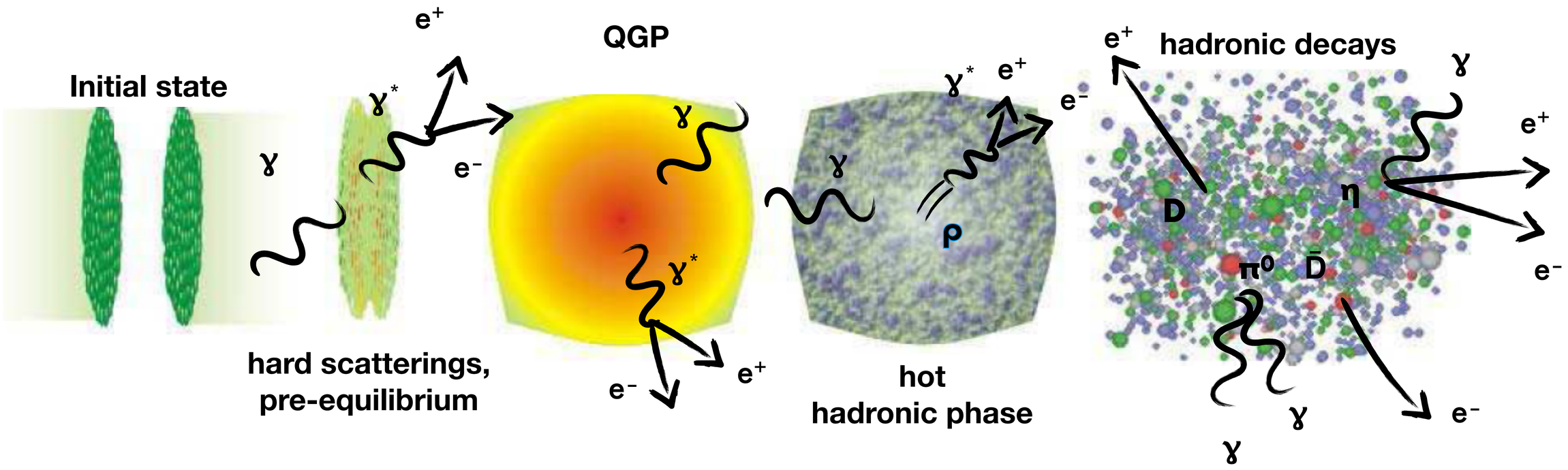
Electromagnetic Probes

Raphaelle Bailhache
Goethe University Frankfurt

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Electromagnetic probes



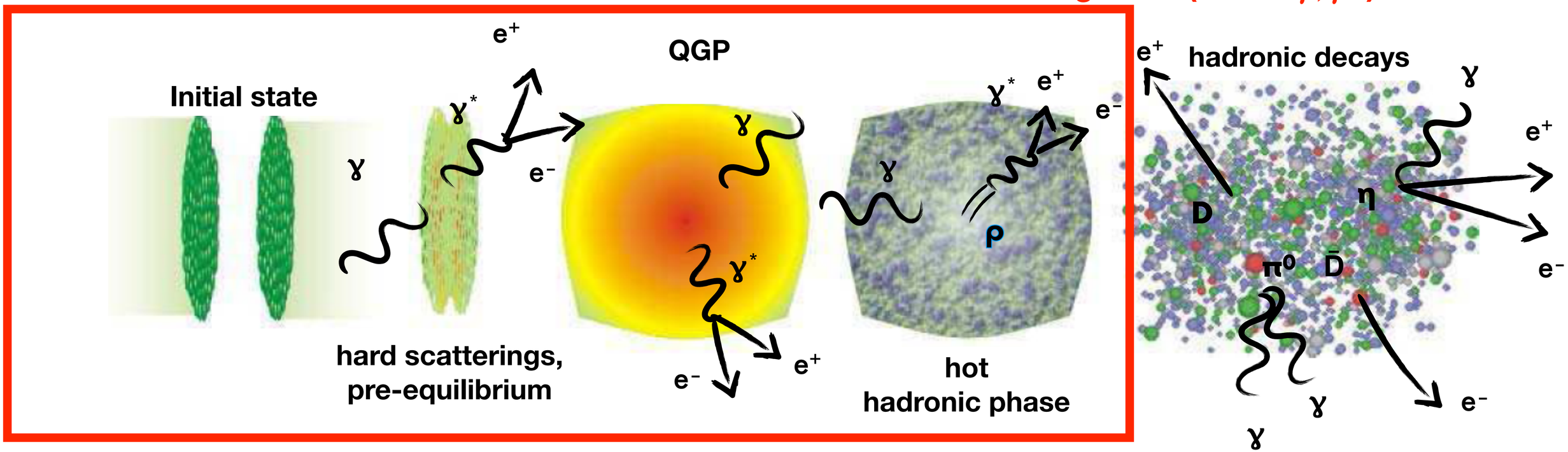
γ, γ^*

Emitted at all stages of the heavy-ion collisions
with negligible final-state interactions contrary to hadronic probes !

→ **Undistorted information about the medium at the same of their emission**

Electromagnetic probes

Most interesting ones (Direct γ, γ^*)



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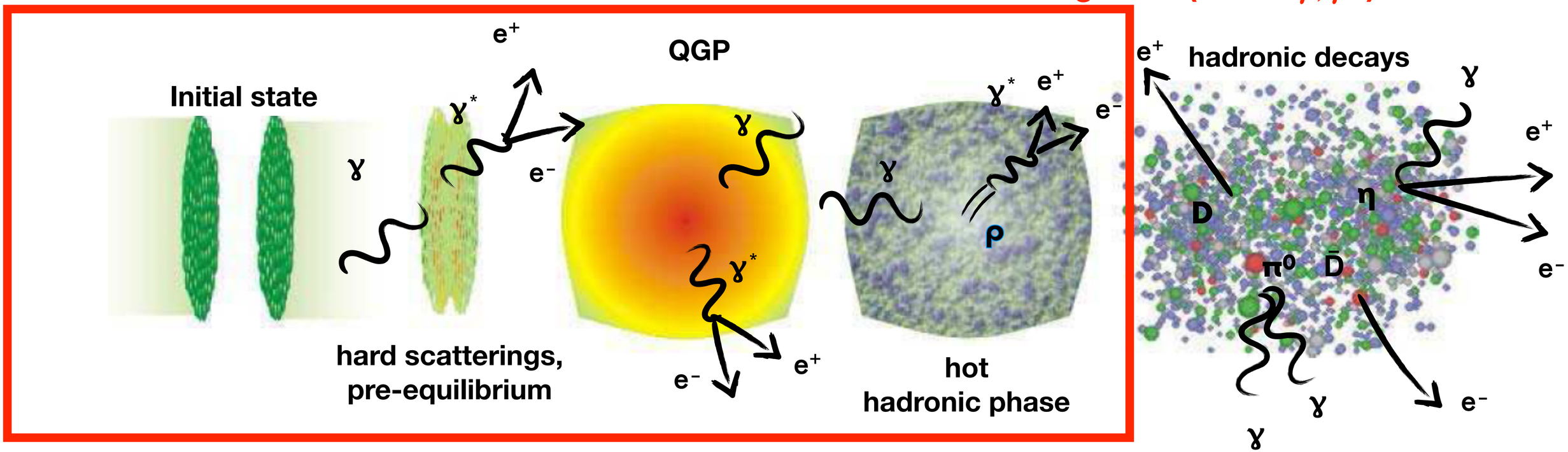


Initial hard scattering
- Test N_{coll} scaling
- Constrain nuclear PDFs
- Candle for energy loss studies: γ-tagged jets..

Pre-equilibrium phase
- Mechanism of equilibration

Thermal radiation
- Effective QGP temperature
- Constrain space-time evolution

Chiral symmetry restoration with dileptons
- ρ broadening
- Constrain mechanisms: $\rho - \mathrm{a}_1$ mixing

Outline

Focus on soft (thermal) radiation

- Direct photons: low-p_{T}
- Dileptons

Disclaimer: will not cover initial hard-scattering or UPC

Direct photons: low p_T

C. Gale, J-F Paquet, B. Schenke, and C. Shen Phys. Rev. C 105 (2022) 014909

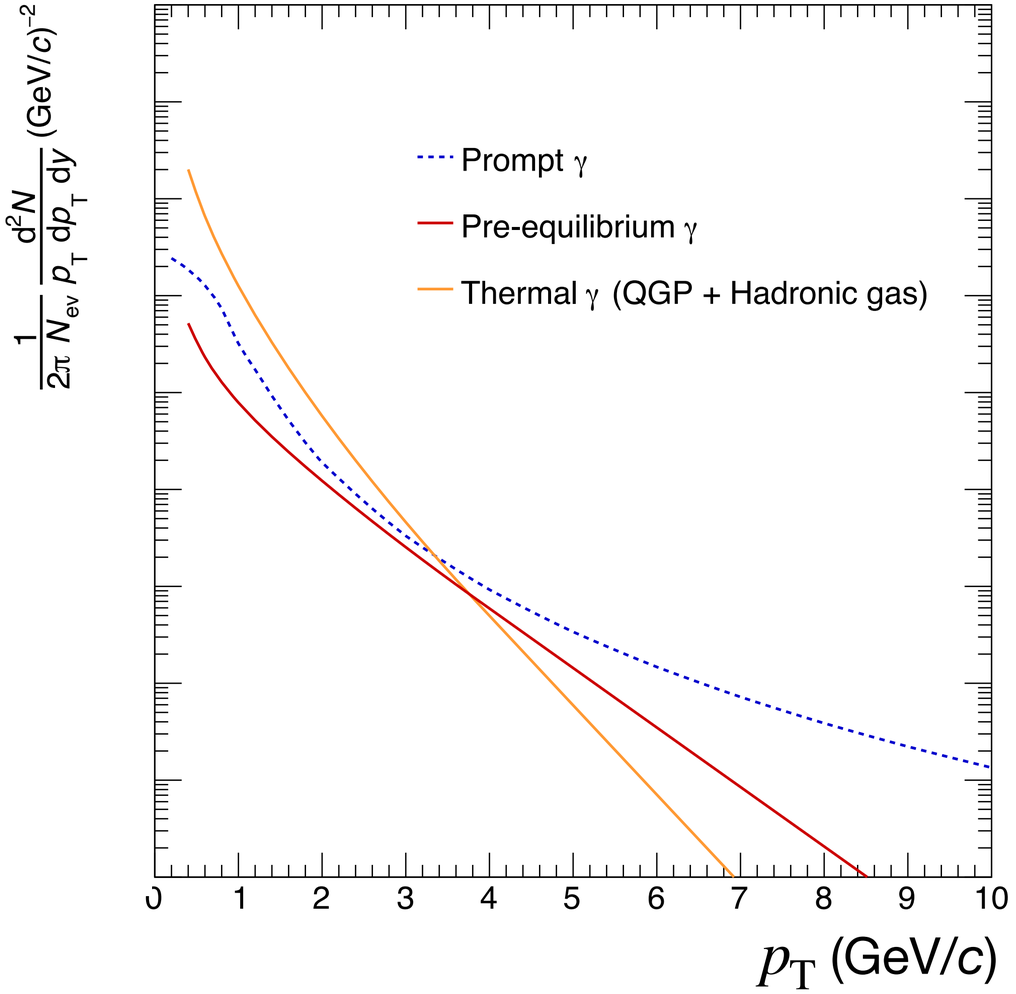
Direct photons

Sources populate different p_T ranges:

- **Hard scattering: prompt photons**
  - **Direct production**
  - **Fragmentation photons**
- **Pre-equilibrium**
- **Thermal radiation from QGP and hot hadronic matter**

+ possible jet-medium interaction

Schematic view of direct photon spectrum



Late emission ← Early emission

C. Gale, J-F Paquet, B. Schenke, and C. Shen Phys. Rev. C 105 (2022) 014909

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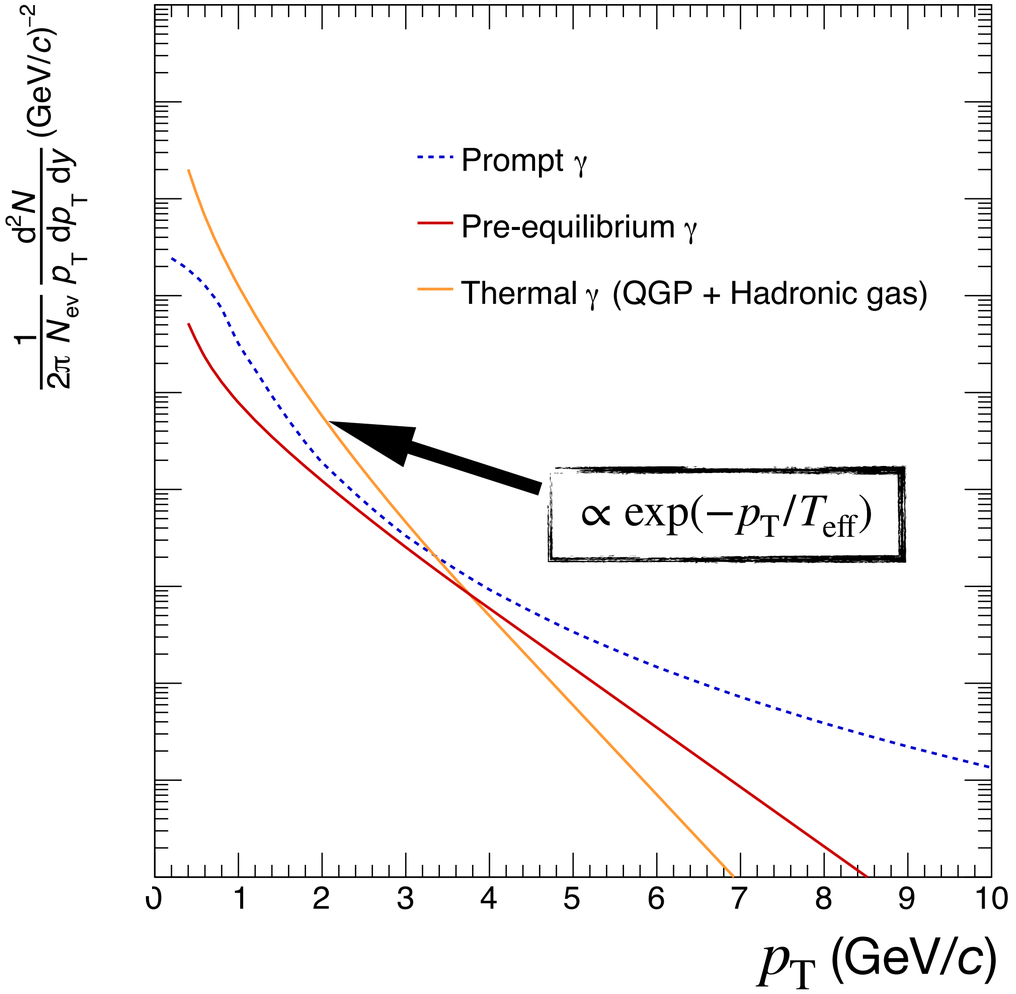
Thermal sources at low p_T:

inverse slope ∝ effective fireball temperature T_{eff}

- Blueshifted due to radial flow
- Averaged over time

→ Need models to disentangle sources

Schematic view of direct photon spectrum



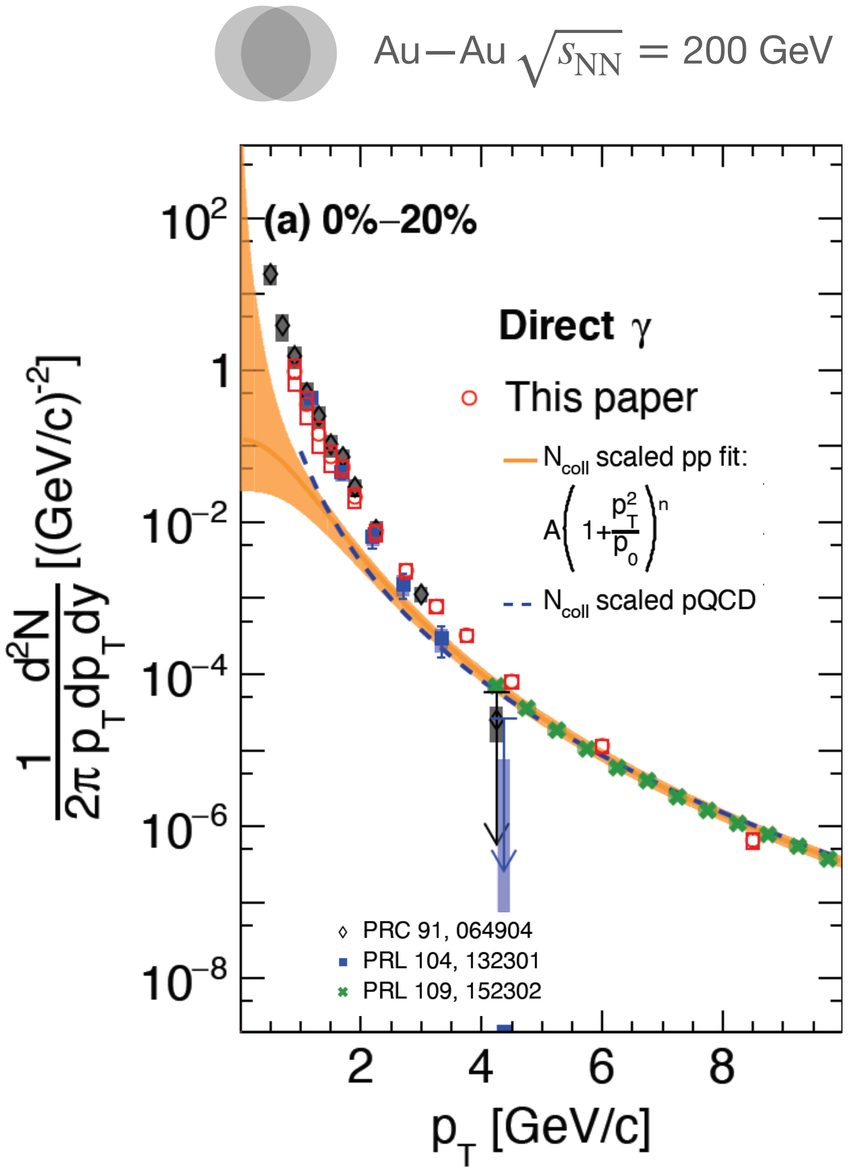
Late emission ← Early emission

Carolina Arata #174
Vassu Doomra #655

Direct photons: status before QM

Direct γ yield at low p_T in A+A collisions above prompt hard-scattering γ expectation observed by:

- PHENIX with different methods at different energies $\sqrt{s_{NN}}$ = 39-200 GeV
- ALICE with different methods at $\sqrt{s_{NN}}$ = 2.76 TeV (ALICE results link)



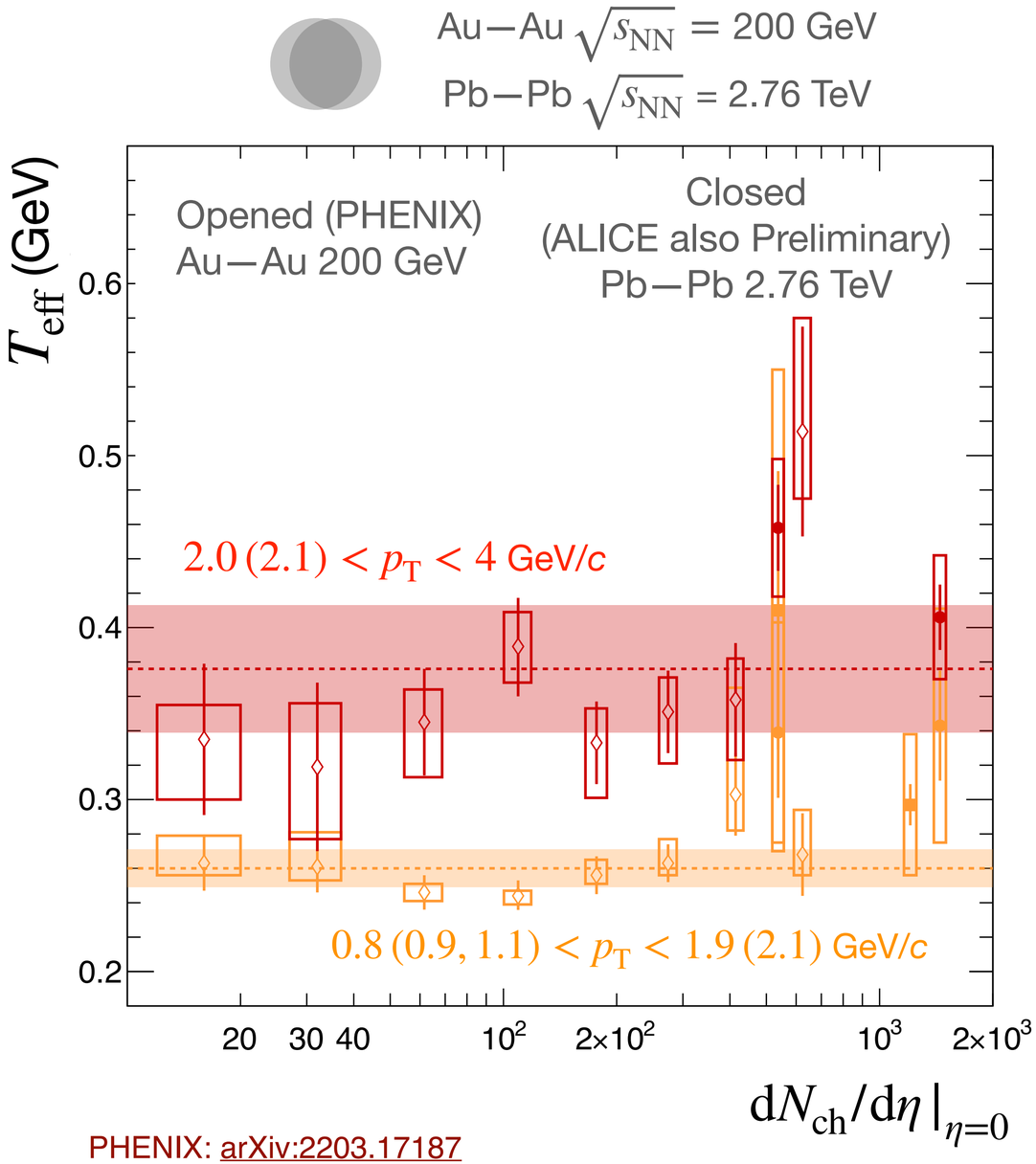
PHENIX: Phys. Rev. C 107, 024914 (2023); arXiv:2203.17187
ALICE: Phys. Lett. B 754 (2016) 235-248; Ana Marin Hard Probes 2023

Carolina Arata #174
Vassu Doomra #655

Direct photons: status before QM

Extracted T_{eff} from $\gamma_{\mathrm{non-prompt}} = \gamma_{\mathrm{dir}} - \gamma_{\mathrm{prompt}}^{\mathrm{estimated}}$

- Increases with p_{T} range used to fit
- Above deconfinement temperature
- No obvious variation of T_{eff} with $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}N_{\eta}|_{\eta=0}$ although do not exclude small increase



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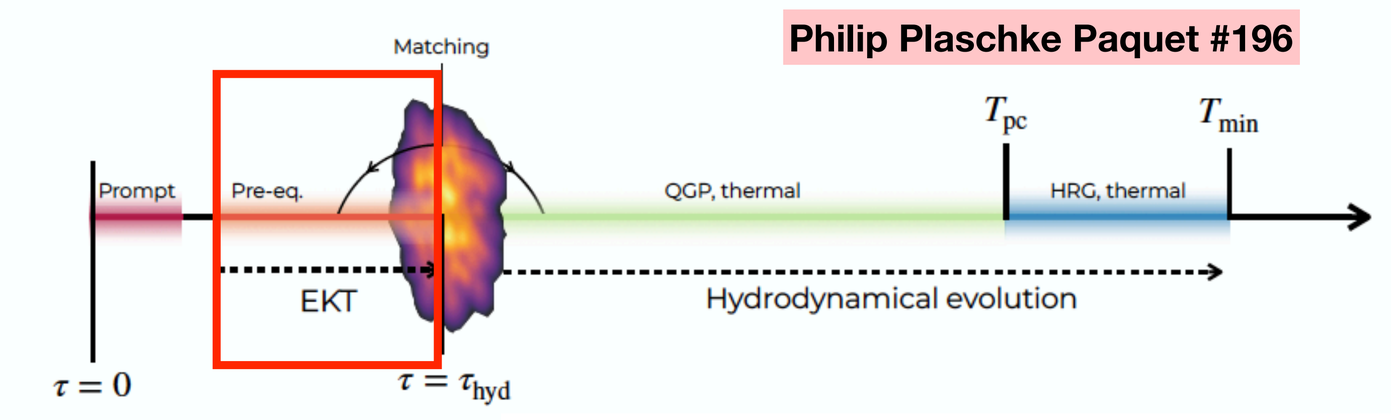
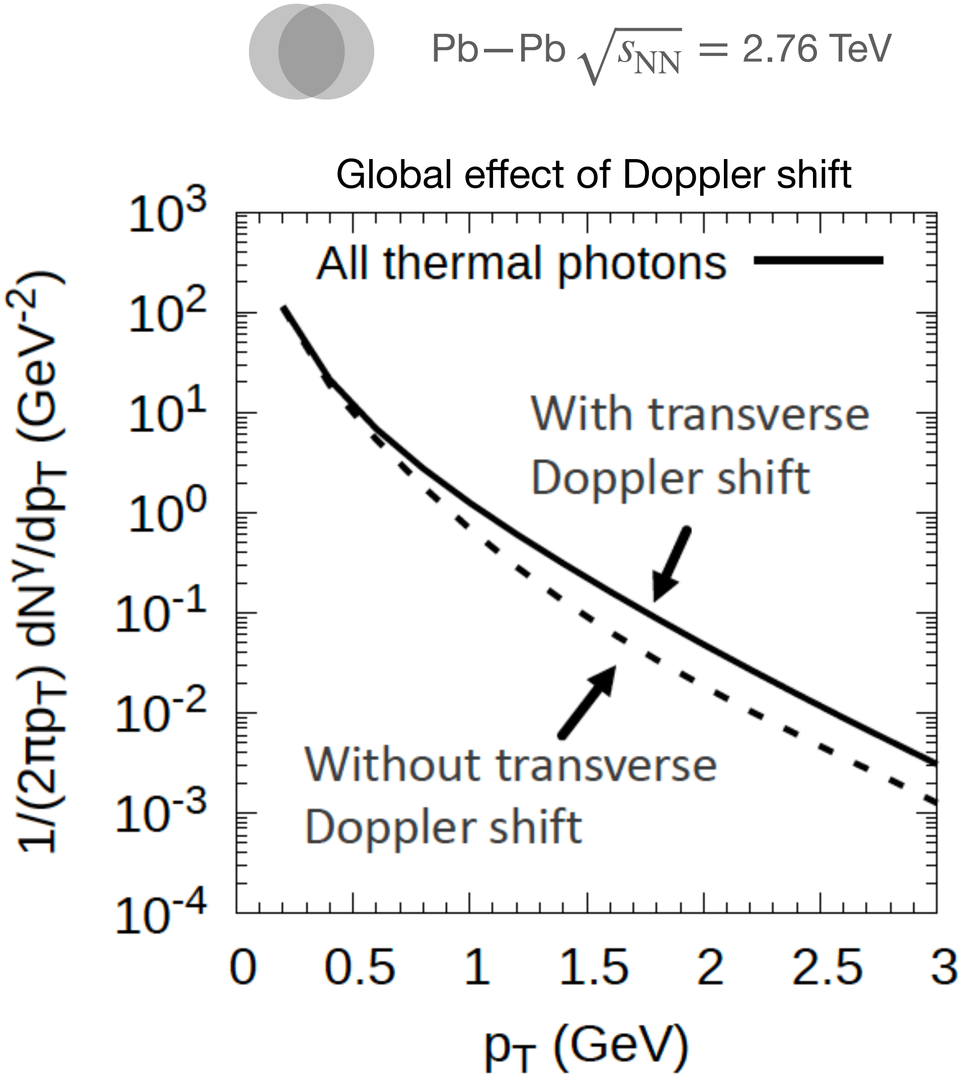
Interpretation of T_{eff}

Jean-Francois Paquet #787

- ***Naive* idea: higher p_{T} , earlier emission, higher T**
- **But:**
  - **Bias due to radial flow:** $T_{\mathrm{eff}}^{\mathrm{w/\,flow}} > T_{\mathrm{eff}}^{\mathrm{w/o\,flow}}$
    - Locally: large for high p_{T} $\gamma_{\mathrm{thermal}}$ emitted at *small* T
    - Globally: integrated over space-time → smaller
  - **Contributions from pre-equilibrium** (without well defined T) for $p_{\mathrm{T}} \geq$ 2.5-3 GeV/*c*



O. Garcia-Montero, A. Mazeliauskas, P. Plaschke, S. Schlichting, arXiv:2308.09747

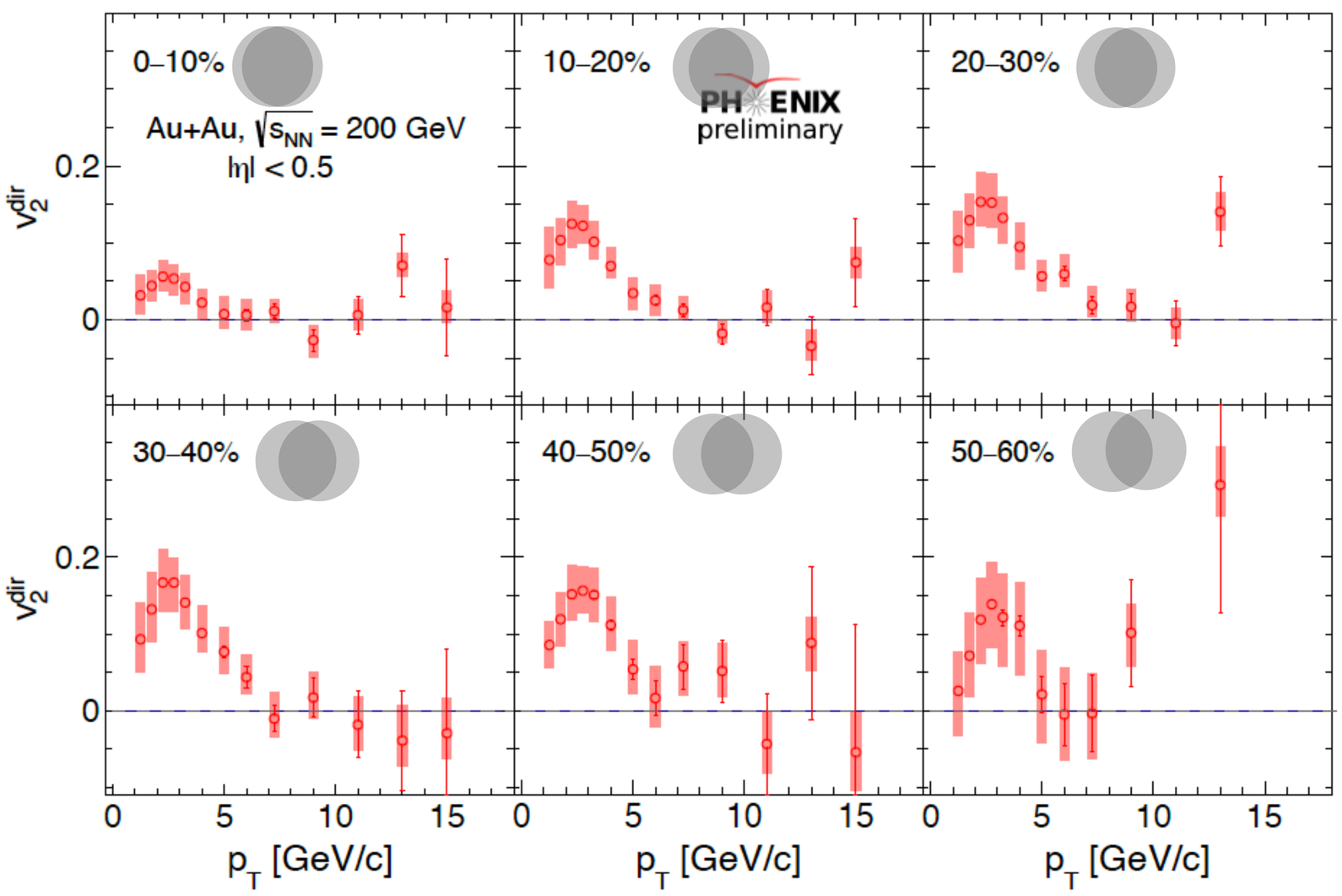


C. Shen, U. W. Heinz, J-F Paquet, C. Gale, Phys. Rev. C 89 (2014) 044910
J-F Paquet, arXiv:2305.10669

News from PHENIX: v_2^{dir} in Au+Au

Vassu Doomra #655

Measure v_2 of direct γ in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} =$ 200 GeV with 10 × larger data sample



Au−Au $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

$$v_2^{\mathrm{dir}} \sim v_2^{\gamma_{\mathrm{decay}}} \sim v_2^{\pi}$$

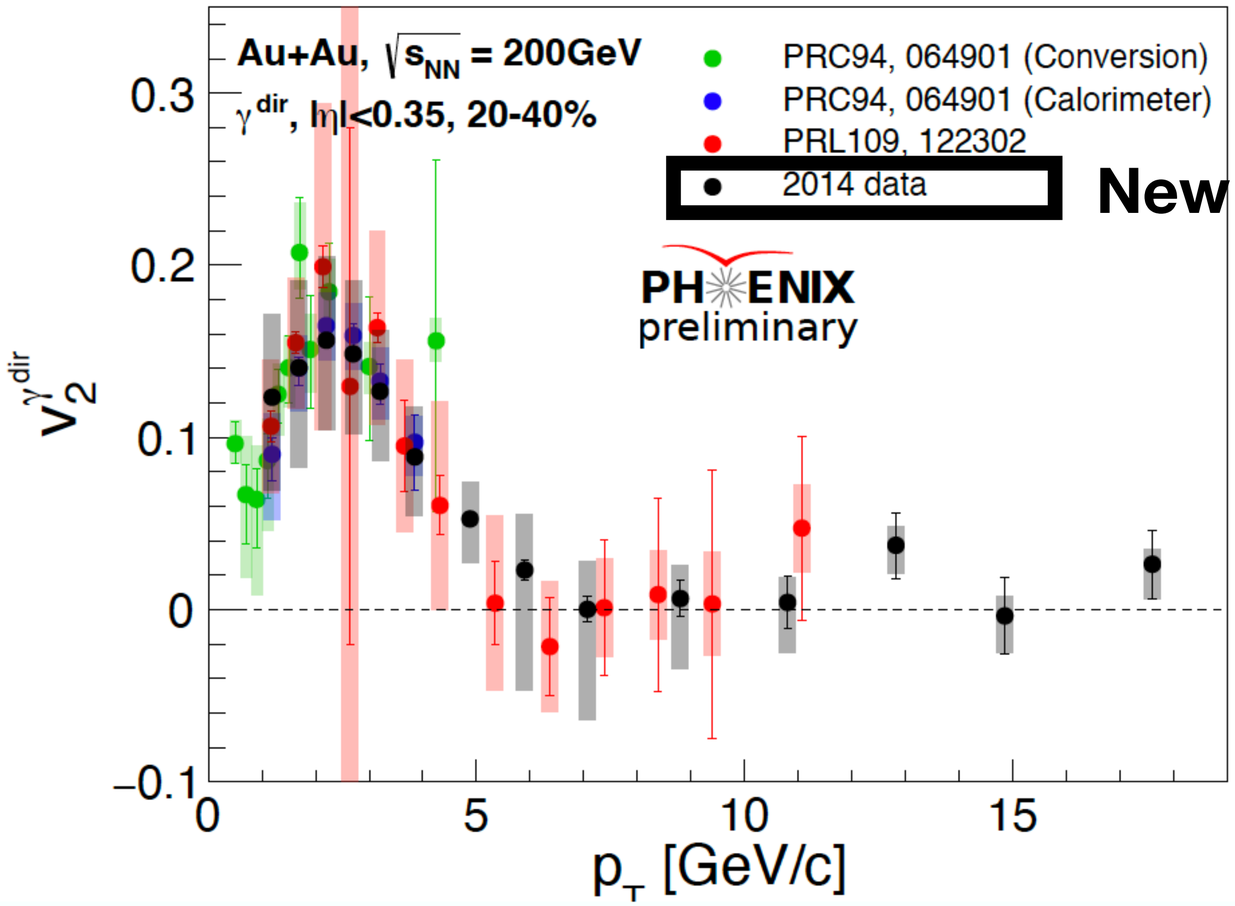
$$v_2^{\mathrm{dir}} \sim 0$$

at high $p_{\mathrm{T,ee}}$

News from PHENIX: v_2^{dir} in Au+Au

Vassu Doomra #655

Results in agreement with previous publication and with significant reduction of uncertainties

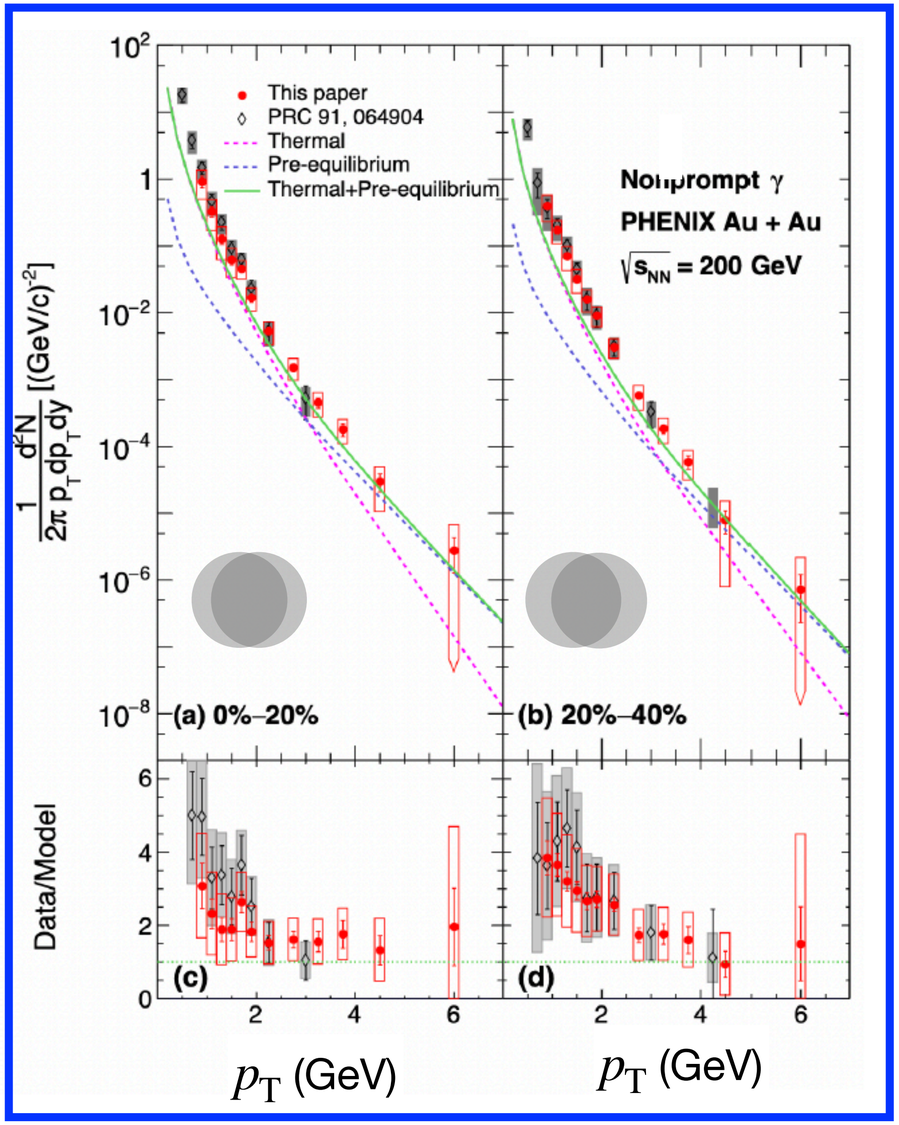


Au−Au $\sqrt{s_{NN}}$ = 200 GeV

Direct photon puzzle still there

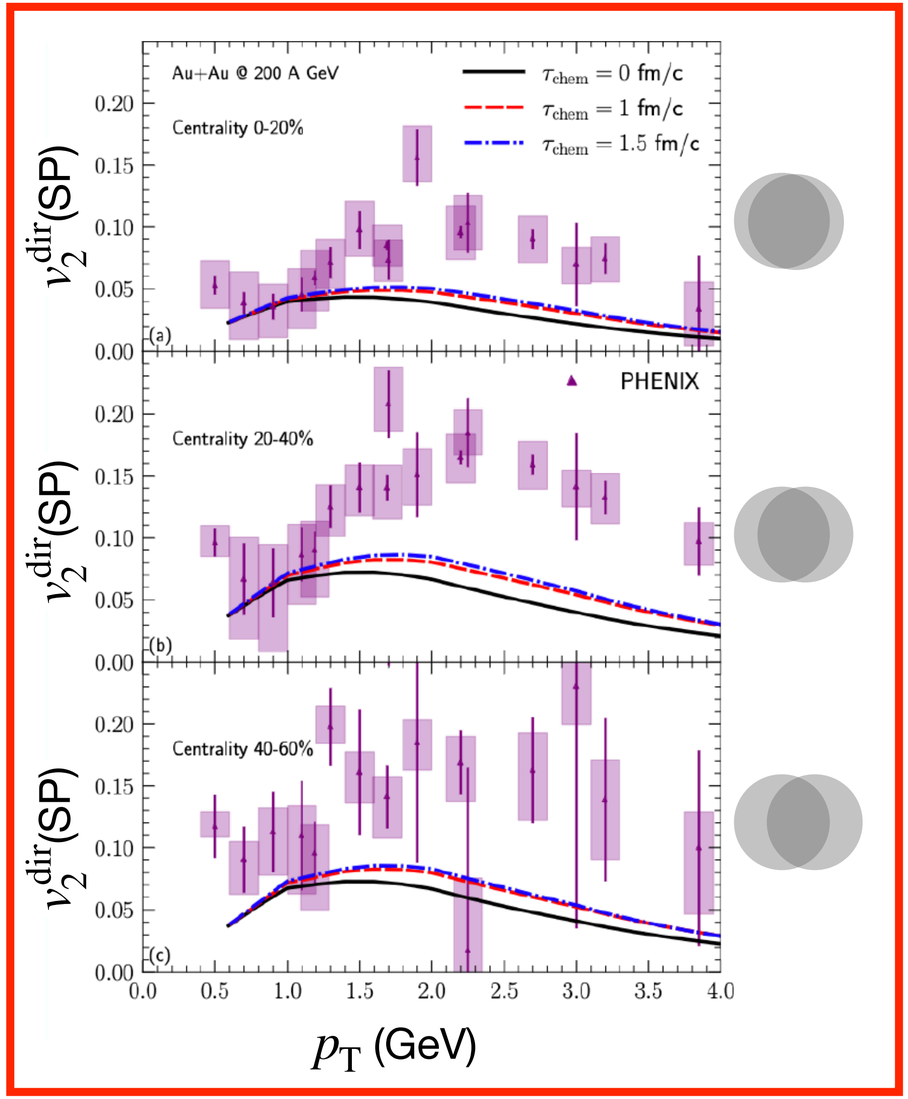
Vassu Doomra #655

Yield



PHENIX, arXiv:2203.17187

v_2^{dir}



C. Gale, J-F Paquet, B. Schenke, C. Shen PRC 105 (2022) 014909

Au−Au $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

Simultaneous description of yield and v_2 challenging for theory

(Same trend at the LHC but ok within large uncertainties)

Trigger some theoretical idea

J-A Sun Poster #236

but only showing v_2^{dir} !

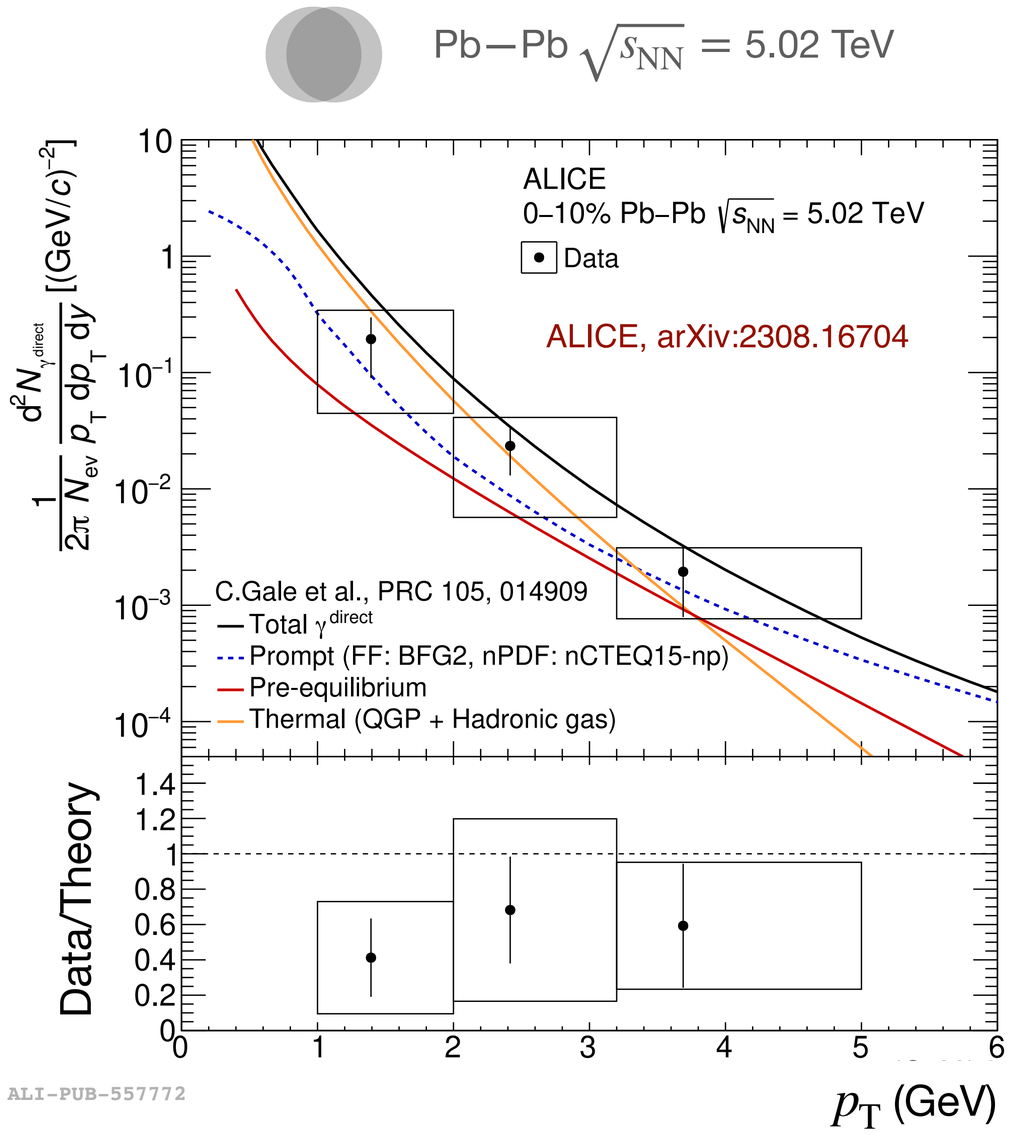
News from ALICE: Pb—Pb 5.02 TeV

Daiki Sekihata #171

- **Finalised γ_{dir} yield in central Pb—Pb collisions at 5.02 TeV** using dielectrons

- Described by calculations including:
  - Prompt photons
  - Pre-equilibrium photons
  - Thermal photons

If anything: model tends to overestimate yield



RHIC and LHC energies

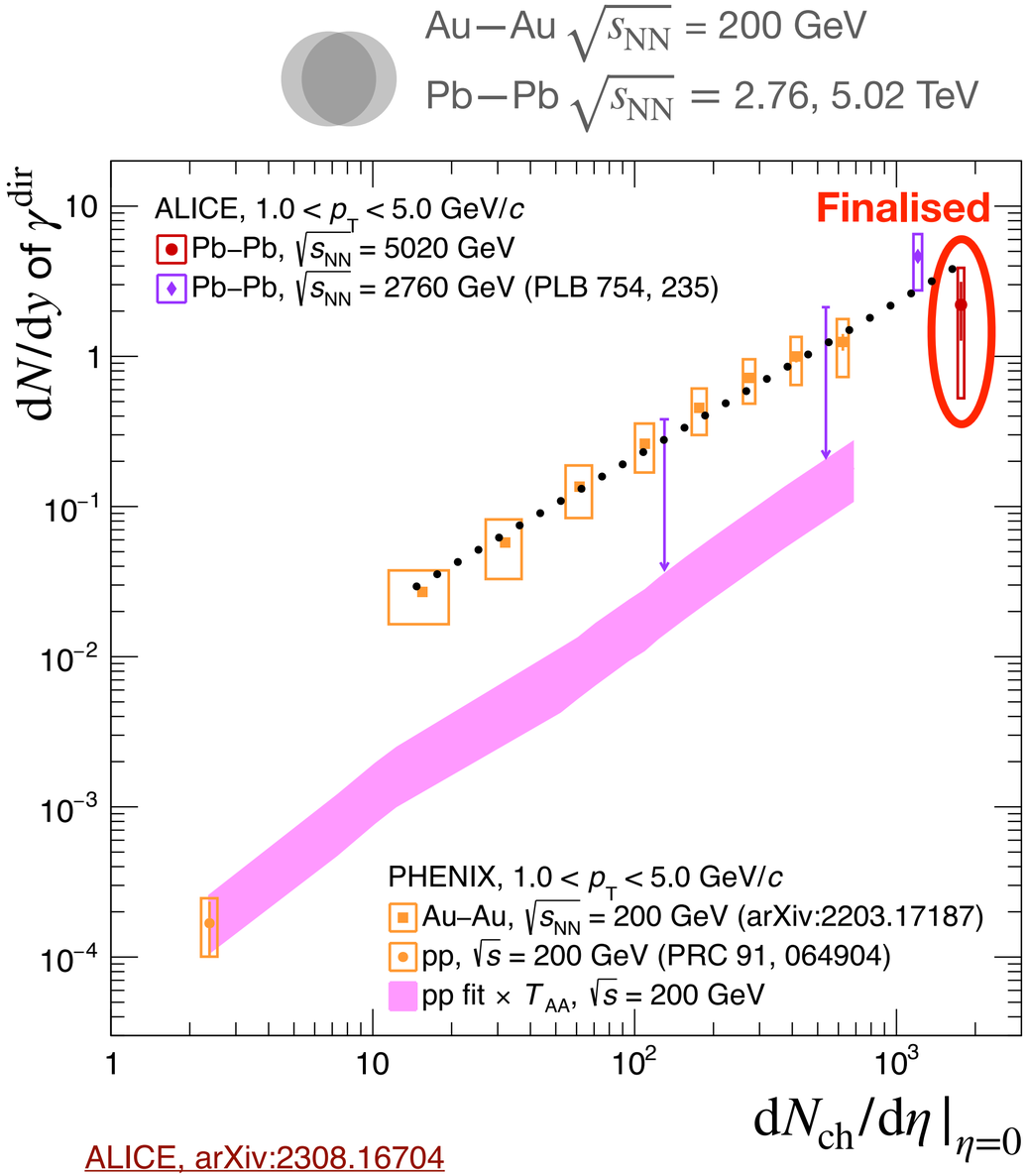
Daiki Sekihata #171

$\mathrm{d}N_{\gamma^{\mathrm{dir}}}/\mathrm{d}y$ **at the LHC**

consistent with universal scaling behaviour seen by PHENIX:

$$\frac{\mathrm{d}N_{\gamma_{\mathrm{dir}}}}{\mathrm{d}y} = C(p_{\mathrm{T}}) \times (\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\,|_{\eta=0})^{\alpha}$$

with no obvious p_{T} dependence of α (not so trivial why)



ALICE, arXiv:2308.16704

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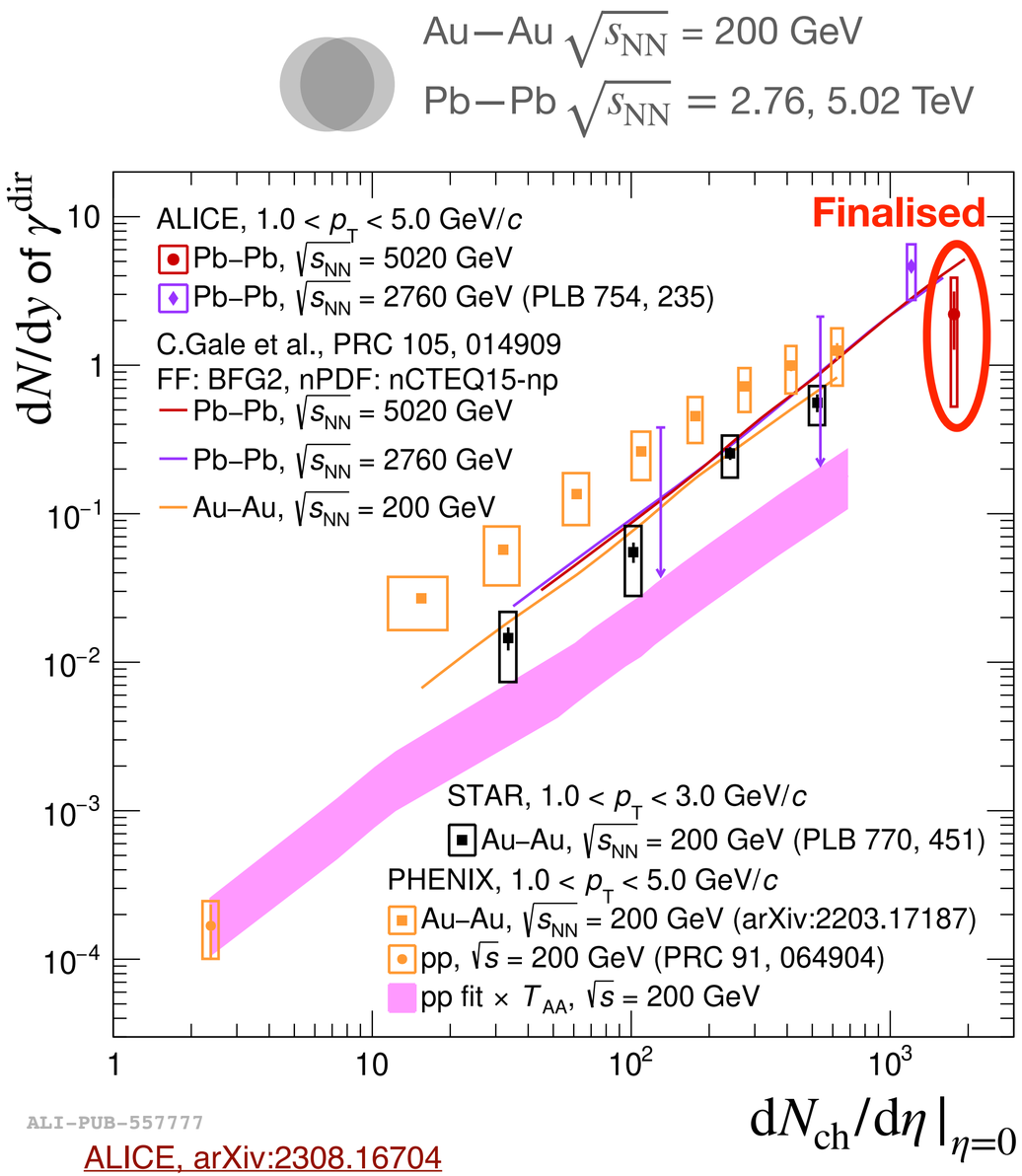
with no obvious p_{T} dependence of α (not so trivial why)

But some issues remained opened:

- Discrepancy between **STAR** and **PHENIX** results
- Same model (lines):
  - Underestimates PHENIX data
    from semi-peripheral to peripheral (increasing discrepancy)
- In agreement with LHC data
  (need to decrease uncertainties)



ALICE, arXiv:2308.16704

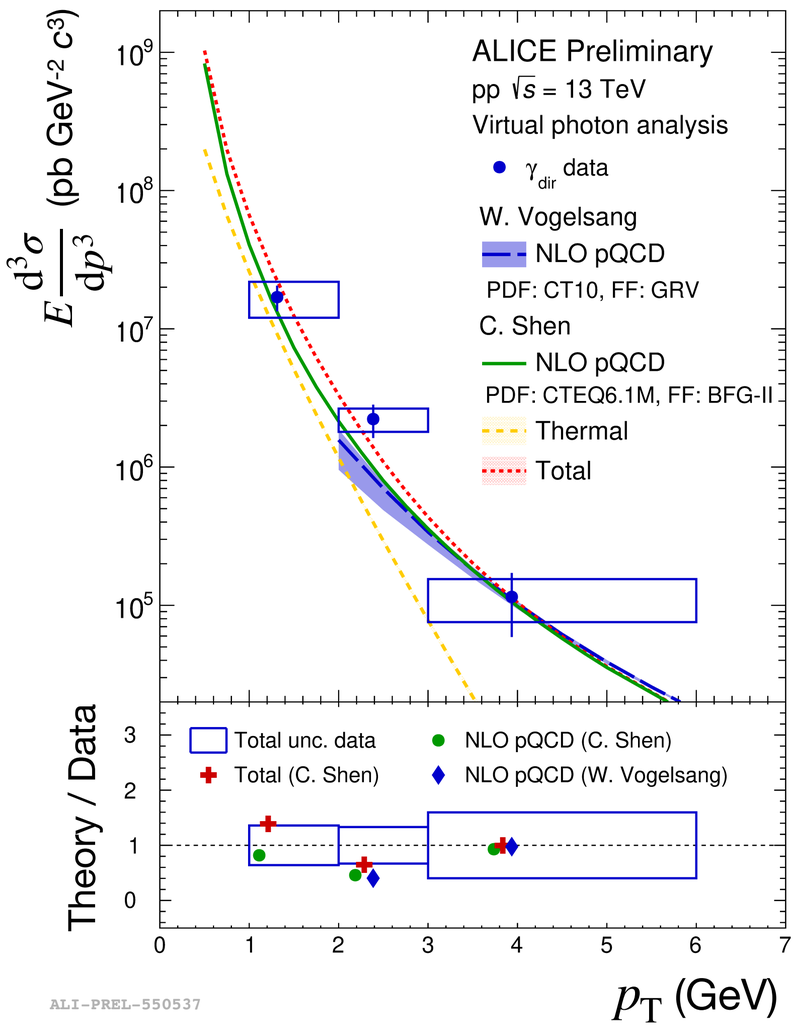
pp collisions at the LHC

Daiki Sekihata #171

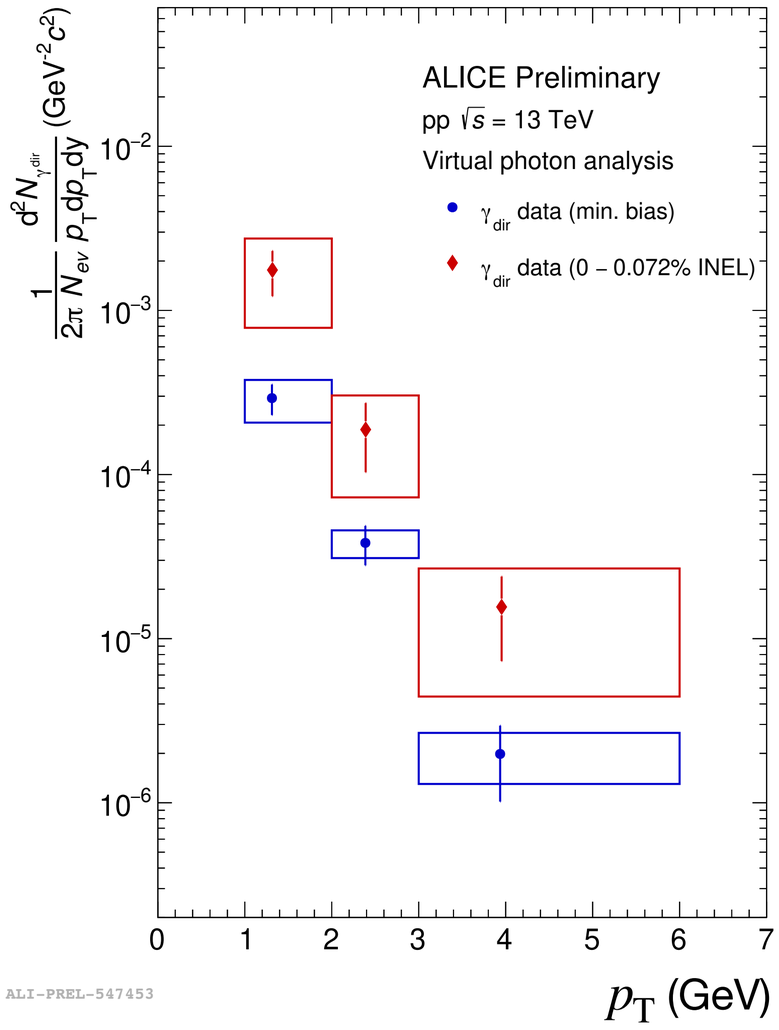
First measurement of direct photons at low p_T in small systems at the LHC

- Minimum bias pp collisions $\sqrt{s}$ = 13 TeV
  - Provide reference
  - Reproduced by both prompt only and prompt + thermal radiation calculations
- High-multiplicity pp collisions $\sqrt{s}$ = 13 TeV
  - Search for onset of thermal radiation
  - Significant higher γ_{dir} yield
  - Call for predictions

Minimum bias pp $\sqrt{s}$ = 13 TeV

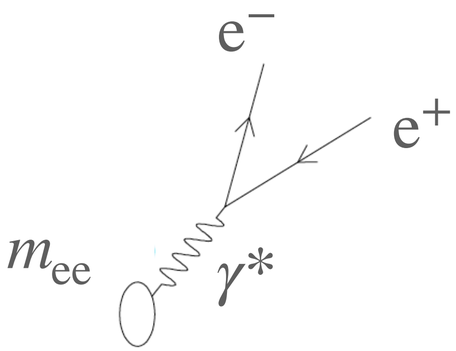


Minimum bias pp
High-multiplicity pp



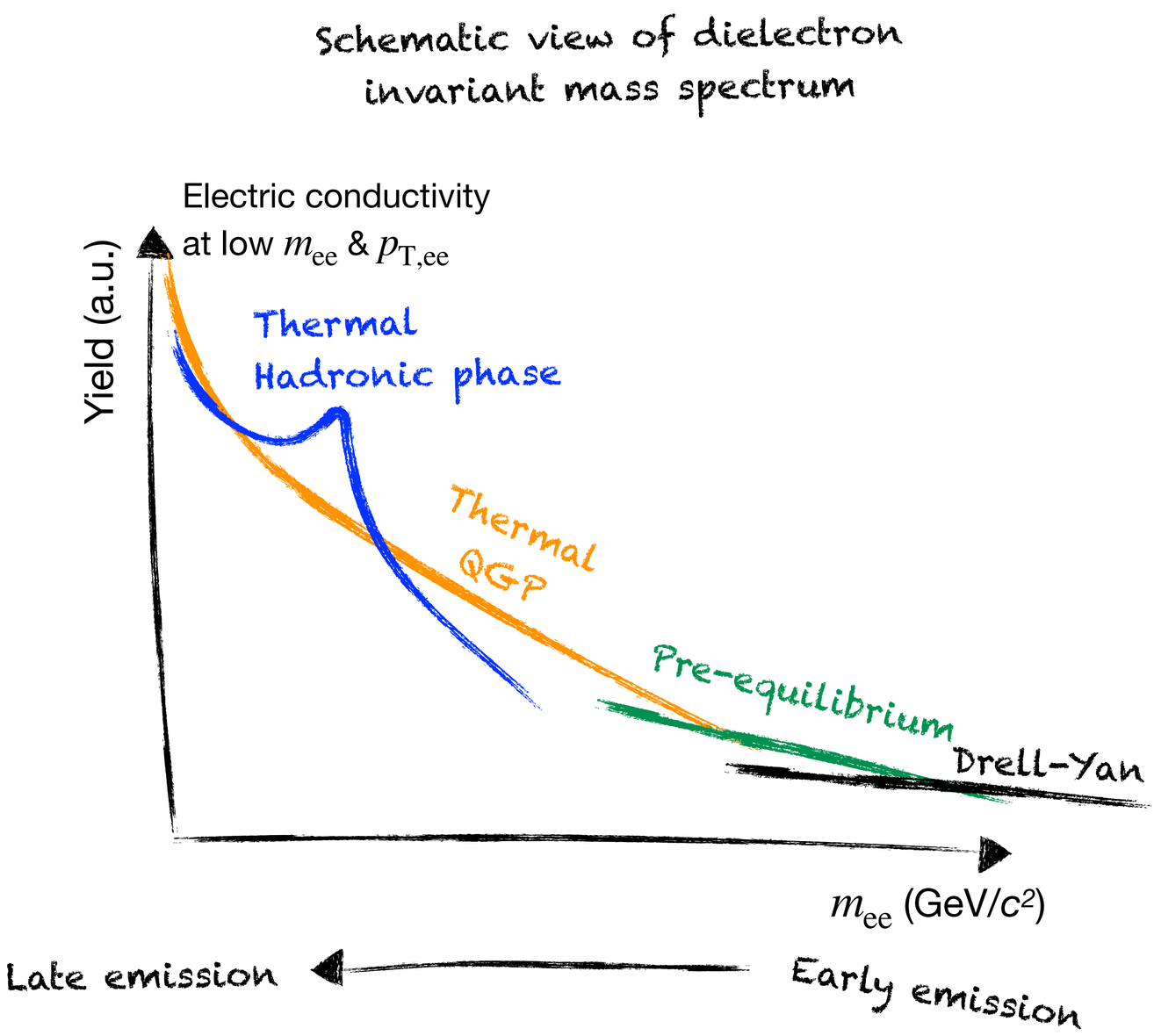
Dileptons

Virtual photons



Carry mass (m_{ee}):

- Can serve as an approximate clock
  → **Separate thermal radiation from different stages**



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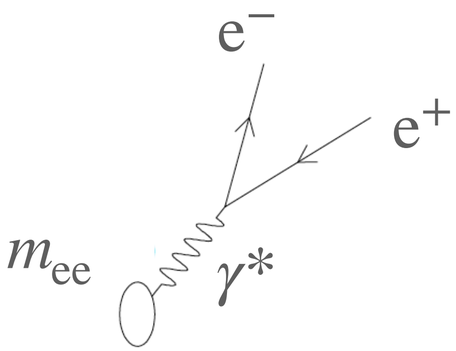

Carry mass (m_{ee}):

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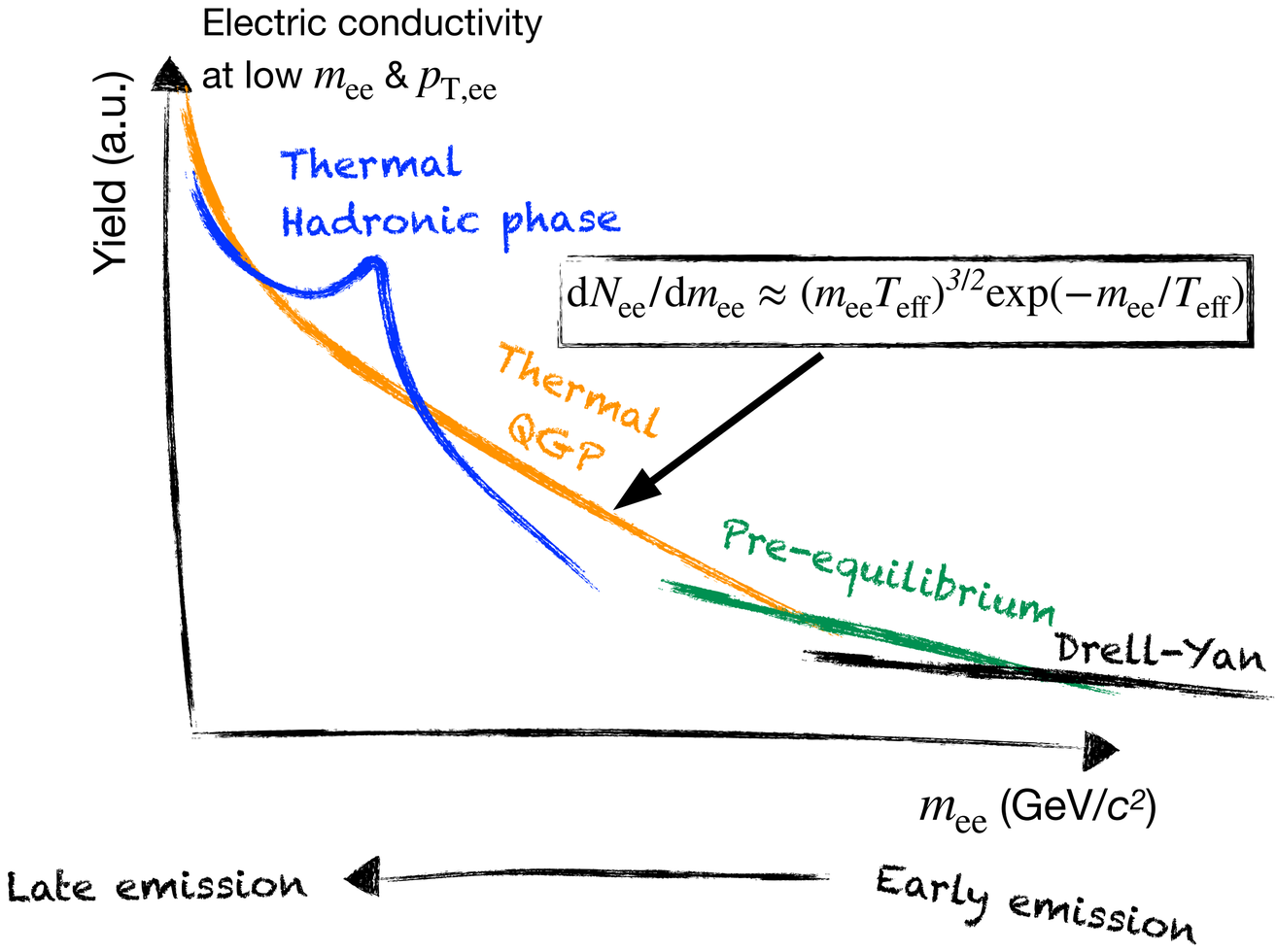
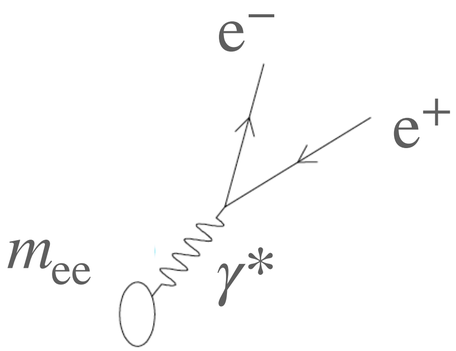
- Invariant mass not affected by radial flow
  → Access to **QGP properties without blue shift**
  Inverse slope → Access to early averaged temperature

Schematic view of dielectron invariant mass spectrum



R. Rapp and H. Van Hees, Phys. Lett. B753 (2016) 586

Virtual photons



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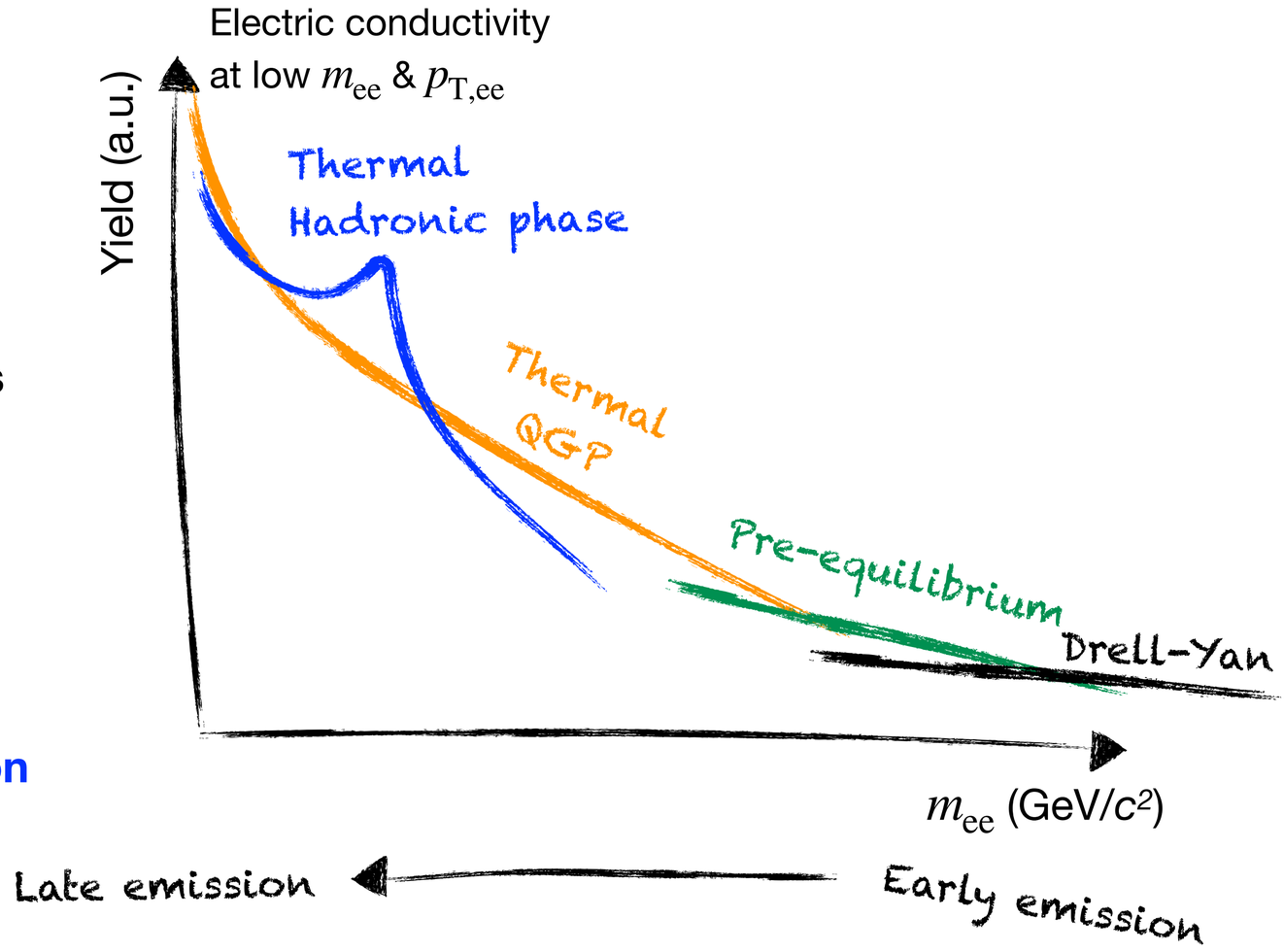
- Can serve as an approximate clock
  → **Separate thermal radiation from different stages**
- Invariant mass not affected by radial flow
  → Access to **QGP properties without blue shift**
  Inverse slope → Access to early averaged temperature
- Radiation from hot-hadronic matter
  Sensitive to in-medium spectral function of ρ meson
  Related to chiral symmetry restoration, lifetime of the fireball

Schematic view of dielectron invariant mass spectrum



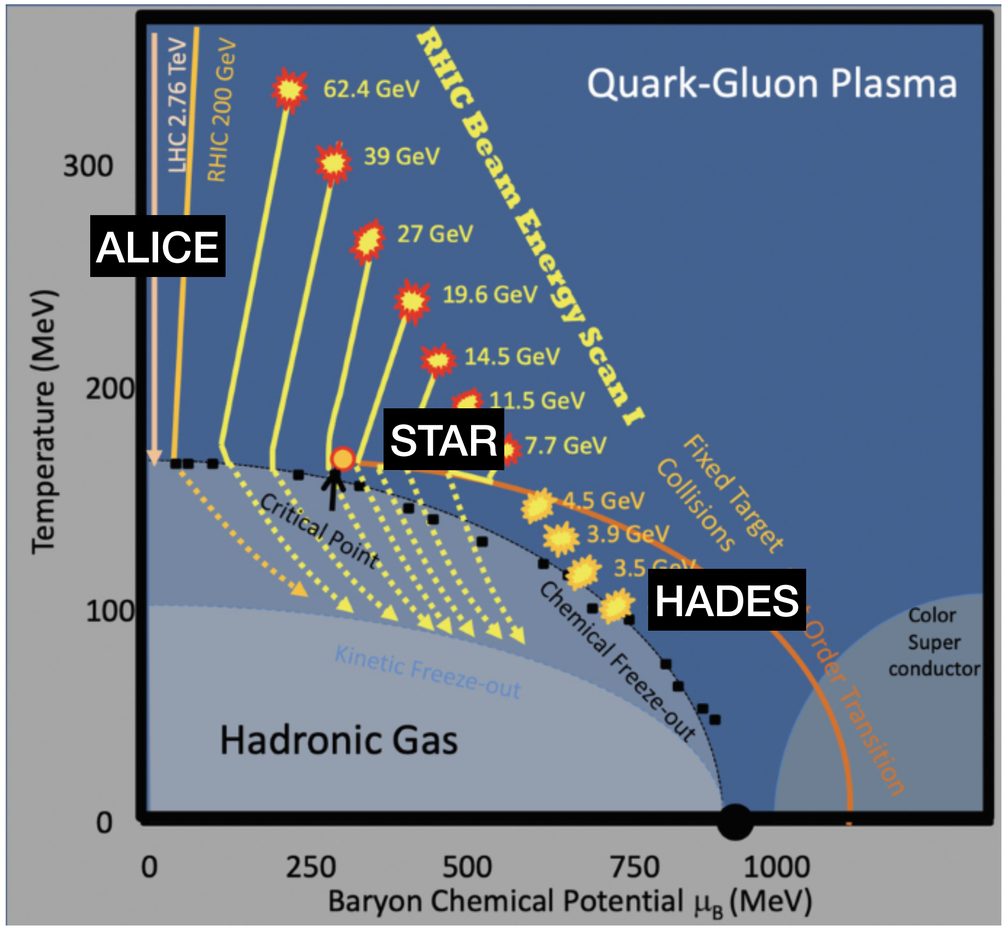
P.M. Hohler and R. Rapp, Phys. Lett. B731 (2014) 103

Results over a wide range of energies

Probe the phase diagram
from (high μ_B/low T) to small (low μ_B/high T)

New results from:

- **HADES:**
  Ag-Ag $\sqrt{s_{NN}}$ = 2.42 and 2.55 GeV
  + pp reference for Ag-Ag $\sqrt{s_{NN}}$ = 2.55 GeV
- **STAR:**
  Au-Au $\sqrt{s_{NN}}$ = 7.7, 14.6, 19.6 GeV (BES-II COL)
- **ALICE:**
  Pb—Pb $\sqrt{s_{NN}} = 5.02$ TeV



Odyniec, G. (2022) In: Blaschke, D., Redlich, K., Sasaki, C., Turko, L. Lecture Notes in Physics, vol 999. Springer, Charm, ISBM 978-3-030-95490-1

Niklas Schild Poster #683

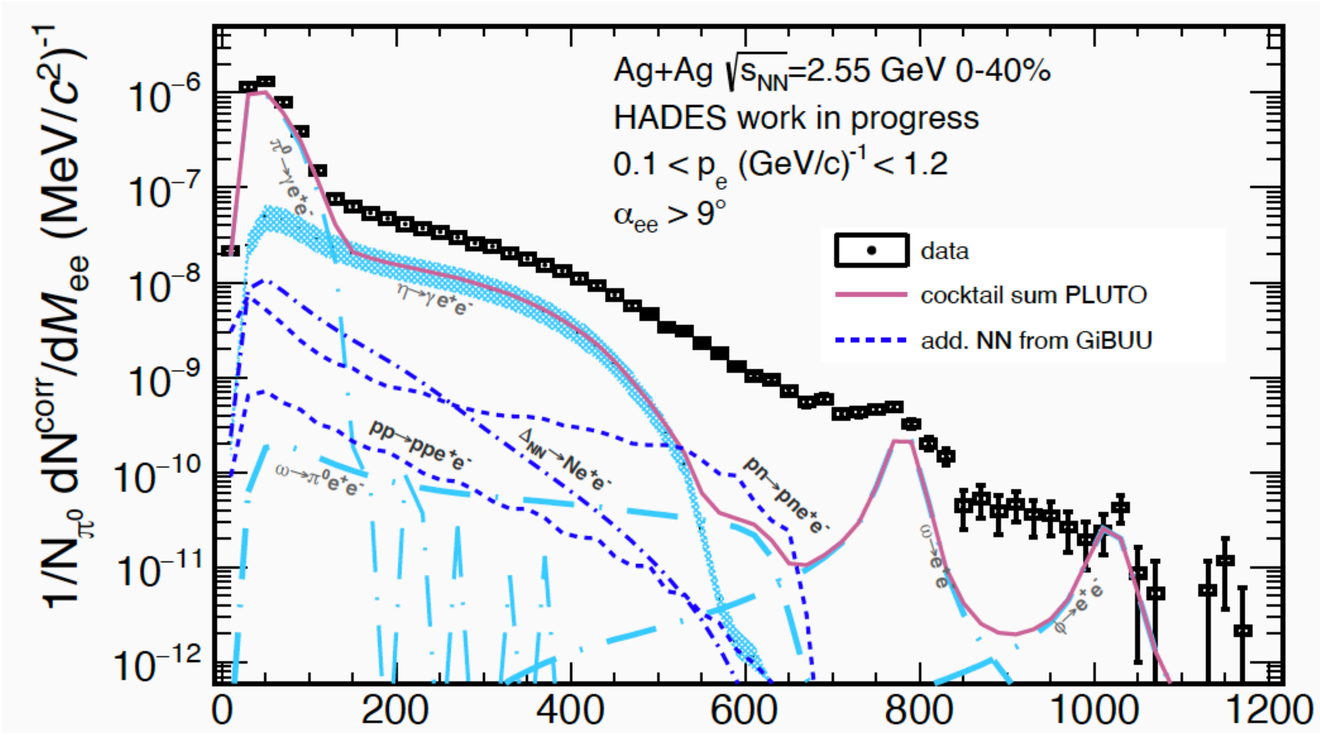
HADES: Ag—Ag at very high μ_B

$\mu_B \approx$ 800 MeV

Ag—Ag $\sqrt{s_{NN}}$ = 2.42, **2.55** GeV

- **Clear excess of e^+e^- pairs** over:
  - Cocktail of hadronic decays at freeze-out
  - + initial NN contributions
    pp analysis for 2.55 GeV ongoing

Karina Scharmann Poster #201



Au—Au at $\sqrt{s_{NN}}$ = 2.42 GeV: HADES, Nature Phys, 15 (2019) 10, 1040
$\pi^-p \to ne^+e^-$ at $\sqrt{s_{\pi^-p}}$ = 1.49 GeV: HADES, arXiv:2205.15914

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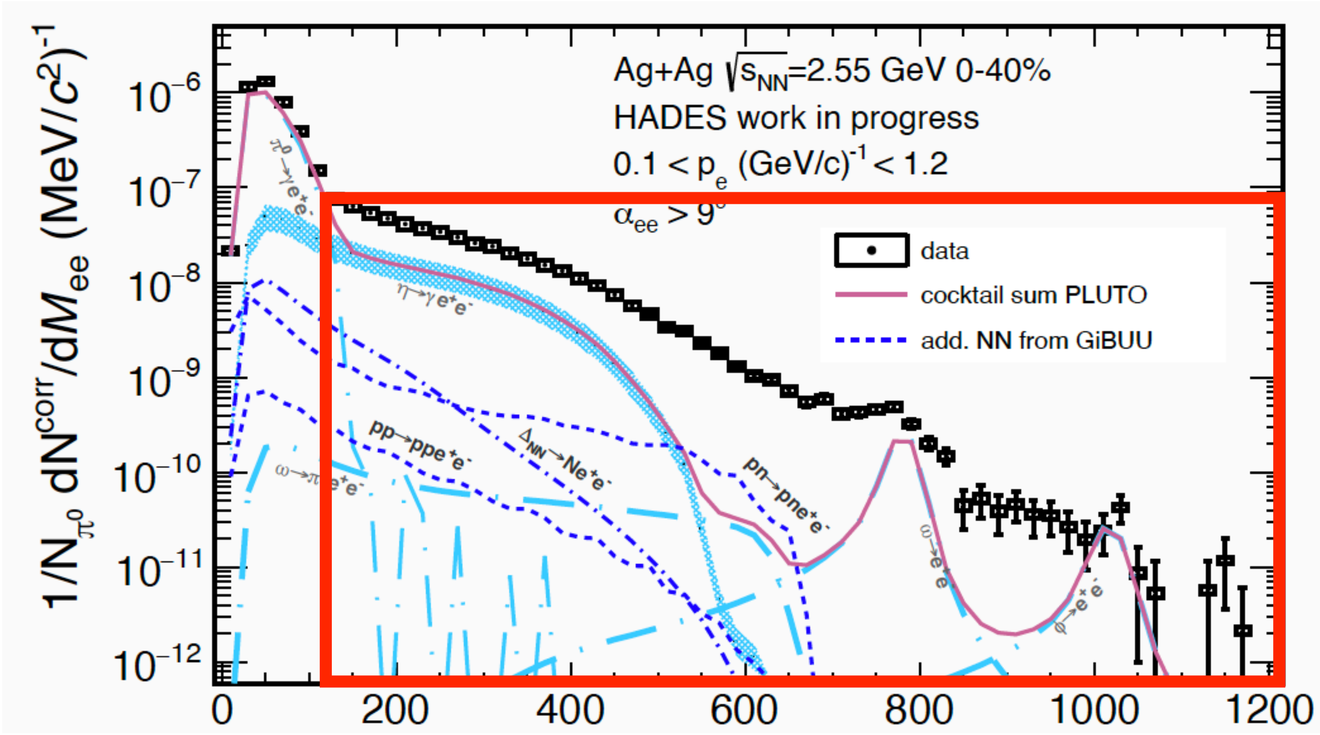

$m_{e^+e^-}$ (MeV/c^2)

Au—Au at $\sqrt{s_{NN}}$ = 2.42 GeV: HADES, Nature Phys, 15 (2019) 10, 1040

$\pi^- p \to n e^+ e^-$ at $\sqrt{s_{\pi^- p}}$ = 1.49 GeV: HADES, arXiv:2205.15914

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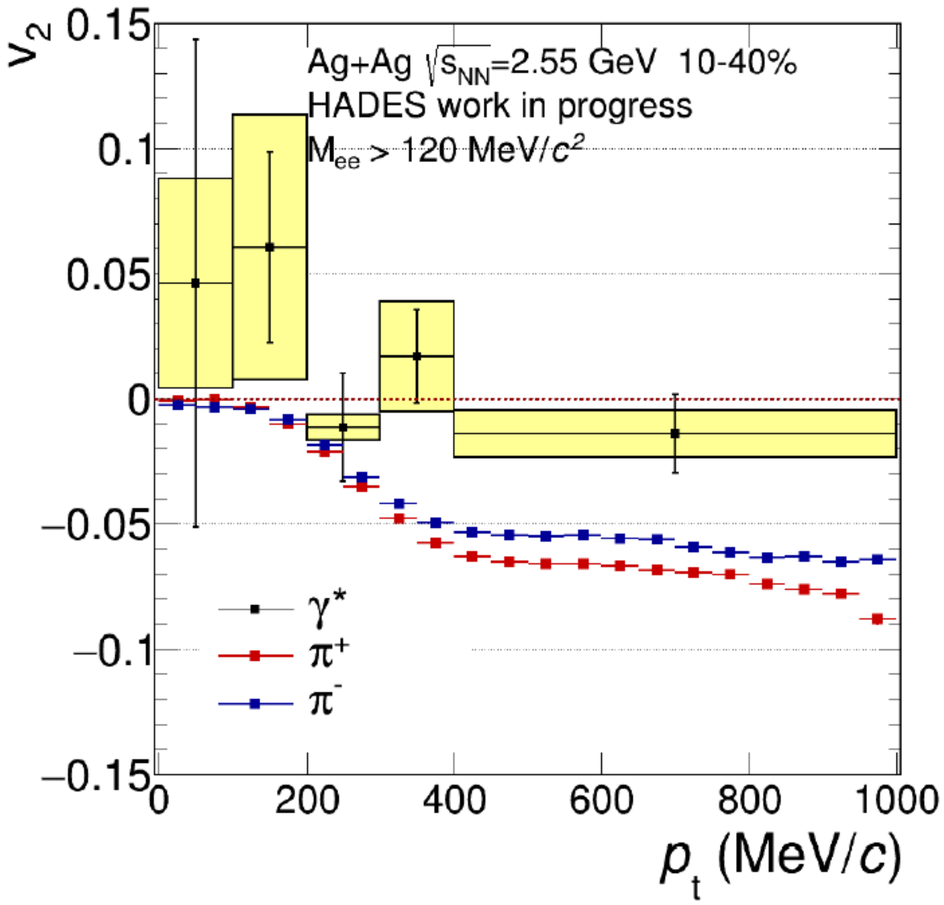
    Karina Scharmann Poster #201

- **v_2 of e^+e^- pairs $\approx$ 0 in excess region**
  At SIS18 energies, $v_2 < 0$ for $\pi^{0,\pm}$ due to spectator shadowing
  Differential studies as a function of mass, p_T, y and centrality
  Comparison with transport model **Renan Hirayama Poster #133**
  → **Confirm penetrating nature**



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HADES: Ag—Ag at very high μ_B

$\mu_B \approx$ 800 MeV

Ag—Ag $\sqrt{s_{NN}}$ = **2.42**, 2.55 GeV

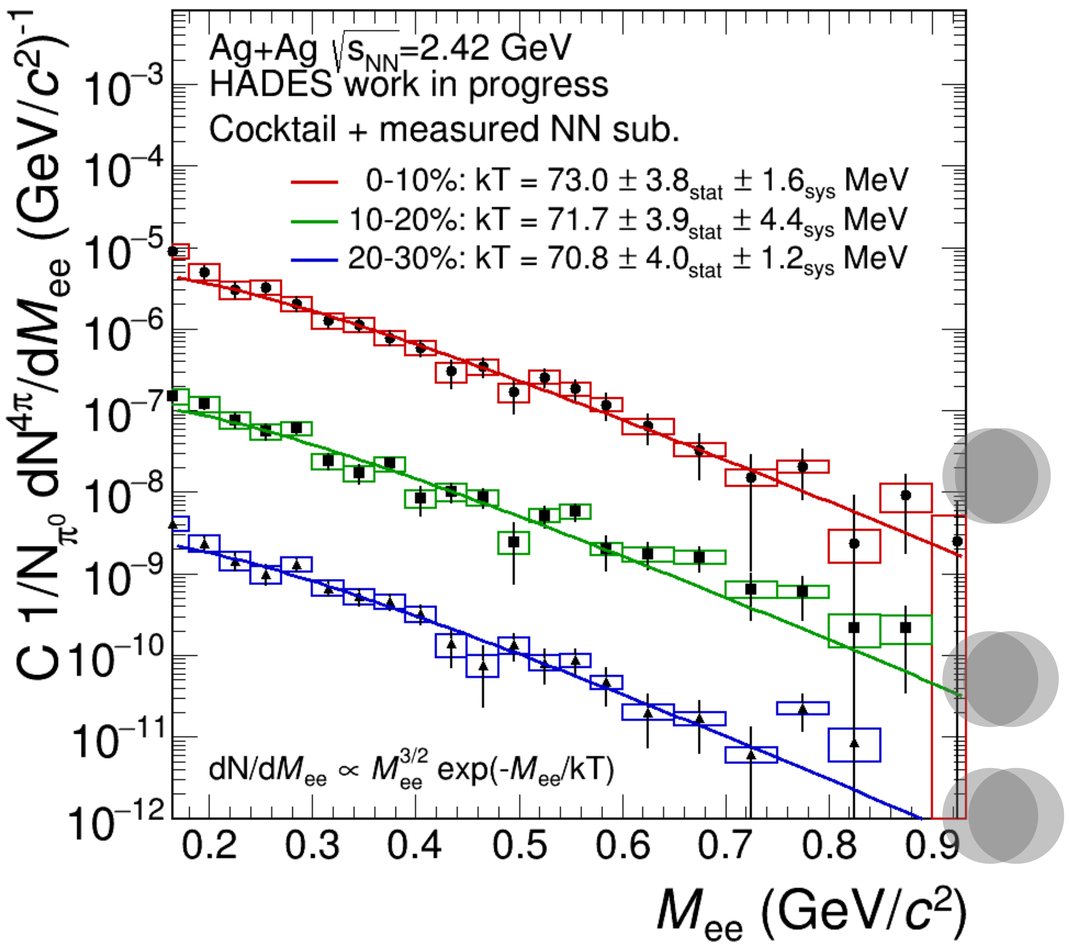
Excess = Data - Cocktail - measured initial NN contributions

has an exponential shape:

$$\frac{dN}{dM_{ee}} \propto M_{ee}^{3/2} \exp(-\frac{M_{ee}}{T_{fit}})$$

→ Extract **integrated fireball temperature** $T_{fit} \approx$ **70 MeV**
for $0.2 < M_{ee} < 0.9$ GeV/c^2
now differentially in centrality classes

Excess **reproduced by hadronic thermal rates**
folded with coarse-grained medium evolution from transport



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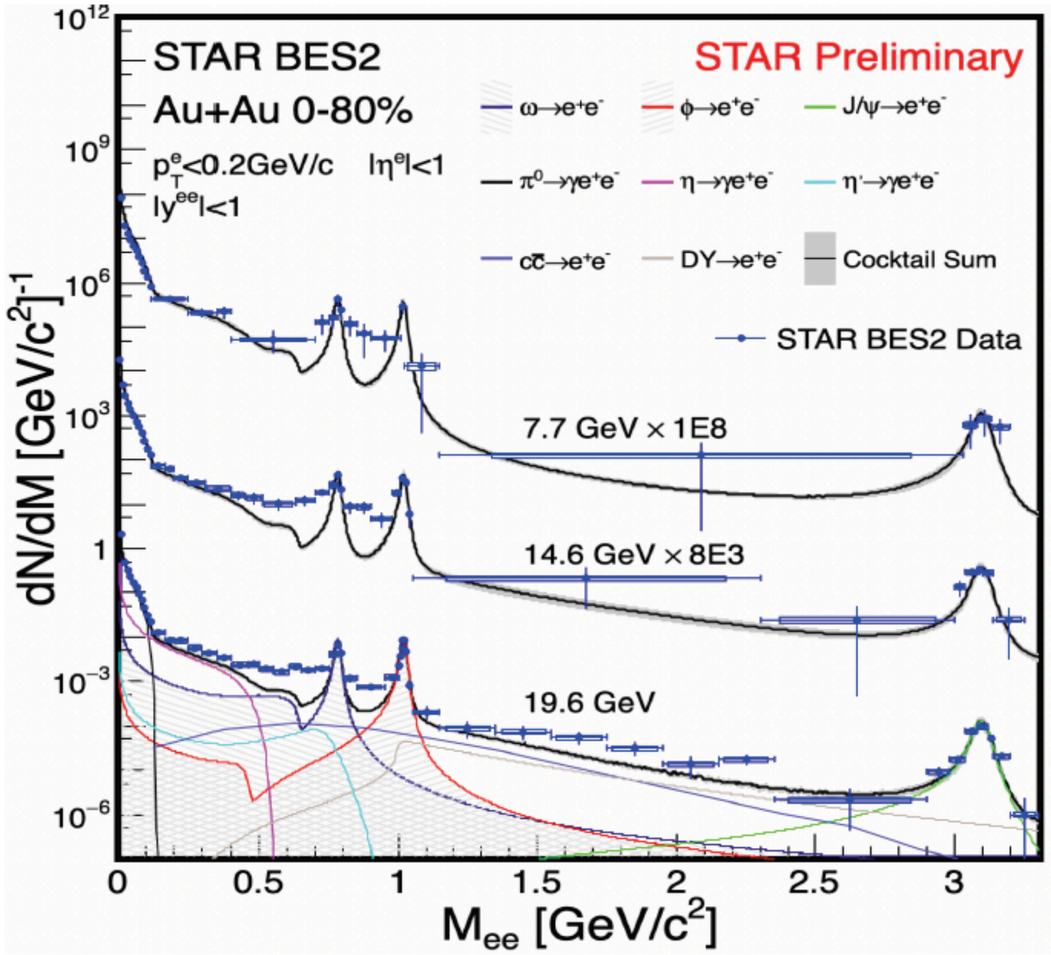
STAR: Au—Au at intermediate μ_B

Yiding Han #301
Chenliang Jin Poster #683

$\mu_B \approx$ 200–500 MeV

Excess of e^+e^- pairs at low $m_{e^+e^-}$

observed over cocktail of hadronic decays at freeze-out (without ρ) + Drell-Yan



Au—Au $\sqrt{s_{NN}}$ = 7.7, 14.6, 19.6 GeV

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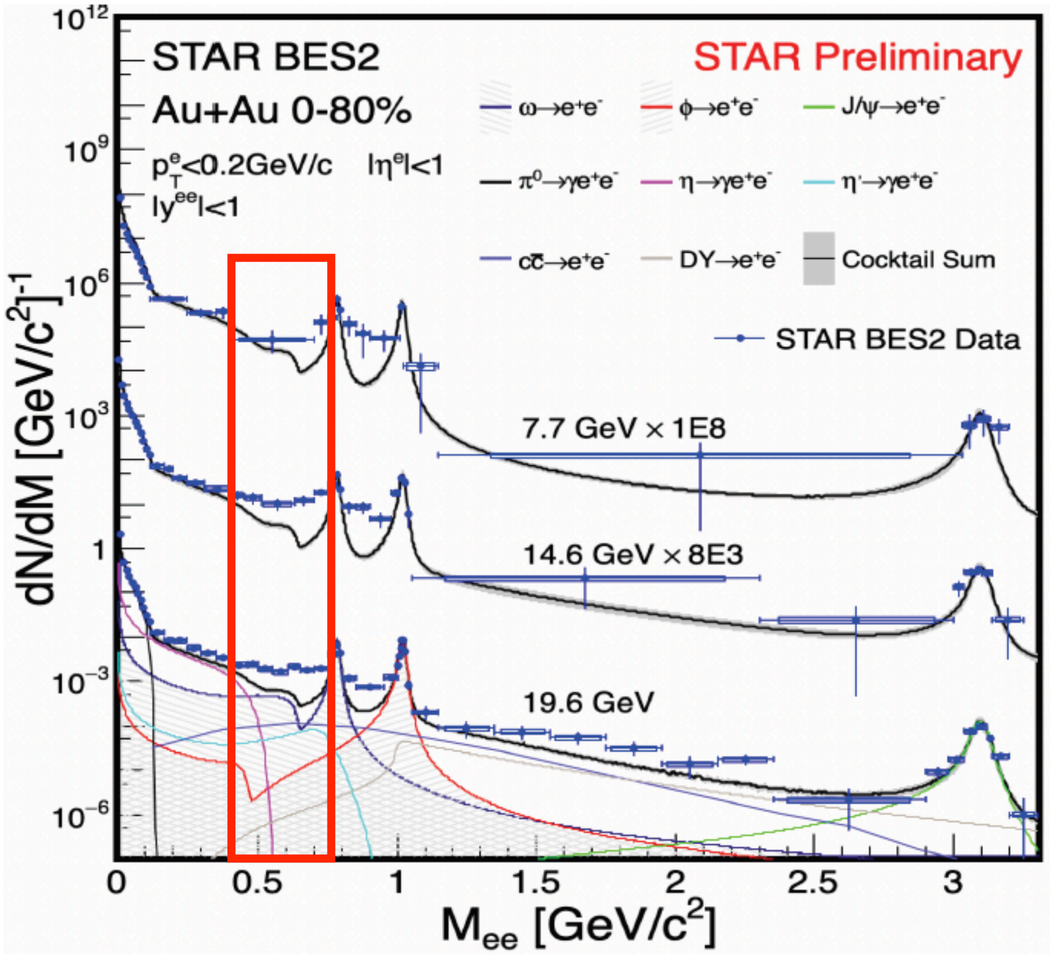


Au—Au $\sqrt{s_{NN}}$ = 7.7, 14.6, 19.6 GeV

Calculate excess = Data - Cocktail Sum
in $0.4 < m_{ee} < 0.75$ GeV/c^2

STAR: excess at low mass

Yiding Han #301
Chenliang Jin Poster #683

$\mu_B \approx$ 200–500 MeV

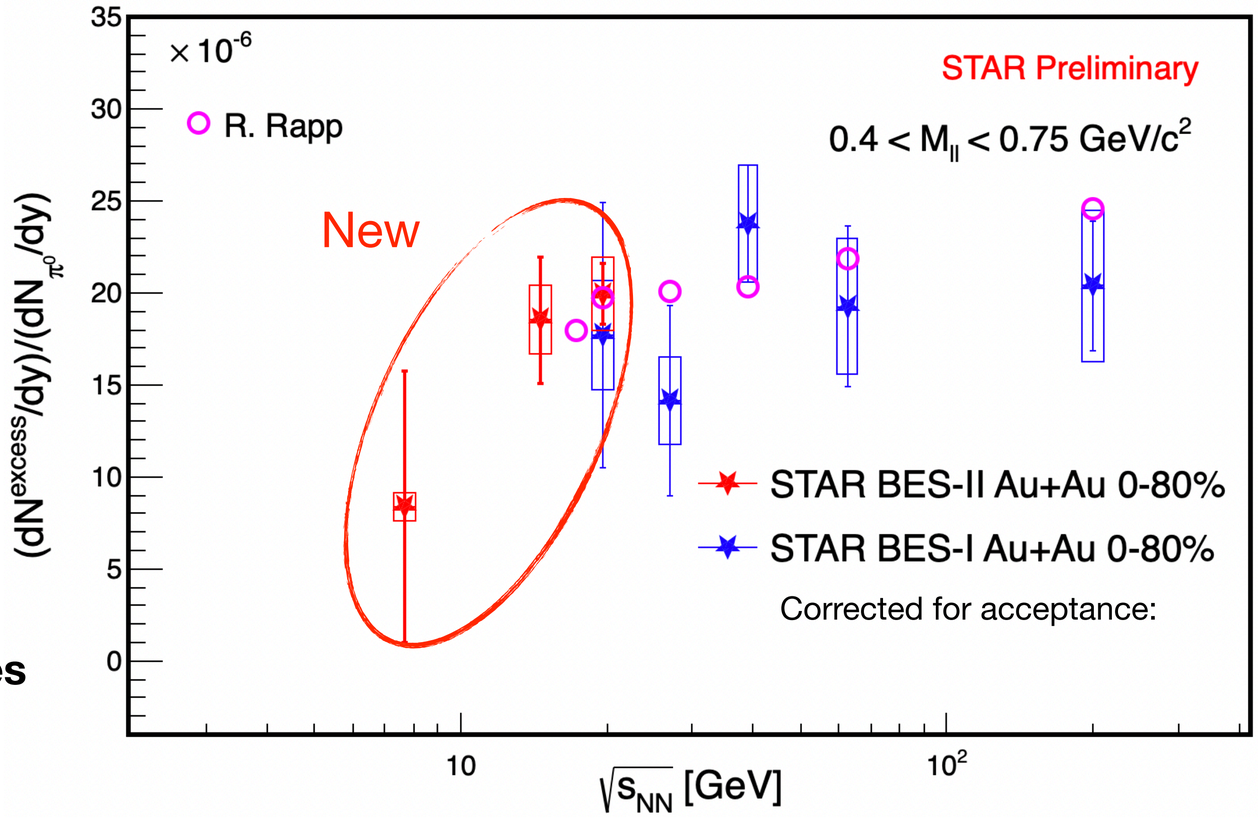
Au—Au $\sqrt{s_{NN}}$ = 7.7, 14.6, 19.6 GeV

Excess yield at low m_{ee} / (dN_{π^0}/dy)

- **For $\sqrt{s_{NN}} \geq$ 17.3 GeV**: described (over larger mass range)
  by **calculations including thermal production of ρ**
  with in-medium broadening spectral function (+ QGP)

- **In BES-II region (NEW):**
  Baryon density increases, T_{ch} decreases
  → Probe the role of baryons and temperature effects

Hint for a decrease with $\sqrt{s_{NN}}$, need to reduce uncertainties (future experiments CBM, NA60+)



STAR BES-I: PRC 107, L061901 (2023)
R. Rapp and H. van Hees, Phys. Lett. B 753, 586 (2016)

STAR: higher mass

C. Gale #626

$\mu_B \approx$ 0–200 MeV

Au—Au $\sqrt{s_{NN}}$ = 19, 27, 39, 62.4, 200 GeV

Excess / ($dN_{ch}/d\eta$) at higher $\sqrt{s_{NN}}$ (> 19 GeV BES-I)

Compared to new calculations for QGP thermal radiation with:

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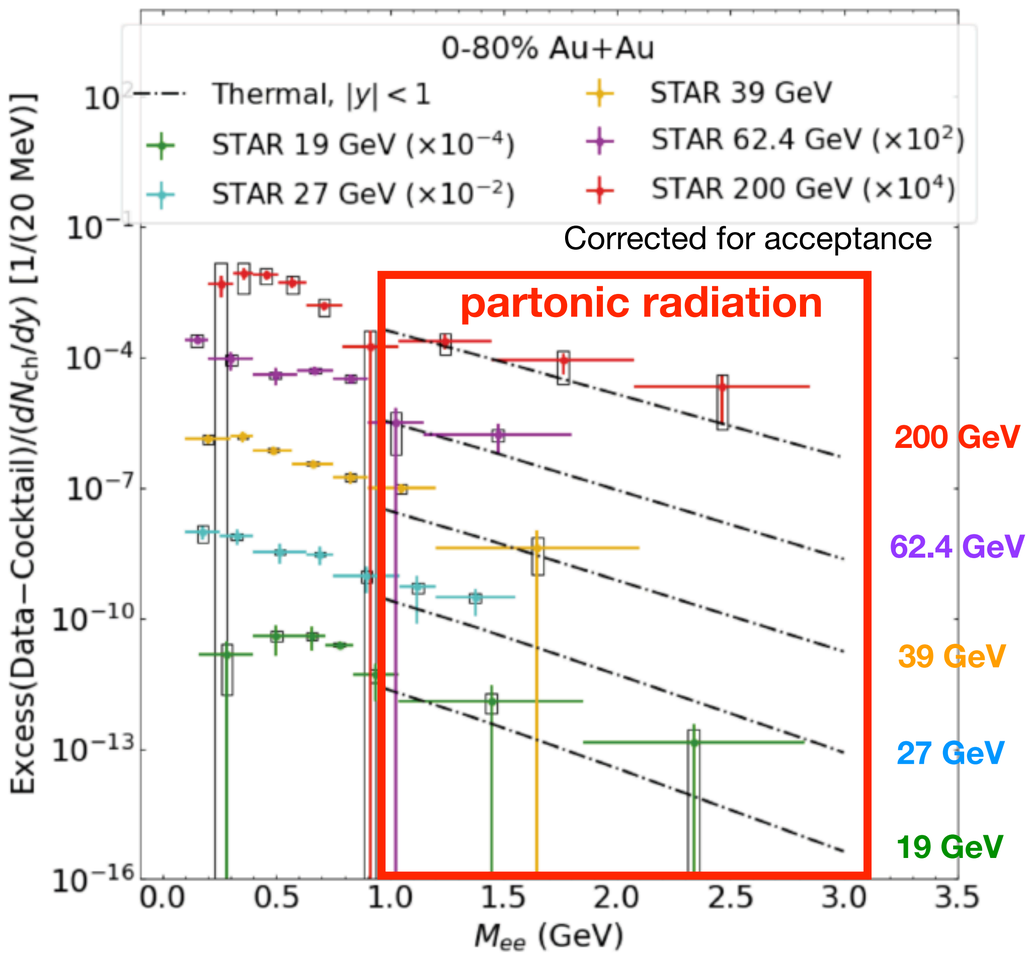
- Integrated over space-time with a realistic hydro

→ **Quite good agreement with the data**



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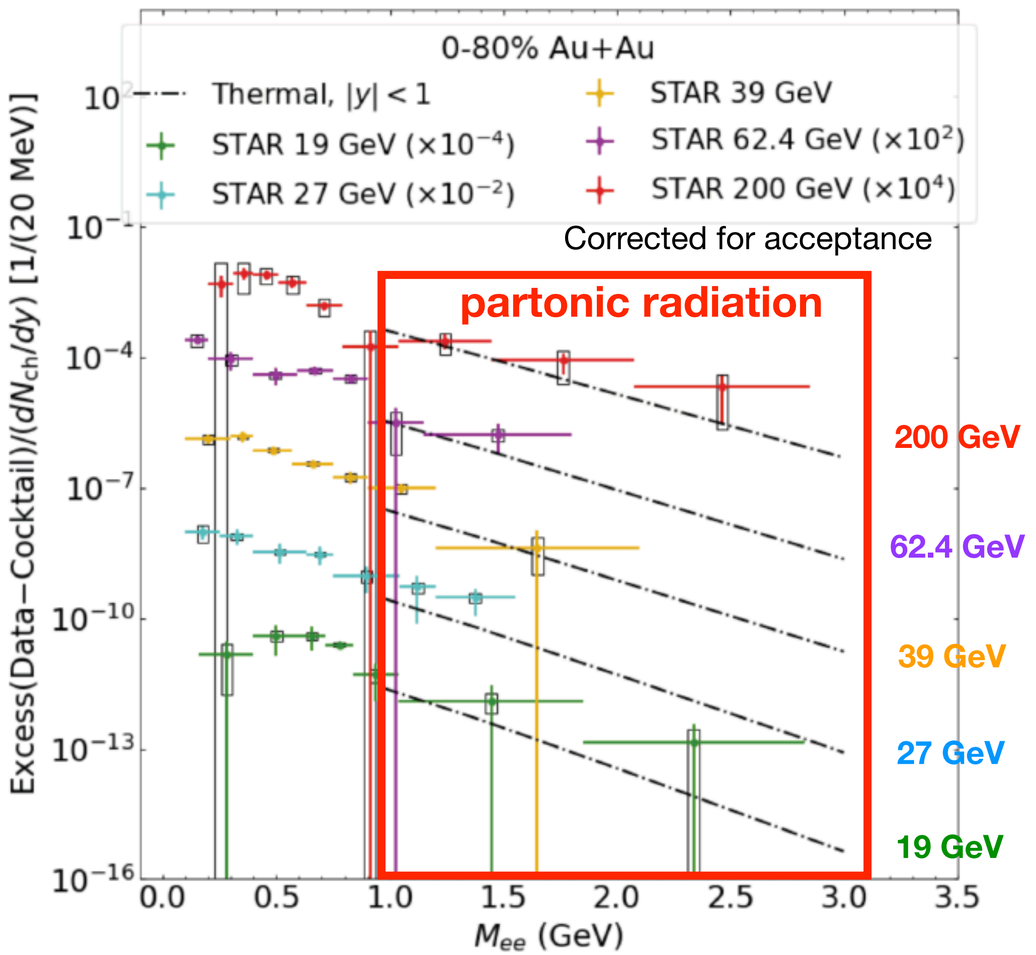
Confirm theoretically:

- **Role of thermal QGP dileptons as thermometers**
- **Discriminating power of dilepton polarisation (e.g. μ_B)**

No pre-equilibrium contributions yet in the calculations

→ **Need more precise data**



STAR BES-I: PRC 107, L061901 (2023)

ALICE: Pb—Pb at $\mu_B \approx 0$

Daiki Sekihata #171

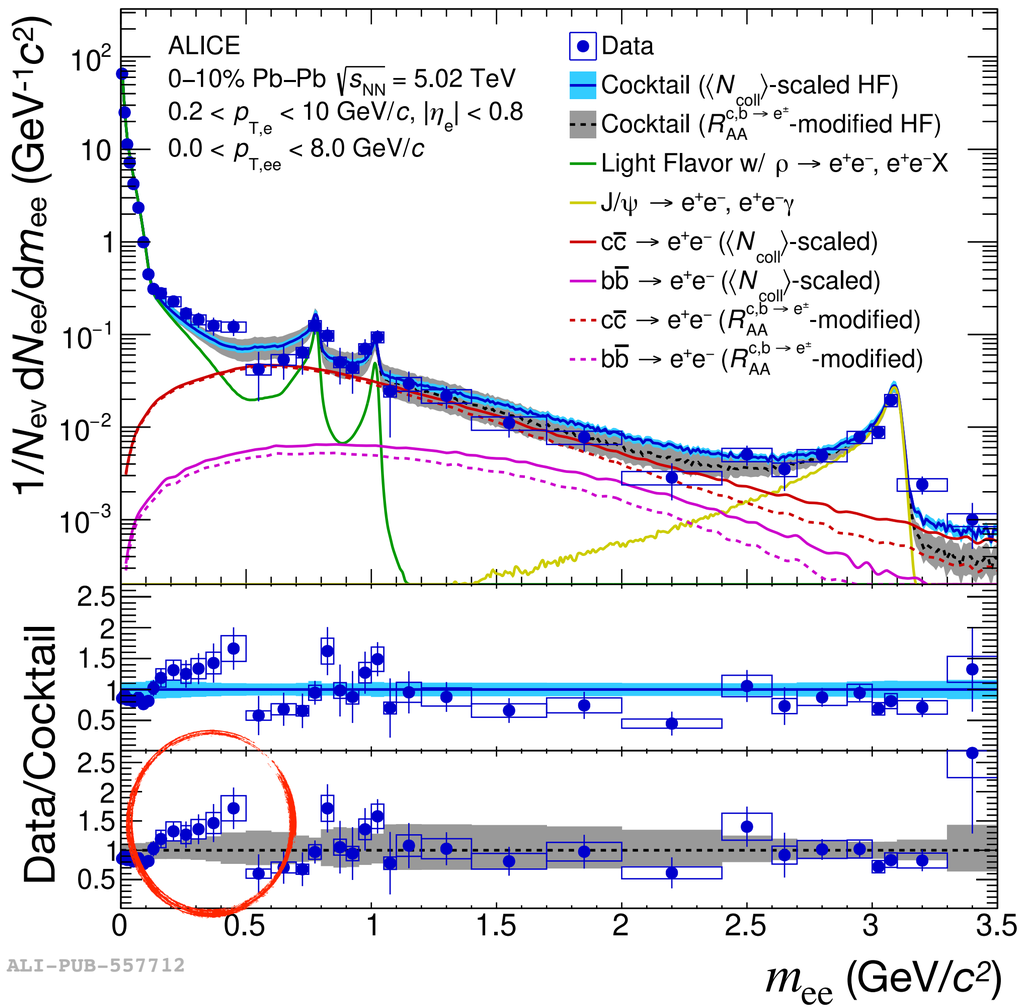
$\mu_B \approx 0$

Pb—Pb $\sqrt{s_{NN}} = 5.02$ TeV

ALICE, arXiv:2308.16704

Finalised dielectron yield
compared to background cocktail from hadronic decays

- Large heavy-flavour (HF) background not easy to estimate:
  → two versions:
  - Vacuum expectations (pp $\times \langle N_{coll} \rangle$)
  - Medium effects (measured $R_{AA}^{c,b \to e^{\pm}}$, EPS09 nPDF)
- **No clear excess over the background**
  → **Hint at low m_{ee} ($0.18 < m_{ee} < 0.5$ GeV/c^2)**



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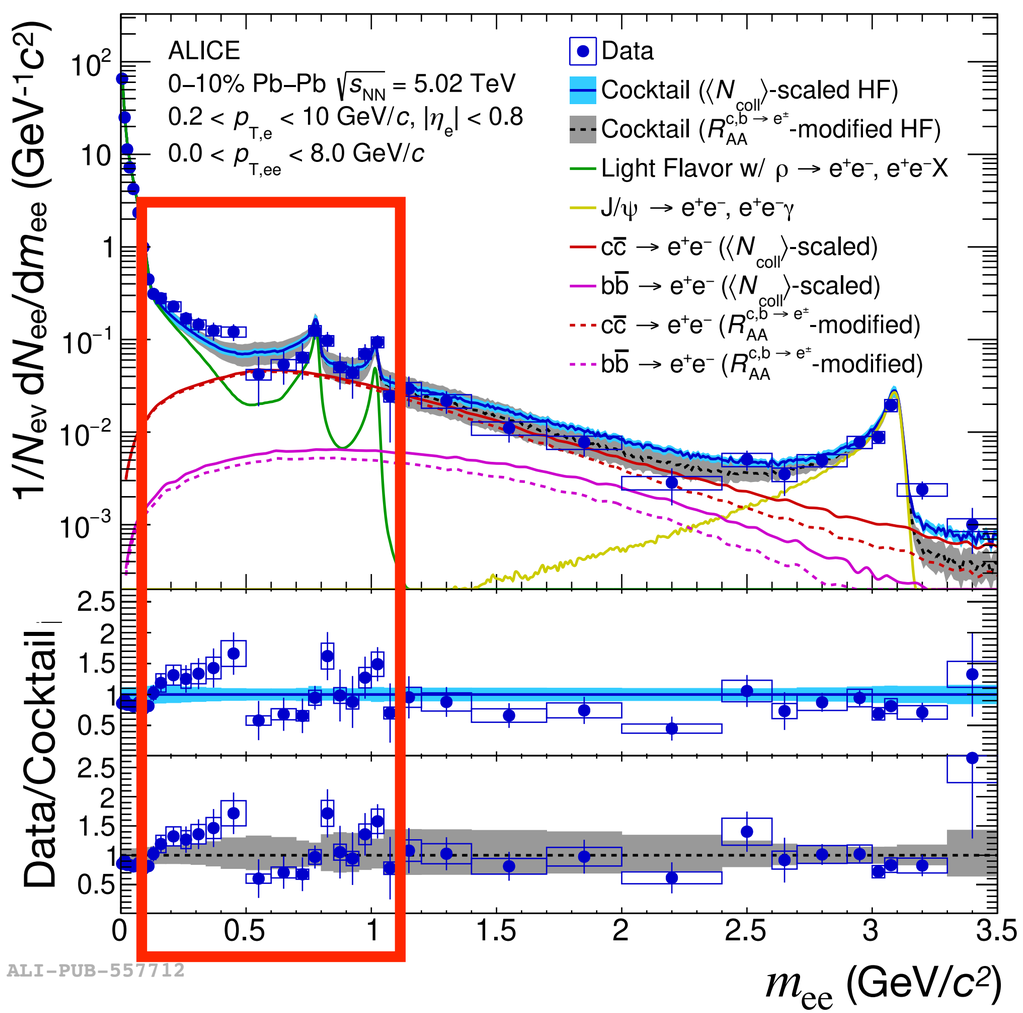


ALICE: *excess* at low mass

Daiki Sekihata #171

$\mu_B \approx 0$

Pb−Pb $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE, arXiv:2308.16704

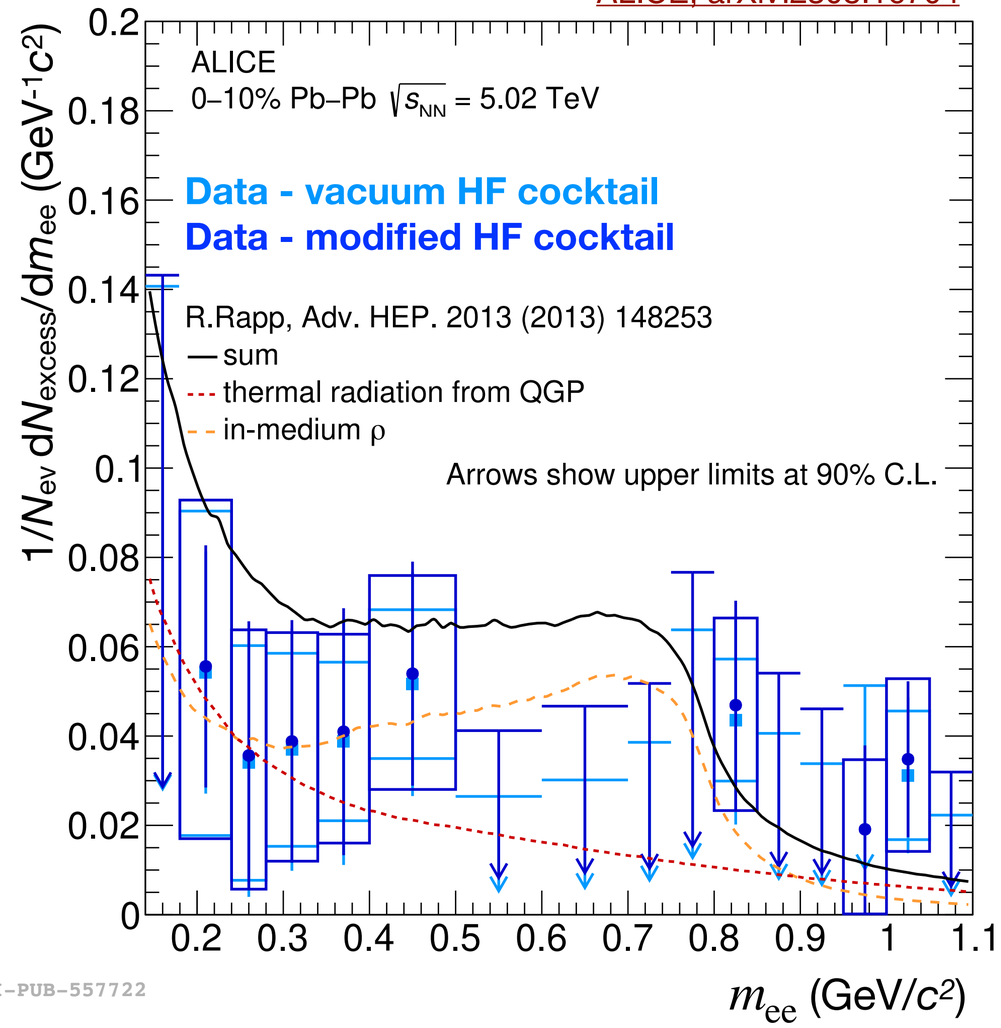
Excess = Dielectron yield - background cocktail (w/o ρ)

Compared to calculations for thermal radiation

- **from hadronic phase (in-medium ρ)**
- from QGP

Tension in $0.5 < m_{ee} < 0.8$ GeV/c^2 ($\sim 3\sigma$)

→ Need to reduce uncertainties



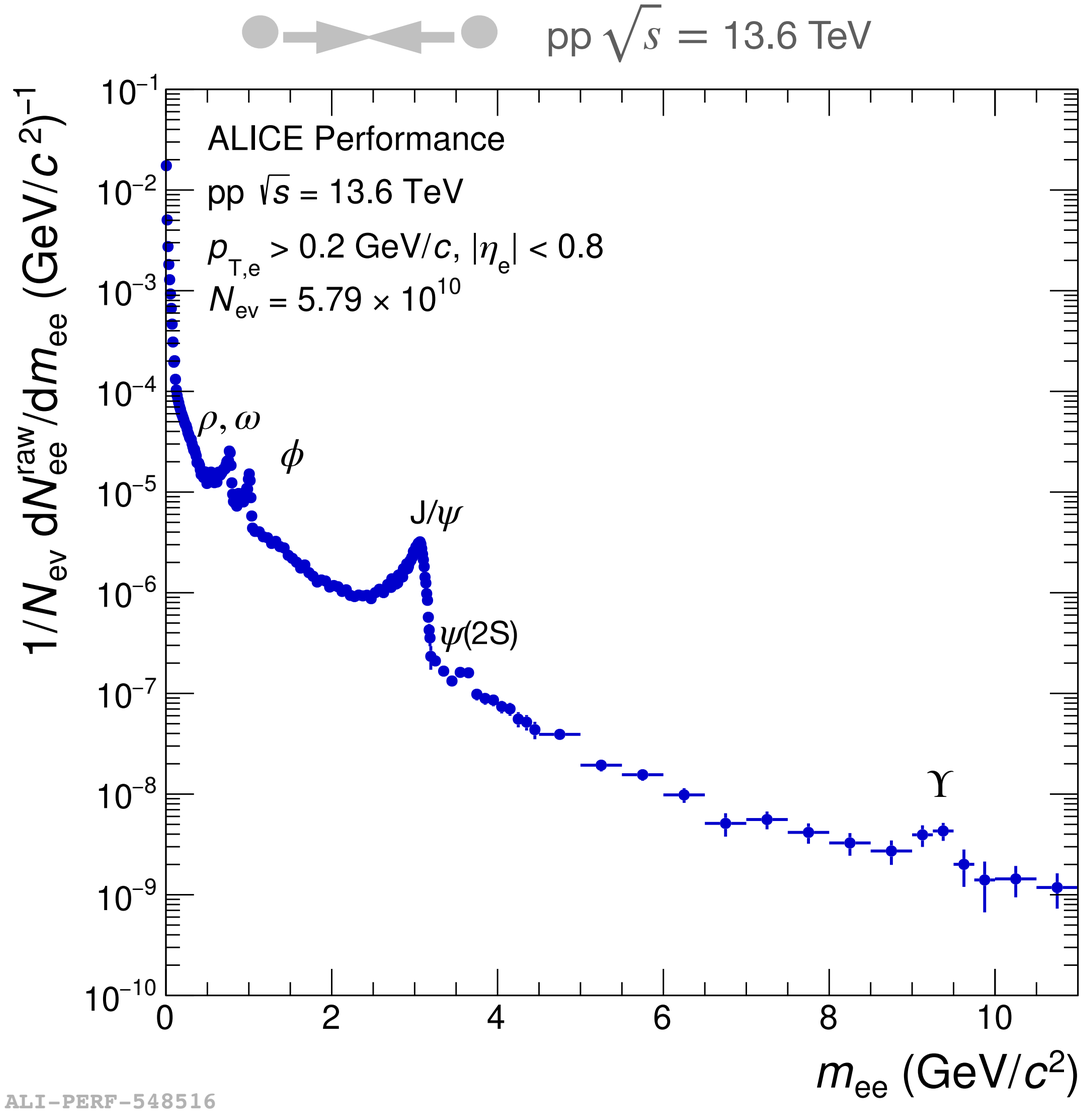
ALICE: Run 3

Daiki Sekihata #171

ALICE: Jerome Jung Poster #665 PHENIX: Roli Esha Poster #217

$\mu_B \approx 0$

Much more data (up to a factor 100 for Pb—Pb)



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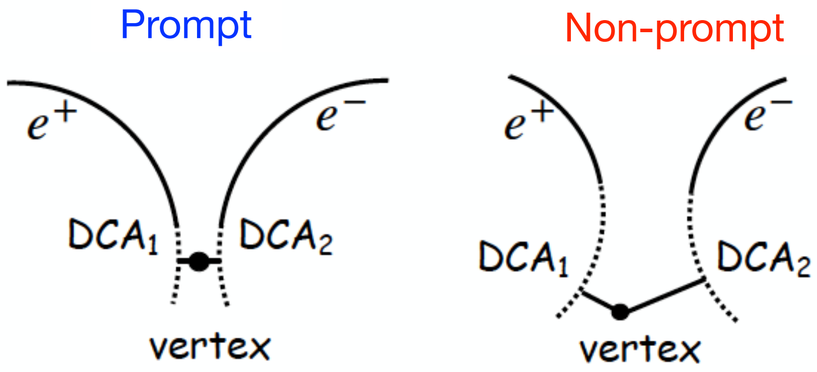
$\mu_B \approx 0$

Much more data (up to a factor 100 for Pb—Pb) and (better) separation of heavy-flavour background and prompt e^+e^-

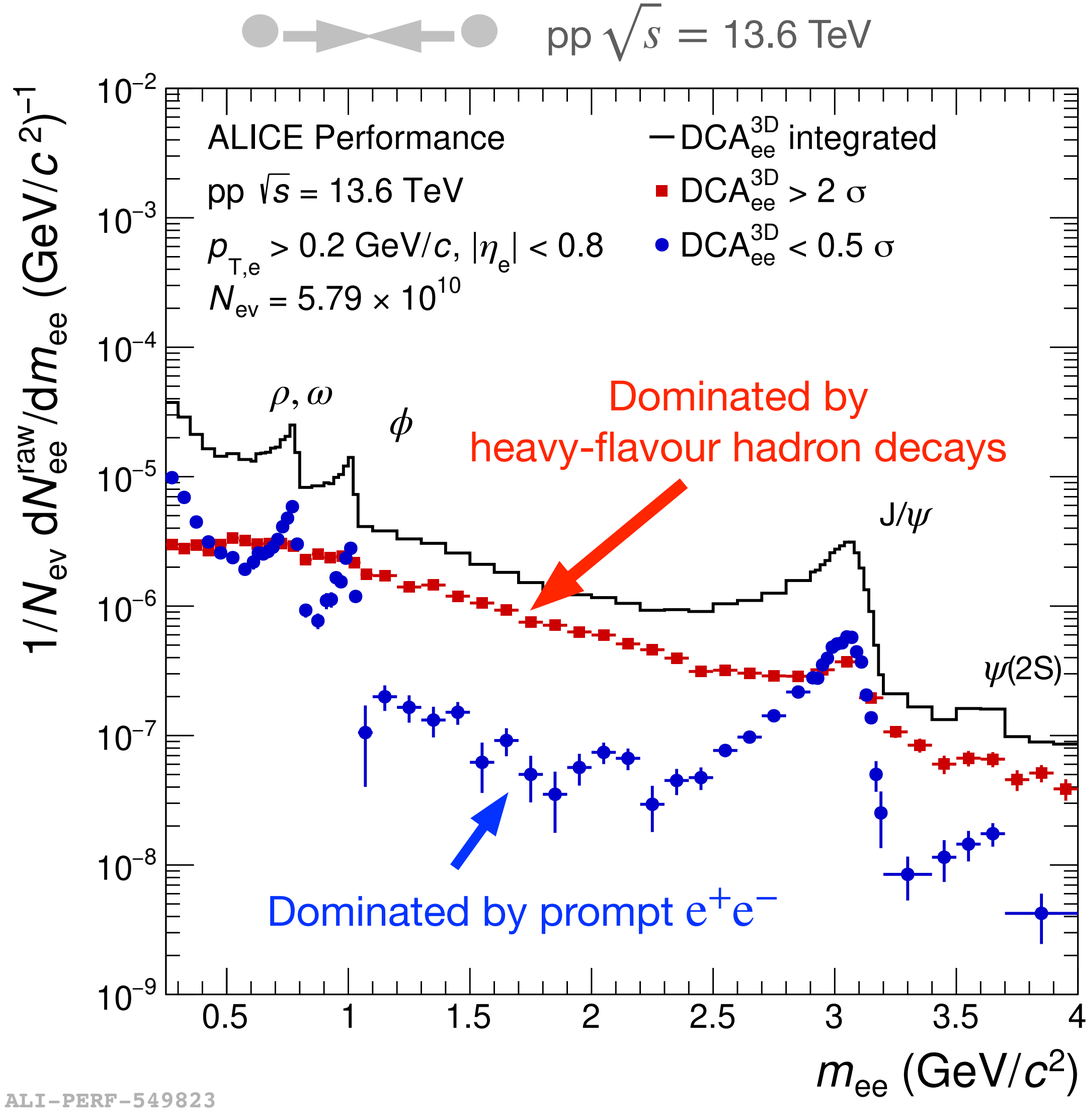
Separate prompt and non-prompt e^+e^-



$$DCA_{ee}^{3D} = \sqrt{\frac{1}{2}\left[\left(\frac{DCA_1}{\sigma_1}\right)^2 + \left(\frac{DCA_2}{\sigma_2}\right)^2\right]}$$

Small DCA_{ee}^{3D}
Light-favour decays
Prompt J/Ψ
Thermal radiation

Large DCA_{ee}^{3D}
heavy-flavour decays
Non-prompt J/Ψ



Key tool to handle the heavy-flavour background at the LHC !

Future measurements

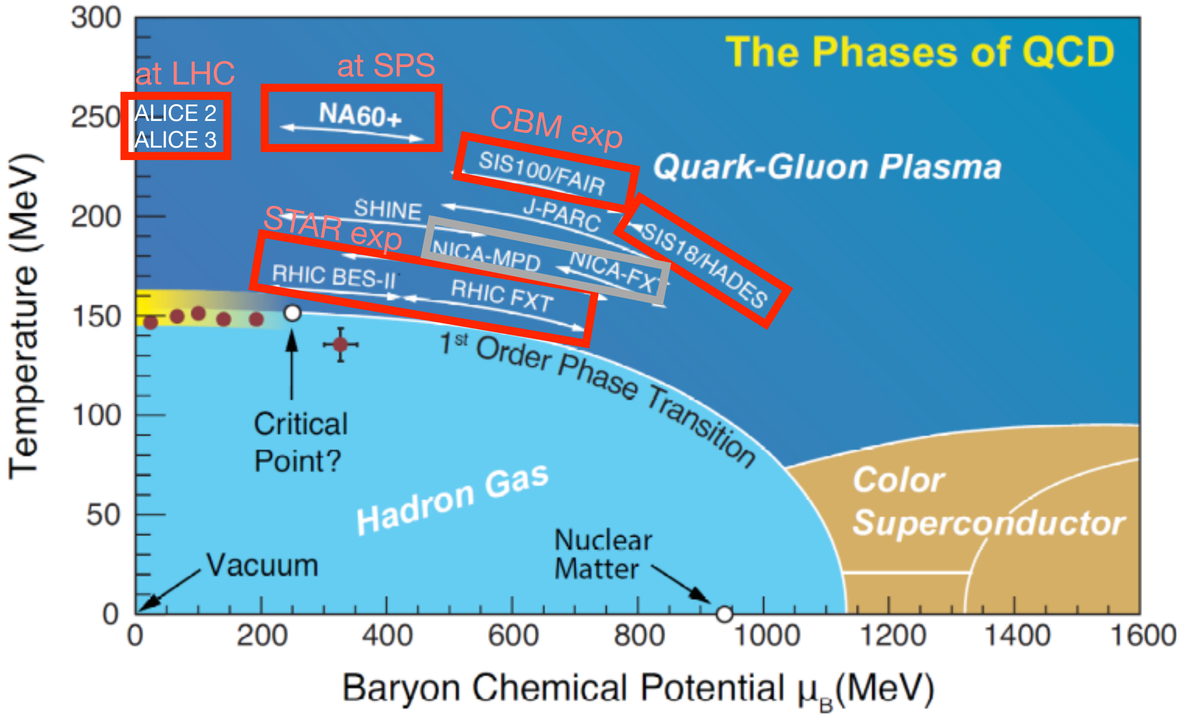
NA60+: Giacomo Alocco #761
CBM: Claudia Hoehne #687
ALICE 3: Isabella Sanna #317
Poster Sebastian Scheid #158

Different experiments at different accelerator facilities

- **From high μ_B to vanishing μ_B**
  HADES, STAR, CBM, NA60+, ALICE 2&3

- **To answer open questions:**

  - Mechanism of Chiral symmetry restoration ($\rho - a_1$ mixing)
  - Dilepton v_2 (Input for direct photon puzzle)
  - Dilepton polarisation (discriminating variable)
  - Equilibrium mechanisms
  - QGP EoS (T_{eff})
  - First order phase transition at large μ_B (T_{eff} in IMR vs $\sqrt{s_{\mathrm{NN}}}$)
  - Electric conductivity



Courtesy of Thomas Ullrich

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  Azumi Sakai #721

  - Mechanism of Chiral symmetry restoration ($\rho - a_1$ mixing)
  - Dilepton v_2 (Input for direct photon puzzle)
  - Dilepton polarisation (discriminating variable) **Florian Seck #741**
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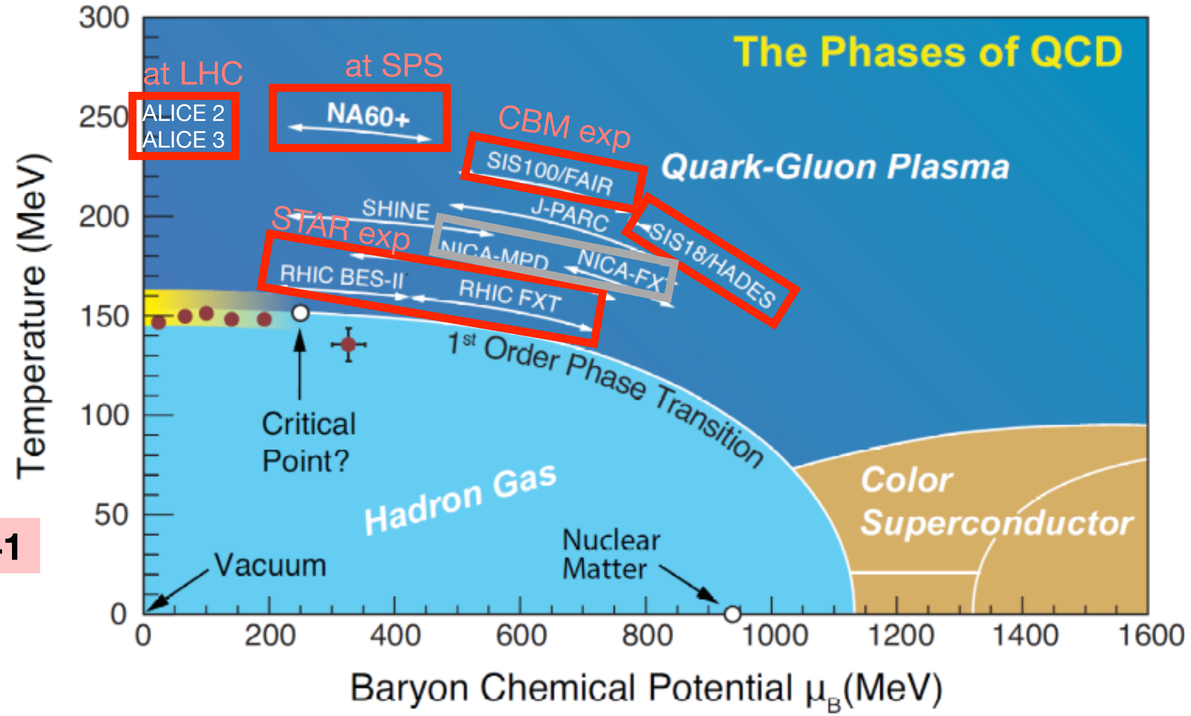


Courtesy of Thomas Ullrich

Summary

- Direct photons: low-p_{T}
    - Uncertainties of measurements improving in time at RHIC and at the LHC (effort still on going)
    - Some issues remain opened (direct photon puzzle…)

    $\rightarrow$ Common effort between theorists and experimentalists to solve them

- Dileptons
    - Measurements at very different μ_{B}/T
    - Large potential of dilepton measurements shown by theory at this QM
    - Huge experimental efforts to make such measurements possible…..starting now !

Many thanks to H. Appelshäuser, H. Busching, V. Doomra, R. Esha, T. Galatyuk, C. Hoehne, C. Gale, D. Gabor, Y. Han, J. Jung, A. Marin, T. Nishimura, J-F Paquet, P. Plaschke, R. Rapp, K. Reygers, A. Sakai, M. Sas, N. Schild, S. Scheid, F. Seck, D. Sekihata, J-a Sun

Back-up

High-p_T isolated photons

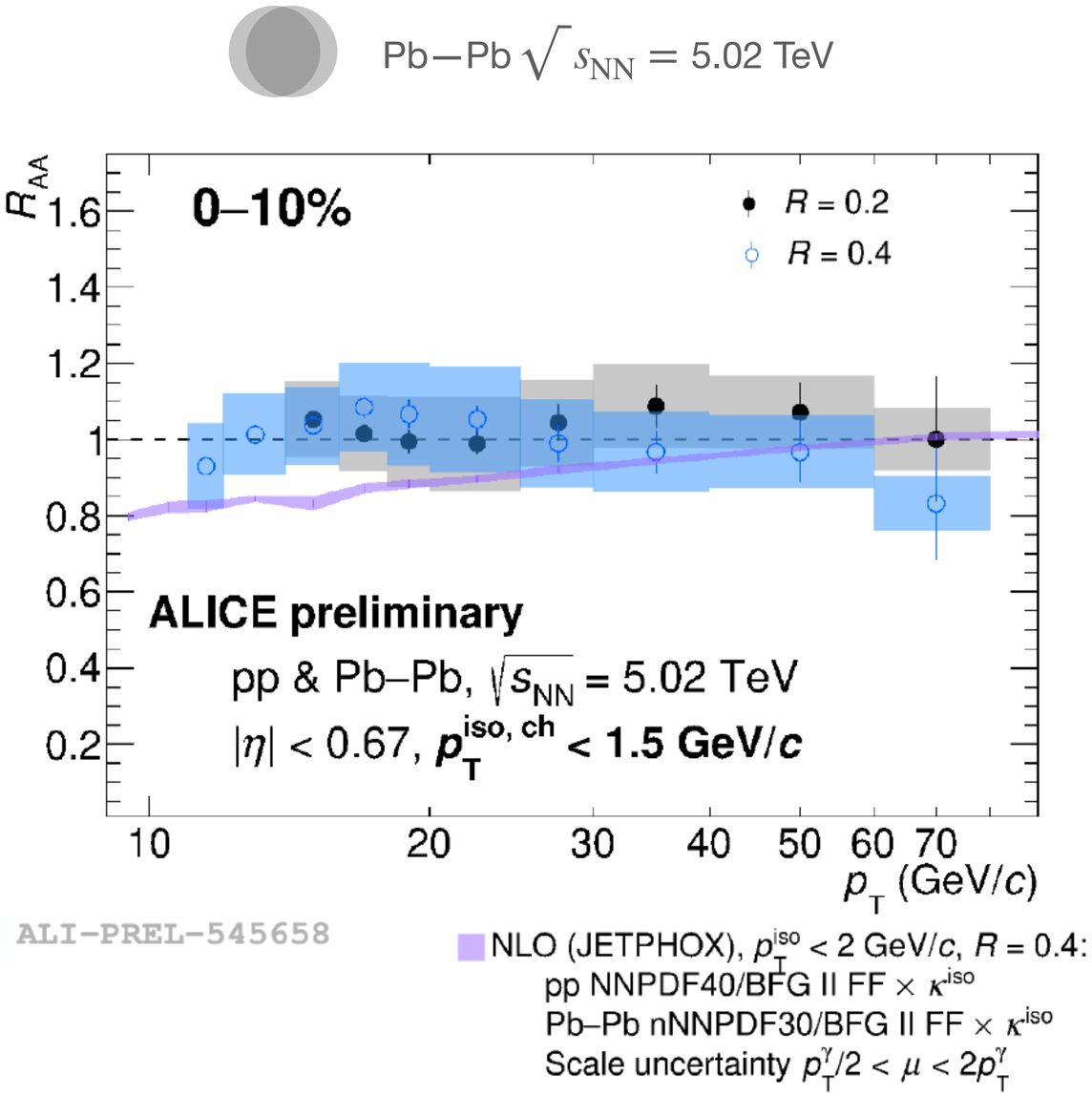
Carolina Arata #174

Prompt photons
with fragmentation contribution suppressed

Central Pb—Pb collisions

- $p_T > 20$ GeV/c: R_{AA} = 1
  → Verify N_{coll} scaling
  → Calibrated reference for γ-h studies

- $p_T < 20$ GeV/c: Cold nuclear matter effects expected
  May be overestimated by JETPHOX
  → Constrain nPDFs



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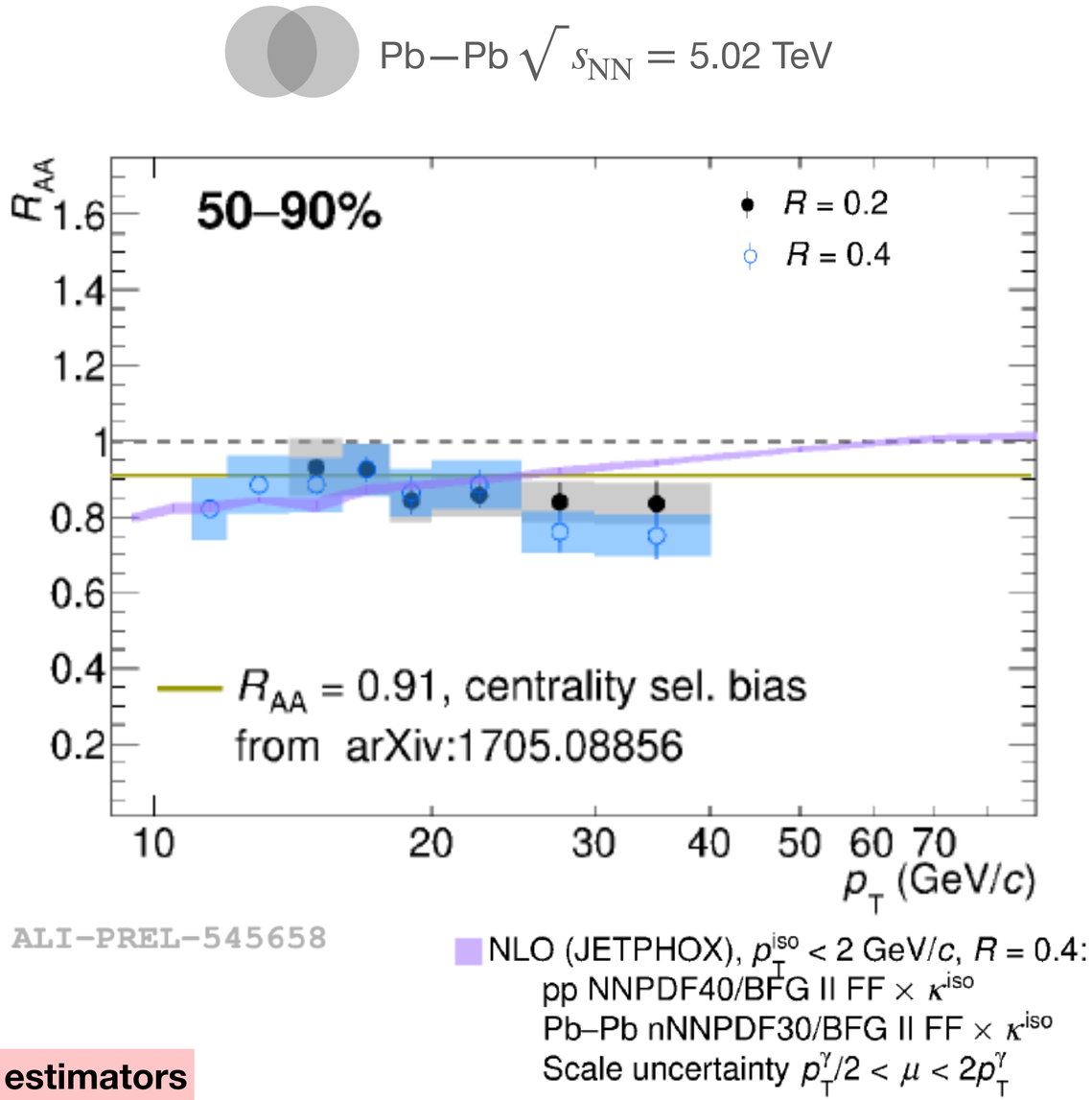
Peripheral Pb—Pb collisions

- $R_{AA} < 1$: centrality selection bias of Glauber model
  Agreement with model by C.Loizides & A. Morsch

C. Loizides & A. Morsch, arXiv:1705.08856



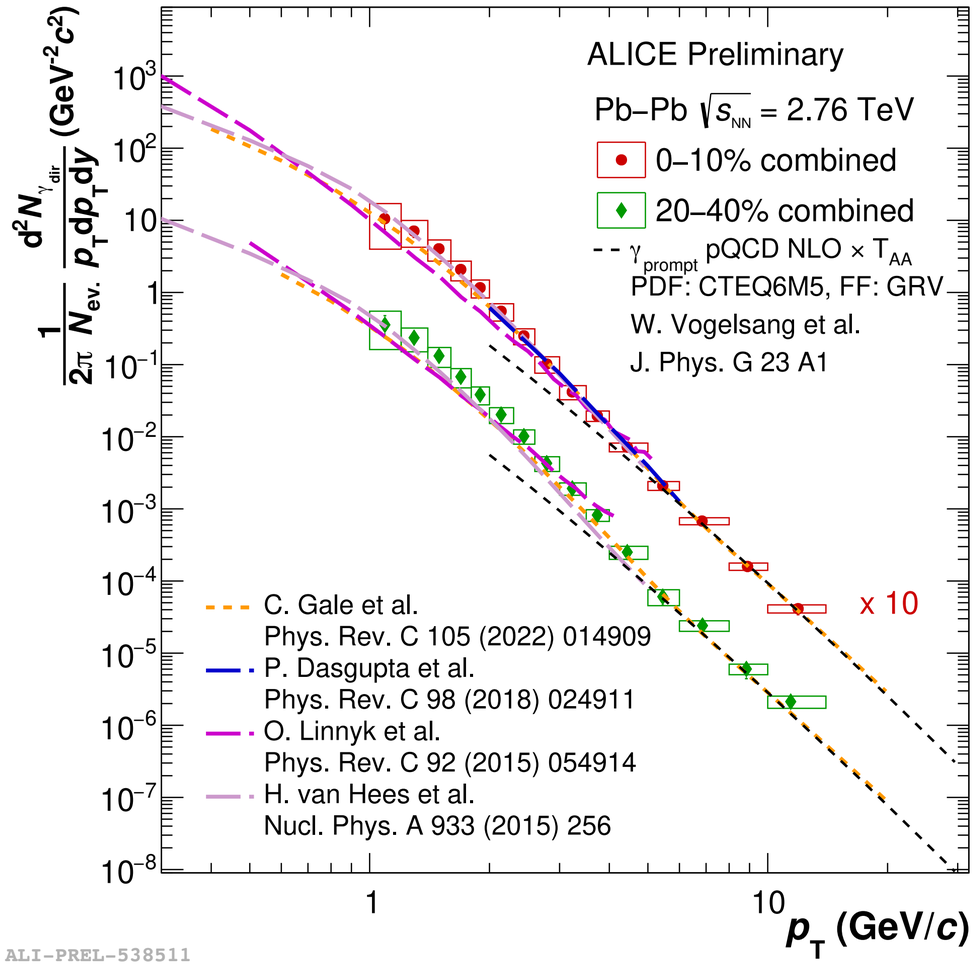
Use prompt photons as centrality estimators
(In peripheral AA and in small systems)
PHENIX Daniel Firak #654

Direct photons: status before QM

Pb−Pb $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

Direct γ yield at low p_{T} in A+A collisions above prompt hard-scattering γ expectation observed by:

- PHENIX with different methods at different energies $\sqrt{s_{\mathrm{NN}}}$ = 39-200 GeV
- ALICE with different methods at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV



PHENIX: Phys. Rev. C 107, 024914 (2023); arXiv:2203.17187
ALICE: Phys. Lett. B 754 (2016) 235-248; Ana Marin Hard Probes 2023

Direct photons: status before QM

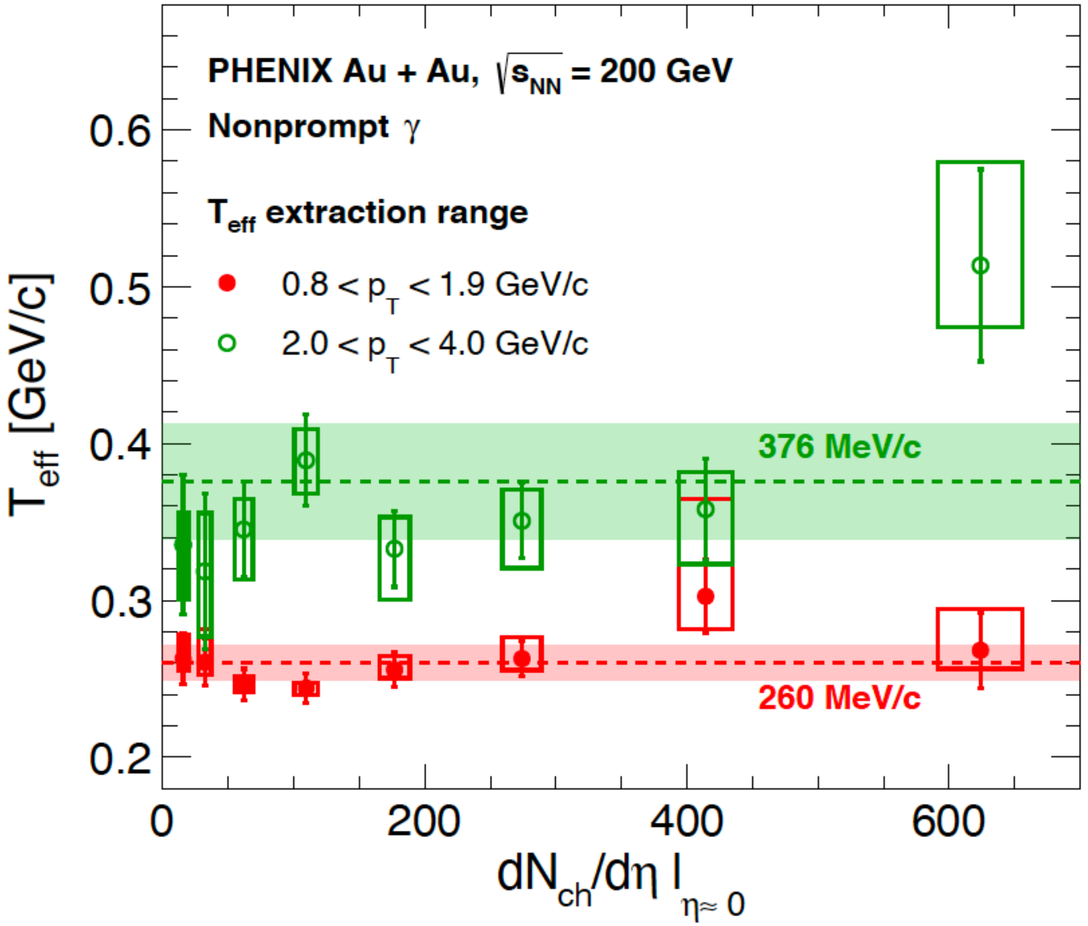
Extracted T_{eff} from $\gamma_{\mathrm{non-prompt}} = \gamma_{\mathrm{dir}} - \gamma_{\mathrm{prompt}}^{\mathrm{estimated}}$

- increases with p_{T} range used to fit
- Above deconfinement temperature
- No obvious variation of T_{eff} with $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}N_{\eta}|_{\eta=0}$

  Although Do not exclude small increase

Au−Au $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

(ALICE results link)



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Interpretation of T_{eff}

Jean-Francois Paquet #787

- ***Naive* idea: higher p_{T} , earlier emission, higher T**
  Analytic expression with simple symmetric hydro (Gubser) solutions

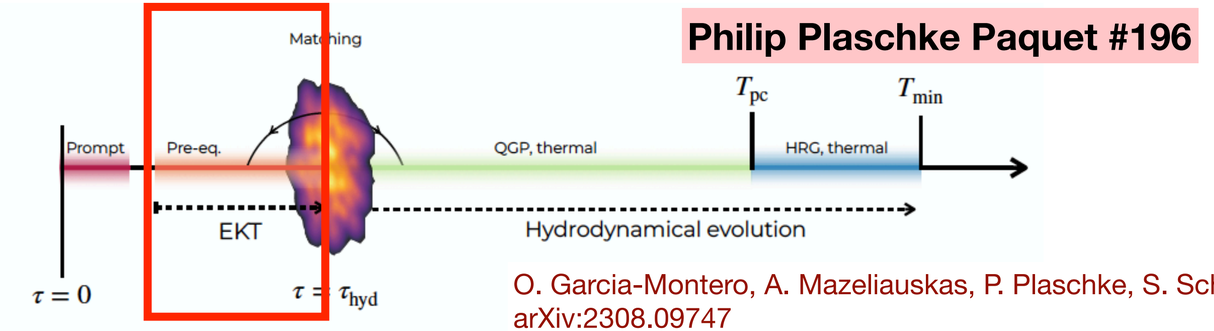
$$T_{\mathrm{eff}} \approx \frac{T_0}{1 + \frac{5}{2}\frac{T_0}{p_{\mathrm{T}}}}$$

Initial maximum T of plasma

p_{T} where T_{eff} is fitted for $\eta = 0$

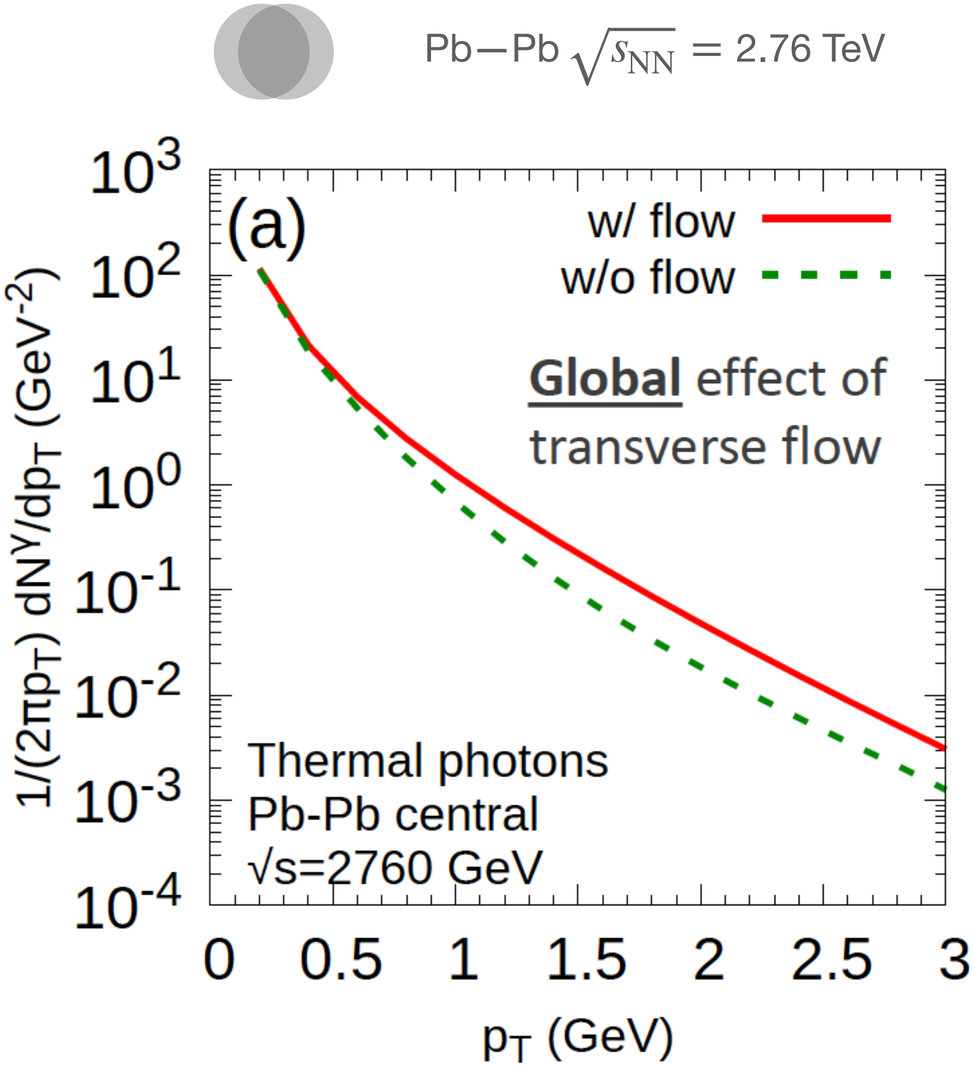
- **But bias due to radial flow:** $T_{\mathrm{eff}}^{\mathrm{w/\,flow}} > T_{\mathrm{eff}}^{\mathrm{w/o\,flow}}$
  - Locally: large for high p_{T} $\gamma_{\mathrm{thermal}}$ emitted at *small* T
  - Globally: integrated over space-time → smaller

And further effects under study e.g:
γ from pre-equilibrium contribution for $p_{\mathrm{T}} \geq 2.5$ GeV/c



Philip Plaschke Paquet #196

O. Garcia-Montero, A. Mazeliauskas, P. Plaschke, S. Schlichting, arXiv:2308.09747



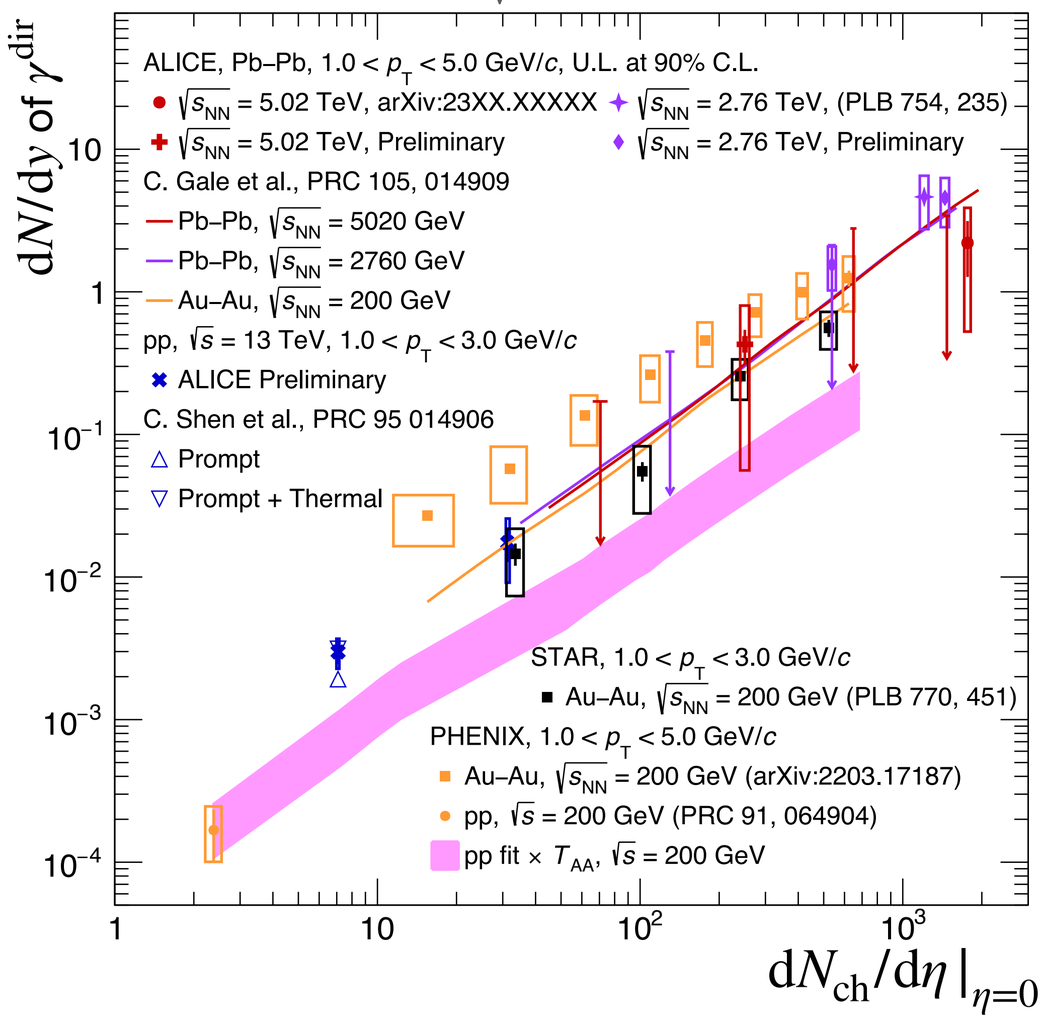
C. Shen, U. W. Heinz, J-F Paquet, C. Gale, Phys. Rev. C 89 (2014) 044910
J-F Paquet, arXiv:2305.10669

RHIC and LHC energies

Daiki Sekihata #171

Au—Au $\sqrt{s_{NN}}$ = 200 GeV

Pb—Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV and pp $\sqrt{s_{NN}}$ = 13 TeV



ALICE, arXiv:2308.16704

RHIC and LHC energies

Daiki Sekihata #171

$\mathrm{d}N_{\gamma^{\mathrm{dir}}}/\mathrm{d}y$ **at the LHC**

consistent with universal scaling behaviour seen by PHENIX:

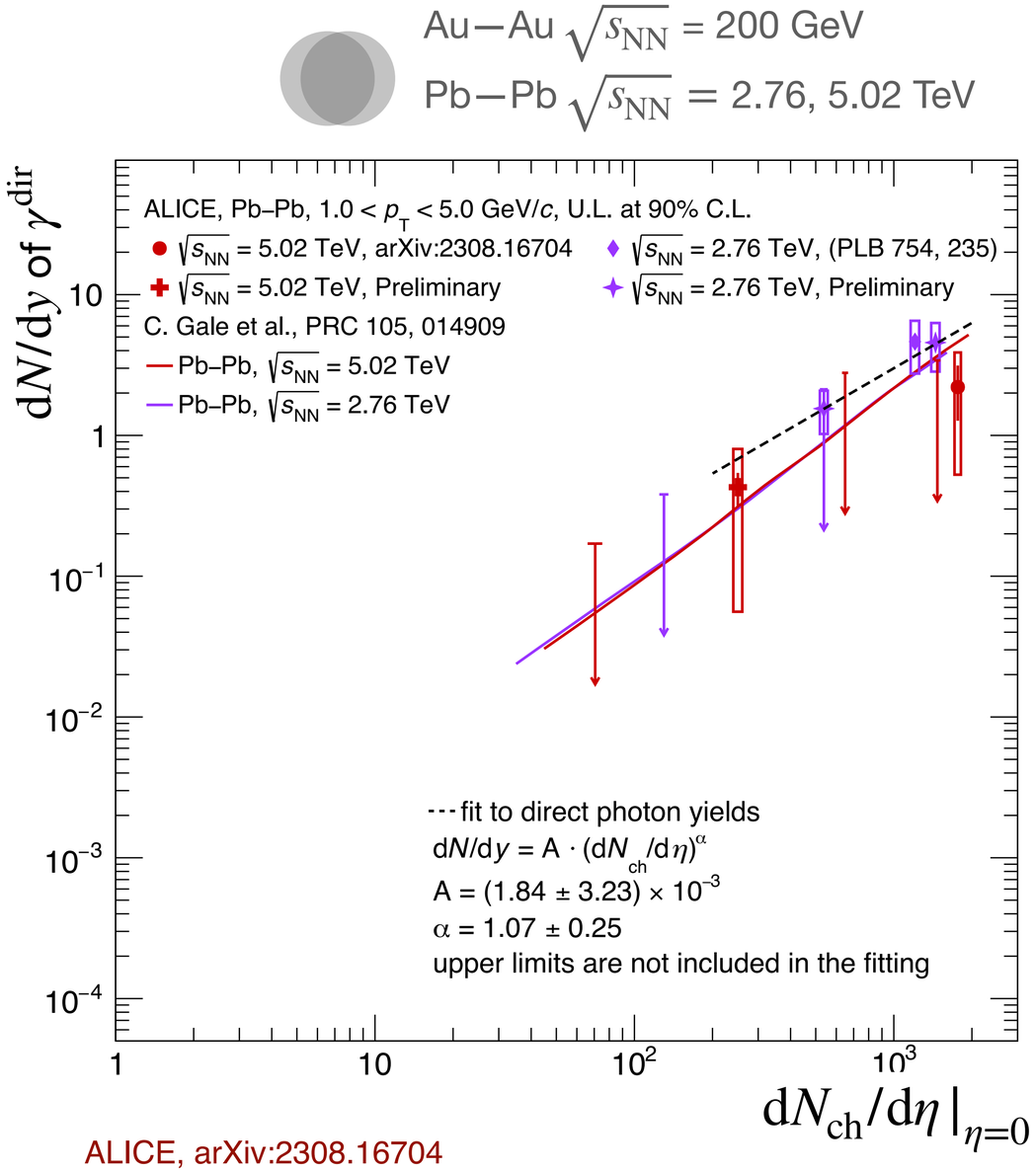
$$\frac{\mathrm{d}N_{\gamma_{\mathrm{dir}}}}{\mathrm{d}y} = C(p_{\mathrm{T}}) \times (\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\,|_{\eta=0})^{\alpha}$$

with no obvious p_{T} dependence of α (not so trivial why)

PHENIX Au—Au data at 200 GeV: $\alpha = 1.11 \pm 0.02$ (stat) $\pm^{0.09}_{0.08}$ (syst)

To be taken with care:

LHC Pb—Pb data at 2.76 TeV and 5.02 TeV: $\alpha = 1.07 \pm 0.25$ (syst + stat)

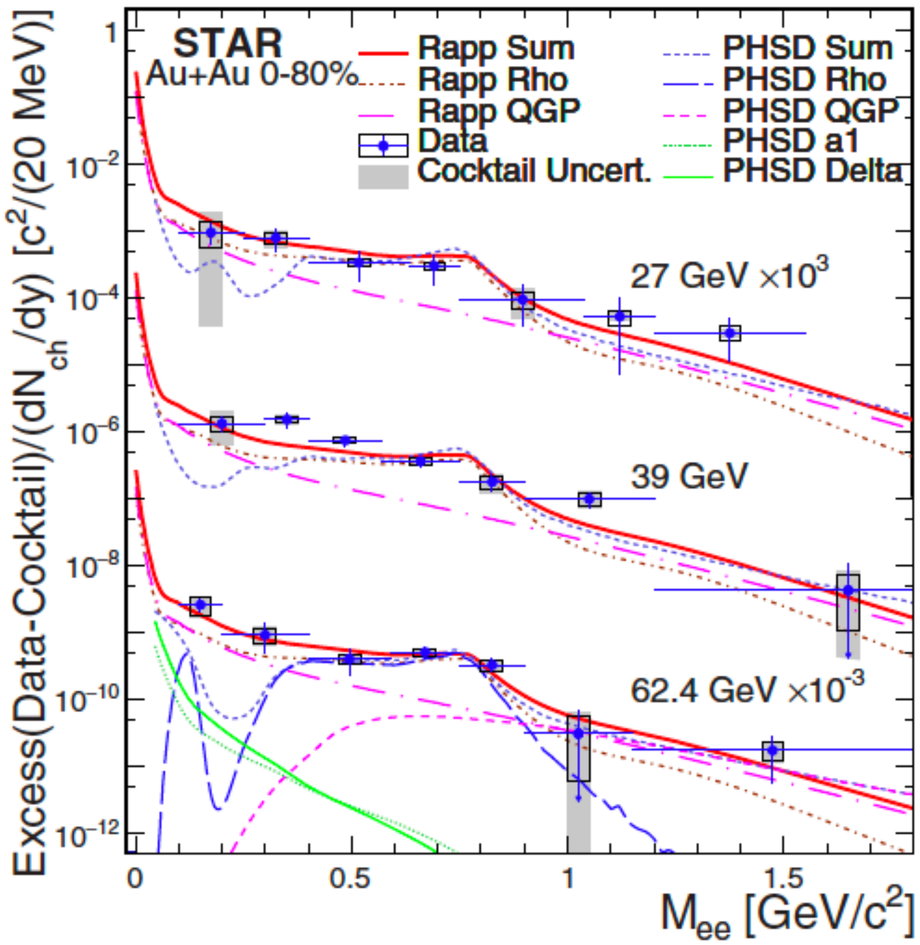


ALICE, arXiv:2308.16704

STAR: excess BES-I

Yiding Han #301
Chenliang Jin Poster #683

Au−Au $\sqrt{s_{NN}}$ = 19, 27, 39, 62.4, 200 GeV



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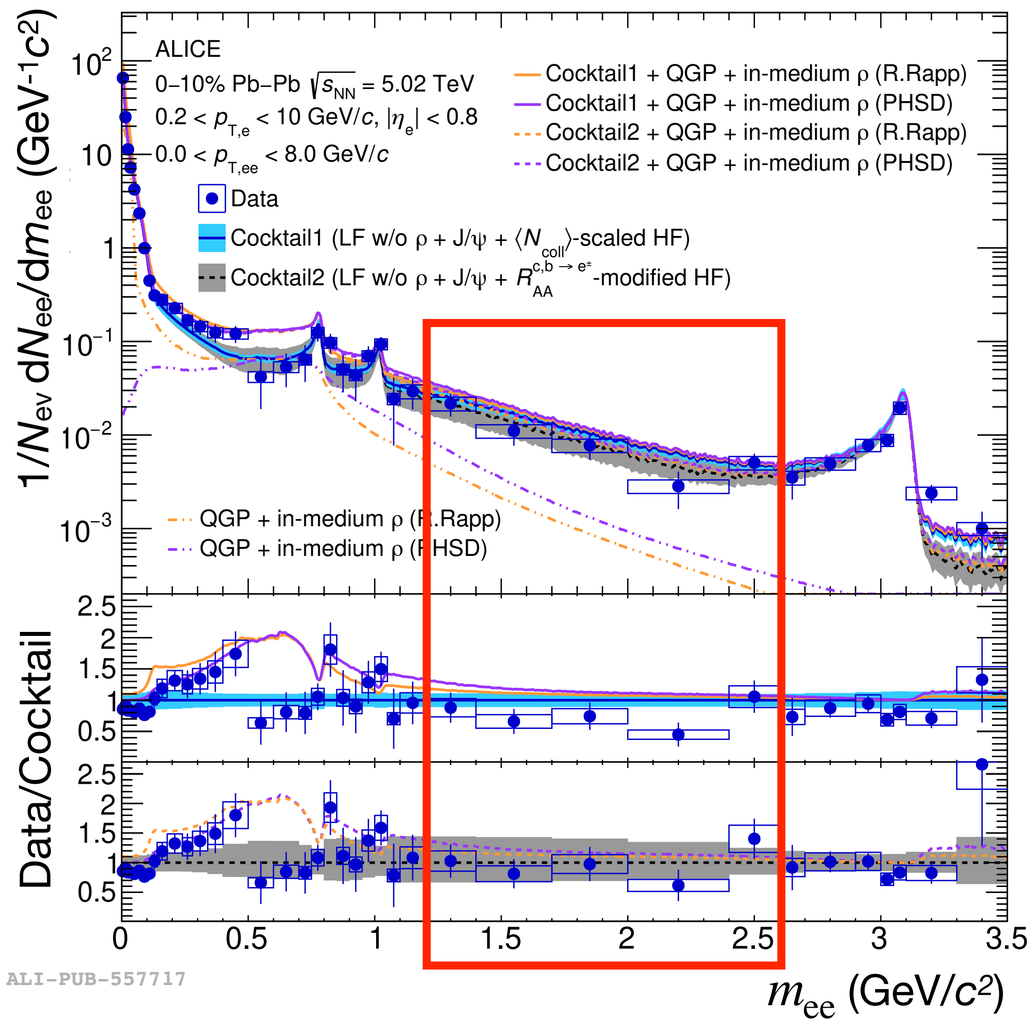

Dielectron yield in the intermediate mass
($1.2 < m_{ee} < 2.6$ GeV/c²)

Predicted thermal contribution from QGP:
- Expanding fireball model
- Transport model

Small compared to heavy-flavour decay background

→ **Need an other approach**

STAR: higher mass

C. Gale #626

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Excess / ($dN_{ch}/d\eta$) at a bit higher $\sqrt{s_{NN}}$ (> 19 GeV BES-I)

Compared to new calculations for QGP thermal radiation with:

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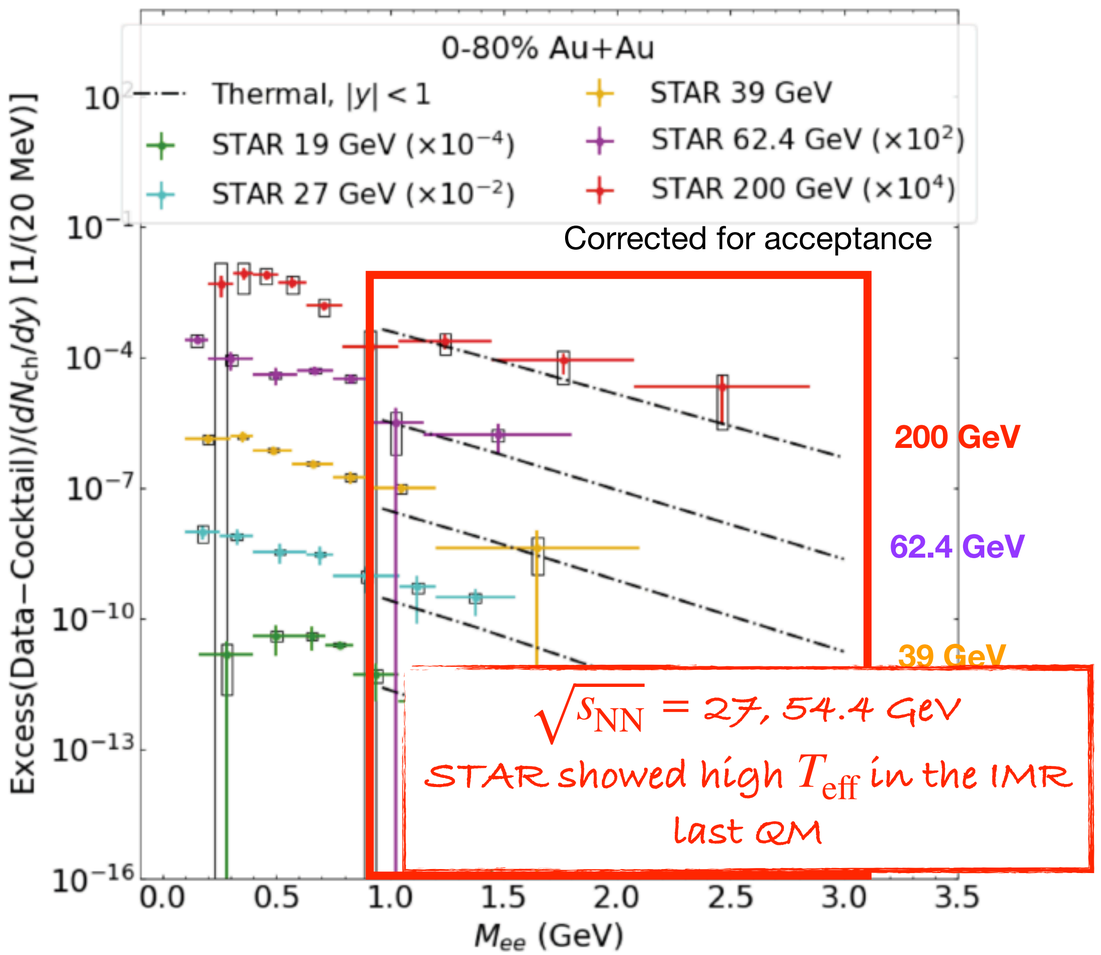


STAR BES-I: PRC 107, L061901 (2023)

ALICE: finalised results in Pb—Pb

Daiki Sekihata #171

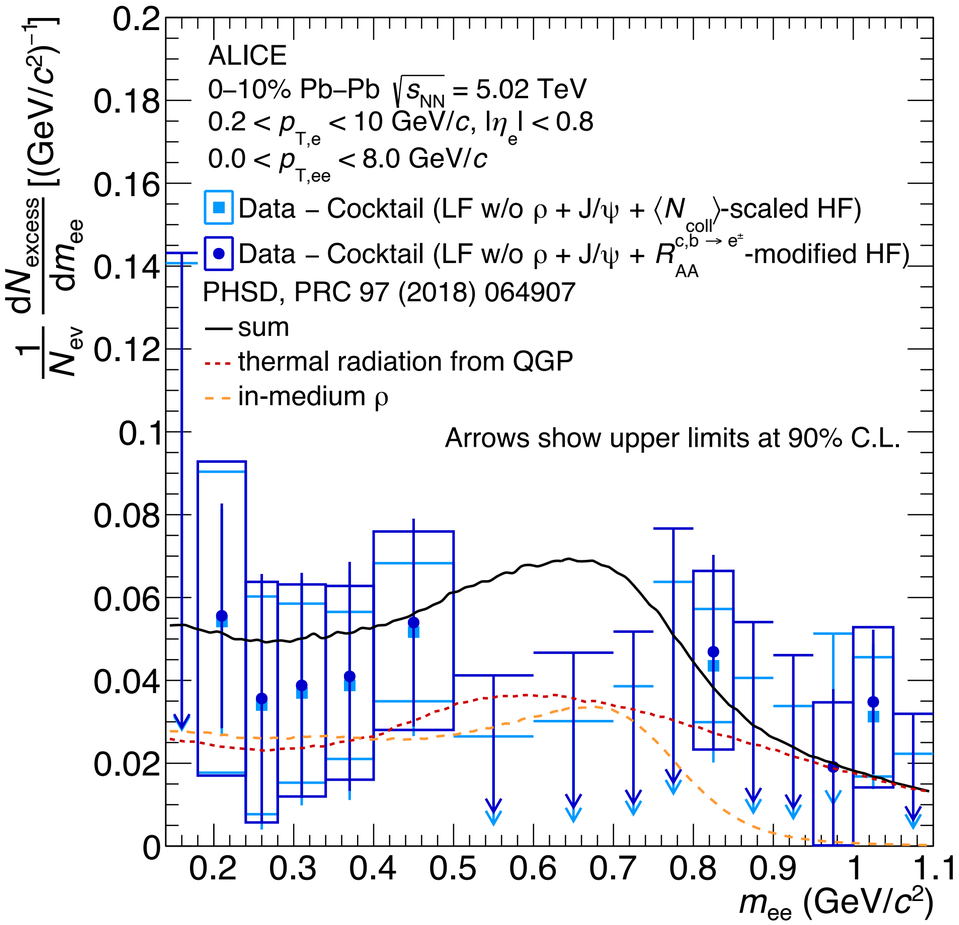
ALICE, arXiv:XXX

Pb—Pb $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Excess = Dielectron yield - background cocktail

- Significance of excess: 1.8σ (1.5σ) in $0.18 < m_{\mathrm{ee}} < 0.5$ GeV/c^2
- Consistent with calculations for thermal radiation
  - from hadronic phase (ρ)
  - from QGP

Parton-Hadron-String Dynamics (PHSD) model = transport model



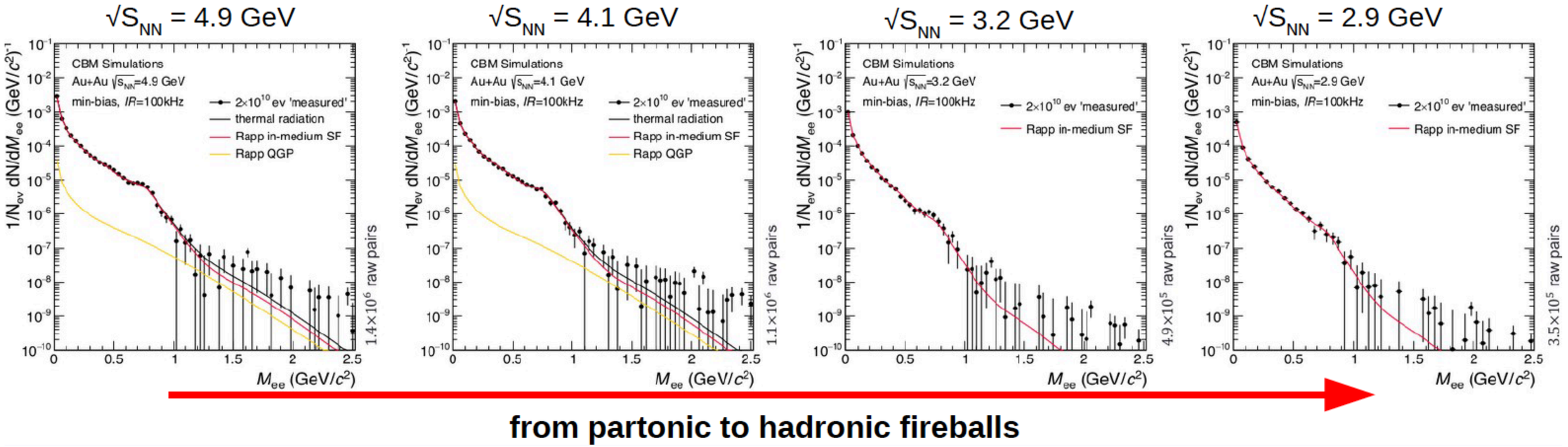
Feasibility studies: CBM dielectrons

After 3 years, 5 days/energy, 100 kHz IR

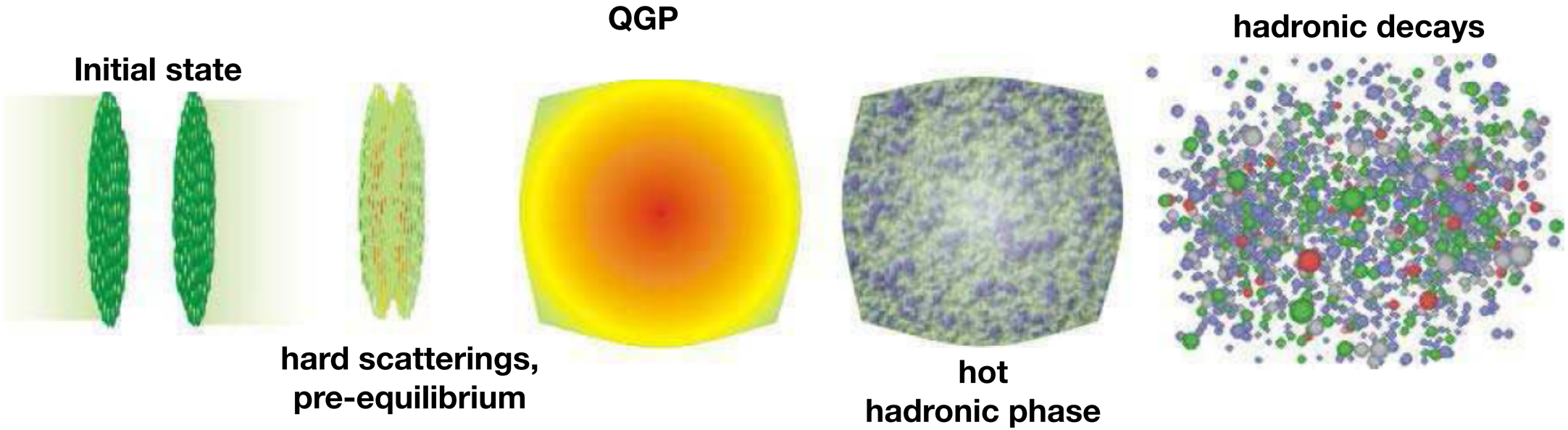
- Low mass (< 1 GeV/c^2) dominated by thermal rho, reconstructed with precision of 1.5- 4.5%

→ Allow for fireball lifetime measurement

- Intermediate mass (> 1 GeV/c^2): accessible, statistics not yet sufficient to extract physics



The little big bang



Initial conditions

pre-equilibrium dynamics

Hydrodynamic phase

Hadronic transport

IP-Glasma,
Trento ansatz

KoMPoST
quark suppression…

Relativistic viscous hydro (MUSIC),
equation of state (Hadron
resonance gas, lattice QCD)

SMASH…