Exploring the phase diagram of strongly interacting matter - experiments at NICA

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28th International Scientific Conference of Young Scientists and Specialists (AYSS-2024), JINR, Dubna, October 27- November 1, 2024

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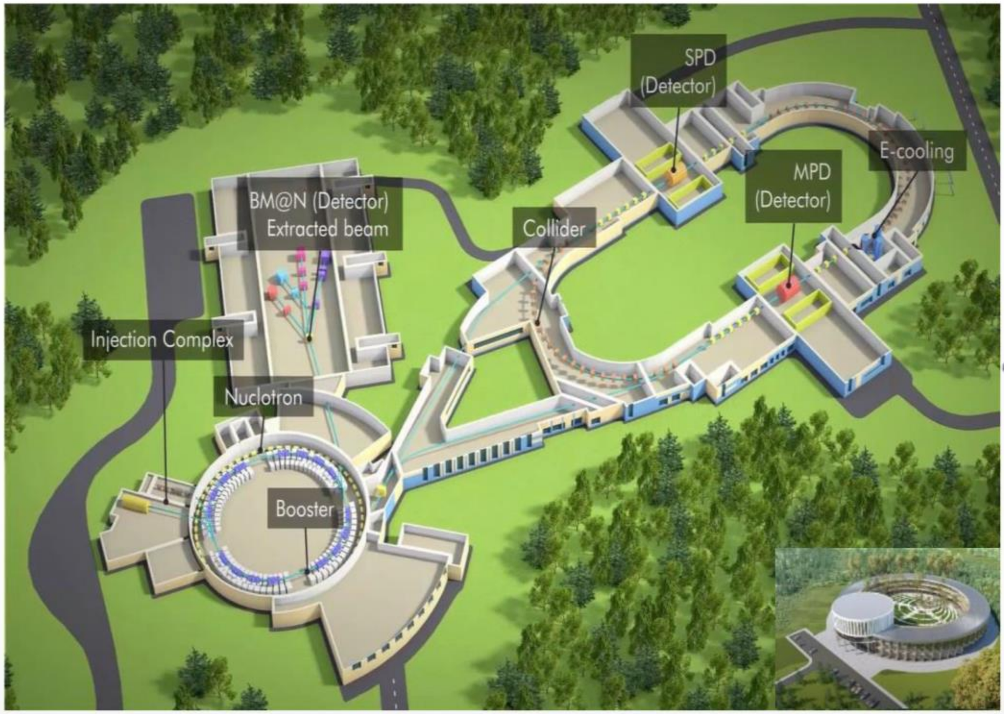
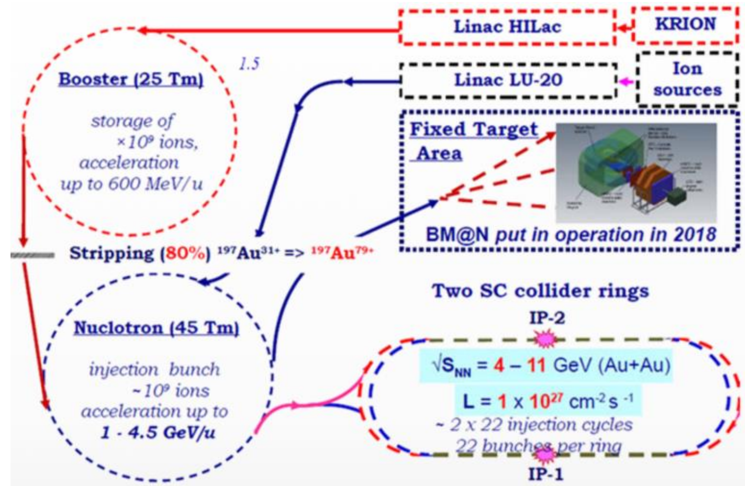
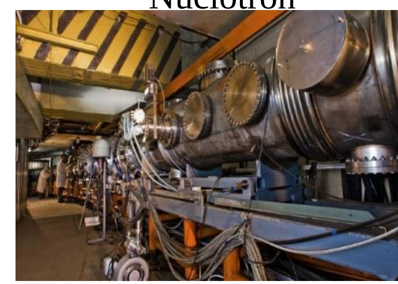
NICA Project at JINR





Booster

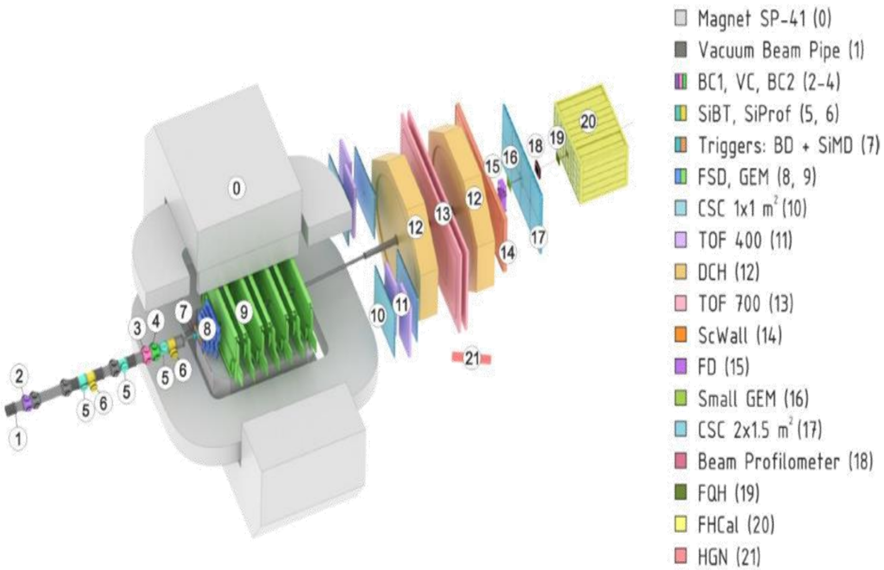
Nuclotron



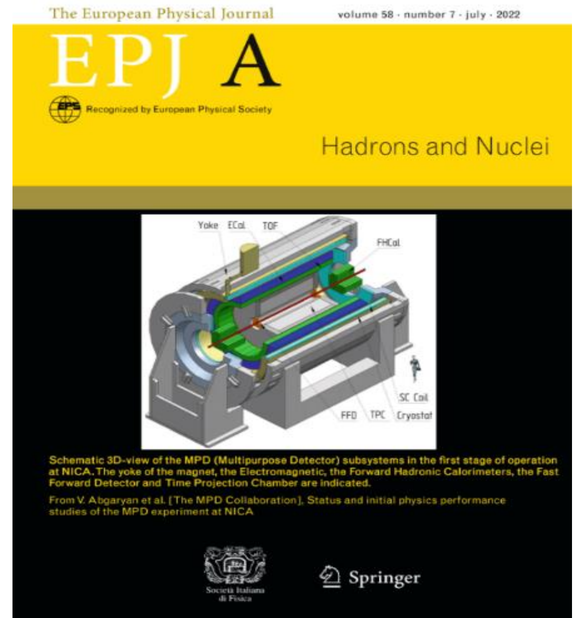
- **Megascience project - JINR, which is approaching its full commissioning:**
  - **Baryonic Matter at Nuclotron (BM@N) –** fixed-target experiment, first physics run Xe+CsI at 3.0 and 3.8 A GeV, 2022-2023
  - **Multi-Purpose Detector (MPD) –** start of operation in 2025-2026

NICA: BM@N and MPD Collaborations

The BM@N spectrometer at the NICA accelerator complex
Nucl.Instrum.Meth.A 1965 (2024) 169352



Status and initial physics performance studies of the MPD experiment at NICA , Eur.Phys.J.A 58 (2022) 7, 140



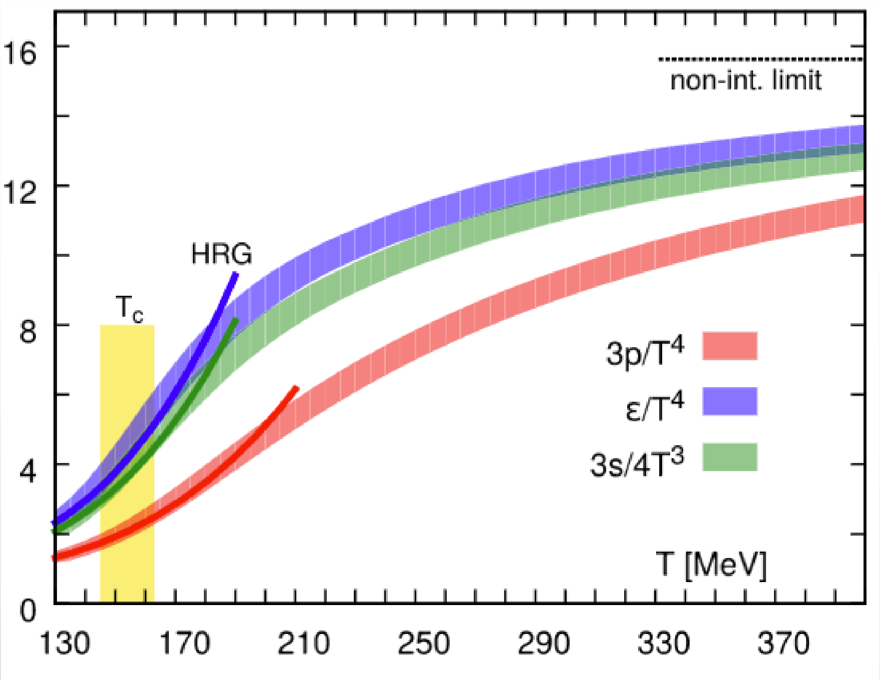
BM@N: ~214 participants из 13 institutes, 5 countries

MPD: ~500 participants из 38 institutes, 12 countries

Phase transition in Lattice QCD

Critical temperature
$T_c \approx$ **156 +/- 9 MeV**

[PRD 90 094503 (2014)]

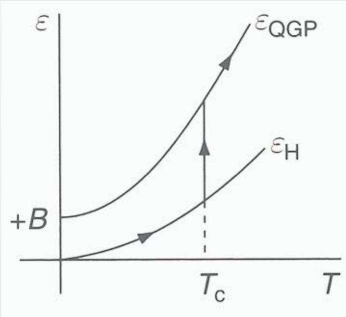


Energy density *ε*
Pressure *p*
Entropy density *s*

For comparison:
T=156 MeV ≙ $1.8 \cdot 10^{12}$ K
Sun core: $1.5 \cdot 10^7$ K
Sun surface: 5778 K

Steep rise in thermodynamic quantities due to change in number of degrees of freedom → phase transition from **hadronic to partonic** degrees of freedom.

Smooth *crossover* for a system with net-baryon content equal 0. For a *first order phase transition*, the behavior would be not continuous.



HADRON → **QGP**

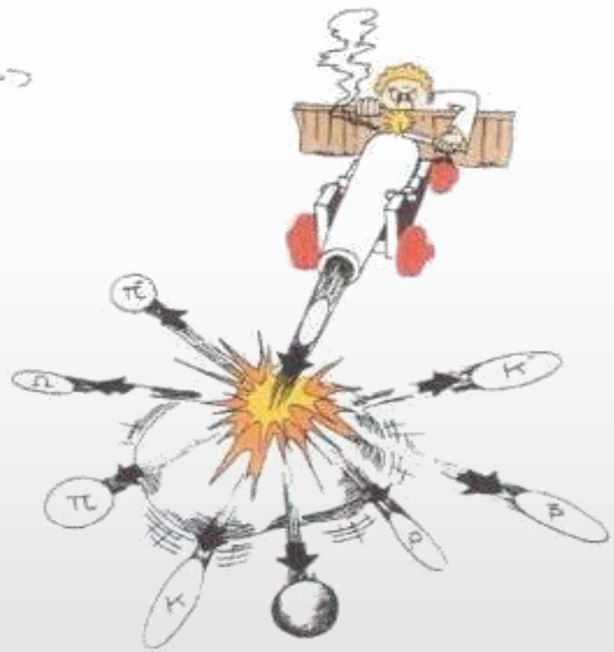
Bevalac ~1 GeV → **AGS** ~5 GeV → **SPS** ~20 GeV → **RHIC** ~100 GeV → **LHC** ~5000 GeV

Increasing the beam energy over the last decades…

..from early fixed target experiments at GSI/Bevalac and SPS to collider experiments at RHIC and LHC.

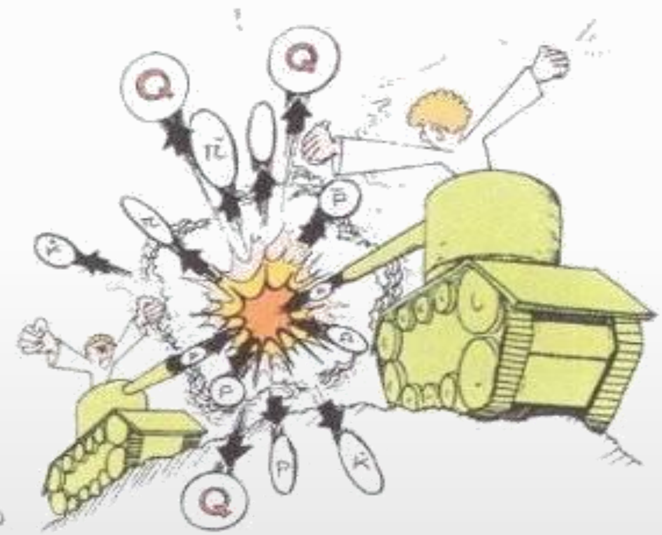
Max mit seinem ersten großen Teilchenbeschleuniger

SIS, GSI Darmstadt, $\sqrt{s_{NN}}$~2.4 GeV



J/Ψ Charm

SPS, CERN, $\sqrt{s_{NN}}$~6-20 GeV



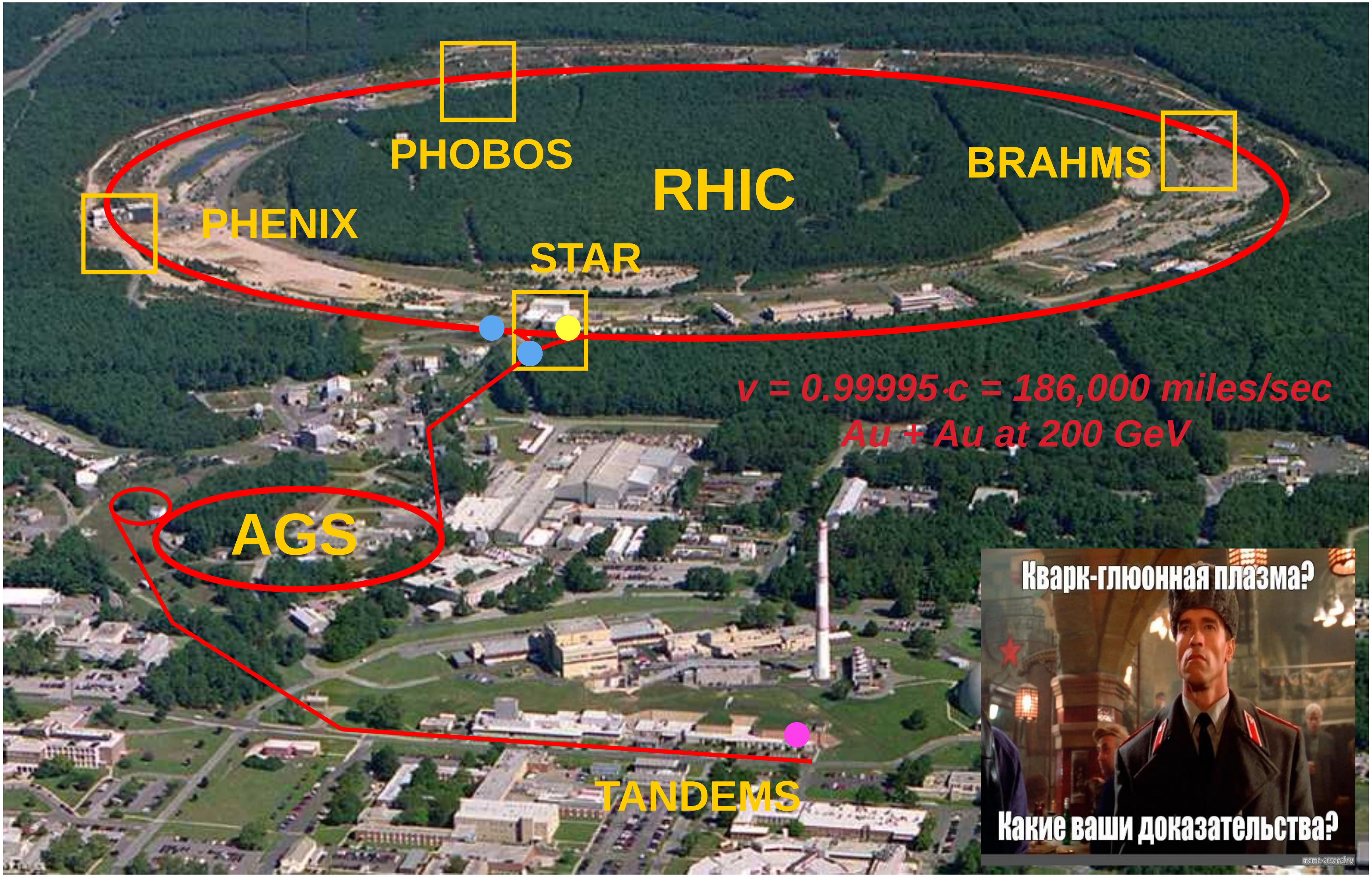
Max mit seinem größten Teilchenbeschleuniger

Brookhaven → RHIC $\sqrt{s_{NN}}$~3-200 GeV (BES)

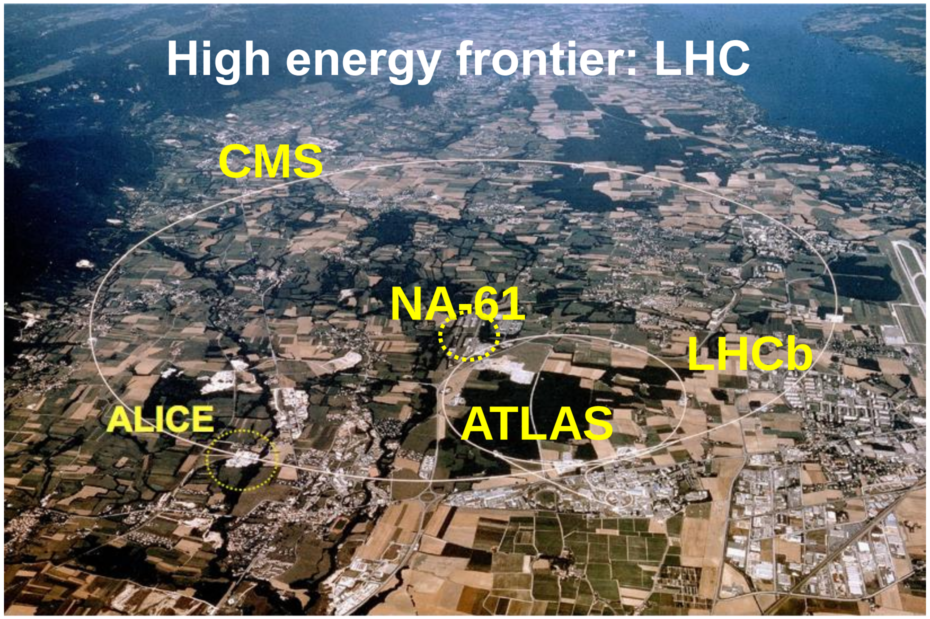
CERN → LHC $\sqrt{s_{NN}}$ = 5.02 TeV

2005: Quark-Gluon Plasma is a “perfect liquid”

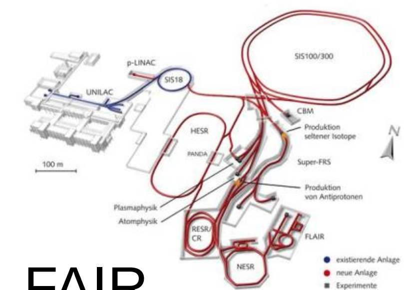
Relativistic Heavy-Ion Collider (BNL), Upton, NY (USA)



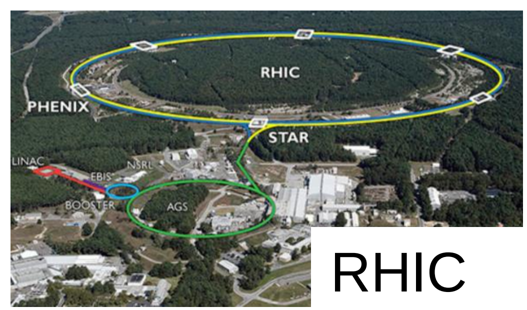
Relativistic Heavy-ion experiments



Low energy frontier: RHIC (BES), SPS
→ future facilities: FAIR (GSI), NICA



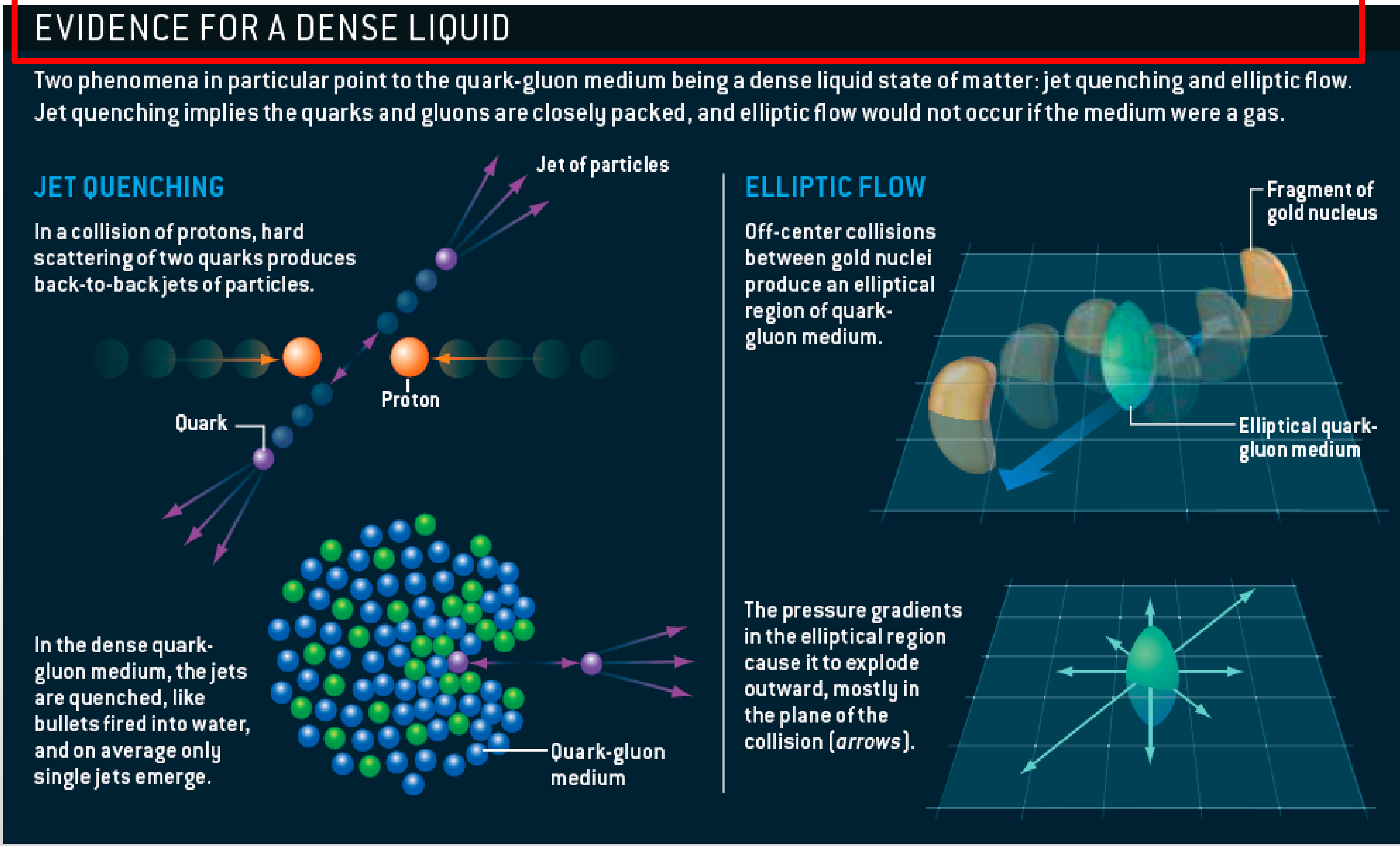
FAIR



RHIC

→ By now **all major LHC experiments have a heavy-ion program**: LHCb took Pb-Pb data for the first time in November 2015.

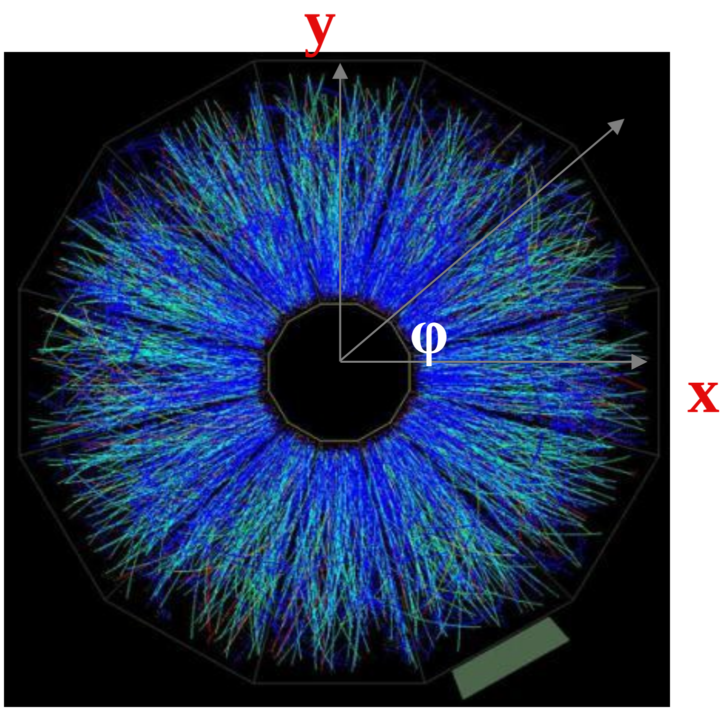
The sQGP Discovered at RHIC: 2005

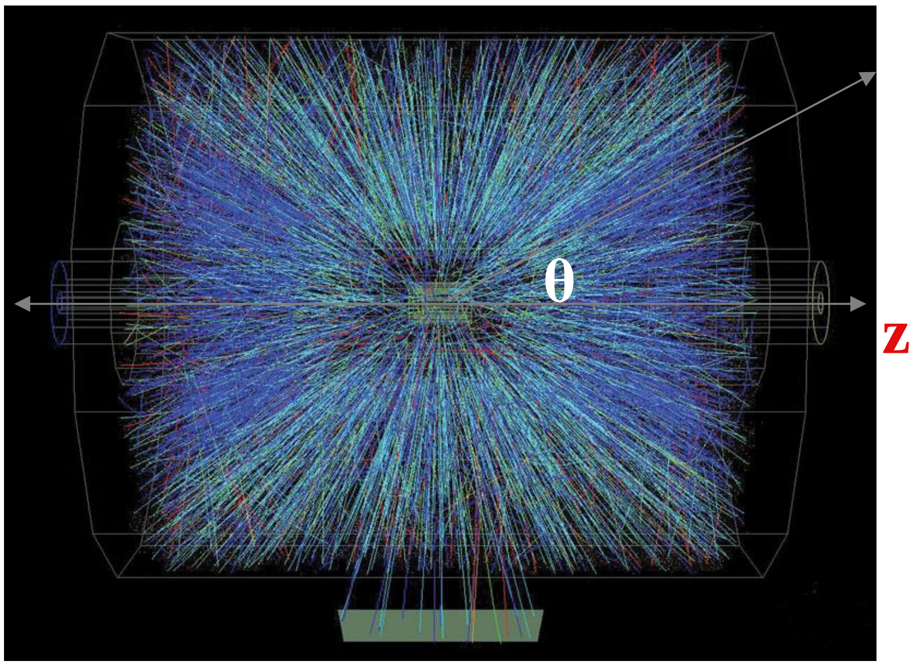


M. Roirdan and W. Zajc, Scientific American, May 2006

Definition of kinematical variables

Momentum , azimuthal angle φ and pseudo-rapidity (η) of the emitted particles are used to study the collision





$$\eta = \frac{1}{2}\log\left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}\right) = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$

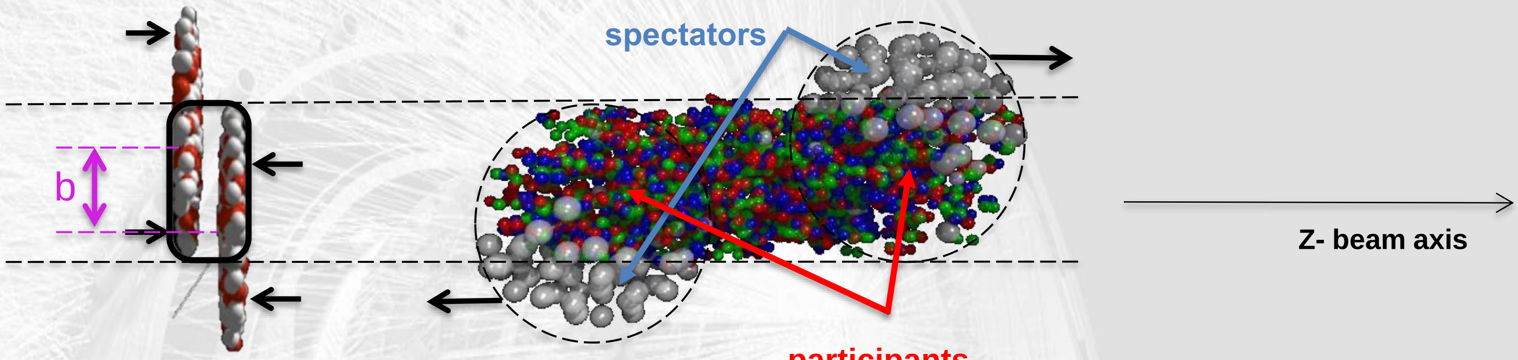
$$p_T = \sqrt{p_x^2 + p_y^2}$$

p_T is generated in the collision (while p_z is already present “before the collision”)

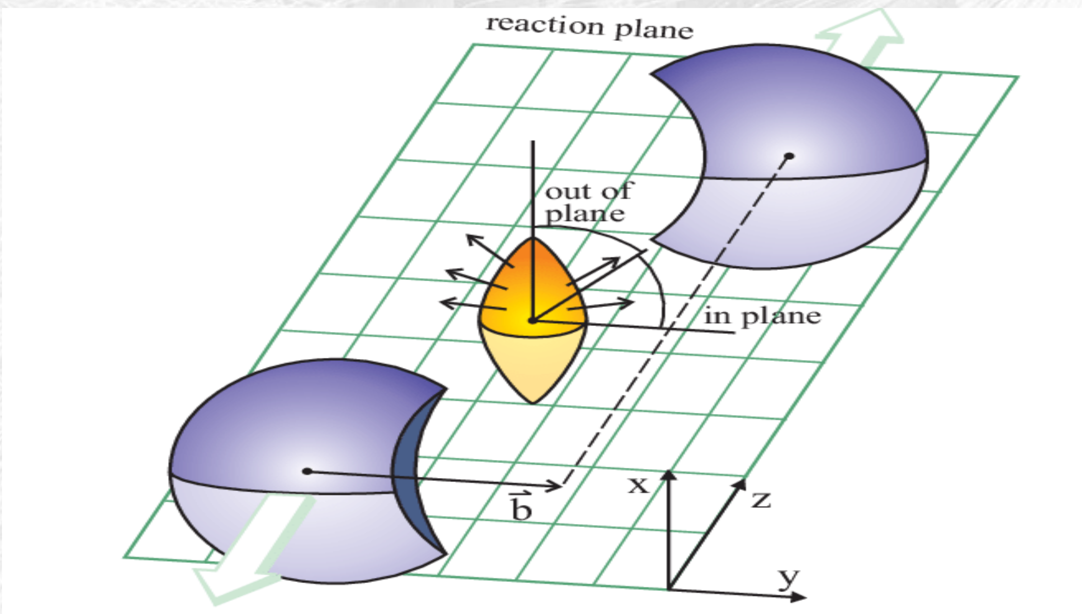
Characterising a heavy-ion collision

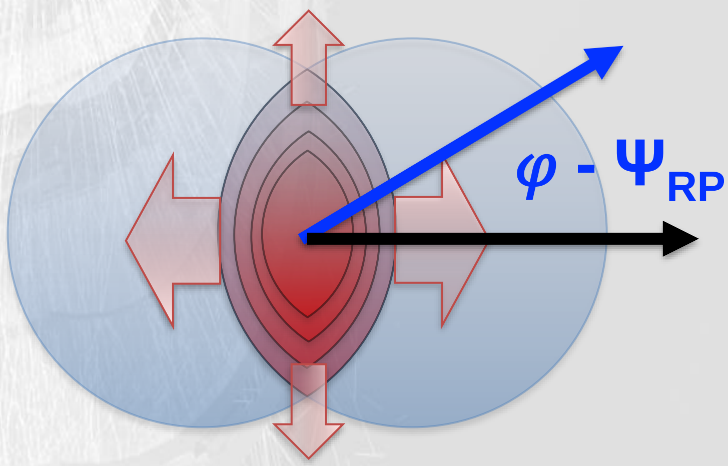
We can control a posteriori the geometry of the collision by selecting in centrality.

Centrality = fraction of the total hadronic cross section of a nucleus-nucleus collision, typically expressed in percentile, and related to **the impact parameter (b)**



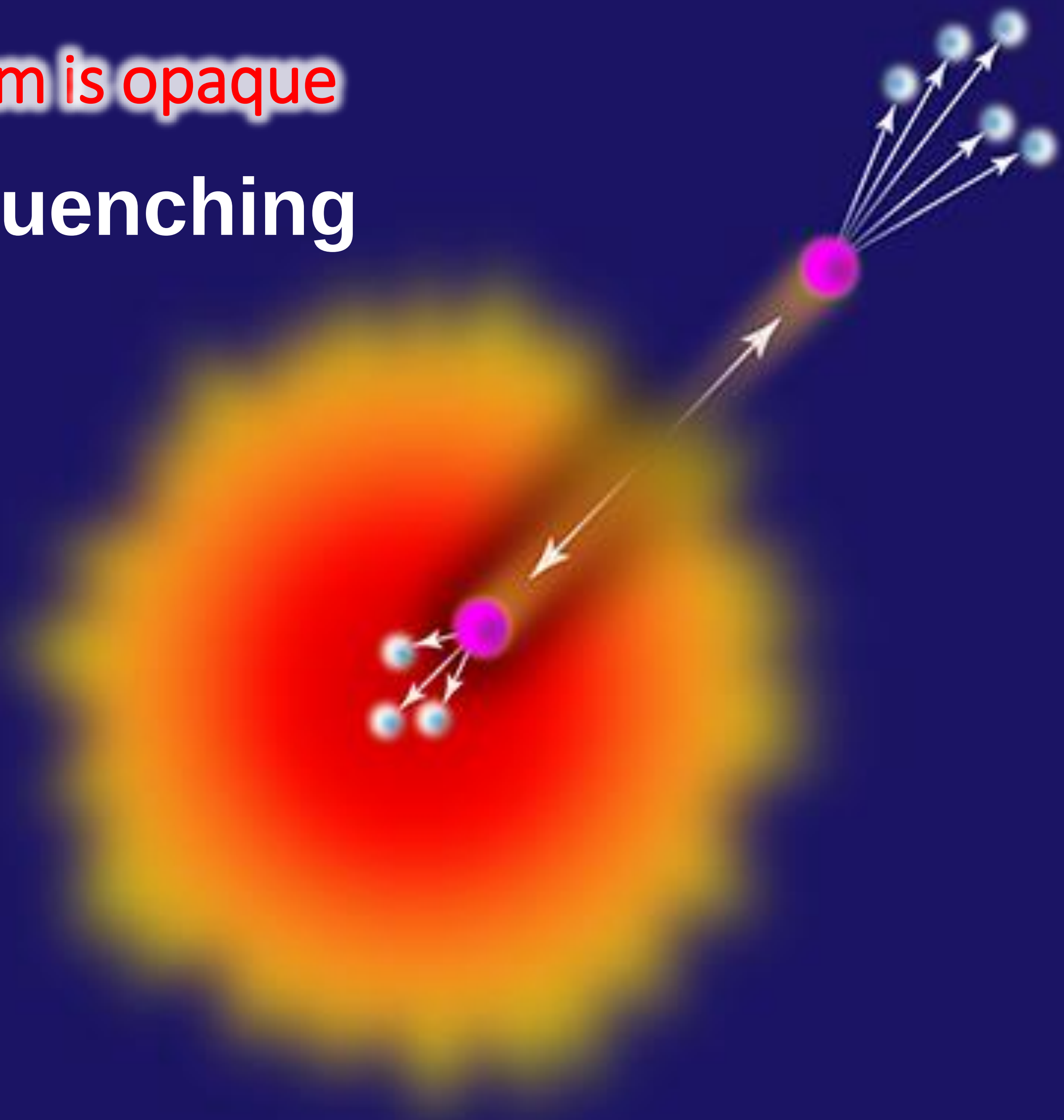
Collision overlap zone





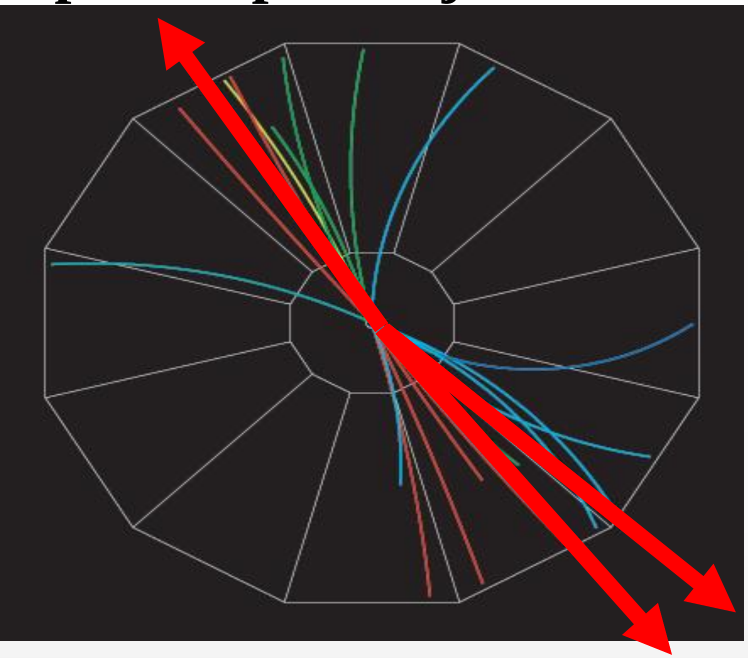
medium is opaque

Jet quenching

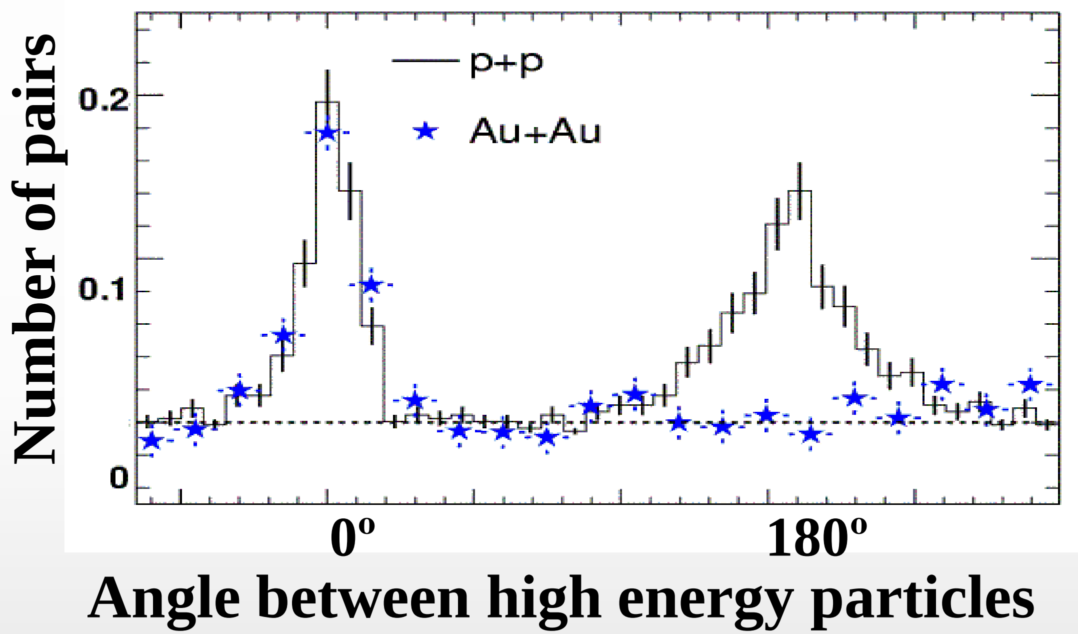


RHIC Experiment: “Jet quenching”

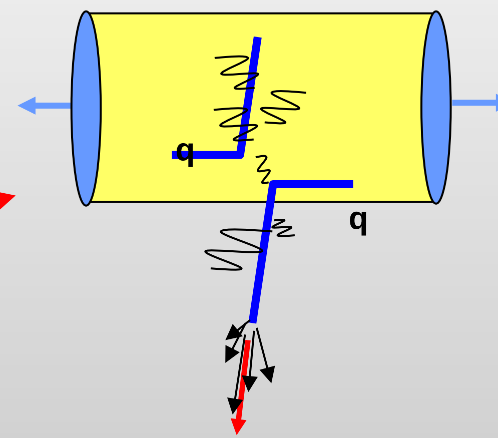
proton-proton jet event



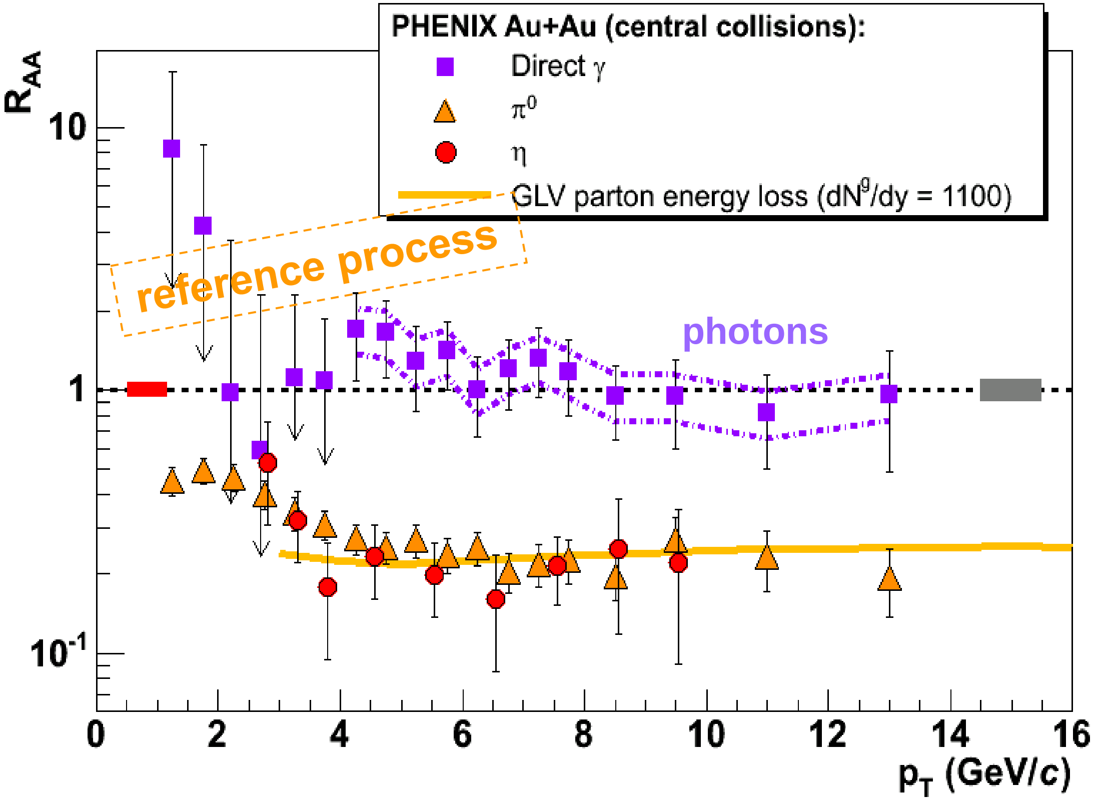
Analyze by measuring (azimuthal) angle between pairs of particles



- **In Au-Au collisions we see only one “jet” at a time !**
- **How can this happen ?**
- **Jet quenching!**



The nuclear modification factor: R_{AA}



If $R_{AA} < 1$ at high p_T

→ **the medium is opaque to the passage of partons**

→ parton-medium final state interactions, energy loss, modification of fragmentation in the medium

$R_{AA} = 1$ at high p_T

→ the medium is transparent to the passage of partons

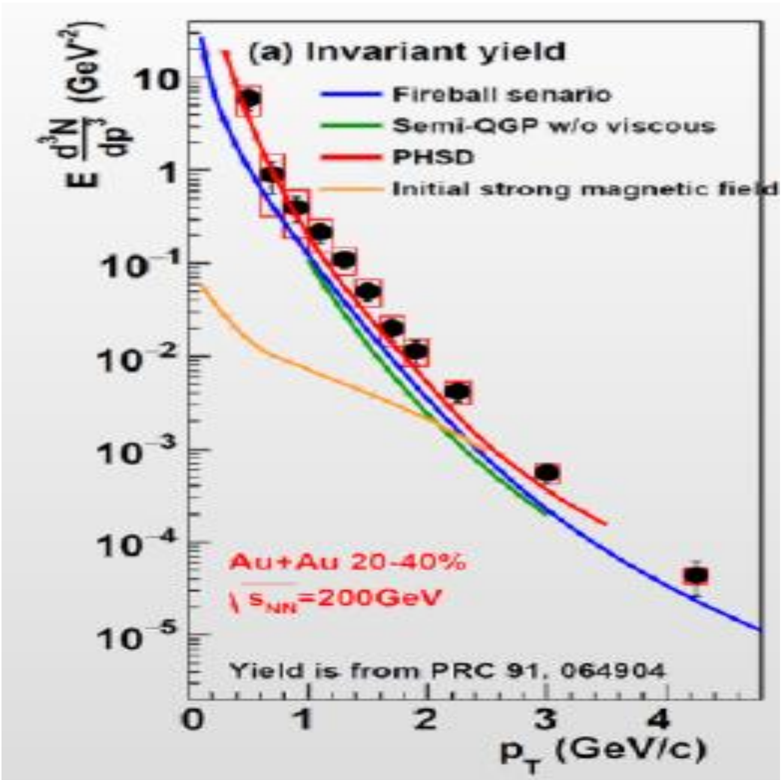
$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{coll} \cdot dN_{pp}/dp_T}$$

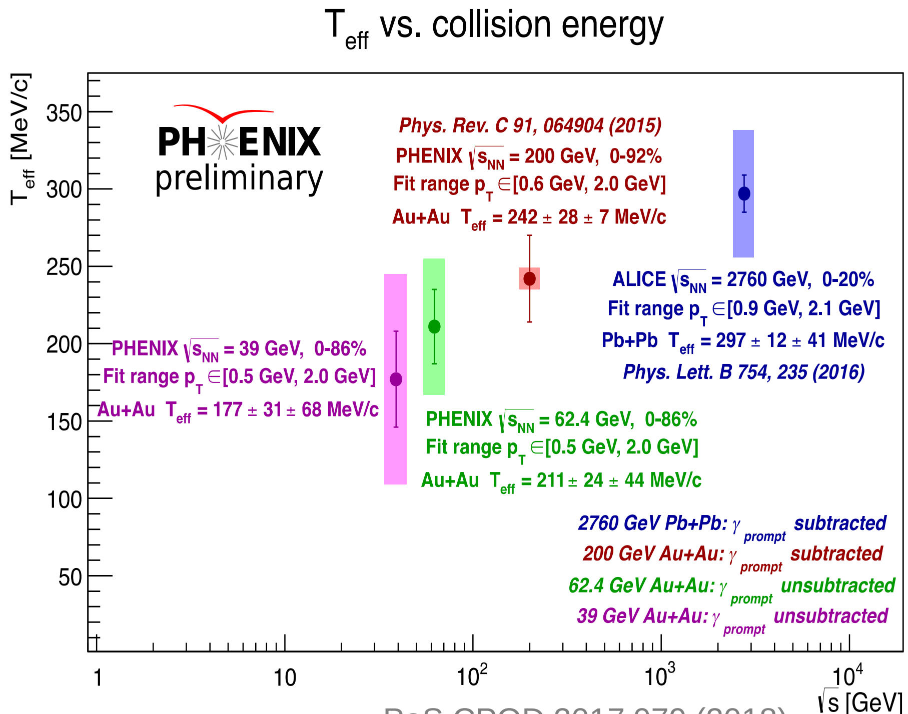
The **meson yield** in central Au-Au is 5 times lower than expected from pp collisions

the **direct photons** are not affected by the dense medium


Medium is hot
Hundreds of thousands of times hotter than the Sun !
Image credit : NASA

Thermal photons in A+A collisions





PoS CPOD 2017 079 (2018)

- Measure the spectrum of thermal photons (non-interacting) emitted from the source.
- The spectrum will display the average temperature over the full lifetime of the partonic source.
- Determining the initial temperature requires modeling.

p_T slope ⇒ Temperature

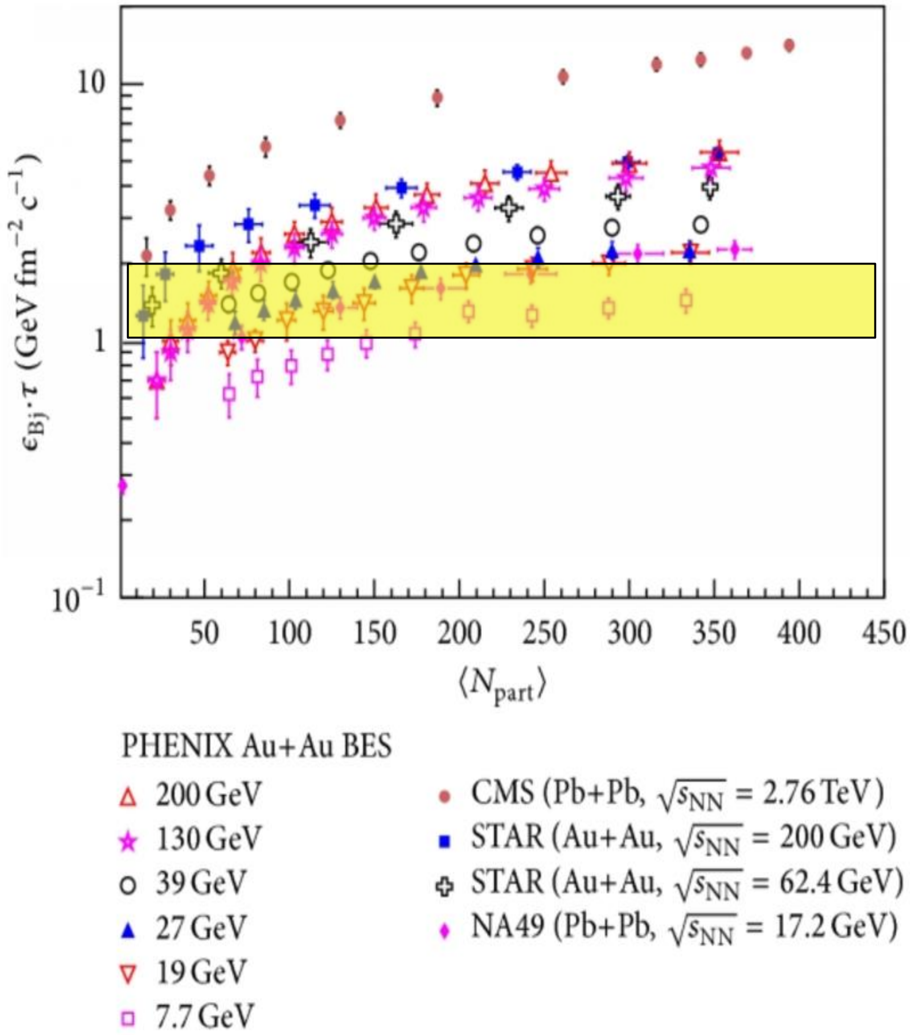
PHENIX: T = 221±19±19 MeV

Critical condition for QGP satisfied.

Medium is dense

Pack the entire Earth inside a stadium !

Energy Density



$$\varepsilon_0 = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

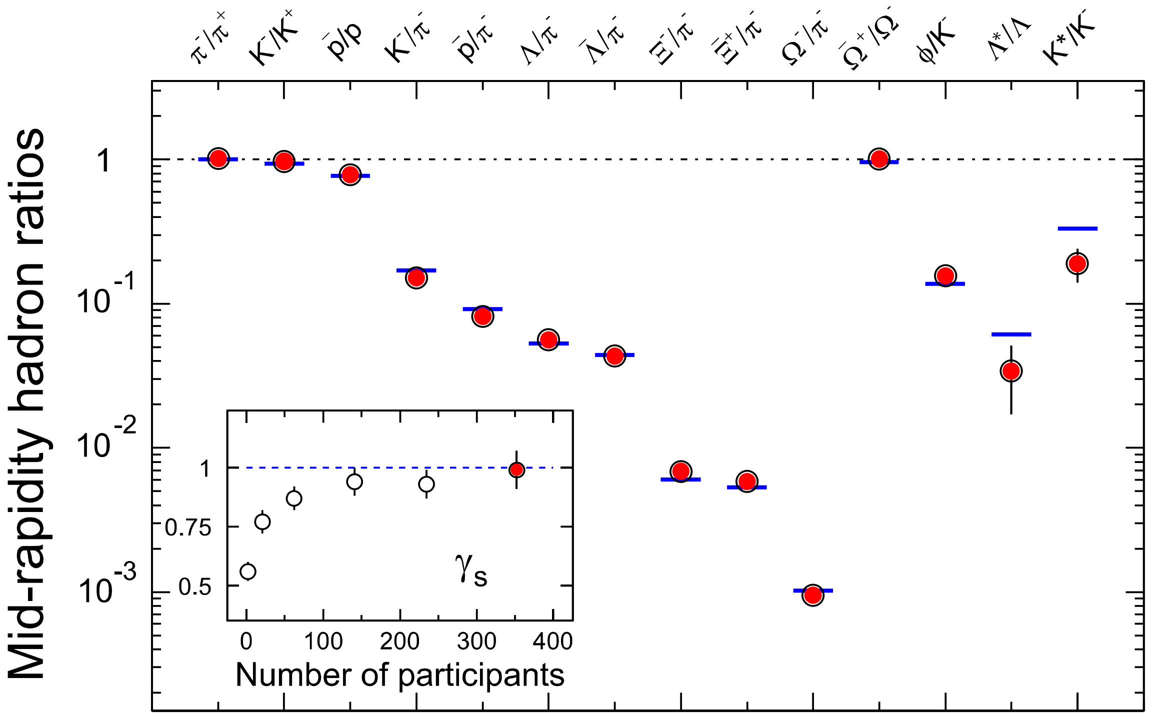
$$\tau_0 \sim 1 \text{ fm}/c,\ R \approx 1.2 A^{1/3} \text{ fm}$$

$$\varepsilon_0 = 4.9 \pm 0.3 \text{ GeV/fm}^3$$

Critical condition for QGP satisfied.

Chemical and Thermal Equilibrium?

Particle yields freeze



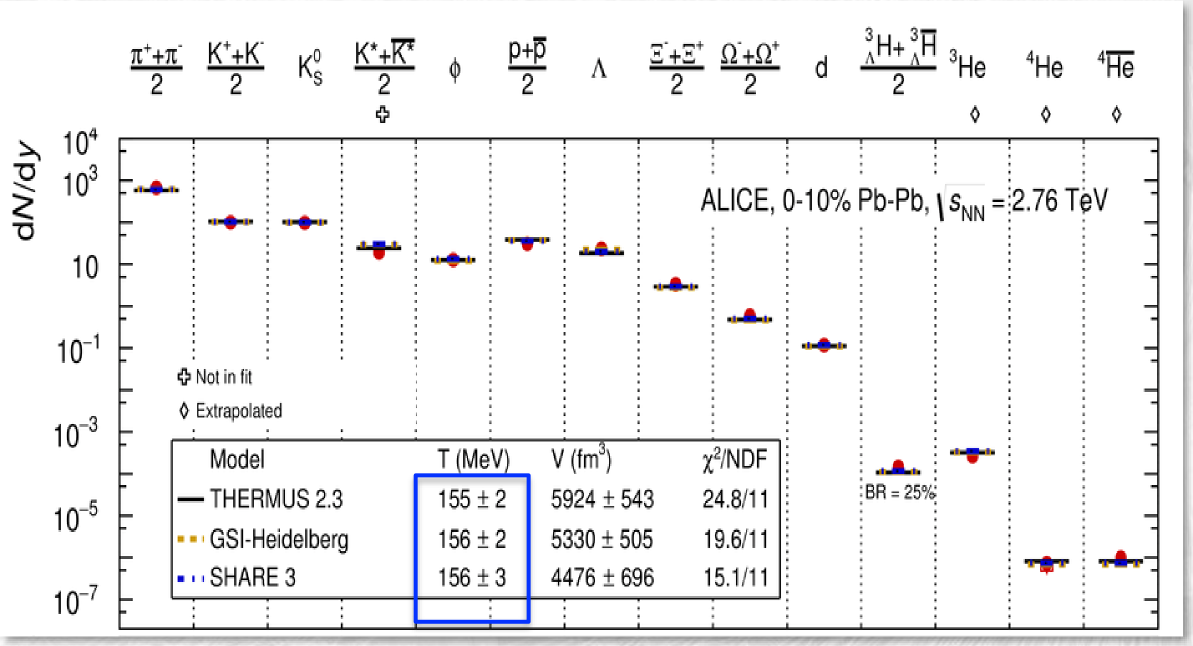
200 GeV ^{197}Au + ^{197}Au central collision

STAR, NPA 757 102 (2005)

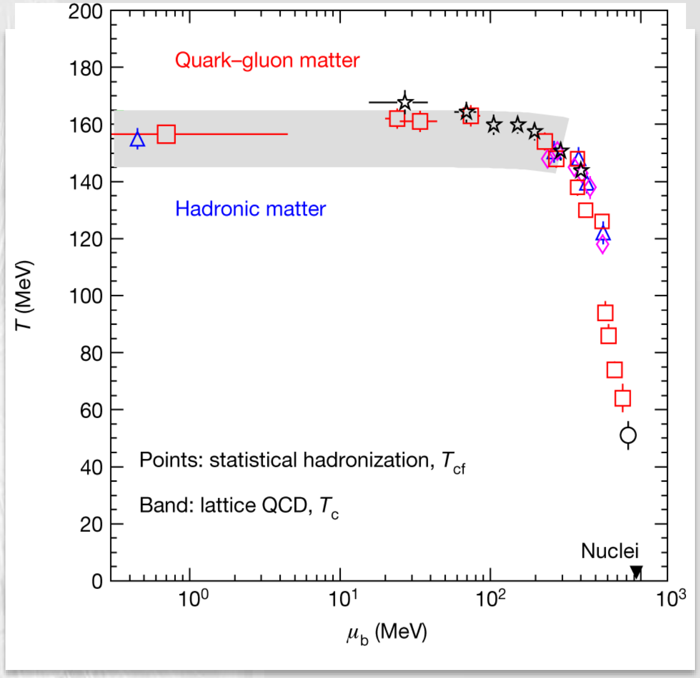
Particle ratios described very well by statistical model assuming thermal and chemical equilibrium

Chemical freeze-out temperature - LHC

Nature volume 561, pages 321–330 (2018)



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11



Production of (most) light-flavour hadrons (and anti-nuclei) is described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out temperature, T_{ch} ≈ 156 MeV**

→ Approaches the critical temperature roof from lattice QCD: limiting temperature for hadrons!

→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system **in local thermodynamical equilibrium**

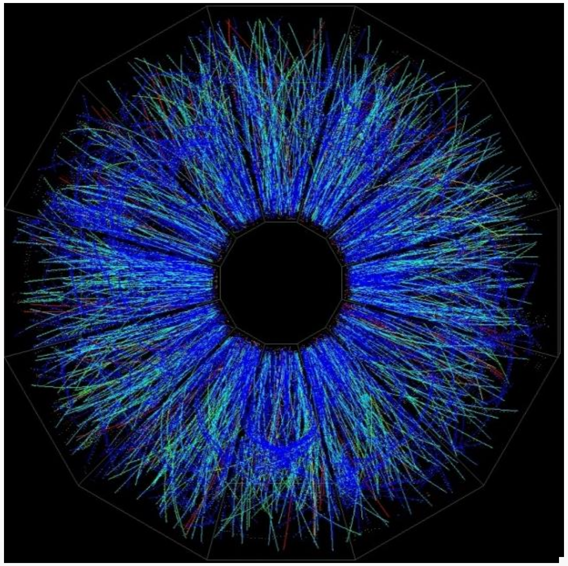
It’s perfect liquid

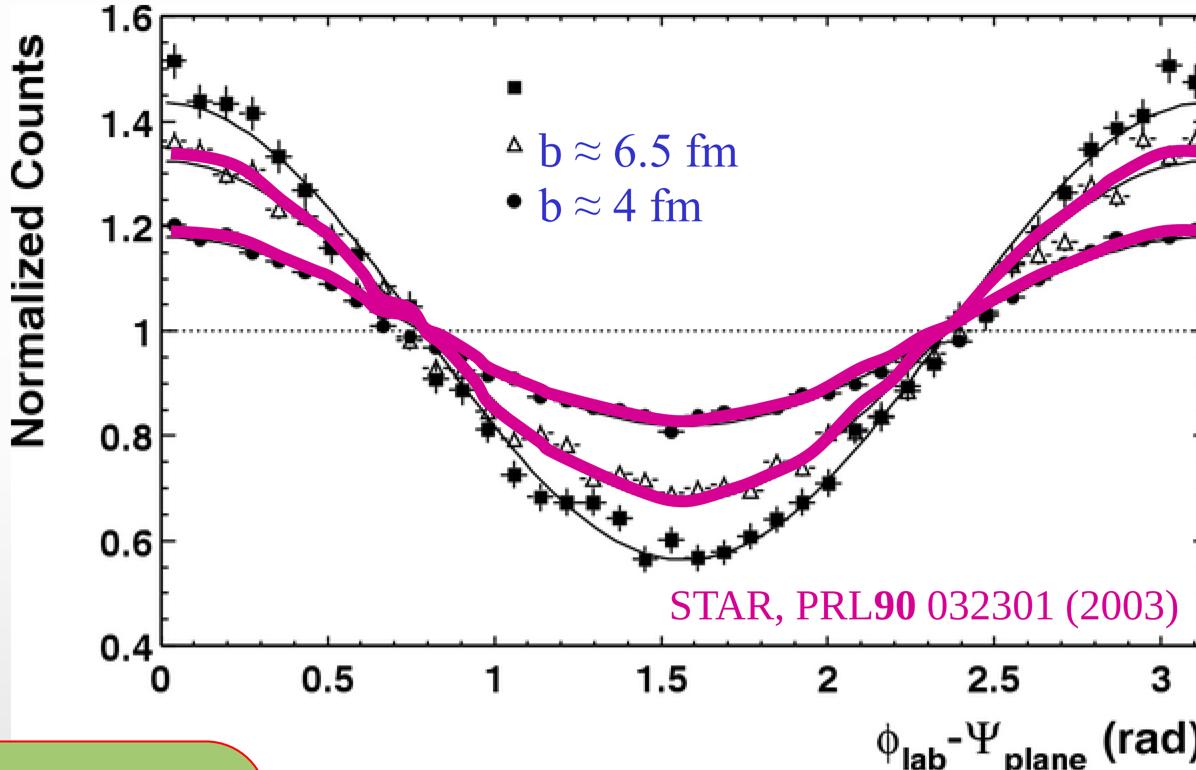
Lowest viscosity possible !

Image credit : SmileTemplates

Azimuthal distributions at RHIC

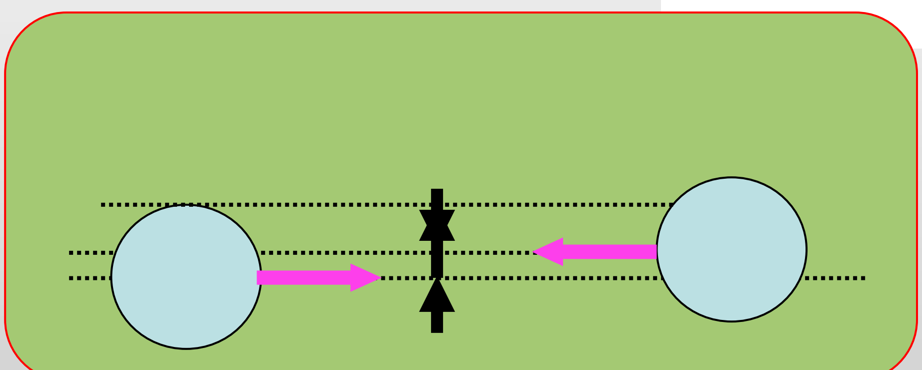
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

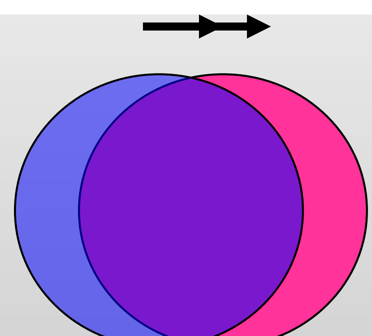




mid-central collisions

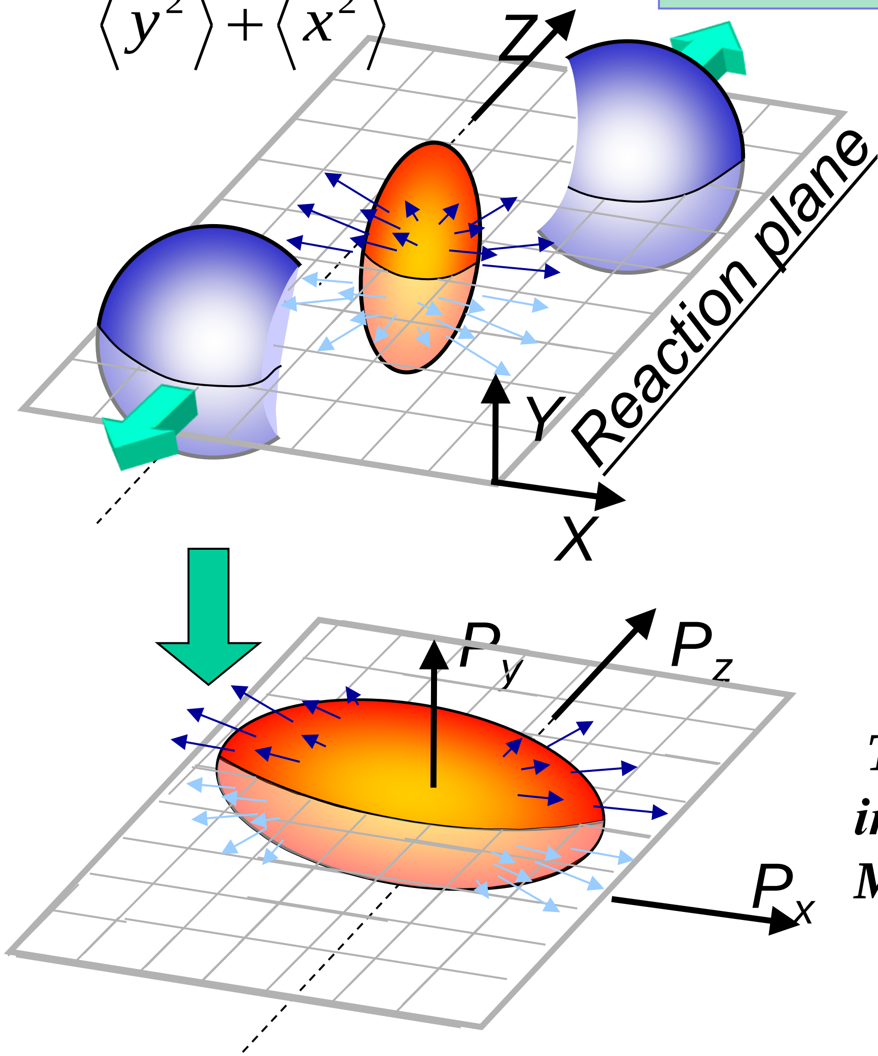
“central” collisions





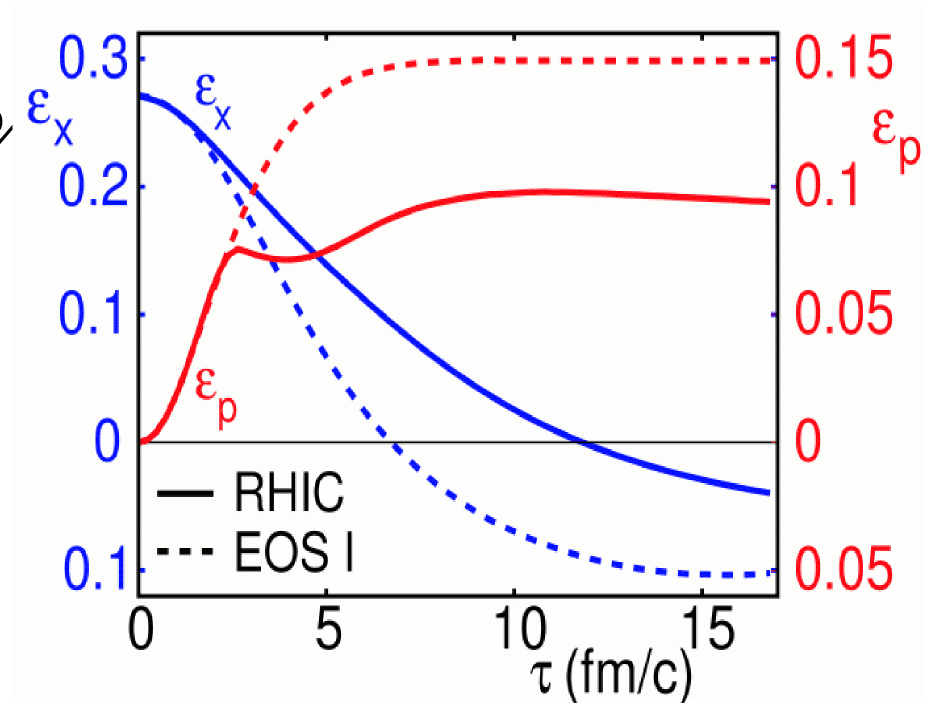
2005 - Elliptic Flow at RHIC

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$



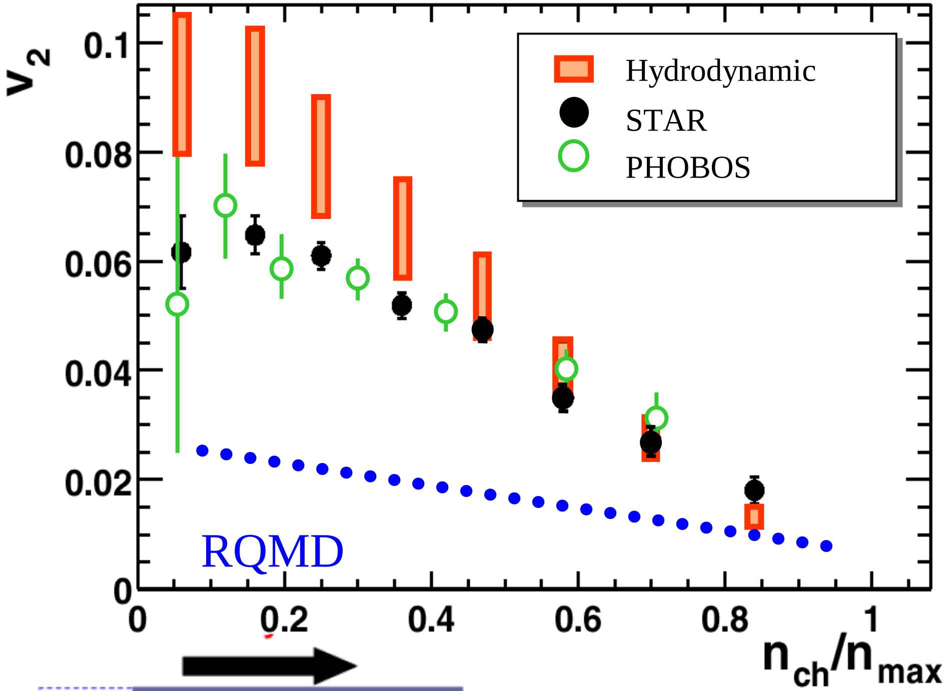
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

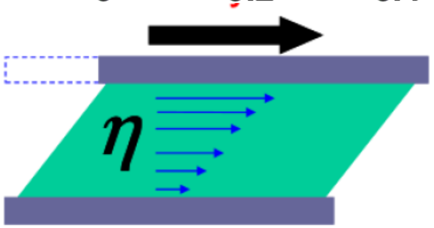
$$v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle$$

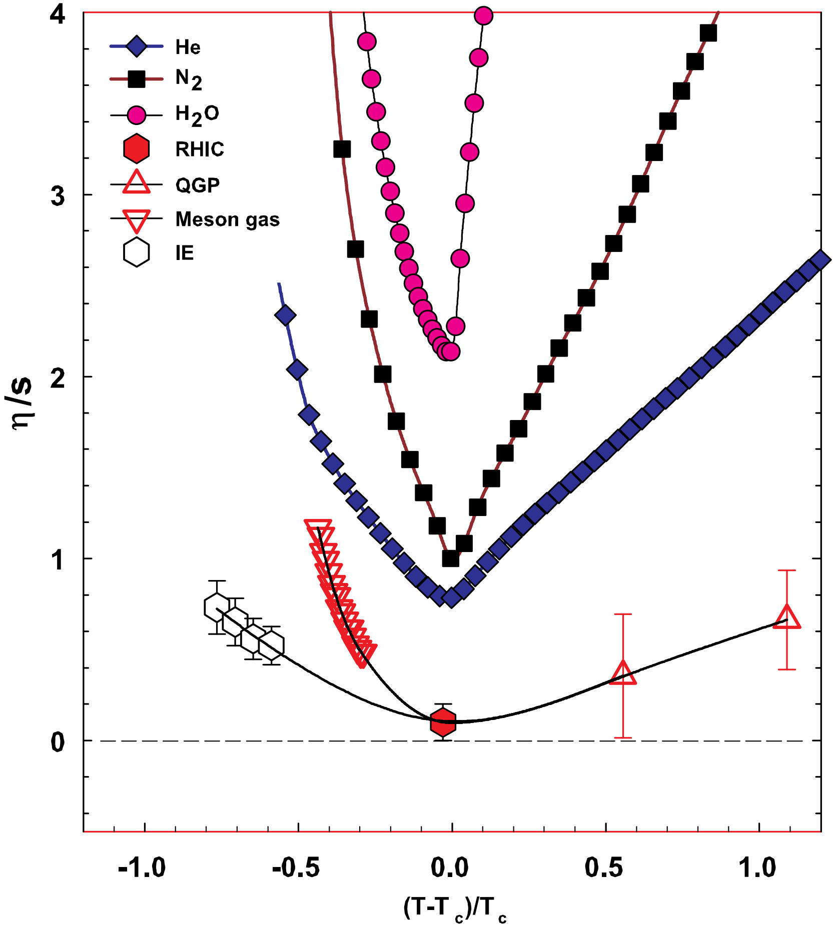


The initial spatial anisotropy evolves (via interactions and density gradients) → Momentum-space anisotropy

Perfect Liquid at RHIC





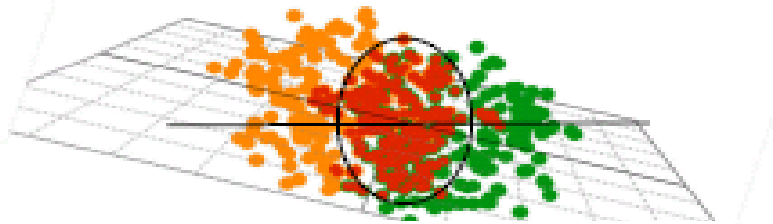


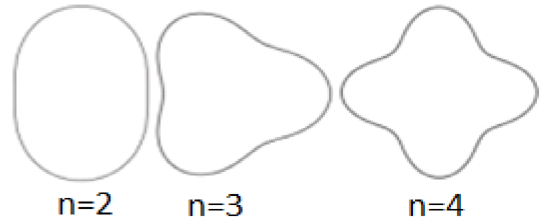
R. Lacey , A. Taranenko, PRL 98 092301 (2007)

Shear Viscosity – resistance to deformation, flow

Data approaching Hydro for central collisions viscosity extracted close to the lowest value set by quantum limit.

Anisotropic Flow at RHIC-LHC

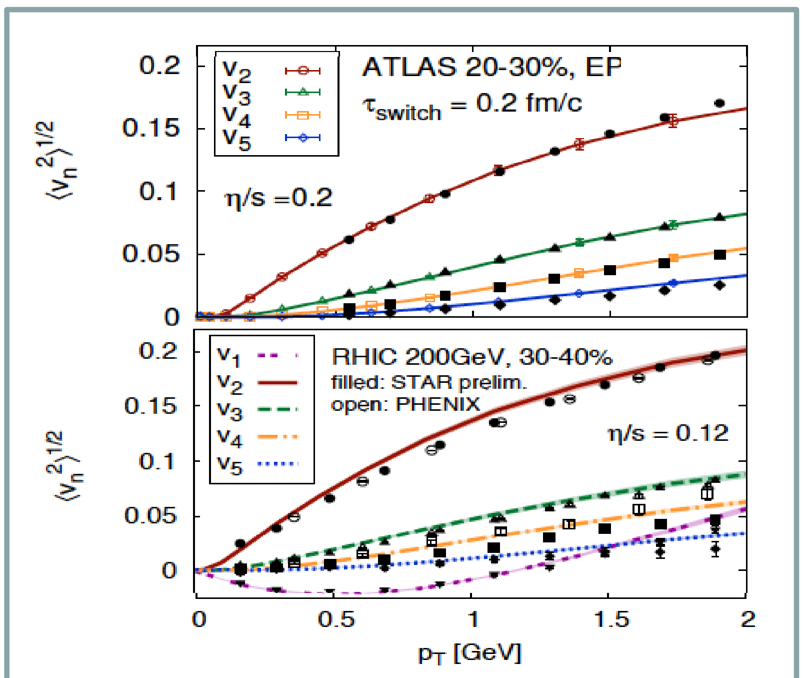




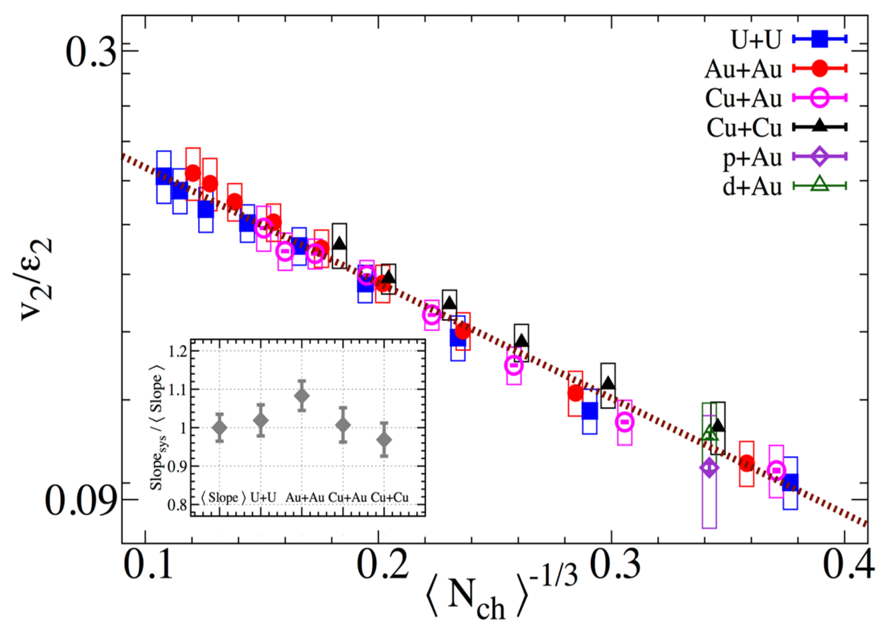
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}} \Rightarrow \frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



Phys. Rev. Lett. 122 (2019) 172301



It’s partons unchained?

Partonic degree of freedom at work ?

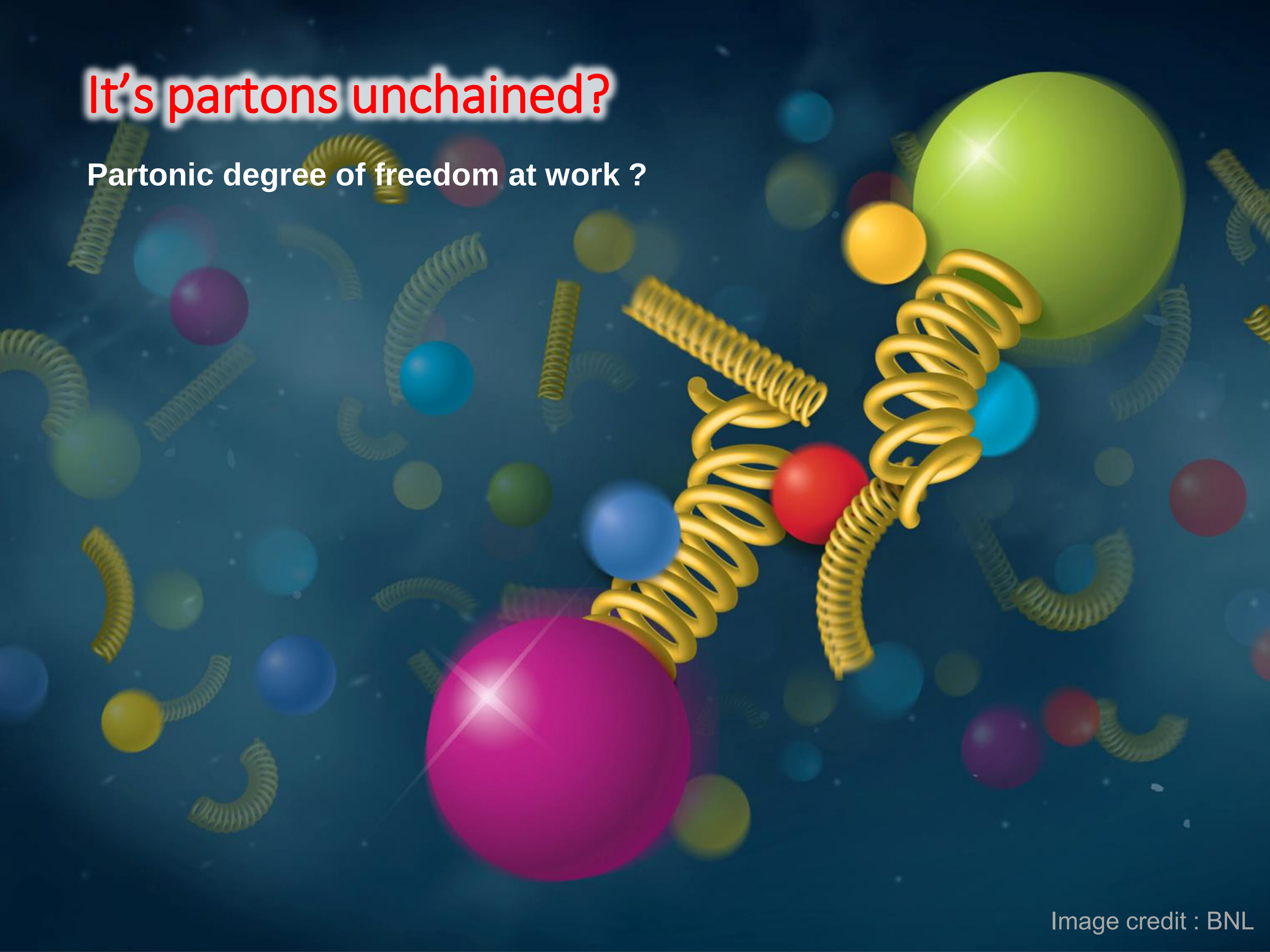
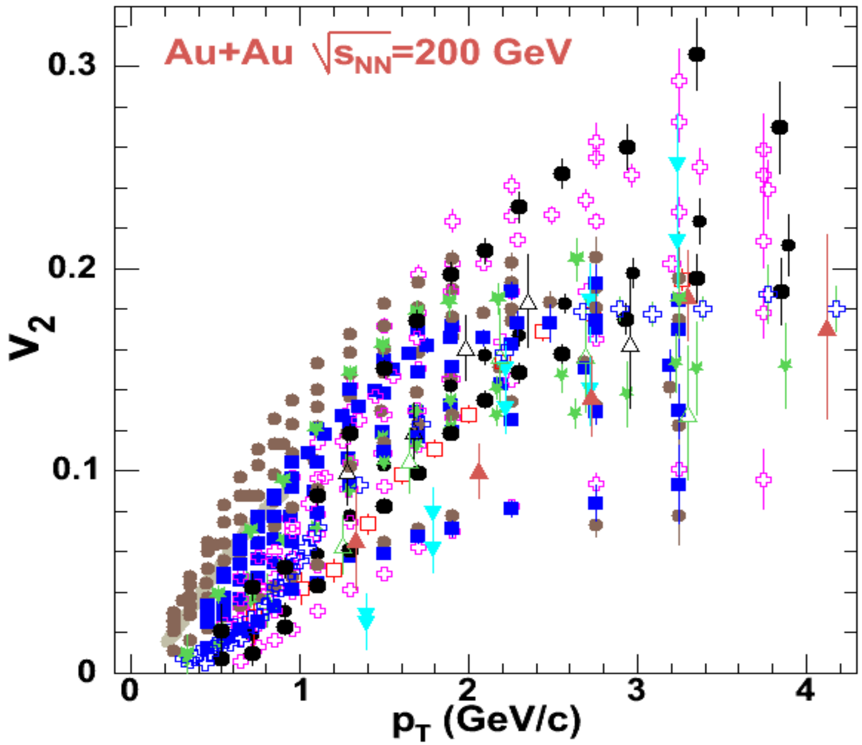


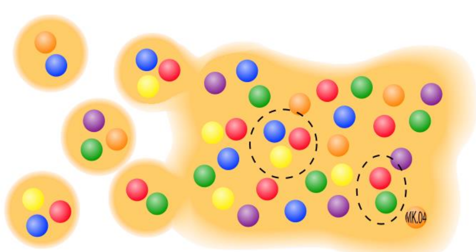
Image credit : BNL

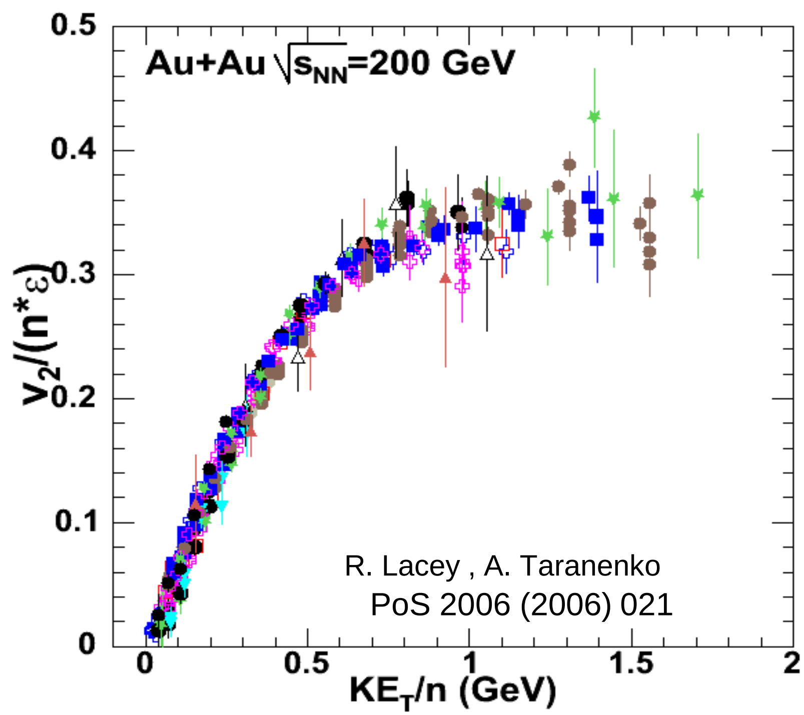
Anisotropic Flow at RHIC – partonic?



PHENIX	(Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)
● - $\pi^+ + \pi^-$:	min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
■ - $K^+ + K^-$:	min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
✚ - $p+\bar{p}$:	min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
▼ - d :	min.bias, 10-50%
△ - ϕ :	20-60%
STAR	(Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)
● - $\pi^+ + \pi^-$:	min.bias
★ - K^0_S :	min.bias, 5-30%,30-70%
✚ - $p+\bar{p}$:	min.bias
● - $\Lambda+\bar{\Lambda}$:	min.bias, 5-30%,30-70%
□ - $\Xi+\bar{\Xi}$:	min.bias
▲ - $\Omega+\bar{\Omega}$:	min.bias
△ - ϕ :	min.bias

$$KE_T = m\,(\gamma_T - 1) = m_T - m$$

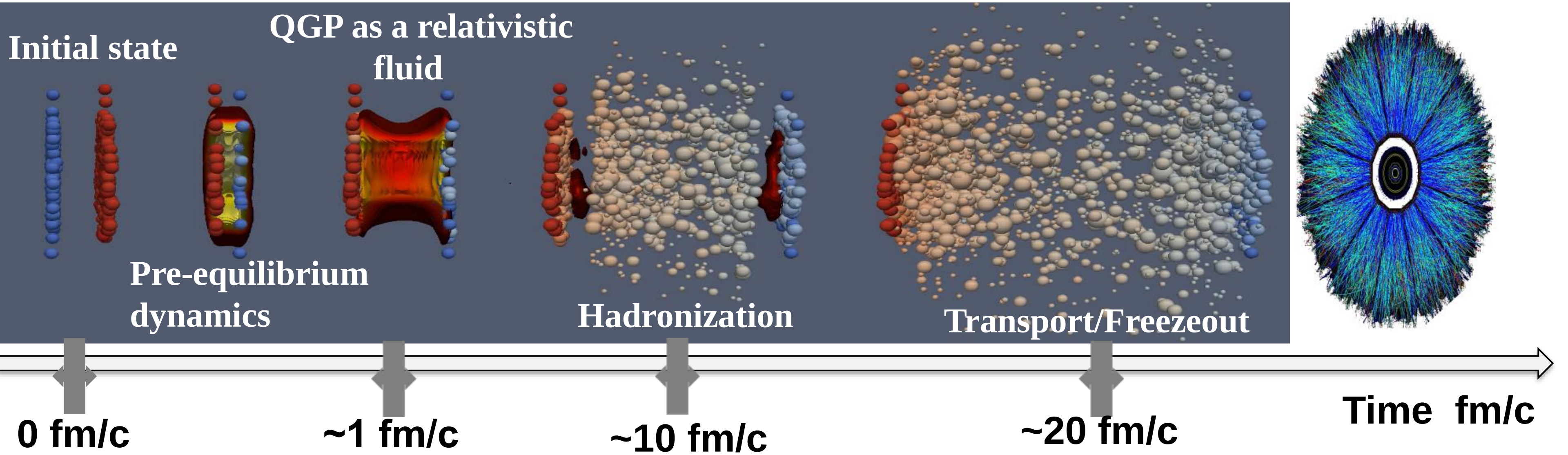




n=2 for mesons and
n=3 for baryons

Evolution of the system created in RHIC

Fireball is ~10^{-15} meters across and lives for ~10^{-23} seconds



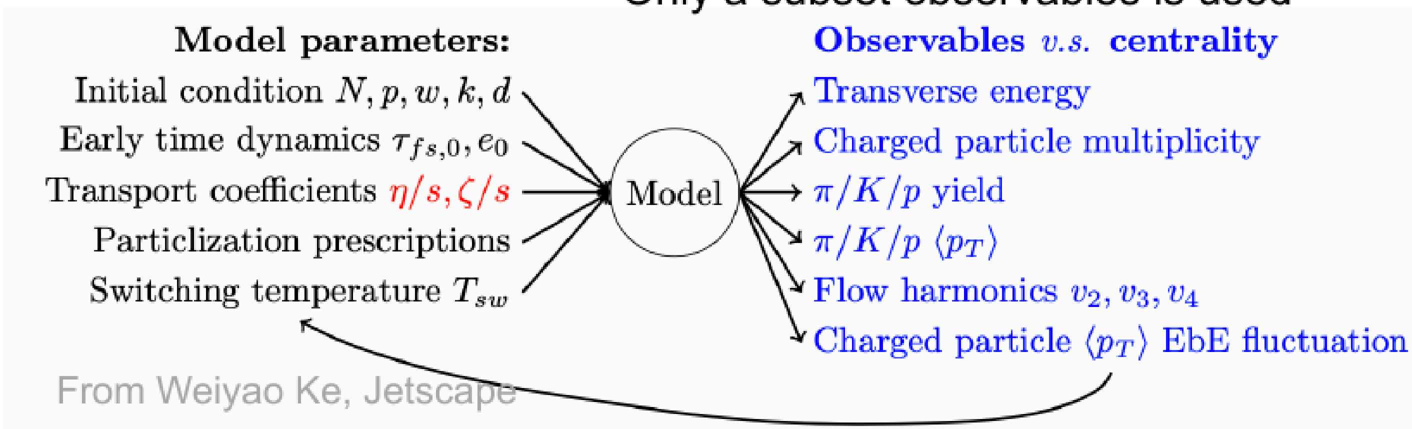
- **Initial state** (heavy Au+Au or Pb+Pb nuclei Lorentz contracted by γ~100 – RHIC, γ~ 1400 – LHC)
- **Pre-equilibrium state:** hard parton scattering & jet production
- **Quark-gluon plasma formation:** thermalization (viscous hydrodynamics)
- **Hadronization**
- **Transport/Freeze-out:** Rescattering & chemical freeze-out, Kinetic freeze-out (stop interacting)

~400 nucleons in 10^{-22} seconds = 1000-30000 hadrons

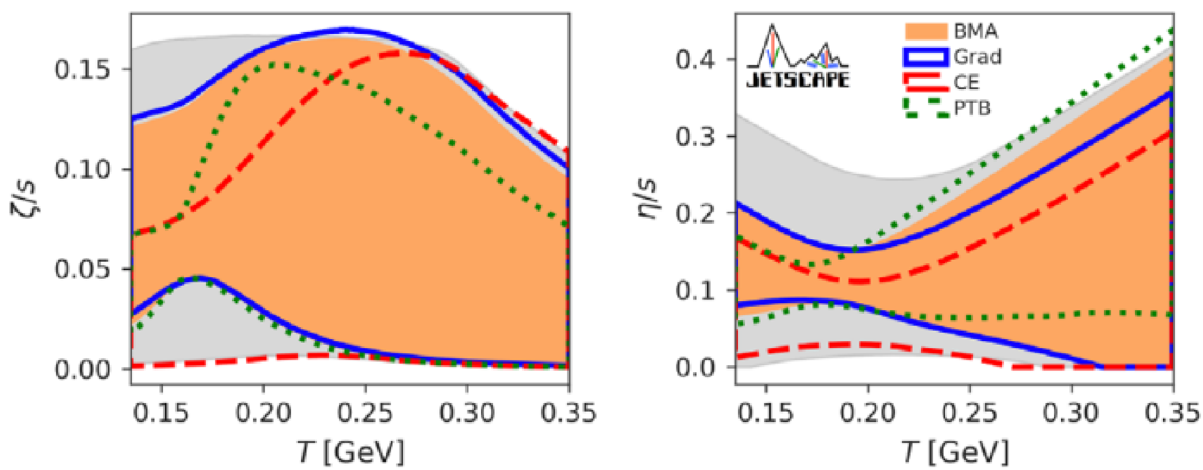
State-of-the-art modeling of HI collisions

- Data-model comparison via Bayesian inference to optimize constraining power.

Only a subset observables is used



- Detailed temperature dependence of viscosity!

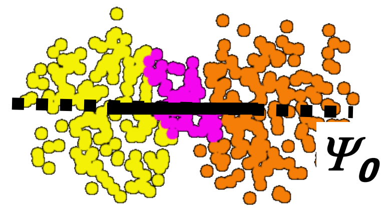


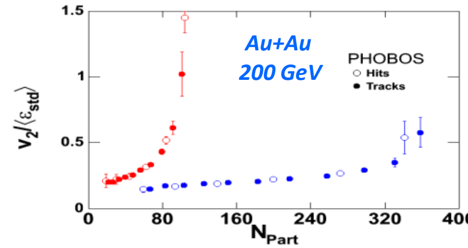
Jetscape PRL.126.242301
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

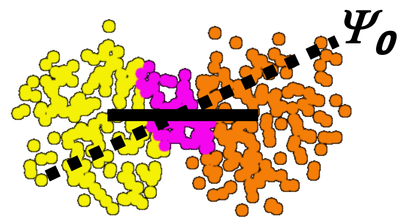
System size scan at top RHIC energy ($\sqrt{s_{NN}}$= 200 GeV)

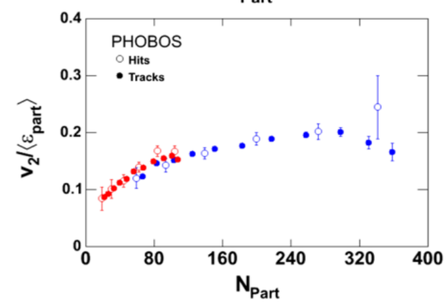
2001-2005 $\varepsilon_{\rm std} = \frac{\sigma_y^2-\sigma_x^2}{\sigma_x^2+\sigma_y^2}$



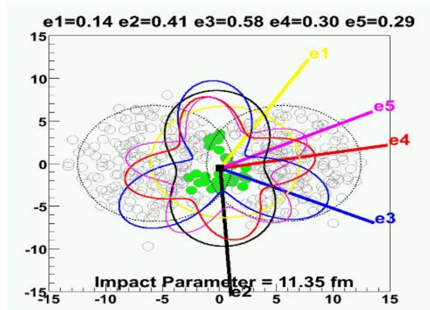


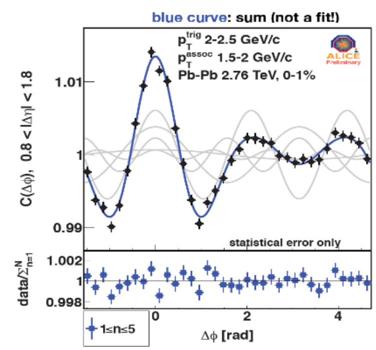
2005-2011 $\langle\epsilon_{\rm part}\rangle = \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{(\sigma_y^2+\sigma_x^2)}$





2011-2012 $\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$

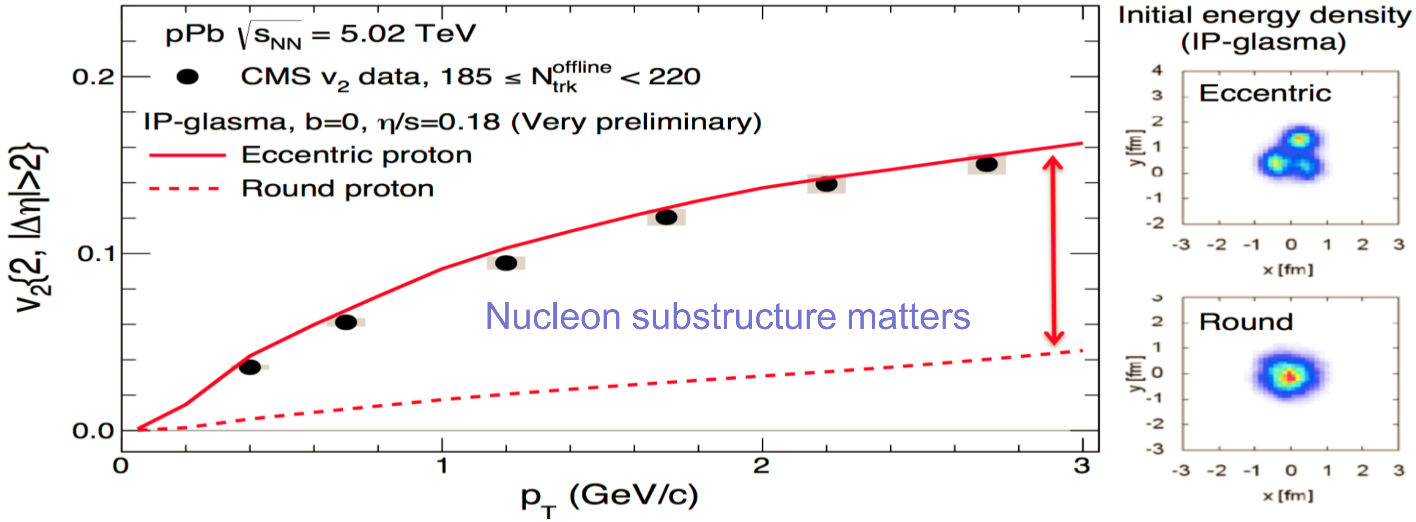




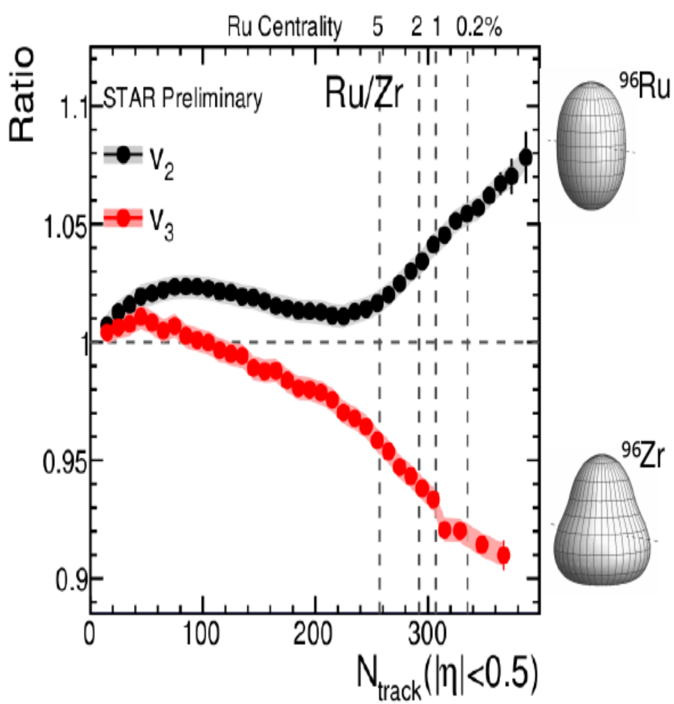
For "lumpy" *profile* $\varphi \neq \varphi + \pi$

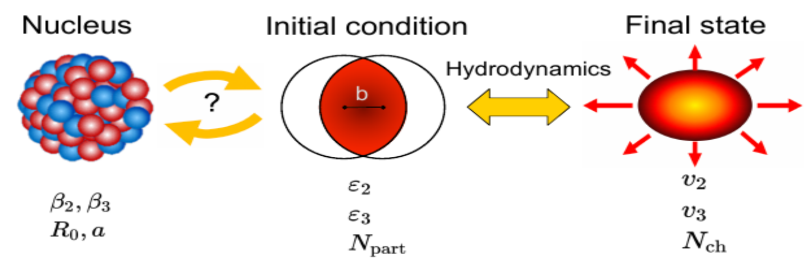
Odd harmonics ≠ 0

2011-2016

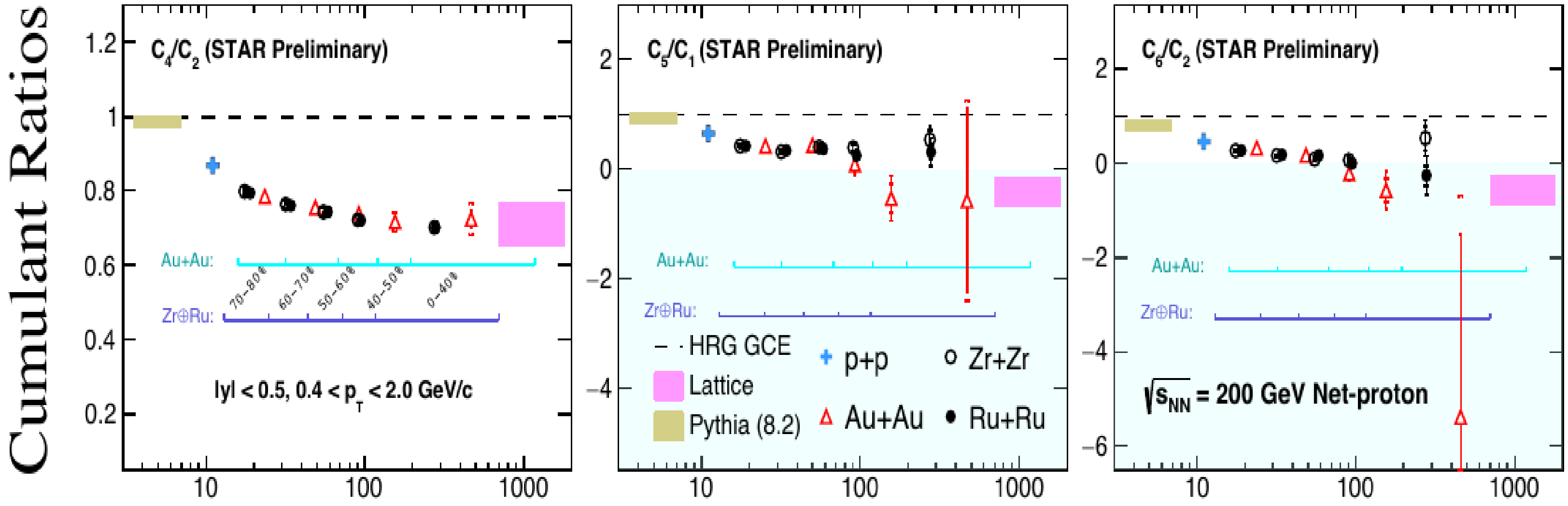


2020-2022





Net-p in 200 GeV p+p and Au+Au Collisions



STAR: CPOD2021, SQM2021, QM2022

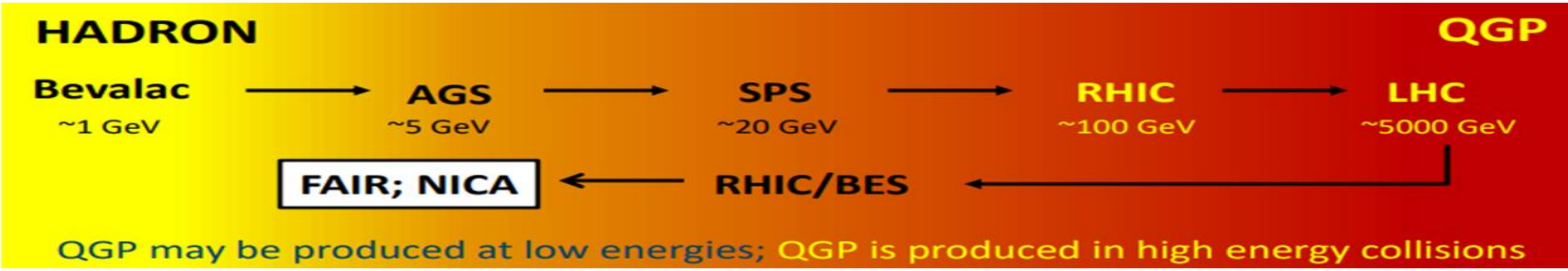
1) In 200GeV p+p collisions, high order cumulants ratios of net-protons are found to be positive for: C_4/C_2, C_5/C_2 and C_6/C_2;

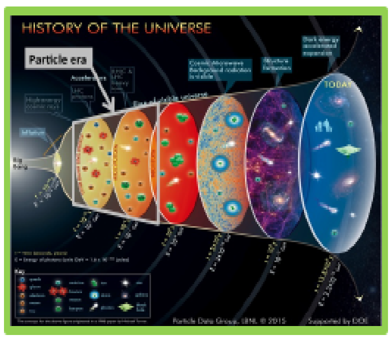
2) For QGP matter, LGT predicted negative net-baryon C_5/C_2 and C_6/C_2;

3) **Direct evidence for the QGP formation in 200GeV Au+Au central collisions!**

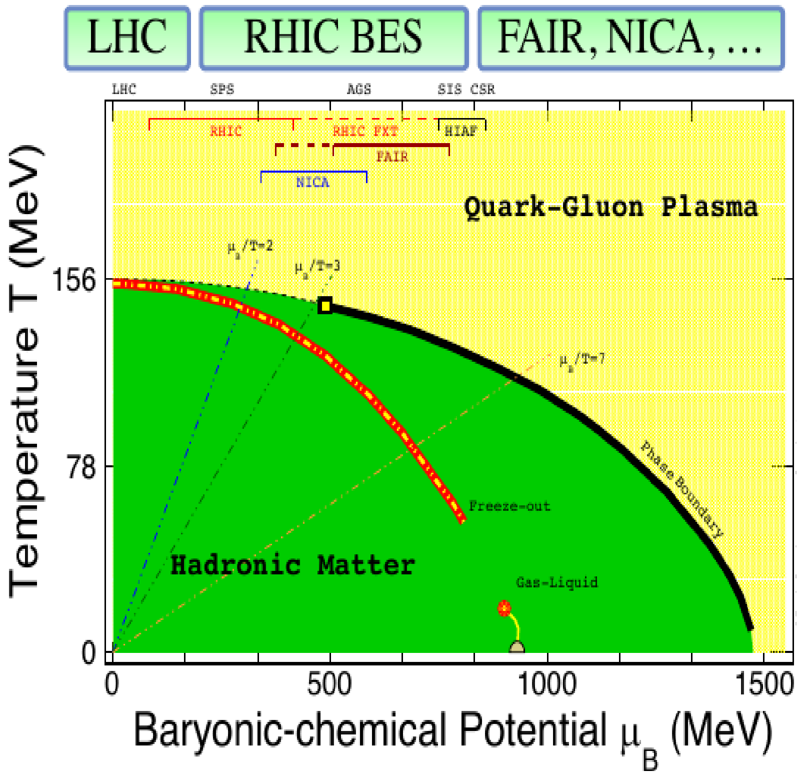
HotQCD Collaboration, PR**D101**, 074502 (2020)

Relativistic Heavy-Ion Collisions and QCD Phase Diagram

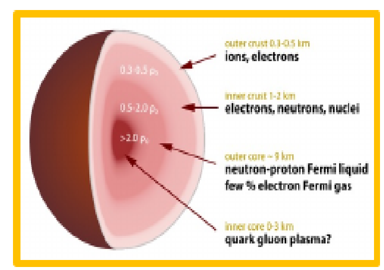




High temperature:
Early Universe evolution



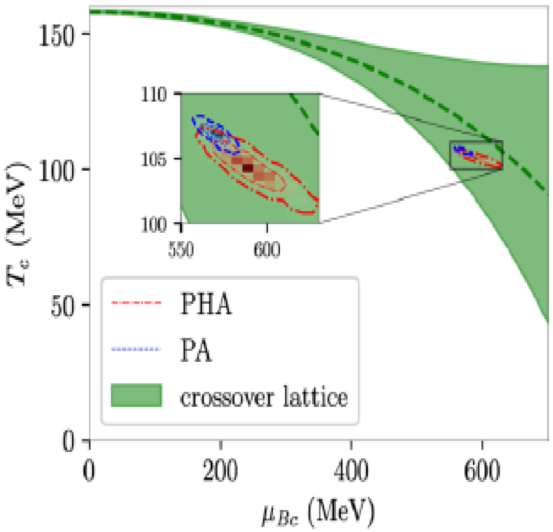
High baryon density:
Inner structure of
compact stars

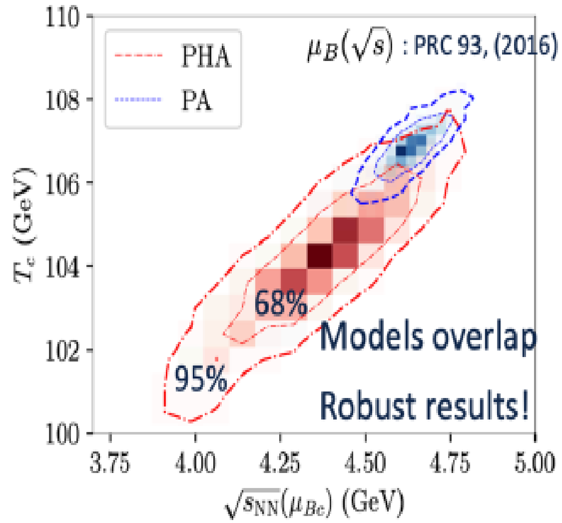


1) At $\mu_B = 0$, smooth crossover (LGT + data) ;

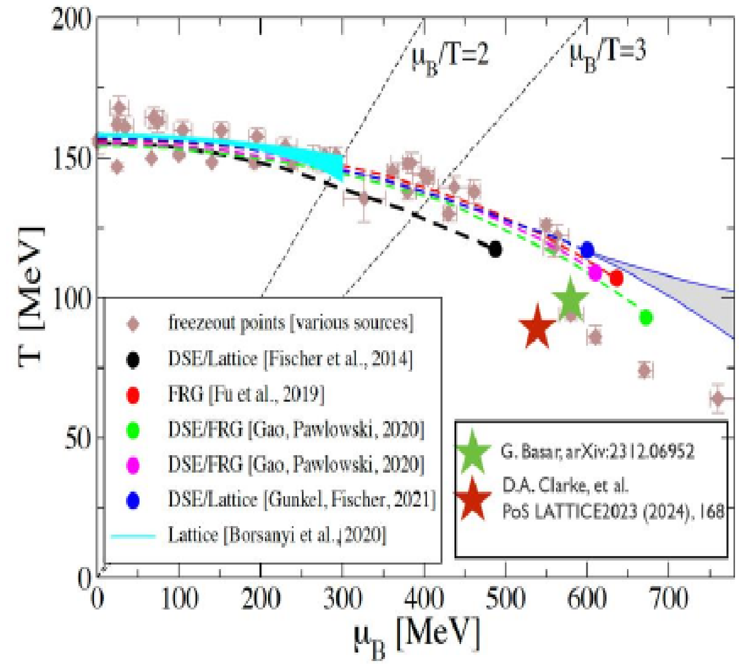
2) Large μ_B, 1st order phase transition → **QCD critical point**

Location of the QCD Critical Point : Theoretical Estimation/Prediction





Holography+ Bayesian : Hippert et al., arXiv : 2309.00579



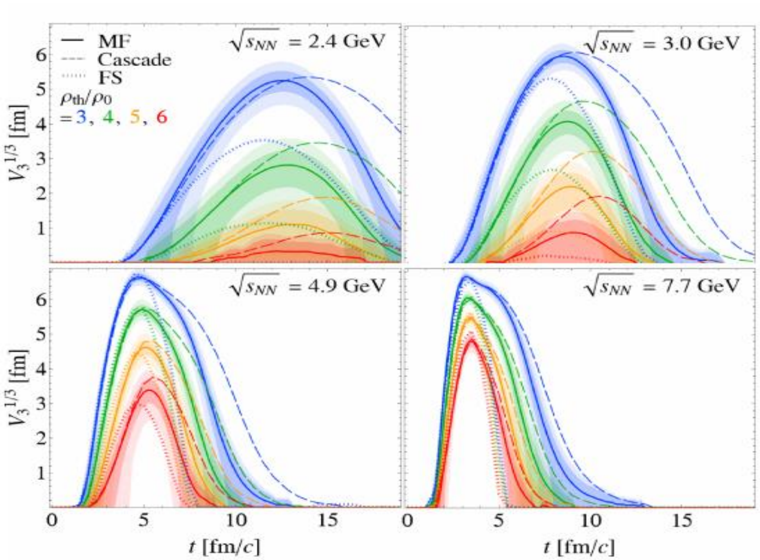
CPOD2024

Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

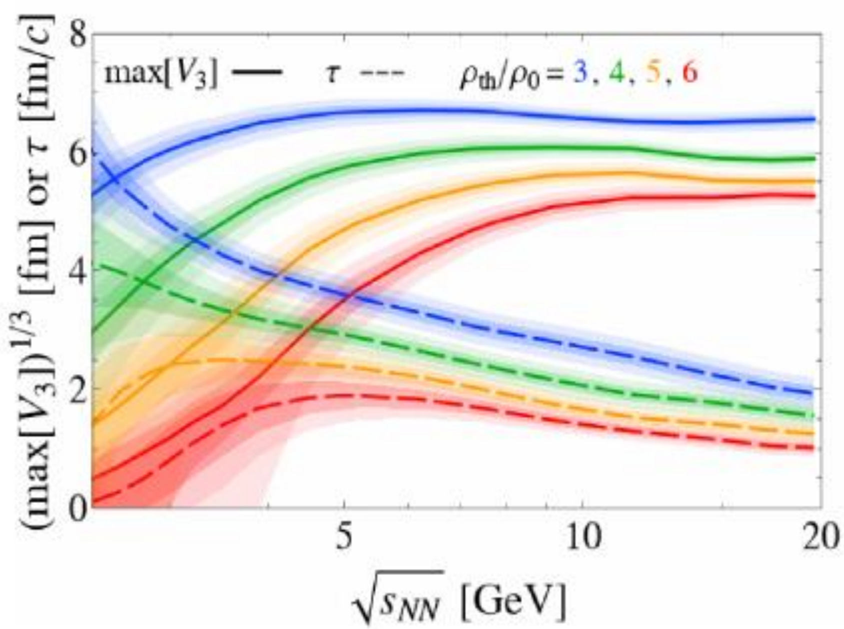
(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

Optimal collision energy for realizing high baryon-density matter

H. Taya, A. Jinno, M. Kitazawa, Y. Nara https://arxiv.org/abs/2409.07685



Dense region disappears more quickly for larger $\sqrt{s_{NN}}$



$\sqrt{s_{NN}}$ dependence of the maximum volume max[V3] (solid) and the lifetime τ (dashed)

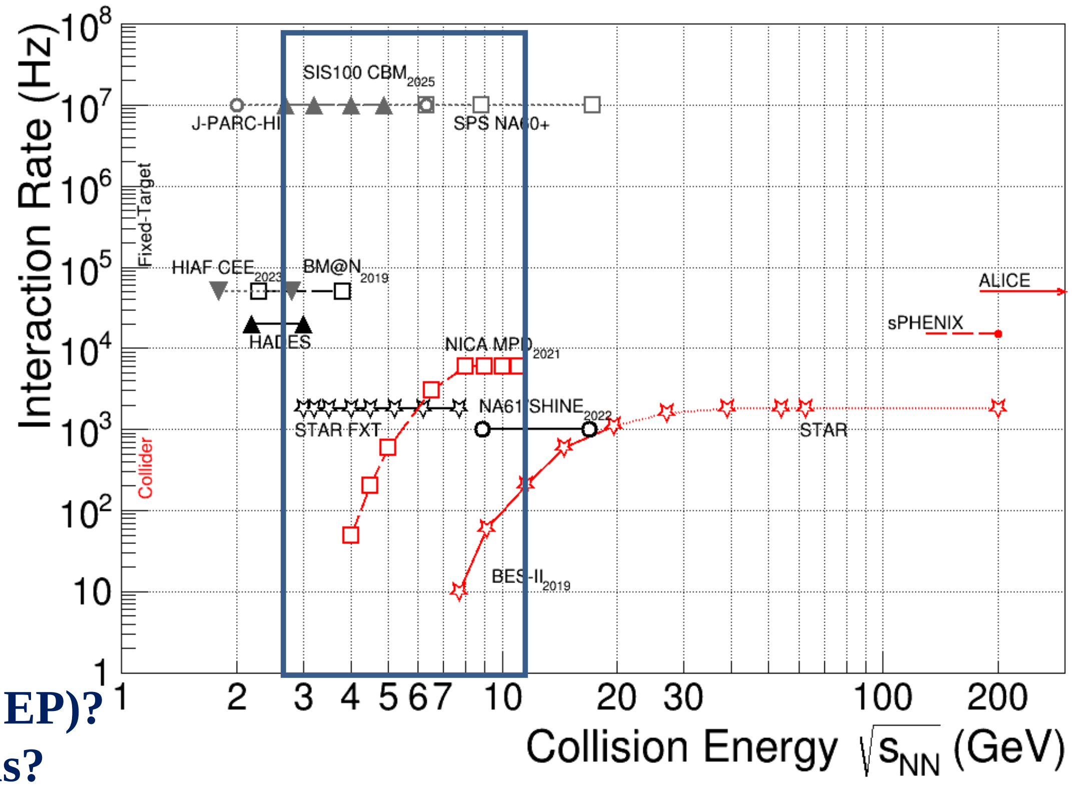
The optimal energy is around $\sqrt{s_{NN}}$=3−5 GeV, where a baryon density ρ/ρ_0 = 3 nuclear density is realized with a substantially large space-time volume. Higher and lower energies are disfavored due to short lifetime and low density

Collision Energy and System Scan Programs

HADES BES (SIS): Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV, Ag+Ag at $\sqrt{s_{NN}}$ = 2.42 GeV, 2.55 GeV.

STAR BES (RHIC): Au+Au at $\sqrt{s_{NN}}$ = 3-200 GeV

NA61/SHINE (SPS): Be+Be, Ar+Sc, Xe+La, Pb+Pb at $\sqrt{s_{NN}}$ = 5.1-17.3 GeV



- Map turn-off of QGP signatures
- Location of the Critical End Point (CEP)?
- Location of phase coexistence regions?
- 1st order phase transition signs
- Detailed properties of each phase?

$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

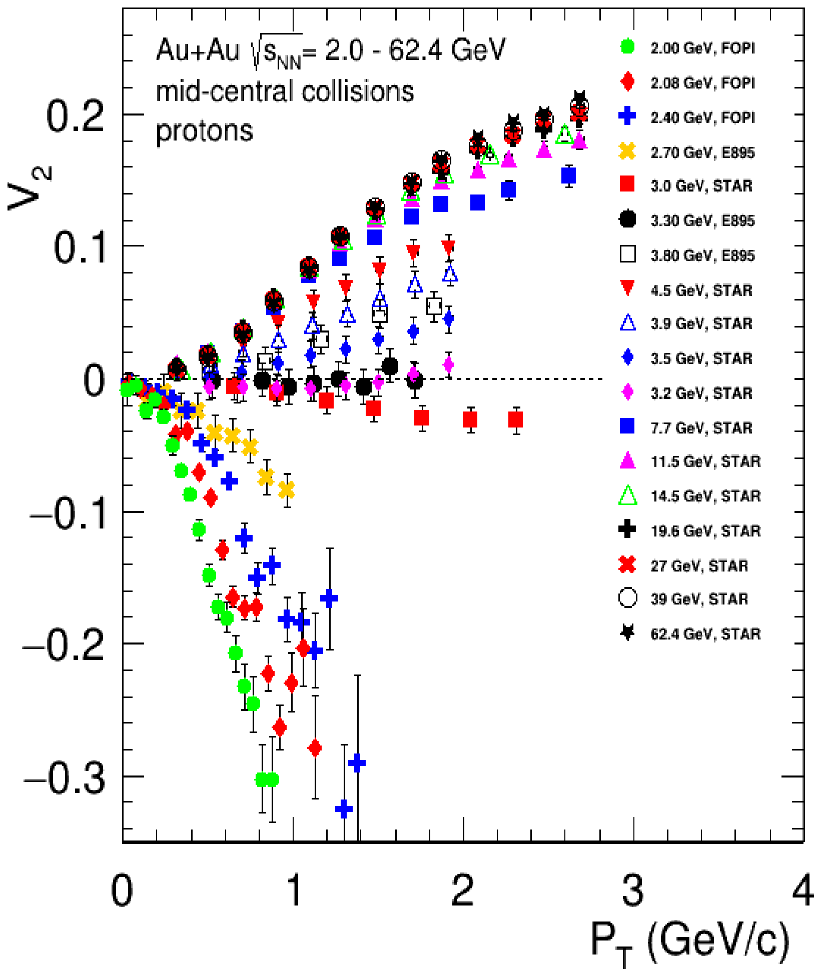
STAR BES-I and BES-II Data Sets

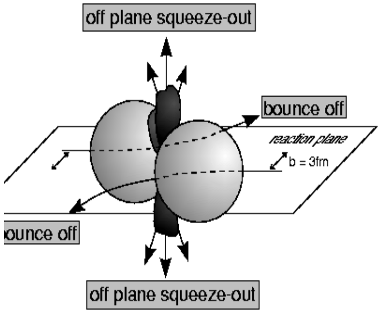
Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	3.0 (3.85)	2000 M	750 MeV	-1.05	Run-18, 21

Precision data to map the QCD phase diagram

$3 < \sqrt{s_{NN}} < 200$ GeV; $750 < \mu_B < 25$ MeV

Beam Energy Dependence of Elliptic Flow (v_2)



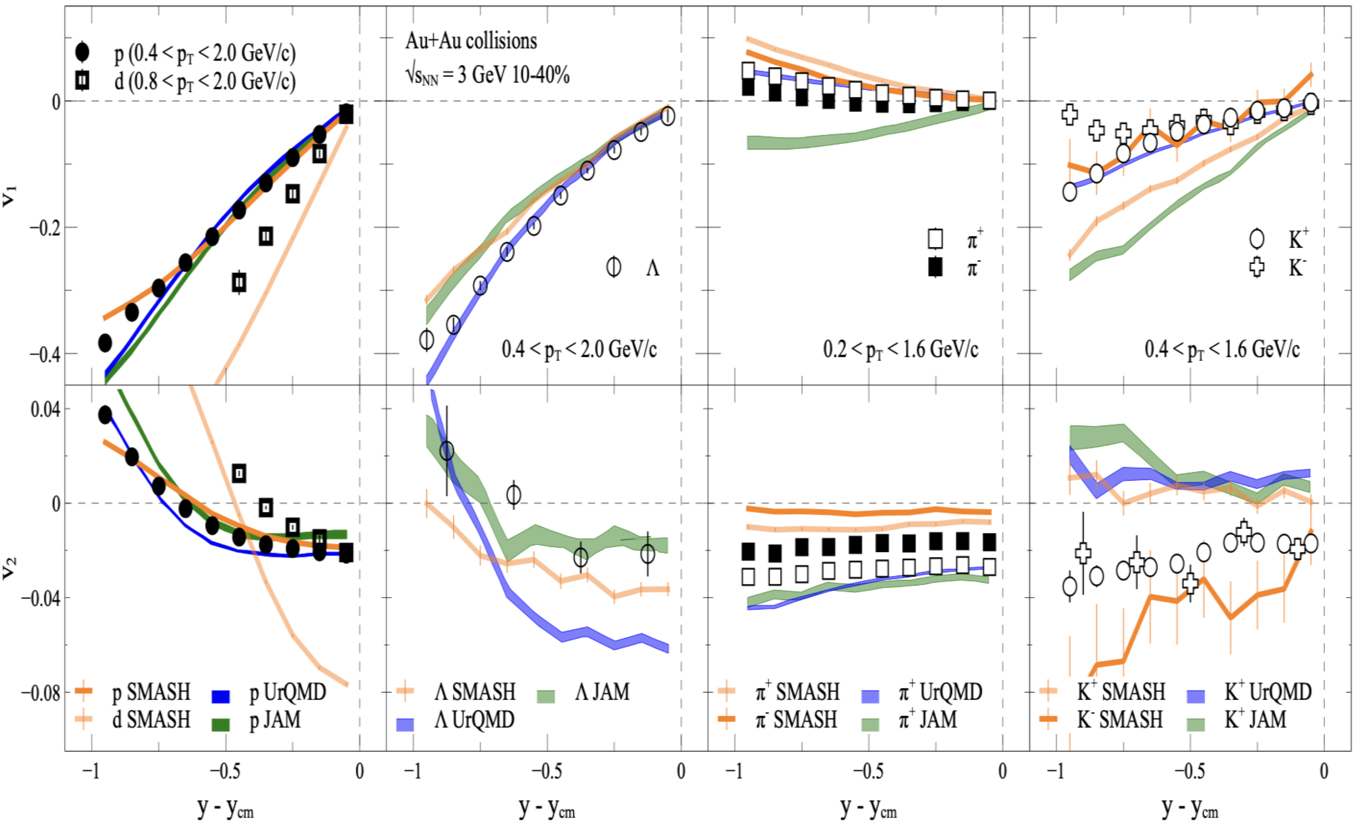


Passage time: $2R/(\beta_{cm}\gamma_{cm})$
Expansion time: R/c_s
$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound

- **Strong energy dependence of v_2 at $\sqrt{s_{NN}}$ = 3-11 GeV**
  - $v_2 \approx 0$ at $\sqrt{s_{NN}}$ = 3.3 GeV and negative below

$v_{1,2}(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: models vs. STAR data

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080



Model description of v_n:

- Good overall agreement for v_n of protons
- v_n of light nuclei is not described
- v_n of Λ is not well described
  - nucleon-hyperon and hyperon-hyperon interactions
- Light mesons (π,K) are not described
  - No mean-field for mesons

Models have a huge room for improvement in terms of describing v_n

Observables: Higher Moments of Conserved Charge Distributions

Conserved Charges: Net Baryon Number (B), Net Charge (Q), Net Strangeness (S)

Measured multiplicity N, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

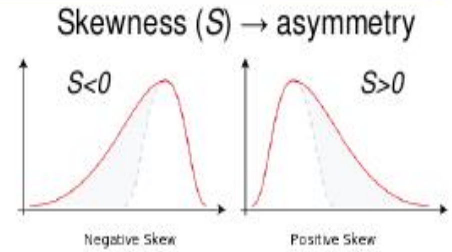
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4 / C_2^2$

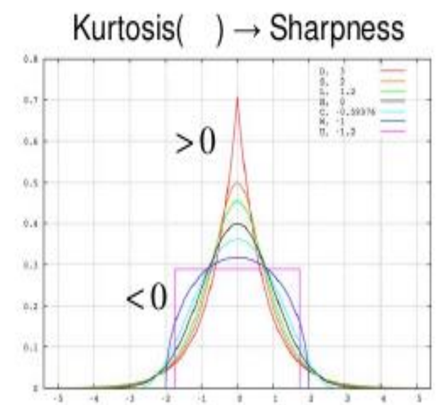
Moments, cumulants and susceptibilities:

2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

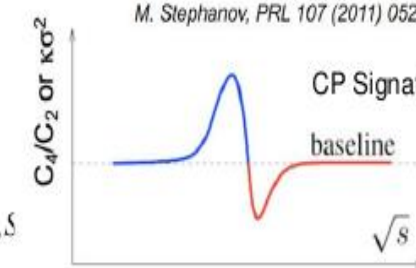
3rd order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$





M. Stephanov, PRL 107 (2011) 052301



1. Sensitive to correlation length (ξ)
2. Directly related to system susceptibility (χ)

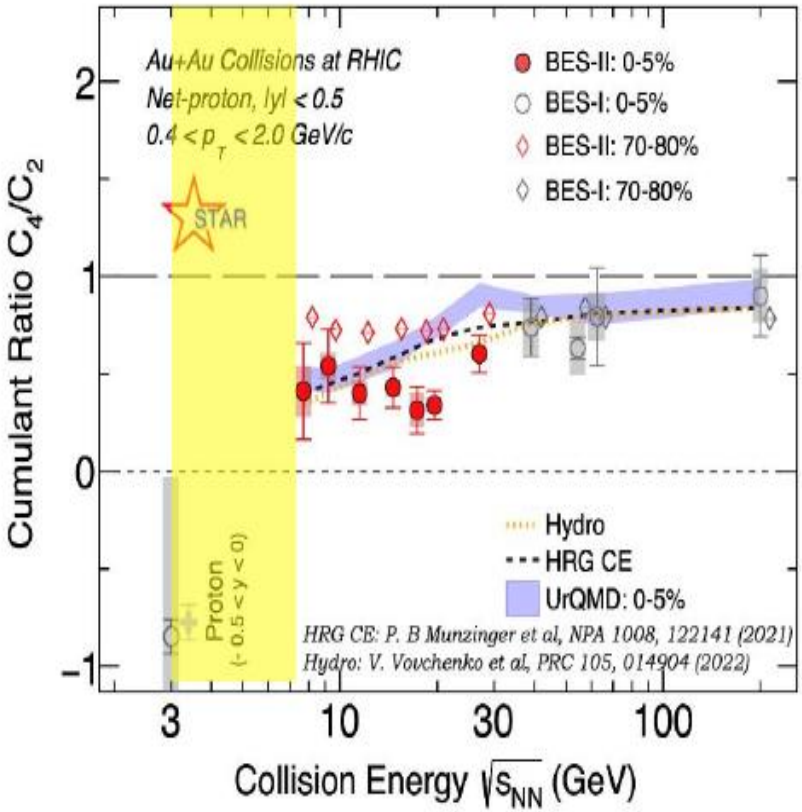
$\langle (\ N)^3 \rangle_c \quad ^{4.5}, \quad \langle (\ N)^4 \rangle_c \quad ^{7}$

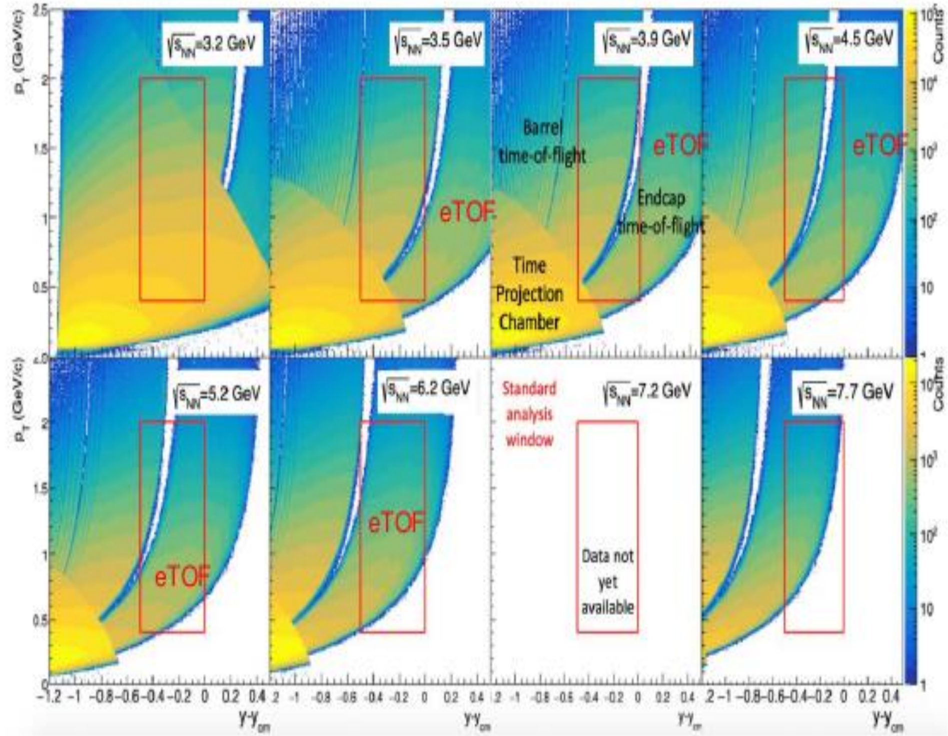
$^{(n)}_{q} = \frac{1}{VT^3} \quad C_{n,q} = \frac{^n(p/T^4)}{(\ _q)^n}, q = B, Q, S$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107, 052301 (2011). M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009). Cheng et al, PRD (2009) 074505. F. Karsch and K. Redlich , PLB 695, 136 (2011). B. Friman et al., EPJC 71 (2011) 1694. S. Gupta, et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13)

Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV





eTOF is crucial for mid-rapidity coverage at 3.5– 4.5 GeV

STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

Energy gap between 3 and 7.7 GeV :
important for **Critical Point search ！**

NICA MPD : 4-11 GeV、CBM: 2.4-4.9 GeV

LQCD ↔ Experiment

Google Translate

Detect language | English | German | Spanish | **LQCD** ⇄ **EXPERIMENT** | Spanish

$$\chi^{BQSC}_{klmn} = \frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B, \hat{\mu}_Q, \hat{\mu}_S, \hat{\mu}_C)/T^4]}{\partial\hat{\mu}_B^k \partial\hat{\mu}_Q^l \hat{\mu}_S^m \partial\hat{\mu}_C^n}\Big|_{\vec{\mu}=0}$$

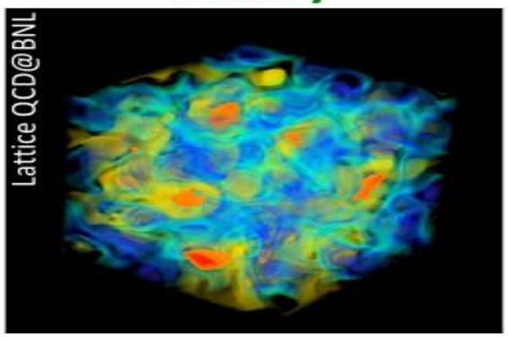
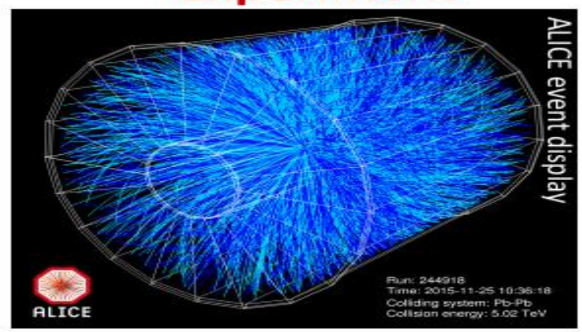
Baryon number **(B)**, Strangeness **(S)**, Electric charge **(Q)**, Cham **(C)** 0 / 5,000

Translation

$$\chi_2^B = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\chi_4^B}{\chi_2^B}$$

$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$

Bridge experimental data to LQCD calculations

Theory	Experiment
	

Static	Dynamic
Coordinate space	Momentum space
Net-baryon	Net-proton
Fixed V	Fluctuating V
...	...

- **Experimental challenges:** Particle identification, efficiency correction, effect of event pileup, volume fluctuations ...
- **Theoretical/phenomenological challenges:** Effect of resonances, charge conservation, effect of magnetic field, cluster formation, baryon annihilation, excluded volume ...

EOS for high baryon density matter

The binding energy per nucleon: $E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$

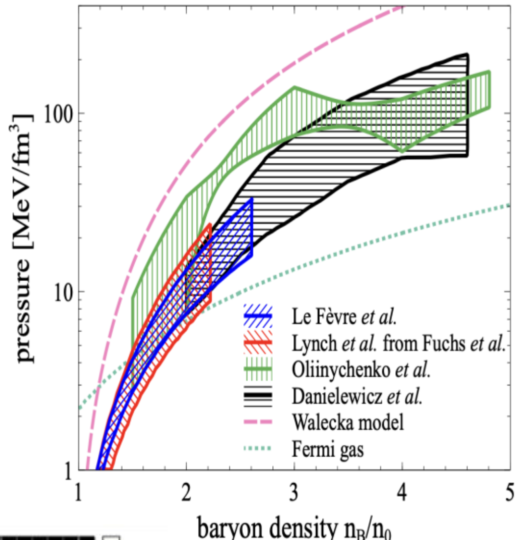
Isospin asymmetry:

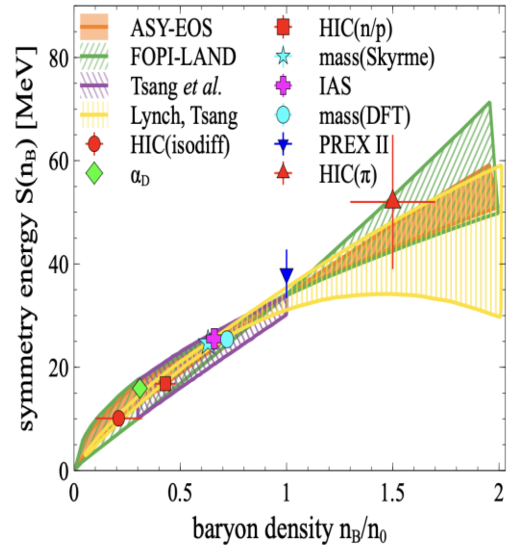
$$\delta = (\rho_n - \rho_p)/\rho$$

Symmetric matter ($E_A(\rho,0)$) — Symmetry energy ($E_{sym}(\rho)$)

Heavy-Ion Collisions and Merging Neutron Stars

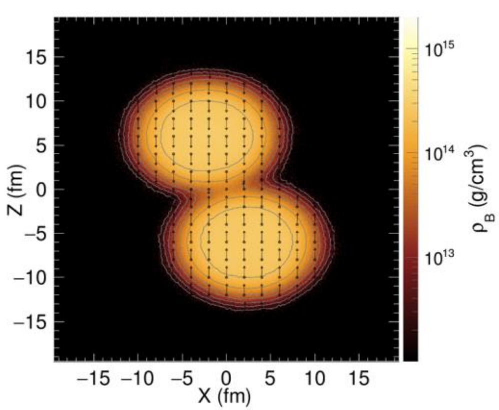
- T<70 MeV, $\rho \cong 3\rho_0$ for both
- Probe NS merger matter in the laboratory



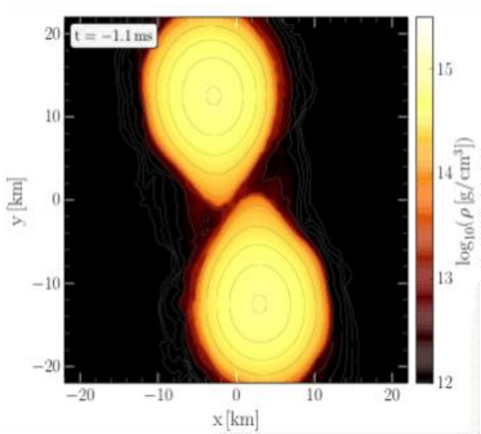


A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

Au+Au 1.25A GeV



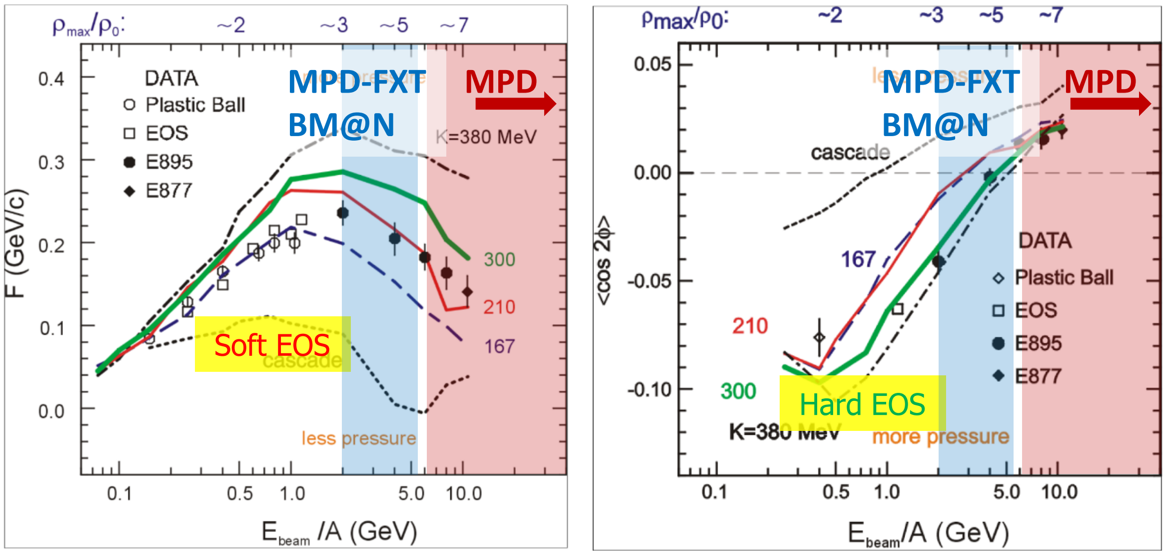
NS mergers



New data is needed to further constrain transport models with hadronic d.o.f.

Sensitivity of the collective flow to the EOS

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



$$F = \left.\frac{d\langle p_x/A\rangle}{d(y/y_{cm})}\right|_{y/y_{cm}=1}$$

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

Mean field usually can be defined using Skyrme potential with:

$$U(n_B) = A\left(\frac{n_B}{n_0}\right) + B\left(\frac{n_B}{n_0}\right)^{\tau}$$

Discrepancy in the interpretation:

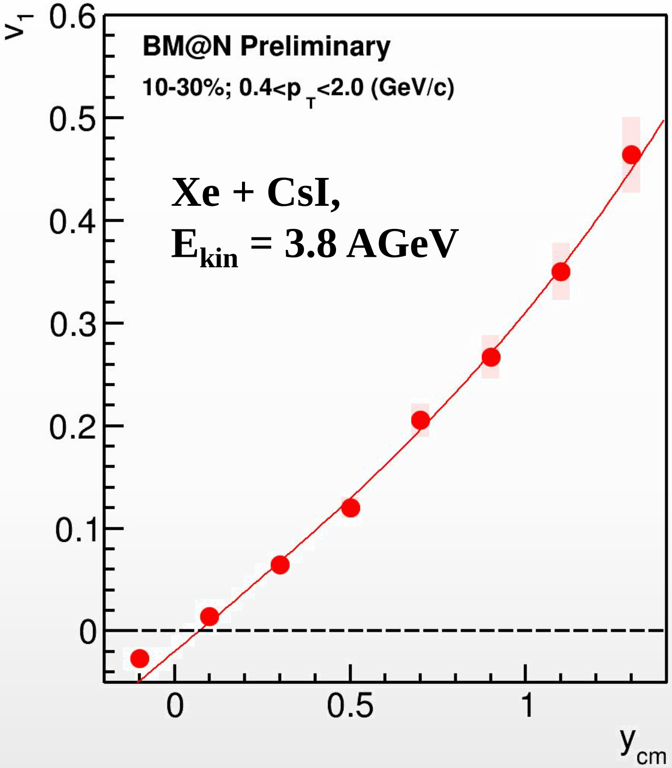
- v_1 suggests soft EoS
- v_2 suggests hard EoS

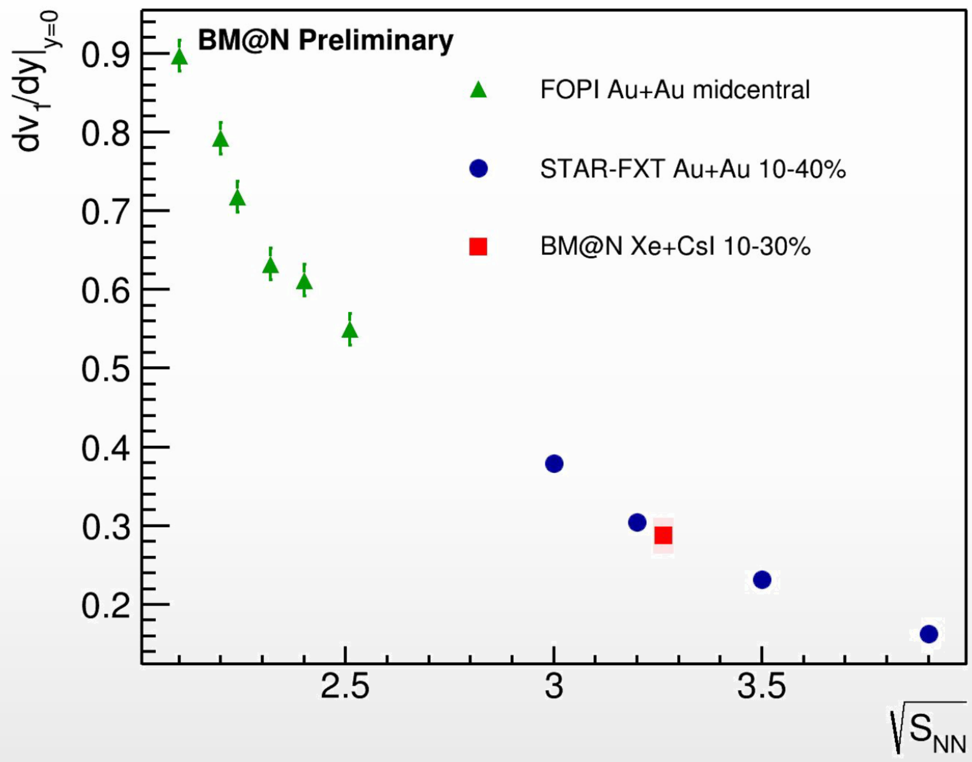
New measurements using new data and modern analysis techniques will address this discrepancy

More detailed model study should be done to address n_B-dependence of incompressibility K_0

Additional measurements are essential to clarify the previous measurements

$dv_1/dy|_{y=0}$ for protons vs. collision energy





- Slope of v_1 is in good agreement with the world data

See Mikhail Mamaev talk at AYSS2024

MPD experiment at NICA

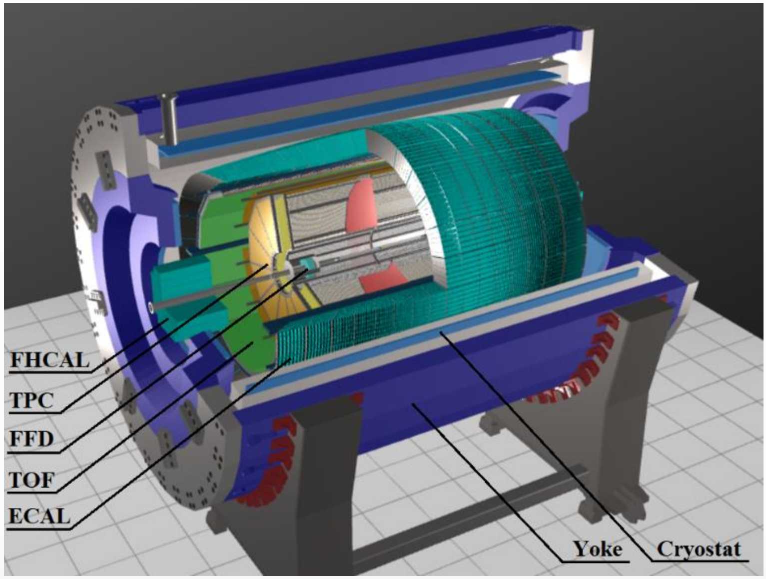
Main subsystems at Stage-I:

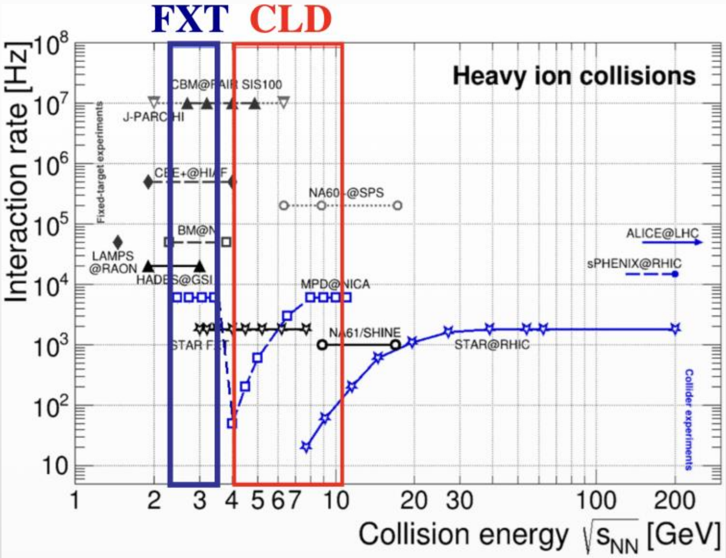
TPC ($|\eta| \leq 1.6$): charged particle tracking + momentum reconstruction + dE/dx identification

TOF ($|\eta| \leq 1.4$): charged particle identification

ECal ($2.9 < |\eta| < 1.4$): energy and PID for $\gamma/e^{\pm}$

FHCal ($2 < |\eta| < 5$) and **FFD** ($2.9 < |\eta| < 3.3$): event triggering + event geometry





Expected beams at the first year(s) of operation (Stage-I):

- MPD-CLD: Xe/Bi+Xe/Bi at $\sqrt{s_{NN}} \sim 7$ GeV
- MPD-FXT: Xe/Bi +W at $\sqrt{s_{NN}} \sim 3$ GeV

Beam energy overlap: HADES, STAR BES, NA61/SHINE and future CBM

MPD physics program

NICA

G. Feofilov, P. Parfenov

Global observables
- Total event multiplicity
- Total event energy
- Centrality determination
- Total cross-section measurement
- Event plane measurement at all rapidities
- Spectator measurement

V. Kolesnikov, Xianglei Zhu

Spectra of light flavor and hypernuclei
- Light flavor spectra
- Hyperons and hypernuclei
- Total particle yields and yield ratios
- Kinematic and chemical properties of the event
- Mapping QCD Phase Diag.

K. Mikhailov, A. Taranenko

Correlations and Fluctuations
- Collective flow for hadrons
- Vorticity, Λ polarization
- E-by-E fluctuation of multiplicity, momentum and conserved quantities
- Femtoscopy
- Forward-Backward corr.
- Jet-like correlations

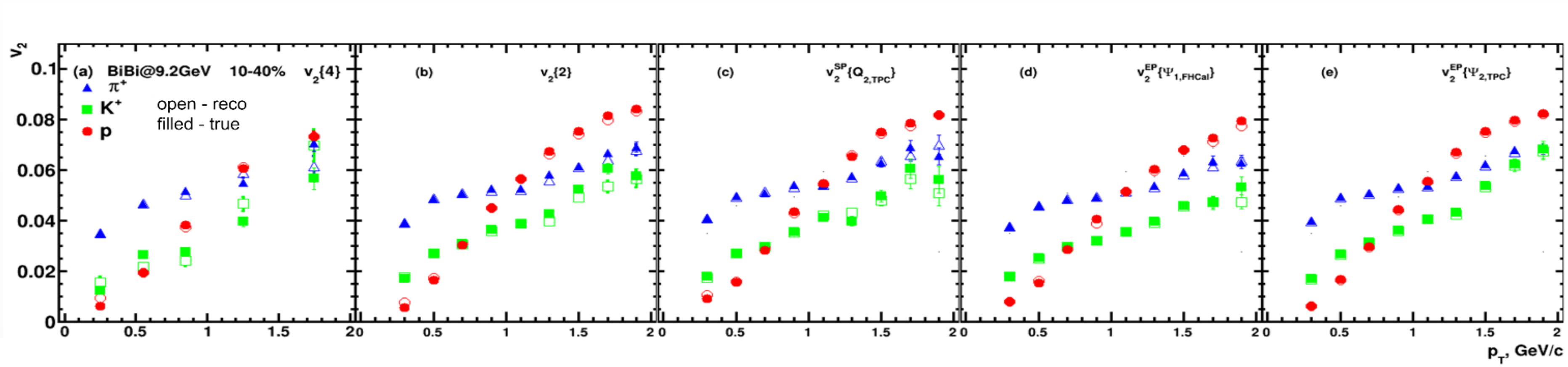
D. Peresunko, Chi Yang

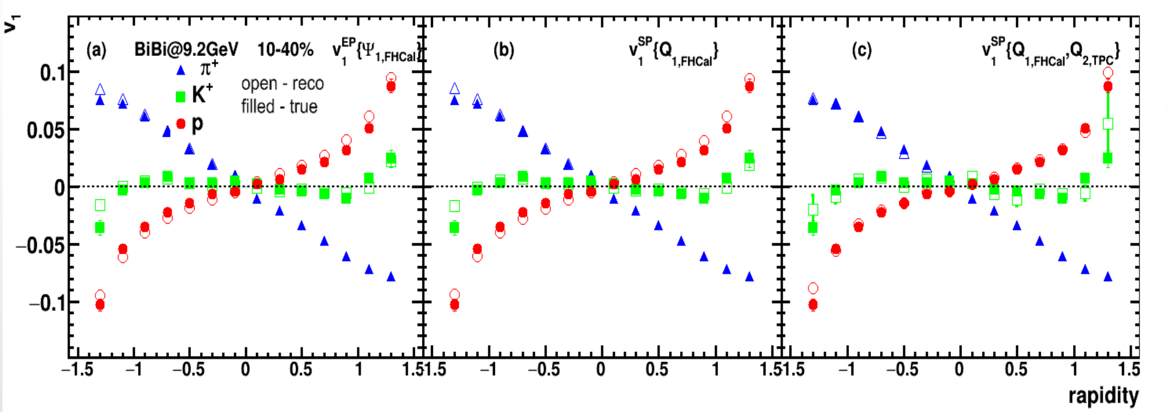
Electromagnetic probes
- Electromagnetic calorimeter meas.
- Photons in ECAL and central barrel
- Low mass dilepton spectra in-medium modification of resonances and intermediate mass region

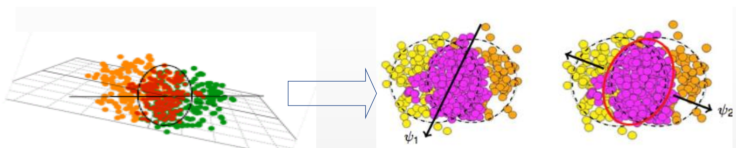
Wangmei Zha, A. Zinchenko

Heavy flavor
- Study of open charm production
- Charmonium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Explore production at charm threshold

Anisotropic flow of identified charged hadrons







v_1 - directed flow v_2 - elliptic flow

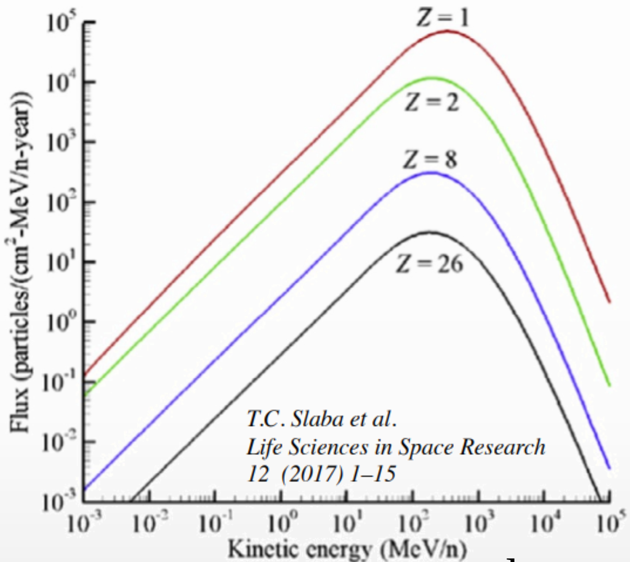
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

$$v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

Good performance for flow measurements for all methods used (EP, SP, Q-cumulants)

High-energy heavy-ion reaction data

- Galactic Cosmic Rays composed of nuclei (protons, … up to Fe) and E/A up to 50 GeV
- These high-energy particles create cascades of hundreds of secondary, etc. particles

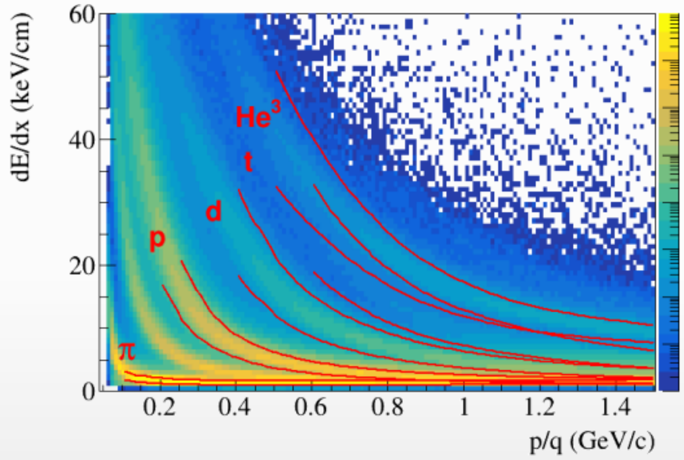


- Cosmic rays are a serious concern to astronauts, electronics, and spacecraft.
- The damage is proportional to Z^2, therefore the component due to ions is important
- Damage from secondary production of p, d, t, ^{3}He, and ^{4}He is also significant
- Need input information for transport codes for shielding applications (Geant-4, Fluka, PHITS, etc.):
  - ✓ total, elastic/reaction cross section
  - ✓ particle multiplicities and coellecense parameters
  - ✓ outgoing particle distributions: $d^2N/dEd\Omega$

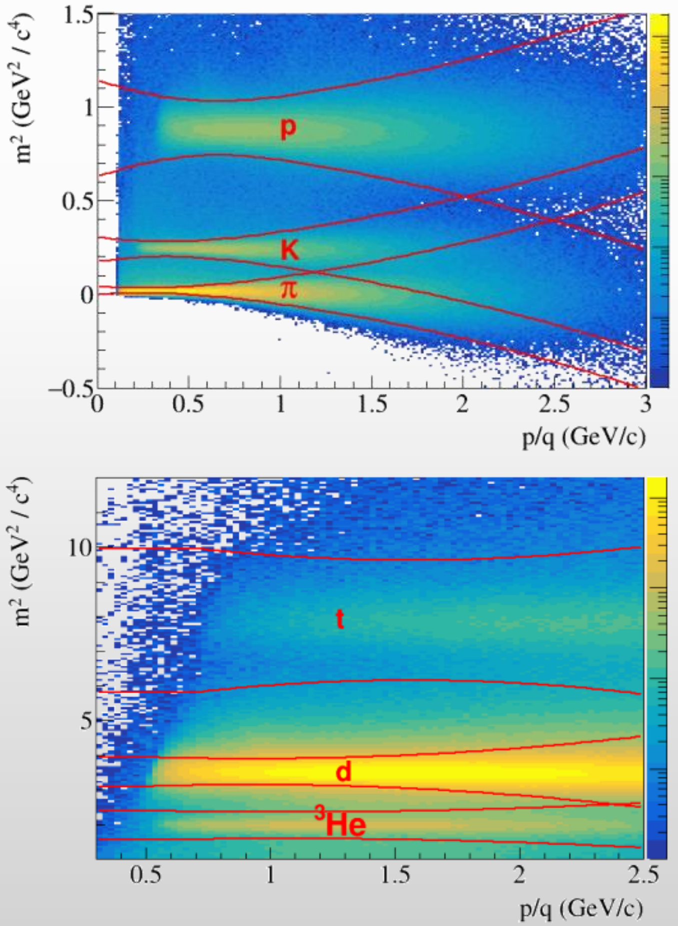
High energy heavy ion reaction data

- NICA can deliver different ion beam species and energies:
  - ✓ Targets of interest (C = astronaut, Si = electronics, Al = spacecraft) + He, C, O, Si, Fe, etc.
- No data exist for projectile energies > 3 GeV/n

dE/dx vs momentum in TPC



m² vs. momentum in TOF



MPD has excellent light fragment identification capabilities in a wide rapidity range → <u>unique capability of the MPD</u> in the NICA energy range

Summary

- NICA open unique opportunities for the exploration of the properties of dense nuclear matter. Complementary energy range, large discovery potential.
- Preparation of the MPD detector and experimental program is ongoing, all activities are continued
- All components of the MPD 1-st stage detector are in advanced state of production
- Commissioning of the MPD Stage-I detector is expected in 2025-2026
- BM@N **first physics run with Xe+CsI - finished – good data**
- Further program will be driven by the physics demands and NICA capabilities

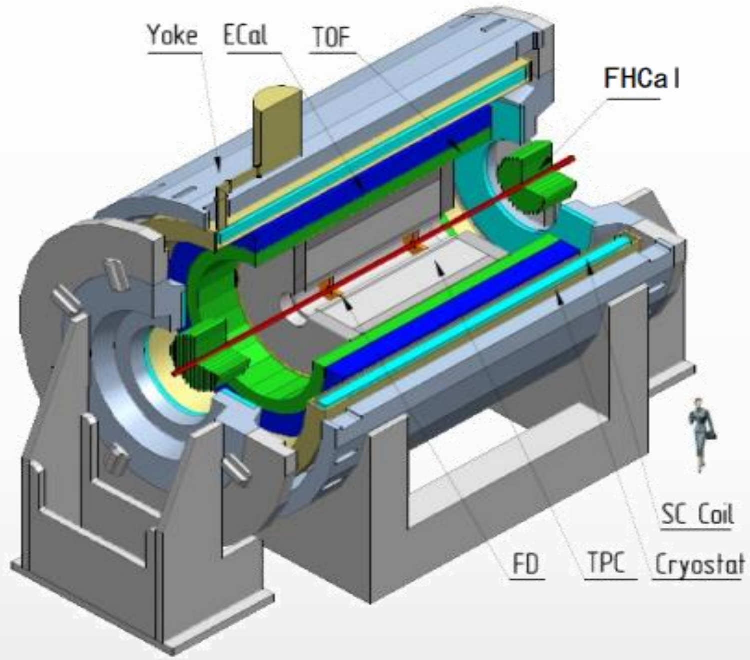
Multi-Purpose Detector (MPD) Collaboration

MPD** International Collaboration was established in **2018
to construct, commission and operate the detector

10** Countries, **>450** participants, **31** Institutes and **JINR

Organization

Acting Spokesperson:	***Victor Riabov***
Deputy Spokesperson:	***Zebo Tang***
Institutional Board Chair:	***Alejandro Ayala***
Project Manager:	***Slava Golovatyuk***



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