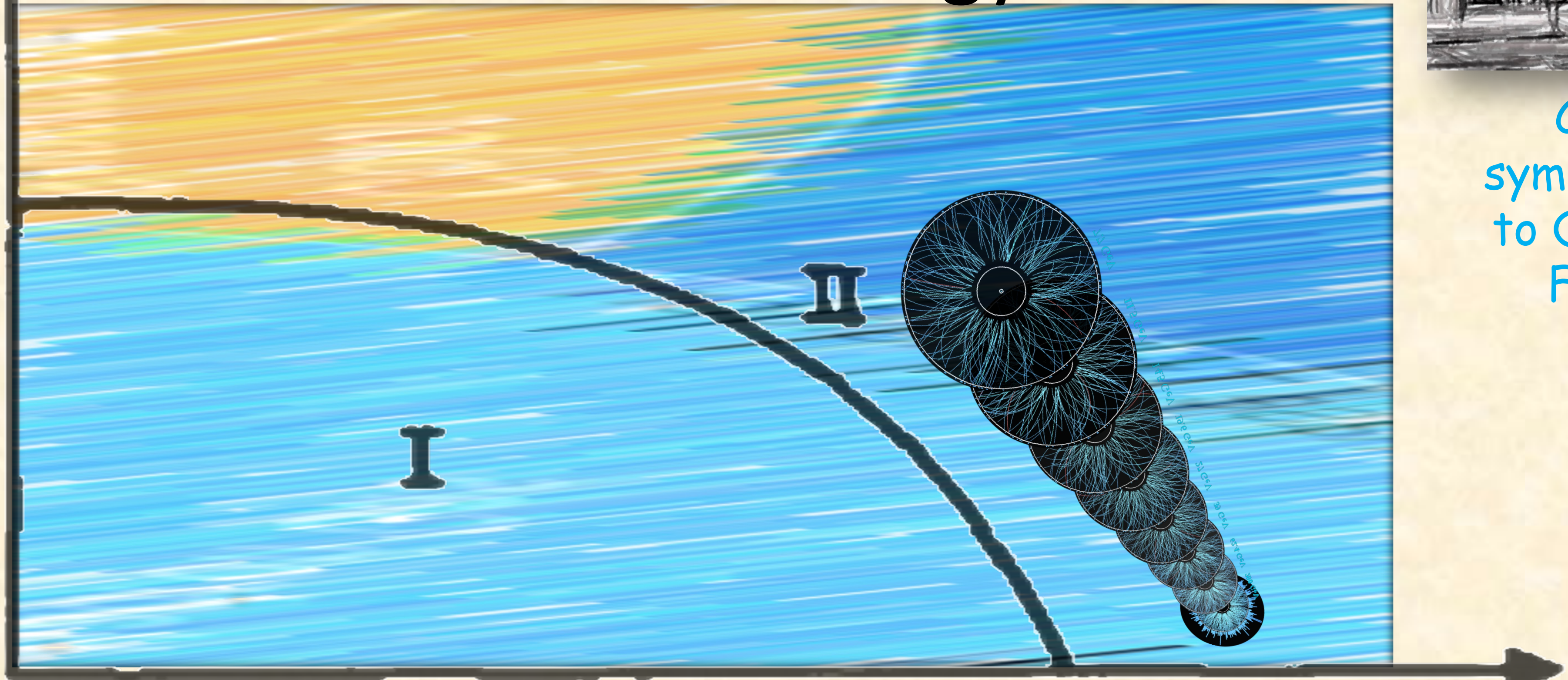
QCD Phase Diagram: An Experimental Overview from the RHIC Beam Energy Scan



Confinement and symmetry from vacuum to QCD phase diagram
Feb. 9 – 15, 2025

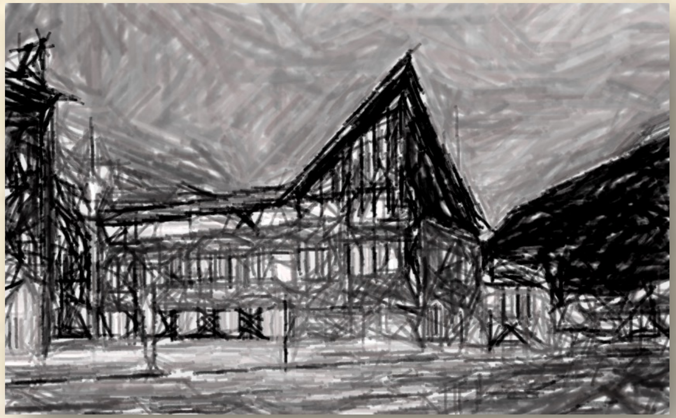
Frank Geurts

Rice University

U.S. DEPARTMENT OF ENERGY | Office of Science

RICE

One Workshop, Two Themes



Confinement and symmetry from vacuum to QCD phase diagram
Feb. 9 – 15, 2025

- Experimental approaches to the study of QCD matter at high temperatures and densities
  - Exploring the QCD phase diagram at RHIC
- Experimental exploration of fundamental symmetries at high temperatures and densities
  - Chiral symmetry restoration
- Let me try to cover both …

QCD Phase Diagram

Experimentally, one can access different regions of phase diagram by varying centre-of-mass energy

- ➢ experimental data over 3-4 orders of magnitude in $\sqrt{s_{NN}}$

LHC and RHIC provide access to low μ_B region

- – cross-over region

Several experiments/facilities give access to μ_B regions that both cover cross-over, possible 1st order PT, and a conjectured CP

- AGS, SPS
- HADES
- NA61/SHINE
- ➢ RHIC beam energy scan (BES)

Cabbibo & Parisi, PLB58 (1975) 67

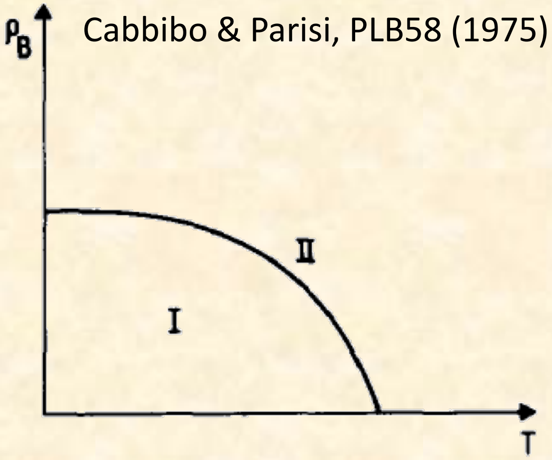
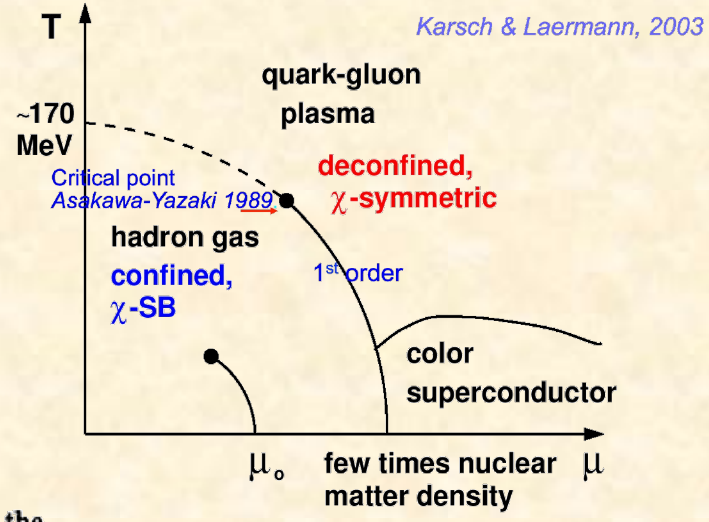
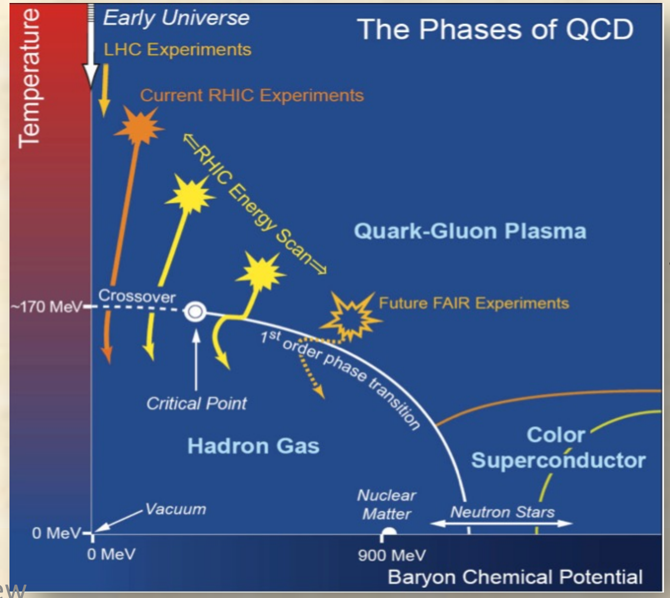


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

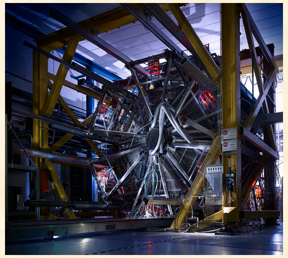
Karsch & Laermann, 2003

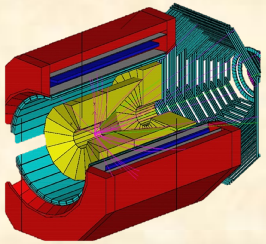




BES-2 White Paper – STAR Note 598

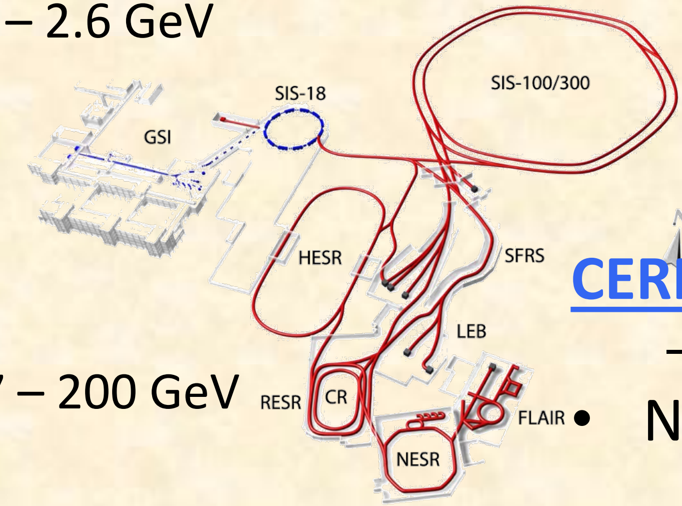
Active Heavy-Ion Experiments around the World

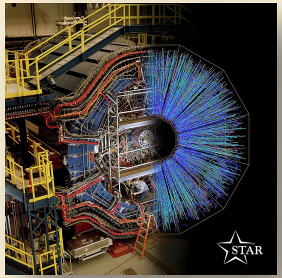




GSI :: SIS18

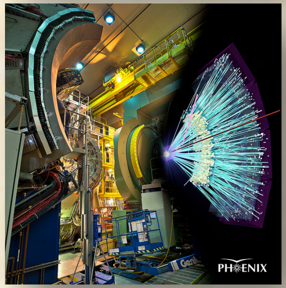
  - $\sqrt{s_{NN}}$=2.0 – 2.6 GeV
- HADES





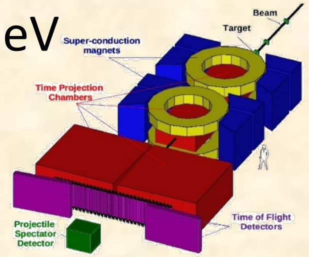
BNL :: RHIC

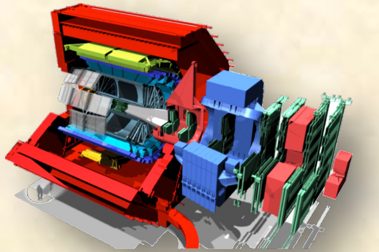
  - $\sqrt{s_{NN}}$= 7.7 – 200 GeV
- STAR
- PHENIX (-2016)
- sPHENIX (2022-)



CERN :: SPS

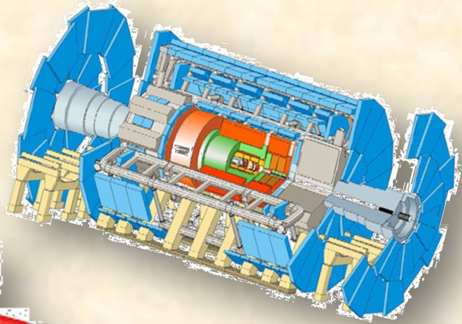
  - $\sqrt{s_{NN}}$= 5.1 – 17.3 GeV
- NA61/SHINE

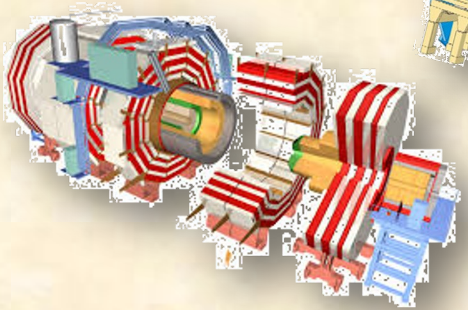




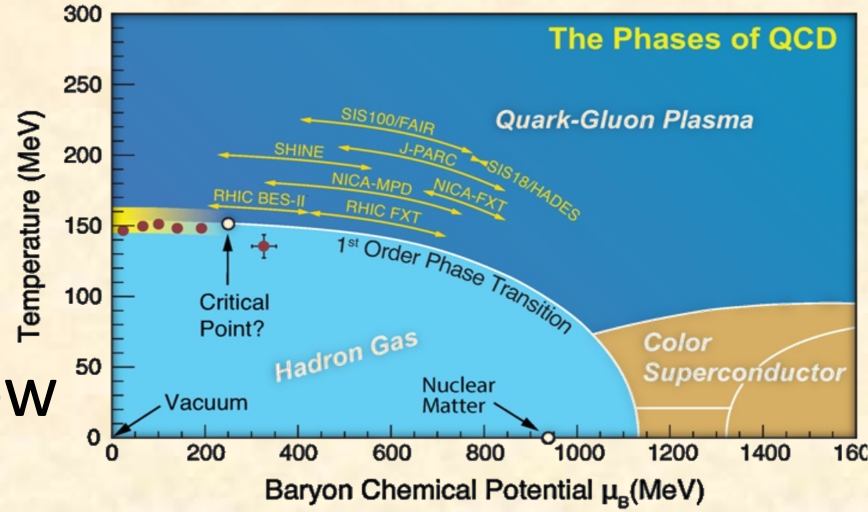
CERN :: LHC

  - $\sqrt{s_{NN}}$= 2.76 – 5.0 TeV
- ALICE
- ATLAS
- CMS
- LHCb (2015)





Charting the QCD Phase Diagram



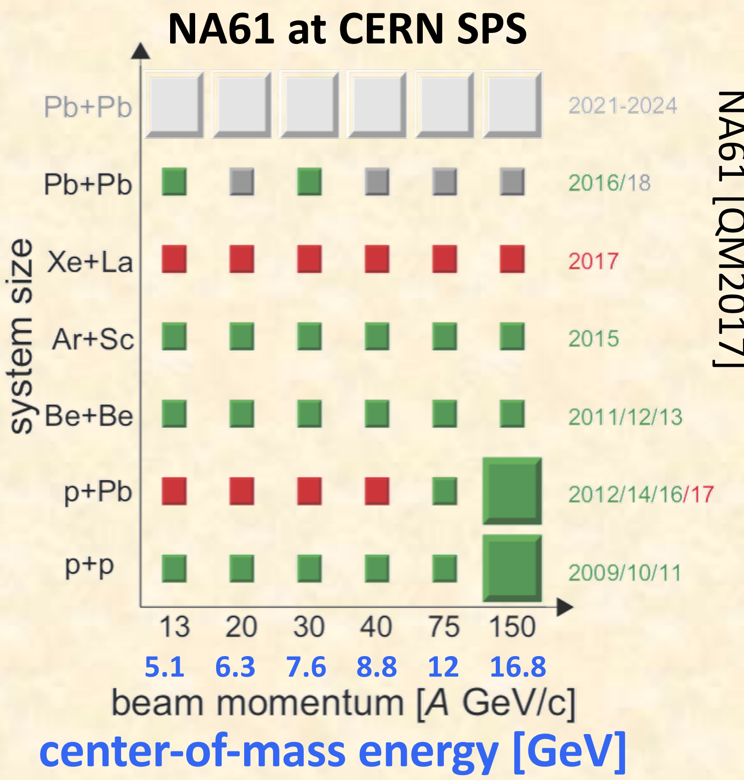
- Turn-off of QGP signatures - suppression, elliptic flow

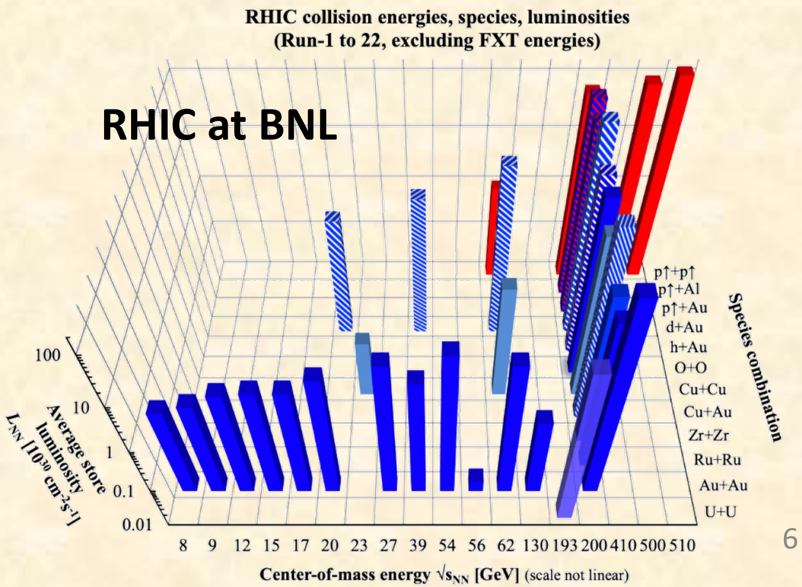
- First-order phase transition - changes in EoS due to attractive force (softest point)
  - "step" in mean transverse mass of identified particles
  - non-monotonic behavior of directed flow slope at mid-rapidity ($dv_1/dy|_{y=0}$)

- Critical point - divergence of the correlation length ⇒ non-monotonic behavior of higher moments of conserved quantities
  - experimentally, skewness S, and kurtosis κ of event-by-event net-particle distributions

The Experimentalist' Toolbox

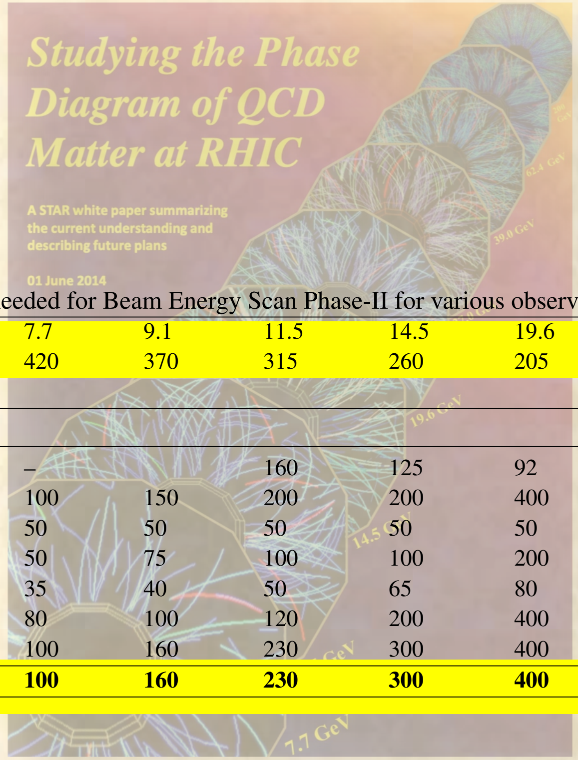
- Wide range of collision energies
  - ➢ versatile accelerators
  - – determine excitation functions; beam energy scan
- Various colliding systems: A+A, p+p, p+A
  - – compare hot nuclear medium (in A+A) to baseline (p+p)
  - – disentangle initial state effects (p+A) from final state observations (A+A)
  - – system size dependence
- Collider and/or Fixed-Target modes
  - – fixed acceptance vs. high rates
- General vs. special purpose detectors





RHIC Beam Energy Scan Program

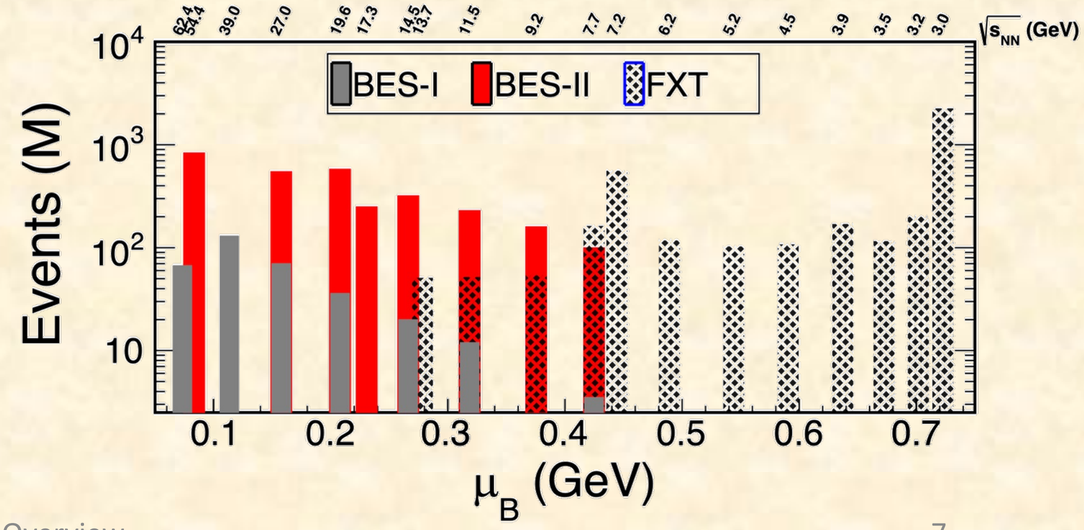
- Phase 1: 2010 – 2011, 2014
  - STAR base line detectors: TPC and BTOF
  - $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39 GeV
  - hints at low $\sqrt{s_{NN}}$ of QGP turn-off, ordered phase transition, and critical point
- Phase 2: 2019 – 2021
  - specific focus on lower $\sqrt{s_{NN}}$
    - including $\sqrt{s_{NN}}$ = 9.2 and 17.3 GeV (plus 27, 54.4GeV)
  - ❖ include FXT program to reach lower energies
    - $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.9, 4.5, 5.2, 6.2 GeV (7.7, 9.2, 11.5, 13.7)
  - improve statistical significance
    - RHIC electron cooling for low beam energies
  - improve systematics
    - STAR detector upgrades: iTPC, EPD, eTOF



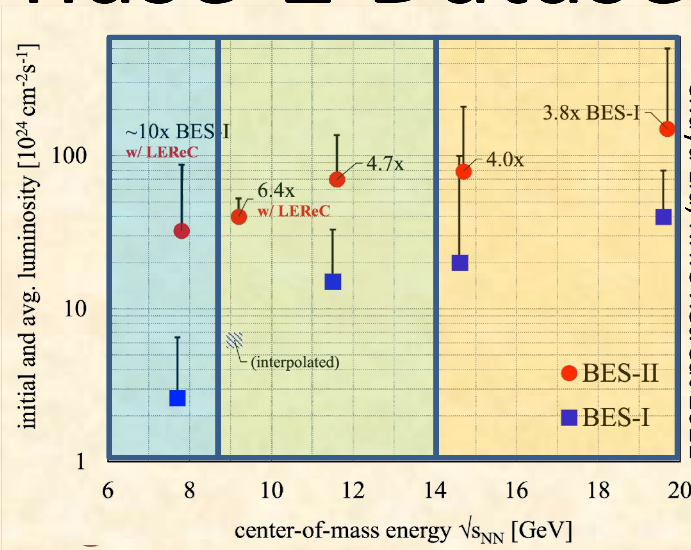
STAR Note 598

Table 2. Event statistics (in millions) needed for Beam Energy Scan Phase-II for various observables.

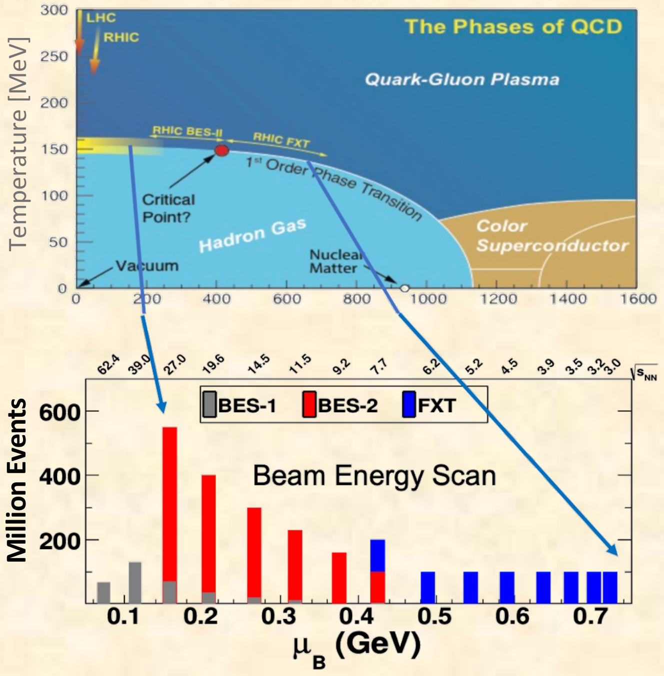
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to p_T = 5 GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	80	100	120	200	400
Dileptons	100	160	230	300	400
Required Number of Events	**100**	**160**	**230**	**300**	**400**



Phase-2 Datasets



Chuyu Liu, RHIC Retreat 2021



Haiyan Gao, RHIC Retreat 2021

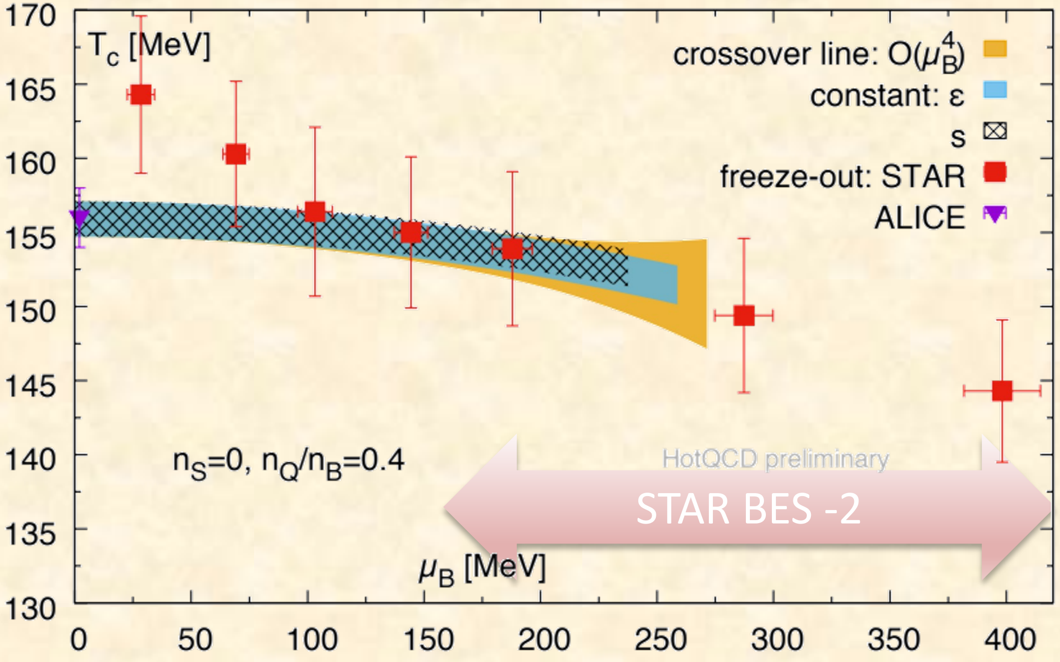
$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

Helen Caines, LBNL BES Workshop 2021

Charting the QCD Phase Diagram

- From theory:
  - cross-over starts at T_0= 156.5 ± 1.5 MeV
  - for μ_B < 250 MeV (and n_S=0, n_Q/n_B=0.4)
    - cross-over along constant ε and *s* densities
    - no indication for CP
- RHIC BES-1 data:
  - (T_{chem},μ_B) with large systematic uncertainties

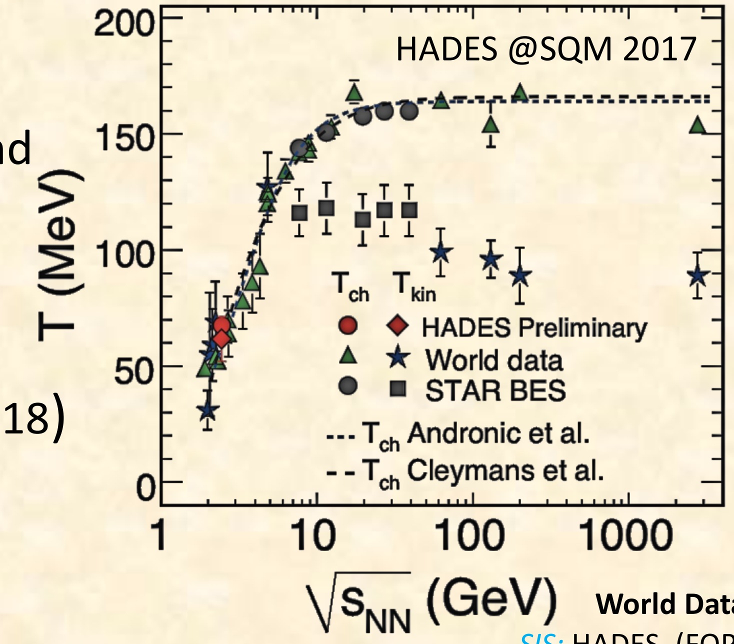
➢ RHIC BES-2 data:
  - reduce systematics in extrapolations
    - ➢ smaller uncertainties in chemical fits
  - additional data points for μ_B > 150 MeV
  - update $\sqrt{s_{NN}}$=200 GeV (Run-19)



Steinbrecher, QM18

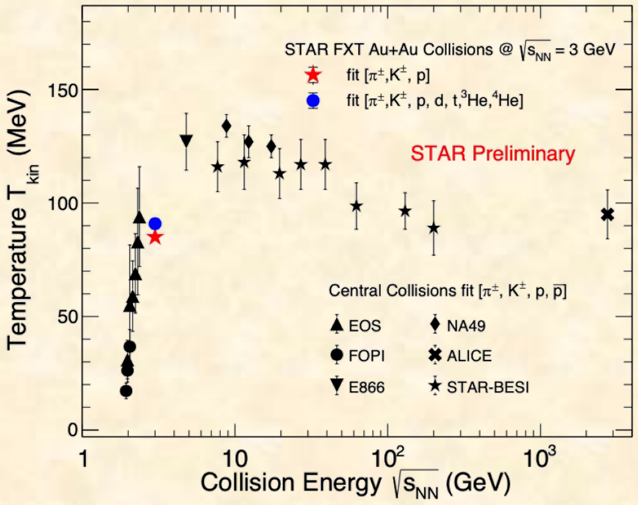
Bulk Properties: Kinetic Freeze-out

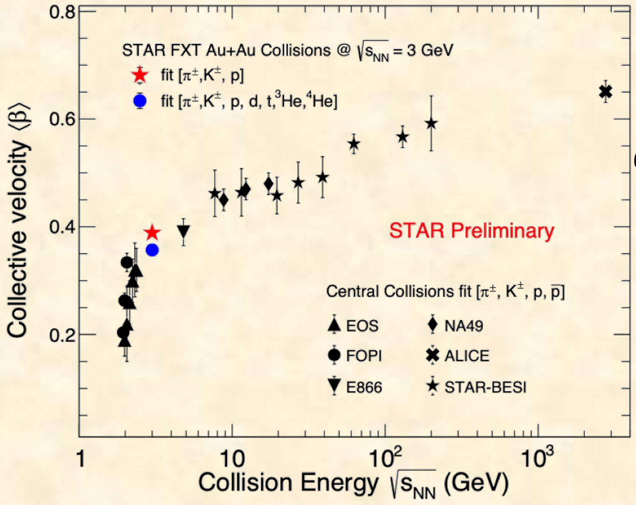
- separation between T_{kin} and T_{chem} grows with increasing energy
  - might suggest effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies
- radial flow velocity $\langle\beta\rangle$ shows rapid increase at very low energies and slower increase at higher energies
- ➢ recent inclusion of light nuclei (d, t, ^{3}He, ^{4}He) from $\sqrt{s_{NN}}$=3 GeV (FXT-2018)



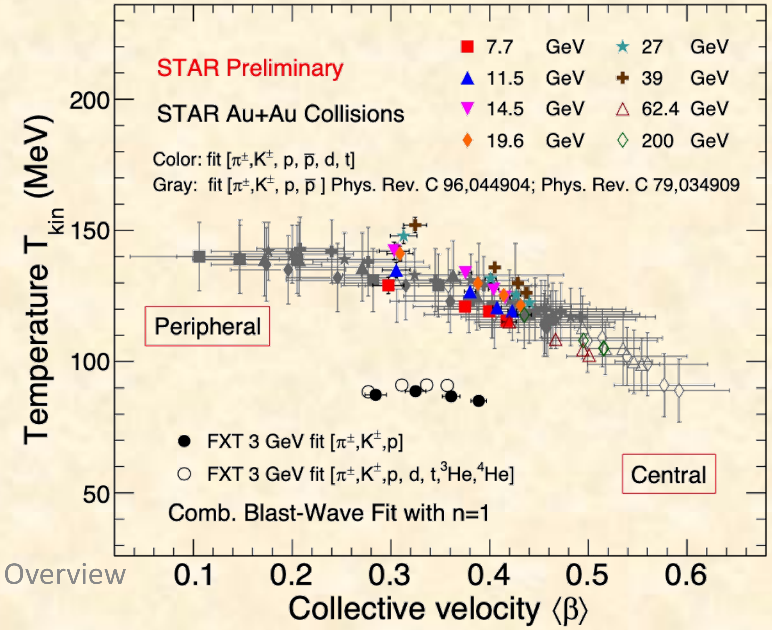
H. Schuldes, EPJ Web of Conf. 171 (2018) 01001

World Data:
SIS: HADES, (FOPI)
AGS: E802,E866, E877,E895, E917
SPS: NA49
RHIC: STAR
LHC: ALICE





H. Liu @ ISMD2021



H. Liu @ ISMD2021

- For central collisions: T_{kin} and $\langle\beta\rangle$ follow world $\sqrt{s_{NN}}$ trend
- ➢ Centrality differential shows different trend
  - compared to higher $\sqrt{s_{NN}}$

Onset of deconfinement

NA49 [PRC 77 (2008) 024903]: onset of deconfinement at $\sqrt{s_{NN}}$ =7.7GeV

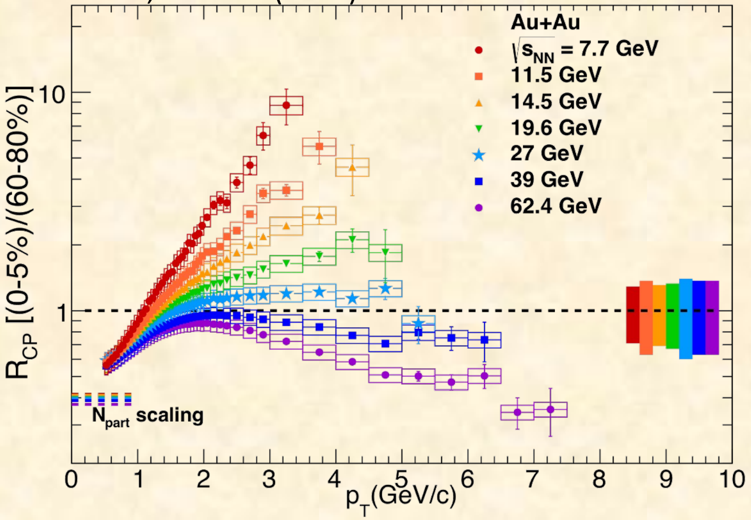
STAR BES-1: $h^{+/-}$ nuclear modification factor R_{CP}

- smooth transition from suppression (high $\sqrt{s_{NN}}$), to enhancement (low $\sqrt{s_{NN}}$)
- below $\sqrt{s_{NN}}$ = 39 GeV no suppression? Turn-off?
  or, competition with enhancements from Cronin effect, flow, etc.

➢ R_{CP} > 1 does not mean "no QGP"

$$Y(\langle N_{part}\rangle) = \frac{B}{\langle N_{coll}\rangle}\frac{d^2N(\langle N_{part}\rangle)}{dp_T d\eta}$$

STAR, PRL 121 (2018) 032301

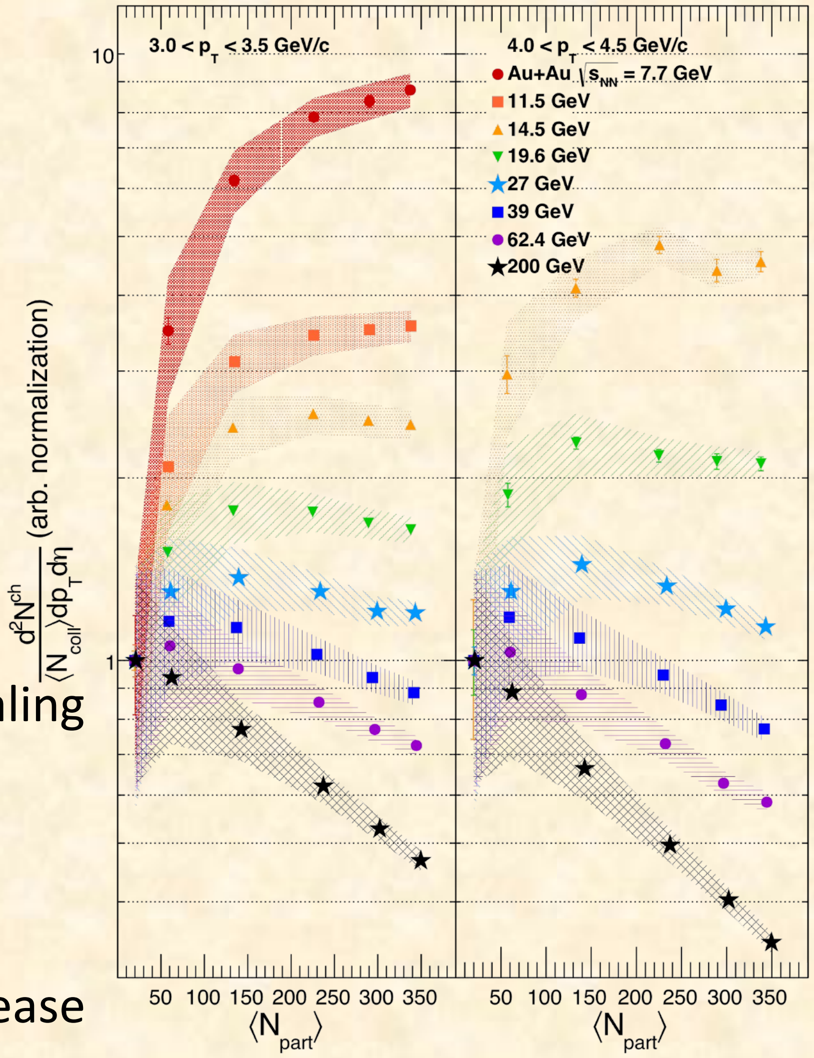


A more differential approach, look at N_{part} scaling

- ≥ 39 GeV : monotonic decrease
  - ➢ suppression > enhancement
- ≤ 11.5 GeV: monotonic increase
  - ➢ enhancement > suppression
- 14.5 – 27 GeV: increase, followed by decrease
  - ➢ enhancement grows fast, but
  - ➢ suppression dominates

➢ Suppression observed down to $\sqrt{s_{NN}}$ =14.5 GeV

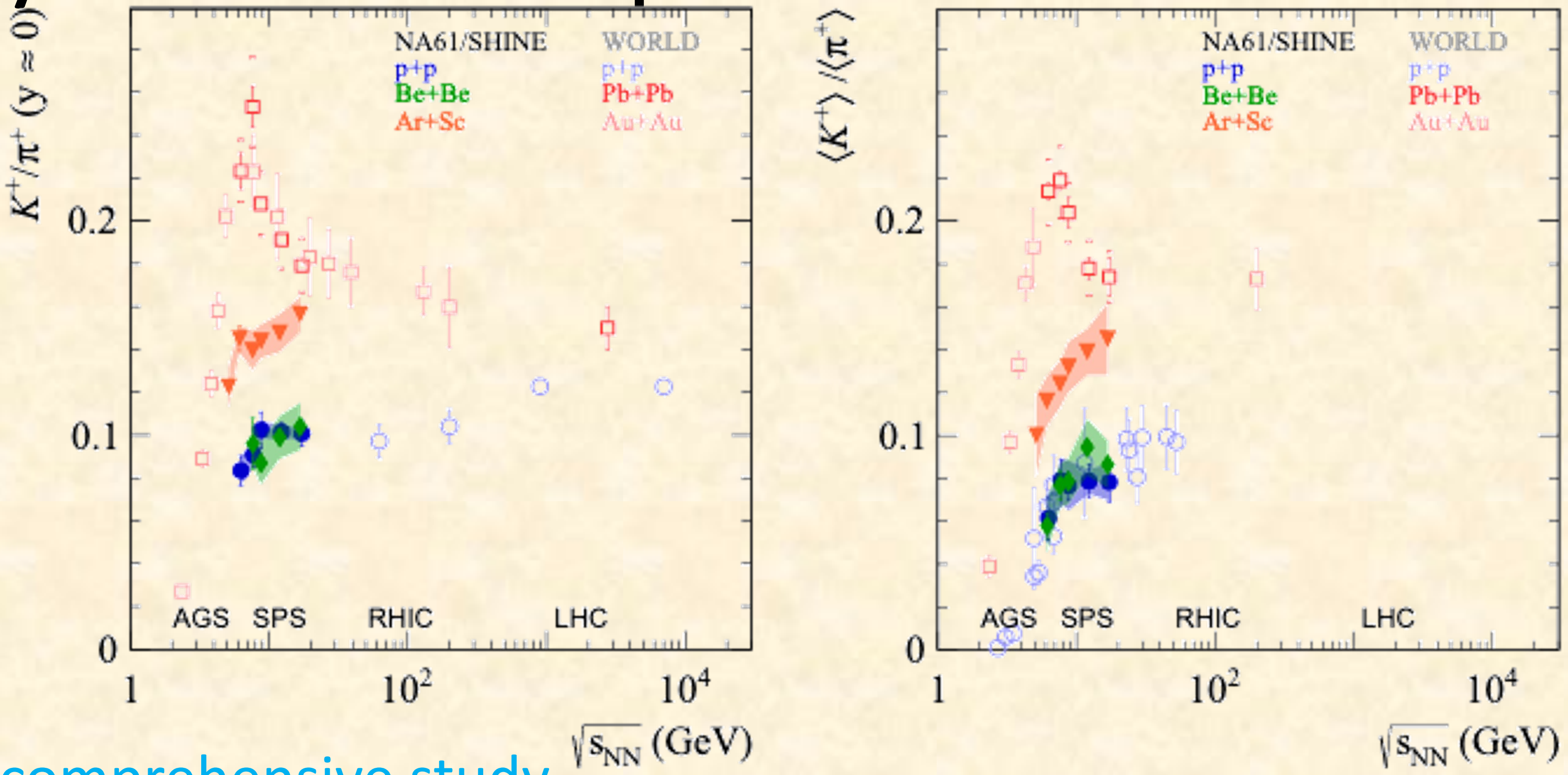
STAR, PRL 121 (2018) 032301



❖ BES-2: expect precision to disentangle

Horn System-size Dependence

NA61, EPJC 84 (2024) 416



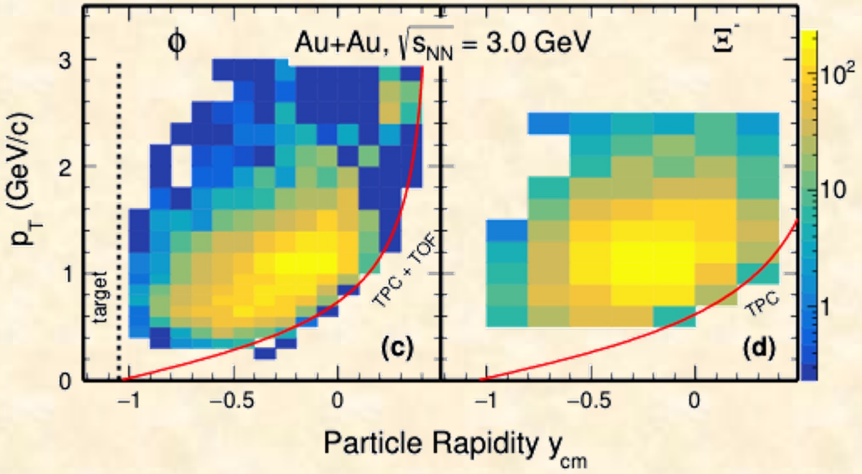
Most central collisions (top 10%)

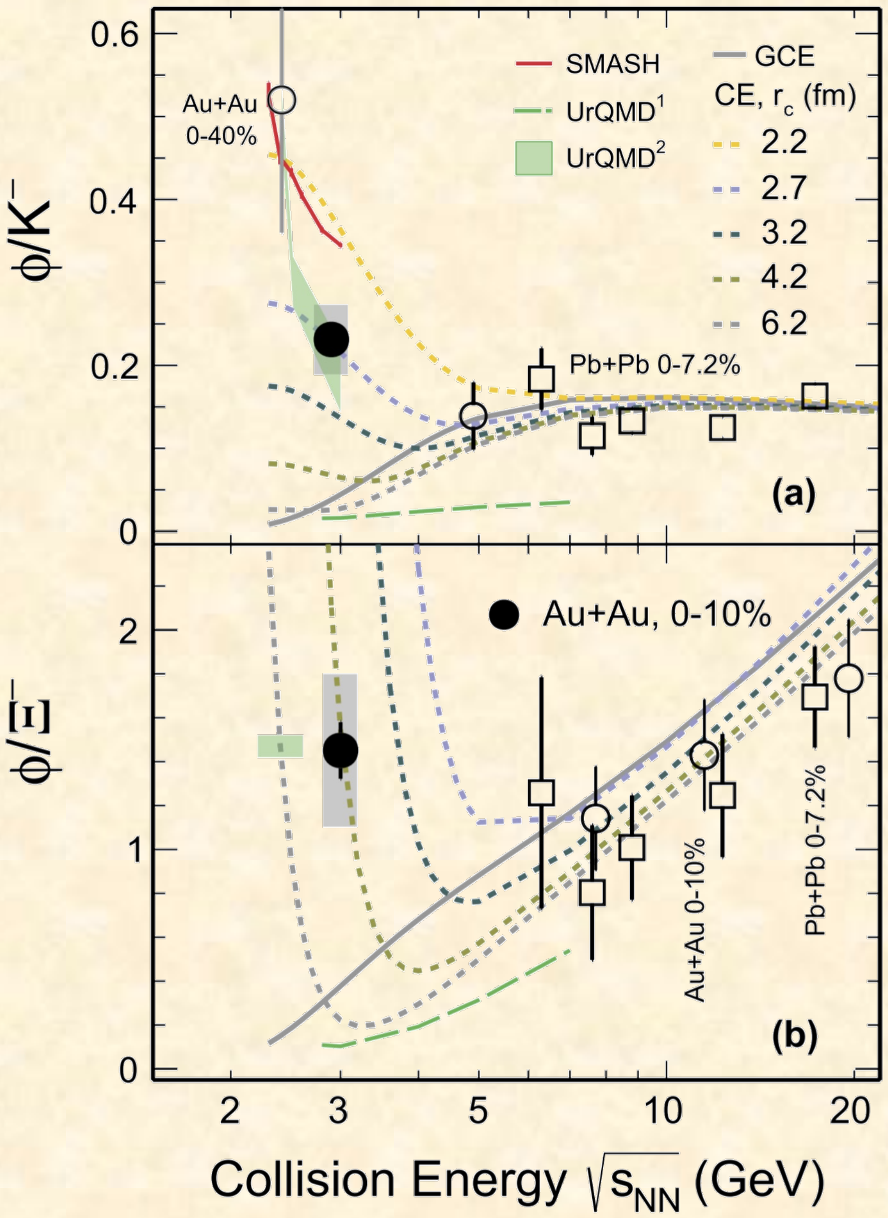
- NA61: comprehensive study
  - p+p, ^{7}Be+^{9}Be, ^{40}Ar+^{45}Sc, ^{208}Pb+^{208}Pb
  - $\sqrt{s_{NN}}$ = 5.12, 6.12, 7.62, 8.77, 11.9, and 16.8 GeV
- Ar+Sc is clearly separated from small systems, but no *horn* structure
  - yields resemble Pb+Pb at high energies collision energies ($\sqrt{s_{NN}} \gtrsim 16.8$ GeV)
  - yields resemble small systems at low energies ($\sqrt{s_{NN}} \lesssim 6.12$ GeV)

Probing Canonical Production

STAR, PLB B 831 (2022) 137152

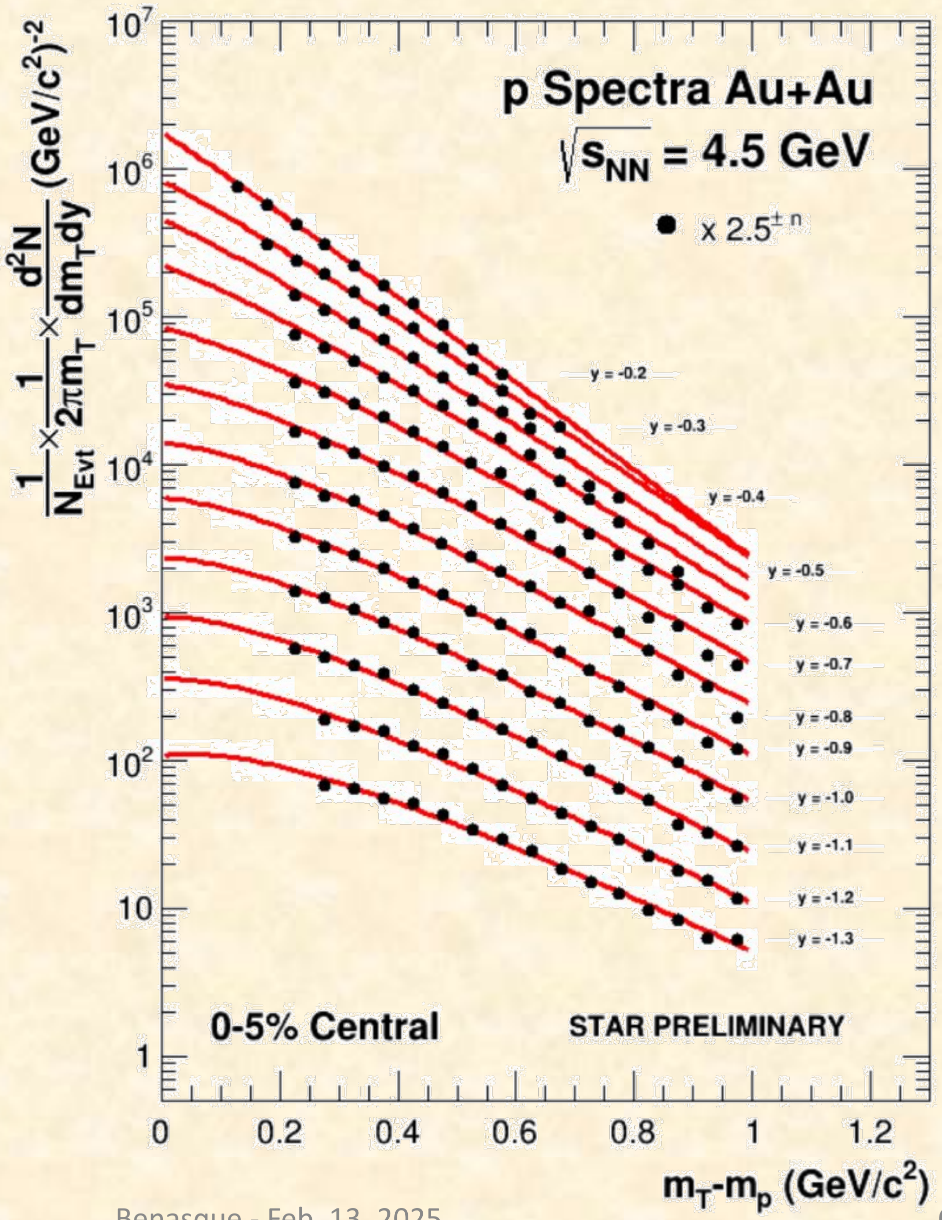
- First multi-differential φ and Ξ at √s_{NN}= 3 GeV (FXT)
  - ➢ p_T and *y* spectra



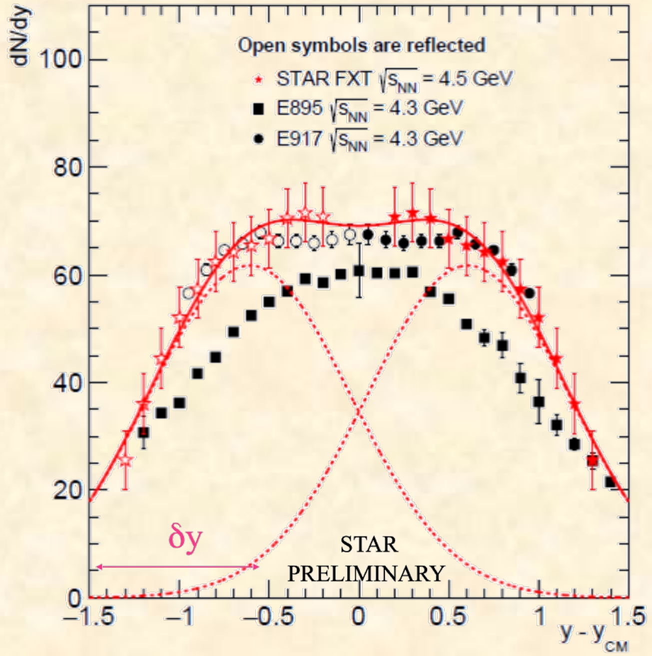


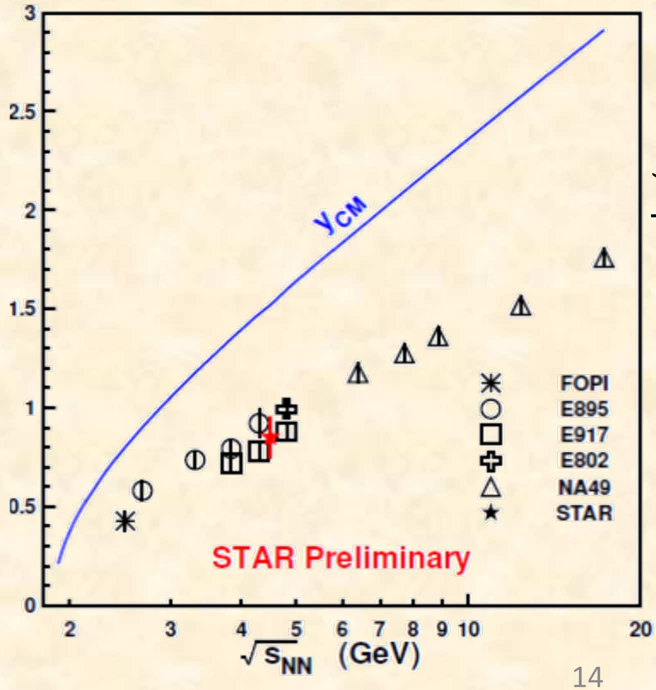
- Collision energy is close to free N-N threshold for φ (~2.89 GeV) and below threshold for Ξ (~3.25 GeV)
  - ➢ local treatment of strangeness conservation is very important
- thermal particle phase space far from GCE limit
- *Canonical Ensemble* prefers small r_C < 4.2 fm
  - – cannot simultaneously describe φ/K⁻ (2.7) and φ/Ξ⁻ (4.2)

Expanding Rapidity Coverage



- BES-2 plans on reporting rapidity distributions
  - protons from $\sqrt{s_{NN}}$=4.5GeV (FXT) consistent with E917
- ➢ baryon stopping systematics
  - amount of stopping determines μ_B
  - Ivanov (PRC87 (2013) 064904): potentially reveal 1st order PT, softening of EoS
  - more precision measurements needed :: BES-2

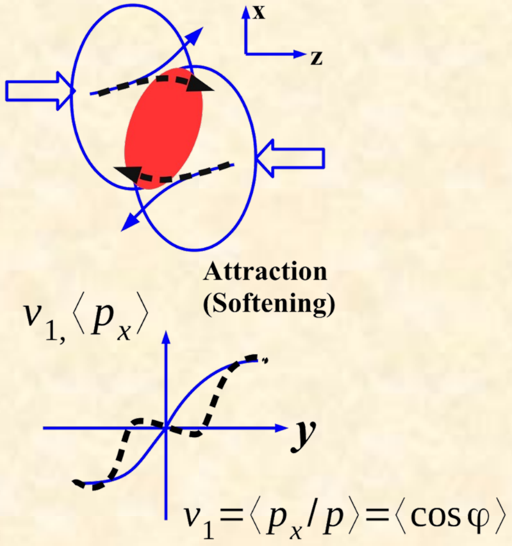




D. Cebra, April APS 2021

Proton Directed Flow

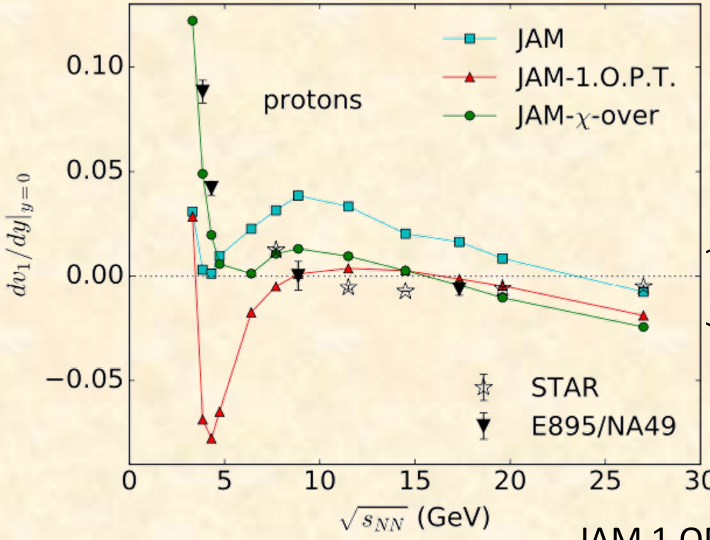
[Akira Ohnishi, CPOD 2016]



- directed flow v_1 describes sideward collective motion
  - sensitive to the EoS

[Yasushi Nara *et al.*, PRC 94 034906 (2016)]

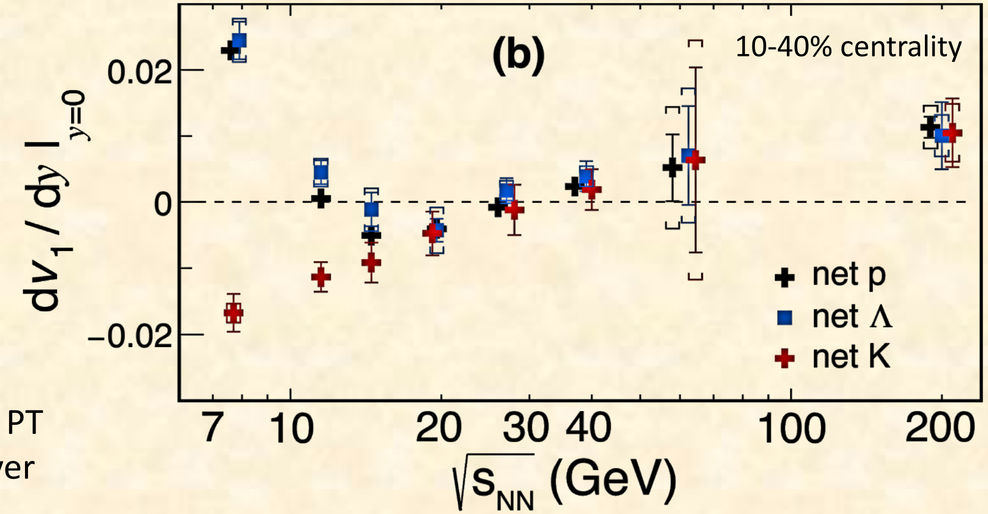
- non-monotonic dependence
  - softening (crossover or 1st order phase transition)
  - geometry (tilted ellipsoid expansion)
    - ➢ relevant at $\sqrt{s_{NN}} \gtrsim 27$ GeV)
  - transport
- ➢ minimum in slope dv_1/dy of baryons in presence of 1st order PT
- "net-protons" help isolate transported baryons



Nara *et al.* PLB769(2017)543

JAM 1.OPT :: 1st order PT
JAM-X-over :: cross-over
JAM :: no transition

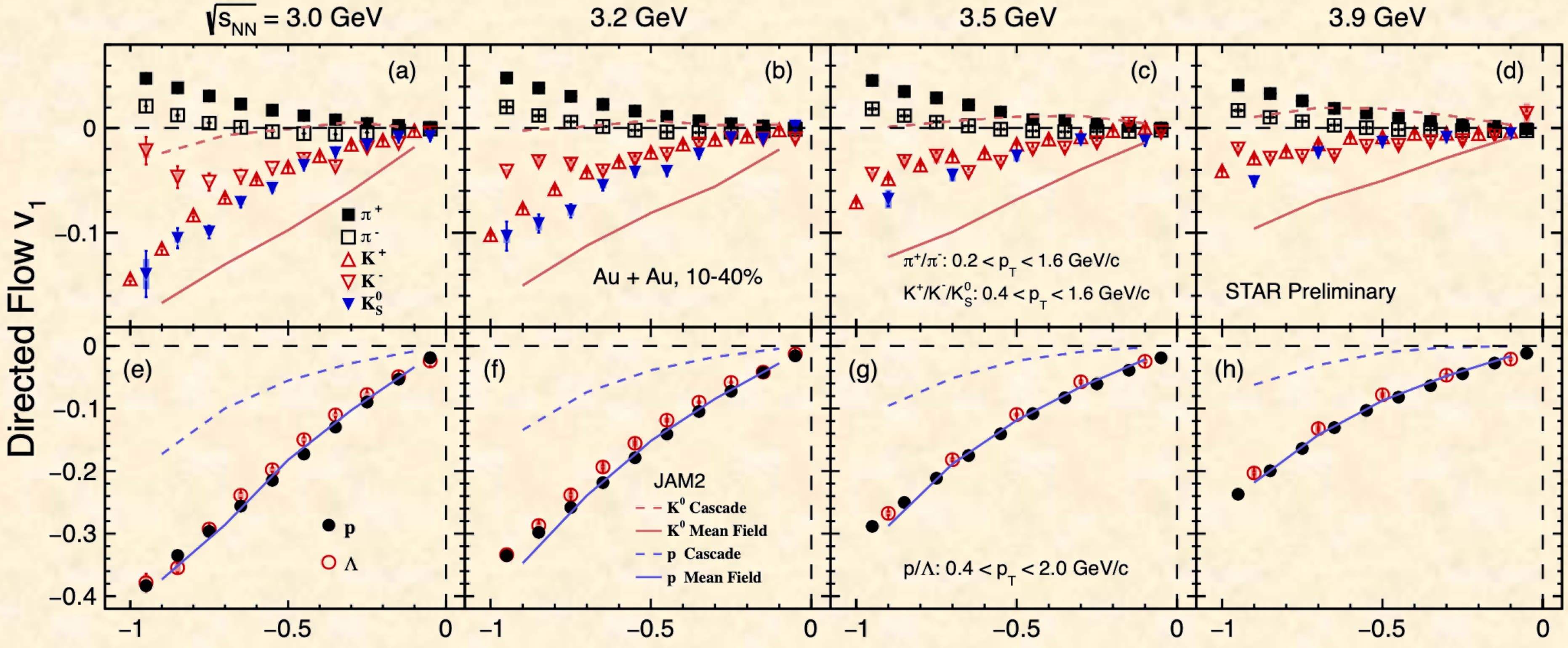
STAR, PRL 120 (2018) 062301



- Double sign change around 15 GeV

➢ BES-2 :: more statistics
- fine centrality binning (~5%)

Directed Flow at high μ_B



Li-Ke Liu (STAR), CPOD'24

- BES-2 preliminary results of v_1 vs. rapidity for $\pi^\pm$, $K^\pm$, K_S^0, p, Λ
  - at $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, and 3.9 GeV ("fixed target" energies)
- JAM Mean Field describes baryon flow
  - p-dependent Soft EOS, with nucl. compression κ = 210MeV

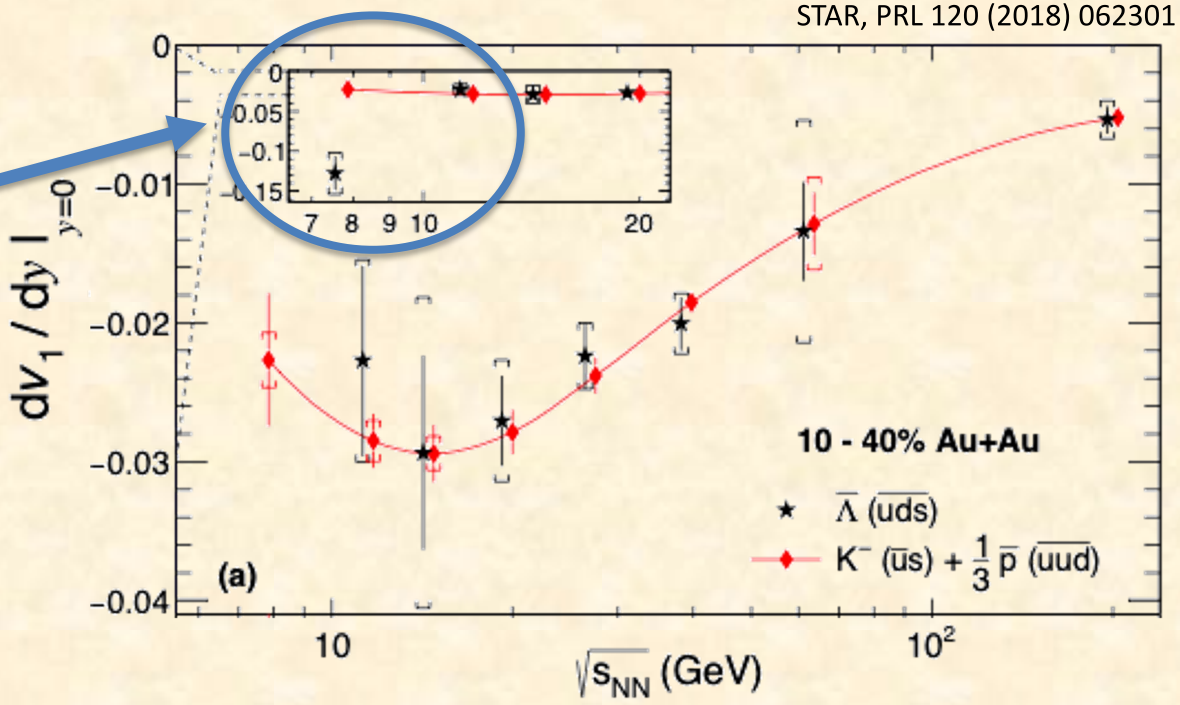
Testing the Coalescense Sum Rule

- If v_1 develops in a pre-hadronic stage
  - *and* hadrons are formed via coalescence
  - *and* $v_1(\bar{u}) = v_1(\bar{d})$, $v_1(s) = v_1(\bar{s})$
- then expect $\bar{\Lambda}$ v_1 from K and p:

  $K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\overline{uud})$

➢ picture breaks down below 11.5 GeV

STAR, PRL 120 (2018) 062301

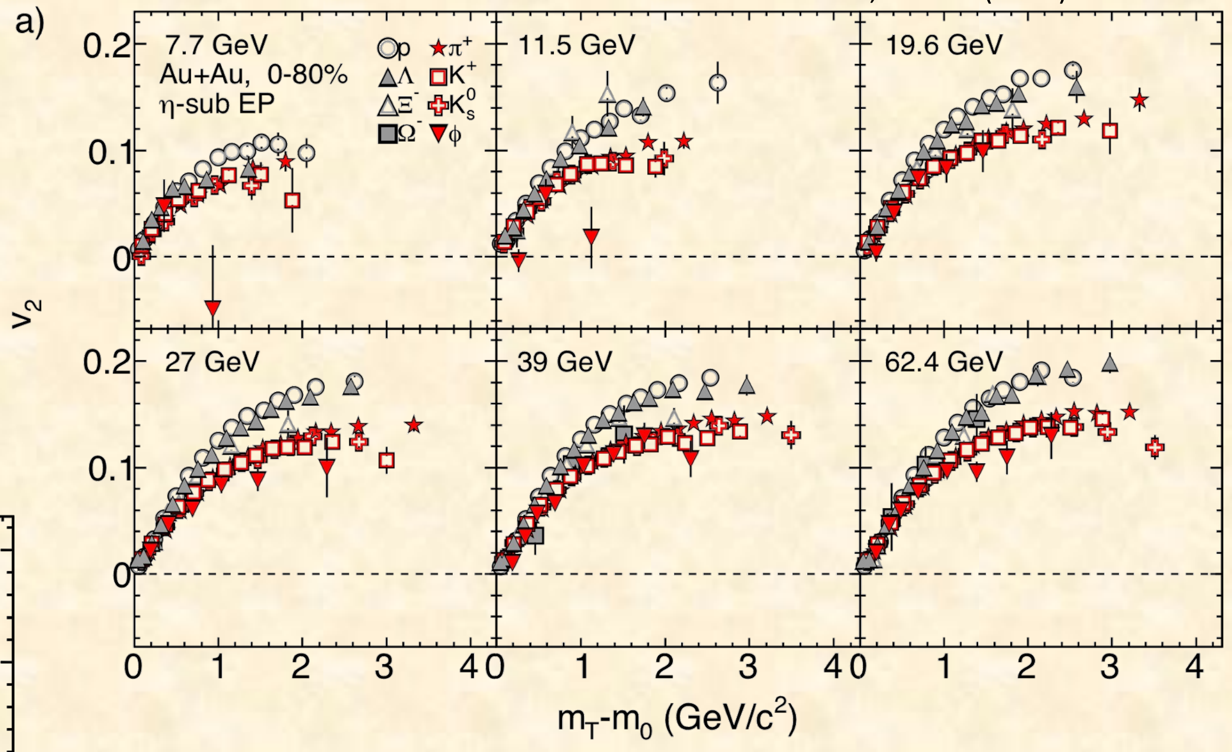


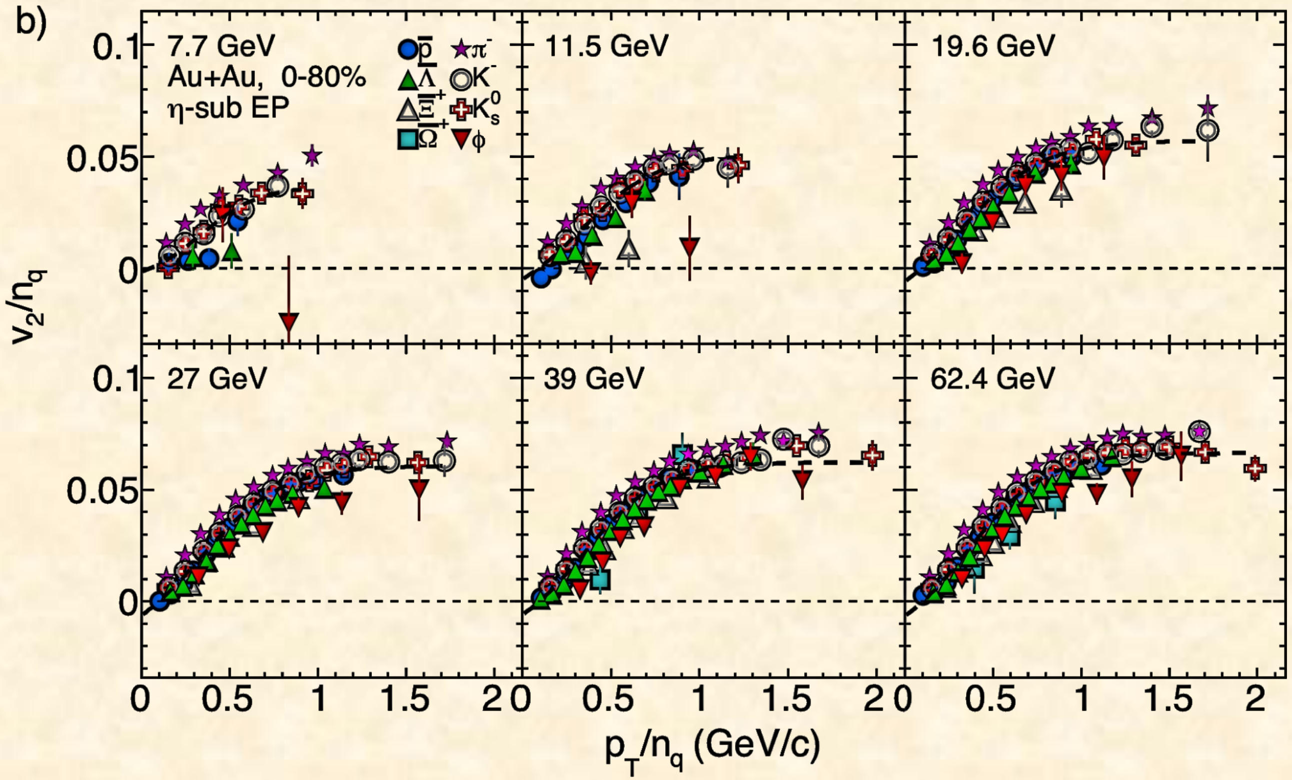
❖BES-2 :: additional energy between 7.7 and 11.5GeV + lower FXT energies

The case for the ϕ meson

STAR, PRC 88 (2013) 014902

- v_2 shows mass ordering for $p_T < 2$ GeV/c
- baryon-meson splitting for $p_T > 2$ GeV/c
  - ➢ indicative of partonic collectivity, NCQ-scaling





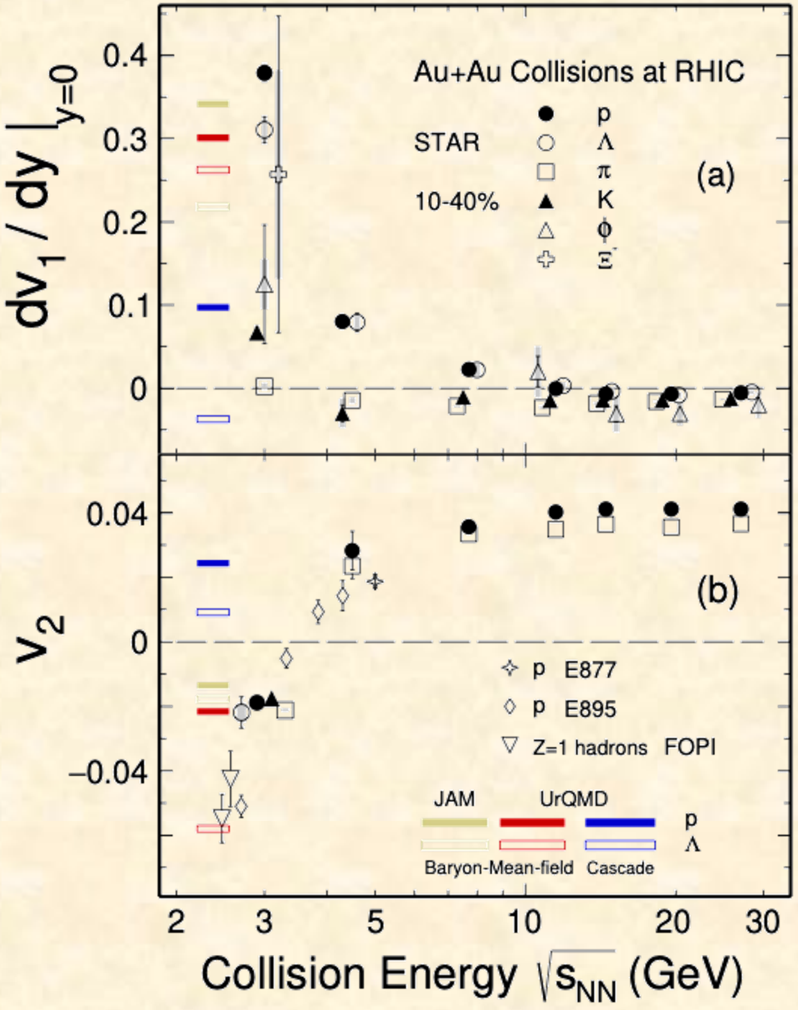
But, at low energies:

- ϕ meson hints at a departure
- ϕ has a small hadronic scattering cross section
  - ➢ hadronic interactions more important for $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV?
  - ❖ BES-2 will provide more statistics

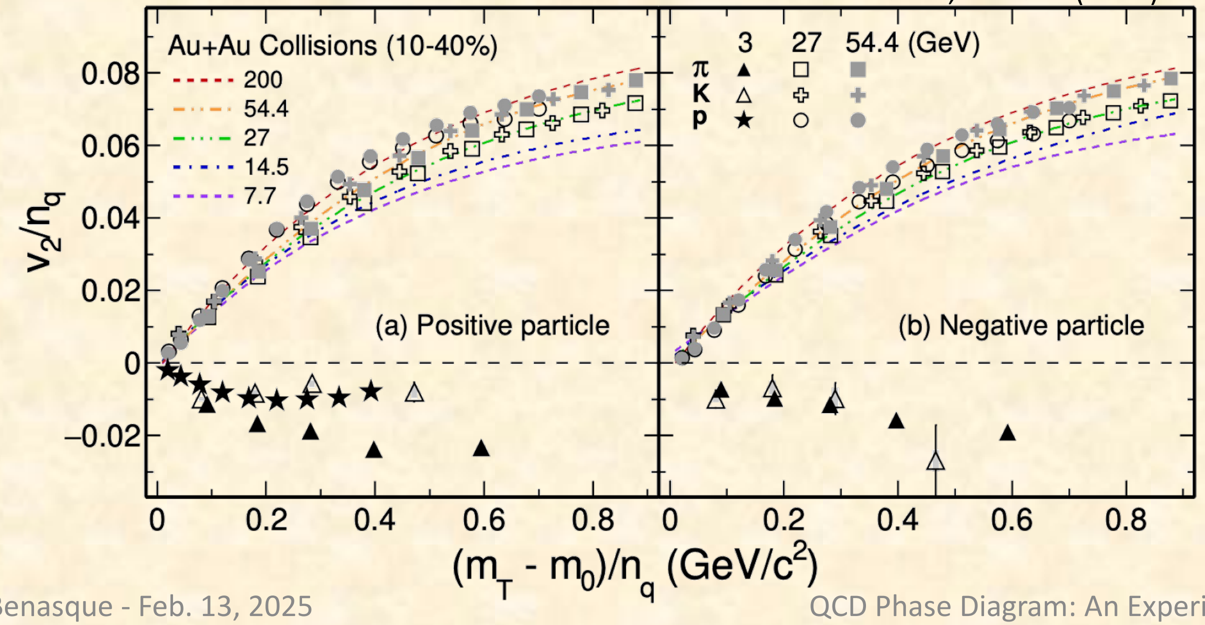
The Disappearance of Partonic Collectivity at 3GeV

STAR, PLB 827 (2022) 137003

- NCQ scaling not observed at $\sqrt{s_{NN}}$= 3 GeV
- v_2 is negative for all particles (out of plane)
  - positive for $\sqrt{s_{NN}} \geq 4.5$ GeV
- v_1 slopes are positive for all particles
  - negative for $\sqrt{s_{NN}} \geq 10$ GeV
- Qualitatively reproduced by transport models that include baryonic mean-fields

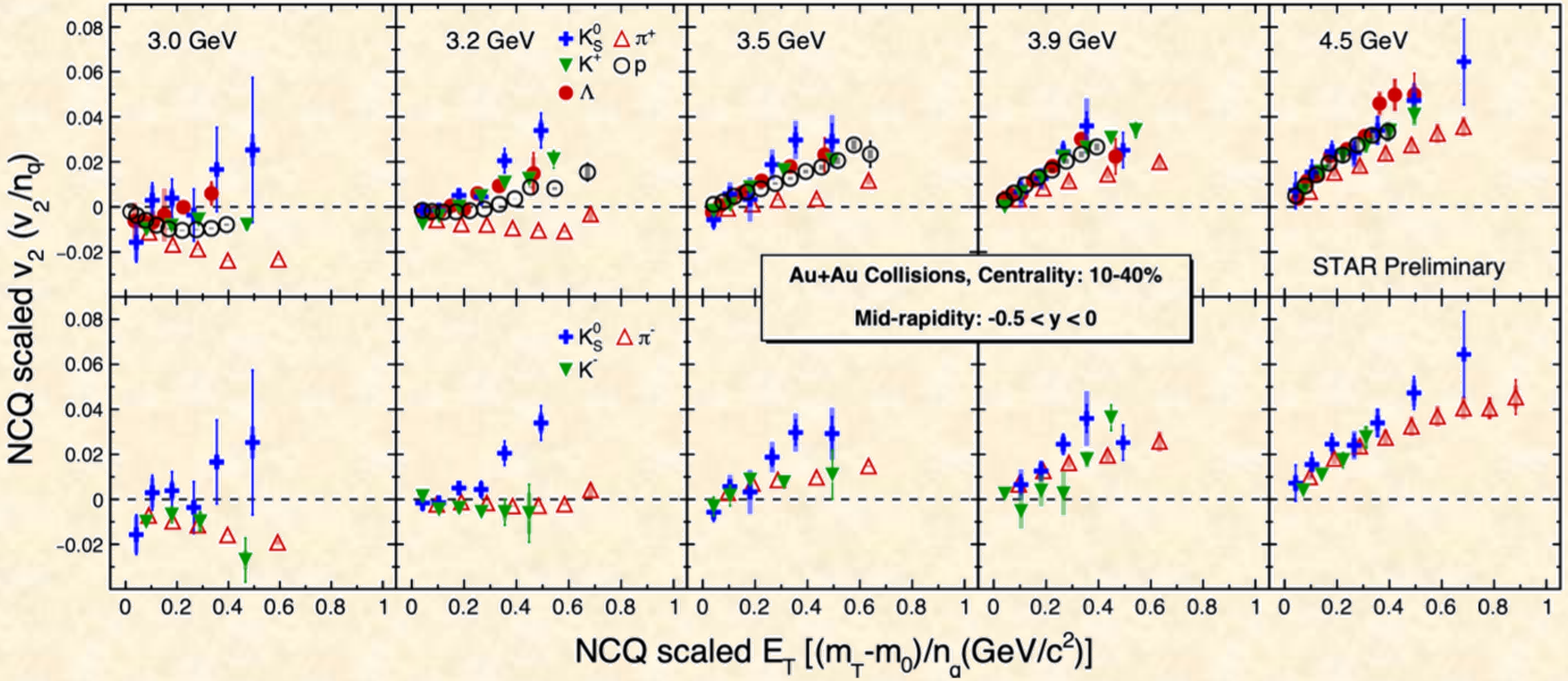


STAR, PLB 827 (2022) 137003



Baryonic interactions dominate, not partonic

The Onset of Partonic Collectivity



Li-Ke Liu (STAR), CPOD'24

STAR FXT program preliminary results complete a picture …

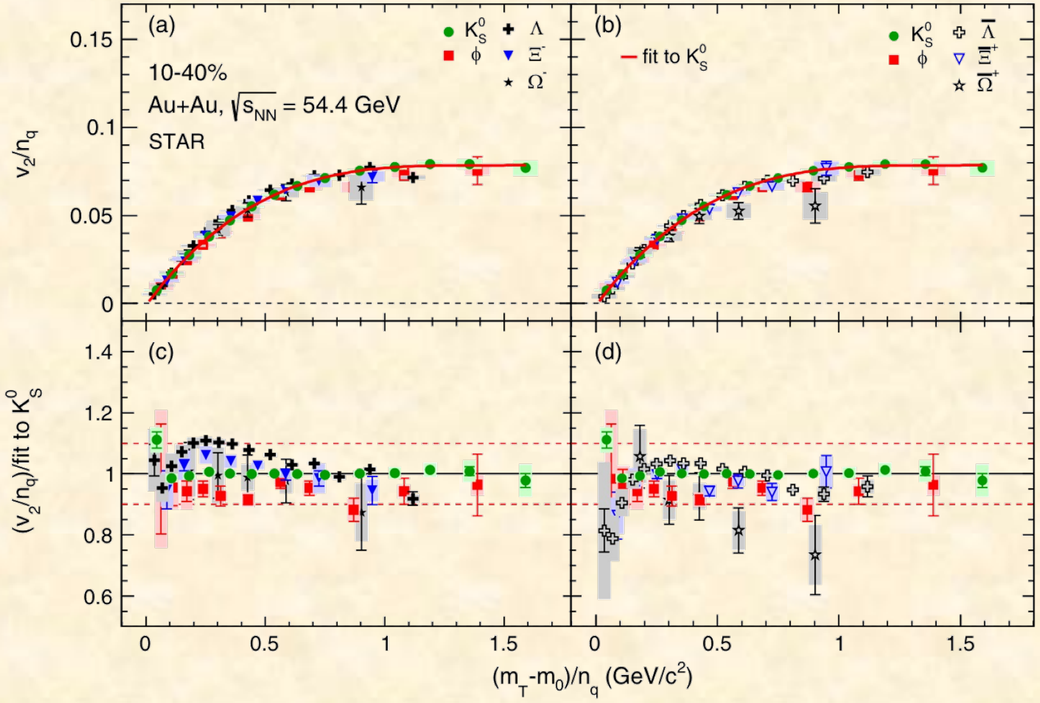
- NCQ scaling broken for $\sqrt{s_{NN}} \leq 3.2$ GeV
- Scaling gradually restores at 4.5 GeV

➢ Indicative of transition from hadron-dominated to parton-dominated matter

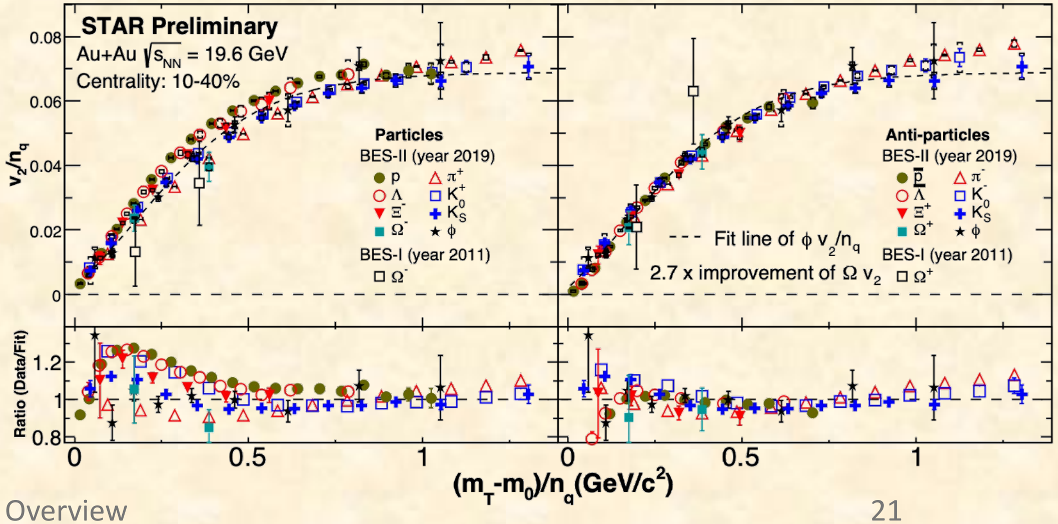
BES-2 v_2 of multi-strange particles

STAR, PRC 107 (2023) 024912

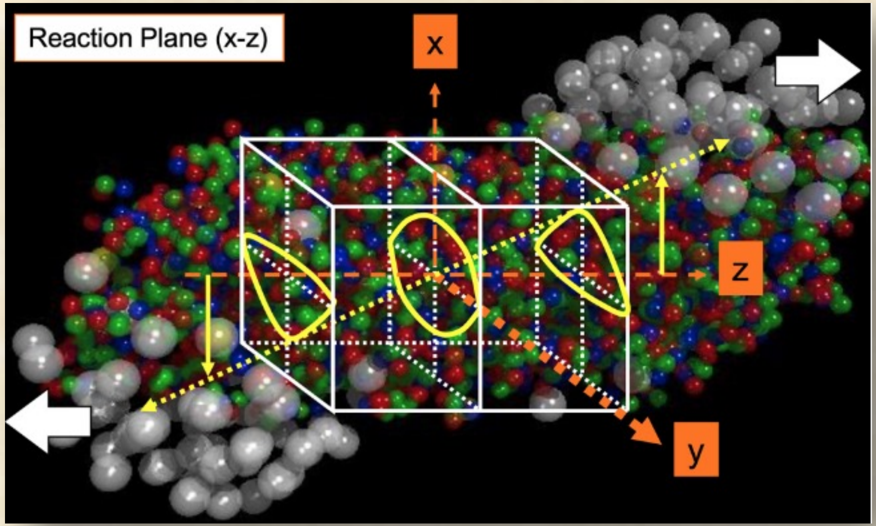
- azimuthal anisotropy of identified particles *vs* p_T and centrality
  - help put substantial constraints on transport and hydro models
- Run-17 54 GeV data for (multi)strange hadrons published
  - ➢ n_q scaling of v_2 holds within 10%



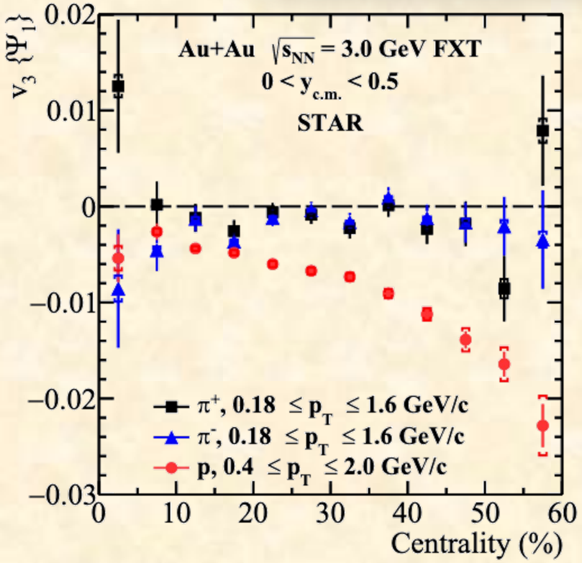
- Preliminary BES-2 results at 14.6 and 19.6 GeV
  - indicate n_q scaling for multi-strange particles is violated



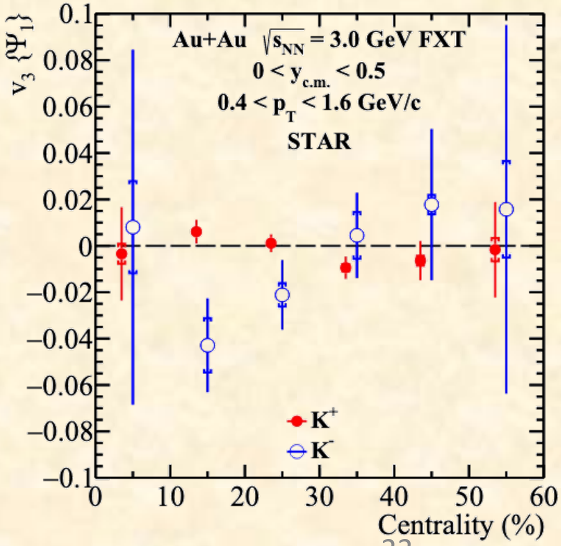
Triangular flow measurements in Au+Au at $\sqrt{s_{NN}}$ = 3 GeV



- $v_3\{\Psi_1\}$ for $\pi^{\pm}$,$K^{\pm}$, p vs. centrality, rapidity, and p_T
  - $v_3\{\Psi_1\}$ correlated with reaction plane
- Comparison with HADES $\sqrt{s_{NN}}$ = 2.4 GeV
  - Considerable differences (5x) in slope
  - Further studies needed to better understand physical drivers of this discrepancy
- Extensive comparison with several models
  - AMPT, RQMD, SMASH, JAM
  - ➢ suggests medium is not in a partonic state
- Larger 3GeV data set (5x) will help improve K^- results
  - will also include forward PID (eTOF)



STAR, PRC 109 (2024) 44914



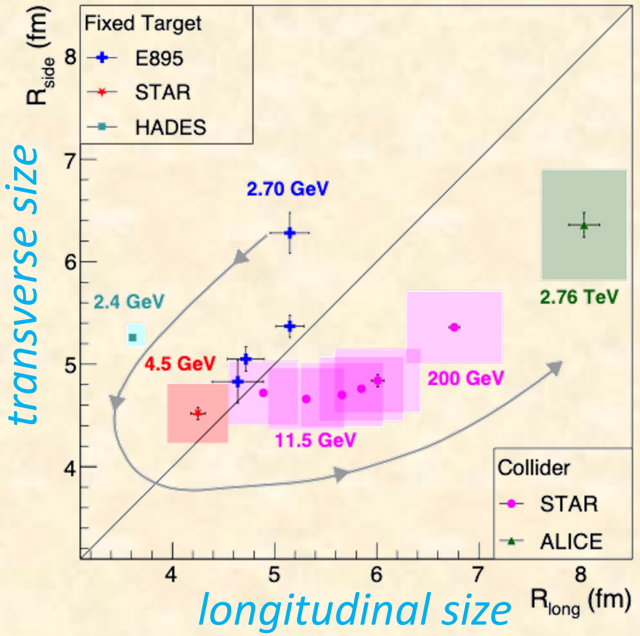
Femtoscopic Probes

- Show transition from stopping (oblate) to boost-invariant (prolate source) dynamics
  - at $\sqrt{s_{NN}}$= 4.5 GeV : $R_{side} \approx R_{long} \approx$ 4.5 fm
- R_{out} = transverse size + emission duration
  $\beta^2 t^2 = R^2_{out} - R^2_{side}$ (if no collective flow)

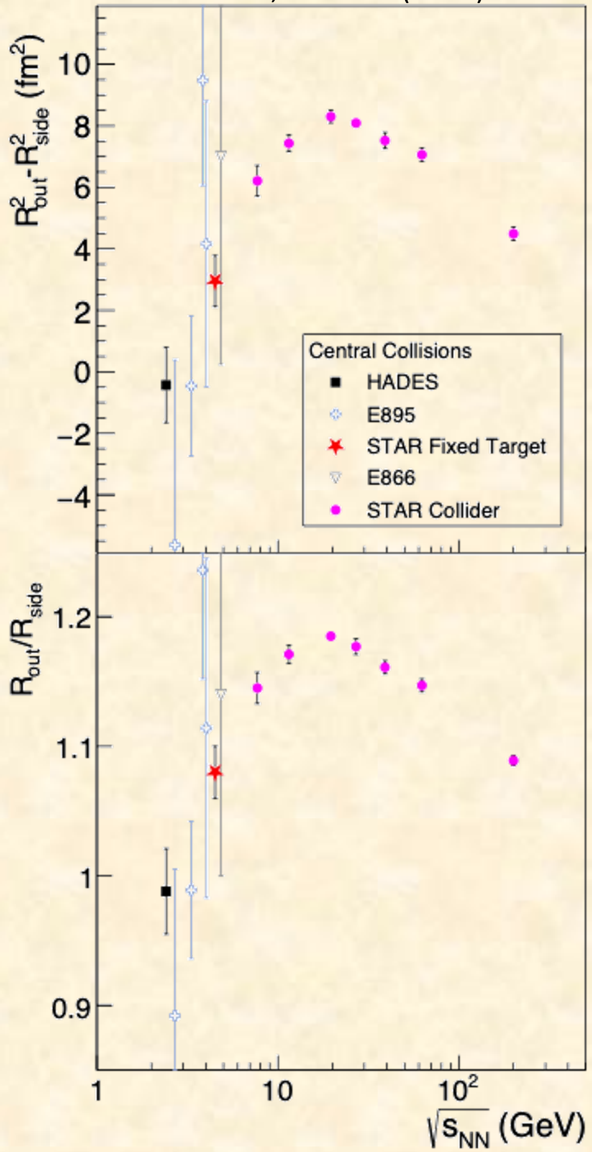
Expect increase of R_{out} relative to R_{side} to reflect extended emission time scale

- may occur if system evolves through 1st order phase transition

➢ combination of STAR and HADES data reveals peak structure

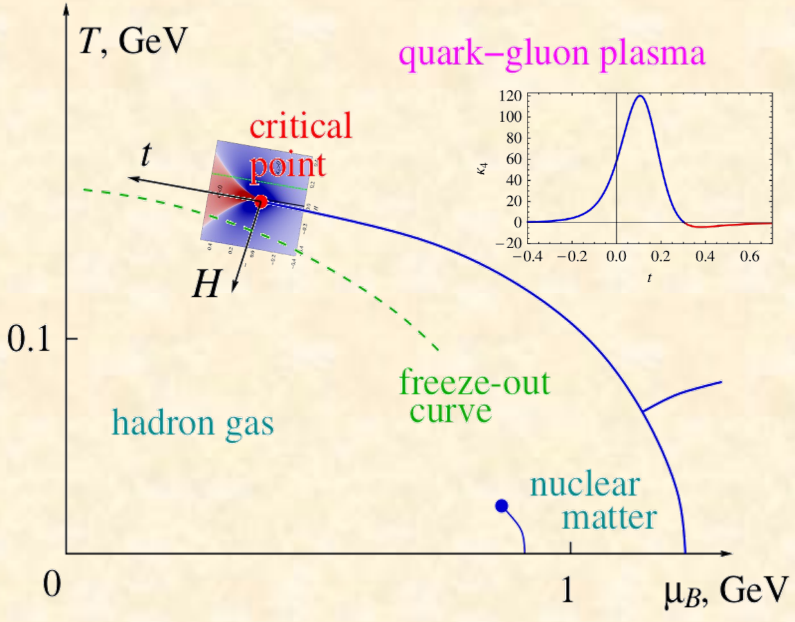


STAR, PRC 103 (2021) 034908



Critical Fluctuations

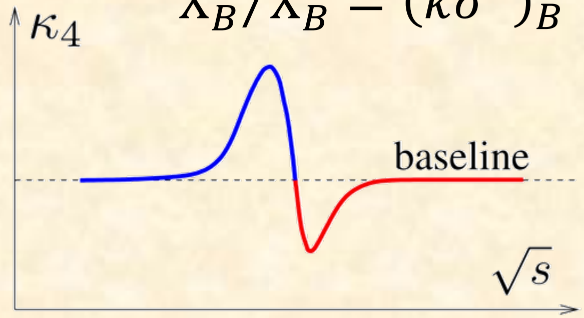
- At low μ_B: smooth cross-over
  - test with higher-order cumulants
- At high μ_B : indications of 1st order phase transition
- Critical Point in a region accessible by heavy-ion collisions?
  - can it be experimentally discovered?
- Look for the divergence of susceptibilities
  - or divergence of correlation lengths
  - non-monotonic behavior of correlations/fluctuations related to conserved quantities, *e.g.* baryon number
- Relate moments of experimentally measurable multiplicity distributions to ratios of susceptibilities



Stephanov, PRL 107 (2011) 052301

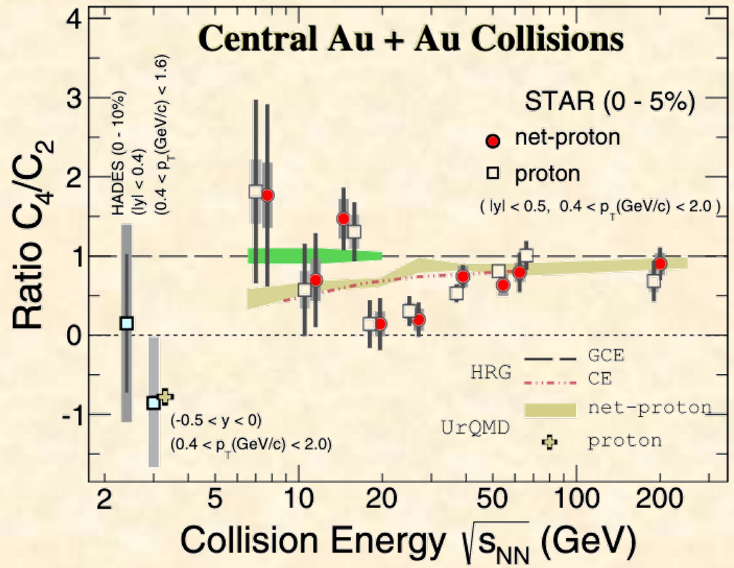
$$X_B^{(n)} = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\Big|_T$$

$$X_B^4/X_B^2 = (\kappa\sigma^2)_B$$



Stephanov, CPOD2014

STAR, PRL 128 (2022) 202303



Hints of critical fluctuations

BES-2 data sets with iTPC & EPD

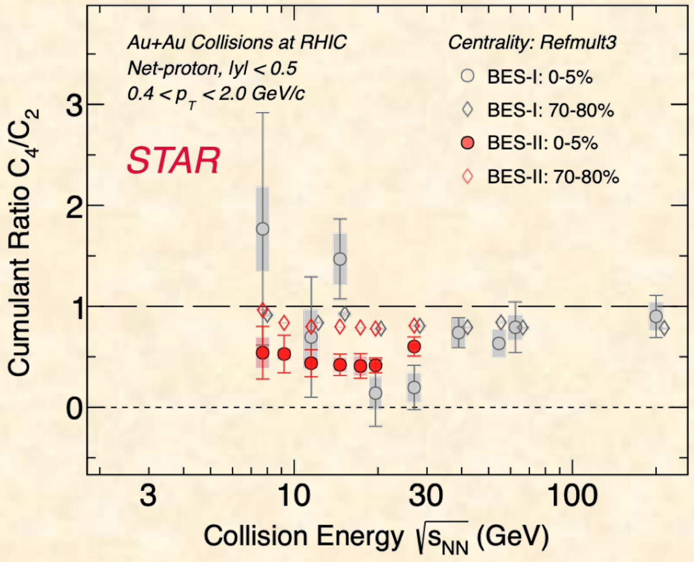
- increase Δy_p acceptance with iTPC
- improve centrality selection with EPD
  - use TPC for measurements

❖ STAR only to release final results

BES Phase-2: net-proton higher moments

- Collider data from 7.7 – 27 GeV
  - 150 < μ_B < 400 MeV
- Precision results on proton cumulants and factorial cumulants
  - from BES-II with greatly improved statistical and systematic uncertainties
  - Reduction factors in uncertainties on 0-5% C_4/C_2 (BES 1 vs BES 2)

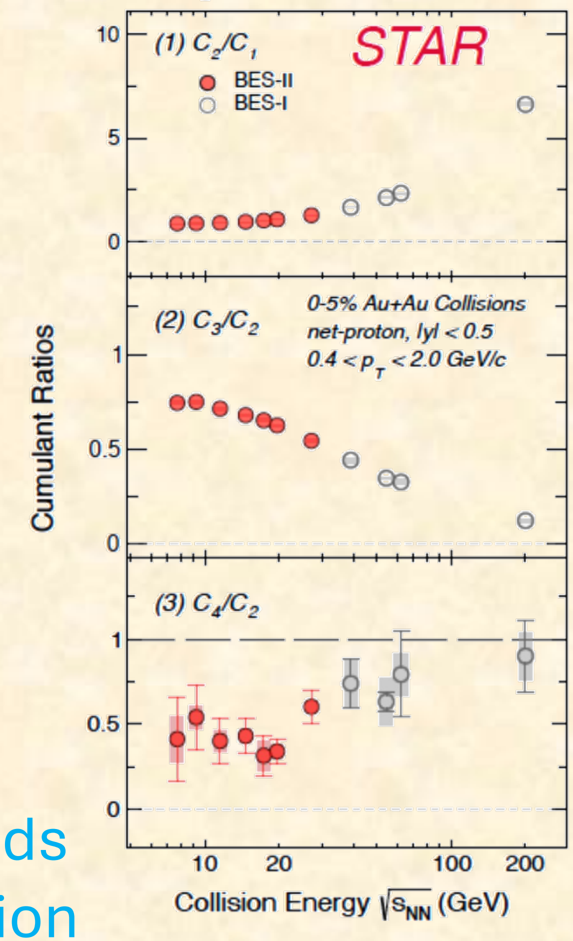
7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4



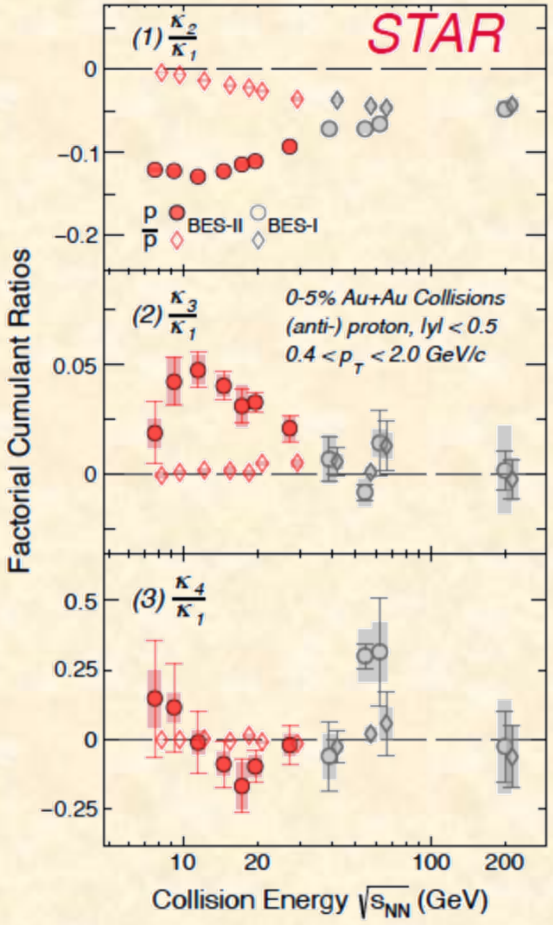
Pandav (STAR, CPOD'24)

➢ Very interesting trends observed as a function of collision energy

Net-proton cumulant ratios



Proton/antiproton factorial cumulant ratios



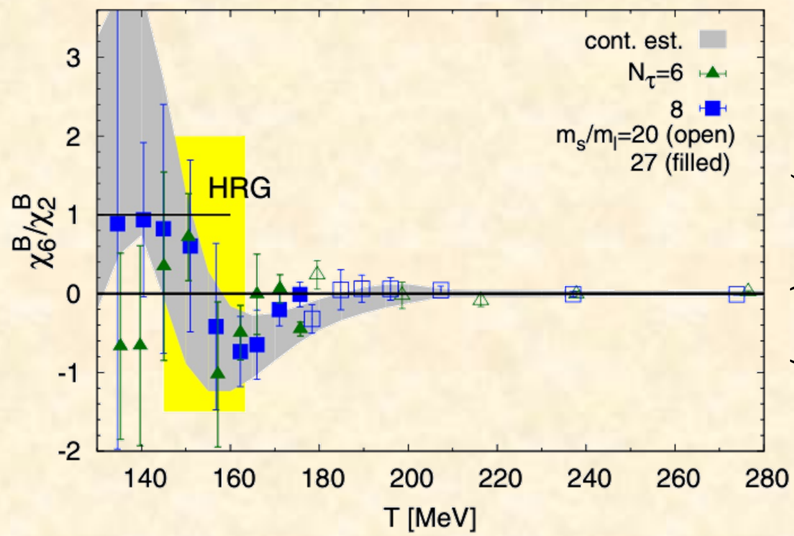
STAR (ready to submit)
CPOD'24, SQM'24

Critical Fluctuations: cross-over

- At low μ_B: smooth cross-over
  - test with higher-order cumulants: expected to be negative

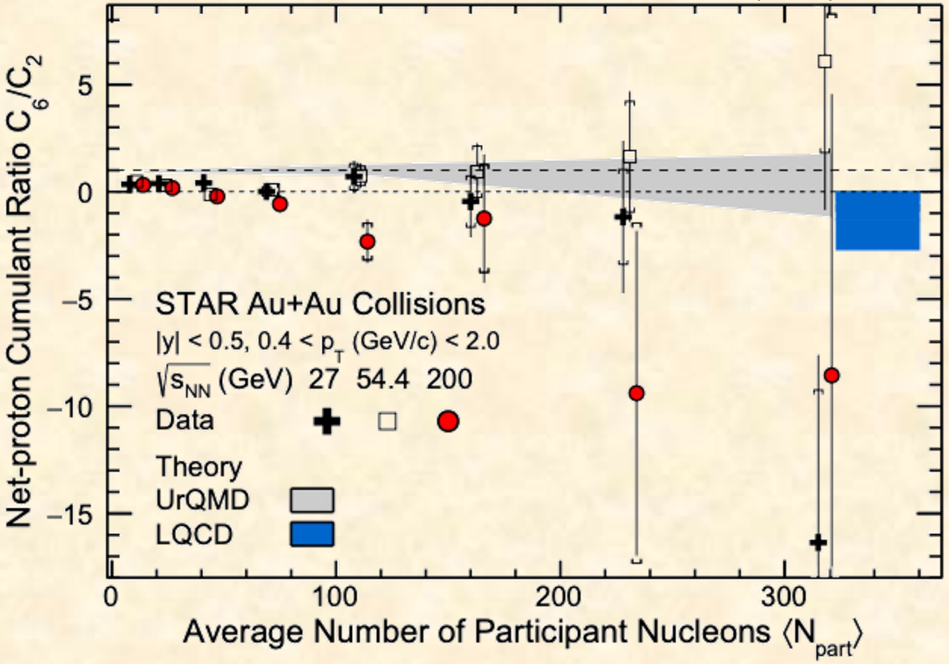
➢ First measurement of net-proton C6/C2
  - statistics limited
  - consistent with 0 for $\sqrt{s_{NN}}$= 27 and 54.5 GeV
  - negative in more central collisions for $\sqrt{s_{NN}}$=200 GeV
    - *caveat*: exp. data involves kinematic cuts that are not incorporated in the lattice calculations

❖ Suggestive of a smooth cross-over at top RHIC energies



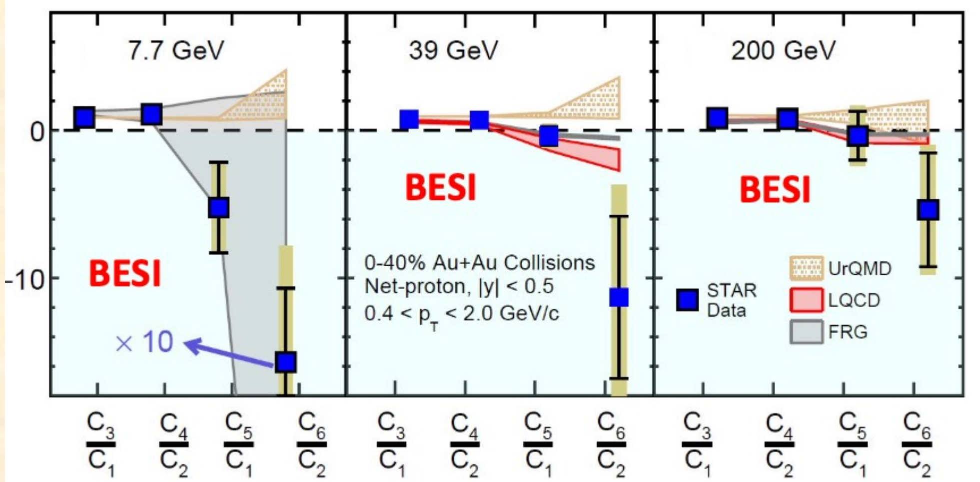
Bazavov *et al.*, PRD95 (2017) 054504

STAR, PRL 127 (2021) 262301



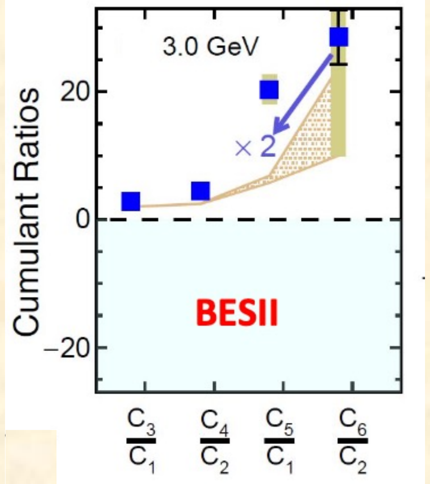
BES-1/2: Hyper-order Cumulant Ratios

- Higher-order cumulants more sensitive to correlation length
- Cumulant ratios cancel volume dependence
  – directly related to susceptibilities
- 7 – 200GeV: falling trend with rising order
  - ➢ $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$
    - predicted by LQCD
      [Bazavov, et al. PRD 101 (2020) 074502]



STAR, PRL 130 (2023) 082301

- 3 GeV:
  - ➢ rising trend with rising order
    - in agreement with UrQMD
    - suggestive of hadronic matter

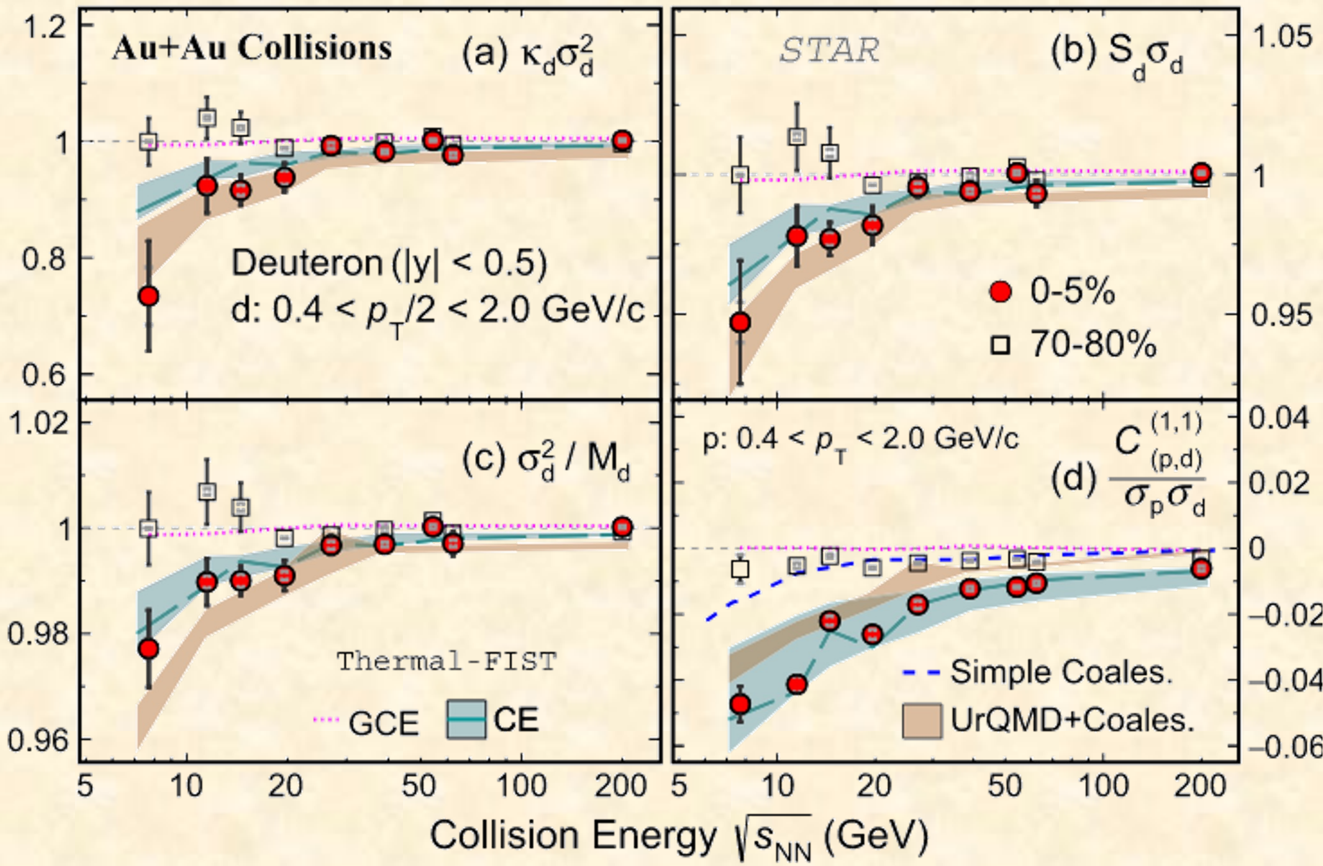


Beam Energy Scan: deuteron cumulants

- First measurement of cumulants, up to 4th order
  - BES Phase-1 data
- ➢ Cumulant ratios favor CE over a GCE in thermal models
  - CE explicitly conserves B number
- Anti-correlation between p and d numbers
  - negative Pearson correlation coefficients

❖ BES Phase-2 data (incl. FXT) will allow for more differential studies

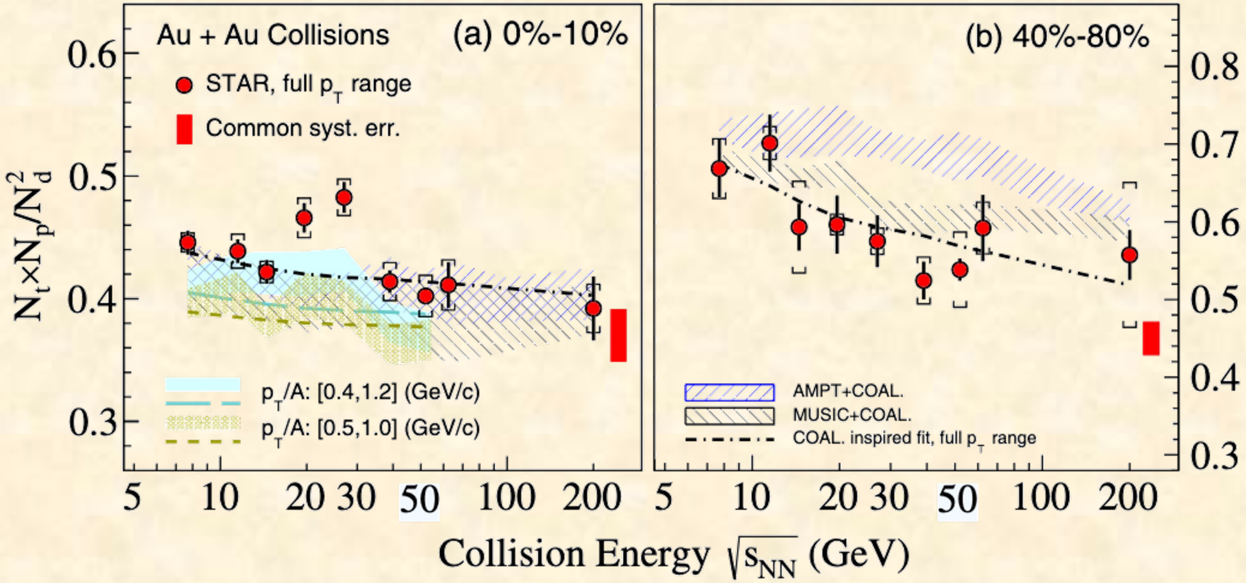
STAR, PLB 855 (2024) 138560



Beam Energy Scan: Triton Production

- Study of ratio of triton to deuteron yields $N_t \times N_p / N_d^2$
  - Coalesence Model: sensitive to fluctuations of the local neutron density

    [Sun, Chen, Ko, and Xu, PLB 774 (2017) 103–107]
  - non-monotonic behavior can be indicative of CP or 1st-order PT

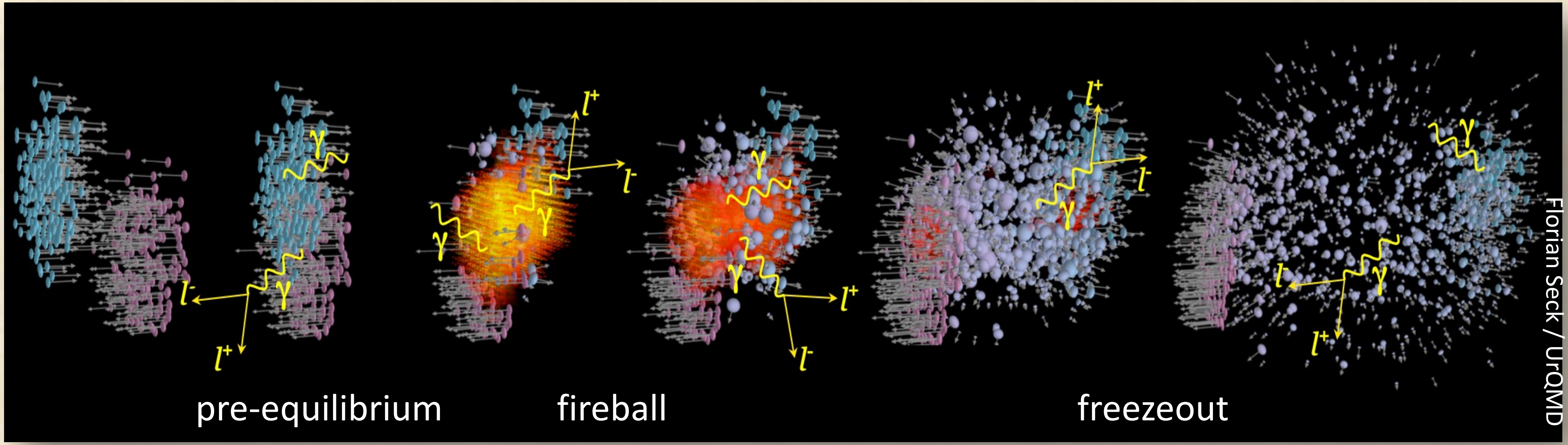


STAR, PRL 130, 202301 (2023)

➢ enhancements relative to the coalescence baseline
  - significance 2.3σ and 3.4σ in 0 –10% central Au+Au collisions at 19.6 and 27 GeV

Exploring Fundamental Symmmetries. What can dileptons do?

© ParticleZoo.net



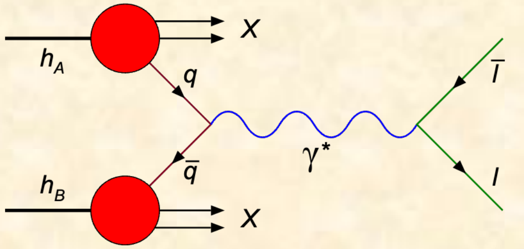
Florian Seck / UrQMD

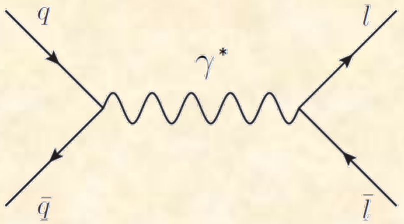
Dileptons are excellent penetrating probes

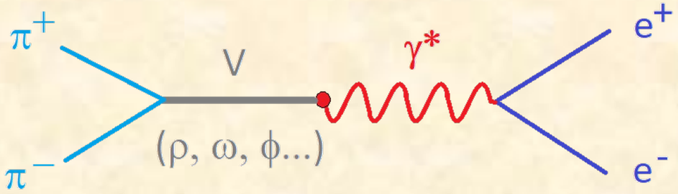
- colorless objects ∴ no coupling to strongly interacting matter
- produced in various ways throughout the system’s evolution
- long mean free paths
- experimentally provide an additional “knob”: invariant mass

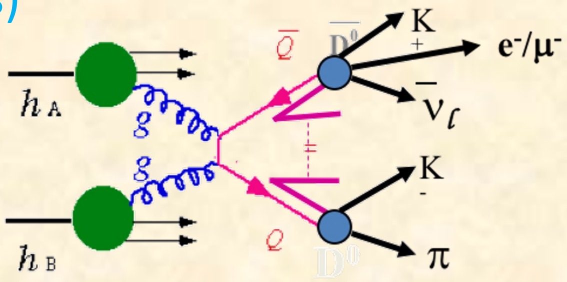
Dilepton invariant mass spectrum

- Primordial emissions, pre-equilibrium
  - Drell-Yan, $NN \rightarrow e^{+}e^{-}X$
  - heavy flavor production ($c\bar{c}, b\bar{b}$), quarkonia & open charm
- Thermal radiation from QGP/hadronic matter
  - QGP thermal radiation $q\bar{q} \rightarrow e^{+}e^{-}$
  - HG thermal radiation $\pi^{+}\pi^{-} \rightarrow e^{+}e^{-}$
  - in-medium ρ
  - other 4π, multi-meson interactions, incl. $\rho - a_1$ mixing
- Long-lived hadron and resonance decays
  - decays of light mesons of π^0, η, ω, φ (incl. Dalitz decays)
    - in-medium modification of vector mesons
  - decays of quarkonia J/Ψ, Ψ' and correlated $D\bar{D}$ *pairs*
    - nuclear modification effects

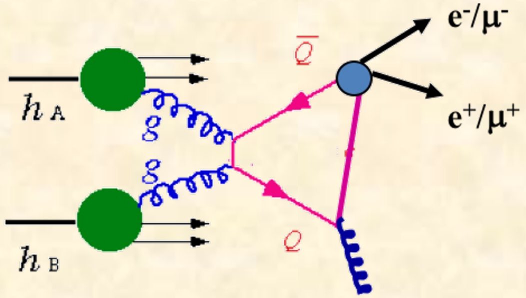








open heavy flavor



heavy quarkonia

Dilepton invariant mass spectrum

- High Mass Range (HMR)

  $M_{ee} > 3$ GeV/c^2

  - primordial emission, Drell-Yan
  - Heavy quarkonia: J/ψ and ϒ suppression
- Intermediate Mass Range (IMR)

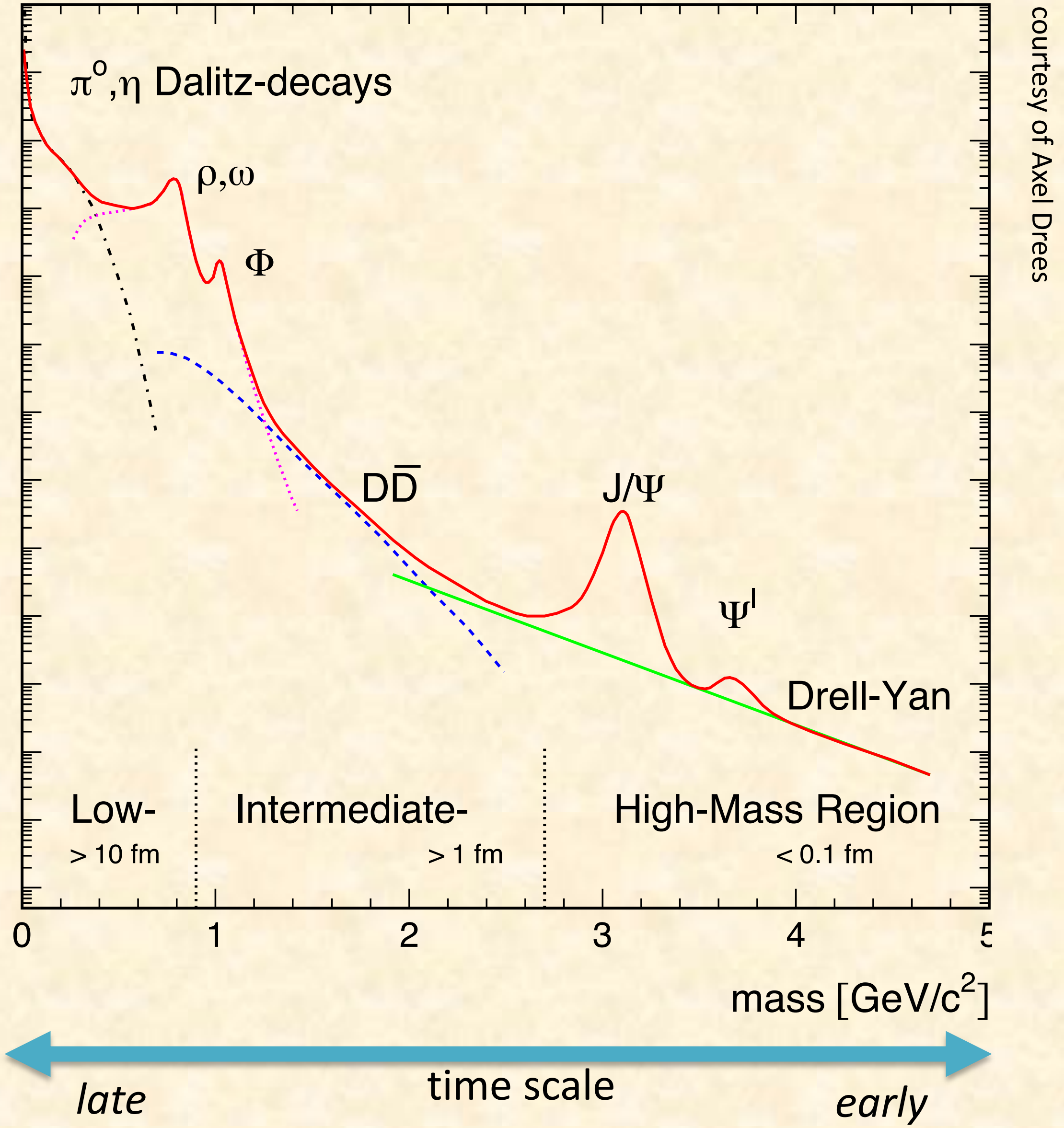
  $1.1 < M_{ee} < 3$ GeV/c^2

  - QGP thermal radiation
  - Semi-leptonic decay of correlated charm

    heavy-flavor modification
- Low Mass Range (LMR)

  $M_{ee} < 1.1$ GeV/c^2

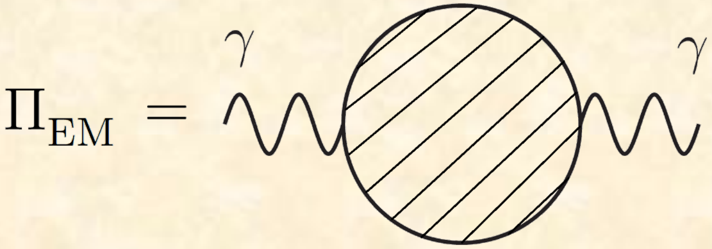
  - in-medium modification of vector mesons
  - fireball lifetime measurement
  - transport coefficients (electrical conductivity)



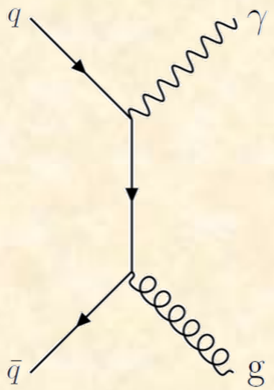
EM production rates

From thermal field theory†, using EM current-current correlation function:

$$\Pi_{em}^{\mu\nu}(q_0, q) = -i \int d^{4x}\, e^{iqx} \Theta(x^0) \langle\langle [j^\mu(x), j^\nu(0)] \rangle\rangle$$



$$j^\mu = \sum_q e_q \bar{q} \gamma^\mu q = \tfrac{2}{3} \bar{u} \gamma^\mu u - \tfrac{1}{3} \bar{d} \gamma^\mu d - \tfrac{1}{3} \bar{s} \gamma^\mu s$$



with the thermal emission rates

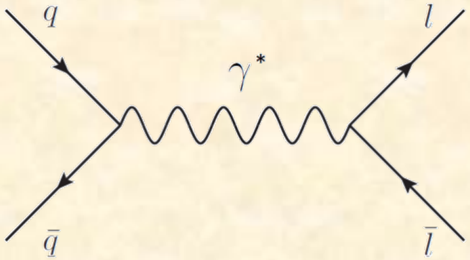
- photons:

$$p_0 \frac{dN_\gamma}{d^4x\, d^3p} = -\frac{\alpha_{em}}{\pi^2} f^B(p_0; T)\ \frac{1}{2} g_{\mu\nu}\ \mathrm{Im}\Pi_{\mathrm{em}}^{\mu\nu}(M = 0, p; \mu_B, T)$$

- dileptons:

$$\frac{dN_{ll}}{d^4x\, d^4p} = -\frac{\alpha_{em}^2}{\pi^3 M^2} L(M) f^B(p_0; T)\ \frac{1}{3} g_{\mu\nu}\ \mathrm{Im}\Pi_{\mathrm{em}}^{\mu\nu}(M, p; \mu_B, T)$$

$L(M)$ is lepton space factor and $f^B(p; T)$ is the thermal Bose distribution



- both governed by same underlying spectral functions
  - but different kinematic regimes (light-like and time-like)

† see e.g. Friman, et al., Lecture Notes in Phys. 814 (2011) 1

Connection with vector mesons

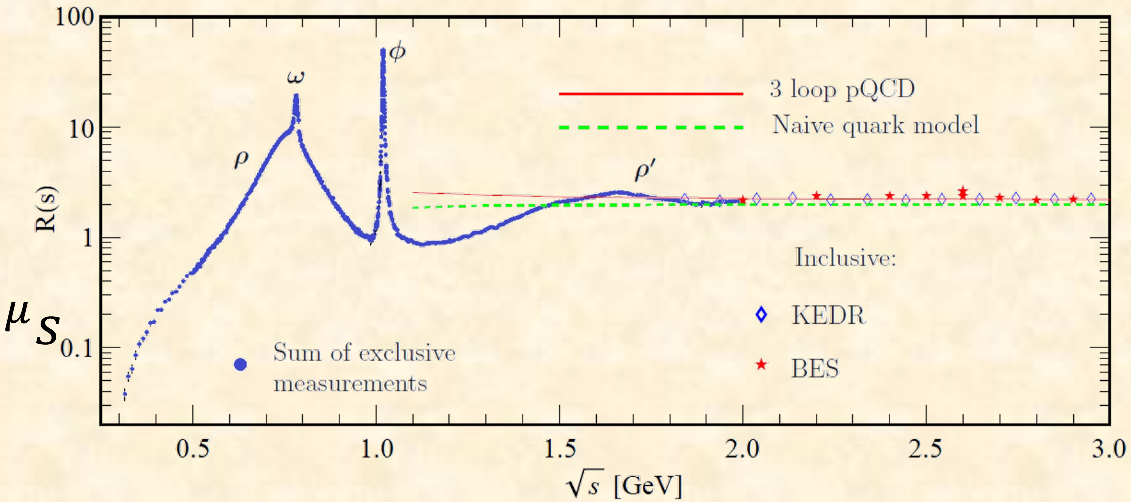
For lightest quarks

$$j^\mu = \sum_q e_q \bar{q}\gamma^\mu q = \tfrac{2}{3}\bar{u}\gamma^\mu u - \tfrac{1}{3}\bar{d}\gamma^\mu d - \tfrac{1}{3}\bar{s}\gamma^\mu s$$

or grouping into isospin states $I = 1(\rho), 0\ (\omega, \varphi)$:

$$j^\mu = \tfrac{1}{2}(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d) + \tfrac{1}{6}\bar{d}\gamma^\mu d(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d) - \tfrac{1}{3}\bar{s}\gamma^\mu s$$
$$= \frac{1}{\sqrt{2}} j^\mu_\rho + \frac{1}{3\sqrt{2}} j^\mu_\omega + \frac{1}{3} j^\mu_\phi$$

$\mathrm{Im}\,\Pi_{\mathrm{em}}$ is well understand in vacuum:

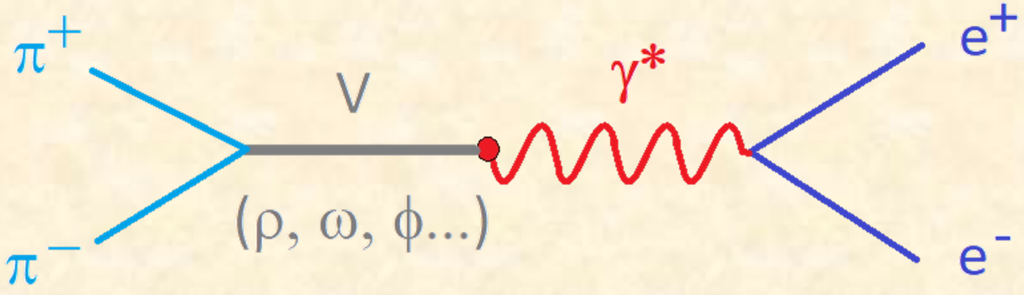


which leads at low M :

$$\mathrm{Im}\,\Pi_{\mathrm{em}} \sim D_\rho + \frac{1}{9} D_\omega + \frac{2}{9} D_\phi$$

vector meson dominance

- carry same quantum numbers as photons
- can directly decay into dileptons
- ρ(770) dominant source



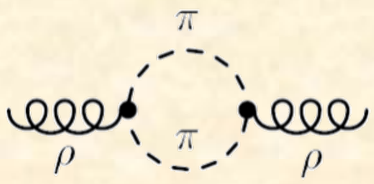
In-medium vector mesons (1)

ρ meson will interact with hadrons in the medium

propagator will have various contributions to the self-energy

$$D_\rho(M,q;T,\mu_B) = \frac{1}{\left(M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B}\right)}$$

$\Sigma_{\rho\pi\pi}$ =

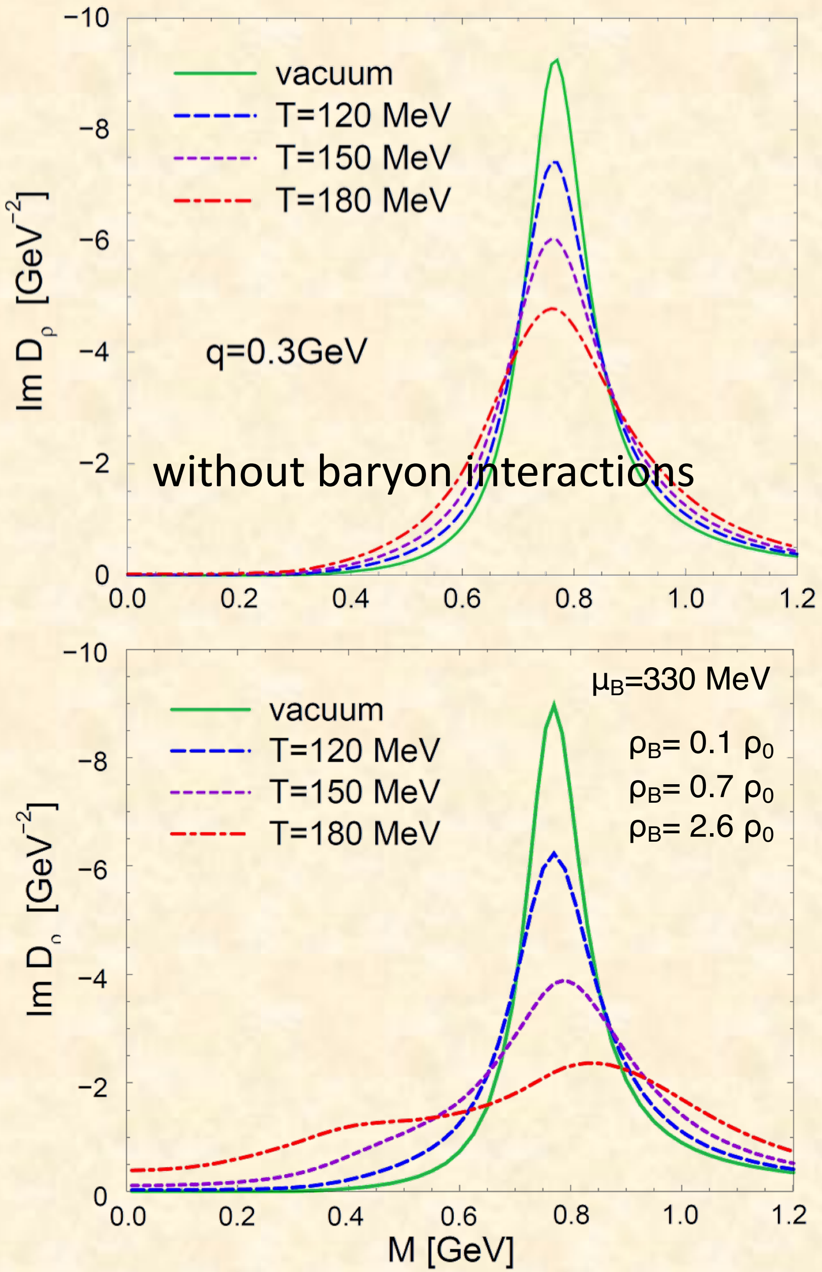


in-medium pion cloud

$\Sigma_{\rho B,M}$ =

direct ρ-hadron scattering

strong broadening of ρ spectral function
→ baryons are important



Rapp, Acta Phys. Polon. B42 (2011) 2823

In-medium vector mesons (2)

QCD langrangian contains subgroup $SU_L(n_f) \times SU_R(n_f)$

- chiral symmetric in limit of vanishing quark masses
  - lattice QCD: dynamical formation of $\langle q\bar{q}\rangle \sim \Delta_{l,s}$

    breaks chiral symmetry
  - profound effect on chiral partners

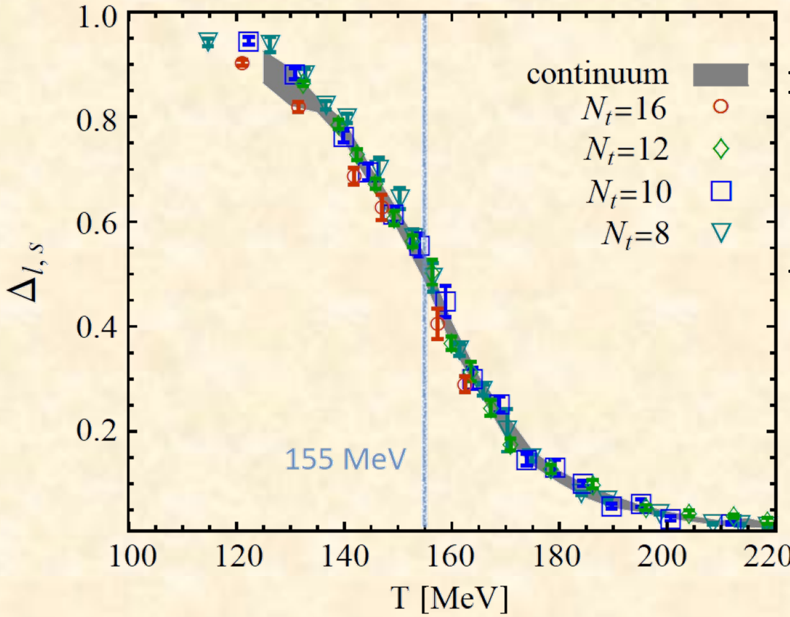
    $$\langle q\bar{q}\rangle = \langle q_L\bar{q}_R + q_R\bar{q}_L\rangle$$

    significant mass splitting between chiral partners

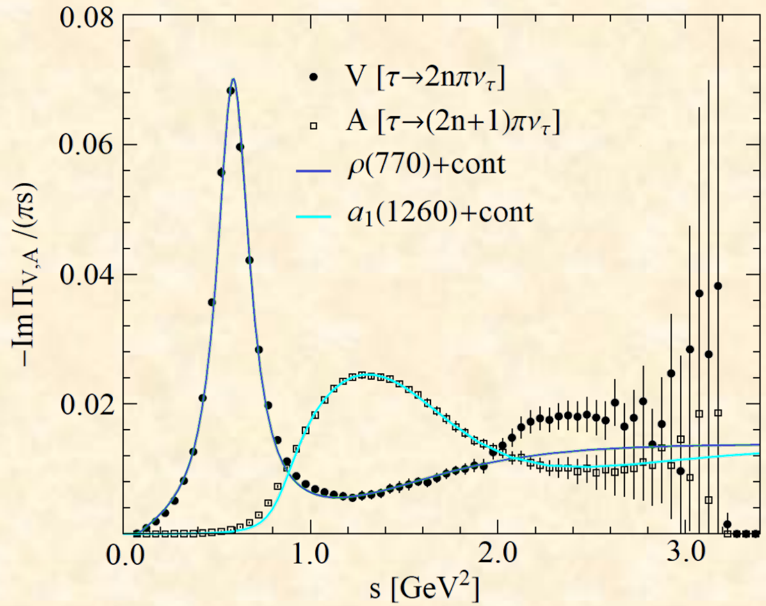
    ρ(770) - a_1(1260), nucleon(940) - N(1535), σ – π

- Weinberg (chiral) sum rules connect SFs to condensates:

$$\int_0^\infty \frac{ds}{\pi}\left(\Pi_V(s) - \Pi_A(s)\right) = m_\pi^2 f_\pi^2 = -2\, m_q\langle q\bar{q}\rangle$$



Wuppertal-Budapest collaboration

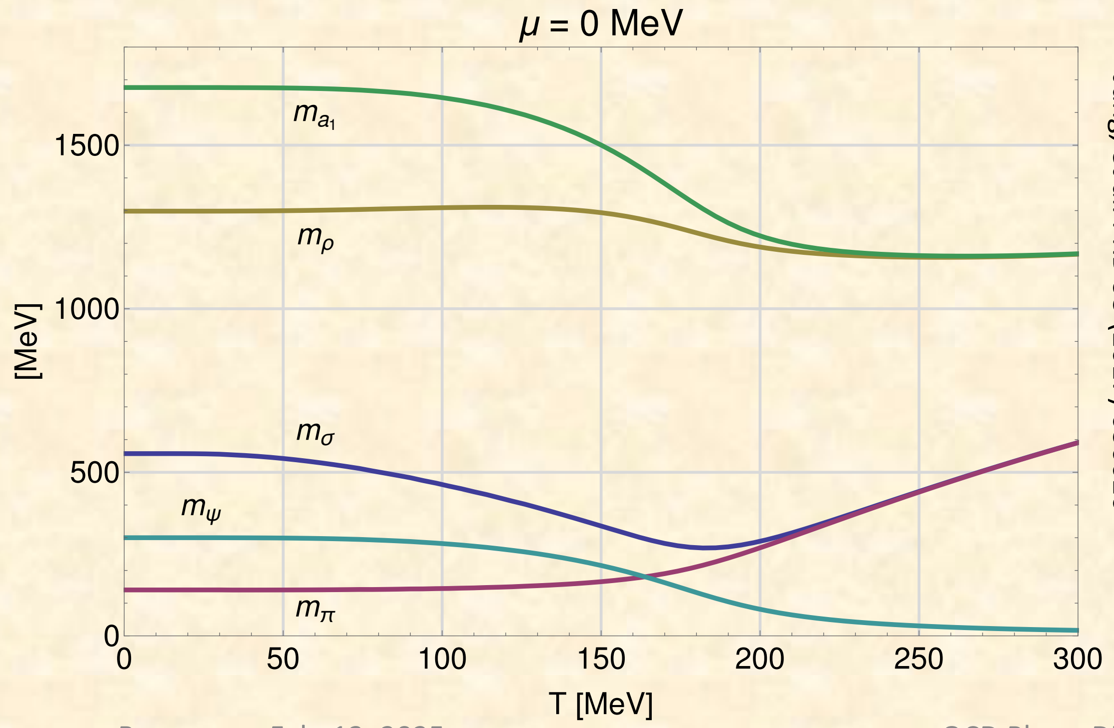


Rapp, Pramana 60 (2003) 675

Chiral symmetry restoration

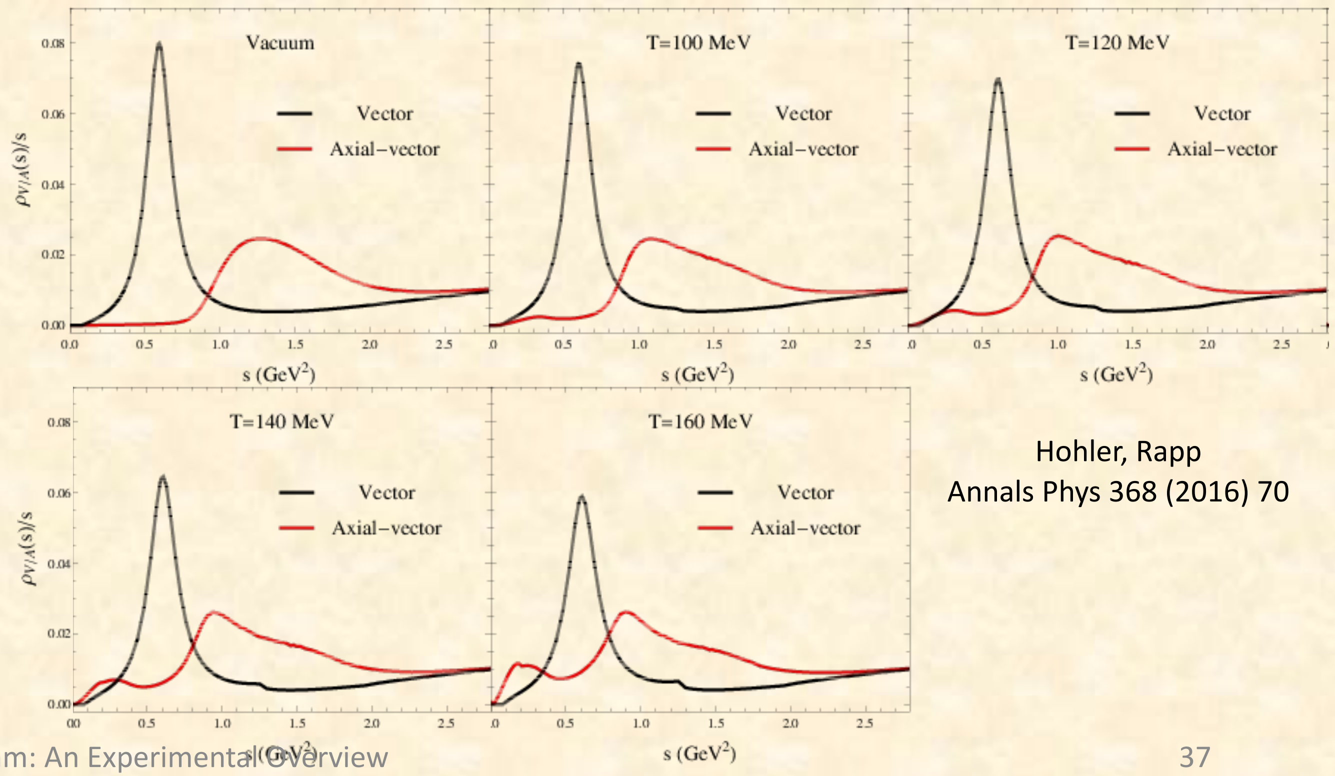
- restoration of chiral symmetry manifests itself in mixing of V and A correlators
- ρ mesons melts in hot matter while a_1 decreases and degenerates

➢ chiral mass splitting ”burns off”



Jung, et al. PRD 95 (2017) 036020

Massive Yang-Mills in hot pion gas



Hohler, Rapp
Annals Phys 368 (2016) 70

Three Decades of ρ melting

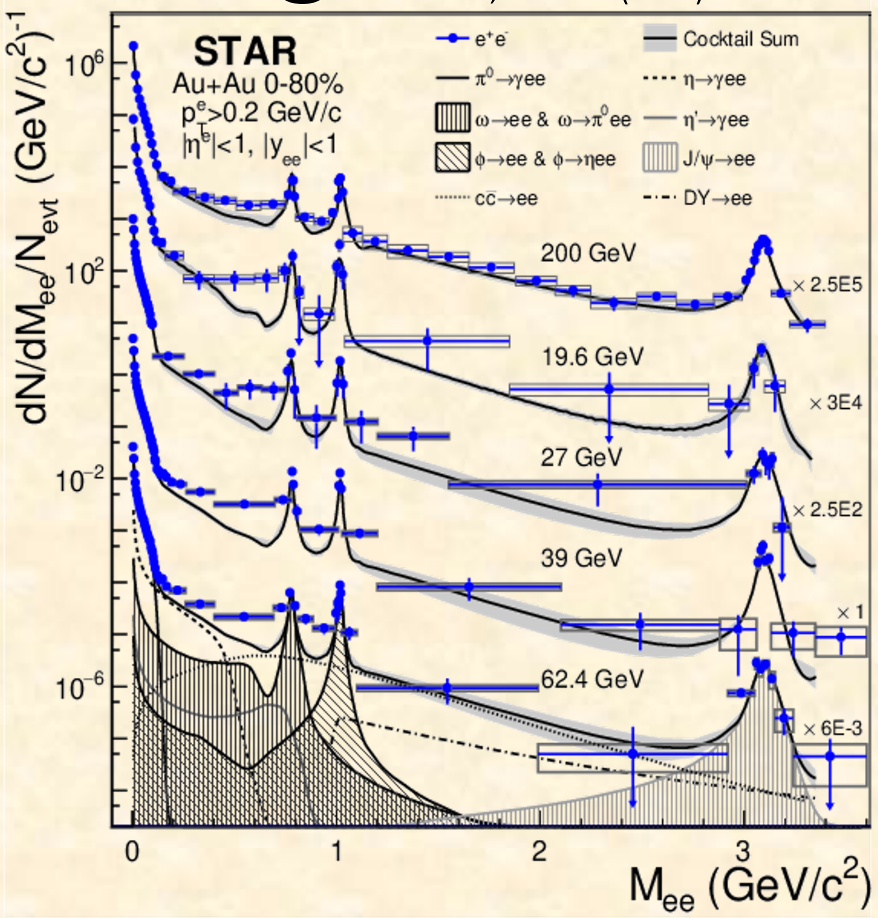
At SPS from CERES to NA60

- Excess in LMR $\mu^+\mu^-$ – EPJ C61 (2009) 711
- rules out: dropping-mass scenario
- very good agreement with Resonance Width Broadening for $M_{\mu\mu} < 0.9$ GeV/c^2

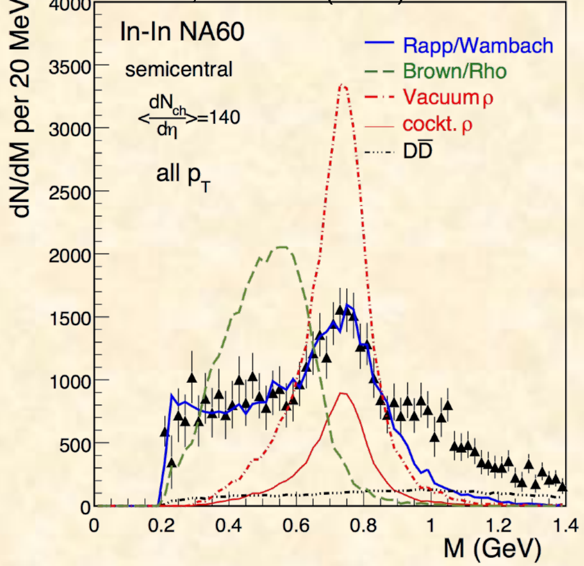
At RHIC from STAR and PHENIX

- systematic beam energy scan
  - $\sqrt{s_{NN}}$ = 7.7 - 200 GeV
- within uncertainties agreement between experiment and theory

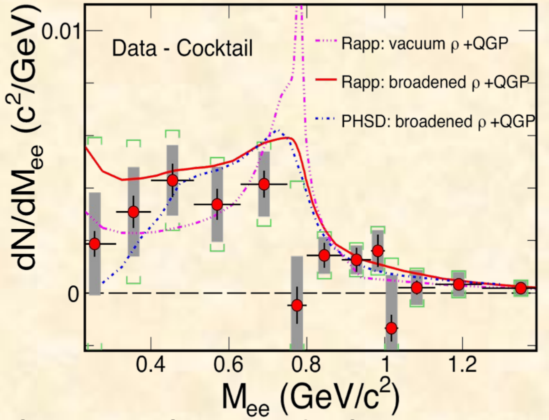
STAR, PRC 107 (2023) L061901



NA60, EPJ C61 (2009) 711



STAR, PRC 92 (2015) 024912



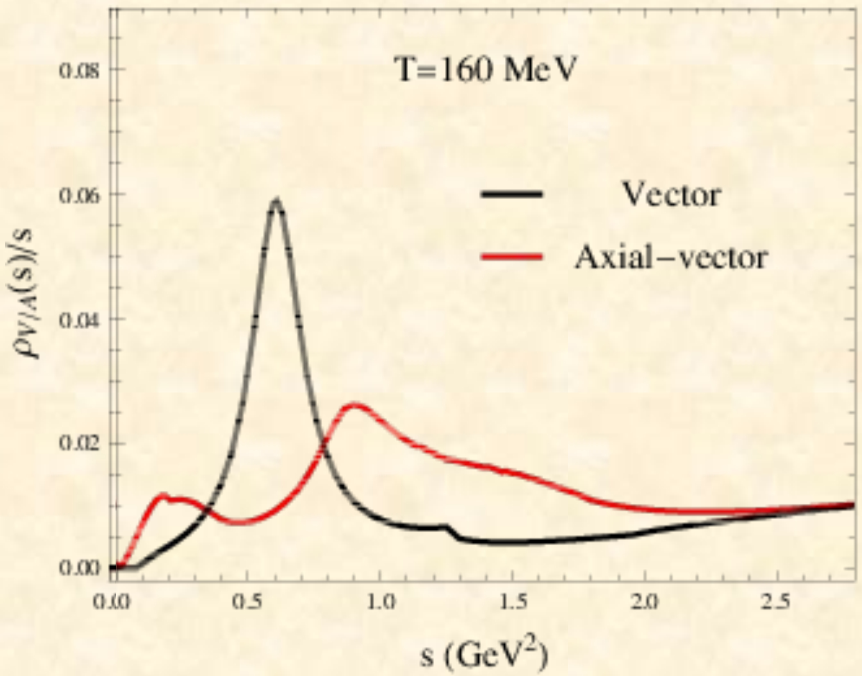
Phenomenological Approach:

compare experimental data against vector SF (ρ meson) from phenomenological model

”Is ρ-meson melting compatible with chiral restoration?” [Hohler, Rapp PLB 731 (2014) 103]

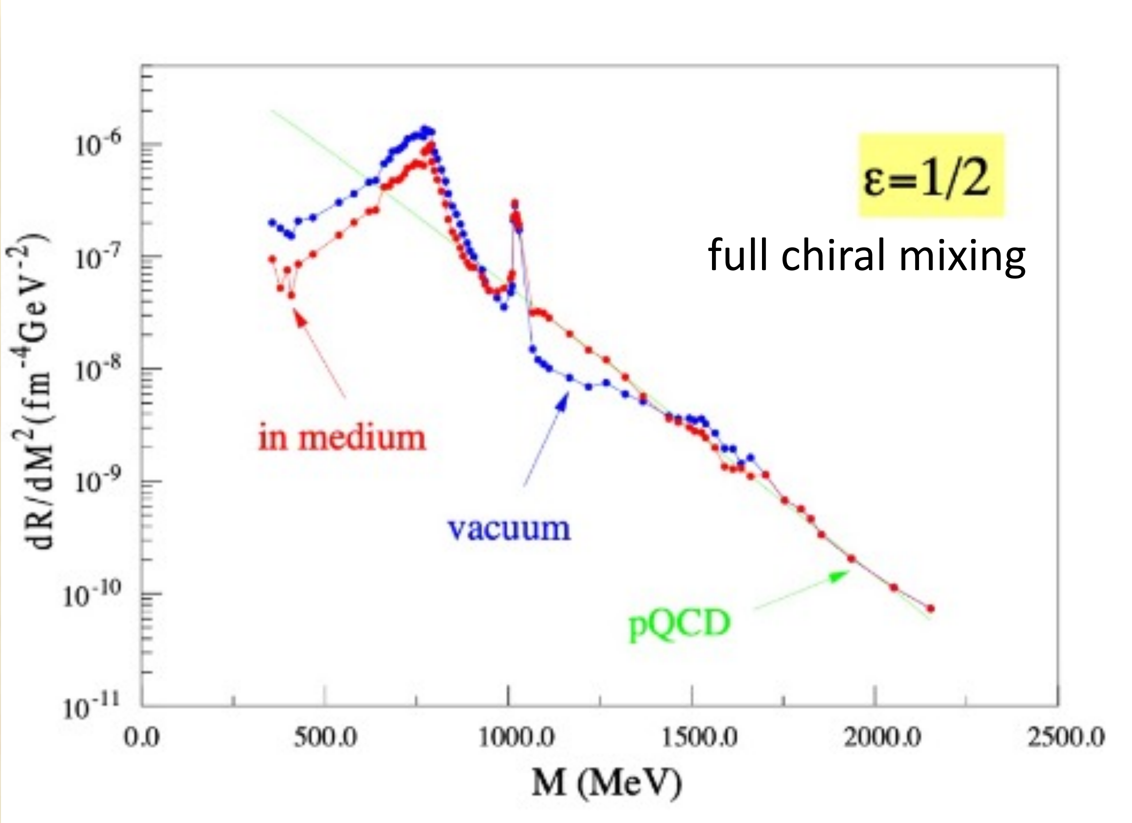
“This establishes a direct connection between dileptons and chiral restoration, and thus the answer to the originally raised question is positive.”

Chiral symmetry restoration: ρ-a_1 mixing



Hohler, Rapp, Annals Phys 368 (2016) 70

$$\pi a_1 \rightarrow \rho' \rightarrow l^+ l^-$$



Stroth, ECT* Trento 2021

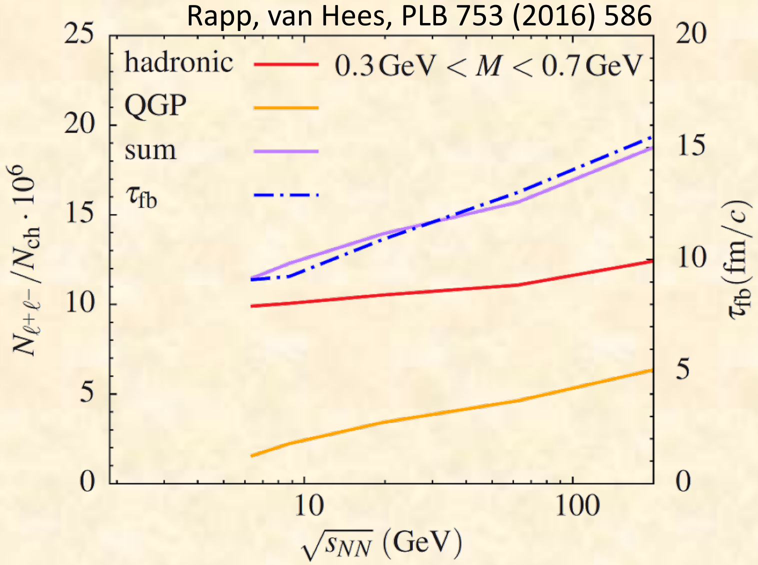
- mixing “moves strength from the axialvector to the vector channel”

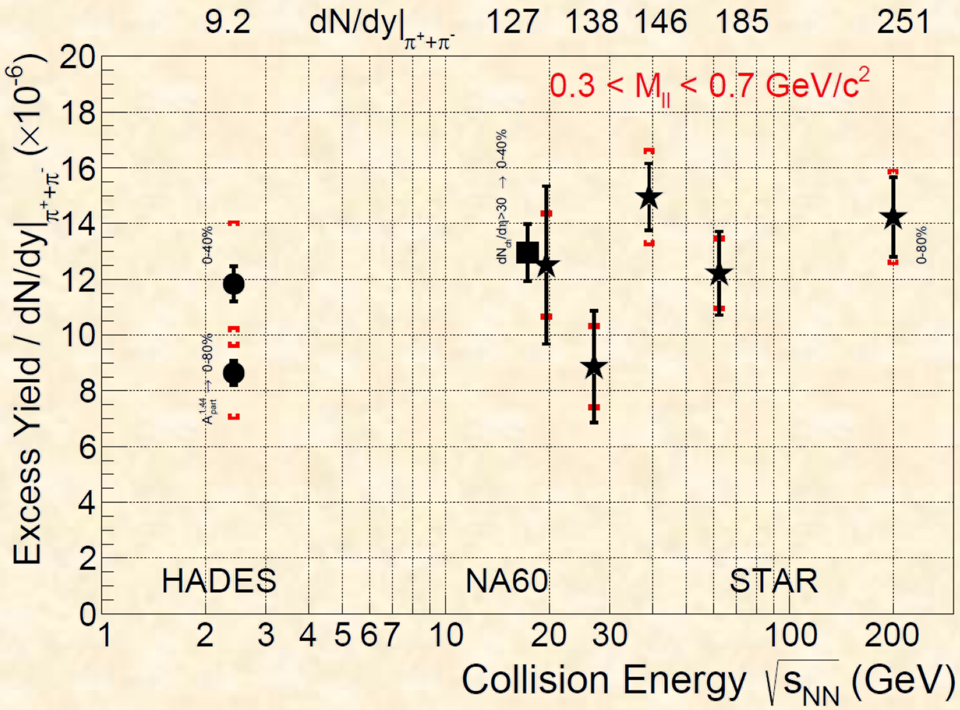
Rapp, Wambach, Adv. Nucl.Phys. 25 (2000) 1

Critical Point: Lifetime Increase

- ρ peak as a clock for fireball lifetimes
  - see e.g., U.Heinz, KS.Lee, PLB 259 (1991) 162
- Dilepton yields sensitive to lifetime of the system
  - close to Critical Point expect increase in correlation lengths
  - critical slowing down? *anomalous* increase in the lifetime of the fireball?
- Normalized yields in LMR track medium lifetime
  - Rapp & Van Hees, PLB 753 (2016) 586
- ➢ Can we observe this in an increase of e^+e^- rates?
- Integrated excess radiation
  - measured below free ρ/ω mass
  - results from HADES, NA60, STAR look promising
- Experimental uncertainties are large
  - high statistics measurements needed

Rapp, van Hees, PLB 753 (2016) 586





Galatyuk, JPC Conf.32 (2020) 010079

Dileptons as thermometer

Recall thermal dilepton radiation:

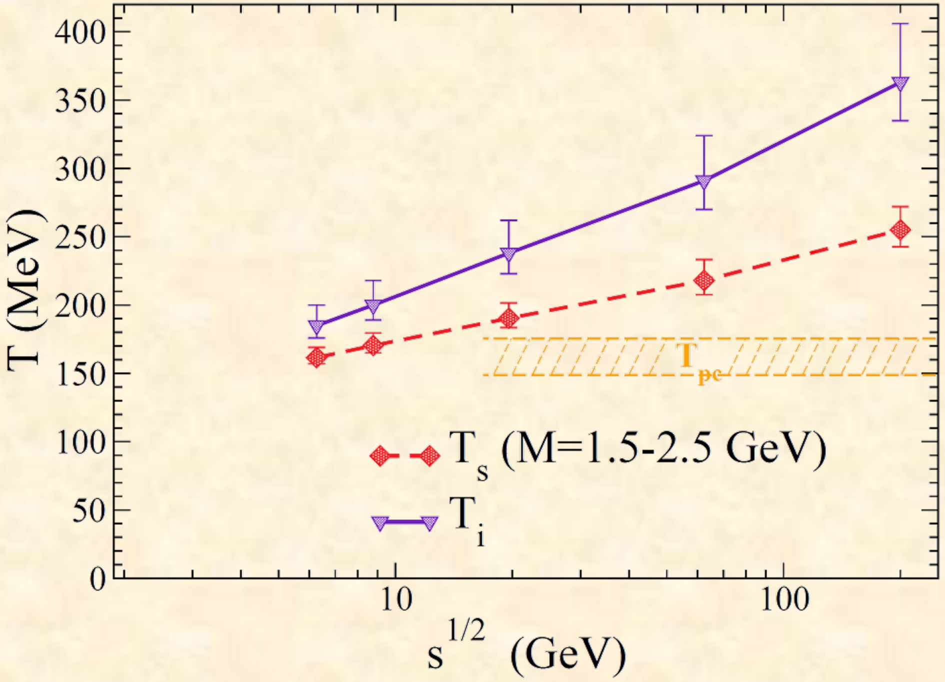
- LMR - dilepton spectra saturated by light vector mesons
- IMR - quark-antiquark continuum

IMR dilepton rate

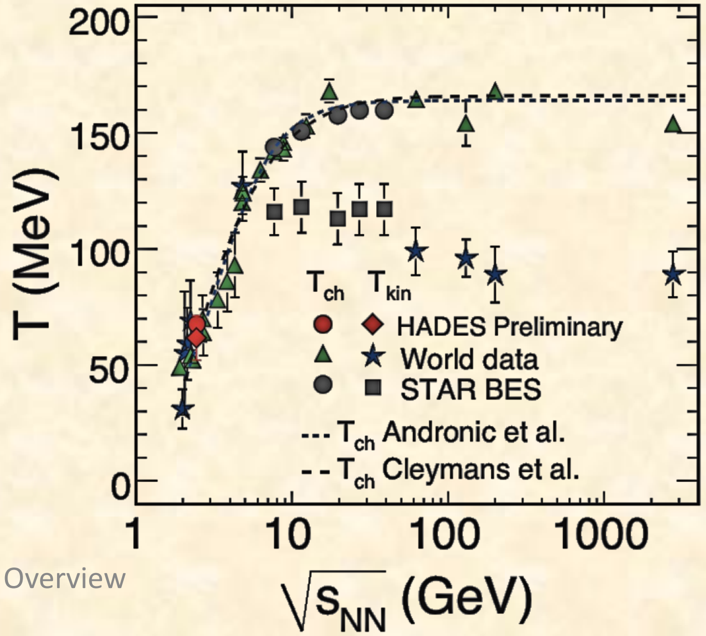
$$\frac{dR_{ll}}{dM} \propto \left(\frac{M}{T}\right)^{\frac{3}{2}} \exp\left(-\frac{M}{T}\right)$$

- *M* by construction Lorentz-invariant
- independent of flow → no blue-shift effects
- average over the system evolution

- Other bulk temperature measurements rely on hadron yields and spectra
  - chemical and kinetic freezout
  - separation between T_{chem} and T_{kin} grows with $\sqrt{s_{NN}}$



Rapp, van Hees, PLB753 (2016) 586

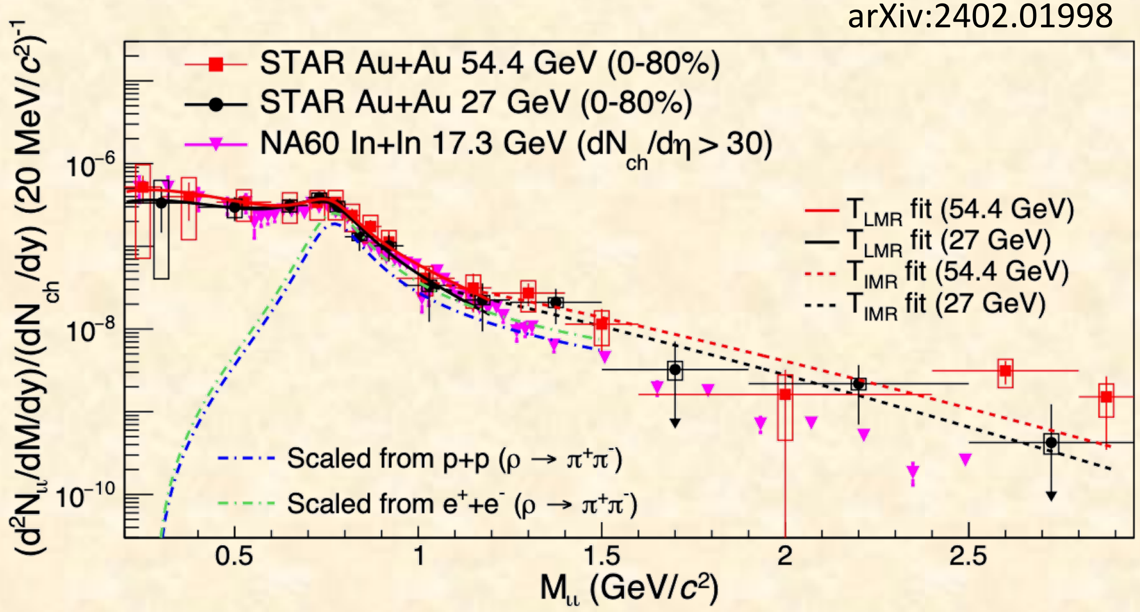


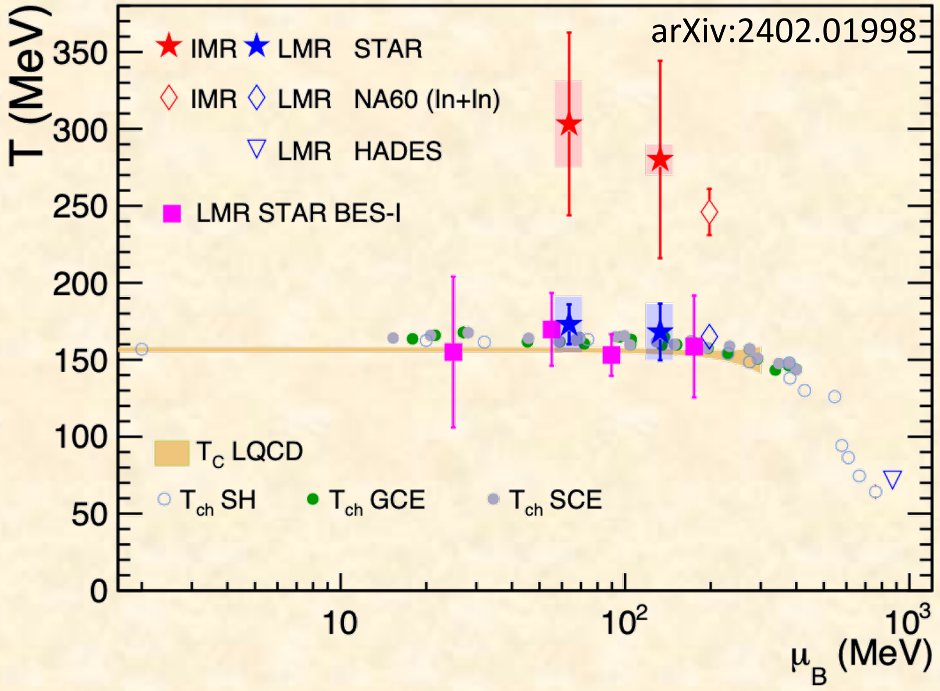
World Data:
SIS: HADES, (FOPI)
AGS: E802,E866, E877,E895, E917
SPS: NA49
RHIC: STAR
LHC: ALICE

LMR/IMR temperature measurements

At SPS/RHIC energies
- predominantly thermal dileptons from in-medium ρ
- include Breit-Wigner in T_{LMR} fit
- recent STAR results at $\sqrt{s_{NN}}$ = 27 and 54 GeV show similar mass spectra and extracted T_{LMR}
  - ➢ compared with NA60 at 17.3GeV

arXiv:2402.01998





➢ LMR temperatures close to T_{ch} and T_{pc}
- emitted from hadronic phase
- predominantly around phase transition

➢ IMR temperatures well above Tpc
- access to $q\bar{q}$ radiation

an experimentalist's Summary

Cornucopia of Experimental Data

- A wealth of experimental data has been collected in two dedicated Beam Energy Scan campaigns at RHIC
  - most BES 1 results have been published
- RHIC program spans a wide μ_B range : Beam Energy Scan Phase 1, 2, and FXT
  - large coverage of the QCD phase diagram
  - bridging LHC to FAIR/NICA/JPARC-HI
- Many STAR BES-2 papers have already been published
  - so far more than 25, and much more to come
  - expect a lot of new results at the upcoming QuarkMatter conference
- Precision, precision, precision: large statistics data sets are coming online

Connecting Theory & Experiment

- "multi-messenger"- the whole is more than the sum …
  - different observables, more differentials
- theory guidance is paramount
  - critical point
  - chiral symmetry restoration
  - *etc.*
- and experimental guidance, too
  - feasibility, cuts, and acceptances
  - accessing to QCD medium

Future Prospects – another "phase diagram"