Jet quenching in high-energy heavy-ion collisions

International School QGP & HIC

Torino, Dec. 8th - 13th 2008

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Massachusetts Institute of Technology

Plan of lectures

1st

0. Introduction: QCD matter, Heavy-ions, jet-quenching

1. High-p_T leading hadron suppression:

- pQCD factorization, quenching factor (R_{AA}): QGP q-hat, dN^g/dy
- $R_{AA}(p_T,\sqrt{s},cent,L,m_q)$: data versus parton energy loss models

2nd

2. High-p_T dihadron correlations

- Away-side suppression: QGP q-hat
- Away-side splitting: QGP speed-of-sound(?)

3rd

3. Full jet measurements:

- Reconstruction: Clustering algo, bckgd subtraction, corrections
- γ -jet: medium Fragmentation-Functions: QGP q-hat

0. Introduction

The many facets of QCD

- QCD is a QFT with very rich dynamical content: asymptotic freedom, confinement, (approx.) χ-symmetry, non-trivial vacuum, $U_A(1)$ anomaly...

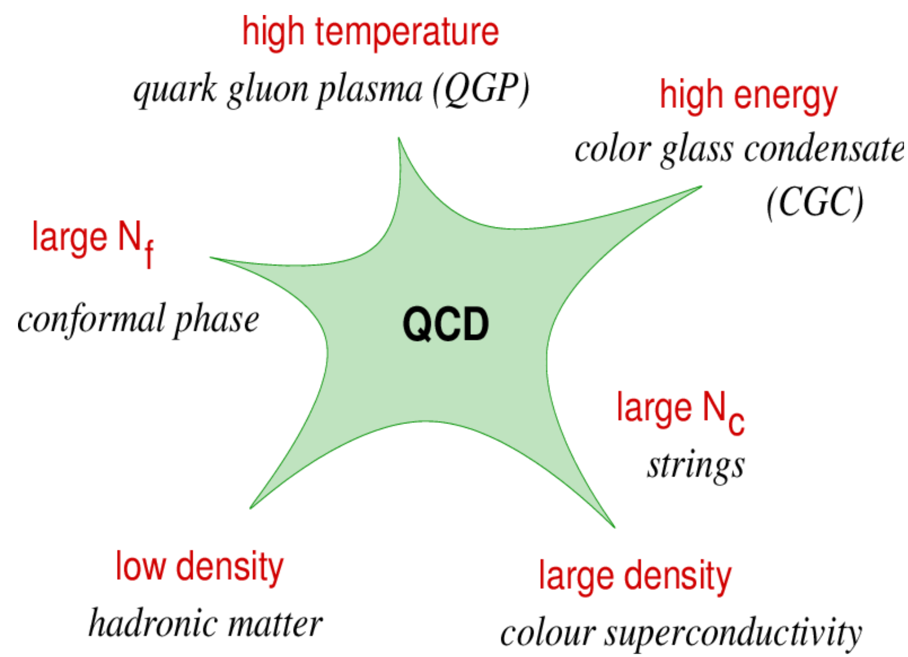
gluon dynamics; quark kinetic energy + mass term, quark-gluon dynamics

$$\mathcal{L}_{QCD} = -\frac{1}{4g^2}\,\mathrm{Tr}(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{nf} \overline{\psi_f}\,(i D_\mu \gamma^\mu + m_f)\,\psi_f$$

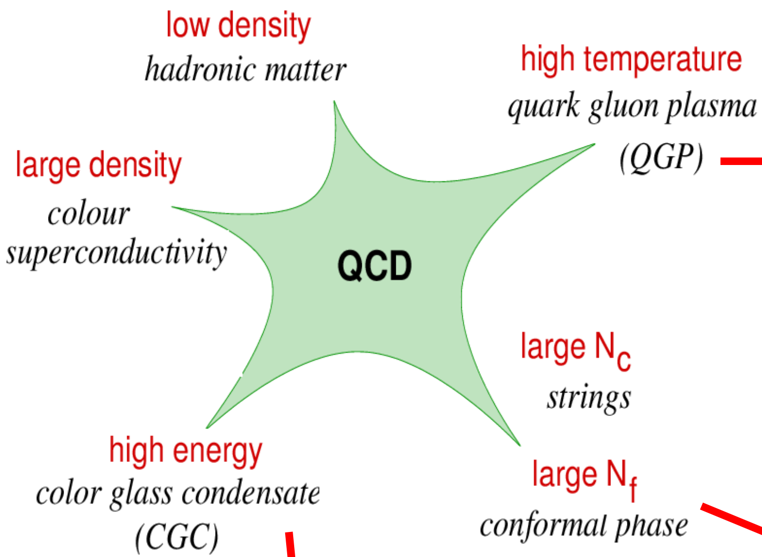
QCD coupling; field strength tensor; covariant derivative; quark field

- The only sector of the SM whose collective behaviour can be studied in the lab: phase transition(s), thermalization of fundamental fields, ...

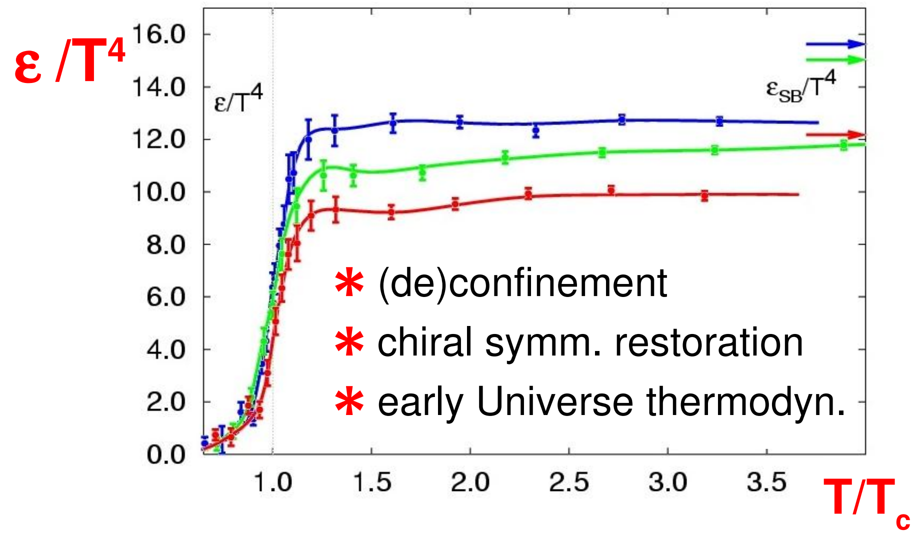
- QCD has a very diverse many-body phenomenology at various limits:



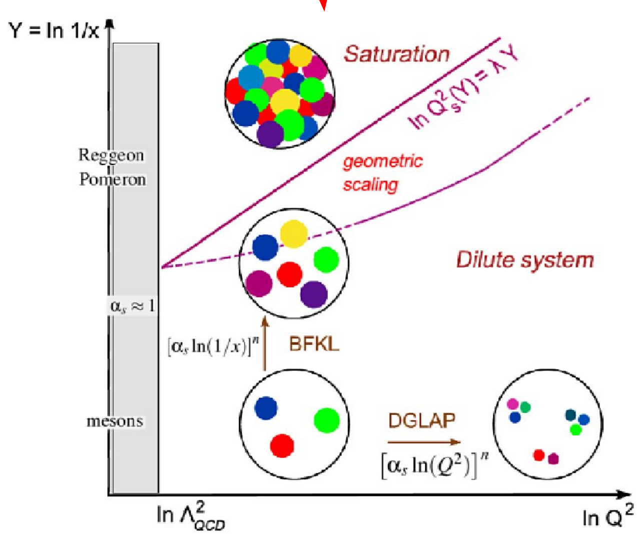
QCD matter with heavy-ions: physics menu



- QCD at high-temperature: QGP



- High-density QCD at small-x: CGC

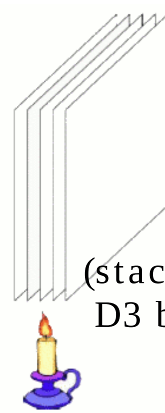


- Gauge-gravity duality: AdS/QCD

$$\mathcal{L} = \frac{1}{2g_{\rm YM}^2}{\rm Tr}(F_{\mu\nu}F^{\mu\nu}) + i{\rm Tr}(\bar\psi\gamma^\mu D_\mu\psi) \longleftrightarrow ds^2 = \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + \frac{R^2}{r^2}d\Omega_5^2$$

$\mathcal{N}$= 4

SU(N_c)



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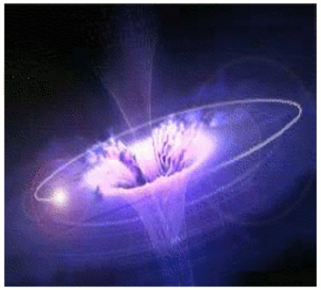
(stack of 4 D3 branes)

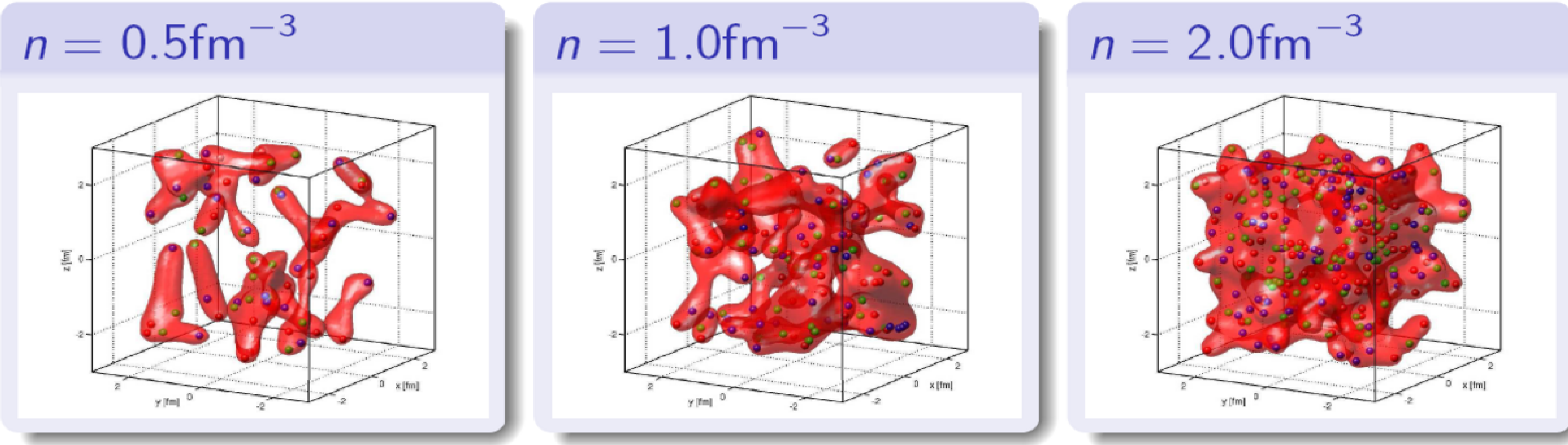


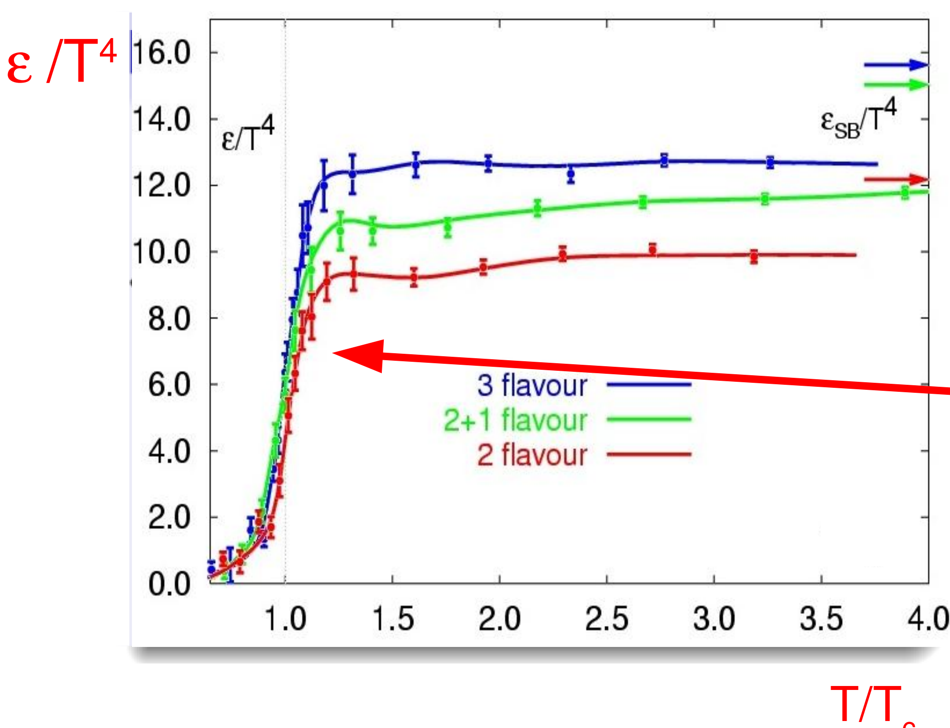
BH in

AdS_5 x S^5

Thermal gauge theory = black hole in anti de-Sitter space

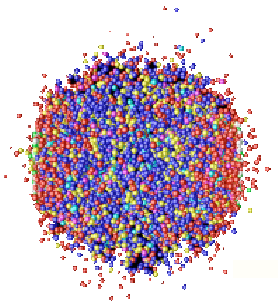
QGP: Study of (bulk) deconfinement



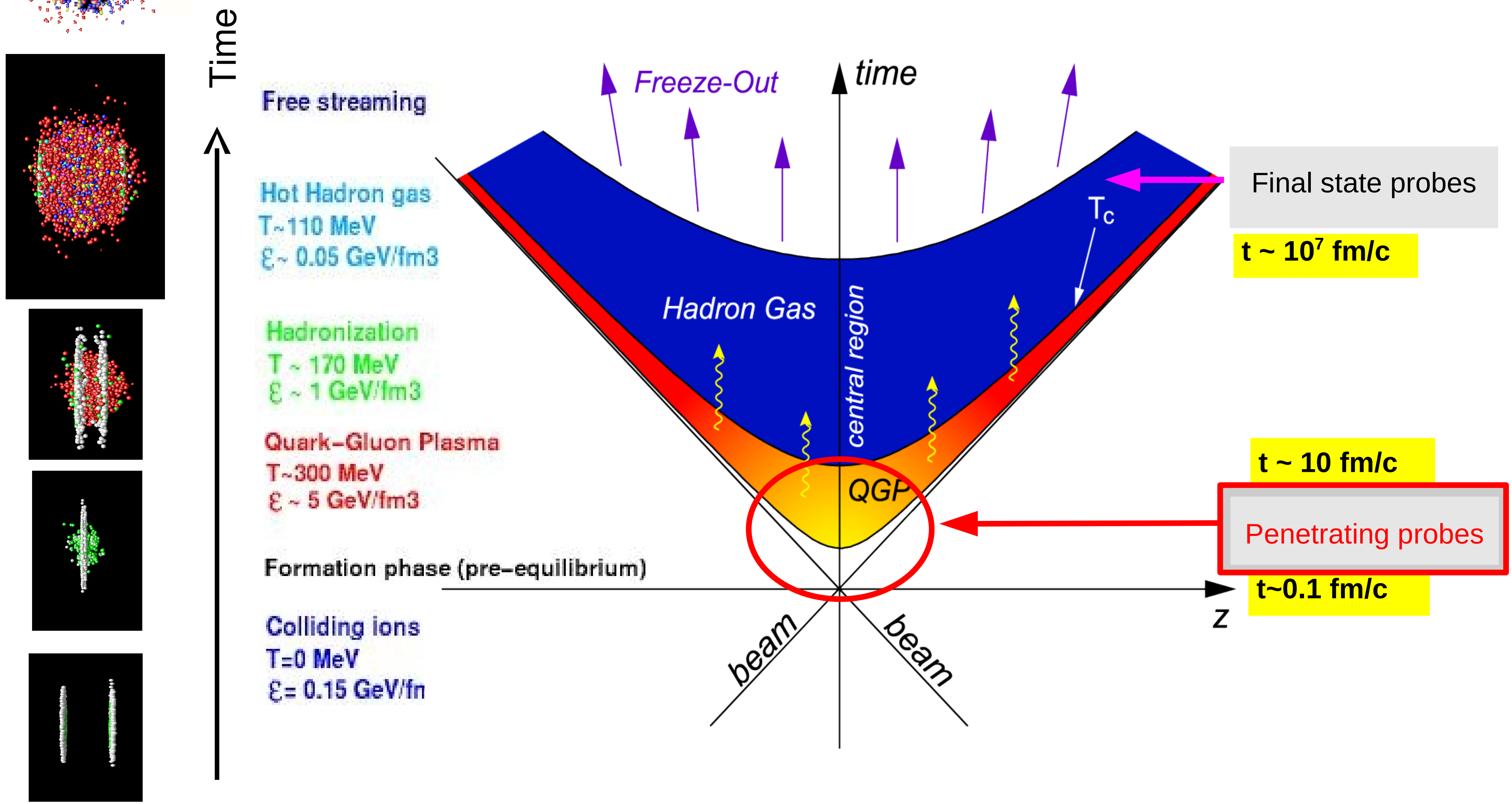


- formation of color neutral clusters at small densities
- particle number/cluster rises
- critical density at maximal overlap ($n \approx 2\text{fm}^{-3}$ or ~1 GeV/fm^3)

QGP production in high-energy nuclear colls.

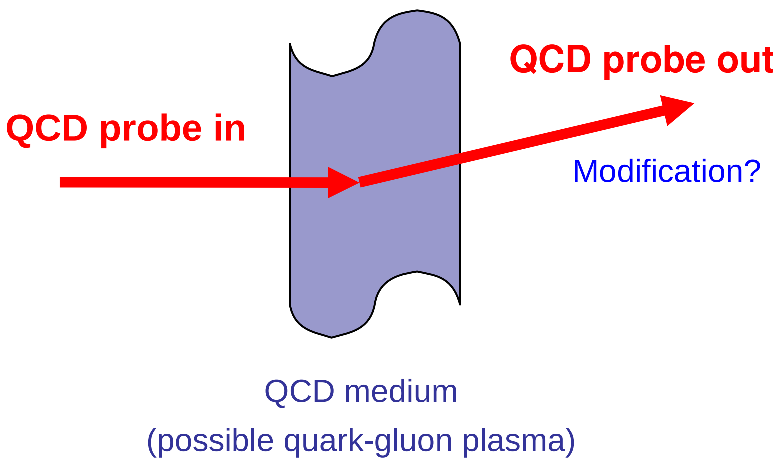


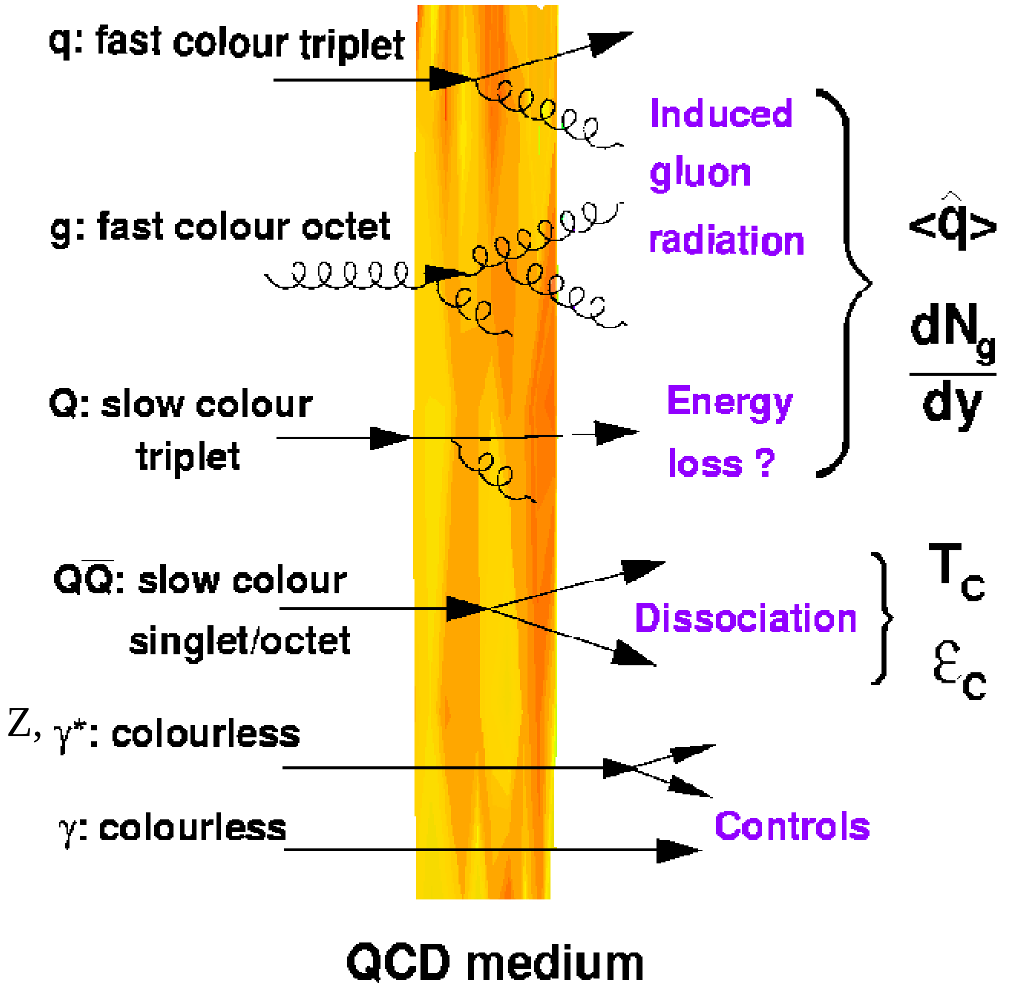
- HE A-A colls. produce expanding QGP: V~$O(10^3 \text{ fm}^3)$ for τ~10 fm/c
- Collision dynamics: Diff. observables sensitive to diff. reaction stages



Hard particles: “tomographic” probes of QGP

- Hard-probes of QCD matter:
  - ♦ large-Q^2 (p_T,m>2 GeV/c): jets, γ, $Q\bar{Q}$ ... well controlled exp. & theoretically (pQCD)
  - ♦ early-time production: self-generated in collision at τ<1/Q~0.1 fm/c
  - ♦ tomographic probes of hottest & densest phases of medium .





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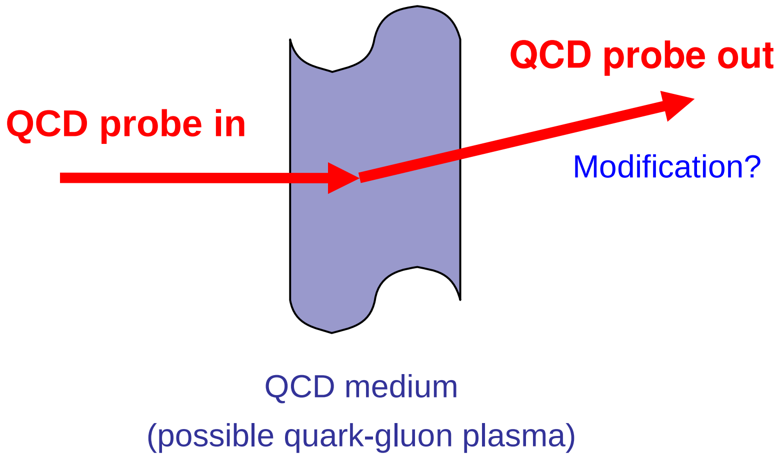
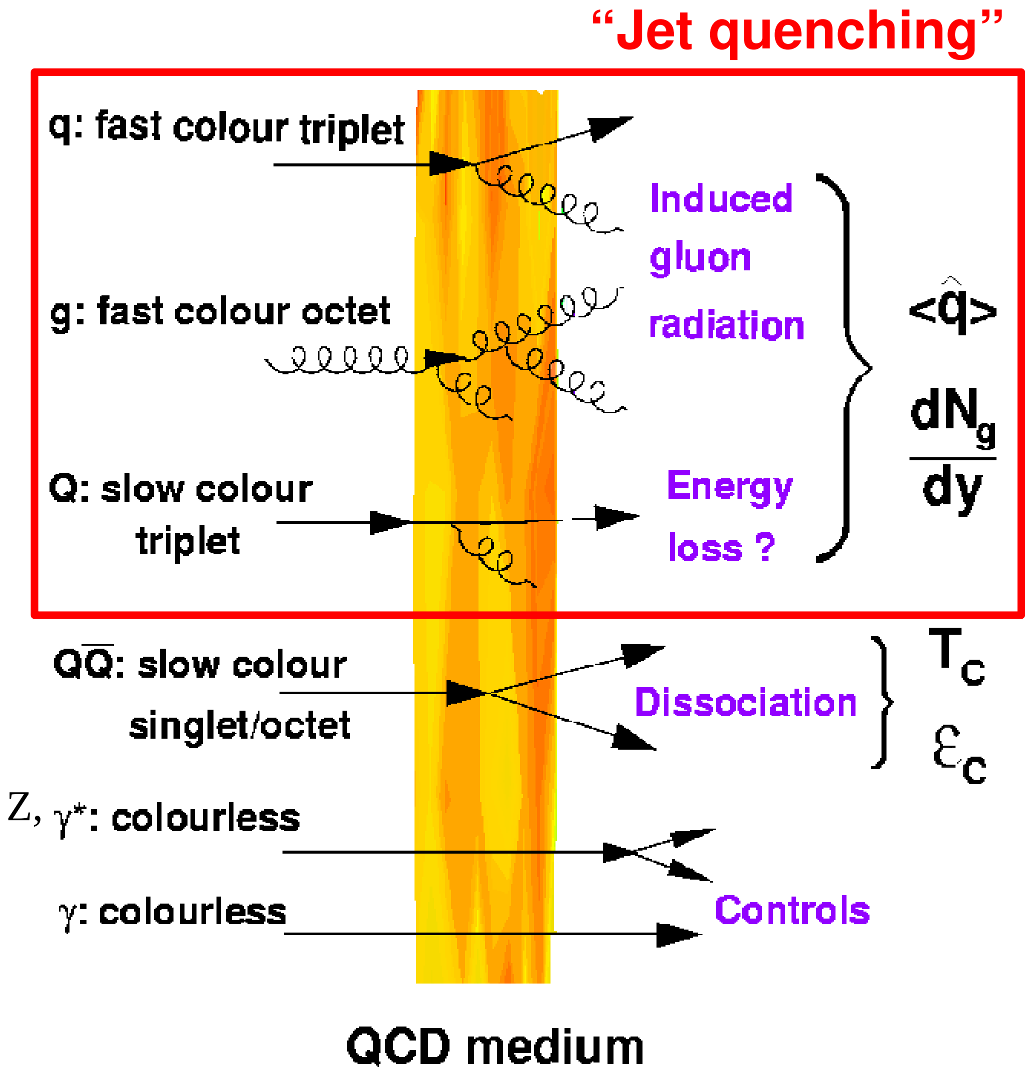
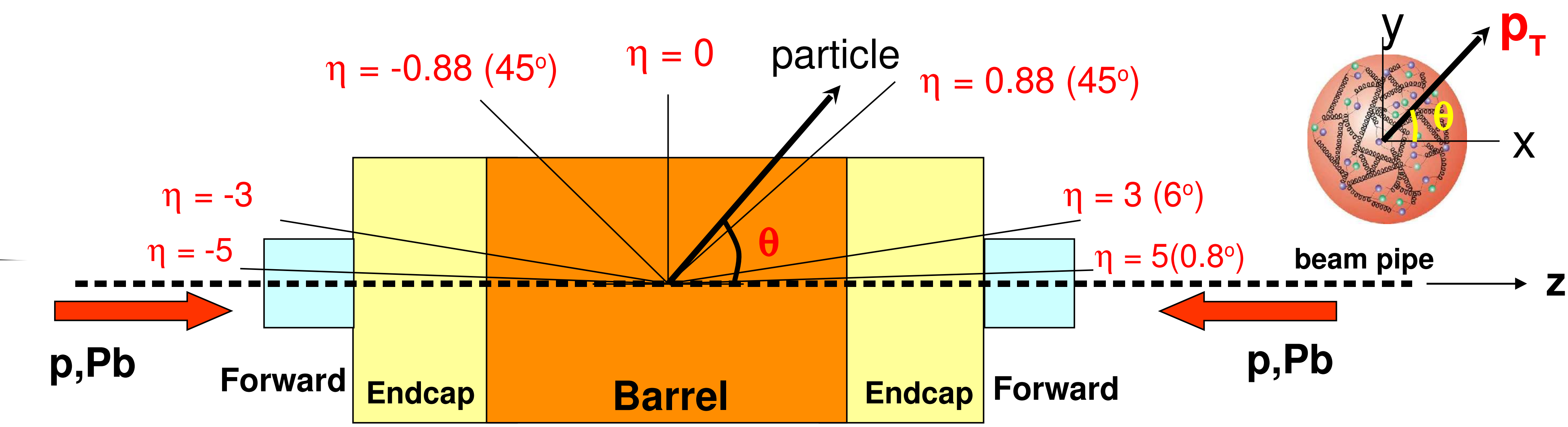




Kinematics A-A collision (reminder)

- Nucleus = "beam" of partons with p_T~0 and fractions ($x_{Bjorken}$) of p_L



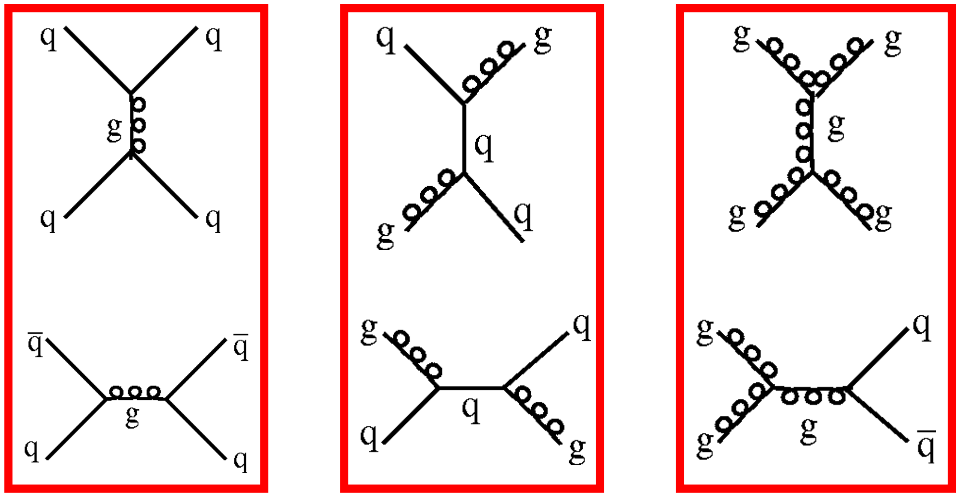
- Transverse momentum: $\mathbf{p}_T = (p_x, p_y) \quad |\mathbf{p}_T| = p\,\sin(\theta)$
- Rapidity: $y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$ (Differences in rapidity conserved under boosts in z-direction: $y' = y - y_{cm}$)

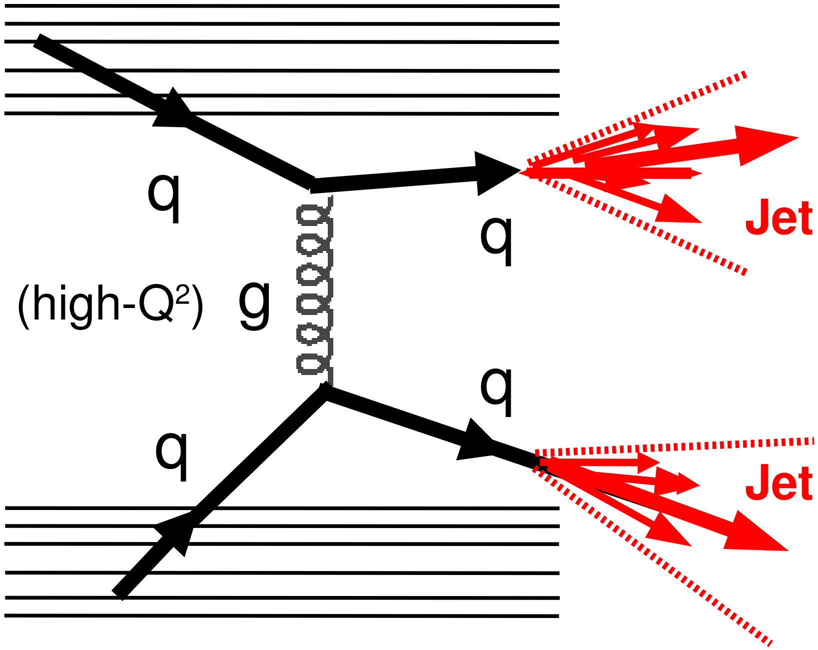
  Pseudorapidity: $\eta = -\ln[\tan(\theta/2)]$ (η~y if E≫m, and θ not too small)
- Azimuthal angle φ: Particles normally (not always!) produced ~isotropically

Jet quenching in the QGP

What is a "jet" ?

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg (also partons/jets produced in decays of heavy particles)
- Jet production processes (leading order):



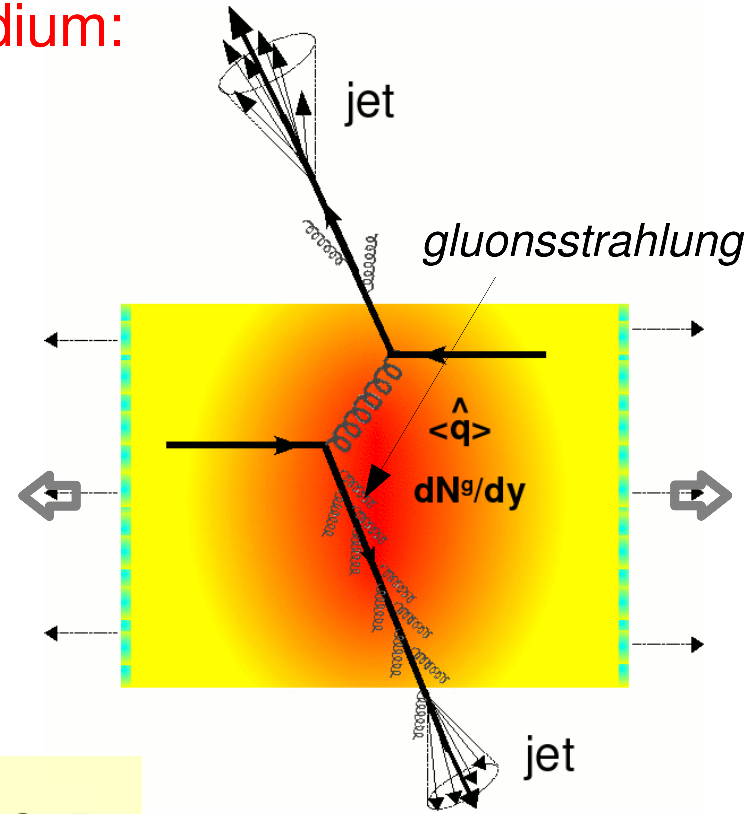


Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet: Collimated spray of hadrons in a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \sim 0.4 - 1$. with total 4-momentum of original fragmenting parton: $p_{T,parton} = \Sigma\, p_{T,hadrons}$

What is "jet quenching" ?

- Parton radiative energy loss: multiple gluon radiation off the produced hard parton induced by the dense QCD medium:



- Energy loss ➠ Medium properties:

$$\Delta E_{\text{GLV}} \propto \alpha_S^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L$$

$$\langle \Delta E \rangle_{\text{BDMPS}} \propto \alpha_S C_R \langle \hat{q} \rangle L^2$$

∝ ($\hat{q}$, gluon density, $L^{(2)}$)

- $\hat{q}$ transport coefficient:

medium "scattering power" $\hat{q} \equiv m_D^2 / \lambda = m_D^2 \rho \sigma$

Debye mass ~ gT; medium density; parton-parton x-section

~0.62GeV2*15fm-3*9mb

- Flavour-dependent energy loss: $\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

(color factor) (dead-cone effect)

q-hat transport coefficient (estimate)

- $\hat{q}$ transport coefficient characterizes the medium "scattering power:

$$\hat{q} \equiv m_D^2/\lambda = m_D^2 \rho \sigma$$

parton-parton x-section

medium density

Debye mass (~ gT): mimimum momentum of plasma particles

- Consider a gluon plasma at T~0.4 GeV, α_s~0.5:

$$\rho_g = 16/\pi^2 \zeta(3) \cdot T^3 \approx 15 \text{ fm}^{-3}$$

$$\text{Debye mass}: m_D = (4\pi\alpha_s)^{1/2} T \approx 1 \text{ GeV}$$

$$\sigma_T^{gg} \simeq 9\pi\alpha_s^2/(2m_D^2) \approx 9 \text{ mb} \quad \text{(LO)}$$

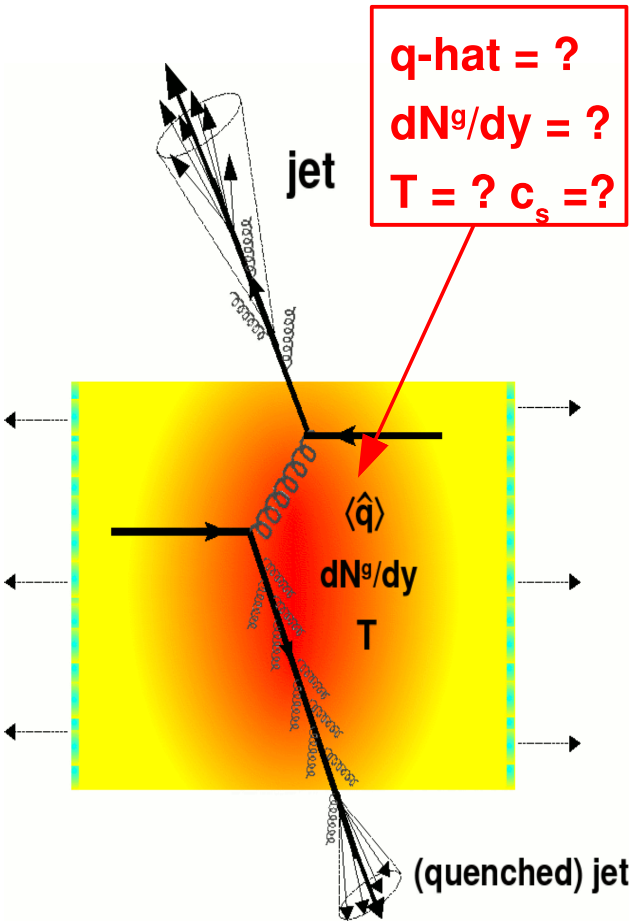
$$\hat{q} \simeq m_D^2/\lambda_g \simeq 2.2 \text{ GeV}^2/\text{fm}$$

$$\lambda_g = 1/(\rho_g \sigma_T^{gg}) \simeq (18/\pi^2 \zeta(3) \alpha_s T)^{-1} \simeq 0.45 \text{ fm}$$

$$\lambda_q = 9/4 \lambda_g \approx 1 \text{ fm}$$

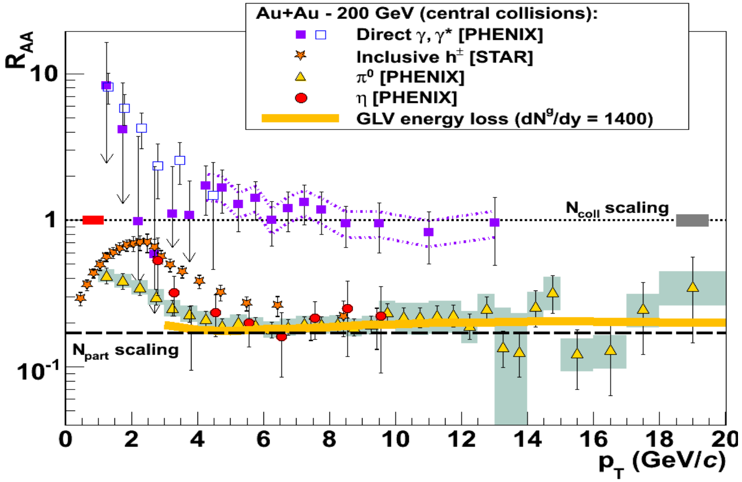
Note: multiply by
hbar·c= 0.2 GeV·fm
to get right units !

Lectures overview

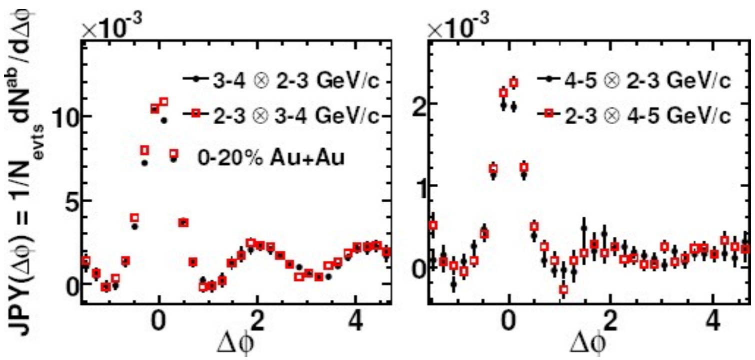


Hot/dense QCD matter properties via "jet quenching"

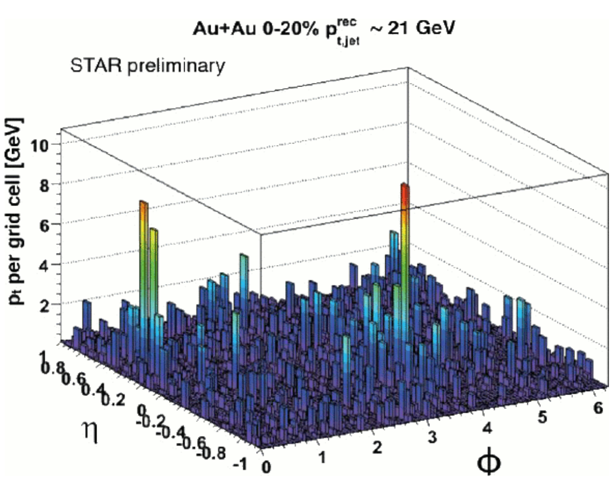
- Suppressed high-p_T hadron spectra:



- Modified high-p_T dihadron $\Delta\phi$-η correlations:



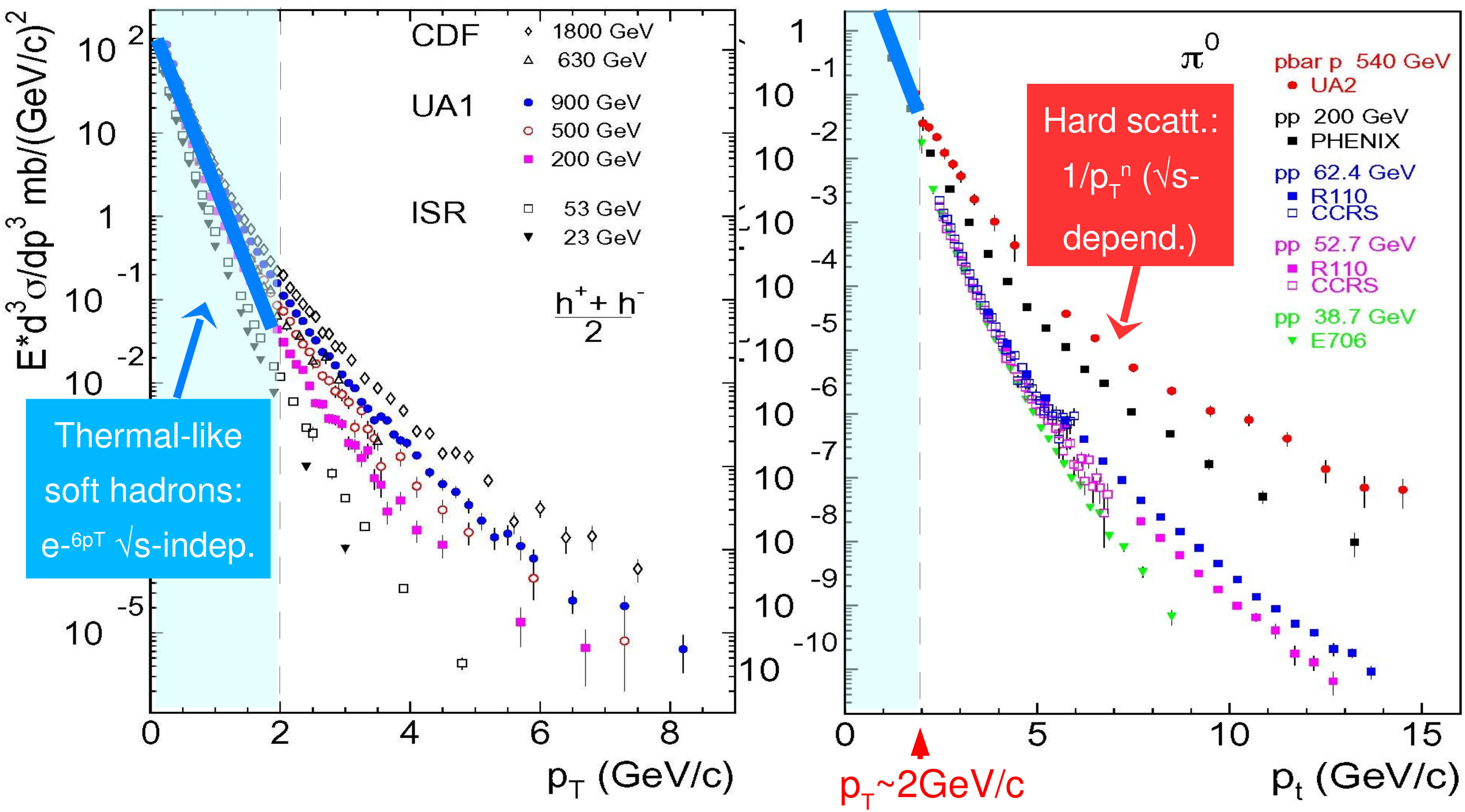
- Full jet reco, γ-jet, modified Fragm. Functions:



I. High-p_T leading hadron spectra

High p_T (leading) hadrons

- Above p_T~ 2 GeV/c: spectra dominated by fragmentation hadrons carrying a large fraction of parent parton p_T : $\langle z \rangle = p_{had}/p_{parton}$ ~ 0.5 – 0.7



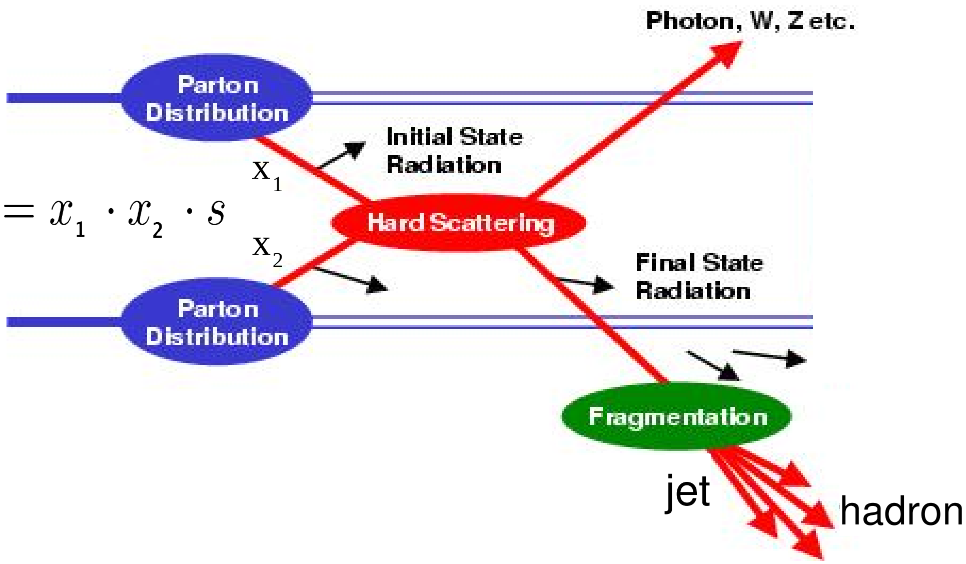
High-p_T hadro-production: pQCD factorization

- Cross section = convolution of 3 terms:

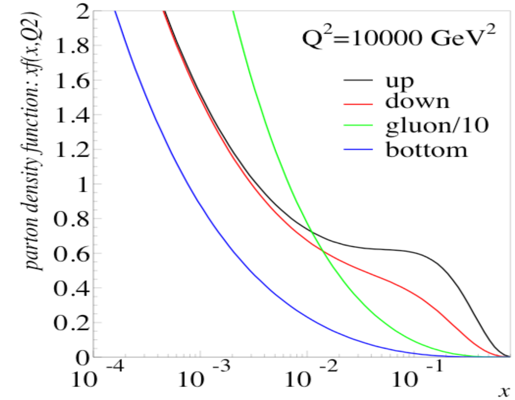
1 short-distance (pQCD $\sigma_{\text{parton-parton}}$) & 2 long-distance (PDF, FF)

$$\sigma^{AB\to h} = f_A(x_1,Q^2)\otimes f_B(x_2,Q^2)\otimes\sigma(x_1,x_2,Q^2)\otimes D_{i\to h}(z,Q^2)$$

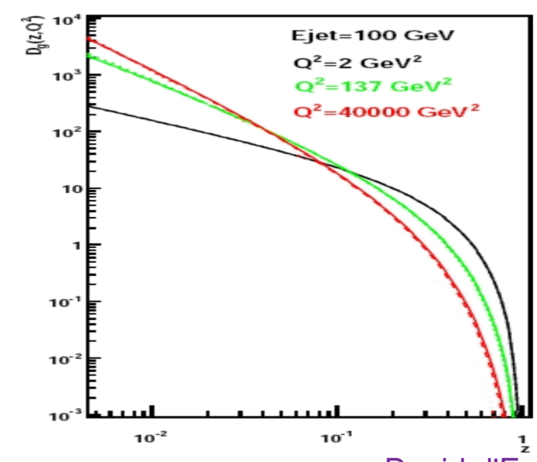
$$\hat{s} = x_1 \cdot x_2 \cdot s$$



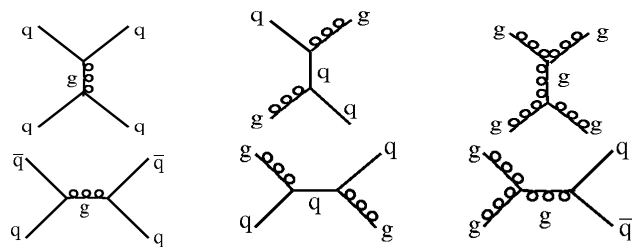
(1) Hadron = collection of partons described by PDFs(x,Q^2):



(3) Parton (jet) fragmentation into hadrons described by a FF(z,Q^2):



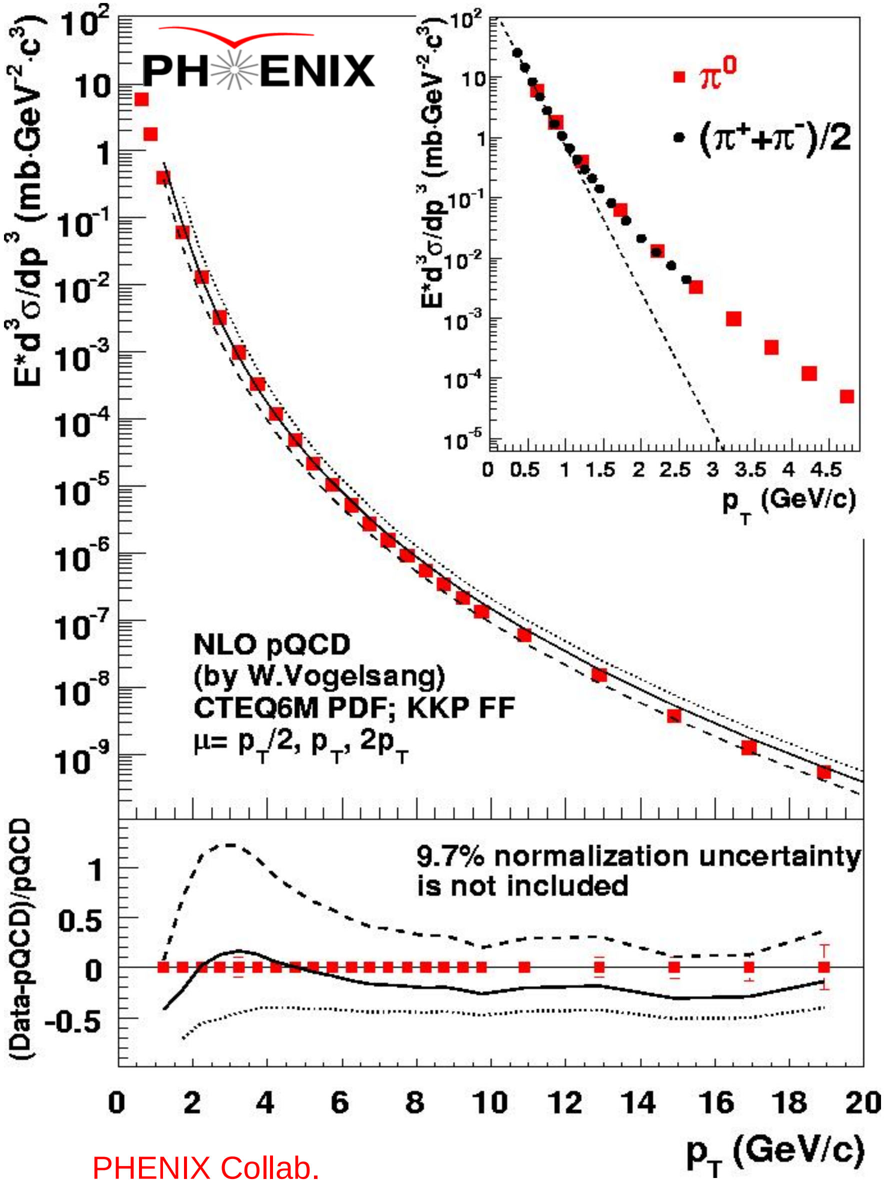
(2) High-Q^2 parton-parton x-sections computed perturbatively at a given $\mathcal{O}(\alpha_s)$:



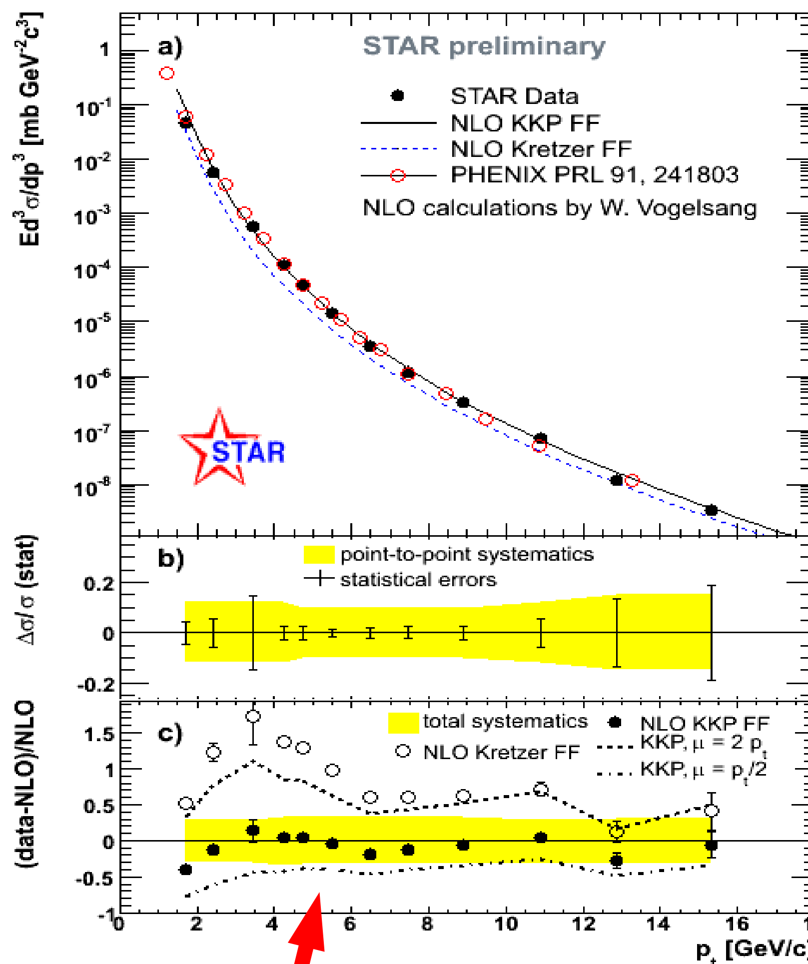
High-p_T hadron spectra: p-p @ 200 GeV

- High p_T hadron spectra very well described by NLO pQCD:

M. Russcher, QM06



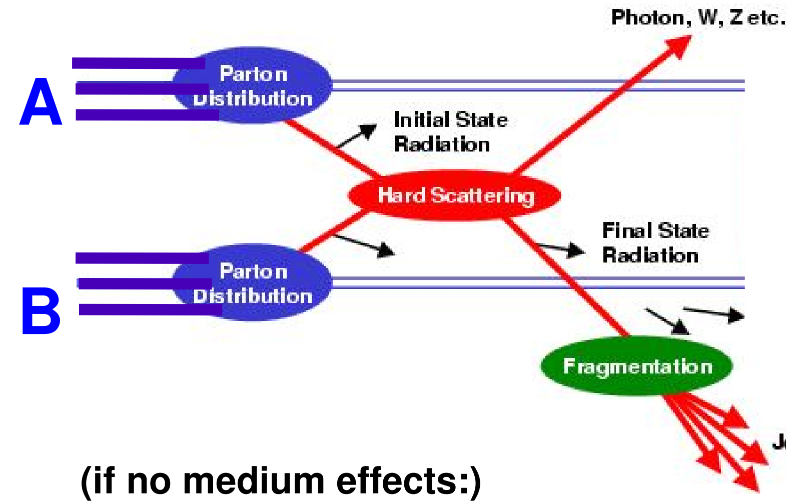
PHENIX Collab.
PRD76, 051106(R) (2007)



- Data sensitive to different parametrizations of gluon FF

High-p_T hadro-production: A-A collisions

- QCD factorization for nuclear collisions:



$$\sigma^{AB\to h} = f_A(x_1,Q^2) \otimes f_B(x_2,Q^2) \otimes \sigma(x_1,x_2,Q^2) \otimes D_{i\to h}(z,Q^2)$$

- Nuclear PDFs:

A-B = "simple superposition of p-p collisions"

nPDF = independent sum of "free" partons:

$$f_{a/A}(x,Q^2) = A\, f_{a/p}(x,Q^2)$$

(if no medium effects:)

$$d\sigma_{AB\to hard} = A\cdot B\cdot d\sigma_{pp\to hard}$$

$$d\sigma_{AB\to hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\to hard}$$

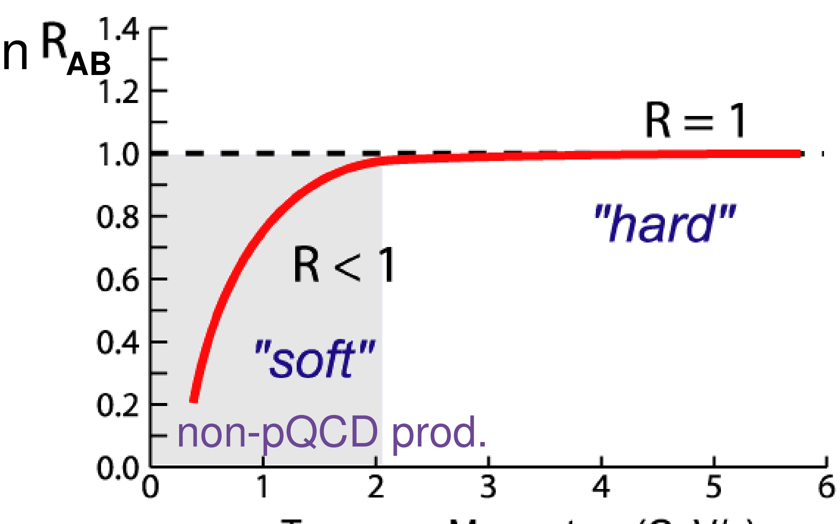
(nuclear overlap at b)

- Nuclear FFs:

Energy loss in QGP: modified DGLAP evolution of vacuum-FFs: $D(z',Q^2)$, $z'\sim z-\delta\varepsilon_{loss}$

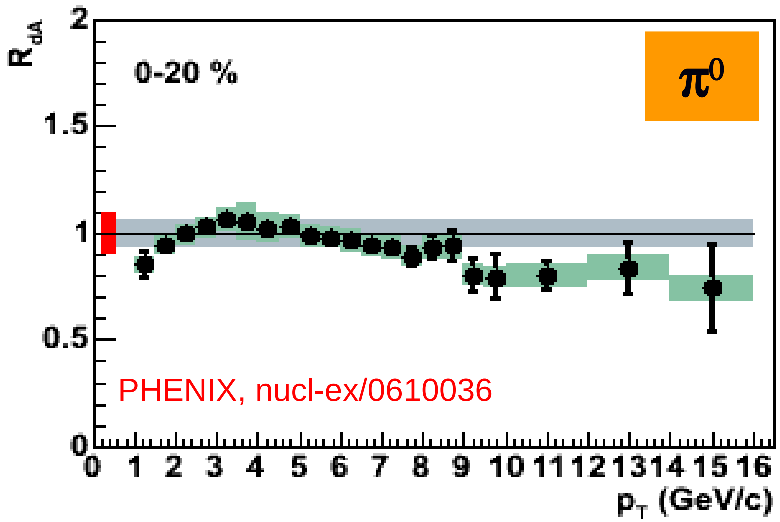
- Nuclear modification factor:

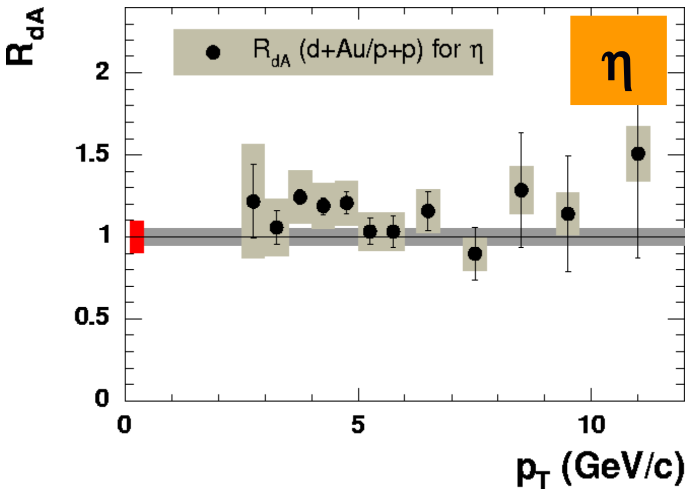
$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$



High p_T hadrons in d-Au @ 200 GeV: R_{dAu}~1

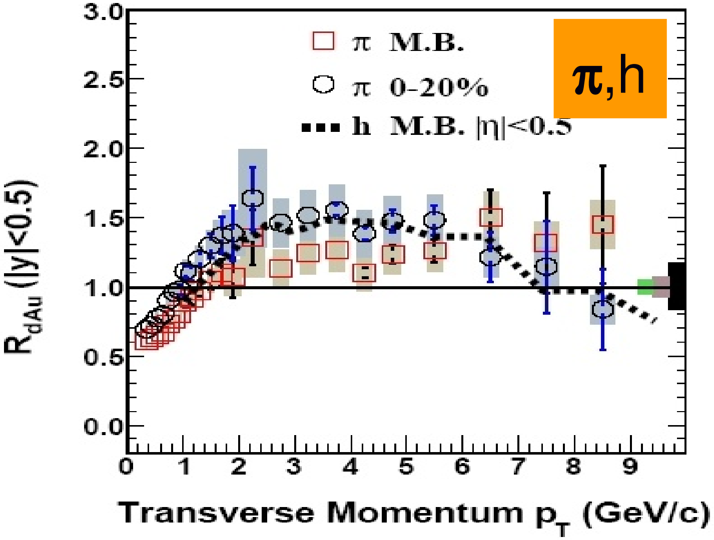
- ~20% "cold nuclear matter" modifications: nPDF (anti)shadowing,Cronin





PHENIX, nucl-ex/0611006

- Only protons (factor ~2 enhancement) deviate from "vacuum" production



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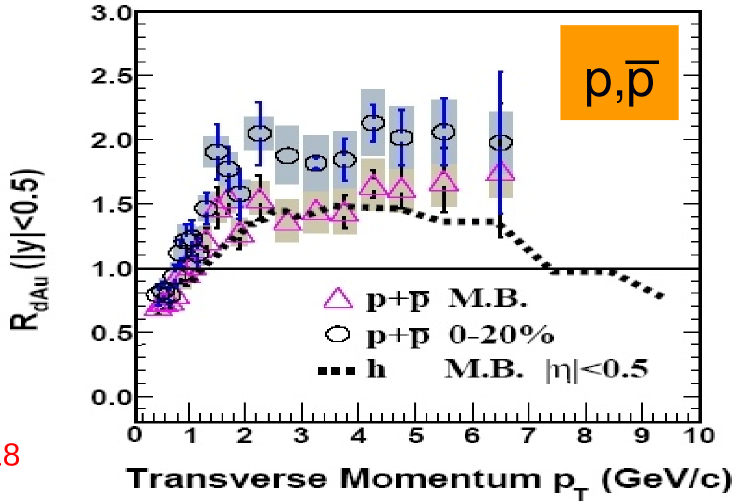
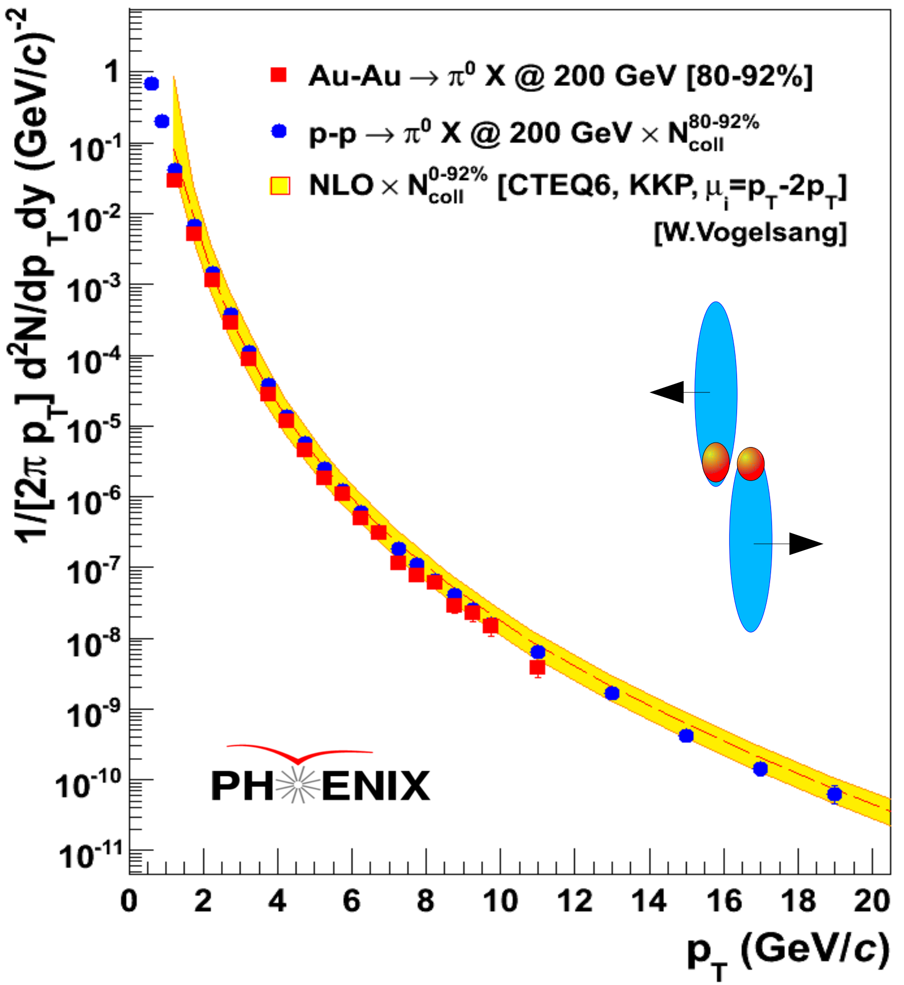


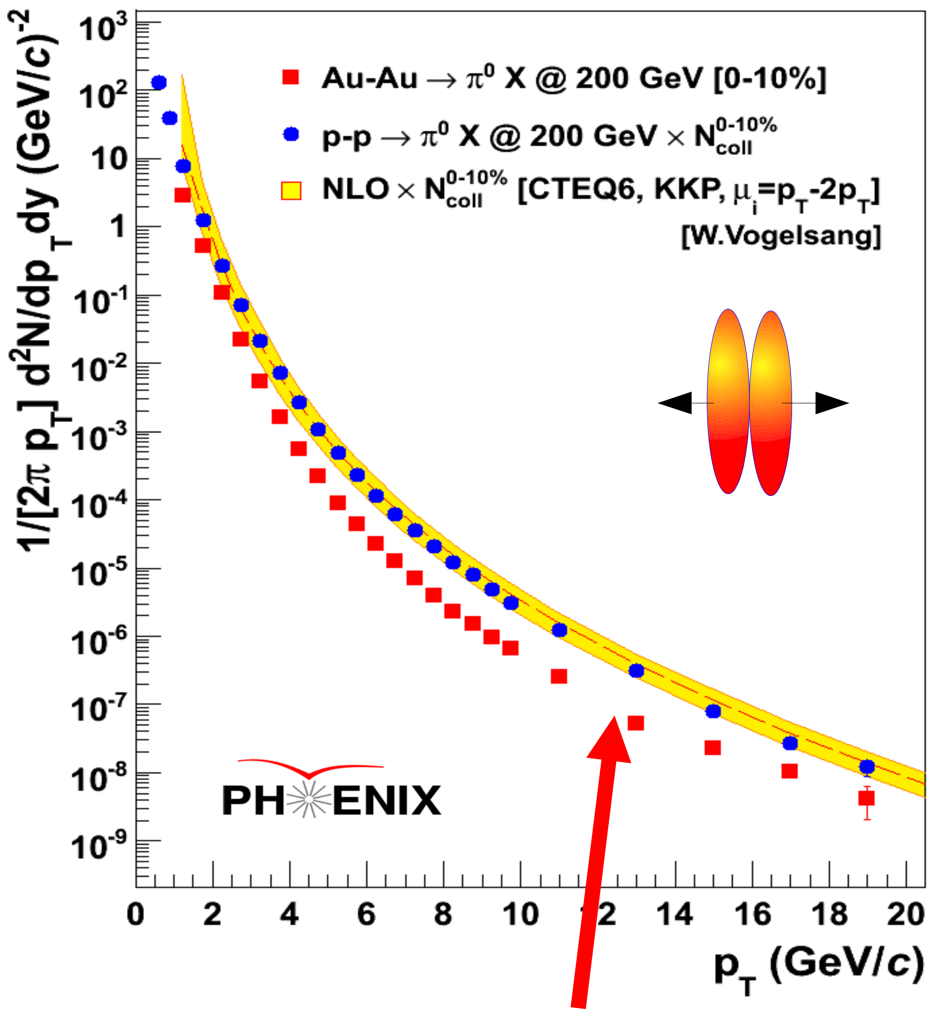
High p_T hadrons in Au-Au @ 200 GeV: $R_{AA} \ll 1$

Au+Au→ $\pi^0 X$ (peripheral)



Peripheral data agree well with p+p (data&pQCD) plus N_{coll} scaling

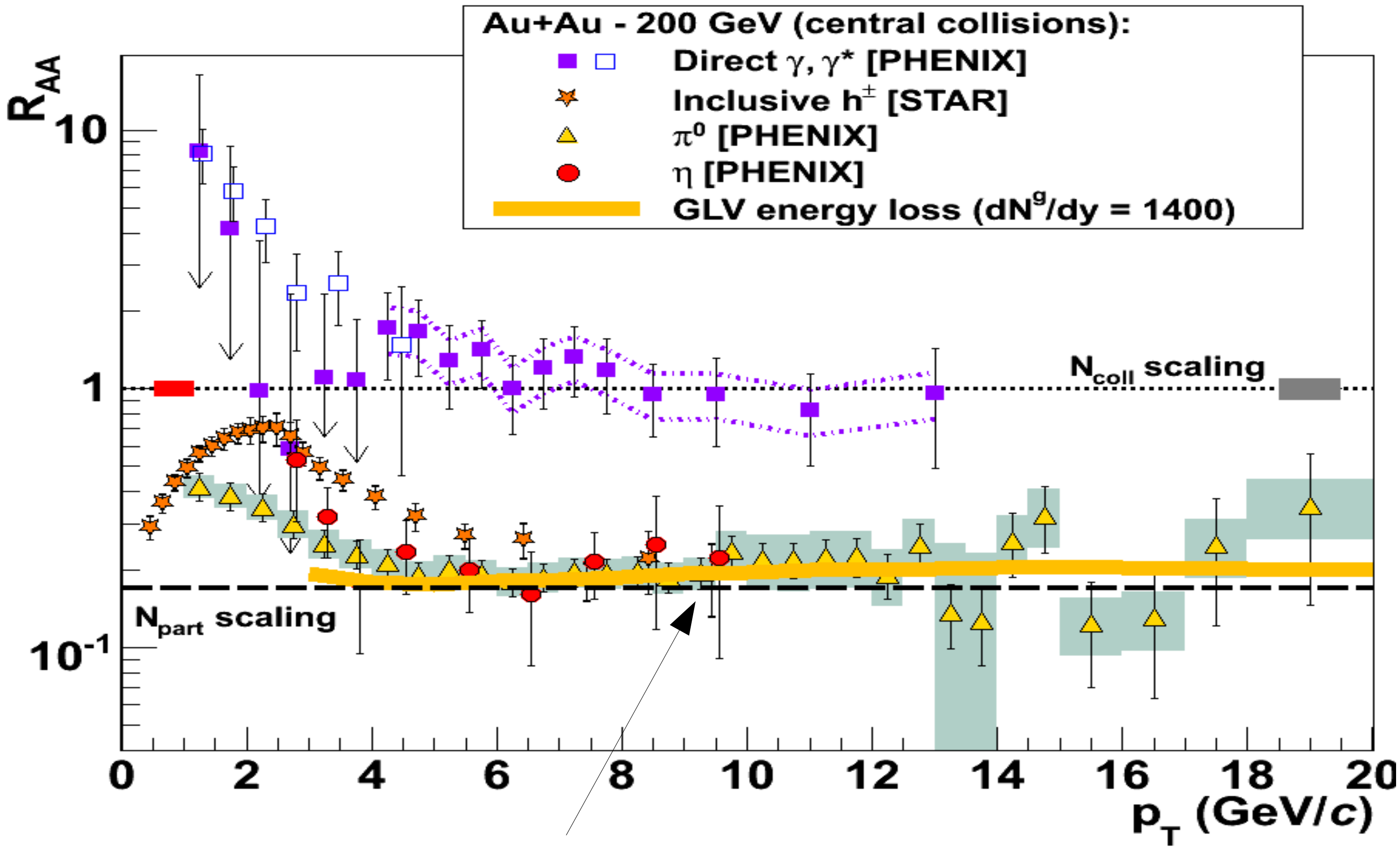
Au+Au→ $\pi^0 X$ (central)



Strong suppression in central Au+Au collisions !

High p_T suppression in Au-Au @ 200 GeV: R_{AA}~0.2

- Photons are unsuppressed but $\pi^0,\eta,h^\pm$ show a common suppression pattern (magnitude, p_T, centrality, ...):



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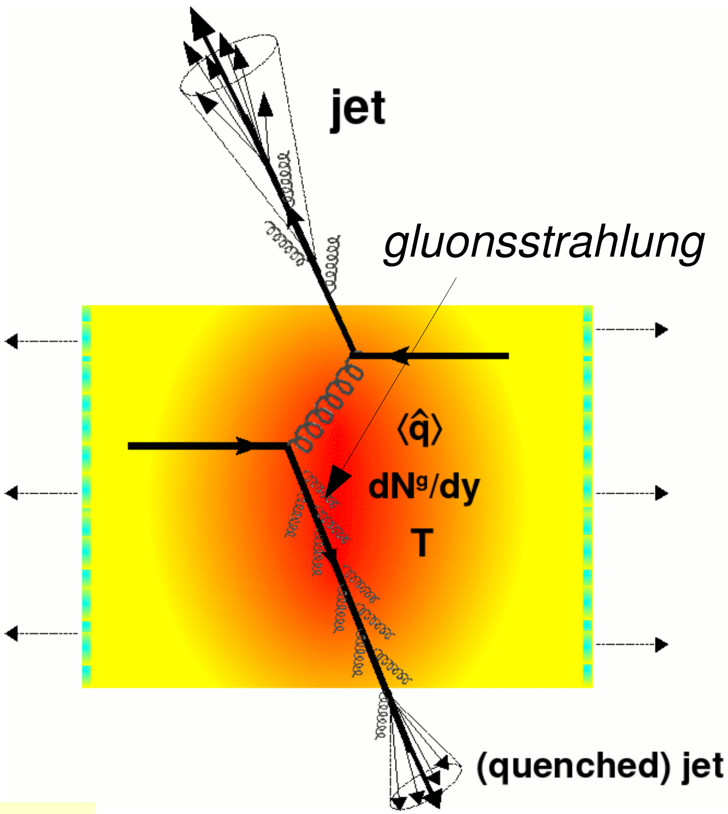
PRL 96, 202301 (2006)

- Only hadrons produced in "surface" escape (N_{part} scaling): R_{AA} ~ 0.2
- Universal suppression consistent with quenching at partonic level prior to q,g fragmentation into leading hadrons according to vacuum FFs.

Parton E-loss ⇒ High p_T suppression (let's test that ...)

- Multiple gluon radiation off the produced hard parton induced by the dense QCD medium:



- Energy loss ➠ Medium properties:

$$\Delta E_{GLV} \propto \alpha_S^3 C_R \frac{1}{A_\perp}\frac{dN^g}{dy} L$$

$$\langle \Delta E \rangle_{BDMPS} \propto \alpha_S C_R \langle \hat{q} \rangle L^2$$

∝ ($\hat{q}$, gluon density, $L^{(2)}$)

- $\hat{q}$ transport coefficient:

medium "scattering power" $\hat{q} \equiv m_D^2/\lambda = m_D^2 \rho \sigma$

parton-parton x-section (σ); medium density (ρ); Debye mass ~ gT (m_D)

- Flavour-dependent energy loss: $\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

(color factor) (dead-cone effect)

High p_T suppression ⇒ QCD medium properties

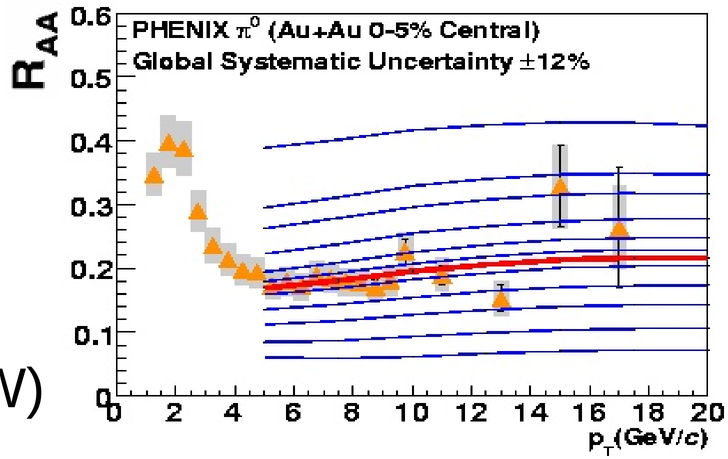
- Medium properties from jet quenching models:

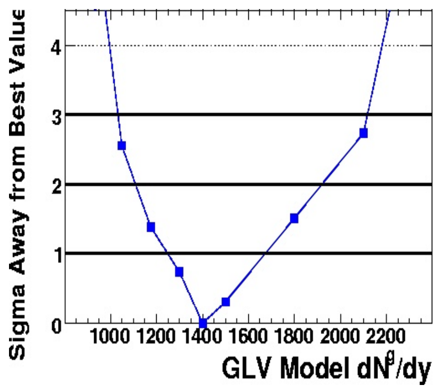
PHENIX, arXiv:0801.1655

Initial gluon density (GLV):

$dN^g/dy = 1400^{+270}_{-150}$

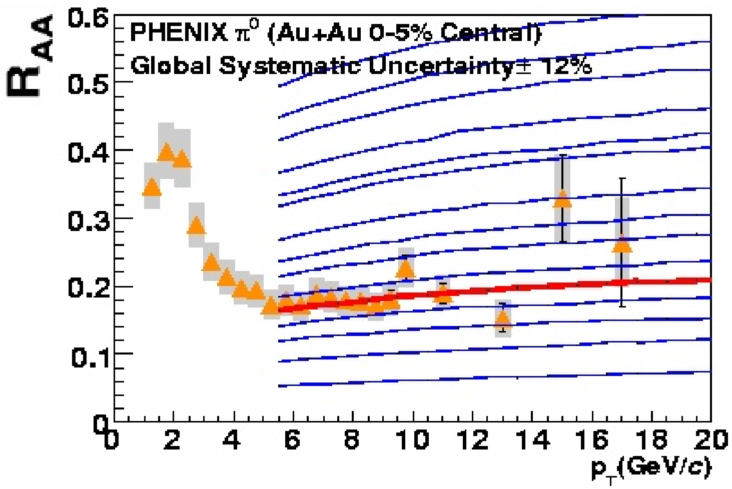
[Vitev & Gyulassy]

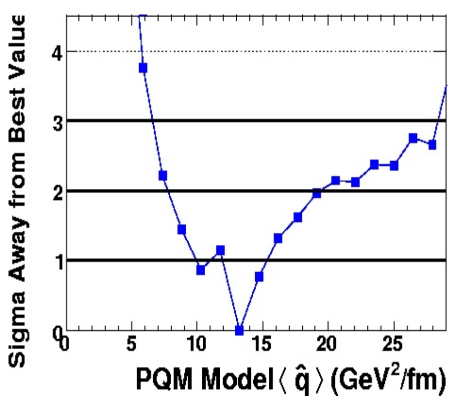




Transport coeffic. (BDMPS/ASW)

$\langle\hat{q}_0\rangle \sim 13.2^{+2.1}_{-3.2}$ GeV²/fm





Yet, other approaches:

$\langle\hat{q}_0\rangle \sim 4$ GeV²/fm

Temperatures [AMY]:

T ~ 0.4 GeV

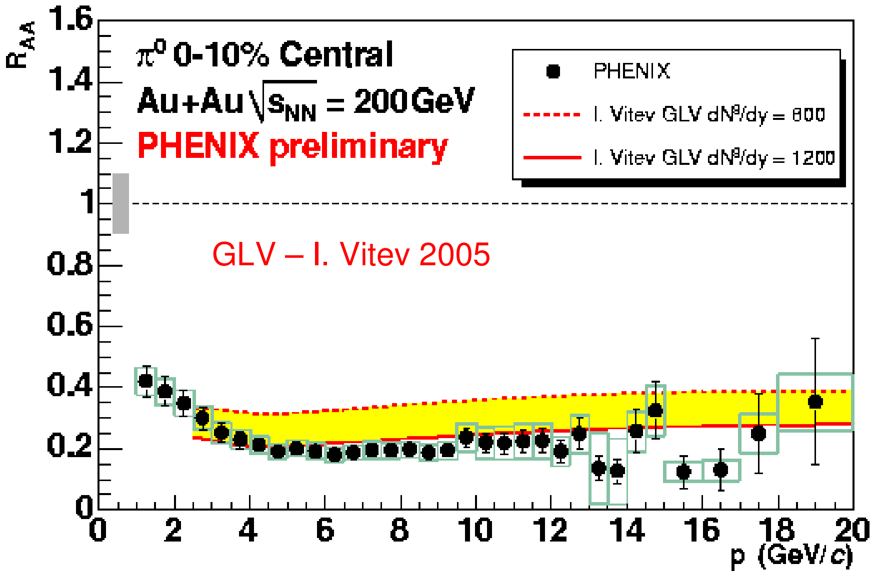
- Within consistent space-time evolution (3D-hydro), diff. calculations agree on q-hat ($\hat{q}\sim\rho$, $dN^g/dy\sim\rho$, $T\sim\hat{q}^{1/3}$) within a factor of ~2-3.

More careful work needed !

Bass-Majumder et al., arXiv:0808.0908

High p_T suppression (I): p_T-dependence ✔

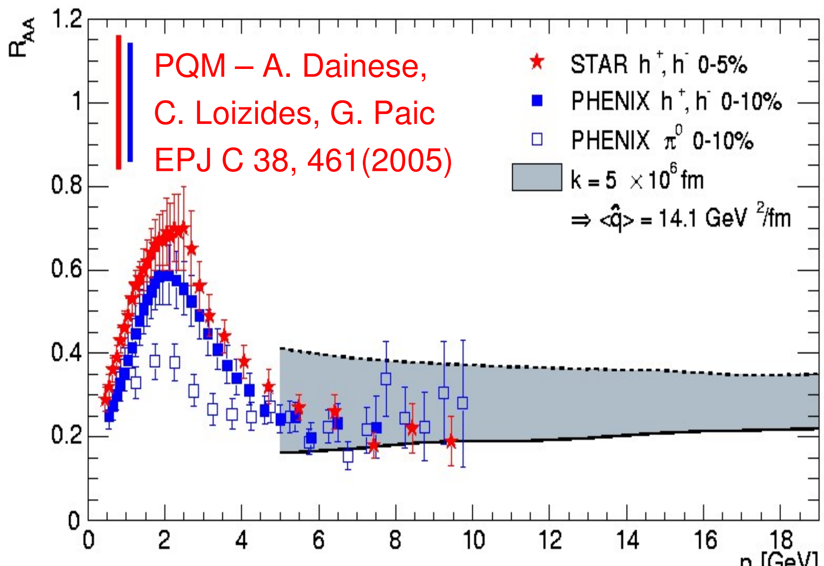
- Energy-dependence of E_{loss} (gluon bremsstrahlung):



$$\Delta E_{rad}^{LPM} \approx \alpha_s C_R \hat{q} L^2 \ln(E/(\hat{q}L))$$

Naively: $R_{AA} \sim \log(p_T)$

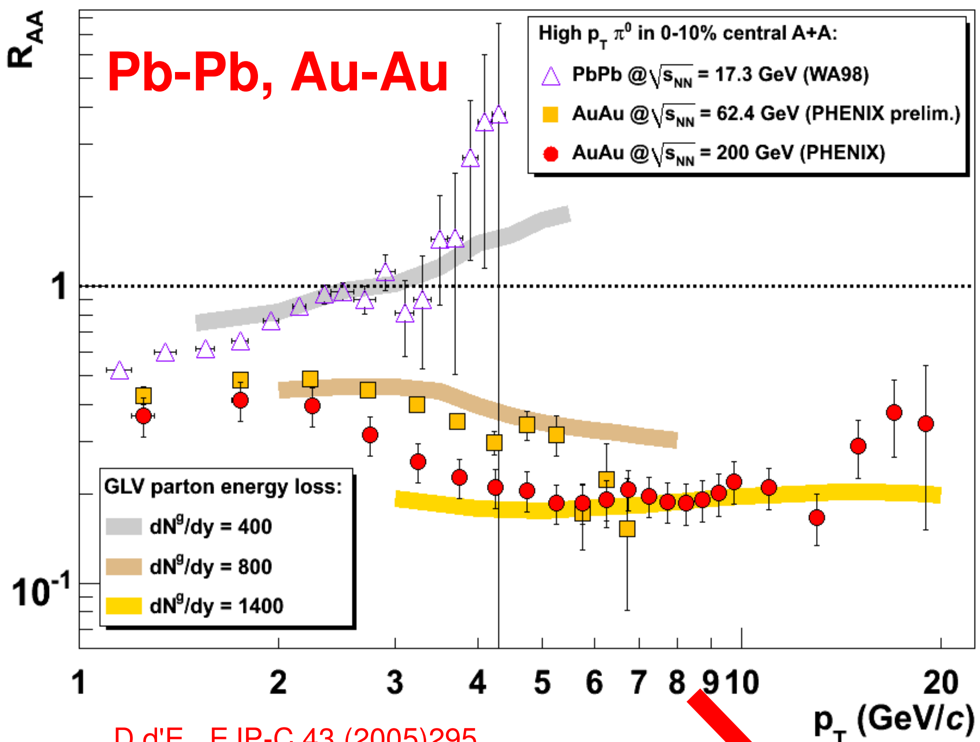
- Flat p_T-dependence (R_{AA}~const) predicted by parton energy loss models:



- Combination of diff. effects (kinematic constraints, local parton p_T slope, nuclear PDFs ...) yields constant quenching factor.

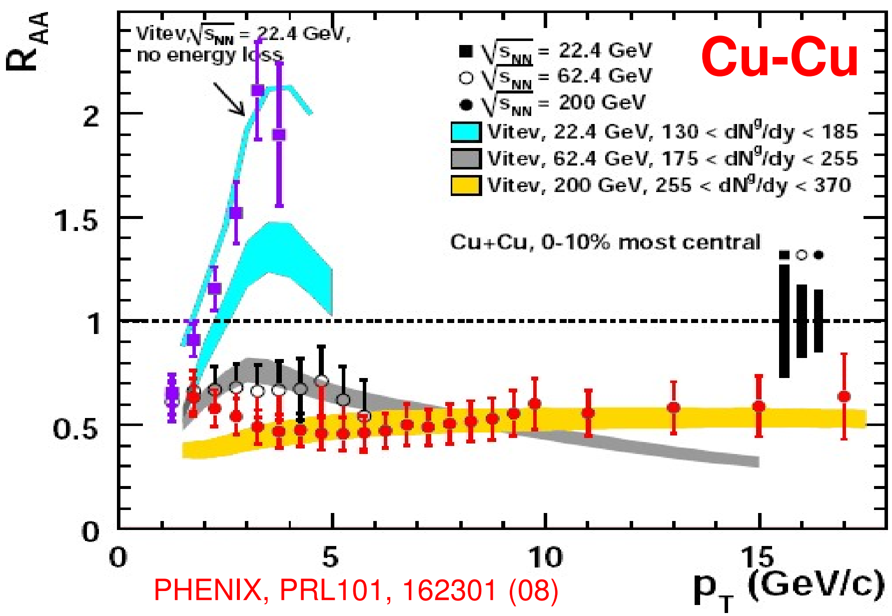
High p_T suppression (II): Excitation function ✔

- sqrt(s)-dependence in agreement with parton energy loss in increasingly dense medium: $\Delta E \propto \alpha_S^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L$



D.d'E., EJP-C 43 (2005)295

(~50% less suppr. in lighter system)



PHENIX, PRL101, 162301 (08)

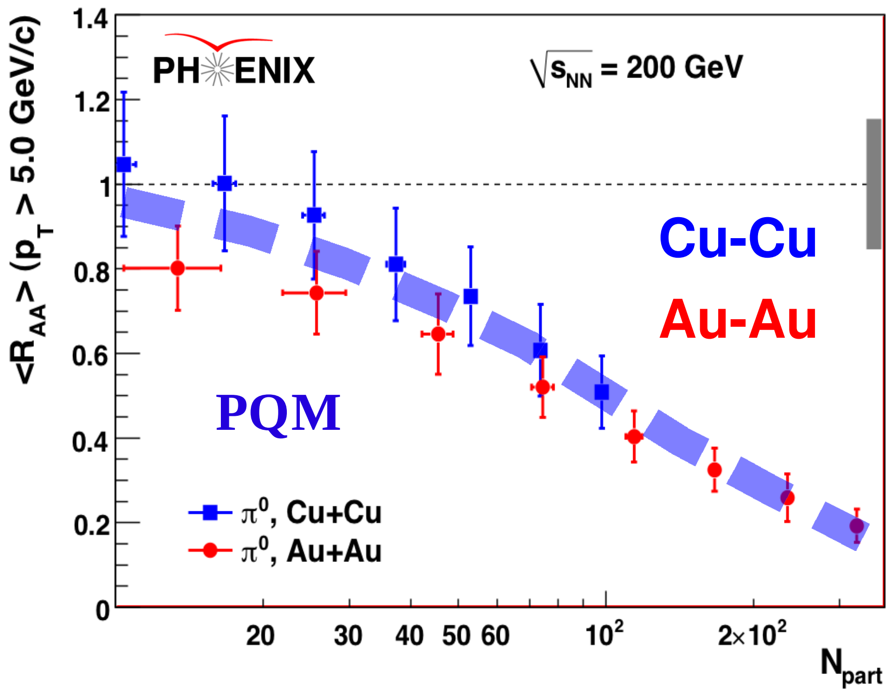
		Initial gluon density:		Medium transport coeff.:
SPS	R_{AA} ~ 1 @ √s ~ 20 GeV ⇒	dN^g/dy ~ 400	,	$\langle q_0 \rangle$ ~ 3.5 GeV²/fm
RHIC	R_{AA} ~ 0.3 @ √s = 62 GeV ⇒	dN^g/dy ~ 800	,	$\langle q_0 \rangle$ ~ 7 GeV²/fm
RHIC	R_{AA} ~ 0.2 @√s =200 GeV ⇒	dN^g/dy ~ 1400	,	$\langle q_0 \rangle$ ~ 14 GeV²/fm

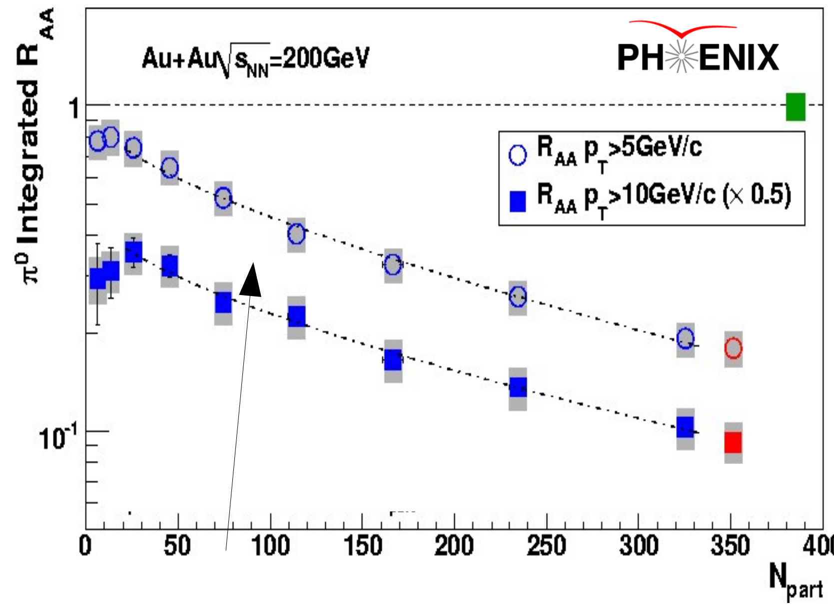
High p_T suppression (III): centrality-dependence ✔

- Increasing centrality ⇒ increased L, ρ ⇒ larger suppression
- Theory: $\Delta E \propto \alpha_S^3 C_R \frac{1}{A_\perp}\frac{dN^g}{dy} L$ ⇒ $\log(R_{AA}) \propto N_{part}^{-2/3}$

PHENIX, arXiv:0801.4020

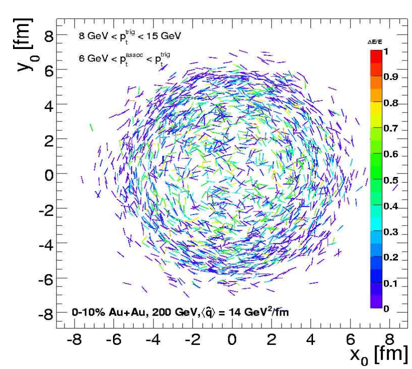
Same suppr. for all systems at equal N_{part}





n_{EXP}~0.58±0.1 consistent with n_{TH}~2/3

- Agreement data ↔ models as expected for suppressions at different geometrical parton production points.



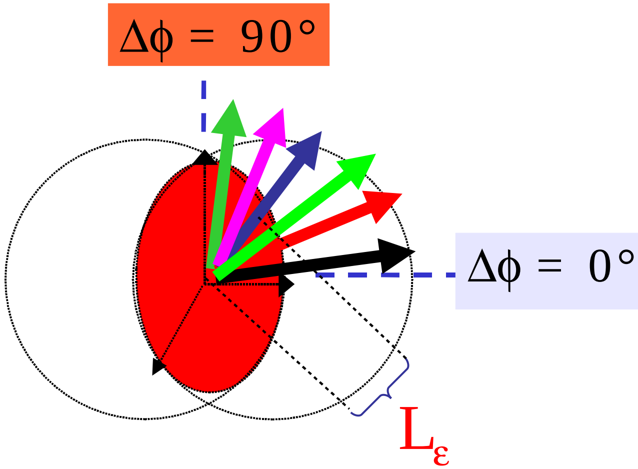
PQM -Loizides
EPJ C 38, 461(2005)

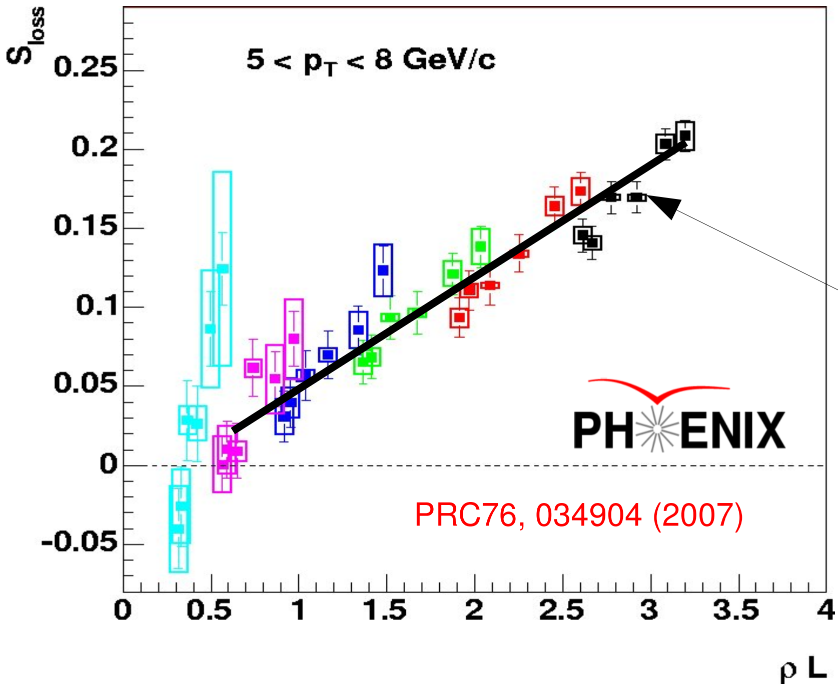
High p_T suppression (IV): path-length dependence ✔

- Parton E_{loss} path-length ∝ L^2 (static), L (expanding):

  Less suppression in-plane ("short" direction)

  More suppression out-of-plane ("long" direction)



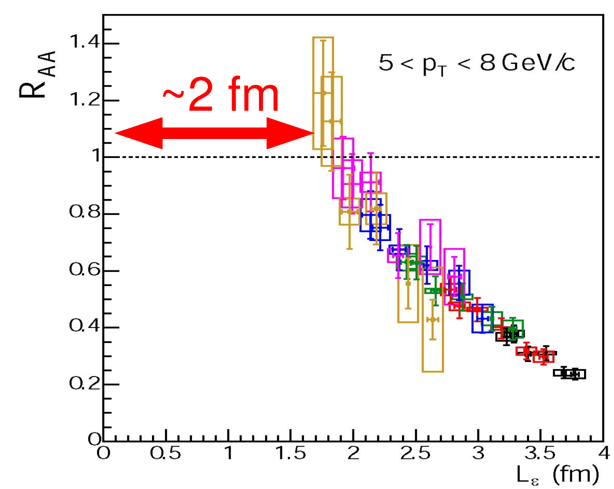


E_{loss} approx. linear with ρL for most centralities,ϕ

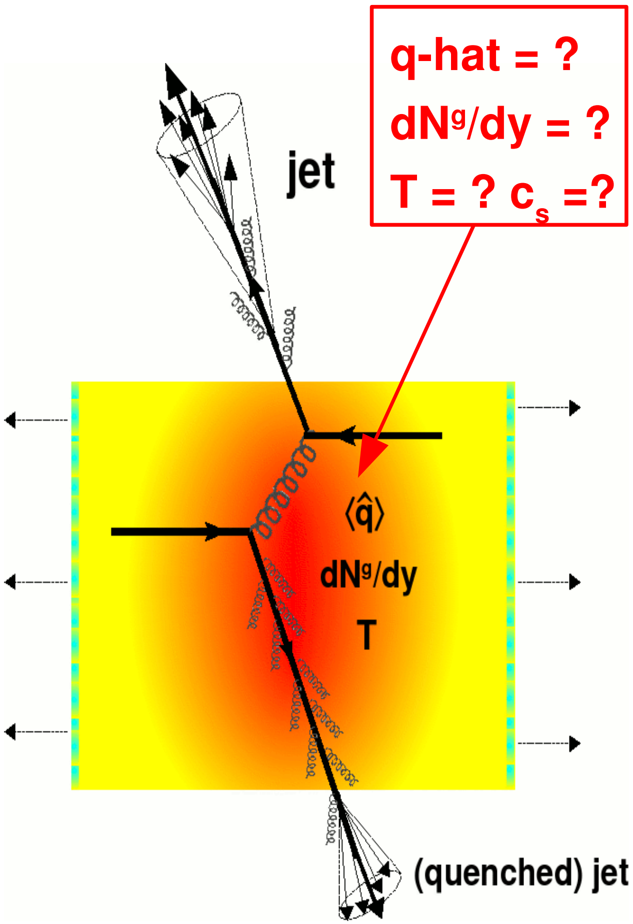
No apparent E_{loss} for L< 2 fm

"Corona effect" effect?

V. Pantuev hep-ph/0506095

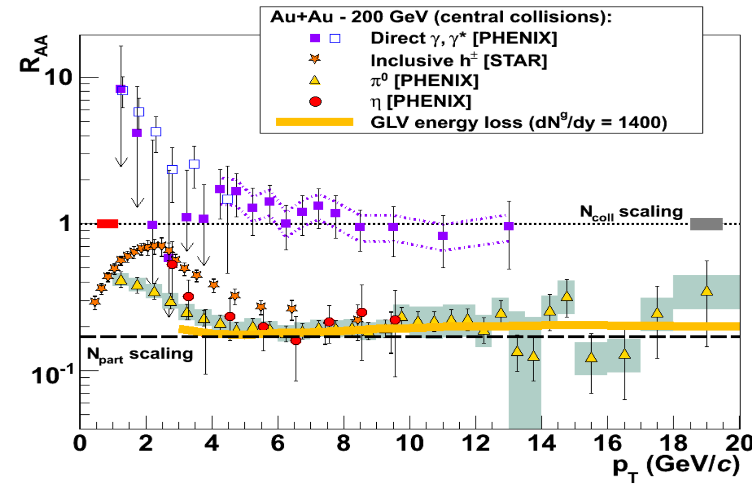


Lectures overview

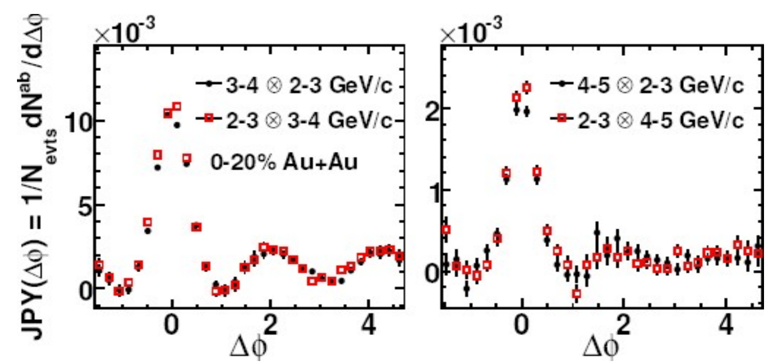


Hot/dense QCD matter properties via “jet quenching”

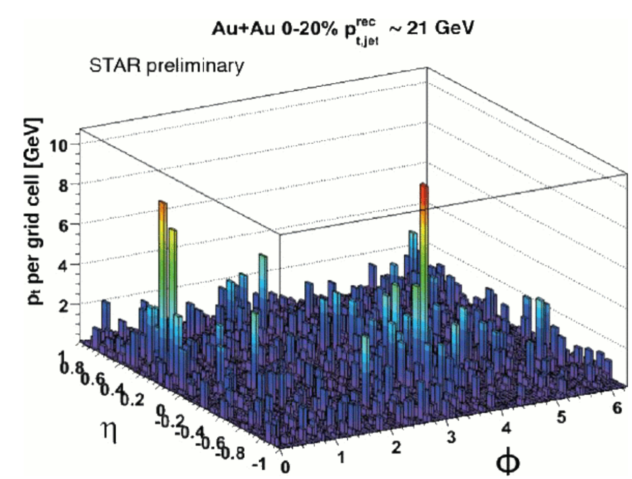
- Suppressed high-p_T hadron spectra:



- Modified high-p_T dihadron Δφ-η correlations:



- Full jet reco, γ-jet, modified Fragm. Functions:



Plan of lectures

1st

0. Introduction: QCD matter, Heavy-ions, jet-quenching

1. High-p_T leading hadron suppression:

- pQCD factorization, quenching factor (R_{AA}): QGP q-hat, dN^g/dy
- $R_{AA}(p_T,\sqrt{s},\text{cent},L,m_q)$: data versus parton energy loss models

2nd

2. High-p_T dihadron correlations

- Away-side suppression: QGP q-hat
- Away-side splitting: QGP speed-of-sound(?)

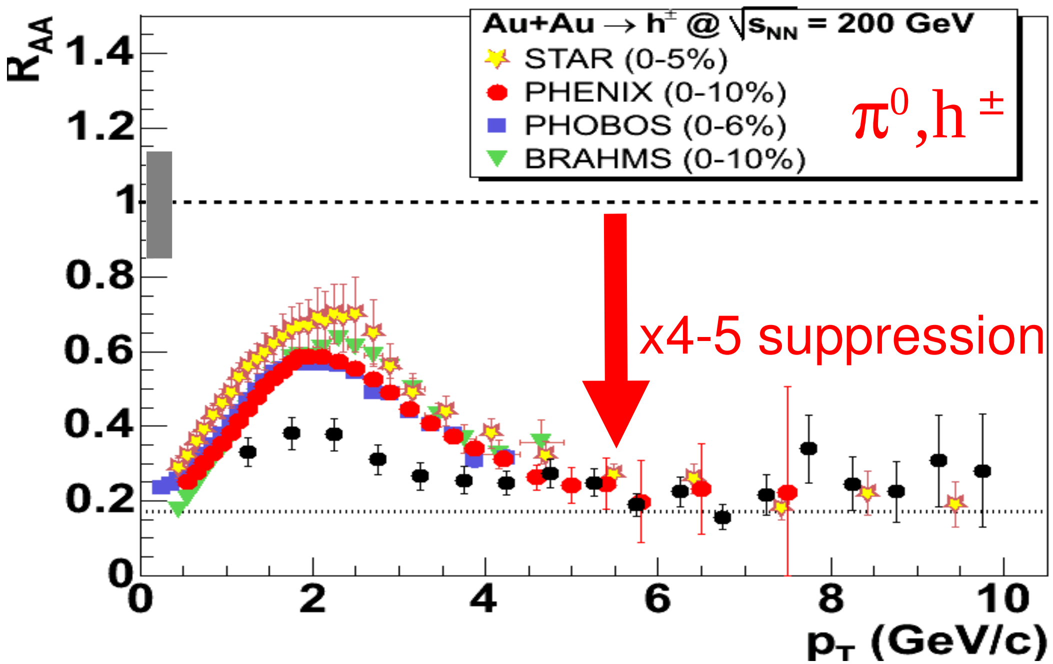
3rd

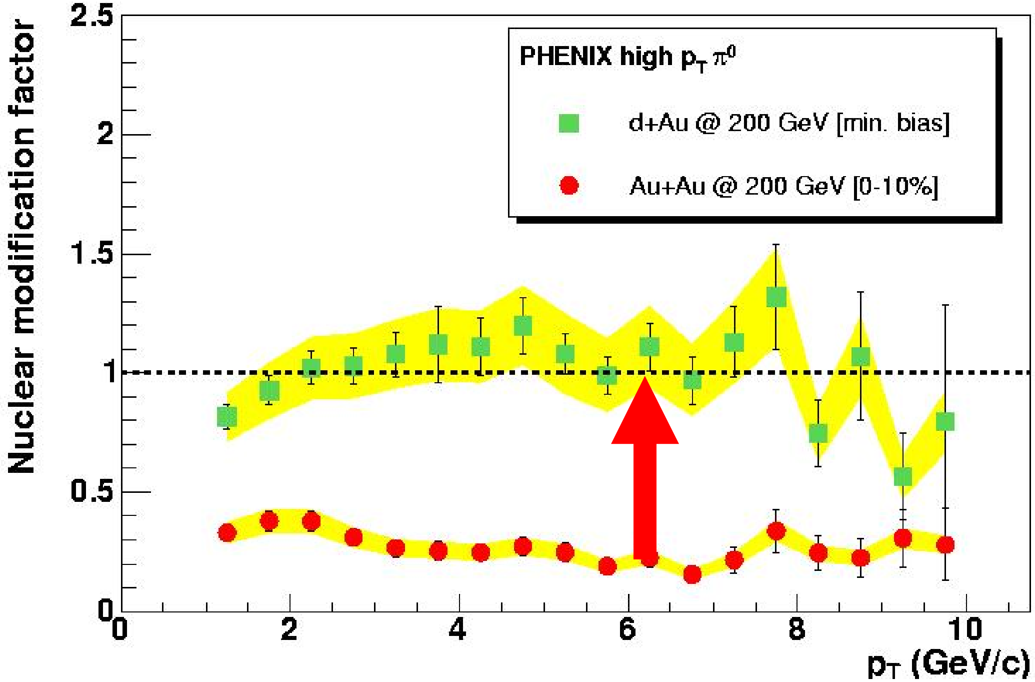
3. Full jet measurements:

- Reconstruction: Clustering algo, bckgd subtraction, corrections
- γ-jet: medium Fragmentation-Functions: QGP q-hat

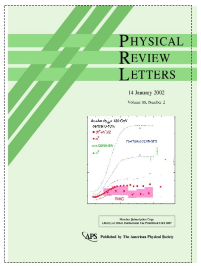
Backup slides

AuAu (dAu) @ 200 GeV: high p_T (un)suppression !





- R_{AA} << 1: well below pQCD expectations for hard scattering x-sections in vacuum



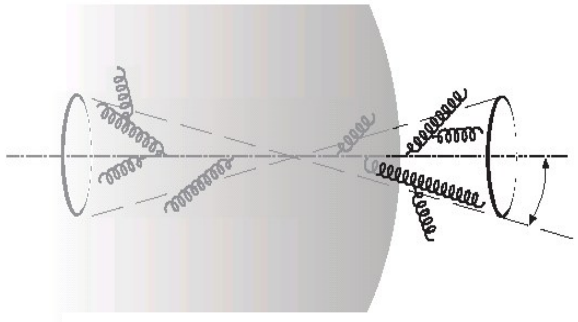
PHENIX, PRL 88, 022301 (2002)

- Au-Au suppression due to final-state interactions absent in “control” d-Au colls.

PRL 91, 0723ii (2003)

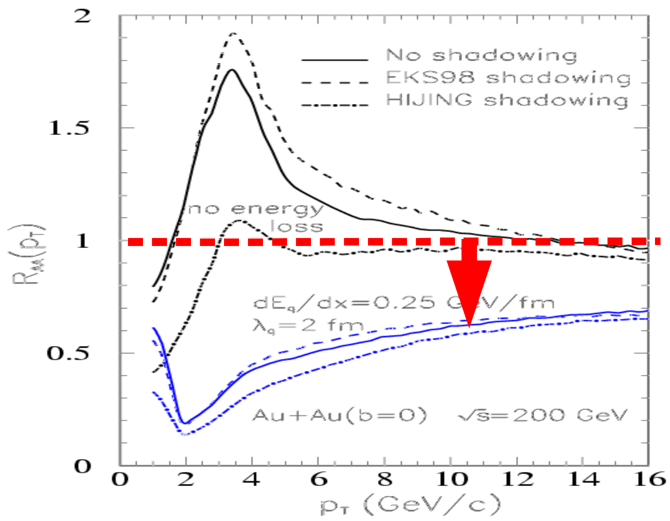
25-years of jet quenching phenomenology

- Mono-jets:



Bjorken, FERMILAB-PUB-82-059-THY.1982

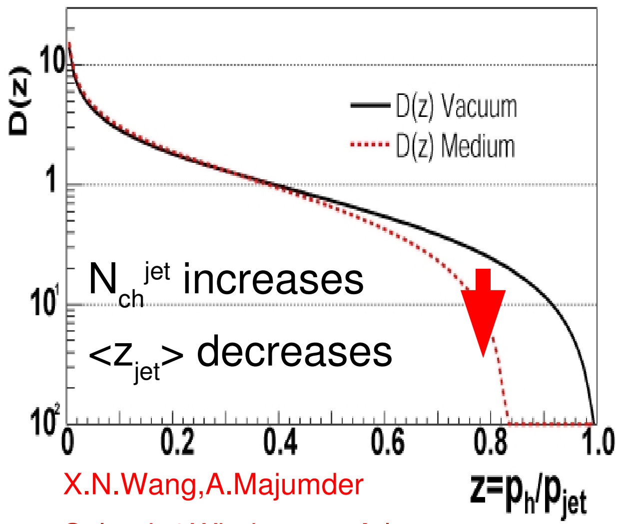
- Leading hadron suppression:



XNWang&Gyulassy PRL 68, 1480 (1992)

...

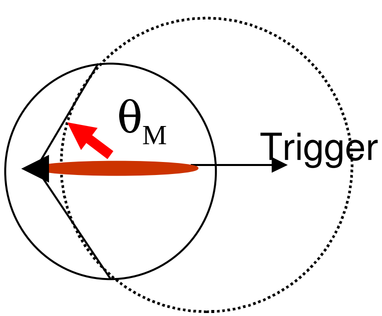
- Medium-modified FFs:



X.N.Wang,A.Majumder
Salgado&Wiedemann;Arleo, ...

- Mach-cones in ϕ:

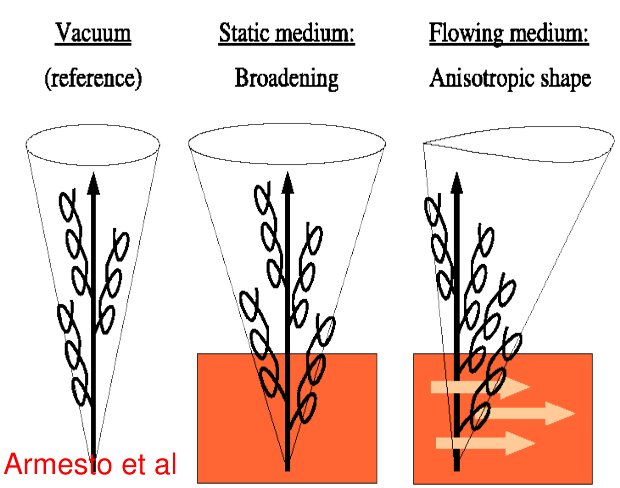
$$\cos\theta_M = c_s$$



Stoecker et al. hep-ph/0505245.
Casalderrey, Shuryak, hep-ph/0411315

Cerenkov angles, ...

- Jet broadening in η:



Armesto et al
hep-ph/0405301

Hadron/Nucleus colliders: luminosity

- Collider luminosity $\mathcal{L}$ characterizes its "ability" to deliver collisions per unit time & cross-section [$m^{-2}s^{-1}$]:

$$\mathcal{L}_L = \frac{kN^2 f}{4\pi\sigma^*_x\sigma^*_y} F(\sigma_{x,y})$$

→

k: # of bunches. k= 2808
N: # of protons/bunch. N = 1.15×10^11
f : revolution frequency. f = 11.25 kHz
σ_x,σ_y: beam size at coll. point. $\sigma_{x,y}$ =16 μm
$F(\phi_{xy})$: x-angle at coll. point. $\sigma_{x,y}$ =165 μrad

→ LHC: $\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$ ~ $10\ nb^{-1}s^{-1}$!

- Events collected in time t for process with cross-section σ: $N = \int \mathcal{L} dt\ \sigma$

- To maximize $\mathcal{L}$:

LHC: $\int \mathcal{L} dt = 100\ fb^{-1}$ in 1-year (10^7 s)

(1) Many bunches (*k*)
(2) Many particles per bunch (*N^2*)
(3) Small beam-size: $\sigma^*_u = (\beta^*\varepsilon)^{1/2}$
(4) Crossing angle: $F(\sigma_{x,y})$

High beam "brilliance" N/ε (particles per phase space vol.) → Injector chain performance !

Small envelope → Strong focusing !

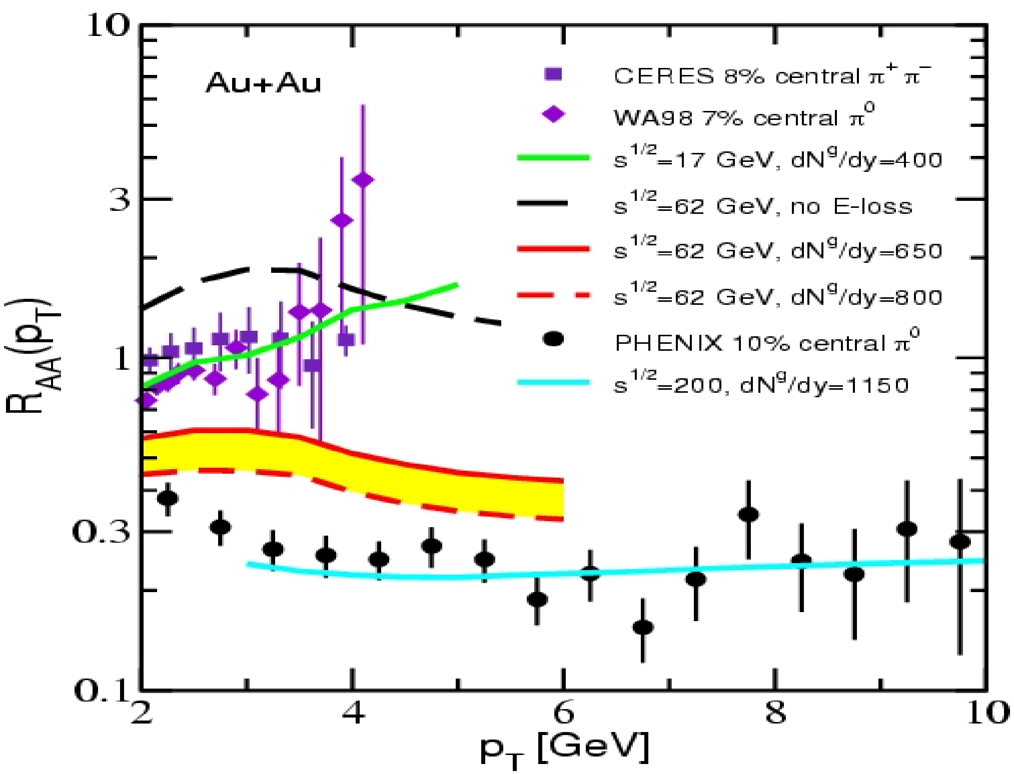
Beam overlap at IP → Beam-lines

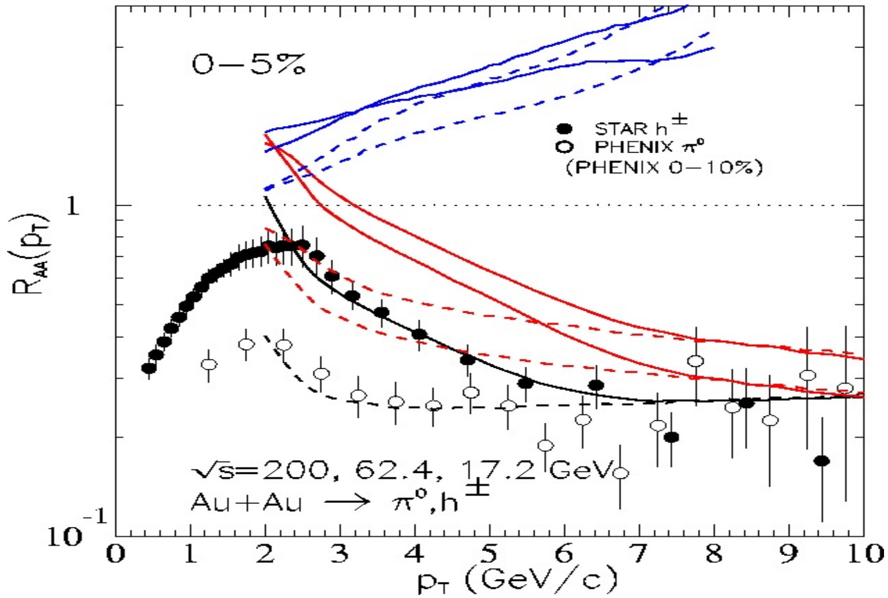
(LHC: $10^{34}\ cm^{-2}s^{-1}$ ≫ Tevatron: $2{\cdot}10^{32}\ cm^{-2}s^{-1}$ ≫ SppS: $6{\cdot}10^{30}\ cm^{-2}s^{-1}$)

Au+Au @ 62.4 GeV (central): suppression predictions

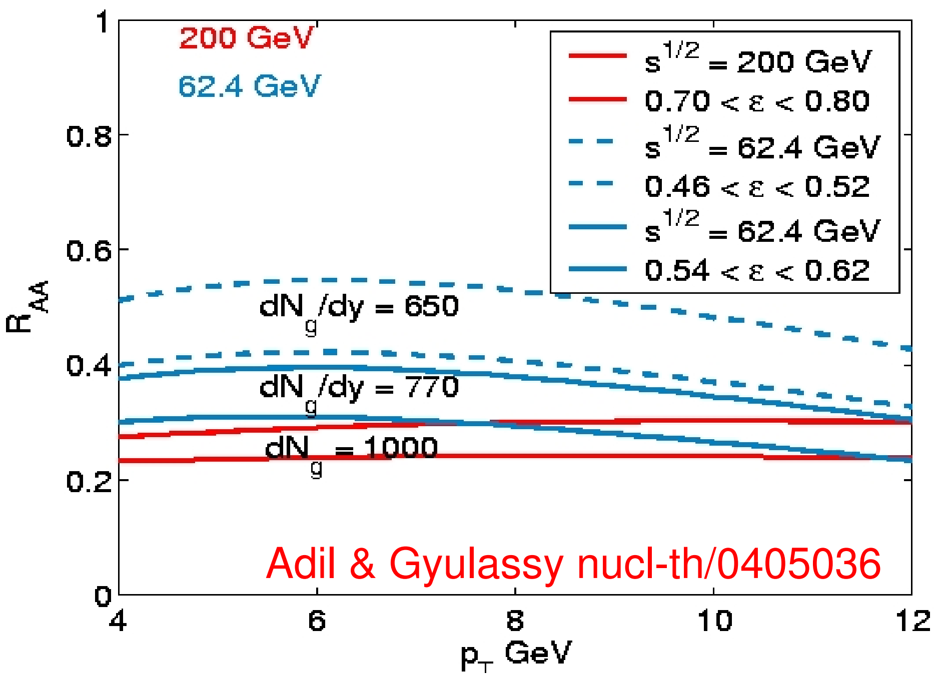
$R_{AA}(\pi^0) \sim 0.5 - 0.3$

I. Vitev nucl-th/0404052





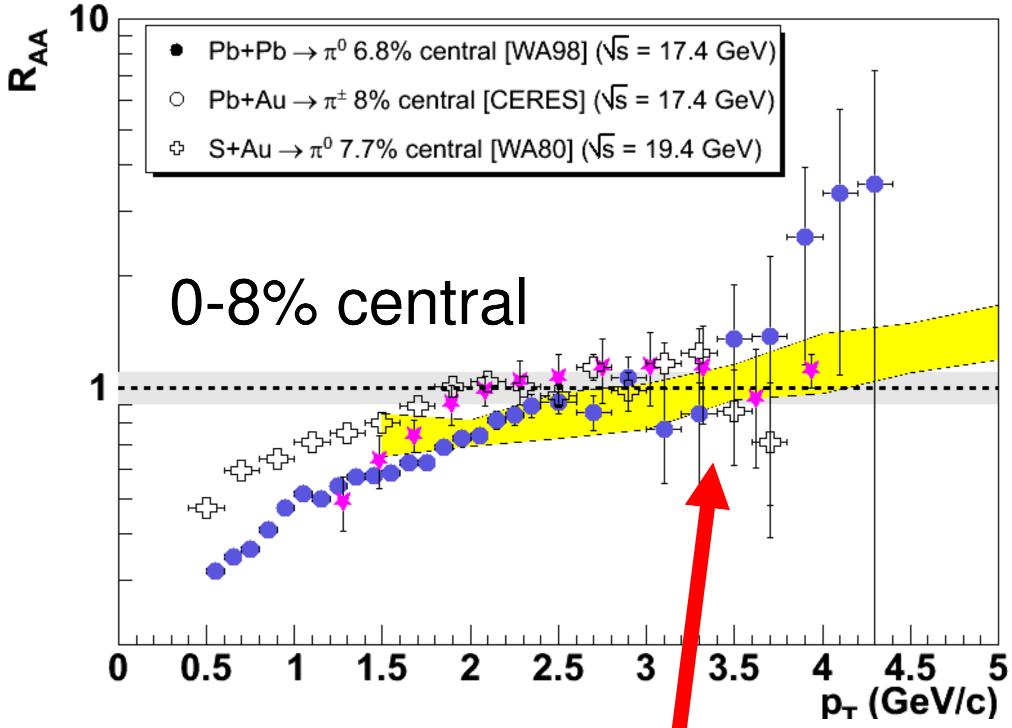
X.N. Wang nucl-th/0405029

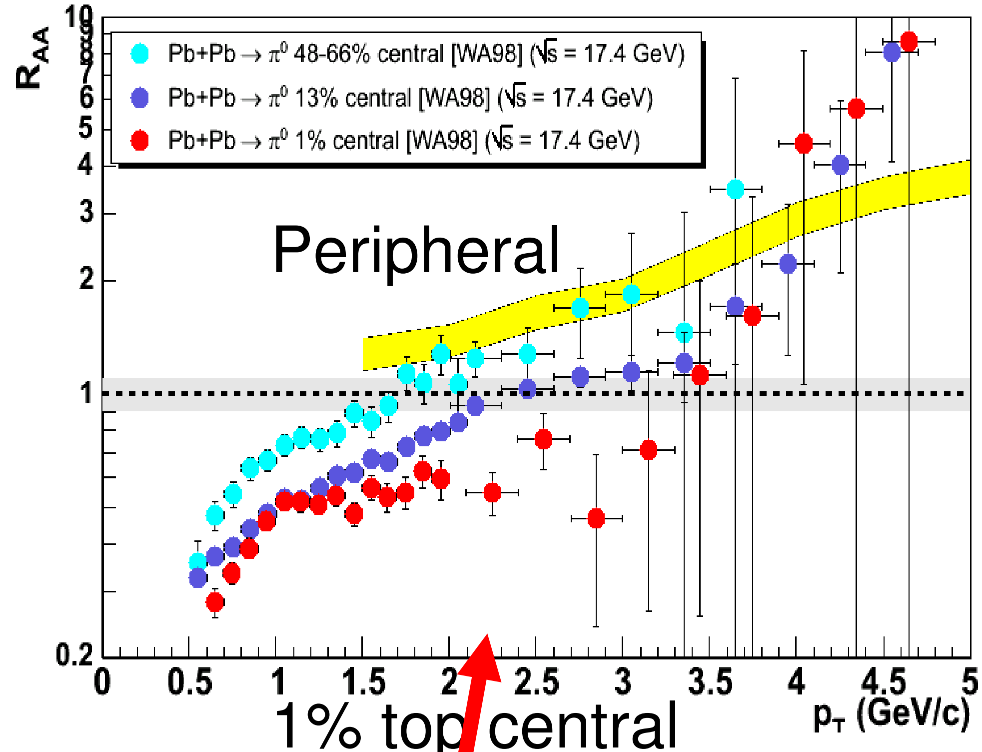


Adil & Gyulassy nucl-th/0405036

High p_T @ CERN-SPS: Cronin or quenching ?

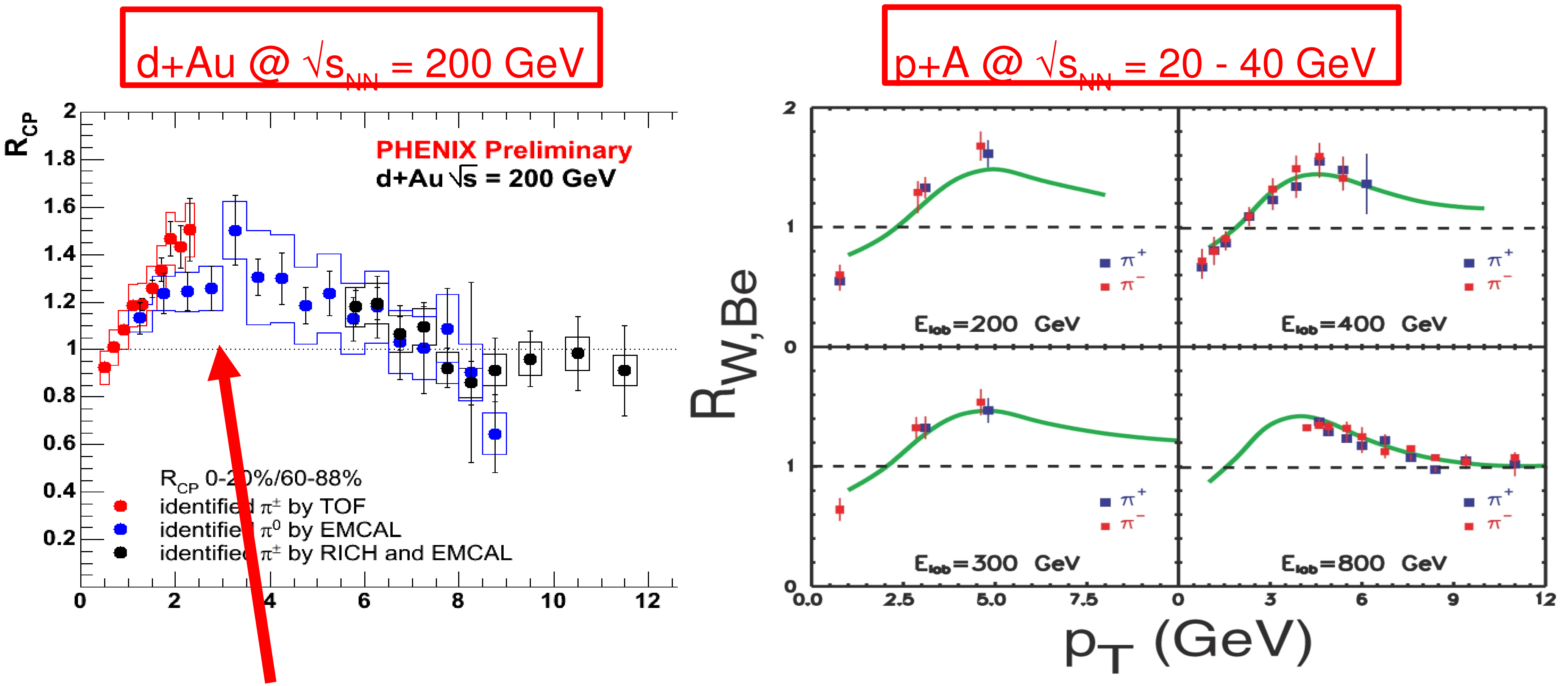
- New nuclear modification factor (better p+p → π^0 ref. @ $\sqrt{s_{NN}}$ = 17.3





- No Cronin effect in central collisions (R_{AA} ~ 1).
- Cronin enhancement in peripheral ... and suppression in top central ?
- Look for onset of suppression at RHIC Au+Au, p+p @ $\sqrt{s_{NN}} \approx$ 20 GeV ?

d+Au nuclear modification factor (at y=0)



- High p_T production in d+Au not suppressed but enhanced ! $R_{dAu} > 1$
  as in p+A "Cronin enhancement":
  p_T broadening due to initial-state soft & semihard scattering.
- "pQCD" cross-sections (R_{AA}~1) recovered at $p_T > 8$ GeV/c
- No Au shadowing effects in kinematic region probed (y= 0).