Power Week pQCD+Energy Loss Introduction

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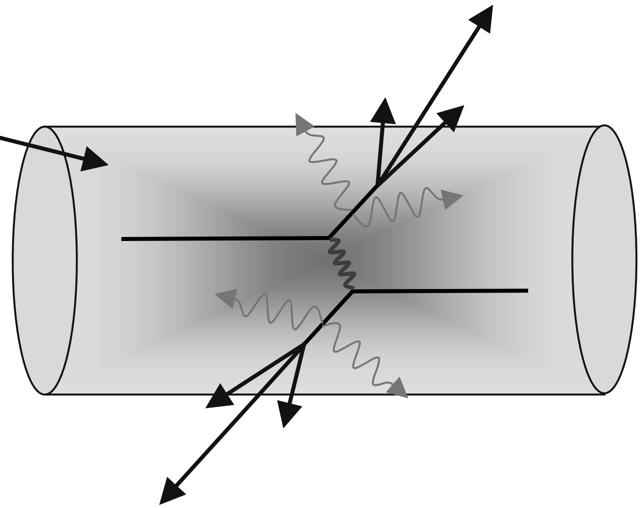
Hard probes of QCD matter

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

Plan of the next few days

Goals:
- Provide hands-on experience with all ingredients of a simple energy loss model
- Increase understanding of the models, the assumptions and uncertainties
- Provide a basic knowledge and experience that allows you to answer your own questions

- Perturbative QCD tools:
  - PDFs, matrix elements, Fragmentation
- DGLAP evolution and Monte-Carlo showers
- Geometry
  - Woods-Saxon geometry, tools
- Energy loss models
  - Using Quenching weights; multiple gluon radiation

Plus introduction to MC techniques

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)

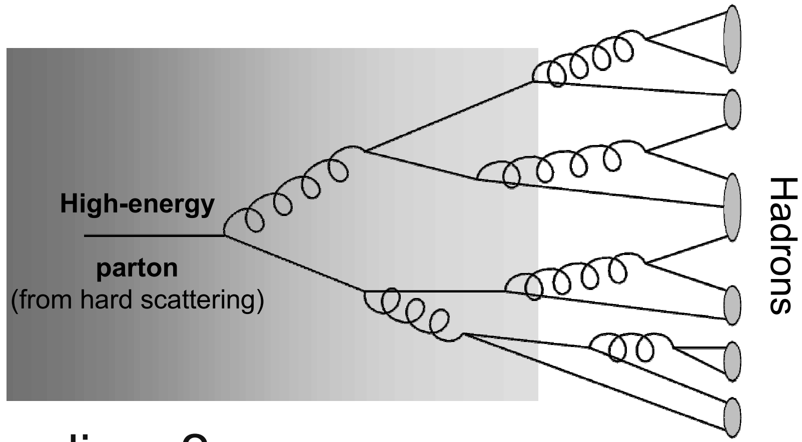
$$\frac{d\sigma_{pp}^{h}}{dyd^2p_T} = K\sum_{abcd}\int \underbrace{dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2)}_{\text{parton density}} \underbrace{\frac{d\sigma}{d\hat{t}}(ab\to cd)}_{\text{matrix element}} \underbrace{\frac{D^0_{h/c}}{\pi z_c}}_{\text{FF}}$$

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

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

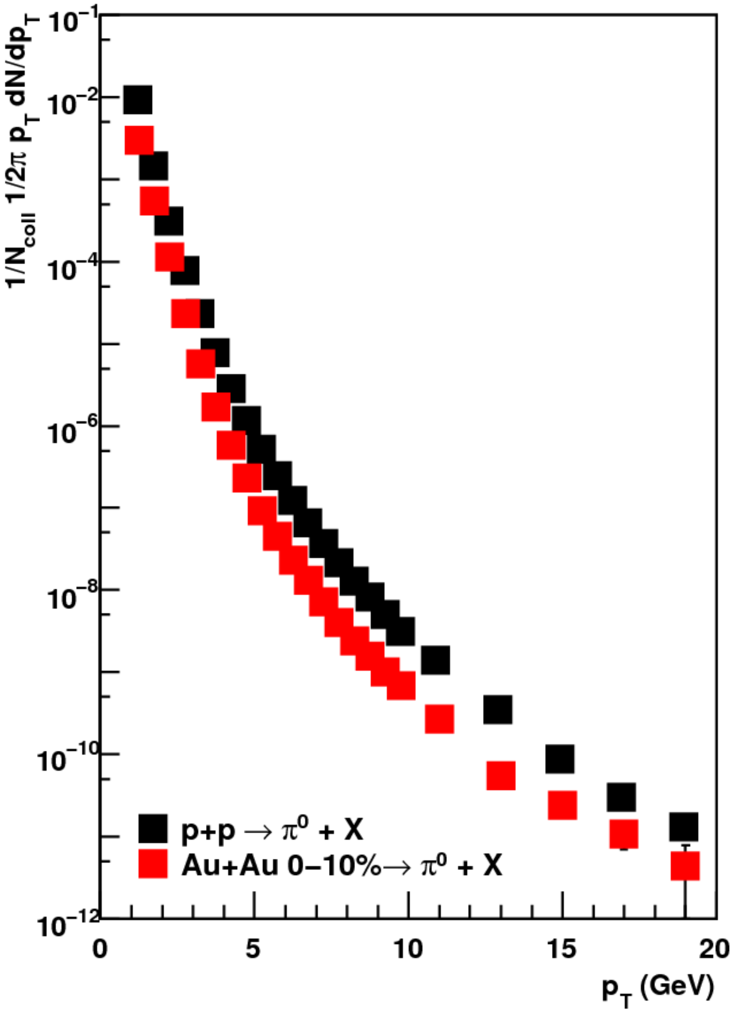
Jet Quenching

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?



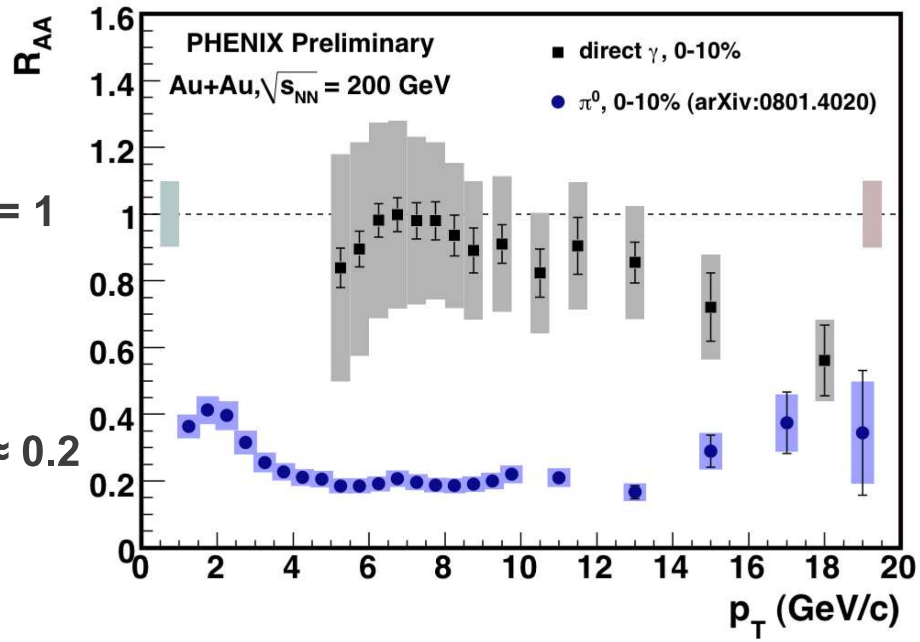
2) What does this tell us about the medium ?
   - Density
   - Nature of scattering centers? (elastic vs radiative; mass of scatt. centers)
   - Time-evolution?

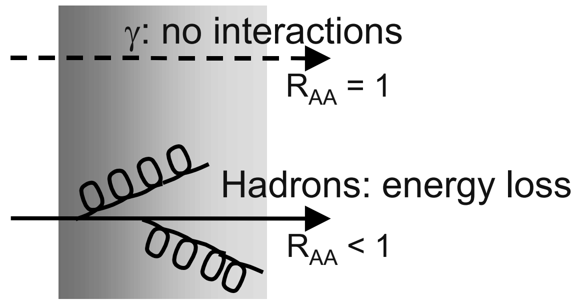
π^0 R_{AA} – high-p_T suppression



γ: R_{AA} = 1

π^0: $R_{AA} \approx 0.2$





Hard partons lose energy in the hot matter

A simple model

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^-

This is where the information about the medium is

P(ΔE) combines geometry
with the intrinsic process
– Unavoidable for many observables

Notes:

- This formula is the simplest ansatz – Independent fragmentation after E-loss assumed
- Jet, γ-jet measurements 'fix' E, removing one of the convolutions

We will explore this model during the week; was 'state of the art' 3-5 years ago

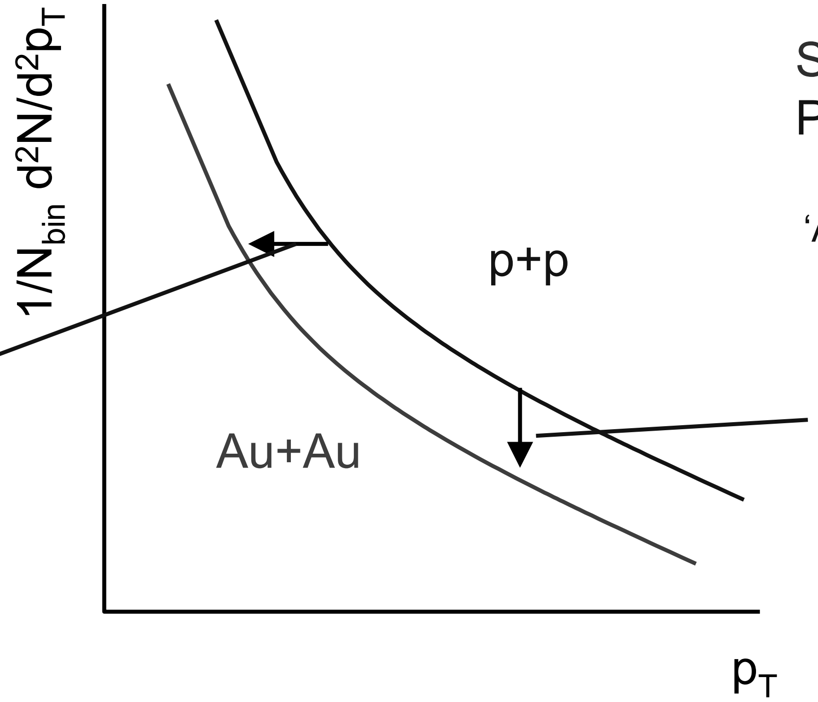
Two extreme scenarios

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

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

'Energy loss'

Shifts spectrum to left



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

'Absorption'

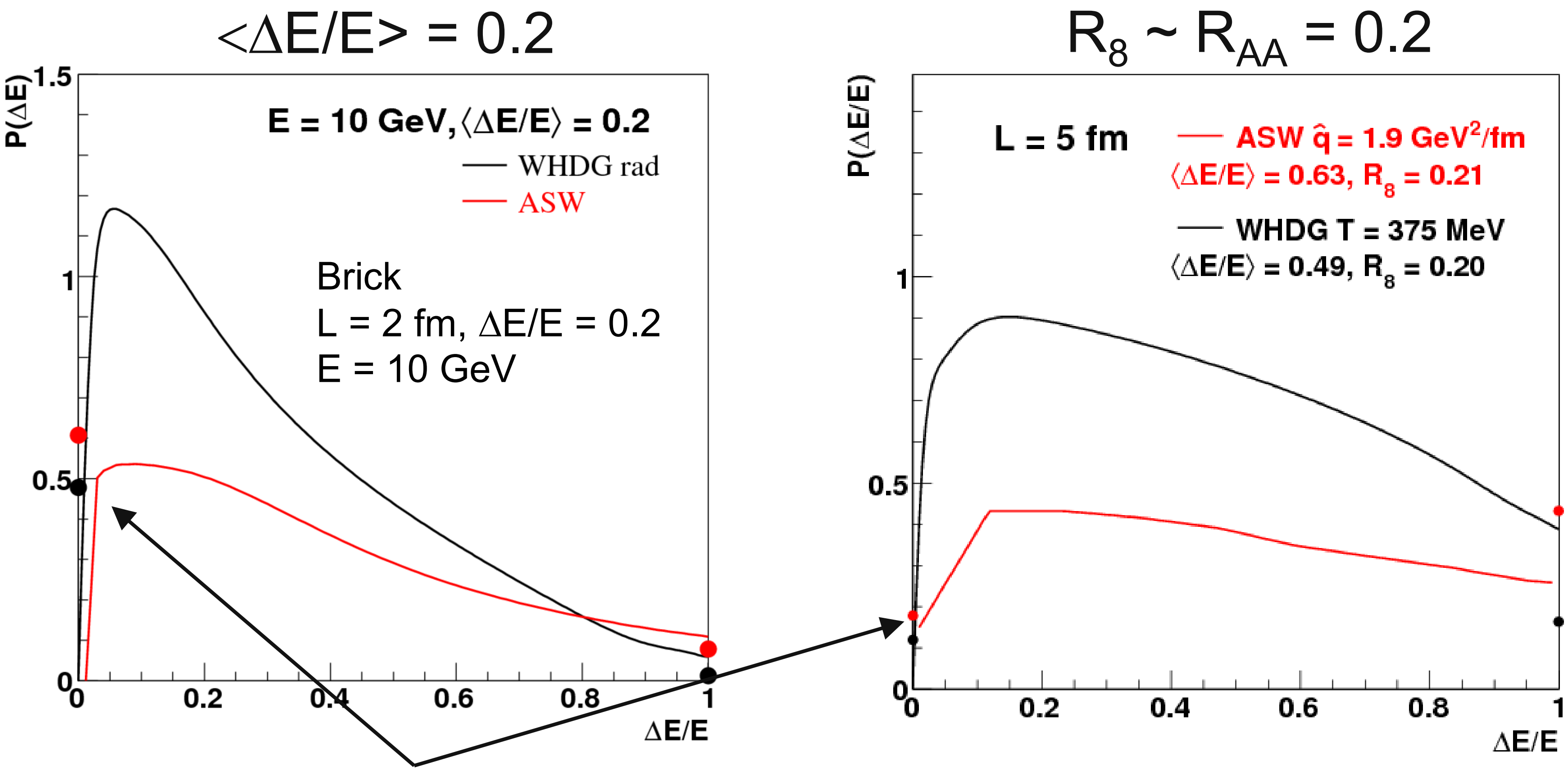
Downward shift

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

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

Energy loss distribution

Typical examples with fixed *L*



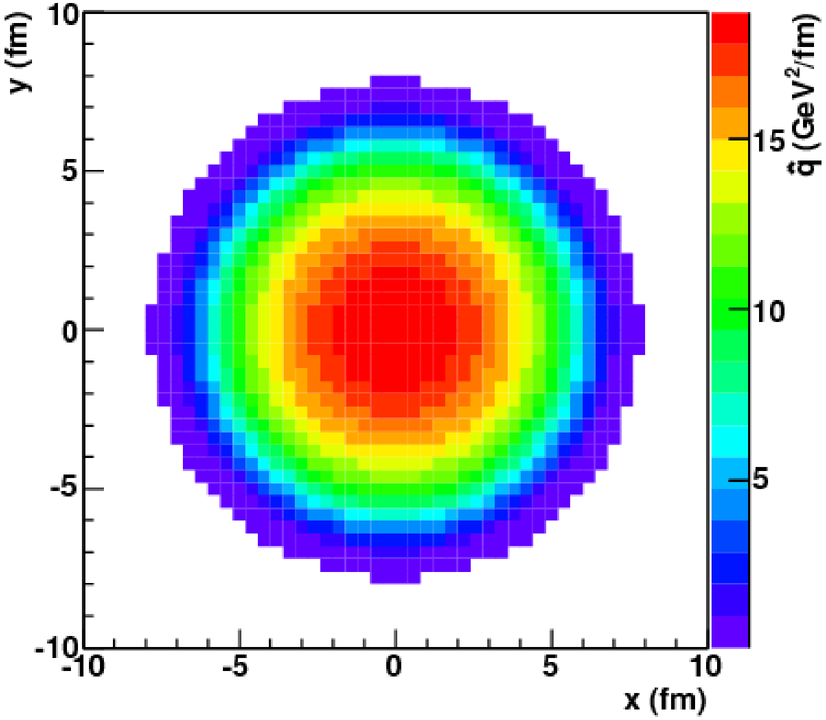
Significant probability to lose no energy (P(0))

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

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

Geometry

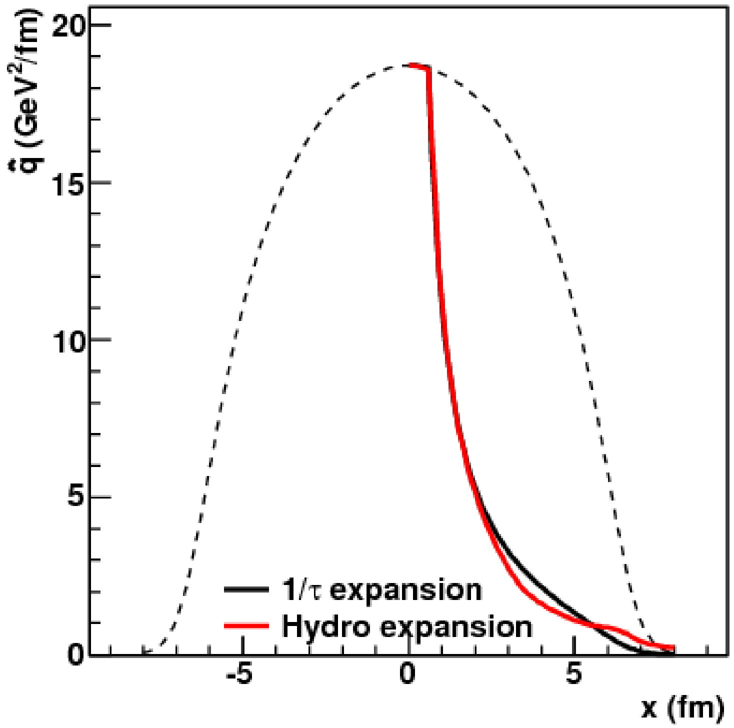
Density profile



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

(Glauber geometry)

Density along parton path



Longitudinal expansion dilutes medium
⇒ Important effect

Space-time evolution is taken into account in modeling

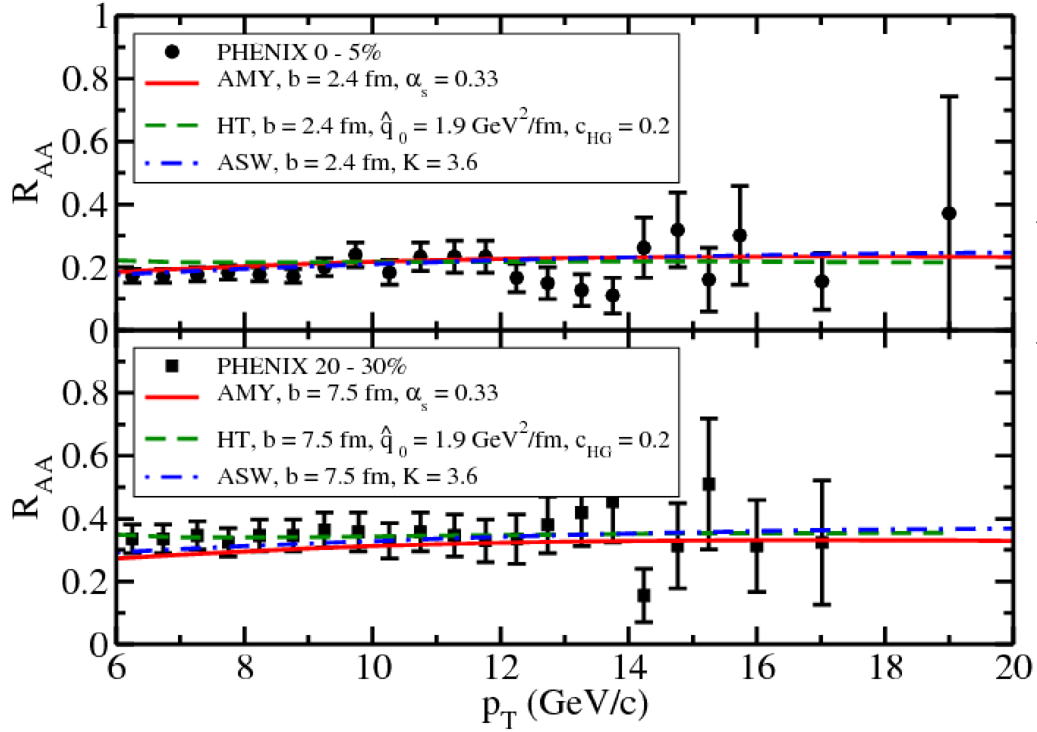
Some existing calculations

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

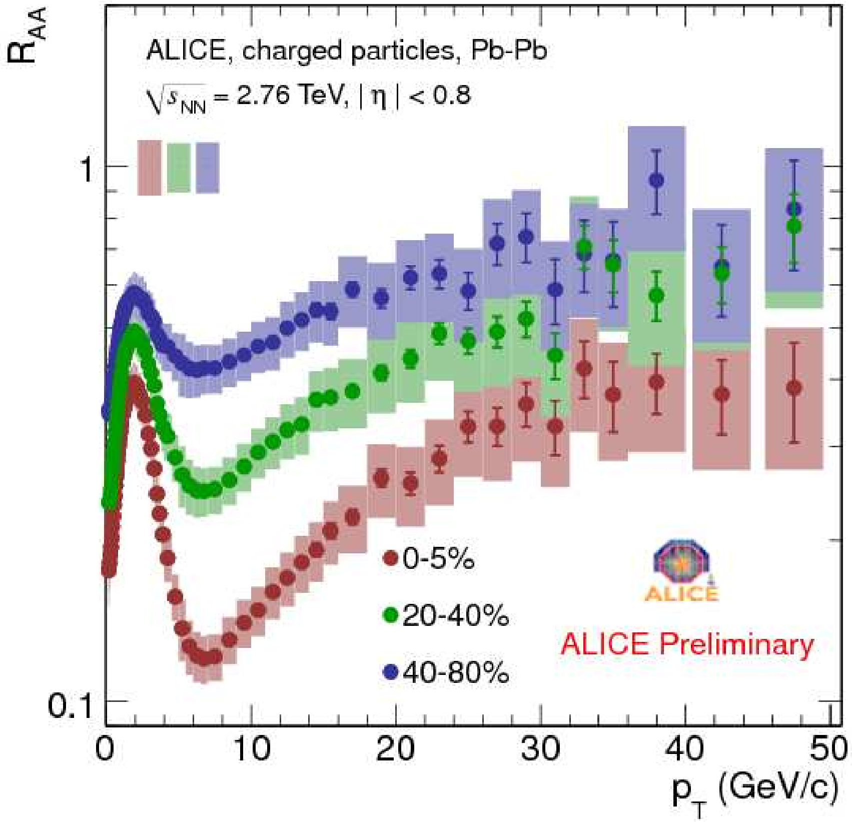
This week: looking behind the scenes for such calculations

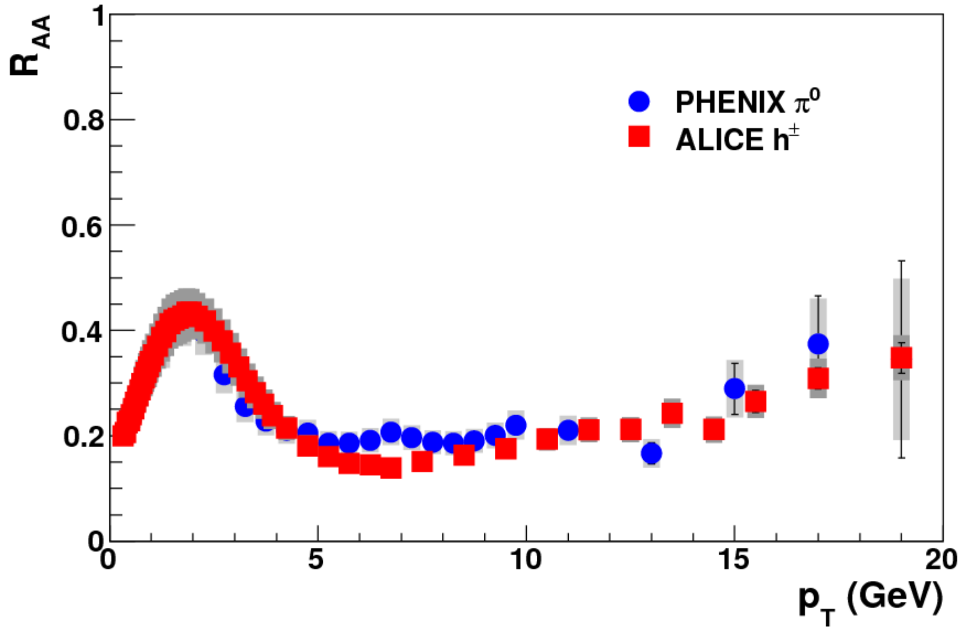
After long discussions, it turns out that these differences
are mostly due to uncontrolled approximations in the calculations
→ Best guess: the truth is somewhere in-between

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

R_{AA} at LHC

Nuclear modification factor $R_{AA} = \frac{dN/dp_T|_{Pb+Pb}}{N_{coll}\, dN/dp_T|_{p+p}}$



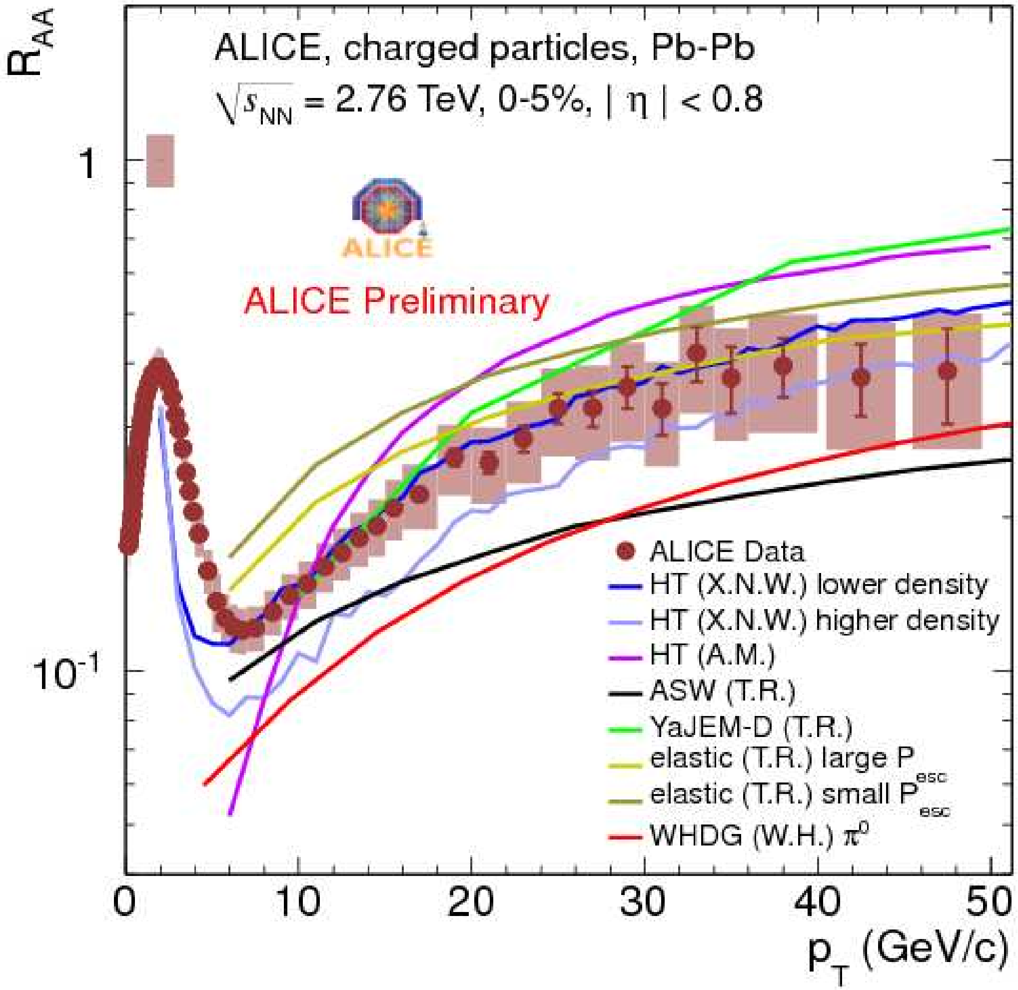


By the way: R_{AA} is also p_T-dependent at RHIC?

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

Comparing to theory

Many theory calculations available



Ingredients:

- pQCD production
- Medium density profile tuned to RHIC data, scaled
- Energy loss model

Large spread of predictions:

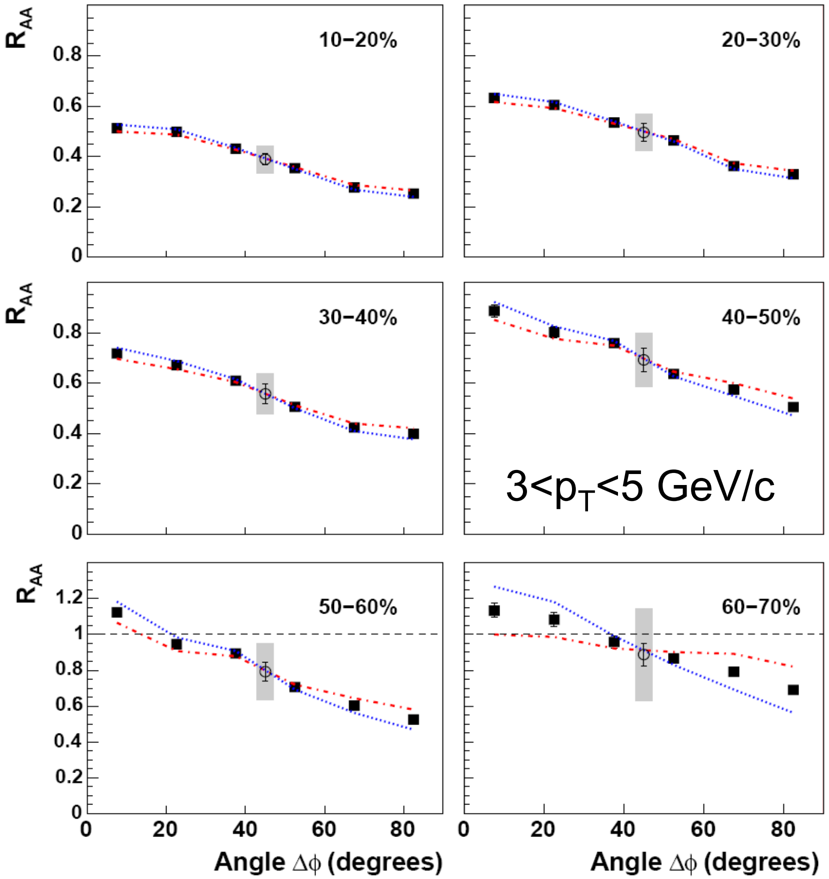
- Will be narrowed down by discussion/thought
- Need to understand models/calculations to sort it out

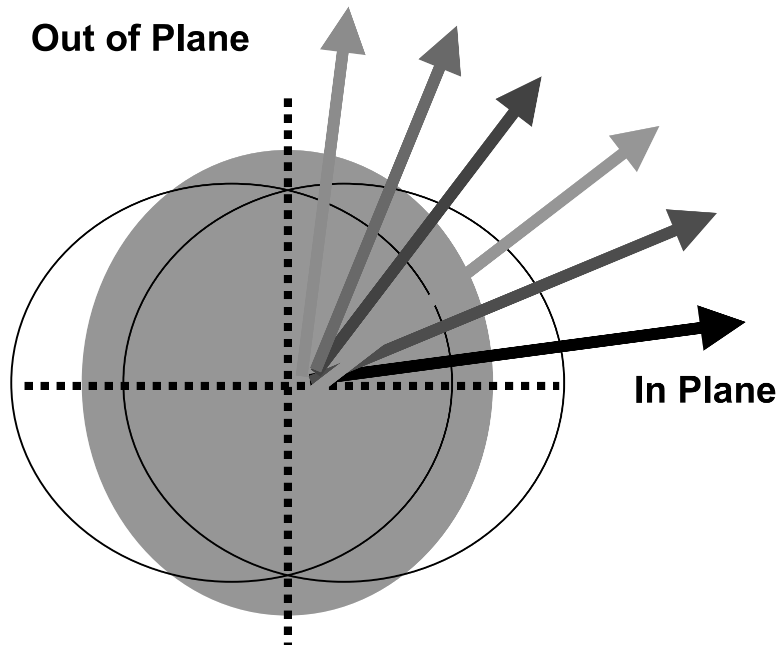
All calculations show increase with p_T

Path length dependence: R_{AA} vs L

R_{AA} as function of angle with reaction plane

PHENIX, PRC 76, 034904



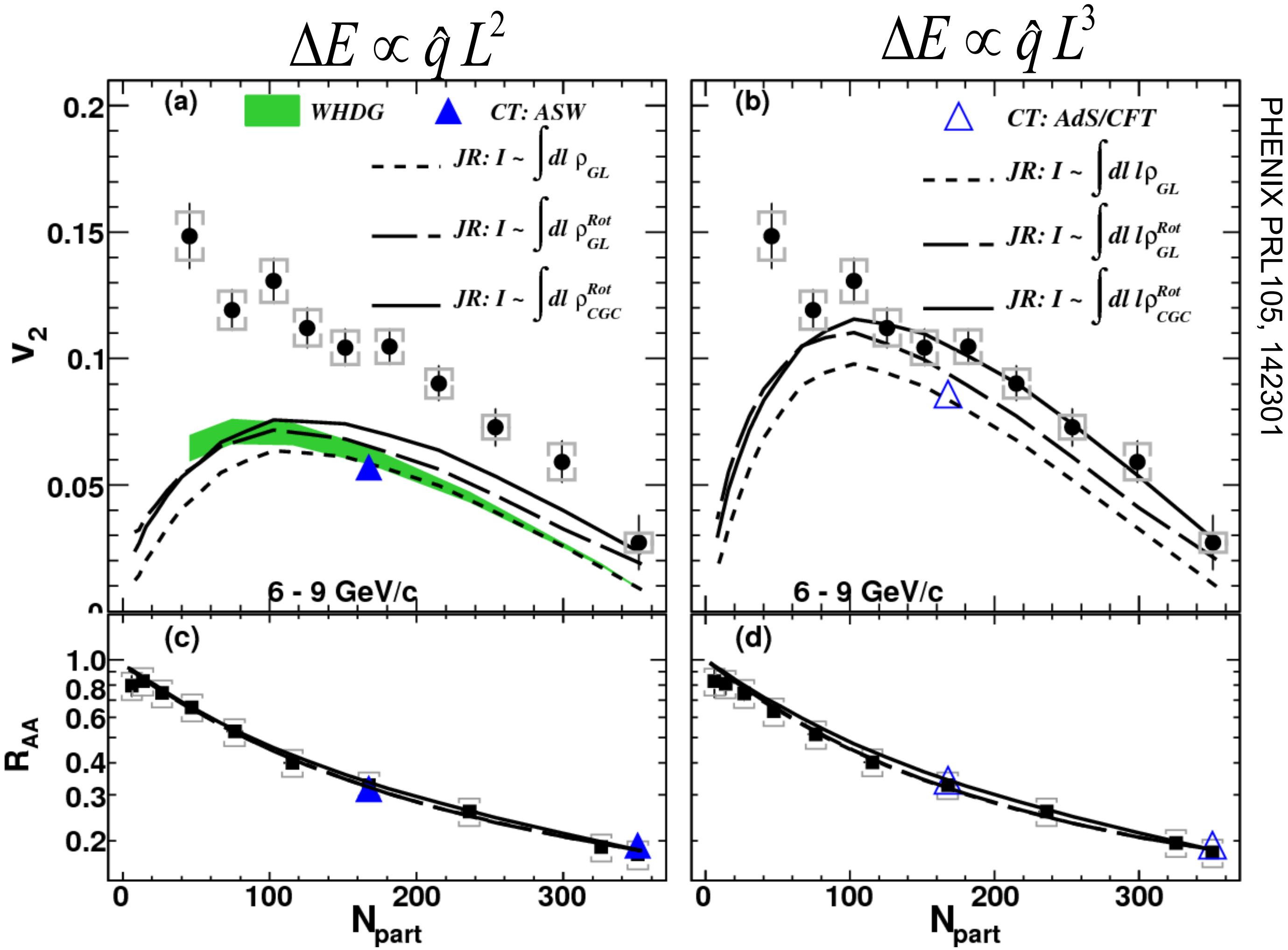


Relation between RAA(φ) and v_2:

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

Suppression depends on angle, path length

Path length dependence and v_2



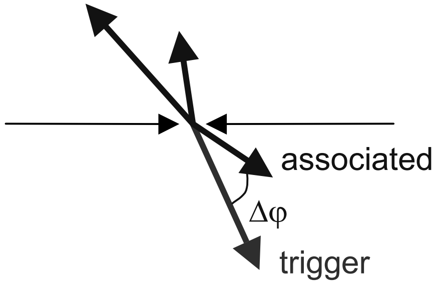
v_2 at high p_T due to energy loss

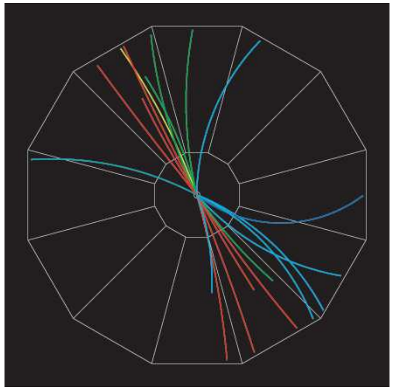
Most calculations give too small effect

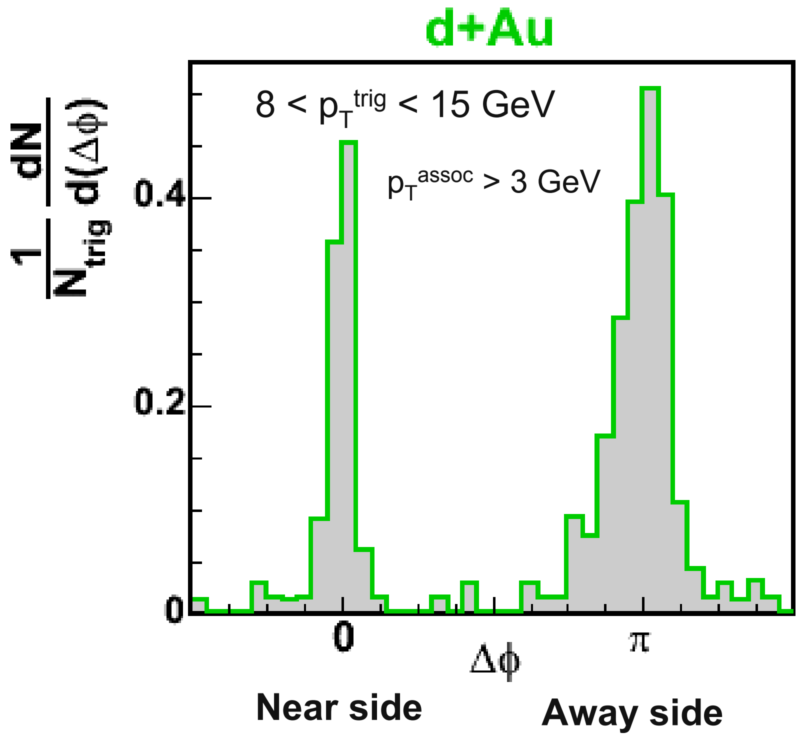
Path length dependence stronger than expected?

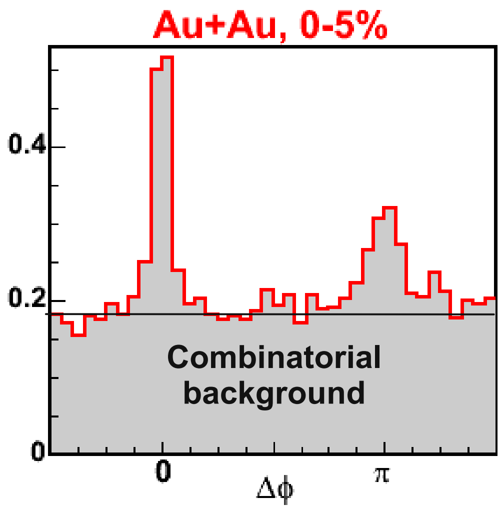
Depends strongly on geometry – stay tuned

Di-hadron correlations



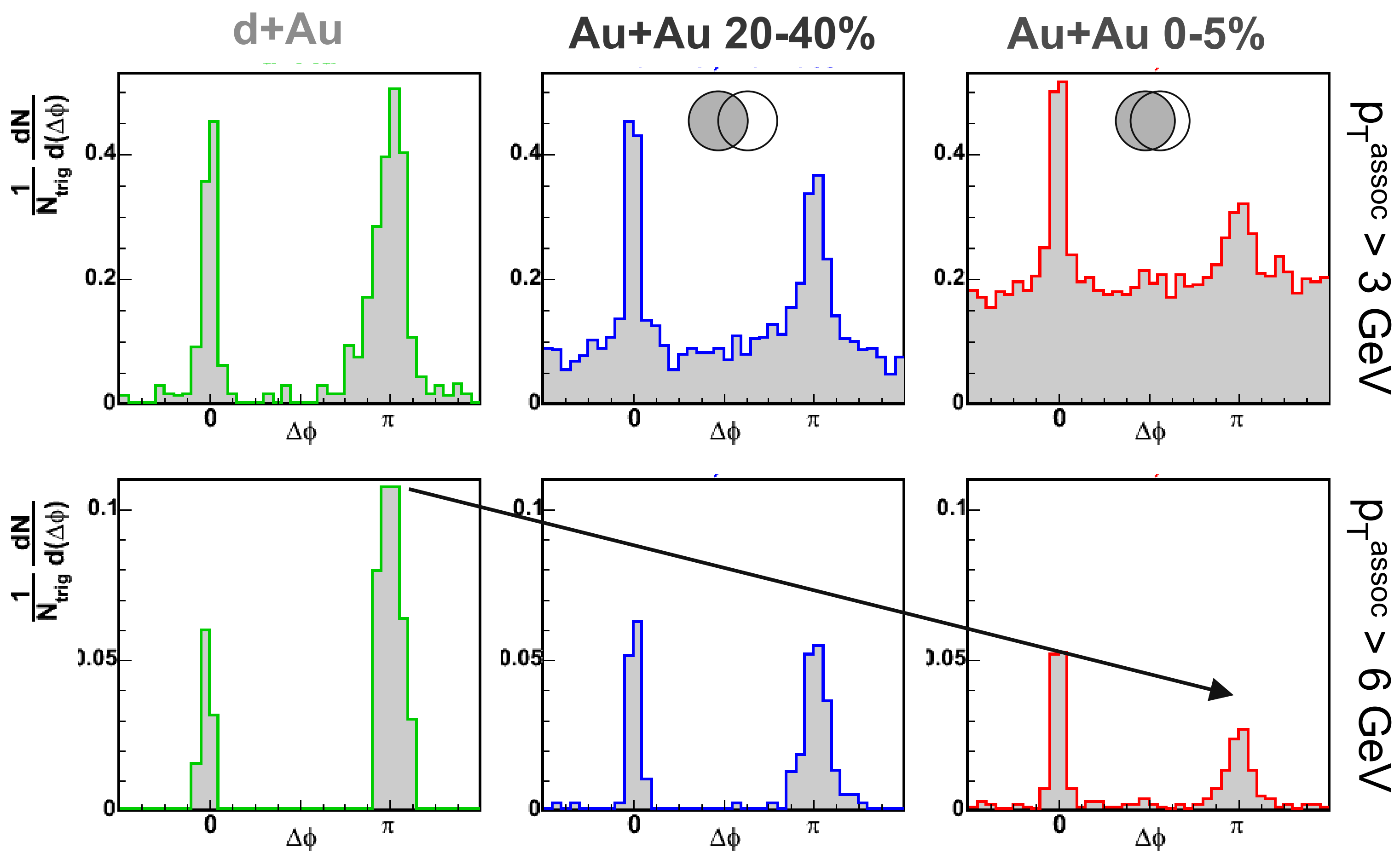






Use di-hadron correlations to probe the jet-structure in p+p, d+Au and Au+Au

Di-hadrons at high-p_T: recoil suppression



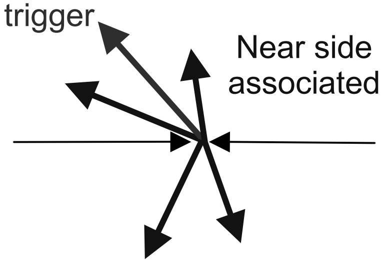
High-p_T hadron production in Au+Au dominated by (di-)jet fragmentation

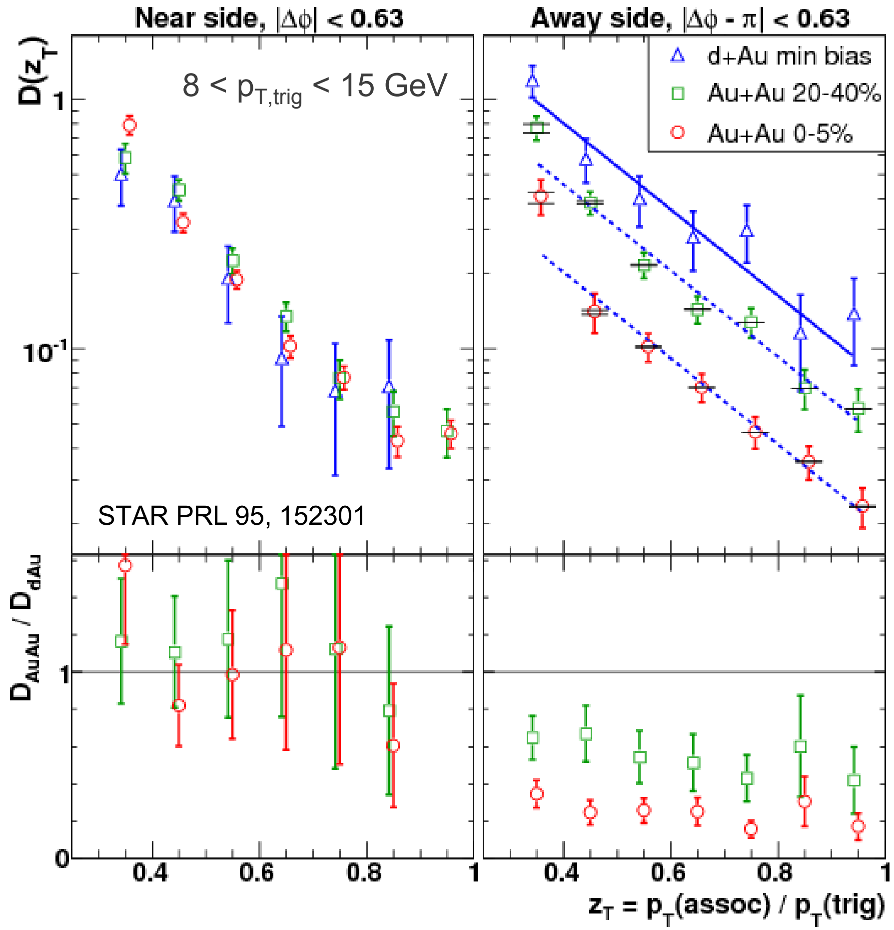
Suppression of away-side yield in Au+Au collisions: energy loss

Di-hadron yield suppression

Near side

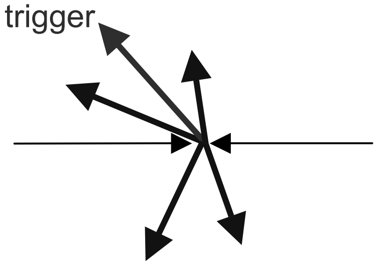
Yield of additional particles in the jet





Away side

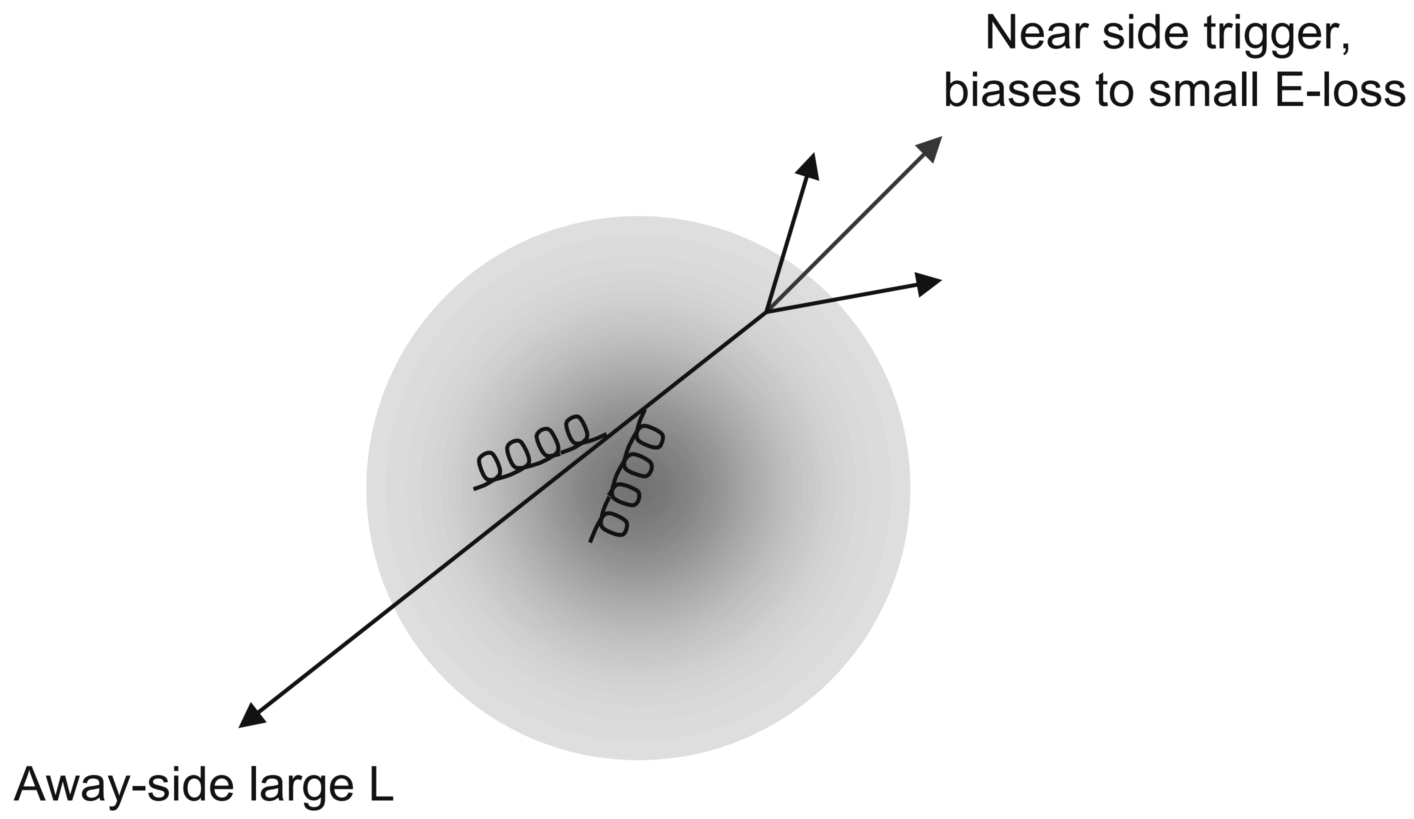
Yield in balancing jet, after energy loss



Near side: No modification
⇒ Fragmentation outside medium?

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

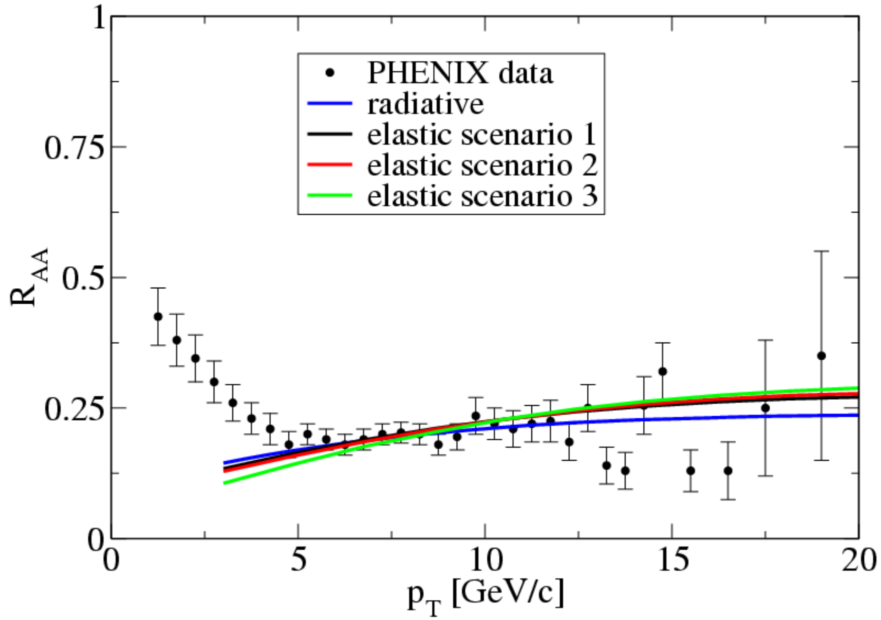
Path length II: ‘surface bias’



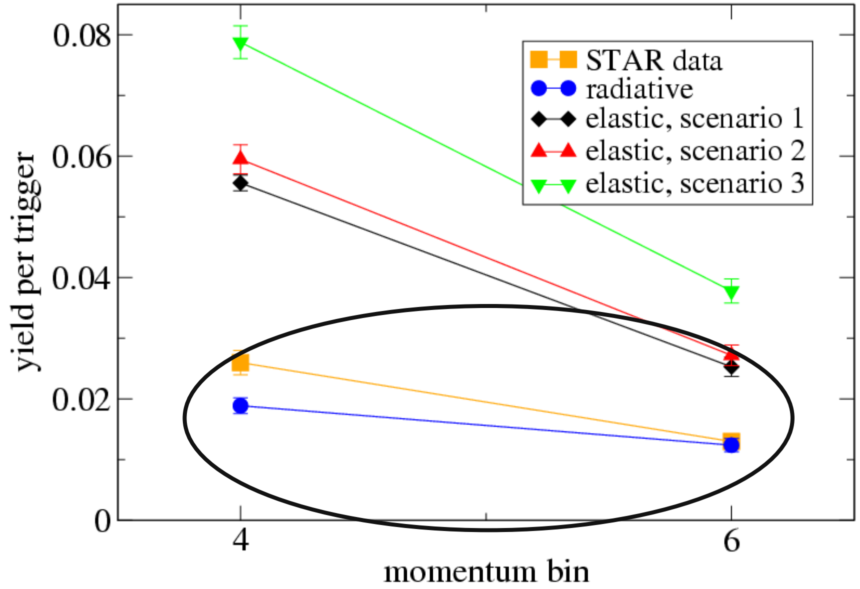
Away-side suppression I_{AA} samples longer path-lengths than inclusives R_{AA}

L scaling: elastic vs radiative

T. Renk, PRC76, 064905



R_{AA}: input to fix density

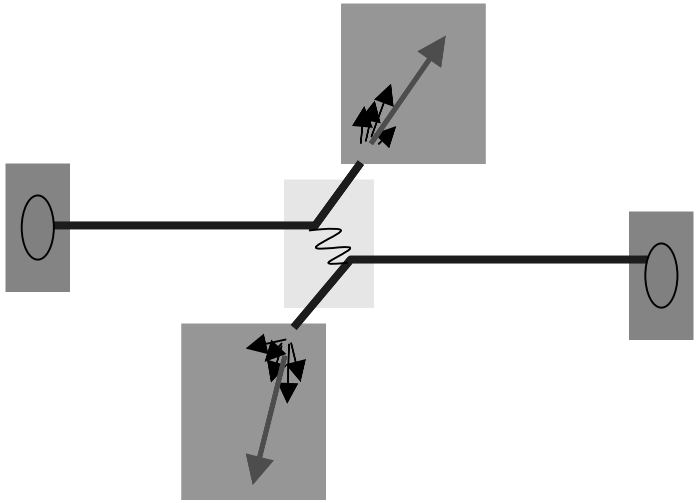


Radiative scenario fits data; elastic scenarios underestimate suppression

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

Confirms L^2 dependence → radiative loss dominates

Factorisation in perturbative QCD

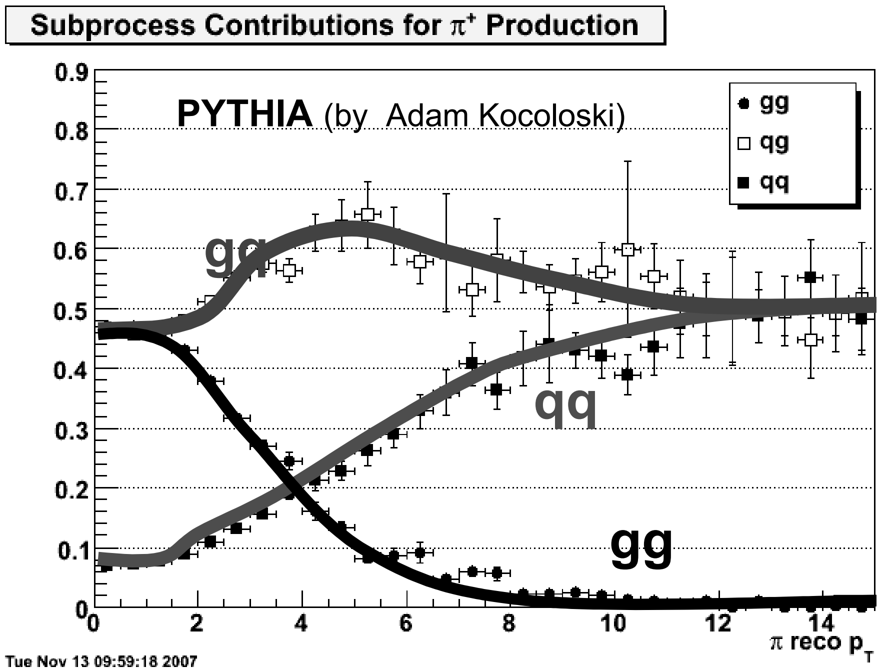


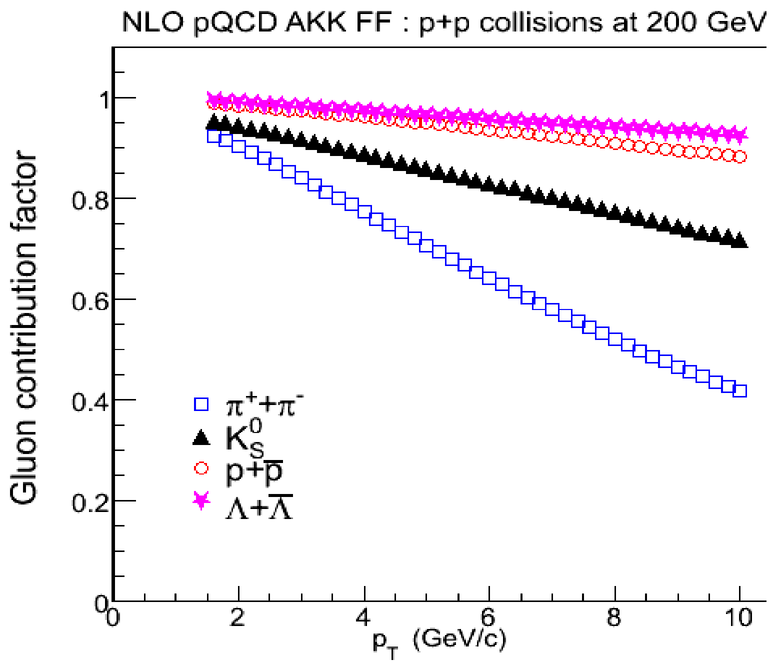
$$\frac{d\sigma^{h}_{pp}}{dy\,d^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab\to cd)\frac{D^0_{h/c}}{\pi z_c}$$

Parton density function	Matrix element	Fragmentation function
Non-perturbative: distribution of partons in proton Extracted from fits to DIS (ep) data	Perturbative component	Non-perturbative Measured/extracted from e+e-

Factorisation: non-perturbative parts (long-distance physics) can be factored out in universal distributions (PDF, FF)

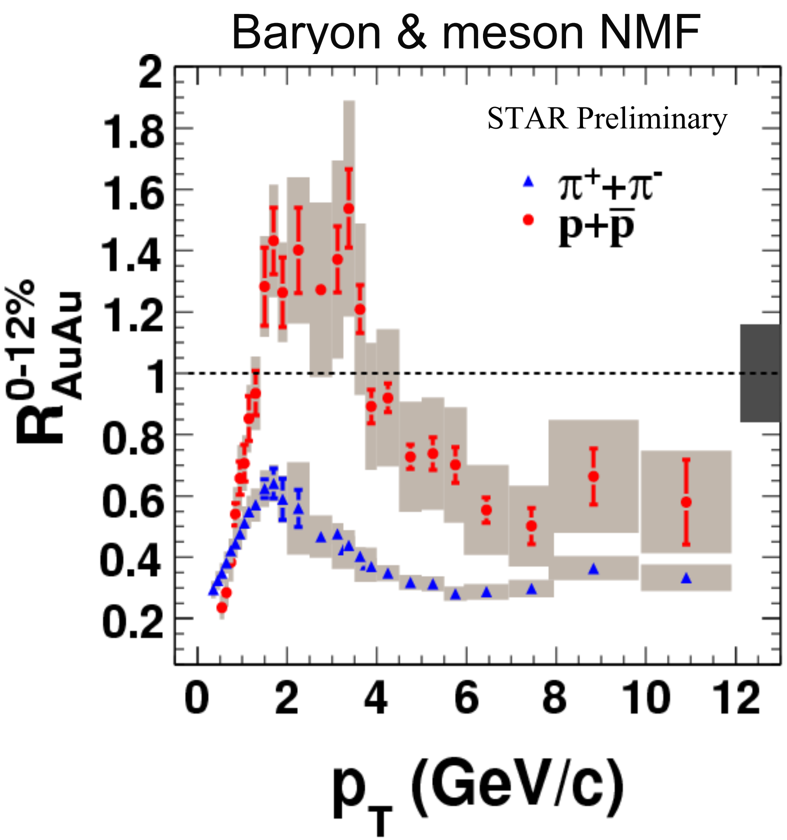
Subprocesses and quark vs gluon



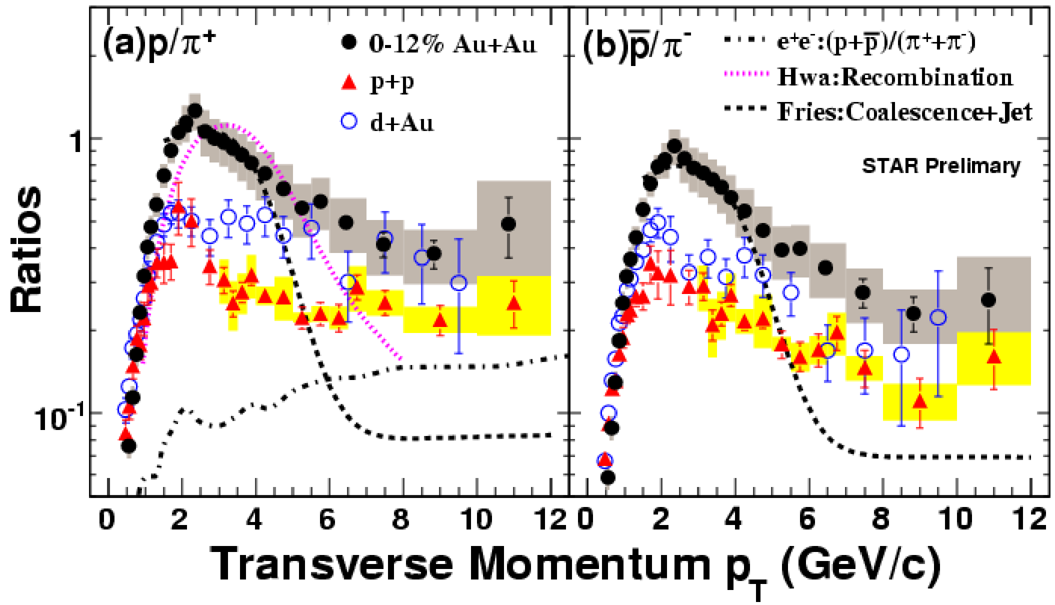


p+pbar dominantly from gluon fragmentation?

Comparing quark and gluon suppression



PRL 97, 152301 (2006)
STAR Preliminary, QM08

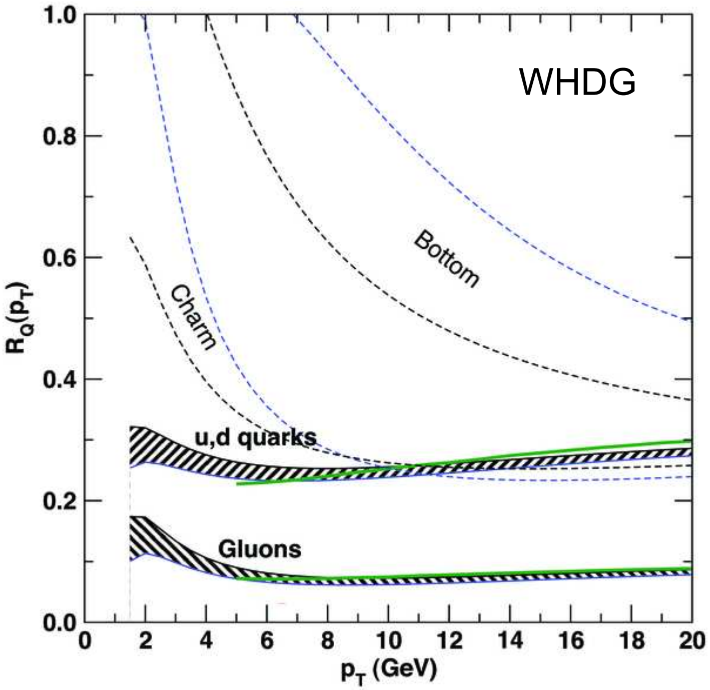


Protons less suppressed than pions, not more

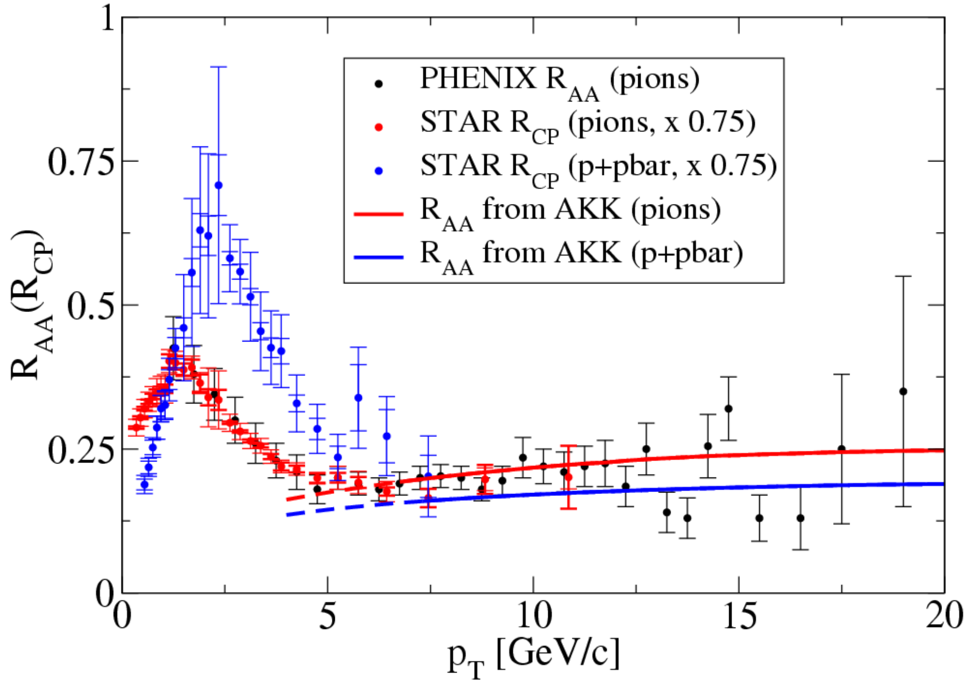
No sign of large gluon energy loss

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... Day 1, 3 of this week

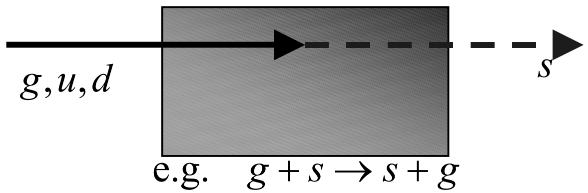
Equalibration of rare probes

- Rare probes: not chemically equilibrated in the jet spectrum.
- Example 1: flavor not contained in the medium, but can be produced off the medium (e.g. photons)

$$\frac{dN^{\text{rare}}}{dt} = \frac{1}{\lambda} N^{\text{jet}} \quad \Rightarrow \quad \frac{N^{\text{rare, excess}}}{N^{\text{jet}}} = \frac{L}{\lambda}$$

  - Need enough yield to outshine other sources of N^{rare}.

- Example 2: flavor chemically equilibrated <u>in the medium</u>



$$w_{jet} = \left(\frac{s}{u+d}\right)_{jet} \approx 5\% \qquad @\,10\text{ GeV for RHIC}$$

$$w_{ce} = \left(\frac{s}{u+d}\right)_{medium} \approx 50\%$$

  - E.g. strangeness at RHIC
  - Coupling of jets (flavor not equilibrated) to the equilibrated medium should drive jets towards chemical equilibrium.

Determining the initial energy

Parton spectrum		Energy loss distribution		Fragmentation (function)
$\left.\frac{dN}{dE}\right\vert_{jets}$	$\otimes$	$P(\Delta E)$	$\otimes$	$D(p_{T,hadr}/E_{jet})$
known pQCDxPDF		extract		`known' from e^+e^-

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

↑

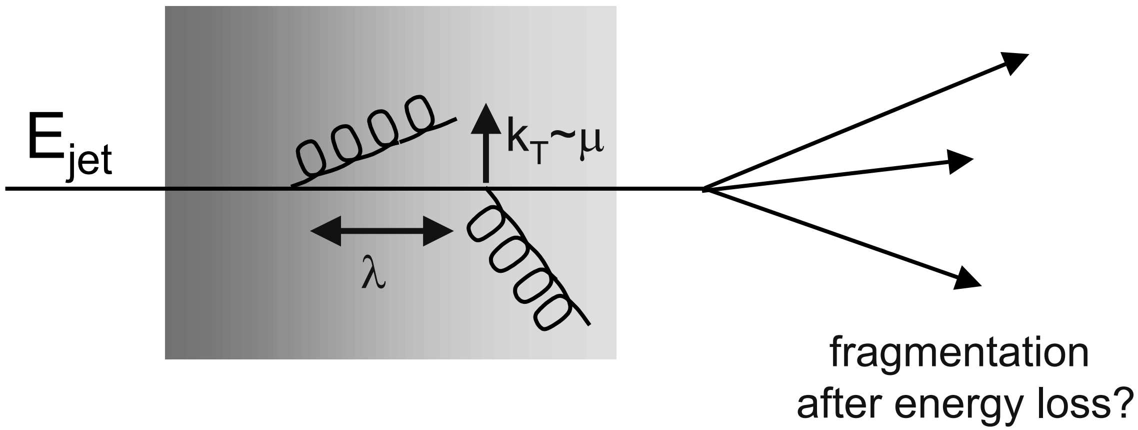
This is where the information about the medium is

P(ΔE) combines geometry
with the intrinsic process

Jet, γ-jet measurements 'fix' E, removing one of the convolutions

Allows to study energy loss as function of E
(at least in principle)

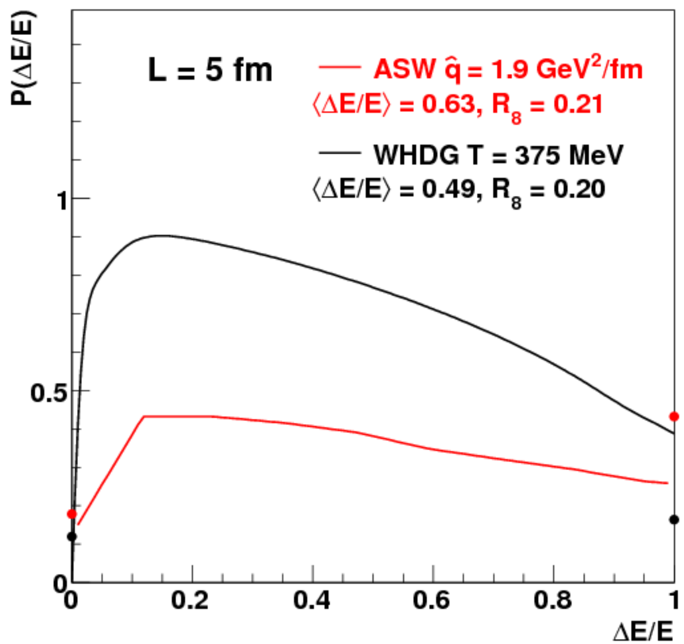
Generic expectations from energy loss

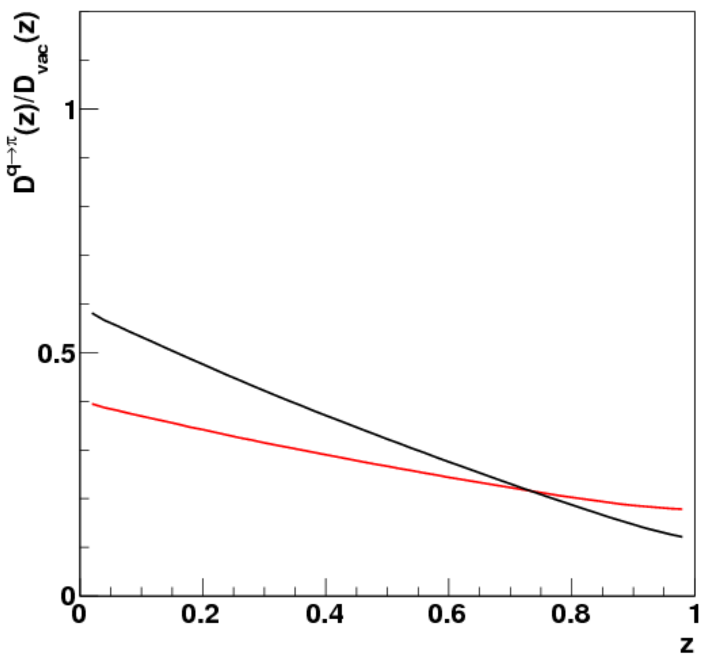


- Longitudinal modification:
  - out-of-cone ⇒ energy lost, suppression of yield, di-jet energy imbalance
  - in-cone ⇒ softening of fragmentation
- Transverse modification
  - out-of-cone ⇒ increase acoplanarity k_T
  - in-cone ⇒ broadening of jet-profile

Fragmentation functions

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



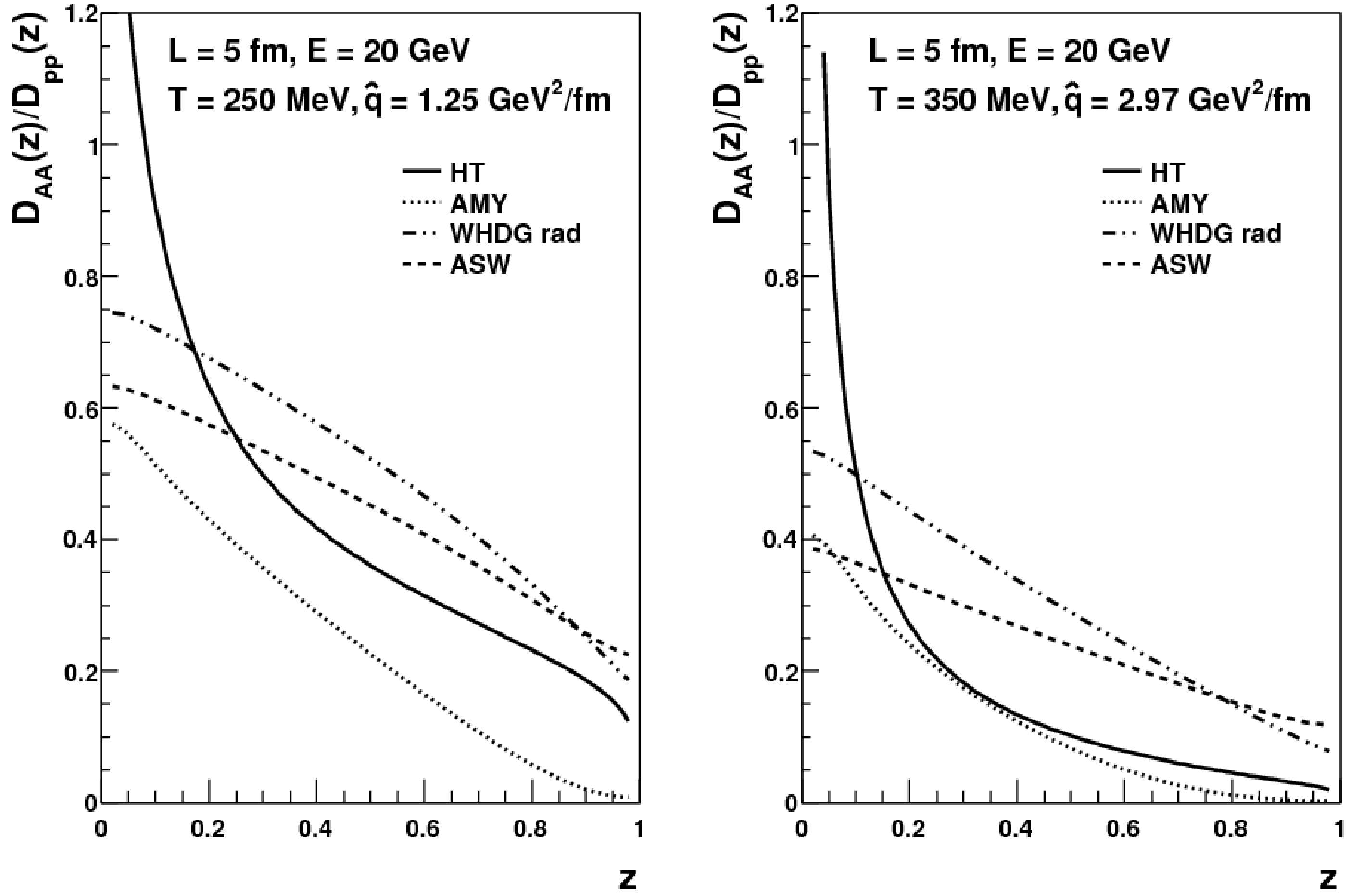


Fragmentation functions sensitive to P(ΔE)

Distinguish GLV from BDMPS?

Modified fragmentation functions

Small-z enhancement from gluon fragments (only included in HT, not important for R_{AA})

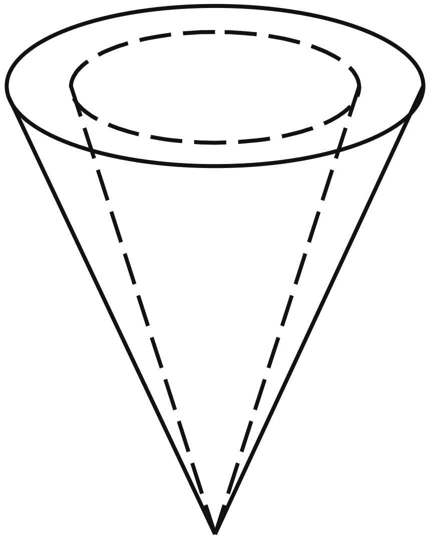


A. Majumder, MvL, arXiv:1002.2206

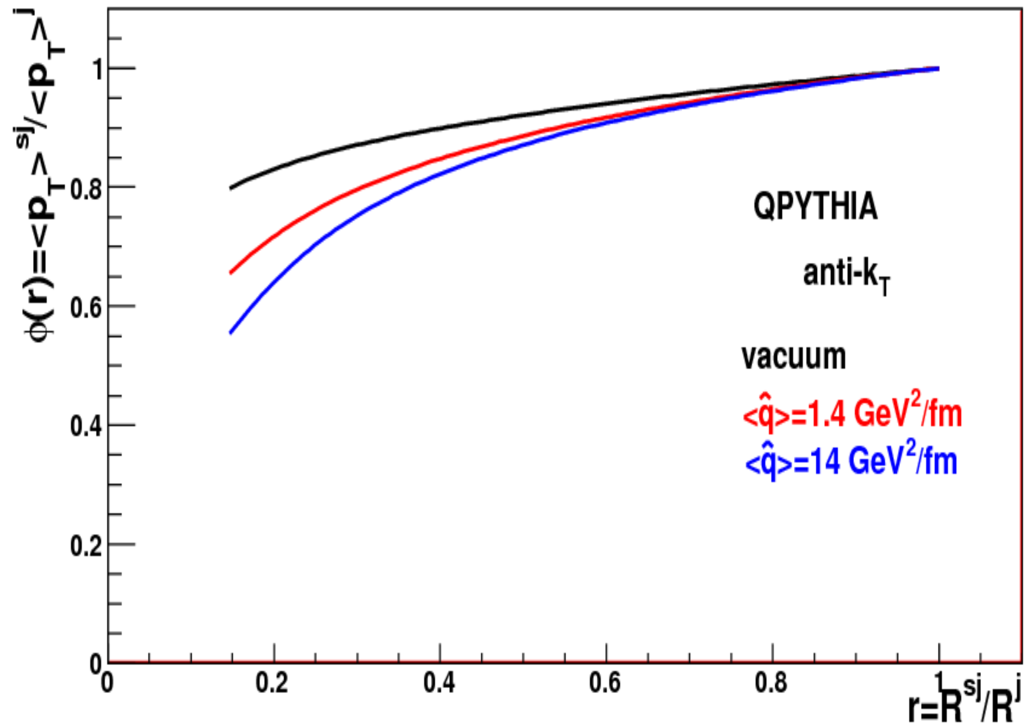
Differences between formalisms large, both magnitude of supresion and z-dependence

Can we measure this directly? Jet reconstruction

Jet shapes



Energy distribution
in sub-jets



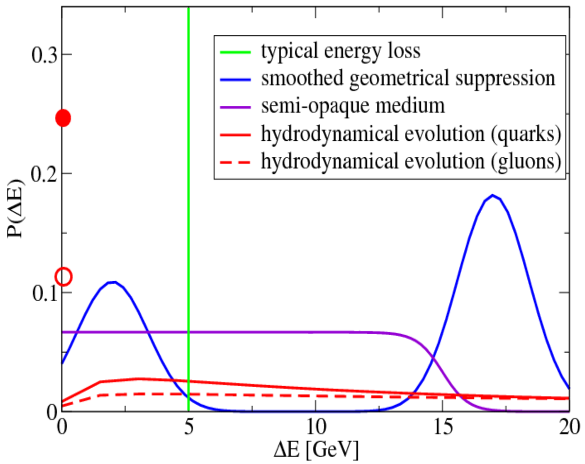
q-Pythia, Eur Phys J C 63, 679

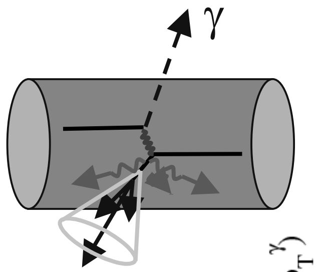
Energy loss changes radial
distribution of energy

Several 'new' observables considered
Discussion: sensitivity ⇔ viability … ongoing

Fixing the parton energy with γ-jet events

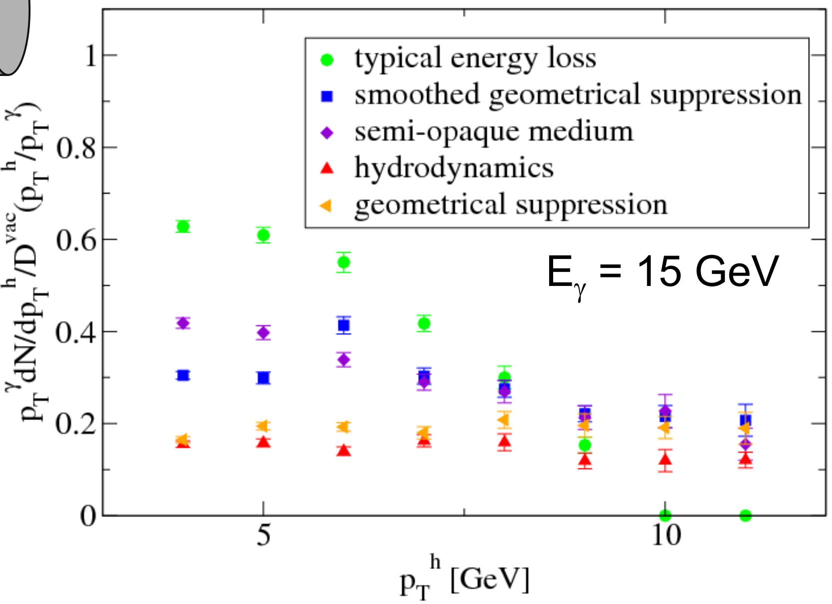
Input energy loss distribution





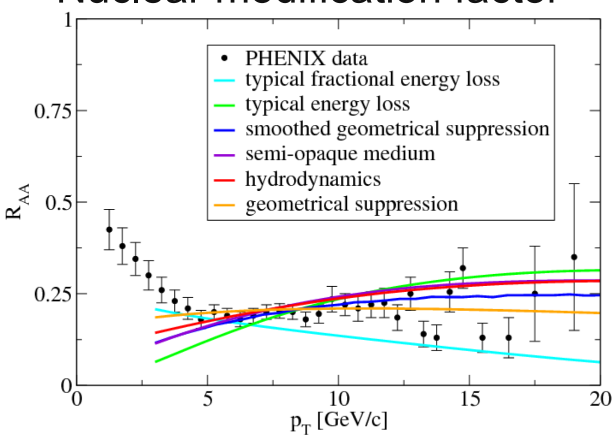
T. Renk, PRC74, 034906

Away-side spectra in γ-jet



Away-side spectra for γ-jet are sensitive to P(ΔE)

Nuclear modification factor

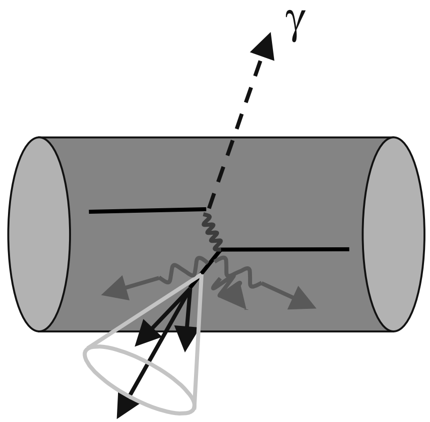


R_{AA} insensitive to P(ΔE)

γ-jet: know jet energy ⇒ sensitive to P(ΔE)

Direct-γ recoil suppression

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

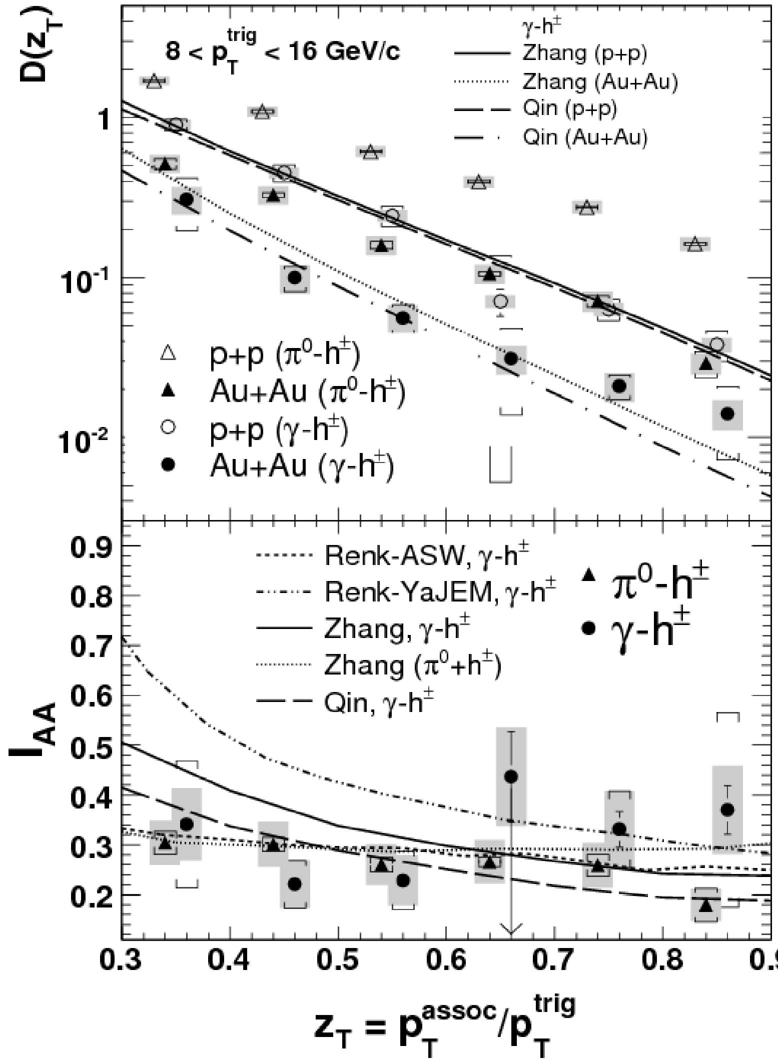


$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$

Large suppression for away-side: factor 3-5

Reasonable agreement with model predictions

NB: gamma p_T = jet p_T still not very large



STAR, arXiv:0912.1871

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 $\eta,\varphi_{jet} = \langle\eta,\varphi\rangle_{particles}$

Sum particles inside jet

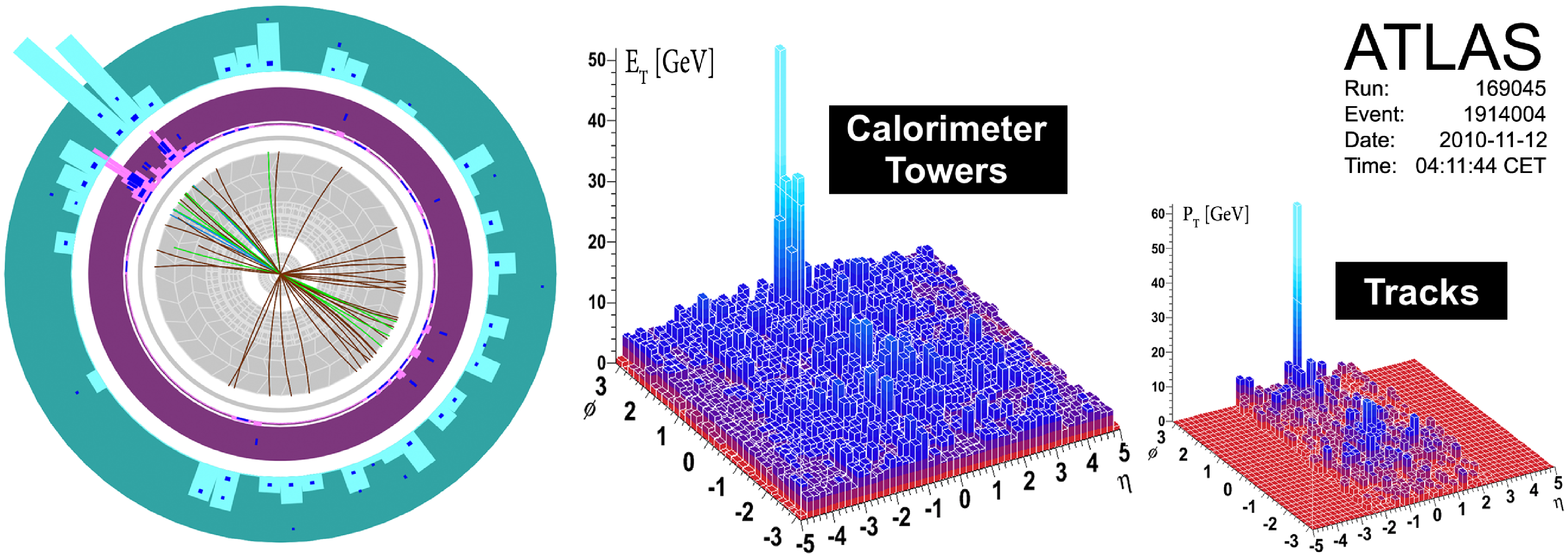
Different prescriptions exist, most natural: E-scheme, sum 4-vectors

Jet is an object defined by jet algorithm

If parameters are right, may approximate parton

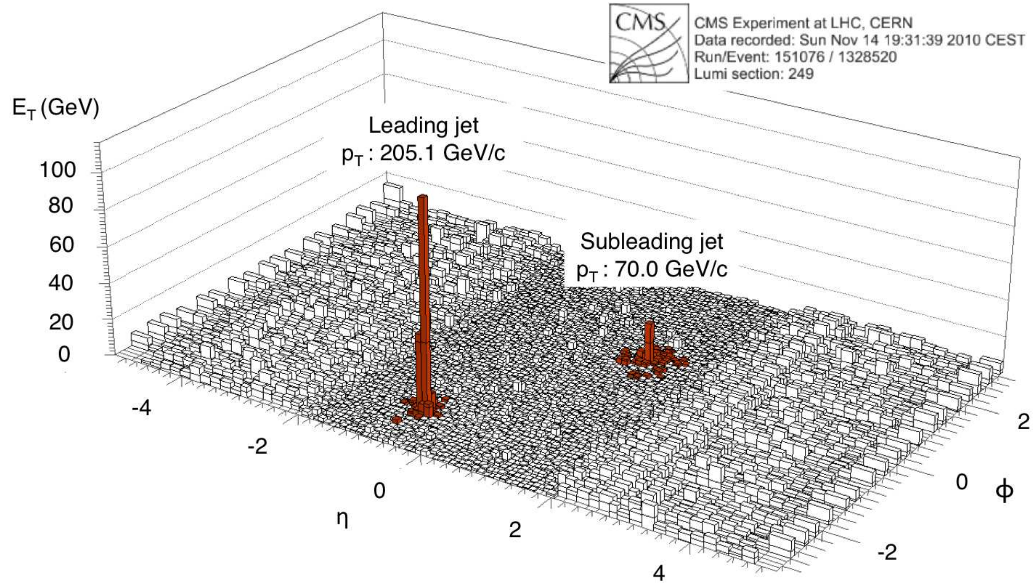
For a complete discussion, see: http://www.lpthe.jussieu.fr/~salam/teaching/PhD-courses.html

Jets at LHC



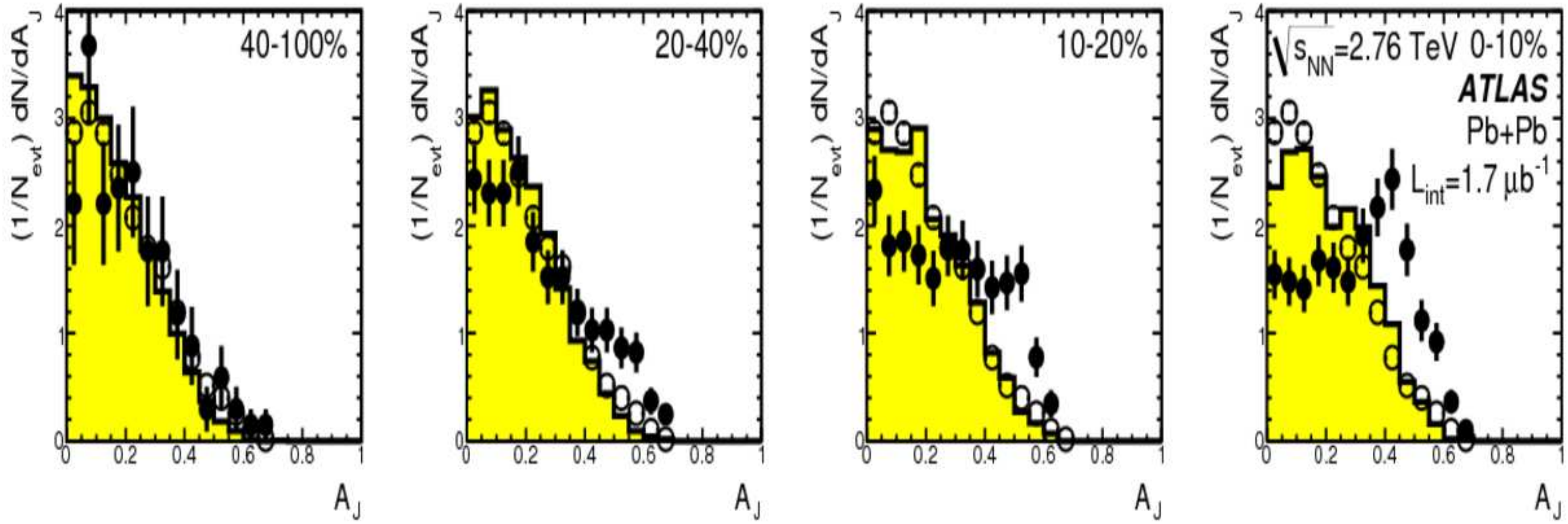
LHC: jet energies up to ~200 GeV in Pb+Pb from 1 ‘short’ run

Large energy asymmetry observed for central events



Jets at LHC

Centrality →



ATLAS, arXiv:1011.6182 (PRL)

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

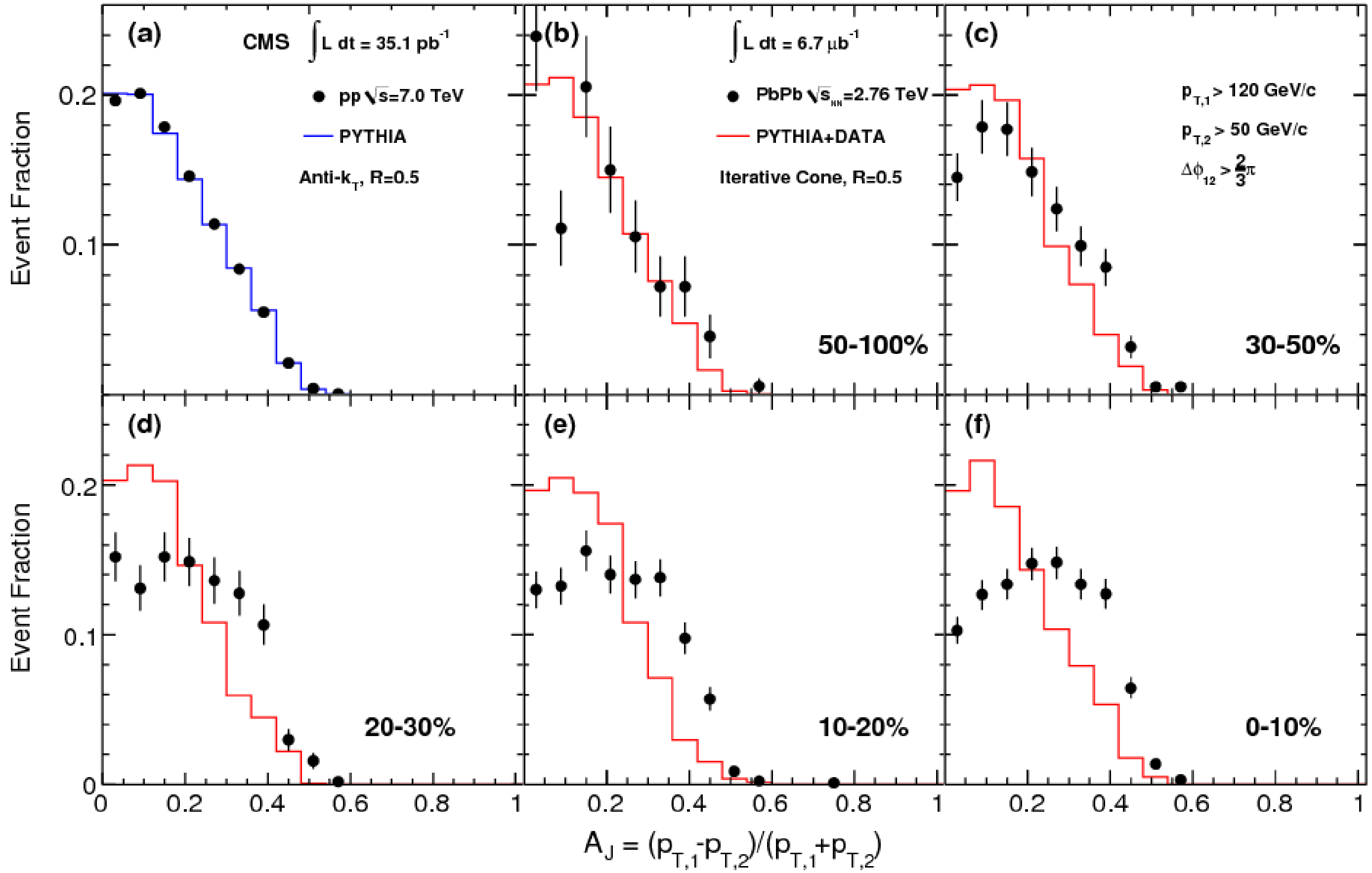
Large asymmetry seen for central events

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

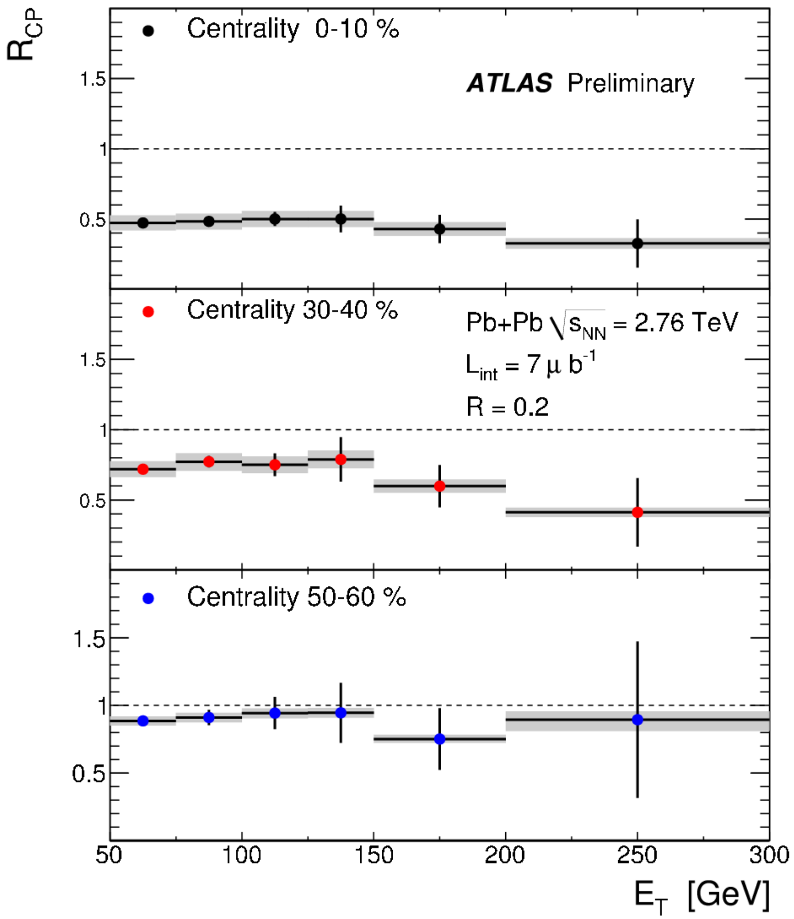


CMS, arXiv:1102.1957

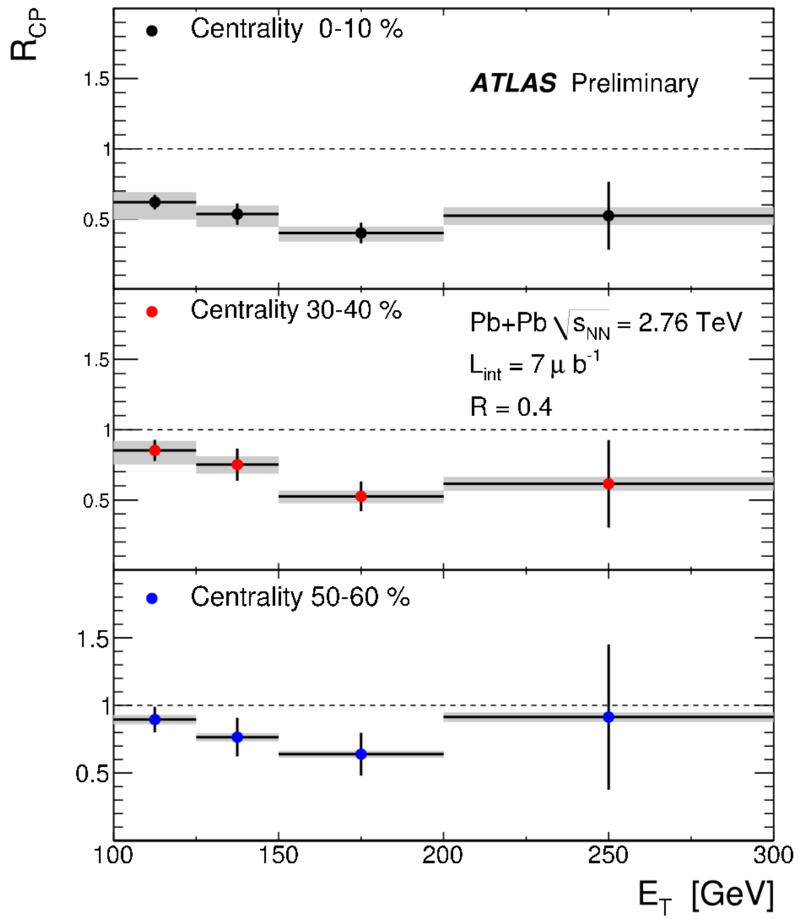
CMS sees similar asymmetries

Jet R_{CP}

R=0.2



R=0.4



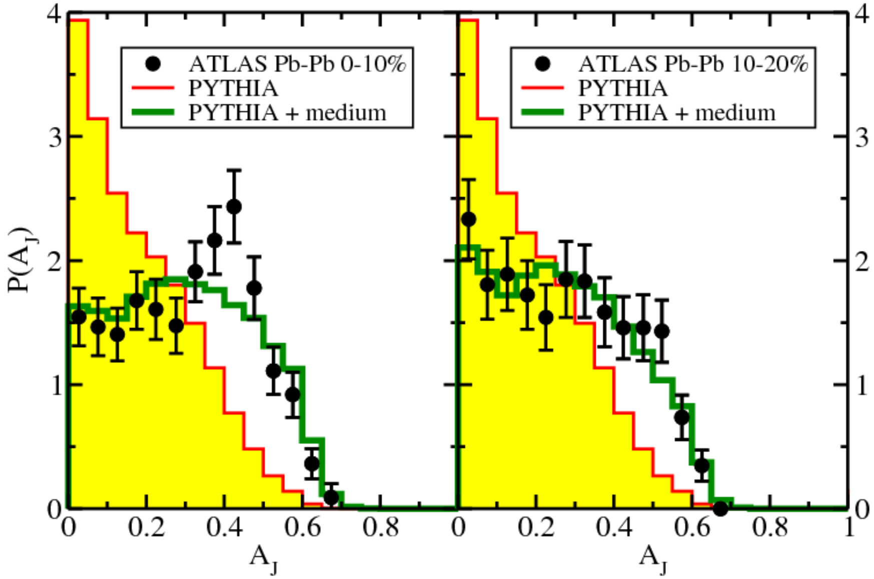
$R_{CP} < 1$: jet production suppressed, even at high p_T

⇒ Out-of-cone radiation with R=0.4 significant

NB: Jet-measurements are difficult: important experimental questions about (trigger) bias and background fluctuations

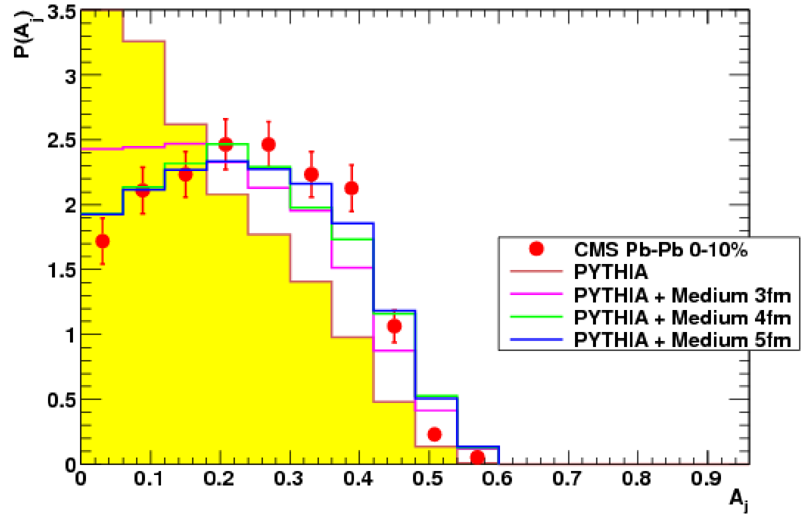
Jet imbalance calculations

Qin, Muller, arXiv:1012.5280



Radiation plus evolution

Coleman-Smith, Qin, Bass, Muller, arXiv:1108.5662

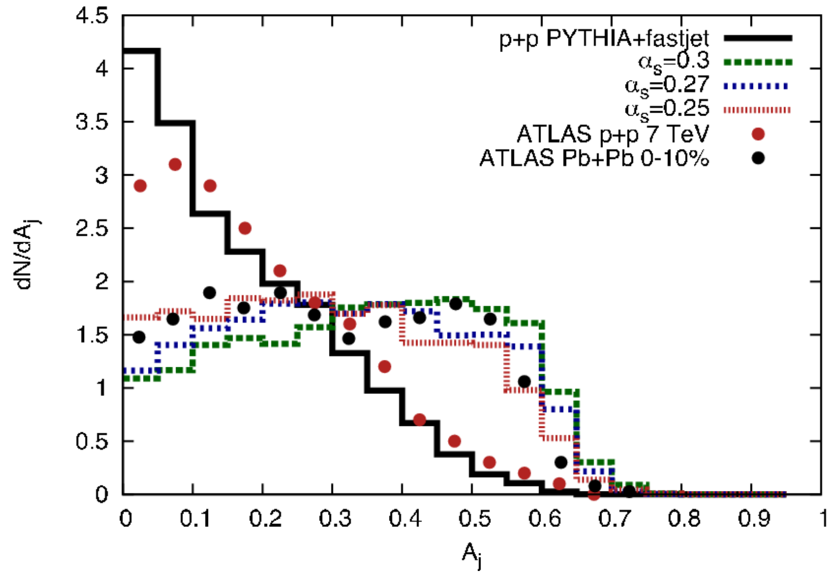


Parton transport (brick)

Several calculations describe measured imbalance

Need to keep track of all fragments: Various approximations made

Most natural approach: parton showers (qPYTHIA, qHERWIG, JEWEL ?)



Young, Schenke, Jeon, Gale, arXiv:1103.5769

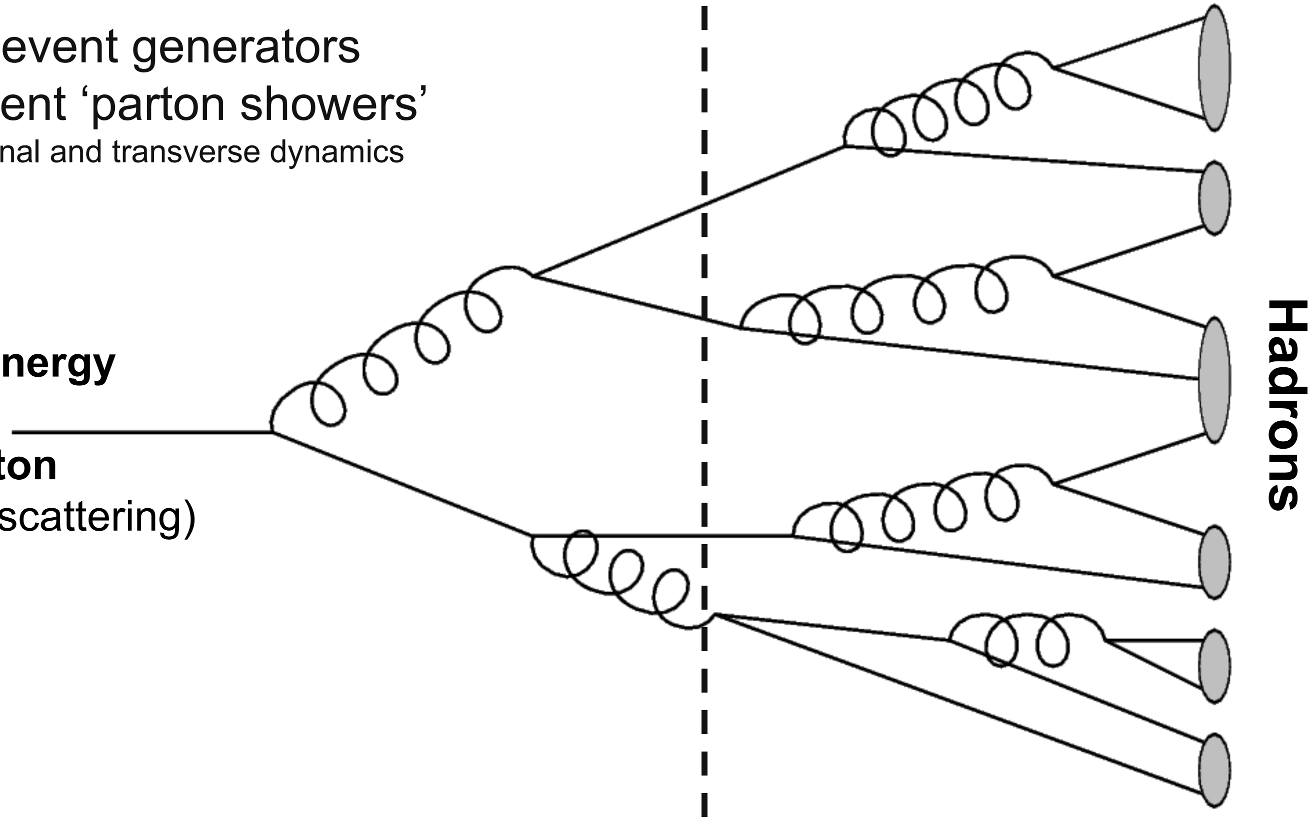
MARTINI: AMY+MC

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

Getting ready

Software set-up:

- ROOT
- LHAPDF
- Fragmentation function libraries
- AliFastGlauber
- AliQuenchingWeights

(ROOT, LHAPDF, Fragmentation function libraries: Day 1; AliFastGlauber: Day 2; AliQuenchingWeights: Day 3)

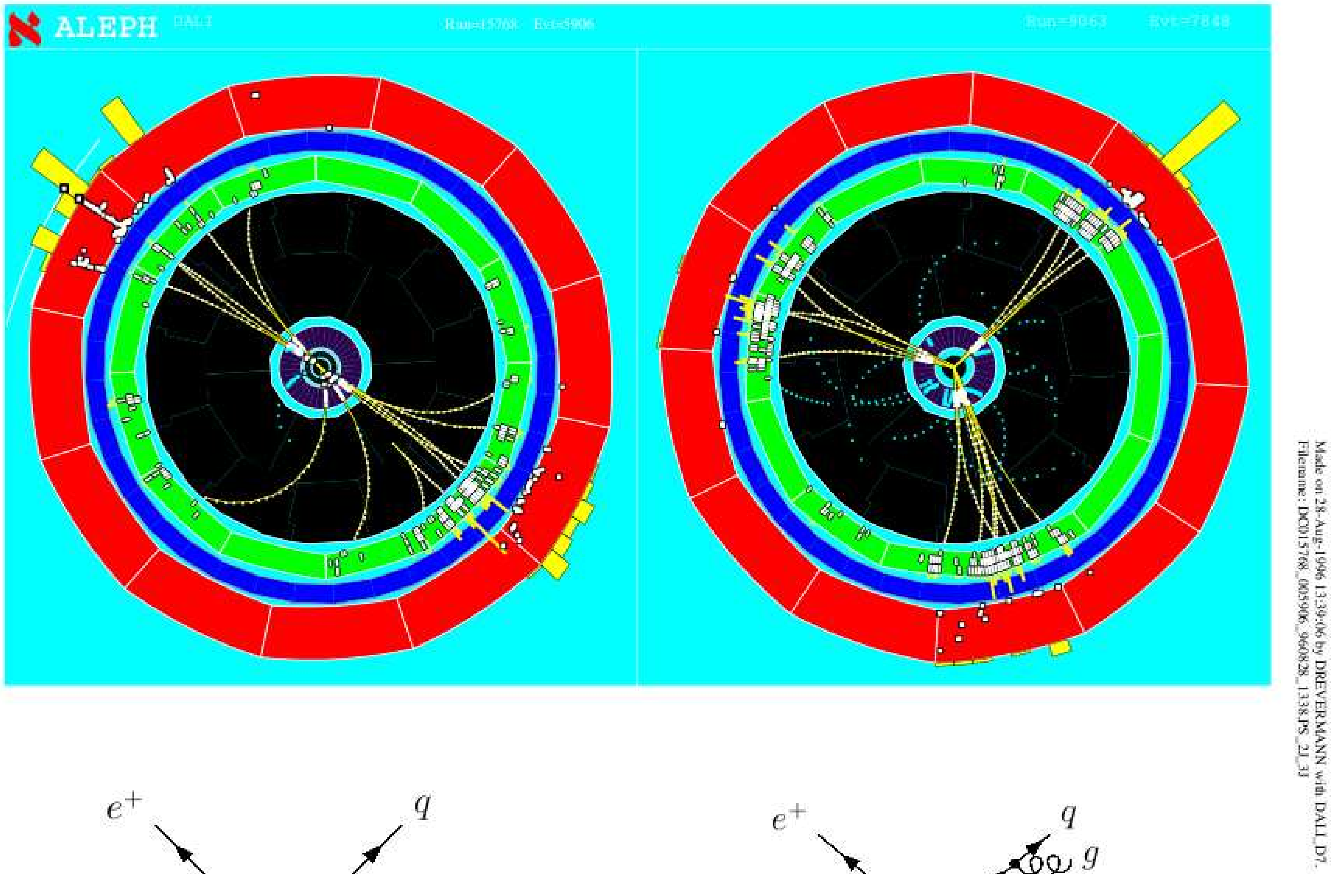
See also http://www.staf.science.uu.nl/~leeuw179/powerweek/software

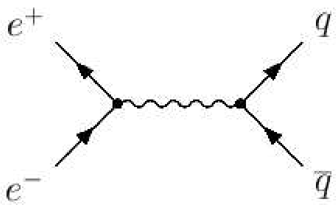
Make sure that you have the code and that the test macros work

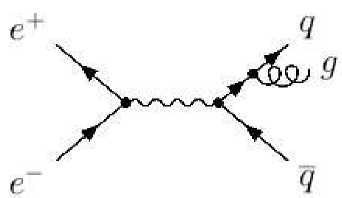
Questions/problems $\Rightarrow$ See me or Andreas

Extra slides

Seeing quarks and gluons







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