Electromagnetic and hard probes to study QGP at RHIC
(Recent highlights)

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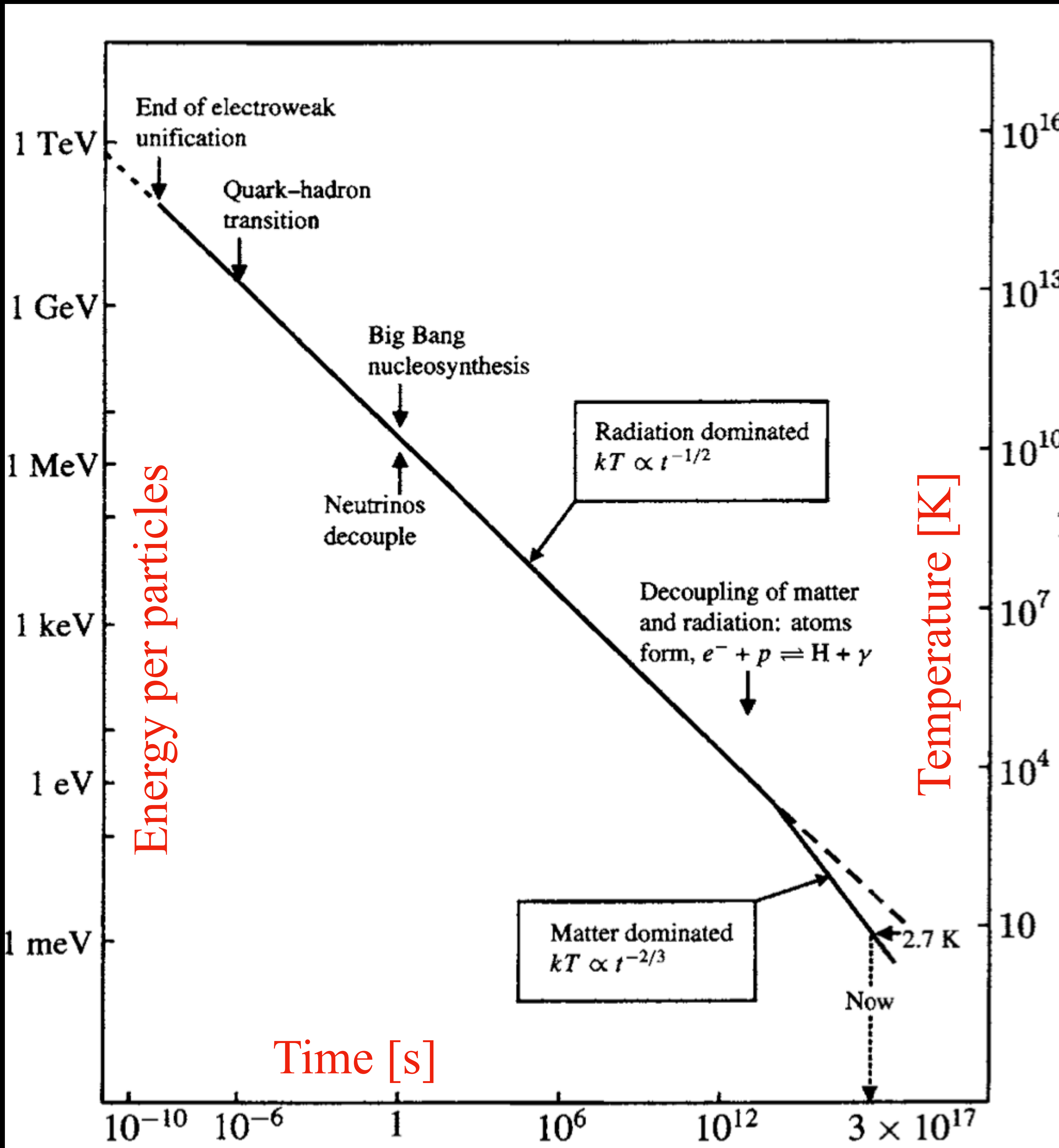
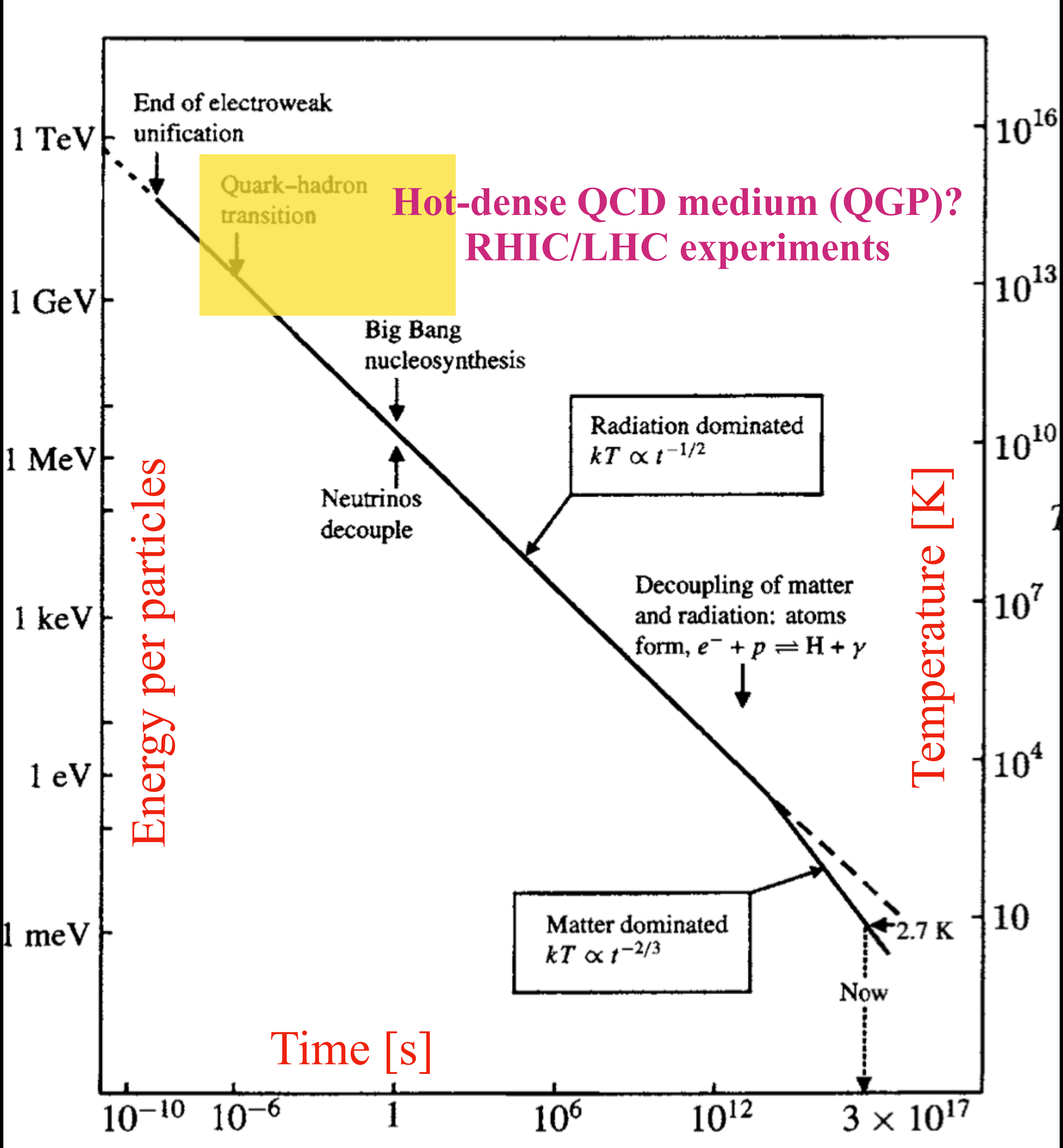
CETHENP 2022, VECC



Era of our universe and temperature-energy scale

Book by Donald H. Perkins: Introduction to high energy physics (Fig-10.3)



Era of our universe
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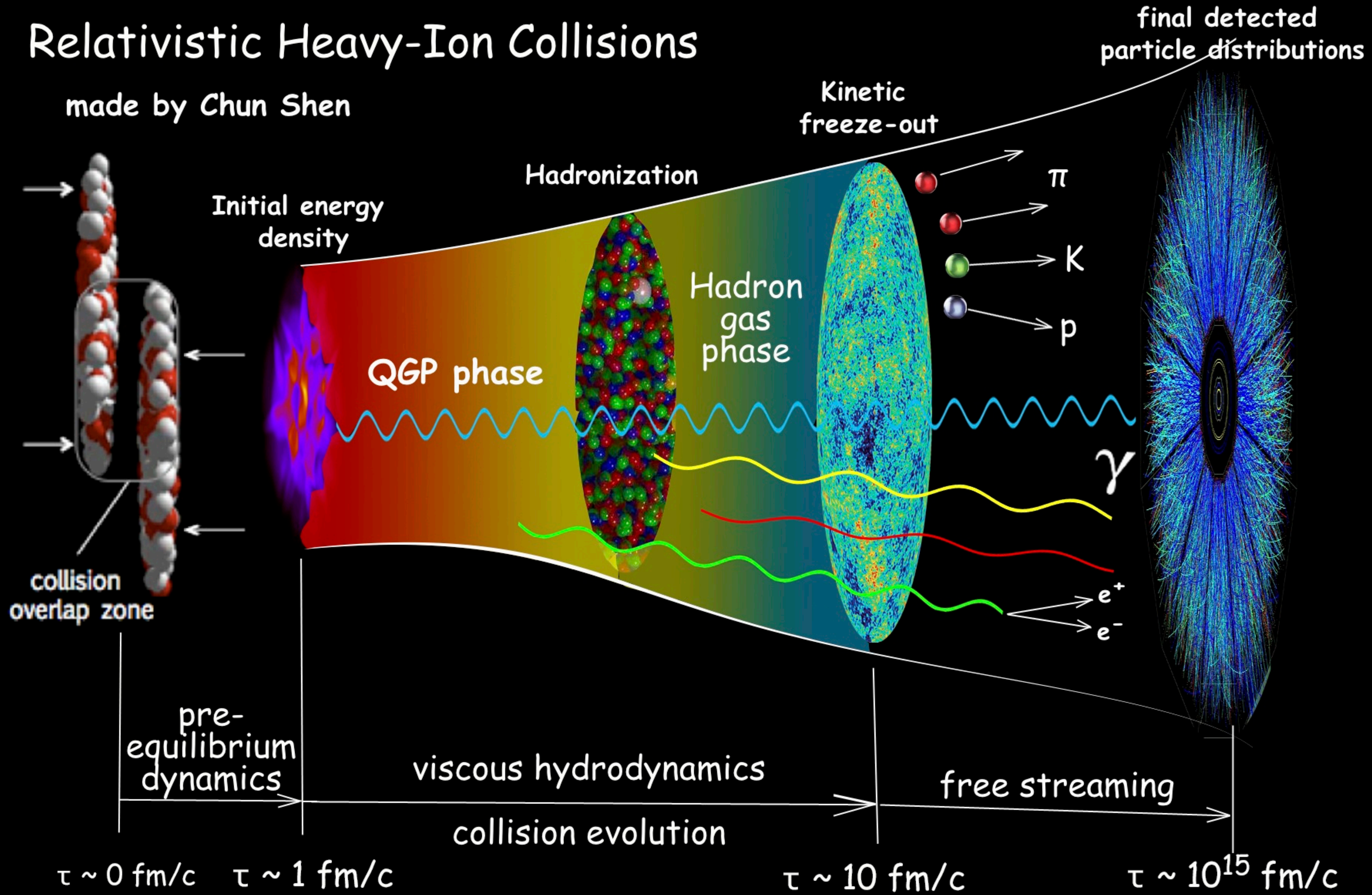
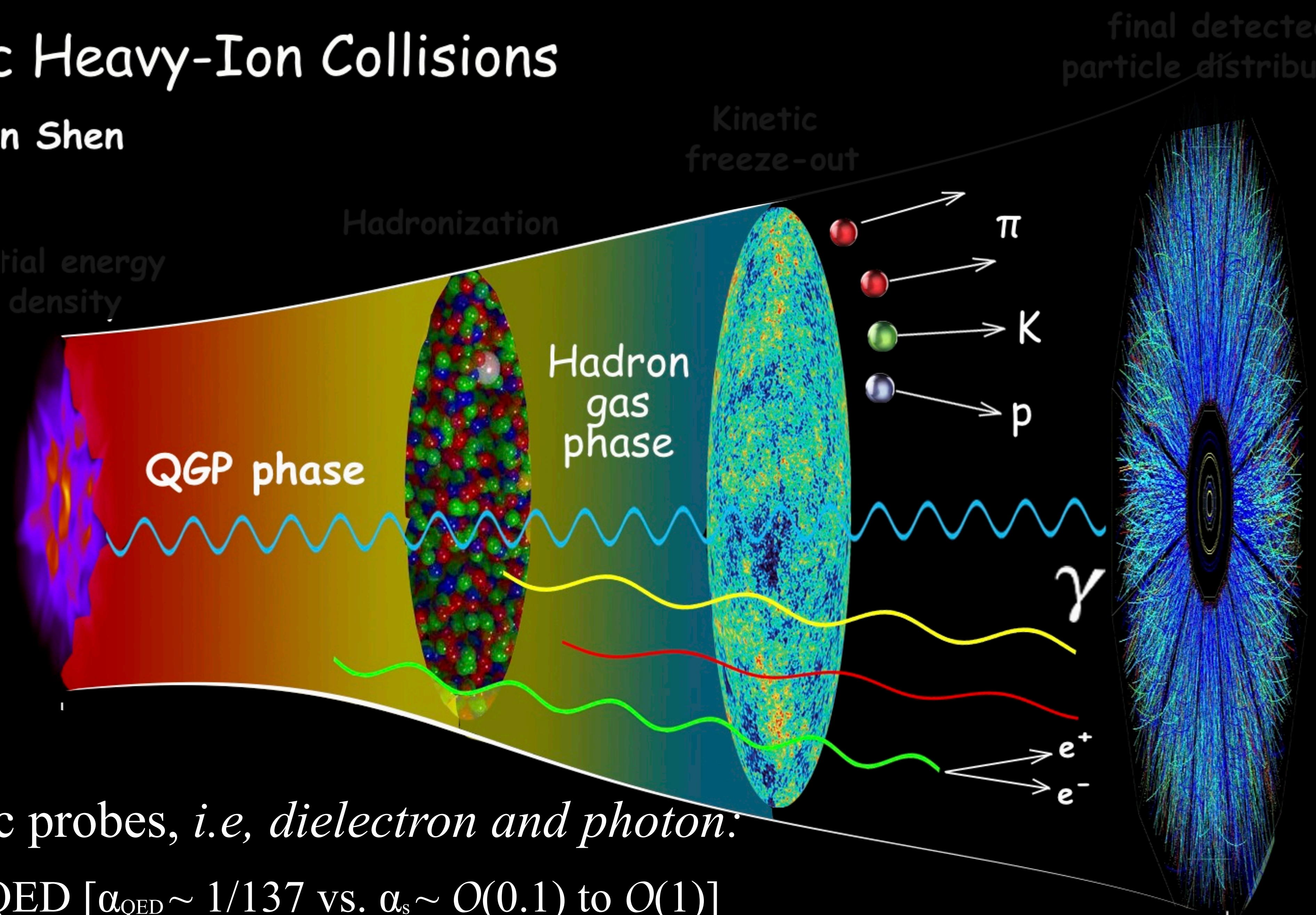

Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e^+
e^-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^{15} fm/c

Relativistic Heavy-Ion Collisions

made by Chun Shen



Electromagnetic probes, *i.e, dielectron and photon:*

- Interact by QED [$\alpha_{QED} \sim 1/137$ vs. $\alpha_s \sim O(0.1)$ to $O(1)$]
- Mean free path larger than size of fireball (l > ~10 fm)
- Produced at all stages of the evolution in heavy-ion collisions

Relativistic Heavy-Ion Collisions

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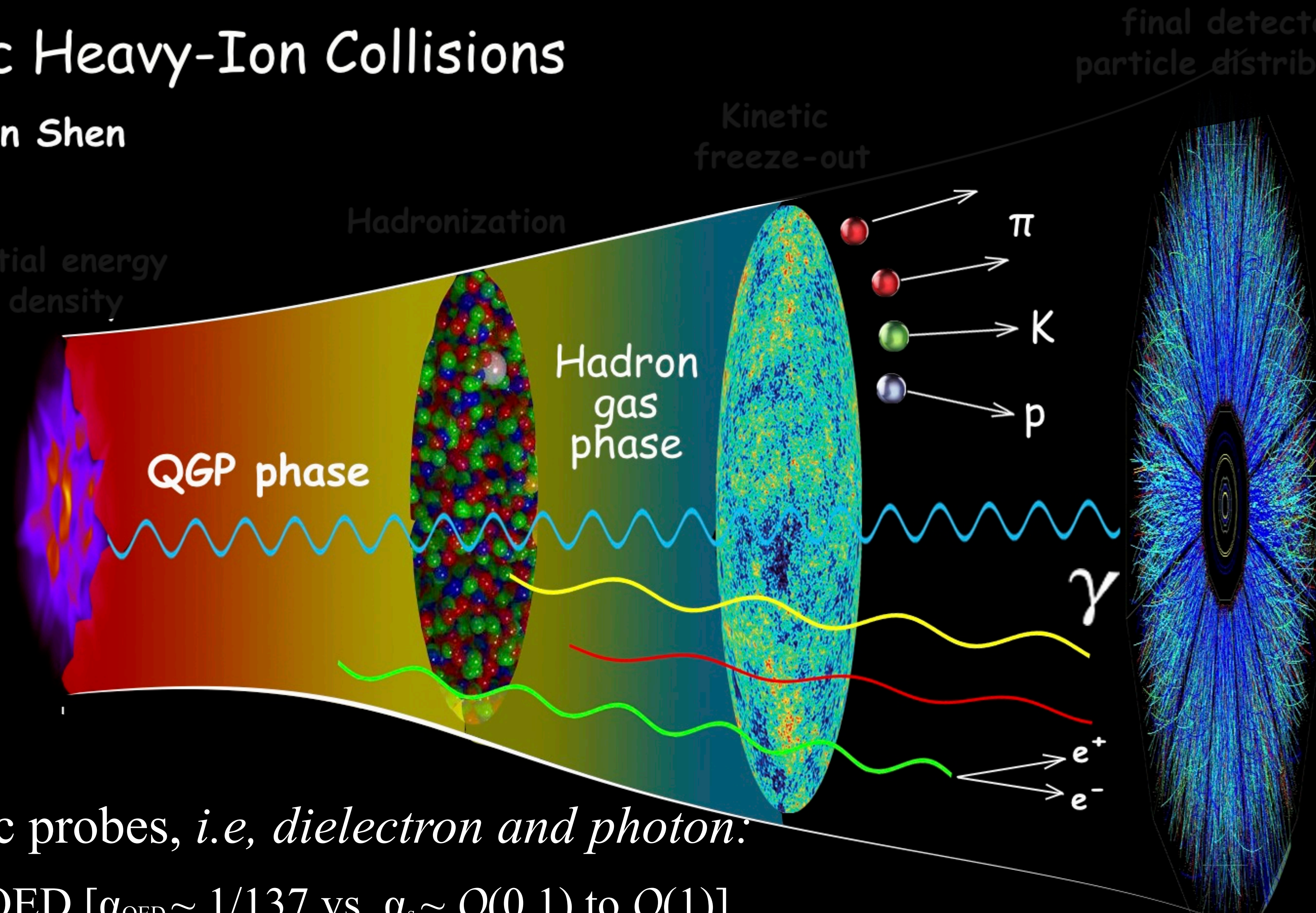

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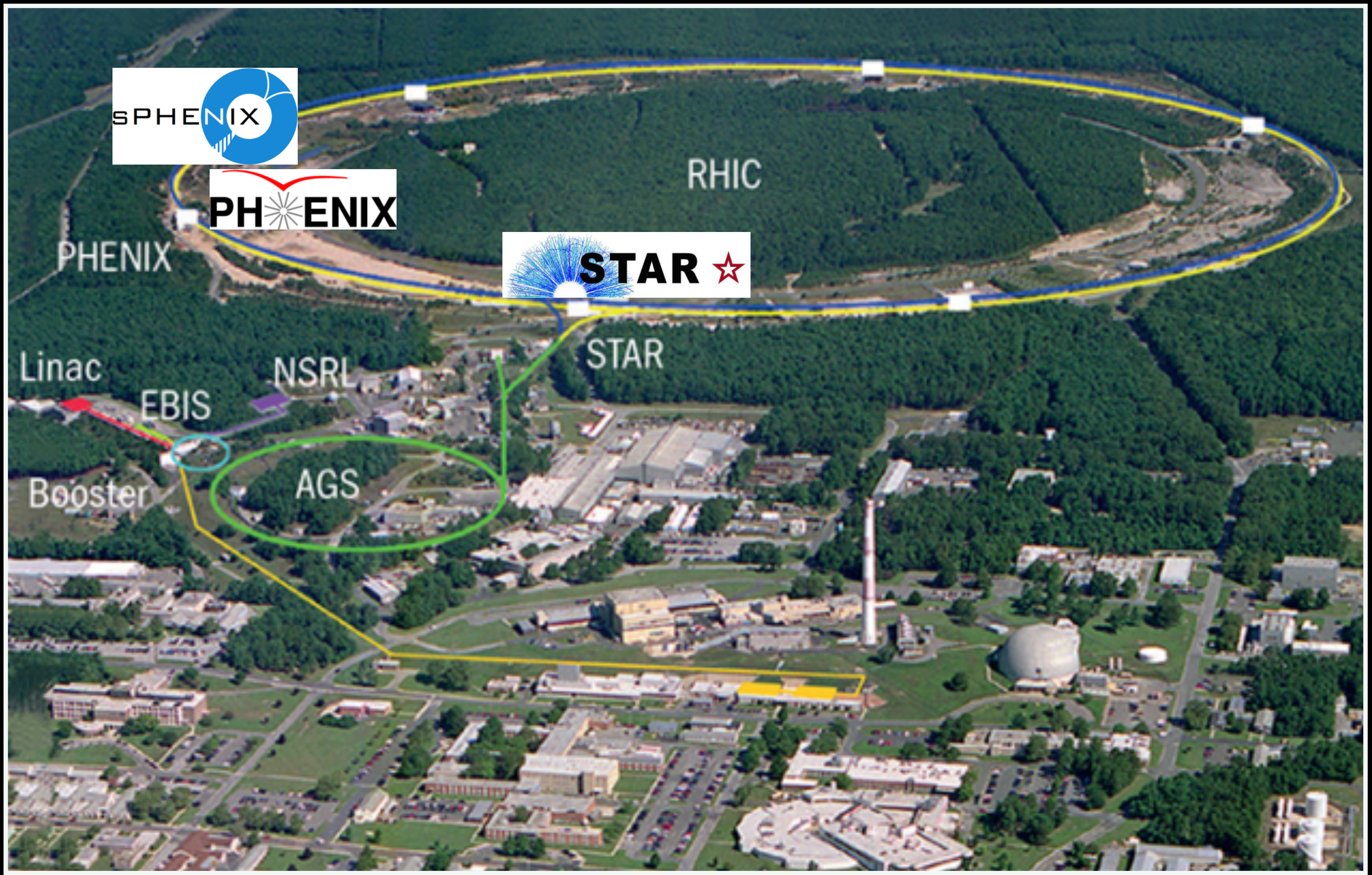
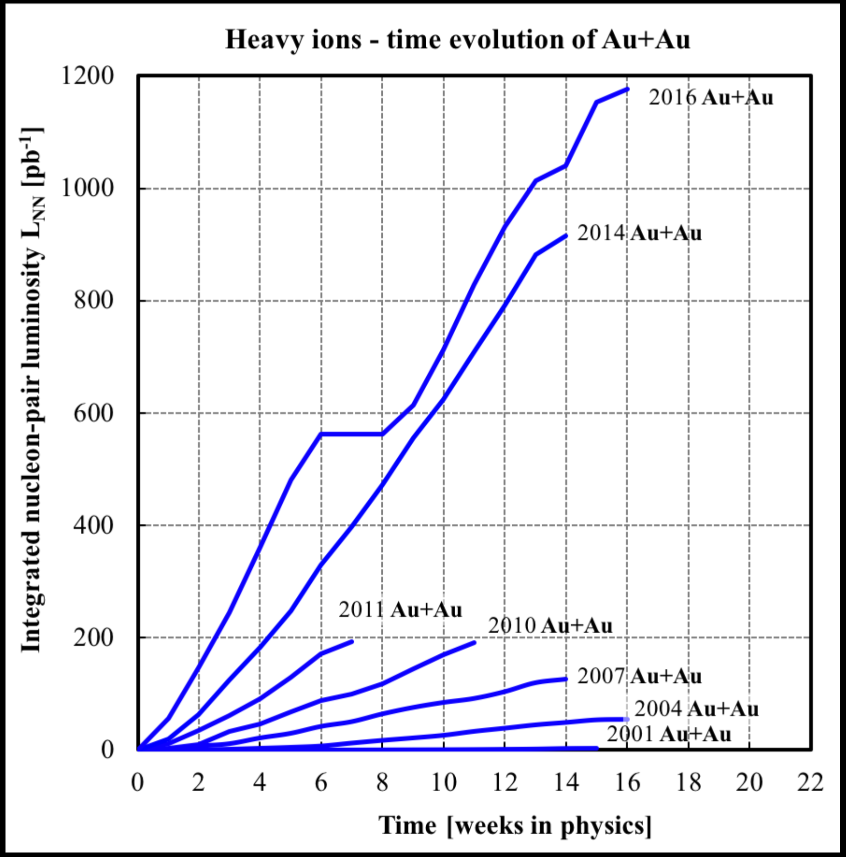
Hard probes, *i.e., jets and heavy-flavors:*

- Produced by hard-scattering (momentum transfer, Q >> Λ_{QCD})
- Produced at very early stage of the collisions ($\Delta t \sim 1/Q$)

Relativistic Heavy-Ion Collider (RHIC), Brookhaven Nation Laboratory, New York, USA





Center of energy: 7.7 to 200 GeV

QCD medium: Au+Au, Cu+Cu, U+U, Ru+Ru, Zr+Zr, p+Au, d+Au
QCD vacuum: p+p

At RHIC energy,

What is the temperature and property of the medium ?

How does an energetic (heavy/light) quark/gluon interact with the finite temperature QCD medium?

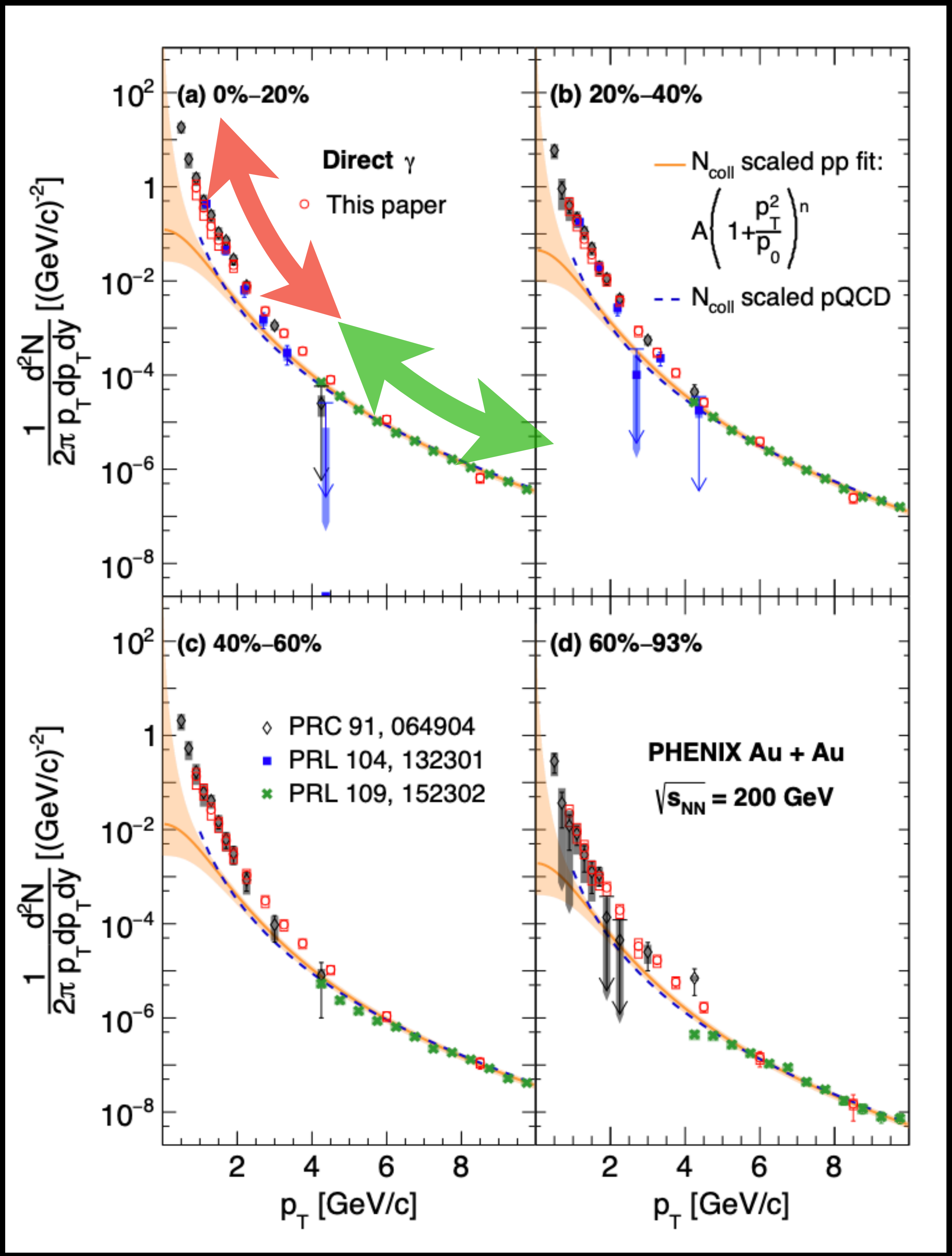
What are the underlying mechanisms of jet quenching at RHIC energies?

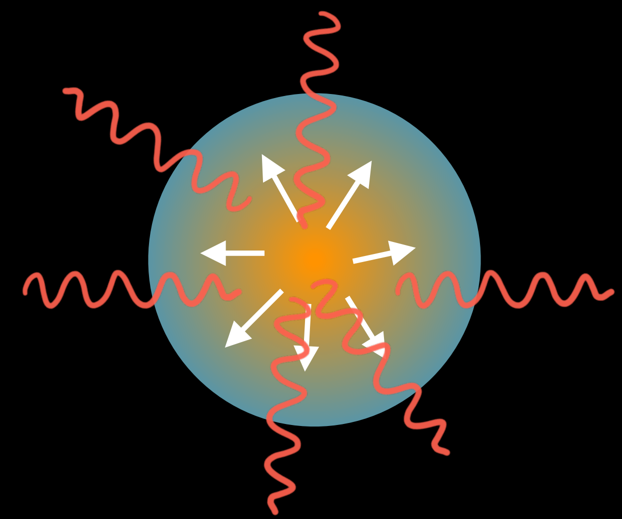
Electromagnetic probes

i.e, dileptron and photon:

Non-prompt direct photon emission in QGP

PHENIX: arXiv:2203.17187





1. High p_T (> 5 GeV/c) :
   N_{coll}-scaled p+p results and pQCD calculation
   → Prompt direct photon

2. Low p_T (< 5 GeV/c) :
   Excess yield compared to prompt photon

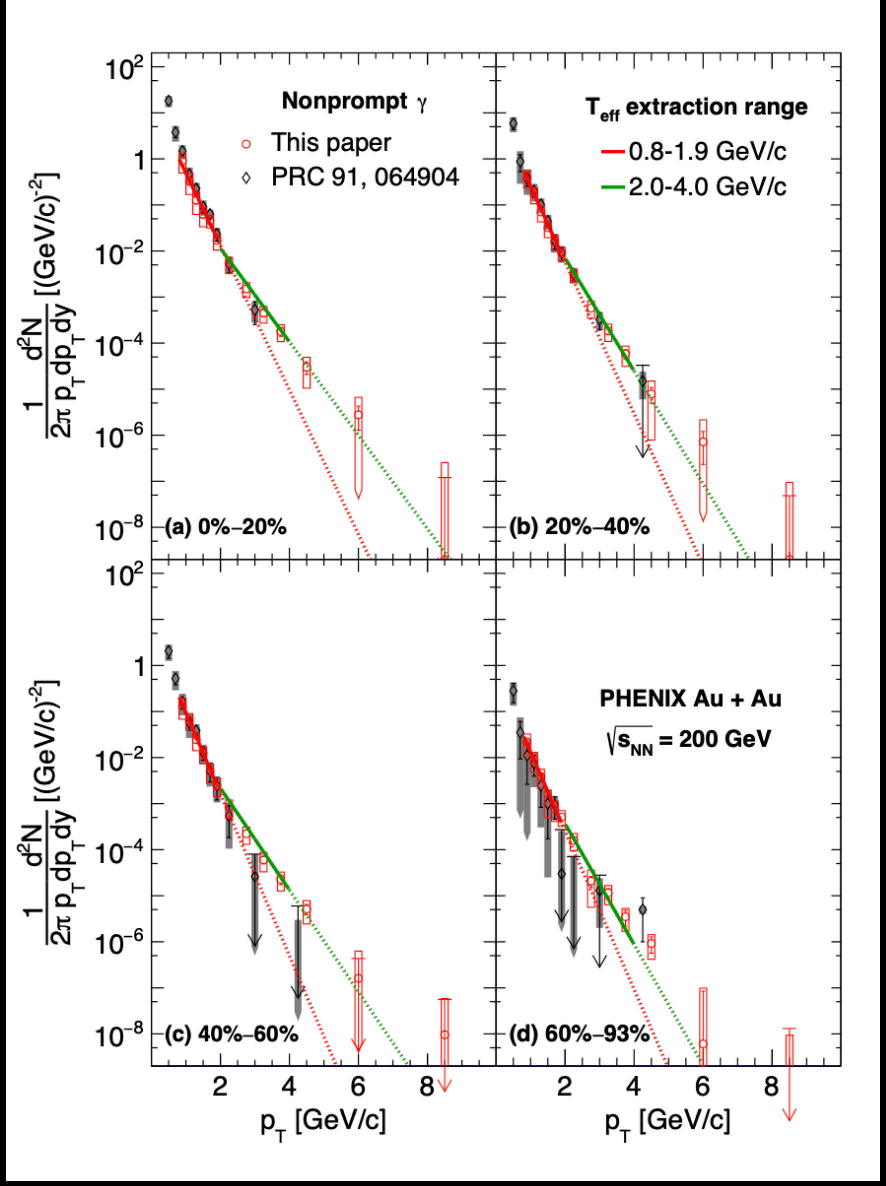
   Being emitted from hot-expanding fireball
   → Non-prompt direct photon

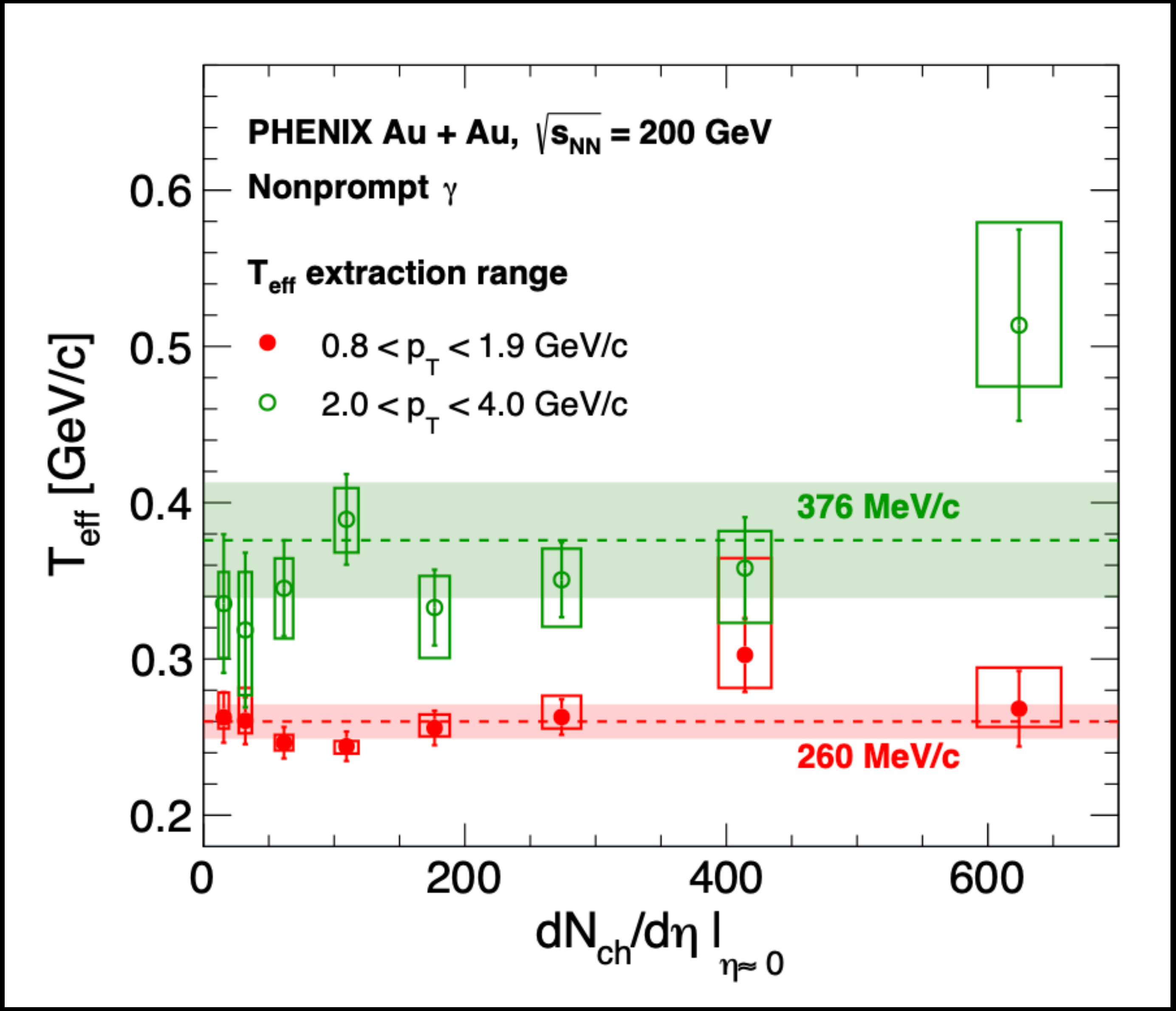
Temperature of medium: from photon measurements

From non-prompt direct photon measurement

$$\frac{d^2N}{p_T dp_T dy} \sim A \,.\exp(-p_T/T_{\rm eff})$$

PHENIX: arXiv:2203.17187





High-pT ($T_{\rm eff}$ = 376 MeV): from earlier phase the evolution

Low-pT ($T_{\rm eff}$ =260 MeV): from QGP phase until FO. → Blue shifted

Hees, Gale, Rapp:
PRC 84 (2011) 054906

Temperature of medium: from photon measurements

From non-prompt direct photon measurement

$$\frac{d^2N}{p_T dp_T dy} \sim A\,.\exp(-p_T/T_{\mathrm{eff}})$$

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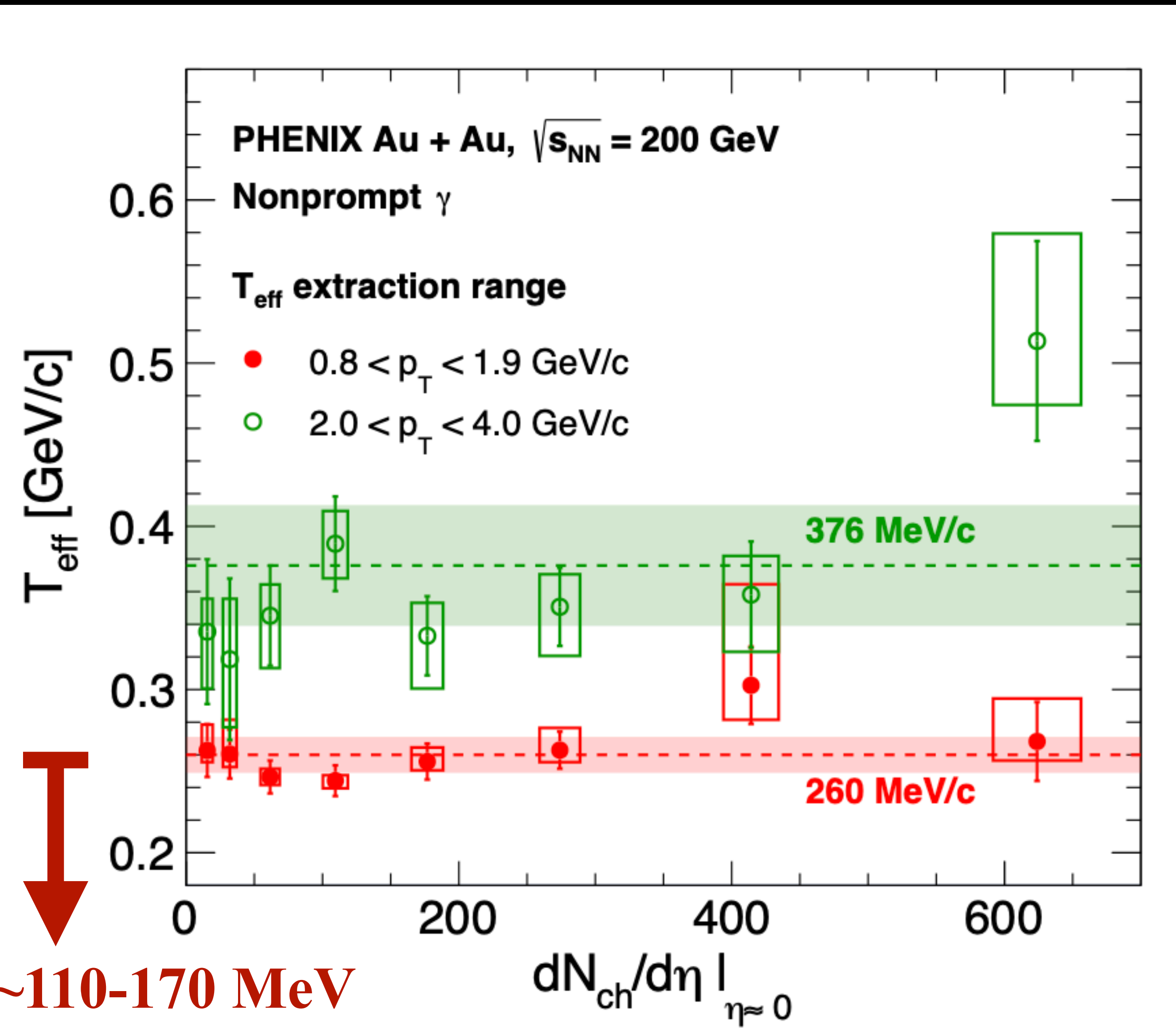
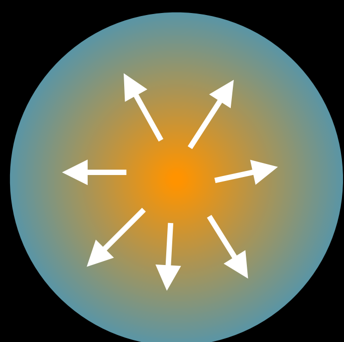


Why blue shift?

Transverse flow of medium



$$T_{\mathrm{eff}} = T\sqrt{\frac{1-\beta}{1+\beta}} \qquad \beta = \mathrm{v}/c$$

True temp. at thermal rest frame, $T < T_{\mathrm{eff}}$

Late QGP stage temperature → **~110-170 MeV**

C. Shen et al., PRC 89, 04491 (2014)

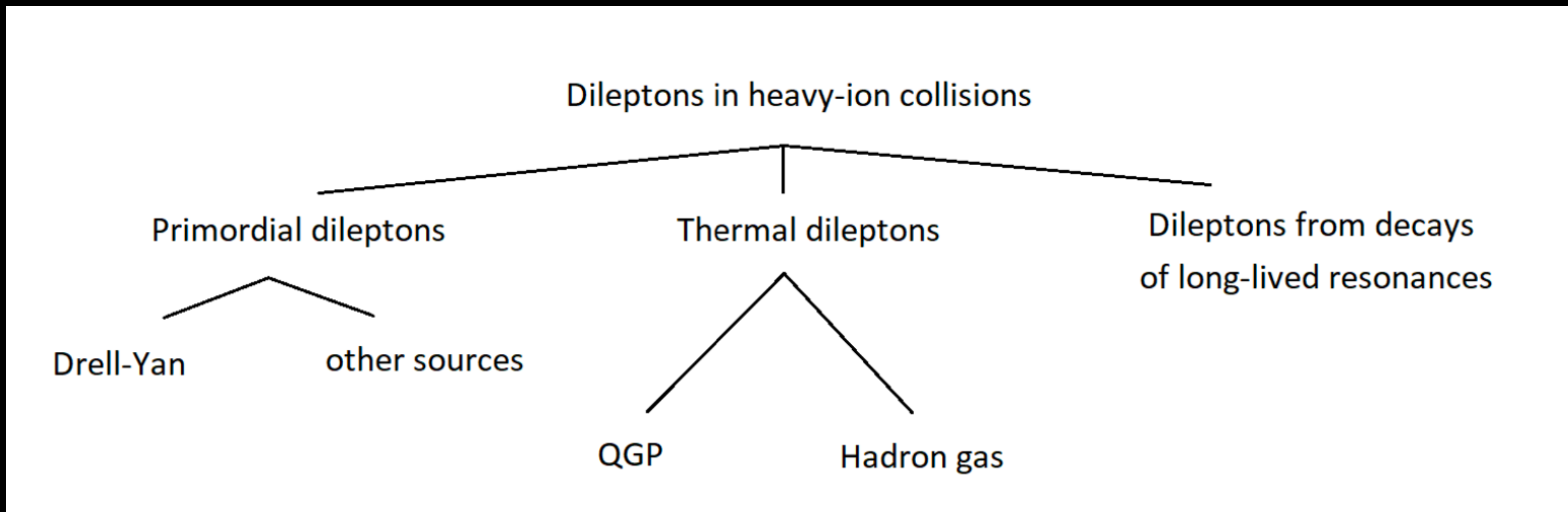
High-pT (T_{eff} = 376 MeV): from earlier phase the evolution

Low-pT (T_{eff}=260 MeV): from QGP phase until FO. → Blue shifted

Hees, Gale, Rapp:
PRC 84 (2011) 054906

Temperature of medium: from dilepton measurement

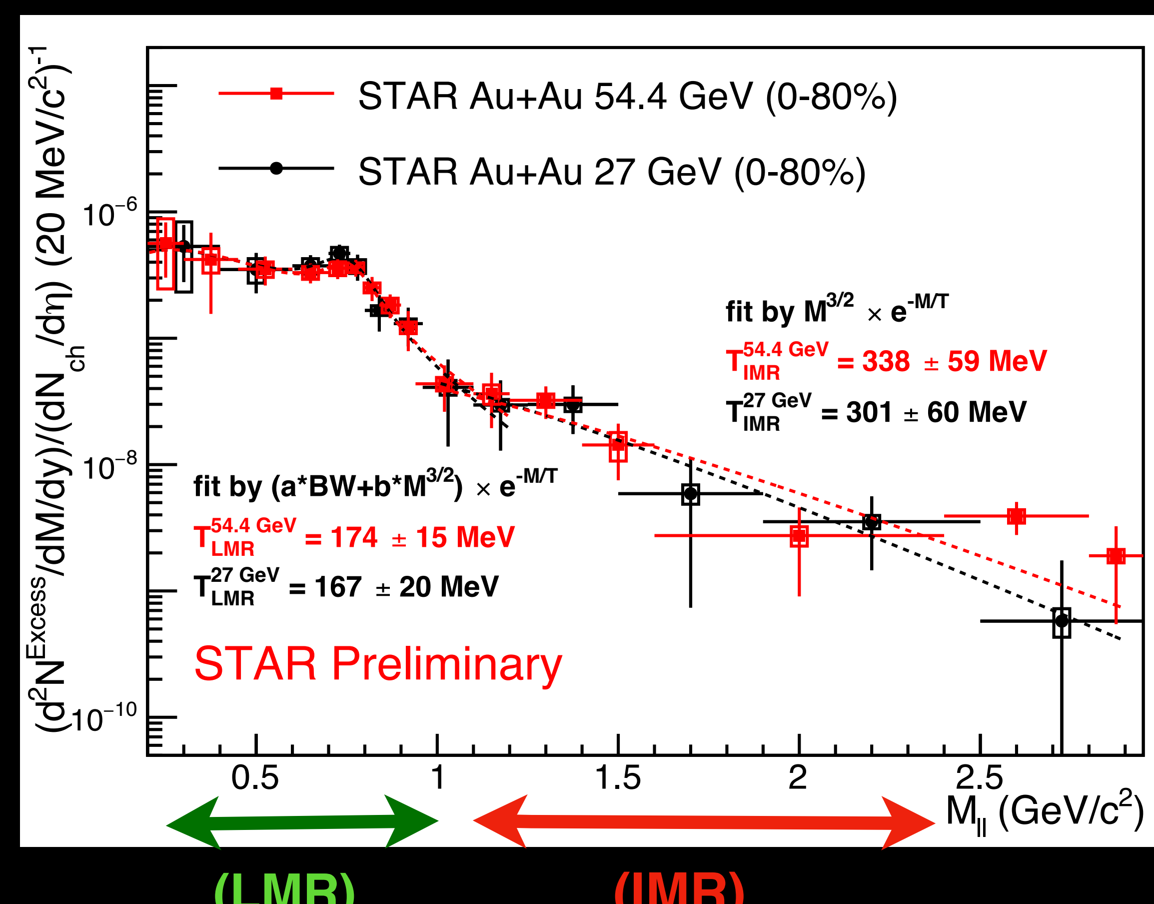
Dileptons in heavy-ion collisions



Tripolt and Geurts (review) arXiv:2210.01622

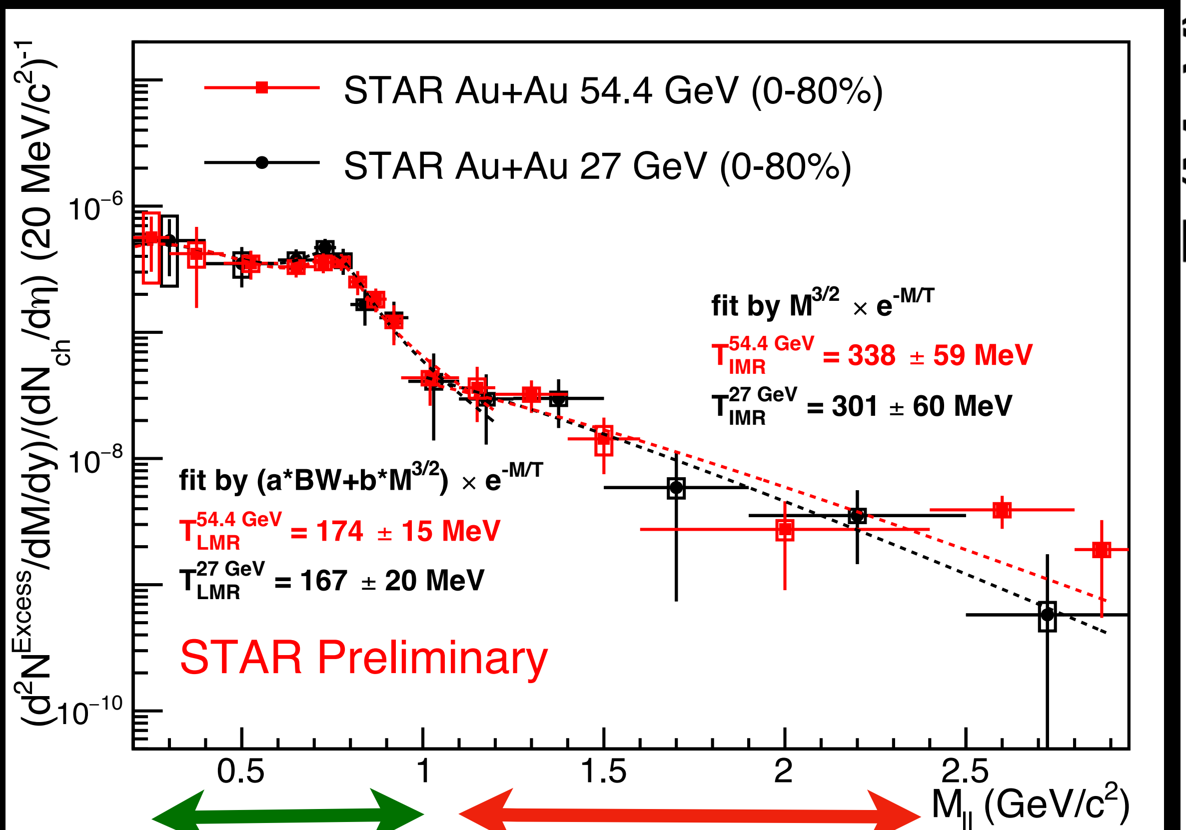
STAR preliminary, QM2022

- Emitted early in collisions
- Temperature without blueshift effect
  - unlike direct photon
  - thermal rest frame, $T = T_{eff}$
- Accessible through in-medium spectral function



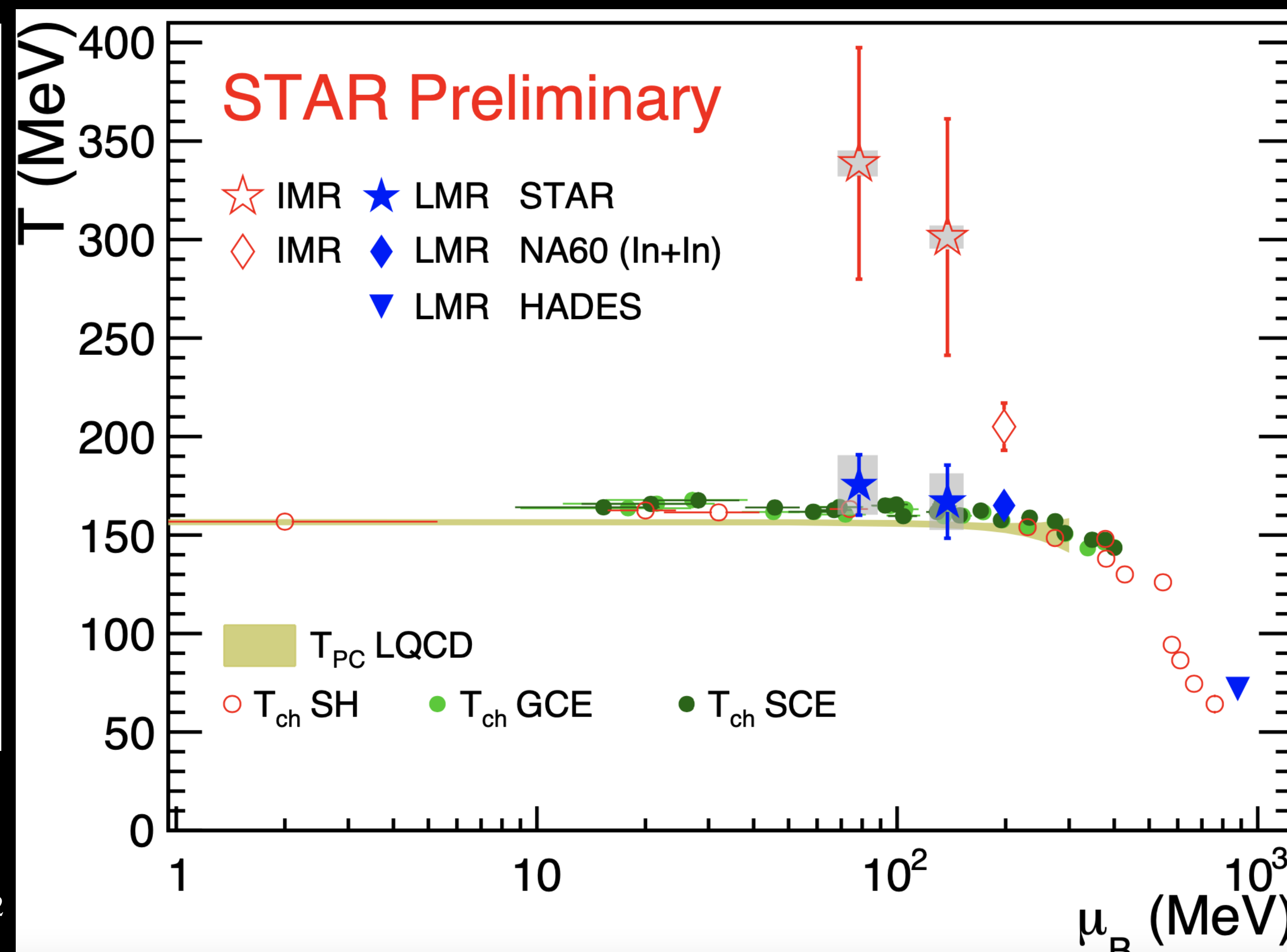
QGP medium temperature with dileptons

Fit function: $M^{3/2}\exp(-M/T)$



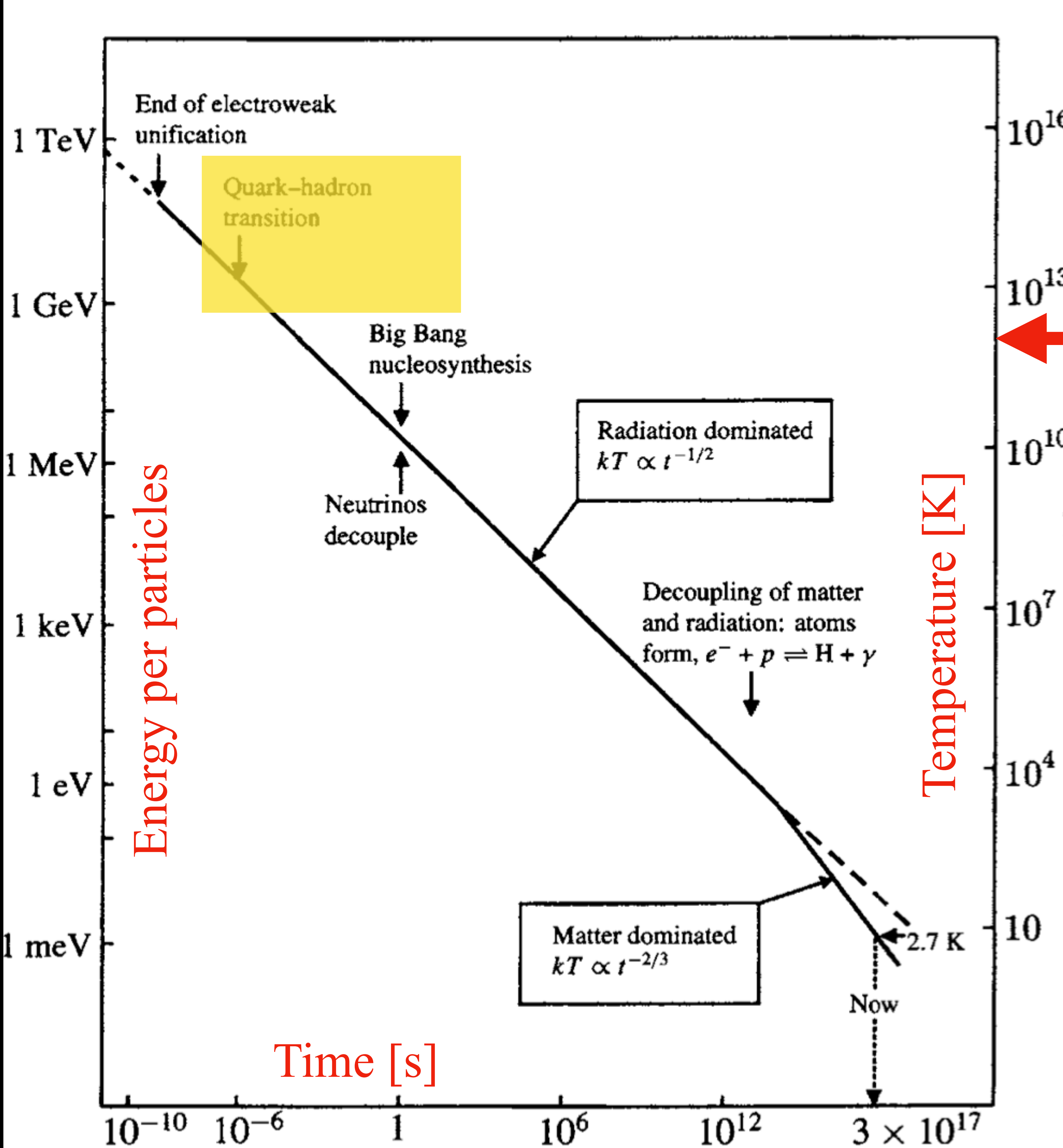
Low Mass region (LMR): $0.2 < M_{ee} < 1.2$ GeV/c^2
Intermediate Mass region (IMR): $1.2 < M_{ee} < 3$ GeV/c^2

STAR preliminary, QM2022



IMR thermal dielectron: $T_{IMR} \sim 320$ MeV

First QGP temperature measurement at RHIC



QGP Temperature at RHIC

~ 3.7 x 10^{12} K

(A quick conversion)

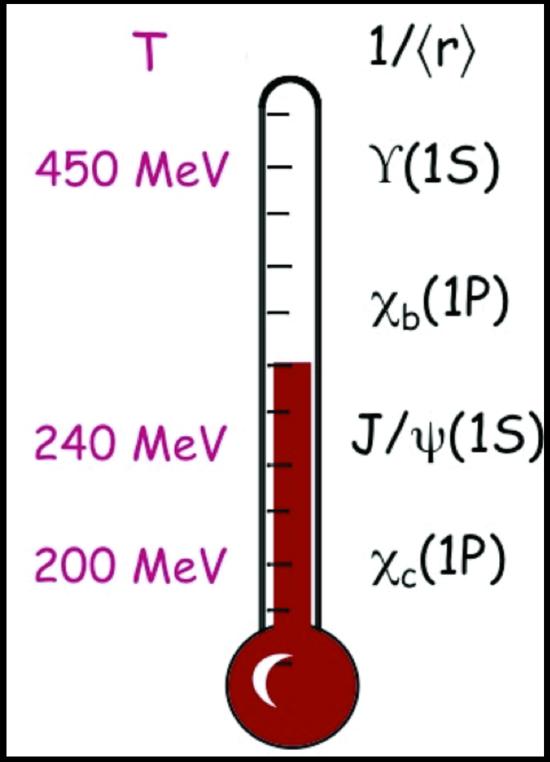
Era of our universe
and
temperature-energy scale

Book by Donald H. Perkins:
Introduction to high energy physics
(Fig-10.3)

Hard probes

i.e, Heavy-flavors and jets

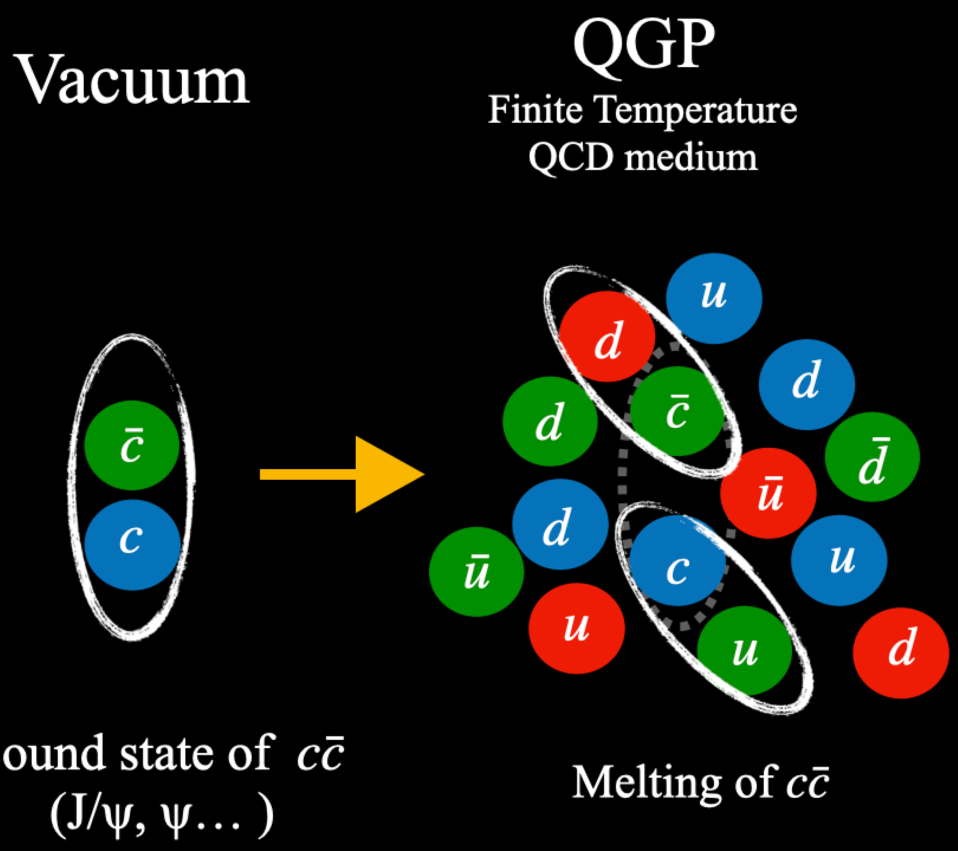
Heavy flavor in QGP



- Heavy flavor

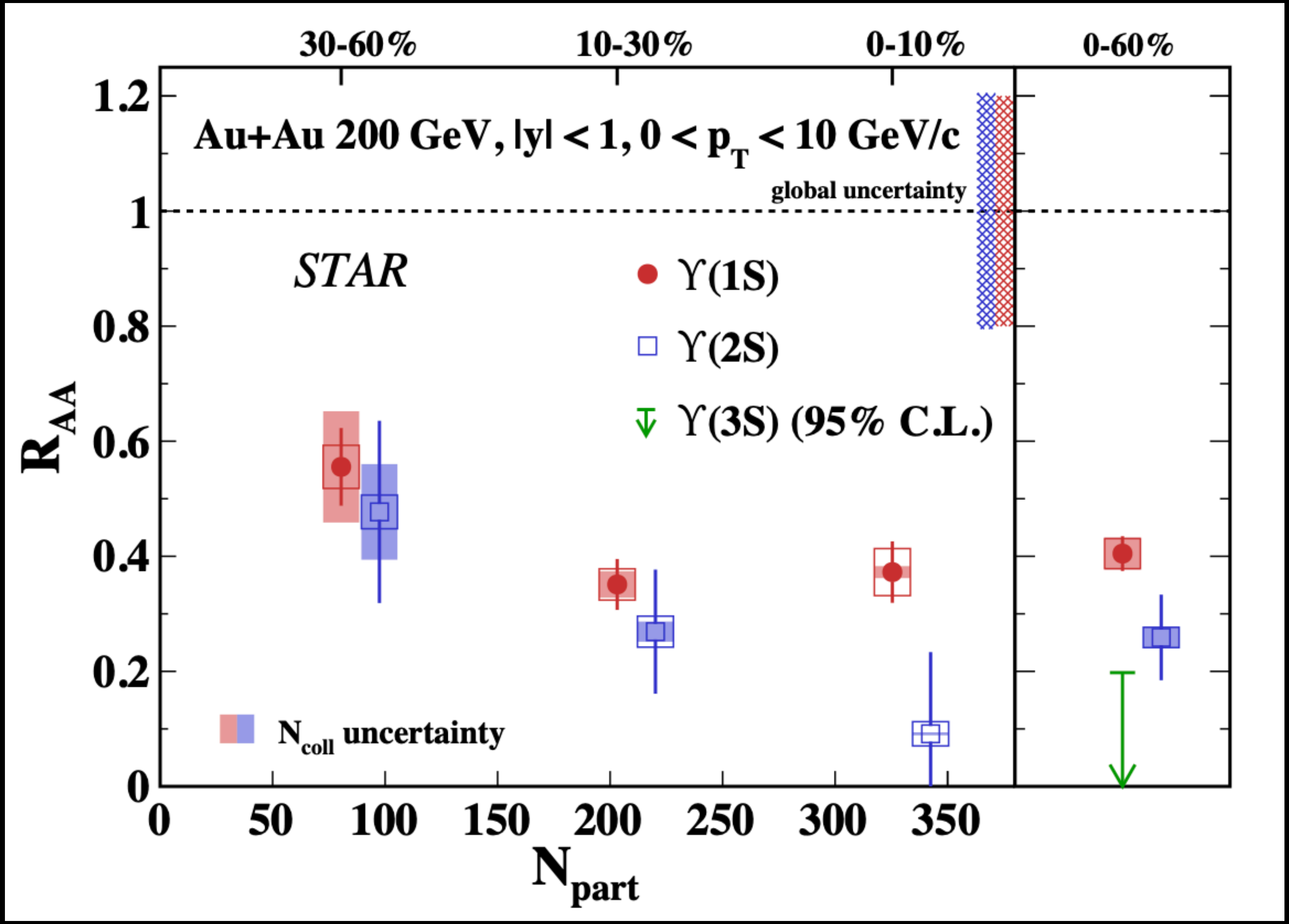
  $m_Q \gg \Lambda_{QCD}$ and T_{QGP}

- Quarkonium (Hidden heavy flavor) $c\bar{c}$, $b\bar{b}$, etc .
  - Debye screening
  - Effect of temperature



Quarkonium melting in the QGP

Studying different states of bottomonia provides information of thermal and dynamical properties of QGP



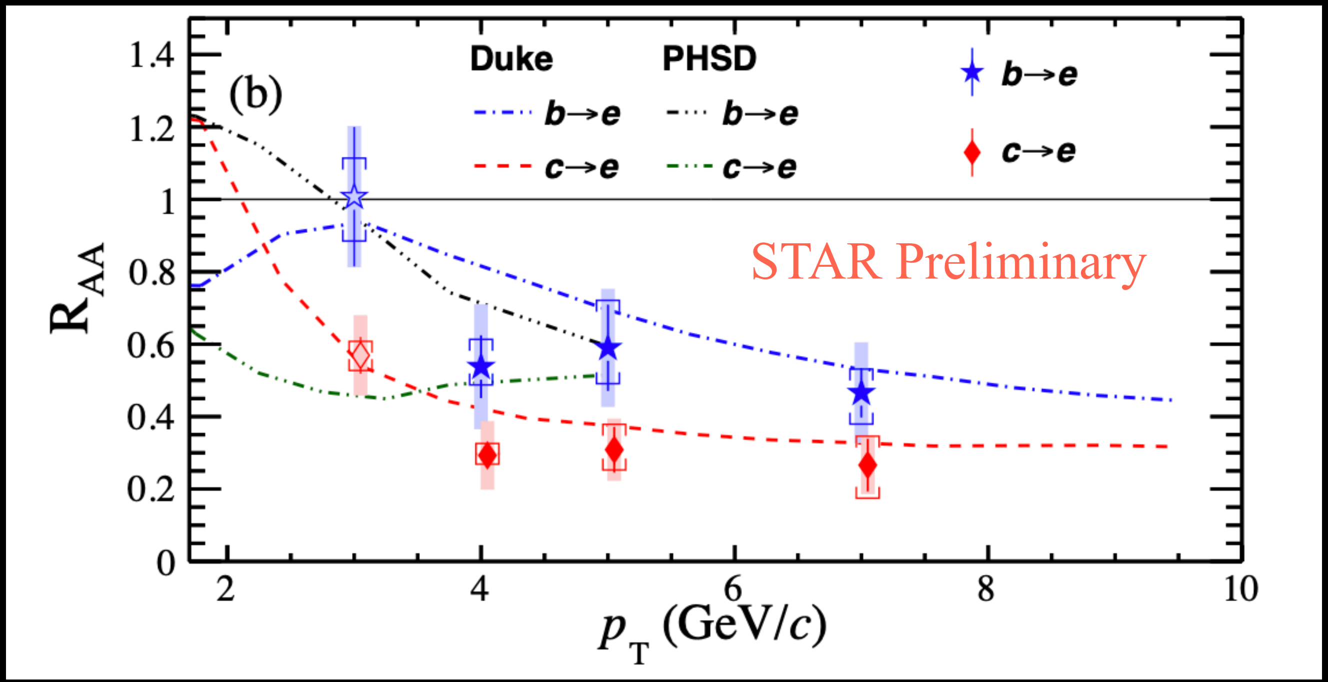
STAR, arXiv: 2207.06568v1

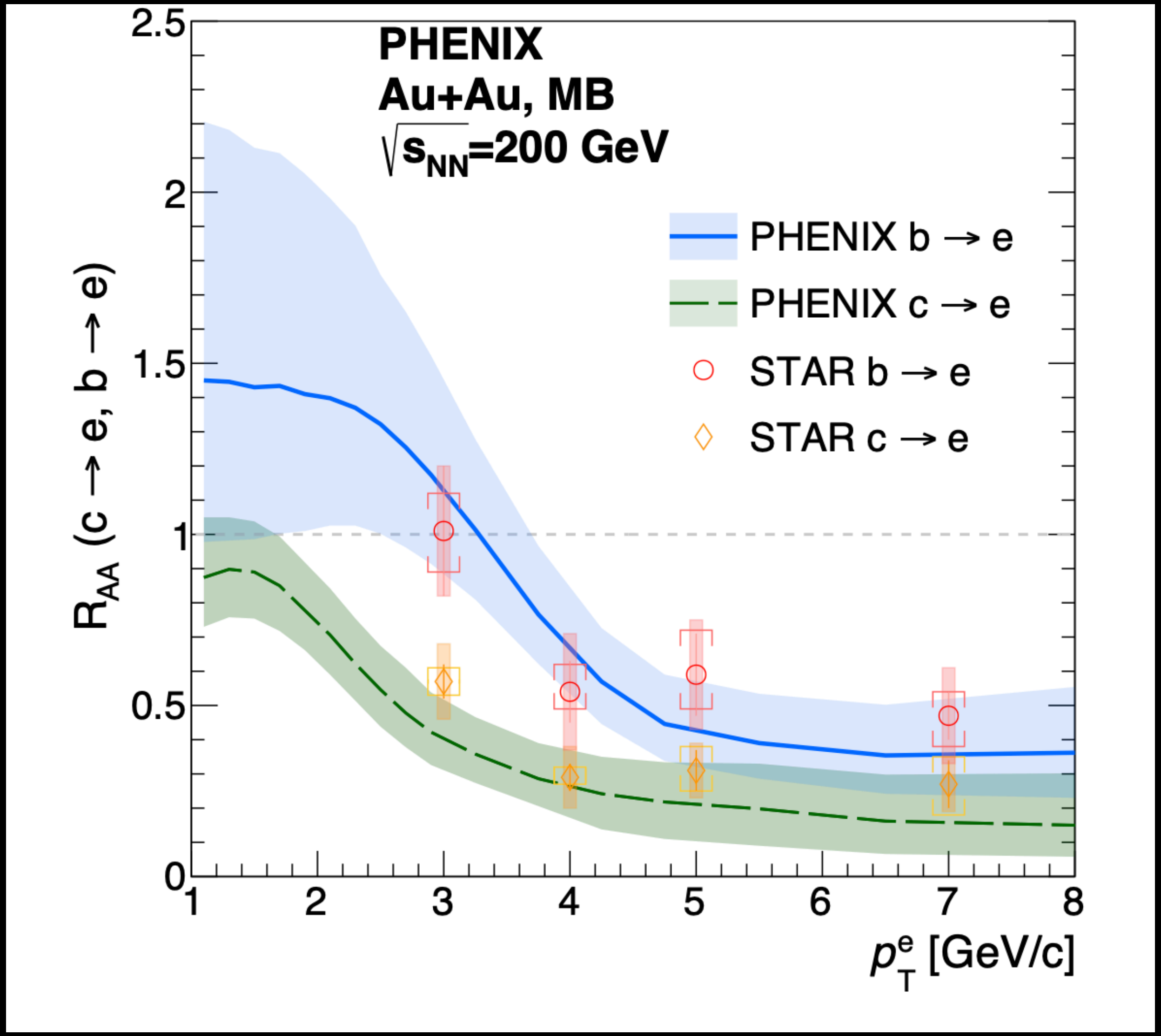
Observed sequential suppression of different $\Upsilon(nS)$ states
$[\Upsilon(1S) > \Upsilon(2S) > \Upsilon(3S)]$

Parton energy loss hierarchy in QGP

- Hierarchy depending upon parton mass and color factor
- RHIC Measurement: electrons from semi-leptonic decays of open charm and bottom hadrons (heavy flavor hadron decay electron- HFE)

PHENIX, arXiv:2203.17058





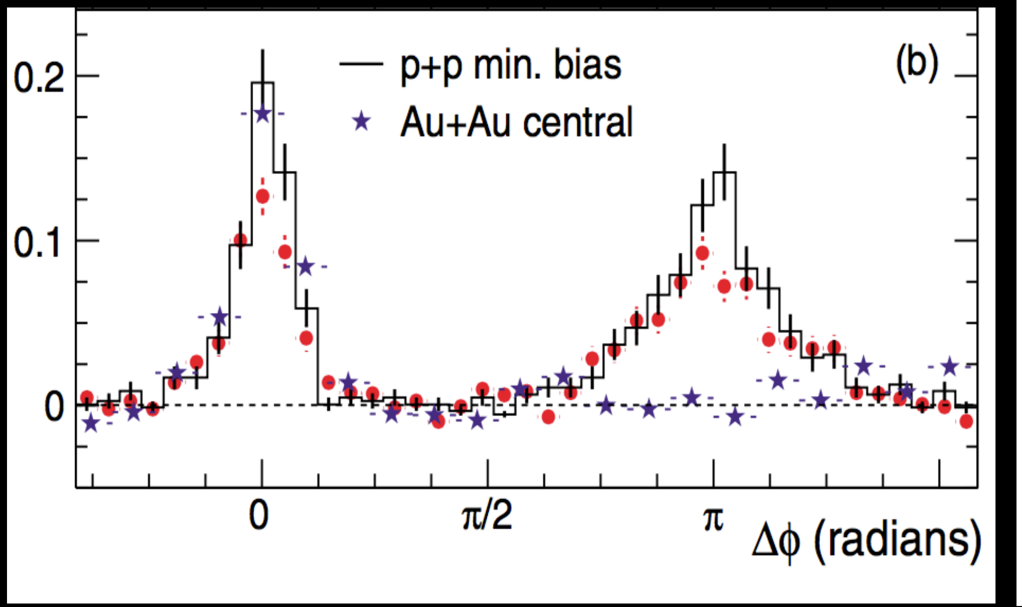
R_{AA} of bottom-decay electron less than that of charm-decay

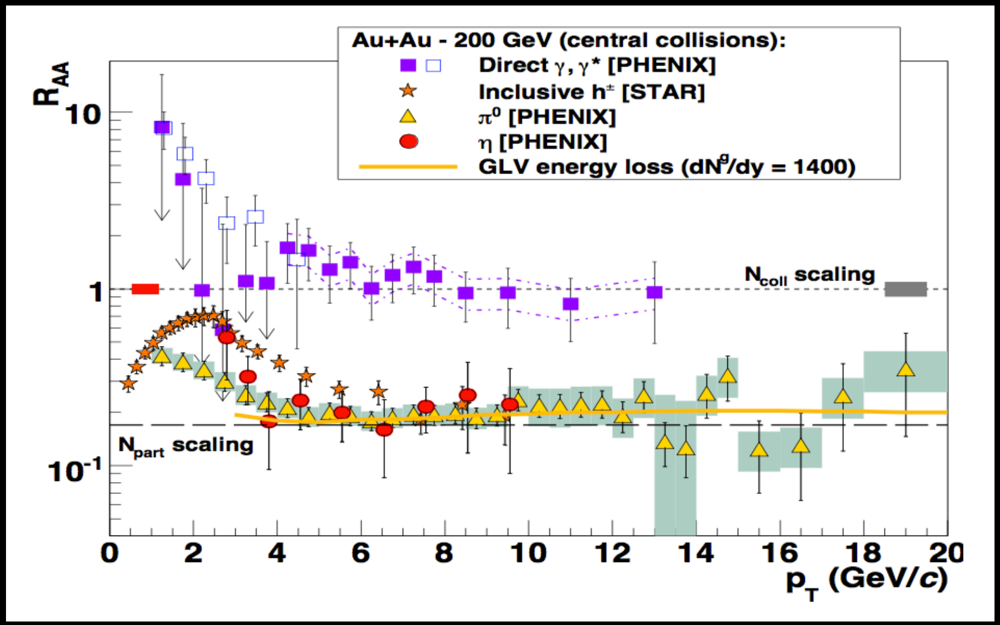
$\Delta E(c) > \Delta E(b)$

Hard probes

jets measurement in heavy-ion collisions at RHIC

Jet quenching at RHIC





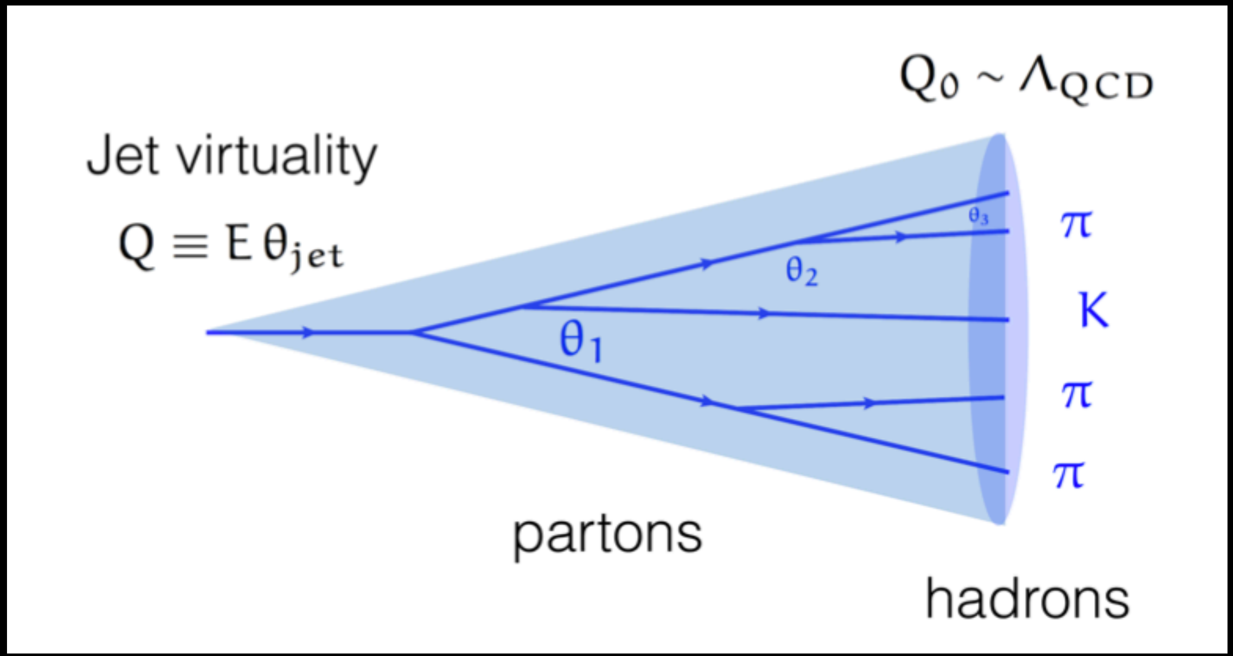
- Suppression of inclusive charged/neutral hadrons at high-p_T
- No suppression of vector boson (γ) $\rightarrow$ T_{AA} scaling holds
- Away-side jet suppression

Jet quenching consequences:

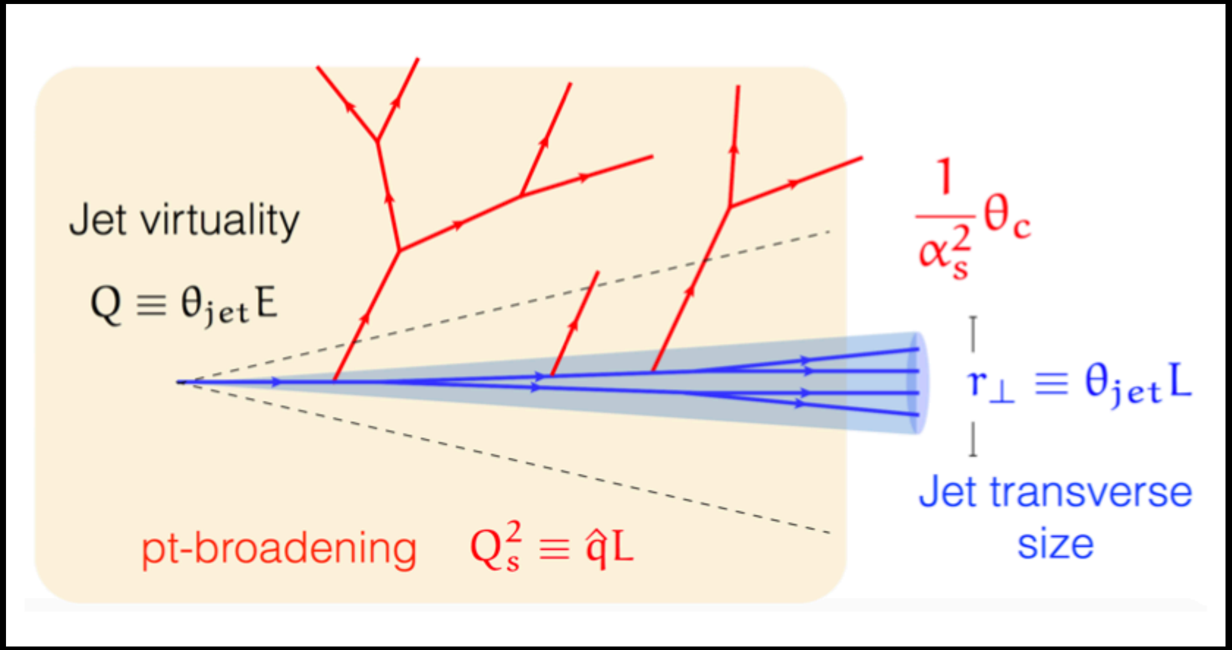
1. Jet energy loss
2. Jet shape modification
3. Jet substructure modification
4. Jet acoplanarity

R-dependence of jet yield: jet shape modification

Vacuums parton shower



Medium-induced gluon radiation



Yacine Mehtar-Tani, arXiv: 1602.01047

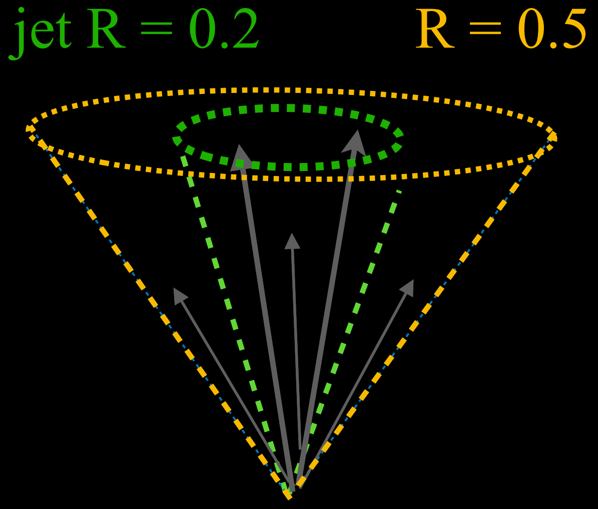
Simultaneous effect of vacuum shower and medium-induced gluon radiation

Jet shape: spread of energy inside a jet

Strategy:

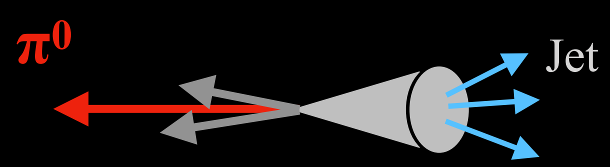
- Take jet yield ratio of smaller over large-R in the same system
- And compare with p+p and heavy-ion collisions

$$\mathfrak{R}^{\text{small}-R}_{\text{large}-R} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-R}}{Y(p_T^{\text{jet,ch}})^{\text{large}-R}}$$



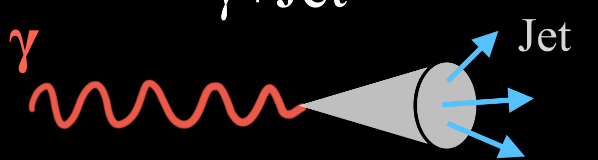
R-dependence of jet yield: jet shape modification in QGP

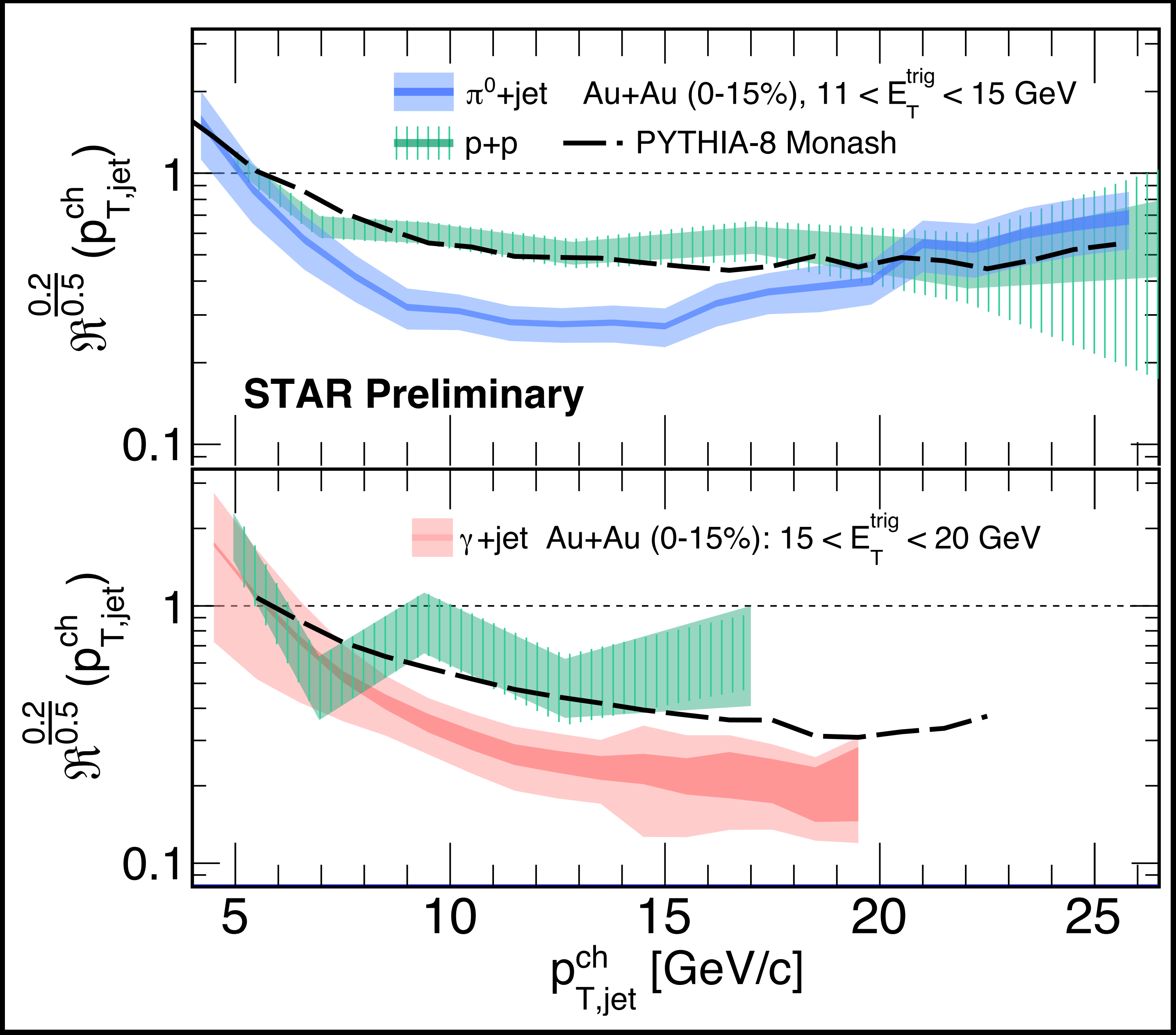
π^0+Jet



$$\mathfrak{R}^{\text{small}-R}_{\text{large}-R} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-\text{R}}}{Y(p_T^{\text{jet,ch}})^{\text{large}-\text{R}}}$$

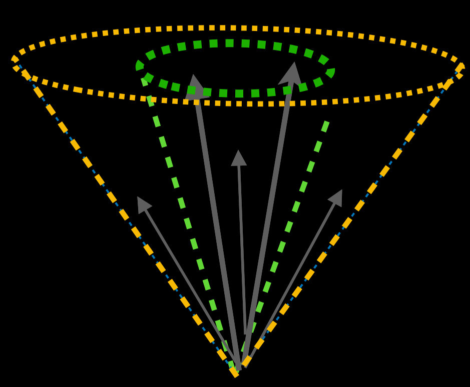
γ+Jet





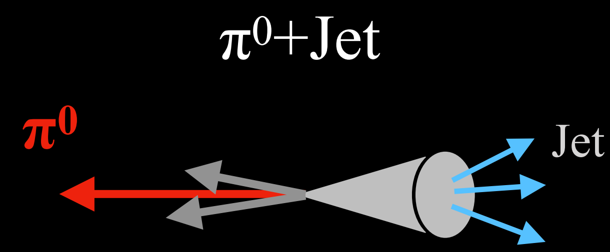
Jet-shape: spread of energy inside a jet

jet R = 0.2 R = 0.5

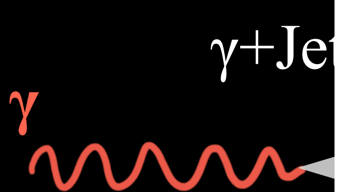


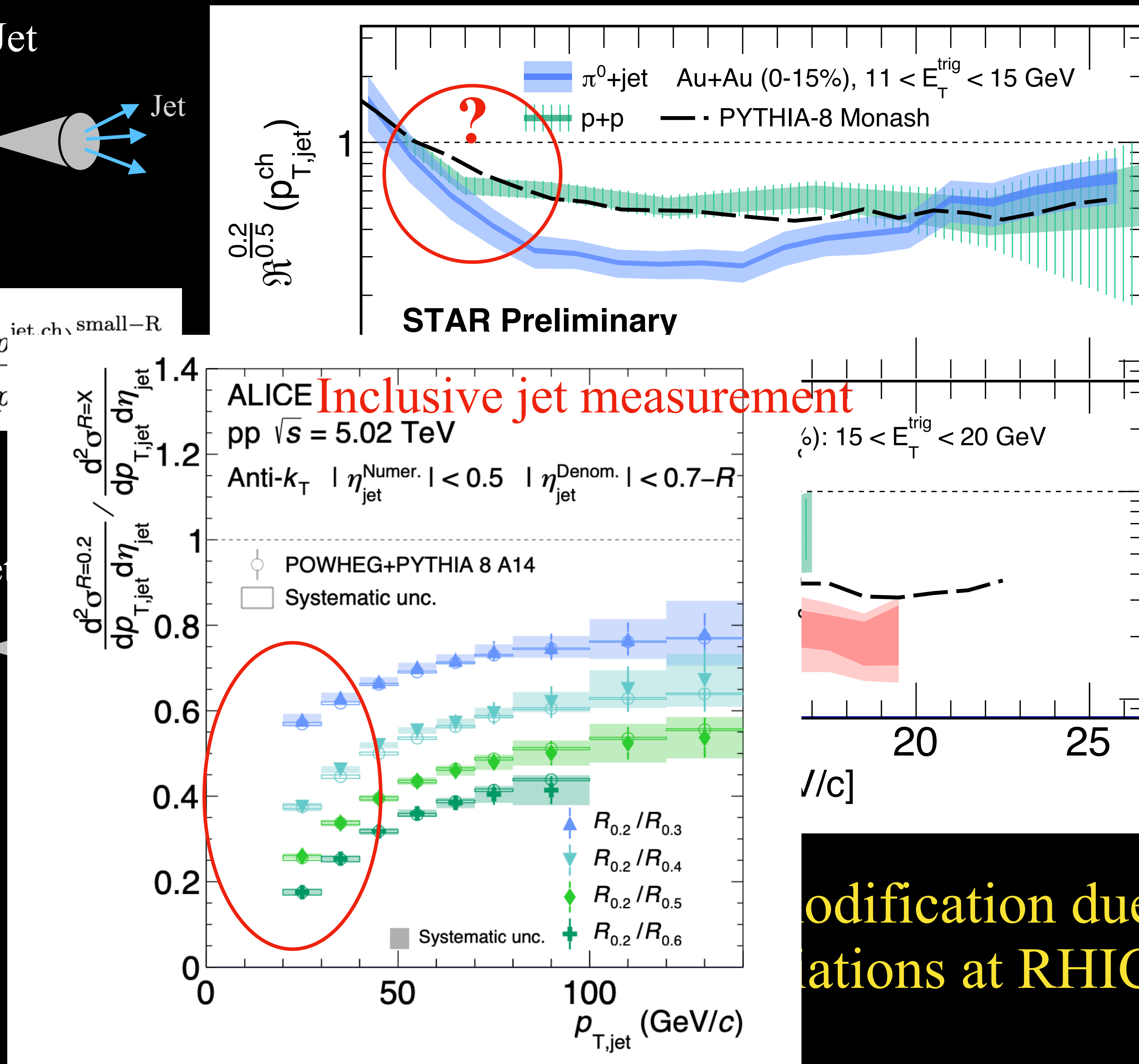
First indication of jet shape modification due to medium induced gluon radiations at RHIC

R-dependence of jet yield: jet shape modification in QGP

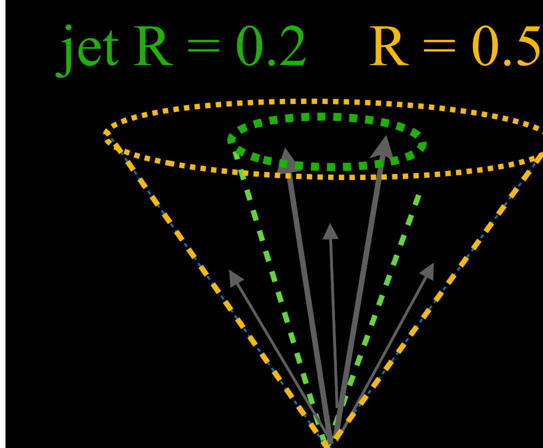


$$\mathfrak{R}^{\,\mathrm{small}-R}_{\,\mathrm{large}-R} = \frac{\mathrm{Y}(p^{\mathrm{jet,ch}})^{\mathrm{small}-R}}{\mathrm{Y}(p \ldots}$$





Jet-shape: spread of energy inside a jet



...odification due to

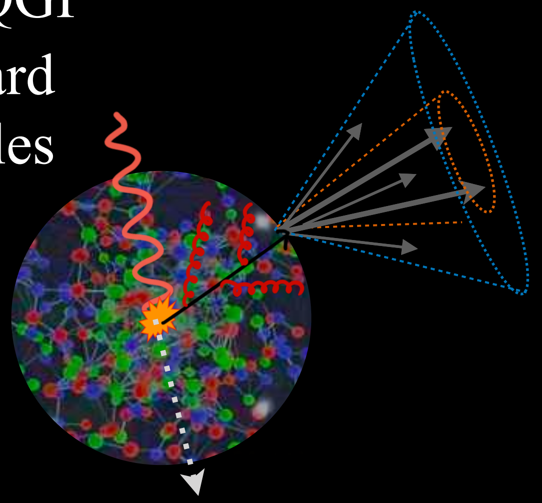
...iations at RHIC

Physics mechanisms for acoplanarity of γ+jet in heavy-ion collisions

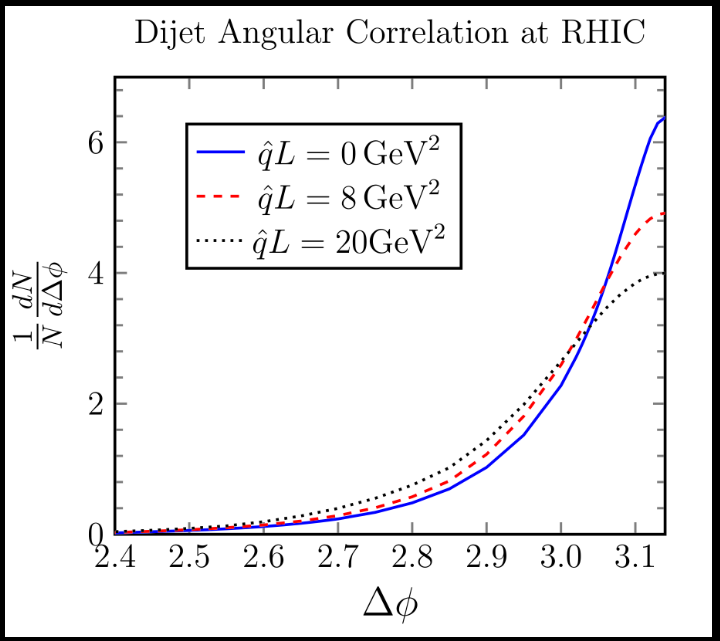
- Rutherford Scattering: Energetic parton resolves microstructure of QGP

  Large-angle deflection of hard partons off quasi-particles

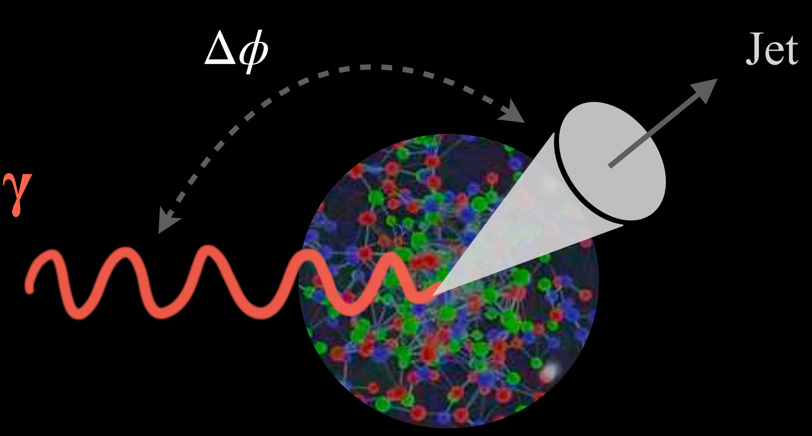
D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172;
D'Eramo, et. All, JHEP 05 (2013) 031

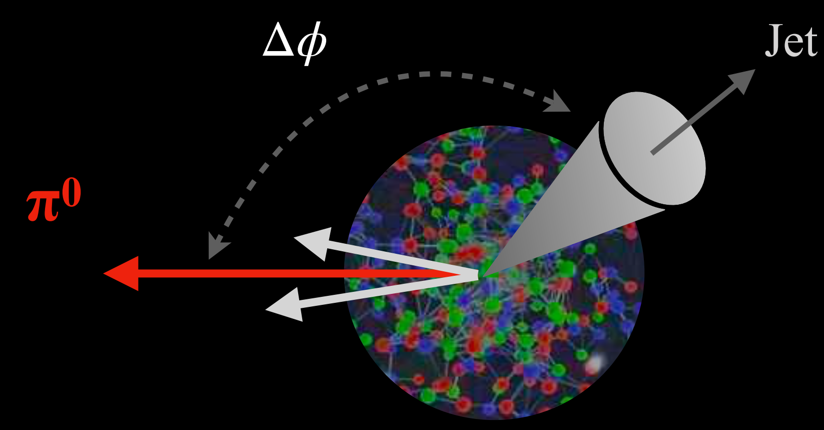


- Vacuum soft gluon radiation
- Medium effect: multiple scattering and medium induced gluon radiation



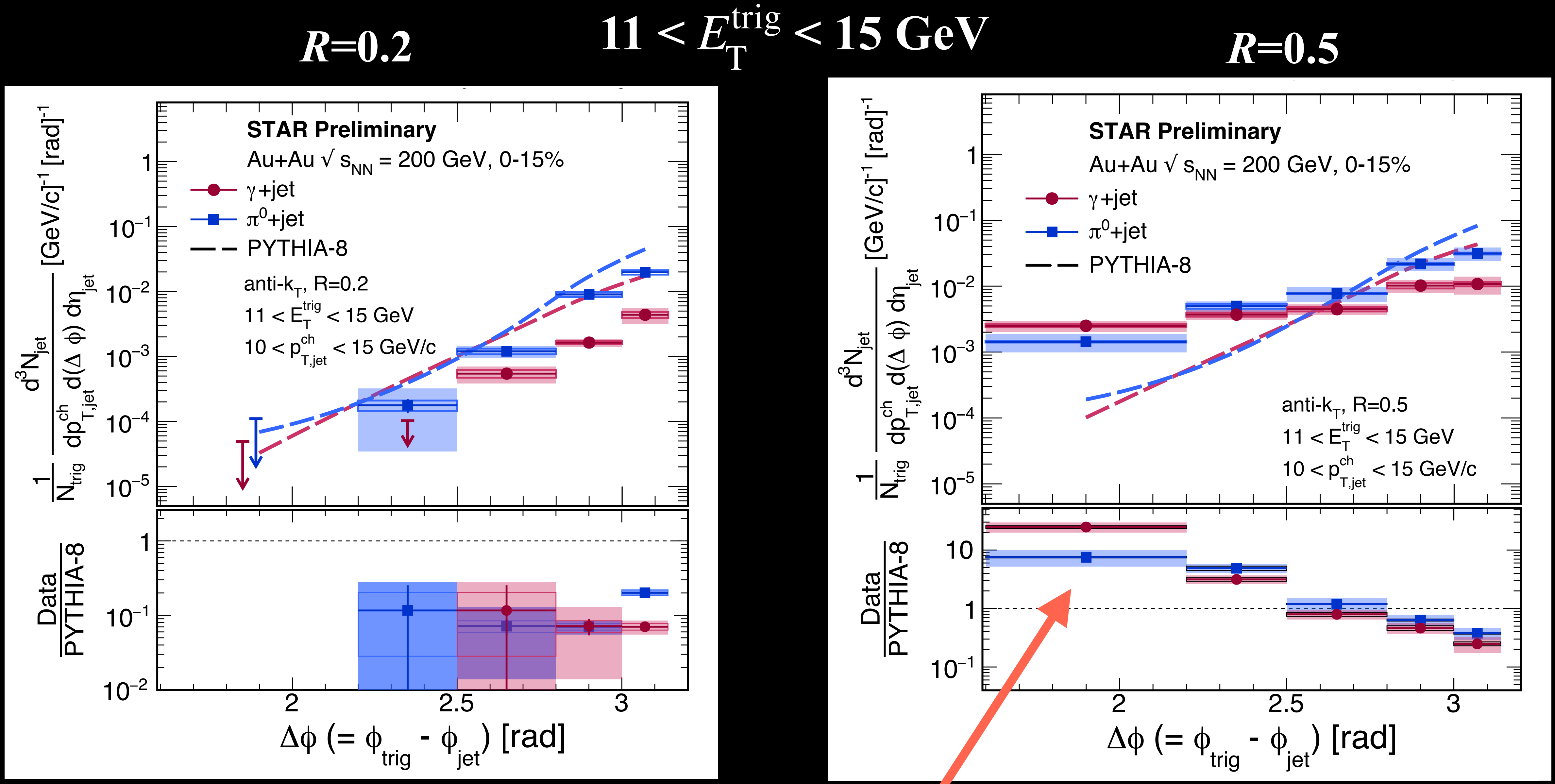
Measuring two probes in STAR experiment





Azimuthal correlations between trigger particle and recoil jet: $\Delta\phi = \phi_{\mathrm{trig}} - \phi_{\mathrm{jet}}$

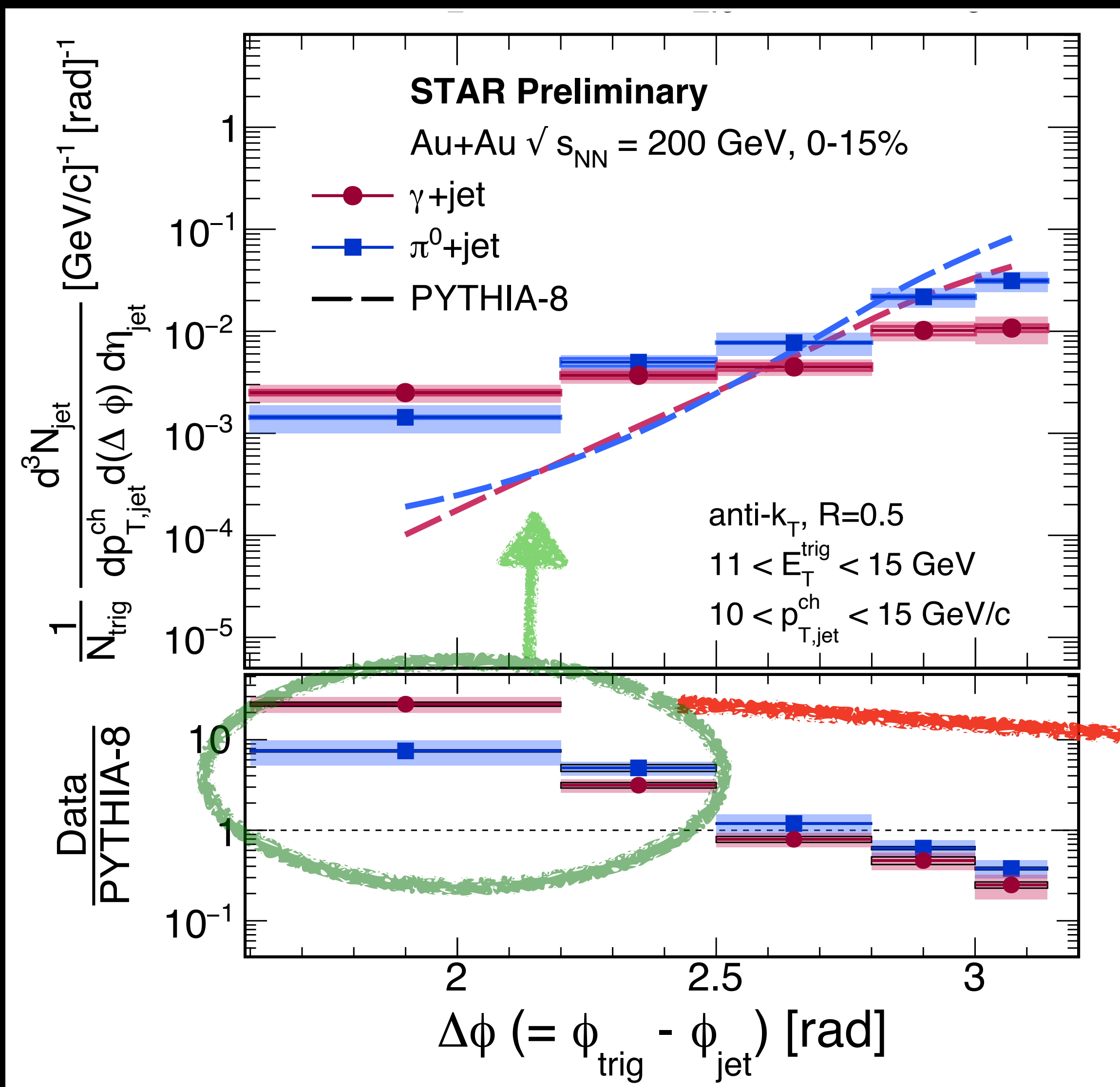
Semi-inclusive γ+jet and π^0+jet azimuthal correlation in Au+Au collisions



First evidence of significant medium-induced jet acoplanarity in QGP for jets with R=0.5

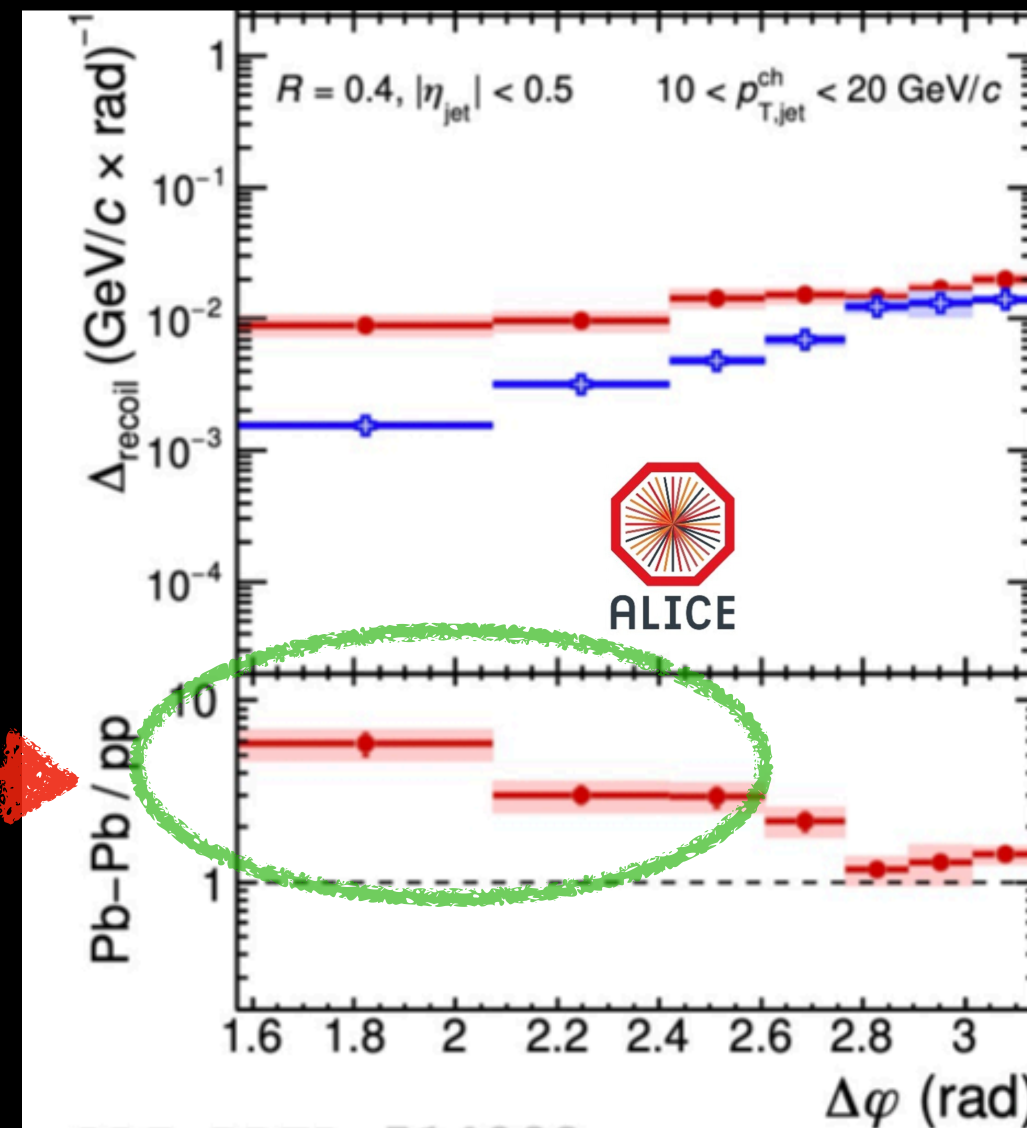
Medium-induced jet acoplanarity at RHIC and LHC

STAR γ+jet and π^0+jet



- Mixed-event subtraction method
- Jet R=0.5

ALICE h+jet



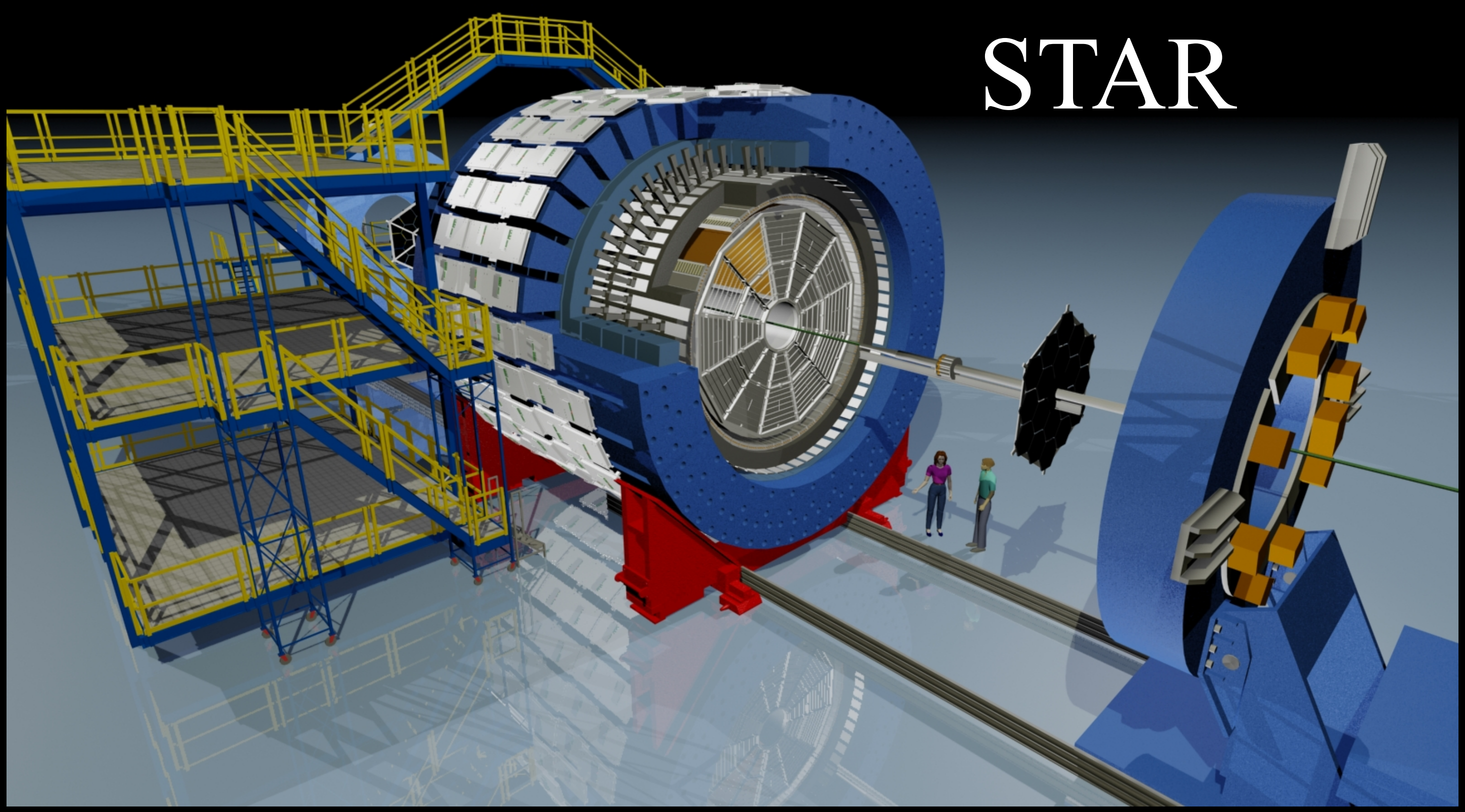
- TT(20,50) - TT(5,7)
- Jet R=0.4

Same observation: Medium-induced acoplanarity with jet (p_T ~ 10 GeV/c) and large R (0.4-0.5)
What happened to larger Sudakov broadening at the LHC?

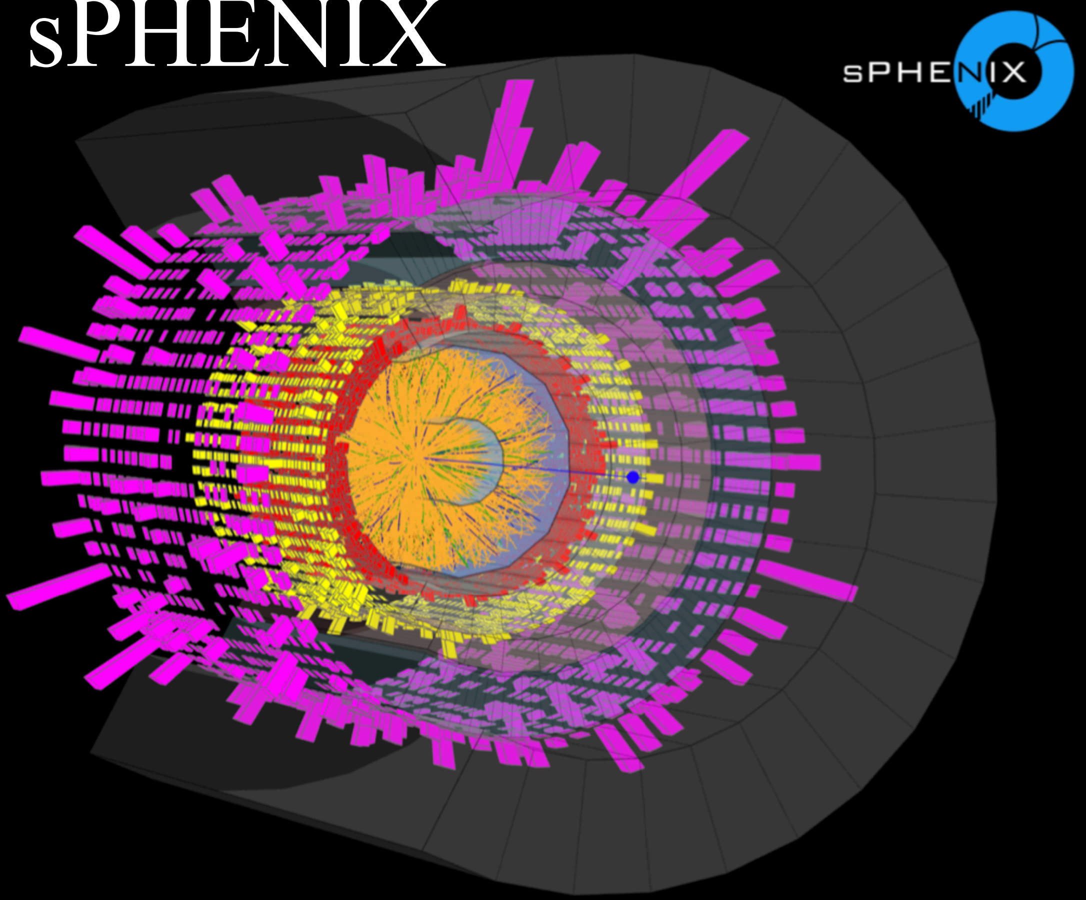
RHIC experiments and future plan (2023-2025)
STAR and sPHENIX

RHIC experiments and future plan

STAR

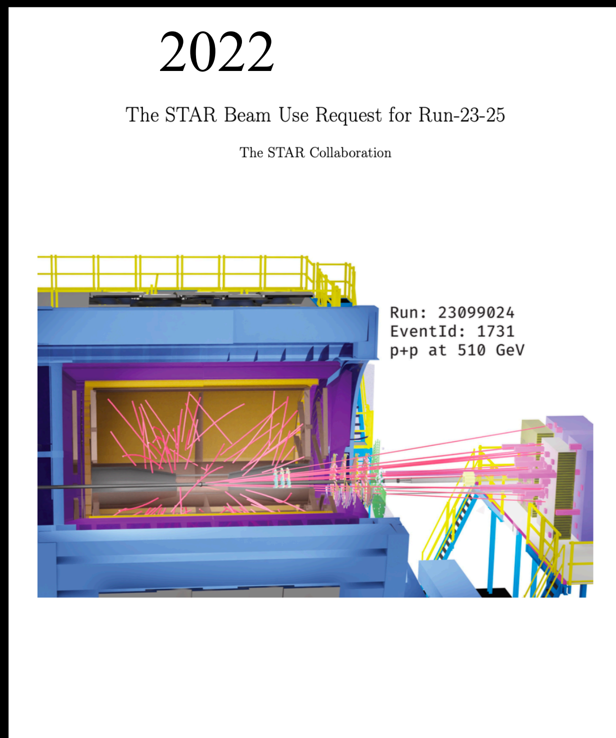


sPHENIX



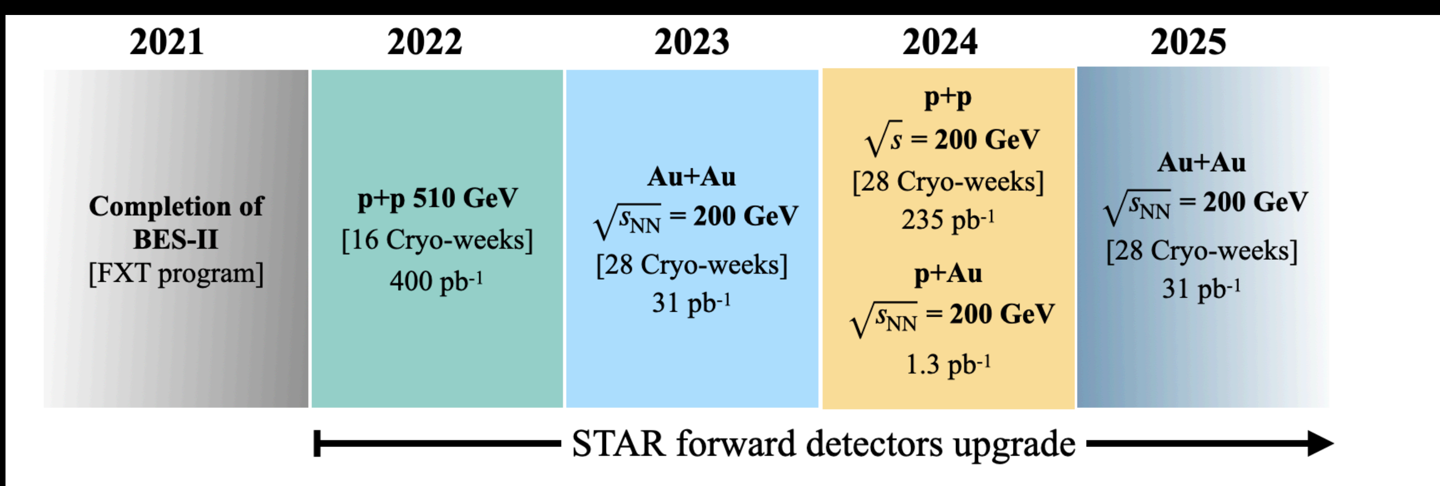
Precision measurements for hard probes to study the properties of QGP

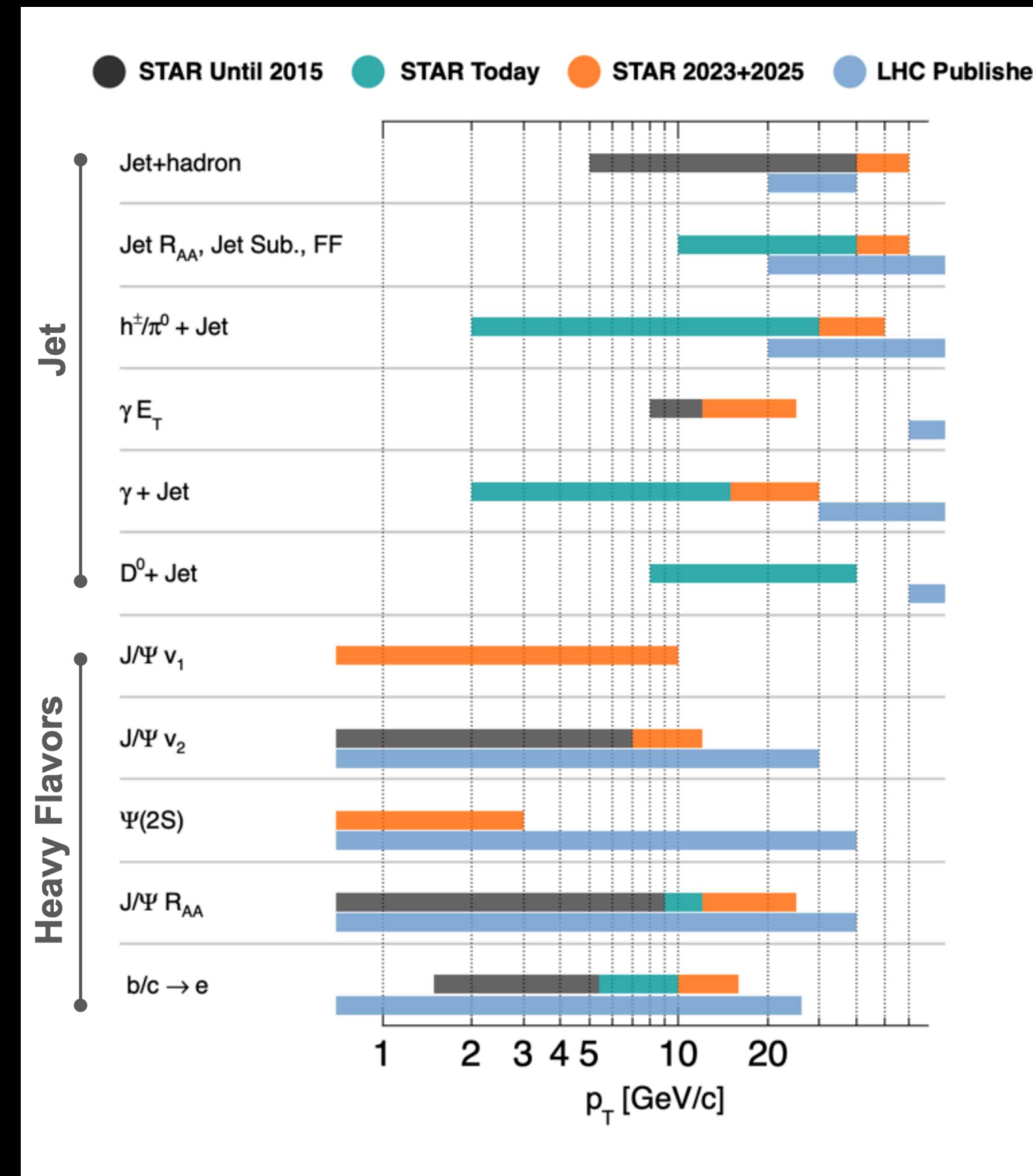
STAR Hard-Probes physics program for Run23+25


2022

The STAR Beam Use Request for Run-23-25

The STAR Collaboration





It includes Hot-QCD and Cold-QCD STAR programs

- Hot-QCD program: Study the microstructure of the QGP (Precision jet and heavy-flavor measurements)
- Cold-QCD program will help for future EIC program

Variety of physics topics ongoing at RHIC from hot QCD to Cold QCD sides

Upcoming RHIC data taking year2023-2025 will be crucial for RHIC scientific mission (Particularly high precision measurement)

Thank you!