Title: Signals from the hot and whirly matter produced in heavy-ion collisions

Speakers: Maria Elena Tejeda Yeomans

Series: Particle Physics

Date: November 01, 2022 - 1:00 PM

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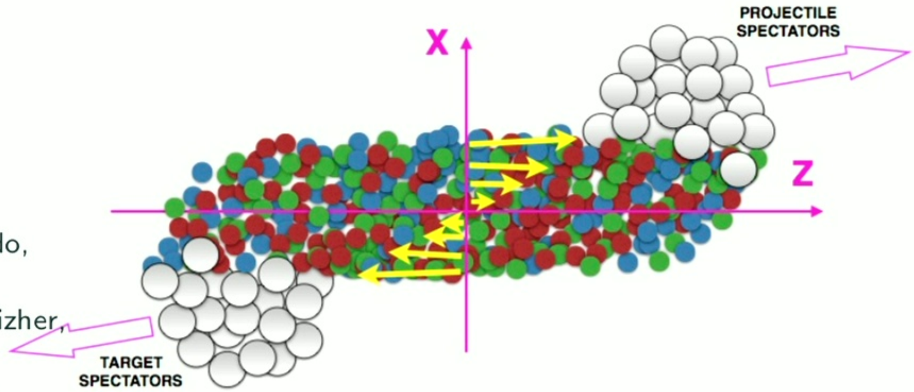
Abstract: The polarization measurements of particles produced in heavy-ion collisions allow us to study amazing phenomena such as, the collective rotation of the nuclear medium, quark spin-alignment with the global angular momenta, local vs global polarization effects and their evolution when there are drastic changes in the properties of the hot, dense and whirly medium. Recently, measurements by the STAR collaboration at RHIC and the HADES collaboration at GSI, show the rising of Lambda and anti-Lambda global polarization with decreasing collision energy and what seems to be a differentiated peak with a sharp decrease at a lower bound in collision energy. In this talk I will report on our recent work where we predict this differentiated peak behavior using a core-corona model, so that measuring the polarization of hyperons becomes a tool to learn about strangeness availability in the medium created in heavy-ion collisions for different initial conditions. I will also present a few new developments we have made to probe the strong magnetic field produced early after the collision with primordial photons and mention other relevant signals that we are working on in order to learn about the critical end-point in the QCD phase diagram.

Zoom link: https://pitp.zoom.us/j/95896792626?pwd=QlovbE5EWEJBSDdOZjUyK2MxYktmQT09

Signals from the hot and whirly matter produced in heavy-ion collisions

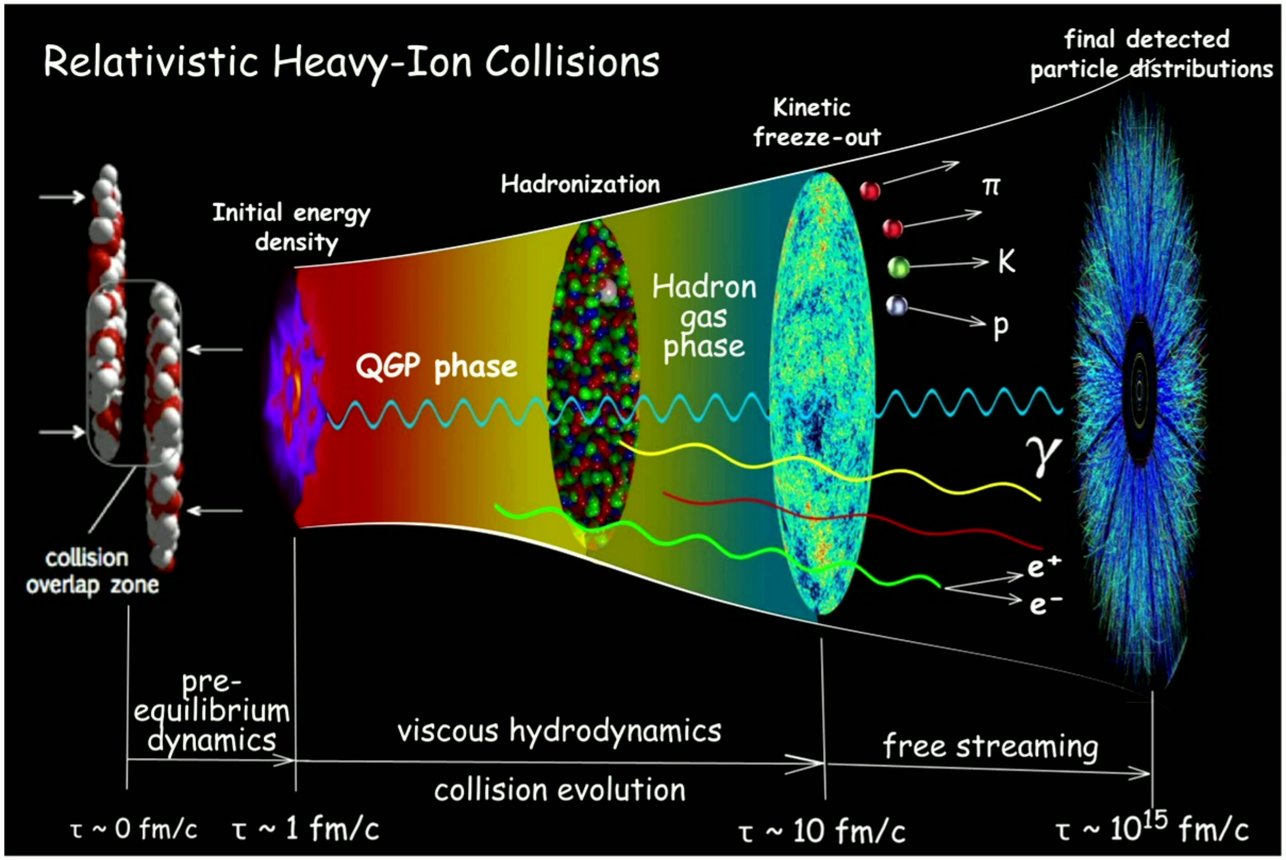
Malena Tejeda-Yeomans

Facultad de Ciencias, Universidad de Colima
Simons Emmy Noether Fellow, Perimeter Institute



Work done with
A. Ayala, I. Domínguez, I. Maldonado, Phys.Rev.C 105 (2022).
J. Castaño, L.A. Hernández, A.J. Mizher, R. Zamora, 2209.09364 [hep-ph].
B. Almeida, J. Cobos, S. Hernández, L.A. Hernández, A. Raya, Eur.Phys.J.A 58 (2022).


"Signals from the hot
and whirly matter
produced in heavy-
ion collisions"
by
Malena
for
Lucca
HIC&QGP
STRANGENESS
THINGS



C. Shen, U. Heinz, Nuclear Physics News Vol. 25, issue 2, 2015. arXiv:1507.01558 [nucl-th]

Outline

Why do Λs and $\bar{\Lambda}$s have such different polarization?

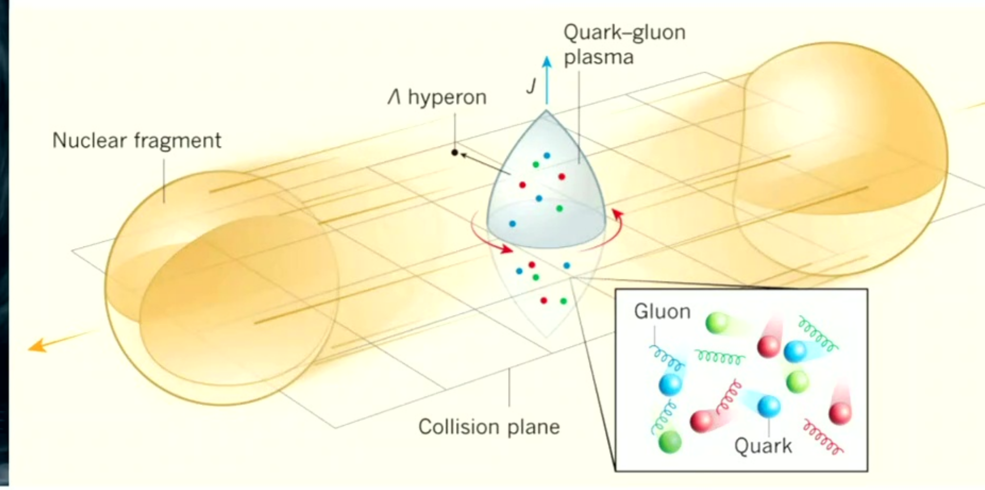
What's up with those extra "early" photons?

Where is that critical end-point?

Final remarks

Hot, dense, whirly QCD matter in HIC

STAR Collaboration, Nature 548 (2017)

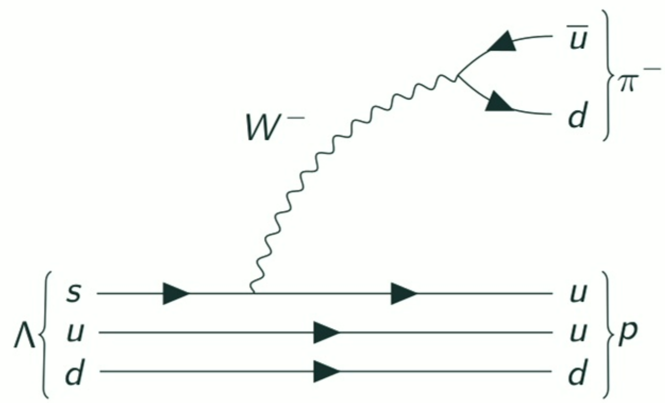


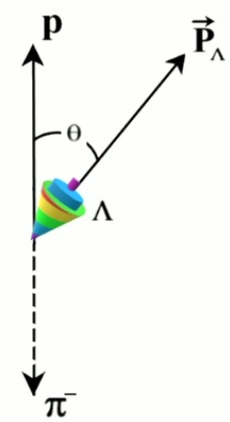
Non-central collisions have large angular momentum $L \sim 10^5 \hbar$.
Shear forces in initial condition introduce vorticity to the QGP.

Spin-orbit coupling: spin alignment, or polarization, along the direction of the vorticity - on average - parallel to J.

Good whirly-ness probe in HICs: Λ hyperon

- Particle Data Group:
  - $m_\Lambda = 1115.683 \pm 0.006$ MeV
  - $\tau = 2.632 \pm 0.020 \times 10^{-10}$ s ($\sim$ 7.9 cm at c)
  - $\Gamma_1(\Lambda \to p\pi^-) = (63.9 \pm 0.5)\%$
  - $\Gamma_2(\Lambda \to n\pi^0) = (35.8 \pm 0.5)\%$
- Advantages:
  - lightest hyperon with s content
  - long lifetime: good for fiducial track/reco
  - parity-violating weak decay - sort of self-analyzing
  - decay dist not-isotropic: p going off in the direction of Λ spin

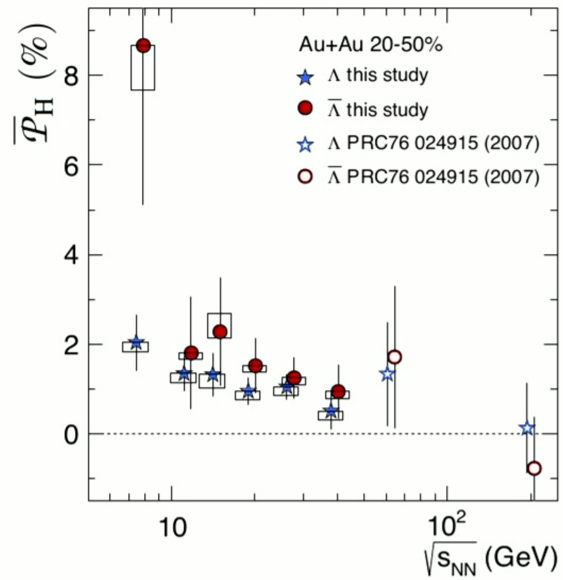




Measurement

Vorticity and Λ global polarization

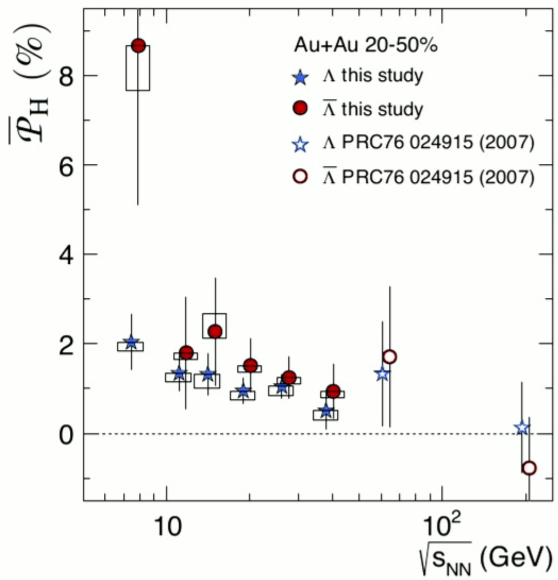
Spin-orbit coupling: spin alignment, or polarization, along the direction of the vorticity - on average - parallel to $\hat{J} = \hat{\mathrm{b}} \times \hat{\mathrm{p}}_{beam}$

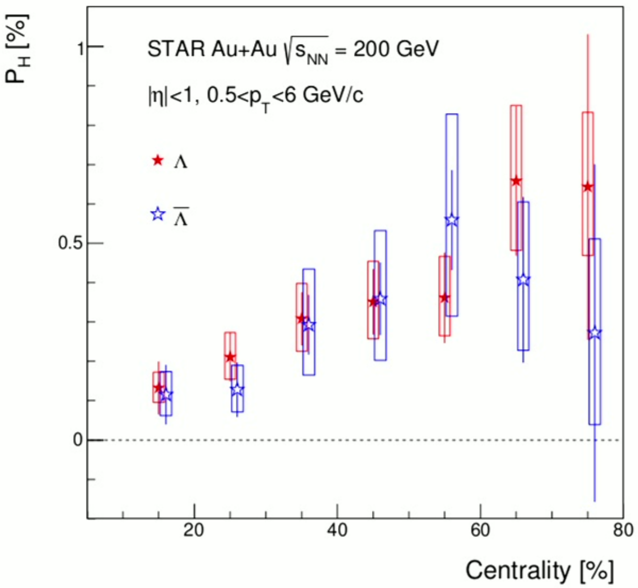


STAR Collaboration, Nature 548 (2017); Phys.Rev.C 98 (2018) 014910

Vorticity and Λ global polarization

Meassurement of angular momentum retained at mid-rapidity. In most central collisions: no initial angular momentum, no polarization.





STAR Collaboration, Nature 548 (2017); Phys.Rev.C 98 (2018) 014910

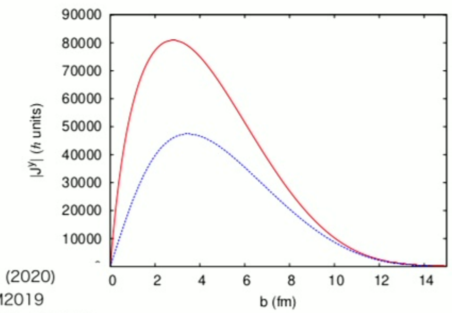
Thermal and kinematic vorticity

F. Becattini et. al. Eur.Phys.J.C 75 (2015), C 78 (2018)

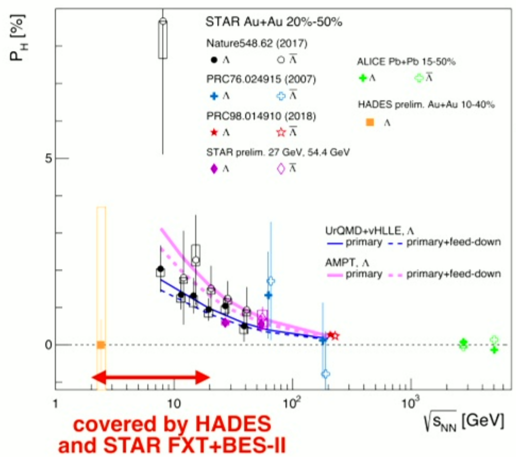
HIC simulations

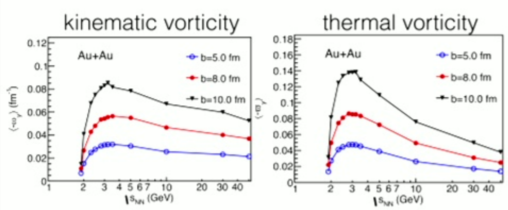
$\beta_\mu = \beta u_\mu,\ u_\mu = \gamma(1, \vec{v}),\ \beta = 1/T$

$$\overline{\omega}_{\mu\nu} = \frac{1}{2}\left(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu\right) \qquad \omega_{\mu\nu} = \frac{1}{2}\left(\partial_\nu u_\mu - \partial_\mu u_\nu\right)$$



ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019





Energy dependence of kinematic and thermal vorticity with UrQMD
X.-G. Deng et al., arXiv:2001.01371

HADES: 2.0-2.4 GeV
STAR FXT: 3-7.7 GeV
STAR BES II: 7.7-19 GeV

$b \sim 5 - 10$ collisions, favor the development of a larger thermal vorticity
$\rightarrow$ study non-central collisions

Other models

T. Niida, INT 20-1c, Chirality and Criticality: Novel Phenomena in HIC

Thermal and kinematic vorticity

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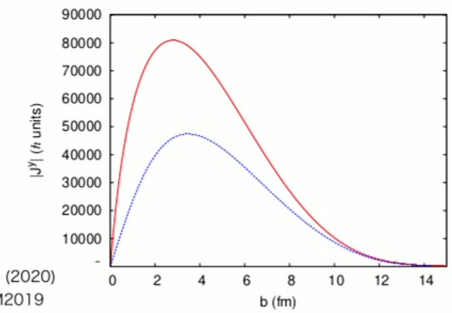

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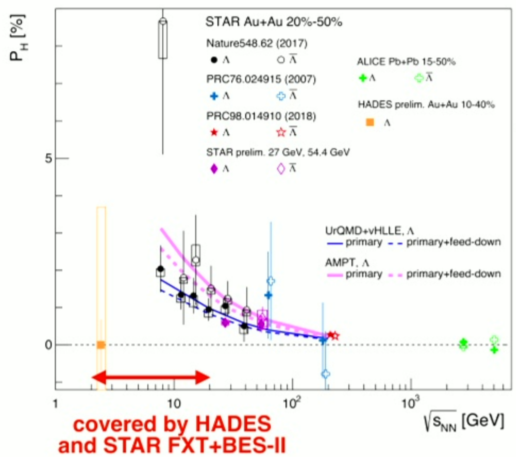

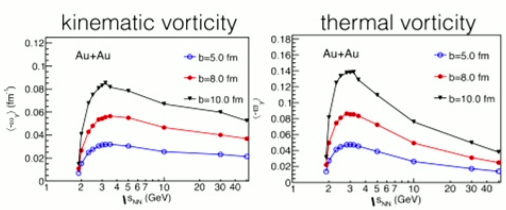

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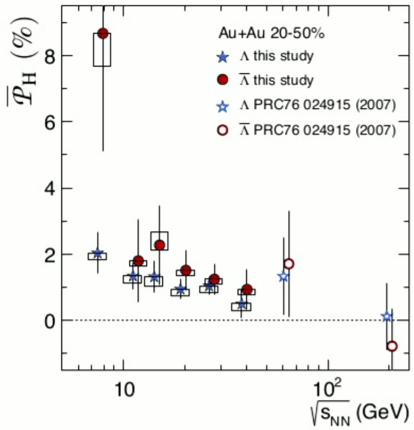
T. Niida, INT 20-1c, Chirality and Criticality: Novel Phenomena in HIC

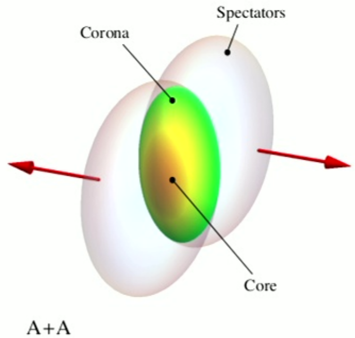
Core meets corona, it rises and it falls.



✓ centrality dependent model for Λ and $\bar{\Lambda}$ production in heavy-ion collisions

+

✓ relaxation time for quark spin-alignment and thermal vorticity in the hot/dense QGP

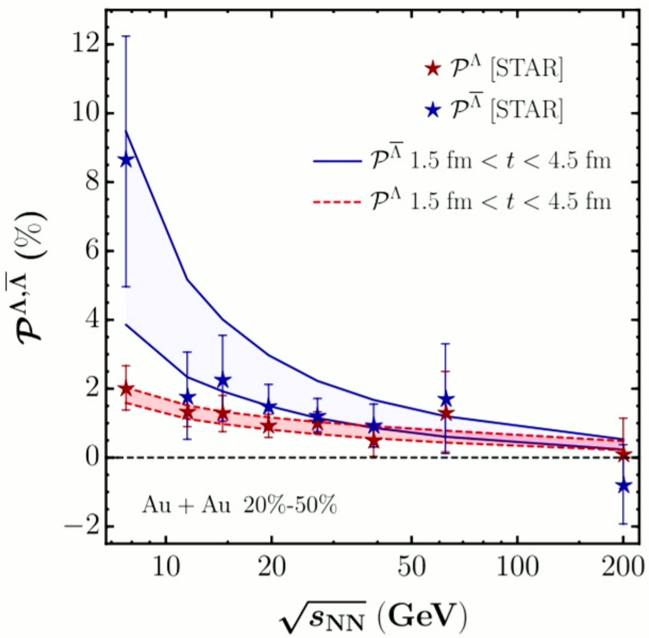


Core meets corona: A two-component source to explain Λ and $\bar{\Lambda}$ global polarization in semi-central heavy-ion collisions. A. Ayala, M. Ayala, E. Cuautle, I. Dominguez, M. Fontaine, I. Maldonado, E. Moreno, P. Nieto, M. Rodríguez, J. Salinas, METY, L. Valenzuela. **Phys.Lett.B 810 (2020); 2003.13757 [hep-ph]**

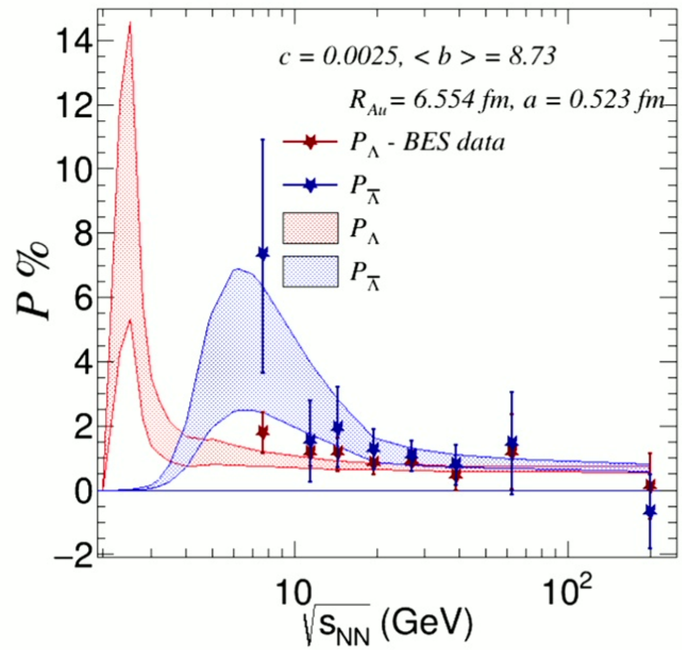
The rise and fall of Λ and $\bar{\Lambda}$ global polarization in semi-central heavy-ion collisions at HADES, NICA and RHIC energies from the core-corona model. A. Ayala, I. Dominguez, I. Maldonado and METY. **Phys.Rev.C 105 (2022); 2106.14379 [hep-ph]**

Results: Λ y $\bar{\Lambda}$ global polarization in Au+Au at RHIC-BES

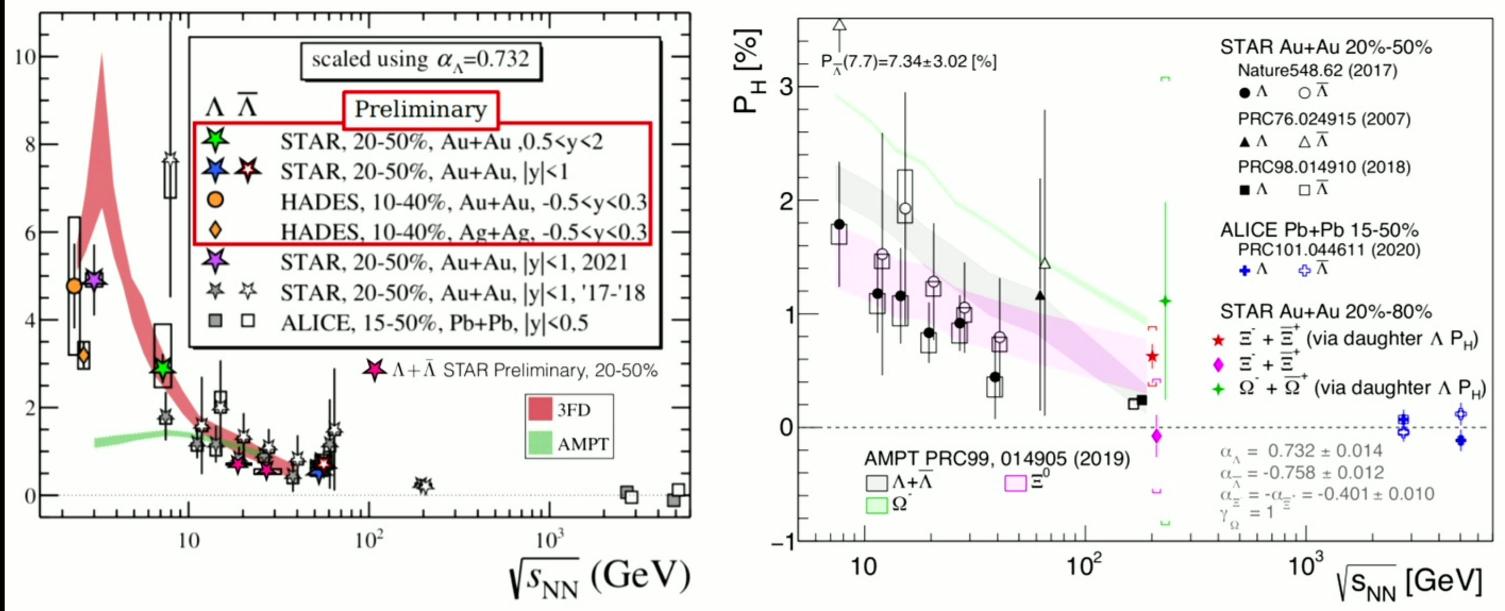
How it started (2020)



How it is going (2022)



Current experimental status



J. Adams (STAR), QM 2022; J. Adam et al. (STAR), Phys. Rev. Lett. 126, 162301 (2021)

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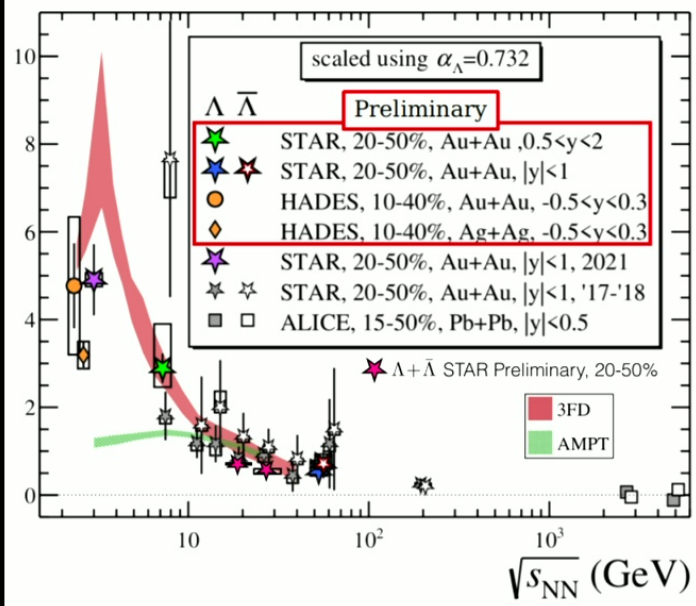
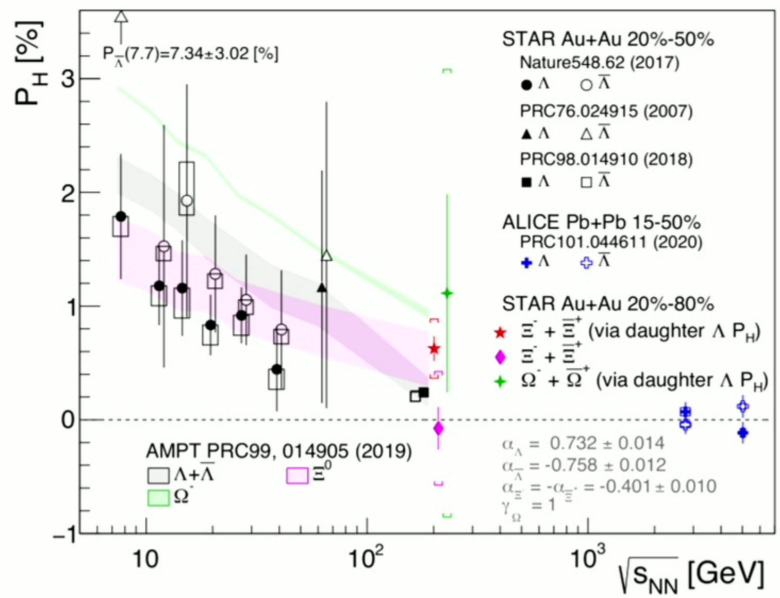
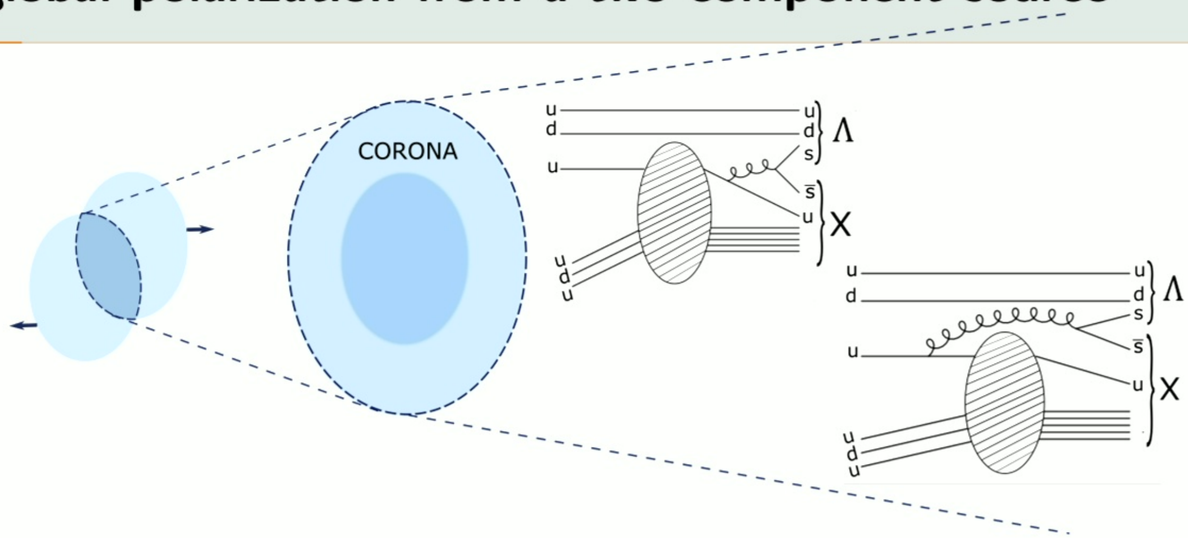




J. Adams (STAR), QM 2022; J. Adam et al. (STAR), Phys. Rev. Lett. 126, 162301 (2021)

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

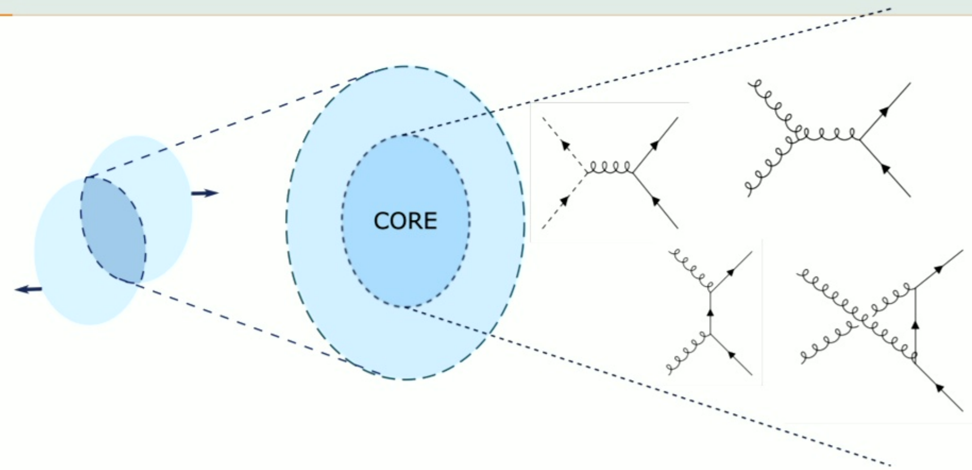


Measurement of Λ pol in inclusive h+N, N-N and N+A (late 70s): Λ spin is that of s-quark (ud-diquark in spin-isospin singlet)

- Lund model: semiclassical model, color dipole field between the diquark of incoming proton stretches and $s\bar{s}$ pair produced in this field.

- DeGrand-Miettinen model: Thomas precession effect in the quark recombination process, s-quark $\vec{v}$ is not parallel to the change of momentum induced by the combination. Spin-orbit interaction term $\vec{s} \cdot \vec{\omega_T}$ where $\vec{\omega_T} \propto \vec{F} \times \vec{v}$
- Gluon bremsstrahlung mechanism: polarized gluon transfers polarization to $s\bar{s}$ pair. A. D. Panagiotou, Int. J. Mod. Phys. A **5** (1990).

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source



Abundance of qs over $\bar{q}$ in HICs leads to a suppression of $\bar{u}$ and $\bar{d}$ and relative enhancement of $\bar{s}$ (not present in the colliding nuclei). So some of the numerous $\bar{s}$ may enter into (qqs) or (qss) anti-baryons.

Rafelski and Hagedorn, CERN-TH-2969 (1980); Rafelski, Phys. Rept. 88, 331 (1982); Rafelski, South Afr. J. Phys. 6, 37-43 (1983)

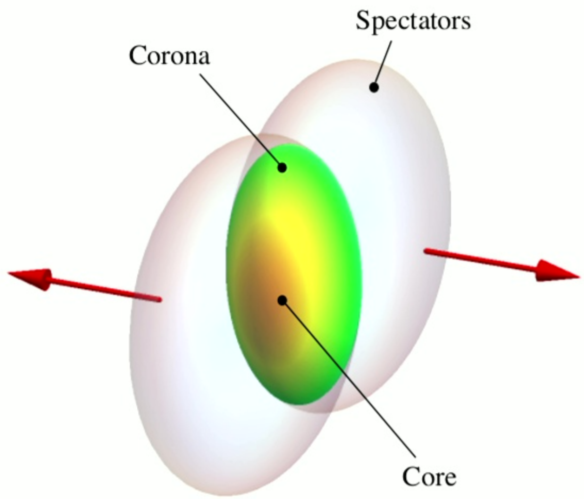
Strangeness reaches chemical equilibrium during the short lifetime of a QGP: LO $q\bar{q} \to s\bar{s}$, $gg \to s\bar{s}$, crucial to include gluon fusion

J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982) [erratum: Phys. Rev. Lett. 56, 2334 (1986)].

Strangeness Things

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

Non-central heavy-ion collision of a symmetric system:
$\Lambda/\bar{\Lambda}$s from core via QGP processes
$\Lambda/\bar{\Lambda}$s from corona via p+p reactions



$$N_\Lambda = \overbrace{N_{\Lambda\,\text{QGP}}}^{core} + \overbrace{N_{\Lambda\,\text{REC}}}^{corona}$$

Choose reference direction:

baryon mom $\rightarrow$ $||$ pol

perp production plane $\rightarrow$ $\perp$ pol

Polarization asymmetry -spin alignment asymmetry- of any baryon species produced in high-energy reactions

$$\mathcal{P} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$N^\uparrow$ and $N^\downarrow$ baryons with spin aligned and opposite to a given direction.

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

Assuming,

$$N_\Lambda = \overbrace{N_{\Lambda\,\mathrm{QGP}}}^{core} + \overbrace{N_{\Lambda\,\mathrm{REC}}}^{corona}$$

$$N_{\bar\Lambda} = \overbrace{N_{\bar\Lambda_{QGP}}}^{core} + \overbrace{N_{\bar\Lambda_{REC}}}^{corona}$$

$$\mathcal{P} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

The contribution to the total global polarization is

$$\mathcal{P}^\Lambda = \frac{\left(\mathcal{P}^\Lambda_{REC} + \frac{N^\uparrow_{\Lambda_{QGP}} - N^\downarrow_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}\right)}{\left(1 + \frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}\right)}$$

$$\mathcal{P}^{\bar\Lambda} = \frac{\left(\mathcal{P}^{\bar\Lambda}_{REC} + \frac{N^\uparrow_{\bar\Lambda_{QGP}} - N^\downarrow_{\bar\Lambda_{QGP}}}{N_{\bar\Lambda_{REC}}}\right)}{\left(1 + \frac{N_{\bar\Lambda_{QGP}}}{N_{\bar\Lambda_{REC}}}\right)}$$

where contribution to the polarization from Λs ($\bar\Lambda$s) produced in the corona is

$$\mathcal{P}^\Lambda_{REC} = \frac{N^\uparrow_{\Lambda_{REC}} - N^\downarrow_{\Lambda_{REC}}}{N^\uparrow_{\Lambda_{REC}} + N^\downarrow_{\Lambda_{REC}}}, \qquad \mathcal{P}^{\bar\Lambda}_{REC} = \frac{N^\uparrow_{\bar\Lambda_{REC}} - N^\downarrow_{\bar\Lambda_{REC}}}{N^\uparrow_{\bar\Lambda_{REC}} + N^\downarrow_{\bar\Lambda_{REC}}}.$$

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

How do we model polarization in the corona?

$$\mathcal{P}^{\Lambda}_{REC} = \mathcal{P}^{\bar{\Lambda}}_{REC} = 0$$

Reactions in cold nuclear matter are less efficient to couple spin with angular momentum. So, the average global polarization for Λs and $\overline{\Lambda}$s from the corona, is negligible.

They are being produced in the corona in abundance, but cannot couple with total angular momentum of system.

Improvements

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

How do we model polarization in the core?

$$\begin{aligned} N^{\uparrow}_{\Lambda_{QGP}} - N^{\downarrow}_{\Lambda_{QGP}} &= z N_{\Lambda_{QGP}} \\ N^{\uparrow}_{\bar{\Lambda}_{QGP}} - N^{\downarrow}_{\bar{\Lambda}_{QGP}} &= \bar{z} N_{\bar{\Lambda}_{QGP}} \end{aligned}$$

Core reactions are more efficient to align particle spin to global angular momentum. Identify *intrinsic* global Λ and $\overline{\Lambda}$ polarizations.

At intermediate to large impact parameters, an amplification effect for the $\overline{\Lambda}$ polarization can occur in spite of $z > \bar{z}$, and this amplification is more prominent for lower collision energies.

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

How likely it is to create $\overline{\Lambda}$s both in the core and in the corona?

$$N_{\bar{\Lambda}_{REC}} = wN_{\Lambda_{REC}}$$
$$N_{\bar{\Lambda}_{QGP}} = w'N_{\Lambda_{QGP}}$$

In the corona, production is through N+N collisions, so use p+p data to extract w.

In the core, for QGP created at high $\sqrt{s_{NN}}$, efficient processes might make it equally as easy to produce Λs as $\overline{\Lambda}$s, given that in this region qs and $\bar{q}$s are freely available and $(\bar{u}, \bar{d}, \bar{s})$ might find each other as easily as (u, d, s)?

At HADES, NICA and RHIC energies, μ and T of the system, matters.

So, in the core, w' will be calculated along the freezeout trajectory, using equilibrium distributions.

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

$$\mathcal{P}^{\Lambda}_{REC} = \mathcal{P}^{\bar{\Lambda}}_{REC} = 0$$

$$\begin{aligned} N^{\uparrow}_{\Lambda_{QGP}} - N^{\downarrow}_{\Lambda_{QGP}} &= zN_{\Lambda_{QGP}} \\ N^{\uparrow}_{\bar{\Lambda}_{QGP}} - N^{\downarrow}_{\bar{\Lambda}_{QGP}} &= \bar{z}N_{\bar{\Lambda}_{QGP}} \end{aligned}$$

$$\begin{aligned} N_{\bar{\Lambda}_{REC}} &= wN_{\Lambda_{REC}} \\ N_{\bar{\Lambda}_{QGP}} &= w'N_{\Lambda_{QGP}} \end{aligned}$$

Λ and $\overline{\Lambda}$ global polarization

$$\mathcal{P}^{\Lambda} = \frac{z\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1+\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$

$$\mathcal{P}^{\bar{\Lambda}} = \frac{\bar{z}\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1+\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$

So, global polarization depends on w, w', z, $\bar{z}$ and the ratio $\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}$, which can be either calculated or extracted from data.

The ratio $w' = N_{\bar{\Lambda}_{QGP}}/N_{\Lambda_{QGP}}$ from equilibrium distributions

At finite $\mu = \mu_B/3$, bias in the production of $\overline{\Lambda}$s vs Λs.

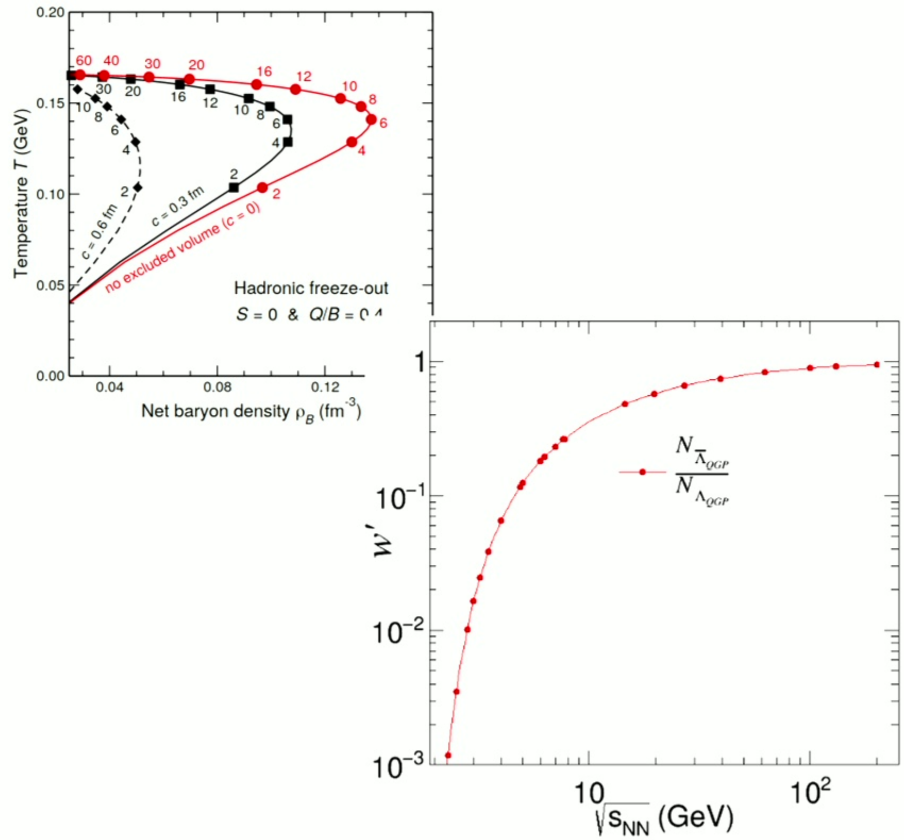
$$w' = \frac{e^{(m_s-\mu)/T}+1}{e^{(m_s+\mu)/T}+1}$$

where $m_s = 100$ MeV and

$$T(\mu_B) = 166 - 139\mu_B^2 - 53\mu_B^4$$

$$\mu_B(\sqrt{s_{NN}}) = \frac{1308}{1000 + 0.273\sqrt{s_{NN}}}$$

Randrup and Cleymans, PRC 74 (2006) and EPJ 52 (2016)

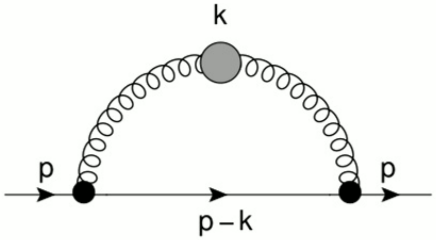


Quark-spin alignment

QCD plasma in thermal equilibrium: temperature T, quark chemical potential μ_q.

The interaction rate Γ of a quark with four-momentum $P = (p_0, \vec{p})$ can be expressed in terms of the quark self-energy Σ as

$$\Gamma(p_0) = \widetilde{f}(p_0 - \mu_q)\mathrm{Tr}\left\{\gamma^0 \ \ \mathrm{Im}\Sigma\right\},$$



with $\widetilde{f}(p_0 - \mu_q)$ being the Fermi-Dirac distribution.

The interaction between the thermal vorticity and the quark spin is modeled by means of an effective vertex

$$\lambda_a^\mu = g\frac{\sigma^{\alpha\beta}}{2}\overline{\omega}_{\alpha\beta}\gamma^\mu t_a, \qquad \text{where } \overline{\omega}_{\mu\nu} = \frac{1}{2}\left(\partial_\nu\beta_\mu - \partial_\mu\beta_\nu\right)$$

and $\sigma^{\alpha\beta} = \frac{i}{2}[\gamma^\alpha, \gamma^\beta]$ is the quark spin operator, t_a are the color matrices in the fundamental representation and $\beta_\mu = u_\mu(x)/T(x)$ with $u_\mu(x)$ the local fluid four-velocity and $T(x)$ the local temperature.

1Lcalc

The ratio $w' = N_{\bar{\Lambda}_{QGP}}/N_{\Lambda_{QGP}}$ from equilibrium distributions

At finite $\mu = \mu_B/3$, bias in the production of $\overline{\Lambda}$s vs Λs.

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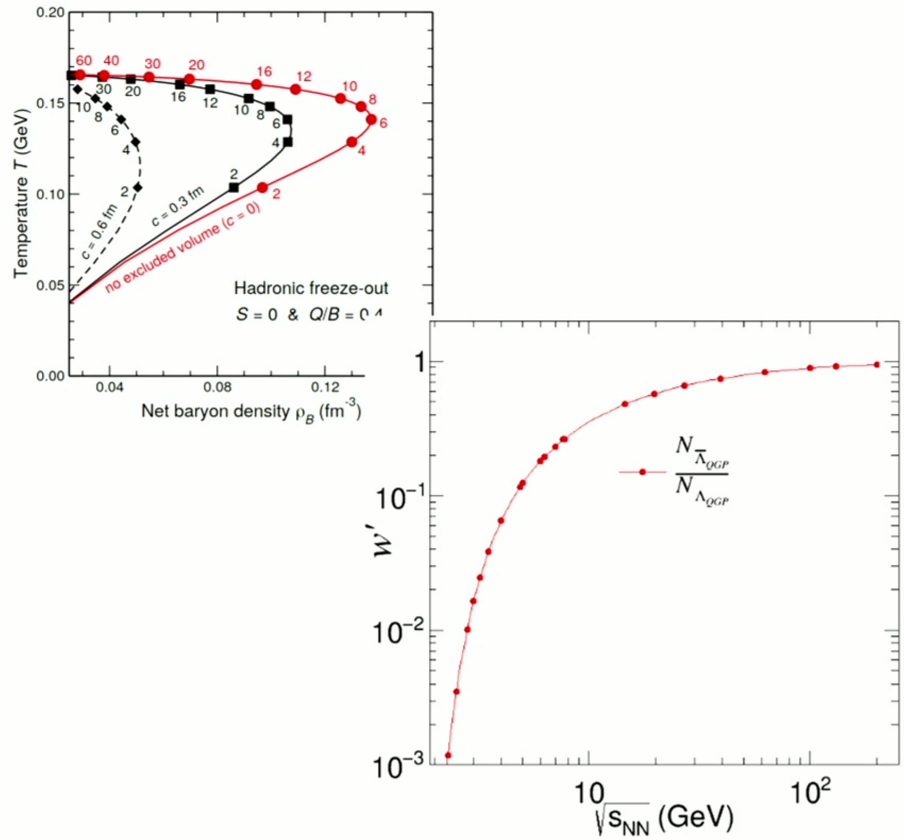
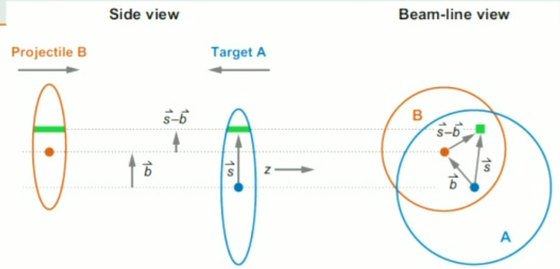
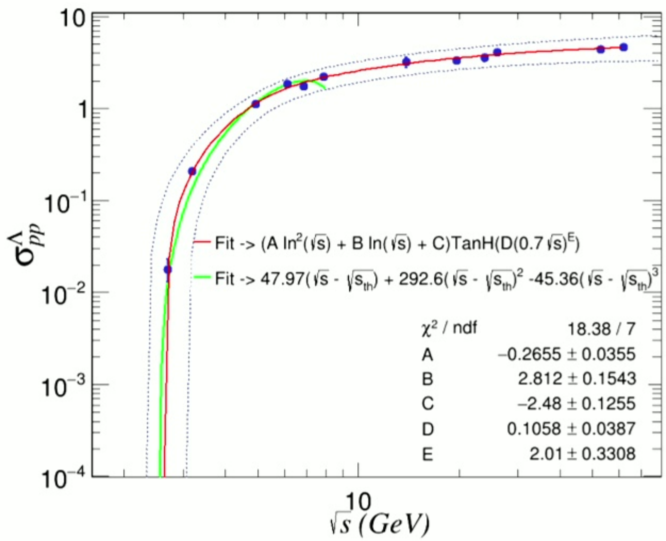


Λ production: core vs corona, $N_{\Lambda_{QGP}}/N_{\Lambda_{REC}}$



Michael L. Miller et. al. Ann.Rev.Nucl.Part.Sci.57 (2007)



$$n_p(\mathbf{s},\mathbf{b}) = T_A(\mathbf{s})[1 - e^{-\sigma_{NN} T_B(\mathbf{s}-\mathbf{b})}]$$
$$+ T_B(\mathbf{s}-\mathbf{b})[1 - e^{-\sigma_{NN} T_A(\mathbf{s})}]$$

$$T_A(z,s) = \int_{-\infty}^{\infty} \rho_A(z,\mathbf{s}) dz$$

$$\rho_A(\mathbf{s}) = \frac{\rho_0}{1 + e^{(r-R_A)/a}}$$

Number of Λs from the corona

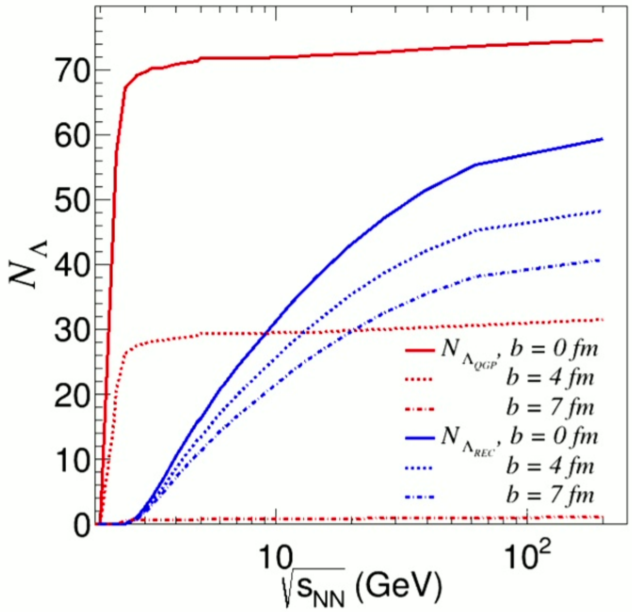
$$N_{\Lambda_{REC}} = \sigma^{\Lambda}_{NN} \int T_B T_A \theta[n_c - n_p(\mathbf{s},\mathbf{b})] d^2 s$$

N_{QGP}

Fits from a few to almost 70 GeV

Gazdzicki and D. Rohrich, ZPC71, 55 (1996); Blobelet et al. NPB69, 454 (1974); Chapman et al PLB47, 465(1973); Bricket et al, NPB164, 1 (1980); Erhan et al PLB 85, 447 (1979); Fickinger et al Phys. Rev.125 (1962); Adamczewski-Muschet (HADES), PRC95, 015207 (2017); Aahlin et al Phys. Scripta21, 12(1980); Boeggildet et al NPB57, 77 (1973); Bogolyubskyet et al. Sov. J. Nucl. Phys.50, 424(1989); Jaeger, et al PRD11, 2405; Shenget al., PRD11, 1733 (1975); Asaiet al.(EHS RCBC), ZPC27, 11 (1985); Drijardet al. ZPC12, 217 (1982).

Λ production: core vs corona, $N_{\Lambda_{QGP}}/N_{\Lambda_{REC}}$



$N_{\Lambda_{QGP}}$ and $N_{\Lambda_{REC}}$ for impact parameters $b = 0, 4, 7$ fm.

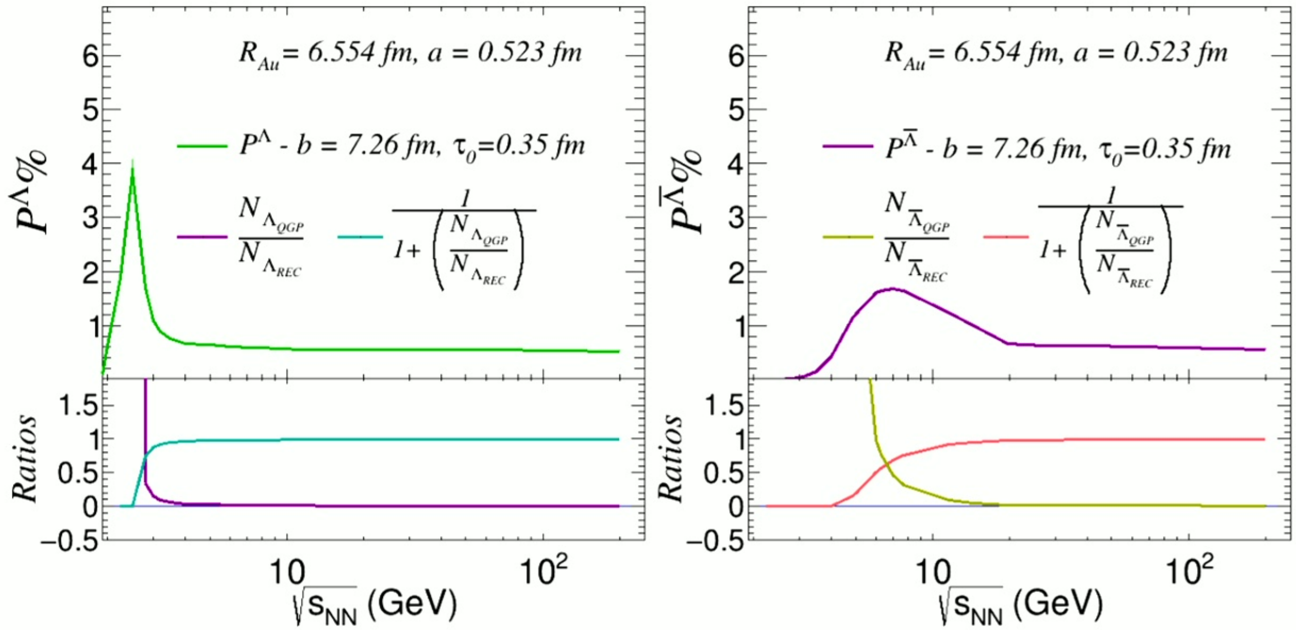
- Small b, Λ production is dominated by core.
- Large b, Λ production is dominated by the corona.
  $\rightarrow$ relevant for vorticity and polarization studies

Recall core-corona model has a critical density of participants n_c above which you can produce the QGP in the core. For peripheral collisions - even for larger energies - n_c is hard to reach.

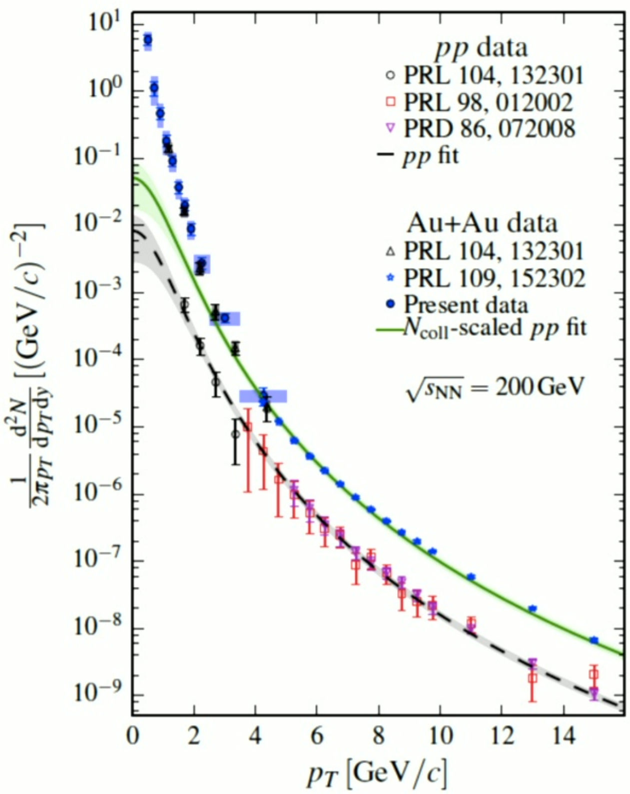
More on n_c

Results: ratio of global to intrinsic polarization

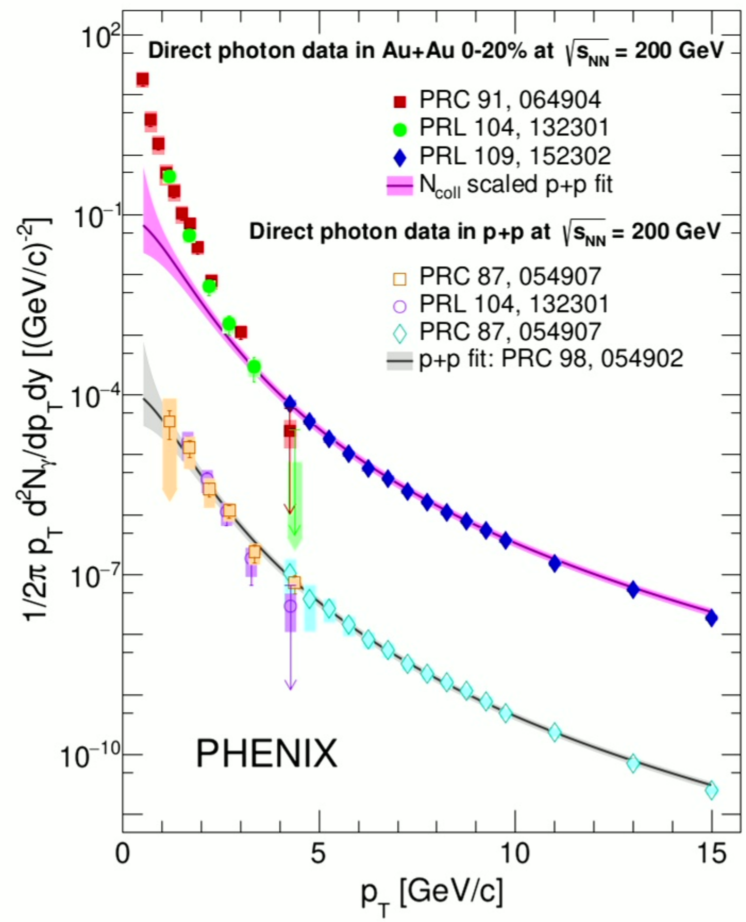
$$\frac{\mathcal{P}^{\Lambda}}{z} = \frac{\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1 + \frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}} \qquad \frac{\mathcal{P}^{\bar{\Lambda}}}{\bar{z}} = \frac{\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1 + \left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$



PHENIX@BNL γ-yield

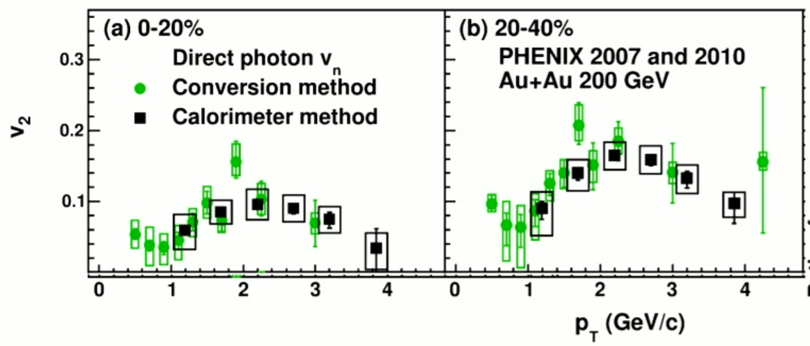


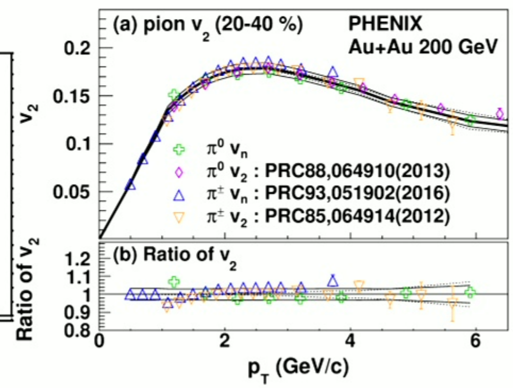
PRC 91 (2015)

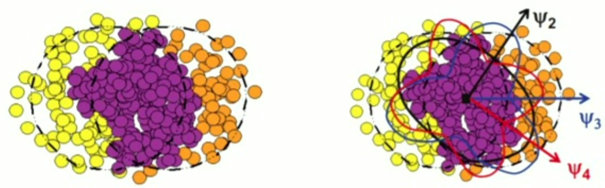


arXiv:2203.12354 [nucl-ex] (2022) ALL

Azimuthal asymmetries as large as those of hadrons







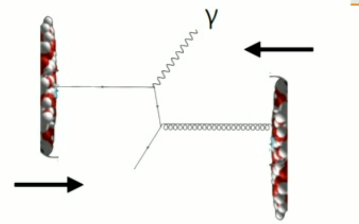
$$\frac{dN}{d\phi} \propto 1 + \sum_n 2 v_n \cos n(\phi - \Psi_n)$$

For "high" p_T: $v_2 \sim 0$ consistent with hard scattering source

For "low" p_T: $v_2 \sim 0.15 - 0.2$ similar to hadrons

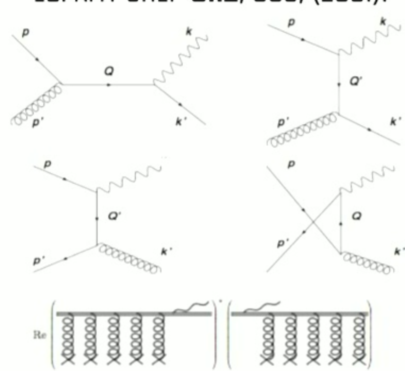
PHENIX@BNL, PRC 94 (2016), 1509.07758 [nucl-ex]

Direct photons: prompt + thermal + non-cocktail



Prompt Photons

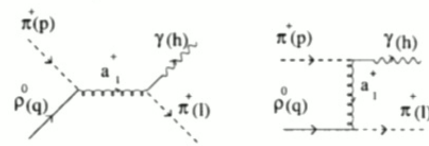
LO: AMY JHEP **0112**, 009, (2001).



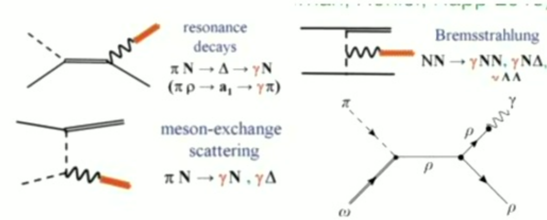
NLO: J. Ghiglieri et al., JHEP **1305**, 010 (2013).

Thermal Photons: Produced in QGP stage.

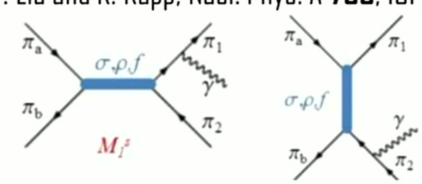
TRG, Phys. Rev. C **69**, 014903 (2004).



R. Rapp and J. Wambach, Eur. Phys. J. A **6**, 415 (1999).

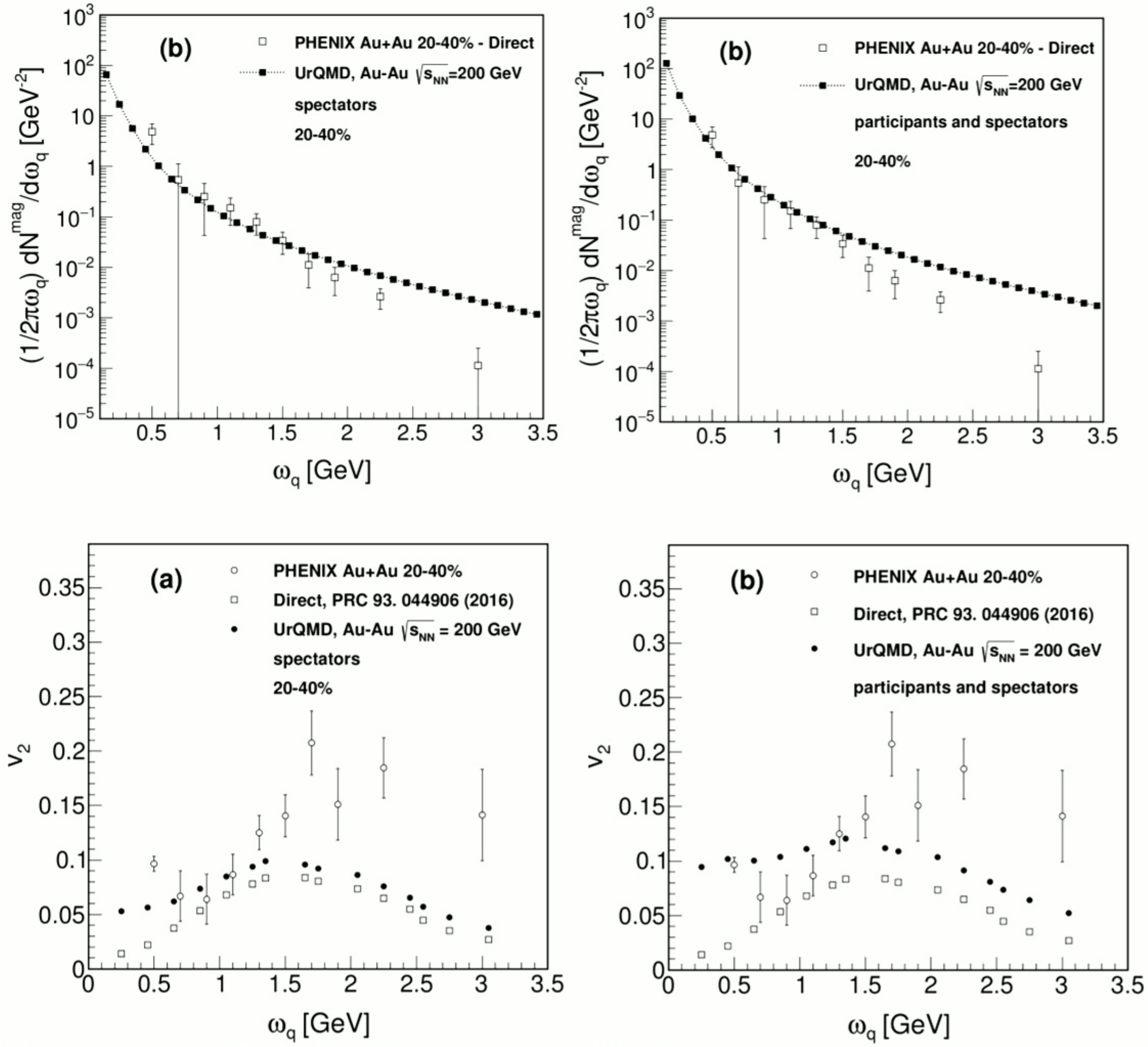


W. Liu and R. Rapp, Nucl. Phys. A **796**, 101 (2007).



Non-Cocktail: Early hadronic decay.

5


(b)
PHENIX Au+Au 20-40% - Direct
UrQMD, Au-Au $\sqrt{s_{NN}}$=200 GeV
spectators
20-40%
$(1/2\pi\omega_q)\ dN^{mag}/d\omega_q\ [GeV^{-2}]$
ω_q [GeV]
(b)
PHENIX Au+Au 20-40% - Direct
UrQMD, Au-Au $\sqrt{s_{NN}}$=200 GeV
participants and spectators
20-40%
$(1/2\pi\omega_q)\ dN^{mag}/d\omega_q\ [GeV^{-2}]$
ω_q [GeV]
(a)
PHENIX Au+Au 20-40%
Direct, PRC 93. 044906 (2016)
UrQMD, Au-Au $\sqrt{s_{NN}}$ = 200 GeV
spectators
20-40%
v_2
ω_q [GeV]
(b)
PHENIX Au+Au 20-40%
Direct, PRC 93. 044906 (2016)
UrQMD, Au-Au $\sqrt{s_{NN}}$ = 200 GeV
participants and spectators
v_2
ω_q [GeV]

Signals from the hot and whirly matter in HIC

- Λs and $\bar{\Lambda}$s have such different -global- polarization and huge values for lower collision energies.
- photon excess in the low p_T spectra with v_2 as large as that of hadrons.
- large fluctuations in the net-proton charge at low collision energies.

QCD, effective models, magnetic fields, vorticity, viscosity, etc.

NOW:

How can I learn from connections between thermal QFT amplitudes and classical amplitudes? $\rightarrow$ scattering amplitudes approach to HTL/kinetic theory

How can I bootstrap info for critical studies or polarization studies in HIC?