Jet Tomography

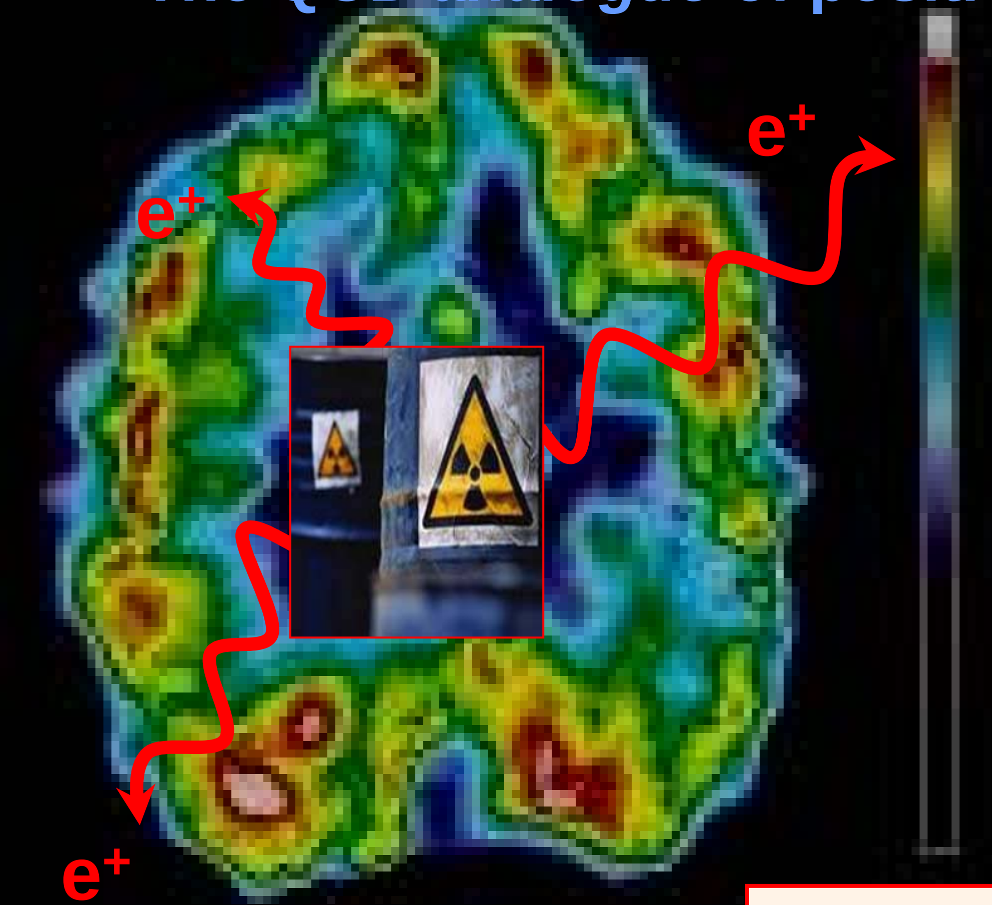
Ivan Vitev
Iowa State University

Outline of the Talk

- **Principles of Jet Tomography**
  - Medium-induced gluon bremsstrahlung in QCD
  - Implementations of jet energy loss
- **Applications of Jet Tomography**
  - Suppression of hadrons in semi-inclusive DIS
  - Jet quenching in hot nuclear matter, transverse momentum, centrality and rapidity dependence
  - Correlations and di-hadron tomography
- **Future Experimental Directions**
  - Entropy growth, reappearance of the lost energy
  - Jet cone and intra-jet correlation studies
- **Conclusions:**
  - Properties of cold and hot nuclear matter
  - Evidence for the creation of the QGP at RHIC

Principles of Jet Tomography

The QCD *analogue* of positron emission tomography



Prerequisites:

- Calibrated source
- Calculable absorption cross sections
- Interpretation of the results

$$I(r) = I_0 e^{-\int_0^r dr' / \lambda_{abs}(r')} = I_0 e^{-\int_0^r dr' \, \sigma_{abs}(r') \rho(r')}$$

Radionuclides:

^{11}C, ^{13}N, ^{15}O, ^{18}F

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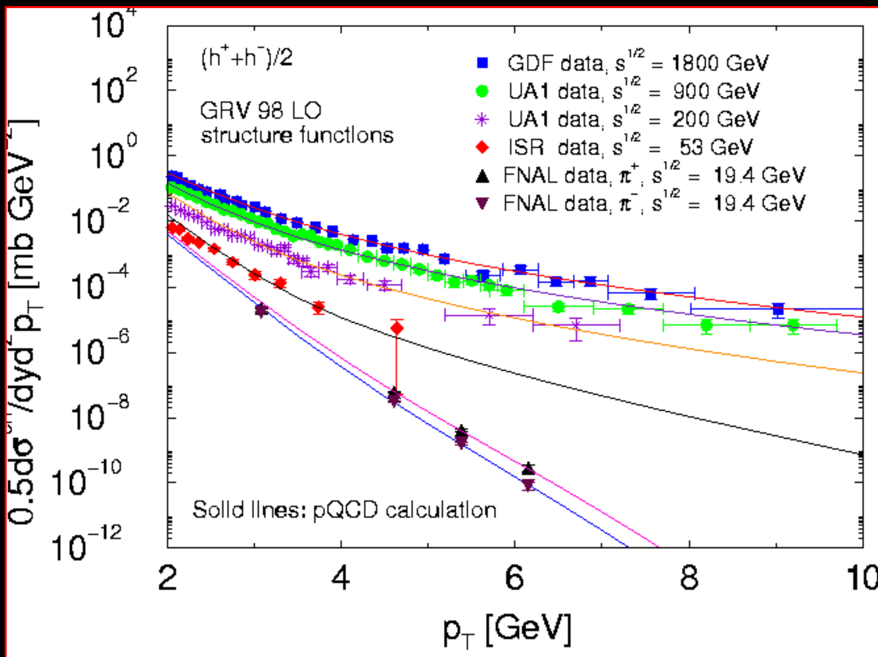
Calibrated Probes

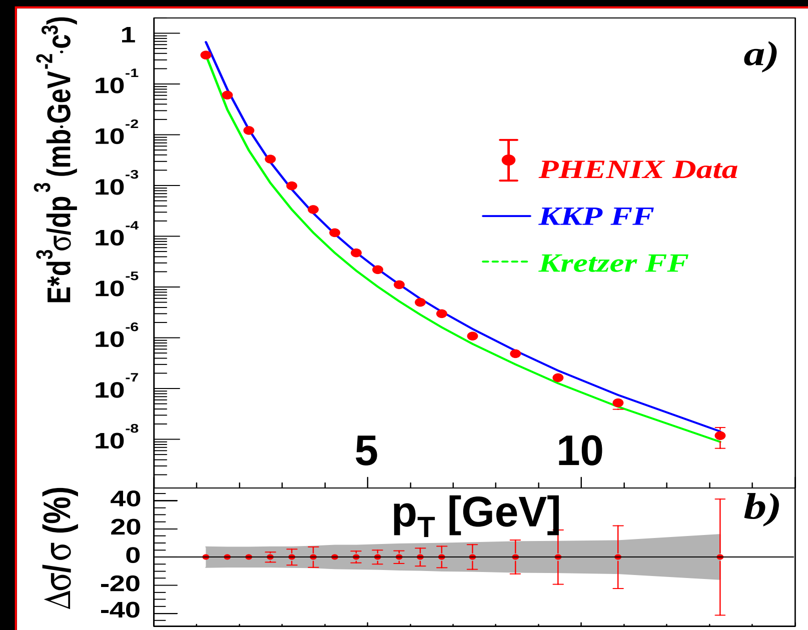
- Inclusive hadron distributions – calculable in perturbative QCD

Leading order pQCD phenomenology



I.V., hep-ph/0212109 [in CERN Yellow report]

Next-to-Leading order pQCD



PHENIX Collab., Phys.Rev.Lett. 91 (2003)

$$E_h \frac{d\sigma}{d^3p} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\sigma^{ab\to cd}}{dt} \otimes D_{h/c}(z_c^*, Q^2)$$

Parton distribution functions

Perturbative cross sections

Fragmentation functions

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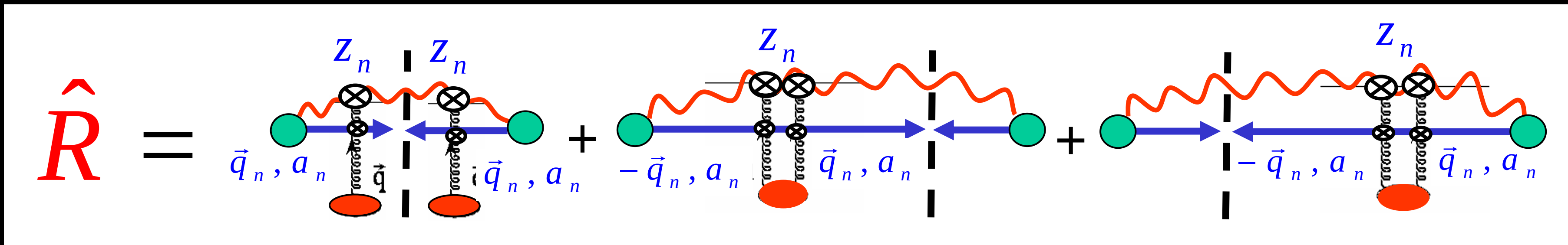
Radiative QCD Energy Loss



Effective 2D Schroedinger equation	Path integral formulation	Exact algebraic recursion (Reaction operator approach)
R.Baier *et al.*, Nucl.Phys.B 483 (1997); *ibid.* 484 (1997)	B.Zakharov, JETP Lett. 63 (1996) U.Wiedemann, Nucl.Phys.B588 (2000)	M.Gyulassy *et al.*, Nucl.Phys.B594 (2001); Phys.Rev.Lett.85 (2000)

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \dots ,$$

– Static medium

$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \dots ,$$

– 1+1D Bjorken

versus

$$\Delta E^{elastic} \approx 6\alpha_s^2 T^2 e^{-\mu/T} \left(1 + \frac{\mu}{T}\right) L \ln \frac{4E_{jet} T}{\mu^2}$$

J.D.Bjorken, SLAC preprint (1982) unpublished

- Radiative energy loss
- Elastic energy loss

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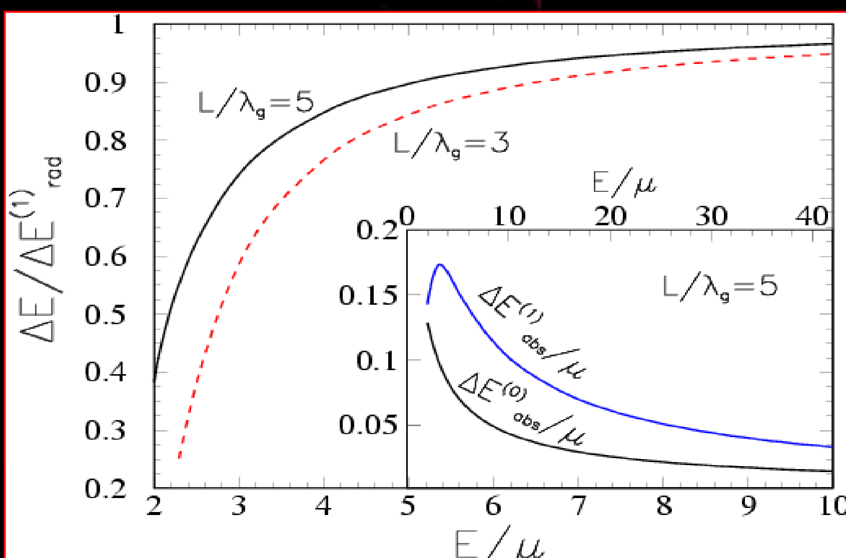
Gluon Absorption and Mass Effects

Detailed balance significantly reduces energy loss for $E_{jet} \leq 2-3\ GeV$ at RHIC

$$\frac{\Delta E^{(1)}_{rad}}{E} = -\frac{\alpha_s C_F \mu^2 L^2}{4\lambda_g E}\left[\ln\frac{2E}{\mu^2 L} - 0.048\right]$$

$$\frac{\Delta E^{(1)}_{abs}}{E} = \frac{\pi \alpha_s C_F L T^2}{3\lambda_g E^2}\left[\ln\frac{\mu^2 L}{T} - 1 + \gamma_E - \frac{6\varsigma'(2)}{\pi^2}\right]$$

$\mu \sim gT \sim 0.5\ GeV$

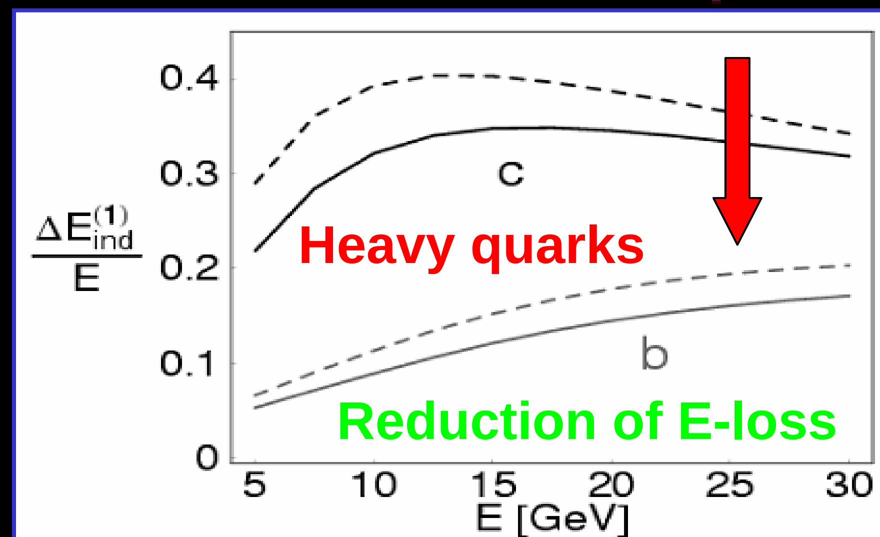


E.Wang, X.-N.Wang, Phys.Rev.Lett. 87 (2001)

Mass corrections and Ter-Mikayelian plasmon effect in QCD

$$\left[\omega_{(1\ldots n)}\right]^{-1} \to \left[\omega_{(1\ldots n)} + \frac{m_g^2 + x^2 M^2}{2xE}\right]^{-1}$$

$$\frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2}} \to \frac{\vec{k}_\perp}{\vec{k}_\perp^{\,2} + m_g^2 + x^2 M^2}, \quad x = \frac{k^+}{p^+} \approx \frac{\omega}{E}$$



M.Djordjevic, M.Gyulassy, nucl-th/0310076

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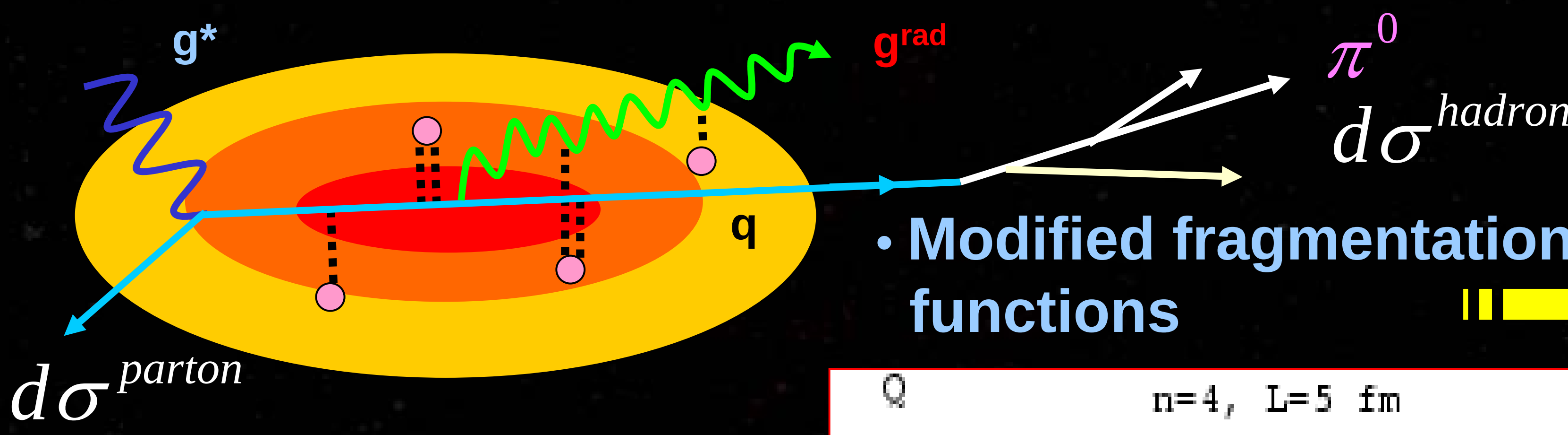
Modified Jet Cross Sections

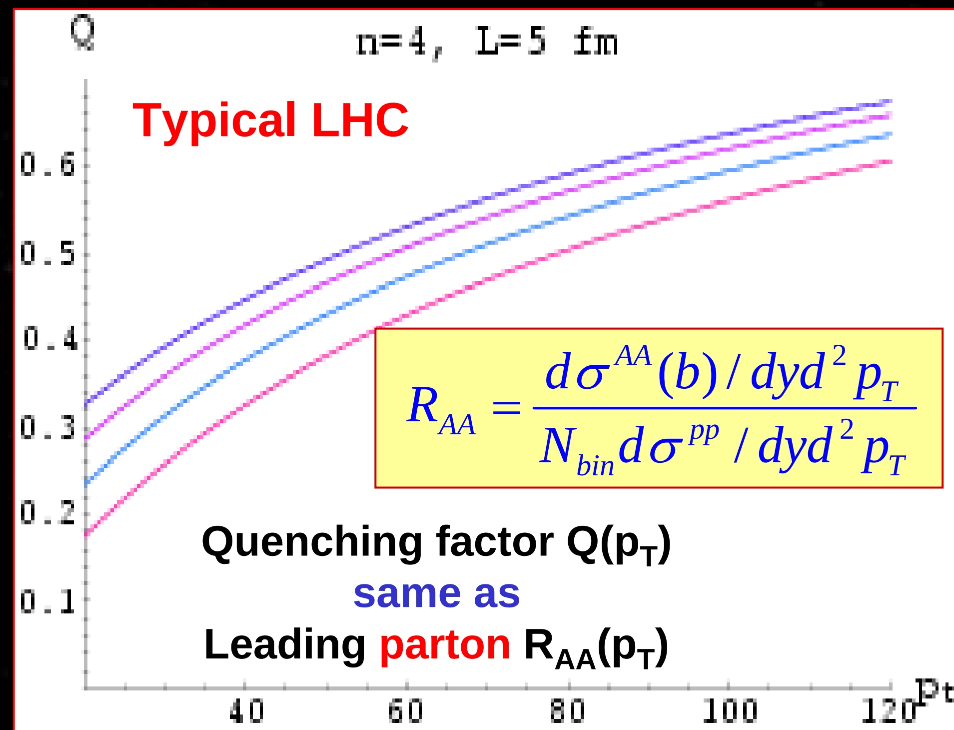


- Modified fragmentation functions

- Reduced partonic cross sections

$$\frac{d\sigma^{vac}}{dp_T^{\,2}} \propto \frac{1}{(p_T)^n}, \quad \omega_c = \frac{\hat{q}L^2}{2} = \frac{\mu^2}{\lambda_g}\frac{L^2}{2}$$

$$Q(p_T) \simeq \exp\left(-2C_R\alpha_s \sqrt{\frac{2n\omega_c}{\pi p_T}} \right)$$



$$R_{AA} = \frac{d\sigma^{AA}(b)/dyd^2p_T}{N_{bin}\, d\sigma^{pp}/dyd^2p_T}$$

$\hat{q}^{cold} \simeq 0.045\ GeV^2/fm, \ \hat{q}^{hot} \simeq 1\ GeV^2/fm$

R.Baier *et al.*, JHEP0109 , (2001)

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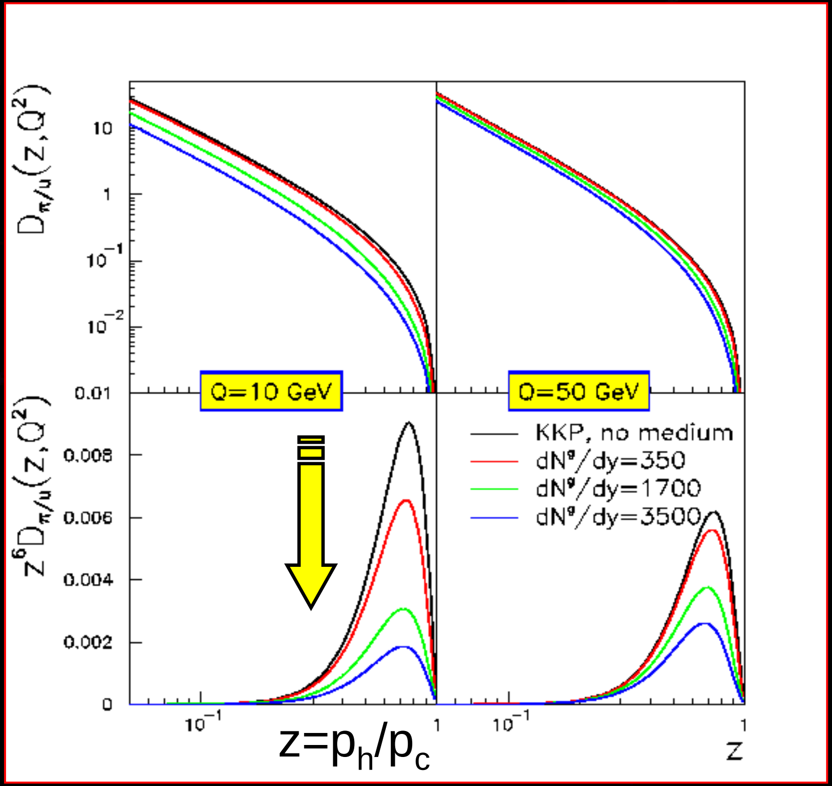
Effective Suppression of Fragmentation Functions

- Independent Poisson approximation for multiple gluon emission

Kniehl, Kramer, Potter fragmentation functions

Probability for fractional energy loss $\varepsilon = \Delta E / E_{jet}$

$$P(\varepsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dN(\omega_i)}{d\omega} \right] \times e^{-\int d\omega \frac{dN}{d\omega}} \, \delta\left(\varepsilon - \sum_{i=1}^{n} \frac{\omega_i}{E_{jet}} \right)$$



Normalized for suppressed leading hadrons (no feedback)

$$D^{med}{}_{h/q}(z,Q^2) = \int_0^1 d\varepsilon \, P(\varepsilon) \frac{1}{1-\varepsilon} D^{vac}{}_{h/q}\left(\frac{z}{1-\varepsilon}, Q^2 \right)$$

C.Salgado, U.Wiedemann, Phys.Rev.Lett. 89 (2002)

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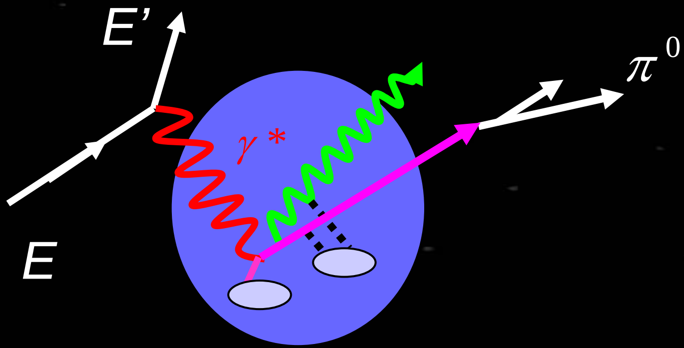
DIS Tomography



$\nu = E - E'$ - energy transfer

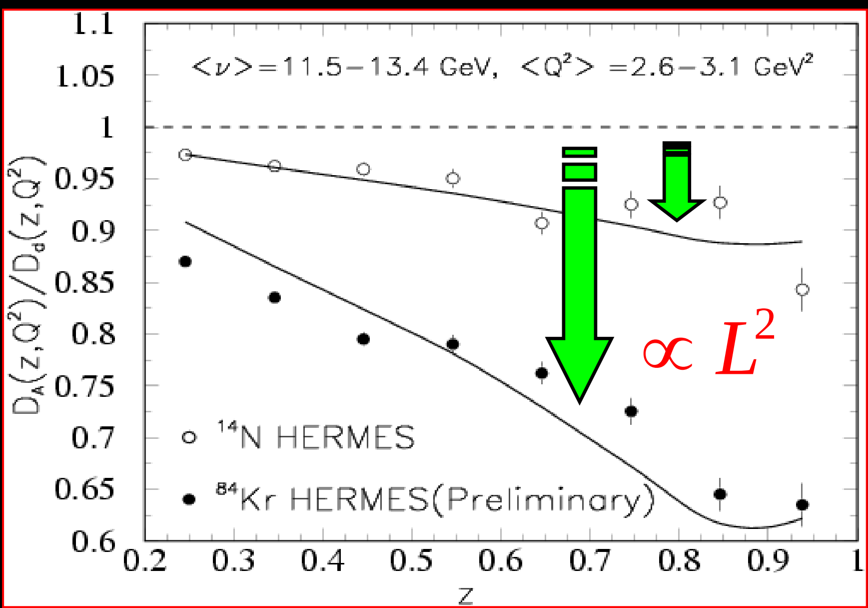
$\langle \Delta z \rangle$ - radiative energy loss fraction

$$\Delta E = \nu \langle \Delta z \rangle = (E - E')\langle \Delta z \rangle$$

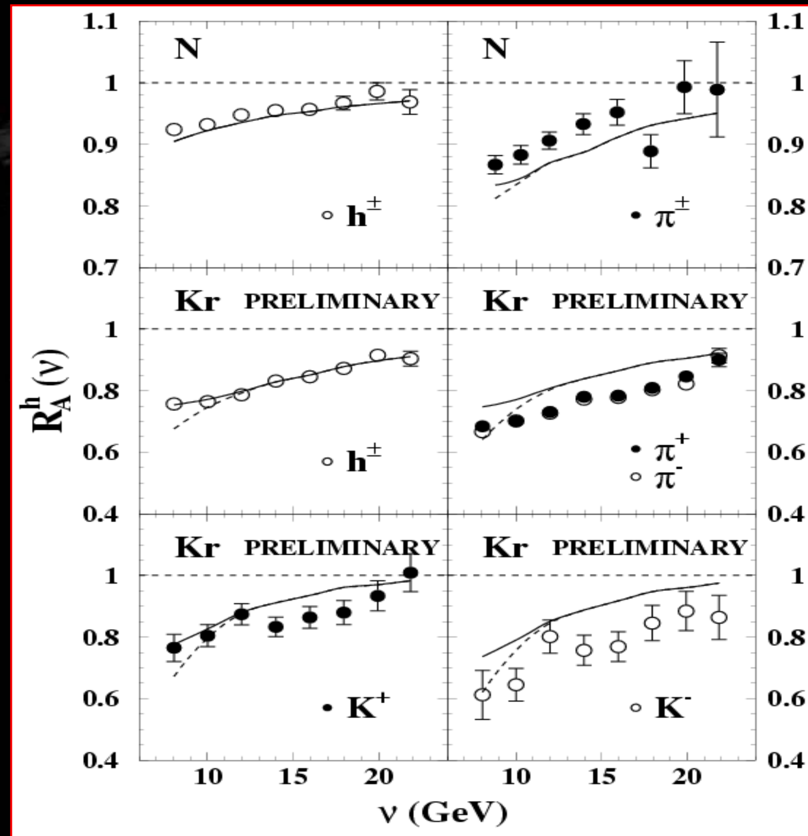
$$x_B = Q^2/(2p\cdot q), \quad x_A = 1/(m_N R_A)$$

$$\langle \Delta z \rangle = \tilde{C}(Q^2)\frac{C_A \alpha_s^2(Q^2)}{N_c}\frac{x_B}{Q^2 x_A^2} 6 \ln \frac{1}{2x_B}$$

$$\langle -dE/dL \rangle_{cold} \approx 0.5 - 0.6 \ GeV/fm$$



E.Wang, X.-N.Wang, Phys.Rev.Lett. 89 (2002)



F.Arleo, Eur.Phys.J. C30 (2003)

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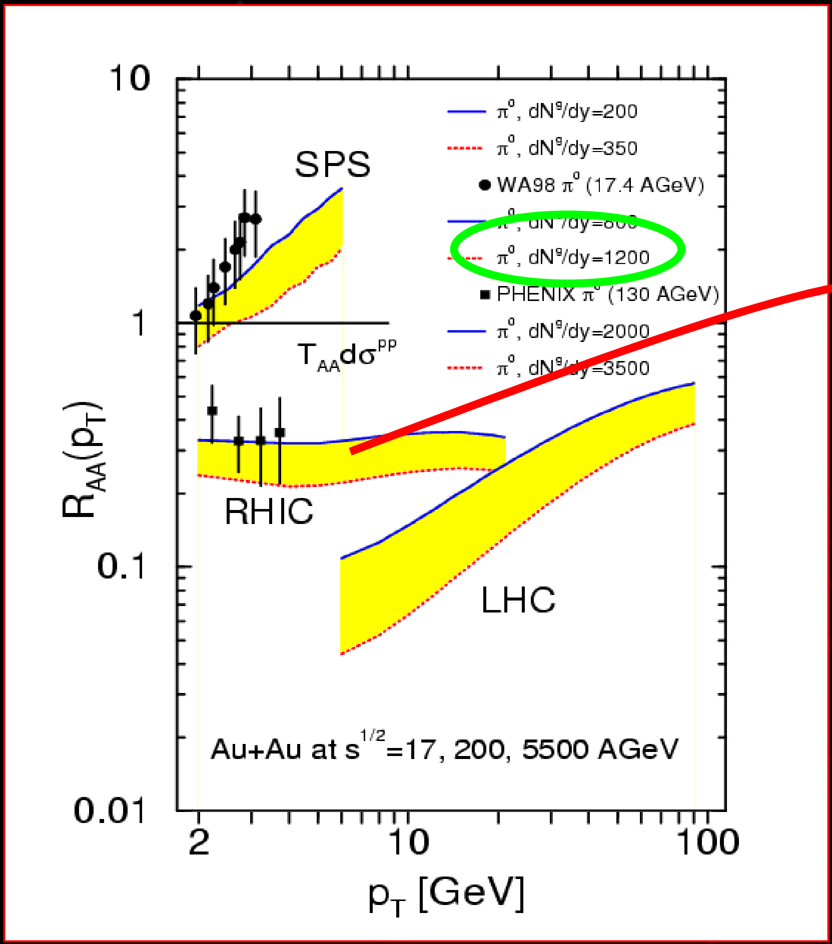
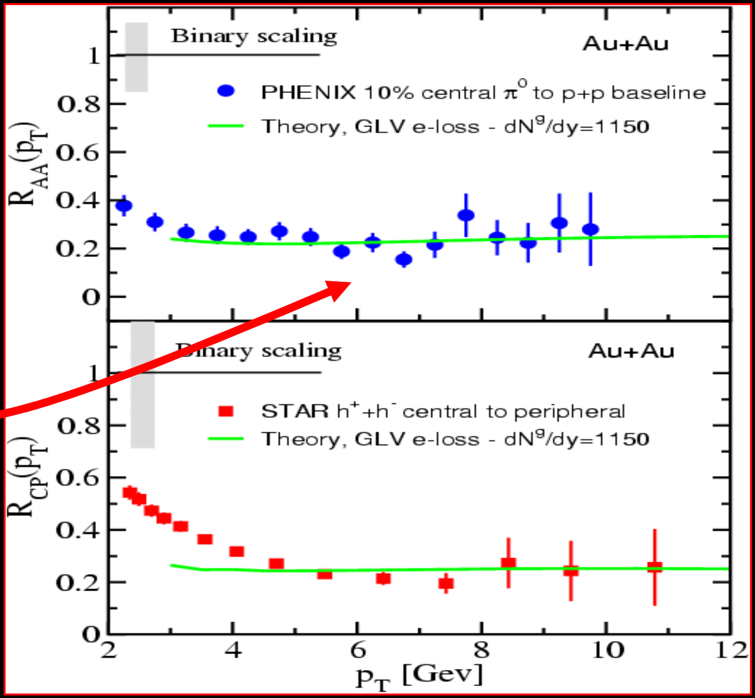
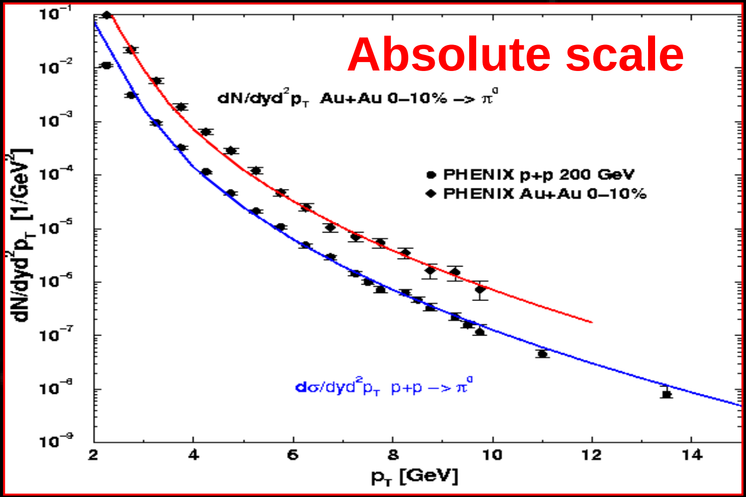
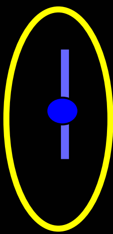
QGP Tomography









I.V., M.Gyulassy, Phys.Rev.Lett. 89 (2002)

$$\mu^2 \sim \omega_{pl}{}^2 \propto T^2,\ \rho \propto T^3,\ \varepsilon \propto T^4$$

PHENIX Collab., Phys.Rev.Lett. 91 (2003)
STAR Collab., Phys.Rev.Lett. 91 (2003)

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Centrality Dependence

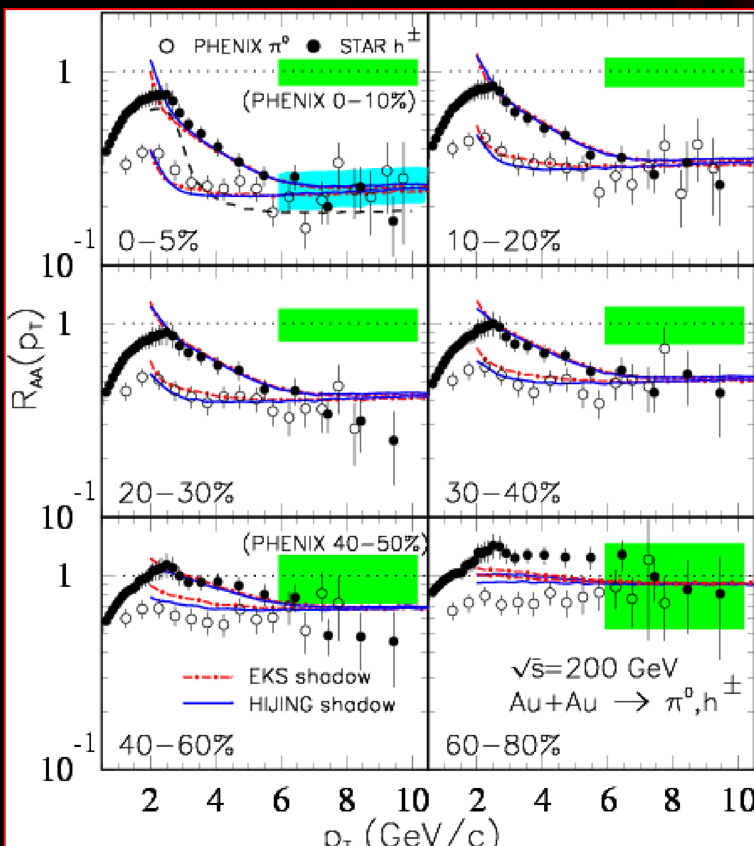
$$R_{AA}(p_T) = (1 + c \cdot \Delta p_T / p_T)^{-n}$$

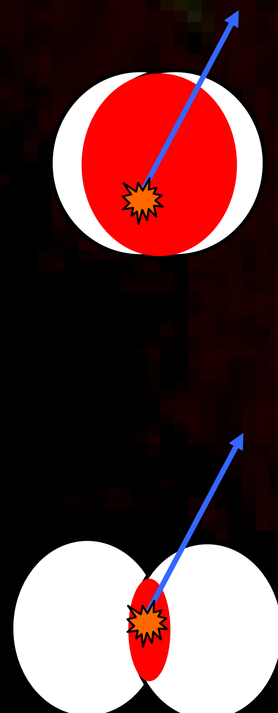
$$\frac{\Delta p_T}{p_T} \approx \frac{\Delta E}{E} \propto N_{part}^{\;2/3}$$

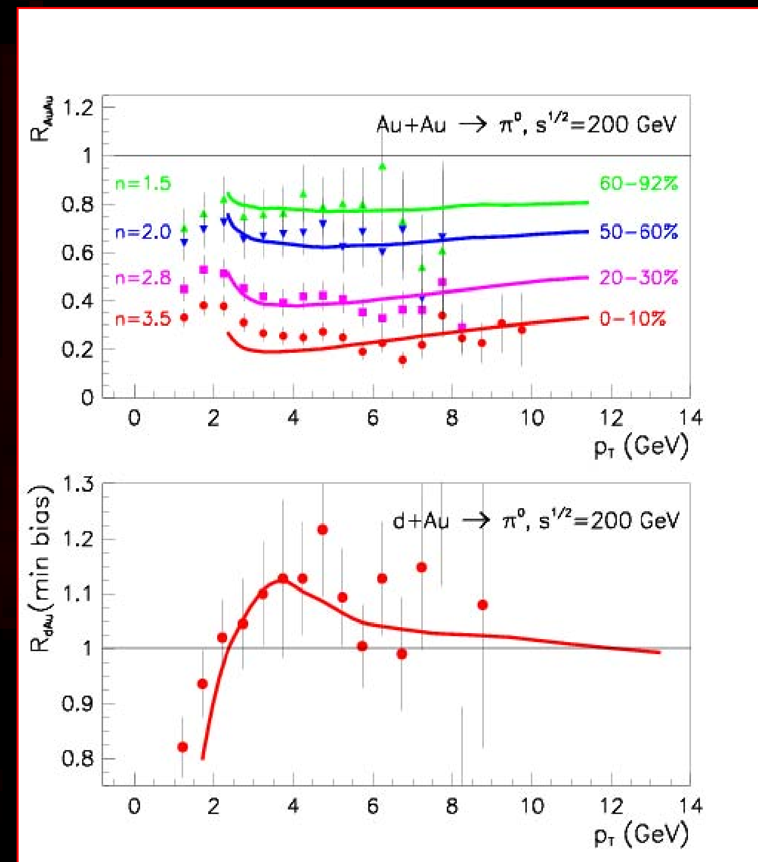
1+1D GLV

Small number of semihard scatterings

$$n_{scat} = 1.5(peripheral) - 3.5(central)$$







X.-N.Wang, nucl-th/0305010

G.G.Barnafoldi *et al.*, hep-ph/0311343

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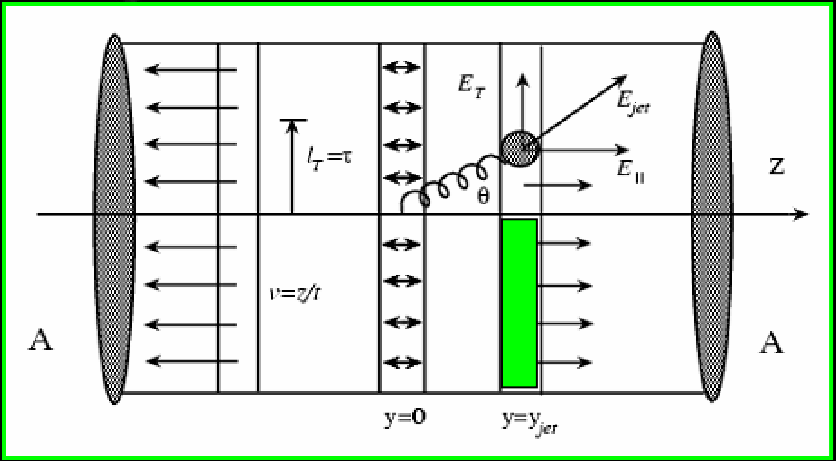
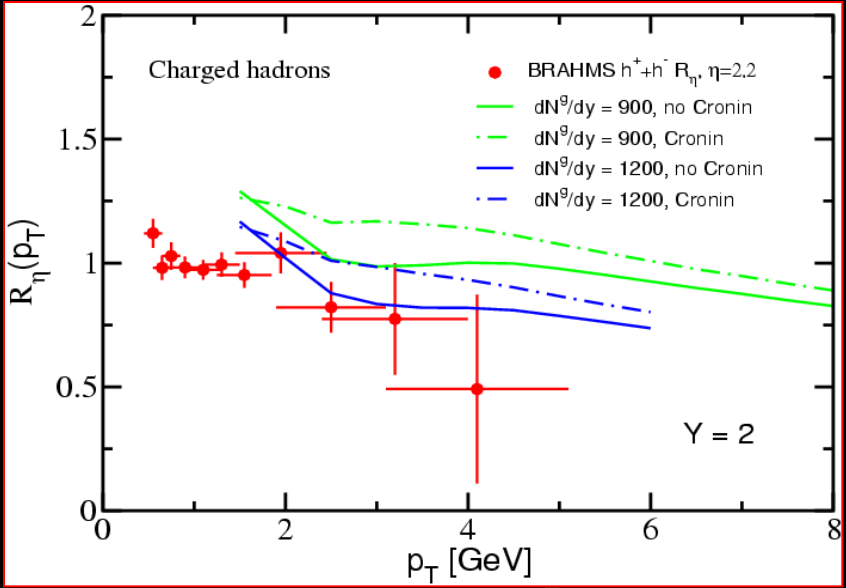
Rapidity Dependence



$$\tau_0 \rho(\tau_0) = \tau \rho(\tau) = (1/A_\perp)\, dN^{parton}/dy$$

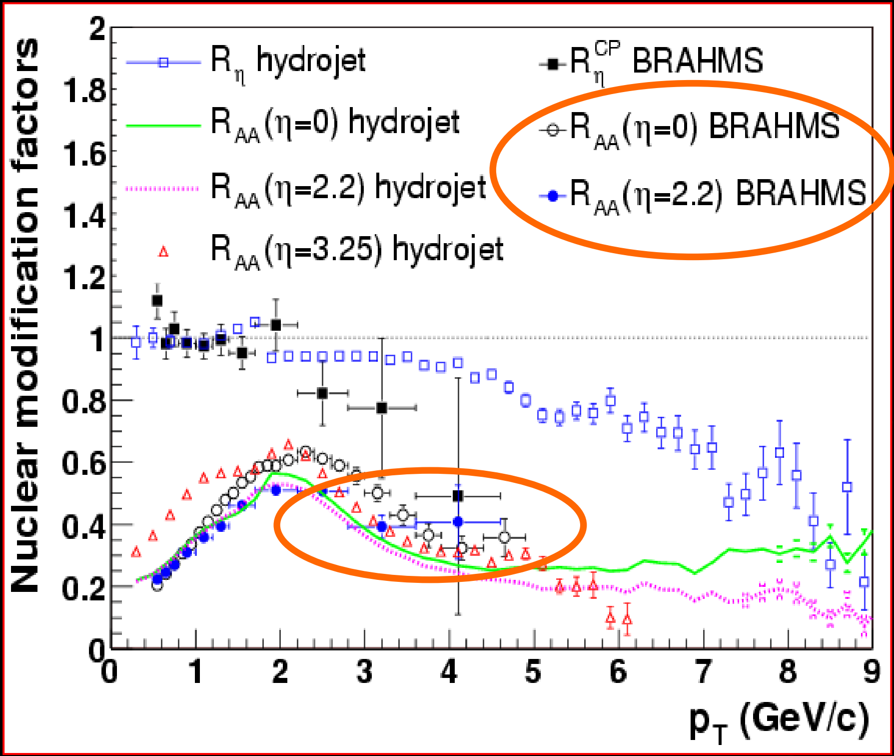


A.Adil, M.Gyulassy, I.V., in preparation

- **Energy loss in a 3+1D hydro**

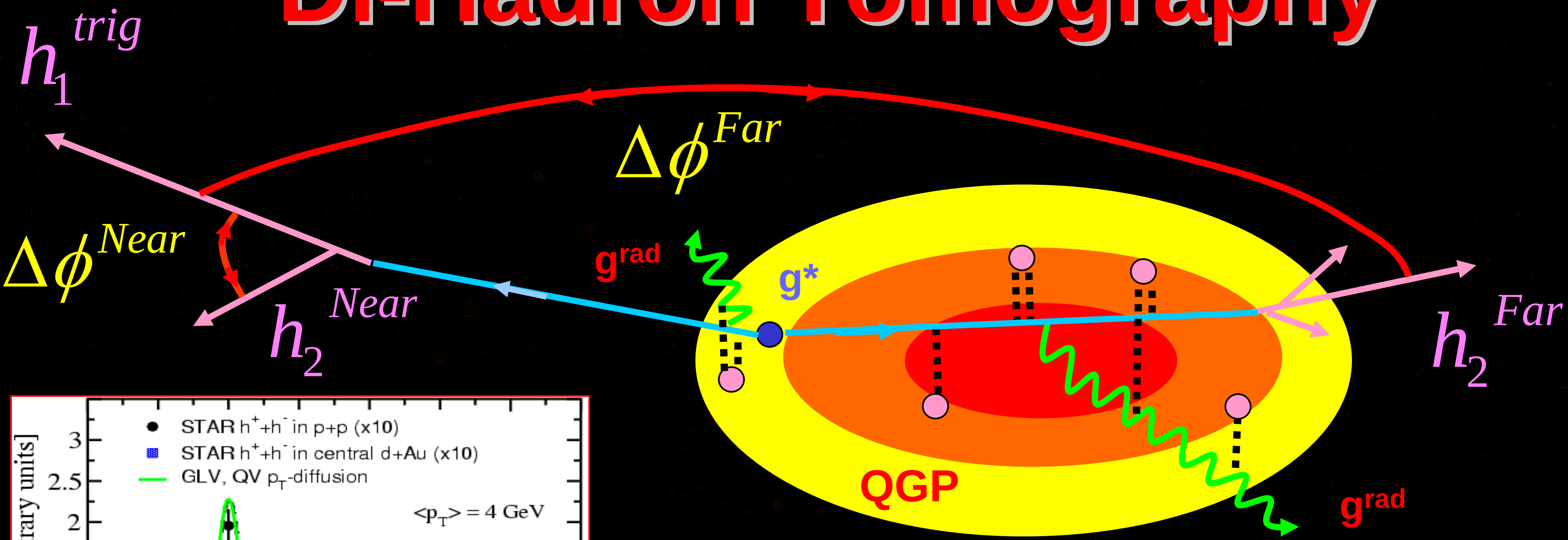
$$R_\eta = R_{AA}(\eta) / R_{AA}(\eta = 0)$$

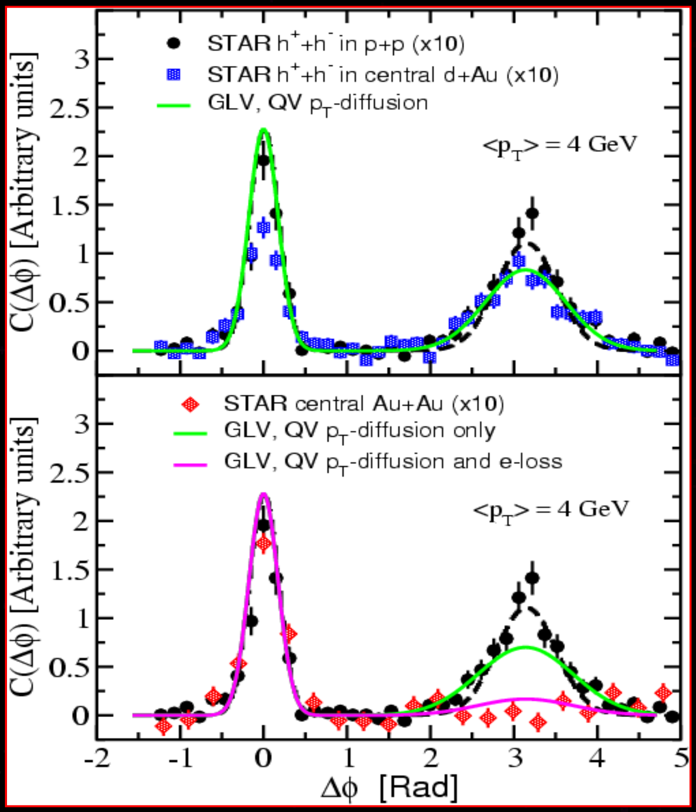
(a double ratio)



T.Hirano, Y.Nara, Phys.Rev.C68 (2003)

Di-Hadron Tomography





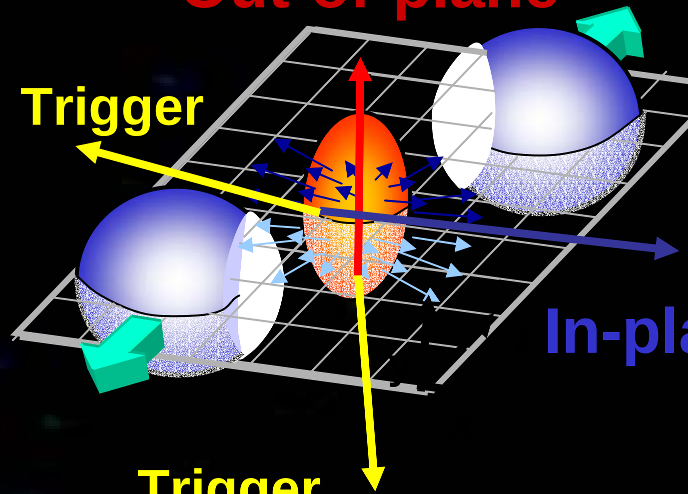
$$E_{h_1} E_{h_2} \frac{d\sigma}{d^3p_1 d^3p_2} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2)$$
$$\otimes\, d\sigma^{ab\to cd}/dt$$
$$\otimes\, D_{h_1/c}(z_c{}^*, j_{Tc}, Q^2) \otimes D_{h_2/d}(z_d{}^*, j_{Td}, Q^2)$$
$$\otimes\, \delta^4\left(p_a + p_b - p_c - p_d\right)$$

- **Di-jet acoplanarity (insufficient)**
- **Away-side quenching**

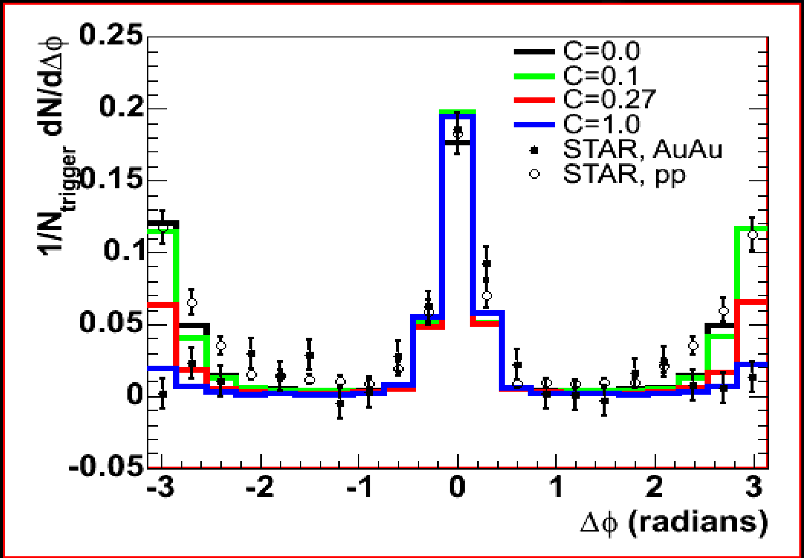
J.W.Qiu, I.V., Phys.Lett.B570 (2003)

Near- and Far-Side Correlations

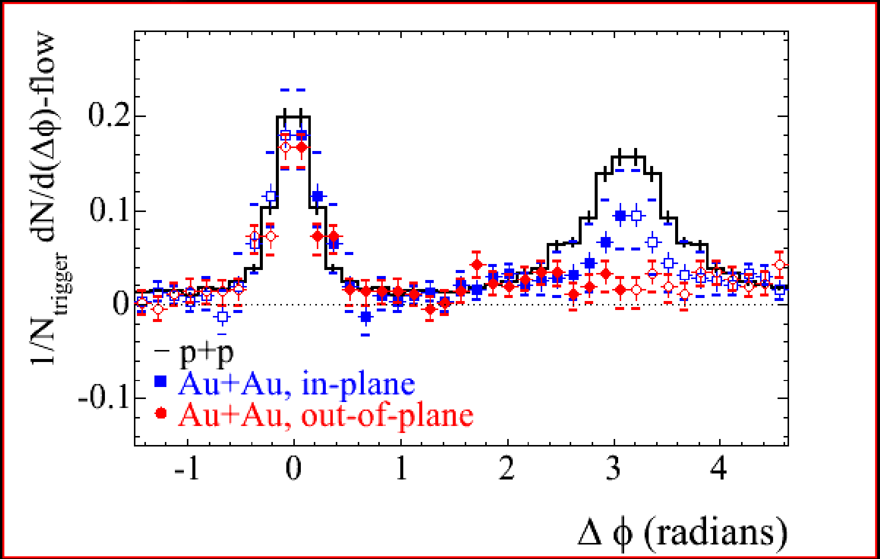
- Unaltered near-side correlations
- Disappearance of the away-side correlations



$$C_2(\Delta\phi) = \frac{1}{N^{trig}} \frac{dN}{d\Delta\phi}$$



T.Hirano, Y.Nara, Phys.Rev.Lett.91 (2003)



K. Filimonov [STAR Collab.], DNP'03 meeting

The "Remnants of Lost Jets"

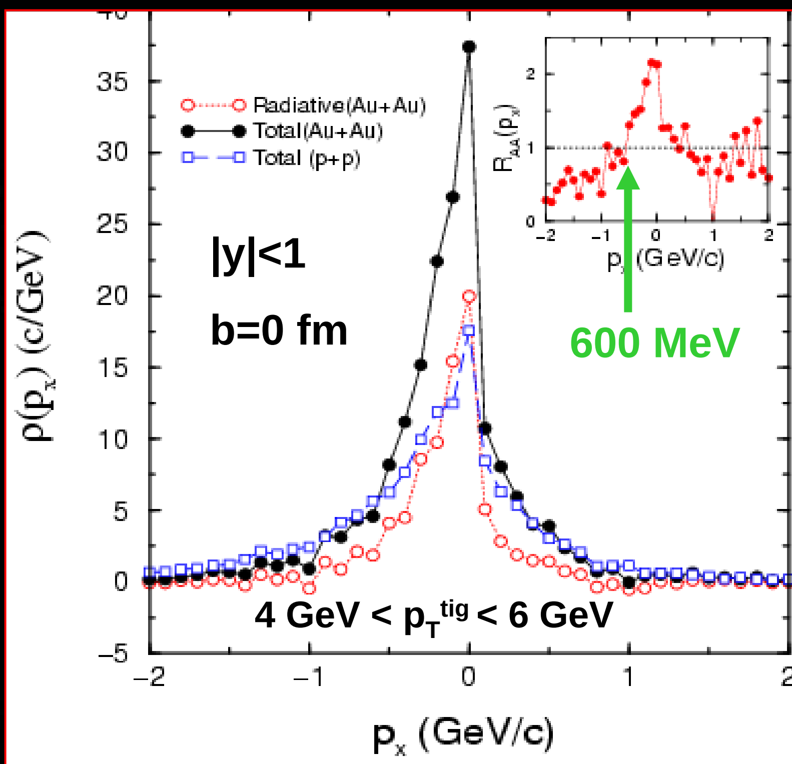
$$\Delta N^{g}(r,\Delta\tau) \approx \frac{1}{4}\Delta S = \frac{1}{4}\frac{\Delta E(r,\Delta\tau)}{T(r,\tau)}$$

$$\int p_x \rho(p_x) dp_x = -p_T^{trig}$$

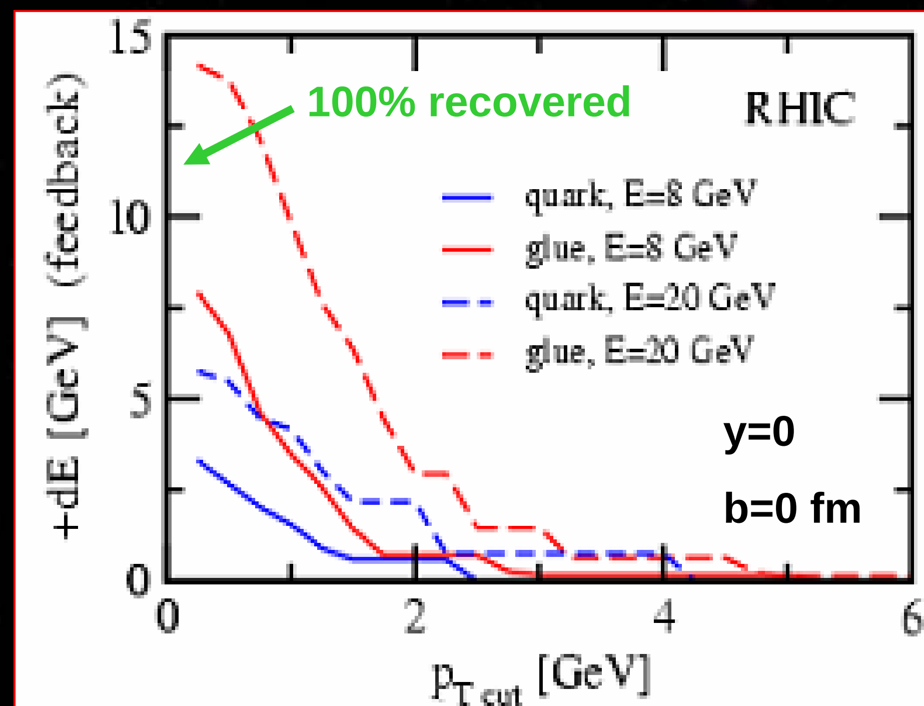
- **Entropy growth**
- **Momentum sum rules**

$$+\Delta E(p_{T\,cut}) = \sum_{n=1,\infty|\bar{z}(\Delta E/n)\geq p_{T\,cut}} (\bar{z}\Delta E) P_n(E_{jet}) + \sum_{n=1,\infty|(1-\bar{z})(\Delta E/n)\geq p_{T\,cut}} ((1-\bar{z})\Delta E) P_n(E_{jet})$$

- **Reappearance of the lost energy**



S.Pal, S.Pratt, Phys.Lett.B574 (2003)



I.V., GLV e-loss simulation

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Broadening of the Jet Cone

- **Intra-jet correlations**

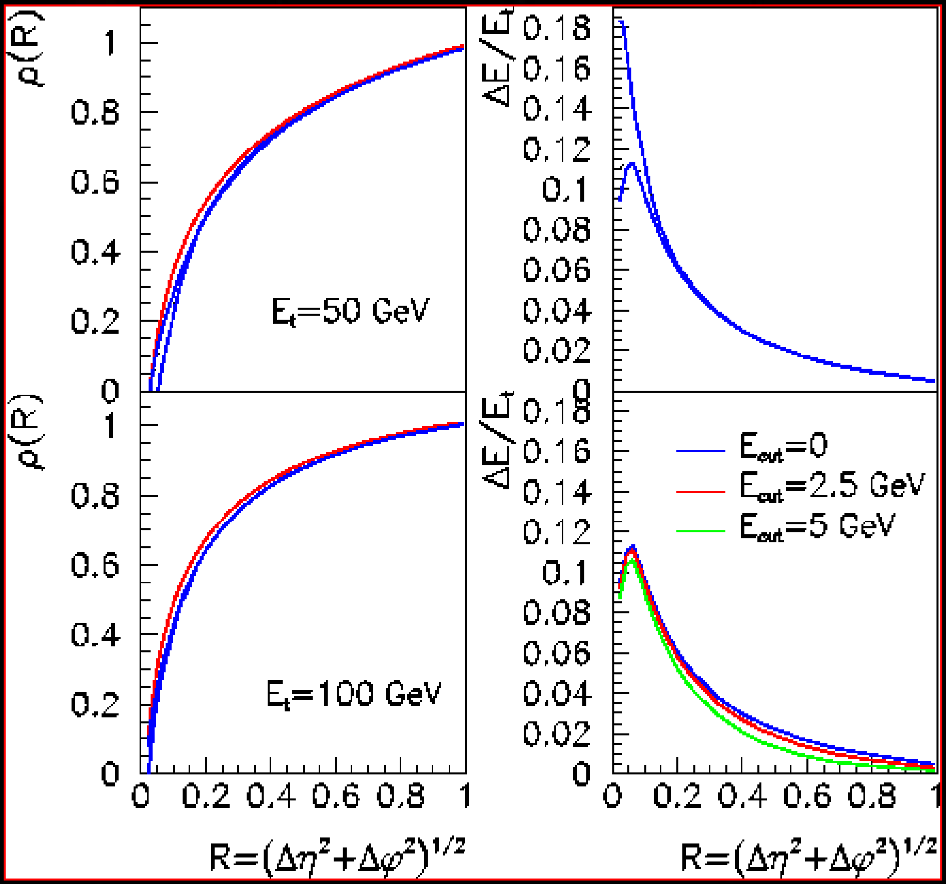
$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

Jet cone opening angle

$\rho(R)$ - **fraction of the total energy within a jet subcone**

$$\rho_{vac}(R) = \frac{1}{N_{jets}} \sum_{jets} \frac{E_t(R)}{E_t(R=1)}$$

$$\rho_{med}(R) = \rho_{vac}(R) - \frac{\Delta E_t(R)}{E_t} + \frac{\Delta E_t}{E_t}\left(1 - \rho_{vac}(R)\right)$$



C.Salgado, U.Wiedemann, hep-ph/0310079

Very small effect even at the LHC

$$R = 0.3 \quad \begin{cases} E_t = 50\ GeV, & 5\%\ \text{effect} \\ E_t = 100\ GeV, & 3\%\ \text{effect} \end{cases}$$

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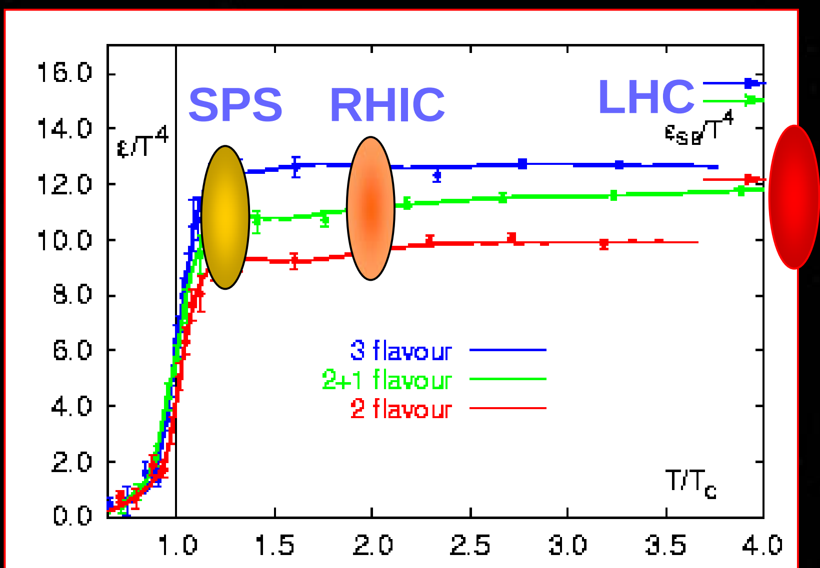
Properties of Dense Nuclear Matter

	$\left\langle \frac{dE}{dz} \right\rangle^{*} \left[\frac{GeV}{fm}\right]$	$\tau_0[fm]$	$T[MeV]$	$\varepsilon[GeV/fm^3]$	$\tau_{tot}[fm]$	dN^g/dy
SPS	2-3.5	0.8	210-240	1.5-2.5	1.4-2	200-350
RHIC	7-10	0.6	380-400	14-20	6-7	800-1200
LHC	17-28	0.2	710-850	190-400	18-23	2000-3500



F.Karsch, Nucl.Phys.A698 (2002)

Hot versus cold nuclear matter

	$\left\langle \frac{dE}{dz} \right\rangle \left[\frac{GeV}{fm}\right]$	$\left\langle \frac{\mu^2}{\lambda_g} \right\rangle \left[\frac{GeV^2}{fm}\right]$
DIS quenching	0.5	0.12
Drell-Yan	0.6 ± 0.45	0.14 ± 0.45
Cronin effect	0.4-0.6	0.1-0.14
Th. estimate	0.2	0.05

F.Arleo, hep-ph/0310274 [CERN Yellow Report]

$$R_{Au} = 6.8\ fm,\ T_c = 175\ MeV,\ \varepsilon_c = 1\ GeV/fm^3$$

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Conclusions

- Significant theoretical advances in understanding non-Abelian bremsstrahlung:
  - Regimes far from asymptopia (E,L) relevant at RHIC
  - Incorporating mass and gluon absorption corrections
- Jet tomographic analysis:
  - Cold nuclear matter $\langle -dE^{rad} / dz \rangle \approx 0.5\ GeV / fm$
  - Suggests energy density $\varepsilon \approx 15-20\ GeV / fm^3$ at RHIC

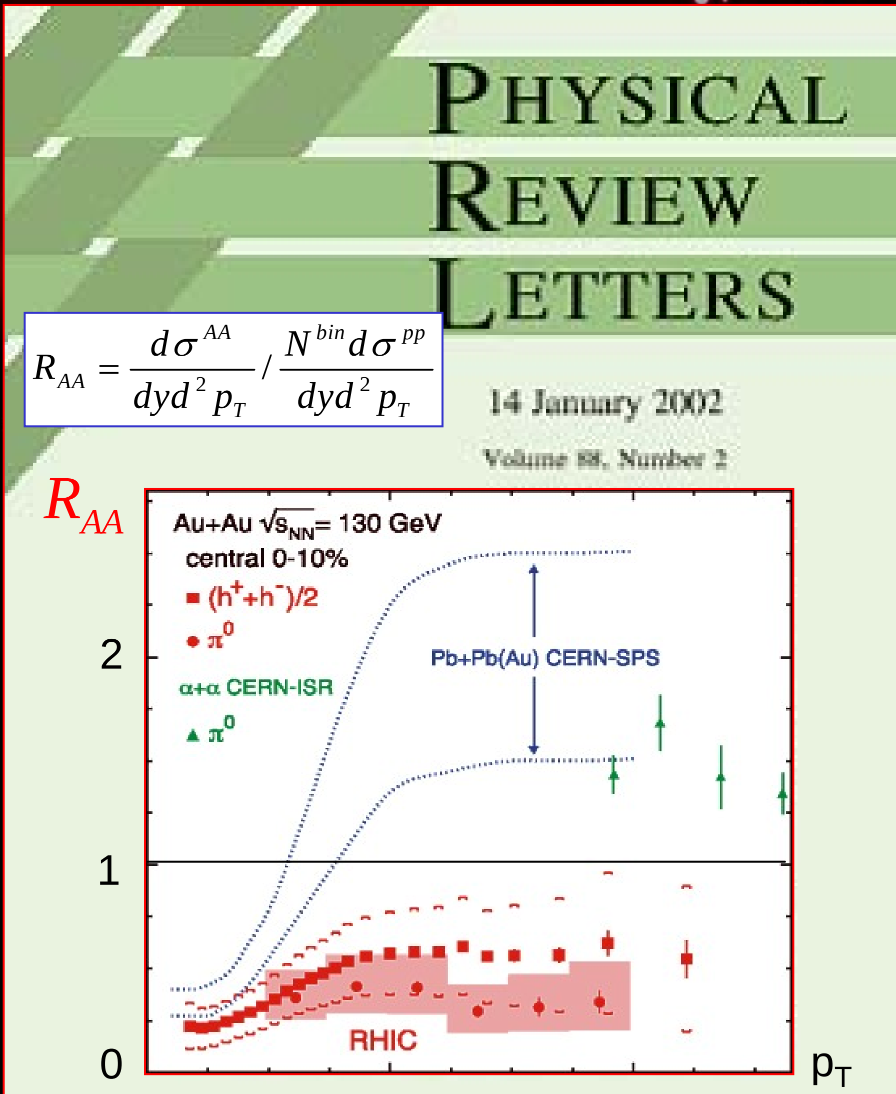
    $\langle -dE^{rad} / dz \rangle \approx 15\ GeV / fm$ (static)
- Future directions of high-p_T studies in dense nuclear matter:
  - Correlations and jet structure, redistribution of ΔE^{rad}
  - Quantitative studies of open charm and direct photons
- Results from Jet Tomography correlated with other theoretical approaches are <u>in strong support of the QGP paradigm at RHIC</u>

Conclusions

- Significant theoretical advances in understanding non-Abelian bremsstrahlung:
  - Regimes far from asymptopia (E,L) relevant at RHIC
  - Incorporating mass and gluon absorption corrections
- Jet tomographic analysis:
  - Cold nuclear matter $\hat{q} = \mu^2 / \lambda_g \approx 0.10 - 0.15 \; GeV^2 / fm$
  - Suggests energy density $\varepsilon \approx 15 - 20 \; GeV / fm^3$ at RHIC more that 100 times cold nuclear matter density
- Future directions of high-p_T studies in dense nuclear matter:
  - Correlations and jet structure, redistribution of ΔE^{rad}
  - Quantitative studies of open charm and J / ψ
- Results from Jet Tomography correlated with other theoretical approaches are <u>in strong support of the QGP paradigm at RHIC</u>

Discovery of “Jet Quenching”

$$R_{AA} = \frac{d\sigma^{AA}}{dyd^2p_T} / \frac{N^{bin} d\sigma^{pp}}{dyd^2p_T}$$



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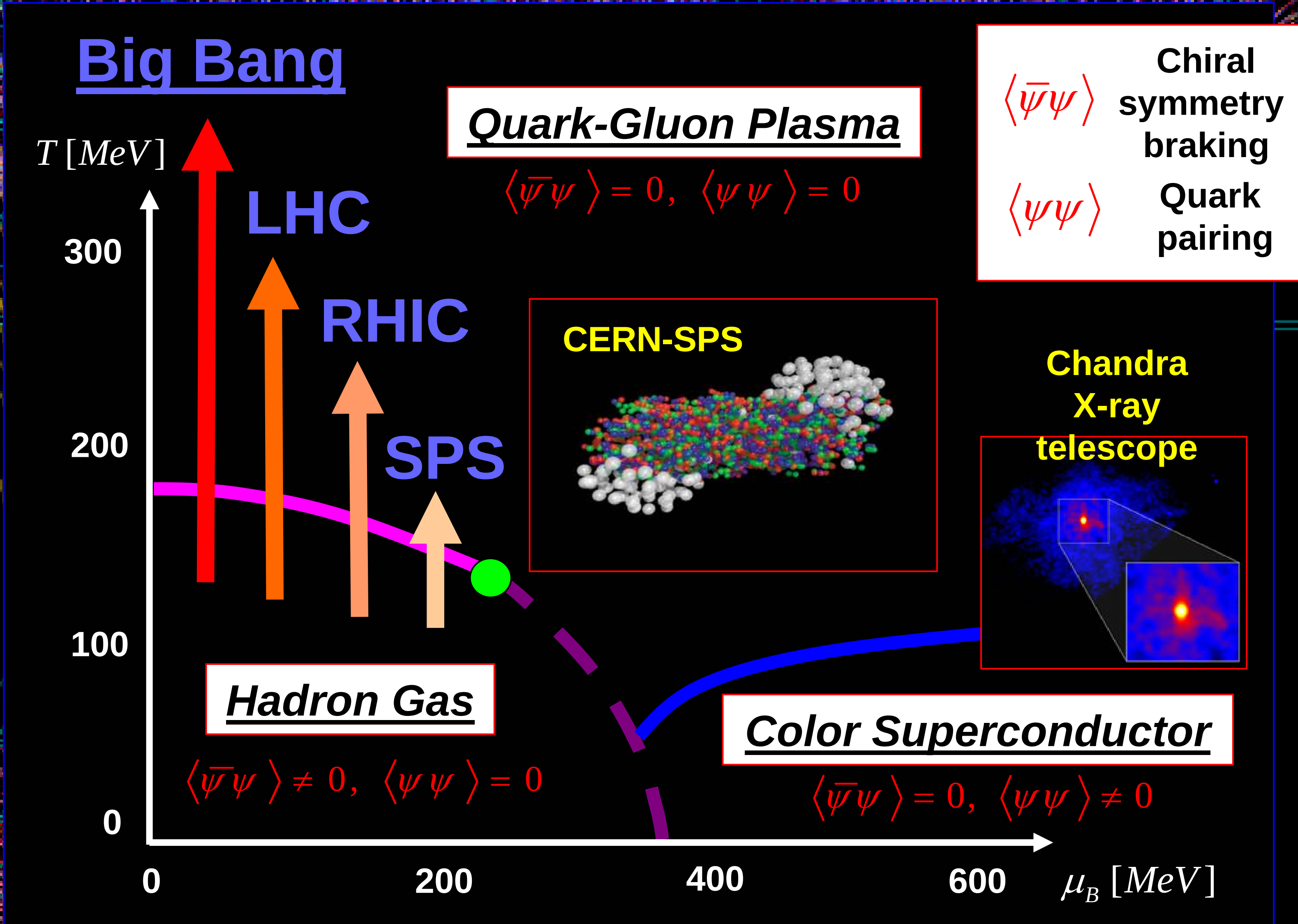
The Phase Diagram of QCD



T.D.Lee, C.G.Wick, Phys.Rev.D 9 (1974)

M.Stephanov,K.Rajagopal,E.Shuryak, Phys.Rev.Lett. 81 (1998)

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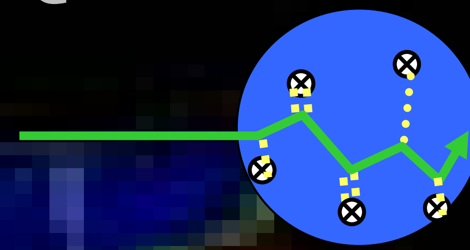
Energy Loss in Dense QCD Matter

- Elastic energy loss



$$\Delta E^{elastic} \approx 6\alpha_s^{\,2} T^2 e^{-\mu/T}\left(1+\frac{\mu}{T}\right) L \ln\frac{4E_{jet}T}{\mu^2}$$

J.D.Bjorken, SLAC preprint (1982) unpublished

Rather small to have significant observable effect

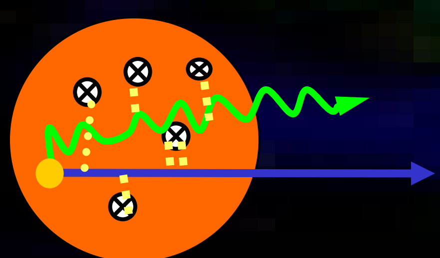
May be significant for large cone ∢

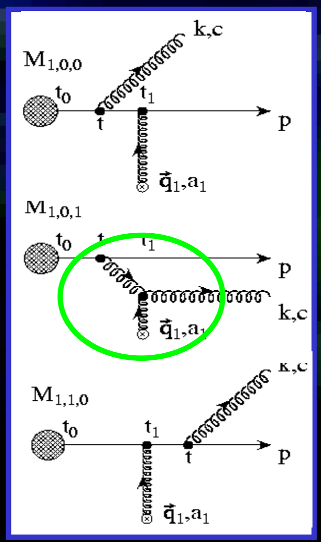
I.Lokhtin , A.Snigirev *in* hep-ph/0310274 [CERN Yellow report]

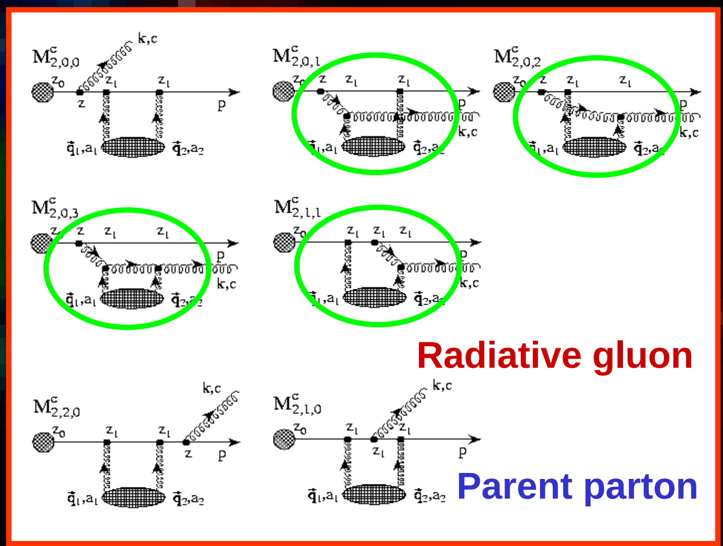
- Radiative energy loss

Landau-Pomeranchuk-Migdal effect in QCD

M.Gyulassy, X.-N.Wang, Nucl.Phys.B420, (1994)







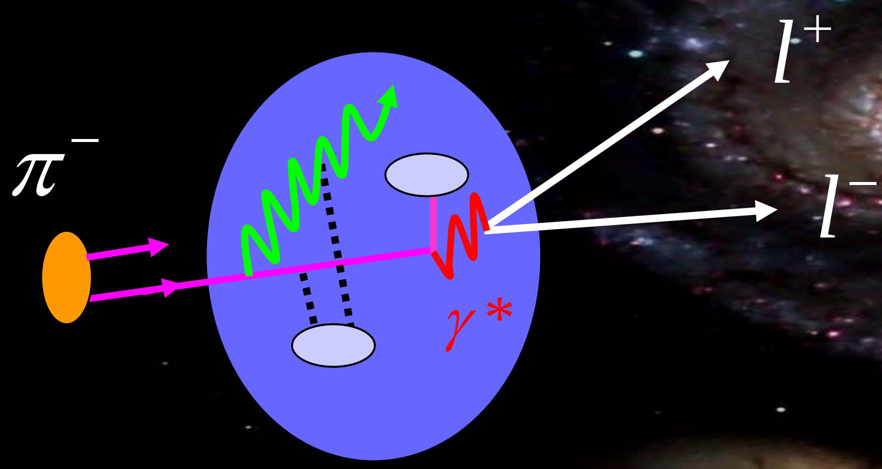
QCD ≠ QED in the ability of the gluon to reinteract

Ivan Vitev, ISU

From Drell-Yan to DIS

- **Gluon transport coefficient fixed from Drell-Yan**

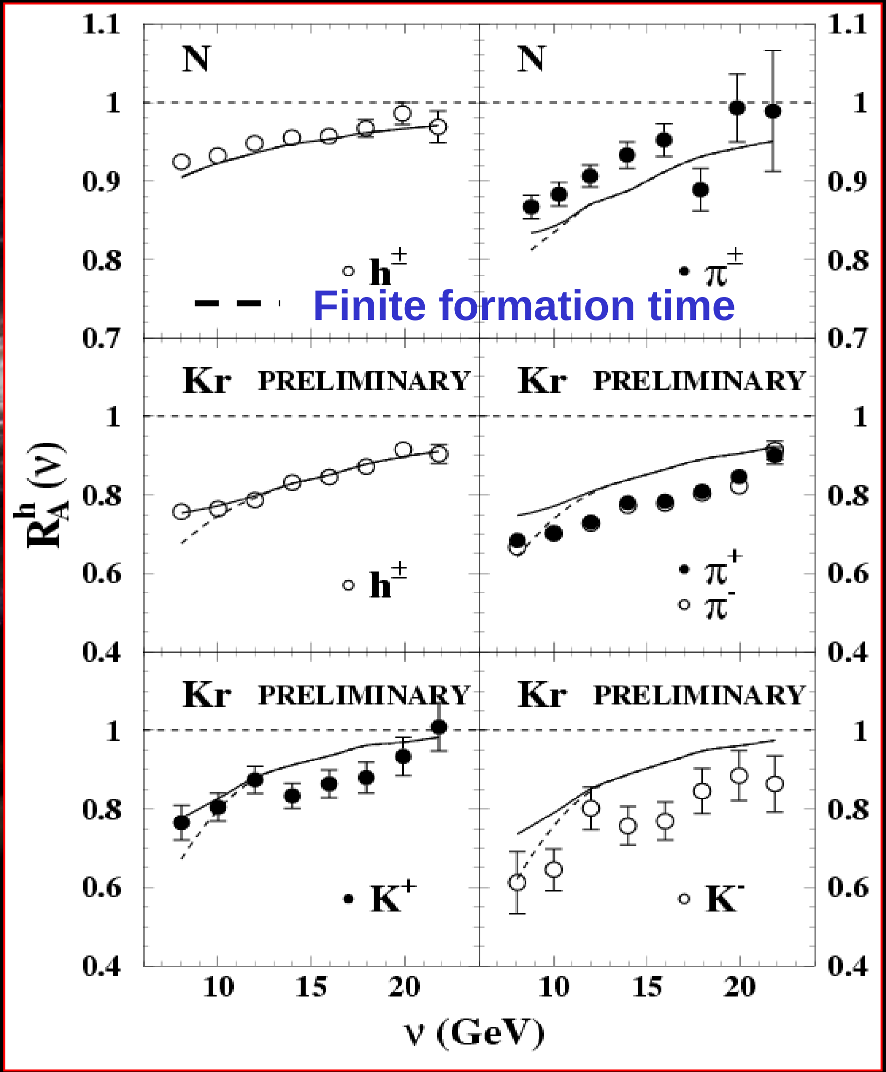
$$\hat{q} = 0.14\ GeV^2 / fm$$



Large number of scatterings approximation

$$\langle -dE/dL \rangle_{final} \approx 3 \langle -dE/dL \rangle_{initial}$$

$$\langle -dE/dL \rangle_{cold}^{final} \approx 0.6\ GeV / fm$$



F.Arleo, Eur.Phys.J. C30 (2003)

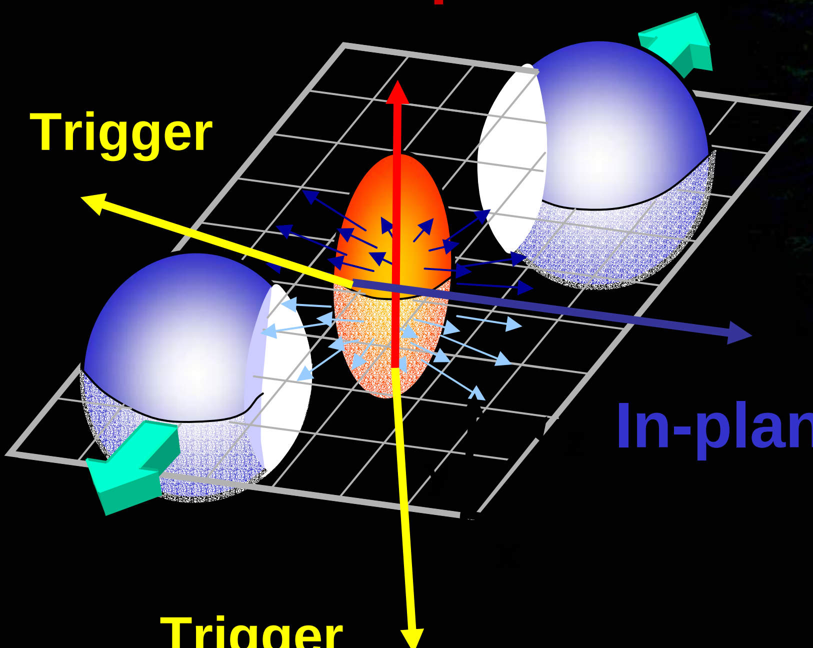
Ivan Vitev, ISU

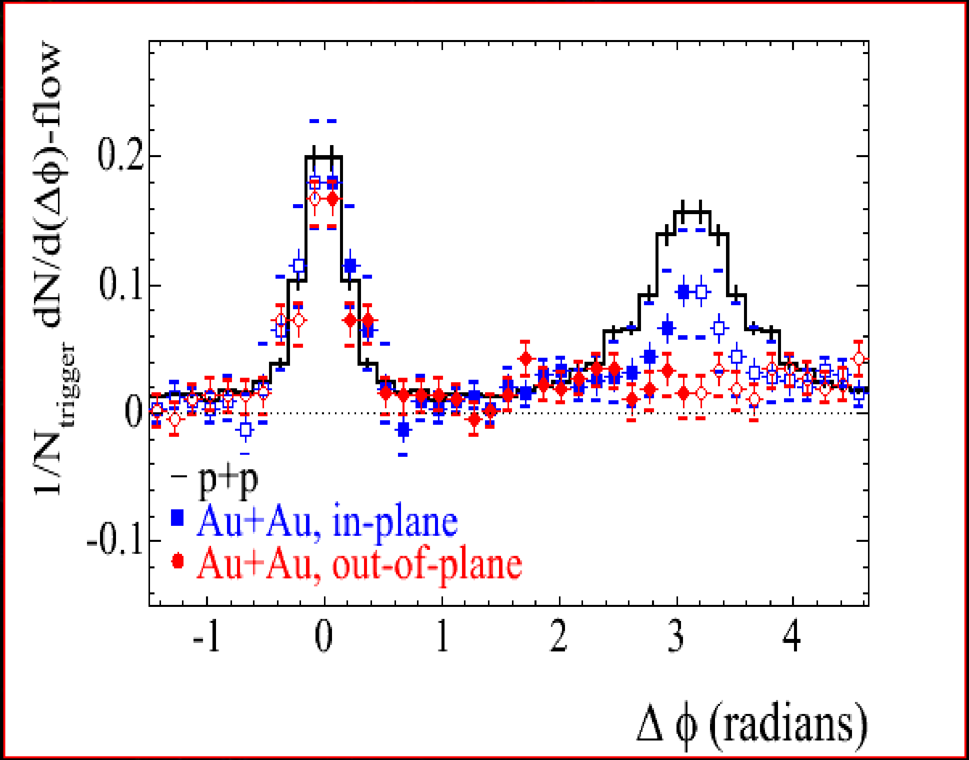
Correlations with Respect to the Reaction Plane

- Very direct evidence for the path length dependence of ΔE^{rad}

$p_T^{trigger}$ = 4-6 GeV/c

2 GeV/c < $p_T^{associated}$ < $p_T^{trigger}$, $|\eta|<1$





K. Filimonov [STAR Collab.], DNP'03 meeting