Hard probes at intermediate energies (including fixed-target programs)

Rongrong Ma

Brookhaven National Laboratory

Hard probes at $5 <\sim \sqrt{s_{NN}} < 200$ GeV (including fixed-target programs)

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Why at Intermediate Energies?

- Why hard probes (jets, heavy flavor, EM probes, etc)?
  - Jets, HF: penetrating through the QGP with "maximal" interactions
    - QGP transport coefficients …
  - EM probes: penetrating through the QGP with minimal interactions
    - Dilepton (IMR: $1 < M < 3$ GeV/c^2); direct photon ($p_T > 2$ GeV/c)
    - QGP temperature …

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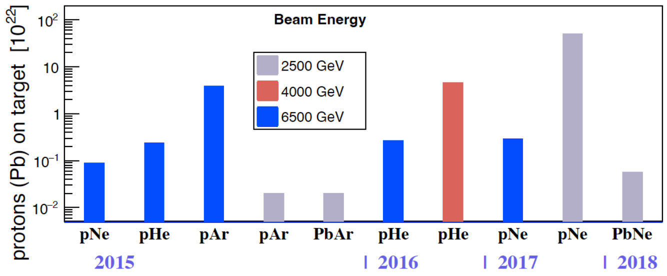
- Why intermediate energies?
  - *p*+A
    - (n)PDF in the valence quark region
    - Intrinsic charm in nucleon?
    - *Reference for A+A*
  - A+A
    - Search for evidence of turn-off of QGP
    - Collision energy dependence of QGP properties

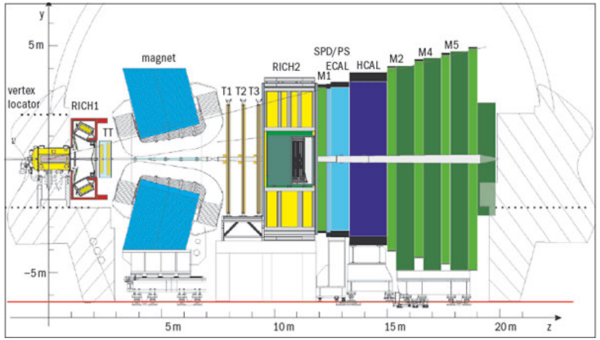
$\sqrt{s_{NN}} =$ **LHCb: 69 ~ 115 GeV**

RHIC: 7.7 ~ 62.4 GeV

SPS: 17.3 GeV

p+A





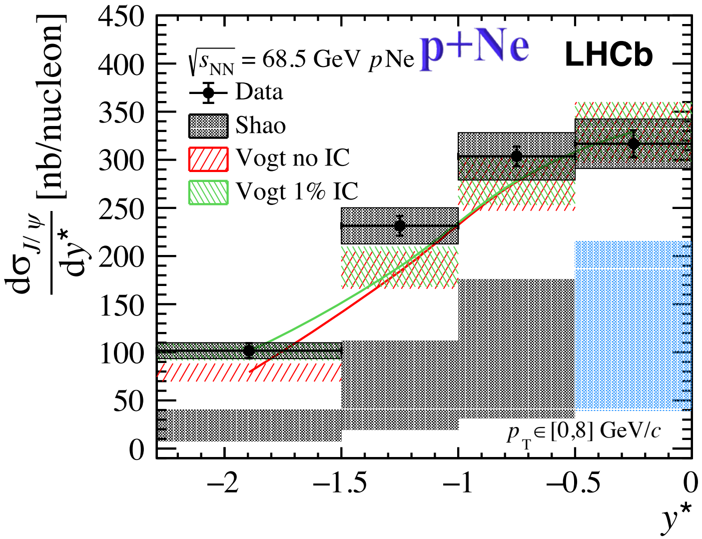
https://cds.cern.ch/record/2649878/

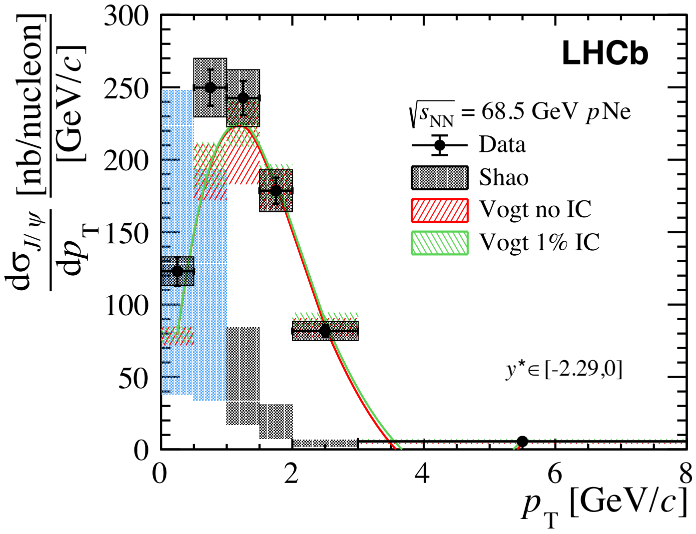
https://cerncourier.com/a/lhcb-a-question-of-asymmetry/

Intrinsic Charm Search at LHCb with J/ψ

$|uud c\bar{c}\rangle$

K. Mattioli, [Mar 28, 15:00]



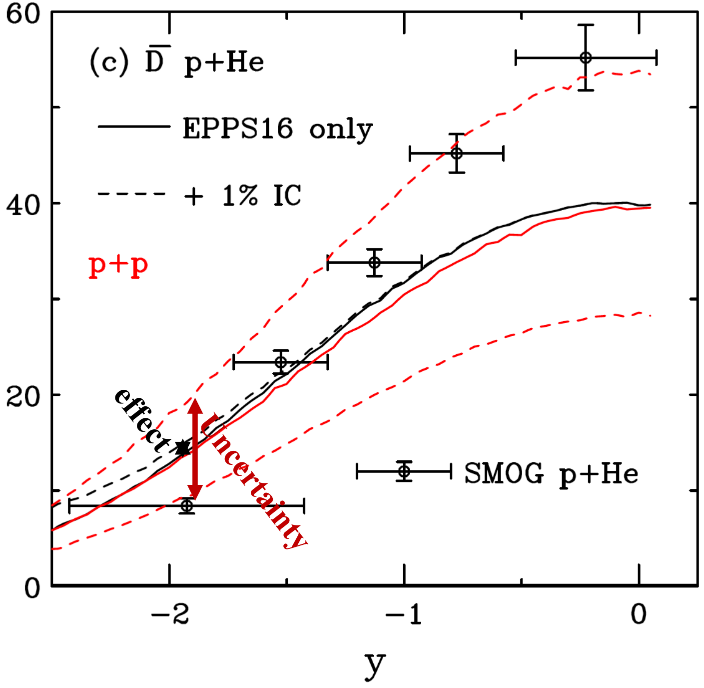


- Cross section: consistent with R. Vogt's calculation w/ and w/o 1% intrinsic charm

LHCb, arXiv:2211.11645, Vogt: PRC 103 (2021) 035204; Shhao: CPC 198 (2016) 238, CPC 184 (2013) 2562

Can We Really See Intrinsic Charm at LHCb?

R. Vogt, [Mar 28, 09:40]



- Cross section: theoretical uncertainties are much larger than the effect of IC
- *What's next?*
  - Find the phase space where the effect is larger than the uncertainties
  - Find an observable to cancel uncertainty

Vogt: PRC 103 (2021) 035204; PRC 106 (2022) 025201

Phase Space with Large Effects

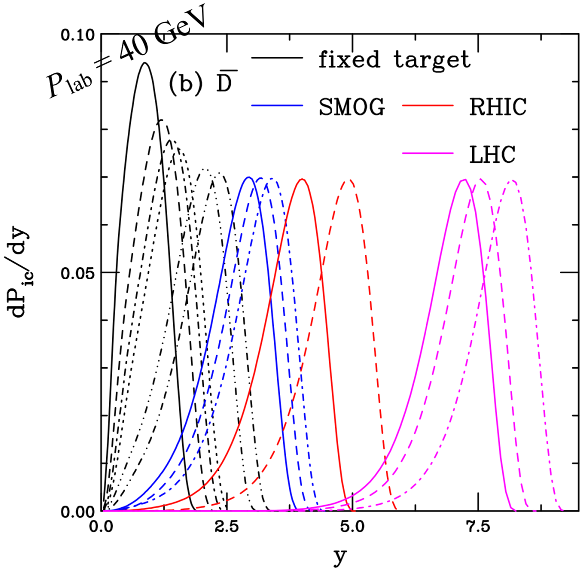
R. Vogt, Mar 28, 09:40

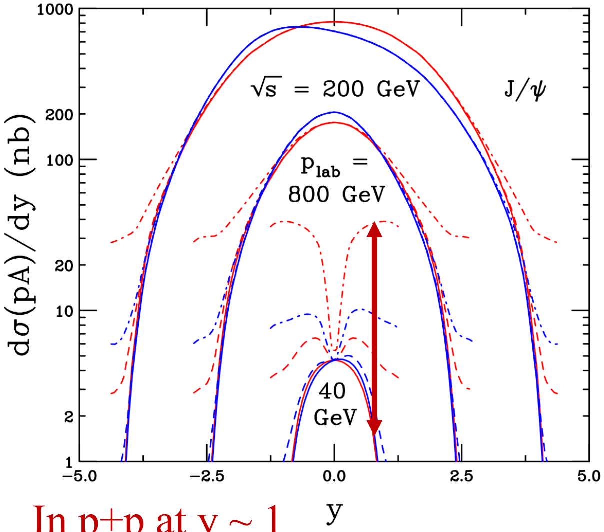
- Phase space: high x_F
  - Lower collision energy; high p_T and/or rapidity

P_{lab} = 40 GeV

Equal to

$\sqrt{s_{NN}}$ = 8.8 GeV





In p+p at y ~ 1

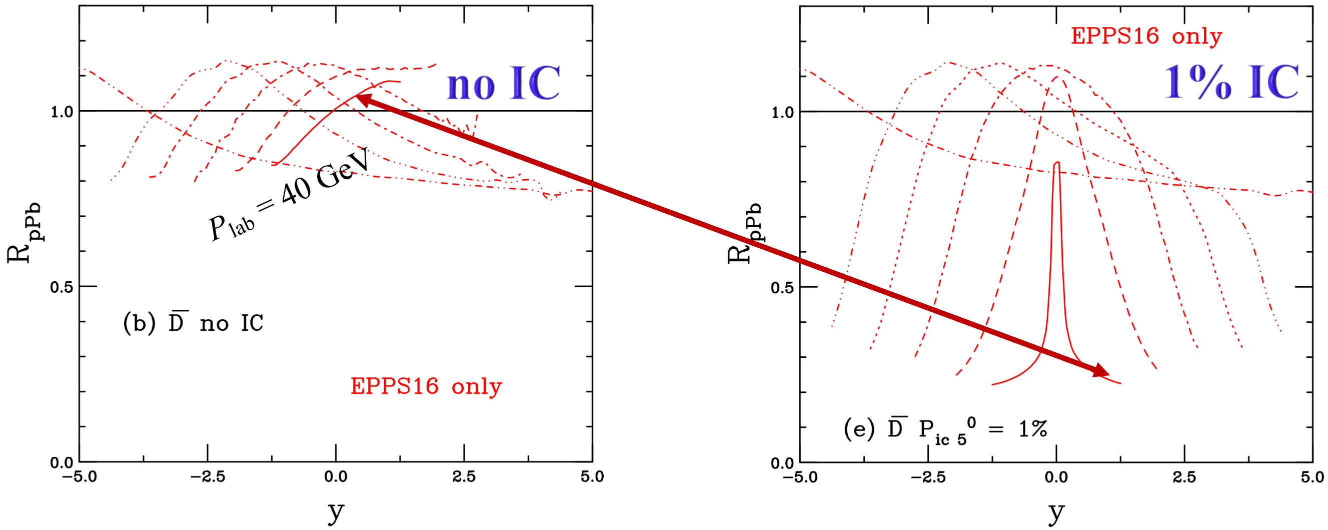
1% IC enhances x-sec by a factor of ~25

Vogt: PRC 103 (2021) 035204; PRC 106 (2022) 025201

Observables (Mostly) Cancel Uncertainties

R. Vogt, Mar 28, 09:40

- R_{pA}: $\sigma_{ic}^{D}(pA) = \sigma_{ic}^{D}(pp) \times A^{0.71}$



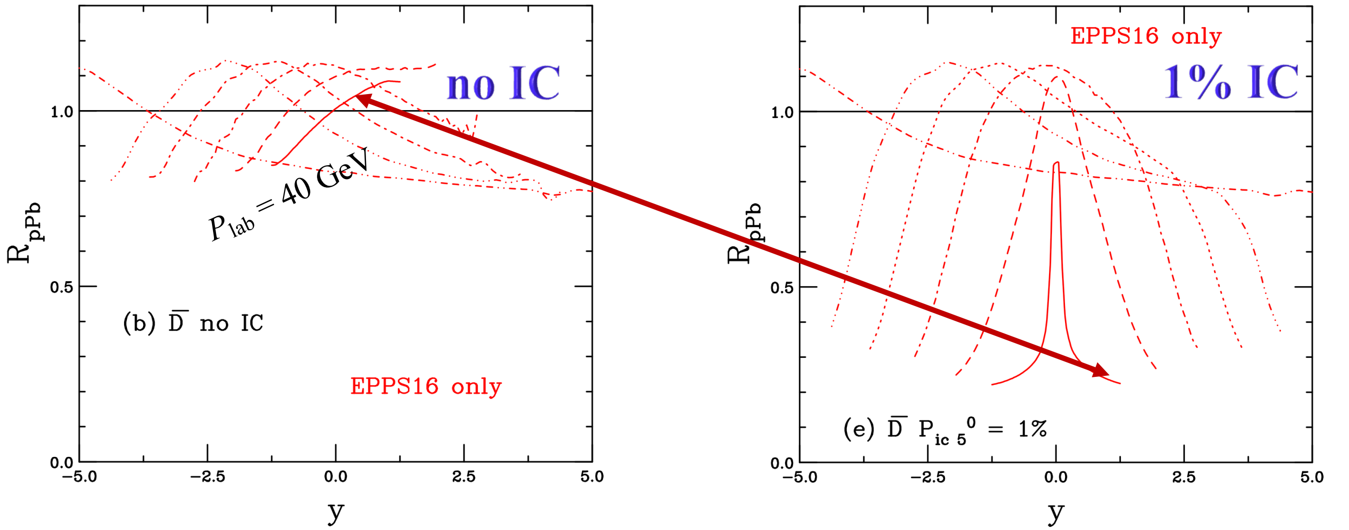
At y ~ 1: 1% IC suppresses R_{pA} by about a factor of ~5

Vogt: PRC 103 (2021) 035204; PRC 106 (2022) 025201

Observables (Mostly) Cancel Uncertainties

R. Vogt, Mar 28, 09:40

- R_{pA}: $\sigma_{ic}^{D}(pA) = \sigma_{ic}^{D}(pp) \times A^{0.71}$

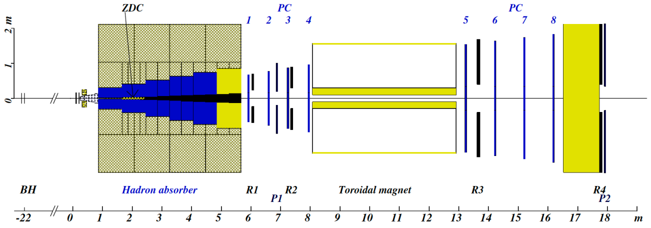


At y ~ 1: 1% IC suppresses R_{pA} by about a factor of 5 ➡ NA60+

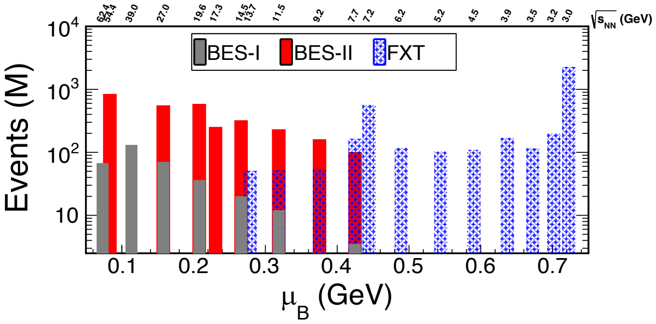
Vogt: PRC 103 (2021) 035204; PRC 106 (2022) 025201

A+A

NA38, NA51, NA50



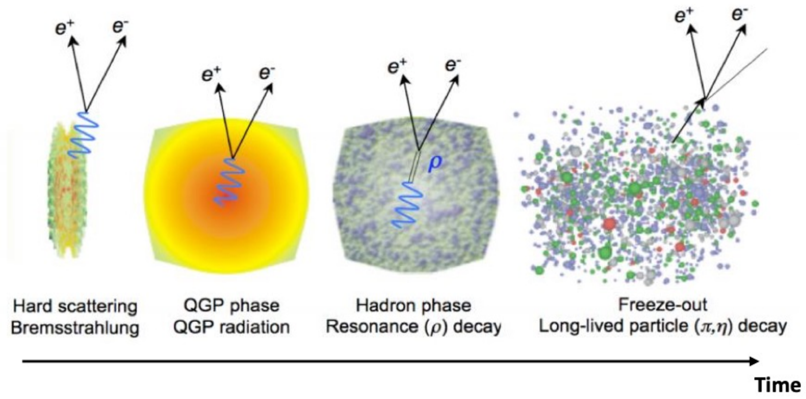
L. Kluberg, EPJC 43 (2005) 145



STAR Beam Use Request

How Does QGP Evolve with Energy?

Dilepton/photon: temperature

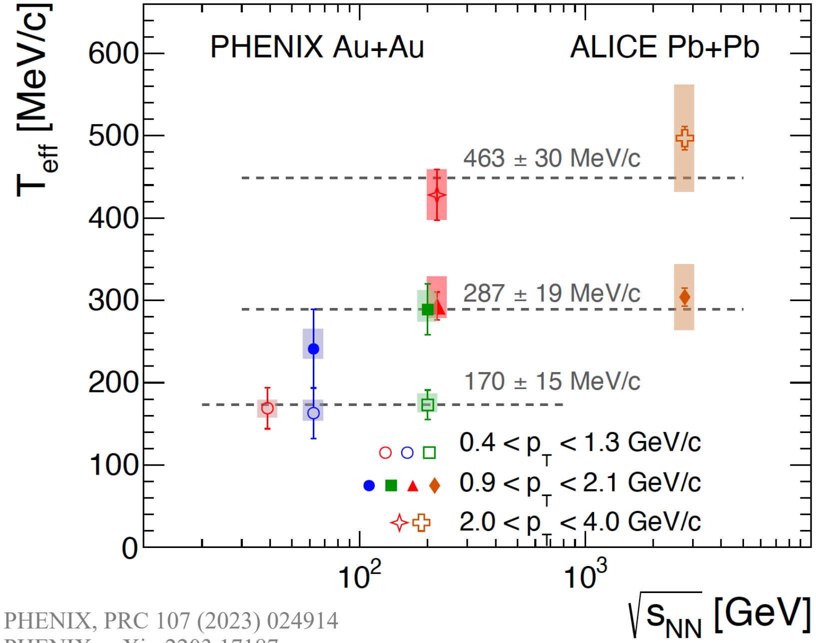


Courtesy of S. Bass and Y. Zhang

Direct photons: T_{eff}

R. Esha, Mar. 28, 17:10

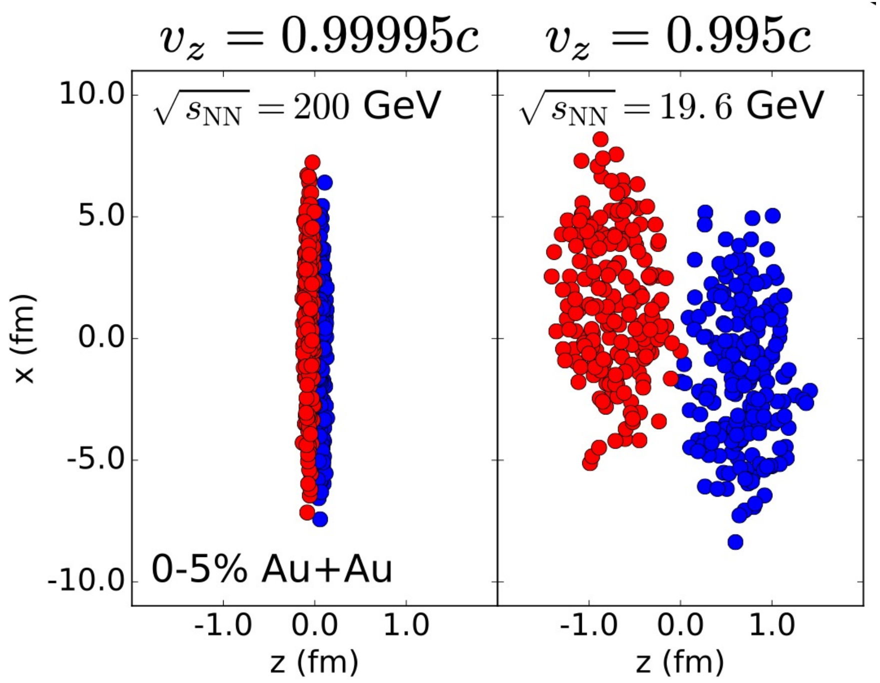
39 GeV: MB
> 62.4 GeV: 0-20%



PHENIX, PRC 107 (2023) 024914
PHENIX, arXiv:2203.17187

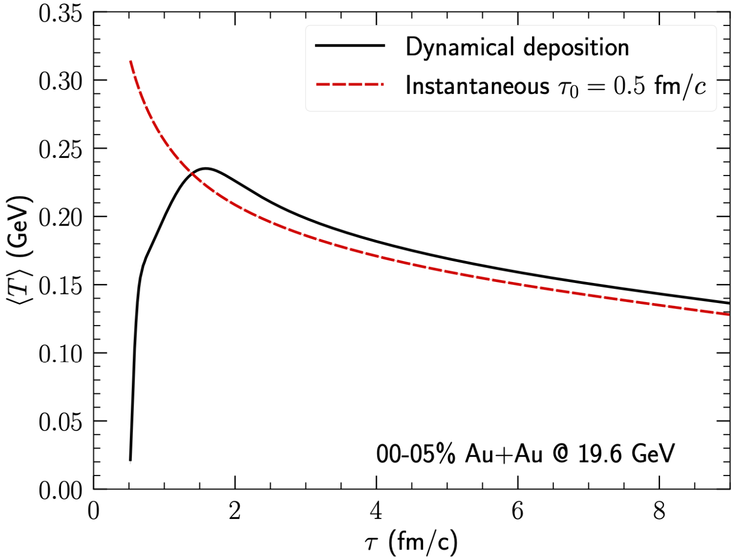
- Sensitive to both medium temperature and radial expansion (blue-shift)
- < 2 GeV/c
  - No strong collision energy dependence ($\sqrt{s_{NN}}$ ~ 39-2760 GeV)
  - Radiation close to phase transition
- 2-4 GeV/c
  - Hint of increasing temperature at higher energy → QGP origin?

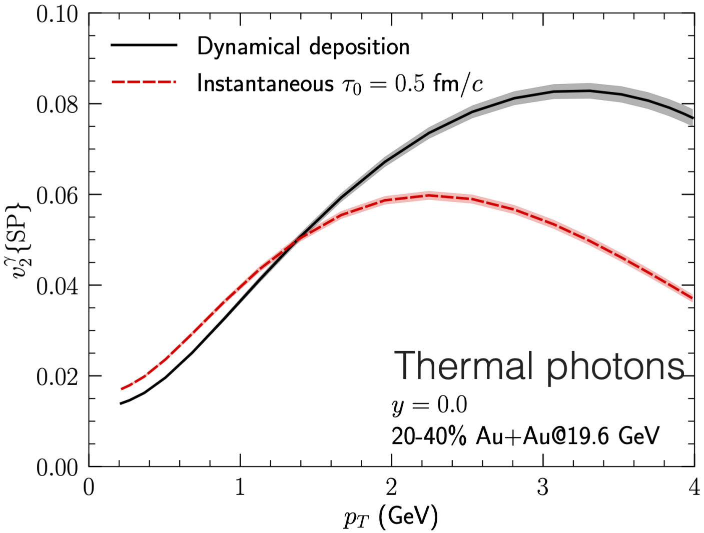
Thermal photons: Initial Dynamics



C. Shen, [Mar. 29, 14:20]

Thermal photons: Initial Dynamics



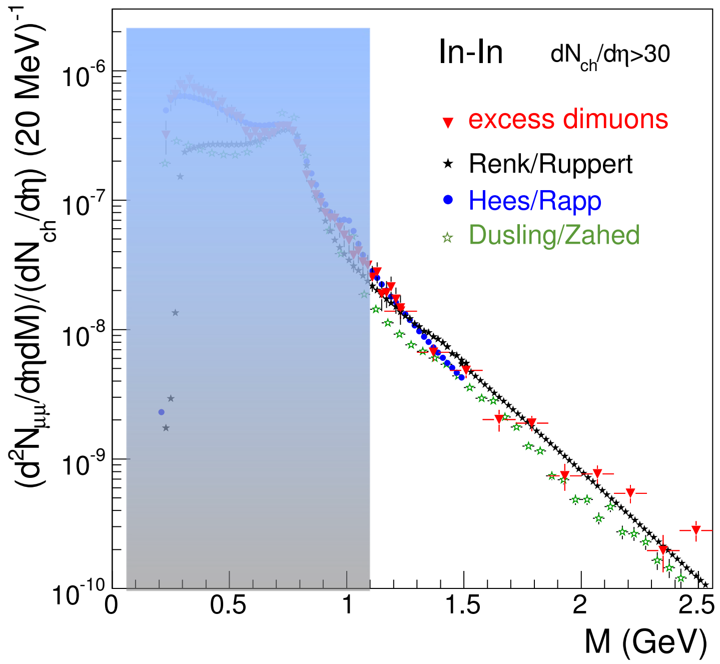


- Thermal photon yield and v_2 are sensitive to dynamics of nuclei passing through each other
- Would be good to constrain prompt photons from p+p measurements (Anyone?)

C. Shen, [Mar. 29, 14:20]

SPS: Temperature at IMR

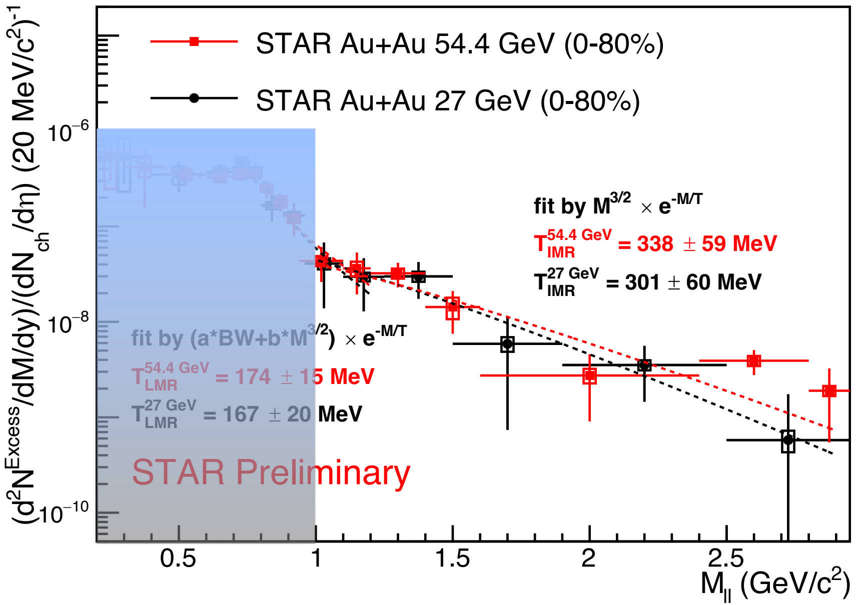
- In+In @ 17.3 GeV
- Excess yields after cocktail subtraction → Genuine measurement of average fireball temperature without blue-shift effect
- Fit the mass range of 1.1 – 2.0 GeV/c^2 with an exponential function ($\sim M^{3/2}e^{-M/T}$) → T = 205 ± 12 MeV
  - When fitting between 1.1 – 2.4 GeV/c^2, T = 230 ± 10 MeV
- Extracted temperature above T_{pc} → Thermal radiation from the deconfined QGP



NA60, EPJC 59 (2009) 607
NA60, AIP Conf. Proc. 1322 (2010) 1

RHIC: Temperature at IMR

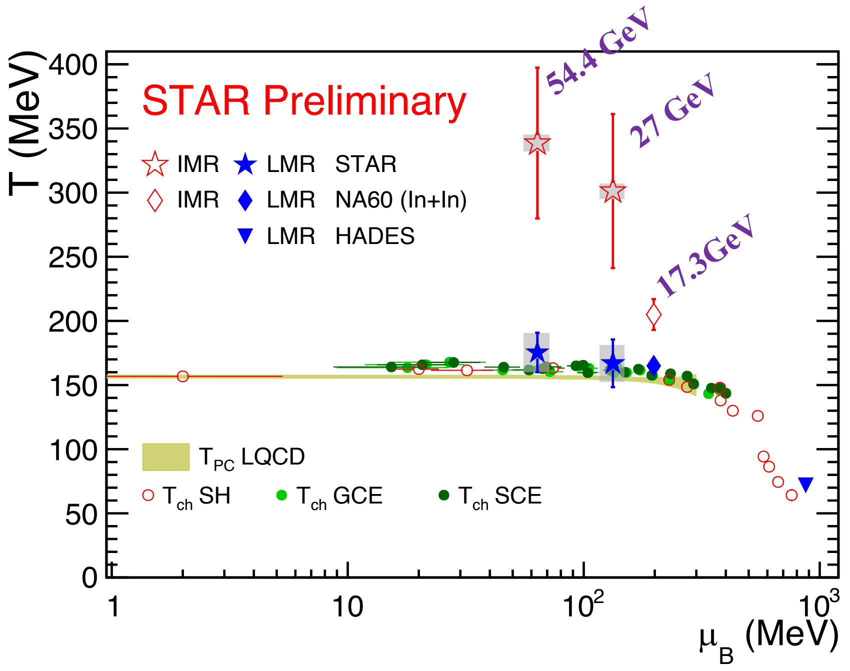
- Au+Au @ 27, 54.4 GeV
- Fit the mass range of 1-3 GeV/c^2
  - $T^{54.4\mathrm{GeV}} = 338 \pm 59$ MeV
  - $T^{27\mathrm{GeV}} = 301 \pm 60$ MeV
- Extracted temperature above T_{pc} → Thermal radiation from the deconfined QGP



NA60, EPJC 59 (2009) 607

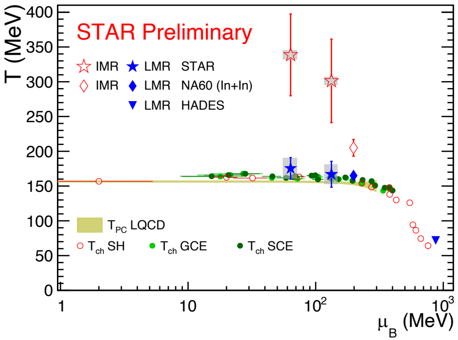
Temperature vs. μ_B

- Thermal dileptons at IMR
  - Emitted from the QGP phase
  - QGP temperature larger than T_{pc} for $\sqrt{s_{NN}}$ > 17 GeV
  - Hint of decreasing temperature with deceasing energy

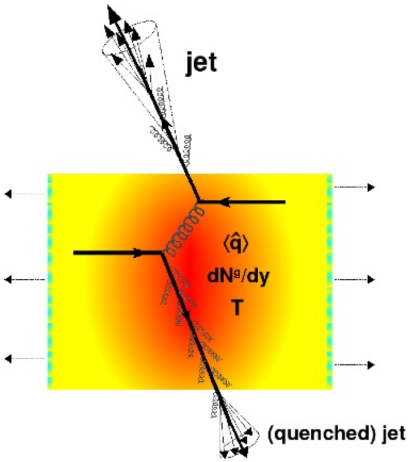


STAR, PLB 750 (2015) 64; STAR, arXiv:1810.10159; STAR, PRC 96 (2017) 044904
HotQCD: PLB 795 (2019) 15; P. Braun-Munzinger, et. al., Nature 561 (2018) 321
NA60, EPJC 59 (2009) 607; NA60, AIP Conf. Proc. 1322 (2010) 1
HADES, Nature Physics 15 (2019) 1040

How Does QGP Evolve with Energy?



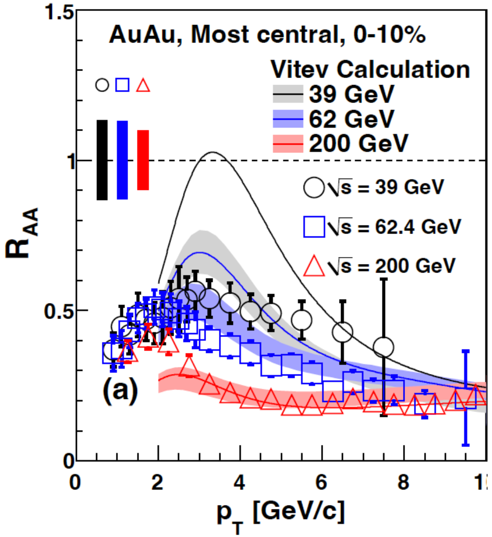
Jet quenching



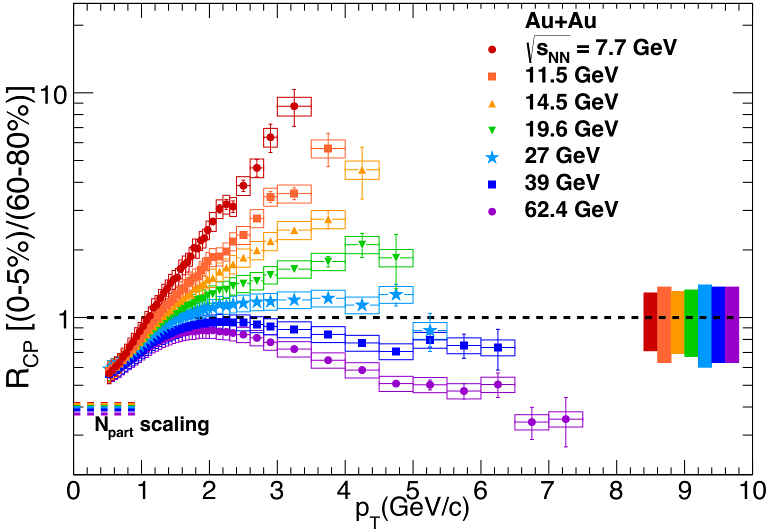
D. d'Enterria, arXiv:0902.2011

Charged Hadron Suppression

PHENIX, PRL 109 (2012) 152301

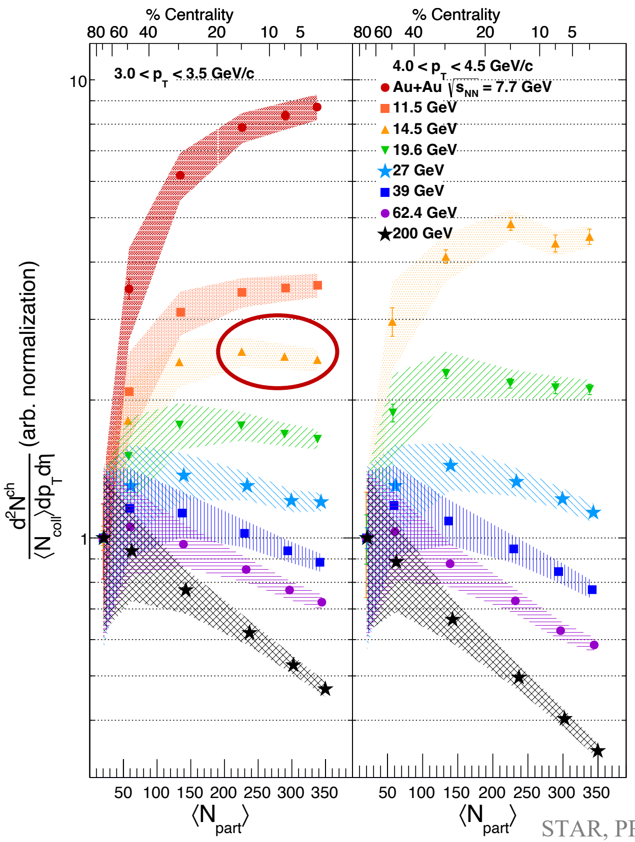


STAR, PRL 121 (2018) 032301



- 200 → 7.7 GeV: suppression transitions to enhancement
  - High-p_T: increasing R_{AA} + steeper spectrum → decreasing energy loss
  - Competing effects: jet quenching, Cronin effect, radial flow, coalescence
  - Need to measure Cronin effect (NA61: data on tape with p_T reach to 4 GeV/c) SPSC-SR-239.pdf

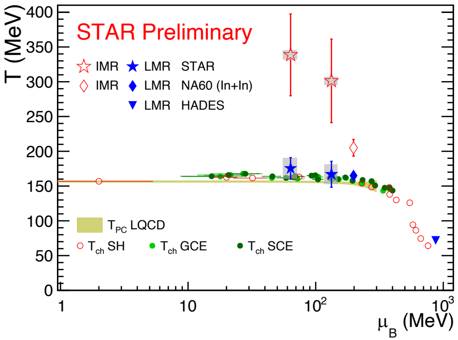
Relative Suppression vs. Centrality

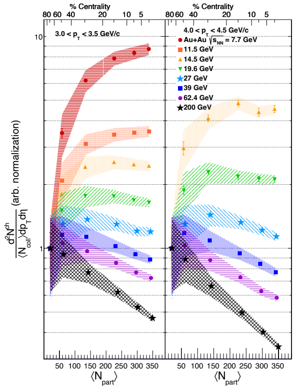


STAR, PRL 121 (2018) 032301

- N_{coll} scaled charged hadron yield vs. centrality
  - Competition between suppression and enhancement effects
  - More sensitive to jet quenching
- Signature of jet quenching for $\sqrt{s_{NN}}$ >~ 14.5 GeV

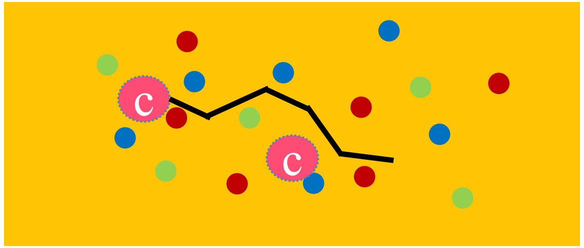
How Does QGP Evolve with Energy?



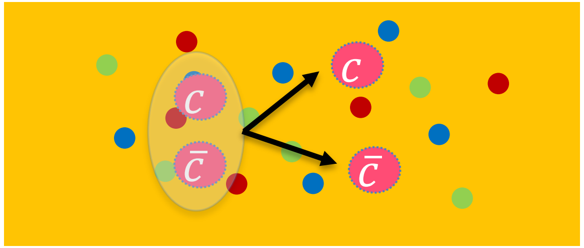


Heavy Flavor

Open HF

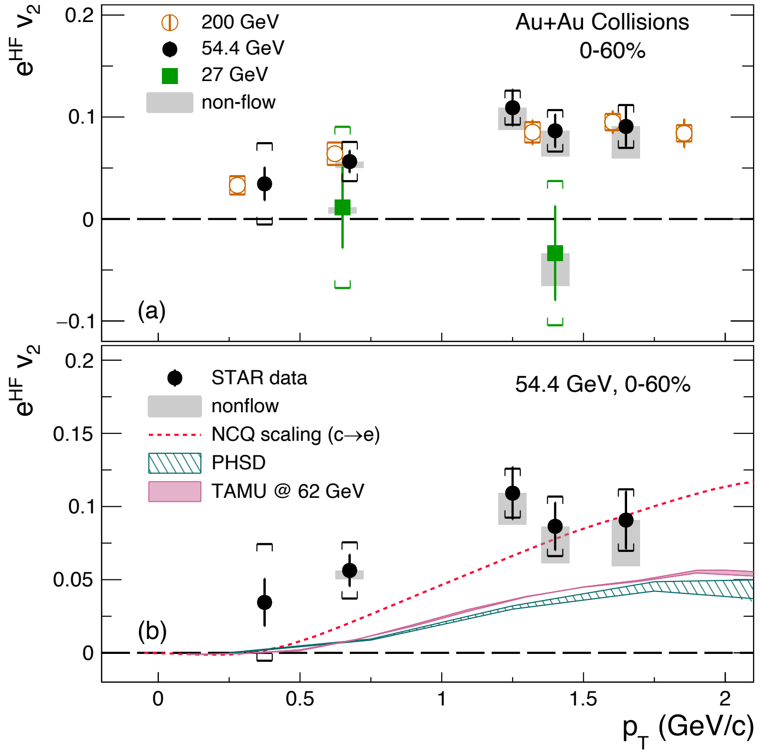


Quarkonium



HF Electron v_2 at 54.4 and 27 GeV

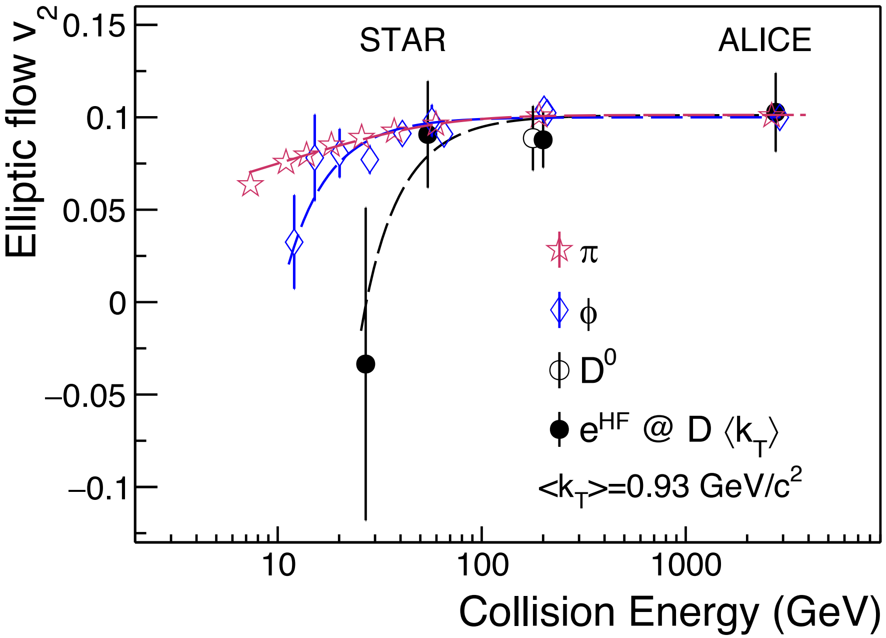
STAR, arXiv: 2303.03546



- 27 GeV: consistent with zero
- 54.4 GeV:
  - Significant v_2 comparable to that at 200 GeV
  - Charm quarks gain v_2 at later stage
  - Transport models seem to underpredict v_2 (1-2σ for $p_T > 0.5$ GeV/c)
  - Consistent with NCQ scaling → may reach local thermal equilibrium with the QGP?

Compared to Light Flavor

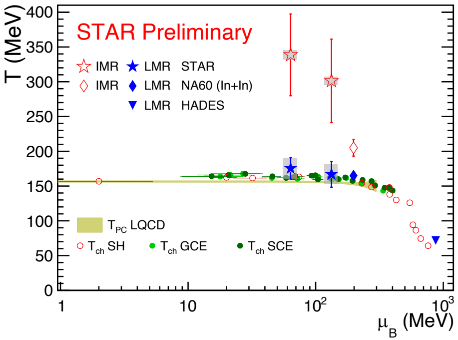
STAR, arXiv: 2303.03546

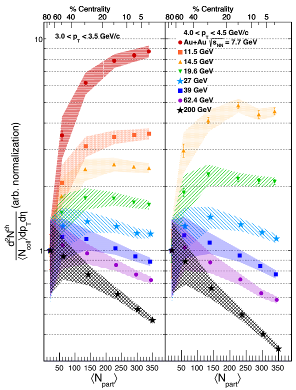


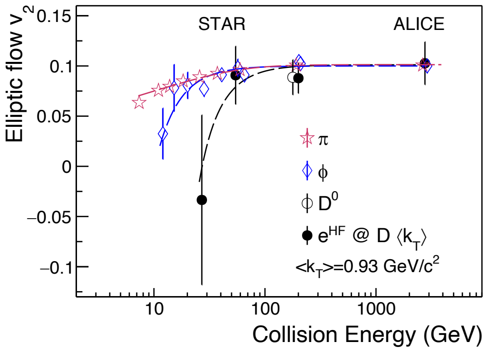
$$\langle k_T \rangle = \langle m_T - m_0 \rangle$$

- v_2 comparison: π vs. ϕ vs. D^0 vs. e^{HF}
- Above 54.4 GeV: similar v_2 for all particles
- Below 54.4 GeV: heavier particles seem to drop faster than light particles with deceasing collision energy → seems QGP lifetime too short and/or energy density too low to thermalize heavy quarks?

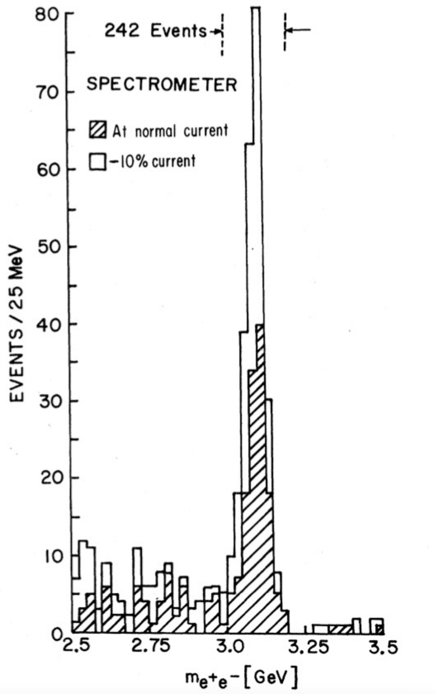
How Does QGP Evolve with Energy?



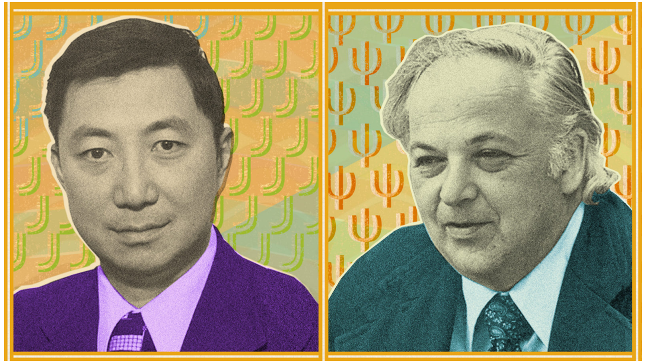




J/ψ: Discovered at AGS and SLAC



Nobel Prize in 1976

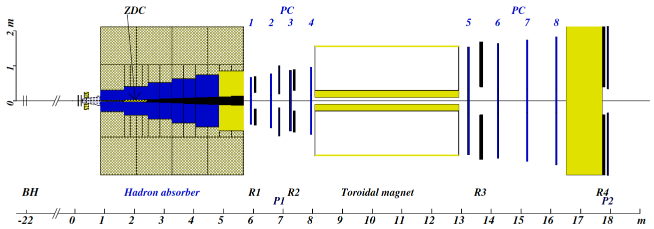


https://www.symmetrymagazine.org/article/november-2014/the-november-revolution

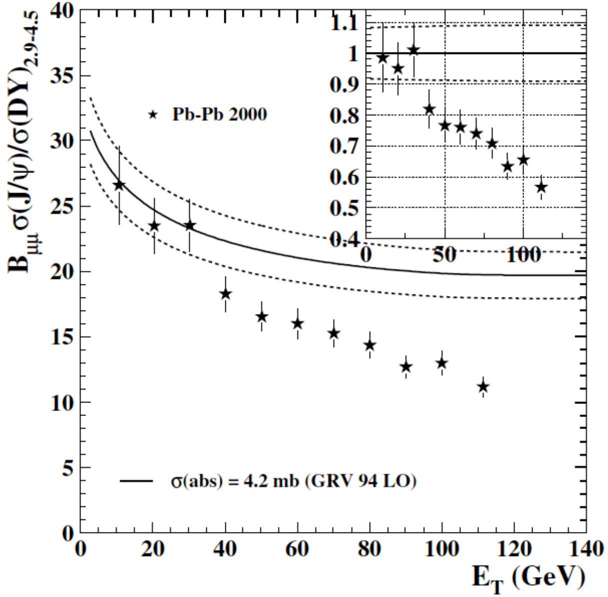
E598, PRL, 33:1404-1406, 1974
SLAC-SP-017, PRL, 33:1406-1408, 1974

Anomalous J/ψ Suppression :20-Year Journey at SPS

NA38, NA51, NA50



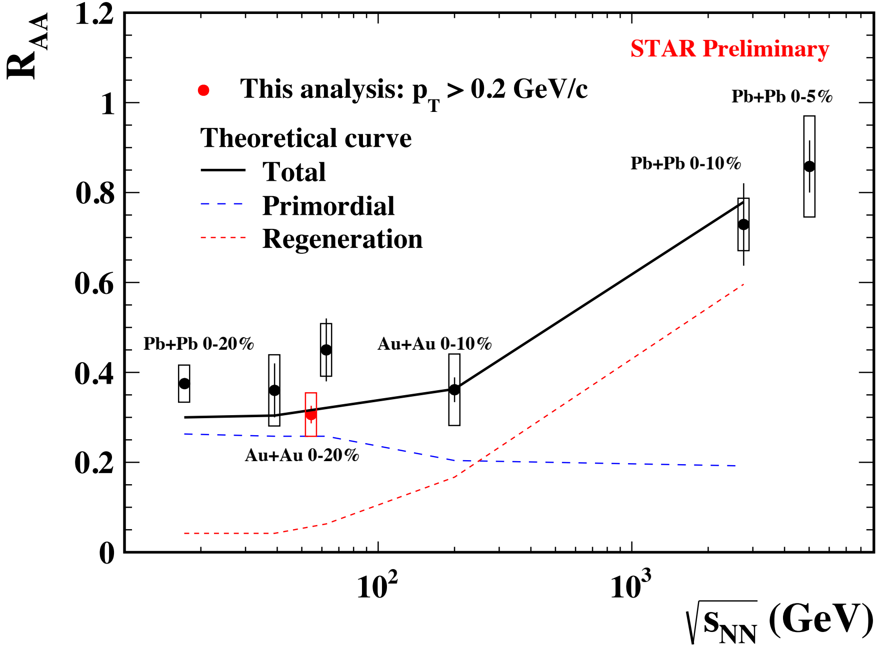
L. Kluberg, EPJC 43 (2005) 145



NA50, EPJC 39 (2005) 335

- Normal suppression: significant absorption observed in p-A and light ion collisions
- Anomalous suppression: larger suppression in Pb+Pb collisions than the expectation, and increases with centrality
  - Mainly from very strong suppression of excited states NA50, EPJC 49 (2007) 559

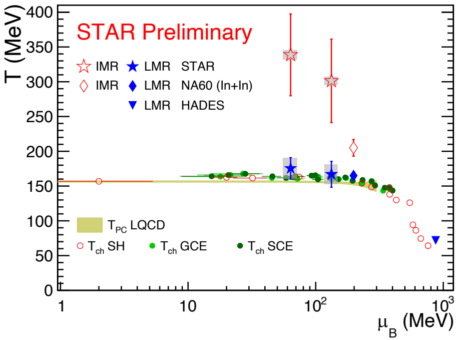
J/ψ R_{AA} as a Function of Collision Energy

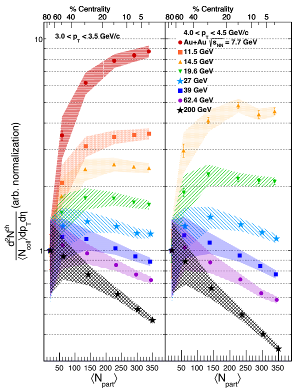


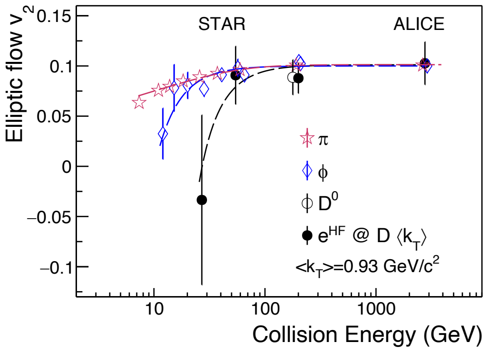
X. Zhao, R. Rapp, PRC 82 (2010) 064905
NA50, PLB 477 (2000) 28, STAR, PLB 771 (2017) 13, STAR, PLB 797 (2019) 134917
ALICE, PLB 734 (2014) 314, ALICE, NPA 1005 (2021) 121769

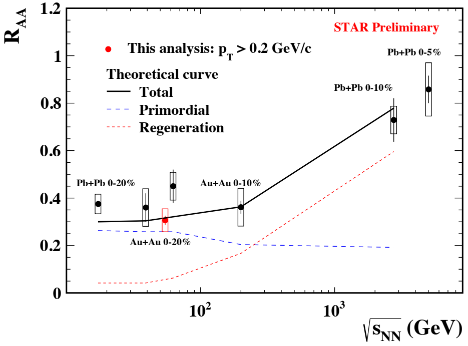
- No strong energy dependence up to 200 GeV → interplay of CNM, regeneration and dissociation
  - Can be well described by transport model calculation

How Does QGP Evolve with Energy?





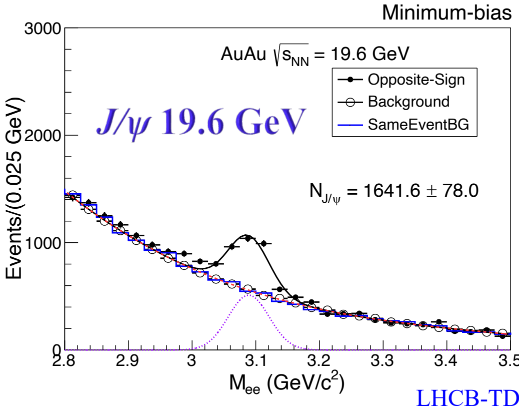




- $\sqrt{s_{NN}}$ >~ 14.5 GeV: clear signal of jet quenching (QGP formation)
- $\sqrt{s_{NN}}$ >~ 54.4 GeV: seems dense/big enough to thermalize charm quarks
- With decreasing collision energy, QGP has *i) lower temperature; ii) less opaque to jets: iii) shorter lifetime and/or lower density to thermalize heavier quarks and dissociate J/ψ*

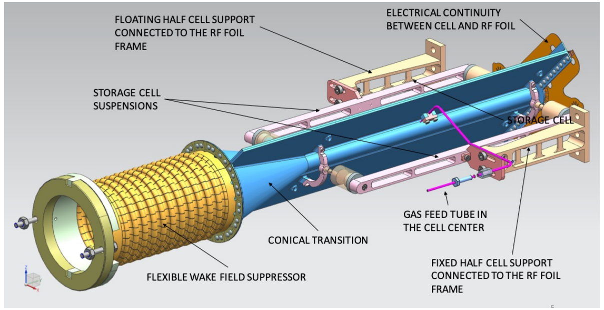
In the Near Future

- **RHIC**: BES-II (7.7-19.6 GeV) data analysis ongoing
  - Larger kinematic reach; better precision
  - High-p_T charged hadron, J/ψ, thermal dielectrons



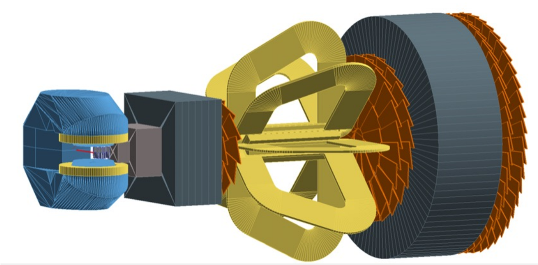
LHCB-TDR-020

- **LHCb**: SMOG2
  - Started data-taking in Run3
  - pA @ 115 GeV, PbAr @ 72 GeV
  - Orders of magnitude larger sampled luminosity
    - pAr @ 115 GeV (45 nb^{-1}): J/ψ (15M), D^0 (150M), Υ(1S) (7k)

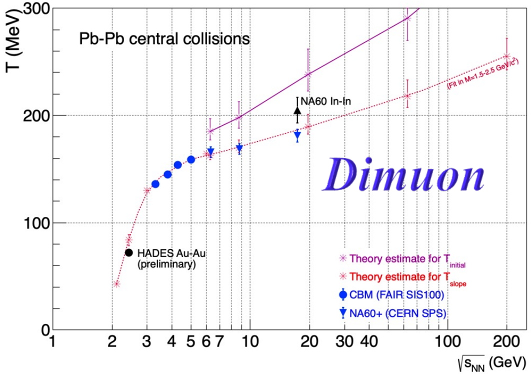


The Next Big Thing: NA60+

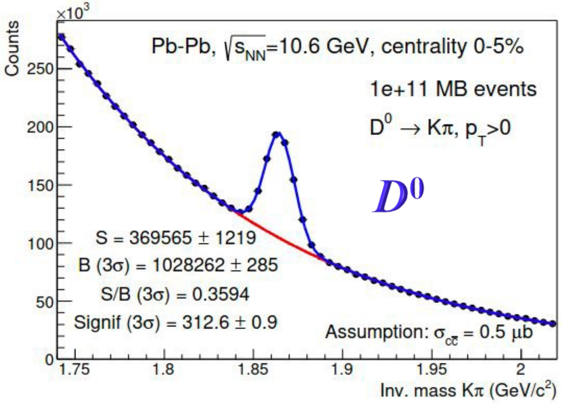
NA60+, arXiv:2212.14452

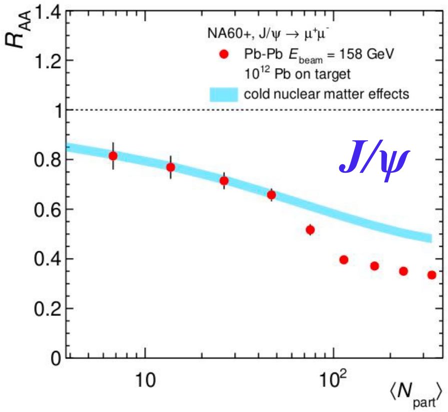


- **Pb+Pb @ 6 – 17.3 GeV**
  - Corresponding p+A data for quantifying CNM effects
  - **CBM @ 2-5 GeV**
- Proposed timescale: **2029+**
- Physics goals: **study high-μ_B QGP and phase transition**
  - Dimuon, open and hidden charm …



Hees, Rapp PLB 753 (2016) 586
Galatyuk et al. EPJA 52 (2016) 131





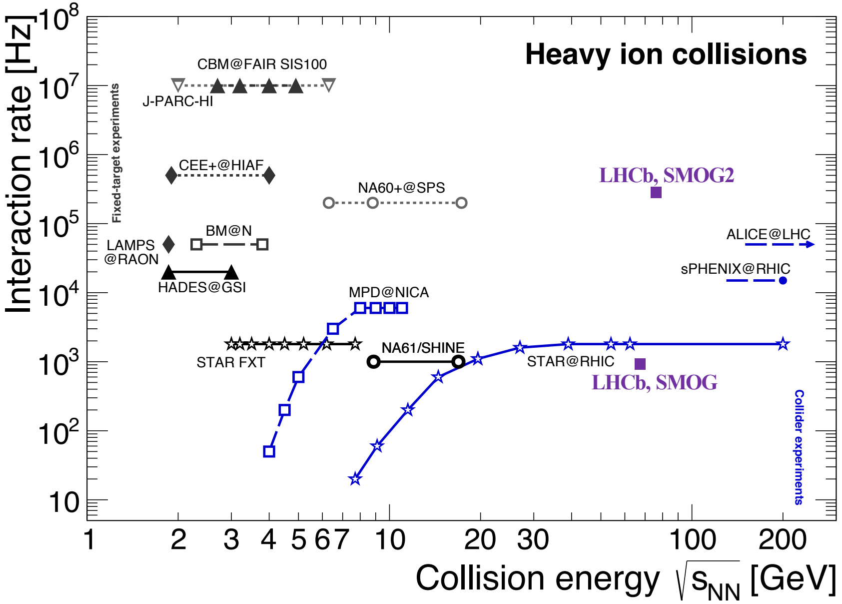
G. Usai, Mar 28, 15:00 | R. Arnaldi, Mar 29, 15:40 | E. Scomparin, Mar. 30, 17:45

Current and Future Landscape

E. Scomparin, Mar. 30, 17:45

C. Pauly, Mar. 30, 18:00

- Dilepton: *STAR, NA60+, MPD, CBM, HADES, J-PARC …*
- Charm physics: *STAR, NA61, NA60+, CBM, J-PARC …*
- High-p_T hadrons: *STAR, NA61 …*



Comprehensive program with extensive coverage!

NA60+, arXiv:2212.14452
LHCB-PUB-2018-015
T. Galatyuk, NPA 982 (2019) 163

Summary

- p+A
  - Not conclusive on intrinsic charm
- A+A
  - Smooth evolution of QGP properties
  - *Qualitative changes at 14.5 and 54.4 GeV?*

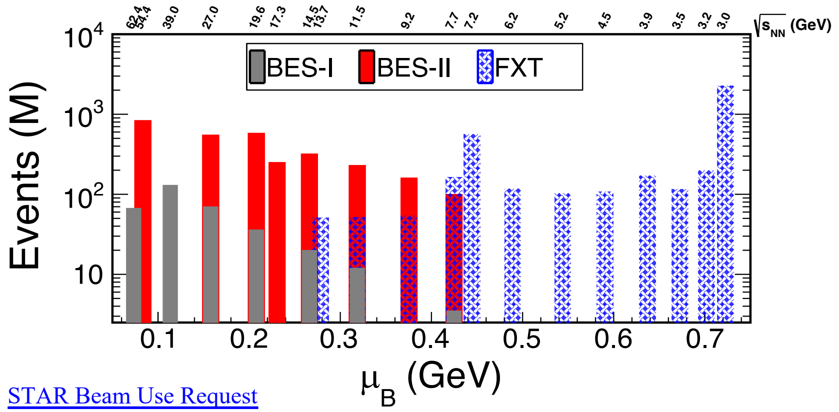
- *(my incomplete view of) What's still needed?*
  - Quantify CNM for interpretation of heavy ion measurements, such as high-p_T hadron, J/ψ
  - Excitation function for J/ψ suppression: can we see the sequential melting? what does complete melting mean?
  - Better precision for high-p_T hadron, open HF …

Backup

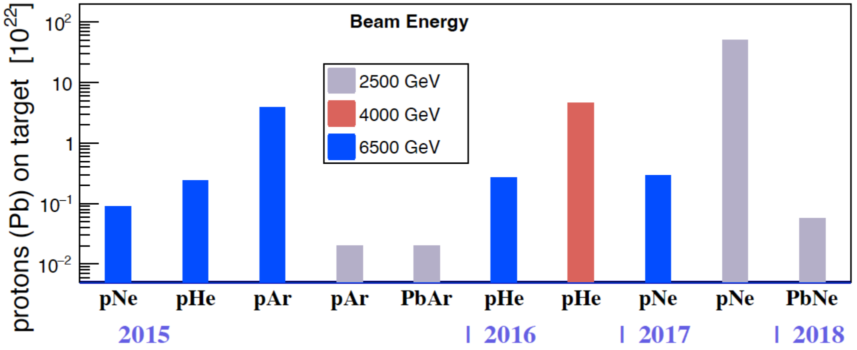
Available Datasets

RHIC
- **Collider: 7.7 – 62.4 GeV**
- **FXT: 3.0 – 13.7 GeV**

LHCb (SMOG)
- **FXT: 40 – 115 GeV**



STAR Beam Use Request

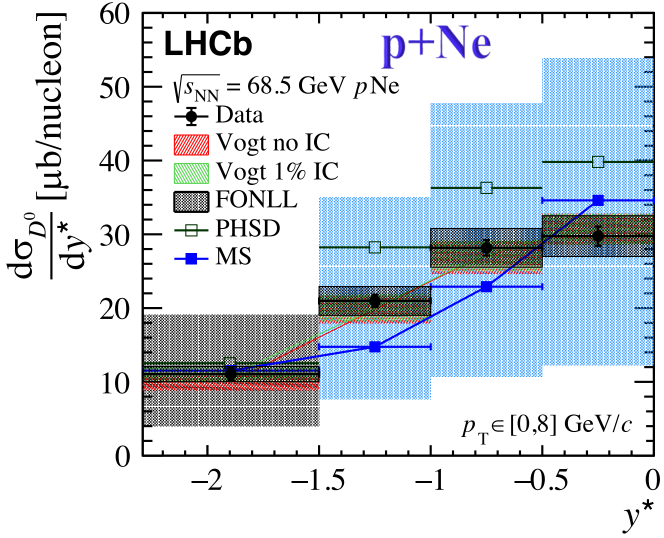


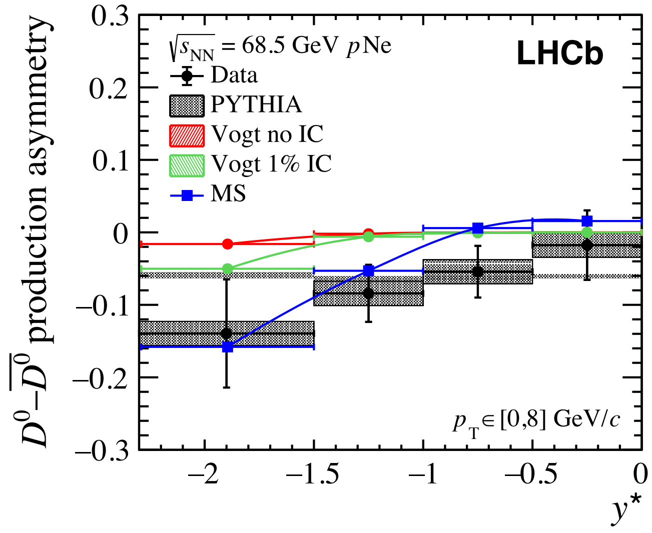
https://cds.cern.ch/record/2649878/

Intrinsic Charm Search at LHCb with D^0

$|uud c\bar{c}\rangle$

K. Mattioli, Mar 28, 15:00



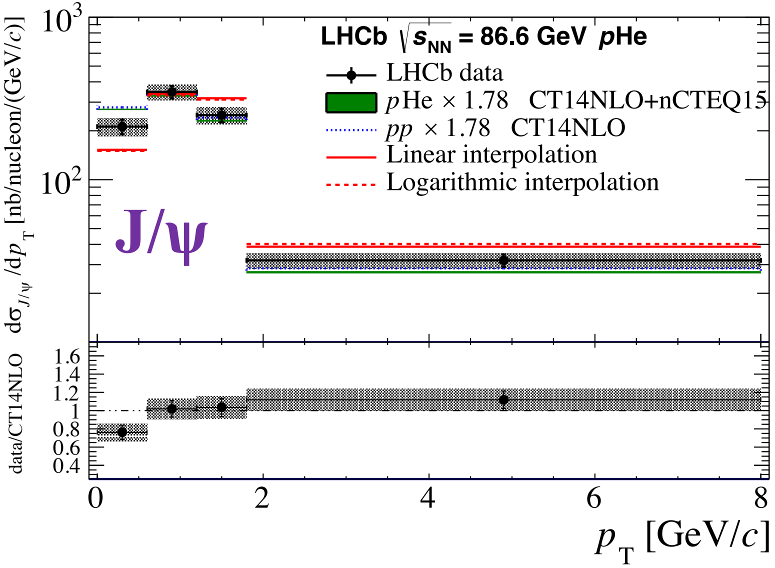


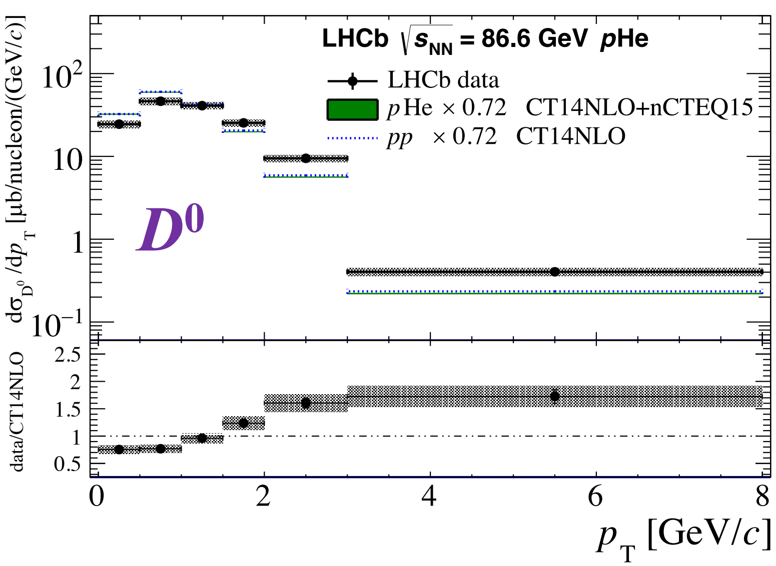
- Cross section: consistent with R. Vogt's calculation w/ and w/o 1% intrinsic charm
  - PDF and scale uncertainties only shown for FONLL
- Asymmetry: consistent with MS calculation with 1% intrinsic charm and 10% recombination

LHCb, arXiv:2211.11633, Vogt: PRC 103 (2021) 035204; MS: PLB 835 (2022) 137530; FONLL: PRL 95 (2005) 122001, JHEP 05 (2998) 007; PHSD: PRC 96 (2017) 014905

Charm Production in pHe @ 86.6 GeV

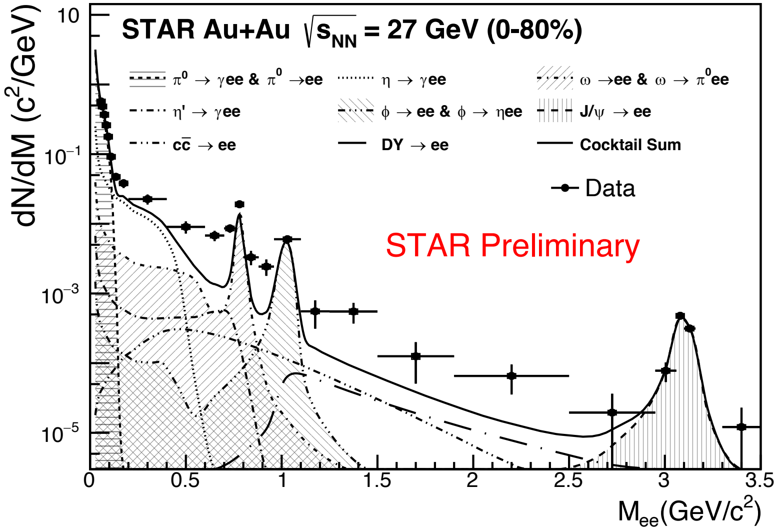
LHCb, PRL 122 (2019) 132002

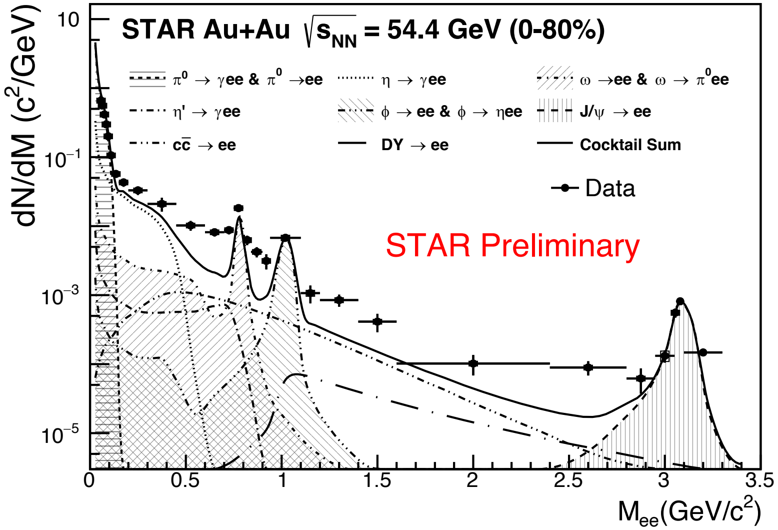




- First measurement of heavy-flavor cross section using FXT data at LHCb
- CT14NLO+nCETQ15 under(over)predicts total J/ψ (D^0) cross section, and could not reproduce the shapes. → No sign of intrinsic charm.
- Need p+p reference to quantify cold nuclear matter effects

Fully Corrected Invariant Mass Distribution



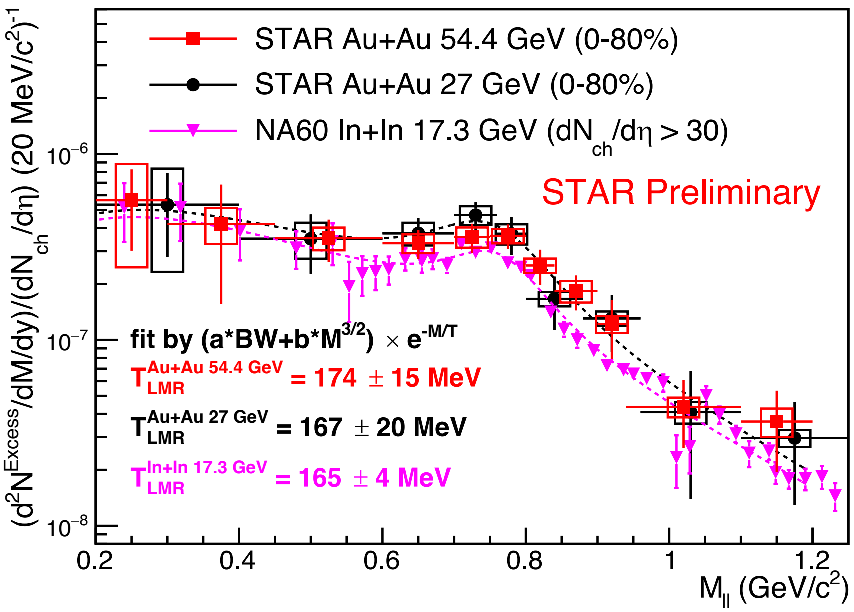


- Cocktail of hadronic sources, except for ρ, are subtracted to obtain excess yields

Temperature at Low Mass Region

- Fit invariant mass < 1.2 GeV/c^2 with relativistic Breit-Wigner function multiplied by $e^{-M/T}$

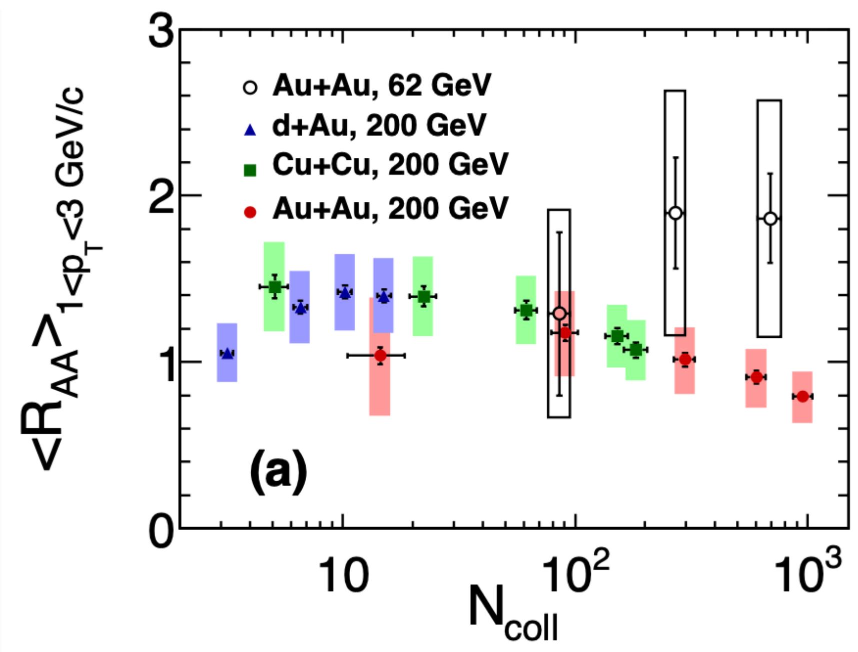
- *T* close to the phase transition temperate (T_{pc})
  - Similar *T* at 17.3 - 54.4 GeV despite a factor of 3 difference in collision energy
  - In-medium ρ mainly produced close to the phase boundary



NA60, EPJC 59 (2009) 607

HF Electron R_{AA} at 62.4 GeV

PHENIX, PRC 91 (2015) 044907



- Hint of enhancement at 62.4 GeV compared to suppression at 200 GeV for $1 < p_T < 3$ GeV/c
  - Larger Cronin effects
  - Less jet quenching

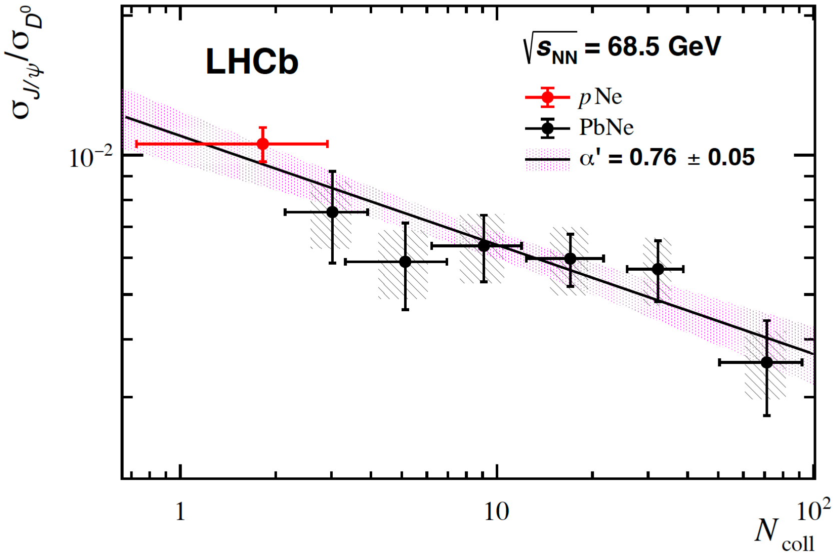
First Measurement in Pb+Ne FXT at LHCb

K. Mattioli, Mar 28, 15:00

LHCb, arXiv:2211.11652
LHCb, arXiv:2211.11645

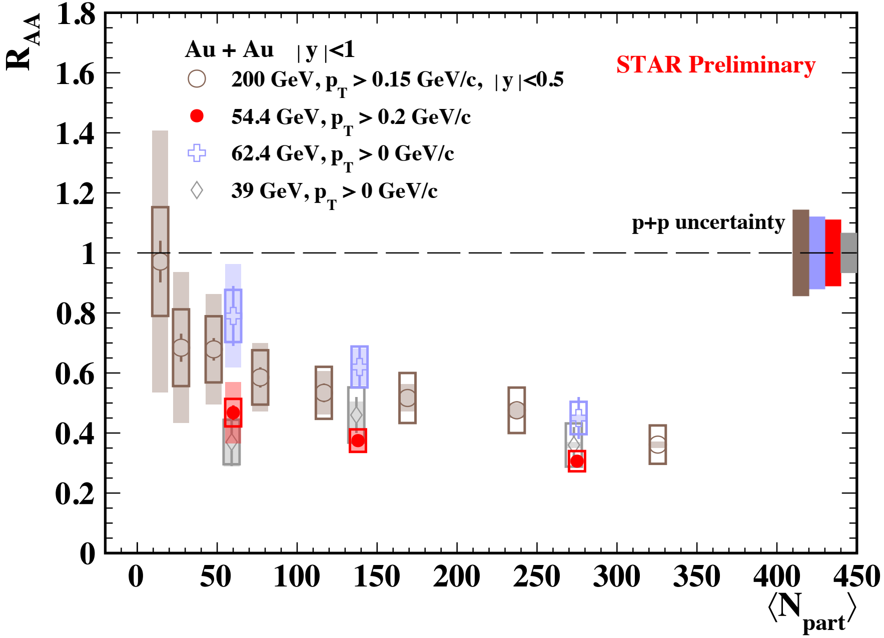
Assuming

$$\sigma_{D^0}^{AB} = \sigma_{D^0}^{pp} \times AB$$
$$\sigma_{J/\psi}^{AB} = \sigma_{J/\psi}^{pp} \times AB^{\sigma}$$
$$\frac{\sigma_{J/\psi}^{AB}}{\sigma_{D^0}^{AB}} = C \times AB^{\sigma-1}$$



- Clear nuclear effects on *J/ψ* compared to D^0
- Need more data in pA collisions to be conclusive

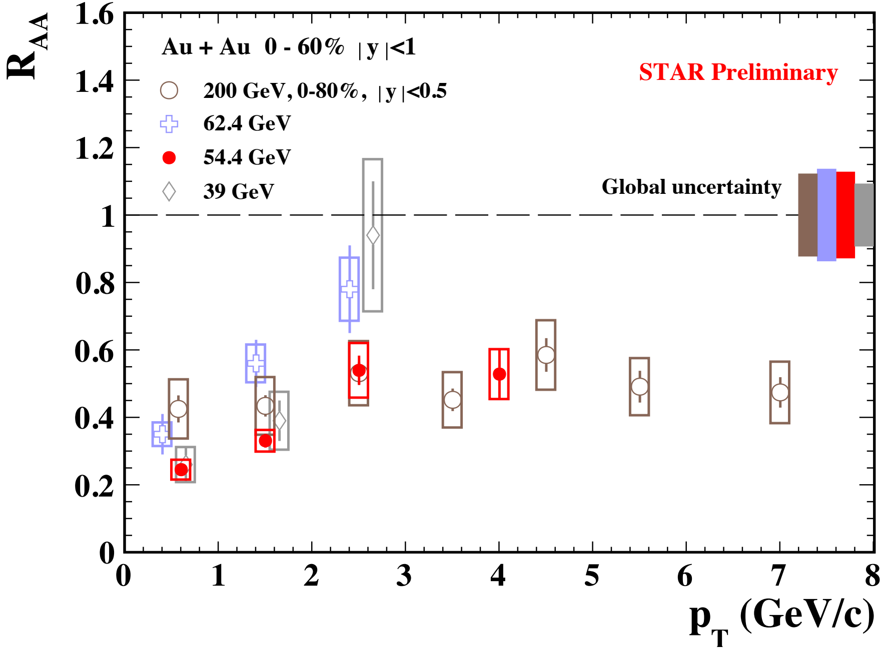
J/ψ R_{AA} as a Function of Centrality



STAR, PLB 771 (2017) 13
STAR, PLB 797 (2019) 134917

- Significant J/ψ suppression in central collisions at 39 – 200 GeV
- Similar suppression levels at different energies for a given centrality
  - Competition of dissociation and regeneration

J/ψ R_{AA} as a Function of p_T



STAR, PLB 771 (2017) 13
STAR, PLB 797 (2019) 134917

- Different p_T dependences
  - 200 GeV: almost flat
  - 39-62.4 GeV: clear rising trend
- At lower energies
  - Low p_T: more cold nuclear matter effects, e.g. nuclear break, and less regeneration contribution