YIPQS Symposium: Perspective in Theoretical Physics

-- from quark-hadron sciences to unification of theoretical physics

# Properties of Dense Matter in High-energy Heavy-ion Collisions


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# Phases of Matter

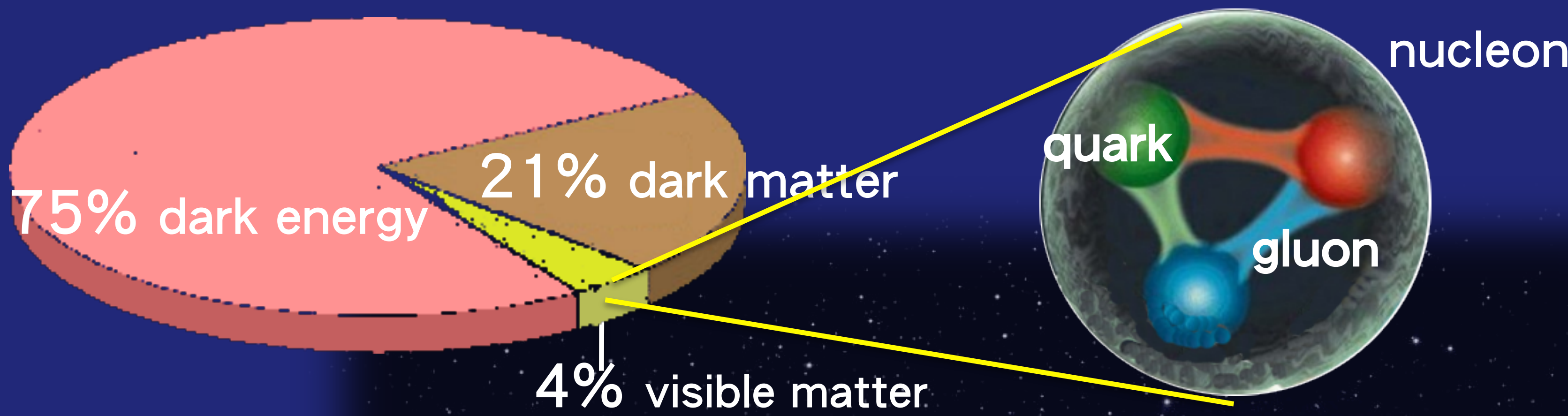
火 (gas) 水 (liquid) 土 (solid)

Bose-Einstein condensate, fermionic condensate, superfluids, supersolids, paramagnetic, ferromagnetic, liquid crystals, …

Hadron properties

Quark-gluon Plasma (QGP)

# Composition of Matter in our Universe




$$m_N \bar{u}(p) u(p) = \langle N(p) | \frac{\alpha_s}{2\pi} F^a_{\mu\nu} F^{\mu\nu}_a + \sum_q m_q \bar{\psi}_q \psi_q | N(p) \rangle$$

95% of nucleon's mass from gluon sector

# QCD Theory

$$L_{QCD} = \sum_{f=1}^{n_f} \bar{\psi}\gamma_\mu (i\partial^\mu - gA_a^\mu \frac{\lambda_a}{2} - m)\psi - \frac{1}{4}\sum_a F_a^{\mu\nu} F_{a,\mu\nu}$$

- SU(3) gauge symmetry (non-Abelian)
  - Asymptotic freedom at short distance
  - Confinement at long distance

$$\alpha_s(Q^2) = \frac{4\pi/(11 - \frac{2}{3}n_f)}{\ln(Q^2/\Lambda_{QCD}^2)}$$

- Chiral symmetry and its spontaneous breaking
  - Goldstone boson and chiral condensate

$$\langle \bar{\psi}\psi \rangle \neq 0$$

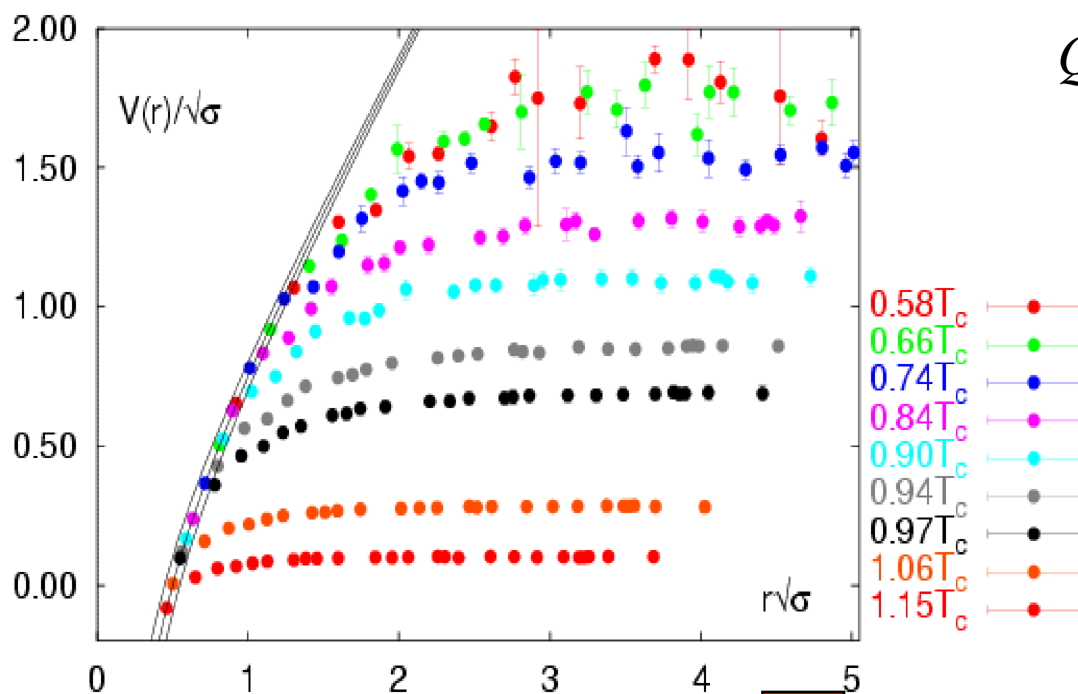
- Scale and $U_A(1)$ anomaly
- ….

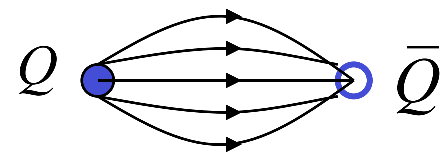
# Confinement-deconfinement

SU(3) non-Abelian gauge interaction → confinement

$$V(r) = -\frac{\alpha}{r} + \sigma r$$

**Heavy quark potential:**



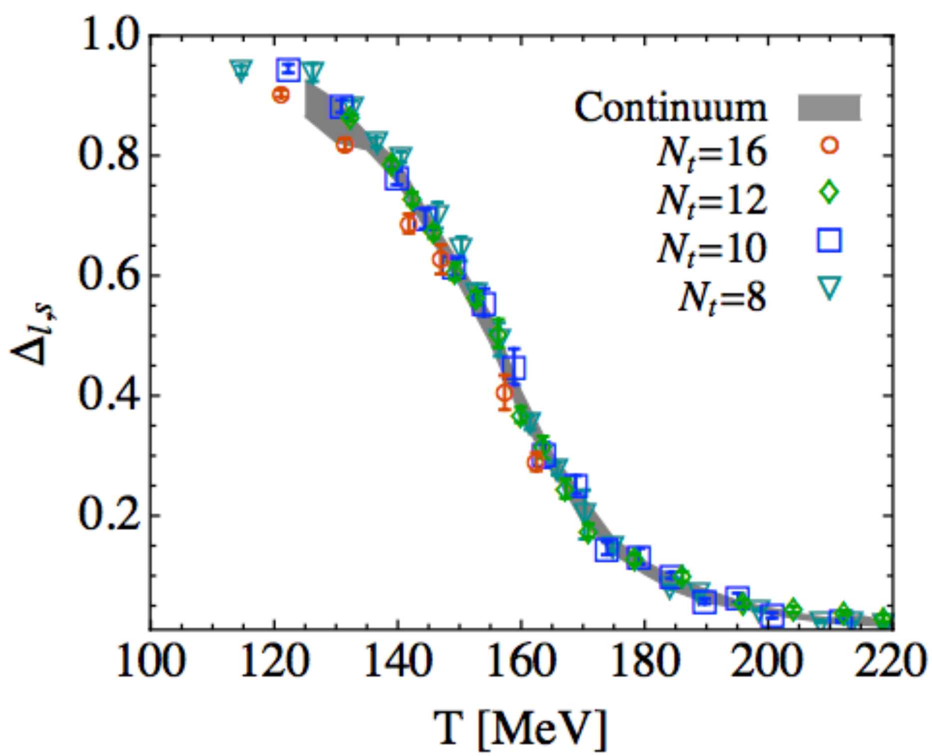

Karsch, Laermann and Peikert 2001

**Dissociation of J/Ψ**

# Chiral Symmetry Restoration

T=0: $\langle \bar{\psi}\psi \rangle \neq 0$ $SU(3)_L \otimes SU(3)_R \to SU_{L+R}(3)$

Spontaneously broken: Goldstone bosons (π,K,η)



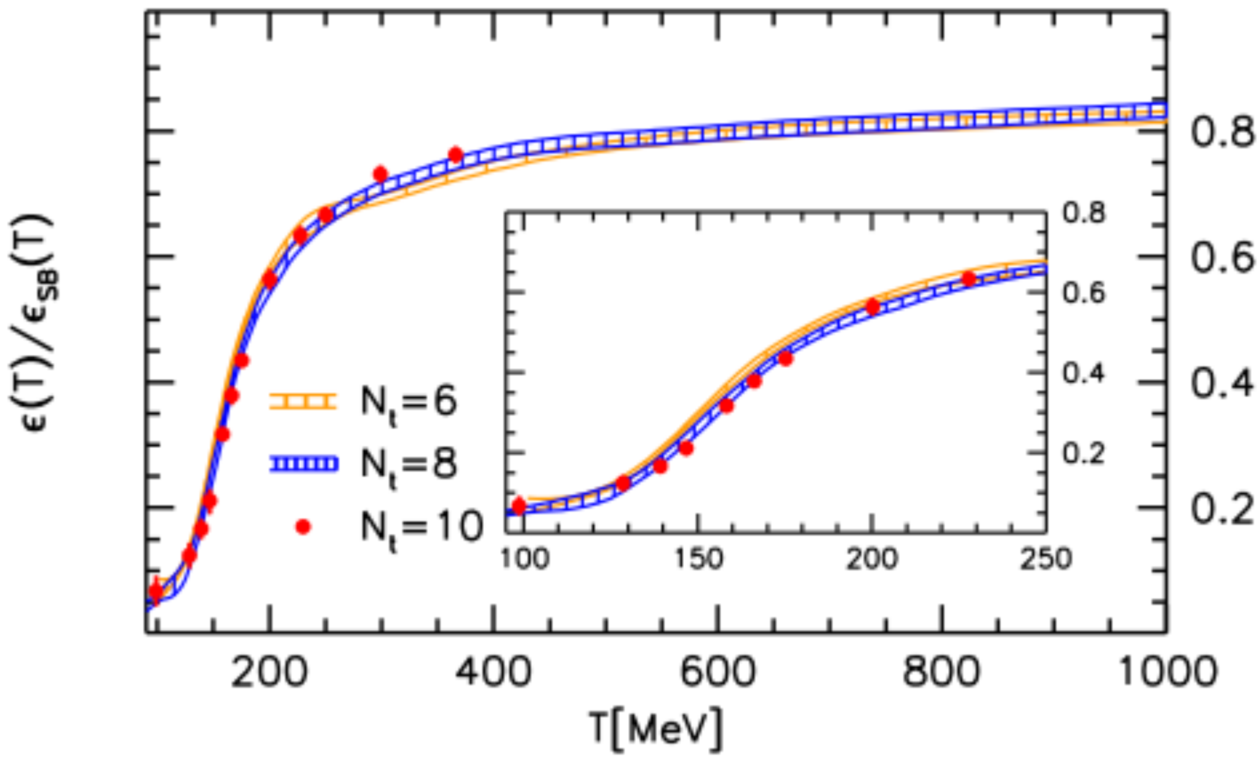

Wuppertal-Budapest, JHEP 1009 (2010) 073

QCD phase transition is a cross-over (μ=0)

No unique $T_c$

# QCD phase transition from lattice QCD

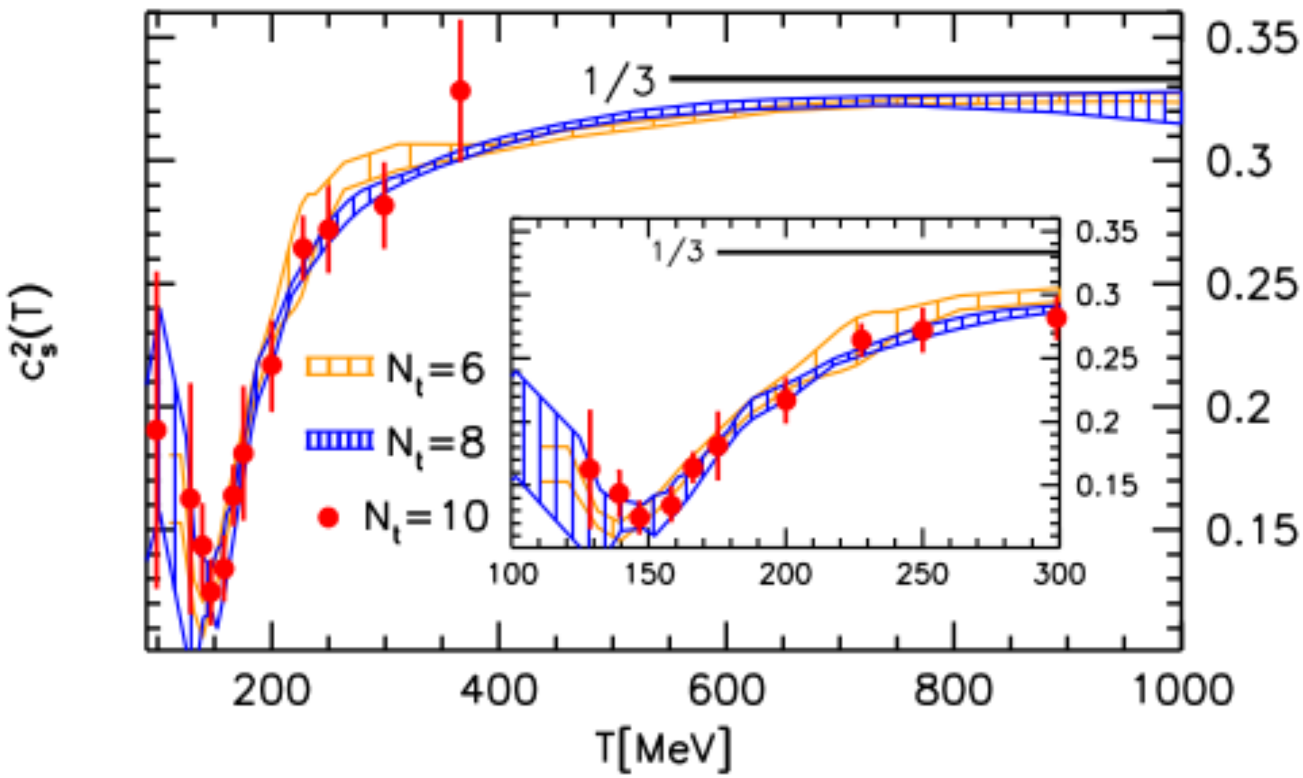
Fodor et al. 2006 (Wuppertal-Budapest)



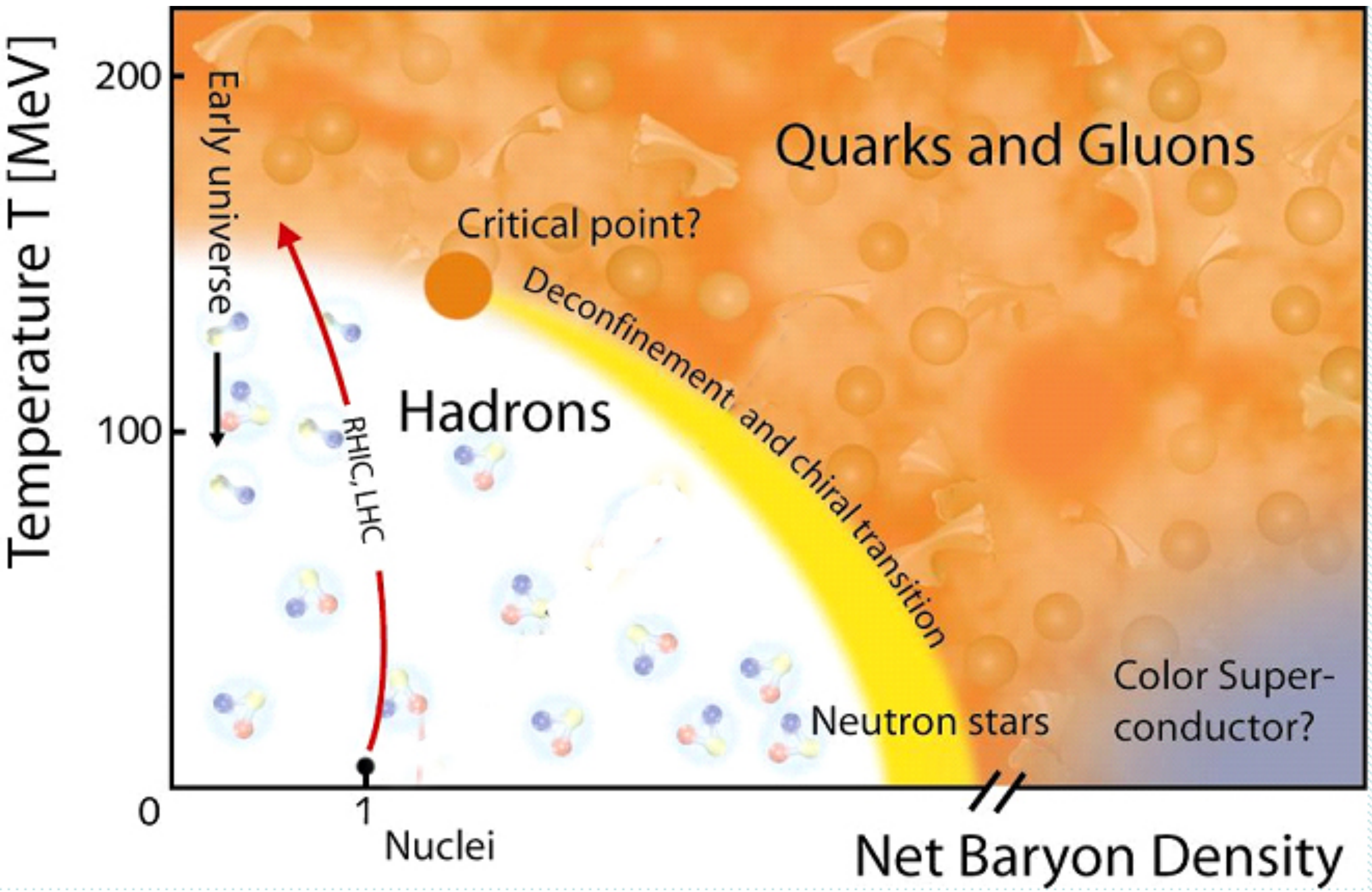

At T ~ 5Tc, ε still 80% of the Stefan-Boltzmann value:
Quasi-particle modes at high T (Blaizot, Iancu, Rebhan '2001)

# EOS from lattice QCD

Sound velocity $$c_s^2(T) = \frac{\partial \epsilon(T)}{\partial P}$$



# QCD Phase Diagram



# Heavy-ion Colliders


RHIC

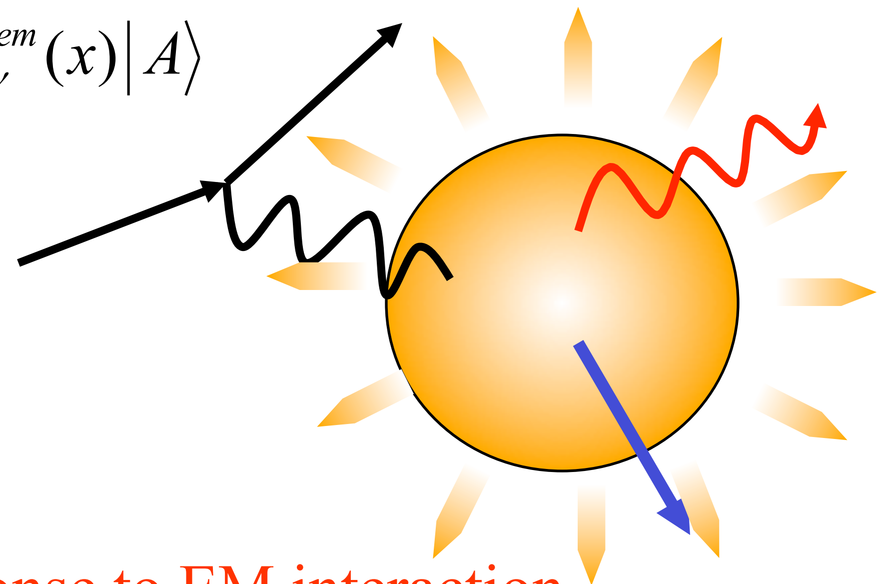
LHC

# Heavy Ion Collisions

# Study properties of QGP in AA Collisions

$$W_{\mu\nu}(q) = \frac{1}{4\pi}\int d^4x e^{iq\cdot x} \langle A | j_\mu^{em}(0) j_\nu^{em}(x) | A \rangle$$

$$F_1(x_B) \qquad x_B = -\frac{q^2}{2p\cdot q}$$



**Dynamic System**:

- EM emission: Medium response to EM interaction

  γ production, J/Ψ suppression

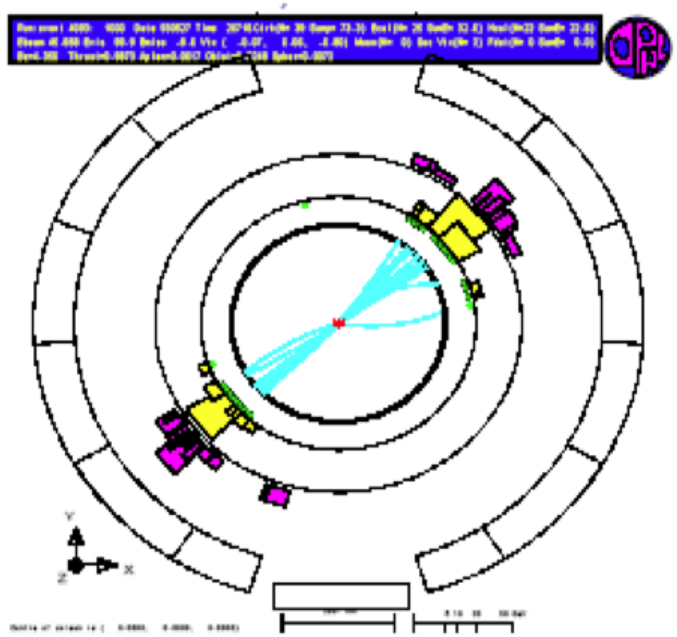
- Hard probes: Medium response to strong interaction

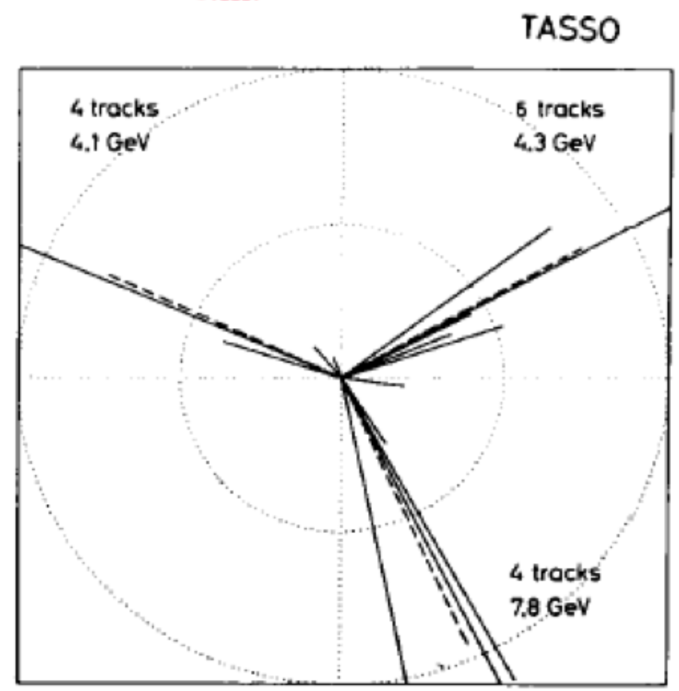
  Jet quenching

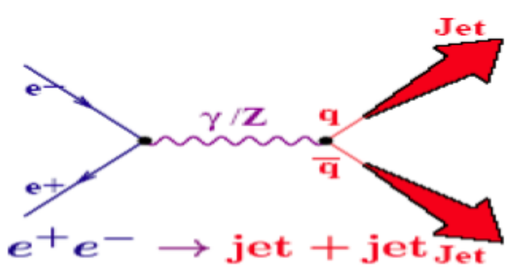
- Soft hadrons: Bulk properties of medium, collective behavior

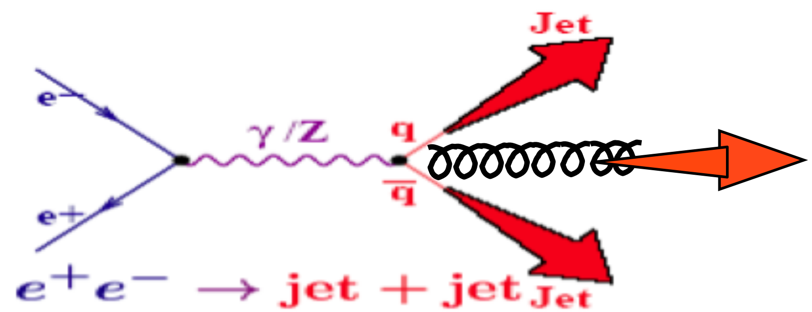
# Jets in high-energy reactions

LEP ($\sqrt{s} = 90 - 205$ GeV)

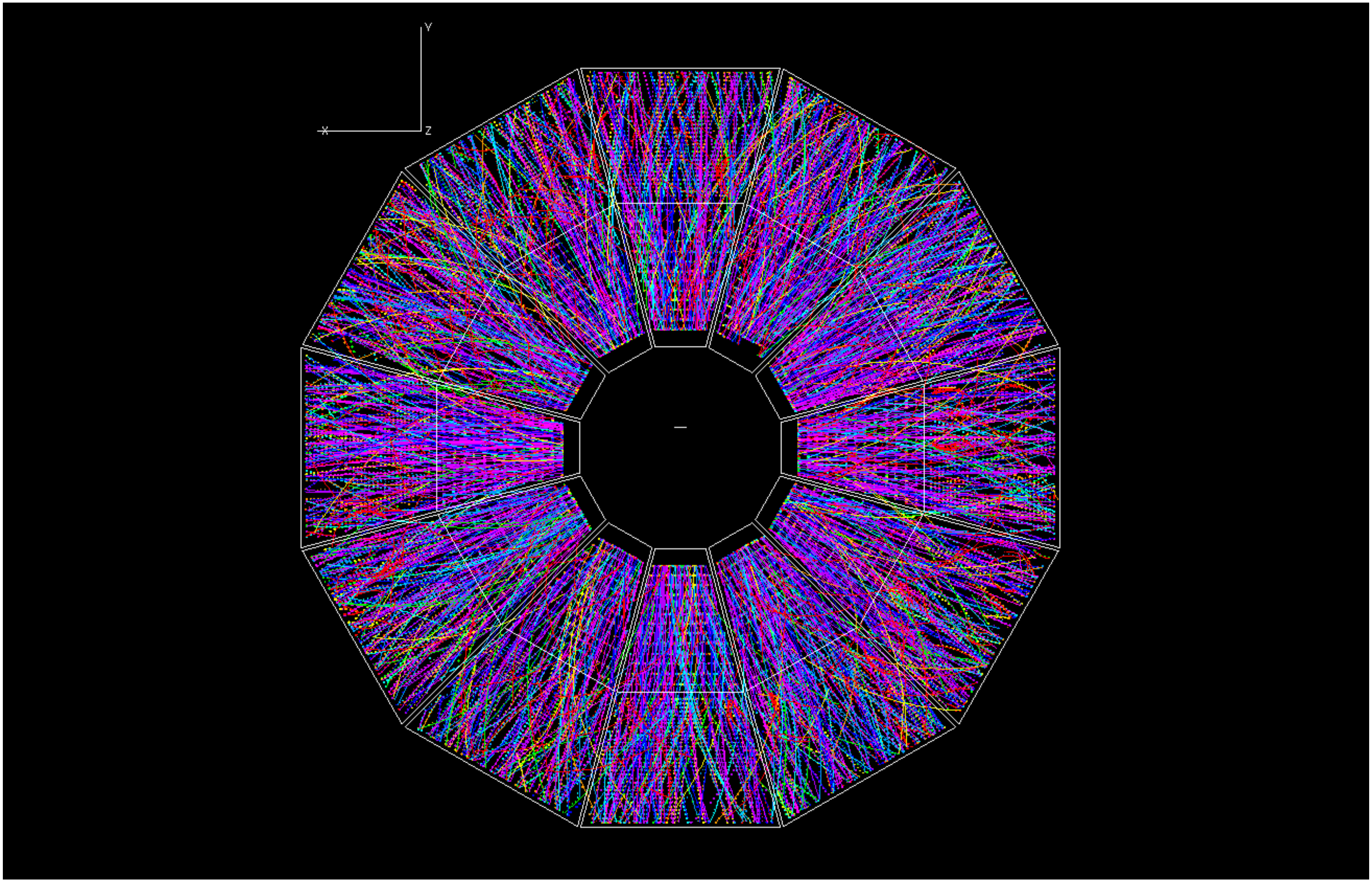




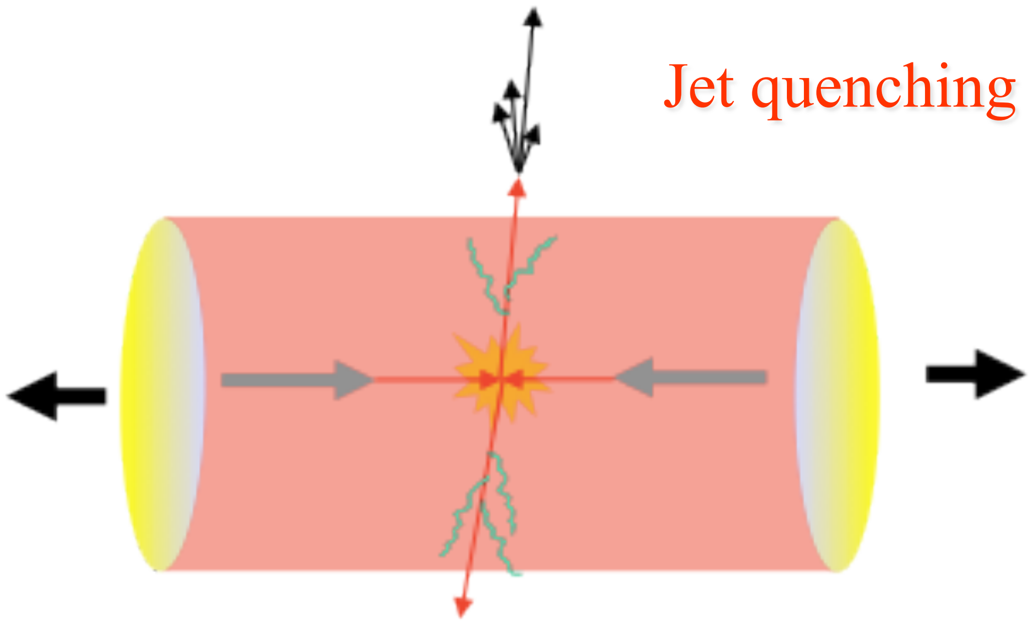



# Jets in Heavy-ion Collisions



# Hard Probes of Dense Matter



Jet quenching

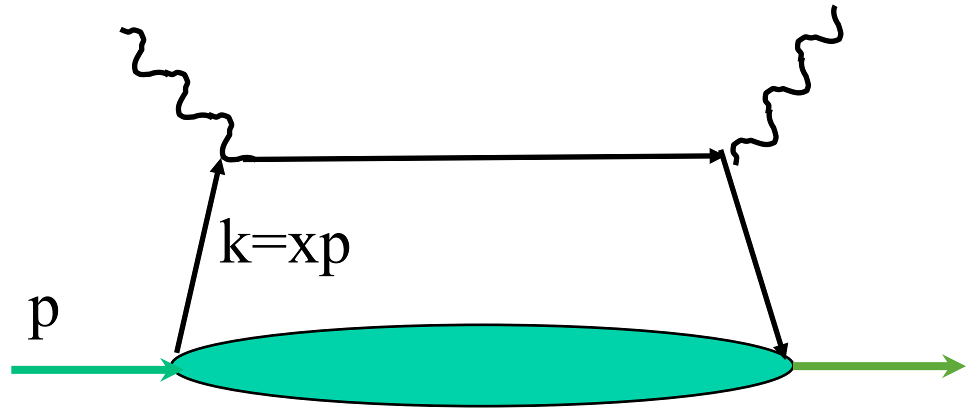
$\Delta D(z, k_\perp)$

$k_T$ broadening

$\frac{dE}{dx}$

$\hat{q}$

# Deeply Inelastic Scattering

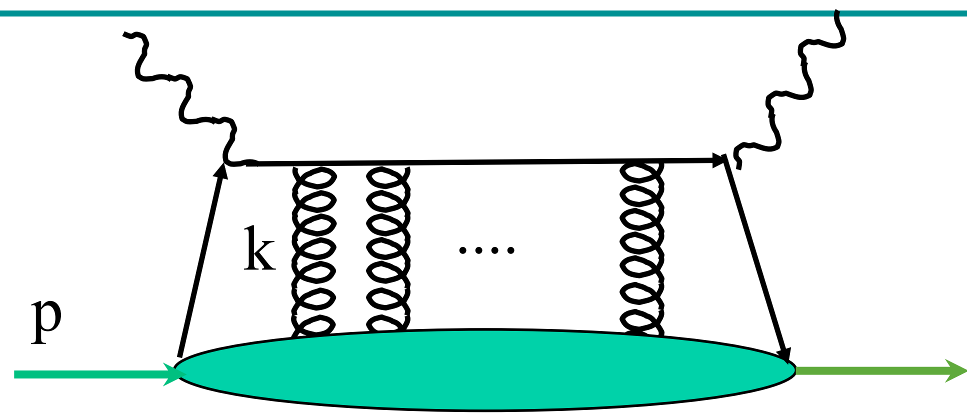



Quark distribution in collinear factorized pQCD parton model:

$$f_A^q(x) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-} \langle A|\bar{\psi}(0)\gamma^+\psi(y^-)|A\rangle$$

quarks carrying momentum fraction x of the nucleon (nucleus)

# Gauge Invariance and Multiple Interaction

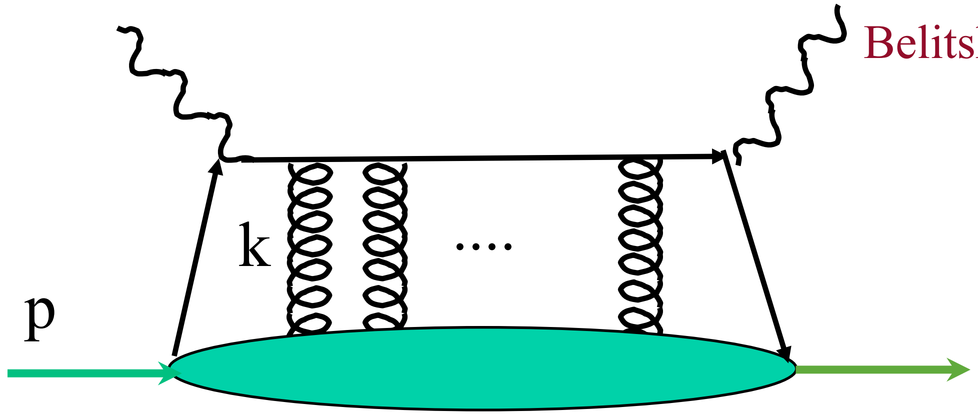



$$f_A^q(x) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-} \langle A|\bar{\psi}(0)\gamma^+ \mathcal{L}_{||}(0, y^-; \vec{0}_\perp)\psi(y^-)|A\rangle$$

$$\mathcal{L}_{||}(0, y^-; \vec{0}_\perp) = \mathcal{P}\exp\left[ig \int_0^{y^-} d\xi^- A_+(\xi^-, \vec{0}_\perp)\right]$$

# TMD parton distribution in DIS

Belitsky, Ji and Yuan (2002)

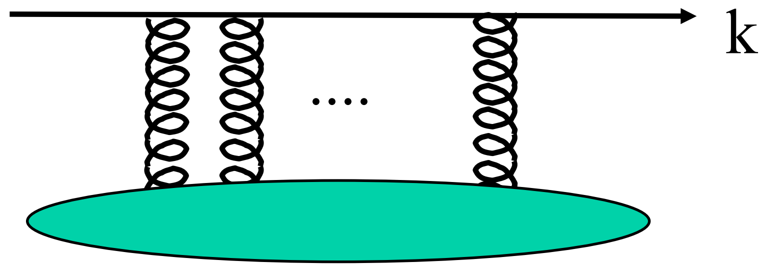



$$f_A^q(x,\vec{k}_\perp) = \int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp} \langle A|\bar{\psi}(0)\gamma^+\mathcal{L}(0,y)\psi(y)|A\rangle$$

$$\mathcal{L}(0,y) = \mathcal{L}_{||}^\dagger(\infty,0;\vec{0}_\perp)\ \mathcal{L}_\perp^\dagger(\infty;\vec{y}_\perp,\vec{0}_\perp)\ \mathcal{L}_{||}(\infty,y^-;\vec{y}_\perp)$$


$$\mathcal{L}_{||}(0,y^-;\vec{0}_\perp) = \mathcal{P}\exp\left[ig\int_0^{y^-} d\xi^- A_+(\xi^-,\vec{0}_\perp)\right] \quad \mathcal{L}_\perp(\infty;\vec{y}_\perp,\vec{0}) = \mathcal{P}\exp\left[-ig\int_{\vec{0}_\perp}^{\vec{y}_\perp} d\vec{\xi}_\perp\cdot\vec{A}_\perp(\infty,\vec{\xi}_\perp)\right]$$

# Jet Transport in Medium




Classical Lorentz force: $\frac{d\vec{p}_\perp}{d\tau} = g\vec{F}_{\perp\mu} v^\mu$

$$\vec{W}_\perp(y^-, \vec{y}_\perp) \equiv i\vec{D}_\perp(y) + g\int_{-\infty}^{y^-} d\xi^- \vec{F}_{+\perp}(\xi^-, y_\perp)$$

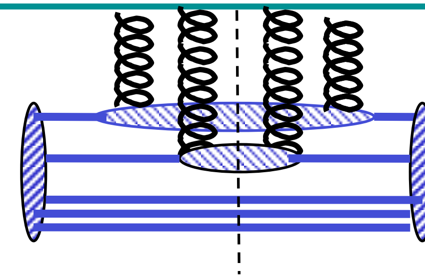
Jet Transport Operator

$$f_A^q(x, \vec{k}_\perp) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-} \langle A|\bar{\psi}(0)\gamma^+ \exp[\vec{W}_\perp(y^-)\cdot\nabla_{k_\perp}]\psi(y^-)|A\rangle \delta^{(2)}(\vec{k}_\perp)$$

Liang, XNW & Zhou（2008）

# Momentum Broadening

$$\left\langle\left\langle W_\perp^{2n}\right\rangle\right\rangle_A \sim \left[\int dy \frac{\rho_A(y)}{2p^+}\langle N|F_{+\perp}F_{+\perp}|N\rangle\right]^n \sim \left[\int dy \rho_A(y) x G_N(x)\right]^n$$



2-gluon correlation approximation

$$f_A^q(x,\vec{k}_\perp) \approx \frac{A}{\pi\Delta}\int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp-\vec{q}_\perp)^2}{\Delta}\right] f_N^q(x,\vec{q}_\perp)$$

$$\Delta = \langle \Delta k_\perp^2\rangle = \int d\xi_N^- \hat{q}(\xi_N)$$

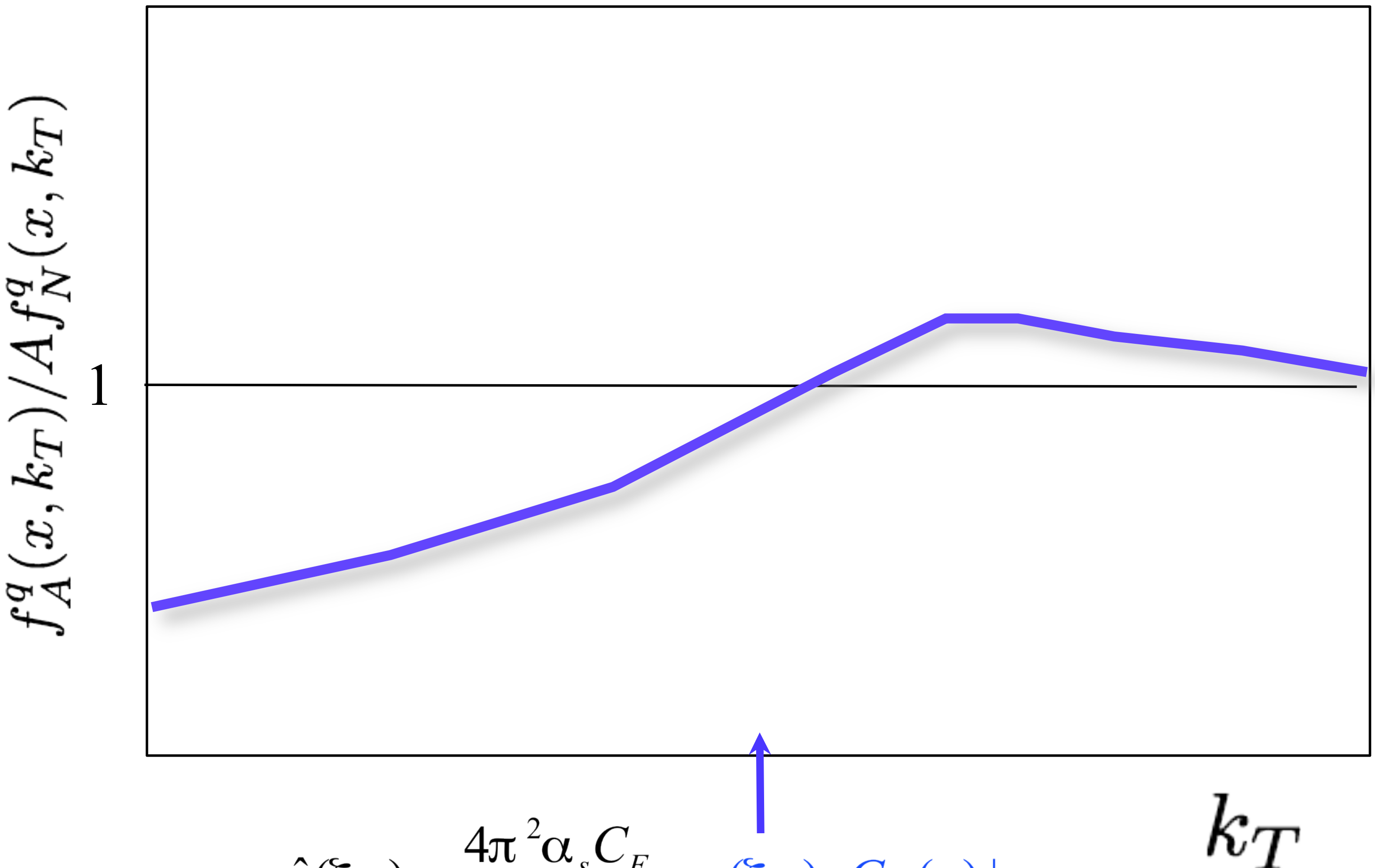
Liang, XNW & Zhou' 08
Majumder & Muller' 07
Kovner & Wiedemann' 01
BDMPS' 96

$$\hat{q}(\xi_N) \equiv \frac{4\pi^2\alpha_s C_F}{N_c^2-1}\rho_A(\xi_N) x G_N(x)|_{x\approx 0}$$

Jet transport parameter

# $P_T$ Broadening

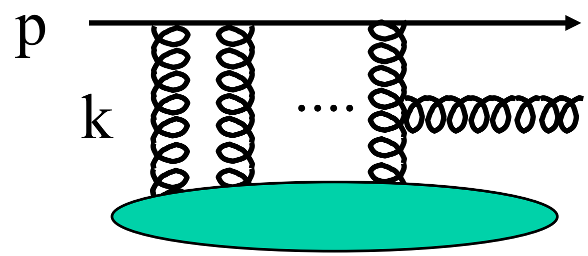
$$f_N^q(x, k_T) \sim 1/(k_T^2 + p_0^2)^\alpha$$




$$\hat{q}(\xi_N) \equiv \frac{4\pi^2 \alpha_s C_F}{N_c^2 - 1} \rho_A(\xi_N) x G_N(x)|_{x \approx 0}$$

2

# Parton Energy Loss



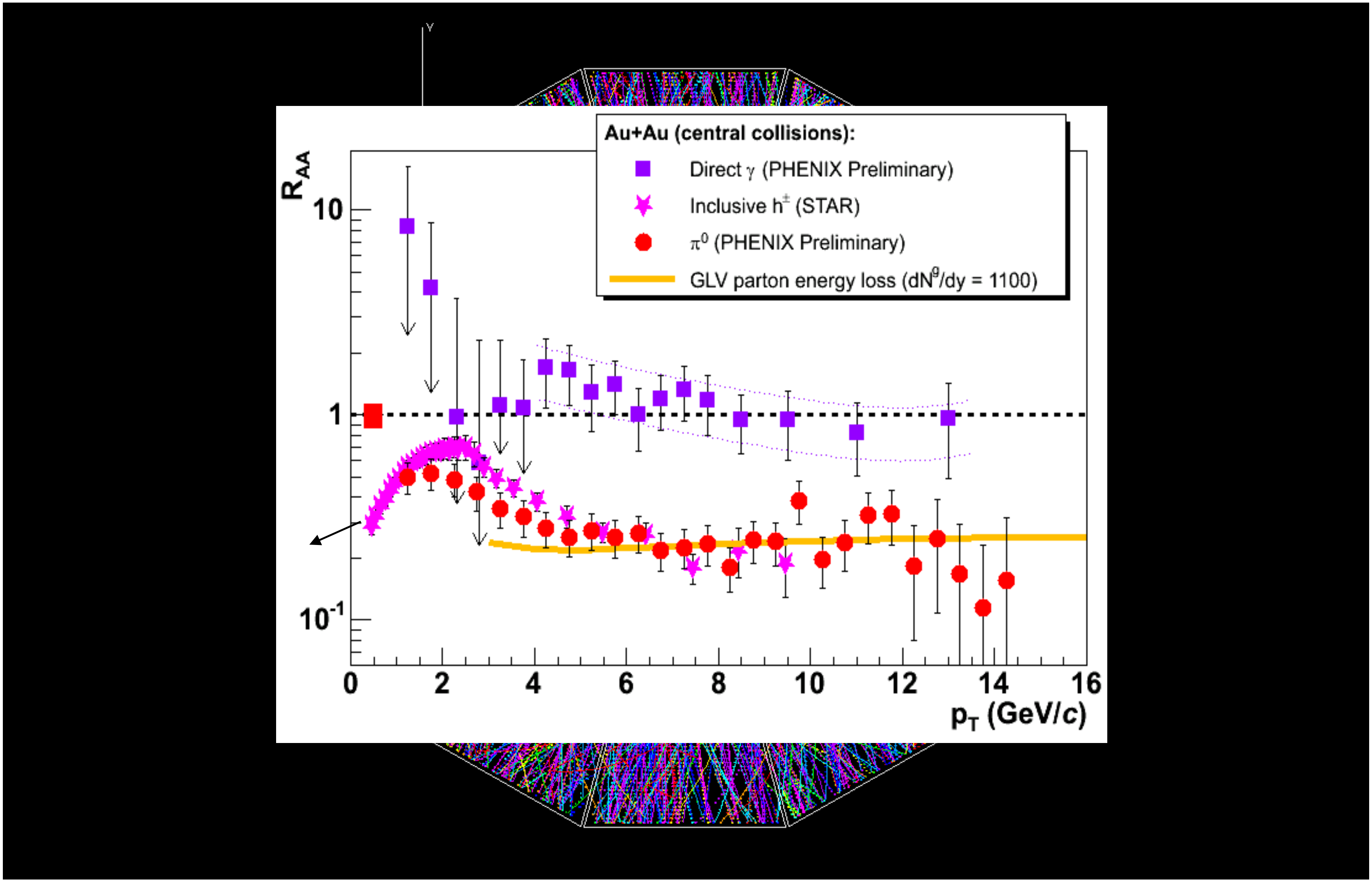

Splitting functions in medium

$$\Delta\gamma(z,\ell_\perp^2) = C_A \frac{1+z^2}{(1-z)_+}\frac{2}{\ell_\perp^4}\int d\xi^- \hat{q}(\xi)[1-\cos(x_L p^+ \xi^-)]$$

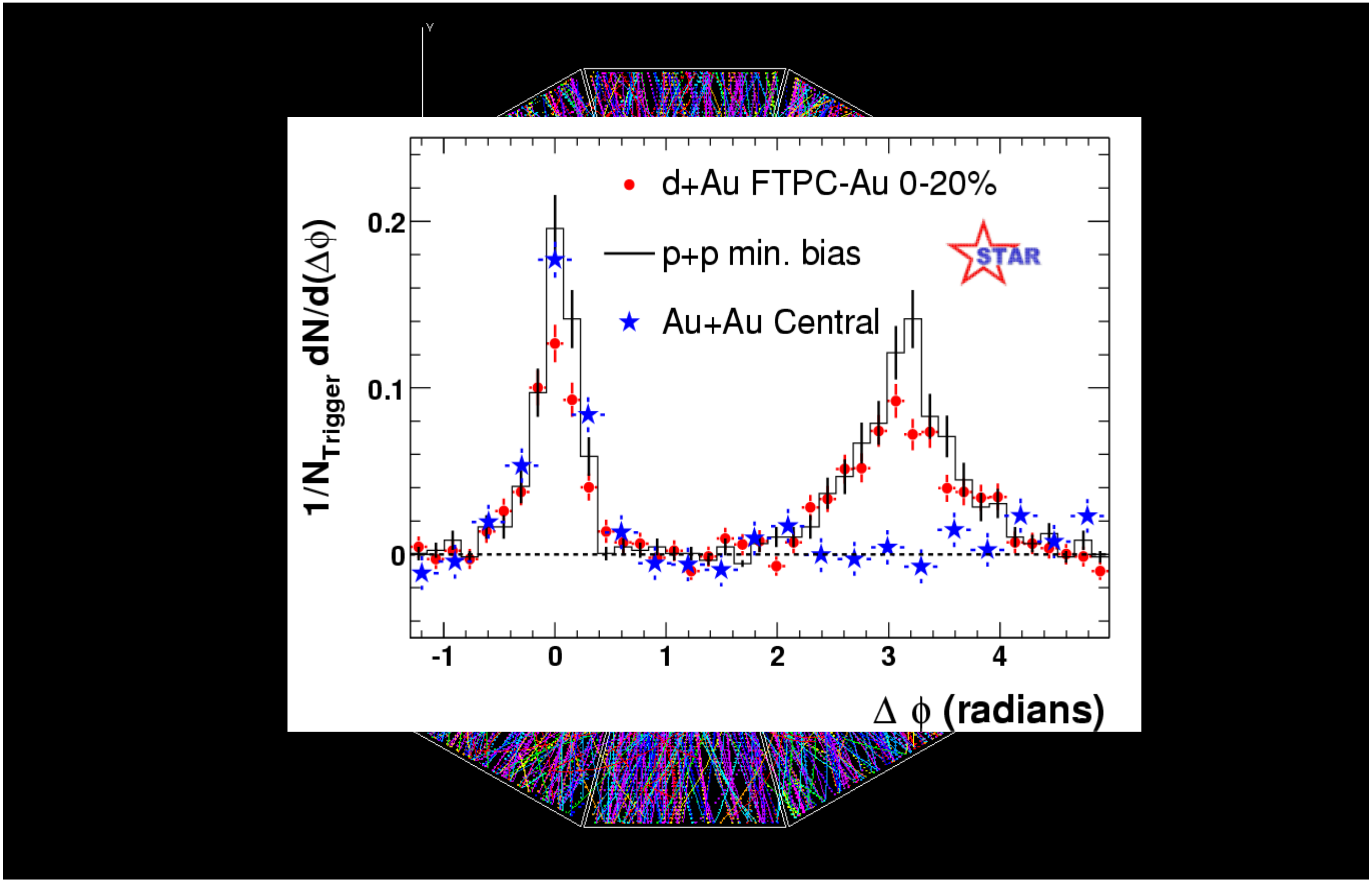
Parton Energy Loss

$$\frac{\Delta E}{E} = C_A \frac{\alpha_s}{2\pi}\int \frac{dl_T^2}{l_T^4}\int dz[1+(1-z)^2]\int d\xi^- \hat{q}(\xi) 4\sin^2(x_L p^+ \xi^-/2)$$

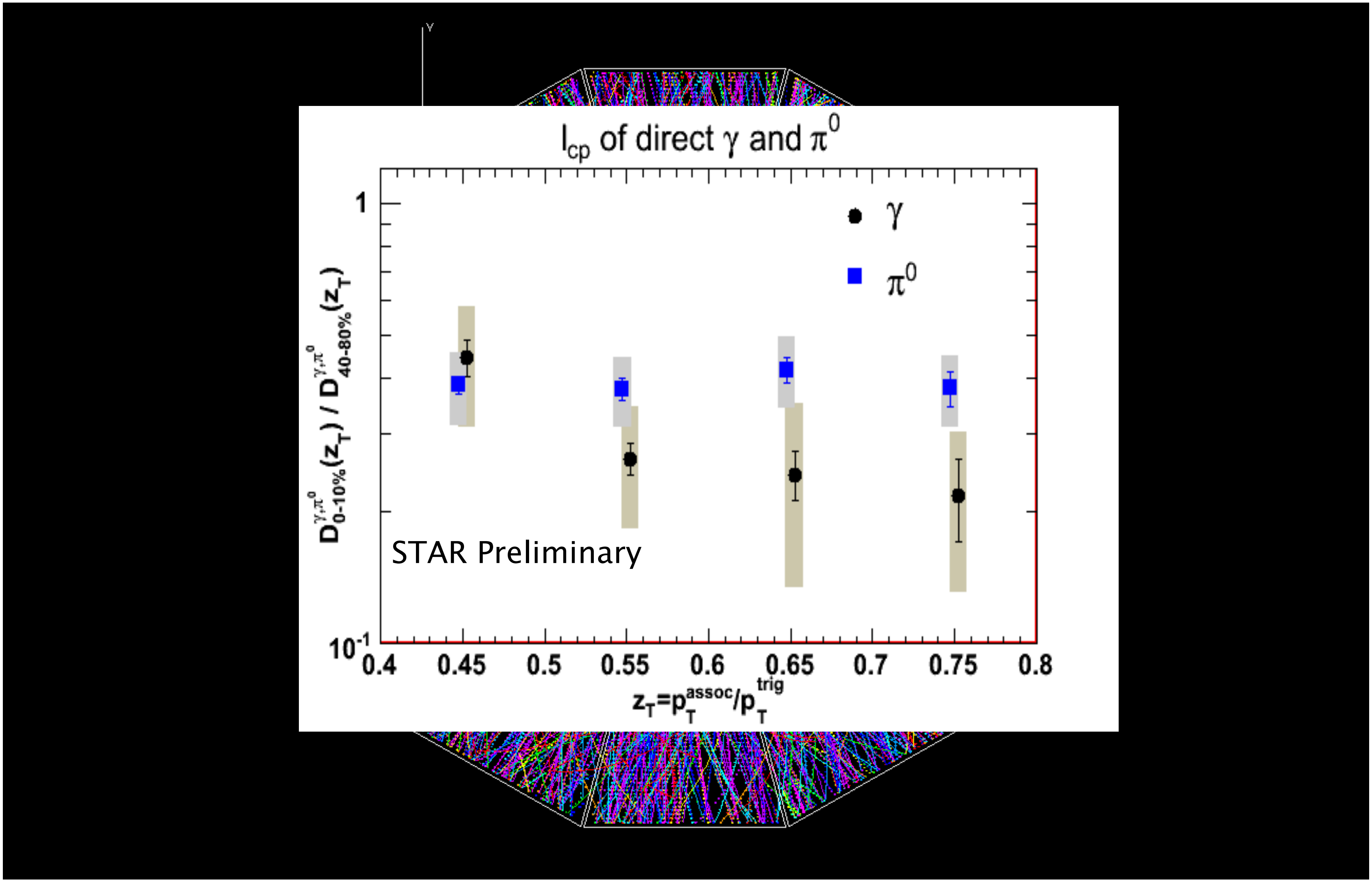
# Jet Quenching phenomena at RHIC



# Jet Quenching phenomena at RHIC

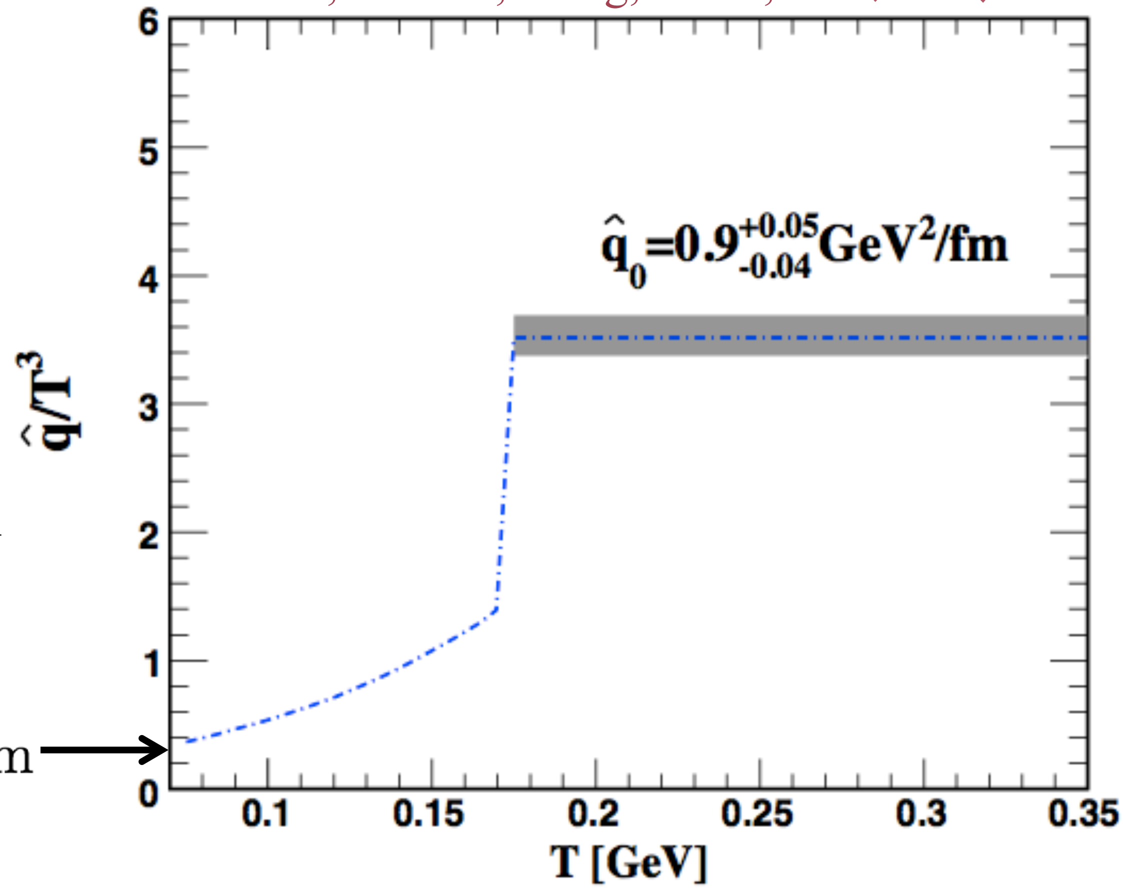


# Jet Quenching phenomena at RHIC



# Jet quenching in QGP & hadronic phase

Chen, Greiner, Wang, XNW, Xu (2010)

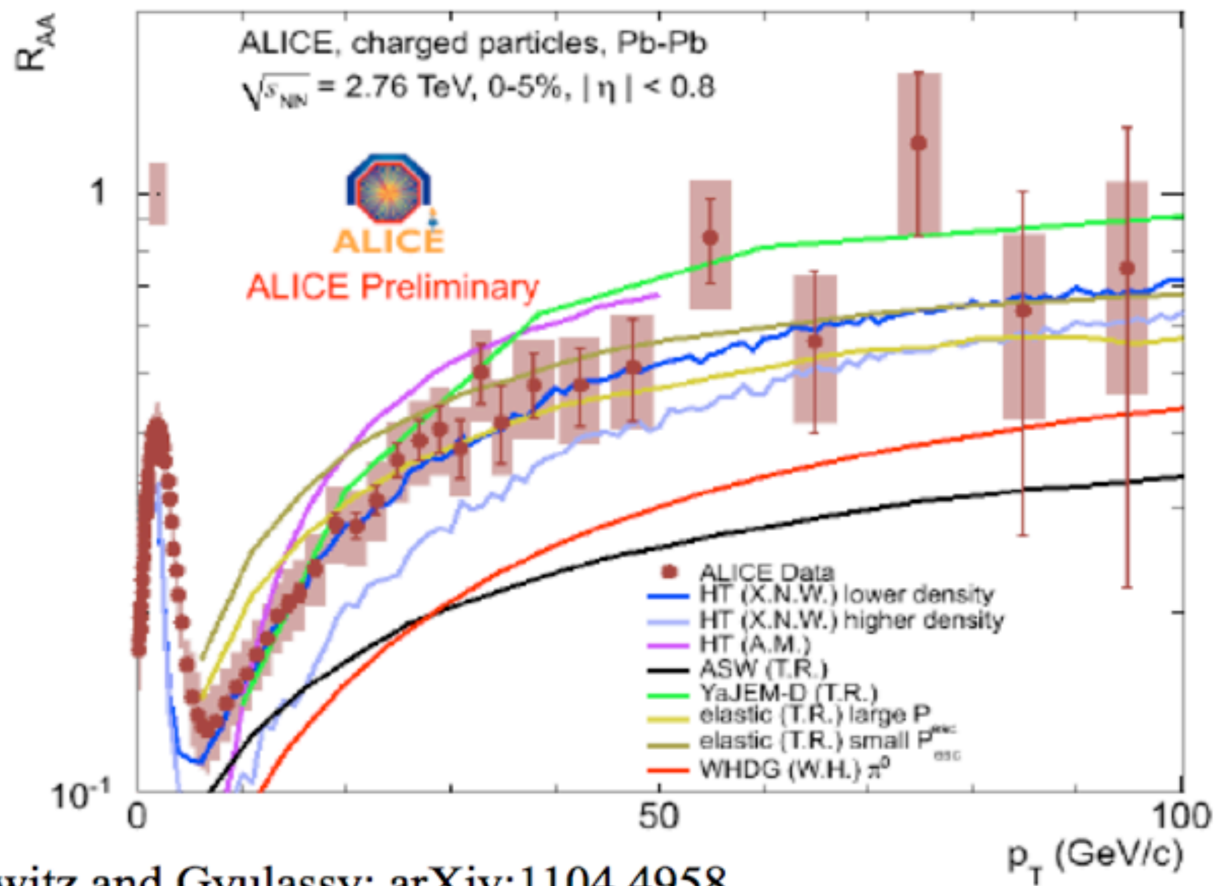



DIS & Drell-Yan

$\hat{q}_N = 0.02\ \mathrm{GeV}^2/\mathrm{fm}$

30% quenching from hadronic phase

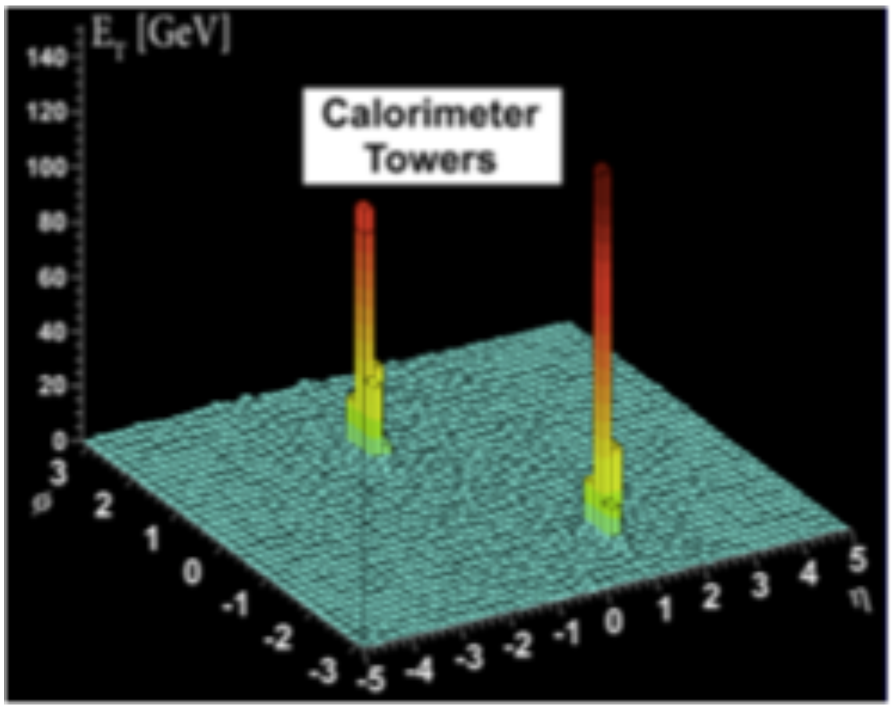
# Jet quenching at LHC

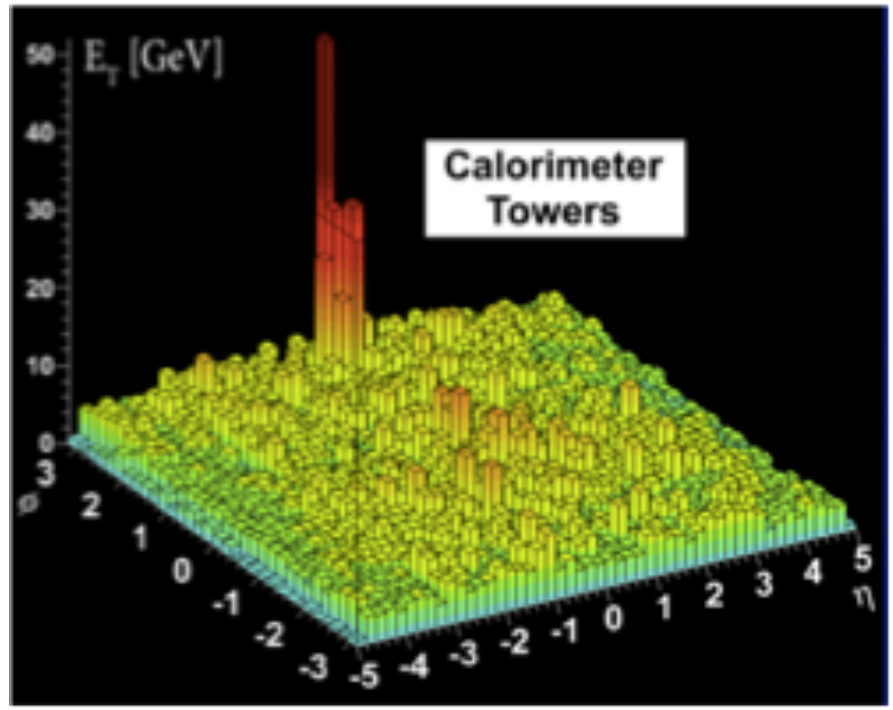



$$\hat{q} \propto \frac{1}{\tau_0 \pi R_A^2} \frac{dN_{ch}}{d\eta}$$

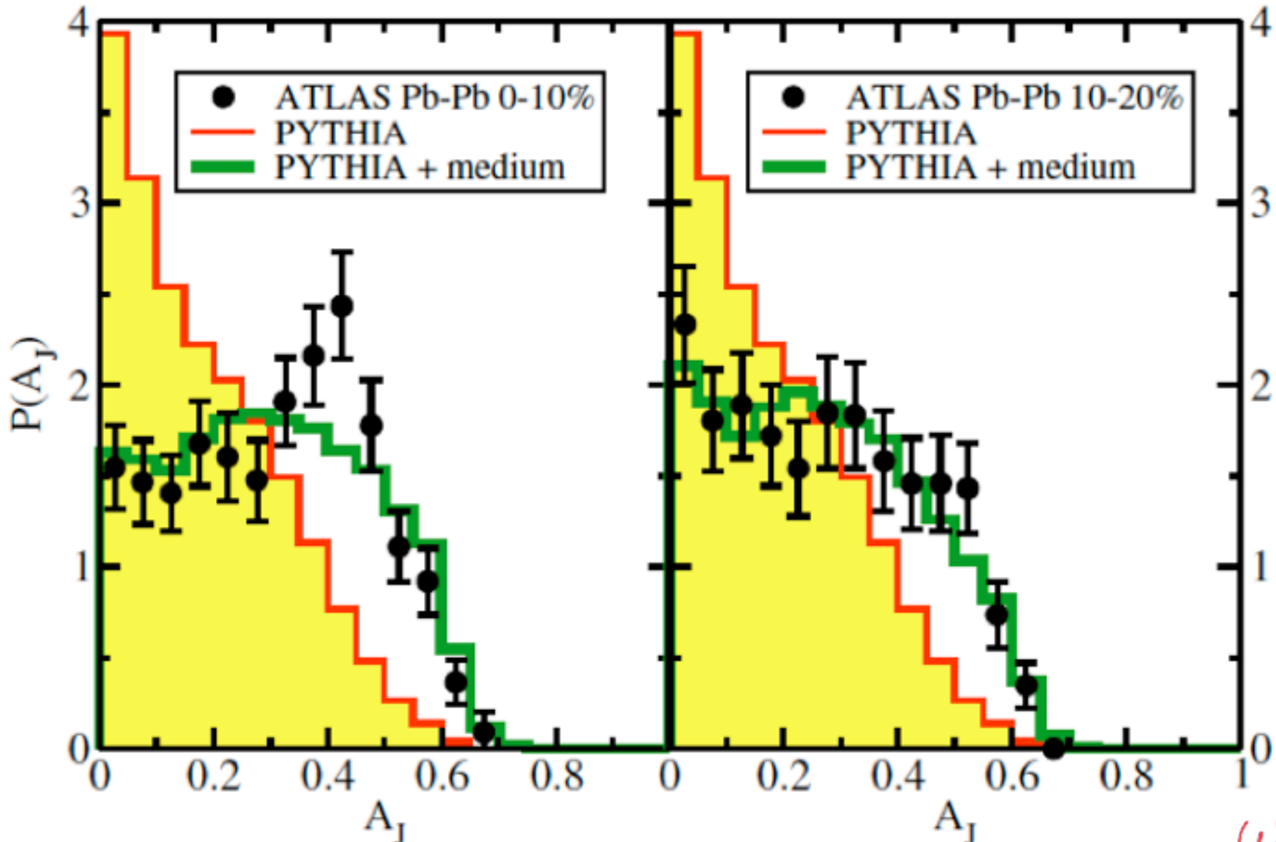
Horowitz and Gyulassy: arXiv:1104.4958
Majumder and Shen: arXiv:1103.0809
Chen et. al. arXiv:1102.5614

# Jet Quenching at LHC



# Di-Jet Asymmetry




$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

$\omega > \omega_c$

$\omega_c = 1 - 2 \text{ GeV}$

Qin and Muller Phys.Rev.Lett.106:162302,2011

B. Schenke, C. Gale, S. Jeon, Phys.Rev.C80:054913 (2009)

Y. He, Vite, B.W. Zhang, arXiv:1105.2566

# Relativistic Hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Delta T^{\mu\nu}$$

$$\Delta T^{\mu\nu} = \eta(\Delta^\mu u^\nu + \Delta^\nu u^\mu) + (\frac{2}{3}\eta - \zeta)H^{\mu\nu}\partial_\rho u^\rho$$

Inputs:

$\eta$ shear viscosity

$\zeta$ bulk viscosity

EOS

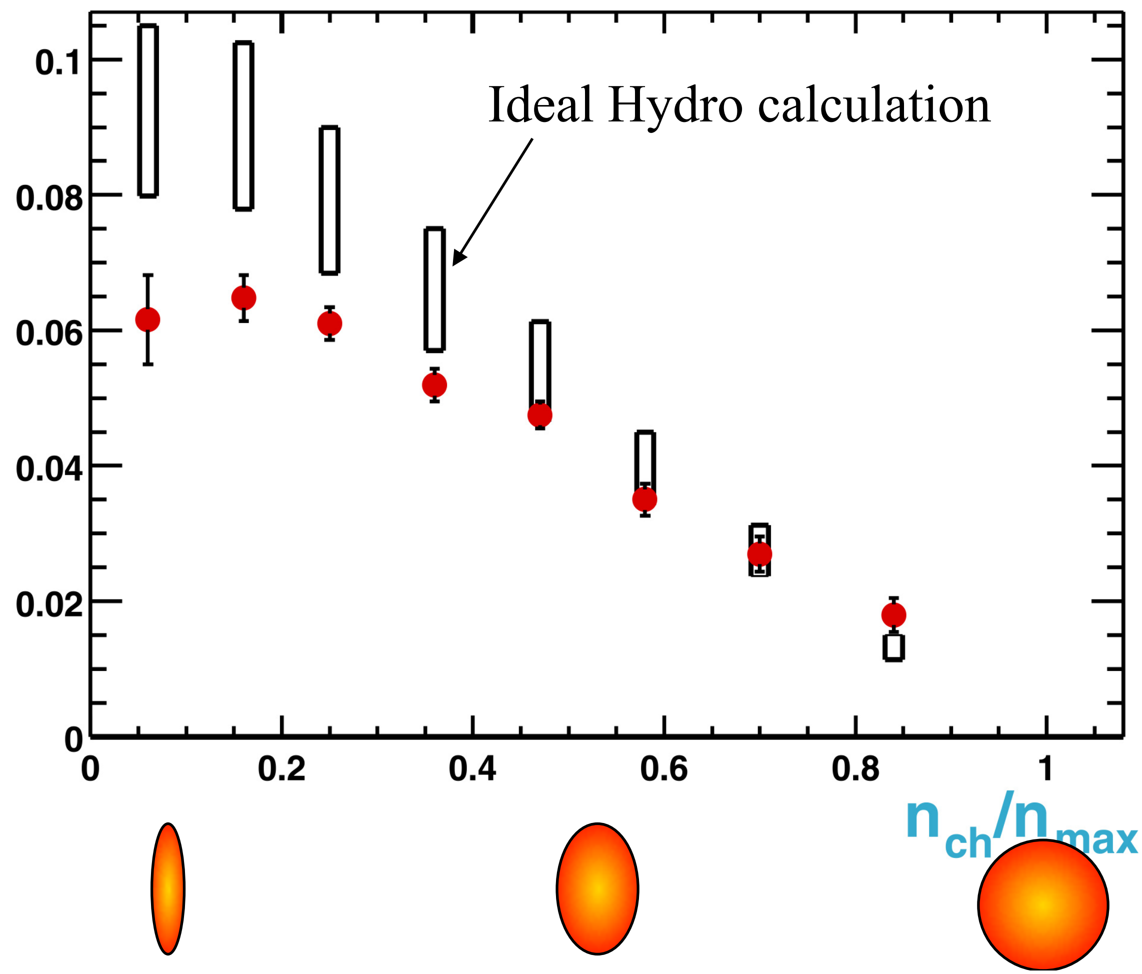
Initial conditions for ε & u

# Elliptic Flow

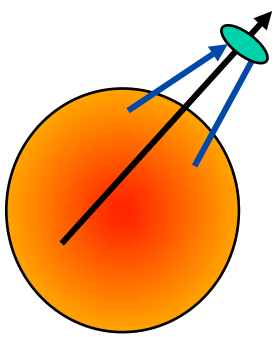
$$\frac{dN_{ch}}{d\varphi} = N_0(1 + v_1 \cos\varphi + 2v_2 \cos 2\varphi + \cdots)$$

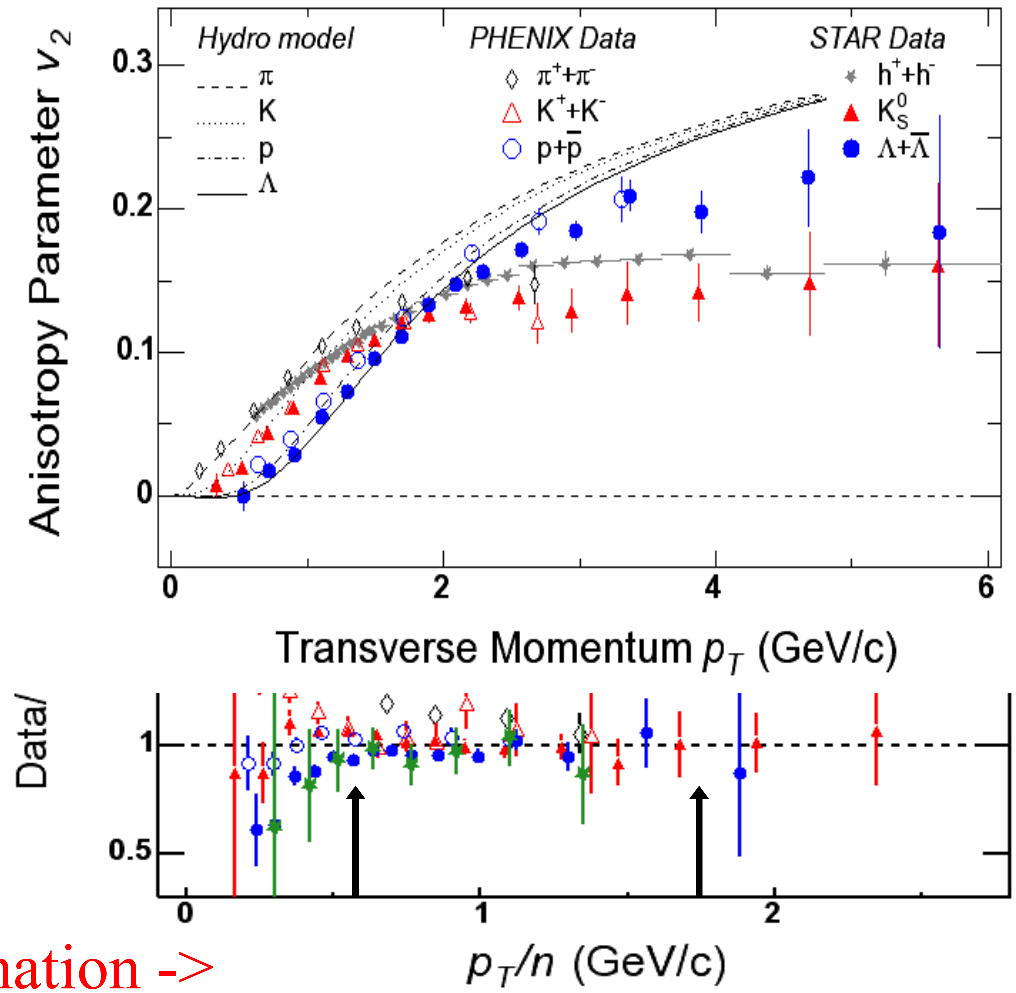
**Pressure gradient anisotropy**

$$v_2 = \langle \cos 2\varphi \rangle$$



# Partonic flows






n = number of constituent quarks

Parton recombination -> Partonic degrees of freedom

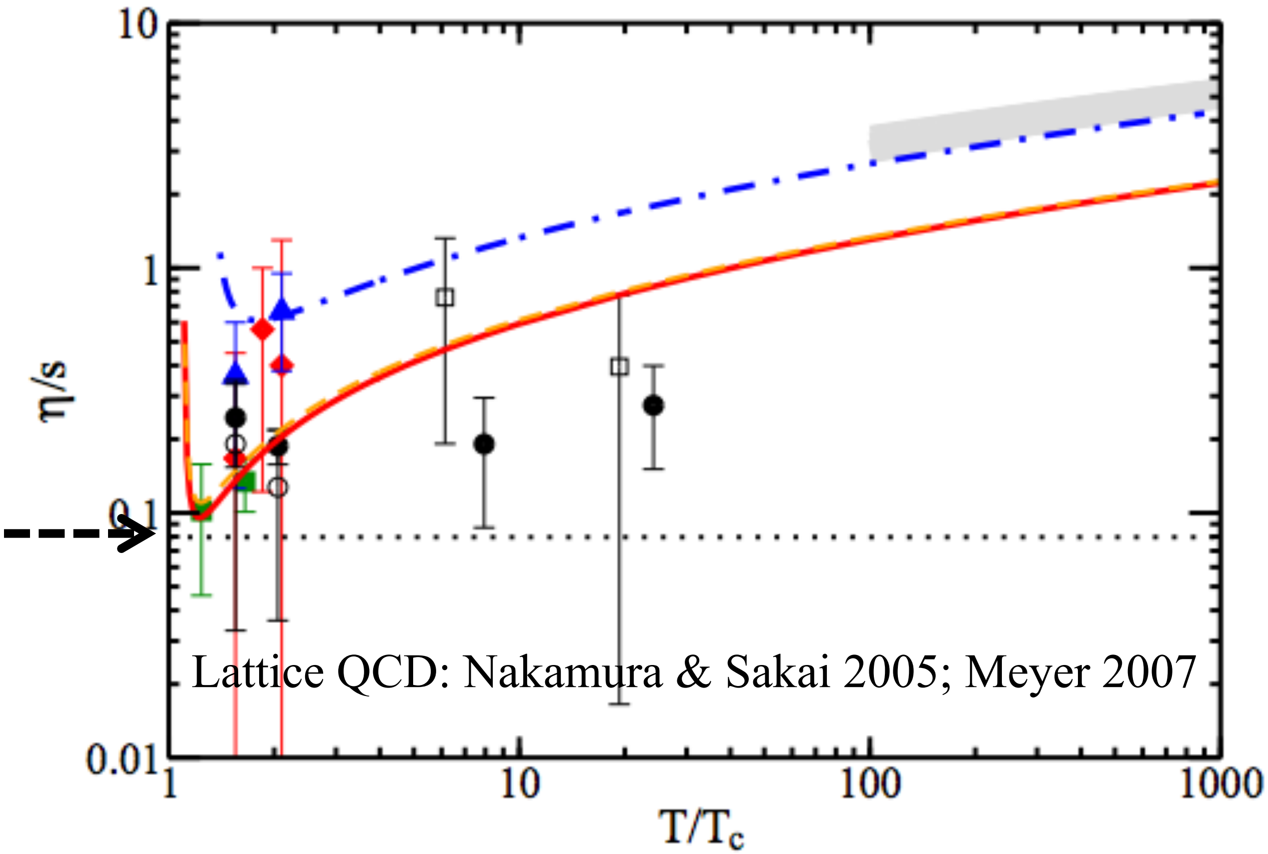
# Transport properties of QGP

Bluhm, Kampfer & Redlich 2010

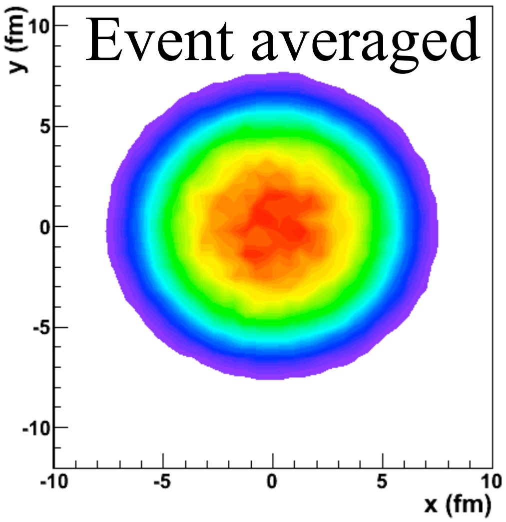
$$\frac{\eta}{s} = \frac{15}{16\pi}\frac{f_\pi^4}{T^4}$$

For pion gas

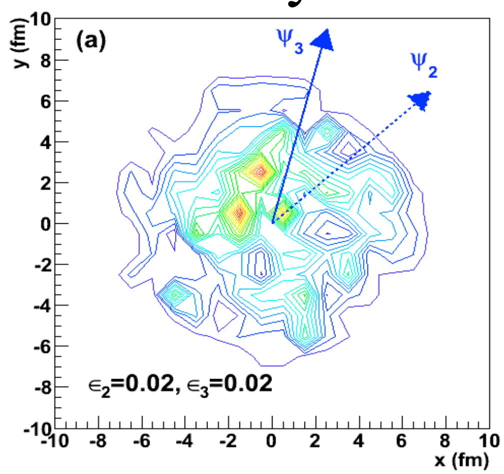
AdS/CFT



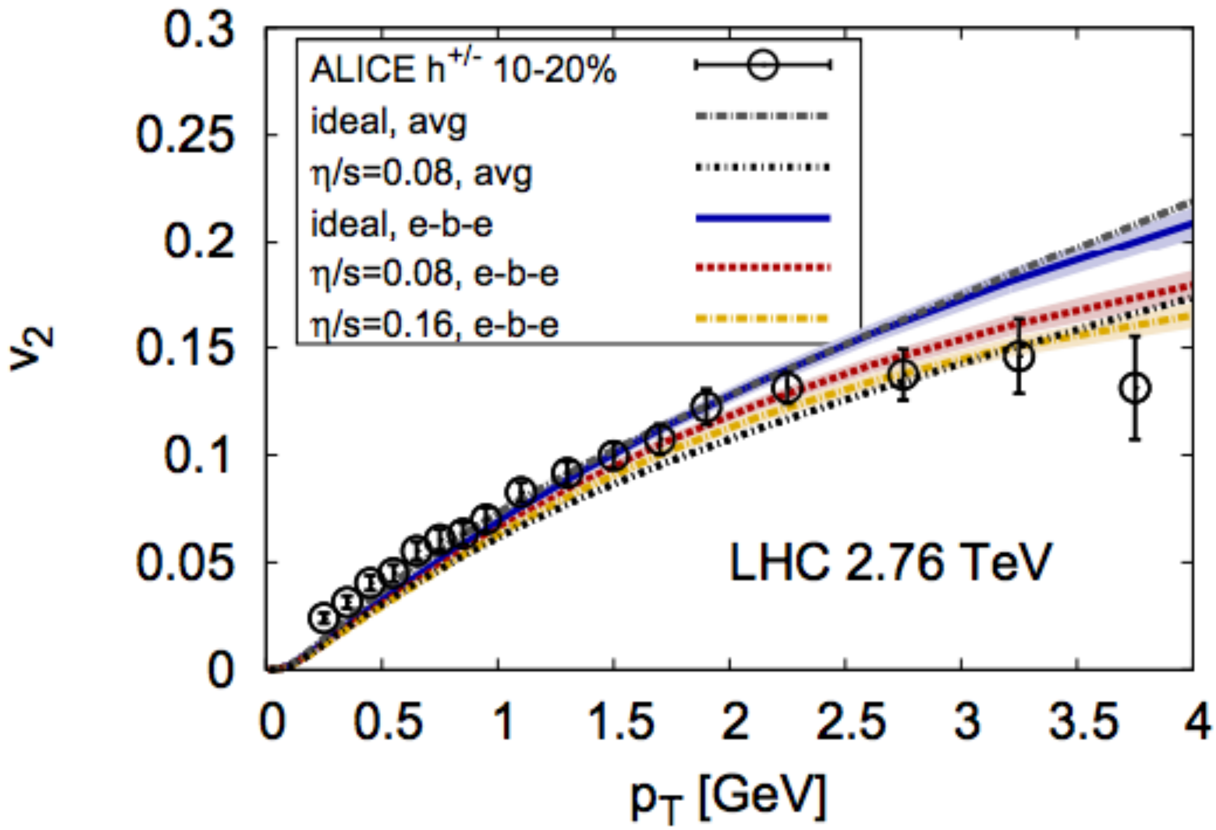
# Event-by-event viscous hydrody




Event-by-event

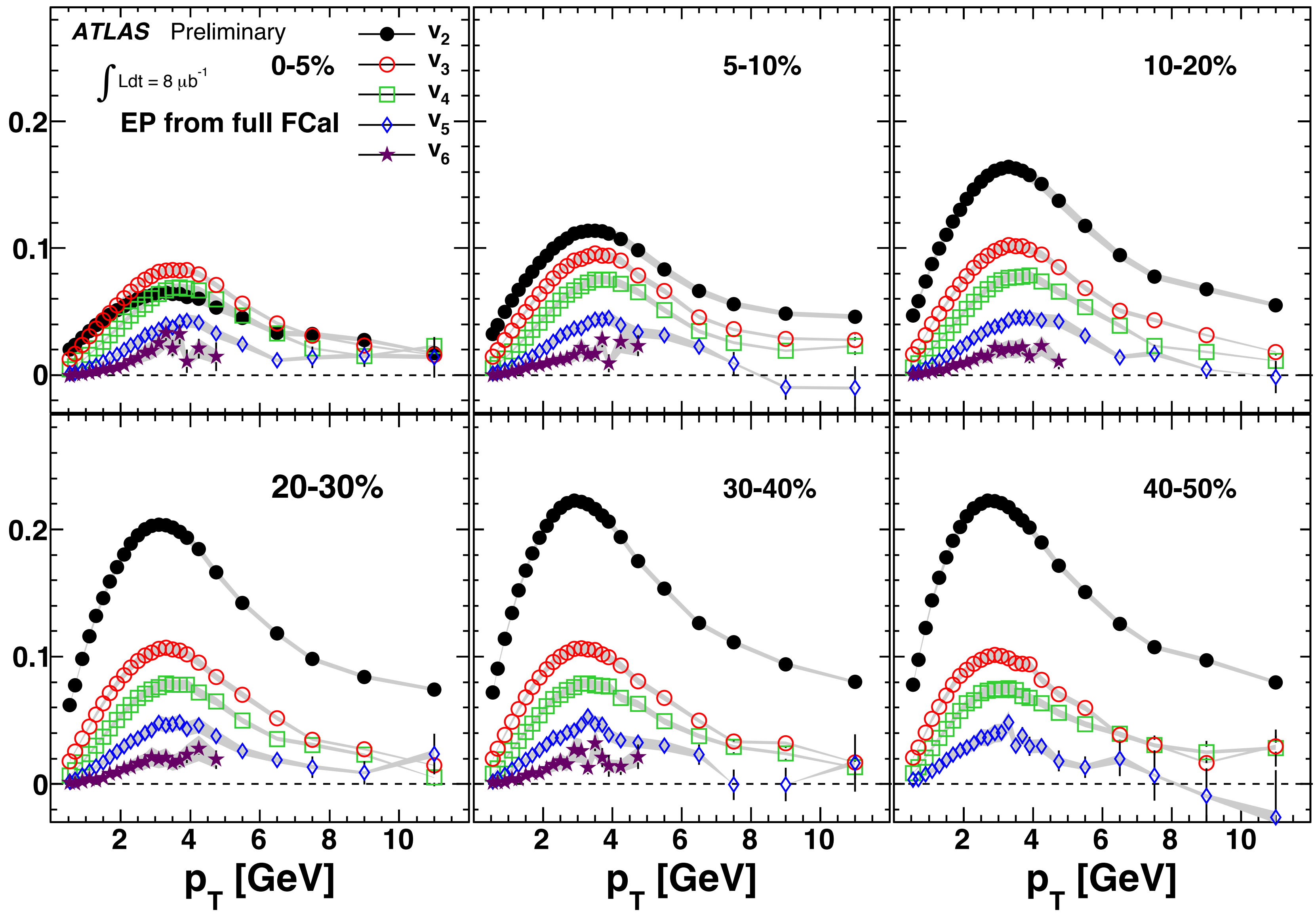



Event-by-event (3+1)D viscous hydro



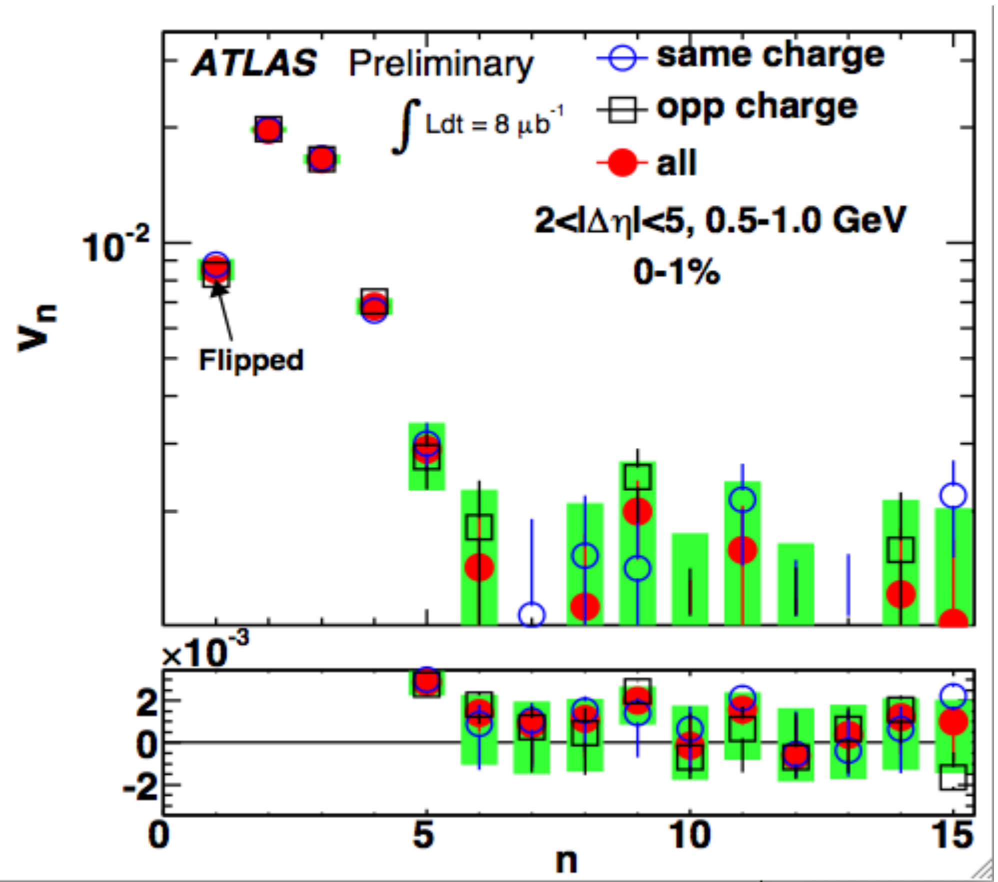

Schenke, Jeon & Gale 2011

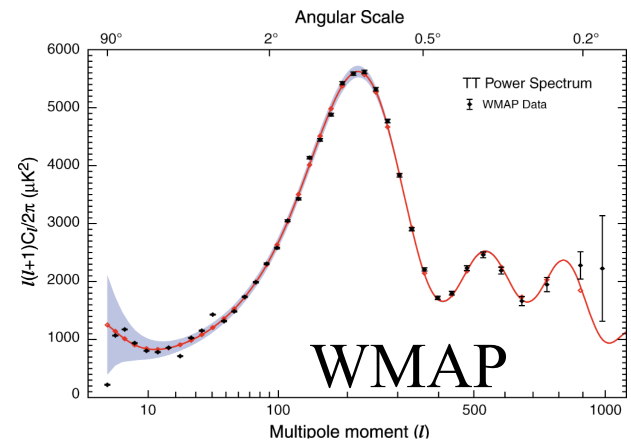
# Anisotropic flow

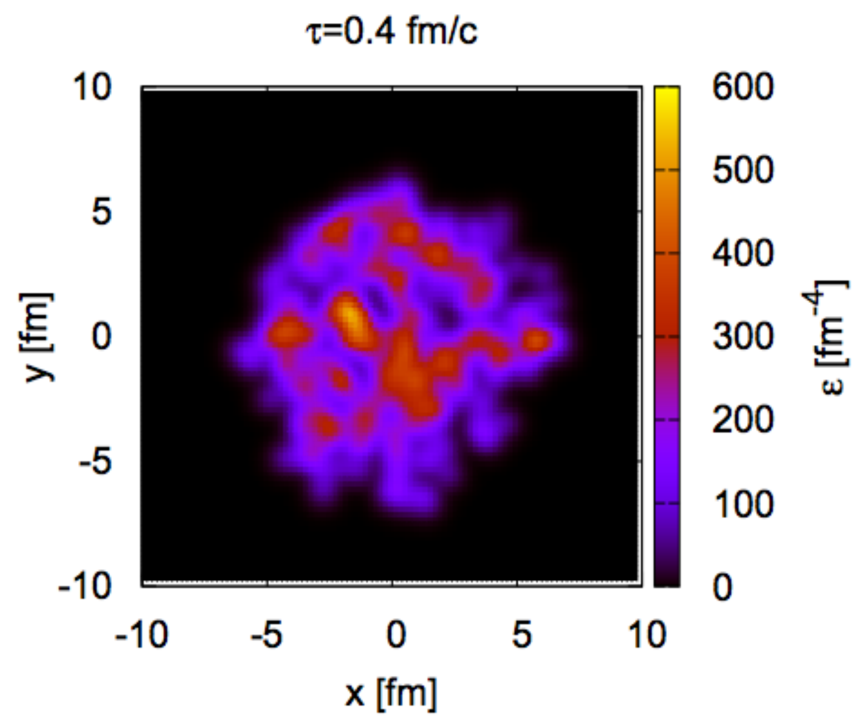


# Hadron Anisotropy Probe of the Little Bang

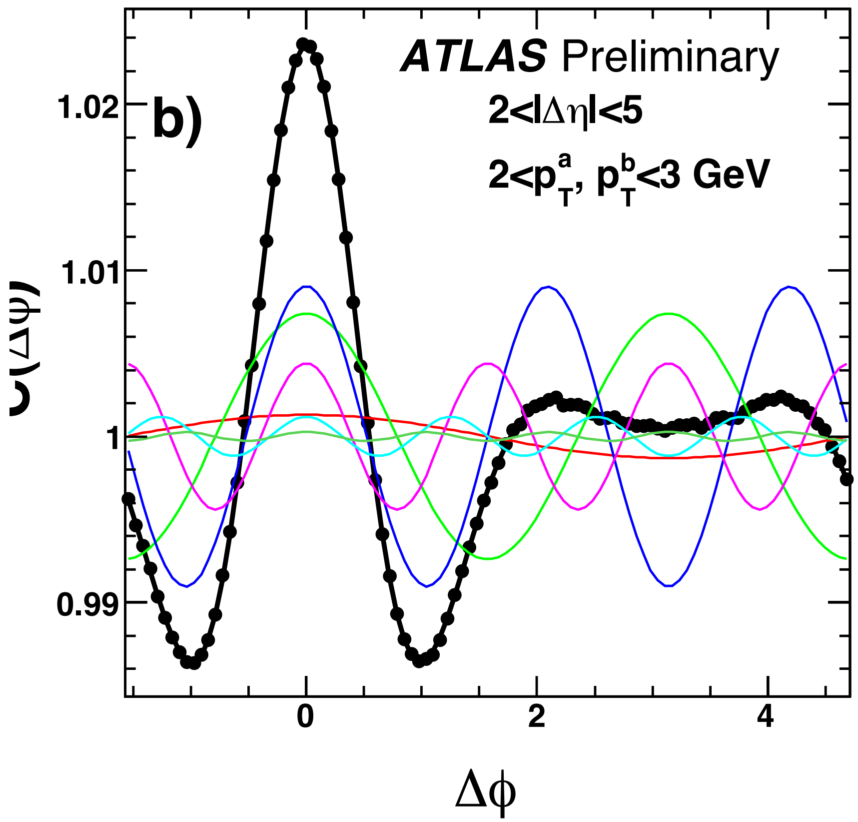
Central Pb+Pb collisions

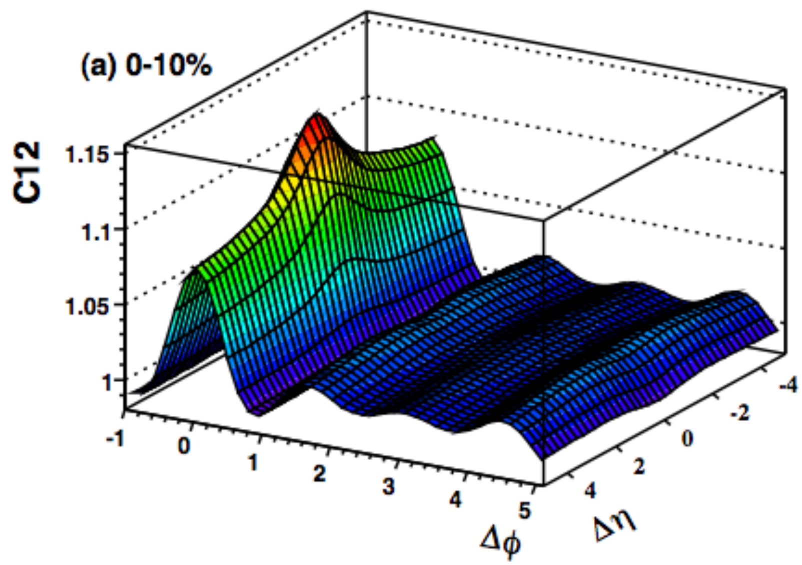


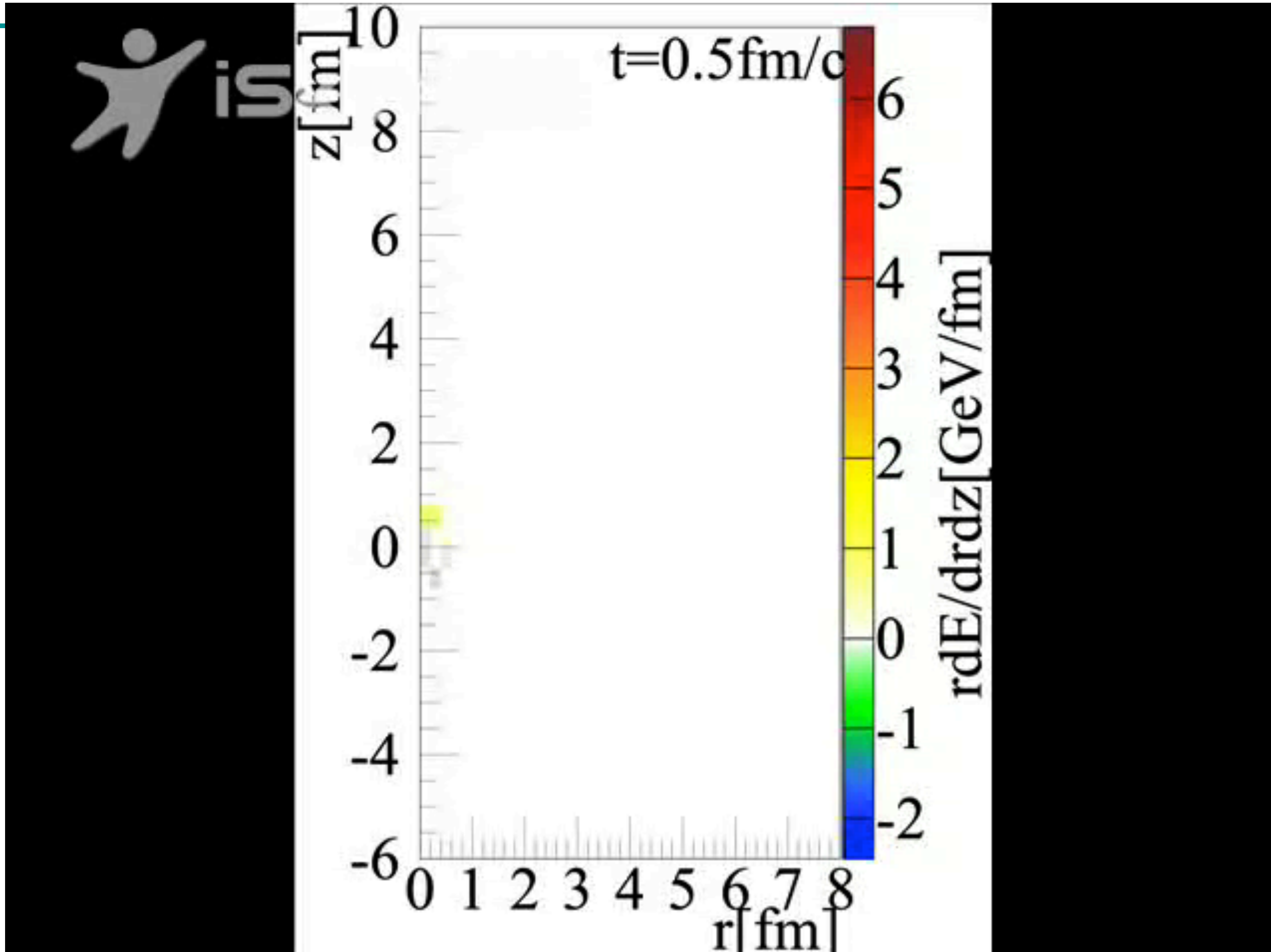
# Long range initial longitudinal correlation



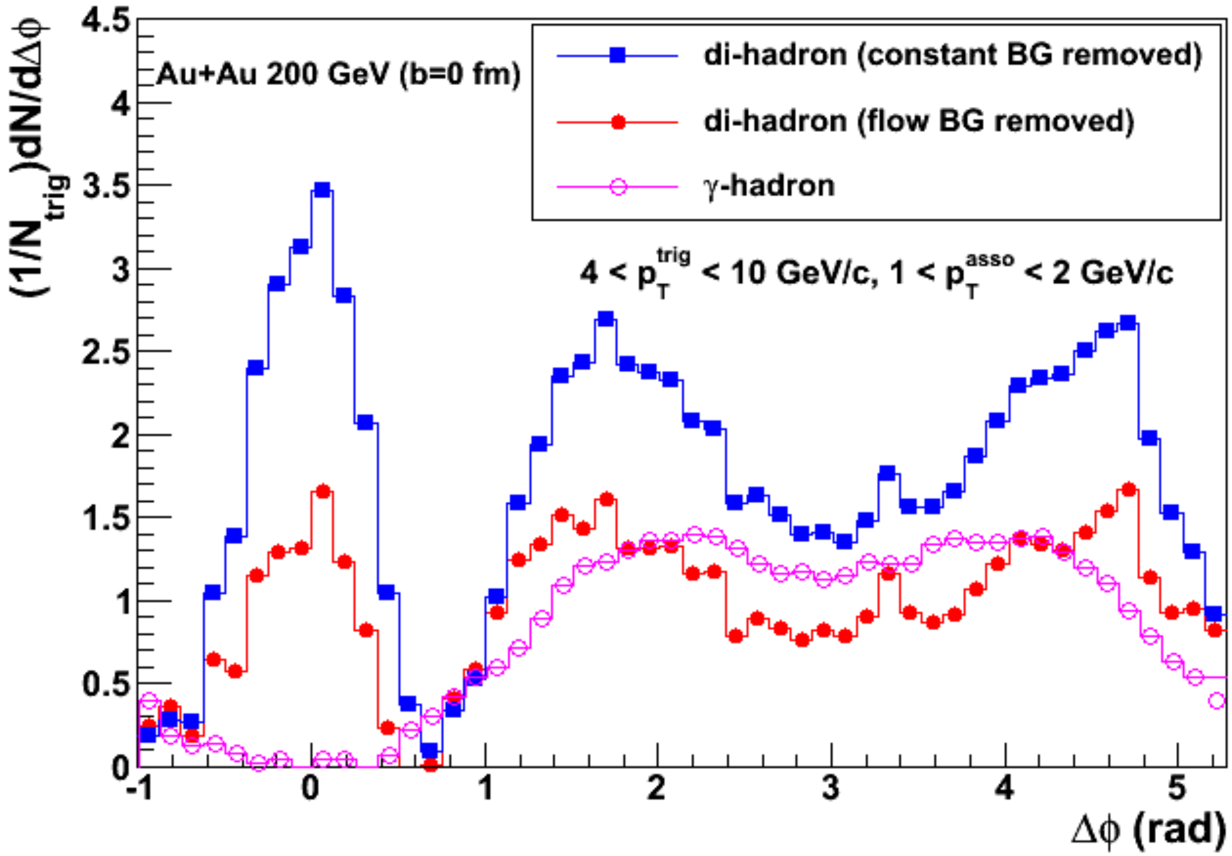

Hydro calculation

# Mach-cone-like excitation



# gamma-hadron correlation

Guo-liang Ma & XNW (2011)



# What I have not talked about

- Initial gluon structure of nuclei: gluon saturation
- Quarkonium suppression
- Chiral symmetry restoration reflected in properties of vector-mesons in dilepton channel
- Search for critical points through measurement of fluctuations of conserved charges: baryon, electric charges, strangeness
- AdS/CFT: viscosity, jet transport, heavy Q diffusion

# Summary

- Heavy-ion collisions can test many properties of QCD
  - Deconfinement phase transition
  - Chiral symmetry restoration
- Current RHIC data indicate formation of strongly interacting QGP
  - High energy density 20 GeV/fm (t0=1 fm/c) from jet quenching, dN/dy, radial flow
  - Elliptic flow→ early thermalization, low viscosity
  - Parton recombination → partonic matter
  - J/Ψ suppression → deconfinement
- Quantitative study at LHC
  - New discoveries

# New opportunities

# Back up slides