Search for Quark-Gluon Plasma from RHIC to LHC:

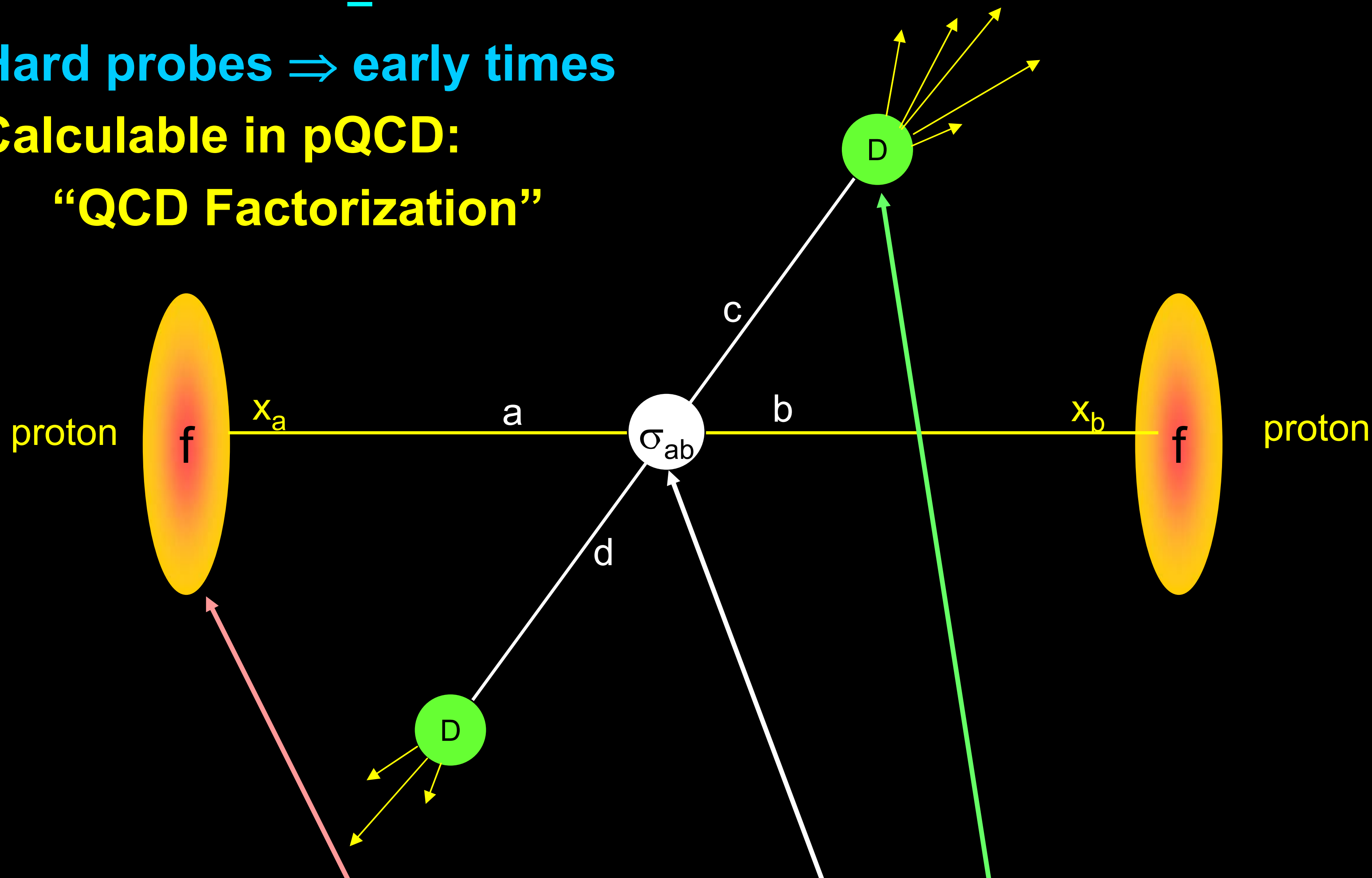
Hard Probes at RHIC & What to "Expect" at LHC!

Jets & High p_T Particles in Proton-Proton Collisions

Hard probes ⇒ early times

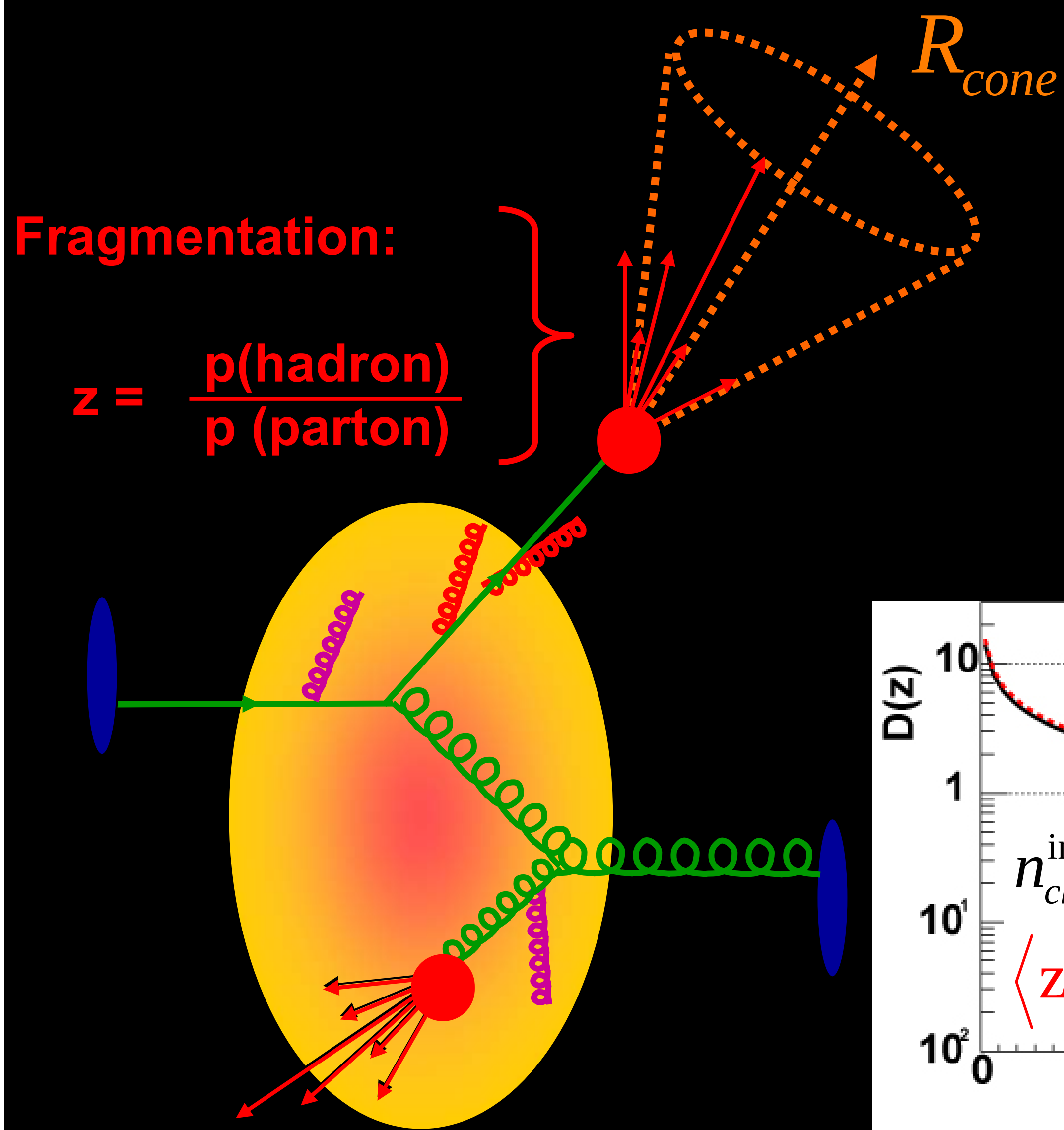
Calculable in pQCD:

"QCD Factorization"



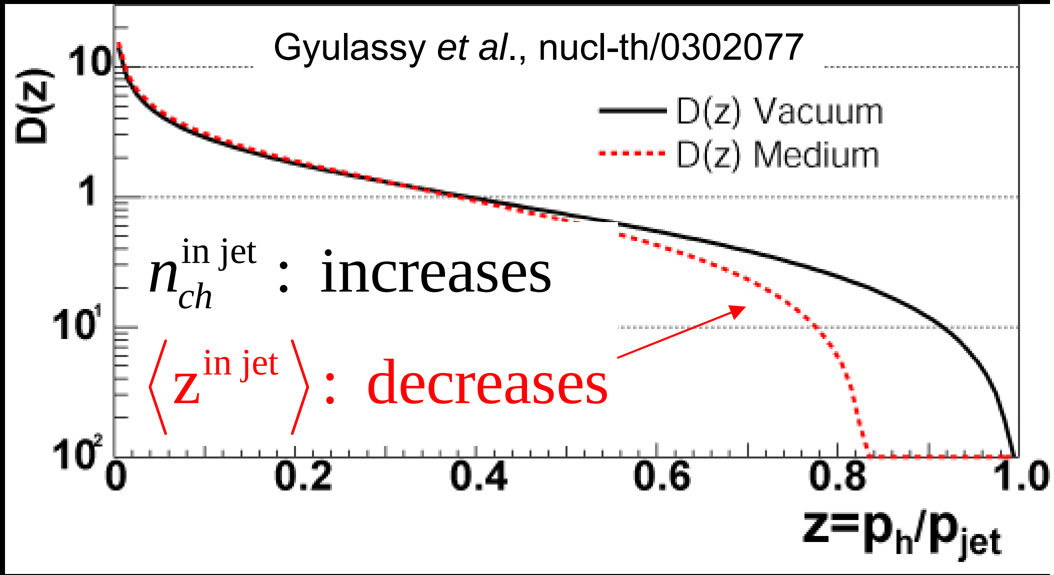
$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a, Q^2\right) \otimes f_{b/B}\left(x_b, Q^2\right) \otimes \frac{d\hat{\sigma}^{ab\rightarrow cd}}{dt} \otimes D_{h/c}\left(z_c, Q^2\right)$$

Jets & High p_T Particles Nucleus-Nucleus Collisions



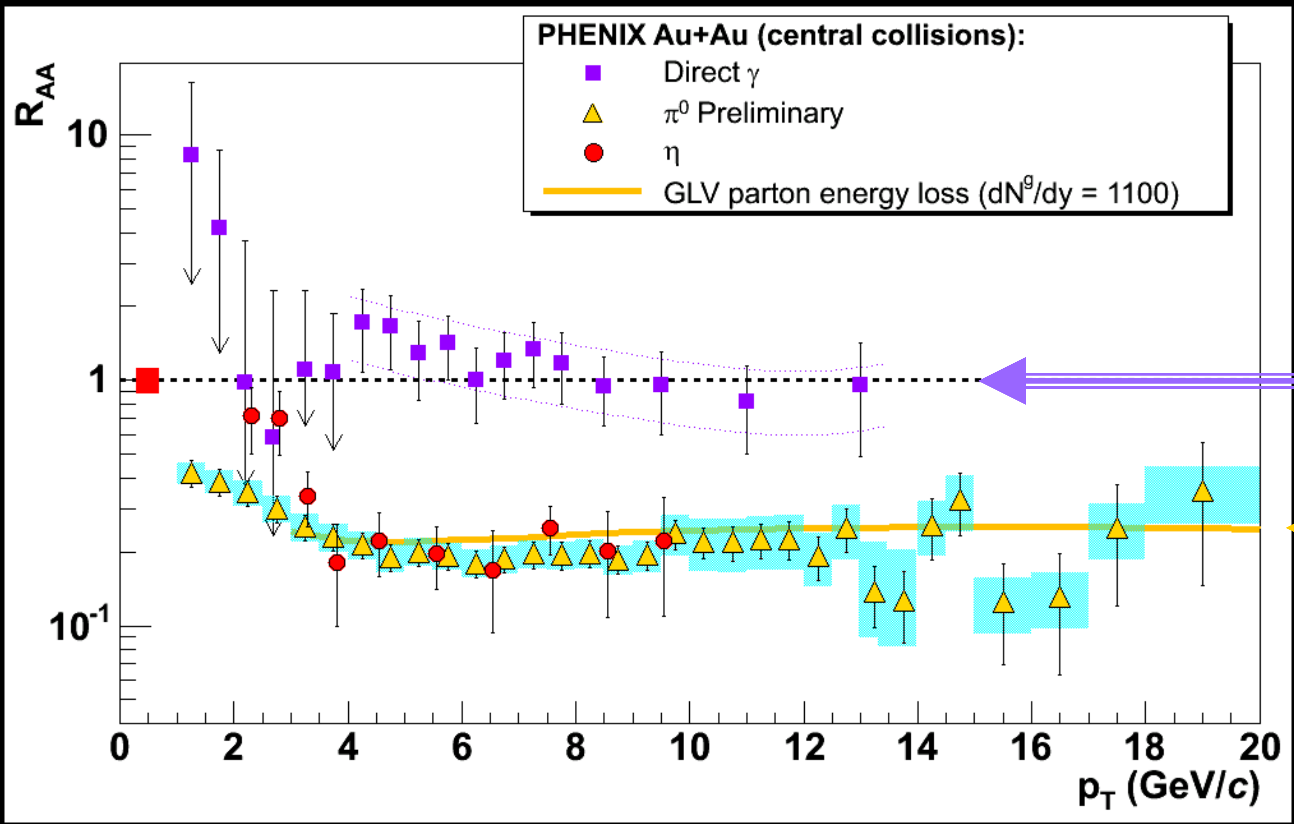
Same as pp case except:
partons propagate in medium

k_T "radiative corrections"
pre- and post-scattering
di-jet: $\Delta\phi \neq \pi$



At RHIC - High Momentum Hadrons Are Suppressed, Photons Not

Deviations from binary scaling of hard collisions: $R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$

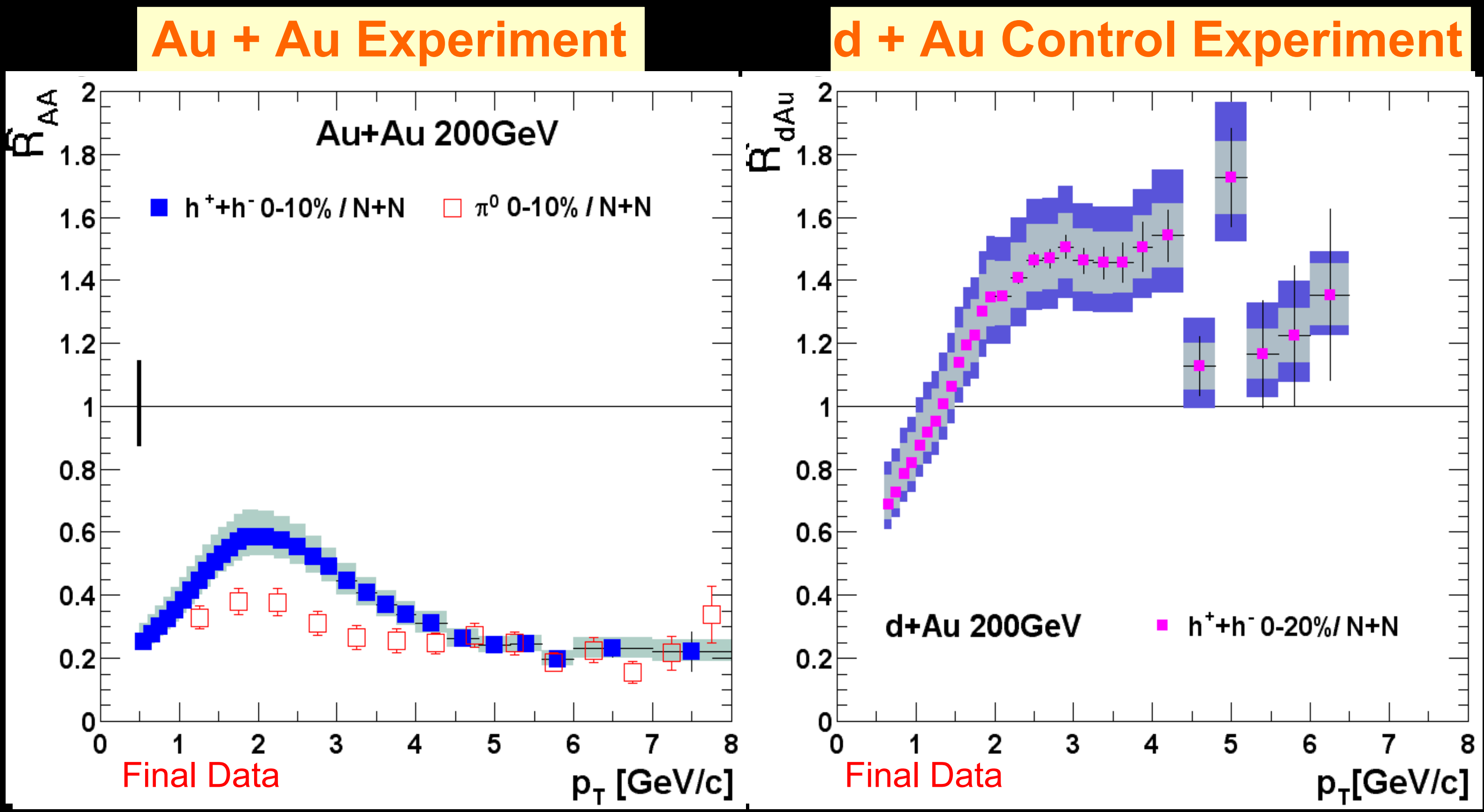


Photons

Hadrons
factor 4 – 5
suppression

RHIC -Compare Au + Au with d + Au (control experiment)

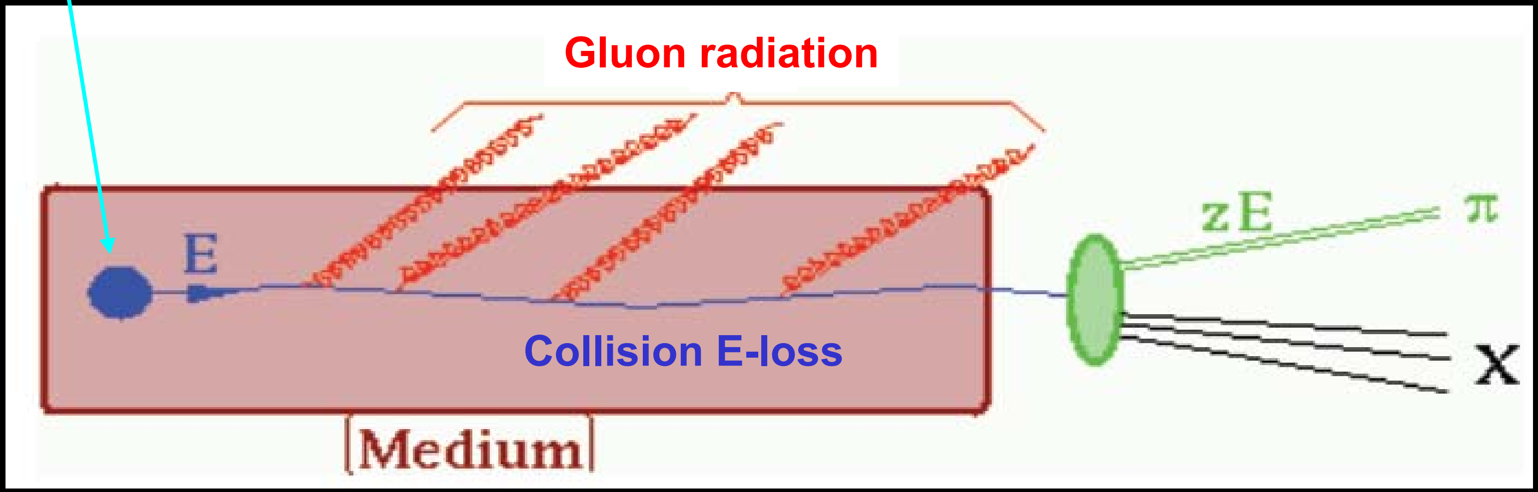
Hadron spectra at RHIC in p+p, Au+Au & d+Au establish existence of *early parton energy loss* from strongly interacting QCD matter in central Au-Au collisions



Dynamical Origin of High p_T Hadron Suppression?

How does parton lose energy?

What happens to the radiation?



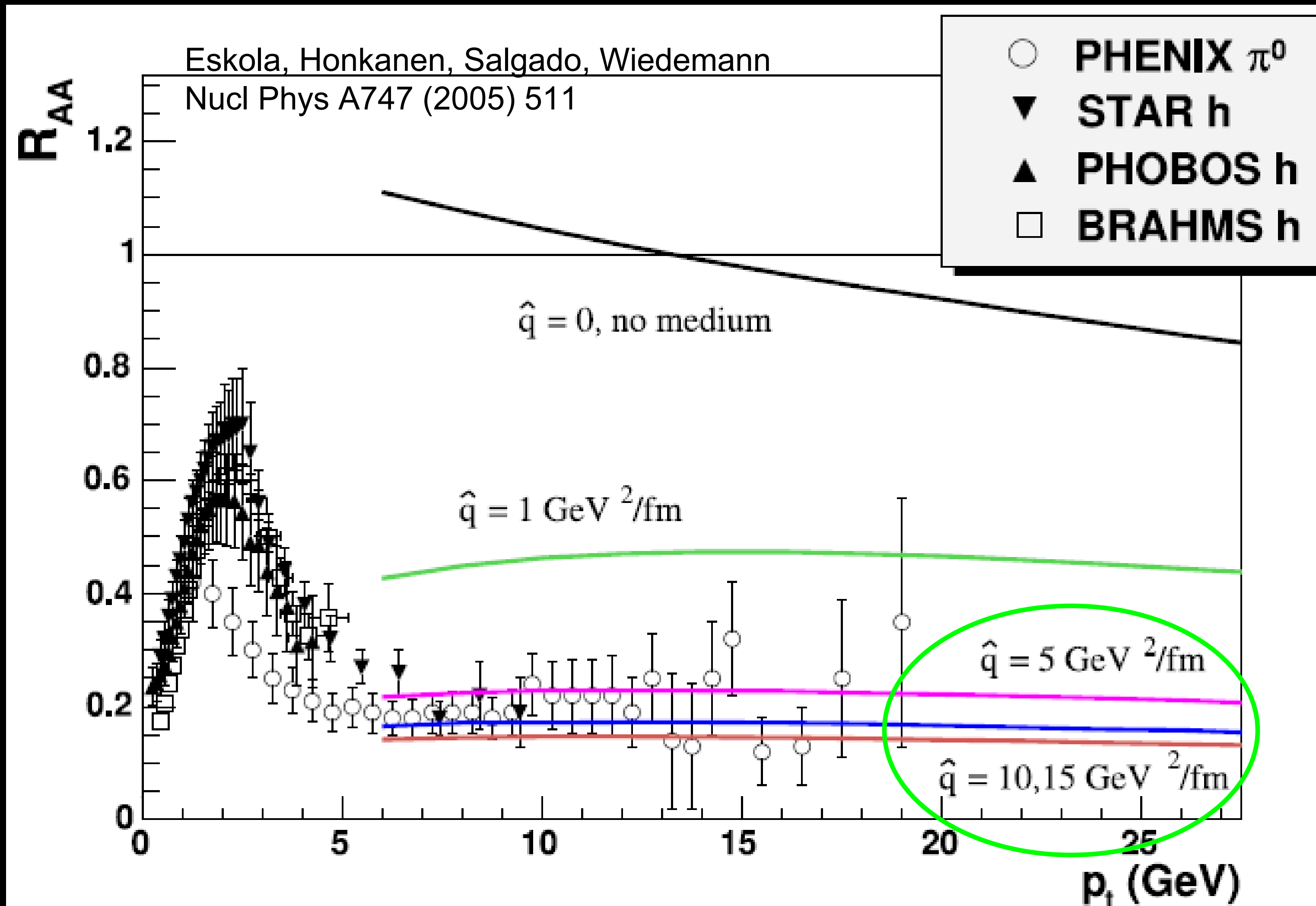
How does ΔE depend on the type of parton?

For collisional energy loss what about recoil energy?

$$\Delta E_{gluon} > \Delta E_{quark,\ m=0} > \Delta E_{quark,\ m>0}$$

One parameterization of energy loss $\rightarrow$ $\hat{q} = \mu^2 / \Lambda$

$\hat{q}$ Parameterization of Parton Energy Loss



$\hat{q}$ = 5 – 15 GeV^2 / fm from RHIC R_{AA} Data

Interpretation of the Parton Energy Loss at RHIC

Energy loss requires large $\langle \hat{q} \rangle \approx 5 - 15\ \mathrm{GeV}^2/\mathrm{fm}$

(also : Dainese, Loizides, Paic, hep-ph/0406201)

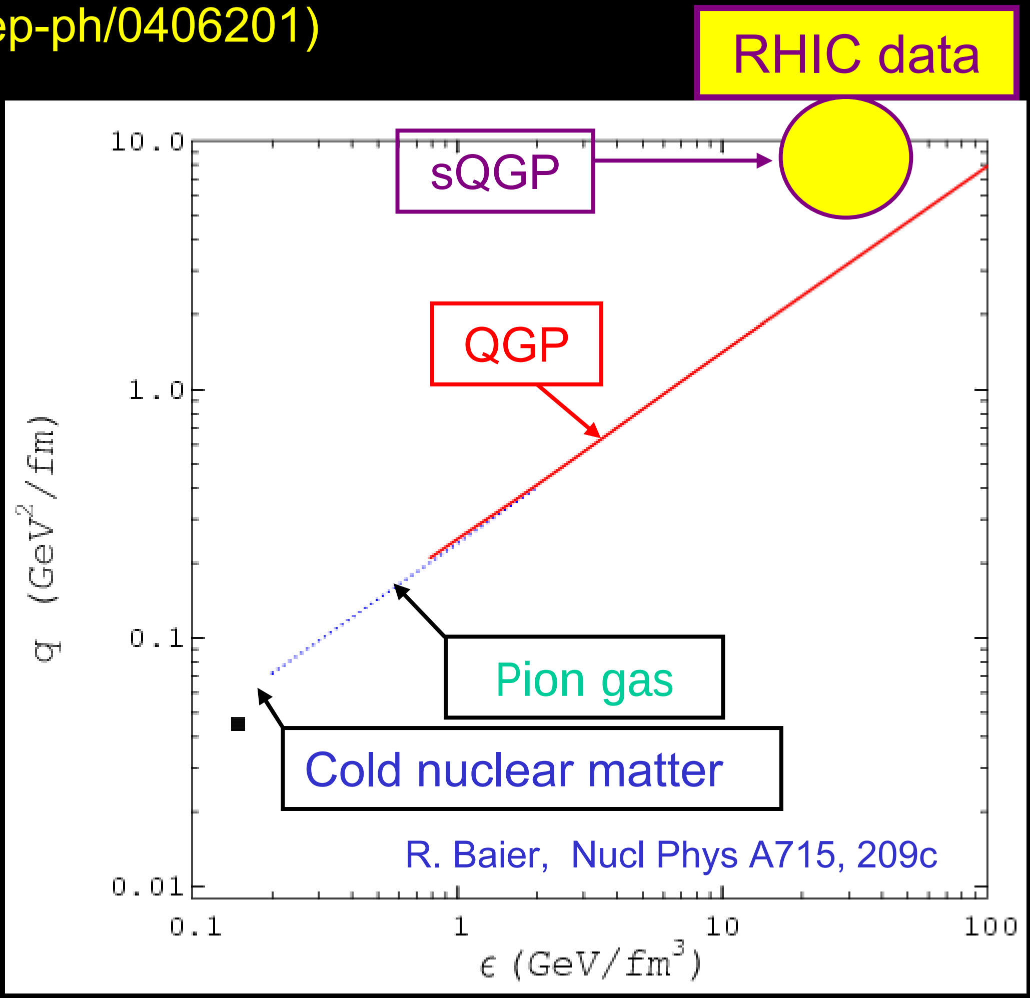
$$\hat{q}_{pQCD} = \frac{4\pi^2 \alpha_S N_C}{N_C^2 - 1} \rho_{medium} \left[xG(x, \hat{q}L) \right]$$

Equilibrated gluon gas:

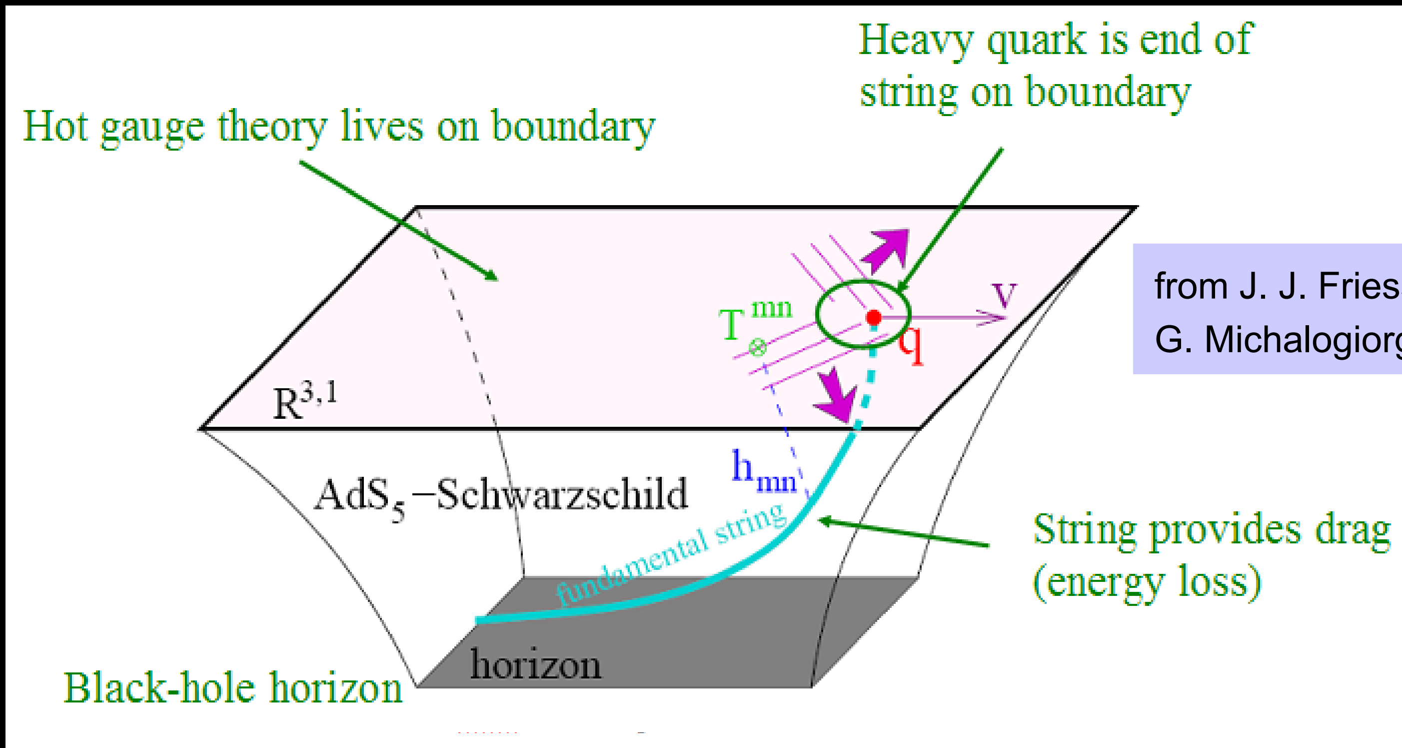
$\rho_{medium} \sim T^3$

energy density $\varepsilon \sim T^4$

$$\rightarrow \quad \hat{q} = c\varepsilon^{\frac{3}{4}}$$



AdS$_5$/CFT *Again! - Initial Results on Jet Quenching*



from J. J. Friess, S. S. Gubser and G. Michalogiorgakis,arXiv:hep-th/0605292.

Calculating the Jet Quenching Parameter from AdS/CFT

Hong Liu,[1] Krishna Rajagopal,[1,2] and Urs Achim Wiedemann[3,4]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Nuclear Science Division, MS 70R319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Department of Physics and Astronomy, University of Stony Brook, NY 11794, USA*
[4] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*

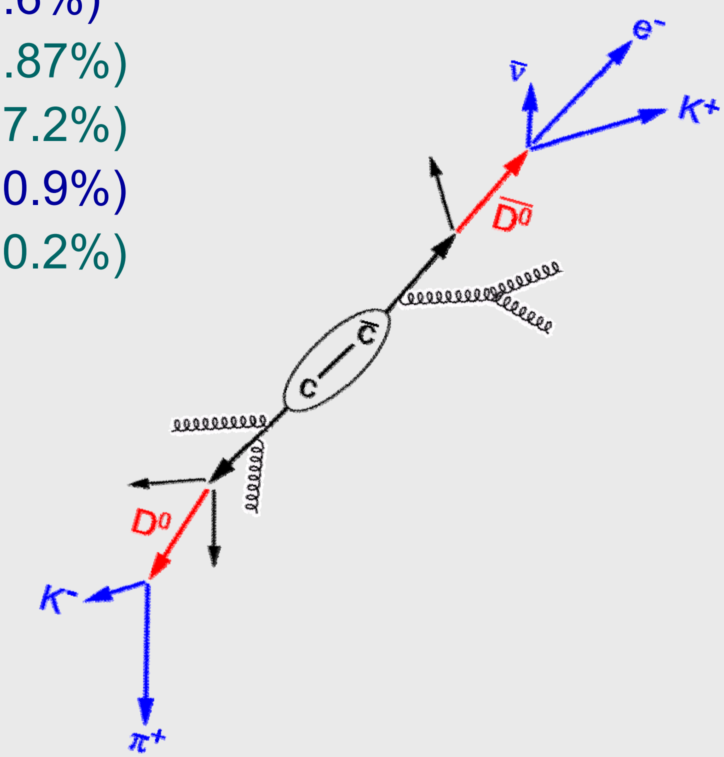
(Dated: May 16, 2006)

H. Liu, K. Rajagopal and U. A. Wiedemann, arXiv:hep-ph/0605178, recent PRL

transition, we shall use $\lambda = 6\pi$ to make estimates. From (15), we find $\hat{q}$ =3.2, 7.5, 14.7 GeV^2/fm for T = 300, 400, 500 MeV. In a heavy ion collision, $\hat{q}$ decreases with time τ as the hot fluid expands and cools. The time-averaged $\hat{q}$ which has been determined in comparison with RHIC data is $\bar{\hat{q}} \equiv \frac{2}{(L^-)^2}\int_{\tau_0}^{\tau_0+L^-} \tau\,\hat{q}(\tau)\; d\tau$, found to be of order 10 GeV^2/fm [4, 5]. If we assume a one-

R_{AA} of Heavy Quarks from Non-photonic Electrons

- Non-photonic electrons come from
  semi-leptonic decays of heavy quarks
  - $c \rightarrow e^{+} + \text{anything}$ (B.R. = 9.6%)
    - $D^{o} \rightarrow e^{+} + \text{anything}$ (B.R. = 6.87%)
    - $D^{\pm} \rightarrow e^{\pm} + \text{anything}$ (B.R. = 17.2%)
  - $b \rightarrow e^{+} + \text{anything}$ (B.R. = 10.9%)
    - $B^{\pm} \rightarrow e^{\pm} + \text{anything}$ (B.R. = 10.2%)
  - plus small contribution from Drell-Yan
    for $p_T < 10$ GeV/c



Heavy quarks thought too massive to be attenuated by medium!

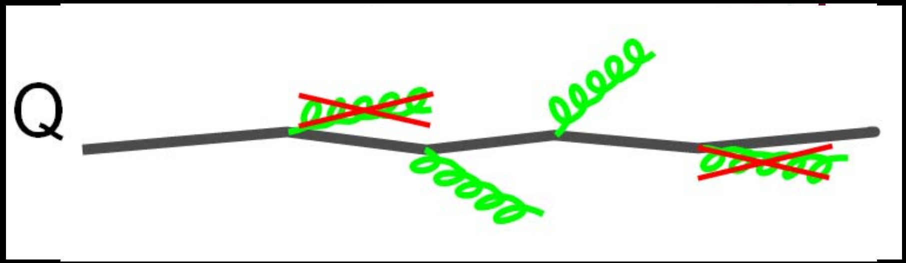
“Dead Cone Effect” for Heavy Quarks

Dead Cone Effect
(Y. Dokshitzer & D. Kharzeev et al., Phys. Lett. B 519 (2001) 1999):

Gluon radiation from a massive parton is suppressed at small angles

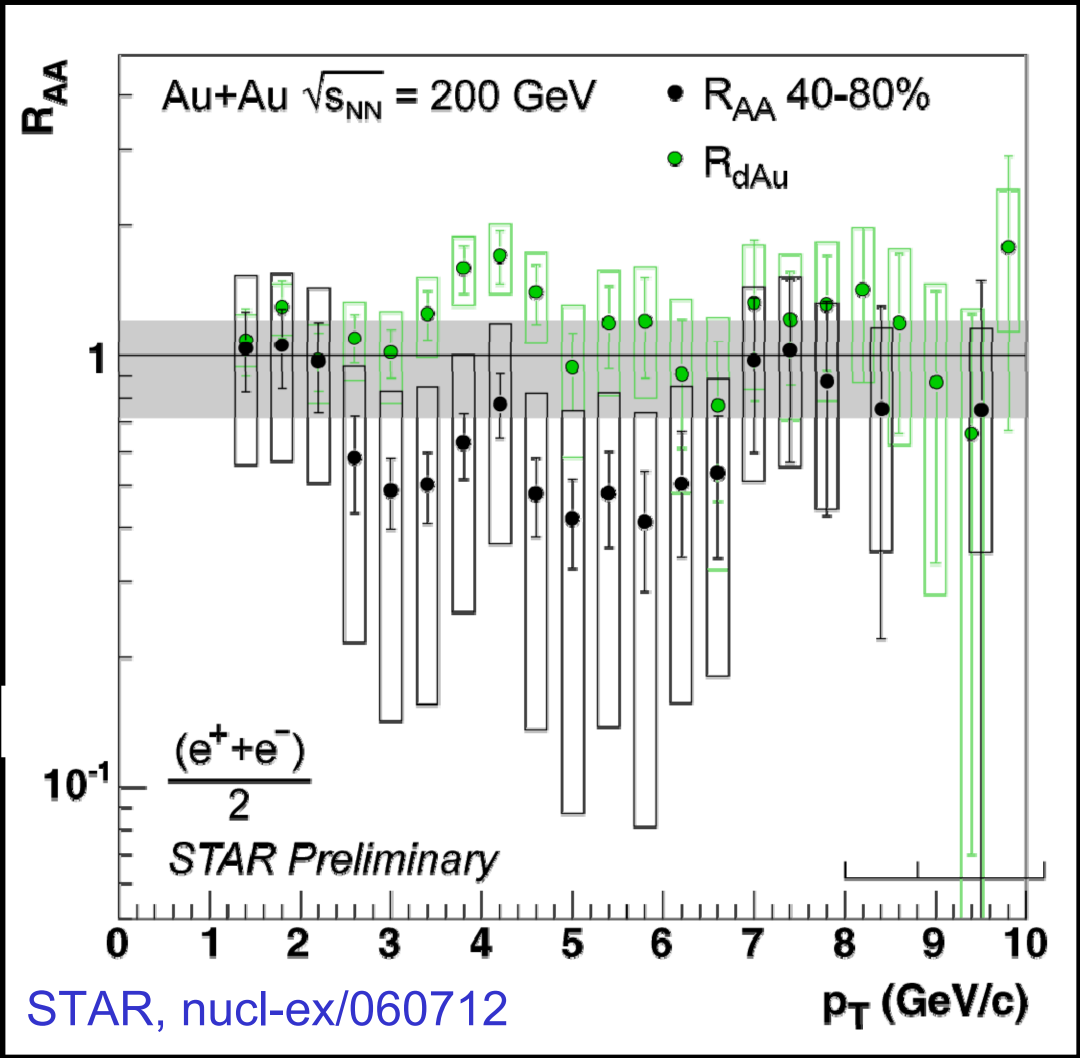
$\Theta < m_q / E_q$

(result of causality since $v_q < c$)



Energy loss is therefore reduced.
Heavy quarks up to ~ 10 - 20 GeV/c

RHIC - R_{AA} of Heavy Quarks from Non-photonic Electrons

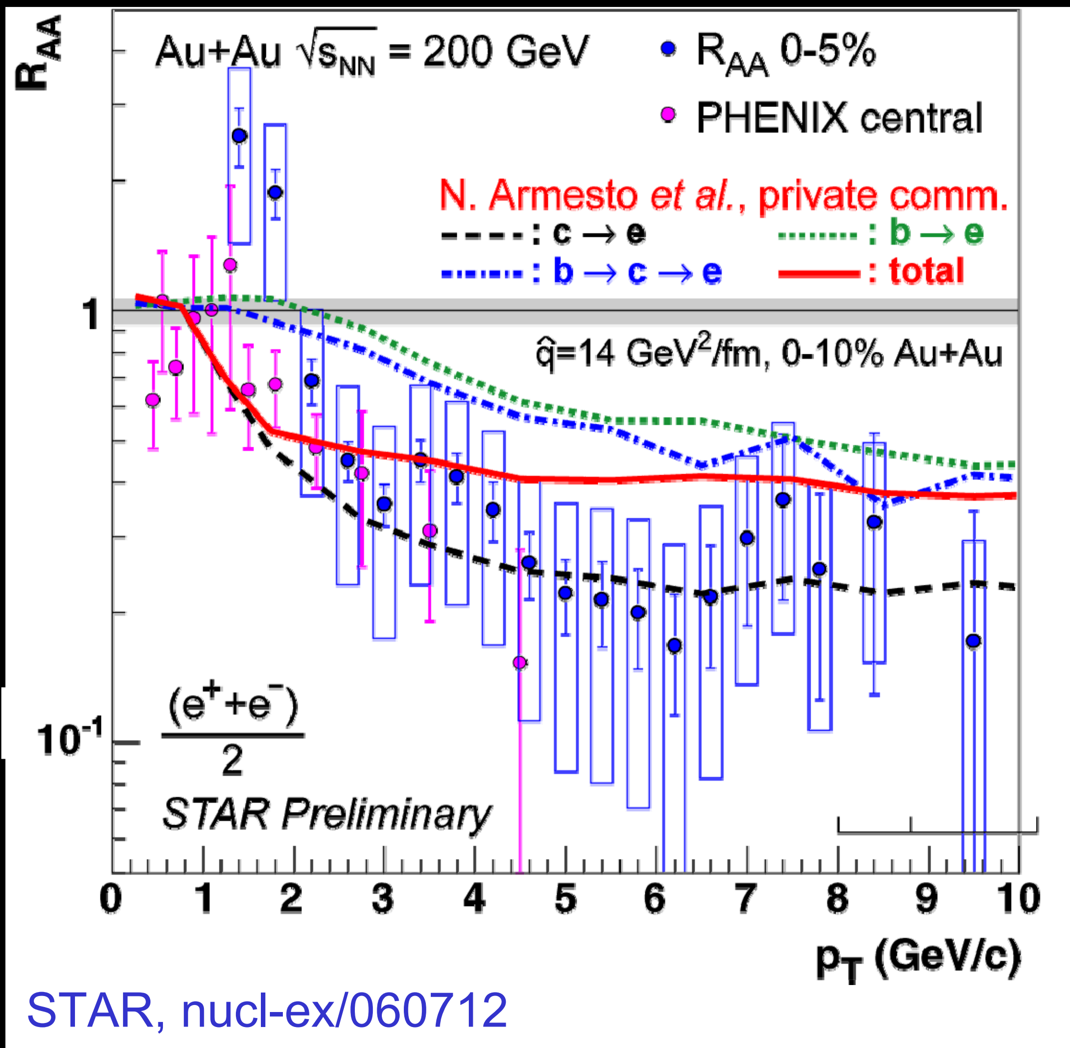


$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

Suppression observed

~ 0.4-0.6 in 40-80% centrality

RHIC - R_{AA} of Heavy Quarks from Non-photonic Electrons



$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

Suppression observed

~ 0.4-0.6 in 40-80% centrality

~ 0.3 -0.4 in 10-40%

~ 0.2 in 0-5%

Max suppression at p_T ~ 5-6 GeV

Theories currently cannot describe the data!

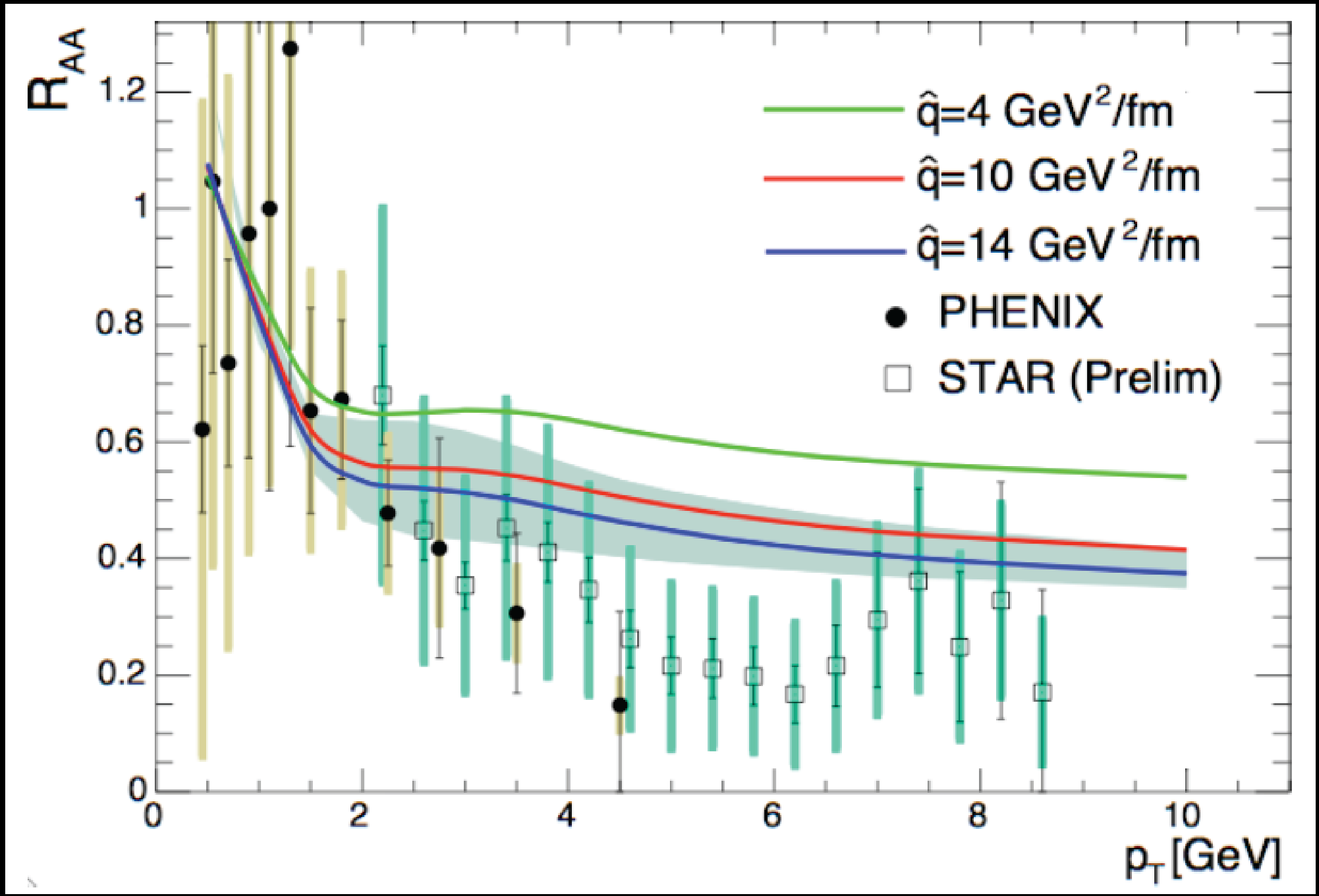
Only c contribution describes R_{AA} but not p + p spectra

Heavy quarks suppressed like light quarks

RHIC - Heavy Quark Suppression

- **Using fixed order next-to-leading log (FONL) cross sections for charm and beauty**

Armesto, Cacciari, Dainese, Salgado, Wiedemann, PLB637:362, 2006



Insufficient suppression!

Heavy Quark Suppression and Elliptic Flow

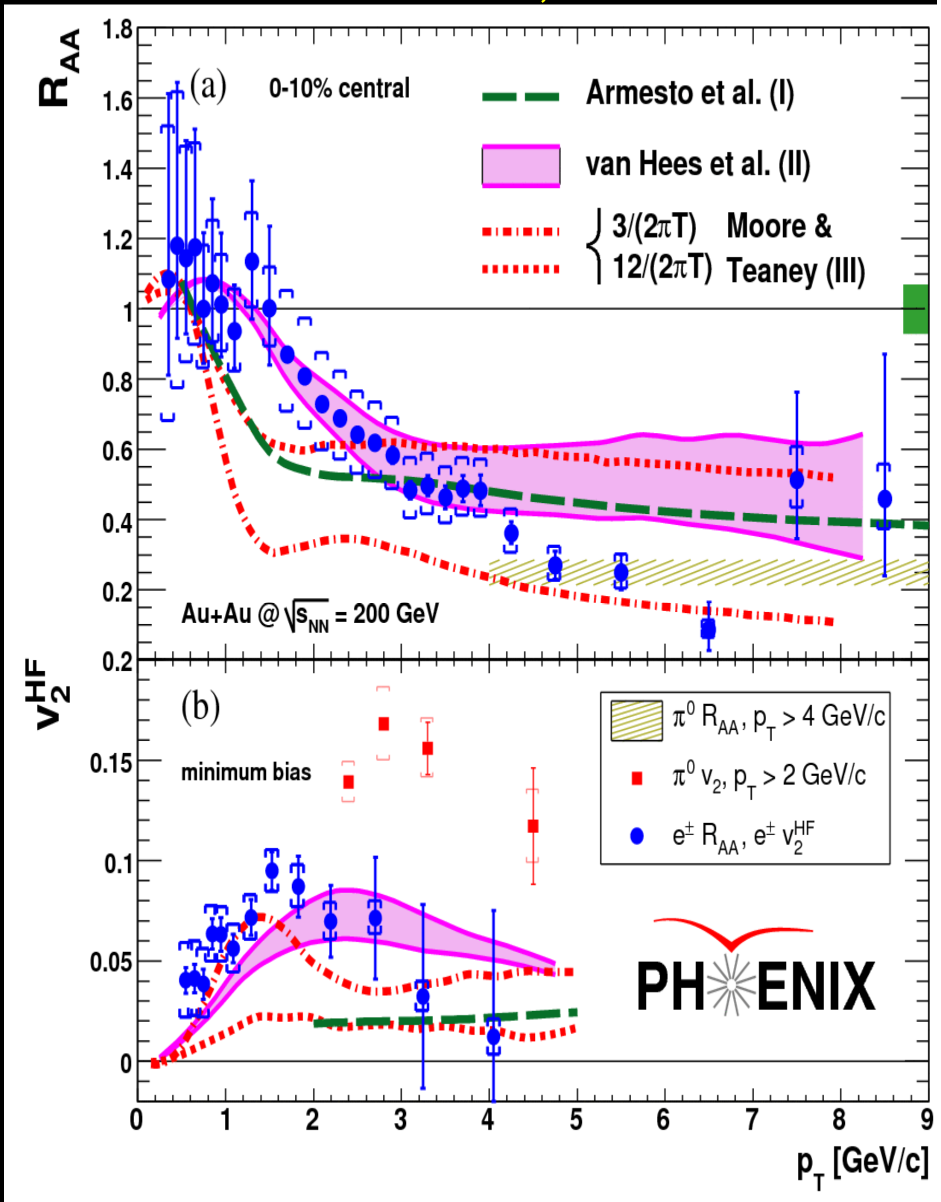
large suppression &

large v_2 of electrons

→ charm thermalization?

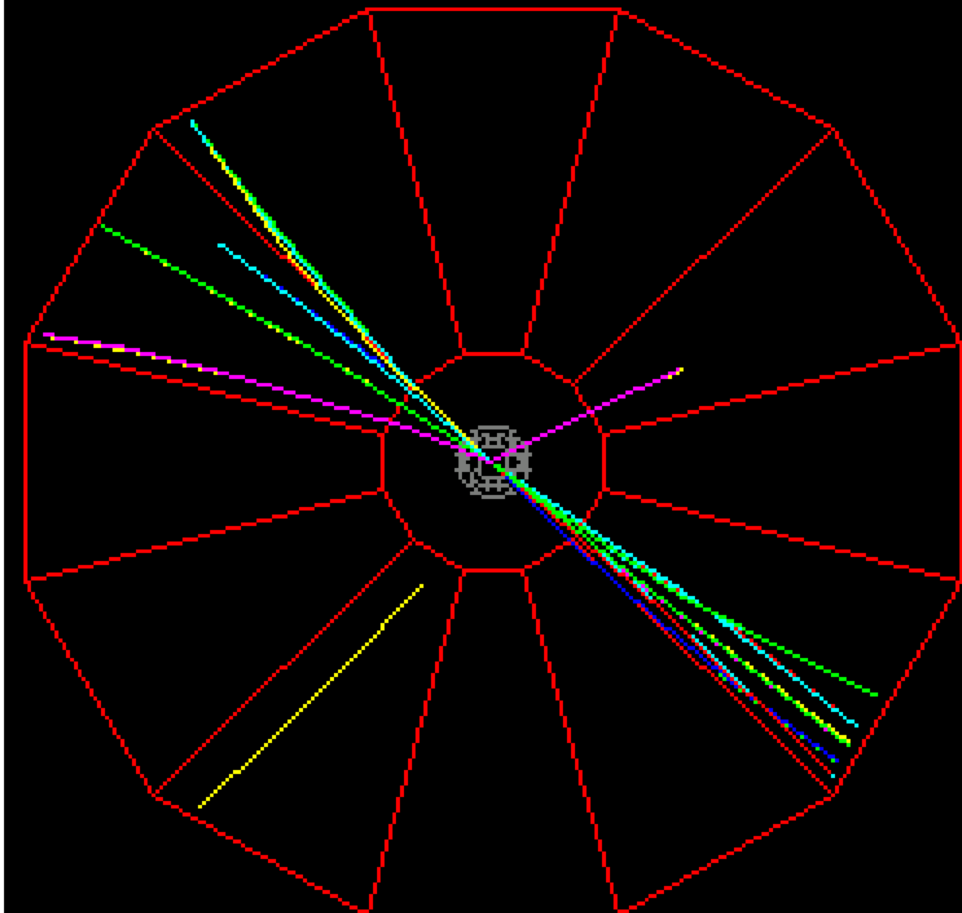
- transport models require
  - small heavy quark relaxation time
  - small diffusion coefficient
    D_{HQ} x ($2\pi T$) ~ 4-6
- These constrain viscosity/entropy
  - η/s ~ (1.5 – 3) / 4π
    within factor 2 - 3 of
    conjectured lower bound
  - consistent with light hadron v_2

PHENIX, nucl-ex/0611018

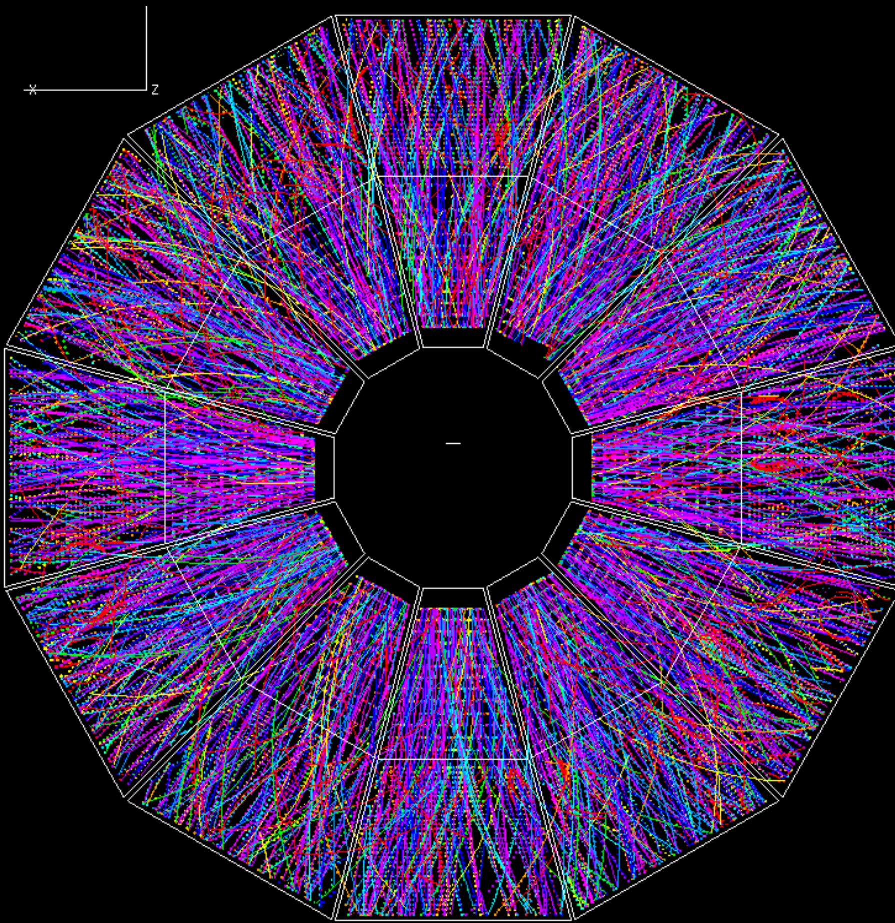


Hard Scattering (Jets) as a Probe of Dense Matter

STAR p + p → jet event



STAR Au+Au (jet?) event



Can we see jets in high energy Au+Au?

STAR Hard Scattering: Two-Particle Azimuthal Correlations

Technique:

$$C_2(\Delta\Phi) = \frac{1}{N_{trigger}} \frac{1}{efficiency} \int d(\Delta\eta) N(\Delta\Phi, \Delta\eta)$$

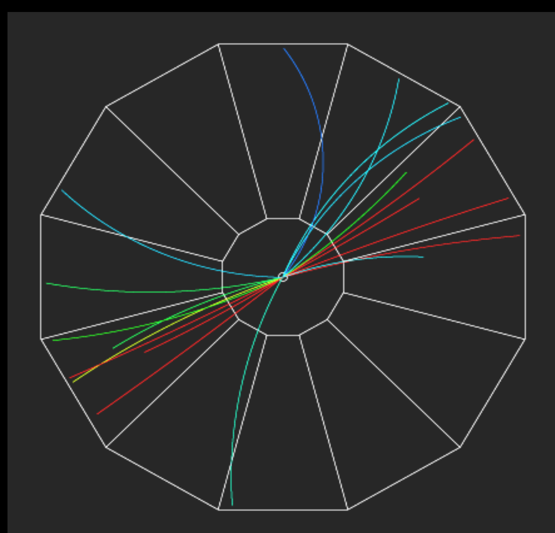
Azimuthal correlation function

Trigger particle

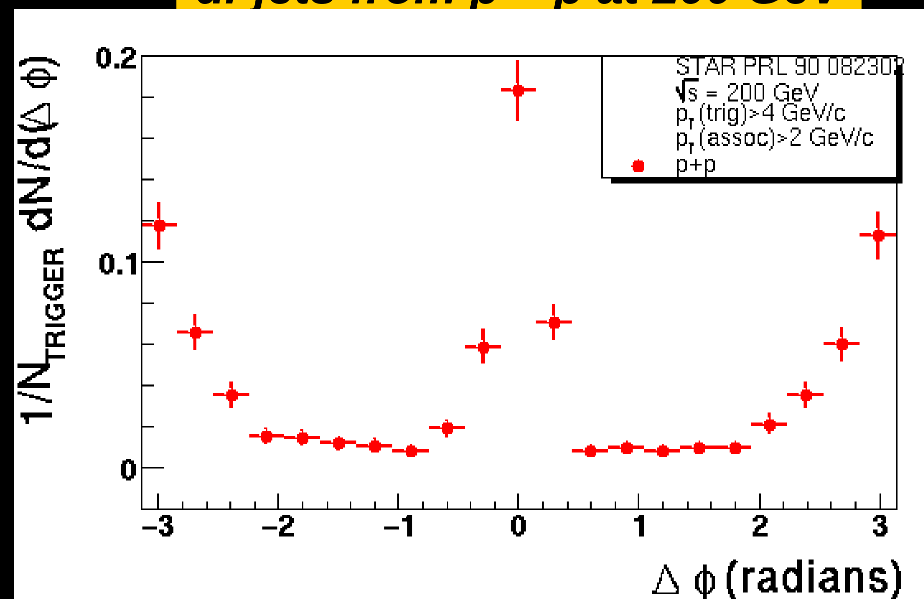
$p_T > 4$ GeV/c

Associate tracks

$2 < p_T < p_T$(trigger)



di-jets from p + p at 200 GeV



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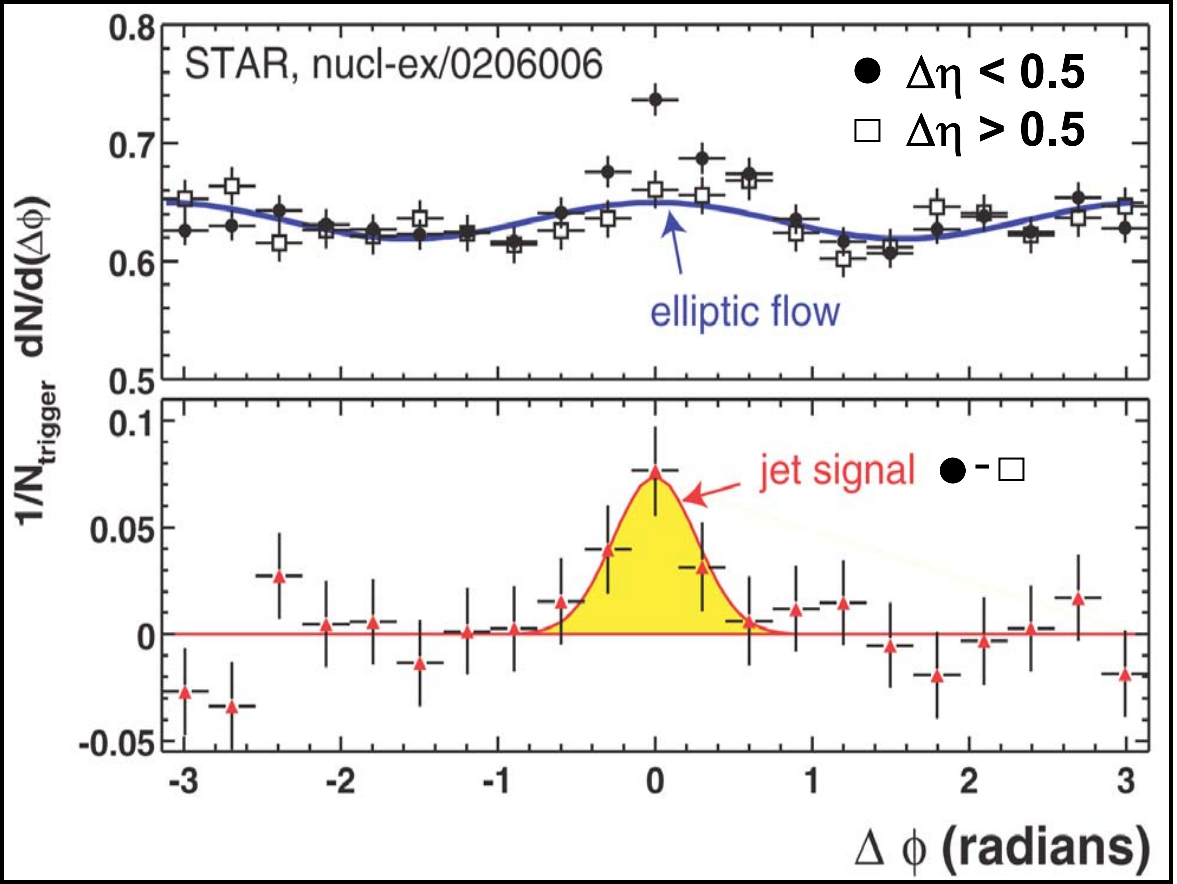
Associate tracks

$2 < p_T < p_T$(trigger)

130 GeV Au + Au, central trigger



short range η correlation:

jets + elliptic flow

long range η correlation:

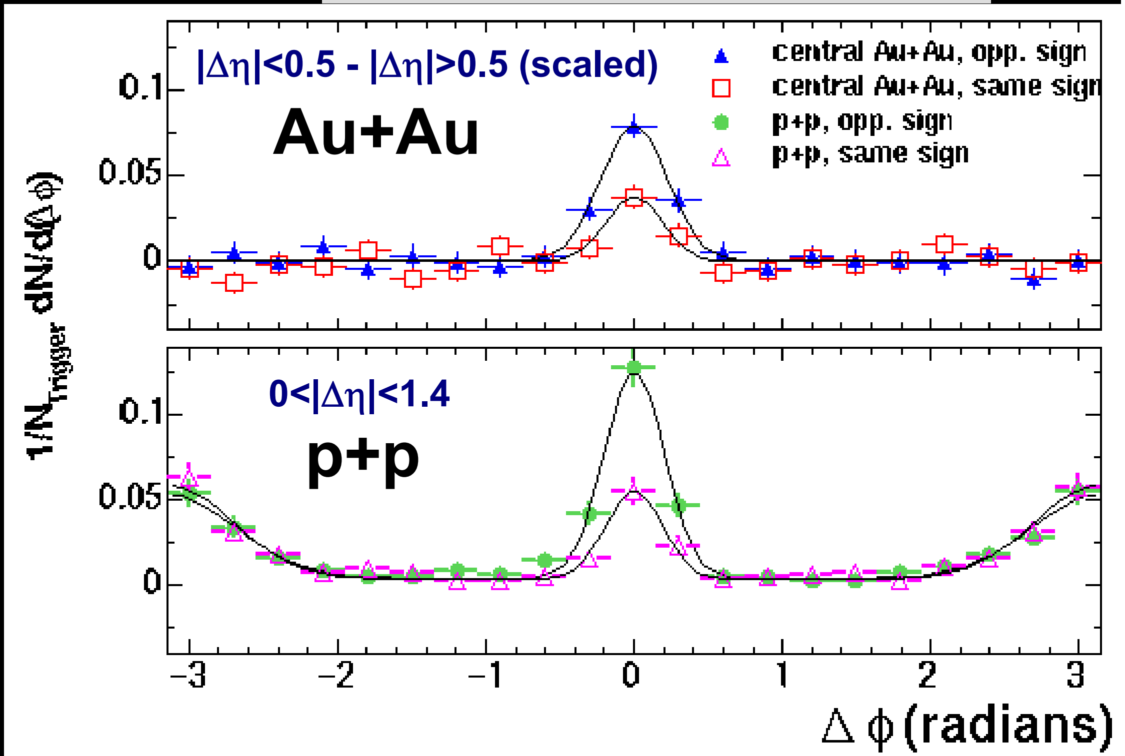
elliptic flow

Relative Charge Dependence

Compare ++ and - - correlations to +-

System	(+-)/(++ & --)
p+p	2.7+-0.6
0-10% Au+Au	2.4+-0.6
Jetset	2.6+-0.7

STAR Preliminary @ 200 GeV/c
0-10% most central Au+Au
p+p minimum bias
$4<p_T(\text{trig})<6$ GeV/c
$2<p_T(\text{assoc.})<pT(\text{trig})$



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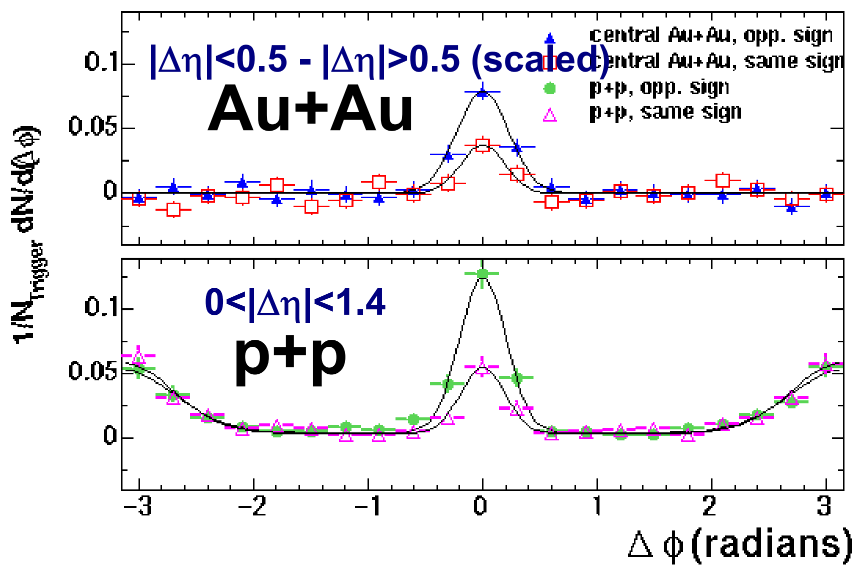
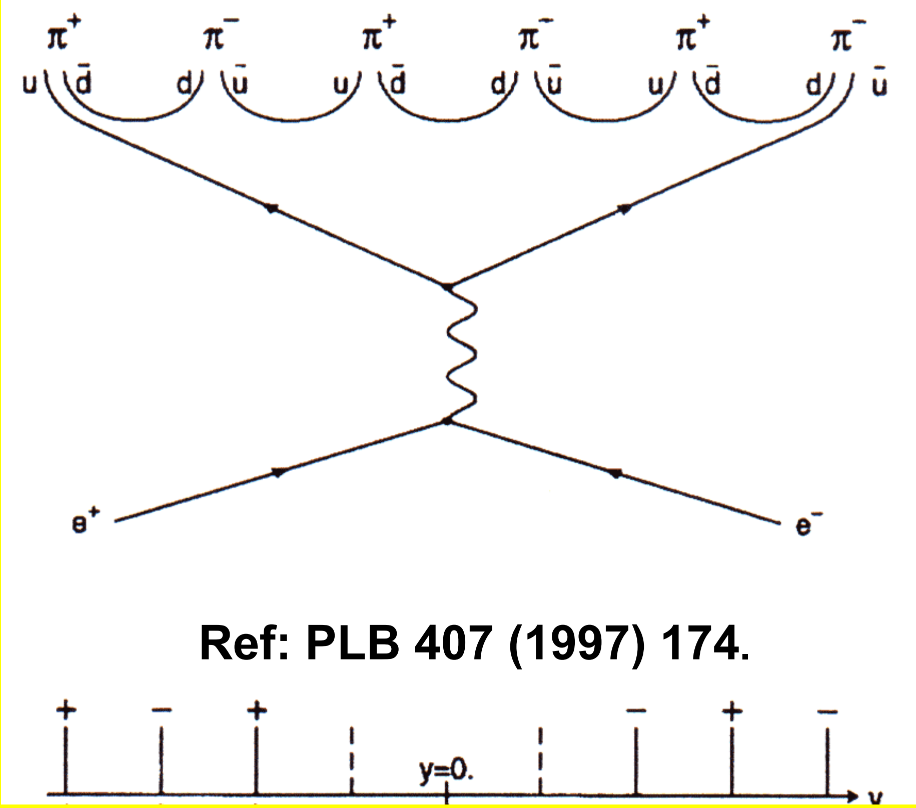


Strong dynamical charge correlations in jet fragmentation → "charge ordering"



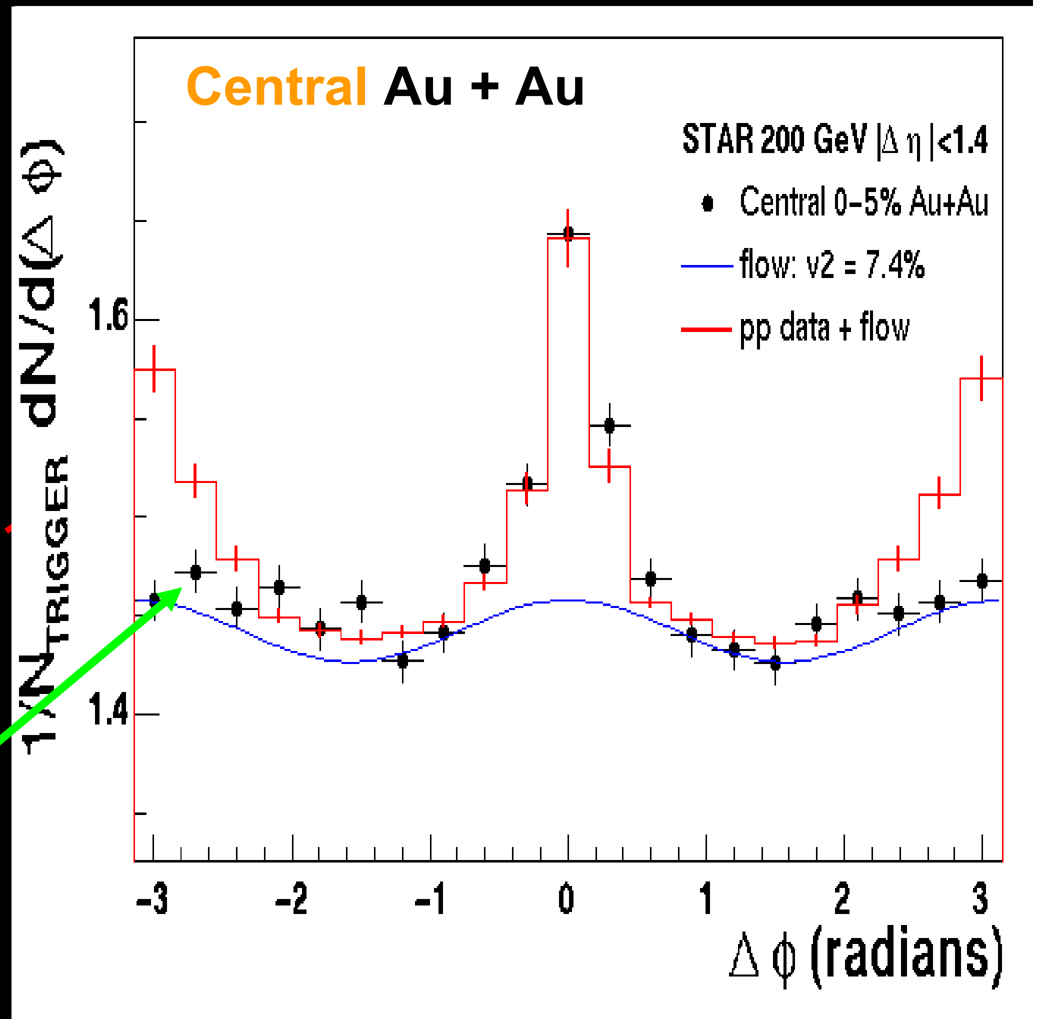
Ref: PLB 407 (1997) 174.

p_T > 4 GeV/c particle production mechanism same in central Au+Au & pp

Using p+p to Study Au+Au Jet Correlations at RHIC

STAR 200 GeV/c
peripheral & central Au+Au
p+p minimum bias
$4<p_T(\text{trig})<6$ GeV/c
$2<p_T(\text{assoc.})<pT(\text{trig})$

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$



Assume:

high p_T triggered Au+Au event
is a superposition:
high p_T triggered p+p event +
elliptic flow of AuAu event

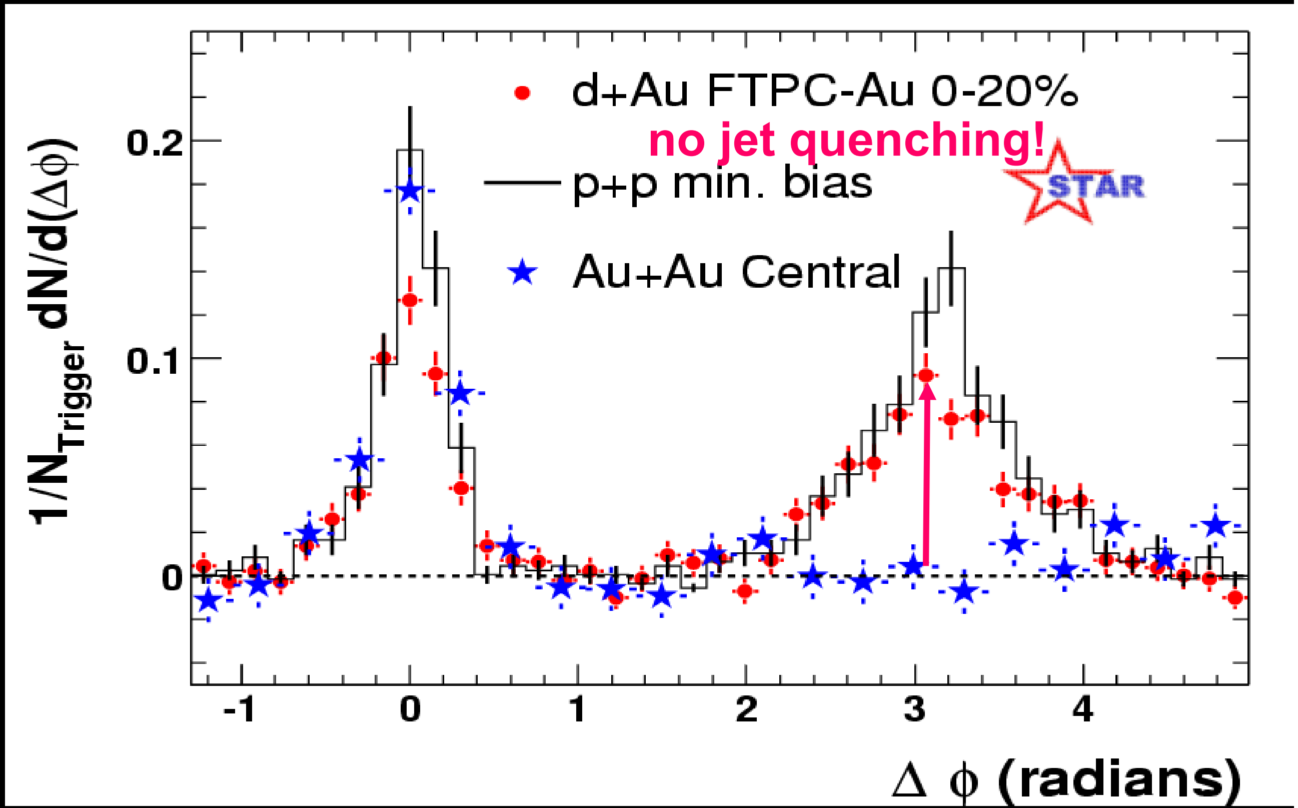
- v_2 from reaction plane analysis
- A from fit in non-jet region ($0.75 < |\Delta\phi| < 2.24$)

disappears

Hammering the Nail in the Coffin

Au + Au
away-side correlation quenched!

d + Au
"di-jet" correlations similar to p + p



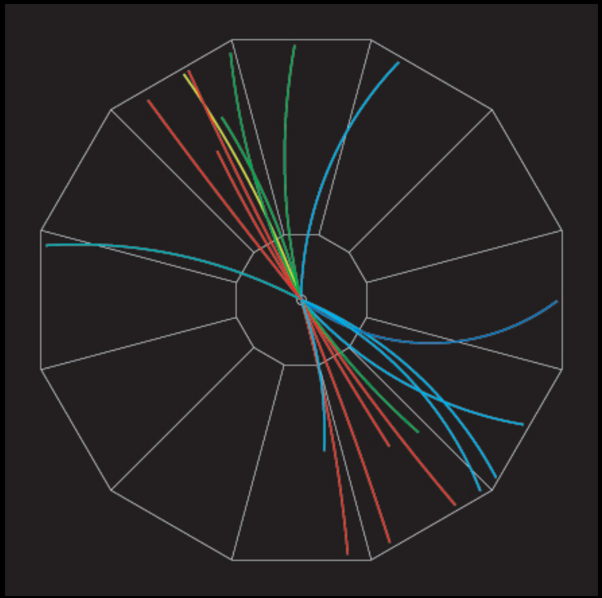
Quenching of Away-side "jet" is final state effect

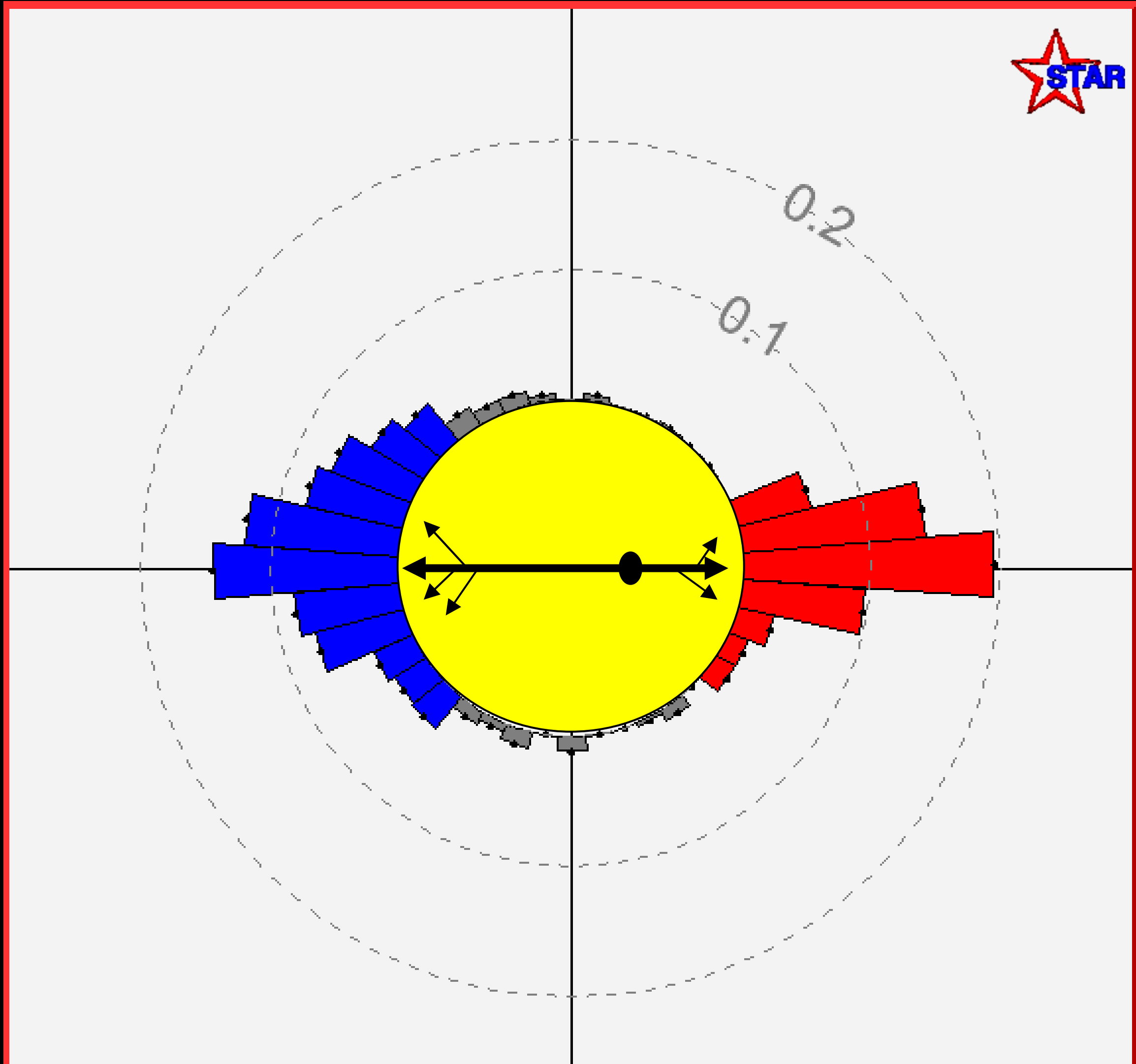
Where Does the Energy Go?

$4 < p_T(trig) < 6$ GeV/c

Jet correlations in proton-proton reactions.

Strong back-to-back peaks.





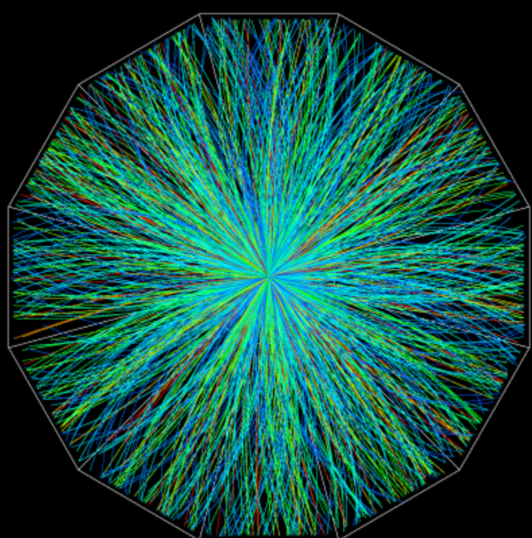
Azimuthal Angular Correlations

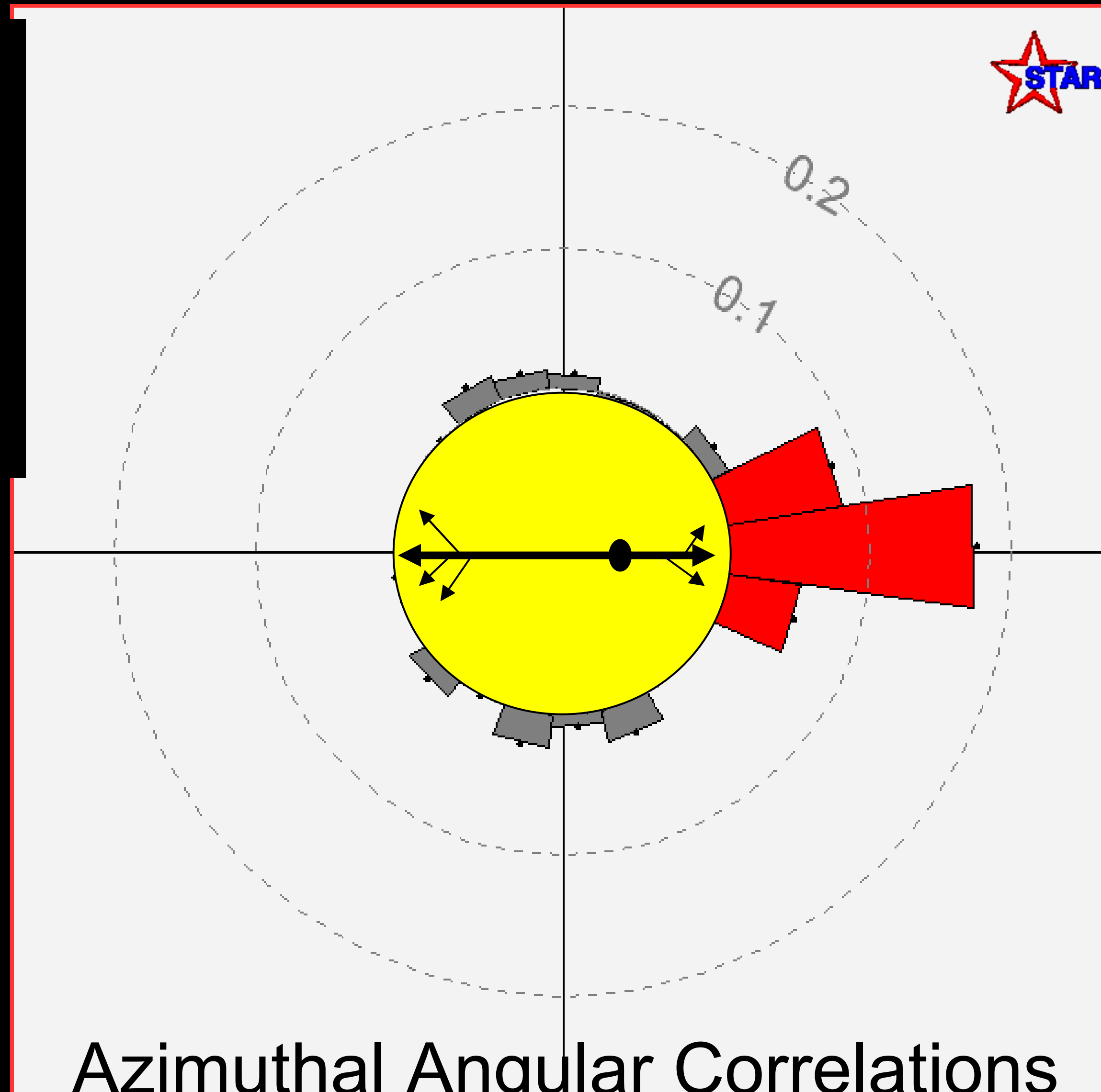
Where Does the Energy Go?

4 < p_T(trig) < 6 GeV/c

Jet correlations in central Gold-Gold.

Away side jet disappears for particles p_T > 2 GeV



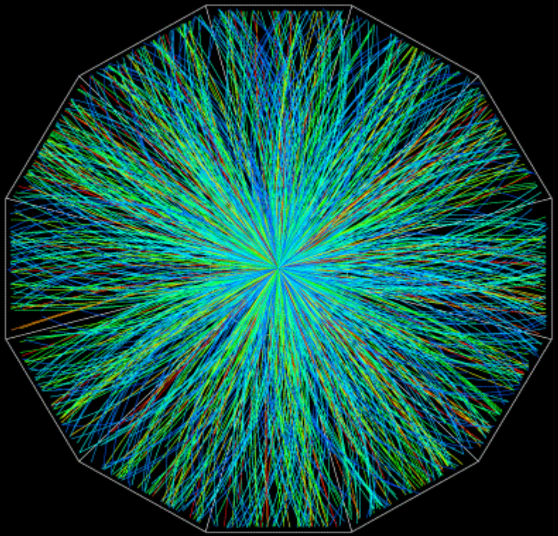


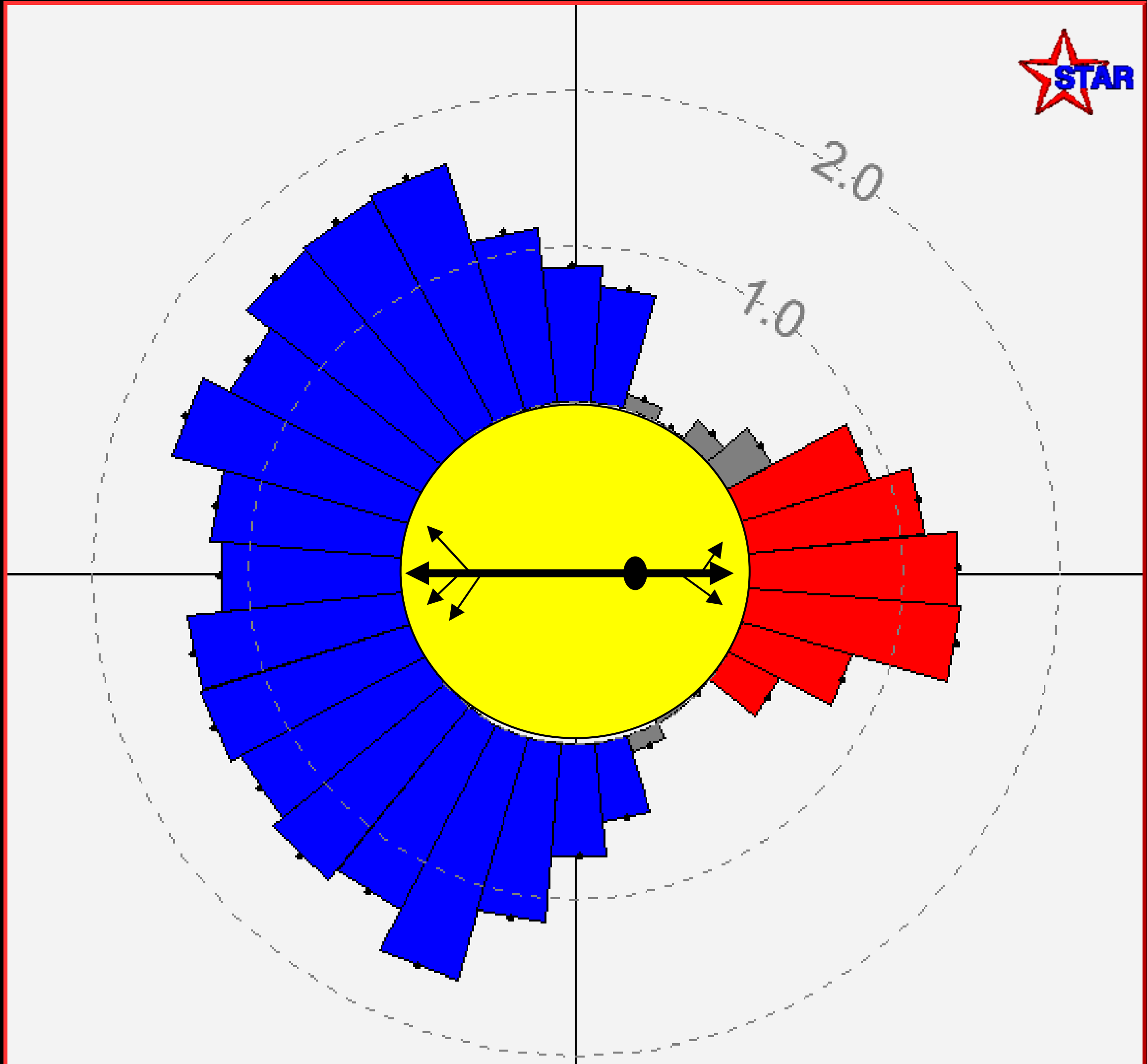
Where Does the Energy Go?

4 < p_T(trig) < 6 GeV/c

Jet correlations in central Gold-Gold.

Away side jet reappears in particles p_T > 0.2 GeV

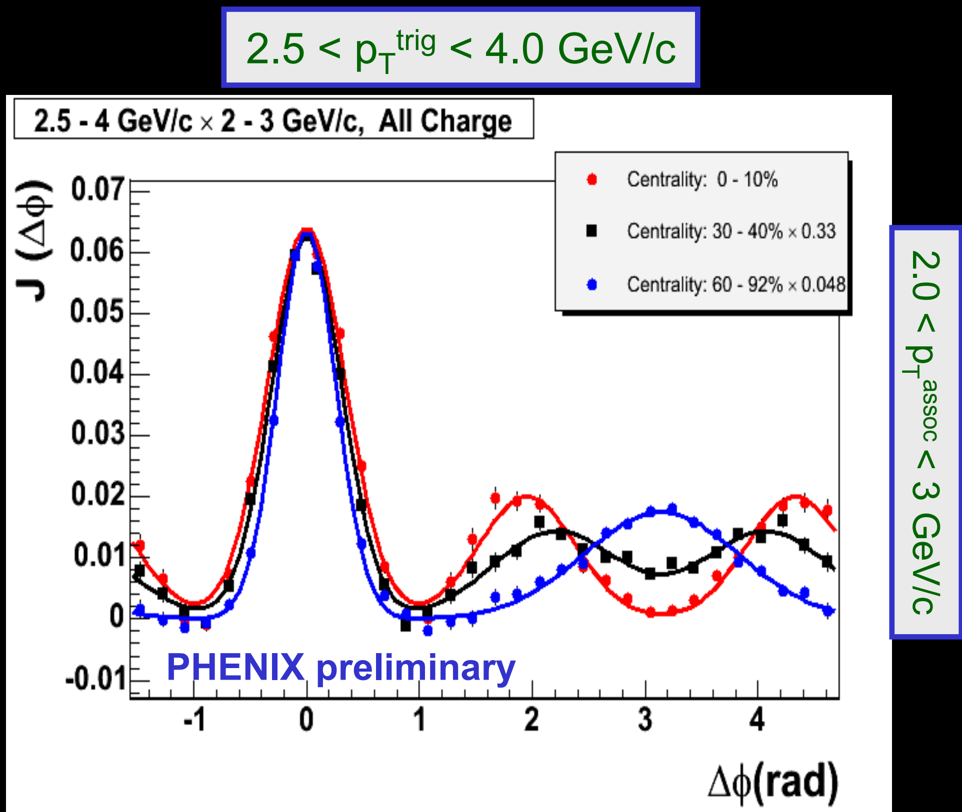


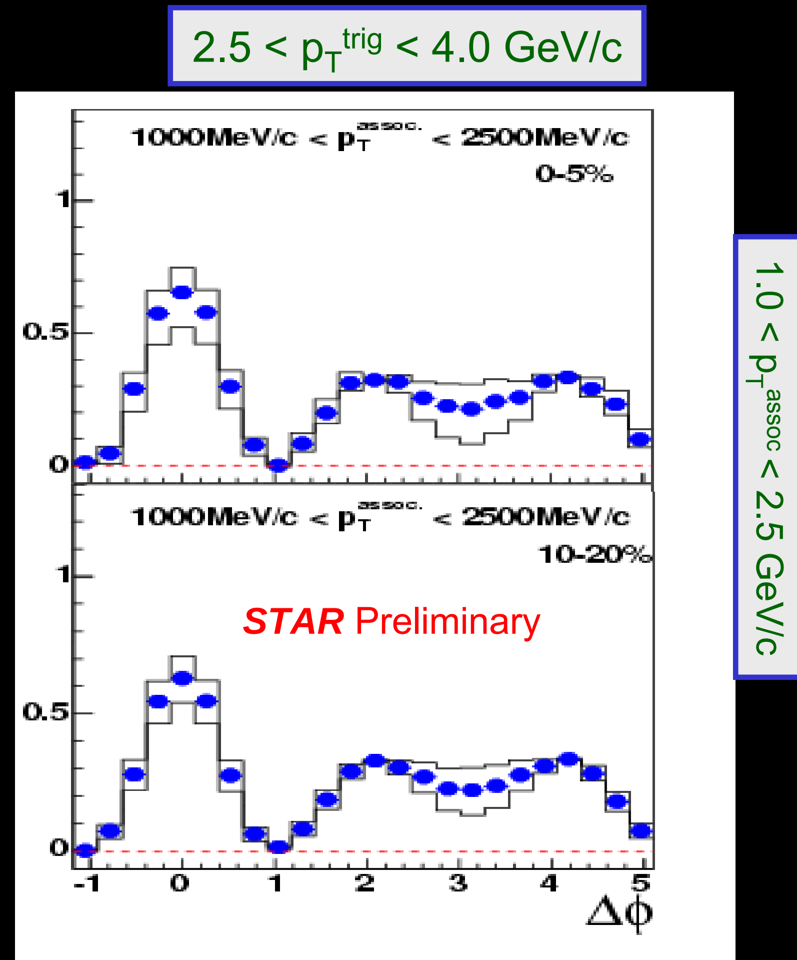


Azimuthal Angular Correlations

Lost energy of away-side jet is redistributed to rather large angles!

A Closer Look at the Away-Side of Jets

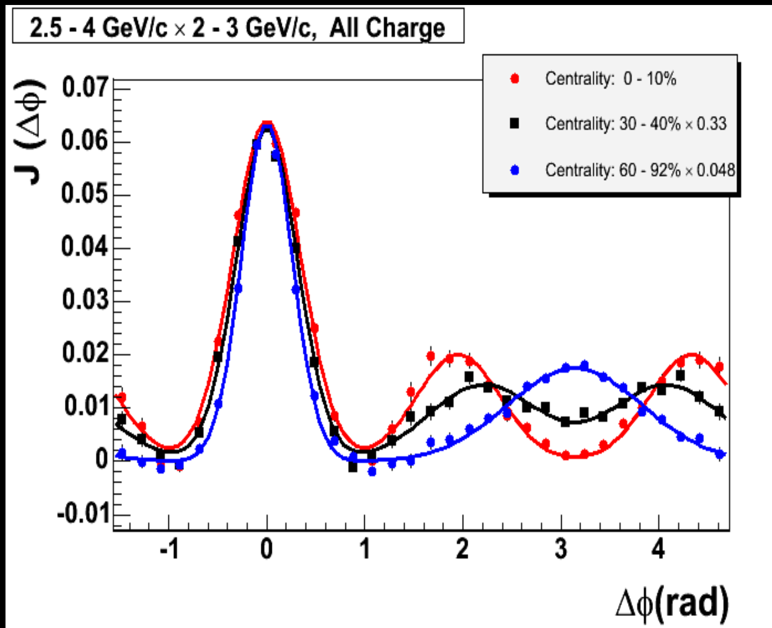


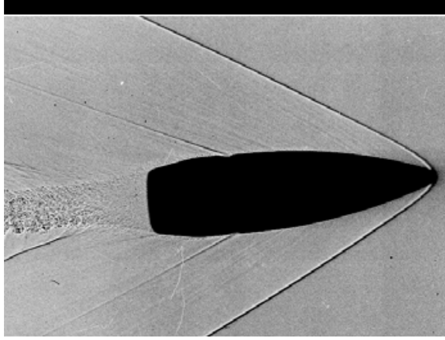


Measure low-p_T associated hadrons

Shapes of jets are modified by the medium

Response of the Medium?





Possibilities:

- Deflected jets
- Cerenkov radiation
  - I.M. Dremin, Nuc. Phys. A750 (2006) 233.
  - V. Koch et al, PRL 96 (2006) 172302.
- Mach cone from hydrodynamics
  - H. Stoecker, Nuc.Phys. A750 (2006) 121.
  - J. Casseldary-Solana et al, Nuc.Phys.A774 (2006) 577.
  - T. Renk & J. Ruppert, Phys. Rev. C73 (2006) 011901.
- Mach cone from color wakes
  - J. Ruppert & B. Muller, Phys. Lett. B618 (2005) 123.
- Mach cone from AdS/CFT
  - S. Gubser, S. Pufu, A. Yarom, Phys. Lett. B618 (2005) 123.
  - P. Chesler & L. Yaffe, hep-ph/0706.0368

- Properties of the medium can be determined from these shapes!
  - Sound velocity
  - Di-electric constant

The suppression of high p_T hadrons and the quenching of jets indicates the presence of a high density, strongly-coupled colored medium!

Response of the Medium in AdS/CFT

The wake of a quark moving through a strongly-coupled $\mathcal{N}=4$ supersymmetric Yang-Mills plasma

hep-ph/0706.0368

Paul M. Chesler and Laurence G. Yaffe
Department of Physics, University of Washington, Seattle, WA 98195, USA

(Dated: July 31, 2007)

The energy density wake produced by a heavy quark moving through a strongly coupled $\mathcal{N}=4$ supersymmetric Yang-Mills plasma is computed using gauge/string duality.

$v = v_s$

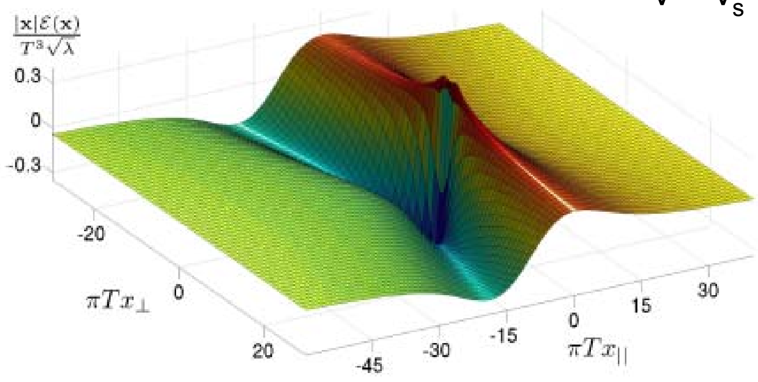


FIG. 3: Plot of $|\mathbf{x}|\,\mathcal{E}(\mathbf{x})/(T^3\sqrt{\lambda})$ for $v = 1/\sqrt{3}$, with the $T=0$ and near zone (20) contributions removed. A planar shock front perpendicular to the quark velocity is evident.

$v >> v_s$

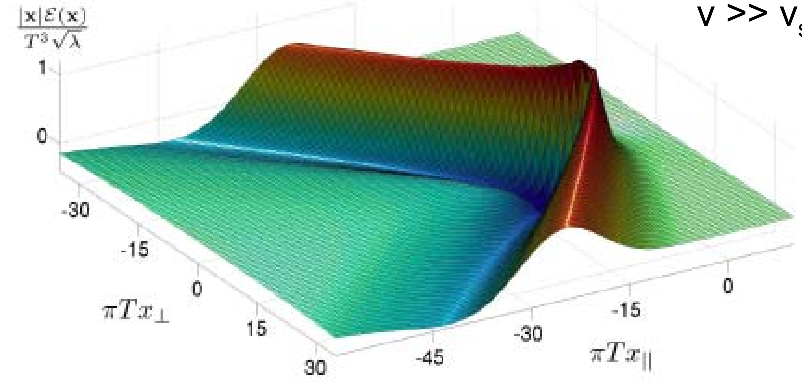
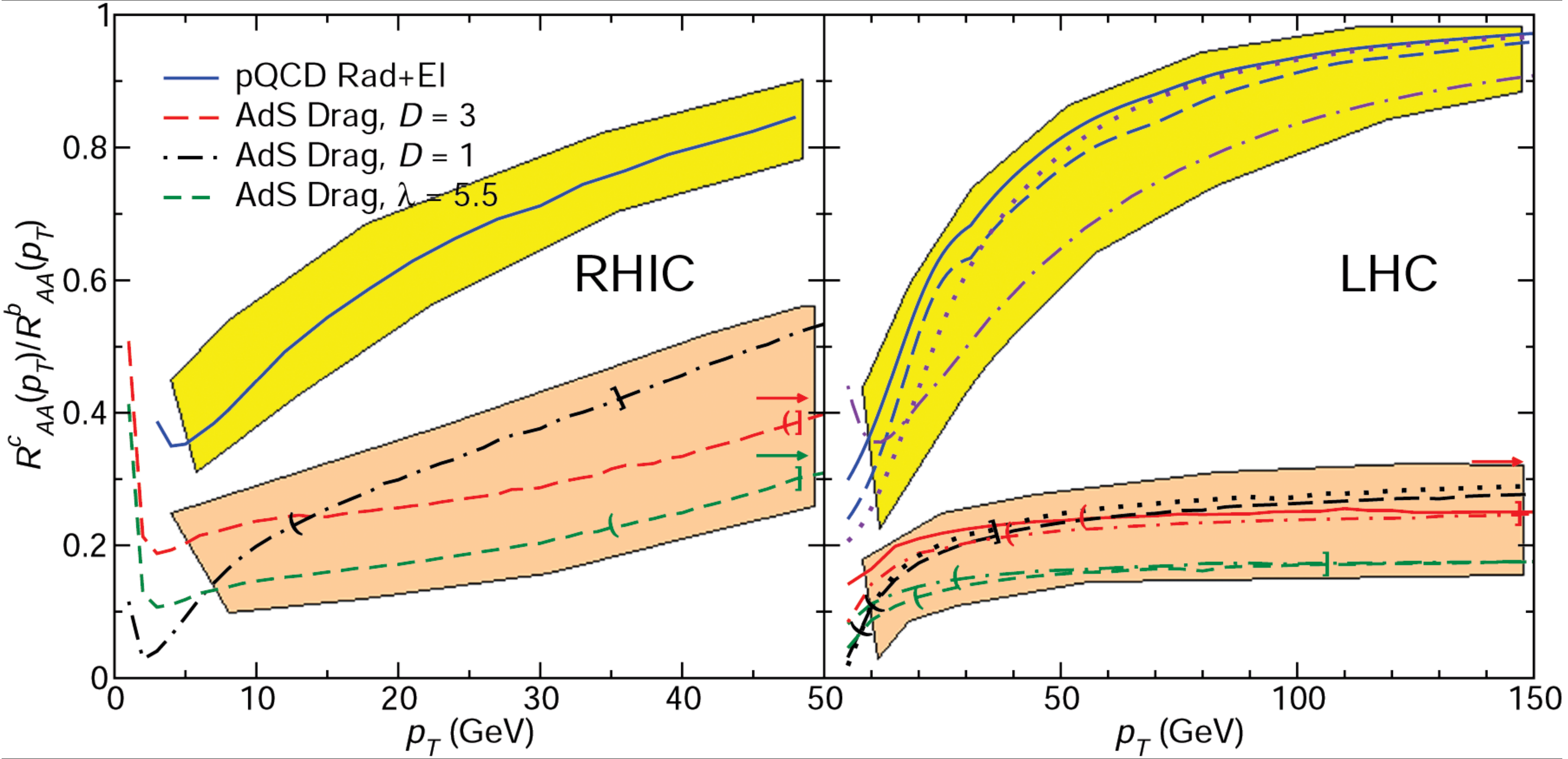


FIG. 2: Plot of $|\mathbf{x}|\,\mathcal{E}(\mathbf{x})/(T^3\sqrt{\lambda})$ for $v = 3/4$, with the $T=0$ and near zone (20) contributions removed. A Mach cone is clearly visible, with an opening half-angle $\theta \approx 50°$.

Also see: Gubser, Pufu, Yarom, hep-th/0706.0213

A Real Test of "Theories" in the Future from Heavy Flavors at RHIC & LHC?

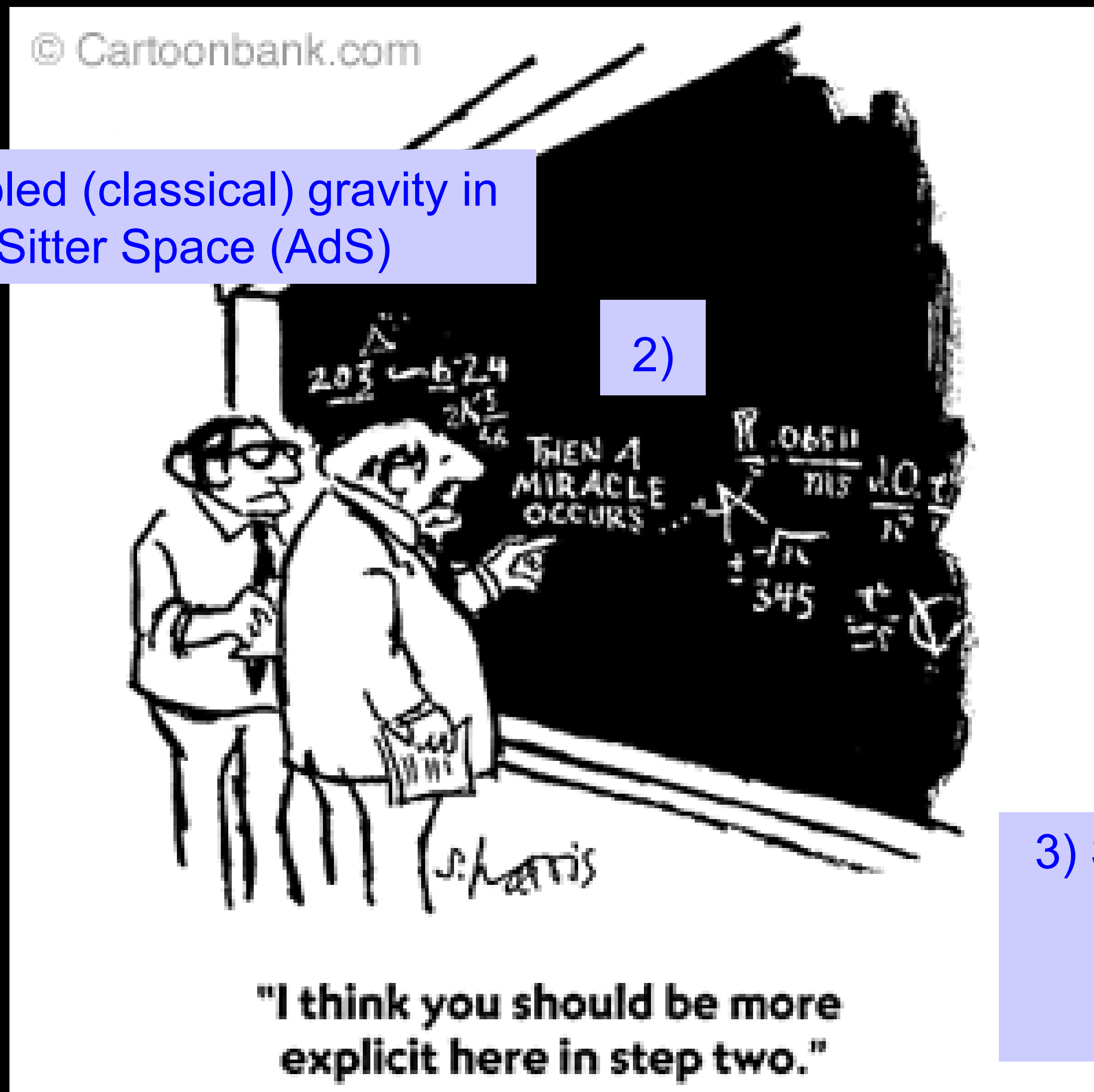


W. Horowitz, M. Gyulassy, arXiv:0804.4330v1

Explaining the AdS/CFT Equivalence

1) Weakly Coupled (classical) gravity in Anti-deSitter Space (AdS)

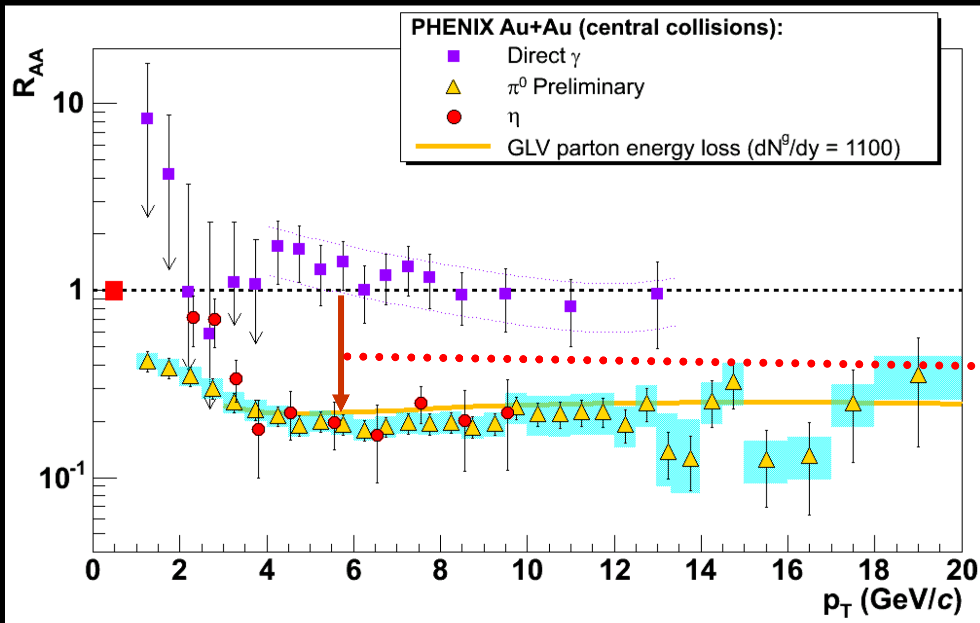
2)

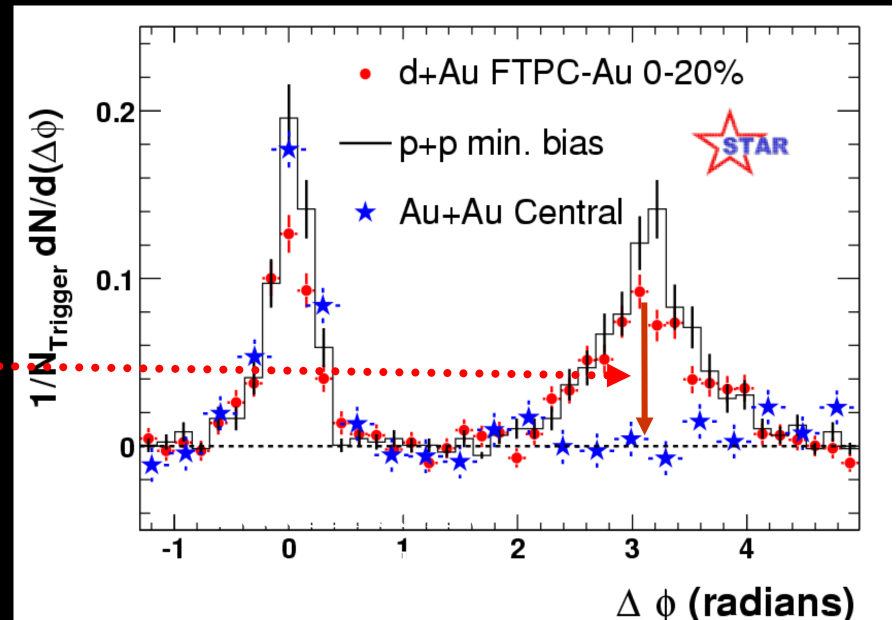


3) Strongly Coupled (Conformal) Gauge Field Theories (CFT)

Maldacena's Conjecture

Summary of Hard Scattering at RHIC





High Pt hadrons

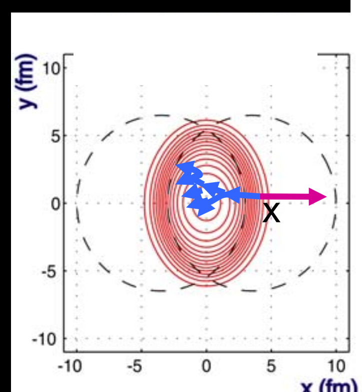
- suppressed in central Au + Au
- enhanced in d + Au

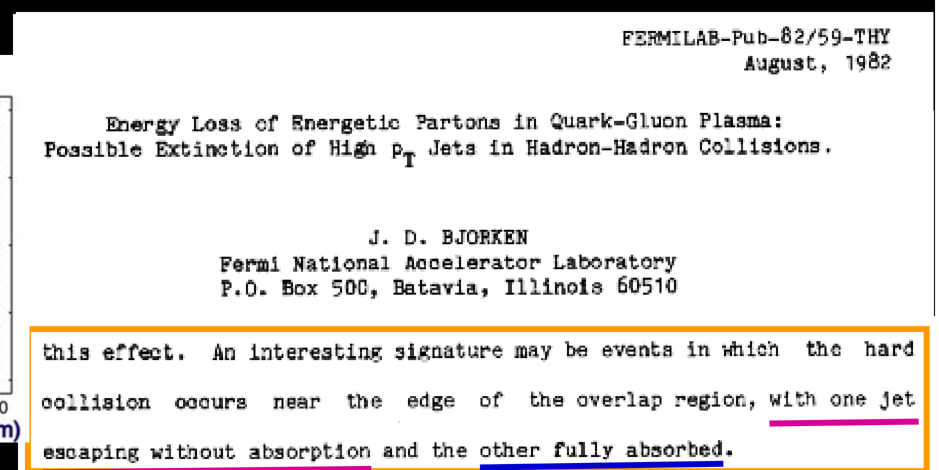
Back-to-back Jets

- Di-jets in p + p, d + Au (all centralities)
- Away-side jets quenched in central Au + Au

→ *emission from surface*

→ strongly interacting medium





FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

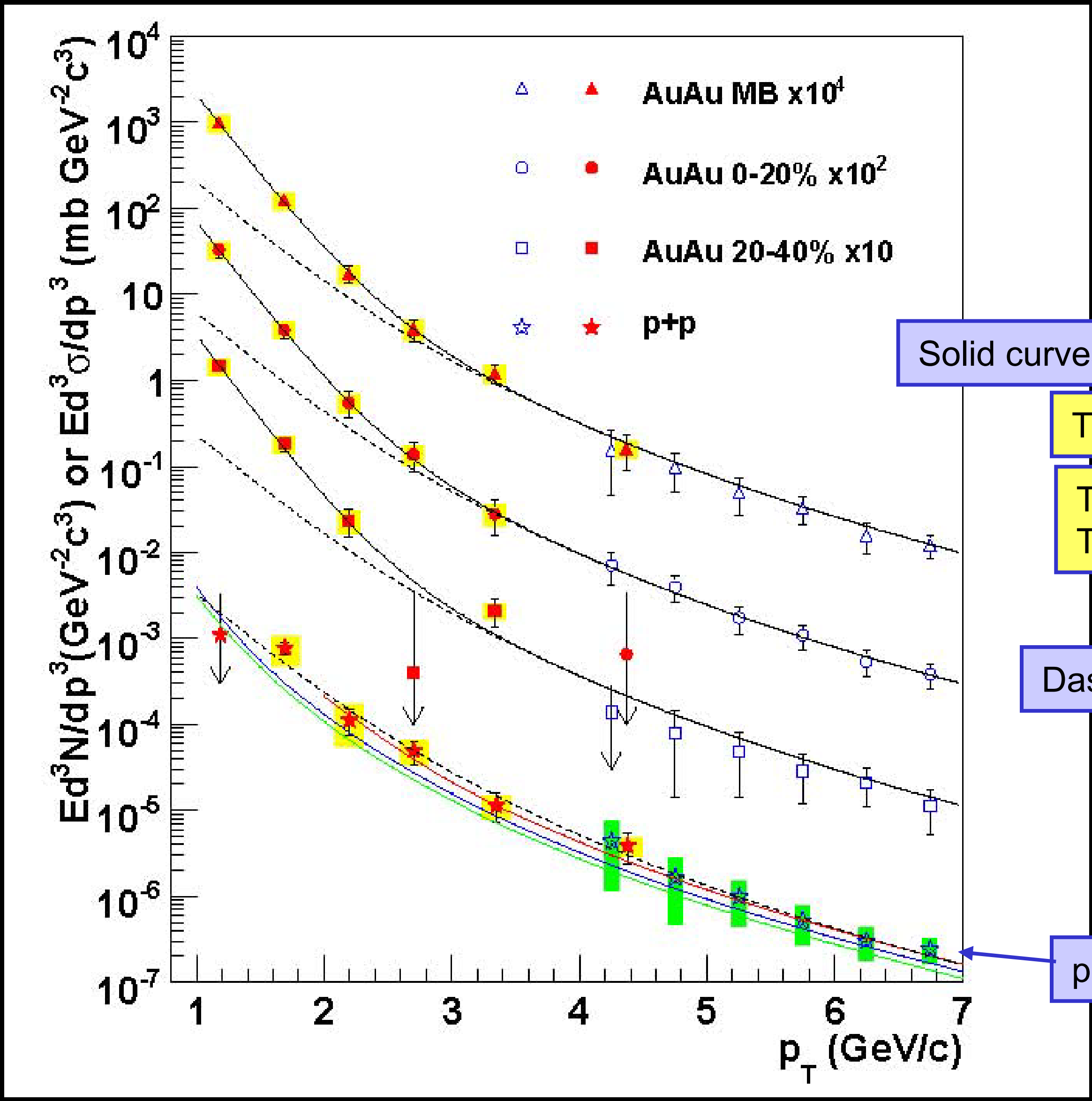
this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

A Couple More RHIC Results of Interest

- Observation of Thermal Photons

- Charmonium Suppression

Thermal Photons at RHIC



PHENIX, arXiv: 0804.4168v1

Solid curves are binary-scaled pp data + thermal

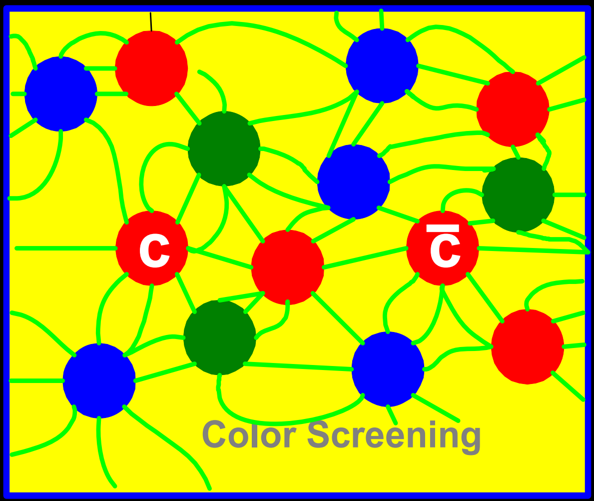
T = 221 ± 23(stat) ±18(sys) MeV

This spectrum fit by hydrodynamics with T_{init} 300 − 600 MeV at 0.6 - 0.15 fm/c

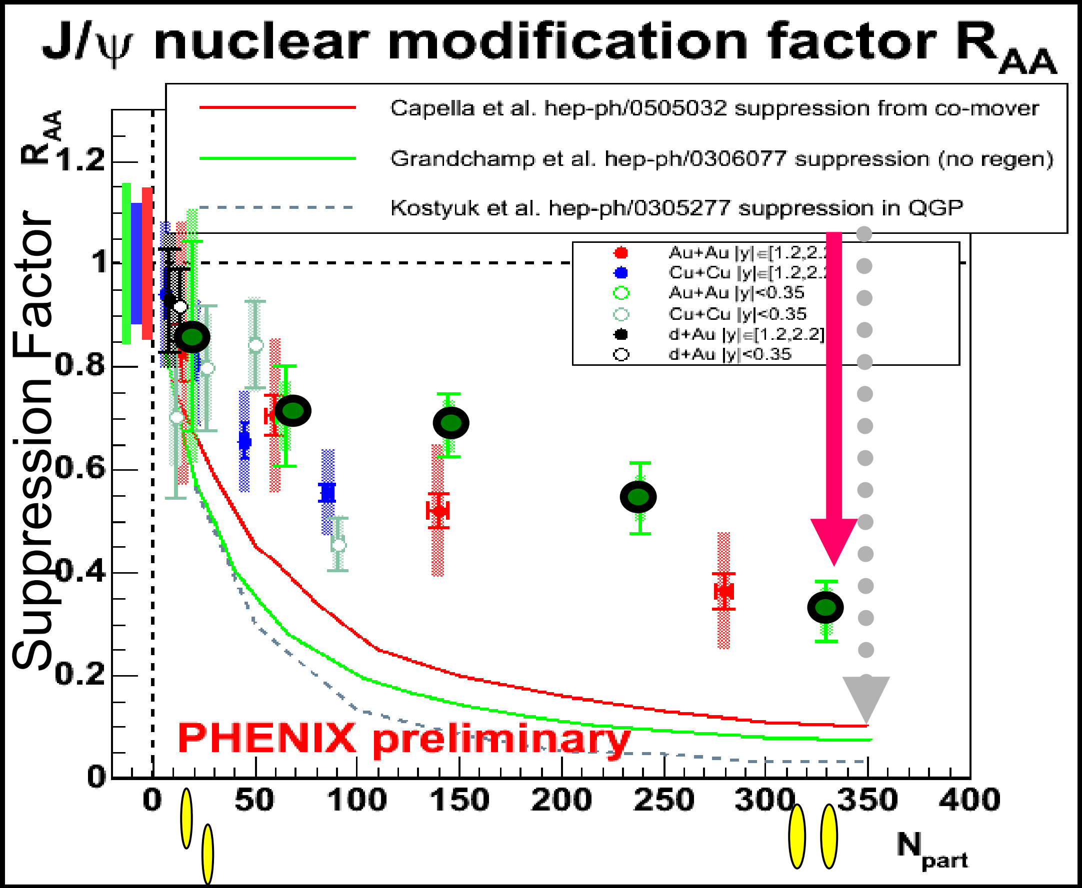
Dashed curves are binary-scaled pp data

pp data and 3 different NLO calculations

Charmonium Suppression at RHIC



Color screening of $c\bar{c}$ pair results in J/ψ ($c\bar{c}$) suppression!



J/ψ suppressed

but less than expected?

Perhaps, regeneration!

(more to do!)

Quarkonium Suppression at LHC – Deconfinement?

at LHC:

Large heavy flavor cross sections

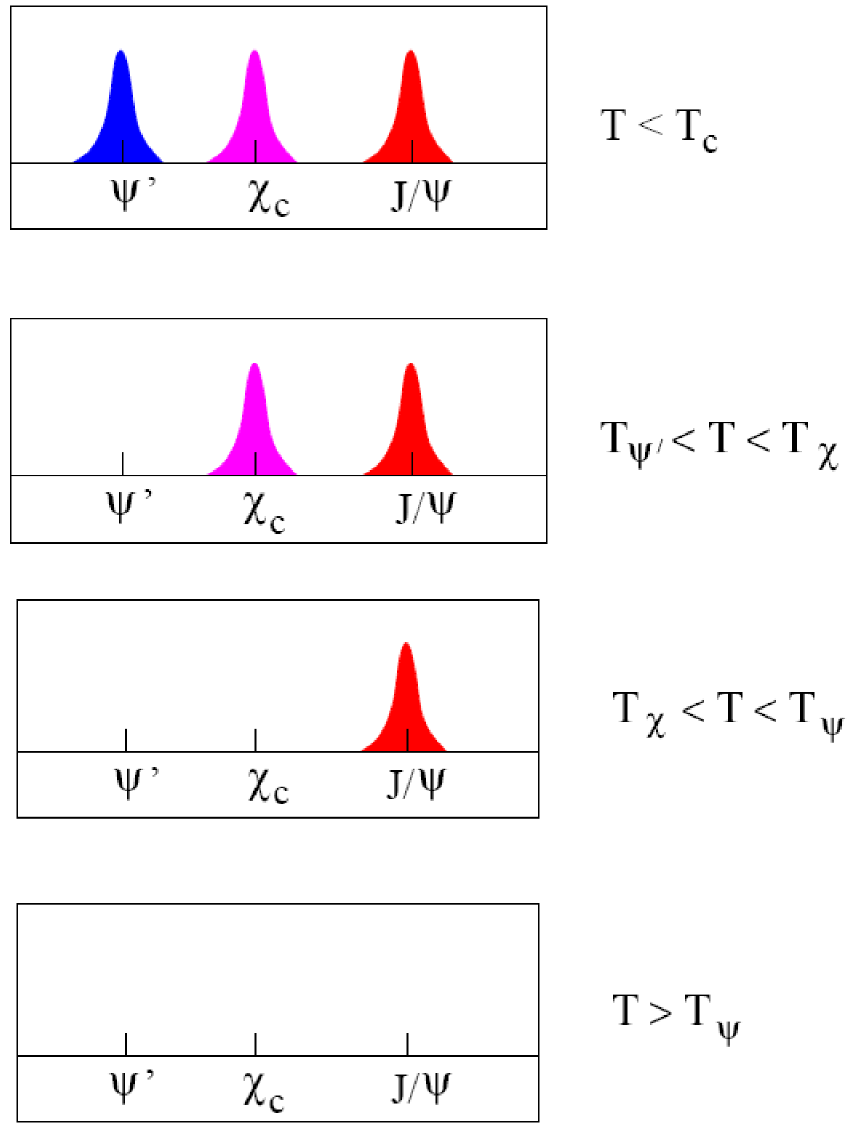
Measure melting order of $c\bar{c}$:

Ψ', χ_c, J/ψ

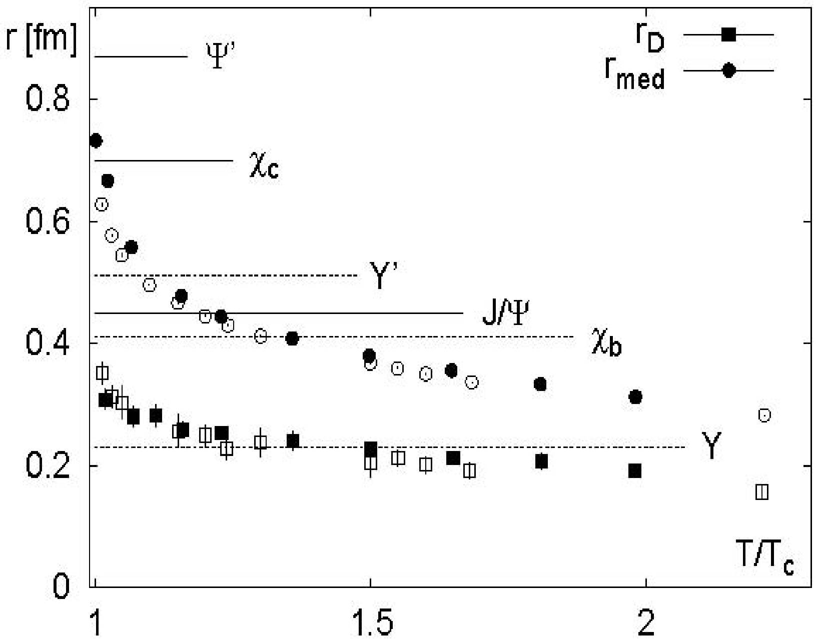
Also $b\bar{b}$:

Υ', Υ, Υ''

H. Satz' lecture



Karsch hep-lat/0502014v2



LHC Heavy Ions

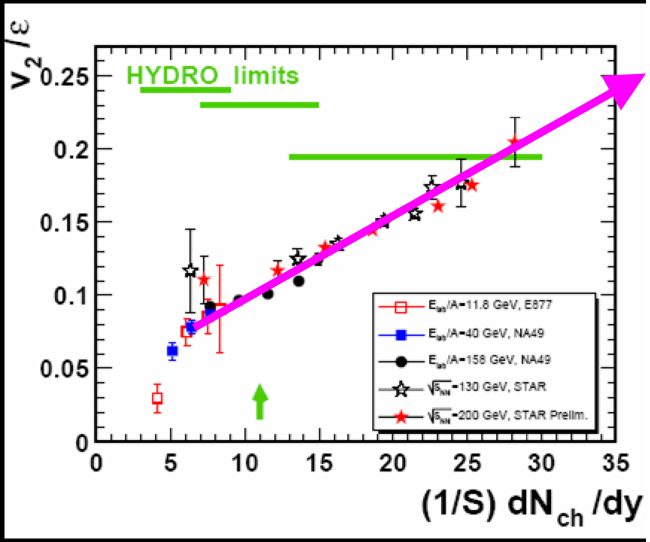
Heavy Ion Physics at the LHC

LHC Heavy Ions –

- guided by pQCD predictions
- expectations (detector simulations) based on RHIC extrapolations and theory
- lesson from RHIC – guided by theory + versatility + **"expect the unexpected"**

Soft Physics at LHC –

- smooth extrapolation from **SPS → RHIC → LHC?**
- expansion will be different (v_2, HBT, T_{chem} & T_{kin}, strange/charm particles & resonances)



Heavy Ion Physics at the LHC

LHC Heavy Ions –

- guided by pQCD predictions
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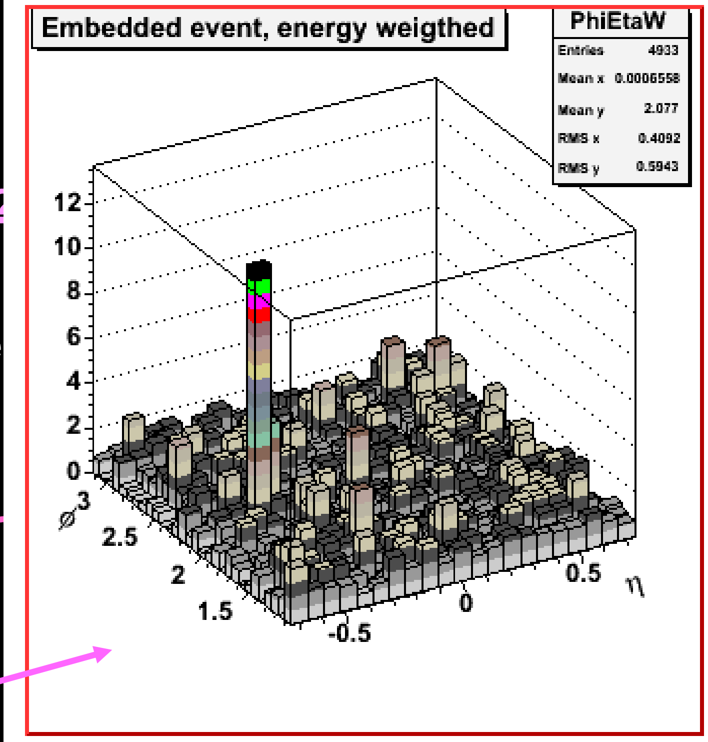
- lesson from RHIC – **"expect the unexpected"**



Soft Physics at LHC –

- smooth extrapolation from **SPS $\rightarrow$ RHIC $\rightarrow$ LHC?**
- expansion will be different (v_2, HBT, T_{chem} & T_{kin},

  strange/charm particles & resonance

Hard Probes at LHC –

- **significant increase in hard cross sections**

  $\rightarrow \sigma_{hard} / \sigma_{total} \sim$ 2% at SPS

  50% at RHIC

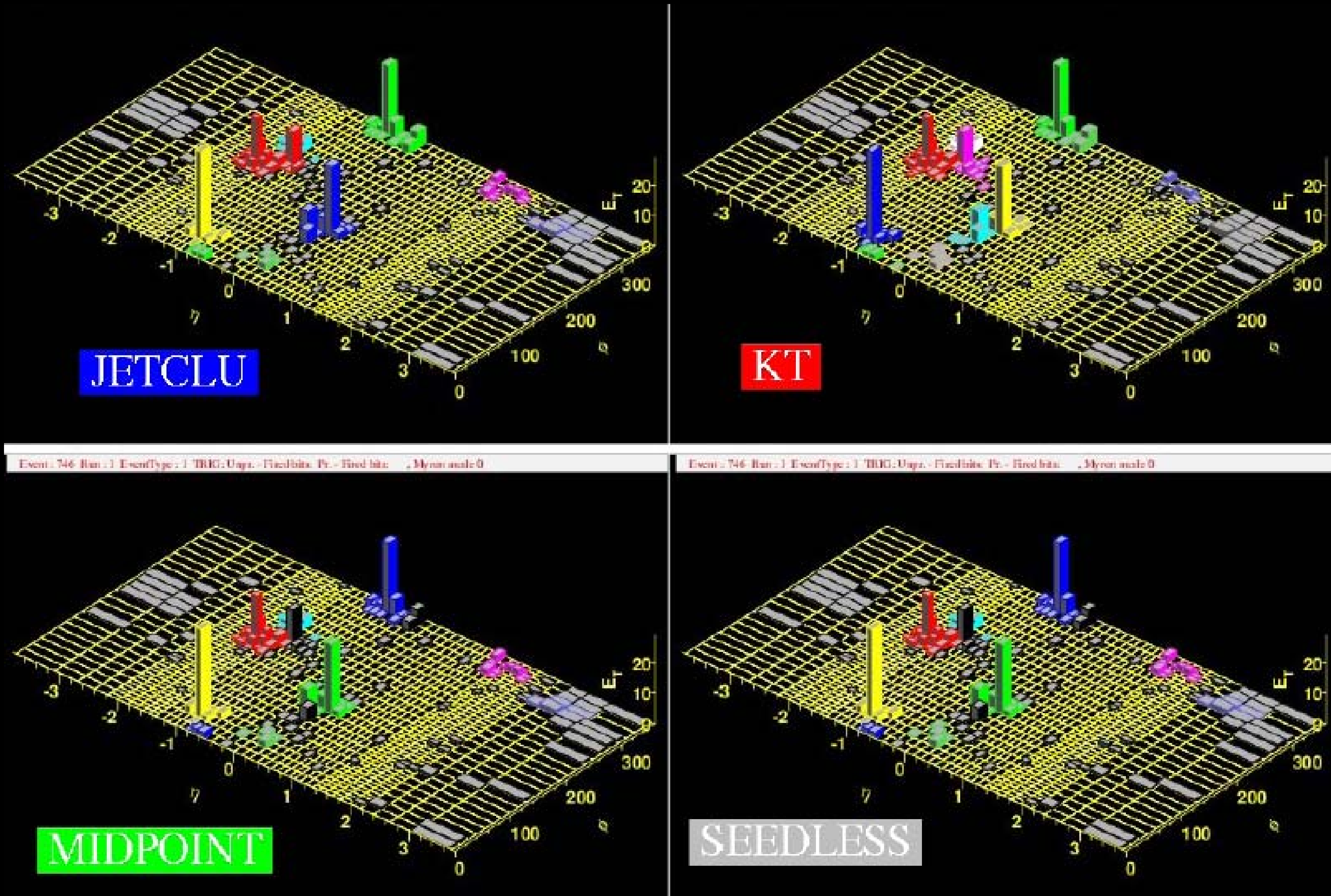
  98% at LHC

  - "real" jets, large p_T processes
  - abundance of heavy flavors
  - probe early times, calculable $\rightarrow$ **precision studies!**

σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC

σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)

Jet-finding – Much Work Already at LEP & Tevatron

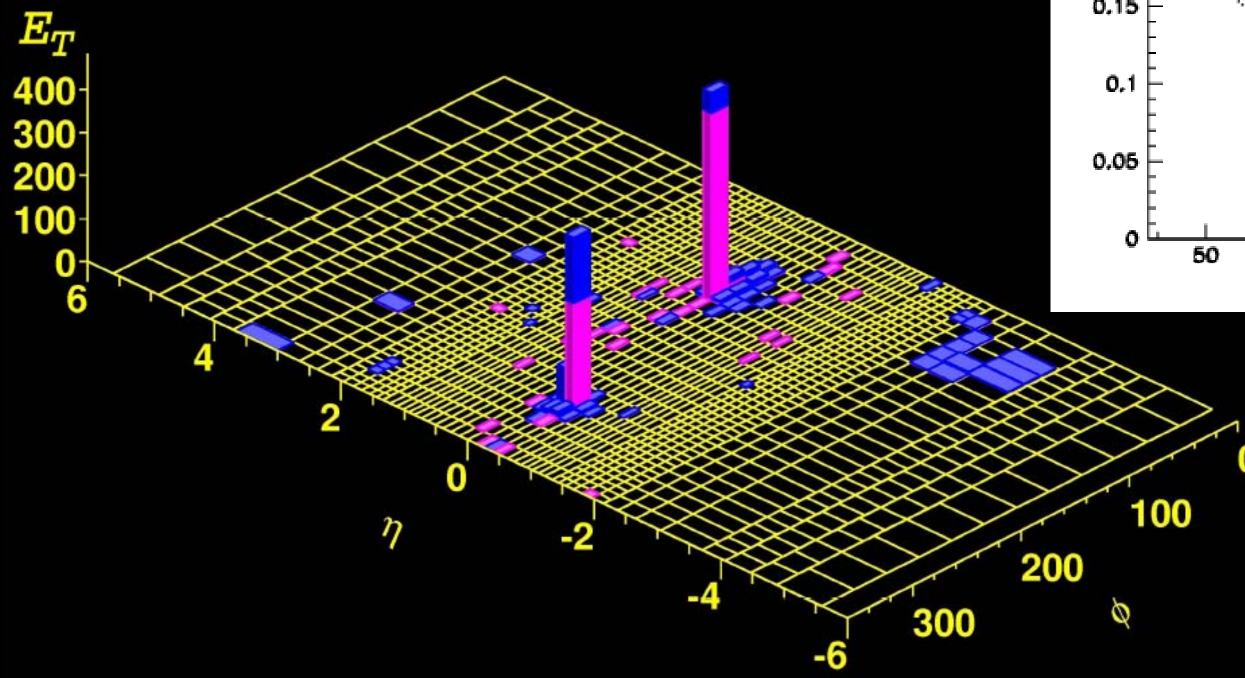


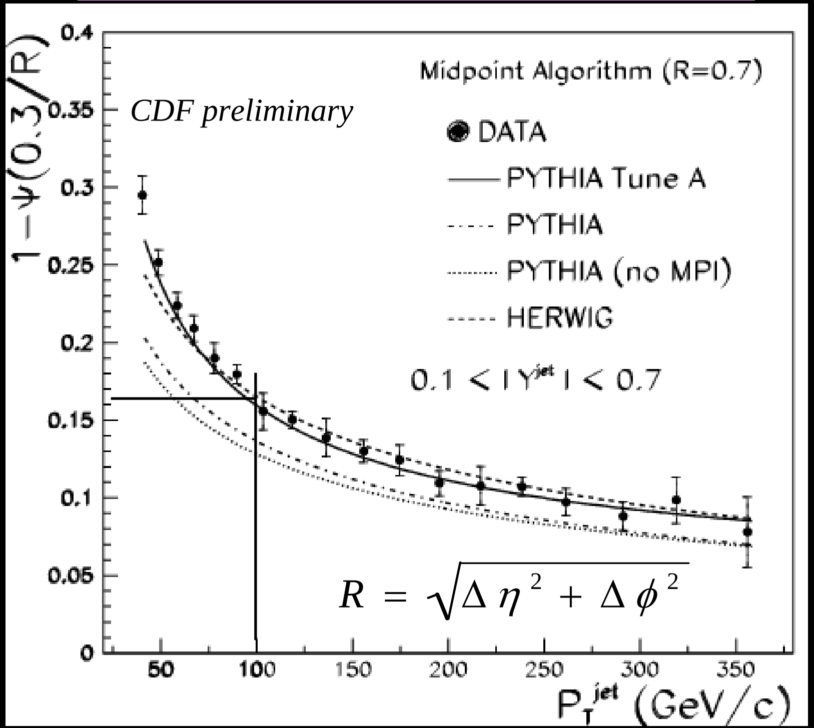
Jet-finding - Learning from the Tevatron

p + p experience (CDF)

- most of energy within R = 0.3

fraction of energy outside R = 0.3





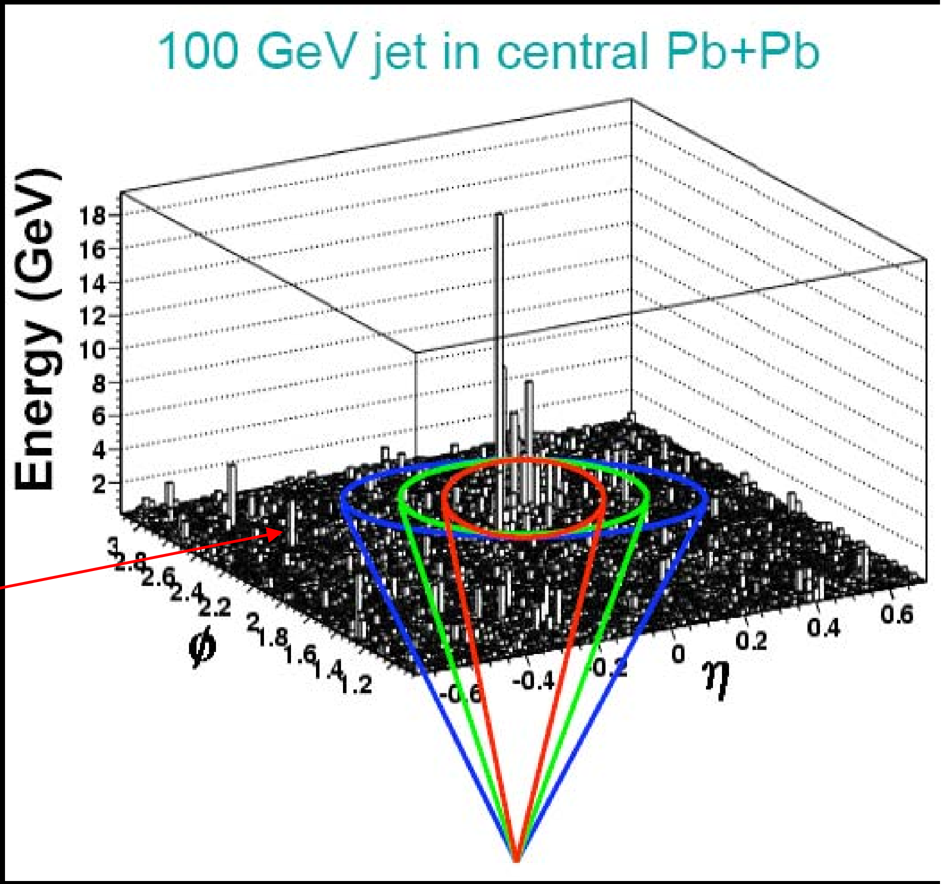
Jet-finding Approach with Heavy Ions

p + p experience (CDF)

- most of energy within R = 0.3

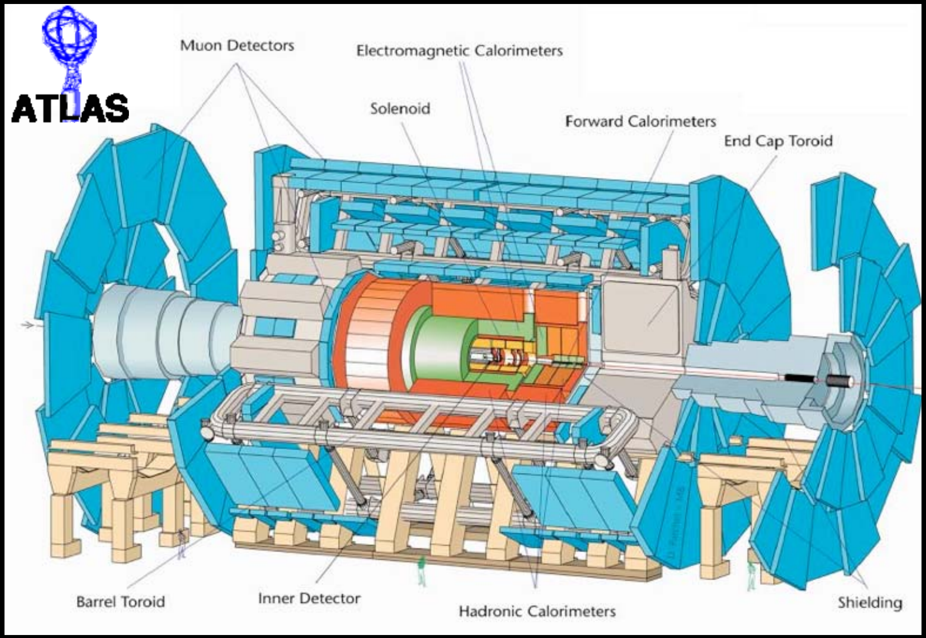
A + A approach (current attempts)

- suppress "soft" heavy ion background by
  - p_T cut: $p_T > 1 – 2$ GeV/c
  - use small jet cones R = 0.3 – 0.4
- estimate remaining background by
  - EbyE out-of-cone background energy



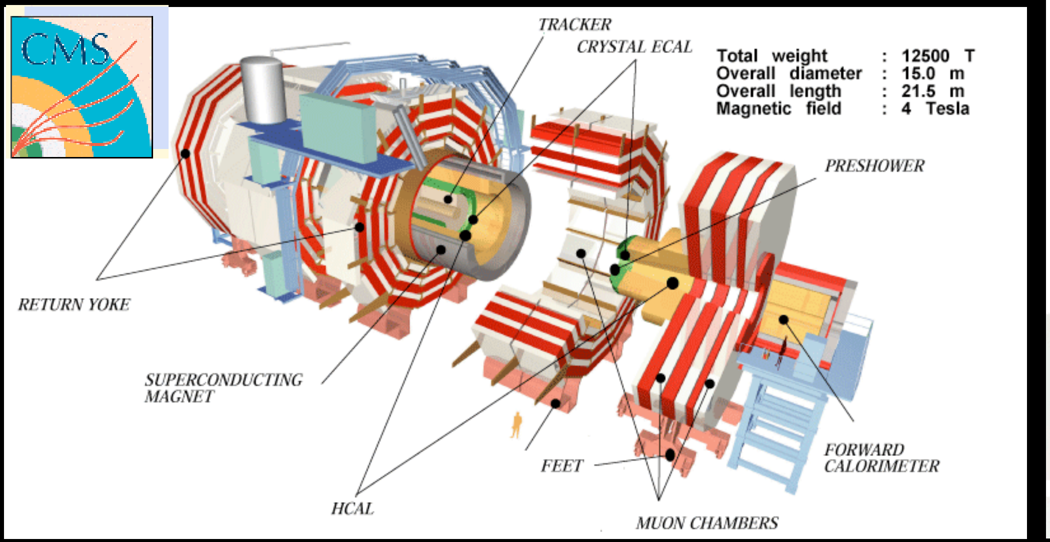
Issues to understand:
- effects of acceptance
- event-by-event fluctuations
- elliptic flow
- other effects of real data!

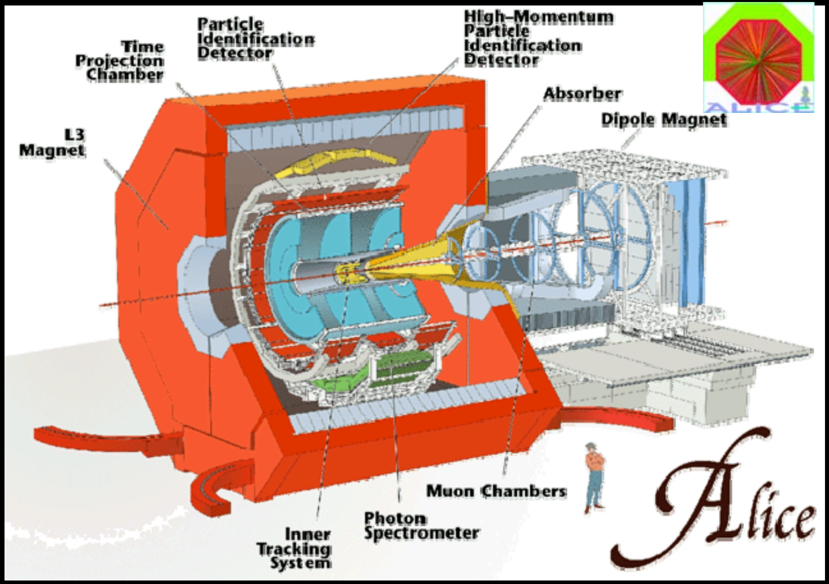
LHC Heavy Ion Programs



Heavy Ion Data-taking

Pb + Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

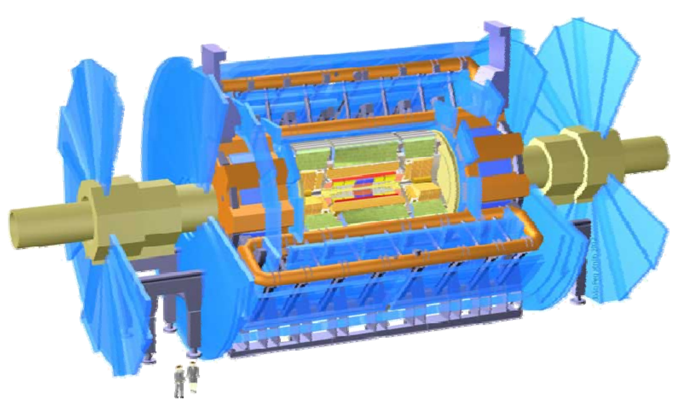




ATLAS Heavy Ion Program

Overview:

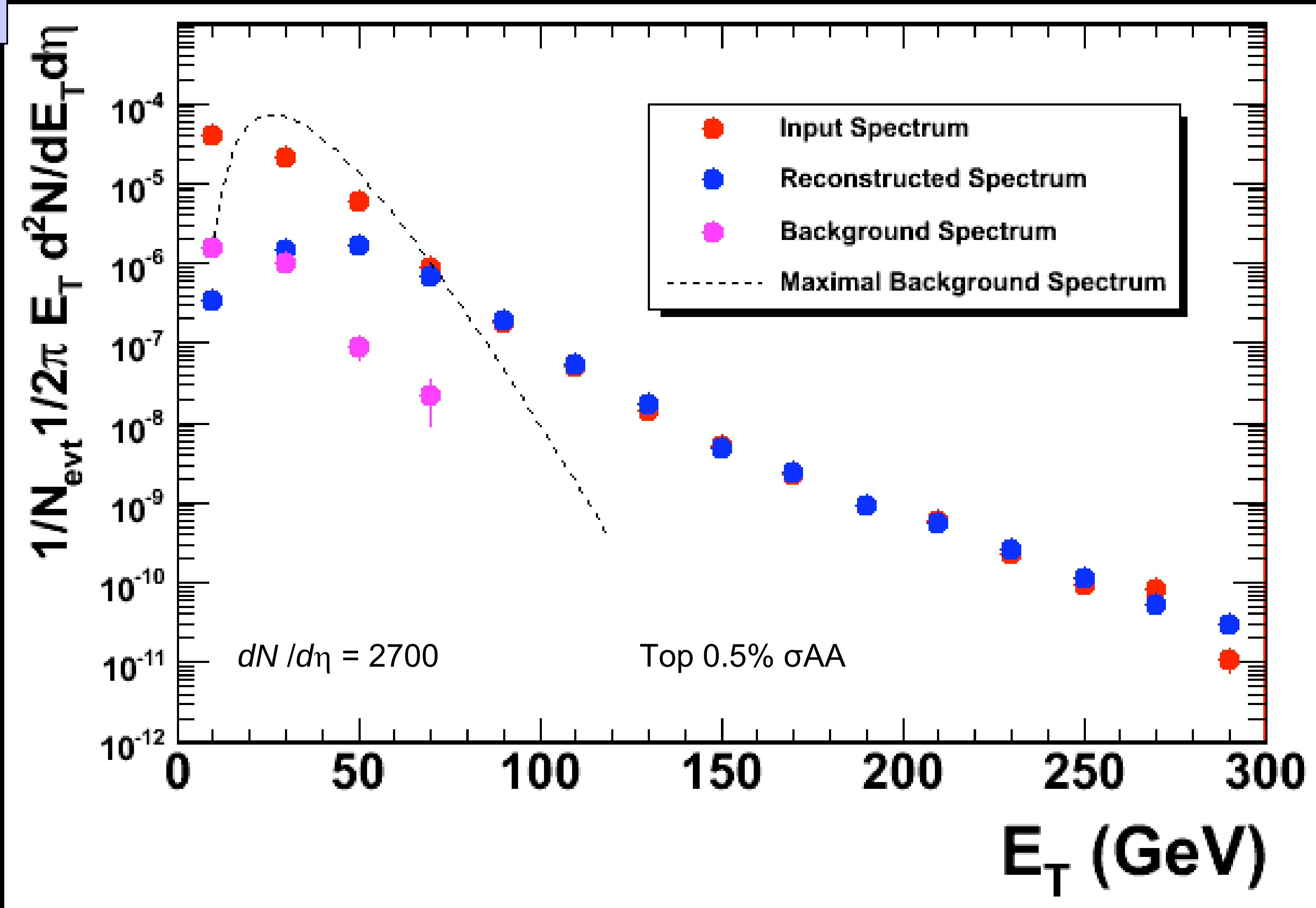
ATLAS has a broad heavy ion physics program
- excels at jet and photon measurements



Jets
- reconstruct jets in a large kinematical range, E_T > 40 GeV and $|\eta|<5$
- perform key fragmentation measurements
- jet shape and FF modifications
- multi-jet studies

Photons
- isolate / measure photons in large range, E_T > 10 GeV and $|\eta|<2.5$
- unique calorimeter design allows additional rejection beyond isolation

Example of Anticipated Jet Measurements



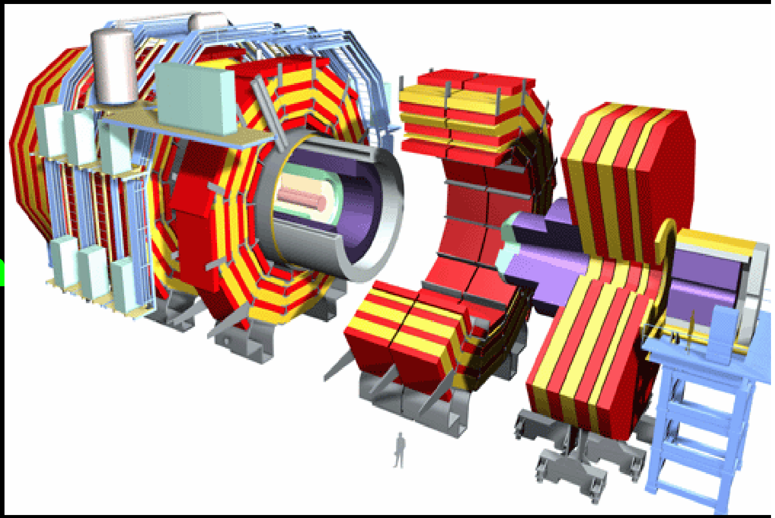
Reconstructed spectra not corrected
for efficiency and energy resolution.

CMS Heavy Ion Program

Overview:

CMS has a broad heavy ion physics program

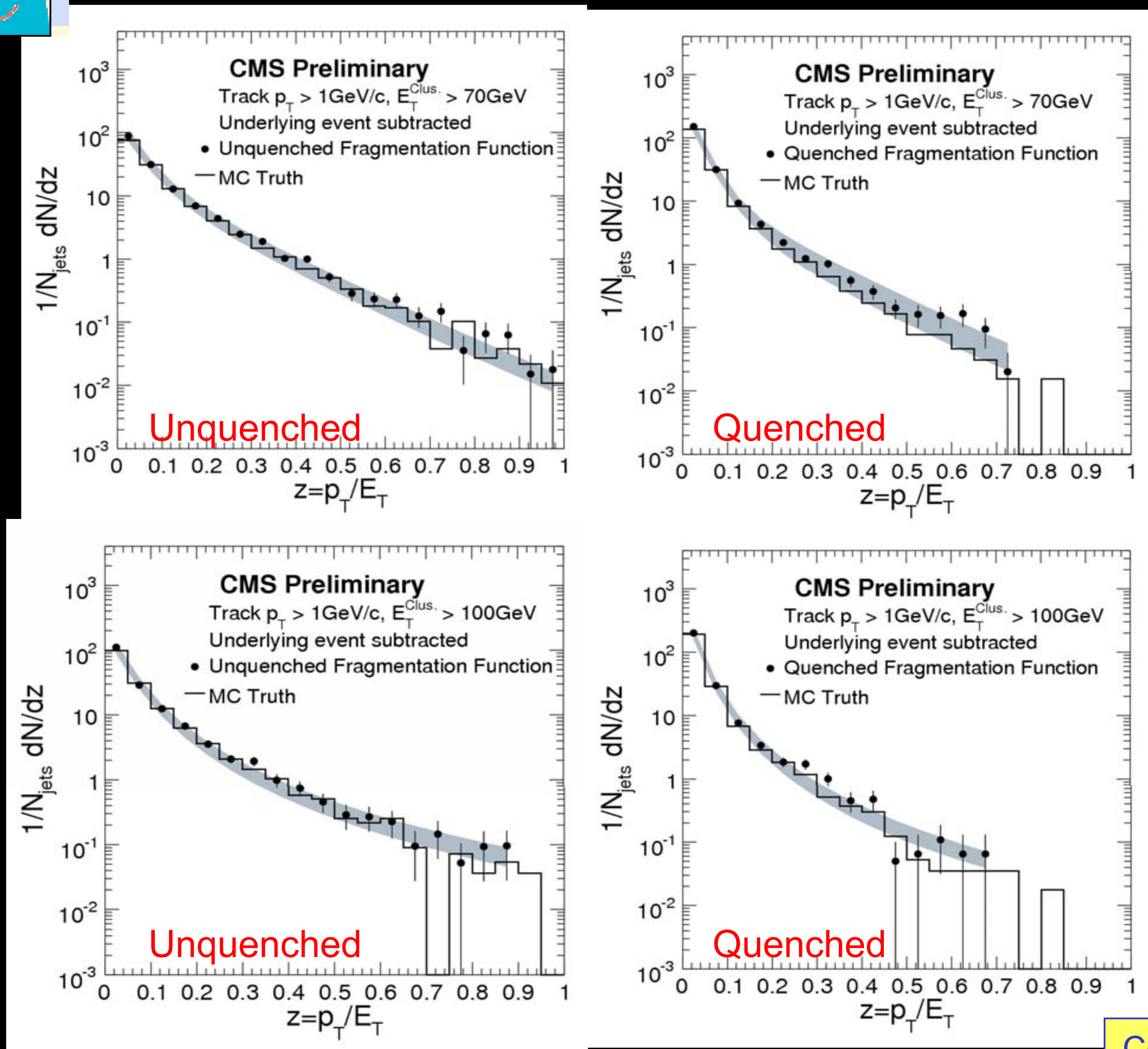
- precision tracking $|\eta| < 2.5$
- muon identification $|\eta| < 2.5$
- high-res calorimetry $|\eta| < 5$
- forward coverage



CMS expects to excel at

- photon-tagged jet measurements (FF modifications)
- quarkonium measurements

Fragmentation Functions in CMS



$E_{T,\gamma}$ > 70GeV

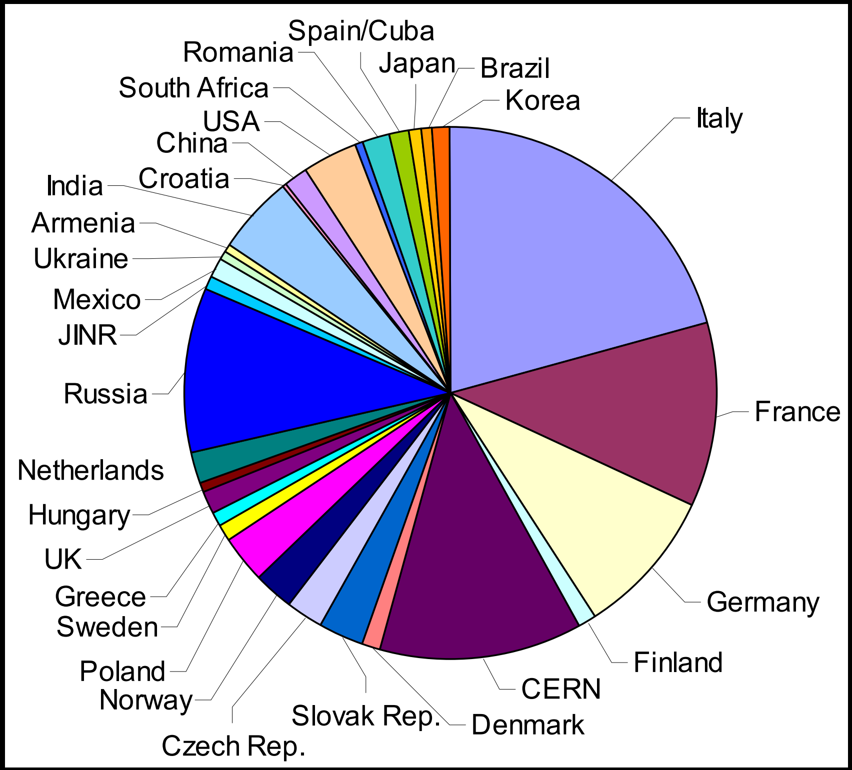
$E_{T,\gamma}$ > 100GeV

Courtesy: C. Roland and CMS

A Little More About ALICE

the Dedicated Heavy Ion Experiment

(a huge Italian involvement, including Frascati!)

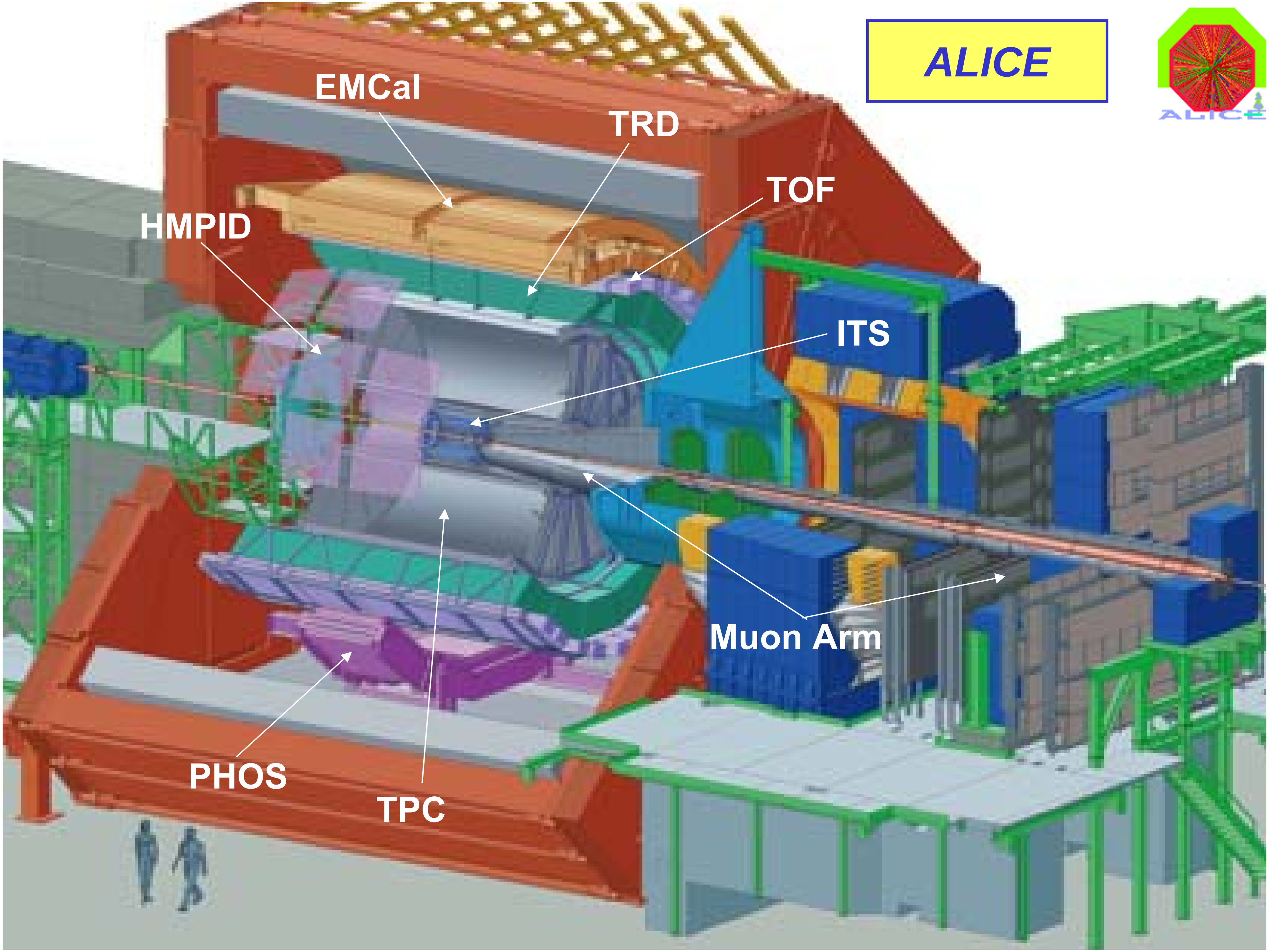


~ 1000 Members

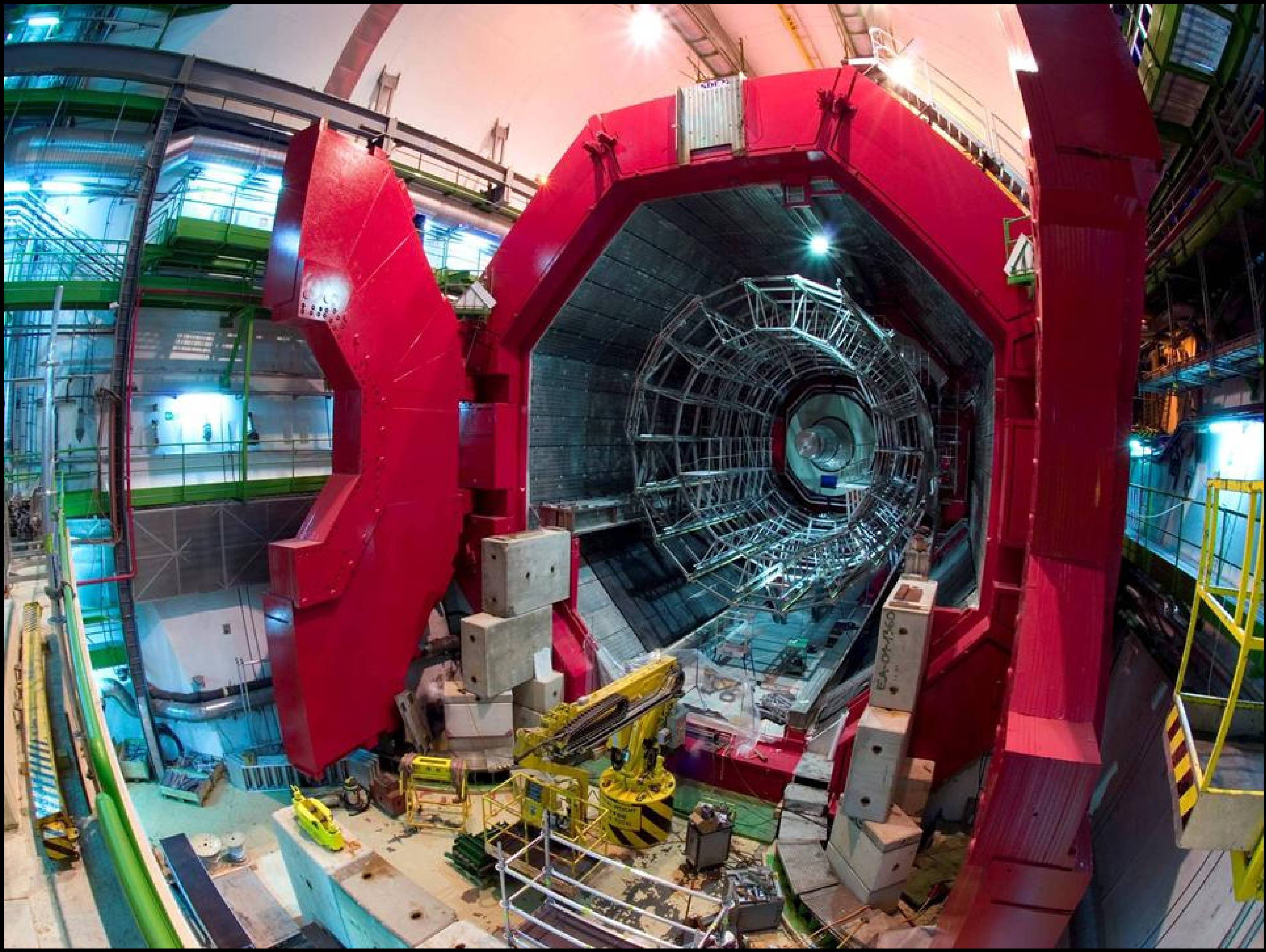
~ 30 Countries

~ 100 Institutes

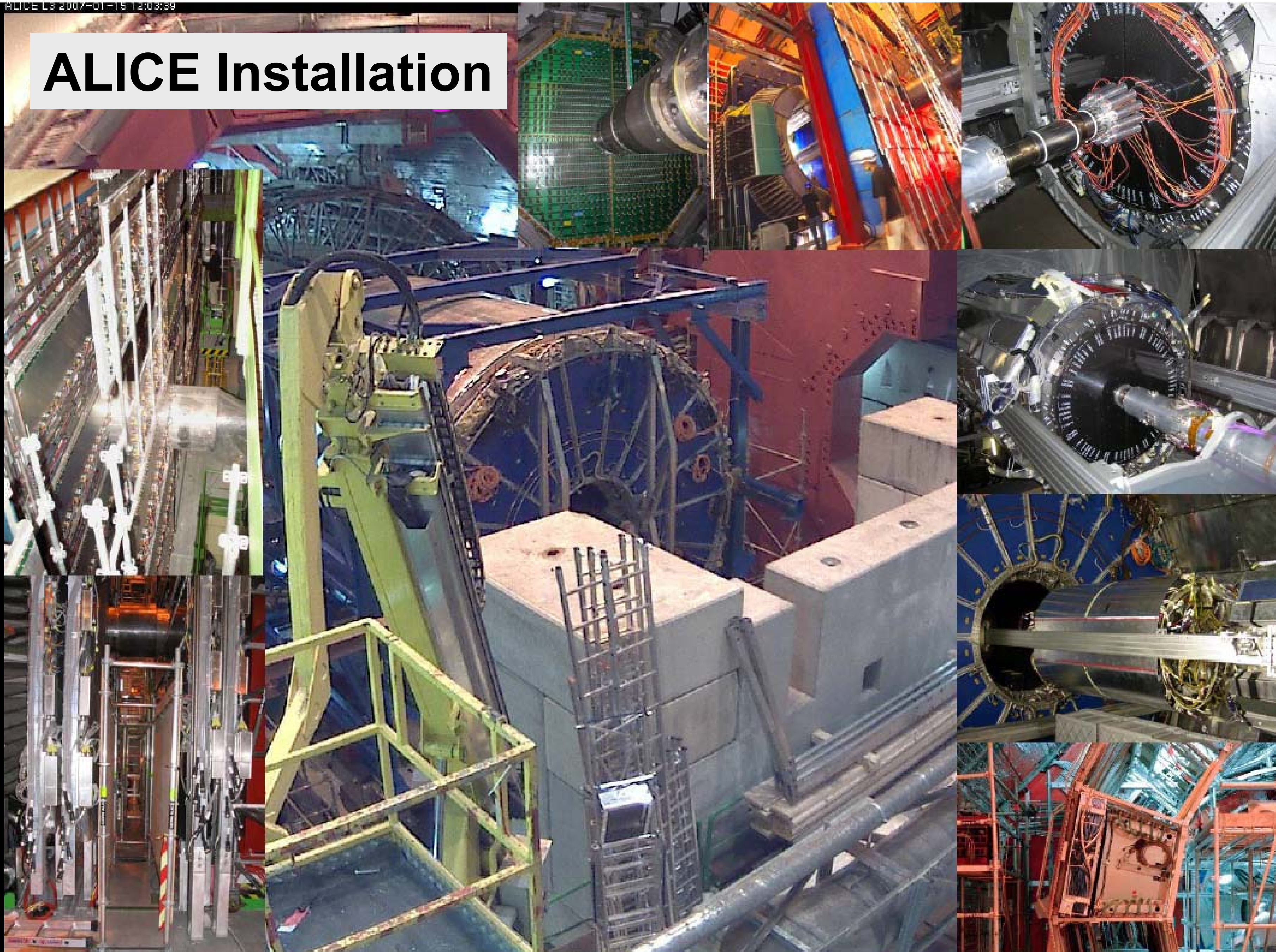
ALICE



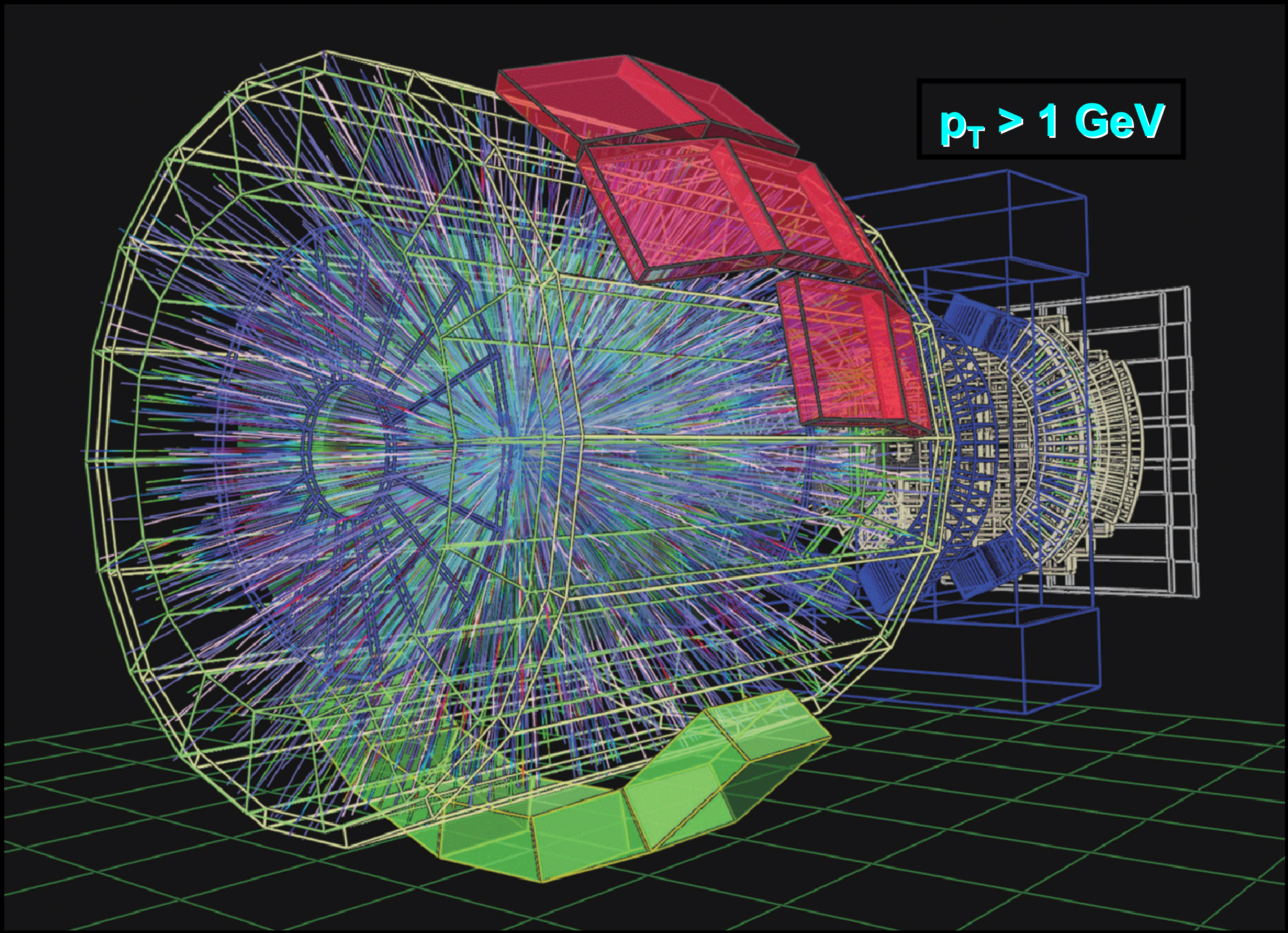
A View of ALICE Under Construction



ALICE Installation



An ALICE PbPb Event



ALICE Physics Measurements

Soft Probes – “ala RHIC”

- Expansion dynamics different from RHIC due to timescales, densities
- All soft physics measurements as at RHIC so far (+ extended PID)
- Day 1 physics +

Hard Probes – Jet Quenching

- Jets, γ , pi-zeros, leading particles to large p_T

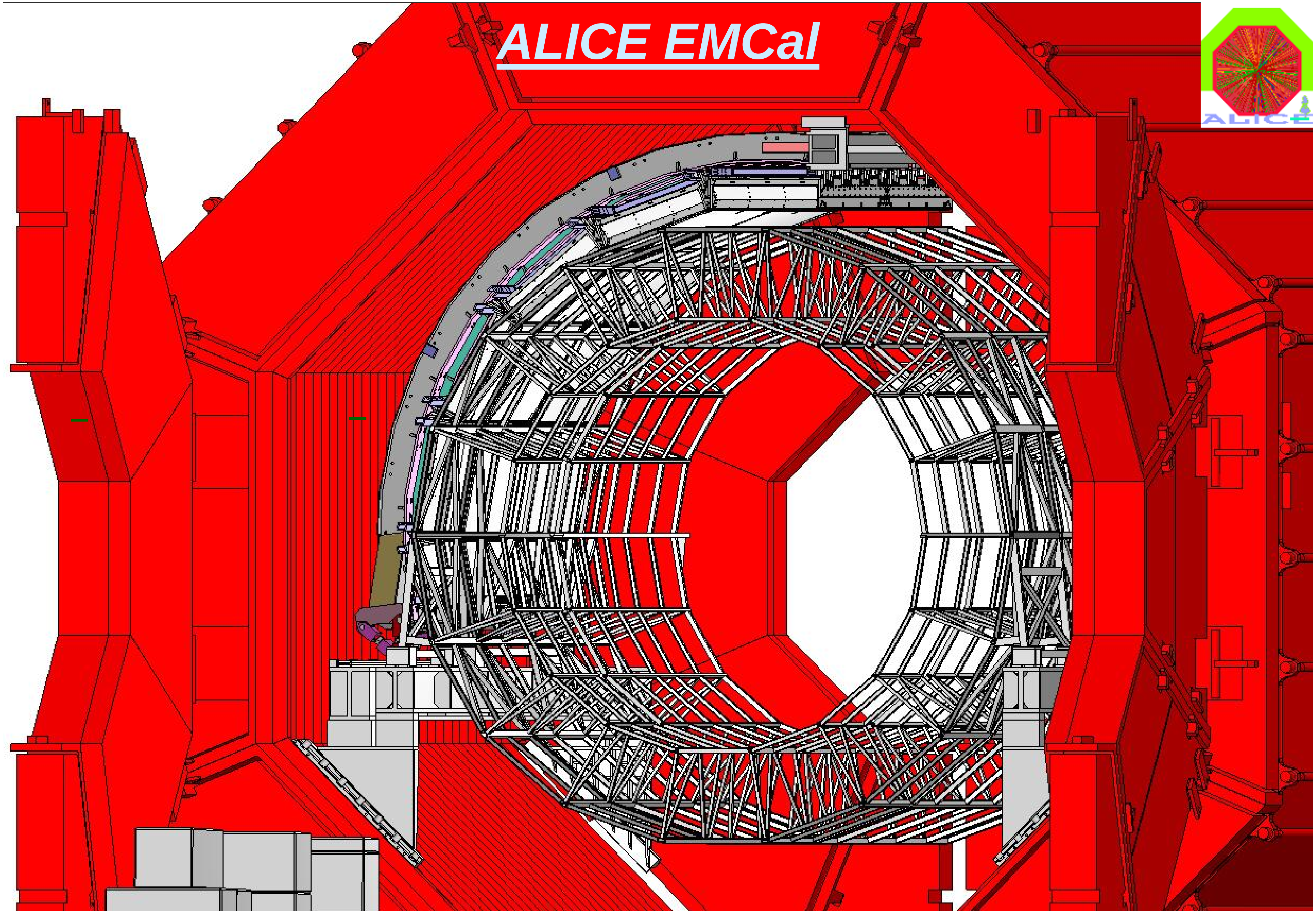
Hard Probes – Heavy Quarks

- Displaced vertices ($D^o \rightarrow K^- \pi$+) from TPC/ITS
- Electrons in Transition Radiation Detector (TRD)

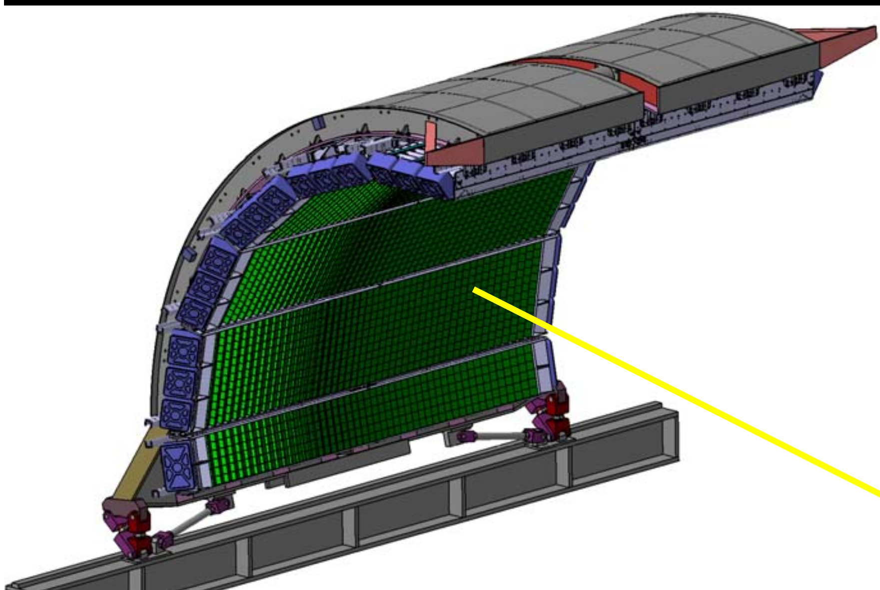
Hard Probes – Quarkonia

- J/ψ, Υ, Υ' (excellent), Υ''(2-3 yrs), ψ' ???

ALICE EMCal



ALICE EMCal



Approved for funding Jan. 2008

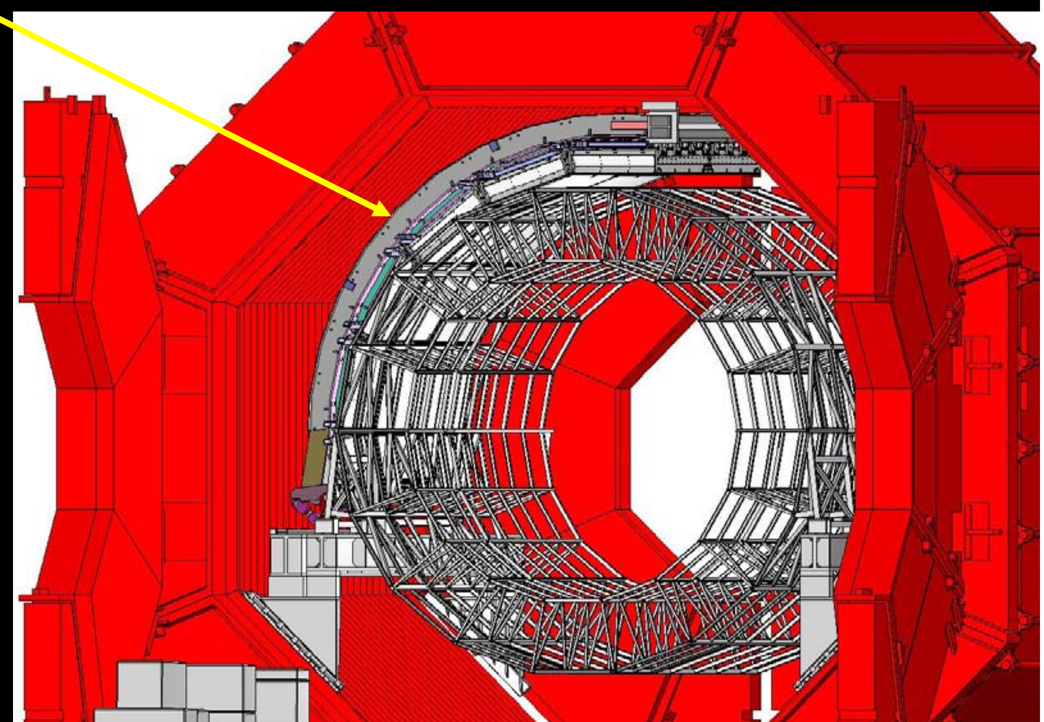
10 ½ Super-Modules

7 ½ SM from US

3 SM from Italy (Frascati, Catania)

& France (Grenoble, Nantes)

Construct / install: 2009 $\rightarrow$ 2011



Lead-scintillator sampling calorimeter

$\Delta\eta = 1.4, \quad \Delta\phi = 110^o$

Shashlik geometry, APD photosensor

~13K towers ($\Delta\eta$ x $\Delta\phi$ ~ 0.014 x 0.014)

Energy resolution = 10.6%/$\sqrt{E}$ + 2.1%

over-takes tracking above ~ 30 GeV

π^o/γ discrimination to p_T ~ 30 GeV

Hard Probe Capabilities of ALICE with EMCal

EMCal improves detector capabilities:

- Fast trigger ~10 -100 enhancement of jets
- Improves jet reconstruction (plus TPC)
- Good γ/π^0 discrimination
  increases coverage
- Good electron/hadron discrimination

EMCal extends the physics of ALICE:

10^4/year in minbias Pb+Pb:

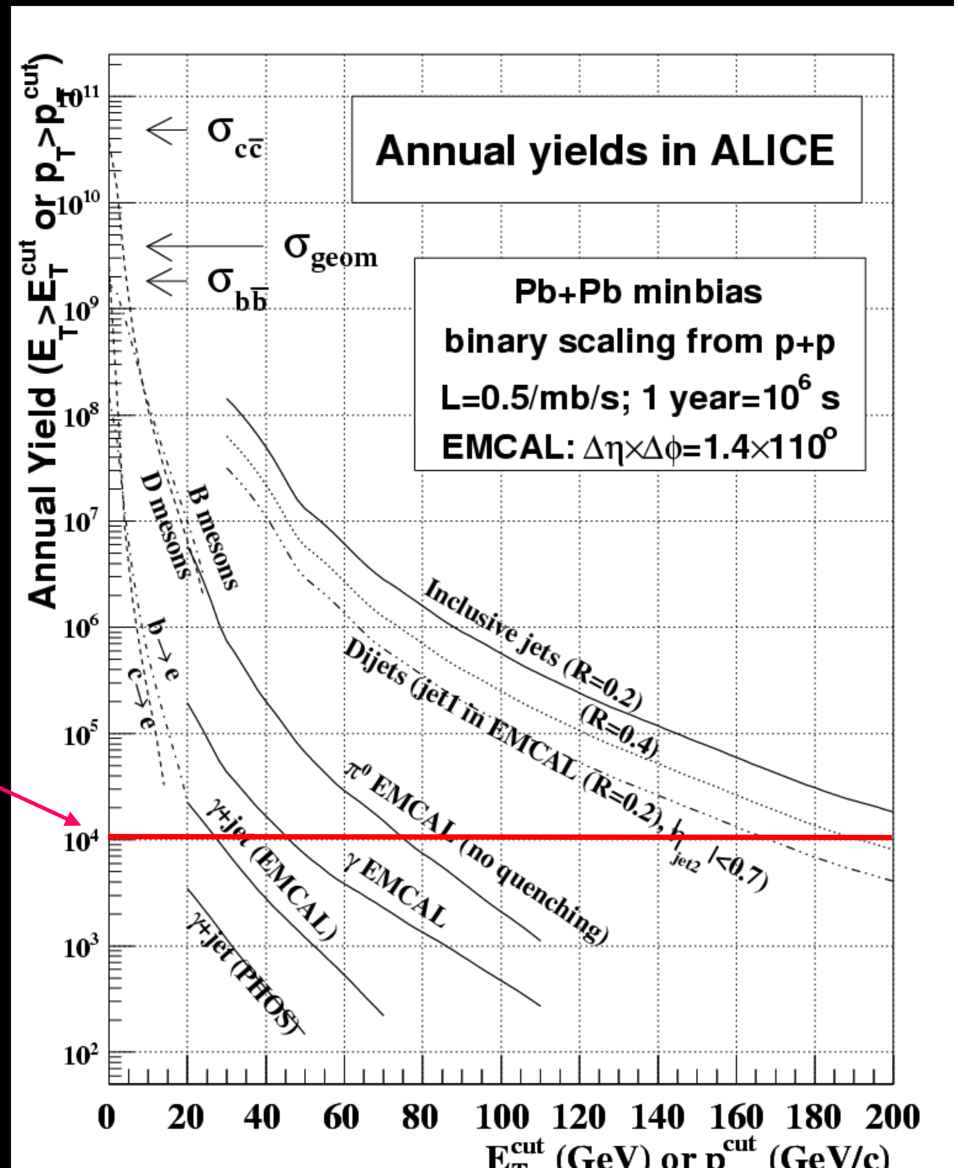
inclusive jets: E_T ~ 200 GeV

dijets: E_T ~ 170 GeV

π^0: p_T ~ 75 GeV

inclusive γ: p_T ~ 45 GeV

inclusive e: p_T ~ 30 GeV

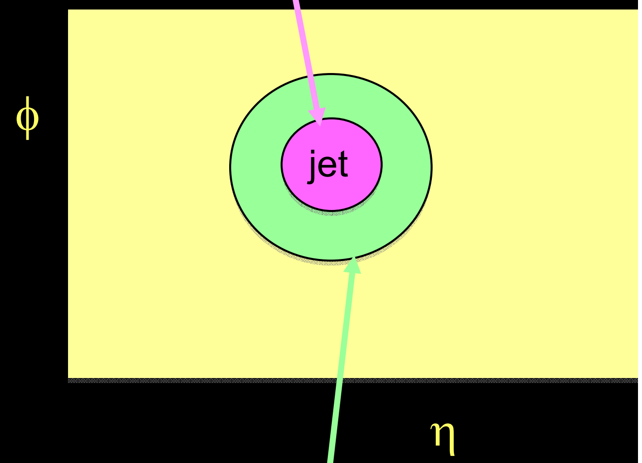


Thanks – Peter Jacobs

Measuring the PbPb Fragmentation Function

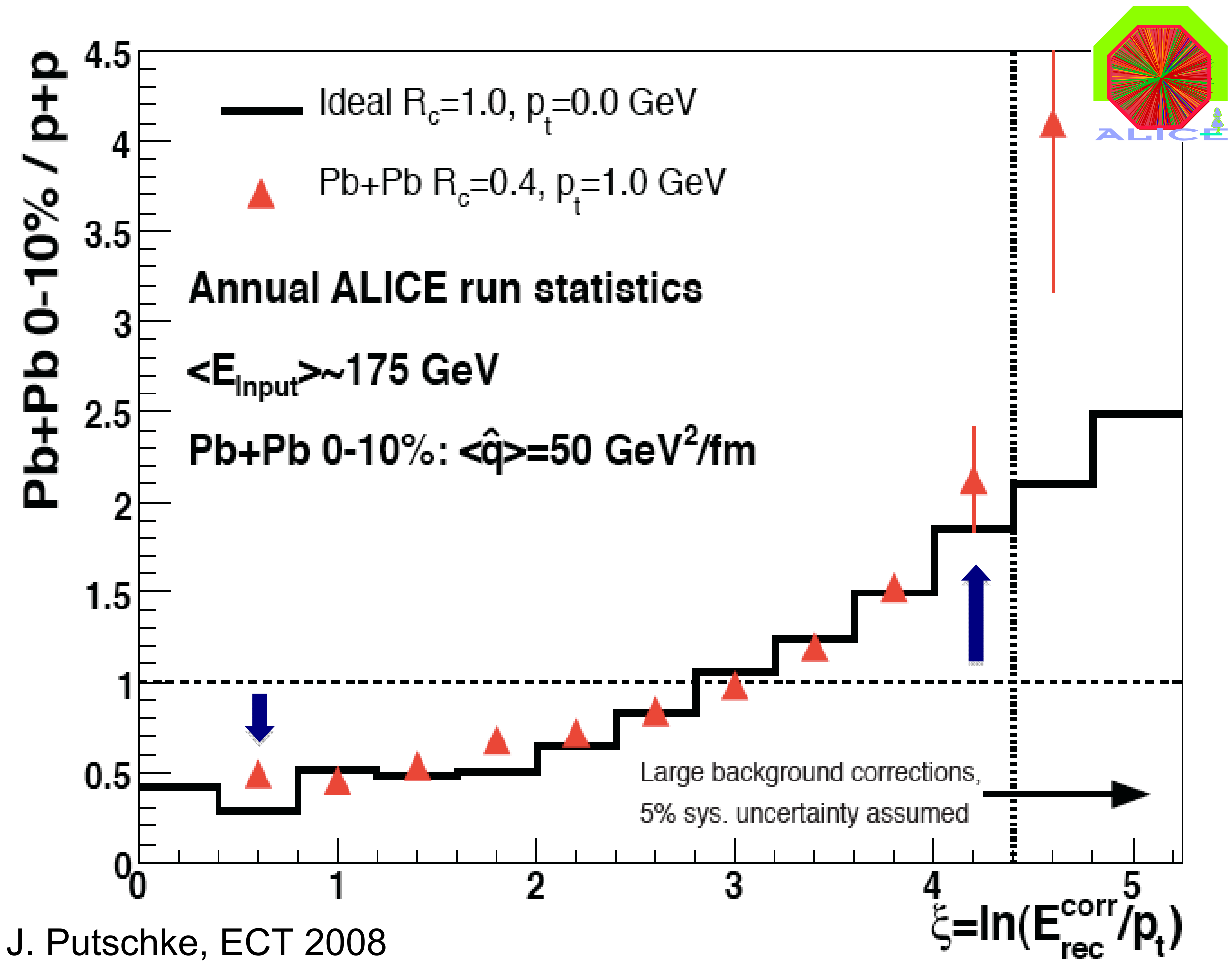
Jet energy determination:

R_c=0.4 p_T > 1 GeV/c



Charged particles for FF ξ:

R_c=0.7 p_T > 0 GeV/c



J. Putschke, ECT 2008

More studies of background are needed & underway!

The Quark-Gluon Plasma - Today's View from RHIC

Synopsis of Experimental Results –

- Successfully heated matter to temperature $T > 2 \times 10^{12}$ K (200 MeV)

- This is > 100,000 times hotter than the core of Sun

- This is more than hot enough to make a Quark-Gluon Soup

What are its characteristics?

- It flows like a liquid, better than any we know or have made

- It behaves like a soup of quarks (and gluons)

- It is opaque to the most energetic probes (fast quarks)

RHIC and new Large Hadron Collider (LHC) at CERN in Geneva:

Cover 2 – 3 decades of energy ($\sqrt{s_{NN}}$ ~ 20 GeV – 5.5 TeV)

To discover the properties of hot QCD at T ~ 150 – 600 MeV)

Many Things to Do with Heavy Ions at the LHC!

My Laundry List!

Day 1 – Elliptic Flow

Multiplicities (just to check the models) and spectra

Flavor (Gluon and Quark mass) dependence of parton energy loss

Use jets and/or photons to establish hard-scattered parton energy

Jet and high pt particle correlations

Jet modifications - longitudinal & transverse "heating" – due to medium

Medium response to jet-heating (near- and away-side)

Separate open charm and beauty decays

cc and bb states (screening, suppression, enhancement?)

Direct Photon Radiation?

………..to name a few………….

New phenomena…….

Developments in theory (lattice, hydro, parton E-loss, string theory…)

"the next frontier!"

Special Thanks for Contributions to This Presentation!!

<u>Miklos Gyulassy</u>

<u>Peter Jacobs</u>

<u>Thomas Ullrich</u>

<u>Urs Wiedemann</u>


Relativistic Heavy Ion Group at Yale

The End