Why fsPHENIX is interesting for heavy ion physics

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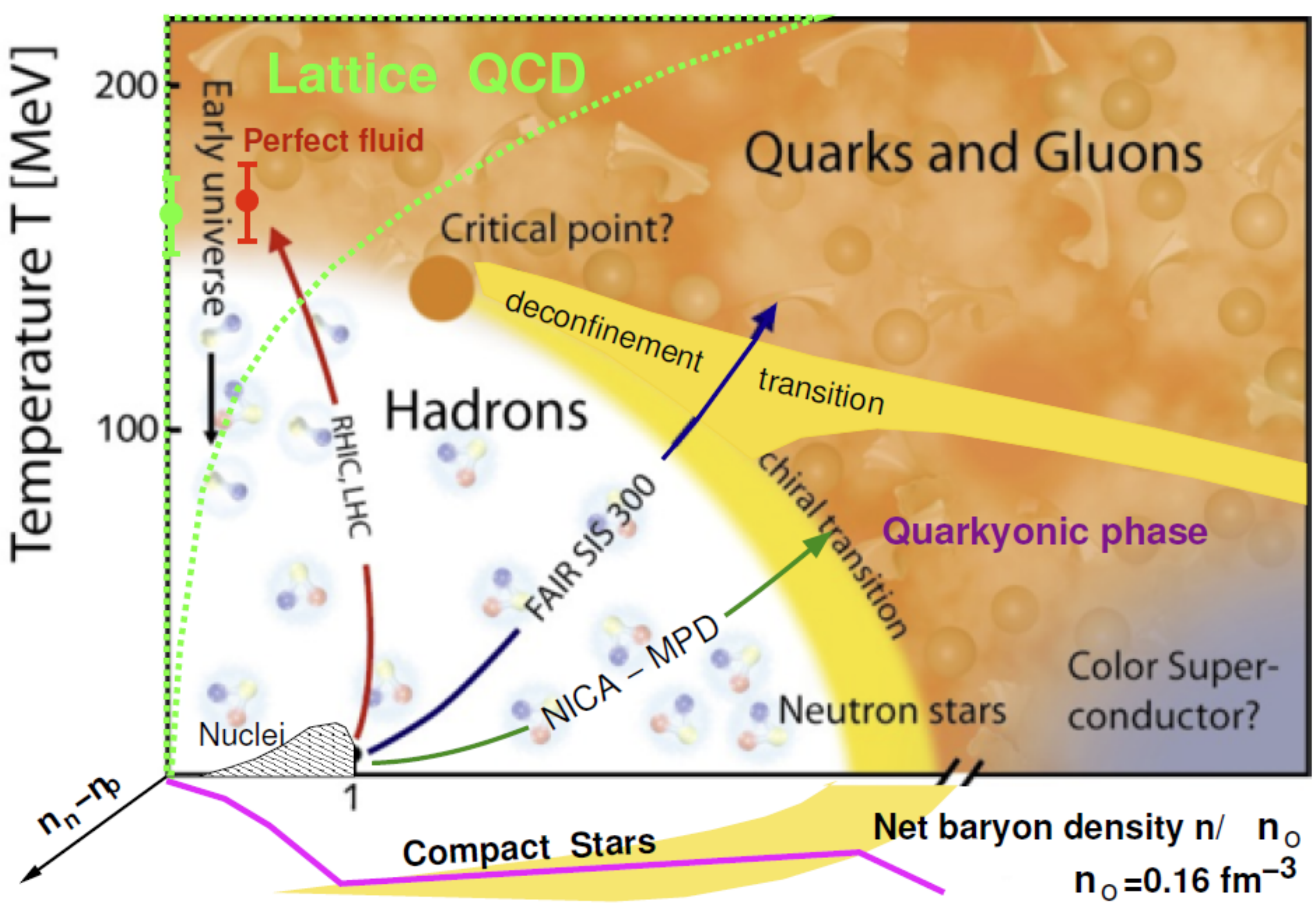
Contents

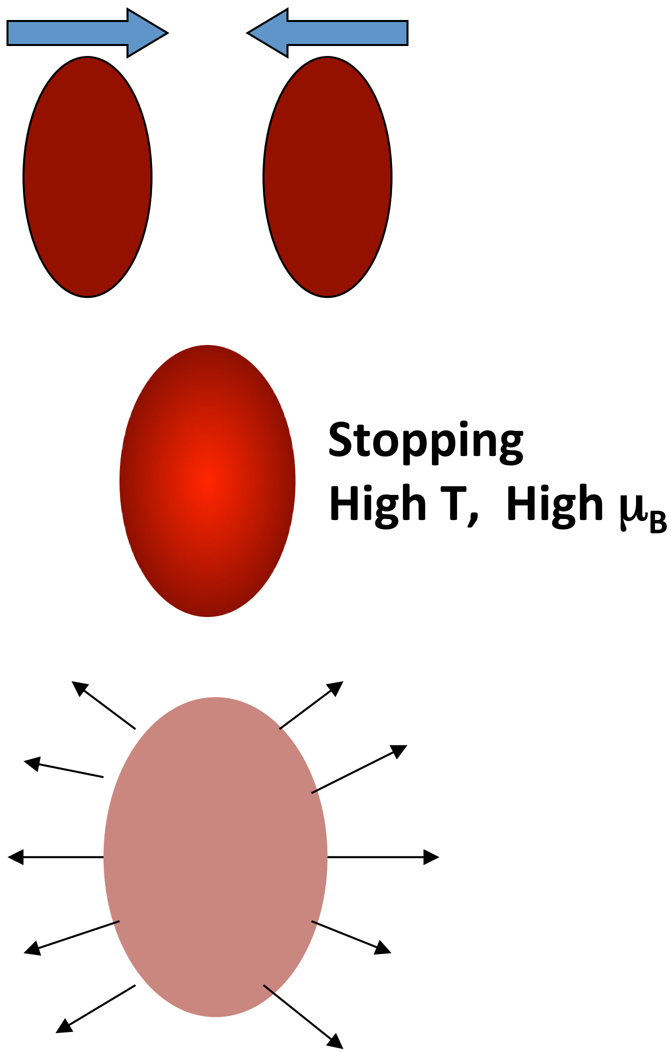
- Introduction to HI physics
- Review of highlight results at PHENIX related to forward measurement
- New measurement at fsPHENIX

HI physics field: QCD phase diagram

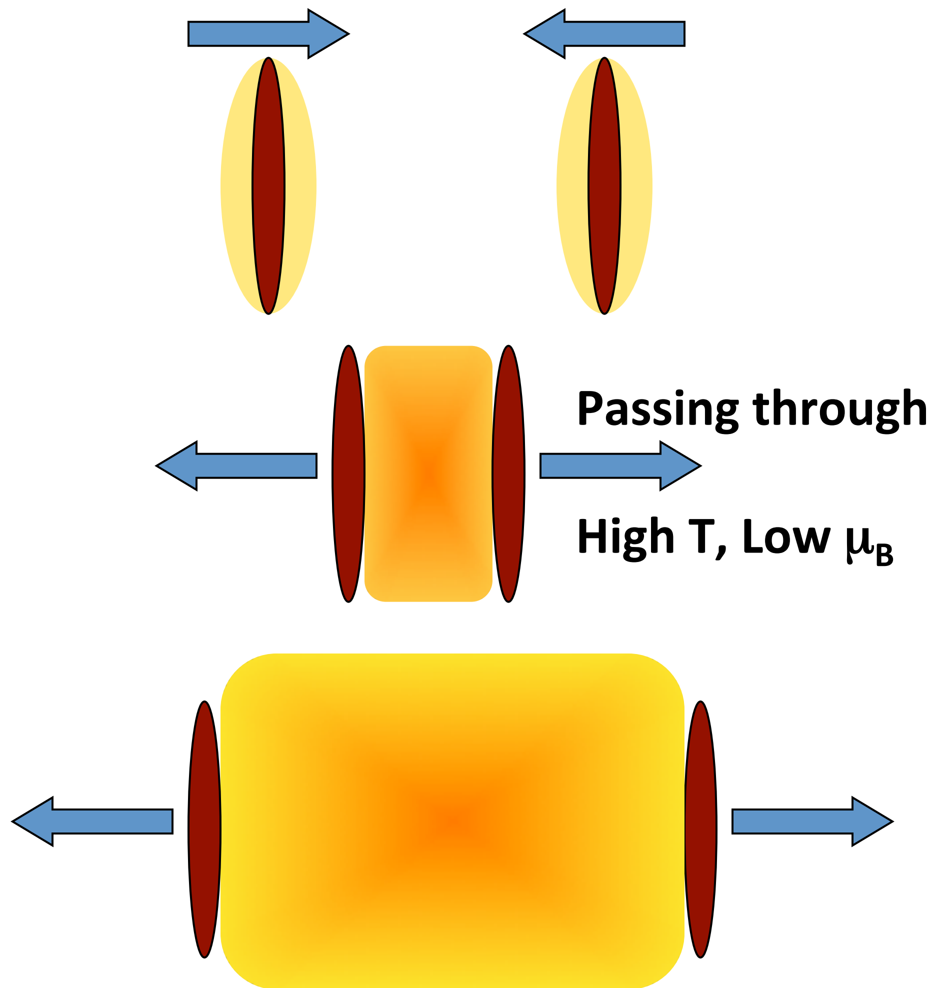


Reality of collisions

Low energy（Landau picture）



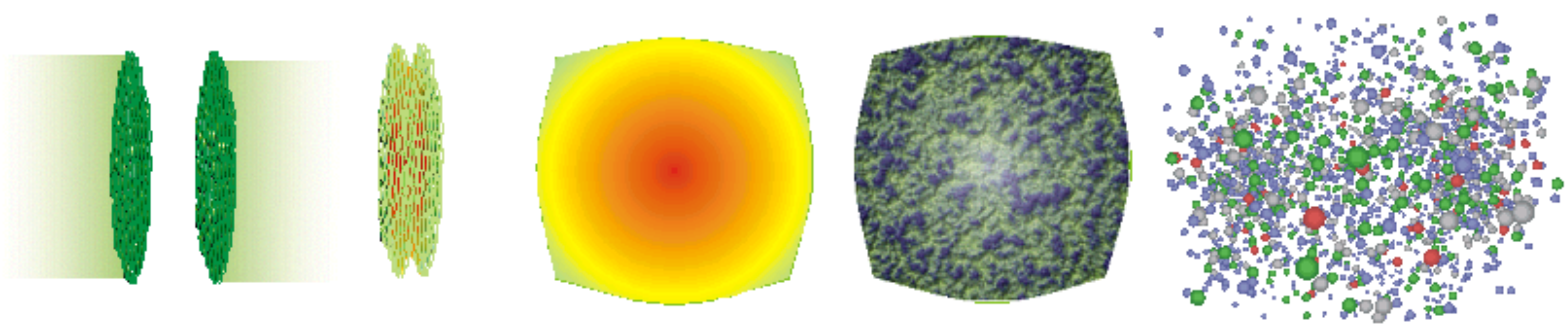
High energy（Bjorken picture）



Dynamics after collisions

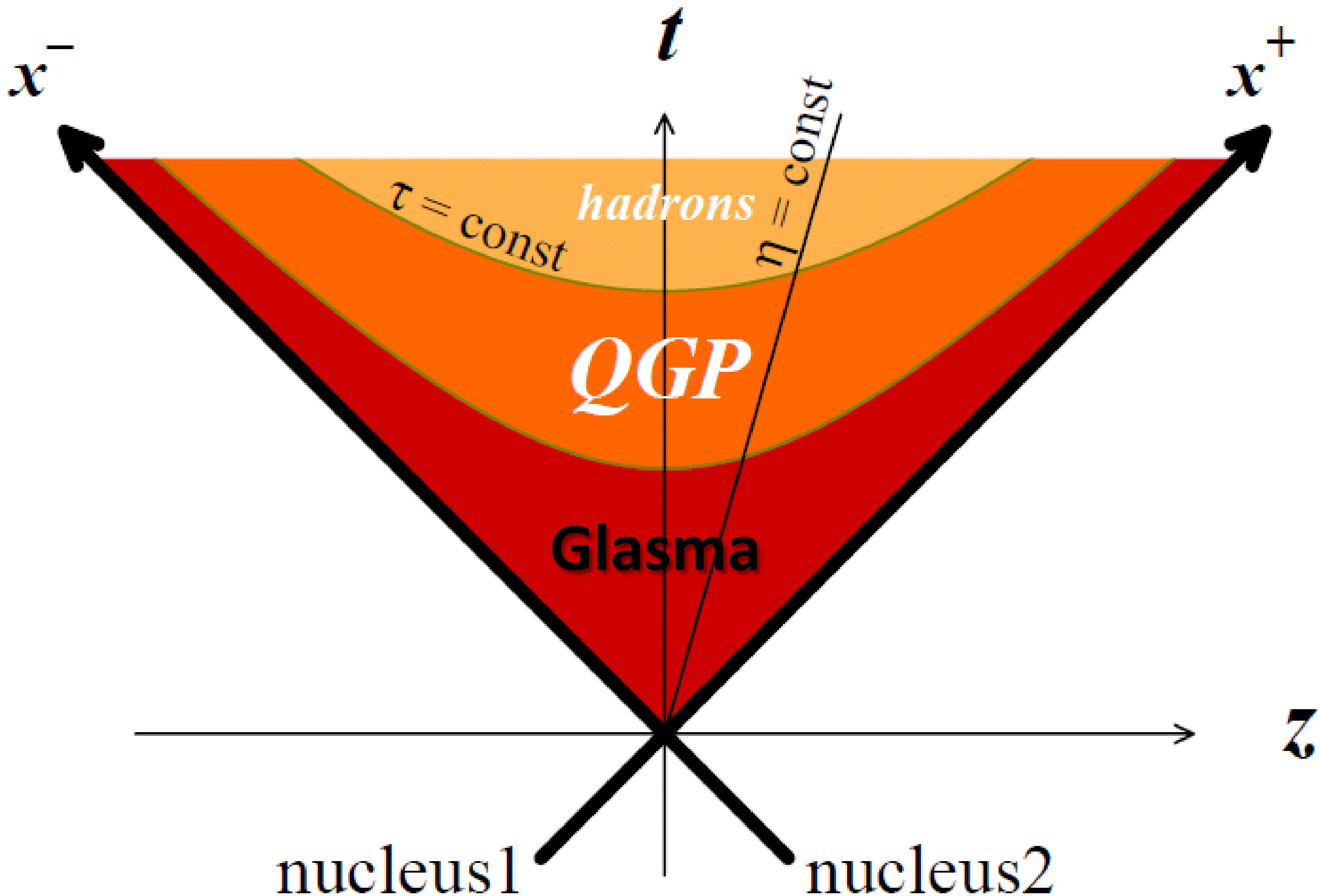
- Gold ions pass through each other
  - High-x partons fly away
  - Low-x gluons remain in the mid-rapidity (y=0), and create "gluon matter"
  - people says this is color glass condensate (CGC)
- CGC→ Gluon Plasma→ QGP→Mixed phase→ Hadronization+expansion
- Transition temperature (quark to hadron) : T_{chem}=~180MeV

Parameters
At Hadronization: T_{chem}, μ_b
At Expansion: T_{kin}, β



Gluon Plasma QGP phase Mixed phase Hadronization + Expansion

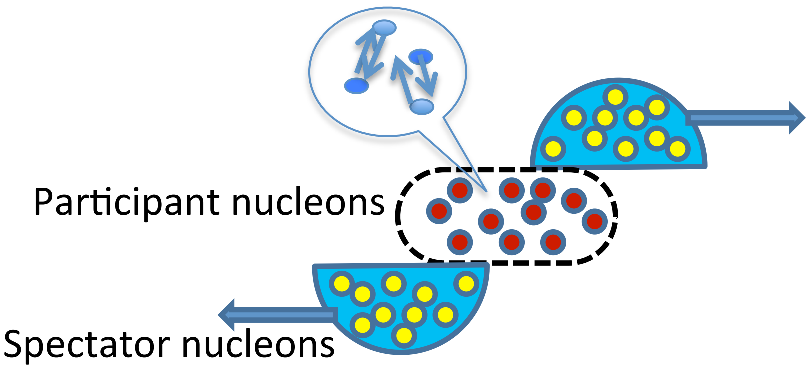
Another way to look at dynamics



Color Glass Condensate

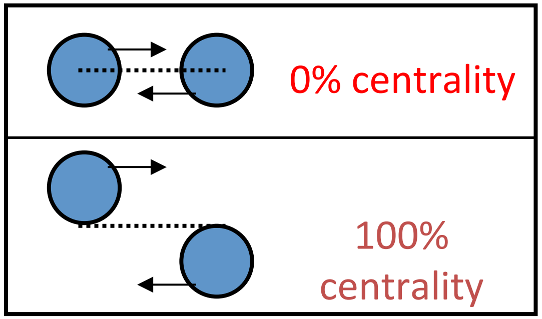
Several quantities for HI

- Number of participant nucleons (Npart)
  - Calculable from impact parameters
  - A measure of energy density



- Number of nucleon collisions (Ncoll)
  - Number of nucleon collisions in an event
  - Nucleons are considered to collide individually in high energy collisions

- Centrality: Event class variable proportional to impact parameters
  - 0%: b=0, **Central collisions**
  - 100%: b=bmax, **Peripheral collisions**



Know your position

- Temperature and Baryo-chemical potential ($\propto$baryon density) at freezeout is estimated from particle ratios and by using Grand Canonical Stat Model

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \, \mathrm{d}p \ln[1 \pm \exp(-(E_i - \mu_i)/T)],$$

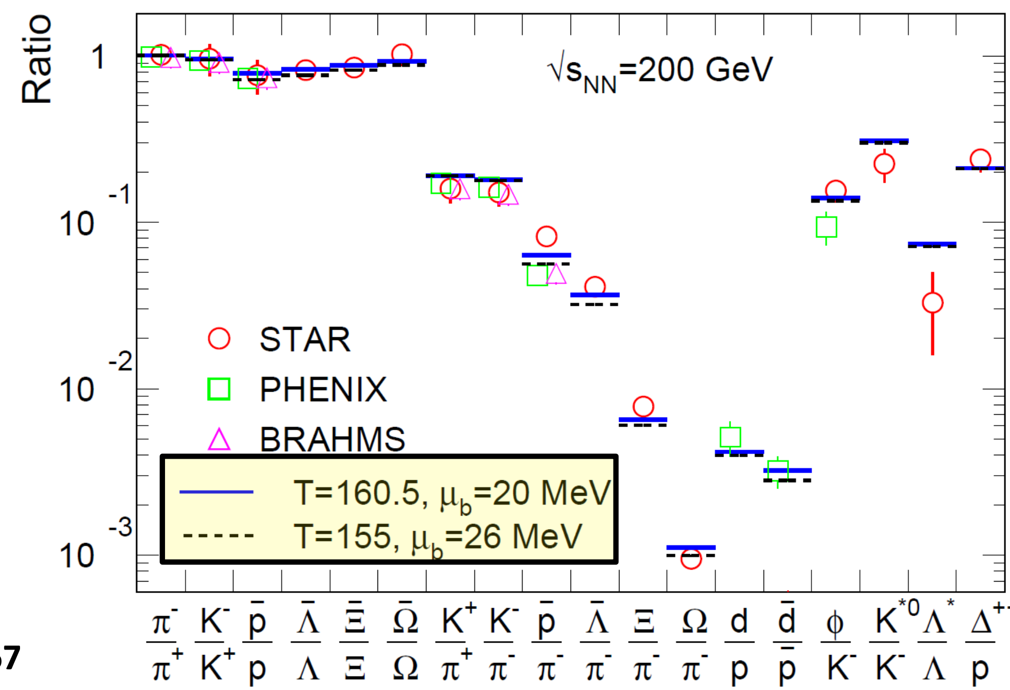
$$\mu_i = \mu_b B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$$

$$g_i = (2J_i + 1)$$ Spin DOF

Chemical potential μ_i
μ_b: Baryon, μ_{I3}: Isospin
μ_S: Strangeness, μ_C: Charm

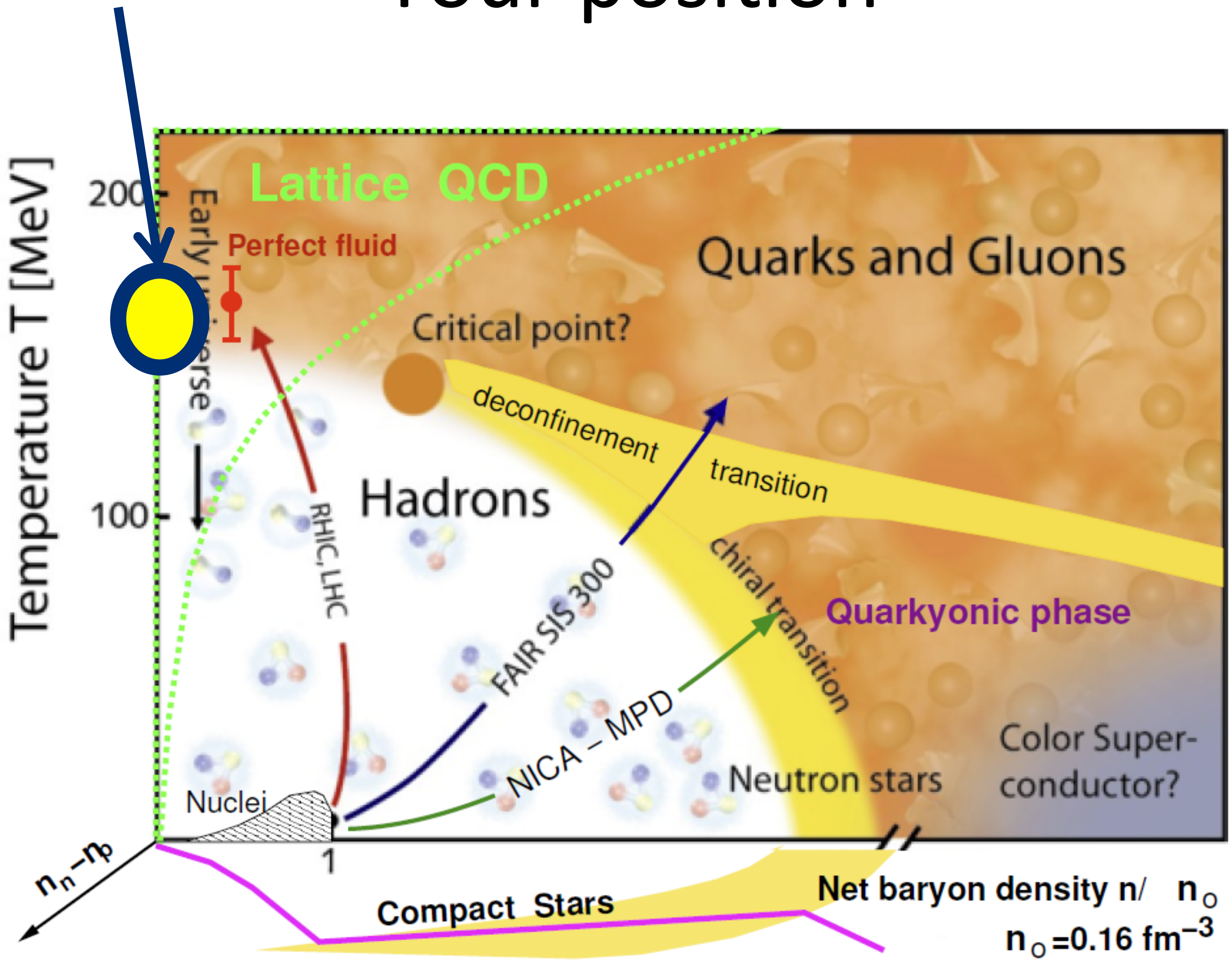
Number of particles: n_i

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu}$$
$$= \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \, \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1},$$



See, e.g., A. Andonic, et al., NPA 772(2006)167

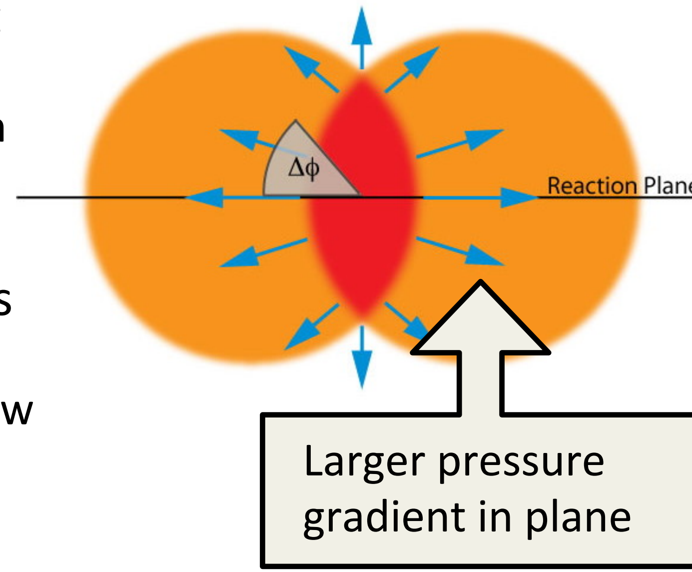
Your position

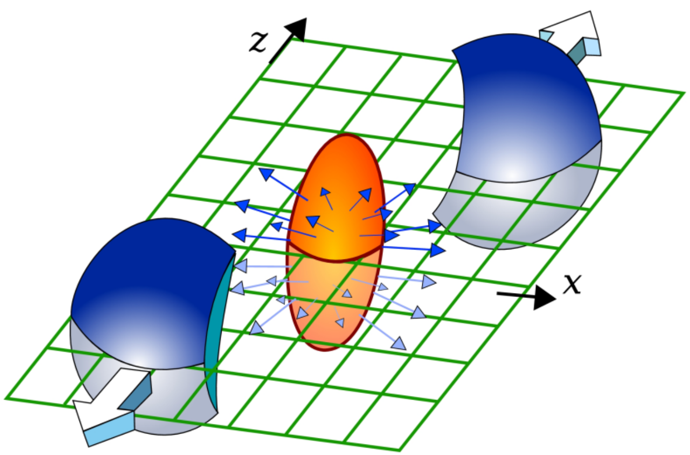


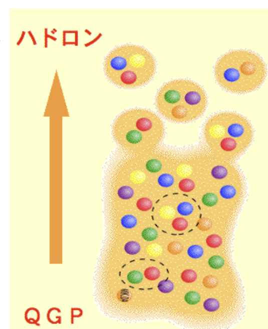
Highlights related to forward measurement

1. Particle flow

- In non-central collisions, the collision area is not isotropic
  - Different pressure gradient produces momentum anisotropy of emitted particles
- Measure the angular distribution of the particles with respect to the reaction plane
  - 2^{nd} order Fourier coefficient shows the elliptic flow







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

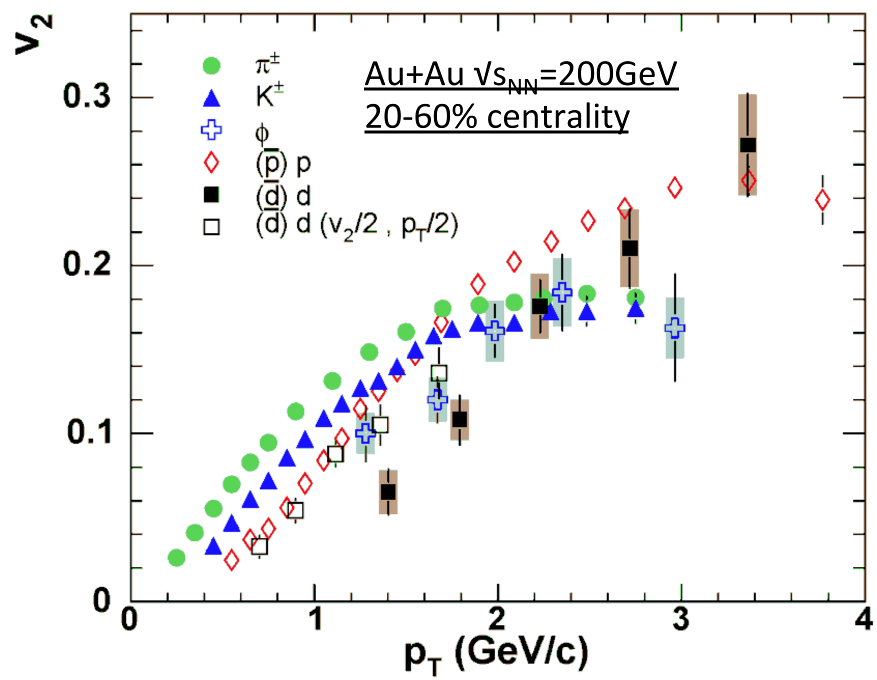
Mom. Asymmetry
elliptic flow $v_2 = \frac{\langle p_y^2 \rangle - \langle p_x^2 \rangle}{\langle p_y^2 \rangle + \langle p_x^2 \rangle}$

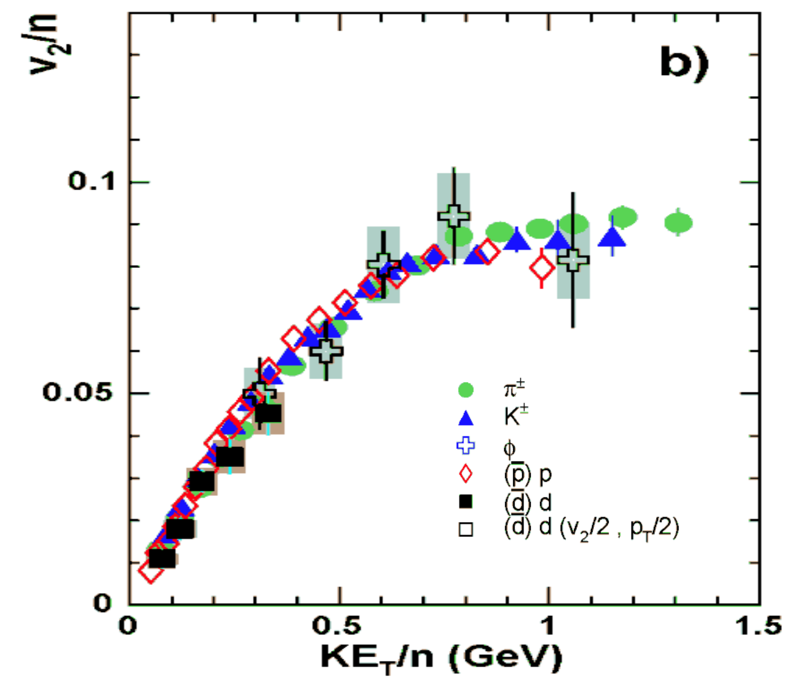
$$\frac{d^3N}{p_T dp_T dy d\varphi} \propto [1 + 2v_2(p_T)\cos 2(\varphi - \phi_{RP}) + ...]$$

Elliptic flow result (v_2)

- Large flow is observed as a function p_T
  - As particles become heavier, the flows become smaller in low p_T
- Plotting the per-quark v_2 (v_2/n) vs kinetic energy (KE_T/n)
  - *All the particles follow a universal line, suggesting the flow is built at quark level*

PHENIX, PRL99, 052301(2007)





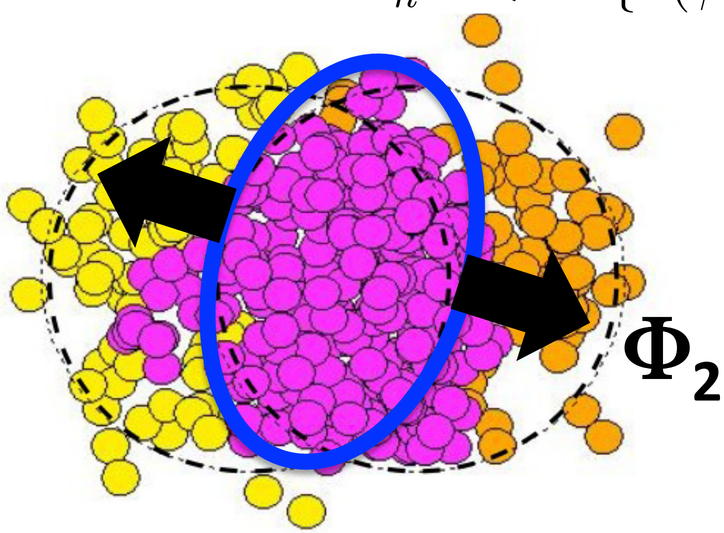
Fluctuation of nucleon positions yields…

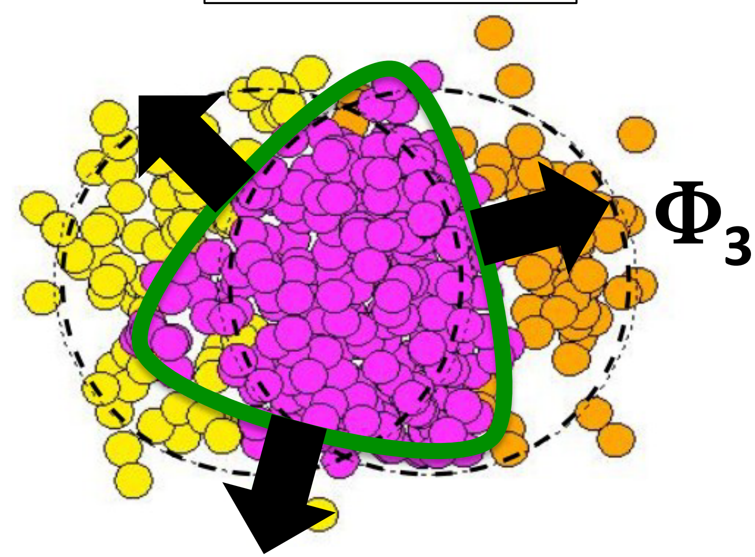
- Fluctuation of nucleon position yields higher order anisotropy
  - **Higher order flow（v_3, v_4, … v_n)**
- Higher order flows are sensitive to the properties of the matter
  - Equation of state E=E(P), shear viscosity (η) to Entropy density (s) ratio (η/s)

$$\frac{dN}{d(\phi-\Psi_n)} = N_0[1+2\sum_{n=1}^{\infty} v_n cos\{n(\phi-\Phi_n)\}]$$

$$\nu_n =< cos\{n(\phi-\Phi_n)\} >$$

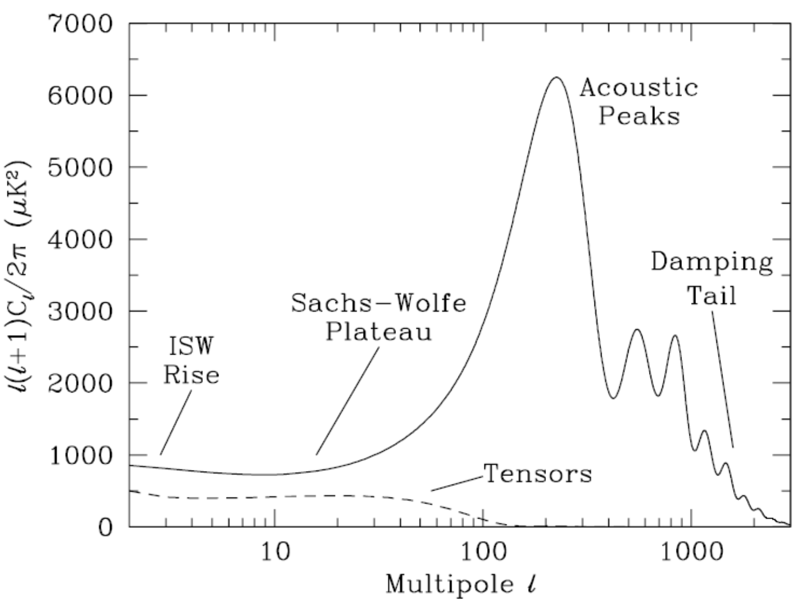
Φ_n : Event Plane

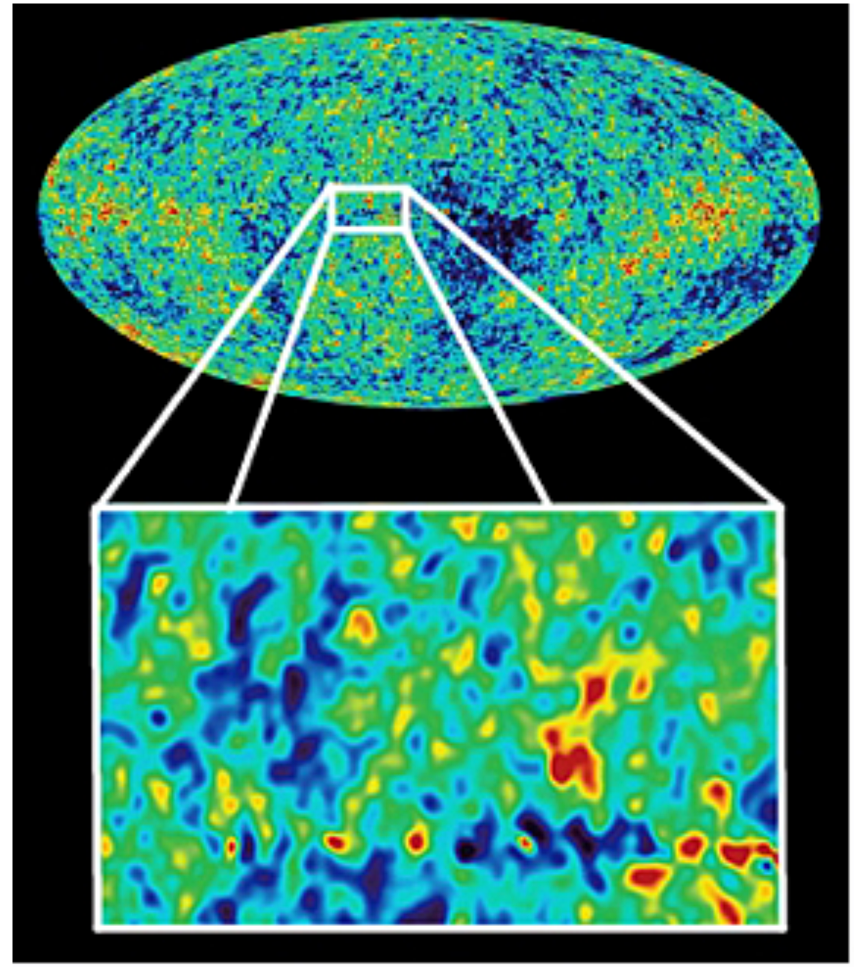




Analogy to cosmology

- Fluctuation of temperature in cosmic microwave background
  - A trace of phase transition.
- Input to cosmological model

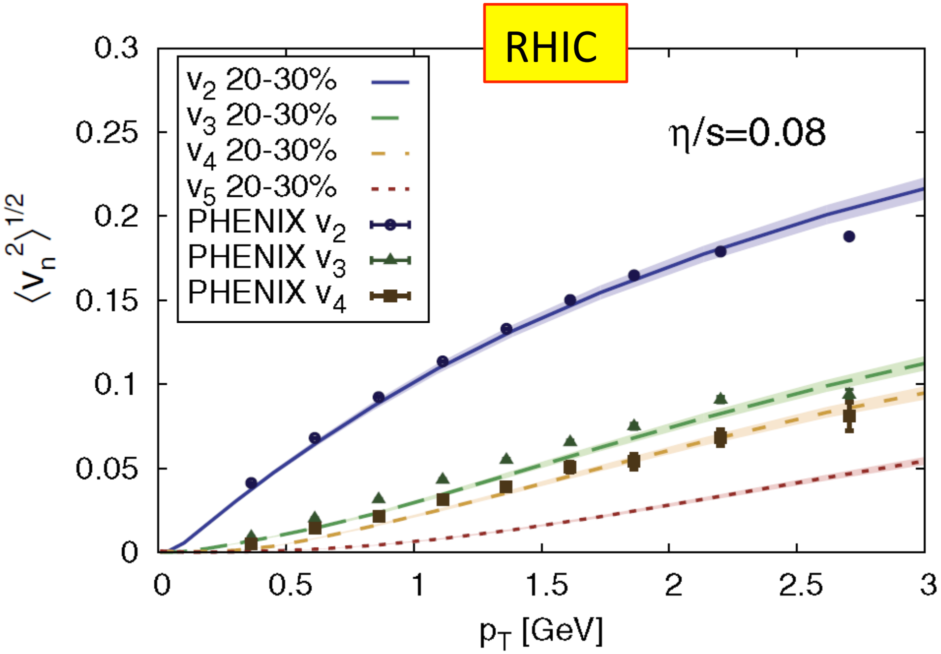




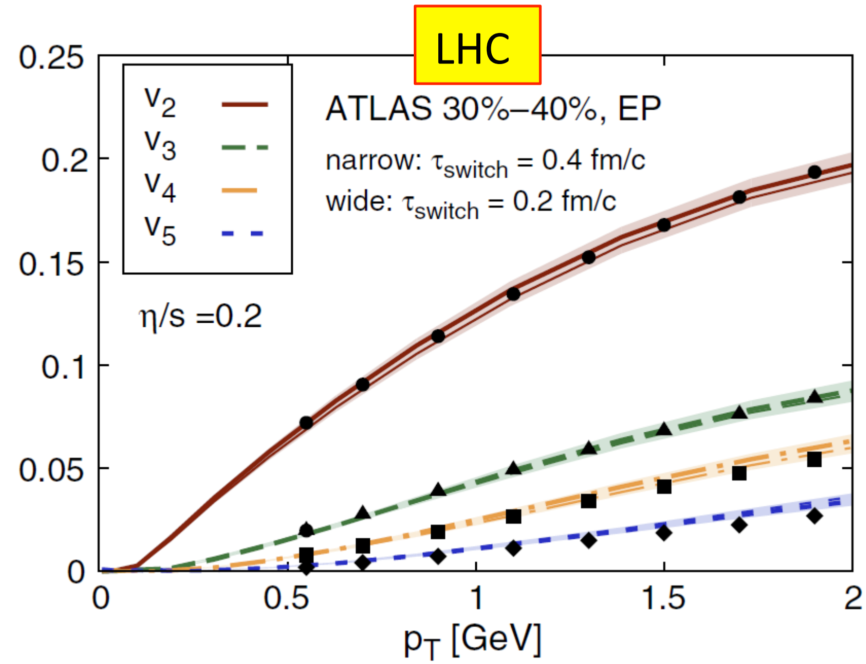
From NASA and Rev. of Part. Phys.

v_n results with hydrodynamics model

- PHENIX (RHIC) and ATLAS (LHC) v_n are compared with a hydrodynamics model
  - QGP as fluid consisting of partons
- The model reproduces the higher order flow at RHIC, LHC very well
  - Almost perfect fluid is realized at RHIC（η/s from quantum limit: ~$1/4\pi$）



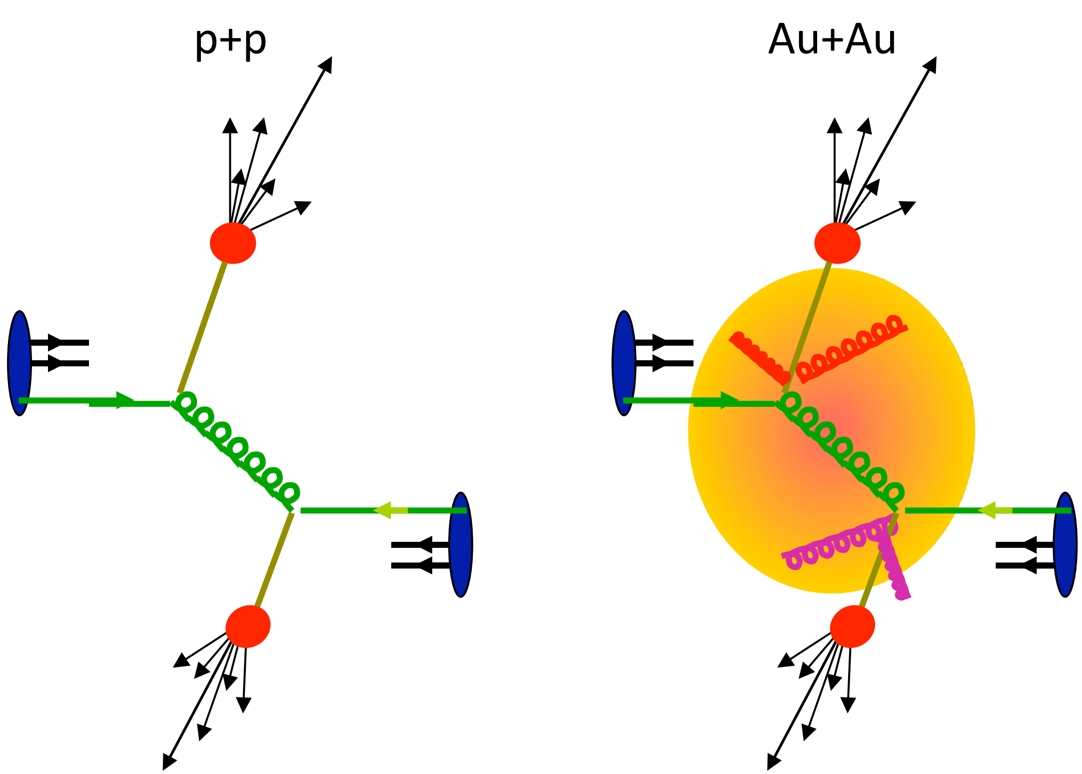
B. Schenke, S. Jeon and C. Gale, PRC 85, 024901 (2012)

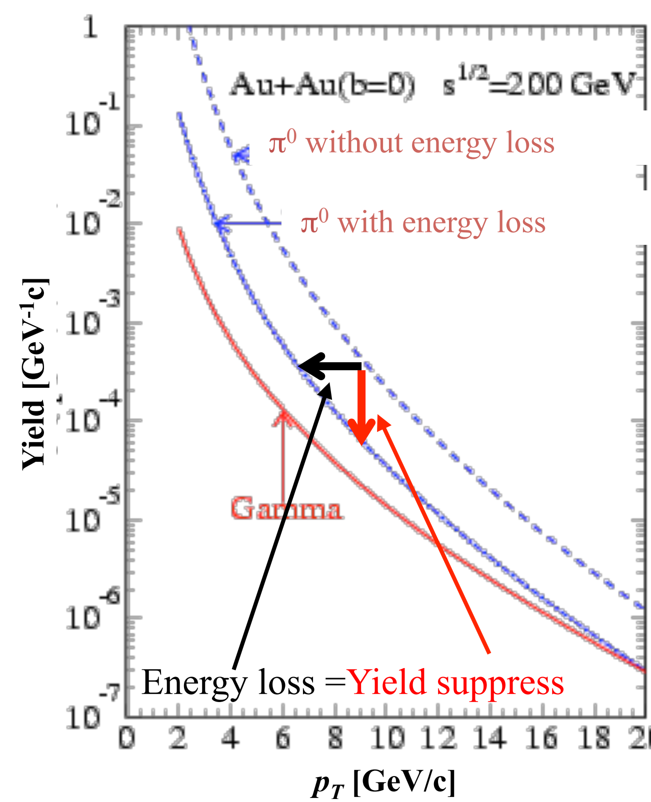


C. Gale et al., PRL110, 012302(2013)

2. Jet energy loss

- High p_T hadrons (π^0 etc.) are leading particles from jets (hard scattered partons)
  - A large fraction of jet momentum are carried
- Energy loss is turned into the yield suppression of high pT hadrons



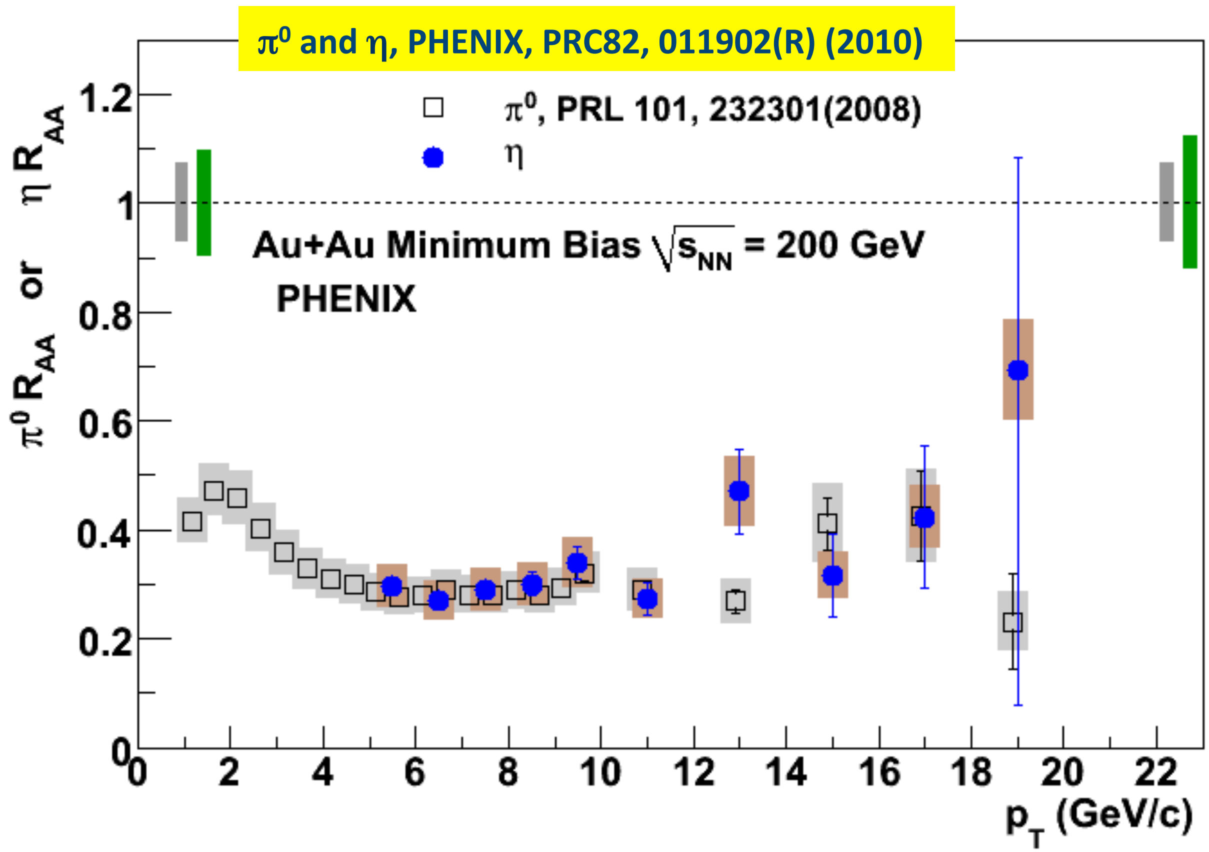


X.-N., Wang, PRC **58** (1998)2321

Yield suppression of leading particles

- Nuclear Modification Factor (R_{AA})
  - (Yield in A+A collision)/(Yield in p+p collision × Ncoll)
  - R_{AA} =1: No nuclear effect
  - R_{AA} <1: Suppression due to energy loss, etc.

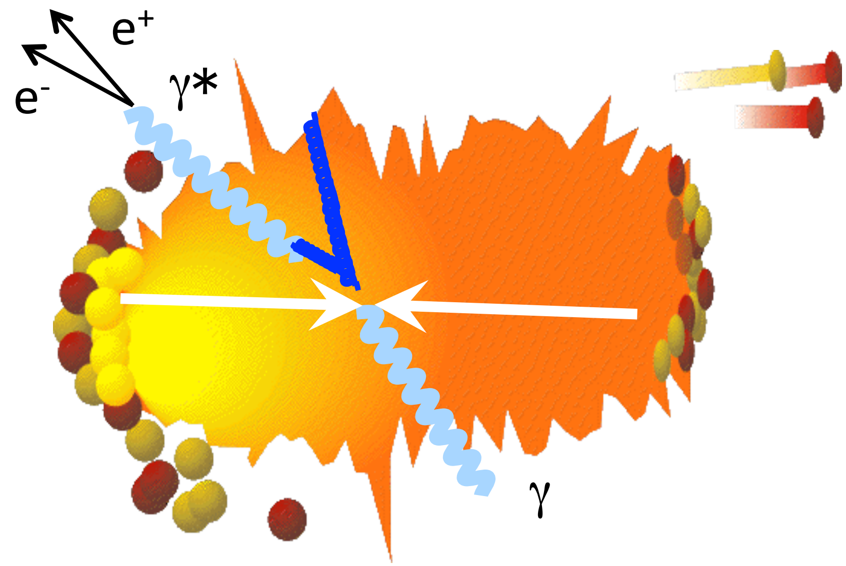
$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{\frac{Ncoll}{\sigma_{inel}} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$



3. Thermal photons

Small Rate: Yield ∝ $\alpha\alpha_s$

- Emitted from all the stages after collisions
- Penetrate the system unscathed after emission
  - Carry out thermodynamical information such as temperature
- Photons will be produced by Compton scattering or qqbar annihilation at LO



$$E\frac{dR_\gamma}{d^3p} = -\frac{\alpha_{em}}{\pi^2}\,\mathrm{Im}\Pi_{em}(\omega,k)\frac{1}{e^{E/T}-1}$$

Π_{em}: photon self energy

$$\mathrm{Im}\Pi_{em}(\omega,k) \approx \ln\left(\frac{\omega T}{(m_{th}(\approx gT))^2}\right)$$

•Product of Bose distribution and transition probability

•Slope at E>>T tells temperature (T~200MeV)

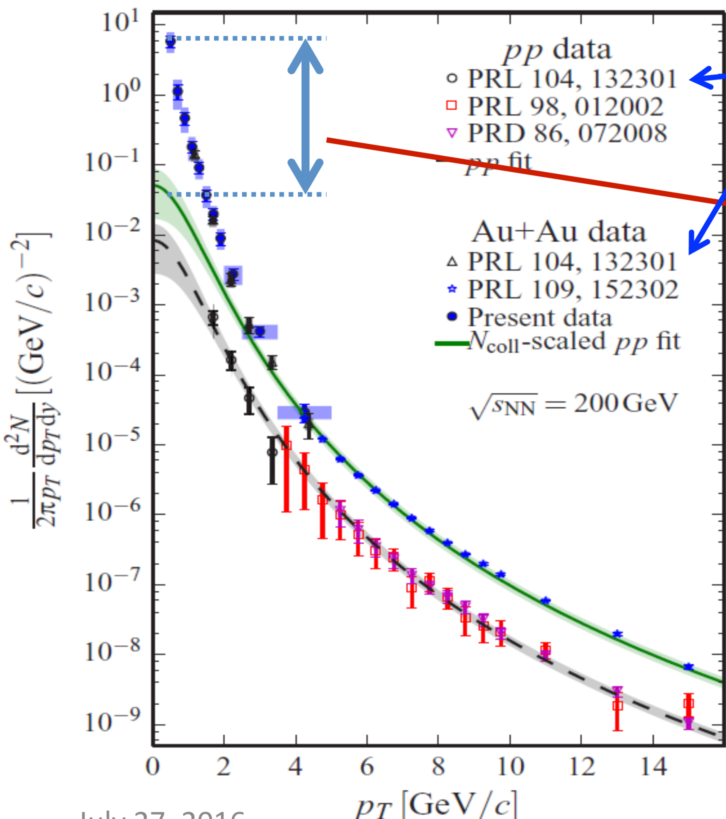
A recent review: TS, Pramana 84, 845(2015)

Temperature of the system

- T_{ave} = 239 ± 25(stat) ± 7(syst) MeV (0-20%)
  - c.f. LHC, Pb+Pb 2.76TeV: T_{ave} = 304 ± 51(stat+syst) MeV (0-40% centrality)

***Phase transition would occur at T~180MeV**

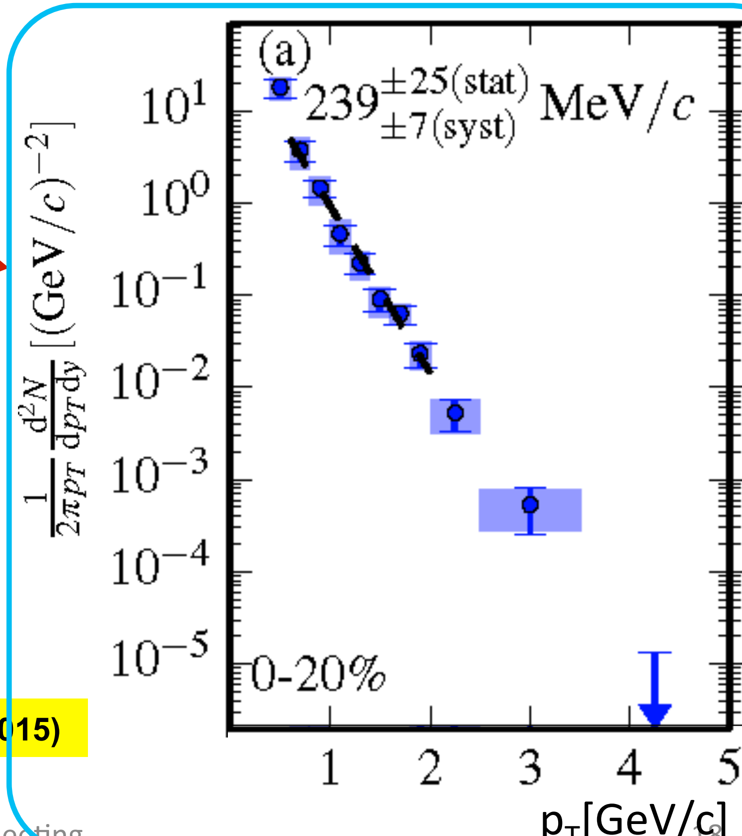
Direct photon spectra



Virtual photon

PRC91, 064904 (2015)

Thermal photon spectra

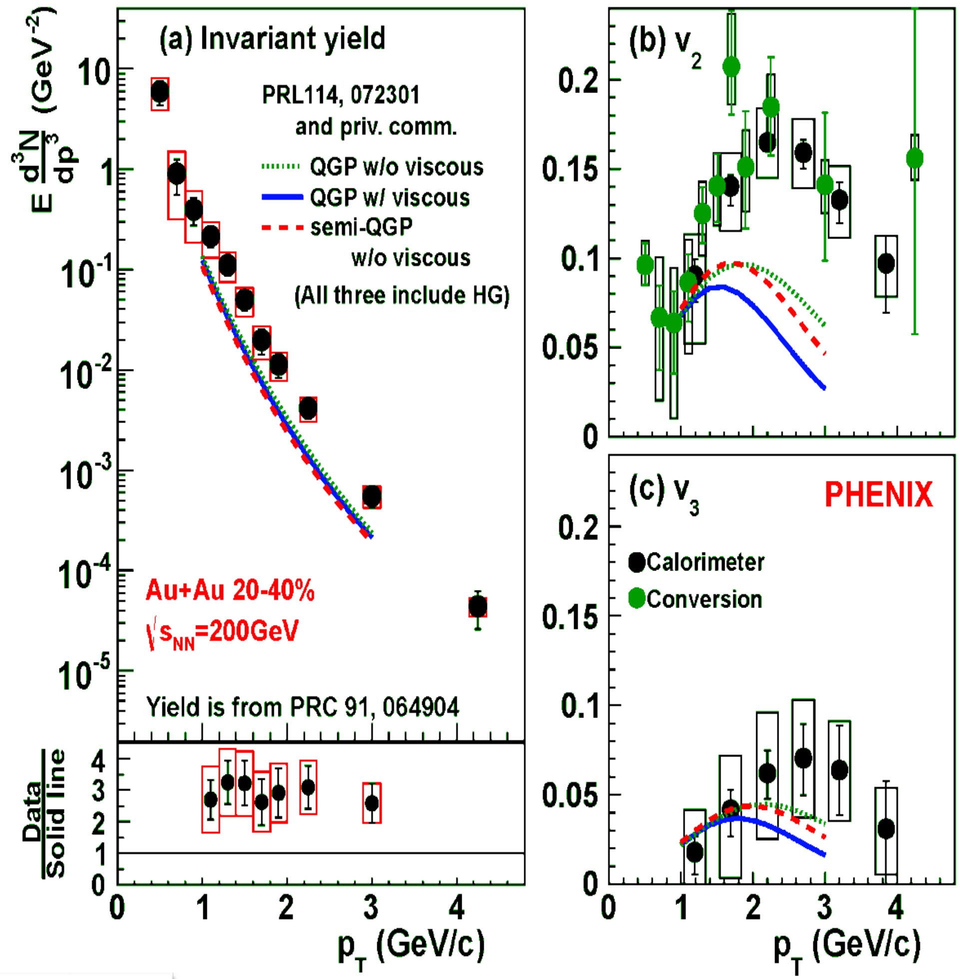


Result improved theories

arXiv:1509.07758

- **Large yield**
  - Emission from the early stage where temperature is high
- **Large elliptic flow (v_2)**
  - Emission from the late stage where the collectivity is sufficiently built up
- A big input to the time profile of the theoretical model
  - A latest calculation of hydrodynamics model did a fairly good job
    - PRL 114, 072301(2015)
- Ingredients discovered
  - Late stage emission (near freezeout)
  - Blueshift of spectra
  - Viscosity correction is necessary

Comparison with 20-40% cent data



$$T_e = \sqrt{\frac{1+v}{1-v}}\,T$$

Doppler shift

Achievement and next steps

- Most of the observables are in mid-rapidity
  - People assume that Bjorken scenario of expanding system works

- 3D and time profile of the QGP is not measured in detail
  - Hadronic observables are from the hadronization (freezeout) stage
  - Photons have been the tool for exploring pre-freezeout phase
  - Longitudinal profile of the system is very little known
    - And, the recent theoretical model says it is not trivial

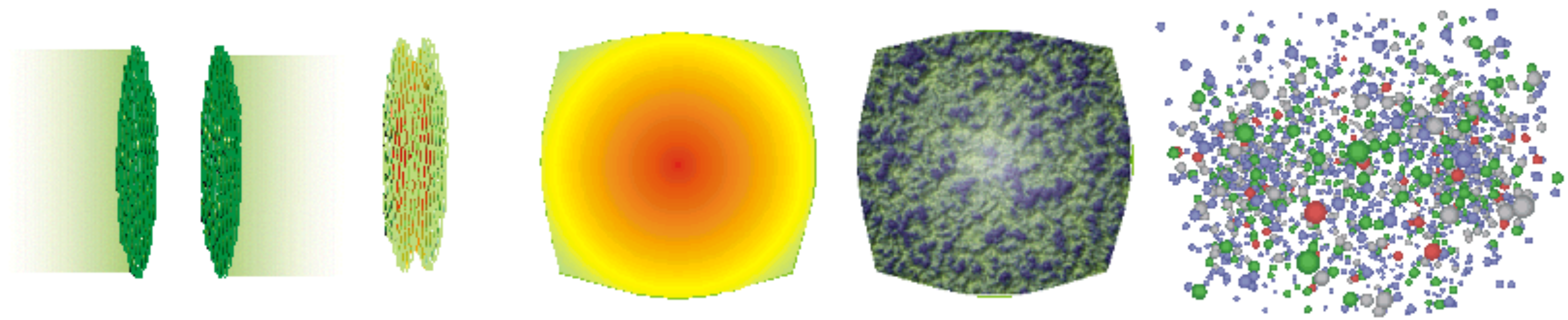
- How the system develops from the color glass condensate (CGC) to glasma and to QGP?

- Measurement at forward rapidity can help answer the questions
  - Observables are similar to the ones in midrapidity

Remainder: dynamics after collisions

- The system expands longitudinally (beam direction) as well as transversely (normal to beam direction)
- Question is whether the expansion is isotropic (and uniform)

<u>Parameters</u>
At Hadronization: T_{chem}, μ_b
At Expansion: T_{kin}, β

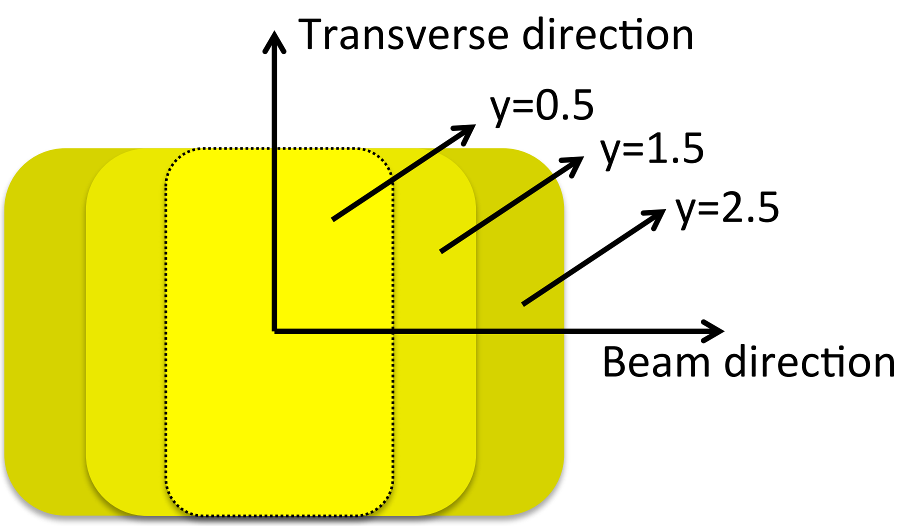


3D scan of QGP

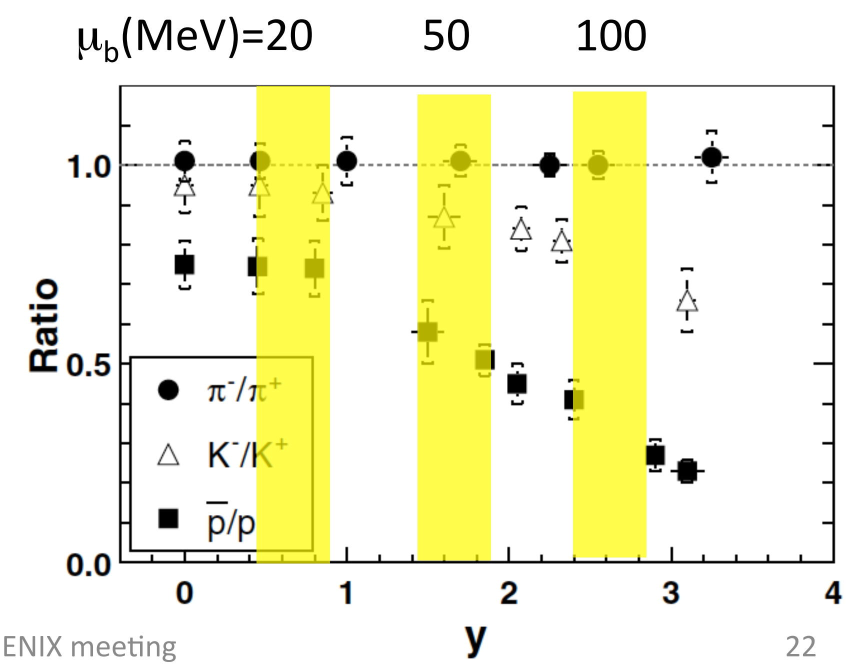
- BRAHMS data showed that mid- and forward rapidity have different μ_b
  - Possibility of exploring different path in phase diagram

- 3D scan of QGP using photons and high ***p*** hadrons at forward rapidity will be interesting.

- How about the temperature at forward rapidity?



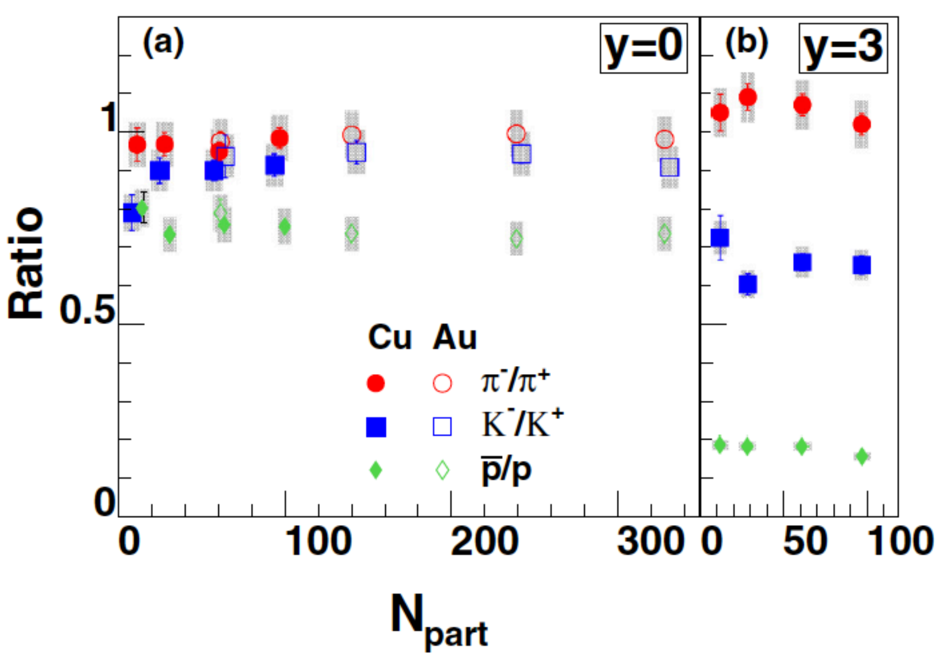
BRAHMS, PRL90, 102301 (2003)

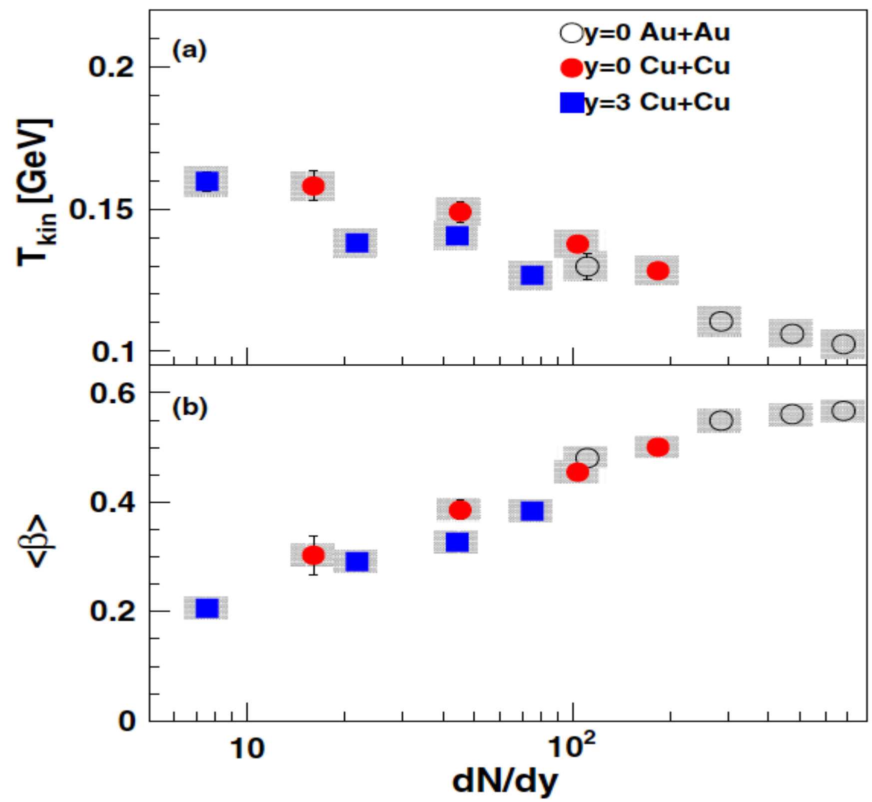


BRAHMS also measured this

- BRAHMS published π/K/p spectra in forward region in Cu+Cu collisions
- Particle ratios (related to T_{chem} and μ_b), T_{kin} and β are compared with those from Au+Au collisions
- As found in mid-rapidity before, the parameters scales with N_{part} (dN/dy)
  - 3D profile of Au+Au and Cu+Cu collisions look similar

BRAHMS, PRC94, 014907(2016)

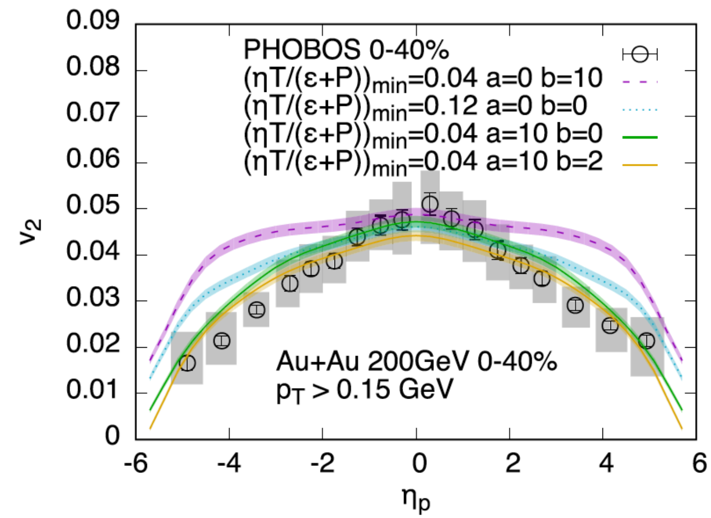




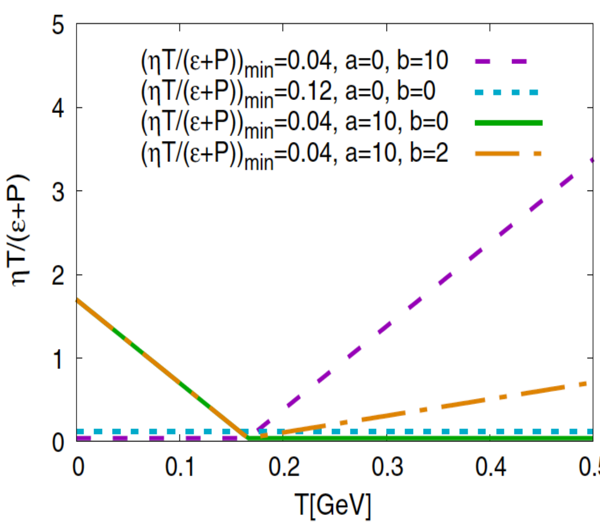
Flow tells "liquidity" of the system

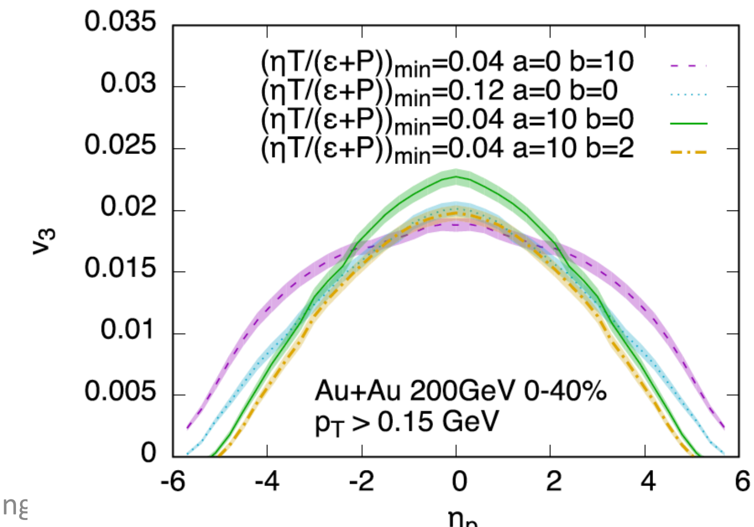
- State-of-art hydrodynamical calculations were compared with v_2 measurement by PHOBOS
- Without changing shear viscosity as a function of temperature (assumed), the data is not reproduced
  - Shear viscosity = "liquidity"
- More differential measurement help determine spatial structure
  - Higher order flow, and their fluctuation, etc.

G. Denicol, A. Monnai, and B. Schenke, PRL116, 212301(2016)



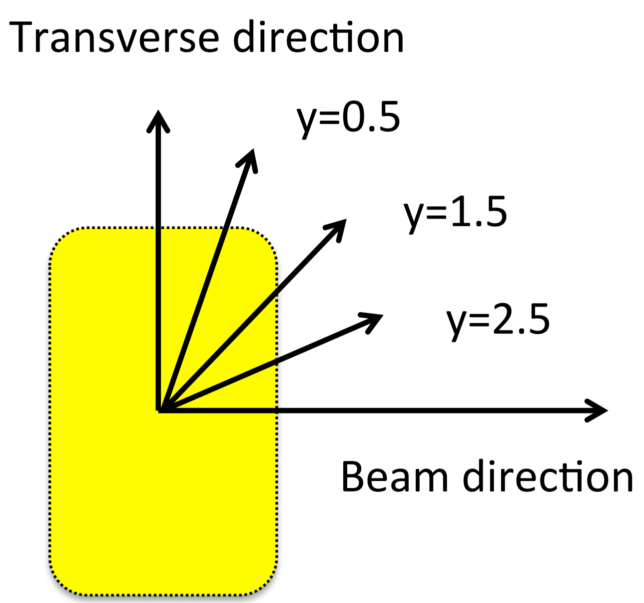
$$[\eta T/(\varepsilon+P)](T) = [\eta T/(\varepsilon+P)]_{\min} + a\times(T_c - T)\theta(T_c - T) + b\times(T - T_c)\theta(T - T_c)$$



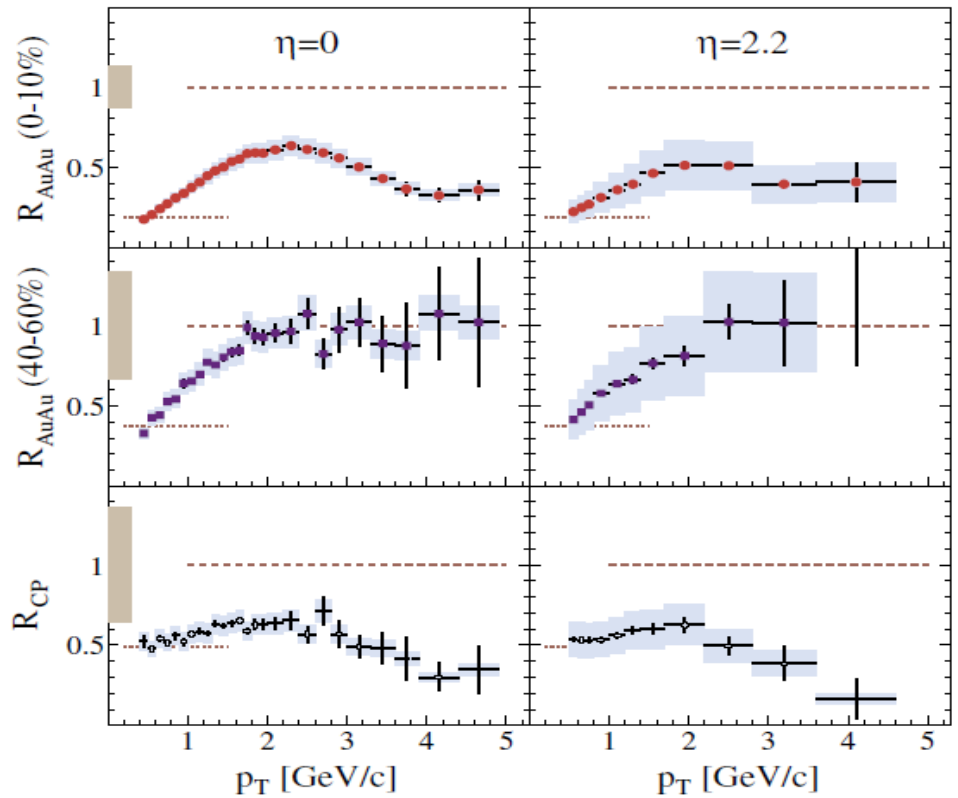


Jet suppression tells size of the matter

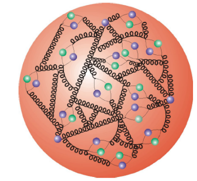
- Degree of the suppression can tell how much matter that the hard scattered partons passed through
- We should scan more continuously over rapidity
  - → Need large statistics with fsPHENIX



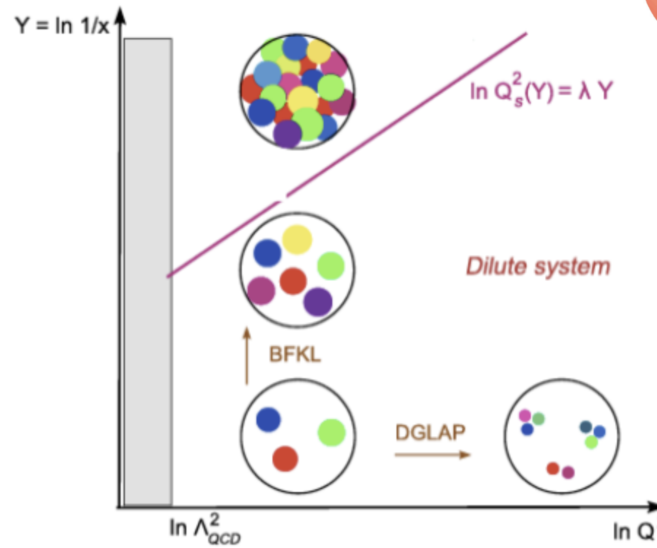
BRAHMS, PRL91, 072305(2003).

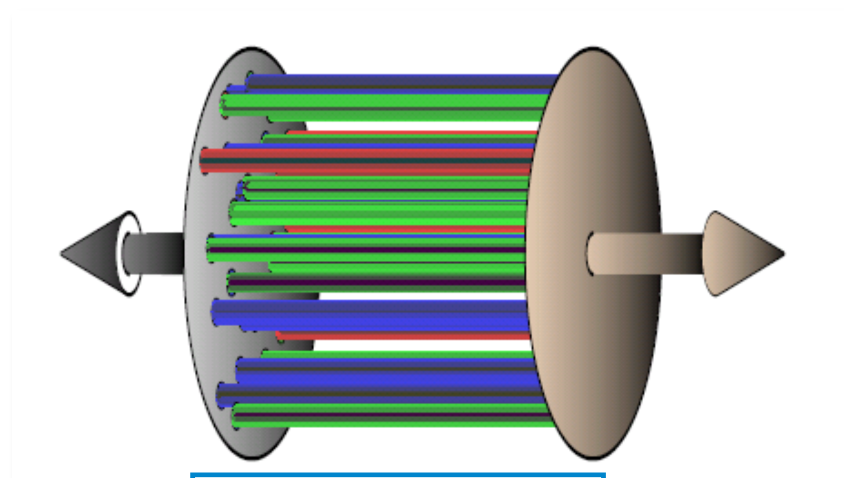


Before QGP = CGC?



- The collision area is full of gluons in the very initial stage
  - Gluon plasma → q-qbar -> QGP
- At very high energy, the small x gluons increasing exponentially, which eventually violates unitarity
  - Small x gluons have to merge and turn into higher x gluons
- **Color Glass Condensate (CGC)**
  - In highly non-linear state and has strong correlation
- Hadron yield will be reduced in low pT at forward (backward) rapidity)
  - Small x region

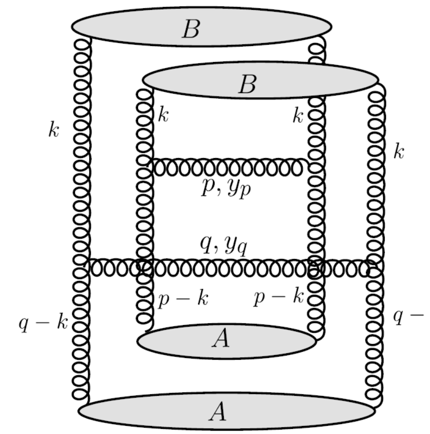


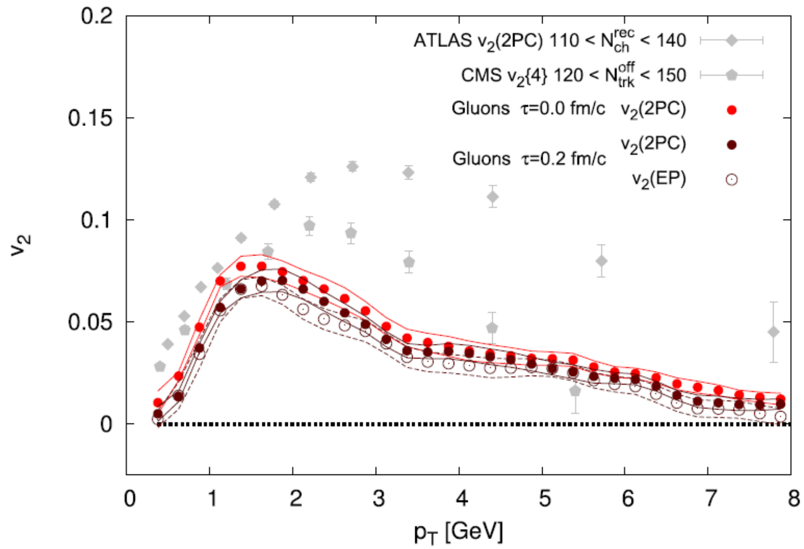


$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

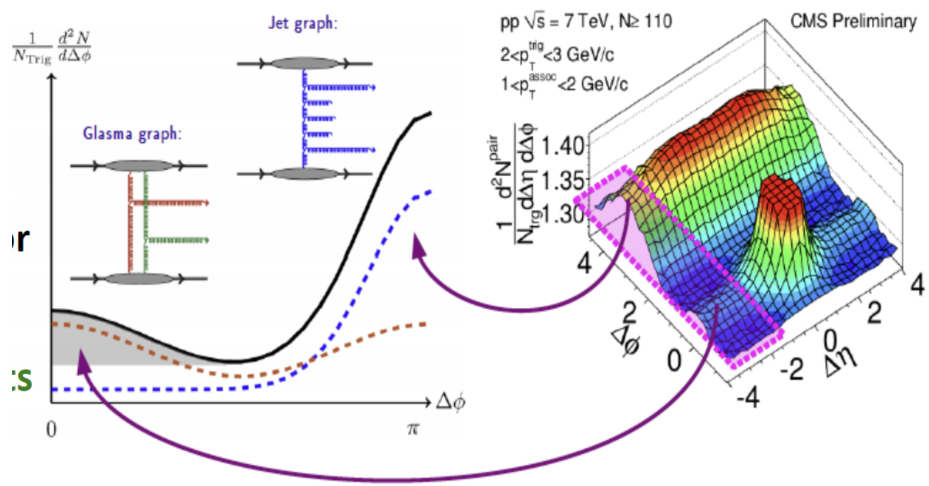
CGC explains the p+A flow?

- Strong correlation from the initial high density gluonic state (CGC) may have survived until final state
- Part of the v_2 measured in p+Pb collisions at LHC can be explained, but not perfect
  - No quantitative calculation is shown for RHIC





B. Schenke et al., PLB747 (2015)76

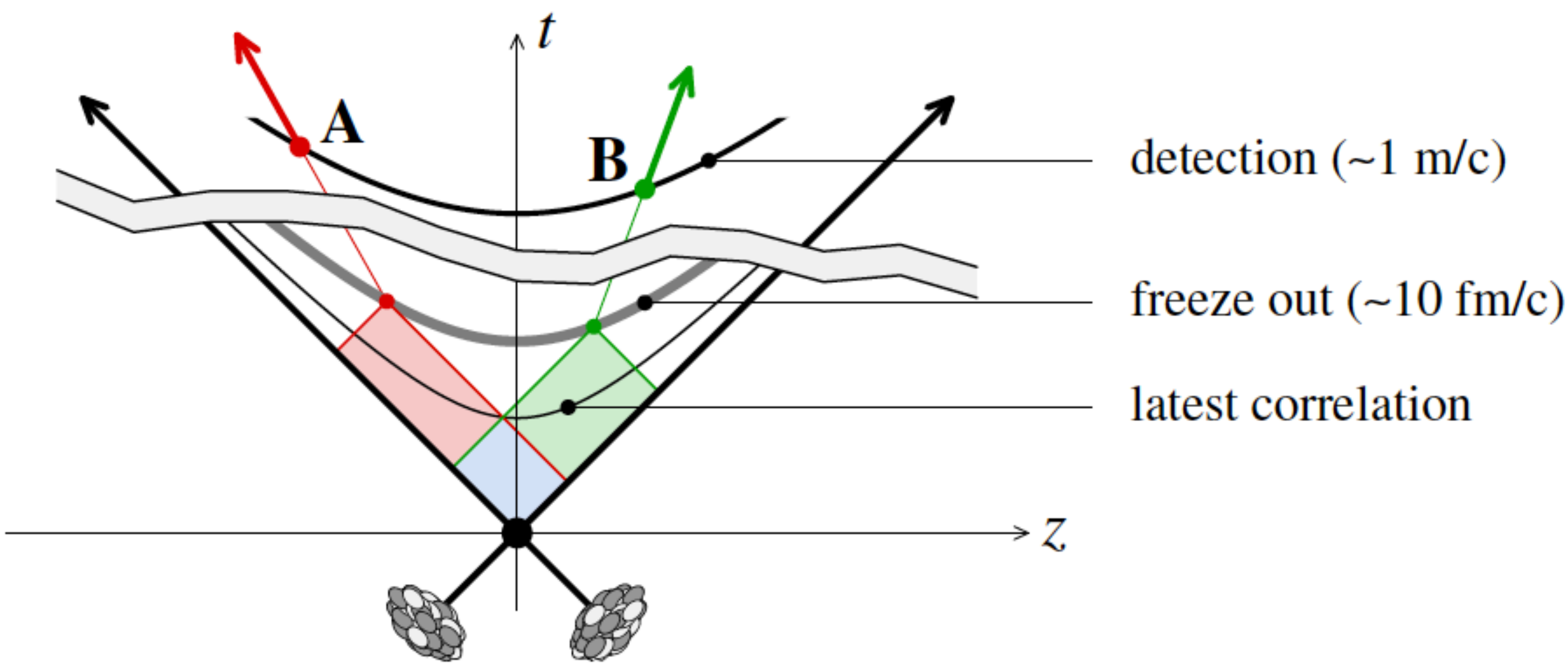


A. Dumitru et al, PLB697 (2011)21
K. Dusling and R. Venugopalan, PRD87, 094034(2013)

Spotting particular state

- It is said that the correlation of particles with large rapidity gap comes from the initial state of the collisions
  - Simple causality argument (e.g. arXiv:1412.0471)

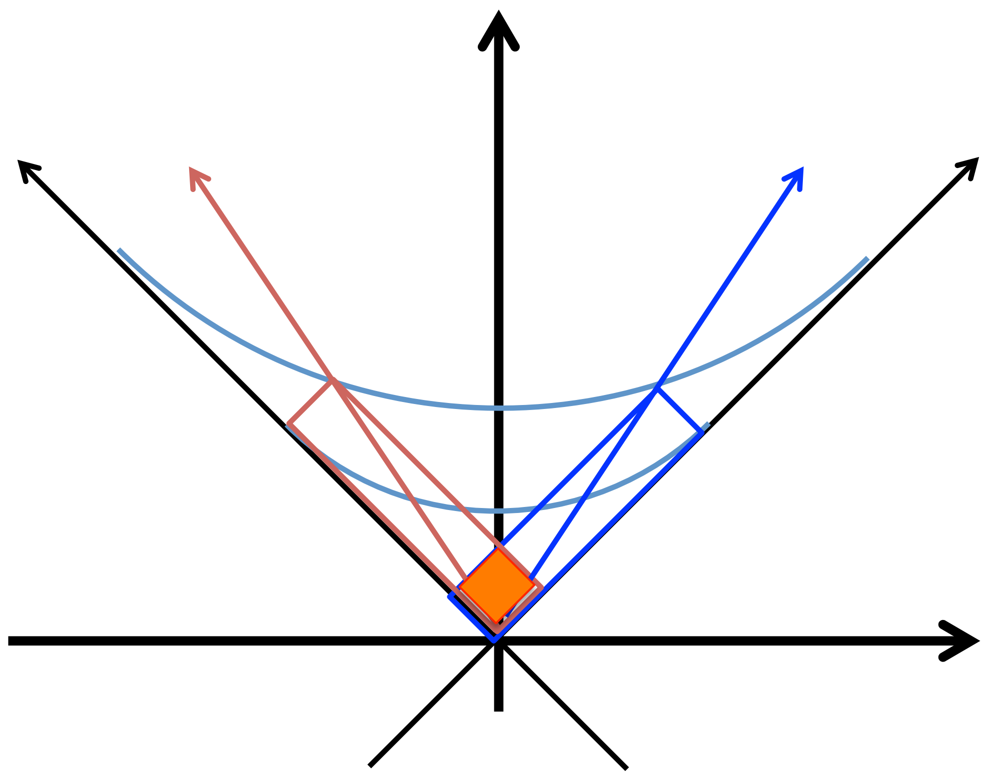
- Using this fact, one can spot the particular time of the collision?
  - e.g. CGC?



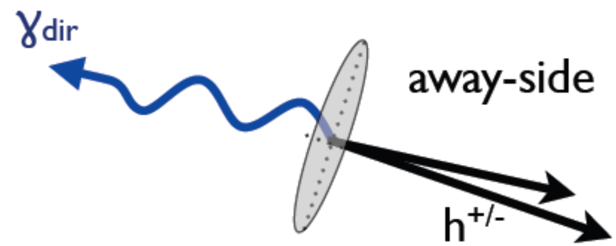
Using A+A and p+A

- One can dial the time in the system evolution

Both particles in very forward rapidity: tuning to very initial stage: CGC



$z_T = p_{Ta}/p_{Tt}$
$\xi = \ln(1/z_T)$

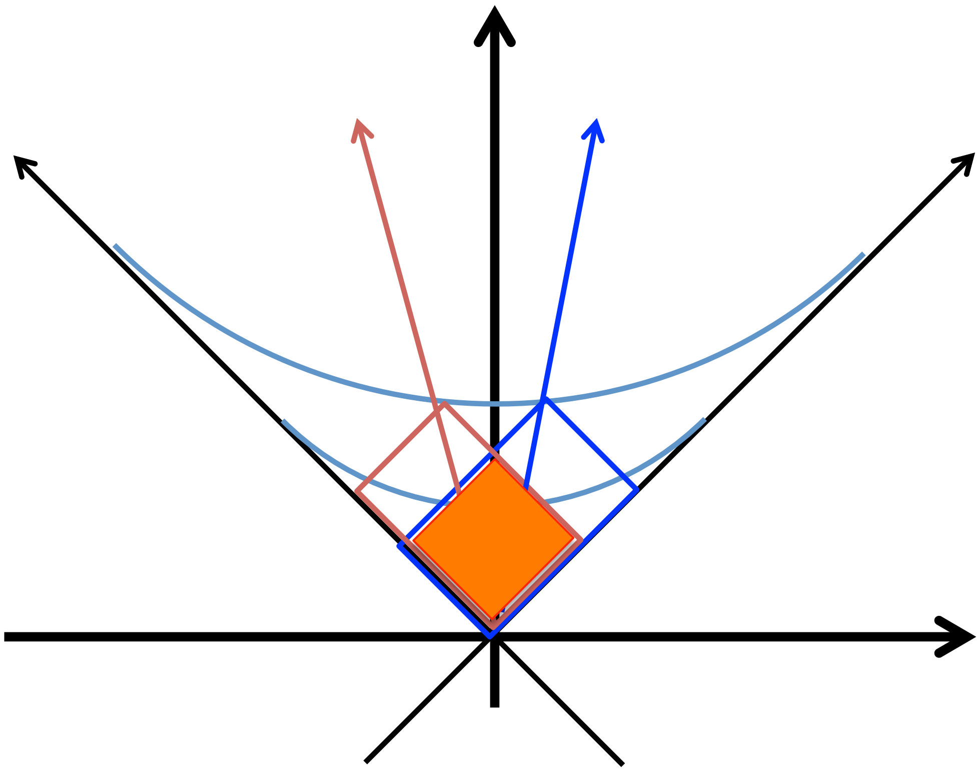


$h^{+/-}$: e.g. π^0

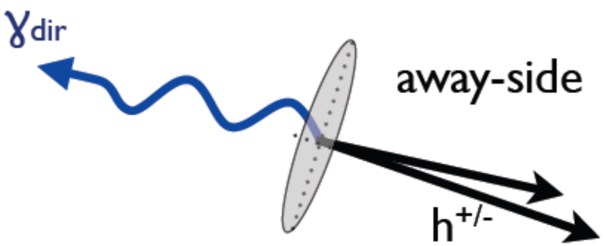
Using A+A and p+A

- One can dial the time in the system evolution

Both particles in mid-forward rapidity: tuning also into later stage: CGC+QGP



$z_T = p_{Ta}/p_{Tt}$
$\xi = \ln(1/z_T)$

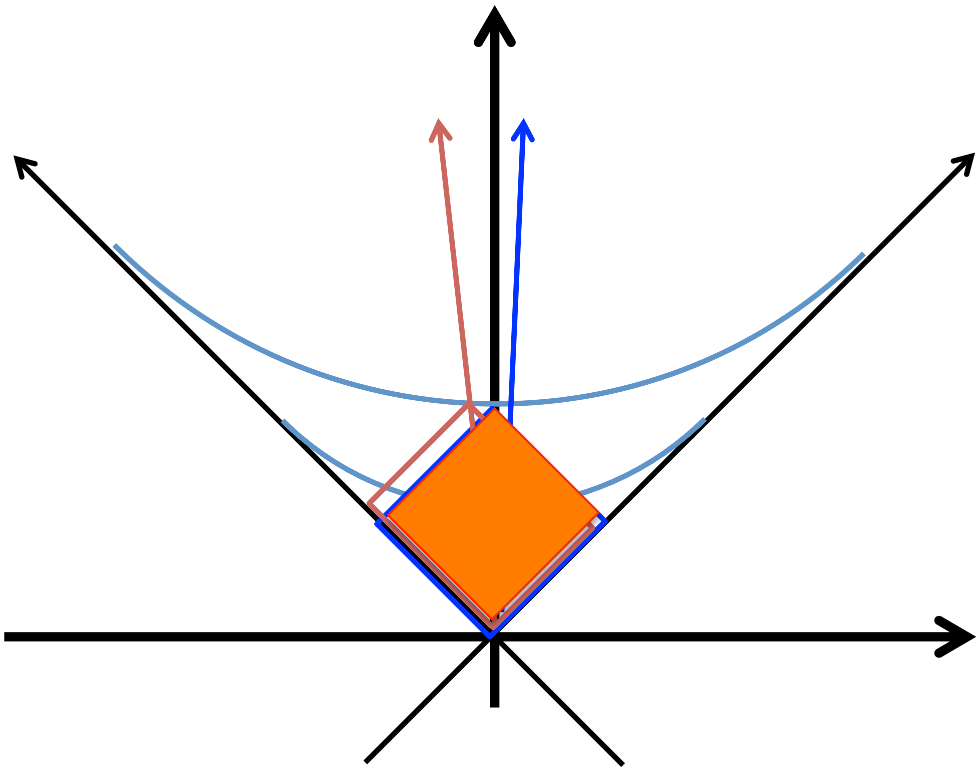


$h^{+/-}$: e.g. π^0

Using A+A and p+A

- One can dial the time in the system evolution

Both particles in mid rapidity: tuning more into later stage: CGC+QGP



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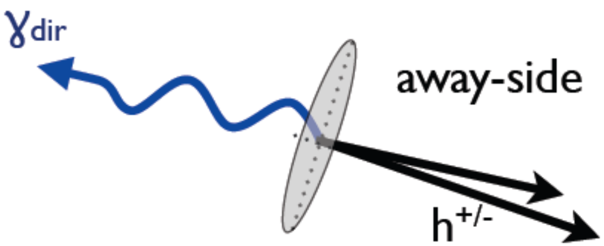
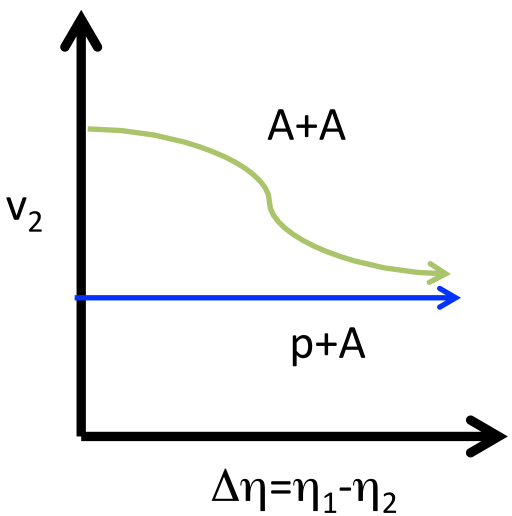
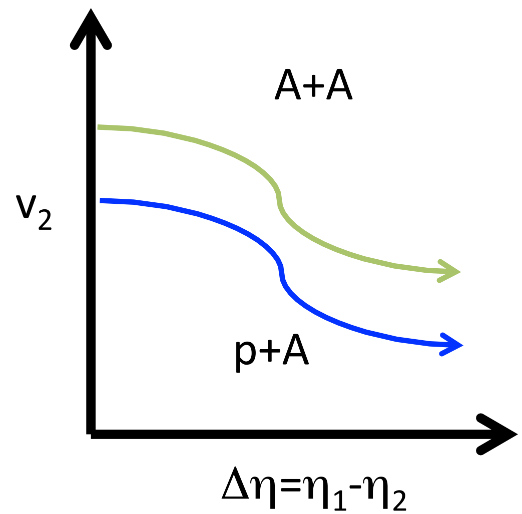


$h^{+/-}$: e.g. π^0

Taking flow (v_2) as an example

- If there is no hydrodynamical flow in p+A, i.e., the flow is built only by CGC (left)





- If there is hydrodynamical flow in p+A, i.e., the flow is built by CGC+QGP (right)

Why RHIC even after LHC?

- We (think) we confirmed that RHIC produced QGP and also at LHC
- More hard scattering background at LHC as compared to RHIC
  - Soft production is increased by $T = E^{1/4}$ while hard scattering is by $(\sqrt{s})^8$
  - RHIC is suitable place for detail investigation of QGP
- ATLAS published forw-backward multiplicity correlation in $|\eta|<2.4$
  - arXiv:1606.08170
  - Sensitive initial state and fluctuation of longitudinal expansion
  - Rapidity range is still in QGP region
- fsPHENIX rapidity is closer to the beam rapidity compared to LHC
  - e.g. ATLAS measurement in $|\eta|<2.4$. ALICE FOCAL upgrade: ($2.5<\eta<6$)
    - Note that the beam rapidity for 2.76TeV collisions is y=8.7, **Δy = 8.7-6 = 2.7**
  - At RHIC, beam rapidity is y=5.5, so if we instrument up to y=3.5, **Δy=2**.
    - Covering more forward rapidity compared to LHC.

Addition to current fsPHENIX design

- Instrumentation both forward and backward, ideally
  - In order to perform wide-rapidity correlation measurement
  - We can do forward-central correlation, too

- EMCal with good position/energy resolution
  - Higher granularity
  - π^0 and/or η, single photon separation is needed
  - PbSc+pre-shower is another option

- Good tracking in high multiplicity environment

- A device to separate π/K/p (if possible)
  - K/p separation may be enough, assuming π^0 is well identified down to low p_T in EMCal
  - A candidate device is time-of-flight?
  - Feasibility study is needed, which is not trivial, though.

To conclude

- HI measurement at forward (and backward) rapidity is definitely new and there are likely many discoveries.
  - Very little measurement so far
  - Theory community rapidly gets interested in this region
- Not necessarily to be done in most central HI collisions in Au+Au
  - Or, we can collide lighter nuclei
- Close tag with p+A/p+p collisions is essential
- I think it is worth mentioning this in fsPHENIX proposal to make the case stronger
  - I'd be happy to write one section on this in the proposal

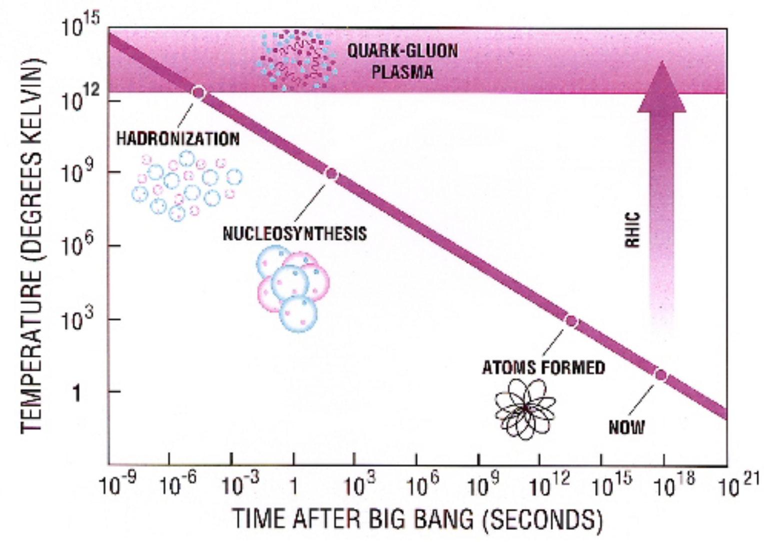
backup

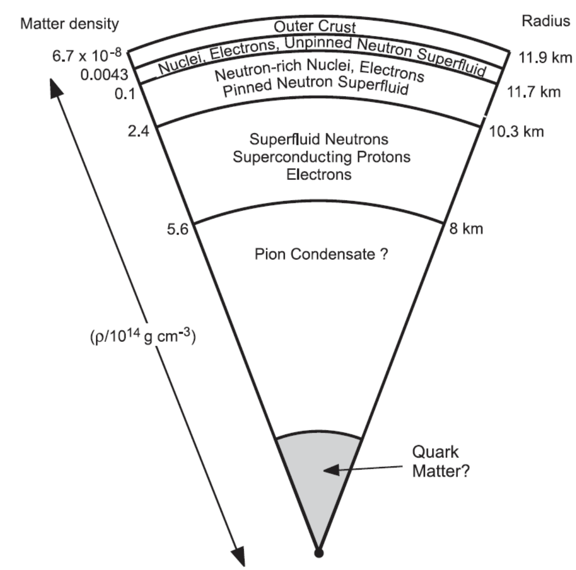
Quark Matter: Quark Gluon Plasma (QGP)

- Quarks and Gluons confined in nucleons will be liberated in a hot and dense environment
  - Quark Gluon Plasma (QGP)
  - Understanding quark confinement
  - Origin of nucleon mass (Chiral symmetry restoration)

- This phase is believed to have existed in the early Universe
  - Possibly existing in the core of neutron stars

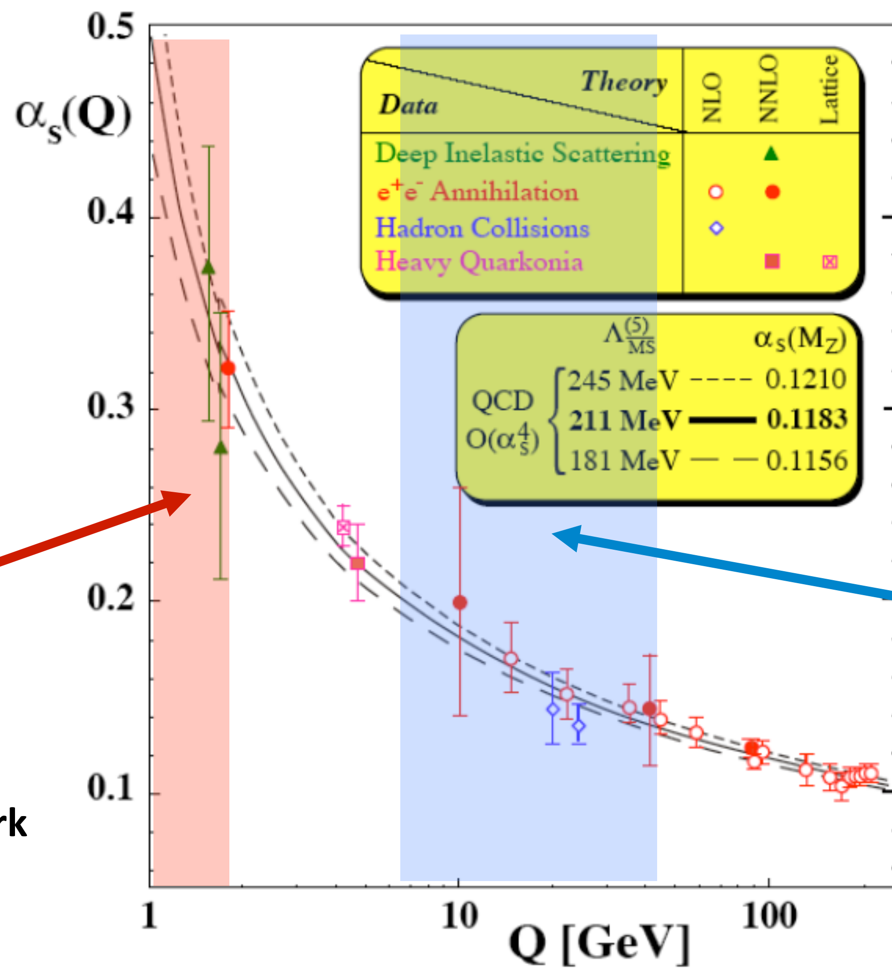
- Can we produce QGP?
  - Use of relativistic heavy ion collisions
  - Hot and dense medium is produced. Energy, density and size of the system is controllable
  - Measure thermodynamical properties such as temperature or entropy





2. Jet quenching (new from RHIC)

- Yield of **jets** can be calculated using perturbative QCD (pQCD)
- Exploring non-perturbative region with perturbative probes



Thermal region

QGP

Perturbative QCD (pQCD) doesn't work

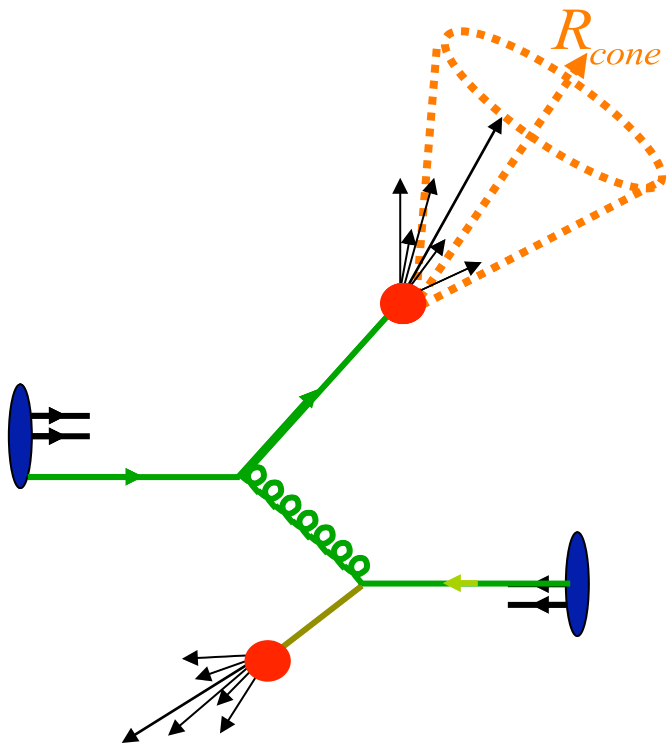
Hard region

Jets

Perturbative QCD (pQCD) works

Jets in p+p (primordial hard scattering)

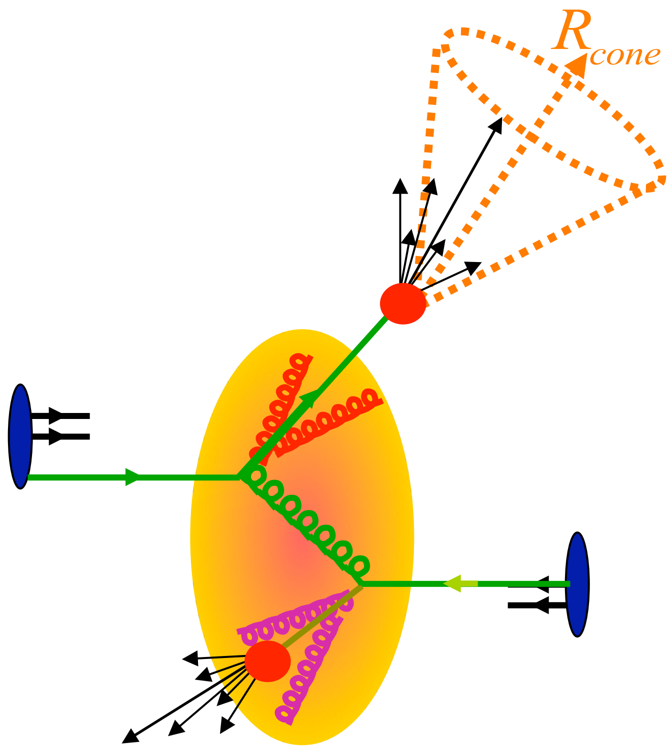
Yield in A+A collisions ∝ Ncoll × p+p collisions

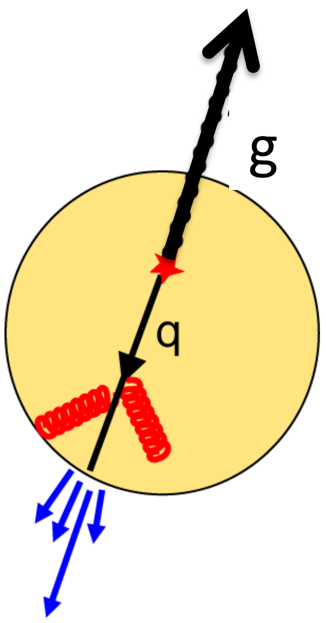


Jets in QGP

- Hard scattered partons lose their energies in the QGP via gluon radiation or parton collisions
- Jets that are fragments of the partons accordingly reduce their energies

Yield in A+A collisions ∝ Ncoll × p+p collisions





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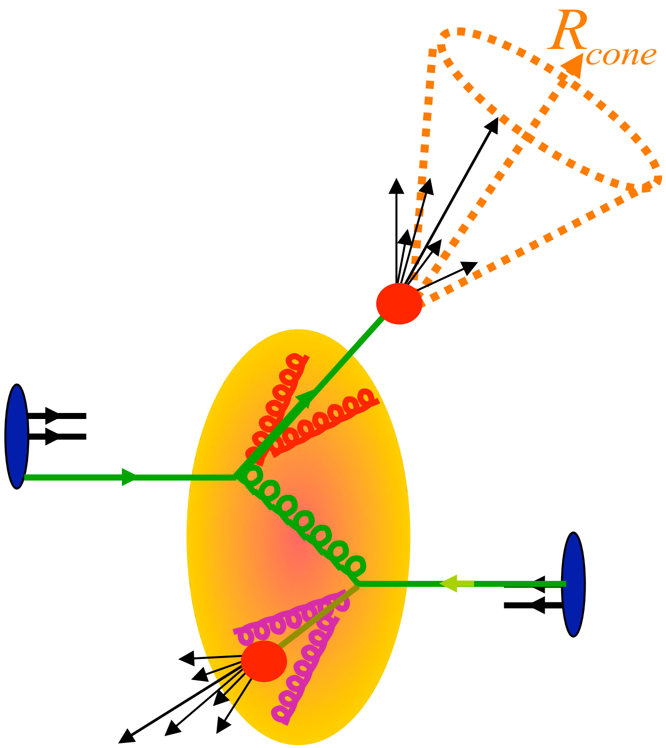
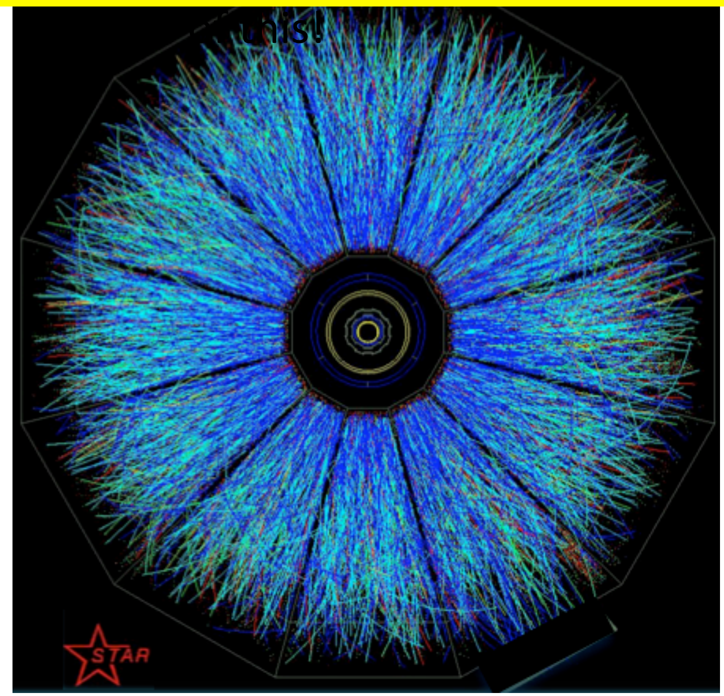
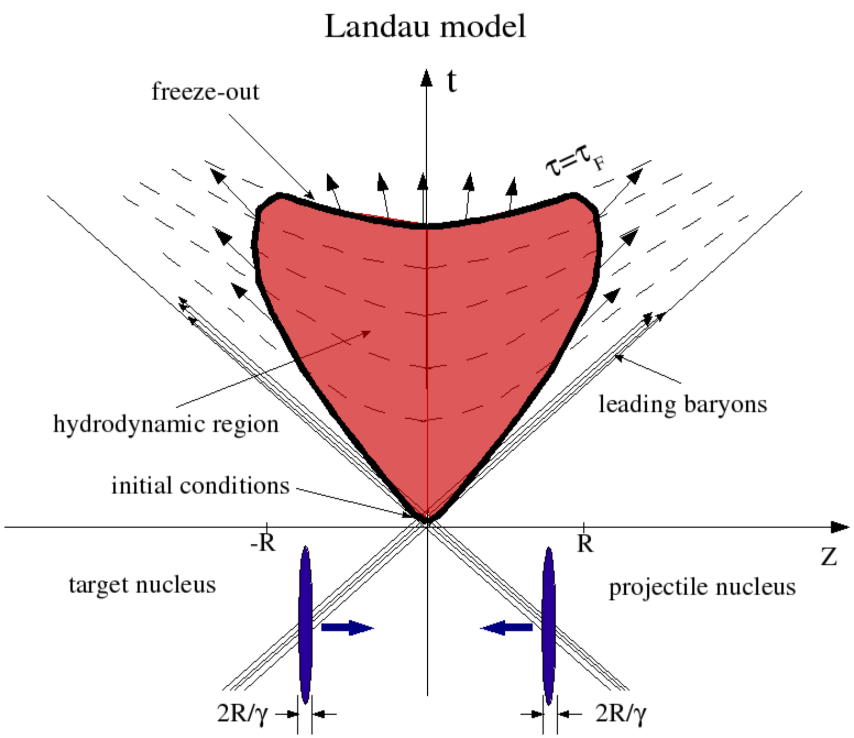


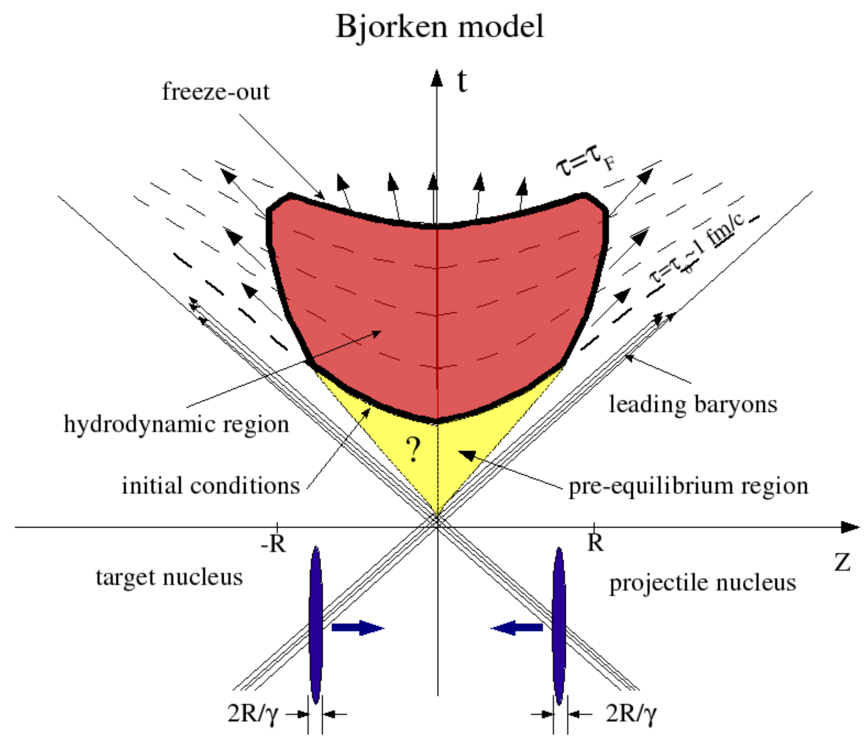
Reconstruction of jets in HI collisions is extremely difficult



Landau and Bjorken expansion models

central collision of equal nuclei at $\gamma = \sqrt{s_{NN}} / 2m_N$

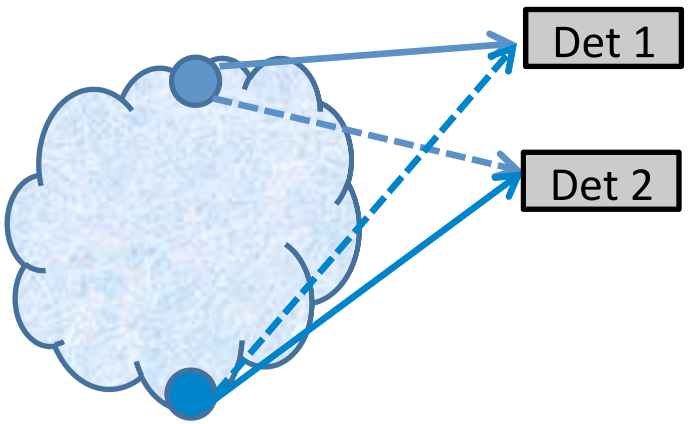




differ mostly by initial conditions

proper time $\tau = \sqrt{t^2 - z^2}$ space-time rapidity $\eta = \frac{1}{2} \ln \frac{t+z}{t-z}$

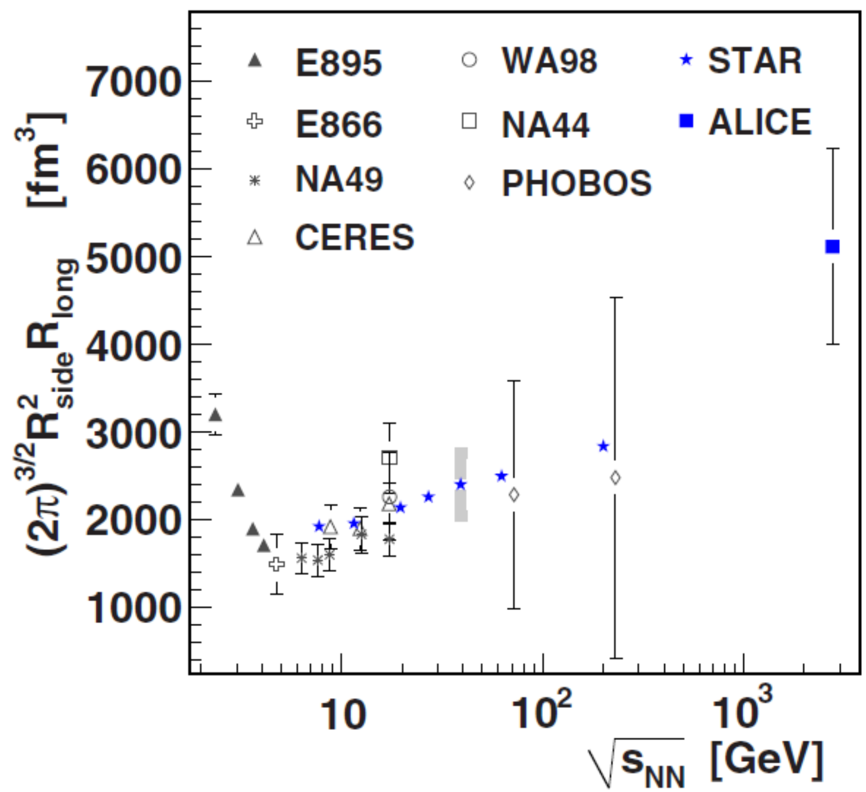
Source size from Interferometry



$$A_{12} = \frac{1}{\sqrt{2}}[e^{ip_1\cdot(r_1-x)}e^{ip_2\cdot(r_2-y)}+e^{ip_1\cdot(r_1-y)}e^{ip_2\cdot(r_2-x)}]$$

$$P_{12} = \int d^4xd^4y|A_{12}|^2\rho(x)\rho(y) = 1+|\tilde{\rho}(q)|^2 \equiv C_2(q)$$

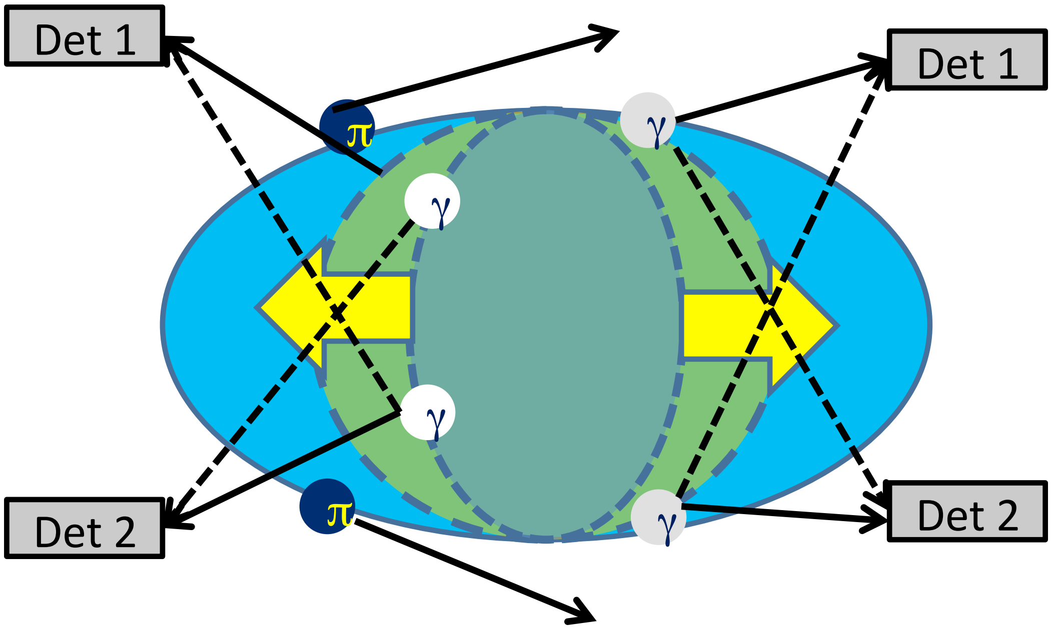
- Interference of two identical particles from incoherent sources
  - First applied by Hanbury-Brown and Twiss for star size measurement
  - Hanbury-Brown Twiss (HBT) effect
- In heavy ion collisions, we use π, K, etc. as probes.
  - Measurement can be basically made at freezeout



Direct photon HBT

- One can study time-dependent size of the QGP
  - Photons penetrate systems. Momentum will tell the time they are emitted.
  - Angle dependent HBT measurement is also possible → shape measurement

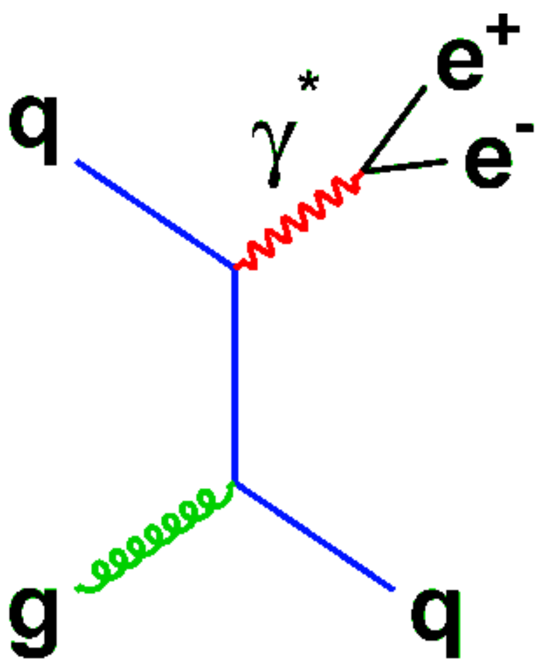
- This measurement will be best done at RHIC. Background from the hard scattering makes the measurement difficult at LHC.



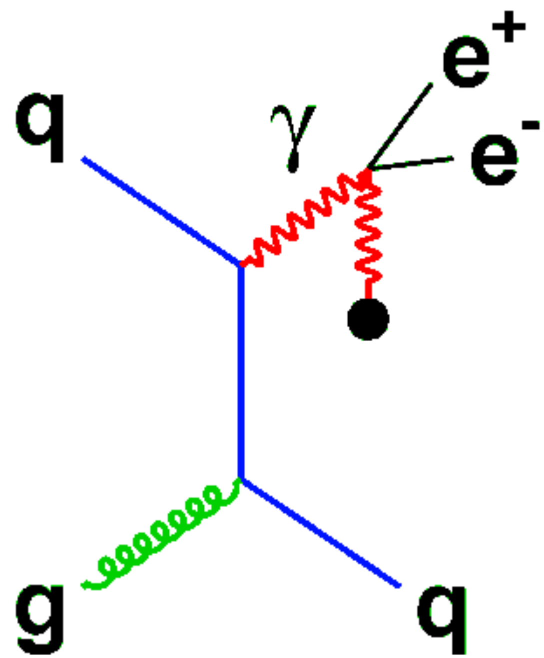
Shooting thermal photons

- Hadron contamination to the photon samples has been a big issue
- Smallest hadron contamination when using photons converted to electron pairs

Internal conversions (virtual photon)



External conversions (real photon)

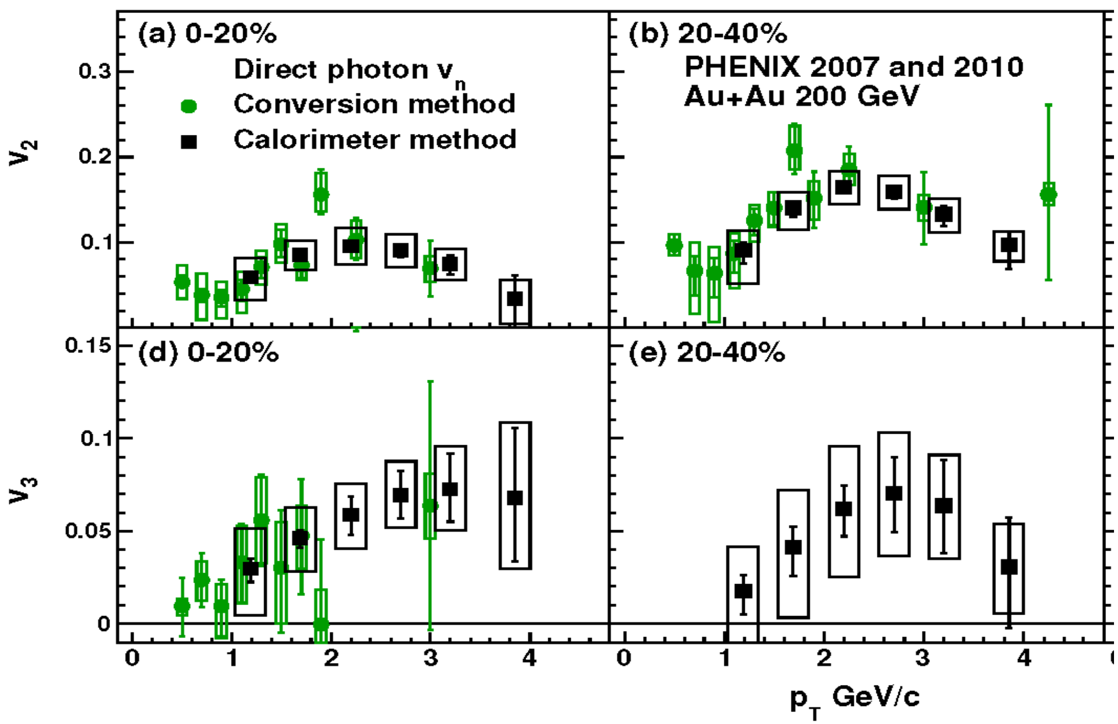


Direct photon flow: v_2 and v_3

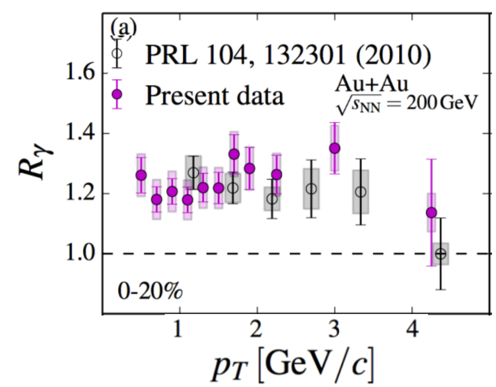
- Subtract hadron-decay photon v_n from inclusive photon v_n
  - Decay photon v_n is calculated from the measured π^0 v_n
  - v_n for other hadrons are obtained by KE_T-scaling + m_T scaling from π^0 and *Kaon*

- Sizable positive flow is observed.
  - Similar trend as $h^{+/-}$ and π^0 (PRL 107, 252301 (2011))
  - Late stage emission?

arXiv:1509.07758



$$v_n^{dir.} = \frac{R_\gamma v_n^{inc.} - v_n^{dec.}}{R_\gamma - 1}$$

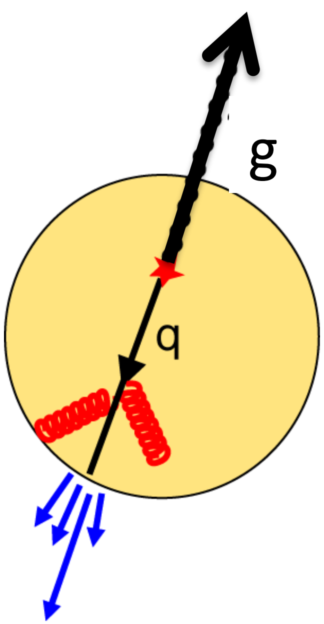


3. Direct photons: answer to suppression

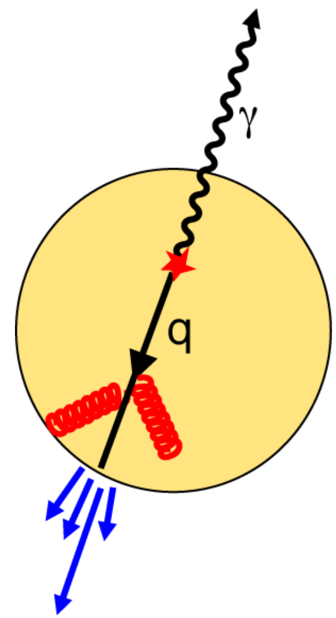
- Is the suppression due to energy loss of hard scattered partons?
- Or, the hard scattering cross-section simply does not scale between p+p and Au+Au?
- We need something produced in the hard scattering and emerging unmodified

Direct photons is a tool to answer:

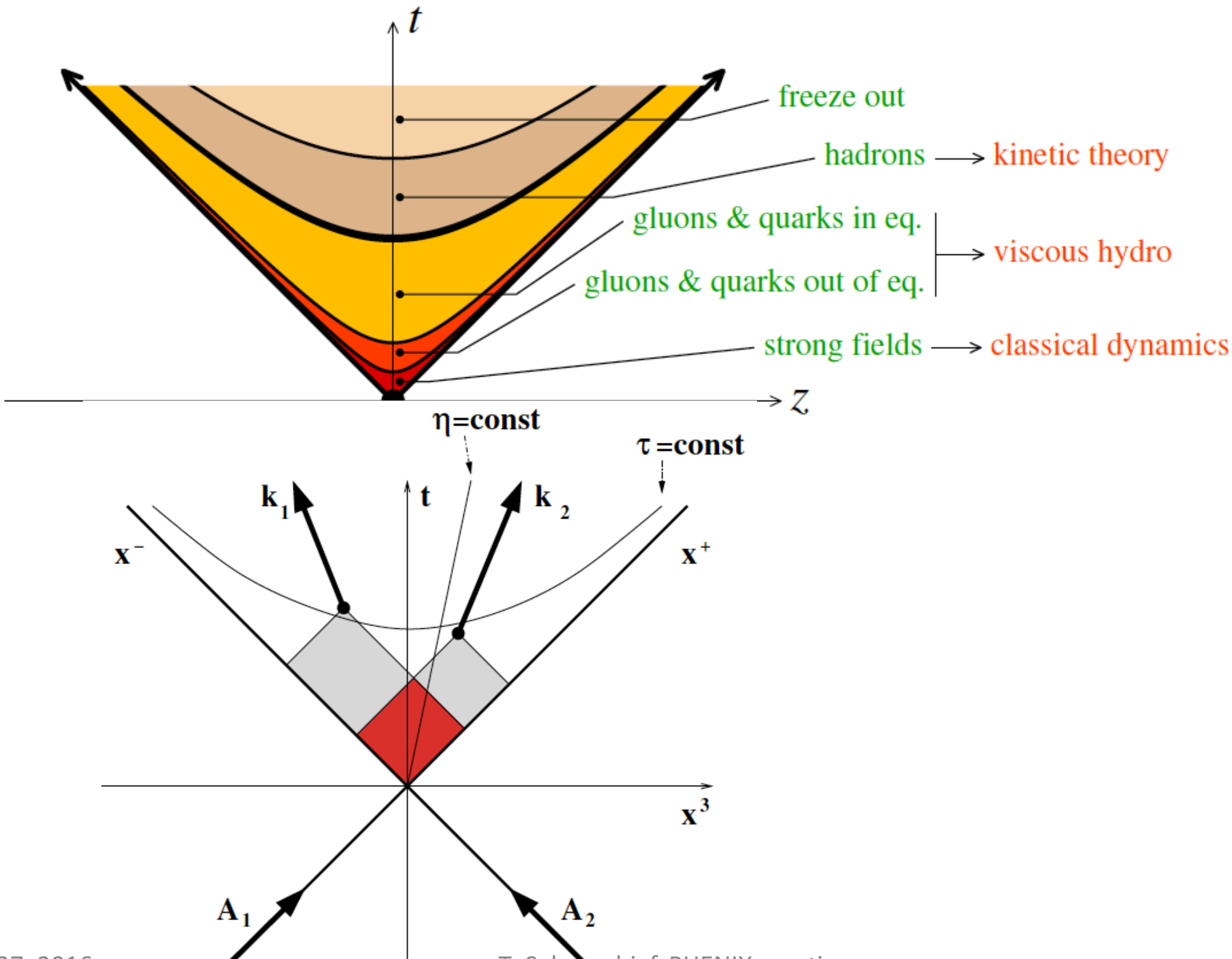
Jet Production: **Yield** $\propto \alpha_s^2$



Photon Production: **Yield** $\propto \alpha\alpha_s$

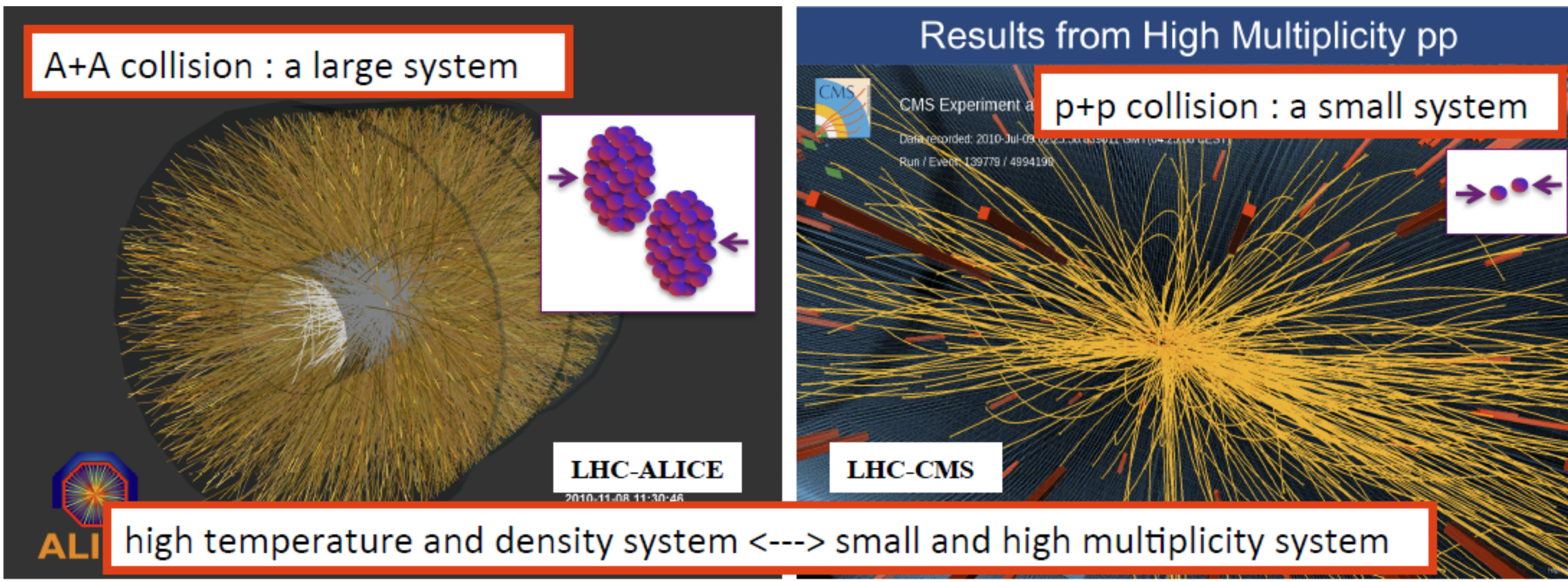


Cartoon from F. Gelis (e.g. arXiv:1412.0471)



Similarity in A+A, p+A and p+p?

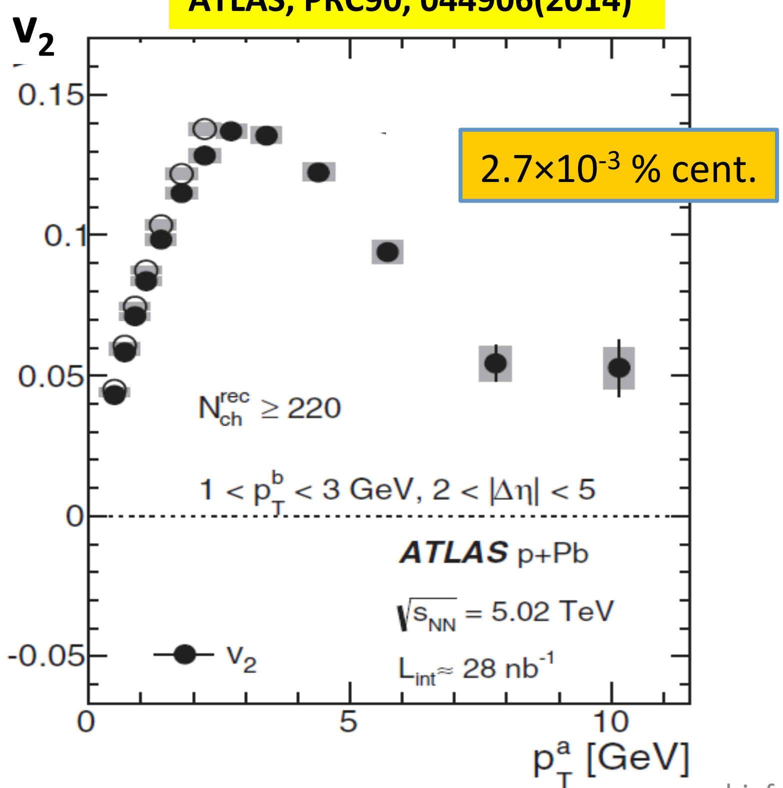
- p+p and p+A collisions have been used as a reference to investigate the phenomena in A+A collisions
- In very high energy collisions, the situation is different?



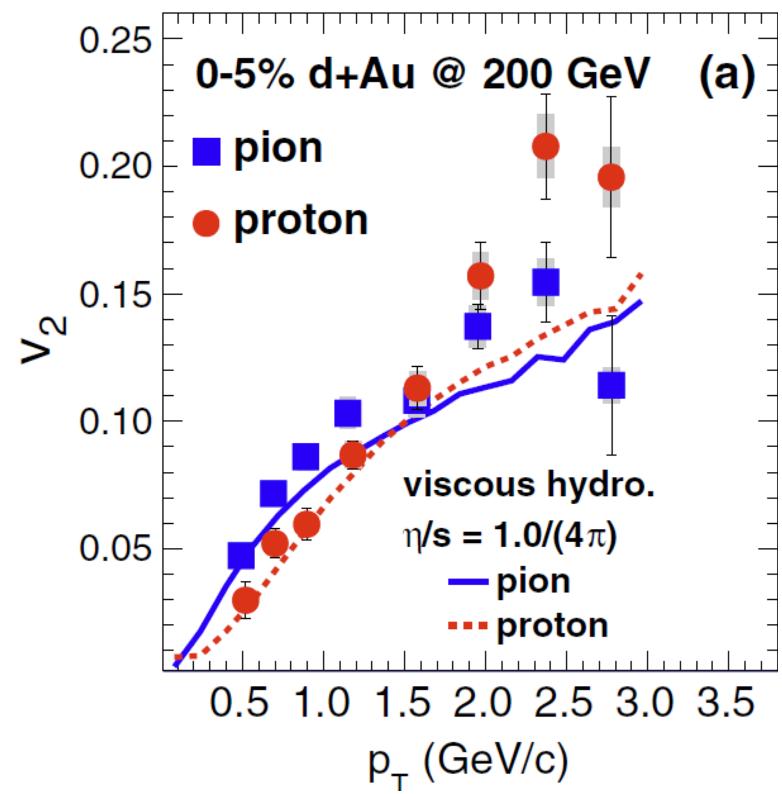
Flow is also seen in p+Pb and d+Au

- Flow is also observed in most central p+Pb and d+Au collisions at LHC and RHIC at $\sqrt{s_{NN}}$= 5.02TeV and 200GeV, respectively
- The intensity is as much as that in Pb+Pb and Au+Au collisions
- ***Possible QGP production in the small systems?***

ATLAS, PRC90, 044906(2014)

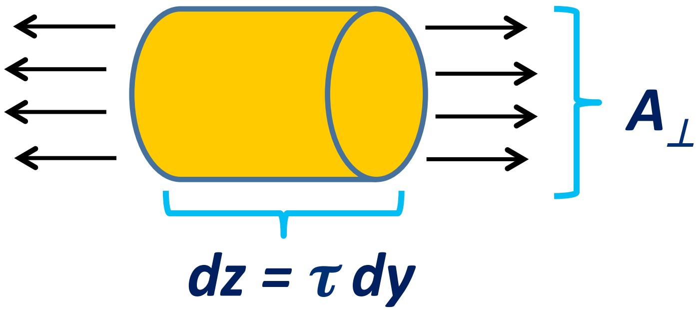


PHENIX, PRL114, 192301 (2015)



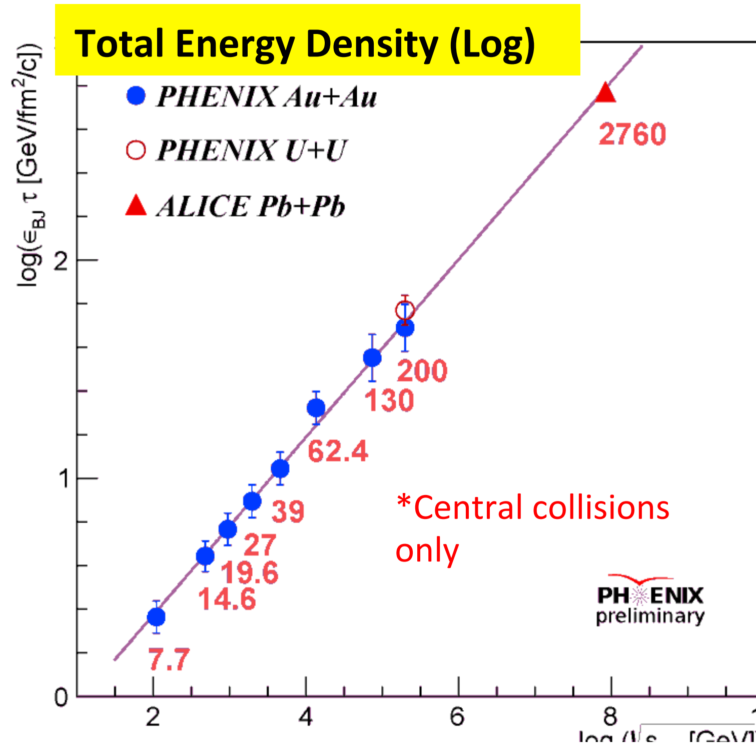
2. Energy density

- Total transverse energy is related to the energy density (Bjorken formula)



$$\varepsilon_{BJ} = \frac{1}{\tau A_\perp}\frac{dE_T}{dy}$$

τ: QGP formation time, $A_\perp$: collision area



- 5.7GeV/fm³ @ Au+Au $\sqrt{s_{NN}}$=200GeV

(phase transition expected at ~2GeV/fm³)

$$\varepsilon_{BJ}\tau \propto \left(\sqrt{s_{NN}}\right)^{\alpha}, \alpha \approx 0.41$$