Strangeness and Heavy Flavor
in Relativistic Heavy Ion Collisions

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22nd Strangeness in Quark Matter 2026
March 23, 2026
UCLA

"Strangeness in Quark Matter"

Question: Why is there a conference series with such a "strange" name?

Answer: Because Quark Matter is inherently *strange* (as opposed to nuclear matter)

QM at equilibrium *always* contains many strange quarks, because

$$m_s^{\mathrm{Higgs}} \approx 93.5\,\mathrm{MeV}/c^2 < \{T_c, \mu_c\}$$

At $T > T_c \approx 155\,\mathrm{MeV}$ thermal gluons ensure the rapid chemical equilibration of all light quark flavors (*u, d, s*).

At $\mu > \mu_c \approx 400\,\mathrm{MeV}$ Pauli pressure of and Coulomb energy drives the weak conversion $u \rightarrow s\, \nu_e\, e^+$ of *u* quarks into strange quarks to nearly equalize the light flavor content of astrophysical cold quark matter.

Outline

- Focus on flavor
  - Historical timeline
  - Quark Matter phase boundary
- Quarko-chemistry from strangeness to charm
- Bulk dynamics of QGP
  - System size dependence
- Hadronization
  - Fragmentation, string breaking, recombination (coalescence)
- Quark transport processes

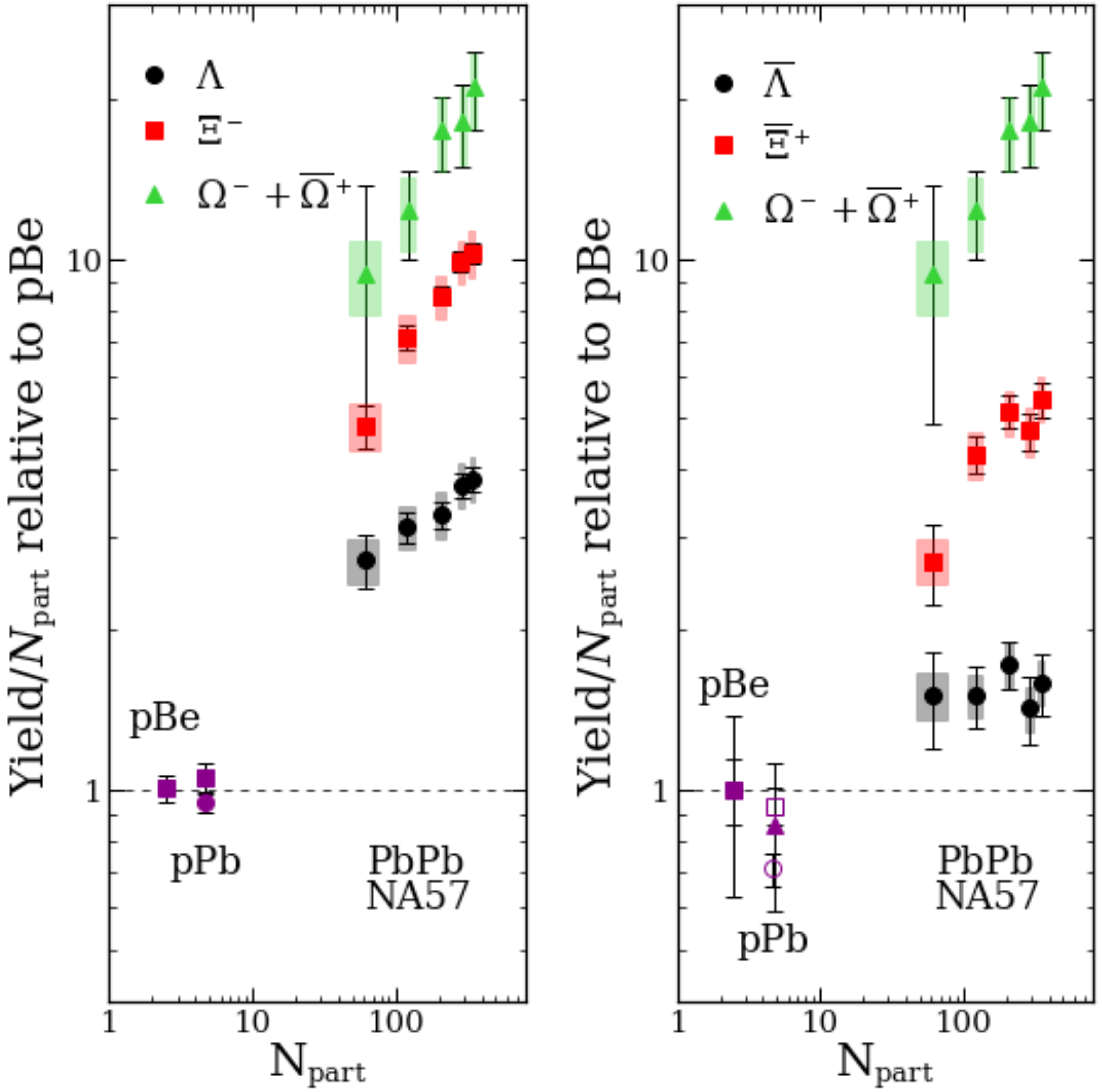
Historical Timeline

History I: Strangeness

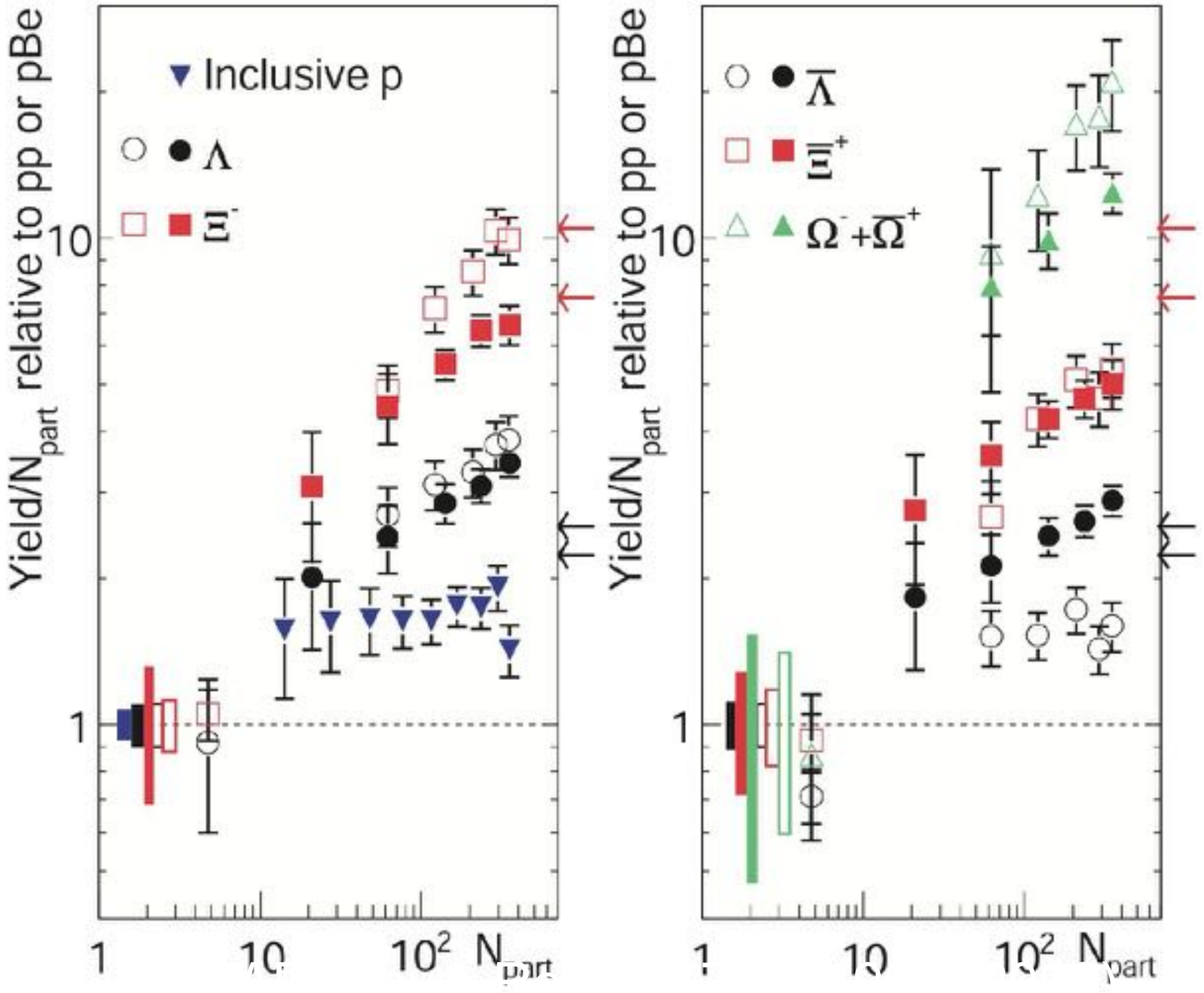
- *s, c, b* quarks are not present in normal nuclei and are only produced in collisions or (probably) by weak interactions at high density in collapsed stars.
- ⟶ *s* quark flavor as probe for reaction mechanism and thermodynamic conditions
  - 1980: Abundance of multi-strange baryons at SPS (Rafelski)
  - 1982: Rapid *s*-quark equlibration in QGP (Rafelski-Müller-Koch)
  - 1983: Quarkochemistry (Biro-Zimanyi)
  - 1984: Metastable multi-strange hadrons = “strangelets” (Liu-Shaw)
  - 1984: Cosmological production of strangelets (Witten)
  - 1986: Strange quark stars (Alcock-Farhi-Olinto)
  - 1987: Strangeness separation mechanism (Greiner-Koch-Stöcker)
  - 1991: Workshop on Strange Quark Matter in physics and astrophysics (Aarhus)
  - 1999: (Multi-)strange baryon enhancement at SPS (WA97)

Multi-strange Baryon Enhancement

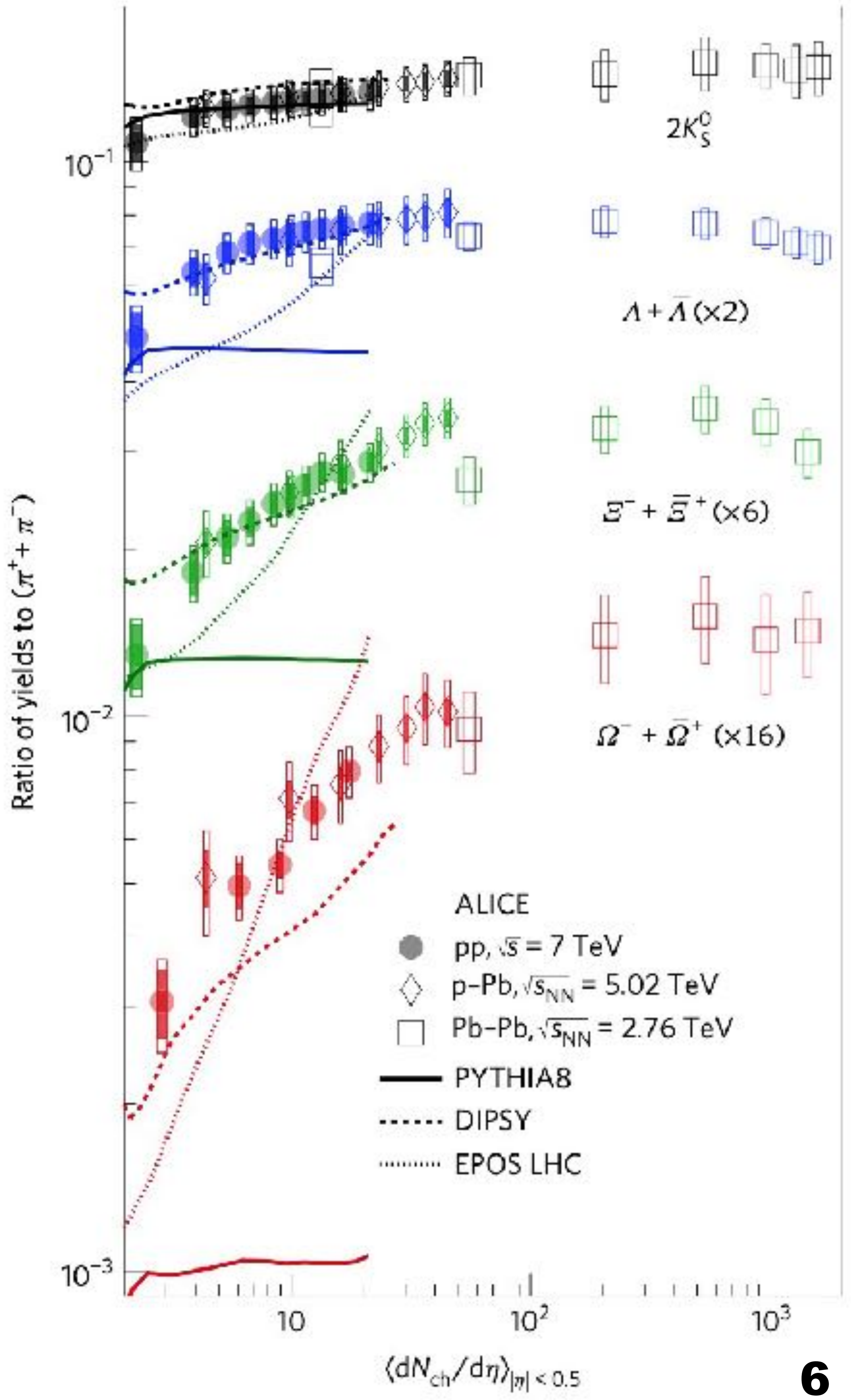
Na57 (SPS)
$\sqrt{s_{NN}}$ = 17.3 GeV Pb+Pb



STAR (RHIC)
$\sqrt{s_{NN}}$ = 200 GeV Au+Au



ALICE (LHC)
$\sqrt{s_{NN}}$ = 2.76 TeV Pb+Pb



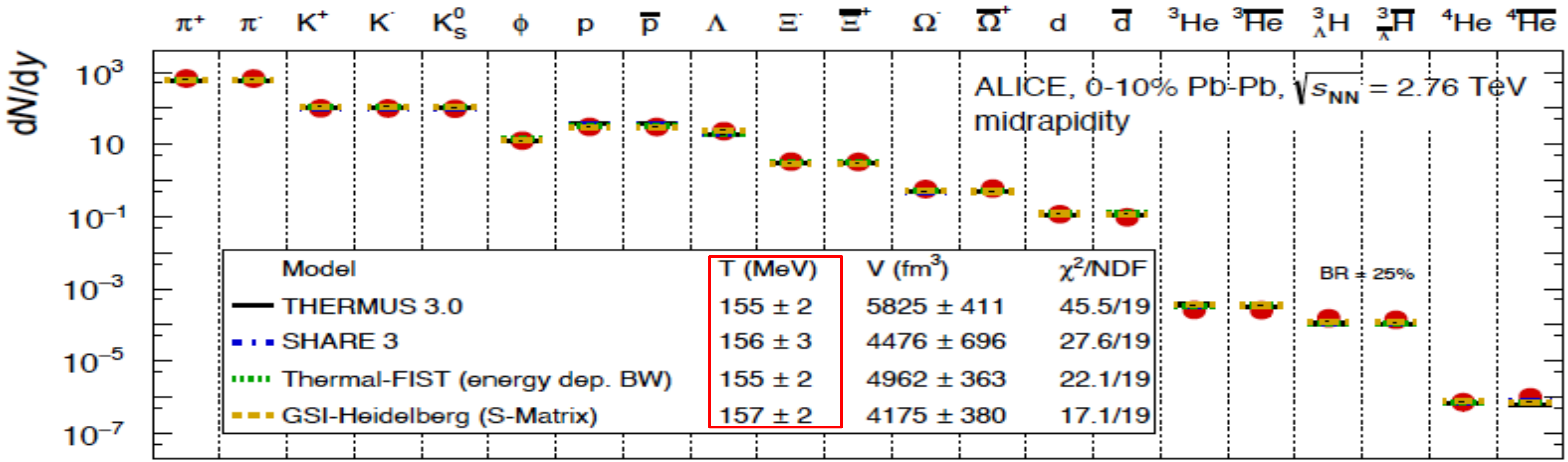
History II: From strangeness to charm

- 1995: 1st SQM conference in Tucson, AZ
- 1995: ALCOR recombination model (Biro-Levai-Zimanyi)
- 1999: No strangelets seen at AGS (E864)
- 2000: Statistical hadronization of charm (Braun Munzinger-Stachel)
- 2001: J/ψ recombination (Thews-Schroedter-Rafelski)
- 2003: Quark recombination (Fries-Müller-Nonaka-Bass; Greco-Ko-Levai; Voloshin)
- 2003/04: Valence quark scaling of collective flow (PHENIX/STAR)
- 2012: Open charm elliptic flow (ALICE)
- 2017: Global Λ spin polarization (STAR)
- 2020: Λ_c^+ enhancement (ALICE)
- 2022: Complete open charm chemistry and transport (ALICE 3 LoI)
- 2026: $\Lambda/\overline{\Lambda}$ spin correlation during hadronization (STAR)

QM Phase Boundary

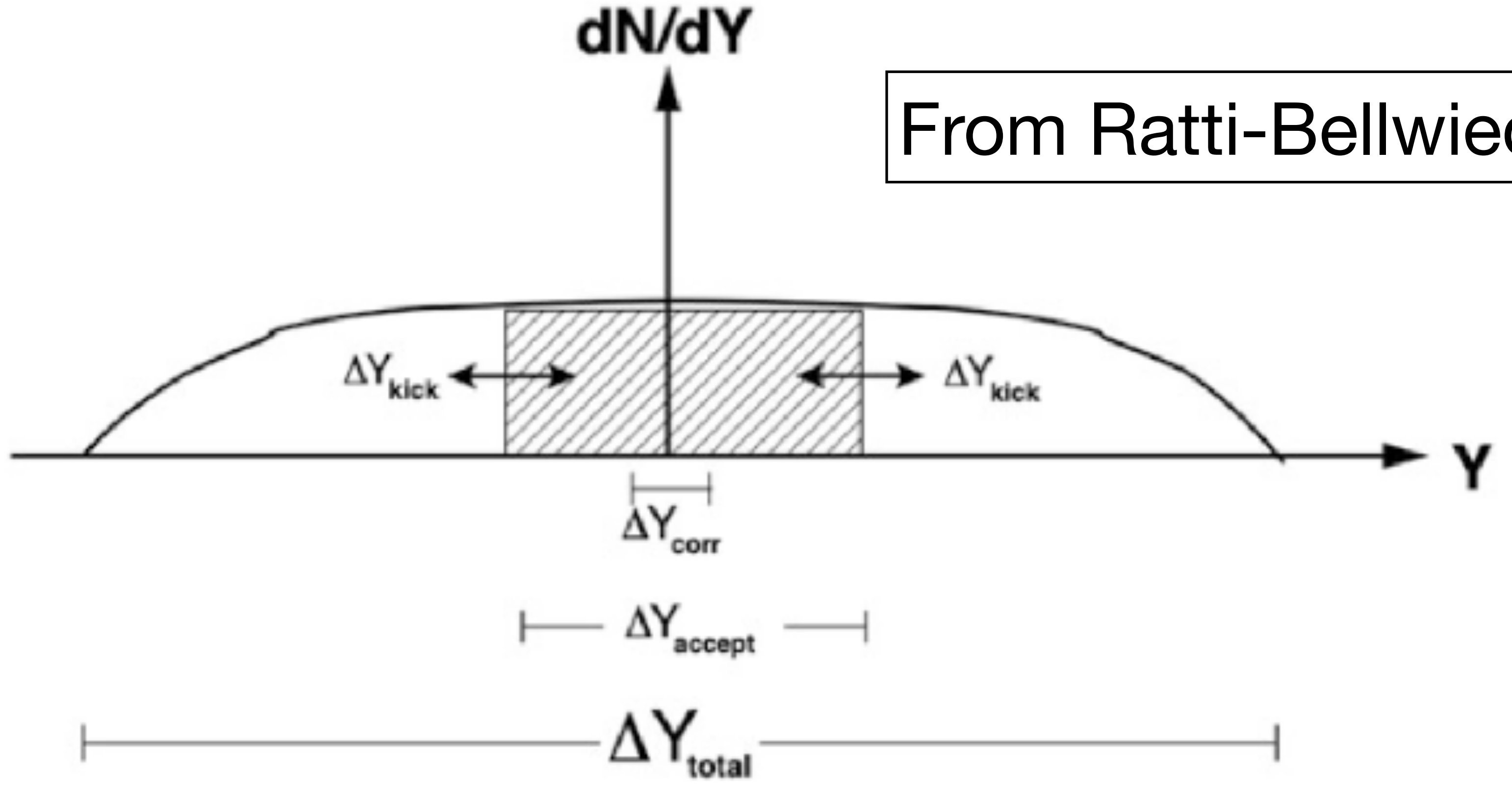
u,d,s chemistry in action

The temperature T_c of the transition from QGP to hadronic matter can be deduced from the chemical abundance of different hadrons: Yield ~ $\exp(-m/T_c)$. Method can be extended to measure the baryon chemical potential $\mu_c(T_c)$ → Phase boundary of the QGP!

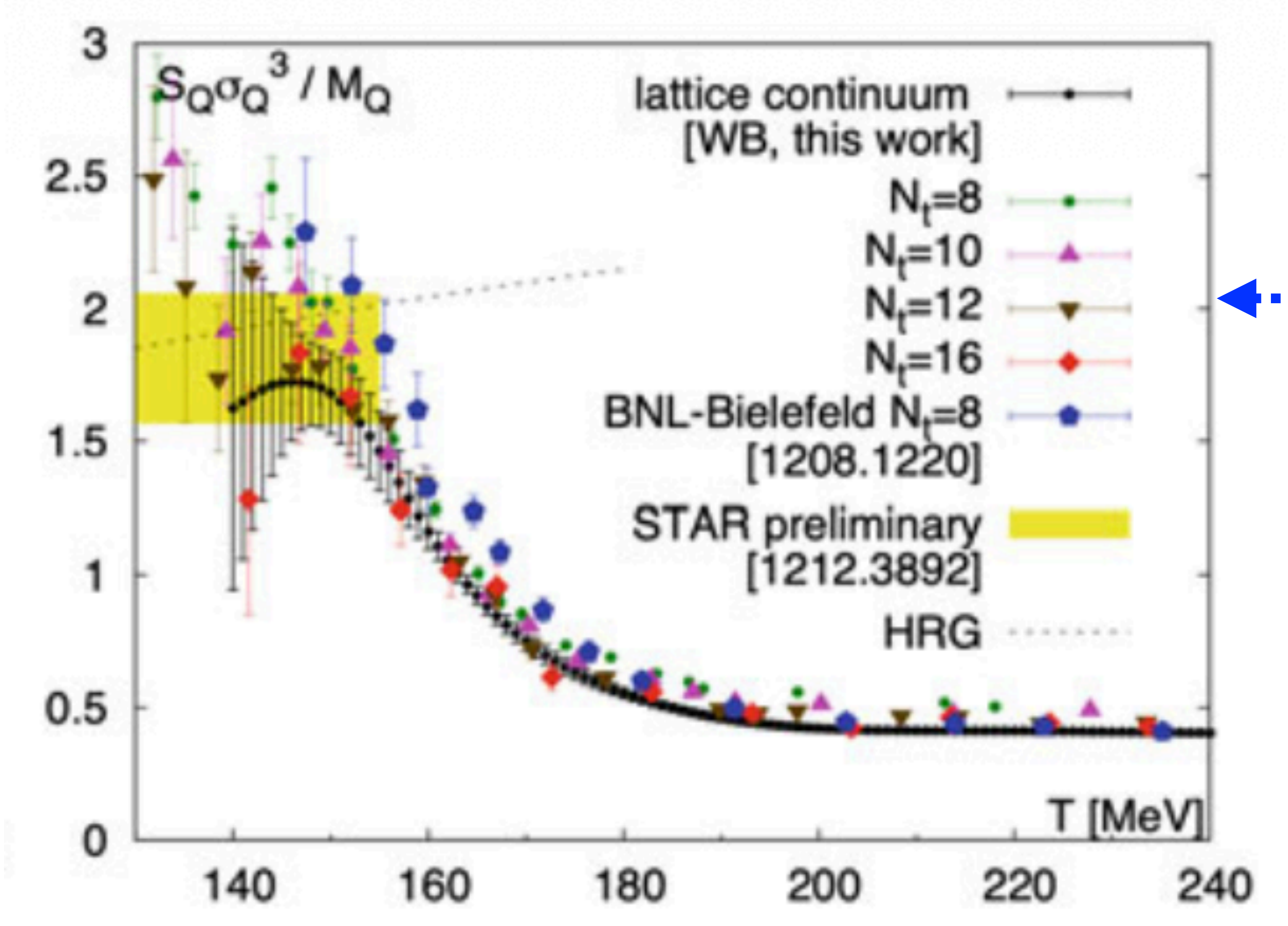


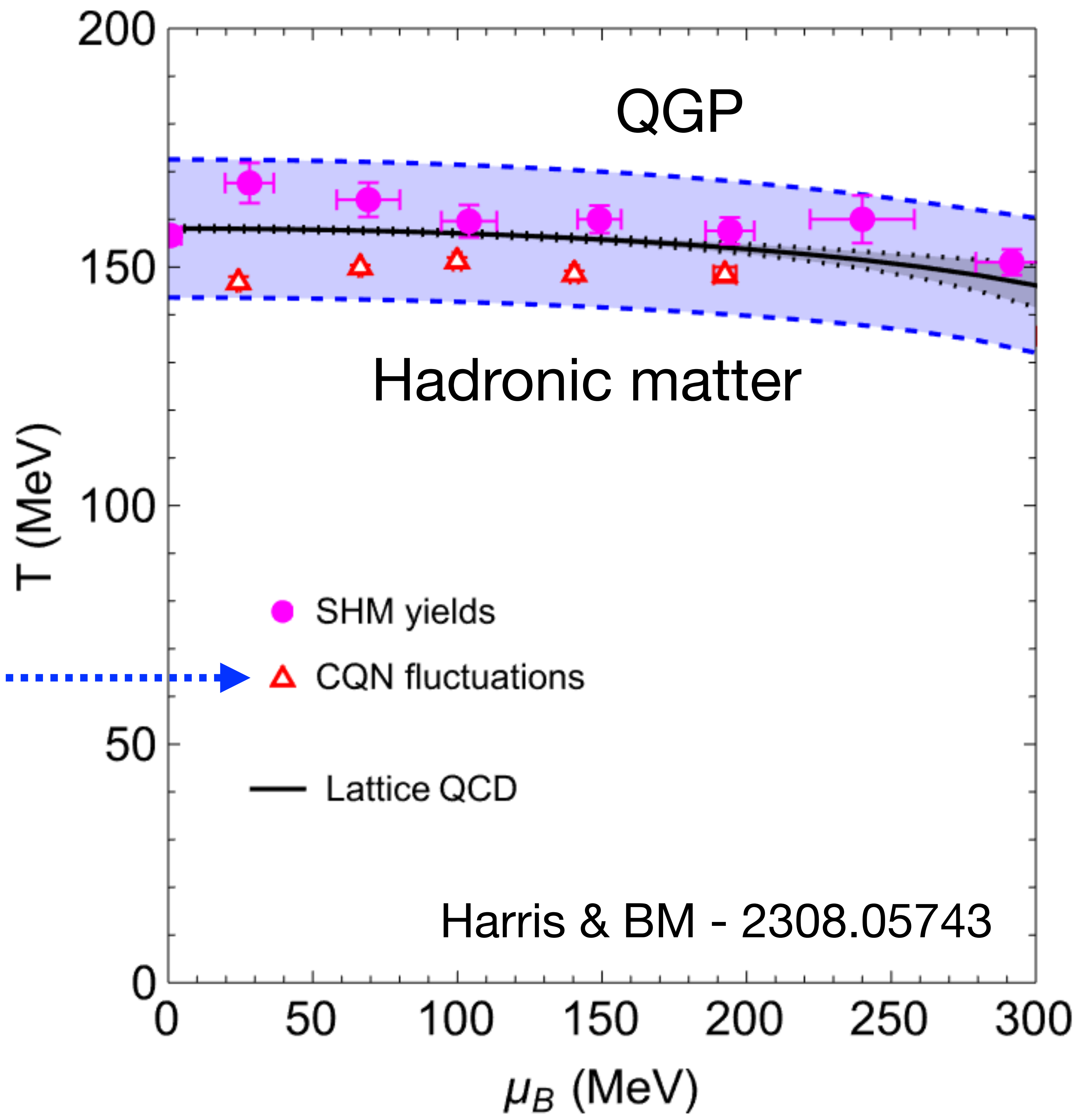
Model	T (MeV)	V (fm³)	χ^2/NDF
THERMUS 3.0	155 ± 2	5825 ± 411	45.5/19
SHARE 3	156 ± 3	4476 ± 696	27.6/19
Thermal-FIST (energy dep. BW)	155 ± 2	4962 ± 363	22.1/19
GSI-Heidelberg (S-Matrix)	157 ± 2	4175 ± 380	17.1/19

QGP Phase boundary: $T_c(\mu_B)$



From Ratti-Bellwied



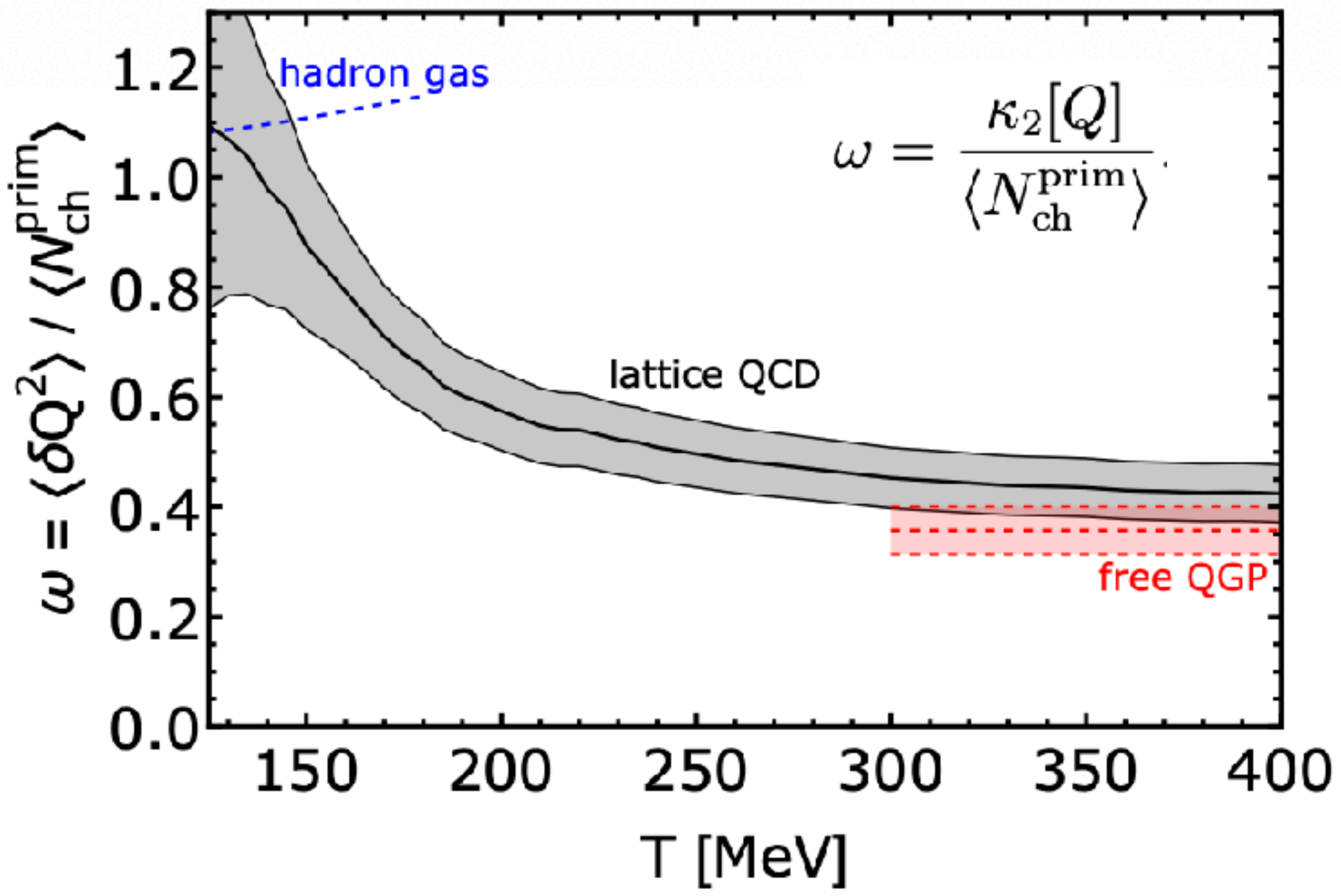


Harris & BM - 2308.05743

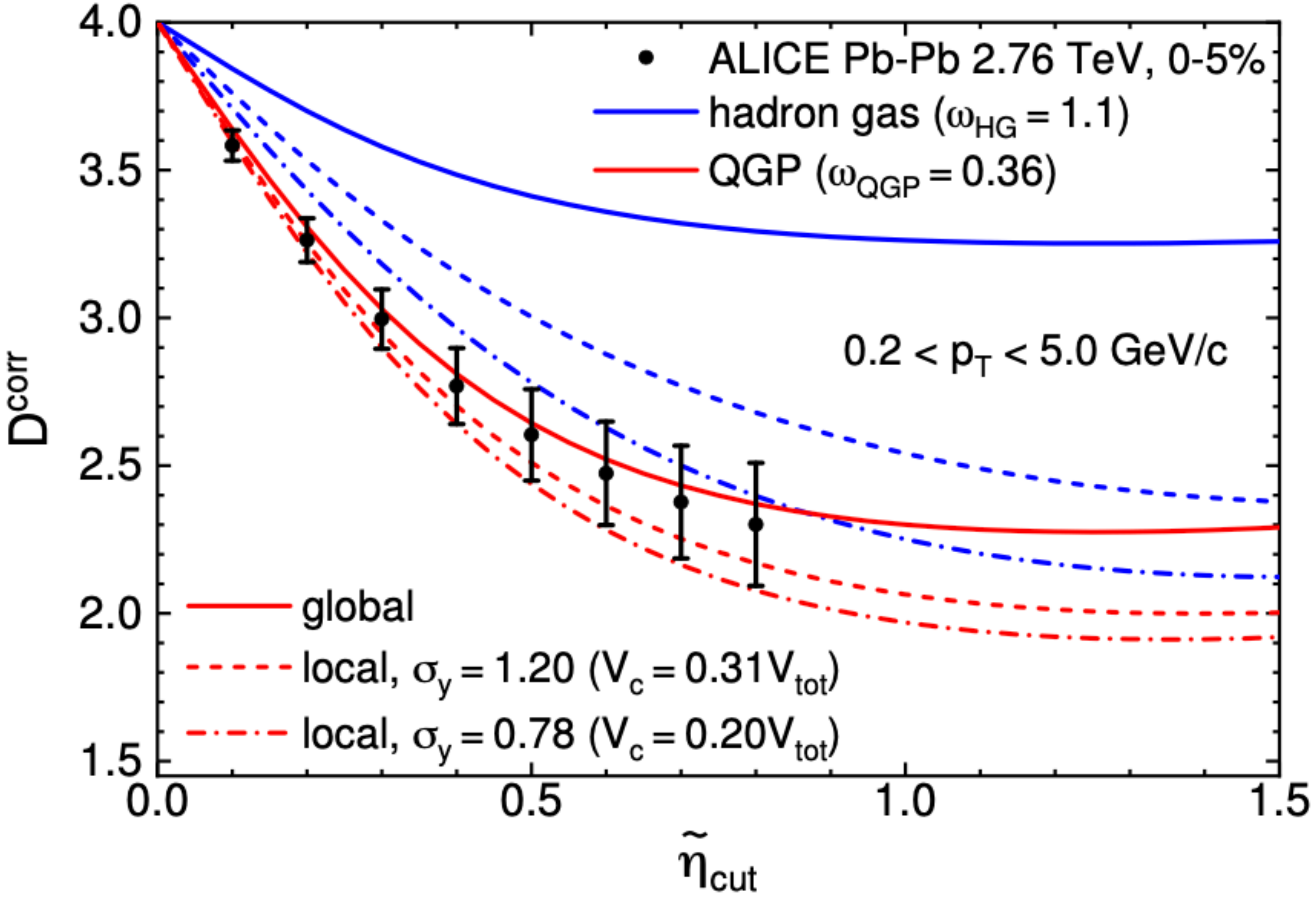
Net charge fluctuations

Proposed as deconfinement probe in 2000
(Jeon-Koch; Asakawa-Heinz-BM)

New analysis by Parra et al., 2504.01085



$$D \approx 4\omega_{\rm corr}$$

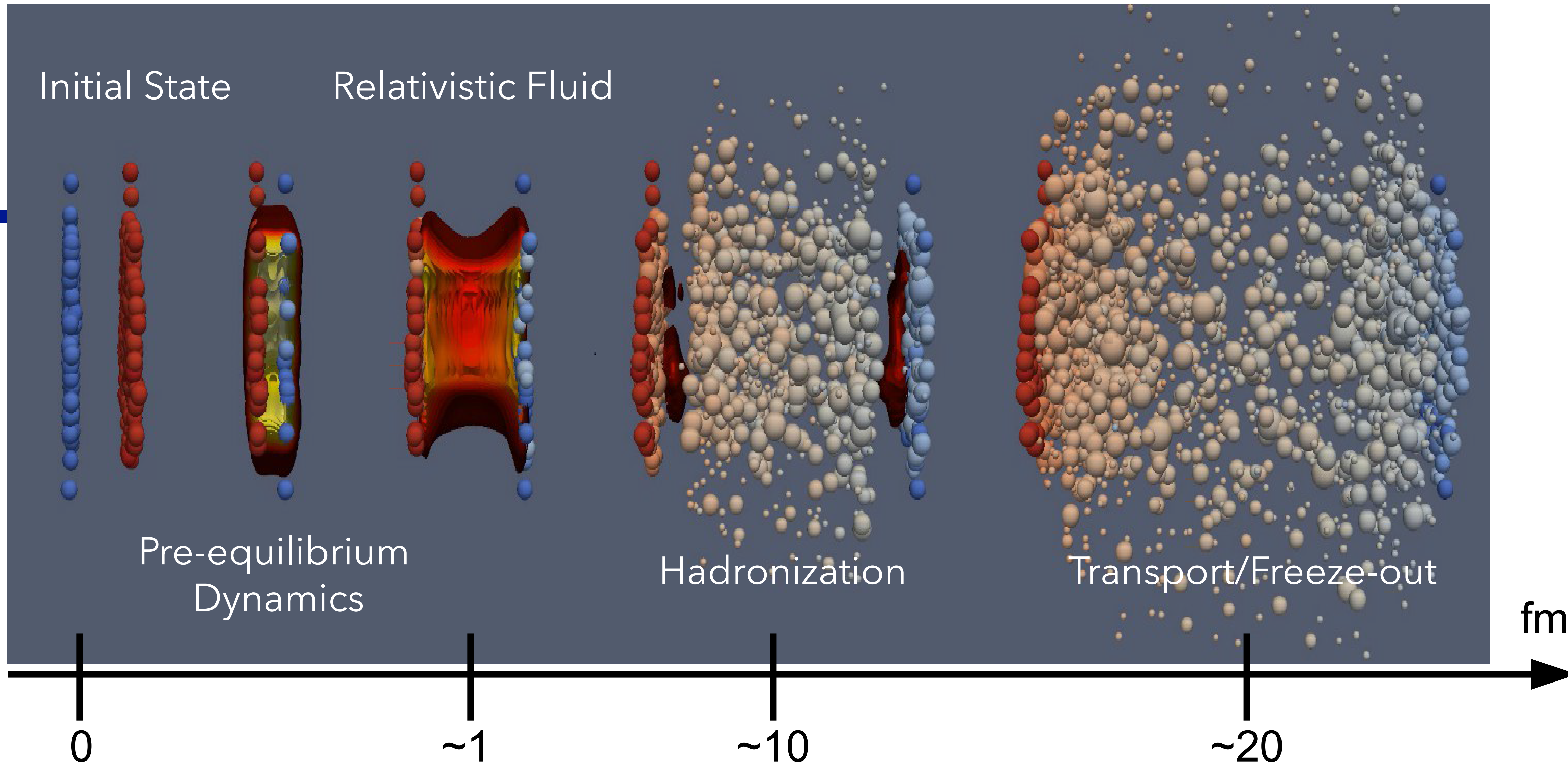


Quarko-chemistry

Quarkochemistry

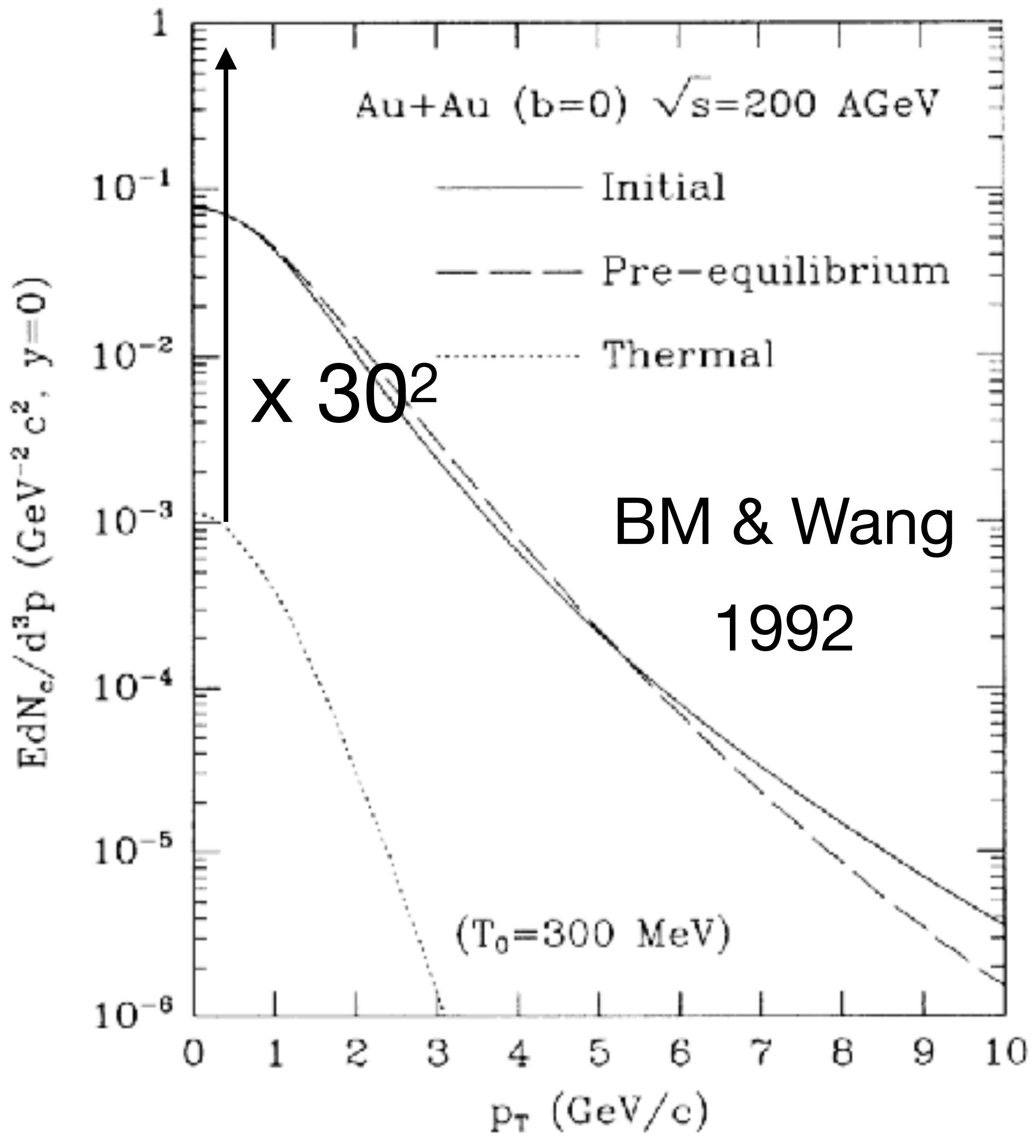
- *s*-quarks can be produced
  - Pre-equilibrium (glasma)
  - In QGP: $\tau_s(gg/q\bar{q} \to s\bar{s})$
  - At hadronization (string breaking)

Deduce contributions and τ_s from data?



- *c*-quarks can be produced
  - Initial PDFs and pre-equilibrium (glasma)
- *c*-quarks can be annihilated
  - In QGP: $\tau_c^{\text{ann}} = \tau_c^{\text{th}}(T)/g_c^2$ with $g_c^{\text{LHC}}(T_c) \approx 30$

Deduce contributions from data and simulations?

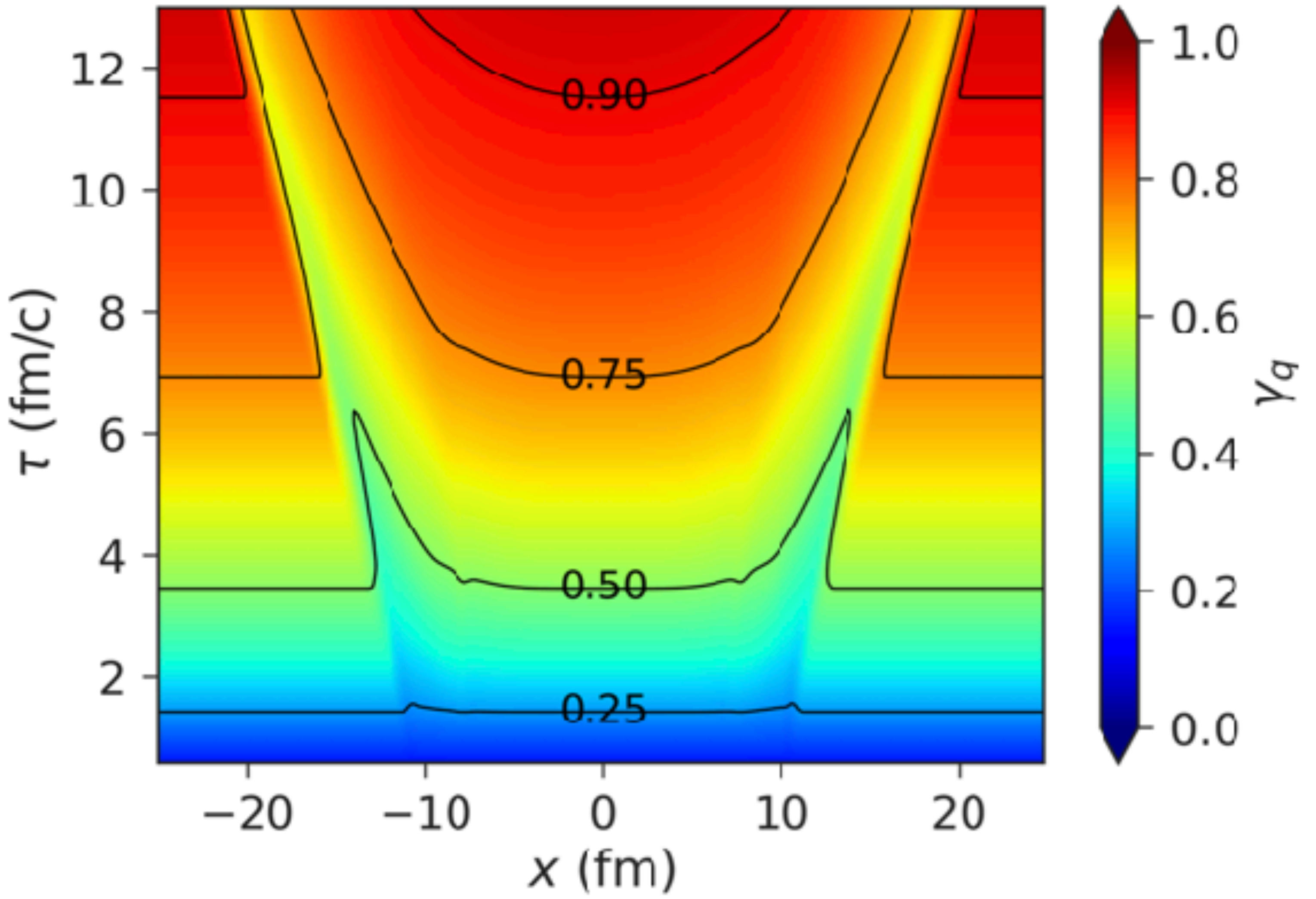


BM & Wang 1992

Flavor equilibration (*u,d,s*)

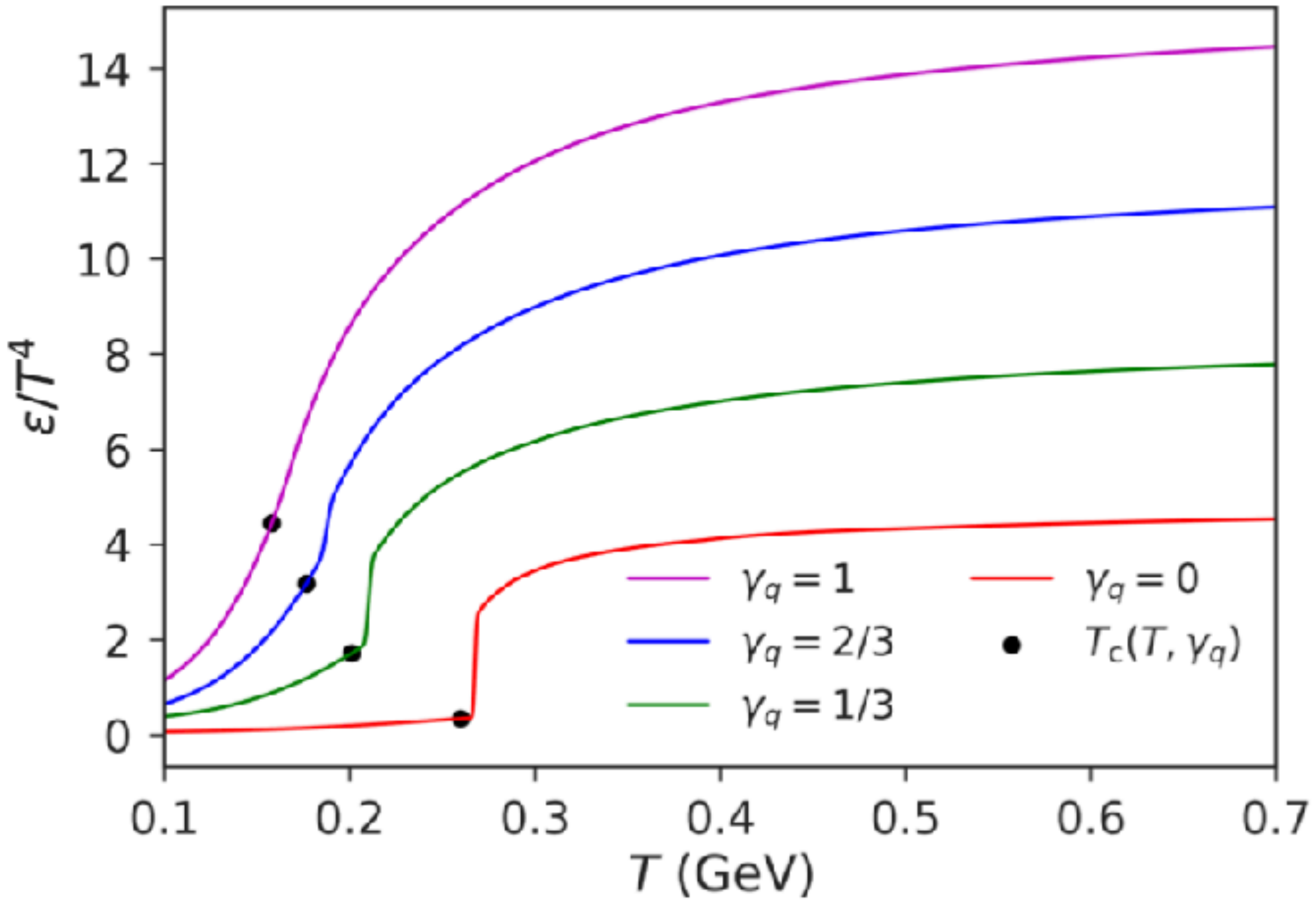
$$gg \to q\bar{q} \quad \leftrightarrow \quad \gamma_q$$

A. Gordeev
Tu (II) - 9:45

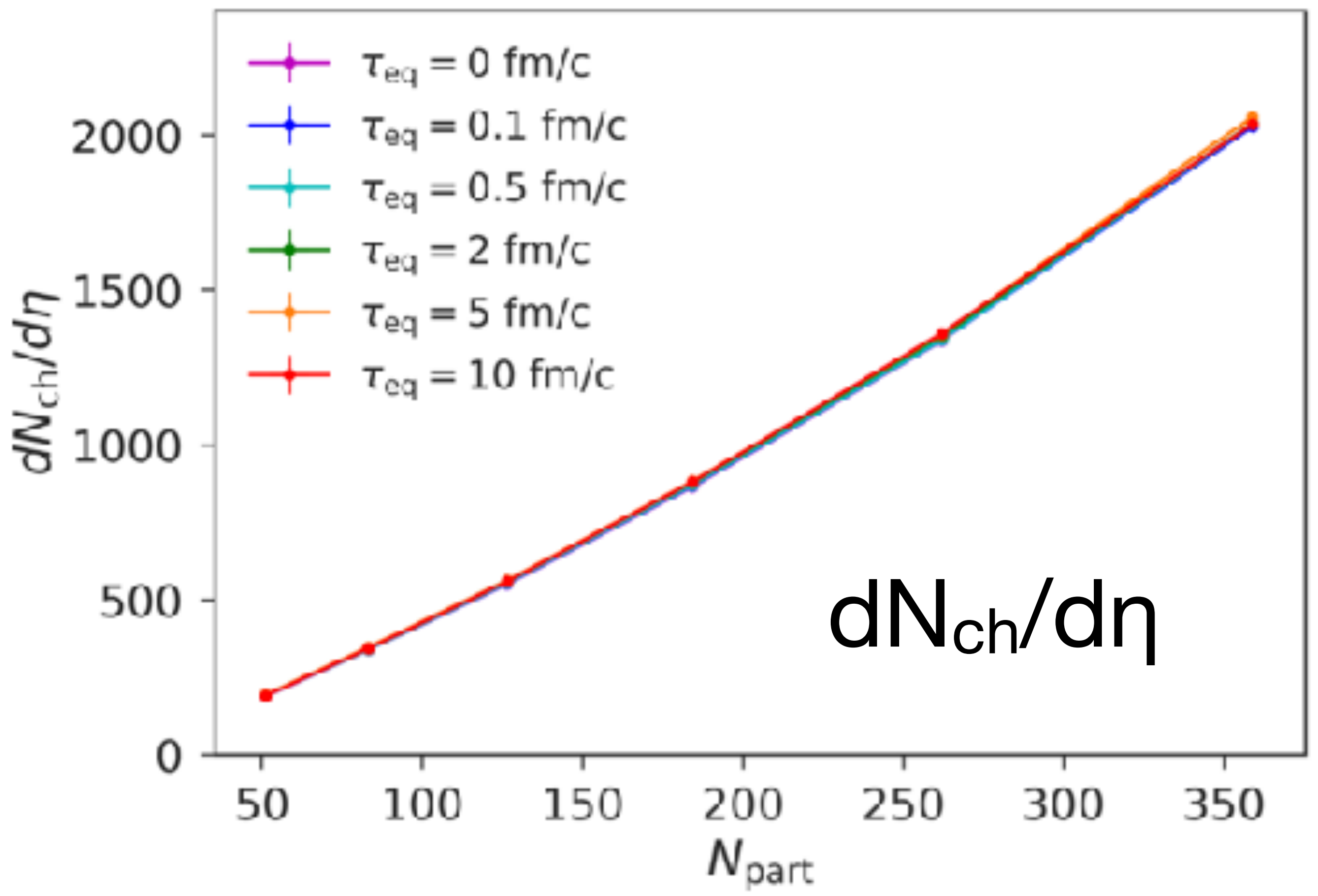


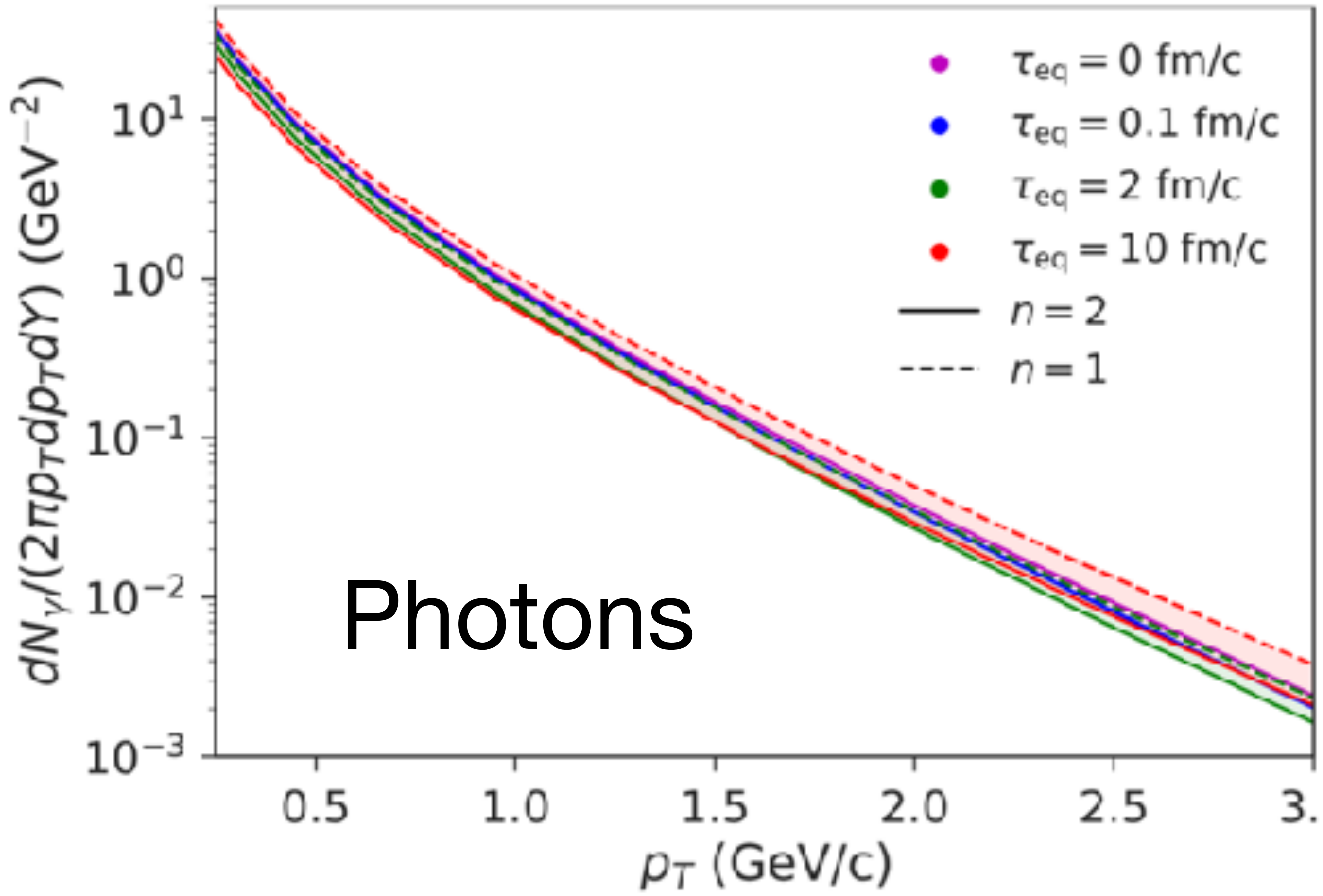
Tricky problem, because EOS changes with γ_q requires lattice-inspired modeling

Gordeev, Bass, BM, 2501.06433



$dN_{ch}/d\eta$ and even dN_γ/dp_Tdy are nearly invariant against τ_{eq}





Most promising discriminant: $v_2(p_T)$

Hadrochemistry can be “charming”

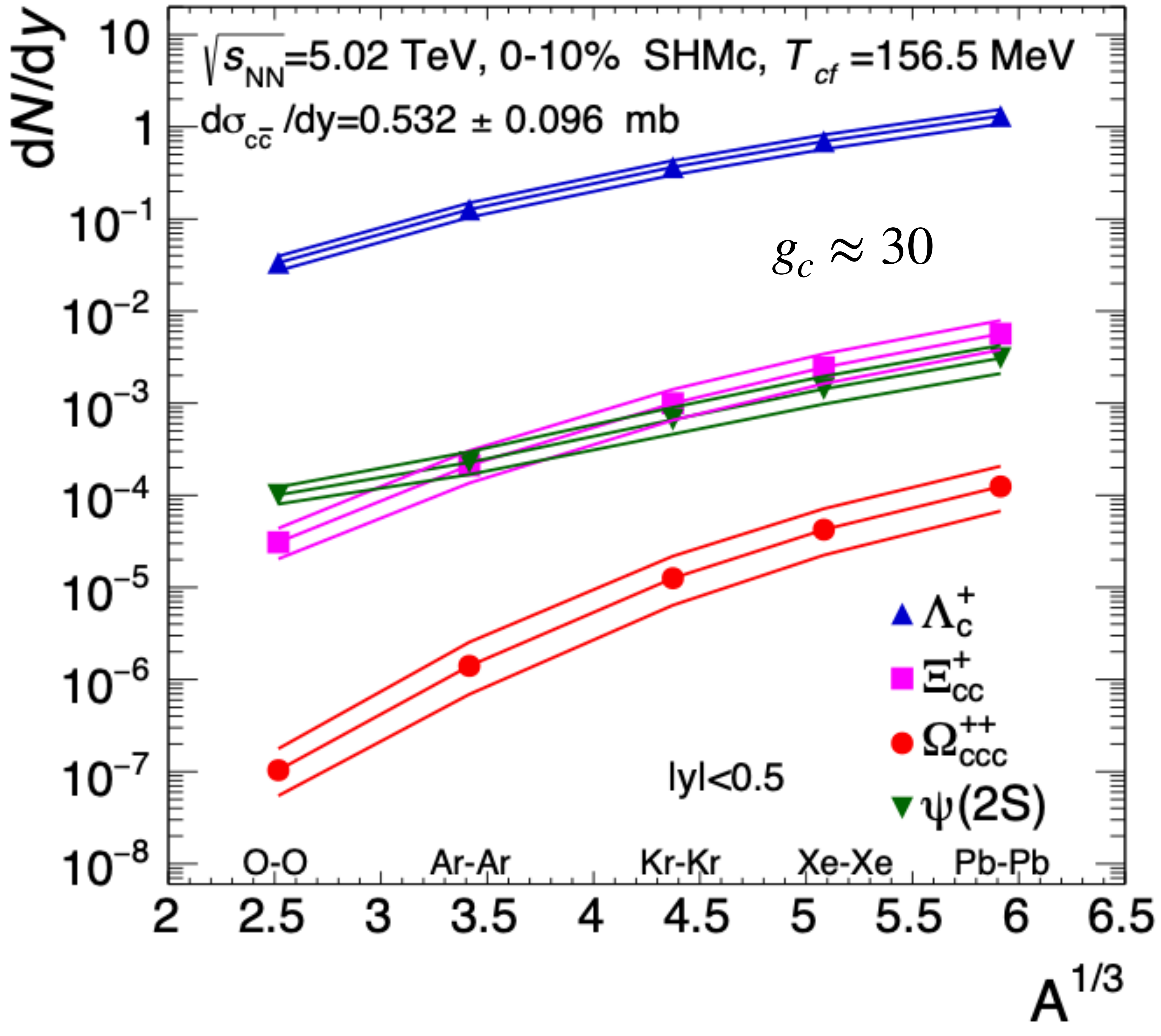
Vast overabundance of *c*-quarks

[Andronic et al. 2104.12754]

⇒

Large exothermic reaction rates in final-state HG that can persist for long times: Example: $D\overline{D} \to J/\psi$

[Lap & BM 2208.04368]



$(Q - \overline{Q})$ and $Q, \overline{Q}$ transport in QGP is closely linked [Yao & BM, 1709.03529].

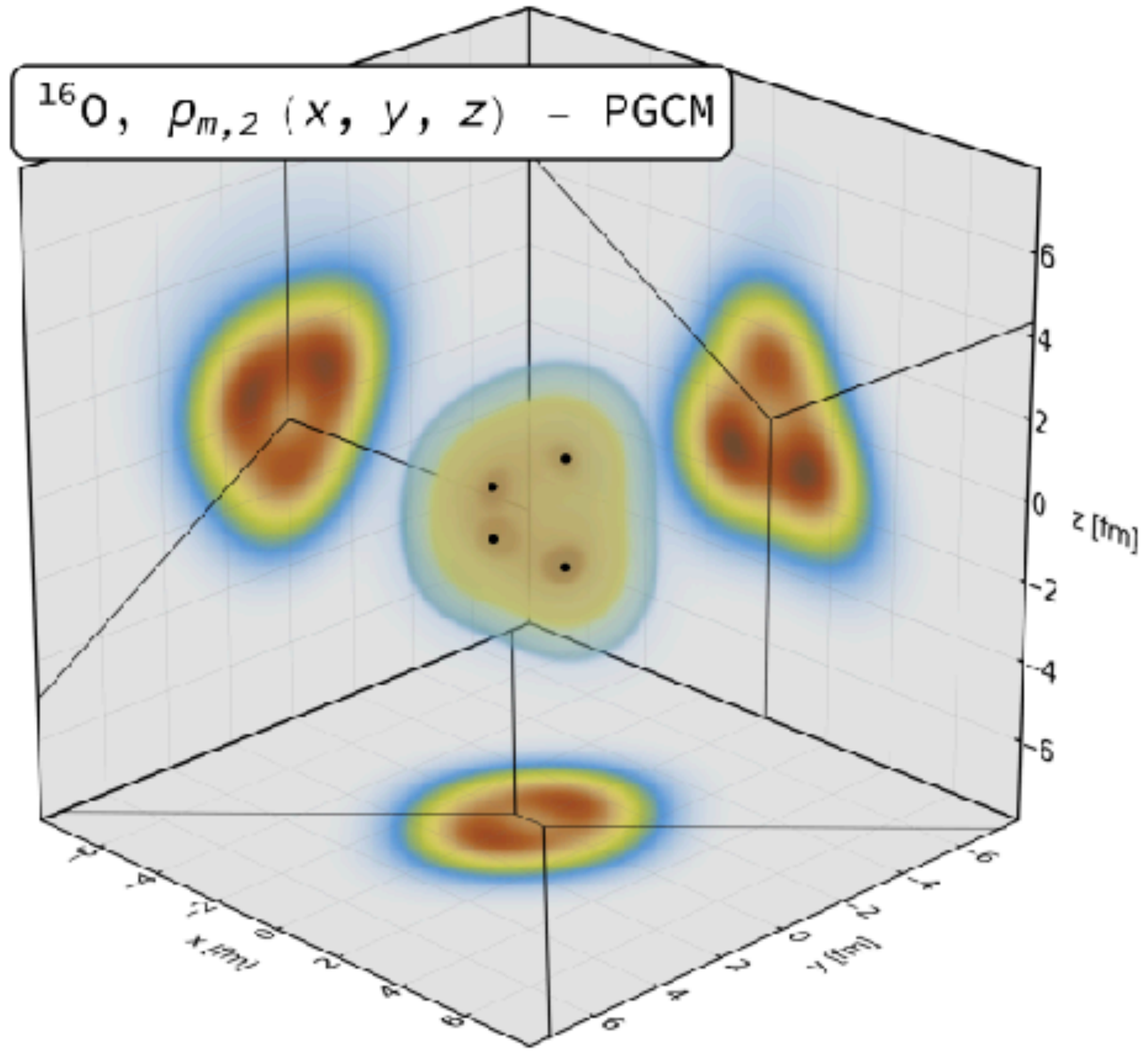
Negligible $c\bar{c}$ annihilation in the QGP [Andronic et al, nucl-th/0611023].

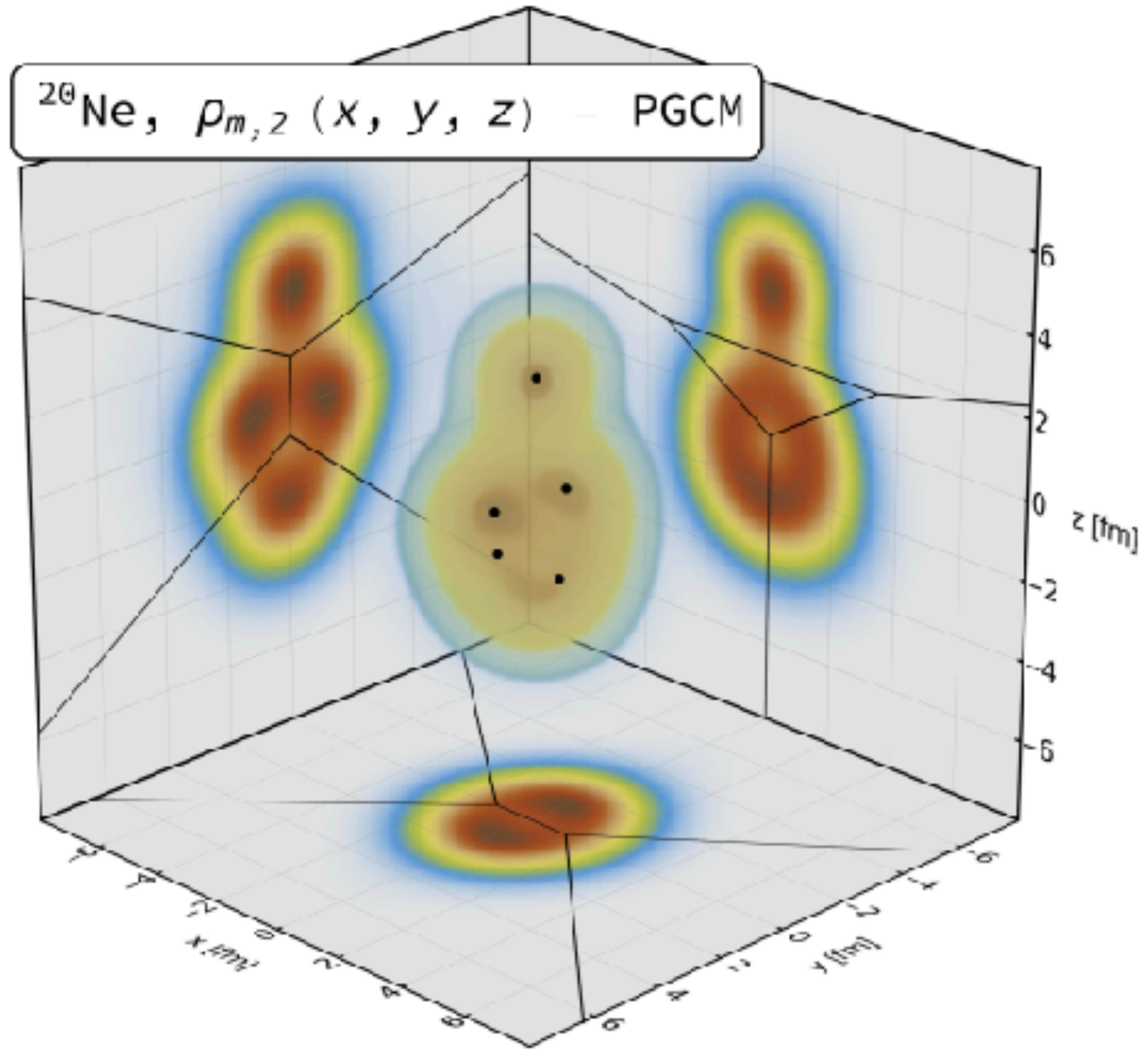
State-of-the art 4-flavor Bayesian analysis with full chemistry in QGP and HG will be needed to interpret LHC run-4/5 data.

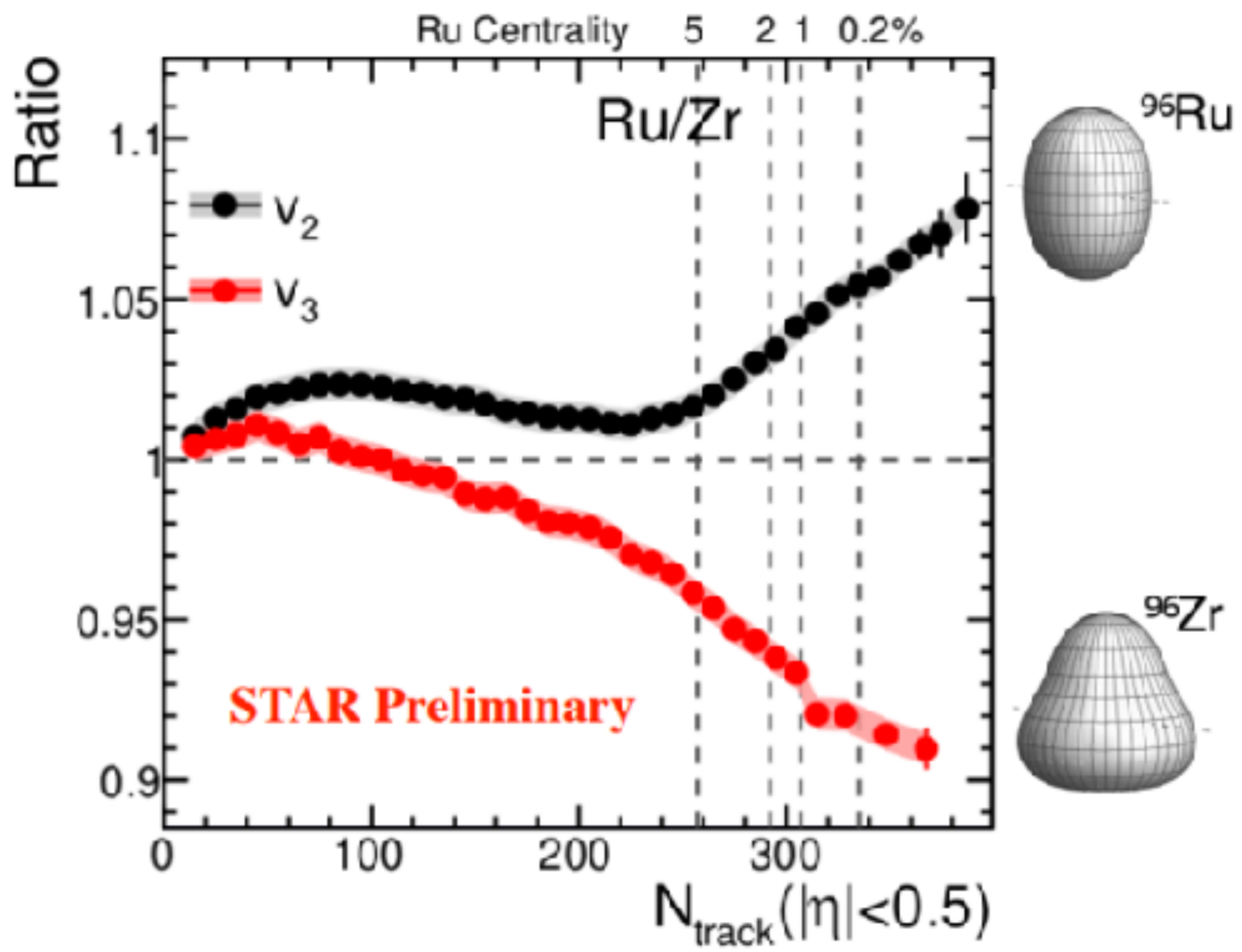
Bulk dynamics

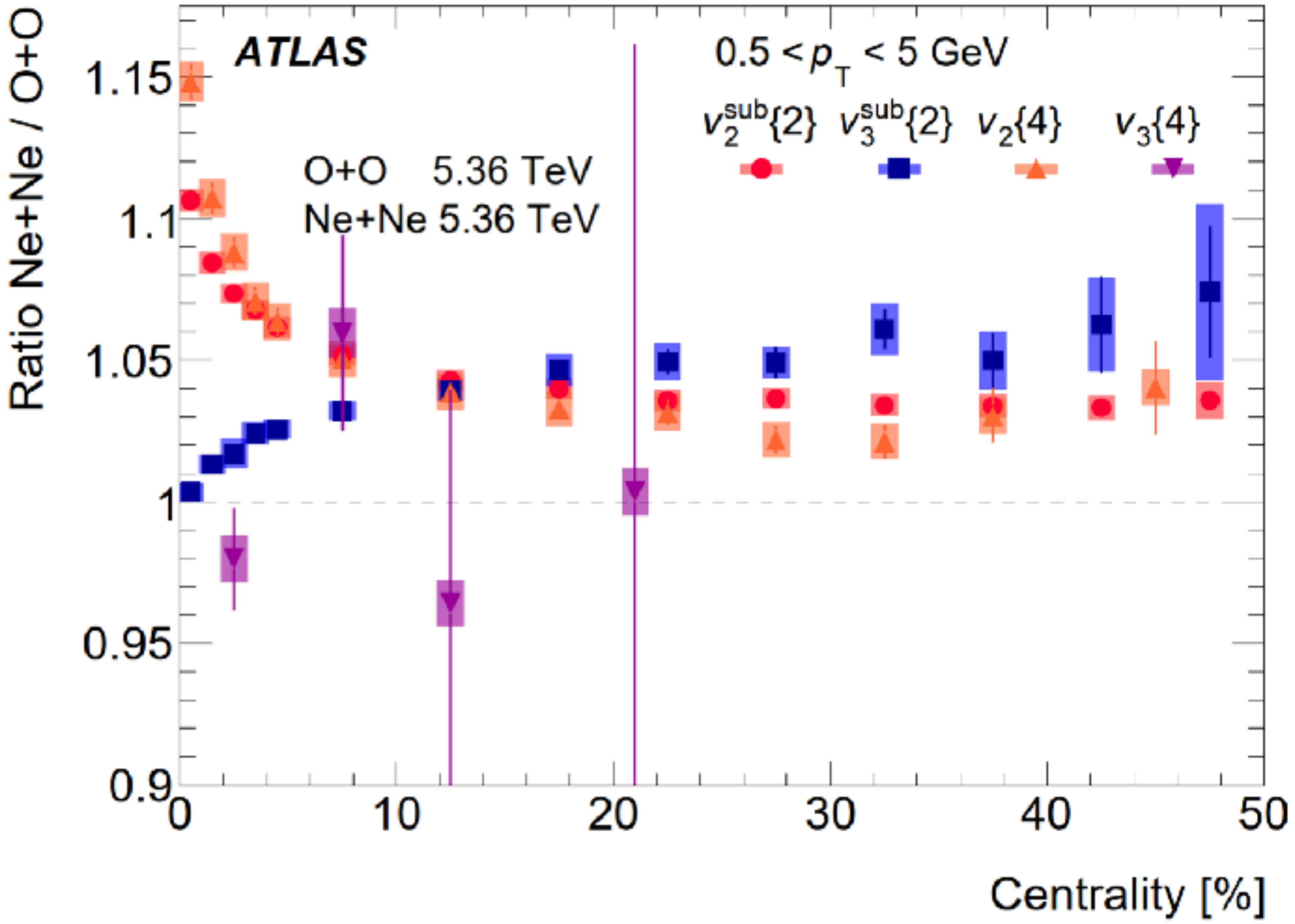
System size/shape dependence

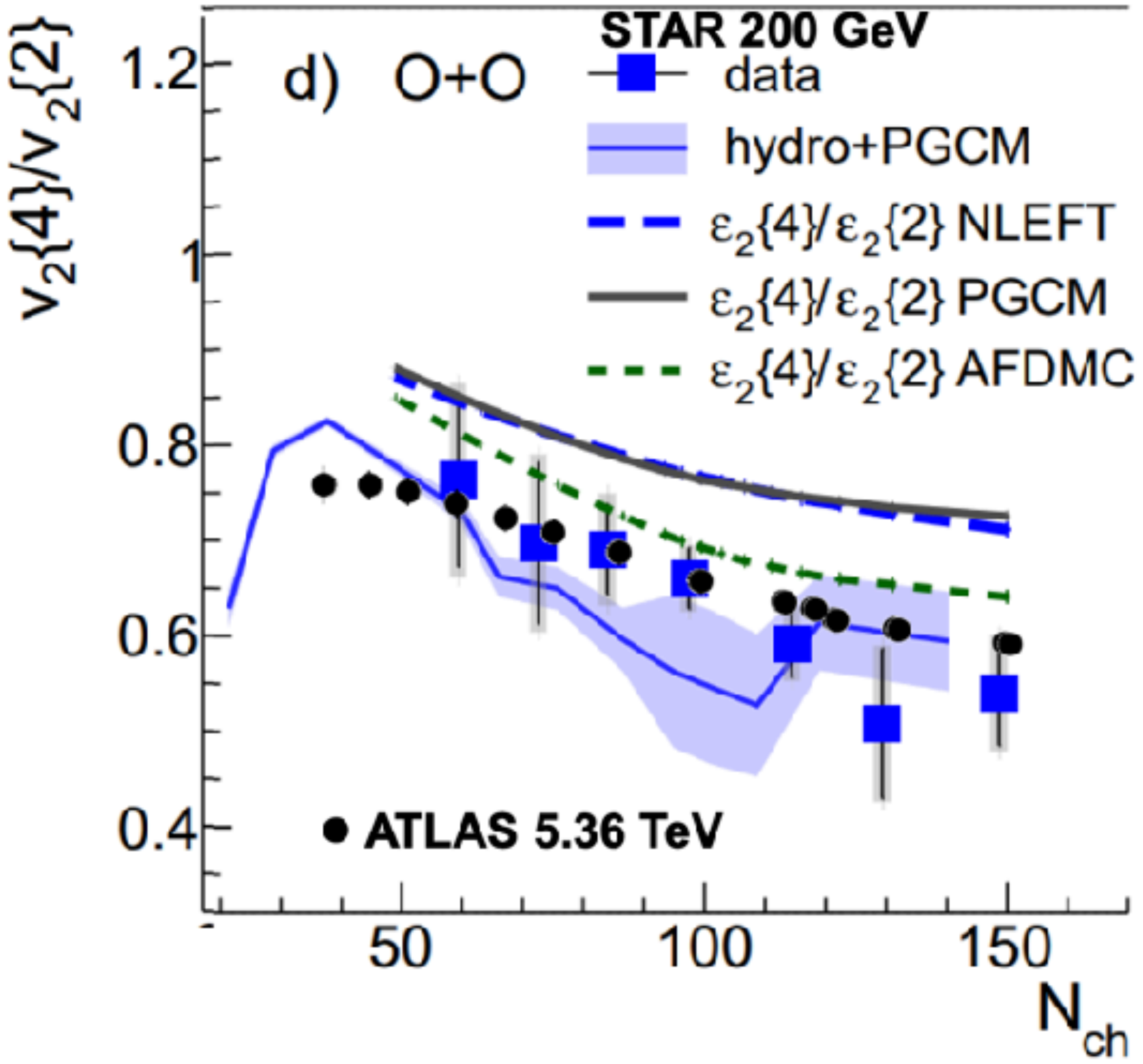
- Not new: centrality (*b*) dependence always there!
- Nuclear size/shape provides different angle:
  - Cu+Cu vs Au+Au ⟶ triangular flow, v_n
  - U+U, Xe+Xe ⟶ importance of deformation
  - Zr+Zr vs Ru+Ru ⟶ precision measurement of shape
  - p+p, p+Au, d+Au, ^{3}He+Au ⟶ collectivity in tiny systems
  - ^{16}O+^{16}O, ^{20}Ne+^{20}Ne ⟶ collectivity in small (not tiny) systems
- Relevant parameters:
  - Transverse radius $R_\perp \sim A^{1/3}$ vs. $L_{\rm th} \sim 1/T$
  - Initial state fluctuation scale $L_{\rm fluc} \sim Q_s^{-1} \sim A^{-1/6}$
  - Parton-based Glauber vs. nucleon-based Glauber

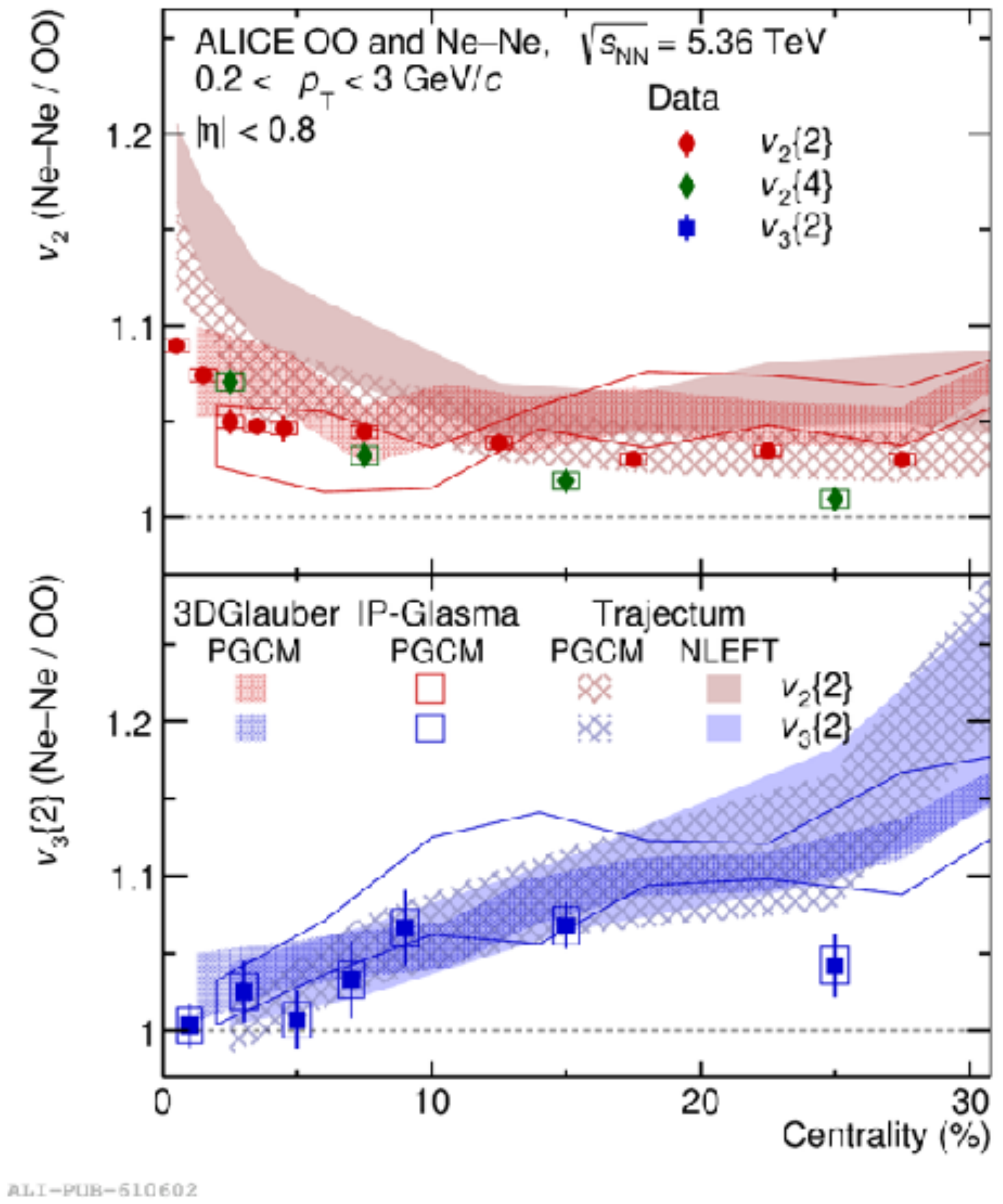


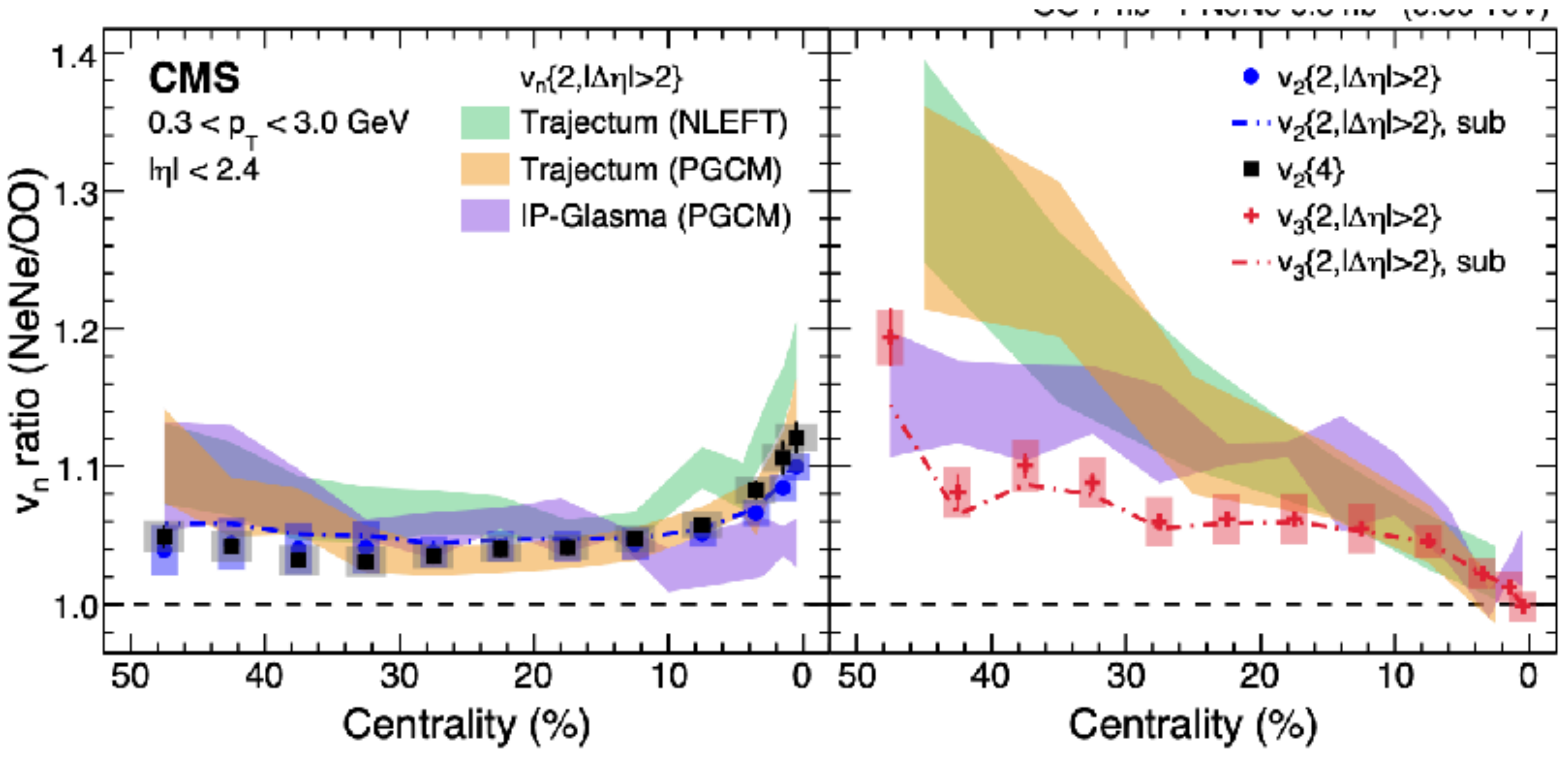


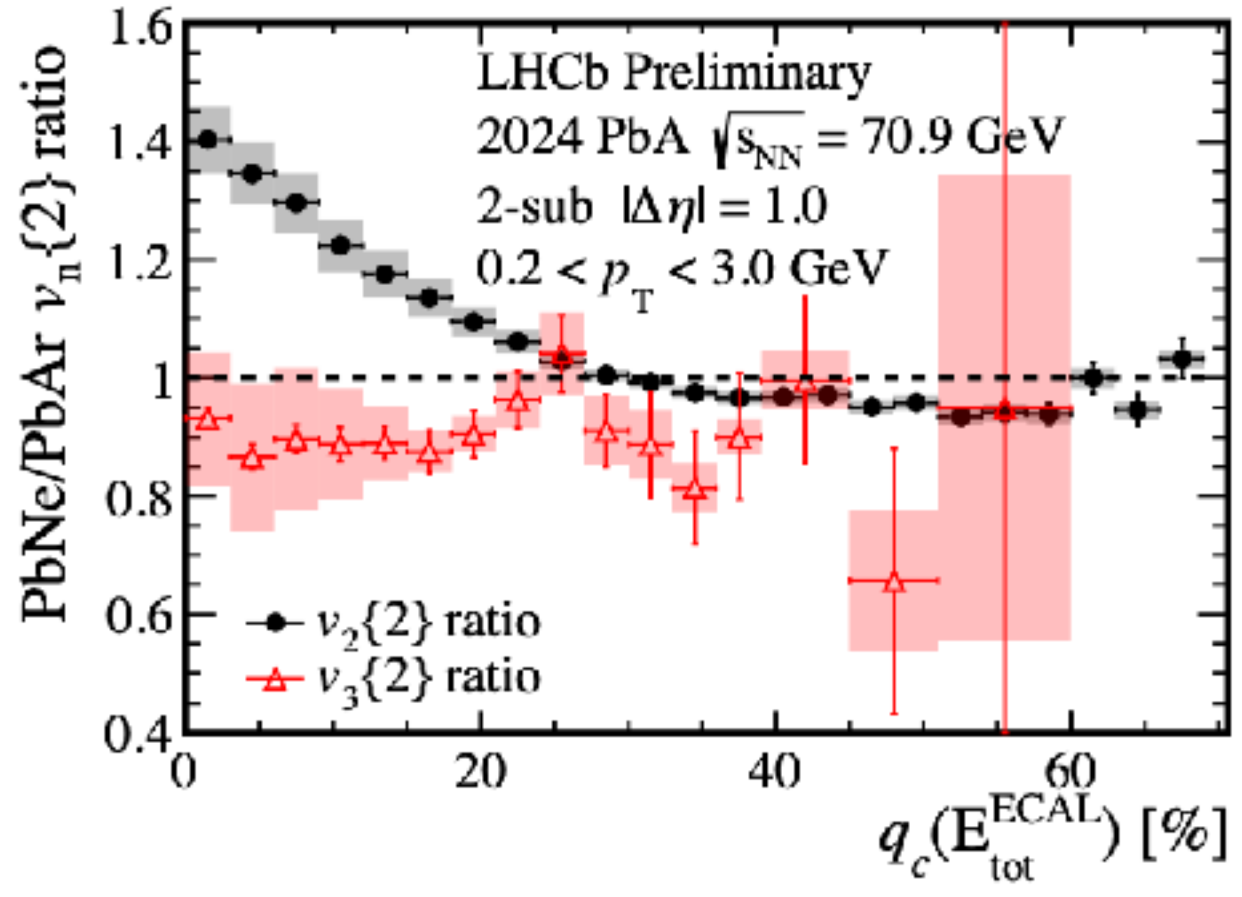

Ru Centrality 5 2 1 0.2%
Ratio
Ru/Zr
v_2
v_3
STAR Preliminary
^{96}Ru
^{96}Zr
$N_{track}(|\eta|<0.5)$
1.1
1.05
1
0.95
0.9
0
100
200
300


ATLAS
$0.5 < p_T < 5$ GeV
$v_2^{sub}\{2\}$ $v_3^{sub}\{2\}$ $v_2\{4\}$ $v_3\{4\}$
O+O 5.36 TeV
Ne+Ne 5.36 TeV
Ratio Ne+Ne / O+O
Centrality [%]
1.15
1.1
1.05
1
0.95
0.9
0
10
20
30
40
50

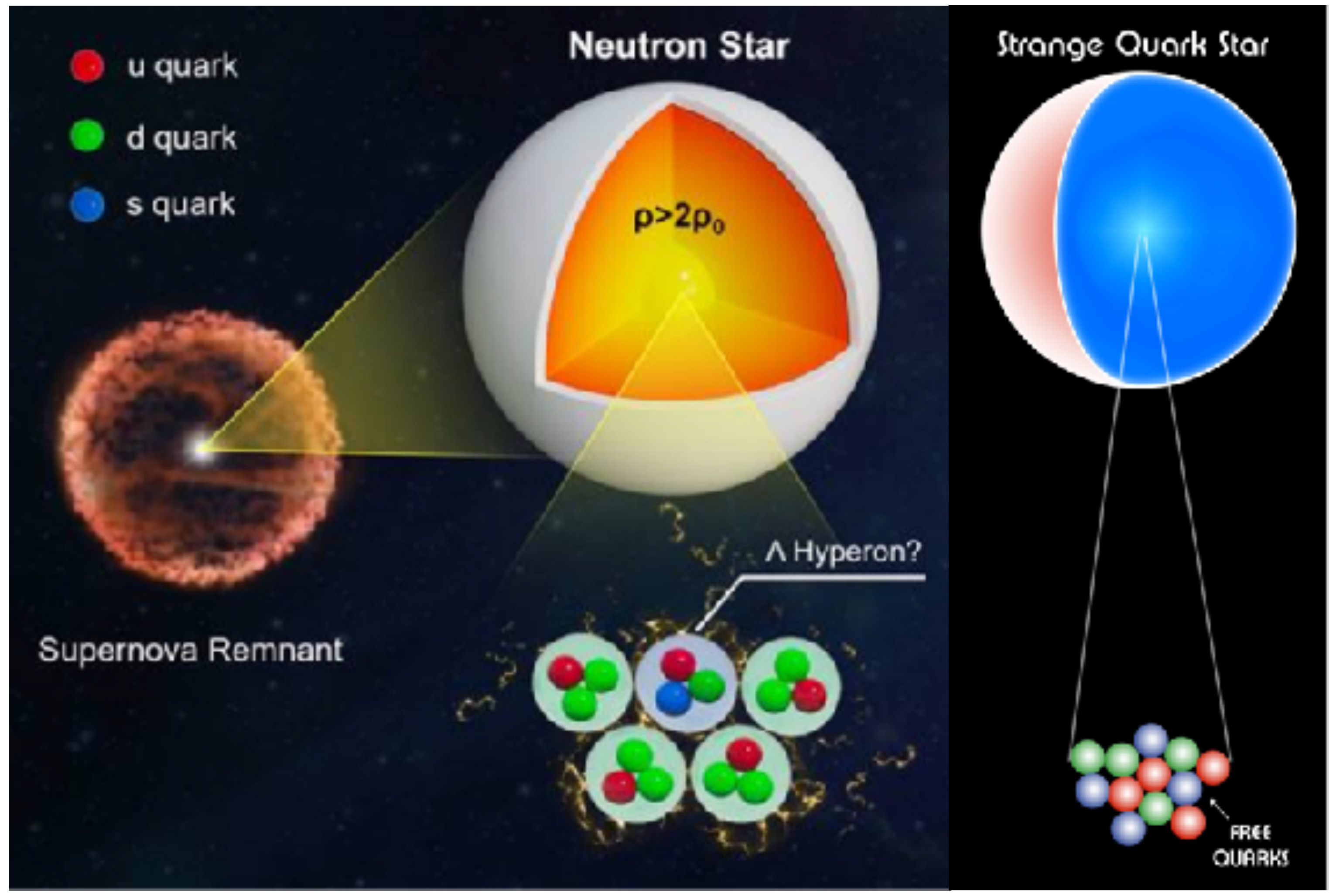

STAR 200 GeV
d) O+O
data
hydro+PGCM
$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ NLEFT
$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ PGCM
$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ AFDMC
ATLAS 5.36 TeV
$v_2\{4\}/v_2\{2\}$
N_{ch}
1.2
1
0.8
0.6
0.4
50
100
150

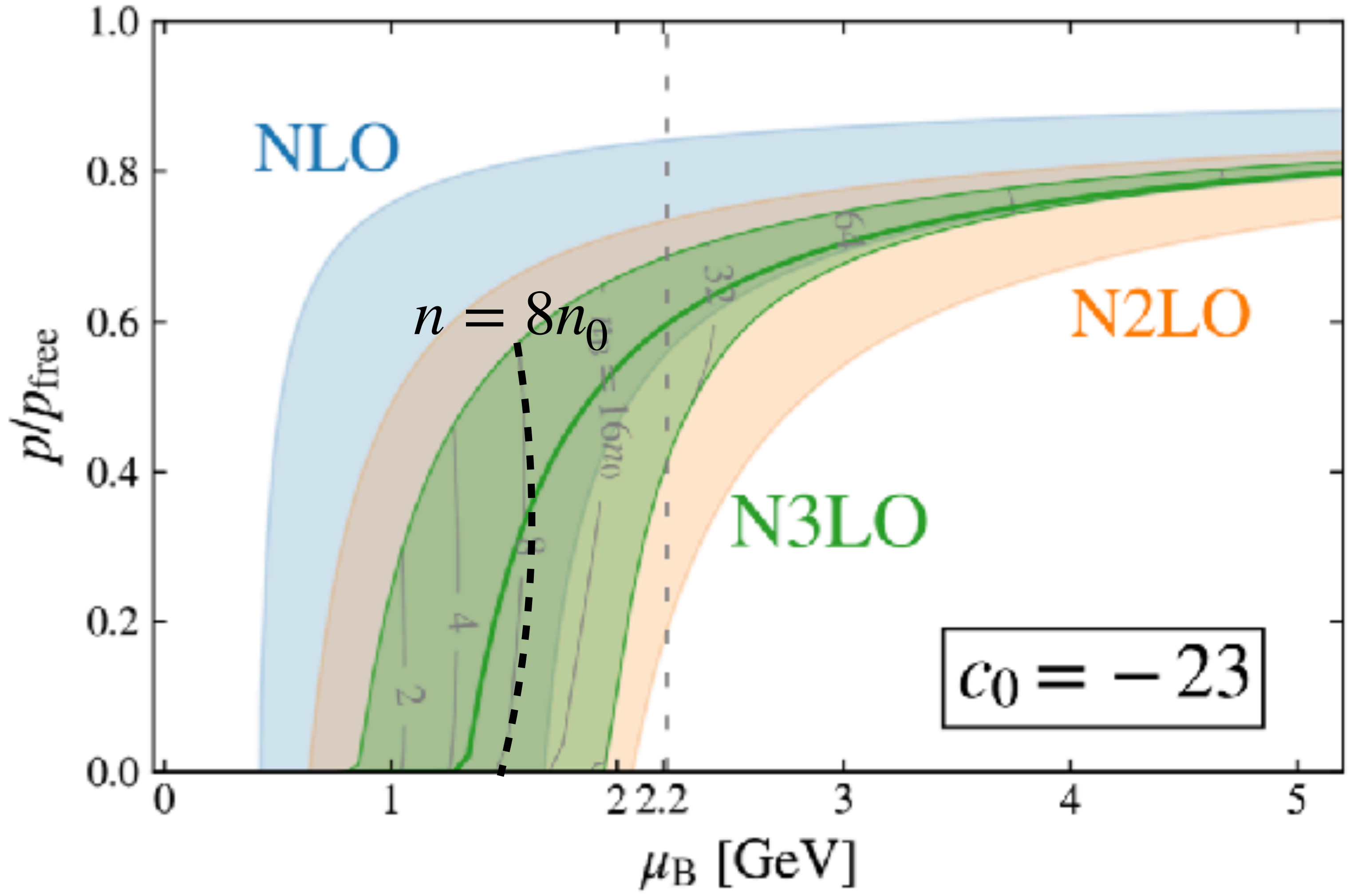

ALICE OO and Ne–Ne, $\sqrt{s_{NN}}$ = 5.36 TeV
$0.2 < p_T < 3$ GeV/c
$|\eta| < 0.8$
Data
$v_2\{2\}$
$v_2\{4\}$
$v_3\{2\}$
v_2 (Ne–Ne / OO)
3DGlauber PGCM
IP-Glasma PGCM
Trajectum PGCM NLEFT
$v_2\{2\}$
$v_3\{2\}$
$v_3\{2\}$ (Ne–Ne / OO)
Centrality (%)
1.2
1.1
1
0
10
20
30
ALI-PUB-610602


CMS
$0.3 < p_T < 3.0$ GeV
$|\eta| < 2.4$
$v_n\{2,|\Delta\eta|>2\}$
Trajectum (NLEFT)
Trajectum (PGCM)
IP-Glasma (PGCM)
$v_2\{2,|\Delta\eta|>2\}$
$v_2\{2,|\Delta\eta|>2\}$, sub
$v_2\{4\}$
$v_3\{2,|\Delta\eta|>2\}$
$v_3\{2,|\Delta\eta|>2\}$, sub
v_n ratio (NeNe/OO)
Centrality (%)
1.4
1.3
1.2
1.1
1.0
50
40
30
20
10
0

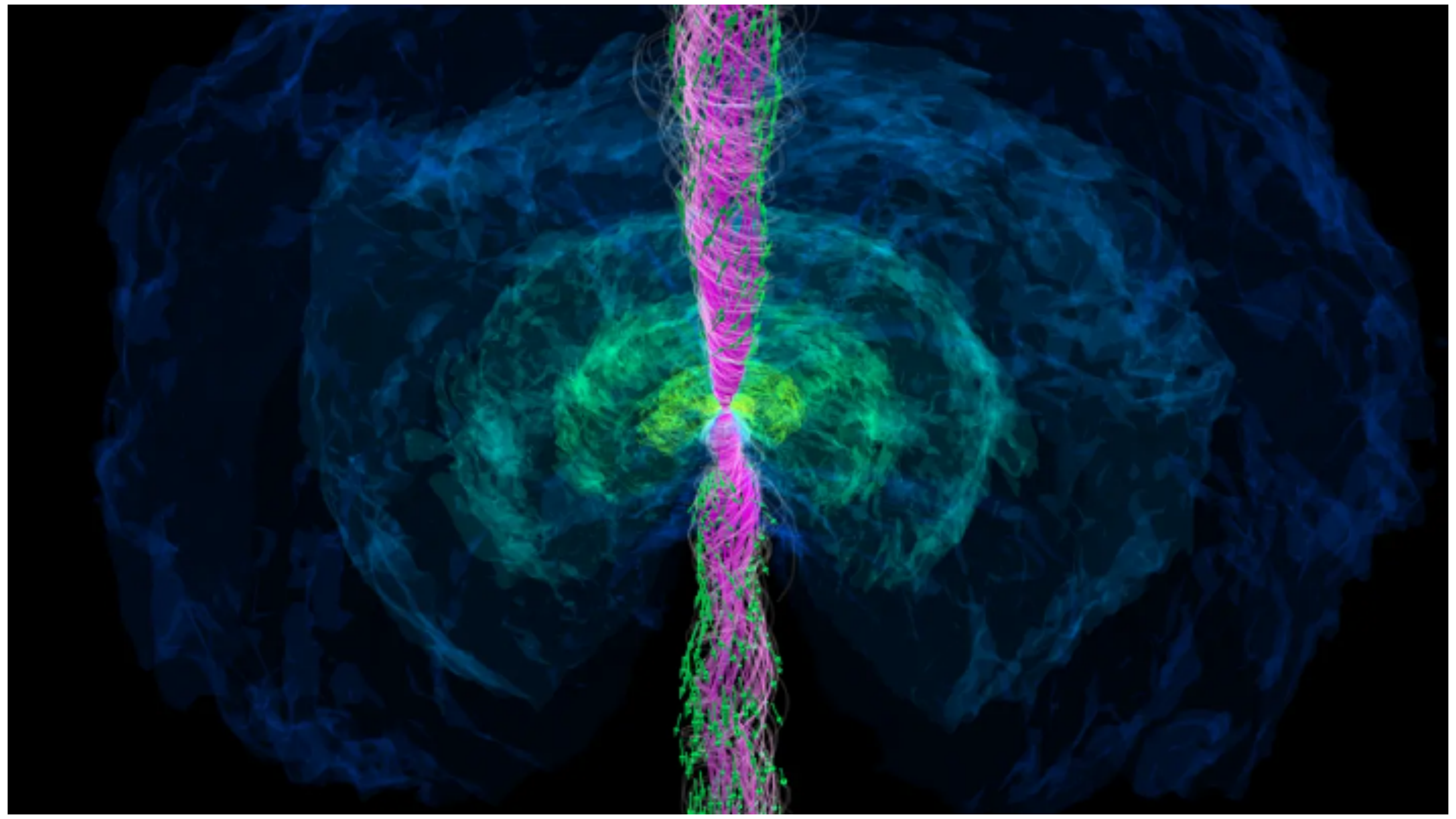

LHCb Preliminary
2024 PbA $\sqrt{s_{NN}}$ = 70.9 GeV
2-sub $|\Delta\eta|$ = 1.0
$0.2 < p_T < 3.0$ GeV
$v_2\{2\}$ ratio
$v_3\{2\}$ ratio
PbNe/PbAr $v_n\{2\}$ ratio
$q_c(E_{tot}^{ECAL})$ [%]
1.6
1.4
1.2
1
0.8
0.6
0.4
0
20
40
60

Cold strange quark matter?





T. Gorda, et al.,
PRL 131 (2023) 181902

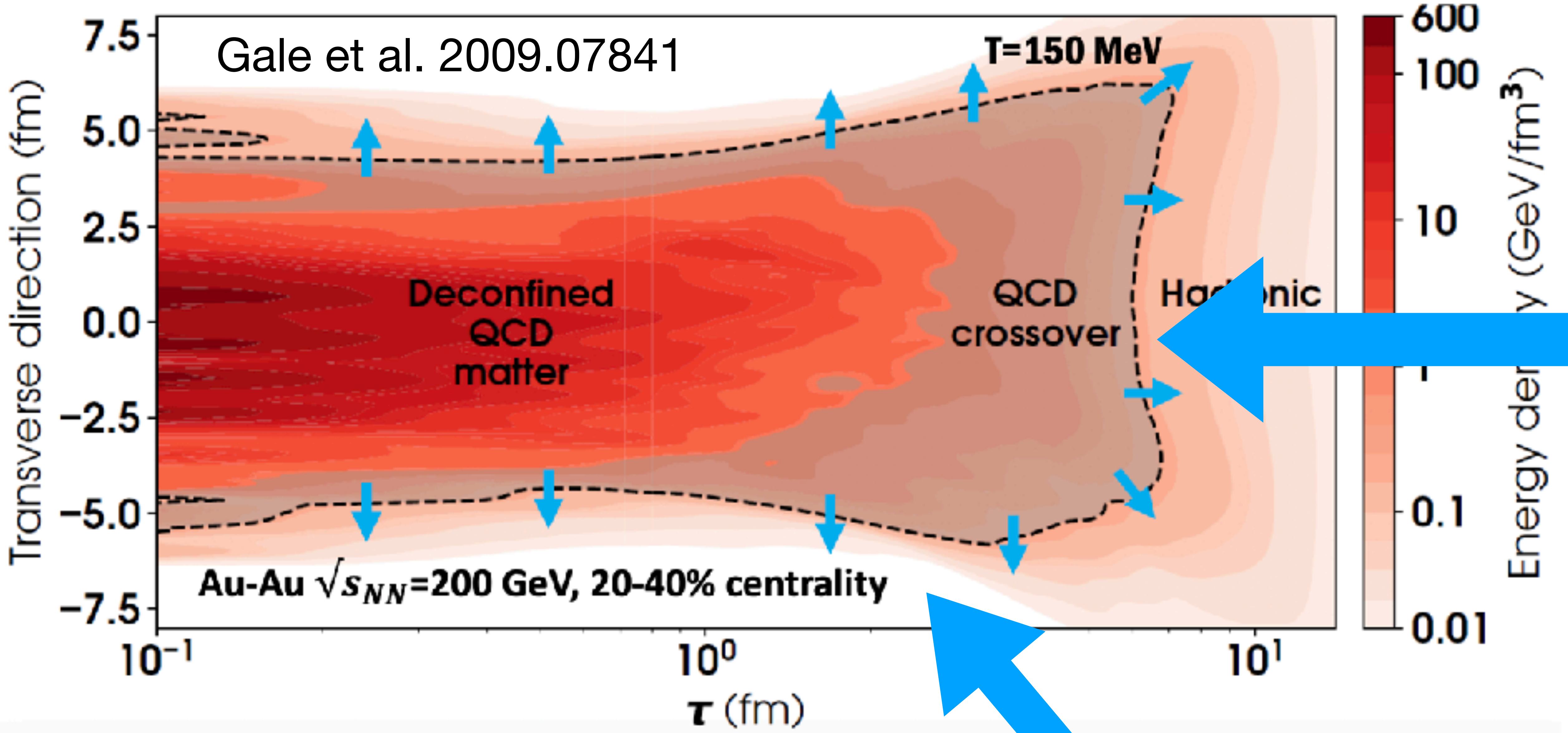


Neutron star merger simulation (1.3 s)

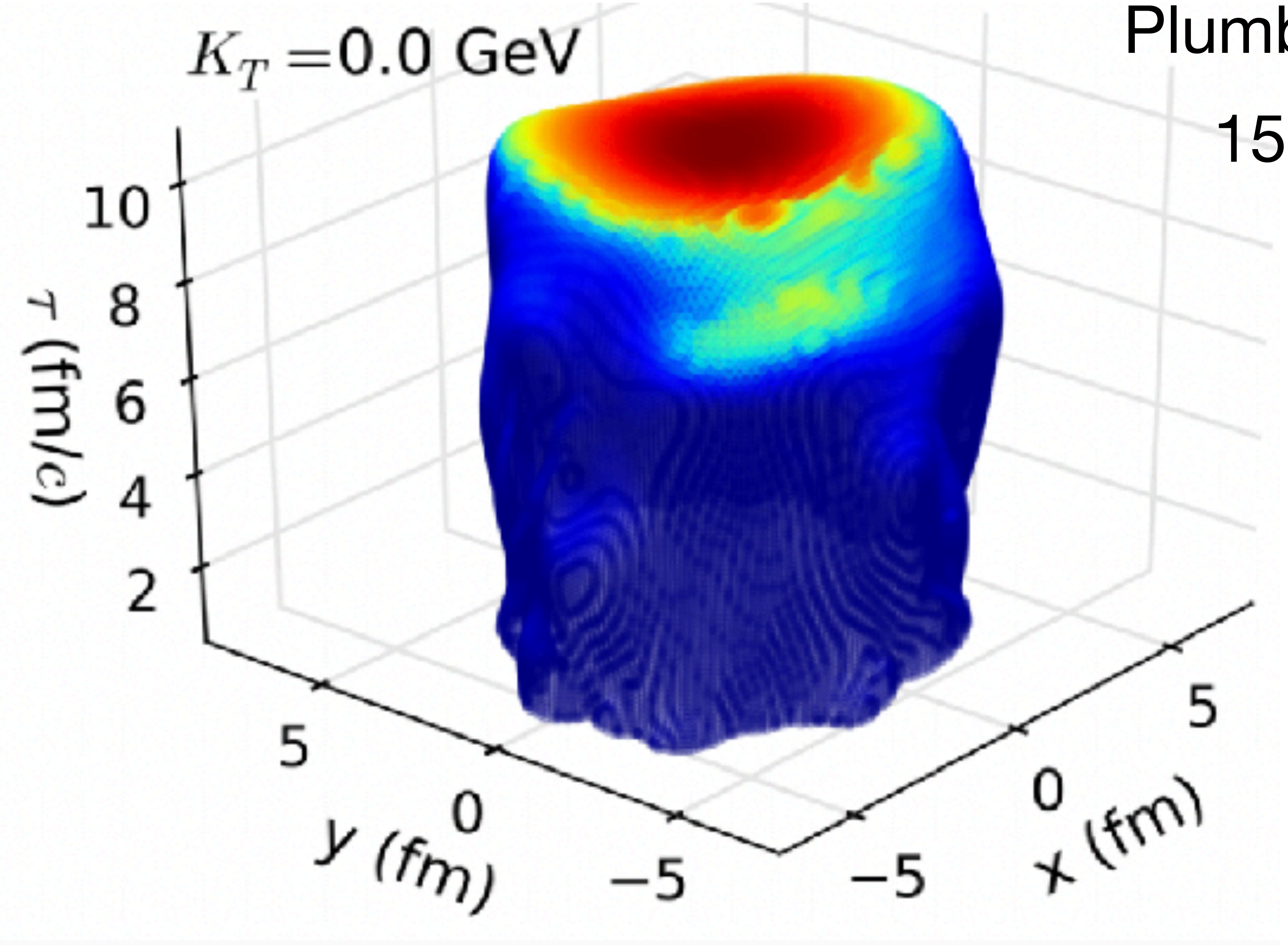
Using 130M CPUh

K. Hayashi (MPI-GP) on “Fugatsu” comp.

Hadronization



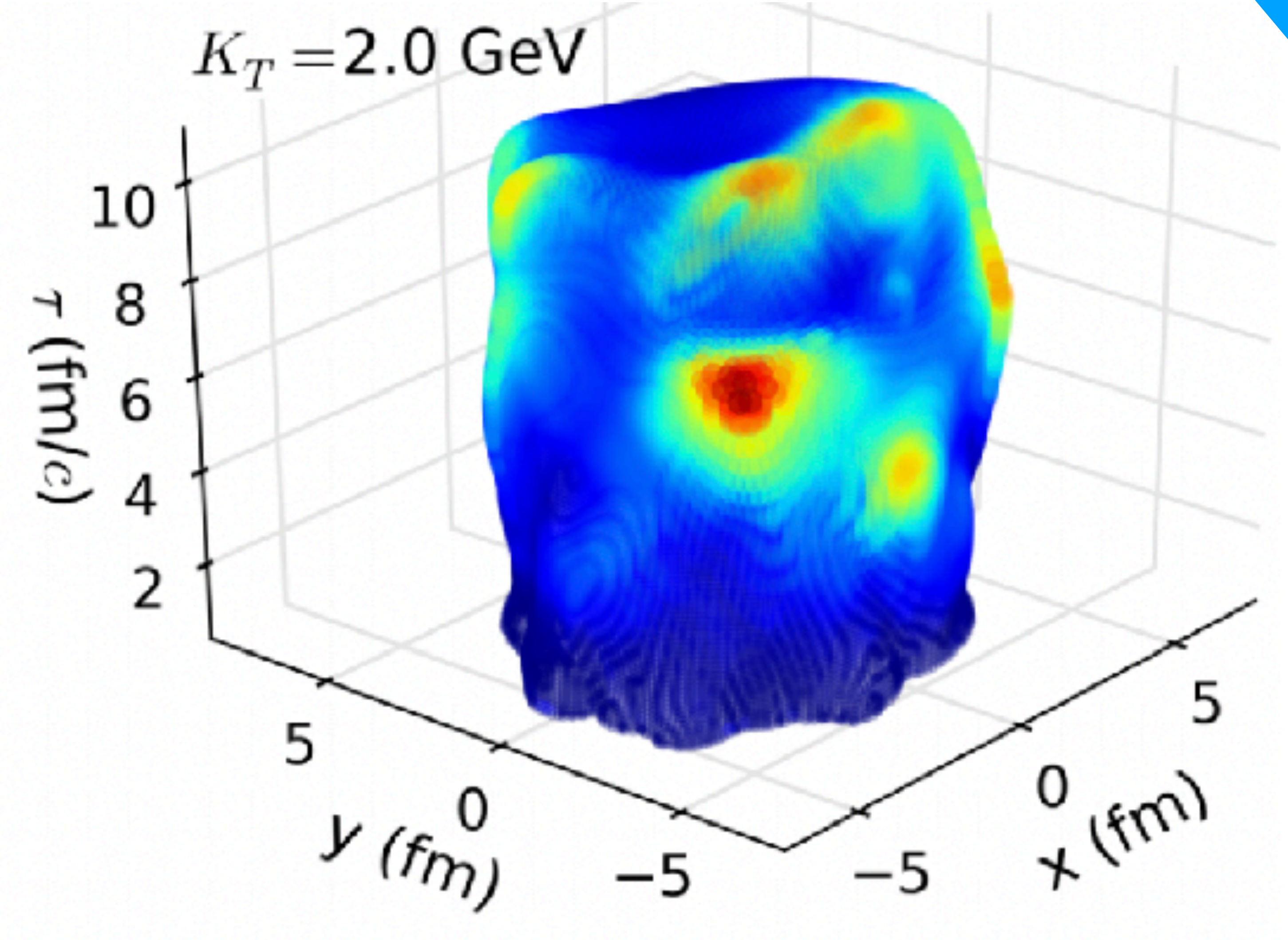
Gale et al. 2009.07841



Plumberg & Heinz 1503.05605

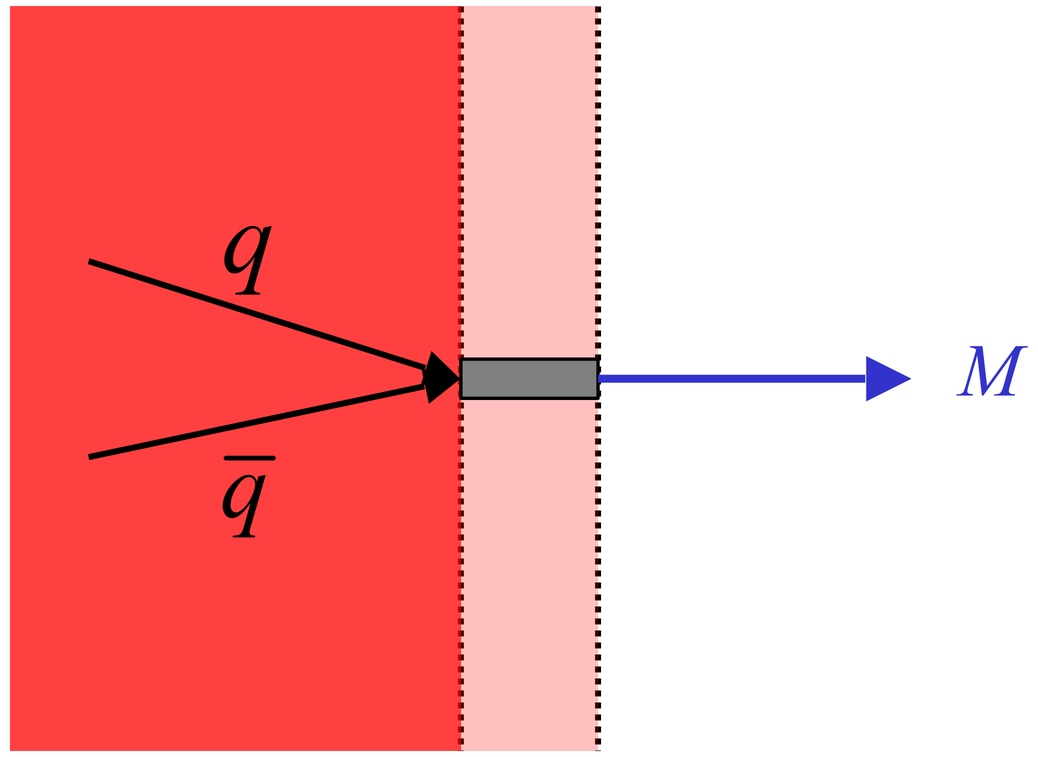
Spacelike hypersurface

Statistical coalescence

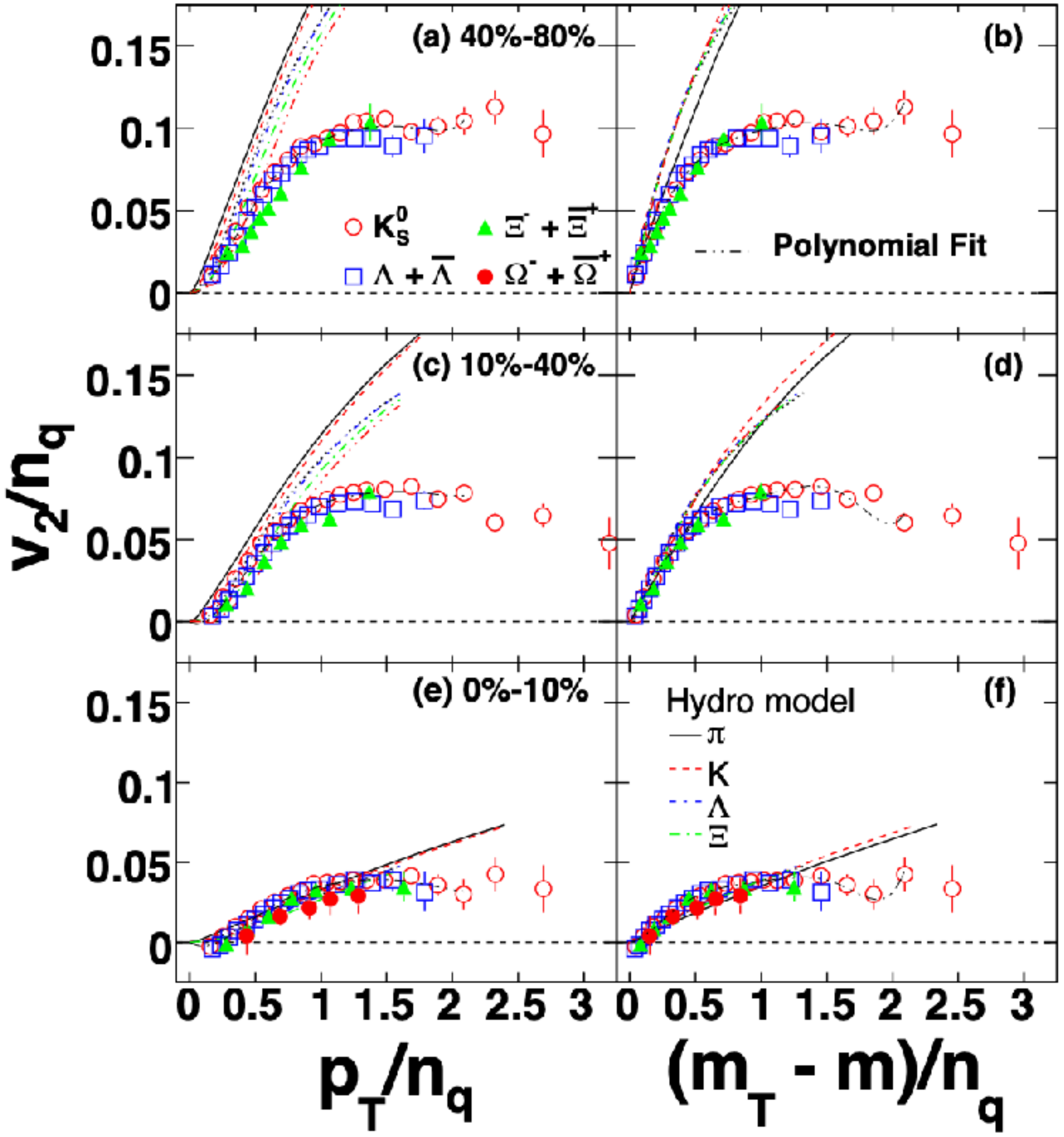


Timelike hypersurface

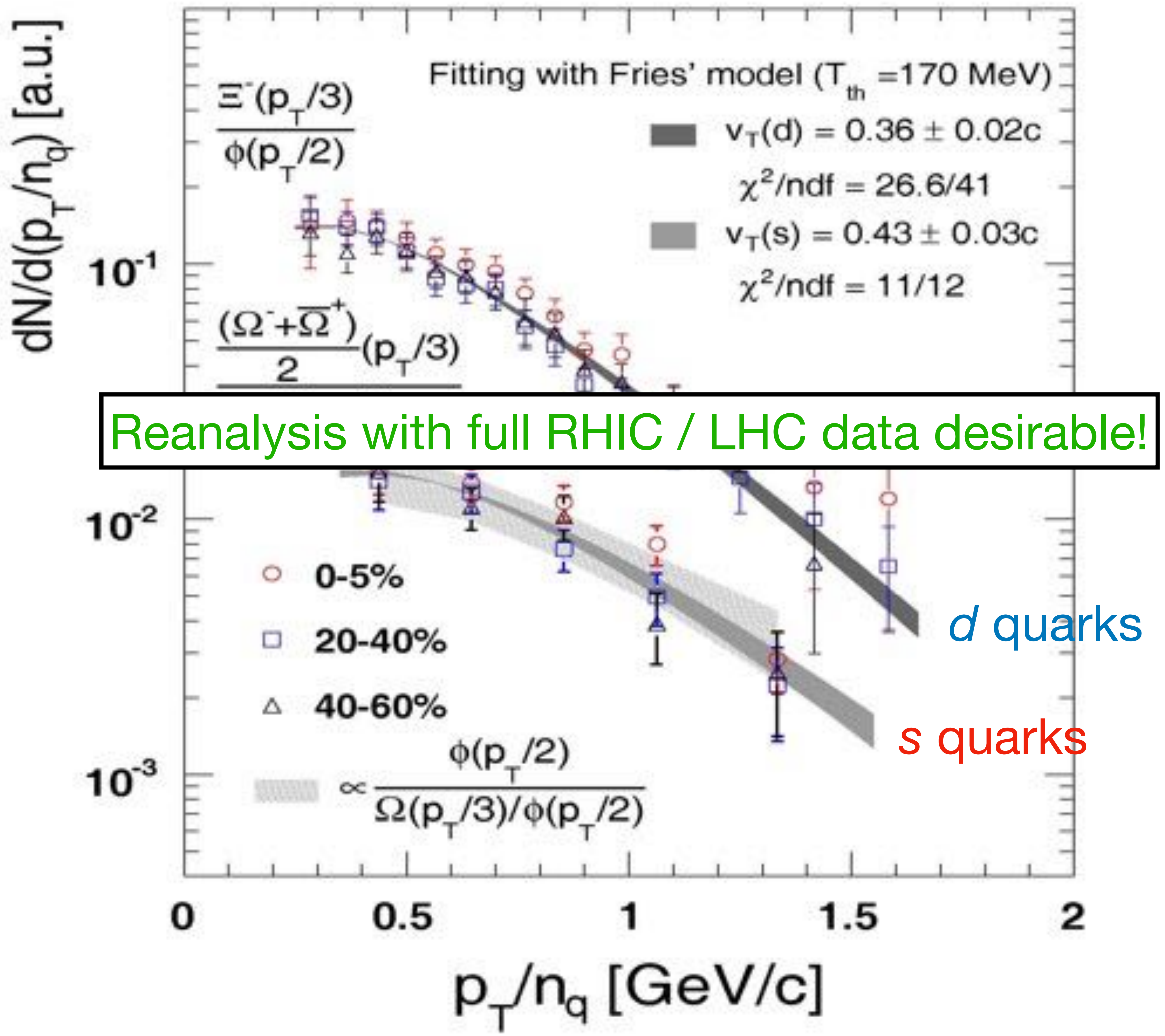
Sudden recombination



u, d, s quarks flow

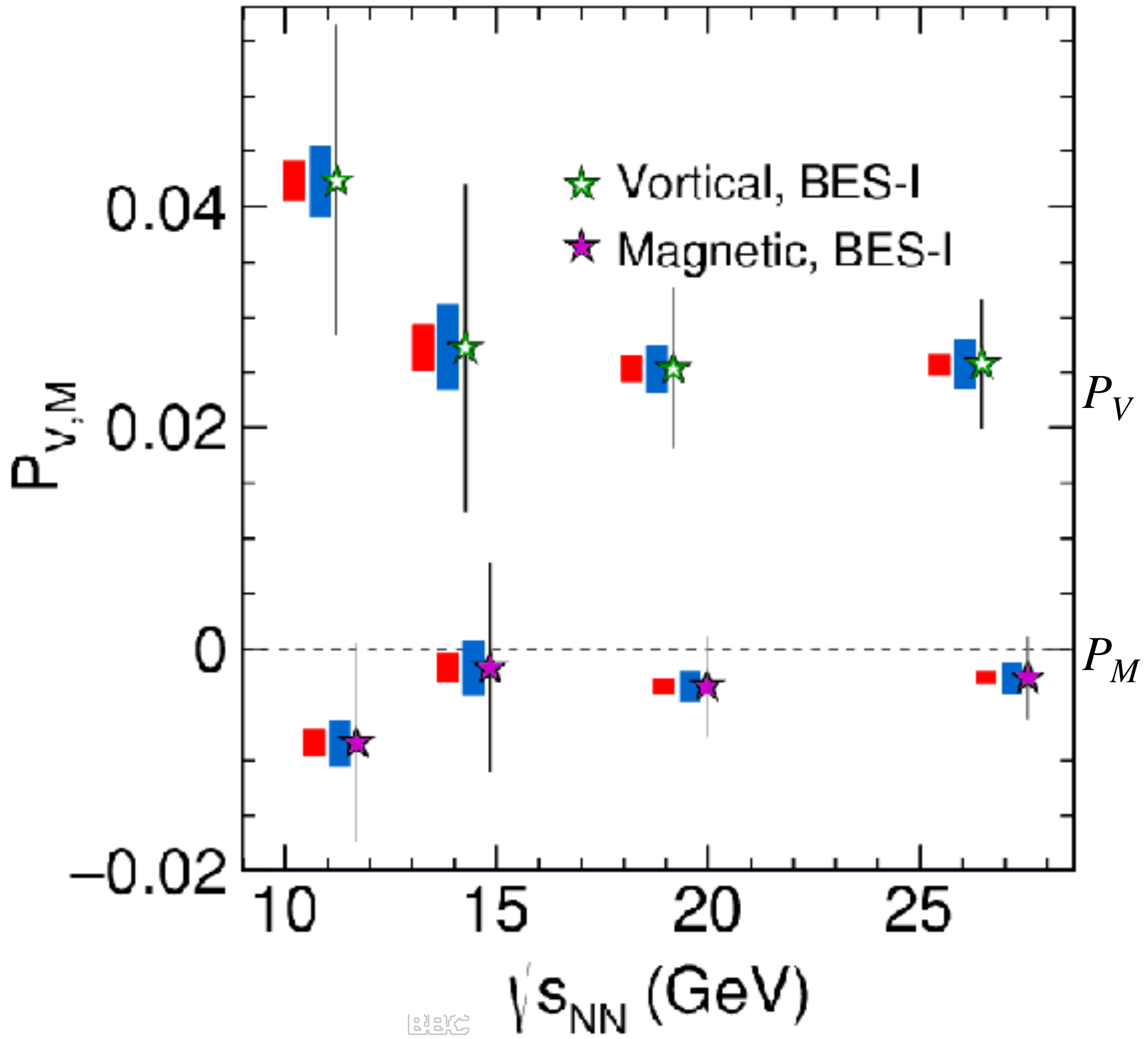


STAR/UCLA group (ca 2005)



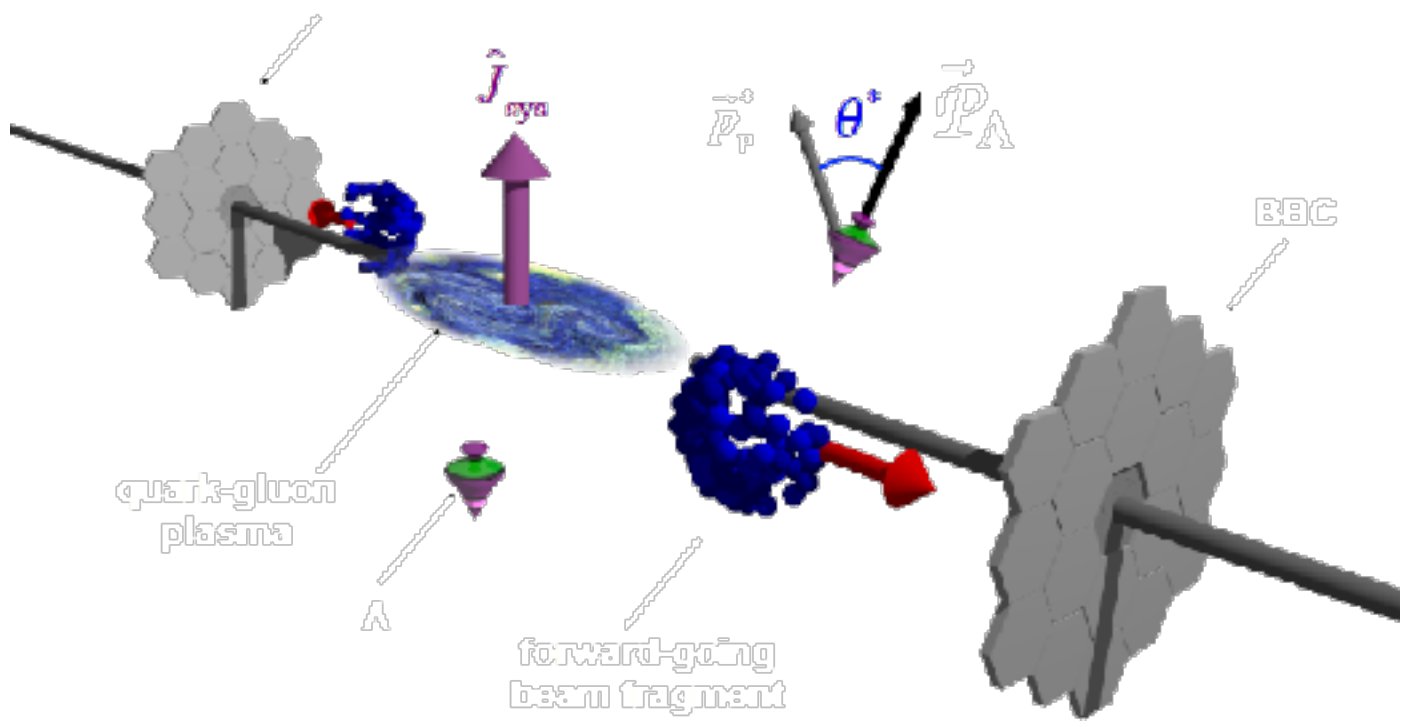
Reanalysis with full RHIC / LHC data desirable!

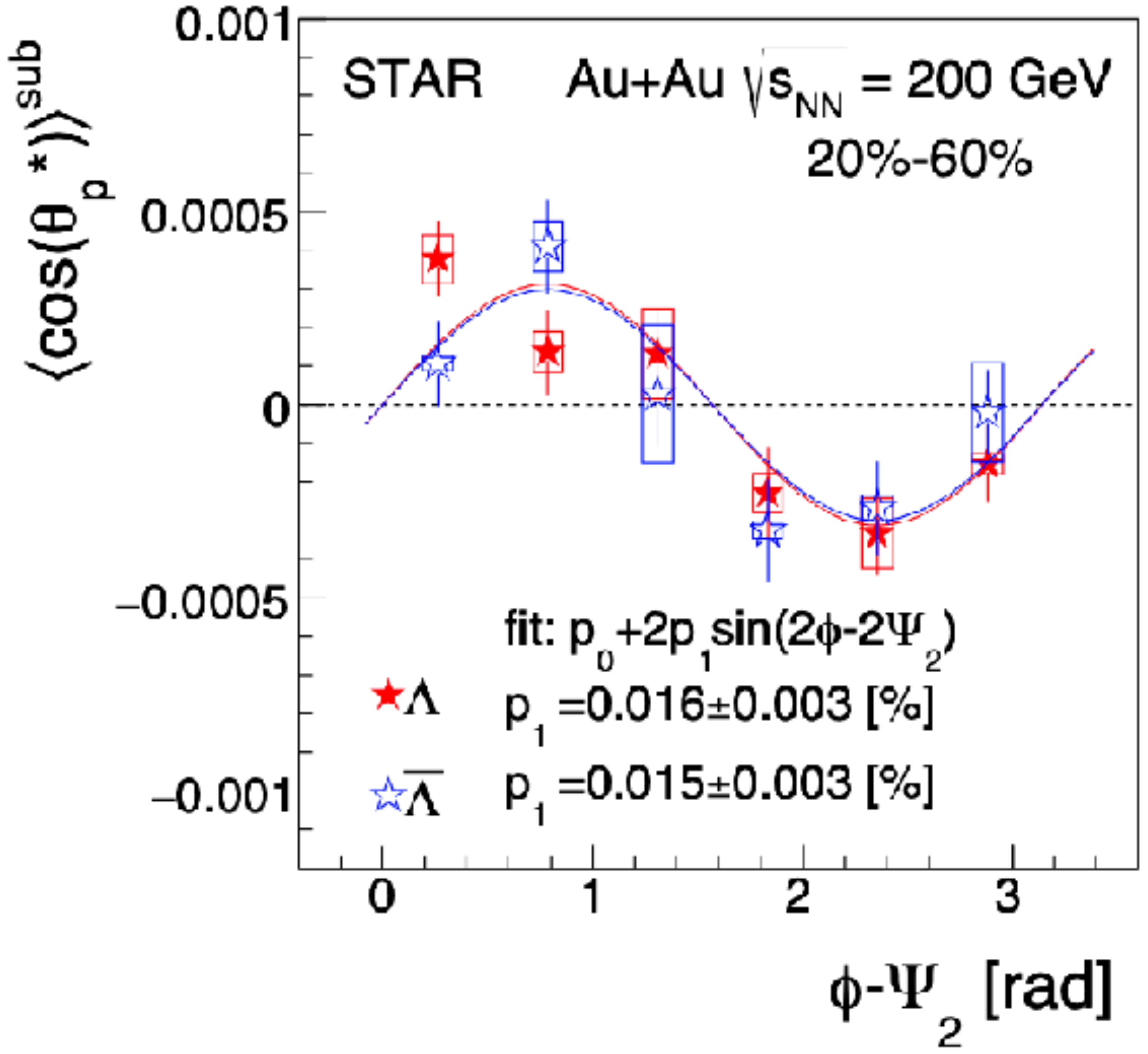
Global (and local) Λ polarization



$$P_V = \frac{P_\Lambda + P_{\bar\Lambda}}{2}$$

$$P_M = \frac{P_\Lambda - P_{\bar\Lambda}}{2}$$





New idea:

Glasma fields and spatial anisotropy

[Haesom Sung

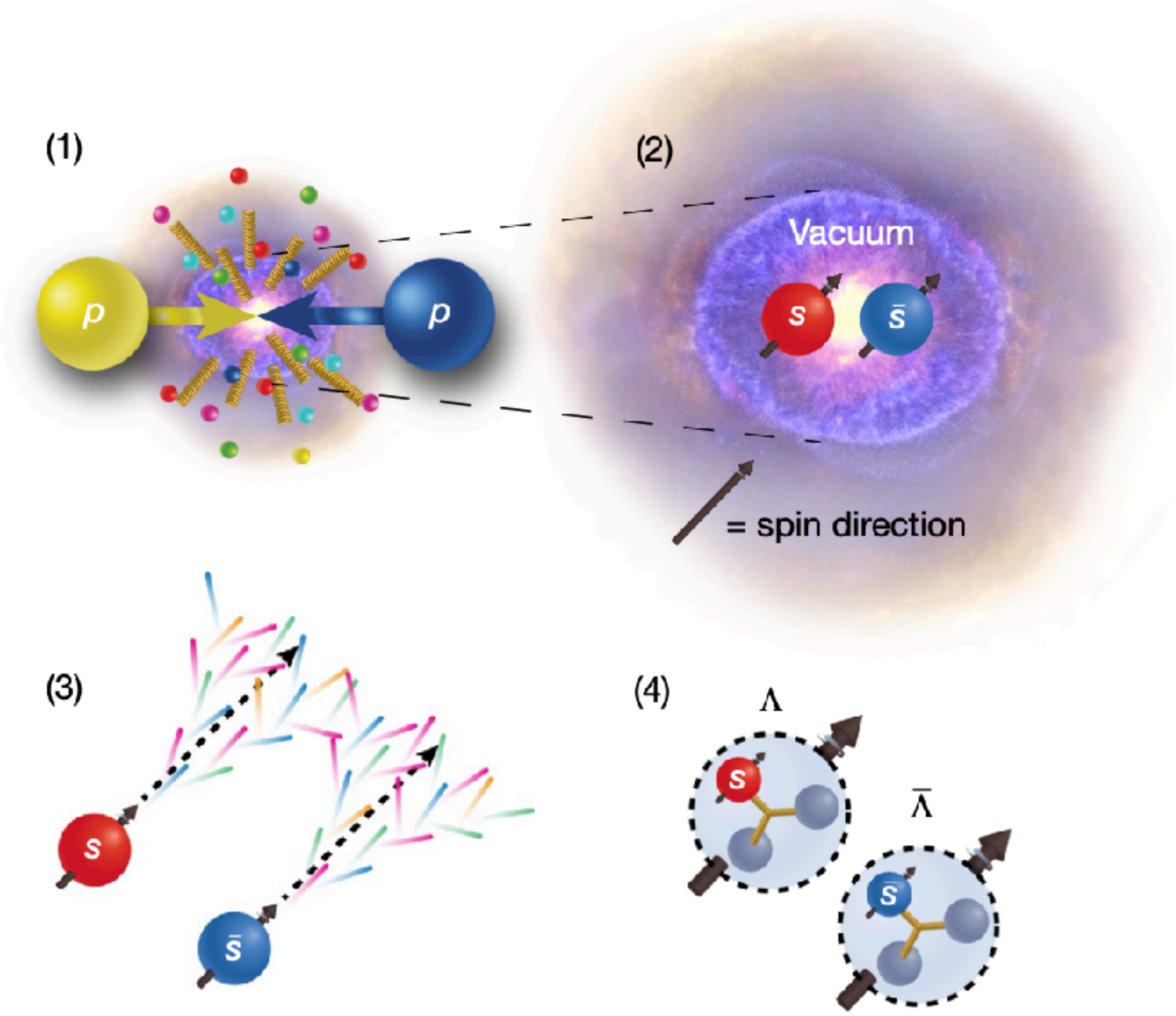
Tu (I) - 9:05]

$P_\Lambda + P_{\bar\Lambda}$ measures late-time vorticity $\omega \approx 0.02\ \mathrm{fm}^{-1}$

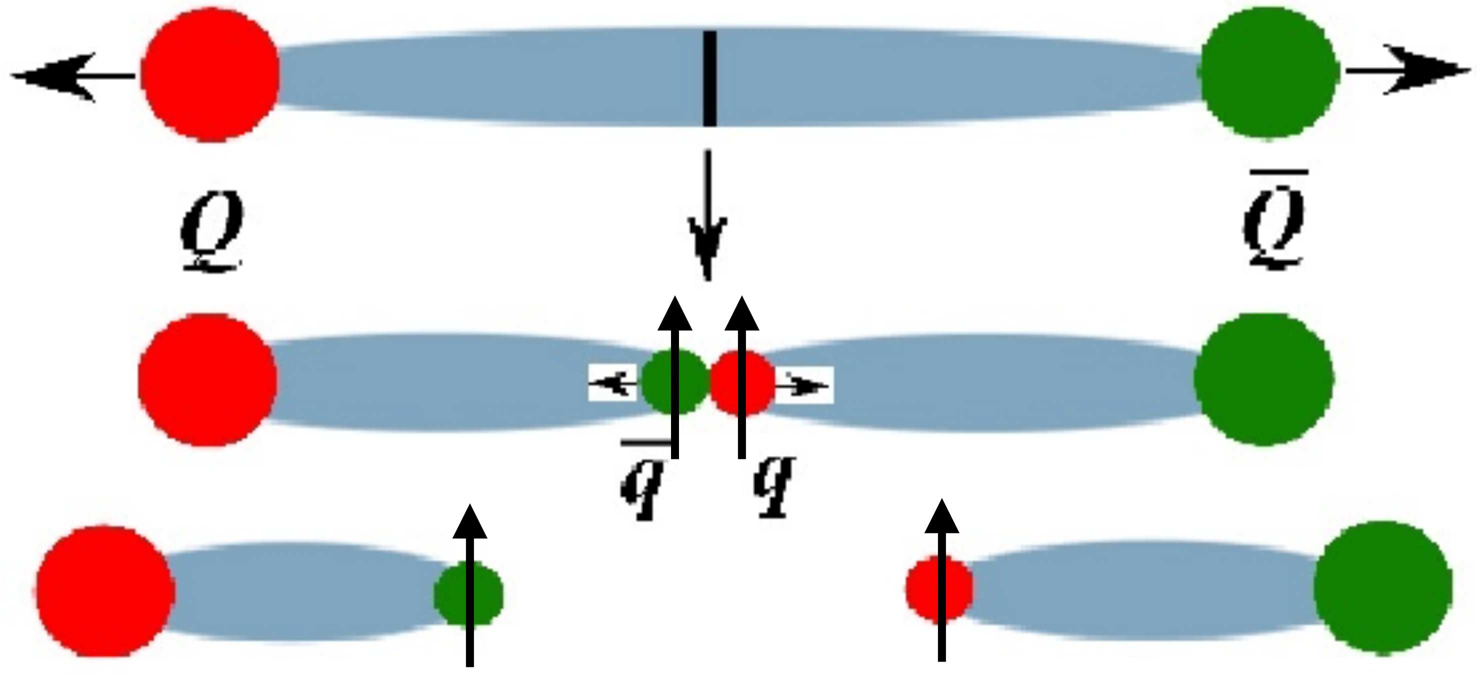
$P_\Lambda - P_{\bar\Lambda}$ constrains late-time magnetic field: $B \lesssim 10^{12}\ \mathrm{T}$

Hadronization mechanisms

STAR, *Nature* 650 (2026) 65

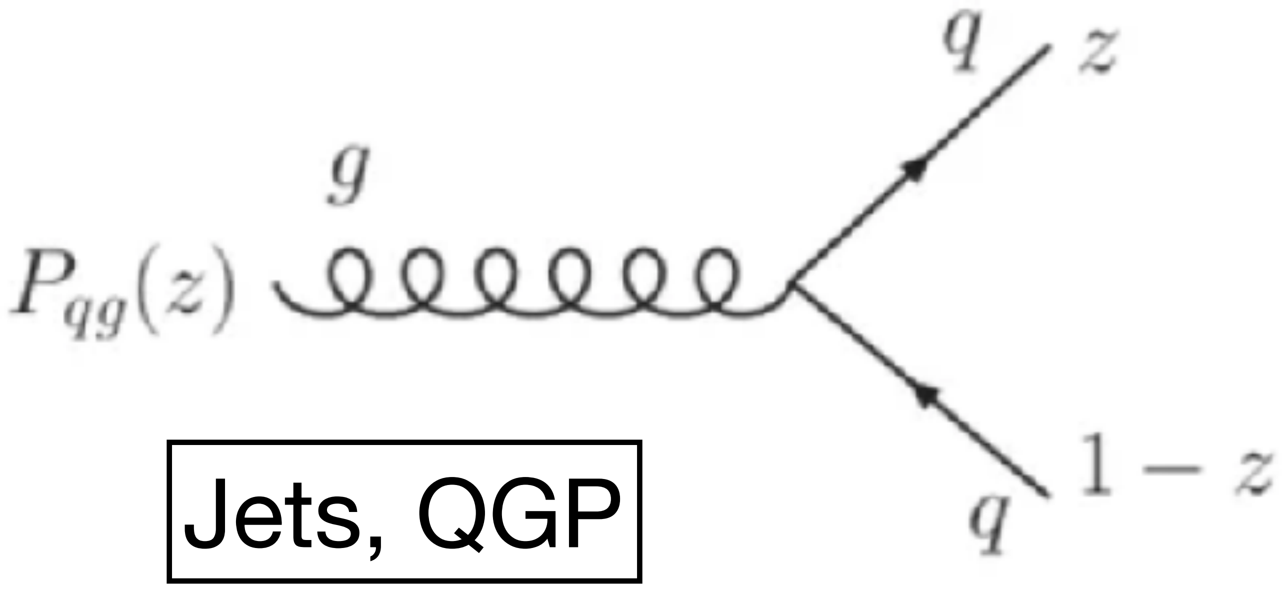


String breaking $^{2s+1}L_J = {}^3P_0 \leftrightarrow 0^{++}$



Hadronization

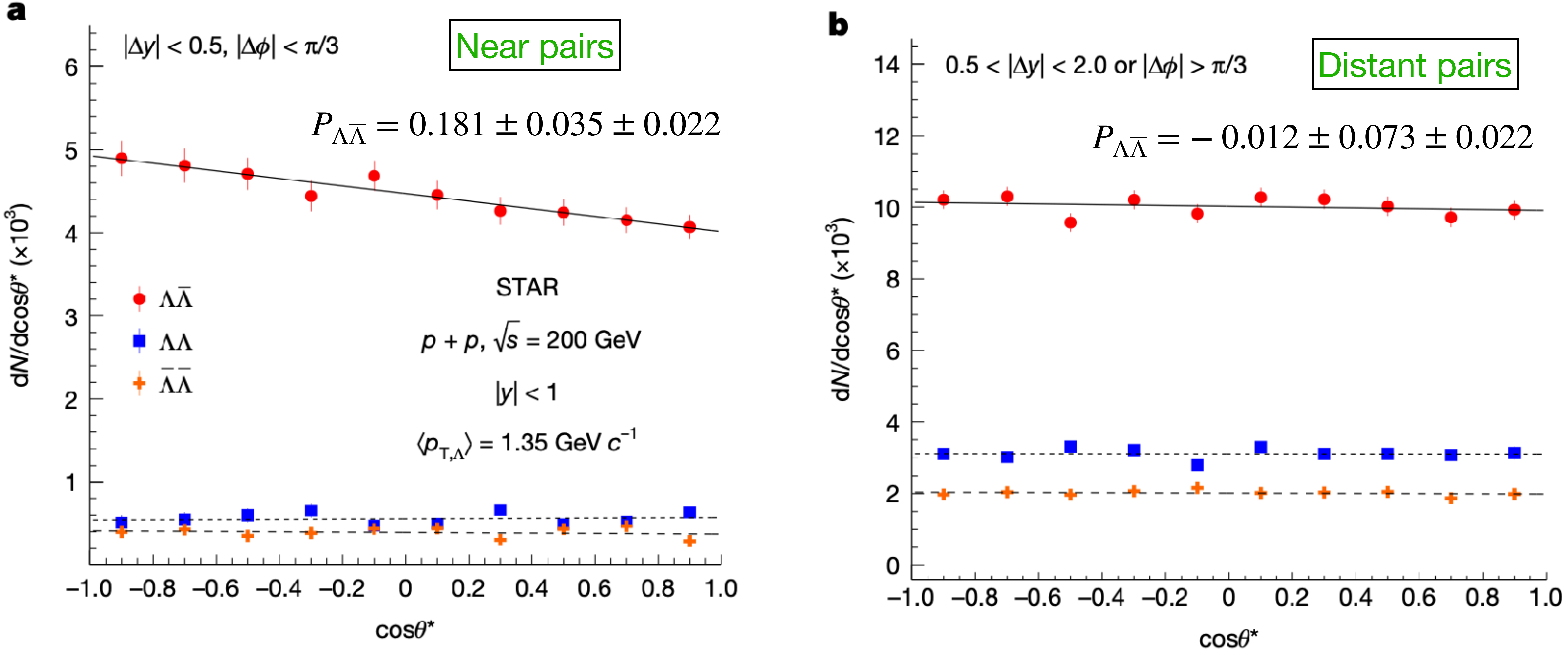
Gluon splitting $^{2s+1}L_J = {}^3S_1 \leftrightarrow 1^{--}$



Jets, QGP

$\Lambda/\overline{\Lambda}$ spin correlation in pp

$$\frac{2}{N}\frac{dN}{d\cos\theta^*} = 1 + \alpha_1\alpha_2 P_{12}\cos\theta^* \qquad \alpha_\Lambda \approx -\alpha_{\overline{\Lambda}} \approx 0.75 \qquad P_{12}^{SU(6)} = 1/3\ \ (-1) \quad \text{for } \upuparrows\ (\uparrow\downarrow)$$



Near pairs

$P_{\Lambda\overline{\Lambda}} = 0.181 \pm 0.035 \pm 0.022$

Distant pairs

$P_{\Lambda\overline{\Lambda}} = -0.012 \pm 0.073 \pm 0.022$

Transport

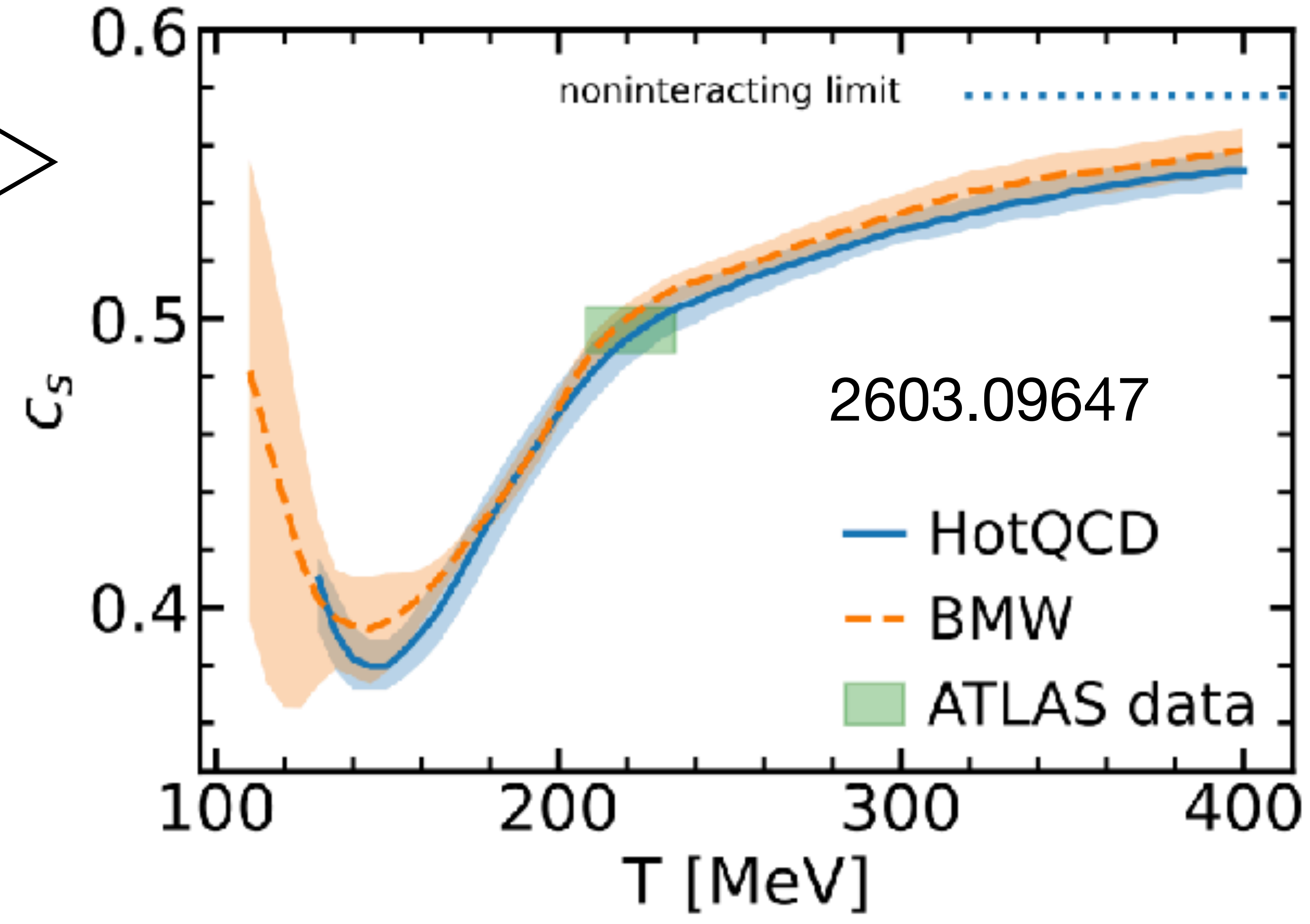
Quark transport properties

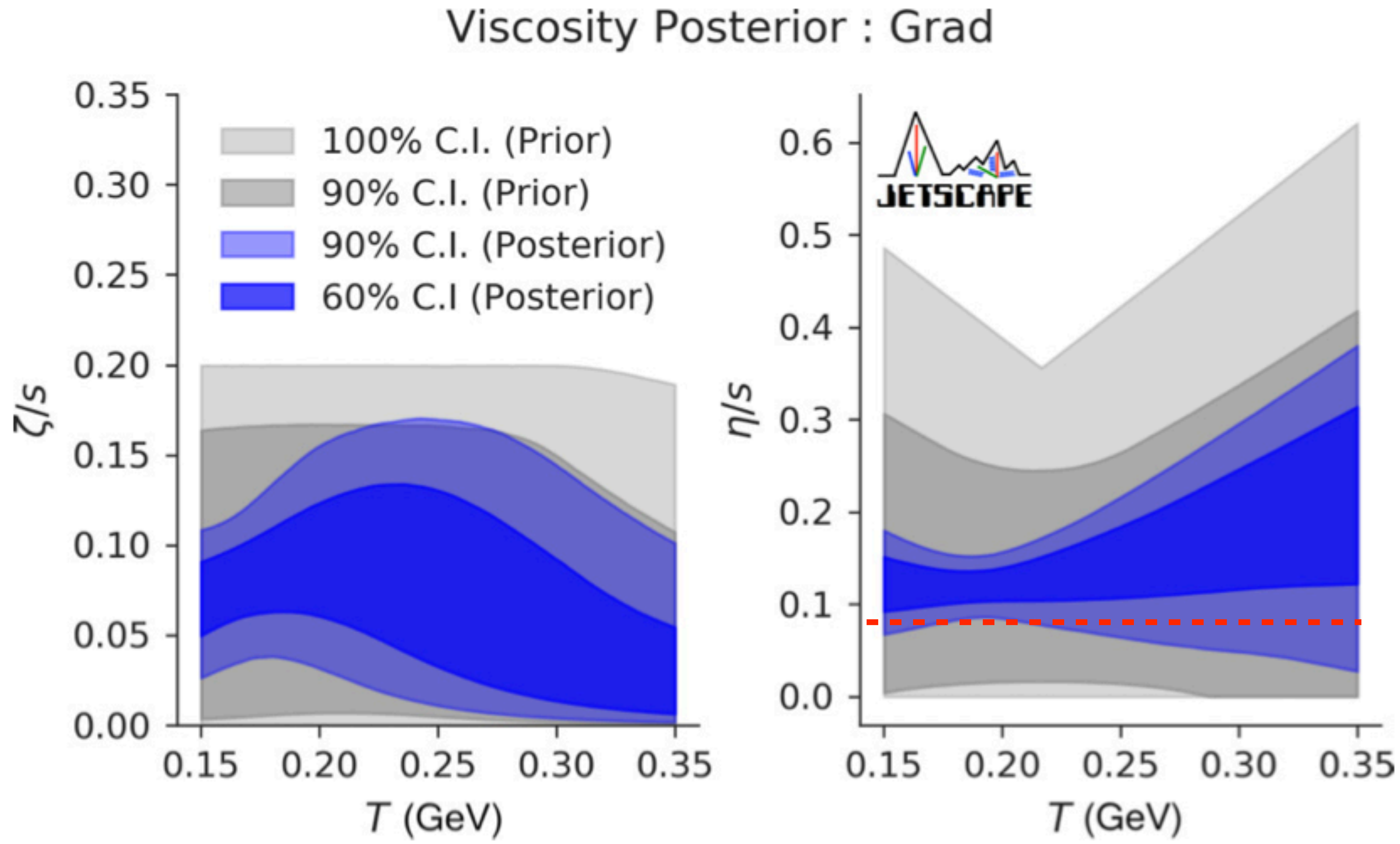
- QGP viscosities *η*, *ζ*, speed of sound
- *u*, *d*, *s* flavor chemical equilibration rates
- Light quark diffusion constants (important for conserved QN observables)
- Heavy quark momentum diffusion constants
- Heavy quark — fluid EFT
- Coupled *c*-quark + charmonium transport

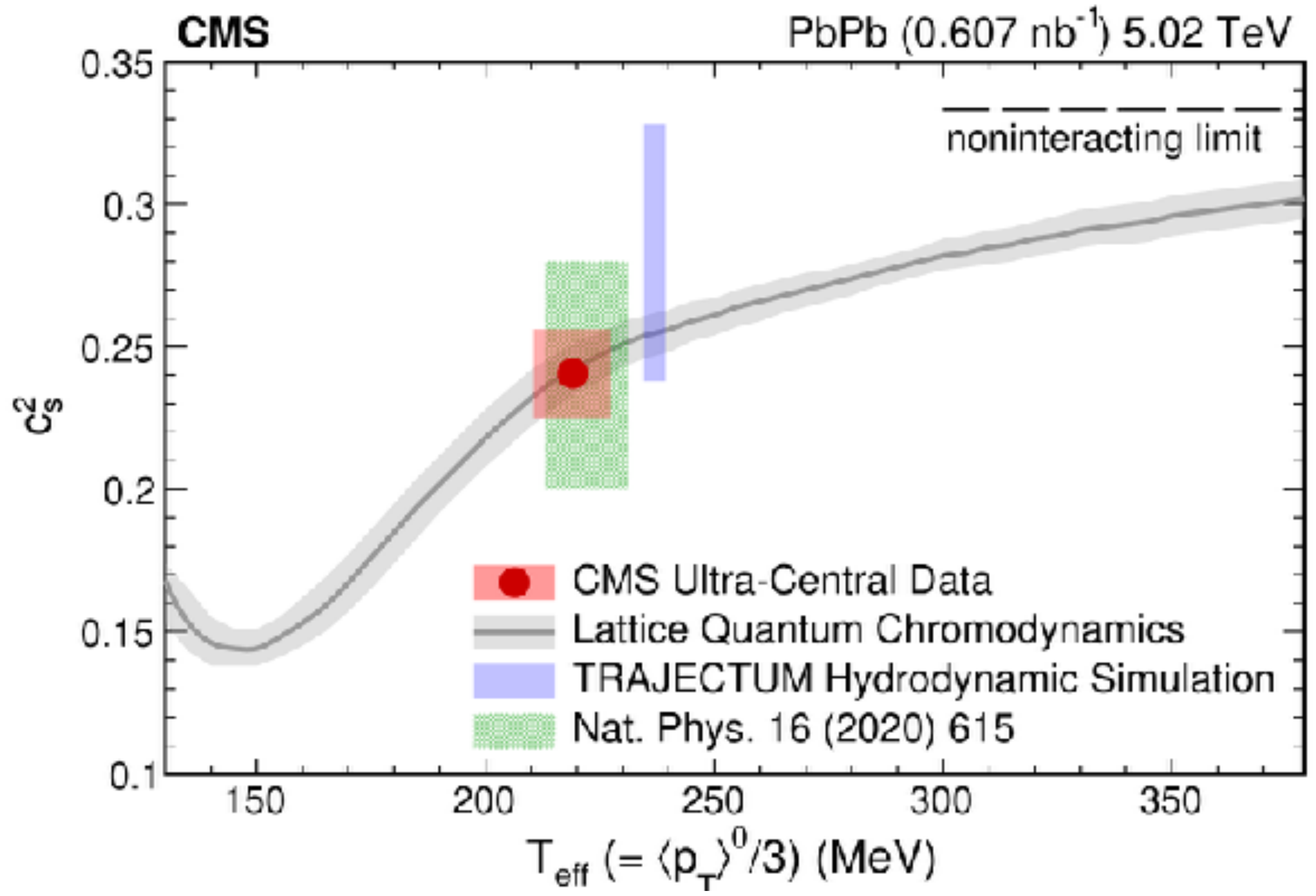
- For all: System size/shape dependence

QGP bulk transport properties

Speed of sound







Heavy quark diffusion

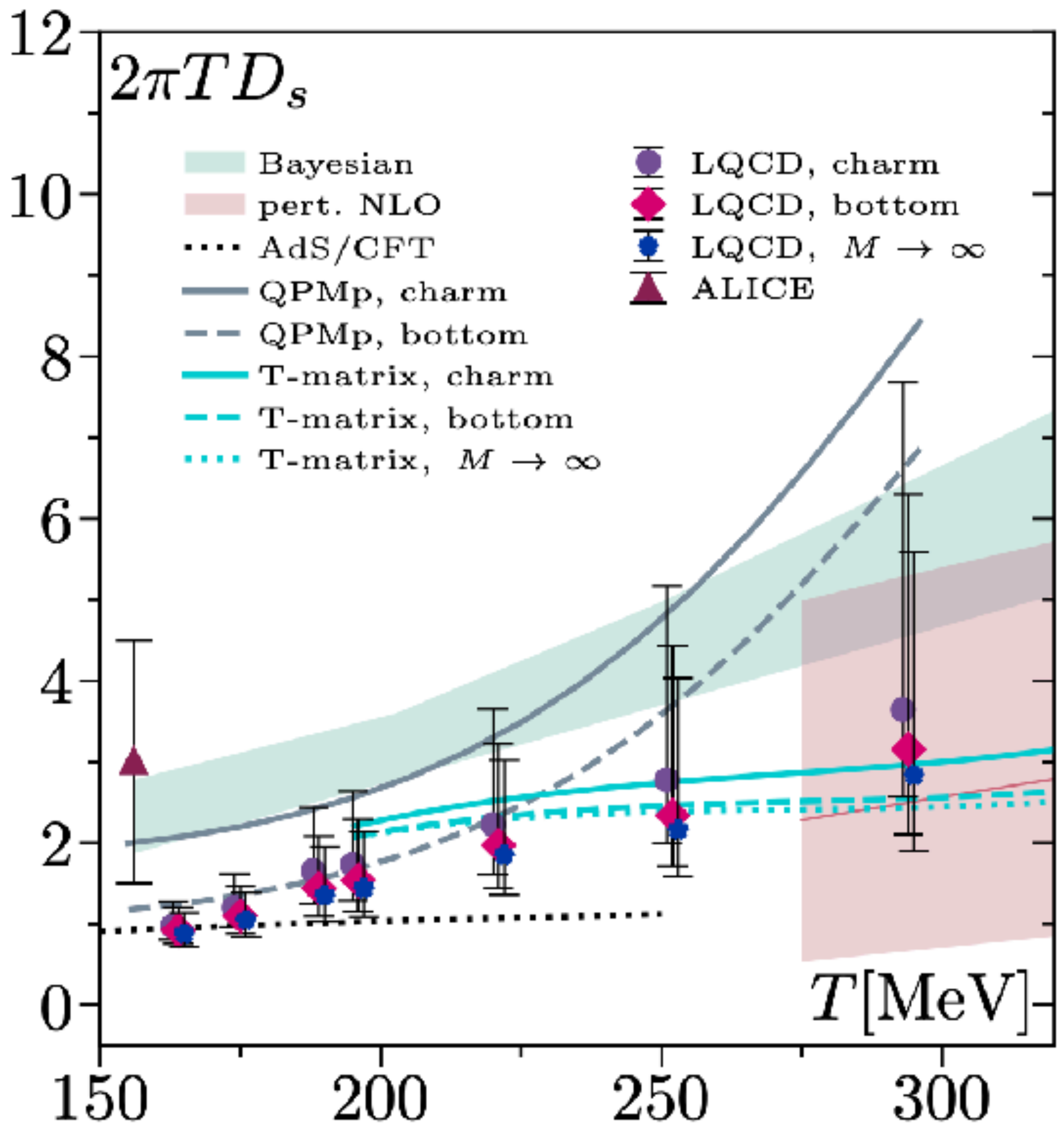
Yu Fu - Tu (I) 16:45

D_s = spatial diffusion coefficient

κ = momentum diffusion coefficient

$$D_s = \frac{2T^2}{\kappa}$$

HotQCD - 2506.11958



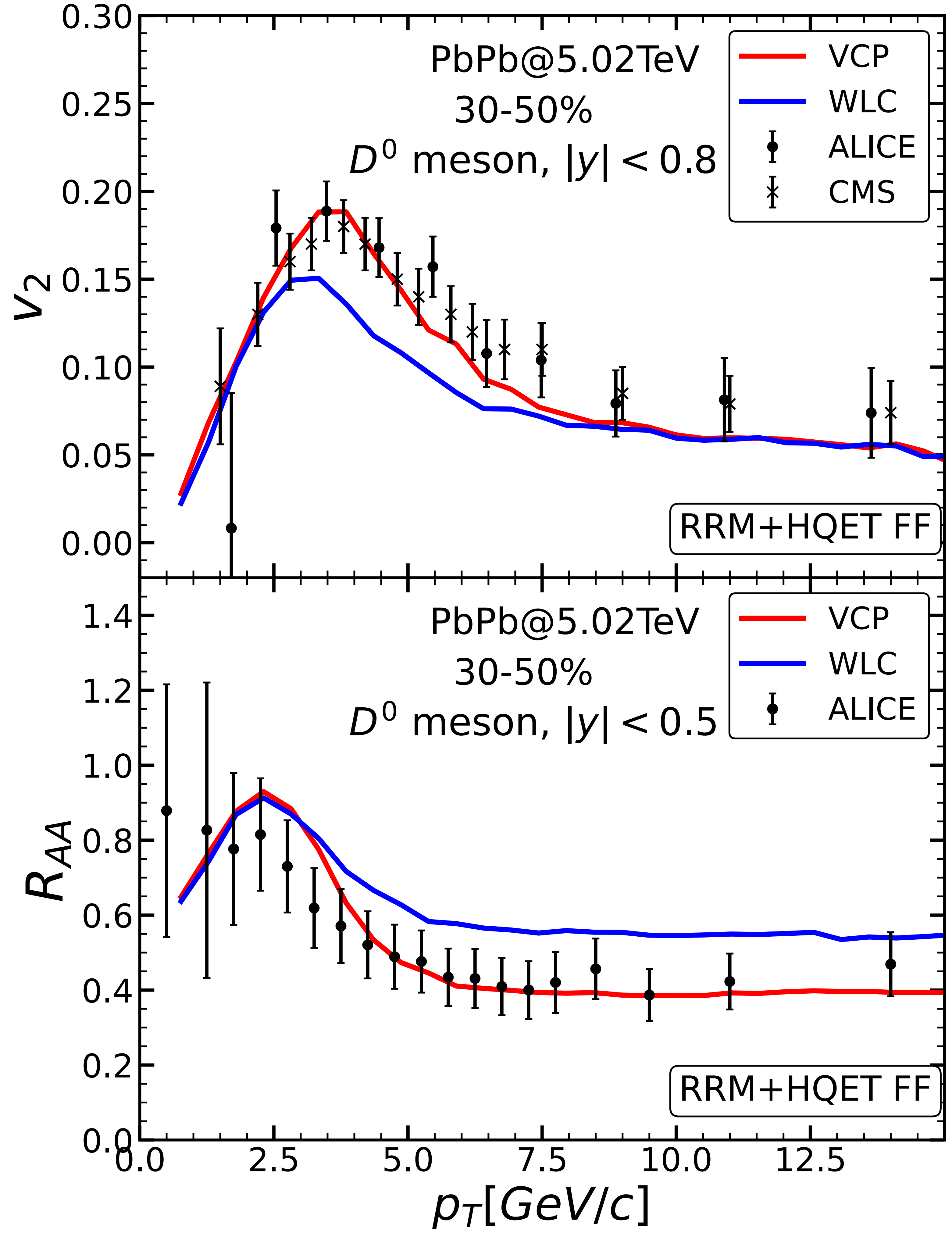
$$\frac{\mathrm{d}f_Q}{\mathrm{d}t} = \mathcal{D}[f_Q] + C_{1\leftrightarrow 2}[f_Q]$$

D = Fokker-Plack op.

Linear Boltzmann

Recombination

HEFTY Collab. - 2509.13881

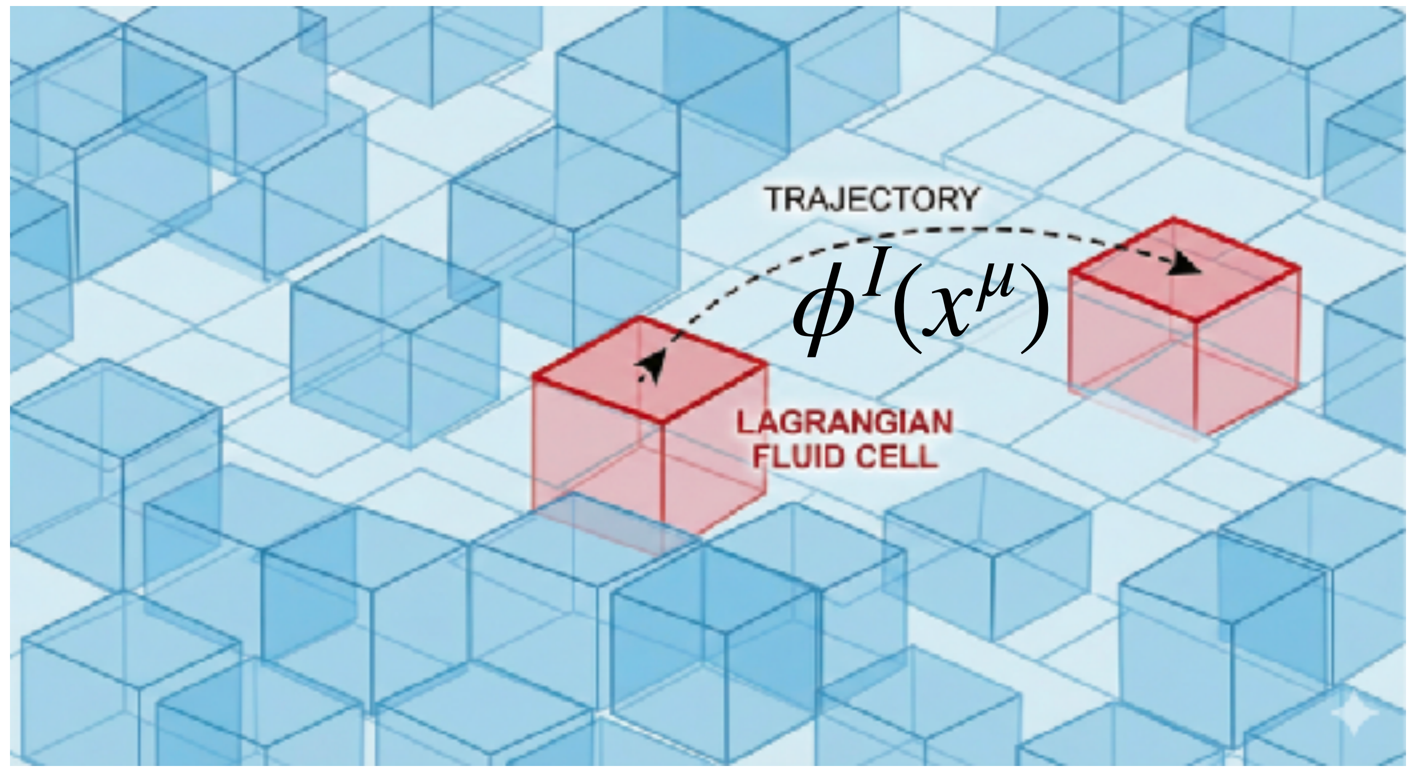


Fluid EFT

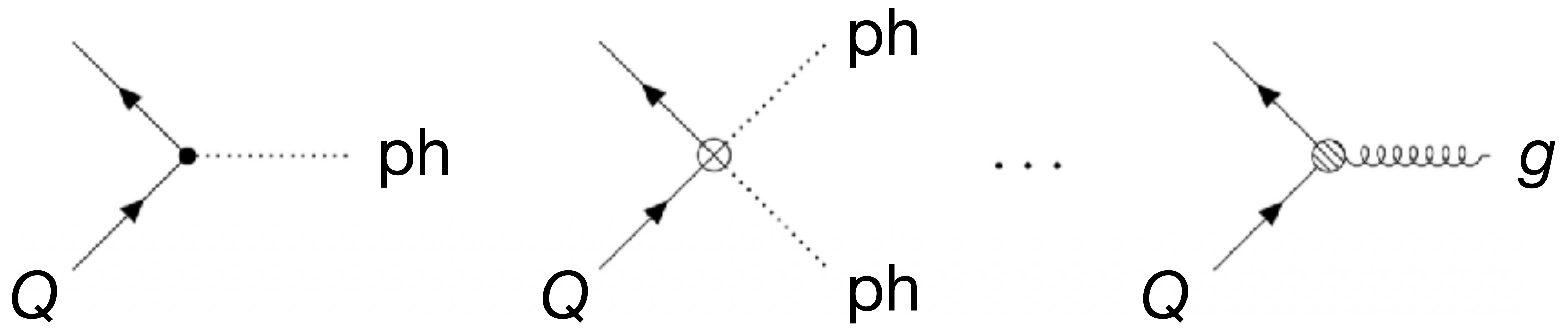
A. Kirchner - Tu (VIII) 16:45

Treat fluid as effective scalar field with phonon excitations

$$\mathscr{L} = F(J^\mu J_\mu) \qquad J^\mu = \frac{1}{3!}\varepsilon^{\mu\nu\rho\sigma}\varepsilon_{IJK}\partial_\rho\phi^J\partial_\nu\phi^K\partial_\sigma\phi^I$$



Couple heavy quark to fluid field (phonons) and gluons

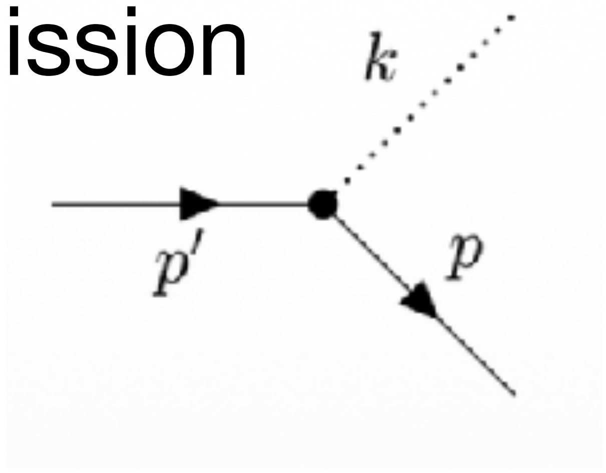


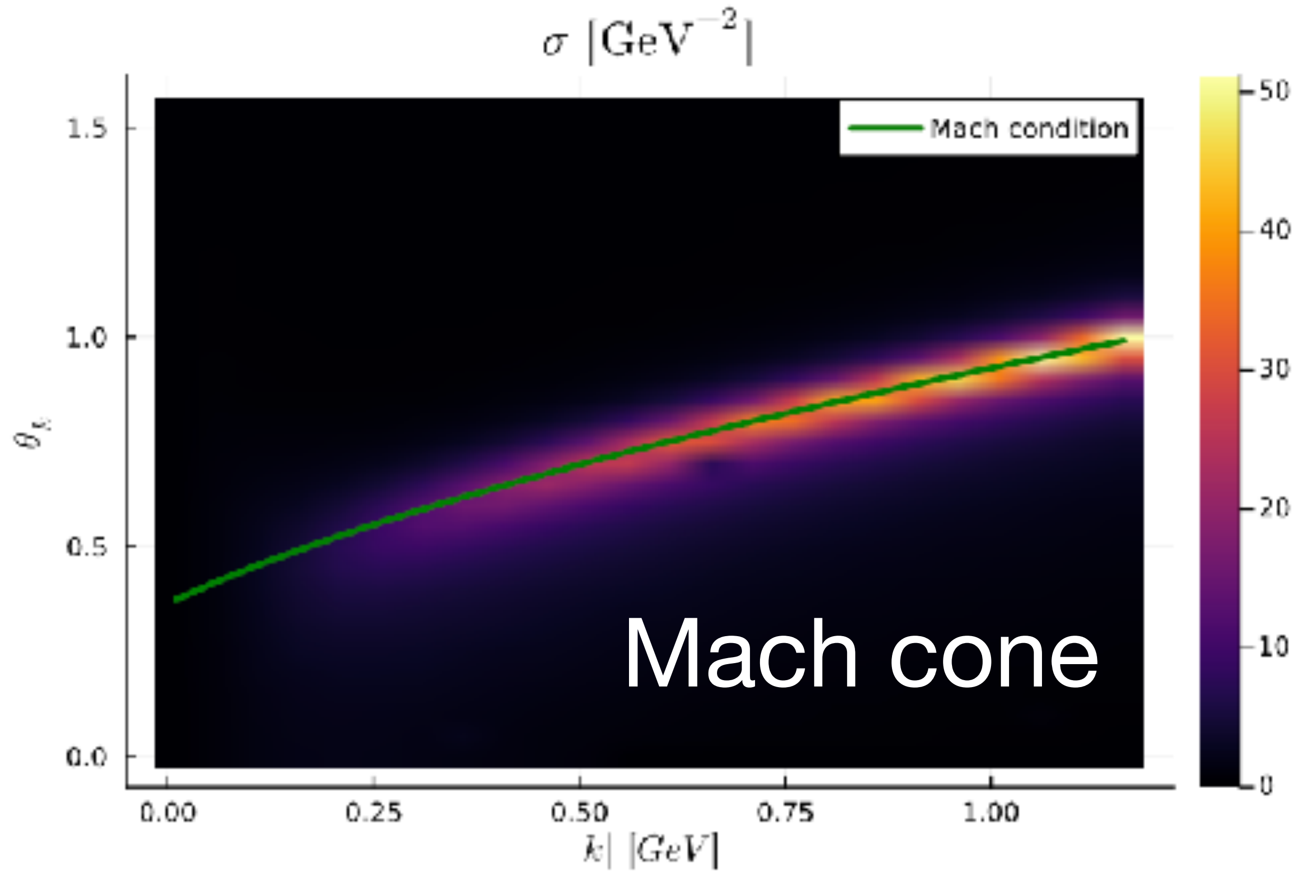
Phonons live below hydro scale Λ_h

$$3T \lesssim \Lambda_h \lesssim 6T$$

Heavy quark-thermal phonon scattering

Phonon emission





Questions?

Will be answered during this conference!

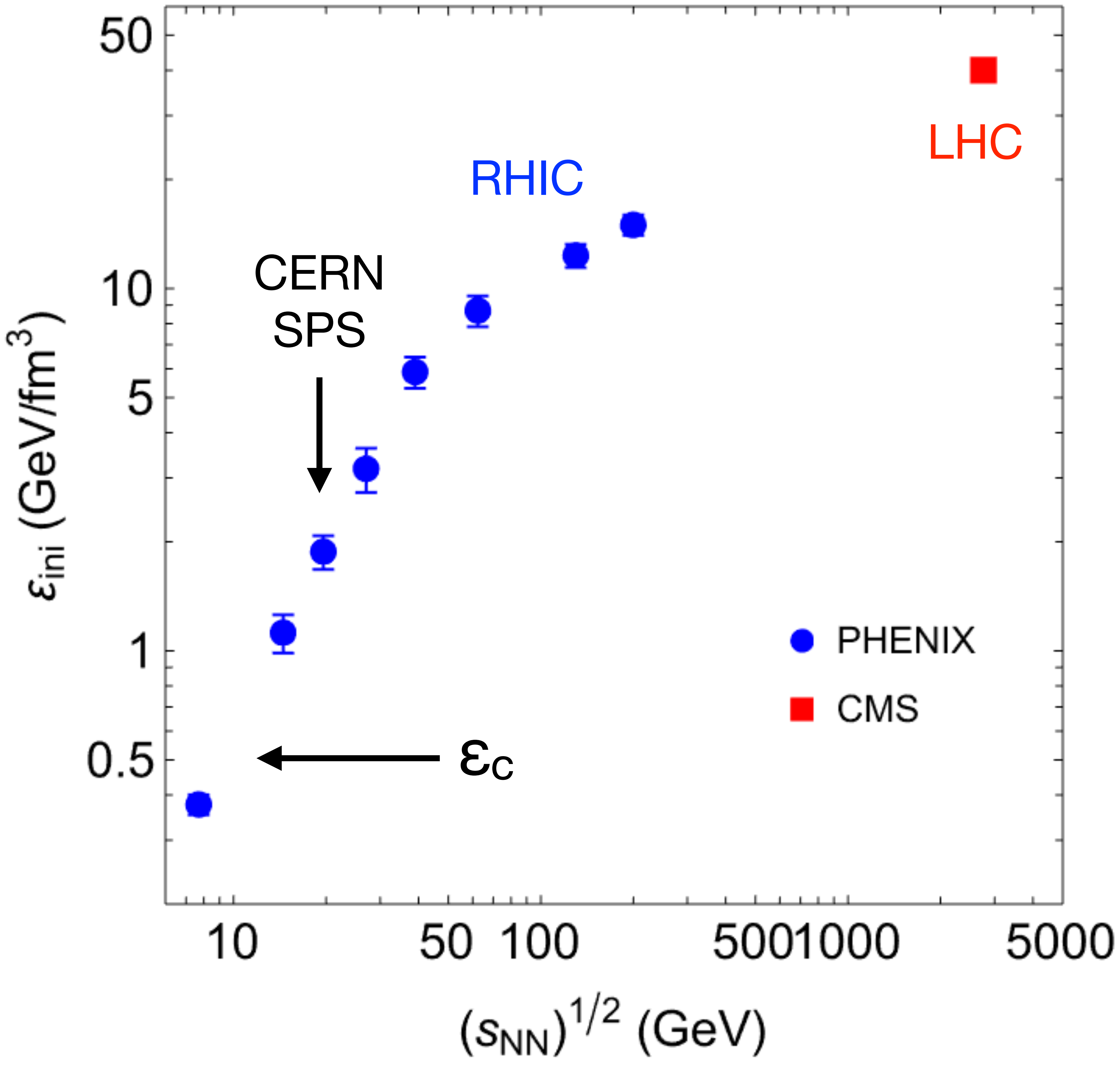
Backup slides

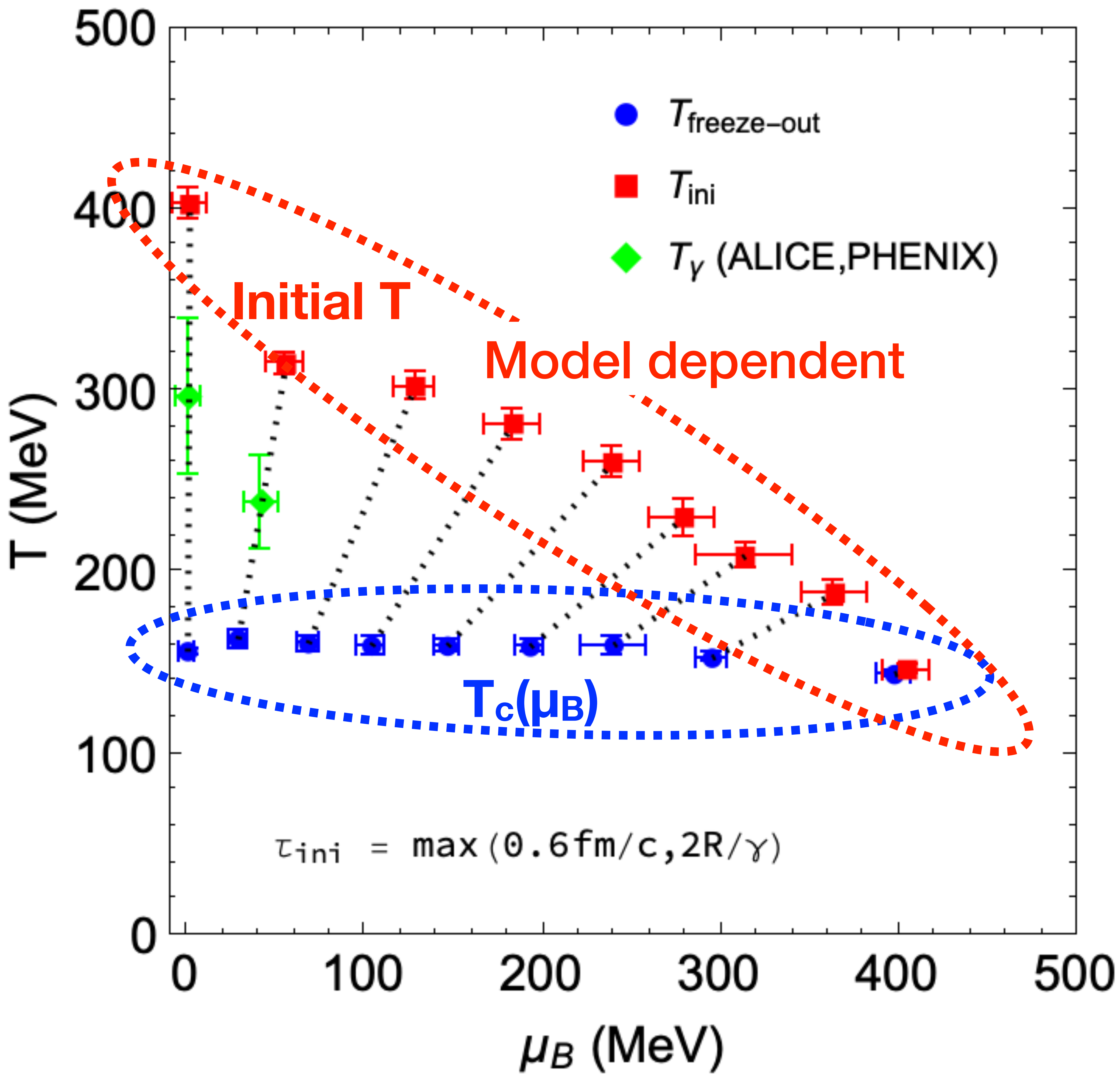
Hadronization

- Statistical hadronization model (SHM): Hadronization of QGP is treated as statistical equilibrium process at the “phase boundary” given by T, μ_α, g_α, V.
- Kinematic extension: Cooper-Frye equilibrium hadronization.
- Alternative: Hadronization by valence quark coalescence / recombination, which views QGP-HG transition as a dynamical process subject to conservation laws.
- Does SHM work beyond bulk yields? There already is evidence for dynamics, e.g. at $p_T \gg 3T$, where valence quark scaling of v_n is observed?
- Is there a controlled description that interpolates between bulk QGP hadronization and vacuum/medium hadronization of jets?

Thermodynamic conditions

ε_{ini} in 5% central Au+Au (Pb+Pb) collisions

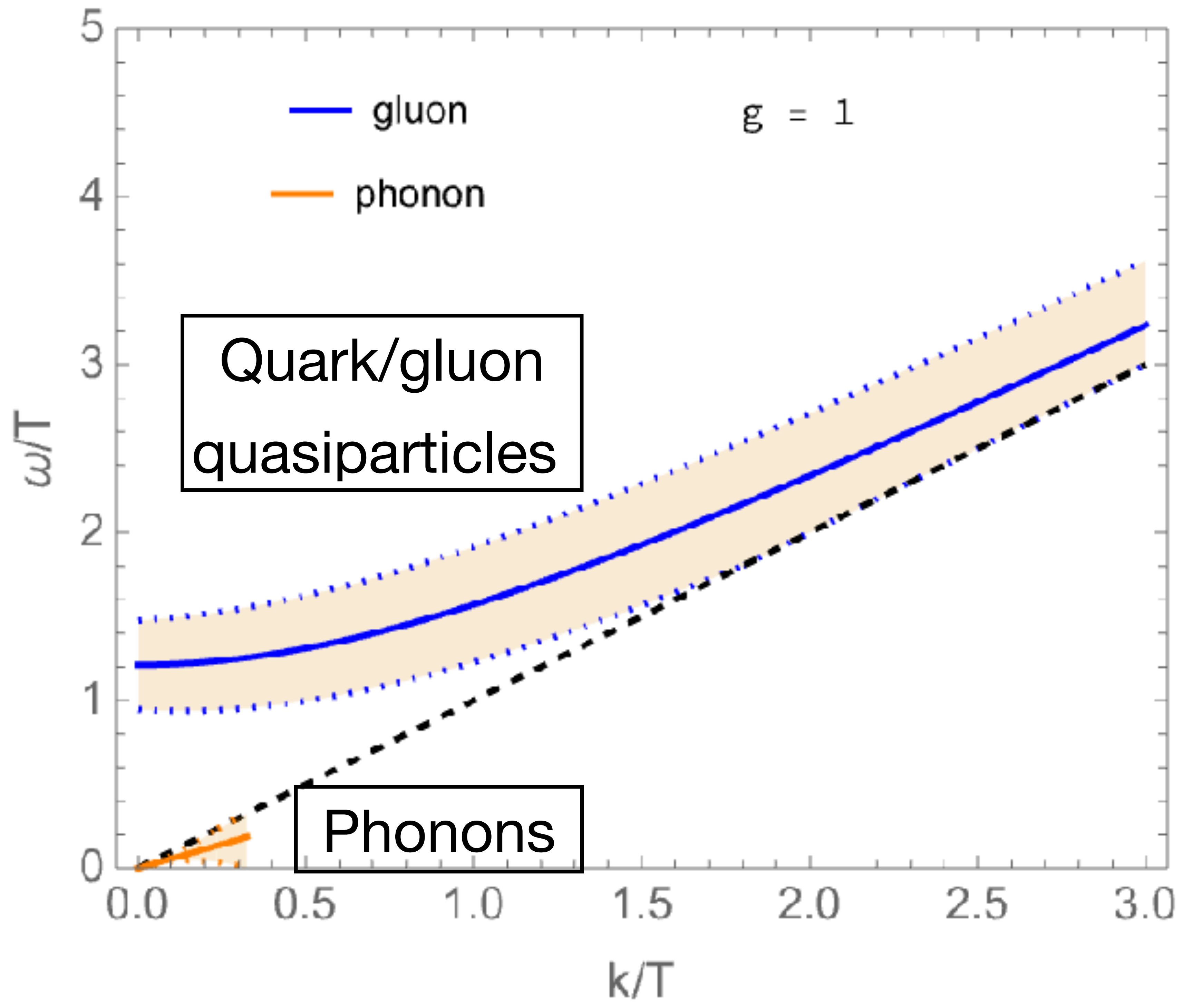




QGP Structure

The extremes

Weak coupling: QCD at $\alpha_s = \frac{1}{4\pi} = 0.08$

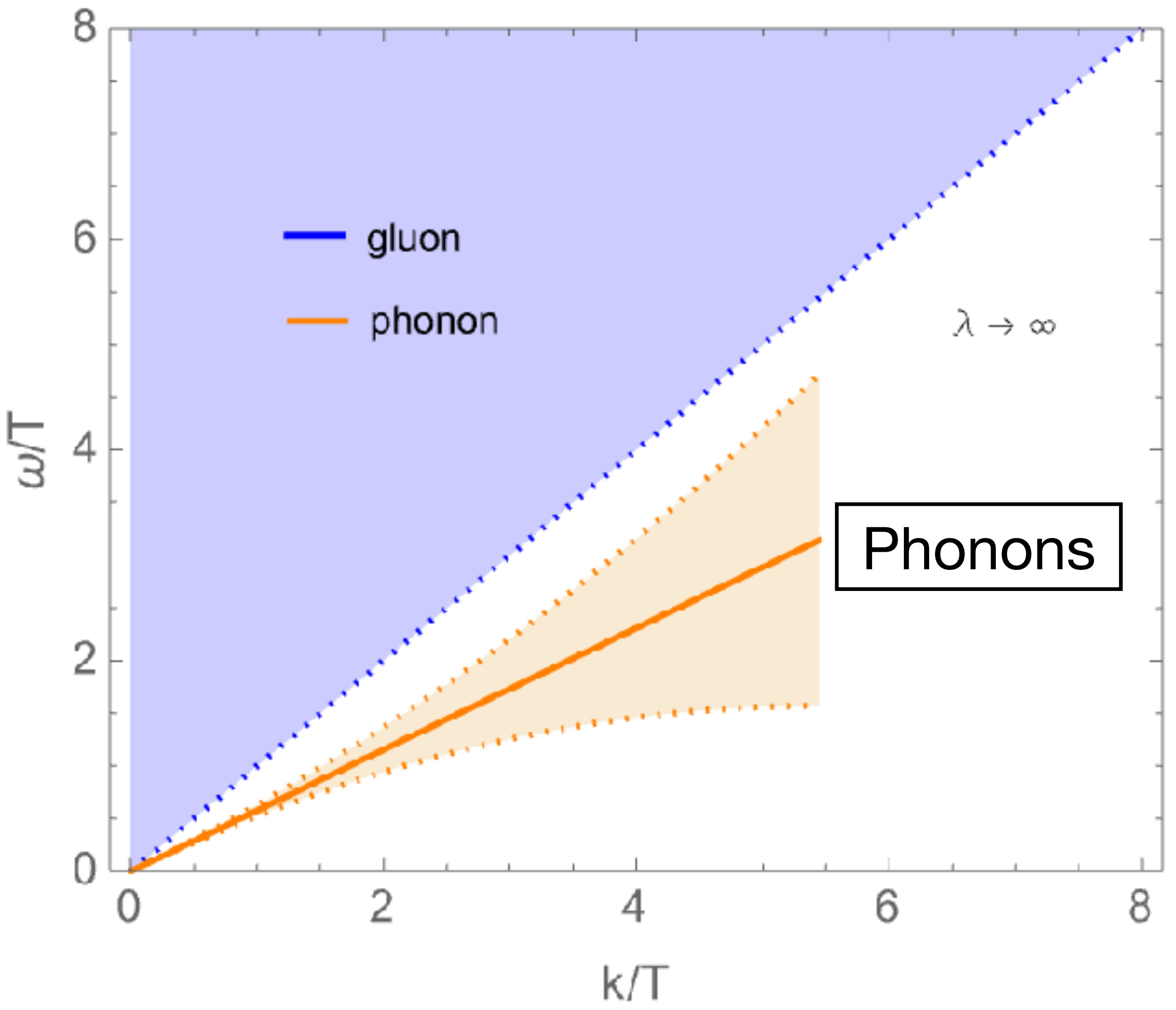


Quark/gluon quasiparticles

Phonons

Dilute quasiparticle plasma

Strong coupling: *N* = 4 SYM at $\lambda \to \infty$



Phonons

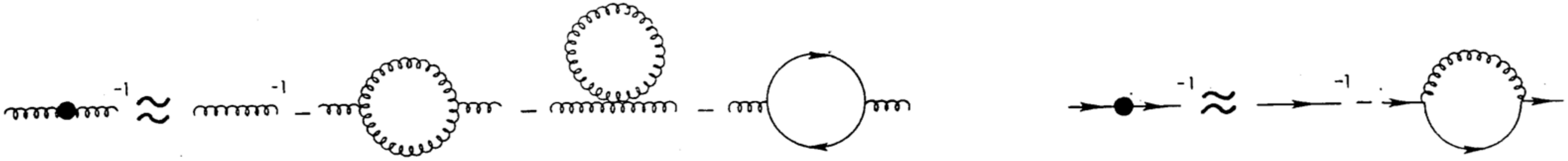
Structurless liquid plasma

Hard-thermal loops

QCD at finite temperature is highly infrared divergent with two relevant scales:

Chromoelectric regime: *k ~ gT,* characterized by Debye mass $m_D^2 = \frac{N_c + \frac{1}{2}N_f}{2} g^2 T^2 = \frac{3}{2}(gT)^2$

$$\mathscr{L}_{\mathrm{HTL}} = -\frac{1}{2}\mathrm{tr}\, F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_D^2 \int d^2\hat{u}\, \mathrm{tr}\, F^{\mu\alpha}u_\alpha \frac{1}{(u \cdot D(A) + i\epsilon)^2} u^\beta F_{\beta\mu} + \mathscr{L}_{\mathrm{quarks}}$$



Static chromomagnetic sector: *k ~ g*^{2}*T,* representing a three-dimensional confining euclidean gauge theory: Truly nonperturbative; requires lattice simulation.

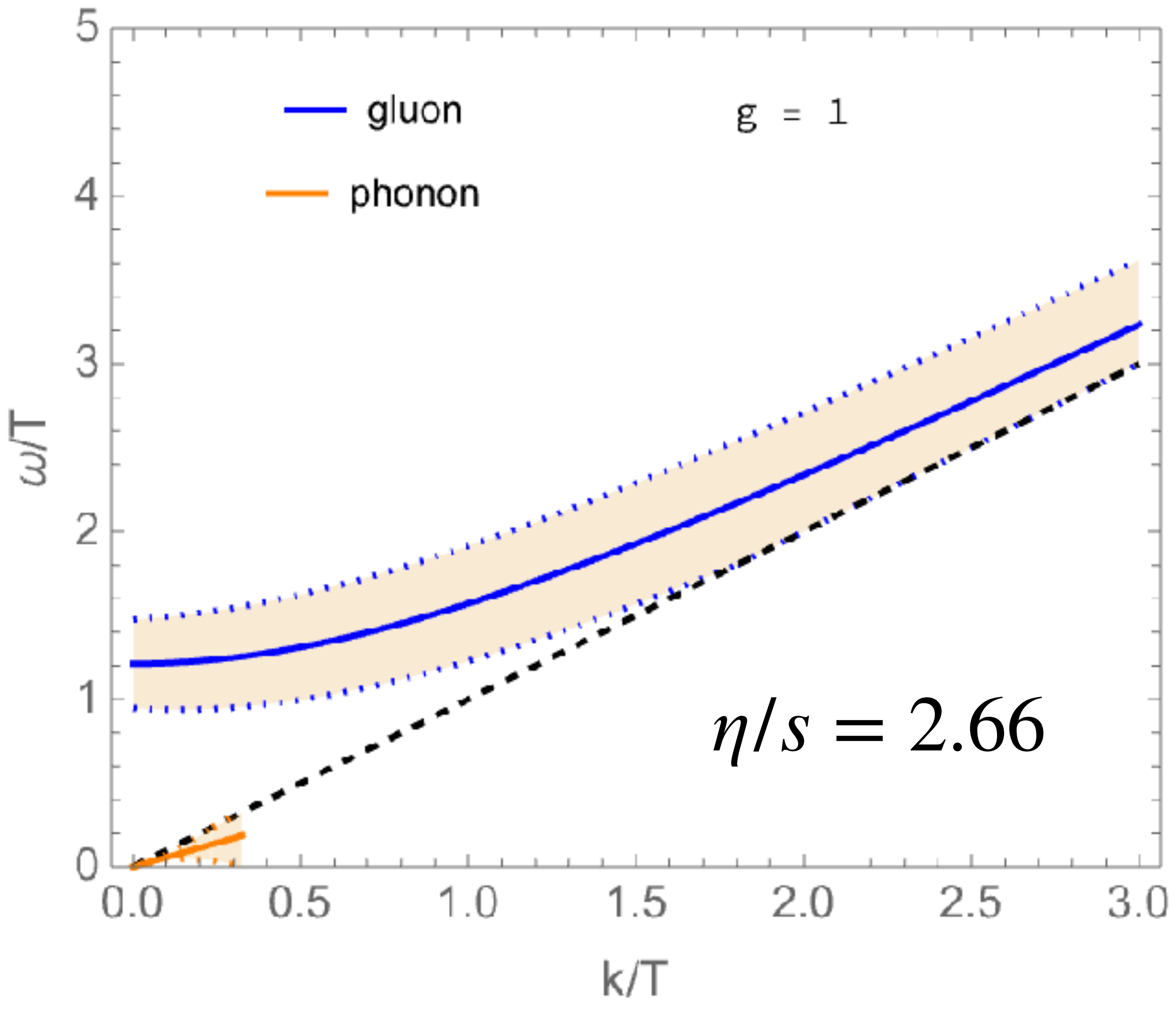
Dynamical magnetic mass scale (confinement scale): $m_M \approx \frac{g^2 N_c T}{2\pi}$

HTL Dispersion Relations

$g = 1 \quad \alpha_s = 0.08$

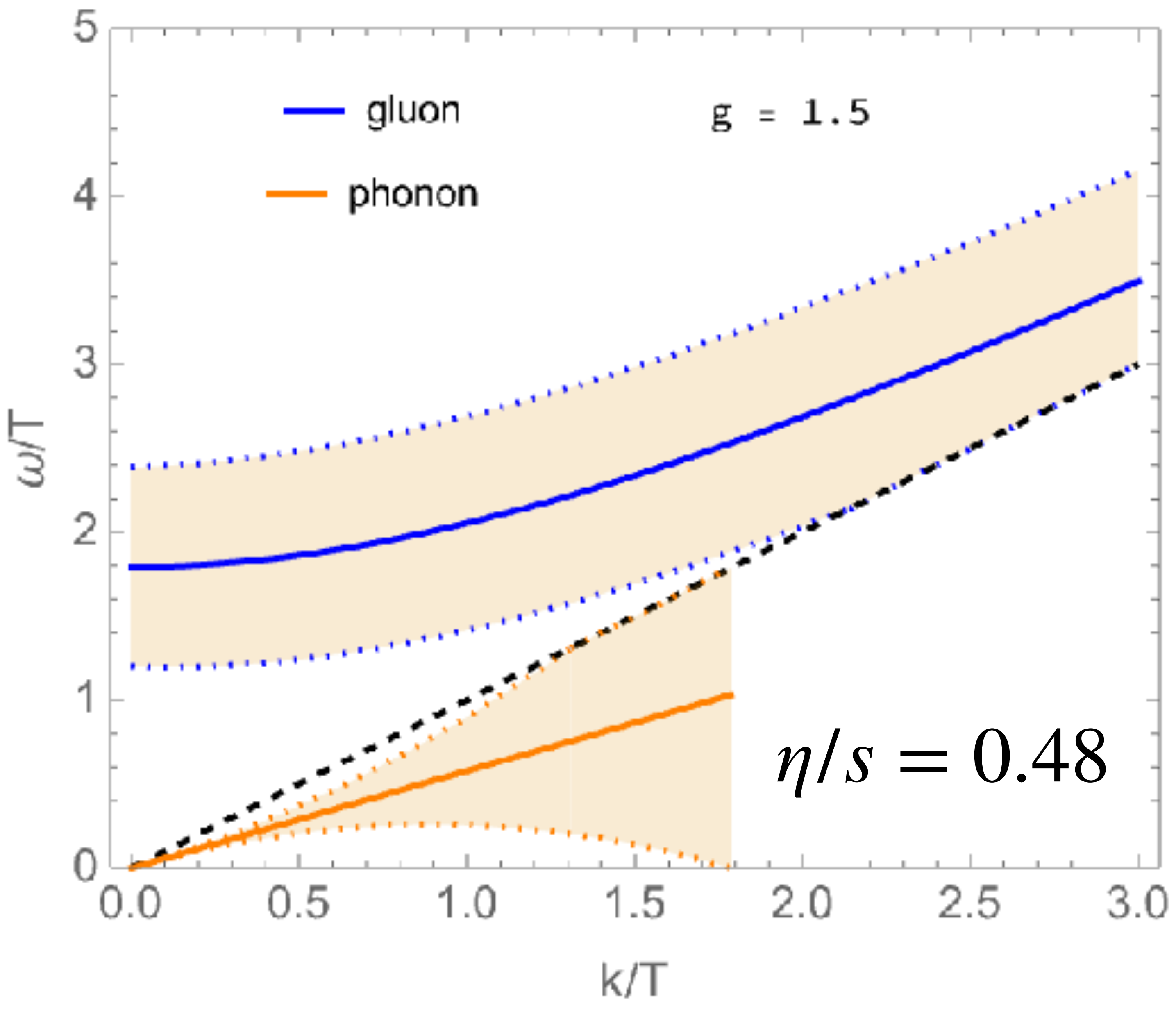
Weak coupling

Gluons are good quasiparticles at all momenta



$g = 1.5 \quad \alpha_s = 0.18$

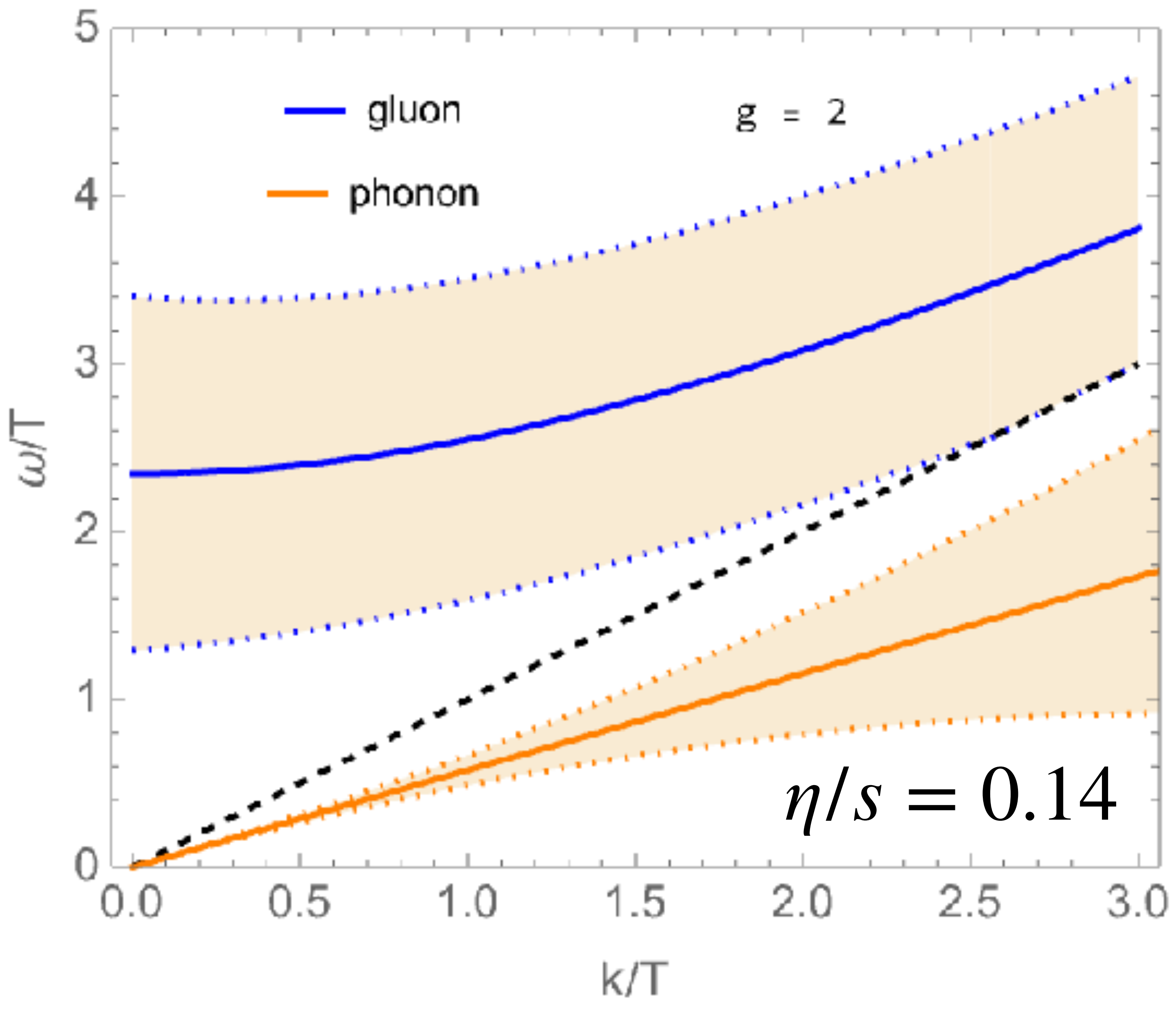
Intermediate coupling



$g = 2 \quad \alpha_s = 0.32$

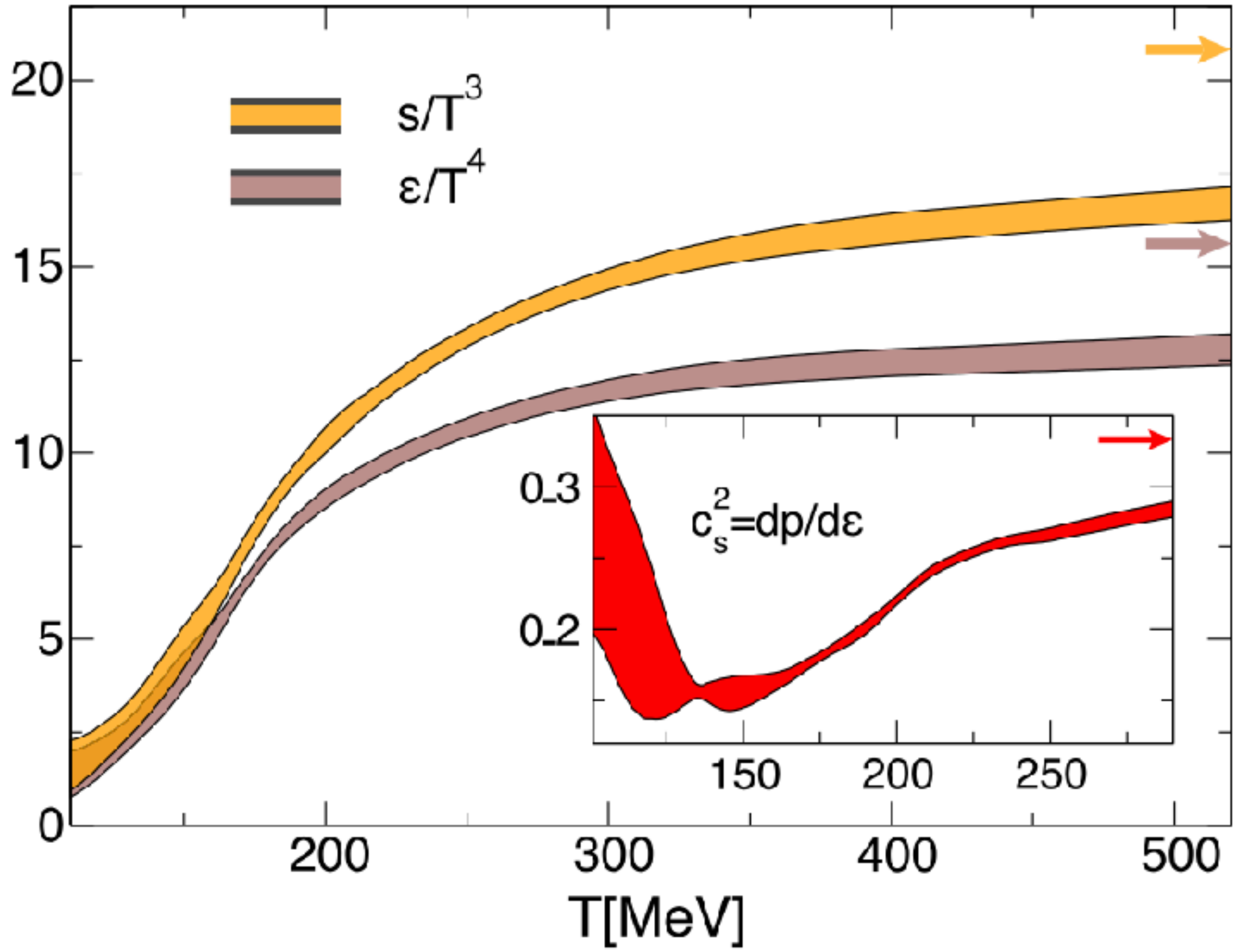
Strong coupling

Phonons are good quasiparticles at thermal momenta



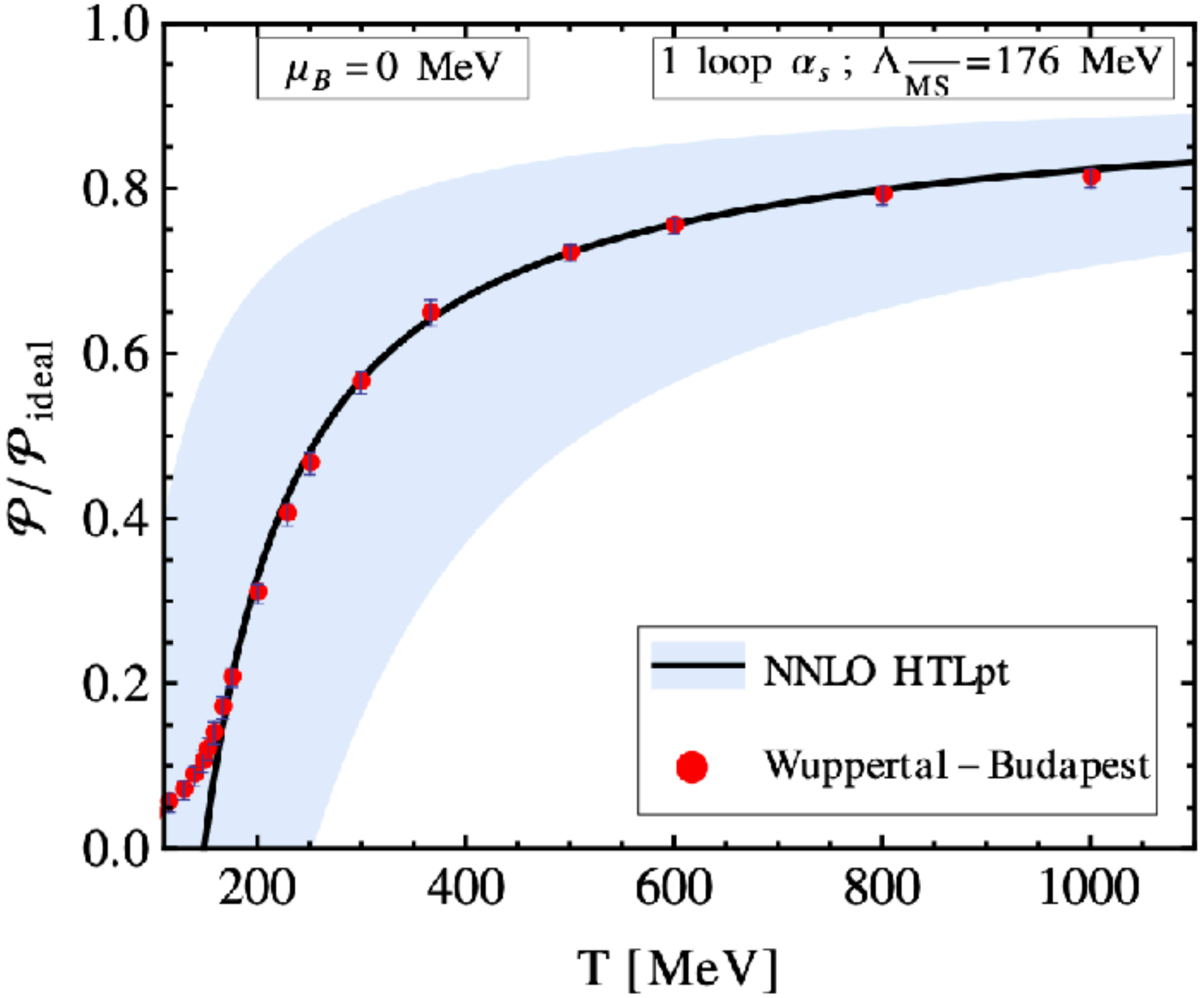
QGP equation of state

$N_f = 3$ equation of state



Borsanyi et al., PLB 730 (2014) 99

HTL resumed perturbation theory at NNLO



J.O.Andersen et al., 1411.1253 [hep-ph]

Functional RG

Based on RG equation of the effective action $\Gamma_k[\phi]$ as function of scale k in euclidean space:

$$\frac{\partial}{\partial \ln k}\Gamma_k[\phi] = \frac{1}{2}\mathrm{Tr}\left[\left(\frac{\delta^2\Gamma_k}{\delta\phi(x)\delta\phi(y)} + R_k(x-y)\right)^{-1}\frac{\partial R_k(x-y)}{\partial \ln k}\right]$$

[Wetterich, PLB 301 (1993) 90]

with cut-off function $R_k(x-y) \sim r(k\,|\,x-y\,|\,)$ such that $r(z) \to 0$ for $z \to 0$ and $r(z) \to 1$ for $z \gg 1$.

Minimal fields for QCD are: Gluons (A_μ^a), ghosts (c^a) and quarks (ψ).

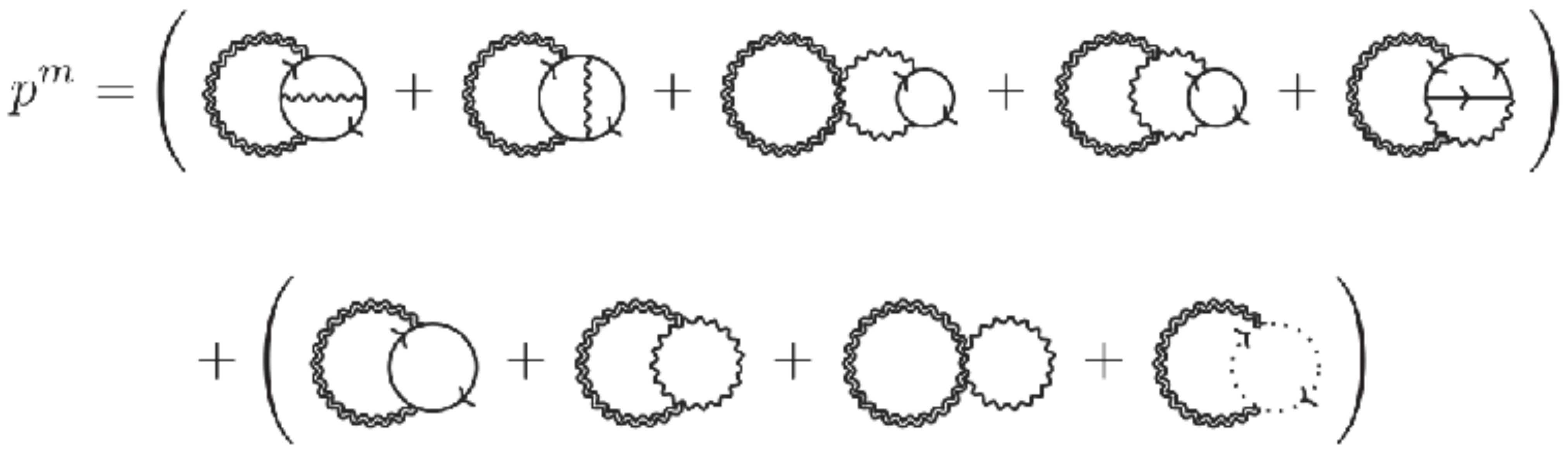
Convergence for $k < \Lambda_{:\mathrm{QCD}}$ requires introduction of composite fields (hadrons, Polyakov loop), which are dynamically generated by the RG equation (see e.g. J. Braun et al., PRD94 (2016) 034016).

At $T > T_c$ the composite fields are not needed, but they can be useful to explore the transition from QGP to hadron matter around T_c. Most extensively studied: $\Phi = (\sigma, \vec{\pi})$.

EOS at high μ

T. Gorda, et al., PRL 131 (2023) 181902

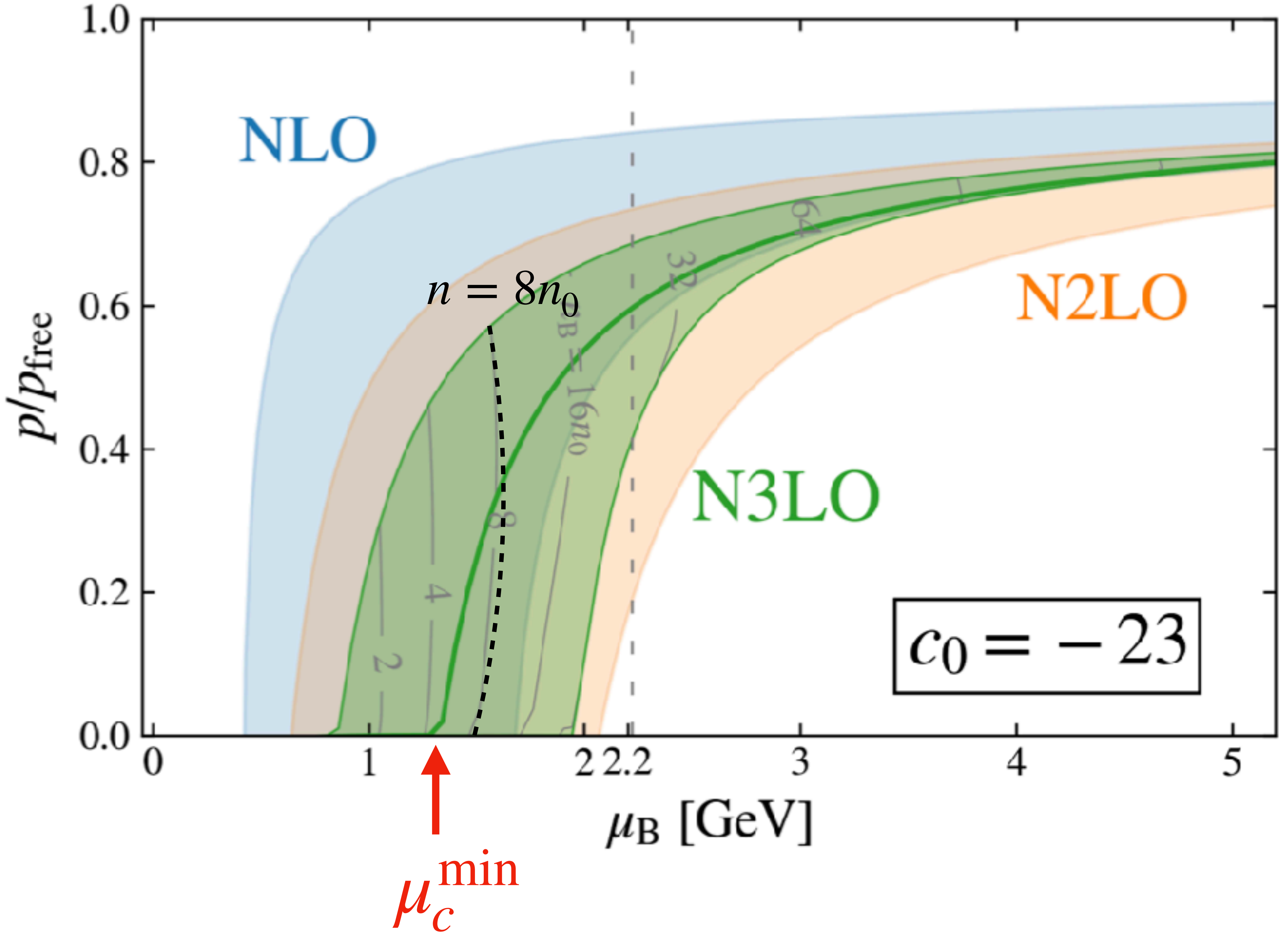
EOS at N3LO = $O(\alpha_s^3 \ln \alpha_s)$



$$\frac{p}{p_{\rm free}} \simeq 1 - 2\left(\frac{\alpha_s}{\pi}\right) - 3\left(\frac{\alpha_s}{\pi}\right)^2 \left[\ln\left(3\frac{\alpha_s}{\pi}\right) + 3\ln X + 5.0021\right] \cdot$$

$$+9\left(\frac{\alpha_s}{\pi}\right)^3 \left[c_{3,2}\ln^2\left(3\frac{\alpha_s}{\pi}\right) + c_{3,1}(X)\ln\left(3\frac{\alpha_s}{\pi}\right) + c_{3,0}(X)\right]$$

Bayesian analysis of “most likely” value of $c_{3,0}$

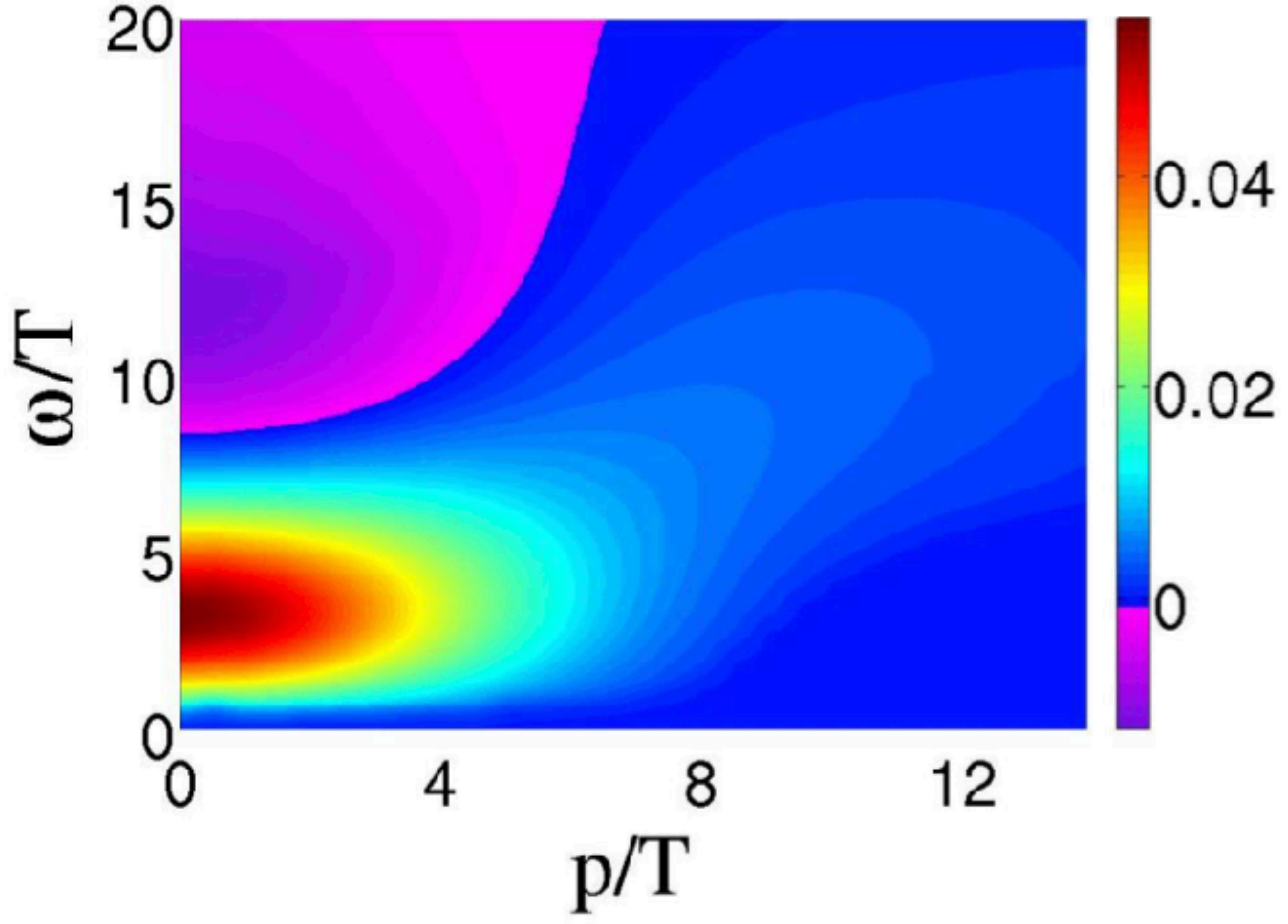


Gluon transport properties

Gluon spectral function shows
broad quasiparticle peak

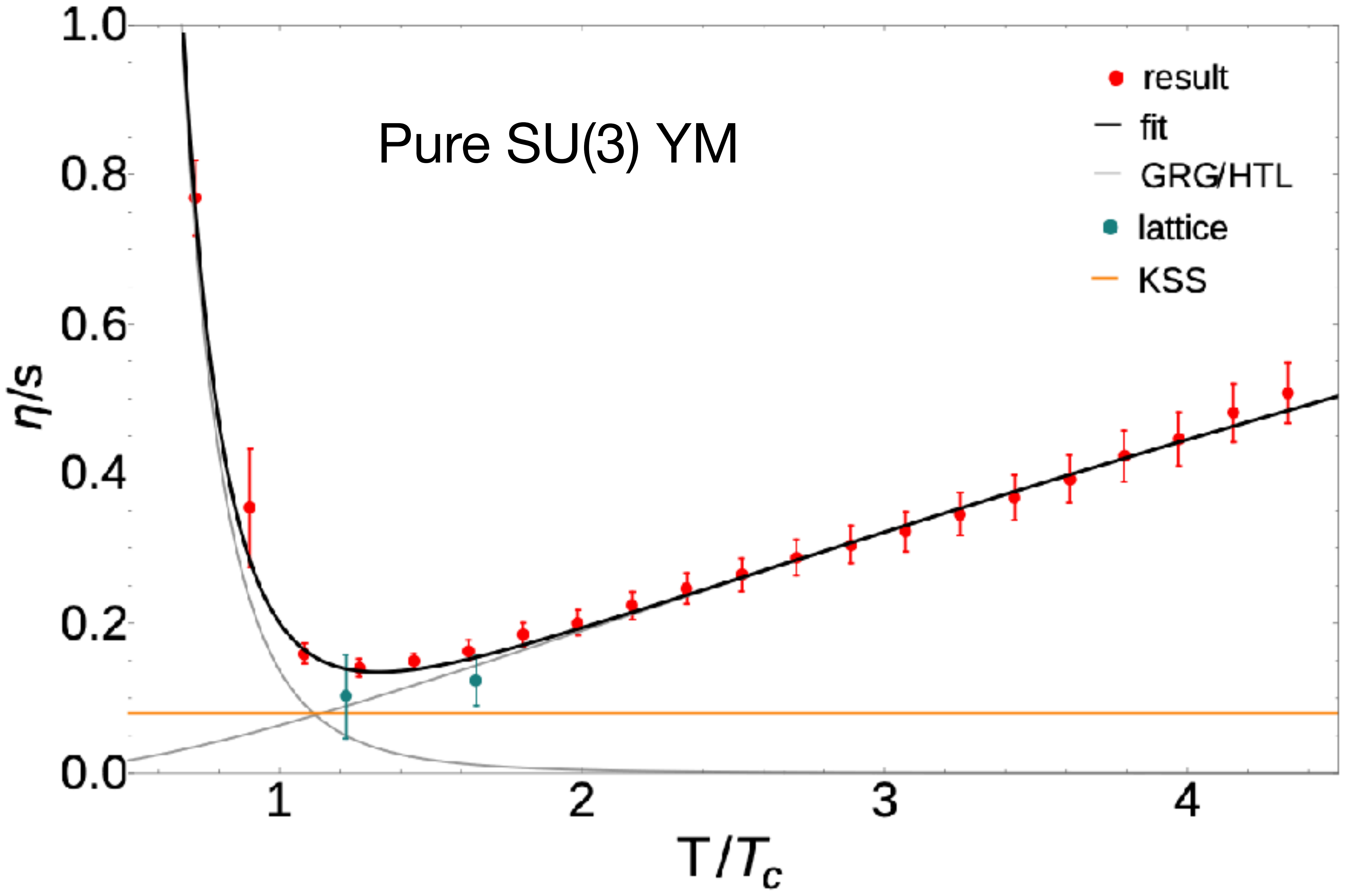
Kinematic shear viscosity η/s

Haas et al., PRD 90 (2014) 091501



(c) $T = 2.77\,T_c$.

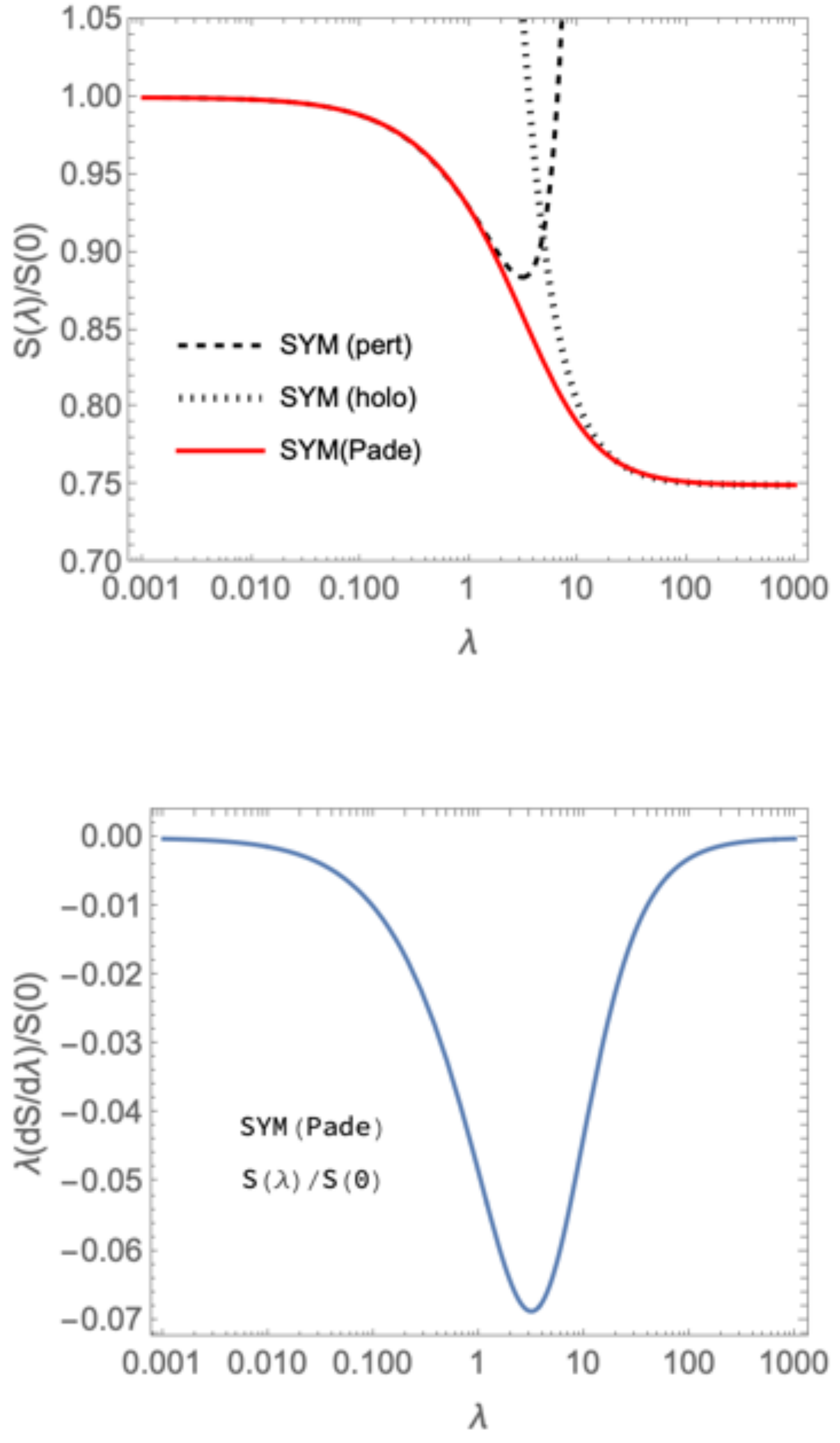
Christiansen et al., PRL 115 (2015) 112002



Weak vs. Strong Coupling in $N = 4$ SYM

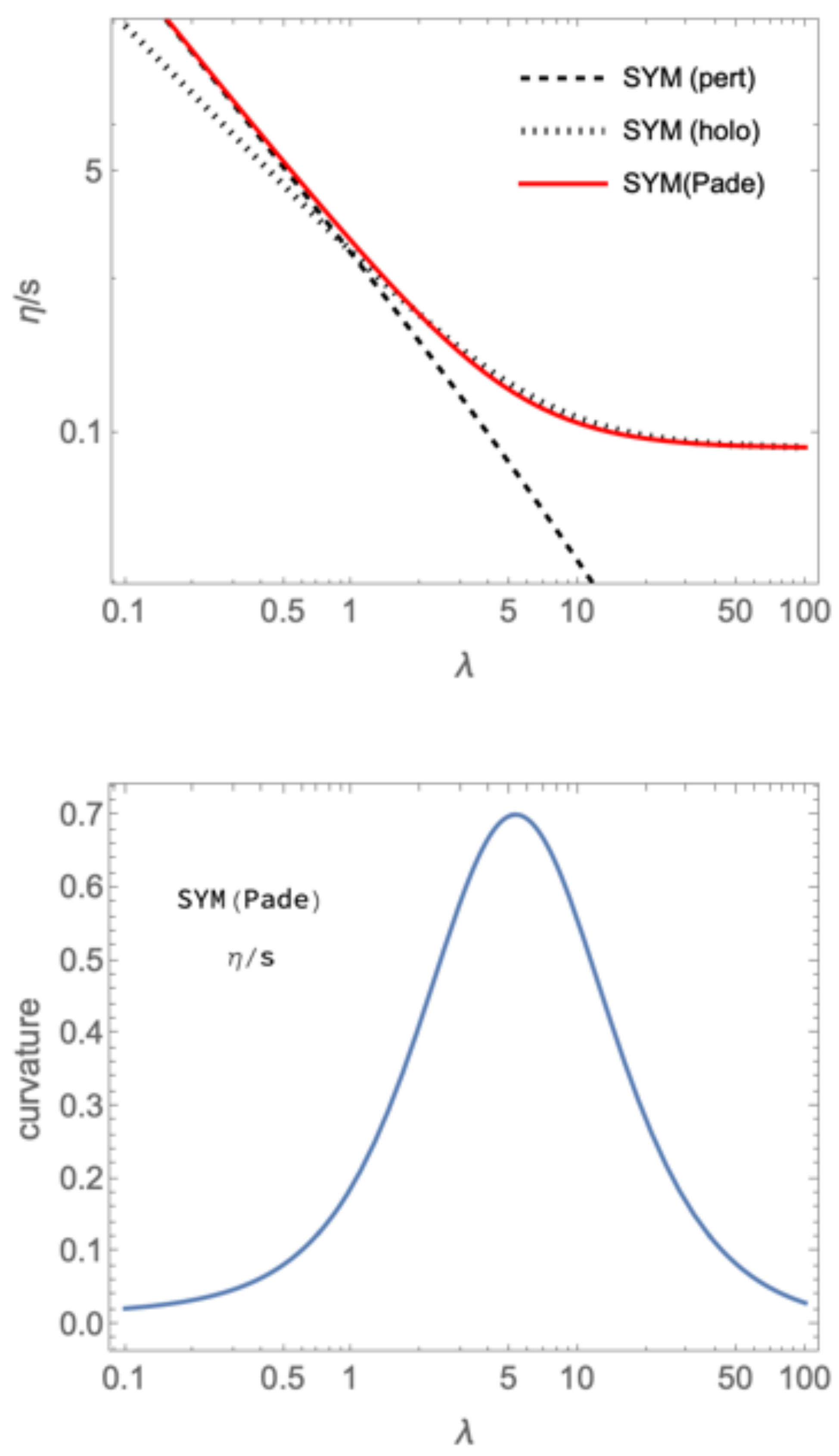
Entropy (normalized)

$s(\lambda)/s_0$



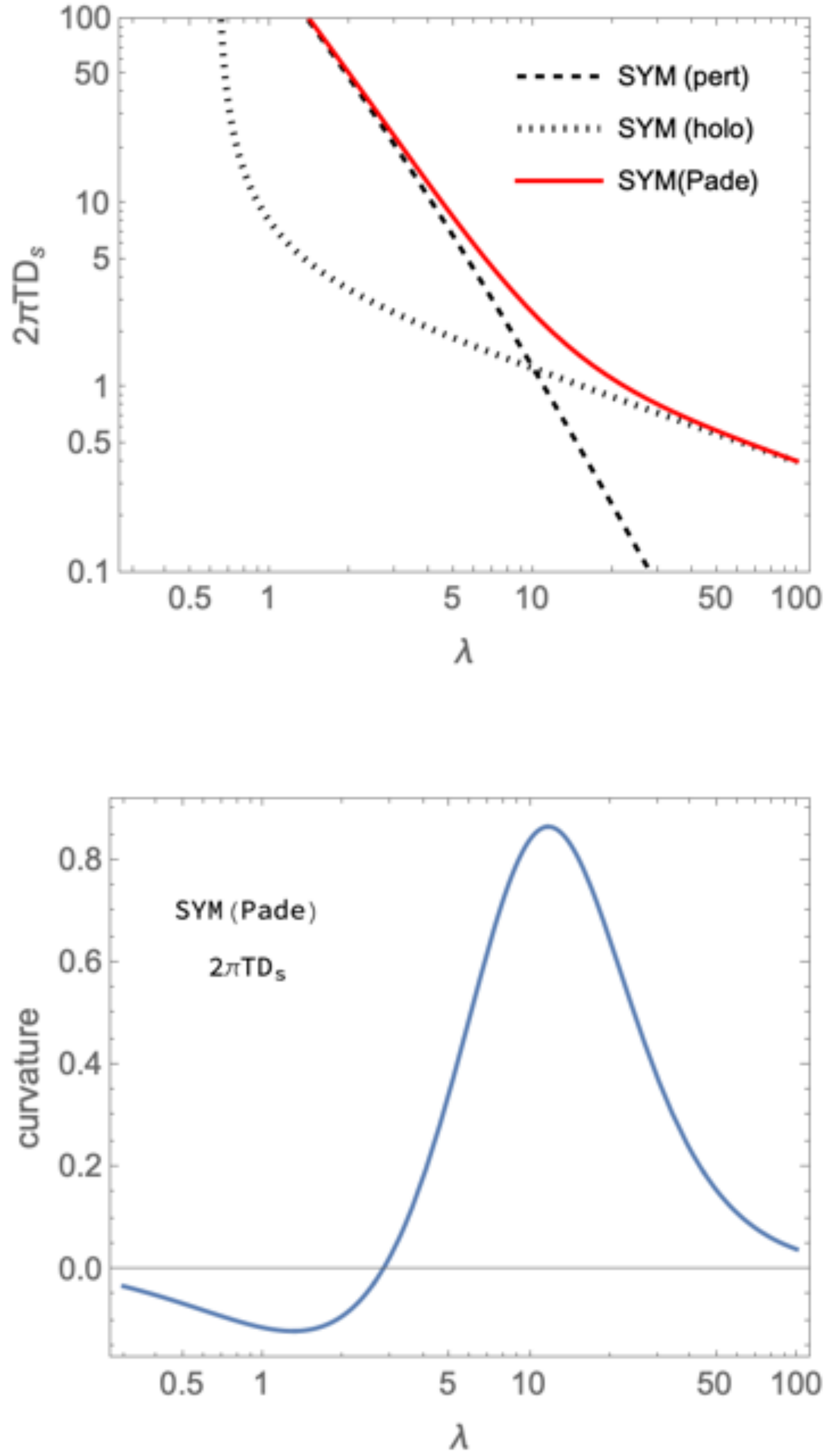
Kin. shear viscosity

η/s



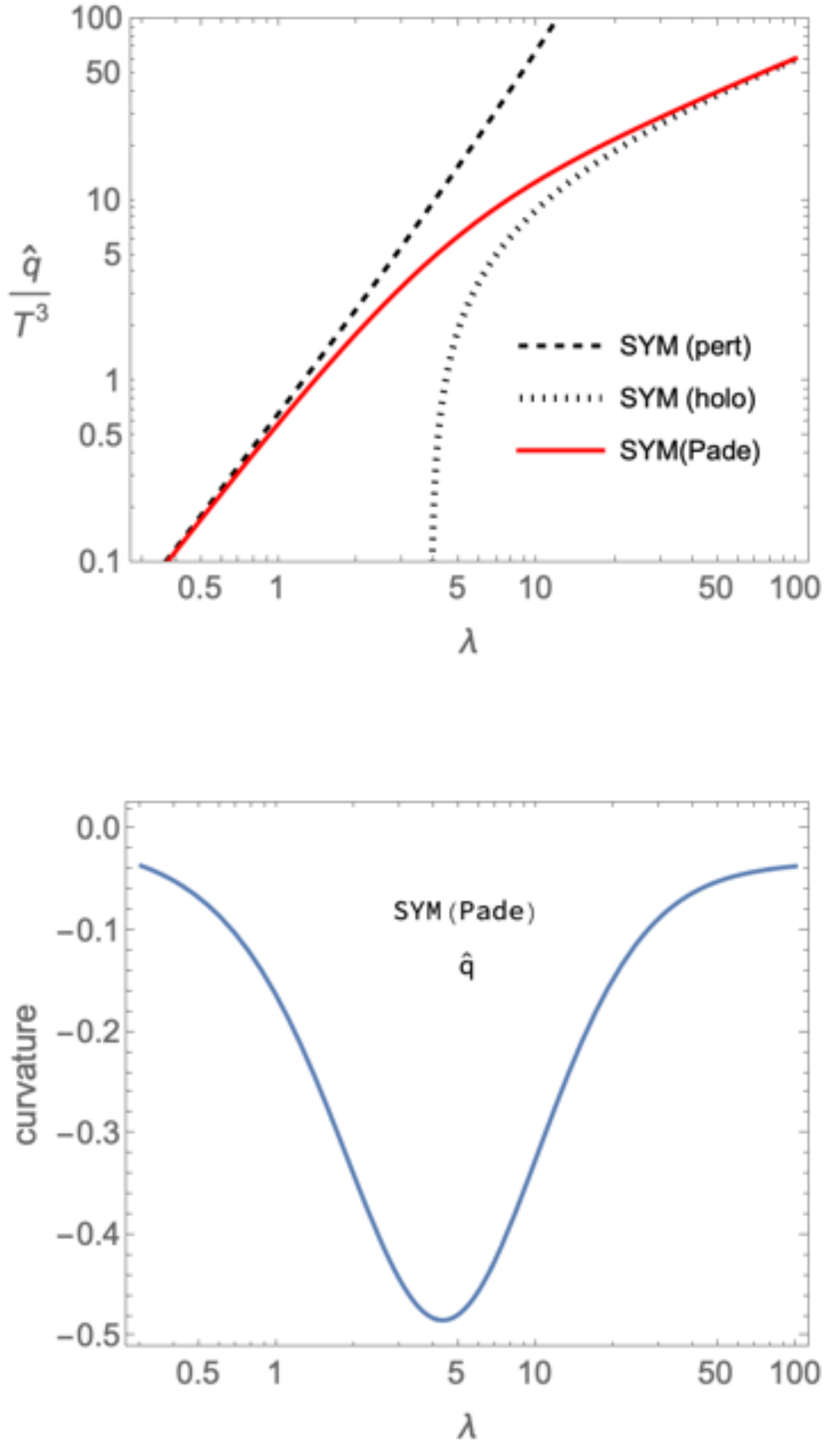
Diffusion constant

$2\pi TD_s$

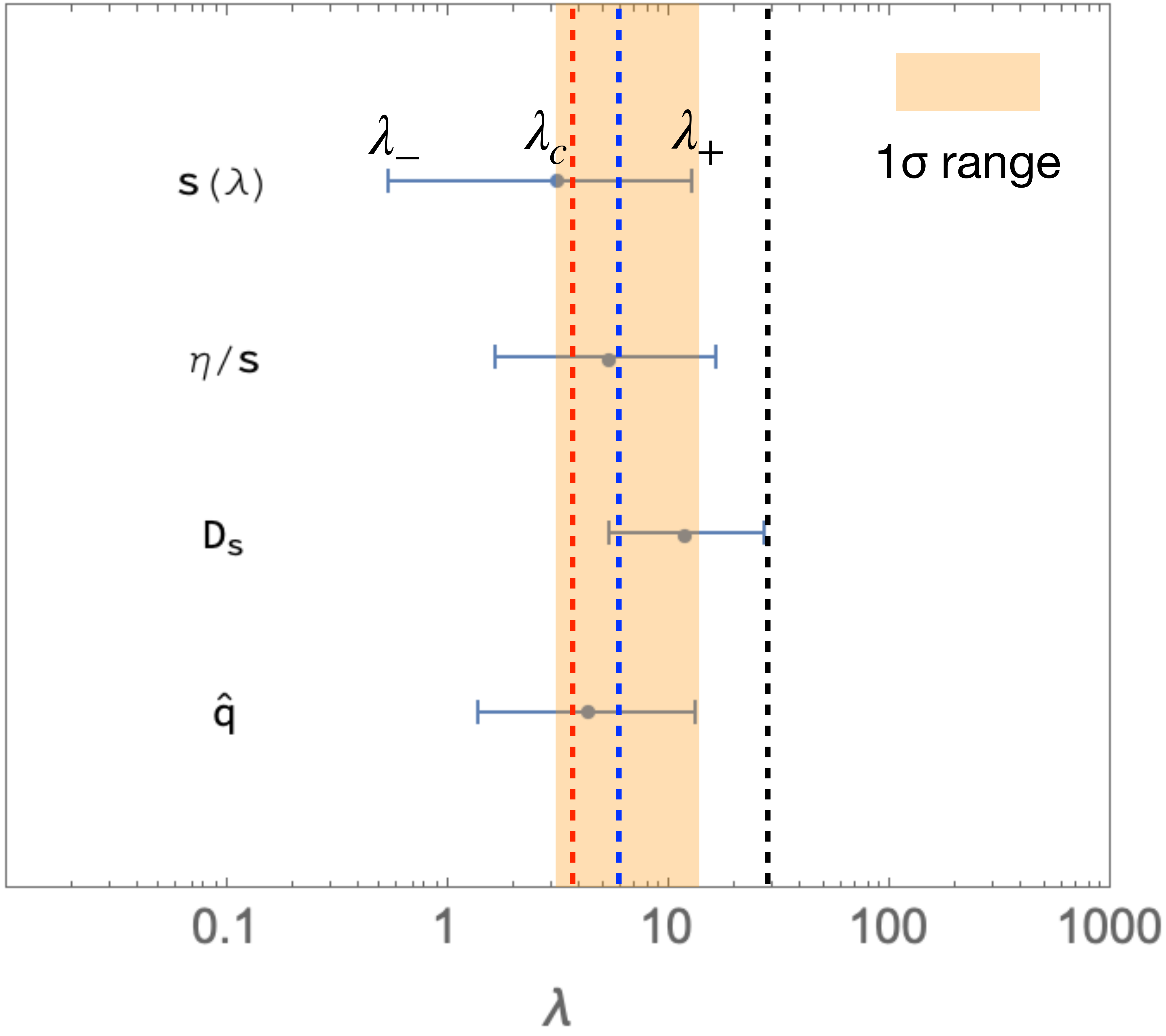


Momentum broadening

$\hat{q}/T^3$



Transition Region



’t Hooft coupling:

$$\lambda = g^2 N_c \rightarrow 12\pi\alpha_{\mathrm{YM}}$$

Quantity	λ_c	λ_-	λ_+	$f(\lambda_c)$
$s(\lambda)/s_0$	3.14	0.54	12.95	0.859
η/s	5.28	1.69	16.38	0.180
$2\pi T D_s$	11.74	5.54	27.36	2.04
$\hat{q}/T^3$	4.36	1.39	13.25	5.47

Transition region: $3 < \lambda < 14$