Electromagnetic signatures in heavy-ion collisions

V. Riabov

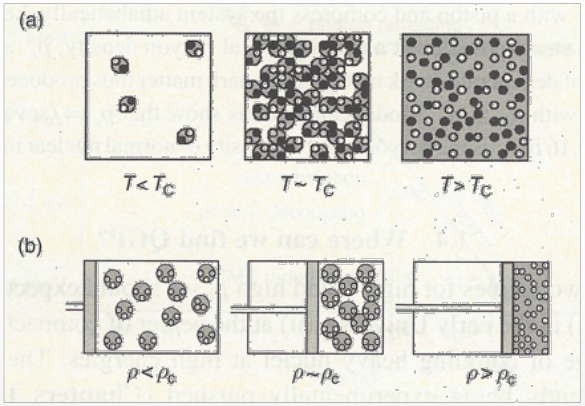
Heavy-ion collisions

- QCD is a fundamental theory of strong interactions
- Only colorless particles observed in the experiment (no free quarks or gluons) → confinement
- QGP is a state of matter in which quarks and gluons are free to move in space >> size of the nucleon
- QGP matter formation:

Two recipes:

(a) at high T - Early universe

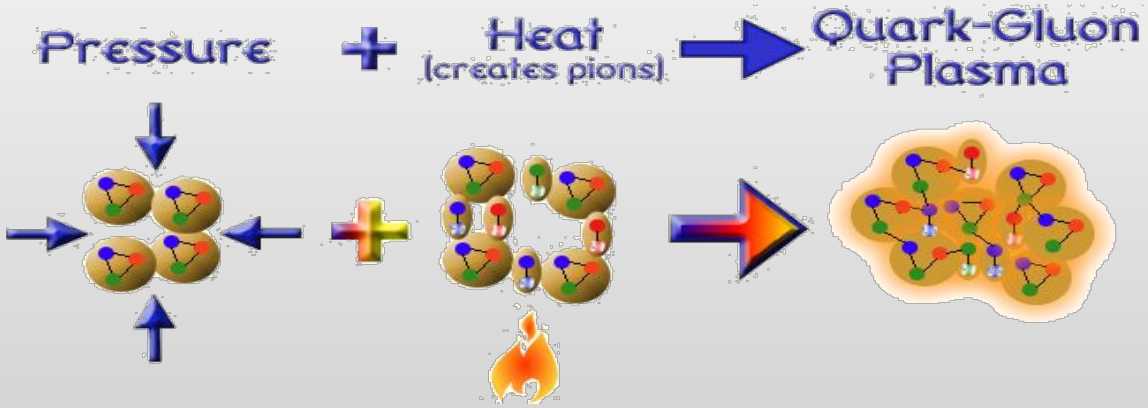
(b) at high baryon density – Neutron stars



T_c → x10^5 hotter than in the Sun center

ρ_c → Earth compressed in a ball with R ~ 30 m

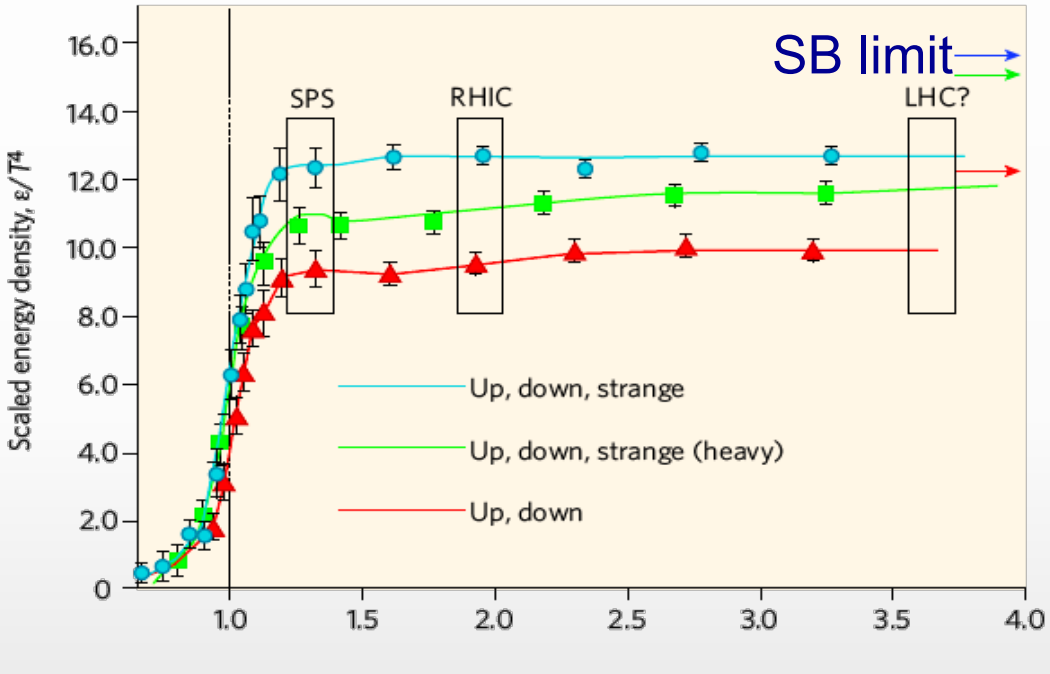
Relativistic heavy ion collisions - A combination of the two recipes



LQCD calculations

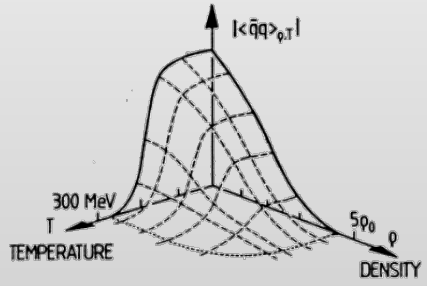
- The QGP is predicted by numerical calculations of QCD on the lattice

Bazavov et al., PLB 795,15 (2019) PLB 478, 447 (2000)



Recent *l*QCD calculations show that the critical temperature is: T_c (at $\mu_B = 0$) = 156.5 ± 1.5 MeV

- Accompanied by chiral symmetry restoration → constituent quark mass ~ 300 MeV turns into current quark mass ~ 5-10 MeV

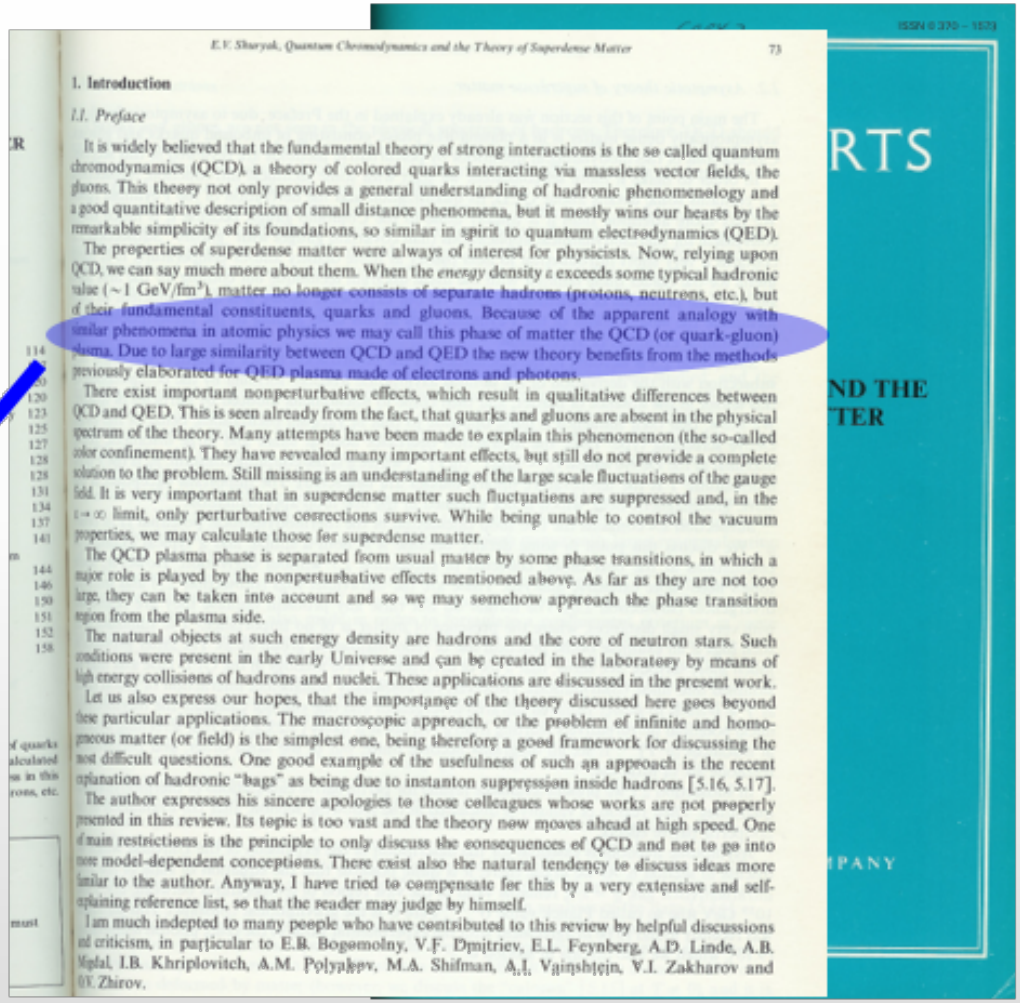


Coining of a name

Ed Shuryak - Physics Reports 1980

First review on QCD at extreme density conditions

"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma."



E.V. Shuryak, Quantum Chromodynamics and the Theory of Superdense Matter 73

1. Introduction

1.1. Preface

It is widely believed that the fundamental theory of strong interactions is the so called quantum chromodynamics (QCD), a theory of colored quarks interacting via massless vector fields, the gluons. This theory not only provides a general understanding of hadronic phenomenology and a good quantitative description of small distance phenomena, but it mostly wins our hearts by the remarkable simplicity of its foundations, so similar in spirit to quantum electrodynamics (QED).

The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value (~ 1 GeV/fm^3), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

There exist important nonperturbative effects, which result in qualitative differences between QCD and QED. This is seen already from the fact, that quarks and gluons are absent in the physical spectrum of the theory. Many attempts have been made to explain this phenomenon (the so-called color confinement). They have revealed many important effects, but still do not provide a complete solution to the problem. Still missing is an understanding of the large scale fluctuations of the gauge field. It is very important that in superdense matter such fluctuations are suppressed and, in the $\varepsilon \to \infty$ limit, only perturbative corrections survive. While being unable to control the vacuum properties, we may calculate those for superdense matter.

The QCD plasma phase is separated from usual matter by some phase transitions, in which a major role is played by the nonperturbative effects mentioned above. As far as they are not too large, they can be taken into account and so we may somehow approach the phase transition region from the plasma side.

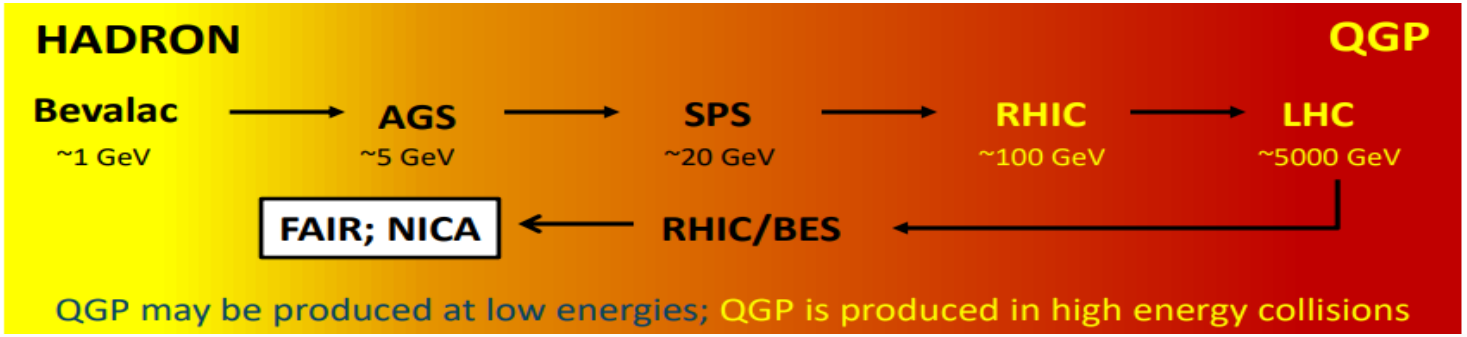
The natural objects at such energy density are hadrons and the core of neutron stars. Such conditions were present in the early Universe and can be created in the laboratory by means of high energy collisions of hadrons and nuclei. These applications are discussed in the present work.

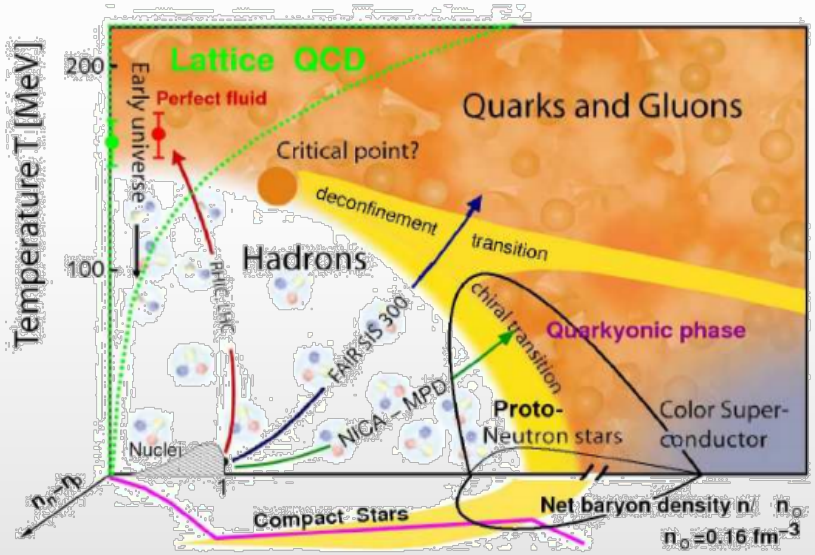
Let us also express our hopes, that the importance of the theory discussed here goes beyond these particular applications. The macroscopic approach, or the problem of infinite and homogeneous matter (or field) is the simplest one, being therefore a good framework for discussing the most difficult questions. One good example of the usefulness of such an approach is the recent explanation of hadronic "bags" as being due to instanton suppression inside hadrons [5.16, 5.17].

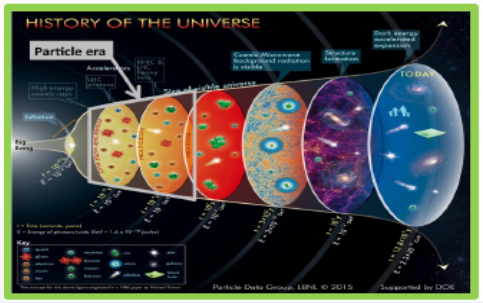
The author expresses his sincere apologies to those colleagues whose works are not properly presented in this review. Its topic is too vast and the theory now moves ahead at high speed. One of main restrictions is the principle to only discuss the consequences of QCD and not to go into more model-dependent conceptions. There exist also the natural tendency to discuss ideas more similar to the author. Anyway, I have tried to compensate for this by a very extensive and self-explaining reference list, so that the reader may judge by himself.

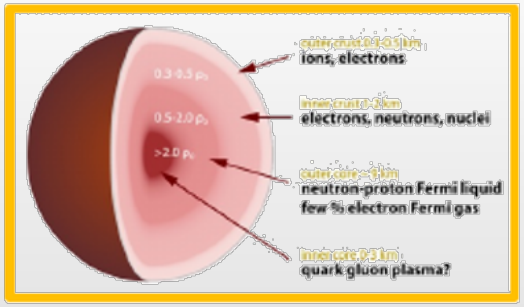
I am much indepted to many people who have contributed to this review by helpful discussions and criticism, in particular to E.B. Bogomolny, V.F. Dmitriev, E.L. Feynberg, A.D. Linde, A.B. Migdal, I.B. Khriplovitch, A.M. Polyakov, M.A. Shifman, A.I. Vainshtein, V.I. Zakharov and Ya.B. Zhirov.

Heavy-ion collisions





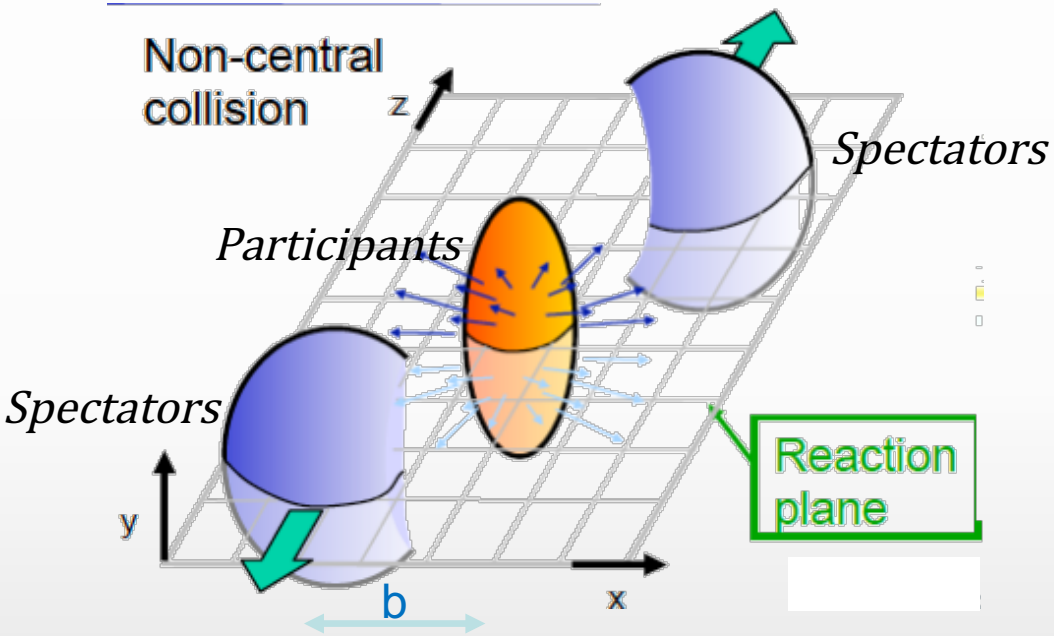


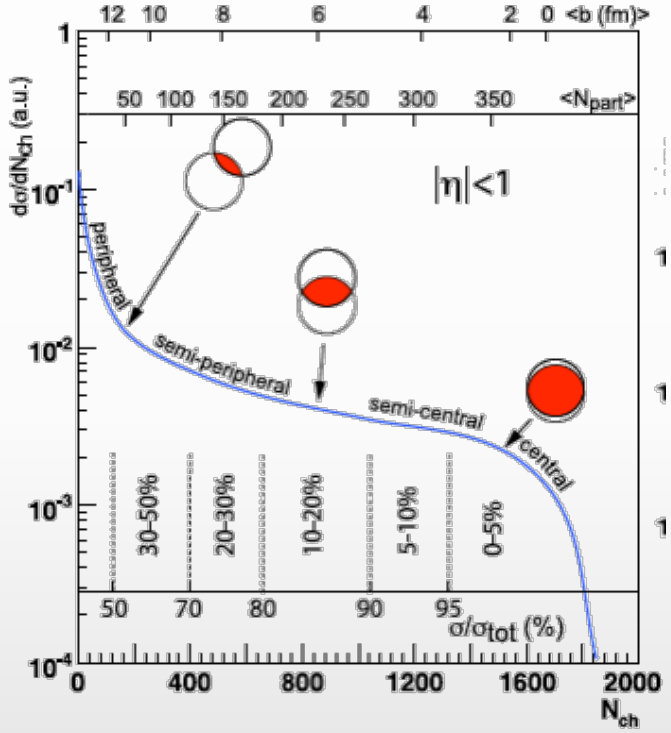


- Heavy-ion collisions are used to map the QCD phase diagram in different ranges of T and μ_B
- Probe conditions that existed during the first microseconds after the Big Bang or may exist in cores of compact neutron stars or in neutron star mergers

Geometry of Heavy-Ion Collisions

Collisions are not all the same



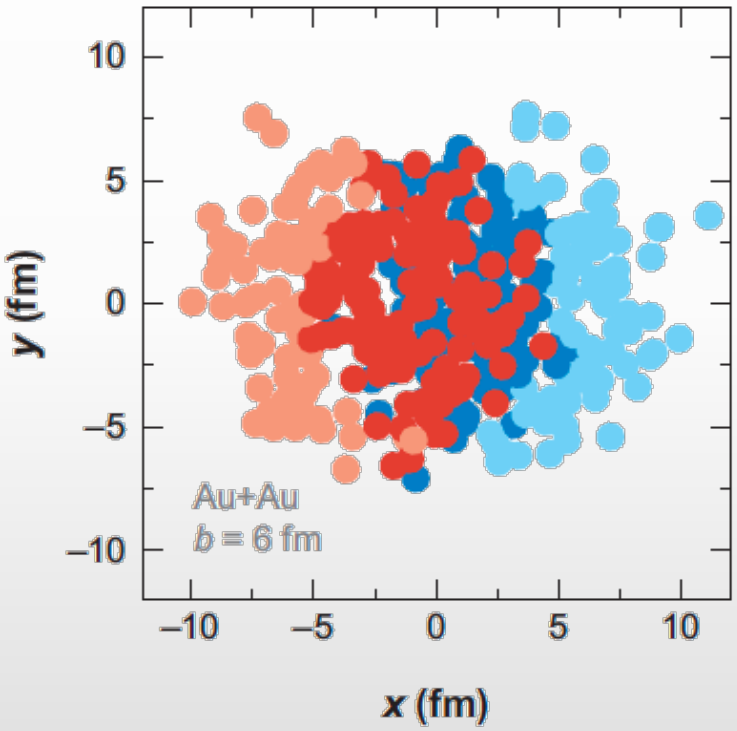


- $N_{participants}$: number of nucleons in the overlap region
- $N_{collisions}$: number of inelastic nucleon-nucleon collisions
- Reaction plane: defined by beam axis and impact parameter
- Centrality: percentile of the total cross section

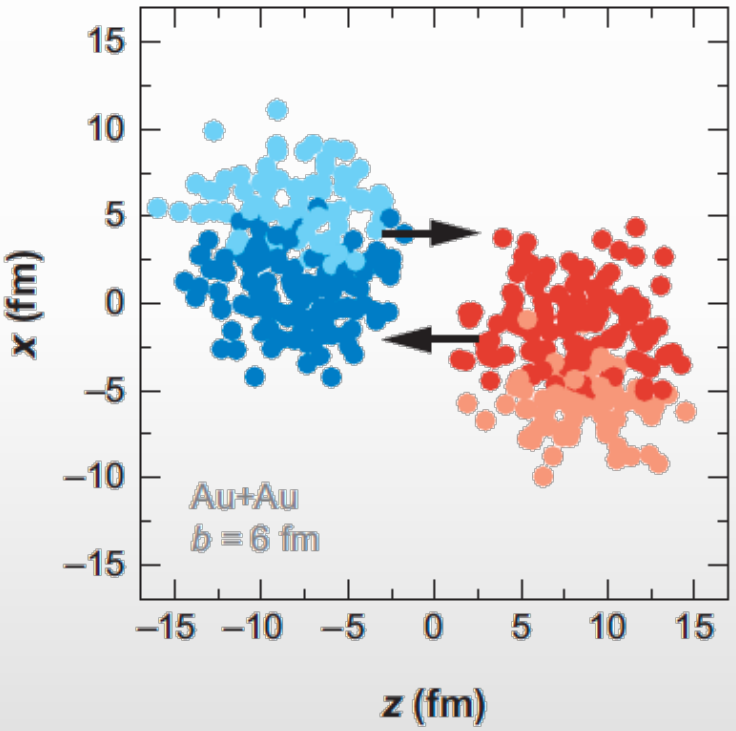
MC Glauber event

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV b = 6 fm

Transverse plane



Along the beam axis

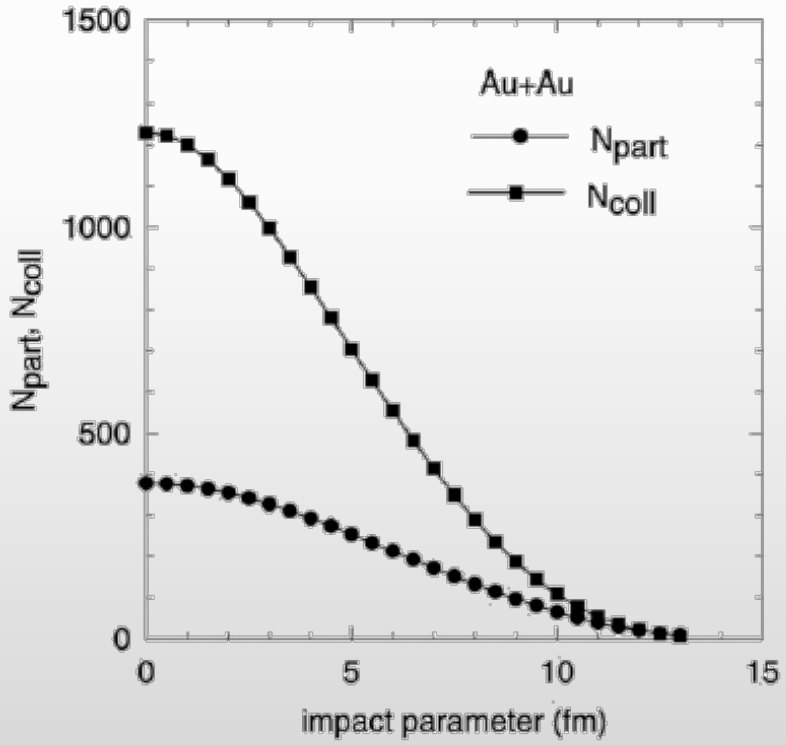


The nucleons are drawn with radius $\sqrt{\sigma_{\text{inel}}^{\text{NN}}/\pi}/2$

Darker circles represent participating nucleons

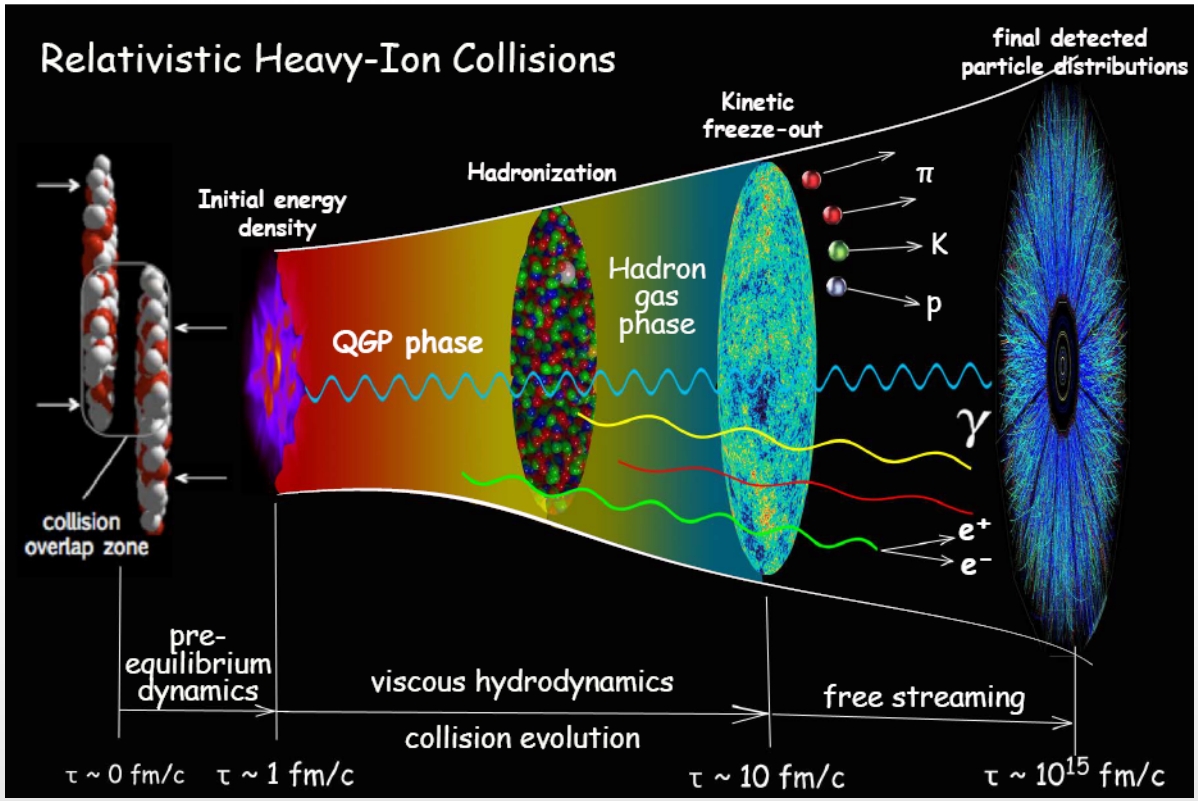
$\langle N_{part} \rangle$ and $\langle N_{coll} \rangle$

$\sqrt{s_{NN}}$= 200 GeV Au+Au collision
Inelastic NN cross section σ_{NN} = 42 mb
a = 0.53 fm R_{Au} = 6.38 fm



System evolution in heavy-ion collisions

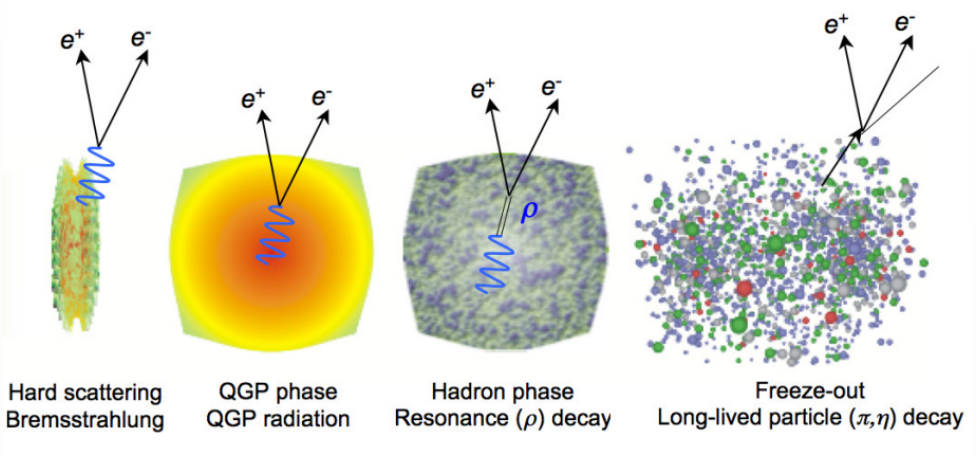
Fireball is ~10^{-15} meters across and lives for $5x10^{-23}$ seconds



- Properties of the QGP are studied by measuring momentum/energy and angular distributions of particles in the final state → probes of the early state of relativistic heavy-ion collisions
- Most of produced particles are hadrons, up to 10^4 particles per event

Electromagnetic probes

- **Photons** and **electrons/muons** emitted from different stages of heavy-ion collisions
- Photons and electrons do not participate in strong interactions → produced strongly interacting system (QGP) is transparent → penetrating probes
- Provide undistorted information about the system at the production time



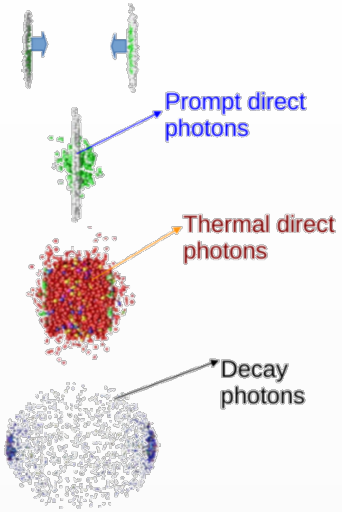
- Problems:
  - ✓ low emission rate, 10^{-3} – 10^{-4}
  - ✓ overlapping signals from different stages of heavy-ion collisions
  - ✓ huge background from hadronic decays → precise measurement of the neutral meson production is a needed

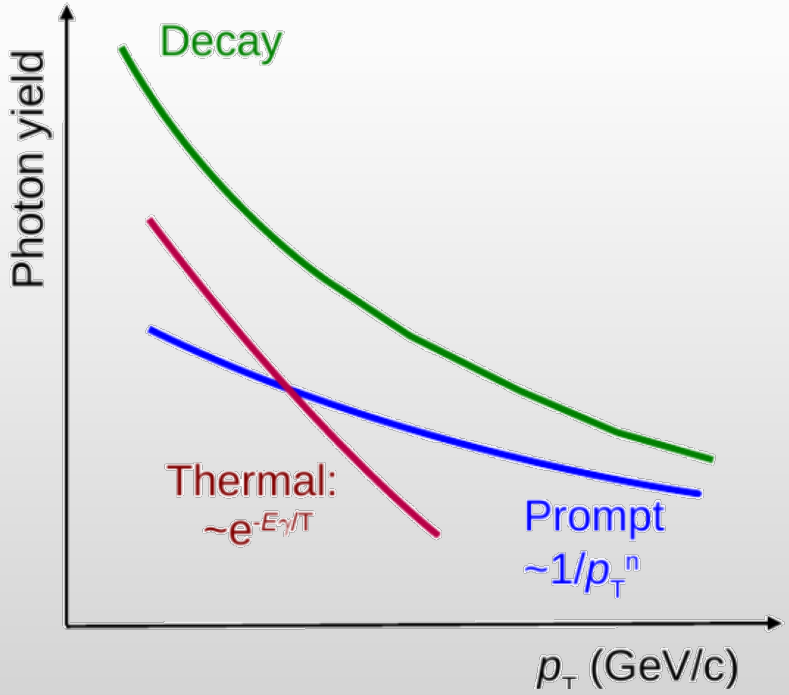
- Photons and electrons are promising signals of the phase transition and chiral symmetry restoration
- Interpretation of results requires theoretical models that would describe the dynamics of heavy-ion collisions during the whole system evolution

Direct photons

Direct photons

- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
- Photons are produced throughout the system evolution at different times
- Photons do not interact strongly and carry undisturbed information about system evolution, event about its earliest stages → penetrating probe



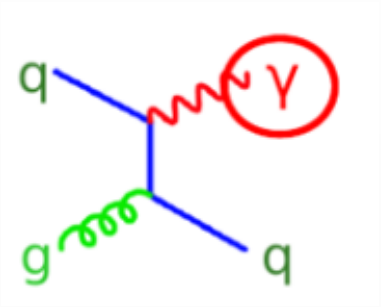


- Typical photon spectra:
  - ✓ overwhelmed by photons from hadronic decays, mostly $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$
  - ✓ low-E direct photons – thermal radiation from the hot source(s) → most direct estimation of the effective system temperature and collective expantion
  - ✓ high-E direct photons – produced in hard-scattering processes → test of initial conditions (N_{coll} scaling, modification of PDFs)

Direct photon production mechanisms

- Production mechanisms in hadronic interactions:

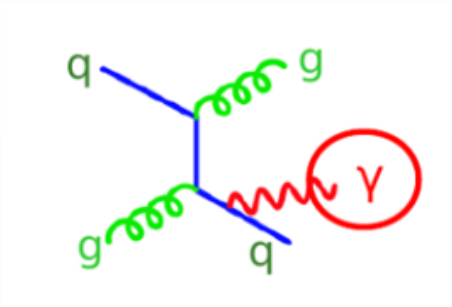
Compton scattering



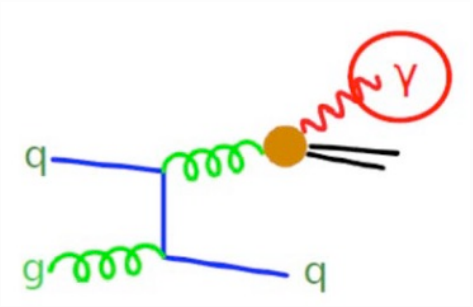
Annihilation



Bremsstrahlung



Gluon fragmentation



- pQCD: direct photon spectrum is a convolution of nucleon structure function ($F_{i/h}$), cross-section of the elementary process (σ_{ij}) and fragmentation function ($D_{\gamma k}$)

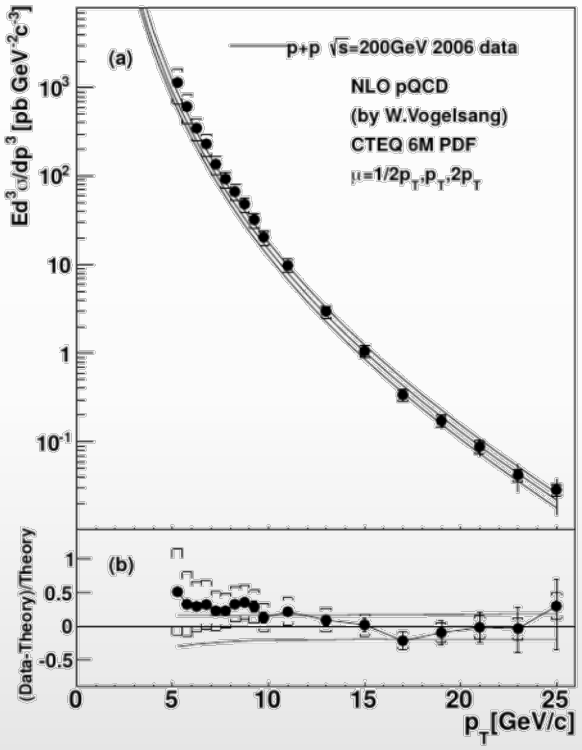
$$\frac{d\sigma^{\gamma,\mathrm{dir}}}{dp_T d\eta} = F_{i/h} \otimes \sigma_{ij} \otimes D_{\gamma/k} \propto 1/p_T^n$$

- Direct photons are of interest in different collision systems:
  - ✓ pp: baseline, test of QCD calculations (resummation techniques, PDF parameterization)
  - ✓ pA: search for the cold nuclear matter effects
  - ✓ AA: probe the QGP and system time-space evolution

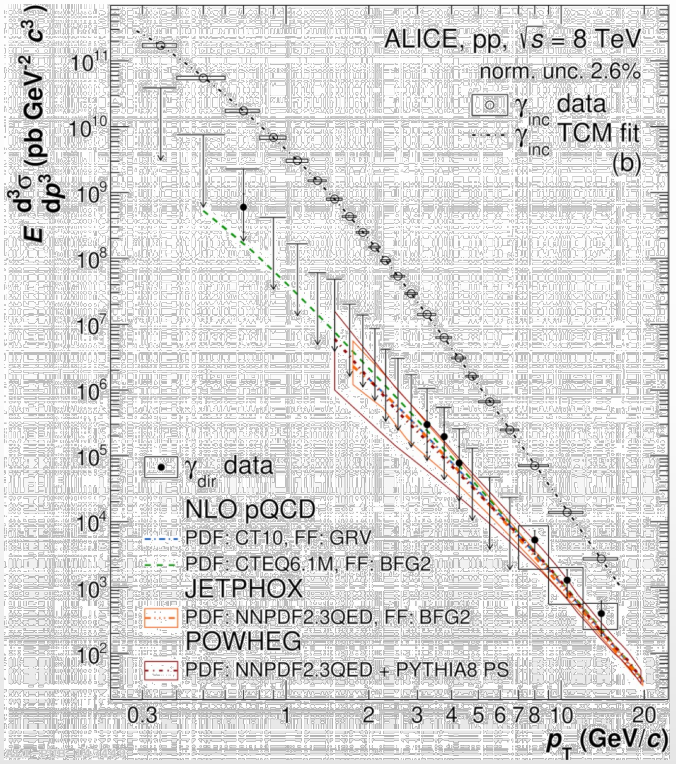
Direct photons in pp collisions - I

- Direct photon production spectra at RHIC and LHC energies compared to pQCD calculations

Phys.Rev.D 86 (2012) 072008



Phys. Rev. C 99, 024912 (2019)



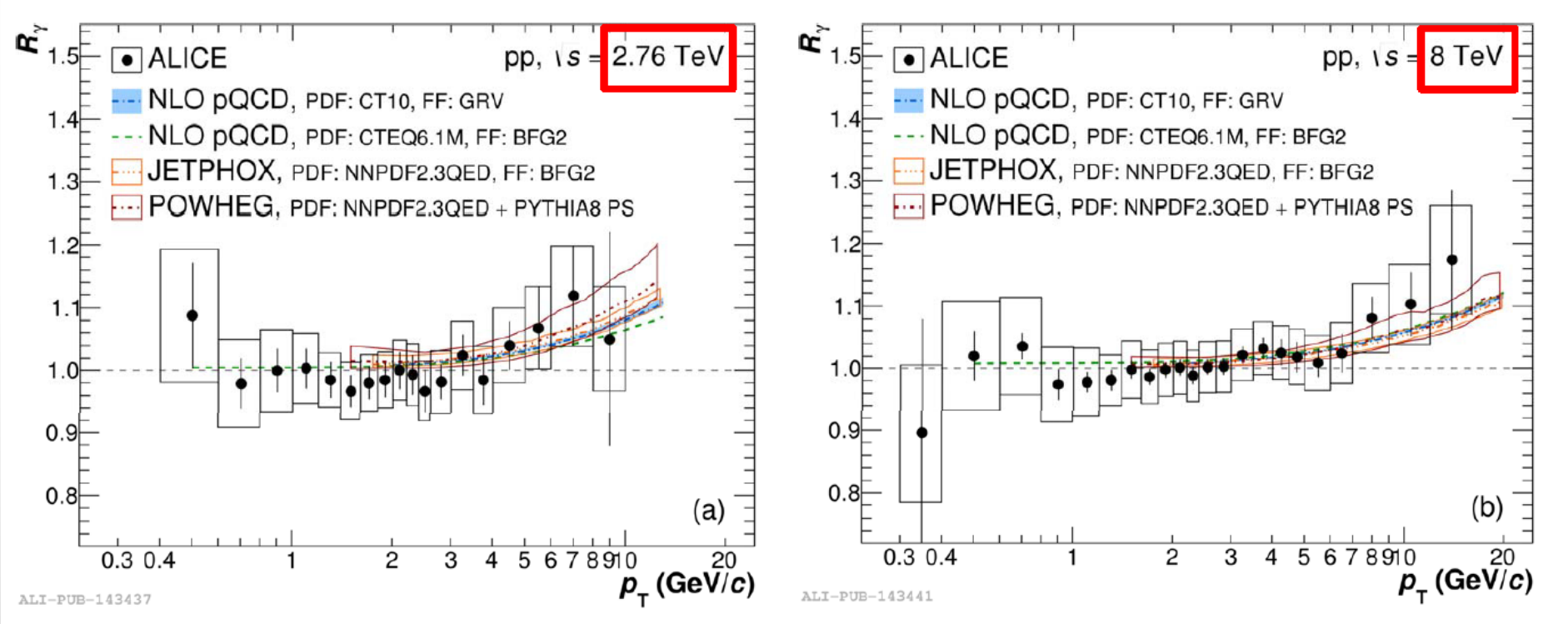
Low-p_T direct photon production in pp collisions is reproduced with NLO pQCD calculations

→ calibrated baseline available

Direct photons in pp collisions - II

- Part of uncertainties cancel out in the ratio:

$$R_\gamma = \gamma_{inc}/\gamma_{decay} \approx \gamma_{inc}/\pi^0 \Big/ \gamma_{decay}/\pi^0{}_{param}$$

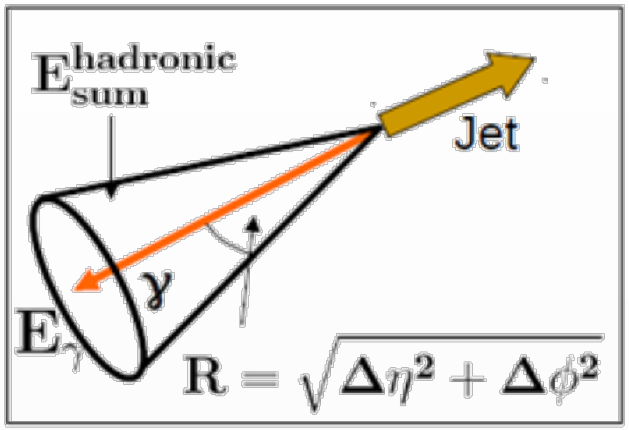


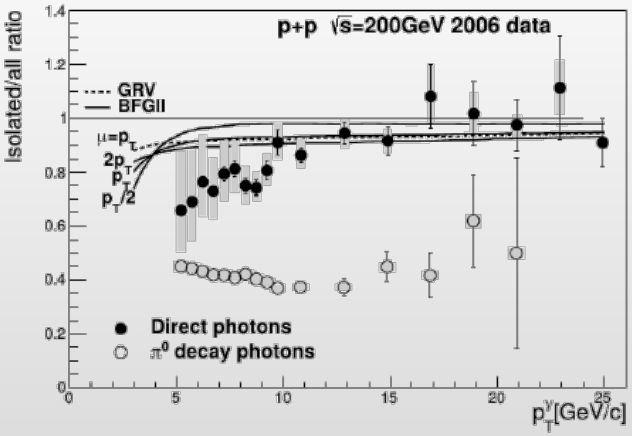
High $p_T > 5$ GeV/c – good agreement with pQCD

Low $p_T < 5$ GeV/c – yields are consistent with hadronic sources → no thermal radiation

Conception of isolated photons

- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
- Measured as a difference $N_\gamma^{dir} = N_\gamma^{incl} - N_\gamma^{dec}$
- Can not be measured in event-by-event



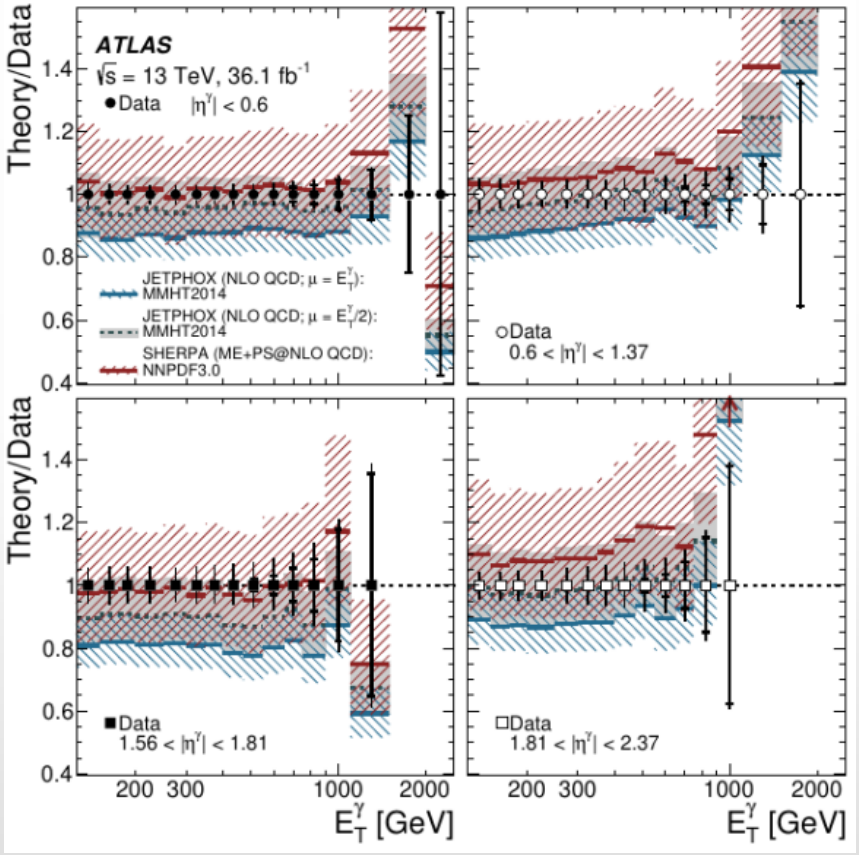


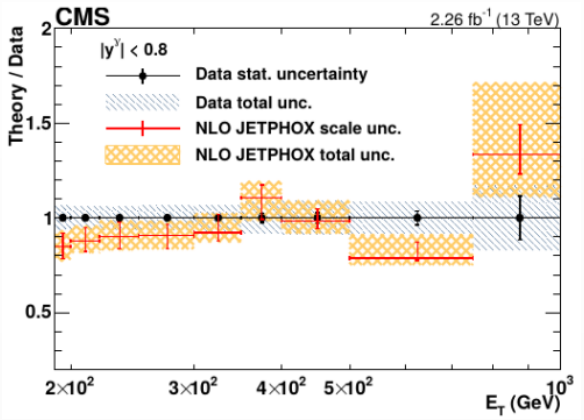
Phys.Rev.D 86 (2012) 072008

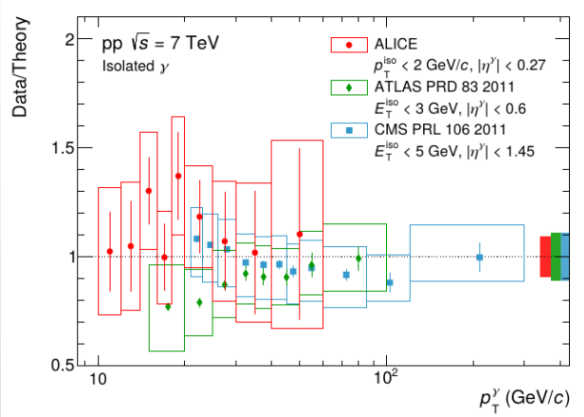
- Isolated photons: photons without hadronic activity in some cone ($R \sim 0.4$) around the photon
- Can be measured in event-by-event basis
- Purity rapidly decreases with decrease at p_T <10-20 GeV/c => can not measure at lower p_T
- Difference between direct and isolated photons diminish at high p_T

Direct photons in pp collisions - III

- Isolates photon production well reproduced with NLO pQCD calculations
- Good agreement between LHC experiments







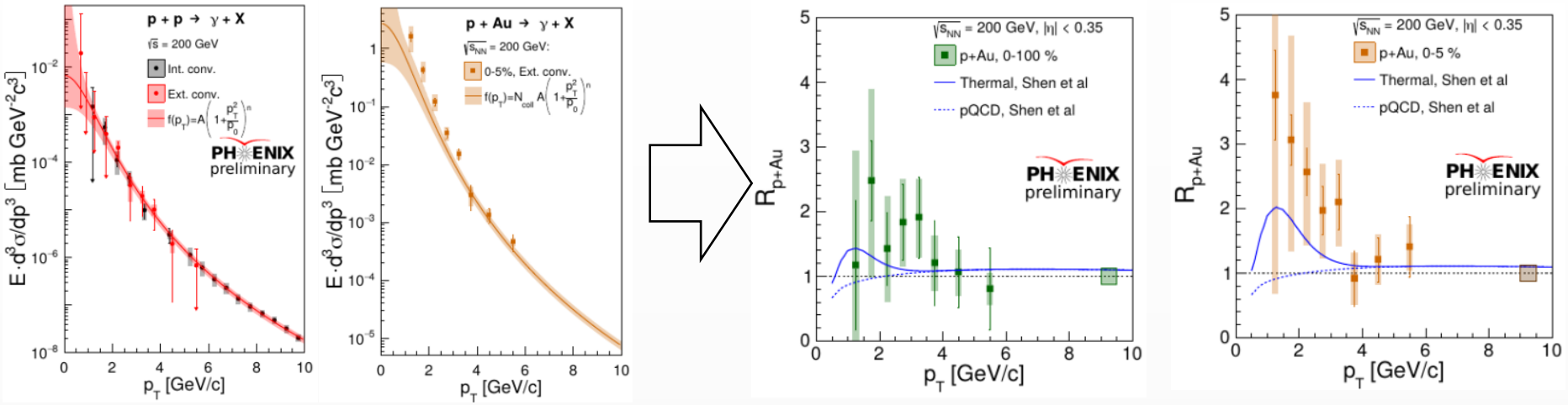
Direct photons is a well calibrated probe in elementary hadronic collisions at high energies!

Direct photons in pA collisions

❖ Measurements at RHIC:

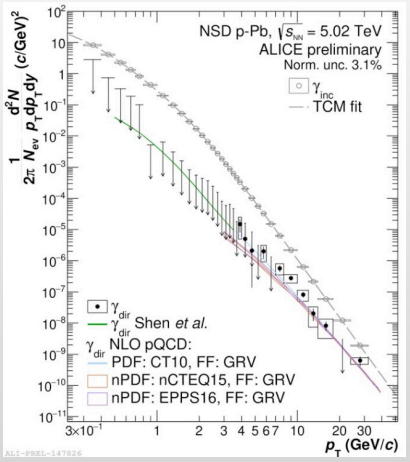
$$R_{pA} = \frac{dN/dy_{AA}}{N_{coll}\, dN/dy_{pp}}$$

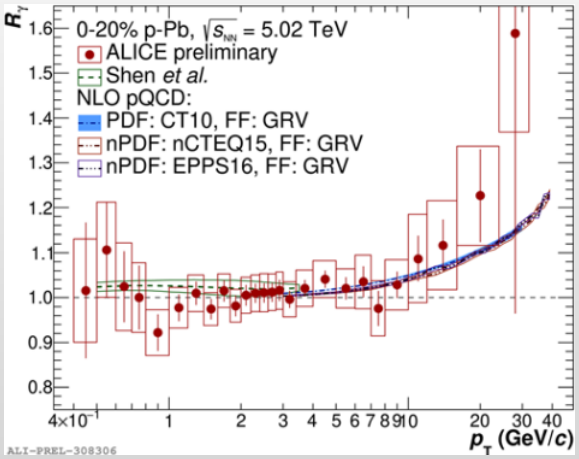
V. Khachatryan, J.Phys.Conf.Ser. 1602 (2020) 1, 012015



❖ Measurements at LHC:

N. Schmidt, PoS HardProbes2018 (2018) 183



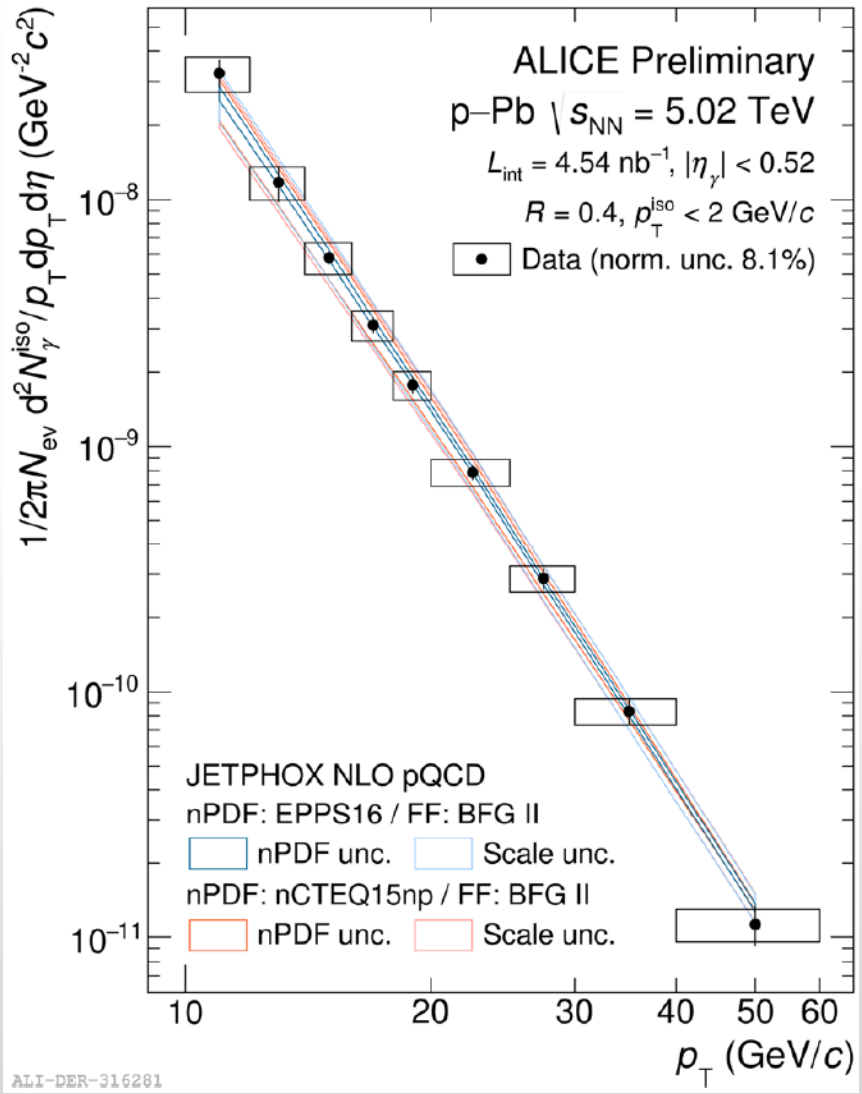


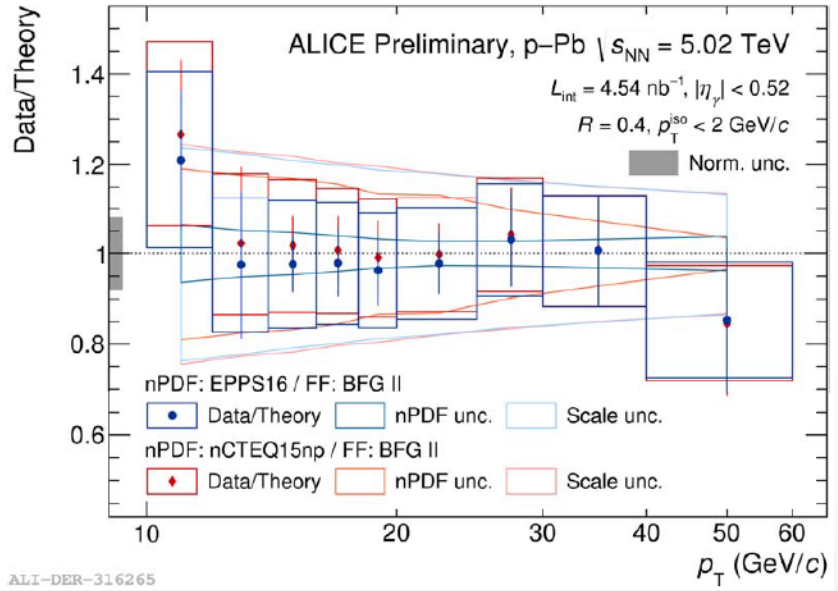
PHENIX@RHIC: observes a hint of excess of direct photon production at low momentum $p_T < 4$ GeV/c in high-multiplicity pAu collisions. The excess is observed with respect to N_{coll}-scaled pp results → thermal radiation, MPI ???

ALICE@LHC: no excess, measurements are consistent with N_{coll}-scaled pp results and pQCD calculations in the whole momentum range

Isolated photons in pPb collisions

- Isolated photons production measured in pPb at $\sqrt{s_{NN}}$ = 5.02 TeV





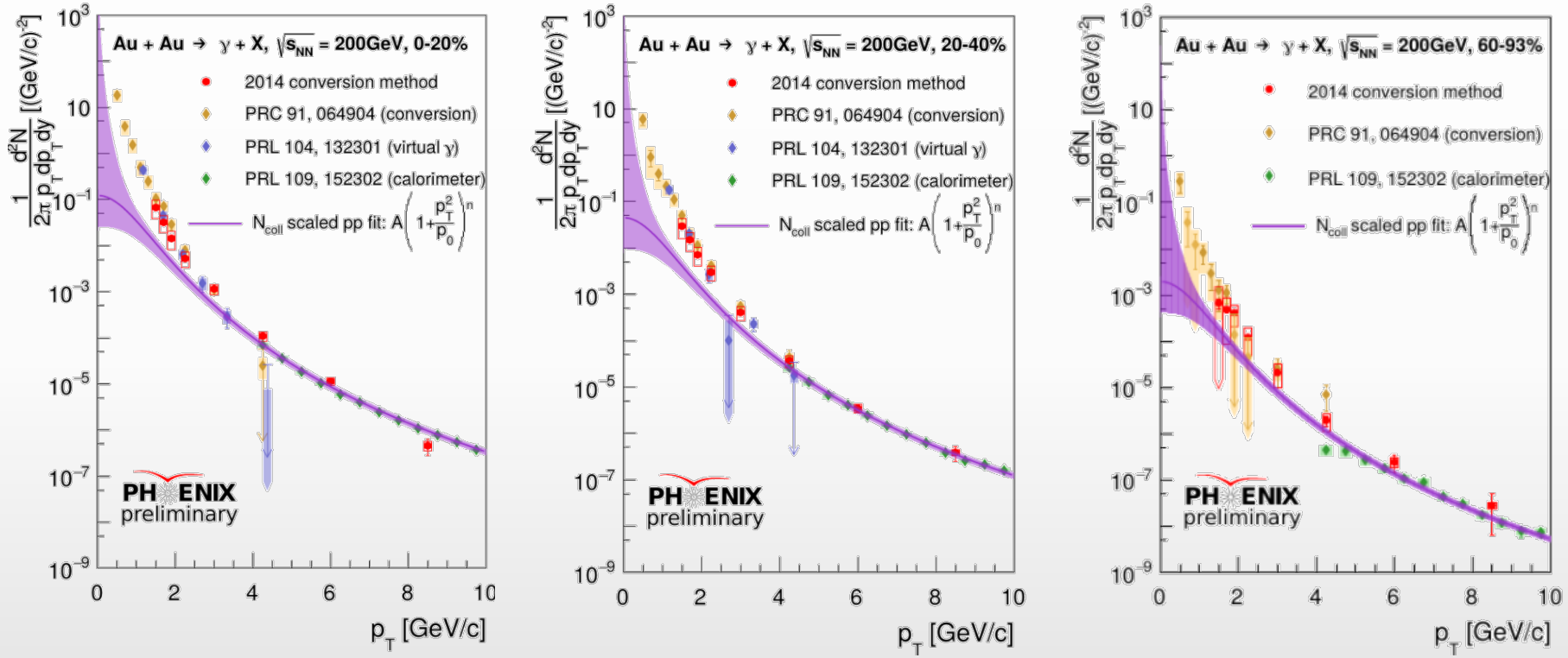
Production spectrum is consistent with NLO pQCD predictions

→ direct photons remain to be a very well calibrated probe at high p_T

Direct photons in heavy-ion collisions

❖ Production spectra measured by PHENIX@RHIC in AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV

W. Fan, EPJ Web of Conf. 182, 02041I



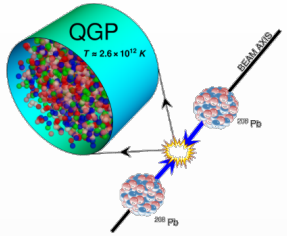
At high p_T yield agrees with N_{coll}-scaled pp results (prompt direct photons)

At low p_T < 3 GeV/c observe a clear excess, larger in central collisions (**thermal radiation**)

Closer look at thermal photons

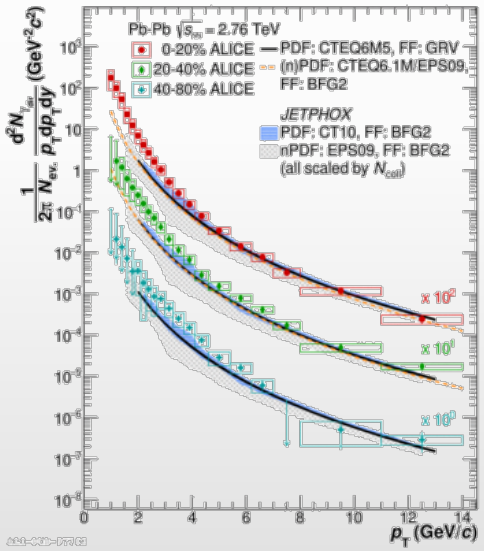
- Thermal photons were observed at RHIC and LHC energies

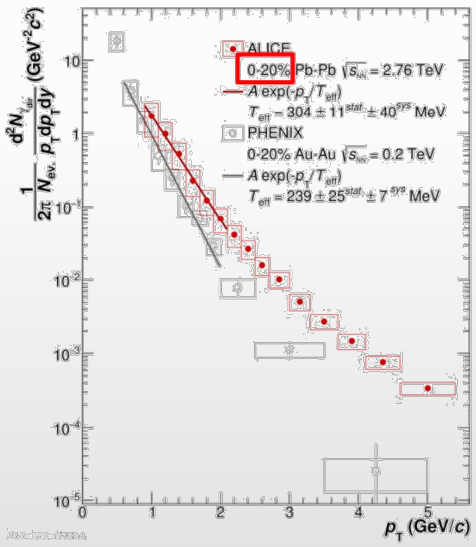
  - Radiated low-E photons
    → effective temperature of the system:



$$E_\gamma \frac{d^3N_\gamma}{d^3p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}}$$

- Fit the observed excess by exponential function to estimate T_{eff}



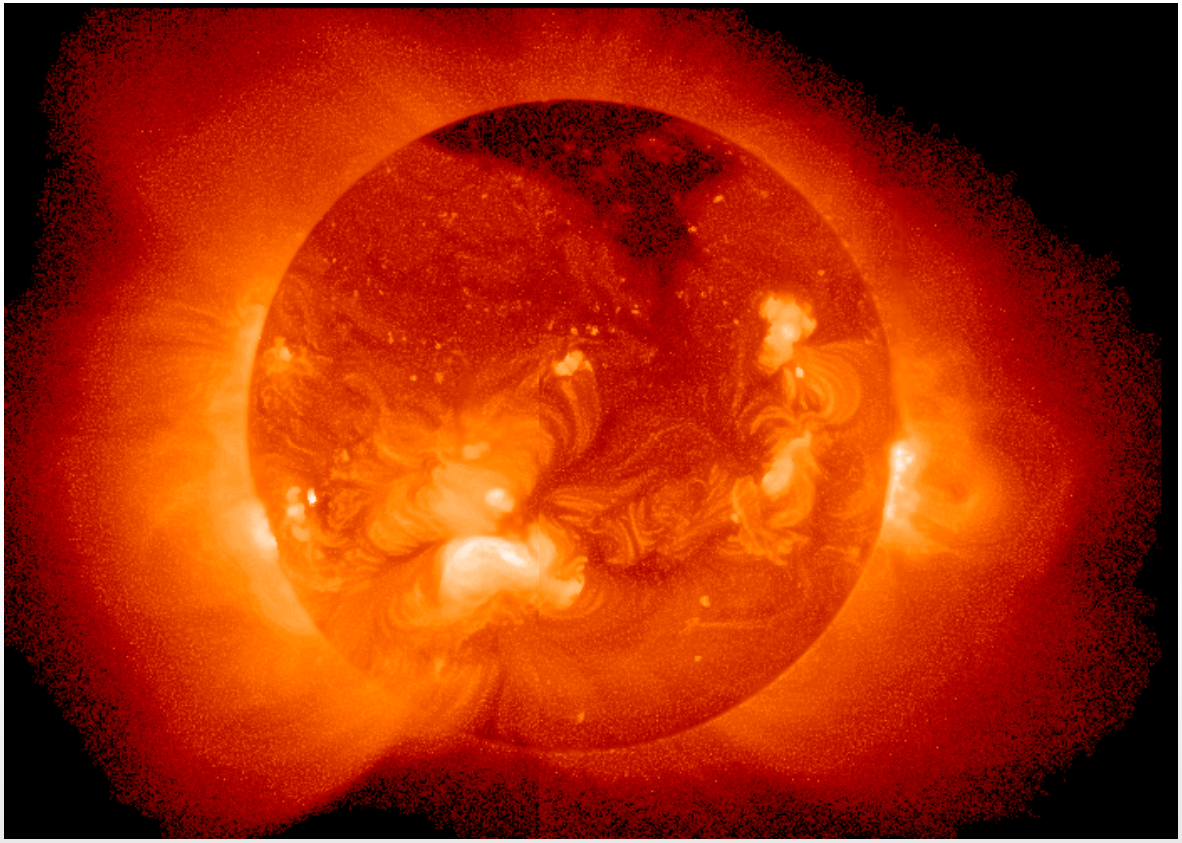


T_{eff} ~ 240 MeV at RHIC
T_{eff} ~ 300 MeV at the LHC
$T_{eff} >> T_c$ ~ 150 MeV predicted by *l*QCD

Relativistic A+A collisions → the highest temperature created in laboratory ~ 10^{12} K

Measurements suggest very **early emission** of thermal photons while system is extremely hot !

Temperature at the center of the Sun ~ 15 000 000 K



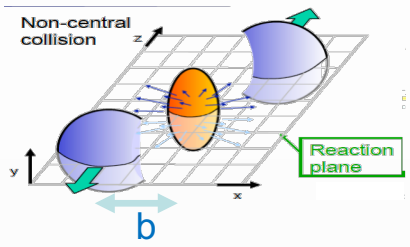
A medium of ~ 200 MeV is more than 100 000 times hotter !!!

Conditions achieved in heavy ion collisions (laboratory) could have existed only during the first microseconds after the Big Bang!

Flow of direct photons

❖ Initial eccentricity and its fluctuations drive momentum anisotropy v_n with specific viscous modulation

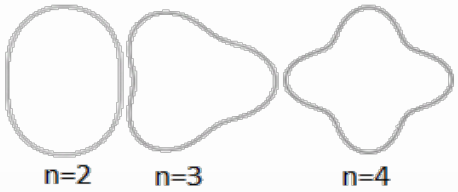
Spatial anisotropy of the nuclear overlap region



$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

$\epsilon_n \propto v_n$

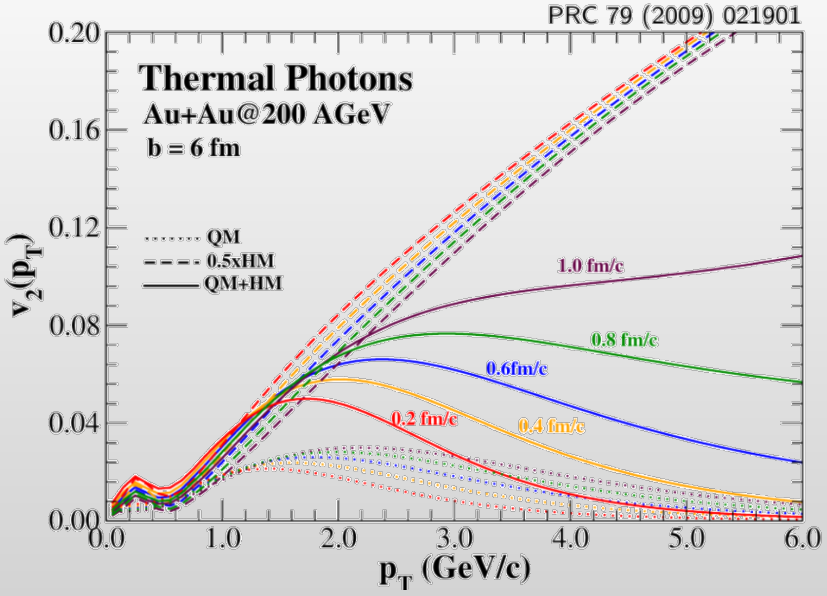
Azimuthal distribution of produced particles wrt to reaction plane (Ψ_n)



$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Anisotropic flow: $v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle$

❖ Direct photon flow should be sensitive to the emission time



Flow takes time to develop → thermal photons, emitted early from hotter fireball carry smaller collective flow than those, emitted at later stages.

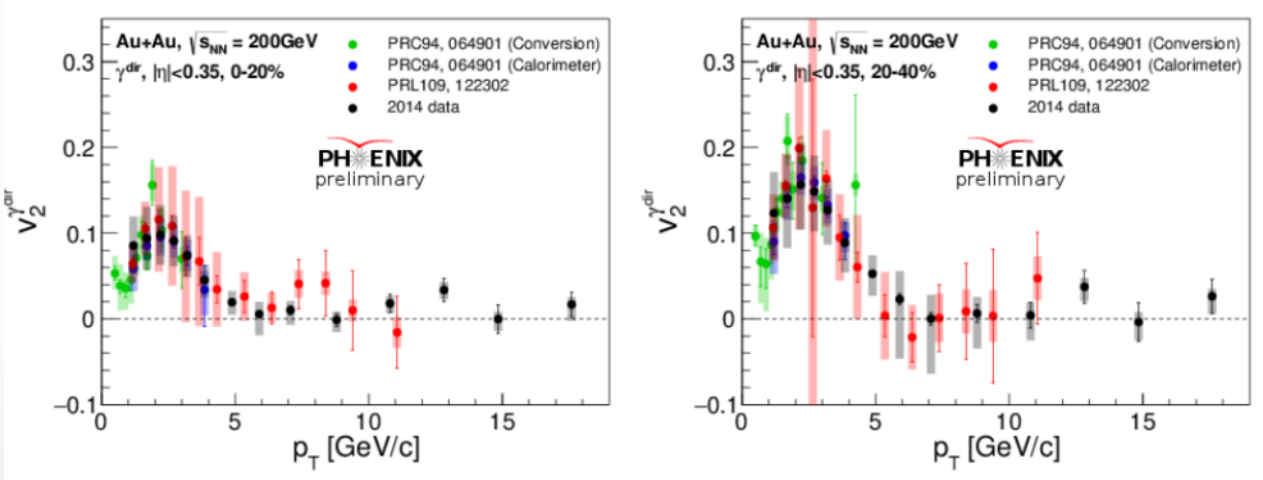
Flow measurements probe the emission time!

Direct photon flow at RHIC

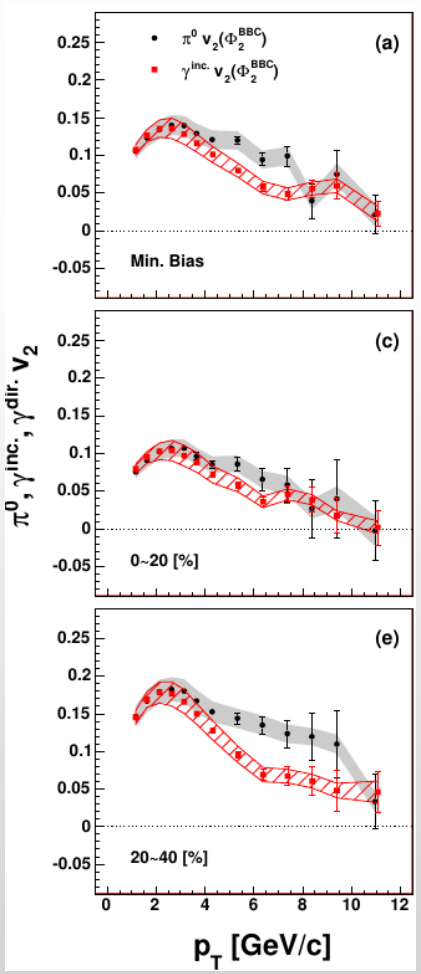
- Measurements with different methods agree

$$v_2^{\gamma,dir} = \frac{R_\gamma v_2^{\gamma,inc} - v_2^{\gamma,dec}}{R_\gamma - 1} \qquad R_\gamma = \frac{N_\gamma^{inc}}{N_\gamma^{dec}}$$

G. David, Rept.Prog.Phys. 83 (2020) 4, 046301



PRL 109, 122302



Direct photon flow in AuAu collisions is comparable with flow of decay photons and considerably stronger than predicted by hydro models

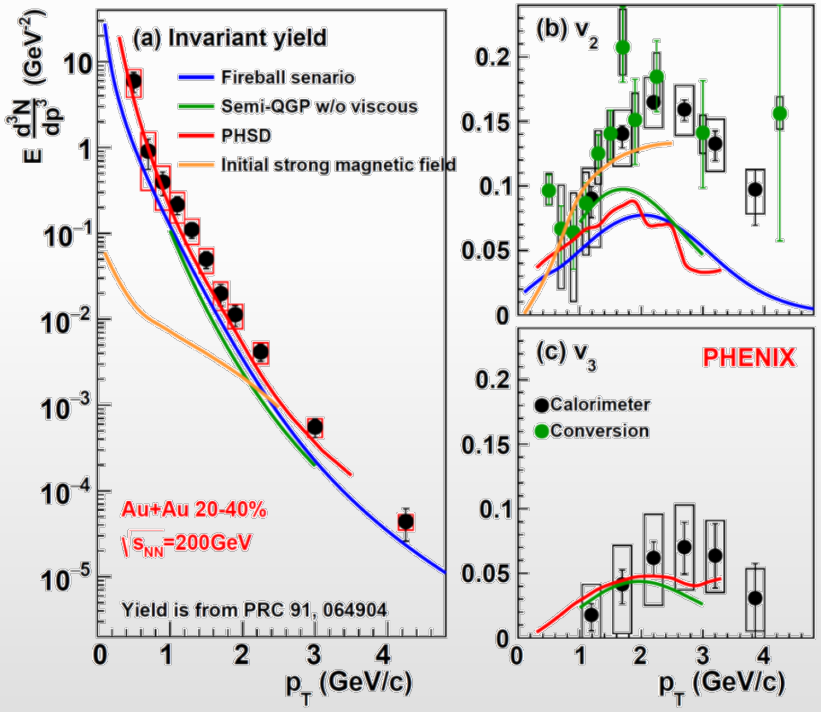
Flow measurements suggest **late emission** of direct photons when flow has well developed in the system!

Direct photon “puzzle”

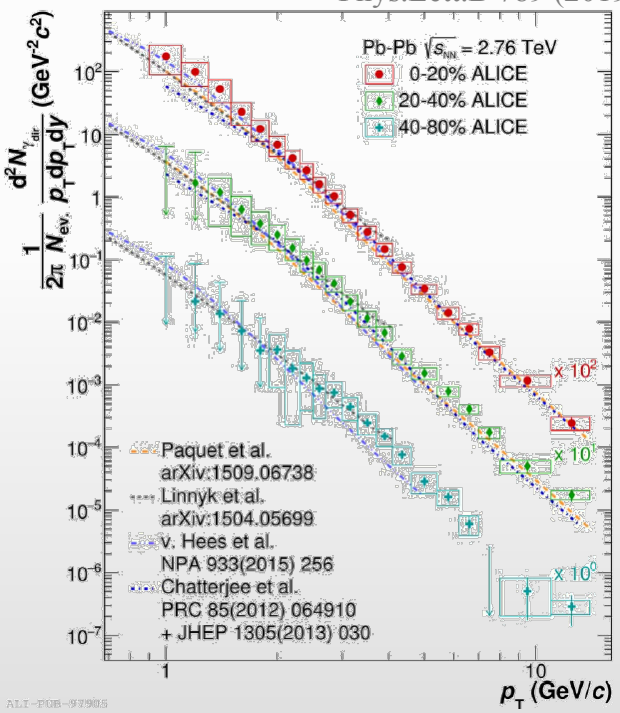
- Simultaneous description of direct photon yields and elliptic flow (v_2) is problematic:
  - ✓ direct photon flow is similar to flow of decay photons, underestimated by hydro → favors late emission
  - ✓ large yields of low-E direct photon yields require early emission in to be described by hydro models

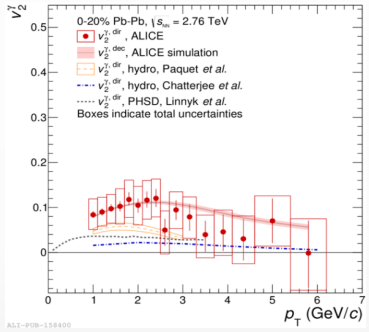
- Compare to hydro model calculations for numerical comparisons

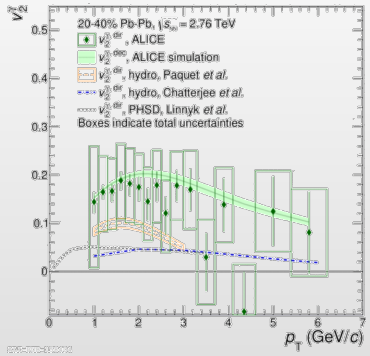
Phys.Rev. C94 (2016) no.6, 064901



Phys.Lett.B 789 (2019) 308-322



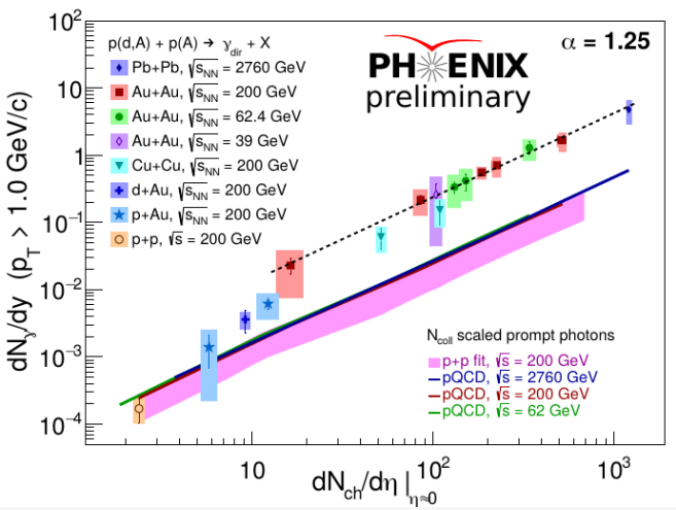




Simultaneous description of the large photon yields and flow is a challenge for theoretical models at RHIC and the LHC → “direct photon puzzle” → still unresolved

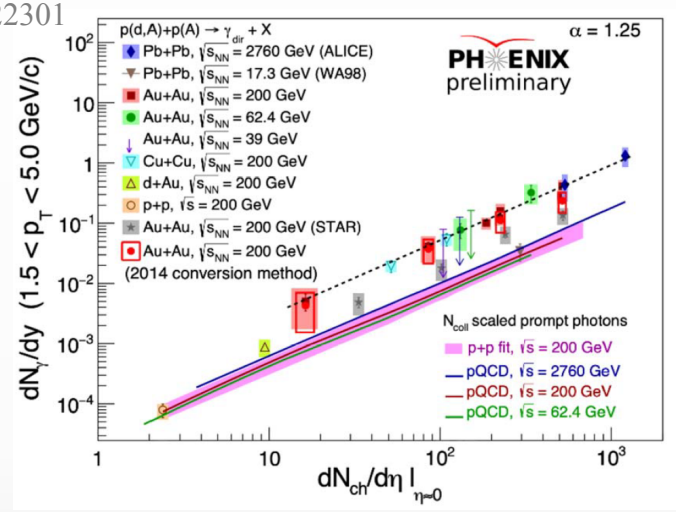
Experimental puzzle(s)

- PHENIX observed scaling of direct photon yield with charged particles multiplicity with smooth transition from pp to central AA collisions → fails if STAR@RHIC and WA98@SPS points are added

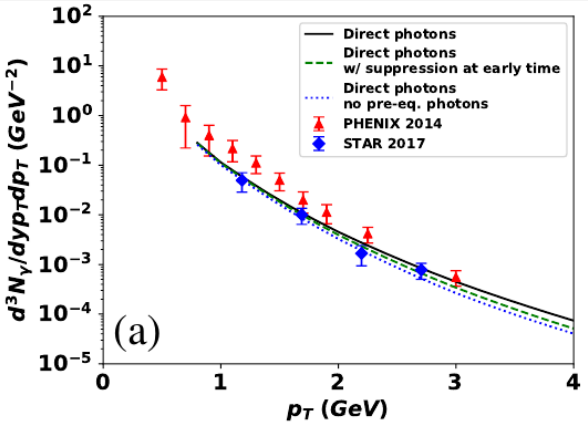


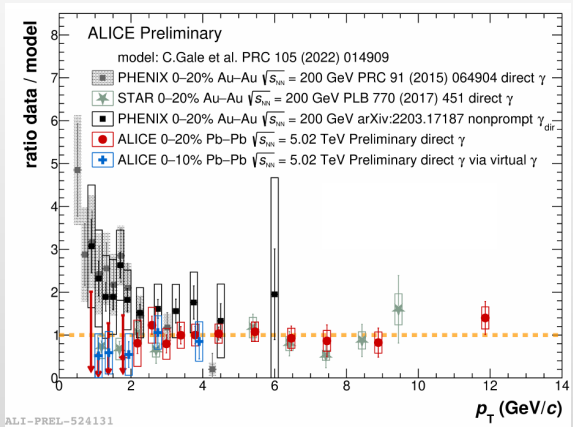
Add STAR & WA98

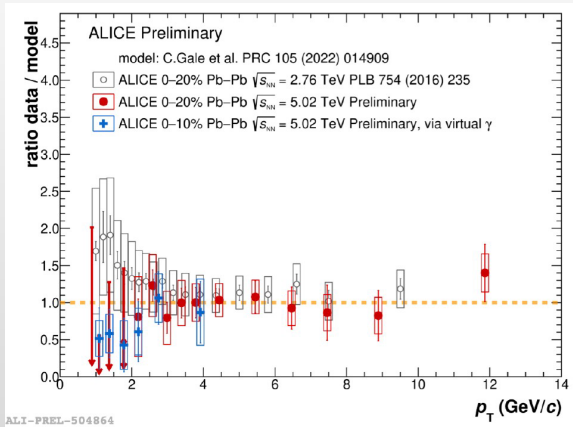
Phys.Rev.Lett. 123 (2019) 2, 022301



Quark Matter 2019, arxiv 2002.05191



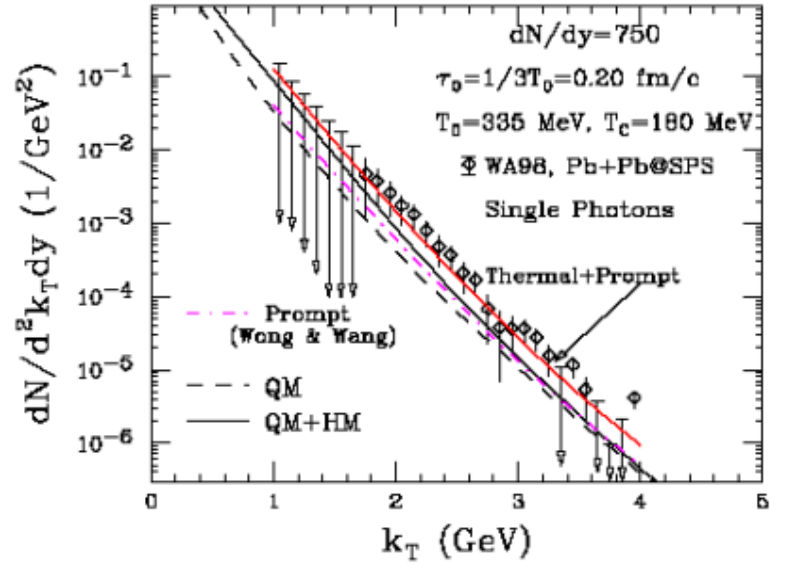




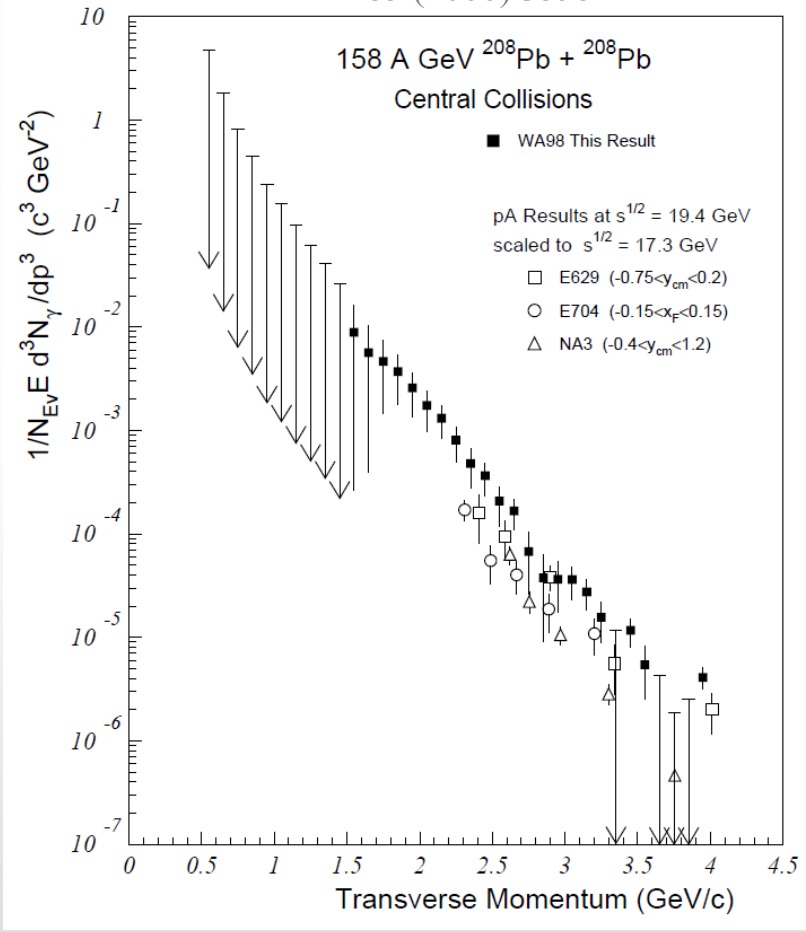
Measurements from a single experiment are not immune to interpretation errors
→ confirmation from multiple experiments + take seriously the quoted uncertainties !

What about low collision energies?

- Measurements are scarce, mostly upper limits at low-E, from last century (old)



PRL 85 (2000) 3595



For low colliding energies (SPS, NICA, FAIR) prompt photon contribution does not dominate at high p_T → possibility to explore high p_T tail of quark spectrum

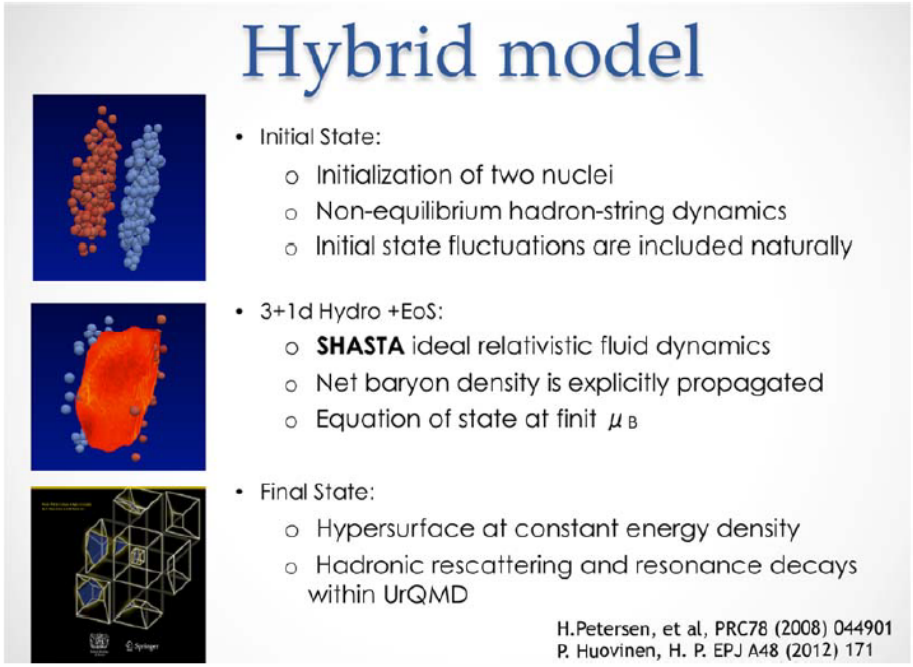
To which extend hydro + emission at equilibrium applicable? Should transport approach be used?

Measurements at NICA energies are missing → terra incognita !

Direct photons at NICA

- Estimate thermal direct photon yield and direct photon excess ratio (R_γ) for top and low NICA energies for central and semi-central collisions.
  - Use UrQMD model in hybrid mode (transport + hydro code) [1]
  - Use parameterizations of thermal radiation from hadron gas [2] and QGP [3]
- Estimate prompt direct photon yield using Jetphox model [4]
- Compare with previous studies (M. Bleicher et al.) [5,6]
- Estimate direct photon elliptic flow

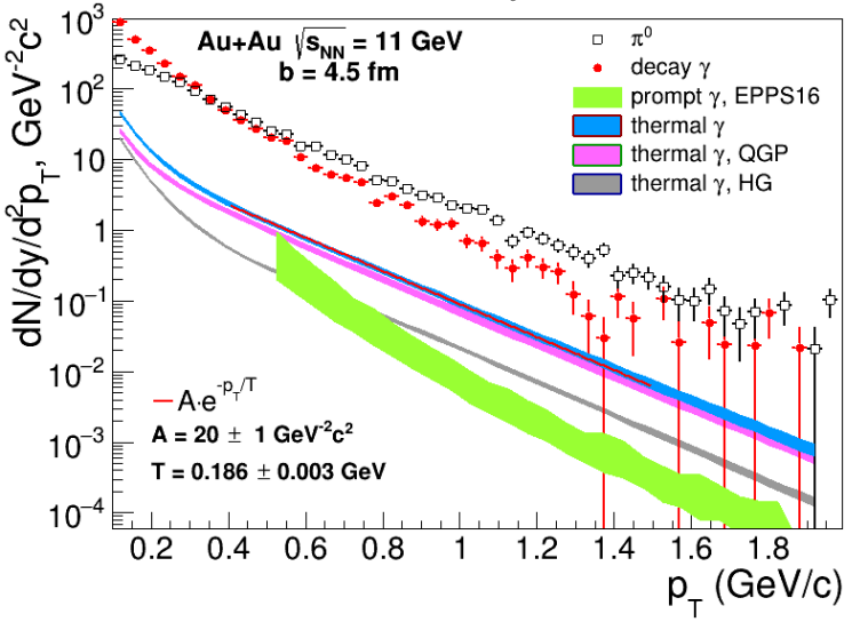
[1] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[2] S. Turbide, R. Rapp, and C. Gale, Phys. Rev.C 69(2004) 014903
[3] P. Arnold, G. D. Moore, L. G. Yaffe, JHEP12(2001) 009
[4] P. Aurenche et al., Phys.Rev.D73:094007, 2006 https://lapth.cnrs.fr/PHOX_FAMILY/jetphox.html
[5] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[6] S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 93, 054901 (2016)

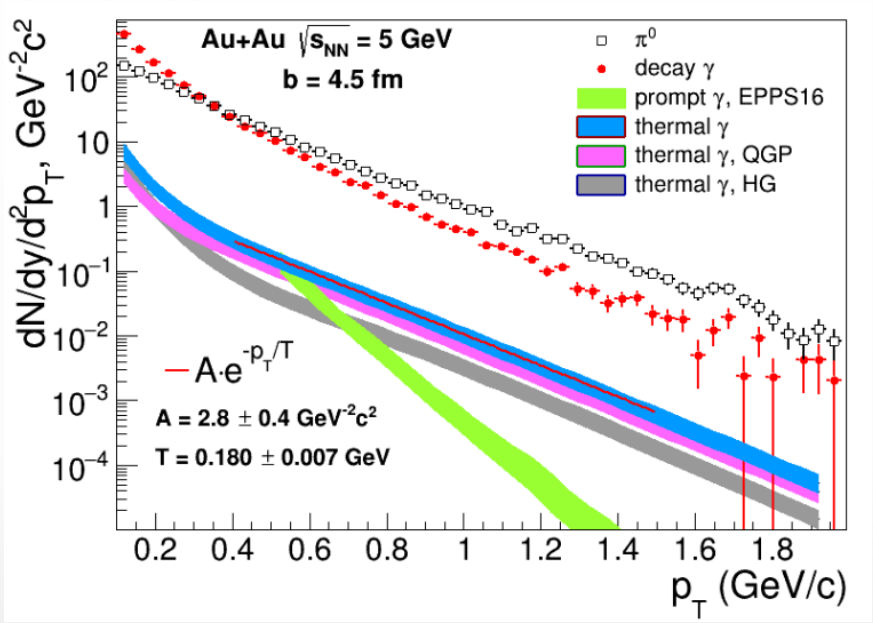


Direct photon spectra at NICA

❖ Inclusive spectra of photons, neutral pions, and direct photons divided in different contributions:

Physics of Particles and Nuclei (2021) 52(4):681-685





- Model results are consistent with previous calculations by M. Bleicher for SPS energies → cross check
- Contribution of prompt photons is small → good for high-p_T parton spectrum studies
- Much smaller yield at 5 GeV than that at 11 GeV due to smaller hydro evolution time
- Actual direct photon yields might be larger, usually hydro calculations underpredict spectra by x 2-5

Measurements are very challenging due to small S/B ratios

Direct photon reconstruction

Direct photon spectrum calculated as difference between inclusive and decay photons

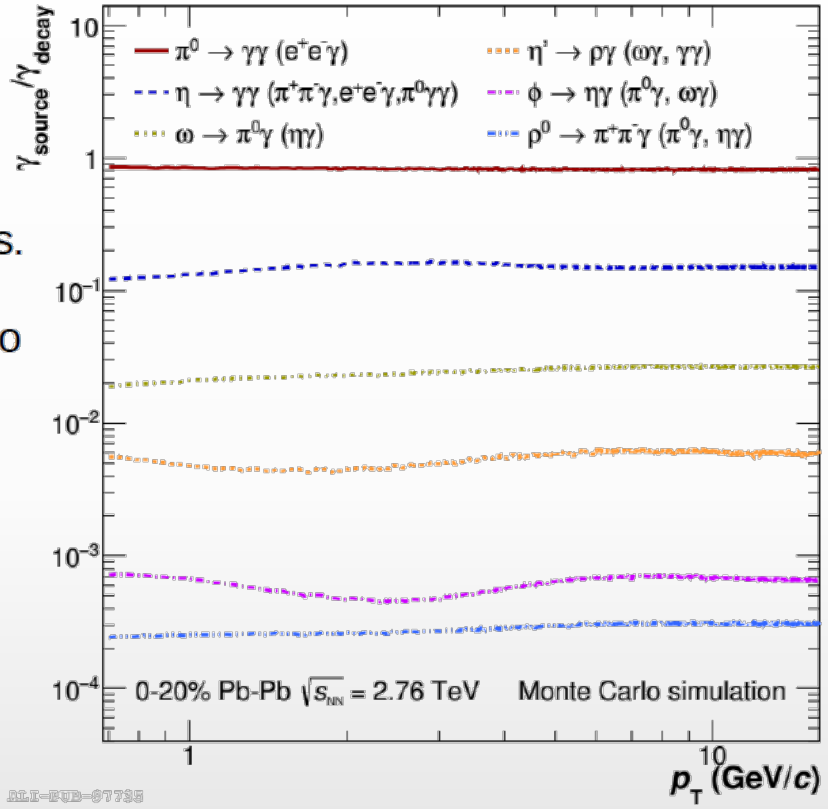
$$N_{\gamma}^{dir} = N_{\gamma}^{incl} - N_{\gamma}^{decay}$$

Up to ~90% of decay photons comes from π^0 decays. Some largest sys. uncertainties (fully: energy scale, partially: non-linearity, material budget) cancel in ratio

$$R_{\gamma} = \frac{N_{\gamma}^{incl}}{N_{\gamma}^{decay}} = \frac{\frac{N_{\gamma}^{incl}}{N_{\pi^0,meas}}}{\frac{N_{\gamma}^{decay}}{N_{\pi^0,MC}}}$$

Direct photon spectrum calculate as

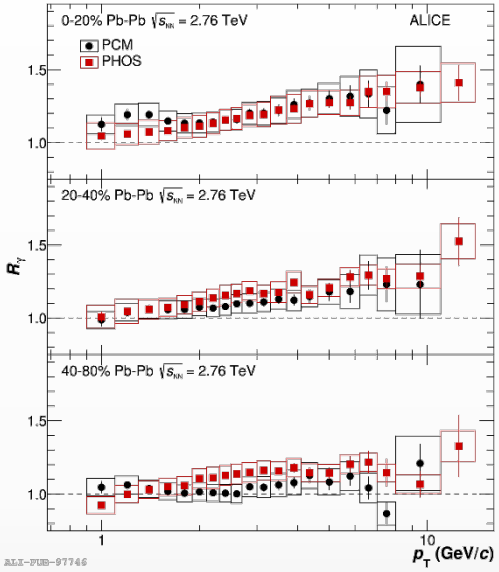
$$N_{\gamma}^{dir} = N_{\gamma}^{incl}\left(1 - \frac{1}{R_{\gamma}}\right)$$

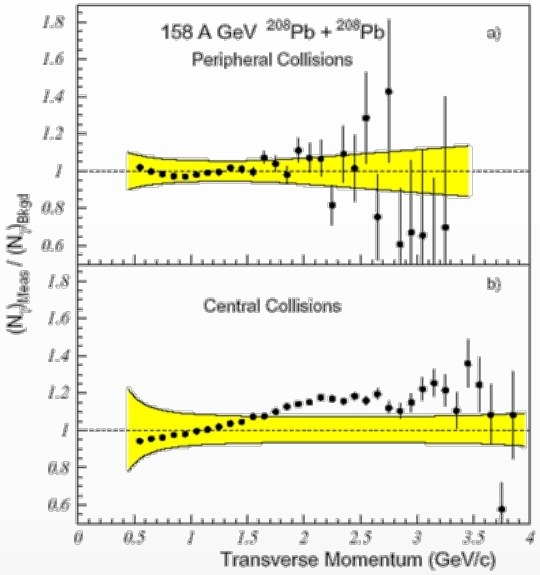


$\delta R_{\gamma} / R_{\gamma} \sim 5\%$ is the typical size of systematic uncertainty
→ naturally limits the experimental accessibility

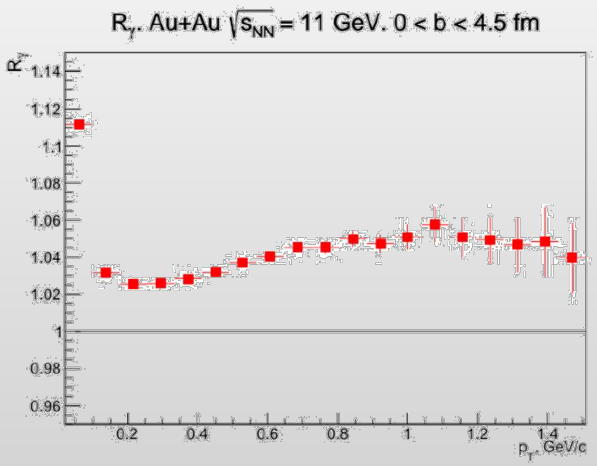
Comparison to higher-energy experiments

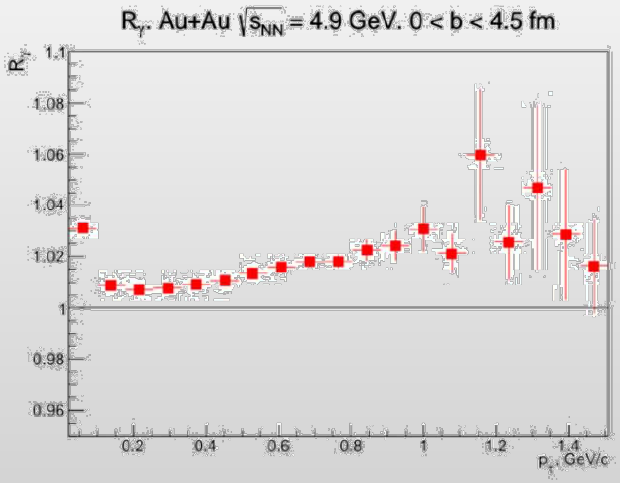
- Rγ ~ 1.05-1.2 in heavy-ion collisions at SPS/RHIC/LHC, $\sqrt{s_{NN}}$ = 17.2-2760 GeV

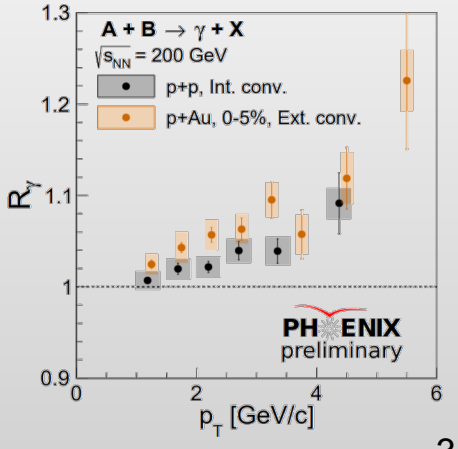




- Rγ < 1.05 at NICA, $\sqrt{s_{NN}}$ = 5-11 GeV → on the edge of experimental possibilities (achieved by PHENIX)

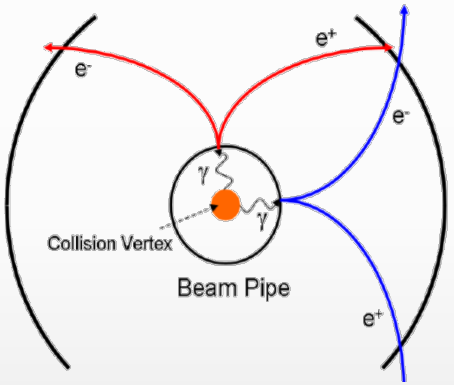


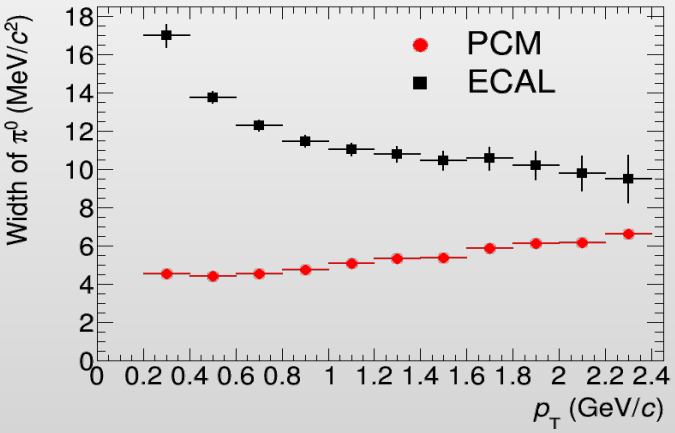


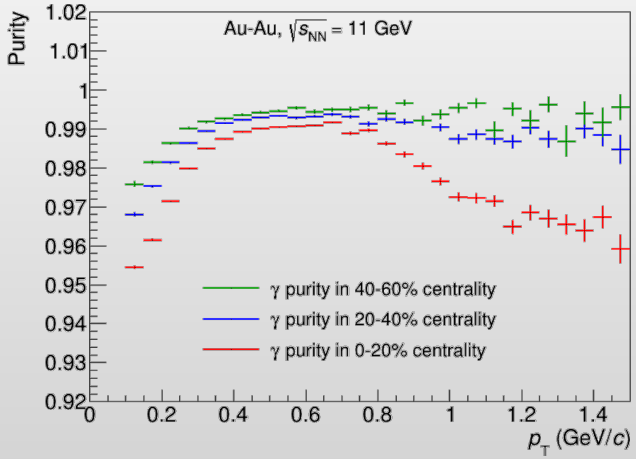


Prospects for MPD @ NICA

- Electromagnetic calorimeter ECAL:
  - ✓ dedicated detector to measure electromagnetic signals like $\gamma/e^{\pm}$ (energy, position, time of flight)
  - ✓ energy resolution ~ $1/\sqrt{E}$, better suited for high-E signals
  - ✓ suffer from large hadronic background at low energies
  - ✓ shower shape and time-of-flight selections for identification of photons
- Photon conversion method (PCM) :
  - ✓ photons are identified as e^+e^- pairs with small invariant mass after some second vertex topology, single track and pair selection cuts optimized for better S/B ratio
  - ✓ energy resolution ~ E, better suited for low-E
  - ✓ typically provides very high photon purity
  - ✓ suffer from small γ conversion probability



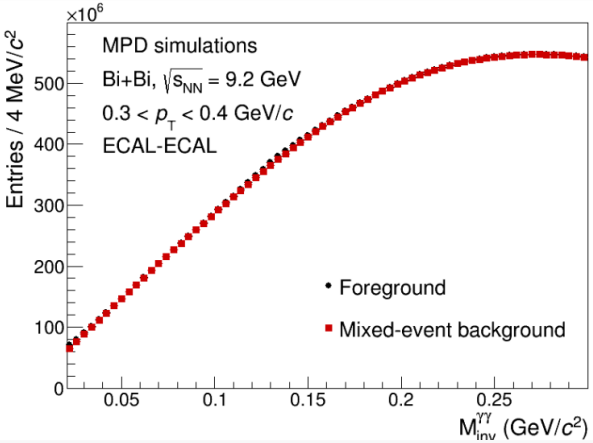


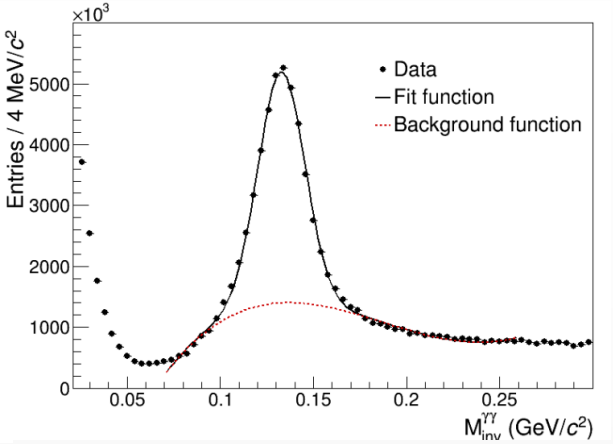


Neutral mesons in MPD

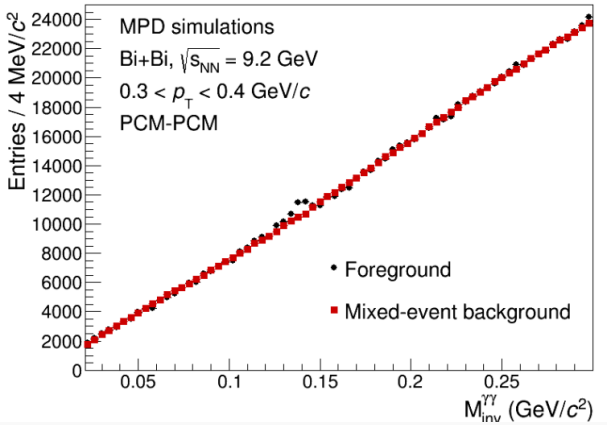
- Neutral mesons are the main source of background for direct photon and (di)electron measurements
- 15M AuAu@11 (UrQMD v.3.4) events, realistic vertex distribution

Photon pairs in the ECAL

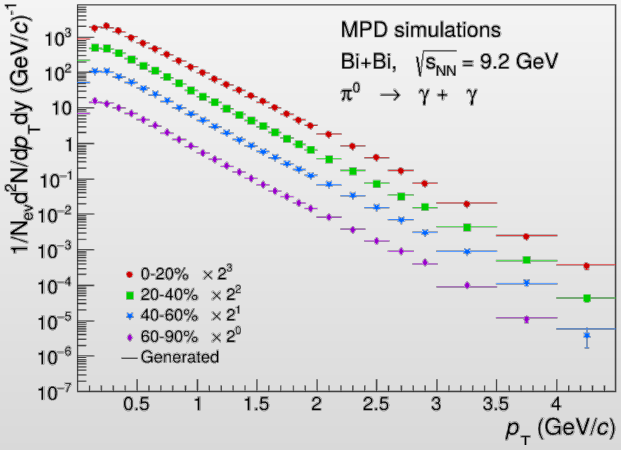


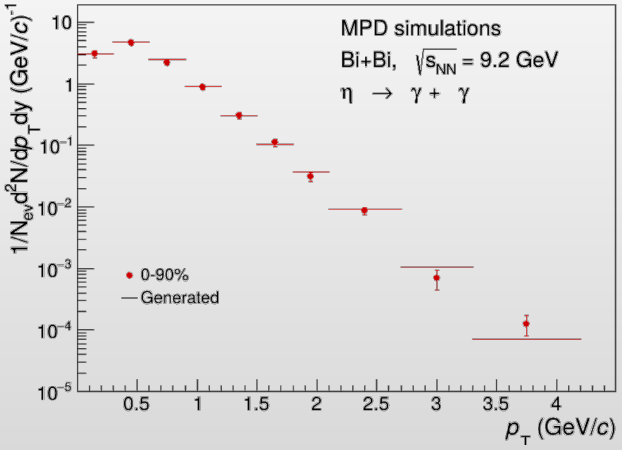


Photon pairs with PCM



- Reconstructed π^0 and η spectra match the generated ones within statistical uncertainties

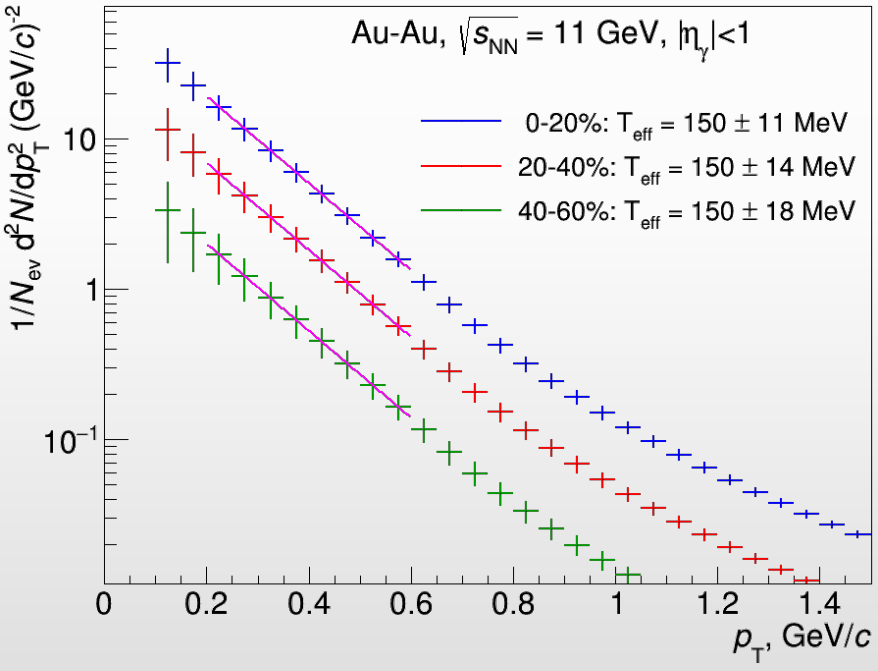




- Measurements of neutral mesons will be possible with ~ 10M sampled heavy-ion collisions

Direct photons in MPD

- Use ECAL and PCM for photon reconstruction (signal) and neutral mesons (background)
- Main sources of systematic uncertainties for direct photons:
  - ✓ detector material budget → conversion probability
  - ✓ π^0 reconstruction efficiency
  - ✓ p_T-shapes of π^0 and η production spectra



- ✓ With Rγ ~ 1.1 and δRγ/Rγ ~ 3% → uncertainty of T_{eff} ~ 10%
- ✓ Development of reconstruction techniques and estimation of needed statistics are in progress

MPD can provide unique measurements of direct photon production at NICA energies

Dielectrons

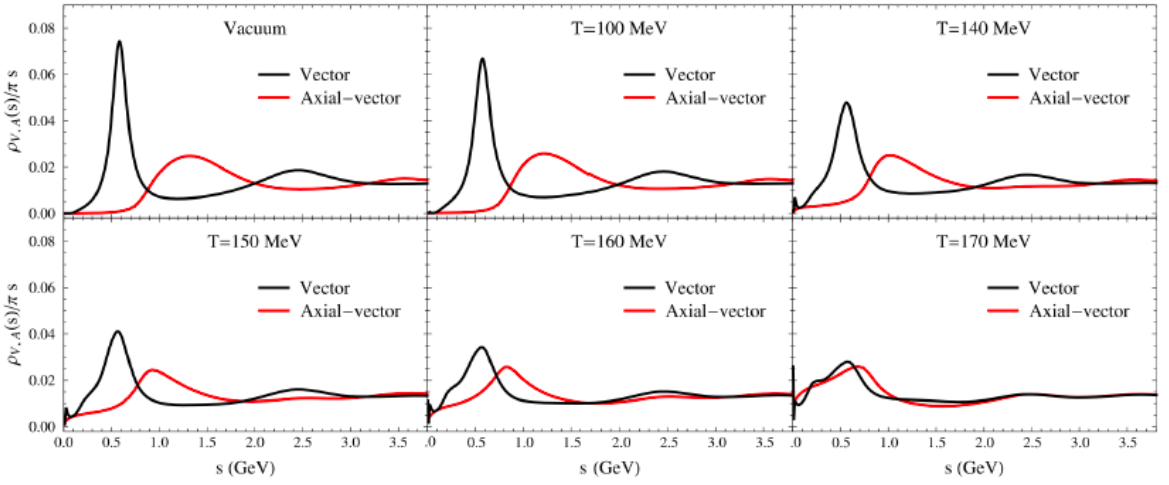
Why dielectrons?

- The Quark Gluon Plasma created in relativistic heavy ion collisions is characterized by two fundamental properties:
  - ✓ Deconfinement
  - ✓ Chiral Symmetry Restoration (CSR)
- Dileptons (e^+e^-, $\mu^+\mu^-$) are sensitive probes of both properties and in particular dileptons are unique probes of CSR.
- Thermal radiation emitted in the form of real photons or virtual photons (dileptons) provides a direct fingerprint of the matter formed (QGP and HG) and a measurement of its temperature.
  - ✓ QGP: $q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^-$
  - ✓ HG: $\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow l^+l^-$

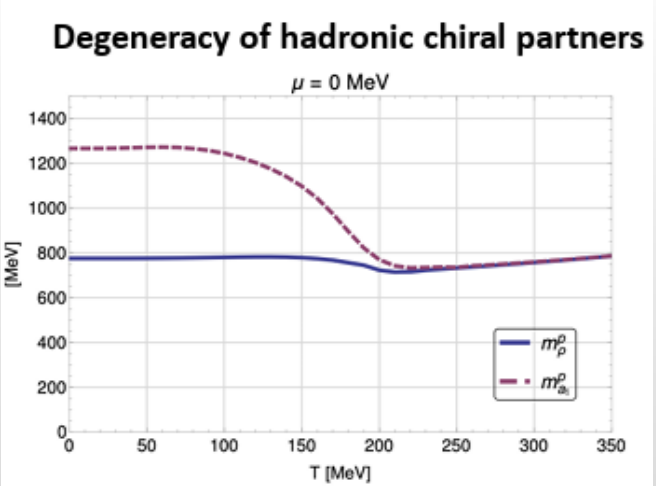
Connection to CSR

- Chiral symmetry is spontaneously (dynamically) broken in nature
  - ✓ current masses of light quarks are small ($m_u \approx 4$ MeV, $m_d \approx 7$ MeV), close to chiral limit
  - ✓ quarks have large "effective" masses $m_u \approx m_d \approx 1/3 m_N \approx 300$ MeV/c^2
- Numerical *l*QCD calculations show that at high temperature ($T>T_C$) or high baryon density ($\rho>\rho_C$), the CS can be (approximately) restored → coincides with the deconfinement ???
- At CSR the chiral partners (for example ρ and a_1) become degenerate → ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass ???

R. Rapp et al., Annals Phys. 368, 70-109 (2019); R. Rapp et al., Phys. Rev. D87, 076010 (2013)



C. Jung et al., Phys. Rev. D9, 036020 (2017)



$\rho - a_1$

If CS is restored the masses of the a_1 and ρ mesons should become equal.

Problem: very hard to measure the a_1 meson

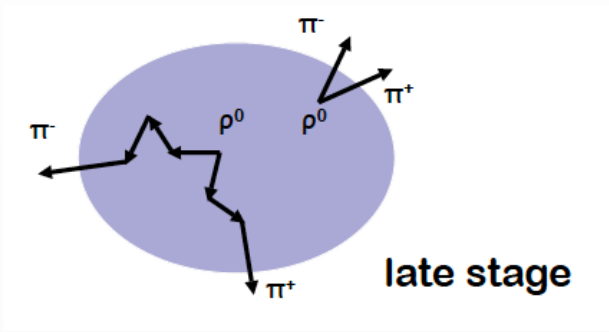
$a_1(1260)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^0$	
Γ_2	$\pi^0\pi^0\pi^0$	
Γ_3	$(\rho\pi)_{S-\text{wave}}$	seen
Γ_4	$(\rho\pi)_{D-\text{wave}}$	seen
Γ_5	$(\rho(1450)\pi)_{S-\text{wave}}$	seen
Γ_6	$(\rho(1450)\pi)_{D-\text{wave}}$	seen
Γ_7	$\sigma\pi$	seen
Γ_8	$f_0(980)\pi$	not seen
Γ_9	$f_0(1370)\pi$	seen
Γ_{10}	$f_2(1270)\pi$	seen
Γ_{11}	$K\overline{K}^*(892)+$ c.c.	seen
Γ_{12}	$\pi\gamma$	seen

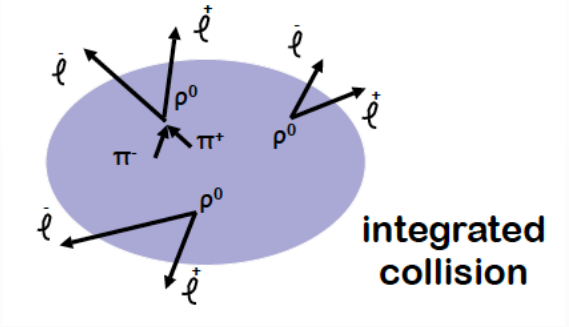
Experimental efforts focused on the ρ meson

ρ → e^+e^- decay and CSR

- ρ → $\pi^+\pi^-$ BR ~100%



ρ → e^+e^- BR = 4.7 10^{-5}



- Low-mass dileptons are the best probes to look for CSR effects:

  * **Large mfp:** → no final state interaction

  carry information from place of creation to detectors.

	m [MeV]	Γ_{tot} *[MeV]*	τ *[fm/c]*
ρ	*770*	*150*	*1.3*
ω	*782*	*8.6*	*23*
ϕ	*1020*	*4.4*	*44*

❖ **Best candidate: the ρ-meson**

short lifetime compared to the medium lifetime ($\tau \approx 10$ fm/c)

can decay and be regenerated in the medium

Advantages and Chellenges

- No final state interaction: large mfp compared to the size of the system. Once produced they leave the fireball without any further interaction
  ⟹ carry direct information from place of production to detectors

- Production rate strongly increasing function of T and density
  ⟹ most abundantly produced at the early stage of the collisions

- …But very difficult measurements
  ⟹ large combinatorial background

- Emitted by a variety of sources all along the history of the collision
  ⟹ need a very good understanding of all these sources to disentangle the interesting ones.

The double challenge (I)

1. Experimental challenge

- Need to detect a very weak source of e^+e^- pairs

  hadron decays ($m>150$ MeV/c^2 $p_T > 200$ MeV/c) ~ 10^{-6} / π^0

- in the presence of hundreds of charged particles

  central mid-rapidity Au-Au collision at RHIC ($dN_{ch}/d\eta$) 650

- and several pairs per event from trivial origin

  π^o Dalitz decays ~ 10^{-2} / π^0

  + γ conversions (assume 1% radiation length) 2 . 10^{-2} / π^0

huge combinatorial background $\propto (dN_{ch} / dy)^2$
S/B ~ 1/100-1/200 are typical

Consequences of poor S/B ratio

- The signal is obtained by subtracting the combinatorial background (estimated by the like-sign pair yield or a mixed event technique) from the total unlike sign yield:

  $S = U - B$

- The ***statistical error*** of S is not dictated by the magnitude of S but by the magnitude of the background. In the case S<<B

  $\Delta S \approx \sqrt{2B}$

- It is useful to consider the *"background free equivalent"* signal, i.e. the signal with the same relative error as in a situation of zero background:

  $S_{bfe} = S^2 / 2B$

  A signal S = 10^4 pairs measured with a S/B = 1/200 has the same relative statistical error as 25 pairs measured in free background conditions.

- The ***systematic uncertainty*** in S is dominated by the systematic uncertainty in B. Even if the event mixing technique is mastered to a fantastic precision of ±0.25%, the resulting systematic uncertainty in ΔS/S is ~50% (assuming S/B=1/200). Even in an infinite statistics measurement the systematic uncertainty will be very large.

The double challenge (II)

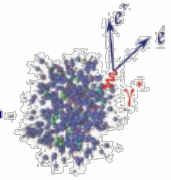
2. Analysis challenge

Electron pairs are emitted through the whole history of the collision (from the QGP phase, mixed phase, HG phase and after freeze-out)

- need to disentangle the different sources.
- need excellent reference pp and dA data.
- need independent information about the known sources in nuclear collisions → hadronic cocktail to extract signal beyond normal hadronic contributions

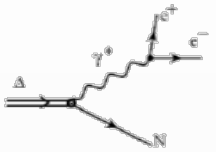
Dilepton invariant mass spectra

Physics with dileptons

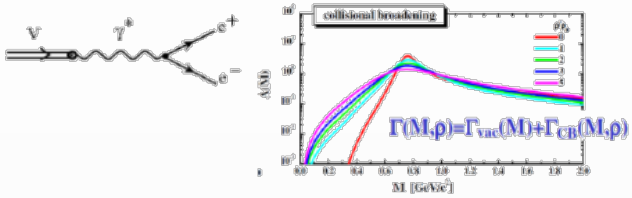


❑ **Low mass dileptons**
- probe of **hadronic in-medium effects – chiral symmetry restoration**
(late time emission)

- Bremsstrahlung
- Dalitz decay of mesons and baryons (π^0,η, Δ,...)



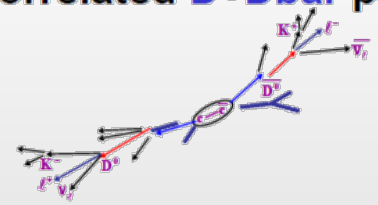
- direct decay of vector mesons

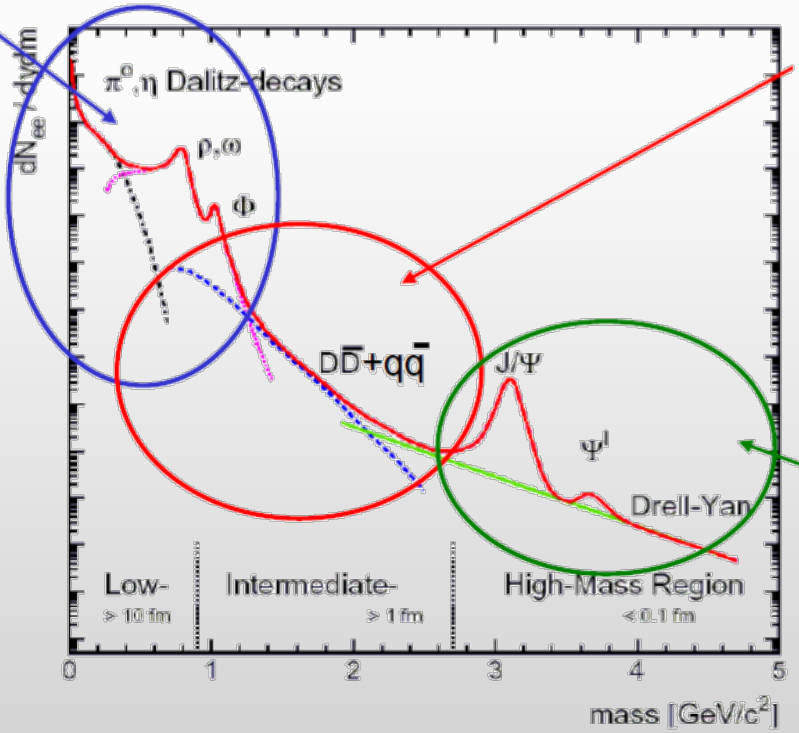


❑ **Intermediate mass dileptons**
– probe of ‚thermal QGP'



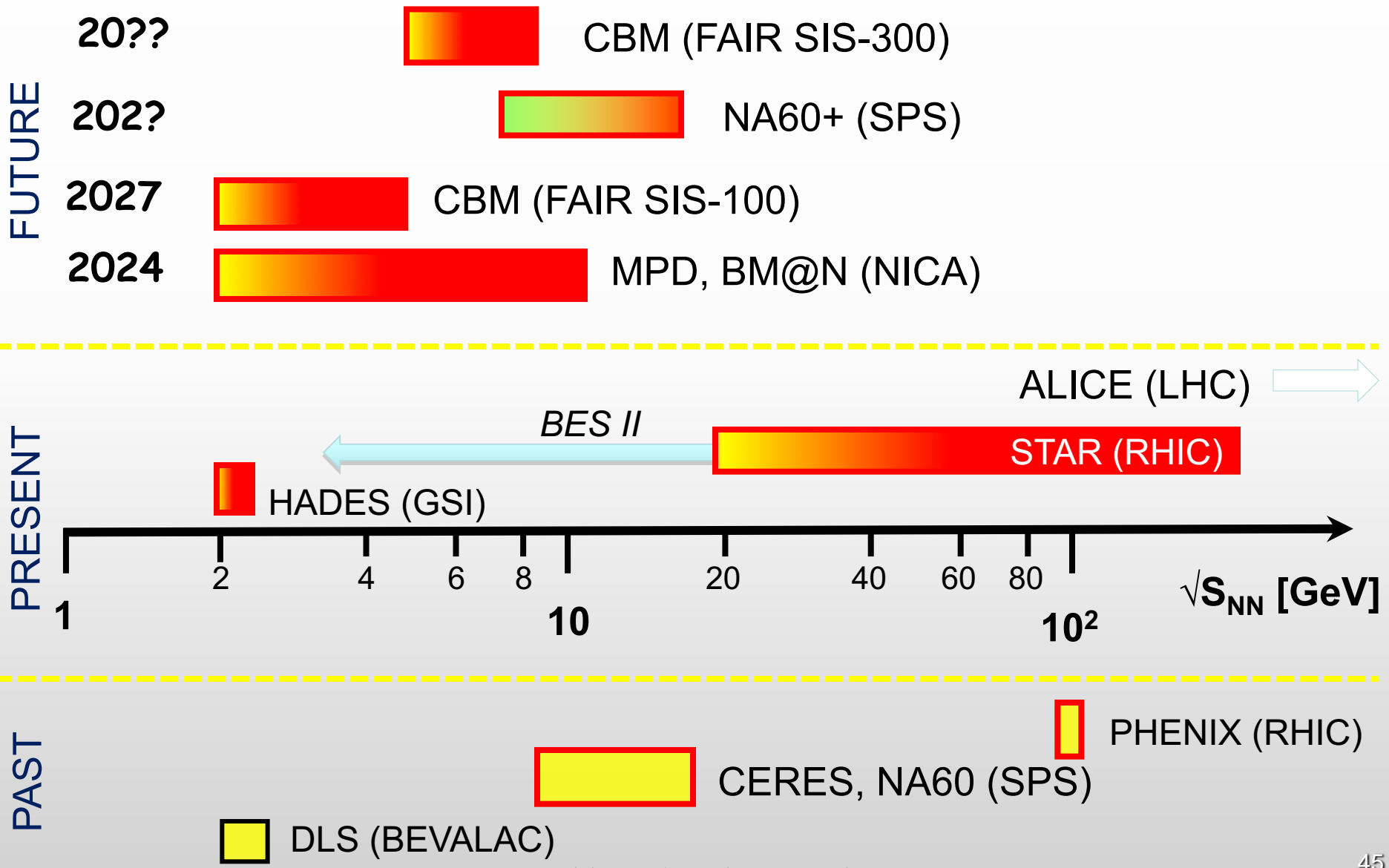
– correlated D+Dbar pairs

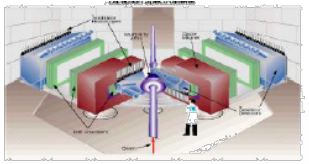




❑ **High-mass dileptons**
– probe of **pQGP (DY)** and **hard probes**
(early time emission)

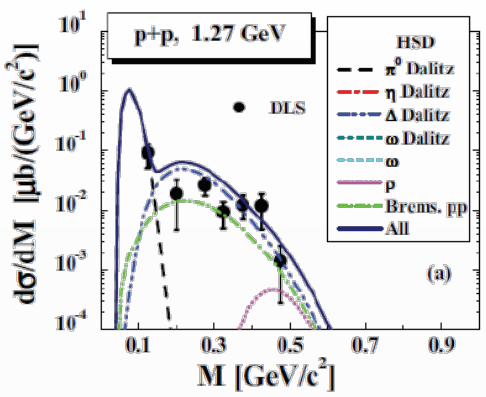
Dilepton experiments

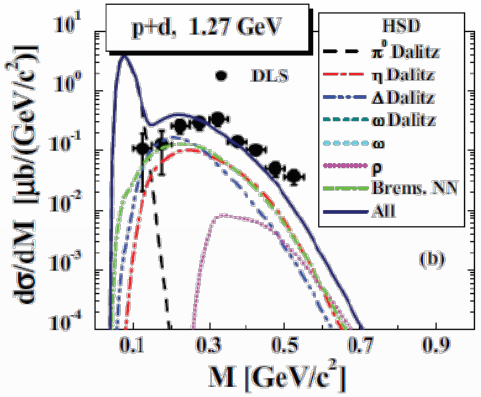


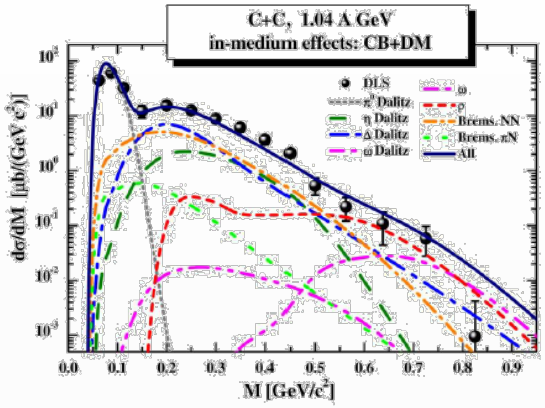


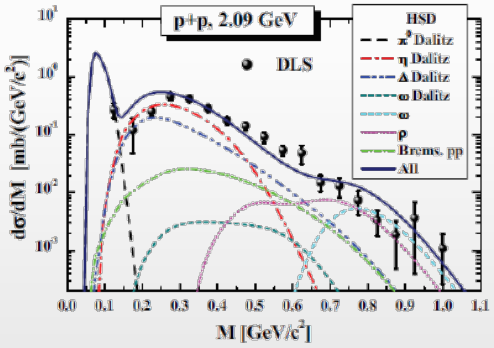
HSD: Dileptons from p+p, p+d, A+A - DLS

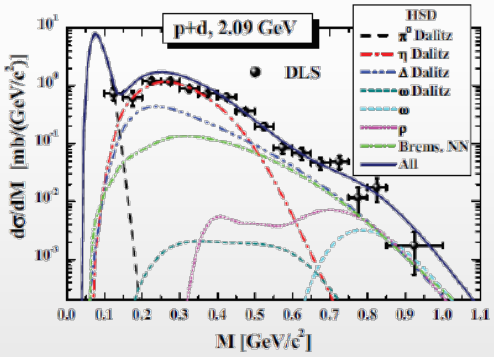
DLS: W.K. Wilson et al., PRC 57 (1998) 1865

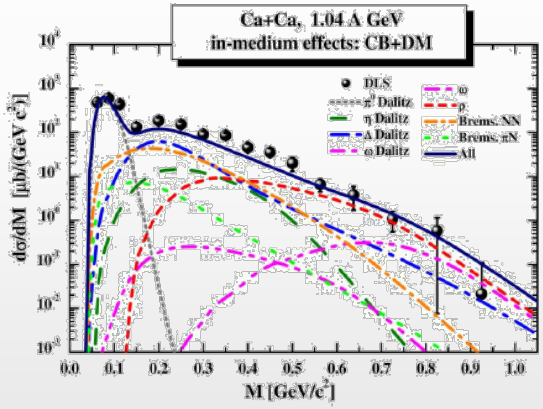










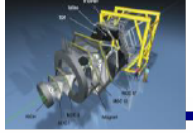


- bremsstrahlung* and Δ-Dalitz decay are the dominant contributions in low energy p+p, p+d and A+A collisions for 0.15 < M < 0.55 GeV (HSD solution of ‚DLS puzzle')
- in-medium ρ width for A+A
- off-shell dynamics in HSD derived from Kadanoff-Baym many-body theory

* OBE model: L. Kaptari, B. Kämpfer, NPA 764 (2006) 338

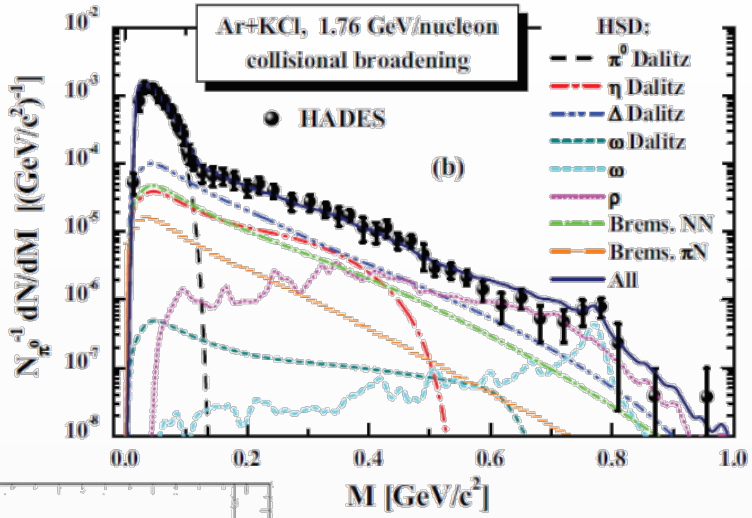
E.B., W. Cassing, NPA 807 (2008) 214

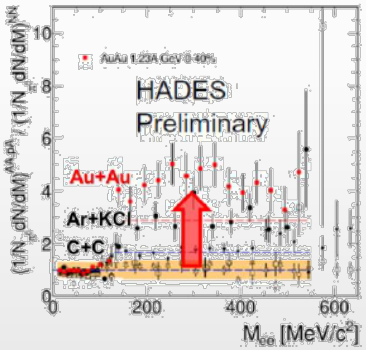
Slide is courtesy of Elena Bratkovskaya



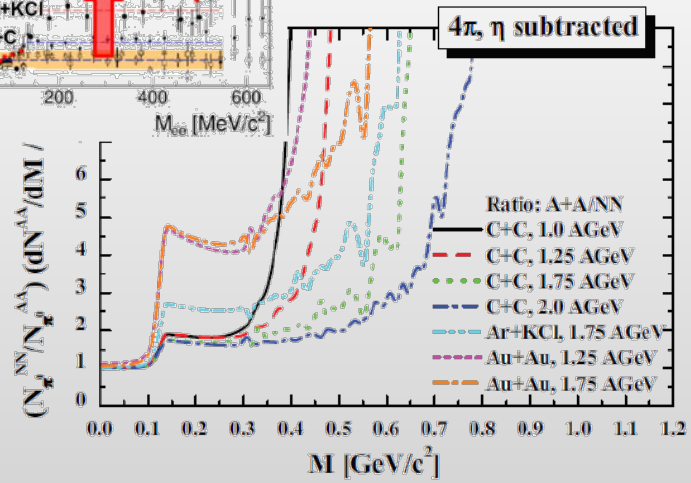
Dileptons at SIS energies - HADES

E. B., J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, PRC 87 (2013) 064907

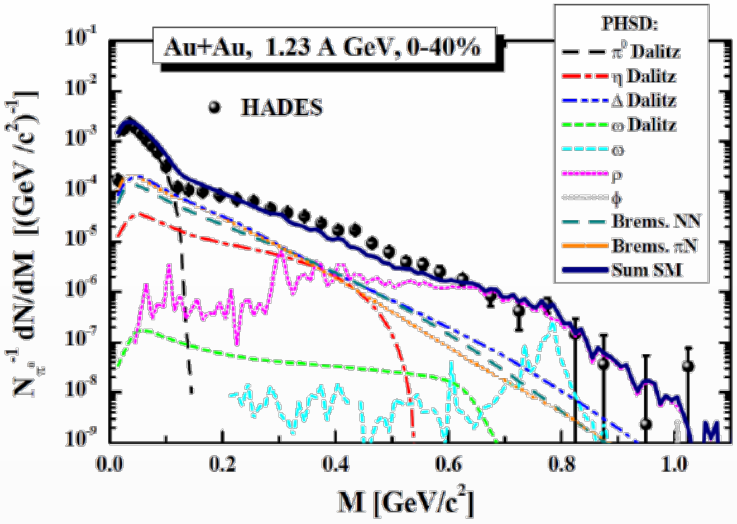




Ratio $\frac{N_{\pi^0}^{NN}}{N_{\pi^0}^{AA}} \frac{\frac{dN^{AA}}{dM}}{\frac{dN^{NN}}{dM}}$ NN=(pp+pn)/2



I. Schmidt, E.B., M. Gumberidze,R. Holzmann, PRD 104 (2021), 015008



- **Strong in-medium enhancement** of dilepton yield in Au+Au vs. NN
- **Increases with the system size:**

1) **multiple Δ regeneration** – dilepton emission from intermediate Δ's which are part of the reaction cycles Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

2) **pN bremsstrahlung** which scales with N_{bin} and not with N_{part} , i.e. pions

3) **Collisional broadening** of ρ,ω,ϕ mesons

Slide is courtesy of Elena Bratkovskaya

Dilepton spectra

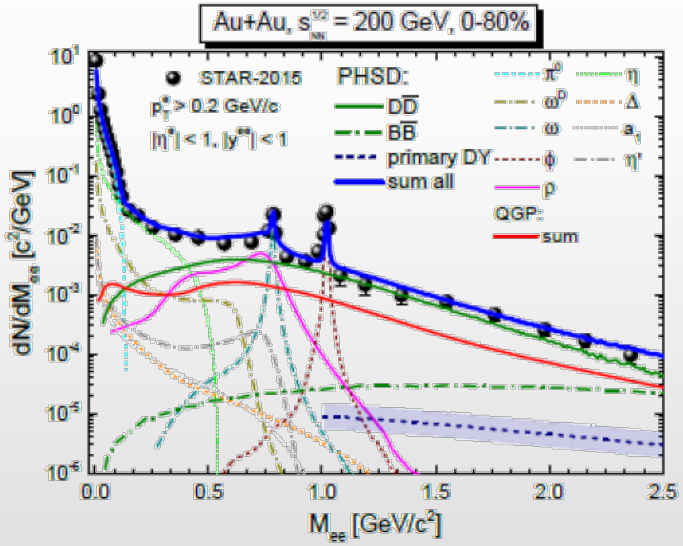
PHSD dilepton spectra including:

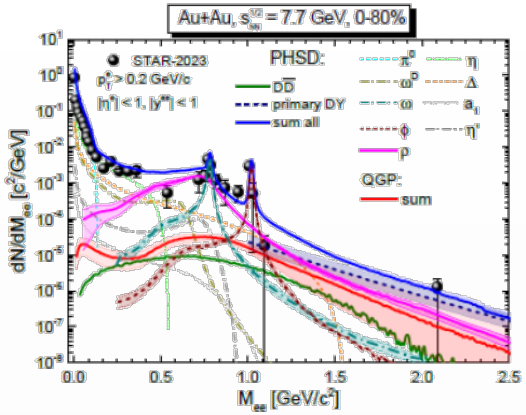
a collisional broadening of the vector meson spectral functions

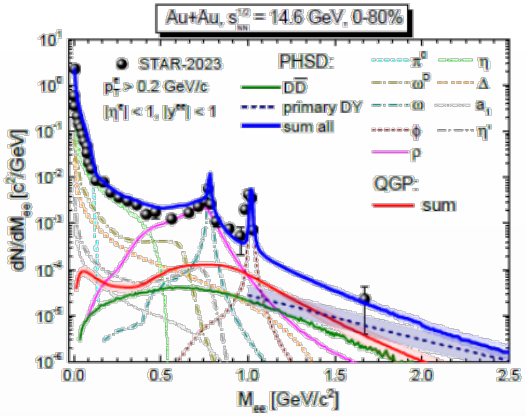
+ primary DY

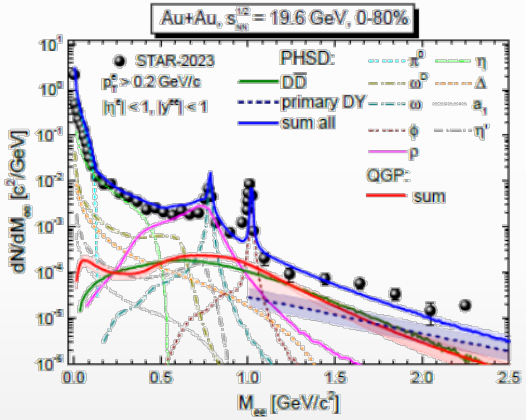
+ correlated charm + beauty

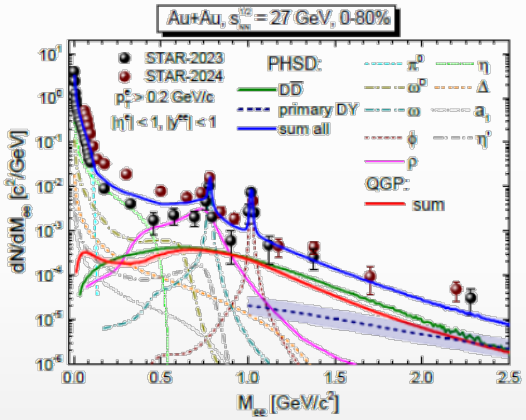
+ QGP $\begin{cases} q\bar{q} \to e^+e^- \\ q\bar{q} \to ge^+e^- \\ gq(\bar{q}) \to q(\bar{q})e^+e^- \end{cases}$

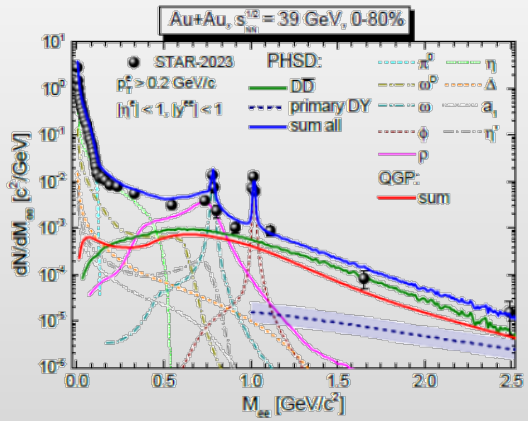


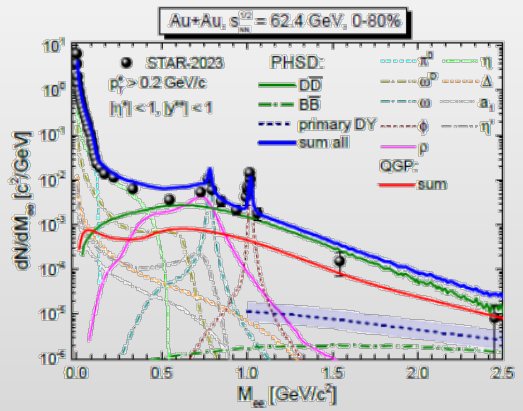










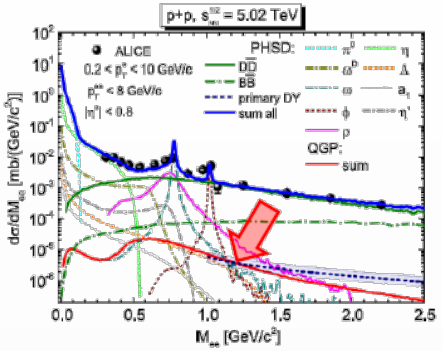


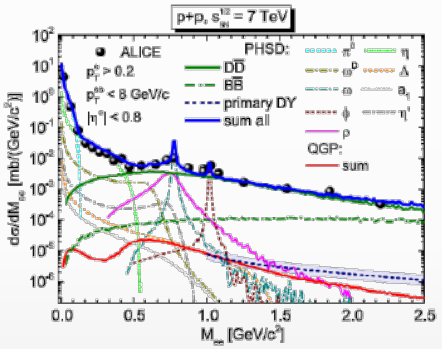
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

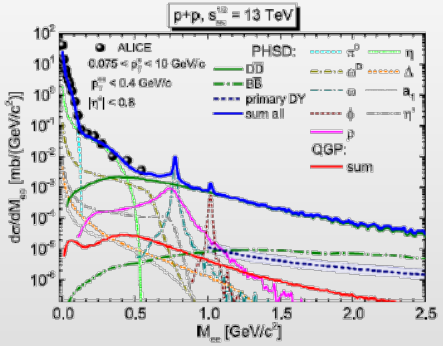
Slide is courtesy of Elena Bratkovskaya

Dileptons at LHC

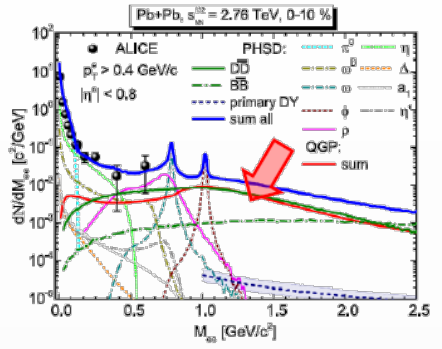
p+p

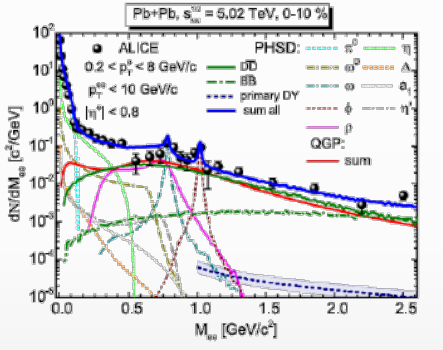


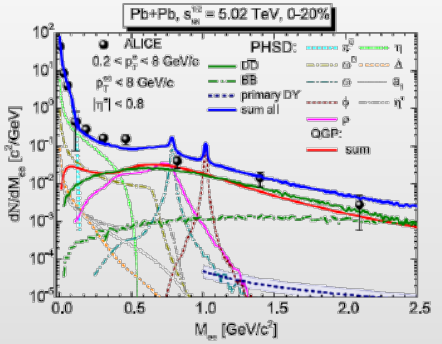




Pb+Pb







- **p+p:** (M>1.2GeV) correlated charm (dominant) + dileptons from QGP droplets
  A+A: dilepton yield from QGP = dilepton yield from correlated charm

Slide is courtesy of Elena Bratkovskaya

A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

Dilepton measurements - summary

- Excess of low-mass dielectron yields with respect to known hadronic sources is observed at all collision energies from DLS@Bevalac to ALICE@LHC
- Excess consistently reproduced by microscopic many body models
- Low energies:
  - ✓ only LMR is accessible
  - ✓ dilepton excess is from multiple Δ regeneration, pN brake radiation, in-medium ρ contribution
- High energies:
  - ✓ LMR: dominated by HG thermal radiation, QGP contribution increases with energy
  - ✓ IMR: dominated by QGP radiation and correlated charm from semileptonic $D\overline{D}$ decays, fraction of QGP increase with energy
- In-medium effects can be observed at all energies from SIS to LHC → emerging CSR ???

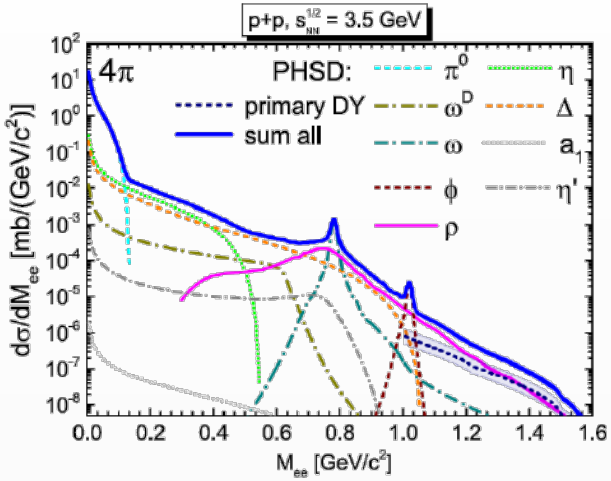
PHSD predictions for CBM / MPD

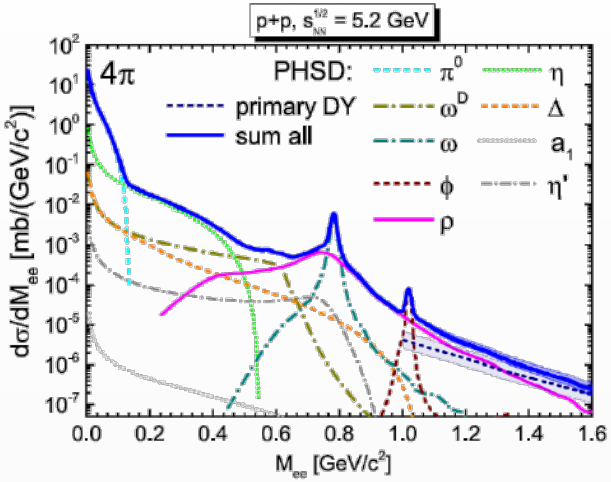
$s_{NN}^{1/2}$ = 3.5 GeV

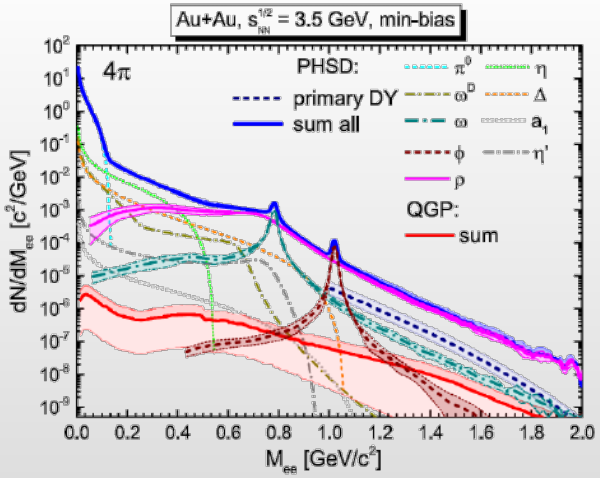
$s_{NN}^{1/2}$ = 5.2 GeV

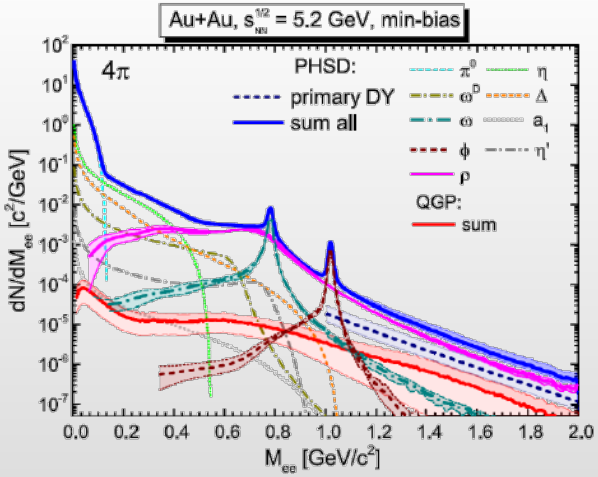
p+p

Au+Au









Au+Au vs p+p : dominant contributions -

in-medium vector meson decays + DY + QGP

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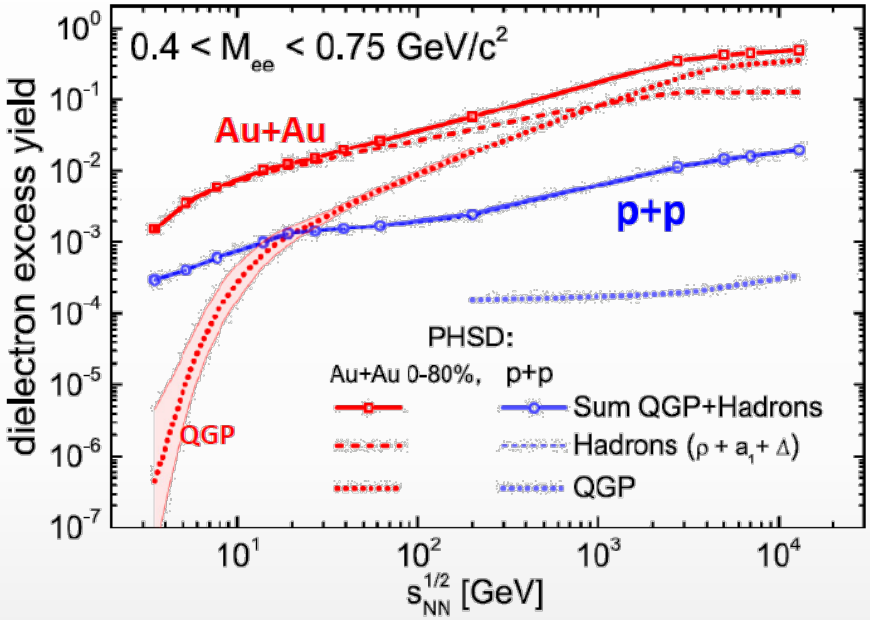
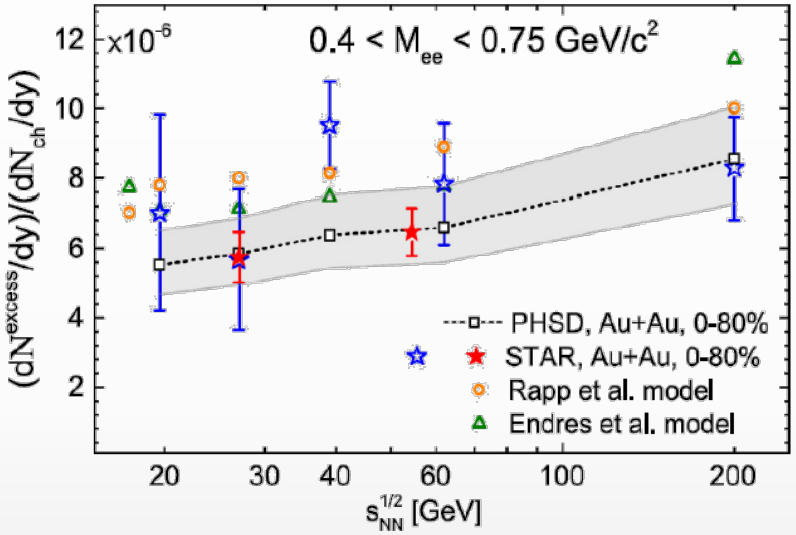
Slide is courtesy of Elena Bratkovskaya

Dileptons: excitation functions for 0.4<M<0.75GeV

Excitation function of dilepton excess yield integrated for 0.4 < M < 0.75 GeV

Dilepton excess yield = total – 'cocktail' (expected contributions from hadronic decays at freezeout)





For 0.4 < M < 0.75 GeV:

- **Dominant contribution – vector meson decays**
  - ➔ **favours in-medium modifications of vector meson spectral function – collisional broadening**
- **QGP contribution increases with energy**
- **p+p: dileptons are dominated by hadronic channels (vector mesons)**

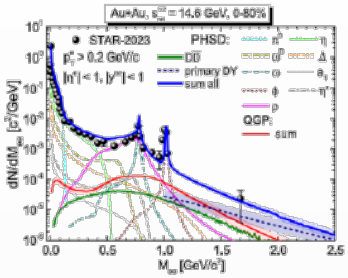
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

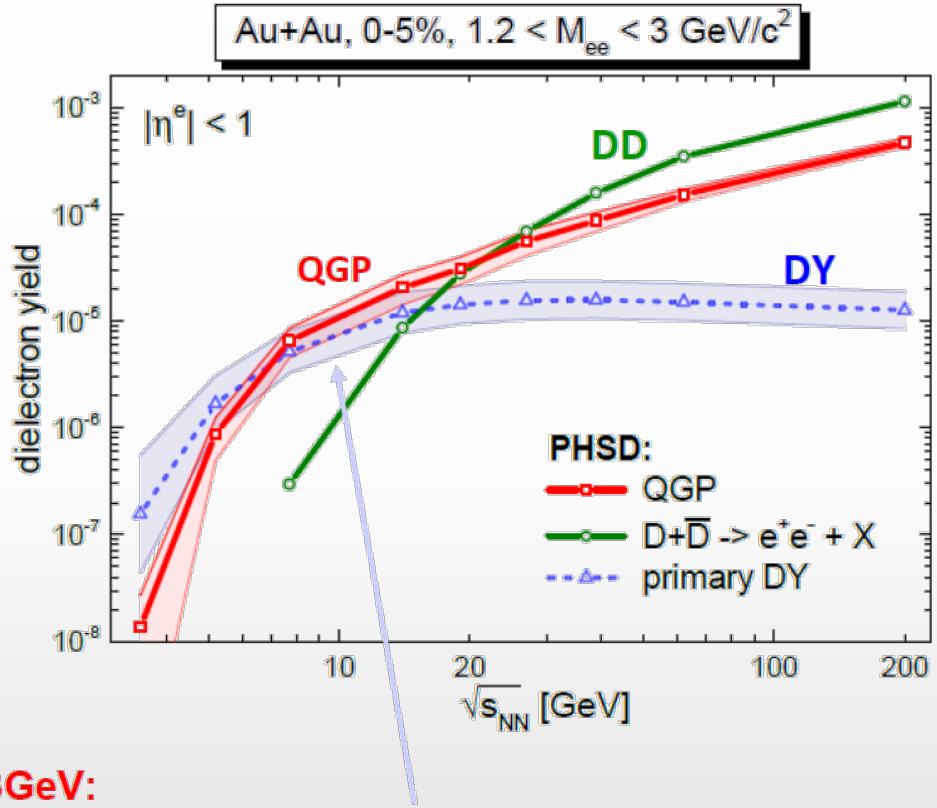
Cf. T. Song et al., Phys. Rev. C97 (2018), 064907

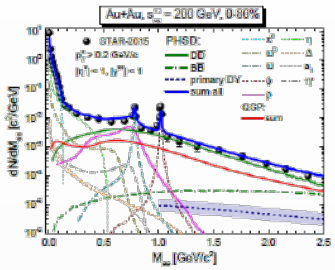
Slide is courtesy of Elena Bratkovskaya

Dileptons: excitation functions for 1.2<M<3GeV

Excitation function of dilepton yield integrated for 1.2 < M < 3GeV







For 1.2 < M < 3GeV:

- Dileptons from QGP overshine charm dileptons (D-Dbar) with decreasing beam energy
- Primary DY could be "subtracted" from AA dilepton spectra using pp data

➔ Good perspectives for NICA / FAIR!

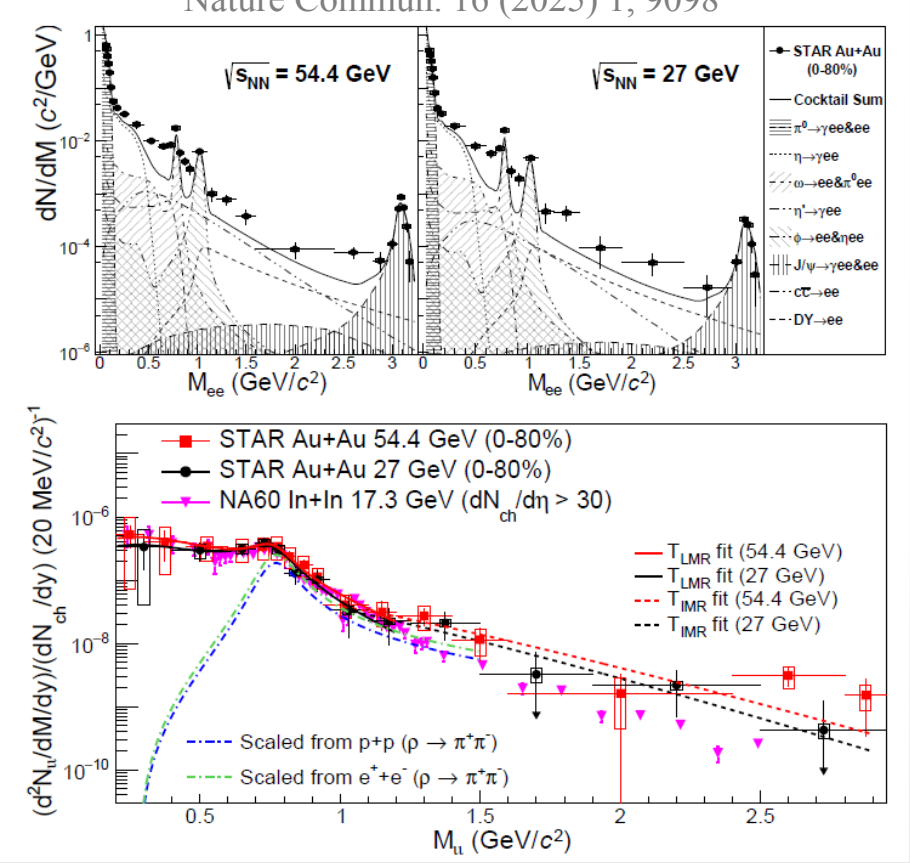
A. W. R. Jorge et al., 2503.05253, PRC111 (2025) 064904

Cf. T. Song et al., Phys. Rev. C97 (2018), 064907

Slide is courtesy of Elena Bratkovskaya

Dileptons as a thermometer

Nature Commun. 16 (2025) 1, 9098

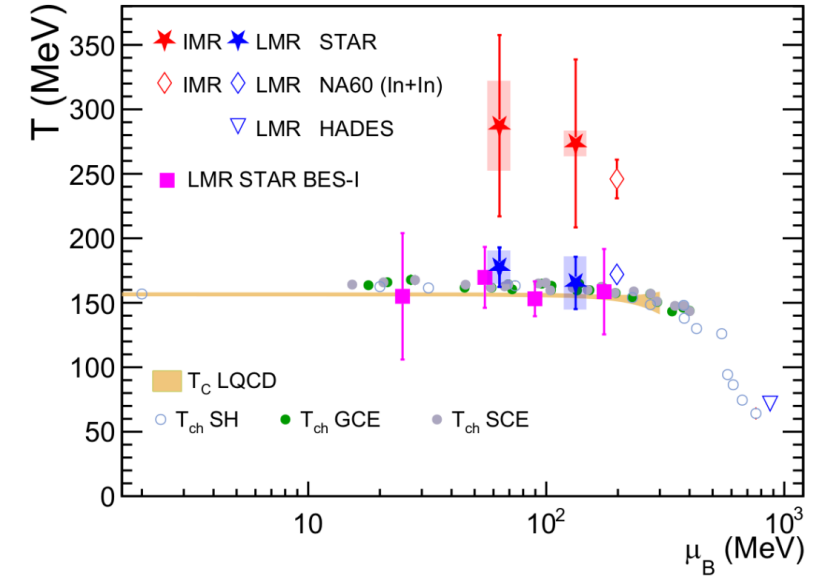


- "Thermal spectra" = correlated e^+e^- pairs – known hadronic sources (except for ρ^0)
- Available for collision energies from SIS18-SPS-RHIC
- Two distinct regions:
  - ✓ LMR (0.4 < Mee < 1.2 GeV/c2): similar shapes → originate from radiative sources with a similar temperature??
  - ✓ IMR (1.0 < Mee < 2.9 GeV/c2): dominated by quark-antiquark annihilation in the QGP → originate from sources with different temperatures???

Average temperatures

Nature Commun. 16 (2025) 1, 9098

- LMR (0.4 < Mee < 1.2 GeV/c2): fit to model predictions for in-medium ρ^0 resonance structure + thermal yields → extract "hadronic" temperature T_{LMR}
- IMR (1.0 < Mee < 2.9 GeV/c2): fit to Boltzman distribution $M^{3/2}e^{-M/k_BT}$ → extract "QGP" temperatire T_{IMR}

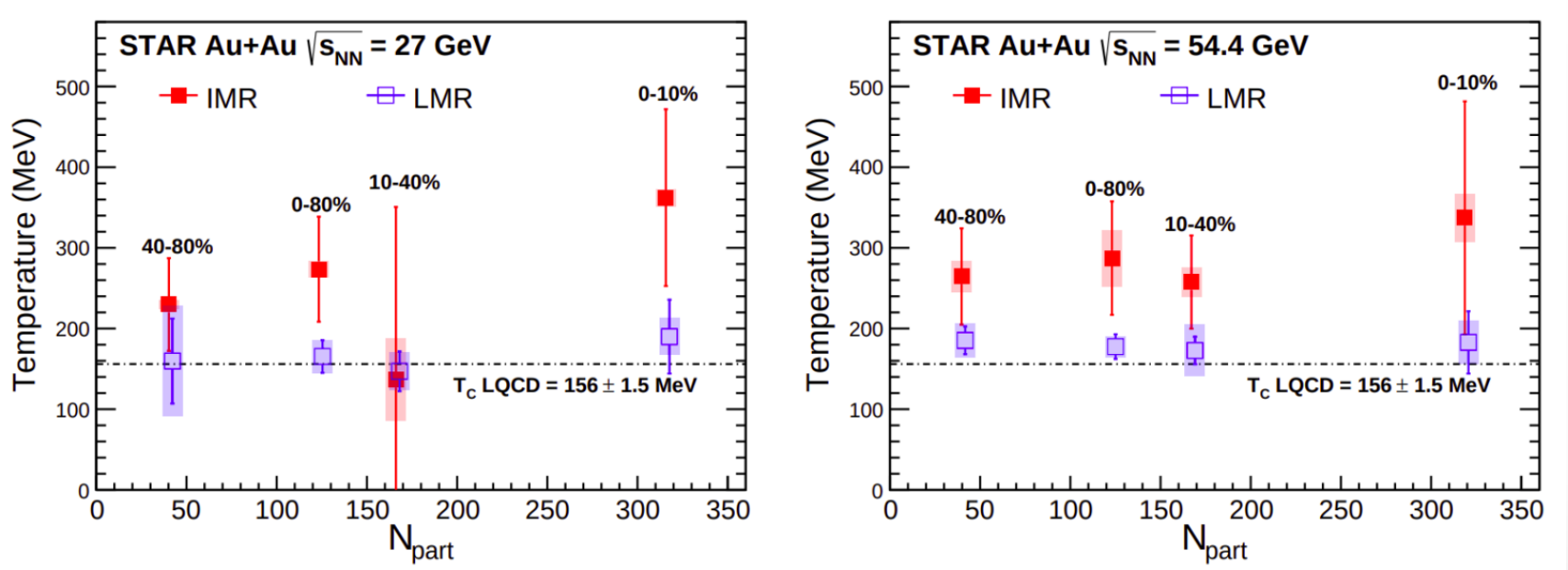


- ✓ STAR (27 GeV):
  - $T_{LMR} \approx 165 \pm 20 \pm 21$ MeV
  - $T_{IMR} \approx 274 \pm 65 \pm 10$ MeV
- ✓ STAR (54.4 GeV):
  - $T_{LMR} \approx 178 \pm 15 \pm 13$ MeV
  - $T_{IMR} \approx 287 \pm 70 \pm 34$ MeV
- ✓ NA60 (17.3 GeV):
  - $T_{LMR} \approx 172 \pm 6$ MeV
  - $T_{IMR} \approx 245 \pm 17$ MeV
- ✓ HADES (2.4 GeV):
  - $T \approx 72$ MeV (hadronic)

- Two distinct temperature regimes: LMR (hadronic) and IMR (QGP)
- T_{LMR} temperature matches lattice QCD Tc (~156 MeV) → phase transition region
- T_{IMR} temperature higher → direct evidence of deconfined quarks ($T >> T_c$)

Temperature centrality dependence

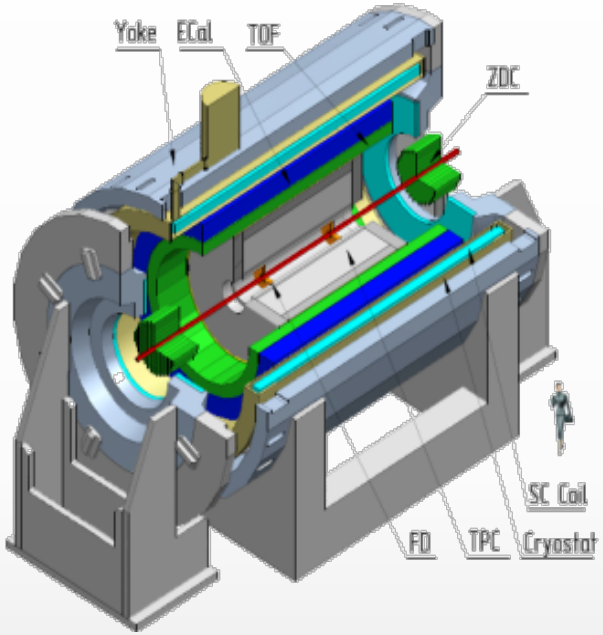
Nature Commun. 16 (2025) 1, 9098



- Nearly constant temperature within uncertainties across centralities\

Multi-Purpose Detector

Stage- I



Length	340 cm
Vessel outer radius	140 cm
Vessel inner radius	27 cm
Default magnetic field	0.5 T
Drift gas mixture	90% Ar+10% CH_4
Maximum event rate	7 kHz ($L = 10^{27}$ cm^{-2}s^{-1})

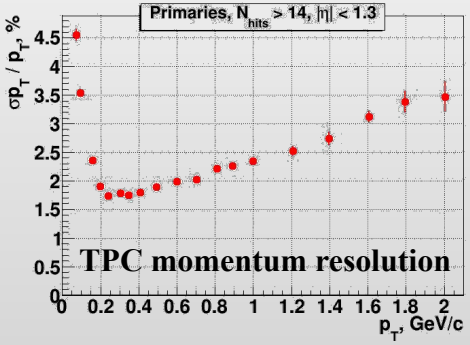
TPC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.6$

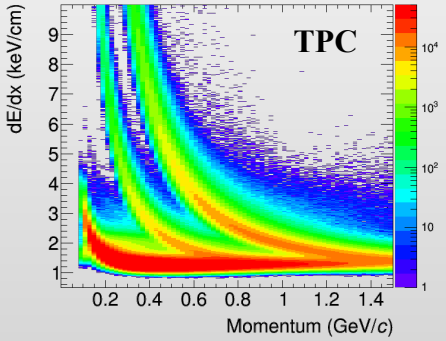
TOF, EMC: $|\Delta\varphi| < 2\pi$, $|\eta| \leq 1.4$

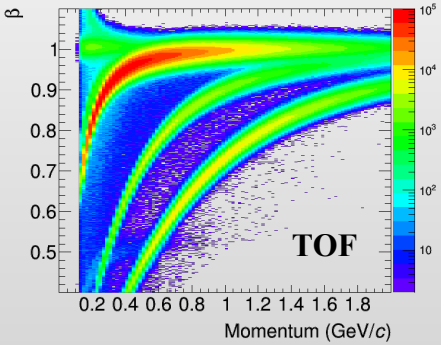
FFD: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$

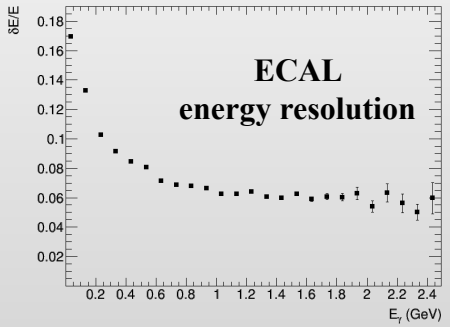
FHCAL: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

Au+Au @ 11 GeV (UrQMD + full chain reconstruction)





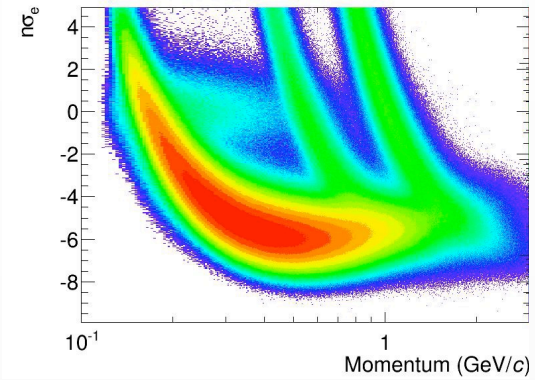




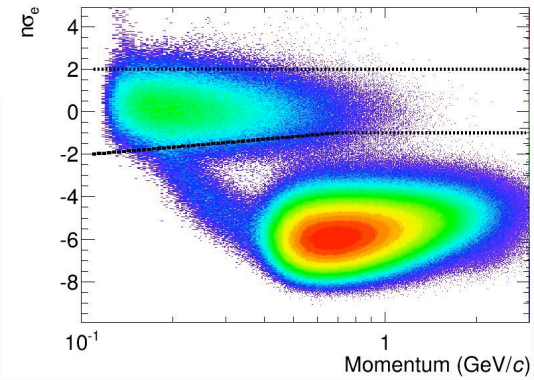
Reconstruction of electrons

- Charged particle tracks are reconstructed in the TPC
- Particles are identified in the TPC (<dE/dx>), TOF (v/*c* ~ 1) and ECAL (E/p ~ 1)

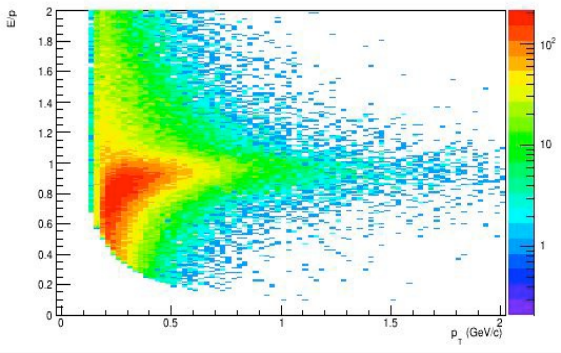
TPC for all tracks



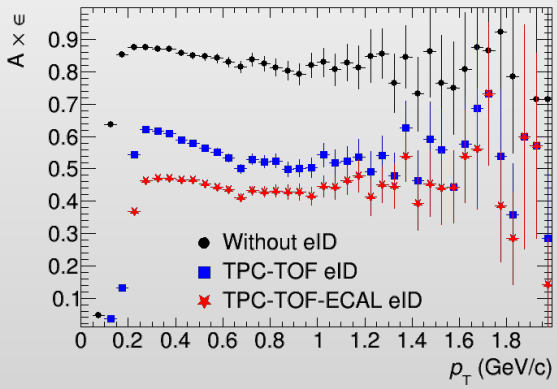
TPC for tracks with eID in TOF

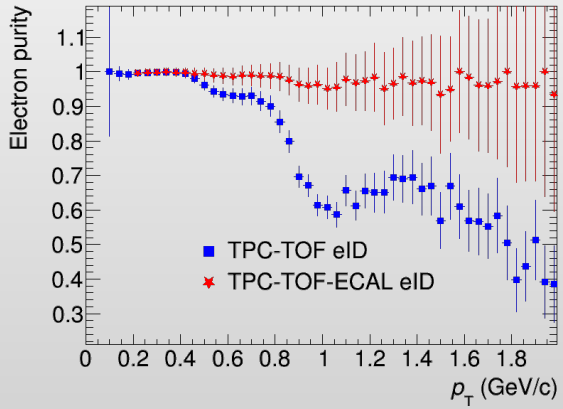


E/p for electron tracks



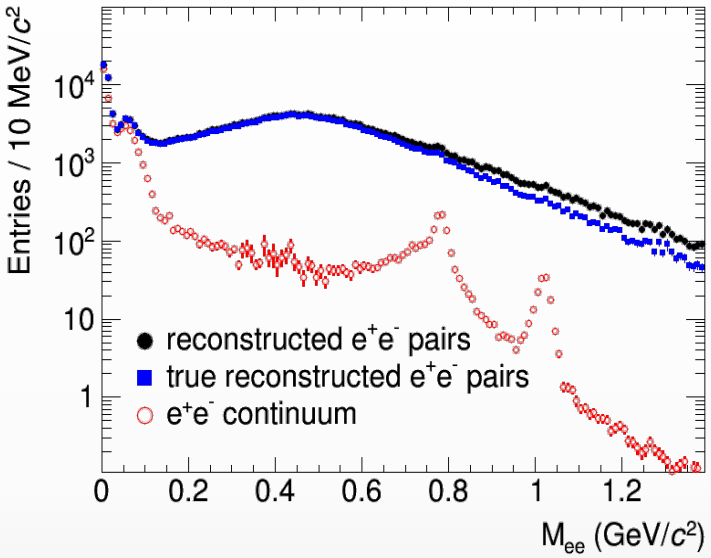
- Each of the detectors provides more efficient electron identification in a limited range of momenta
- Combined use of the TPC-TOF-ECAL signals enhances the probability for a selected track to be true $e^{\pm}$
- Reasonable electron track reconstruction efficiency and electron purity after optimization of selections



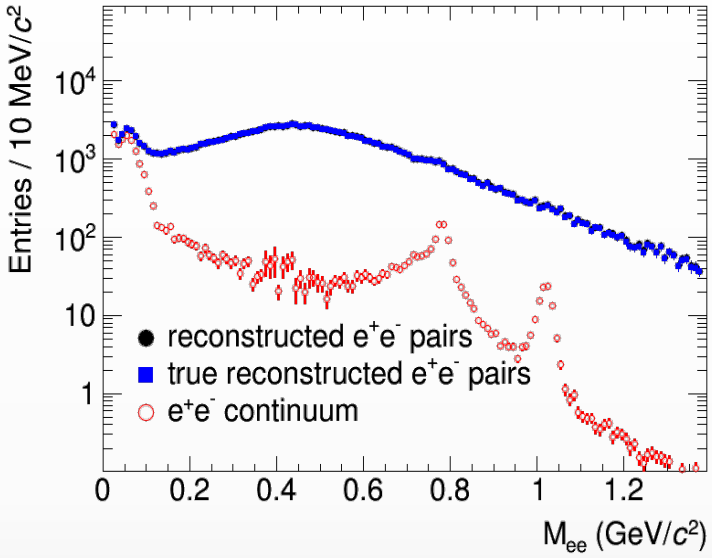


Dielectron continuum in MPD, BiBi@9.2 GeV

eID with TPC/TOF-eID



eID with TPC/TOF/EMC-eID

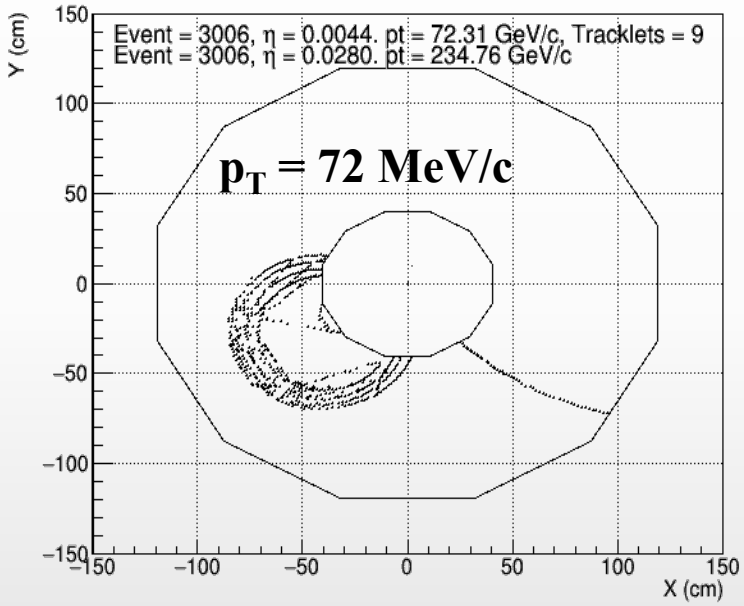


- High purity eID provides a clean sample of e^+e^- pairs with small hadronic contamination
- However, S/B ratio is ~ 1/100 in the mass range 0.2-1.5 GeV/c^2
- Background is dominated by true e^+e^- pairs, where one of the particles is either from π^0/η Dalitz decay or photons conversion (photons are from $\pi^0/\eta \rightarrow \gamma\gamma$ decays)
- Minimization of combinatorial background is required for reliable measurements:
  - ✓ identification of $e^{\pm}$ originating from Dalitz decays and conversion
  - ✓ possible only if both tracks are reconstructed and identified !!!

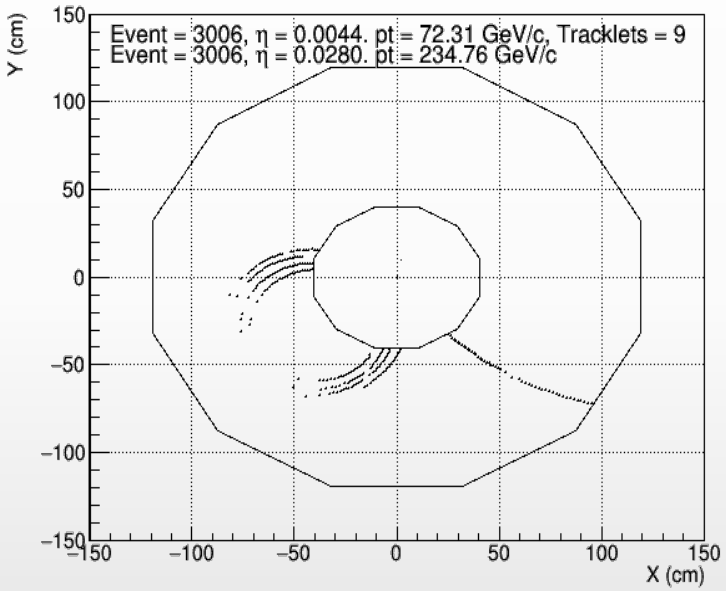
Experimental challenges

- MPD provides high efficiency of electron track reconstruction and identification
- Dielectron measurements suffer from huge combinatorial background, pairs with electrons from Dalitz decays of neutral mesons (π^0, η)

Reconstructed hits



Reconstructed tracks

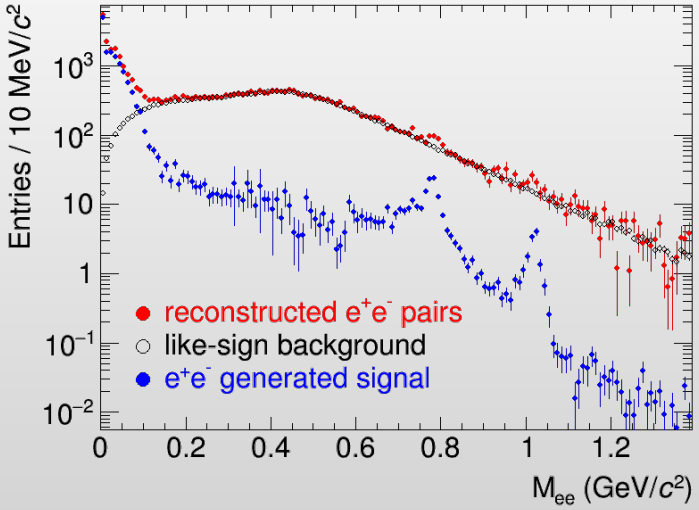


- With the existing track reconstruction algorithms, low p_T tracks are not reconstructed properly even though full hit information is available in the detector for tracks with $p_T > 30$ MeV/c
- Tracks with $p_T < 100$ MeV do not cross the TPC (lower identification probability)

Possible solutions

- Improved reconstruction of low-p_T electron tracks (optimized DCA and track quality selections)
- Tagging and rejection of electrons from conversion → test e^+e^- pairs for consistency with being a conversion pair based on pair topology, mass, pointing angle, DCA, etc.
- Tagging and rejection of electrons from Dalitz decays of $\pi^0 \rightarrow \gamma\, e^+e^-$ → test e^+e^- pairs for consistency with being a pair from the Dalitz decay by mass ($M_{ee} < 100$-150 MeV/c^2)
- Increase efficiency of tagging by selecting electrons in a limited rapidity acceptance ($|y| < 0.5$) and pairing them with electrons reconstructed in the whole detector acceptance with looser e-ID selections
- Multiparametric analysis to optimize signals statistical significance (smaller statistical uncertainties) and increase S/B ratio (decrease systematic uncertainties)

BiBi@9.2 GeV (UrQMD+PHSD), 10 M events→ full event/detector simulation and reconstruction



- S/B (integrated in 0.2-1.5 GeV/c^2) ~ 10%
- Methods to improve S/B ratio with a minimal penalty for pair reconstruction are being matured
- Meaningful measurements for e^+e^- continuum and LVMs would require ~ 100M events, first observations will be possible with ~ 50M events

Conclusions

- Direct photons and dileptoons are excellent probes for studying high-temperature and high-density matter produced in relativistic heavy ion collisions
- Unique probes of deconfinement and CSR (dielectrons), penetrating probes
- Continuous progress in measurements and interpretation of results → temperature measurements
- Interesting prospects in measuring direct photons and dileptoons at low energies: the onset of deconfinement, the onset of CSR effects, first-order phase transition?
- MPD experiment is well equipped to measure production of direct photons and dielectrons