No Pain, no Gain:
Hard Probes of the QGP Coming of Age

Berndt Müller

Hard Probes 2012

Cagliari - May 28, 2012

The “Hard Probes” manifesto

“The aim of high energy heavy ion collisions is to produce and study a medium of deconfined quarks and gluons in the laboratory. Deconfinement occurs when the density of quarks and gluons becomes so high that long range confining forces cease to be effective. It is thus intimately connected to short spatial scales, and to resolve and study phenomena at such scales, hard probes are essential and have to be developed into as precise tools as possible. Hence it is necessary to study the production of heavy flavours and quarkonia, of jets, and of photons and dileptons in strongly interacting media.”

(C. Lourenço and H. Satz, Preface to Hard Probes 2004, Ericeia, Portugal)

The questions to be asked at the opening of Hard Probes 2012 are:

Where are we on the path toward this goal? What have we learned? What is still missing? What needs to be done?

Hard Probes

- High-p_T partons & jets
- Heavy quarks / open flavor hadrons
- Quarkonia (J/ψ, ϒ)
- Electroweak probes (l^+l^-, γ, Z)

- Production rates are calculable in SM
  - Caveats: quarkonia, nuclear PDFs, etc.
- Final-state interactions can be factorized from production
- A+A results can be normalized to p+p and/or p(d)+A
- Final state interactions are negligible for EW probes

HP Methodology

- Formulate production in A+A as hard QCD process with factorizable final state interactions (FSI)
- Formulate FSI in terms of medium properties (e.g. transport coefficients) that can be calculated for any medium model
- Identify observables that are sensitive to certain aspects of the structure of the medium, e.g.:
  - Weakly vs. strongly coupled plasma
  - Scale separating weak from strong coupling
  - Quasiparticle structure
- Calculate medium properties relevant to FSI on the lattice

Hot QCD matter properties

Which **properties of hot QCD matter** can we hope to determine with the help of hard probes ?

Easy for LQCD

$$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln\left\langle E^a(x) E^a(0) \right\rangle$$

Color screening: Quarkonium states

Hard for LQCD

$$\Pi^{\mu\nu}_{\text{em}}(k) = \int d^4x\, e^{ikx} \left\langle j^\mu(x) j^\nu(0) \right\rangle$$

QGP Radiance: Lepton pairs, photons

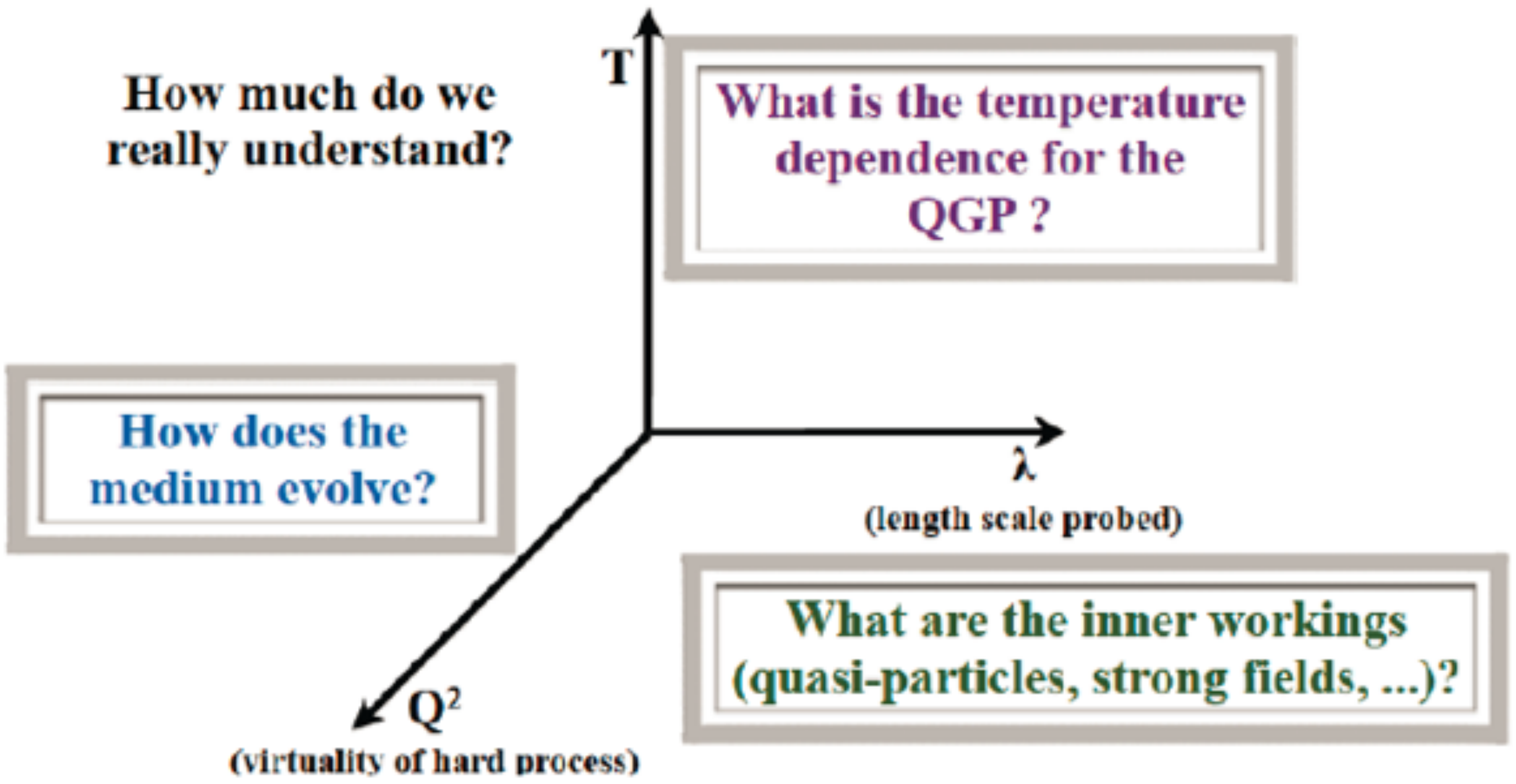
Very Hard for LQCD

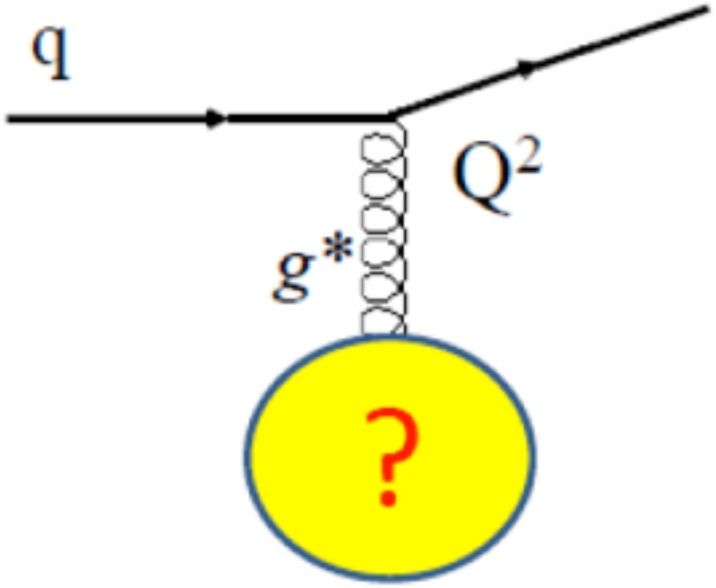
$$\left.\begin{aligned} \hat{q} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1} \int dy^- \left\langle F^{a+i}(y^-) F_i^{a+}(0) \right\rangle \\ \hat{e} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1} \int dy^- \left\langle i\partial^- A^{a+}(y^-) A^{a+}(0) \right\rangle \\ \hat{e}_2 &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1} \int dy^- \left\langle F^{a+-}(y^-) F^{a+-}(0) \right\rangle \end{aligned}\right\}$$

Momentum diffusion:
parton energy loss, jet quenching

What we hope to learn

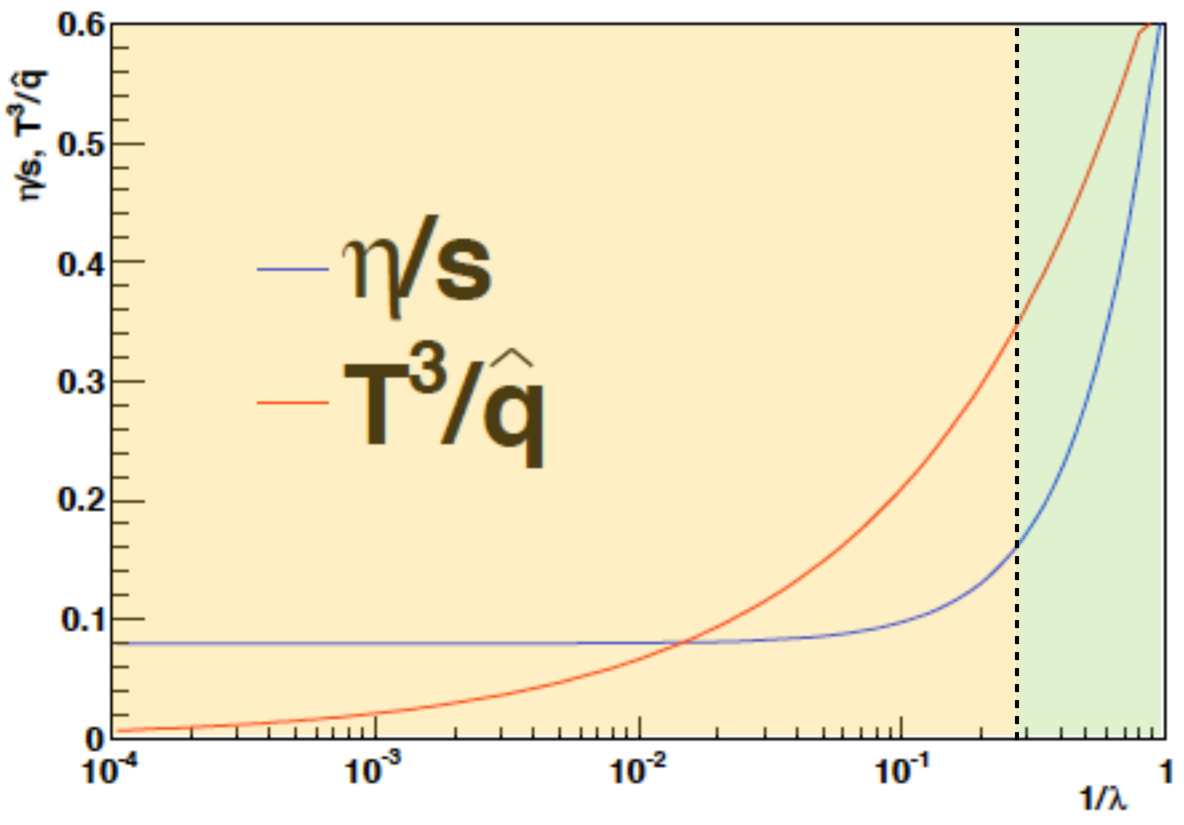
Apart from $\Pi^{\mu\nu}$ all medium properties are expressed as correlators of color gauge fields. They reflect the gluonic structure of the QGP.





At high Q^2 and/or high T, the QGP is weakly coupled and has a quasiparticulate structure. At which Q^2 (T) does it become strongly coupled? Does it still contain quasiparticles? Can we use hard partons to locate the transition? Which quantities tell us where the transition occurs?

How hard probes could work



Majumder, BM, Wang argued that η/s and q̂ are related at weak coupling in gauge theories [PRL 99, 192301 (2007)]:

$$\eta / s = \mathrm{const} \times \mathrm{T}^3 / \hat{q}$$

At strong coupling, η/s saturates at 1/4π, but q̂ increases without limit. Unambiguous criterion for weak vs. strong coupling?

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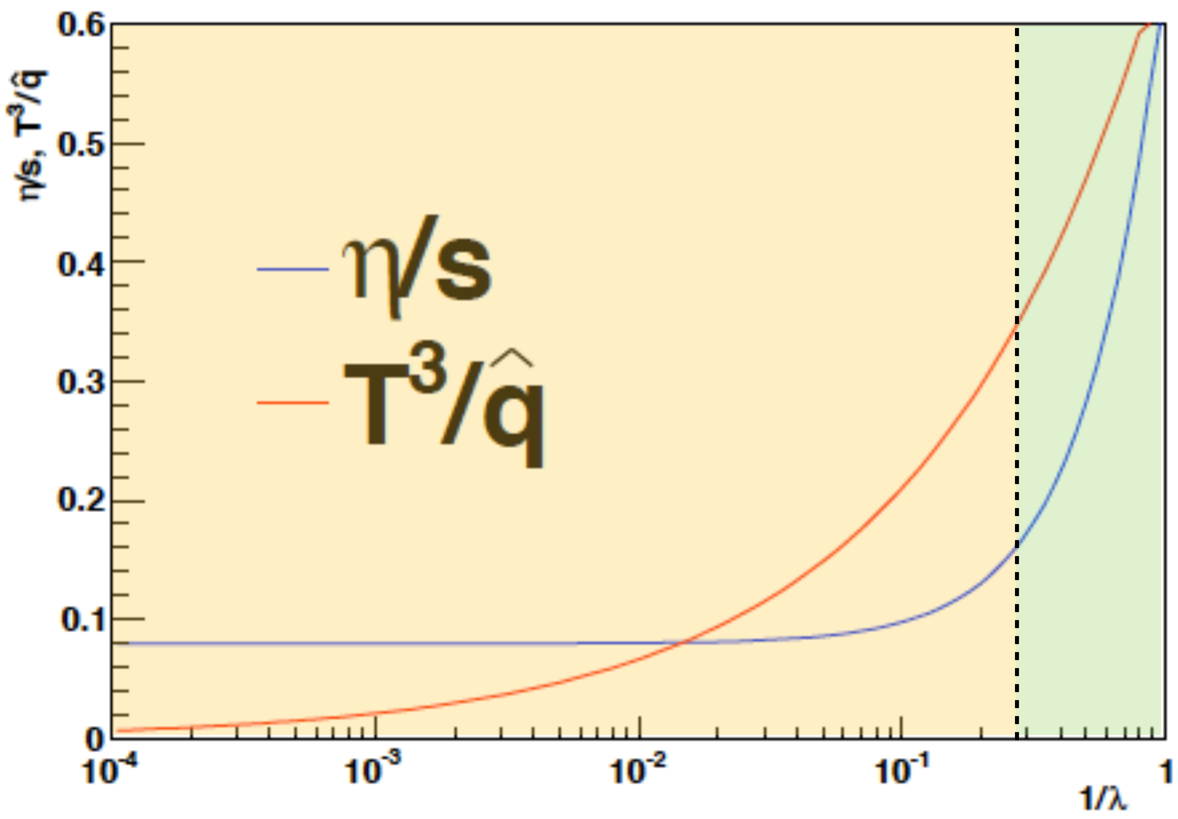

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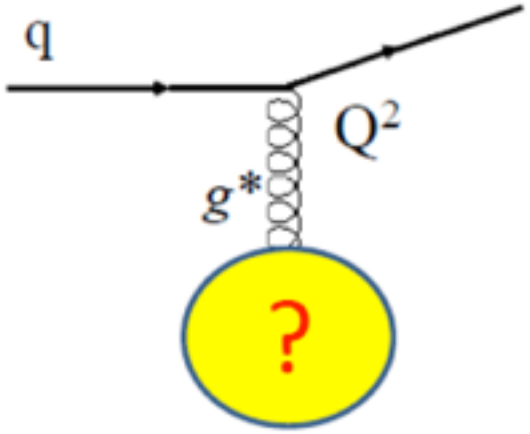
Collisional energy loss parameter ê is sensitive to mass *m* of scatterers, goes to zero in *m* →∞ limit, unless scatterings centers have a dense spectrum of excited states (*think*: atoms). Thus ê is a probe of medium structure at color screening scale.

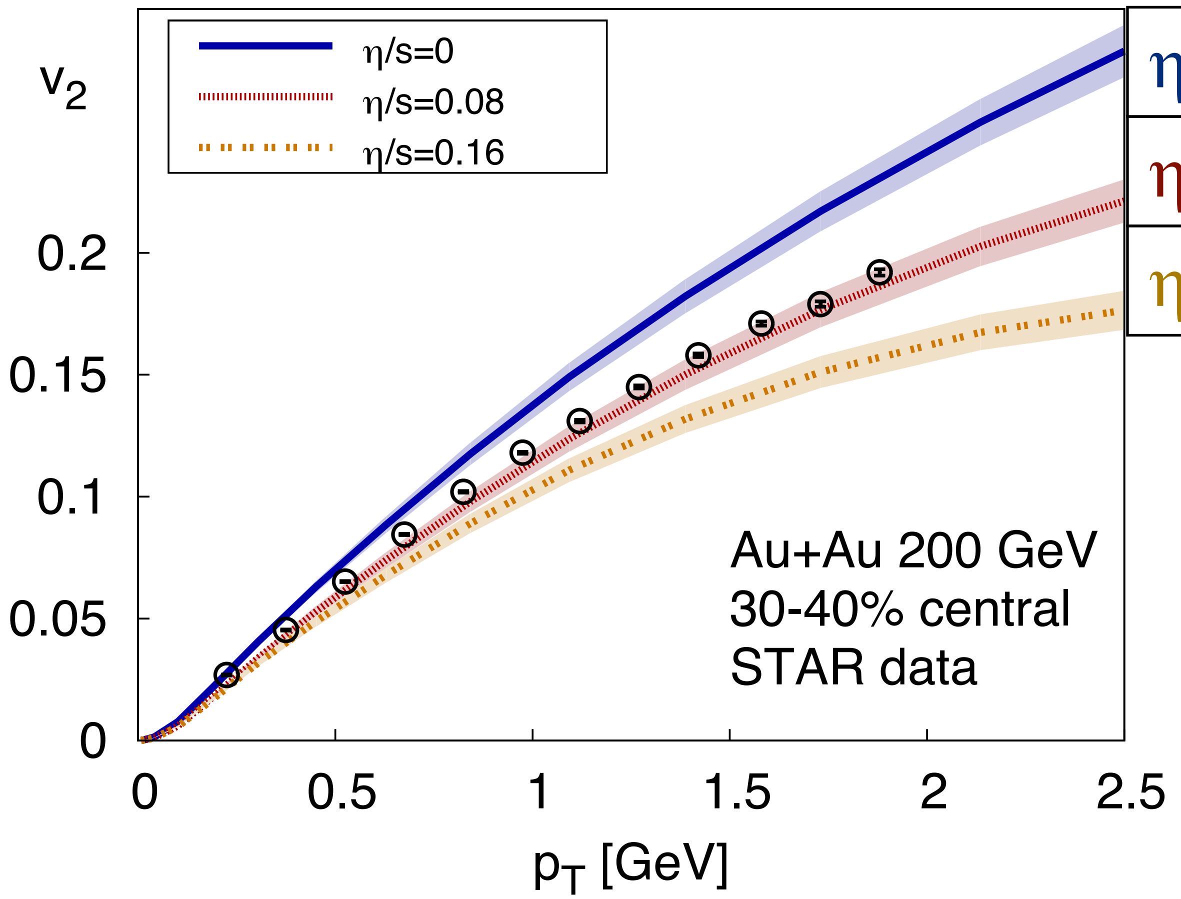


News item #1

Global properties
of relativistic heavy ion collisions
are <u>no longer</u> the limiting factor !

Elliptic flow “measures” η_{QGP}

Schenke, Jeon, Gale, PRL 106 (2011) 042301



$\eta/s = 0$

$\eta/s = 1/4\pi$

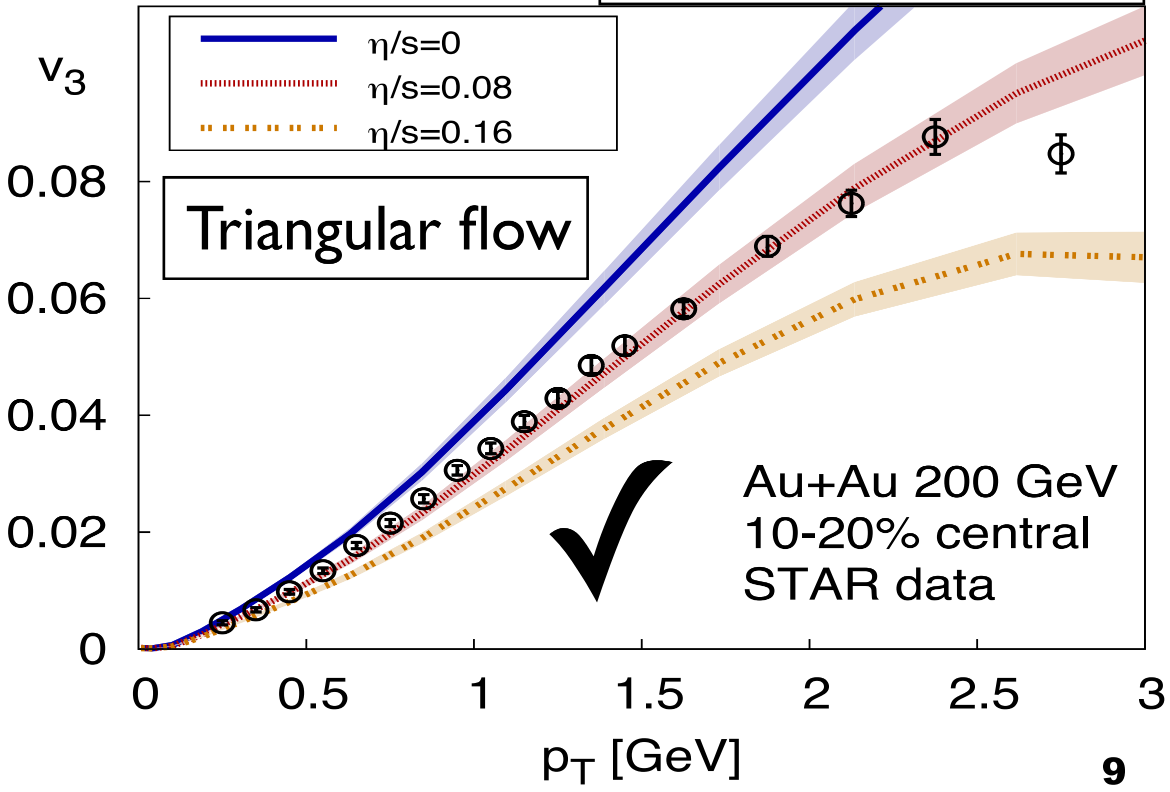
$\eta/s = 2/4\pi$

Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$\eta/s \to 1/4\pi$

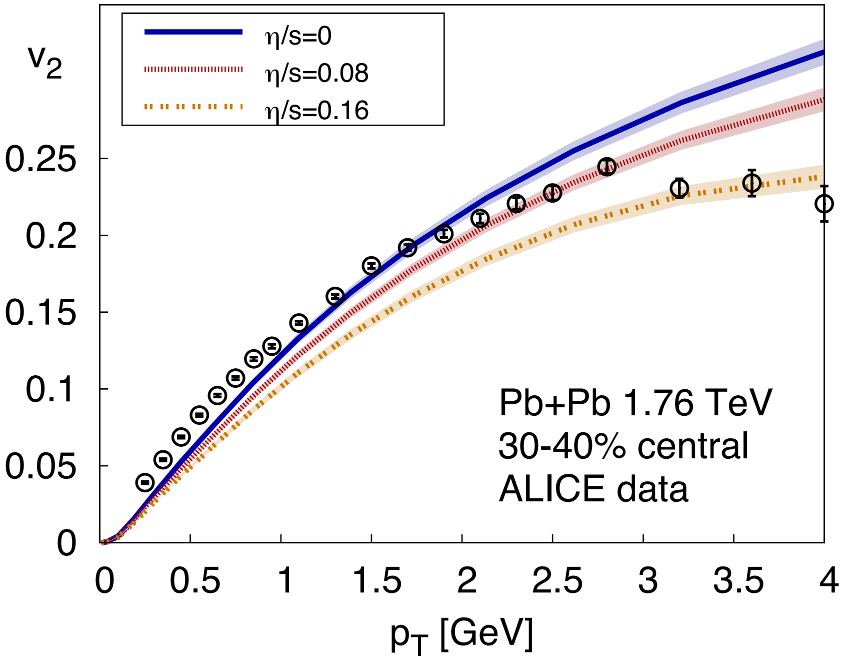
aka: the “perfect” liquid

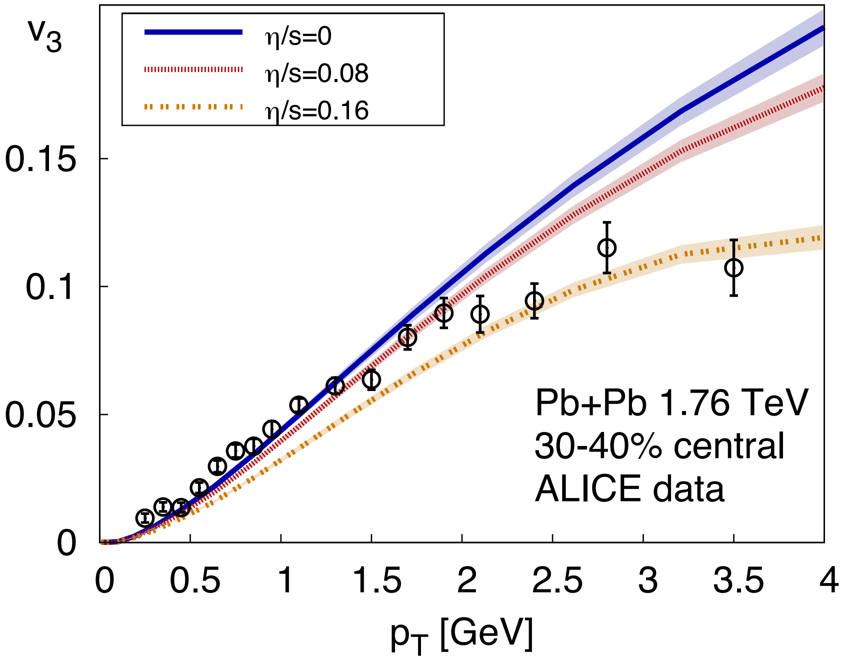
Consistency check:

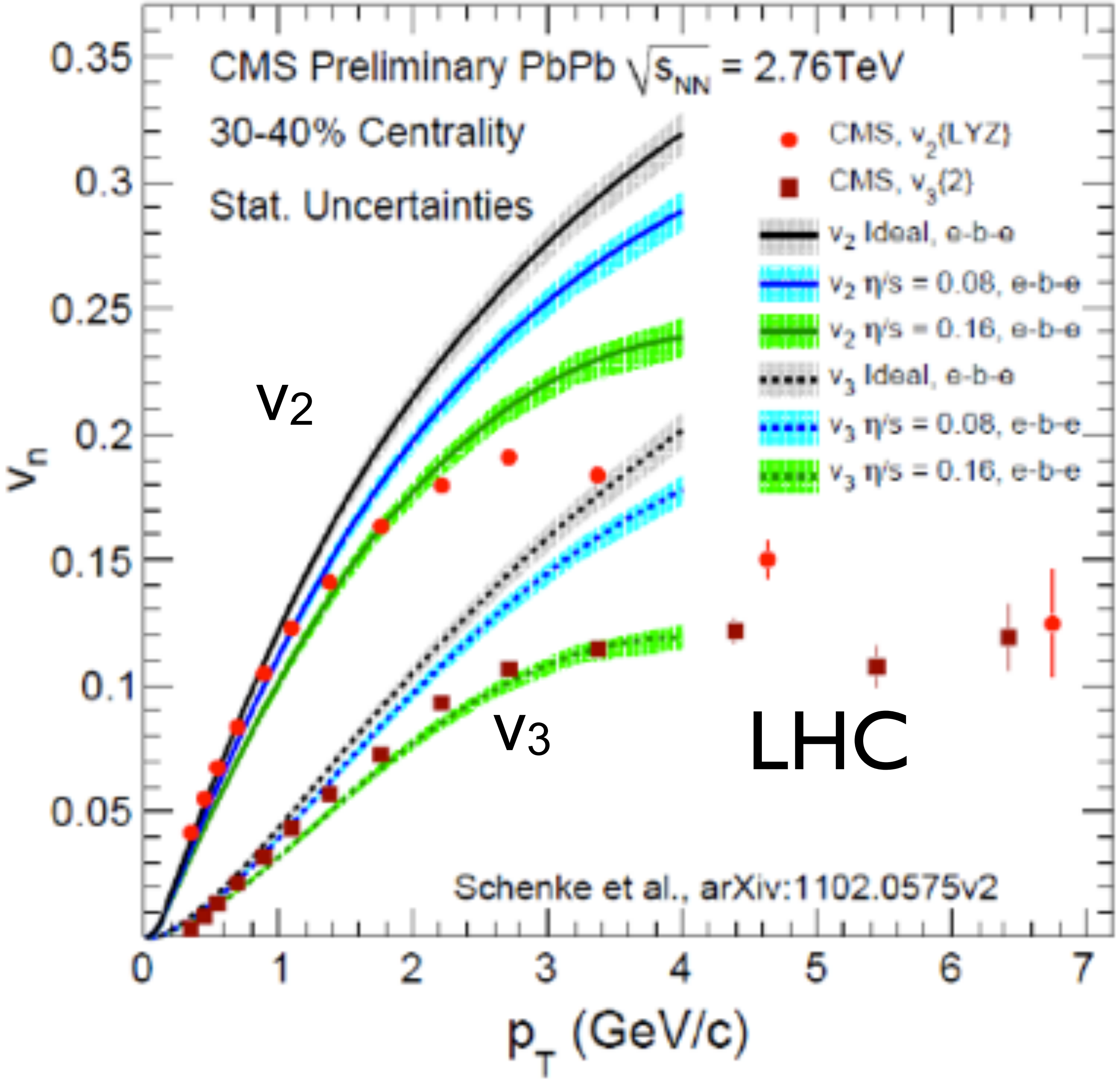


v_2 & v_3 @ LHC

Flow results agree nicely with RHIC

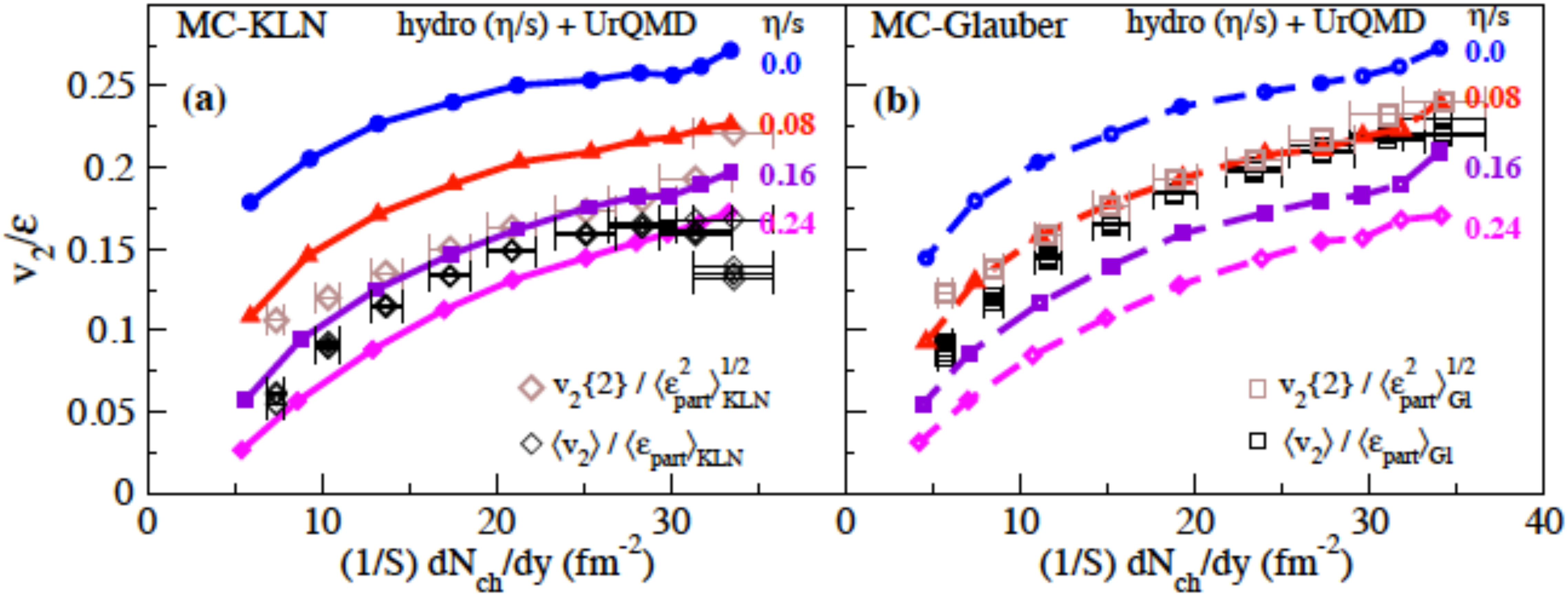






Shear viscosity

Song, Bass, Heinz, Hirano, Shen, PRL 106 (2011) 192301



Conclusion: $1 \leq 4\pi\eta/s \leq 2.5$

Remaining uncertainty mainly due to initial density profile

Bulk evolution is under good control

Theorists' ennui

"But my QGP Brick calculation worked beautifully before all the high precision data arrived!"

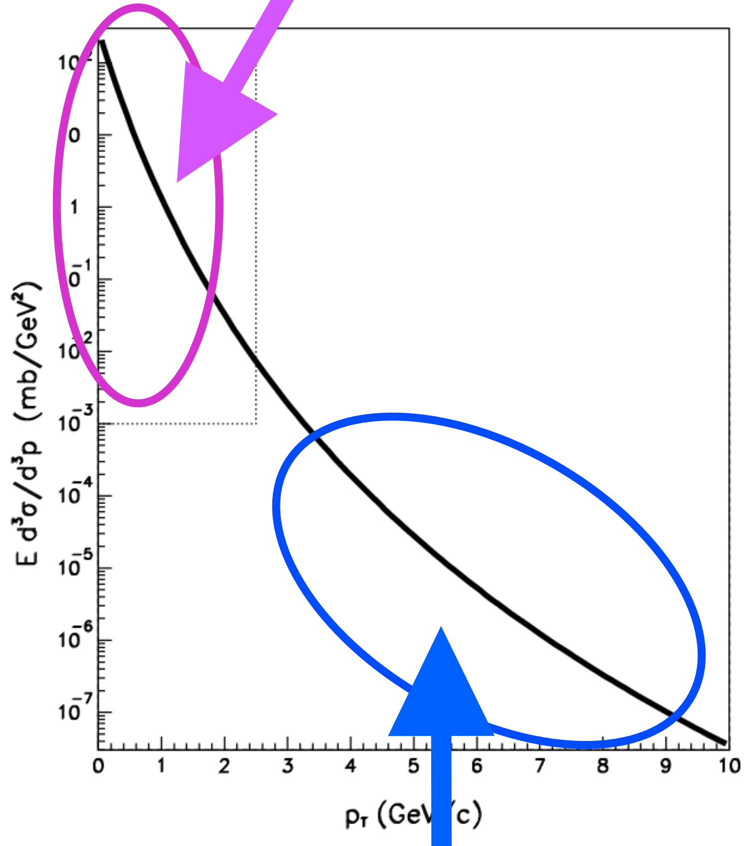
Theorists’ ennui

No more “QGP bricks”when comparing to data!

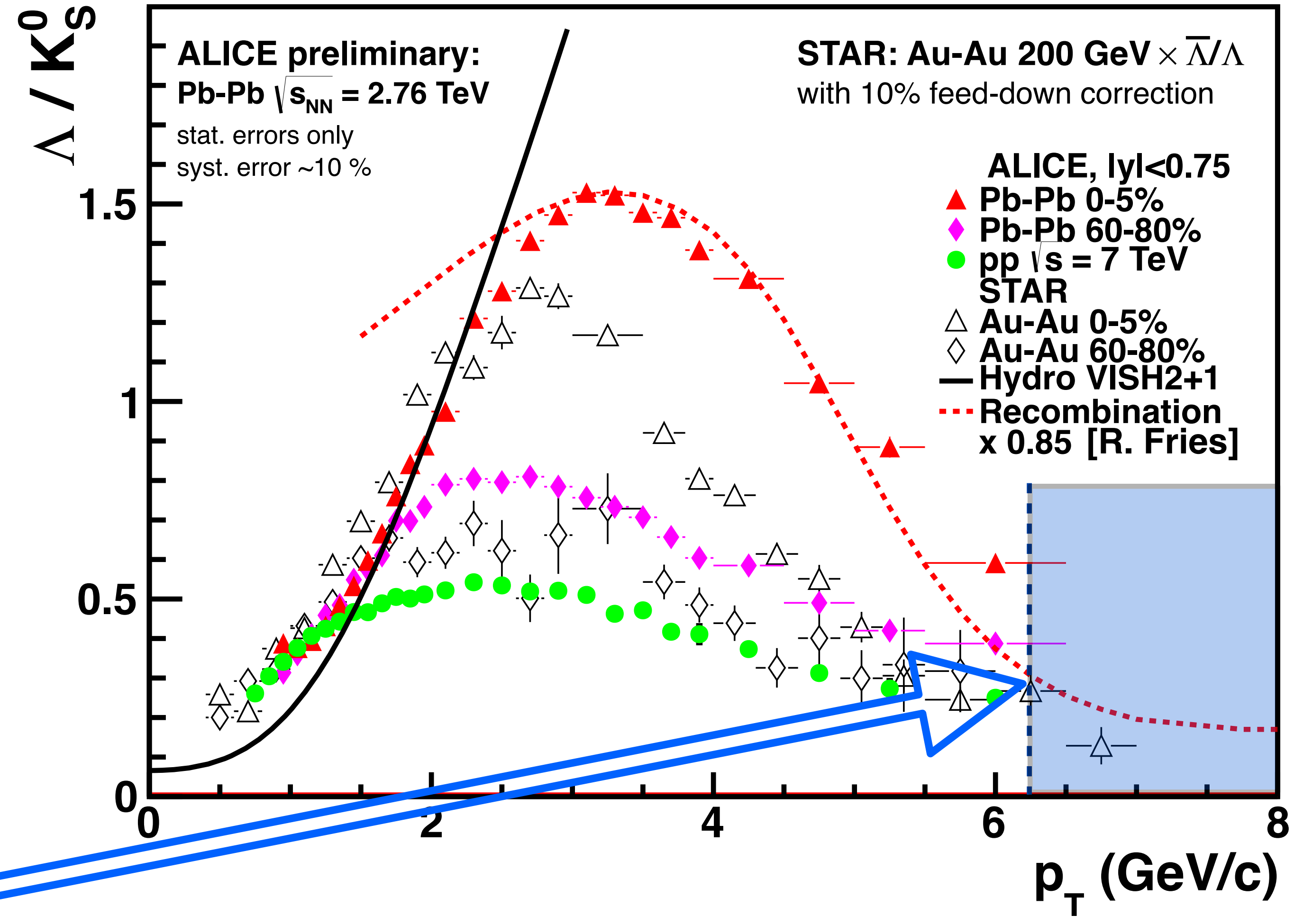
“But my QGP Brick calculation worked beautifully before all the high precision data arrived!”

Where does “hard” start?

p_T < 1.5 - 2 GeV/c
“thermal” particles
radiated from bulk medium



How do we know what “X” is ?

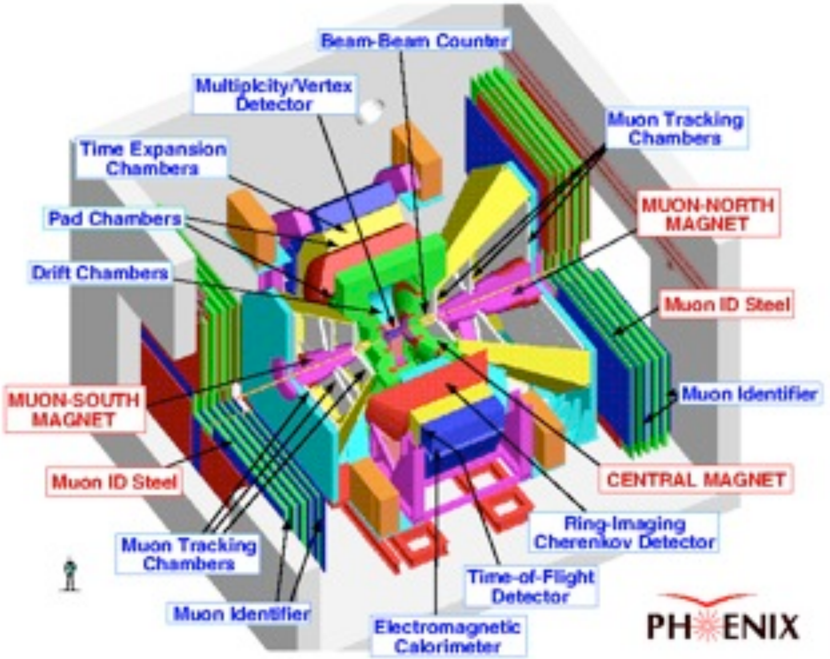


p_T > X GeV/c
autogenerated “external”
probes described by pQCD

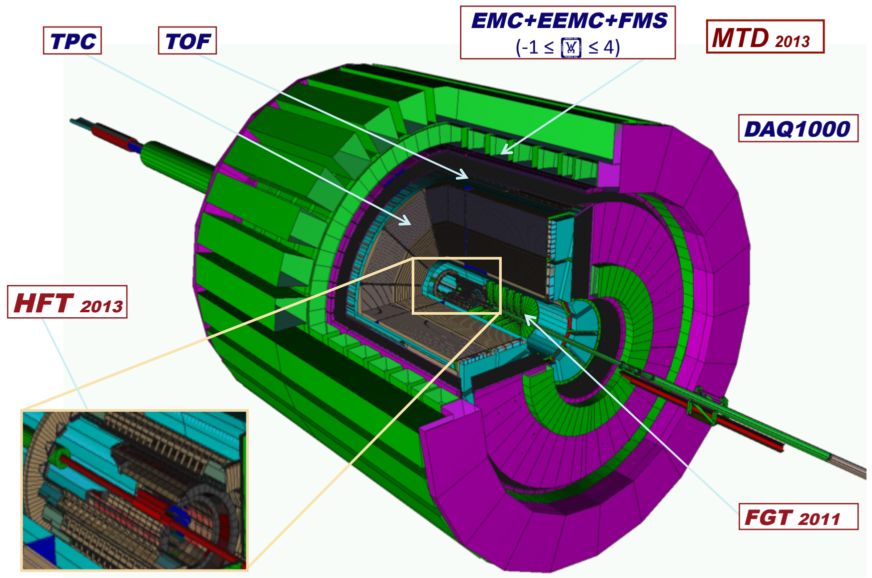
News item #2

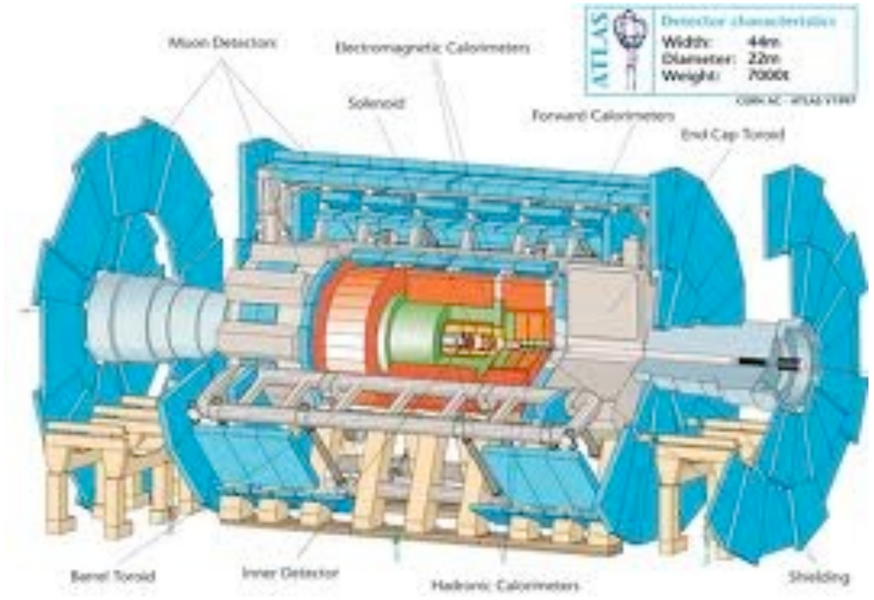
Welcome to the era
of full jet reconstruction!

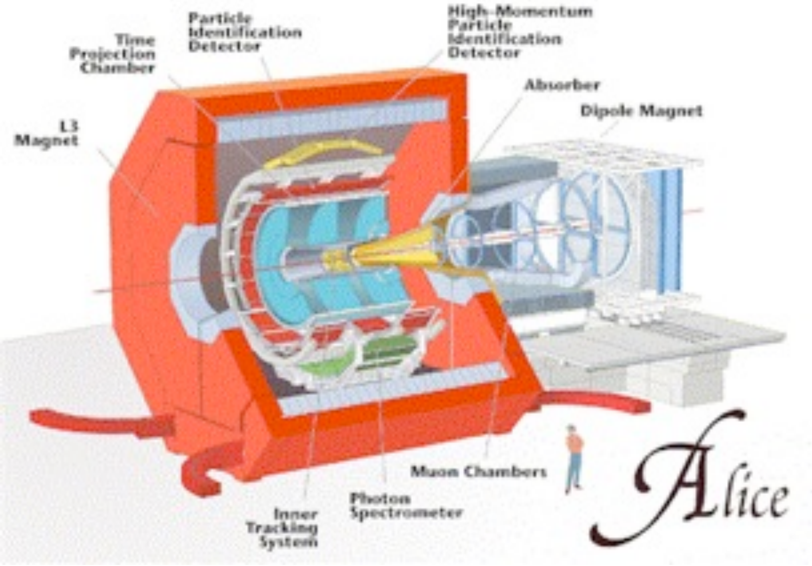
The instruments

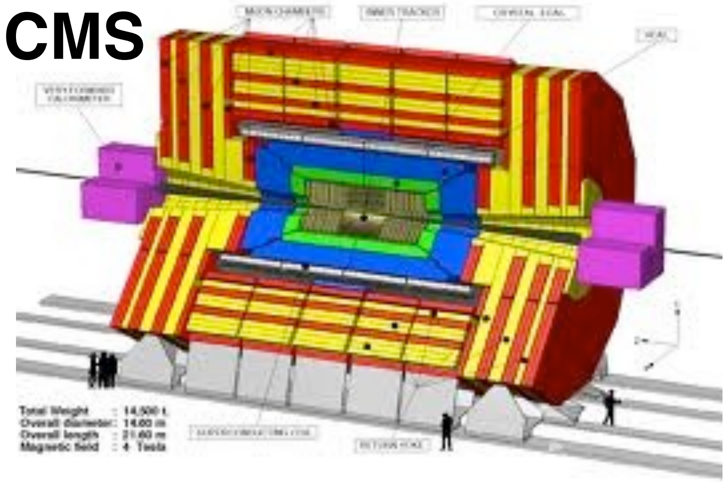


STAR Detector

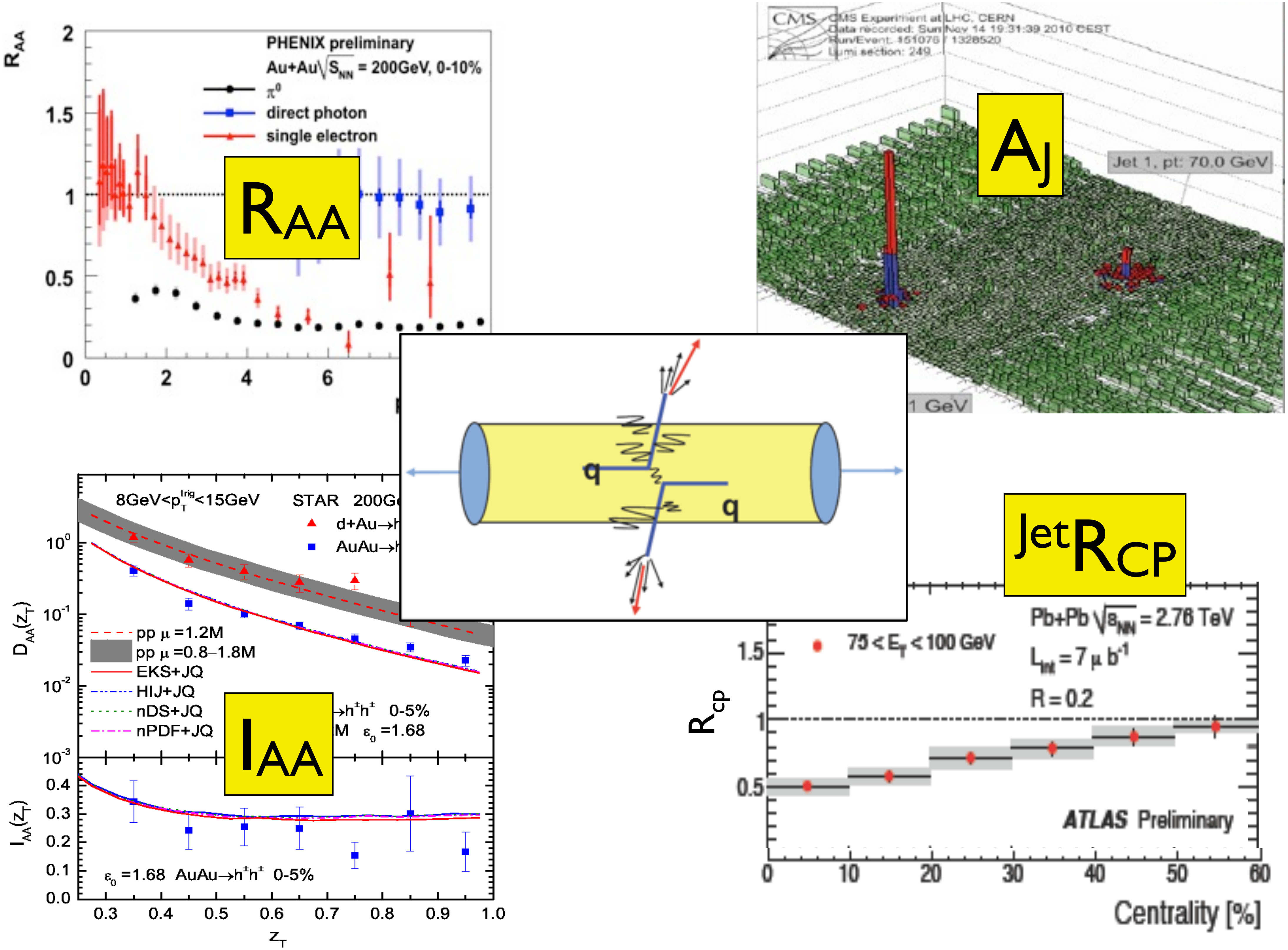






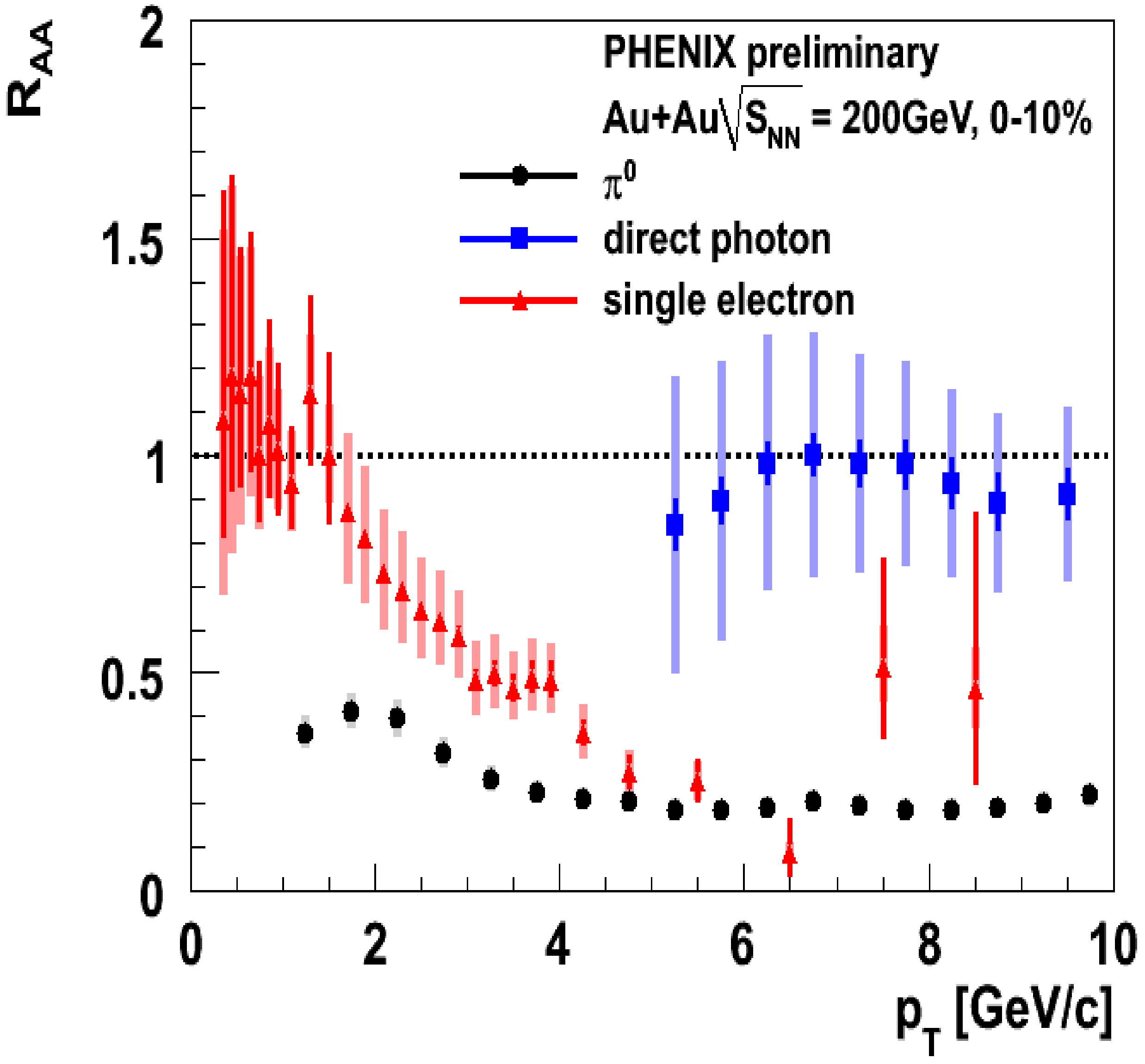


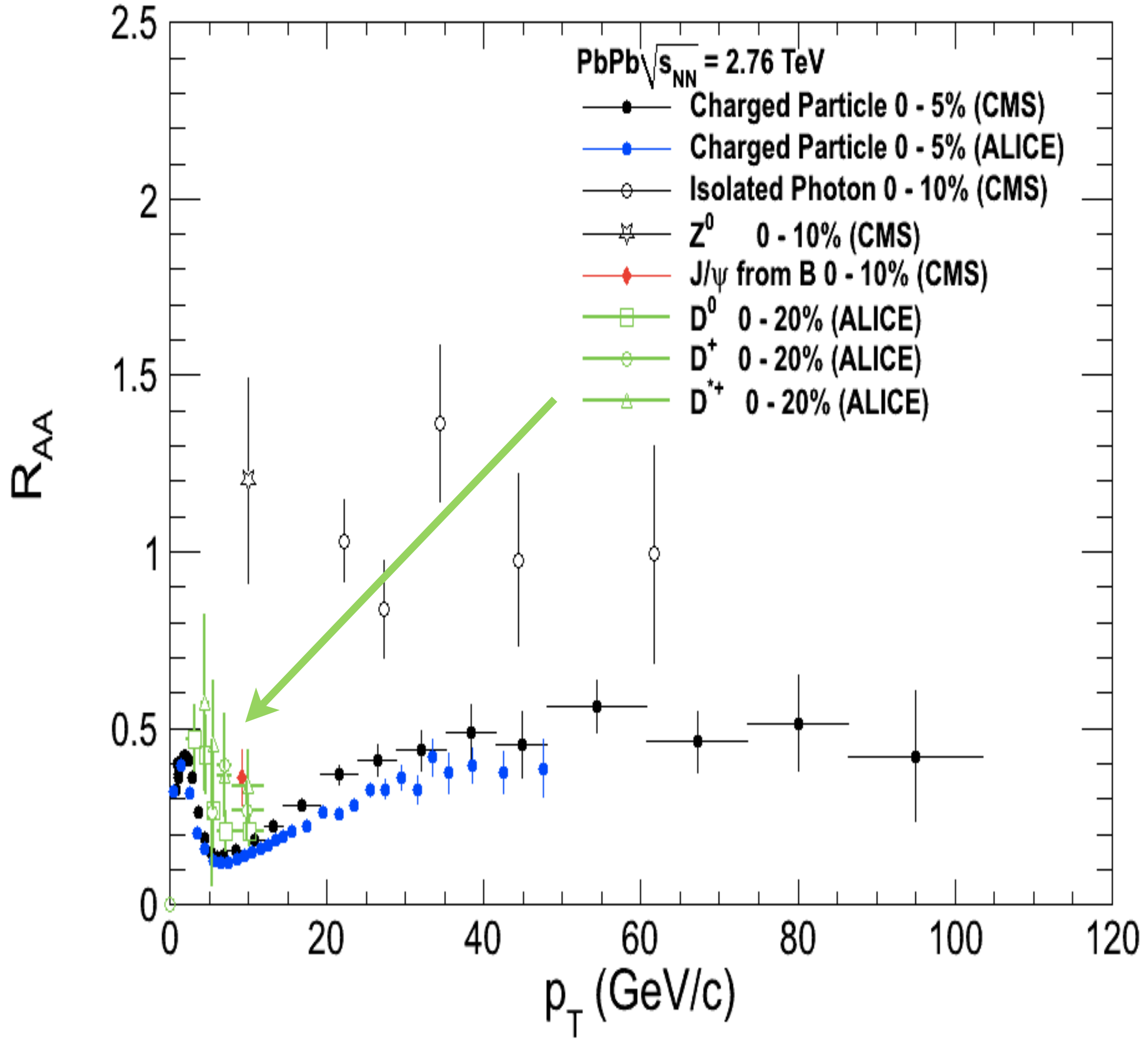
Observables proliferate



Single particle R_{AA}

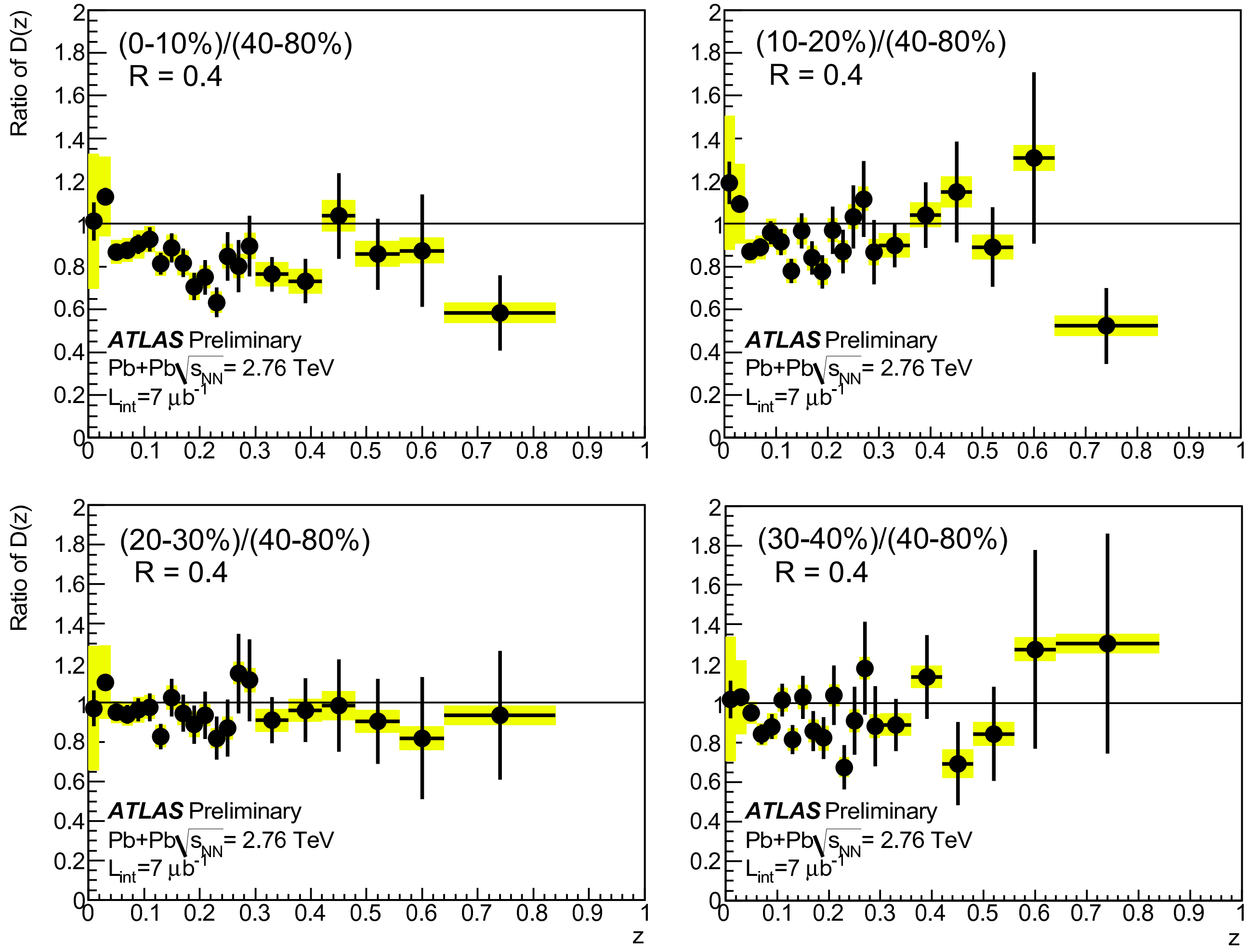
Heavy hadrons are (almost) as much suppressed as light ones
direct photons and Z-bosons are unsuppressed.

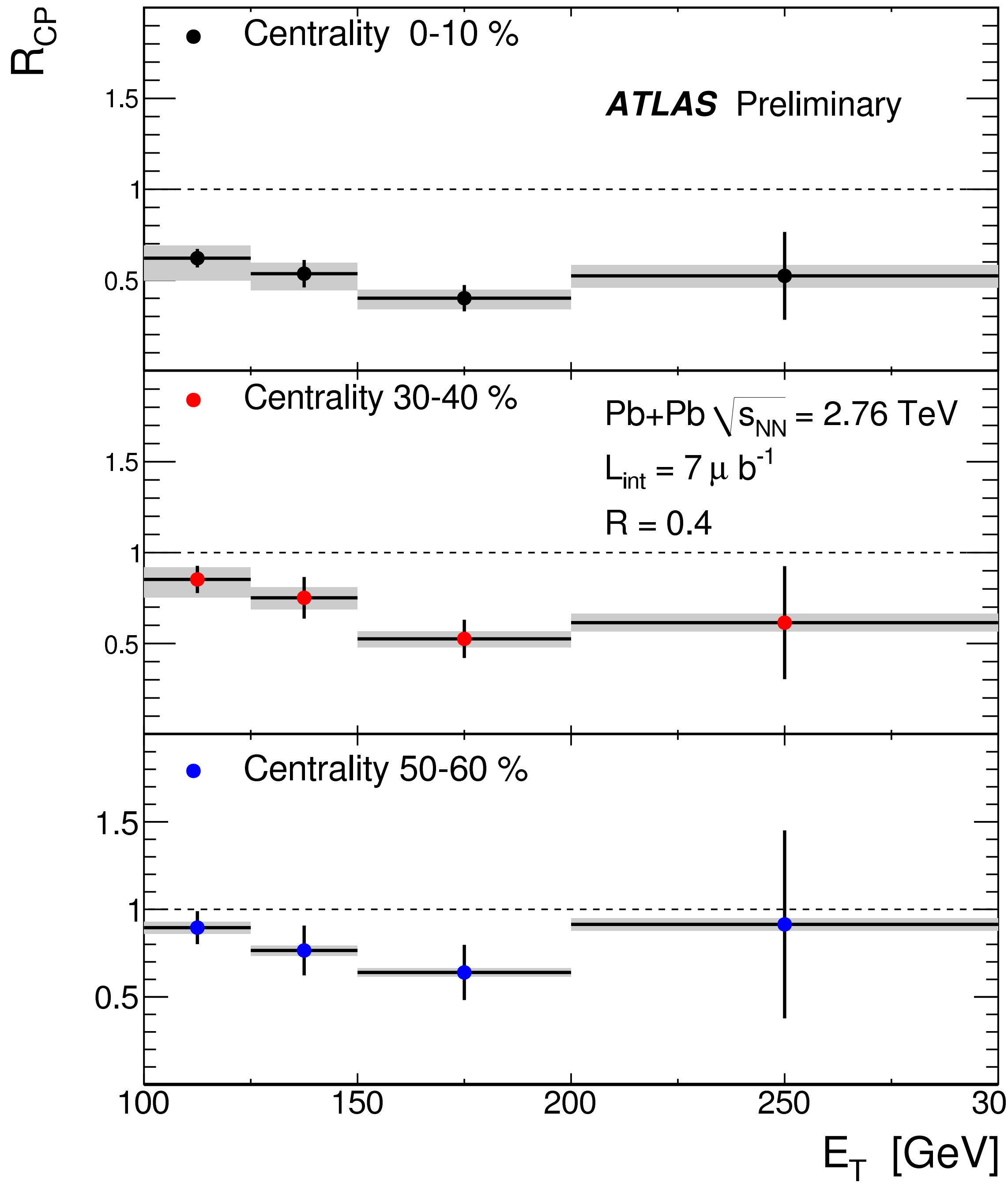




Jet R_{CP}

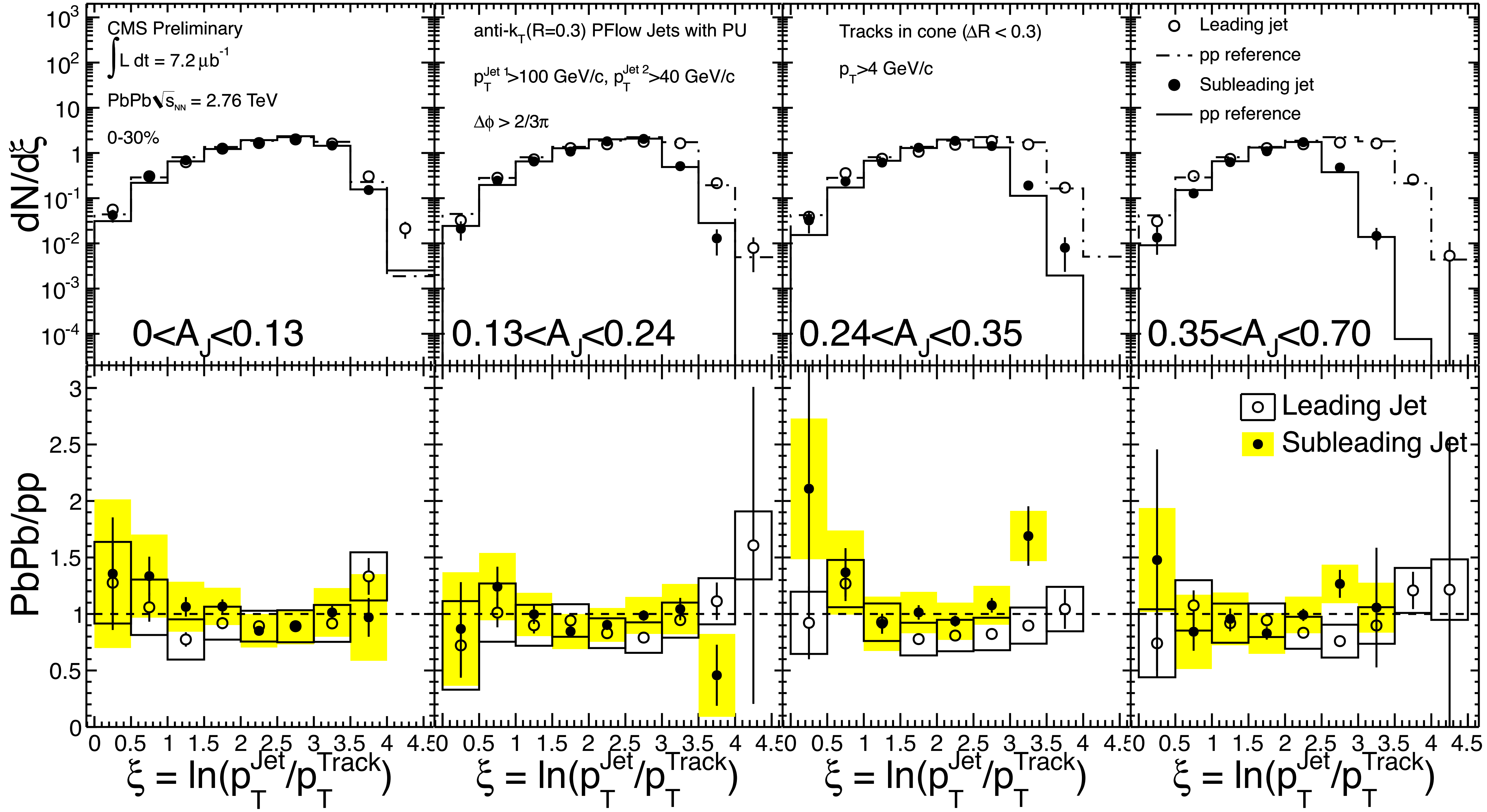
Little, if any, change seen in E_T dependence and in fragmentation function





Jet fragmentation

Degraded jet fragments just like a in-vacuum jet of reduced energy?



For theorists:

Welcome to the hell
of MC event generators
and jet finding algorithms

Lasciate ogni speranza ?

A conundrum

Some theorists (e.g. T. Renk) have argued that fully reconstructed jets are less sensitive as probes of energy loss mechanisms (because of the infrared sensitivity of jet finders) than triggered few particle correlations.

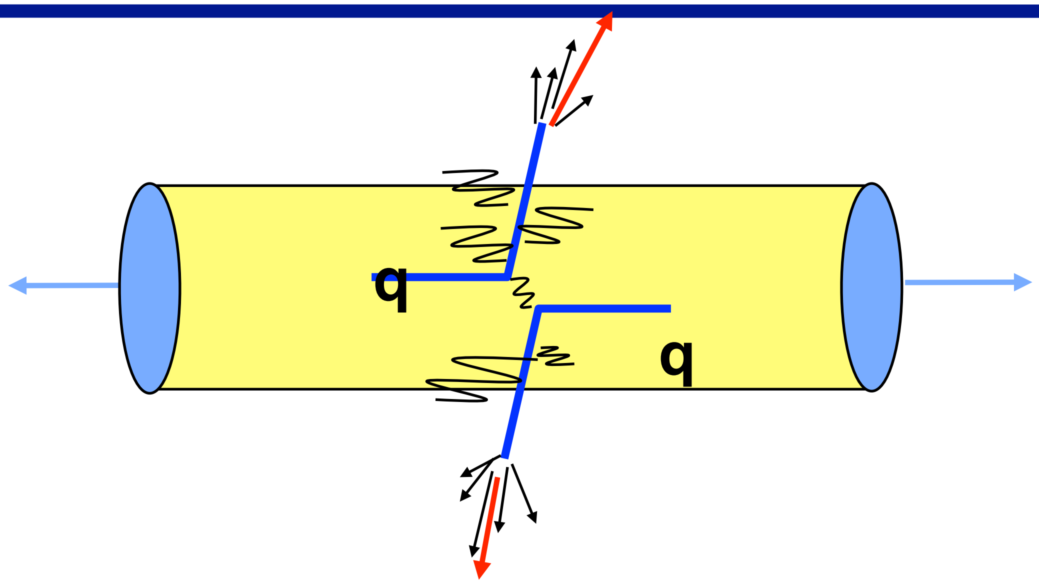
Is this true? If so, does it have to be true, or can jet reconstruction be made “transparent”?

Will “hard probe” jet quenching physics degenerate into comparing theoretical MC with experimental MC?

Not so news item #3

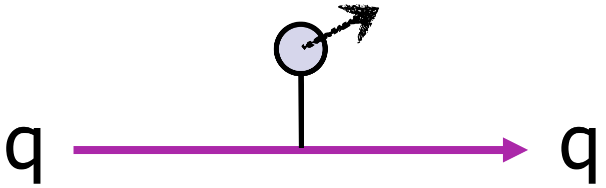
The opaque QGP

Parton energy loss

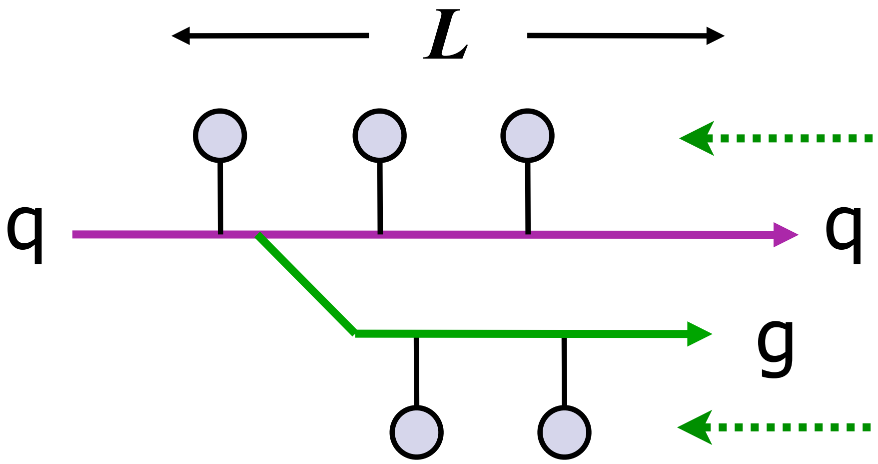


Elastic energy loss:

$$\frac{dE}{dx} = -C_2\,\hat{e}$$



Radiative energy loss:



Scattering centers

⇔ color charges

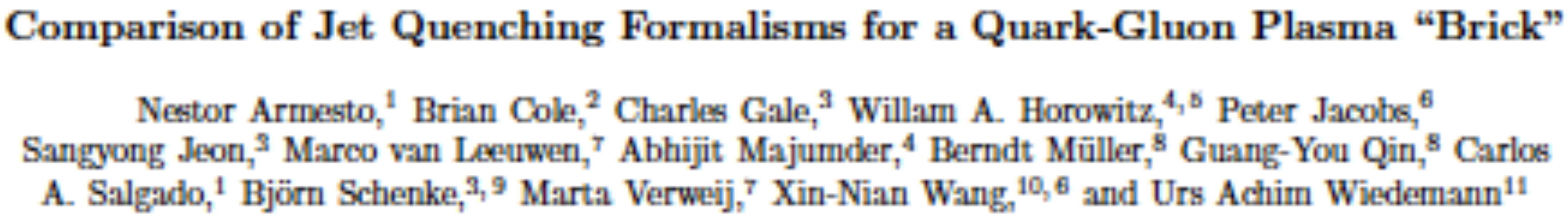
$$\frac{dE}{dx} = -C_2\,\hat{q}\,L$$

$$\hat{q} = \rho\int q^2\,dq^2\,\frac{d\sigma}{dq^2} = \int dx^-\left\langle F_i^{+}(x^-)F^{+i}(0)\right\rangle$$

Core questions

- What is the mechanism of energy loss ?
    - “radiative” = into non-thermal gluon modes
    - “collisional” = directly into thermal plasma modes
- How are radiative and collisional energy loss affected by the structure of the medium (quasiparticles or not)?
    - e.g.: Bluhm et al, 1204.2469; Kolevatov & Wiedemann, 0812.0270
    - AdS/CFT inspired models with weak-strong coupling transition?
- What happens to the lost energy and momentum ?
    - If “radiative”, how quickly does it thermalize = what is its longitudinal momentum (z) distribution ?
    - What is its angular distribution (the jet “shape”) = how much is found in a cone of angular size R ?
- How do the answers depend on the parton flavor ?

TEC-HQM



Comparison of Jet Quenching Formalisms for a Quark-Gluon Plasma "Brick"

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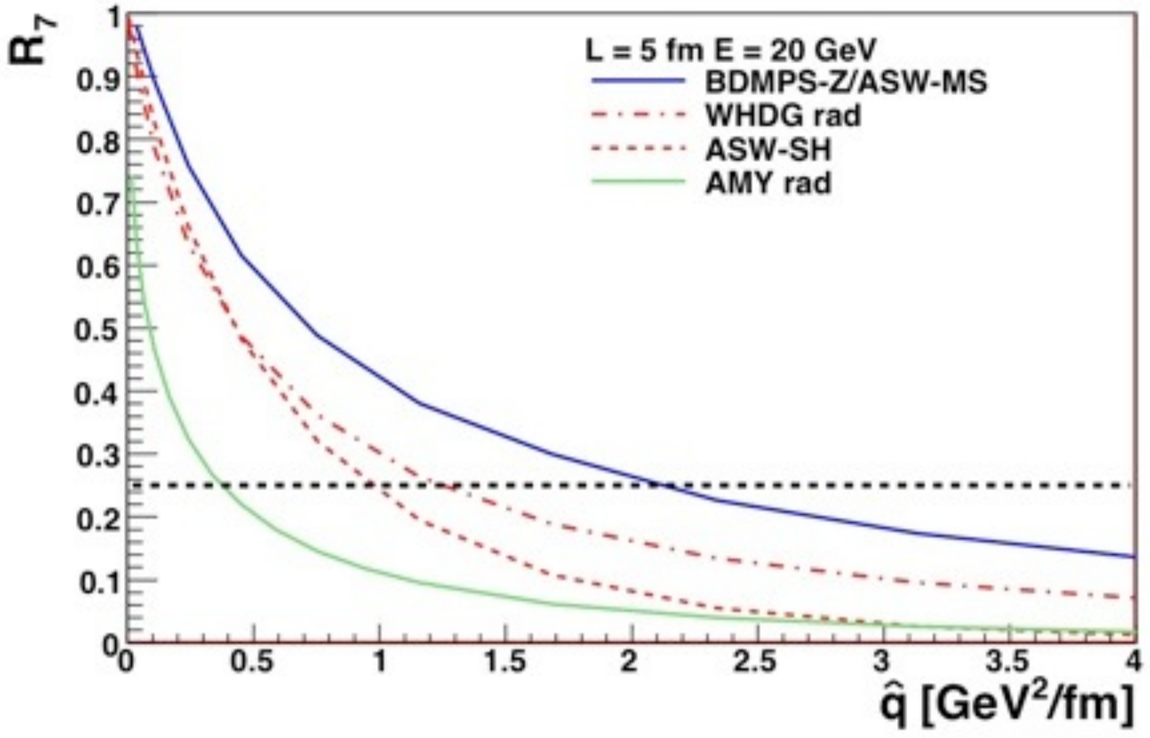
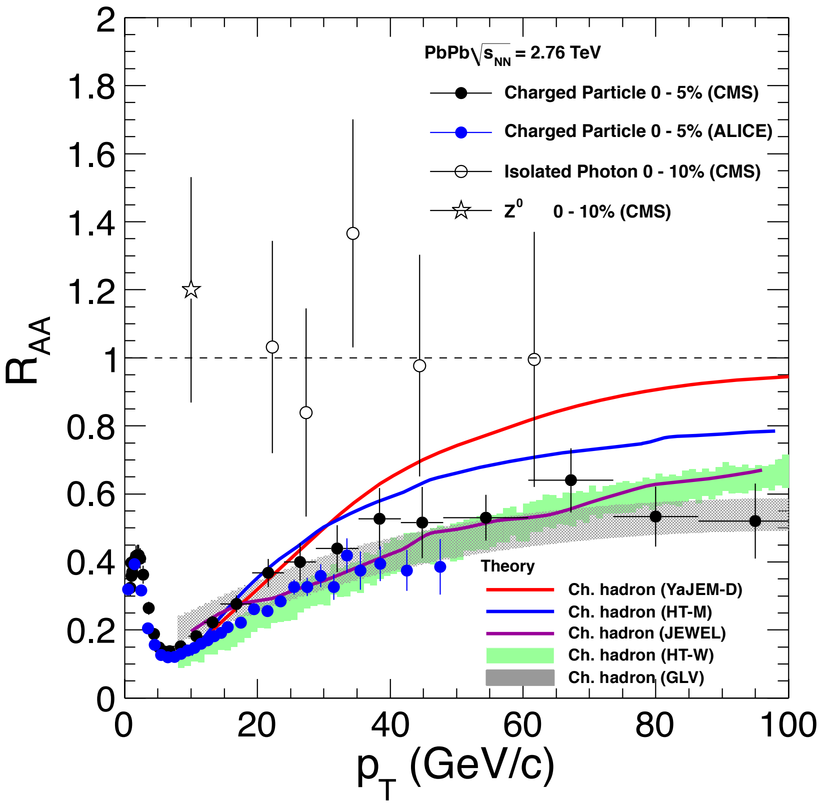
arXiv:1106.1106

Wide differences confirmed for standardized "QCD Brick"

→

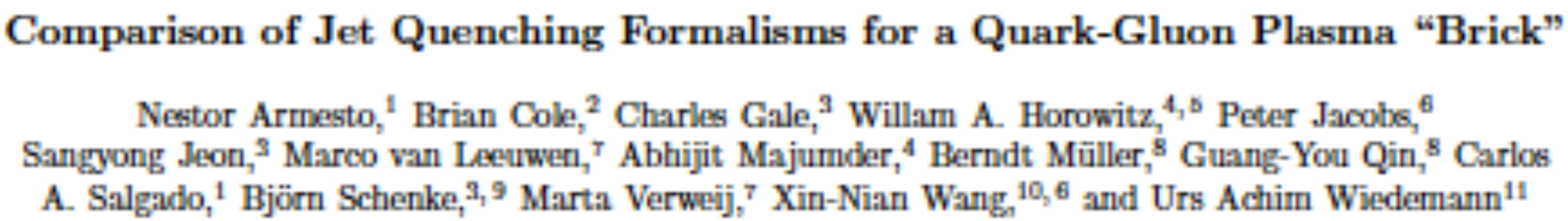
MC schemes and NLO treatment of wide-angle radiation required to reduce inherent uncertainties (*in progress*).





LHC: pQCD theory of jet quenching is alive but needs refinement

TEC-HQM



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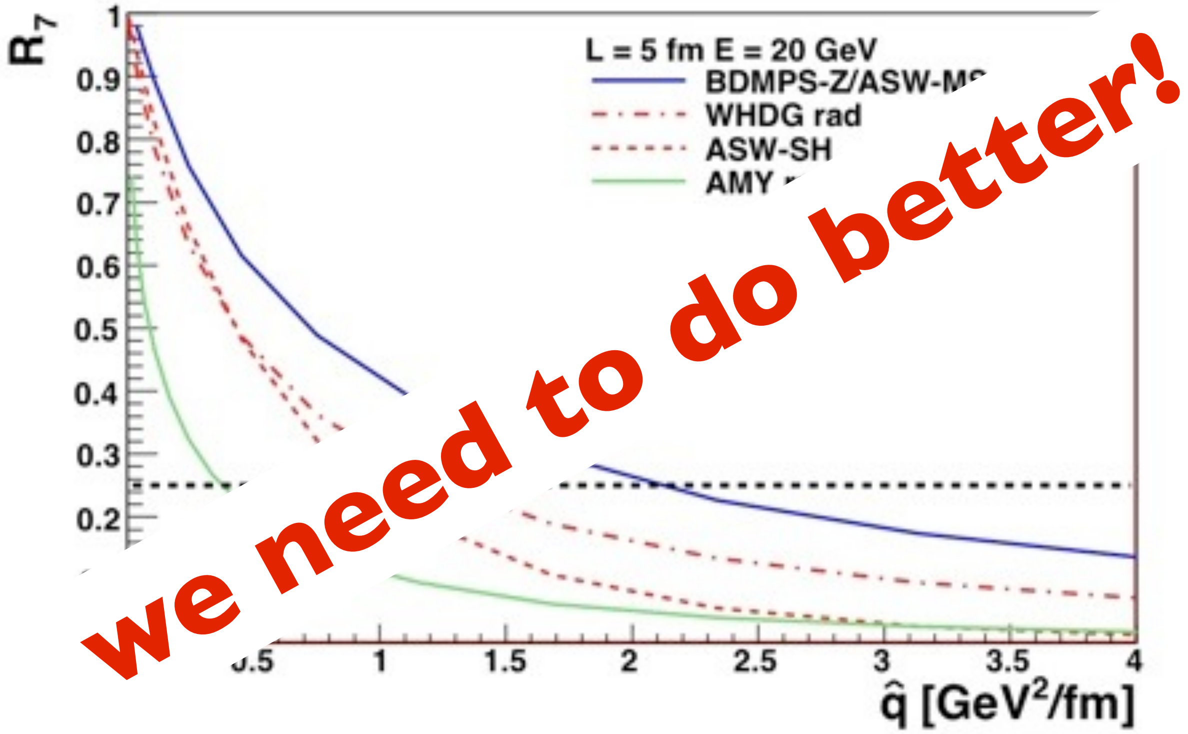
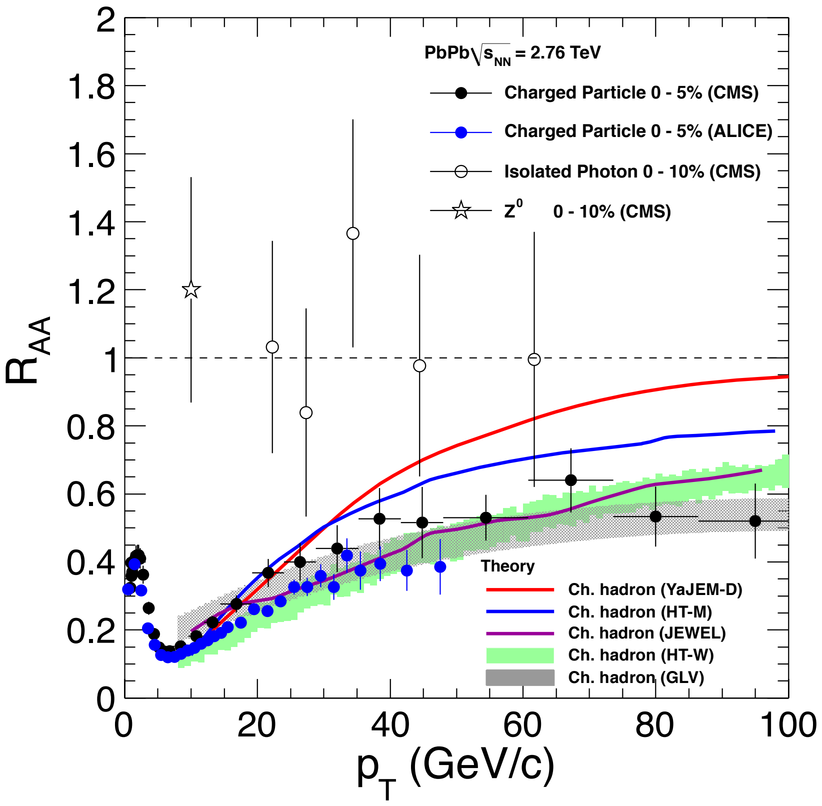


we need to do better!



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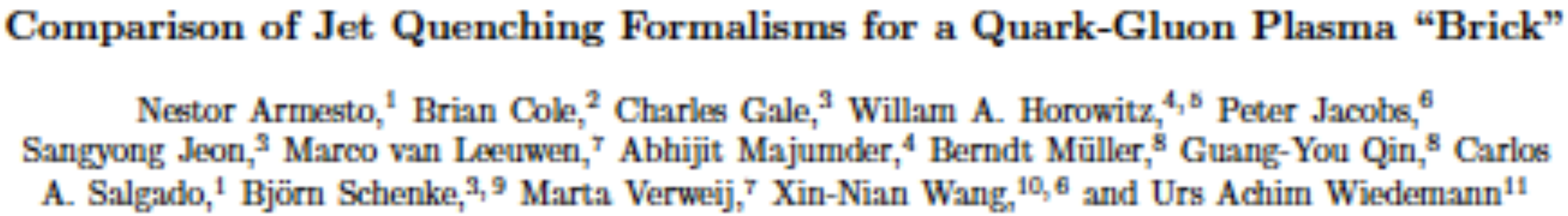

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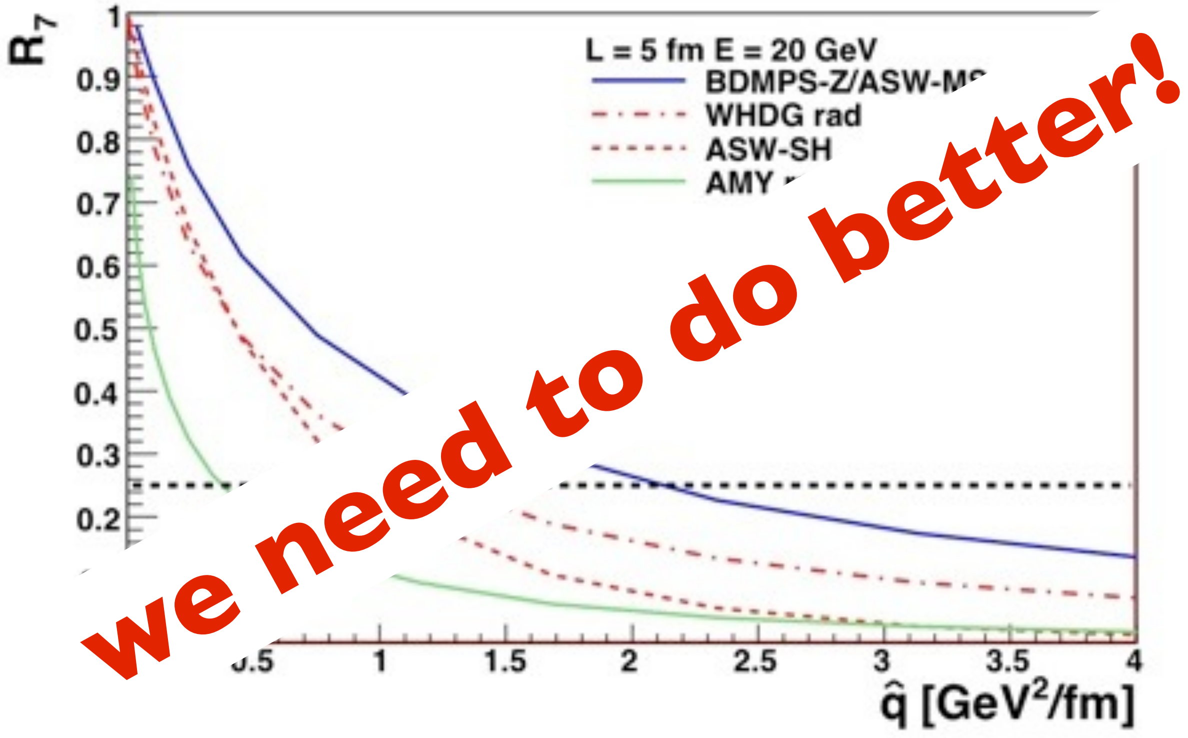

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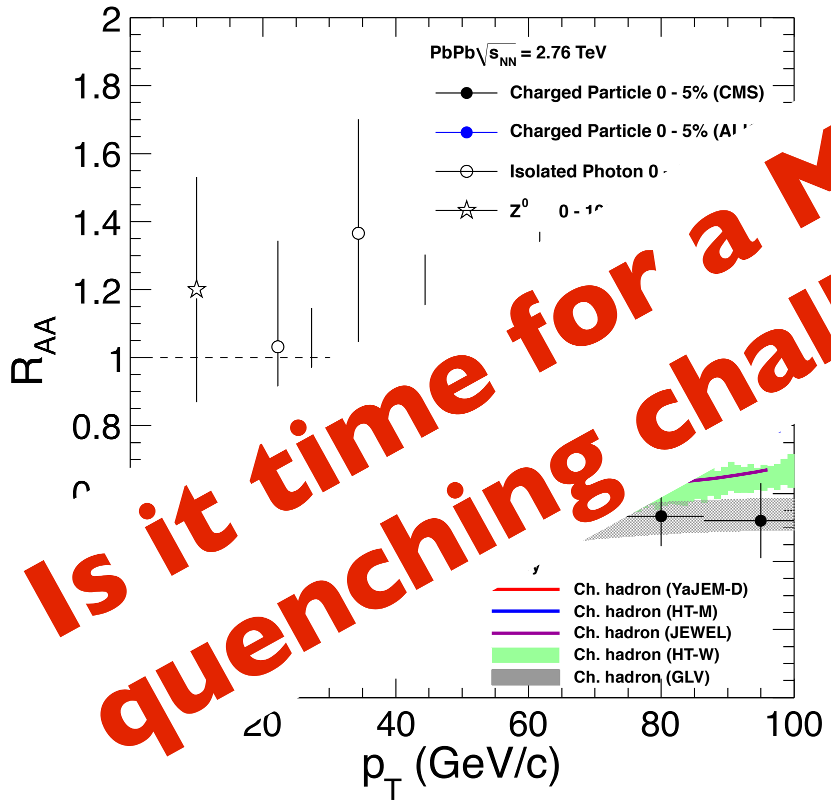
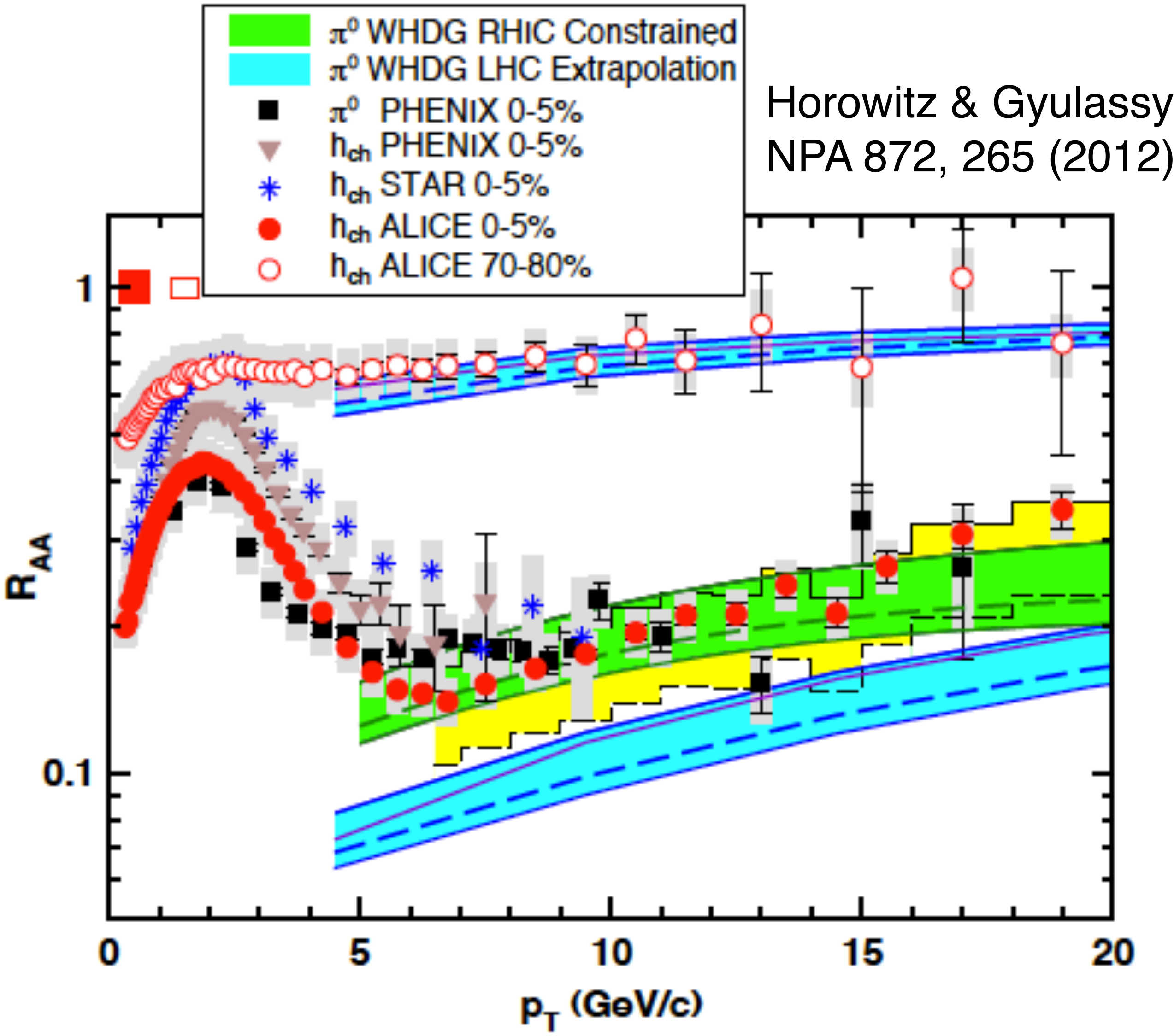


Is it time for a MC jet quenching challenge ?

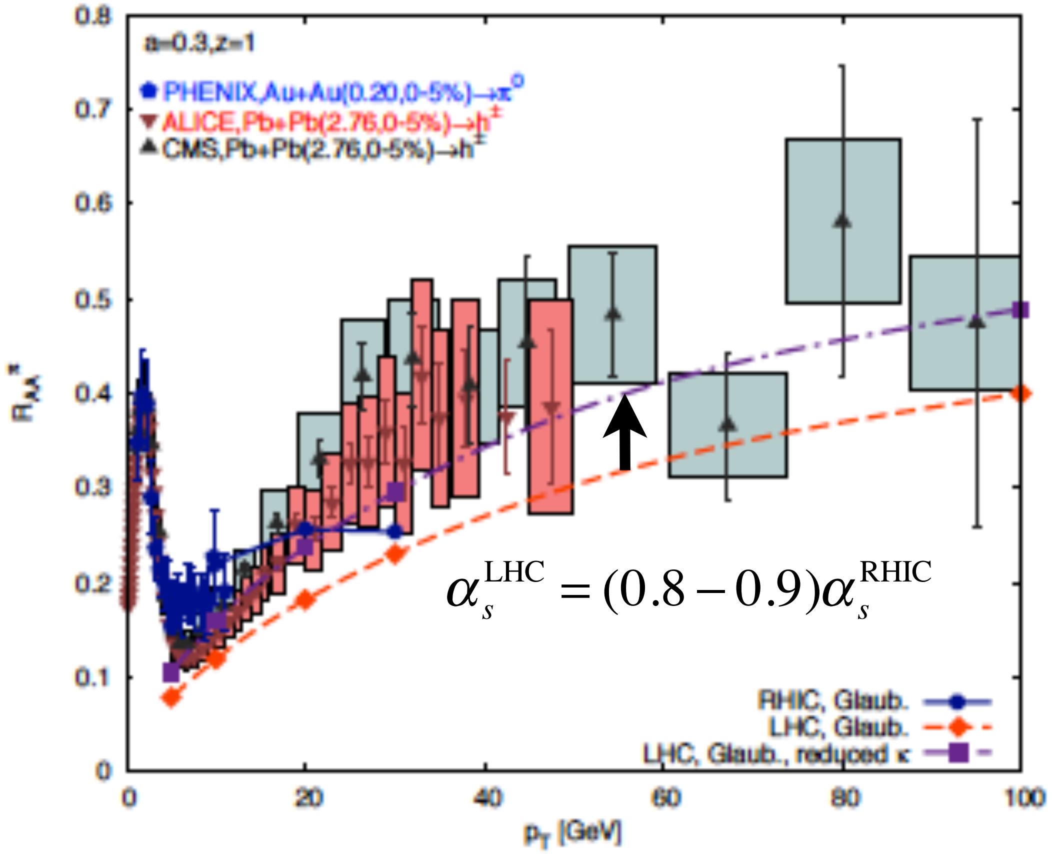
ory of jet quenching is alive but needs refinement

From RHIC to LHC



Horowitz & Gyulassy,
NPA 872, 265 (2012)

Betz & Gyulassy, arXiv:1201.0281



$$\alpha_s^{\mathrm{LHC}} = (0.8 - 0.9)\alpha_s^{\mathrm{RHIC}}$$

In WHDG jet quenching scheme, extrapolation of RHIC R_{AA} overpredicts jet quenching at LHC. Could be explained by (10–20)% reduction in coupling.

Virtuality matters

Virtuality Q² of the parton in the medium controls physics of radiative energy loss:

$$Q^2(L) \approx \max\left(\underset{\substack{\uparrow \\ \text{medium}}}{\hat{q}\,L}, \underset{\substack{\uparrow \\ \text{vacuum}}}{\frac{E}{L}} \right)$$

Weak coupling scenario

RHIC: 20 GeV parton, *L* = 3 fm

$$\hat{q}\,L \approx 4.5\,\mathrm{GeV}^2 \quad \gg \quad \frac{E}{L} \approx 1.5\,\mathrm{GeV}^2$$

Virtuality of primary parton is medium dominated and small enough to “experience” the strongly coupled medium

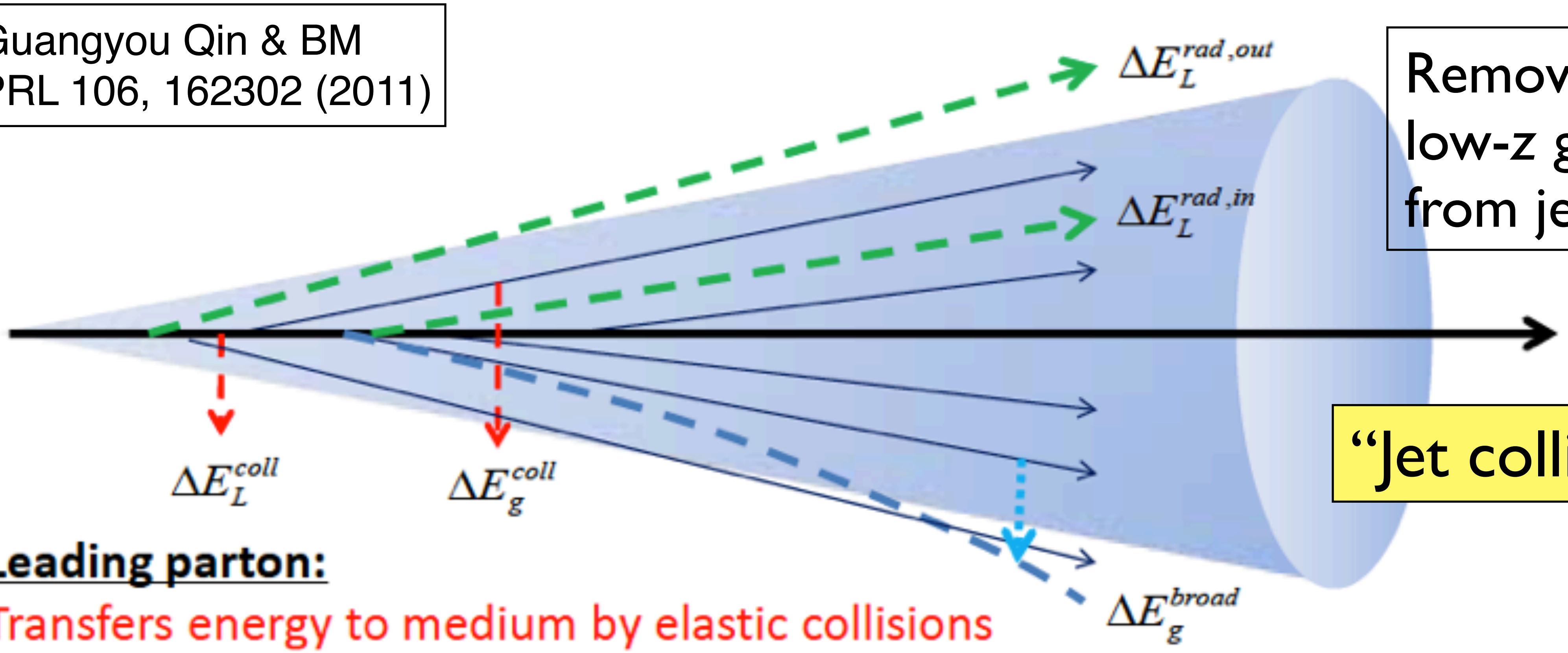
LHC: 200 GeV parton, *L* = 3 fm

$$\hat{q}\,L \approx 9\,\mathrm{GeV}^2 \quad < \quad \frac{E}{L} \approx 13\,\mathrm{GeV}^2$$

Virtuality of primary parton is vacuum dominated and only its gluon cloud “experiences” the strongly coupled medium

Parton shower in matter

Guangyou Qin & BM
PRL 106, 162302 (2011)



Removes mostly low-z gluons from jet cone

"Jet collimation"

Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons scattering in the medium (*inside* and *outside* jet cone)

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Radiated gluons (*vacuum* & *medium-induced*):

Transfer energy to medium by elastic collisions

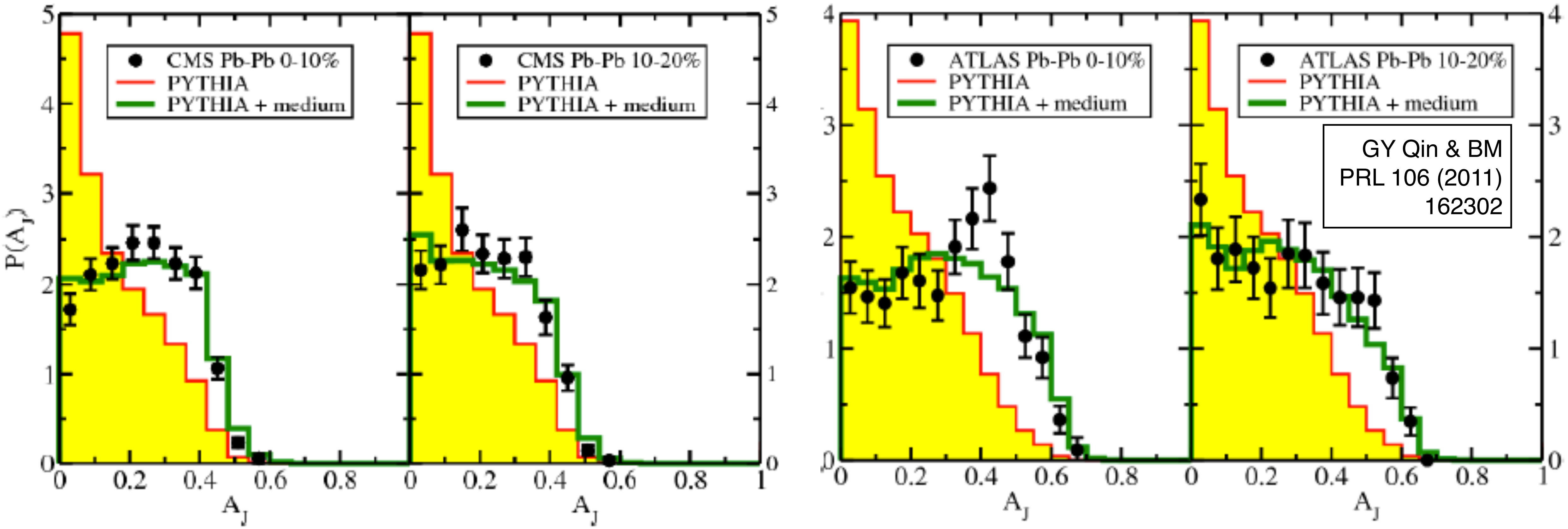
Be kicked out of the jet cone by multiple scatterings after emission

$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Di-jet asymmetry

CMS data

ATLAS data



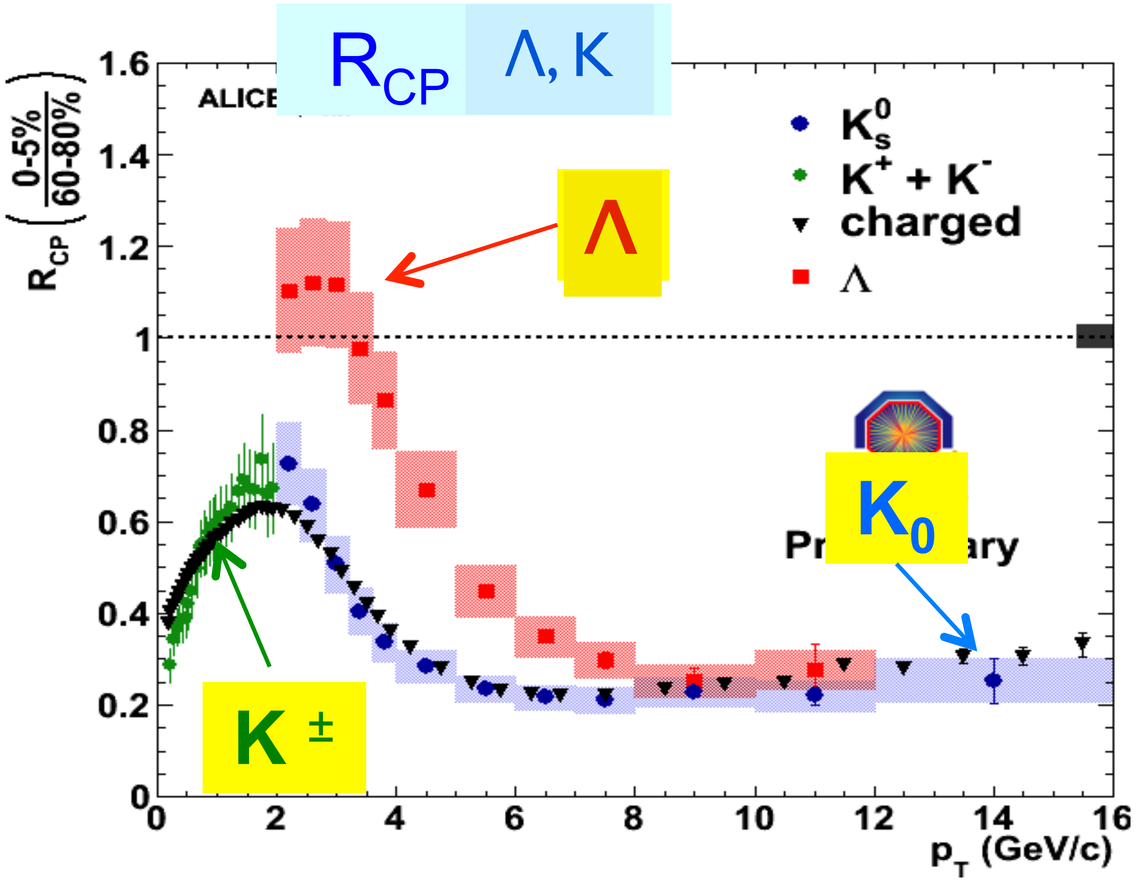
GY Qin & BM
PRL 106 (2011)
162302

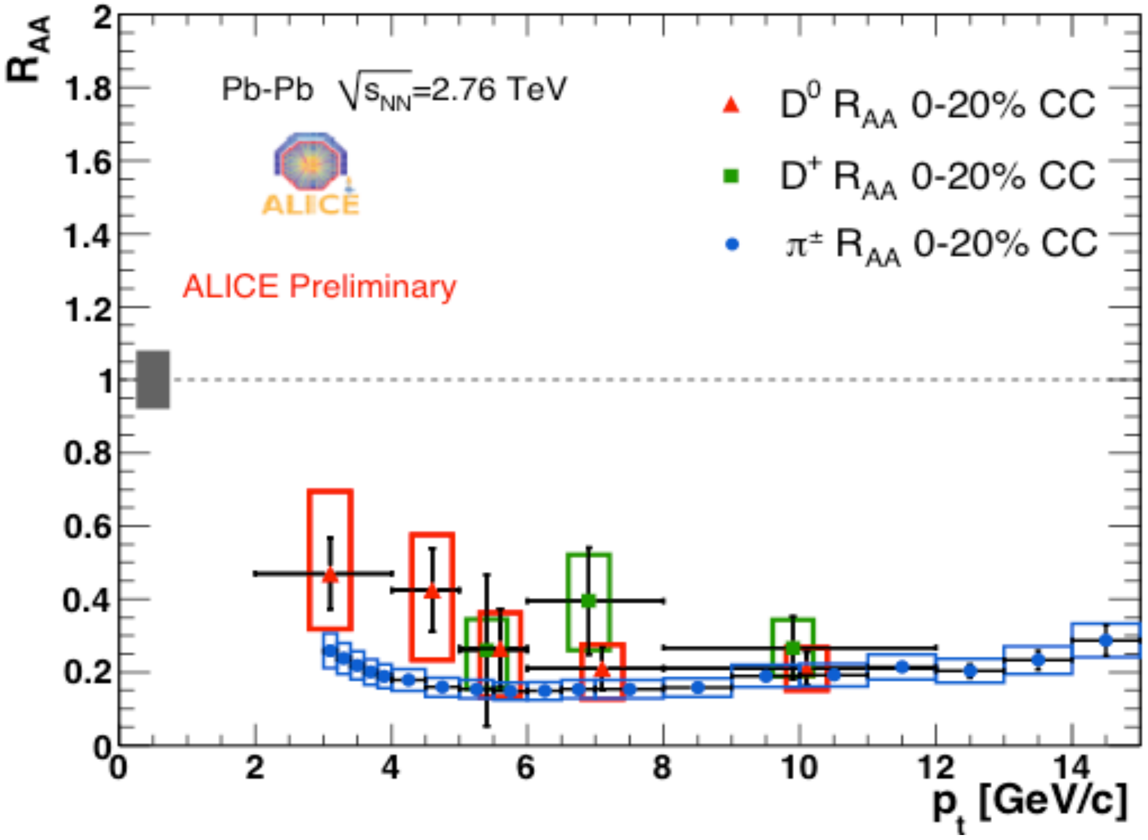
ATLAS and CMS data differ in cuts on jet energy, cone angle, etc; results depend somewhat on precise cuts and background corrections.
Fits of CMS and ATLAS data require ~20% different parameters.
Several other calculations using pQCD physics input also fit the data.

General conclusion: *pQCD jet quenching can explain these data.*

Flavor dependence

R_{AA} of all hadrons (including D-mesons) appear to converge at $p_T > 10$ GeV.





Will this continue to be true for b-quarks ?

Heavy work ahead...

"You know what I hate about this place?
The heavy quarks in the liquid I serve."

News item #4

Color screening:

The essence of “**Plasma**”!

Plasma screening

- Plasma: An globally neutral state of matter with mobile charges

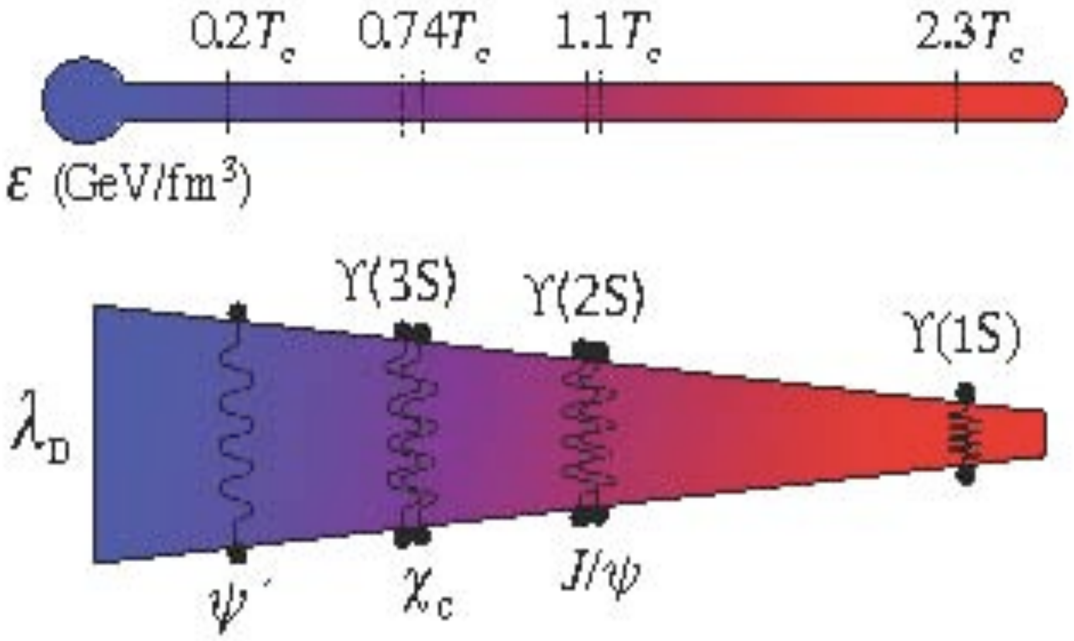
- Interactions among charges of many particles spread charge over a characteristic (Debye) length ➠ (chromo-) electric screening

- Strongly coupled plasmas: Only few particles in Debye sphere ➠ Nearest neighbor correlations ↔ liquid-like properties

- *Test* QGP *screening with heavy quark bound states*
  Do they survive? Which ones?

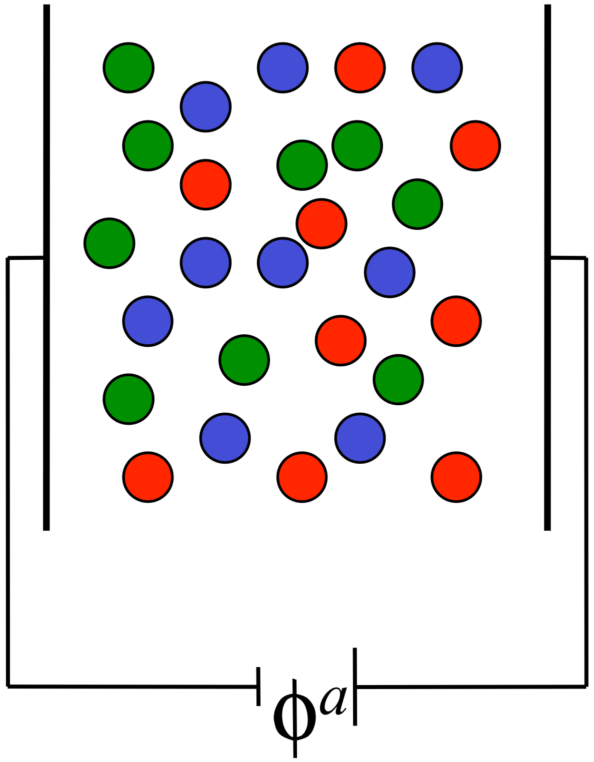
- Ideal system: Upsilon states

- Do residual correlations enhance recombination?

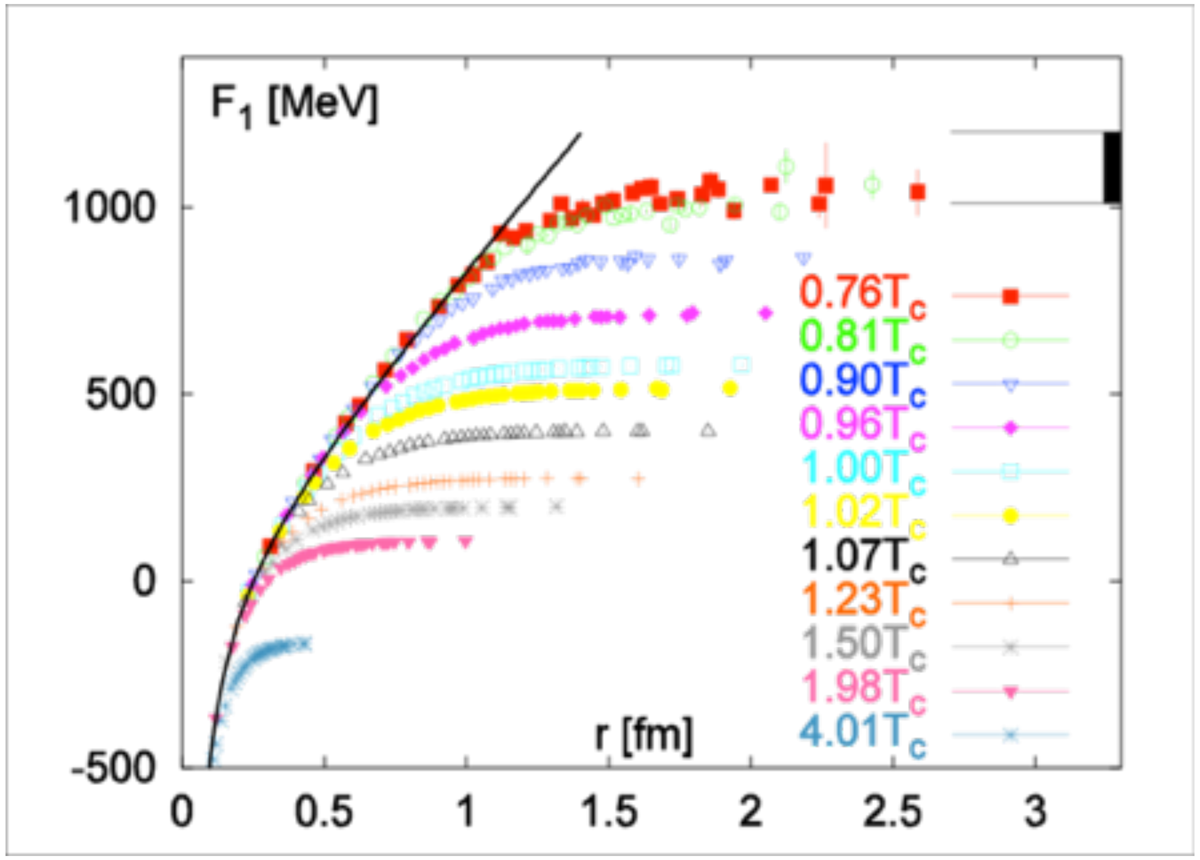


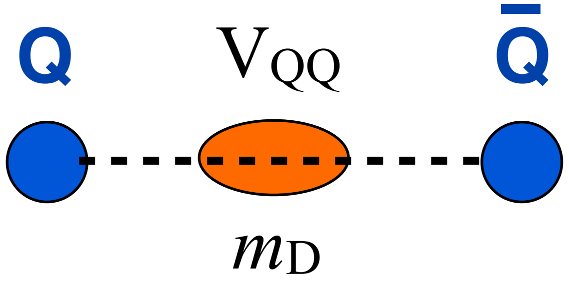
In the good old days...

... life seemed so simple:



Lattice QCD





$m_D \sim gT$

The real story...

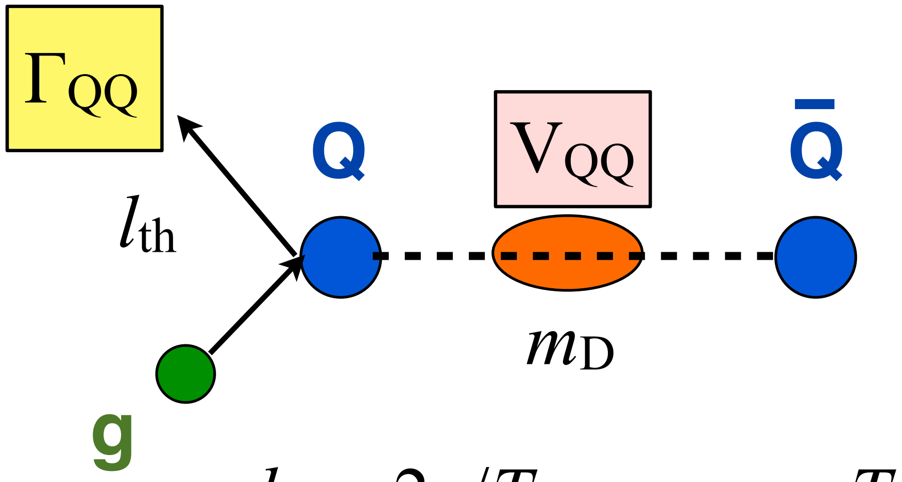
...is more complicated that just *m*D.

Q-Qbar bound state interacts with medium elastically and inelastically!

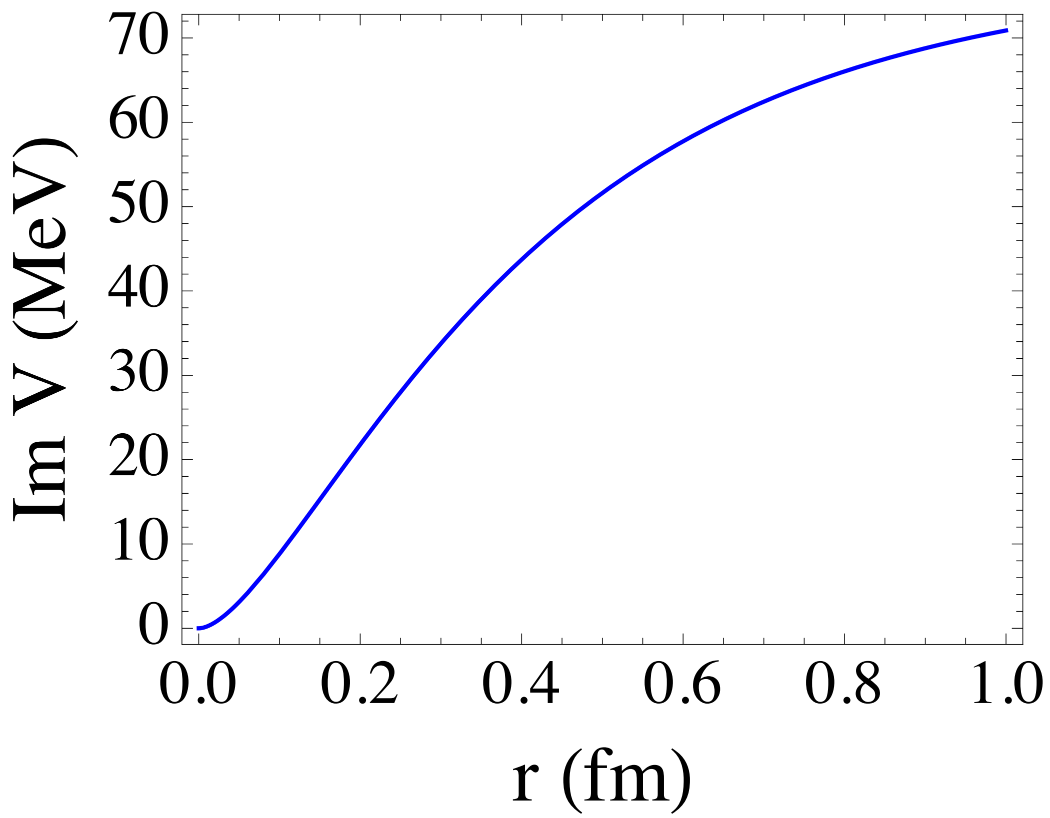
$$i\hbar\frac{\partial}{\partial t}\Psi_{Q\bar{Q}}=\left[\frac{p_Q^2+p_{\bar{Q}}^2}{2M}+V_{Q\bar{Q}}-\frac{i}{2}\Gamma_{Q\bar{Q}}+\eta\right]\Psi_{Q\bar{Q}}$$

Strickland, arXiv:1106.2571, 1112.2761;
Akamatsu & Rothkopf, arXiv:1110.1203

➠ heavy-Q energy loss and Q-Qbar suppression cannot be separated

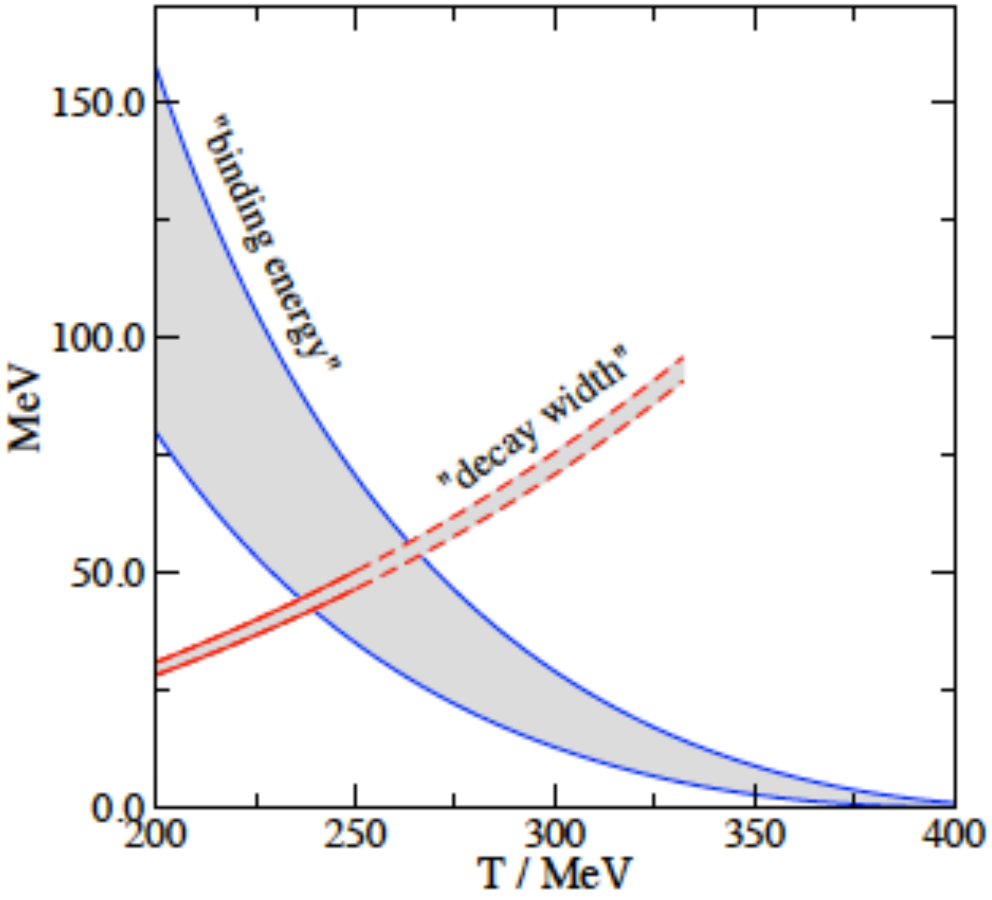


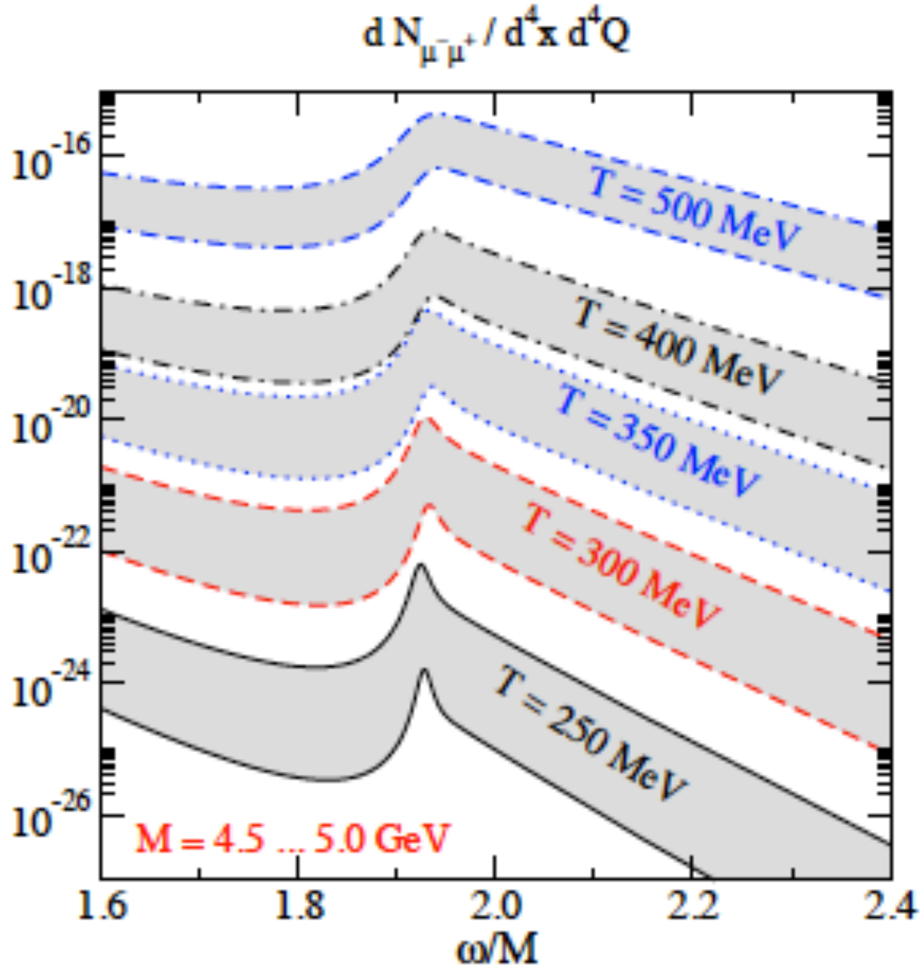
$l_{th} \sim 2\pi/T, \quad m_D \sim gT$



ϒ melting revisited

Decreasing QQ binding due to screening and increasing width due to thermal gluon absorption lead to gradual melting of quarkonium states [here ϒ(1s)]. See M. Laine, arXiv:1108.5965. Similar to ρ^0 melting at SPS?

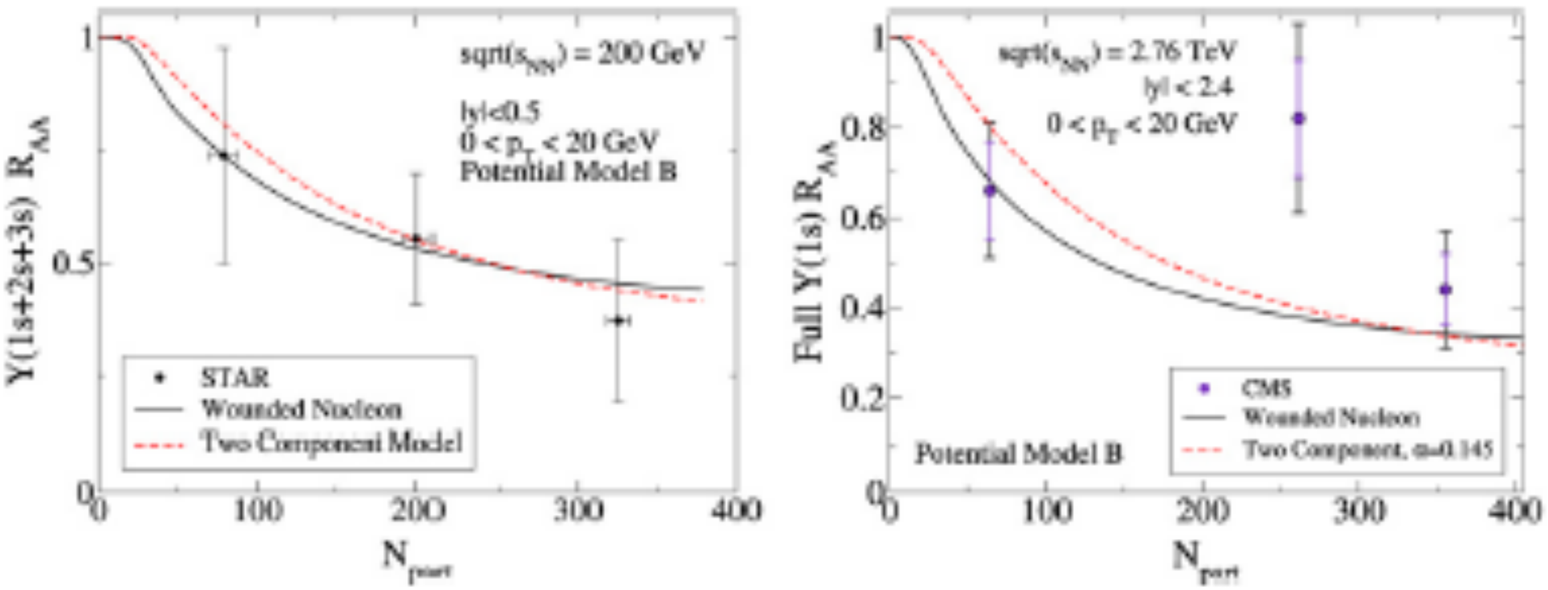




State of art

Tour de force calculation of ϒ suppression by M. Strickland, PRL 107, 132301 (2011):

- Re(V), Im(V) in anisotropic HTL / NRQCD + T-dep. confining pot.
- Schrödinger equation for ϒ states ➠ E_{QQ} , Γ_{QQ}
- Anisotropic (viscous) hydrodynamics for medium evolution
- Time integrated suppression factor: $R_{AA} = \exp\left(- \int_{\tau_{\mathrm{form}}}^{\tau_f} \Gamma_{QQ}(\tau, x_\perp, \xi) d\tau \right)$



Borghini & Gombeaud, arXiv - 1109.4271:

Treat dipole transitions between QQ states induced by thermal gluons dynamically.

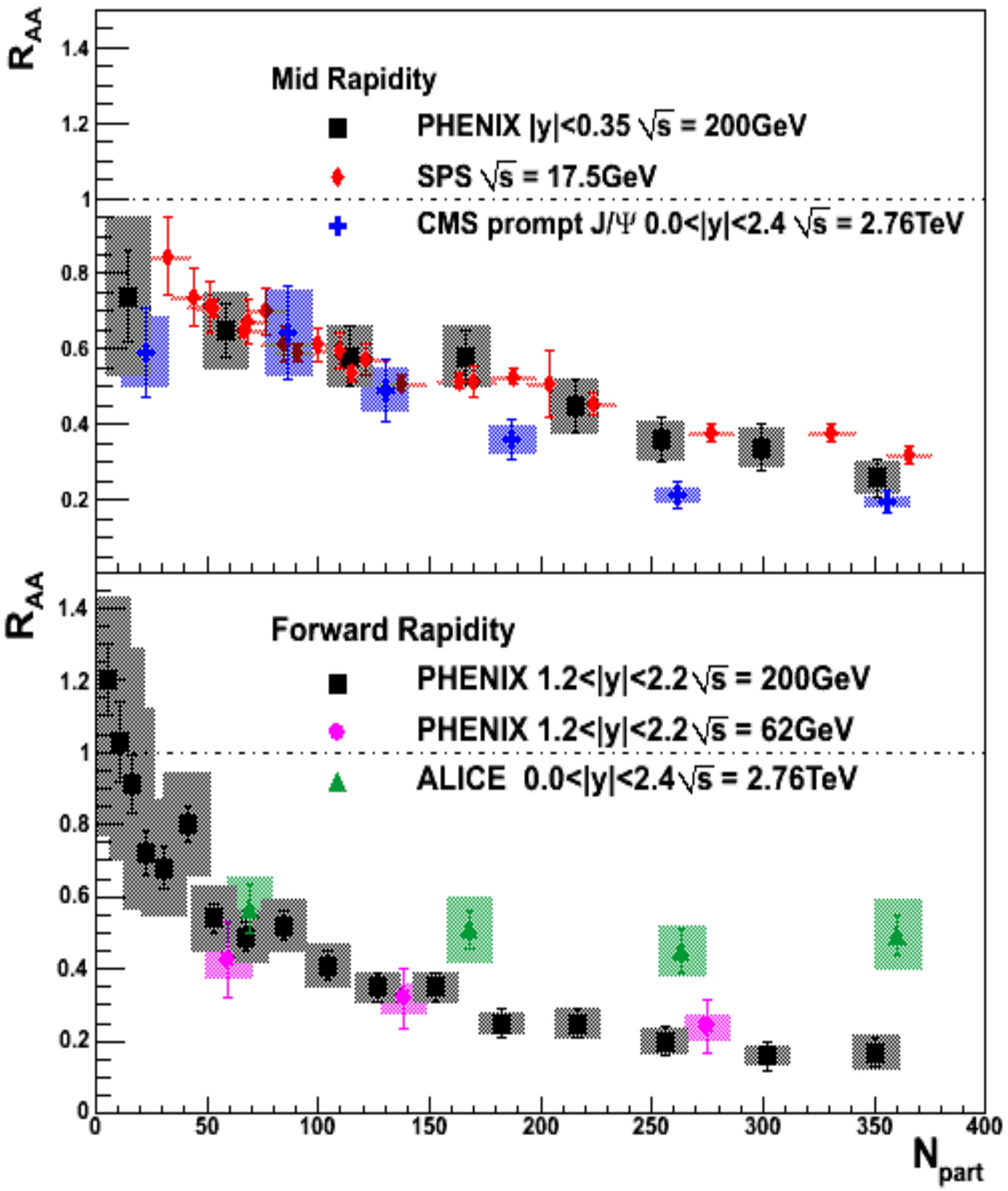
J/ψ suppression

Bewildering observations:

RHIC - more suppression at forward rapidity

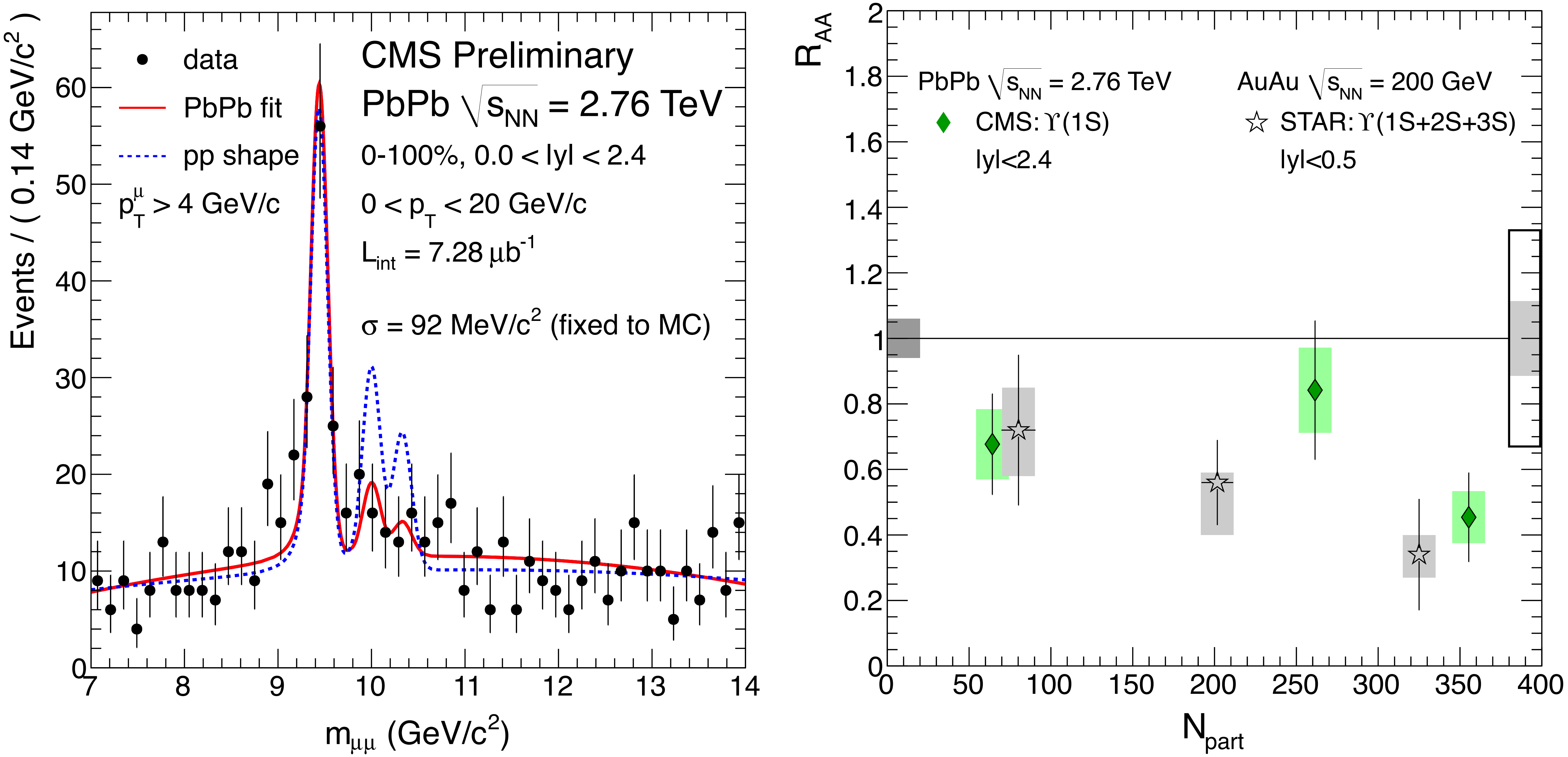
LHC - more suppression at central rapidity

Same suppression at SPS and RHIC at midrapidity



ϒ suppression

Differential suppression of ϒ states clearly observed



News item #5

The shining QGP

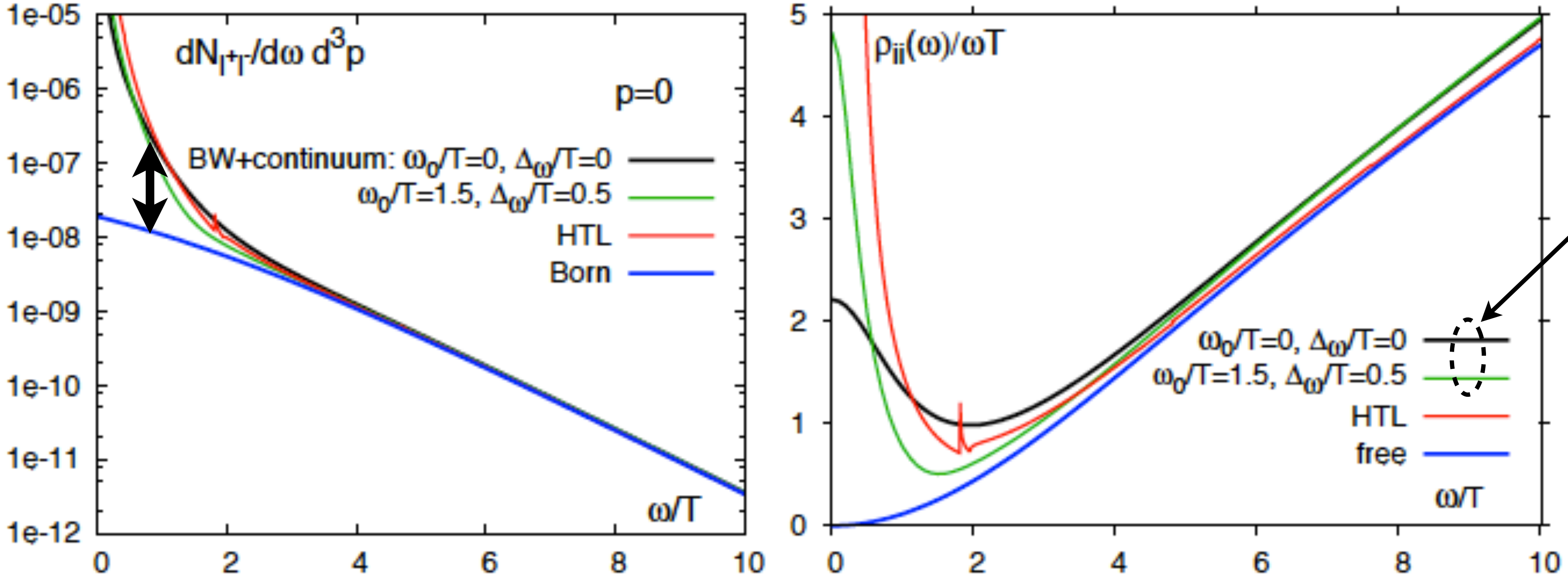
Photons & lepton pairs

- Theory in relatively good shape; no strong final state interactions!

$$\frac{dN_{\ell^+\ell^-}}{d^4x\,d^4Q} = \frac{e^4}{6(2\pi)^4 Q^2}\left(1+2m^2/Q^2\right)\left(1-4m^2/Q^2\right)g_{\mu\nu}\Pi^{\mu\nu}(Q)$$

with $\Pi^{\mu\nu}(Q) = \int d^4x\, e^{iQ\cdot x}\left\langle j^\mu(x)\, j^\nu(0)\right\rangle,\qquad Q=(\omega,\vec{q})$

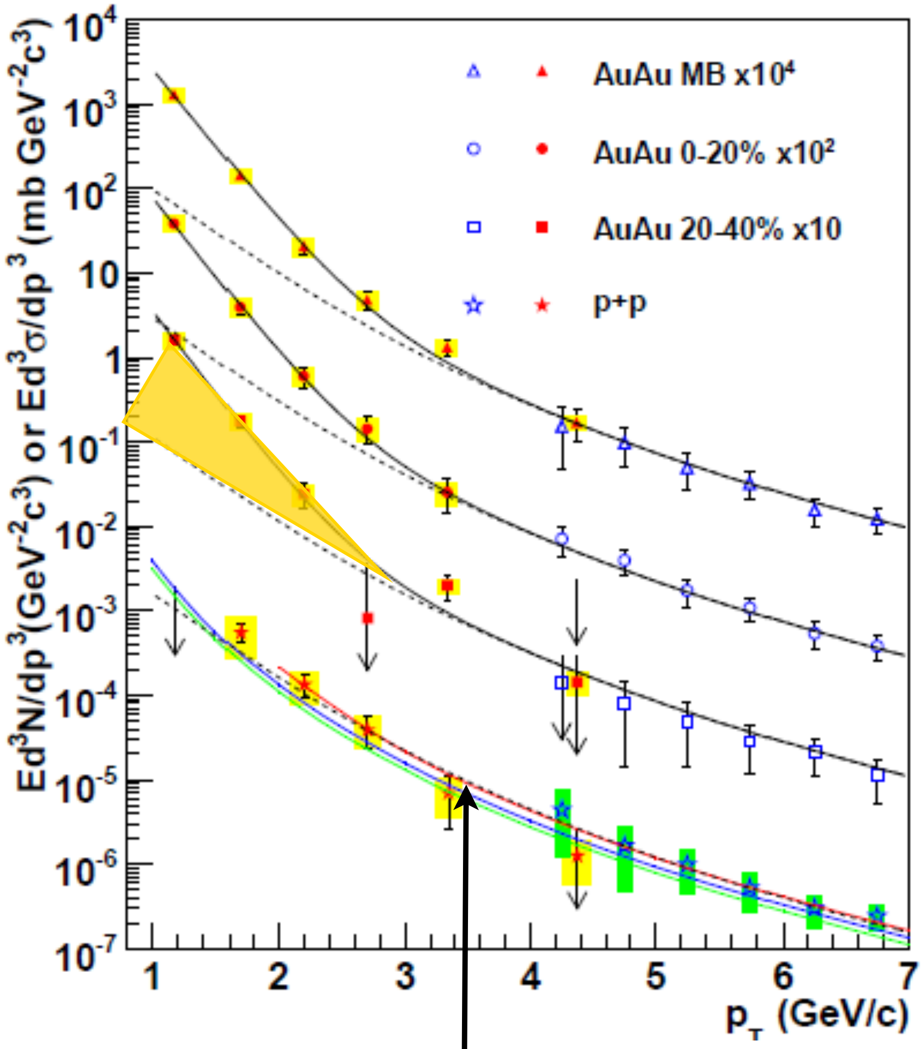
- Lattice results show enhancement for ω < 2T, but less than HTL



Quenched LQCD

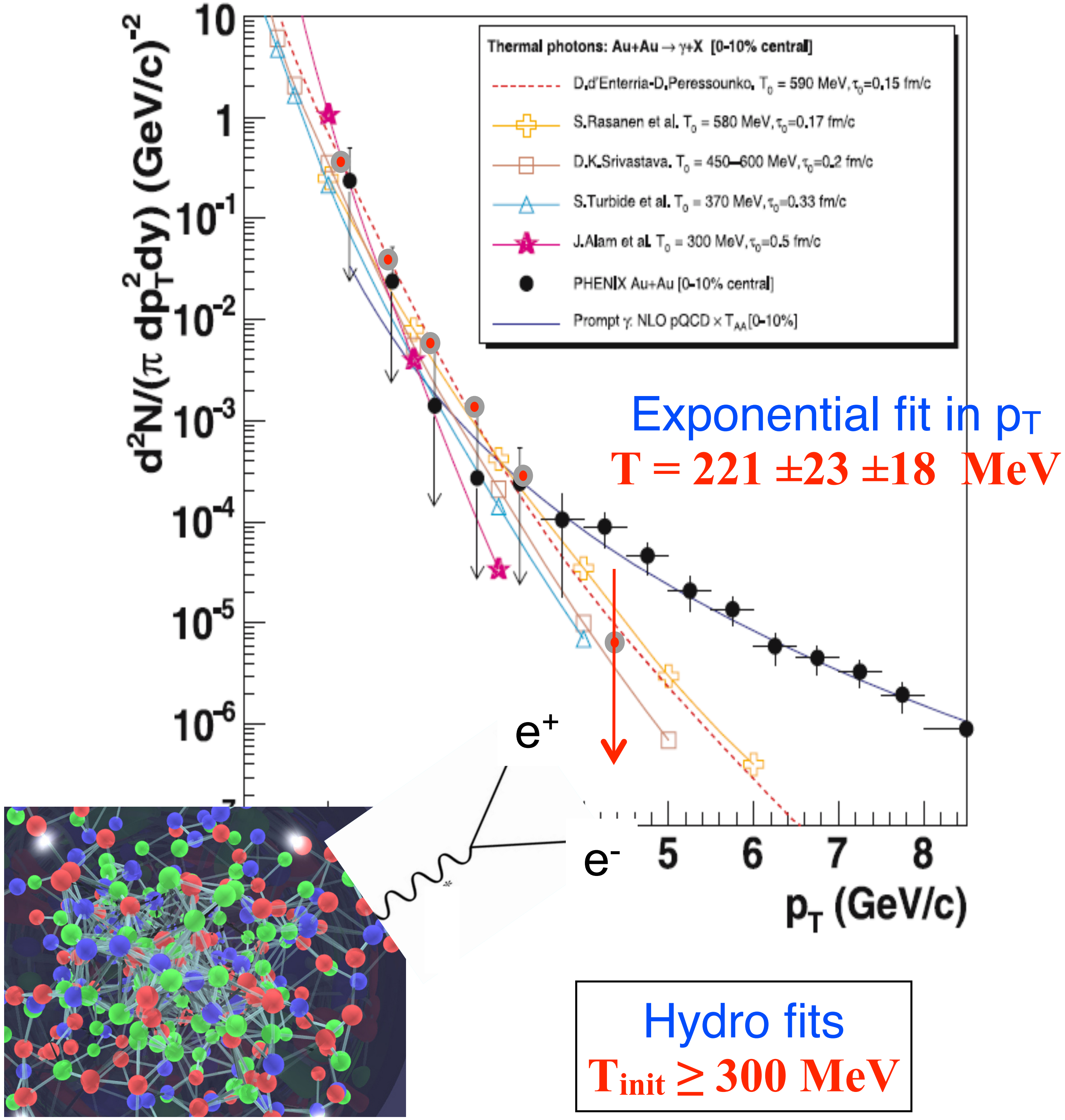
H.T. Ding et al.
PRD 83, 034504
(2011)

Electroweak probes



PRL 104, 132301 (2010)

pQCD photon spectrum agrees with p+p data



Exponential fit in p_T

T = 221 ±23 ±18 MeV

Hydro fits

$T_{init} \geq 300$ MeV

Challenges

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- The theory of jet quenching must become quantitative
  - *Validation of pQCD based jet MC's & NLO theory*
  - *Kinematic span RHIC − LHC is crucial for model discrimination; RHIC provides better medium-vacuum virtuality match*
  - *Do reconstructed jets really provide additional information?*
  - *Sensitivity of jet transport coefficients to medium structure?*

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- Electroweak probes:
    - *High statistics, low background data needed*

The Manifesto revisited

"To resolve and study a medium of deconfined quarks and gluons at short spatial scales, hard probes are essential and have to be developed into as precise tools as possible." [Lourenço & Satz, HP2004]

^ ^

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As of 2012, **hard probes have yet to fulfill their promise**.

In the case of jets and quarkonia, the study is mainly theory limited. Given good data, we do not yet know how to reliably extract q̂ and ê. We do not yet know which jet observables are most sensitive to the physics we want to learn.

A quantitative theory of quarkonium suppression is just emerging. In the case of photons and dileptons, better data are needed.

But progress is being made, as HP2012 promises to show in abundance, and the goal appears ultimately reachable.

All's well that ends well.

William Shakespeare

All’s well that ends well.

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If all is not well, it’s not the end!

Indian movie theme, quoted after Helmut Satz