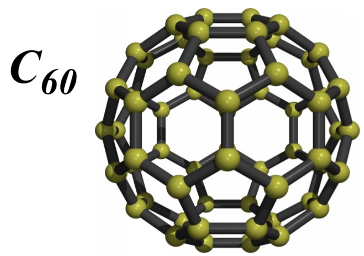
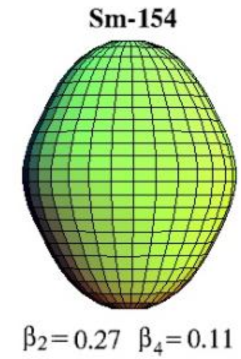
Influence of Vibration and Deformation of Nuclei ON the ELLIPTIC FLOW

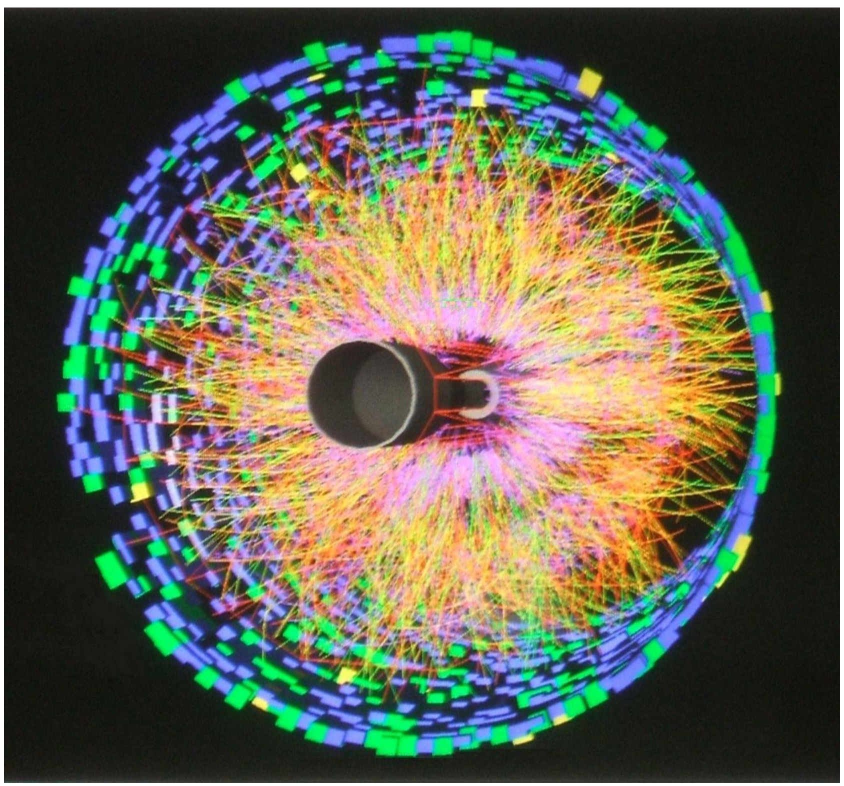




Peter Filip

(IP SAS, Bratislava)

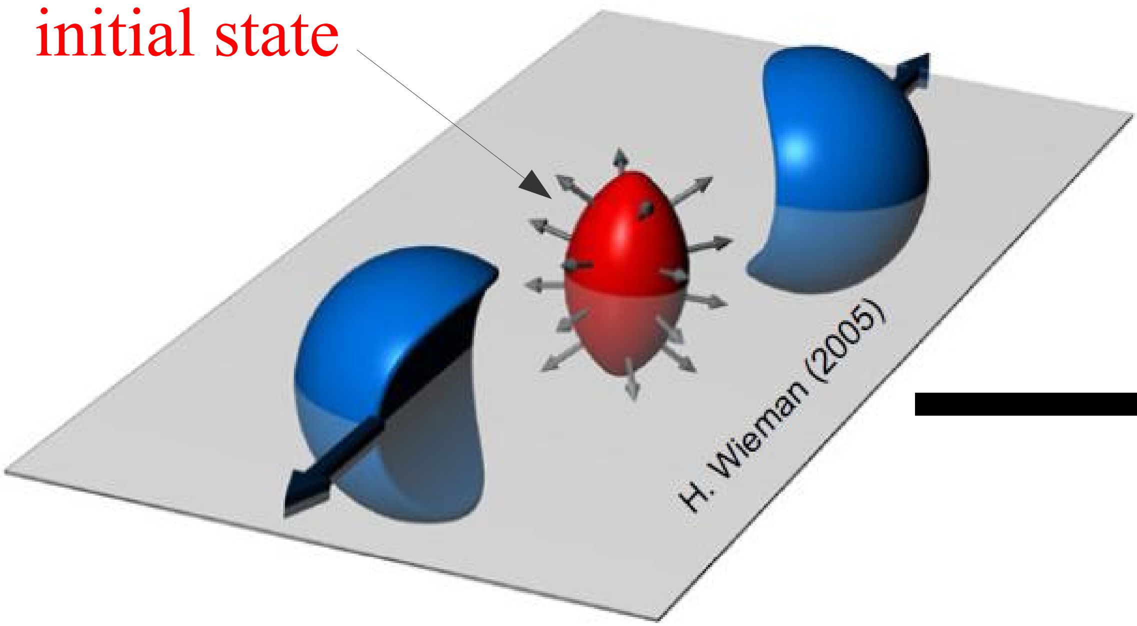
XXI Baldin Seminar, 10-15. Sept. Dubna 2012

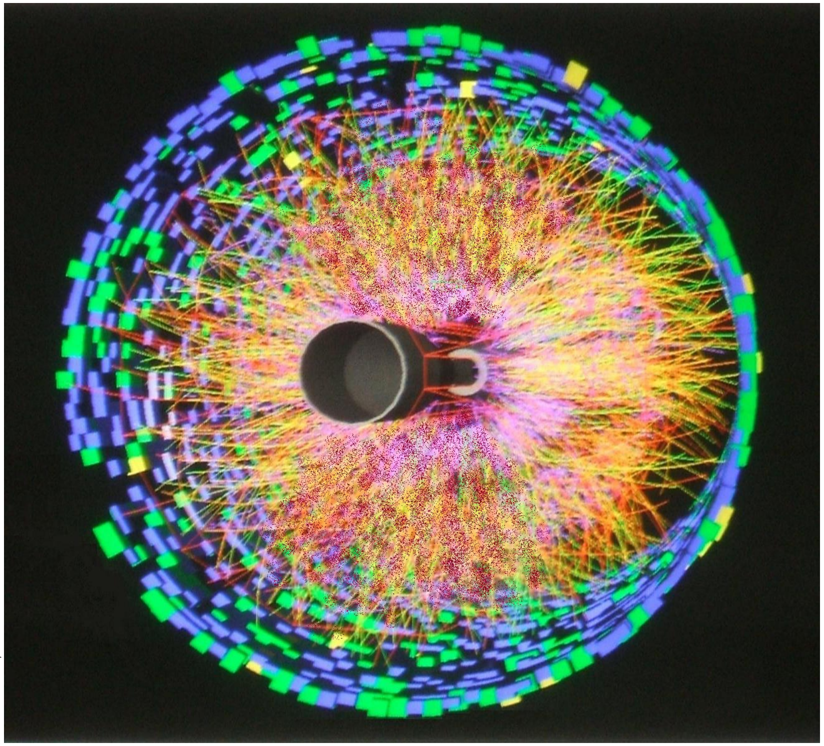


- Elliptic Flow
- Initial eccentricity
- Deformation effects
- GMC simulations
- Vibrations of nuclei
- Summary

Elliptic Flow: v_2

initial state

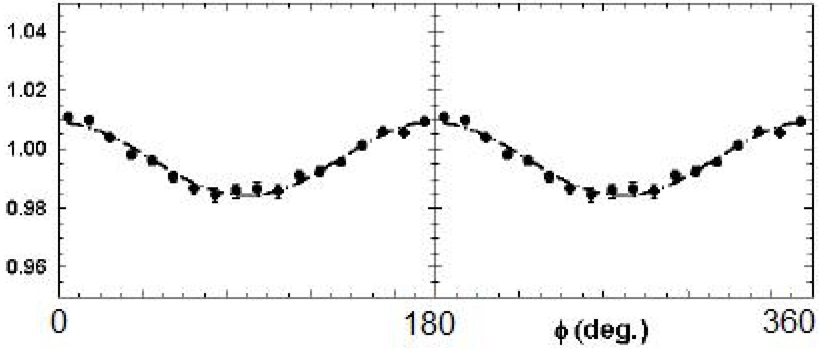




Azimuthal asymmetry

Asymmetry in Spatial distribution leads to

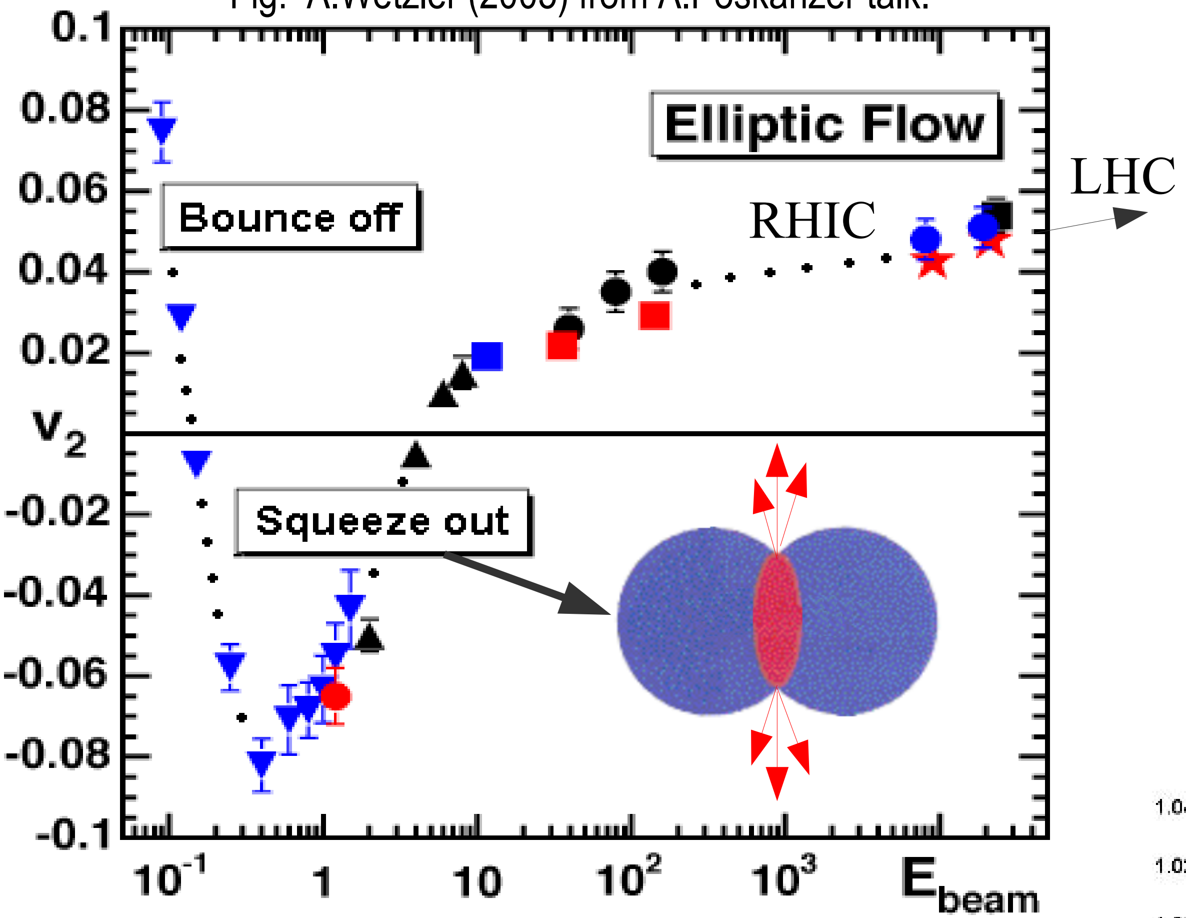
→ asymmetry in **Momentum** distribution

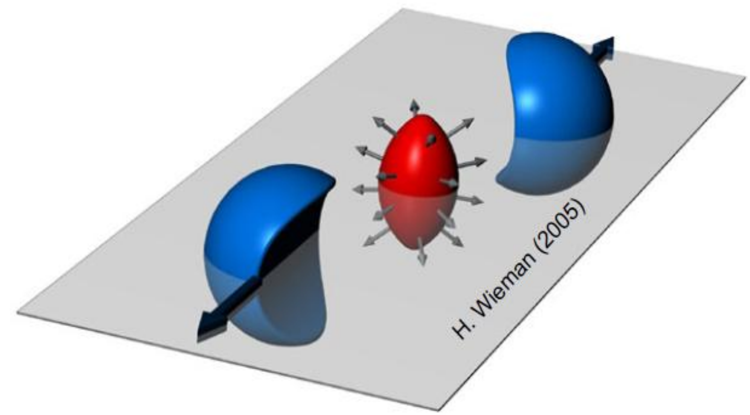


Asymmetry Effect depends on the COLLISION ENERGY

Elliptic Flow: v_2 energy dependence

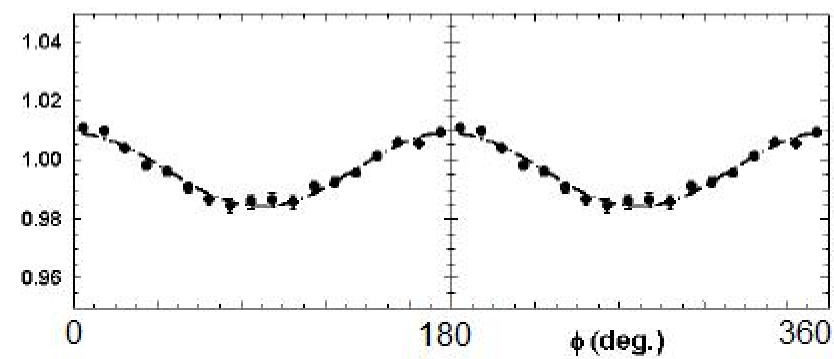
Fig: A.Wetzler (2005) from A.Poskanzer talk.





Asymmetry strength: v_2

$$dN/d\phi = (N/2\pi)[1+2v_2 \cos(2\phi)]$$



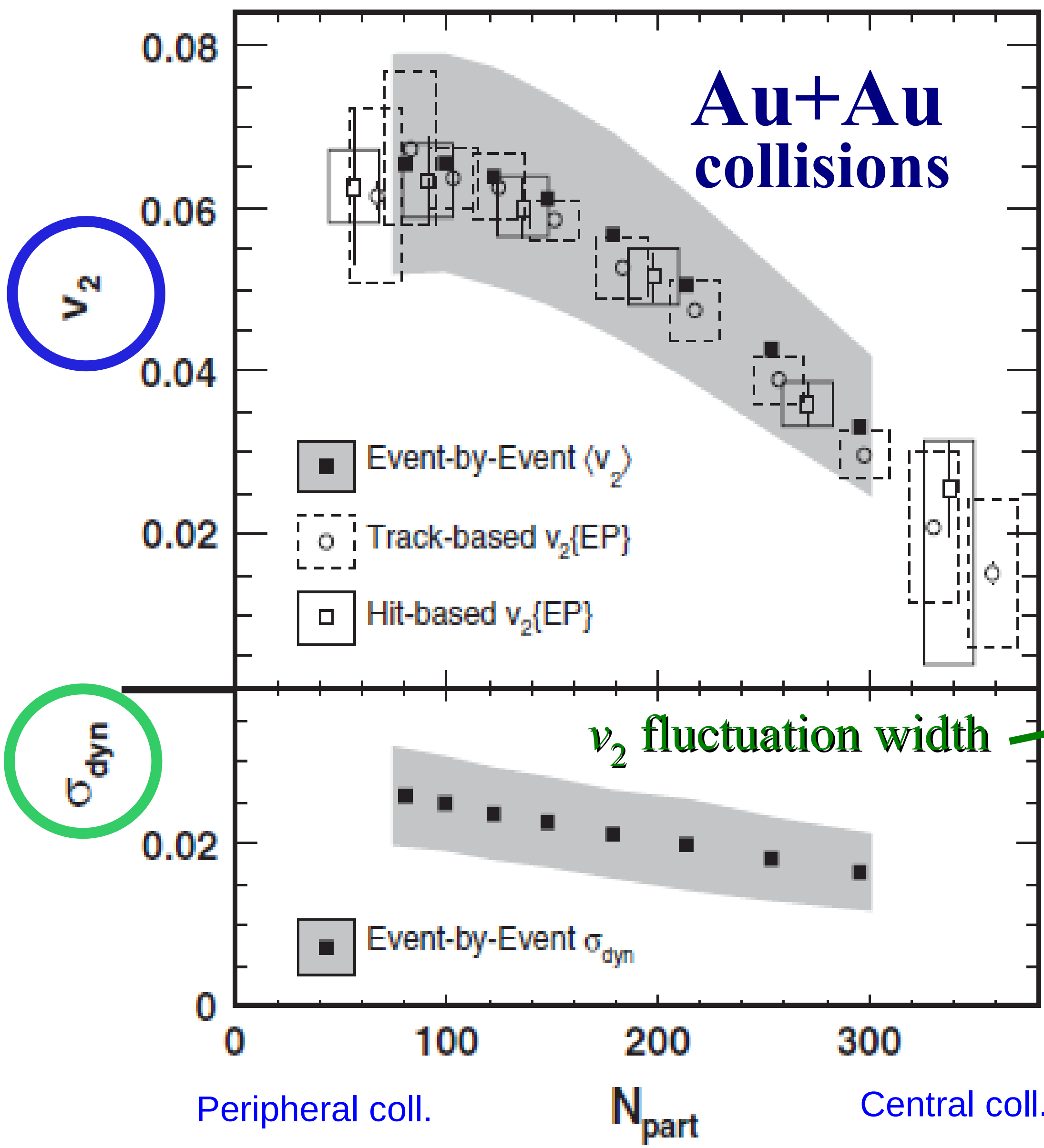
Azimuthal Momentum distribution

v_2: has **strength = magnitude** $\langle v_2 \rangle$

and **fluctuations**: σ_{v_2}

Elliptic flow v_2: magnitude & fluctuations

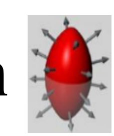
PRL 104, 142301 (2010)



- Magnitude of v_2 decreases
  → for central collisions

- *We believe = assume:*

  v_2 fluctuation

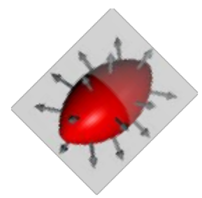
  comes from: the initial **eccentricity fluctuation** 

  (at given N_{ch} or N_{part})

Centrality dependence of initial eccentricitry **ε**:

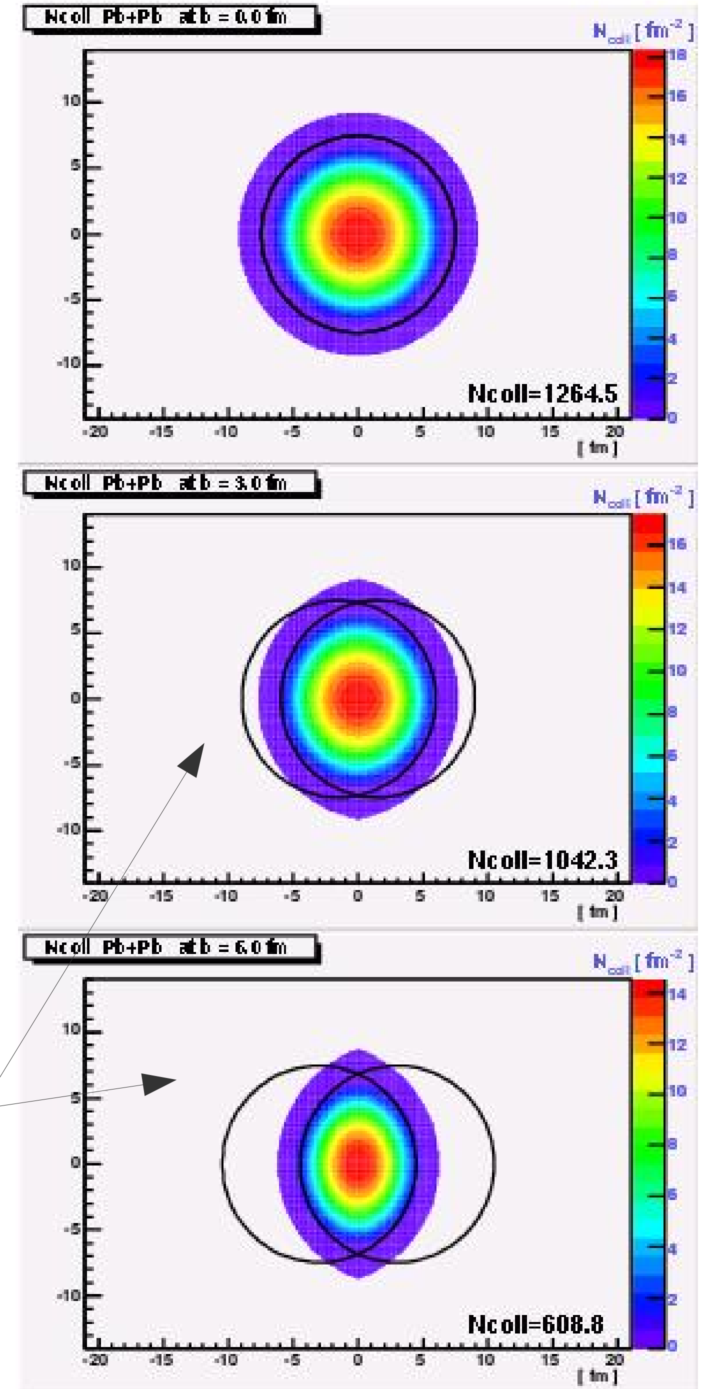
Rotation-ivariant formula

$$\varepsilon = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

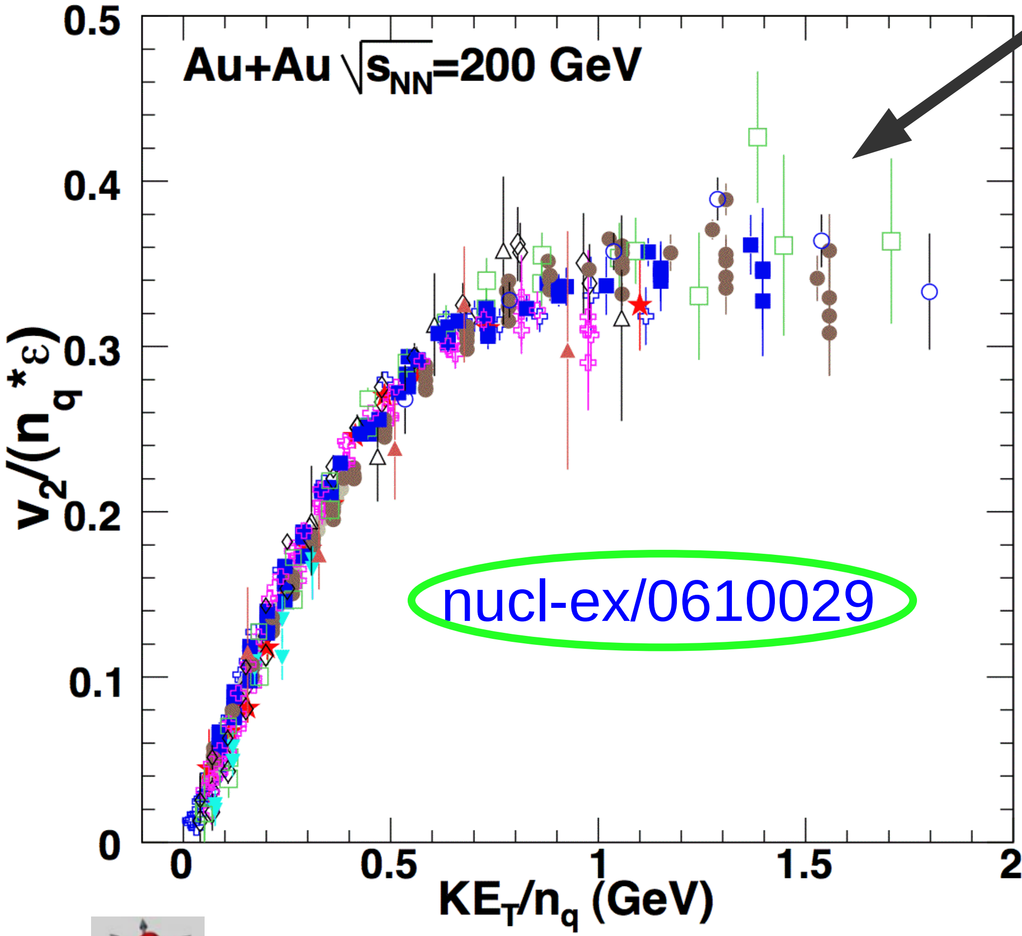


- Eccentricity → Elliptic flow is larger

  for non-central collisions



Elliptic flow at *RHIC*: partonic expansion



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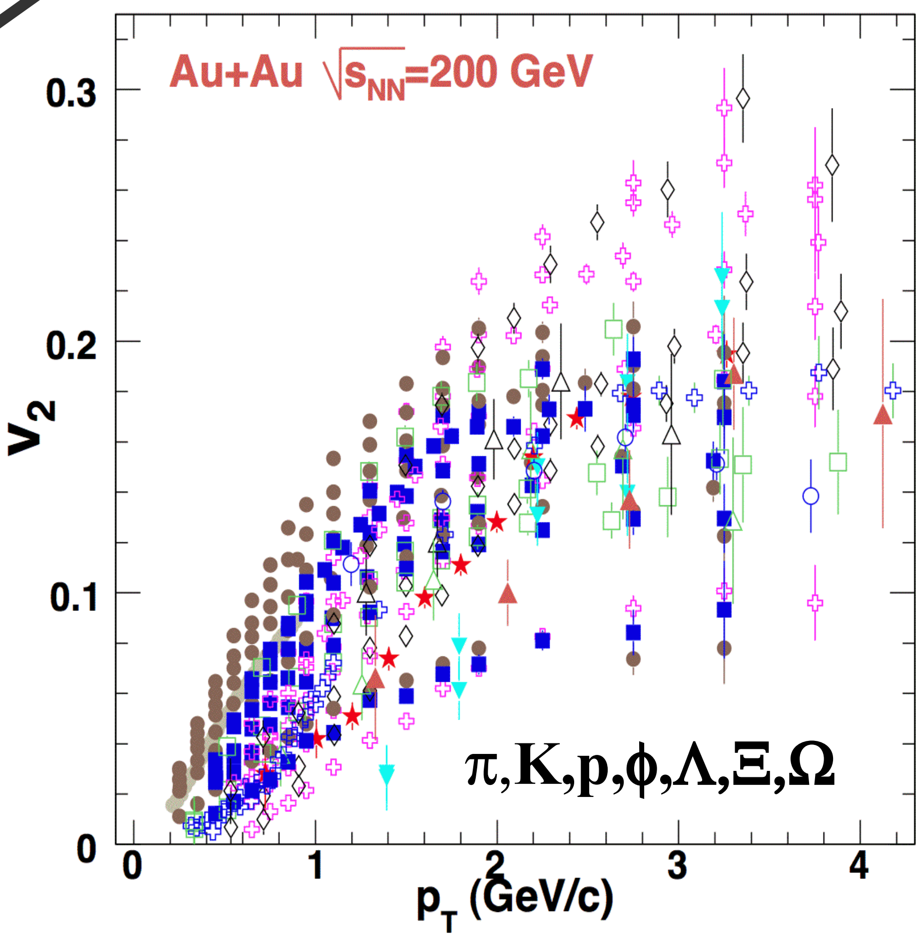
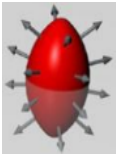




Very nice !

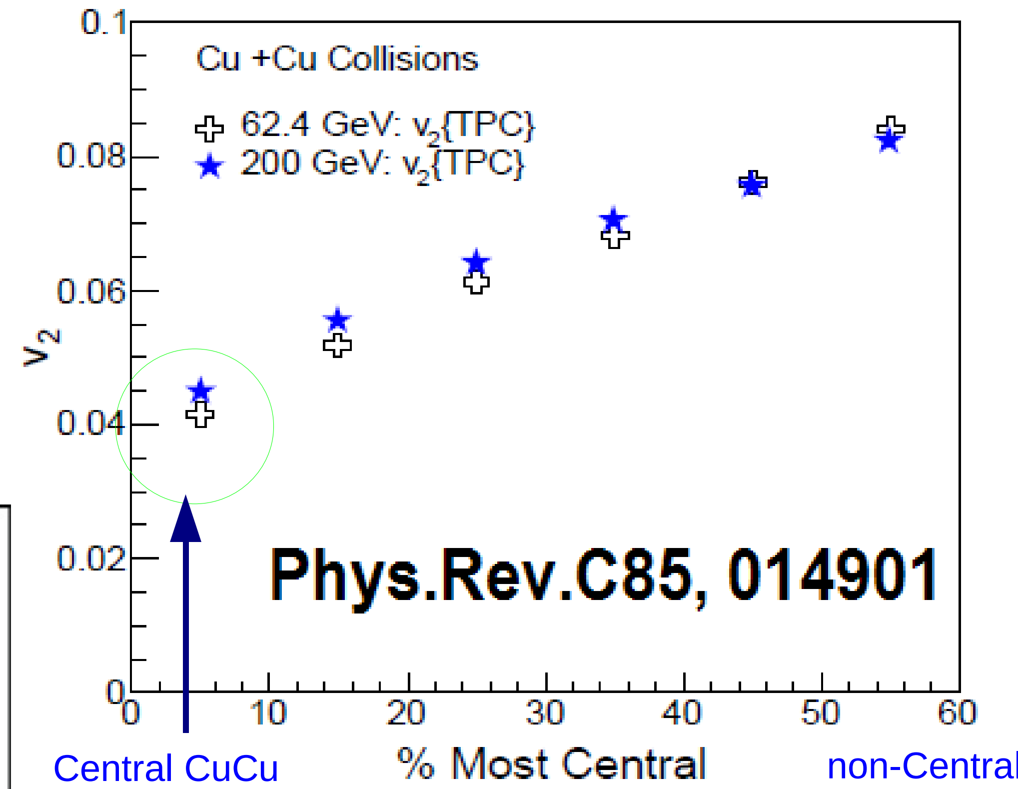
However: Cu+Cu →

Elliptic flow v_2 strength in Cu+Cu

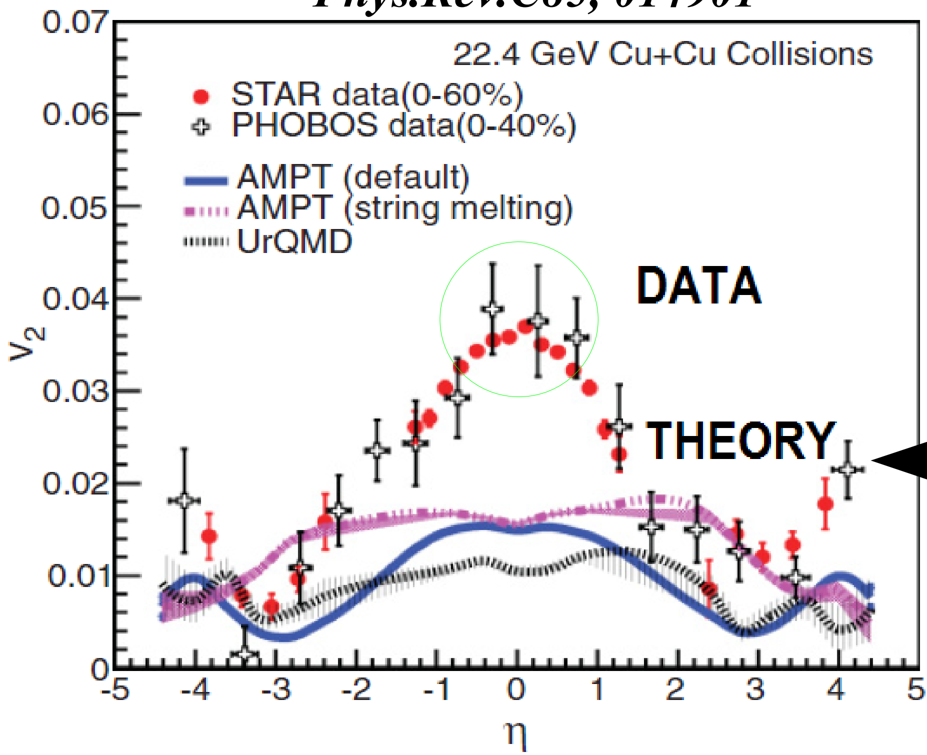
- v_2 strength = $< v_2 >$

  → average v_2 value

  (at given centrality, η)



Phys.Rev.C85, 014901



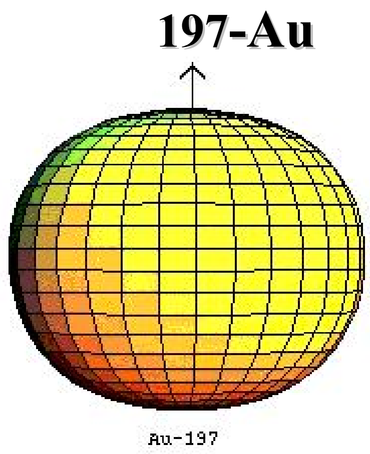
v_2 __strength__ in Cu+Cu

(RHIC at 22.4 GeV/n)

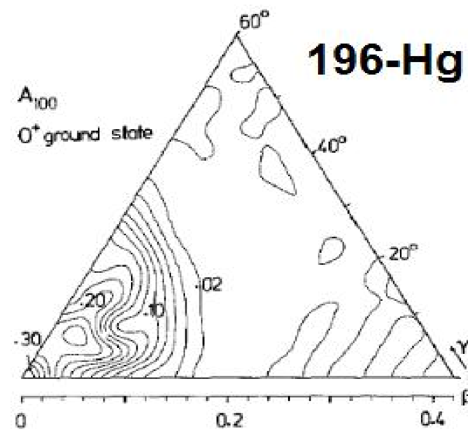
is not understood ...

In this talk

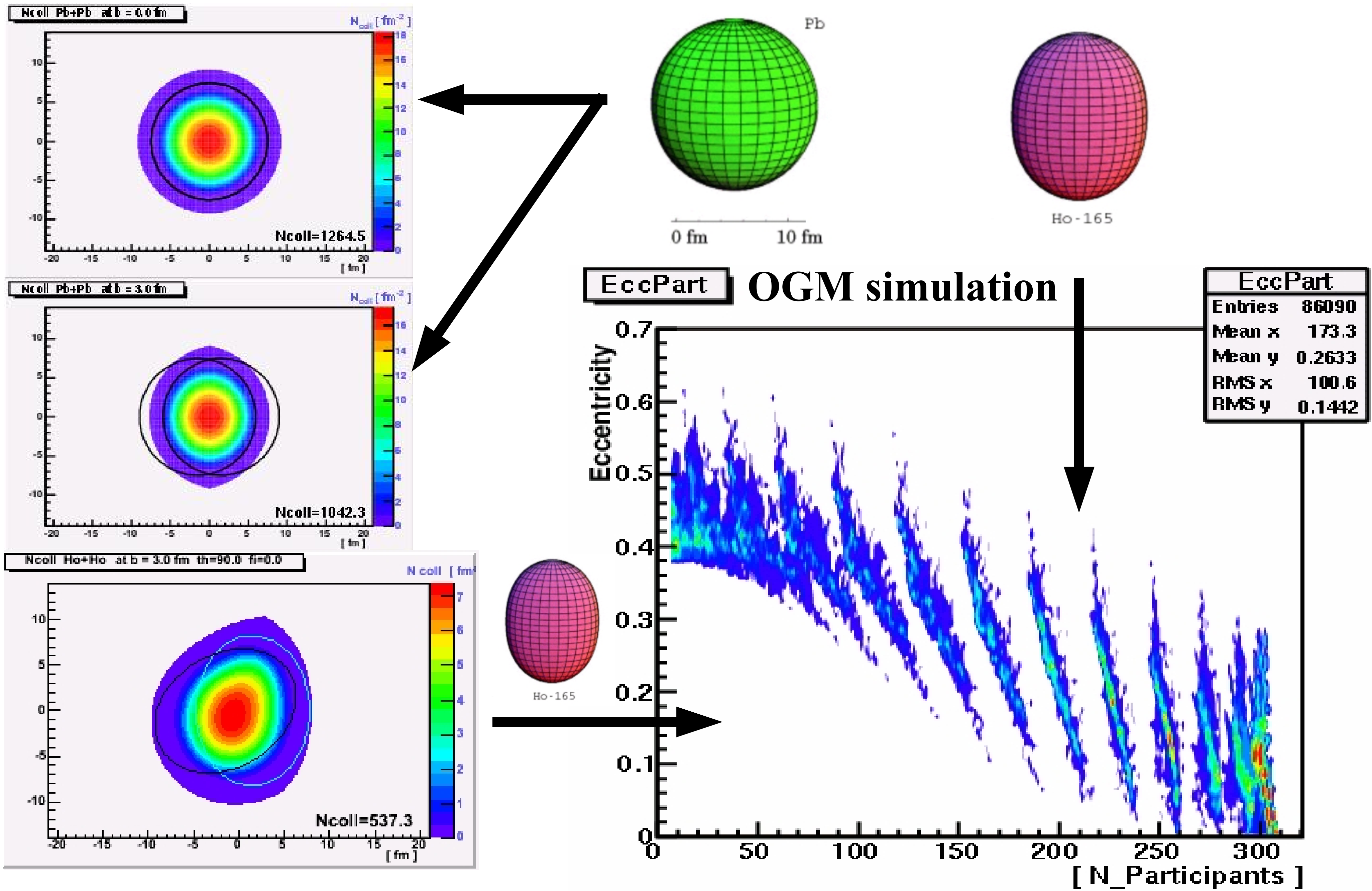
Two initial-state effects:
→ influence Elliptic flow.



- Ground-state **deformation**
- Ground-state **Vibration** **(2012)**

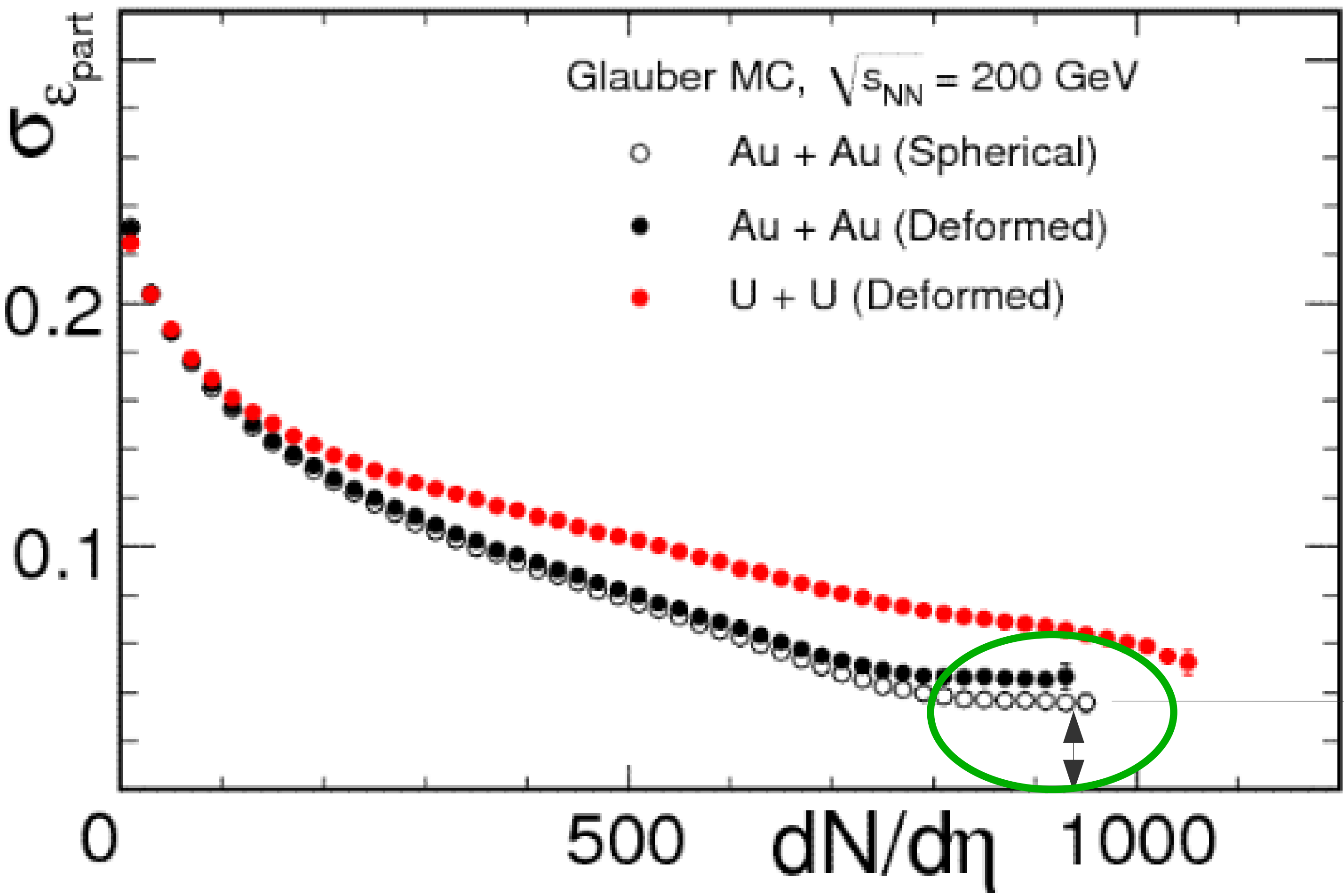


Fluctuating Eccentricity: fixed impact param. [b]



Deformation of nuclei in MC Glauber:

→ **increased** Eccentricity **fluctuations**



$$\sigma_{\varepsilon} = \sqrt{\sigma_{\beta_2}^2 + \tilde{\sigma}_{\varepsilon}^2}$$

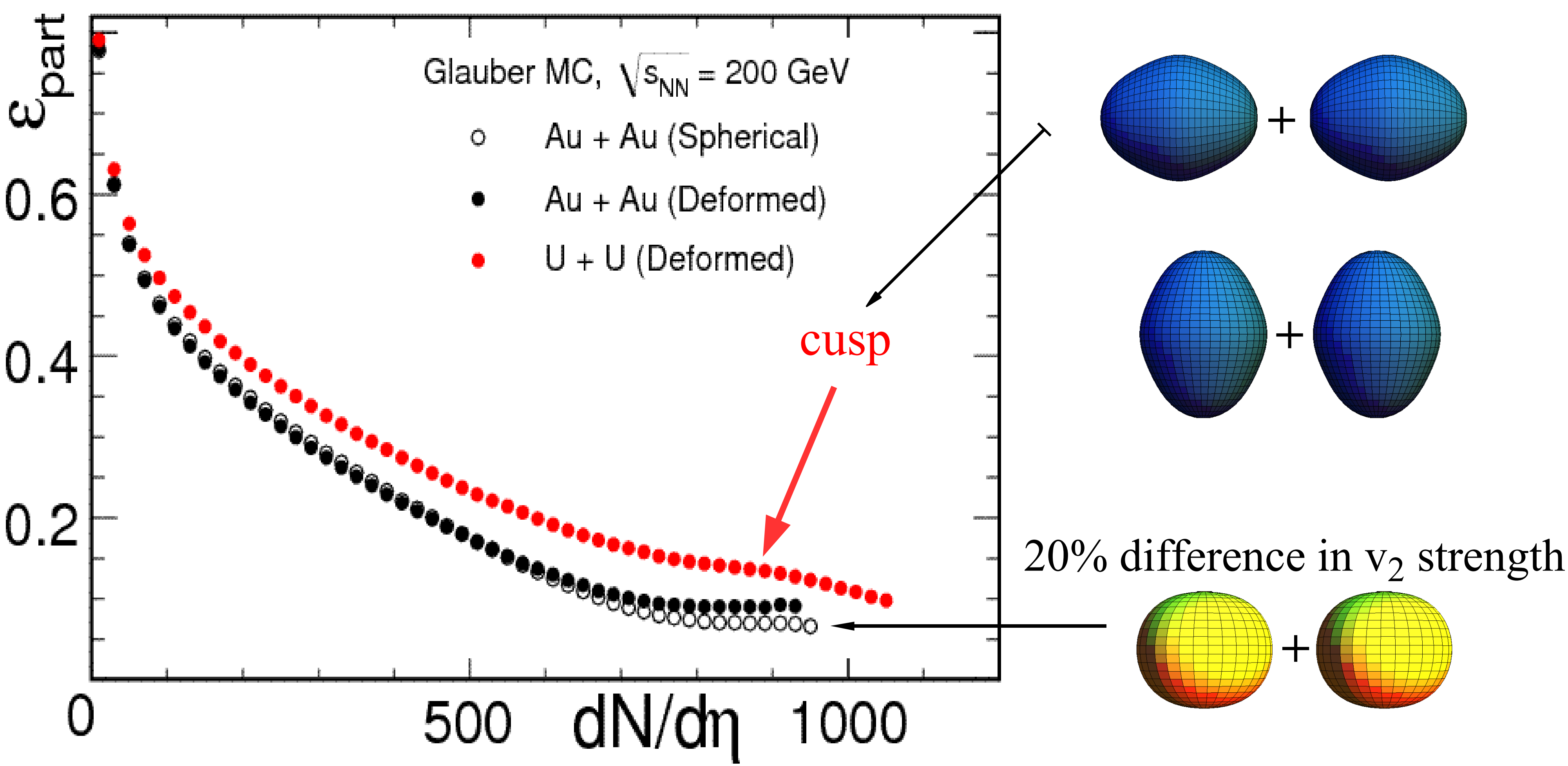
due to deformation

standard fluctuation

Phys.Rev.C80, 054903: Deformation effects on σ_{v_2} (fluctuation of v_2)

Deformation influence on v_2 strength:

→ self-orientation effect in central UU collisions



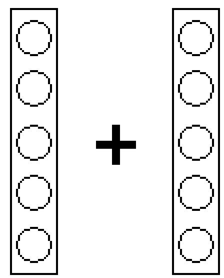
MC Glauber simulation: Phys.Rev.C80, 054903: ε CUSP → v_2 CUSP

Self-orientation effect:

- for very high N_{ch} multiplicity collisions

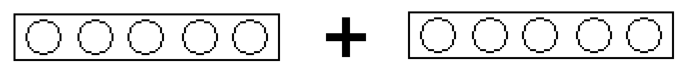
  $\rightarrow$ max. binary NN collisions $\rightarrow N_{ch} \rightarrow$ orientation

extremal case:

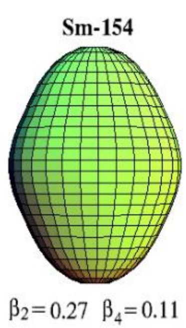


NN coll. = 5
N part. = 10

Binary n-n collisions sensitivity to orientation



NN coll. = 25
N part. = 10

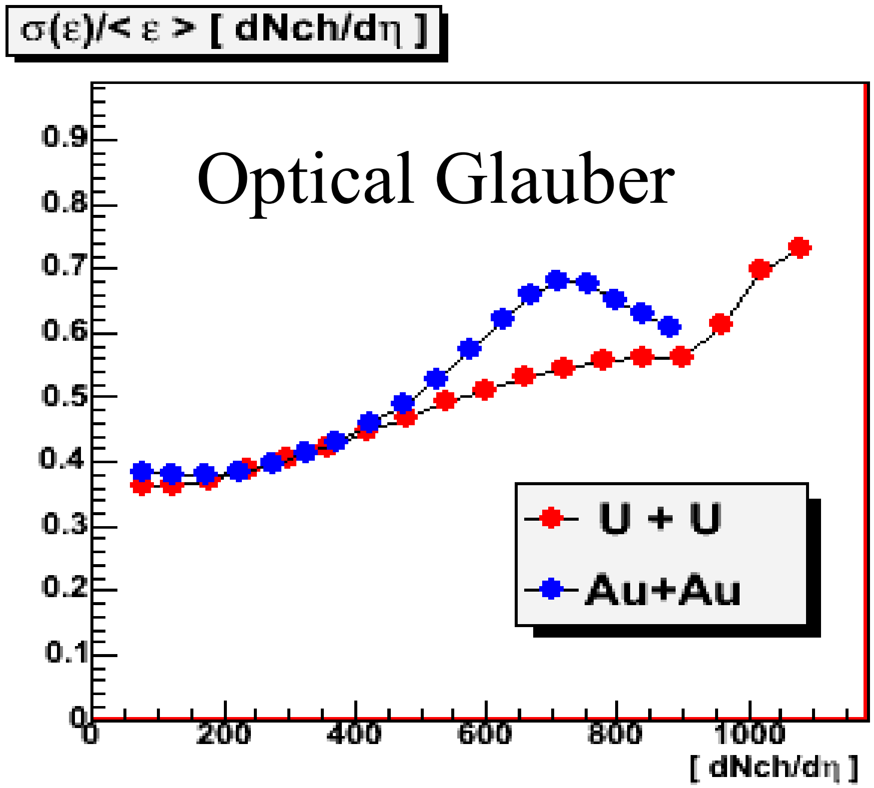


$$dN_{\rm ch}/d\eta = (1-x)\cdot n_{pp}\frac{N_{\rm part}}{2} + x\cdot n_{pp}\,N_{\rm coll}$$

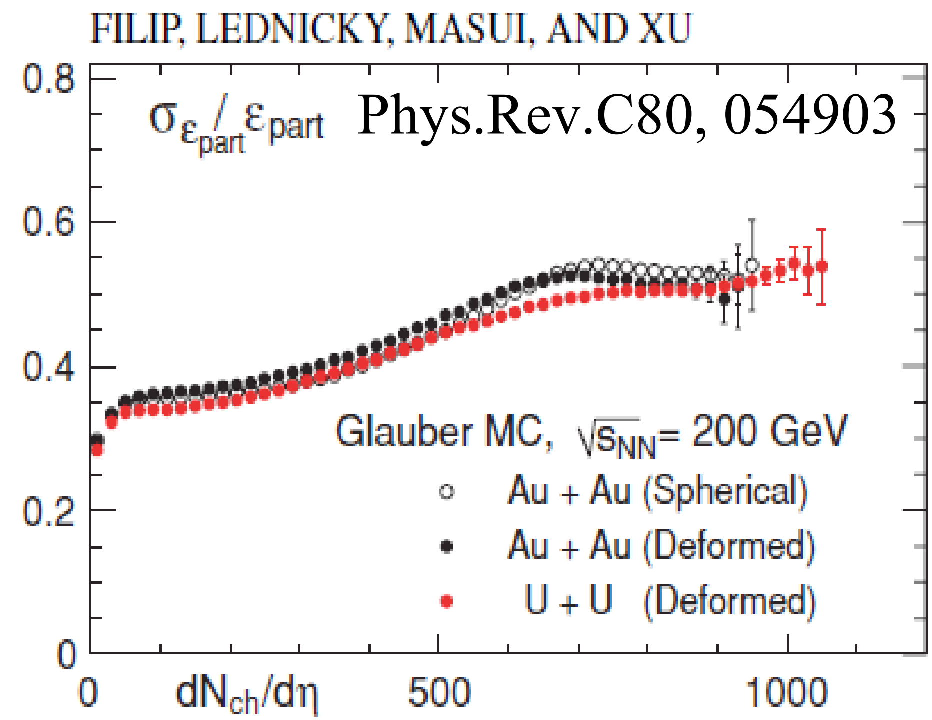
Deformation effects: σ_{v_2} / v_2 [N_{ch}]

Assuming hydrodynamical expansion: σ_{v_2} / v_2

→ $\sigma_{v_2}/v_2 \approx \sigma_\varepsilon / <\varepsilon>$ → **sensitive to deformation of nuclei**

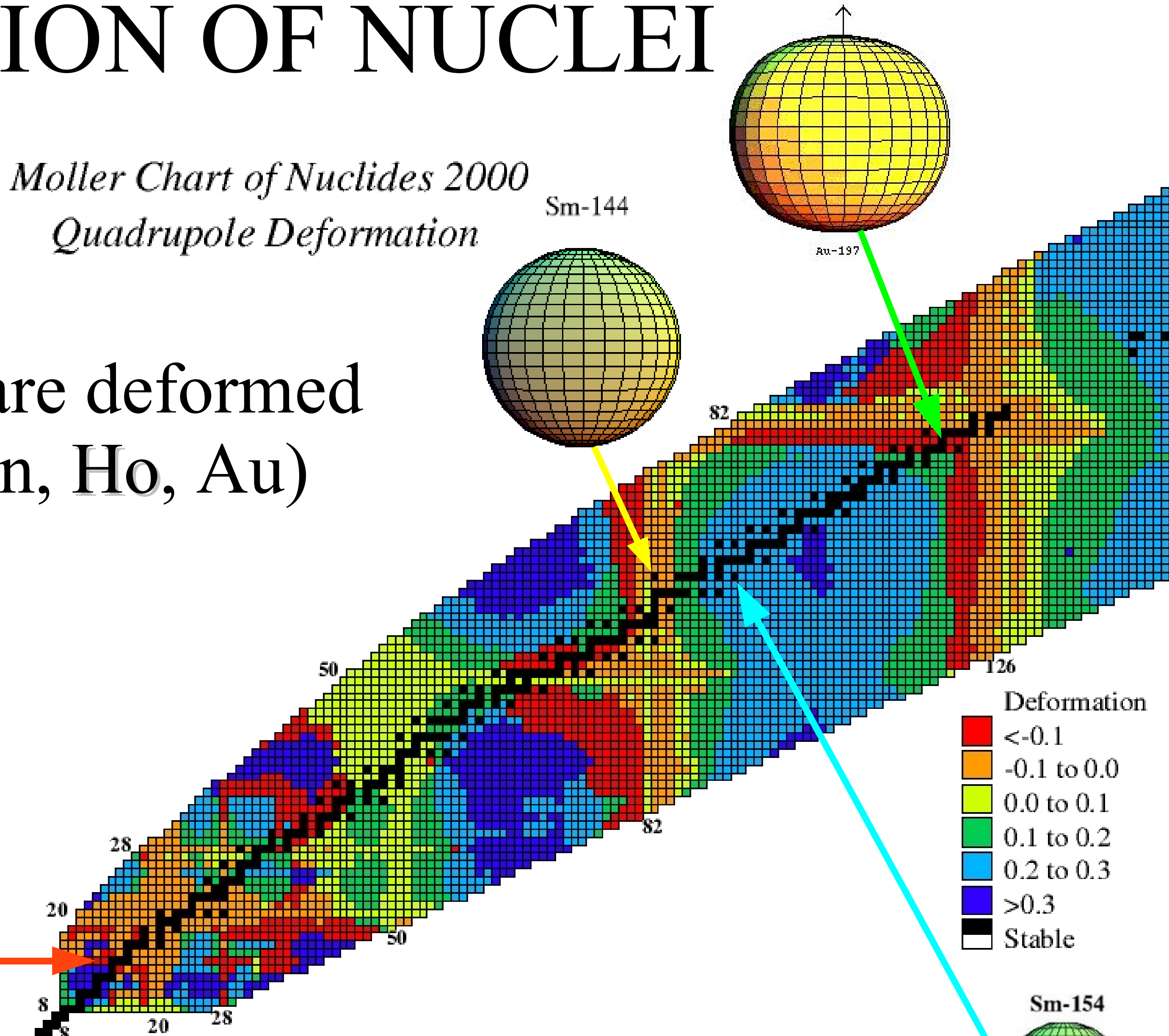


Optical Glauber Model



Full MC Glauber simulation

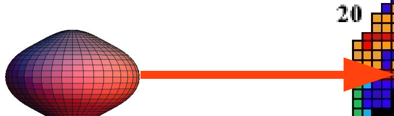
DEFORMATION OF NUCLEI

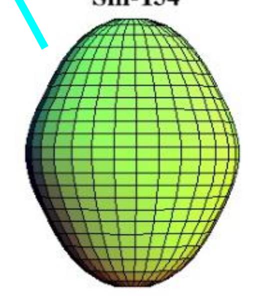


- Most of nuclei are deformed (including Cu, In, Ho, Au)
- **Au:** β_2 = -0.13

  Ho: β_2 = 0.30

  Si^{28}: β_2 = -0.4





- **Study** Nd,Sm,Ho,Si collisions at LHC/Nica/SPS

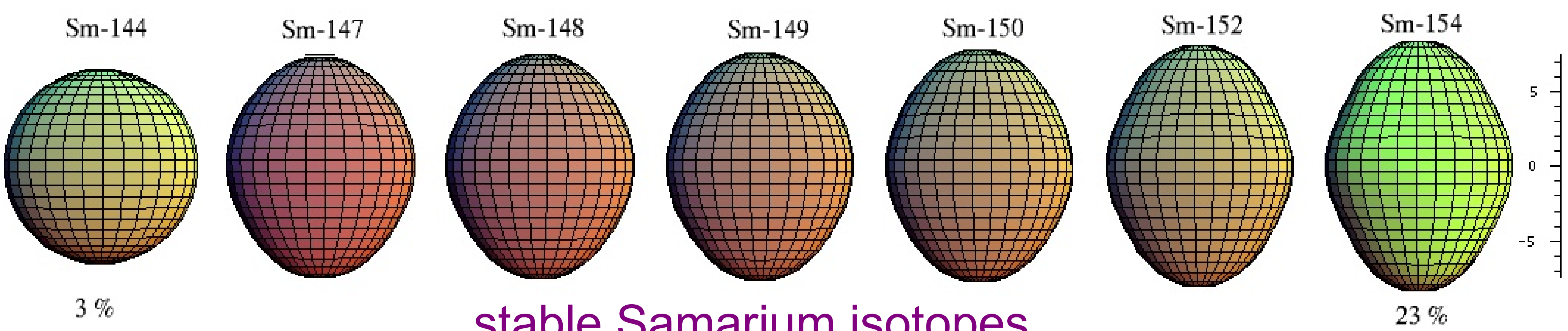
  → to verify our understanding of the Elliptic flow.

Suggestion N.1:

Deformation of nuclei: $\rightarrow \beta_2$

in relativistic Nucleus-Nucleus collisions

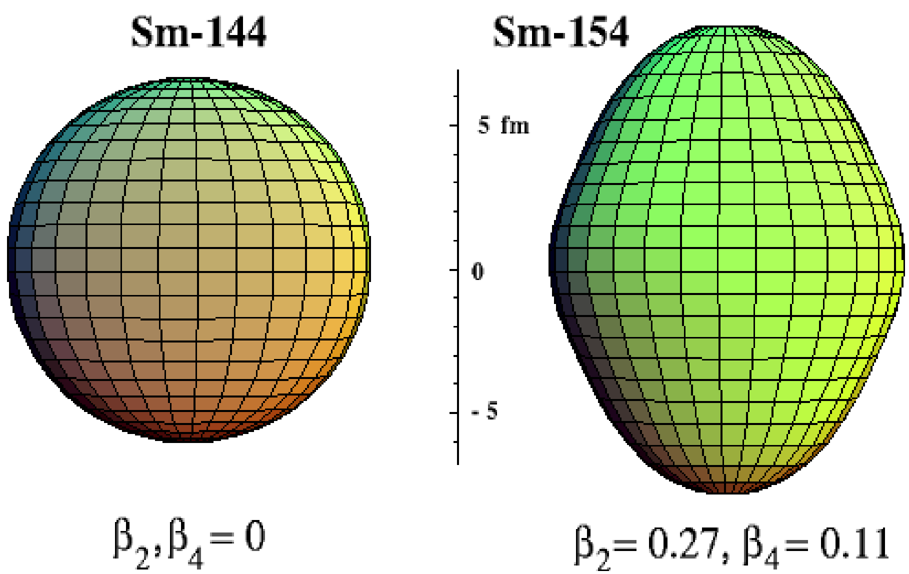
$\rightarrow$ may allow a more detailed understanding of the elliptic flow phenomenon.



stable Samarium isotopes

Comparing v_2 strength & fluctuations:

→ for spherical & deformed *Sm+Sm collisions*



$$\sigma_\varepsilon = \sqrt{\sigma^2_{\beta_2} + \tilde{\sigma}^2_\varepsilon}$$

due to deformation (→ $\sigma^2_{\beta_2}$)

all other fluctuations (→ $\tilde{\sigma}^2_\varepsilon$)

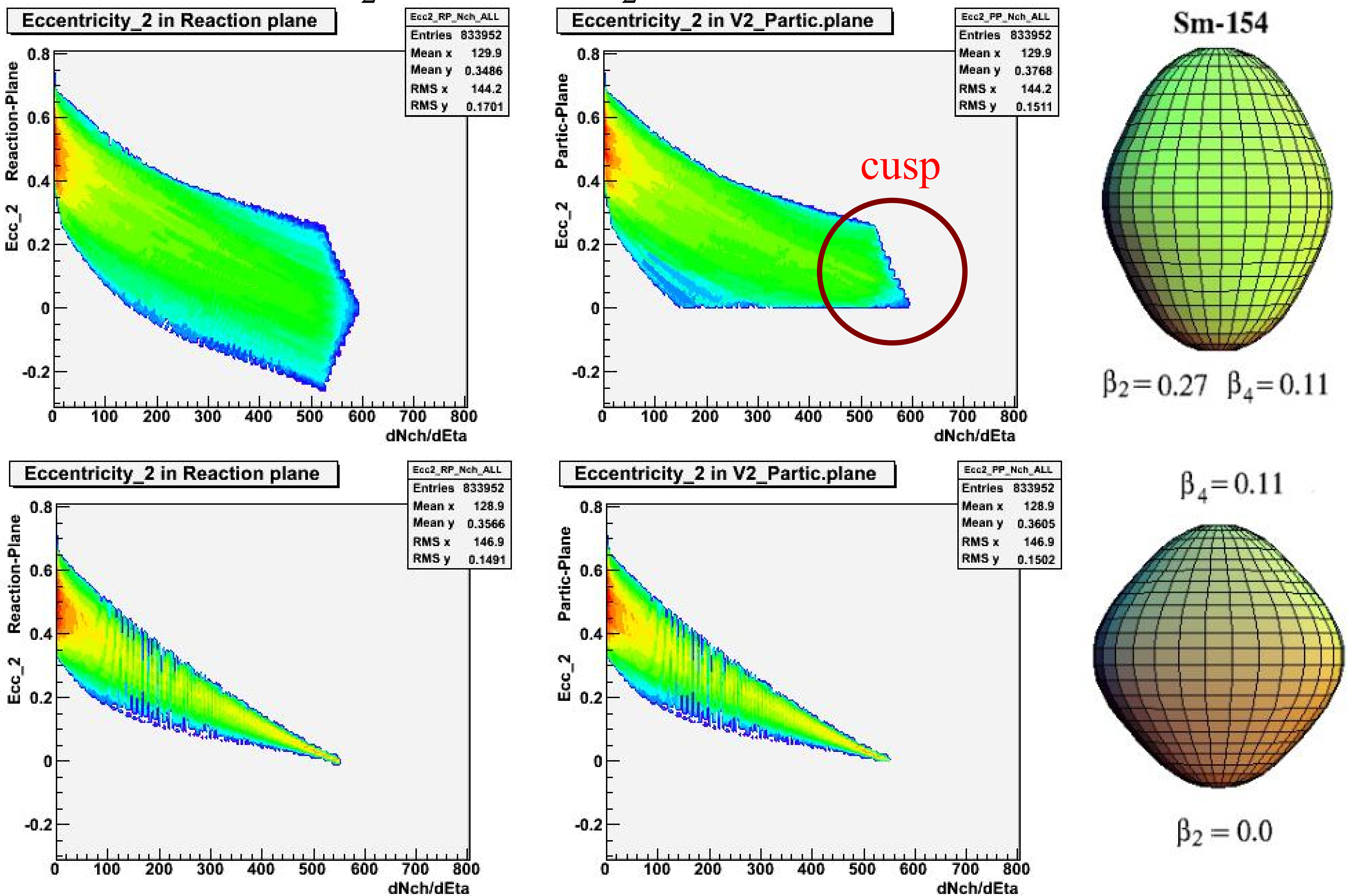
- We know initial eccentricity fluctuation increases for Sm^{154} collisions

→ Experimentally **measured v_2 fluctuation**:

→ **should increase: How much ?**

v_2 eccentricity for Sm+Sm

(OGM: larger $\beta_2 \rightarrow$ larger ε_2 (v2) fluctuations)

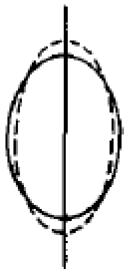


Other initial-state effect:

→ GROUND-STATE nuclear Vibration (ZPV)

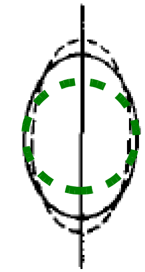
- **What is it ? (Zero-Point-Shape-Vibration)**
  → present in deformed nuclei ?
  → present also in spherical nuclei ?
  → **Is it stronger or weaker for light nuclei ?**
- **Does it really exist ?**
  → has anybody observed Ground-State vibration = GSV ?
  (in molecular physics ?)

- **Should we include it in MC simulations of HIC ?**



β-vibration

Bohr and Mottelson on ZPV
Nuclear Structure II



β-vibration

Occurrence of shape oscillations

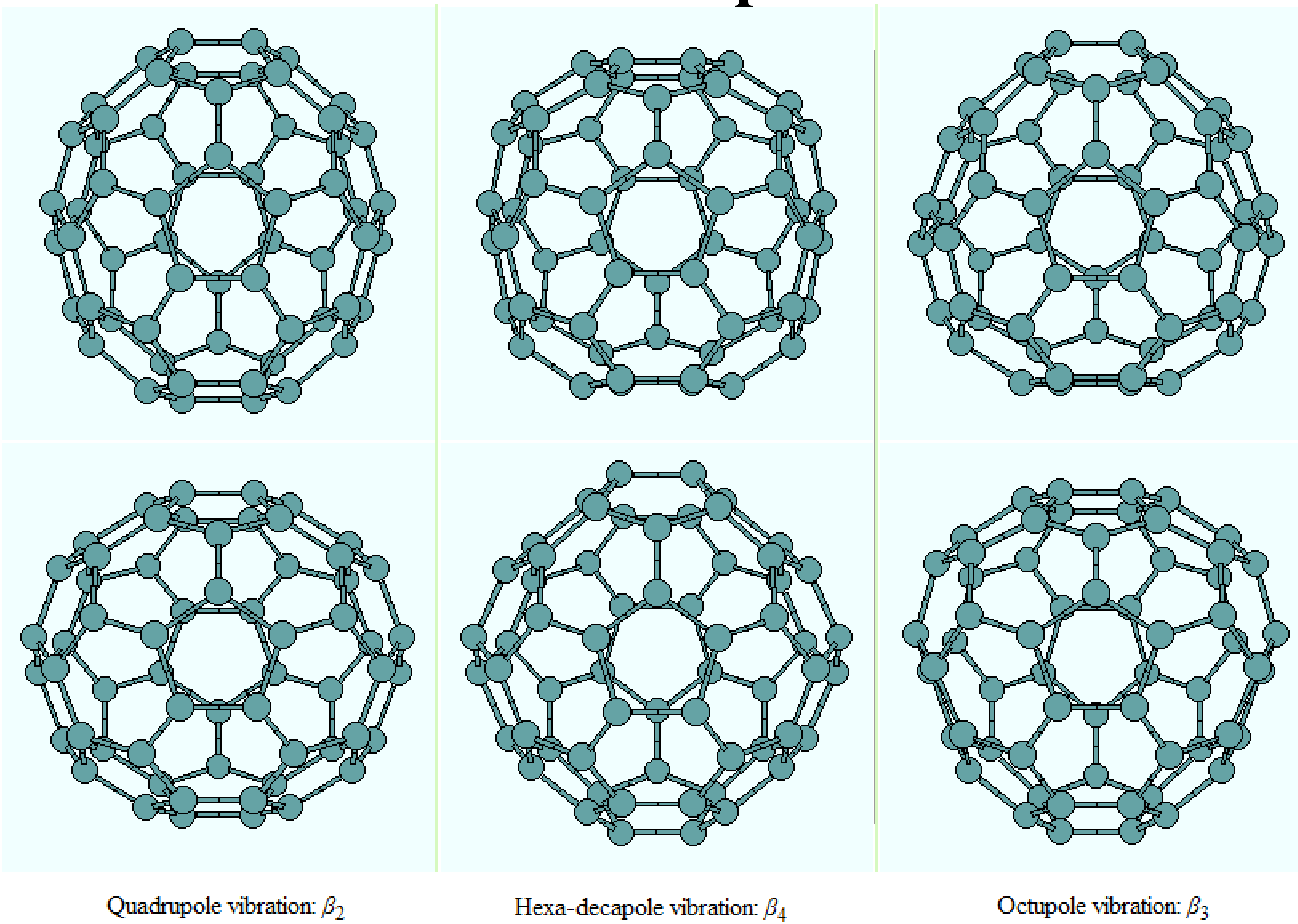
The study of the low-energy spectra of the even-even nuclei has revealed the systematic occurrence of $I\pi = 2+$ and $3-$ states with properties suggesting a vibrational interpretation. The collective character of the excitations is implied by the large transition probabilities and by the fact that the properties vary rather smoothly with N and Z. The systematics of the excitation energies of the $2+$ and $3-$ modes are shown in Fig. 2-17a, b, Vol. I, pp. 196–197, and Fig. 6-40, p. 560, respectively. The transition probabilities are an order of magnitude larger than the single-particle unit, and if interpreted as shape oscillations, as in Eq. (6-65), correspond to zero-point amplitudes β_2 and β_3 typically of order 0.2 (see Fig. 4-5)

→ nuclei do oscilate = vibrate in the ground state

→ **amplitude is comparable to static deformation β_2**

Molecular Physics: C_{60}

Ground-state-shape vibration

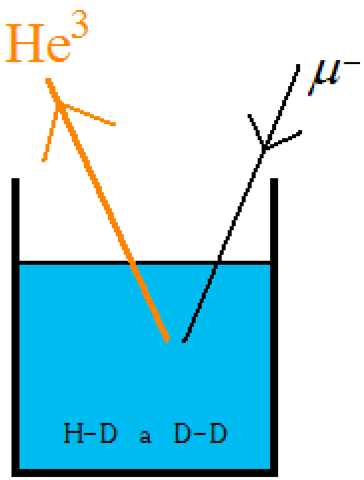


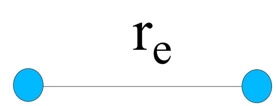
From → J.Ménendez and J.Page:"Vibrational spectroscopy of C_{60}" **Nuclei may vibrate similarly!**

Mollecular Ground-state VIBRATION important in: μ–cF

(1956)

Berkeley





200x smaller

→ vibrating...

μ^- meson serves as a *catalyst*

The reaction rate $T \sim 2.5 \times 10^{-6}$ sec can be written

$$1/T = A\,|\Psi(0)|^2$$

where reaction constant is $A \sim 10^{-22}$ cm^3/sec

$\Psi(0)$ is value of wave function at zero separation

CATALYSIS OF NUCLEAR REACTION

J. D. Jackson

Princeton University

$(p+d+\mu^-) \longrightarrow He^3$

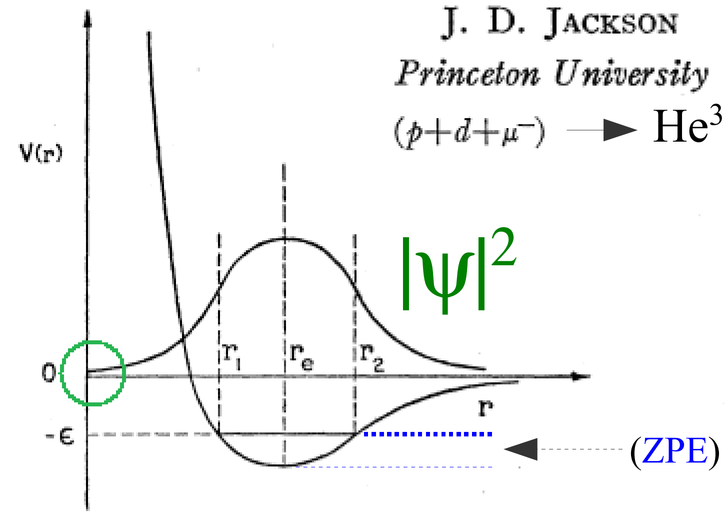


Fig. 1. Nuclear potential energy curve in μ-mesonic hydrogen molecule, and ground-state vibrational wave function for the

$$\Psi_{\mathrm{vib}}(x) = (\alpha/\pi)^{\frac{1}{4}} \exp\left[-\tfrac{1}{2}\alpha(x-x_0)^2\right]$$

PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

Catalysis of Nuclear Reactions between Hydrogen Isotopes by μ^- Mesons

J. D. Jackson*
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received January 10, 1957; revised manuscript received February 4, 1957)

[Observation of Coherent Mollecular Quantum vibrations: see Nature 343 (1990) p. 737]

Bohr and Mottelson on ZP Vibration

Nuclear Structure II

The vibrational wave functions $\varphi_n(\alpha)$ have the form

$$\varphi_n(\alpha) = (2\pi)^{-1/4}(2^n n!\alpha_0)^{-1/2} H_n\left(2^{-1/2}\frac{\alpha}{\alpha_0}\right)\exp\left\{-\frac{1}{4}\frac{\alpha^2}{\alpha_0^2}\right\} \qquad (6\text{-}14)$$

where H_n is the nth Hermite polynomial ($H_0(x)=1$, $H_1(x)=2x$)

while α_0 is the zero-point amplitude

$$\alpha_0 \equiv \langle n=0|\alpha^2|n=0\rangle^{1/2} = \left(\frac{\hbar}{2D\omega}\right)^{1/2}$$

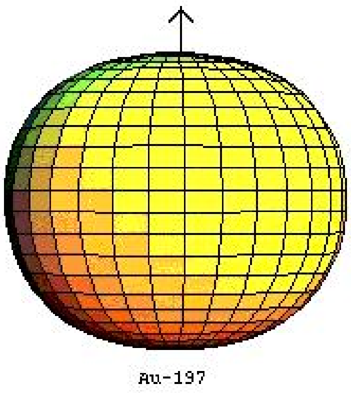
← depends on Nucleus

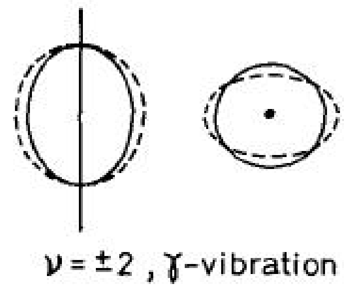
→ Ground-state vibration = Quantum effect !

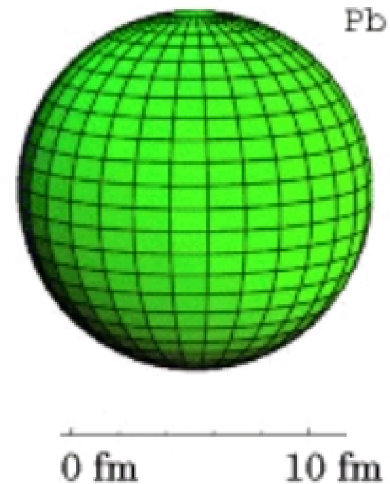
→ well known from Molecular physics: C_{60} and μCF

^{197}Au (RHIC,GSI) & ^{207}Pb (SPS,LHC) → shape vibrations...

How large they are ?







SHOULD WE INCLUDE (? Cu+Cu ?)

SHAPE VIBRATION

into Elliptic Flow (eccentricity) SIMULATIONS ?

→ Does it affect v_2 physics at BNL / LHC ?

Frequency of Shape vibrations:

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

- For molecules: $f \approx 10^{12\text{-}13}$ Hz (microwave)
- For Nuclei e.g. ^{196}Hg: $E_{ZPE} \approx 2$ MeV

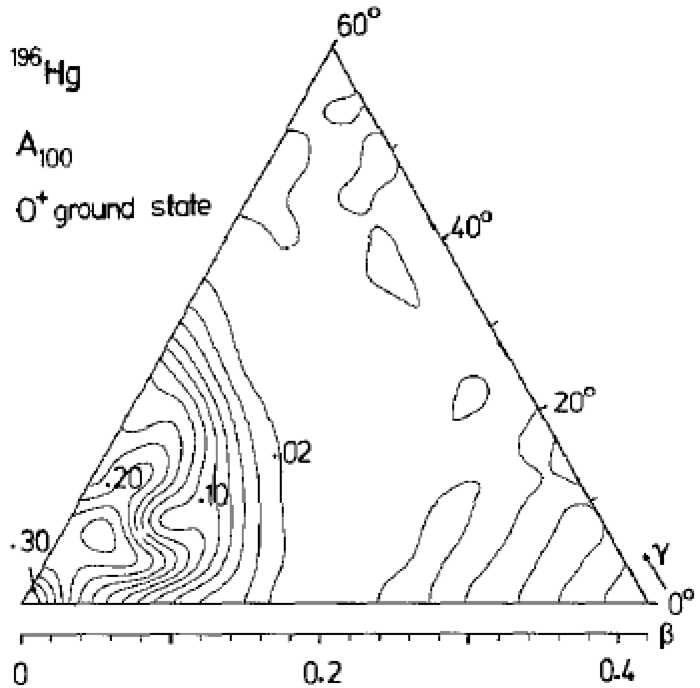
$$\mathbf{f_V \approx 5 * 10^{20}\ Hz}$$

- Comparing to HIC initial overlap time:

$1 / f_V \approx$ **$2*10^{-21}$ s** **>>** **$2*10^{-23}$ s** $= T_{init} \approx 6$ fm/c

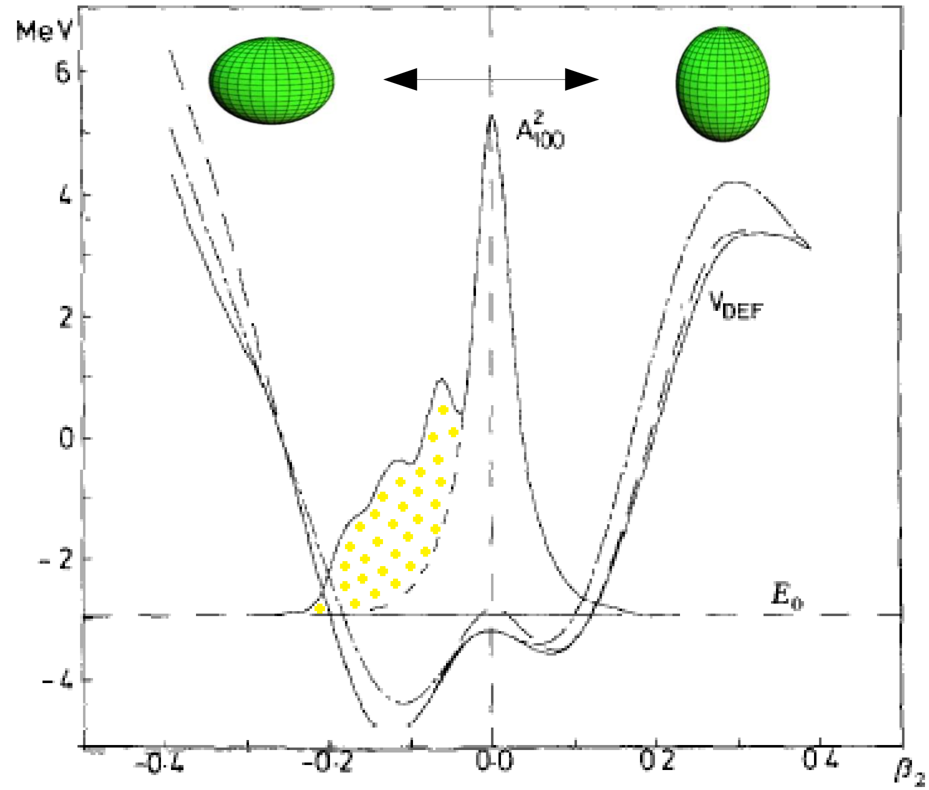
- Initial **overlap is** fast → collision in **frozen** vibrational state

Ground-state wave function: ^{196}Hg



Contour plot of the ground-state wave function $A_{100}(\beta,\gamma)$ for ^{196}Hg. Remark the pronounced maximum of the wave function for $\beta = 0$. The ground-state energy relative to the deformation potential V_{def} (fig. 2) is $E_0 = -2.959$ MeV and the rms values are $\beta_{rms} = 0.126$ and $\gamma_{rms} = 38°$.

Nucl.Phys.A403 (1983) p.263



deformation energy V_{def} for different values of the hexadecapole parameter $\beta_4 = 0.0$, $\beta_4 = -0.036$, $\beta_4 = \beta_{4\,min}$). ground-state wave function A^2_{100} is also shown E_0 is ground-state energy

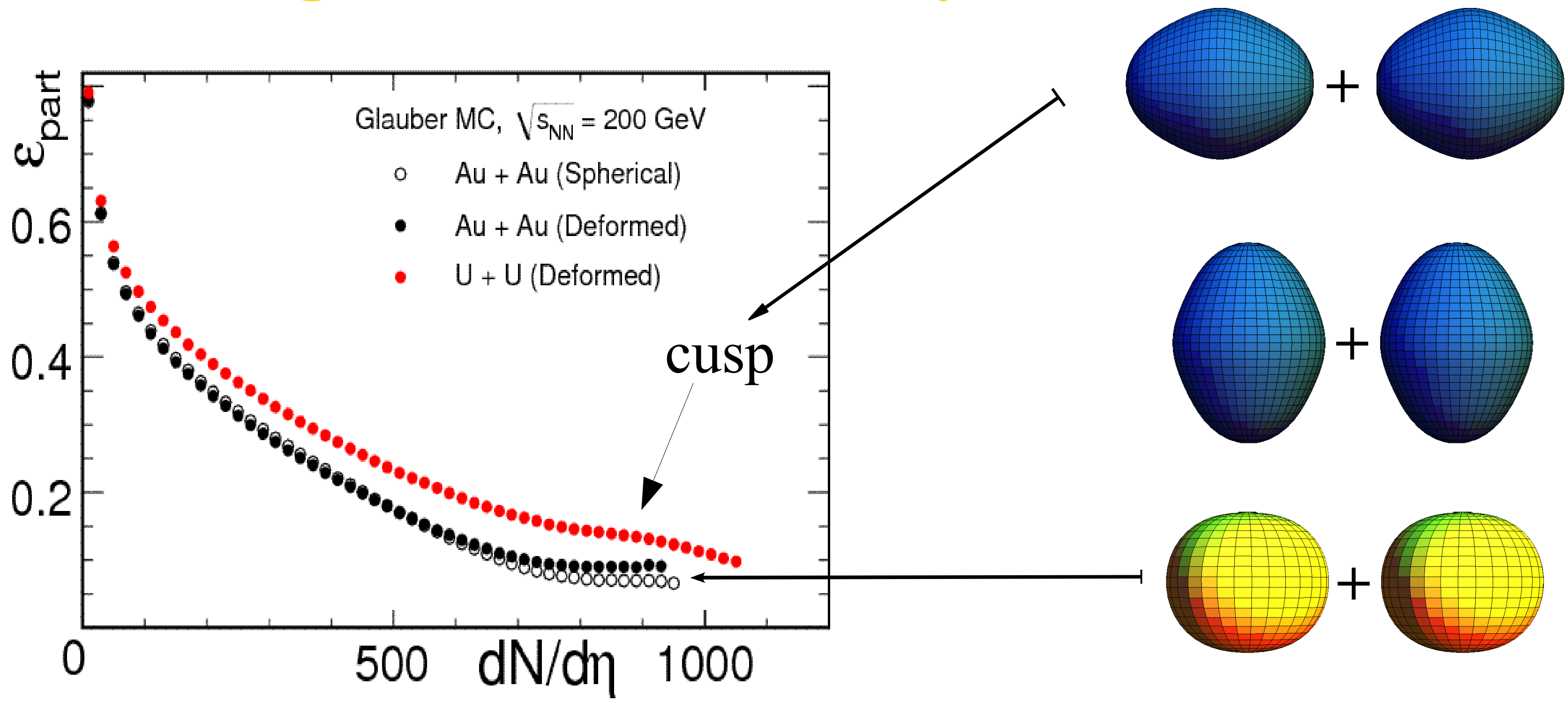
Fluctuating β_2 parameter !!! ($<\beta_2> = -0.13$)

→ ^{197}Au similar behavior (proton hole in ^{198}Hg).

ZPVibration of deformed nuclei in RHIC

→ enhanced self-orientation (CUSP) effect in central UU ?

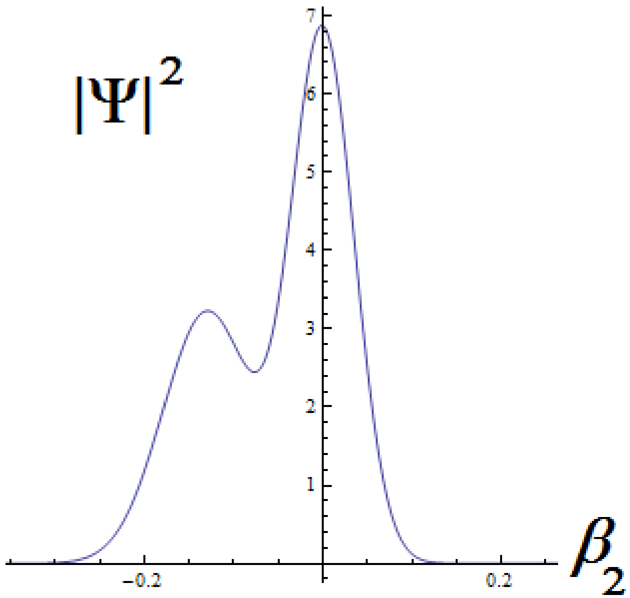
→ influencing AuAu eccentricity ?

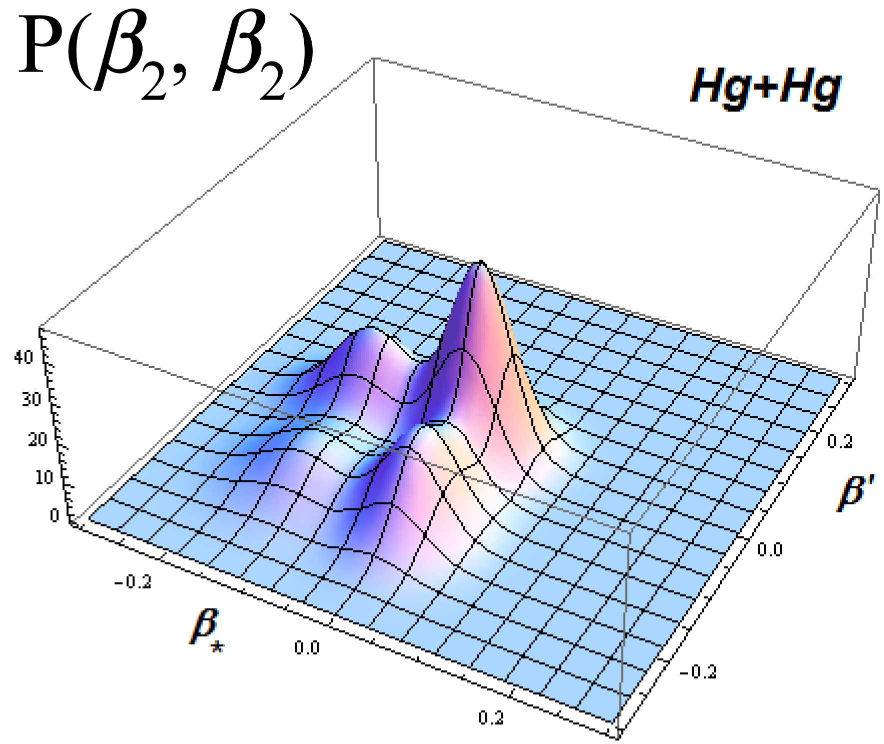


- in Phys.Rev.C80, 054903 (ZPE vibrations were neglected)

→ need to be studied to obtain a correct < initial state >

Collisions of deformed vibrating nuclei:



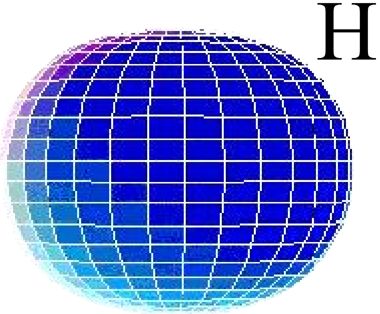


- Collision probability distribution of Hg shapes:

→ spherical + spherical (40%)

→ spherical + deformed (45%)

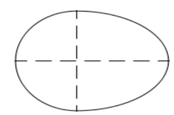
→ deformed + deformed (15%)

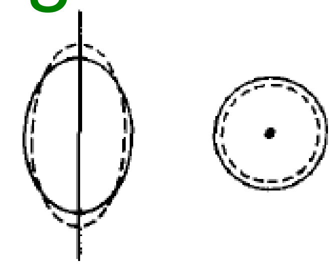


Conclusion:

- Quadrupole vibration of the colliding nuclei

  → expected in Ground state

  other (β_3) ZP vibrations possible: 



$\nu = 0$, β-vibration
$\delta R \propto (3\cos^2\Theta - 1)\cos\omega t$

- Amplitudes up to $|\beta - \beta_o| \approx 0.2 – 0.3$ (for deformed nuclei)

  in frozen vibrational state: Ho,U may have large $\beta_2 \approx 0.45$

  → STRONGER CUSP EFFECT in Ultra-Central Collisions

- During A+A collision: vibration is frozen

Vibrational properties of Nuclei

(comparing B(E2) transition probability with Q_o)

→ some nuclei **Vibrate**: Ca, Fe, Ni, Zn, Ge, Kr, Sr, Pd, Cd, **Sn**

→ some nuclei do Not vibrate: Zr, Nd, Sm, Gd, Dy, Er, **W**, Os

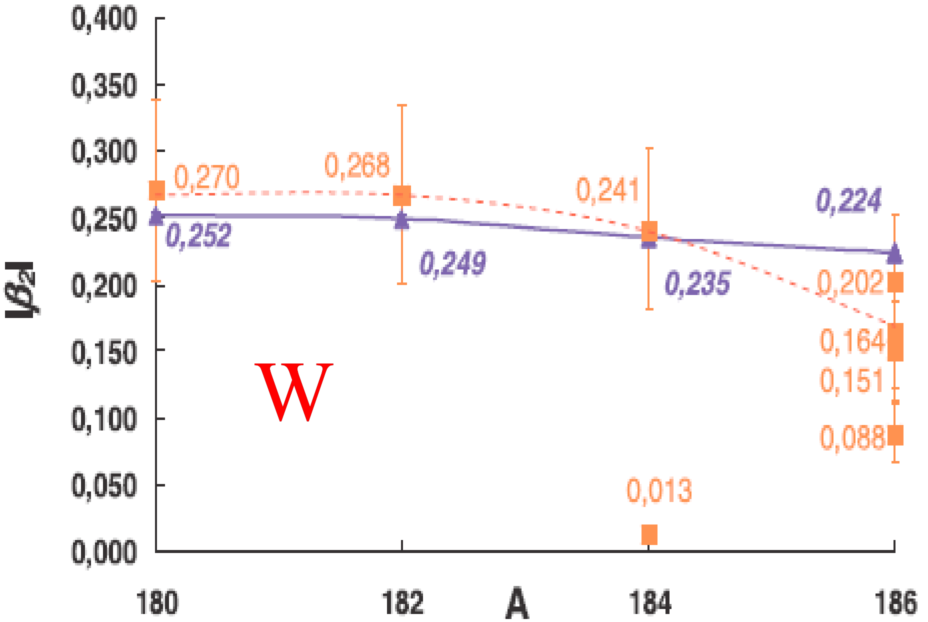


Fig. 1. Comparison of $|\beta_2|$ values obtained from B(E2) ↑ data (blue triangles, solid line) and from Q data (red squares, dotted line) for W

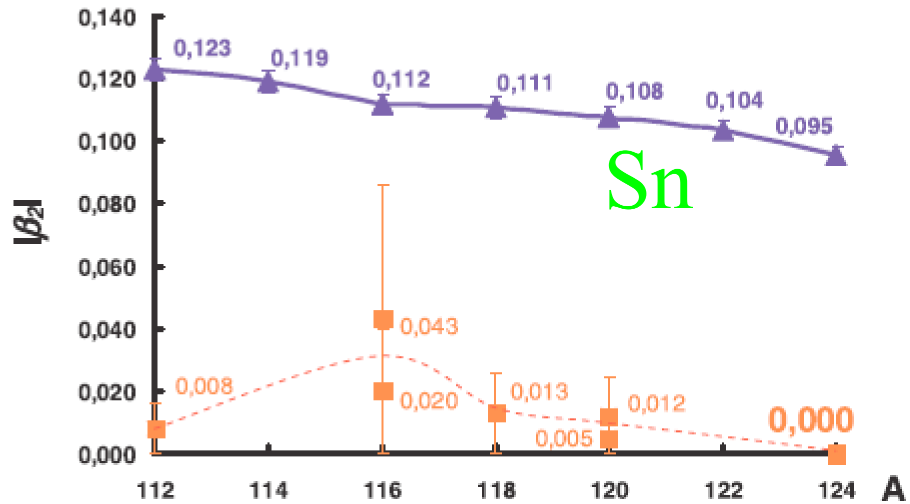


Fig. 2. Comparison of $|\beta_2|$ values obtained from B(E2) ↑ data and from Q data for Sn ("group 2"). ^{124}Sn case ($|\beta_2|_Q = 0$) is indicated

Publication: I. Boboshin et al.

"Investigation of quadrupole deformation of nucleus and its surface dynamic vibrations"

International Conf. on Nuclear Data for Science and Technology 2007 (DOI: 10.1051/ndata:07103)

Summary:

- Ground-state **vibration** + **deformation** of nuclei

  can influence initial state → Elliptic Flow v_2 in HIC.

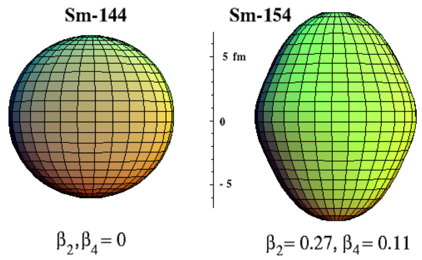
- Enhancement of eccentricity "cusp" is possible

  → in Ultra-central collisions of prolate vibrating nuclei (U+U)

  → eccentricity in Au+Au may be affected.

- Comparing v_2 in $(^{144}Sm+^{144}Sm)$ and $(^{154}Sm+^{154}Sm)$

  → was suggested for R-HIC



- Collisions of *Cd* (vibrating) nuclei and *Nd,Sm* (non-vibrating) nuclei

  → **may clarify influence of vibrations**

THANK YOU

for

Your kind ATTENTION

Backup Slide

- We expect ^{114}Cd to be strongly vibrating ($<\beta_2> = +0.16$)
- We think ^{148}Sm, ^{146}Nd do Not vibrate ($<\beta_2> = +0.16$)
- ^{63}Cu properties ?