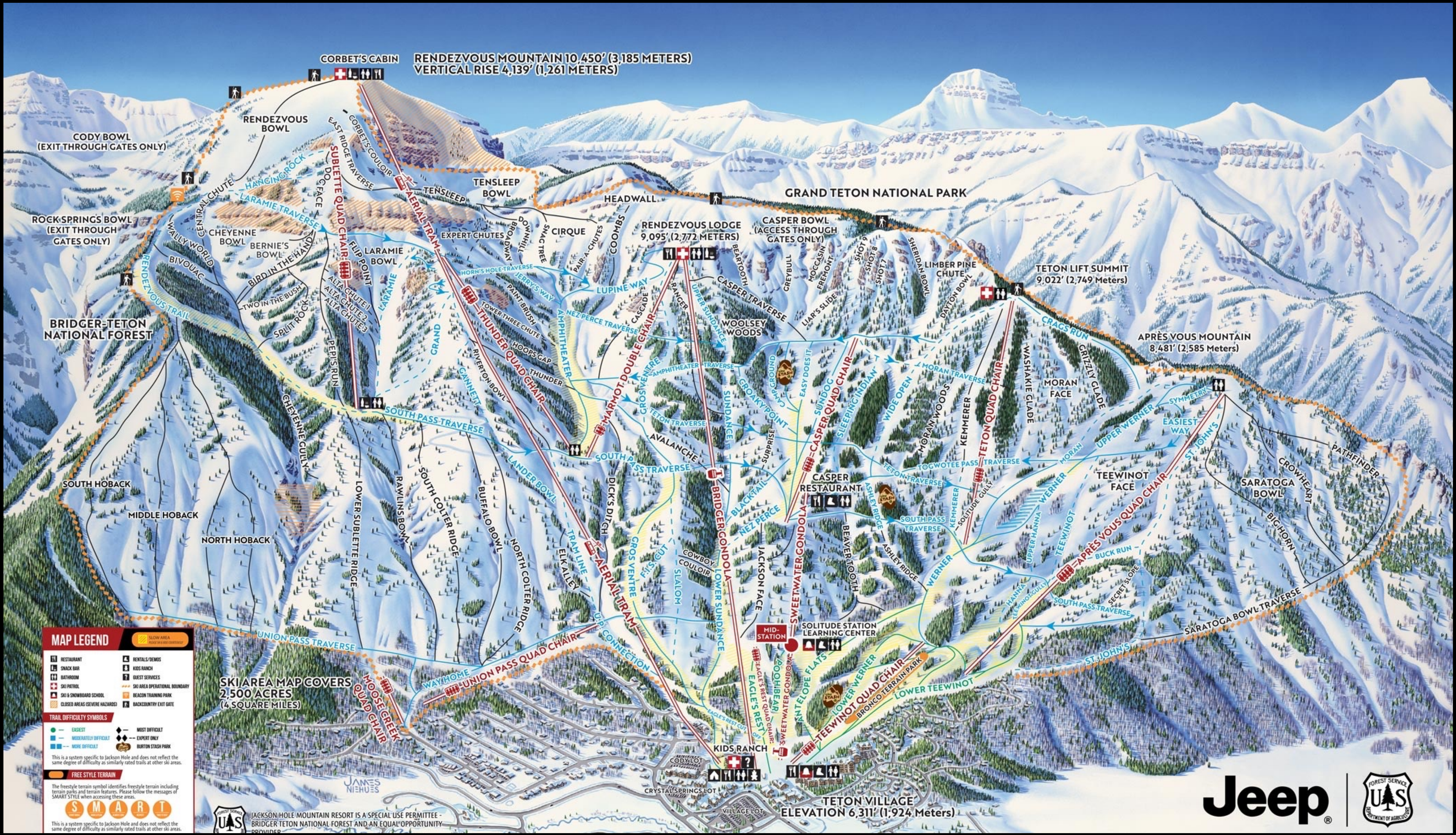

RENDEZVOUS MOUNTAIN 10,450' (3,185 METERS)
VERTICAL RISE 4,139' (1,261 METERS)
CORBET'S CABIN
RENDEZVOUS BOWL
CODY BOWL (EXIT THROUGH GATES ONLY)
TENSLEEP BOWL
HEADWALL
GRAND TETON NATIONAL PARK
ROCK SPRINGS BOWL (EXIT THROUGH GATES ONLY)
CHEYENNE BOWL
LARAMIE BOWL
CIRQUE
RENDEZVOUS LODGE 9,095' (2,772 METERS)
CASPER BOWL (ACCESS THROUGH GATES ONLY)
TETON LIFT SUMMIT 9,022' (2,749 Meters)
BRIDGER-TETON NATIONAL FOREST
APRÈS VOUS MOUNTAIN 8,481' (2,585 Meters)
MORAN FACE
TEEWINOT FACE
SARATOGA BOWL
CASPER RESTAURANT
SOUTH HOBACK
MIDDLE HOBACK
NORTH HOBACK
AERIAL TRAM
THUNDER QUAD CHAIR
SUBLETTE QUAD CHAIR
MARMOT DOUBLE CHAIR
BRIDGER GONDOLA
CASPER QUAD CHAIR
TETON QUAD CHAIR
APRÈS VOUS QUAD CHAIR
SWEETWATER GONDOLA
TEEWINOT QUAD CHAIR
UNION PASS QUAD CHAIR
MOOSE CREEK QUAD CHAIR
SOUTH PASS TRAVERSE
UNION PASS TRAVERSE
SARATOGA BOWL TRAVERSE
SOLITUDE STATION LEARNING CENTER
MID-STATION
KIDS RANCH
SKI AREA MAP COVERS 2,500 ACRES (4 SQUARE MILES)
TETON VILLAGE ELEVATION 6,311' (1,924 Meters)
MAP LEGEND
JACKSON HOLE MOUNTAIN RESORT IS A SPECIAL USE PERMITTEE - BRIDGER TETON NATIONAL FOREST AND AN EQUAL OPPORTUNITY PROVIDER
Jeep

Photos courtesy Kong!

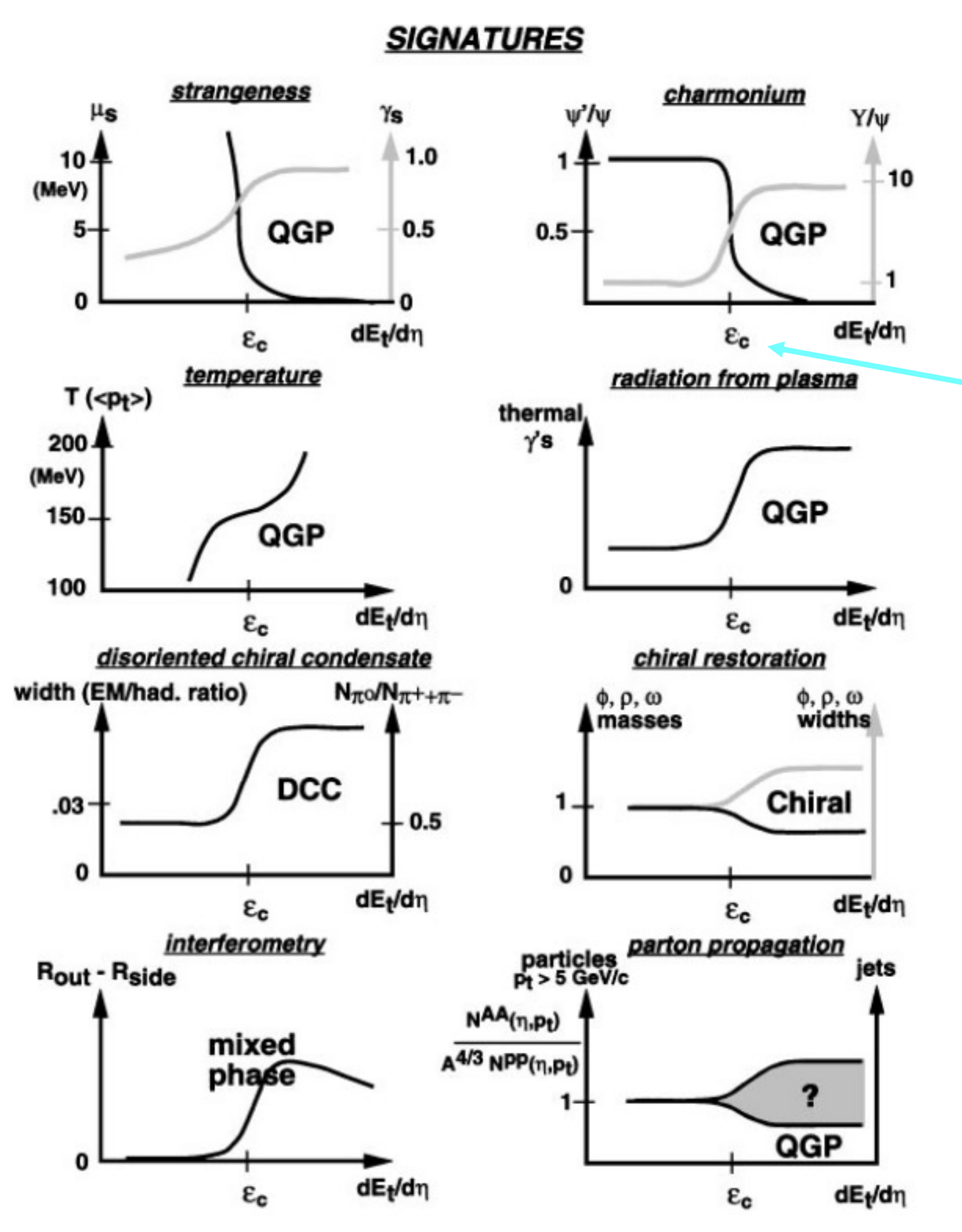
QGP Signatures – Then and Now

John W. Harris
Yale University

Special thanks to Berndt Müller!

Reference: "QGP Signatures" Revisited
J. W. Harris & B. Müller, European Physical Journal C (2024) in press, [arXiv:2308.05743 [hep-ph]]

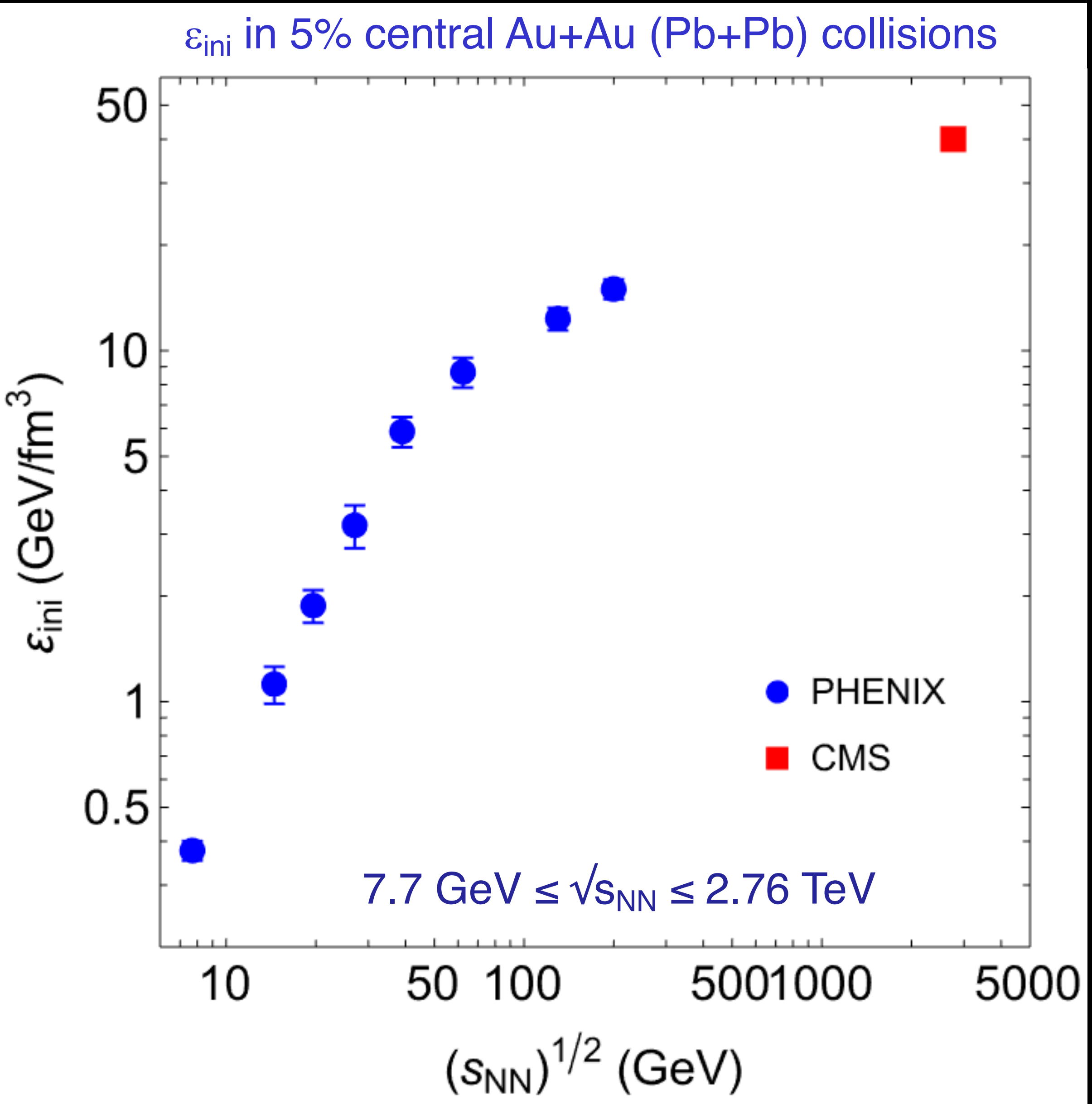
Signatures - Then



Note – common abscissa $dE_t/d\eta$ relative to transition ε_0

Original publication:
"The Search for the Quark – Gluon Plasma," J. W. Harris & B. Müller, Ann. Rev. Nucl. Part. Sci. 46, 71 (1996) [arXiv:hepph/9602235 [hep-ph]].

Average Initial Energy Density



Energy Density:

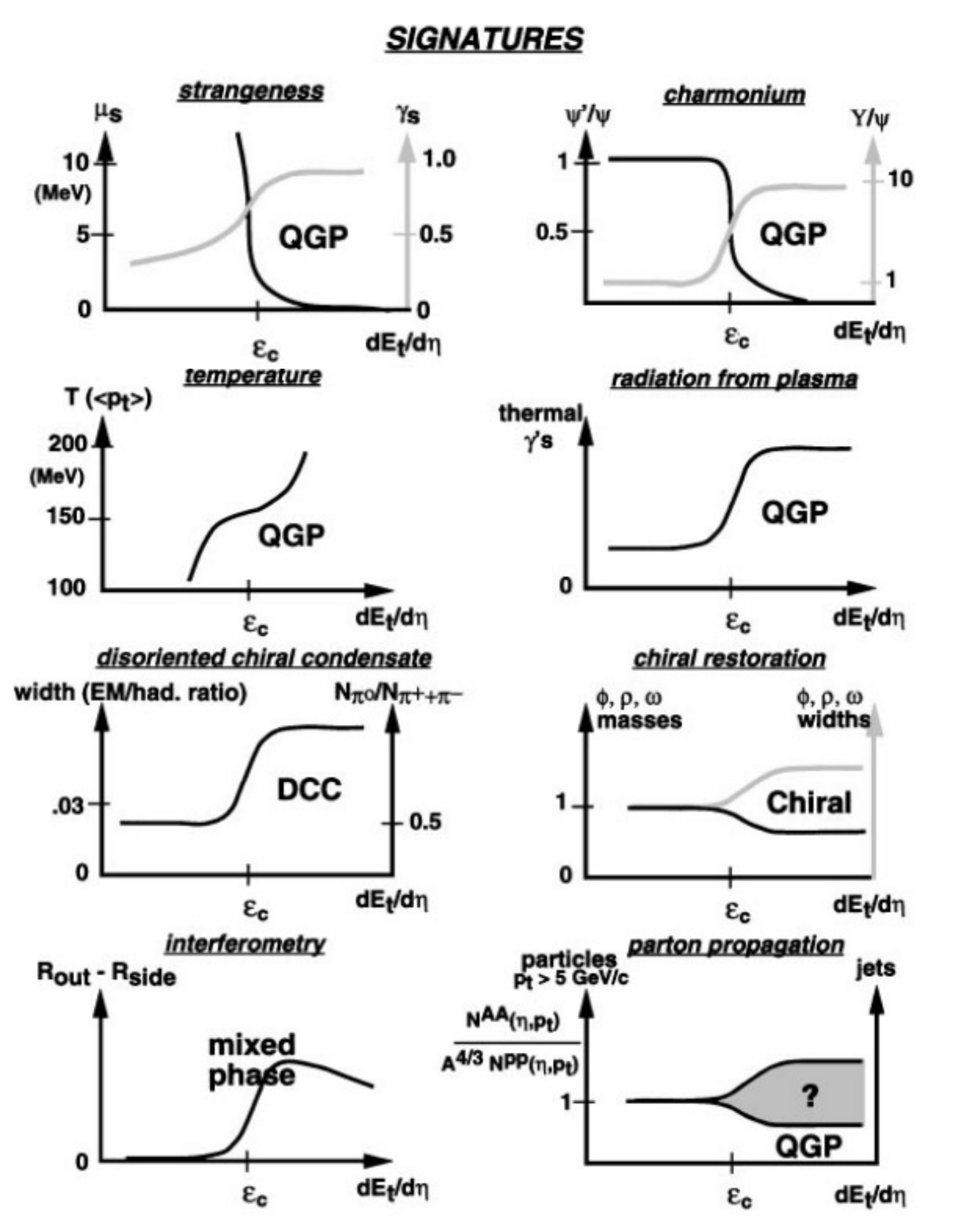
$$\epsilon_{Bj} = \frac{1}{A_{\perp}\tau}\frac{dE_T}{dy}$$

J.D. Bjorken, Phys. Rev. D27, 140 (1983)

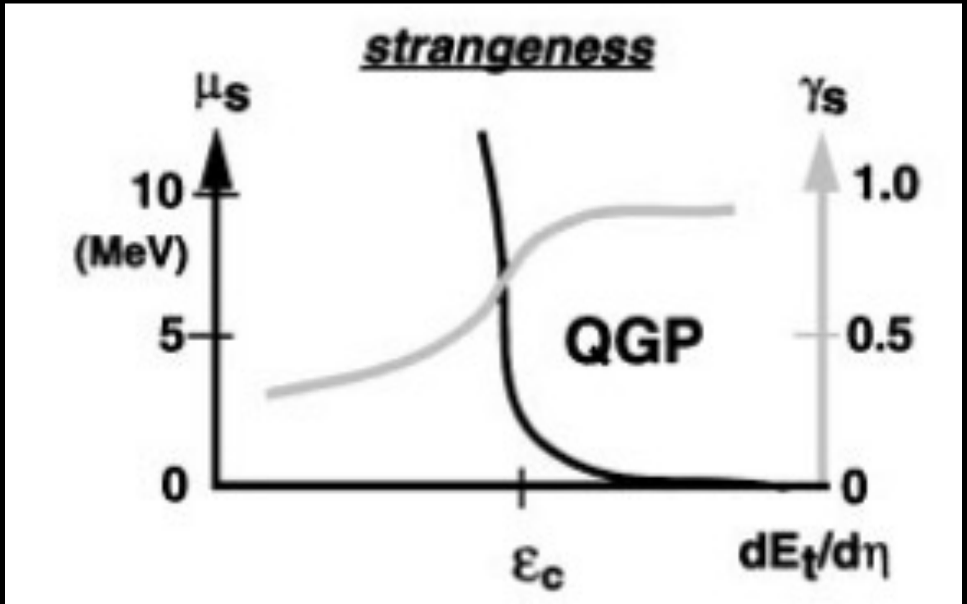
Data:

PHENIX, Phys.Rev. C 93, 024901 (2016)

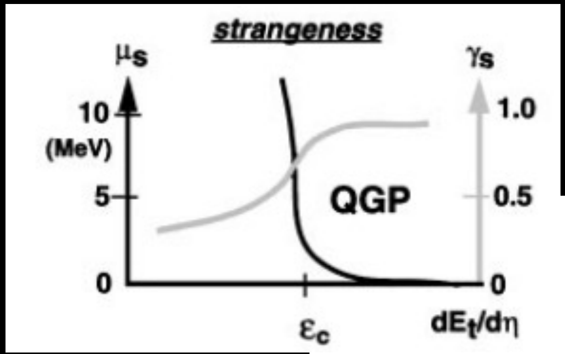
CMS, Phys. Rev. Lett. 109, 152303 (2012)



Signatures - Strangeness



μ_s – strangeness chemical potential
γ_s – strangeness fugacity



Strangeness Then

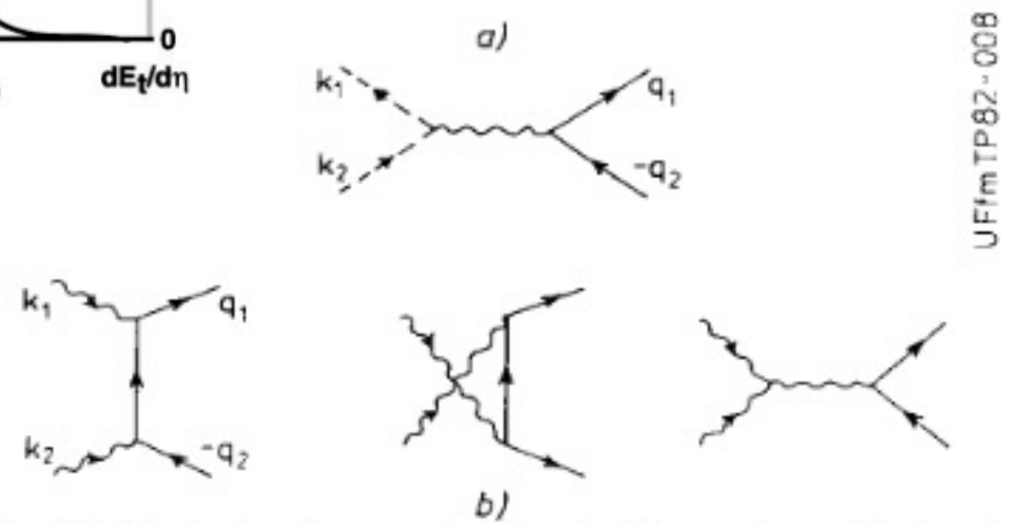


Fig. 2.7. First order diagrams for $s\bar{s}$ production reactions; (a) $q\bar{q} \rightarrow s\bar{s}$, (b) $gg \rightarrow s\bar{s}$.

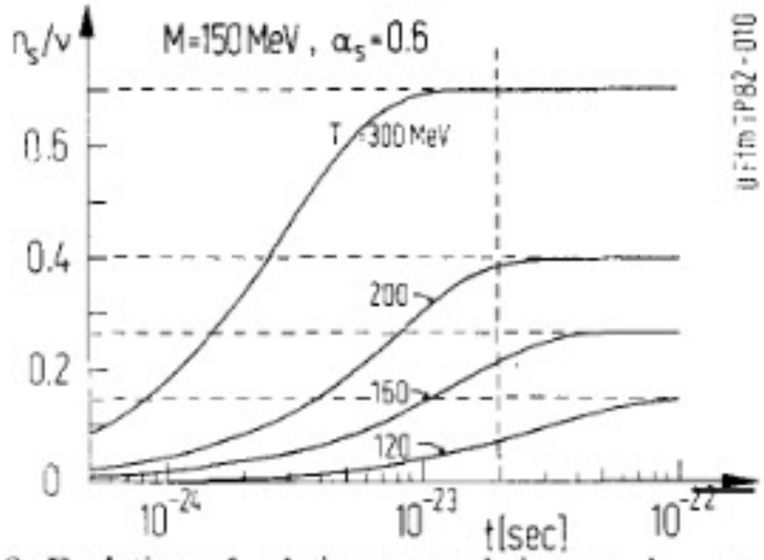


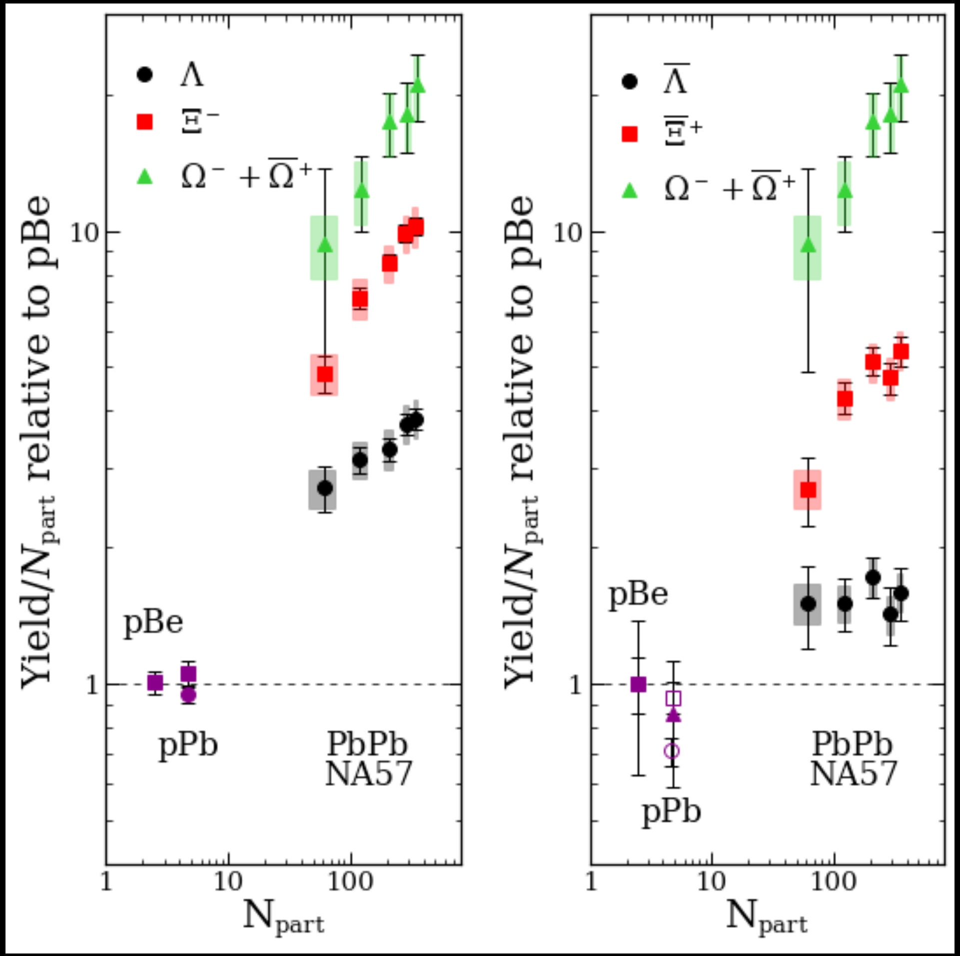
Fig. 2.8. Evolution of relative s population per baryon number as function of time in the plasma. For $T \geq 160$ MeV chemical saturation is noticeable in about 2×10^{-23} sec, the anticipated minimal plasma livetime.

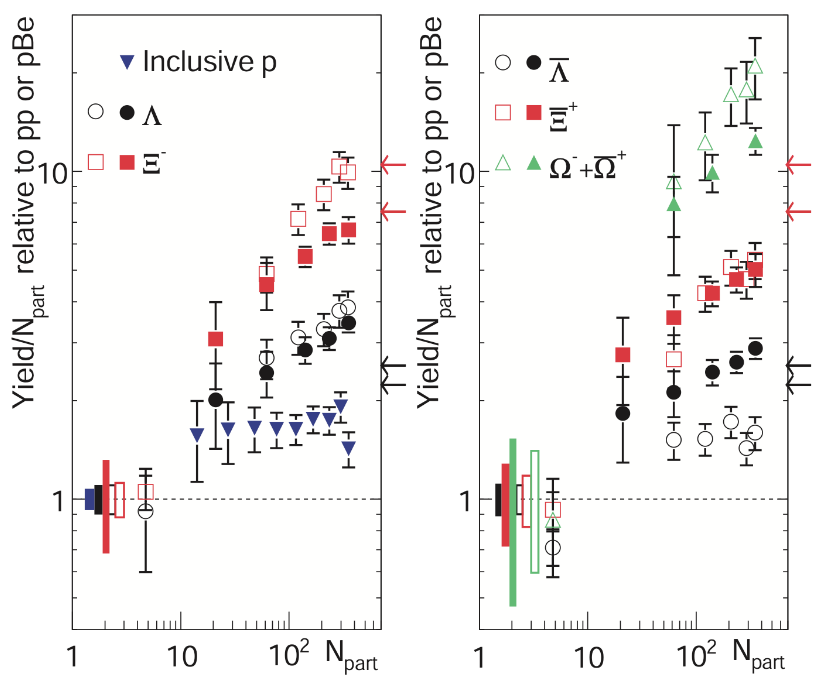
J. Rafelski, "Formation and Observables of the Quark-Gluon Plasma," Phys.Rep. 88,331 (1982).

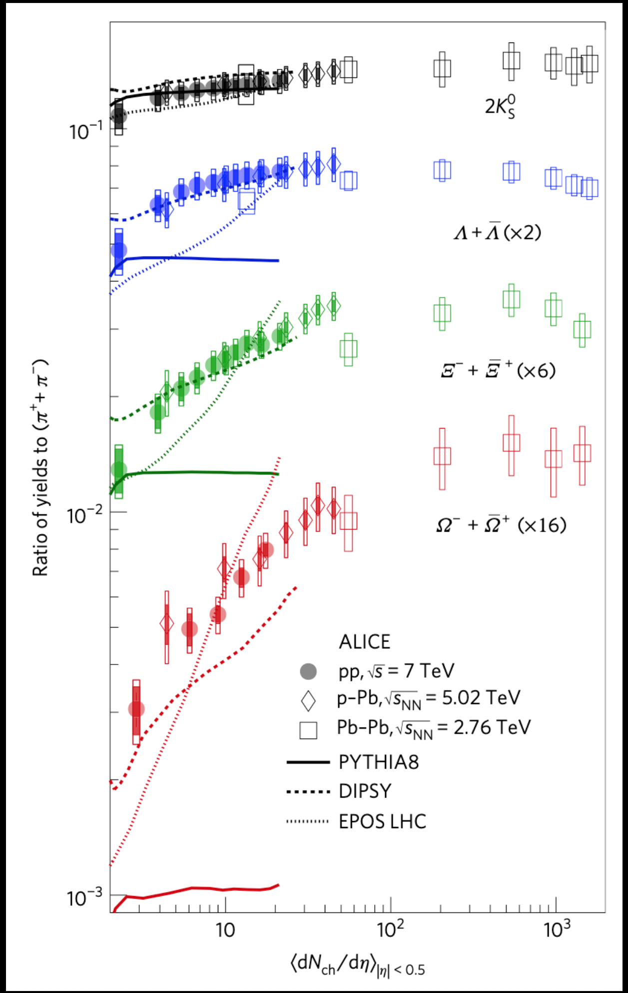
J. Rafelski and B. Müller, "Strangeness Production in the Quark - GluonPlasma,"
Phys. Rev. Lett. 48, 1066 (1982) [erratum: Phys. Rev. Lett. 56, 2334 (1986)].

P. Koch, B. Müller and J. Rafelski, "Strangeness in Relativistic Heavy Ion Collisions," Phys. Rep. 142, 167 (1986).

Strangeness – Now –> Multi-strange Baryon Enhancement vs N_{part} and $\sqrt{s_{NN}}$







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

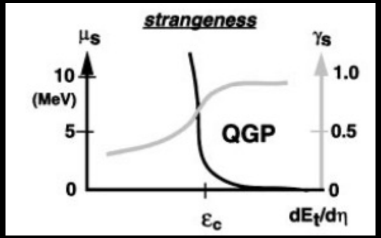
NA57, J. Phys.G 32, 427 (2006)

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

STAR, Phys. Rev. C 77, 044908 (2008)

ALICE
$\sqrt{s_{NN}}$ = 2.76 TeV Au+Au

ALICE, Nature Phys. 13, 535 (2017)



Strangeness – Then and Now

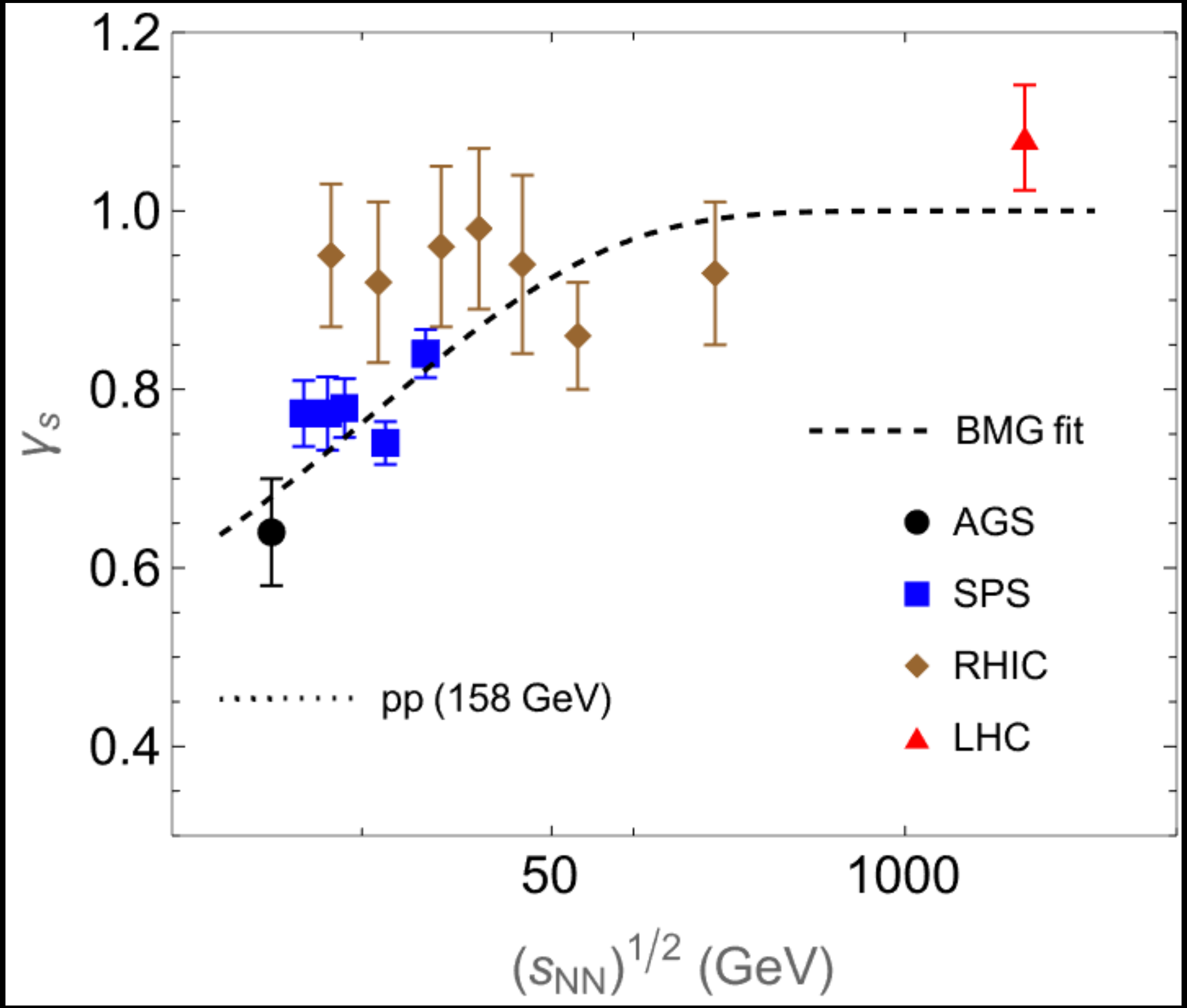
Evolution of the strangeness fugacity γ_s in central Au+Au & Pb+Pb.

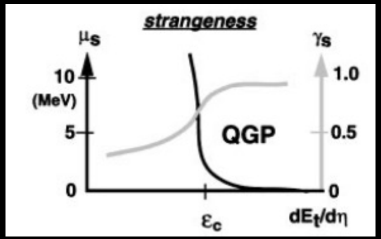
Chemical fit uses grand canonical ensemble:

$$\gamma_s(A, \sqrt{s_{NN}}) = 1 - \zeta \exp\left(-\xi \sqrt{A \sqrt{s_{NN}}}\right)$$

Data indicate $\gamma_s \to 1$ as collision energy increases.
–> full saturation of strange quark density at hadronization.

This confirms the expectation depicted schematically for strangeness!





Strangeness – Then and Now

Ω / π ratio measured in p+p, p+Pb, Pb+Pb compared to fit.

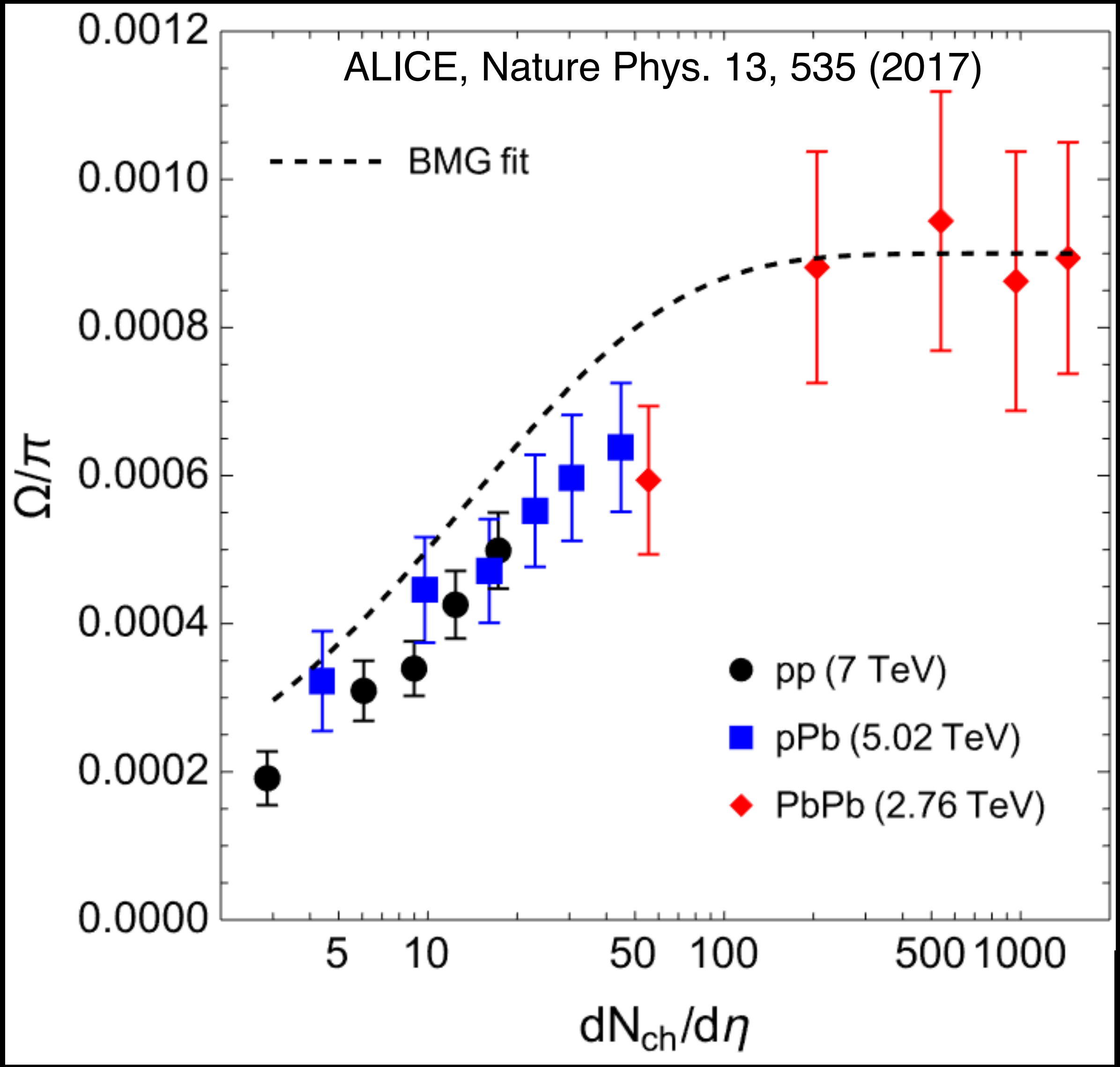
Evolution of the strangeness fugacity γ_s in central Au+Au & Pb+Pb.

Chemical fit uses grand canonical ensemble:

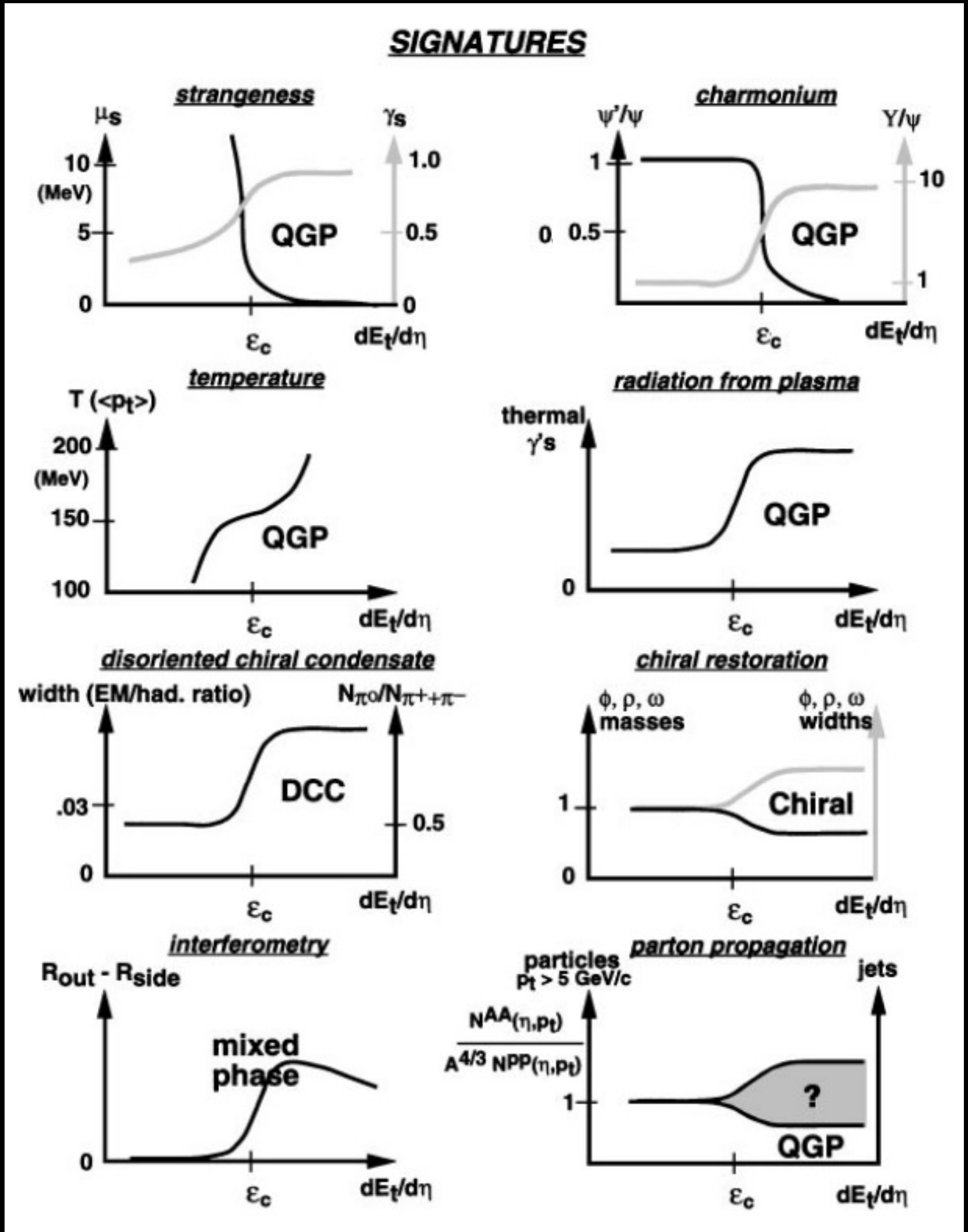
$$\gamma_s(A, \sqrt{s_{NN}}) = 1 - \zeta \exp\left(-\xi\sqrt{A\sqrt{s_{NN}}}\right)$$

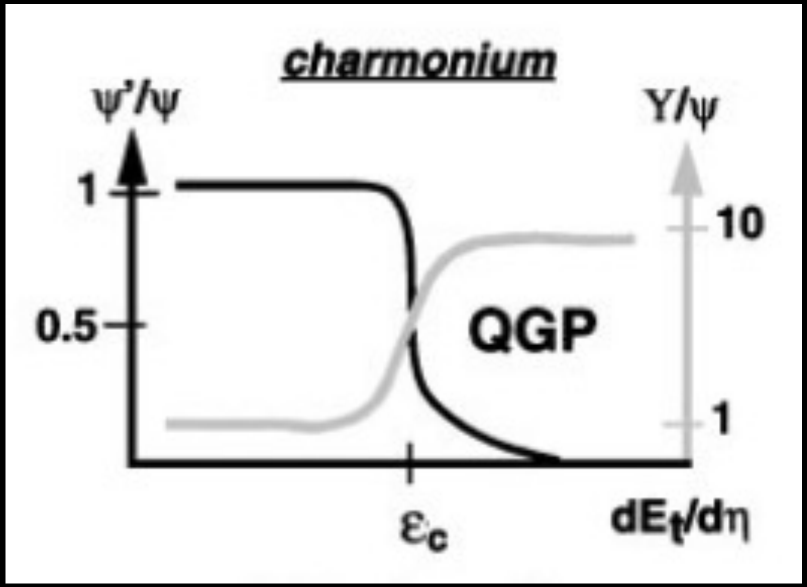
Data indicate $\gamma_s \rightarrow 1$ as collision energy increases.
–> full saturation of strange quark density at hadronization.

This confirms the expectation depicted schematically for strangeness!

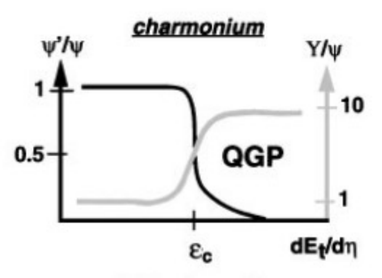


Signatures – Charmonium (& Bottomonium)



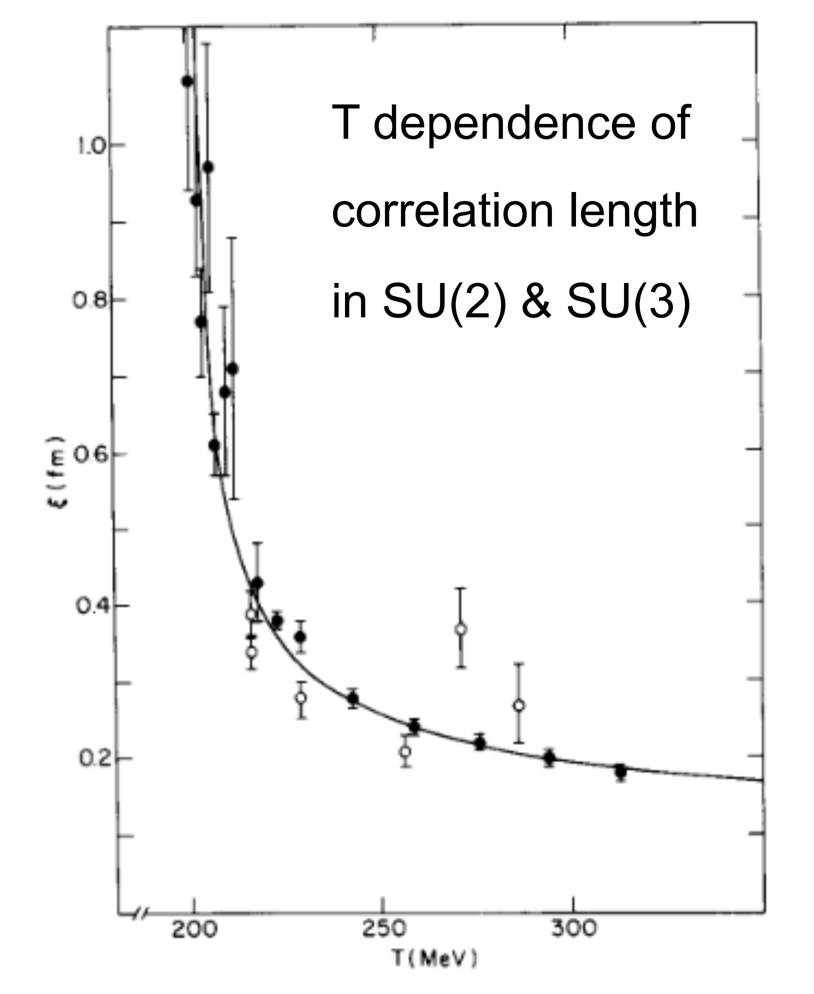


T. Matsui and H. Satz, "J/ψ Suppression by Quark-Gluon Plasma Formation," Phys.Lett. B 178, 416 (1986)

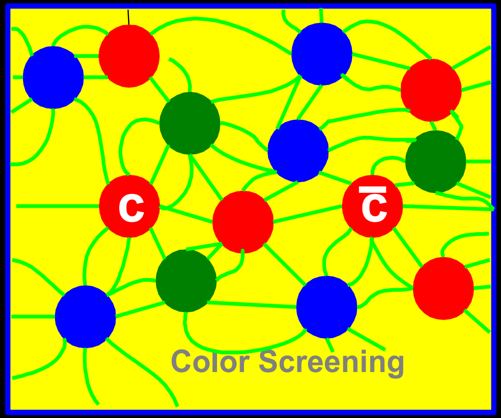


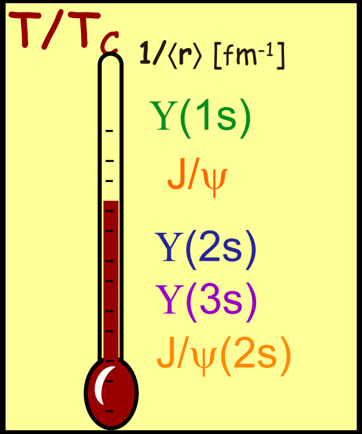
Charmonium – Then

T. Matsui and H. Satz, "J/ψ Suppression by Quark-Gluon Plasma Formation," Phys.Lett. B 178, 416 (1986)



The quark-antiquark interaction in SU(N) gauge theory can be parameterized by the temperature and correlation length.





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

Charmonium – J/ψ is suppressed!

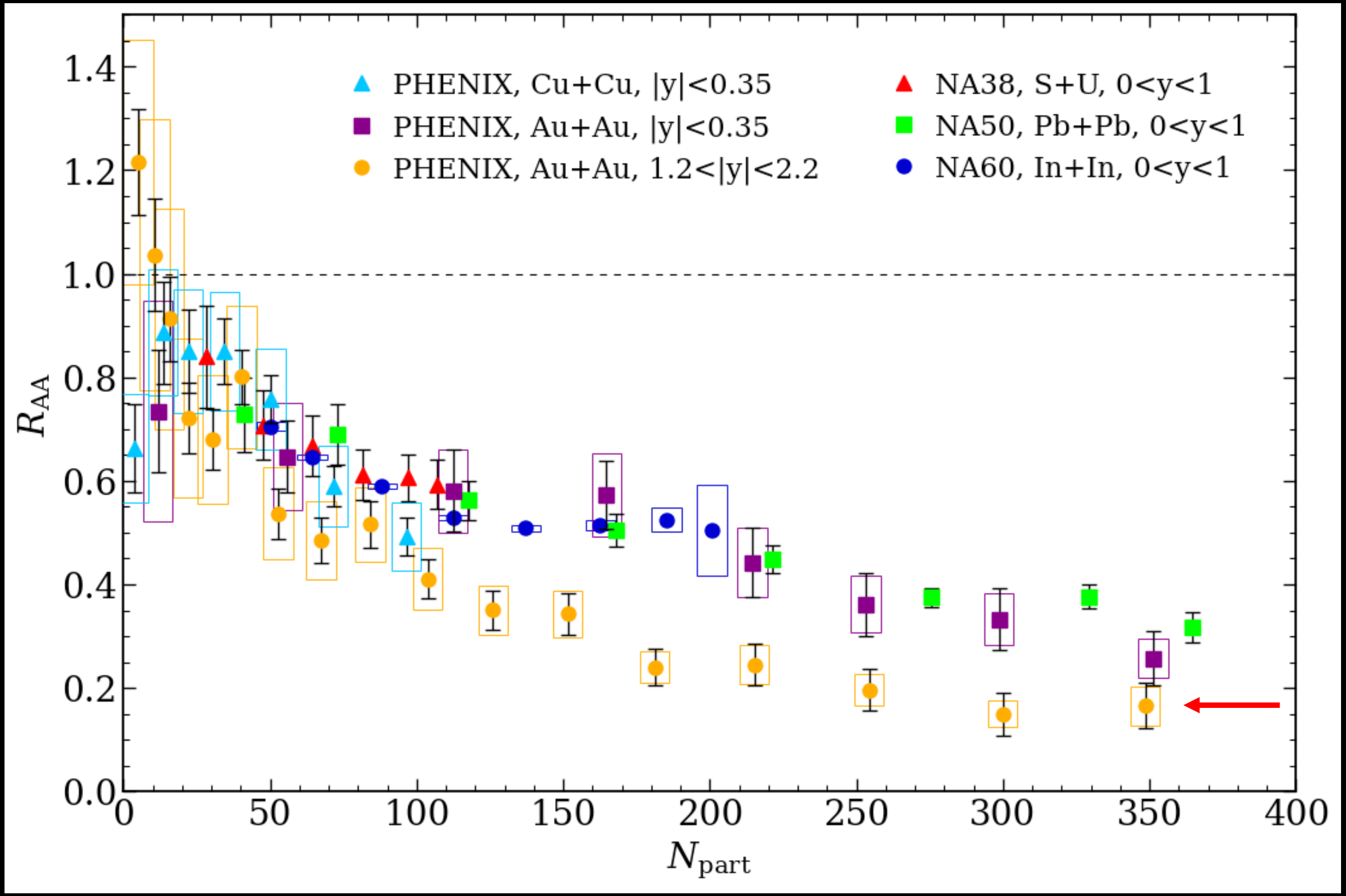
The J/ψ is suppressed!

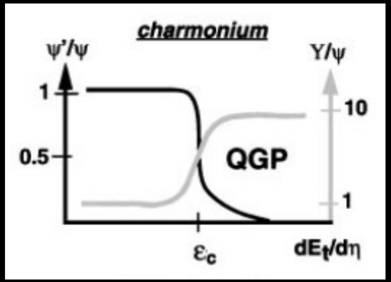
Suppression stronger

for central collisions

at forward rapidities.

NA38, NA50, NA60, PHENIX

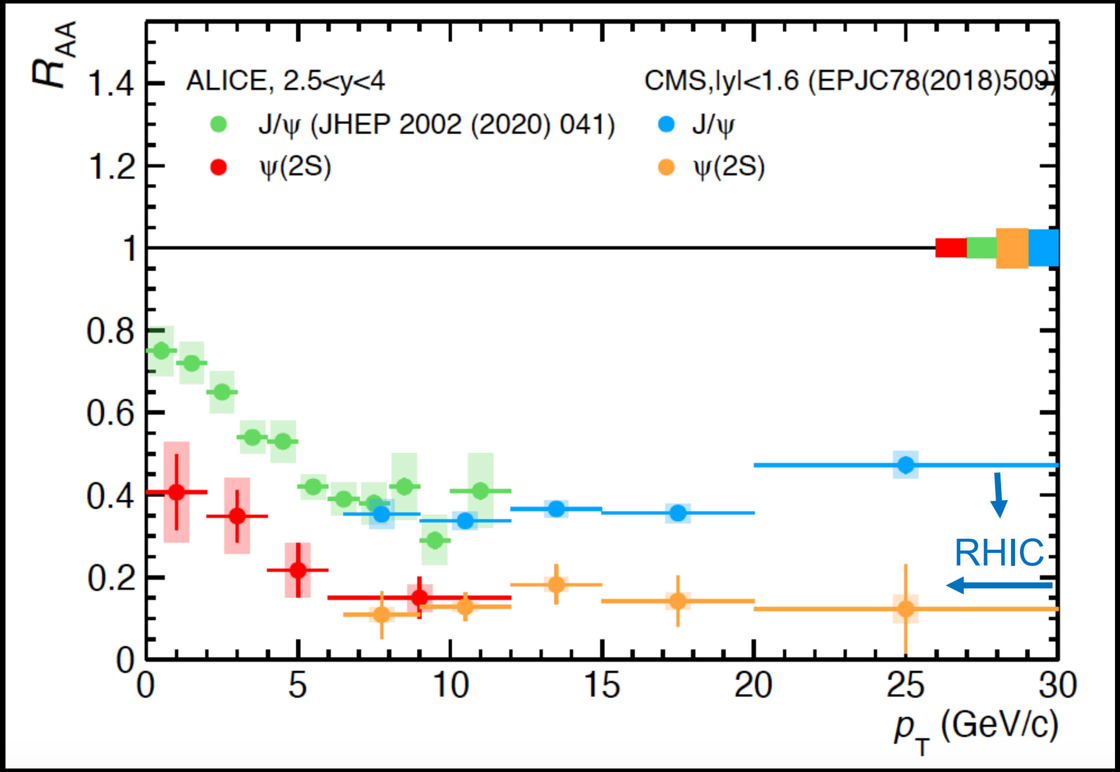




Quarkonia – Sequential Suppression

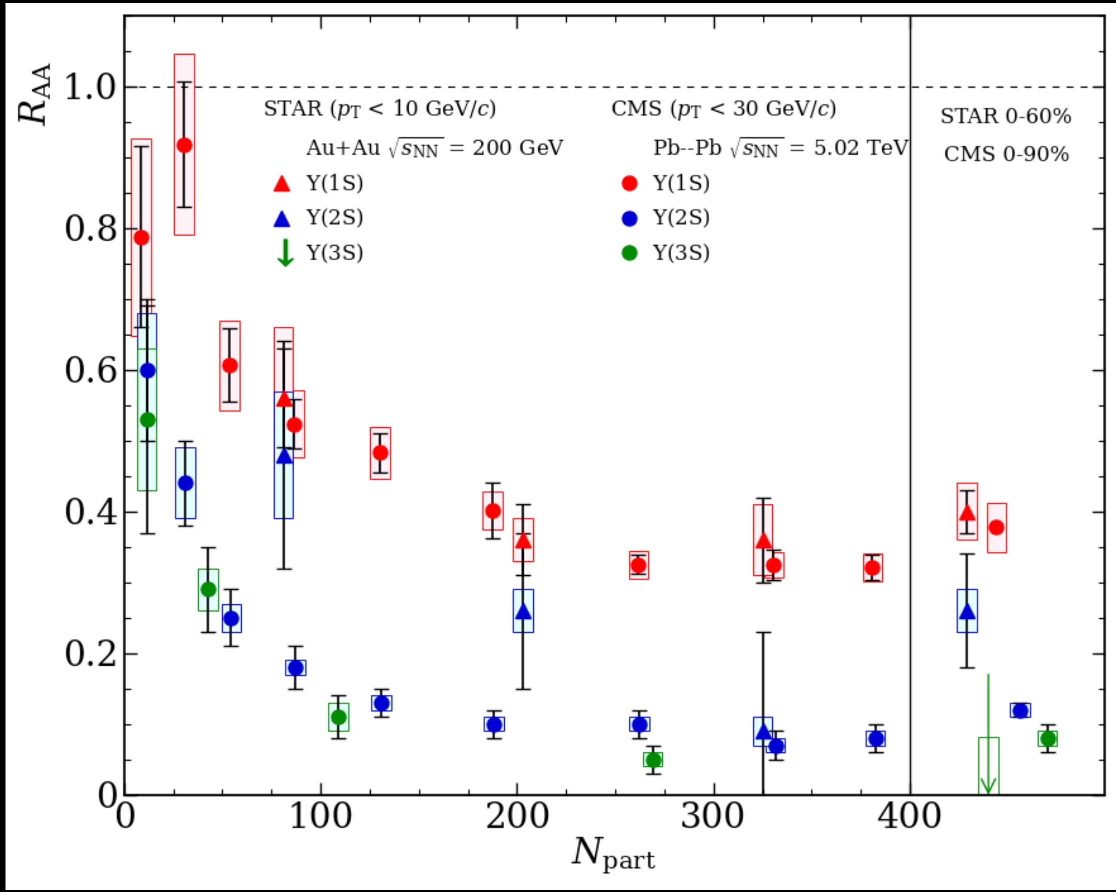
Sequential suppression of J/ψ and Υ at RHIC and LHC!

ALICE, CMS



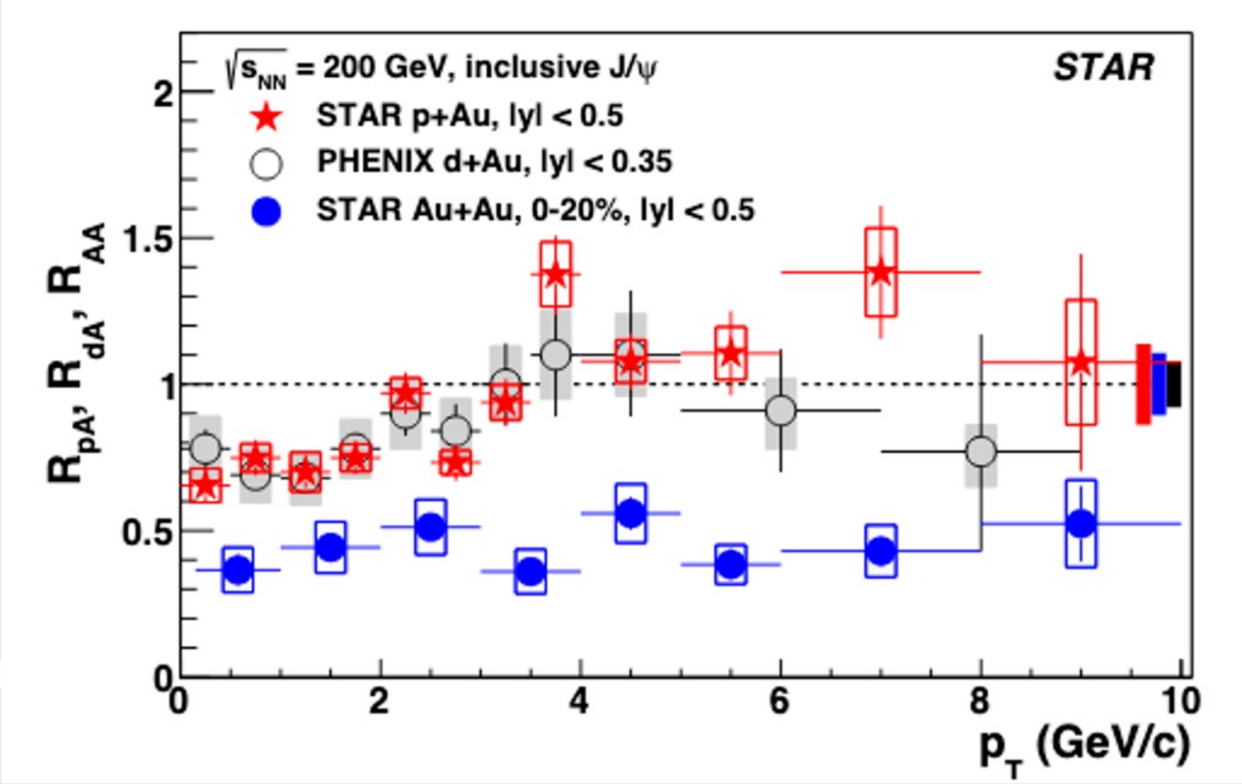
J/ψ observed to be less suppressed at LHC than at RHIC!

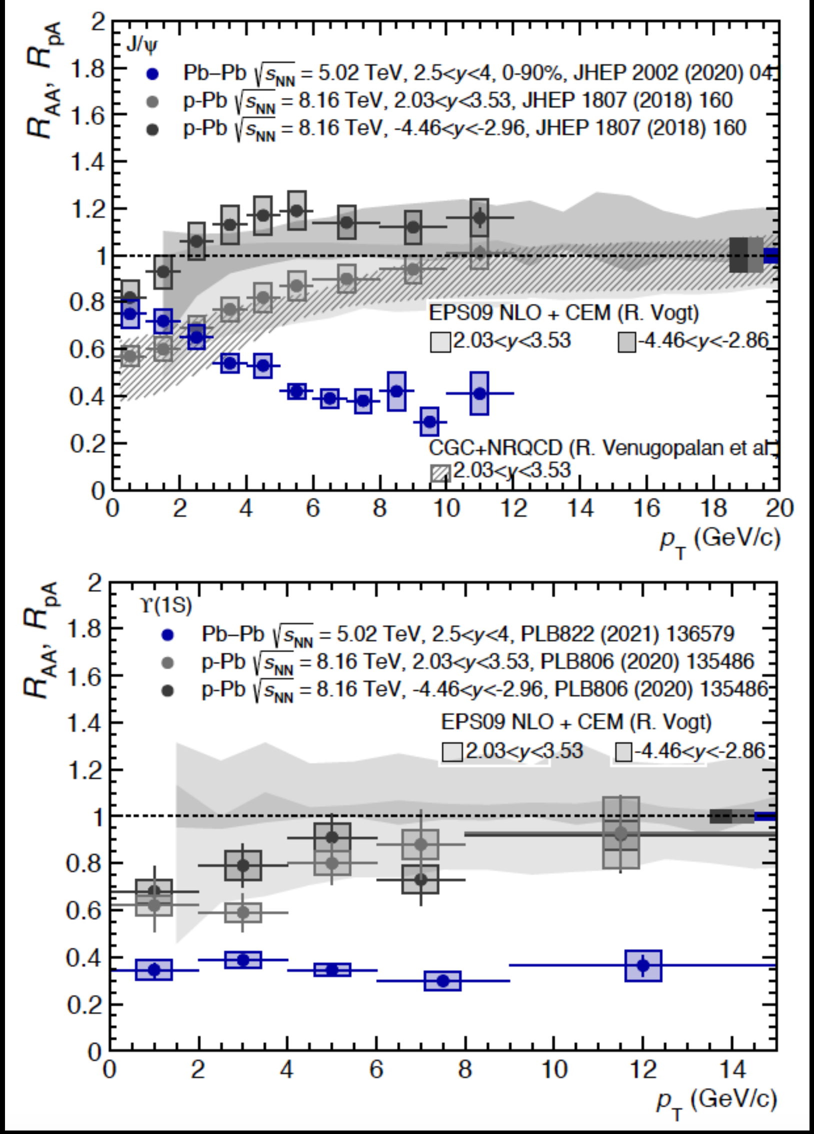
STAR, CMS



Υ(1s) similar suppression at RHIC and LHC!

Cold Nuclear Matter (CNM) Effects - Quarkonia

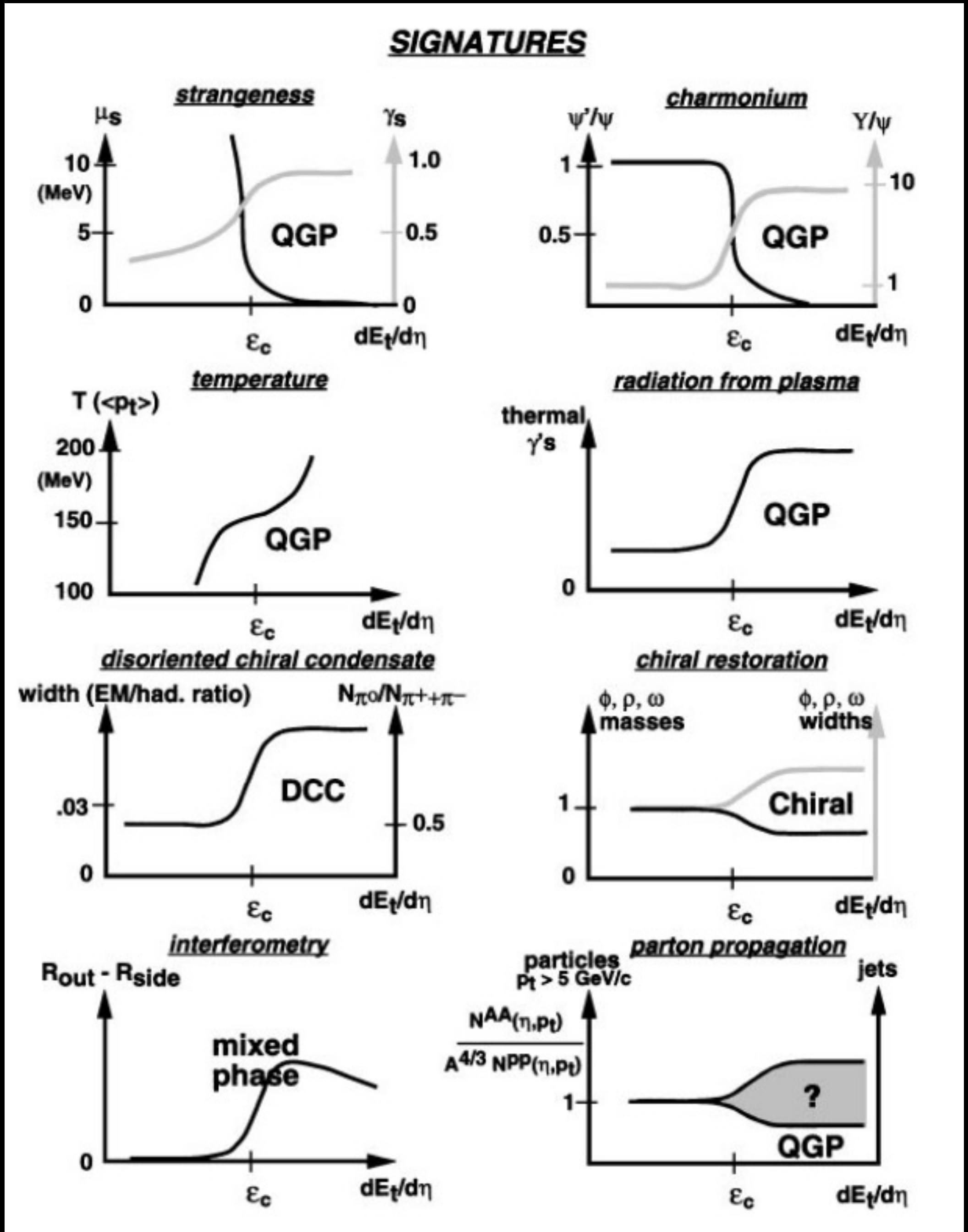




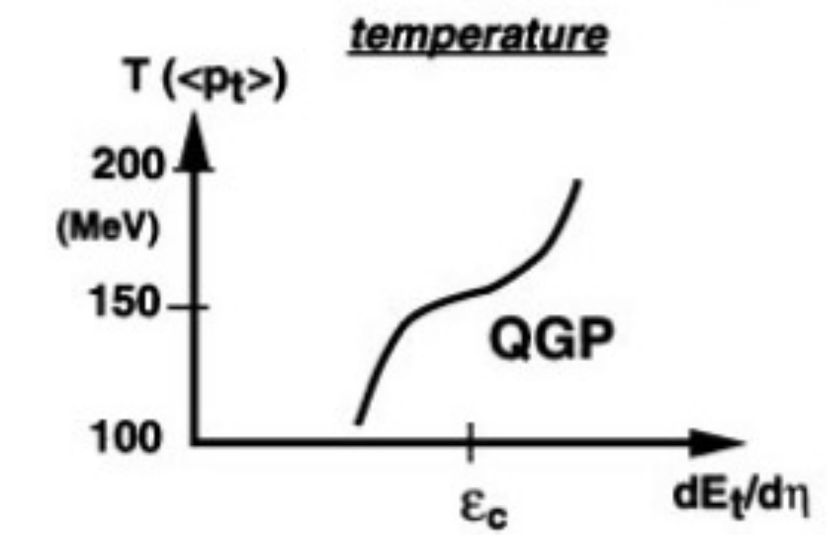
J/ψ CNM suppression seen in p(d)+Au at low p_T at RHIC!

J/ψ and ϒ CNM suppression in p+Pb at low p_T at LHC!

Signatures - Temperature

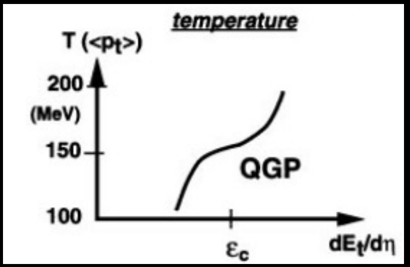


Goal of measuring T versus ε
-> determine the equation of state of QCD matter.



Change in number of degrees of freedom changes entropy density s(T) at a given T.

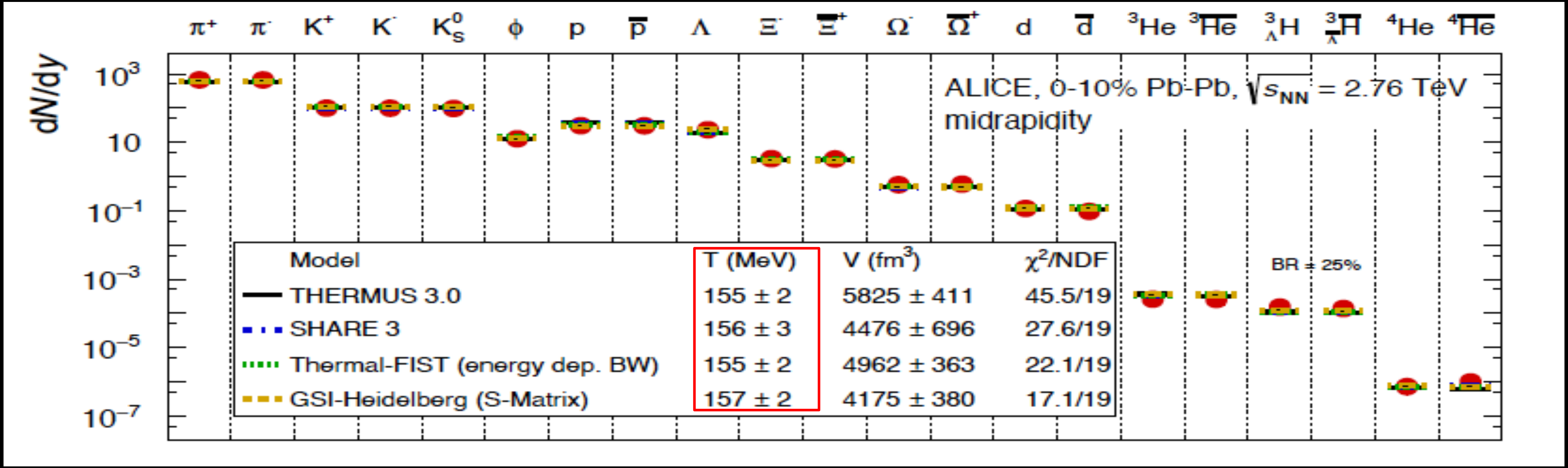
s(T) related to ε by $s(T) = (\varepsilon + P)/T$



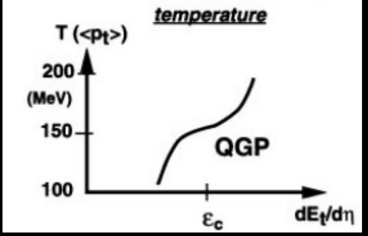
Temperature T

Thermal slopes of spectra of emitted particles "corrupted" by expansion of fireball.

Yields of particles with different masses -> T thermo-chemical freezeout

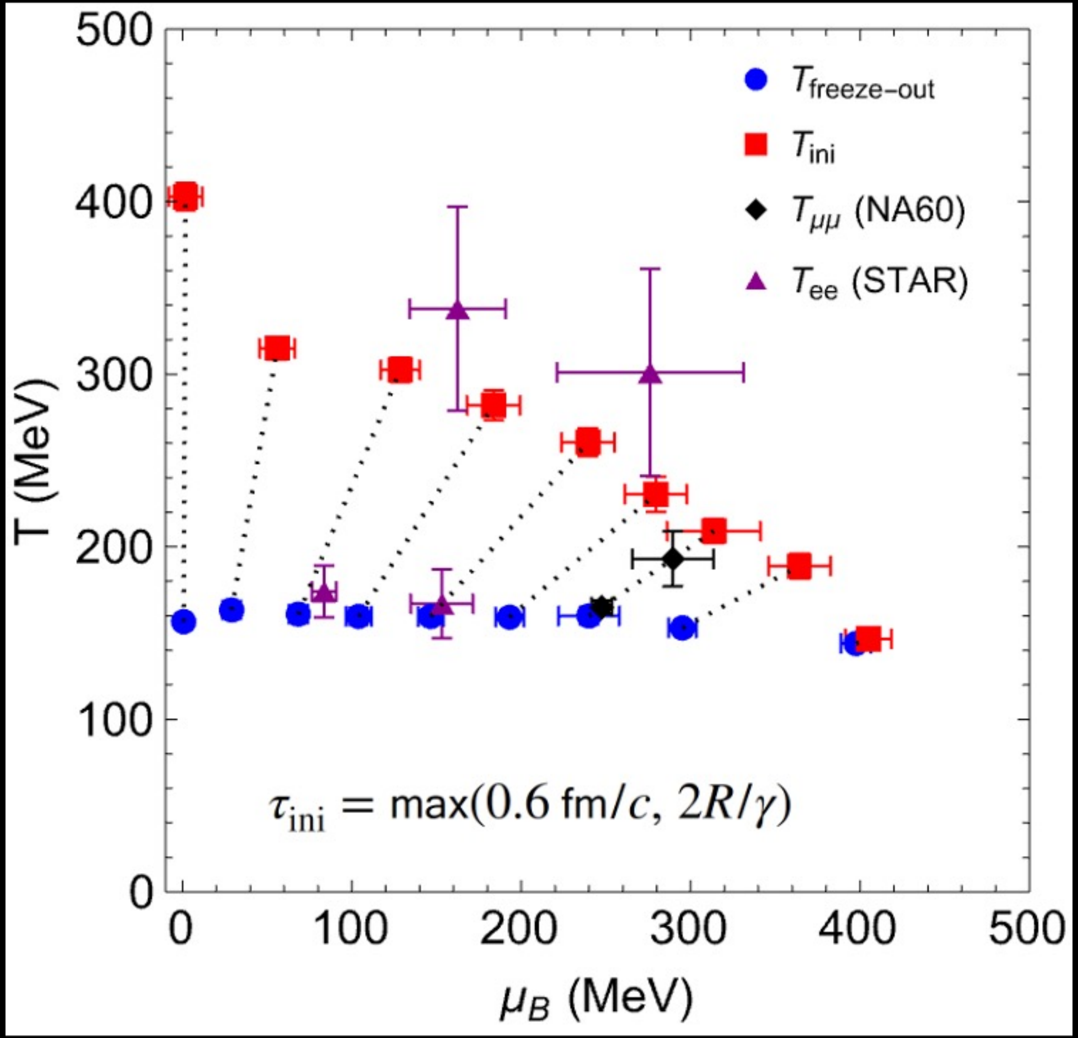


ALICE, "The ALICE experiment – A journey through QCD," arXiv:2211.04384 [nucl-ex]



Temperature T

Invariant mass spectrum of lepton pairs - > time-averaged T of medium emitting pairs



QCD Phase Diagram

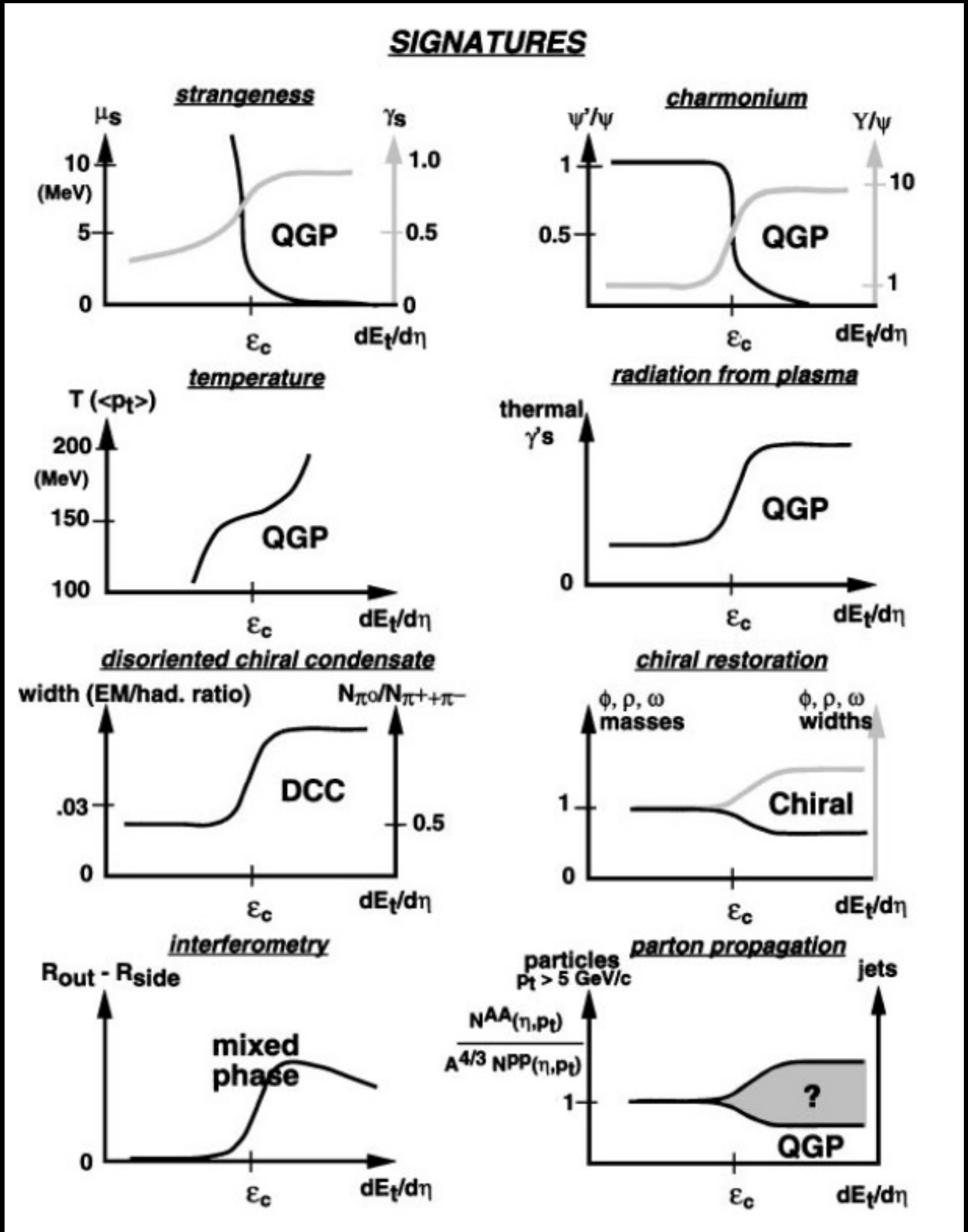
The dotted lines - lines of constant T/μB,

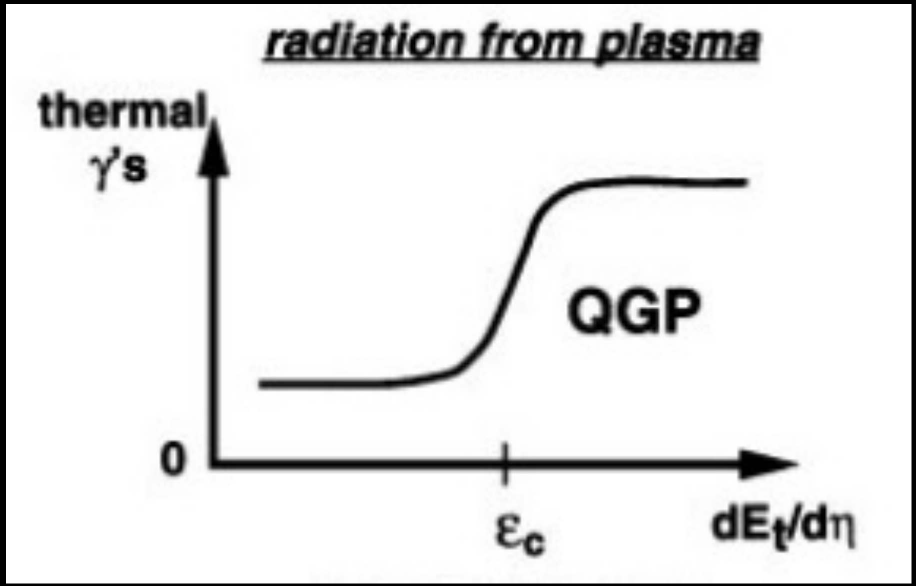
~ constant entropy per baryon in the QGP phase.

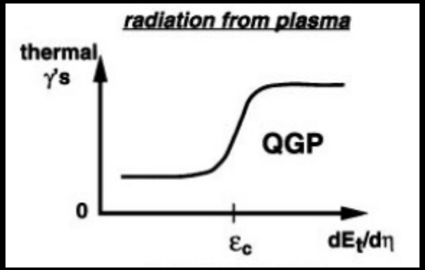
QCD phase diagram showing:

- chemical freezeout points (blue dots)
- average T_{ini} (red squares)
- T of intermediate and low mass dilepton invariant mass spectra (NA60, STAR).

Signatures – Radiation from QGP







Radiation from QGP - Measurements

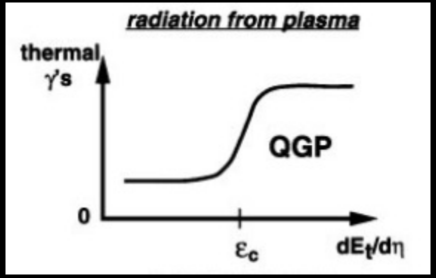
Direct photons carry information about the T of the emitting QGP

- T of QGP changes with time during collision ->

  photon spectrum is blue-shifted by the expansion

- There also can be contributions from photons radiated by the final-stage hadron gas.

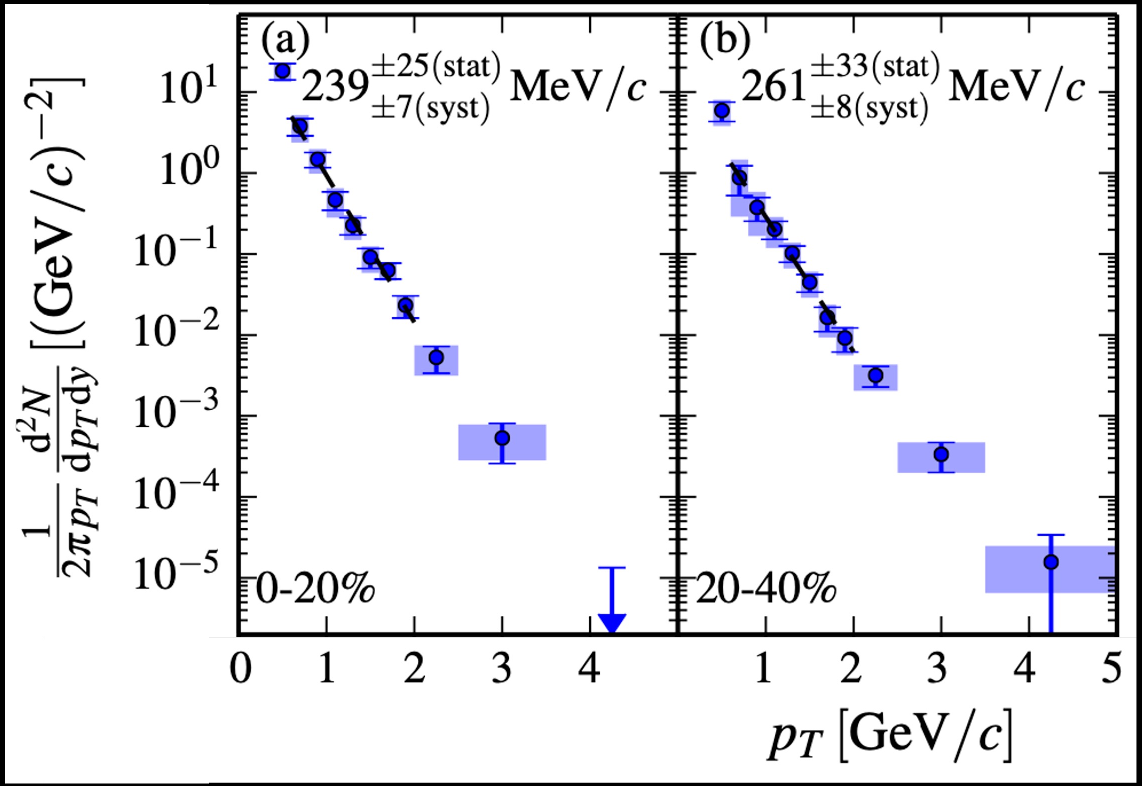
- Thus, any interpretation of measured photon spectra is therefore model dependent.



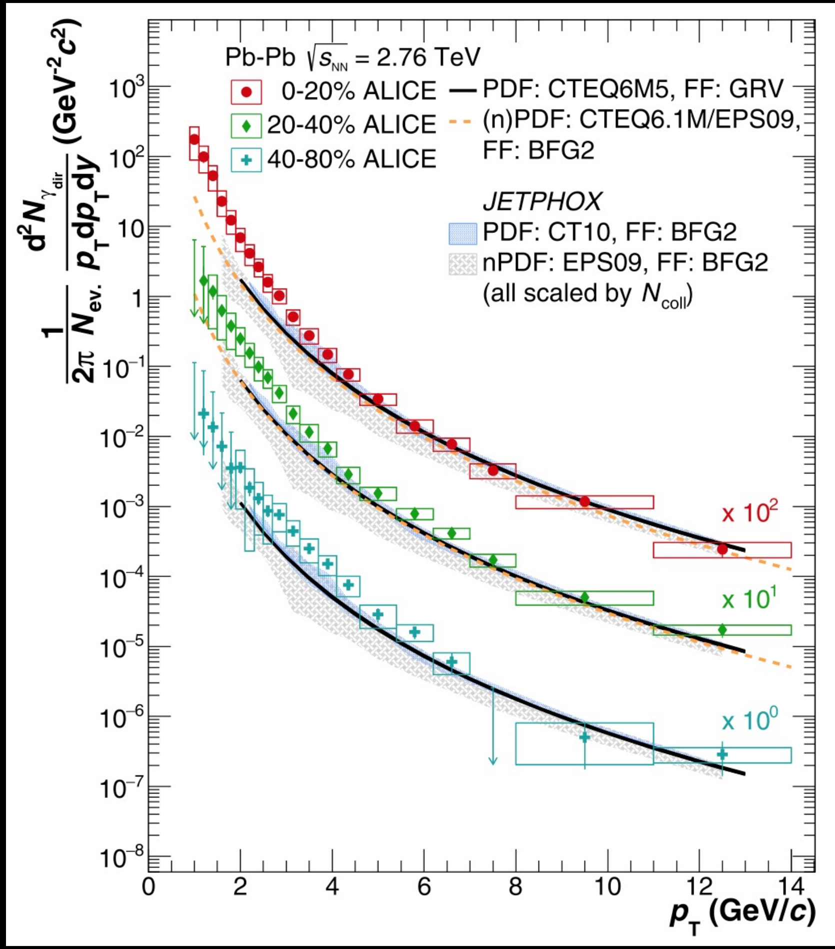
Radiation from QGP

Teff

Direct photon spectra after subtraction of N_{coll} scaled p+p

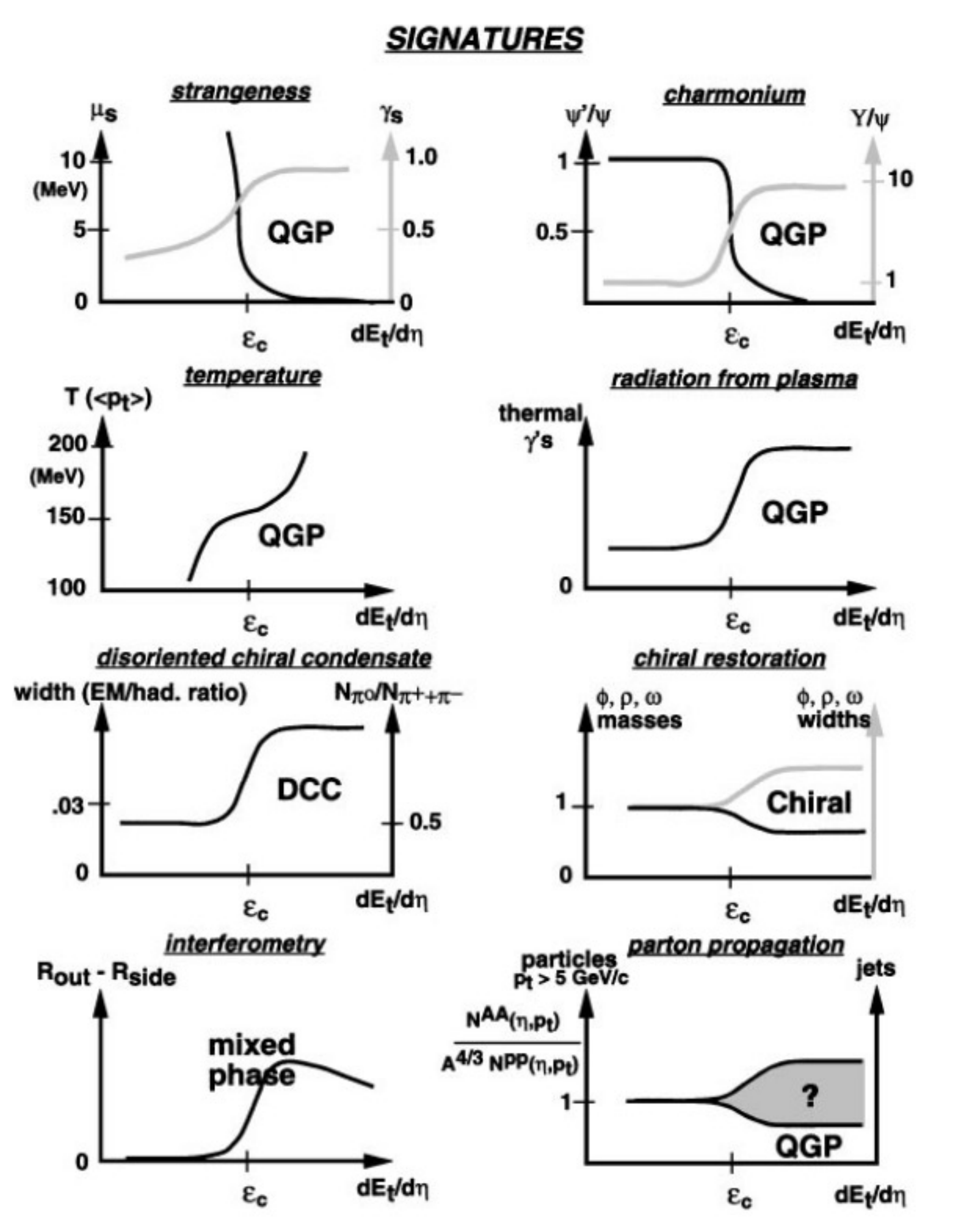


PHENIX, Phys. Rev. C 91, 064904



Teff = 297+/-12+/-41 MeV for 0-20% centrality and Teff = 410+/-84+/-140 MeV 20-40%

ALICE, Phys. Lett. B 754, 235 (2016)



Signatures – DCC

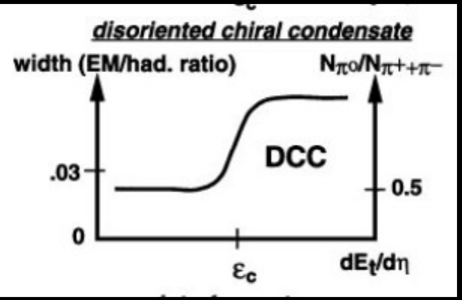
If the QGP makes a sudden transition from

A supercooled phase without chiral symmetry breaking, quark condensate q-qbar= 0,

➔ to a broken phase with a large q-qbar, with extended domains with random orientation of the chiral quark condensate q-qbar

➔ could form -> Disoriented Chiral Condensates (DCC)

K. Rajagopal and F. Wilczek, "Emergence of coherent long wavelength oscillations after a quench: Application to QCD," Nucl.Phys. B 404, 577-589 (1993).



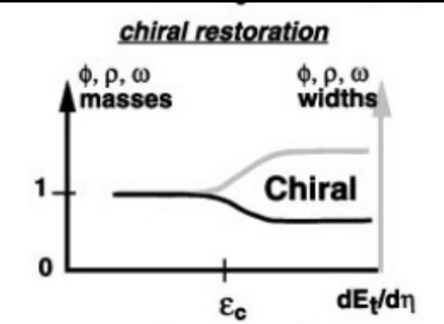
Signatures – DCCs So Far

The formation and decay of domains of DCCs would reveal itself by non-Poissonian fluctuations of the neutral-to-charged pion ratio $N(\pi^0)/N(\pi^{+/-})$. Precondition for such a scenario is that the fireball evolves far out of equilibrium during the chiral transition.

None found so far!

B. Mohanty and J. Serreau, “Disoriented chiral condensate: theory and experiment,” Phys. Rept. 414, 263 (2005).

L. Adamczyk et al. [STAR], “Charged-to-neutral correlation at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV,” Phys. Rev. C 91, 034905 (2015)



Signatures – Chiral Restoration

A defining characteristic of the QGP is restoration of chiral symmetry

Lattice QCD identifies crossover transition at Tc between hadronic gas phase and a QGP phase.*

For T < Tc

the chiral condensate approaches its vacuum value

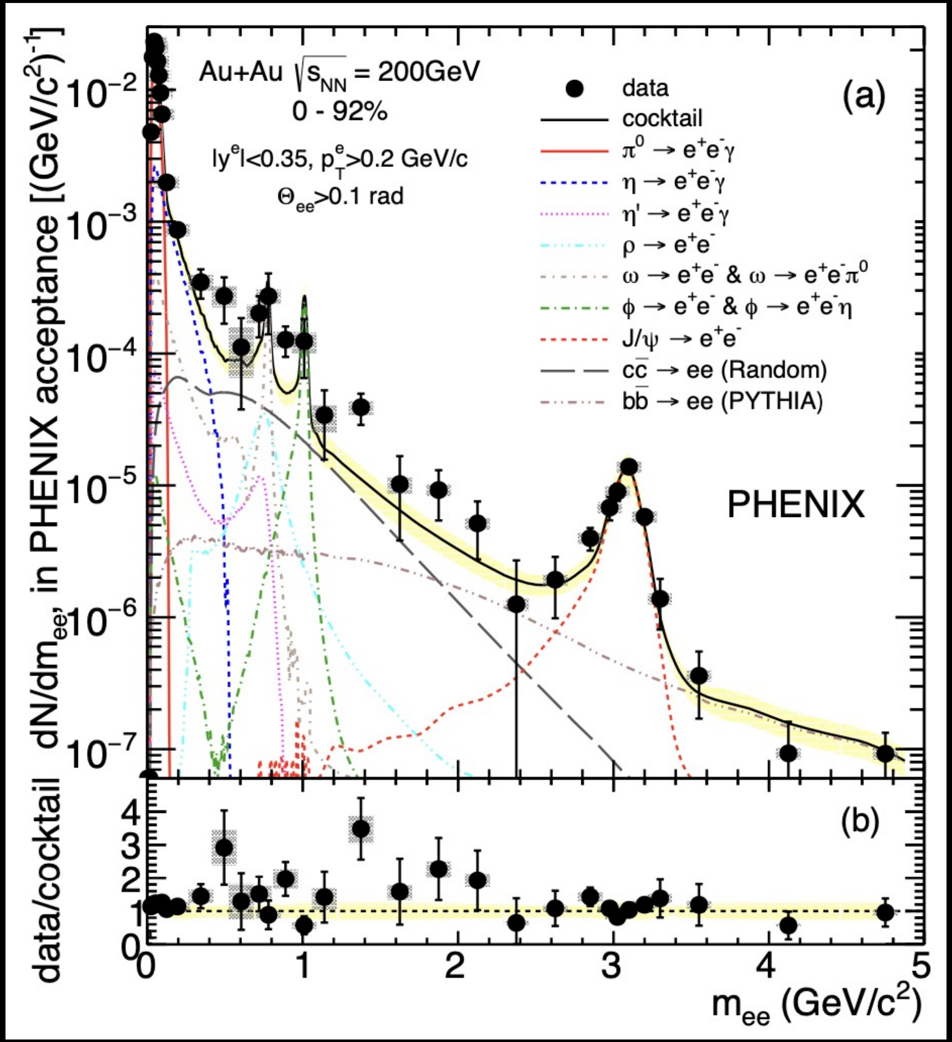
For T > Tc

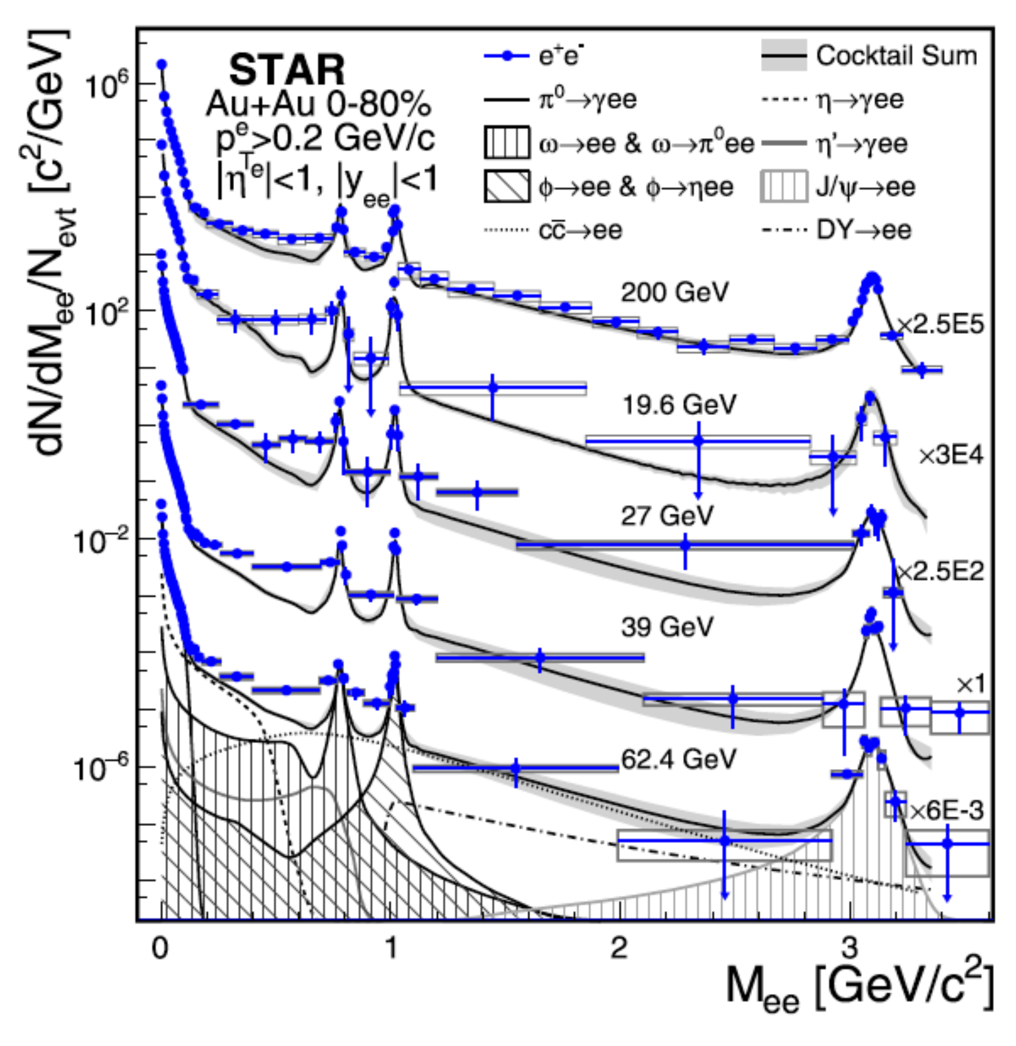
the condensate rapidly approaches 0 -> restoration of spontaneously broken chiral symmetry

A direct consequence of chiral symmetry restoration above Tc is that excitation modes that differ only by parity must become degenerate!

* Tc is the inflection point in the T dependence of the renormalized chiral condensate ⟨ψbar ψ⟩, i.e. by the location of the maximum of the chiral susceptibility.

Chiral Restoration

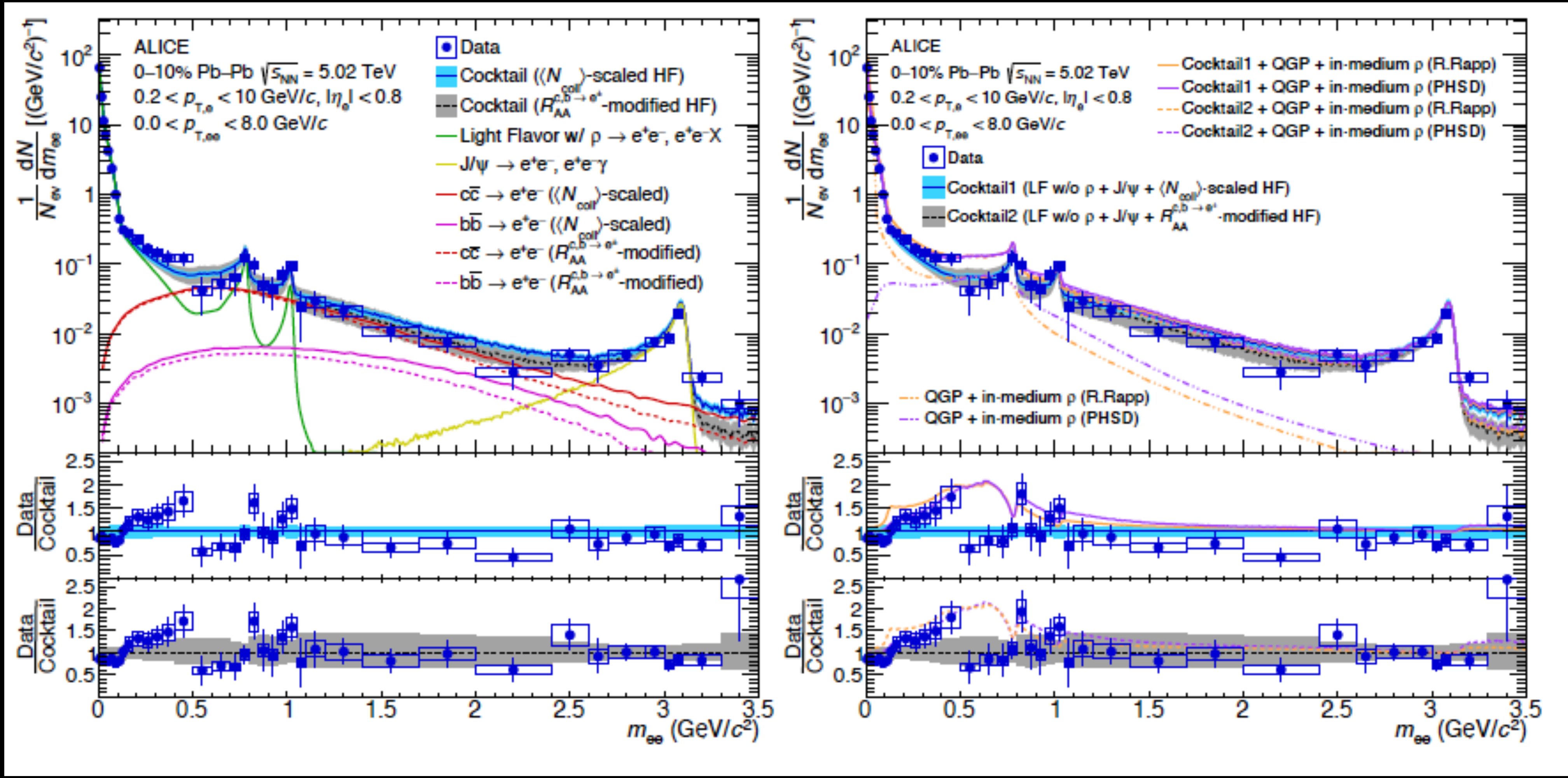




[PHENIX], “Dielectron production in Au+Au collisions … ,” Phys. Rev. C 93, 014904 (2016)

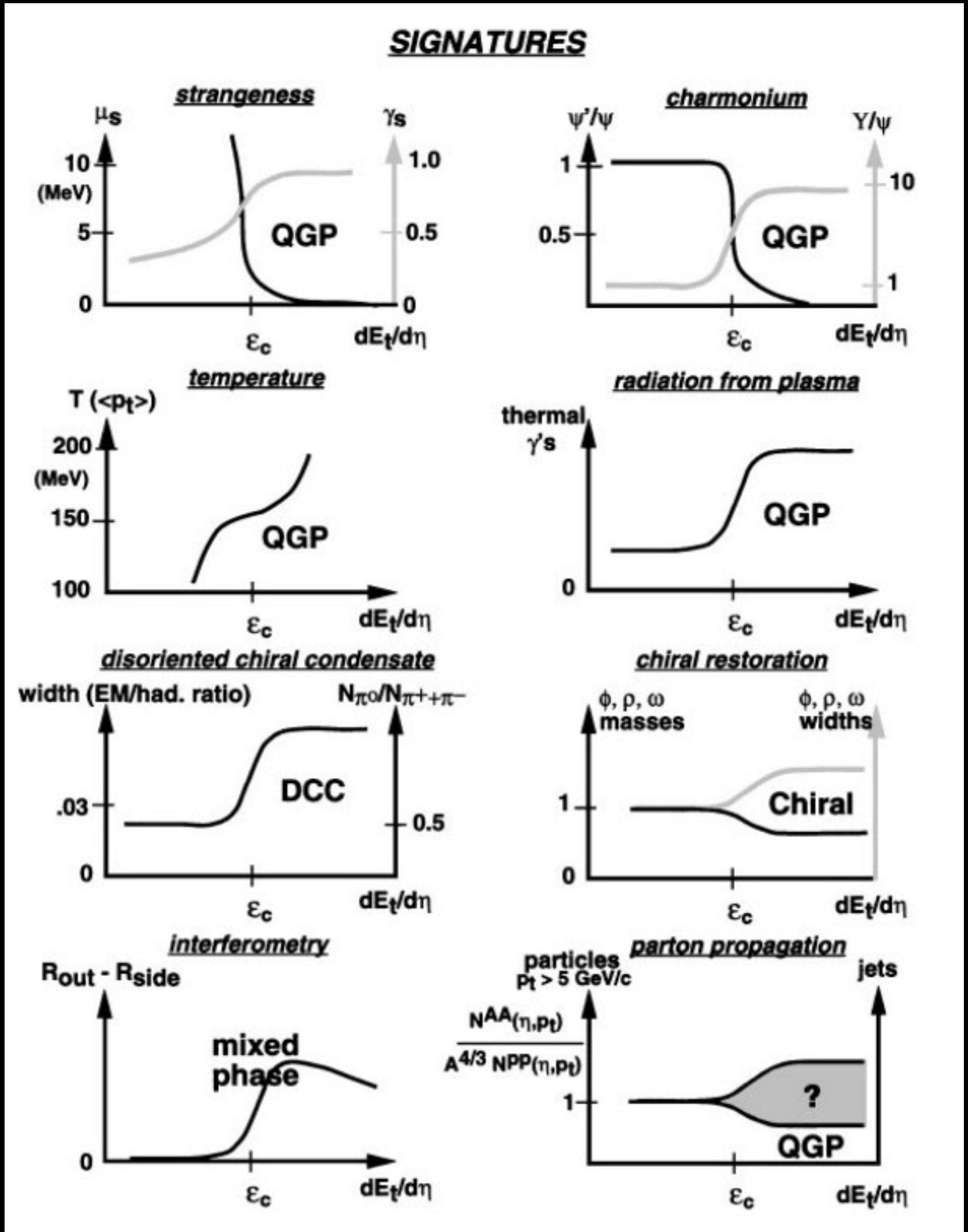
STAR, “Measurements of dielectron production in Au+Au collisions in …,” Phys. Rev. C 107, L061901 (2023)

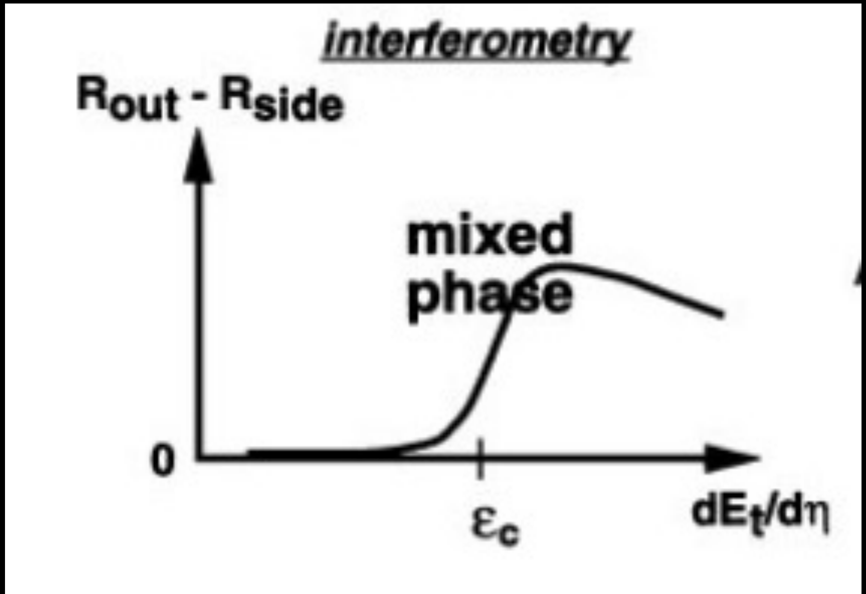
Chiral Restoration – Now

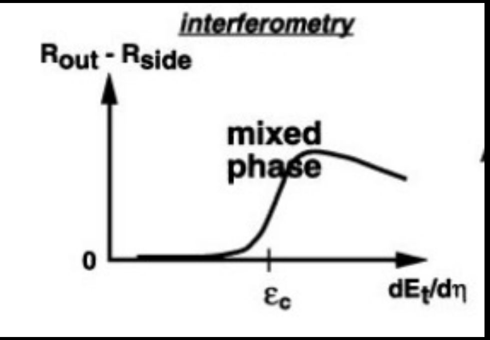


ALICE, "Dielectron production in central Pb–Pb collisions at 5.02 TeV," [arXiv:2308.16704 [nucl-ex]].

Signatures – Femtoscopy

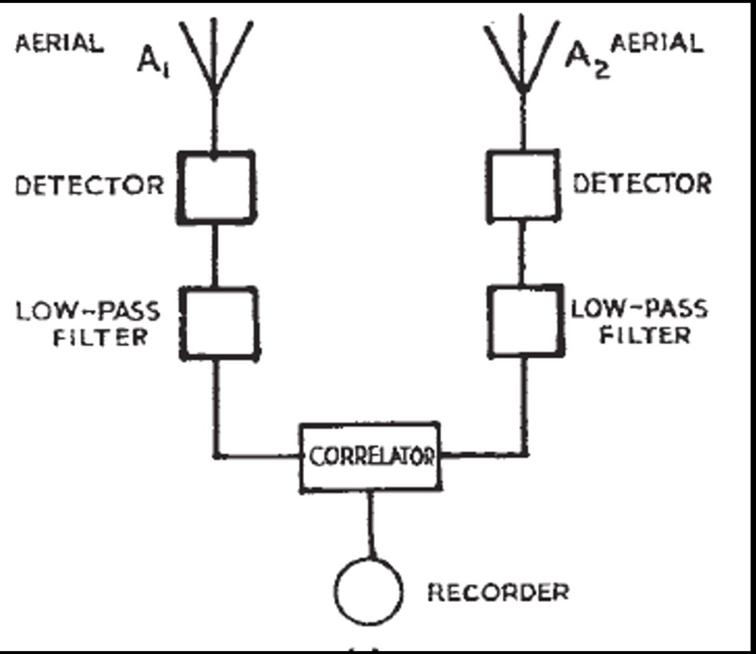






Femtoscopy Then

Brown, R., Twiss, R. “Correlation between Photons in two Coherent Beams of Light,” *Nature* **177**, 27–29 (1956).



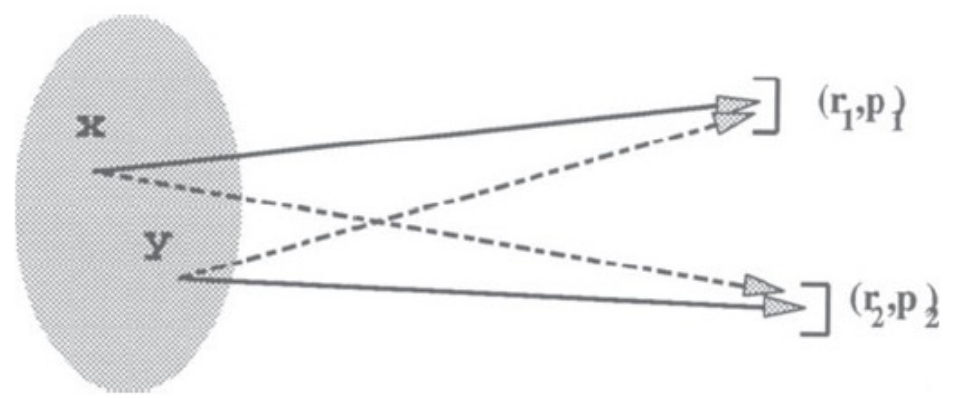
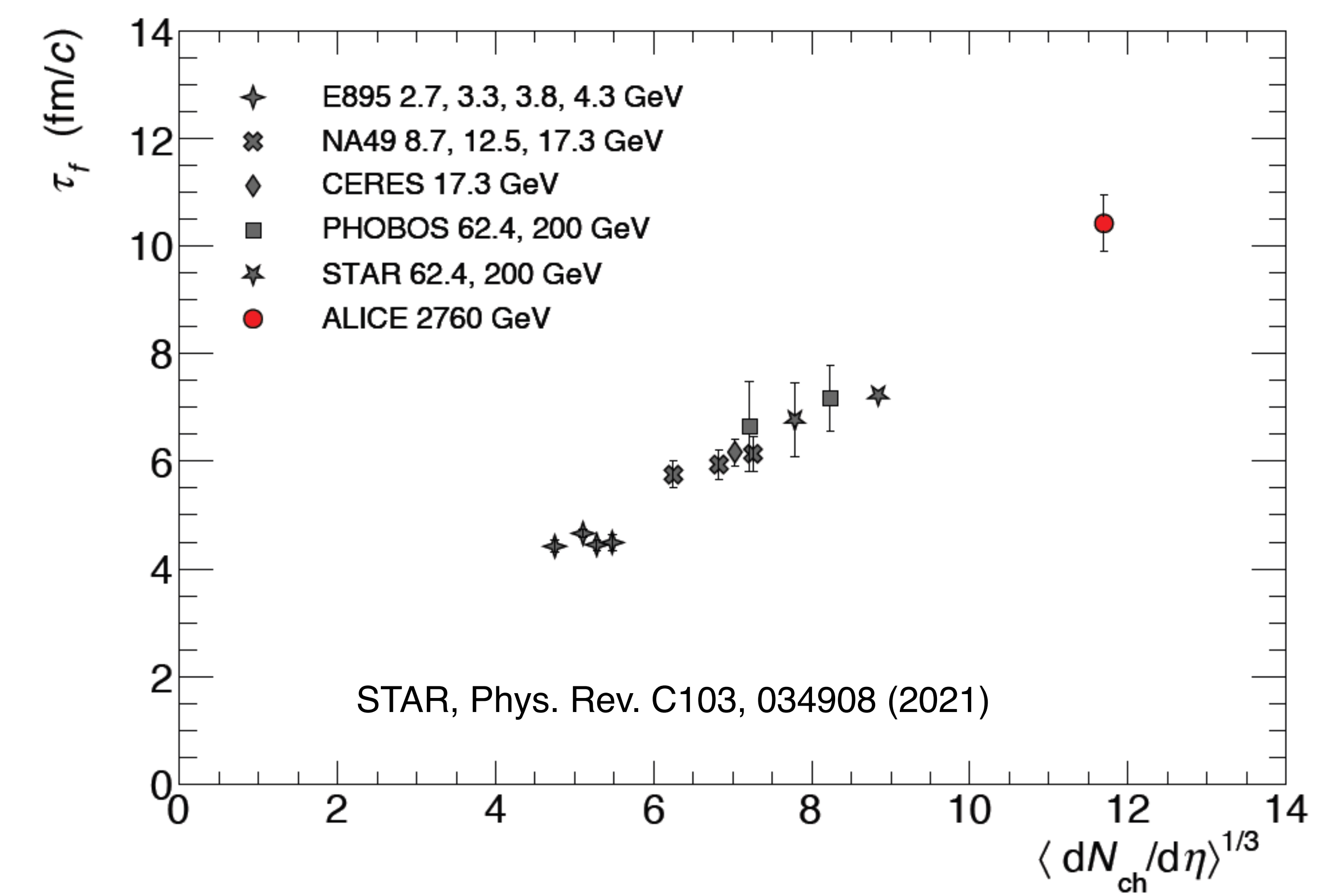


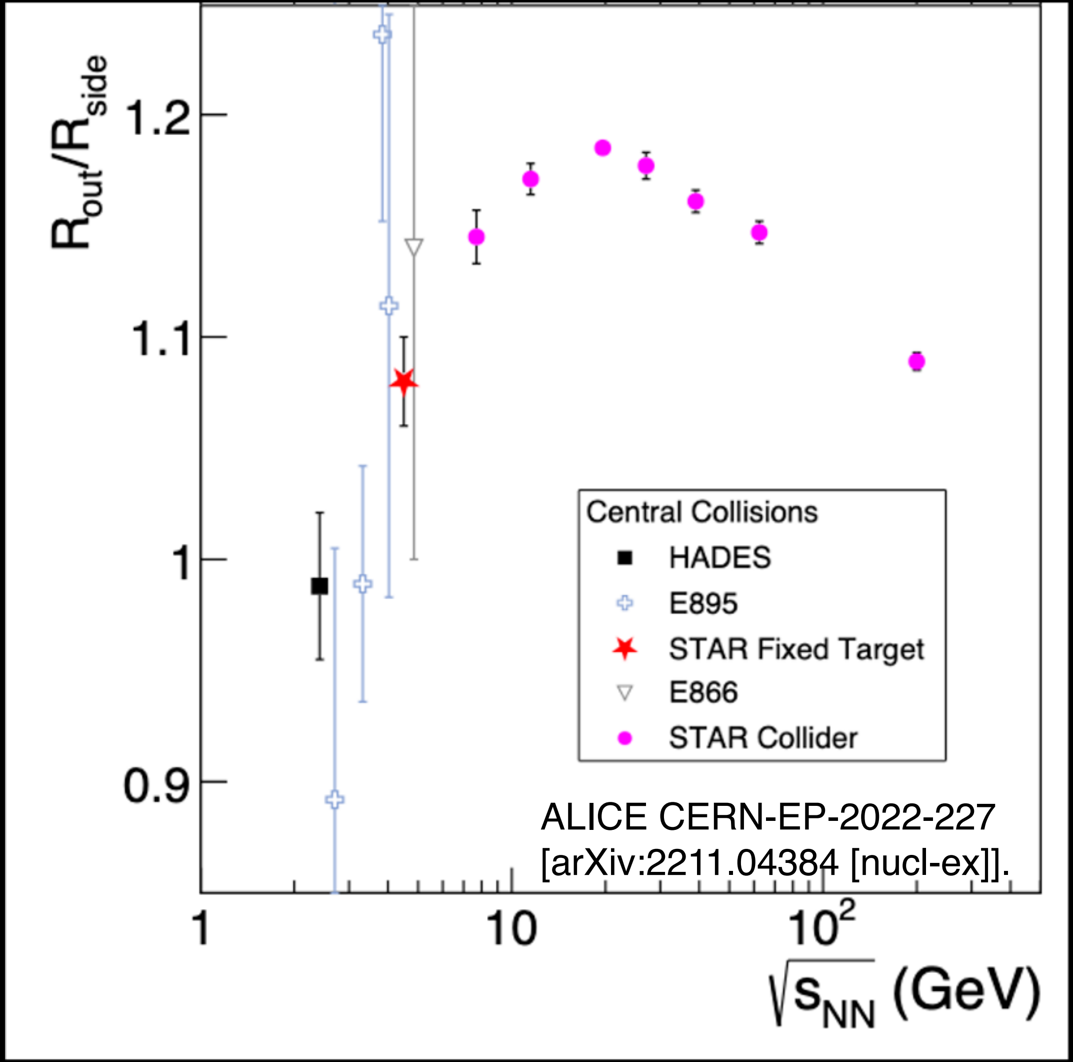
Figure 1: The two indistinguishable processes leading to the detection of identical pions with momentum p_1 at r_1 and p_2 at r_2.

W. A. Zajc, “A pedestrian’s guide to interferometry,” NATO Sci. Ser. B 303, 435 (1993).

Femtoscopy Since

Life-time parameter as a function of the $(dn/d\eta)^{1/3}$ vs c.m. energy

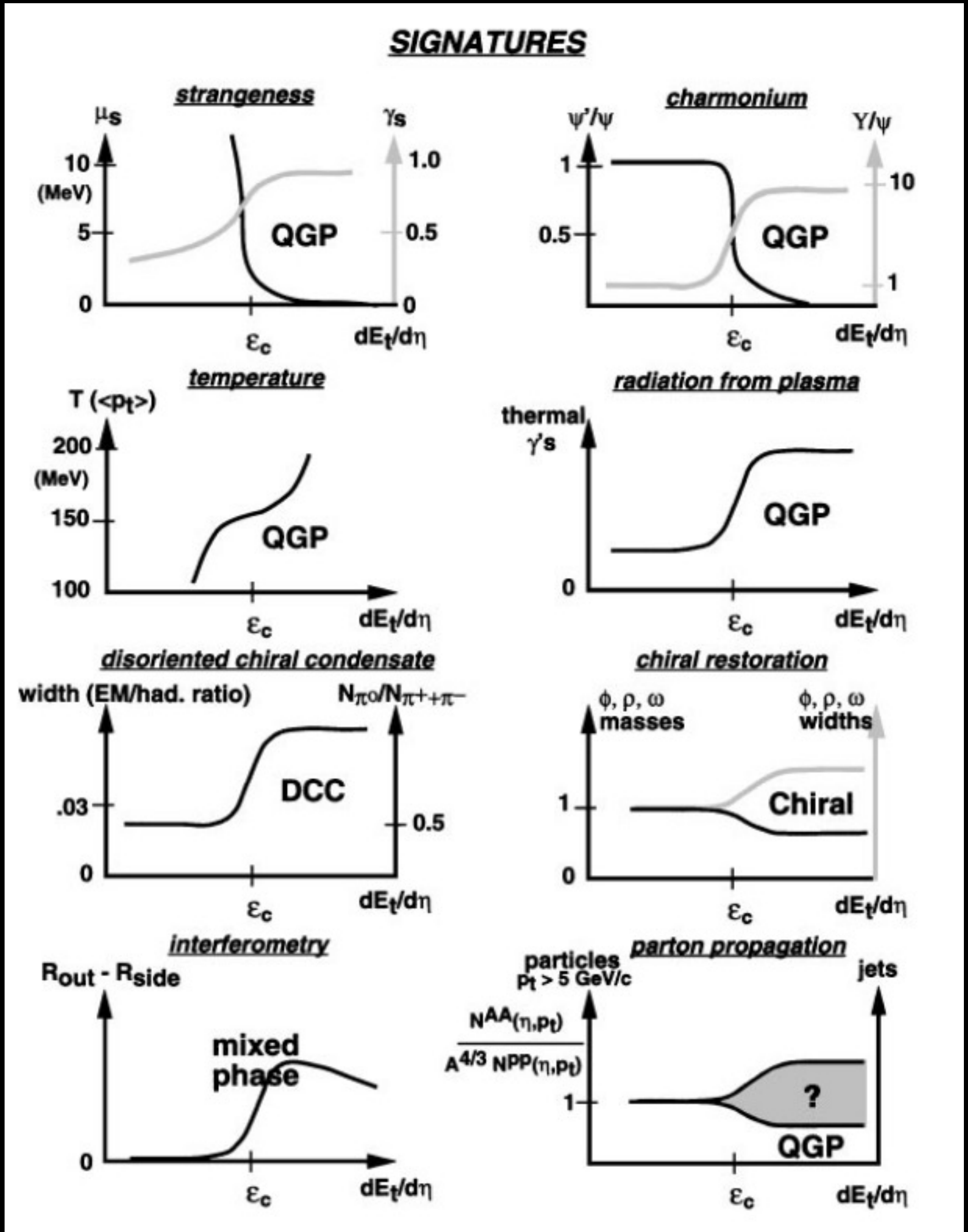


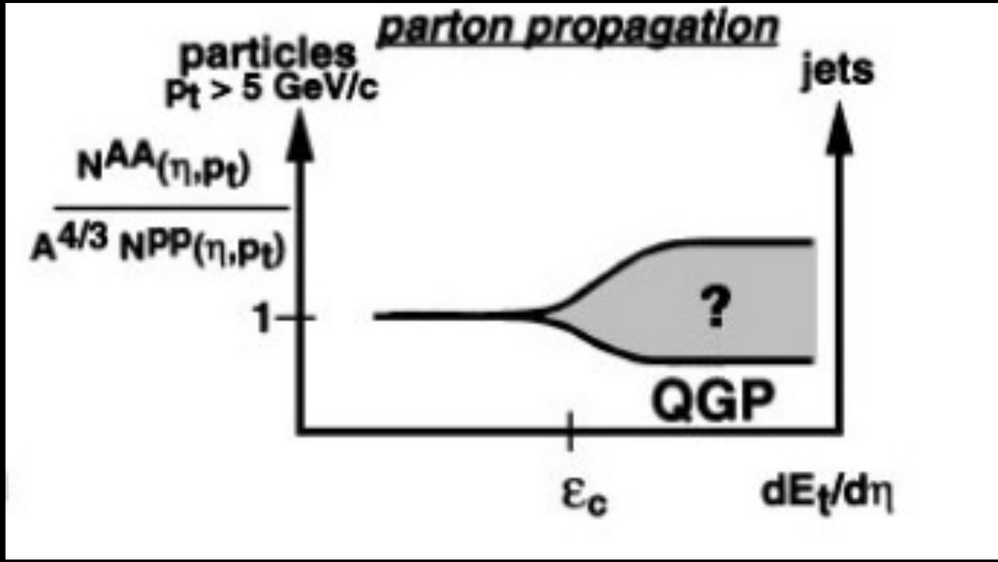


Life-time increases smoothly from 4 ~ 10 fm/c

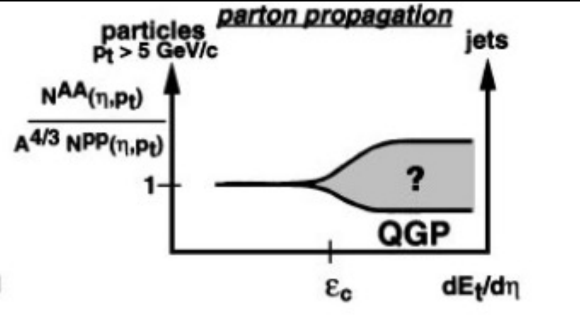
Minimum of the compressibility around Tc during hadron emission?

Signatures – Parton Propagation





Parton Propagation – Jets Then



FERMILAB-Pub-82/59-THY
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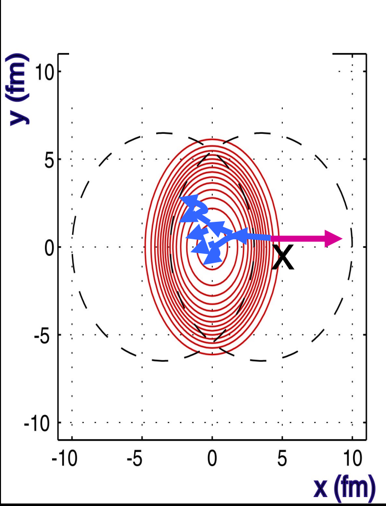
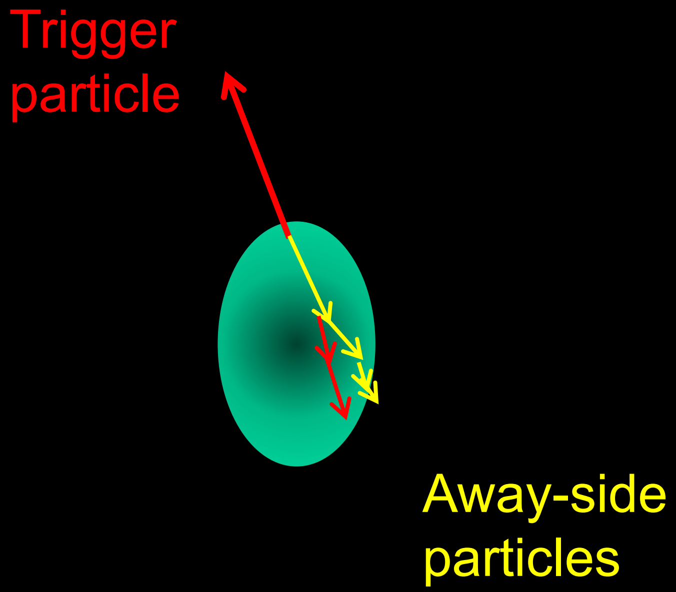
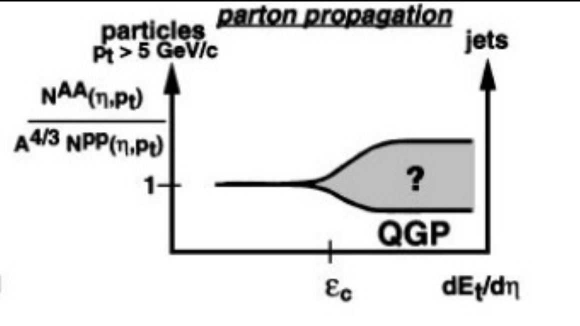






Parton Propagation (High p_T Particles) Then

M. Gyulassy and M. Plumer, "Jet Quenching in Dense Matter," Phys. Lett. B 243 (1990), 432

X. N. Wang and M. Gyulassy, "Gluon shadowing and jet quenching in A + A collisions at 200 GeV," Phys. Rev. Lett. 68 (1992), 1480

VOLUME 68, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1992

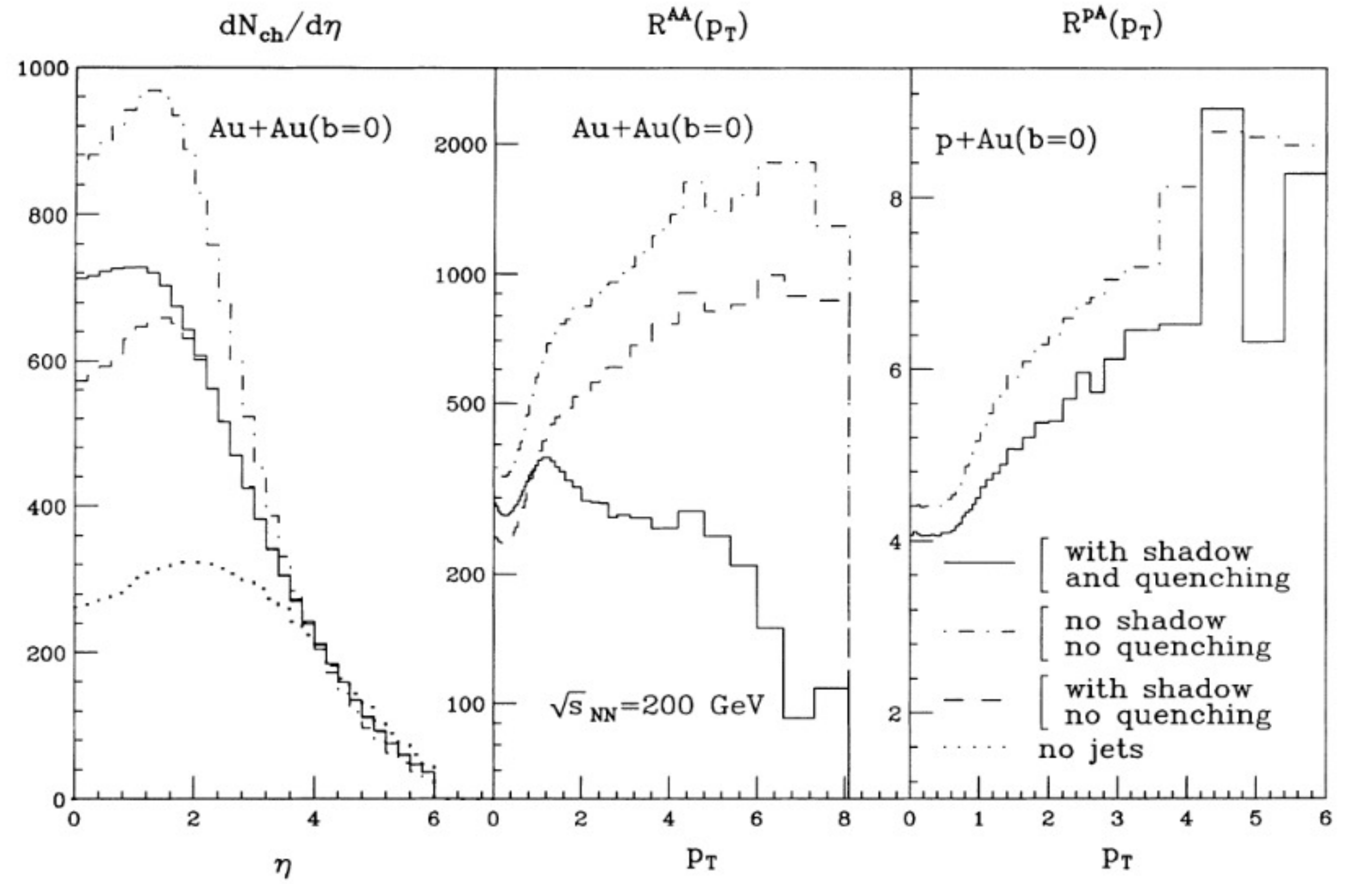
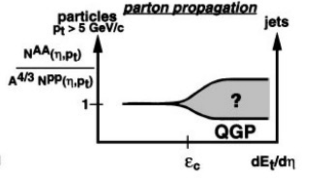
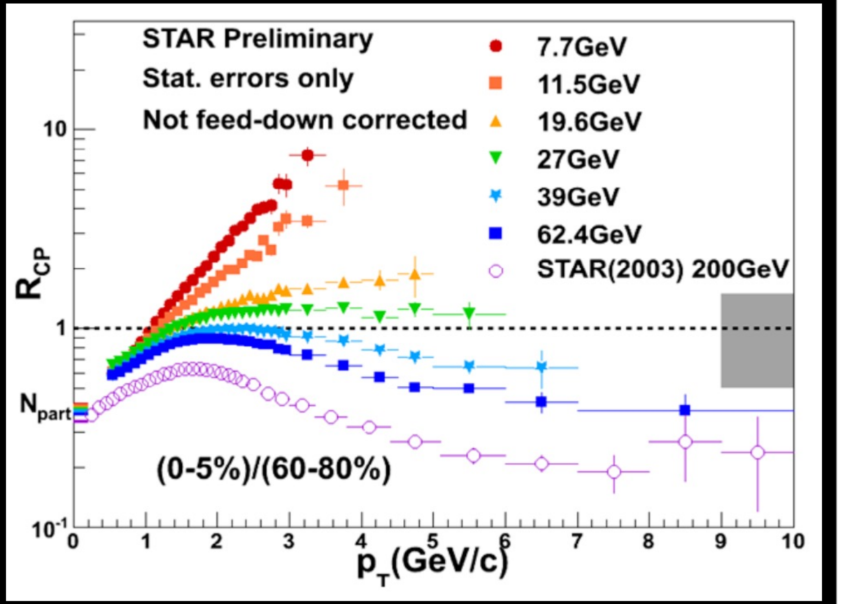
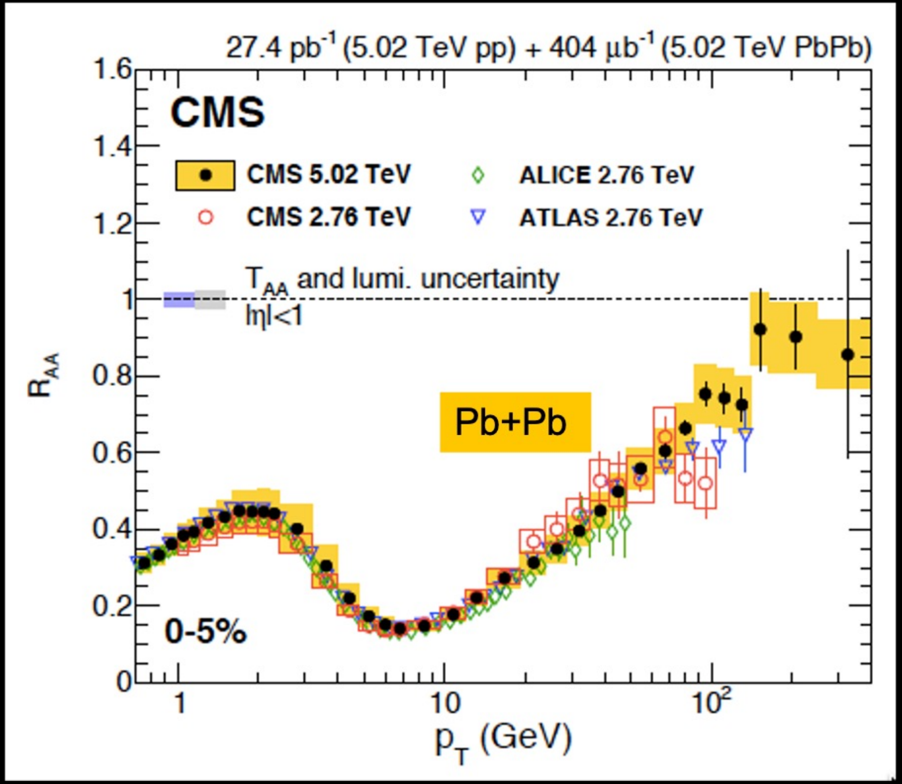


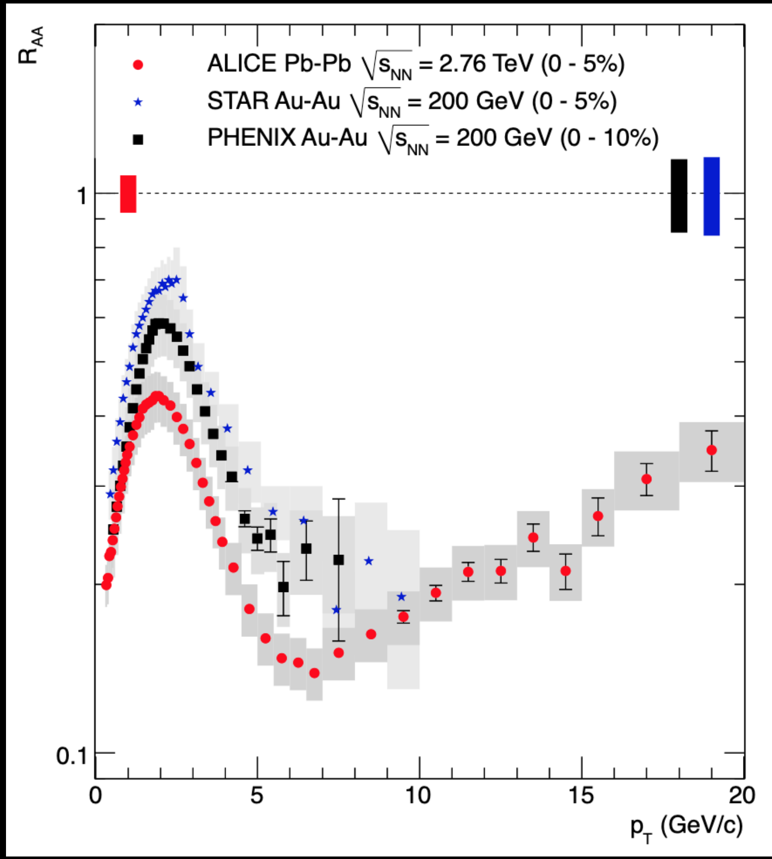
FIG. 1. Results of HIJING on the dependence of the inclusive charged-hadron spectra in central Au+Au and p+Au collisions on minijet production (dash-dotted line), gluon shadowing (dashed line), and jet quenching (solid line) assuming that gluon shadowing is identical to that of quarks and $dE/dl = 2$ GeV/fm with $\lambda_s = 1$ fm. $R^{AB}(p_T)$ is the ratio of the inclusive p_T spectrum of charged hadrons in $A+B$ collisions to that of $p+p$.



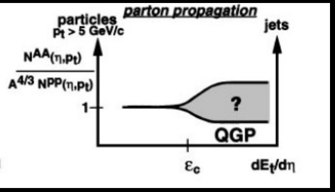
Parton Propagation – High p_T Particles Suppressed



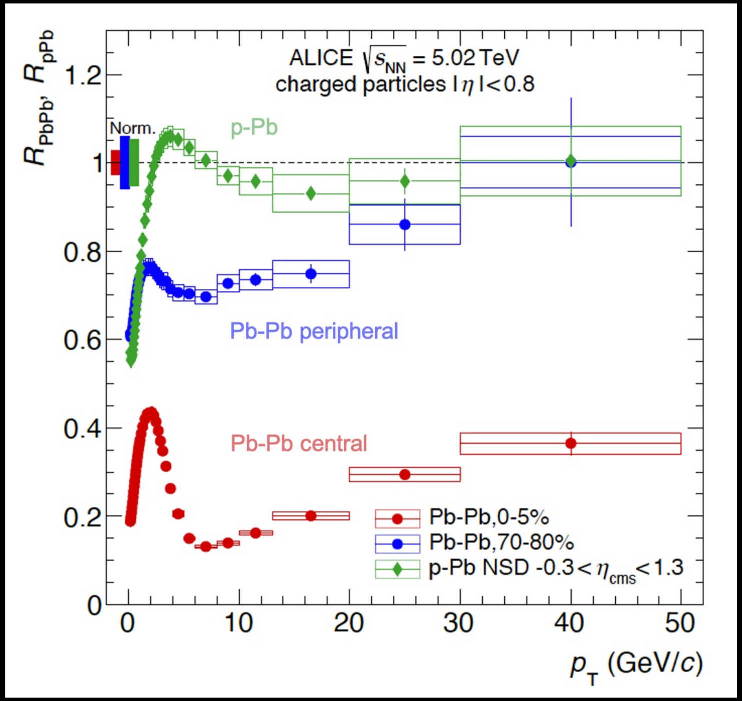


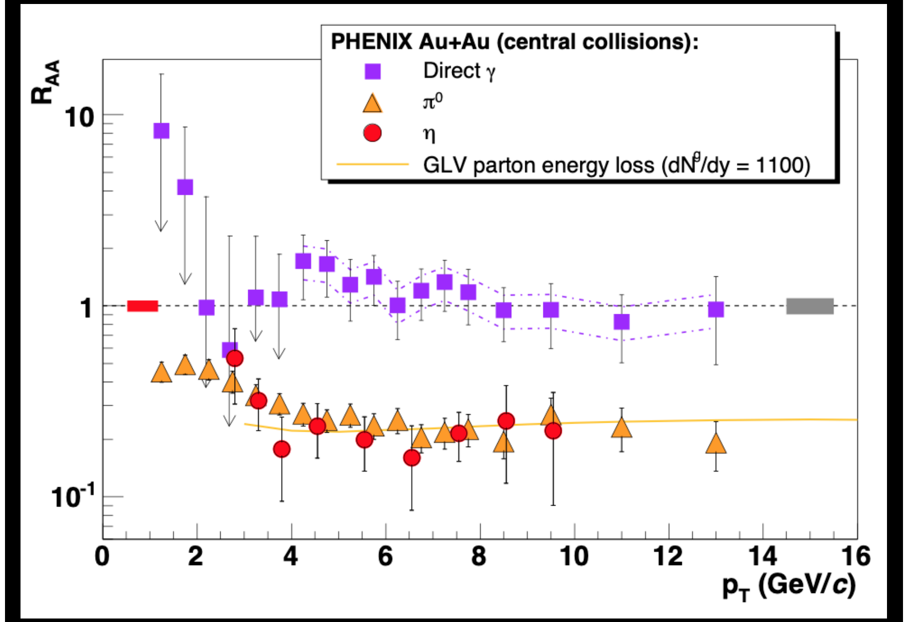


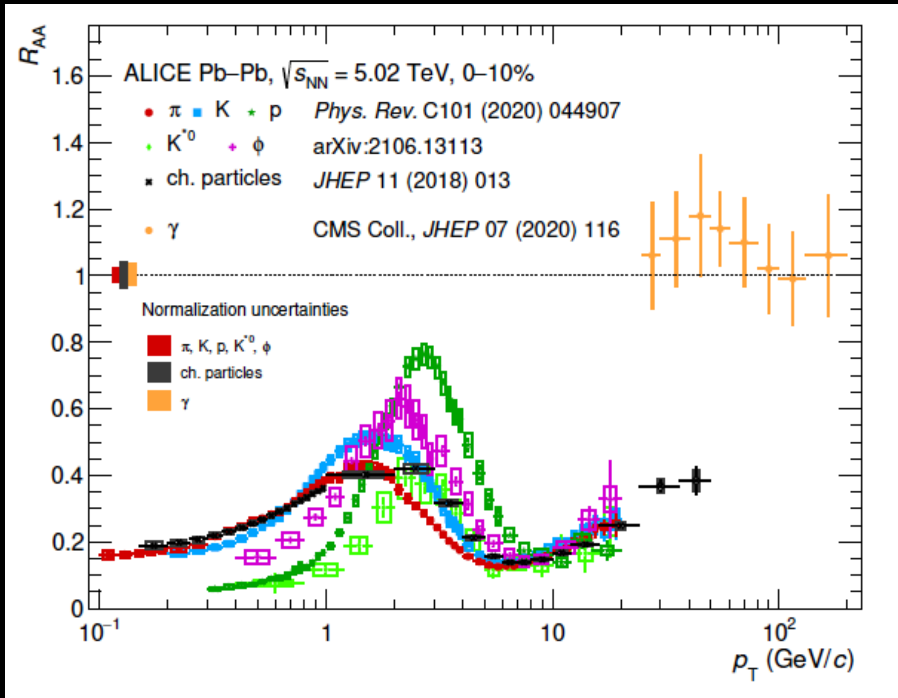
Charged particles in Au+Au (Pb+Pb) are suppressed compared to scaled-pp at high p_T
over large collision energy range



Parton Propagation – EM Probes Not Suppressed

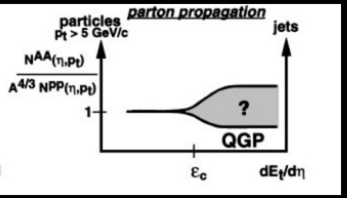




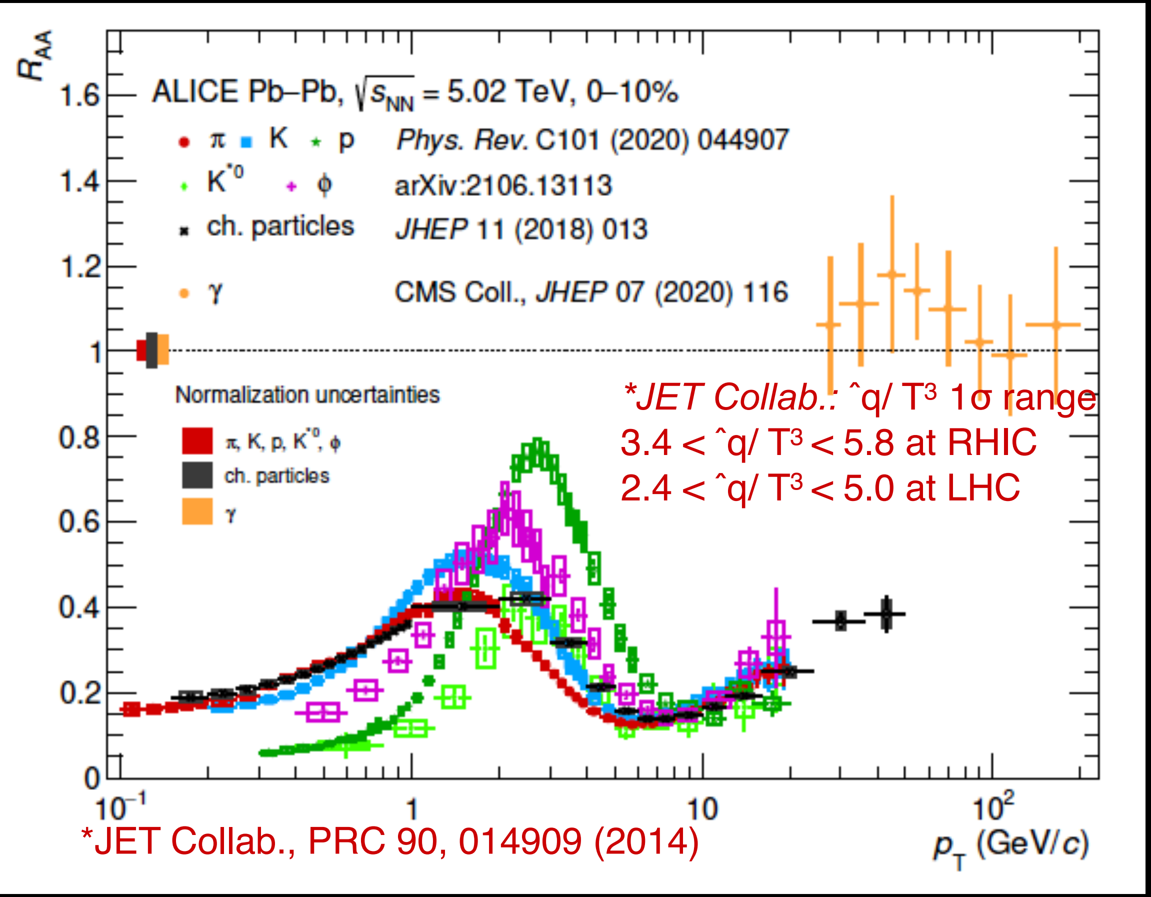


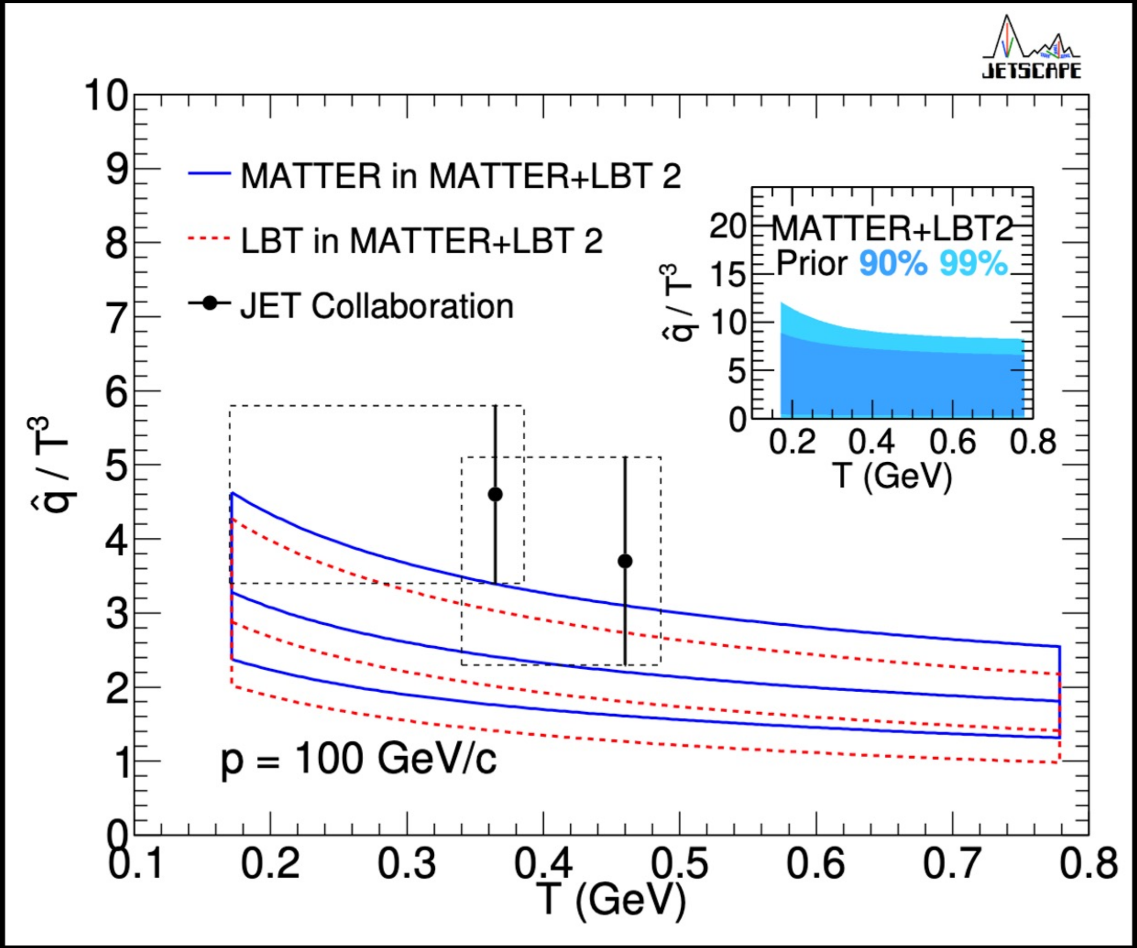
Charged particles in Au+Au (Pb+Pb) suppressed at high p_T
Not suppressed in p+A

EM probes unaffected at RHIC & LHC
Pattern differences when particles identified!



Parton Propagation – Parton Energy Loss in QGP

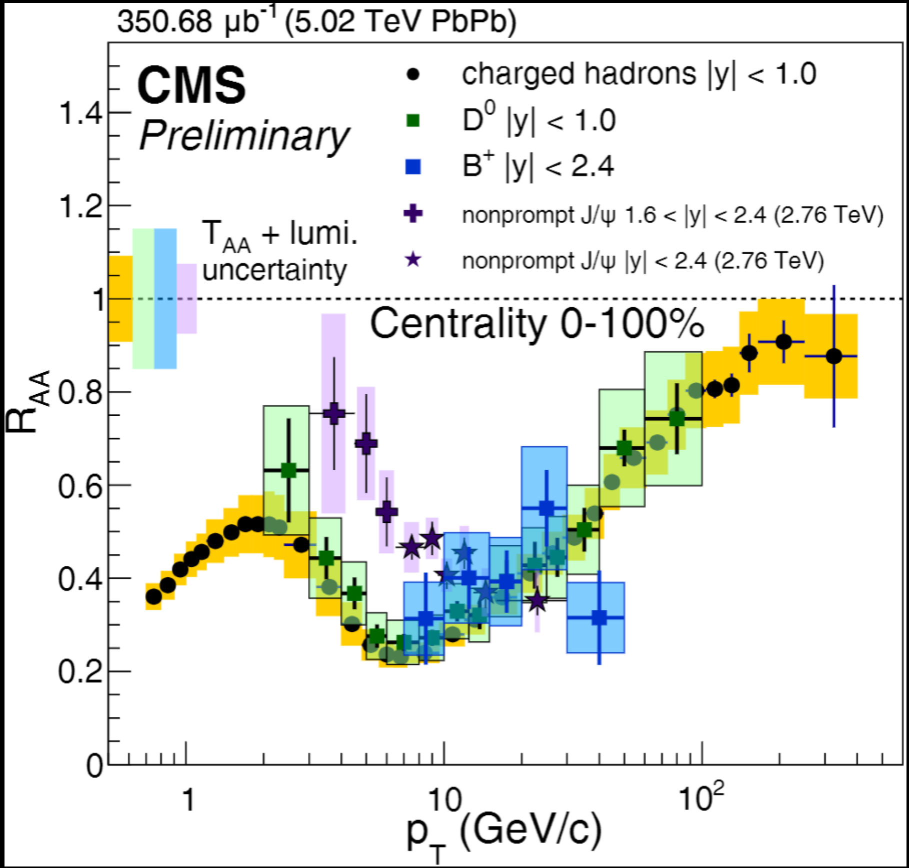




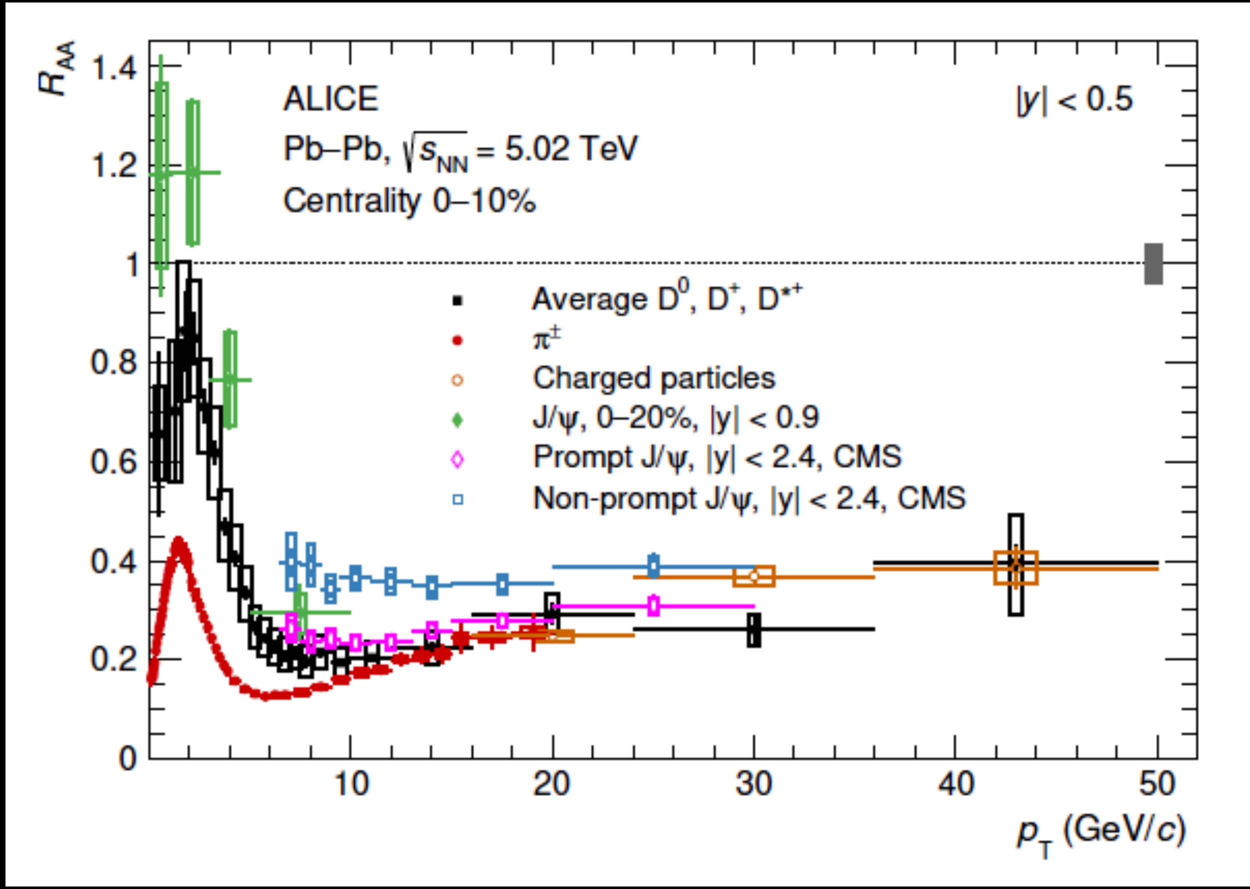
Particle-specific effects at low p_T
[R_{AA} affected by collective flow & recombination]
→ Universal behavior of "light" hadrons at high p_T

Flavor Dependence of Identified-Hadron Suppression

CMS, arXiv: 1611.01664,1610.00613

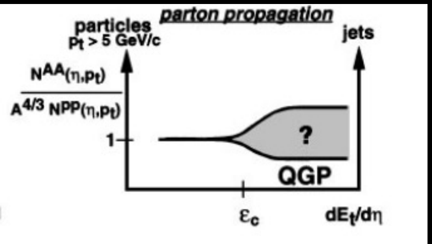


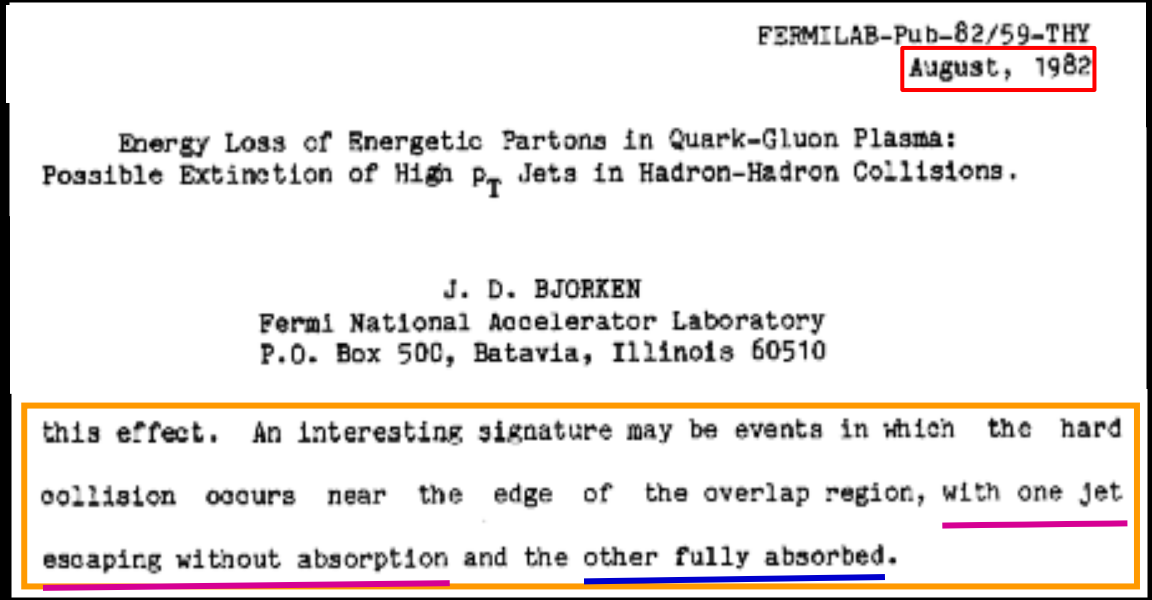
ALICE, arXiv:2211.04384 [nucl-ex] (2022)



→ Flavor dependence seen in inclusive CMS data for p_T < 10 GeV/c
Enhanced suppression hierarchy (J/ψ, D, π) observed in 0-10% central collisions

Parton Propagation – High Momentum Correlations





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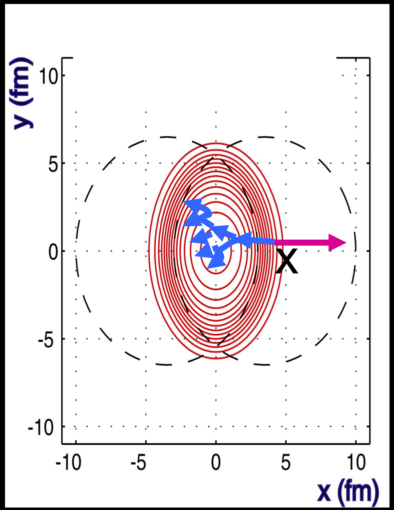
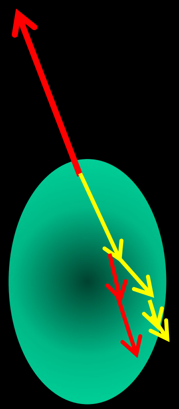
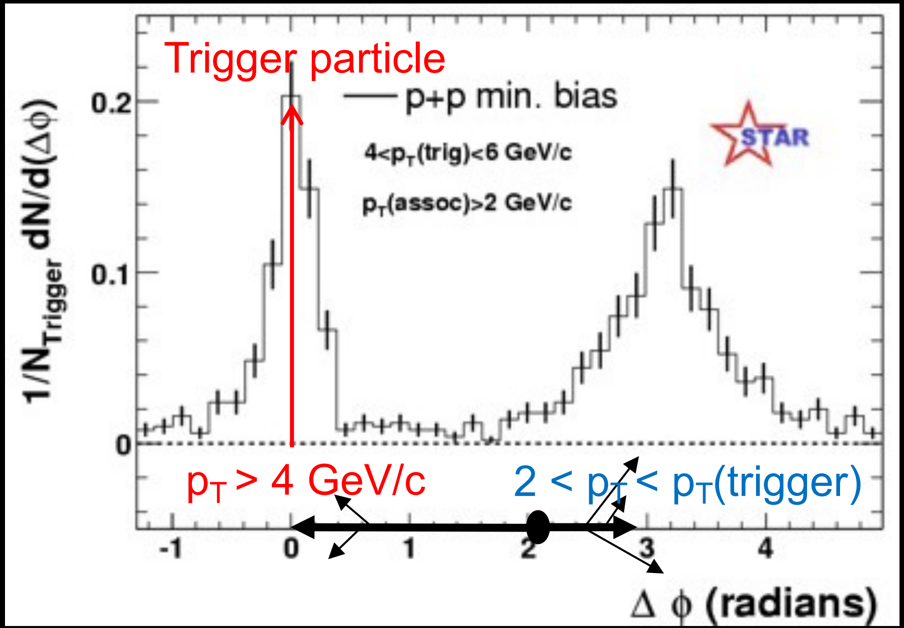
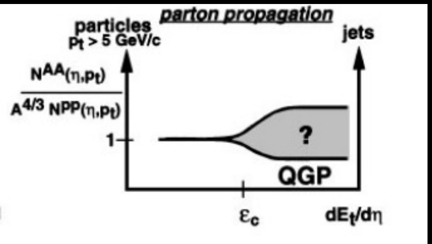


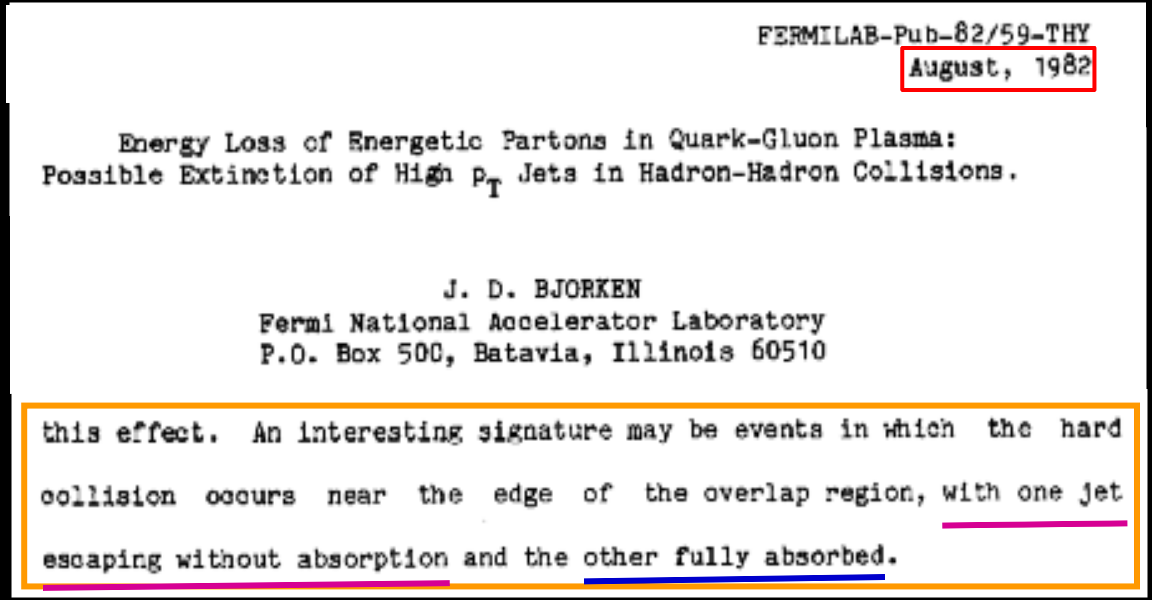




STAR, Phys.Rev.Lett. 91 (2003) 072304

Parton Propagation – High Momentum Correlations





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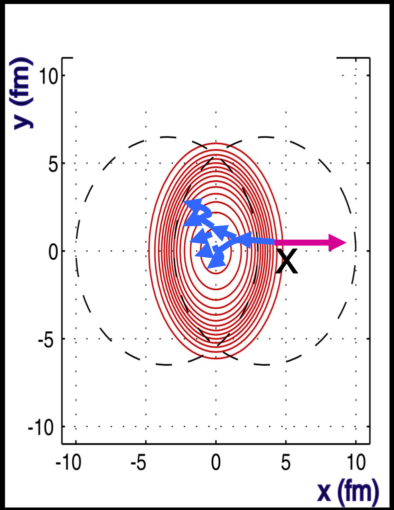
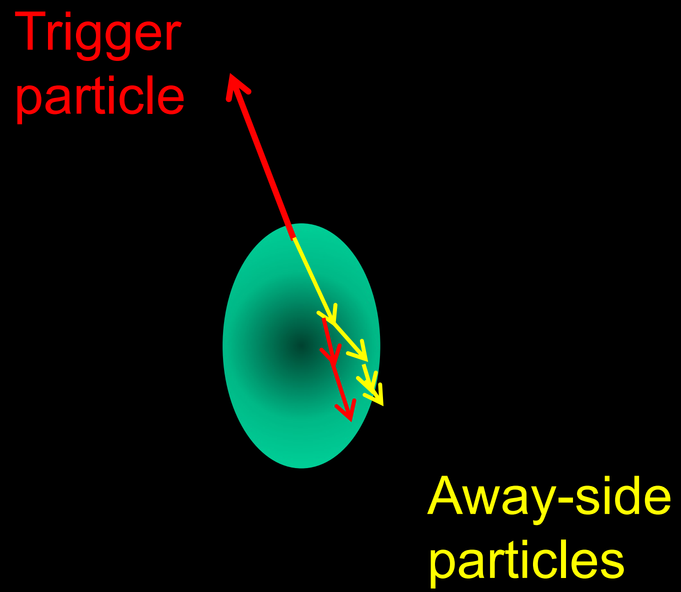
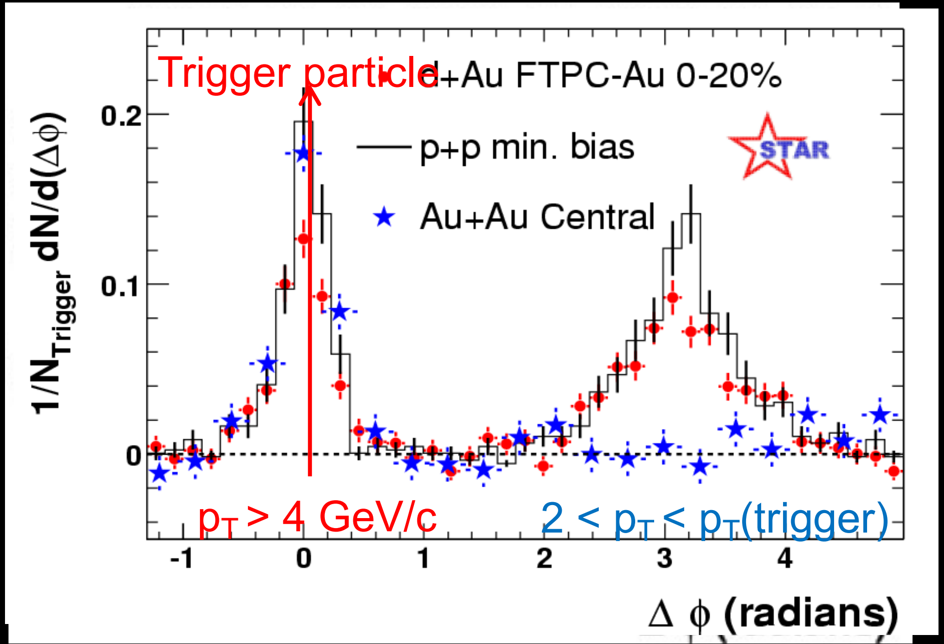


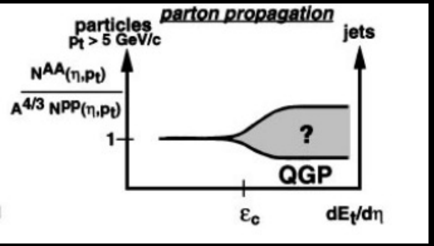


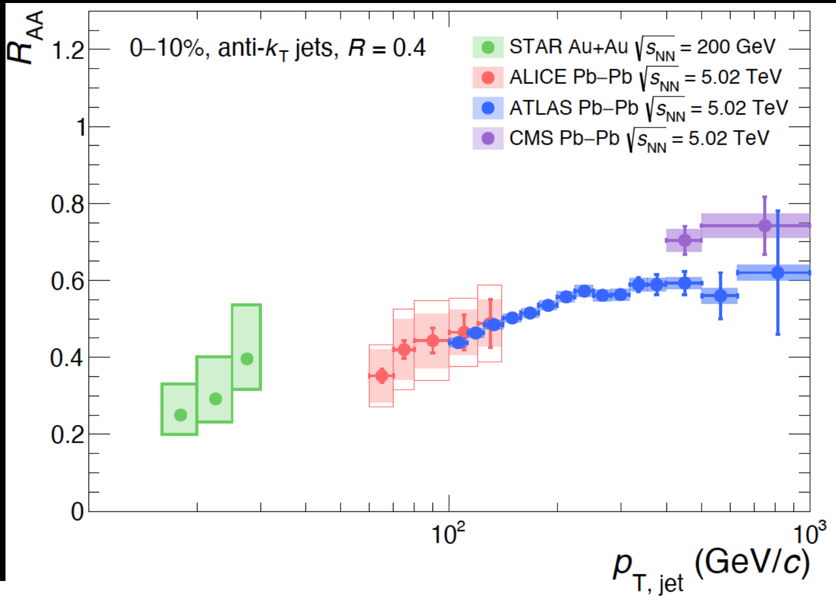
Quenching of Away-side "jet" is a final state effect

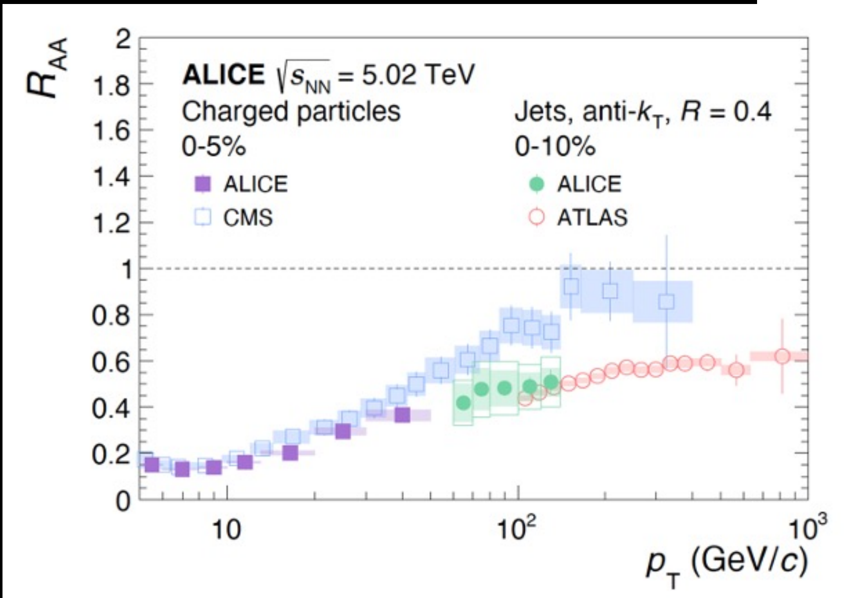
STAR, Phys.Rev.Lett. 91 (2003) 072304

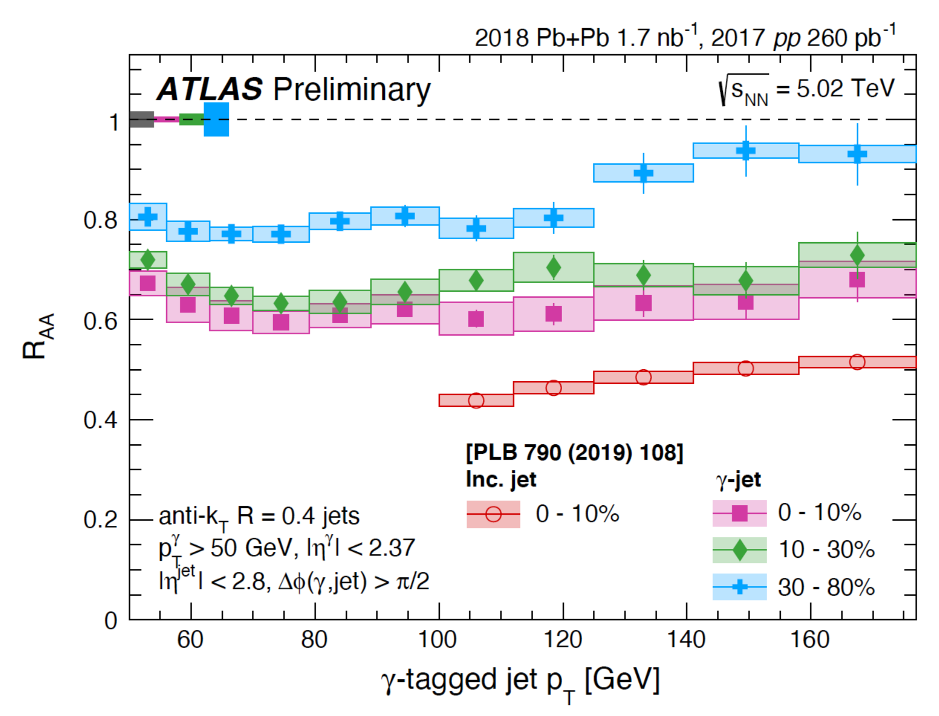


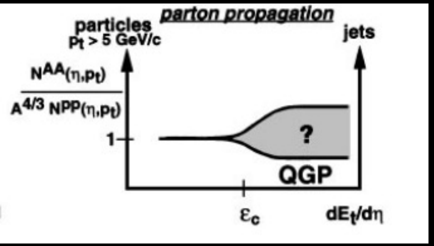
Parton Propagation – Particles and Jets











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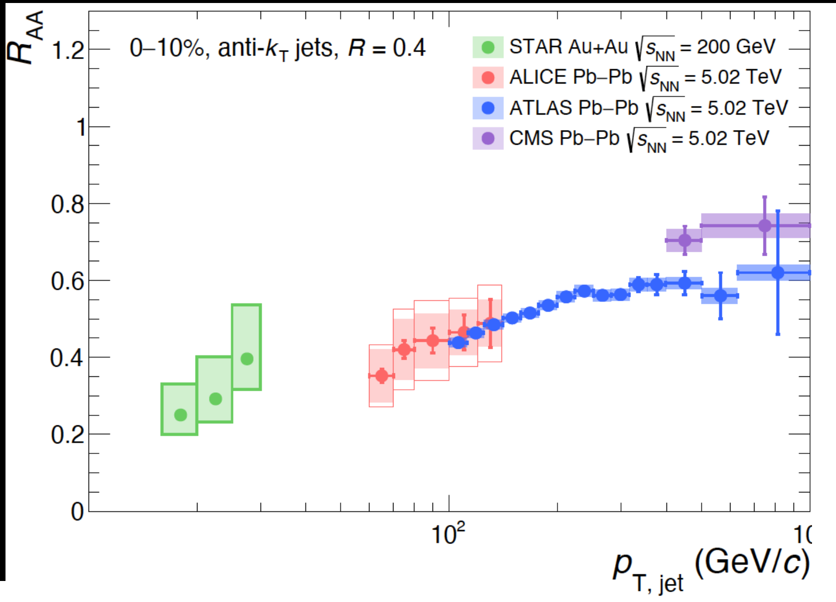
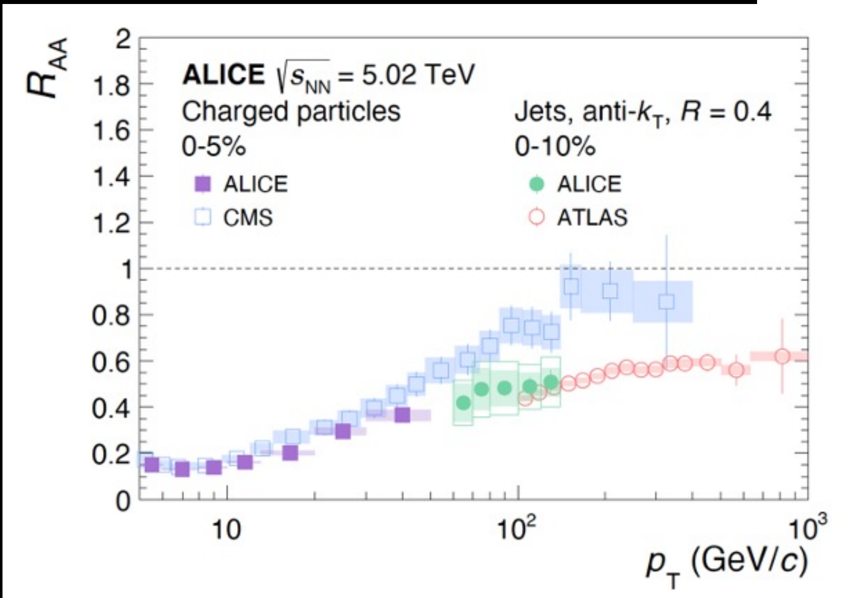
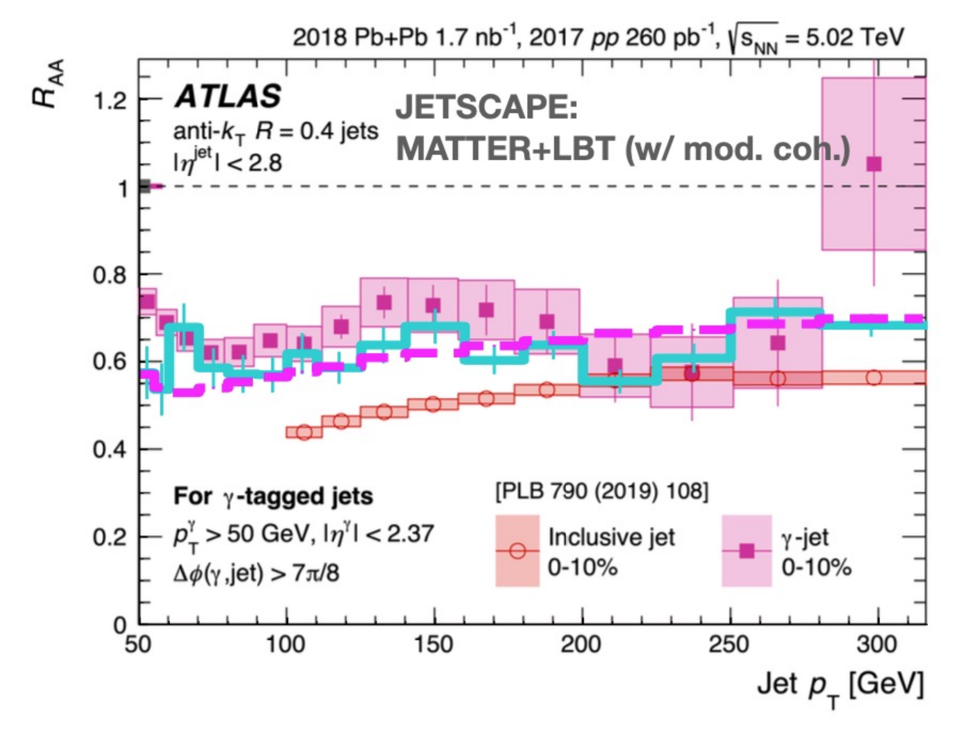
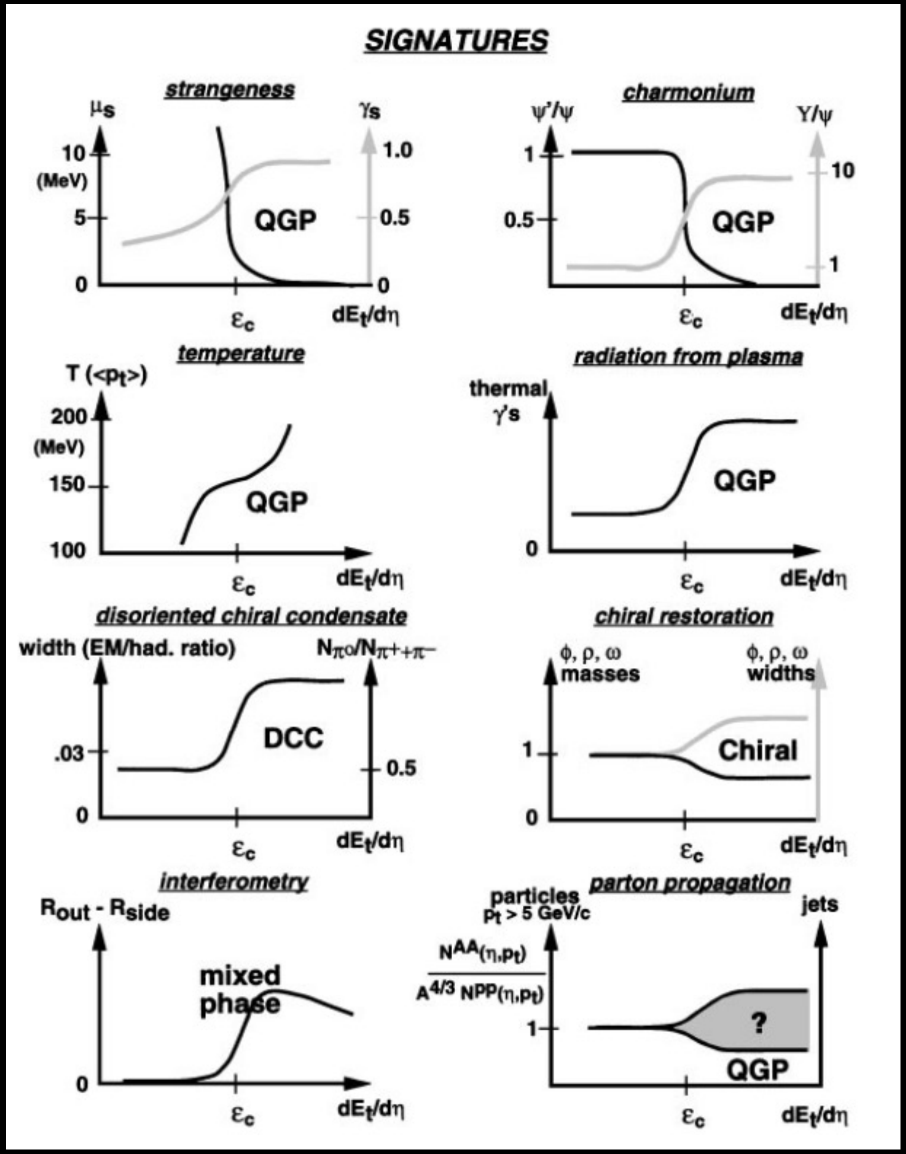




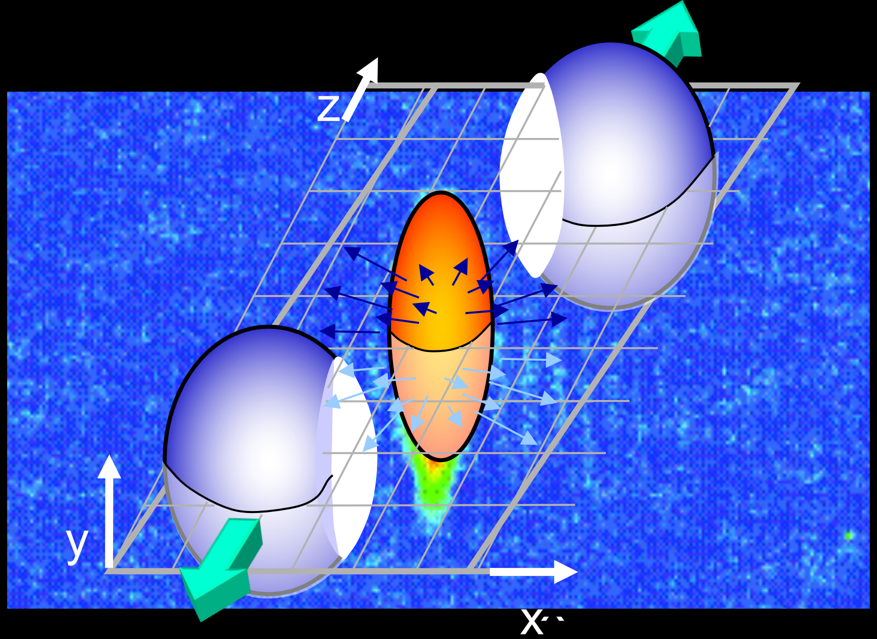




Signatures – Unanticipated & New Developments

- Collective Flow
- Jet Substructure
- Energy Energy Correlations
- Small Systems (including pp)
- Equation of State & Other Subfields
- Baryon Junctions?
- DICs?
- Deadcone
- Others

"QGP Signatures" Revisited, J. W. Harris & B. Müller, European Journal of Physics, in press [arXiv:2308.05743 [hep-ph]].



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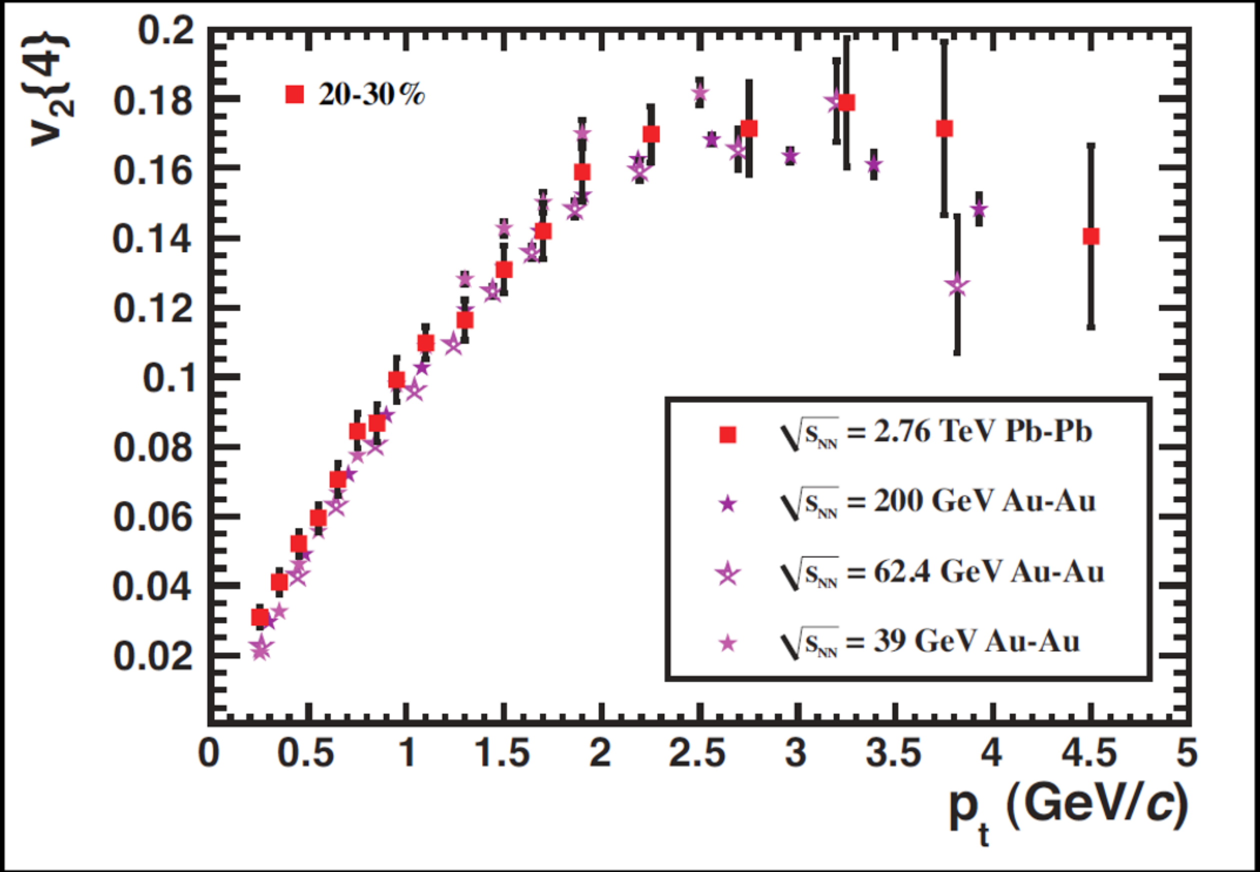
Unanticipated Impact ->
A Nearly Perfect Strongly-coupled Fluid

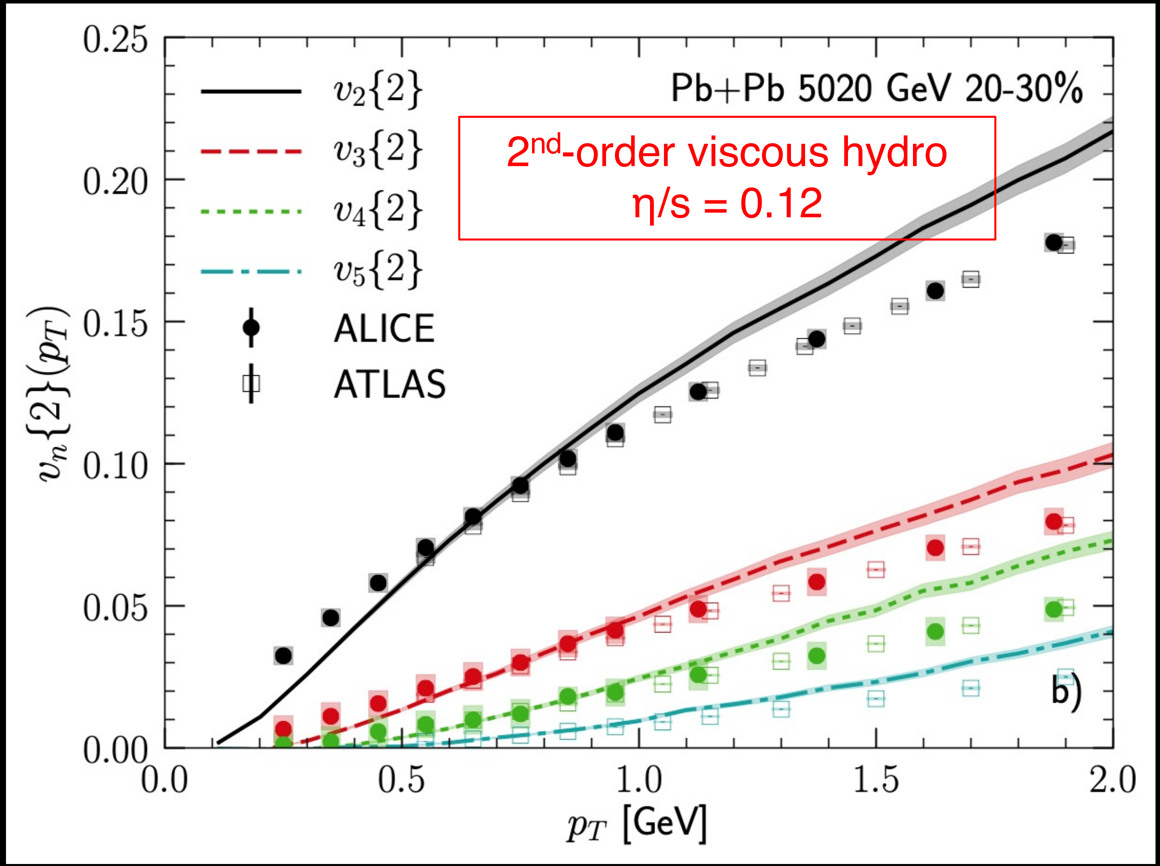
Collective Flow

v2(p_T) in 20–30% central Au+Au (Pb+Pb)
$\sqrt{s_{NN}}$ .039 - 2.76 TeV



Follow same curve – elliptic flow driven by hydrodynamic expansion of fireball with the initial geometric shape of the initial nuclear overlap

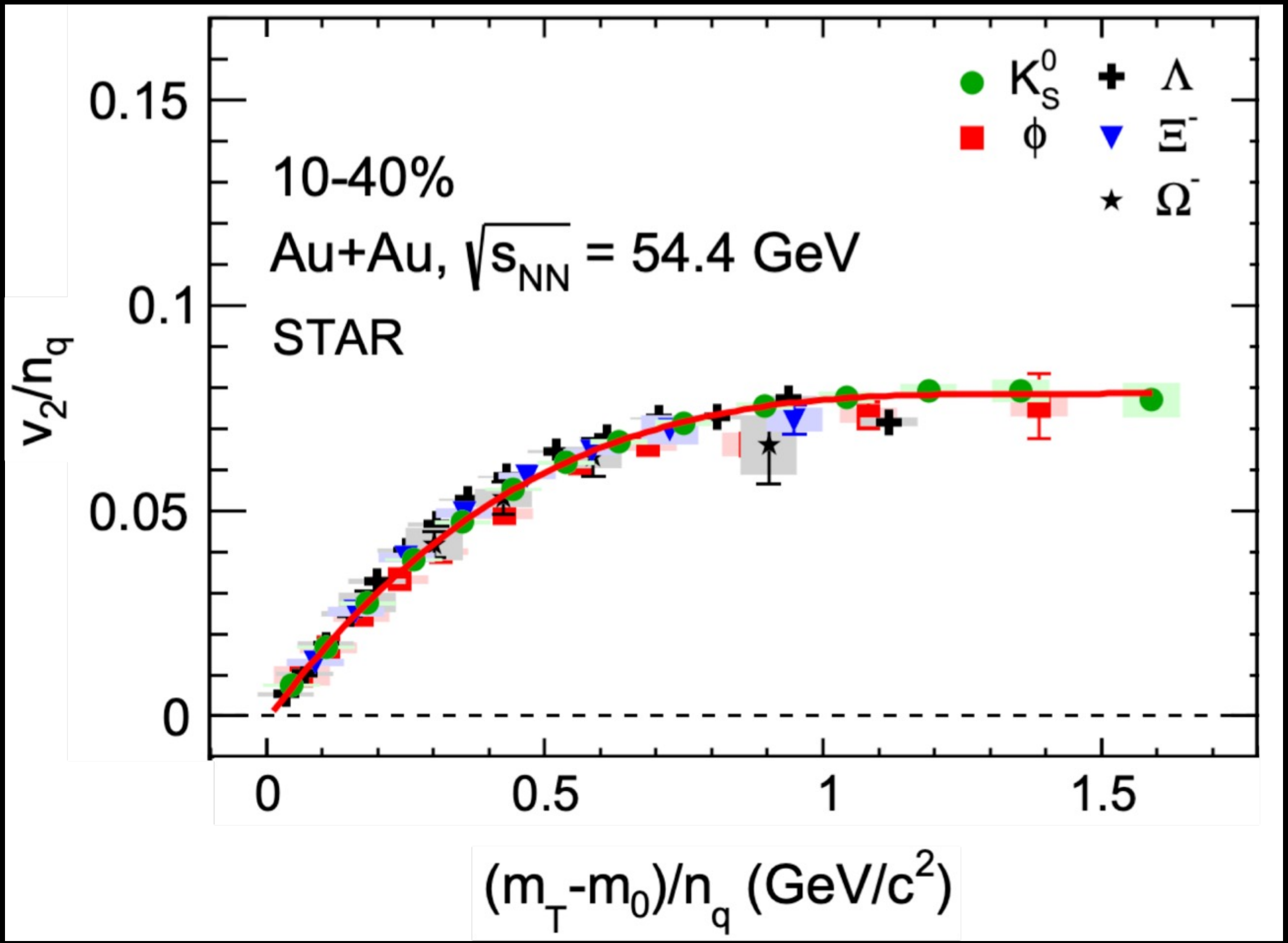
Hybrid model – IP-Glasma initial state model, Music viscous fluid dynamics, UrQMD hadronic transport



B. Schenke, C. Shen and P. Tribedy, Phys. Rev. C 102, 044905 (2020)

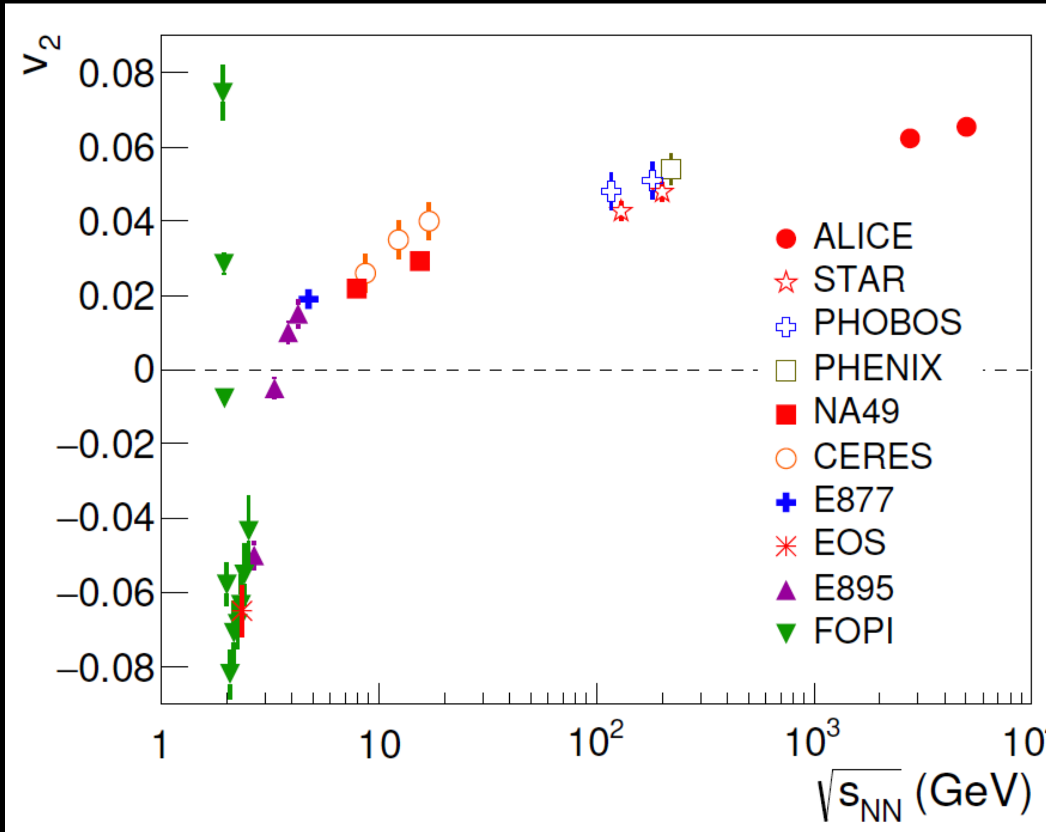
Collective Flow – Trends

Identified particles – constituent quark scaling



Constituent quark scaled elliptic flow coefficient v_2/n_q for five different hadron vs. scaling variable $(m_T – m_0)/n_q$

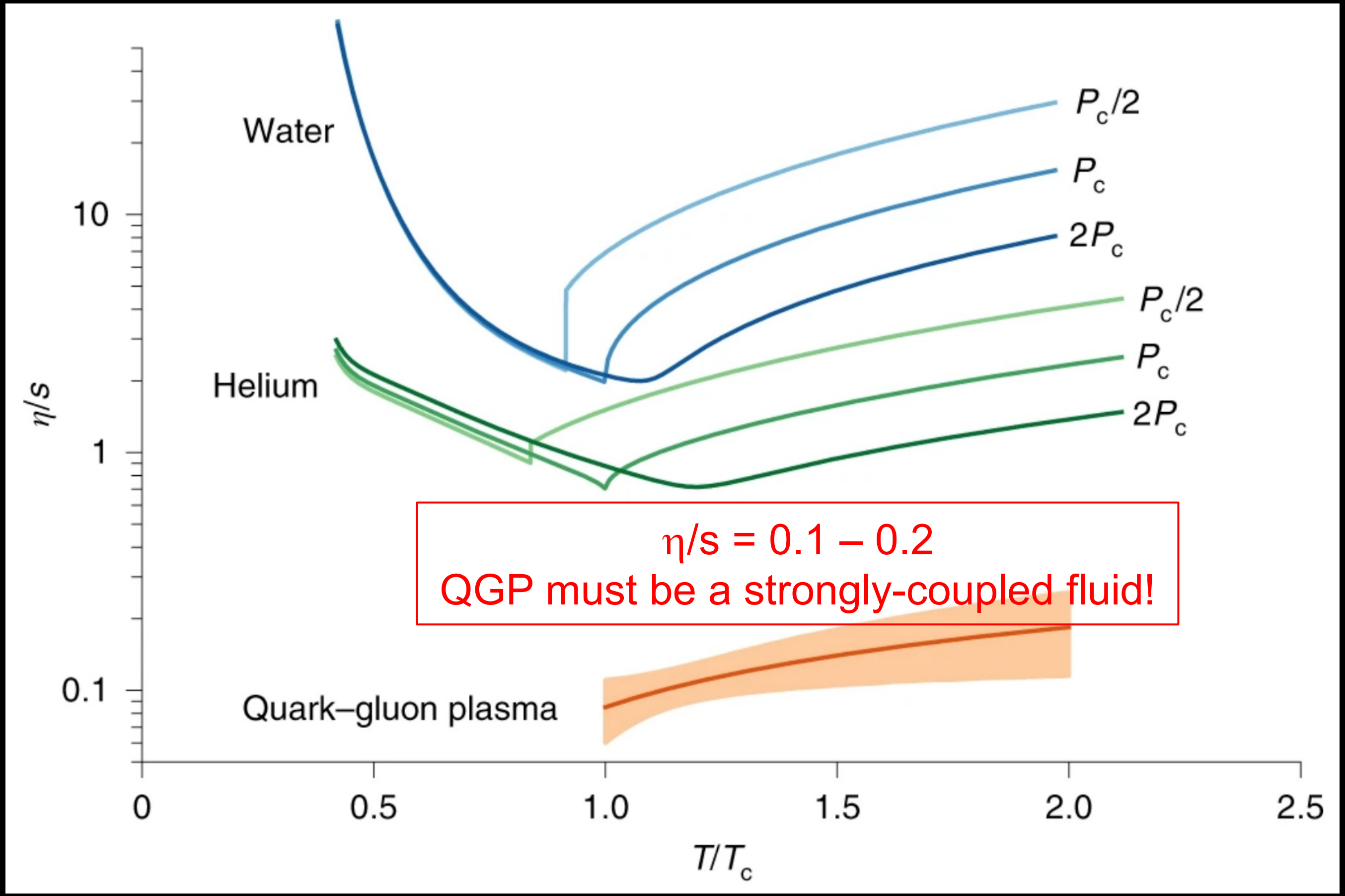
v2 as function of $\sqrt{s_{NN}}$



Mechanism driving v_2 changes for $\sqrt{s_{NN}} < 10$ GeV. Slow increase for above 10 GeV due to invariant behavior of $v_2(p_T)$ and gradual increase in the mean p_T of particle spectrum with increasing $\sqrt{s_{NN}}$

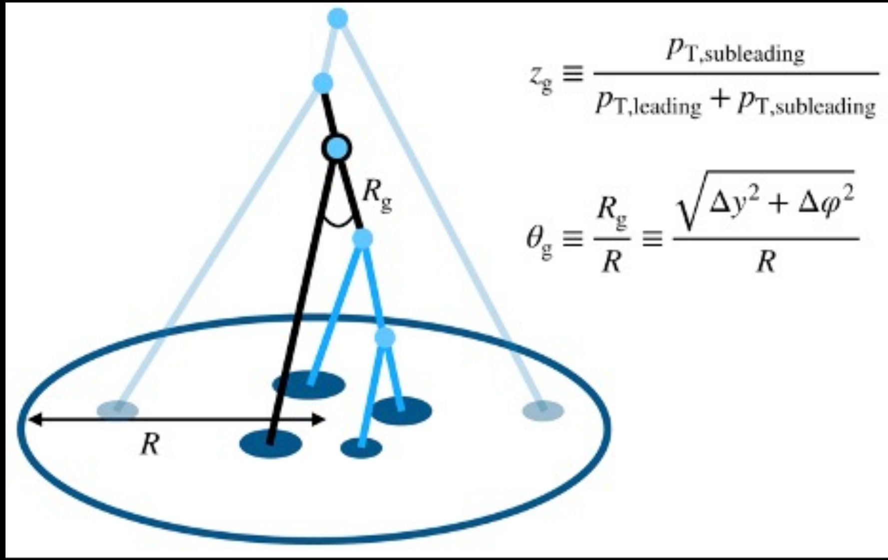
Collective Flow

Comparison of specific shear viscosity η/s values –
QGP from heavy-ion collisions to measured values for He and H_2O

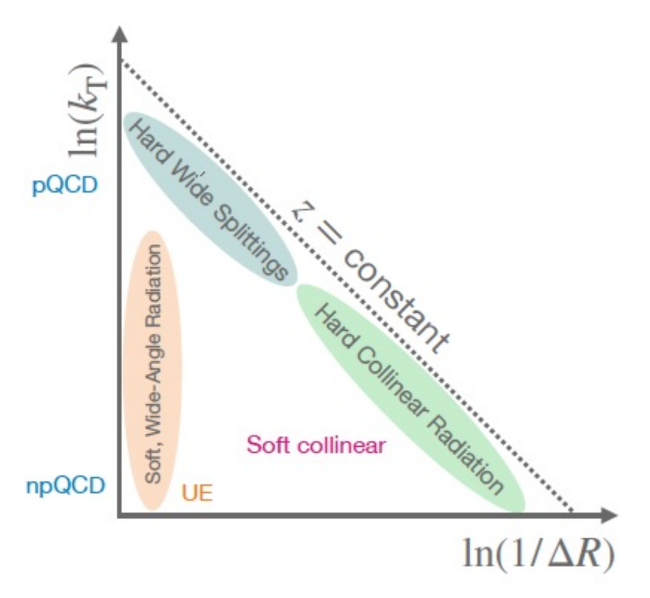


J. E. Bernhard, J. S. Moreland and S. A. Bass, "Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma," Nature Phys. 15, 1113 (2019)

Signatures – Unanticipated & New Developments



WWND: Mooney, Majumder, Lebedev, Song , Salur



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- Deadcone
- Others

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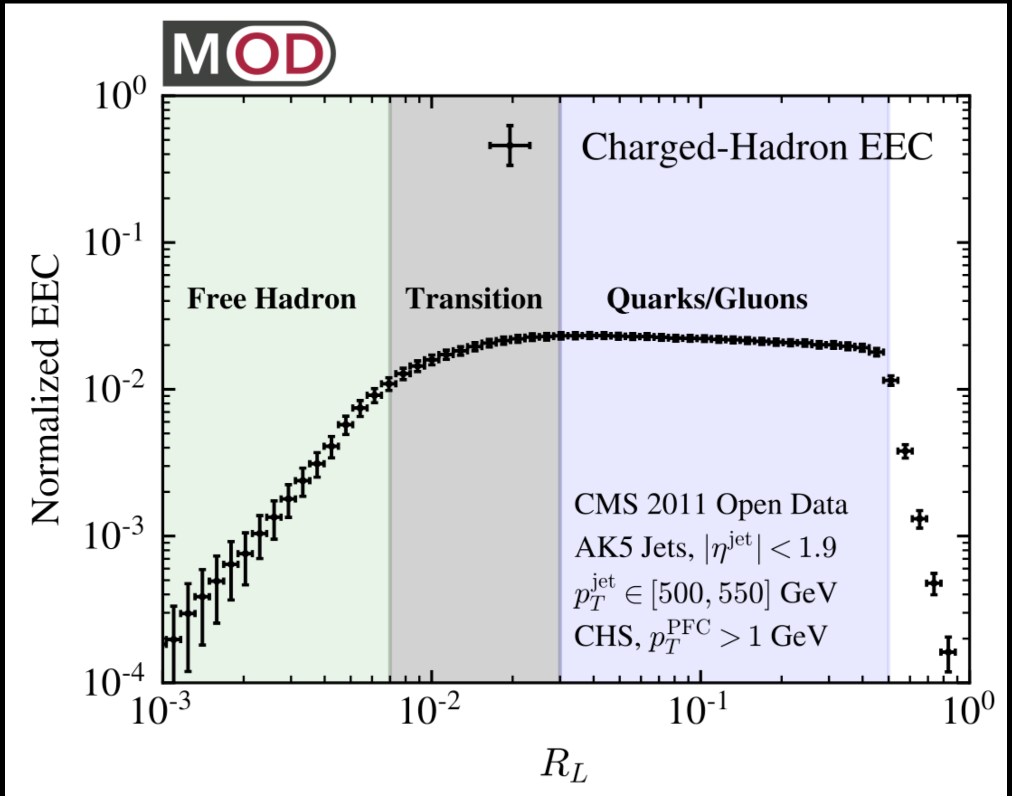

WWND: Moult, Lebedev, Viinikainan, Rai

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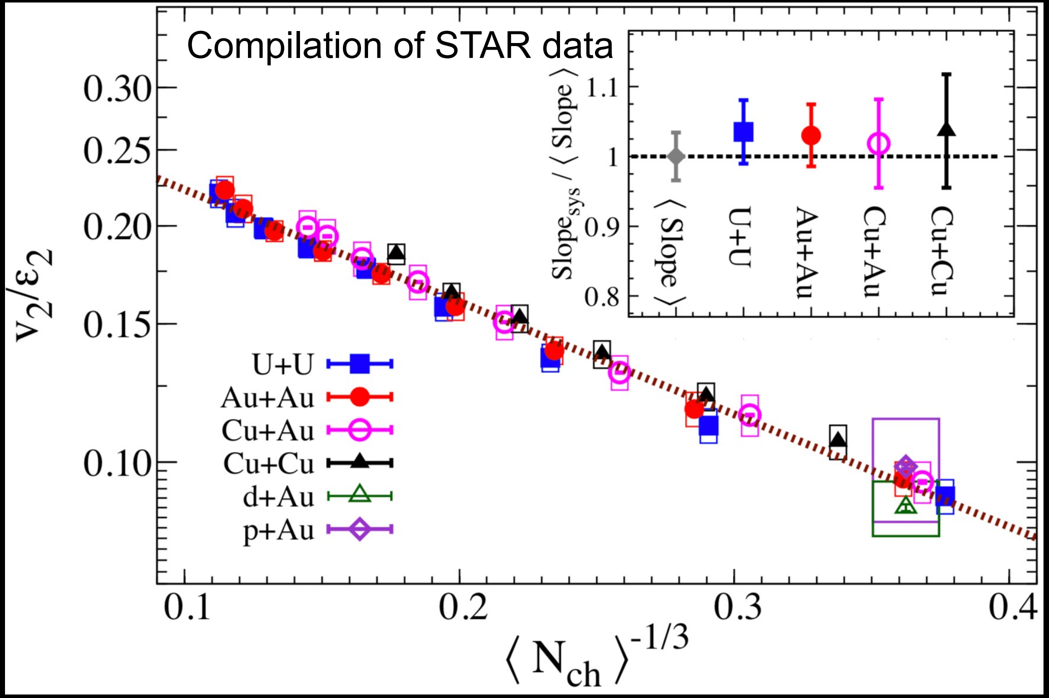
Signatures – Unanticipated & New Developments

Does Size really matter on the overall scale of things?



Multiplicity matters!

WWND: Ma, Majumder

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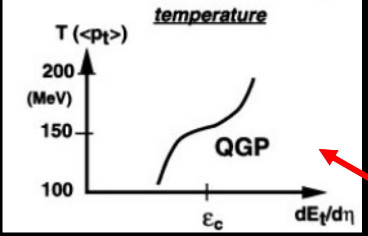
What about pp and the QGP?



Signatures – Unanticipated & New Developments

EoS of QCD matter - a centerpiece of RHIC program.

EoS experiments shifted back to few-GeV range as explored in the second RHIC beam energy scan (μ_B above reliable LQCD calculations).

Does the smooth crossover from hadronic matter to QGP become a 1st-order phase transition with a threshold critical point? (TBD)

Transport properties? Connection to nuclear astro!

- Collective Flow
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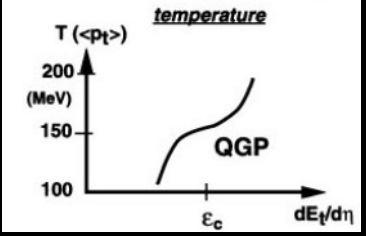
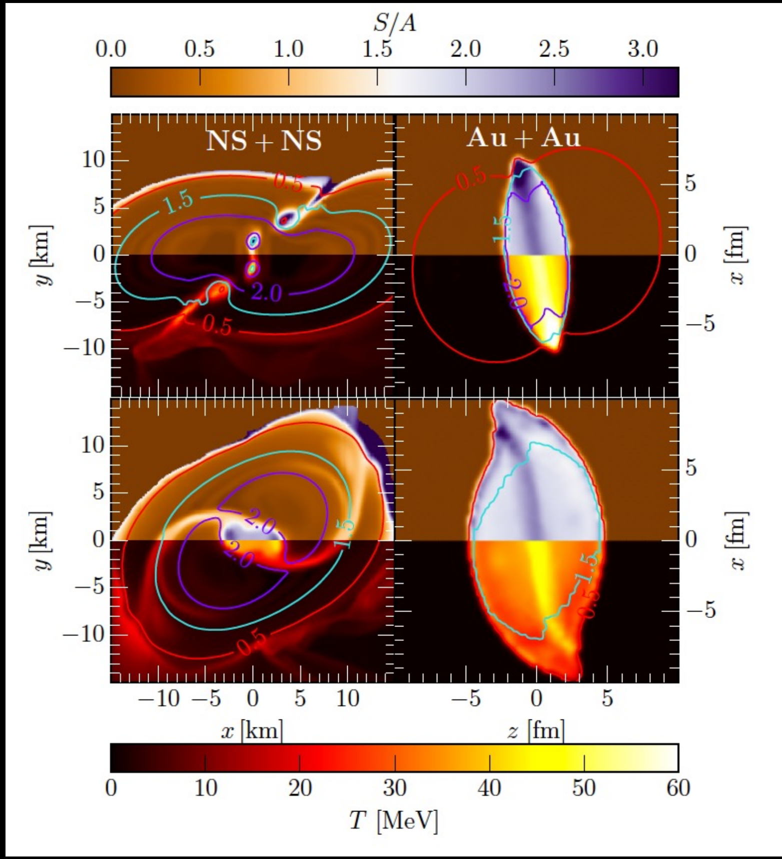
WWND:
Grefa – Holographic Black Hole, Transport Properties and EOS
Li – Speed of sound in QGP
Ratti – EoS (HIC, Neutron Star Binaries,.. (Dexheimer)



Signatures – Unanticipated & New Developments



“Probing neutron-star matter in the lab: connecting binary mergers to heavy-ion collisions,” E.R. Most et al, Phys.Rev.D 107 (2023) 4, 043034

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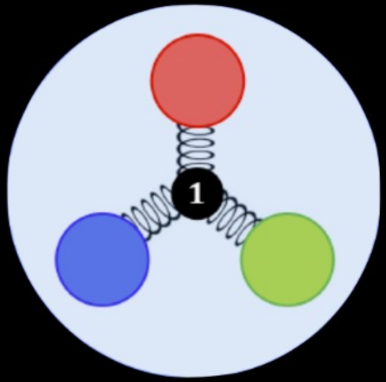
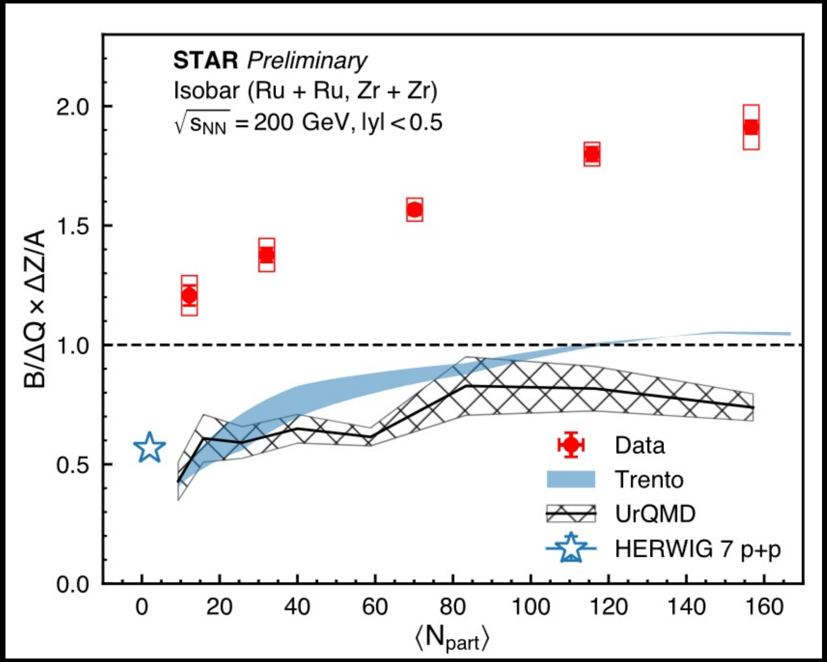
(Dexheimer)

Signatures – Unanticipated & New Developments





WWND: Frenklakh, Ma, Tribedy

- Collective Flow
- Jet Substructure
- Energy Energy Correlations
- Small Systems (including pp)
- Equation of State & Other Subfields
- Baryon Junctions?
- DICs?
- Deadcone
- Others

Signatures – Unanticipated & New Developments

"Static and dynamic critical phenomena at a second order QCD phase transition," K. Rajagopal and, F. Wilczek Nuclear Physics B399 (1993) 395

"Kaon and pion fluctuations from small disoriented chiral condensates" S. Gavin and J. I. Kapusta, Phys. Rev. C 65, 054910 (2002)

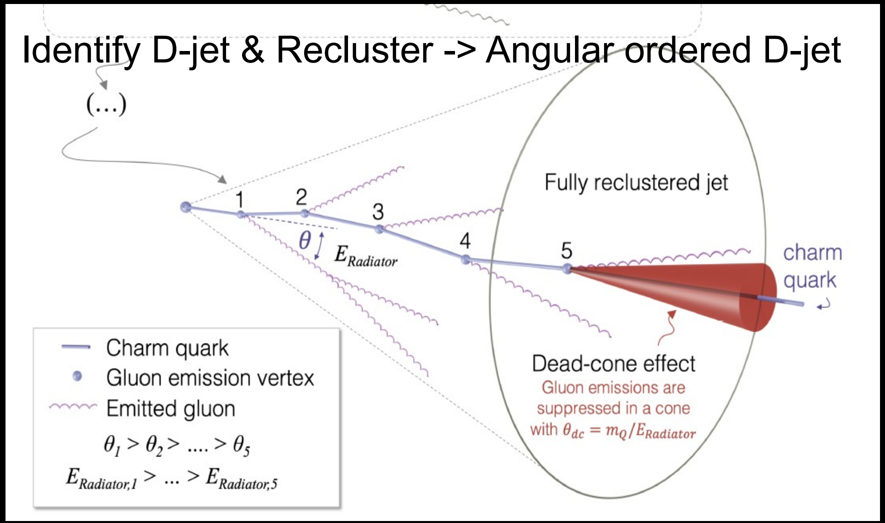
"Modeling of charged kaon and neutral kaon fluctuations as a signature for the production of a disoriented chiral condensate in A−A collisions" R. Nayak, S. Dash, B. Nandi and C. Pruneau, Phys. Rev. C 101, 054904 (2020)

"Neutral to charged kaon yield fluctuations in Pb – Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV," ALICE Collaboration, Phys. Lett. B 832, 137242 (2022)

"Disoriented isospin condensates may be the source of anomalous kaon correlations measured in Pb-Pb collisions.." J.I. Kapusta, S. Pratt, and M. Singh, arXiv:2306.13280 [hep-ph].

- Collective Flow
- Jet Substructure
- Energy Energy Correlations
- Small Systems (including pp)
- Equation of State & Other Subfields
- Baryon Junctions?
- DICs?
- Deadcone
- Others

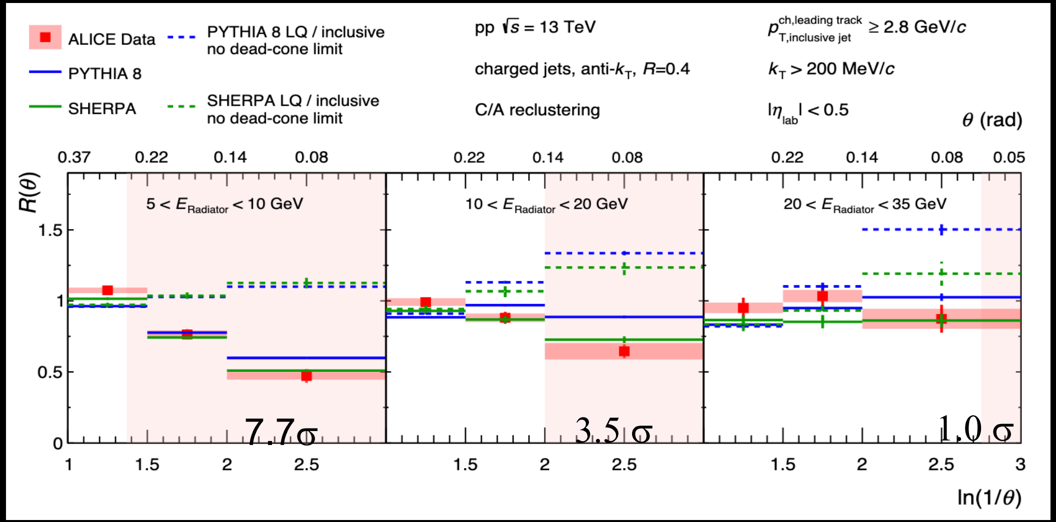
WWND: Singh, Pruneau



Signatures – Unanticipated & New Developments

- Collective Flow
- Jet Substructure
- Energy Energy Correlations
- Small Systems (including pp)
- Equation of State & Other Subfields
- Baryon Junctions?
- DICs?
- Deadcone in AA?

Ratio of D-jets to inclusive in pp

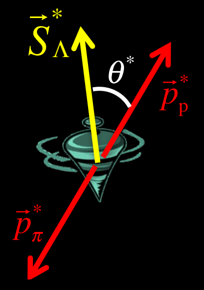


$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}},\,E_{\mathrm{Radiator}}}$$

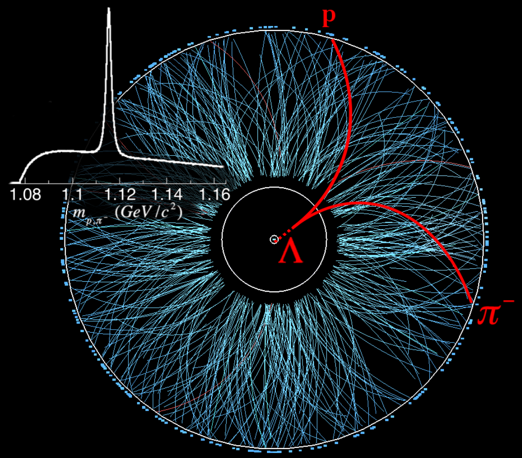
Y.L. Dokshitzer, V.A. Khoze, and S.I. Troian, "On specific QCD properties of heavy quark fragmentation ('dead cone')", J. Phys. G17 (1991) 1602–1604

ALICE, Nature 605 (2022) 440-446

Signatures – Unanticipated & New Developments



$\Lambda \rightarrow p + \pi^-$



- Collective Flow
- Jet Substructure
- Energy Energy Correlations
- Small Systems (including pp)
- Equation of State & Other Subfields
- Baryon Junctions?
- DICs?
- Deadcone
- Others – Vortical flow, CME, Exotic nuclei, Multi-quark states…..

Many Topics & Results Not Presented (or not in detail)

- Vortical Flow
- Exotic Nuclei (hyper-triton, anti-alpha, exotic multi-quark states)
- Chiral Magnetic Effect
- Directed Flow and link of Net-proton BES data to EOS
- Ultra-Peripheral Collisions
- Cold Nuclear Matter studies
- Higher order flow harmonics
- Fluctuations, correlation lengths and susceptibilities
- Fragmentation Function studies
- Various new approaches (theoretical and experimental)
- and more…

In Lieu of a Summary

Tonight let's wish the 3 Renes a Happy 65th Birthday! ⭐ 🌈 🌪️

Thanks for your Attention!

Apologies to those not mentioned

Let's Get "Back to the Future"!