Exploration of Hot QCD Matter

The Next Decade

Berndt Müller

CERN Theory Institute **(HIC10)**
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Phases of exploration

Phases of exploration

Smoking Gun
Phase

Phases of exploration

Smoking Gun
Phase

Charting
the Territory
Phase

Phases of exploration

Charting the Territory Phase

Smoking Gun Phase

Tourist Attraction Phase

Phases of exploration

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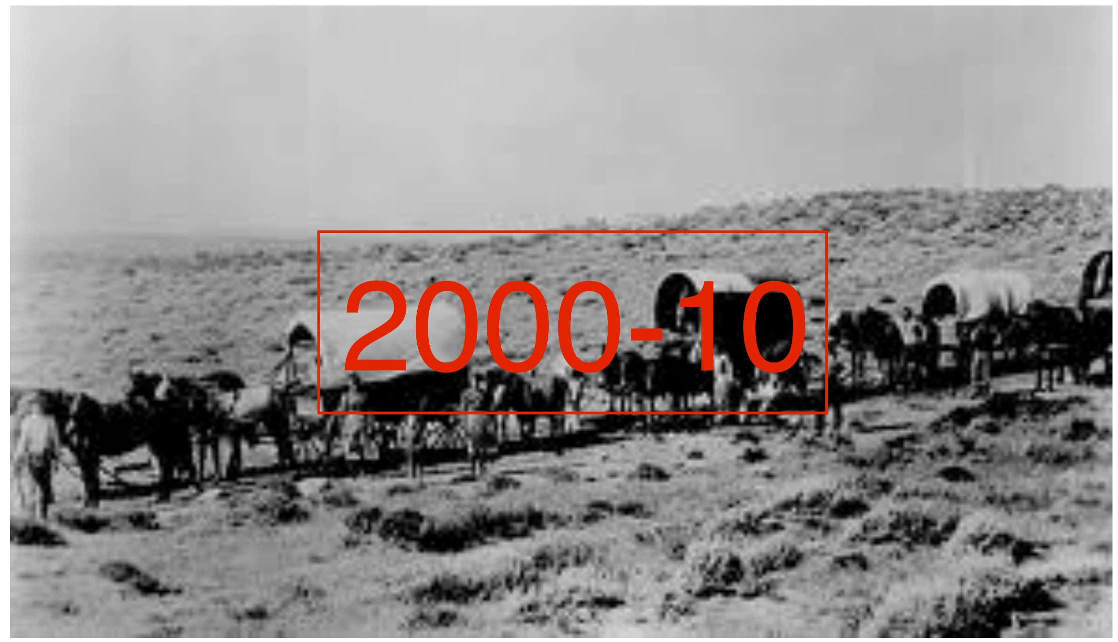

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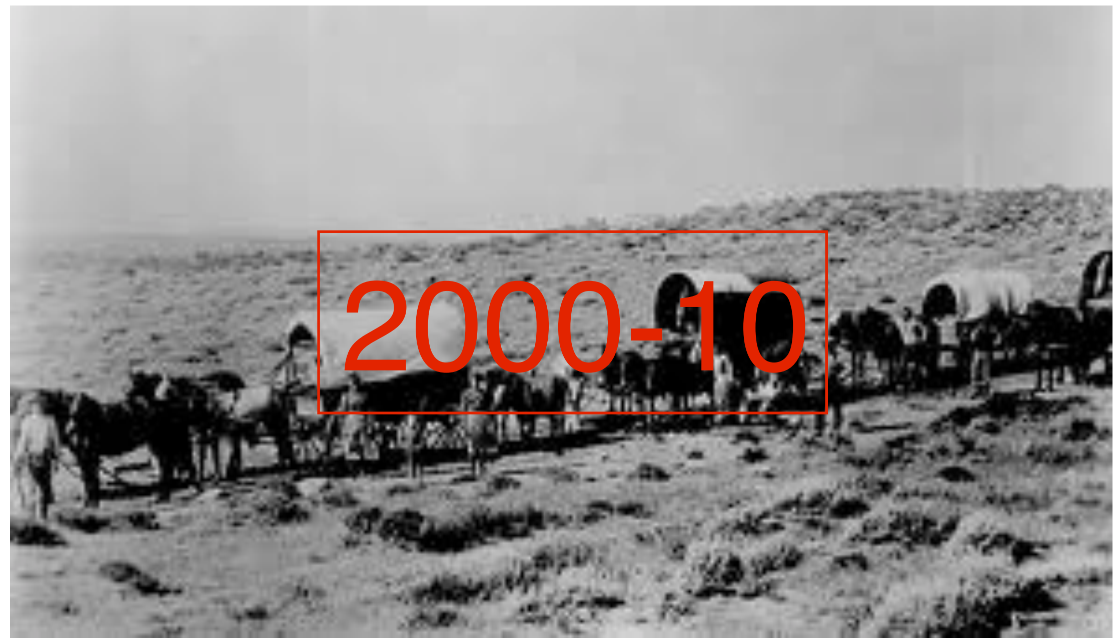

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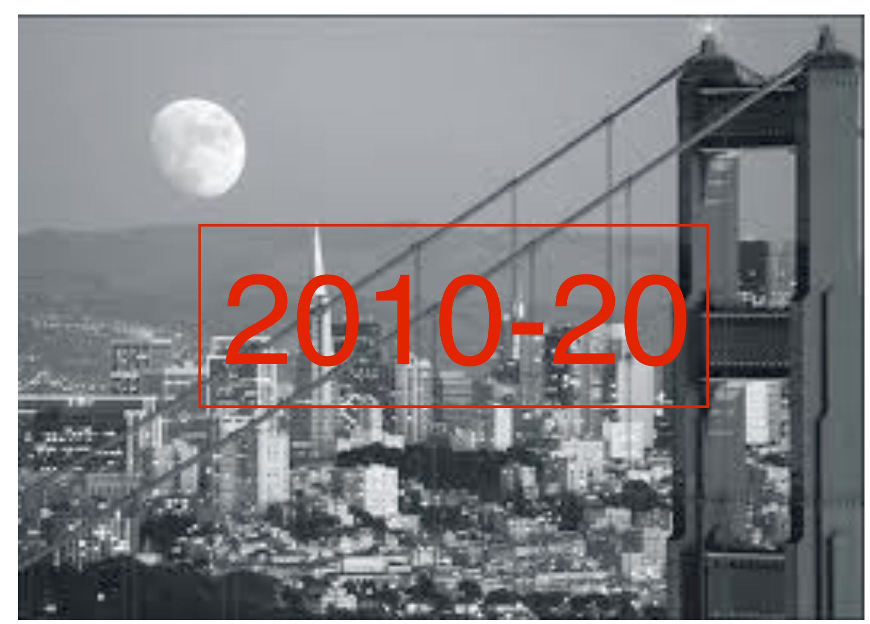

Phases of exploration

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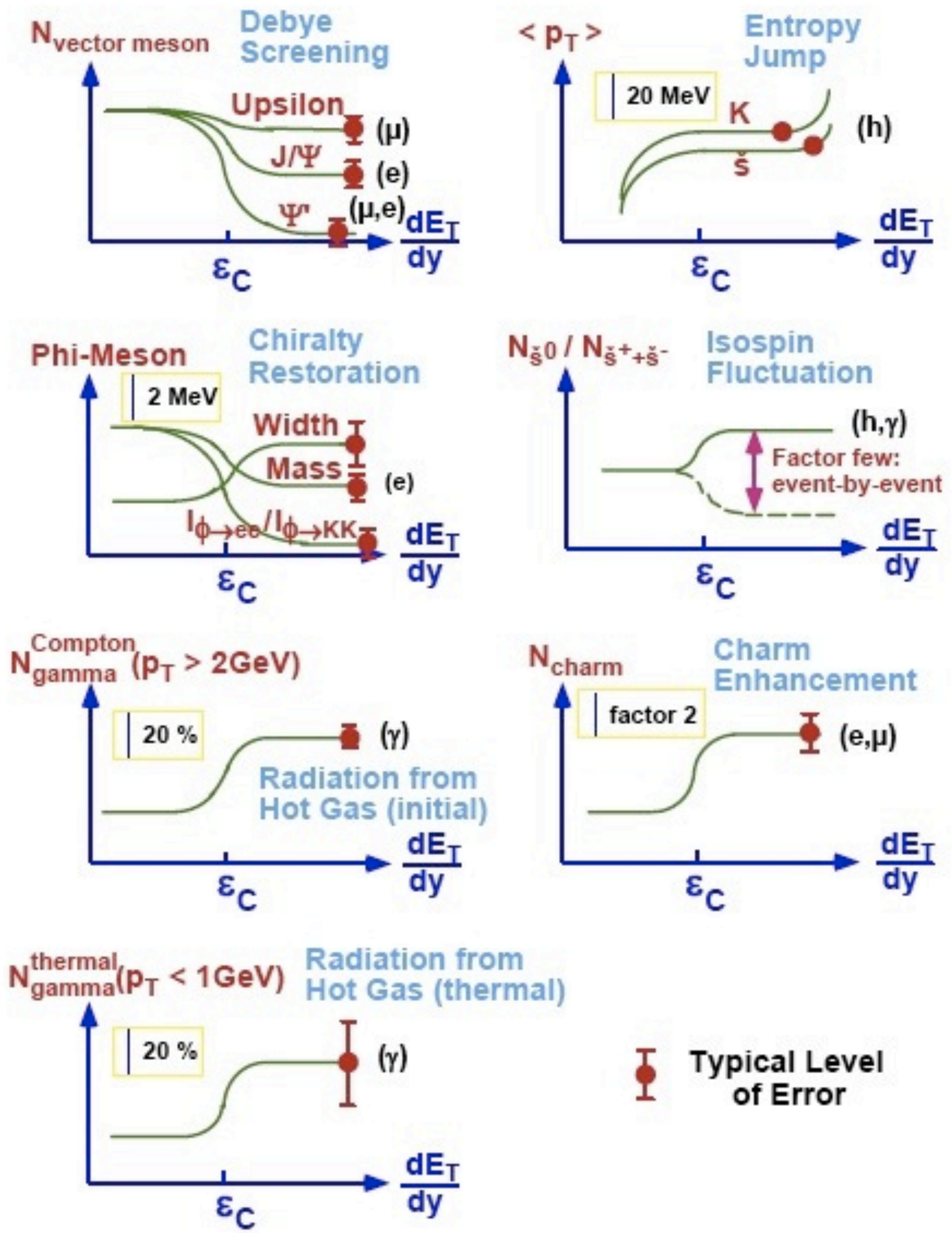
Smoking guns - NSAC style



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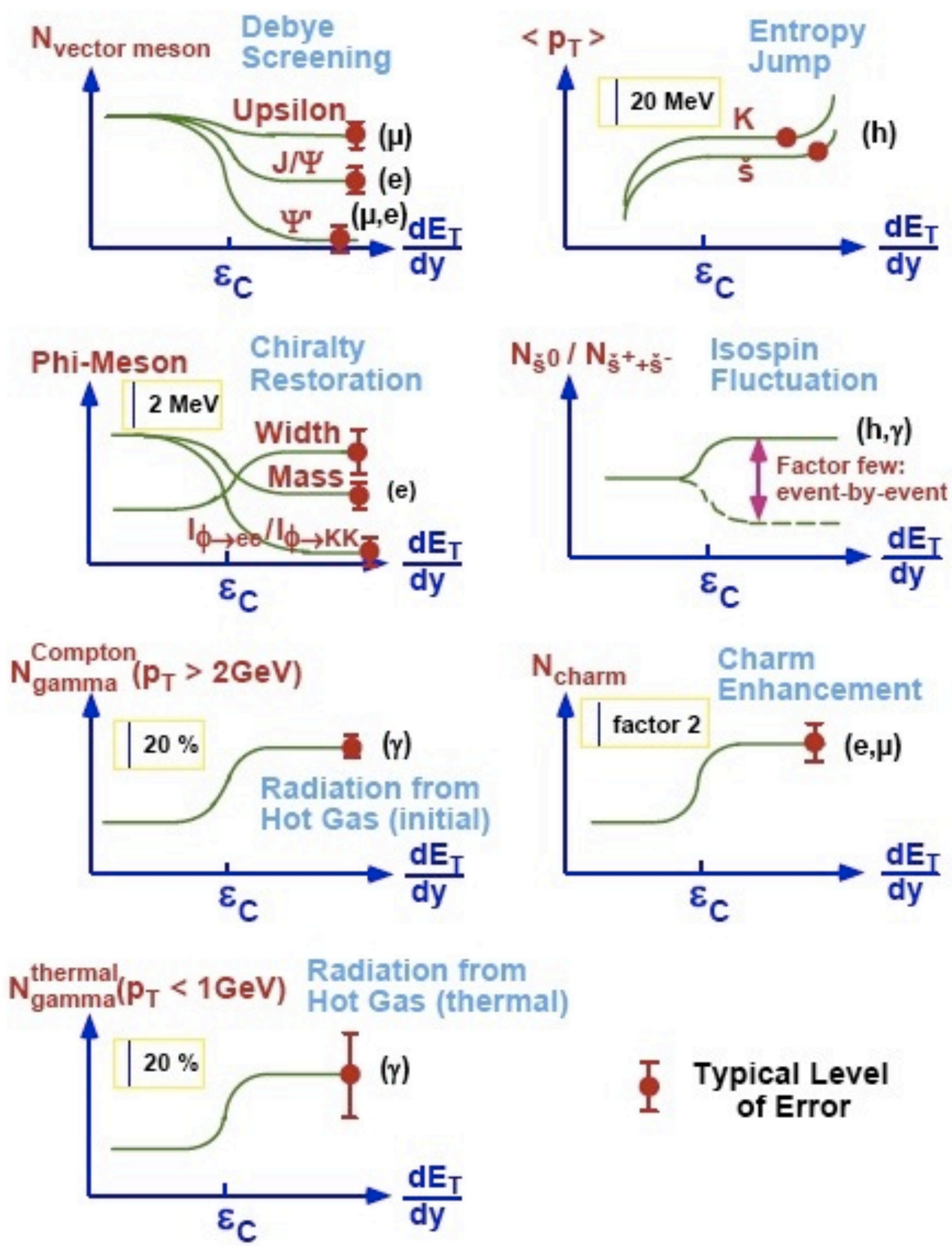
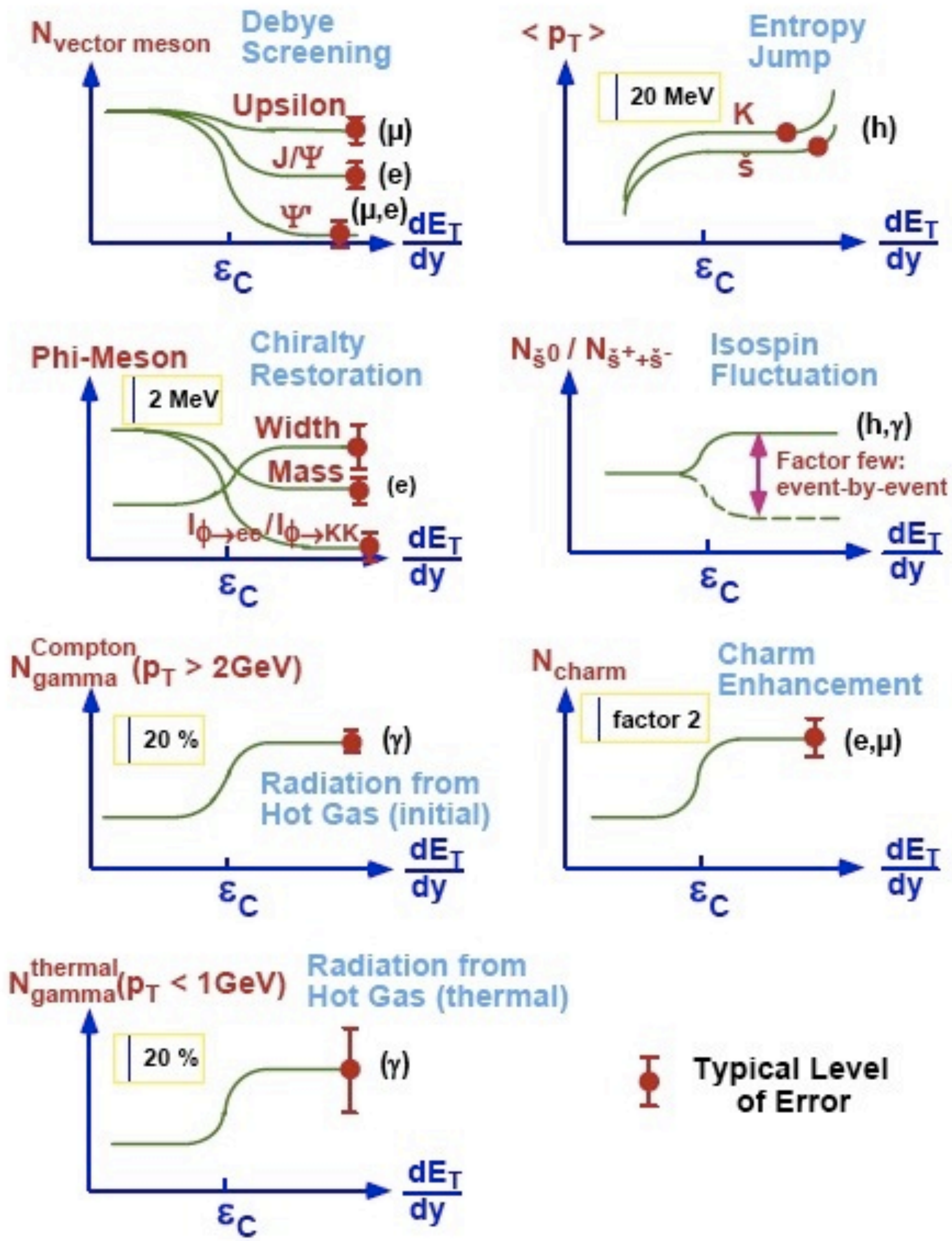


But note what's missing:

- Jet quenching !
- Elliptic flow !!
- Quark recombination !!!
- Shear viscosity !!!!
- Critical point !!!!!

Smoking guns - NSAC style



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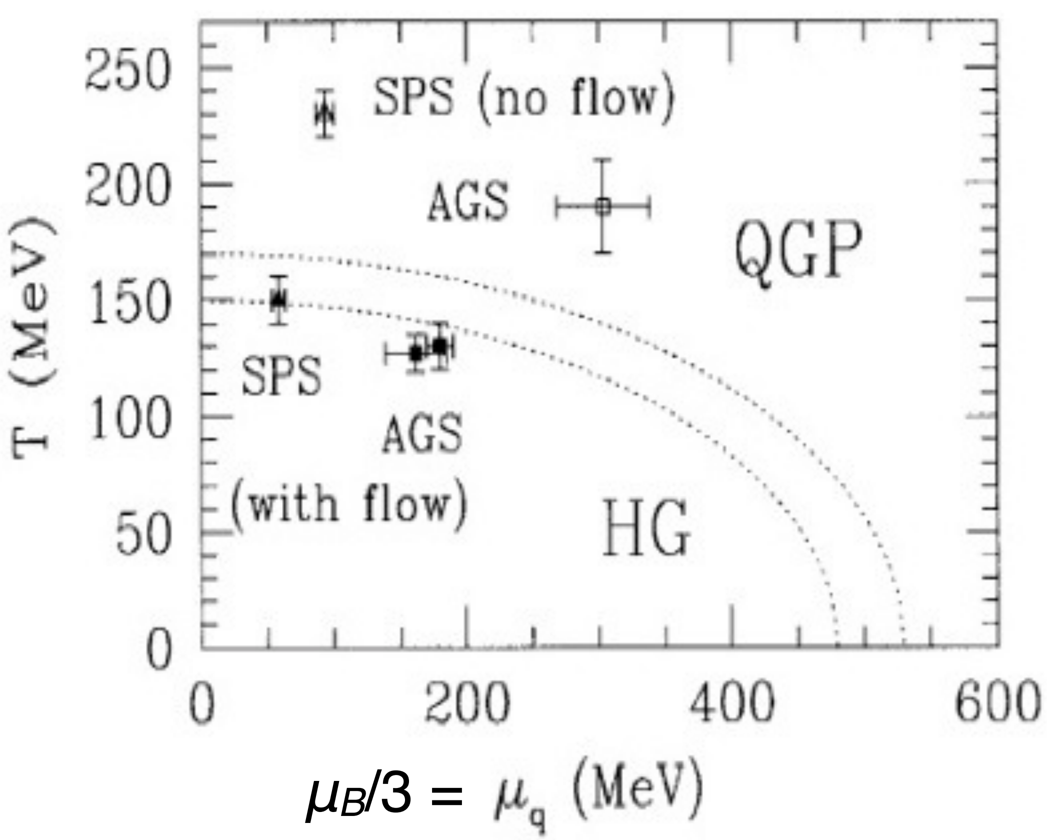
Disclaimer:

If the 1995 NSAC Committee could not accurately predict the future of heavy ion physics, would you expect **me** to be able to do so ???

Charting the territory

Experimental evidence
for the QCD phase boundary
[B.M., NPA 590 (1995) 3c]



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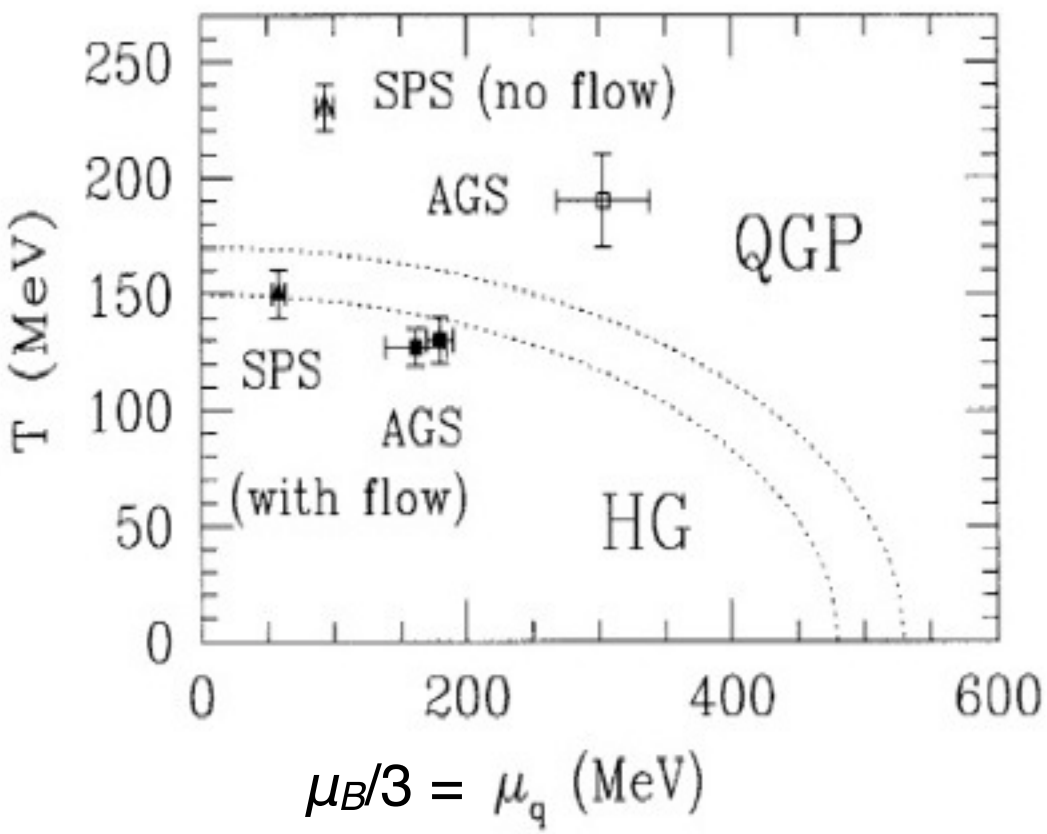

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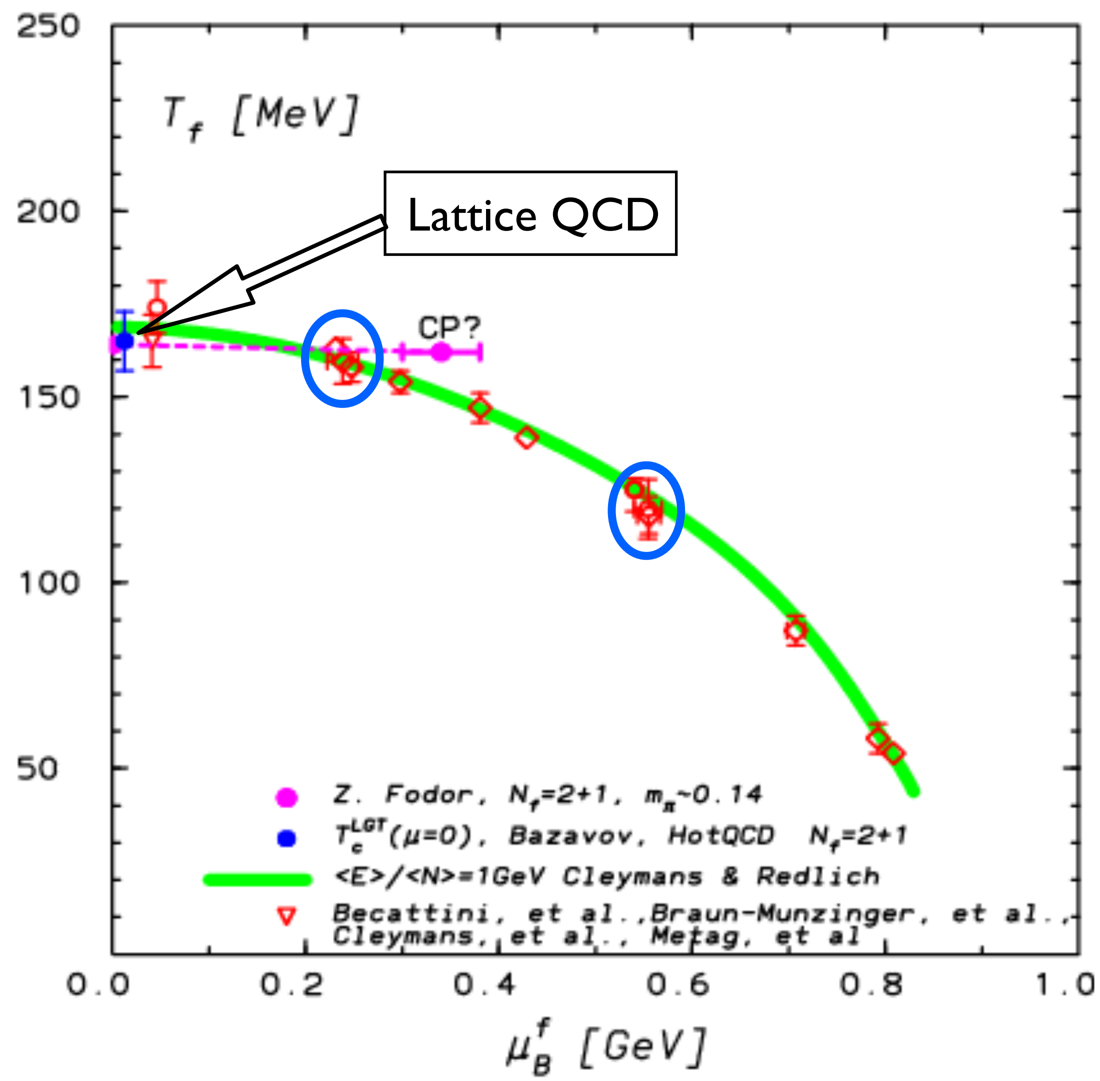
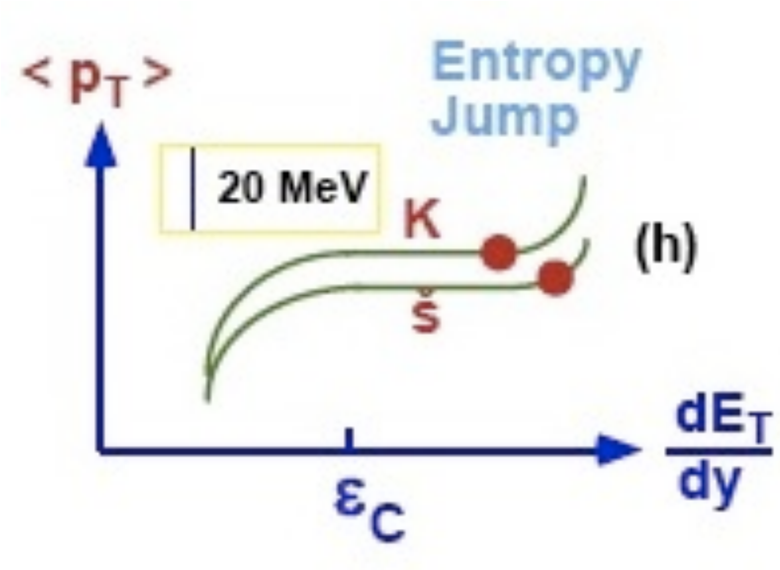
[K. Redlich, 2010]



Was van Hove right?



Signal of a phase transformation:

S-shaped relationship between $<p_T>$ and energy density or entropy, where the flat region spans the domain in which frozen degrees of freedom (color) are unthawed.

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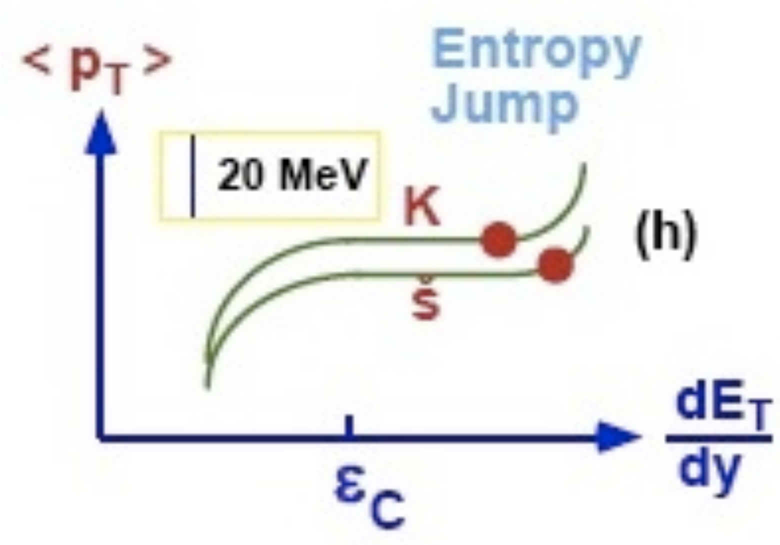

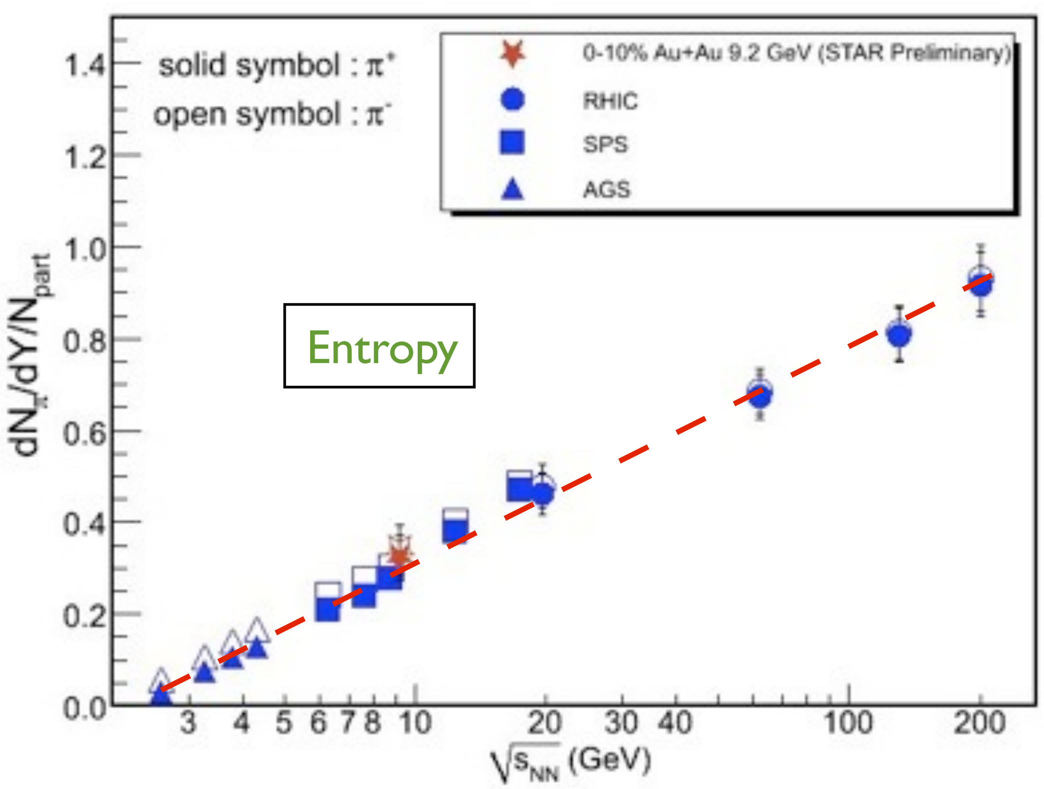

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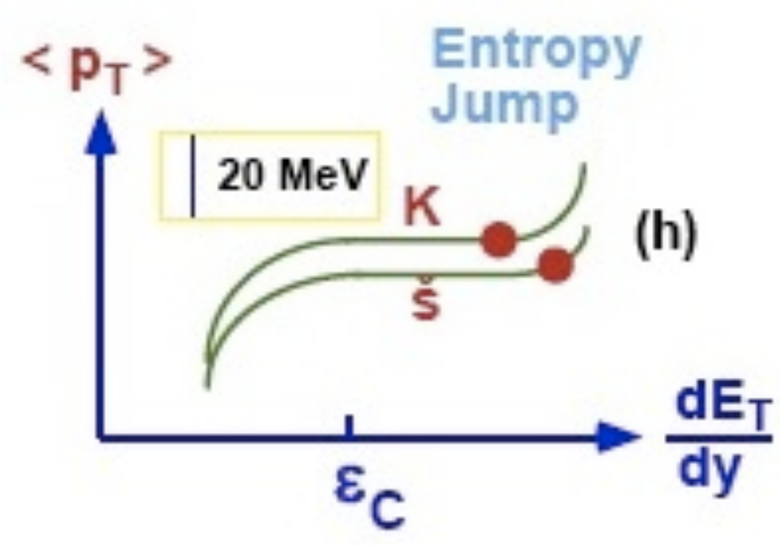

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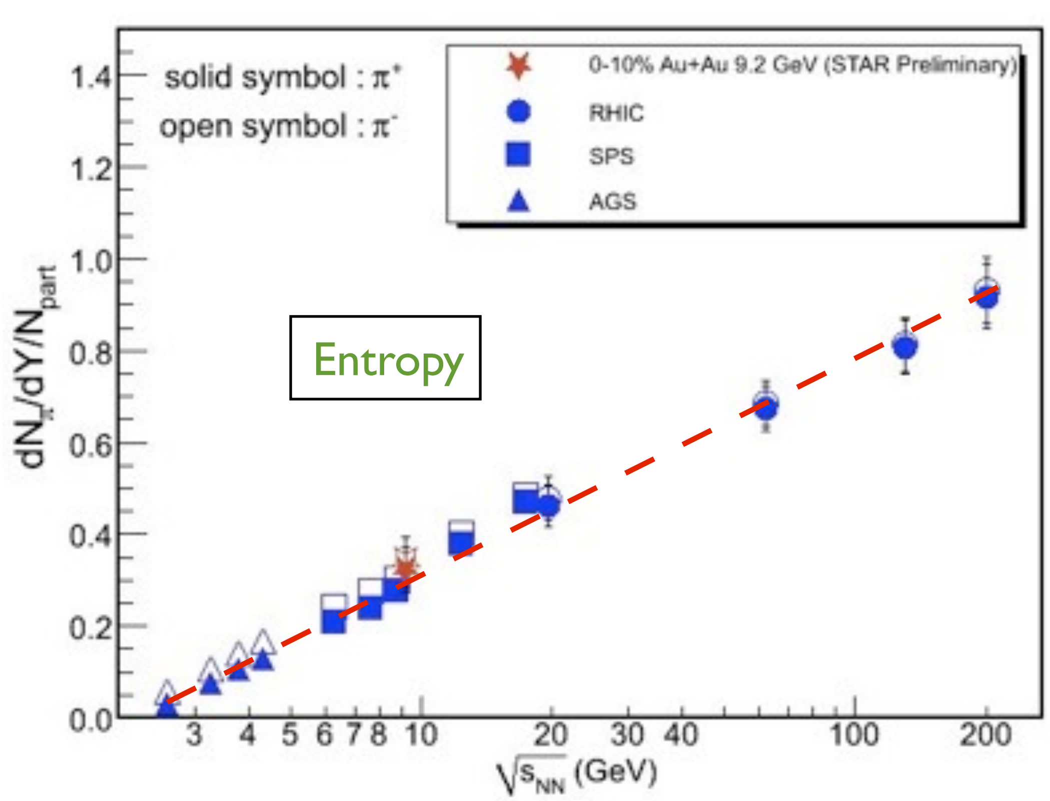
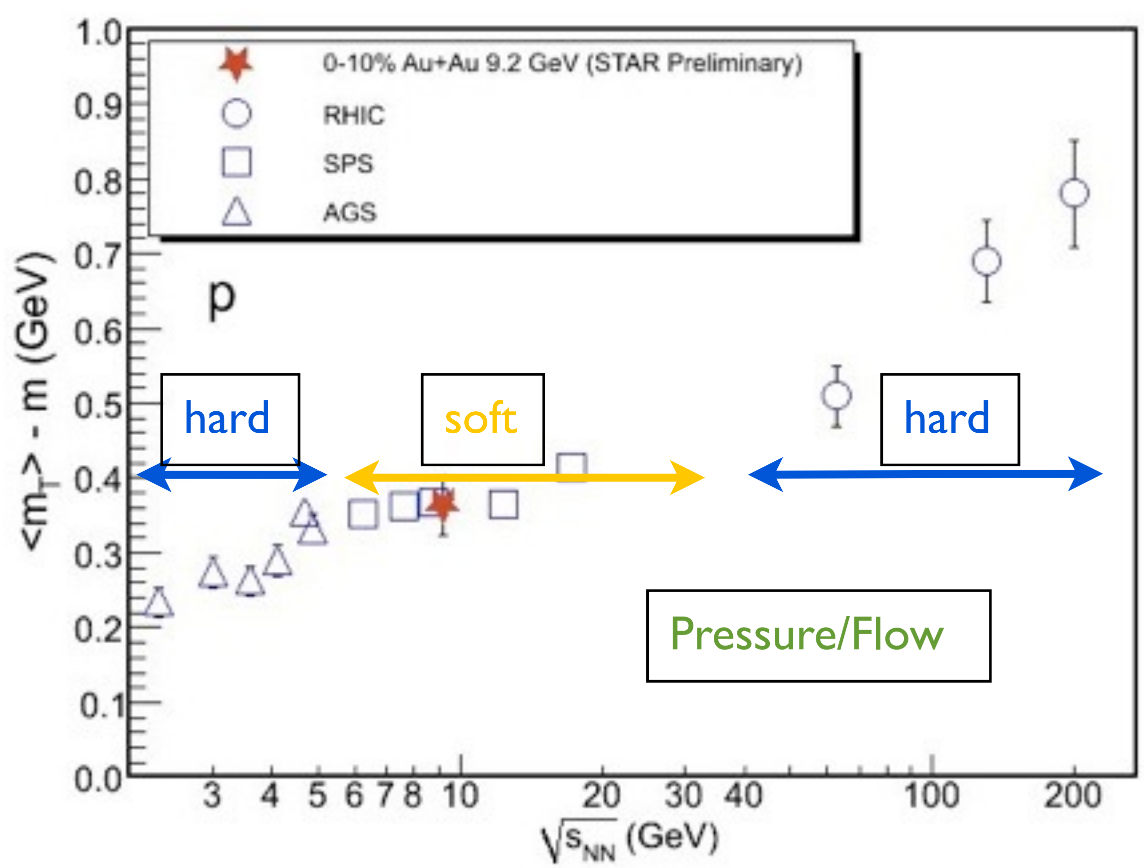
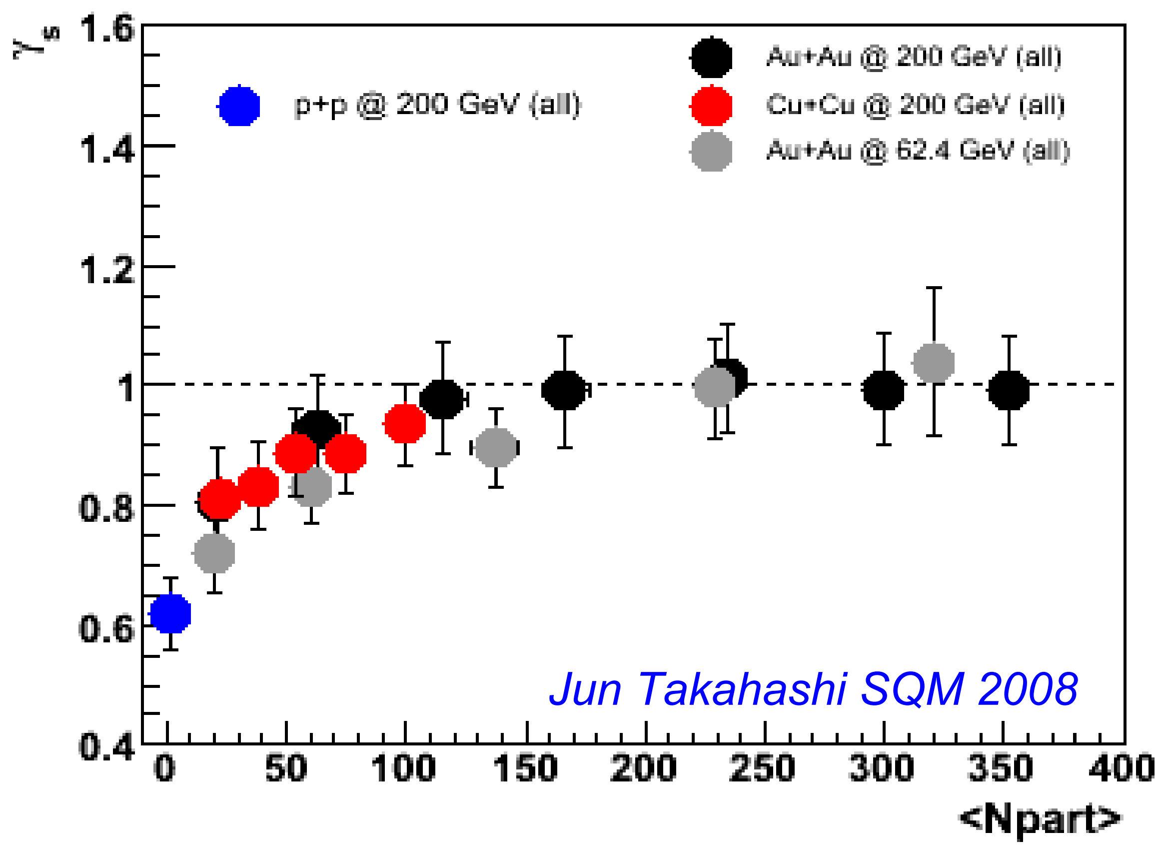




Chemical tracers

Strange quarks *are* chemically equilibrated at hadronization of the quark-gluon plasma

Strangeness saturation



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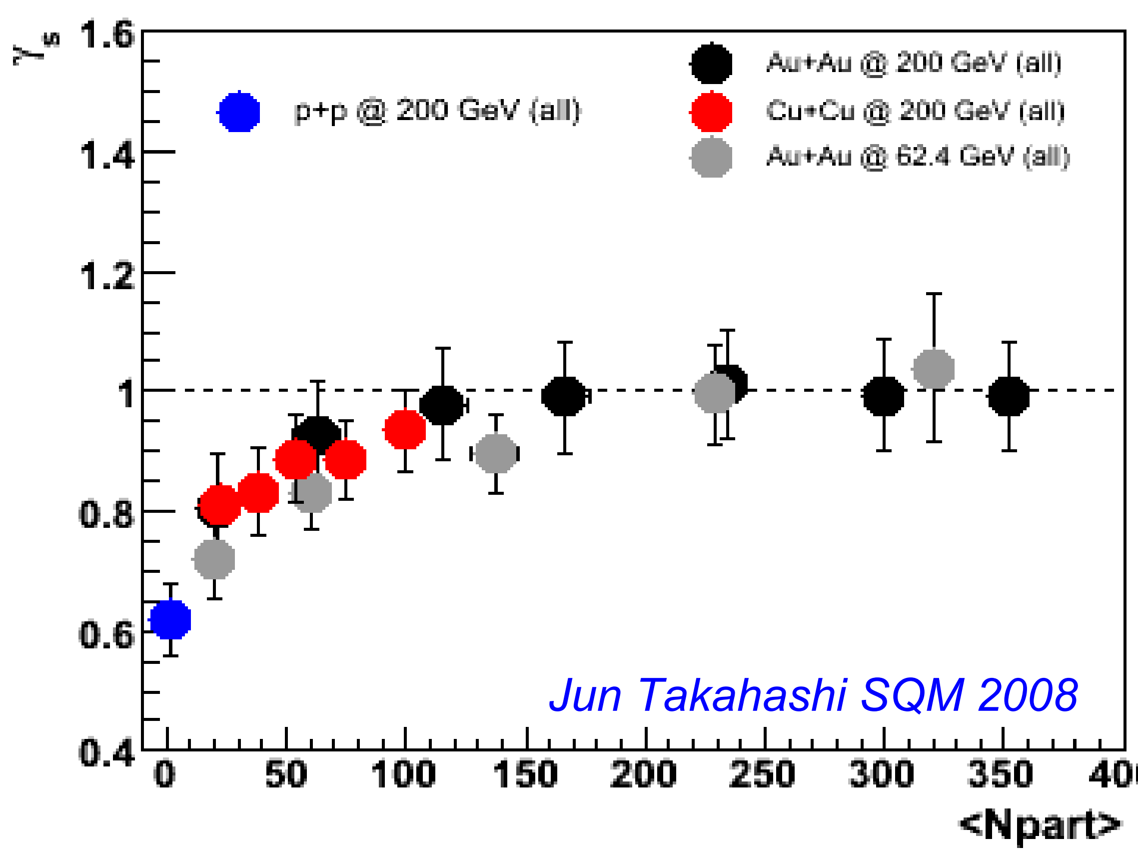
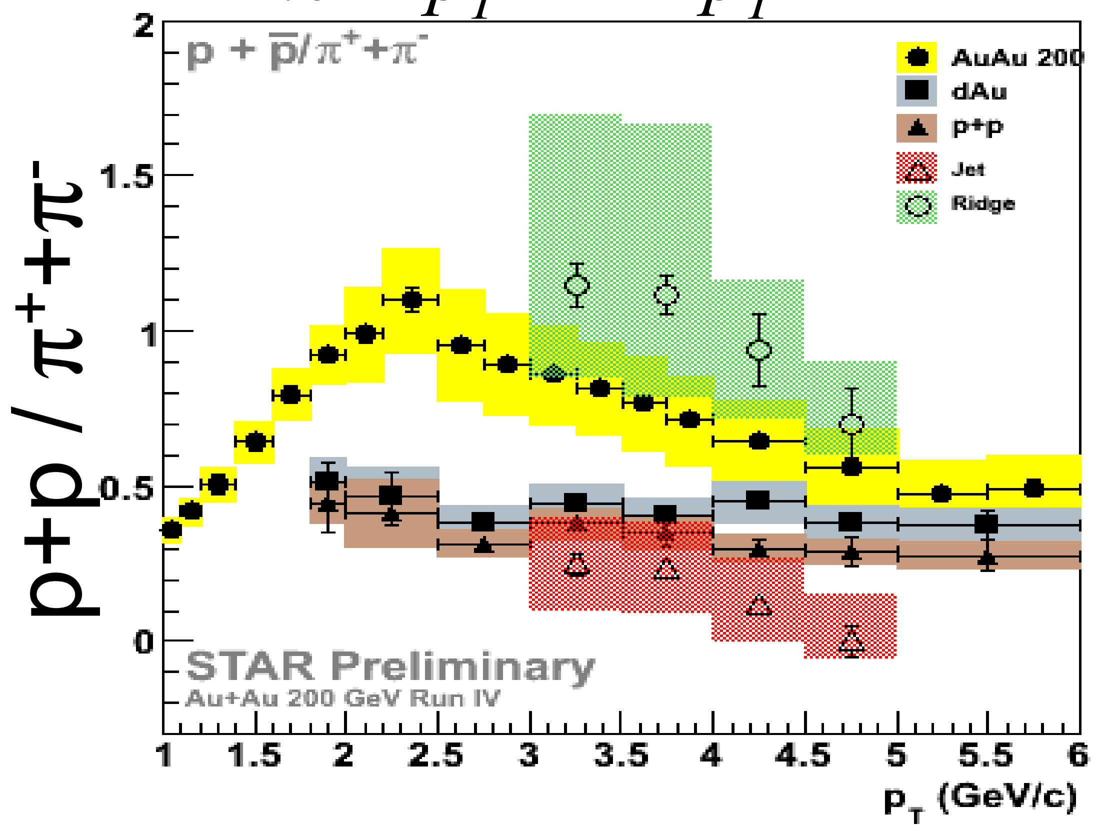
Hadrochemistry was put to good use demonstrating that the "hard" ridge is composed of bulk matter, not jet fragments

Strangeness saturation



$p_T^{trig} > 4.0\ GeV/c$

$2.0 < p_T^{Assoc} < p_T^{trig}$



- Theory breakthroughs of 2000-10:
  - Application of gauge-gravity duality to strongly coupled plasma
  - "Universal" quantum limit of (shear) viscosity
  - Consistent theory of relativistic dissipative fluid dynamics
  - *Ab initio* QCD equation of state at $\mu_B = 0$
  - *Qualitative* connection between properties and observables
  - *Conceptual* theory of the low-x parton structure of nuclei

Hot QCD matter (I)

Which **properties of hot QCD matter** can we hope to determine from relativistic heavy ion data (RHIC and LHC, maybe FAIR) ?

$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$ **Equation of state**: spectra, coll. flow, fluctuations

$c_S^2 = \partial p / \partial \varepsilon$ **Speed of sound**: multiparticle correlations

$$\eta = \frac{1}{T} \int d^4x \langle T_{xy}(x) T_{xy}(0) \rangle$$

Shear viscosity: anisotropic collective flow

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

Momentum/energy diffusion: parton energy loss, jet fragmentation

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

Color screening: Quarkonium states

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Duke Theory

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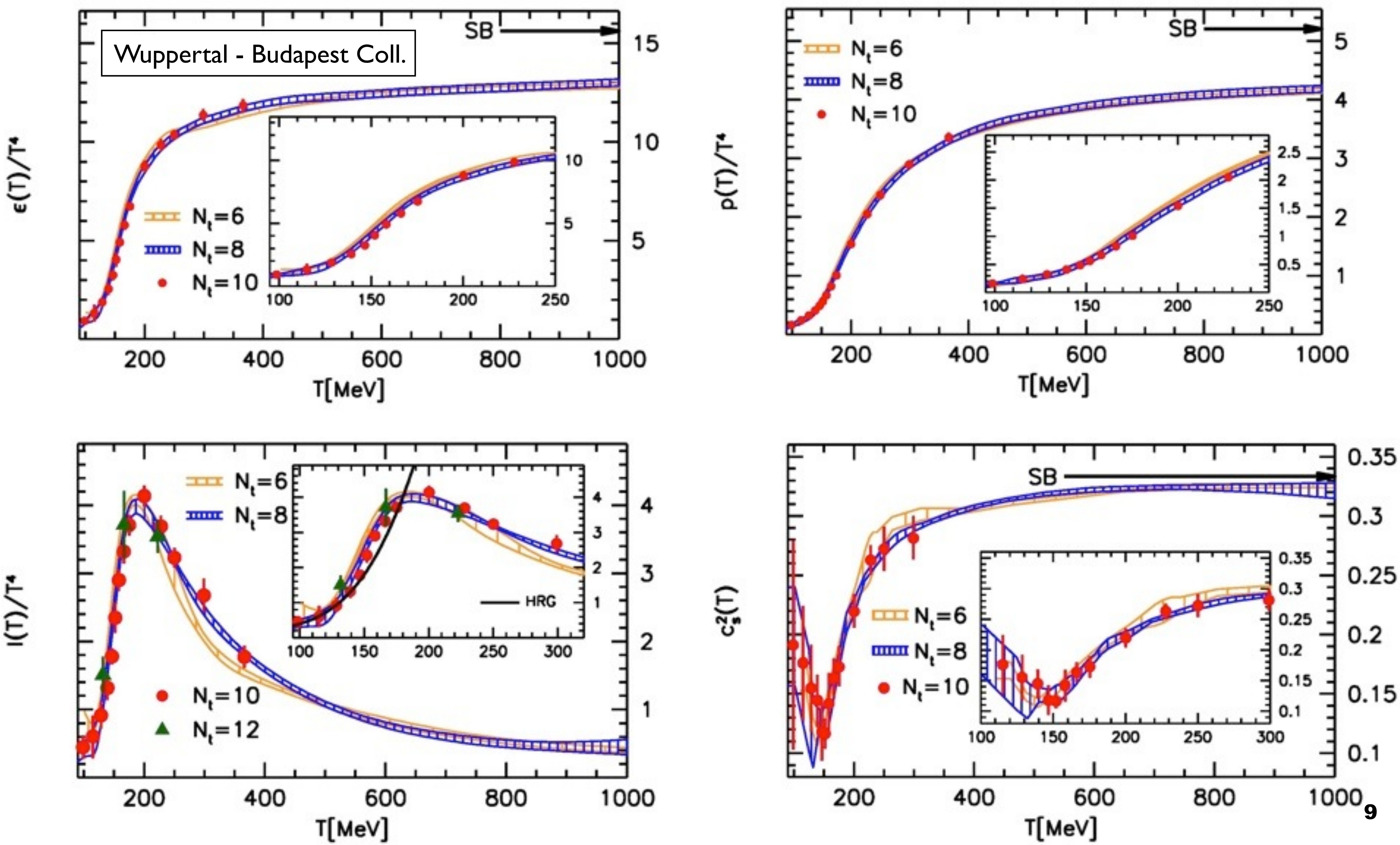
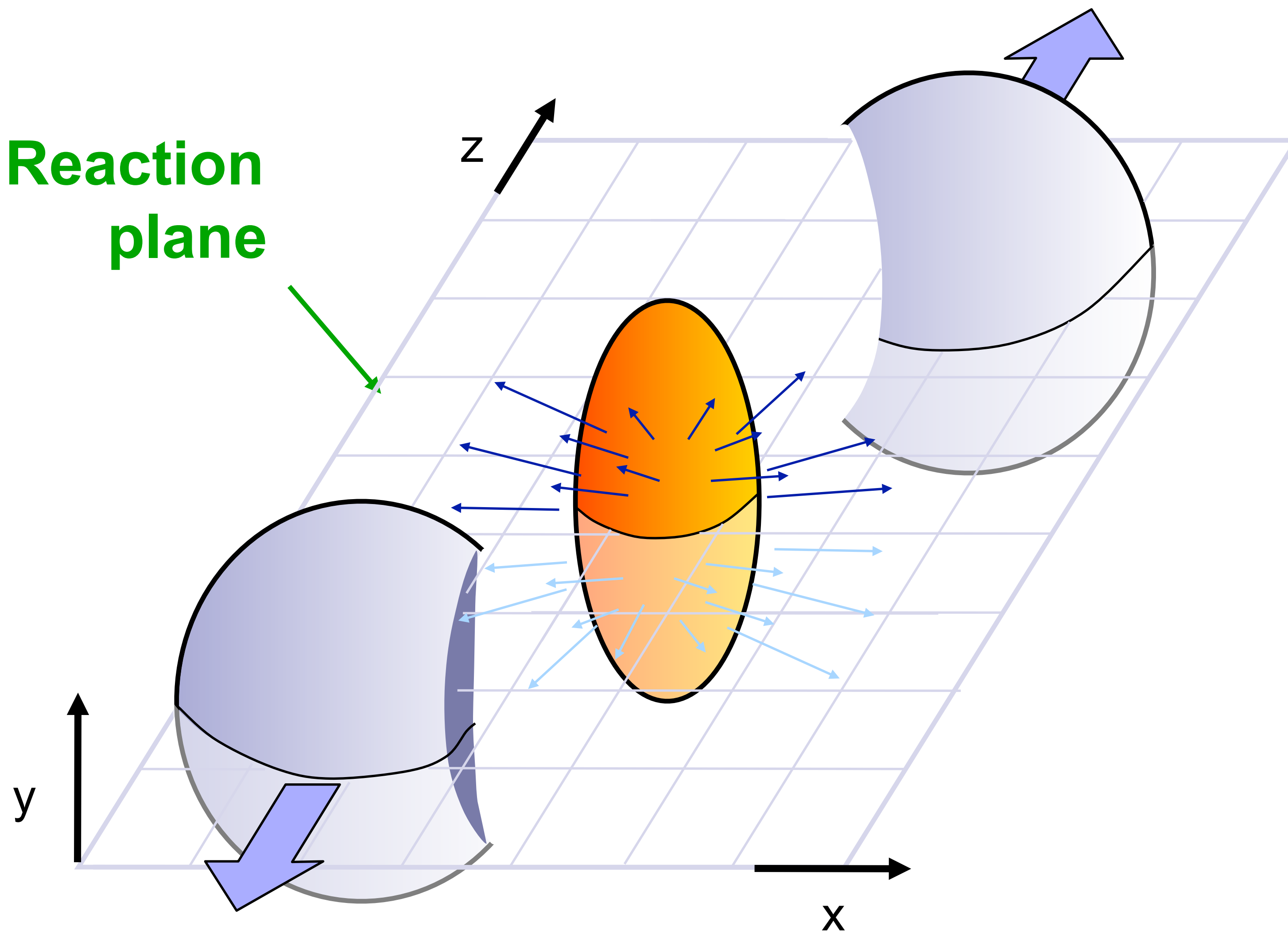
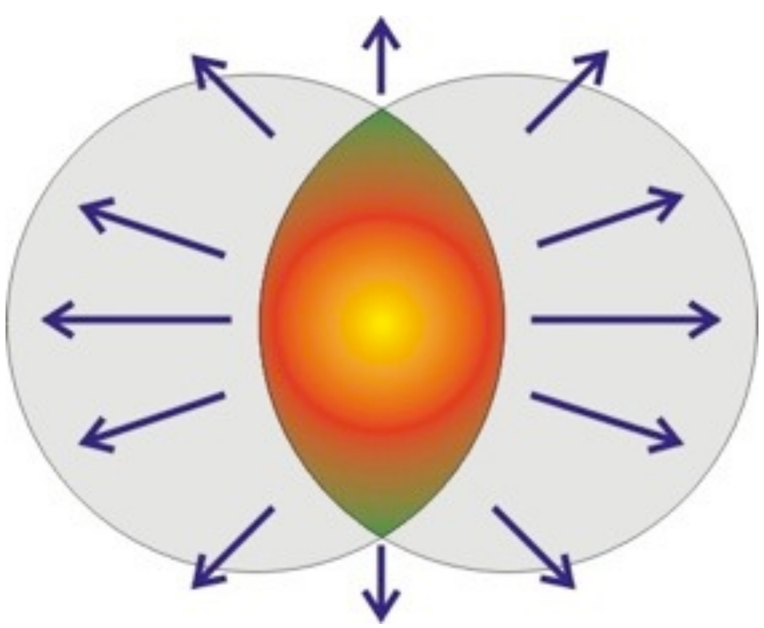
Lattice QCD - 2010



Elliptic Flow (v_2)



$v_2 = \langle\cos(2\phi)\rangle$
coefficient of the
azimuthal distribution

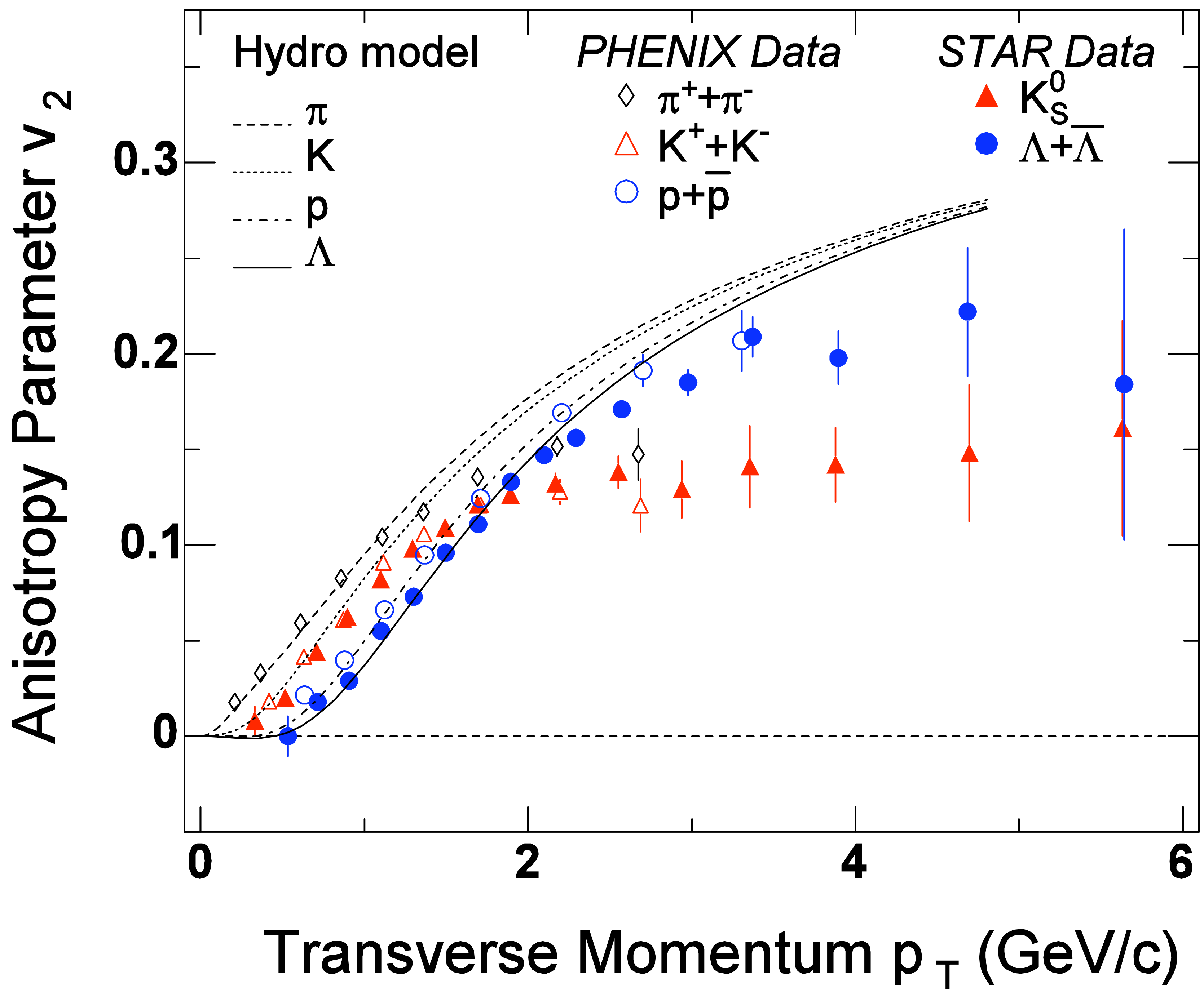


Hydrodynamics:

Flow is generated by ∇P

∇P(↔) > ∇P(↕)

$v_2(p_T)$ vs. hydrodynamics



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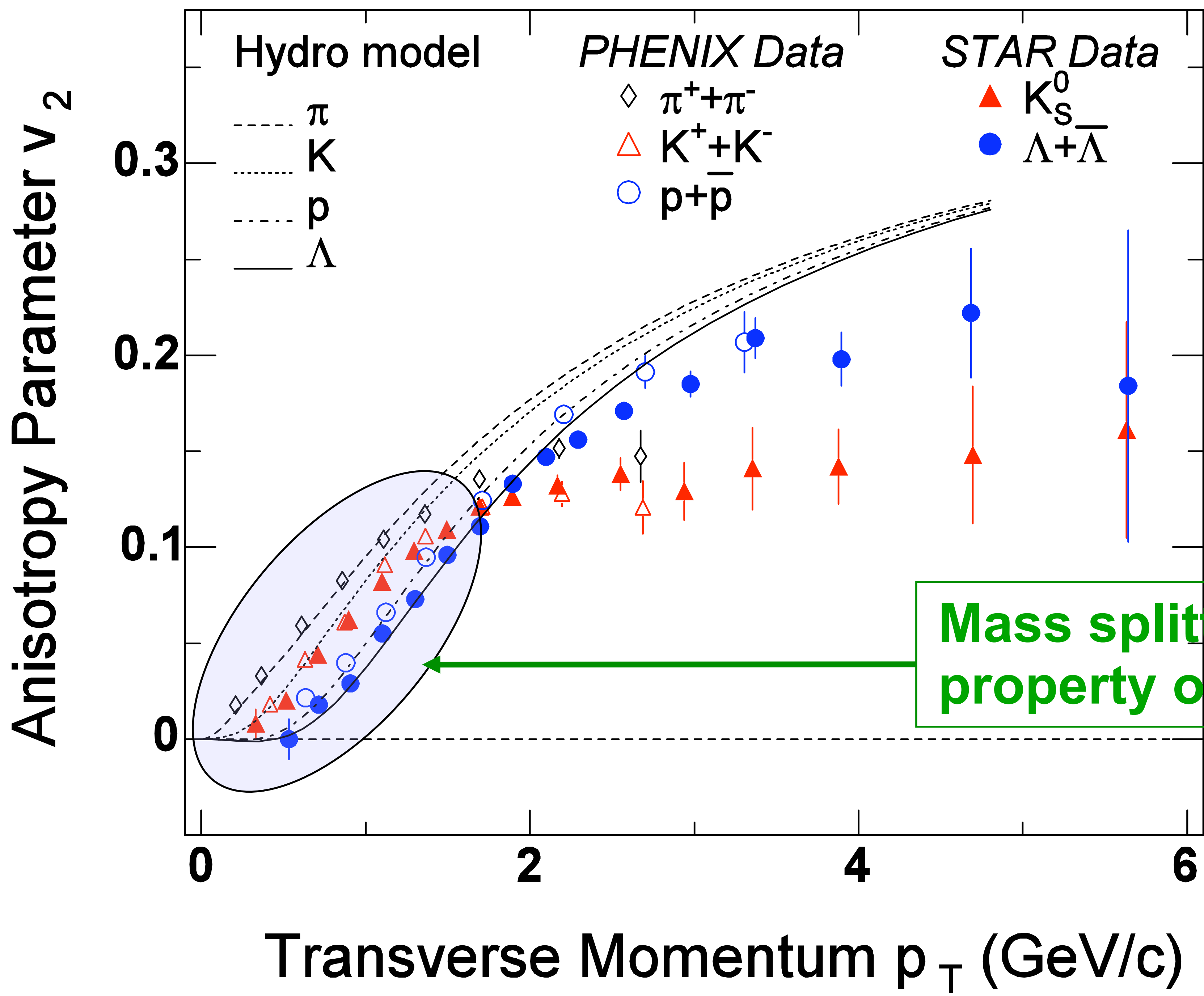

Mass splitting characteristic property of hydrodynamics

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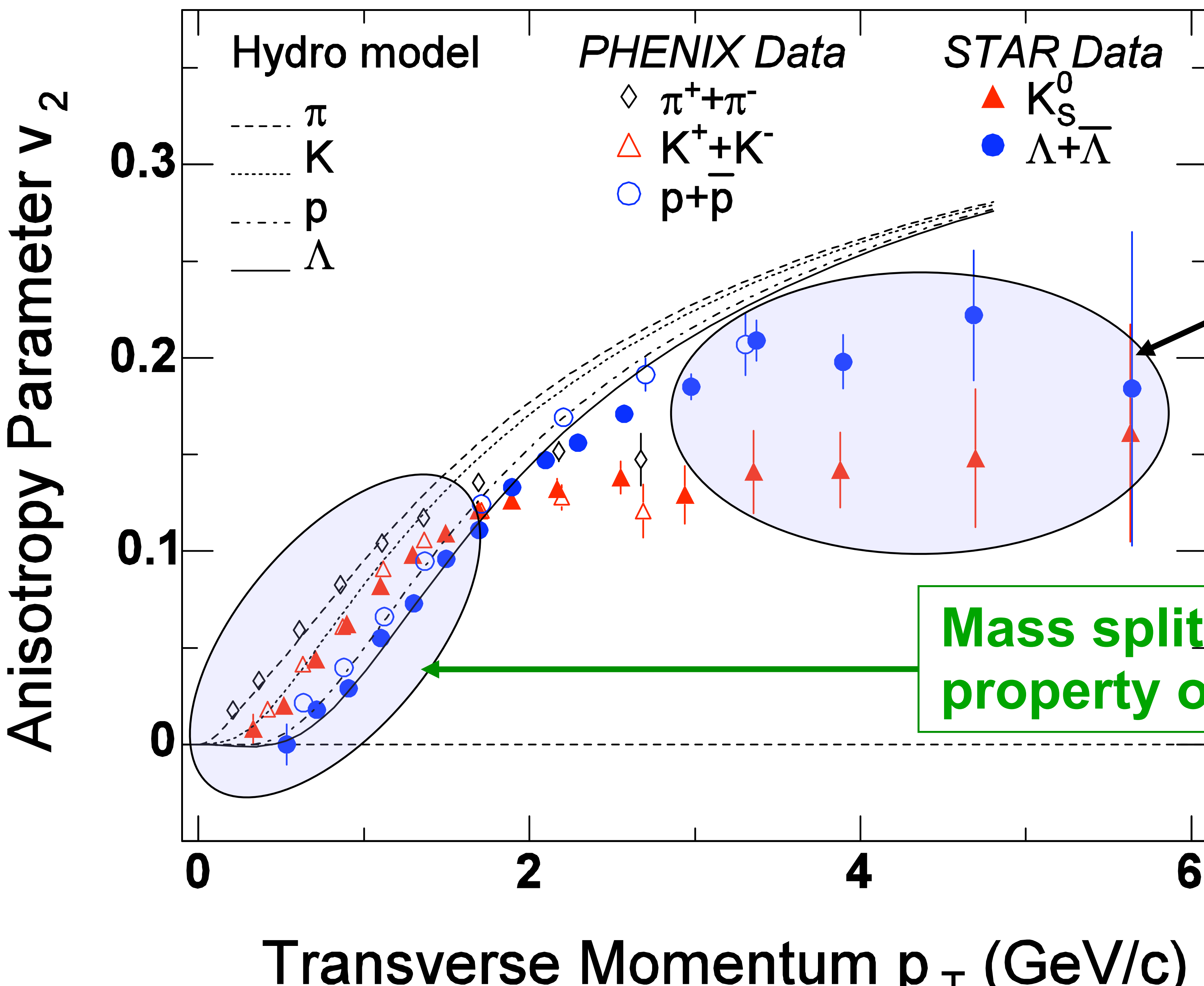

Failure of ideal hydrodynamics tells us how hadrons form

Mass splitting characteristic property of hydrodynamics

Elliptic flow "measures" η_{QGP}

We finally have a complete, causal formulation of relativistic viscous hydrodynamics:

Shear viscosity

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

$$\tau_\Pi \left[\frac{d\Pi^{\mu\nu}}{d\tau} + \left(u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda} \right) \frac{du^\lambda}{d\tau} \right] = \eta \left(\partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace} \right) - \Pi^{\mu\nu}$$

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$$\begin{aligned}
\Pi &= \Pi_{NS} - \tau_\Pi \dot{\Pi} \\
&+ \tau_{\Pi q}\, q \cdot \dot{u} - \ell_{\Pi q}\, \partial \cdot q - \zeta\, \hat{\delta}_0\, \Pi\, \theta \\
&+ \lambda_{\Pi q}\, q \cdot \nabla \alpha + \lambda_{\Pi\pi}\, \pi^{\mu\nu} \sigma_{\mu\nu}\,, \\
q^\mu &= q^\mu_{NS} - \tau_q\, \Delta^{\mu\nu} \dot{q}_\nu \\
&- \tau_{q\Pi}\, \Pi\, \dot{u}^\mu - \tau_{q\pi}\, \pi^{\mu\nu} \dot{u}_\nu + \ell_{q\Pi}\, \nabla^\mu \Pi - \ell_{q\pi}\, \Delta^{\mu\nu} \partial^\lambda \pi_{\nu\lambda} + \tau_q\, \omega^{\mu\nu} q_\nu - \frac{\kappa}{\beta} \hat{\delta}_1\, q^\mu \theta \\
&- \lambda_{qq}\, \sigma^{\mu\nu} q_\nu + \lambda_{q\Pi}\, \Pi \nabla^\mu \alpha + \lambda_{q\pi}\, \pi^{\mu\nu} \nabla_\nu \alpha\,, \\
\pi^{\mu\nu} &= \pi^{\mu\nu}_{NS} - \tau_\pi\, \dot{\pi}^{<\mu\nu>} \\
&+ 2\,\tau_{\pi q}\, q^{<\mu} \dot{u}^{\nu>} + 2\,\ell_{\pi q}\, \nabla^{<\mu} q^{\nu>} + 2\,\tau_\pi\, \pi_\lambda^{\ <\mu} \omega^{\nu>\lambda} - 2\,\eta\, \hat{\delta}_2\, \pi^{\mu\nu} \theta \\
&- 2\,\tau_\pi\, \pi_\lambda^{\ <\mu} \sigma^{\nu>\lambda} - 2\,\lambda_{\pi q}\, q^{<\mu} \nabla^{\nu>} \alpha + 2\,\lambda_{\pi\Pi}\, \Pi\, \sigma^{\mu\nu}\,,
\end{aligned}$$

Complete set of causal, dissipative relativistic hydrodynamics eqs.
(B. Betz & D. Rischke, JPG36, 2009)

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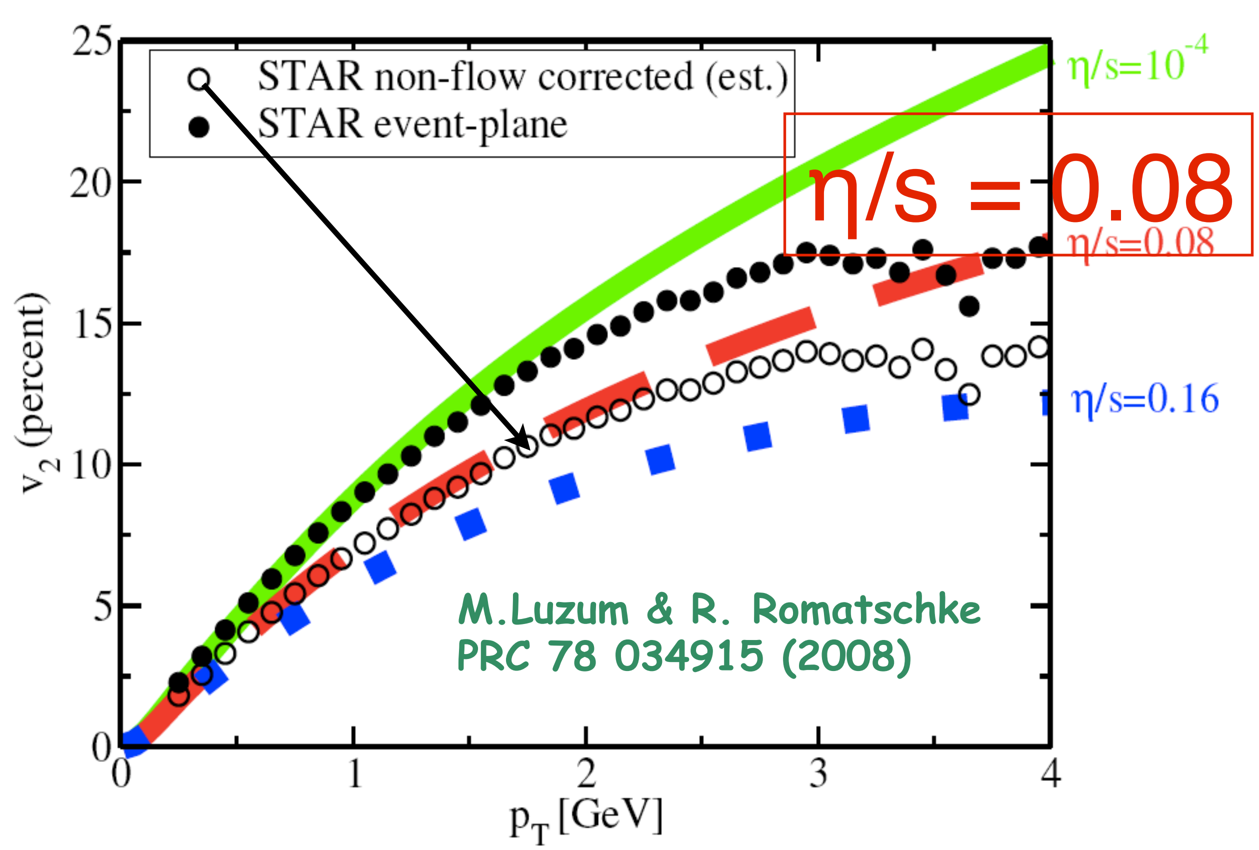
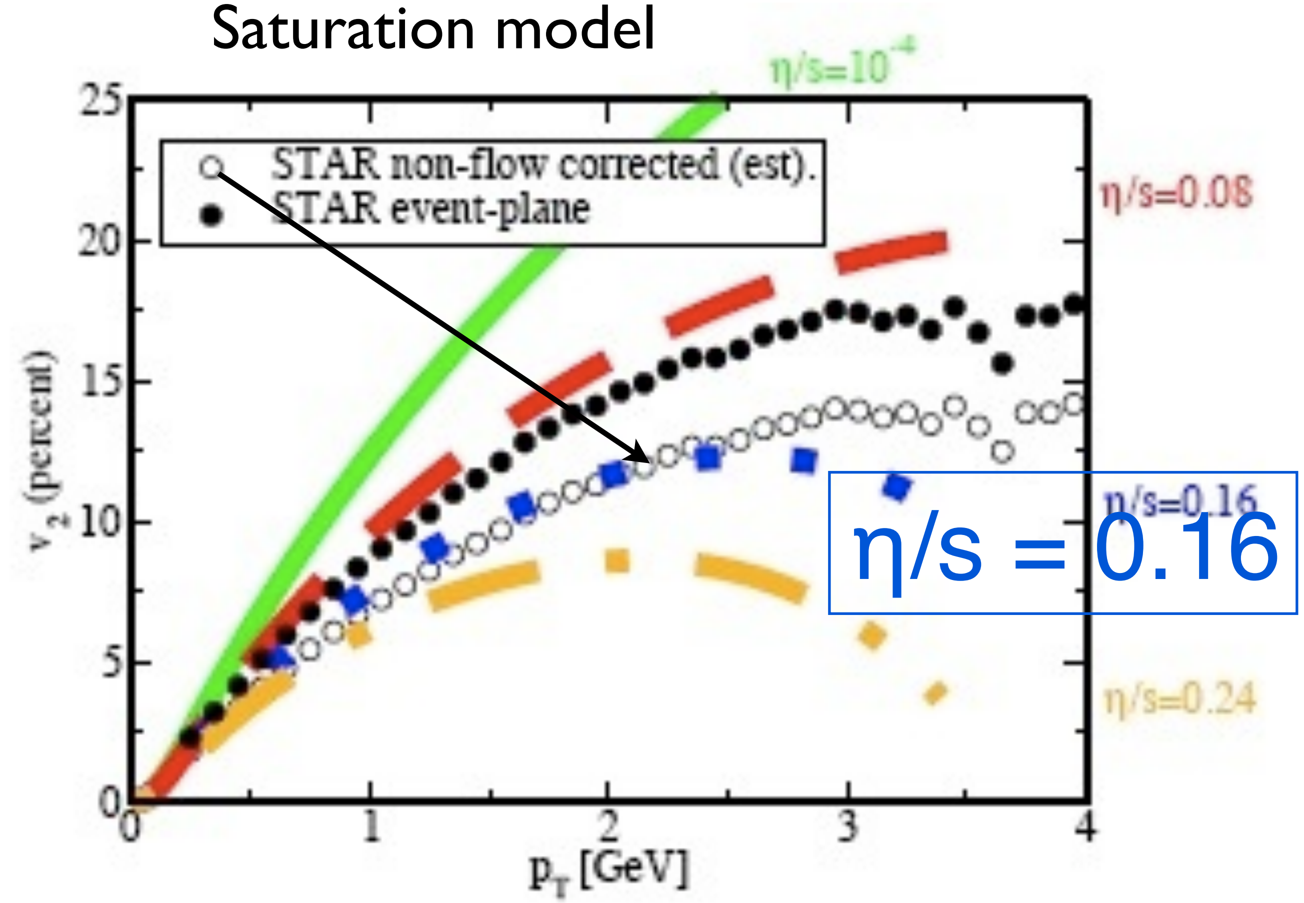
Glauber model



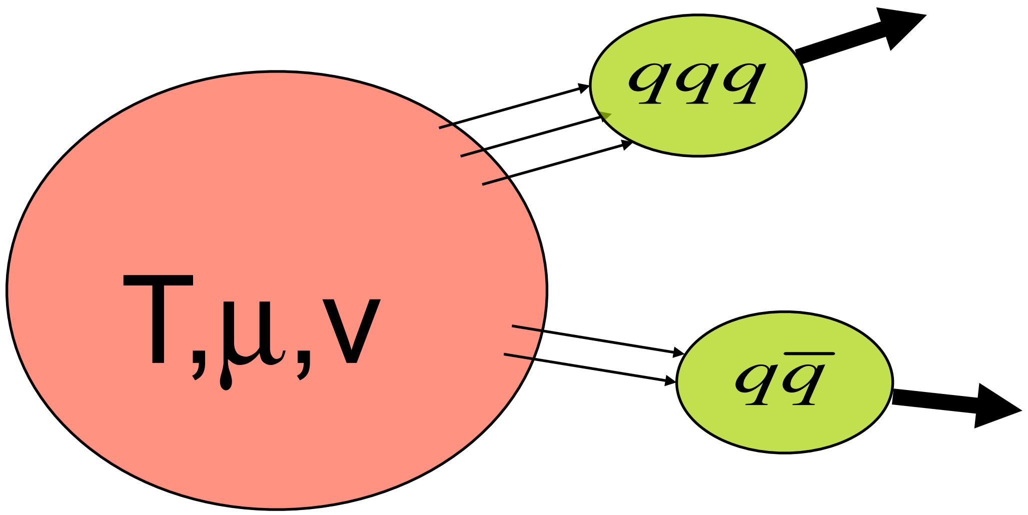
Saturation model



Bulk hadronization

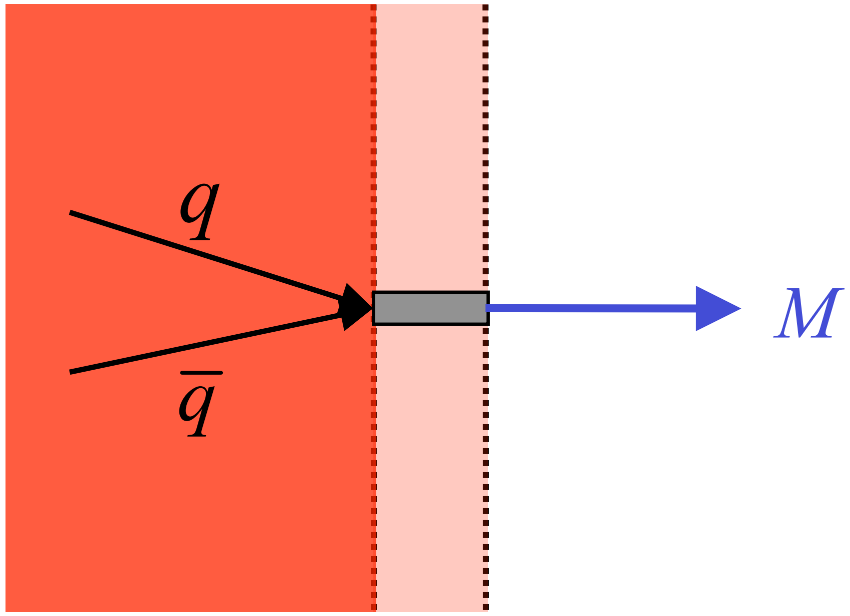
Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons

Sudden recombination



$$p_B \approx 3p_Q$$

$$p_M \approx 2p_Q$$



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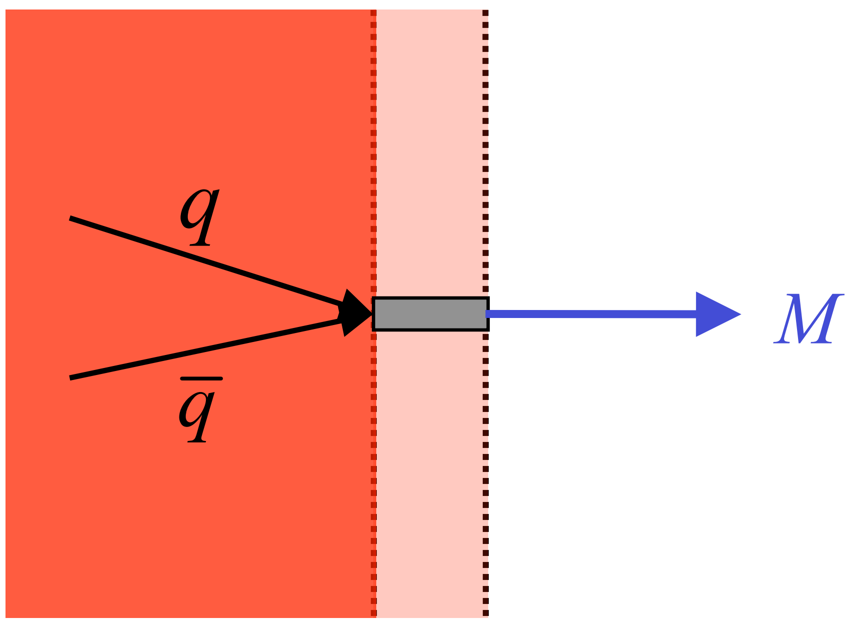

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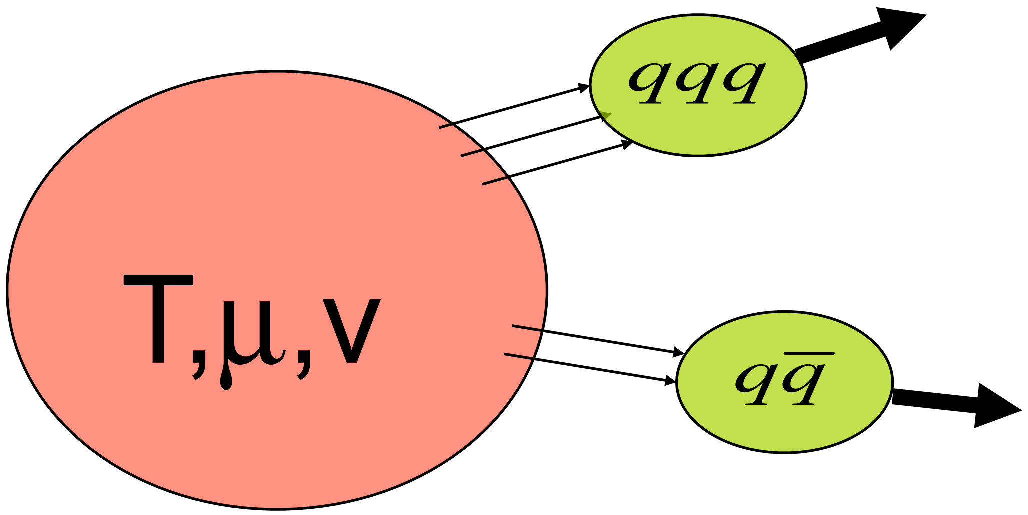


$$p_B \approx 3 p_Q$$

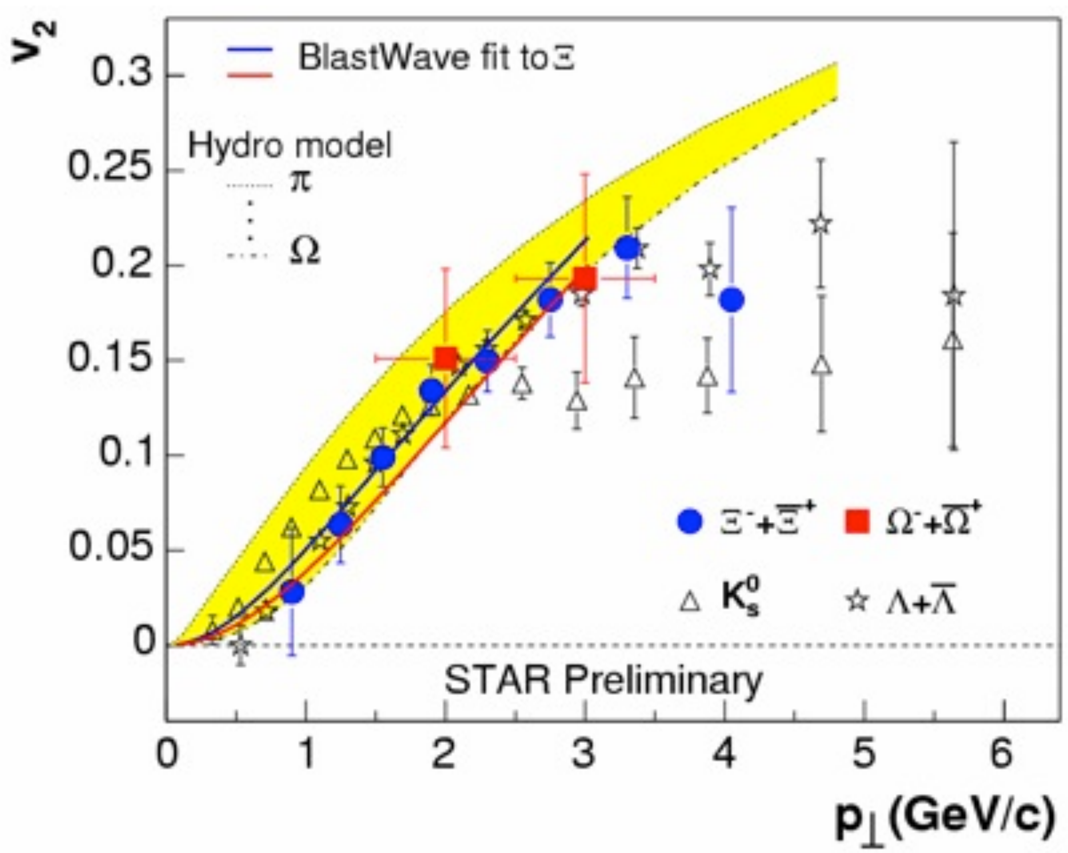
$$p_M \approx 2 p_Q$$

$$v_2^M(p_t) = 2 v_2^Q\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3 v_2^Q\left(\frac{p_t}{3}\right)$$

Quark number scaling of v_2

$$\frac{1}{2}v_2^M(p_t) = v_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3}v_2^B(p_t) = v_2^Q\left(\frac{p_t}{3}\right)$$



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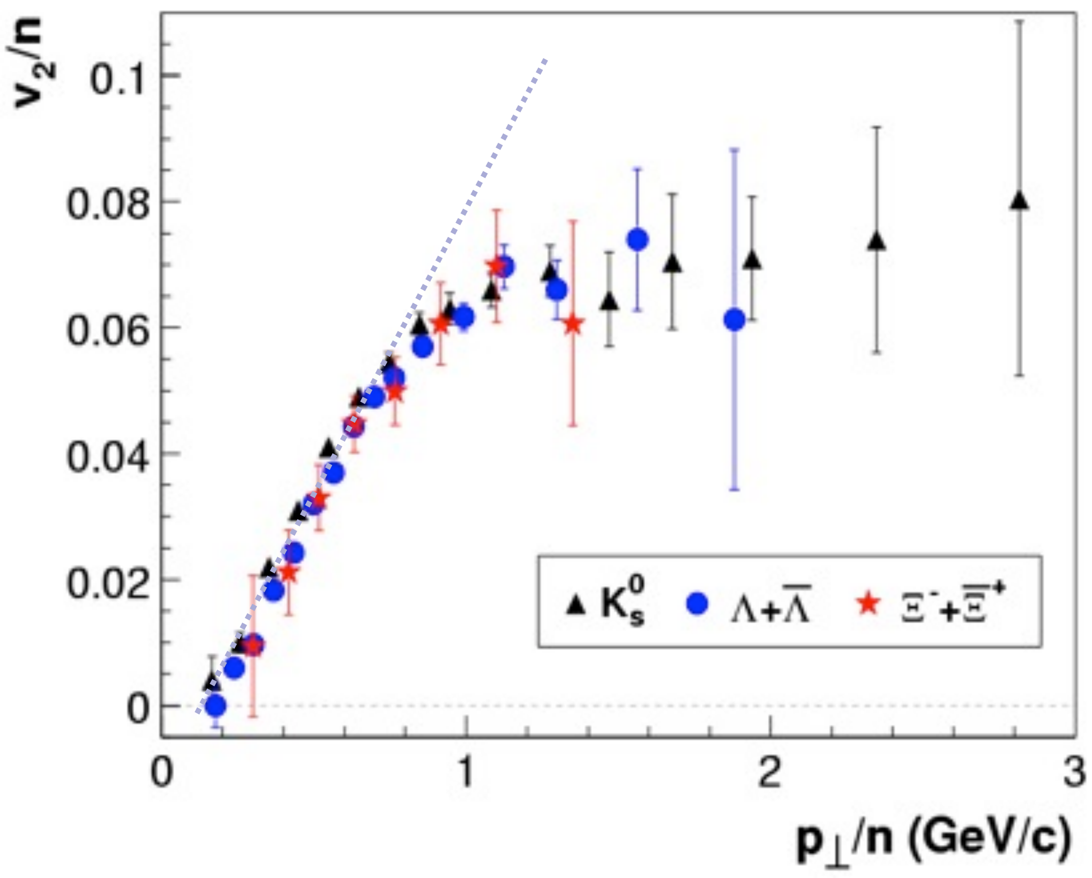

Emitting medium is composed of unconfined, flowing quarks.

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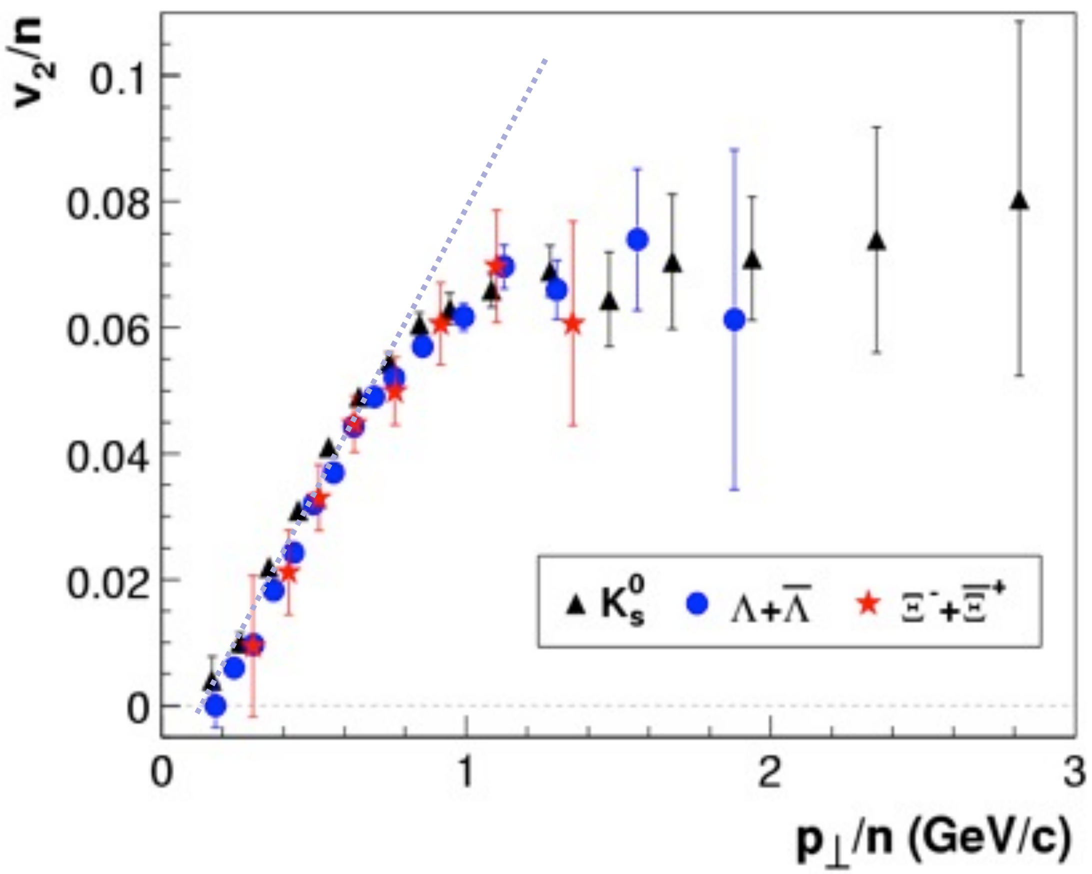

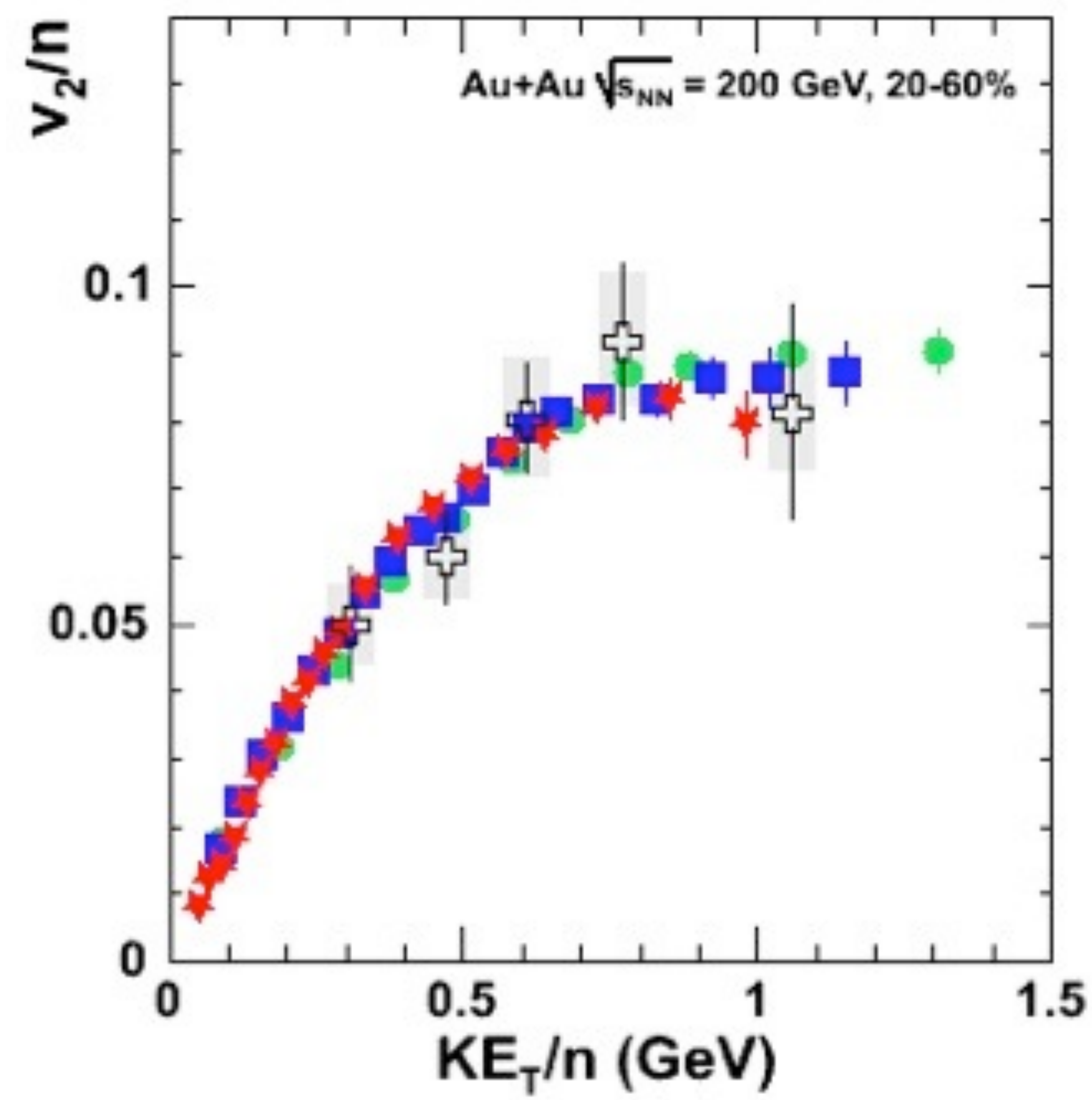

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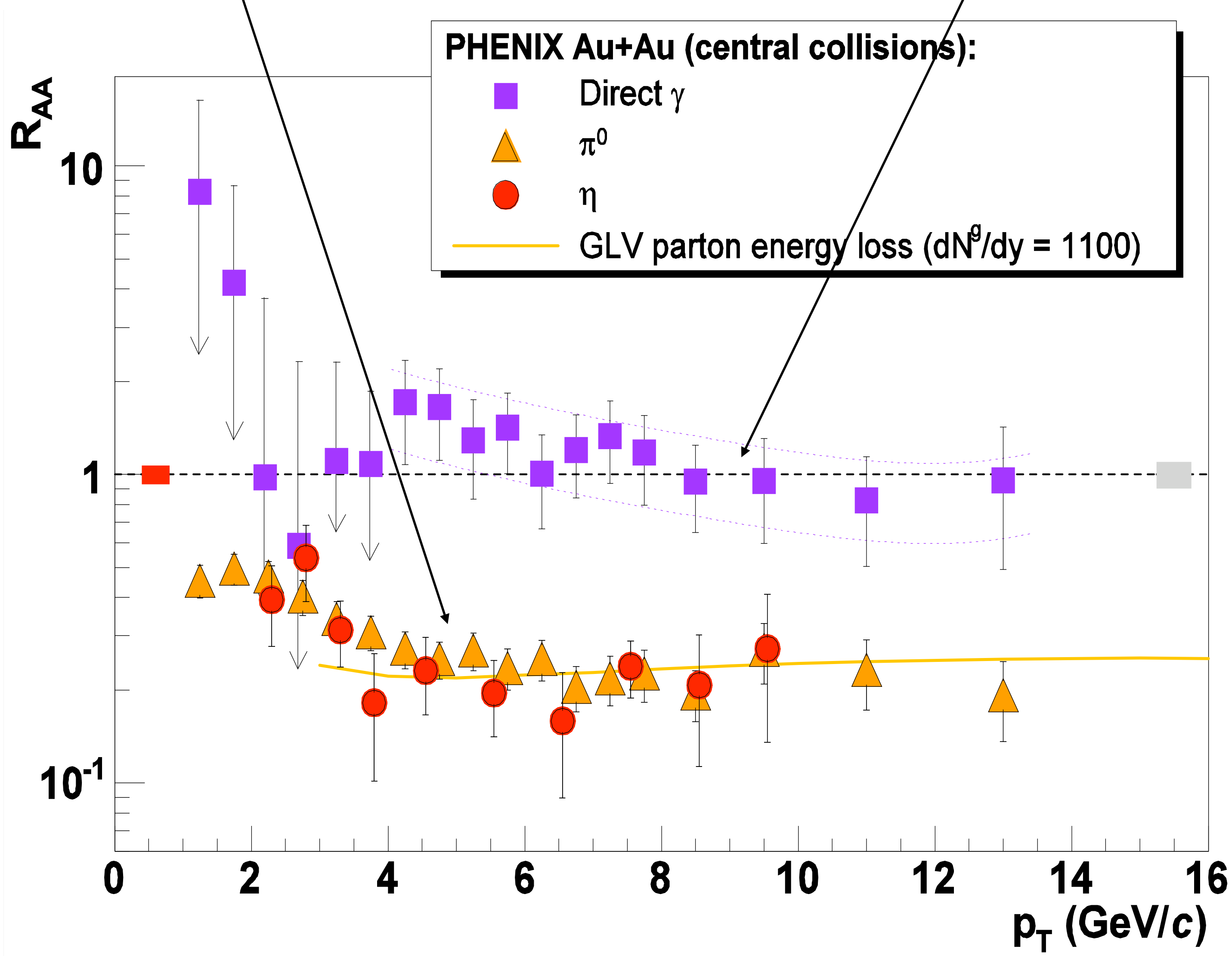
Jet quenching in Au+Au

No suppression for photons

Suppression of hadrons



Yield in A+A

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T dy}{T_{AA}\left(d^2\sigma_{NN}/dp_T dy\right)}$$

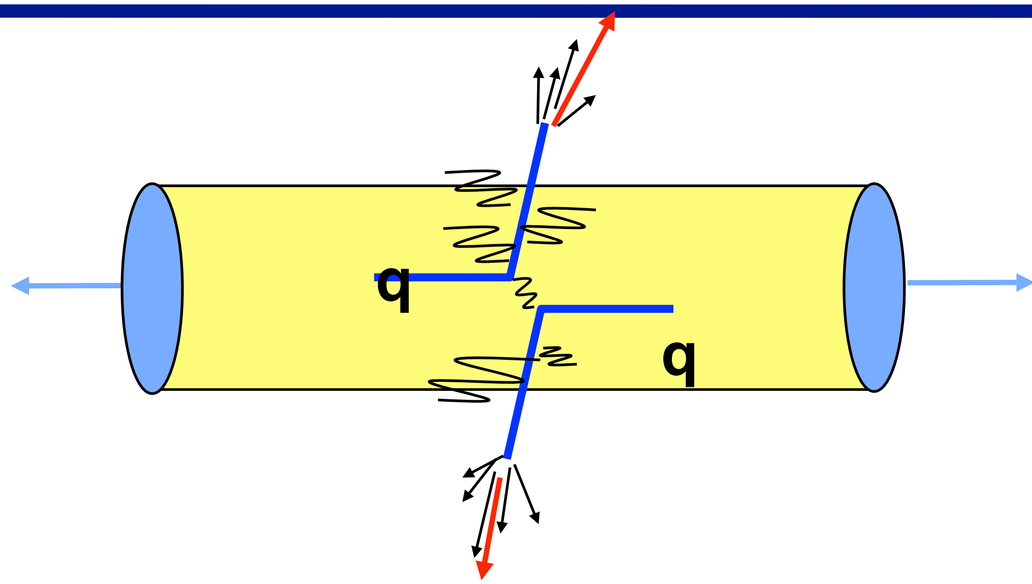
Area density of p+p coll's in A+A

Cross section in p+p coll's

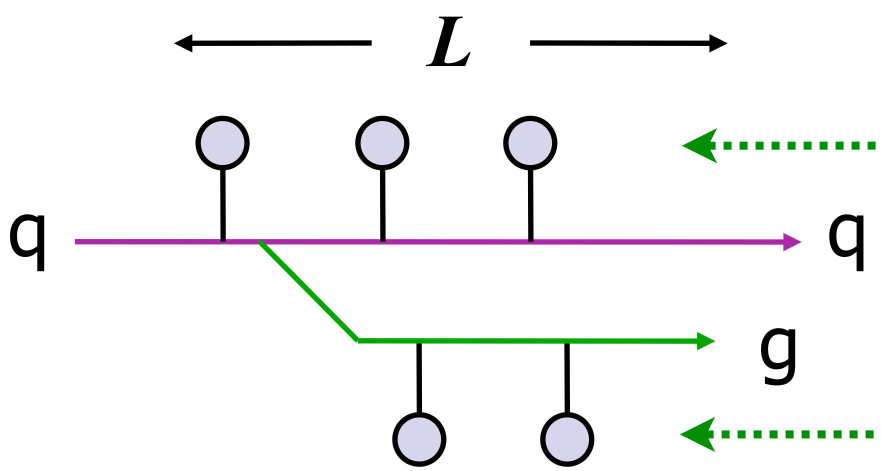
Without nuclear effects:

$R_{AA} = 1$.

Radiative energy loss



$$\Delta E \sim \rho L^2 \left\langle k_T{}^2 \right\rangle$$



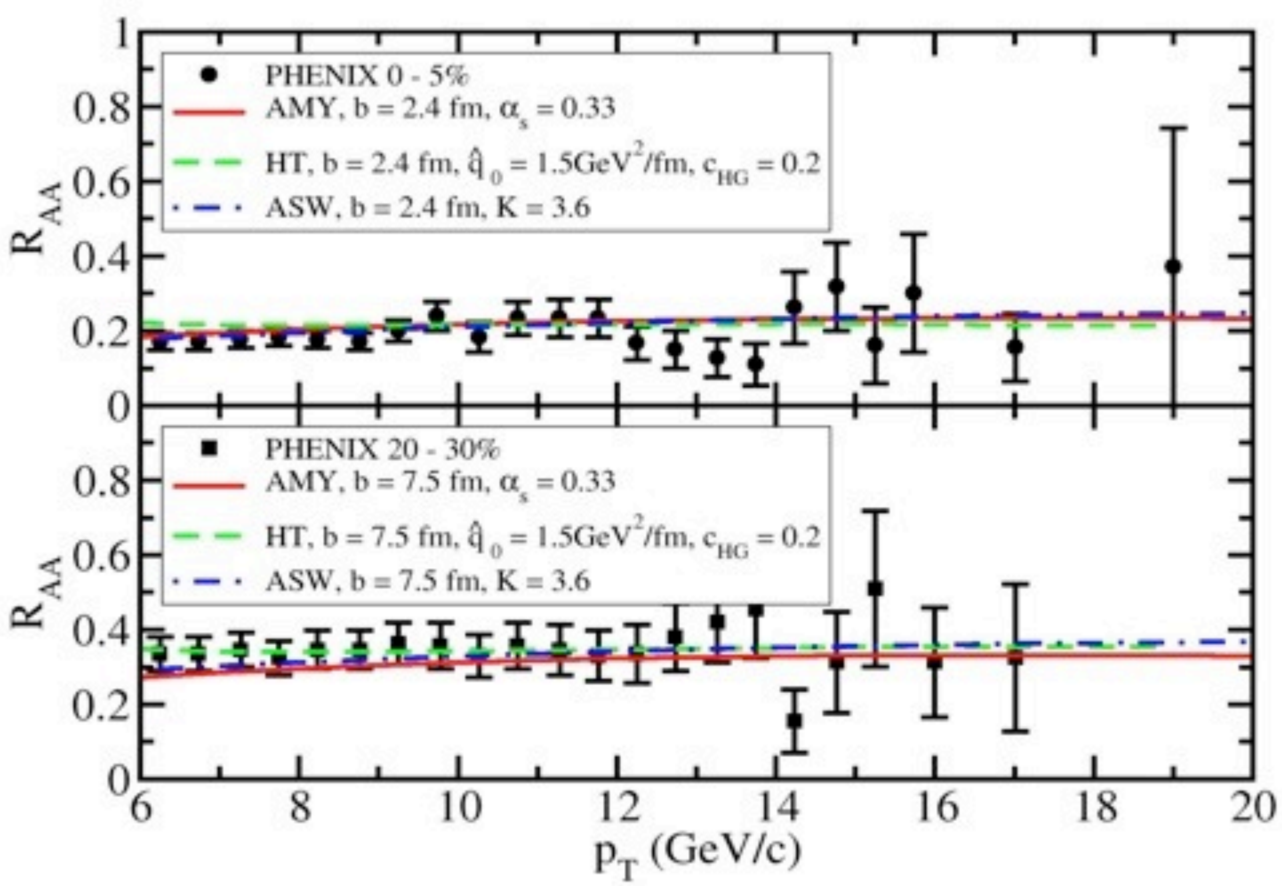
Scattering centers
= color charges

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

Towards measuring $\hat{q}$

Good fits for light hadrons are obtained for all rad. energy loss models in 3-D hydrodynamics

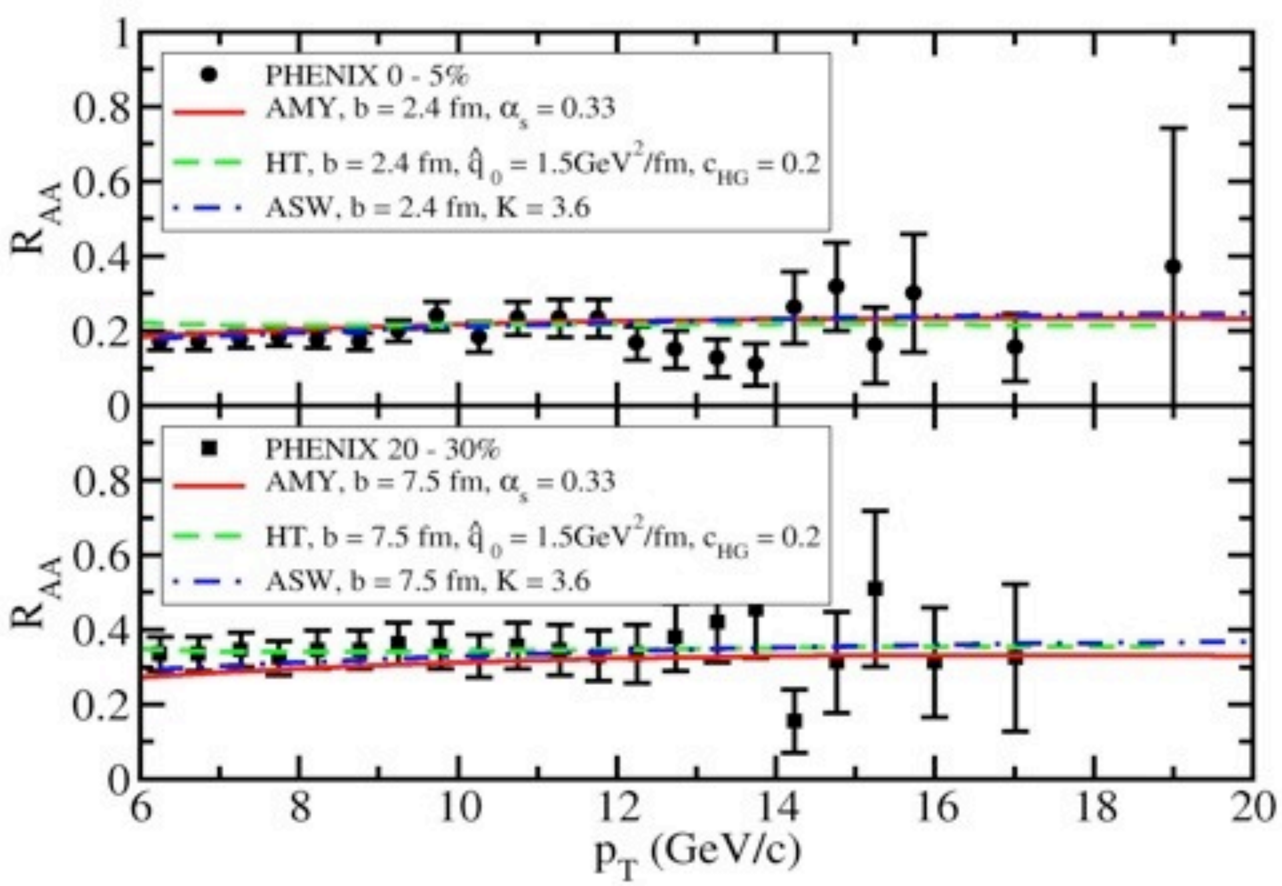
Bass, Gale, Majumder, Nonaka, Qin, Renk & Ruppert



Towards measuring $\hat{q}$

Good fits for light hadrons are obtained for all rad. energy loss models in 3-D hydrodynamics

Bass, Gale, Majumder, Nonaka, Qin, Renk & Ruppert



Transport parameter $\hat{q}$ deviates by more than factor 2 between different implementations.

Caused by differences in the cut-offs in collinear approximation used in all implementations of gluon radiation.

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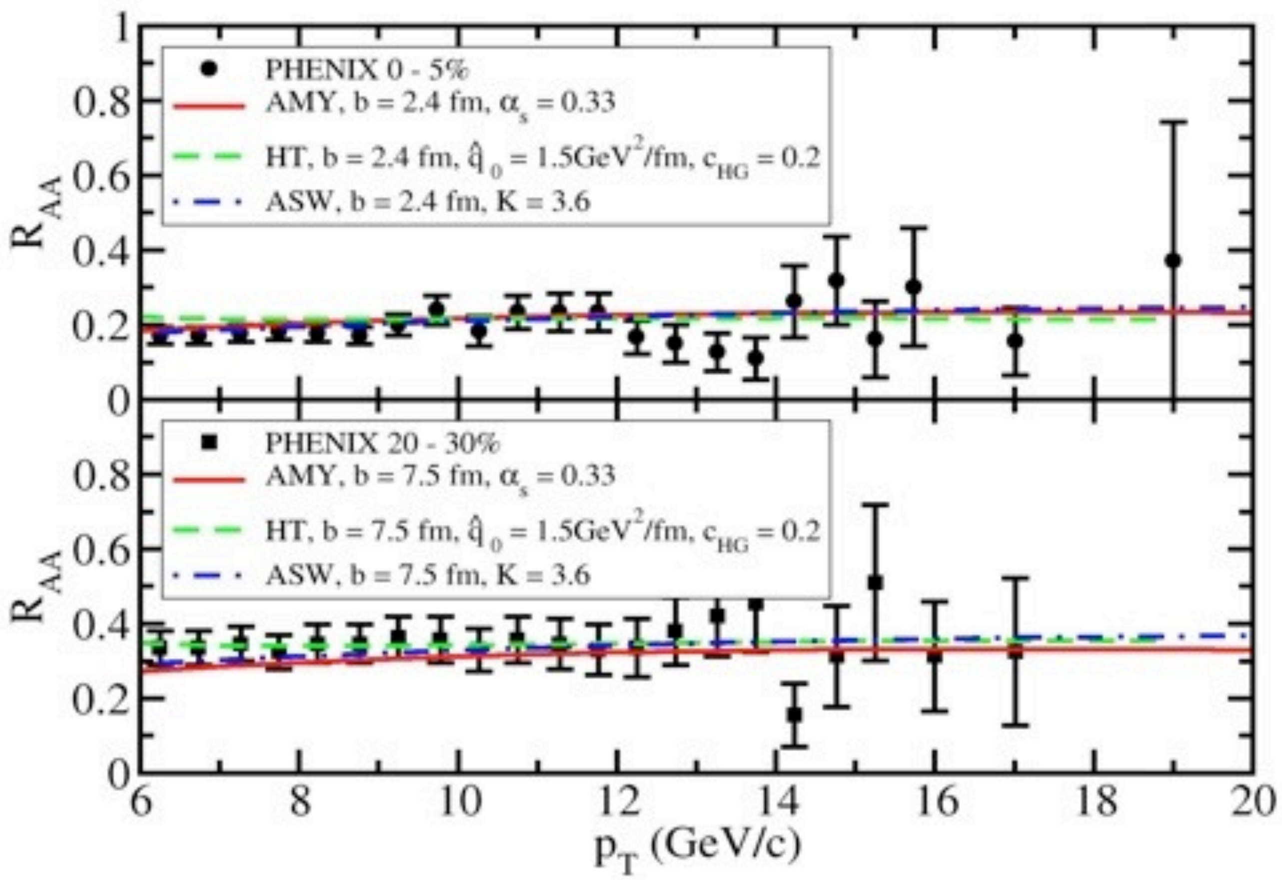


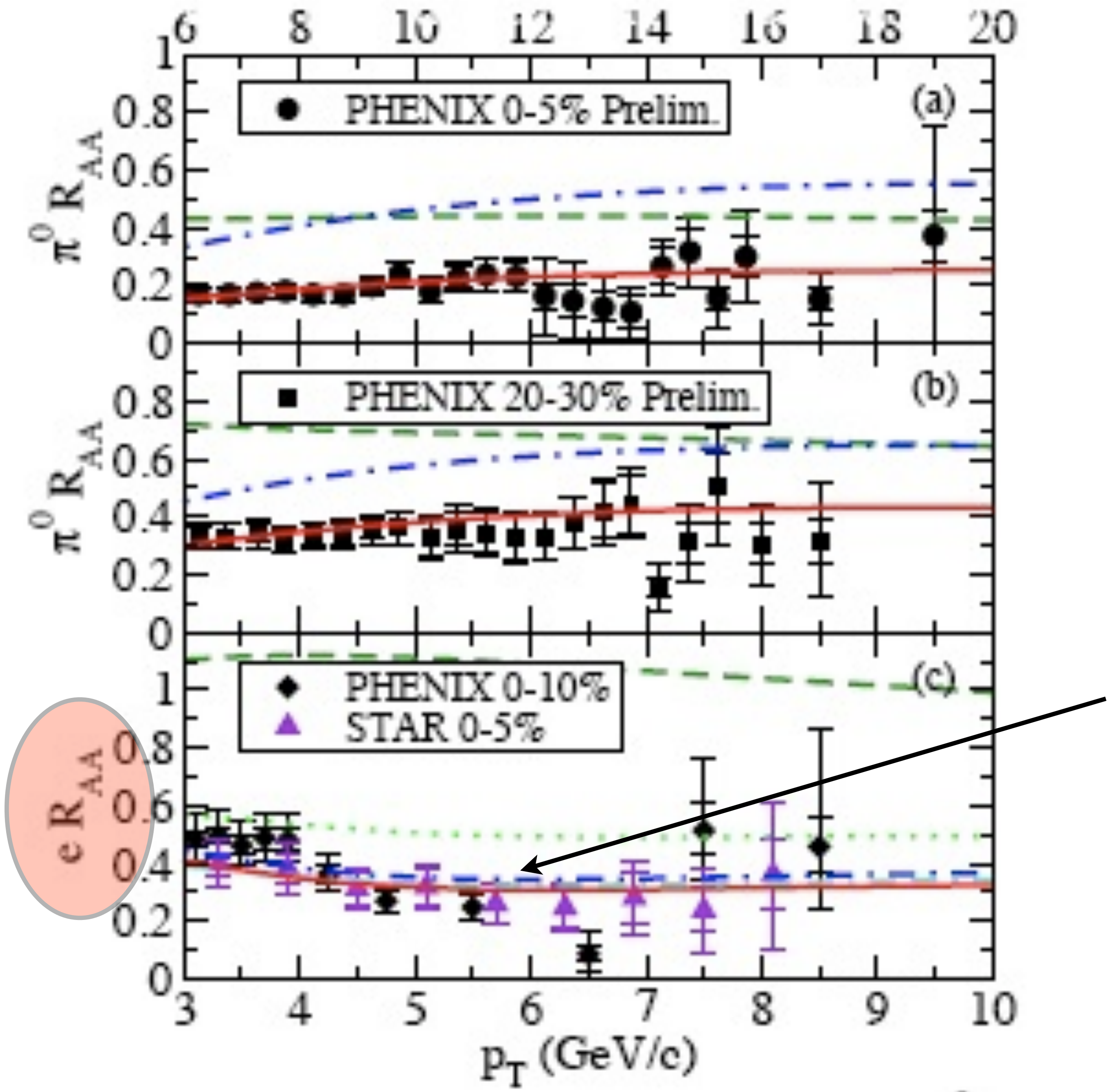
Transport parameter $\hat{q}$ deviates by more than factor 2 between different implementations.

Caused by differences in the cut-offs in collinear approximation used in all implementations of gluon radiation.

Generalized, robust new approach needed.

The heavy quark conundrum

GY Qin & A Majumder



Heavy quark (c, b) energy loss deduced from suppression of weak decay electron spectrum

Suppression stronger than expected.

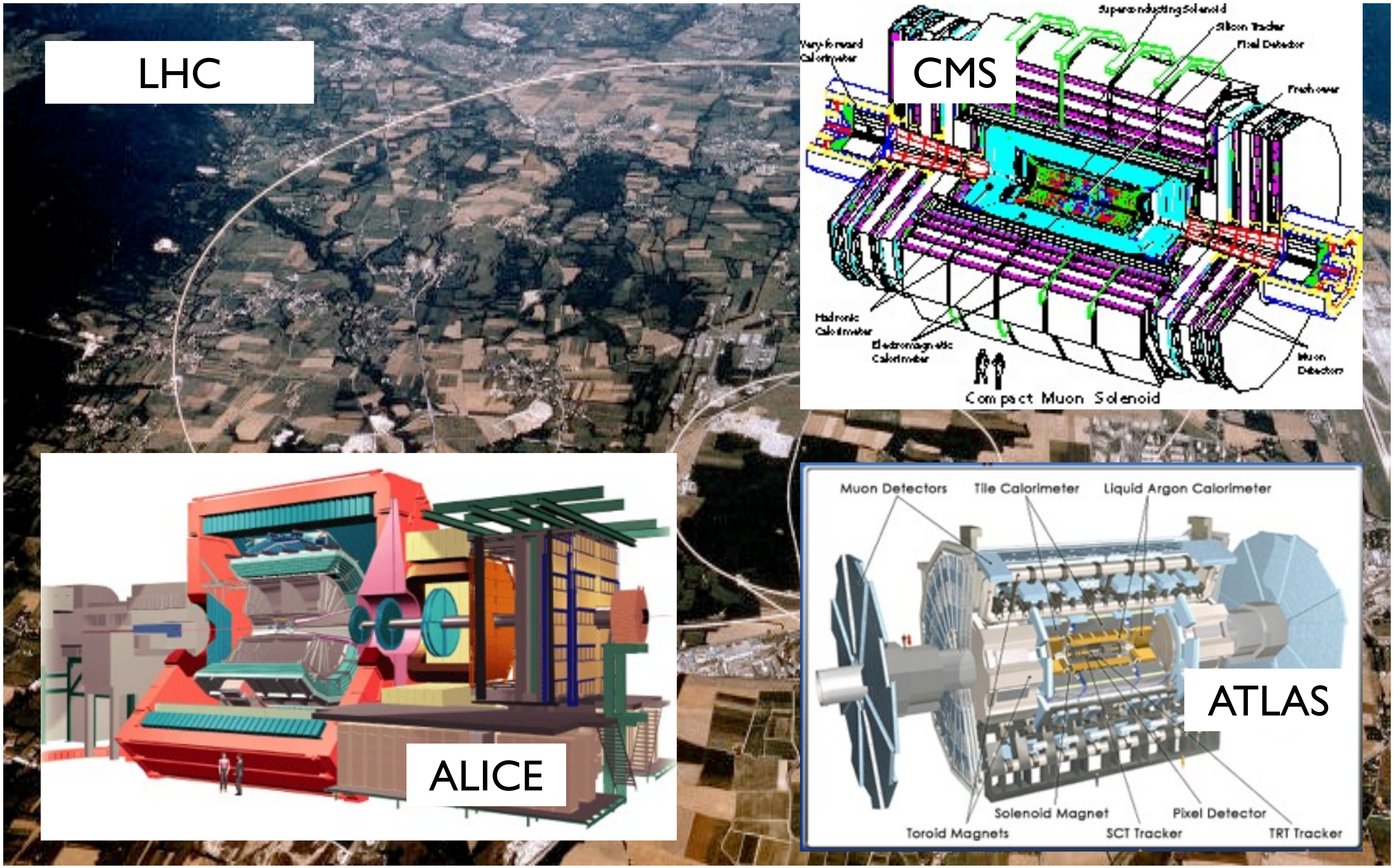
3 parameters: $\hat{q}, \quad \hat{e}, \quad \hat{e}_2$

Fit: $\frac{\hat{q}_c}{\hat{q}_{u/d/g}} \approx 1.1 \quad \frac{\hat{q}_b}{\hat{q}_{u/d/g}} \approx 1.6$

contrary to expectations for a weakly coupled QGP.

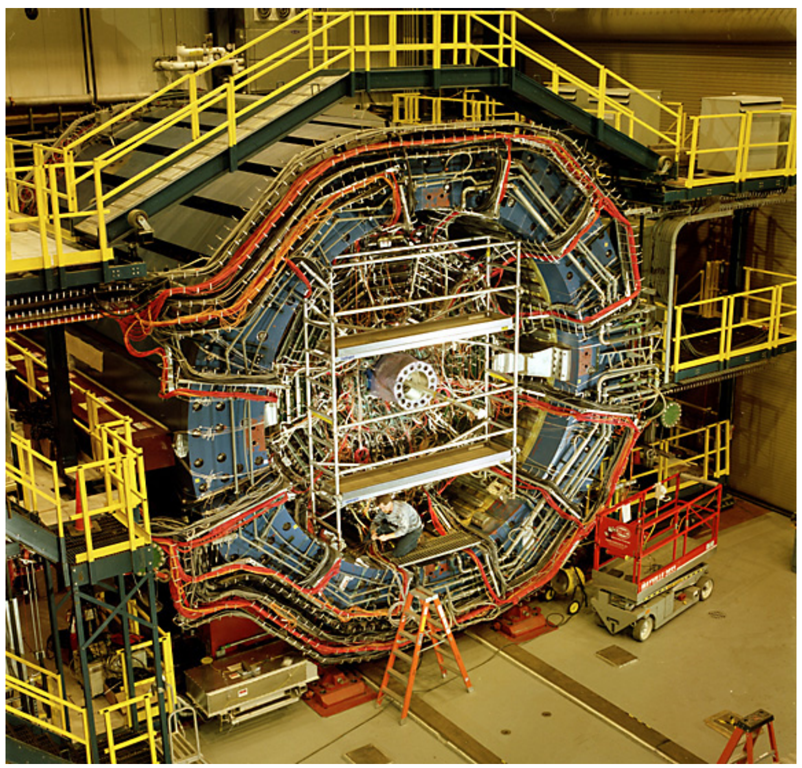
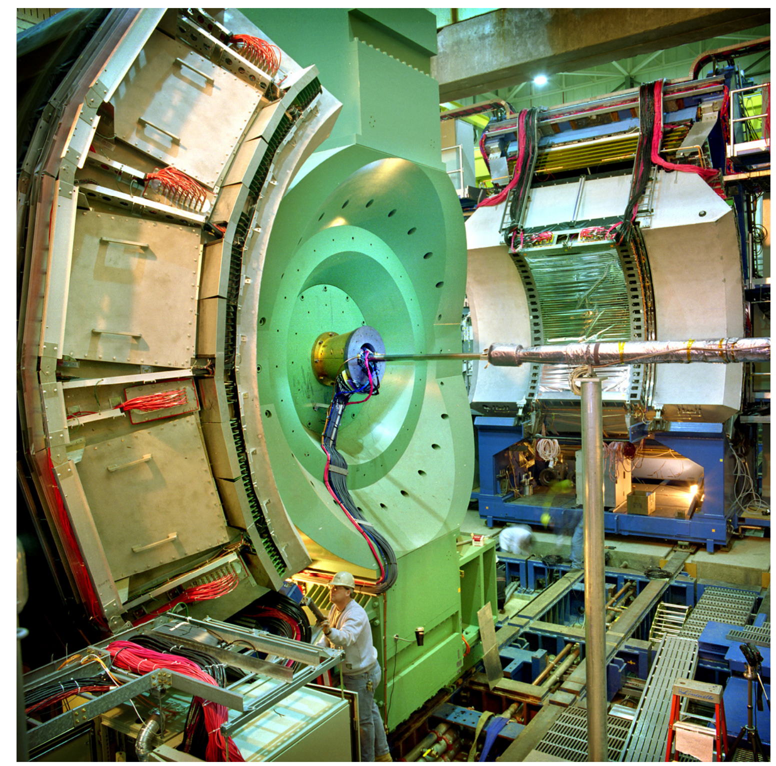
Toward higher energies…

Toward higher energies…



Toward rarer probes

RHIC detector upgrades

STAR		PHENIX
		
forward meson spectrometer	-completed –	hadron blind detector
DAQ & TPC electronics Time of Flight barrel	ongoing	muon Trigger silicon vertex barrel (VTX)
heavy flavor tracker barrel silicon tracker forward tracker	in preparation	forward silicon forward EM calorimeter

Toward more powerful theory

Toward more powerful theory

https://wiki.bnl.gov/TECHQM/index.php/Main_Page

Toward more powerful theory

https://wiki.bnl.gov/TECHQM/index.php/Main_Page

NSF

Duke UNIVERSITY

MICHIGAN STATE UNIVERSITY

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Renci Renaissance Computing Institute

http://mo.pa.msu.edu/~scottepratt/madai/

Toward more powerful theory

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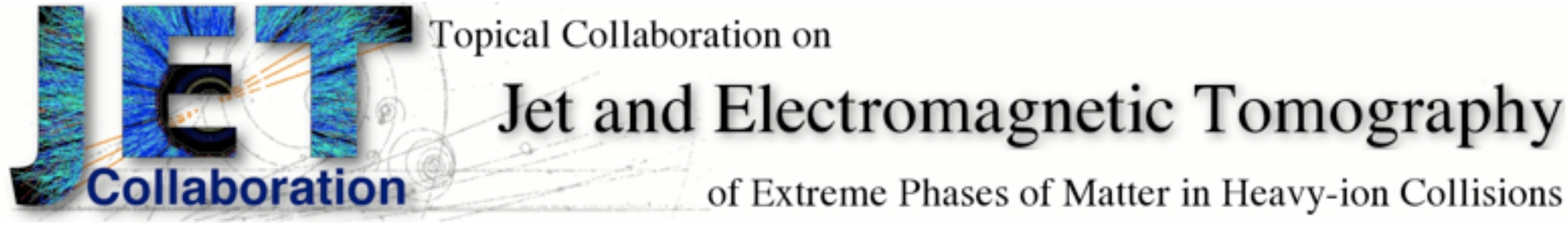

http://www-nsdth.lbl.gov/jet/

The challenge

The challenge

Can we beat the deadline
and prove that
the world was once
(*13.7 × 10^9 years ago*)
a perfect fluid ?

Observables revisited

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data ?

$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$ **Equation of state**: spectra, collective flow

$c_s^2 = \partial p / \partial \varepsilon$ **Speed of sound**: multiparticle correlations

$\eta = \frac{1}{T} \int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$ **Shear viscosity**: anisotropic collective flow

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

Momentum/energy diffusion:
parton energy loss
modified jet fragmentation

Color screening: Quarkonium states

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Serious theoret. develop-ments needed

$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{a+i}(y^-) F_i^{a+}(0) \rangle$$

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Momentum/energy diffusion:
parton energy loss
modified jet fragmentation

$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln \langle E^a(x) E^a(0) \rangle$ — **Color screening**: Quarkonium states

Challenge #1

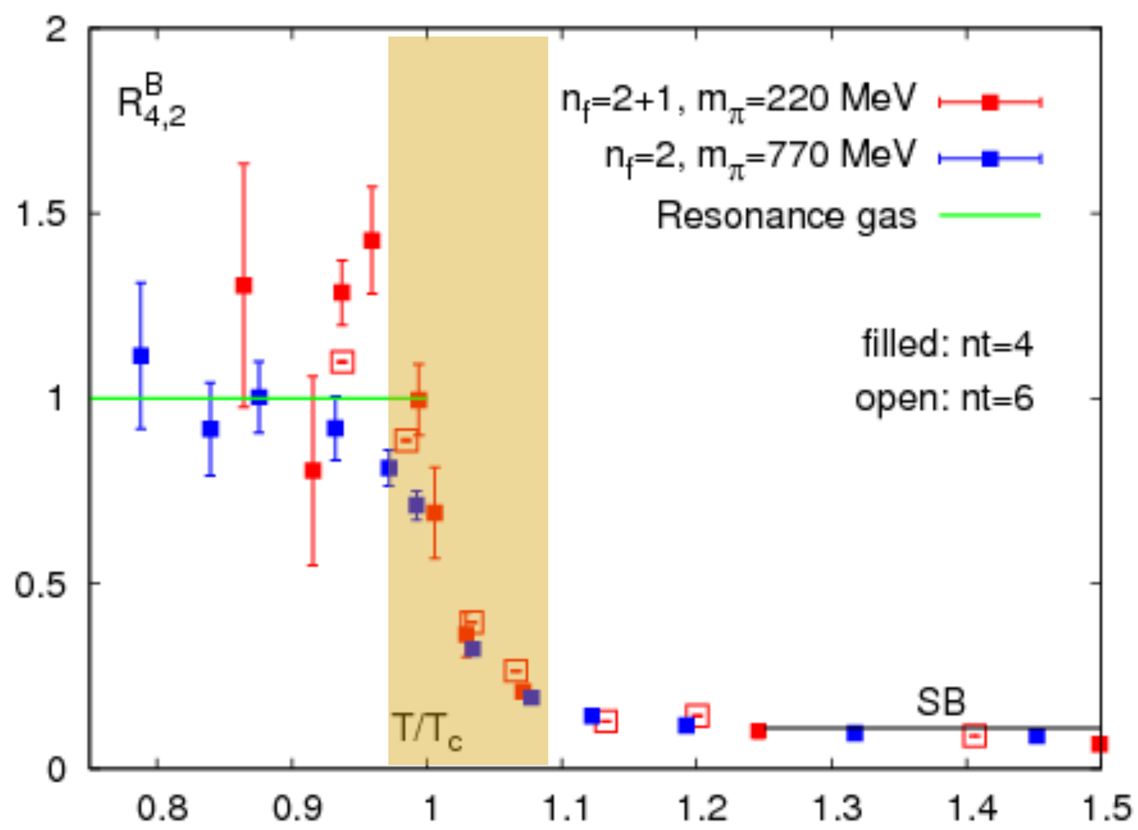
The Strong Coupling
“Conundrum”

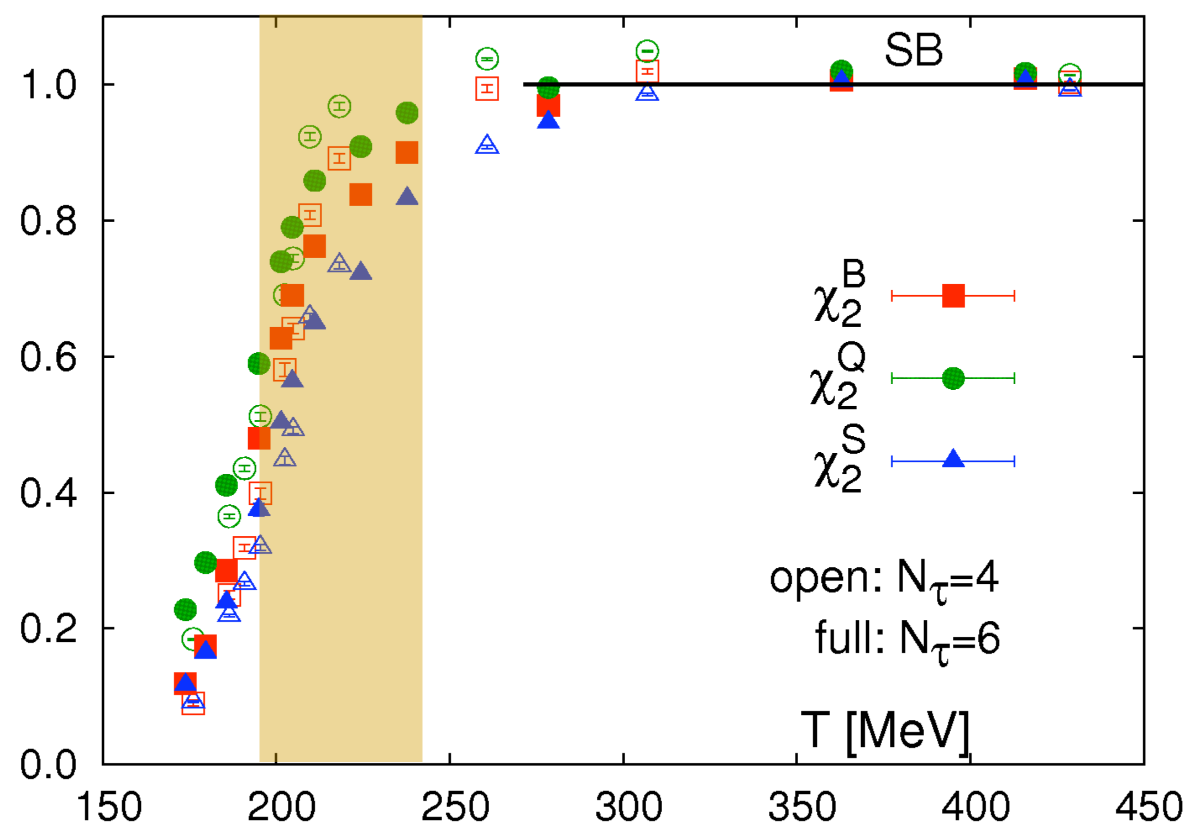
Conserved charges

$$R_{4,2}{}^{B} = \frac{1}{9}\frac{c_4}{c_2} \qquad \frac{c_4^q}{c_2^q} = \frac{\langle(\delta N_q)^4\rangle}{\langle(\delta N_q)^2\rangle} - 3\langle(\delta N_q)^2\rangle$$

B = baryon number
Q = electric charge
S = strangeness

Baryon number kurtosis

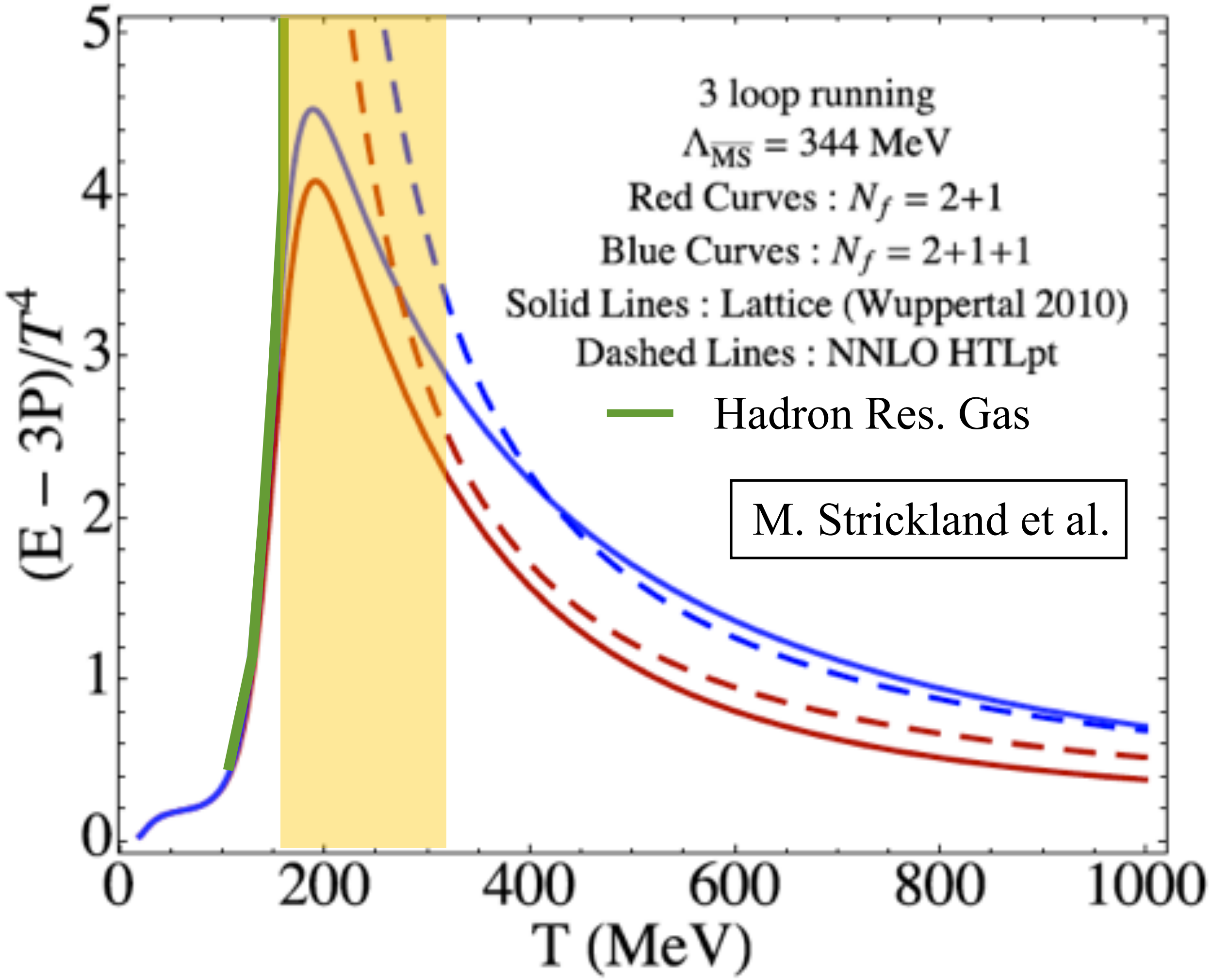


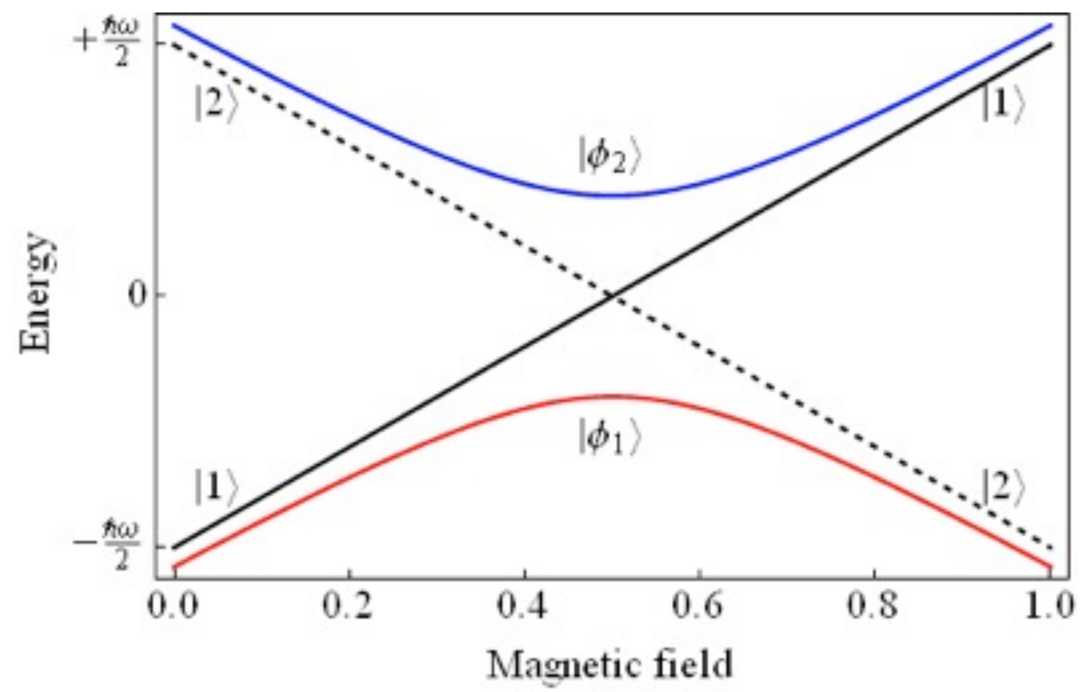


Question: Are these properties compatible with "strong coupling"? Is the dependence of thermodynamic quantities on conserved quantum numbers "oblivious" to interactions?

Crossing the "wall"?

Possible scenario:
HRG works up to 0.9 T_c ;
HTL-QGP works above 2 T_c
or even lower.





Is there an analogy to the Landau-Zener formula of ordinary QM in QFT ?

Can one construct a model in which the transition between two quasi-particle regimes occurs smoothly by "mixing" ?

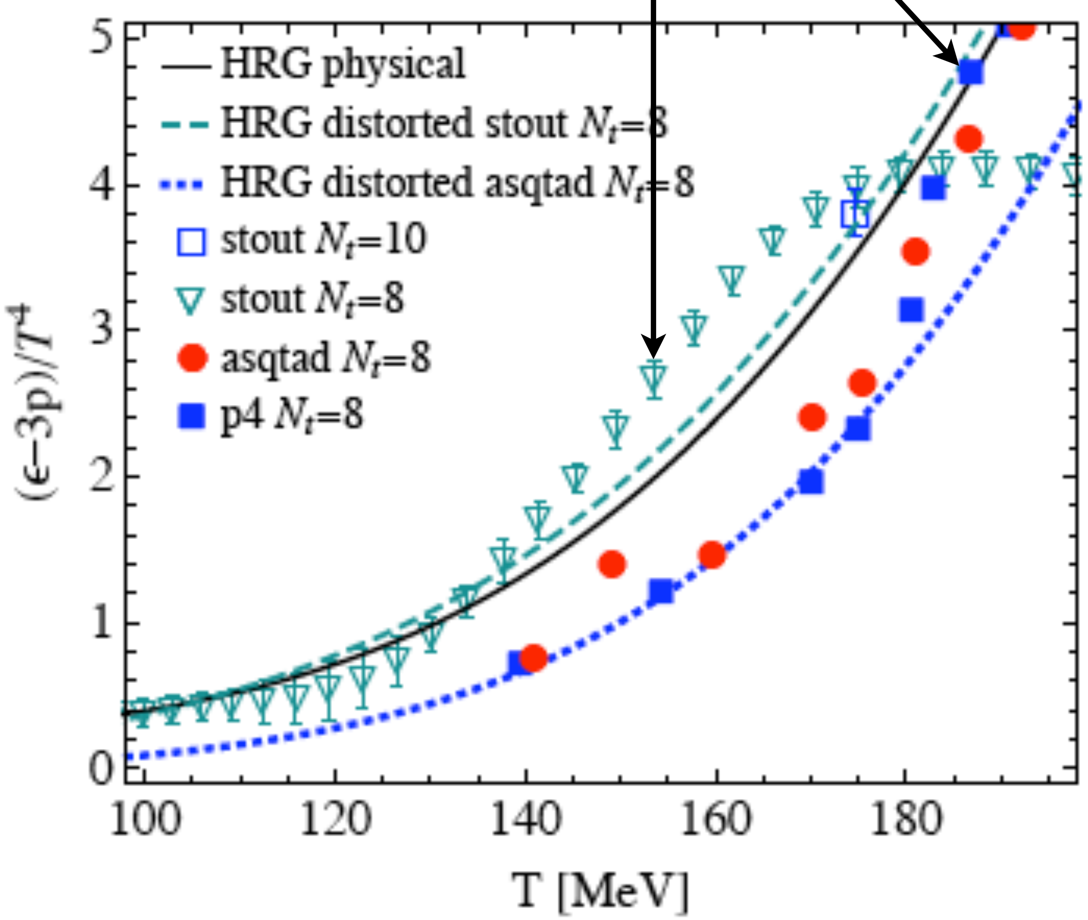
Can the transition be explained without a need for "strong coupling" ?

Exploring the hadron mass spectrum

Lines: Hadron resonance gas (HRG)

Data points: Lattice QCD

LQCD lies above HRG for T > 140 MeV



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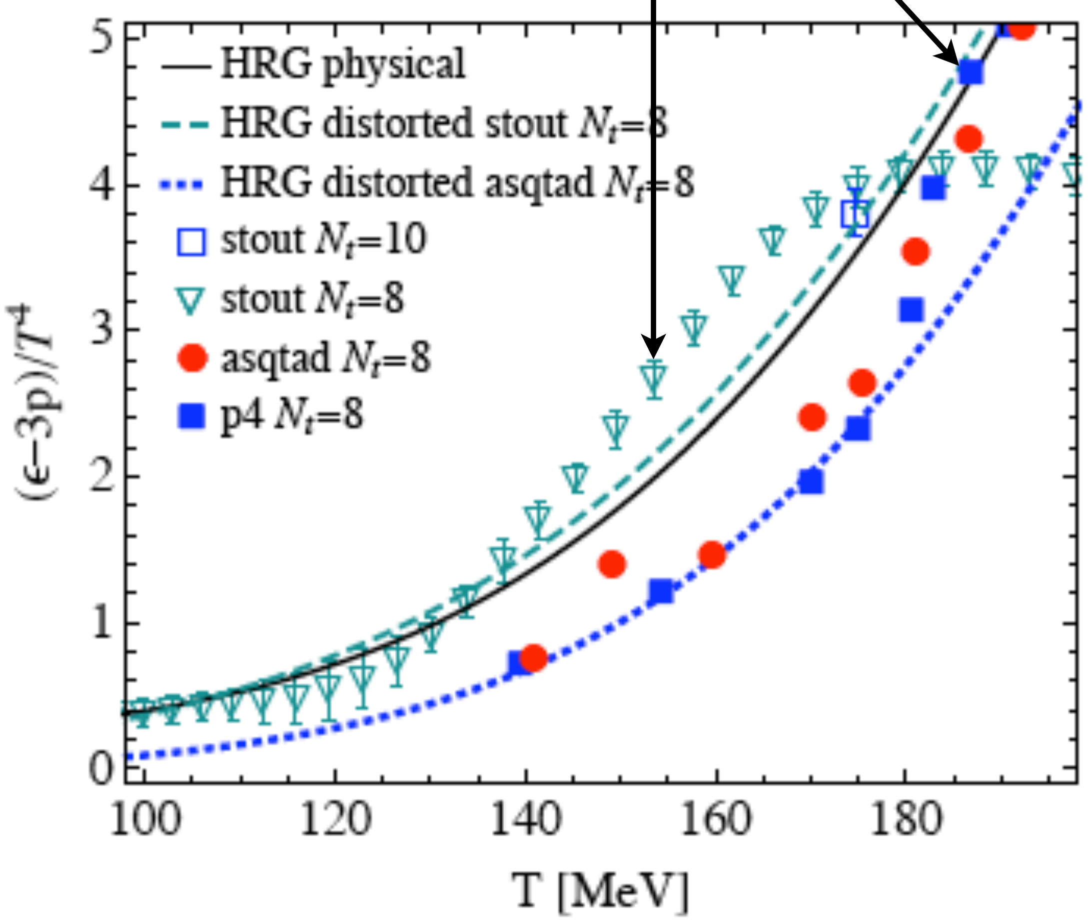


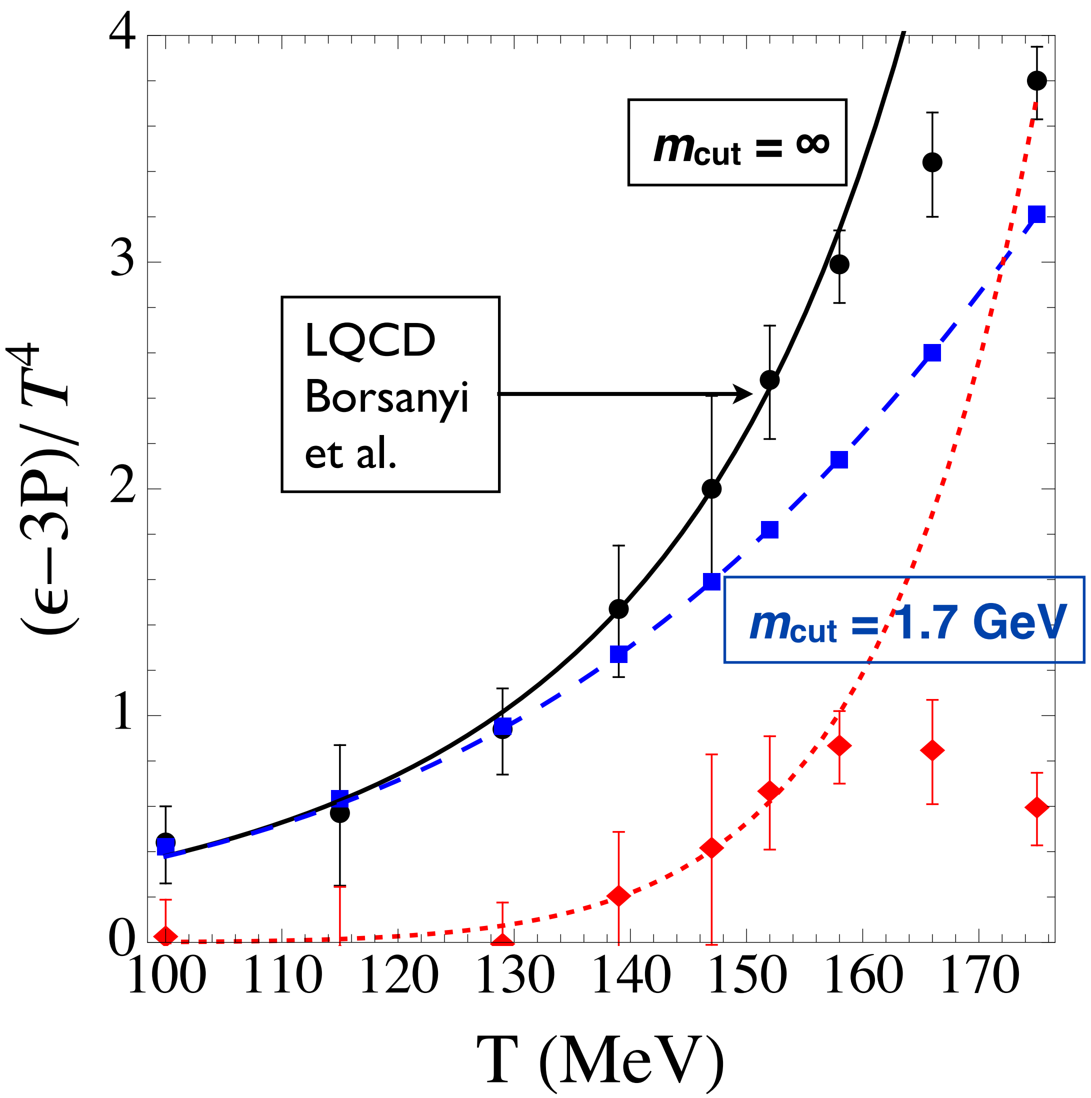
Three possible explanations:

1. Lattice artifact
2. Hadronic interactions
   (e.g. in-medium mass changes)
3. Many presently unknown hadrons with masses > 1.7 GeV

($\varepsilon-3p$) measures the level density of massive hadronic excitations of the QCD vacuum. Are there many more Baryons? Hybrids? Glueballs?

Note:The JLab (Halls B & D) program studies precisely this question!

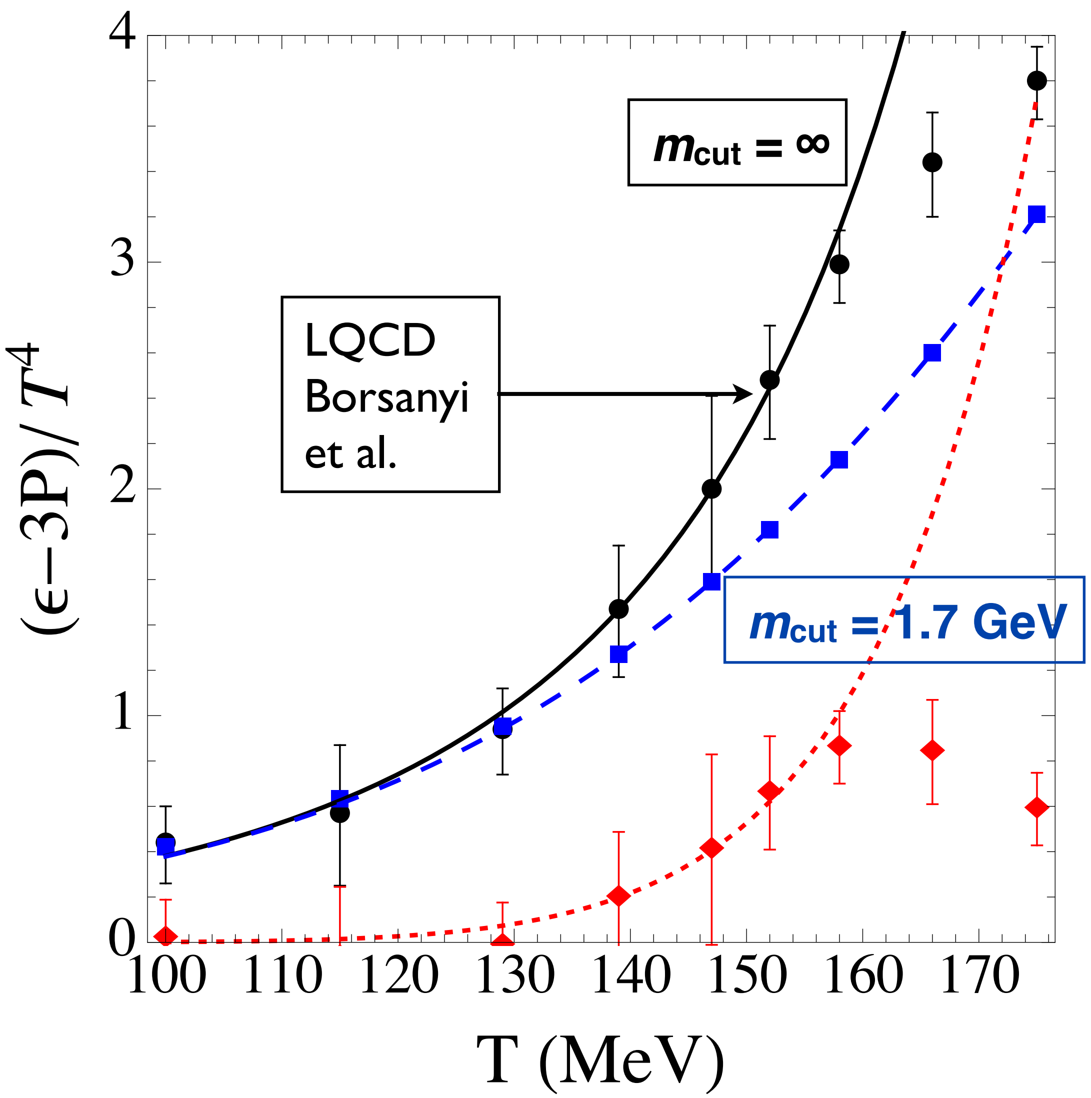
LQCD & hadron spectrum



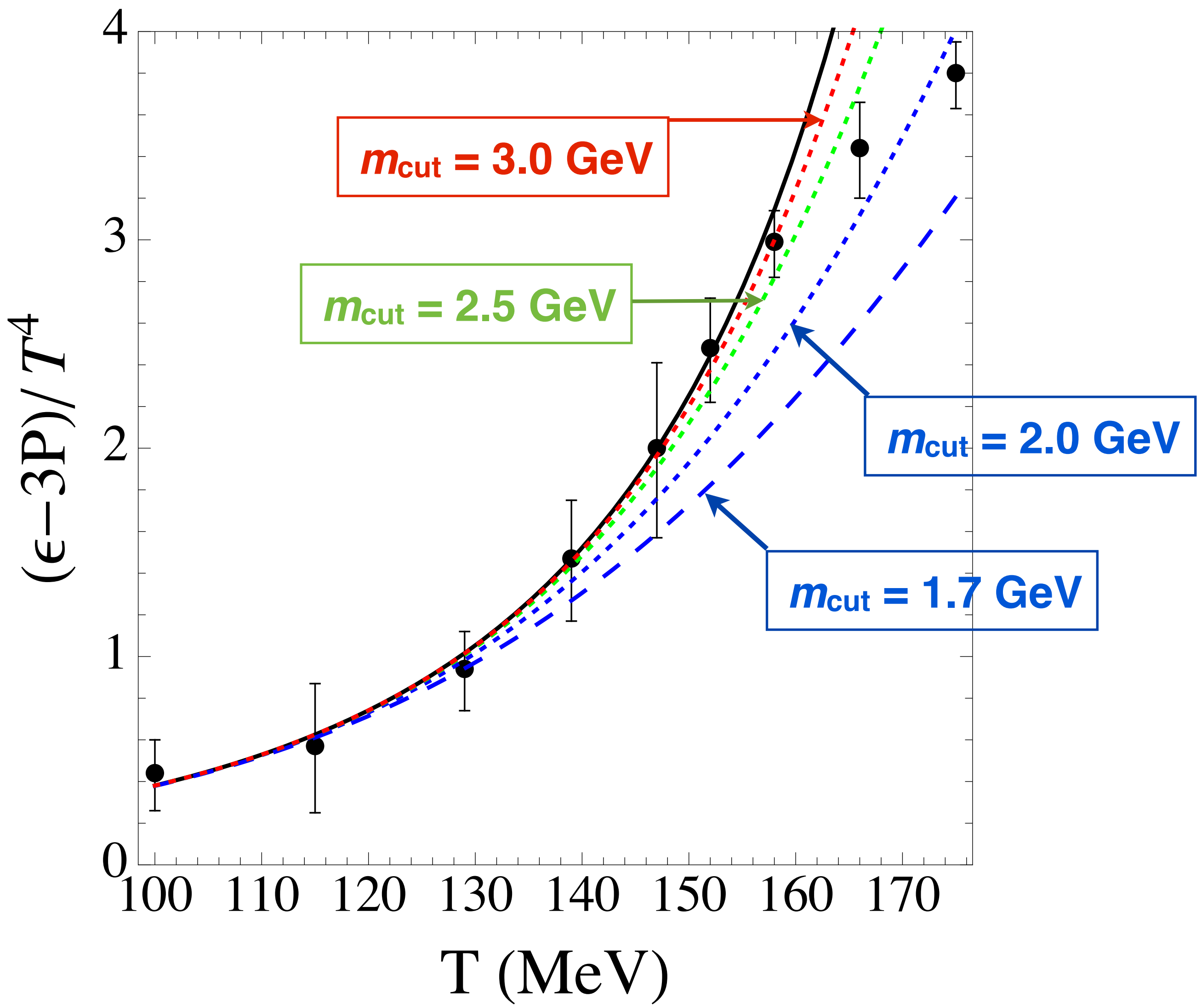
$$\rho(m) = A\, e^{bm}$$

A. Majumder & B.M. (arXiv:1008.1747)

LQCD & hadron spectrum



Hadrons up to at least 2.5 GeV (maybe 3 GeV) mass contribute



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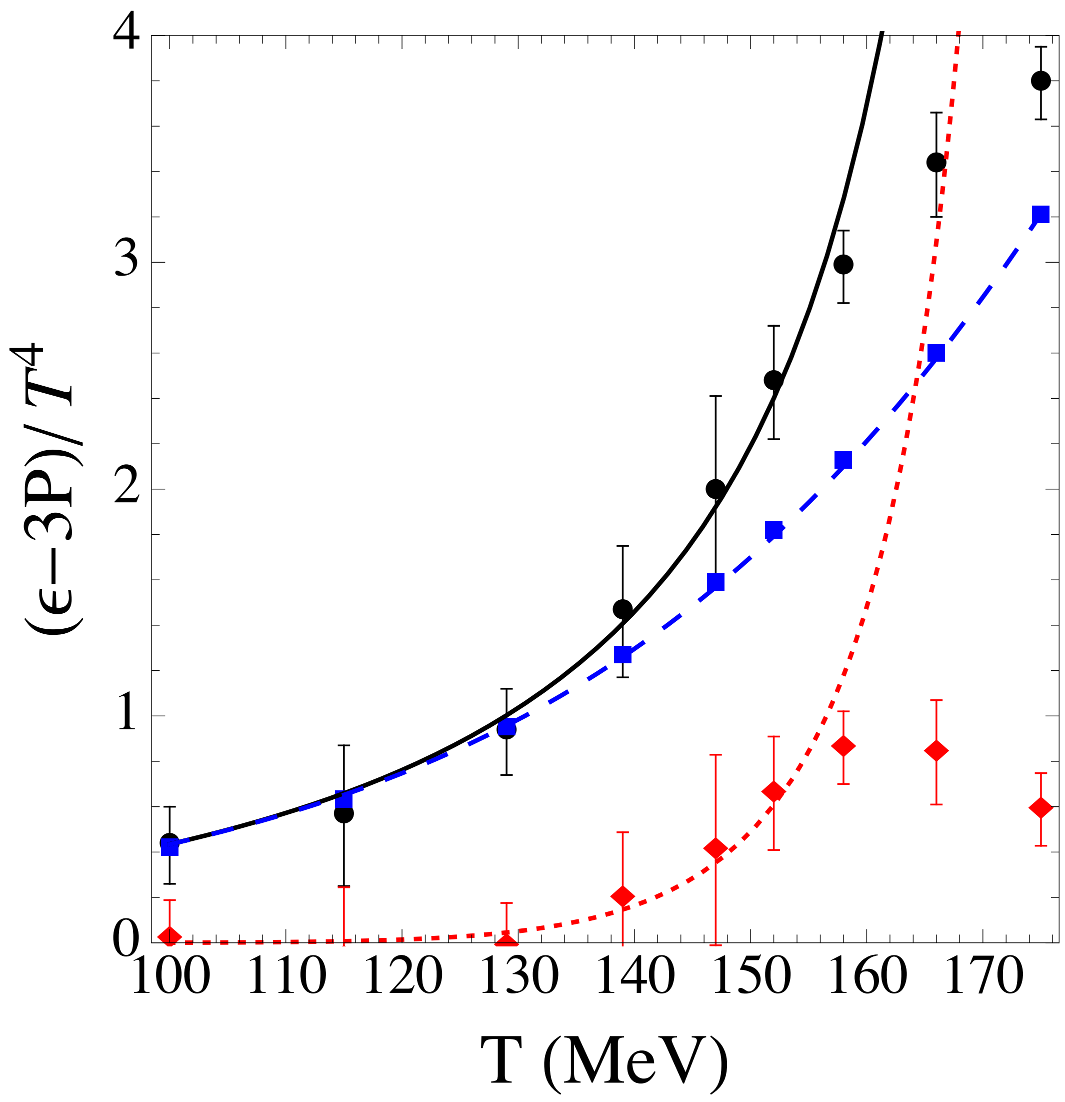

$$\rho(m) = A\ (m^2+m_0^2)^{-5/4}\ e^{bm}$$

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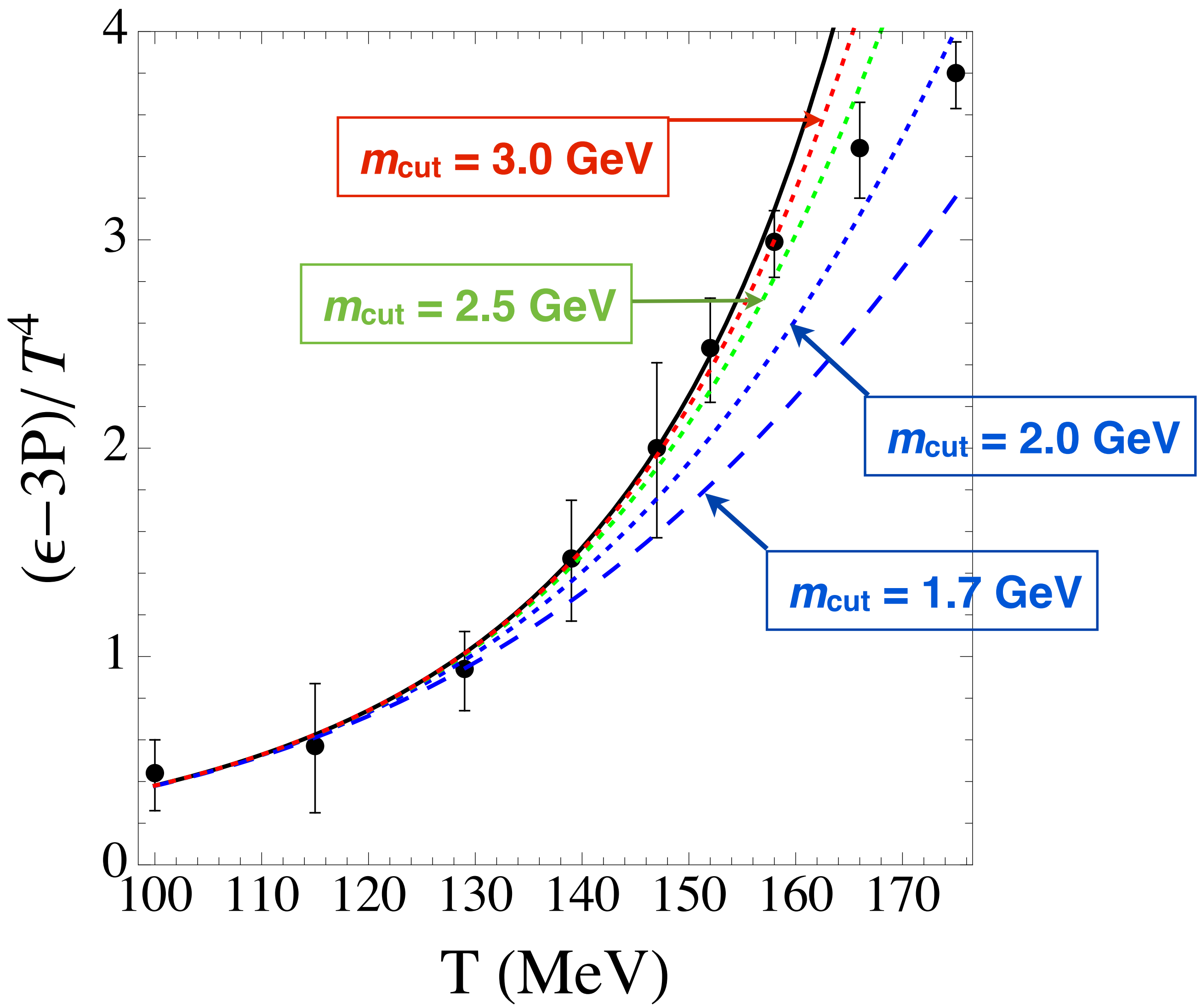

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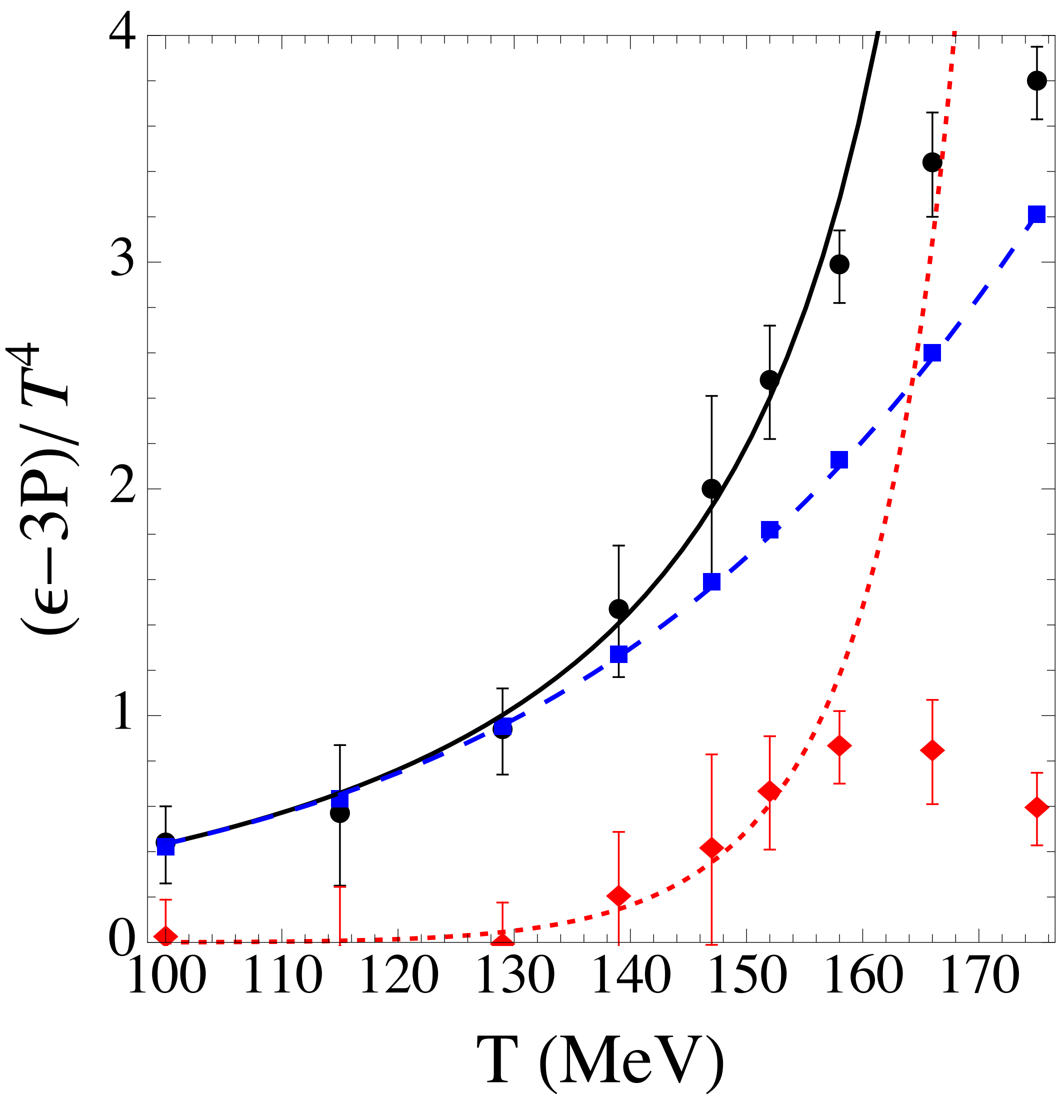

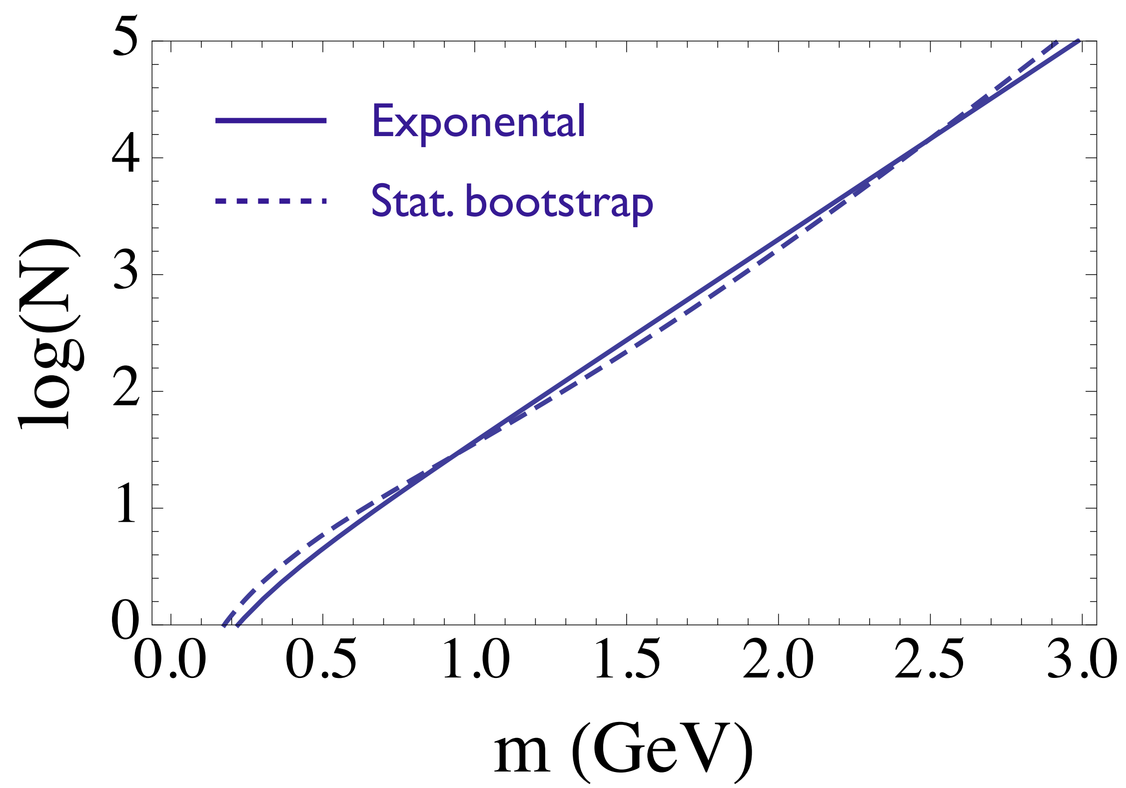

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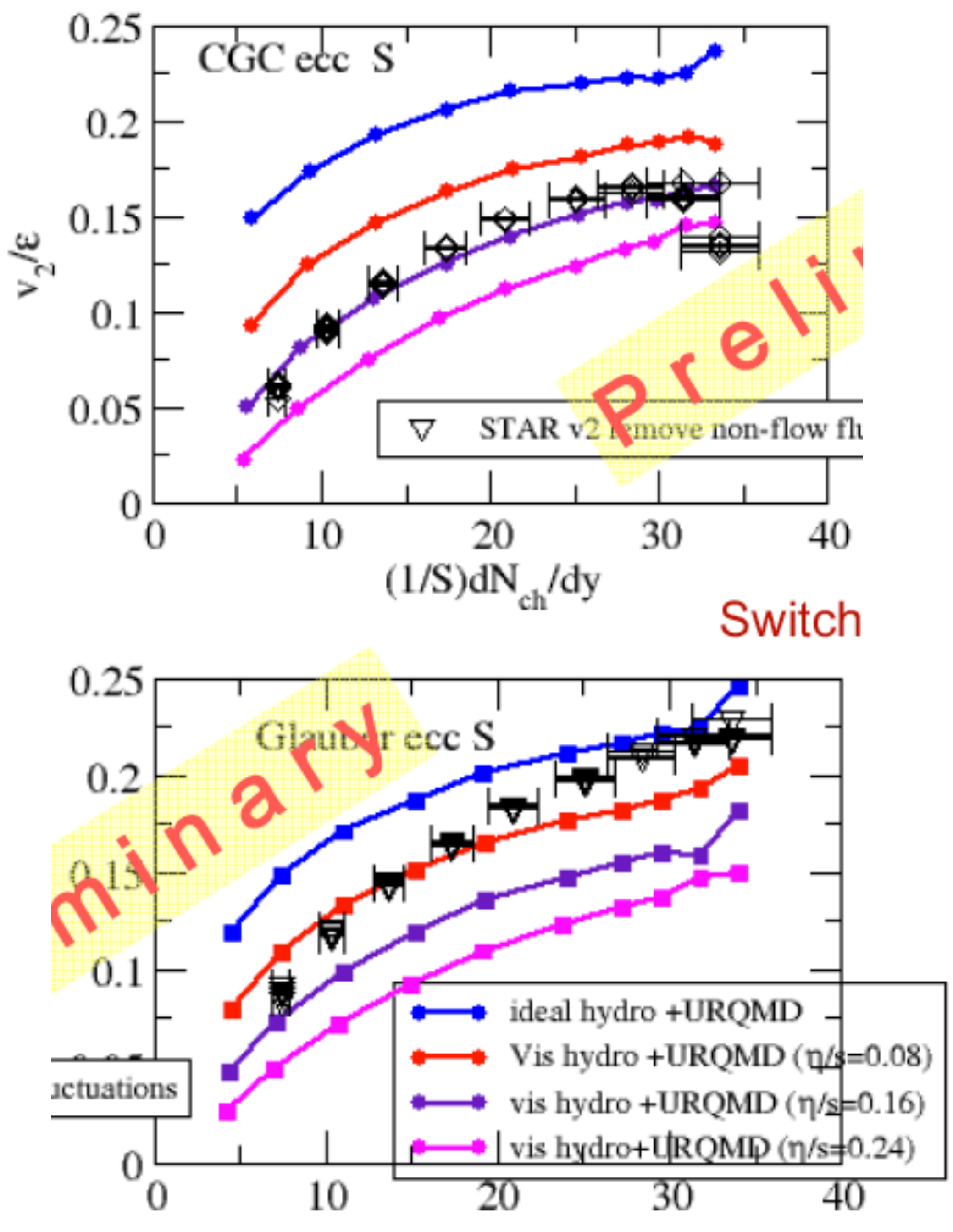
Challenge #2

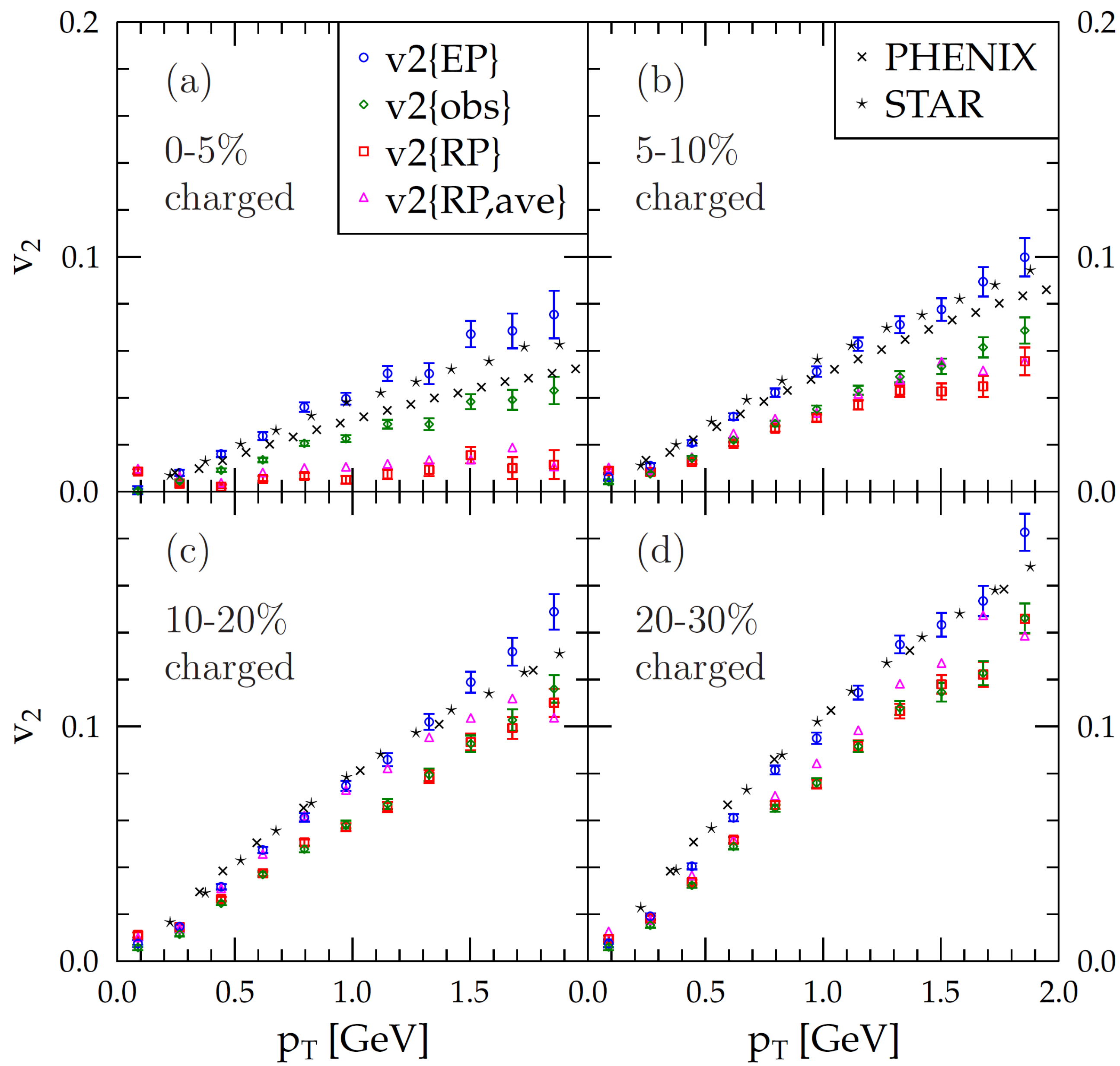
The Perfect Fluid

Deducing η/s from the data

H. Song, U. Heinz, et al.



K.Eskola, H. Holopainen, H. Niemi



Deducing η/s from the data

Five effects have been identified as important ingredients:

- Shear viscosity
- Equation of state
- Differential freeze-out
- Initial transverse profile
- Initial-state fluctuations

Any compelling extraction of η/s from the data must account for **all five** !

Multiple dependencies require more than v_2 data; also spectra, identified particle data, HBT, etc.

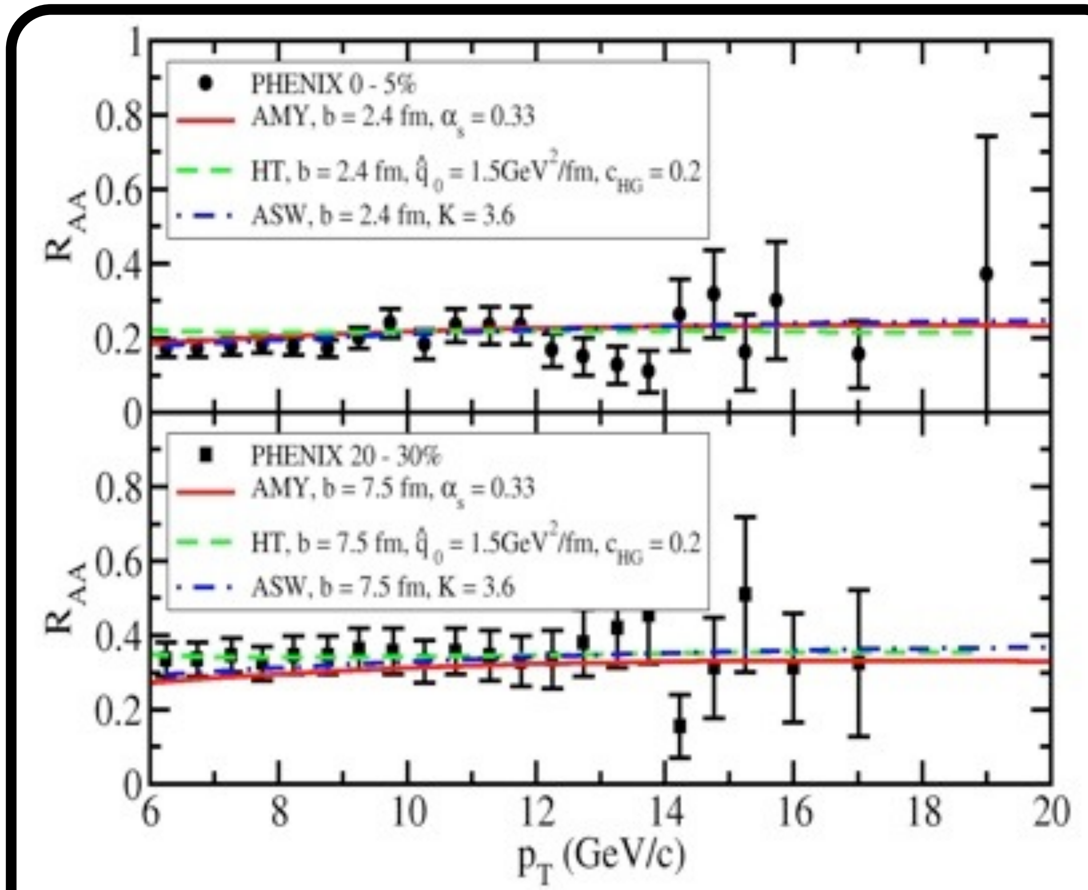
In other words, global description of bulk “soft” observables.

MADAI collaboration will do it - but a competitor would be good.

Challenge #3

Jet quenching

Deducing q^ from the data



same 3D-hydro medium, 3 different schemes:

- R_{AA} in (semi-)central collisions is well described by all jet energy-loss schemes
- parameters reflect response of medium structure hard-wired into schemes
- large variation in extracted q-hat: 4-18 !!

How does the transport coefficient scale with the thermodynamic properties of the medium? Does the choice of T, ε or s matter?

- EoS for ideal QGP
- common choices for scaling:

  $\hat{q} \sim T^3$ $\hat{q} \sim \varepsilon^{3/4}$ $\hat{q} \sim s$

- for non-ideal EoS, value is affected by choice of scaling variable!

q_0 [GeV²/	ASW	HT	AMY
T	10	2.3	4.1
ε	18.5	4.5	X
s		4.3	X

Deducing *q*^ from data

Any compelling extraction of *q*^ from the data requires:

- Convergence of jet quenching schemes
- Improvement over eikonal-collinear approximation
- Realistic simulation of the bulk medium
- Treatment of elastic and radiative energy loss on equal terms
- Multi-gluon correlations?
- Explanation for large v_2 at large p_T

Is there a *golden channel* for energy loss theory?

B-quark energy loss at $p_T(b)$ = 50 GeV could be it: p_T , m_b , are large scales, $p_T/m_b >> 1$ ensures hadronization outside the medium.

Ideal measurement for the LHC. State of the art theory are needed !

Challenge #4

Quarkonium

Q-Qbar effective theory

Up to order $m\alpha_s^5$ [J. Ghiglieri, N. Brambilla, et al., arXiv:1007.4156]

$$\delta E_{n,l} = \frac{\pi}{9} N_c C_F\, \alpha_s^2\, T^2 \frac{a_0}{2}\left[3n^2 - l(l+1)\right] + \frac{\pi}{3} C_F^2\, \alpha_s^2\, T^2\, a_0$$
$$+ \frac{E_n \alpha_s^3}{3\pi}\left[\log\left(\frac{2\pi T}{E_1}\right)^2 - 2\gamma_E\right]\left\{\frac{4C_F^3\delta_{l0}}{n} + N_c C_F^2\left[\frac{8}{n(2l+1)} - \frac{1}{n^2} - \frac{2\delta_{l0}}{n}\right]\right.$$
$$\left. + \frac{2N_c^2 C_F}{n(2l+1)} + \frac{N_c^3}{4}\right\} + \frac{2E_n C_F^3 \alpha_s^3}{3\pi} L_{n,l}$$
$$+ \frac{a_0^2 n^2}{2}\left[5n^2 + 1 - 3l(l+1)\right]\left\{-\left[\frac{3}{2\pi}\zeta(3) + \frac{\pi}{3}\right] C_F\, \alpha_s\, T\, m_D^2\right.$$
$$\left. + \frac{2}{3}\zeta(3)\, N_c C_F\, \alpha_s^2\, T^3\right\}$$

$$\Gamma_{n,l} = \frac{1}{3} N_c^2 C_F \alpha_s^3 T + \frac{4}{3}\frac{C_F^2 \alpha_s^3 T}{n^2}(C_F + N_c)$$
$$+ \frac{2E_n \alpha_s^3}{3}\left\{\frac{4C_F^3\delta_{l0}}{n} + N_c C_F^2\left[\frac{8}{n(2l+1)} - \frac{1}{n^2} - \frac{2\delta_{l0}}{n}\right] + \frac{2N_c^2 C_F}{n(2l+1)} + \frac{N_c^3}{4}\right\}$$
$$- \left[\frac{C_F}{6}\alpha_s T m_D^2\left(\ln\frac{E_1^2}{T^2} + 2\gamma_E - 3 - \log 4 - 2\frac{\zeta'(2)}{\zeta(2)}\right) + \frac{4\pi}{9}\ln 2\; N_c C_F\, \alpha_s^2\, T^3\right]$$
$$\times\, a_0^2 n^2\left[5n^2 + 1 - 3l(l+1)\right]$$
$$+ \frac{8}{3} C_F \alpha_s\, T m_D^2\, a_0^2 n^4\, I_{n,l}$$

Lattice QCD etc:
See M. Asakawa's
and H. Satz' talks
next week.

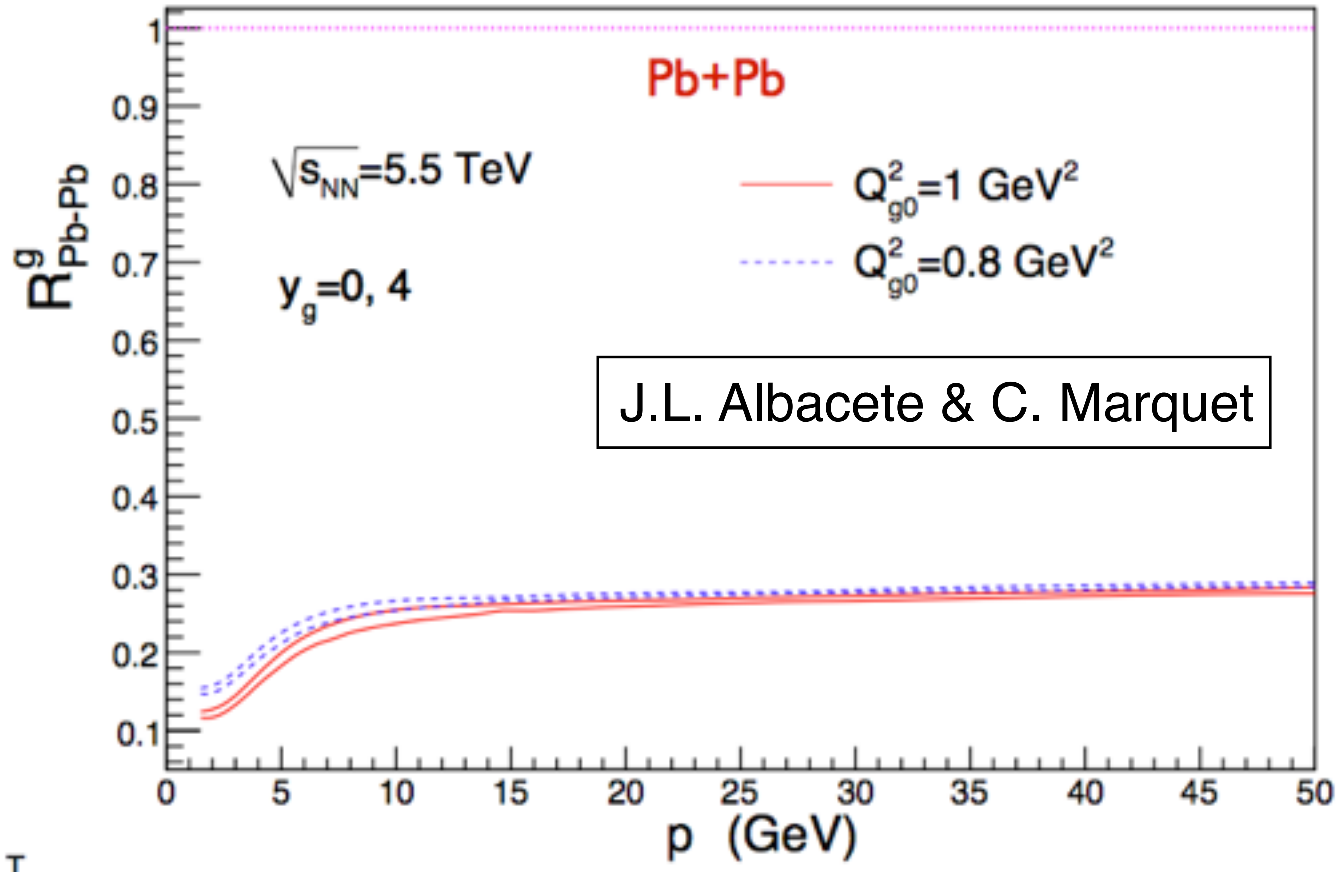
Challenge #5

CGC or not CGC

...that is the question...

Gluon shadowing

Nuclear gluon density suppression at LHC in the NLO CGC formalism.



Critical (?) test:

Calculate direct photon yield in Pb+Pb at p_T = 30 GeV/c in

- the k_T-factorized NLO CGC formalism;
- the collinear pQCD formalism with HT-generated shadowing;
- other formalisms.

Should be done before LHC data become available!

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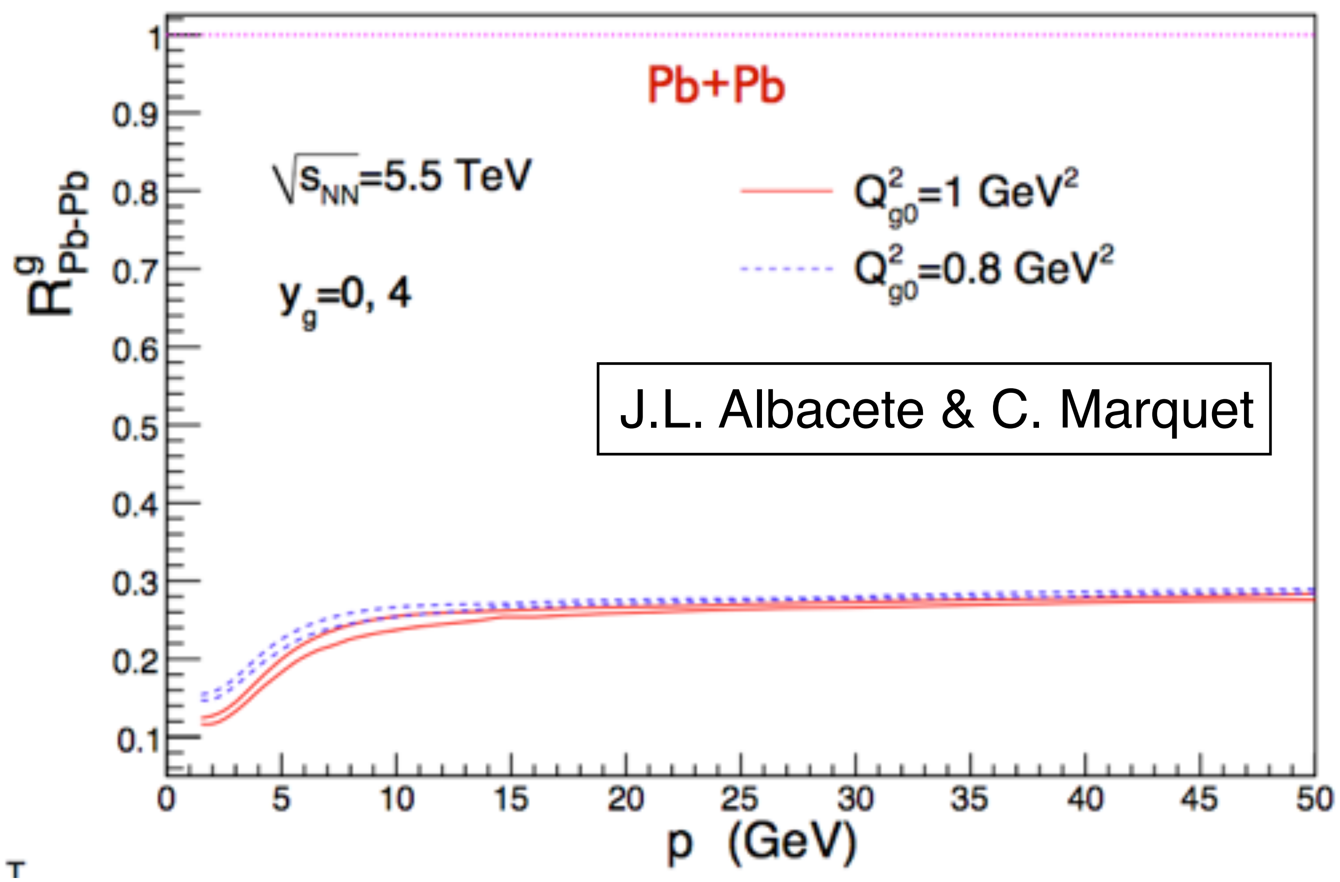

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If this test does not provide clarity, we may need to wait for p+Pb.

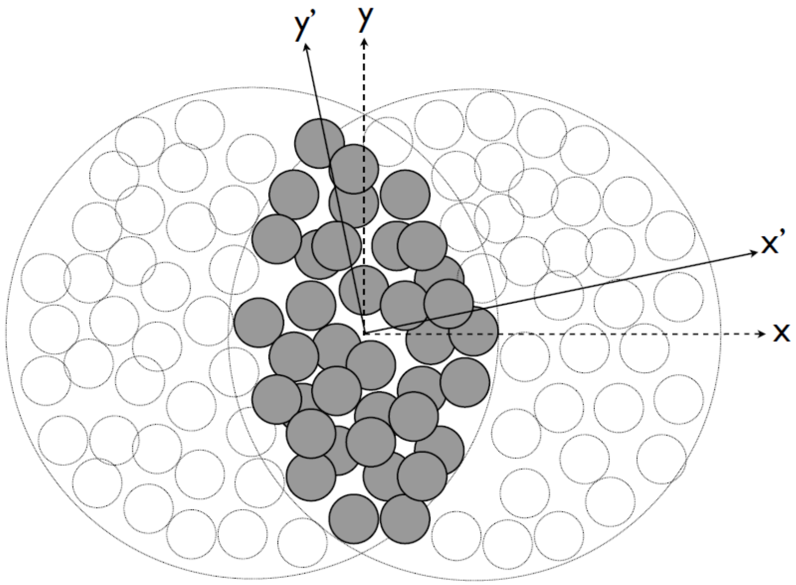
Challenge #6

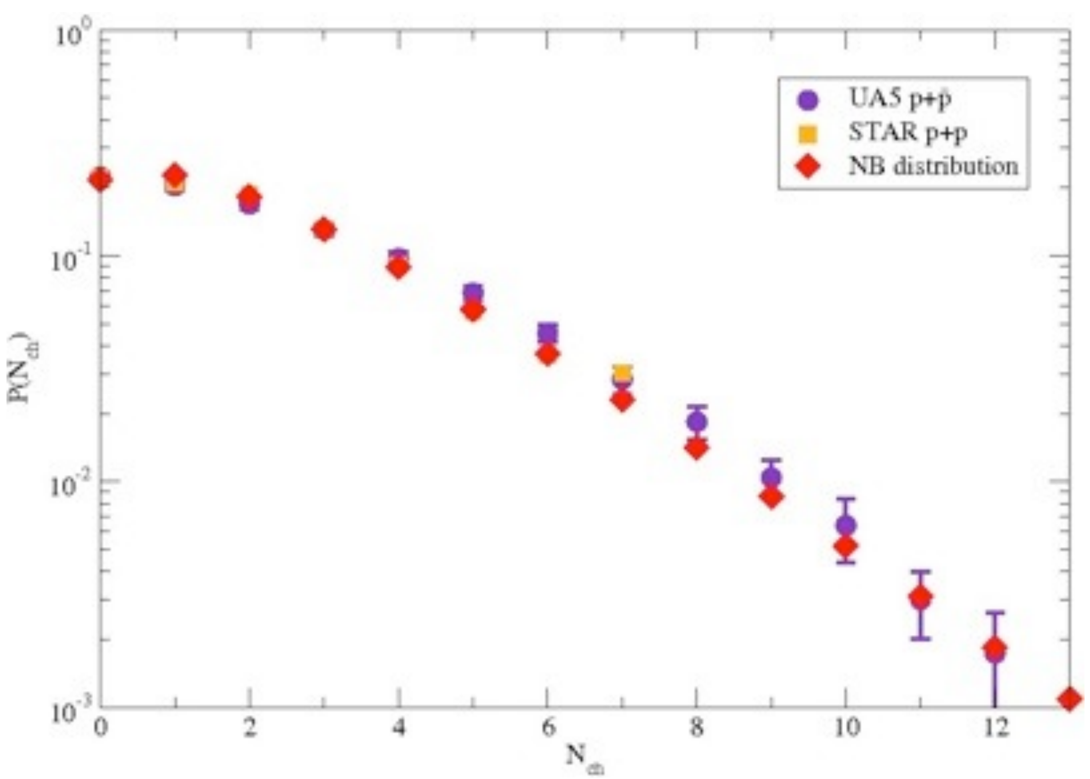
One event at a time...

Initial state fluctuations

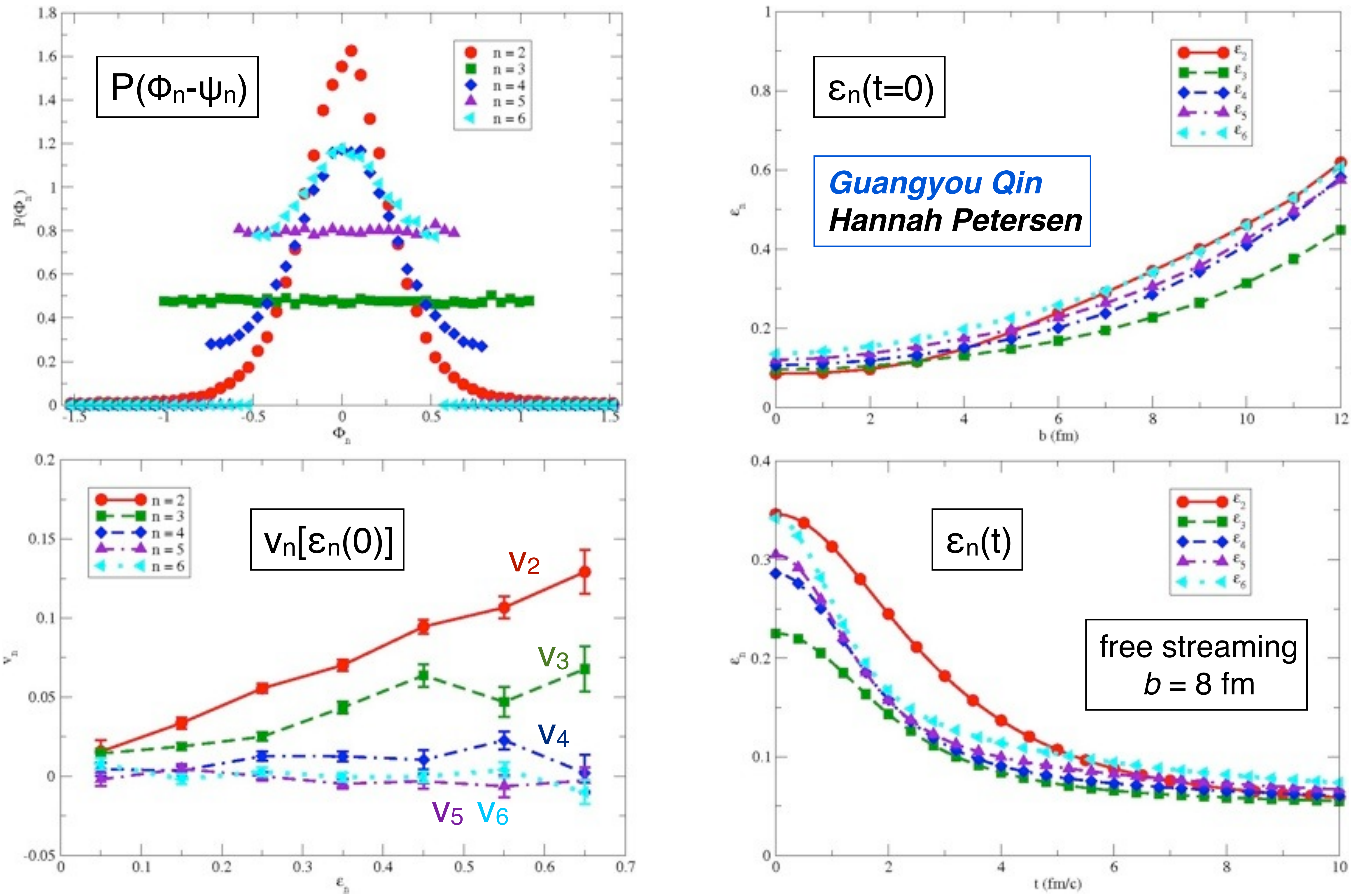
... need to account for fluctuations in:

- the locations of nucleons in colliding nuclei
- the *NN* cross section
- the energy deposition in *NN* collisions
- or, the leading color charge distributions (CGC).



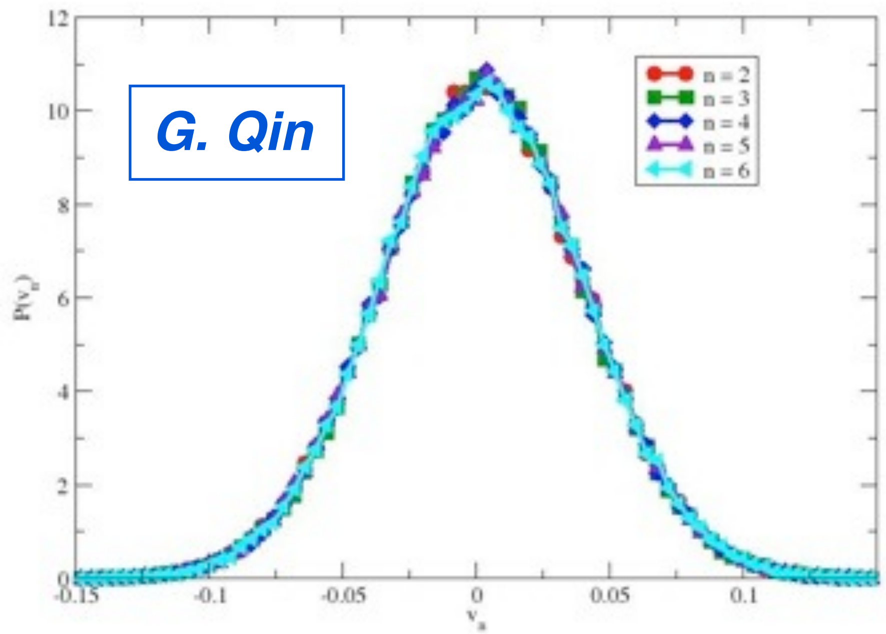


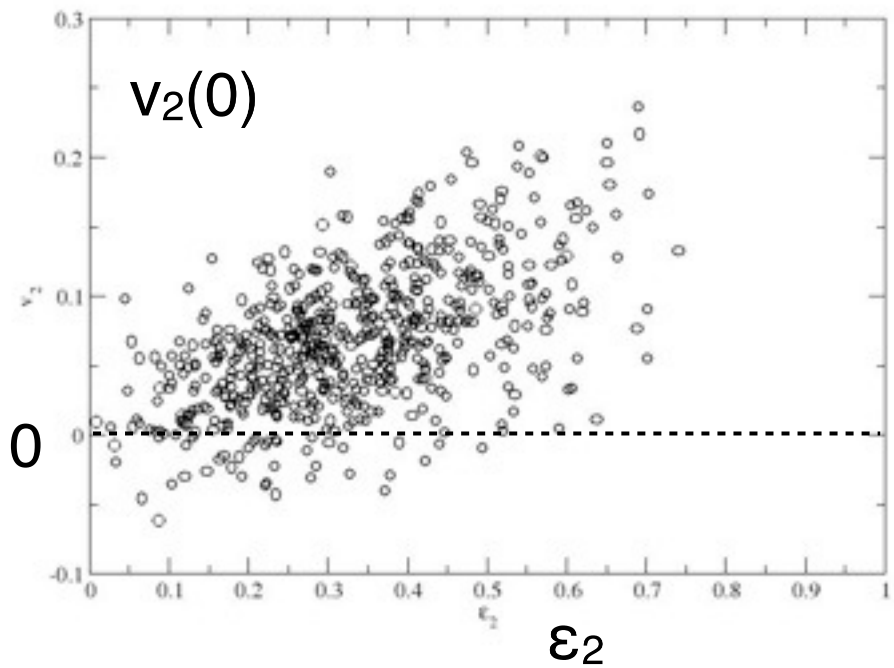
Multipole analysis

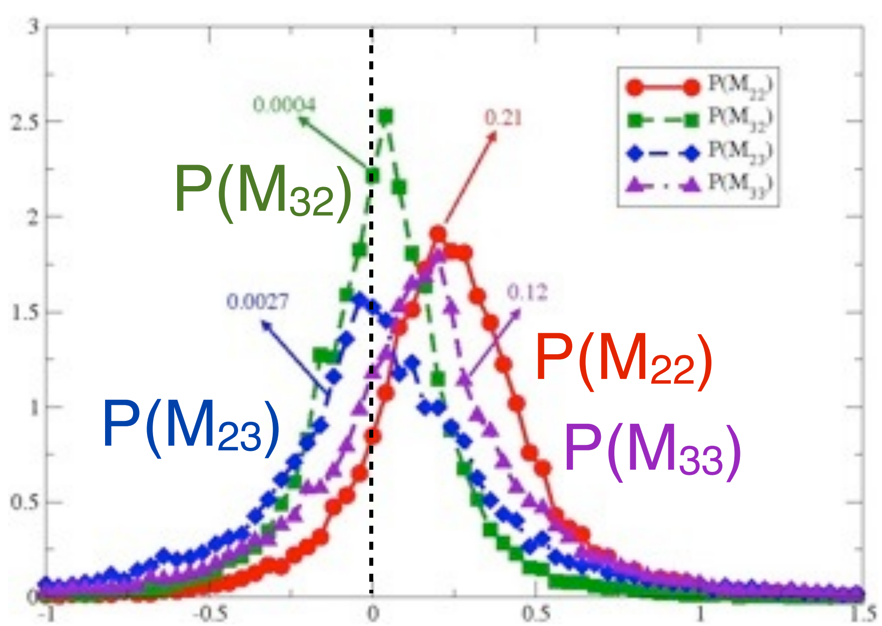


Initial v_n

Finite particle number (invoking "hadron-parton duality") implies that $v_n(0) \neq 0$!







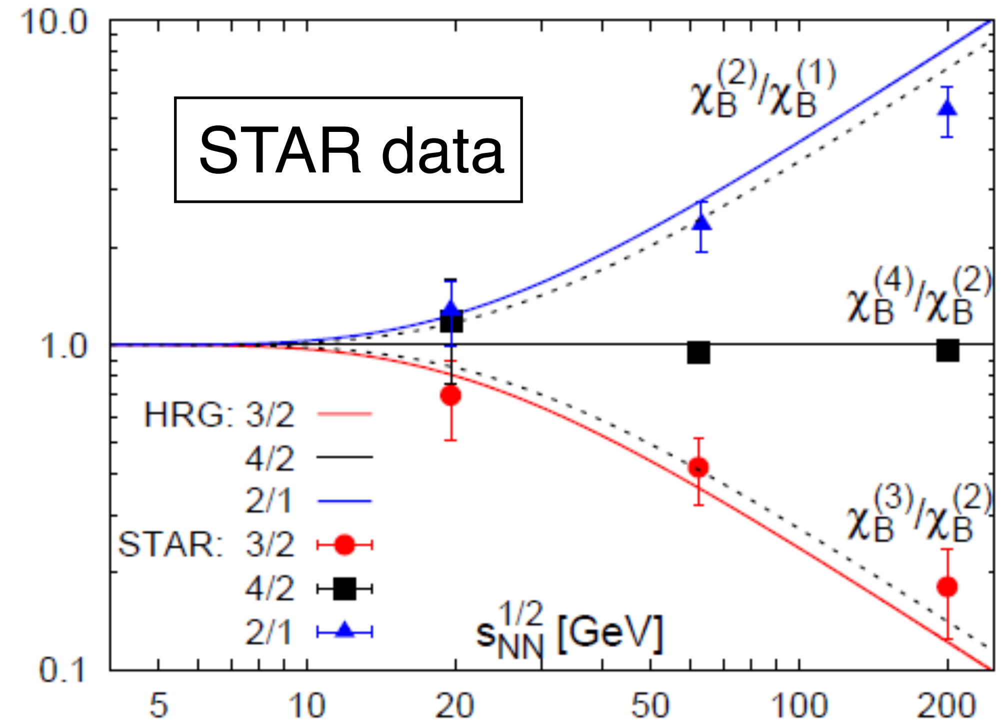
Correlation between v_n and ε_n:

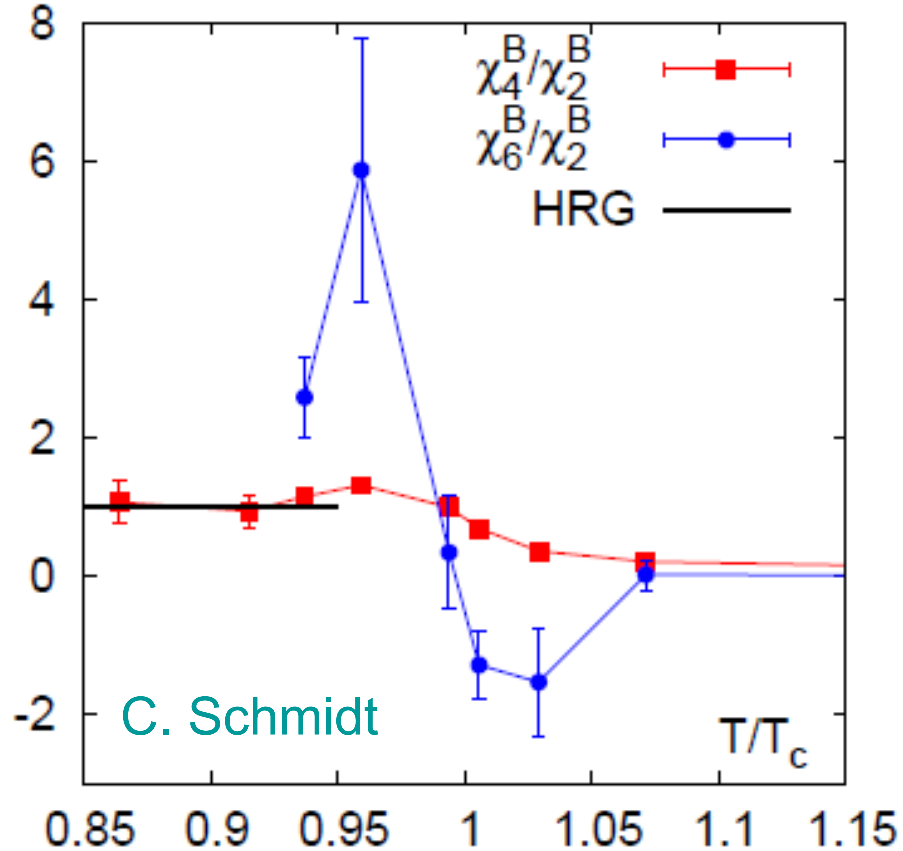
$$\begin{pmatrix} v_2 \\ v_3 \end{pmatrix} = \begin{pmatrix} M_{22} & M_{23} \\ M_{32} & M_{33} \end{pmatrix} \begin{pmatrix} \varepsilon_2 \\ \varepsilon_3 \end{pmatrix}$$

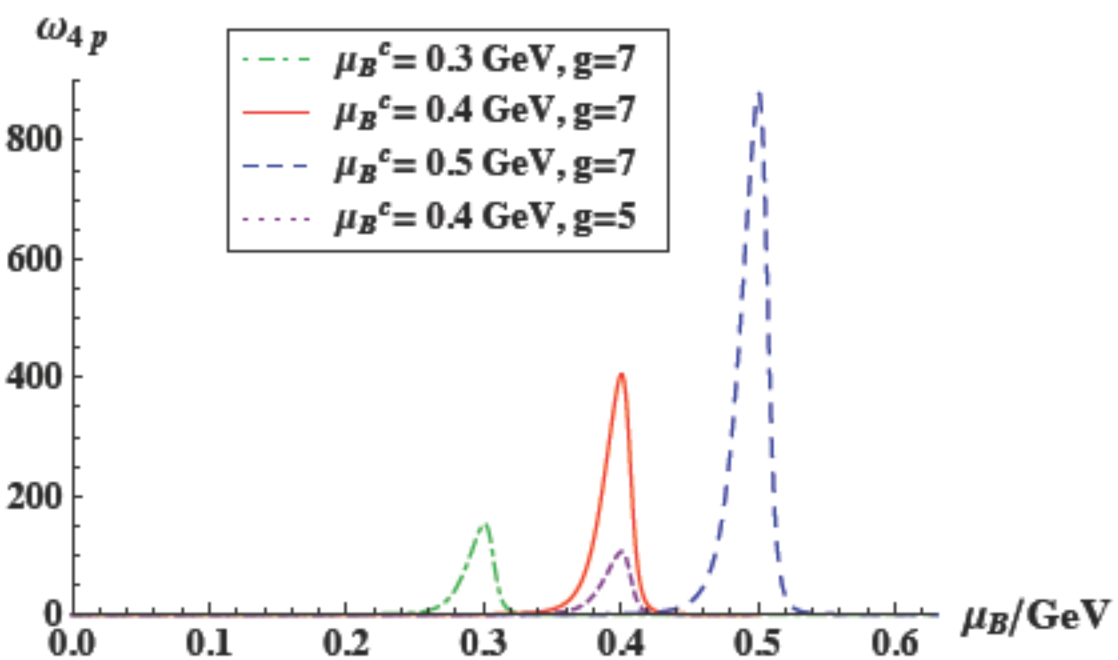
Final-state fluctuations

Ratios of susceptibilities are good probes of QCD critical point (Karsch, Redlich)

Ratios of cumulants of particle yields are experimental analogue (Athanasiou, Rajagopal, Stephanov)







- Challenges for the 2010's:
  - *Quantitative* connection between matter properties and observables
  - *Ab initio* QCD equation of state at $\mu_B \neq 0$, critical point
  - *Ab initio* calculation of transport coefficients
  - Theoretical understanding of QCD at intermediate coupling
  - *Quantitative* theory of the low-x parton structure of nuclei

Paths to progress

Progress in the exploration of hot QCD matter in the coming decade will require:

- Consensus among theorists about the "valid" approaches to problems
- Resolution of limitations of formalisms
- Realistic simulations of observables
- Collaboration among champions of different approaches (TEC-HQM may be a good model)
- Of course, there is always the traditional alternative....

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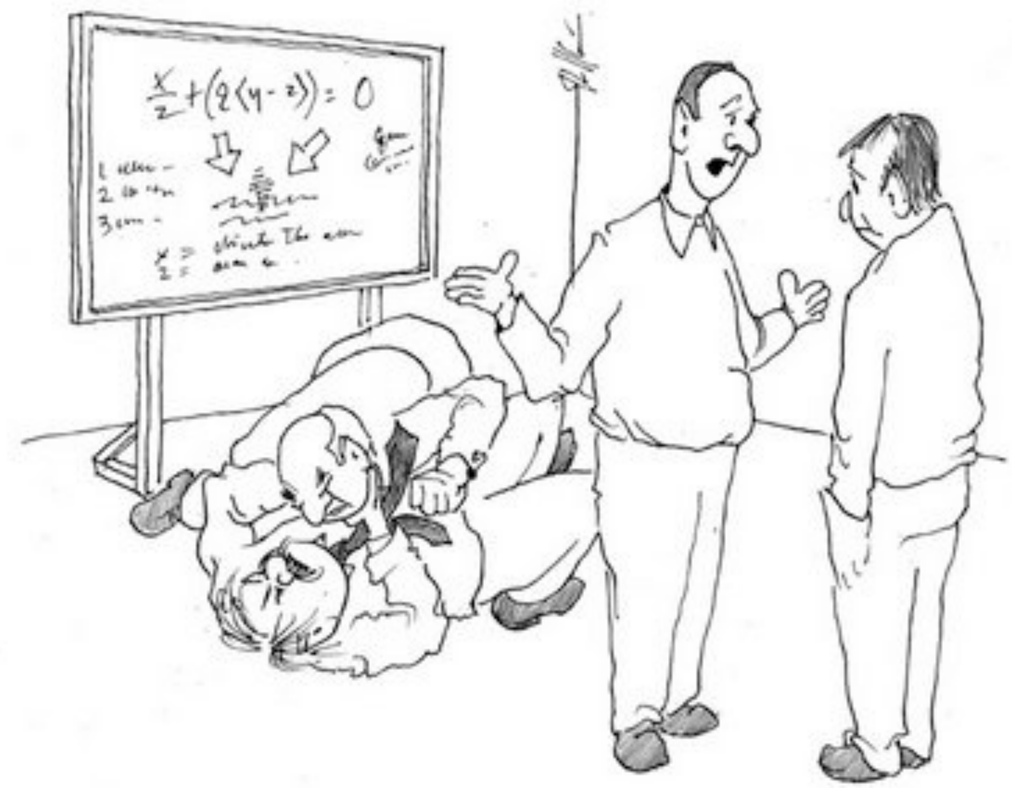
The world before TEC-HQM



"Hey, that's scientists for you. Keswick and Murphy just can't seem to agree on the theory of jet quenching."