QCD in Heavy-Ion Physics

Helen Caines - Yale University
Many phases and phase transitions in the early universe

So far only QGP-hadron phase transition can be recreated and studied in lab
Exploring the phase diagram of QCD

By changing beam energy we alter initial temperature and $\mu_B$

Quark-Gluon Plasma

Hadron Gas

Nuclear Superconductor

Vacuum

Critical Point?

Temperature (MeV)

Baryon Chemical Potential $\mu_B$ (MeV)

Lattice Gauge Theory - increasing accuracy at $\mu_B=0$

$T_c = 154(9) \text{ MeV}$

$\varepsilon_c = 0.18-0.5 \text{ GeV/fm}^3 = (1.2-3.3) \rho_{\text{nuclear}}$
Exploring the phase diagram

By changing beam energy we alter initial temperature and $\mu_B$

Calculations disfavor C.P. in region $\mu_B/T < 2$ and $T/T_C(\mu_B=0) > 0.9$

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Early conditions: Temperature

Initial temperature well above $T_c$ even at $\sqrt{s_{NN}} = 39$ GeV

$T_{eff}$ vs. collision energy $\sqrt{s_{NN}}$

- **PHENIX** $\sqrt{s_{NN}} = 200$ GeV, 0-94%
  - Fit range $p_T \in [1.0 \text{ GeV}, 5.0 \text{ GeV}]
  - Cu+Cu $T_{eff} = 288 \pm 49 \pm 50$ MeV/c

- **PHENIX** $\sqrt{s_{NN}} = 62.4$ GeV, 0-86%
  - Fit range $p_T \in [0.5 \text{ GeV}, 2.0 \text{ GeV}]
  - Au+Au $T_{eff} = 211 \pm 24 \pm 44$ MeV/c

- **PHENIX** $\sqrt{s_{NN}} = 39$ GeV, 0-86%
  - Fit range $p_T \in [0.5 \text{ GeV}, 2.0 \text{ GeV}]
  - Au+Au $T_{eff} = 177 \pm 31 \pm 68$ MeV/c

- **ALICE** $\sqrt{s_{NN}} = 2760$ GeV, 0-20%
  - Fit range $p_T \in [0.9 \text{ GeV}, 2.1 \text{ GeV}]
  - Pb+Pb $T_{eff} = 297 \pm 12 \pm 41$ MeV/c

- **PHENIX** $\sqrt{s_{NN}} = 200$ GeV, 0-92%
  - Fit range $p_T \in [0.6 \text{ GeV}, 2.0 \text{ GeV}]
  - Au+Au $T_{eff} = 242 \pm 28 \pm 7$ MeV/c

- **PHENIX** $\sqrt{s_{NN}} = 62.4$ GeV, 0-86%
  - Fit range $p_T \in [0.5 \text{ GeV}, 2.0 \text{ GeV}]
  - Cu+Cu: $\gamma$ prompt subtracted
  - Au+Au: $\gamma$ prompt unsubtracted

- **PHENIX** $\sqrt{s_{NN}} = 39$ GeV, 0-86%
  - Fit range $p_T \in [0.5 \text{ GeV}, 2.0 \text{ GeV}]
  - Au+Au: $\gamma$ prompt unsubtracted

$T_c$ from direct photon $p_T$ spectra
Searching for a Critical Point

Critical Points:
- divergence of susceptibilities
e.g. magnetism transitions
- divergence of correlation lengths
e.g. critical opalescence

Lattice QCD:
Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point
Searching for a Critical Point

Critical Points:
- divergence of susceptibilities
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  e.g. critical opalescence

Lattice QCD:
Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point

Divergences of conserved quantities may survive in the final state
⇒ non-gaussian fluctuations of net-baryon density

Kurtosis x Variance$^2 \sim \chi^{(4)}/\chi^{(2)}$
**Presence of Critical Point?**

Correlation lengths diverge

→ Net-p $\kappa \sigma^2$ diverge

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**Peripheral collisions:** smooth trend

- HADES: Preliminary
  - (Net-)protons
    - HADES 0-10 %
    - HADES 30-40 %
  - STAR 0-5 %
  - STAR 30-40 %

NB: Different $y$ and $p_T$ ranges
Presence of Critical Point?

Correlation lengths diverge
→ Net-p κσ² diverge

Peripheral collisions:
smooth trend
Top 5% central collisions:
Non-monotonic behavior

NB: Different y and p_T ranges
**Presence of Critical Point?**

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→ Net-p $\kappa \sigma^2$ diverge

**Peripheral collisions:**
- smooth trend
**Top 5% central collisions:**
- Non-monotonic behavior

Hints of Critical fluctuations

NB: Different $y$ and $p_T$ ranges

Net-$p$ $\kappa \sigma^2$ diverge
Presence of Critical Point?

Correlation lengths diverge

→ Net-p $\kappa \sigma^2$ diverge

Peripheral collisions: smooth trend

Top 5% central collisions: Non-monotonic behavior

Hadron gas model (UrQMD) no CP: shows suppression at lower energies - baryon number conservation

Hints of Critical fluctuations
Intermediate summary

A lot happening around 20 GeV - hard to believe its multiple different causes

High statistics exploration of QCD phase diagram and its key features is about to begin

New data from FAIR, NICA, RHIC and SPS just around the corner
Significantly extended detection capabilities compared to existing data

Strong theoretical interest focussed in BEST and HICforFAIR, increased number of focussed workshops

STAR BES-II (2019-2020) Turn trends and features into definitive conclusions
Using “hard” particles as probes

‘Hard’ processes have a large scale in calculation → pQCD applicable:

- **high** momentum transfer $Q^2$
- **high** transverse momentum $p_T$
- **high** mass $m$ (N.B.: since $m\gg0$ heavy quark production is ‘hard’ process even at low $p_T$)

Early production in parton-parton scatterings with large $Q^2$
Using “hard” particles as probes

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Early production in parton-parton scatterings with large $Q^2$

Direct interaction with partonic phases of the reaction

i.e. a calibrated probe

Look for attenuation/absorption/modification of probe
Jet quenching at 5 TeV

When comparing hadrons and jets note that:

A very high $p_T$ hadron comes from a parton that fragmented very hard (low mass) and that consequently suffered less quenching.

Colorless objects should not interact with colored QGP

no suppression

Not significantly different to values at 2.76 TeV

Strong suppression up to $p_T \sim 1$ TeV

$R_{AA}(p_T) = \frac{\text{Yield}(A + A)}{\text{Yield}(p + p) \times \langle N_{\text{coll}} \rangle}$
Jet quenching at 5 TeV

\[ R_{AA}(p_T) = \frac{\text{Yield}(A+A)}{\text{Yield}(p+p) \times N_{\text{coll}}} \]

- Colorless objects should not interact with colored QGP
- No suppression

Pb+Pb 5.02 TeV, 0.49 nb⁻¹
pp 5.02 TeV, 25 pb⁻¹

Strong suppression up to \( p_T \sim 1 \) TeV

Compensating effects of higher \( E_{\text{loss}} \), flatter \( p_T \) spectrum, q/g differences

Not significantly different to values at 2.76 TeV
Charm-medium interactions

At both RHIC and LHC:
- low $p_T$: $D^0$ $v_2$
- high $p_T$: $D^0$ $R_{AA}$ ~ light hadron $R_{AA}$

Strong charm-medium interactions at LHC and RHIC
Charm-medium interactions

At both RHIC and LHC:
- low $p_T$: $D^0 v_2$
- high $p_T$: $D^0 R_{AA} \sim$ light hadron $R_{AA}$

Strong charm-medium interactions at LHC and RHIC

Joint fit: Diffusion coefficient $D_s \sim 1/(2\pi T) \ast (2-12)$

Even at RHIC charm thermalized
Melting charmonia

Low $p_T$: LHC$_{2.76} >$ RHIC
decreasing regeneration; less c quarks

High $p_T$: LHC$_{2.76} <$ RHIC
decreasing dissociation; cooler medium

At LHC many J/$\psi$ result of coalesced thermalized charm

E. Scomparin, Quarkonium production in AA collisions, QM2017, Chicago, February 2017
At LHC
5 TeV - Highest precision yet

Sequential suppression
\( R_{AA}(\Upsilon(1S)) < R_{AA}(\Upsilon(2S)) \)

\( \Upsilon(3S) \) still no observation
Melting bottomonia

At LHC
5 TeV - Highest precision yet

Sequential suppression
$R_{AA}(\Upsilon(1S)) < R_{AA}(\Upsilon(2S))$

$\Upsilon(3S)$ still no observation

At RHIC: First precise results

Sequential suppression
$R_{AA}(\Upsilon(1S)) < R_{AA}(\Upsilon(2S)+\Upsilon(3S))$

Hints of less suppression at RHIC
Determining initial parton energy

Di-jet expectations

Back-to-back in $\phi$

$$\Delta \phi = \phi_1 - \phi_2$$

Equal but opposite momenta

$$A_J = \frac{p_{T_{\text{Lead}}} - p_{T_{\text{SubLead}}}}{p_{T_{\text{Lead}}} + p_{T_{\text{SubLead}}}}$$

$$x_J = \frac{p_{T_{\text{Jet}}}}{p_{T_{\text{T rig}}}}$$

Modification from p-p - reveal details of interaction with QGP
Di-jets are not deflected

Examine $\Delta \phi$ - azimuthal angle between hadron-jets, z-jet, $\gamma$-jet

Leading order expectation: $\Delta \phi \sim \pi$

Little to no azimuthal de-correlation observed

Partons lose energy but are not deflected from original path
**Di-jets are imbalanced**

γ (Z) triggers “Absolute” $E_{\text{loss}}$ calibration.

Z-jet distribution consistent with γ-jet

Fractional $E_{\text{loss}}$ decreases with $p_T$

$p_T > 200$ GeV

Pb-Pb approaches pp

For all centrality inclusive ~ di-b

Inclusive: q and g

di-b: q

Probing parton flavor energy loss with ever enhancing precision
Lost energy of a recoil jet

\[ \beta_s \approx \frac{200 \text{ GeV}}{4 \text{ GeV}} \]

\[ R = 0.2 \]

\[ R = 0.5 \]
Lost energy of a recoil jet

RHIC: Jet $p_T$ = 10-20 GeV

R=0.2: $p_{T,\text{Shift}} \sim -4.4 \pm 0.2 \pm 1.2$ GeV
R=0.5: $p_{T,\text{Shift}} \sim -2.8 \pm 0.5 \pm 1.2$ GeV
Lost energy of a recoil jet

RHIC: Jet $p_T = 10-20$ GeV
R=0.2: $p_{T,\text{Shift}} \sim -4.4 \pm 0.2 \pm 1.2$ GeV
R=0.5: $p_{T,\text{Shift}} \sim -2.8 \pm 0.5 \pm 1.2$ GeV

LHC: Jet $p_T = 60-100$ GeV
R=0.5: $p_{T,\text{Shift}} \sim -8 \pm 2$ GeV

Energy almost recovered at moderate angles at RHIC but not at LHC
Probing the jet substructure

Jet mass: \( M = \sqrt{E^2 - p^2} \)

Angular spread of constituents “generates” mass

Pb-Pb : Closer to pp than quenching models
Probing the jet substructure

Jet mass: \( M = \sqrt{E^2 - p^2} \)

Angular spread of constituents “generates” mass

Pb-Pb : Closer to pp than quenching models

Pb-Pb inclusive jets have “harder cores” than pp jets of same energy

“Groom” jet into two subjets

\[ z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \]

Significant change at LHC for inclusive jets 140<p_T<200 GeV/c
What has all this taught us?

Different initial conditions and evolutionary paths:

\[ \hat{q} = \frac{Q^2}{L} \]

- \( Q \) - mtm transfer to medium
- \( L \) - path length

\[ \hat{q}(t=0.6\,\text{fm/c}) \approx 1.2 \pm 0.3 \quad \text{GeV}^2/\text{fm}^3 \quad T=370 \,\text{MeV} \]
\[ 1.9 \pm 0.7 \quad \text{GeV}^2/\text{fm}^3 \quad T=470 \,\text{MeV} \]

Probes behave differently at RHIC and LHC
What has all this taught us?

Different initial conditions and evolutionary paths:

\[ q = \frac{Q^2}{L} \quad Q \text{ - mtm transfer to medium} \]
\[ L \text{ - path length} \]

\[ q(t=0.6\text{fm/c}) \sim 1.2 \pm 0.3 \quad \text{GeV}^2/\text{fm} \quad T=370 \text{ MeV} \]
\[ 1.9 \pm 0.7 \quad \text{GeV}^2/\text{fm} \quad T=470 \text{ MeV} \]

Probes behave differently at RHIC and LHC

Different virtuality evolutions:

How/when does parton become “aware” of medium
Other significant recent progress

Sophisticated multi-stage modeling
Fluctuating lumpy initial conditions
Event-by-event calculations just as for real data

Bayesian multi-parameter fits
Data prefer:
EoS determined by LQCD
IP-Glasma initial conditions

Precision estimates of $\eta/s$ approaching ever closer to lower bound
- also as function of $\sqrt{s_{NN}}$
Precision measurements of $\eta_{\text{dijet}} = (\eta_1 + \eta_2)/2 \propto 0.5 \log(x_p/x_{pB}) + \eta_{CM}$

Theoretically: can be calculated in pQCD

Experimentally: “avoid” fragmentation and hadronization effects

Neither PDFs nor nPDFs gives good fit across whole range

Evidence of gluon modification in EMC region $x > 0.3$
Minbias $R_{pPb}$

Consistent with nPDF expectations

Nothing enormously unexpected is occurring!
Collectivity in pp and p-Pb

pp:
- No dependence on $\sqrt{s}$
- No dependence of event activity

p-Pb:
- No dependence on $\sqrt{s}$
- Some dependence of event activity

Heavy quarks also reveal signal but $v_2^\mu < v_2^h$

Sufficient (re-)interactions to (partially) thermalize heavy quarks?

High multiplicity events lead to universal observation of long range collective phenomena
Varying the small systems

**V2**

**0-5% \( \sqrt{s} = 200 \text{ GeV} \)**

- **\(^3\text{He+Au} v_2 \sim v_3 \) (PRL 115, 142301)**
- **d+Au \( v_2 \)**
- **SONIC \(^3\text{He+Au} \)**
- **SONIC d+Au**

**PHENIX**

**Preliminary**

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**Changing initial collision geometry changes \( v_n \) as expected from models**

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**200 GeV**

**62.4 GeV**

**39 GeV**

**19.6 GeV**

\( v_2 \) real down to 20 GeV

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No signs of “rapid” onset in \( \sqrt{s} \) or mult.
Our Long Range Plan

Continues as a vibrant field with wide ranging international support

New detectors being designed and built NOW!

New accelerator facilities being designed and built NOW!

sPHENIX, Forward upgrades at STAR, upgrades at LHC, FAIR, NICA, EIC
Spares
The timeline of a heavy-ion collision

Relativistic Heavy-Ion Collisions

made by Chun Shen

Initial energy density

QGP phase

Hadron gas phase

Hadronization

Kinetic freeze-out

final detected particle distributions

\[ \pi \]

\[ K \]

\[ p \]

\[ e^+ \]

\[ e^- \]

\[ \gamma \]

collision overlap zone

pre-equilibrium dynamics

viscous hydrodynamics

collision evolution

free streaming

\[ \tau \sim 0 \text{ fm/c} \quad \tau \sim 1 \text{ fm/c} \]

\[ \tau \sim 10 \text{ fm/c} \]

\[ \tau \sim 10^{15} \text{ fm/c} \]
**Early conditions: Temperature**

**Direct Photons:**
- no charge or color → don’t interact with medium
- emitted over all lifetime → convolution of all $T$

**Theory well developed**

QGP dominates: $1 < p_T < 3$ GeV/c
**Early conditions:** Temperature

**Direct Photons:**
- no charge or color → don’t interact with medium
- emitted over all lifetime → convolution of all T

**Theory well developed**

![Diagram showing direct photon spectra in Pb–Pb collisions at 2.76 TeV](image)

- QGP dominates: $1 < p_T < 3$ GeV/c

![Graph comparing model calculations from Refs. 59–62 with the direct photon spectra in ALICE](image)

- $T_{eff} \approx 300$ MeV

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**Comment:**
- Hadron gas
- QGP ($T=370$ MeV)
- initial pQCD (pp)
- sum

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**Legend:**
- 0-20% ALICE
- 20-40% ALICE
- 40-80% ALICE

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**References:**
- Turbide et al. PRC 69 014903 (2004)
- Linnyk et al.
- Paquet et al.
- Chatterjee et al.
- NPA 933(2015) 256
- JHEP 1305(2013) 030

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**Author:** Helen Caines

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**Note:**
- $s_{NN}=2.76$ TeV
- $T_{eff}$ is the effective temperature at the center of the collision.
- The hadron gas model does not include QCD contributions.
- The QGP model is based on a massive Yang-Mills theory.
- The hydrodynamic calculations are compared to state-of-the-art direct photon spectra.
- The analysis is performed for various centrality classes.

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**For a recent review:**
- Ref. [69].
First order phase transition?

Low $\sqrt{s}$: slope $v_1$ (baryons) positive
slope $v_1$ (mesons) negative

Beam energy baryon $dv_1/dy$ trend
complex interplay of:
$v_1$ baryons transported from beam
$v_1$ from pair production

Low $\sqrt{s}$: slope $v_1$ (baryons) positive
slope $v_1$ (mesons) negative
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slope $v_1$(mesons) negative

Beam energy baryon $dv_1/dy$ trend
complex interplay of:

$v_1$ baryons transported from beam

$v_1$ from pair production

Net-proton isolates directed flow of transported baryons:

Double sign change in $dv_1/dy$

Not seen in net-kaons

Results not yet reproduced by theory
Stalling of the expansion?

d final state coalescence access to nucleon freeze-out volume

\[ E_A \frac{d^3N_A}{d^3p_A} \approx B_A \left( E_p \frac{d^3N_p}{d^3p_p} \right)^A \]

B_2 minimum (V maximum) \( \sqrt{s_{NN}} \approx 20 \text{ GeV} \)

\( B_2 = \frac{6\pi^3 R_{np} m_d}{m_p V_f} \)

\( \tau_f \approx \frac{\langle m_N \rangle}{6\pi^3} \) for the world's data set. A small theoretical calculation.

(\( R_{out}^2 - R_{side}^2 \)) sensitive to emission duration

Maximum at \( \sqrt{s_{NN}} \approx 20 \text{ GeV} \)

Sign of entering compressed baryonic matter regime?

Softening of EoS?
Disappearance of QGP?

High $p_T$ suppression gone

$\phi$ $v_2 \sim 0$

Several standard signals disappear at $\sqrt{s} < 15$ GeV

**STAR Preliminary**

Si Horvat QM2015

**STAR**

**PRC 93 (2016) 14907**

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A lot is happening around 20 GeV

Hard to believe this is a conspiracy of different underlying causes

STAR/PHENIX/ALICE Data

Centaur H1 Collisions

E864/E866/E877/NA49/PHENIX/STAR

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Improving on current data

Current low energy data:
Hints that at low $\sqrt{s}$
QGP turns off
Ordered phase transition
Critical Point

Future data:
Examine regions of interest
Maximizing fraction particles measured
Probe lower $\sqrt{s}$
High(er) luminosities
Change species

Turn trends and features into definitive conclusions
### Planned low energy running

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<th>$\mu_B$ (MeV)</th>
<th>SPS 600 - 230</th>
<th>850 - 670</th>
<th>790</th>
<th>720 - 210</th>
<th>750 - 330</th>
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<td>2 - 3.5</td>
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<td>Onset &amp; Dense Baryon</td>
<td>Onset &amp; Dense Baryon</td>
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Expect wealth of new insights over next ~5 years.
BES-II: Vorticity and Initial B-field

BES-I: First measurement of Λ Global Polarization

Vortical + Magnetic Contributions:
Current data barely stat. significant

EPD:
Improved EP resolution

BES-II: 3σ effect

Unique measurement of B
Significant input to CME/CVE interpretations
**Strong suppression of high $p_T$ particles**

![Graph showing $p_T$ distribution](image)

- **High $p_T$ hadrons:**
  - at RHIC: from quarks
  - at LHC: from gluons

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Light quarks and gluons strongly coupled to the medium
Di-jet imbalance $A_J$ Au-Au 0-20% $R=0.4$

$A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} - p_T^{SubLead}}$

Anti-$k_T$ $R=0.4$, $p_{T,1}>20$ GeV & $p_{T,2}>10$ GeV with $p_T^{cut}>2$ GeV/c

|A_J|

Event Fraction

- tracking eff. 6%
- tower energy scale 2%

Au-Au di-jets more imbalanced than p-p for $p_T^{cut}>2$ GeV/c

Au-Au $A_J \sim p$-p $A_J$ for matched di-jets (R=0.4)
Where does the energy go?

ATLAS Preliminary
Pb+Pb $s_{NN}=2.76$ TeV
$L_{int}=0.14$ nb$^{-1}$

anti-$k_T$ $R=0.3$
$p_T^{jet} > 92$ GeV
0-10%/60-80%

“Lost” hard particles emerge as multiple soft particles

| $|\Delta\phi-\pi| < \pi/6$ |
| $|\Delta\phi-\pi| < \pi/3$ |
| $|\Delta\phi-\pi| < \pi/2$ |

γ-hadron correlations

γ - Energy calibration
$I_{AA}$ as function of “cone R”

E remains correlated to jet axis but at large angles

ATLAS-CONF-2012-115

arXiv:1212.3323

5 < $p_T^{\gamma}$ < 9 GeV/c x 0.5 < $p_T^{h}$ < 7 GeV/c

0-40% Au+Au

PHENIX

- global sys = ± 6% (a)

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Strangeness saturation in pp?

Steep rise in strangeness yields per π as function of event activity

Strong function of strangeness content

Trend in pp same as that in p+Pb with smooth transition to Pb+Pb

Not reproduced by models

Is this increase dependent on p_T and/or event activity definition as for HF?
HF production versus event activity

Self normalized yields grows faster than event activity at both LHC and RHIC

Soft vs hard processes competing?

MPI at work?

Also seen in p+Pb

NPE show no difference above/below 4 GeV/c

b behaves like c

Results depend on where event activity measured

Physics or ill defined reference?
Small systems - an ongoing debate

Evidence of collective motion in high multiplicity p-p, p-Pb, He$^3$-Au, p-Au, p-Al, and d-Au

Some trends fit with those from A-A

Magnitude reduces with $\sqrt{s_{NN}}$

limited evidence at 19.6 GeV