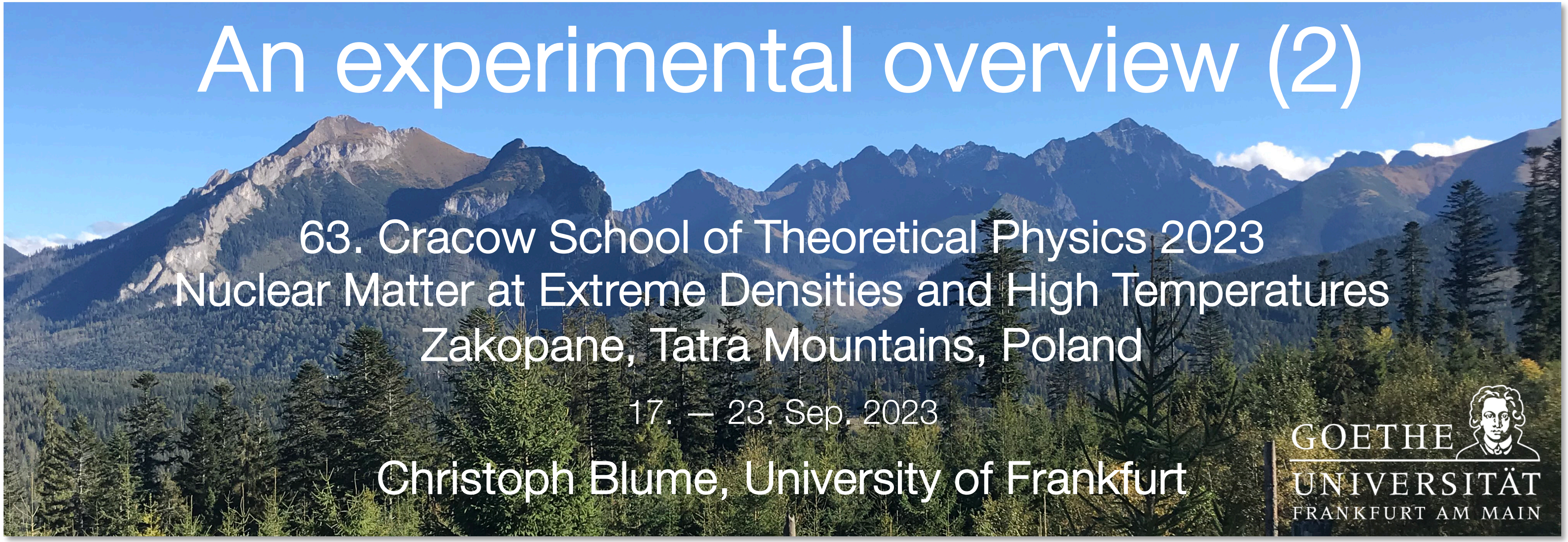
The QCD phase diagram at high densities



An experimental overview (2)

63. Cracow School of Theoretical Physics 2023
Nuclear Matter at Extreme Densities and High Temperatures
Zakopane, Tatra Mountains, Poland

17. — 23. Sep. 2023

Christoph Blume, University of Frankfurt

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Observables

Observables

Collectivity + Vorticity

Radial, directed and elliptic flow (+ higher orders)
Global polarization

Criticality ($\Longrightarrow$ Anar's lecture)

Strangeness in Matter

Maximum in relative strangeness production

Hypernuclei: hyperon interaction $\longrightarrow$ neutron star EOS

Emissivity

Thermal radiation

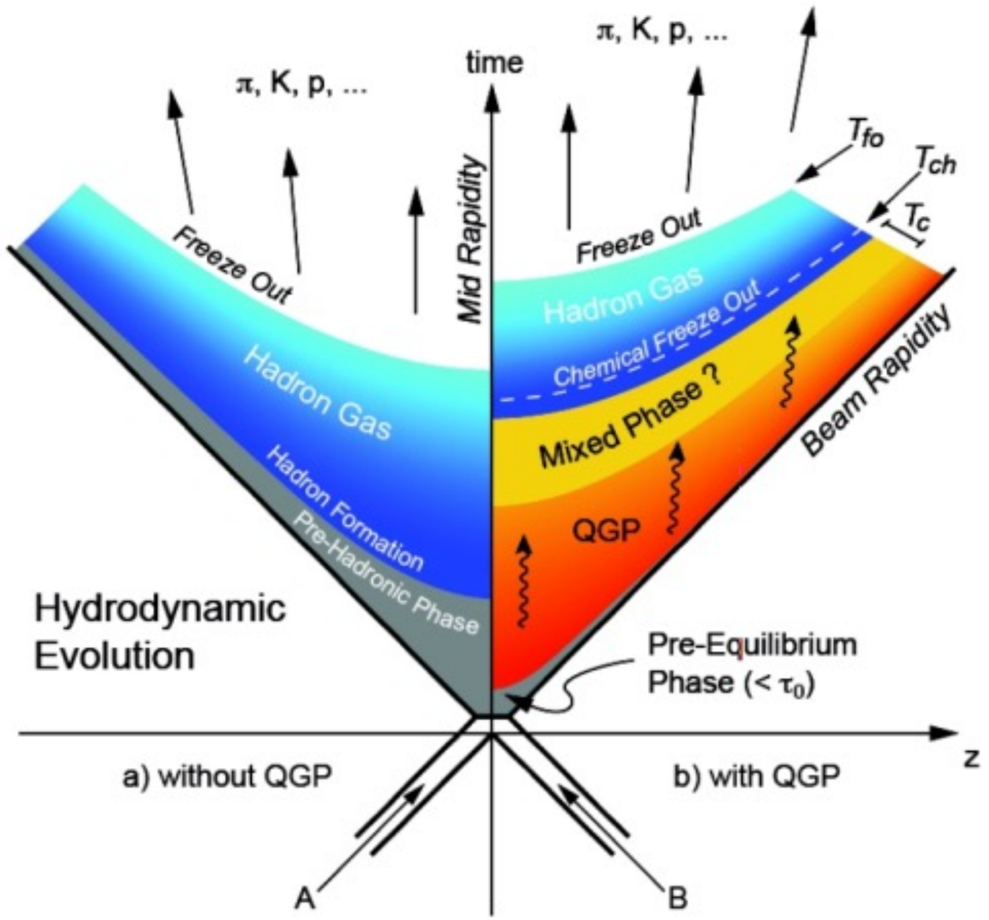
Collectivity

Evolution of a Heavy-Ion Collision

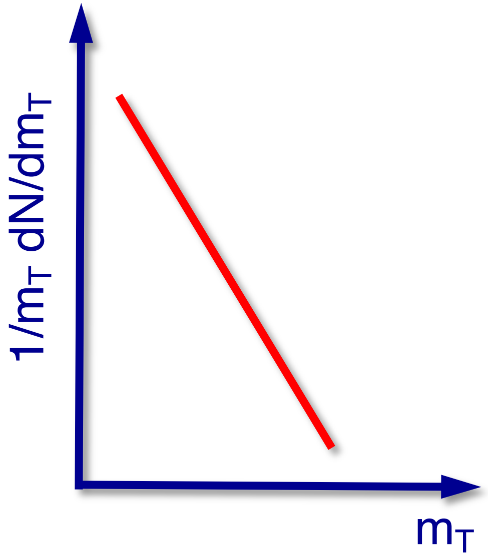
Kinetic freeze-out at T_{fo}:
Elastic collisions cease
Momentum spectra frozen

Chemical freeze-out at T_{ch}:
Inelastic collisions cease
Particle yields frozen (⟶ statistical models)

Pressure generated throughout system evolution
(hadronic and partonic phase)
⟶ Modifies particle spectra

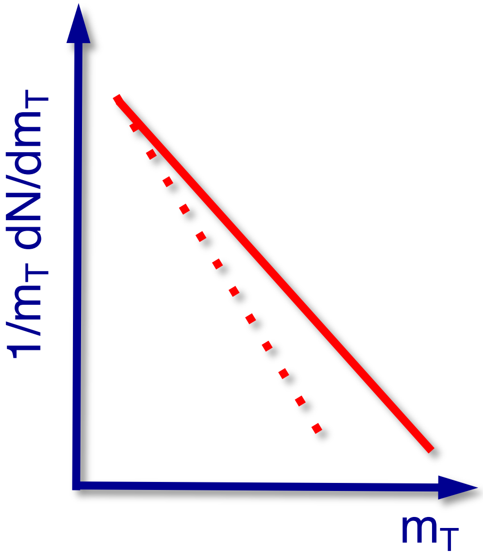


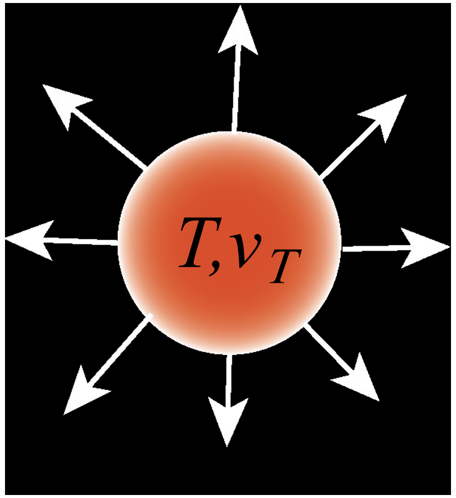
Radial Flow: Transverse Spectra



No radial flow:
exponential spectrum
(e.g.: p+p collisions)

$$\boxed{\frac{1}{m_T}\frac{dN}{dm_T} \propto \exp\left(-\frac{m_T}{T_f}\right)}$$

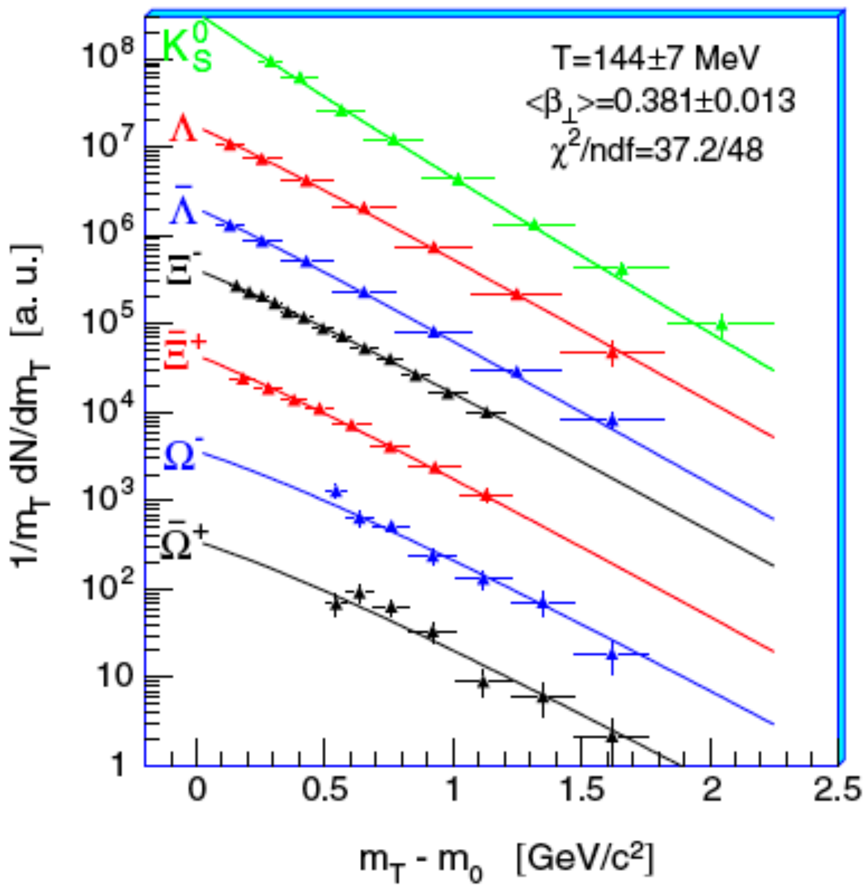


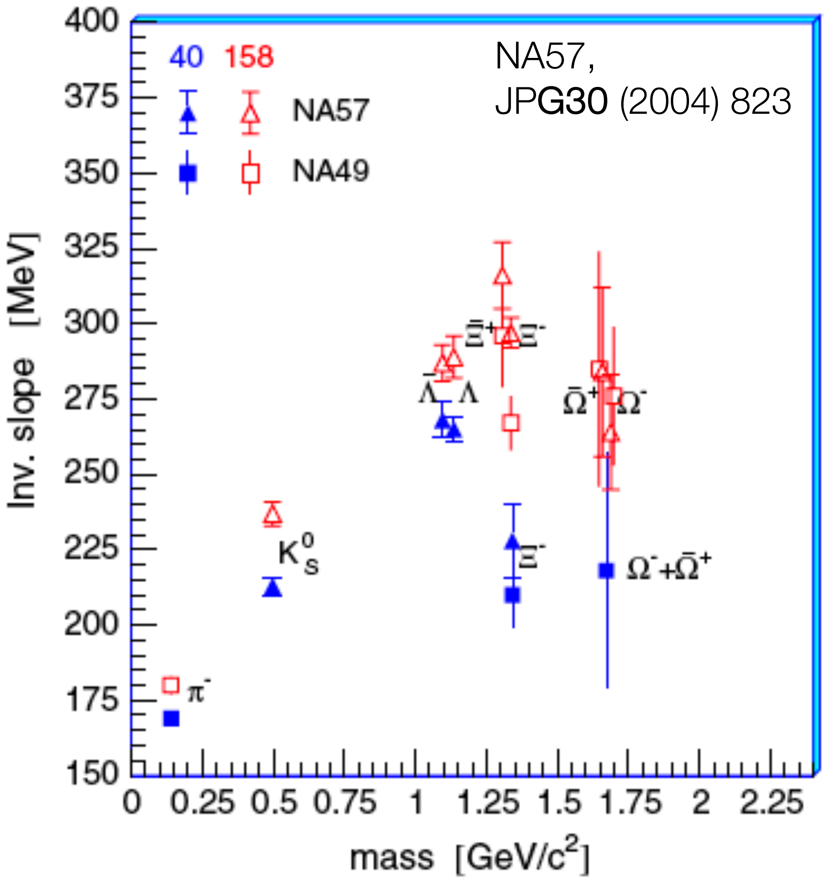


With radial flow:
additional boost by expansion (v_T)
⇒ blue shifted spectrum

$$\boxed{T_{eff} \approx T_f + \frac{1}{2} m v_T^2}$$

Radial Flow: Transverse Spectra



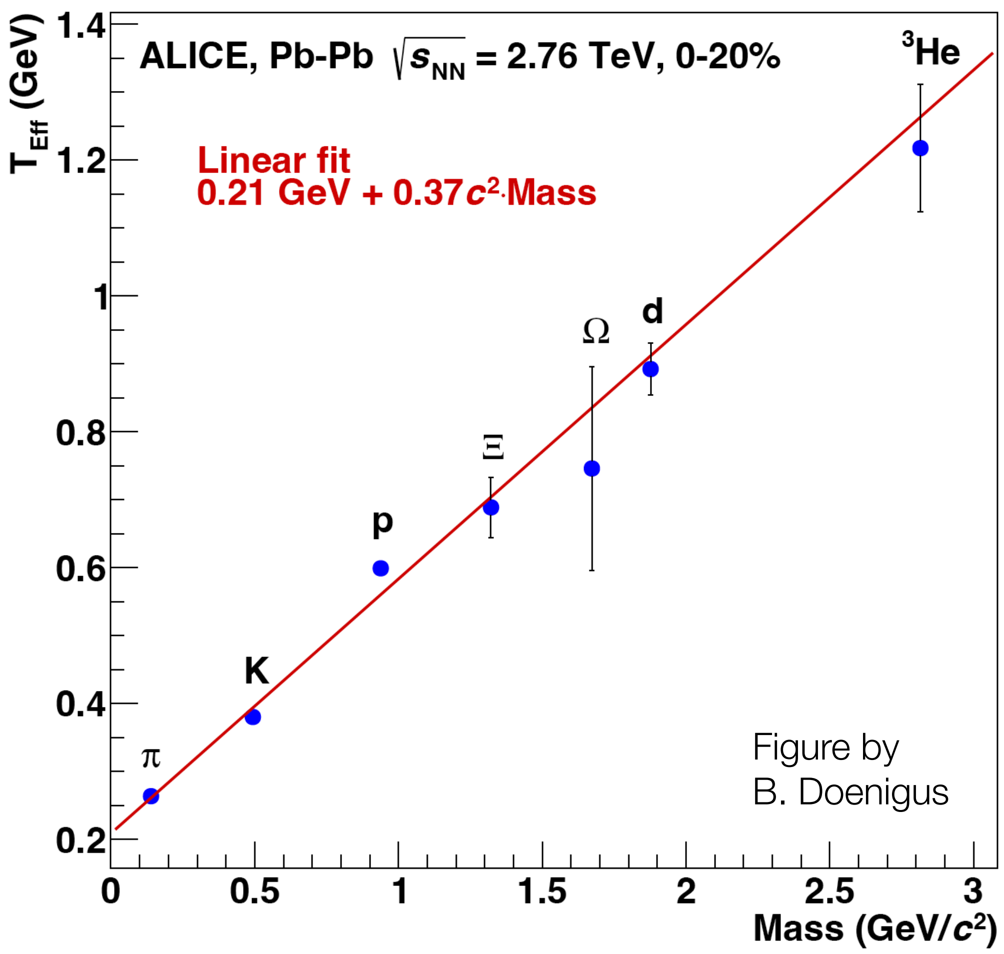


Radial Flow: Transverse Spectra

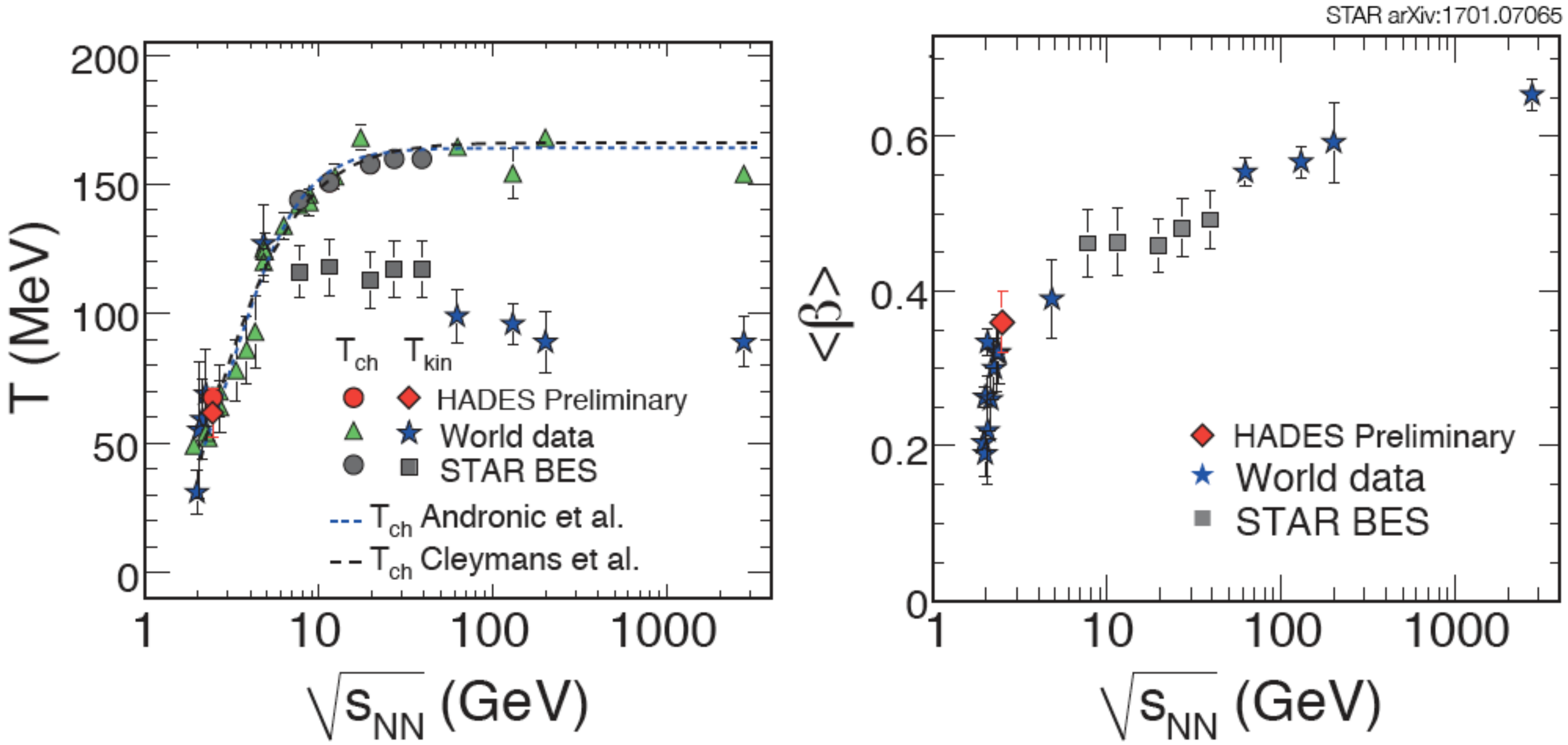
Low hadronic cross section
of rare particles (Ξ, Ω, J/ψ)

Radial flow dominated by partonic
contribution at very high energies

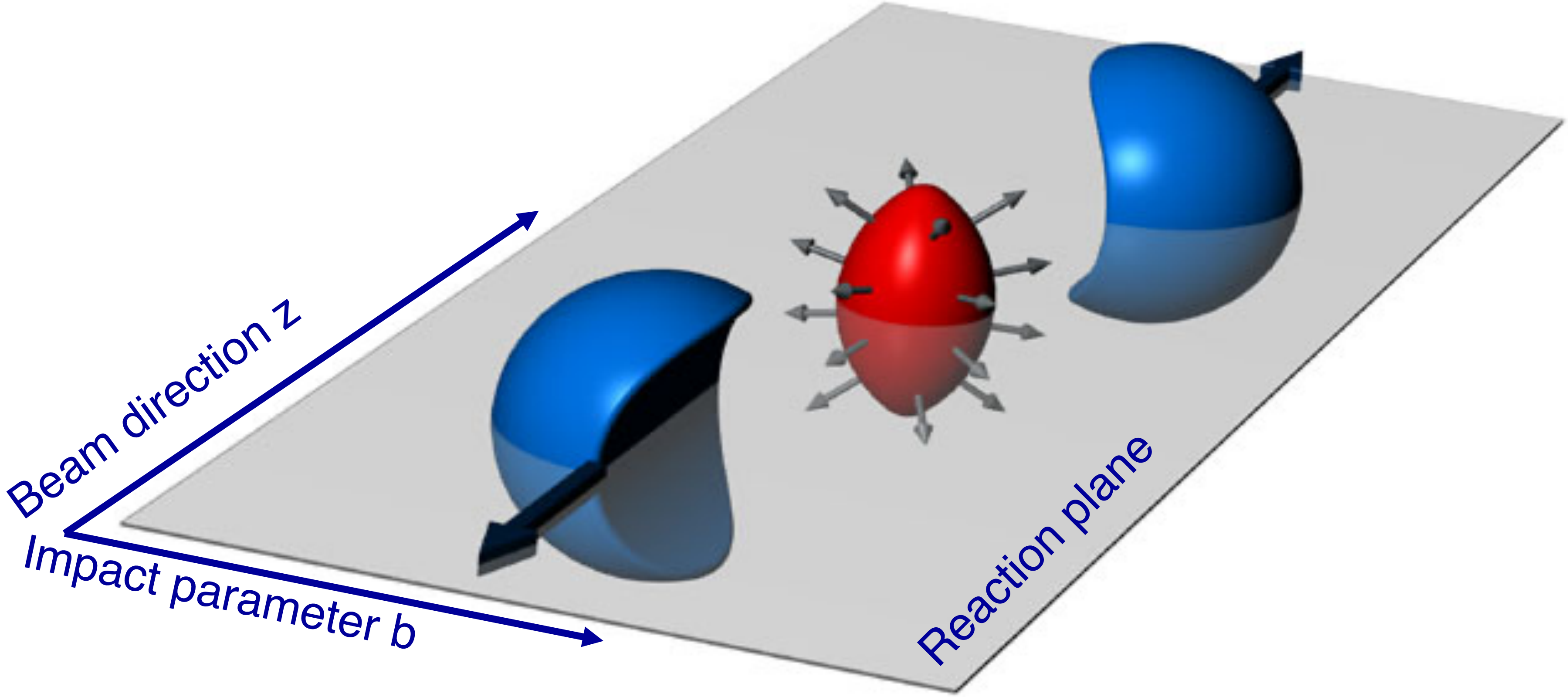
Different to lower energies



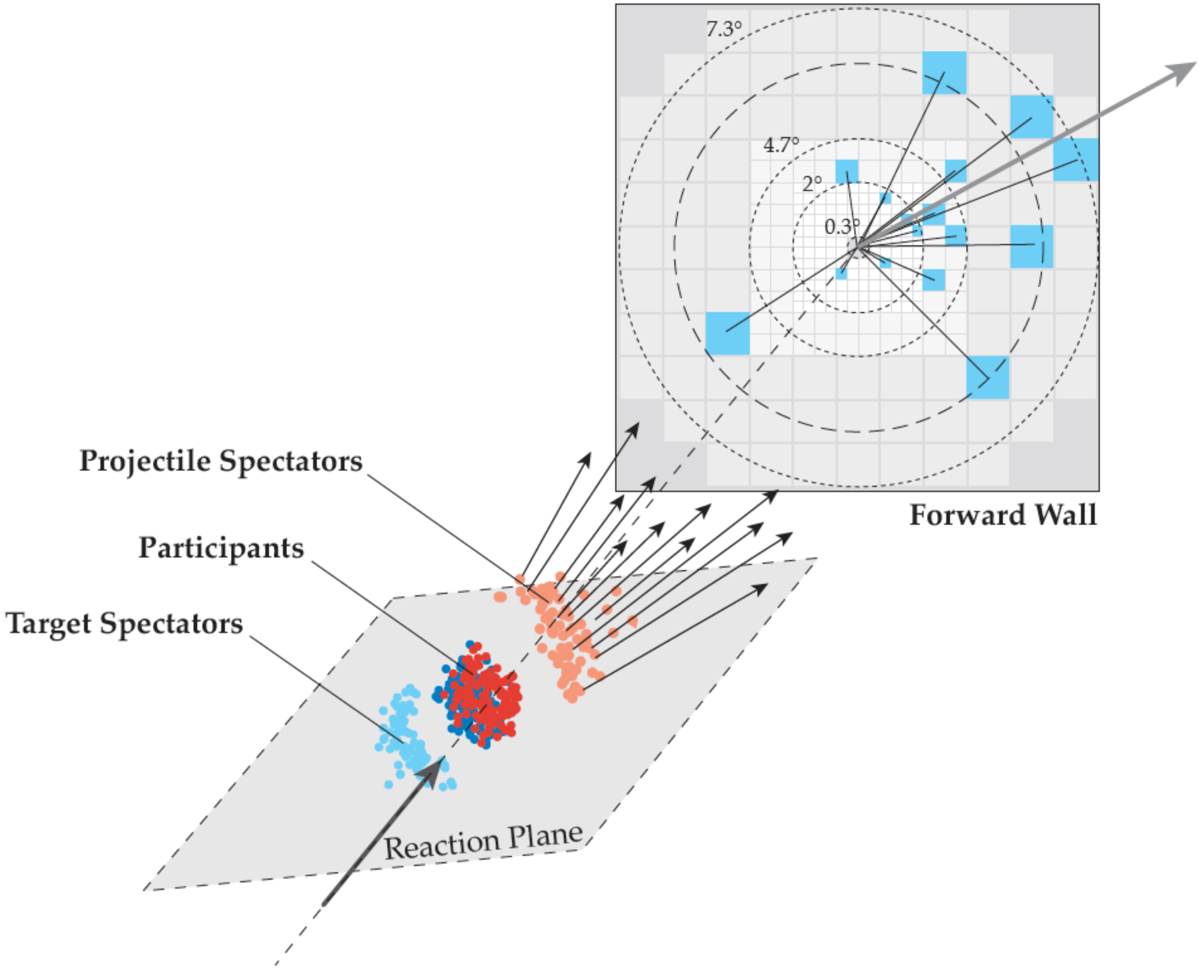
Radial Flow: Transverse Spectra

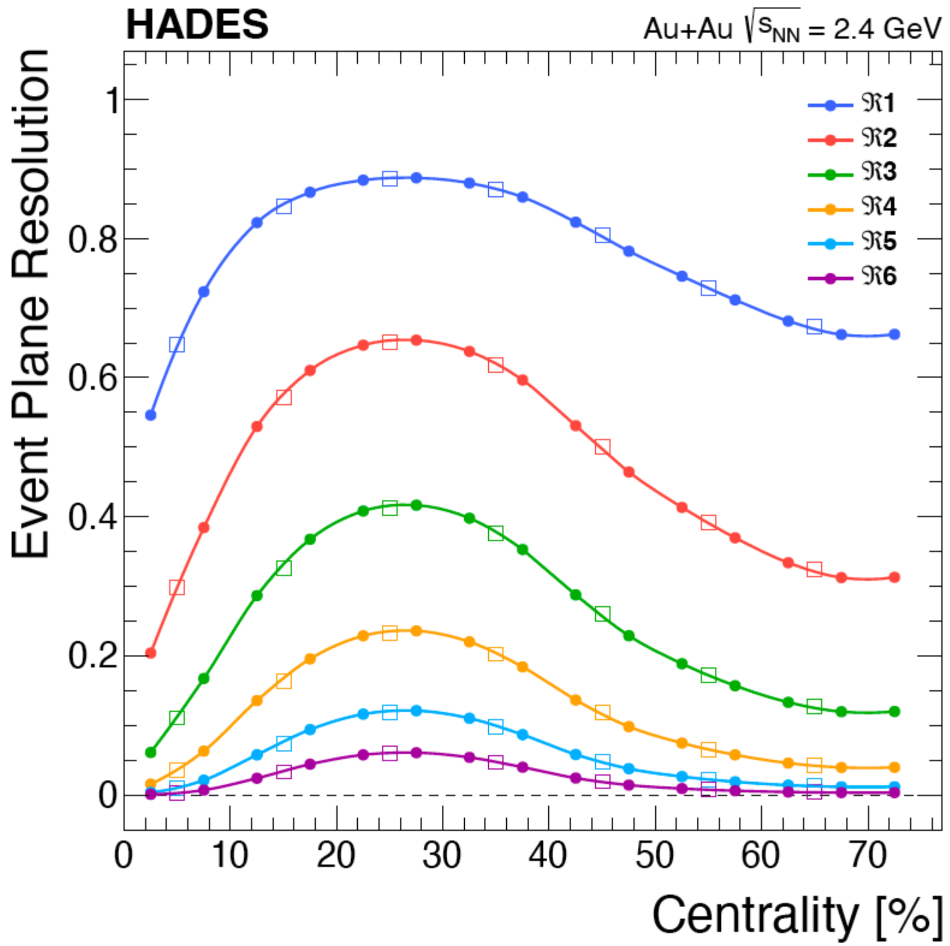


Reaction plane

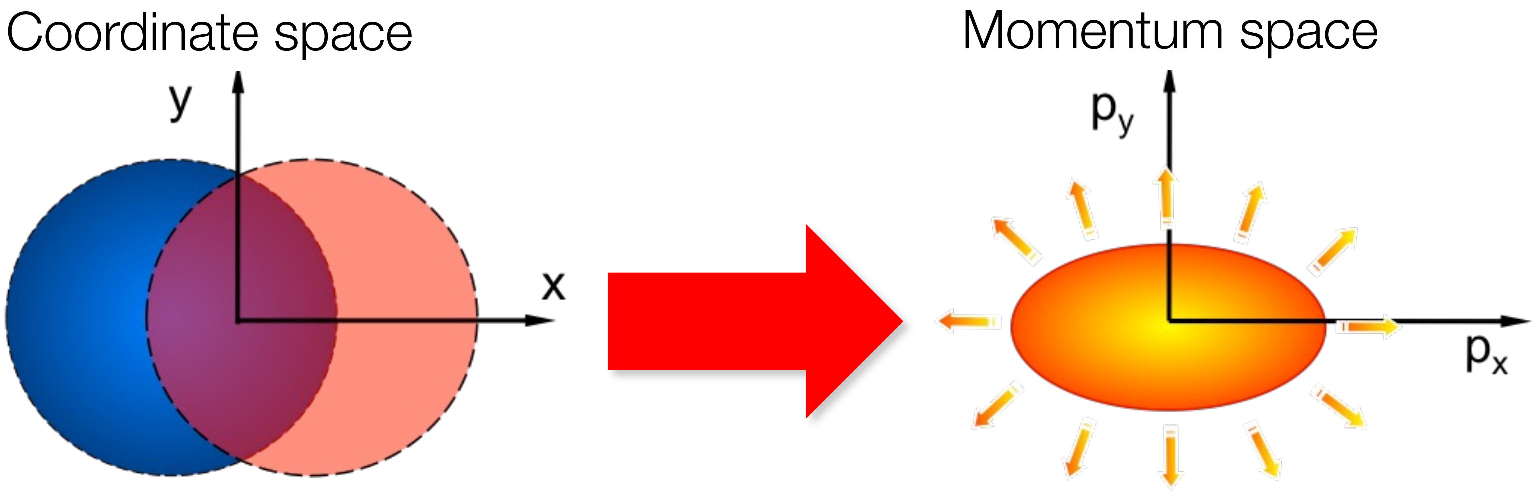


Reaction plane: Measurement





Flow: Fourier Decomposition

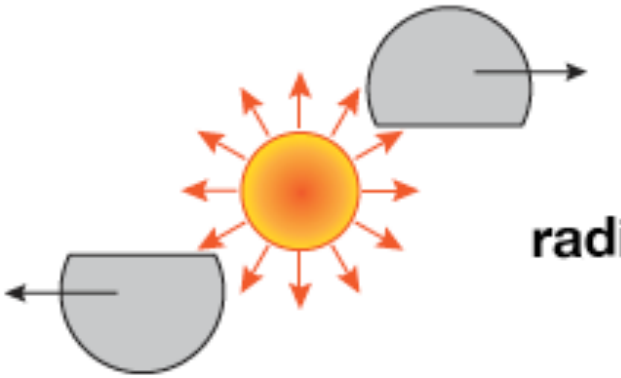


$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

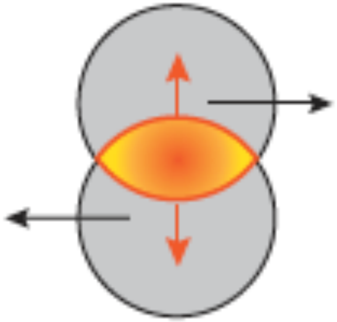
$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

Flow Coefficients

$$\phi = (\varphi - \Psi_{RP})$$

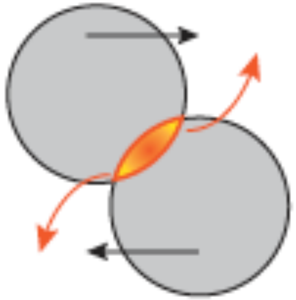


radial flow



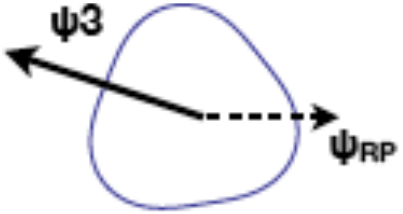
elliptic flow

$$v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$



directed flov

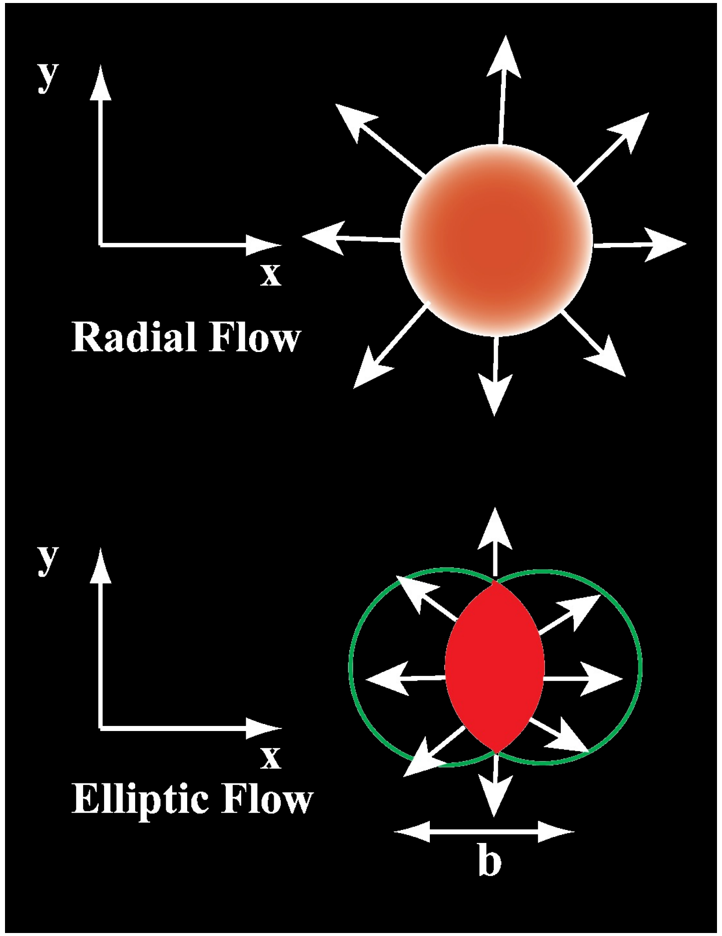
$$v_1 = \langle \cos(\phi) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$

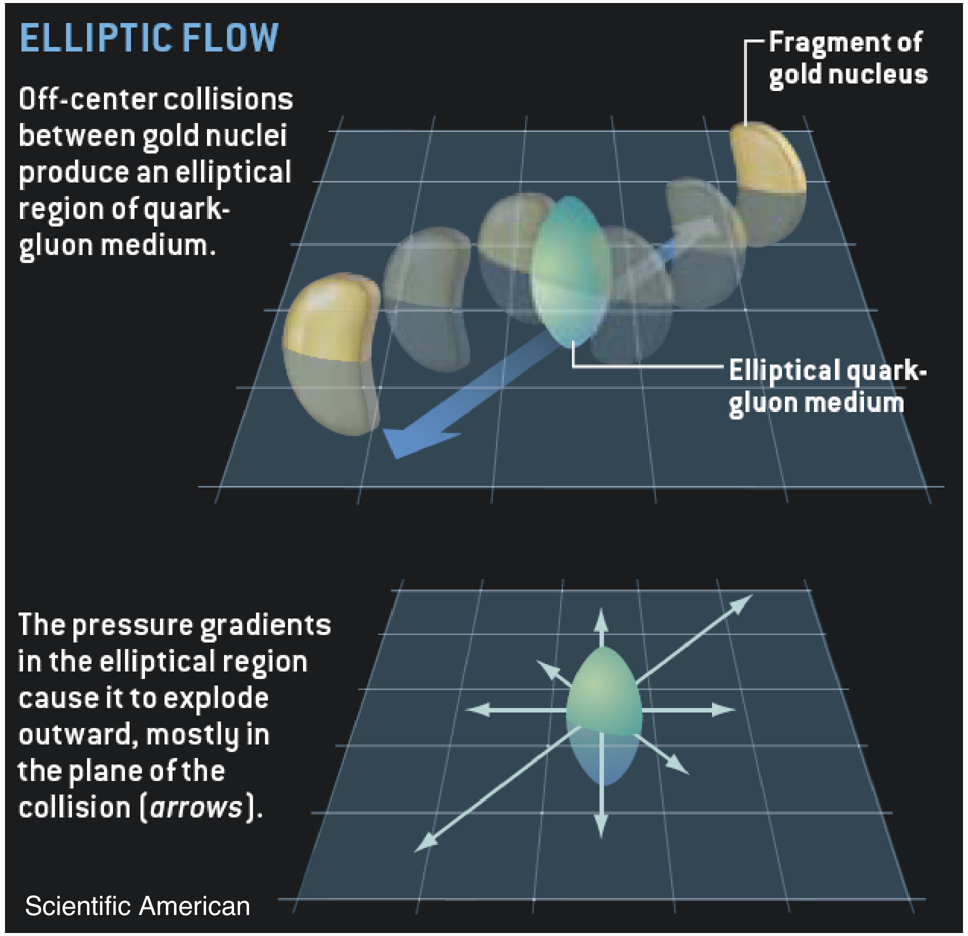


triangular flow

$$v_3 = \langle cos(3\phi) \rangle = \left\langle \frac{p_x^3 - 3p_x p_y^2}{p_t^3} \right\rangle$$

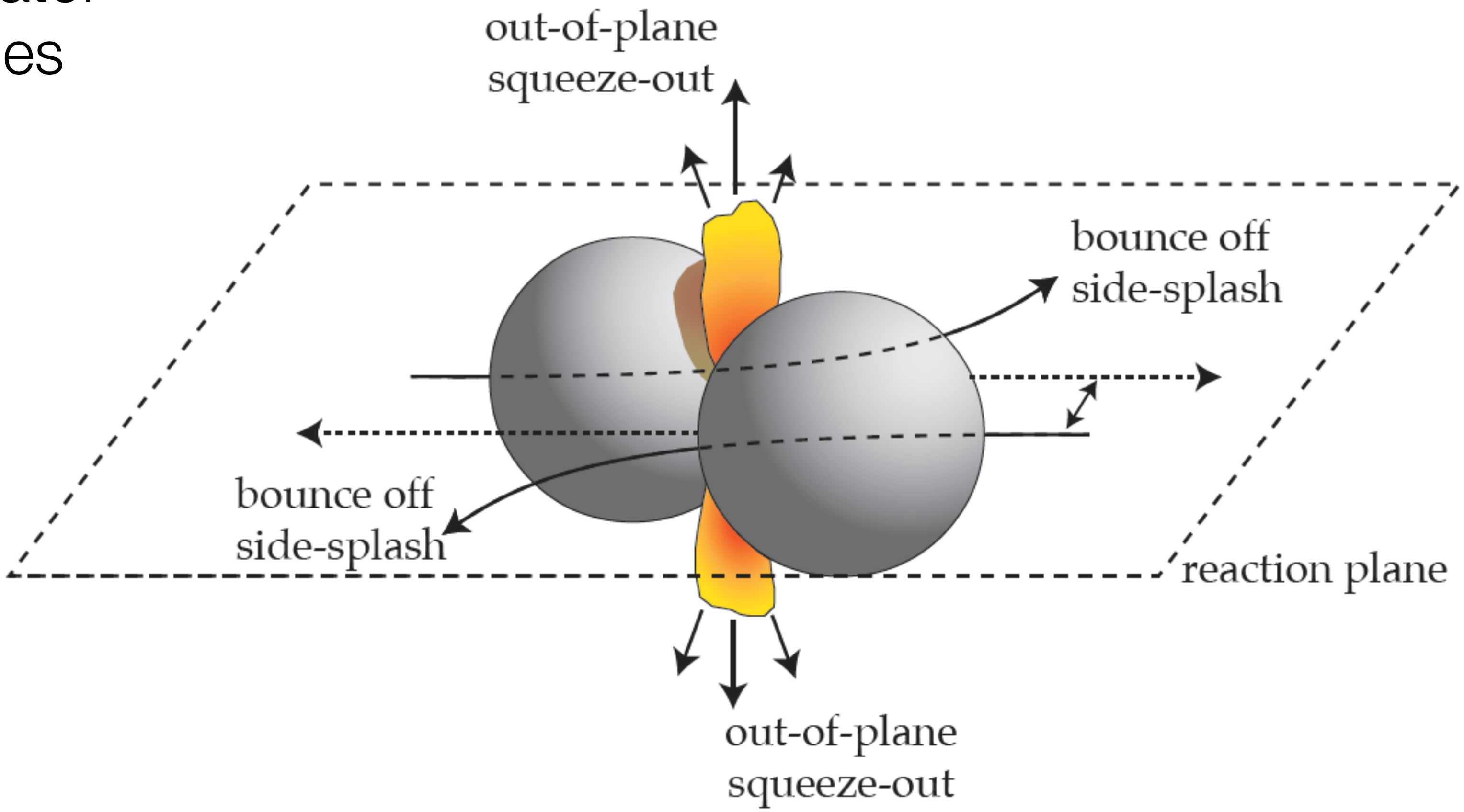
Elliptic Flow





Configuration at Lower Energies

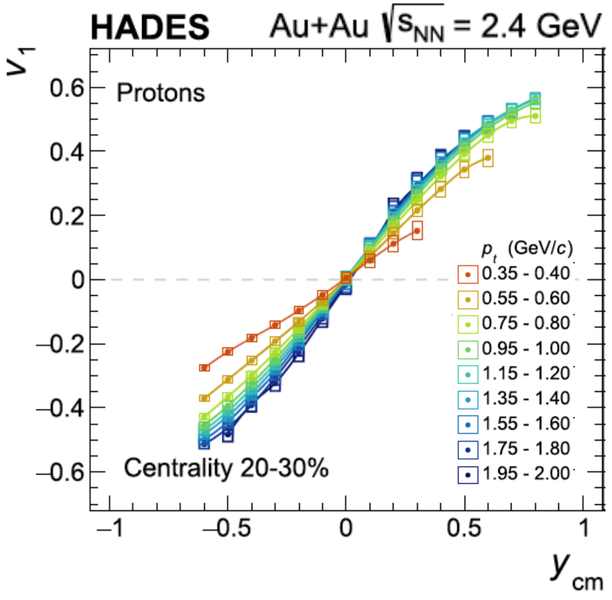
Long spectator passing times

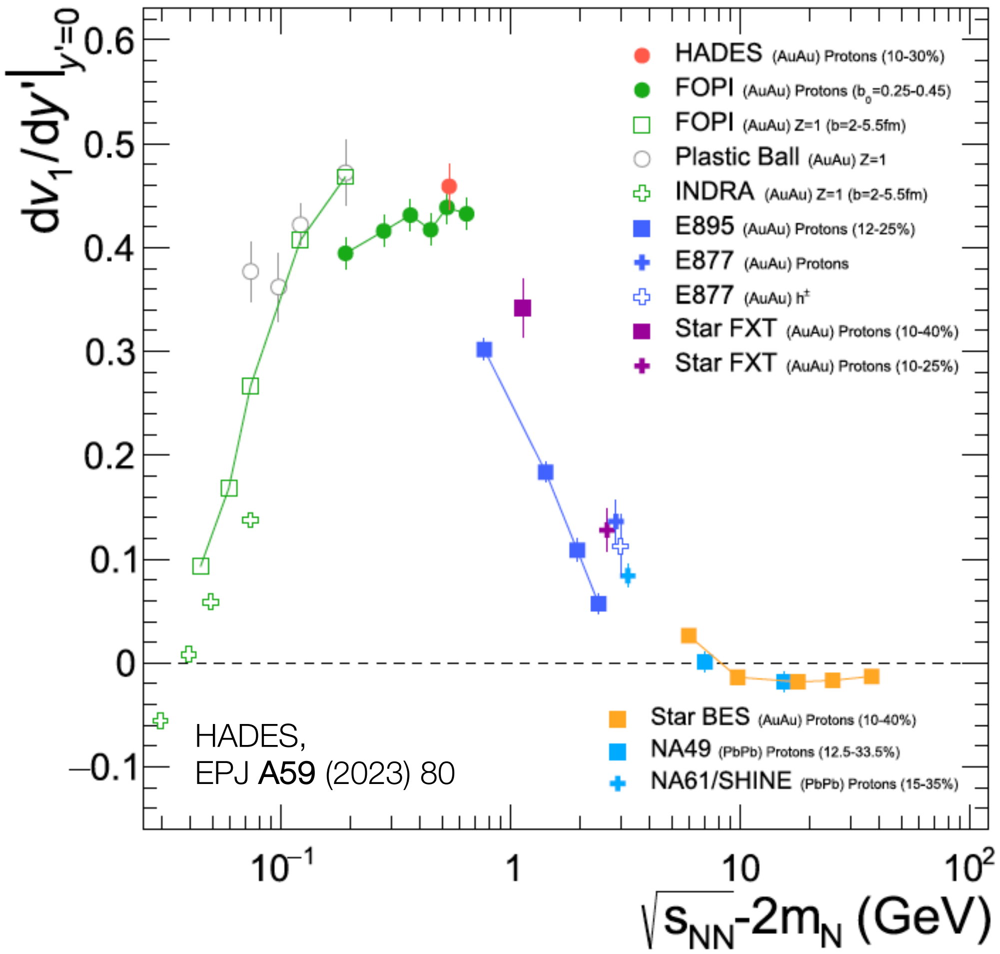


Energy Dependence of v_1

Slope of directed flow (v_1) at mid-rapidity:

$$dv_1/dy'|_{y'=0} \text{ with } y' = y_{cm}/y_{mid}$$

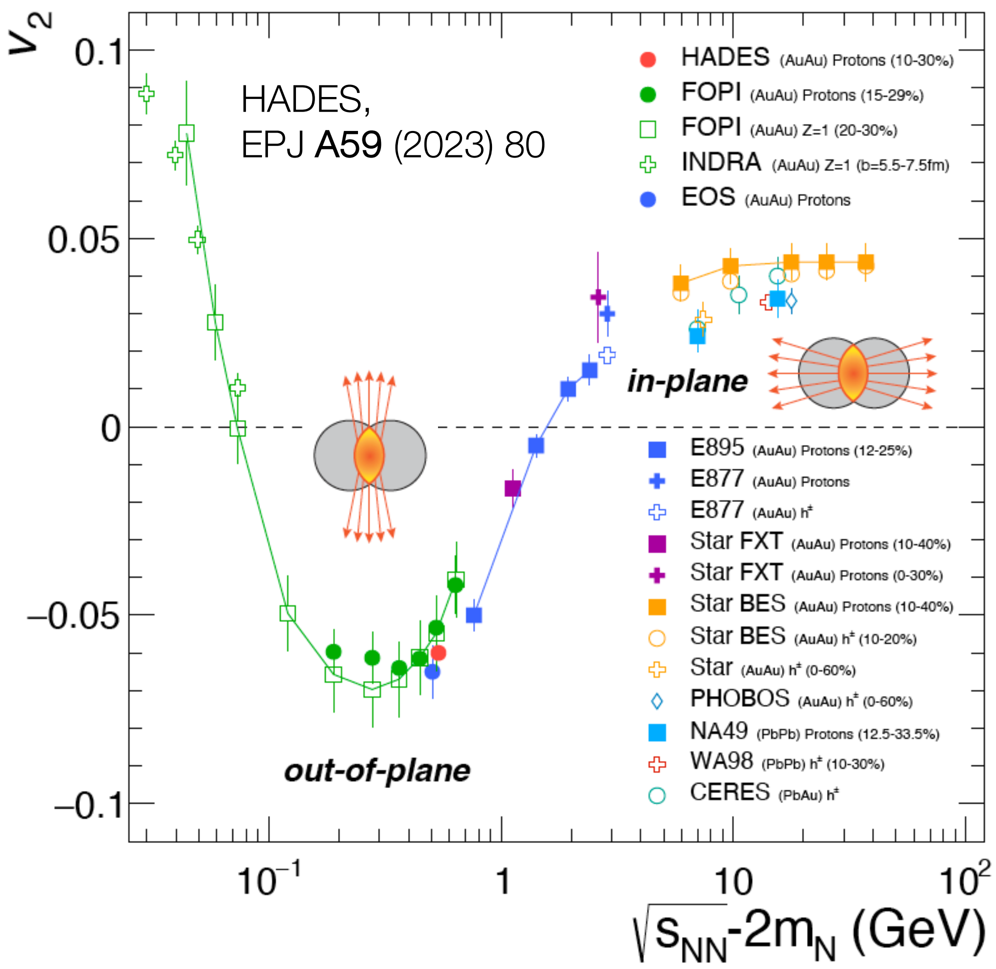




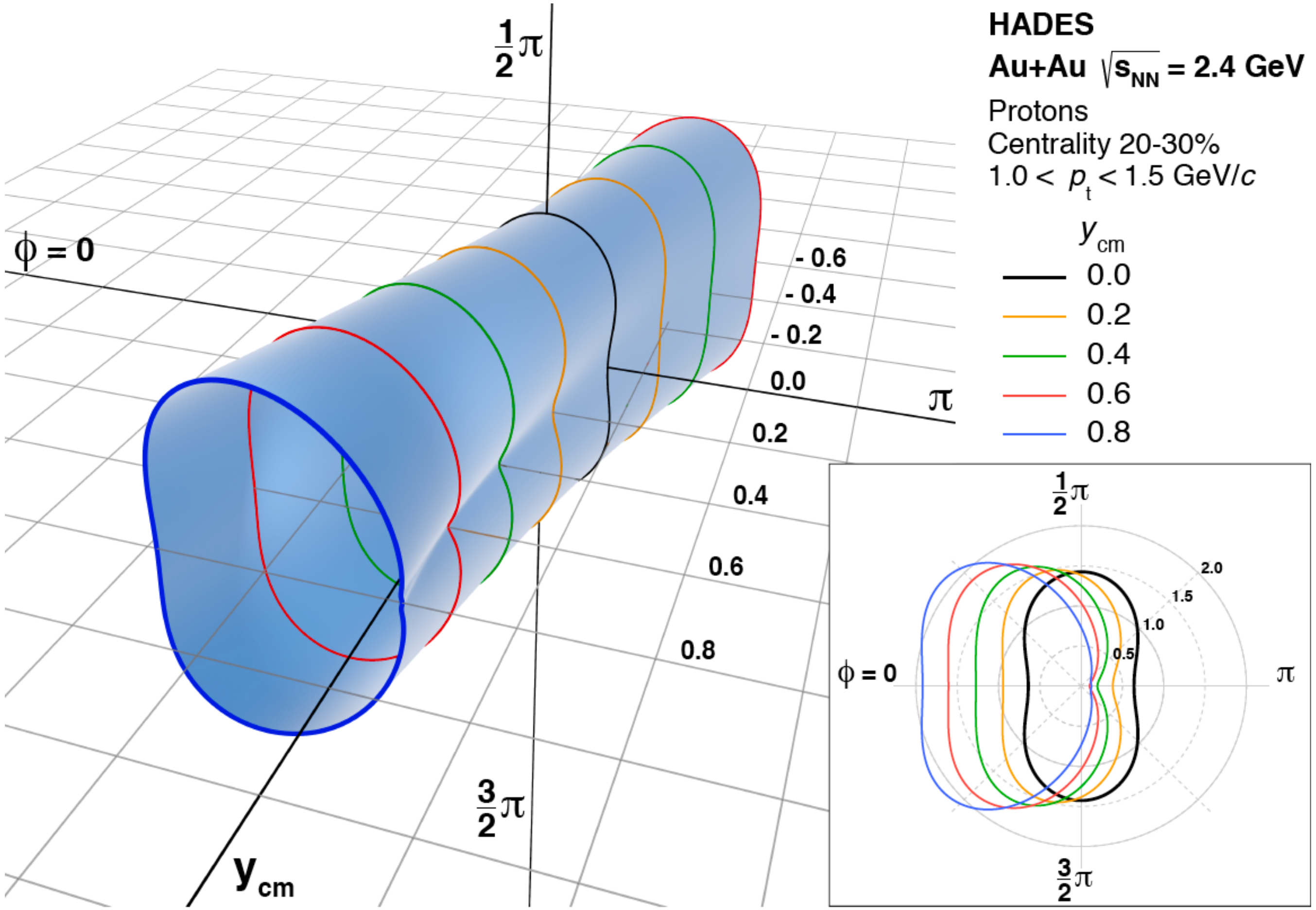
Energy Dependence of v_2

Elliptic flow (v_2) at mid-rapidity:

Evolution from
out-of-plane to in-plane flow

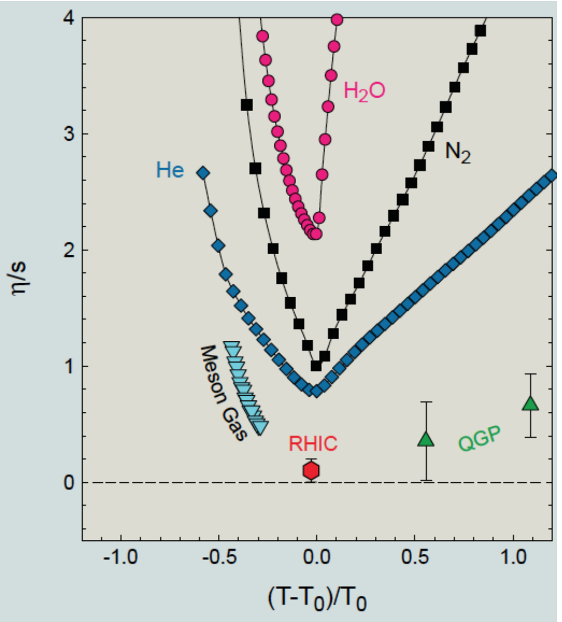


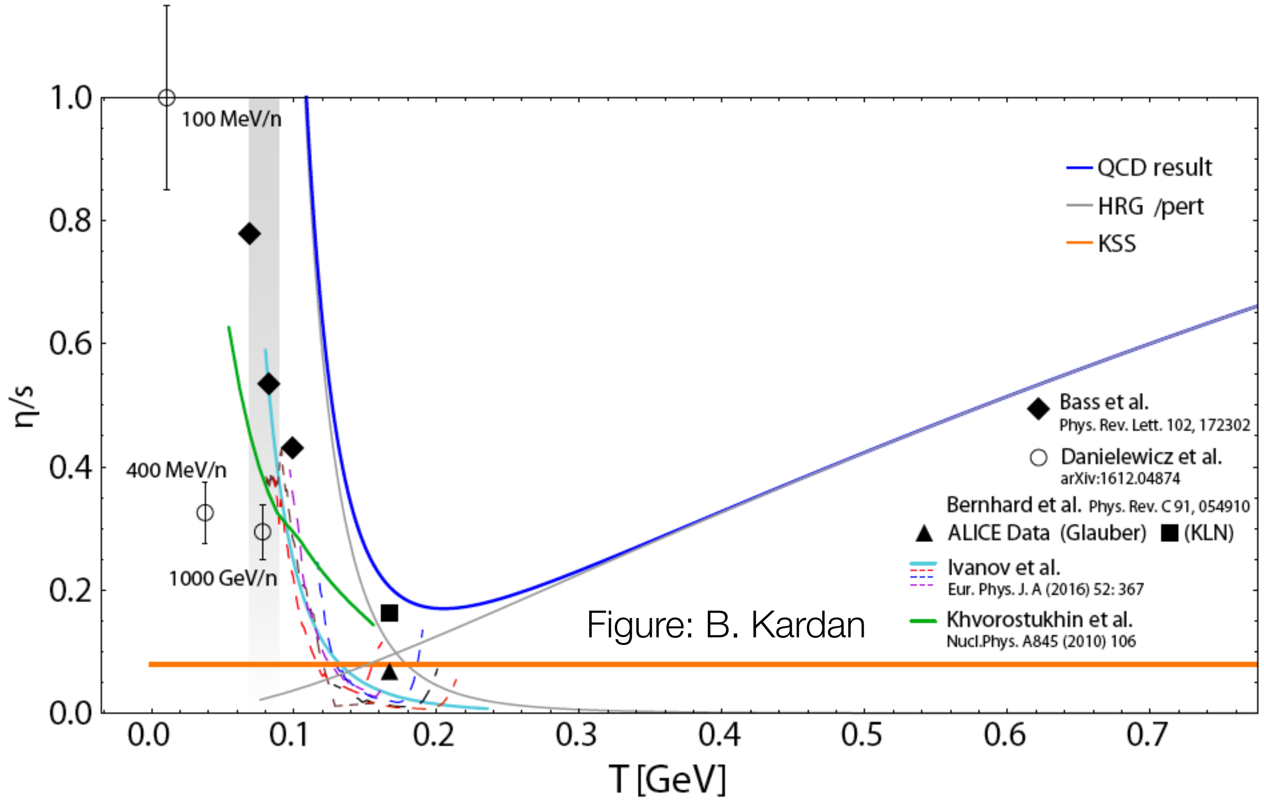
Higher Order Flow Components



HADES,
Phys. Rev. Lett.
125 (2020) 262301

Shear Viscosity over Entropy Ratio





Strongly coupled QGP at high energies (“perfect liquid”)

Baryonic medium at lower energies more difficult to characterize

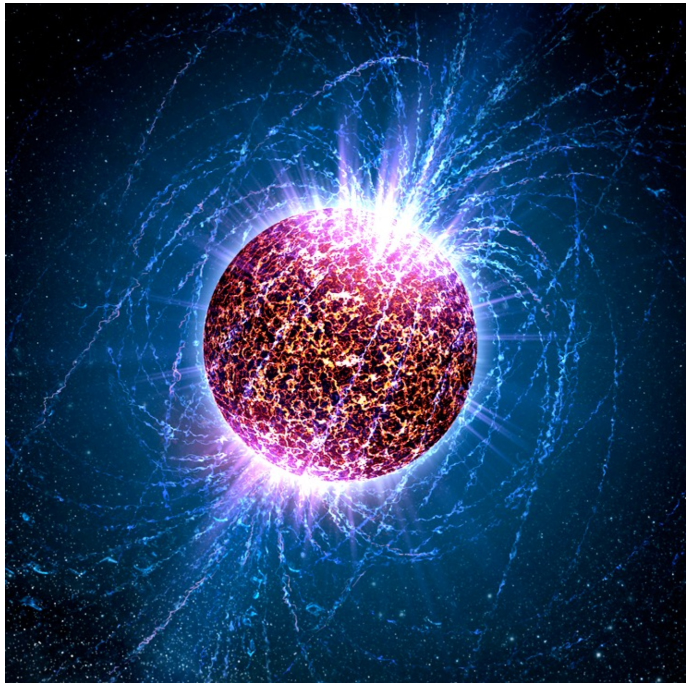
Neutron Stars: Equation-of-State

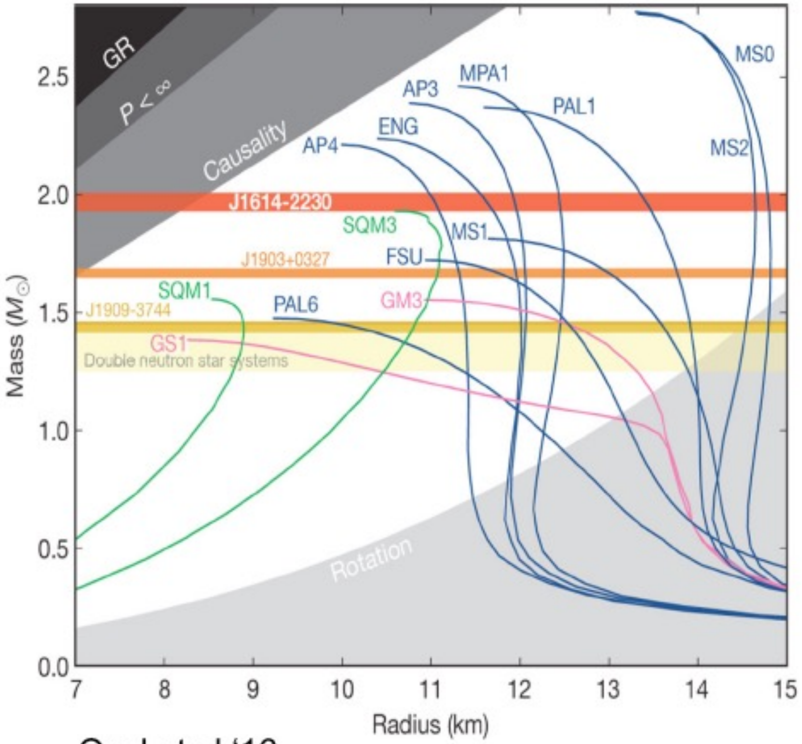
Mass-radius relation

Depends on EOS of
dense nuclear matter

Constraint from astrophysics:
Observation of $M_{NS} \approx 2\,M_{\odot}$

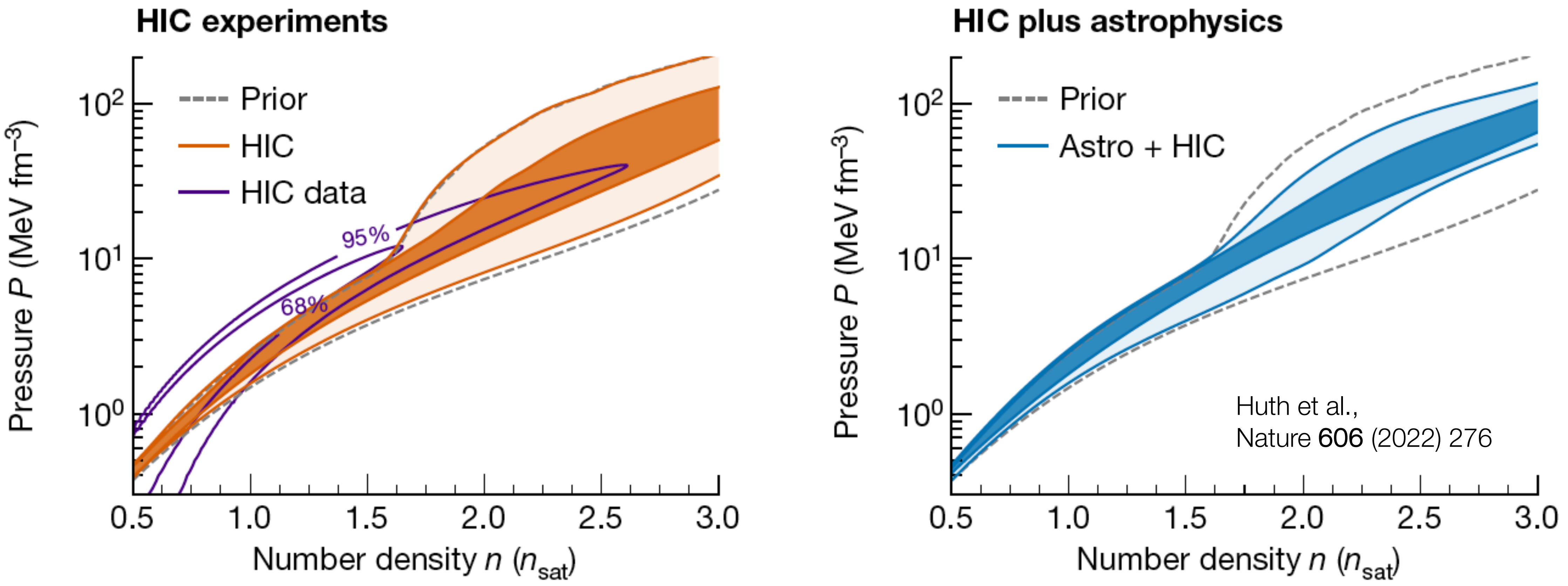
Important information
from heavy-ion physics





Ozel et al ‘16

Flow: Equation-Of-State



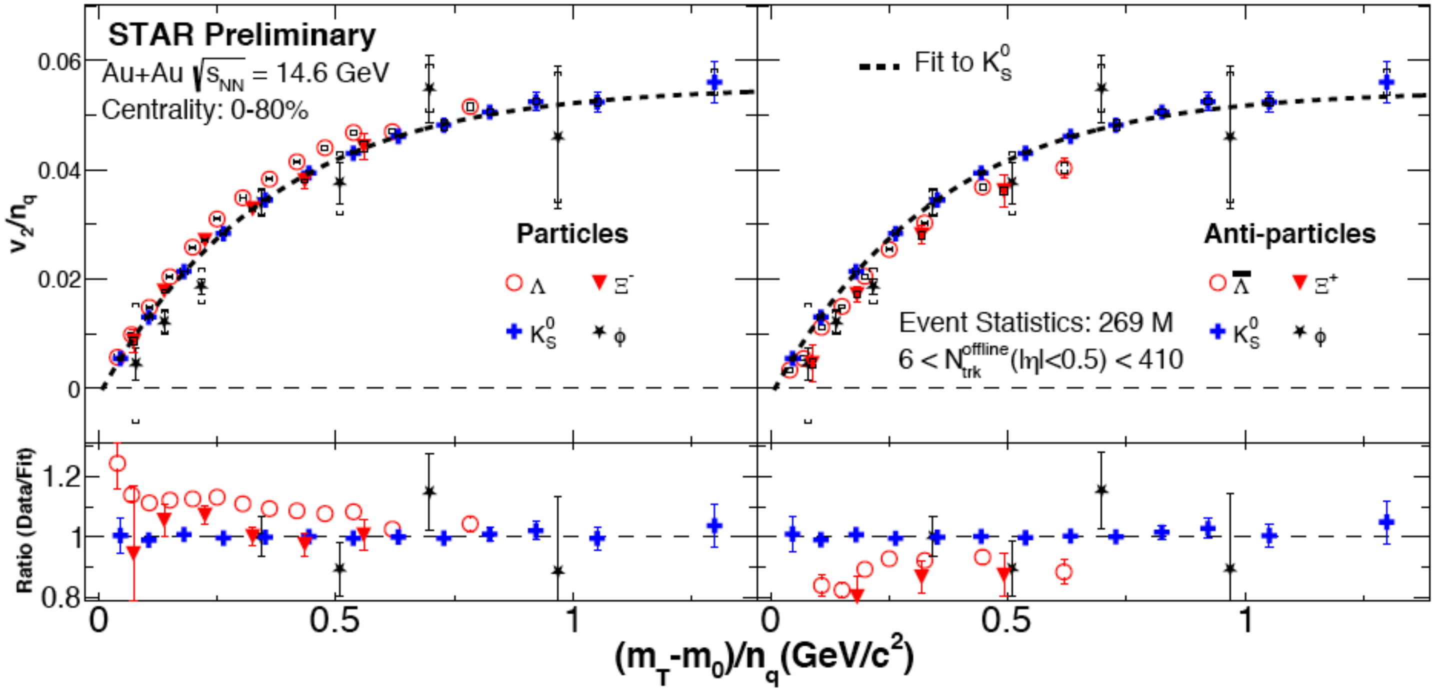
Huth et al.,
Nature **606** (2022) 276

Constituent Quark Scaling

NCQ-Scaling:

v_2 divided by number of constituent quarks n_q

Holds (within ~ 20%) at $\sqrt{s_{NN}}$ = 14.6 GeV



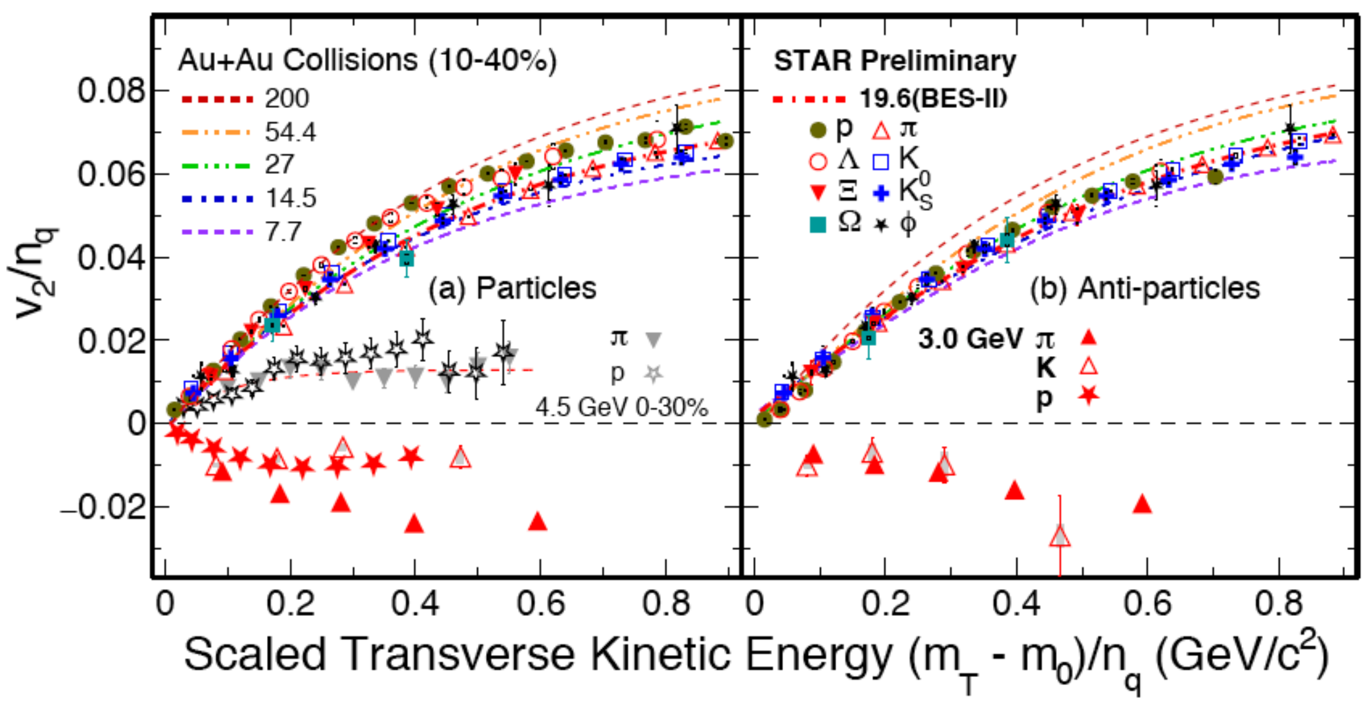
STAR: Md. Nasim, CPOD22

Constituent Quark Scaling

NCQ-Scaling:
v_2 divided by number of constituent quarks n_q

Holds (within ~ 20%) at $\sqrt{s_{NN}}$ = 14.6 GeV

Seems to be broken at $\sqrt{s_{NN}}$ = 3.0 GeV

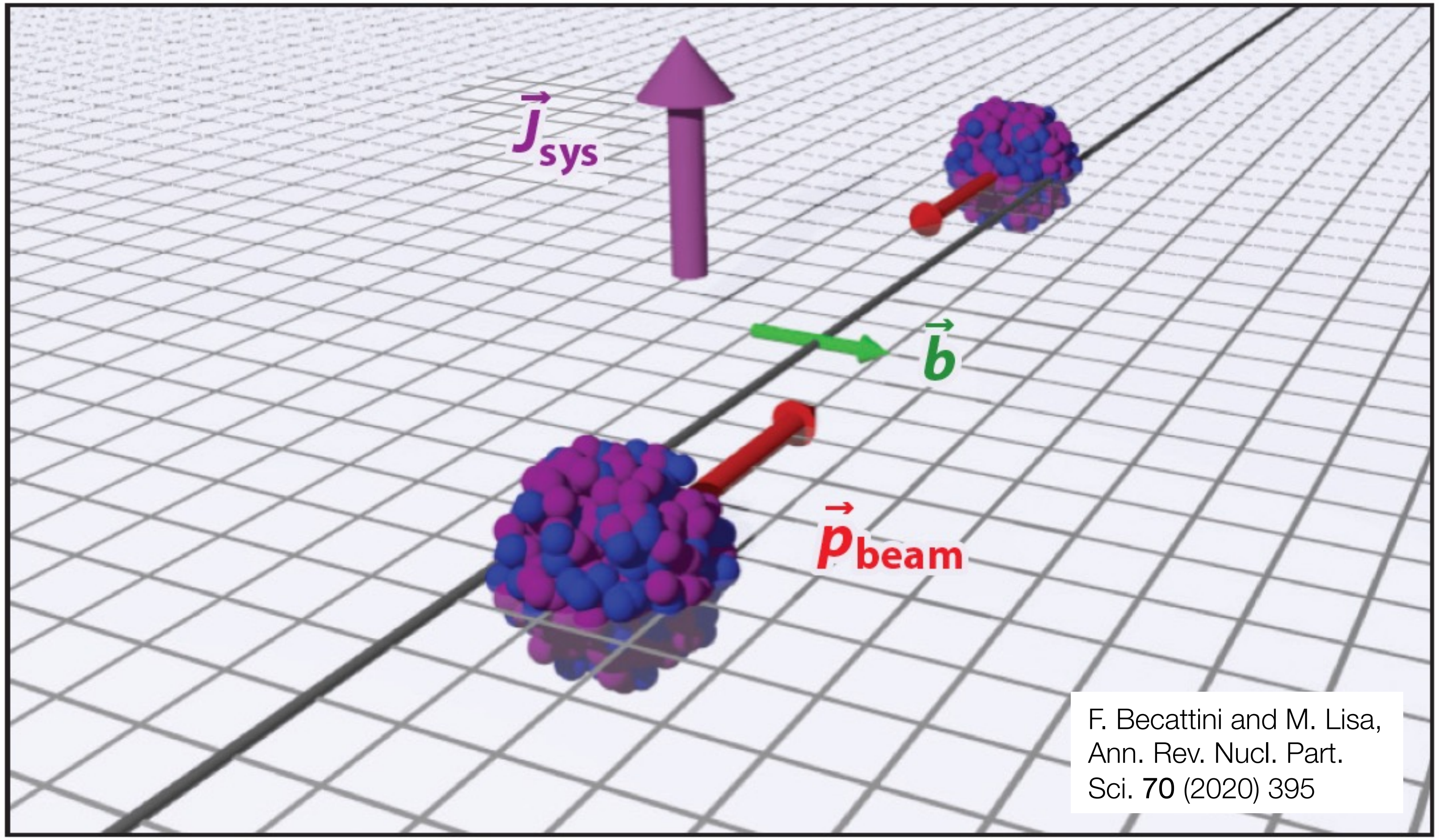


STAR: PLB **827** (2022) 137003

Disappearance of partonic contribution (?)

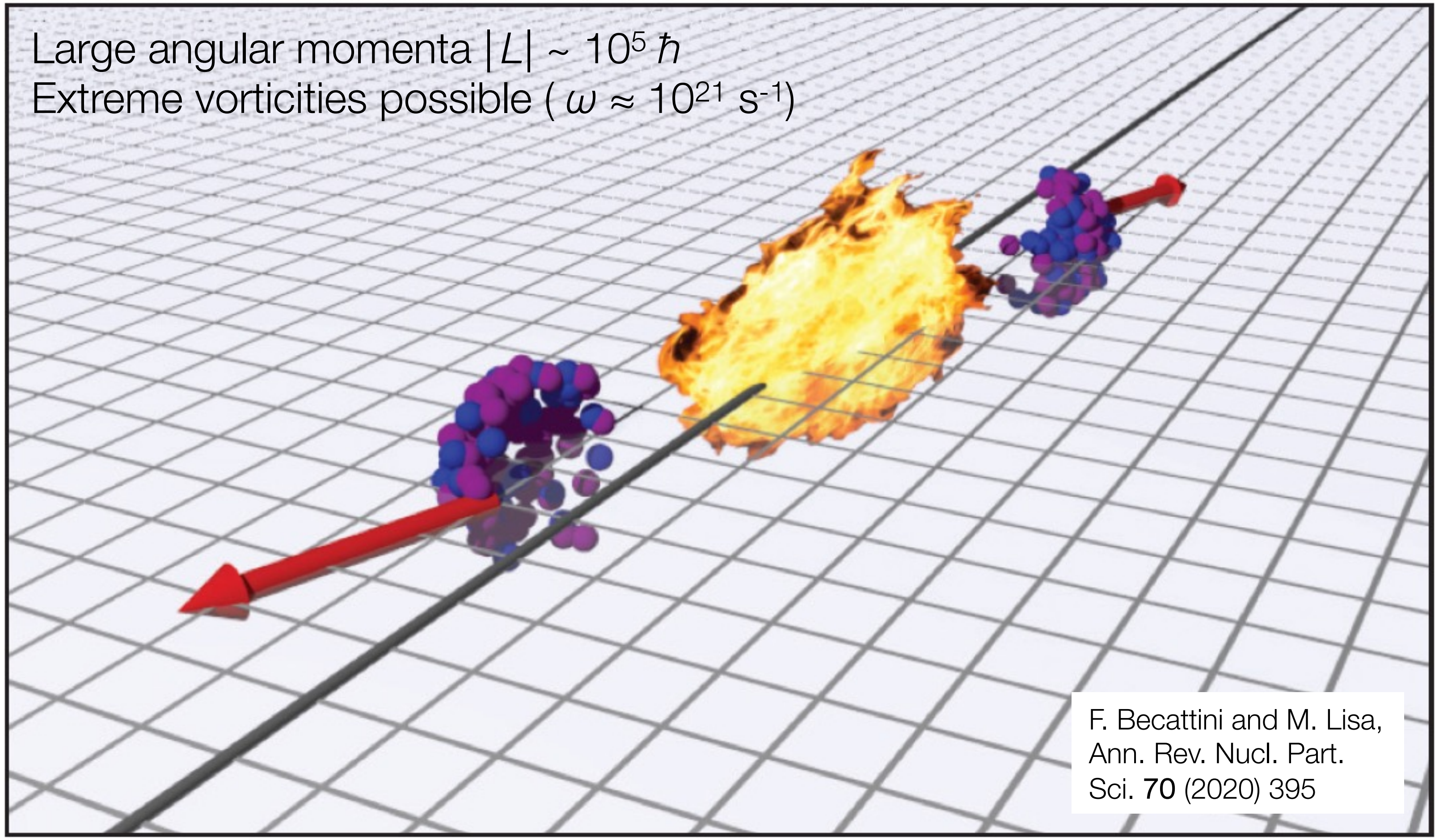
Vorticity

Global Polarization



F. Becattini and M. Lisa, Ann. Rev. Nucl. Part. Sci. **70** (2020) 395

Global Polarization



Global Polarization

Observable: Λ emission

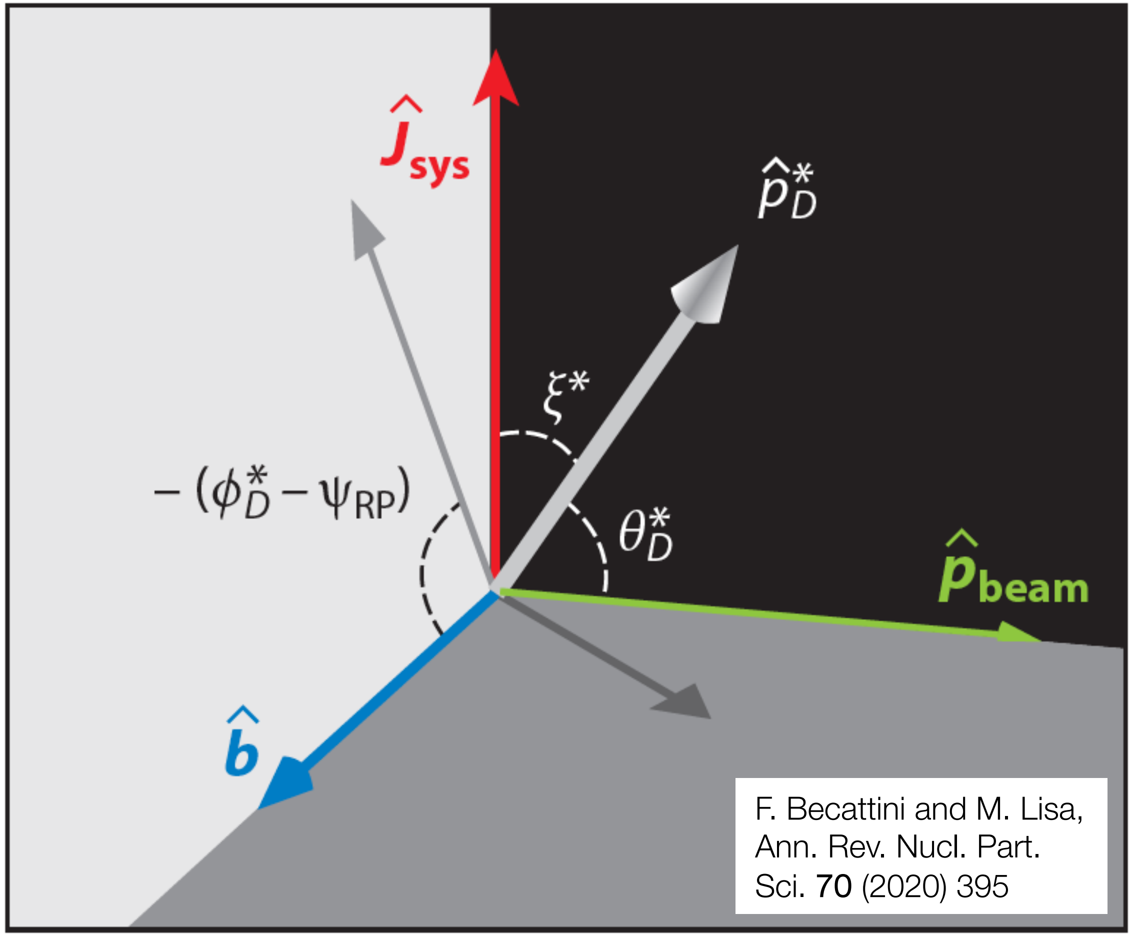
Weak decay: $\Lambda \longrightarrow p + \pi^-$

Proton preferentially in spin direction

$\Longrightarrow$ Polarization P_Λ:

$$P_\Lambda = \frac{8}{\pi\,\alpha_\Lambda}\frac{\langle \Psi_{EP} - \phi^*_D \rangle}{R_{EP}}$$

Λ decay parameter: $\alpha_\Lambda = 0.732 \pm 0.014$
Ψ_{EP} = event plane angle,
R_{EP} = EP-resolution
Φ^*_D = proton azimuth angle relative to EP

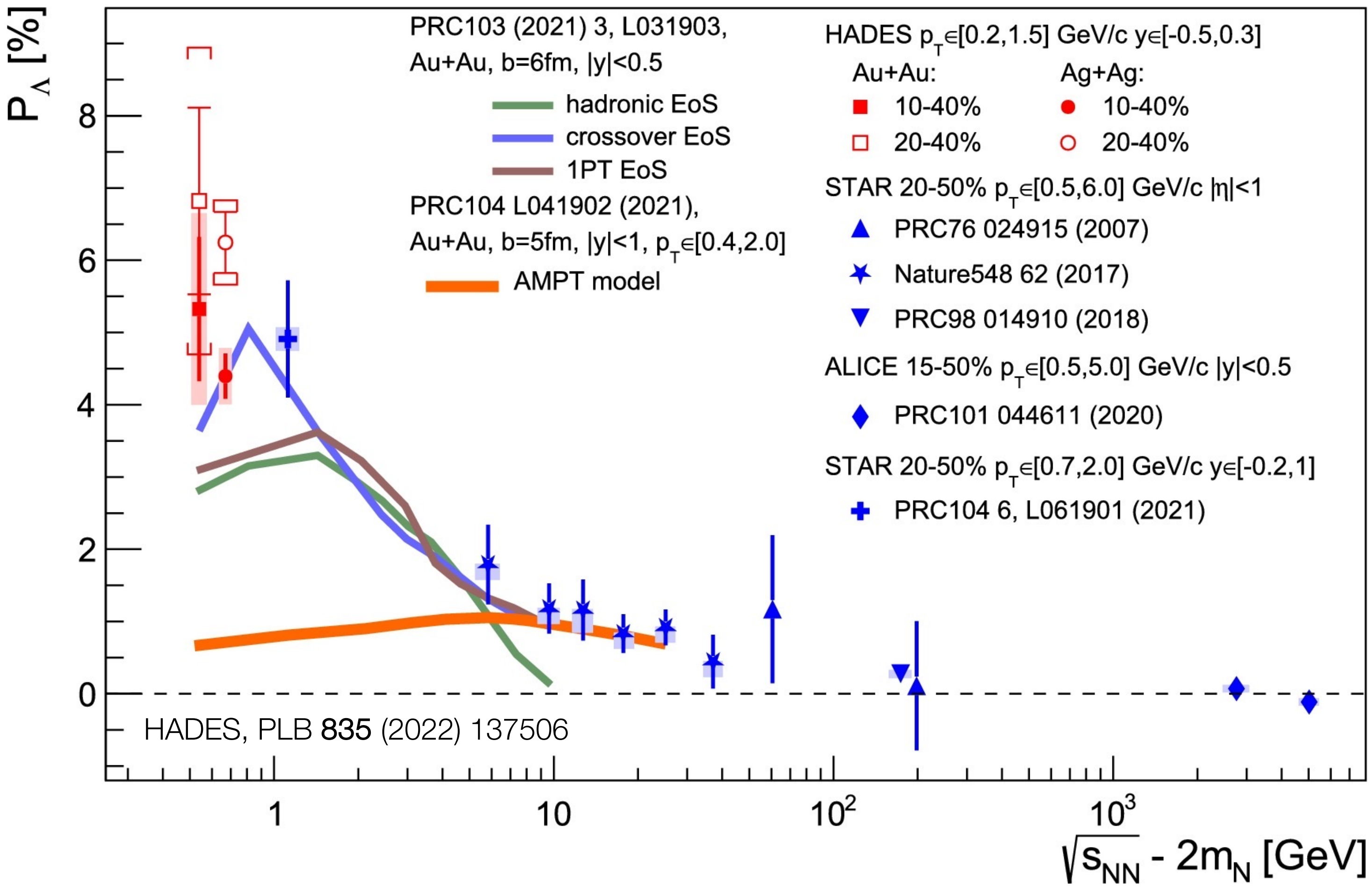


F. Becattini and M. Lisa, Ann. Rev. Nucl. Part. Sci. **70** (2020) 395

Global Polarization

Strong increase of P_Λ towards lower energies

Agreement with 3D-hydro
AMPT model disfavored



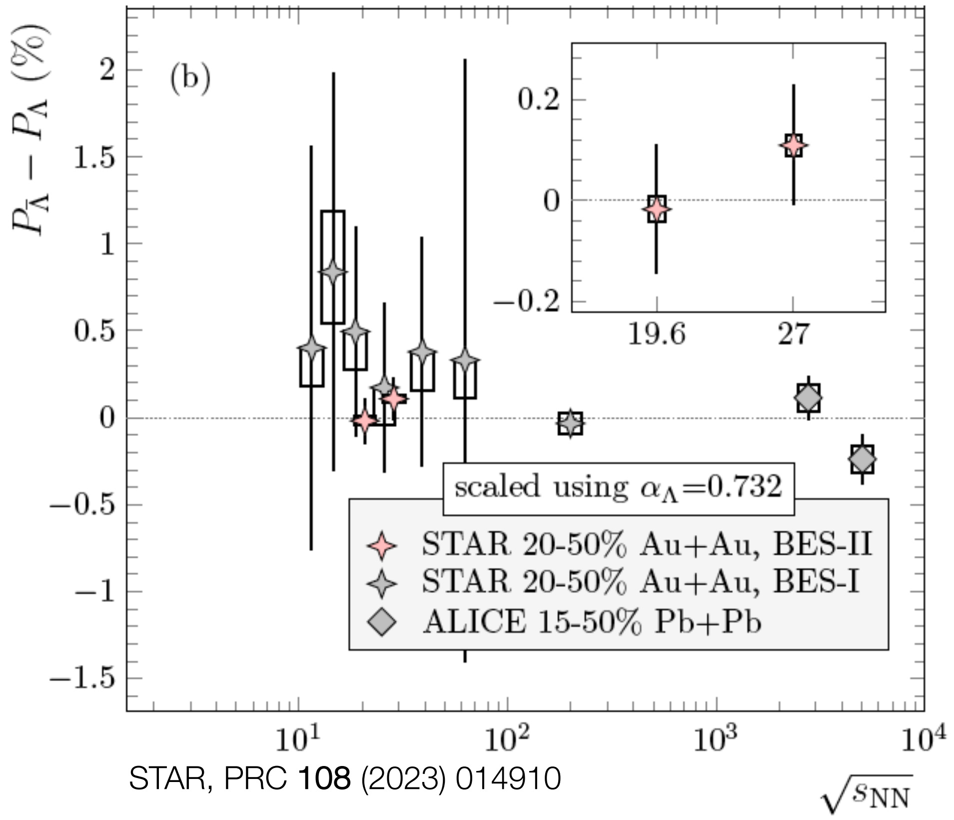
Global Polarization

Difference between $P_{\bar{\Lambda}}$ and P_{Λ}
No evidence for $P_{\bar{\Lambda}} - P_{\Lambda} > 0$

Relation to late stage magnetic field (feed-down effects ignored):

$$|B| \approx \frac{T_s |P_{\bar{\Lambda}} - P_{\Lambda}|}{2|\mu_{\Lambda}|}$$

T_s = Temperature of emitting source
μ_{Λ} = Magnetic moment of Λ

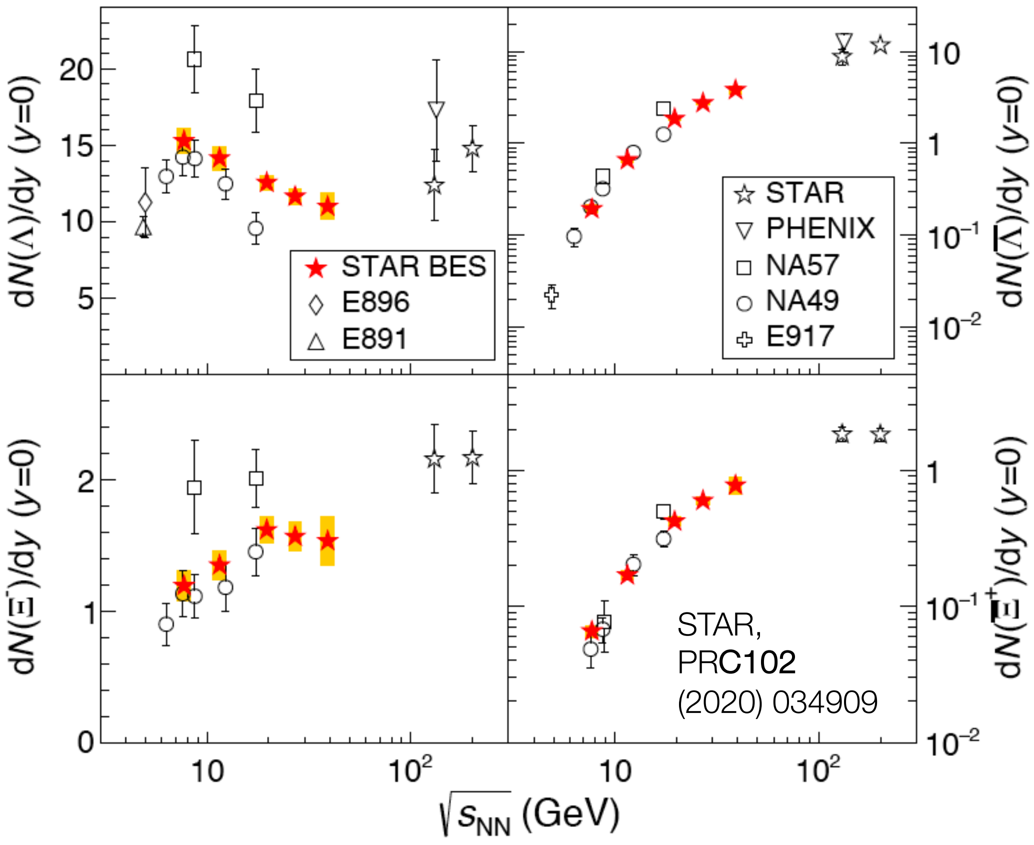


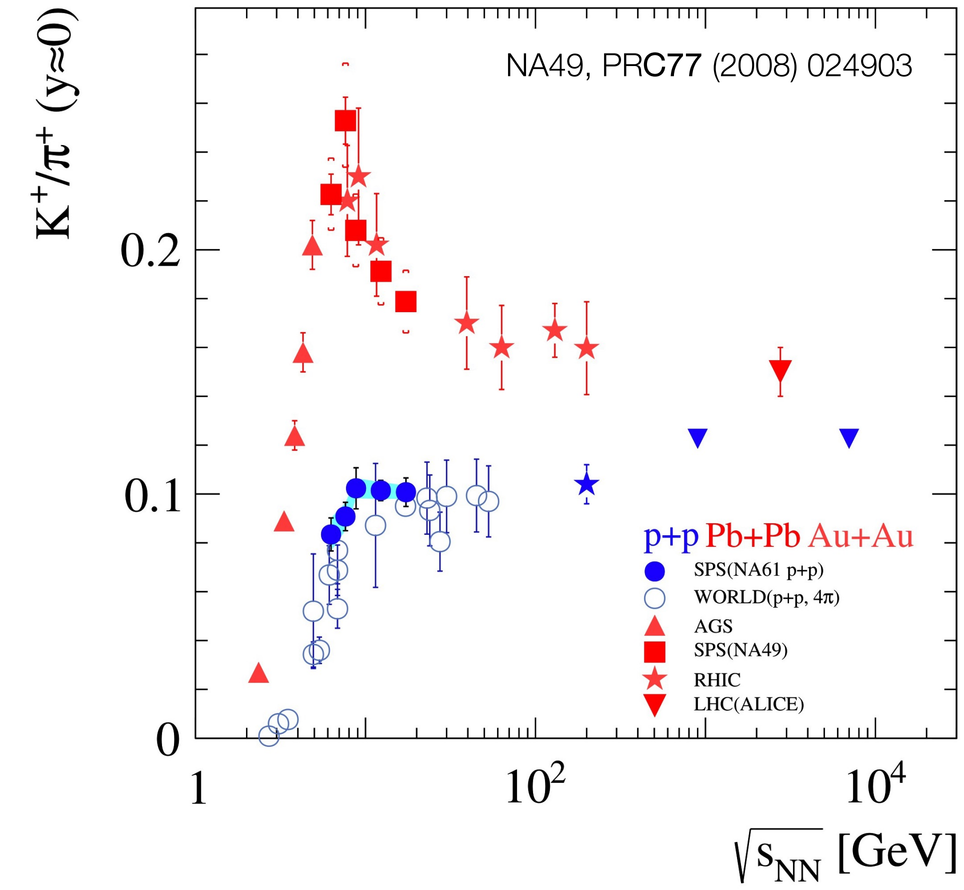
STAR, PRC **108** (2023) 014910

Upper limits:
$B < 9.4 \times 10^{12}$ T at $\sqrt{s_{NN}}$ = 19.6 GeV ($B < 1.4 \times 10^{13}$ T at $\sqrt{s_{NN}}$ = 27 GeV)

Strangeness in Matter
Hypernuclei

Production of Strange Particles

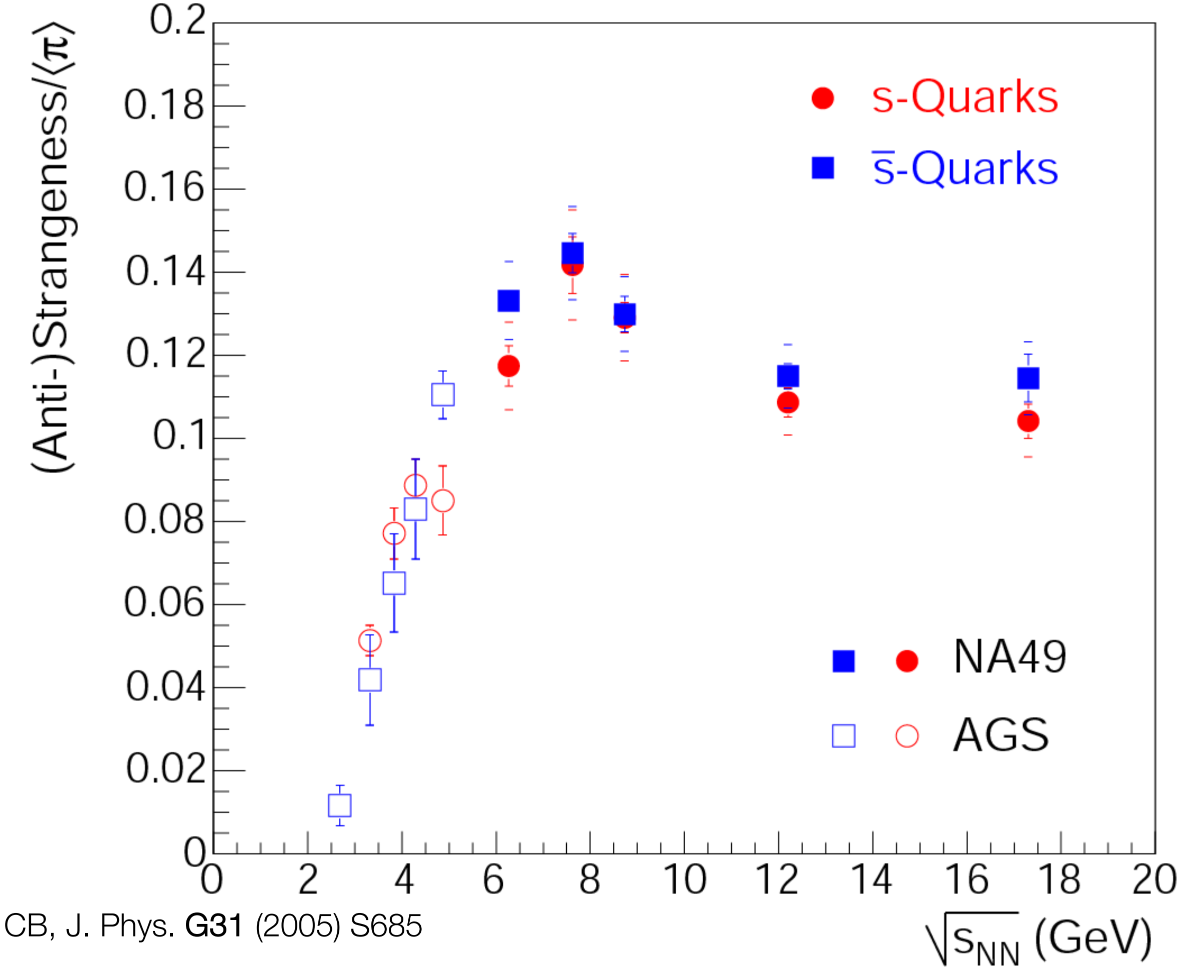




Structures in energy dependence (e.g. maxima for Λ, K^+/π^+)

Production of Strange Particles

Relative strangeness production is maximal around $\sqrt{s_{NN}}$ = 6 – 8 GeV



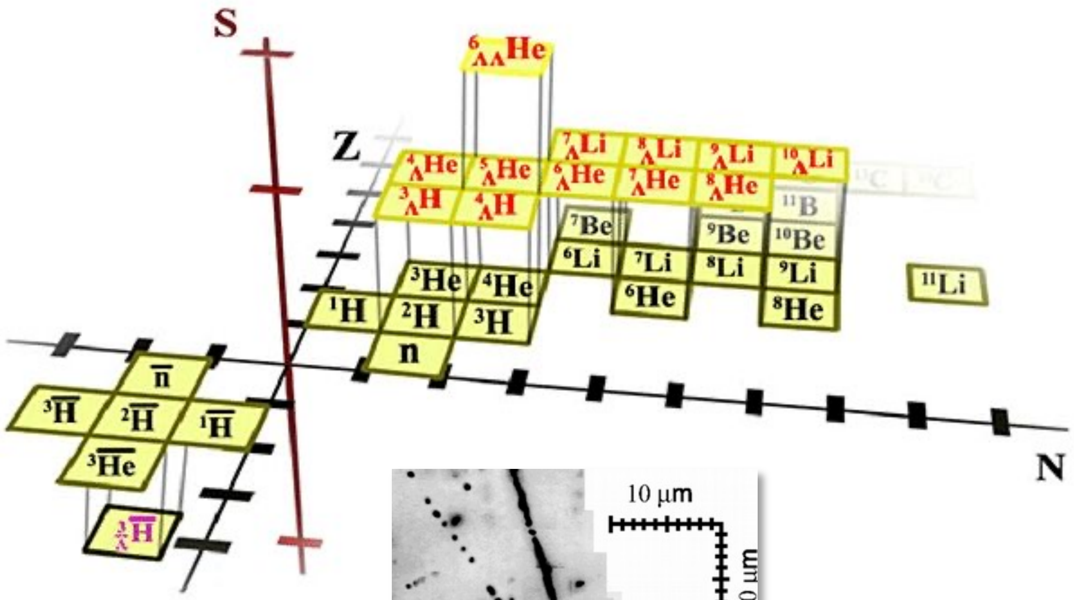
CB, J. Phys. **G31** (2005) S685

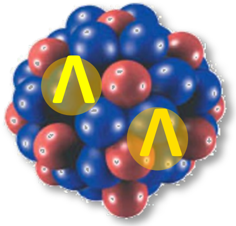
Hypernuclei

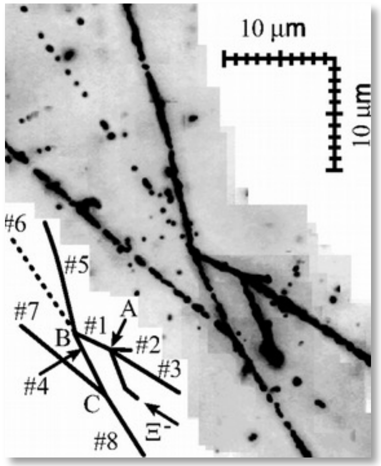
Nuclei with Λ replacing neutron(s)

Important information
hyperon-nucleon interactions
⟹ change in binding energy

Double-Λ hypernuclei
particularly interesting
(so far only handful events!)







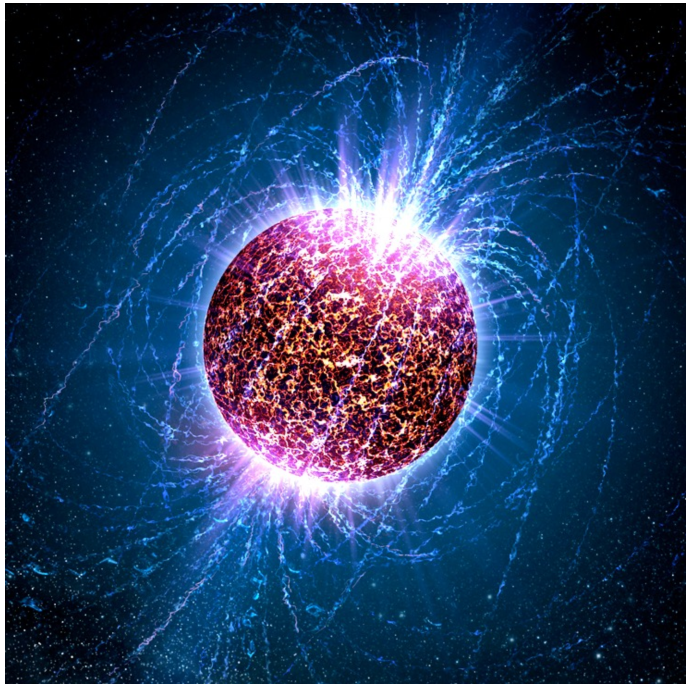
Discovery of $^{6}{}_{\Lambda\Lambda}$He
by Danysz
and Pniewski
in photo emulsion

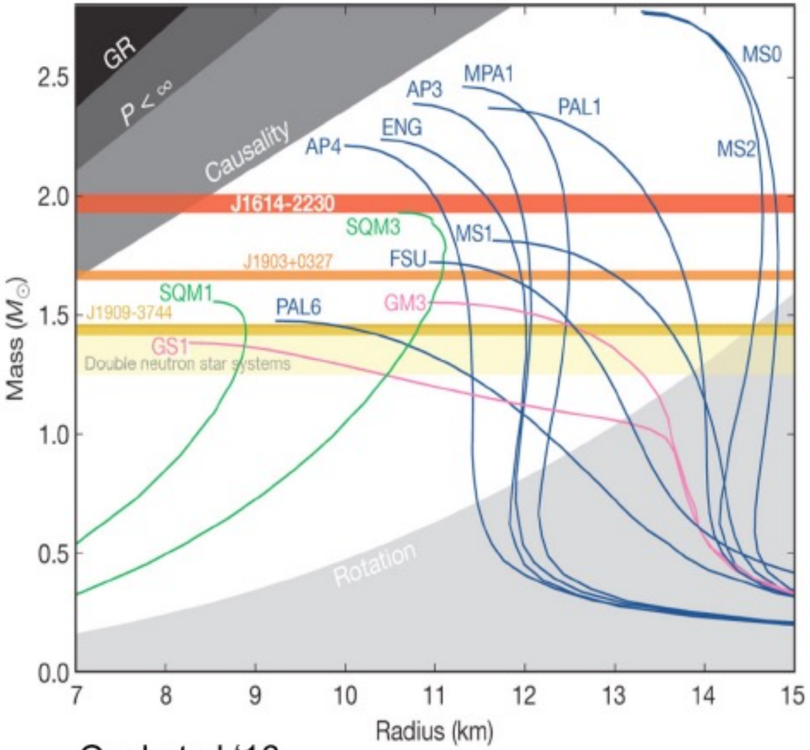
Hypernuclei + Neutron Stars

Mass-radius relation:
Depends on EOS of dense nuclear matter

Constraints form observation of $M_{NS} \approx 2\,M_\odot$

Important information from heavy-ion physics





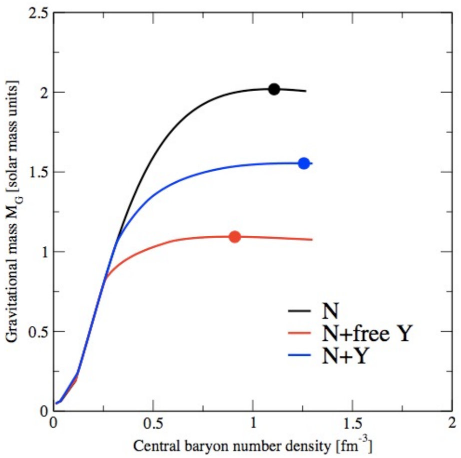
Ozel et al '16

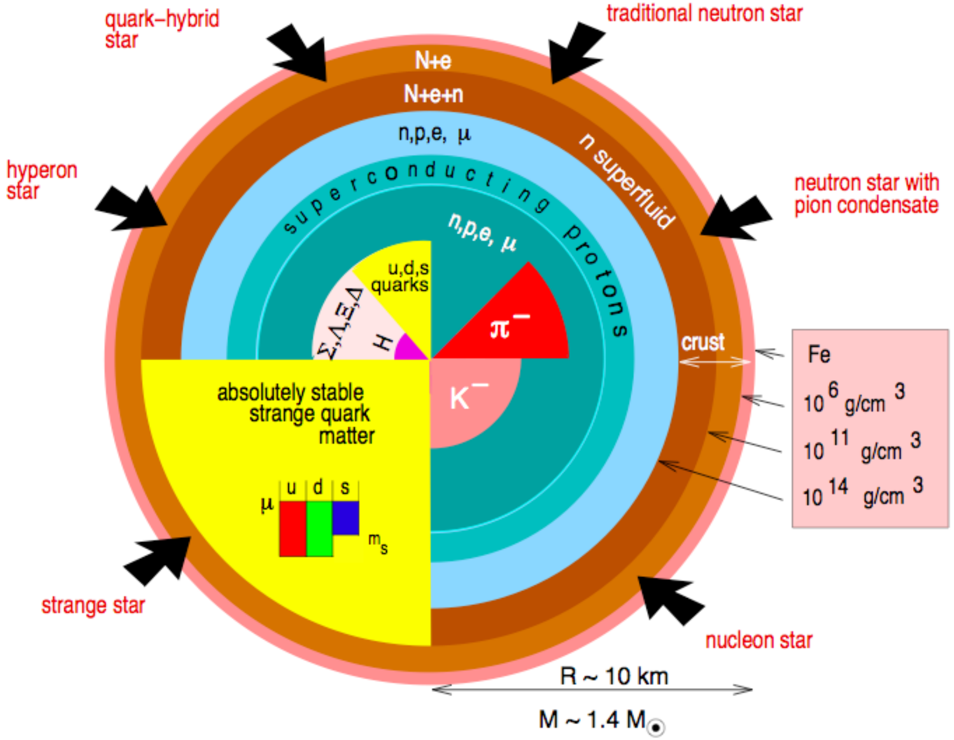
Hypernuclei + Neutron Stars

Hyperon-puzzle

Hyperons should appear
when density increases

$\Longrightarrow$ EOS softens with hyperon matter
$\Longrightarrow$ $2\,M_\odot$ cannot be reached





YN and YY interaction

Repulsive YN and YY
interactions $\Longrightarrow$ stiffer EOS

3-body forces between Ys
Important input from hypernuclei measurements

Production in Heavy-Ion Collisions

Statistical model

Based on parametrization:
$T = T(\sqrt{s_{NN}})$ and $\mu_B = \mu_B(\sqrt{s_{NN}})$

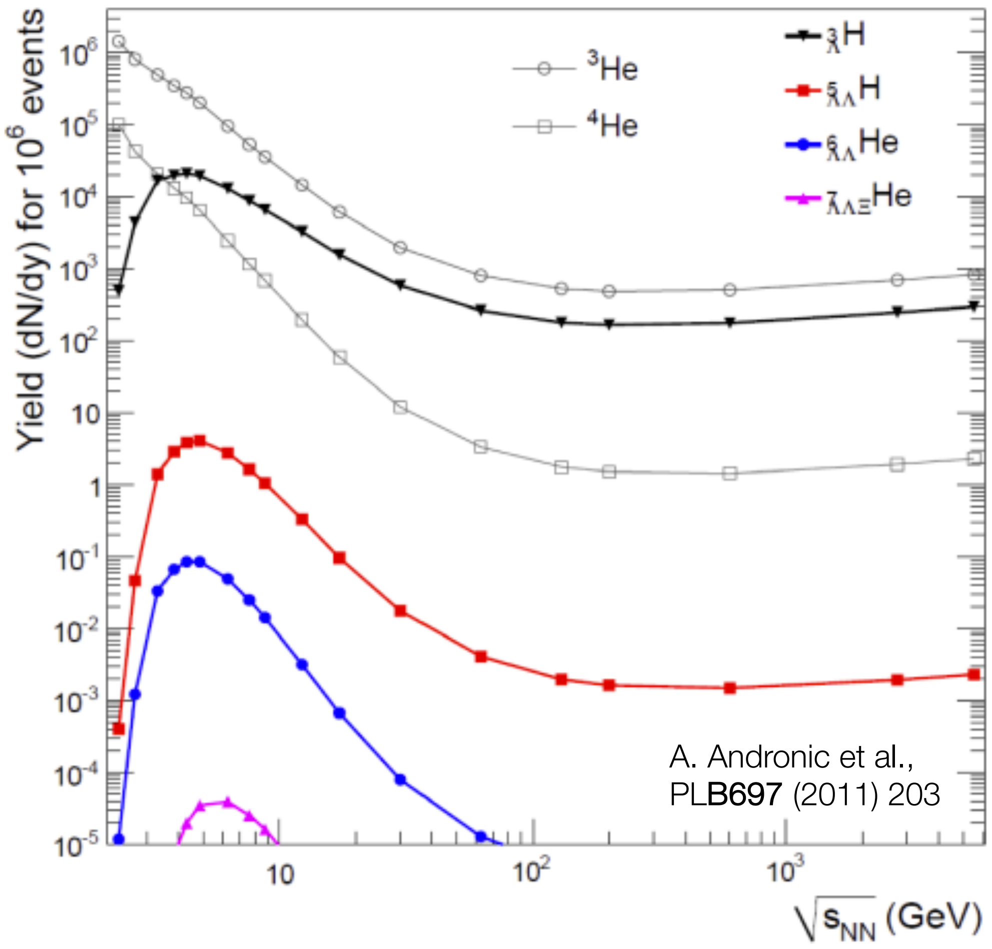
Predictions for the CBM energy range

Hypernuclei production favored
at low $\sqrt{s_{NN}}$, i.e. low μ_B

Expected rates

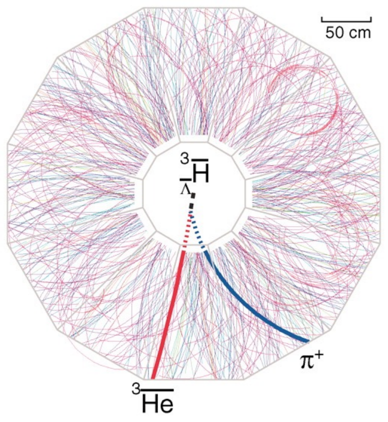
Double-Λ hypernuclei:
~10^{-6}/evt. — ~10^{-11}/evt. in CBM range

High interaction rates needed

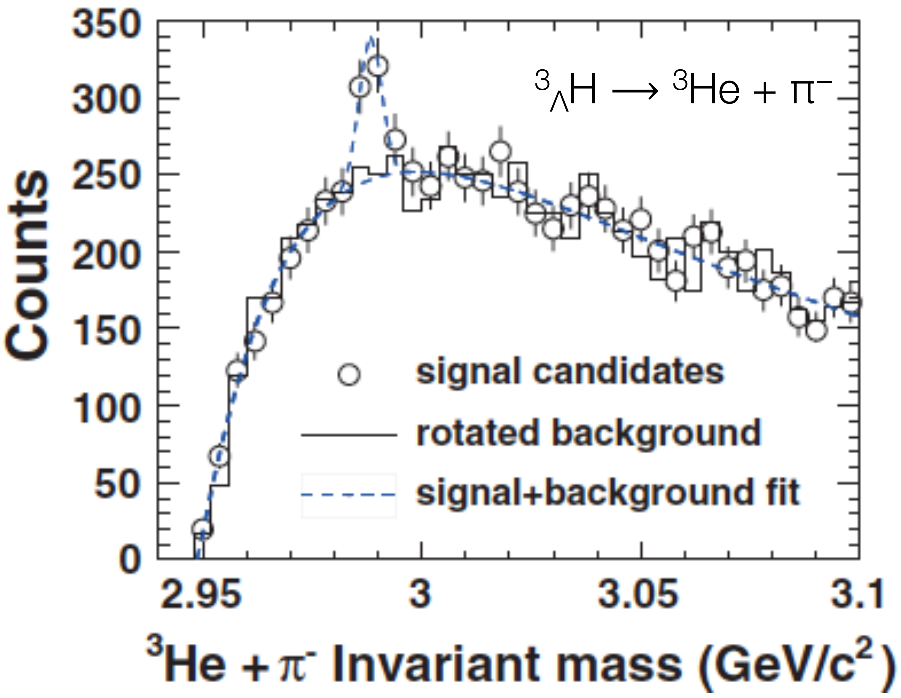


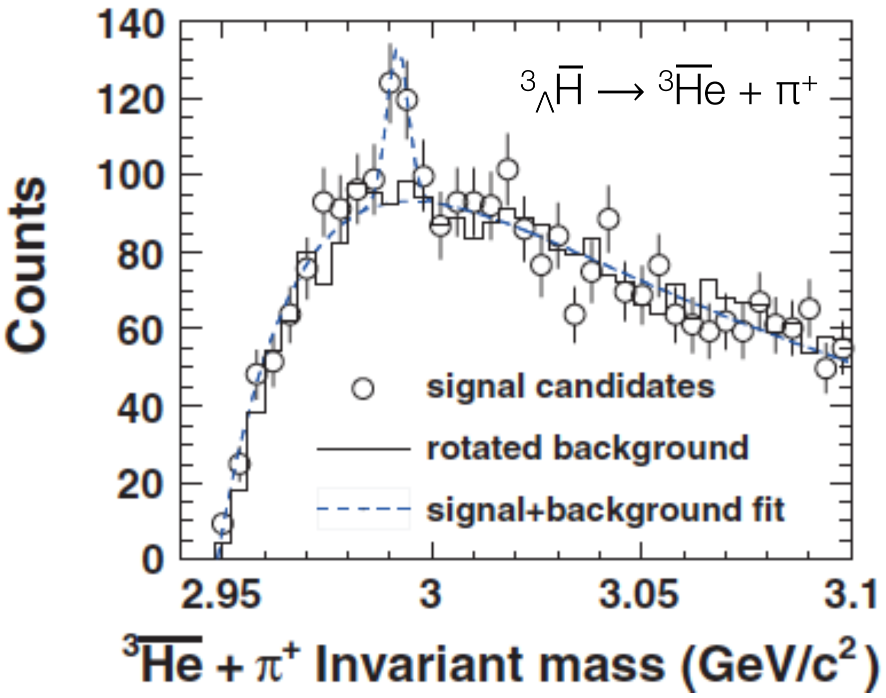
A. Andronic et al.,
PL**B697** (2011) 203

(Anti-)Hypertriton



STAR,
Science **328** (2010) 58





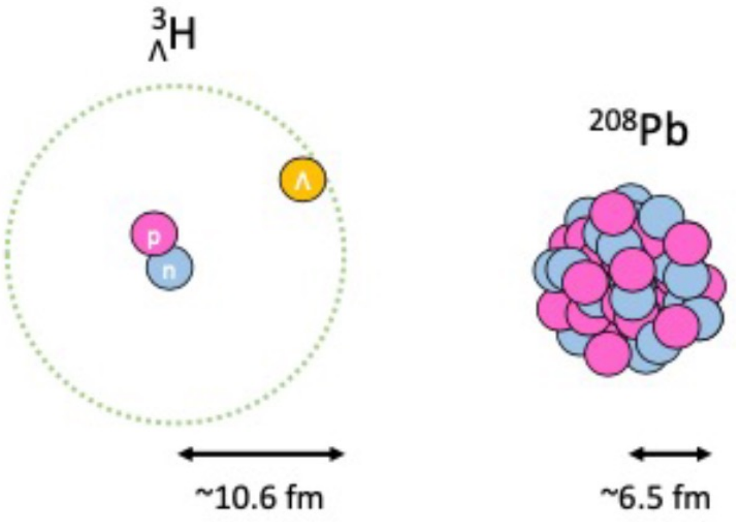
First observation of an anti-hypernucleus (Au+Au at $\sqrt{s_{NN}}$ = 200 GeV)

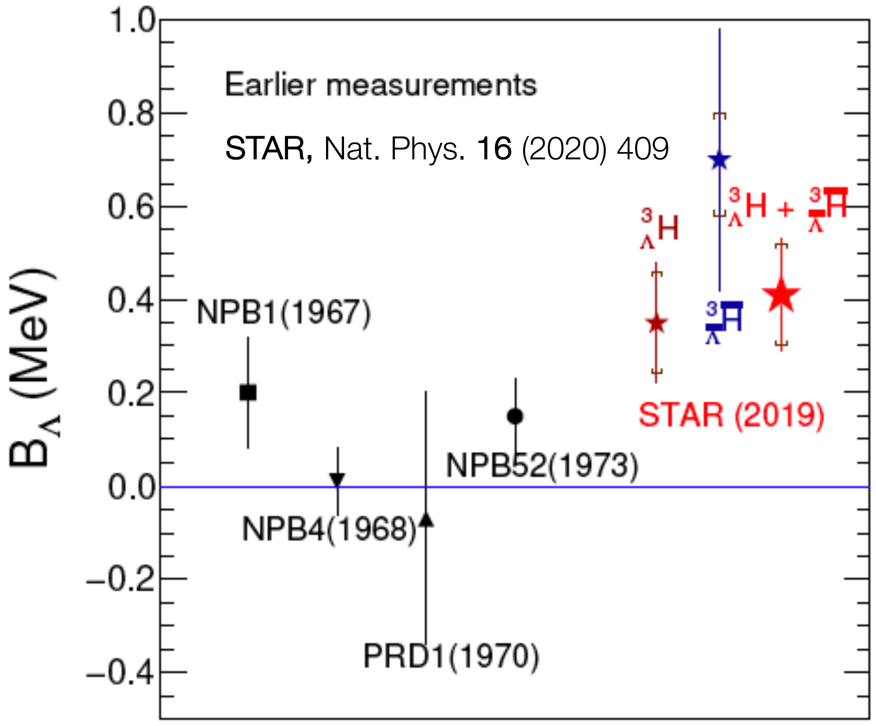
Hypertriton

Loosely bound object

Λ binding energy: $B_\Lambda \approx 400$ keV
(compare $B_d = 2.2$ MeV)

Wavefunction is larger than Pb-nucleus





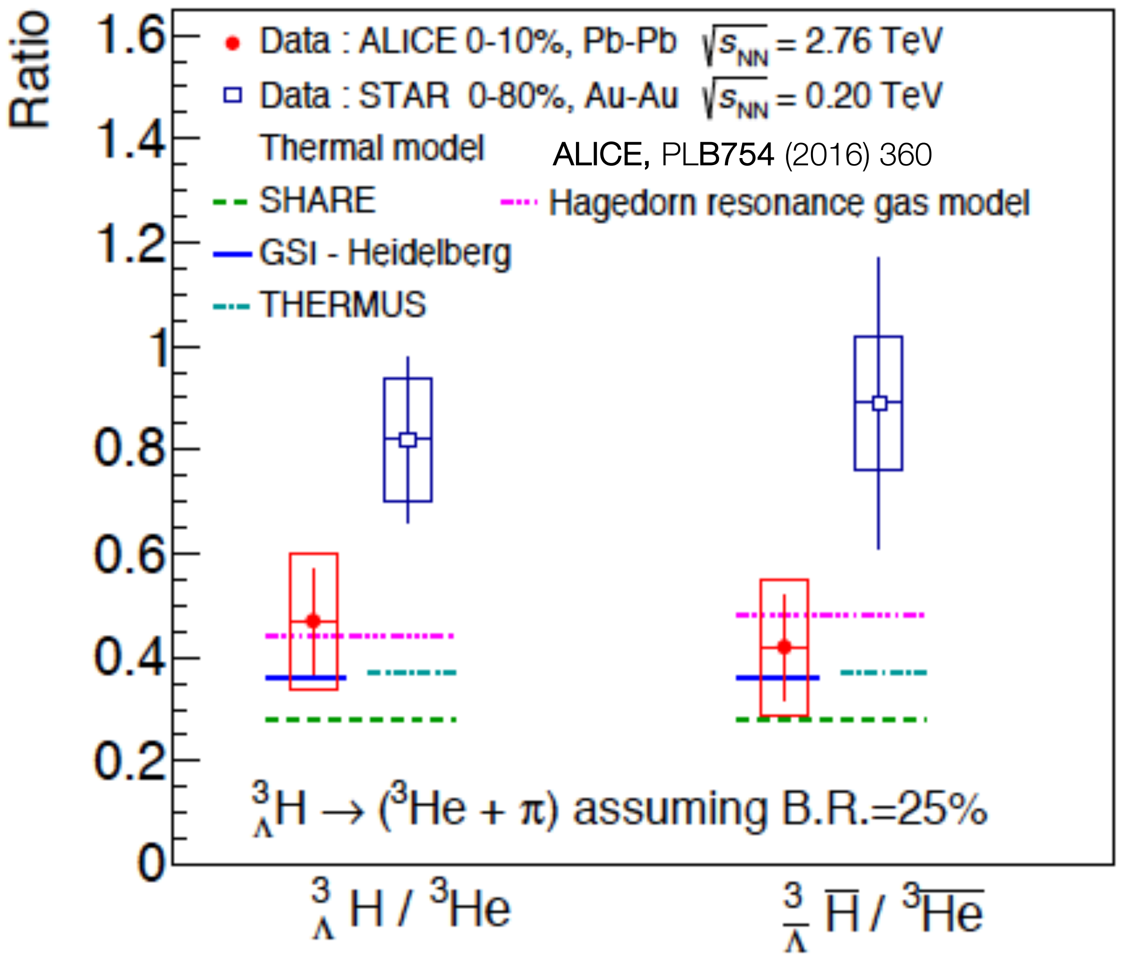
Decay modes

$^3_\Lambda H \longrightarrow {}^3He + \pi^-$
$^3_\Lambda H \longrightarrow {}^3H + \pi^0$
$^3_\Lambda H \longrightarrow d + p + \pi^-$
$^3_\Lambda H \longrightarrow d + n + \pi^0$

Hypertriton Yield

Ratio hypertriton/^{3}He

Good agreement with thermal fireball prediction for temperature T ~150 MeV



"Ice in fire" / "Snowball in hell"

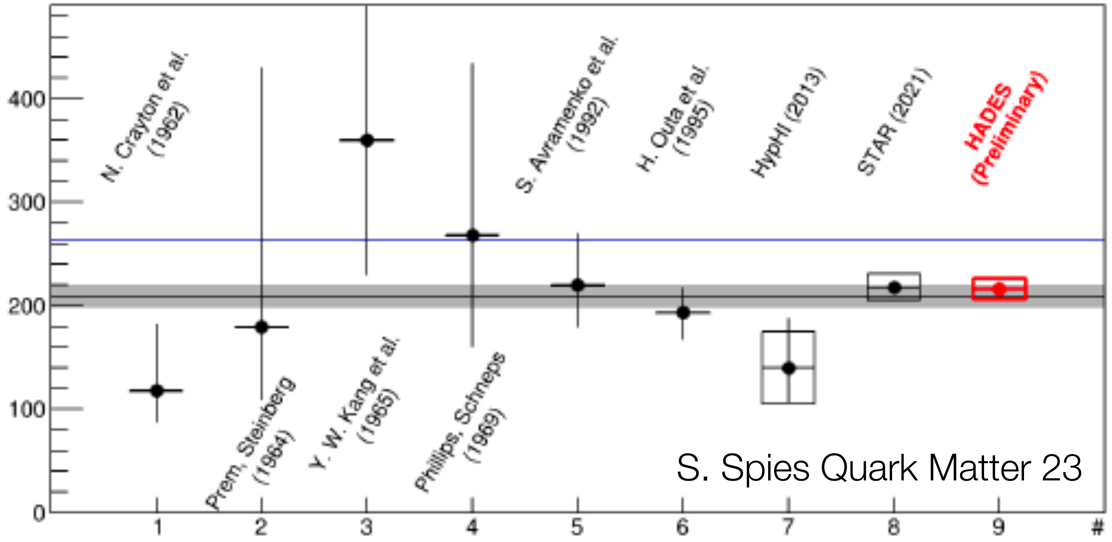
How does a weakly bound object ($B_\Lambda \approx$ 0.4 MeV) survive in a fireball with freeze-out temp. of ~150 MeV ?

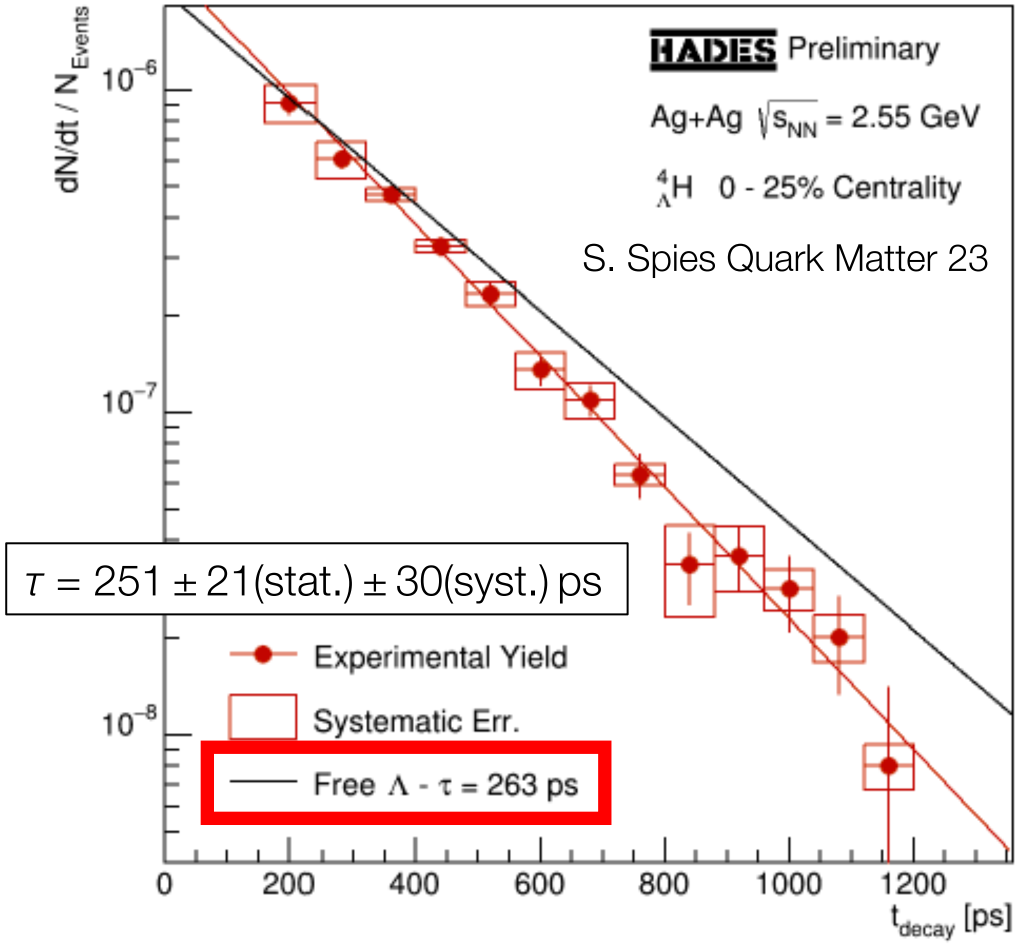
Hypertriton Lifetime

Hypertriton lifetime “puzzle”

Lifetime smaller than the one of free Λ?
Recent data rather agree for ${}^{3}_{\Lambda}H$

${}^{4}_{\Lambda}H$: ~ 4.9σ deviation observed

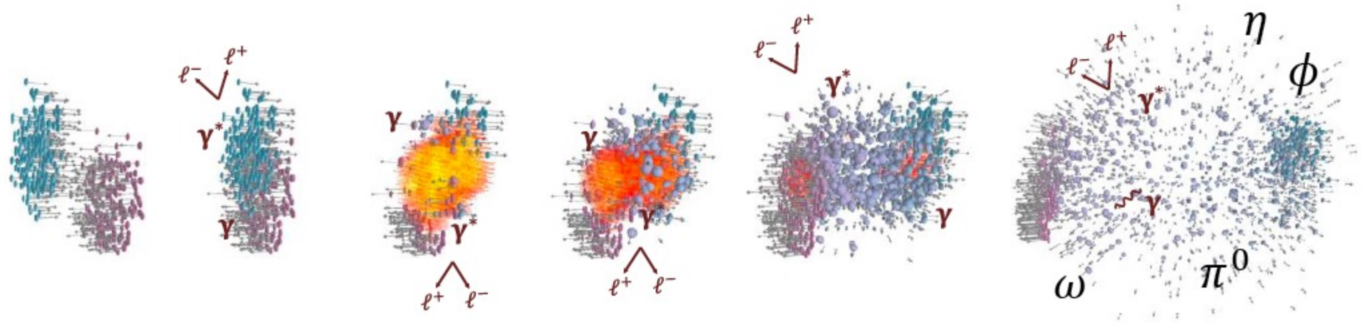




Emissivity

Photons

Electromagnetic radiation (γ and γ^*) emitted during full fireball evolution



No strong interaction with medium $\Longrightarrow$ escape unmodified

Sources of di-leptons ($\gamma^* \longrightarrow e^+ e^-$, $\gamma^* \longrightarrow \mu^+ \mu^-$):

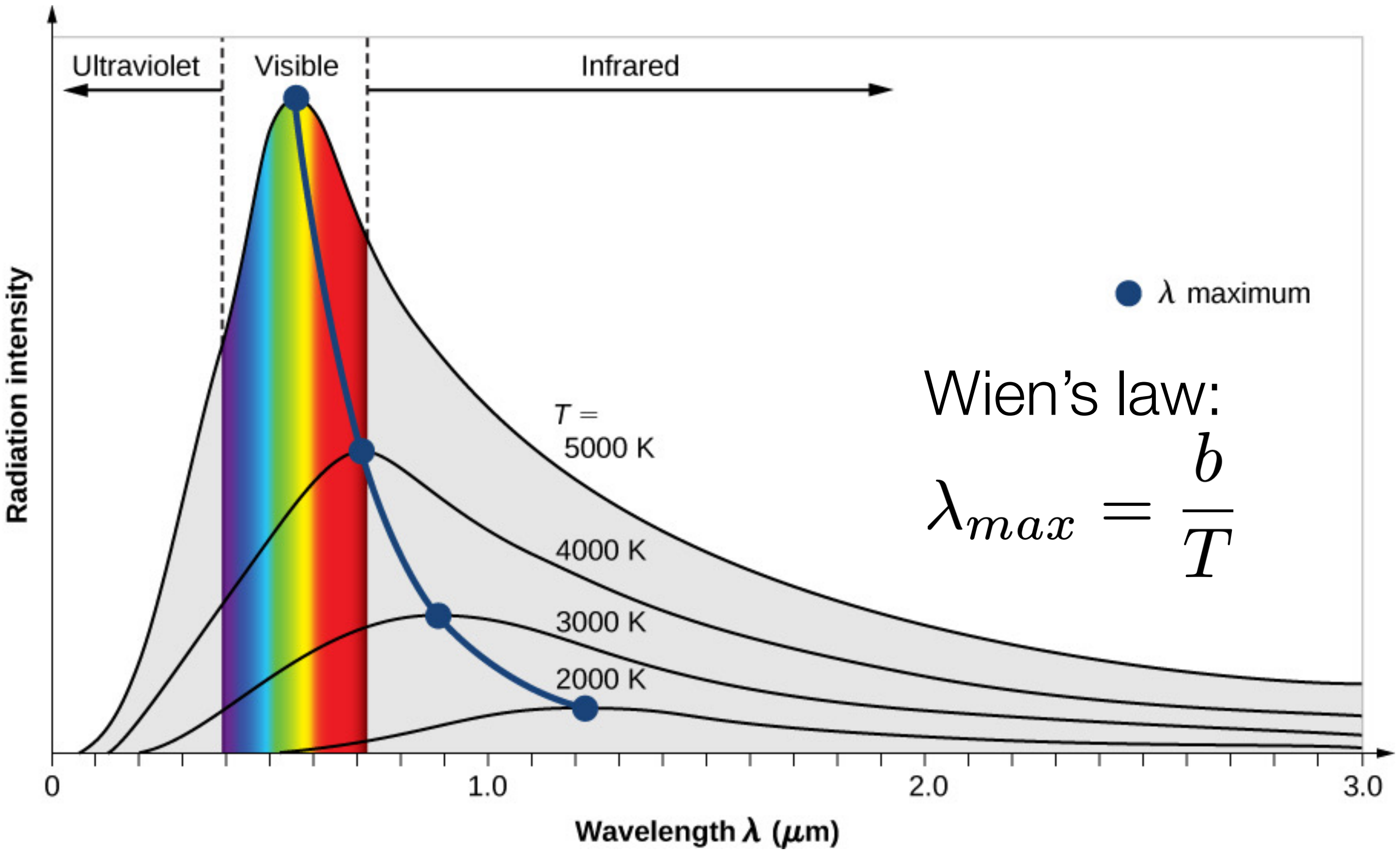
Dalitz-decays ($\pi^0 / \eta \longrightarrow e^+ e^- \gamma$)
Low mass range: vectormeson decays (ρ, ω, ϕ) $\Longrightarrow$ medium modifications
Intermediate mass range: thermal radiation (open charm)

Photons: Thermal Radiation

Black body radiation

$$B(\nu, T) = \frac{2\,h\nu^3}{c^2}\,\frac{1}{\exp\left(\frac{h\nu}{k_B\,T}\right) - 1}$$

Planck's formula



Wien's law:

$$\lambda_{max} = \frac{b}{T}$$

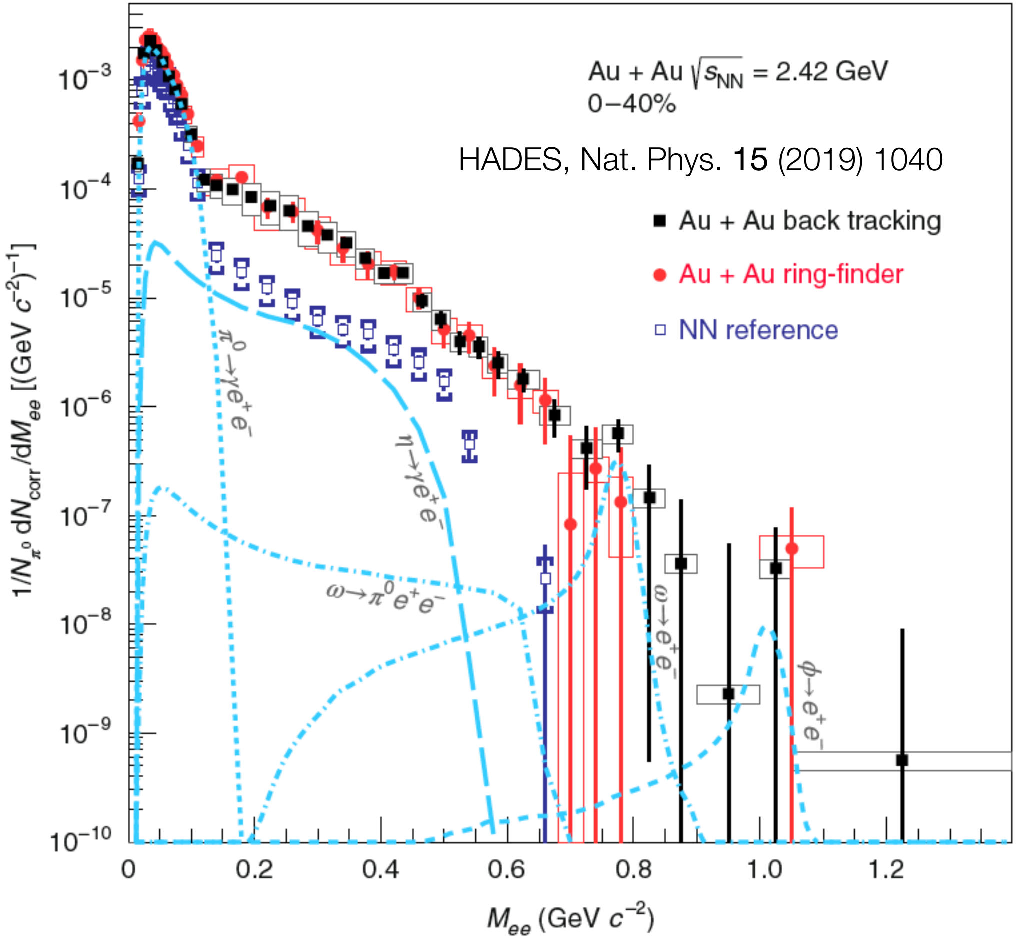
Di-Electron Spectrum

Reference NN spectrum

$$\frac{dN^{NN}_{ref}}{dM_{ee}} = \left(0.54\frac{dN^{pp}}{dM_{ee}} + 0.46\frac{dN^{np}}{dM_{ee}}\right)\langle A_{part}\rangle$$

Hadronic contributions (w/o ρ)

$\pi^0 / \eta \longrightarrow e^+ e^- \gamma$
$\omega / \phi \longrightarrow e^+ e^-$
$\omega \longrightarrow \pi^0 e^+ e^-$

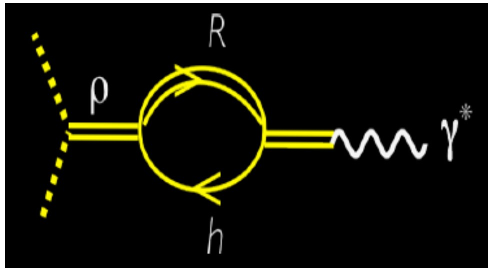


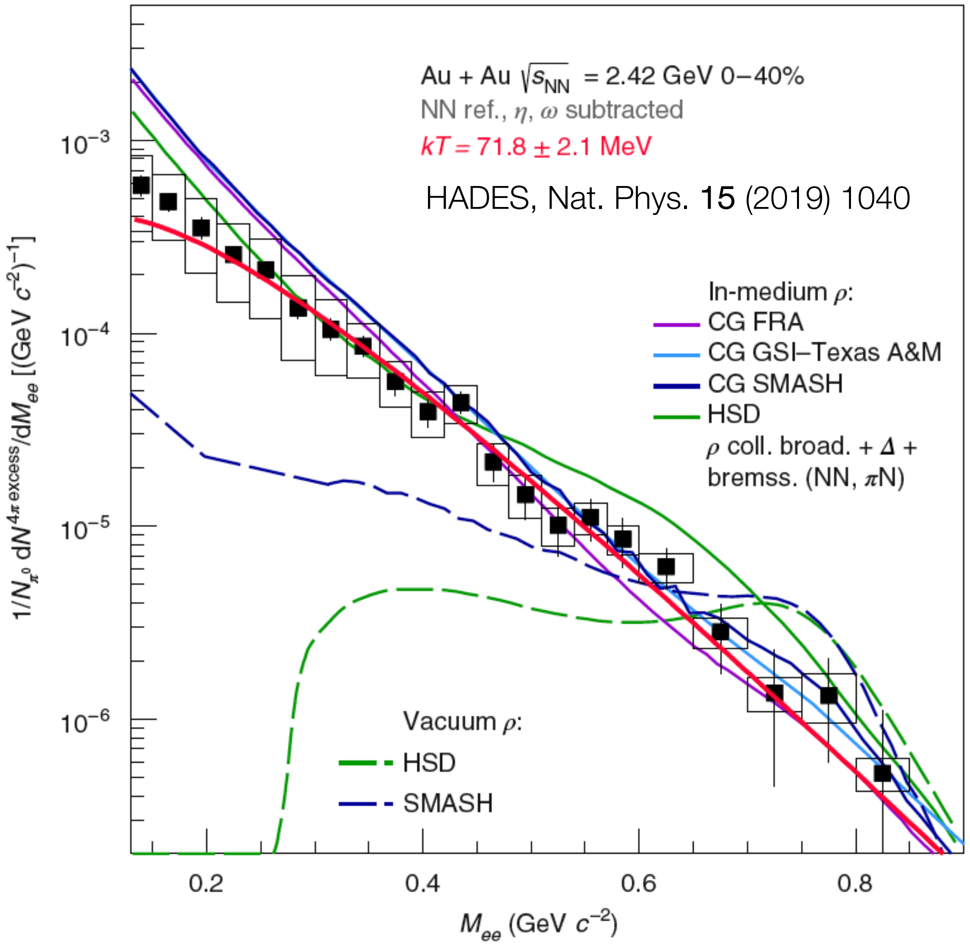
Subtraction of reference
⟹ Excess radiation

Di-Electron Spectrum

Subtraction of reference
⟹ Excess radiation

Not described by vacuum ρ
Broadening due to ρ-baryon scattering





Di-Electron Spectrum

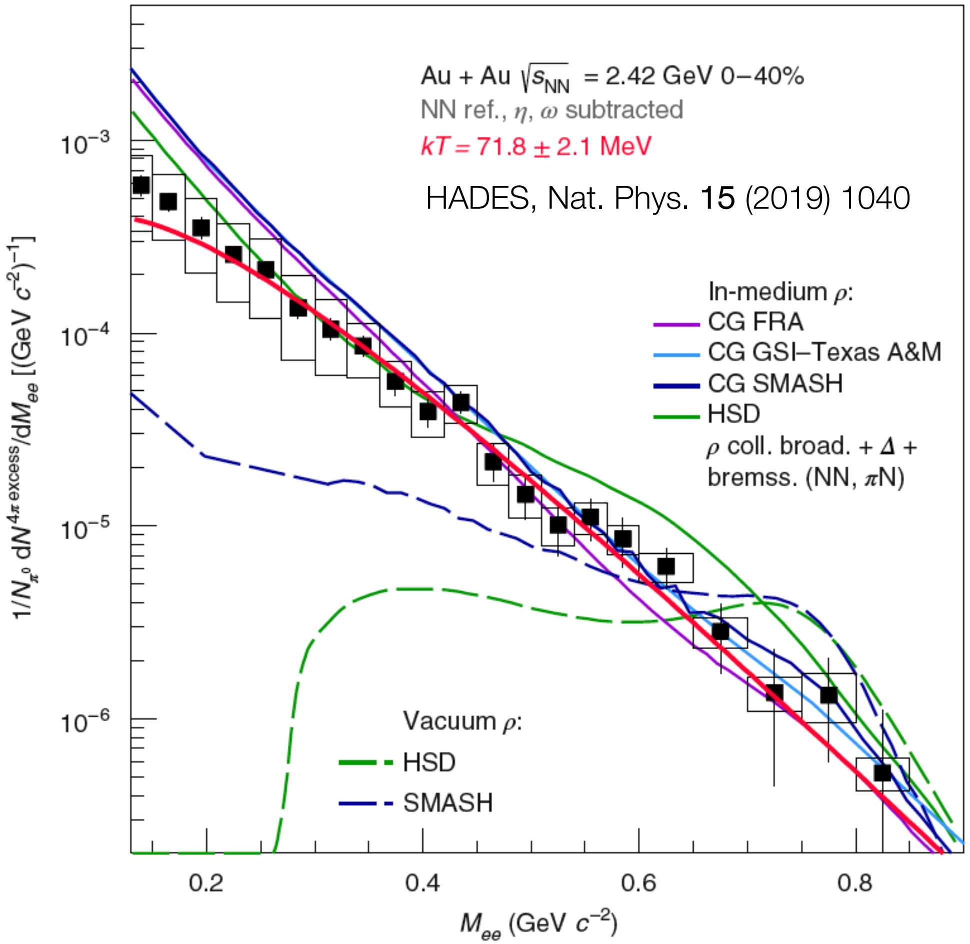
Subtraction of reference
⟹ Excess radiation

Calculations with in-medium ρ spectral functions, folded with fireball evolution from coarse-grained transport

In-medium propagator: R. Rapp and H. van Hees, PLB **753** (2016) 586
$\rho - a_1$ chiral mixing: R. Rapp and P. Hohler, PLB **731** (2014) 103
CG FRA: S. Endres et al., PRC **92** (2015) 014911
CG GSI-TAMU: T. Galatyuk, F. Seck et al., EPJA **52** (2016) 131
CG SMASH: J. Staudenmaier et al., PRC **98** (2018) 054908.
HSD transport model: E. Bratkovskaya et al., PRC **87** (2013) 064907.

Thermal radiation of medium

Exponential spectrum ⟶ black body rad.
Fit result: T_{rad} = 71.8 ± 2.1 MeV

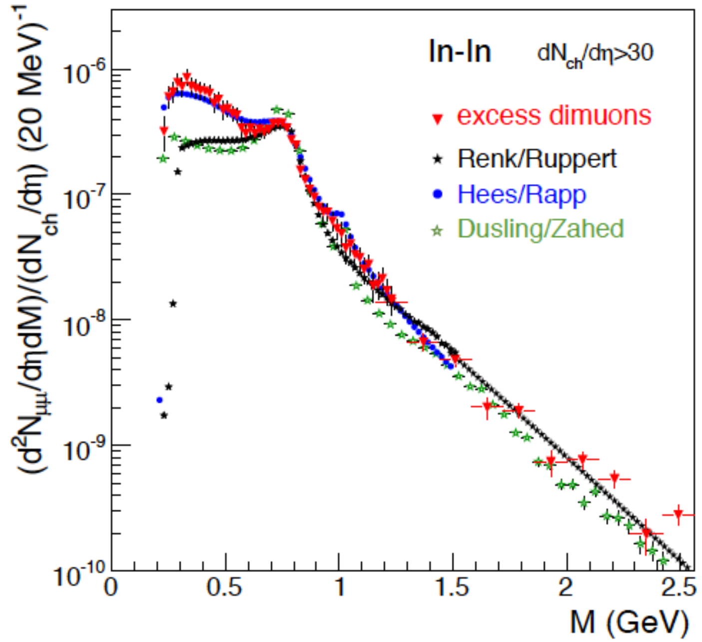


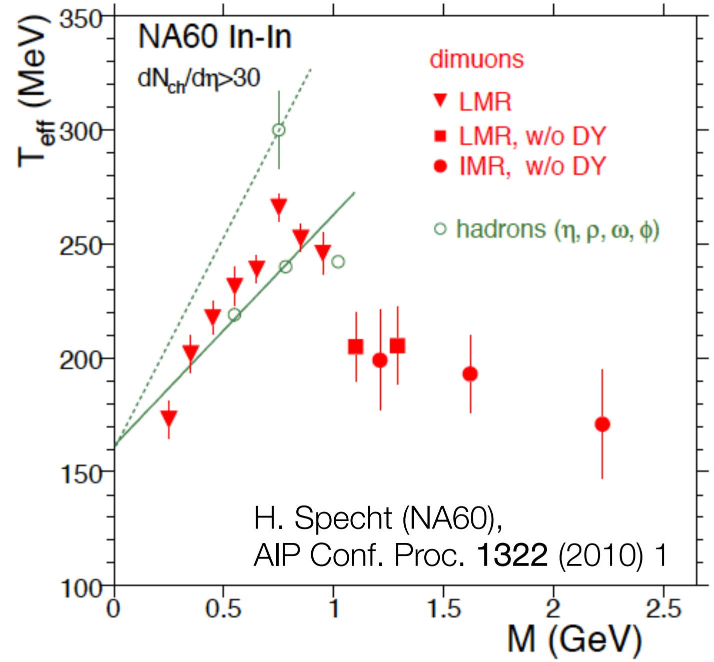
Di-Muon Spectrum

Subtraction of reference
⟹ Excess radiation

Inverse slope parameter T_{eff} depends on mass M of di-muon-pairs

Thermal radiation
at intermediate masses



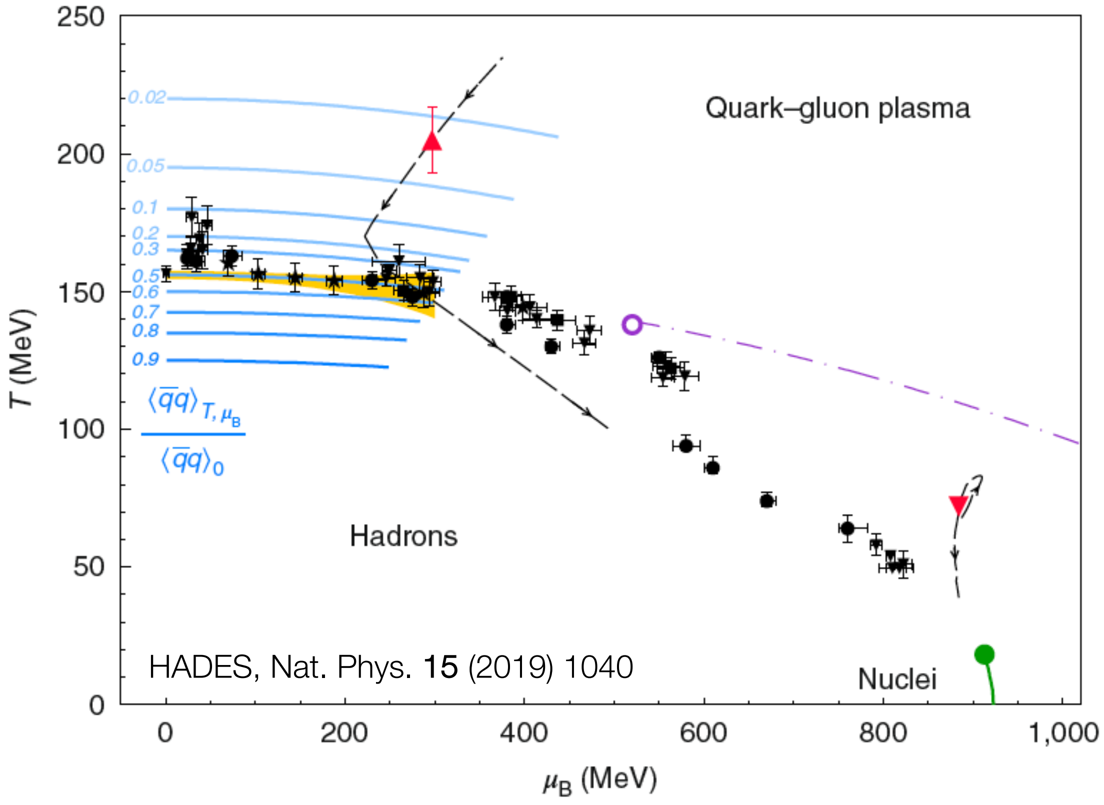


Thermal Radiation

QCD Phase diagram with inverse slope parameters T_{eff}

Information on the early phases of the fireball

Thermometer
Chronometer
Barometer

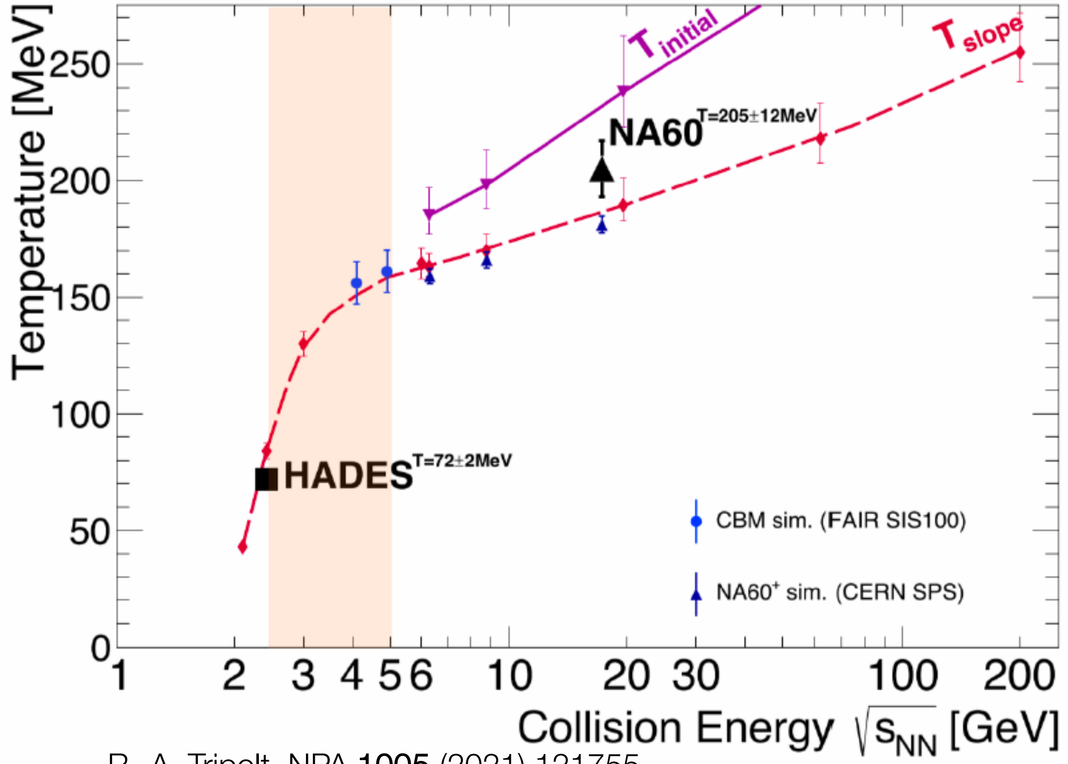


Thermal Radiation

Energy dependence

Sensitivity to the
order of the phase transition?

Important physics case
for CBM and NA60+



R.-A. Tripolt, NPA **1005** (2021) 121755
NA60, EPJC **61** (2009) 711
HADES, Nat. Phys. **15** (2019) 1040
$\sqrt{s_{NN}}$ > 6 GeV: R. Rapp and H. v. Hess, PLB **753** (2016) 586
$\sqrt{s_{NN}}$ < 6 GeV: T. Galatyuk et al.: EPJA **52** (2016) 131

Di-Leptons: Future Experiments