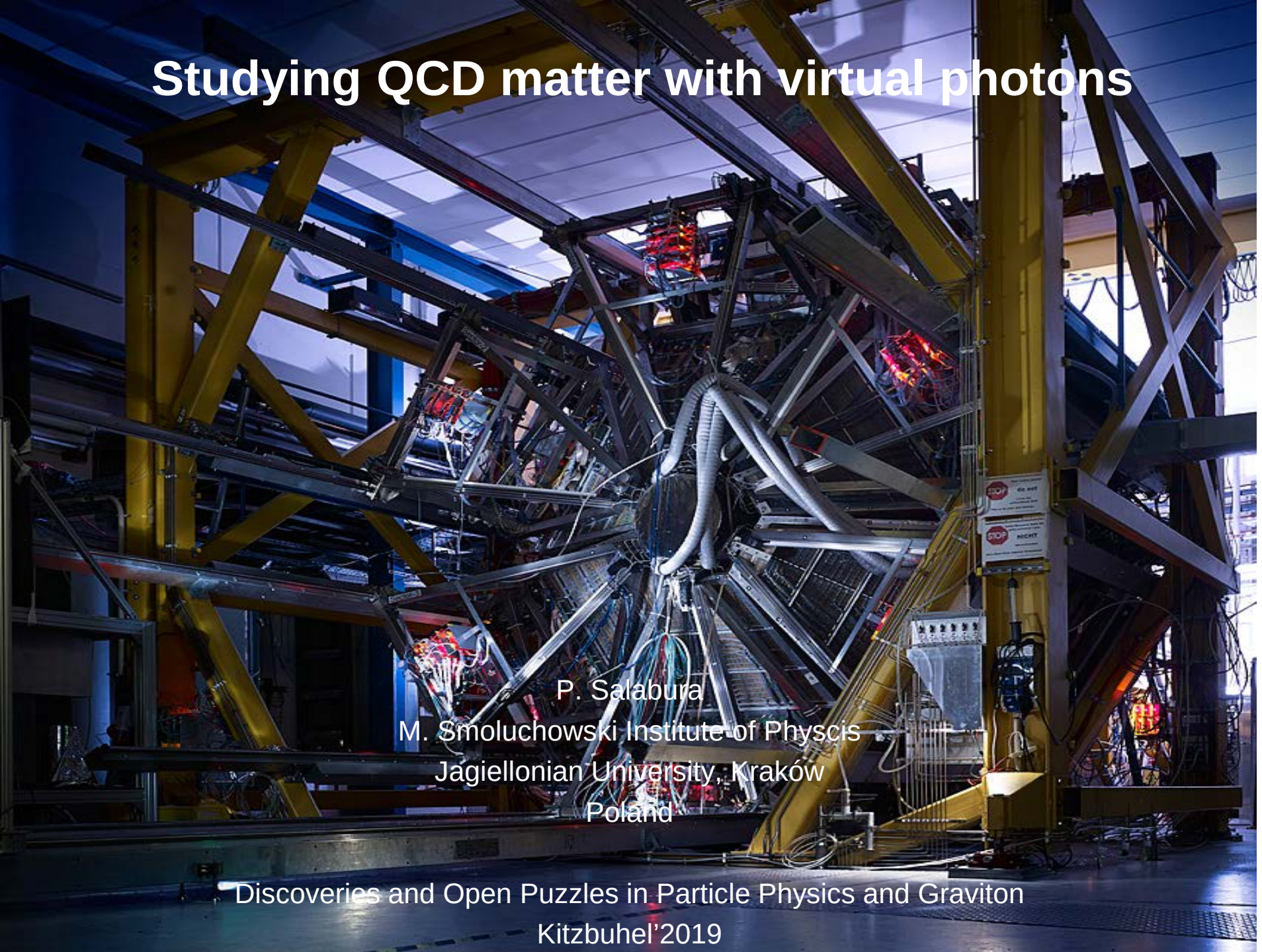
Studying QCD matter with virtual photons



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Discoveries and Open Puzzles in Particle Physics and Graviton
Kitzbuhel'2019

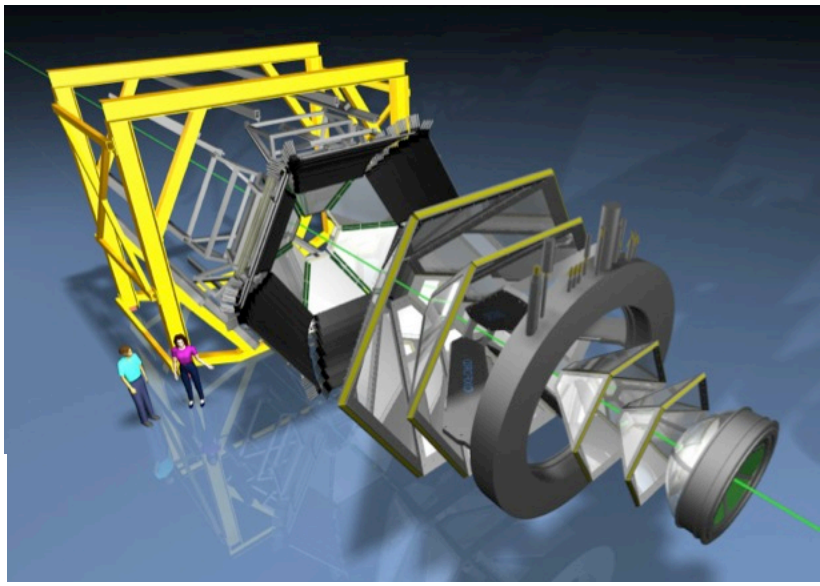
Content

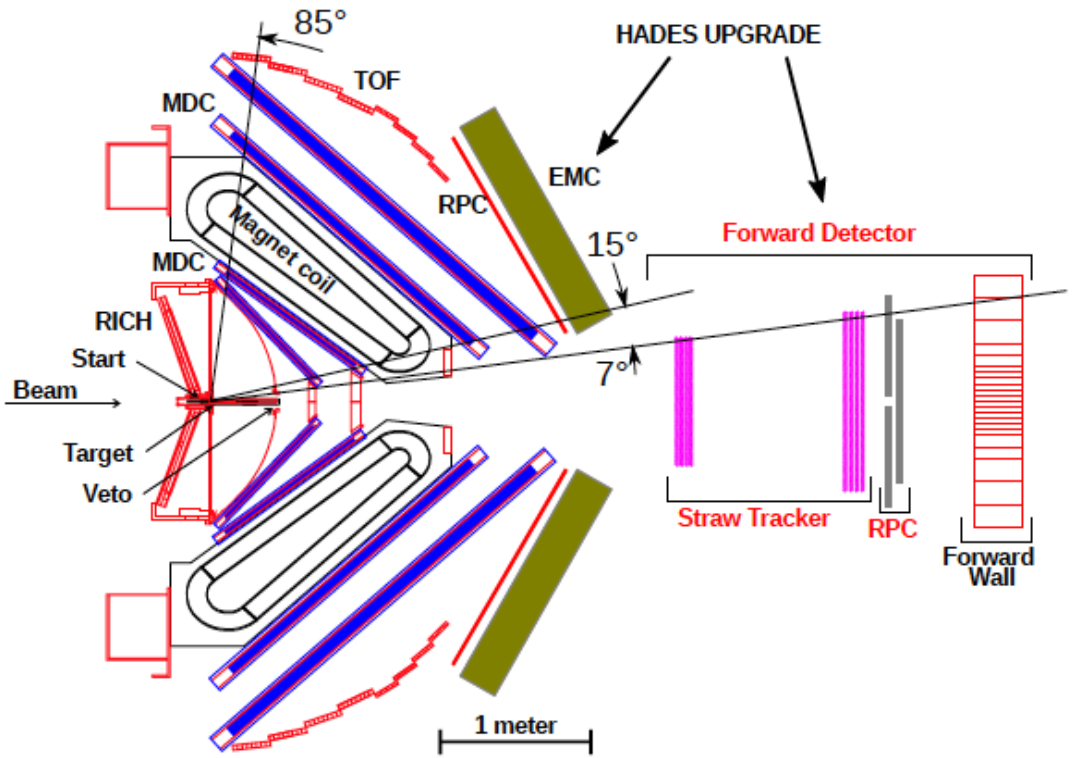
- ✓ HADES experiment at GSI/FAIR
- ✓ Emissivity of QCD matter → in-medium ρ meson spectral function → relation to chiral symmetry restoration
- ✓ Results from HIC
- ✓ Connections to time-like baryon em. transitions
- ✓ Summary & Outlook

High Acceptance Di-Electron Spectrometer

- ✓ Spectrometer with ΔM/M - 2% at ρ/ω @ GSI/FAIR
- ✓ electrons : RICH (hadron blind)
- ✓ hadrons: TOF & dE/dx vs p
- ✓ 2004-2014: HI (A+A √s~2.4-2.6 GeV)

p(d)+ p, p+A √s =2.4-3.0 GeV π+p √s= 1.5 GeV





Upgrade 2018/2019

- New RICH photon det (HADES/CBM) – 2-3 ⊗ e_{eff}
- Forward tracking straws +RPC – Λ/Ξrec. in pp/pA (HADES/PANDA)
- el. Calorimiter (lead glass)- neutrals
- Planned: 200 kHz DAQ , 10⊗ count rate increase

GSI

SIS 18

U^{73+} 1.0 GeV/u 10^9 ions/s
Ni^{26+} 2.0 GeV/u 10^{10}
protons 4.5 GeV 2.8×10^{13}/s
Secondary pion beam 0.5-2 GeV/c

FAIR

SIS 100

Au 8-10 GeV/u 10^{12} ions/s
protons 30 GeV 2.8×10^{13}/s

Secondary beams

Radioctive beams 1.5 GeV/u (Super FRS)
anty-protons

Storage rings

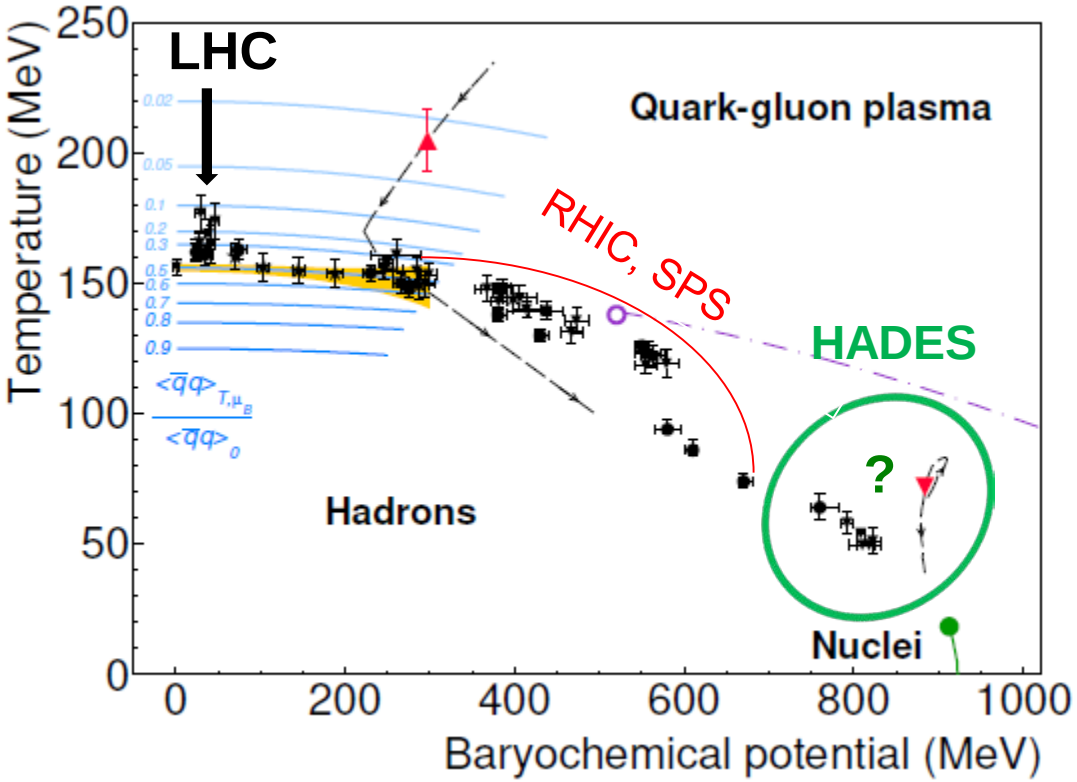
Precision experiments in Atomic Physics
HESR: Anty-protons 1.5- 15 GeV/c – exp PANDA

Phase0: 2018-2025 at SIS18 !

HADES: Ag+Ag @1.65 AGeV(2019)
π+p, π+A, p+p, p+A

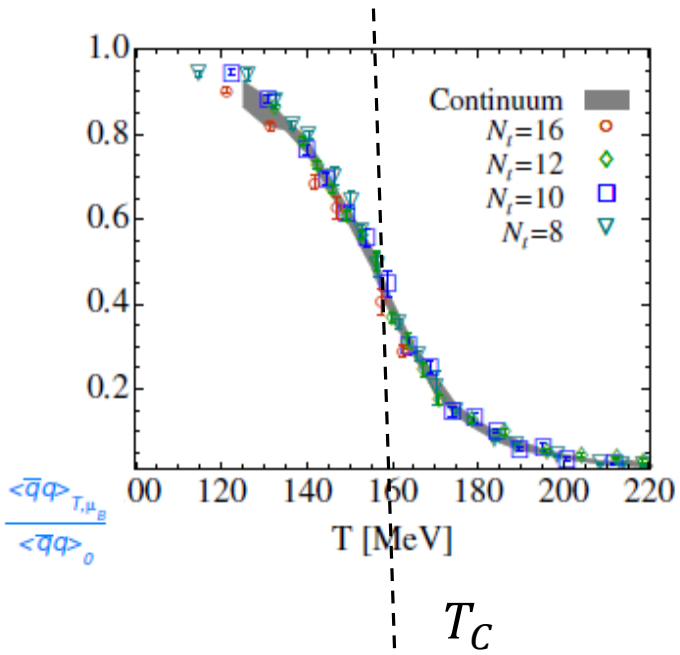
Phase1: > 2025 at SIS100

Various faces of QCD: phase diagram



Lattice QCD S. Borsnyi JHEP'2010

Order par:. **Chiral symmetry restoration**

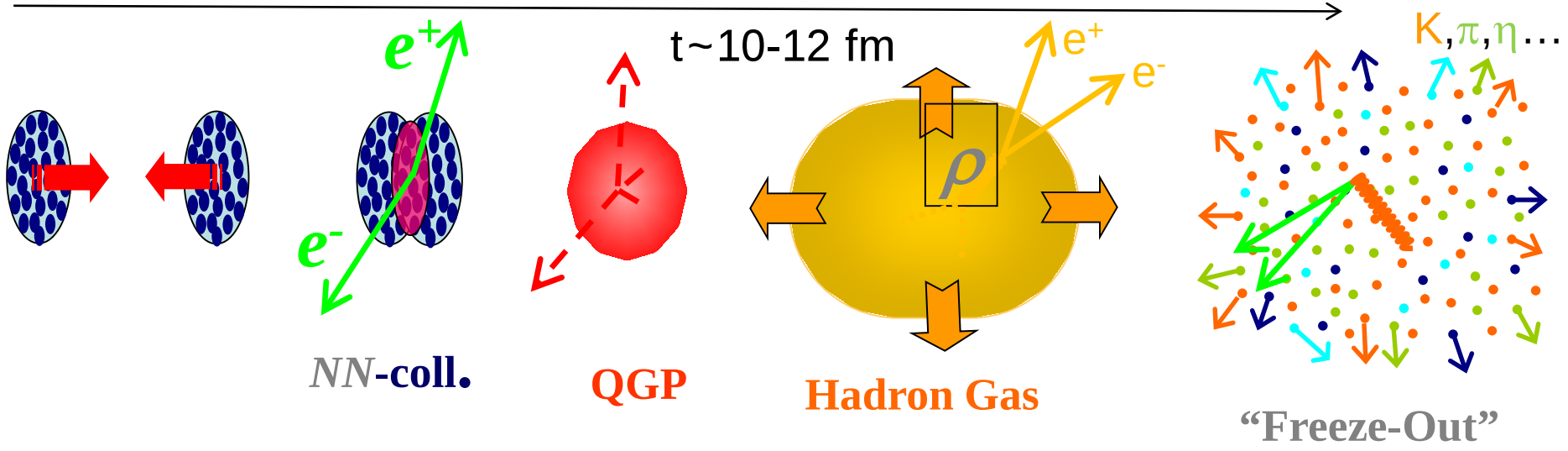


❑ HADES: Primary goal: (first!) measurement of Low Mass (LM) dileptons (e+e-) at high μ_B

❑ Complementary to studies with URHIC (LHC, RHIC, SPS) and new Futue high μ_B facilities NICA, CBM@FAIR

- Substantial depletion od quark condensate close to T_c
- At high μ_B model calculations predict dropping with density

Phases of Heavy Ion collision



Time

- eary phase : quark-quark annihilation
- partonic phase (Quark Gluon Plasma)

} If energy high enough..

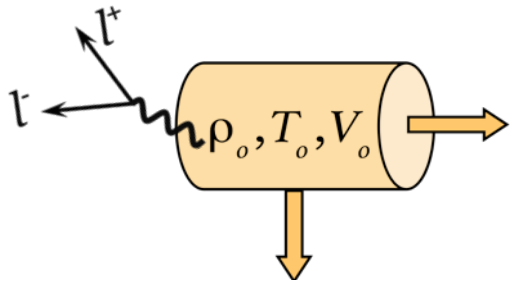
- thermal hadron gas ρ:
- chemical „freeze-out” : particle compositions fixed

„long lived e+,e- sources: $\pi^0 \rightarrow e+e-\gamma$, $\eta \rightarrow e+e-\gamma$ (dalitz) $\phi/\omega \rightarrow \pi e+e-$, $D \rightarrow eX$
Decay outside fireball : their contribution can be subtracted („hadronic cocktail”) based on measured hadron spectra

- excess radiation : total – hadronic cocktail→ excess radiation

Emissivity of QCD matter with dileptons

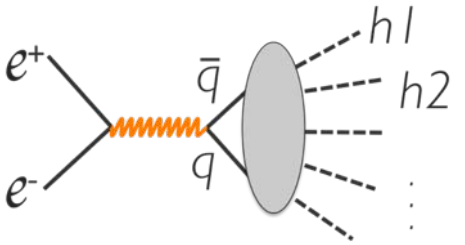
$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

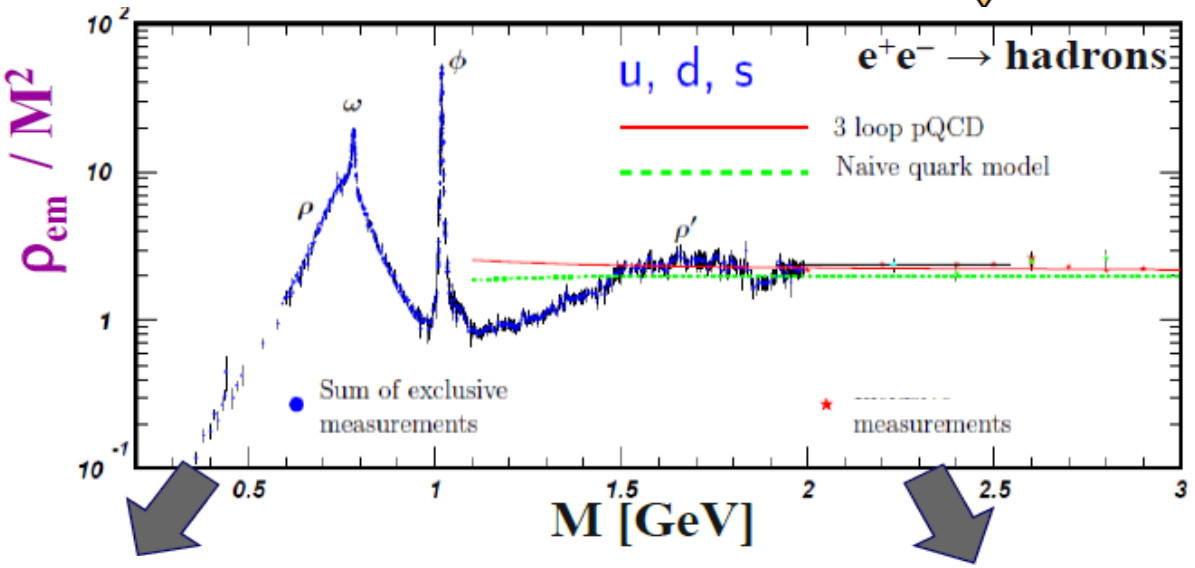


McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

In Vaccuum

$\Im m\Pi^{em}$





Low mass Vector Mesons

• $q\bar{q}$ Continuum

- dileptons: not disturbed by finite state interactions !
- like photons but (!) carry mass :

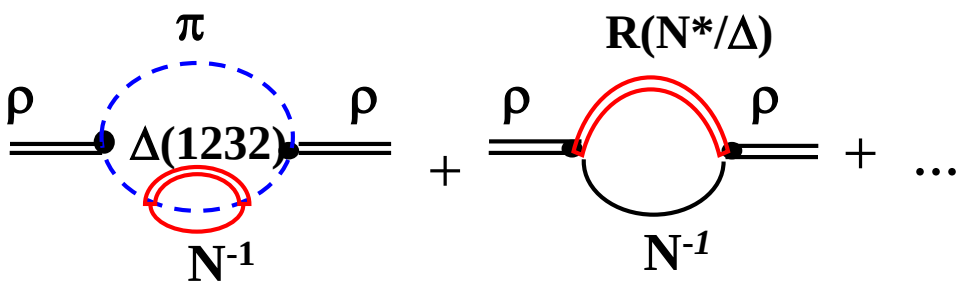
  $q^2 > 1.5$ GeV $\bar{q}q$ radiation pQCD ($\Im m\Pi_{em}$ is flat) → T (thermometer)

- $\Im m\,\Pi_{em}$: *$q^2 < 1$ GeV - in- medium VM (ρ) spectral functions*

In medium ρ spectral function

$$A_\rho(M) = -\frac{2\,Im\Sigma_\rho(M)}{[M^2 - m_\rho^2 - \mathrm{Re}\,\Sigma_\rho(M)]^2 + [Im\Sigma_\rho(M)]^2}$$

In Medium: hadronic loops

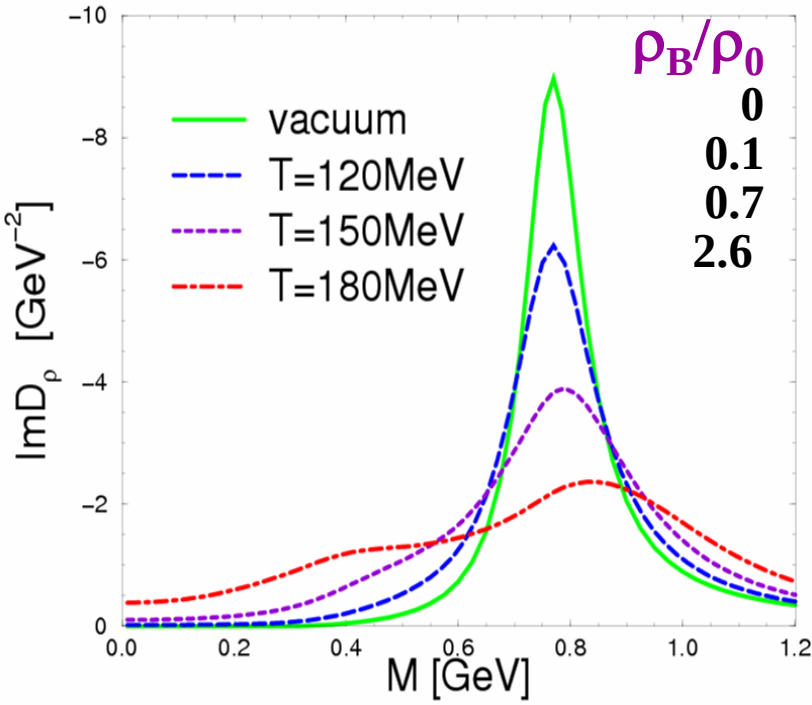


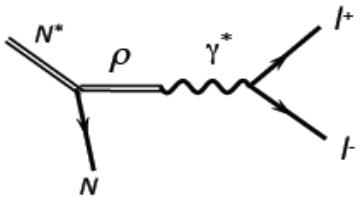
dominant role of ρ-R couplings –

Relies on input from elementary processes

γN, πN→ρN, ρ→e+e-

Rapp, Wambach, Adv. Nucl. Phys. A25 (2000)1





Important one (never measured)

R→Ne+e- (Dalitz decays)

Vector Meson Dominance ?

See later in the talk..

ρ/a_1 -VM : connection to χSR

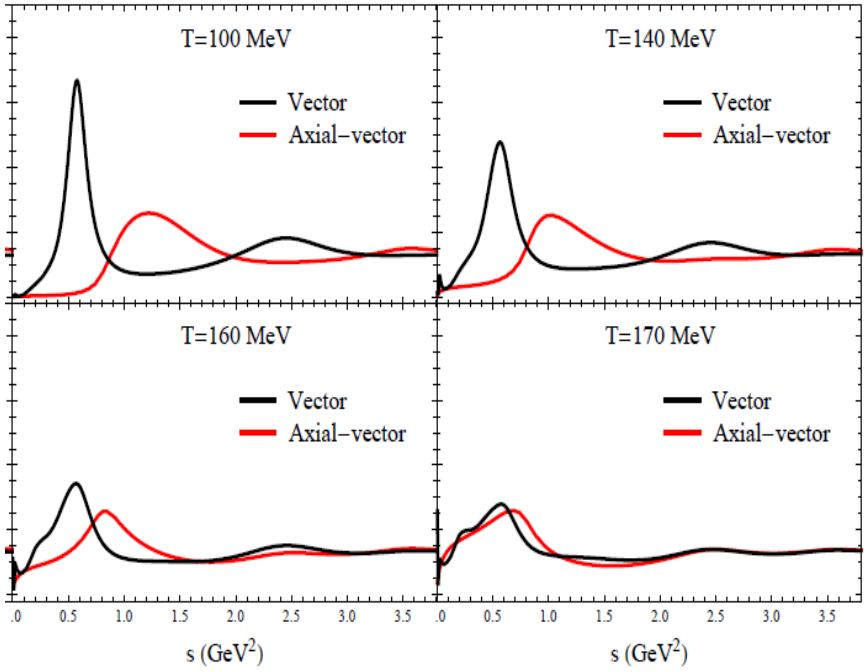
Weinberg Sum rules

[Weinberg '67, Das et al '67; Kapusta+Shuryak '94]

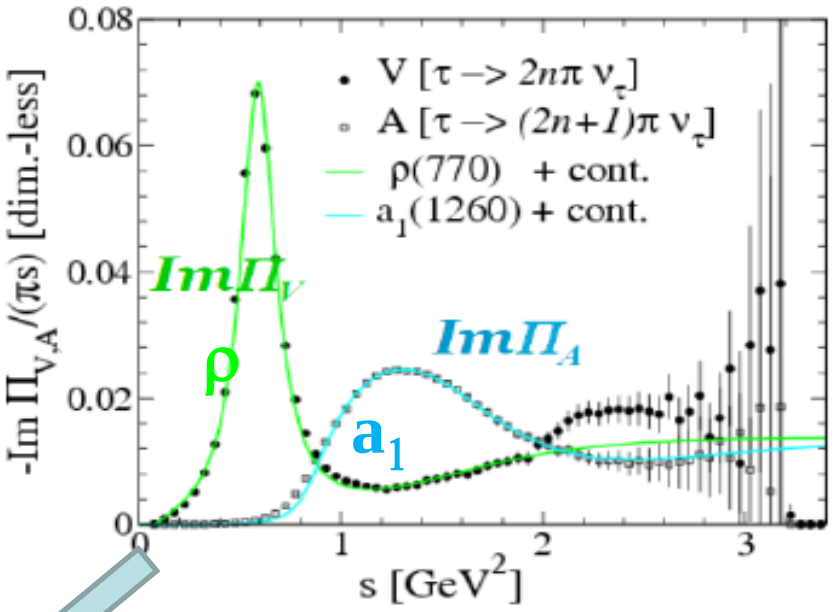
$$\int ds \frac{1}{s}(\rho_V - \rho_A) = f_\pi^2$$

$$\int ds\,(\rho_V - \rho_A) = -m_q \langle \bar{q}q \rangle$$

$$\int ds\, s\,(\rho_V - \rho_A) = c\alpha_s \langle (\bar{q}q)^2 \rangle$$



ρ/a_1 splitting in vaccuum



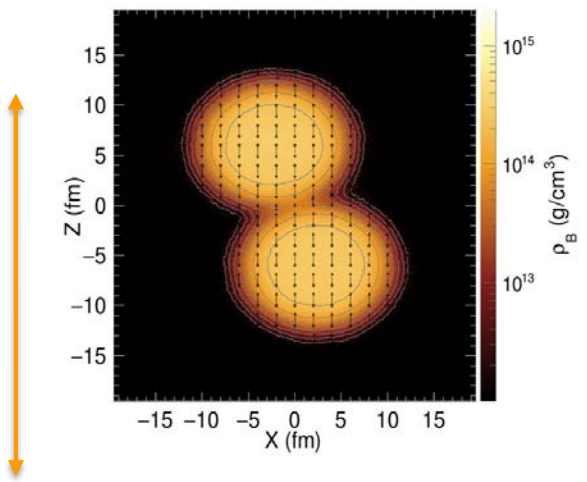
- ❑ evolution of ρ SF from microscopic model Rapp& Wambach
- ❑ a_1 SF predicted from QCD constraints (sum rules) and lattice data on $< q\bar{q} >$ vs T

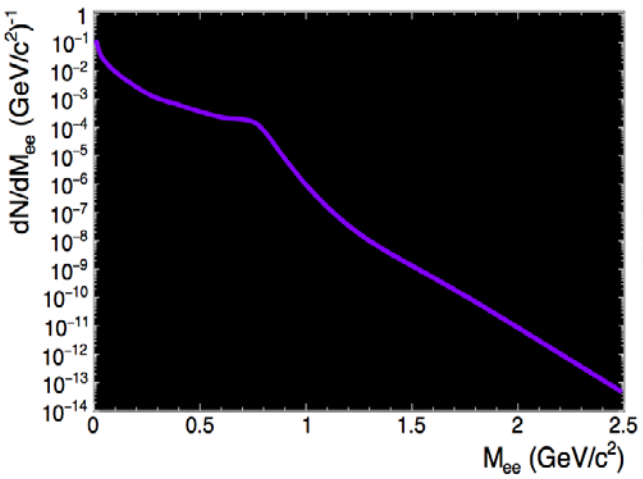
Merging of ρ/a_1 SF at T ~ T_c (calculations for μ_b =0)

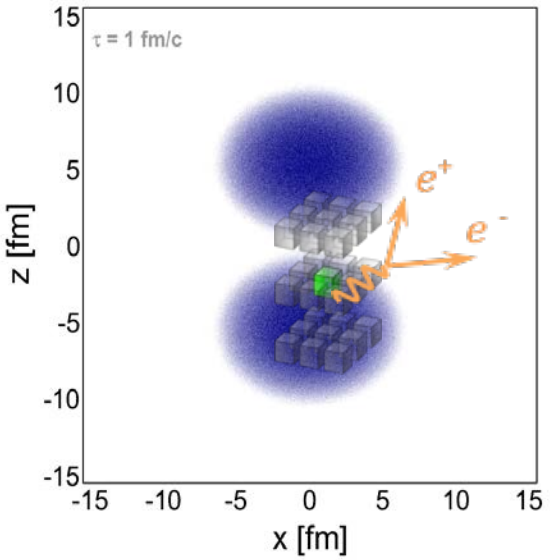
Hohler and Rapp Phys.Lett. B731 (2014)

Dielepton emission in HIC

HI collisions: total emission rate needs integration over full collision time (T,μ_B)







Compilation F. Seck and T. Galatyuk

„coarsed grained approach"

Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131

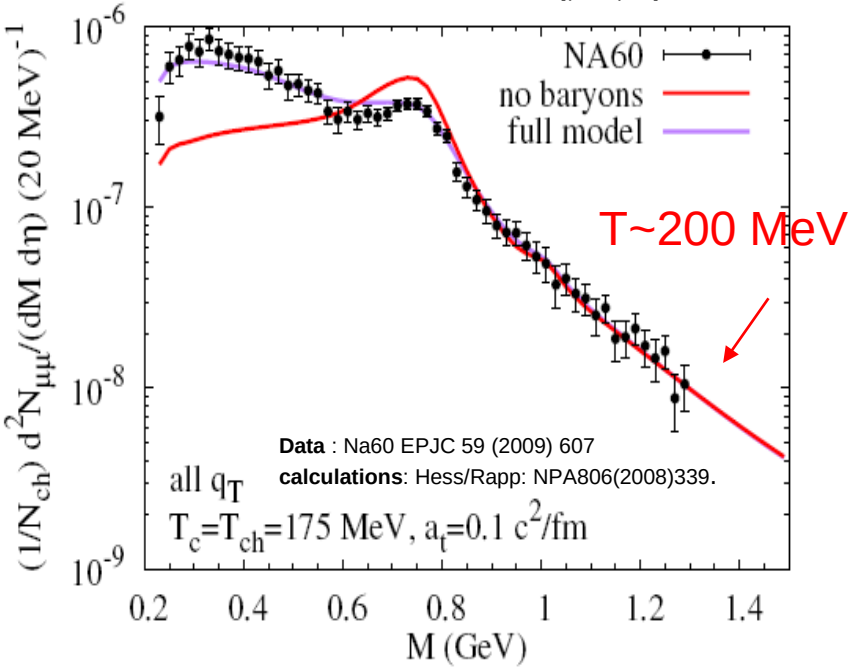
- ✓ energy (ε) and baryon densities (ρ_b) obtained in small cells ($\Delta x,\Delta t$ ~0.8fm,0.2 fm/c) in local rest frames with vanishing net baryon current
- ✓ EOS (hadron gas, QGP-lattice) used to relate ε with (T, ρ_B)
- ✓ Apply emissivity formula with in medium $\Im m\Pi_{em}$

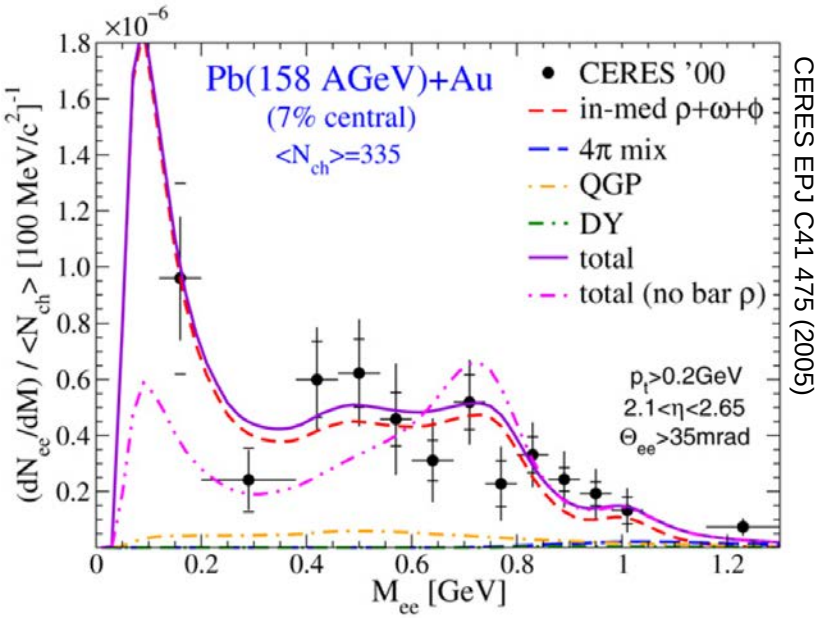
Results from HIC
(highlights)

Dilepton exess spectra from SPS/RHIC

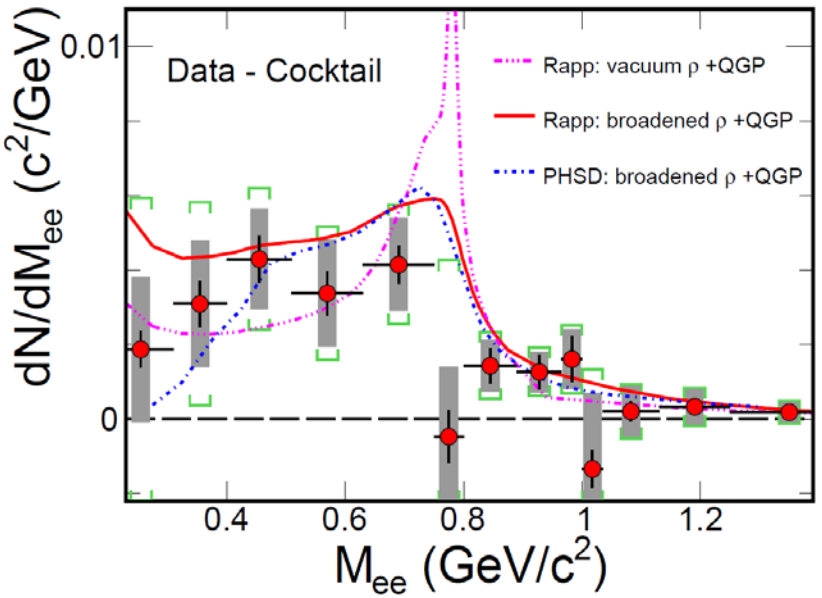
Na60 @ SPS In+In (μ+μ-)

√s=17.3 GeV





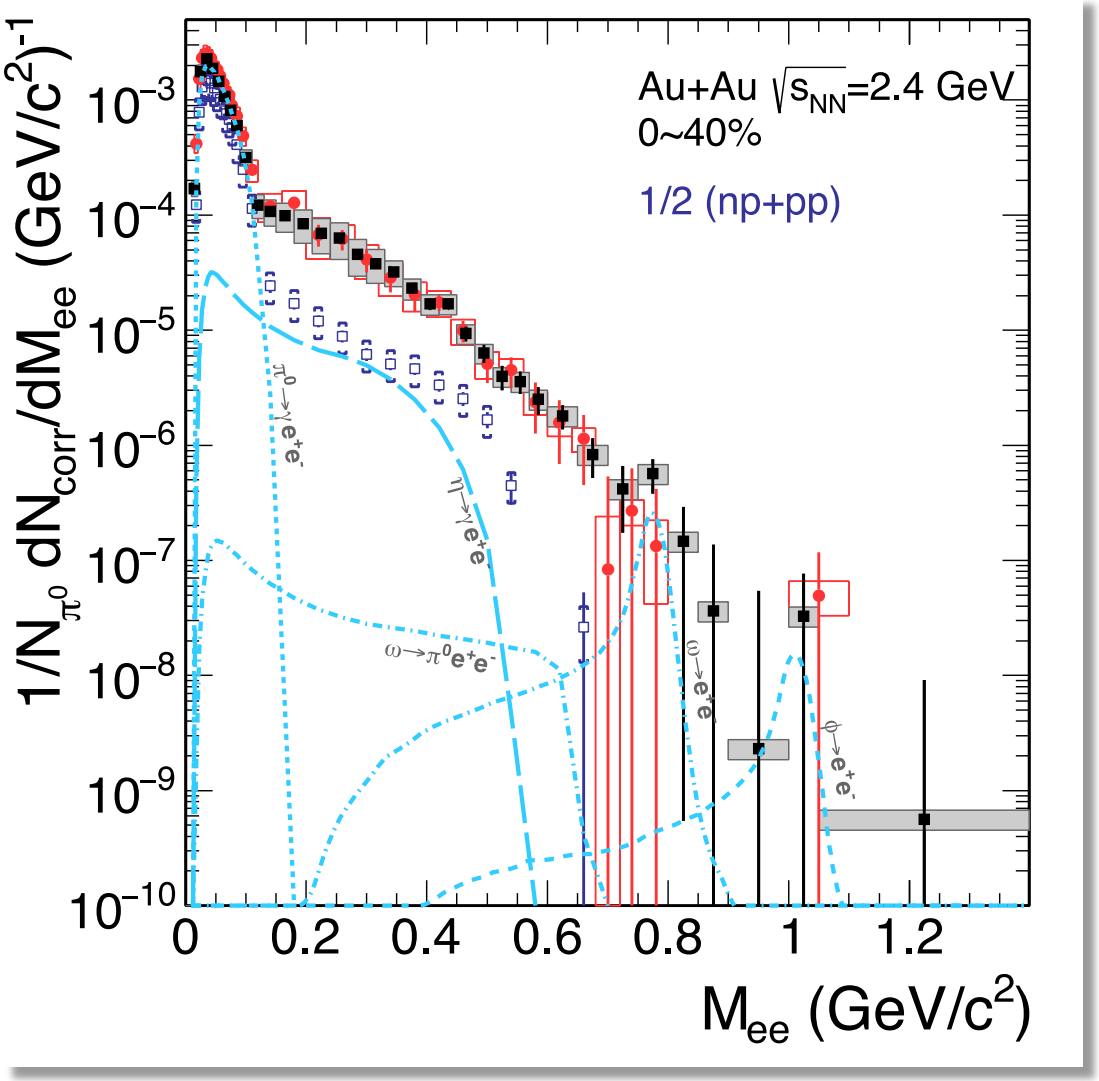
STAR **√s=200 GeV** PRC92 (2015)



- LMR dominated by thermal radiation from ρ at T~T_c (hadronic phase!)
- „Melting" of ρ : **baryon-ρ interactions**
- IMR: T~ 200 MeV - <T> of the early phase (QGP)

Dielectron pairs from Au+Au

HADES: Nature Phys 2019



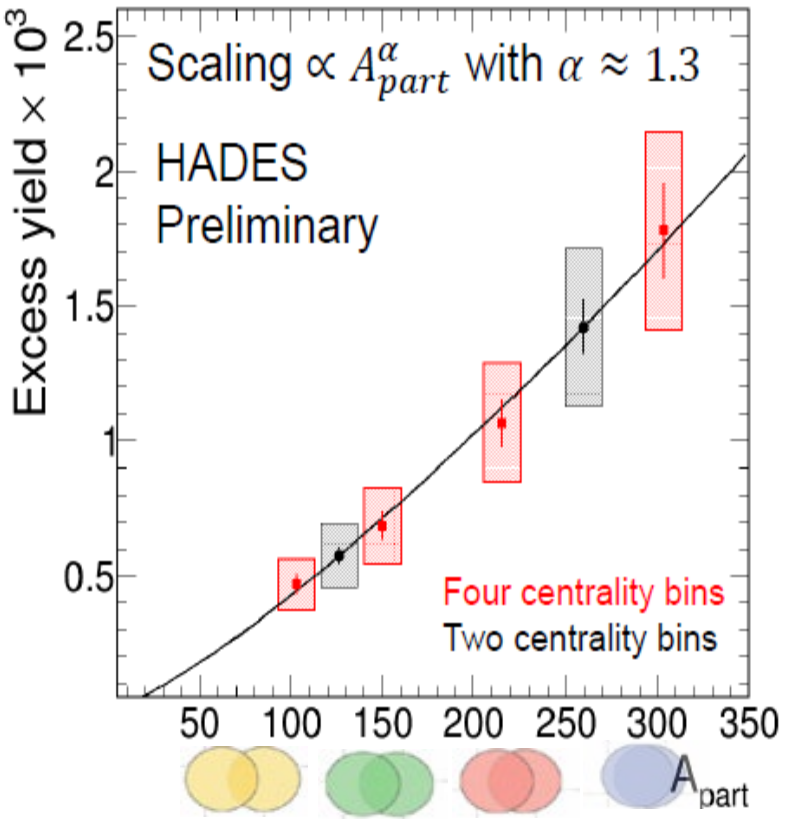
- LM region

Clear excess above **mesonic** (η,ω) and **baryonic sources** (NN bremsstrahlung + $\Delta \rightarrow$Ne+e-) measured in refer.

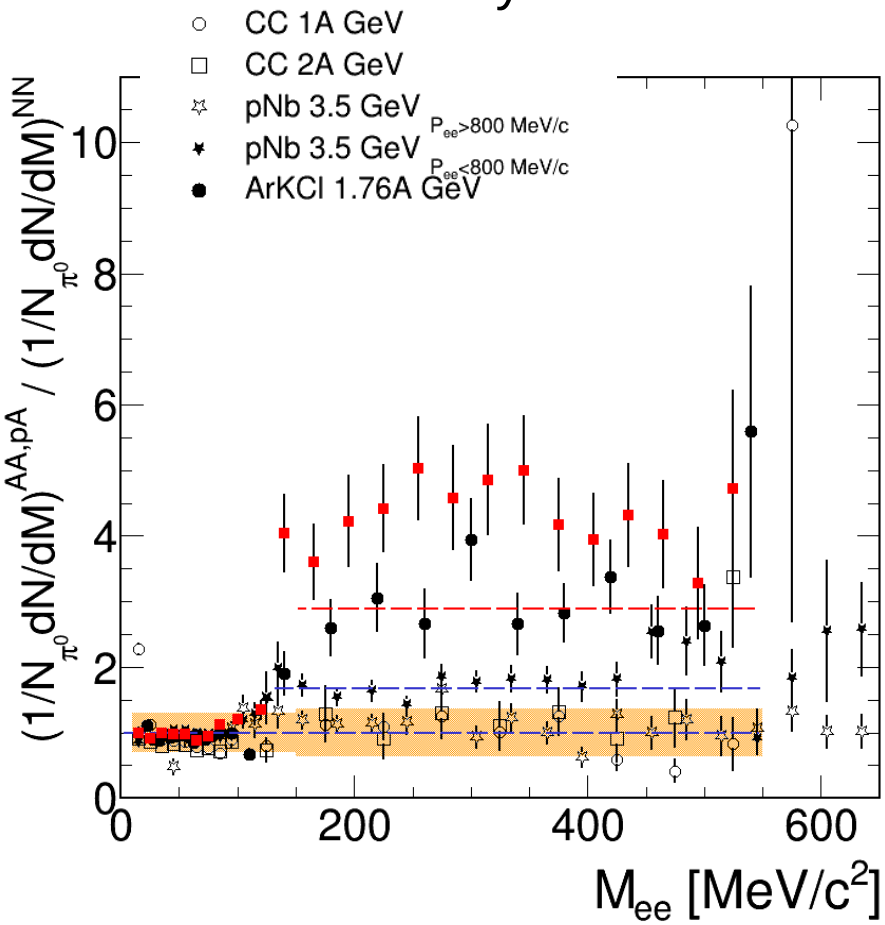
NN reactions scaled by A_{part} (numer of pions)

Onset of the excess radiation

centrality



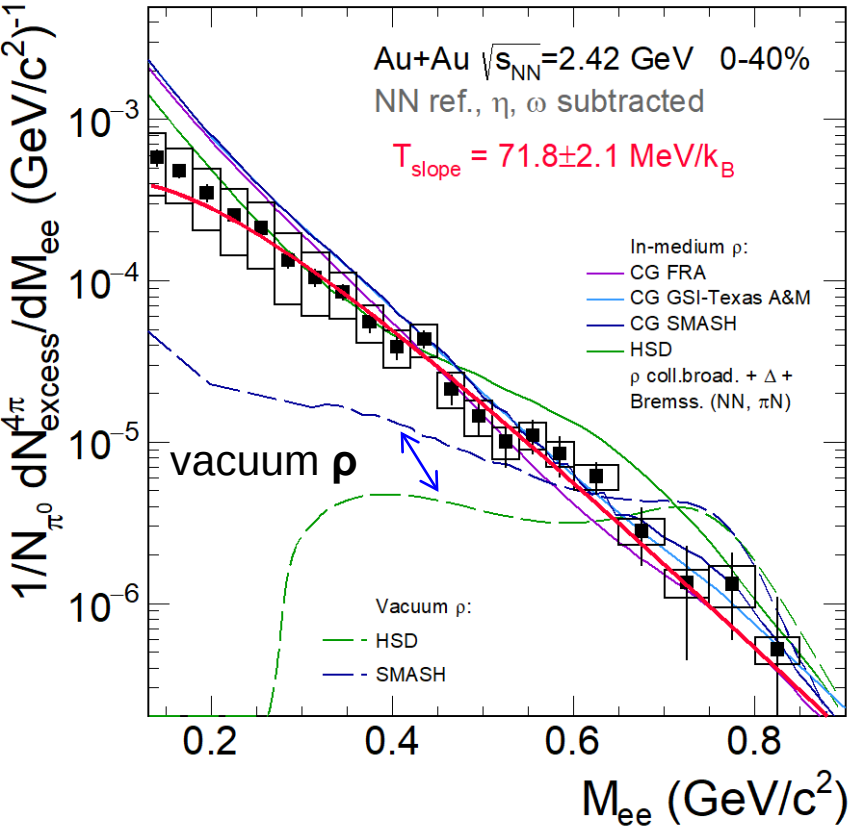
system size



- Strong excess (~V ⊗ τ_{coll} ~A⊗$A^{1/3}$) due to chronometer of the collision time

HADES Au+Au @ √s = 2.4 GeV

Accepted for pub. in Nature Phys. 2019



CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1
HSD: Phys. Rev. C 87, 064907 (2013)

- Successful description with Coarse-Grained approach + emissivity formula

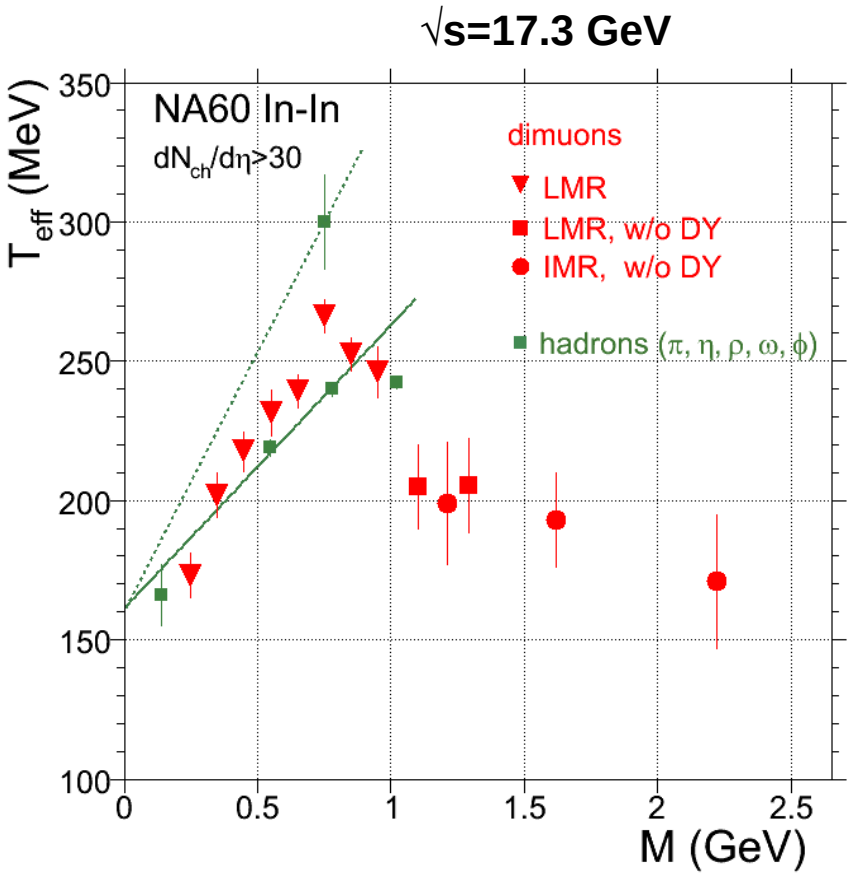
Dileptons as thermometer

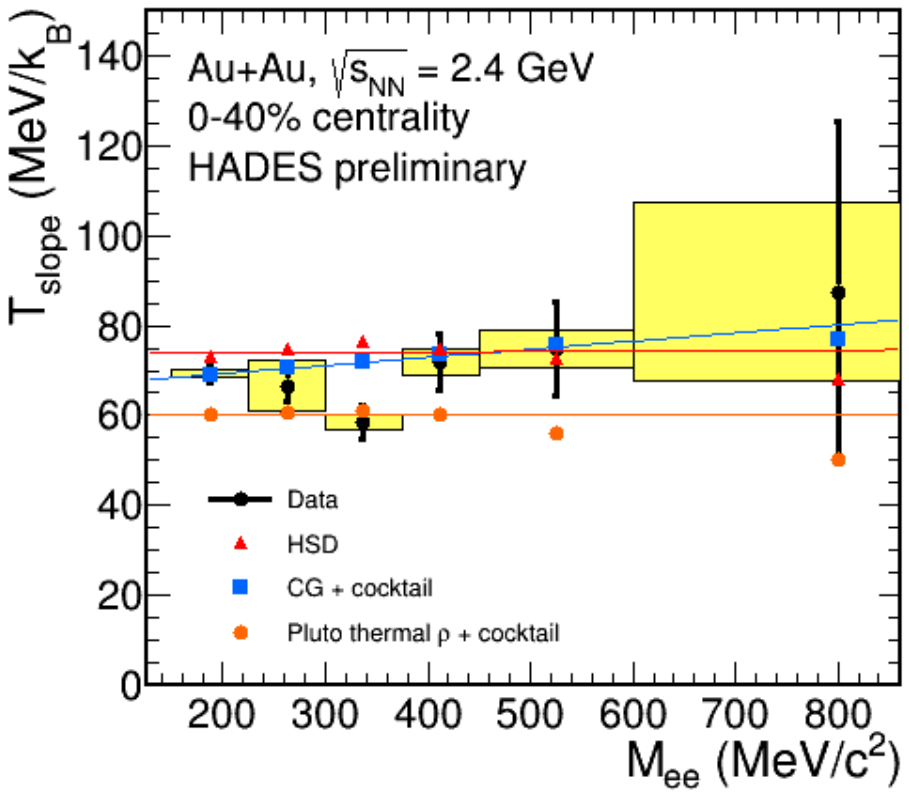
- Mass spectrum falls exponentially → "Planck-like"
- Fit $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$ in range M=0.2-0.8 GeV/c^2
- $\langle T \rangle_{\text{emitting source}}$ = 72 ± 2 MeV/k_B

- Strong melting of ρ meson
- In agreement with microscopic model of Rapp & Wambach (interactions with baryons !)
- Same model describes also RHIC(STAR), SPS (CERES, Na60 data)

Robust understanding across QCD phase diagram

Thermomether: fit to m_T spectra





- Rise in LMR 'Hubble' like expansion
  Initial linear rise of Teff with M
  $T_{eff} \sim T_f + M \langle v_T \rangle^2$ $v_T \sim 0.5c$

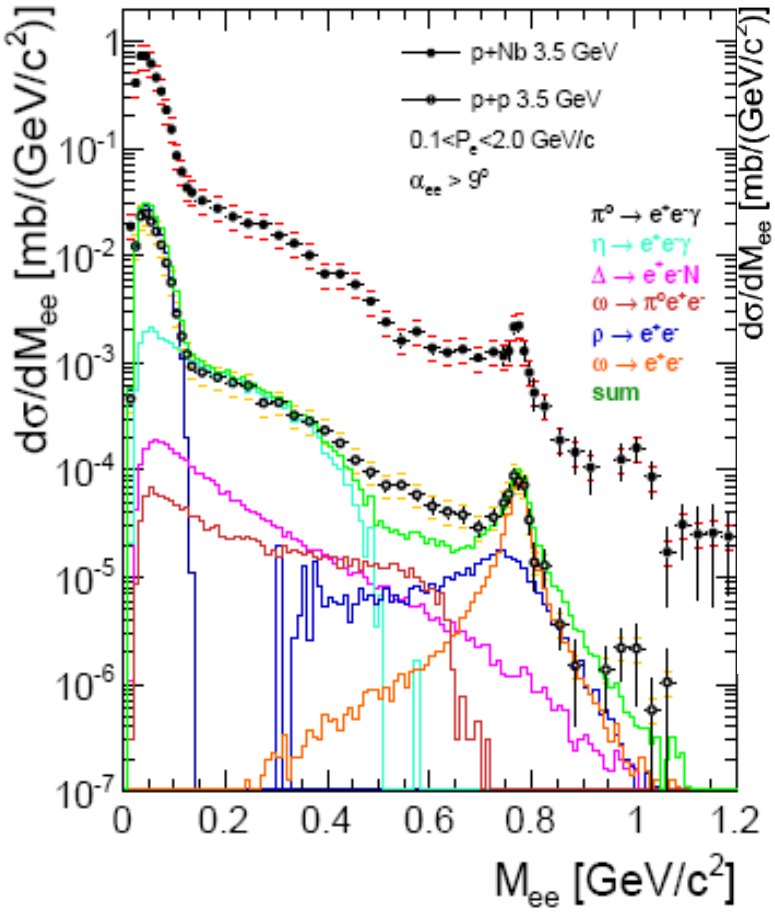
- Drop at 1 GeV signals sudden transition to a low-flow, i.e. an early source af partonic origin (QGP)

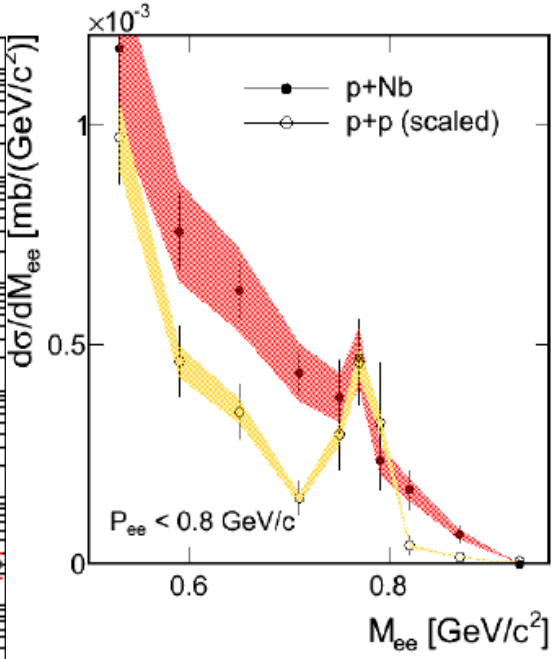
- Almost constant slope at low energy
  smaller flow,
  low mass - longer emission (T↓) + flow

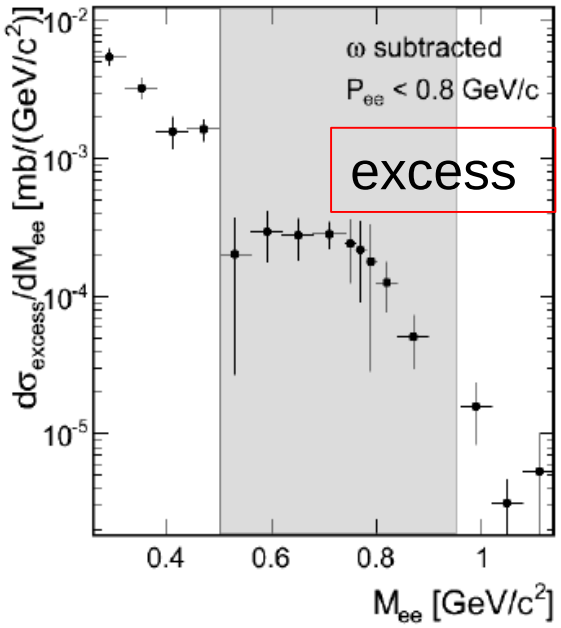
Cold matter p+p @ √s=3.1 GeV vs p+Nb

data: HADES PL715 (2012) 304

„slow sources" $p_{e+e-} < 0.8$ GeV/c







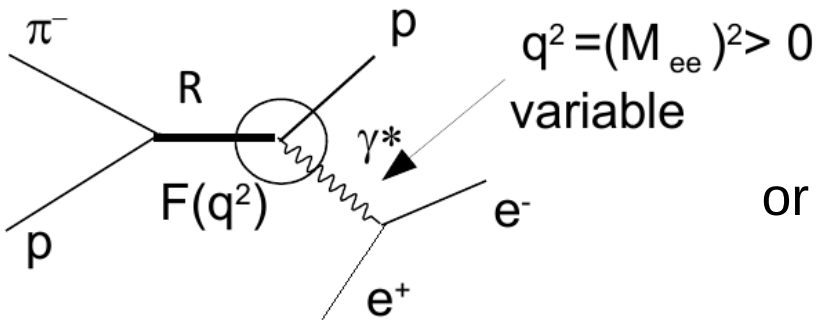
pp data scaled by „A_{part}" scaling

$$R_{pA} = \frac{d\sigma^{pNb}/dp}{d\sigma^{pp}/dp} \times \frac{\langle A^{pp}_{part}\rangle}{\langle A^{pNb}_{part}\rangle} \times \frac{\sigma^{pp}_{reaction}}{\sigma^{pNb}_{reaction}}.$$

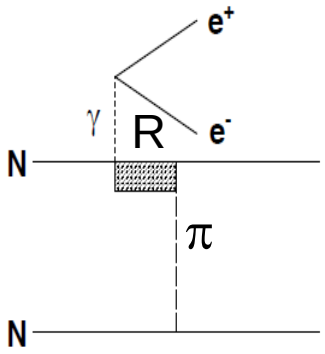
Nuclear modification factor

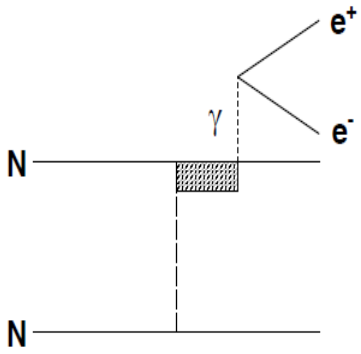
- p+p cockail : based on known sources π^0 /η/ ω/ ρ , Δ
- remarkable difference between p+p, p+A : reduction of ω, broadenning of ρ

em. decays of baryon resonances with π(p)-p



or

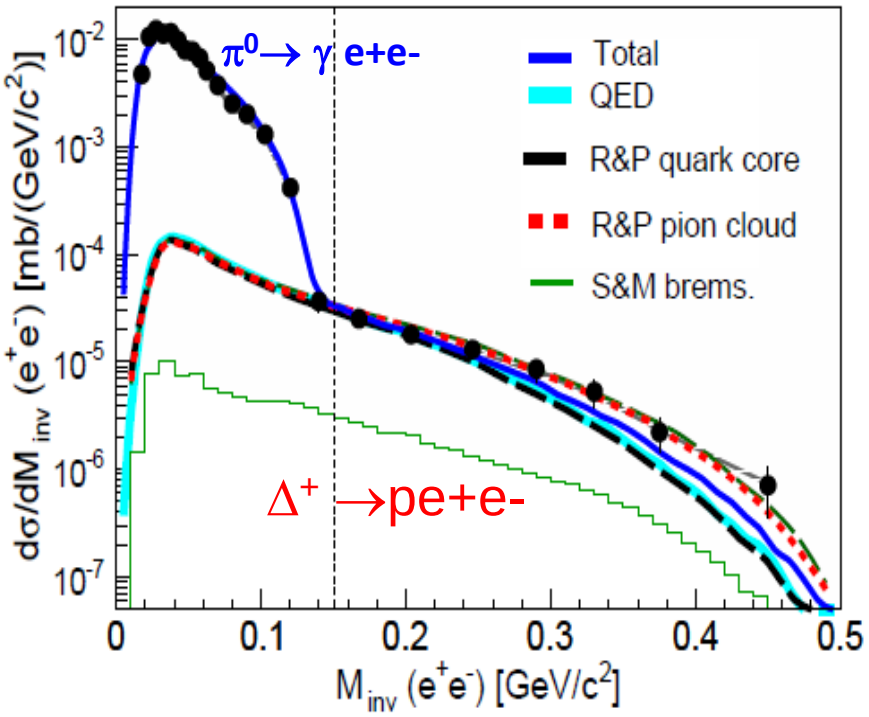




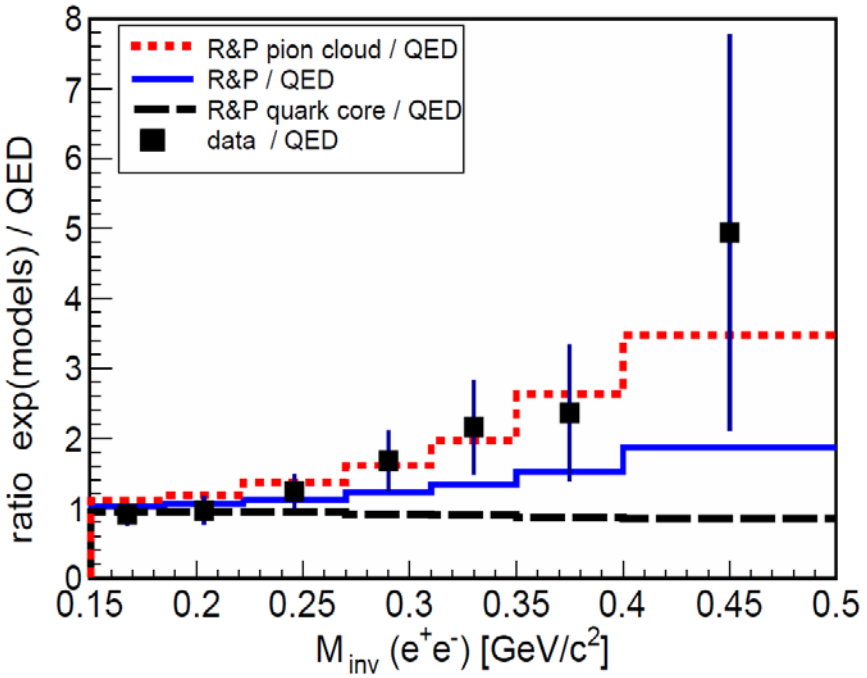
$F(q^2)\ - em. Transition\ Form - Factors$

$pp \rightarrow ppe^+e^-$

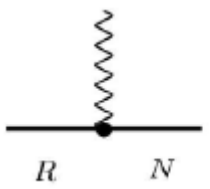
HADES Phys. Rev. C95 (2017) no.6, 065205)



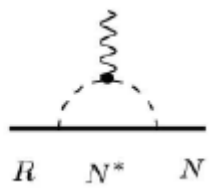
$M_{e+e-} > M_\pi$



Quark core



pion cloud

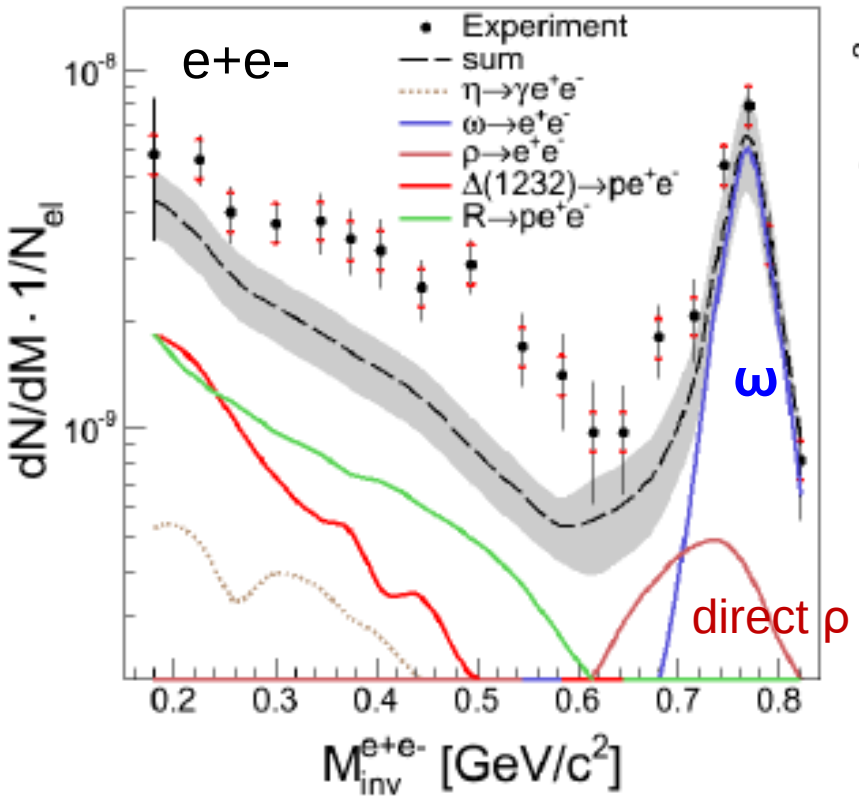


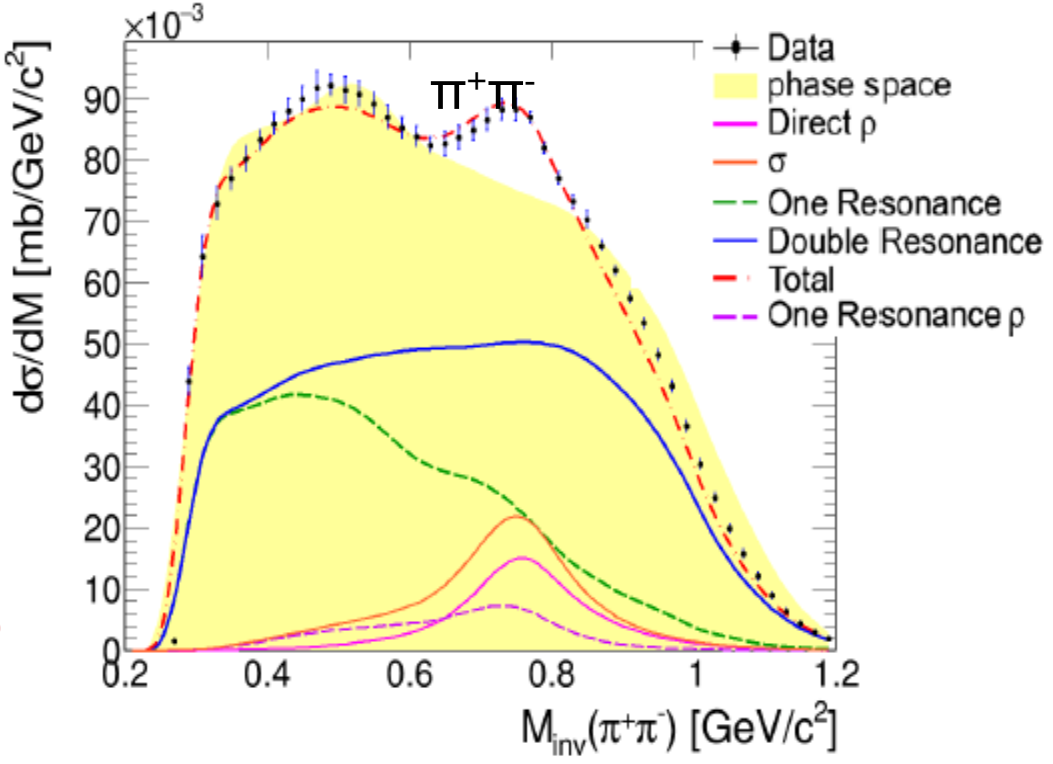
❑ **BR ($\Delta \rightarrow$pe+e-)= 4.19 $10^{-5} \pm 0.62$ (sys) ± 0.32(stat)**
(First measurement PDG entry)

❑ Good agreement with 2 component model of TFF Ramahlo & Pehna (R &P)
->Slight rise v.s mass due to VM(ρ) - pion cloud effect

ρ -meson line shape @ √s=3.1 GeV

HADES coll. EPJA50(2014) 82 **p+p→pp e⁺e⁻ (π⁺ π⁻)**





- Excess above „QED cocktail" due to for subthreshold coupling of R→Nρ→Ne+e-

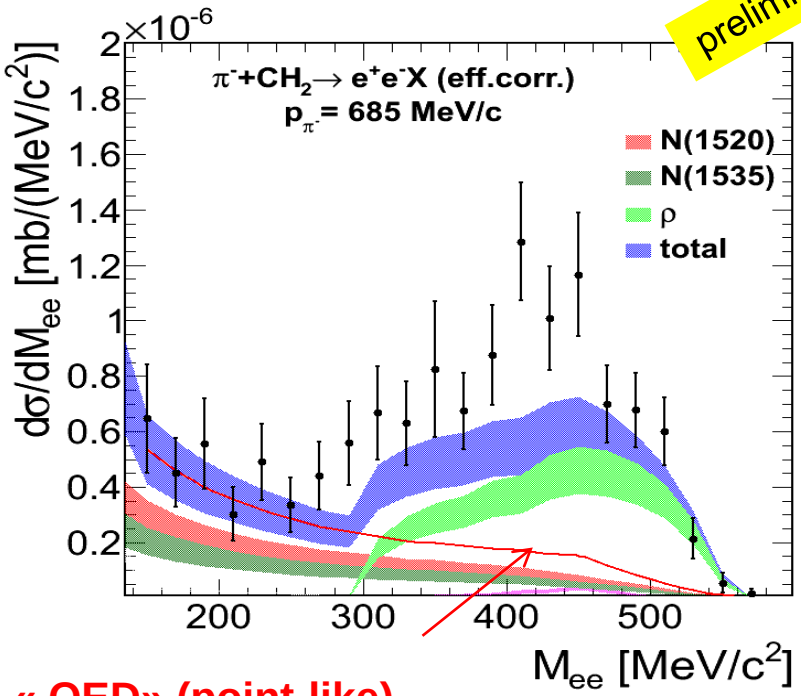
Electromagnetic Transition Form-Factors of Baryon Resonances (Δ(1232), N*(1520), Δ(1620),.)

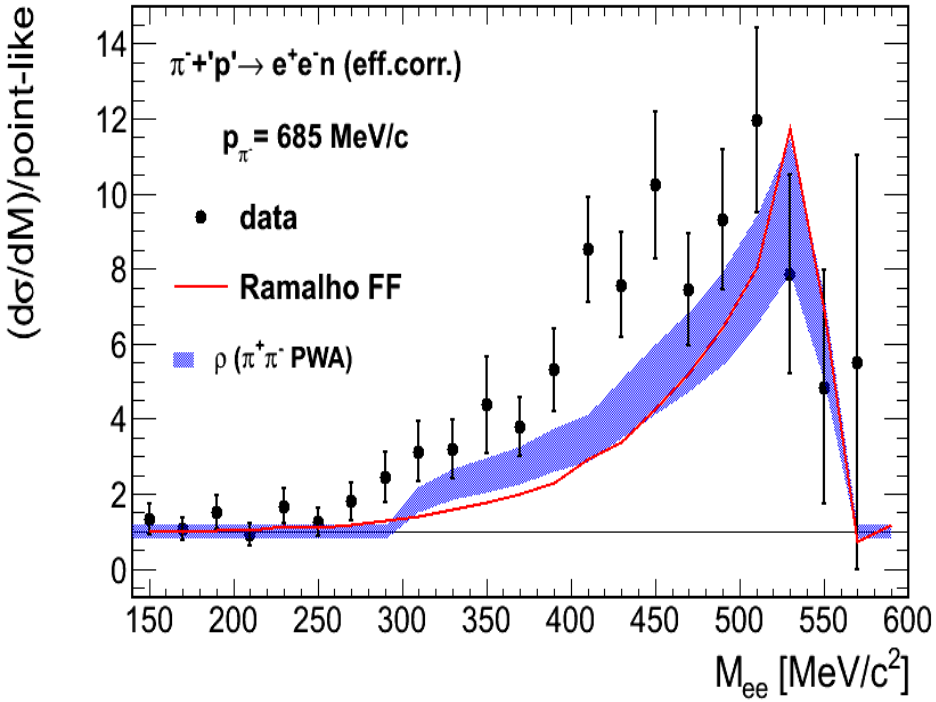
- direct ρ seen in 2 pion channel accounts only for small fraction of the e+e- yield !)

$\pi^- p \to e^+e^- n$ @ $\sqrt{s}$=1.49 GeV

Exclusive channel

preliminary





« QED» (point-like) constrained by π^- p→nγ Partial Wave Analysis

ρ **from measured π+π- : dominat s channel**

D13 (~60%) S11(20%)

ρ→e+e- calculated as $\frac{d\sigma}{dM_{\pi+\pi-}} \frac{M_\varrho}{M^3} BR(\varrho \to e^+e^-)$

- ❑ Strong increase with mass – signature of VDM
- ❑ Yield consistent with ρ contribution expected from ππ (BnGa)
- ❑ Consistent with 2 component model of D13(1520) →ne+e- (Ramahlo & Pena)

Summary

- Dilepton radiation (excess yield) in Low Mass Range in HIC can be described by emission form hot and dense phase using emissivity formula with strongly modified SF of ρ meson for broad range of energies (SIS18-RHIC)
- Modeling of SF requires detailed knowledge of elementary processes involving baryon- meson interactions - $R \rightarrow N \gamma^*$ tranistions (em. Transition Form Factors) are directly related to hadronic loops in self. energy calculations
- Results of studies performed with NN and πN reactions demonstrate important role of intermediate ρ meson in em. transitions for Δ , D13 , along Vector Meson Dominance