Jets, high-p_T hadrons and prompt photons

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QM2011 student lecture
22 May 2011

Universiteit Utrecht

NWO
Netherlands Organisation for Scientific Research

Hard processes in QCD

- Hard process: scale Q >> Λ_{QCD}
- Hard scattering High-p_T parton(photon) Q~p_T
- Heavy flavour production m >> Λ_{QCD}

Factorization

Cross section calculation can be split into

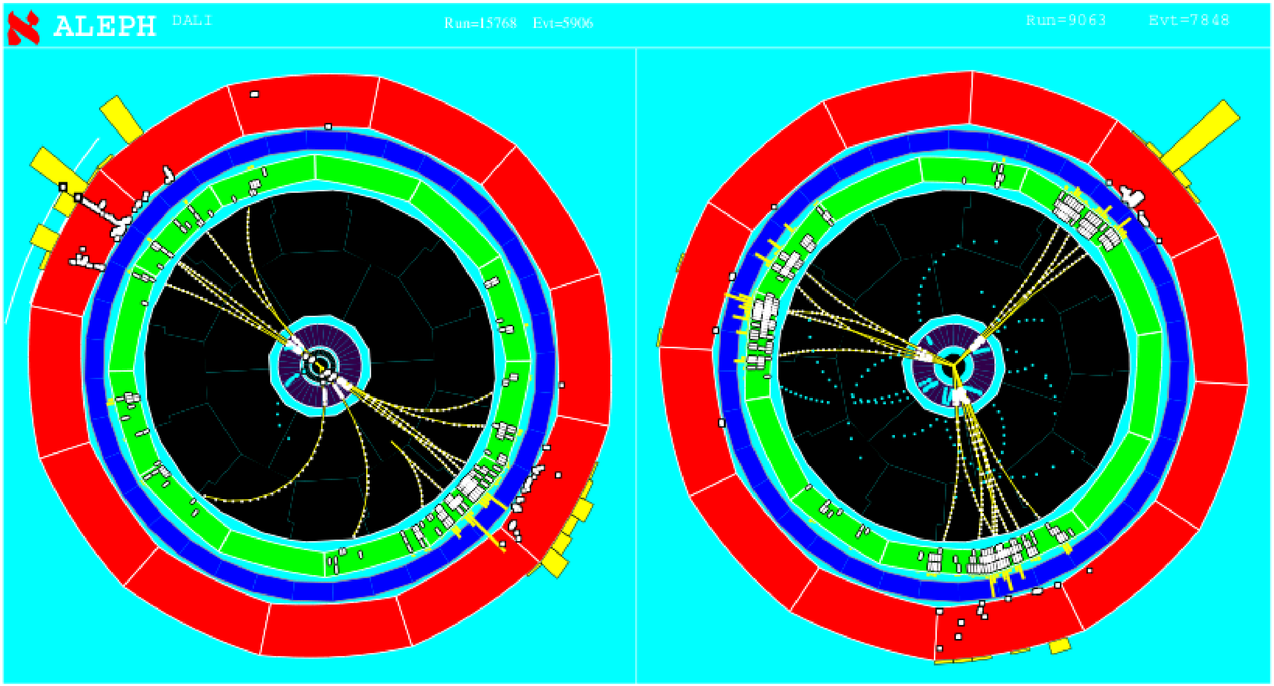
- Hard part: perturbative matrix element
- Soft part: parton density (PDF), fragmentation (FF)

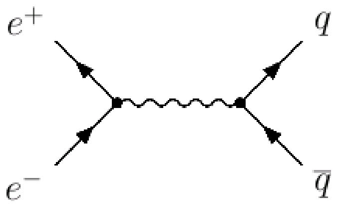
$$\frac{d\sigma_{pp}^{h}}{dy\,d^2p_T} = K\sum_{abcd}\int dx_a\,dx_b\,\underbrace{f_a(x_a,Q^2)\,f_b(x_b,Q^2)}_{\text{parton density}}\,\underbrace{\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)}_{\text{matrix element}}\,\underbrace{\frac{D^0_{h/c}}{\pi z_c}}_{\text{FF}}$$

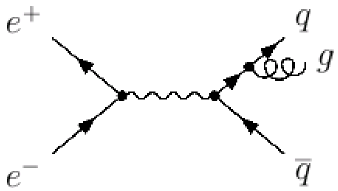
QM interference between hard and soft suppressed (by Q^2/Λ^2 ‘Higher Twist’)

Soft parts, PDF, FF are *universal*: independent of hard process

Seeing quarks and gluons



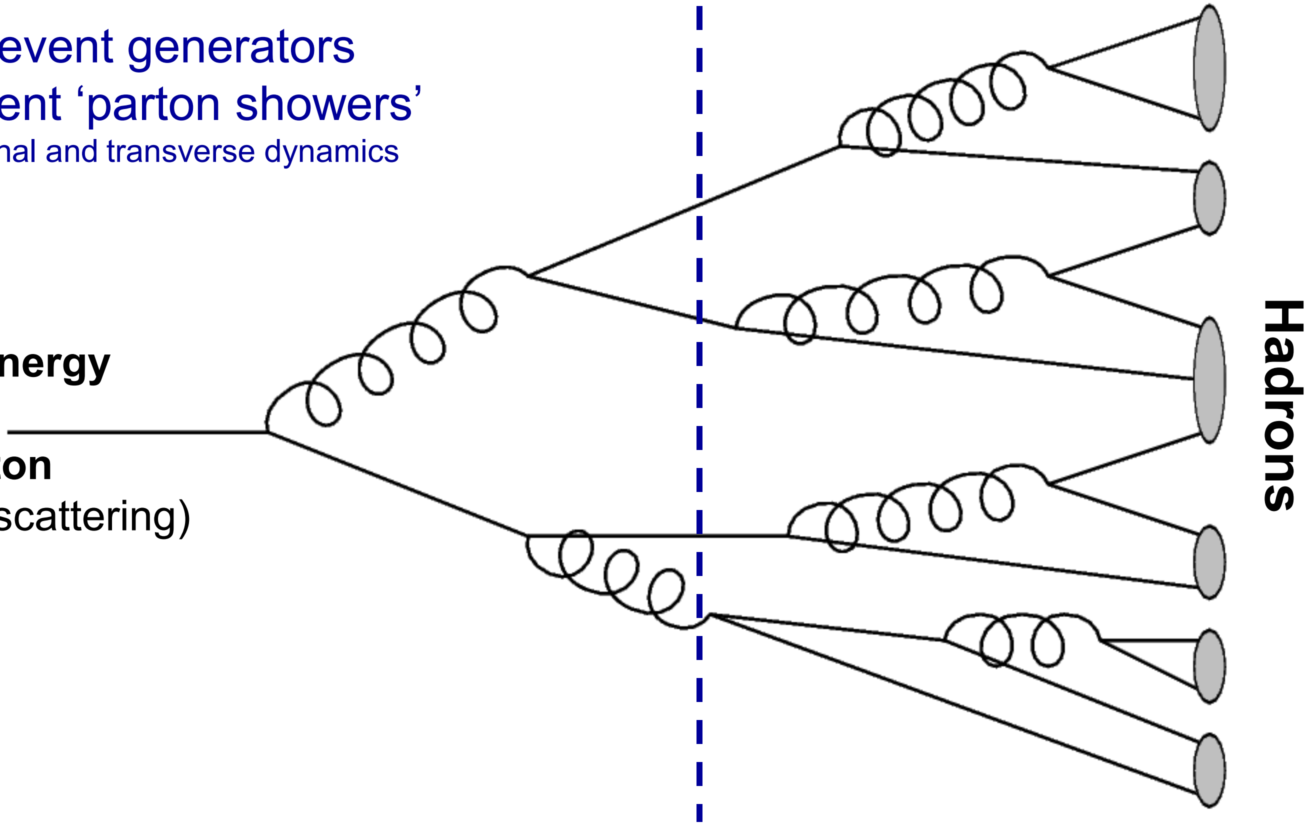




In high-energy collisions, observe traces of quarks, gluons (‘jets’)

Fragmentation and parton showers

MC event generators
implement ‘parton showers’
Longitudinal and transverse dynamics



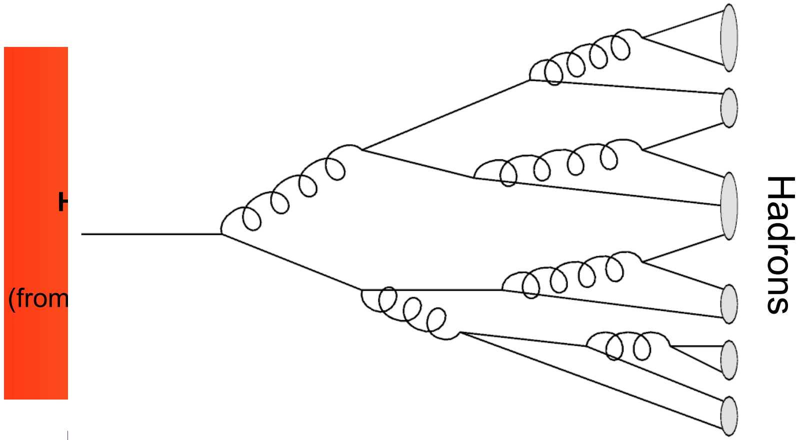
High-energy
parton
(from hard scattering)

large Q^2 μ_F $Q \sim m_H \sim \Lambda_{QCD}$

Analytical calculations: Fragmentation Function $D(z, \mu)$ $z=p_h/E_{jet}$
Only longitudinal dynamics

Jet Quenching

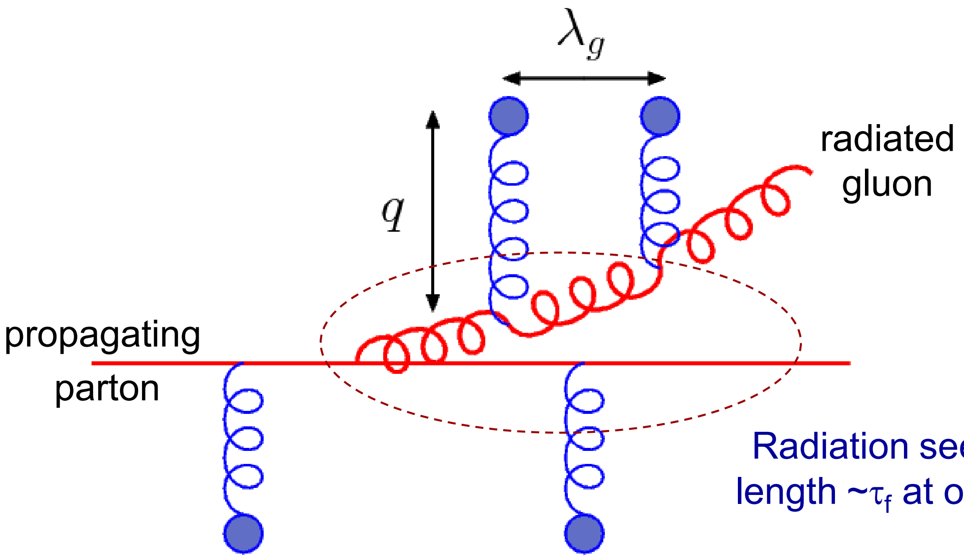
1) How is does the medium modify parton fragmentation?
    - Energy-loss: reduced energy of leading hadron – enhancement of yield at low p_T?
    - Broadening of shower?
    - Path-length dependence
    - Quark-gluon differences
    - Final stage of fragmentation outside medium?



2) What does this tell us about the medium ?
    - Density
    - Nature of scattering centers? (elastic vs radiative; mass of scatt. centers)
    - Time-evolution?

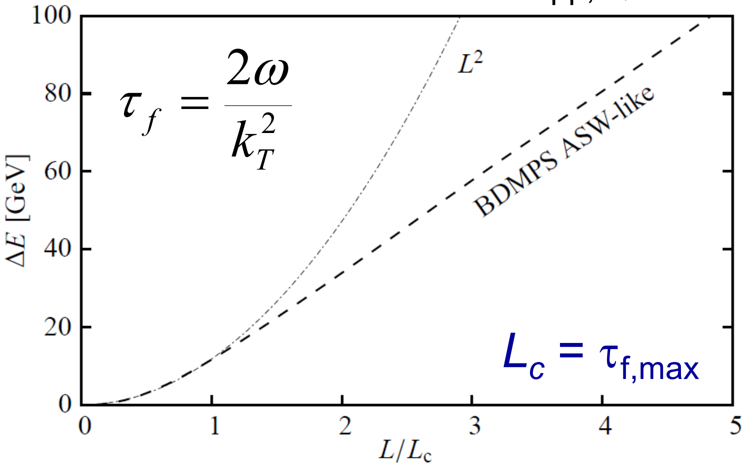
Medium-induced radition

Landau-Pomeranchuk-Migdal effect
Formation time important



Radiation sees length ~τ_f at once

Zapp, QM09



$$\tau_f = \frac{2\omega}{k_T^2}$$

$L_c = \tau_{f,max}$

If $\lambda < \tau_f$, multiple scatterings add coherently

$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

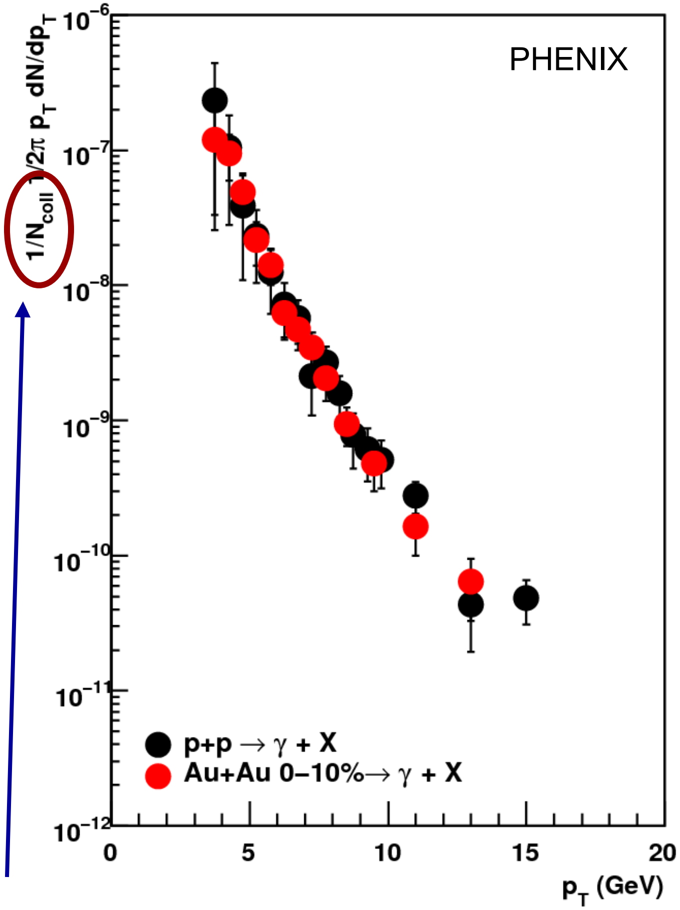
Energy loss depends on density: $\lambda \propto \frac{1}{\rho}$

and nature of scattering centers
(scattering cross section)

Transport coefficient $\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$

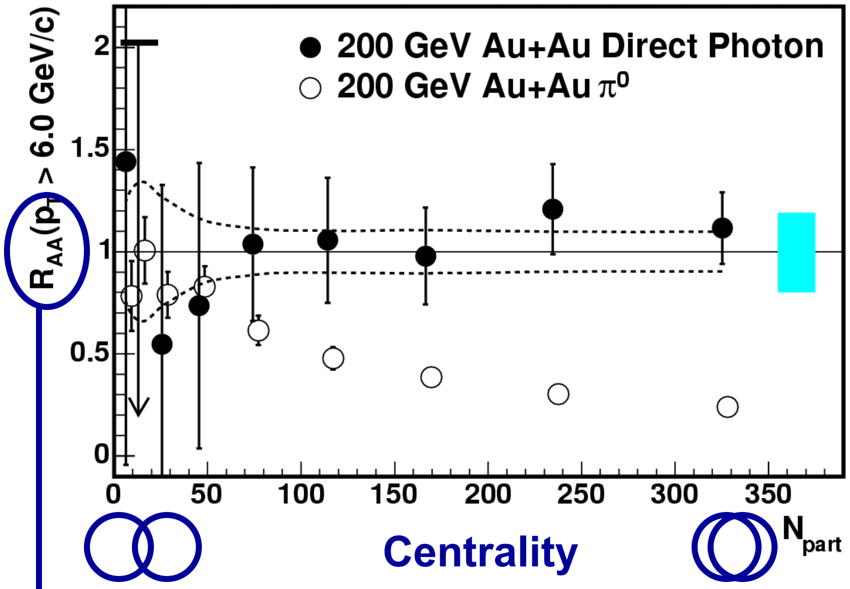
Testing volume (N_{coll}) scaling in Au+Au

Direct γ spectra



Scaled by N_{coll}

PHENIX, PRL 94, 232301

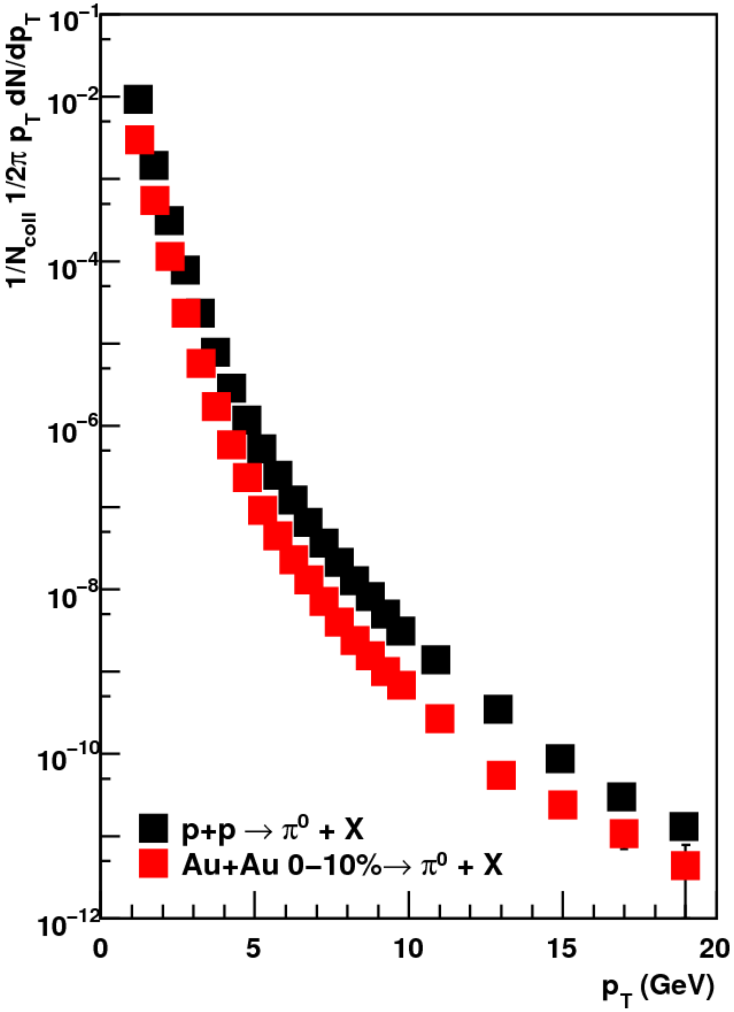


$$R_{AA} = \frac{dN/dp_T\big|_{Au+Au}}{N_{coll}\, dN/dp_T\big|_{p+p}}$$

Direct γ in A+A scales with N_{coll}

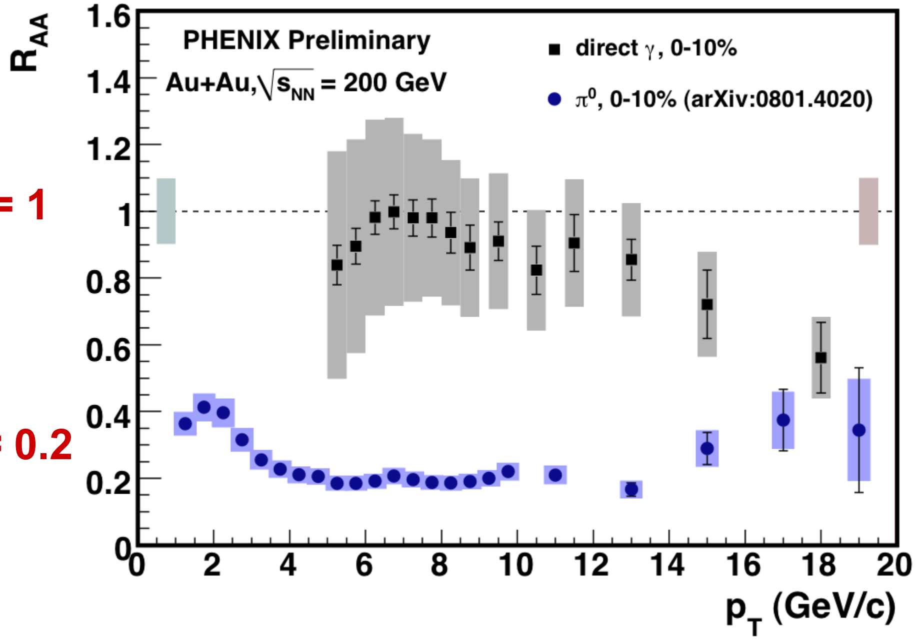
A+A initial state is incoherent superposition of p+p for hard probes

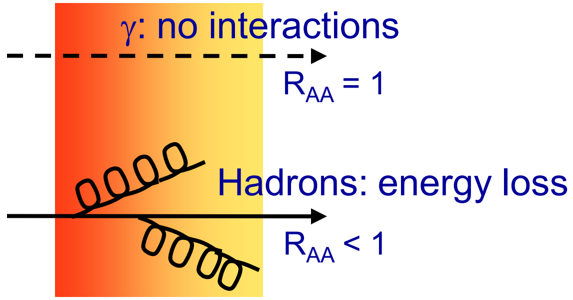
π^0 R_{AA} – high-p_T suppression



γ: $R_{AA} = 1$

π^0: $R_{AA} \approx 0.2$





Hard partons lose energy in the hot matter

Two extreme scenarios

(or how $P(\Delta E)$ says it all)

Scenario I

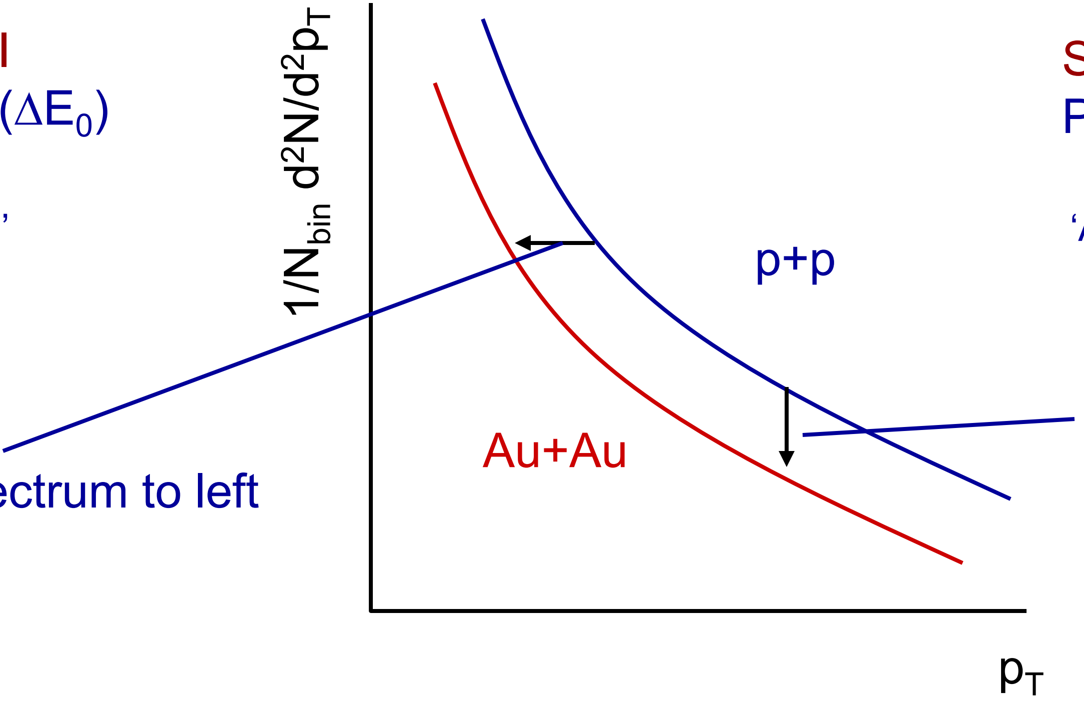
$P(\Delta E) = \delta(\Delta E_0)$

'Energy loss'

Scenario II

$P(\Delta E) = a\,\delta(0) + b\,\delta(E)$

'Absorption'



Shifts spectrum to left

Downward shift

$P(\Delta E)$ encodes the full energy loss process

R_{AA} not sensitive to energy loss distribution, details of mechanism

Four theory approaches

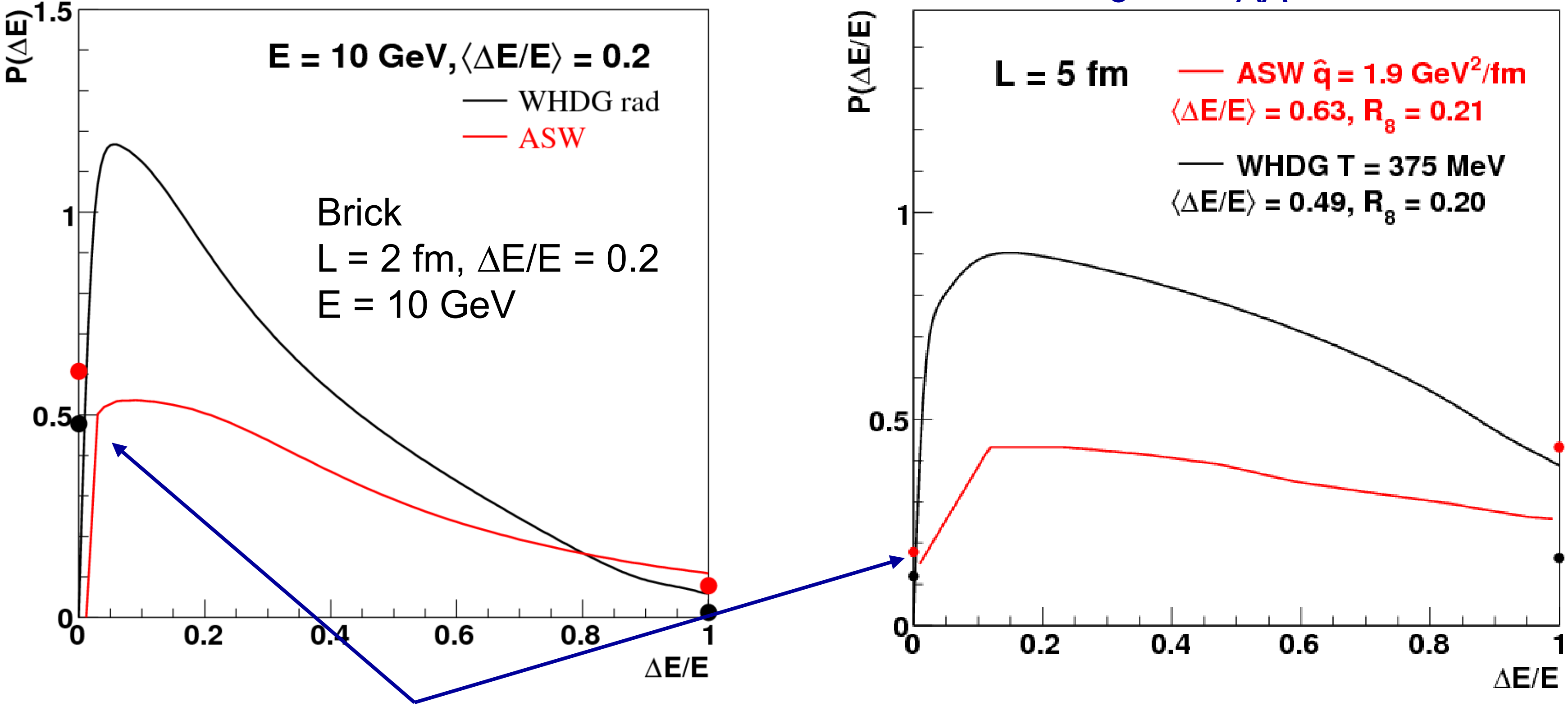
- Multiple-soft scattering (ASW-BDMPS)
  - Full interference (vacuum-medium + LPM)
  - Approximate scattering potential
- Opacity expansion (GLV/WHDG)
  - Interference terms order-by-order (first order default)
  - Dipole scattering potential $1/q^4$
- Higher Twist
  - Like GLV, but with fragmentation function evolution
- Hard Thermal Loop (AMY)
  - Most realistic medium
  - LPM interference fully treated
  - No finite-length effects (no L^2 dependence)

Energy loss spectrum

Typical examples with fixed *L*

$\langle \Delta E/E \rangle = 0.2$

$R_8 \sim R_{AA} = 0.2$



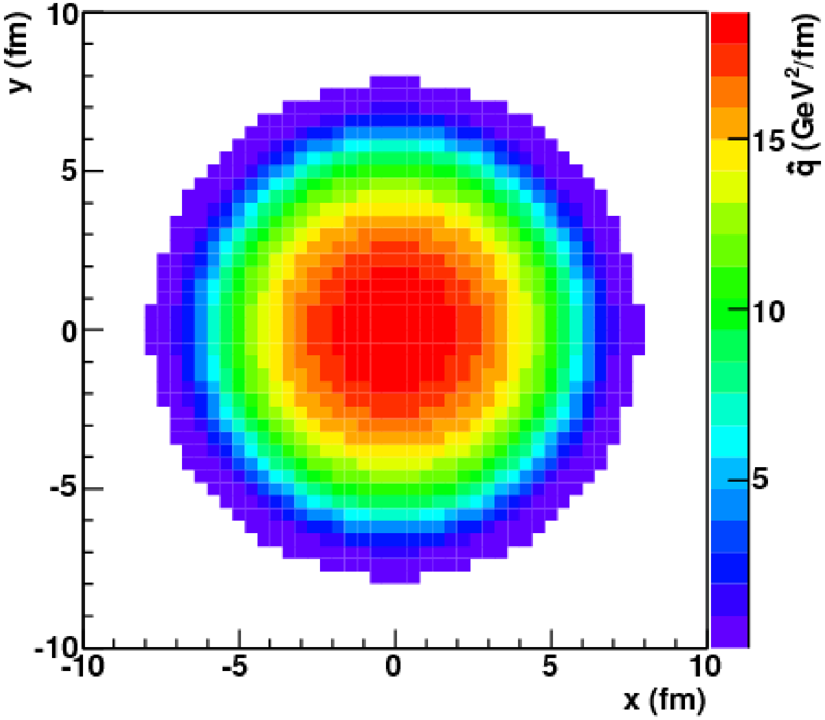
Significant probability to lose no energy (P(0))

Broad distribution, large E-loss (several GeV, up to $\Delta E/E = 1$)

Theory expectation: mix of partial transmission+continuous energy loss – Can we see this in experiment?

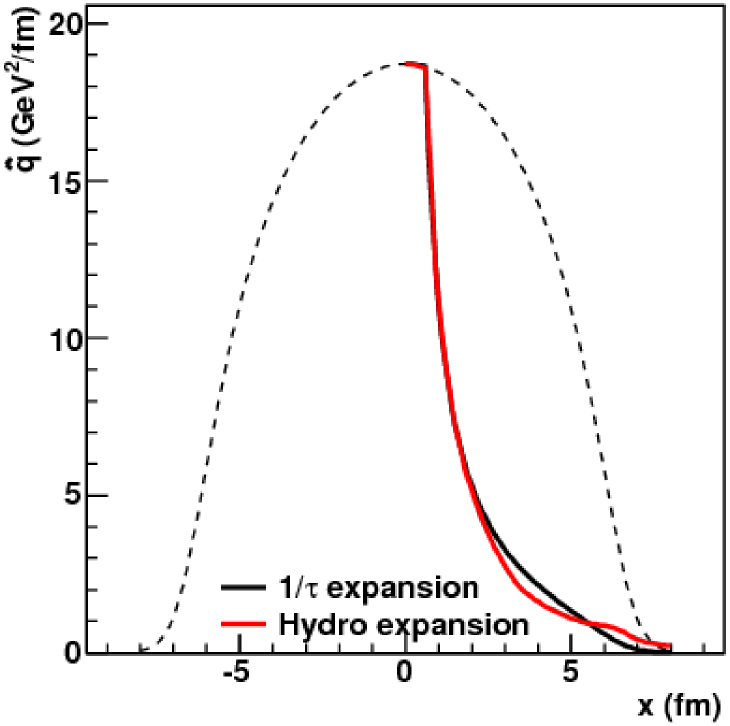
Geometry

Density profile



Profile at $\tau \sim \tau_{form}$ known

Density along parton path



Longitudinal expansion
dilutes medium
⇒ Important effect

Space-time evolution is taken into account in modeling

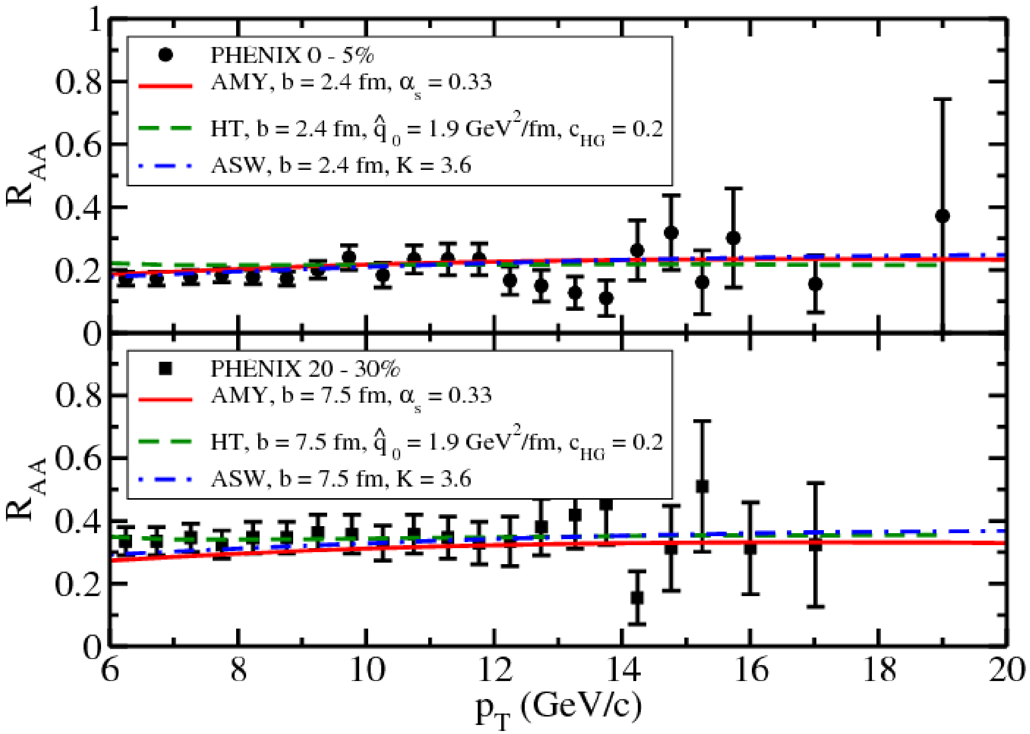
Determining $\hat{q}$

ASW: $\hat{q} = 10 - 20\ \mathrm{GeV}^2/\mathrm{fm}$

HT: $\hat{q} = 2.3 - 4.5\ \mathrm{GeV}^2/\mathrm{fm}$

AMY: $\hat{q} \approx 4\ \mathrm{GeV}^2/\mathrm{fm}$

Large density:
AMY: T ~ 400 MeV
Transverse kick: qL ~ 10-20 GeV



Bass et al, PRC79, 024901

All formalisms can match R_{AA}, but large differences in medium density

After long discussions, it turns out that these differences
are mostly due to uncontrolled approximations in the calculations
→ Best guess: the truth is somewhere in-between

At RHIC: ΔE large compared to E, differential measurements difficult

R_{AA} at LHC

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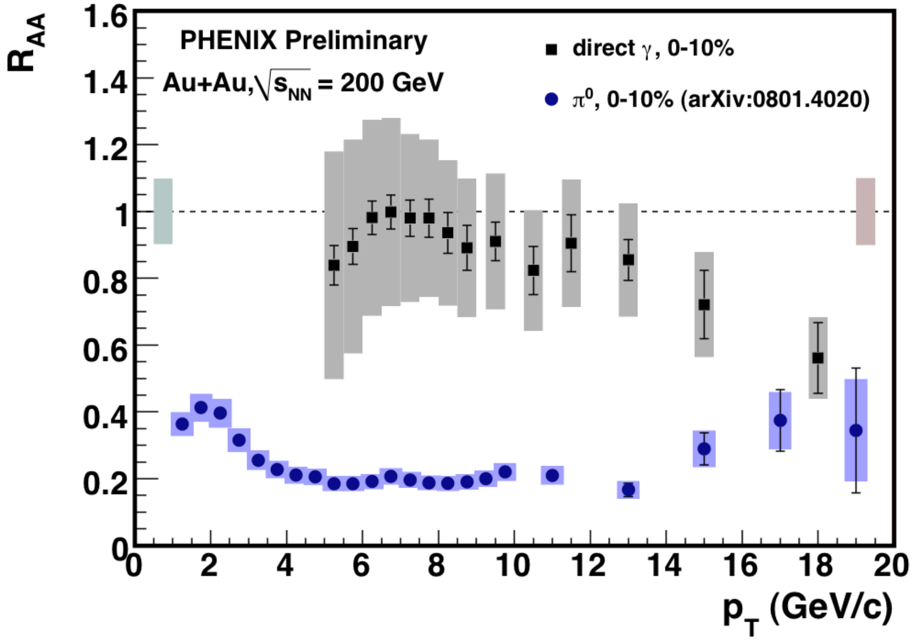
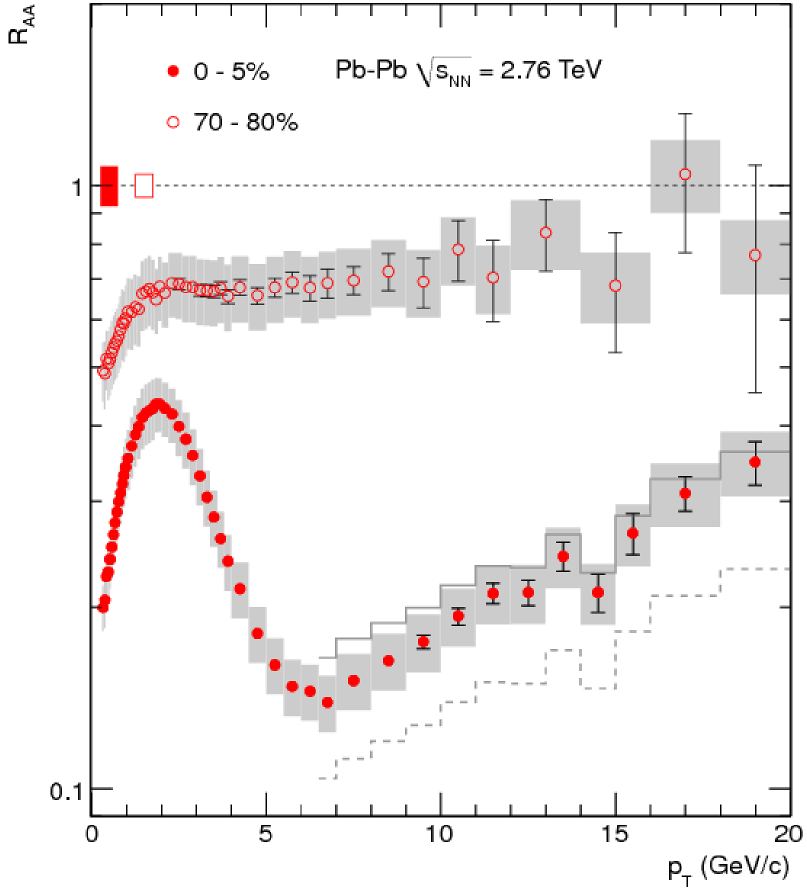


ALICE

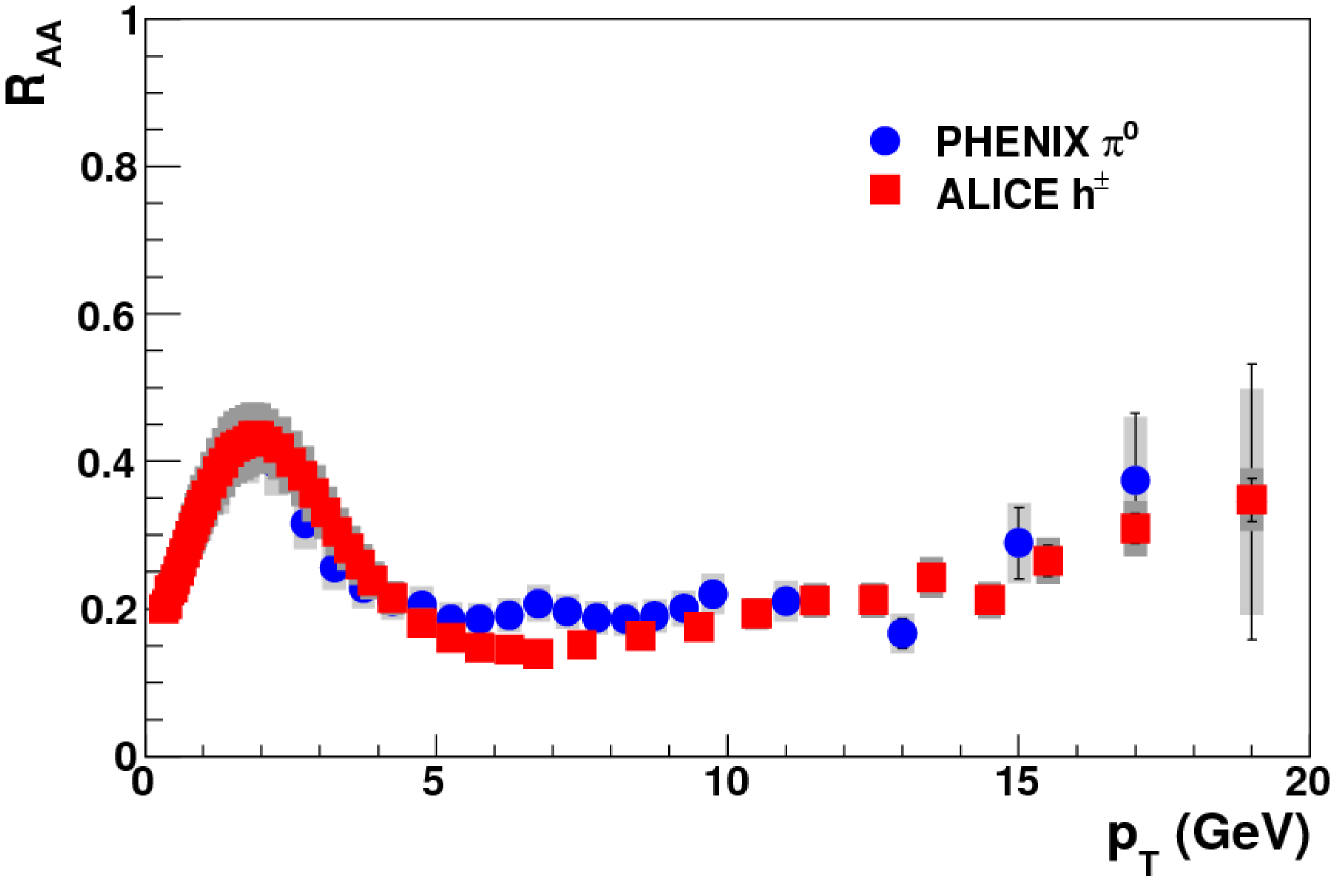


ALICE, PLB 696, 30

R_{AA} at LHC: increase with p_T → first sign of sensitivity to P(ΔE)

Larger ‘dynamic range’ at LHC very important – stay tuned

R_{AA} RHIC and LHC II



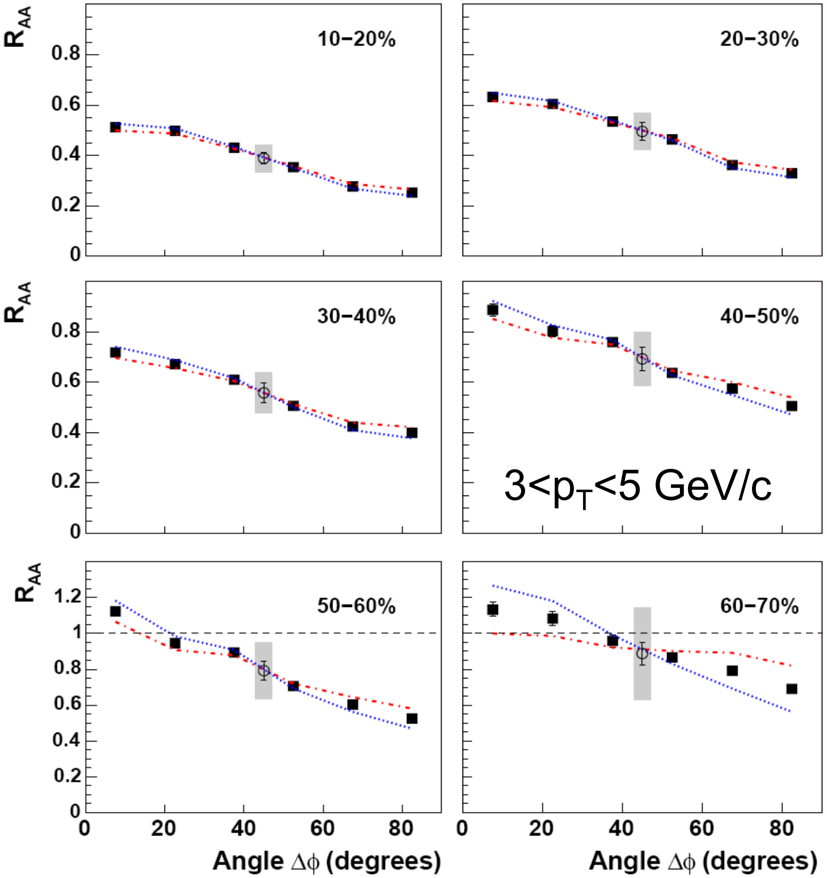
Overlaying the two results:
PHENIX π^0 and ALICE $h^\pm$ p_T-dependence not too different…

N.B.: Large uncertainties in RHIC result at high p_T

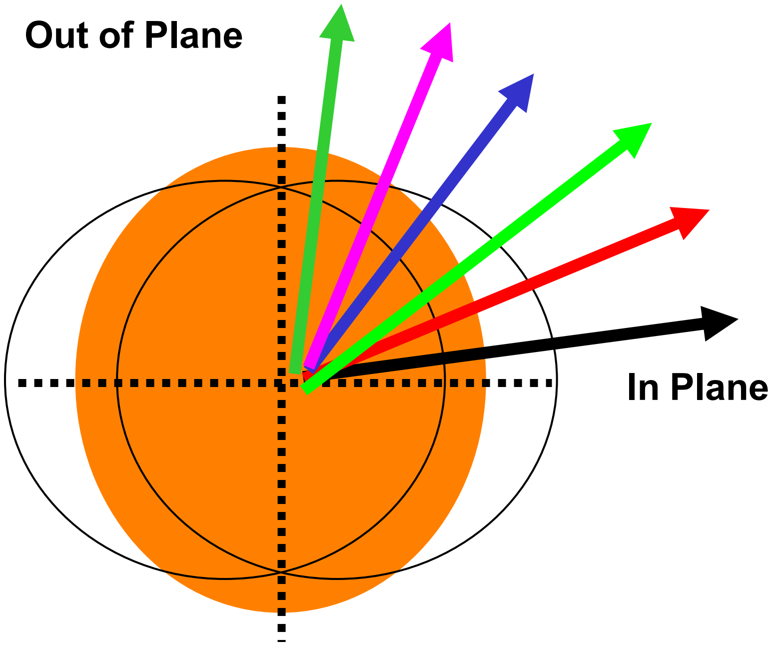
Path length dependence: R_{AA} vs L

R_{AA} as function of angle with reaction plane

PHENIX, PRC 76, 034904



$3<p_T<5$ GeV/c



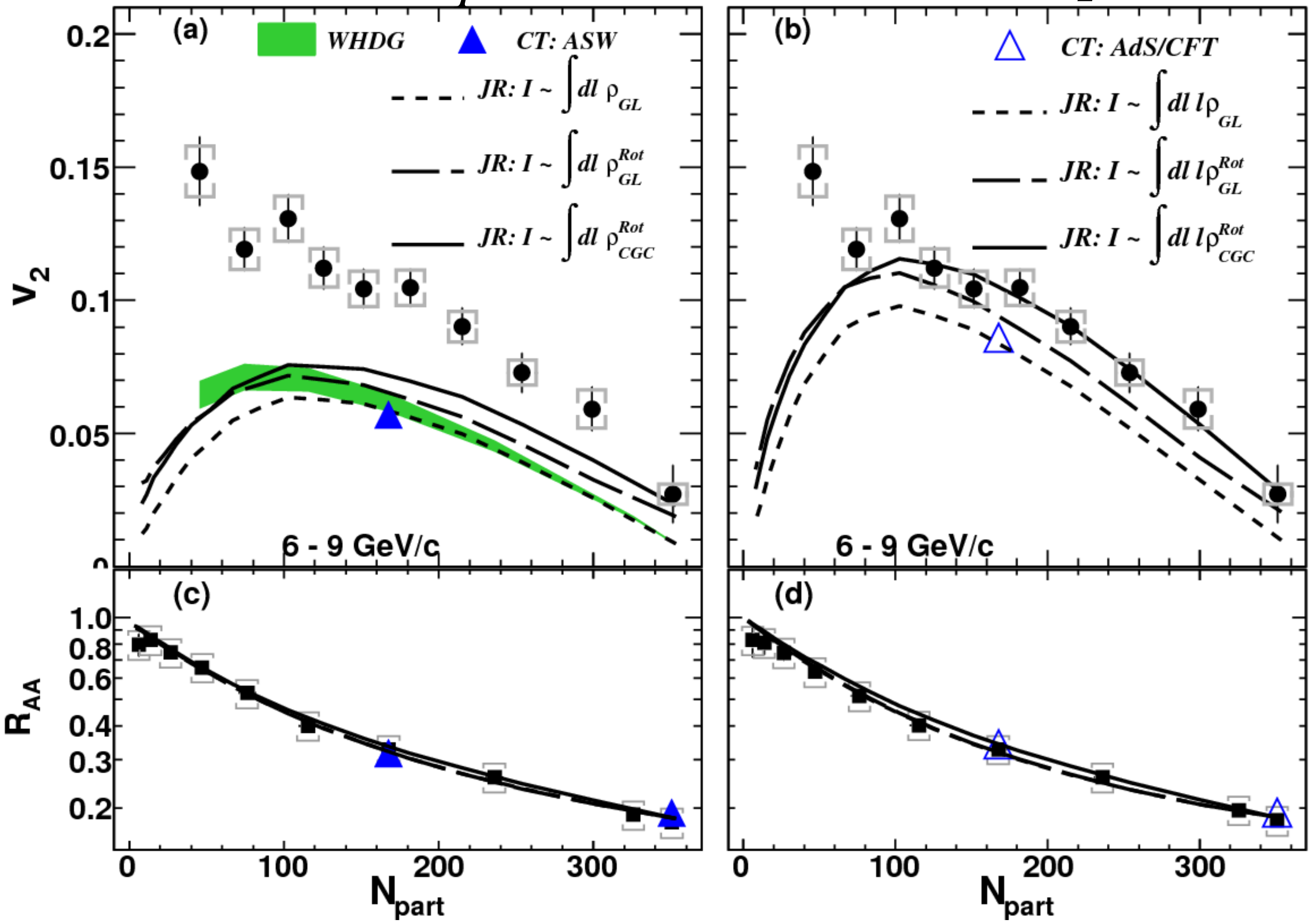
Relation between RAA(φ) and v_2:

$$R_{AA}(\varphi) = R_{AA}\left(1 + 2v_2\cos 2(\varphi - \psi)\right)$$

Suppression depends on angle, path length

Path length dependence and v_2

$\Delta E \propto \hat{q} L^2$ $\Delta E \propto \hat{q} L^3$



PHENIX PRL105, 142301

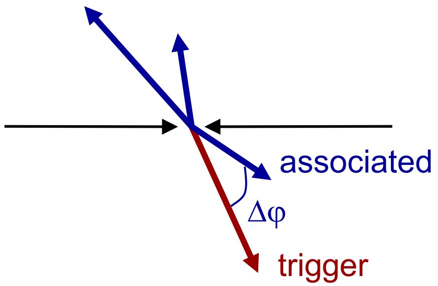
v_2 at high p_T due to energy loss

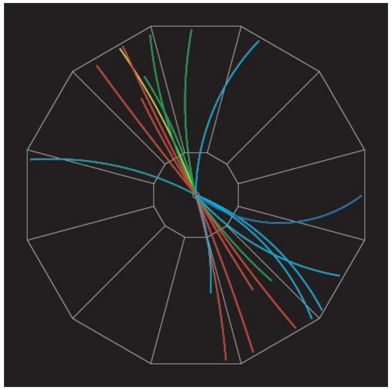
Most calculations give too small effect

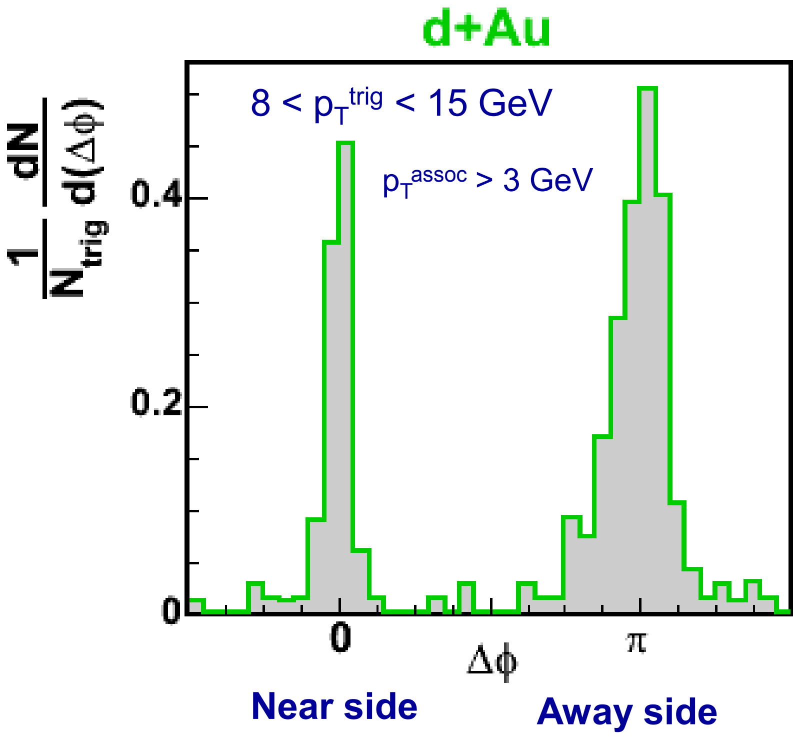
Path length dependence stronger than expected?

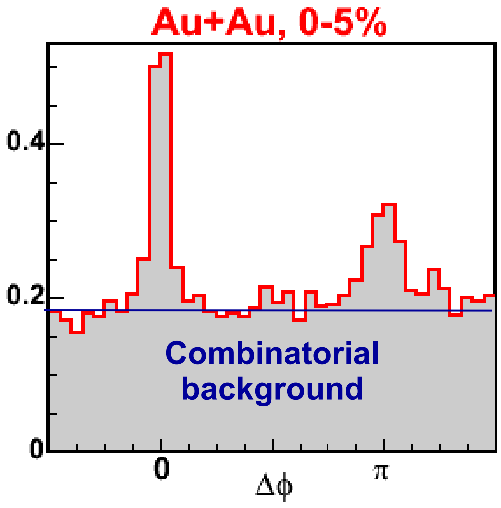
Depends strongly on geometry – stay tuned

Di-hadron correlations



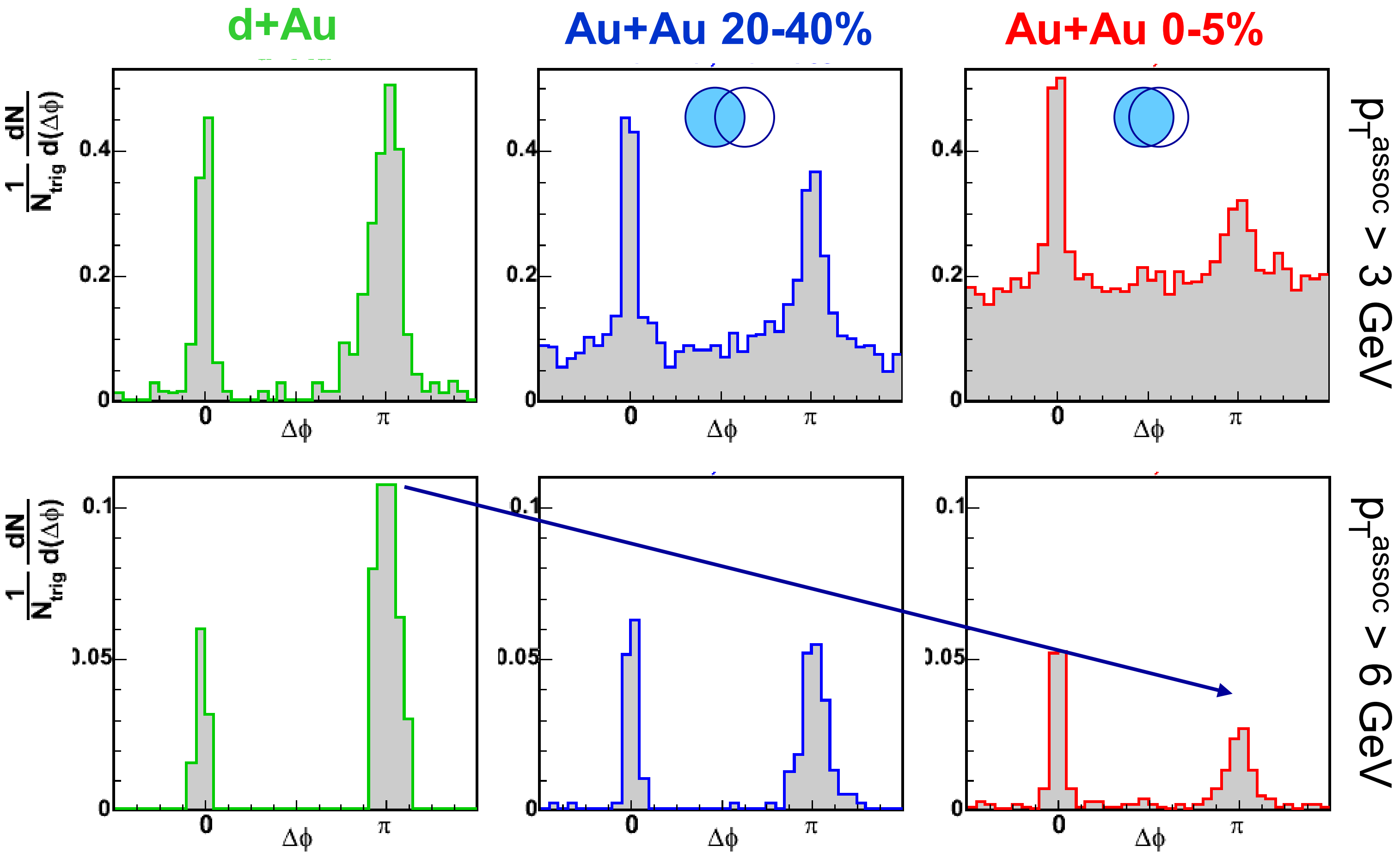






Use di-hadron correlations to probe the jet-structure in p+p, d+Au and Au+Au

Di-hadrons at high-p_T: recoil suppression



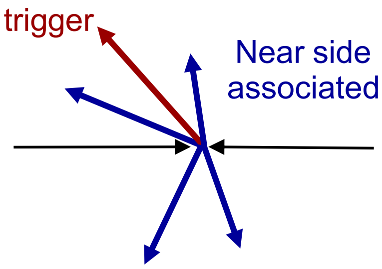
High-p_T hadron production in Au+Au dominated by (di-)jet fragmentation

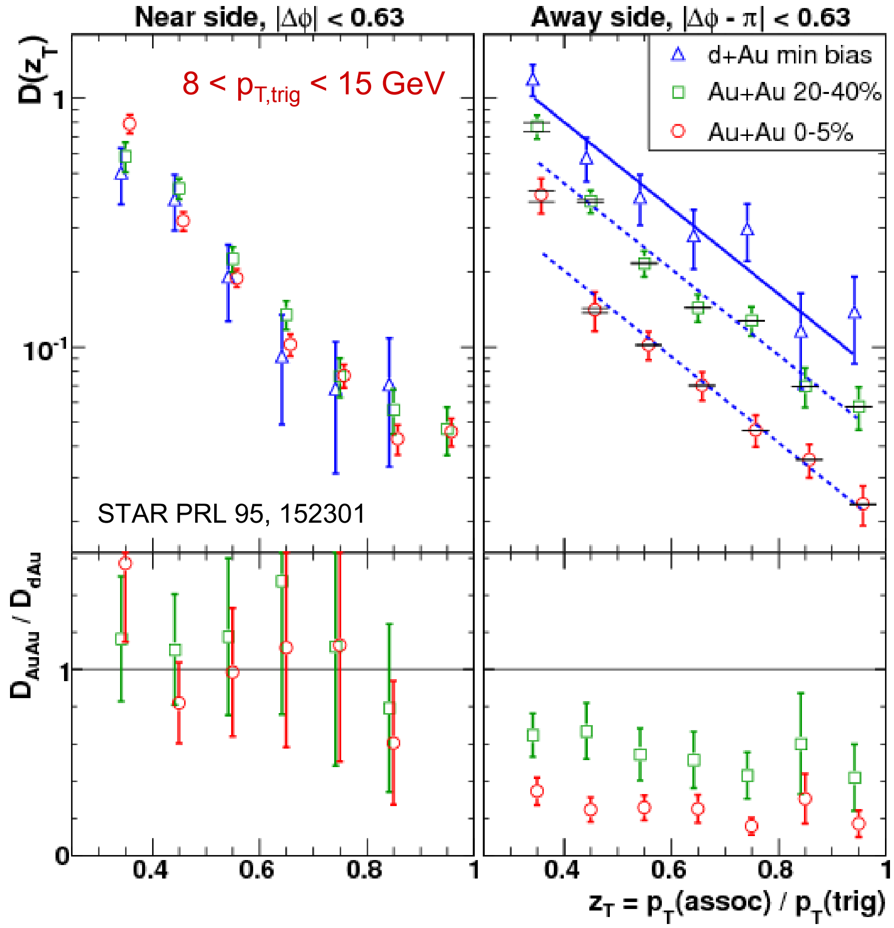
Suppression of away-side yield in Au+Au collisions: energy loss

Di-hadron yield suppression

Near side

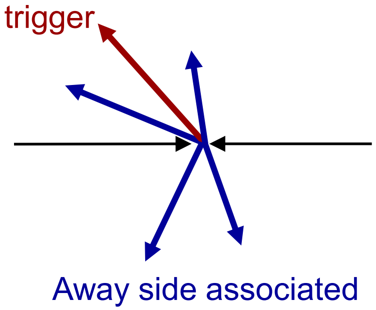
Yield of additional particles in the jet





Away side

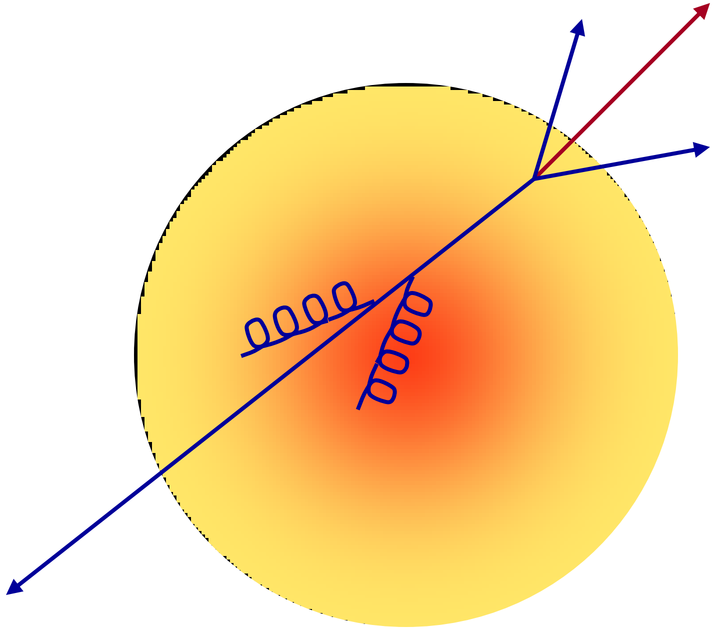
Yield in balancing jet, after energy loss



Near side: No modification
⇒ Fragmentation outside medium?

Away-side: Suppressed by factor 4-5
⇒ large energy loss

Path length II: ‘surface bias’



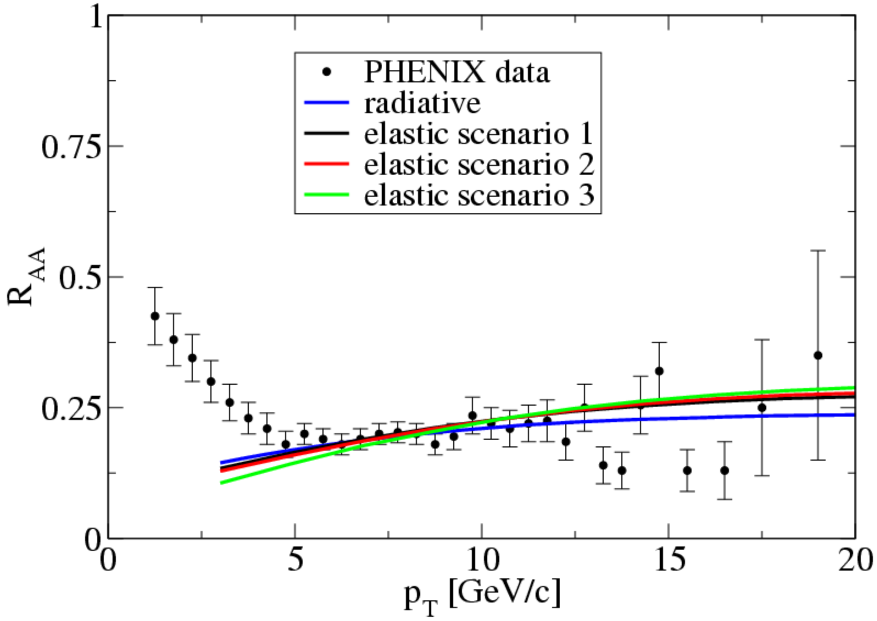
Near side trigger,
biases to small E-loss

Away-side large L

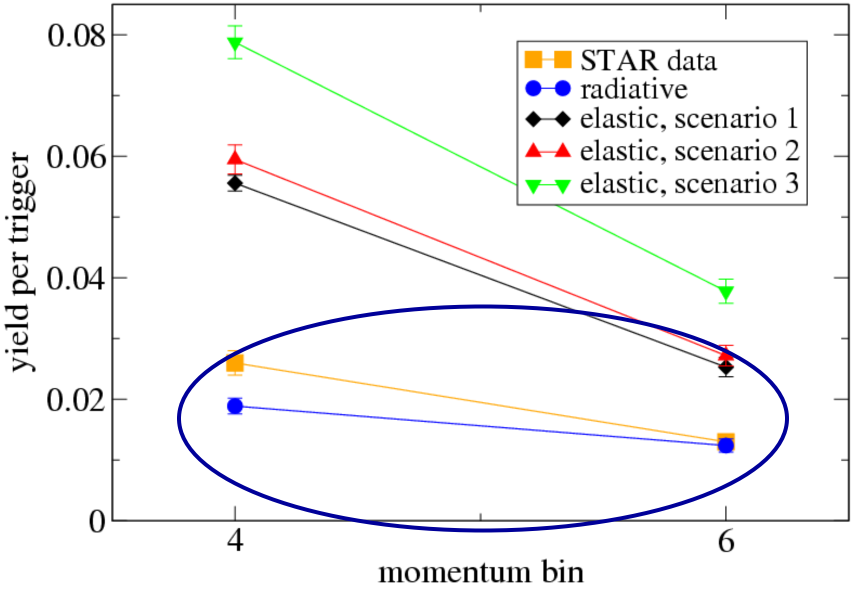
Away-side suppression I_{AA} samples longer path-lengths
than inclusives R_{AA}

L scaling: elastic vs radiative

T. Renk, PRC76, 064905



R_{AA}: input to fix density



Radiative scenario fits data; elastic scenarios underestimate suppression

Indirect measure of path-length dependence:
single hadrons and di-hadrons probe different path length distributions

Confirms L^2 dependence → radiative loss dominates

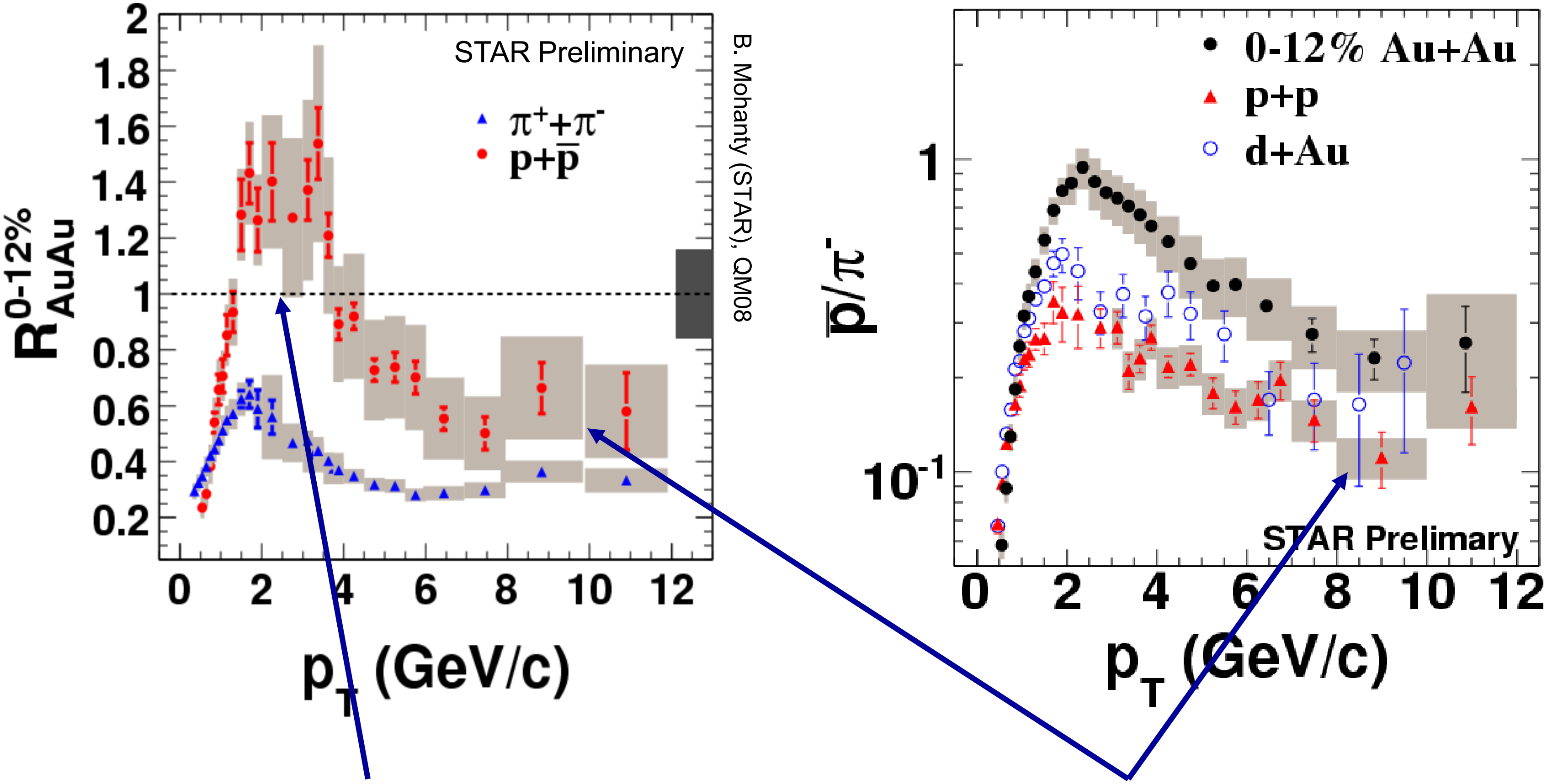
Intermediate p_T

So far, focused on high-p_T
Where factorisation may hold $p_T > 1\text{-}4$ GeV

Some other ‘puzzling’ (i.e. not dominated by jet fragmention+energy loss) observations at intermediate p_T:

- Enhanced baryon/meson ratio
  - Hadronisation by coalescence?
- Enhanced near-side yield at large $\Delta\eta$ ‘ridge’
  - Triangular flow?
- Away-side double-peak structure
  - Mach cone?
  - Triangular flow?

Baryon excess

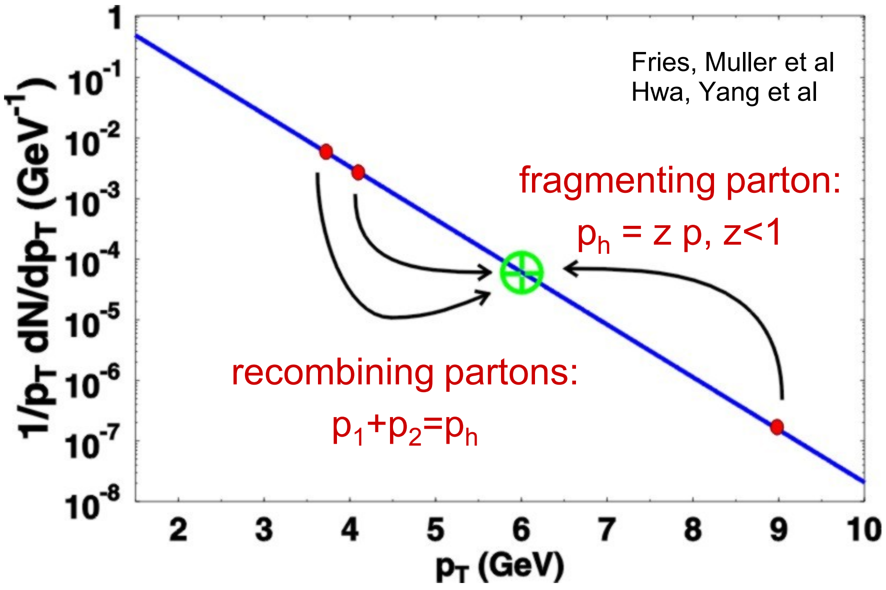


Intermediate p_T, 2 – 6 GeV
Large baryon/meson ration in Au+Au

High p_T: Au+Au similar to p+p
⇒ Fragmentation dominates

Baryon/meson = 0.2-0.5

Hadronisation through coalescence

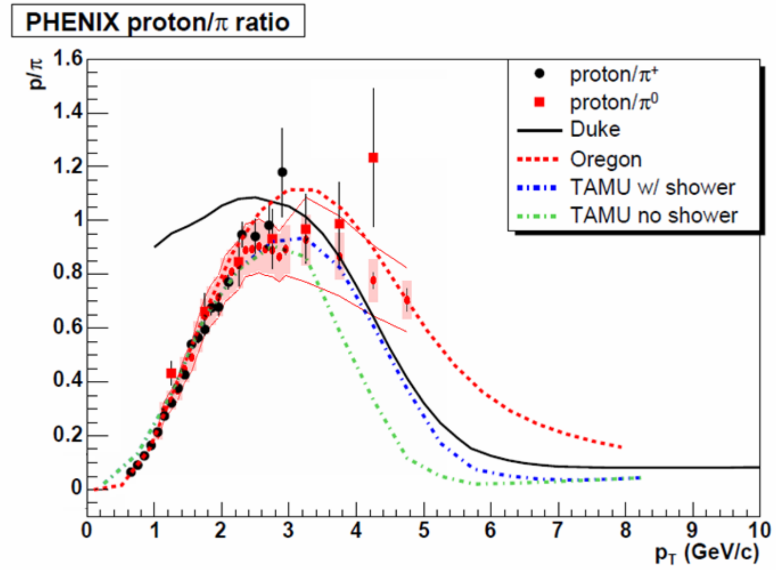


Fries, Muller et al
Hwa, Yang et al

fragmenting parton:
$p_h = z\ p,\ z<1$

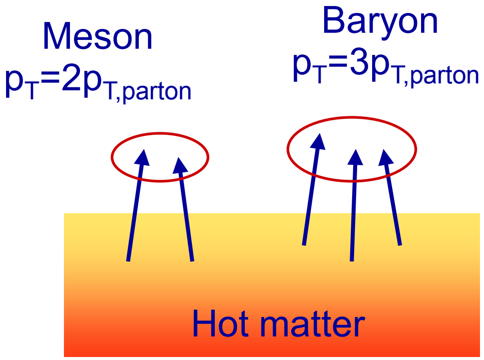
recombining partons:
$p_1+p_2=p_h$

Recombination of thermal ('bulk') partons produces baryons at larger p_T



R. Belmont, QM09

Recombination enhances baryon/meson ratio



Meson
$p_T=2p_{T,\mathrm{parton}}$

Baryon
$p_T=3p_{T,\mathrm{parton}}$

Hot matter

Note also: v_2 scaling

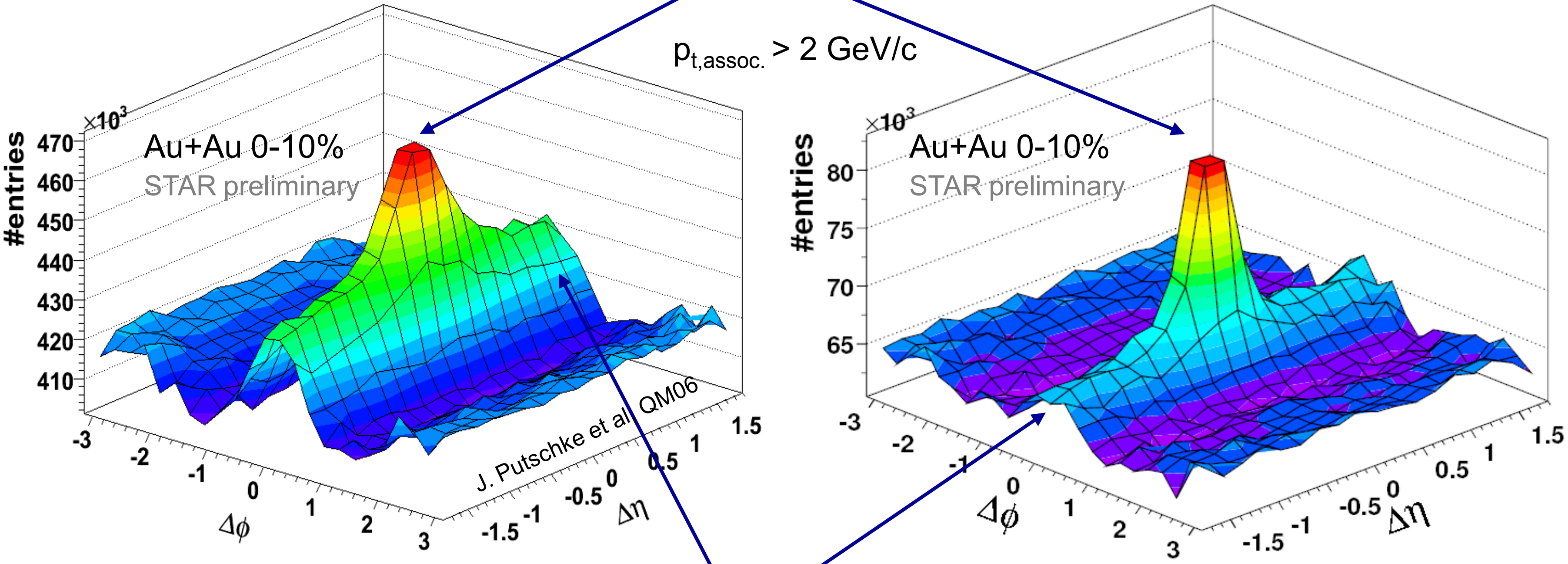
Near-side Ridge

$3 < p_{t,trig} < 4$ GeV/c

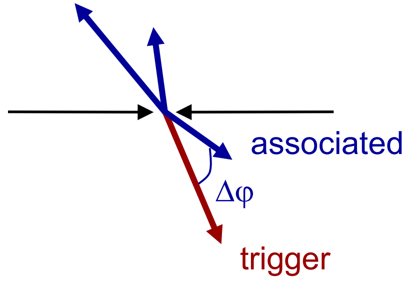
Jet-like peak

$4 < p_{t,trig} < 6$ GeV/c

$p_{t,assoc.} > 2$ GeV/c



J. Putschke et al. QM06



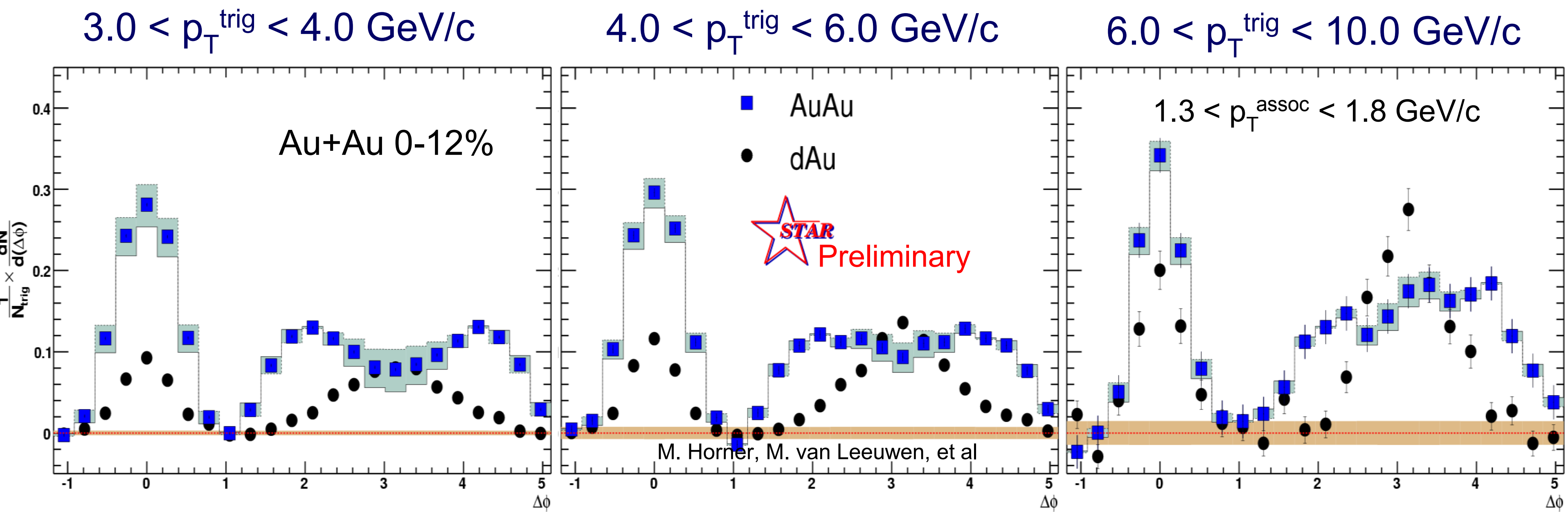
\`Ridge': associated yield at large Δη, small Δϕ

Weak dependence of ridge yield on $p_{T,trig}$

$\Rightarrow$ Relative contribution reduces with $p_{T,trig}$

Ridge softer than jet – medium response → probably v_3

Away-side shapes



$3.0 < p_T^{trig} < 4.0$ GeV/c

$4.0 < p_T^{trig} < 6.0$ GeV/c

$6.0 < p_T^{trig} < 10.0$ GeV/c

Au+Au 0-12%

$1.3 < p_T^{assoc} < 1.8$ GeV/c

M. Horner, M. van Leeuwen, et al

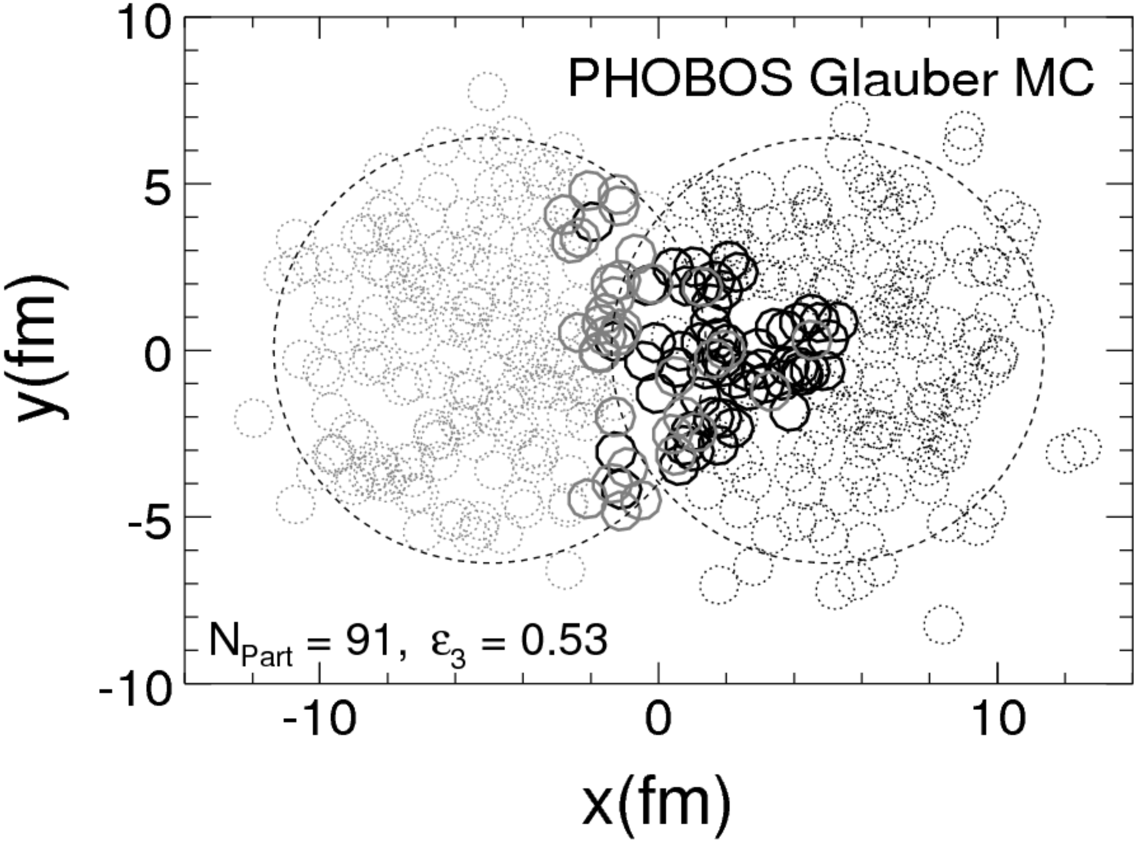
Low p_T^{trig}: broad shape, two peaks

High p_T^{trig}: broad shape, single peak

Fragmentation becomes ‘cleaner’ as p_T^{trig} goes up

Suggests kinematic effect?

v_3, triangular flow



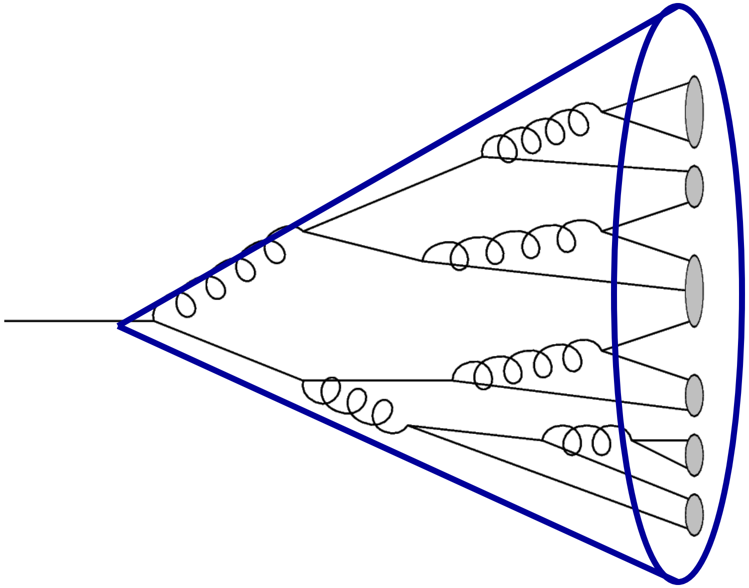
Alver and Roland, PRC81, 054905

Participant fluctuations lead to triangular component of initial state anisotropy

This may well be the underlying mechanism for both ‘ridge’ and ‘Mach cone’

Jet reconstruction

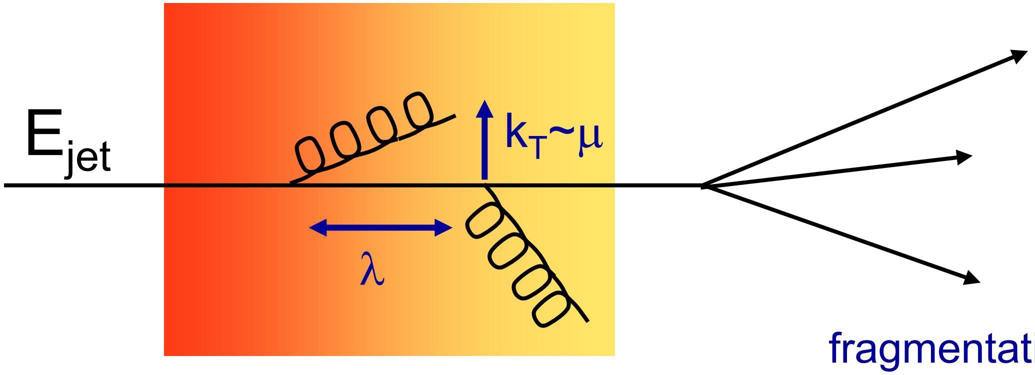
Single, di-hadrons: focus on a few fragments of the shower
→ No information about initial parton energy in each event



Jet finding: sum up fragments in a ‘jet cone’
Main idea: recover radiated energy – determine energy of initial parton
Feasibility depends on background fluctuations, angular broadening of jets

Need: tracking or Hadron Calorimeter **and** EMCal (π^0)

Generic expectations from energy loss

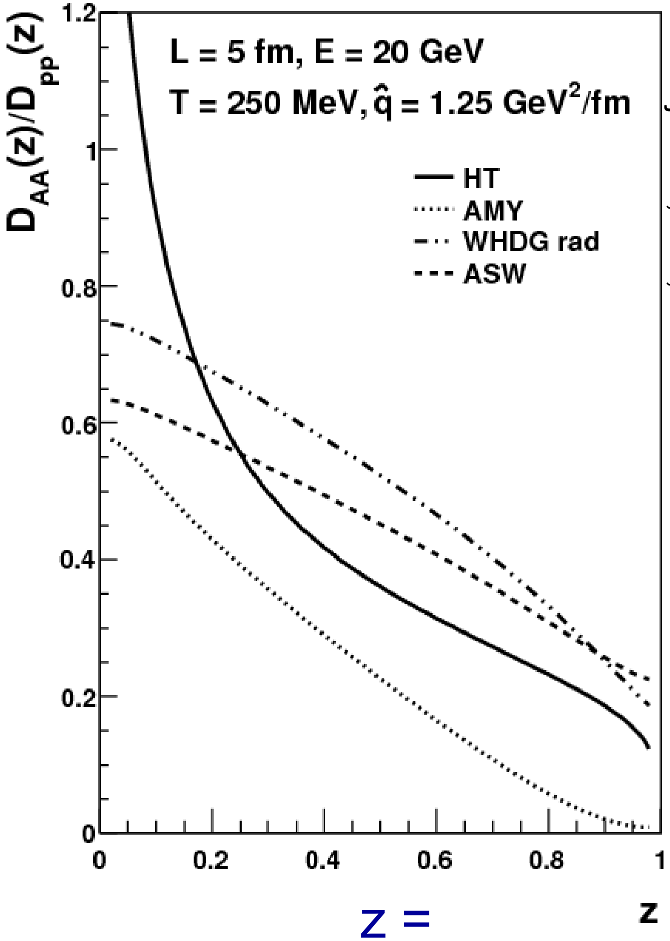


fragmentation
after energy loss?

- Longitudinal modification:
  - out-of-cone ⇒ energy lost, suppression of yield, di-jet energy imbalance
  - in-cone ⇒ softening of fragmentation
- Transverse modification
  - out-of-cone ⇒ increase acoplanarity k_T
  - in-cone ⇒ broadening of jet-profile

Modified fragmentation functions

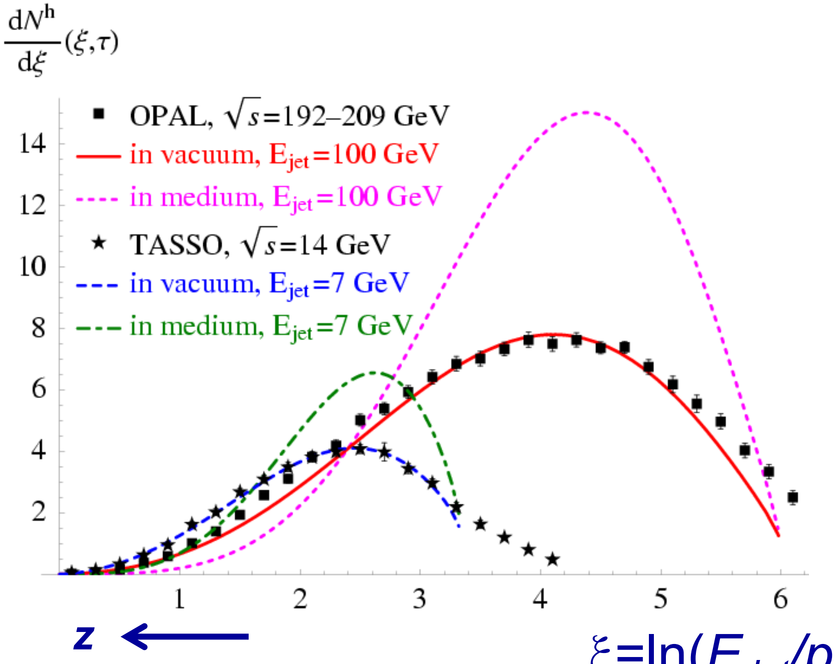
Fragmentation function ratio



A. Majumder, MvL, arXiv:1002.2206

$z = p_{h||}/E_{jet}$

Fragmentation function
'Hump-backed plateau'

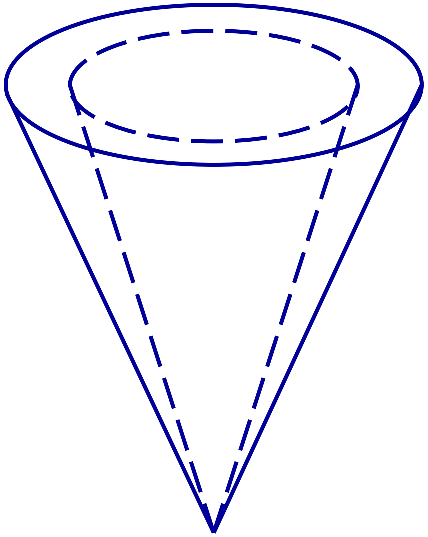


$\xi = \ln(E_{Jet}/p_{hadron})$

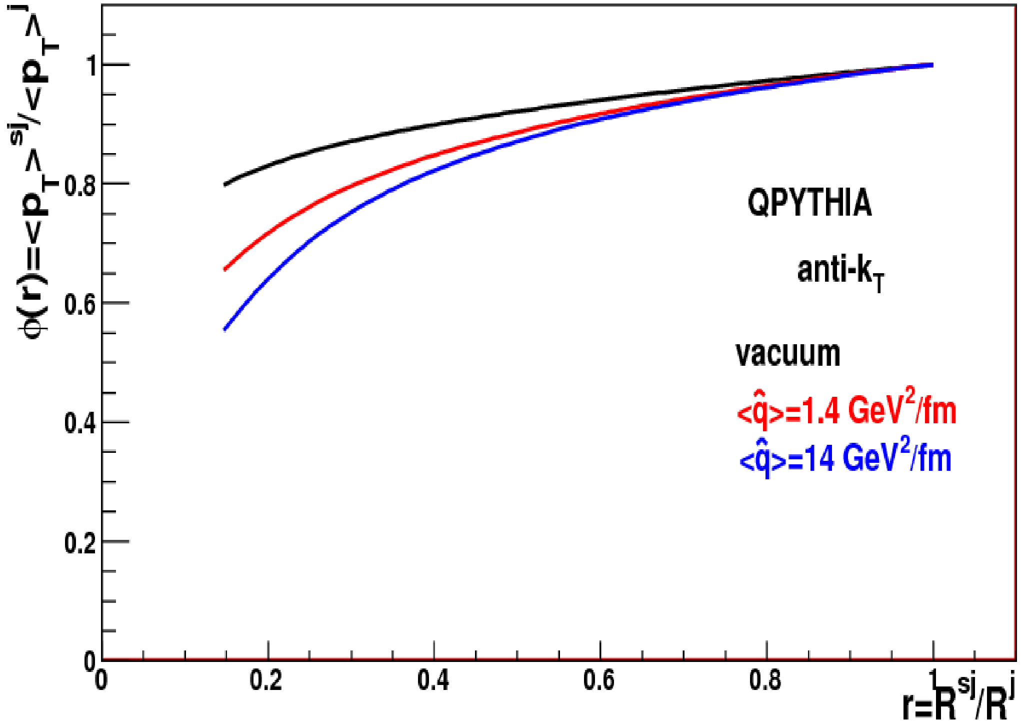
Borghini and Wiedemann

Expect softening of fragmentations: fewer fragments at high p_T, more at low p_T

Jet shapes



Energy distribution
in sub-jets



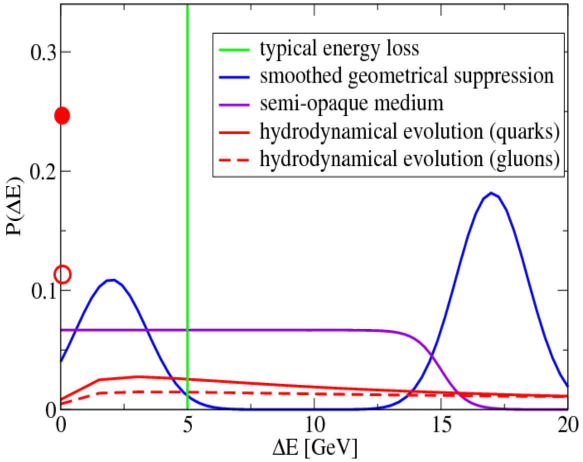
q-Pythia, Eur Phys J C 63, 679

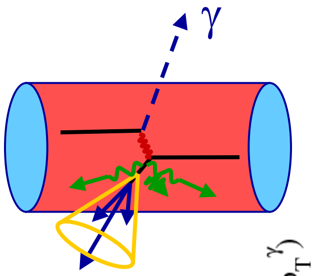
Energy loss changes radial
distribution of energy

Several ‘new’ observables considered
Discussion: sensitivity ⇔ viability … ongoing

Fixing the parton energy with γ-jet events

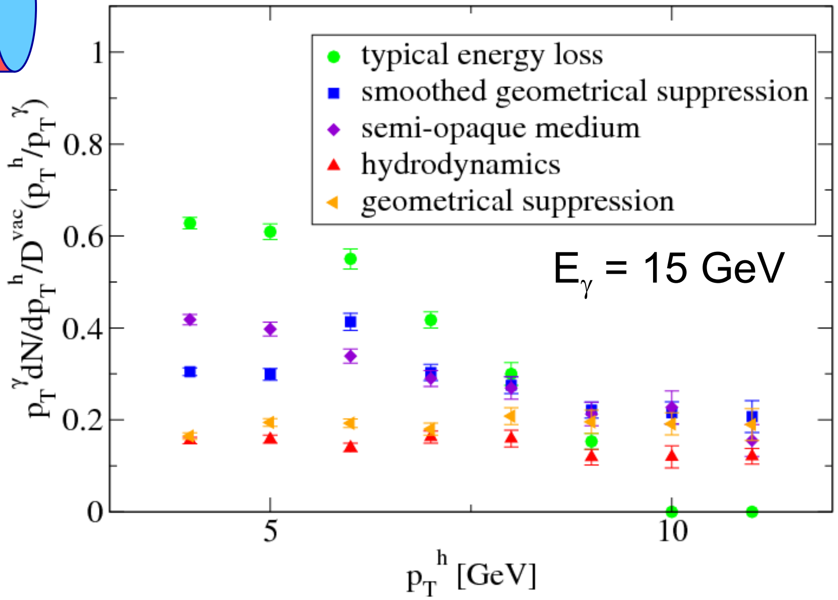
Input energy loss distribution





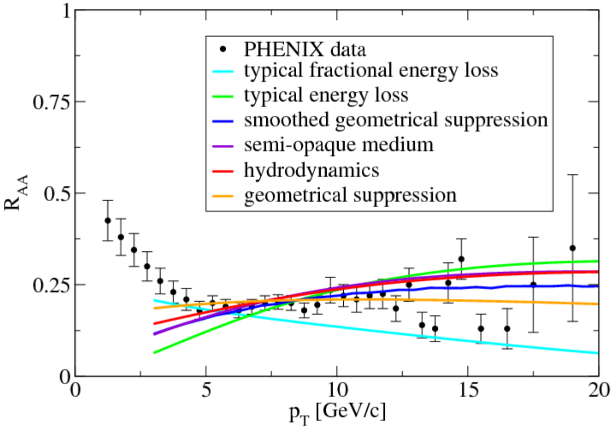
T. Renk, PRC74, 034906

Away-side spectra in γ-jet



Away-side spectra for γ-jet are sensitive to $P(\Delta E)$

Nuclear modification factor

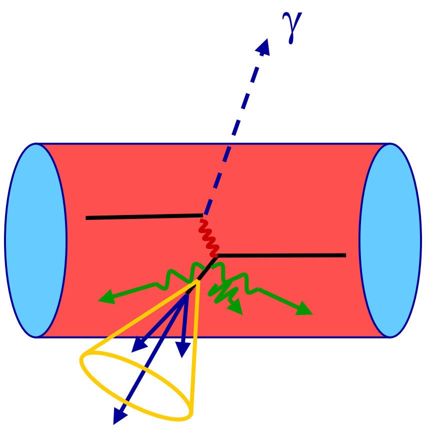


R_{AA} insensitive to $P(\Delta E)$

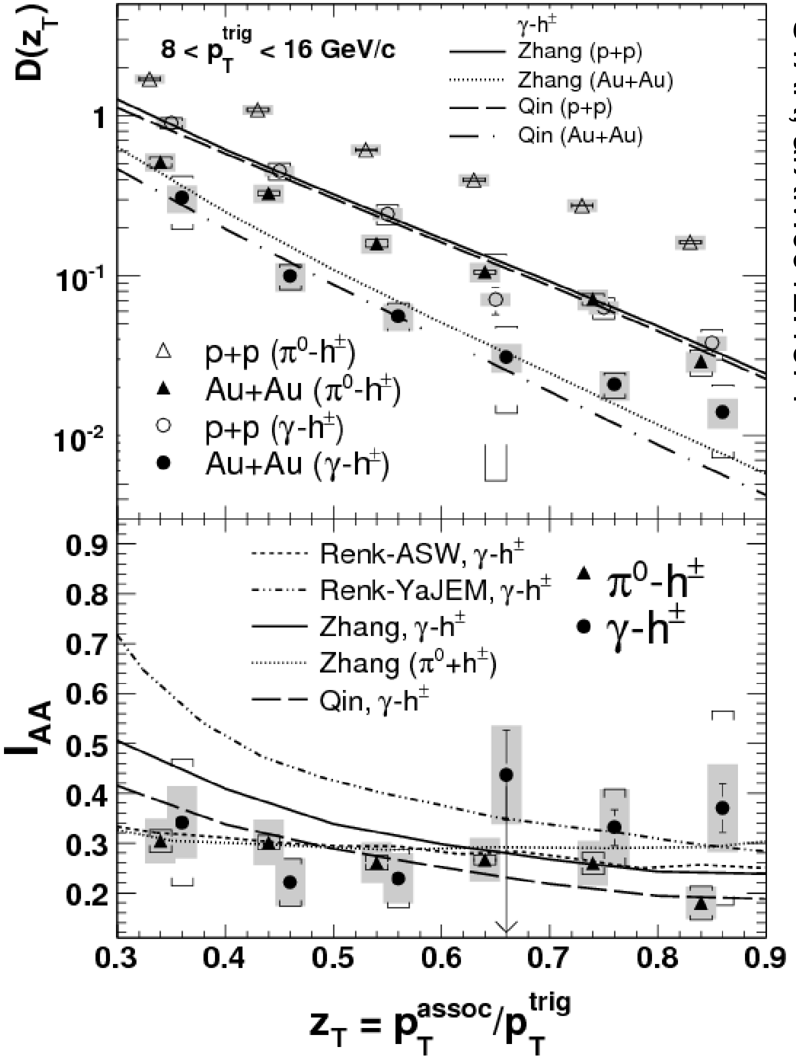
γ-jet: know jet energy $\Rightarrow$ sensitive to $P(\Delta E)$

Direct-γ recoil suppression

$8 < E_{T,\gamma} < 16$ GeV



$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$



STAR, arXiv:0912.1871

Large suppression for away-side: factor 3-5

Reasonable agreement with model predictions

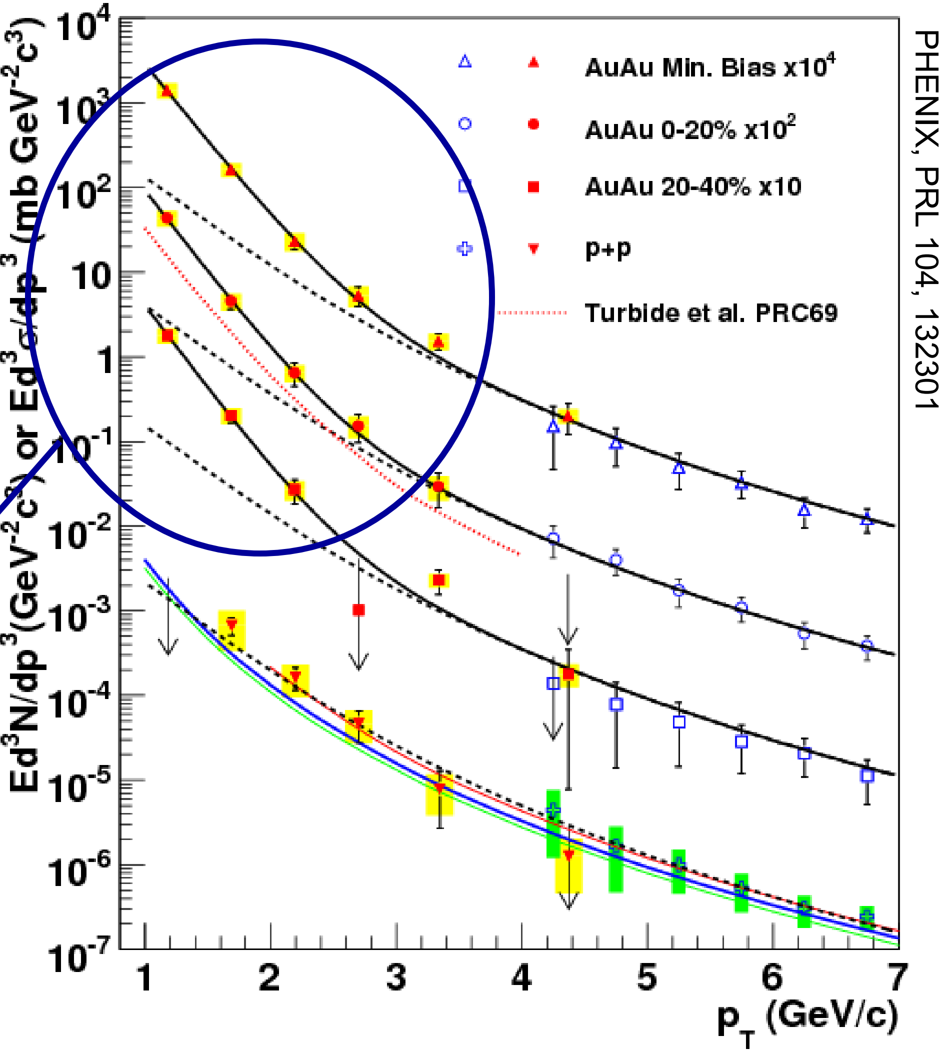
NB: gamma p_T = jet p_T still not very large

Thermal photons

Idea: hot quark-gluon matter radiates photons which escape

Difficult measurement:

- Large background $\pi^0 \rightarrow \gamma\gamma$
- Thermal photons at low p_T



PHENIX, PRL 104, 132301

Excess of photons seen at RHIC

Jet reconstruction algorithms

Two categories of jet algorithms:

- Sequential recombination k_T, anti-k_T, Durham
  - Define distance measure, e.g. $d_{ij} = \min(p_{Ti},p_{Tj})*R_{ij}$
  - Cluster closest
- Cone
  - Draw Cone radius R around starting point
  - Iterate until stable $\eta,\varphi_{jet} = <\eta,\varphi>_{particles}$

Sum particles inside jet

Different prescriptions exist, most natural: E-scheme, sum 4-vectors

Jet is an object defined by jet algorithm
If parameters are right, may approximate parton

For a complete discussion, see: http://www.lpthe.jussieu.fr/~salam/teaching/PhD-courses.html

Collinear and infrared safety

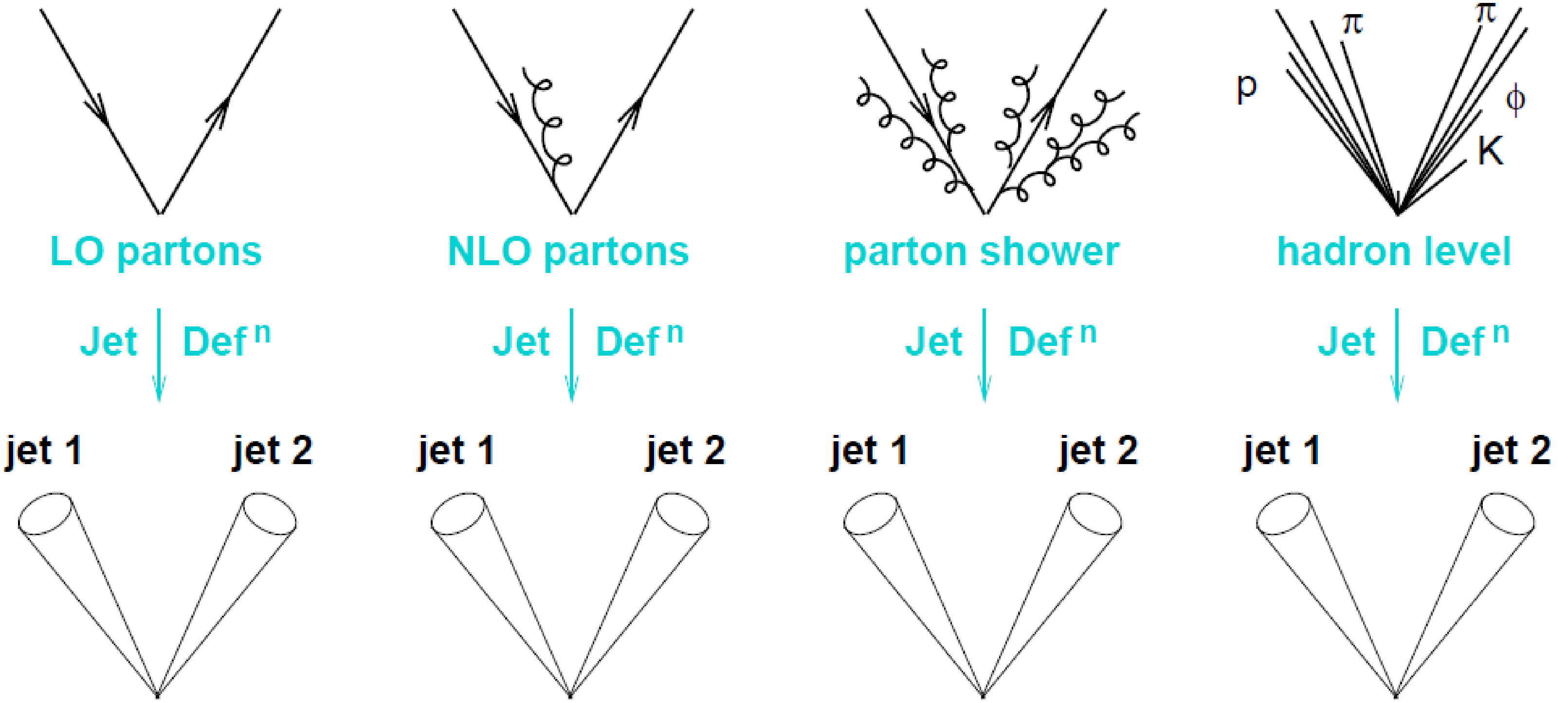


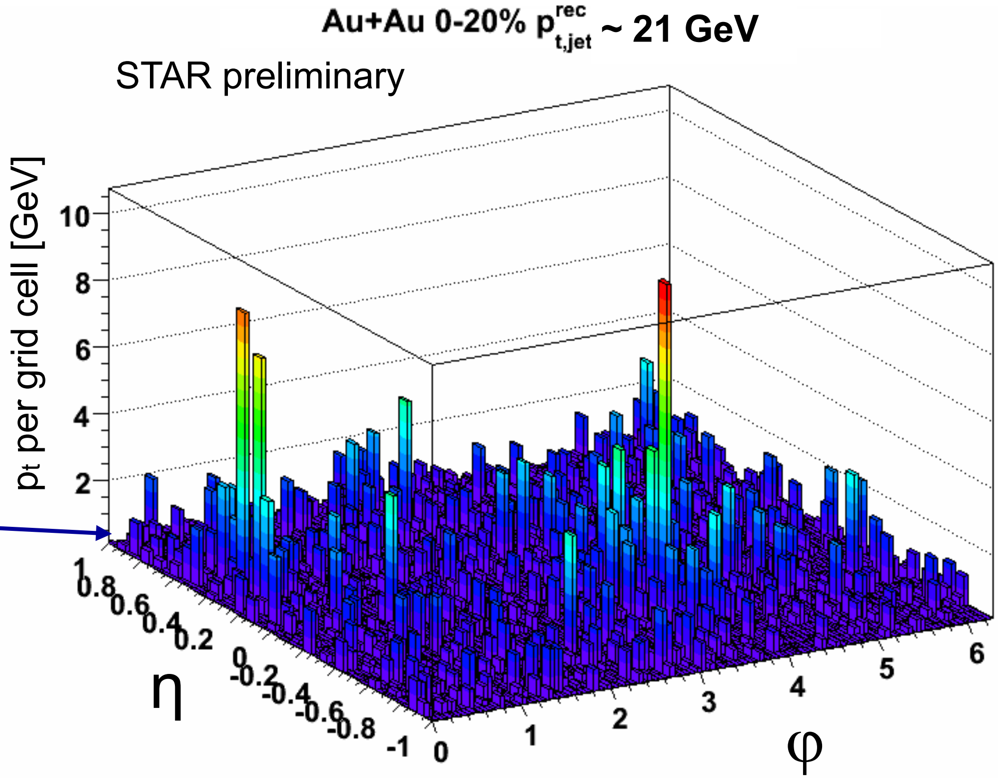
Illustration by G. Salam

Jets should not be sensitive to soft effects (hadronisation and E-loss)

- Collinear safe
- Infrared safe

Jet finding in heavy ion events

Jets clearly visible in heavy ion events at RHIC



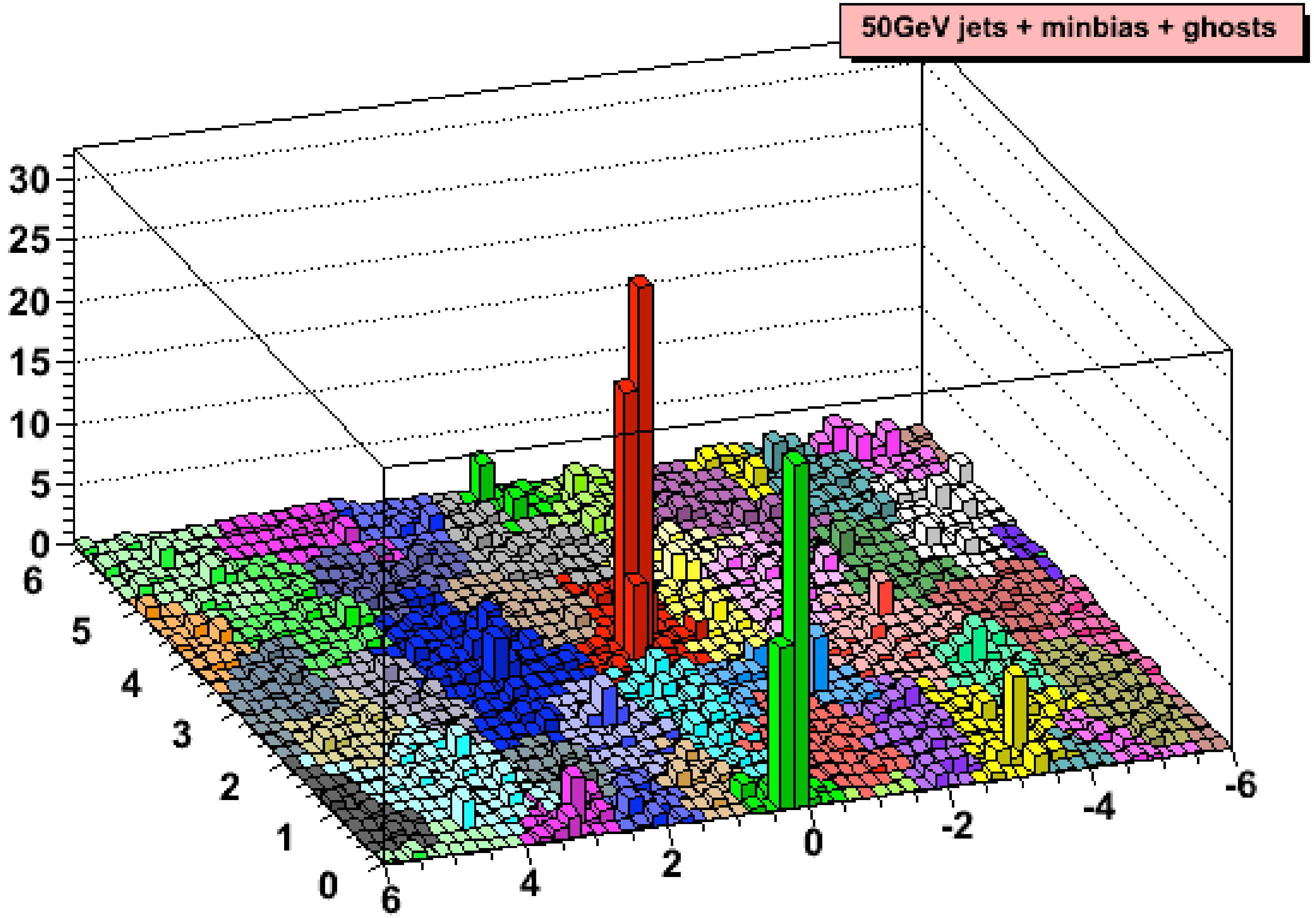
Combinatorial background
Needs to be subtracted

Use different algorithms to estimate systematic uncertainties:

- Cone-type algorithms
  simple cone, iterative cone, infrared safe SISCone
- Sequential recombination algorithms
  k_T, Cambridge, inverse k_T

http://rhig.physics.yale.edu/~putschke/Ahijf/A_Heavy_Ion_Jet-Finder.html
FastJet:Cacciari, Salam and Soyez; arXiv: 0802.1188

Jet finding with background

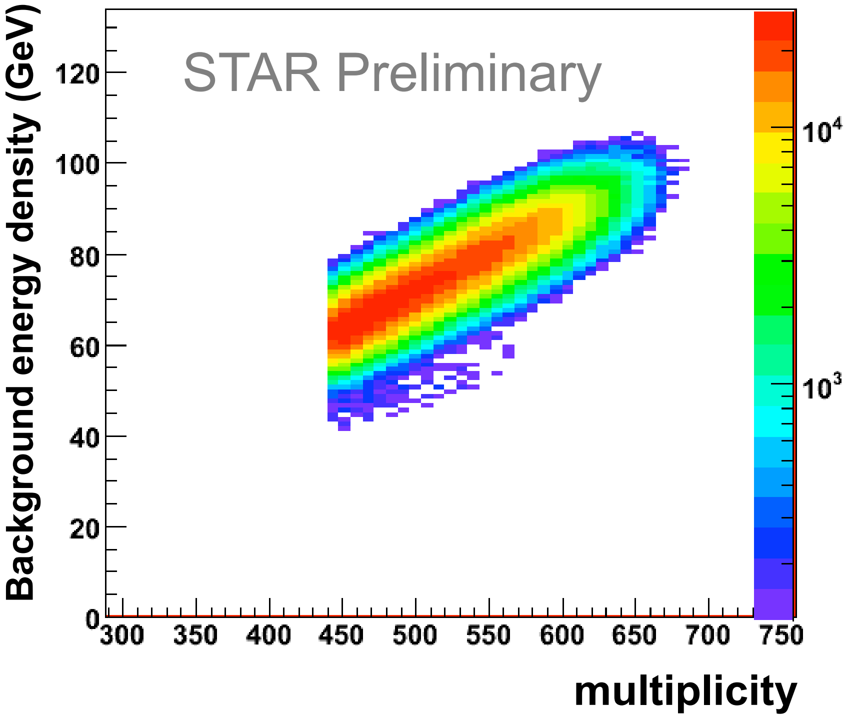


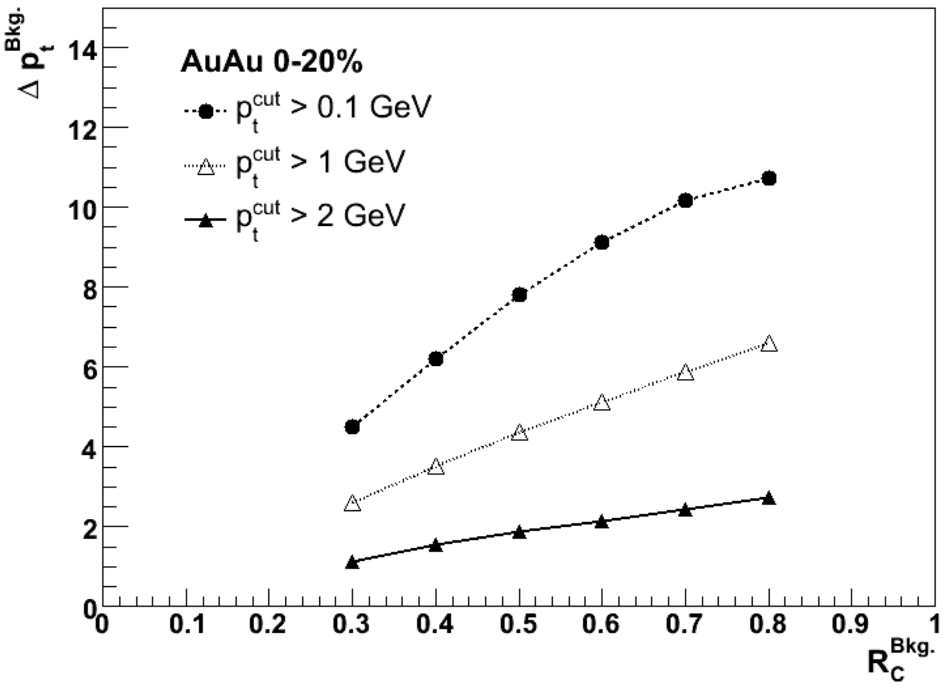
By definition: all particles end up in *a* jet

With background: all η-φ space filled with jets

Many of these jets are ‘background jets’

Background subtraction

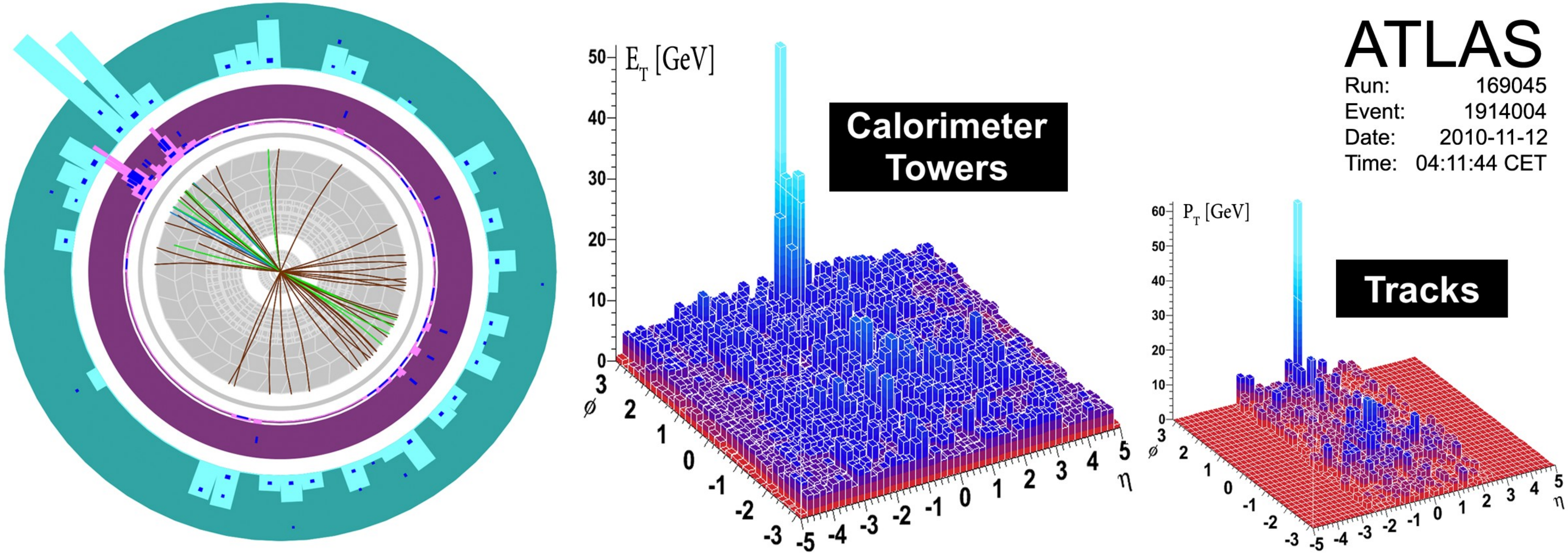




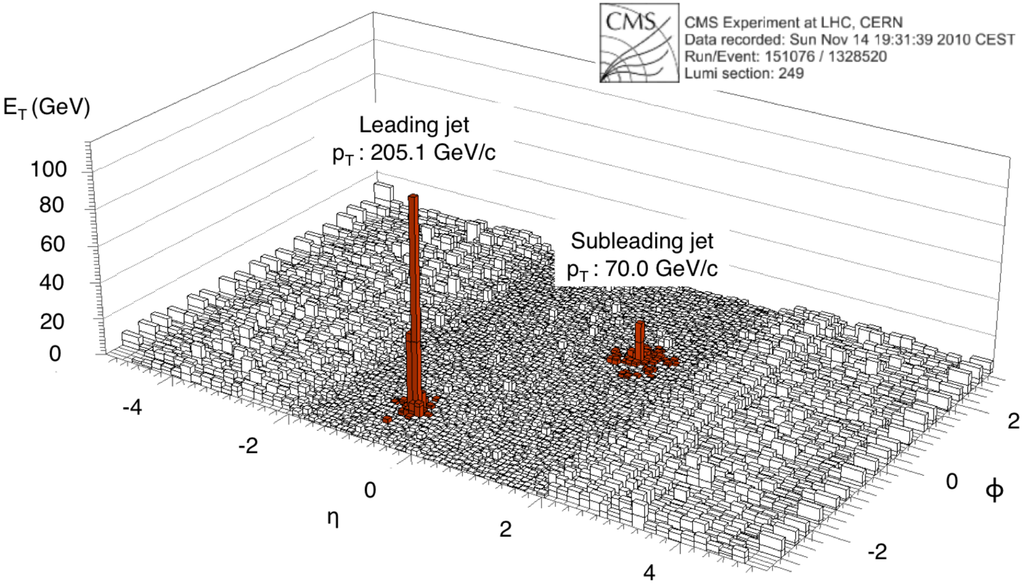
Background density at RHIC:
60-100 GeV
Strong dependence on centrality

Fluctuations remain after subtraction:
RMS up to 10 GeV

Jets at LHC



Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET



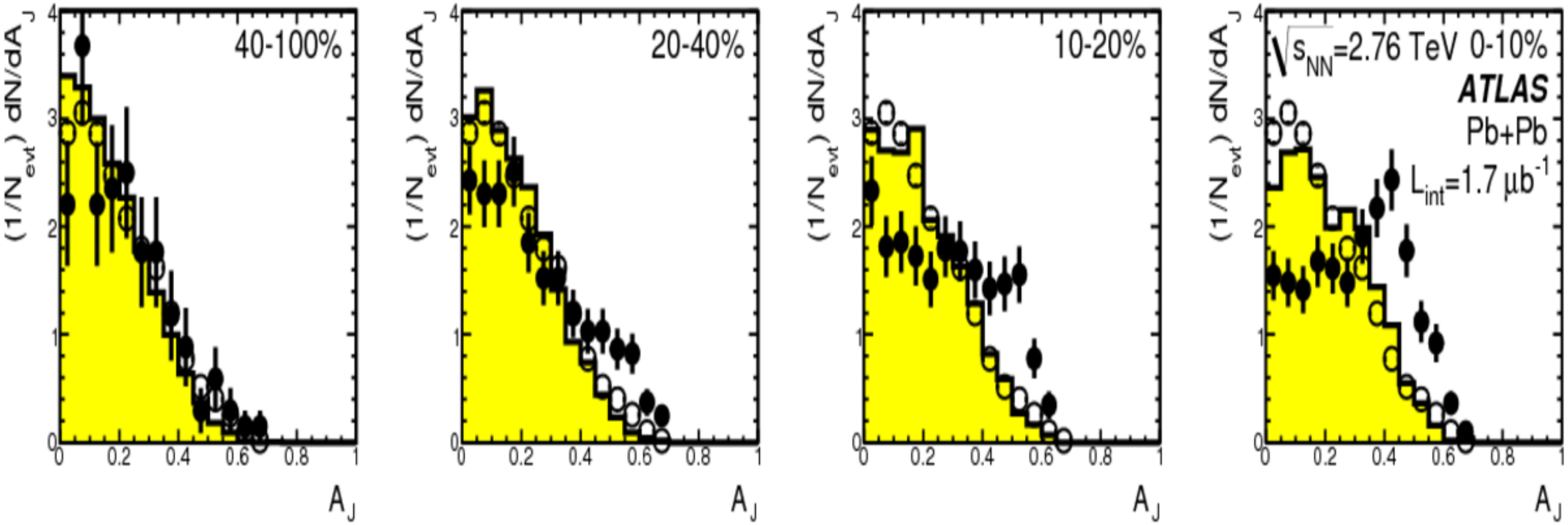
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

LHC: jet energies up to ~200 GeV in Pb+Pb from 1 ‘short’ run

Large energy asymmetry observed for central events

Jets at LHC

Centrality



ATLAS, arXiv:1011.6182 (PRL)

Jet-energy asymmetry $A_J = \dfrac{E_2 - E_1}{E_2 + E_1}$

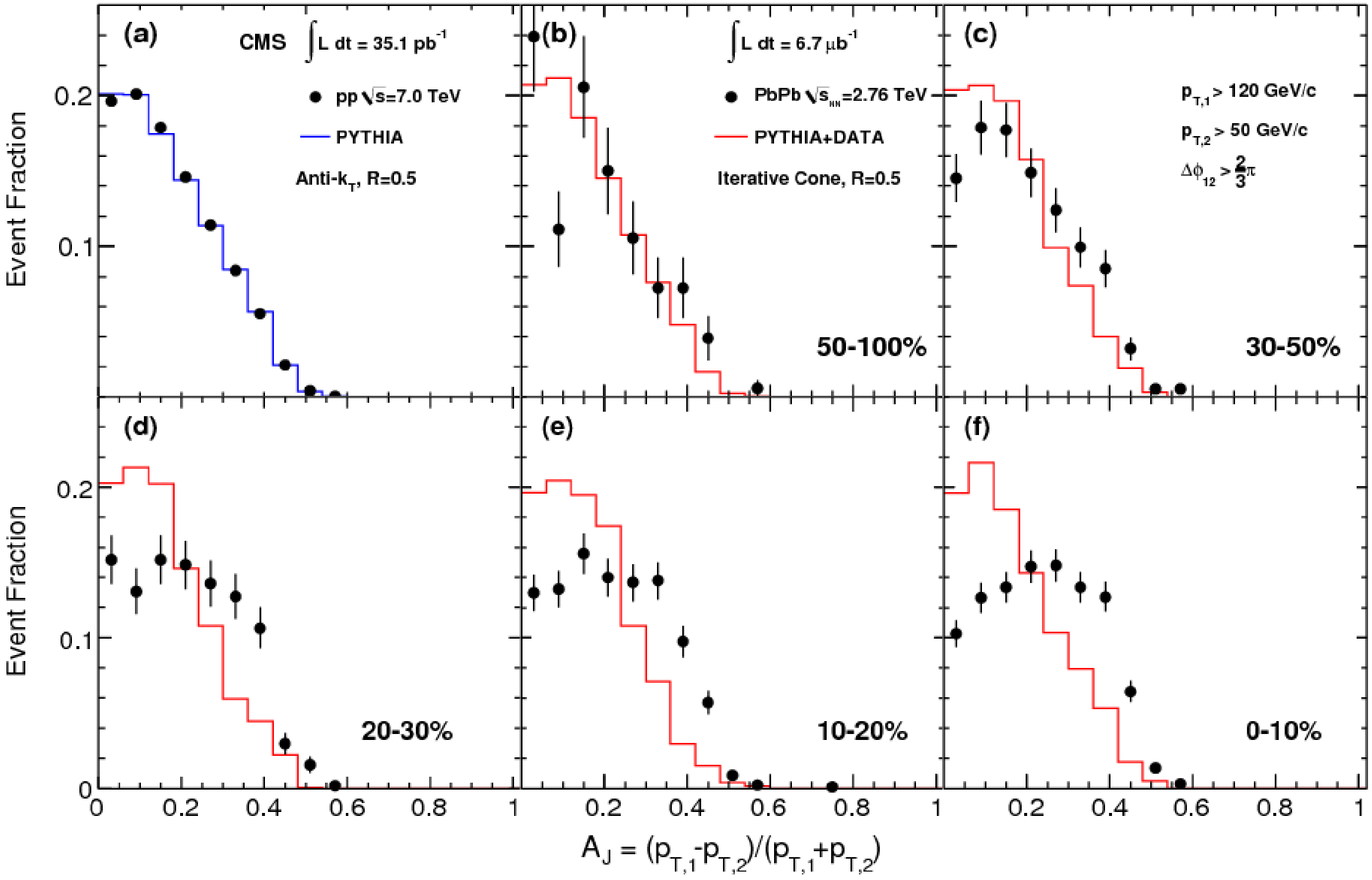
Large asymmetry seen
for central events

Energy losses: tens of GeV, ~ expected from BDMPS, GLV etc
beyond kinematic reach at RHIC

N.B. only measures reconstructed di-jets
Does not show ‘lost’ jets

Large effect on recoil: qualitatively consistent with RHIC jet I_{AA}

Jets at LHC



CMS, arXiv:1102.1957

CMS sees similar asymmetries

Summary

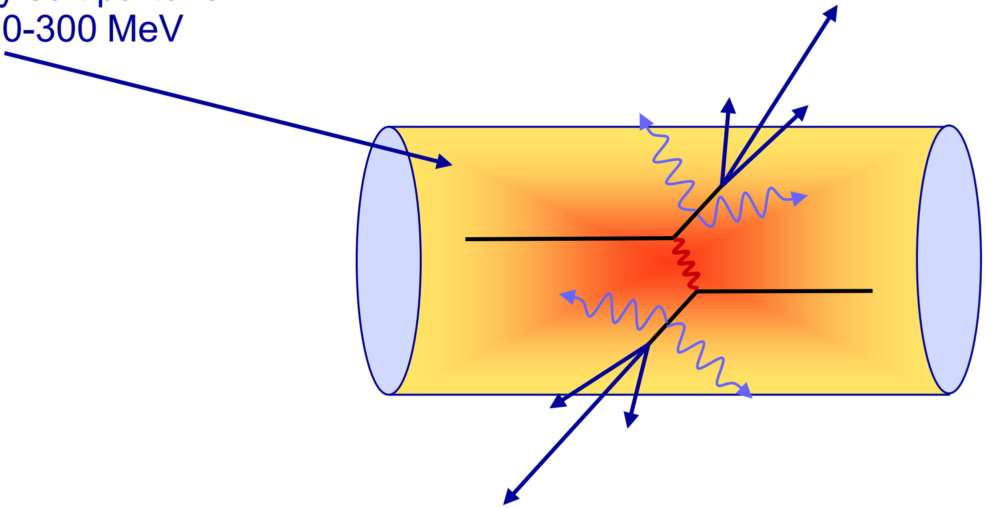
- Hard processes can be used to probe quark-gluon matter
- So far: main focus on energy loss of (leading) high-p_T hadrons
  - Integrates over initial energy, energy-loss
- For radiative energy loss expect $\Delta E \propto L^2$
  - Di-hadron recoil suppression confirms this
  - Azimuthal dependence of energy loss (v_2 at high p_T) not yet quantitatively understood
- Future directions: better handle on initial parton energy
  - Jet finding
  - γ-jet

Extra slides

Hard probes of QCD matter

Heavy-ion collisions produce
'quasi-thermal' QCD matter

Dominated by soft partons
p ~ T ~ 100-300 MeV



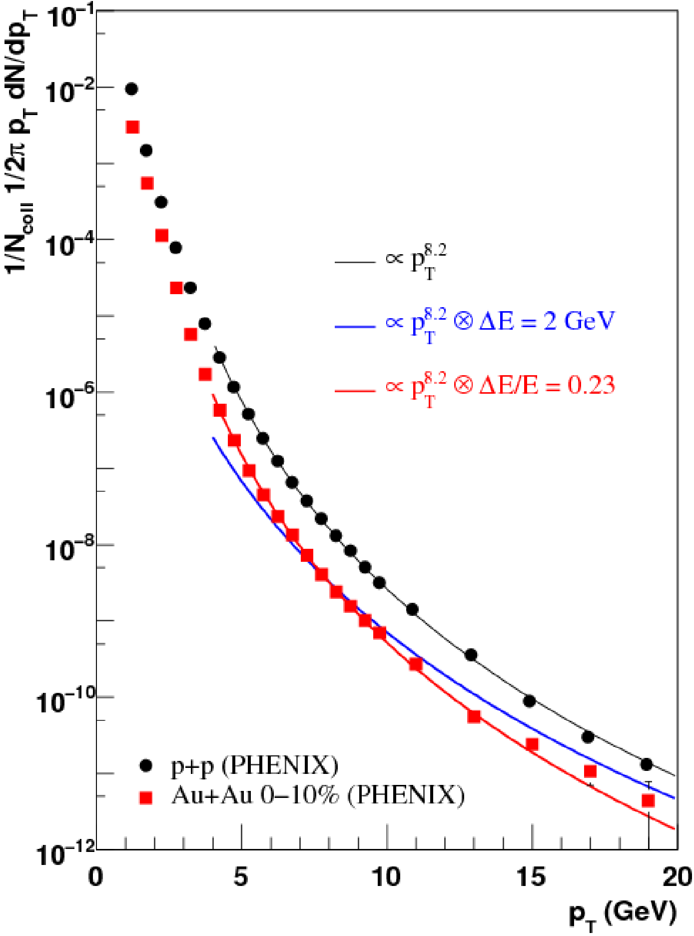
Hard-scatterings produce 'quasi-free' partons
⇒ Initial-state production known from pQCD
⇒ Probe medium through energy loss

Use the strength of pQCD to explore QCD matter

Sensitive to medium density, transport properties

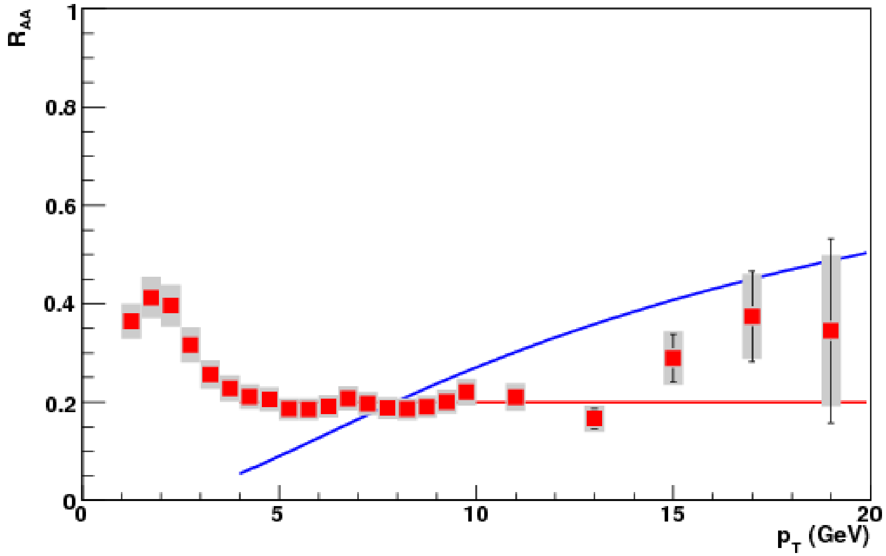
Toy model R_{AA}

π^0 spectra



PHENIX, PRD 76, 051106, arXiv:0801.4020

Nuclear modification factor



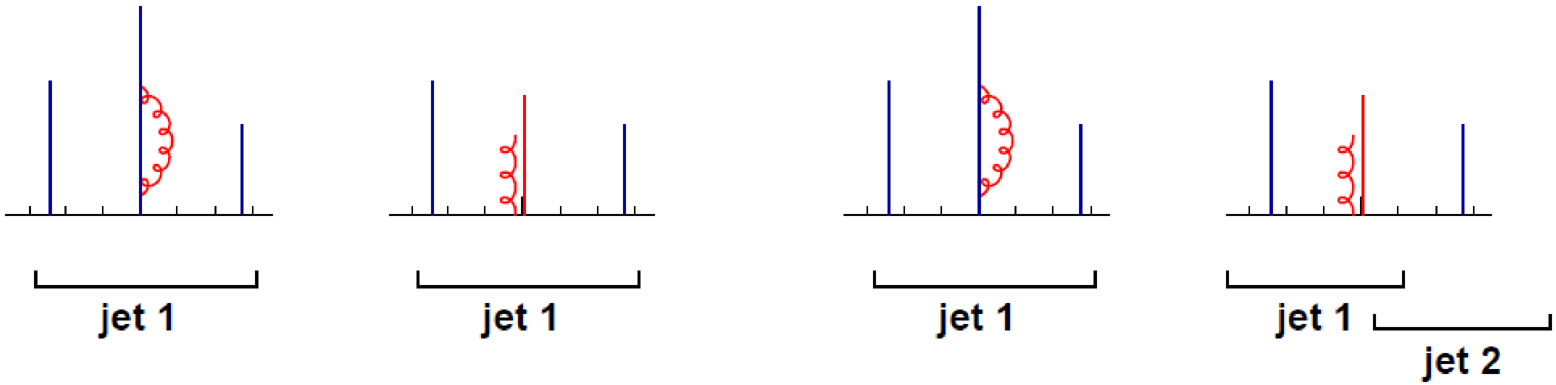
This is a cartoon!
Hadronic, not partonic energy loss
No quark-gluon difference
Energy loss not probabilistic $P(\Delta E)$

Ball-park numbers: $\Delta E/E \approx 0.2$, or $\Delta E \approx 2$ GeV
for central collisions at RHIC

Note: slope of ‘input’ spectrum changes with p_T: use experimental reach to exploit this

Collinear safety

Collinear Safe **Collinear Unsafe**



α_s^n x $(-\infty)$ α_s^n x $(+\infty)$ α_s^n x $(-\infty)$ α_s^n x $(+\infty)$

Infinities cancel **Infinities do not cancel**

Illustration by G. Salam

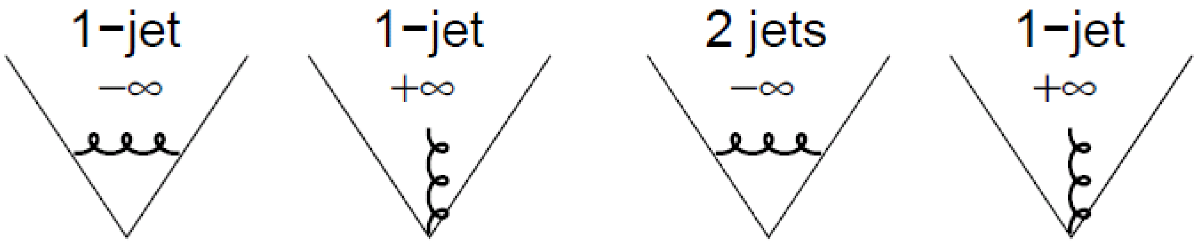
Note also: detector effects,
such as splitting clusters in calorimeter (π^0 decay)

Infrared safety

Soft emission, collinear splitting are both **infinite** in pert. QCD.

Infinities **cancel** with loop diagrams if jet-alg IRC safe

IRC safe **IRC unsafe**



sum is finite sum is infinite

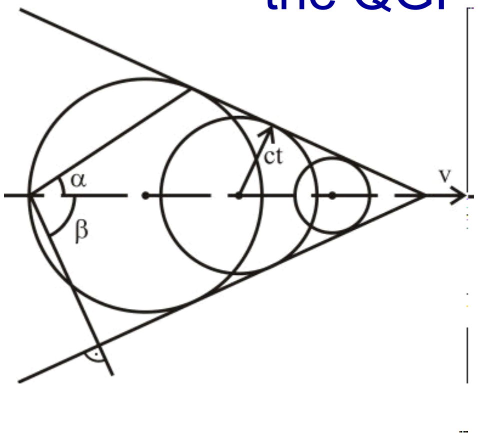
Illustration by G. Salam

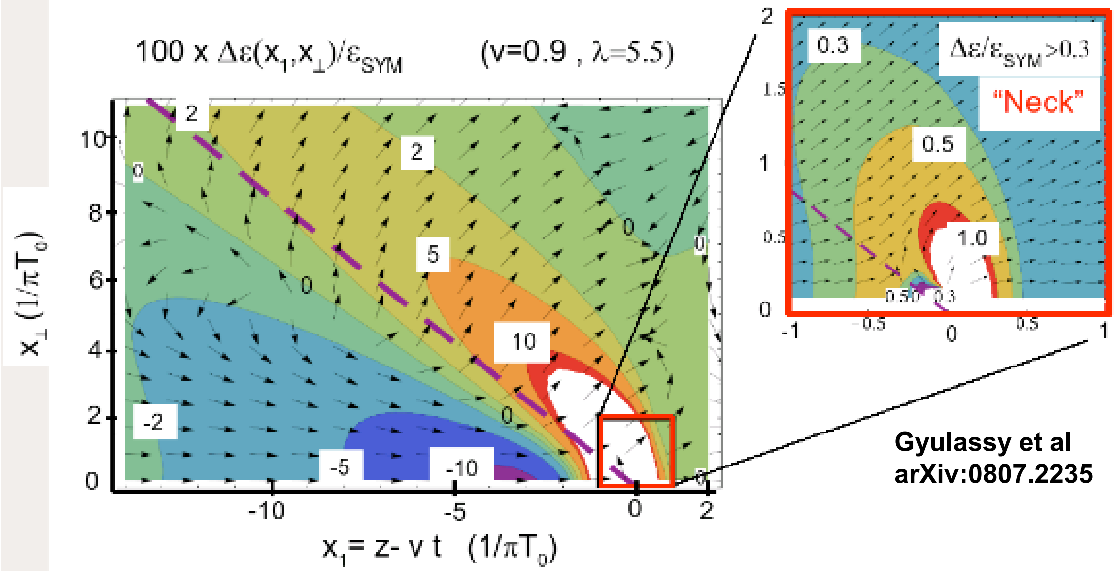
Some calculations simply become **meaningless**

Infrared safety also implies robustness
against soft background in heavy ion collisions

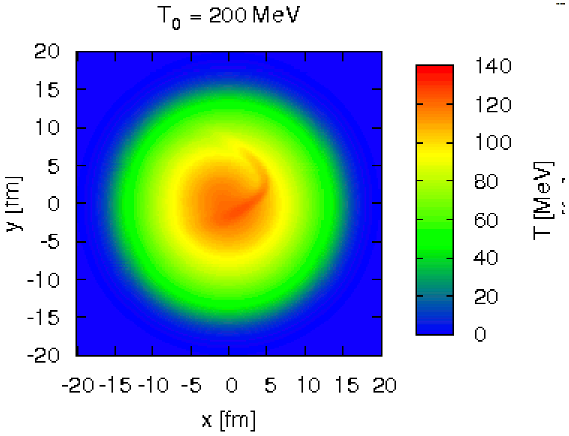
Shockwave/Mach Cone

Mach-cone/shockwave in the QGP?





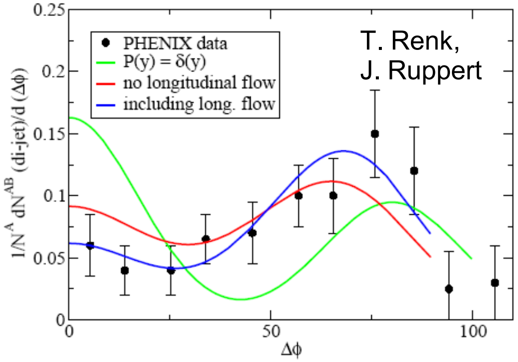
Gyulassy et al arXiv:0807.2235



B. Betz, QM09, PRC79, 034902

Exciting possibility!

Proves that QGP is really ‘bulk matter’
Measure speed of sound?



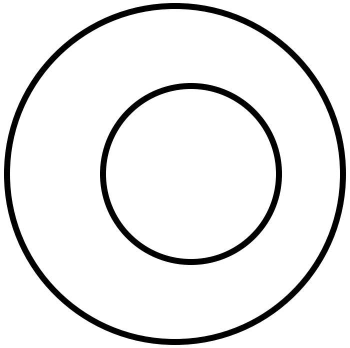
T. Renk, J. Ruppert

Are more mundane possibilities ruled out? – Not clear yet

Jet broadening II

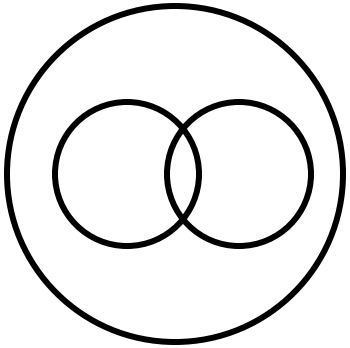
Qualitatively, two different possible scenarios

Diffuse broadening



Radiated energy
'uniformly' distributed

Hard radiation/splitting



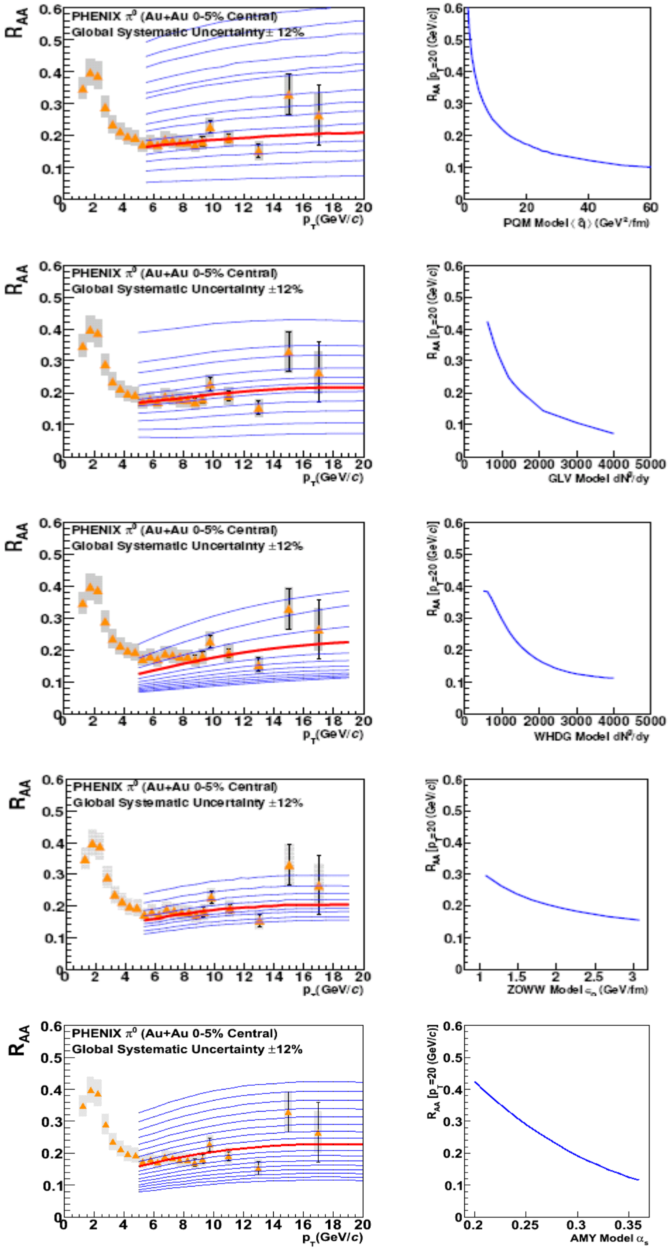
Radiated energy
directional

Different measurements:
- R(0.2/0.4)
- Transverse jet profile

May have different sensitivities

Interesting idea: sub-jet structure; so far no studies available

Determining the medium density



PHENIX, arXiv:0801.1665,
J. Nagle WWND08

For each model:

1. Vary parameter and predict R_{AA}
2. Minimize χ^2 wrt data

Models have different but ~equivalent parameters:

- Transport coeff. $\langle\hat{q}\rangle$
- Gluon density dN_g/dy
- Typical energy loss per L: ε_0
- Coupling constant α_S

Medium density from R_{AA}

PQM $\langle\hat{q}\rangle = 13.2^{+2.1}_{-3.2}$ GeV^2/fm

GLV $dN_g/dy = 1400^{+270}_{-150}$

ZOWW $\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm

WHDG $dN_g/dy = 1400^{+200}_{-375}$

AMY $\alpha_s = 0.280^{+0.016}_{-0.012}$

Data constrain model parameters to 10-20%

Method extracts medium density *given the model/calculation*
Theory uncertainties need to be further evaluated
e.g. comparing different formalisms, varying geometry

But models use different medium parameters
– How to compare the results?

Some pocket formula results

GLV/WHDG: $dN_g/dy = 1400$

$$\rho(\tau) = \frac{dN_g}{dy}\frac{1}{\tau\pi R^2} \qquad \rho(\tau_0 = 1\,\mathrm{fm}) = 12.4\,\mathrm{fm}^{-3} \qquad \rho = \frac{16\cdot 1.202}{\pi^2}T^3$$

$T(\tau_0) = 366$ MeV

PQM: $\hat{q} = 13.2\,\mathrm{GeV}^2/\mathrm{fm}$ (parton average)

$$\hat{q} = \frac{72\cdot 1.202\,\alpha_s^2}{\pi}T^3$$

T = 1016 MeV

AMY: T fixed by hydro (~400 MeV), $\alpha_s = 0.297$

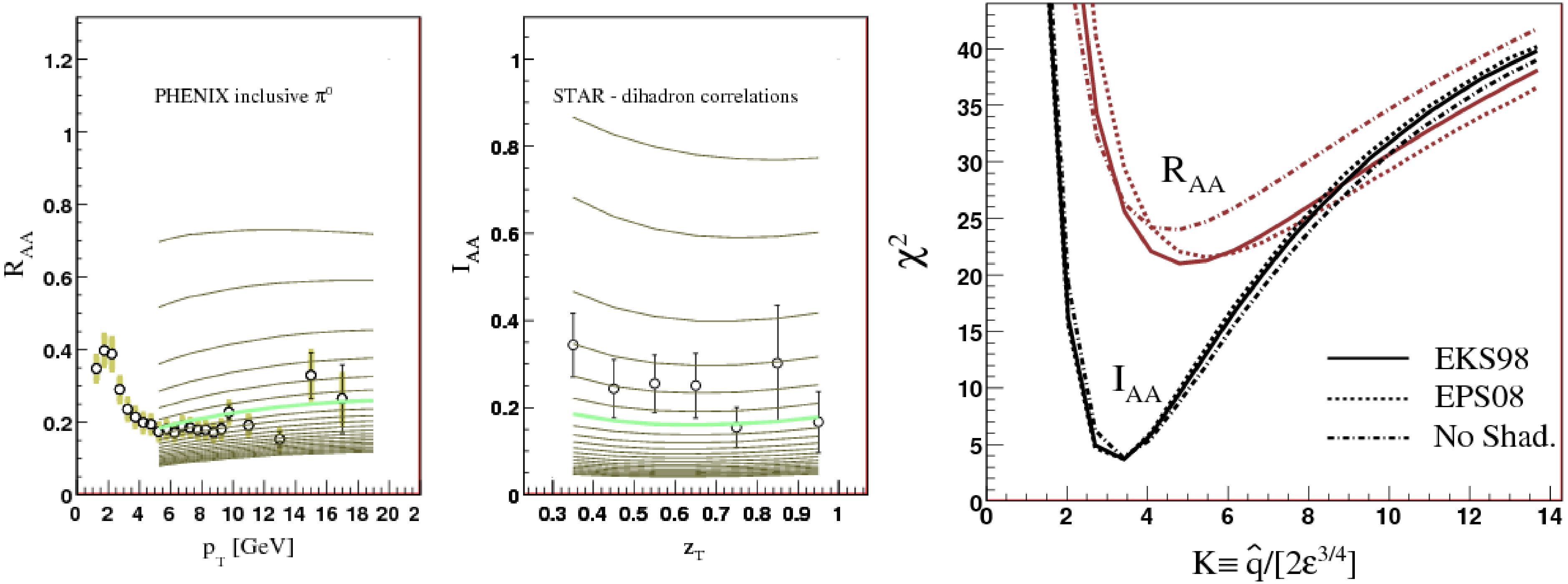
Large differences between models

– After long discussions, it turns out that most of these differences are mostly due to uncontrolled approximations in the calculations

→ Best guess: the truth is somewhere in-between

Comparing single- and di-hadron results

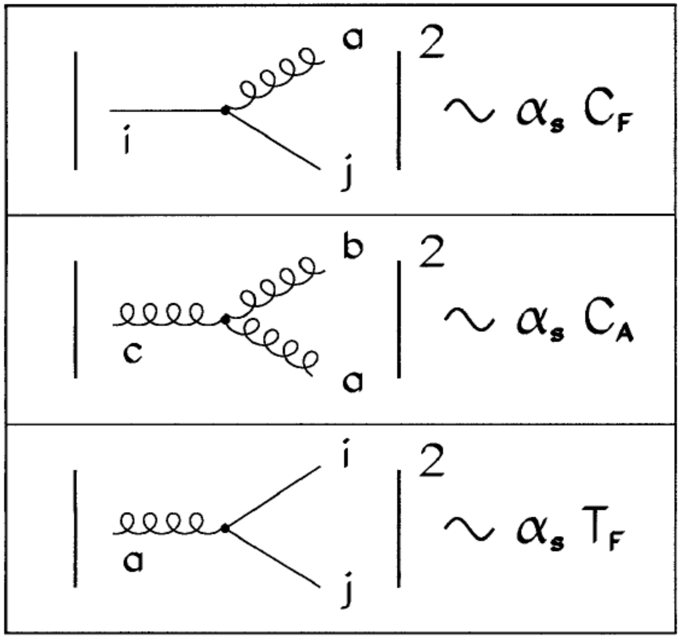
Armesto, Cacciari, Salgado et al.



R_{AA} and I_{AA} fit with similar density

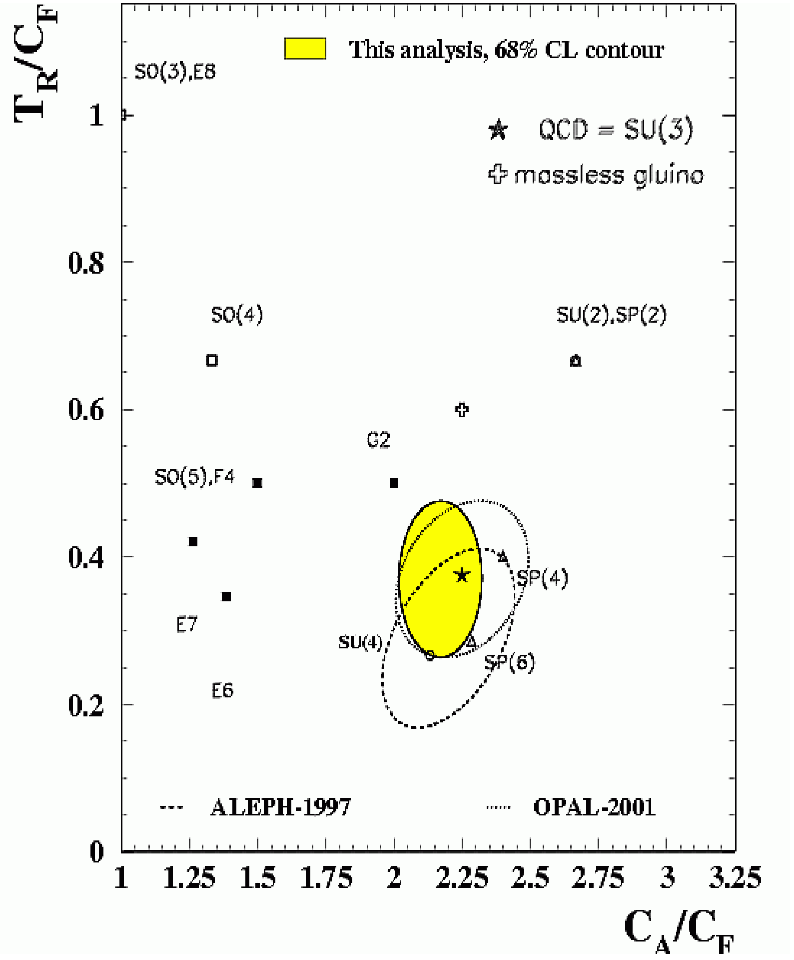
Calculation uses LPM-effect, L^2 dependence

Color factors



C_F ~ strength of a gluon coupling to a quark
C_A ~ strength of the gluon self coupling
T_F ~ strength of gluon splitting into a quark pair

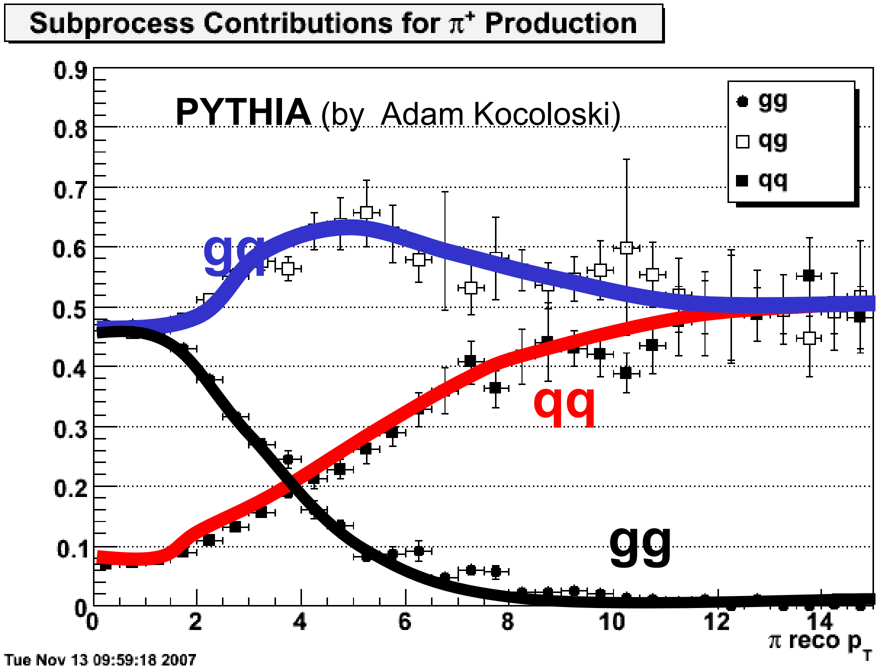
Color factors measured at LEP

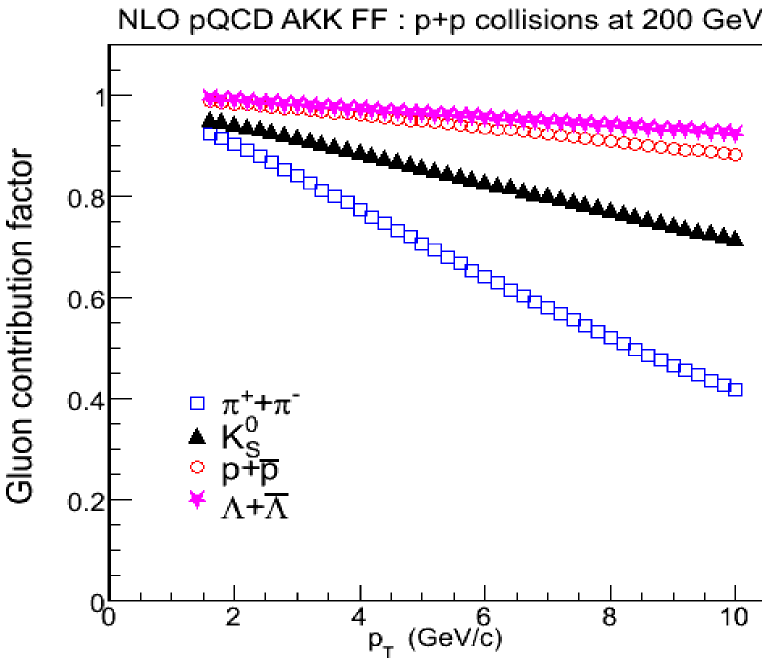


$$\text{Expect} \quad \frac{\Delta E_g}{\Delta E_q} = \frac{C_A}{C_F} = \frac{9}{4}$$

gluons radiate ~ twice more energy than quarks

Subprocesses and quark vs gluon

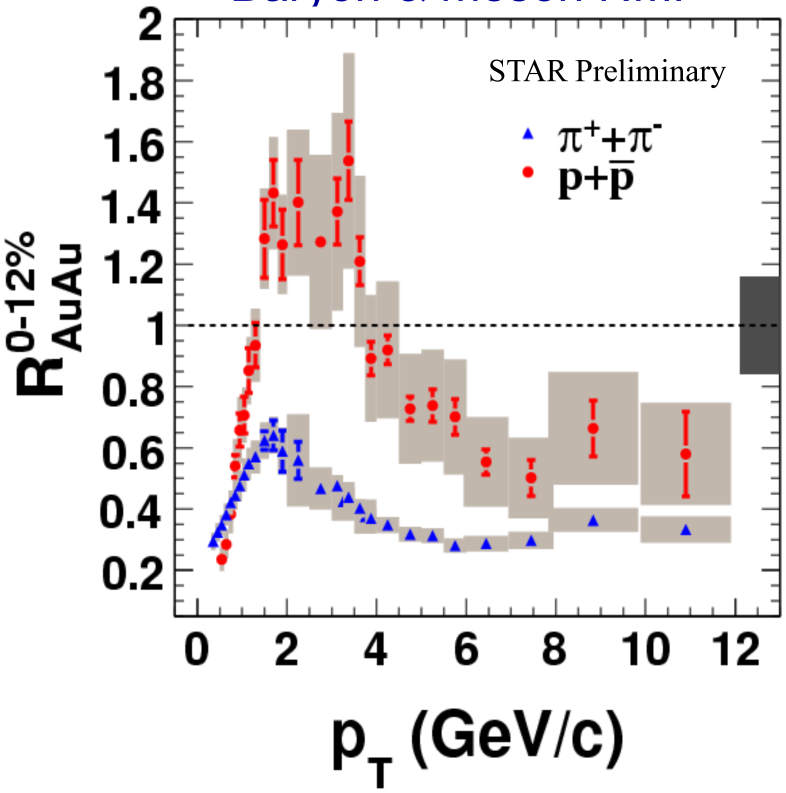




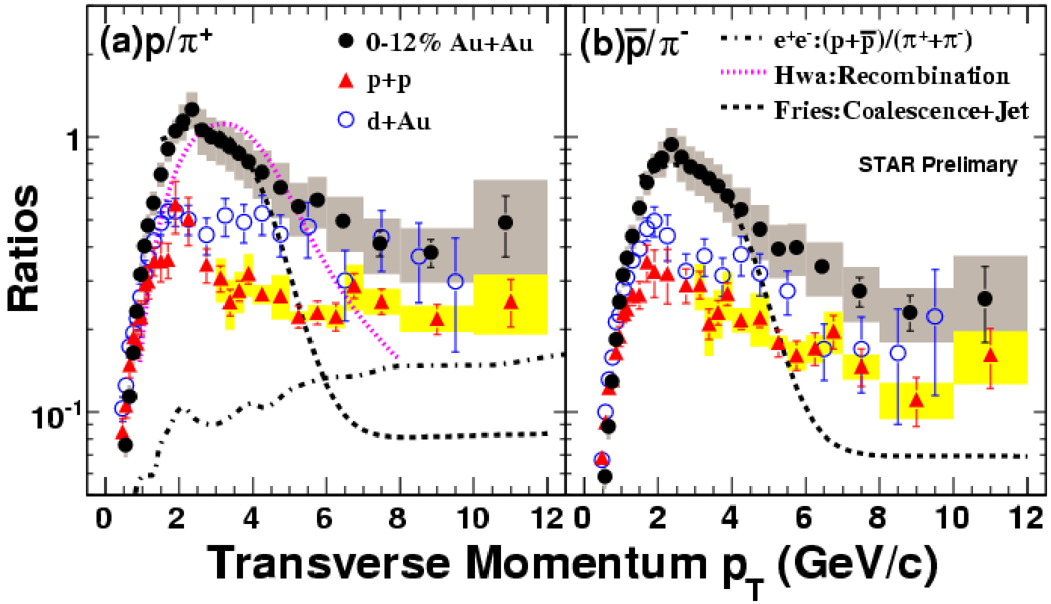
p+pbar dominantly from gluon fragmentation

Comparing quark and gluon suppression

Baryon & meson NMF



PRL 97, 152301 (2006)
STAR Preliminary, QM08

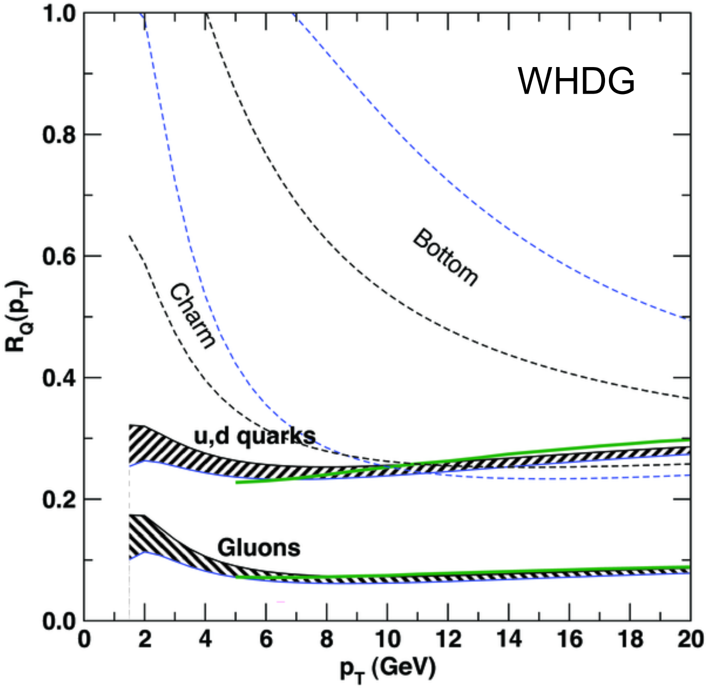


Protons less suppressed than pions, not more

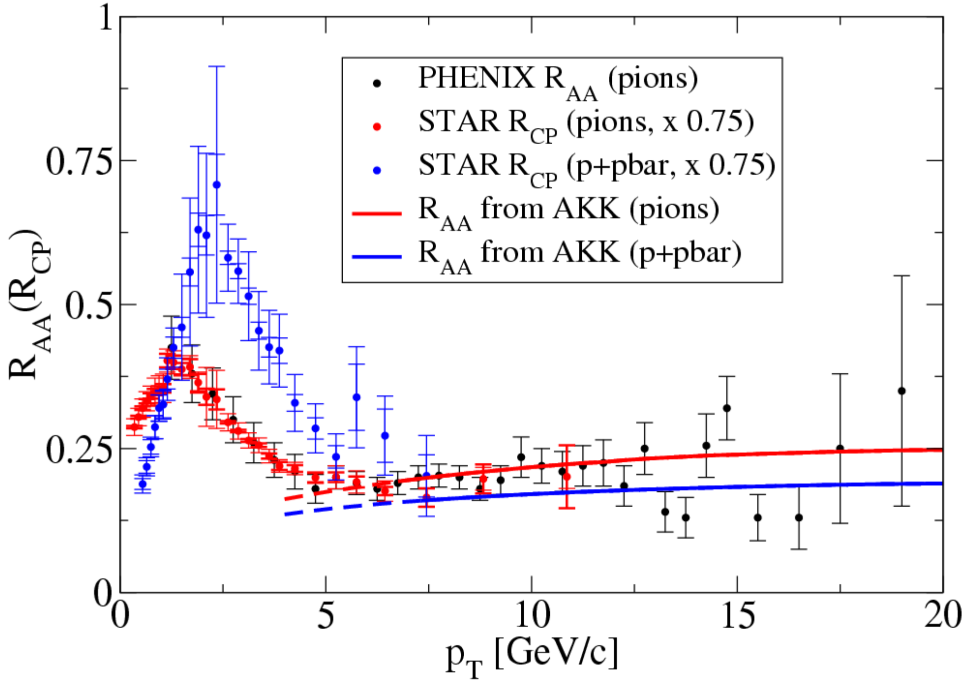
No sign of large gluon energy loss

Quark vs gluon suppression

GLV formalism



BDMPS formalism



Renk and Eskola, PRC76,027901

Quark/gluon difference larger in GLV than BDMPS
(because of cut-off effects $\Delta E < E_{jet}$?)

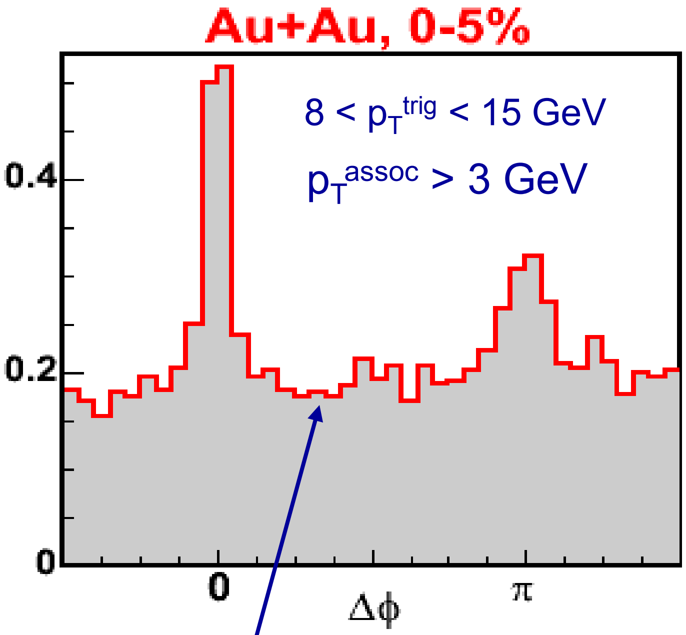
~10% baryons from quarks, so baryon/meson effect smaller than gluon/quark

Are baryon fragmentation functions under control?

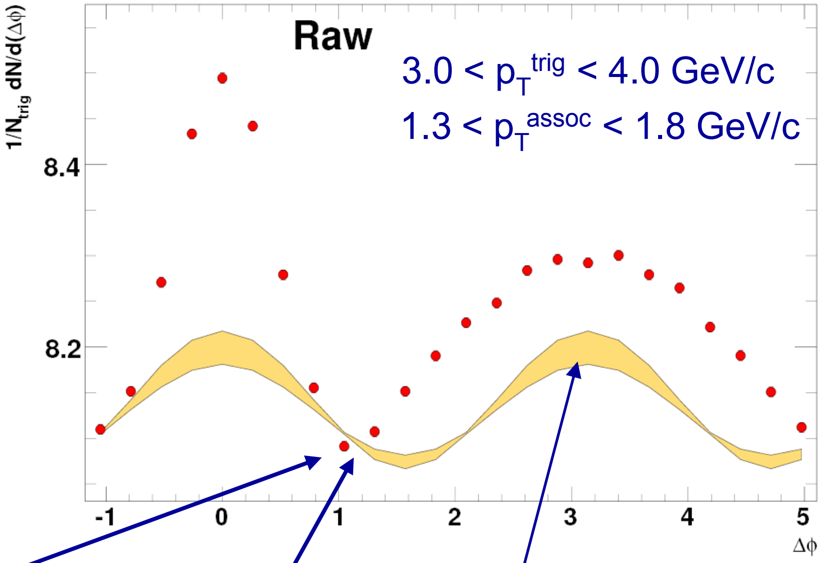
Conclusion for now: some homework to do...

The fine-print: background

High p_T: background <~ signal



Low p_T: background >> signal



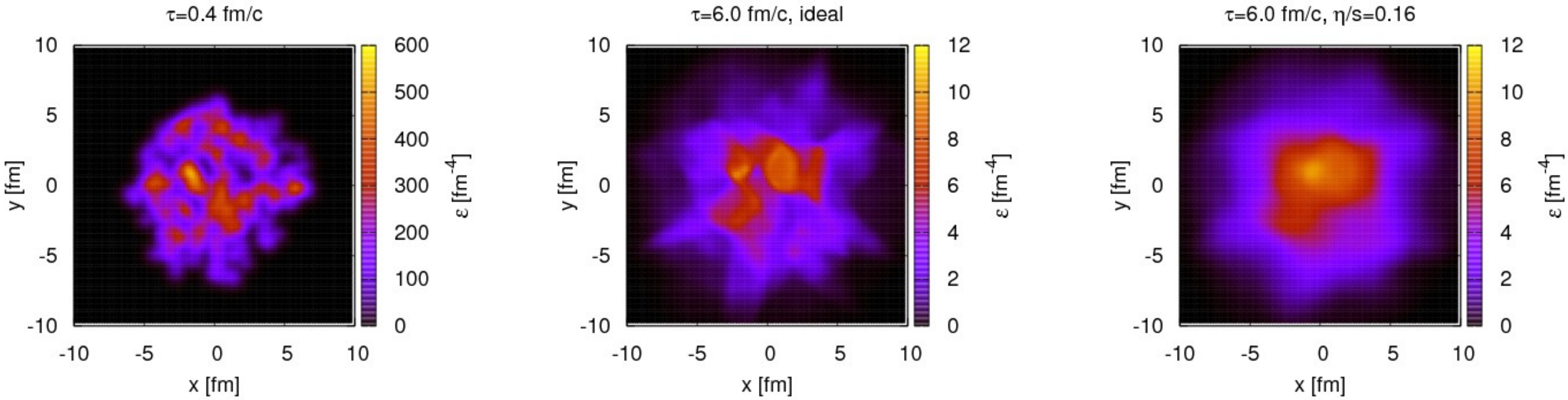
Background normalisation:
Zero Yield At Minimum

v_2 modulated background
$v_{2trig} * v_{2assoc}$ ~ few per cent

N.B. no signal-free region at low p_T

v_3 in Hydro

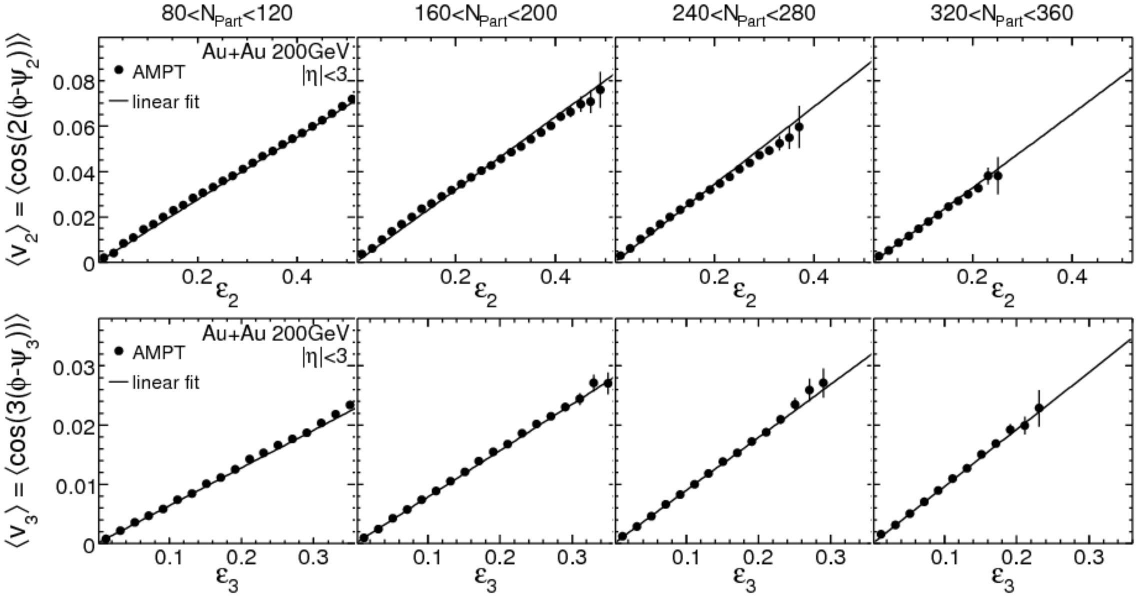
Schenke, Jeon, Gale, PRL 106, 042301



Evolution of initial state spatial anisotropy depends on viscosity

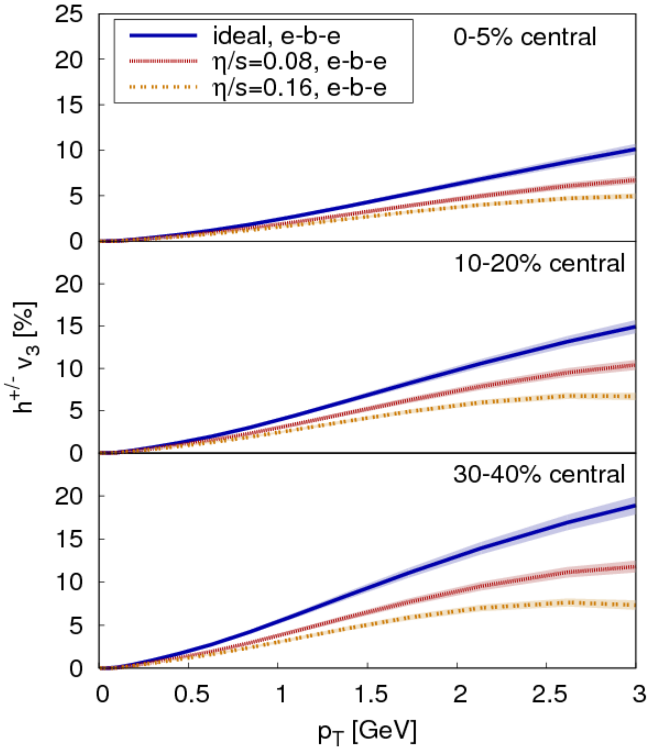
v_3 vs eps

v_3 from AMPT



Alver and Roland

v_3 from Hydrodynamics

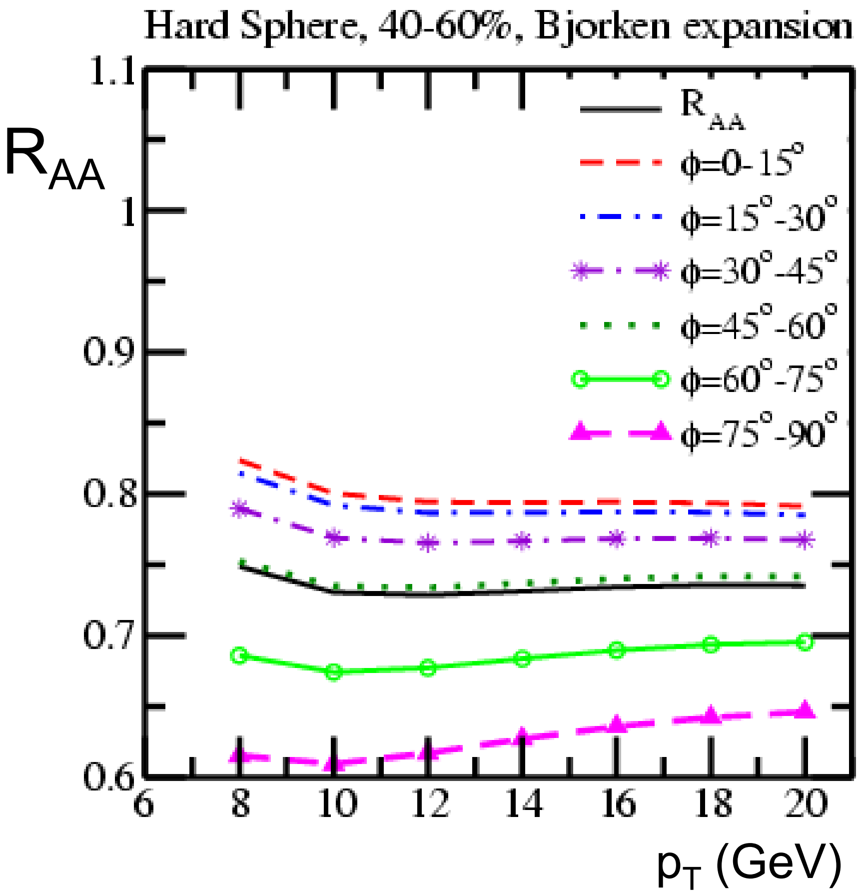


Schenke and Jeon

Initial triangular anysotropy gives rise to v_3
in both parton cascade and hydrodynamics

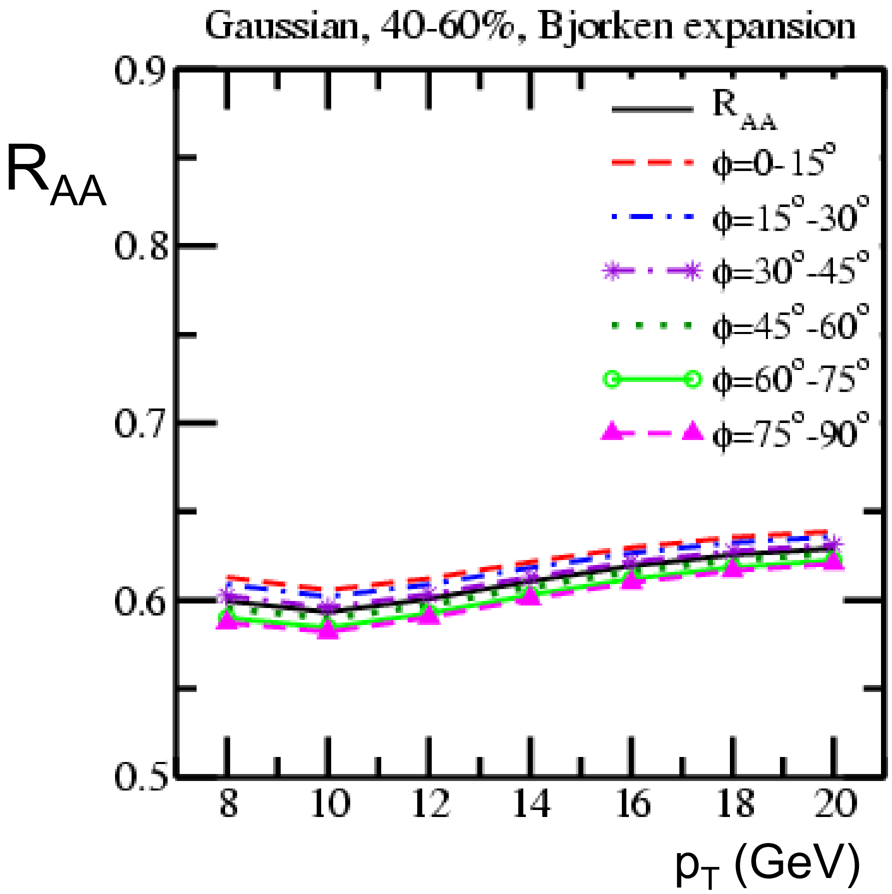
v_3 can be the underlying mechanism for both ‘ridge’ and ‘Mach cone’

Modelling azimuthal dependence



Hard Sphere, 40-60%, Bjorken expansion

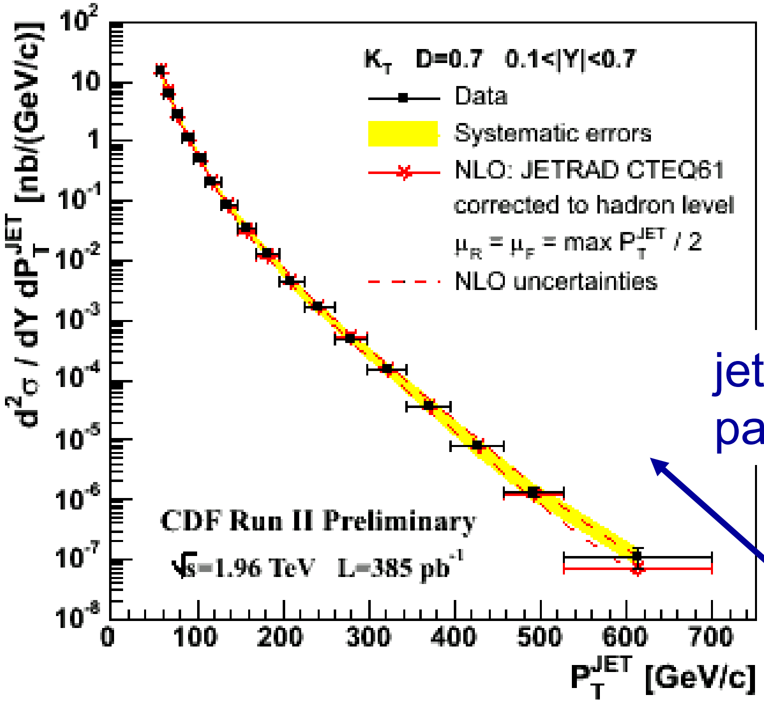
A. Majumder, PRC75, 021901



Gaussian, 40-60%, Bjorken expansion

R_{AA} vs reaction plane sensitive to geometry model

pQCD illustrated

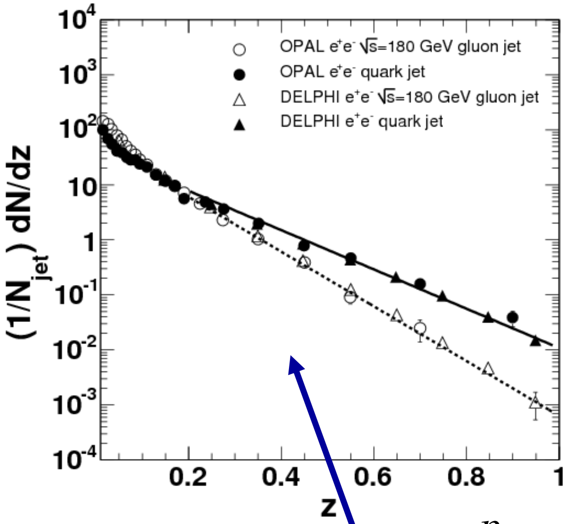


CDF, PRD75, 092006

jet spectrum ~
parton spectrum

$$\frac{dN}{\hat{p}_T d\hat{p}_T} \propto \frac{1}{\hat{p}_T^n}$$

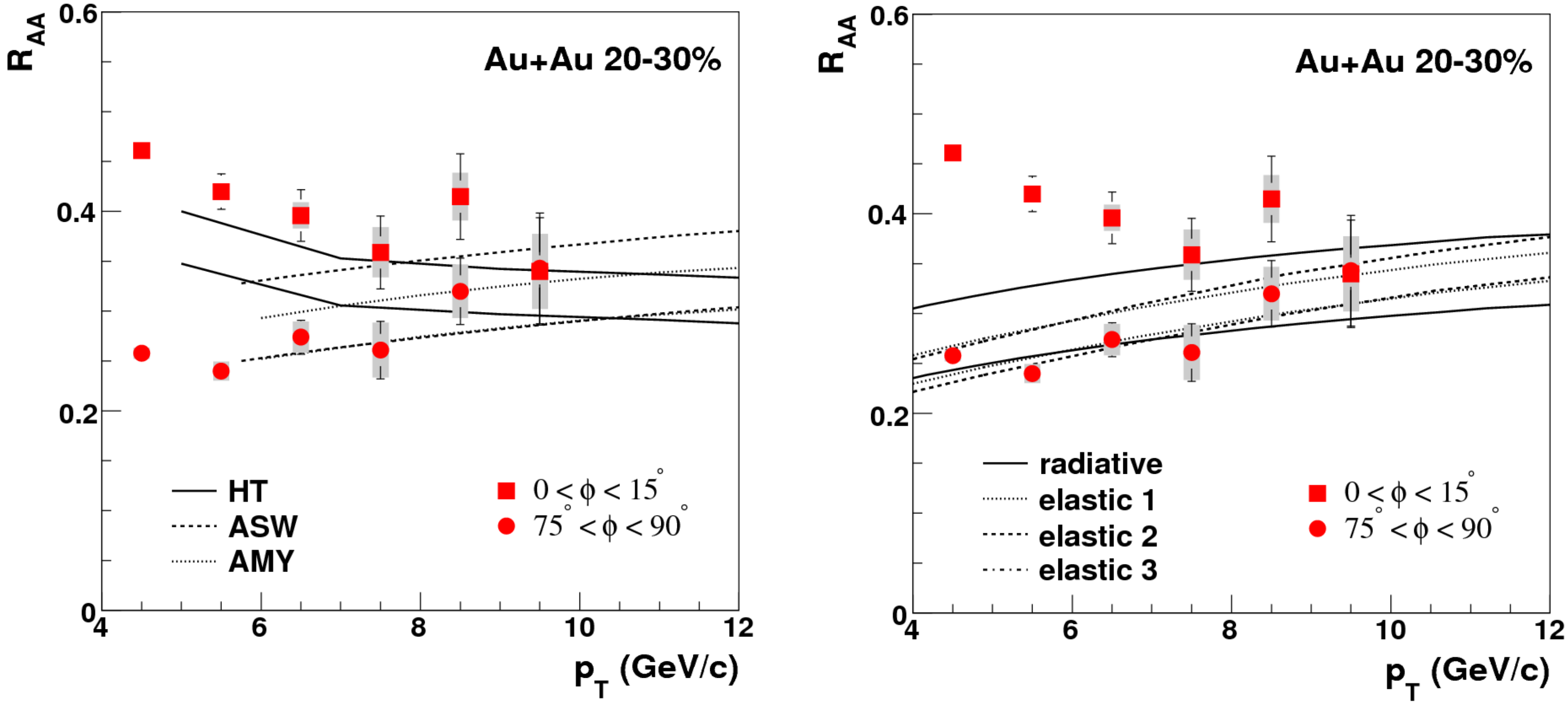
fragmentation



$$z = \frac{p_{T,hadron}}{P_{jet}}$$

$$\frac{d\sigma_{pp}^{h}}{dy\,d^2p_T} = K \sum_{abcd} \int \overbrace{dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd)} \frac{D_{h/c}^0}{\pi z_c}$$

R_{AA} vs reaction plane angle



Majumder, van Leeuwen, arXiv:1002.2206

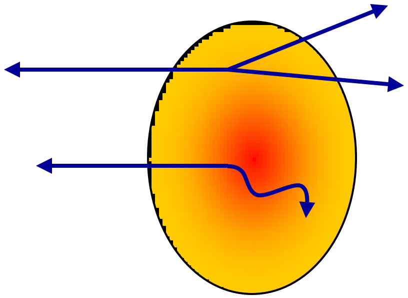
Azimuthal modulation, path length dependence largest in ASW-BDMPS

But why? – No clear answer yet

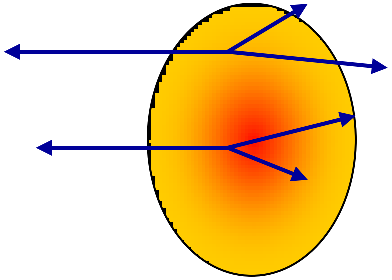
Data prefer ASW-BDMPS

Interpreting di-hadron measurements

Scenario I:
Some lose all,
Some lose nothing



Scenario II:
All lose something



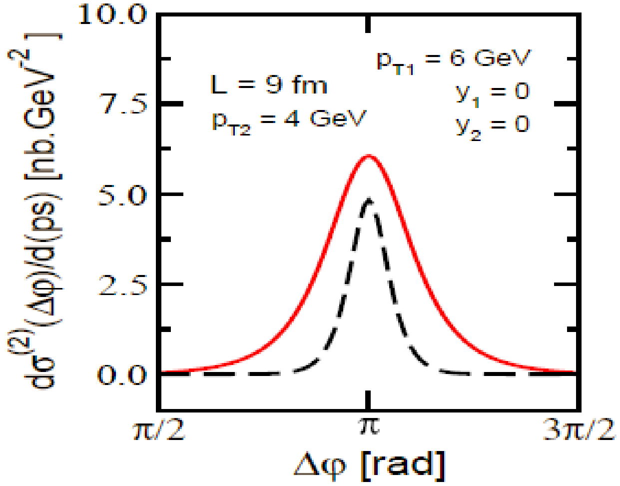
Di-hadron measurement:
Away-side yield is (semi-)inclusive, so does not measure fluctuations of energy loss

Multi-hadron measurements potentially more sensitive

All is encoded in energy loss distribution P(ΔE)

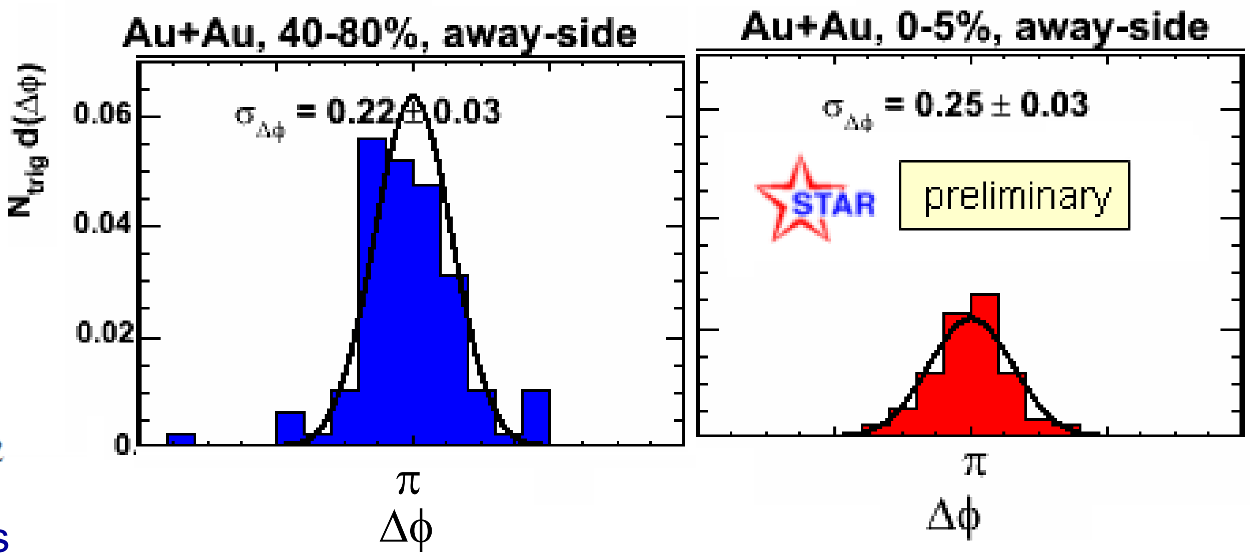
A closer look at azimuthal peak shapes

Vitev, hep-ph/0501225



Broadening due to fragments
of induced radiation

8 < p_T(trig) < 15 GeV/c
p_T(assoc)>6 GeV



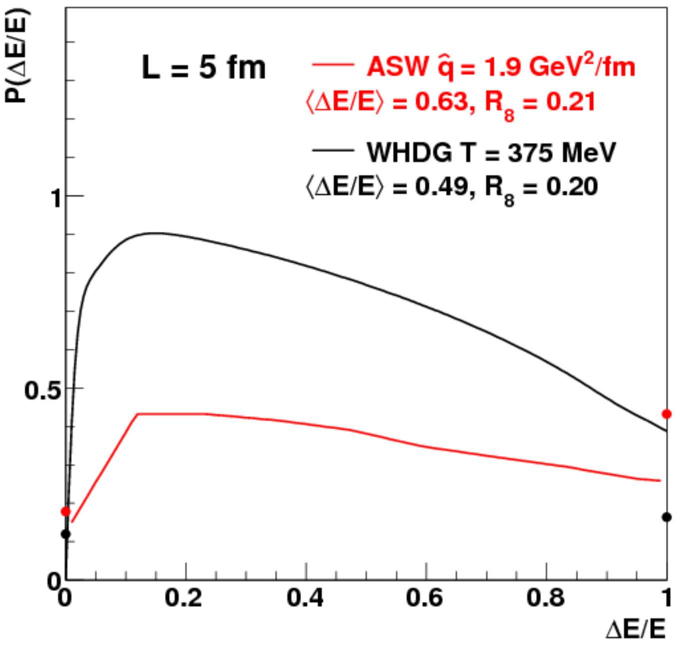
Induced acoplanarity (BDMPS): $-\frac{dE}{dz} = \frac{\alpha_s N_c}{8} \left\langle p_T^2 \right\rangle_{jet}$

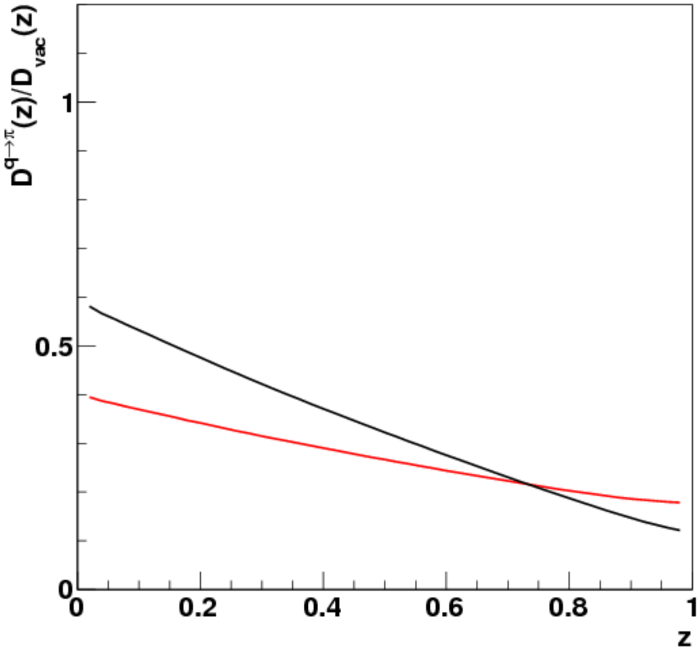
No away-side broadening:

- No induced radiation
- No acoplanrity ('multiple-scattering')

Fragmentation functions

Qualitatively: $D_{med}(z) = P(\Delta E) \otimes D_{vac}(z')$

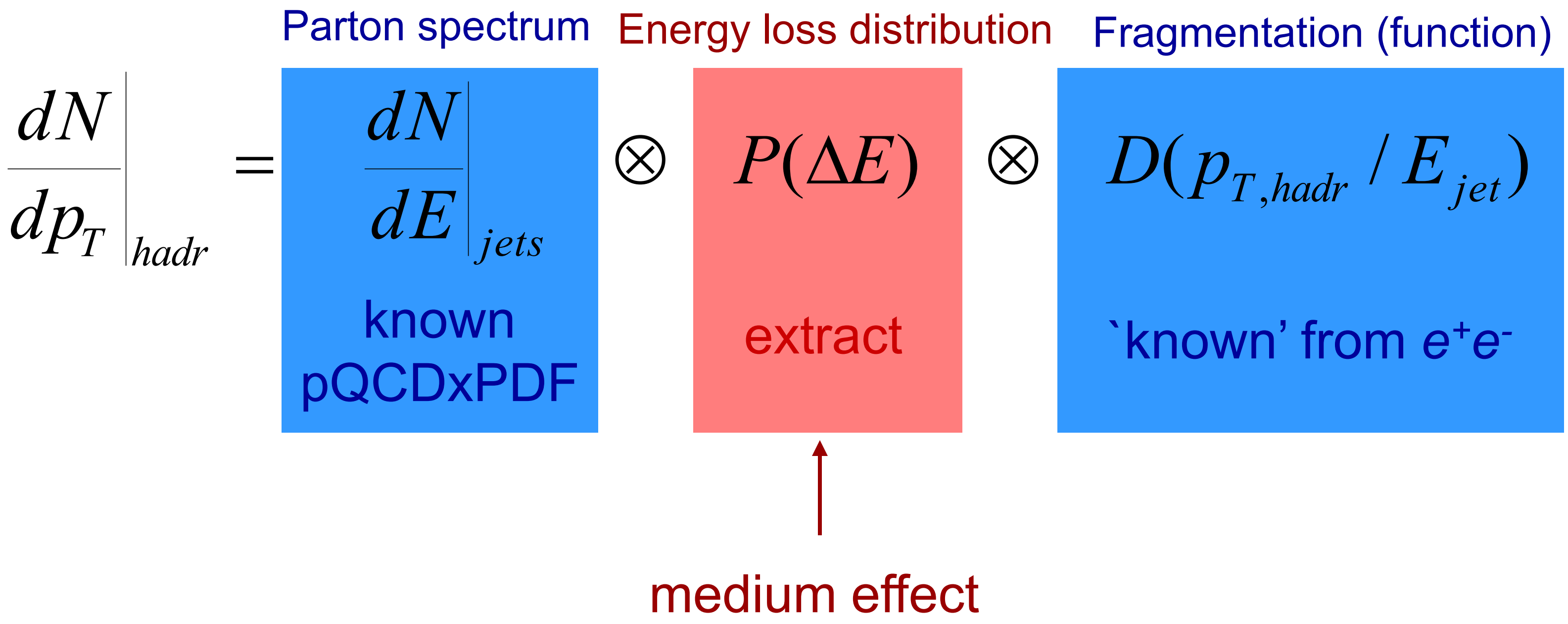




Fragmentation functions sensitive to P(ΔE)
Distinguish GLV from BDMPS?

Parton energy loss and R_{AA} modeling

Qualitatively:



Parton spectrum

Energy loss distribution

Fragmentation (function)

$$\left.\frac{dN}{dp_T}\right|_{hadr} = \left.\frac{dN}{dE}\right|_{jets} \otimes P(\Delta E) \otimes D(p_{T,hadr}/E_{jet})$$

known pQCDxPDF

extract

`known' from e^+e^-

medium effect

Medium effect P(ΔE) is only part of the story
Parton spectrum and fragmentation function are steep
⇒ non-trivial relation between R_{AA} and P(ΔE)