Theoretical Developments on phase diagram and jet quenching

Kang Seog Lee (Chonnam National University)

Contents

- Lattice QCD and phase diagram - Heng Tong Ding, Pawlowski
- Hadron yields and the phase diagram - M. Floris
- Jet quenching - Guang-You Qin, Yen-Jie Lee

Recent lattice QCD results and phase diagram of strongly interacting matter

Heng-Tong Ding
Central China Normal University

XXIV Quark Matter, Darmstadt, May 18-24, 2014

Talks

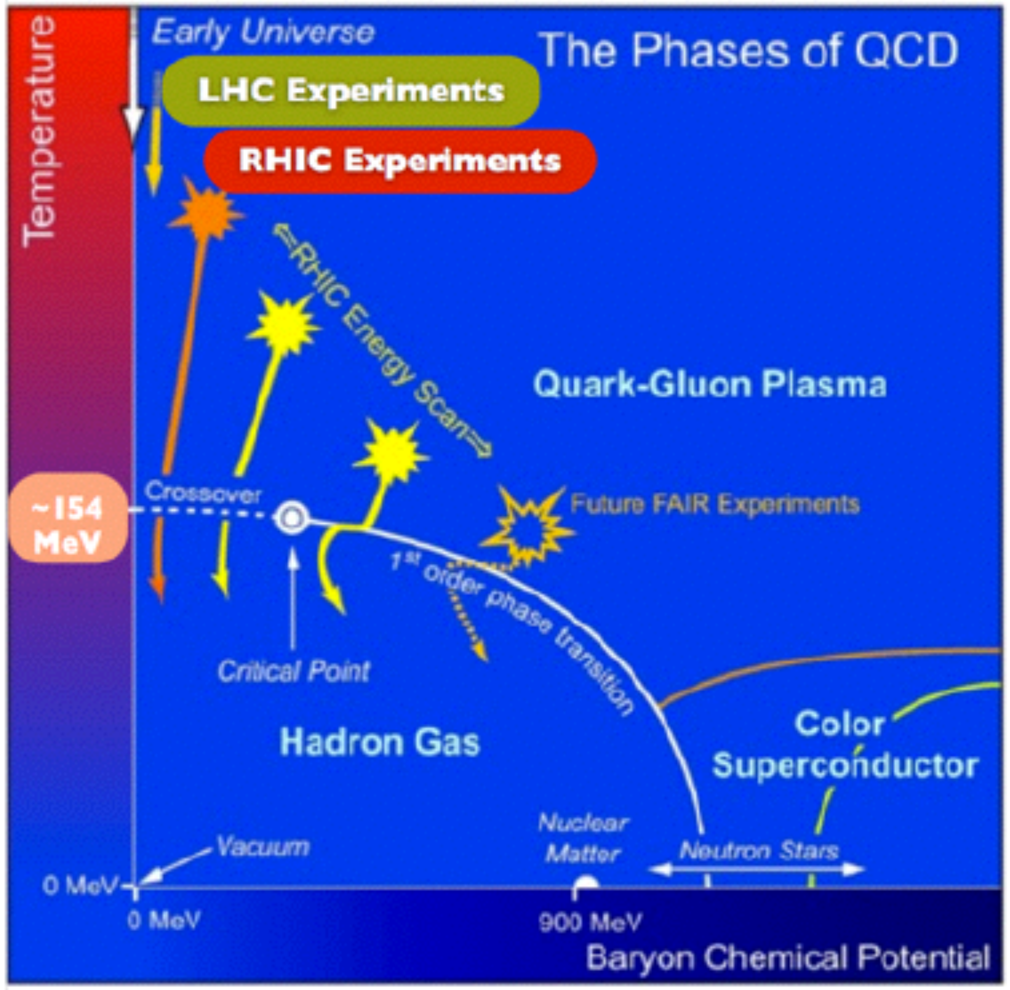
- G. Endrodi, "Effects of magnetic fields on the quark-gluon plasma", Tuesday 09:40
- P. Hegde, "The QCD Equation of State at O((μ_B)**4)", Tuesday 11:50
- D. Sexty, "Simulating full QCD at nonzero density using the complex Langevin equation", Tuesday 12:10
- H. Meyer, "Vector screening masses in the quark gluon plasma and their physical significance", Tuesday 12:30
- A. Bazavov, "The QCD equation of state", Tuesday 12:50
- M. Panero, "Jet quenching from the lattice", Tuesday 11:10
- T. Hatsuda, "New approach to lattice QCD thermodynamics from Yang-Mills gradient flow", Tuesday 11:30
- O. Kaczmarek, "Towards continuum results of heavy quark diffusion coefficient", Tuesday 15:40
- C. Ratti, "Freeze-out conditions from fluctuations of conserved charges: lattice meets experiment", Wednesday 11:30
- C. Schmidt, "From conserved charge fluctuations to the QCD critical point", Wednesday 12:30

Posters

- Y. Burnier, "Complex heavy quark potential at high temperature from lattice QCD", A-05
- A. Francis, "The second order hydro-coefficients kappa_t and anti screening of QED and QCD plasma from lattice QCD", A-06
- E.-M. Ilgenfritz, "Towards the continuum limit of thermodynamics from lattice QCD with dynamic charm", A-11
- A. Ohnishi, "Phase diagram of lattice QCD in auxiliary field Monte-Carlo method in the strong coupling region", B-13
- D. Scheffler, "Chiral restoration and deconfinement in two-flavors of staggered quarks", B-17
- W. Unger, "QCD phase diagram from the lattice at strong coupling: Staggered v.s. Wilson fermions", B-23
- T. Harris, "Bottomonium at finite temperature from lattice QCD", F-17
- H. Ohno, "Lattice QCD study on quark mass dependence of quarkonium properties at finite temperature", F-40
- T. Kim, "First principle calculation of dilepton production rate in strongly interactiing QGP", G-17
- S. Borsanyi, "Freeze-out parameters for the Large Hadron Collider", I-07
- S. Sharma, "The thermodynamics of heavy light hadrons at freeze out", J-13

Outline

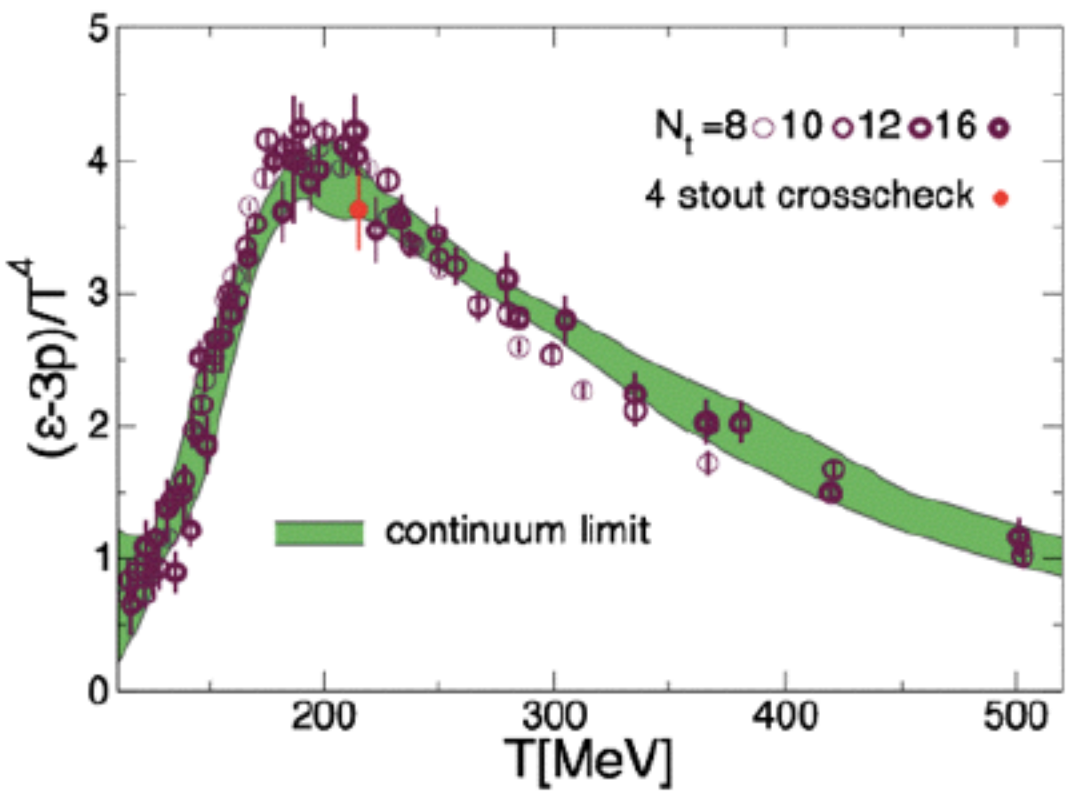
- EoS at zero and non-zero μ_B
  - new results of EoS at zero μ_B
  - EoS at finite μ_B
- Deconfinement aspects of QCD transition
  - deconfinement of open charm & strange hadrons
  - fate of charmonia & bottomonia
- Freeze-out/hadronization conditions in HIC
  - conserved charge fluctuations & freeze out parameters from LQCD
  - Influence of experimentally yet unobserved hadrons on the freeze out conditions



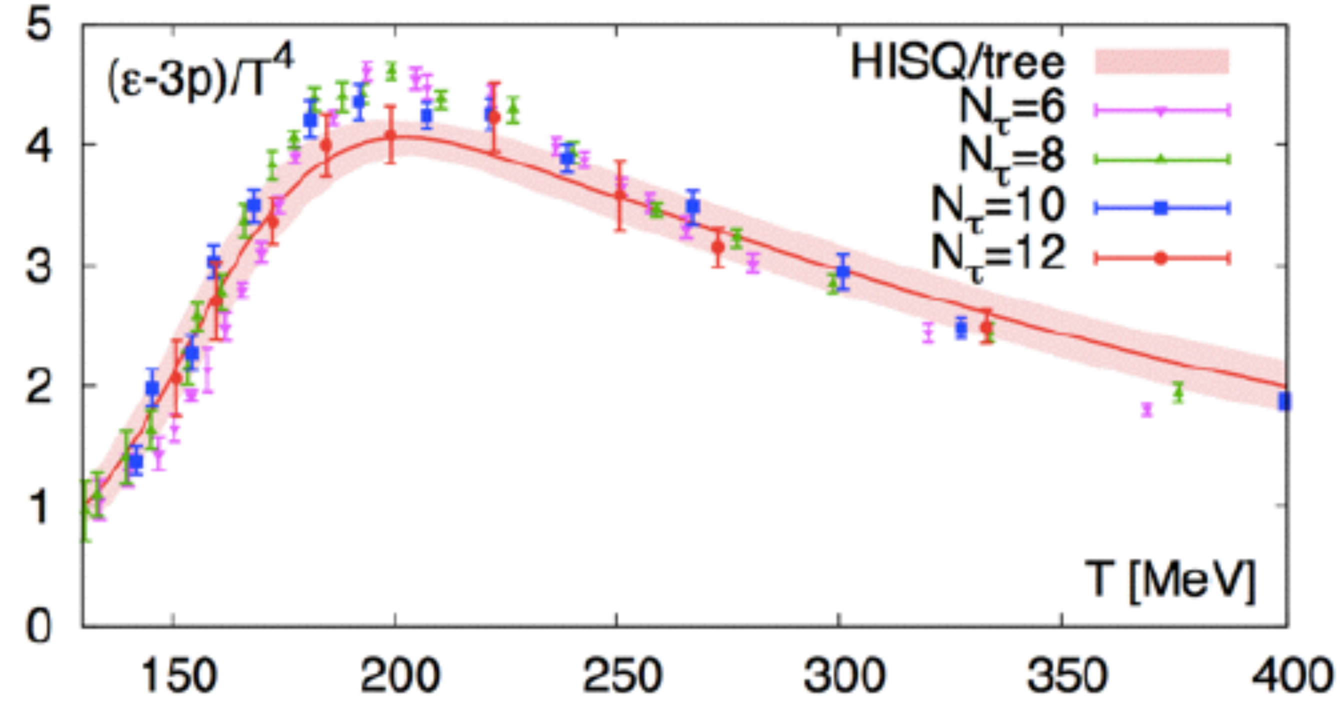
Summary

- New results on EoS from HotQCD and Wuppertal-Budapest collaborations agree
- The EoS is extended to non-zero μ_B up to μ_B**4
- Open strange/charm hadrons starts to get deconfined at temperatures in the chiral crossover region
- Evidence is found for the contribution of experimentally yet unobserved open strange and charm hadrons to the QCD thermodynamics
- Hadron Resonance Gas model including non-PDG listed states are consistent with Lattice QCD below Tc. Such an HRG is preferable to be used to determine freeze out temperatures in HIC

Updated results of interaction measure from Wuppertal-Bupdapest and hotQCD



Wuppertal-Budapest, Phys.Lett. B730 (2014) 99

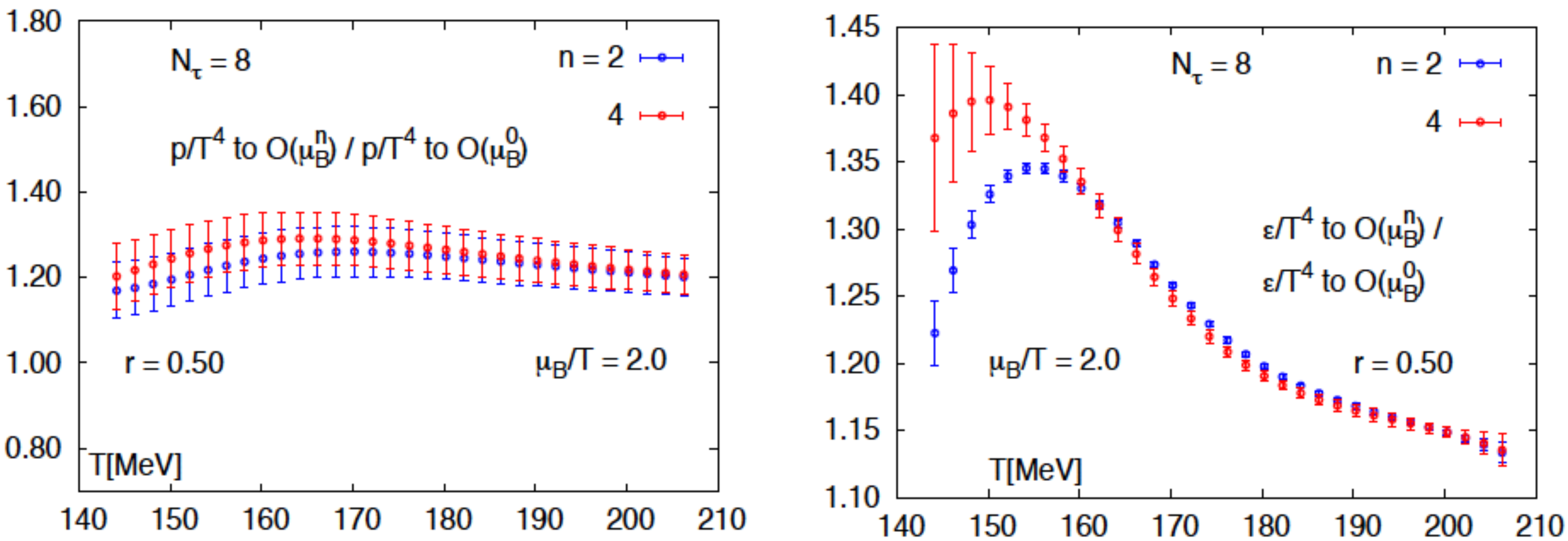


A. Bazavov[hotQCD], talk on Tuesday

Calculations at a high temperature value using the 4 stout action have been done

Continuum extrapolation is performed with additional results on N_T=10 and 12 lattices

EoS at finite μ_B



finite μ_B corrections in p/T^4 at $\mu_B/T \lesssim 2$ under control

4th order μ_B corrections in ε/T^4 needed at $T \lesssim 160$ MeV with $\mu_B/T \lesssim 2$

P. Hegde [BNL-Bielefeld-CCNU], talk on Tuesday

second order corrections obtained from HISQ and stout action agree
corrections up to second order has been computed with stout action

Wuppertal-Budapest, JHEP 08(2012)053

Deconfinement aspects of QCD transition

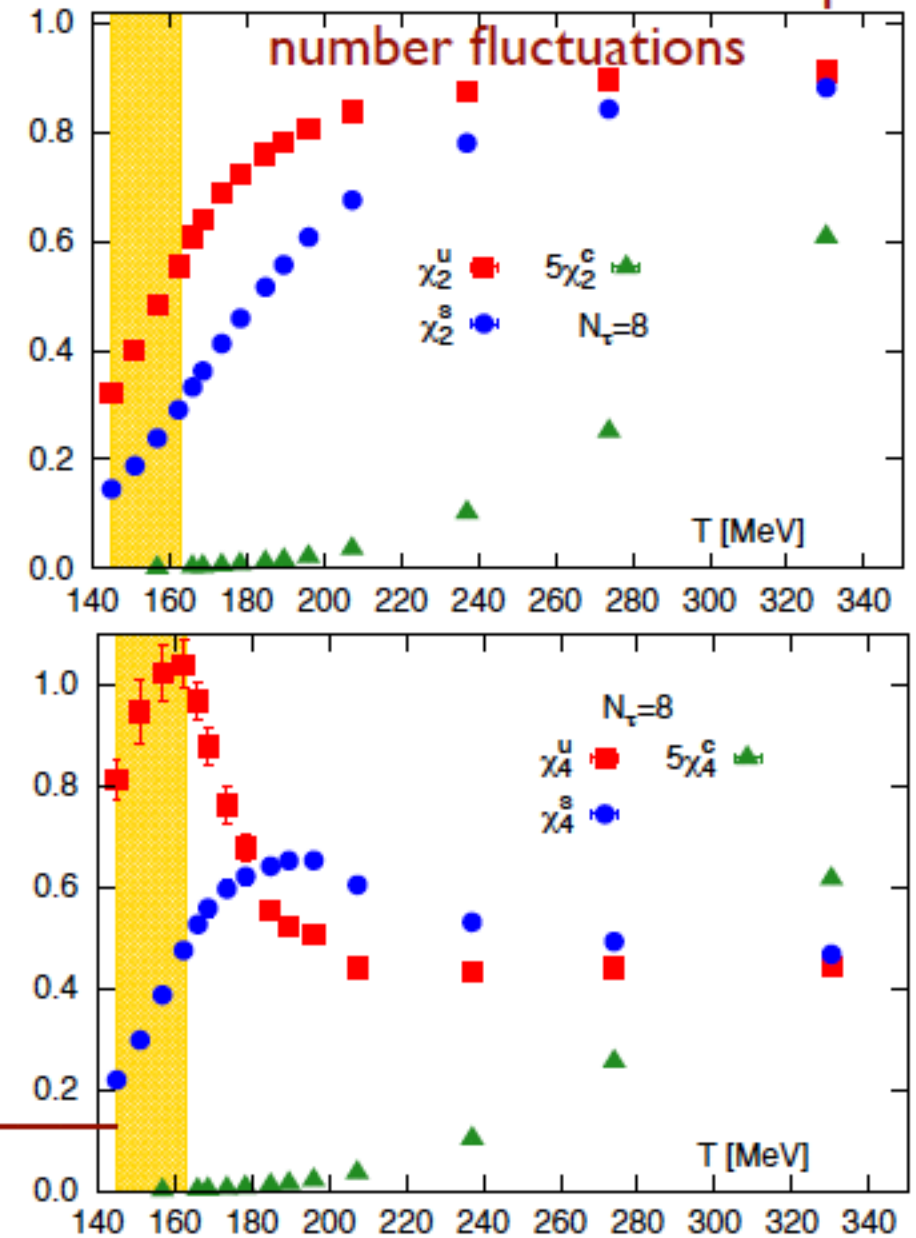
Light-quark hadrons get deconfined around T_c,
charmonia and bottomonia may survive at $T>T_c$ Matsui & Satz PLB '86

Strange quark, less affected by chiral symmetry, may remain confined at $T > T_c$?

Do strange hadrons survive at higher temperature ?
Freeze-out/hadronization hierarchy between light & strange hadrons ?

How about open charm hadrons ?

2nd & 4th order cumulants of quark number fluctuations



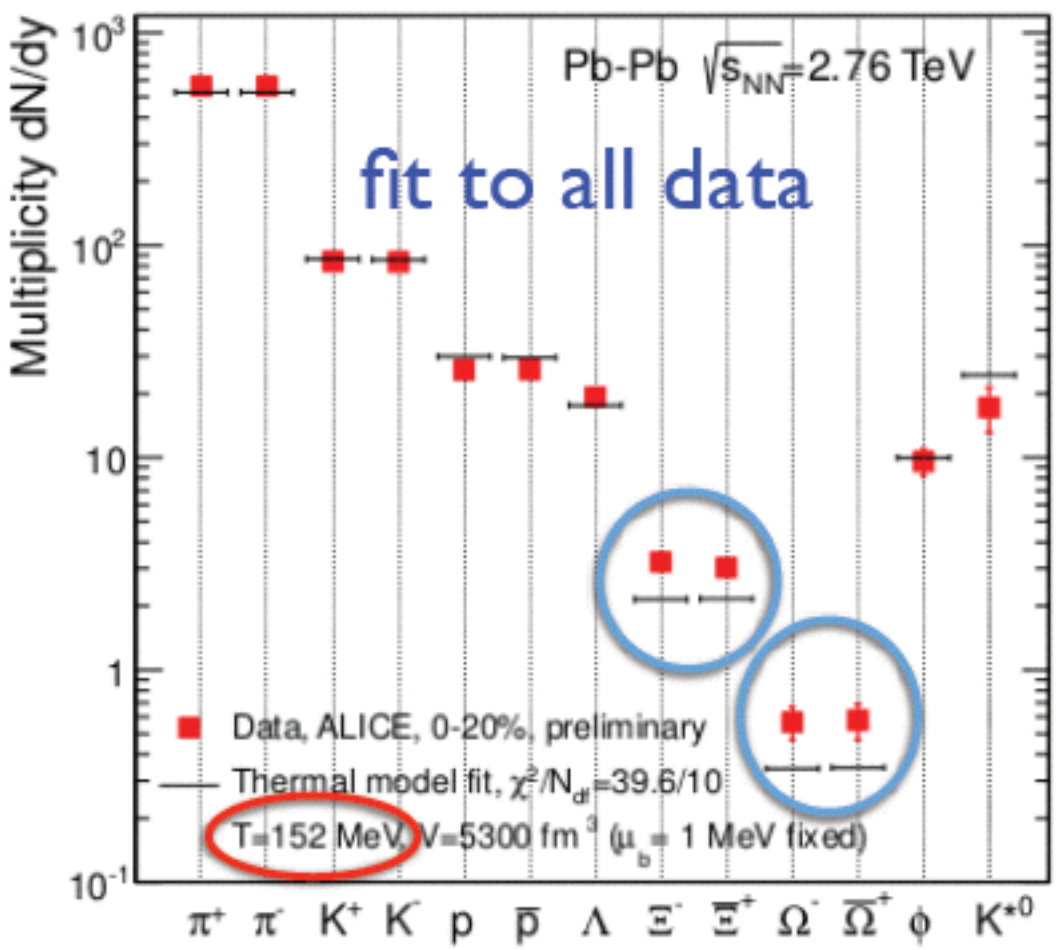
T_c=154(9) MeV

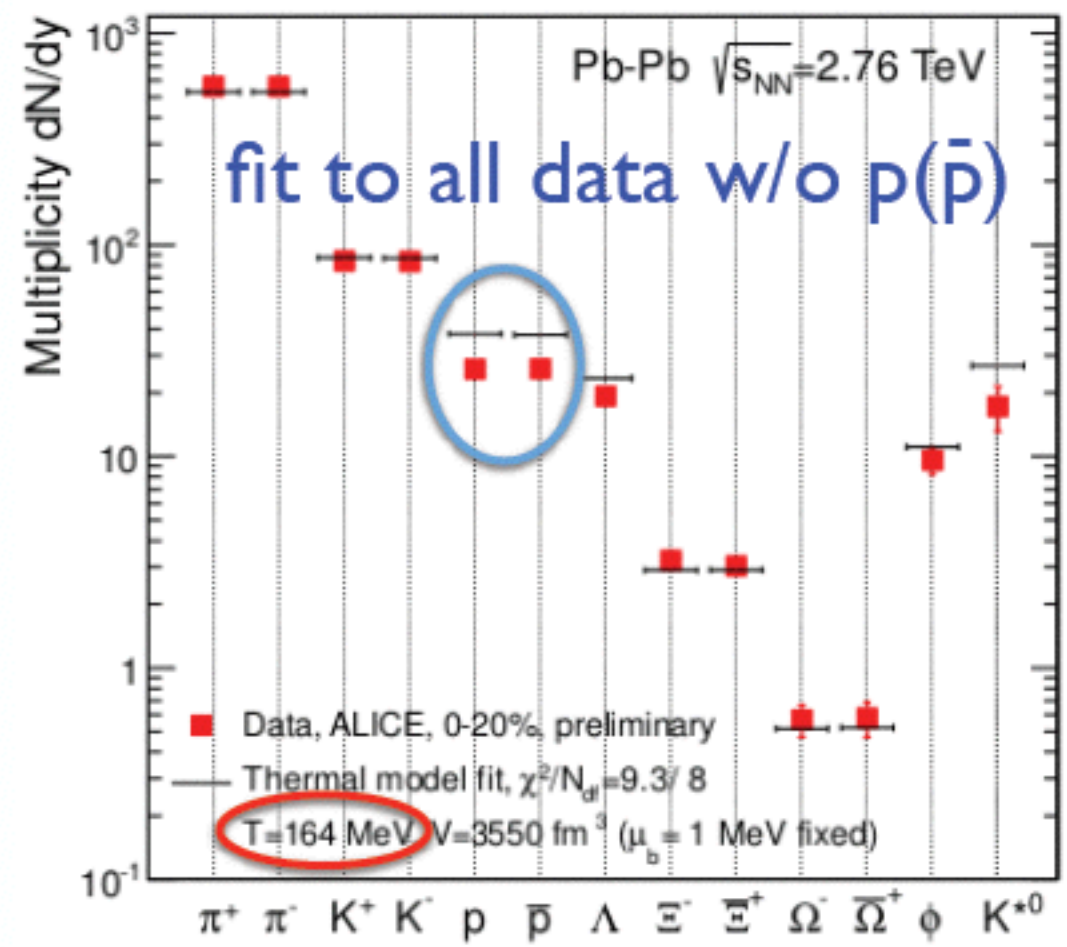
HotQCD, PRD85(2012)054503
Wuppertal-Budapest, JHEP 1009 (2010) 073

Do strange hadrons require a higher freeze out temperature than non-strange hadrons?

The possibility has been discussed frequently

Alba et al., arXiv:1403.4903,
Bugaev et al., EPL 104(2013)22002, **Poster J-04,**
Bellwied et al., [WB Collaboration], Phys.Rev. Lett. 111(2013)202302,
Chatterjee, Godbole, Gupta, PLB 727(2013)554





Andronic et al., Nucl. Phys. A904 (2013) 535c

strangeness chemical potential in HIC

strangeness neutrality in HIC: $N_S=0$ enforces dependence of μ_S on μ_B and T

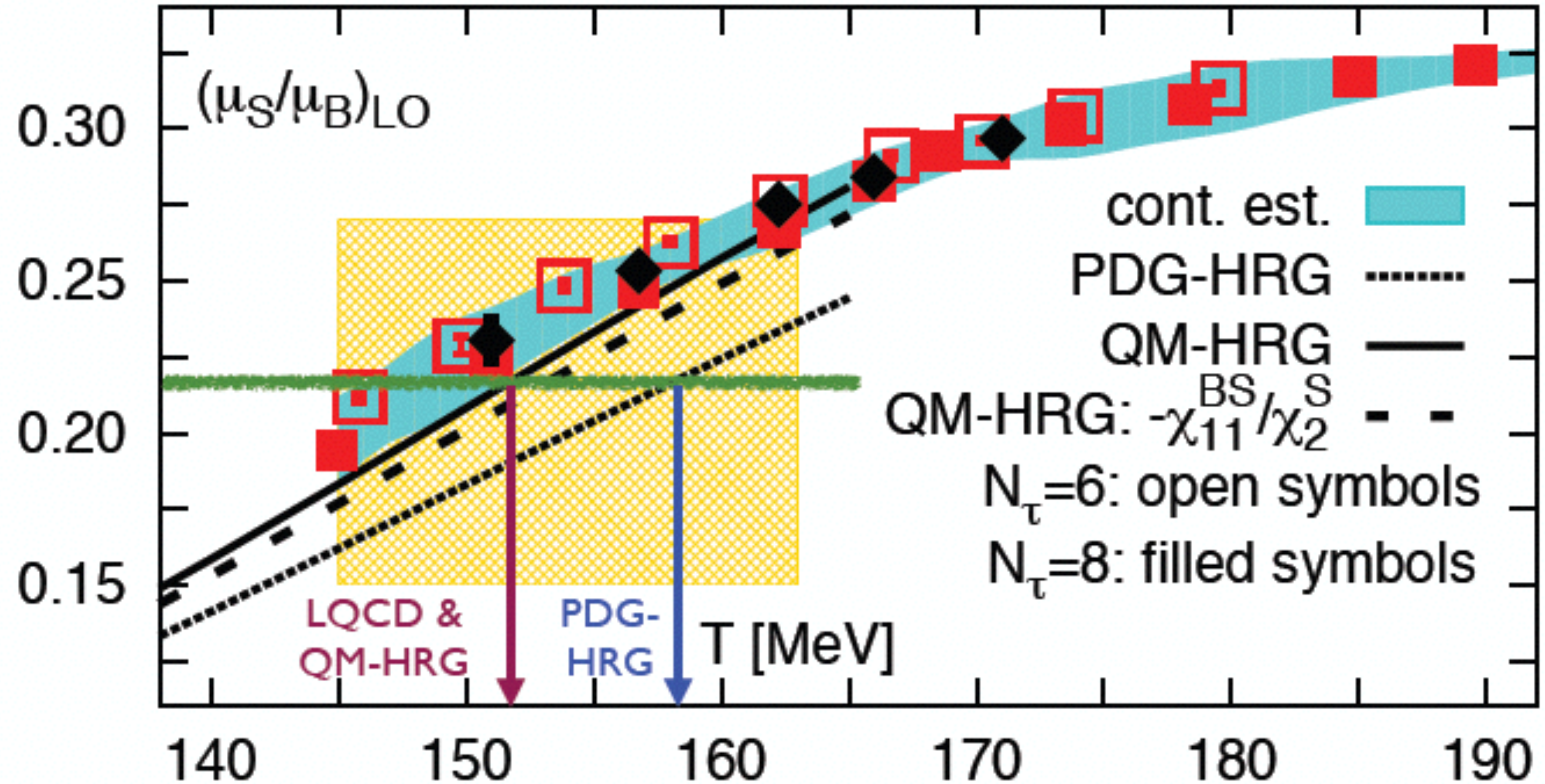
expand μ_S/μ_B in a Taylor series of μ_B:

$$\frac{\mu_S}{\mu_B} \simeq -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B} + \mathcal{O}(\mu_B^2)$$

NLO corrections are small at μ_B <200 MeV

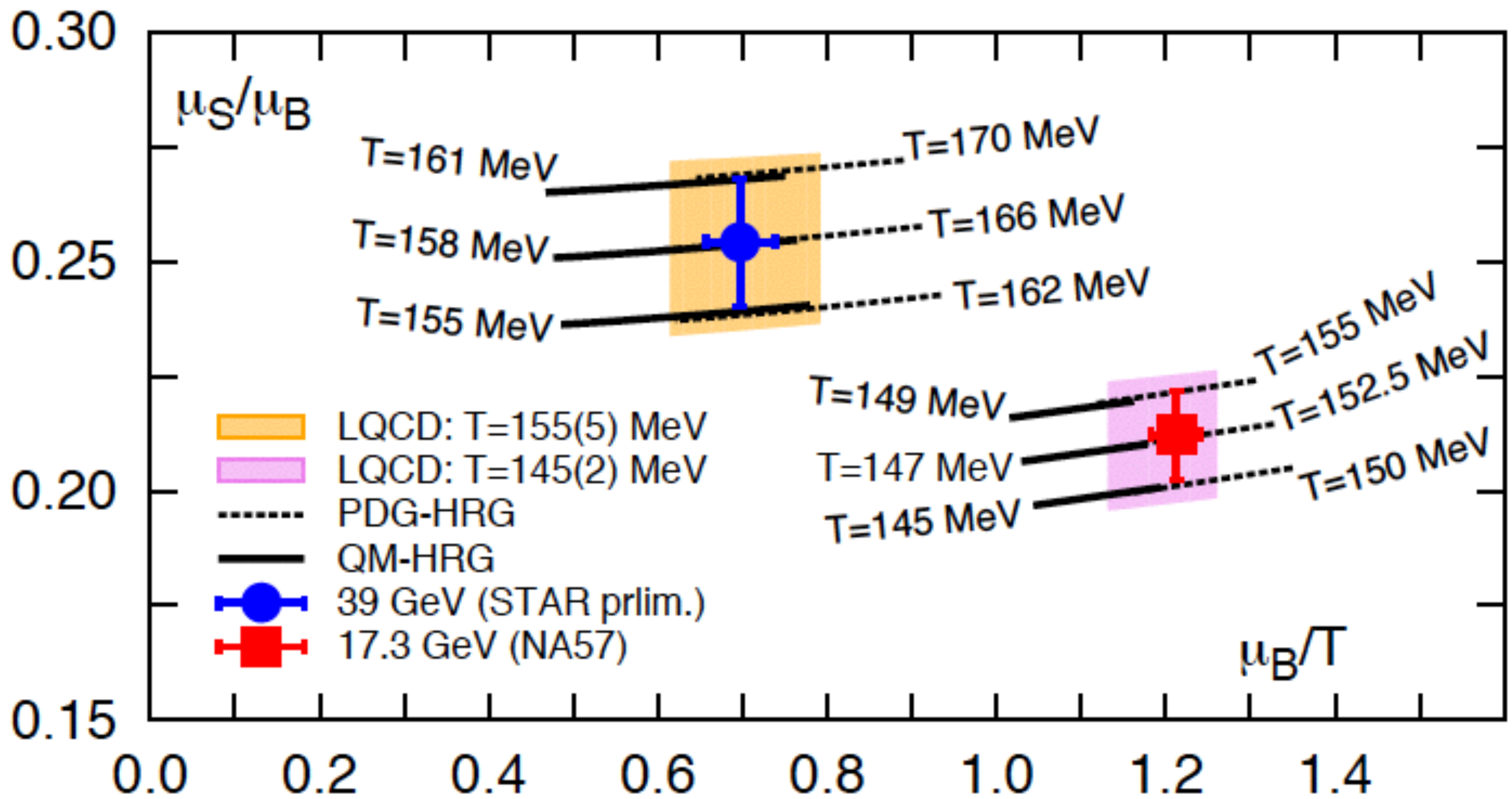
additional states contribute to the relative abundance of strange baryons to open strange mesons

In the strange hadron sector, the PDG-HRG based analyses give a larger freeze out temperature than QM-HRG and lattice QCD



A. Bazavov et al., arXiv:1404.6511

Imprints of unobserved states in strangeness freeze out in HIC



In the strange sector, the PDG-HRG based analysis give larger freeze out temperature than QM-HRG & LQCD by about 5-8 MeV

QM-HRG should be the preferable choice to determine freeze out temperature at large μ_B where LQCD is not applicable

A. Bazavov et al., arXiv:1404.6511

Equation of state and phase diagram of strongly interacting matter

Jan M. Pawlowski

Universität Heidelberg & ExtreMe Matter Institute

Darmstadt, May 22th 2014

Related Talks & Posters

C. Fischer 'Locating the CEP'

L. Fister 'On the phase structure and dynamics of QCD'

M. Hopfer 'The role of the quark-gluon vertex function in the QCD phase transition'

M. Huber 'Nonperturbative gluonic three-point correlations'

M. Mitter 'Phase Structure of Strongly Interacting Matter: Thermodynamics and Chiral Anomaly'

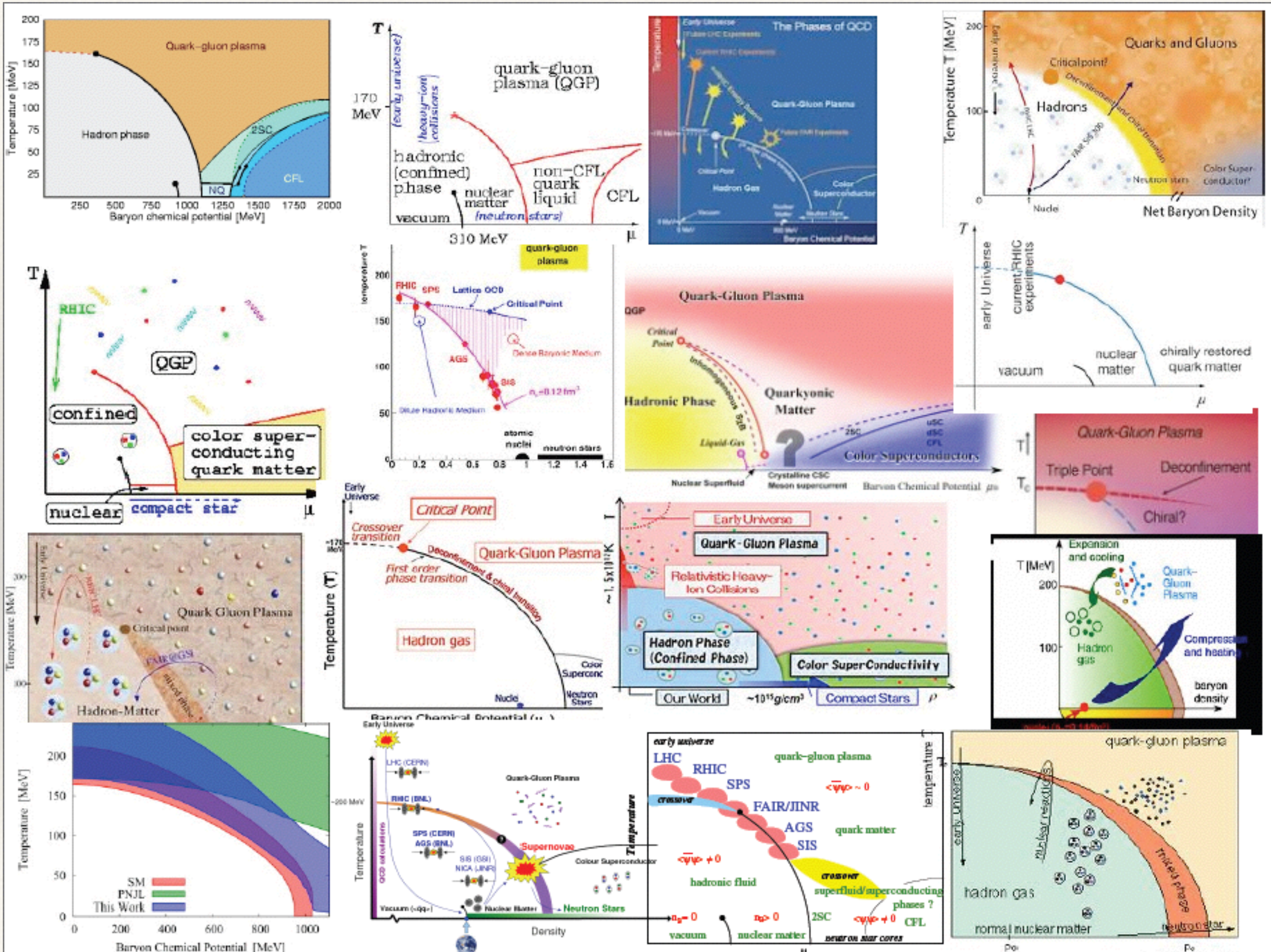
K. Morita 'The Chiral Criticality in the Probability Distribution of Conserved Charges'

R. Stiele 'Thermodynamics and phase structure of strongly-interacting matter'

M. Strickland 'Three loop HTL perturbation theory at finite temperature and chemical potential'

N. Strodthoff 'QCD-like theories at finite density'

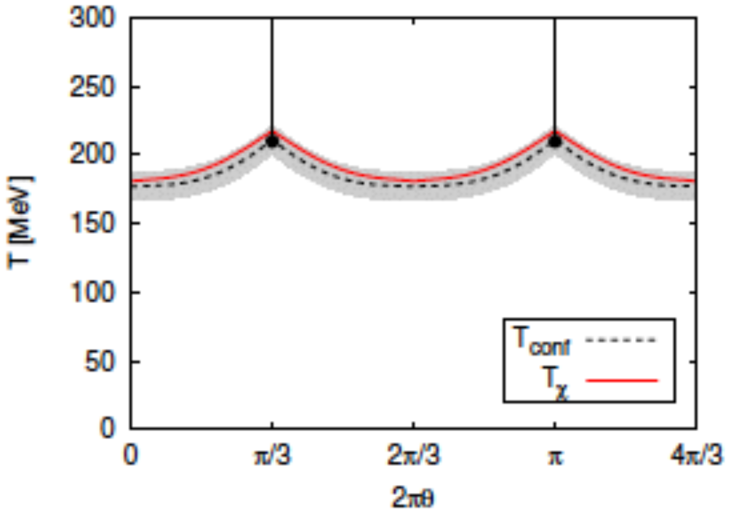
A. Tripolt 'Spectral functions from the functional renormalization group'

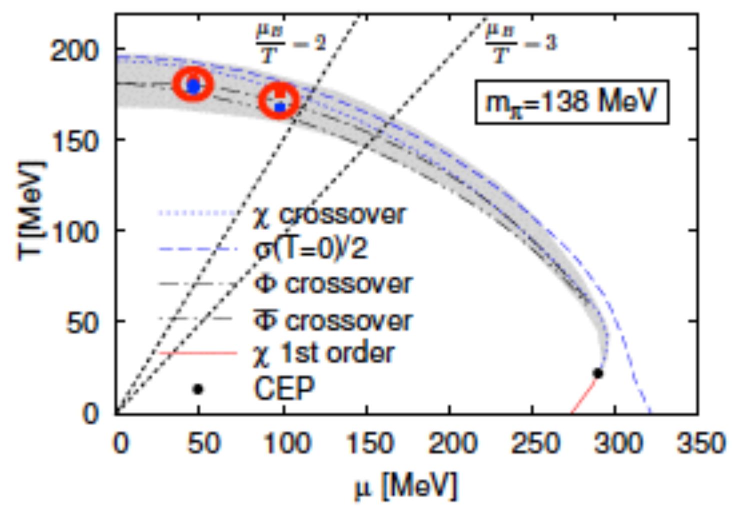


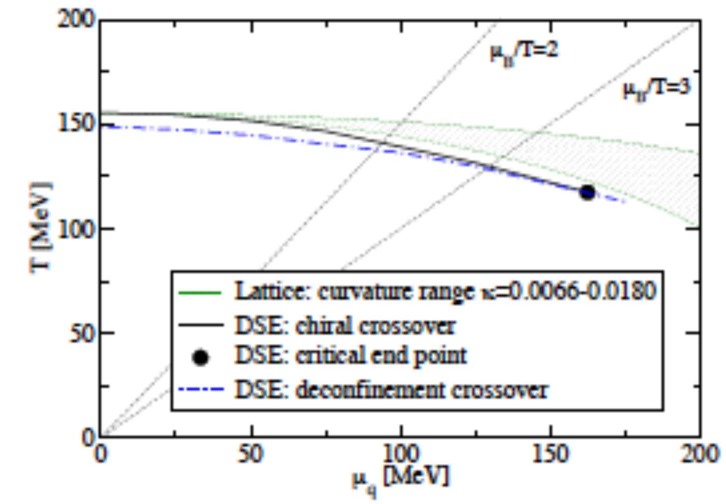
Quark–gluon plasma
Hadron phase
2SC
CFL
NQ
Temperature [MeV]
Baryon chemical potential [MeV]
quark–gluon plasma (QGP)
170 MeV
(early universe)
(heavy-ion collisions)
hadronic (confined) phase
nuclear matter
non-CFL quark liquid
CFL
vacuum
(neutron stars)
310 MeV
The Phases of QCD
Quark-Gluon Plasma
Hadron Gas
Color Superconductor
Baryon Chemical Potential
Temperature T [MeV]
Quarks and Gluons
Critical point?
Hadrons
Color Super-conductor?
Neutron stars
Nuclei
Net Baryon Density
RHIC
QGP
confined
color super-conducting quark matter
nuclear
compact star
quark-gluon plasma
Lattice QCD
Critical Point
AGS
SIS
atomic nuclei
neutron stars
Quark-Gluon Plasma
QGP
Critical Point
Hadronic Phase
Quarkyonic Matter
Liquid-Gas
Color Superconductors
Nuclear Superfluid
Crystalline CSC
Meson supercurrent
Baryon Chemical Potential
early Universe
current RHIC experiments
nuclear matter
vacuum
chirally restored quark matter
Quark-Gluon Plasma
Triple Point
Deconfinement
Chiral?
Early Universe
Critical Point
Crossover transition
First order phase transition
Quark-Gluon Plasma
Hadron gas
Temperature (T)
Nuclei
Neutron Stars
Early Universe
Quark-Gluon Plasma
Relativistic Heavy-Ion Collisions
Hadron Phase (Confined Phase)
Color SuperConductivity
Our World
Compact Stars
Quark Gluon Plasma
Critical point
Hadron-Matter
Temperature [MeV]
T [MeV]
Expansion and cooling
Quark-Gluon Plasma
Hadron gas
Compression and heating
baryon density
Temperature [MeV]
SM
PNJL
This Work
Baryon Chemical Potential [MeV]
Early Universe
Quark-Gluon Plasma
Supernovae
Colour Superconductor
Neutron Stars
Nuclear Matter
Density
Temperature
early universe
LHC
RHIC
SPS
FAIR/JINR
AGS
SIS
quark-gluon plasma
quark matter
hadronic fluid
crossover
superfluid/superconducting phases ?
2SC
CFL
vacuum
nuclear matter
neutron star cores
temperature
quark-gluon plasma
early universe
nuclear reactions
hadron gas
normal nuclear matter
neutron star

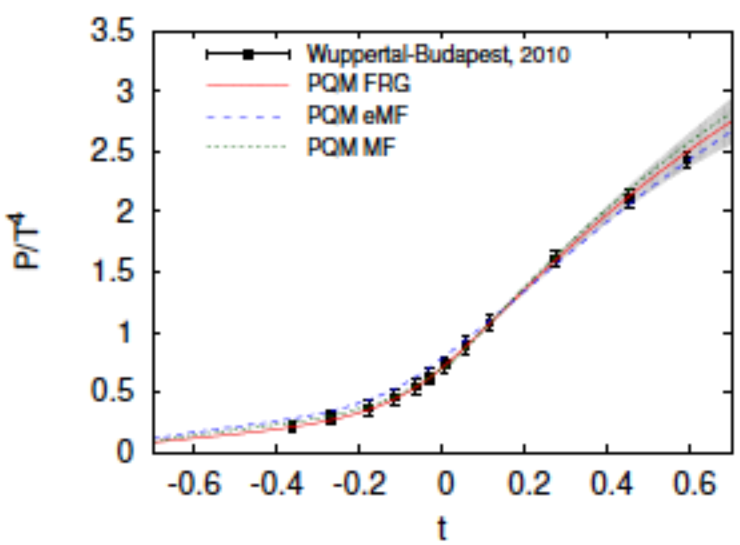
Summary & outlook

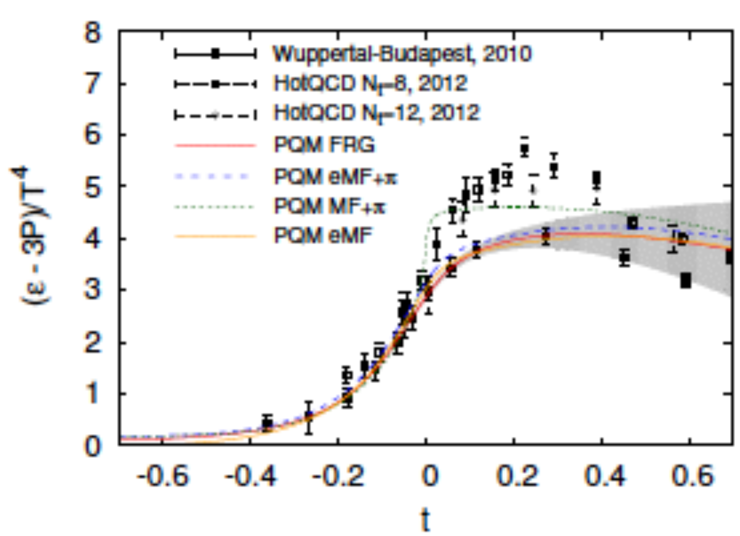
- **Phase structure and Equation of State**







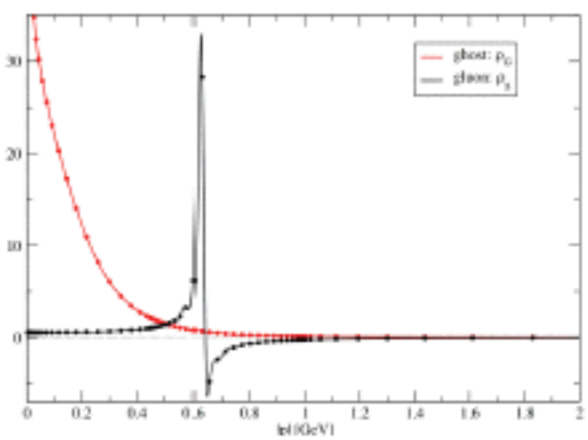


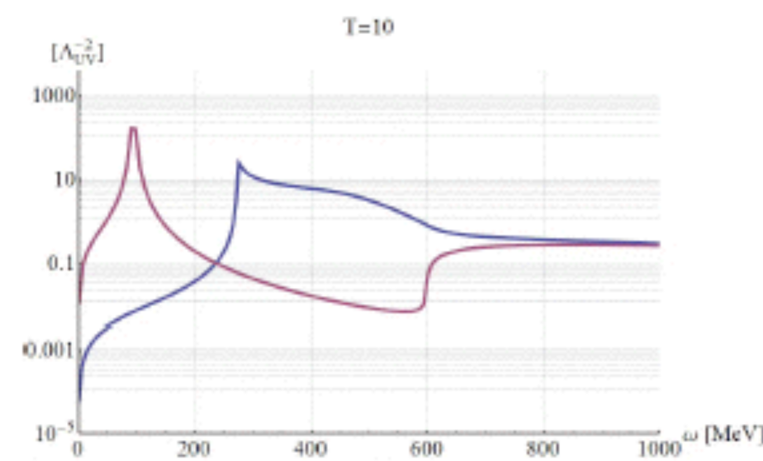


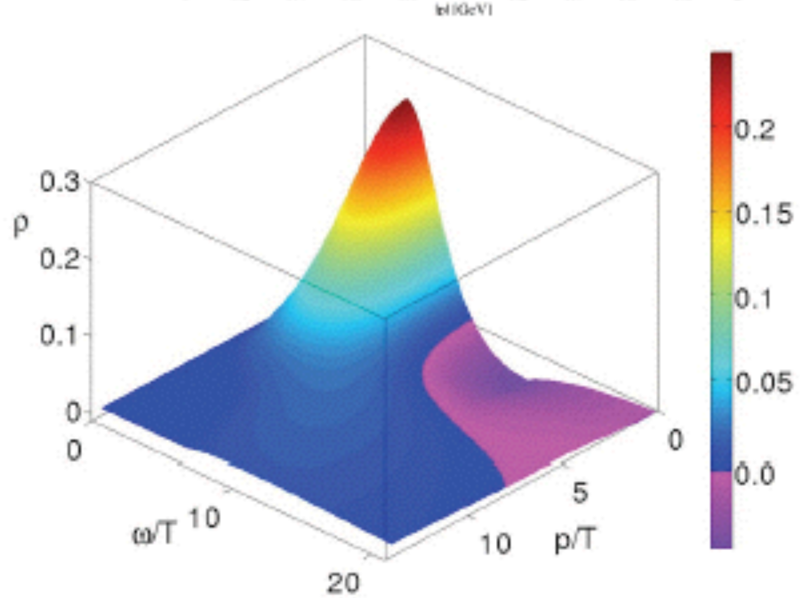
Summary & outlook

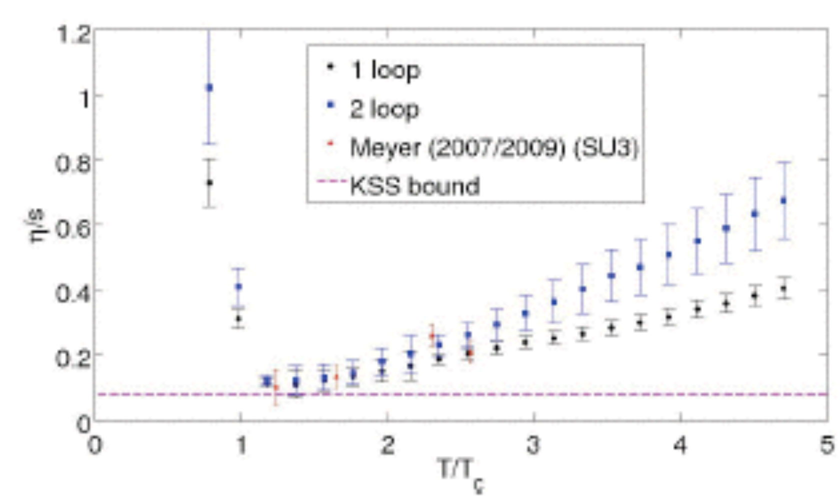
- **Phase structure and Equation of State**

- **Spectral functions and Transport Coefficients**







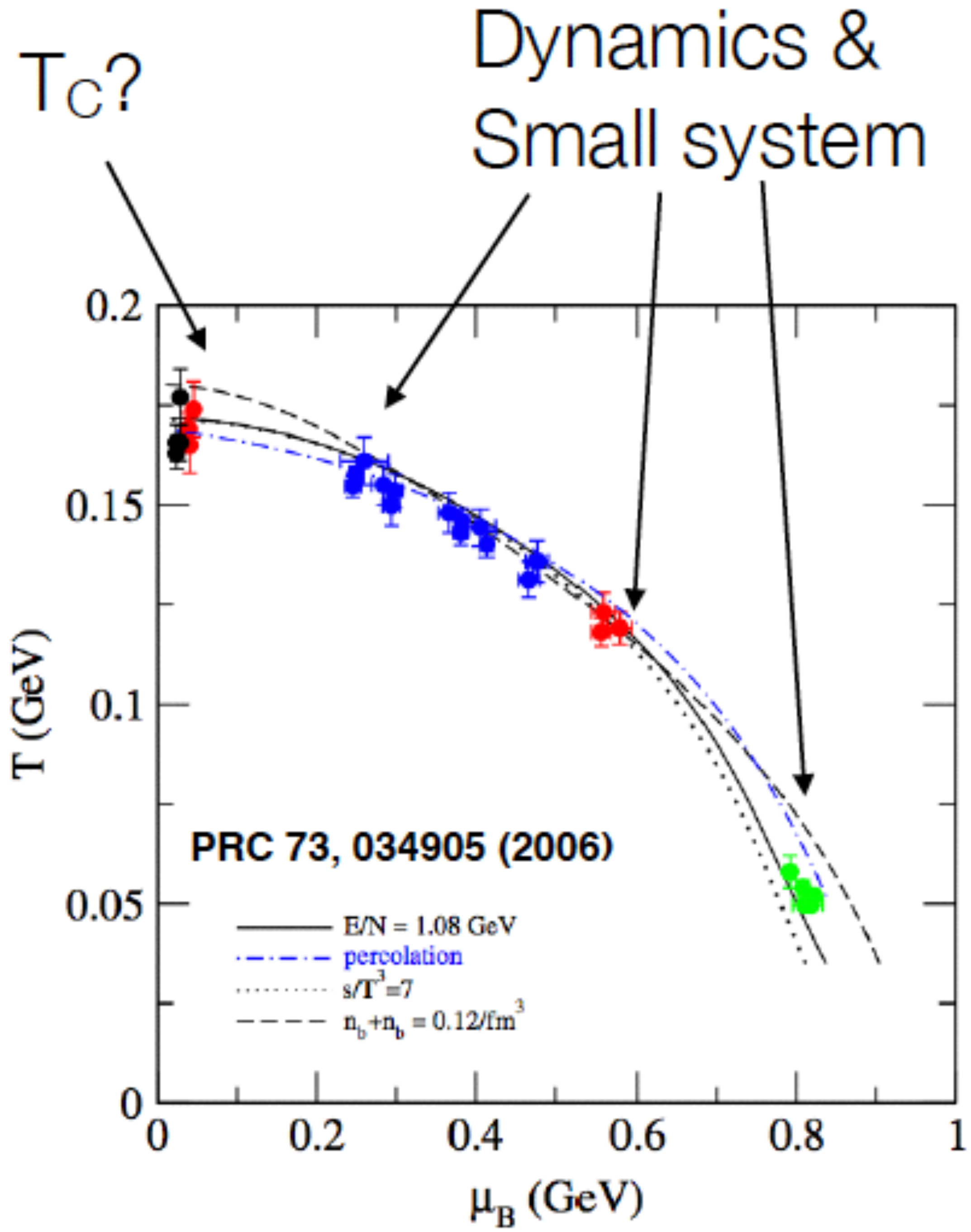


Hadron yields and the phase diagram of strongly interacting matter

(a biased review)

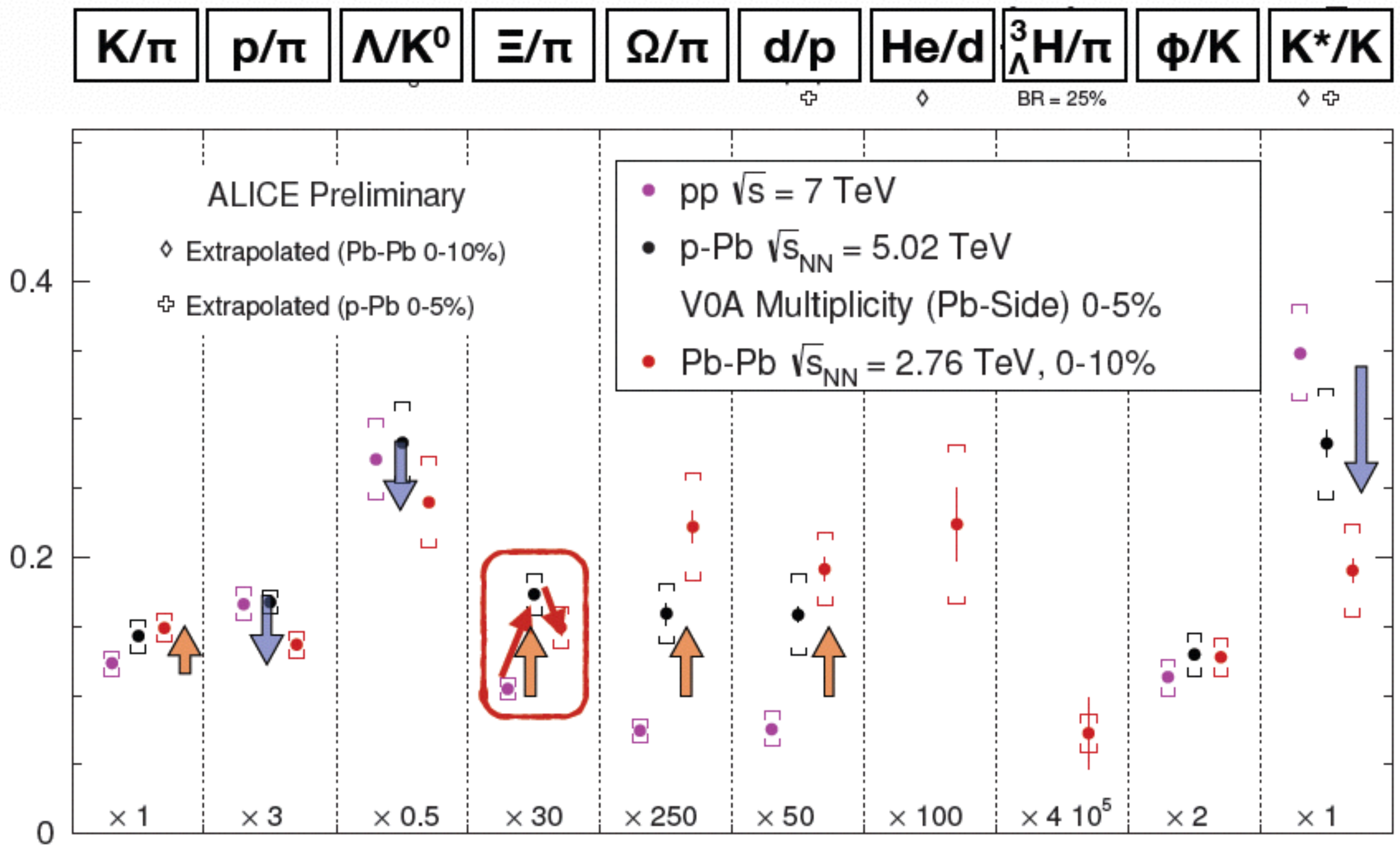
Michele Floris
CERN
May 22, 2014

Hadrons, Phase Diagram and Equilibrium



- Hadrons produced in apparent thermal equilibrium
- Measurements at different √s line up in a hadron freeze-out curve
- Key Questions:
  - What is the relation to the critical temperature?
  - How is this apparent equilibrium reached?
- Precision era (LHC, BES, HADES)
  - (Small) deviations from overall trend and from equilibrium fits can improve our understanding of the underlying physics

Ratios, system size dependence at the LHC



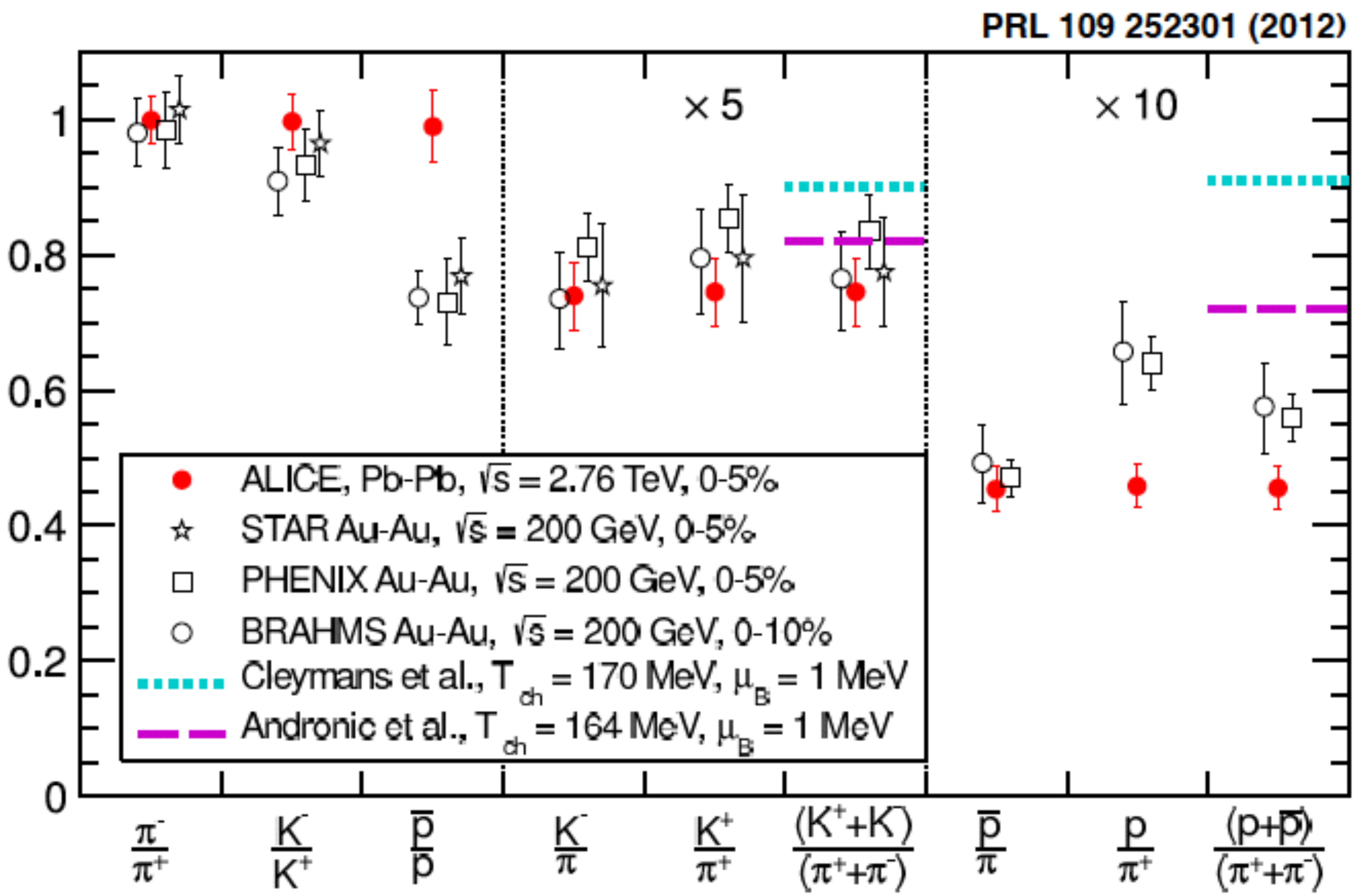
Strangeness enhancement

Deuteron enhancement

K* suppression

Baryon suppression?

Anomalous p/π ratio at the LHC



ALICE, QM11

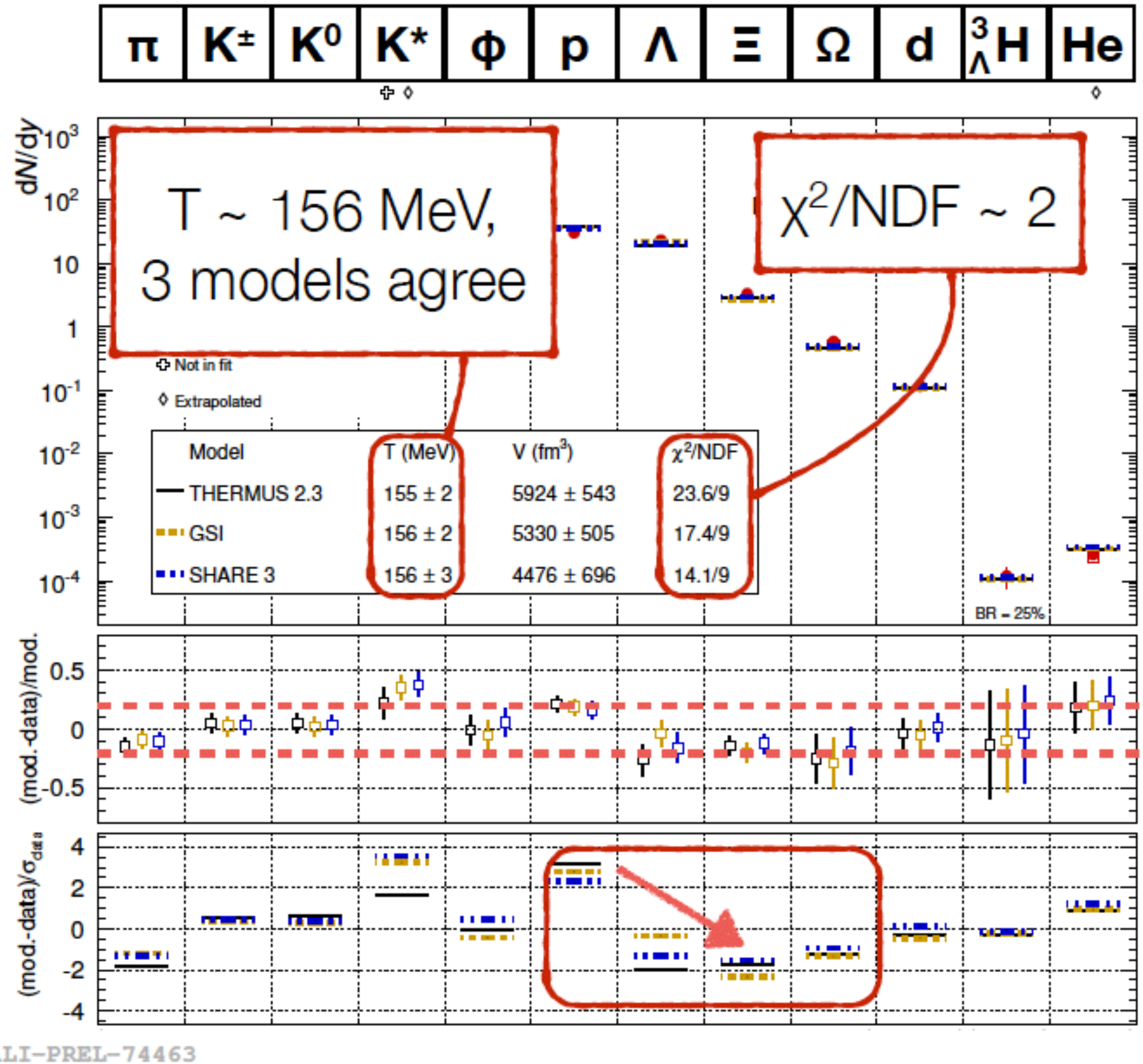
p/π: 1.5 smaller than expectations

Is it only protons or all baryons?

Why?!

(NB with these 3 particles, it would be enough to lower T ~ 140 MeV)

Equilibrium SHM Fits

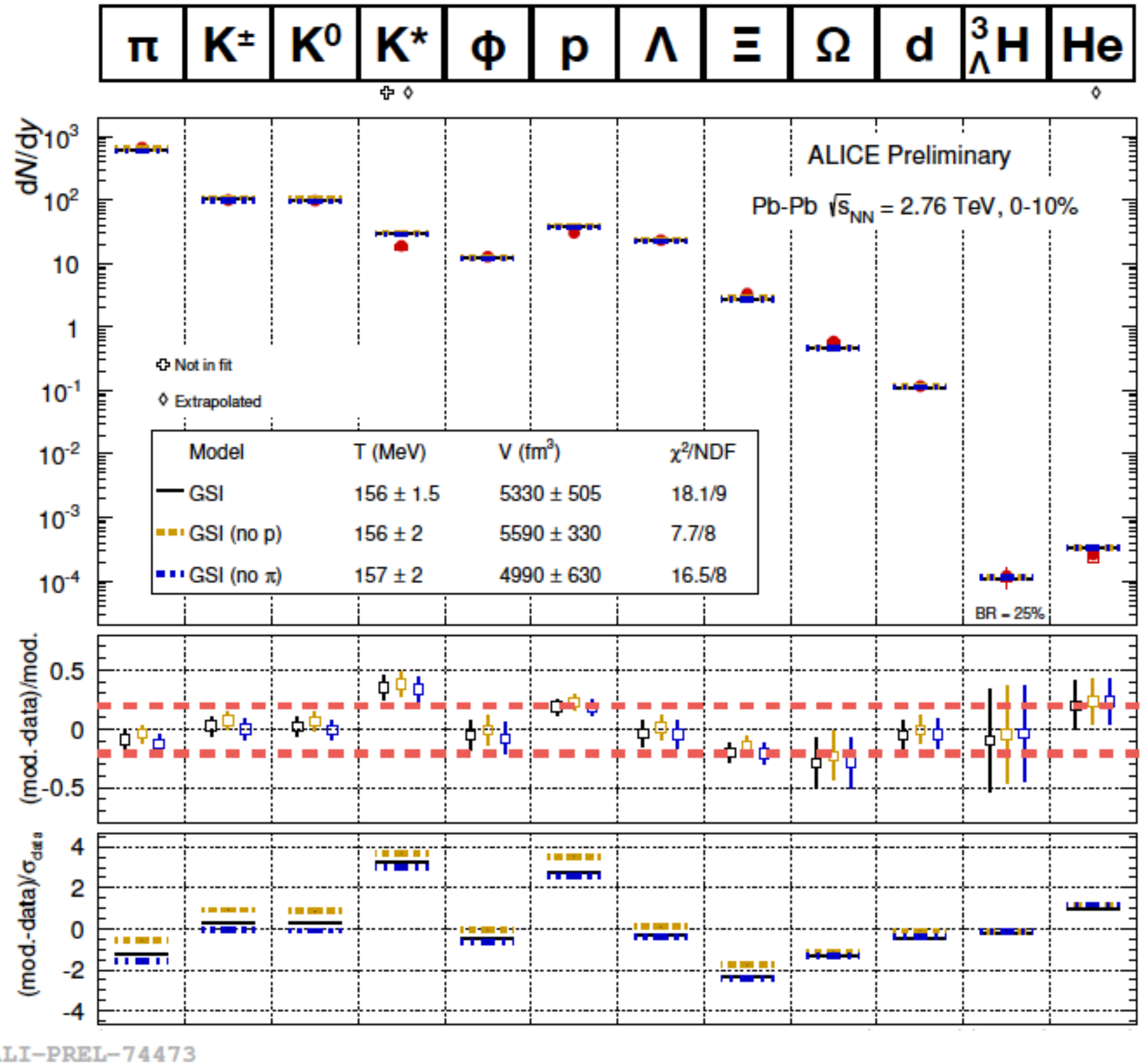


N.B.
RHIC
$\sqrt{s}$ = 200 STAR
χ^2/NDF~1

Better fit in
60-80%,
(feel free to ask about it)

Petran et al, arXiv:1310.5108
Wheaton et al, Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142

Excluding protons or pions (GSI)



No π

Fit quality does not improve (no evidence for pion condensate, as opposed to n.eq. model)

No p

Better fit, proton anomaly?

Excluding protons or pions (GSI)

ALI-PREL-74473

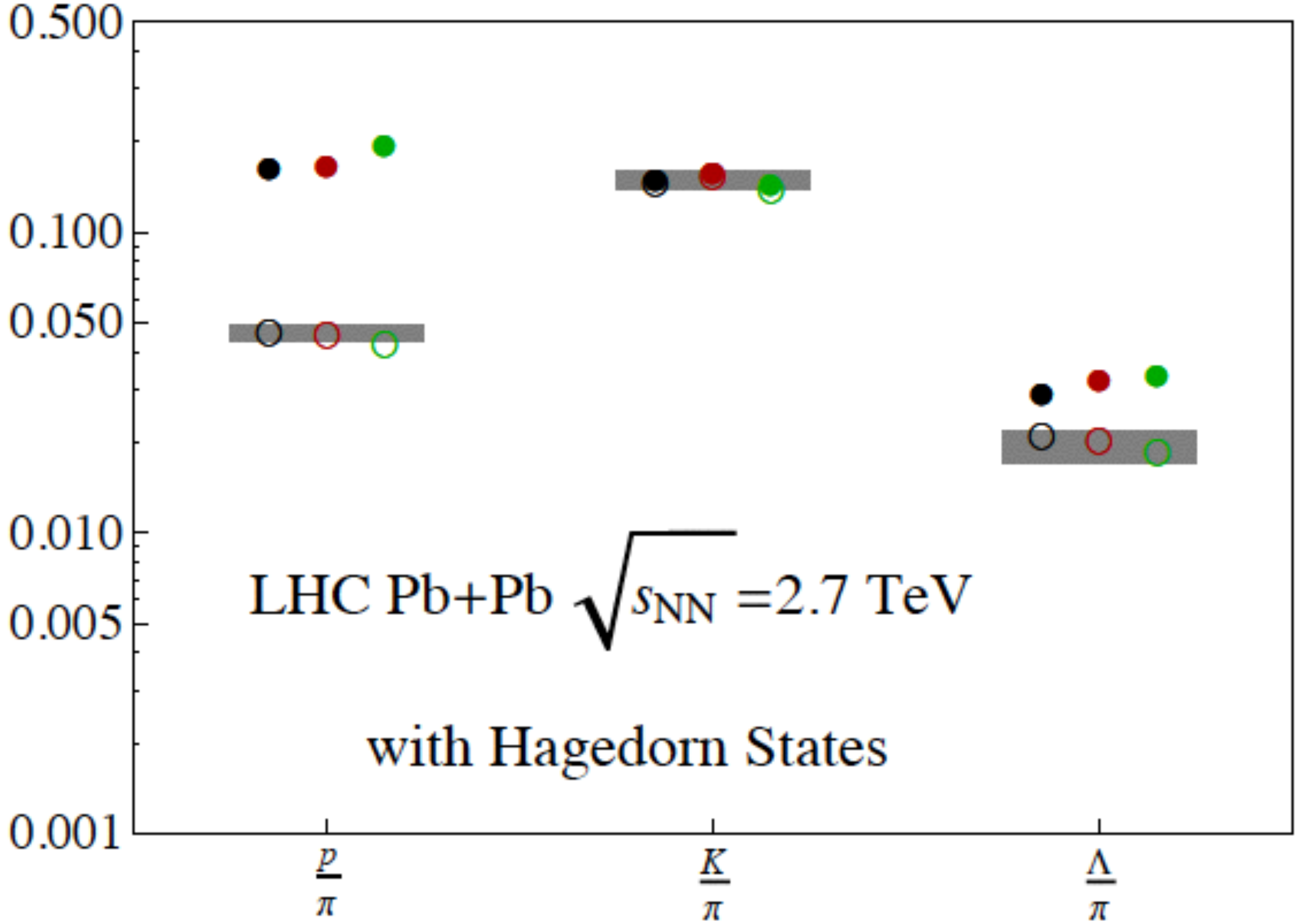
No π

Fit quality does not improve (no evidence for pion condensate, as opposed to n.eq. model)

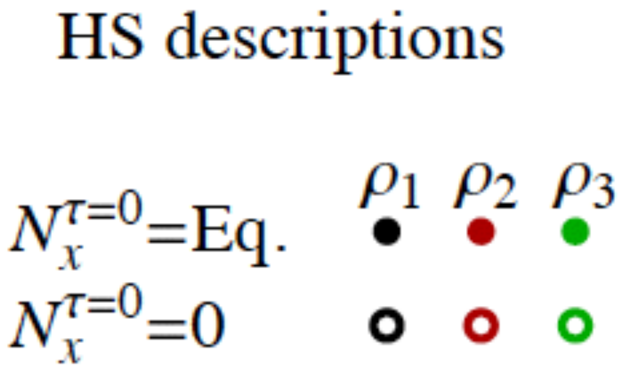
No p

Better fit, proton anomaly?

Incomplete hadron spectrum



Lines: ALICE data
Points: Model based on Hagedorn states



Using assumptions on Hagedorn states, p/π reproduced

See also:

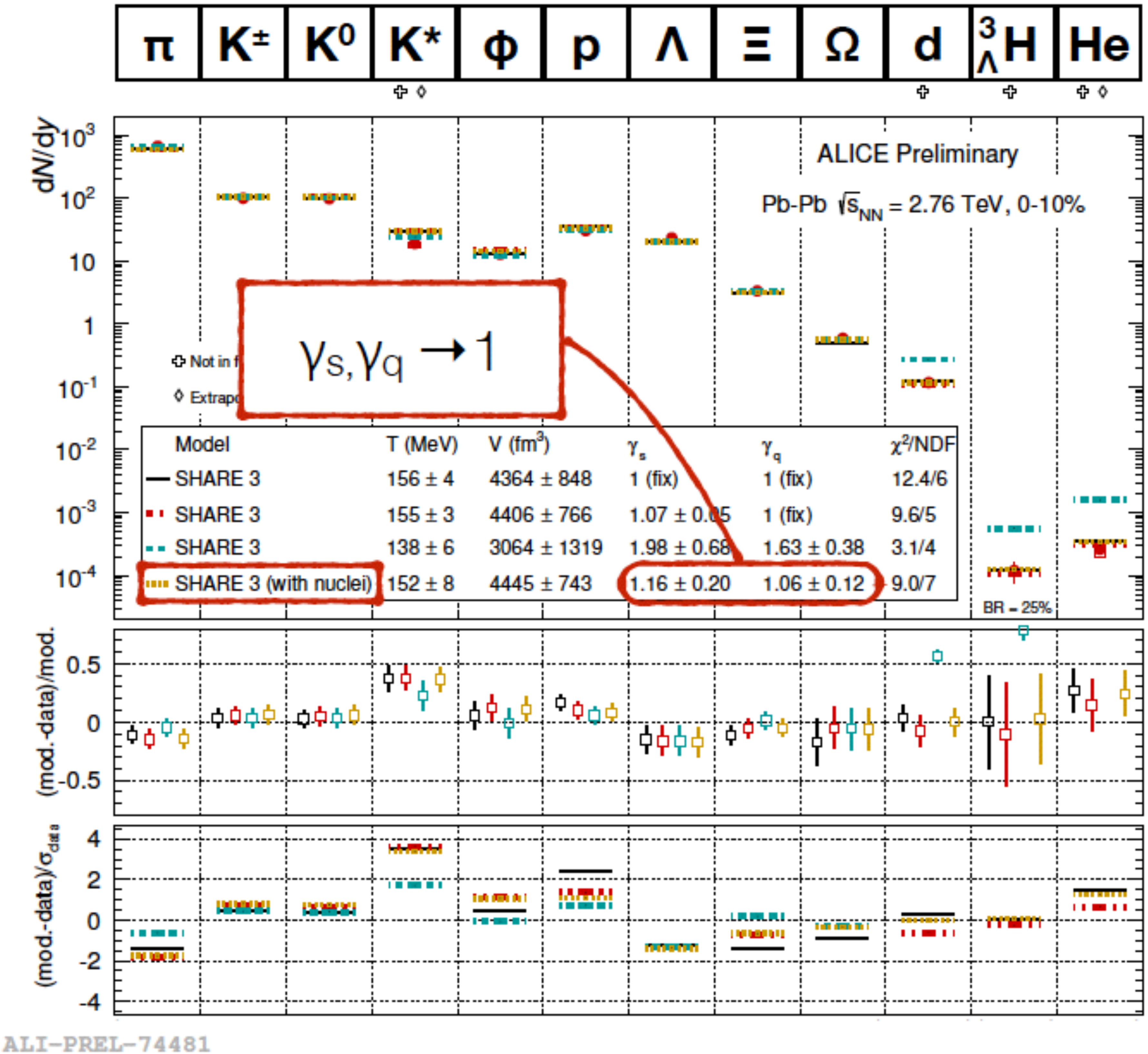
C. Schmidt, Wed 21 (Baryonic strange states)

J. Noronha-Hostler, Wed 21

J. Stachel et al, SQM13

J. Noronha-Hostler, arXiv:0906.3960 (RHIC)

Non equilibrium SHM: Fits



Very good if not including nuclei (similar to Refs)

Nuclei prediction off by factor ~ 5
Try to include nuclei in fit $\gamma_q \rightarrow 1$

Nuclei v_2 in AuAu:

R. Haque, STAR, Mon 19

Petran et al PRC 88 021901
Petran et al, arXiv:1303.2098
Petran et al, arXiv:1310.2551
Petran et al, J. Phys. G 509 012018

Hadronic phase

Late freeze-out for protons?

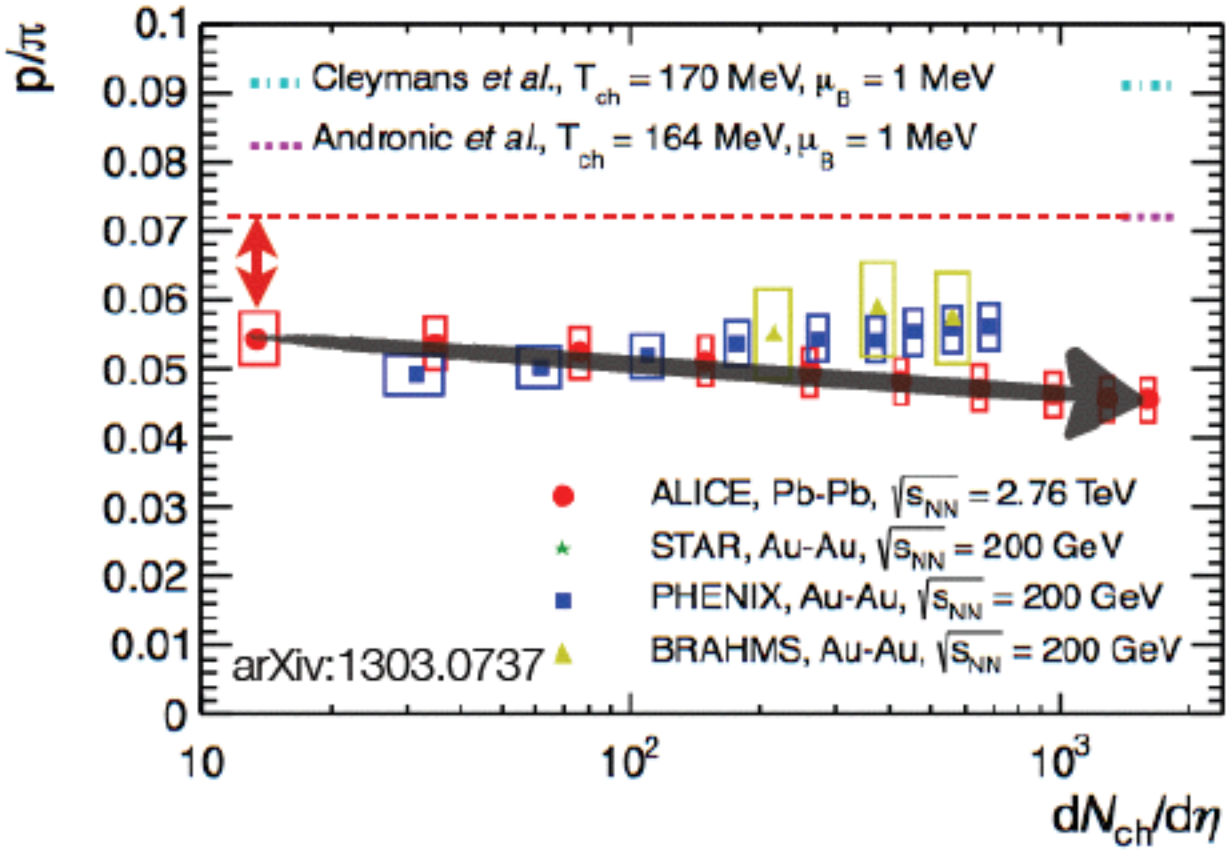
Baryon annihilation ↘ p yield

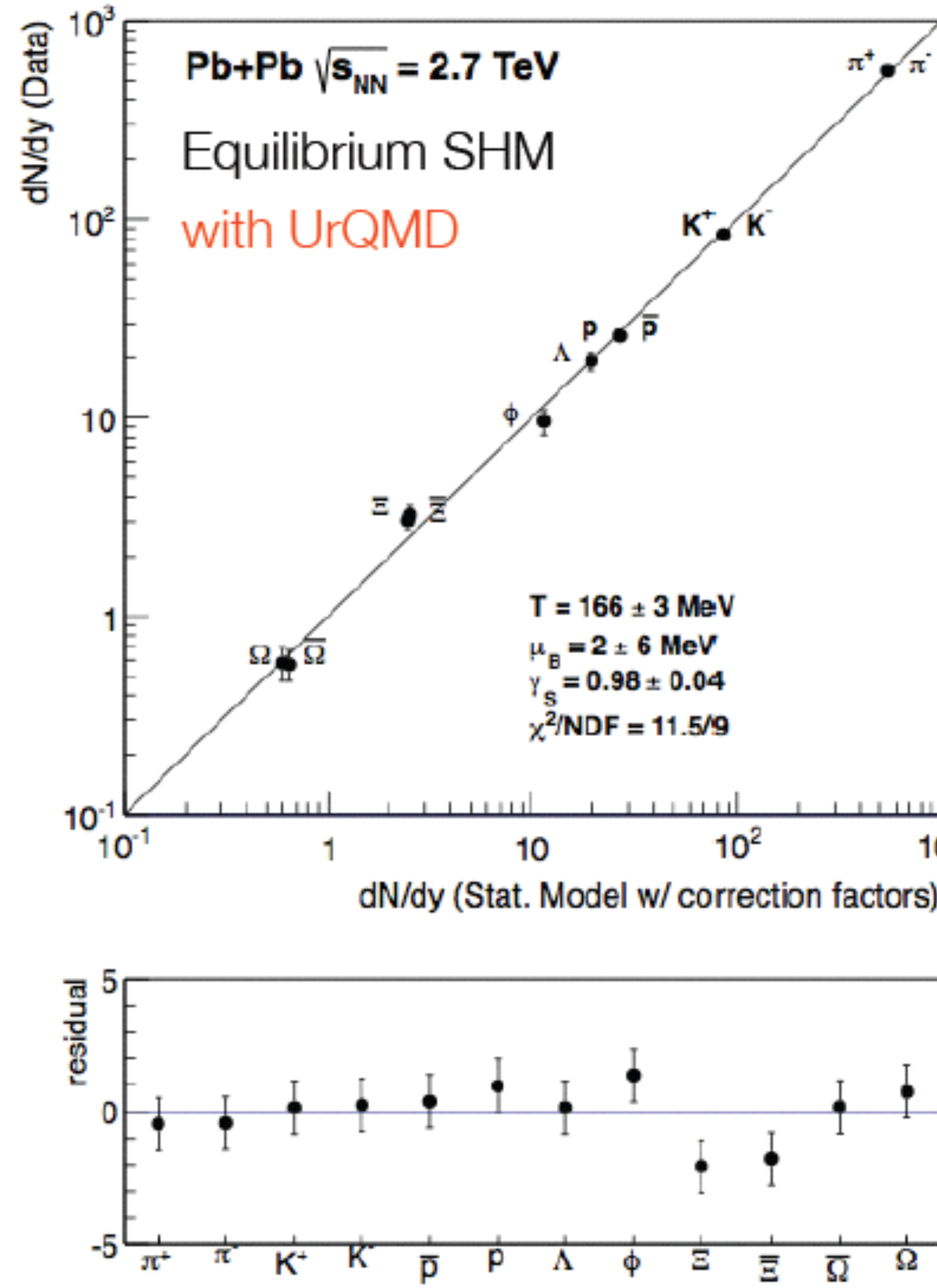
Unmeasured cross sections?

Inverse reactions

($n\pi \rightarrow p\bar{p}$, heavy meson $\rightarrow p\bar{p}$)?

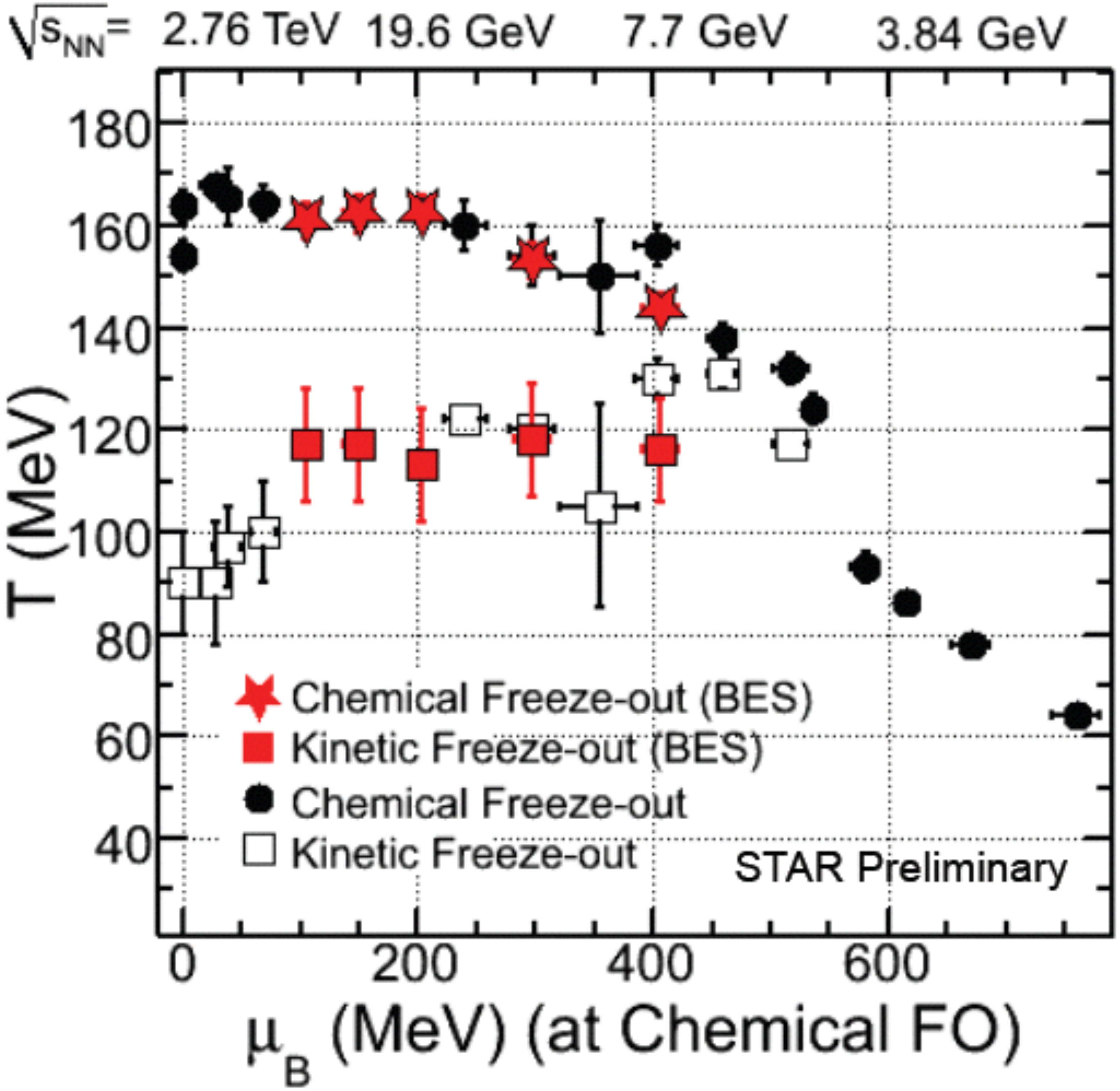
Centrality dependence?





Becattini et al, arXiv:1212.2431

T_{kin} vs T_{ch} vs $\sqrt{s}$ (STAR BES)

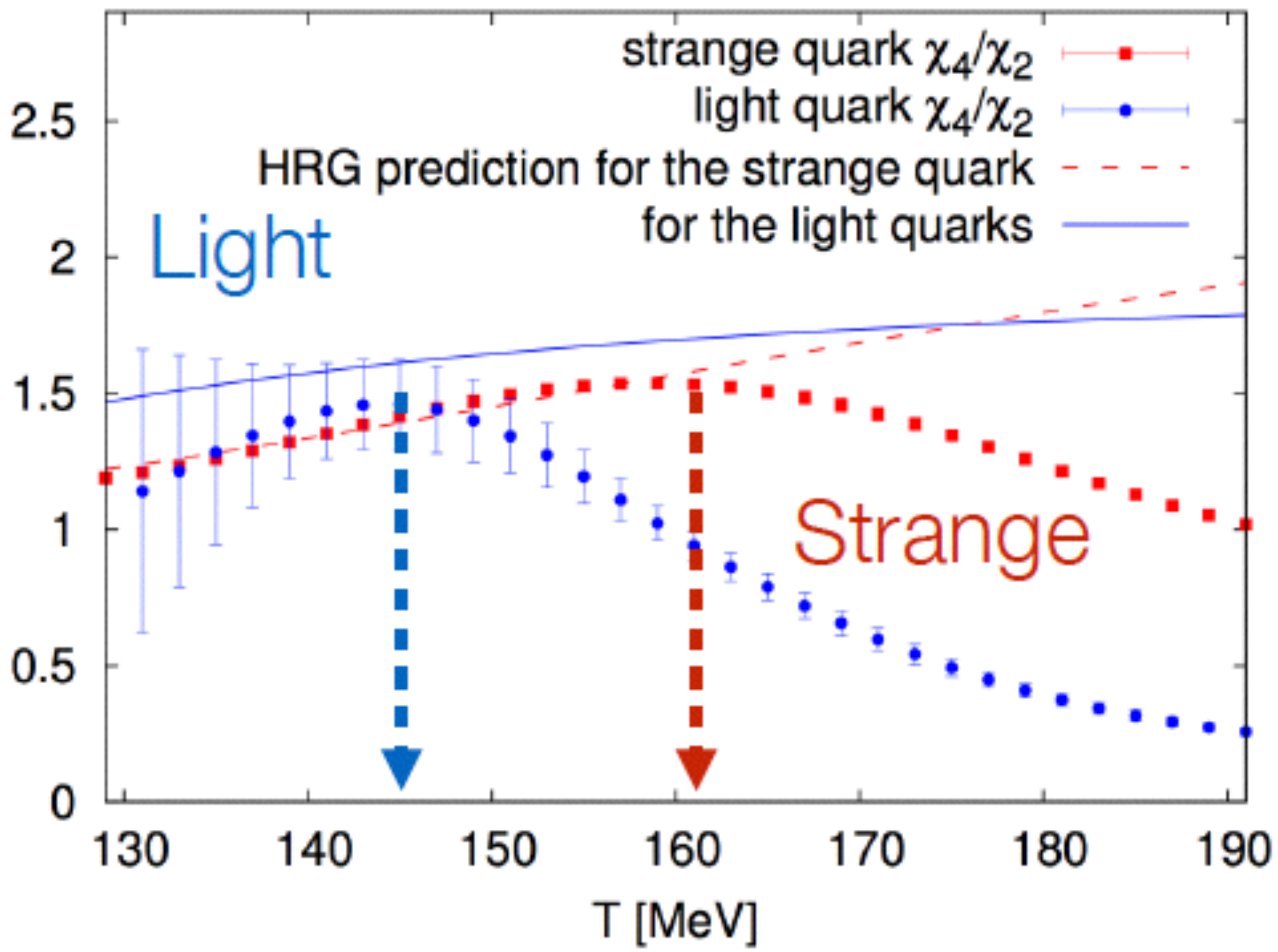


$T_{kin} - T_{ch}$ grows for $\mu_B \rightarrow 0$

Importance of hadronic phase?

L. Kumar, STAR, Wed 21

Flavor hierarchy in the QCD phase transition



Lattice: indication of a **flavor hierarchy** at freeze-out?

Pre-hadronic bound states: strangeness above T_C?

Connection to experiment:

higher order moments of net charges?

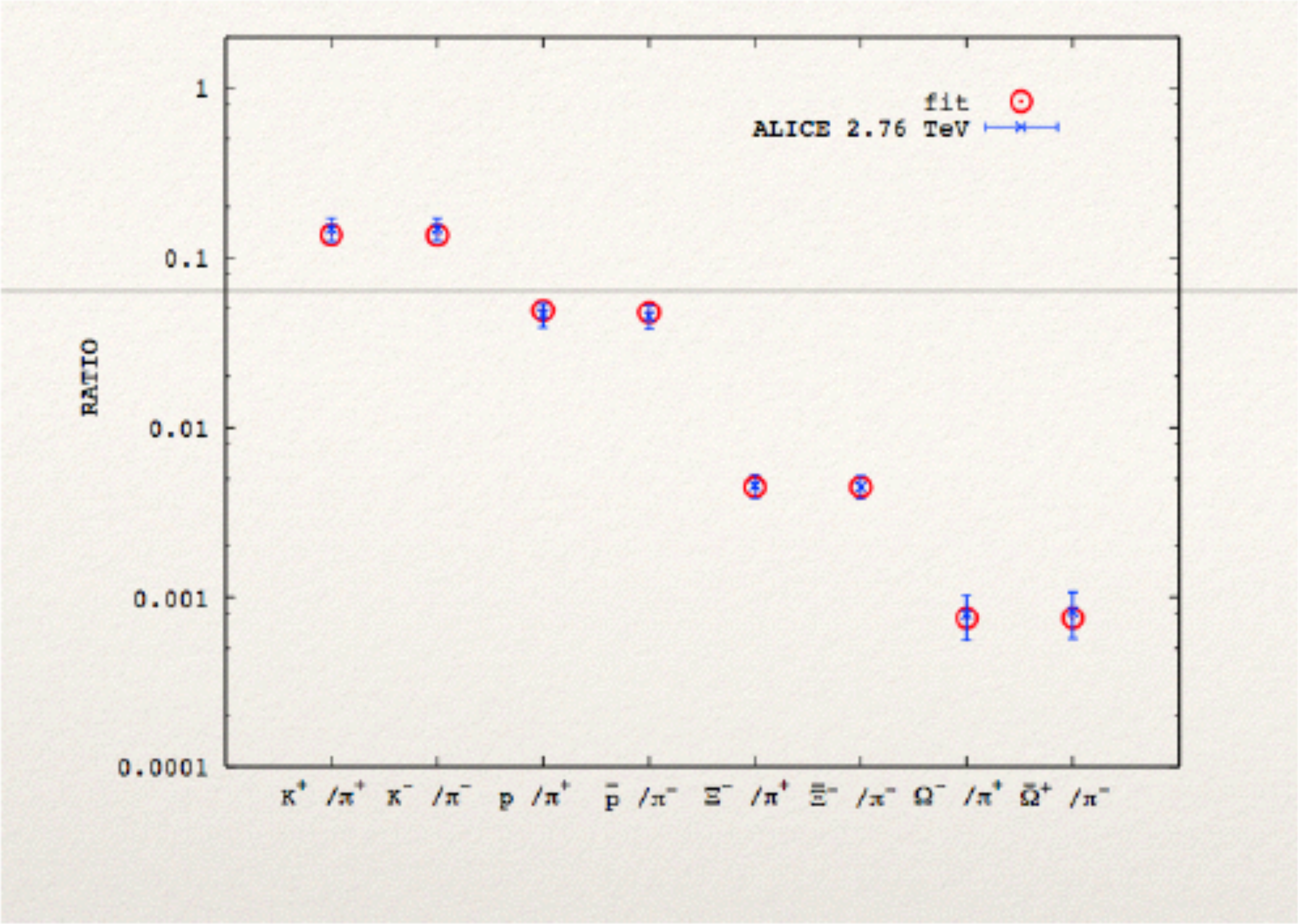
(related to susceptibilities ratios of conserved charges)

Caveats: needs strange baryons, limited phase space, baryons vs protons …

Bellwied et al, PRL 111 202302
Ratti et al PRD85 014004
F. Karsh, Cent. Eur. J. Phys., 10 1234

Chemical and Thermal analysis

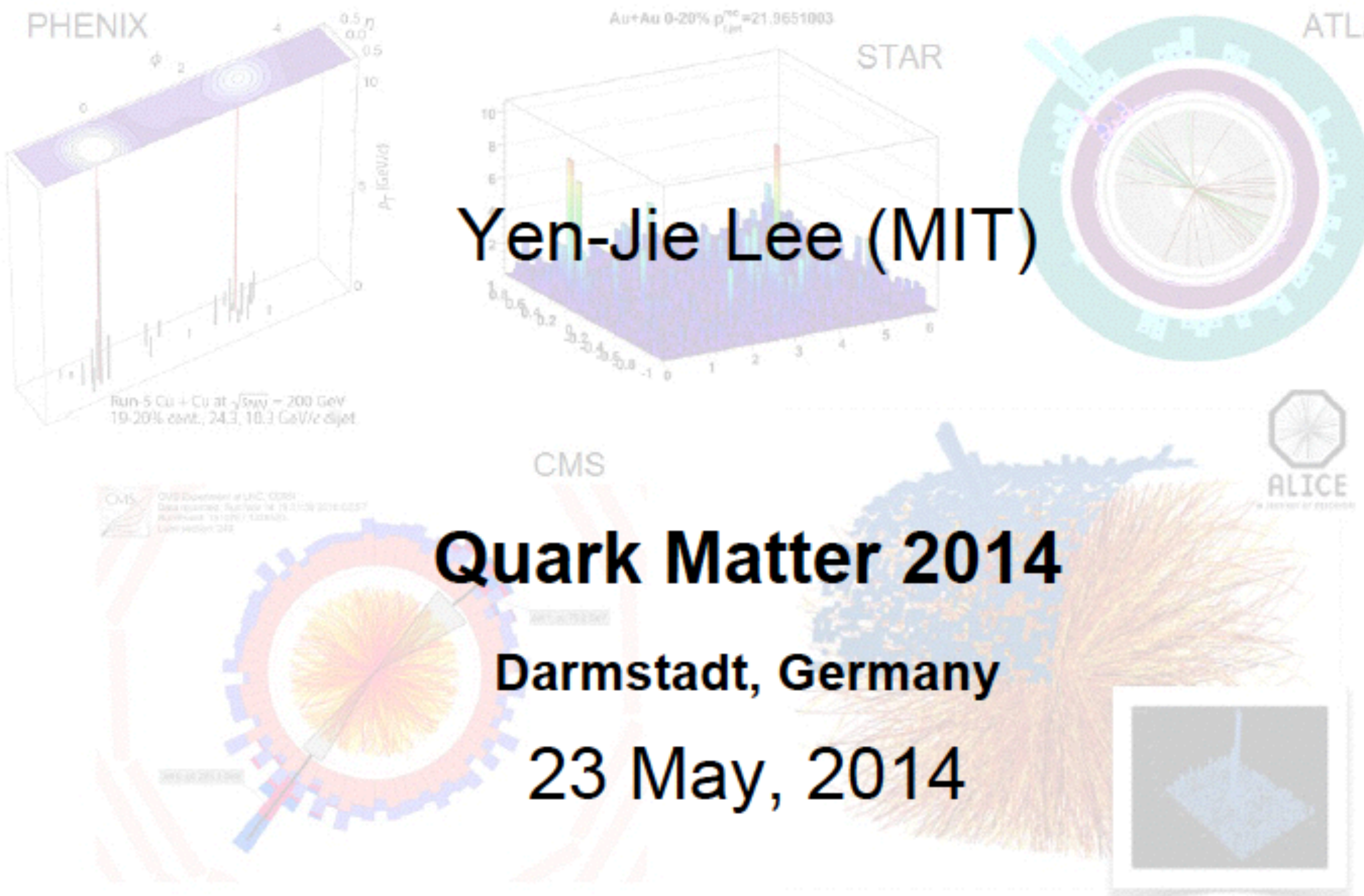
Idea: take into account effect of resonances in a limited acceptance with a 2-freezeout blast wave model, using an iterative procedure



	T	μ_B	μ_S	ρ_0	η_{max}	χ^2/N
C.F.	150.7	0.37	0.15			0.9
T. F.	112.9			1.28	6.05	3.4

K. Seog Lee et al, Poster G-10

Experimental results on jets in ultra-relativistic nuclear collisions



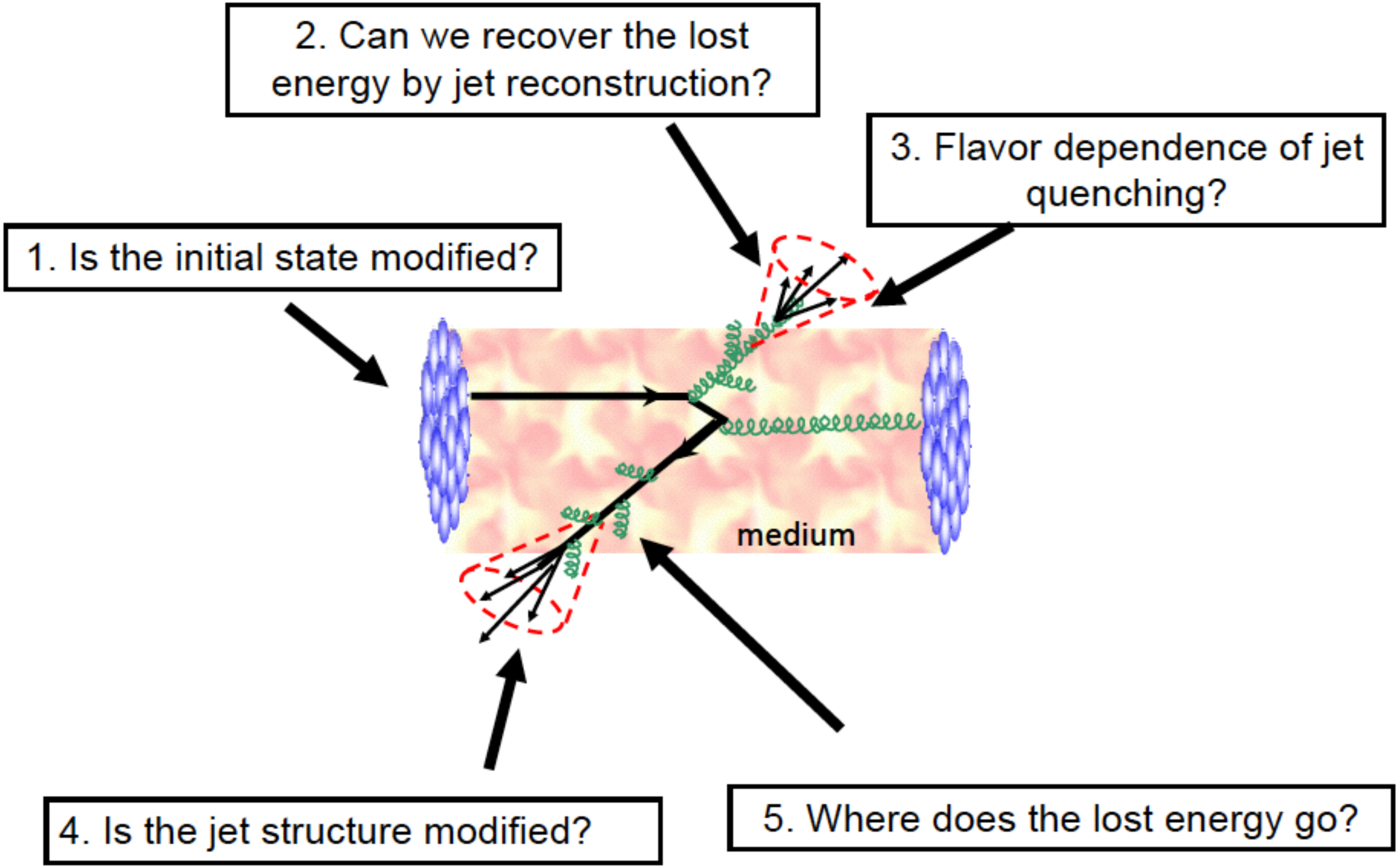
Yen-Jie Lee (MIT)

Quark Matter 2014

Darmstadt, Germany

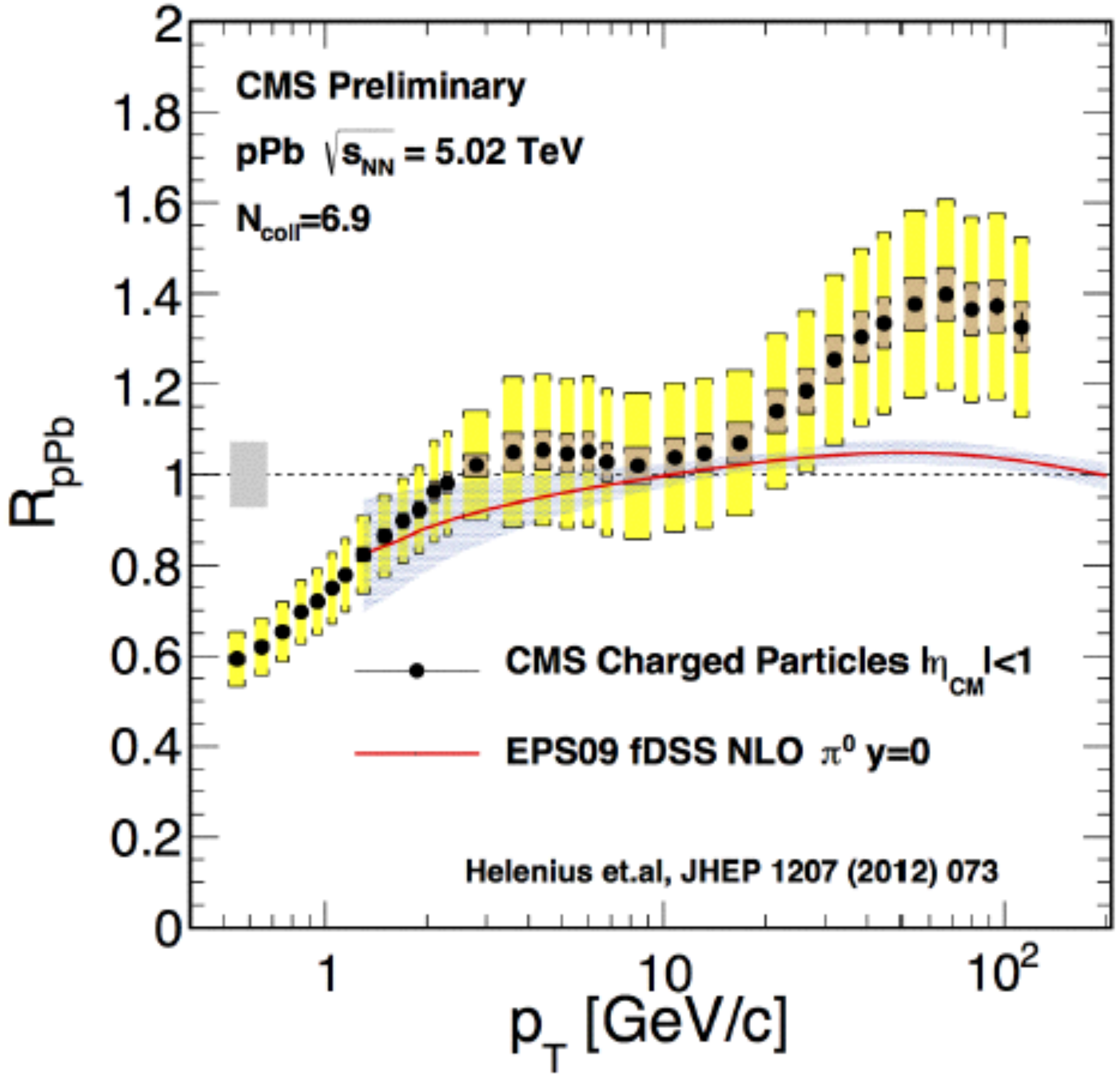
23 May, 2014

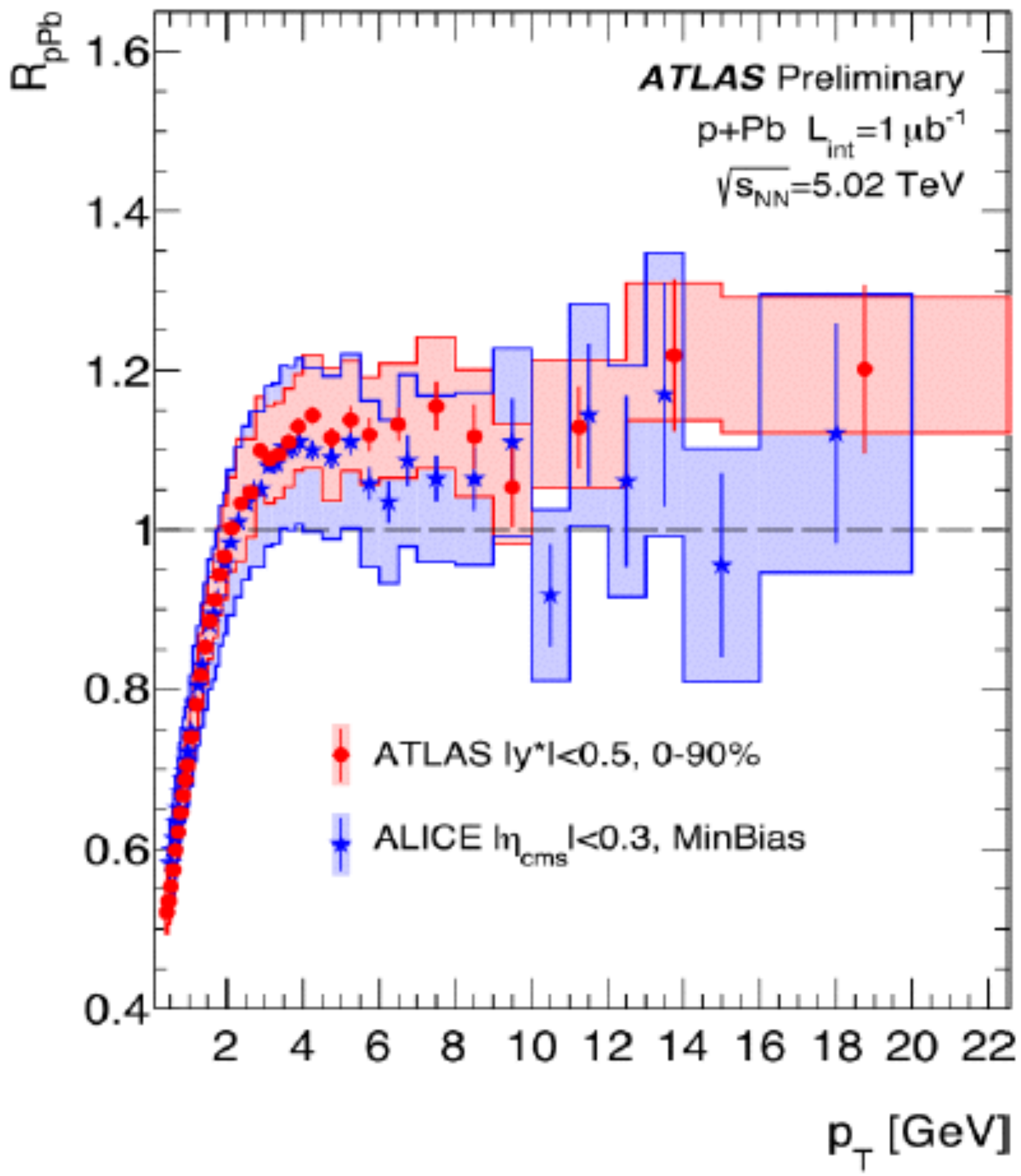
Questions to be answered



Charged particle R_{pPb} (HP2013)

Starting from charged particle spectra





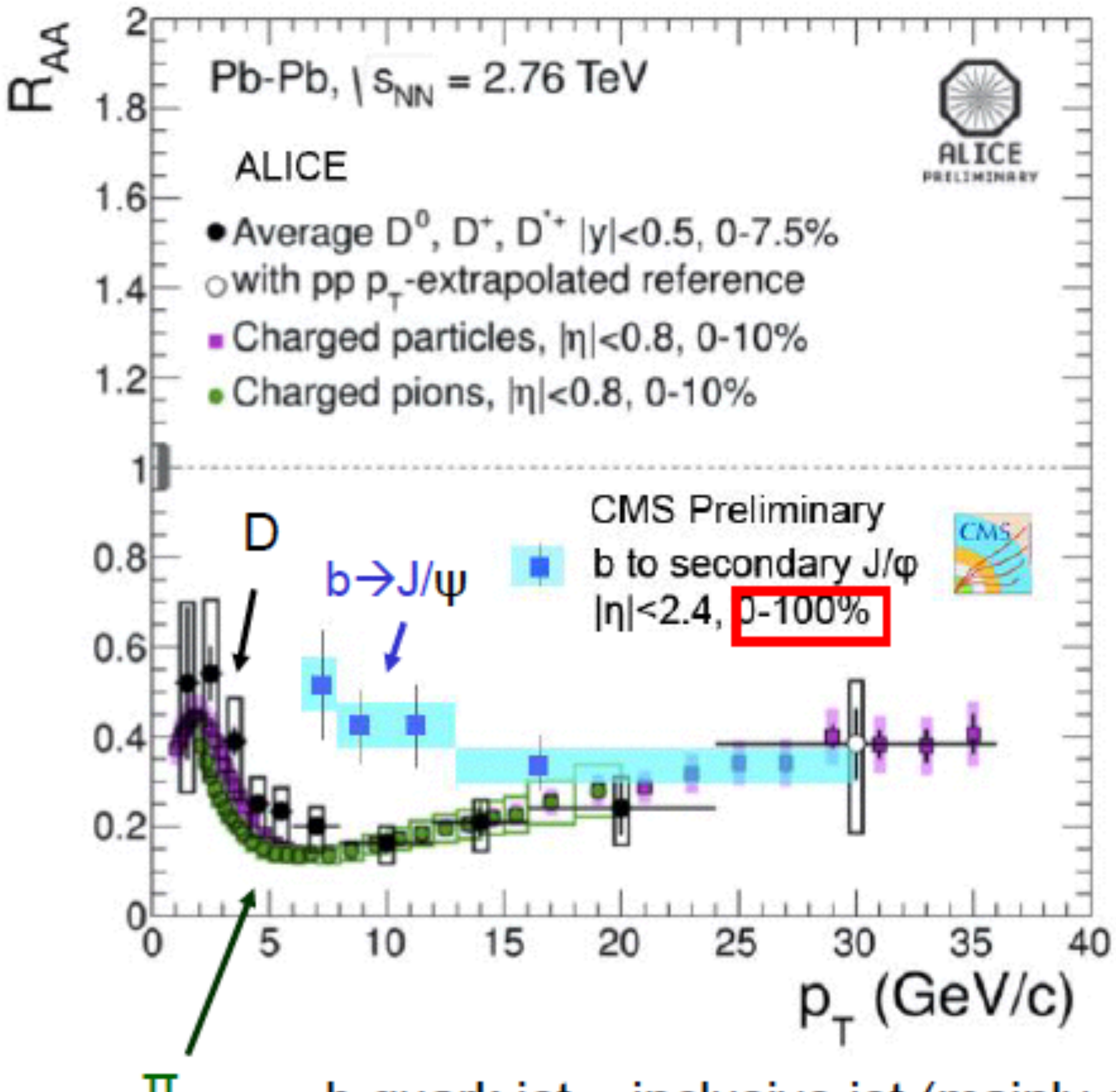
CMS charged particle R_{pPb} can not be described by nPDF (EPS09)

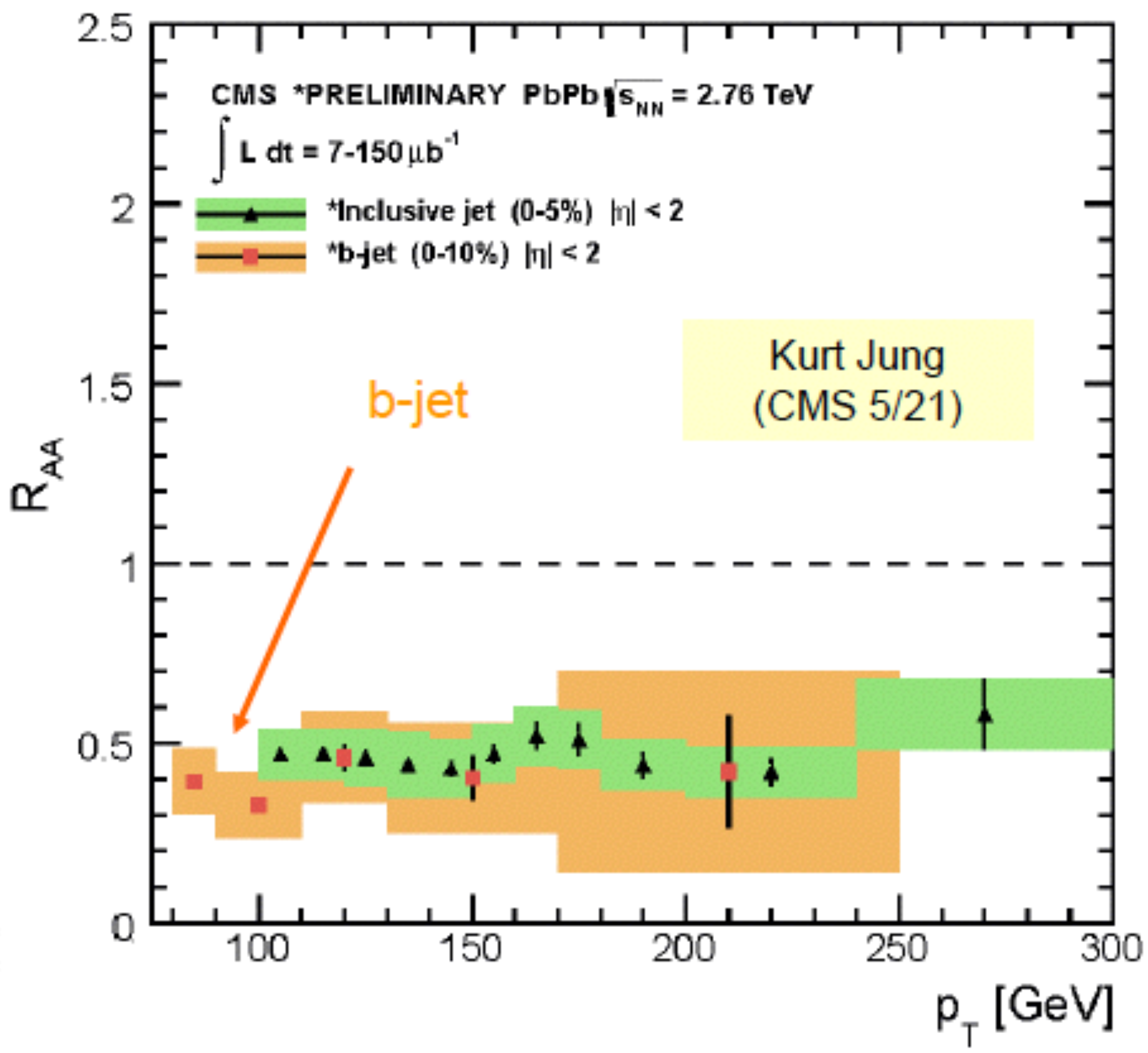
Flavor Dependence of Jet Quenching

Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low p_T

(However, spectra slope are different)

Indication of R_{AA}(b-jet) ~ R_{AA}(all jets) at high jet p_T

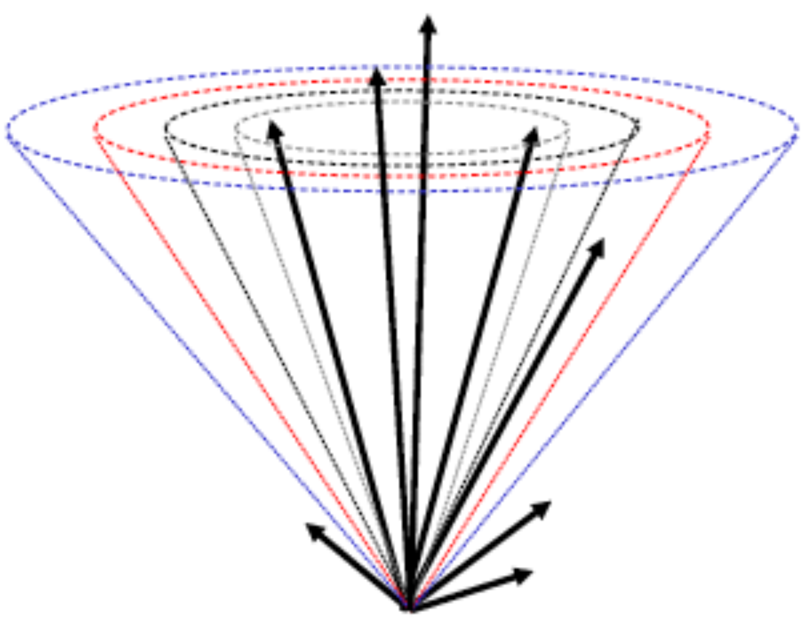




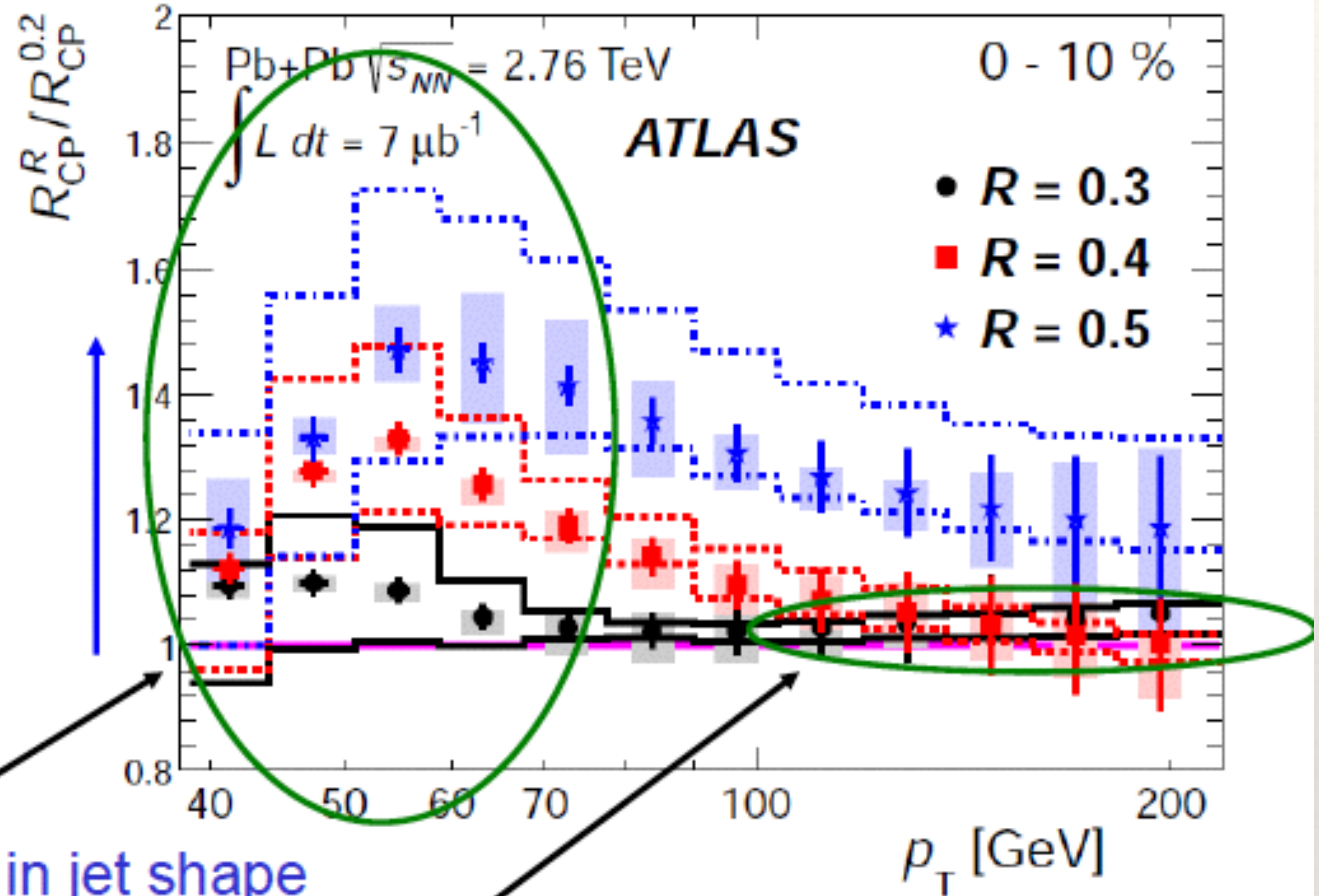
b quark jet ~ inclusive jet (mainly gluon jets), contribution from gluon splitting?

Do we collect the radiated energy with large cone size?

Anti-k_T jets with
R = 0.2, 0.3, 0.4, 0.5



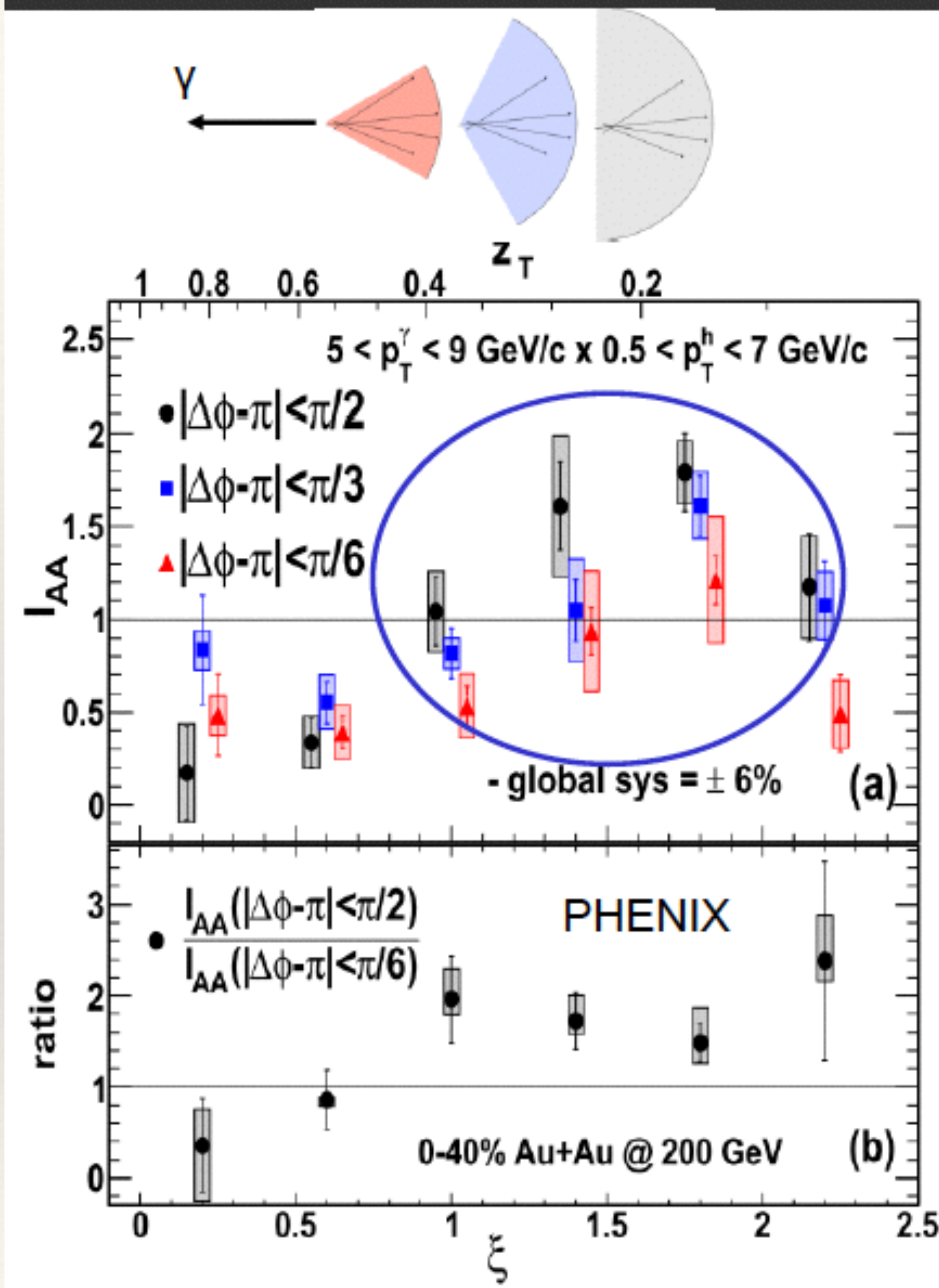
Ratio of R_{CP} with different cone sizes



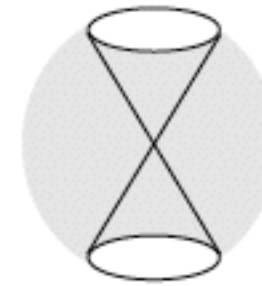
$R_{CP}^{(R=0.5)}/R_{CP}^{(R=0.2)} > 1$
→ recovery of lost energy, change in jet shape
with respect to the pp reference

ATLAS Jet $R_{CP}^{(R=0.3)} / R_{CP}^{(R=0.2)} \sim 1.0 \pm 0.2$
Allows to recover up to 0-4% more jet energy when moving from R=0.2 → R=0.3 in PbPb collisions than pp reference

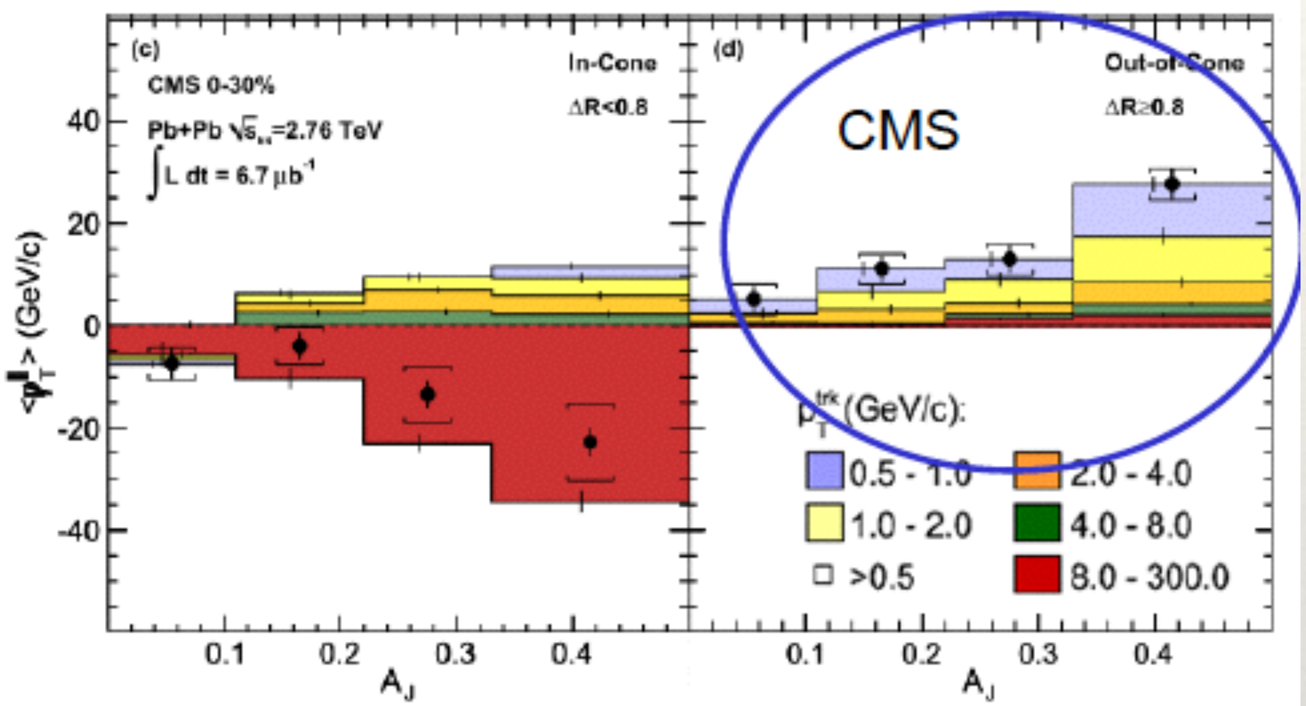
Lost energy at RHIC and LHC



Tracks in the jet cone ΔR<0.8



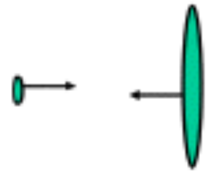
Tracks out of the jet cone ΔR>0.8



Lost energy: found in large Δφ(ΔR) with respect to the away-side jet, converted to low p_T particles.

Summary and outlook (1/2)

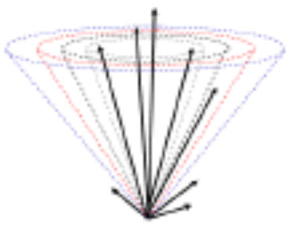
1. Is the initial state modified?



Inclusive pPb collisions: can be described by nPDF

In bins of event activity: interesting effects such as energy conservation (G. Milhano, N. Armesto), fluctuating proton size (M. Strikman) come into play

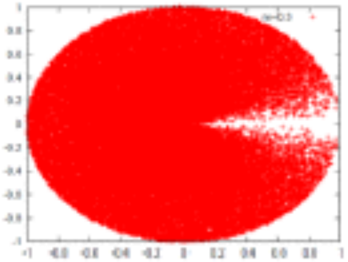
2. Can we recover the lost energy by jet reconstruction?



Lost energy is recovered slowly, R=0.2-0.5 doesn't recover all the lost energy

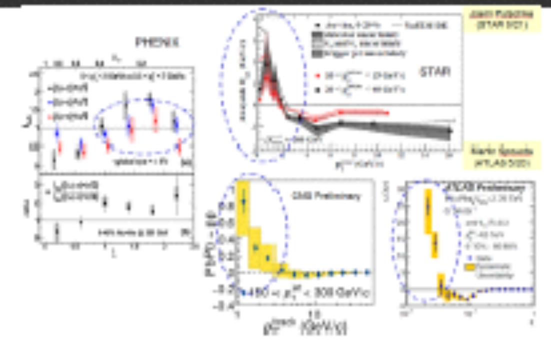
Different behavior observed (in STAR) if biased jet fragmentation selection is used

3. Flavor Dependence of Jet Quenching?



Hint of parton flavor dependence of energy loss at low p_T, disappearance at high p_T
To be followed up by high statistics fully reconstructed D meson, B meson, b-jet angular correlation, and identified jets

Summary and outlook (2/2)



4. Is the jet structure modified?

Excess of low p_T particles inside the jet cone.

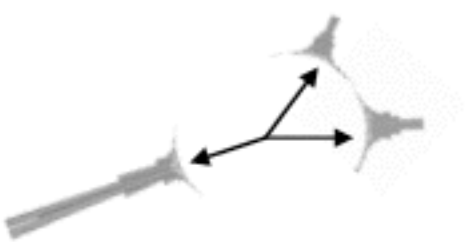
Modified jet FF and/or jet shapes can be explained by different classes of models

Which part of it is coming from the changing q/g fraction?

How does parton energy loss depend on the fragmentation pattern?

Can we learn more using sub-jet reconstruction?

Fluctuation of jet fragmentation modification?



5. Where are the lost energy?

The lost energy is carried by low p_T particles far away from the jet cone

Distribution of lost energy: Initial configuration (2/3/multi-jet) + medium effects

Can we kill the effect by biasing the jet fragmentation?

What are the alternative way to select quenched jets?

Theory of Jet Quenching in Ultra-Relativistic Nuclear Collisions

Guang-You Qin

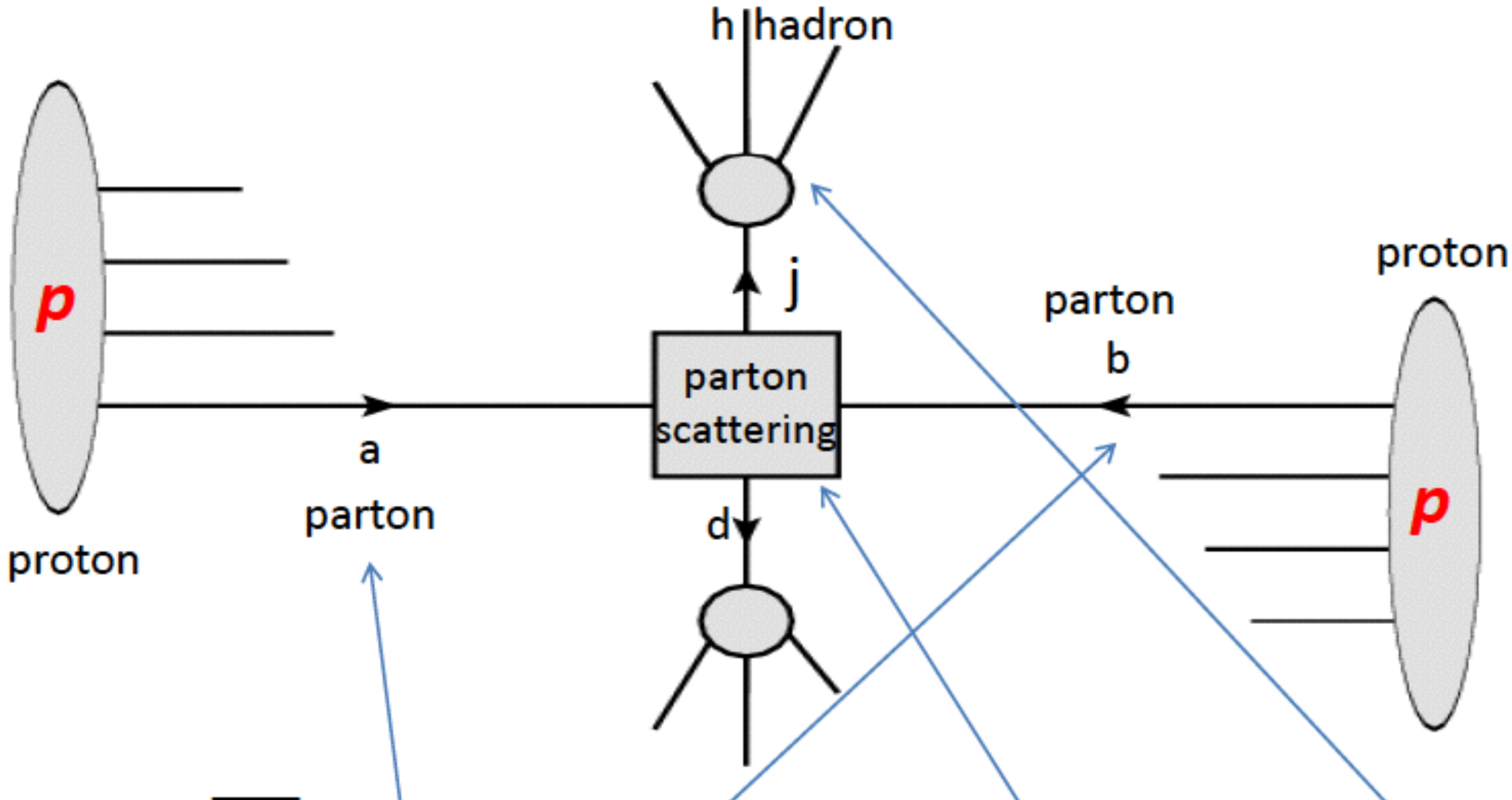
Central China Normal University

Quark Matter 2014 (May 19-24)
Darmstadt, Germany

Outline

- **Jet energy loss**
  - General picture, formalisms
  - RHIC and the LHC hadron R_{AA} (JET collaboration, etc.)
  - NLO (renormalization of q^{hat})
- **Full jet**
  - Full jet evolution and energy loss, multiple gluon emission
  - Jet substructure, Mont-Carlo models
- **Medium response**
  - Jet energy loss/deposition/redistribution
- **Lattice & AdS/CFT**
- **Heavy flavors** (Andrea Beraudo, Friday morning)
- **Summary**

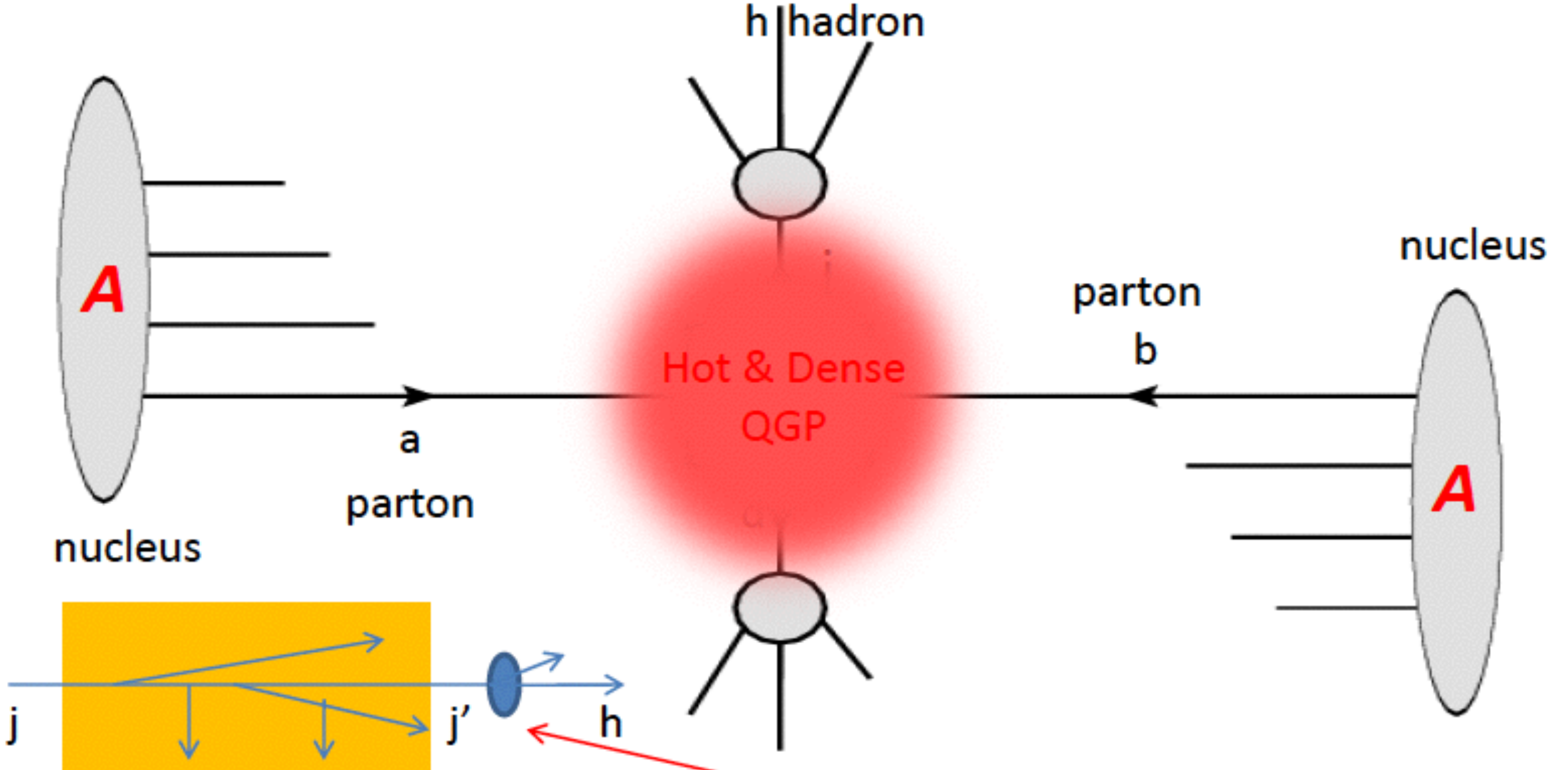
General framework of jet quenching study



$$d\sigma_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jd} \otimes D_{h/j}$$

pQCD factorization: Large-p_T processes may be factorized into **long-distance** pieces in terms of **PDF & FF**, and **short-distance** parts describing **hard interactions** of partons.

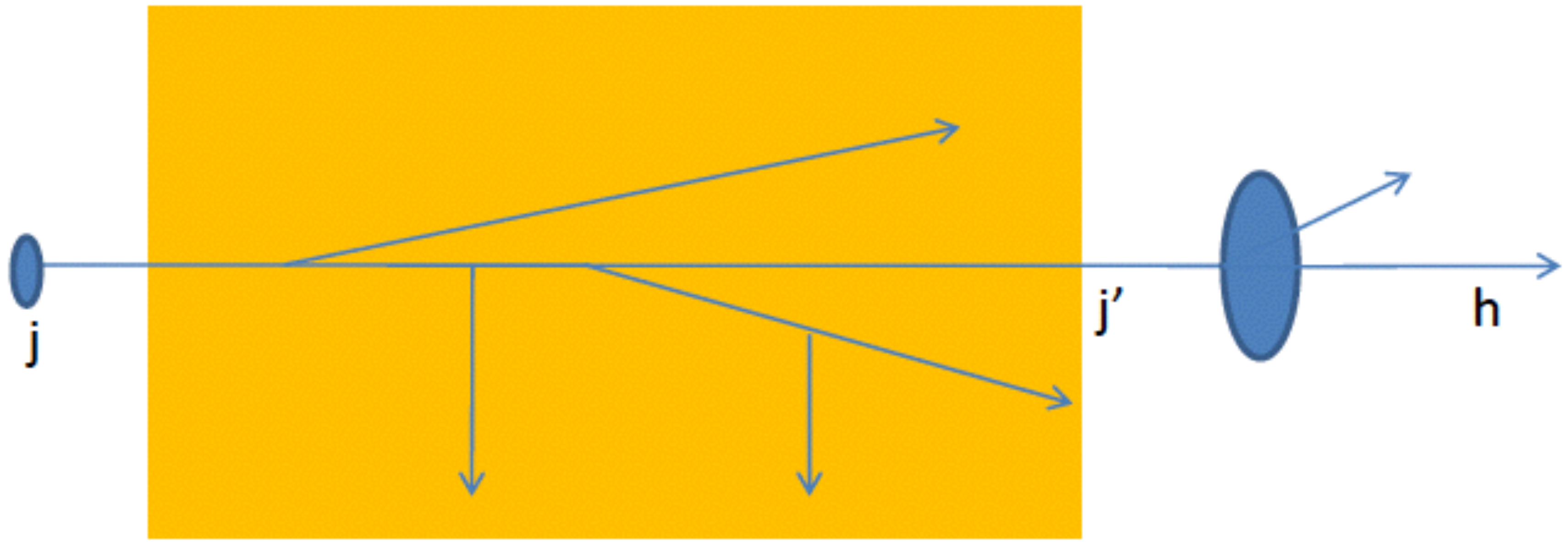
General framework of jet quenching study



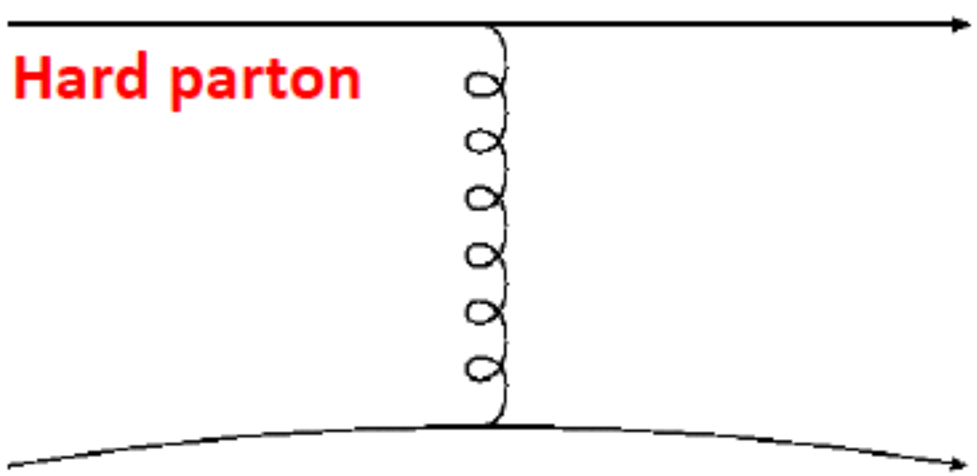
$$d\tilde{\sigma}_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jd} \otimes \tilde{D}_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjj'd} f_a \otimes f_b \otimes d\sigma_{ab\to jd} \otimes P_{j\to j'} \otimes D_{h/j'}$$

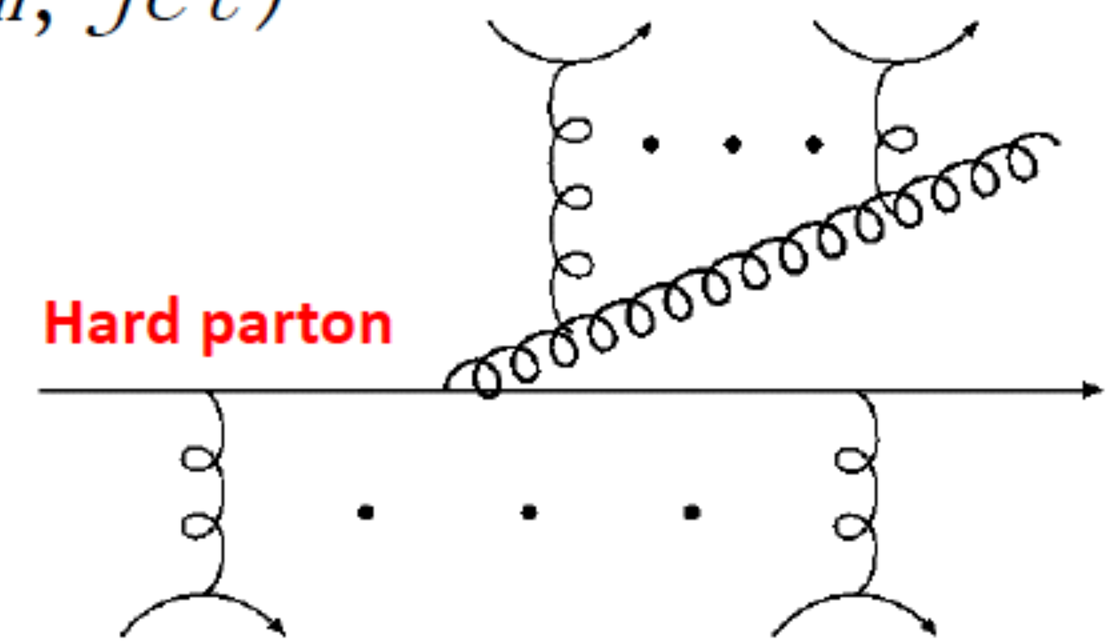
Jet evolution and energy loss in QGP



$$P_{j\to j'}(medium,\ jet)$$



Elastic (collisional)



Inelastic (radiative)

Rad. E-loss

- **Single gluon emission**
  - **Multiple soft scatterings (BDMPS-Z, ASW, AMY)**
  - **Few hard scatterings (DGLV, HT)**
  - **Recent developments:**
    - **AMY: finite L** (Caron-Huot, Gale 2010)
    - **GLV: finite dynamical medium** (Djordjevic, Heinz, 2008)
    - **DGLV: non-zero magnetic mass** (Djordjevic, Djordjevic, 2012)
    - **Higher Twist (HT): multiple scatterings** (Majumder 2012)
- **Mutiple gluon emission**
  - **Poisson convolution (BDMPS/ASW/DGLV)**

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{e^{-\langle N_g \rangle}}{n!} \left[\prod_{i=1}^{n} \int d\omega \frac{dI(\omega)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right)$$

  - **Rate equation (AMY)**

$$\frac{df(p,t)}{dt} = \int dk f(p+k,t) \frac{d\Gamma(p+k,k)}{dkdt} - \int dk f(p,t) \frac{d\Gamma(p,k)}{dkdt}$$

  - **DGLAP-like evolution equation (HT)**

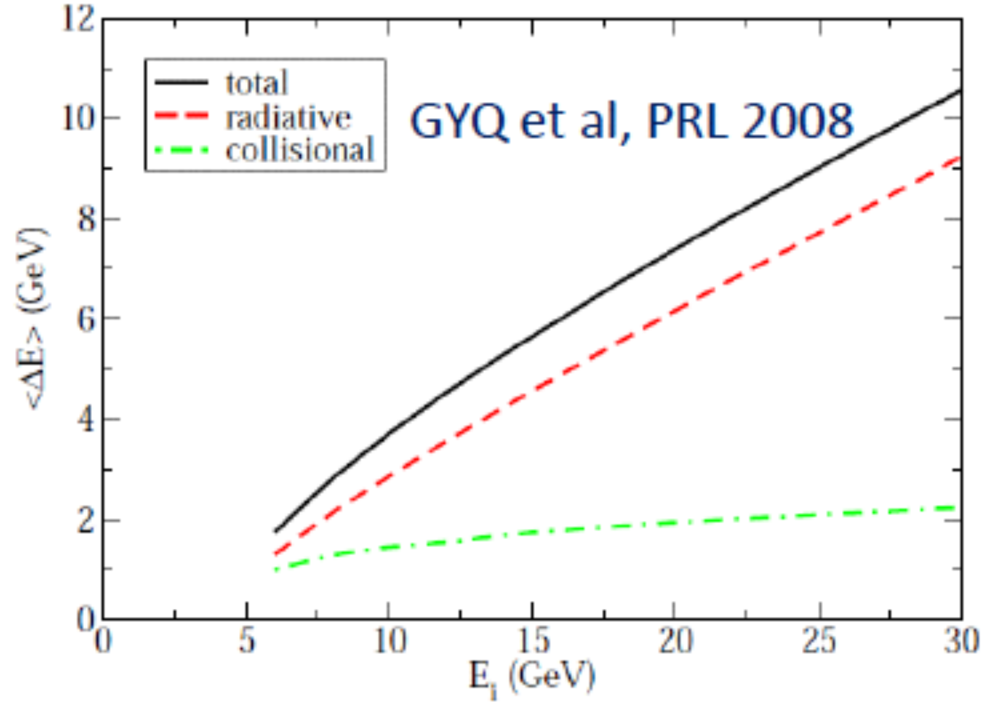
$$\frac{\partial \tilde{D}(z,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P(y) \int d\zeta^- K(\zeta^-, q^-, y, Q^2) \tilde{D}(\frac{z}{y}, Q^2)$$

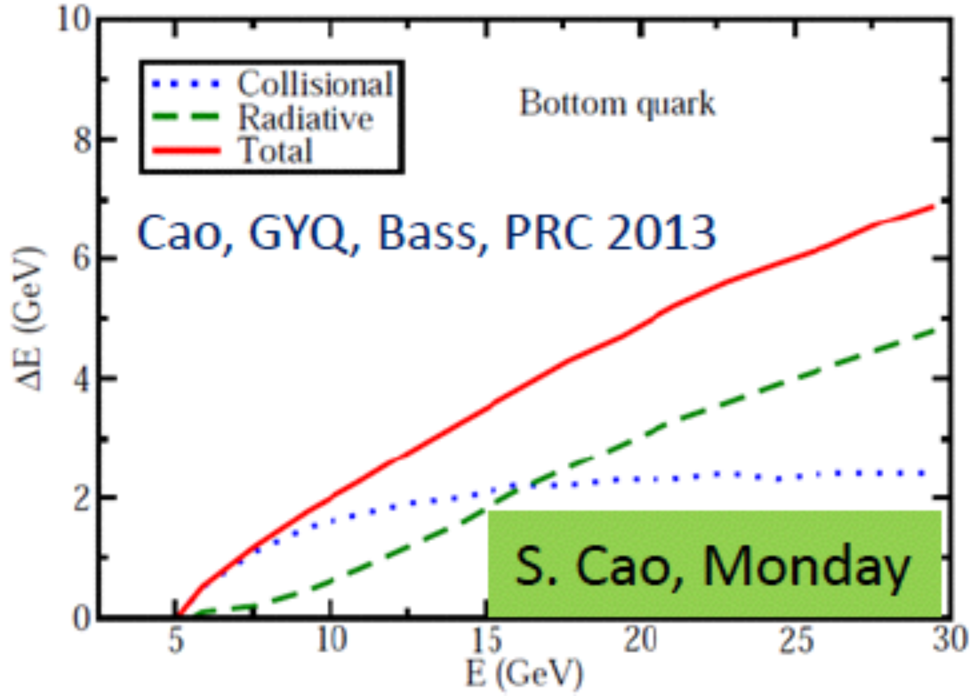
BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe
DGLV: Djordjevic-Gyulassy-Levai-Vitev
HT: Wang-Guo-Majumder

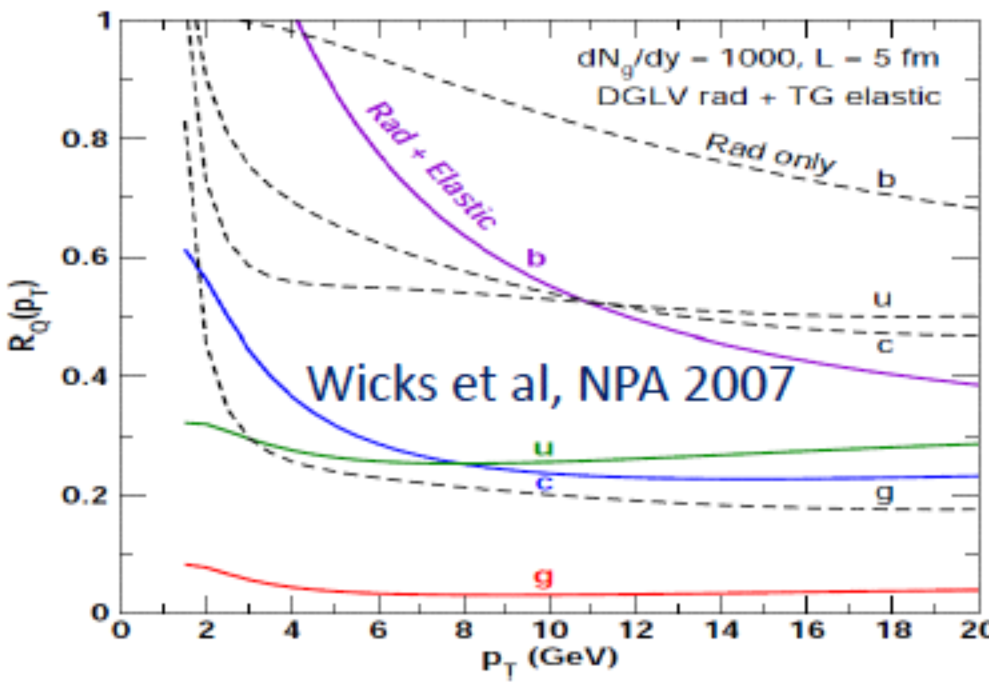
$$\frac{dN_g}{dx dk_\perp^2 dt}(T, E, \ldots) = ?$$

Coll. E-loss

- **First studied by Bjorken:**
  - Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic (GLV), 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008…
- **Main findings:**
  - **dE/E small compared to rad. for large E**
  - **Non-negligible in R_{AA} calculation (especially for heavy flavor)**
  - **Important when studying full jet energy loss and medium response (see later)**







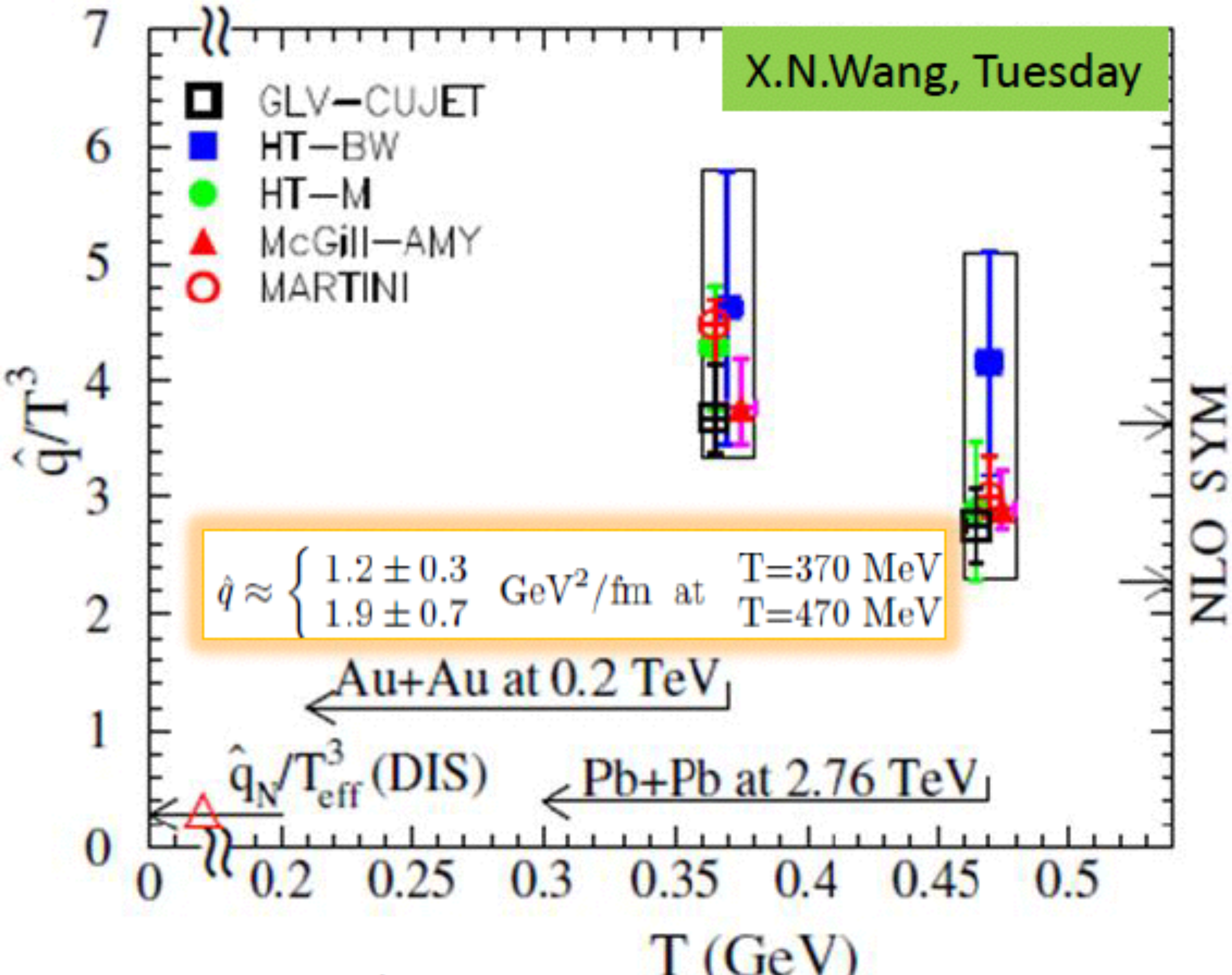
Jet quenching phenomenology

- Achieve better understanding of jet-medium interaction and extract various transport properties of QGP
- Perform systematic study of jet quenching observables and compare to existing experimental data

JET Collaboration

- Build a general framework for numerical implementation of different jet quenching approaches
  - Realistic medium evolution constrained by bulk observables (spectra, flow)
  - Hadronization of both jets and hydro (fragmentation and recombination)
- Deliver a Monte-Carlo package
  - Hydrodynamics + jet transport /evolution + hadronization
- A first step: viscous hydro + semi-analytical jet quenching calculations from a few groups (McGill-AMY, Martini-AMY, HT-BW, HT-M, GLV-CUJET, may include more in the future)

Extracting jet quenching parameter



$$\hat{q} = \frac{1}{L}\int \frac{d^2\vec{k}_\perp}{(2\pi)^2} k_\perp^2 P(\vec{k}_\perp, L) \approx \frac{4\pi^2\alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle F^{\mu+}(0) F_\mu^+(y^-) \right\rangle$$

JET Collaboration, arXiv:1312.5003 [nucl-th]

McGill-AMY:
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008
HT-BW:
Chen, Hirano, Wang, Wang, Zhang, PRC 2011
HT-M:
Majumder, Chun, PRL 2012
GLV-CUJET:
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956
MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009
NLO SYM:
Zhang, Hou, Ren, JHEP 2013

Renormalization of q^{hat}

- **Radiative correction to transverse momentum broadening $\langle p_T^2 \rangle$** (Wu, JHEP 2011; Liou, Mueller, Wu, NPA 2013)

$$\left\langle p_\perp^2 \right\rangle_{rad} = \hat{q}_0 L \left[C_2 \frac{\alpha_s N_c}{\pi} \ln^2\left(\frac{L}{\tau_0}\right) + C_1 \frac{\alpha_s N_c}{\pi} \ln\left(\frac{L}{\tau_0}\right) + C_0 \right]$$

$$\tau_0 \approx 1 / T << L$$

- **The double-logarithmic corrections may be absorbed into a redefinition of jet quenching parameter q^{hat}** (Iancu, arXiv:1403.1996; Blaizot, Mehtar-Tani, arXiv:1403.2323)

$$\hat{q}(\tau) = \hat{q}_0 \left[1 + \frac{\overline{\alpha}}{2} \ln\left(\frac{\tau}{\tau_0}\right) \right]$$

Y. Mehtar-Tani, Wednesday

$$\frac{\partial \hat{q}(\tau, Q^2)}{\partial \ln \tau} = \int_{\hat{q}\tau}^{Q^2} \frac{dq^2}{q^2} \overline{\alpha} \hat{q}(\tau, q^2)$$

- **For large media, anomalous length dependence of q^{hat} and mean energy loss**

$$\hat{q}(L) \propto L^\gamma, \left\langle p_\perp^2 \right\rangle \propto \hat{q}_0 L^{1+\gamma}, \left\langle \Delta E \right\rangle \propto \hat{q}_0 L^{2+\gamma}$$

$$\gamma = 2\sqrt{\overline{\alpha}} = 2\sqrt{\alpha_s N_c / \pi}$$

Renormalization of q^{hat}

- **Calculate NLO QCD corrections to transverse momentum broadening in hadron production in SIDIS**

$$\frac{d\left\langle k_\perp^2 \sigma \right\rangle_{NLO}}{dz} = \sigma_0 T_{qg}(x,0,0,\mu_f^2) \otimes H_{NLO}(x, x_B, Q^2, \mu_f^2) \otimes D(z, \mu_f^2)$$

- **Collinear divergence is factorized into the redefinition of PDF & twist-4 quark-gluon correlation function**

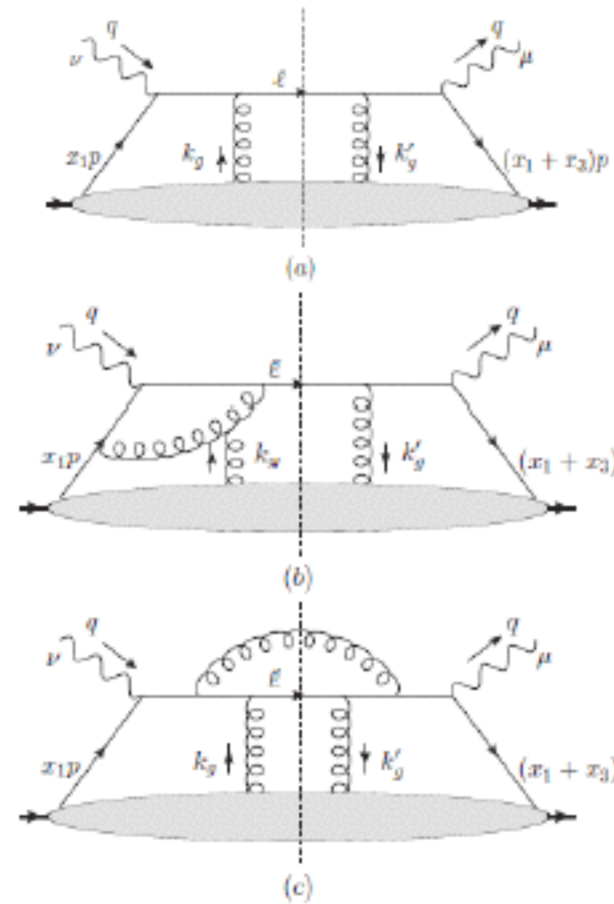
$$\frac{\partial}{\partial \ln \mu_f^2} T_{qg}(x_B,0,0,\mu_f^2) = \frac{\alpha_s}{2\pi}\int_{x_B}^{1}\frac{dx}{x}\left[\mathcal{P}_{qg\to qg}\otimes T_{qg} + P_{qg}(\hat{x})T_{gg}(x,0,0,\mu_f^2)\right]$$

- **Neglecting the momentum and spatial correlations of two nucleons**

$$T_{qg}(x_B,0,0,\mu_f^2) \approx \frac{N_c}{4\pi^2\alpha_s} f_{q/A}(x_B,\mu_f^2)\int dy^- \hat{q}(\mu_f^2, y^-)$$

- **The scale dependence of q^{hat}**

$$\frac{\partial \hat{q}(\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} C_A \ln\left(\frac{1}{x_B}\right)\hat{q}(\mu^2) \qquad \hat{q}(\mu^2) = \hat{q}(\mu_0^2)\exp\left[\frac{\alpha_s}{2\pi} C_A \ln\left(\frac{1}{x_B}\right)\ln\left(\frac{\mu^2}{\mu_0^2}\right)\right]$$



H. Xing, Wednesday

Kang, Wang, Wang, Xing, PRL 2014

Some other studies

- **Systematic comparison to RHIC & the LHC data**
  - **CUJET2.0:** (Xu, Buzzatti, Gyulassy, arXiv: 1402.2956)
  - **DGLV:** (Djordjevic, Djordjevic , arXiv:1307.4098)
  - **dE/dx model:** (Betz, Gyulassy, arXiv:1404.6378)

$$\frac{dE}{dx} = \frac{dP}{d\tau}(\vec{x}_0, \phi, \tau) = -\kappa(T) P^a(\tau) \tau^z T^c \zeta_q$$

- **Converging on initial states using bulk, jets & EM probes**
- **Improve radiative E-loss formalism beyond eikonal approximation (finite energy)** (Apolinario, Armesto, Milhanoa, Salgadoa, arXiv:1404.7079)
- **Non-eikonal effects (large angle rescattering) largely absent above (10–15) GeV parton kinematics** (Abir, PRD 2013)
- **Jet quenching (R_{AA}) from SCET** (Kang, Lashof-Regas, Ovanesyan, Saad, Vitev)
- **Higer order 1->3 splitting in SCET** (Fickinger, Ovanesyan, Vitev, JHEP 2013)
- **Radiative E-loss due to soft rescatterings proportional to E** (Peigne, Arleo, Kolevatov, arXiv:1402.1671, Liou, Mueller, PRD 2014)
- **Viscosity effect on collisional parton energy loss** (Jiang, Hou, Li, arXiv:1405.0083, Elias, Peralta-Ramos, Calzetta. arXiv:1404.7790)
- **q^{hat} enhancement at T_c** (Li, Liao, Huang, arXiv:1401.2035, Renk, arXiv:1402.5798)
- …

M. Djordjevic, Monday

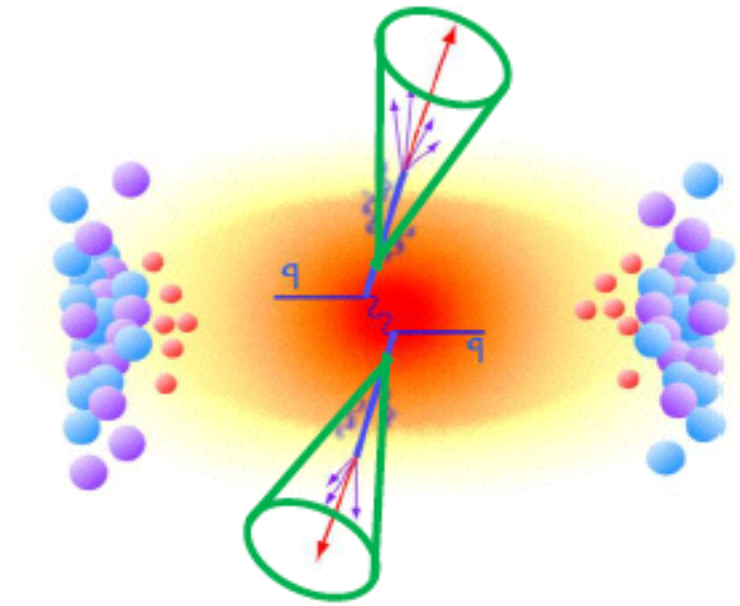
B. Betz, Tuesday

T. Renk, Wednesday

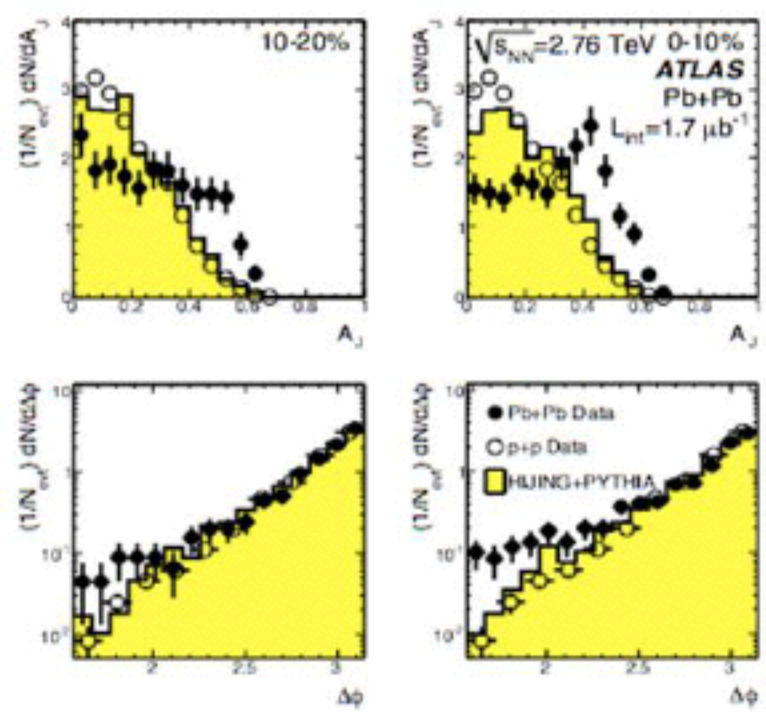
L. Apolinario, Monday

Full jet

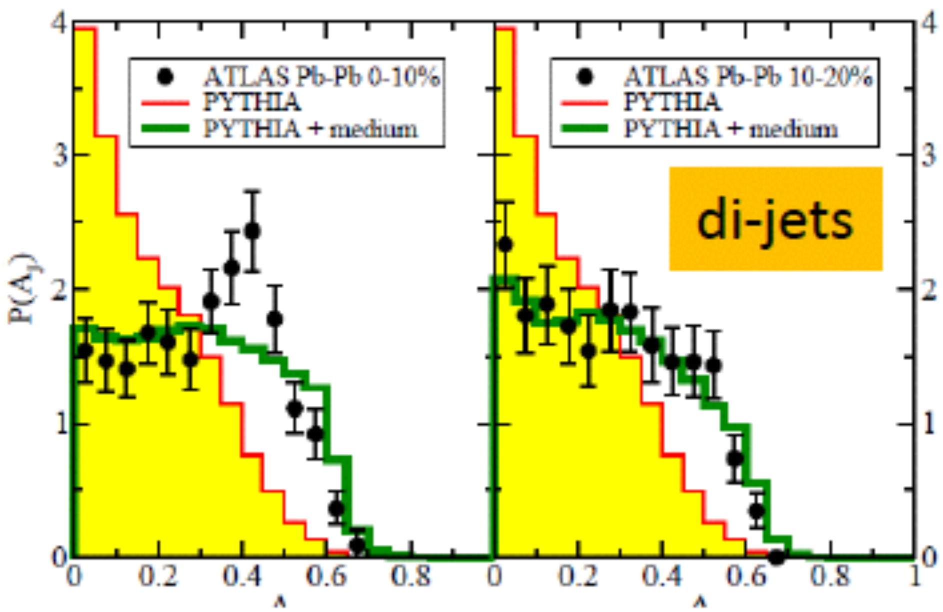
- **Recombining hadron/parton fragments, hoping to get the original parton energy/momentum**
- **Full jets might be more discriminative with sub-leading fragments**
- **Significant contribution from background in AA collisions; need reliable tools to disentangle jets from background**
- **LHC first full jet measurements in AA collisions showed strong modification of dijet energy imbalance distribution, while angular distribution largely unchanged**



$$R = \sqrt{(\phi - \phi_J)^2 + (\eta - \eta_J)^2}$$

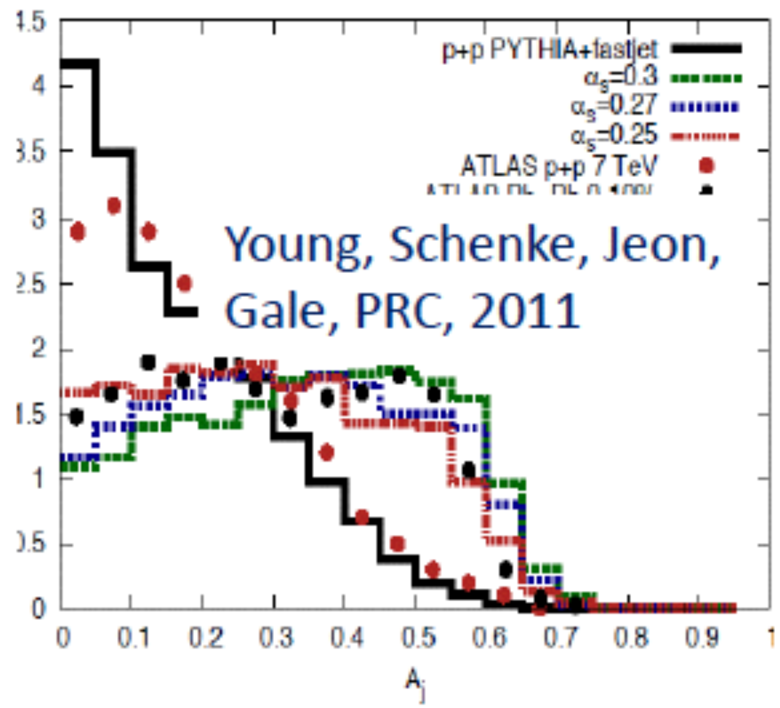


Energy imbalance of di-jets and γ-jets

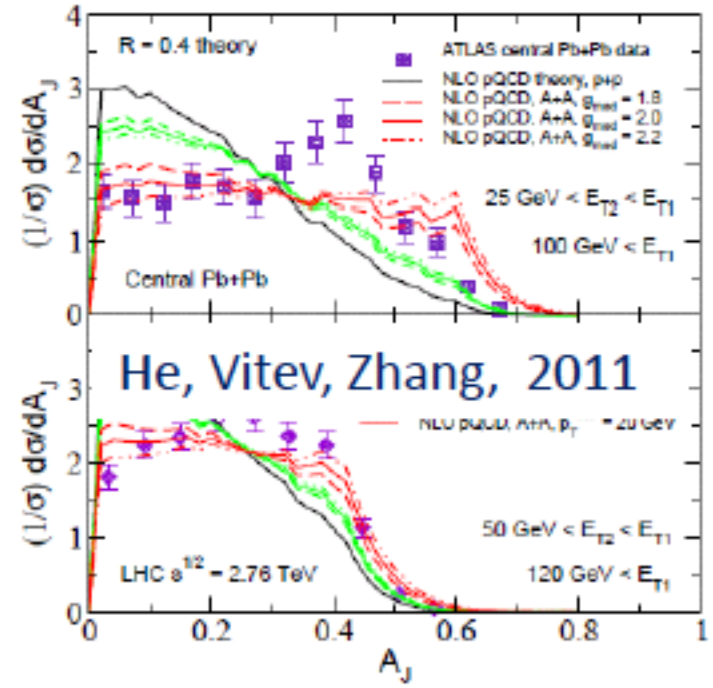


di-jets

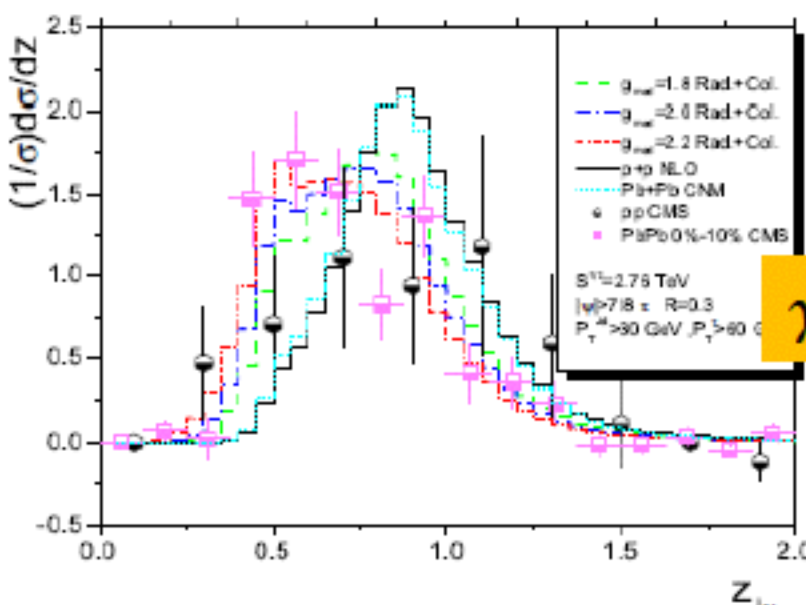
GYQ, Muller, PRL, 2011



Young, Schenke, Jeon, Gale, PRC, 2011

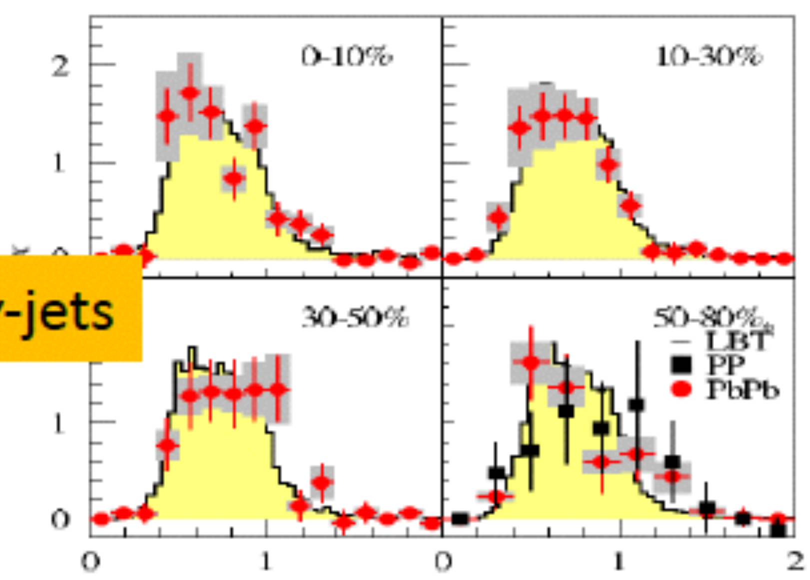


He, Vitev, Zhang, 2011



Dai, Vitev, Zhang, PRL 2013

γ-jets

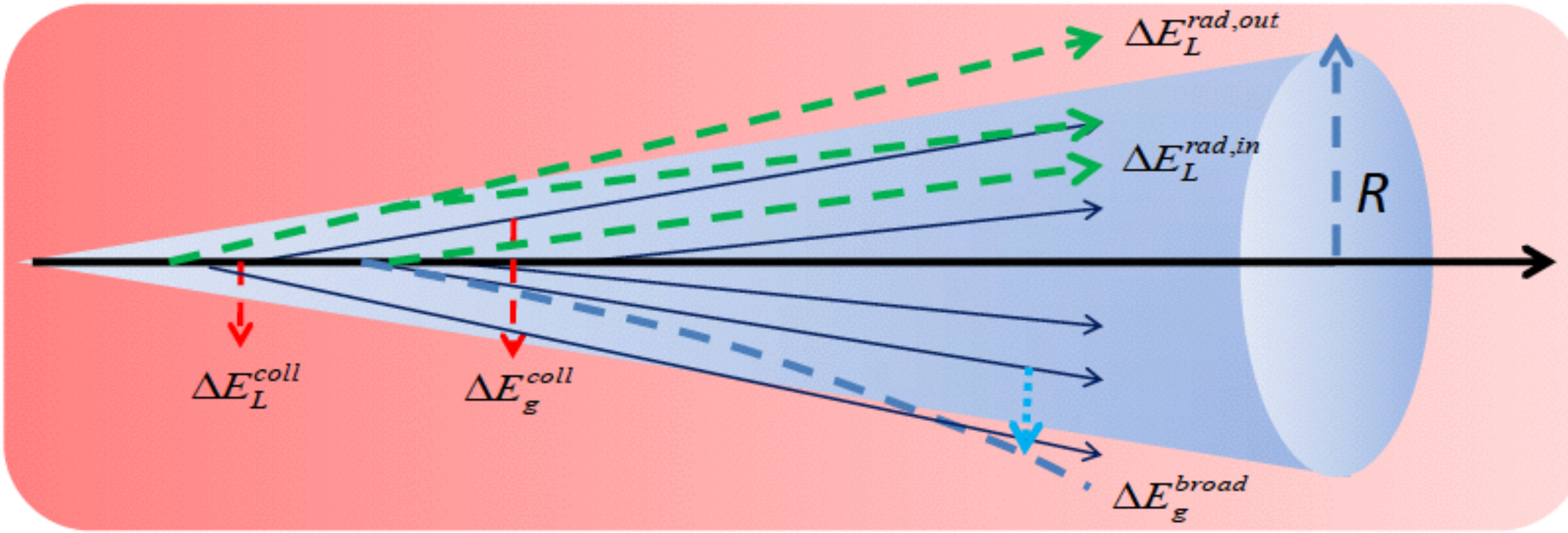


Wang, Zhu, PRL 2013

The distribution shifting towards larger A_J (smaller x) can be explained by energy loss

More quenching (energy loss) in more central collisions

Jet shower evolution in medium



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

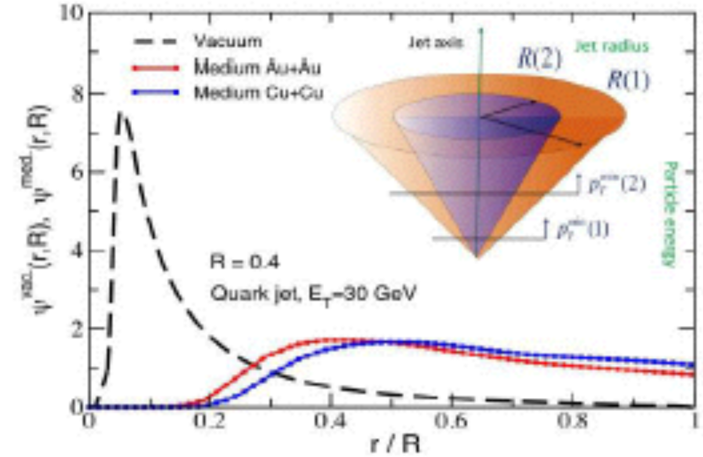
$E_{tot} = E_{in} + E_{lost}$

$= E_{in} + E_{out}$(radiation) + E_{out}(broadening) + E_{th}(collision)

GYQ, Muller, PRL, 2011, arXiv: 1012.5280

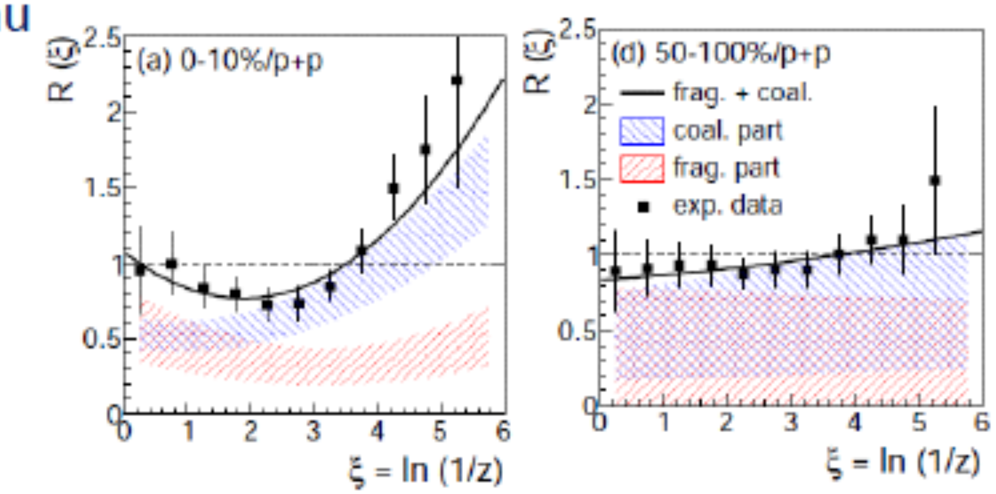
Jet substructure

- **Broadening of jets due to medium-induced radiation** (Vitev, Zhang, Wicks, JHEP 2008, Vitev, Zhang, PRL 2010)



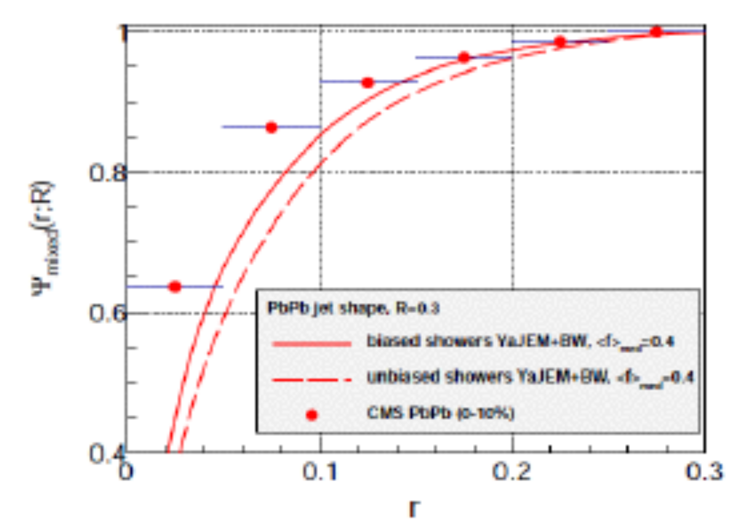
- **Recoiled partons (medium response) affect the jet energy loss and internal structure** (Wang, Zhu PRL 2013)

T. Luo, Wednesday



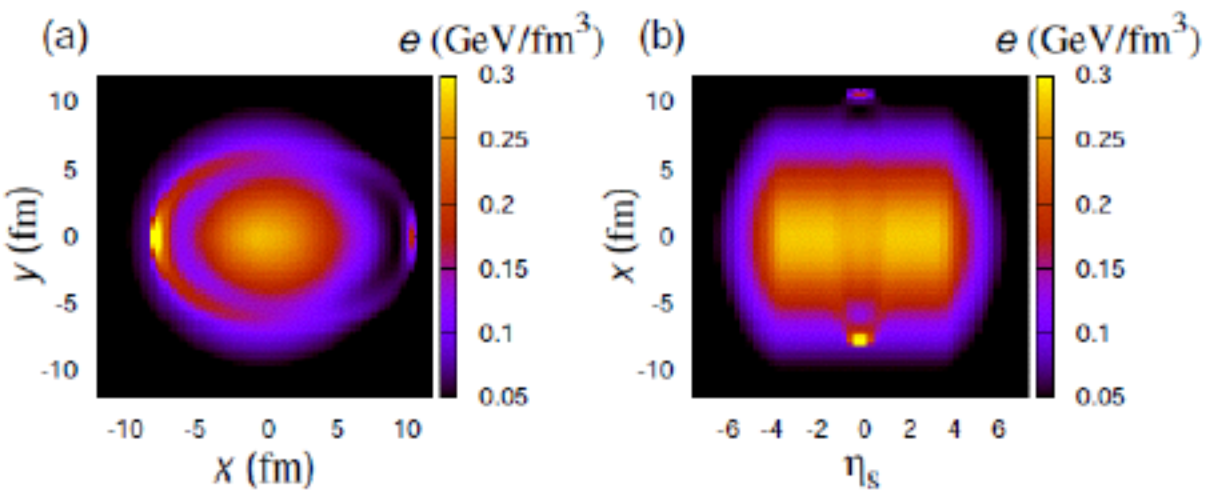
- **Competition between fragmentation and coalescence in medium-modification jet fragmentation profiles** (Ma, PRC 2013)

- **Unbiased jets and biased jets are different; data agree better with biased jets (E_{min}>1GeV) => important to include all experimental jet finding conditions** (Ramos, Renk, arXiv:1401.5283)



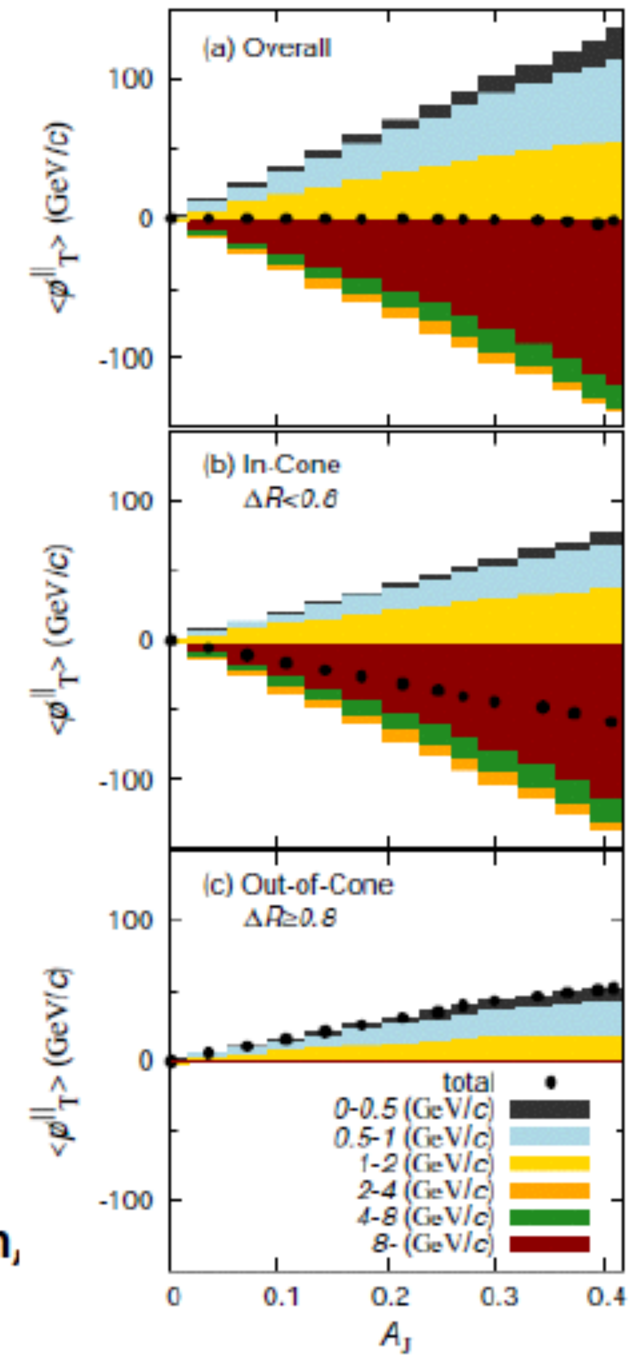
Medium response to lost energy

- **Hard partons lose energy in medium; some of lost energy is deposited into medium and makes medium excitations**



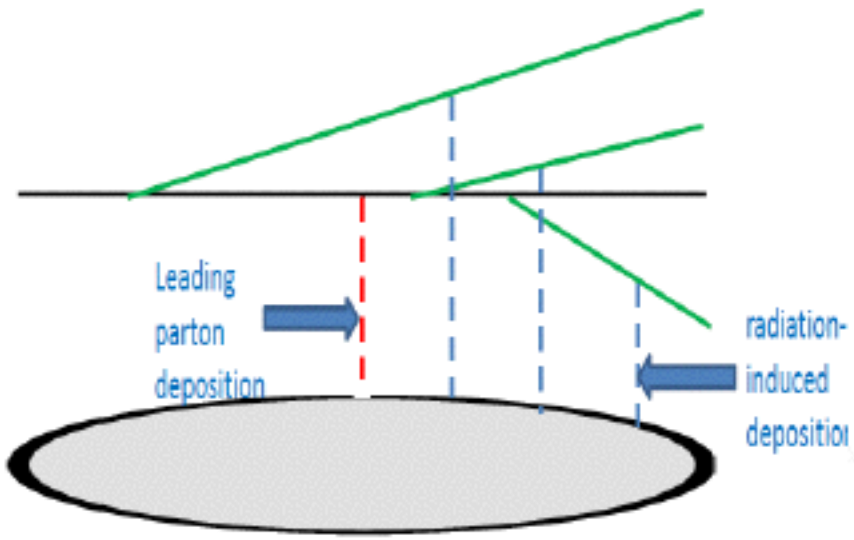
- **Simulate medium response using (3+1)-D ideal hydrodynamics**
- **Calculate the redistribution of deposited energy through hydrodynamic evolution** (Tachibana, Hirano, arXiv:1402.6469)
- **Effect of deposited energy on direct, elliptic, triangular flow** (Andrade, Noronha, Denicol, arXiv:1403.1789)

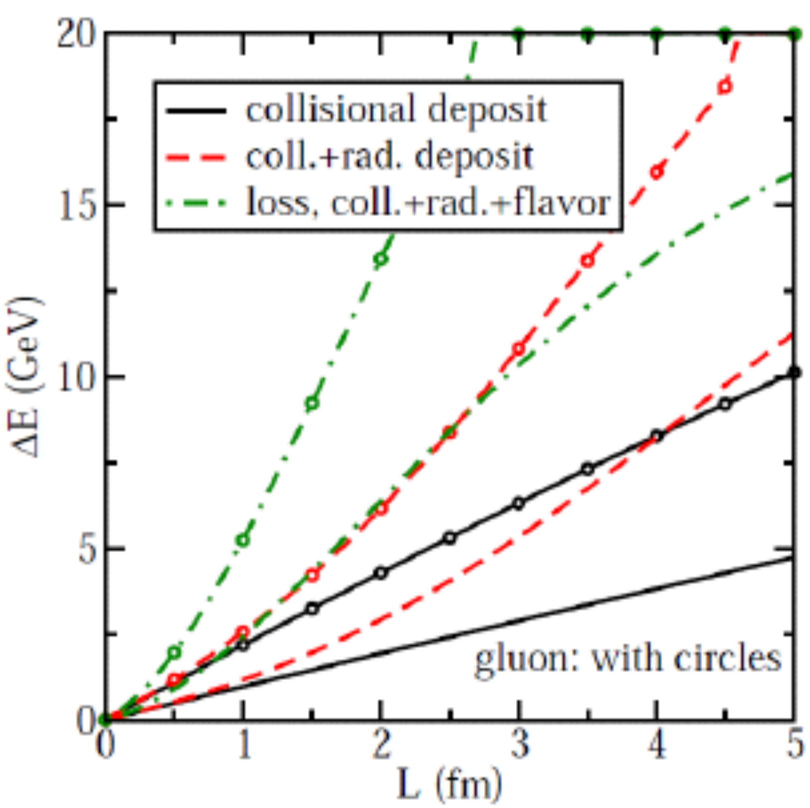
- **SIMPLE energy deposition profiles (back-to-back 2-parton system, not 2 full jets)**

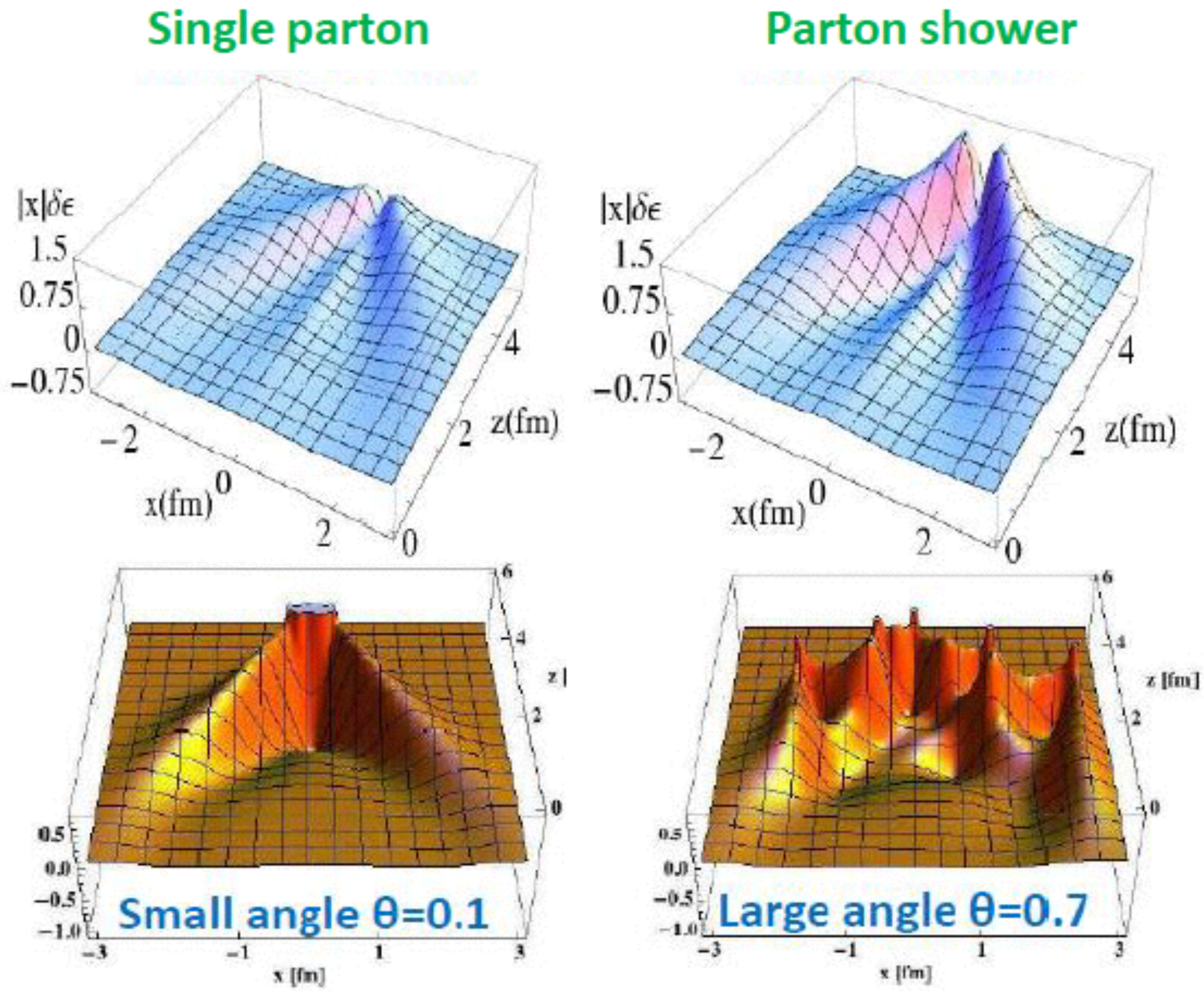


Full jet energy deposition & medium response

Energy deposition & medium response for jet showers are different from single partons







GYQ, Majumder, Song, Heinz, PRL 2009; Neufeld, Muller, PRL 2009 ; Neufeld, Vitev, PRC 2012

Lattice study of jet quenching

$$\hat{q} = \frac{1}{L}\int \frac{d^2\vec{k}_\perp}{(2\pi)^2} k_\perp^2 P(\vec{k}_\perp, L)$$

$$P(\vec{k}_\perp, L^-) = \int \frac{d^2\vec{k}_\perp}{(2\pi)^2} e^{-i\vec{k}_\perp\cdot\vec{y}_\perp} P(\vec{y}_\perp, L^-)$$

$$P(\vec{y}_\perp, L^-) = \frac{1}{N_c} Tr\left\langle W(\vec{y}_\perp, L^-)\right\rangle$$

$$\frac{dP(\vec{y}_\perp, L^-)}{dL} = -V(\vec{y}_\perp) P(\vec{y}_\perp, L^-)$$

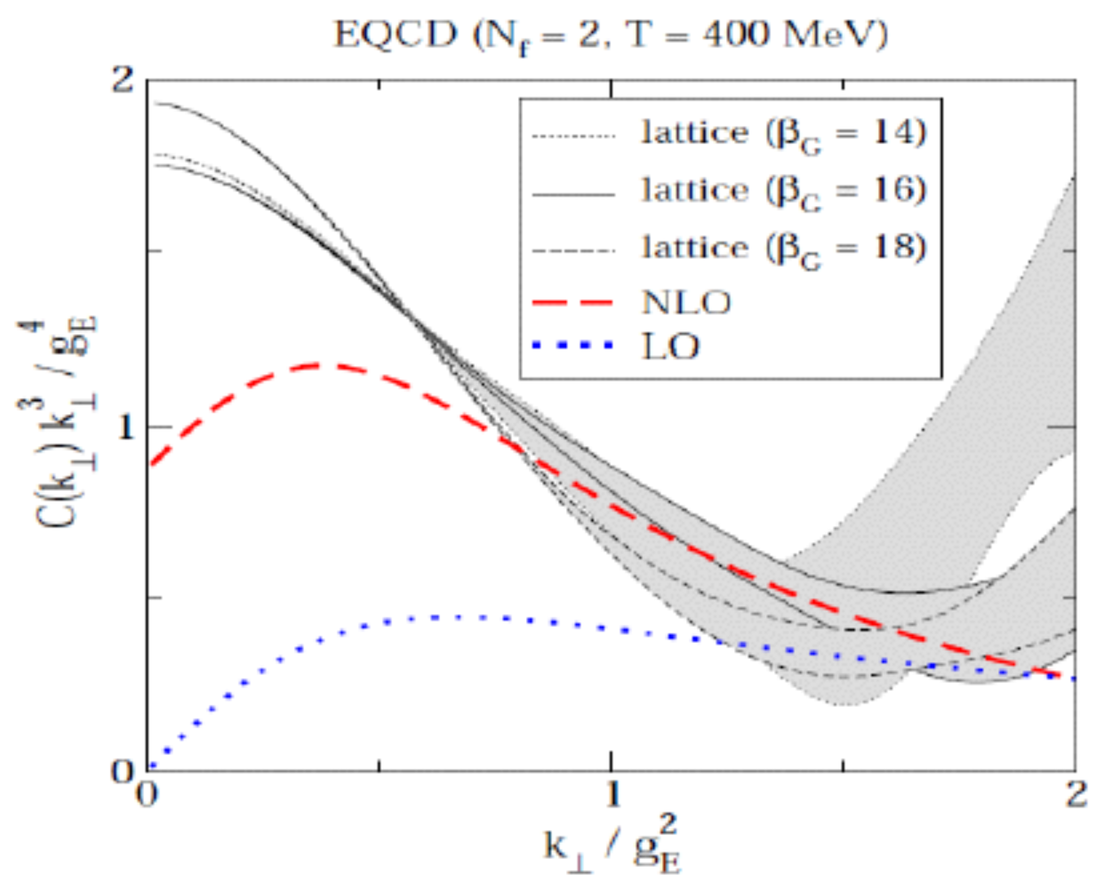
$$V(\vec{y}_\perp) = \int \frac{d^2\vec{k}_\perp}{(2\pi)^2}(1 - e^{i\vec{k}_\perp\cdot\vec{y}_\perp}) \boxed{C(\vec{k}_\perp)}$$

Majumder, PRC 2013; Panero, Rummukainen, Schafer, PRL 2014; Laine, Rothkopf, JHEP 2013; arXiv:1310.2413; Caron-Huot, PRD 2009; Benzke, Brambilla, Escobedo, Vairo, JHEP 2013; D'Eramo, Lekaveckas, Liu, Rajagopal, JHEP 2013

Quenched SU(2): $\hat{q} \approx 1.3 - 3.3\text{GeV}^2/\text{fm}@T = 400MeV$

Lattice EQCD: $\hat{q} \approx 6\text{GeV}^2/\text{fm} \pm 20\%@RHIC$

M. Panero, Tuesday



Discrepancy is unclear so far and needs further investigation

AdS/CFT

- **NLO correction for finite t'Hooft coupling** (Zhang, Hou, Ren, JHEP 2013)

$$\hat{q}_{SYM}(\lambda) = \hat{q}^{(0)}_{SYM}[1 + \kappa\lambda^{-1/2} + O(\lambda^{-1})] \qquad \kappa \simeq -1.97.$$

- **Better agreement with data using finite endpoint momentum shooting strings for more realistic description of an energetic quark** (Ficnar, Gubser, Gyulassy, arXiv:1311.6160)

- **Jets emerging from a slab of plasma have the same shape as vacuum jets, except less energy and broader angle** (Chesler, Rajagopal, arXiV:1402.6756)

K. Rajagopal, Wednesday

- **A hybrid strong/weak coupling model** (Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, arXiv:1405.3864)

D. Pablos, Wednesday

Summary

- **Significant theoretical effort and progress**
  - **Systematic phenomenological studies, q^{hat} from JET Collab., Lattice & AdS/CFT**
  - **Progress in NLO jet energy loss, full jet evolution and modification, Monte-Carlo models, jet energy deposit/redistribution**

- **Future**
  - **Discrepancy in q^{hat} values**
  - **NLO jet energy loss**
  - **Full jet modification (energy loss, substructure…)**
  - **Realistic jet transport and medium response simultaneously (thermalization, lost energy redistribution…)**
  - **…**