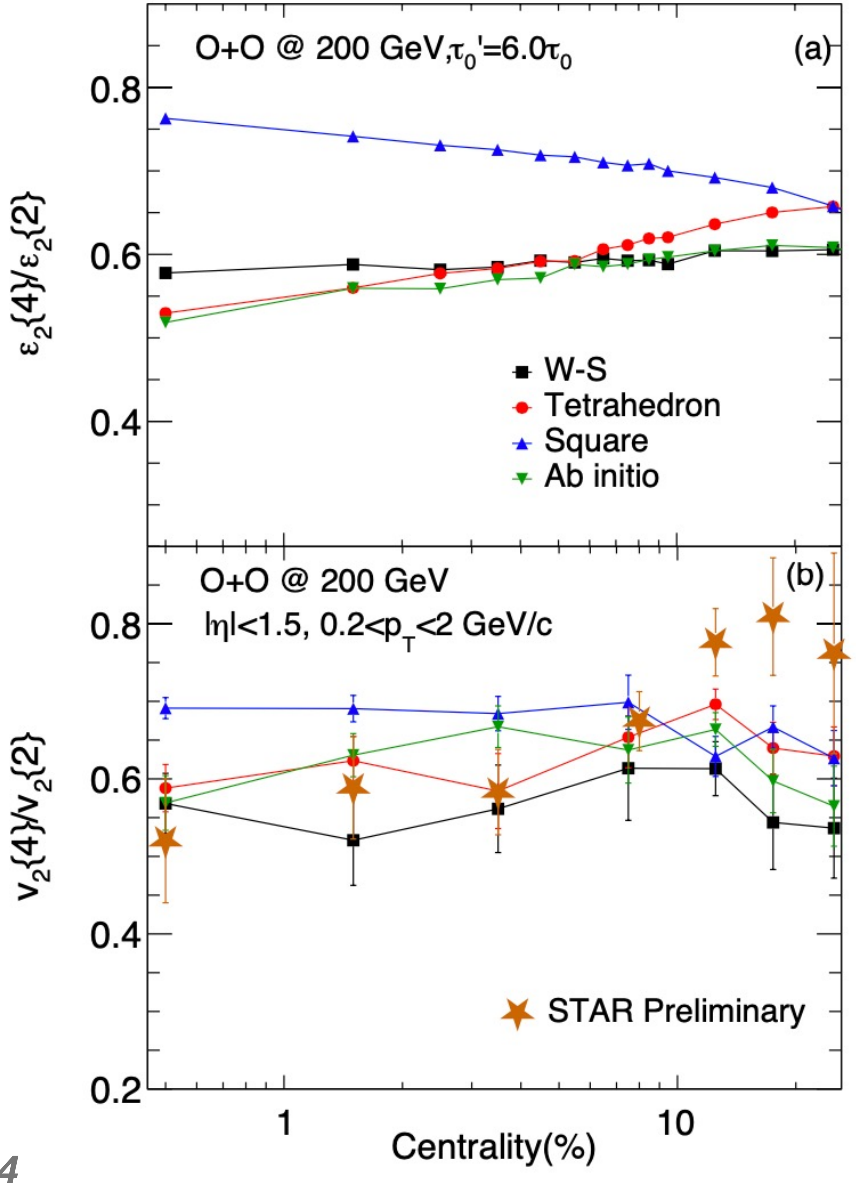
The $v_2\{2\}$ is nearly flat

The $v_3\{2\}$ increases slightly

However, $v_2\{4\}$ clearly decreases

arXiv:2404.09780

AMPT in O+O

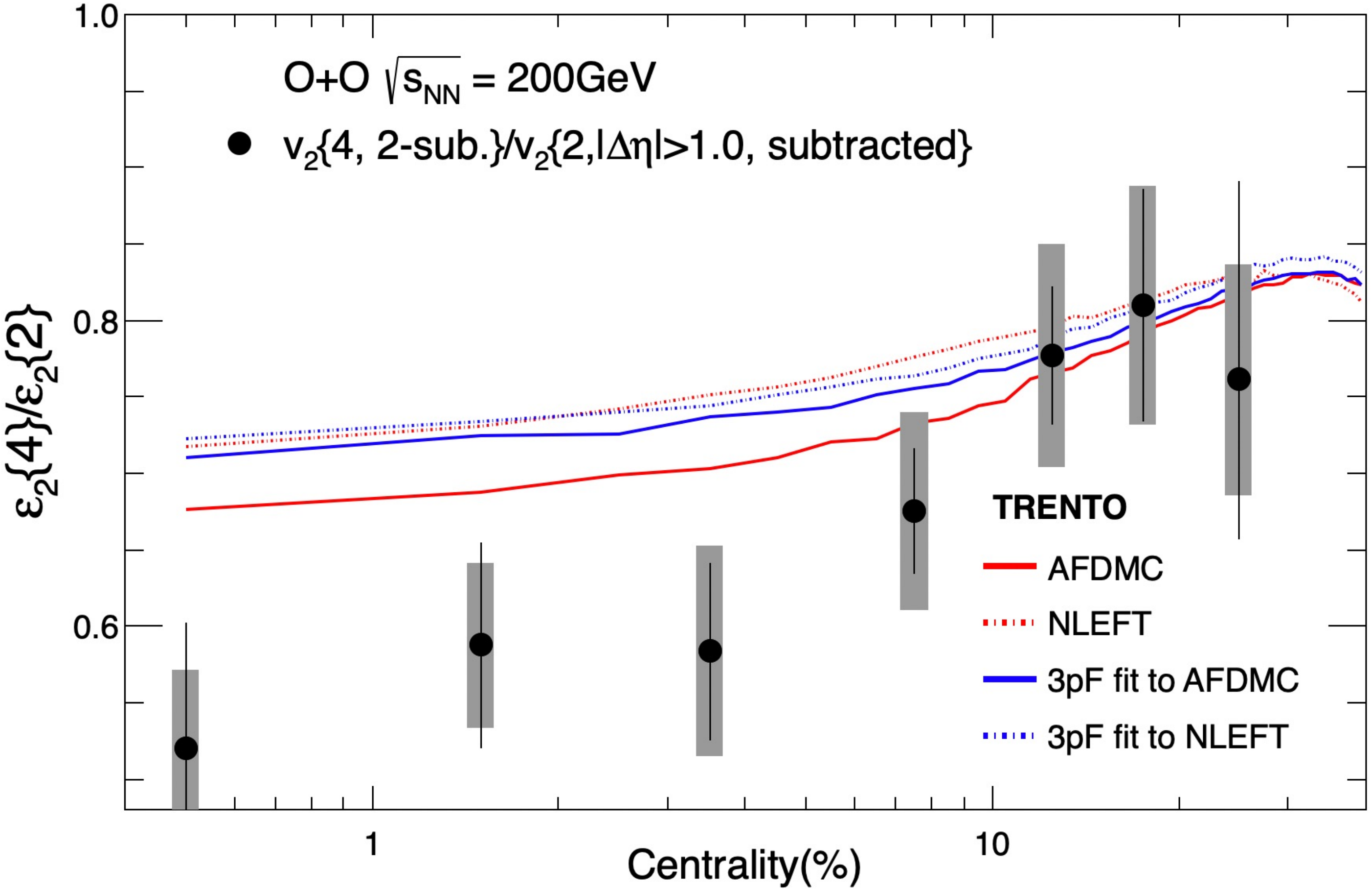


- $v_2\{4\}/v_2\{2\}$ from data shows a strong centrality dependence while it is almost flat from AMPT

- $\boldsymbol{\varepsilon}_2\{4\}/\boldsymbol{\varepsilon}_2\{2\} \approx v_2\{4\}/v_2\{2\}$ from AMPT.

Final state effect has been largely canceled?

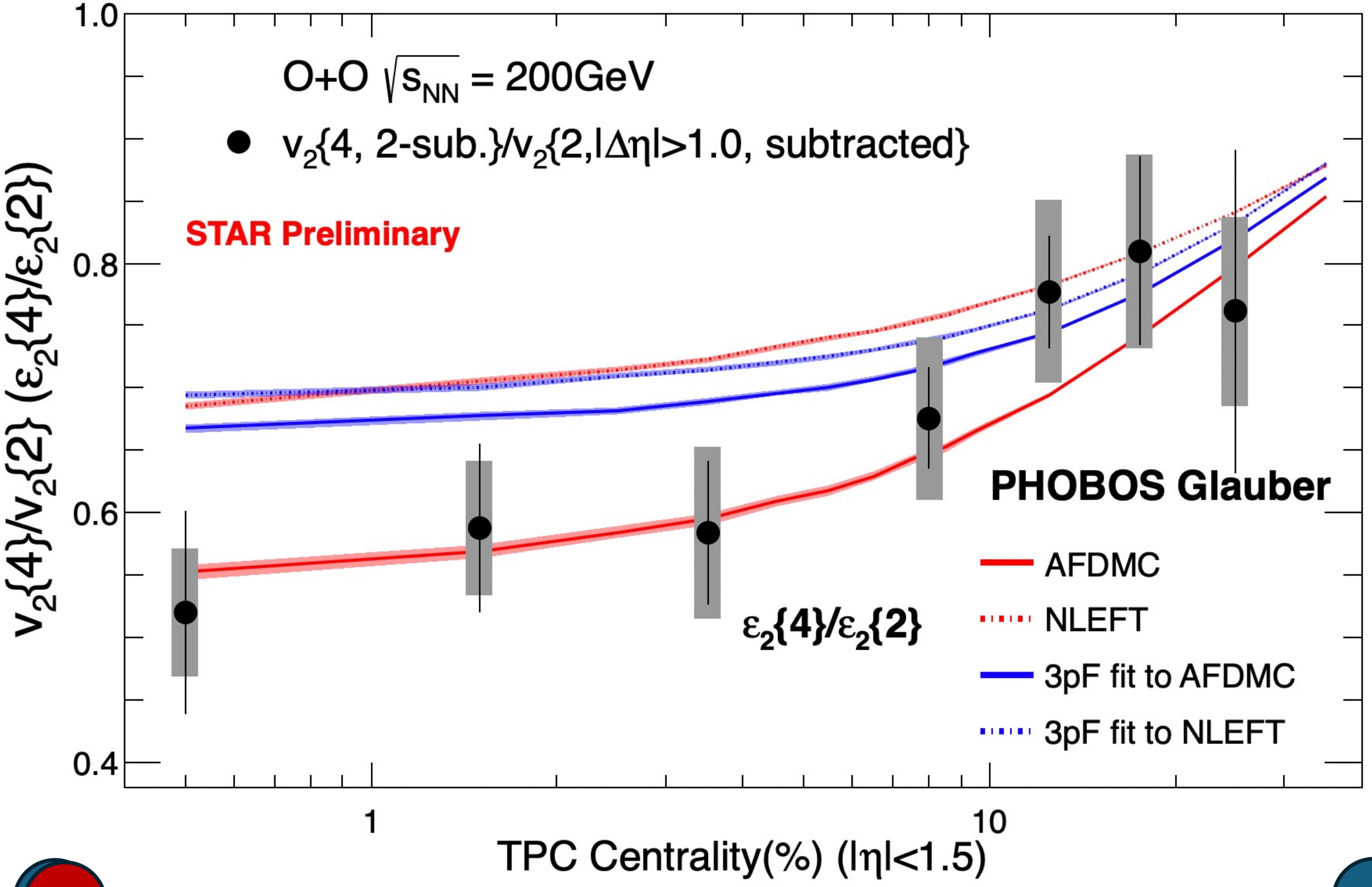
$v_2\{4\}/v_2\{2\}$ vs. TRENTO Model

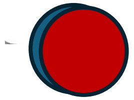


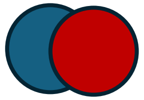
TRENTO:
PRC.92.011901(2015)
Calculated by Giuliano

- $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from TRENTO with NLEFT, AFDMC and 3PF are similar.
- Larger than $v_2\{4\}/v_2\{2\}$.

$v_2\{4\}/v_2\{2\}$ vs. PHOBOS Glauber





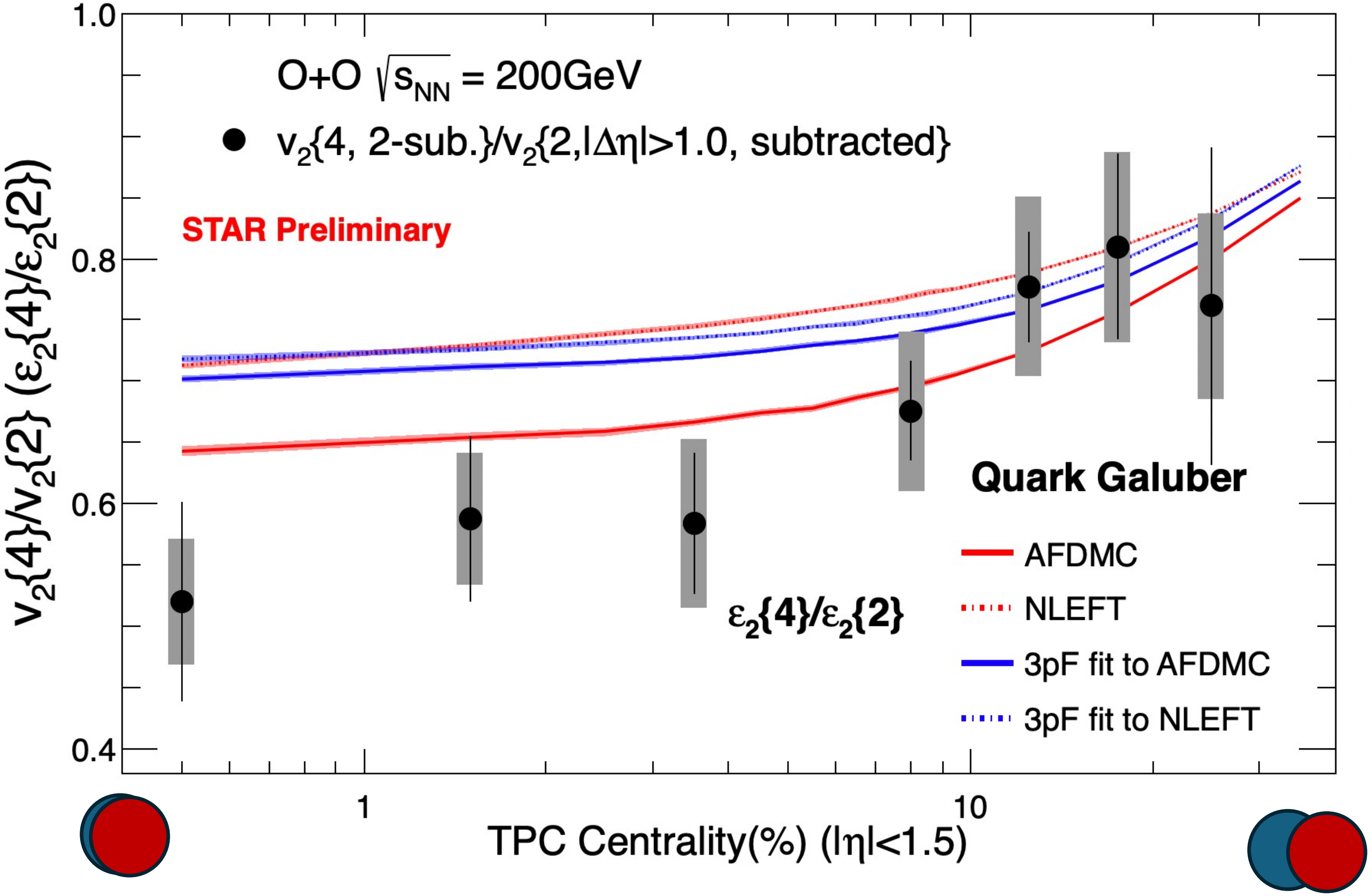


PHOBOS Glauber:
arXiv:0805.4411

$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from AFDMC model in PHOBOS Glauber are much close to $v_2\{4\}/v_2\{2\}$

➔ many-nucleon correlation (e.g. α cluster) enhances the flow fluctuation?

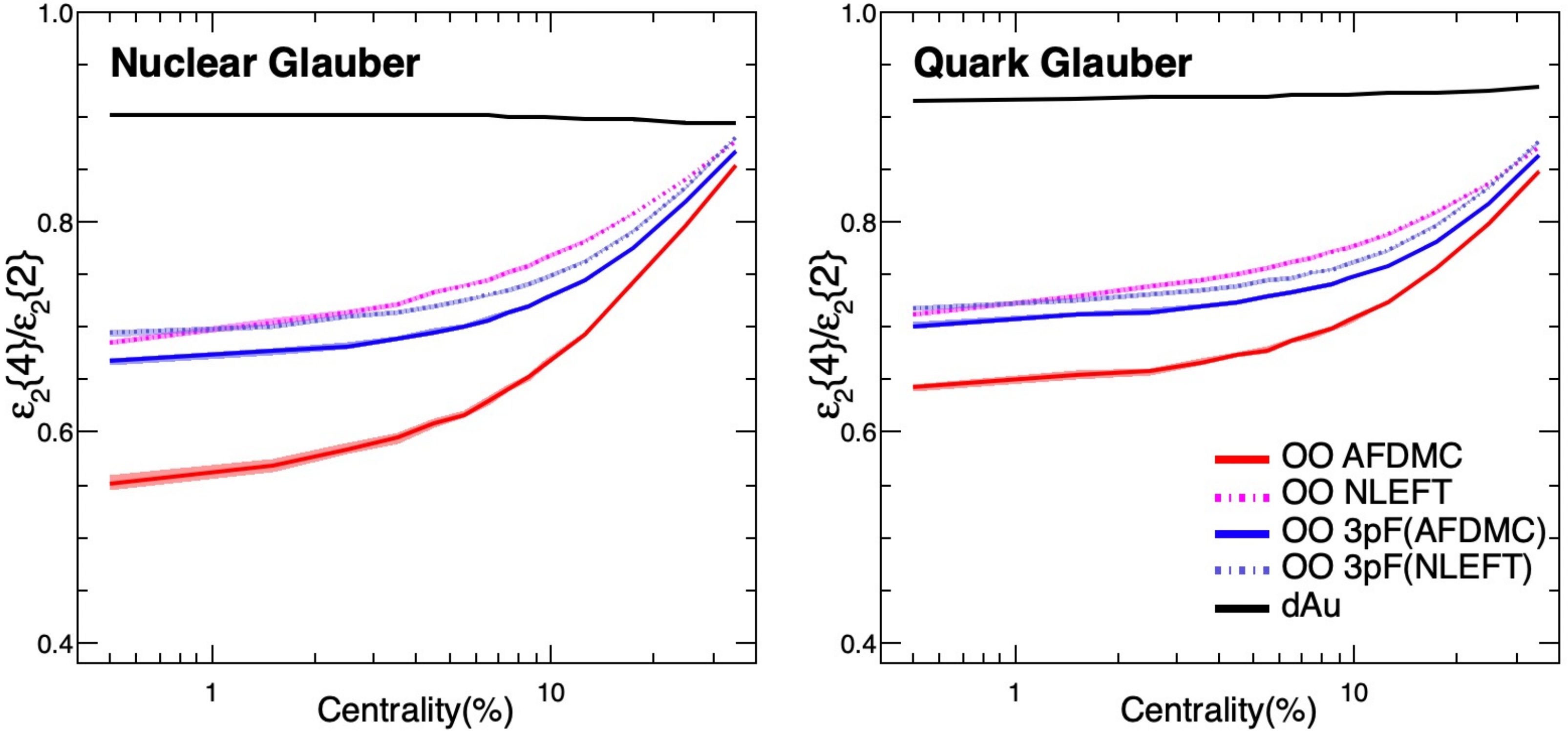
$v_2\{4\}/v_2\{2\}$ vs. Quark Glauber



Quark Glauber:
PRC **94**, 024914 (2016)

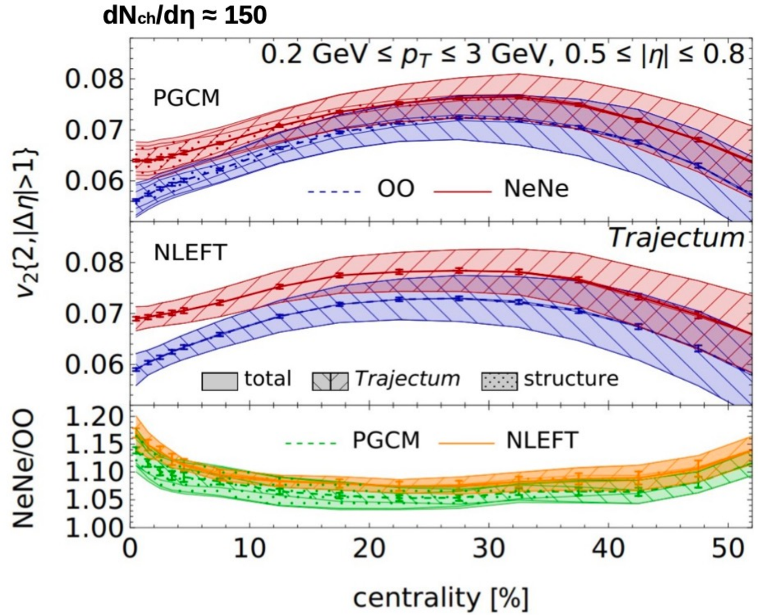
- ✓ $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from quark Glauber over-predicts the $v_2\{4\}/v_2\{2\}$
- ✓ Many-nucleon correlation is diluted by sub-nucleon fluctuation?

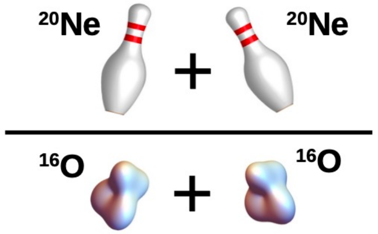
Outlook: $v_2\{4\}/v_2\{2\}$ in small system



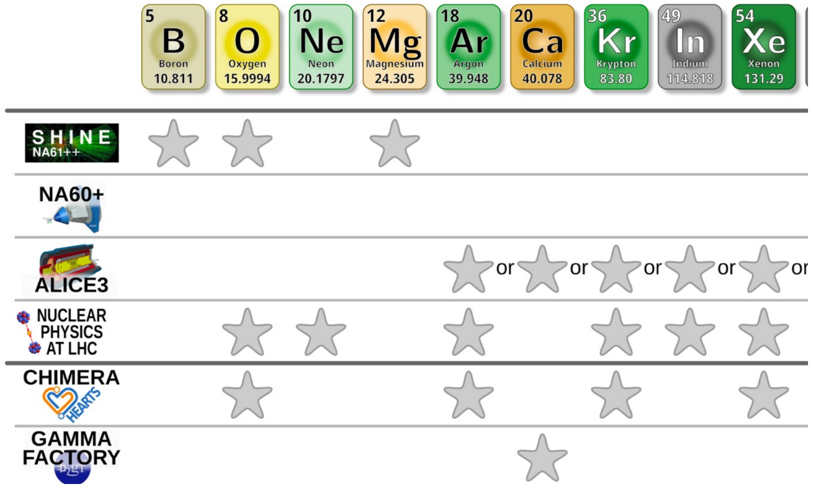
- The ratio $\boldsymbol{\varepsilon}_2\{4\}/\boldsymbol{\varepsilon}_2\{2\}$ remains constant as a function of centrality and is insensitive to sub-nuclear fluctuations in d+Au collisions
- Similarly, $v_2\{4\}/v_2\{2\}$ in d+Au collisions will serve as a good reference for understanding the same ratio in O+O collisions.

Future RUN@LHC





Collider mode



SMOG2 fixed target mode: $\sqrt{s_{NN}} = 65 - 110\text{GeV}$

SMOG2 will provide different ions for system scans in fixed-target mode at the LHCb.

Will RHIC run beyond 2025?

Summary of possible gas targets

✌	H	validated for O(100) h/year
~✌	D	as above (not tested yet)
✌	He	
~✌	N	not tested yet, but ok from simulations
☞	O	to be validated, should be possible at least for short runs
✌	Ne	
✌	Ar	
☞	Kr	to be validated, should be possible for short runs at end of data-taking
☞	Xe	to be validated, should be possible for short runs at end of data-taking

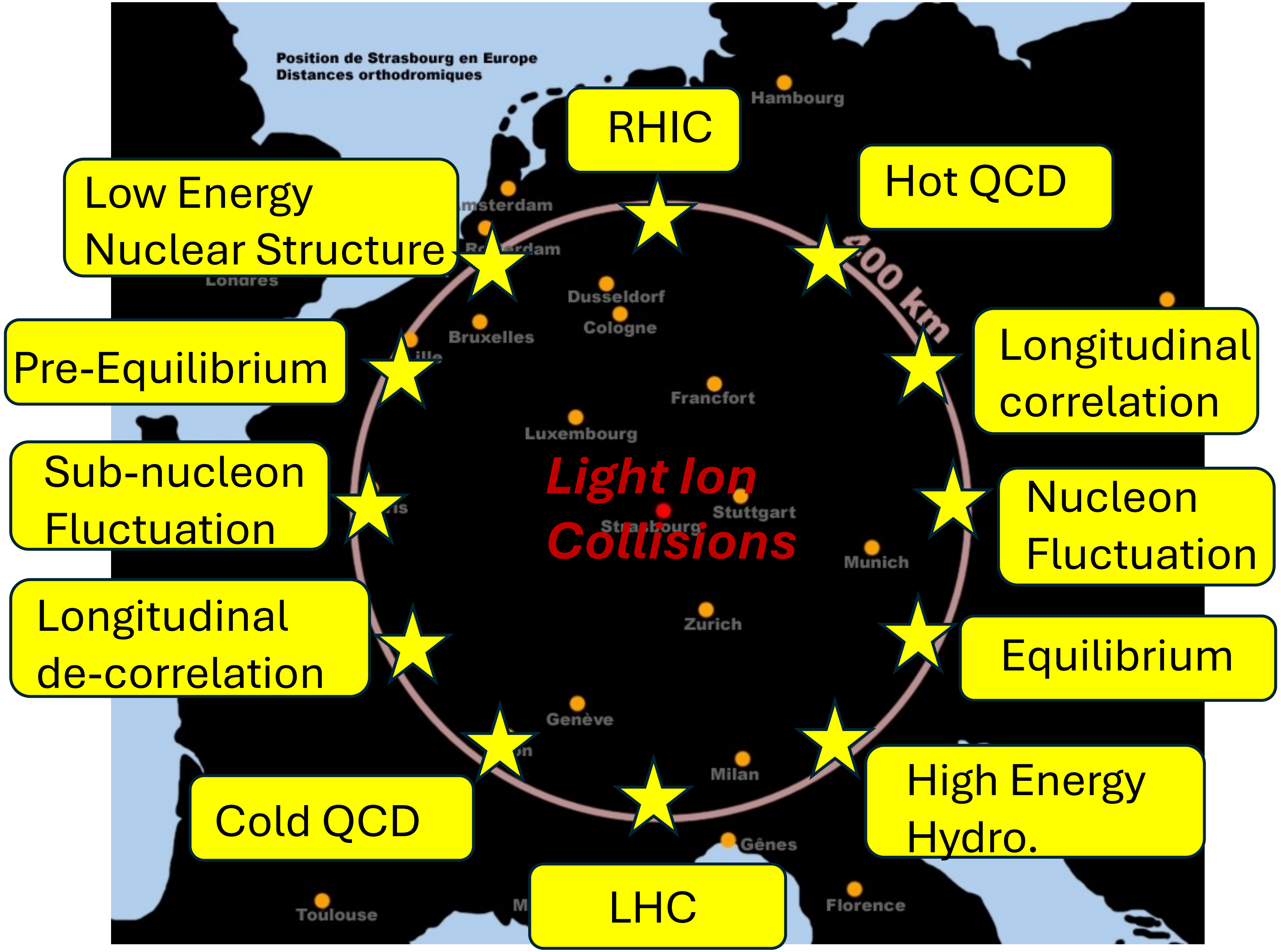
any isotope for approved gas should be ok

Summary

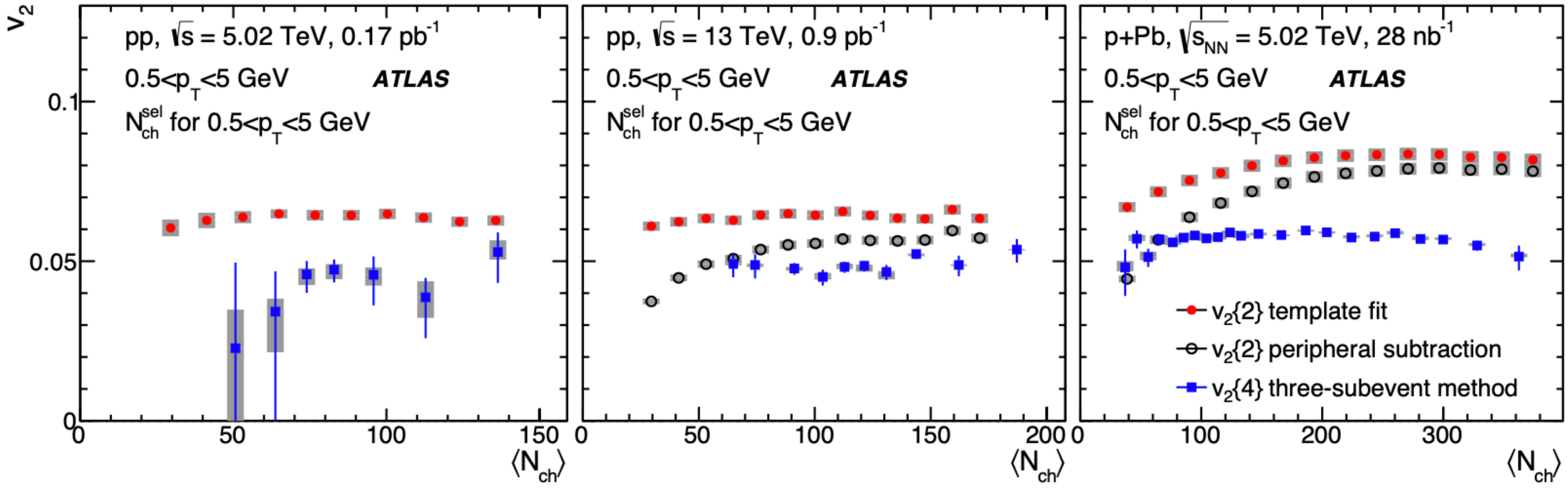
Many interesting measurements has been done in light ion collisions

However, the story is just beginning.

Let us wait for O+O collisions at the LHC in 2025 and for more system scans from RHIC and the LHC



Outlook: $v_2\{4\}/v_2\{2\}$ in small system



- $v_2\{4\}/v_2\{2\}$ show very weak multiplicity and system dependence from pp to p+Pb

- Will it help to find the relation between $v_2\{4\}/v_2\{2\}$ and $\boldsymbol{\varepsilon}_2\{4\}/\boldsymbol{\varepsilon}_2\{2\}$?