Dilepton and Photon production in heavy-ion collisions

International School "Relativistic Heavy Ion Collisions, Cosmology and Dark Matter, Cancer Therapy"
Oslo 22nd May 2017

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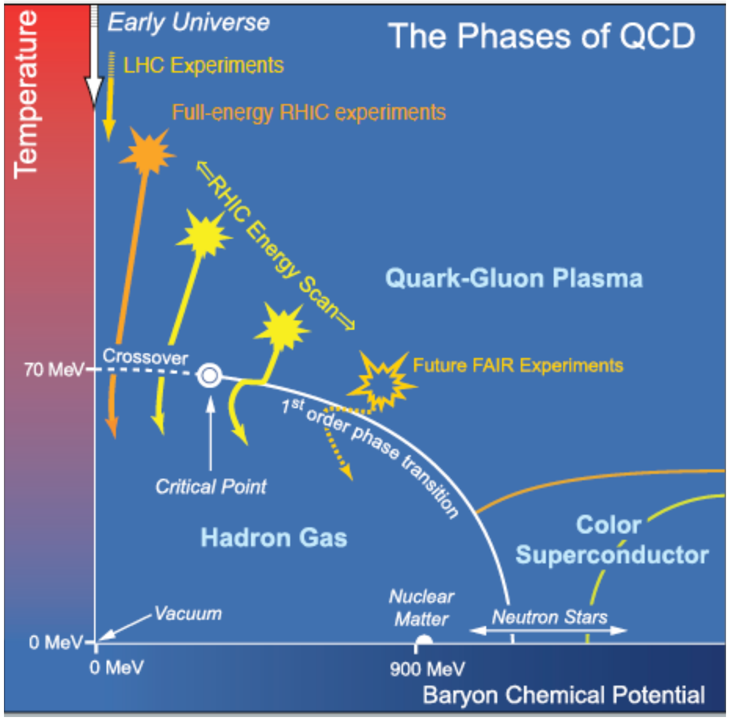
Outline

- Introduction
- Thermal radiation
- Experimental results on photons
- Experimental results on dileptons

Phase diagram of QCD matter



At high T/density

Transition from hadronic to quark matter

Deconfinement

Chiral symmetry restoration

Observables:

Photons

Dileptons (e^+e^-, $\mu^+\mu^-$)

No strong final state interaction

Directly probe the entire evolution of the fireball

(Convoluted with the entire space-time evolution of the collisions)

Thermal electromagnetic radiation

Thermal emission rates:

$$\frac{dR_{ee}}{d^4q} = \frac{-\alpha_{\mathrm{em}}^2}{\pi^3 M^2} f^B(T)\,\mathrm{Im}\,\Pi_{em}(M,q)$$

Depends on the mass

$$q_0 \frac{dR_\gamma}{d^3q} = \frac{-\alpha_{\mathrm{em}}}{\pi^2} f^B(T)\,\mathrm{Im}\,\Pi_{em}(q=q_0)$$

M→0, depends only on q

Low mass is ρ dominated:

$\mathrm{Im}\Pi_{em} \sim [\mathrm{Im}D_\rho + \mathrm{Im}D_\omega/10 + \mathrm{Im}D_\phi/5]$

Photons: p_T
Dileptons: M, p_T

p_T : sensitive to temperature and expansion velocity,
affected by "Doppler" blue shift
M: only sensitive to temperature (Lorentz invariant)

Chiral Symmetry restoration

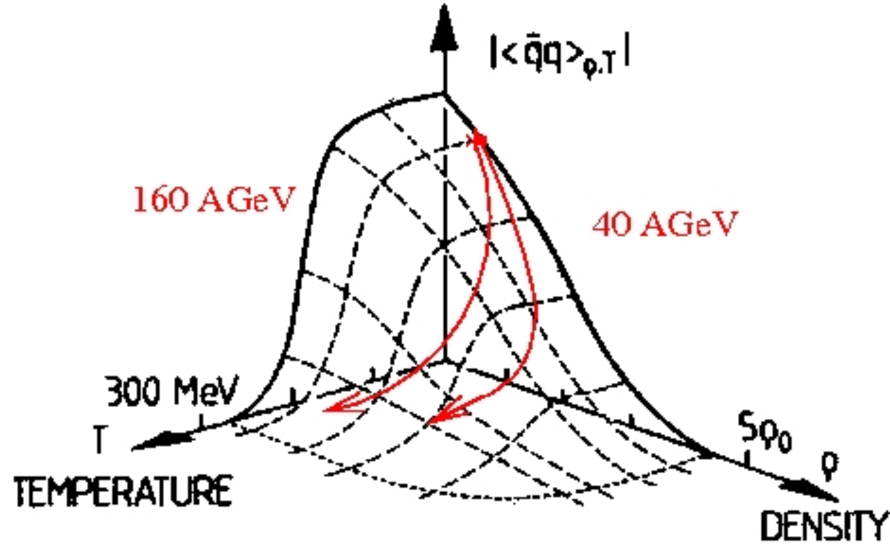
The QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(\mathrm{i}\not{D} - \hat{m}_q)q - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

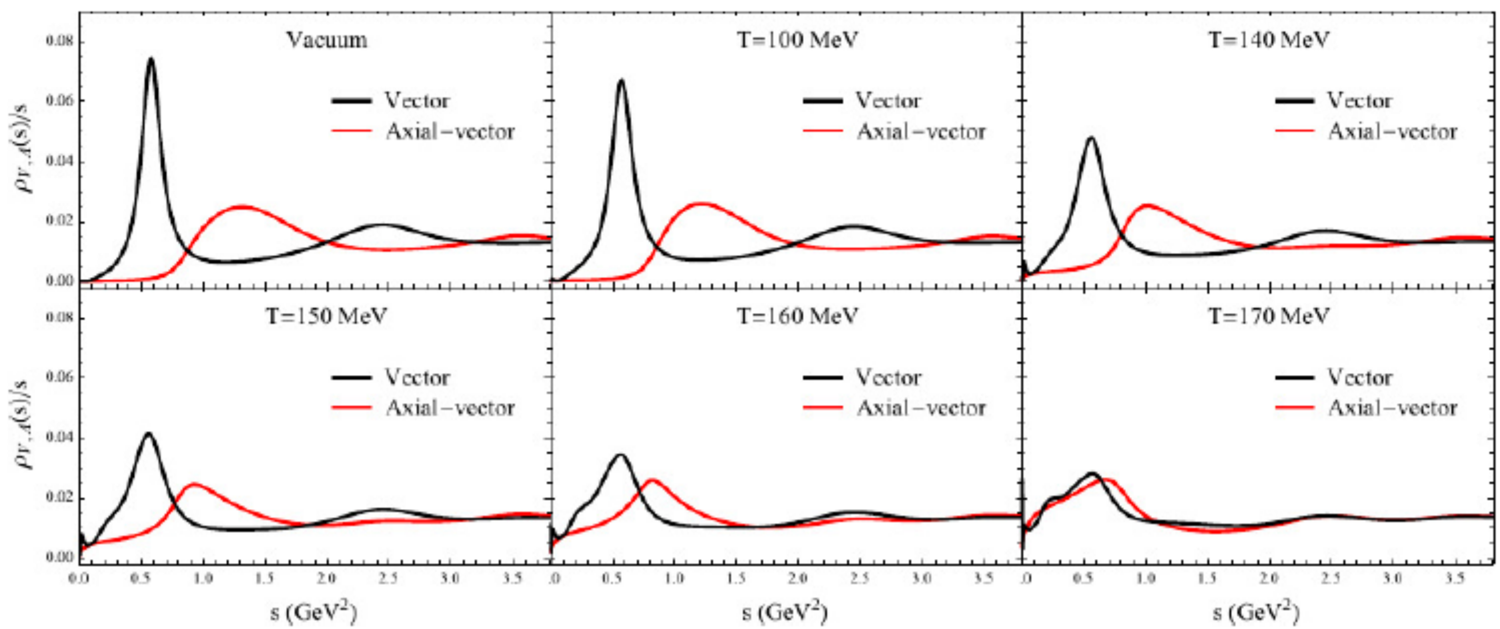
$$\text{with} \quad \mathrm{D}_\mu = \partial_\mu + \mathrm{i}g\frac{\lambda_a}{2}A^a_\mu$$

Spontaneous symmetry breaking
gives rise to a nonzero order parameter

Chiral- multiplets:
ρ–a_1
σ(500)-π(140) N(940)-N*(1535)



Eur. Phys. J. A (2016) 52: 257



PHOTONS

Heavy- ion collisions

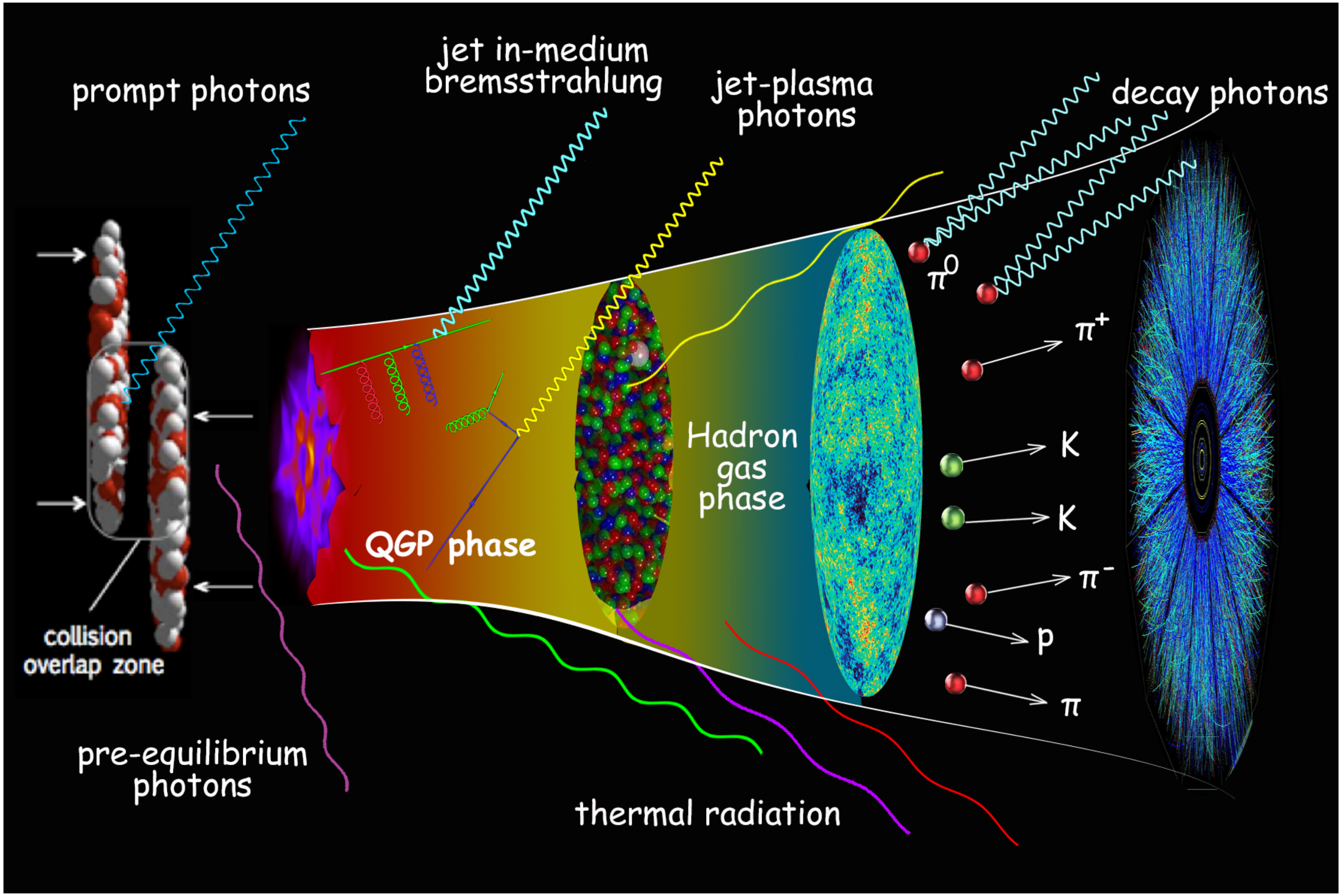


Fig. taken from C. Shen

Photon sources

- **Decay photons:**
  - π^0, η, ω
- **Direct photons:**
  - Hard:
    - Direct:
      - qg Compton Scattering
      - $q\bar{q}$ Annihilation
    - Fragmentation
  - Pre-equilibrium
  - Thermal:
    - QGP
    - Hadron Gas
  - Hard+thermal:
    - Jet-γ-conversion:
      - $q_{hard} + q_{QGP} \rightarrow \gamma + q$
      - $q_{hard} + q_{QGP} \rightarrow \gamma + g$
    - Medium induced γ bremss.

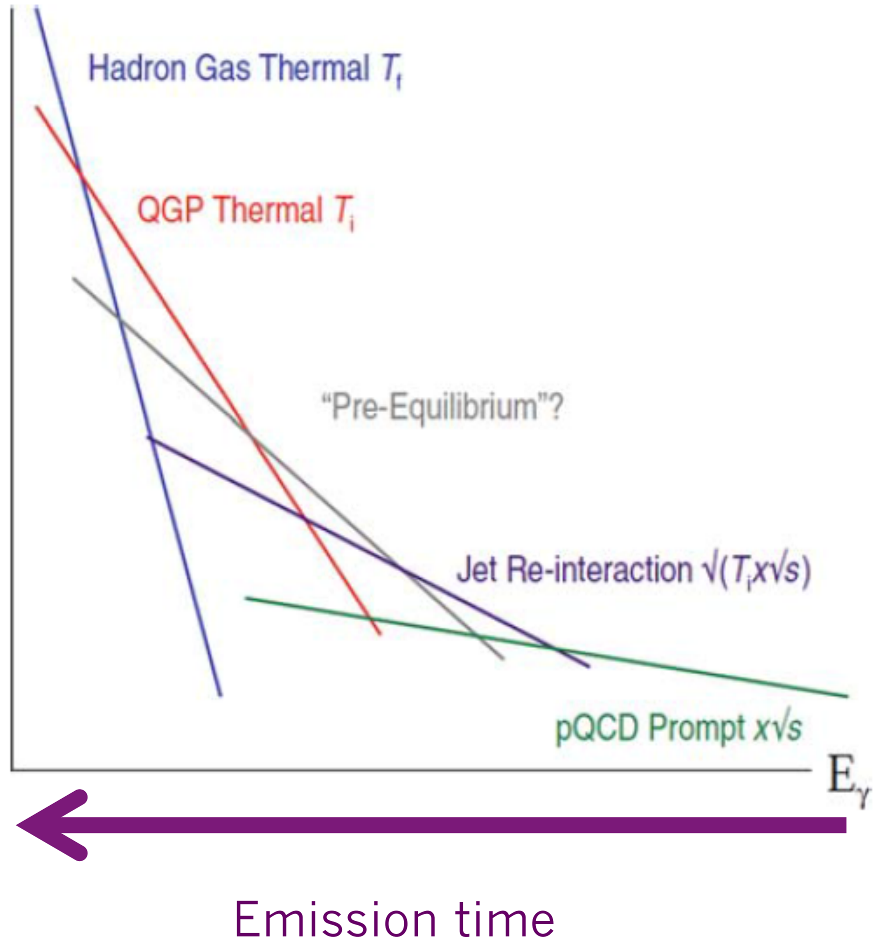
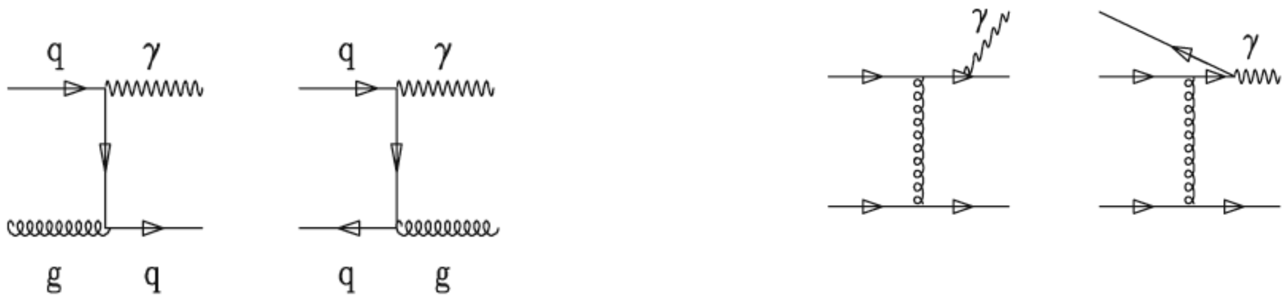


Figure from P. Stankus

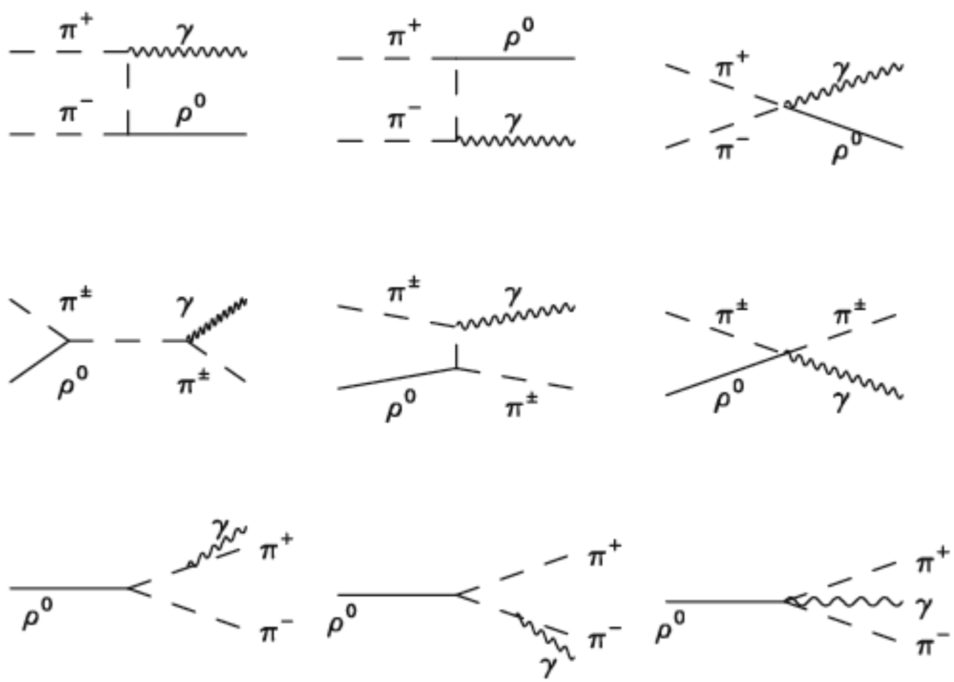
Large background from decays.
Difficult measurement

Photon production: Feynman diagrams

QGP:



Hadron gas:



Photon rates and photon yields

Phys. Rev. C 93 (2016) 044906

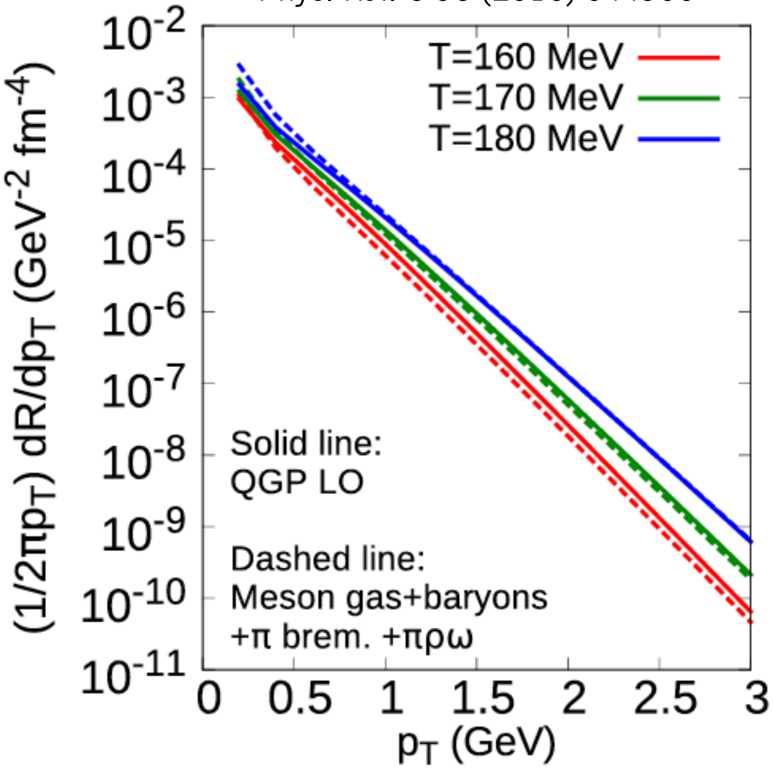


FIG. 3. Ideal QGP and hadronic photon rate near the cross-over region.

$$\underbrace{E_\gamma \frac{dR}{d^3p_\gamma}}_{\substack{\text{Rate per}\\ \text{volume}\\ \text{per time}}} = \underbrace{\frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}}_{\substack{\text{Couplings}\\ \text{and color}\\ \text{factors}}} \underbrace{T^2 e^{-E_\gamma/T}}_{\text{Planck}} \underbrace{\ln\left(\frac{2.912}{g^2}\frac{E_\gamma}{T}\right)}_{\substack{\text{Infrared Cutoff from}\\ \text{Hard Thermal Loop}\\ \text{effective mass } g^2T}}$$

Photon radiation from an equilibrated quark & gluon plasma.

(Kapusta, Lichard, Seibert PRD ‘91)

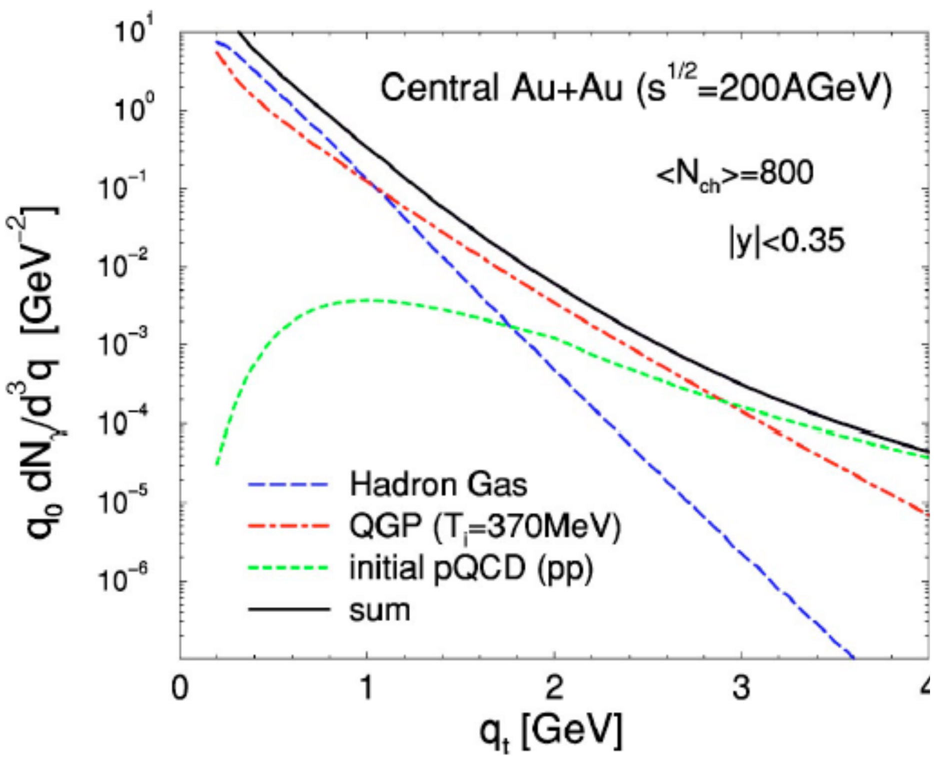
Includes lowest-order Compton and annih. graphs, and lowest order HTL cutoff (Braaten & Pisarski NP ‘88, PRL ‘89).

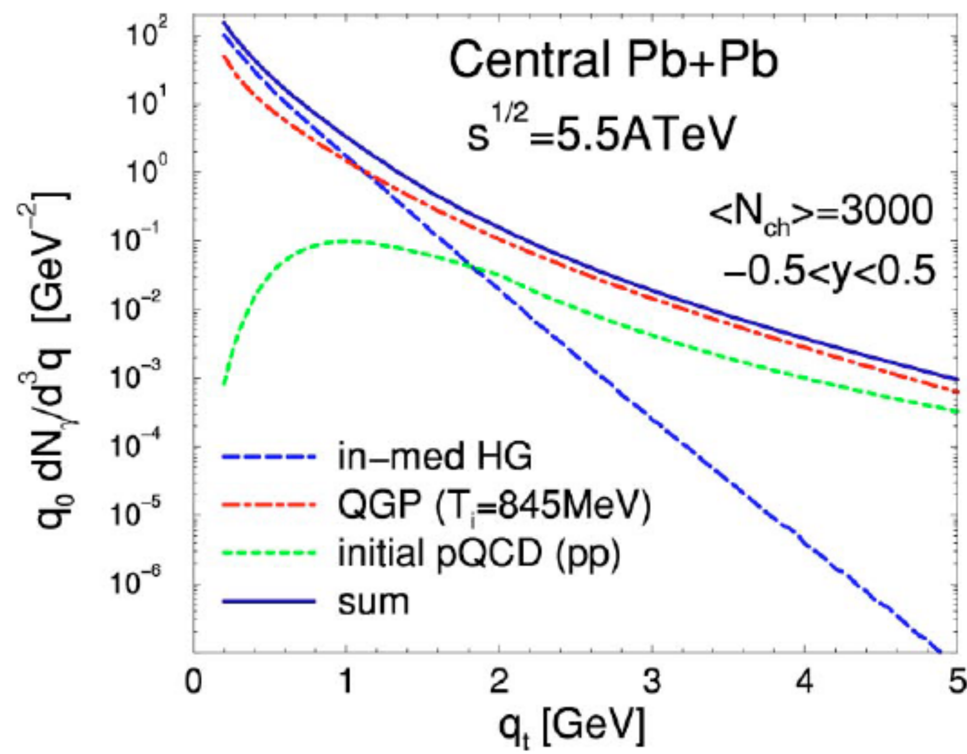
Photon rate QGP (lowest order)

Expected photon yields

Integrated photon emission
Prediction for RHIC and LHC energies

Phys. Rev. C 69 (2004) 014903





Thermal photons: 1.5-3 GeV/c vs 1.5-5 GeV/c

Photon measurements in AA collisions

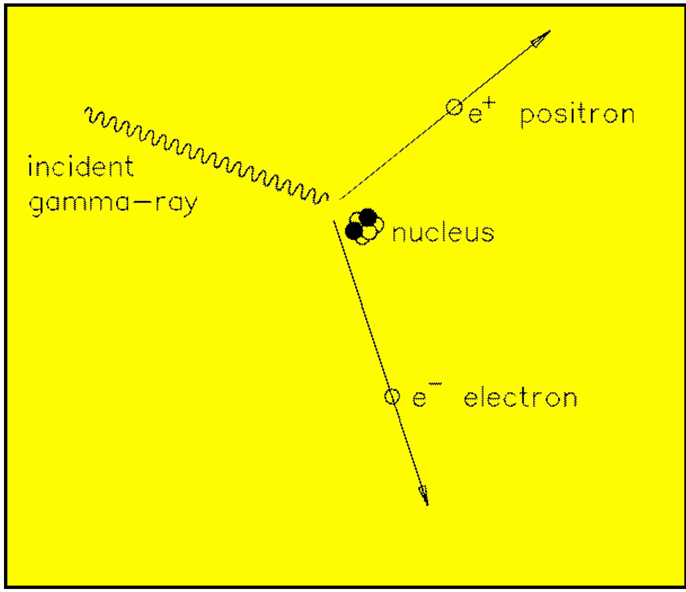
- Upper limits: HELIOS, WA80, CERES
- Measured signal
  - WA98:
    - Pb+Pb $\sqrt{s_{NN}}$ =17.3 GeV
  - PHENIX:
    - Au+Au $\sqrt{s_{NN}}$ =200 GeV
    - Au+Au $\sqrt{s_{NN}}$ = 39, 62.4 GeV
    - Cu+Cu $\sqrt{s_{NN}}$ = 200 GeV
  - ALICE:
    - Pb-Pb $\sqrt{s_{NN}}$ =2.76 TeV

Methods to measure photons

- Electromagnetic calorimeter: WA98, PHENIX, ALICE
- Photon conversion method ($\gamma \rightarrow e^+e^-$): ALICE, PHENIX
- Virtual photons ($\gamma^* \rightarrow e^+e^-$): PHENIX, ALICE

Interaction of photons with matter

- Photoelectric effect
- Compton scattering
- Pair production: $E\gamma > 1.02 MeV$



•Electromagnetic Calorimeters:
The complete photon energy is deposited in the detector (electromagnetic shower)

•Photon measurement via conversion electrons:
Determine photon momentum and direction by measuring e^+/e^- from a single conversion in tracking detectors

Methods to measure direct photons

- Statistical subtraction method
  - Measure inclusive photons and subtract photons from hadron decays
- Virtual photons ($\gamma^* \rightarrow e^+e^-$): PHENIX
- Isolation + (shower shape in case calorimeter is used)
- Tagging method
  - Remove decay photons by tagging decay photons
- Hanbury Brown-Twiss Method
  - Bose-Einstein correlation expected for direct photons
  - Direct photon yield from correlation strength

Direct photons: statistical subtraction method and double ratio

Subtraction method:

$$\gamma_{direct} = \gamma_{inc} - \gamma_{decay} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}).\gamma_{inc} = (1 - \frac{1}{R_\gamma}).\gamma_{inc}$$

Inclusive photons: All produced photons
Decay photons: Calculated from measured particle spectra with photon decay channels (π^0, η,...)

Double ratio:

$$\frac{\gamma_{inc}}{\pi^0} / \frac{\gamma_{decay}}{\pi^0_{param}} \sim \frac{\gamma_{inc}}{\gamma_{decay}}$$

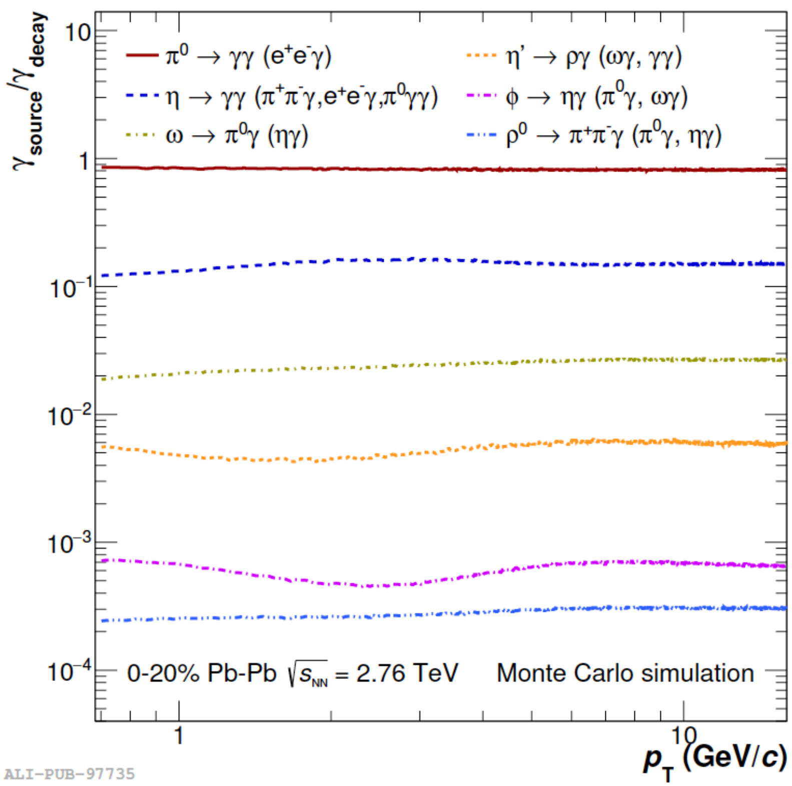
>1 if direct photon signal

Advantage: Cancellation of uncertainties

To obtain γ direct spectrum add systematic uncertainties of the inclusive photon spectrum which canceled in the double ratio

Cocktail generator: γ_{decay}

- γ_{decay} : obtained using a cocktail generator
- Fit to the measured π^0
- Other mesons using m_T-scaling



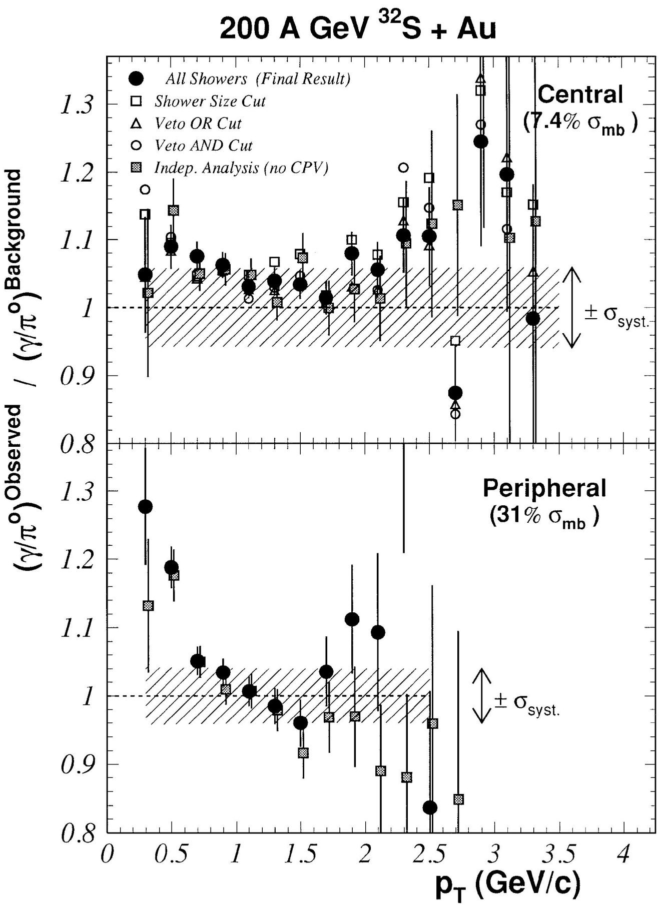
Meson (C_m)	Mass	Decay Branch	B. Ratio
π^0	134.98	$\gamma\gamma$ $e^+e^-\gamma$	98.789% 1.198%
η (0.48)	547.3	$\gamma\gamma$ $\pi^+\pi^-\gamma$ $e^+e^-\gamma$	39.21% 4.77% $4.9 \cdot 10^{-3}$
ρ_0 (1.0)	770.0	$\pi^+\pi^-\gamma$ $\pi^0\gamma$	$9.9 \cdot 10^{-3}$ $7.9 \cdot 10^{-4}$
ω (0.9)	781.9	$\pi^0\gamma$ $\eta\gamma$	8.5% $6.5 \cdot 10^{-4}$
η' (0.25)	957.8	$\rho^0\gamma$ $\omega\gamma$ $\gamma\gamma$	30.2% 3.01% 2.11%
ϕ (0.35)	1019.5	$\eta\gamma$ $\pi^0\gamma$ $\omega\gamma$	1.3% $1.25 \cdot 10-3$ $< 5\%$

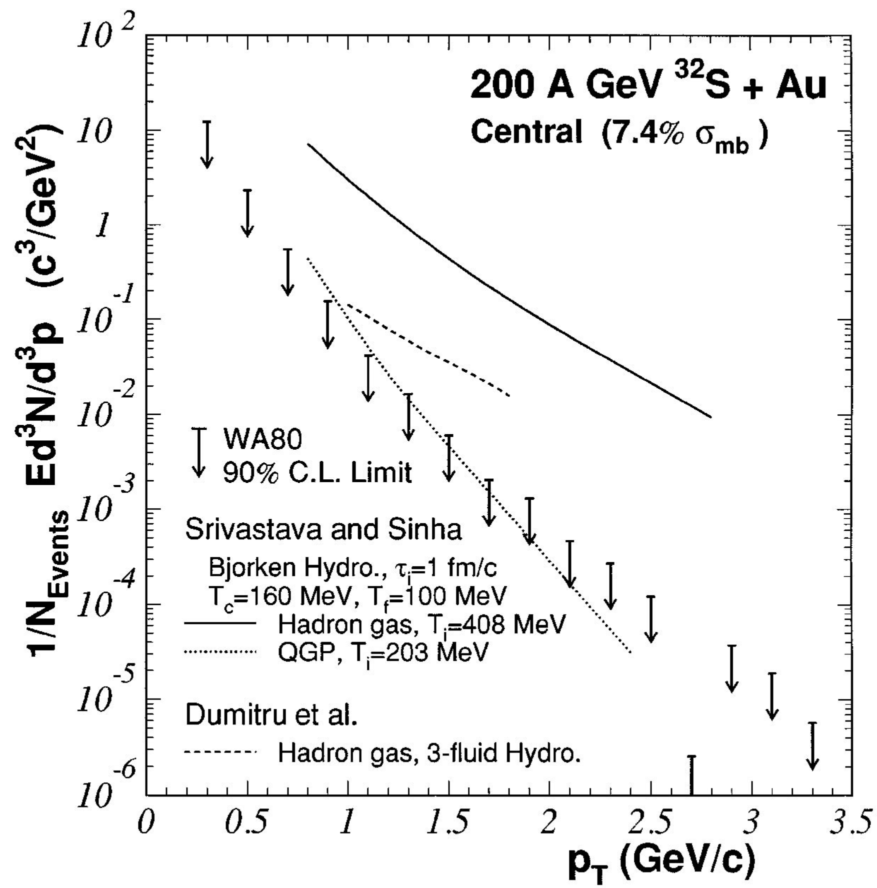
Phys. Rev. C (arXiv:1110.3929)

Early Fixed-Target Photon Results

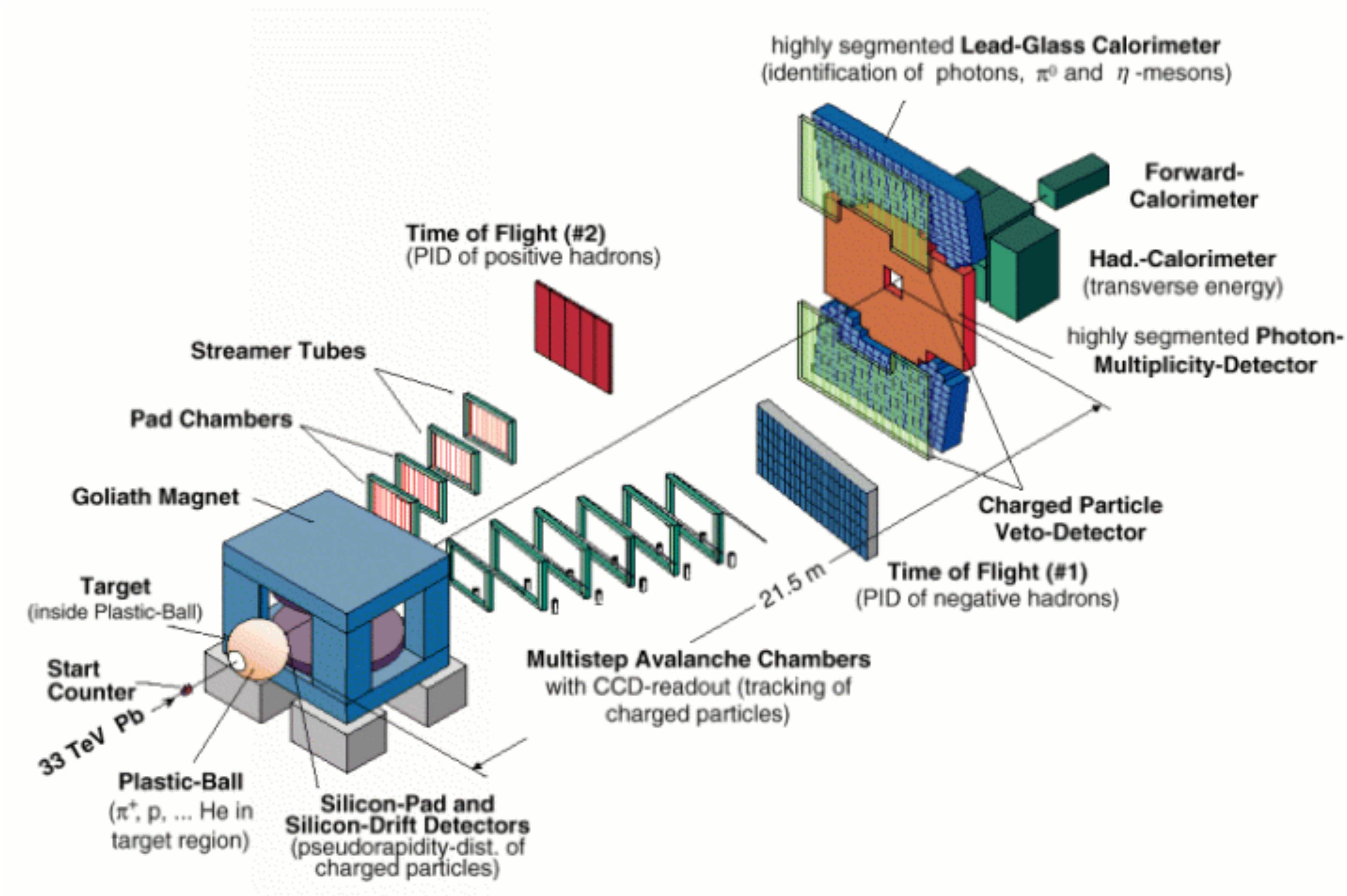
VOLUME 76, NUMBER 19 PHYSICAL REVIEW LETTERS 6 MAY 1996

Limits on the Production of Direct Photons in 200*A* GeV ^{32}S + Au Collisions



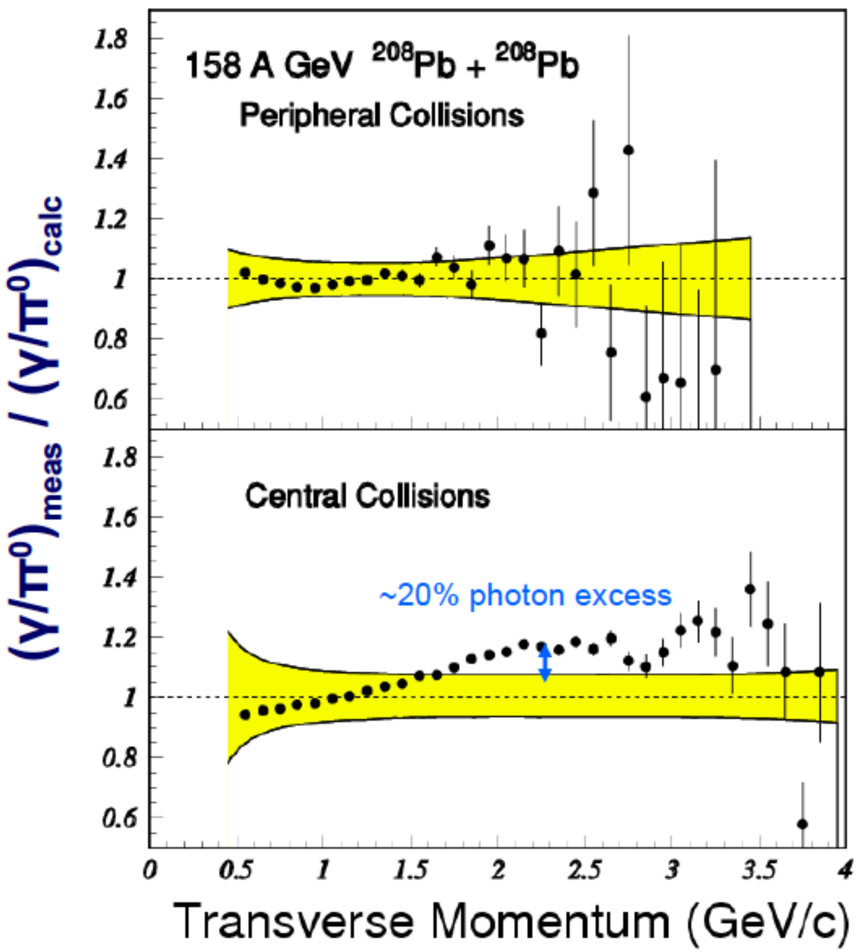


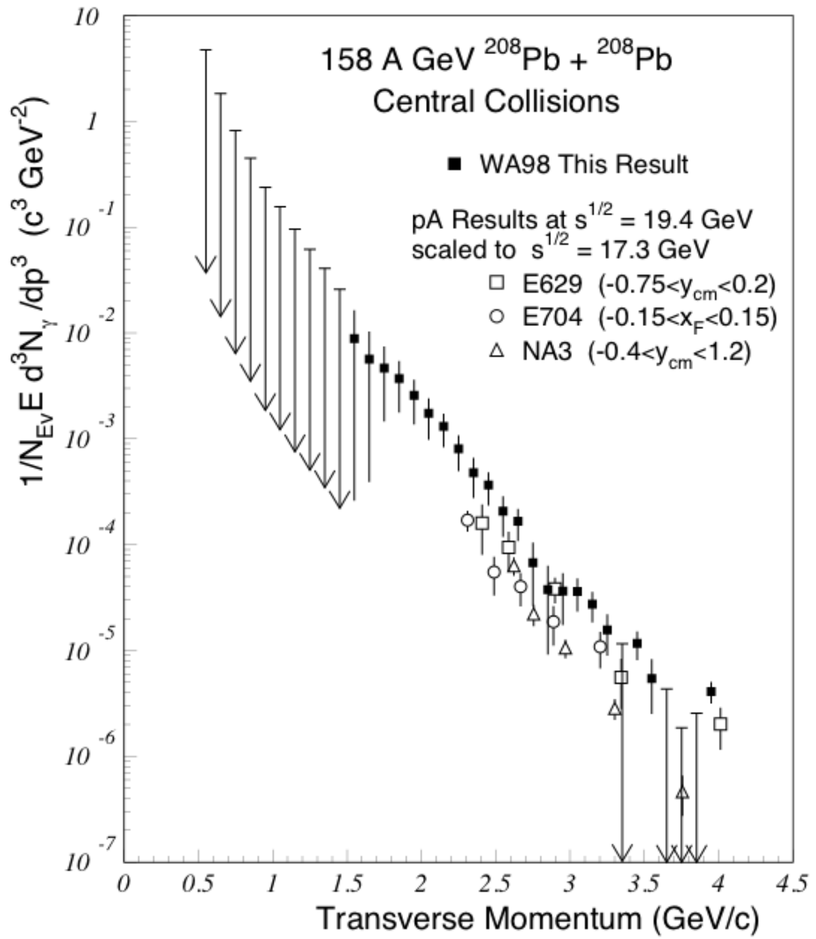
WA98 experiment



WA98: Direct photons

Phys. Rev. Lett. 85: 3595-3599 (2000)



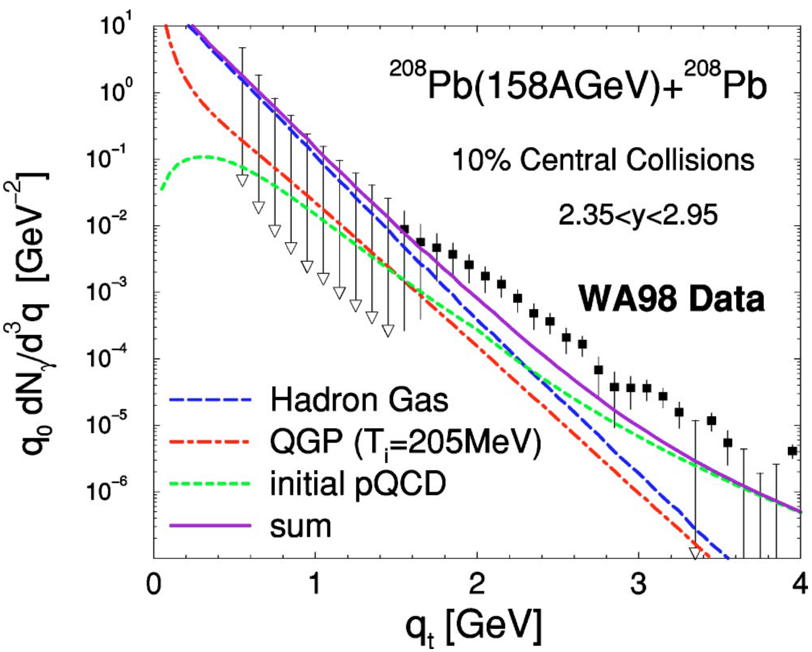


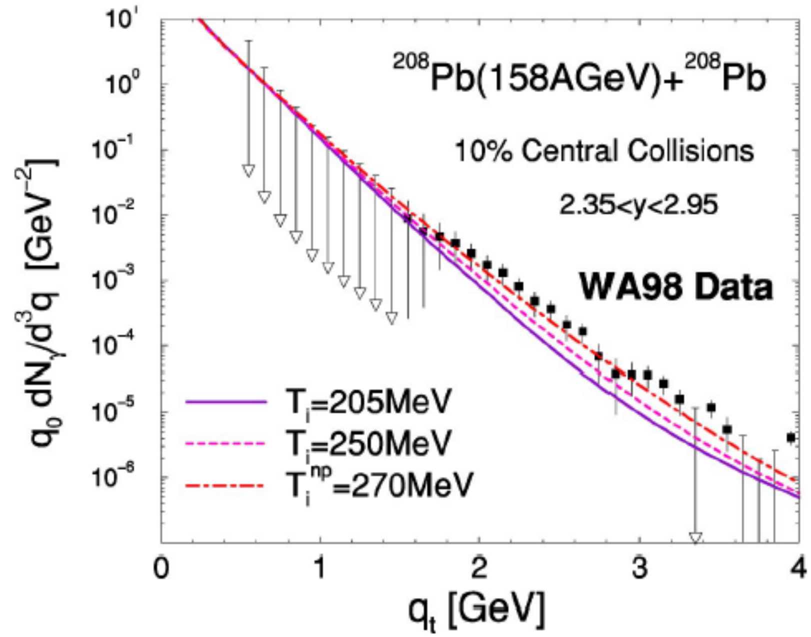
No signal in peripheral collisions

20% photon excess in central collisions

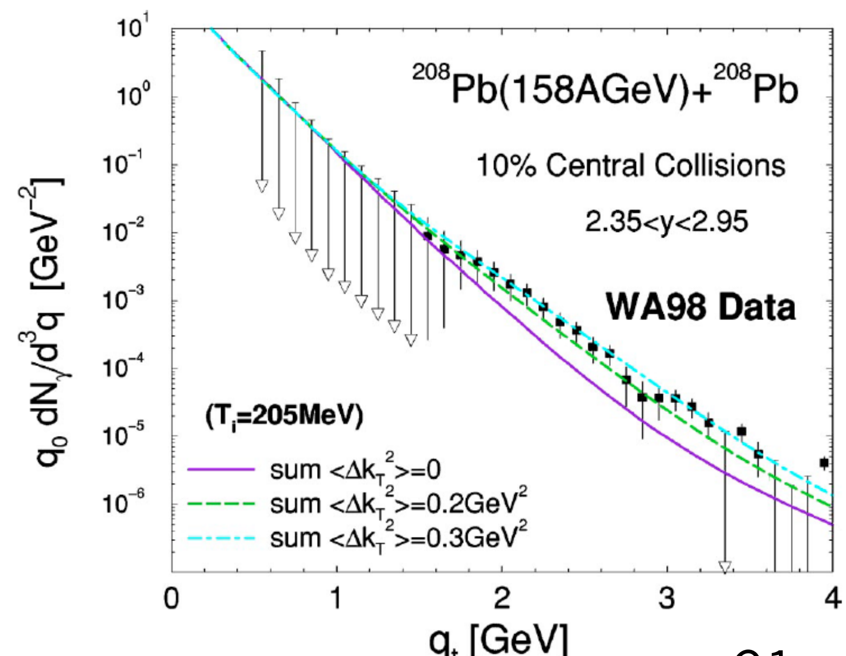
Direct photons WA98

Phys. Rev. C69 (2004) 14903

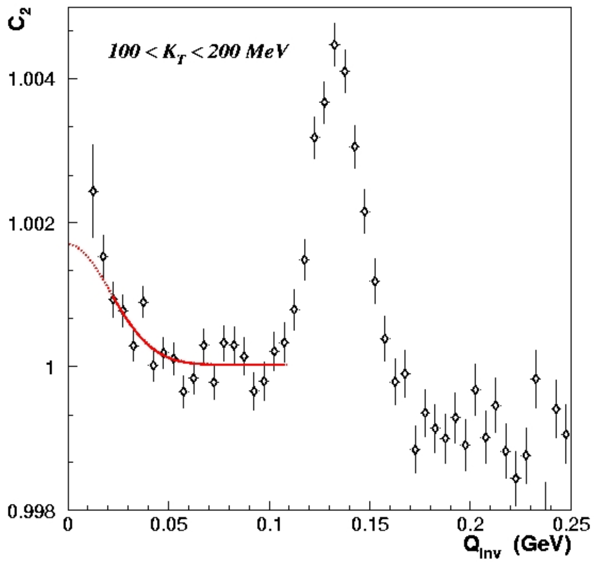


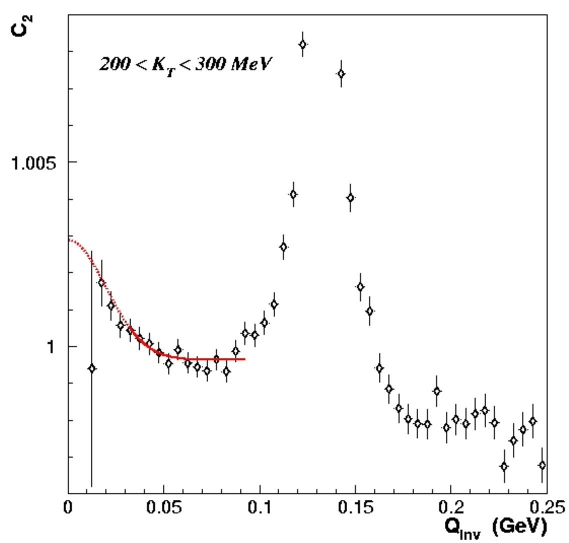


- Fireball evolution
- Photon emission from QGP and HG
- The contribution from QGP is small
- To reproduce the data:
    - Higher initial T
    - Higher intrinsic kT



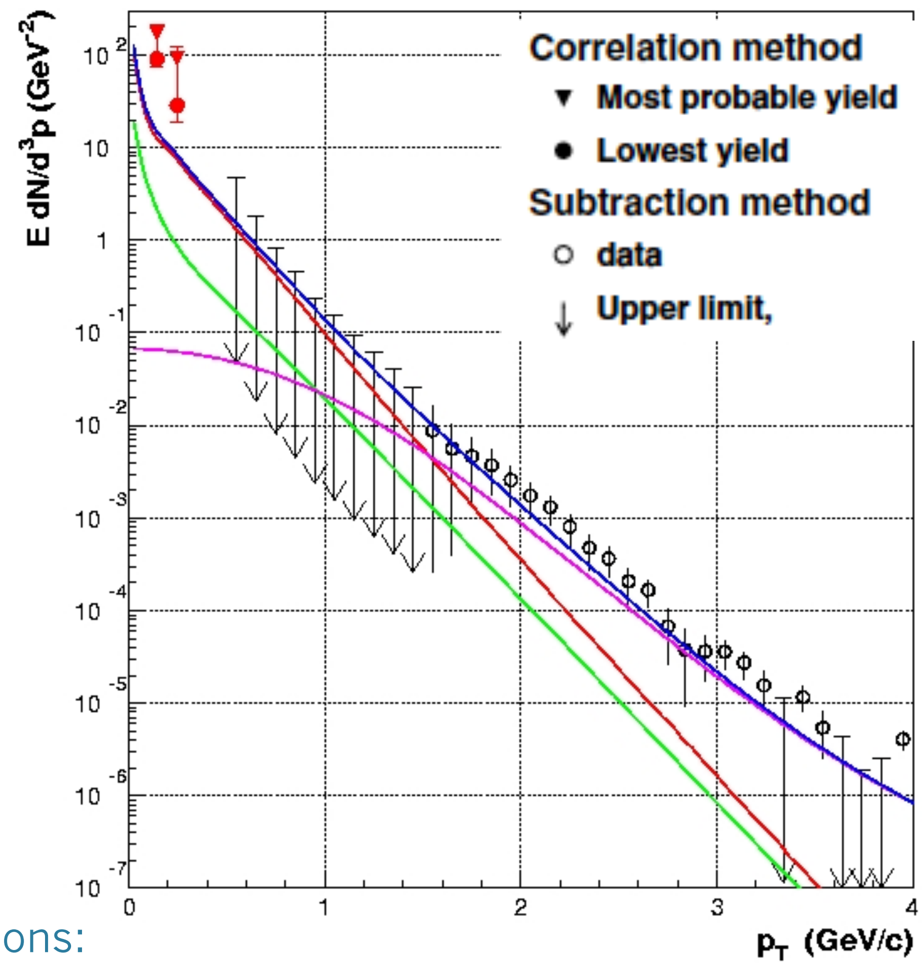
Direct γ yield from HBT





M.M. Aggarwal et al.,
Phys. Rev. Lett. 93: 022301 (2004)

$$N_\gamma^{\text{direct}}/N_\gamma^{\text{total}} = \sqrt{2\lambda} = \sqrt{8\lambda_{\text{inv}}K_T R_O/\sqrt{\pi}\,\text{Erf}(2K_T R_O)}.$$



Predictions:
S. Turbide, R. Rapp, and C. Gale,
hep-ph/0308085.

PHENIX experiment

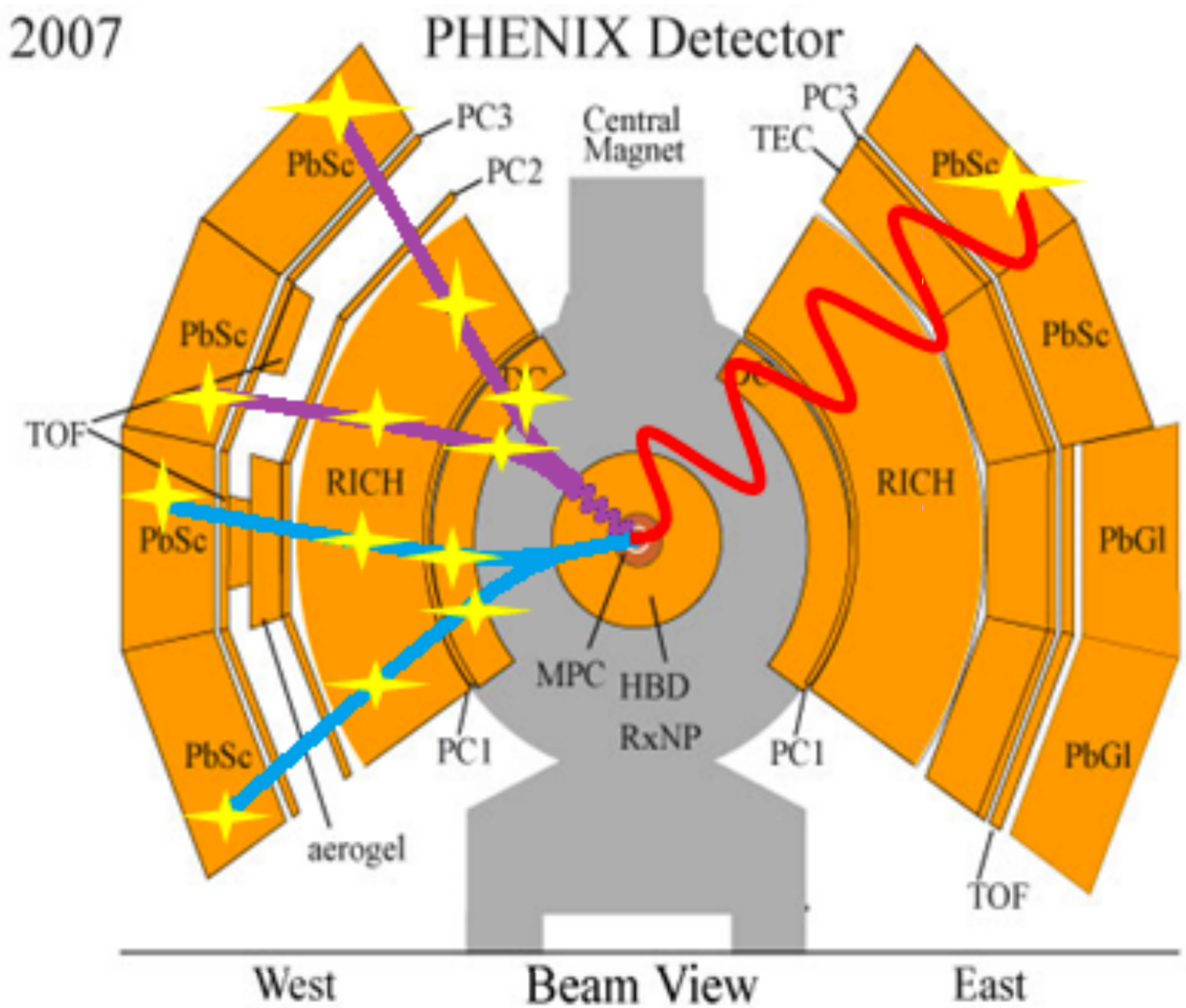
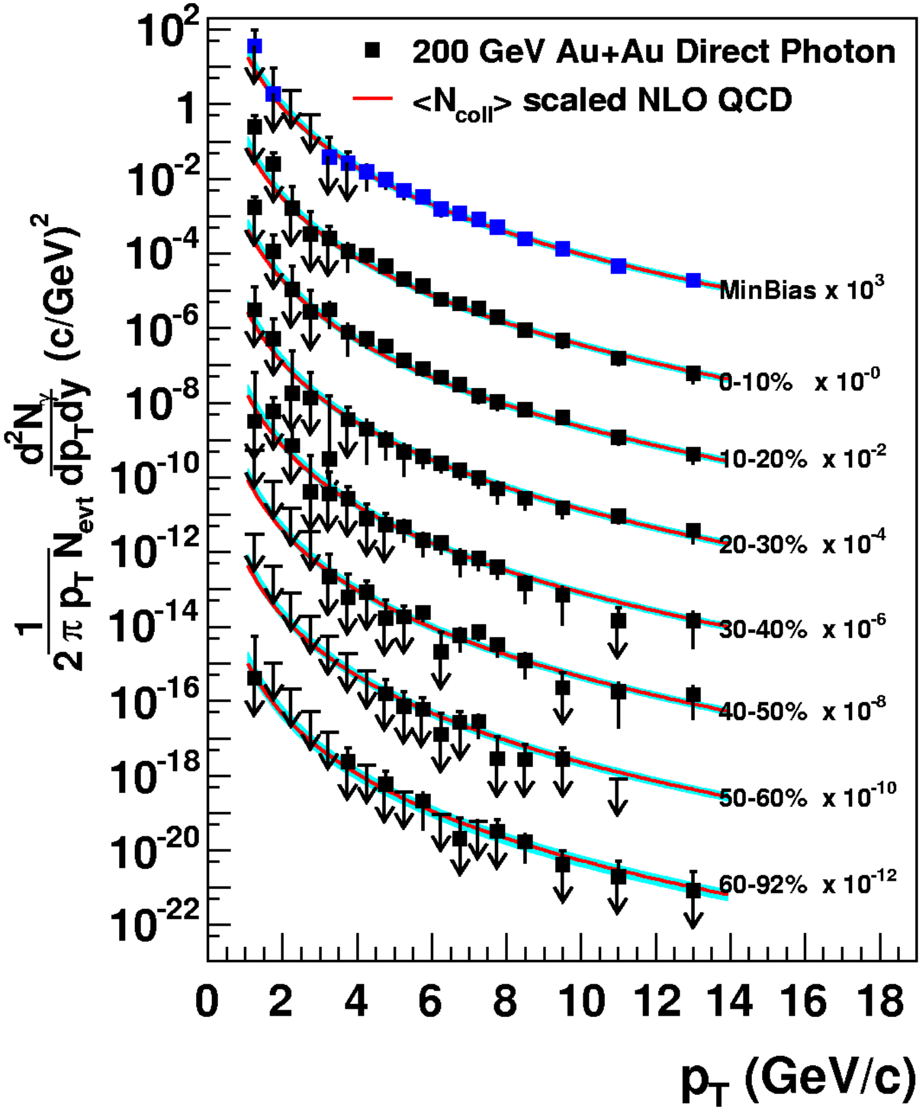


Fig. from D. Sharma QM17

Direct photons at RHIC



PHENIX Coll.:
Phys. Rev. Lett. 94, 232301 (2005)

Statistical subtraction method is difficult for calorimeters at low p_T

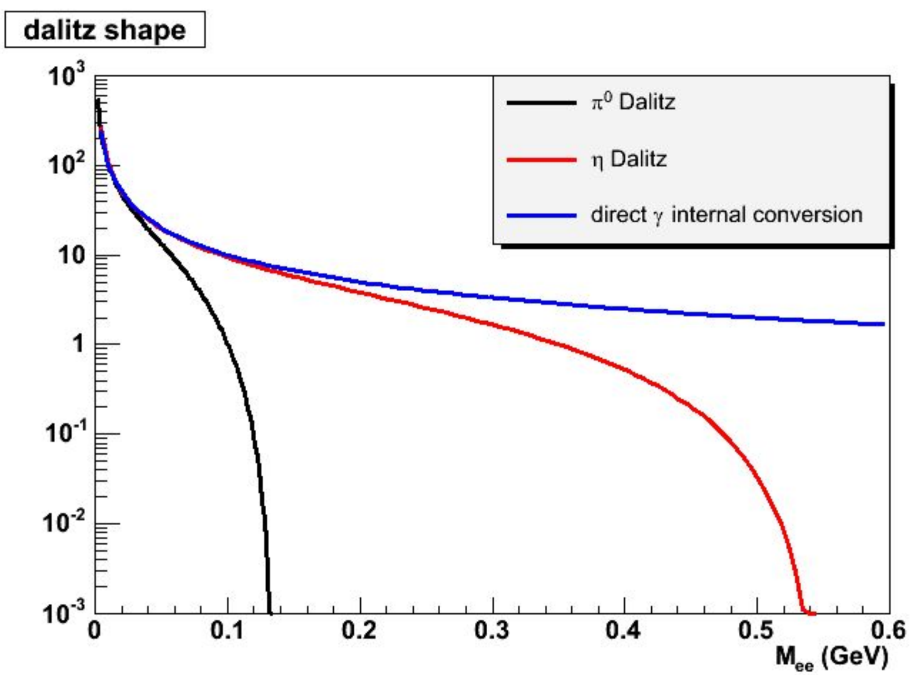
The Idea: Kroll-Wada formula

Any source of real γ produces virtual γ with very low mass
Relation between photon production and associated e^+e^-:

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{1}{m_{ee}}S$$

$$S = \left|F(m_{ee}^2)\right|^2 \left(1-\frac{m_{ee}^2}{M^2}\right)^3$$

- S=1 for direct photons and $m_{ee} >> p_T$



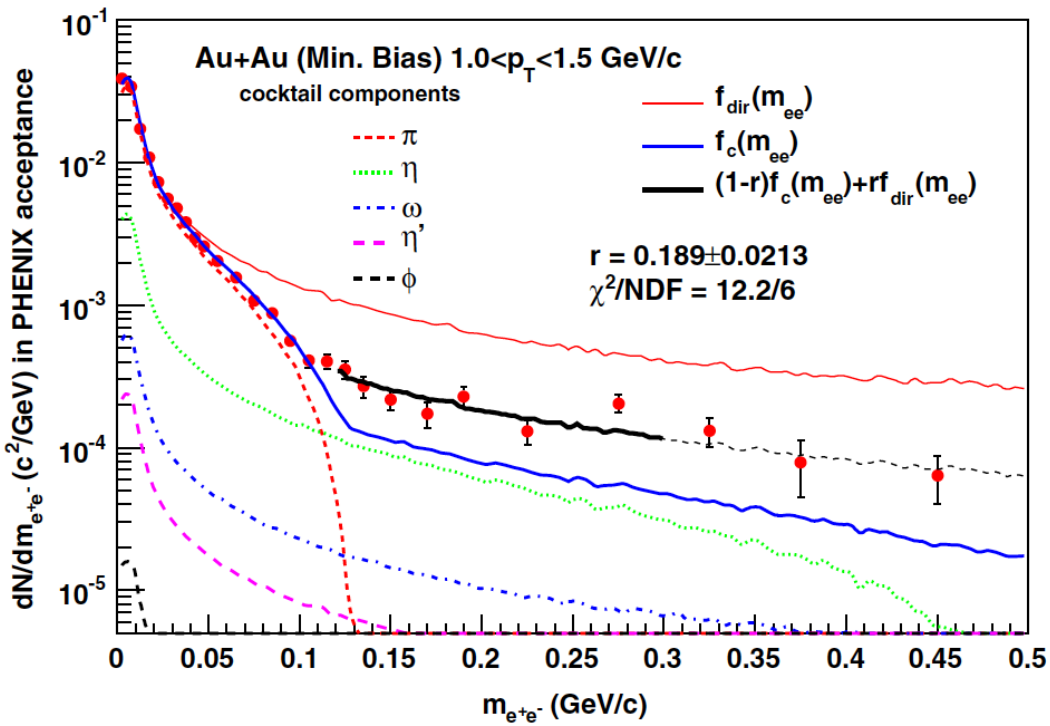
There are 0.002 e^+e^- pairs with $80 < m_{ee} < 300$ MeV for every real photon

Direct photons at RHIC

Phys. Rev. Lett.104 (2010) 132301

$$f(m_{ee}) = (1-r) f_{cocktail}(m_{ee}) + r f_{direct}(m_{ee})$$

$$dN^{dir}(p_T) = r.dN^{incl}(p_T)$$

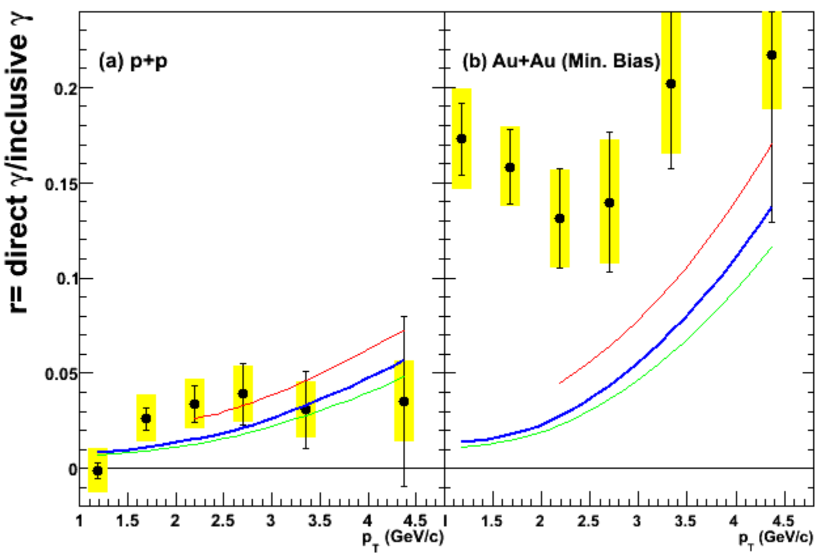


Cocktail normalized to data for m_{ee}< 0.03 GeV/c^2

Fit range: 0.12 < m_{ee}<0.3 GeV/c^2

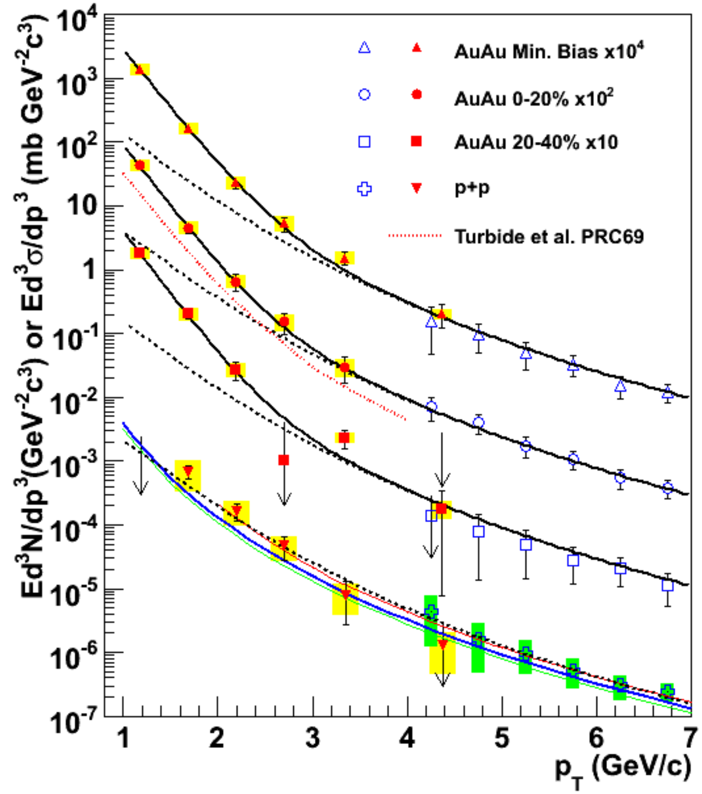
Direct photons at RHIC

PHENIX Coll.:
Phys. Rev. Lett. 104(2010) 132301



•pp consistent with NLO pQCD calculations

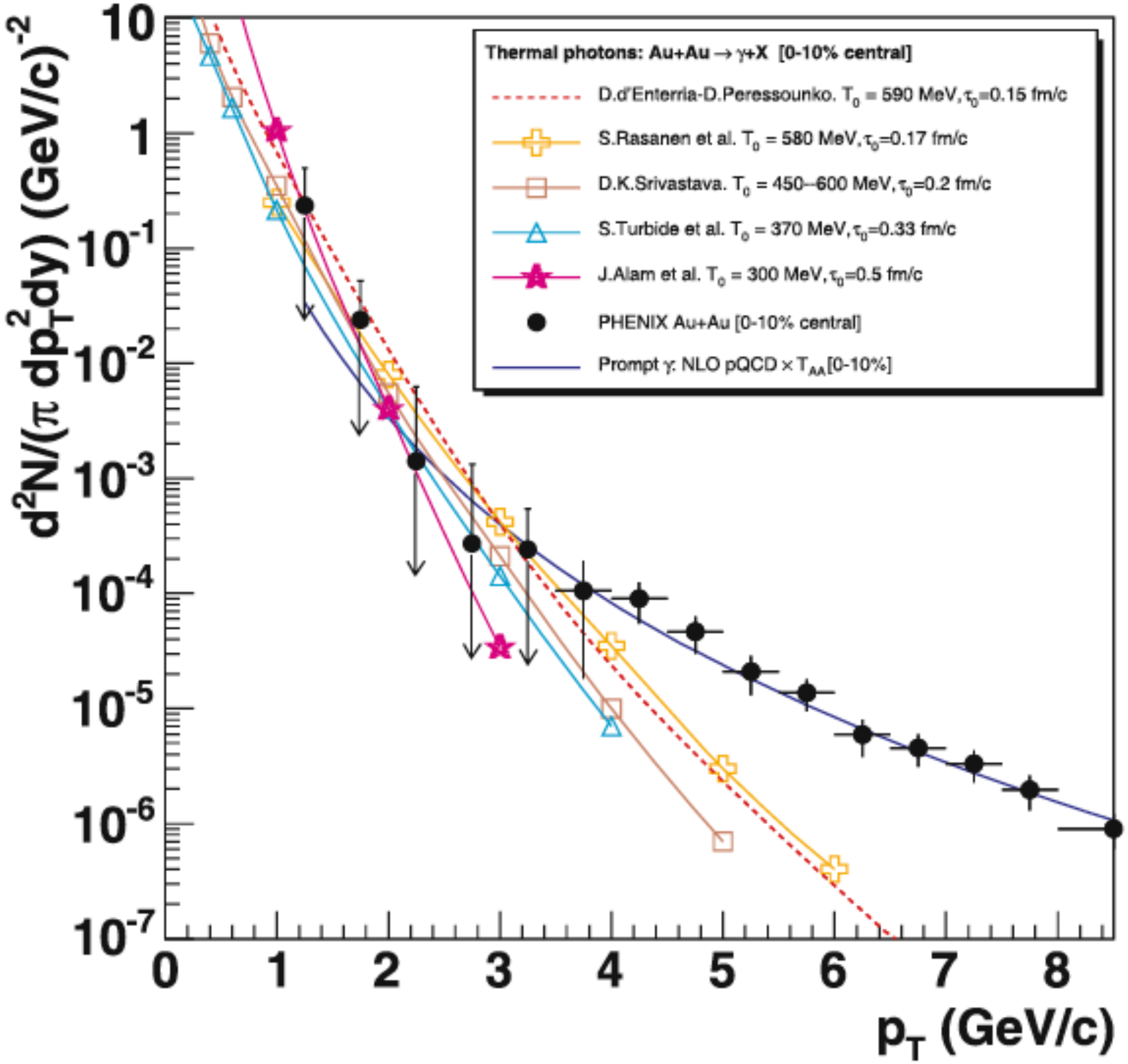
•AuAu larger than calculation for p_T<3.5GeV/c



Excess exponential in p_T (0-20%):

T = 221 ± 23 (stat) ± 18 (sys) MeV

Initial T



Eur. Phys. J C46, 451(2006)

Initial T from several Hydro models

T_i=300-600 MeV

Tagging method

Combine photon conversion with photon in calorimeter

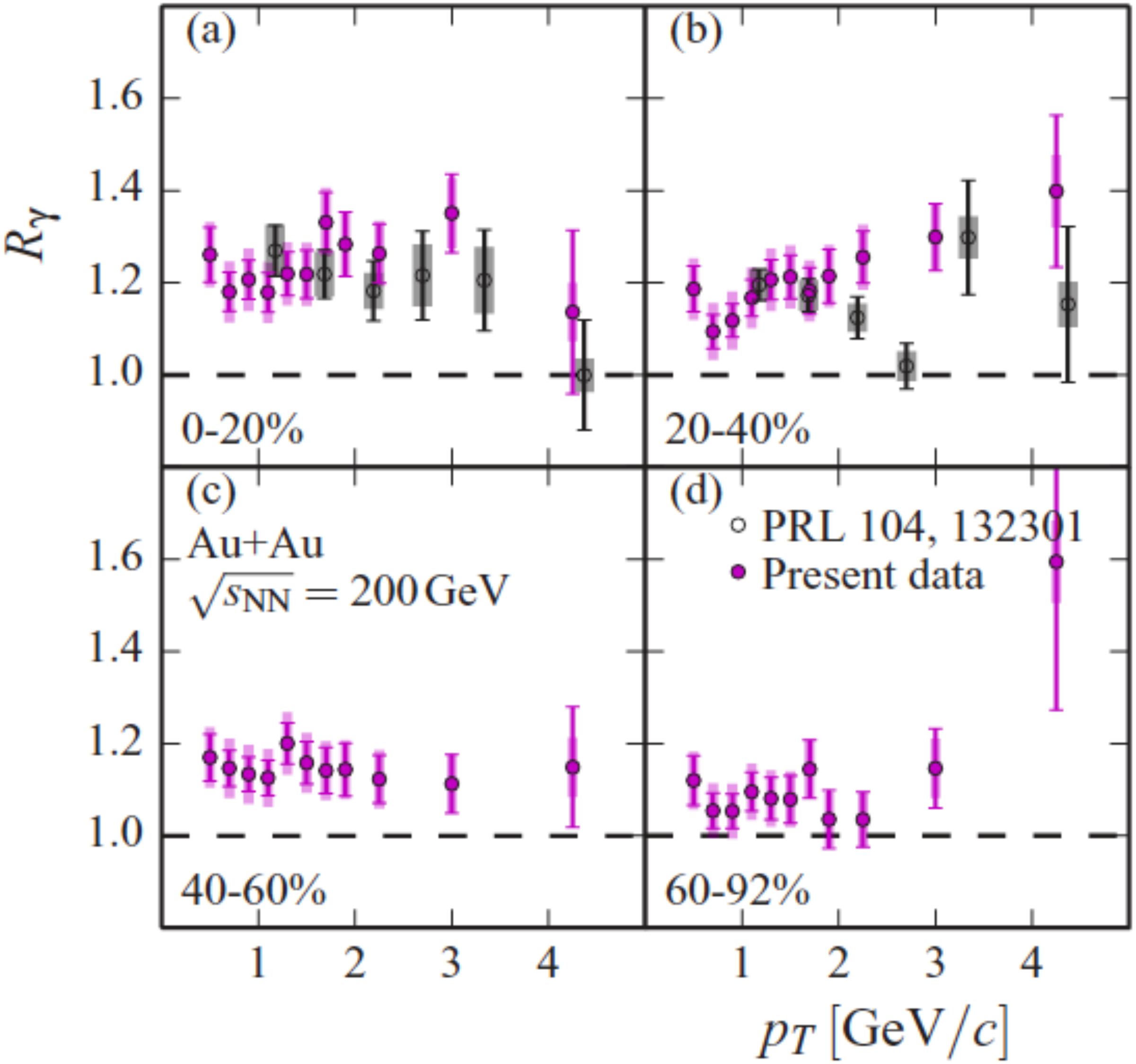
$$R_\gamma = \frac{\gamma^{\text{incl}}}{\gamma^{\text{hadron}}} = \frac{\langle \varepsilon_\gamma f \rangle \left(\frac{N_\gamma^{\text{incl}}}{N_\gamma^{\pi^0,\text{tag}}} \right)_{\text{Data}}}{\left(\frac{\gamma^{\text{hadron}}}{\gamma^{\pi^0}} \right)_{\text{Sim}}}.$$

$$N_\gamma^{\text{incl}} = \varepsilon_{ee} a_{ee}\, c \gamma^{\text{incl}},$$

$$N_\gamma^{\pi^0,\text{tag}} = \varepsilon_{ee} a_{ee}\, c \langle \varepsilon_\gamma f \rangle \gamma^{\pi^0},$$

PHENIX

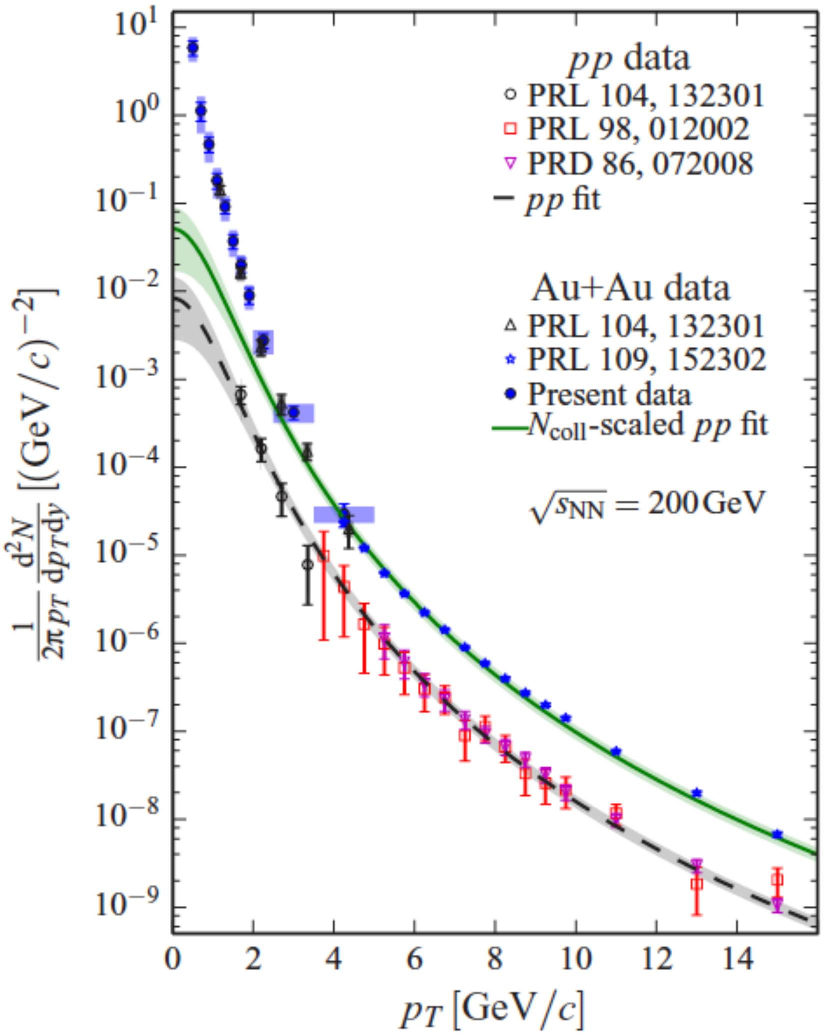
Phys. Rev. C91 (2015) 64904

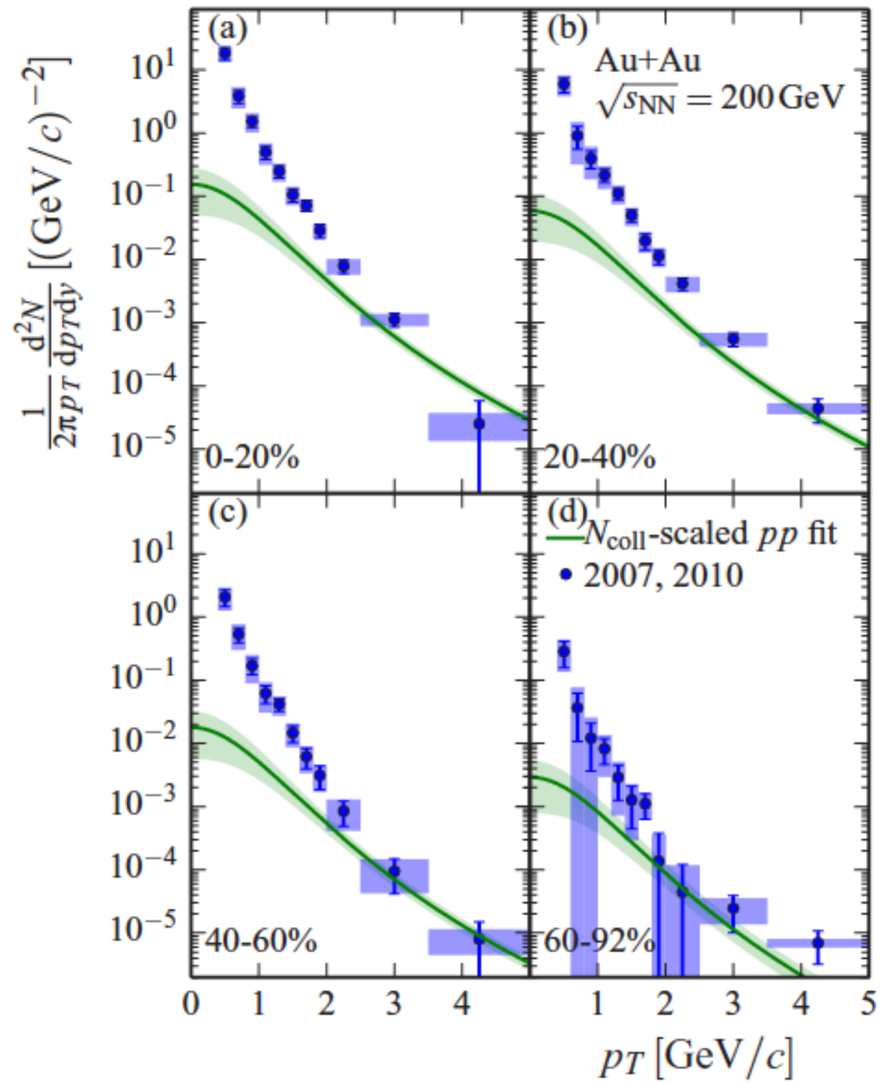


Rγ consistent using two different methods

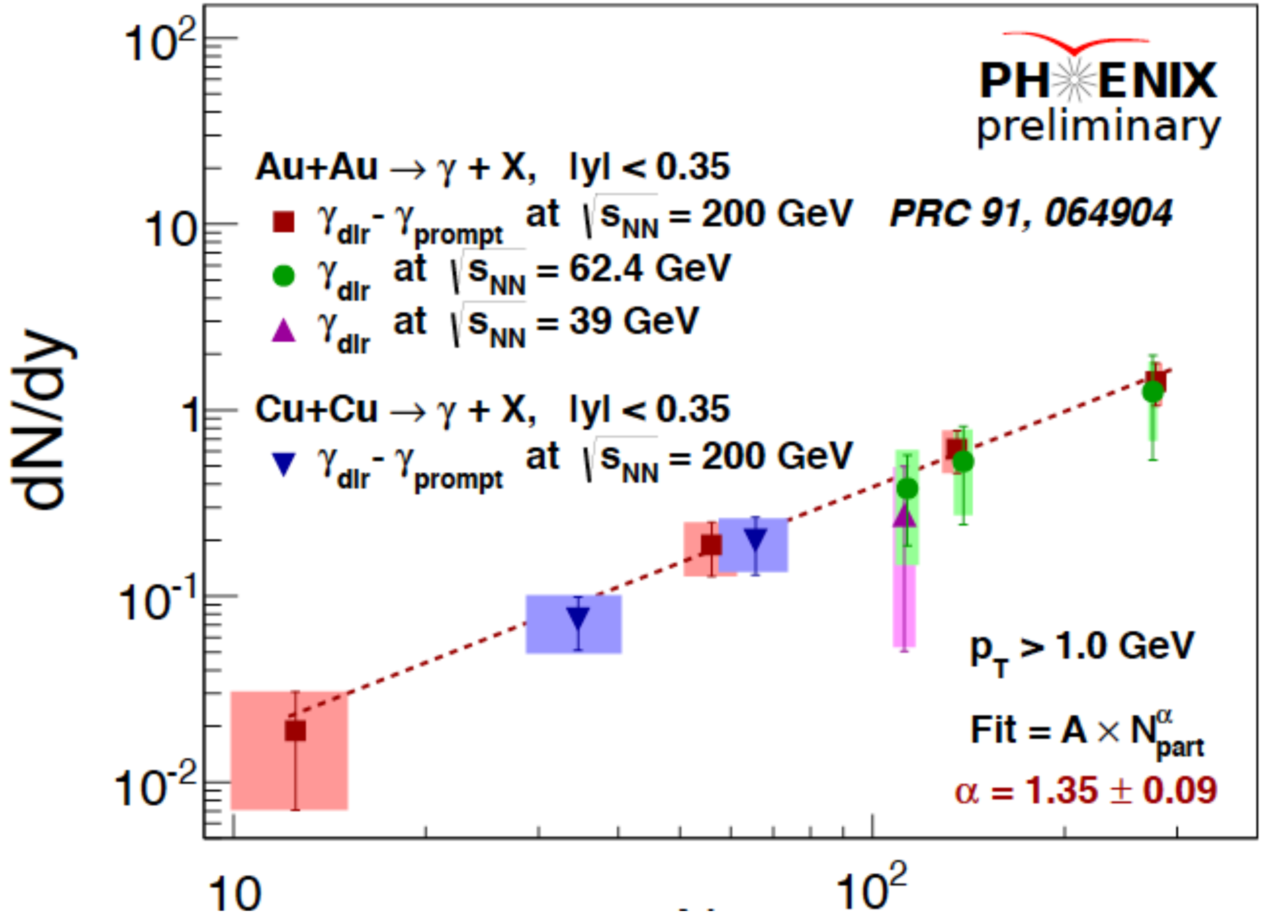
PHENIX: Direct photons

Phys. Rev. C91 (2015) 64904





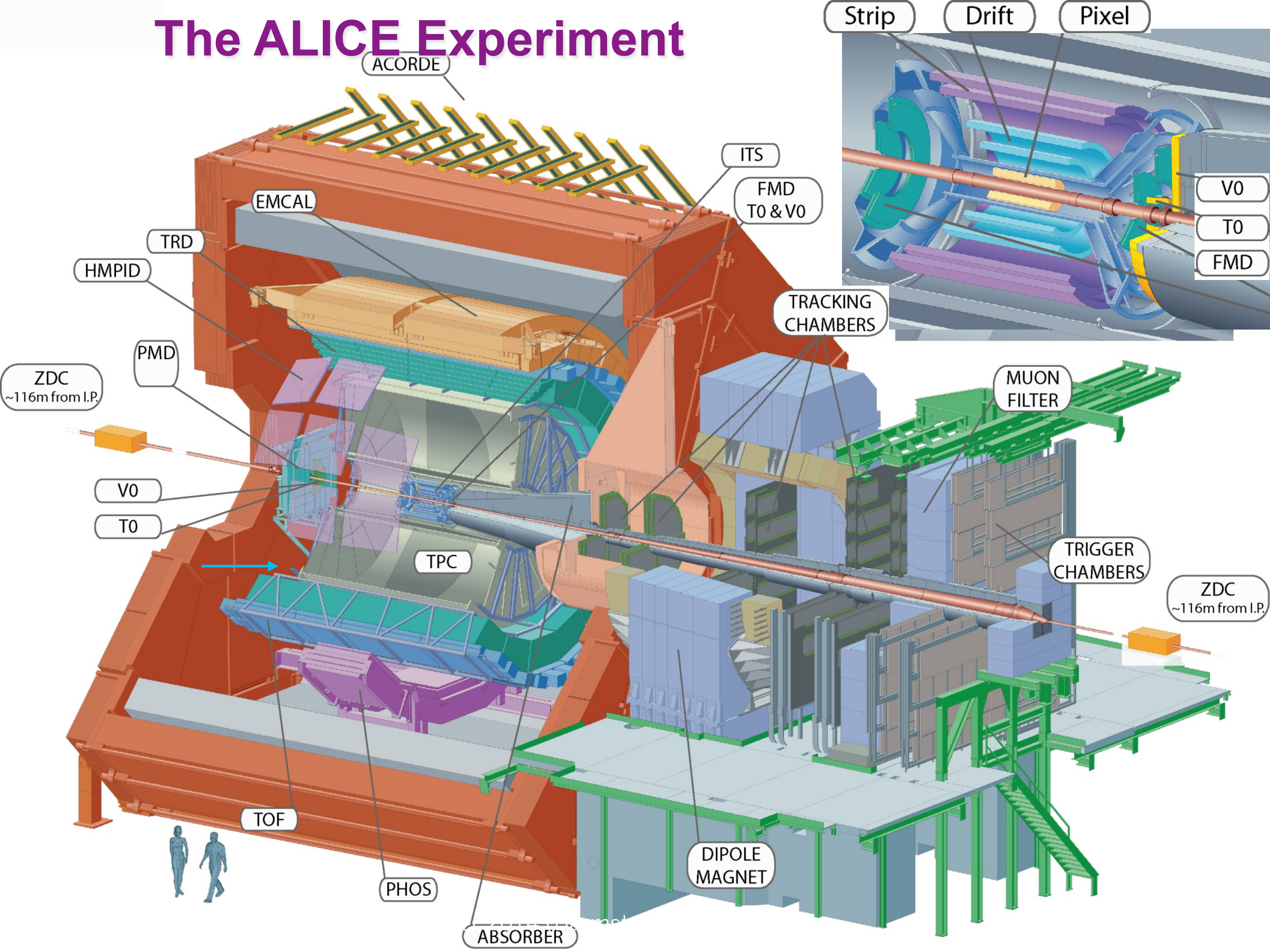
Direct photon yields vs N_{part}



Increase faster than N_{part}

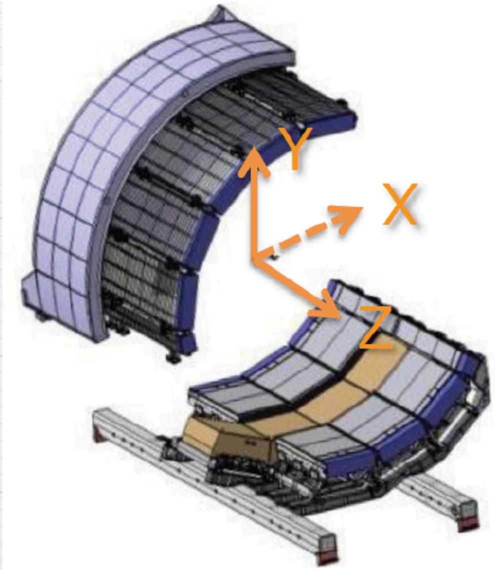
Yields similar at same N_{part}

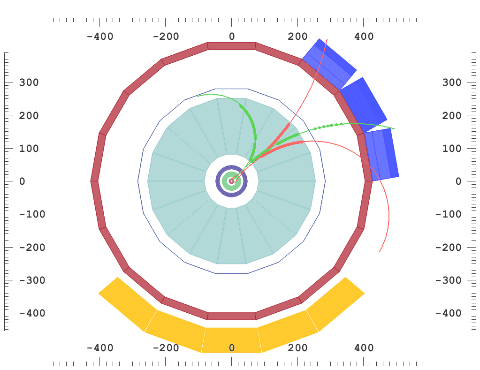
The ALICE Experiment



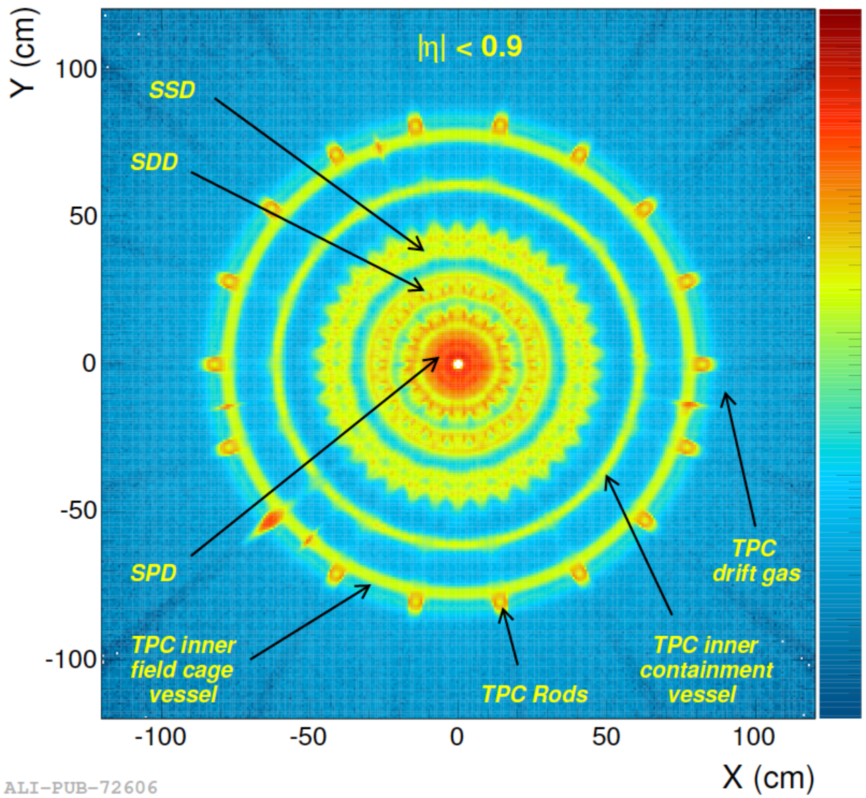
γ detection in ALICE

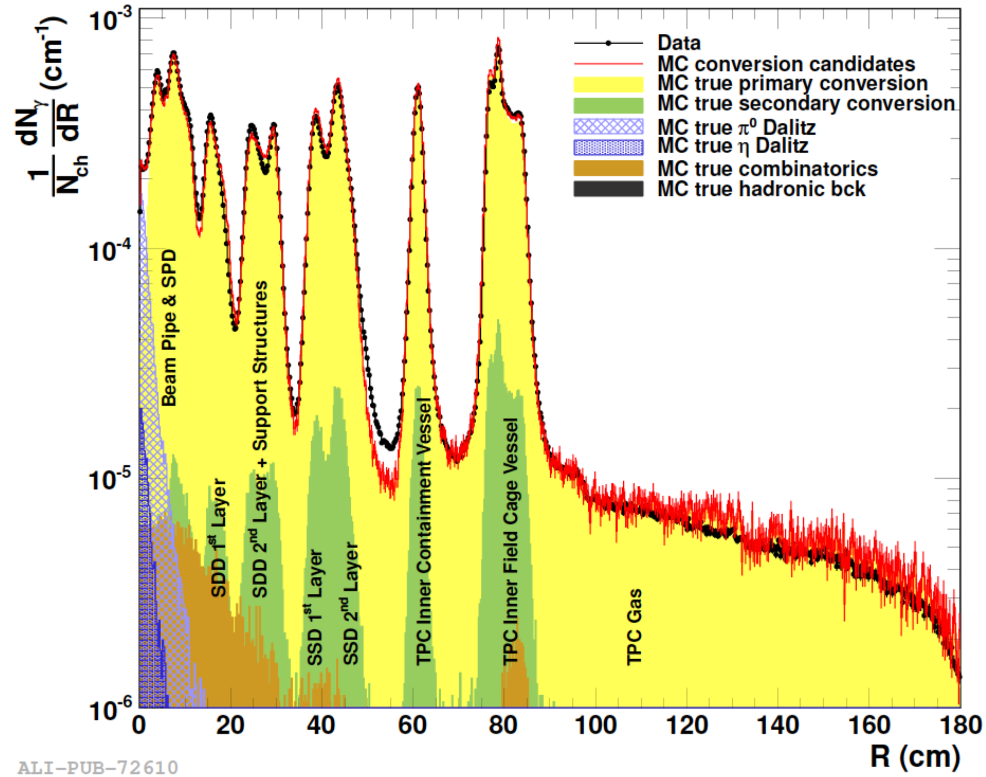
- PHOS calorimeter:
  - $PbWO_4$ crystal
  - 3 modules at 4.6 m from the ALICE IP.
  - $|\eta|<0.13$, $260°<\varphi<320°$
- EMCal/DCal calorimeter:
  - 77 layers 1.4 mm lead + 1.7 mm scintillator
  - 10 modules at 4.4 m from ALICE IP.
  - EMCal: $|\eta|<0.7$, $80°<\varphi<180°$.
  - DCAL: $0.22<|\eta|<0.7$, $\Delta\phi=67°$
- Photon Conversion Method (PCM):
  - Photon conversion in detector material
  - ITS and TPC ($X/X_0=11.4\pm0.5$ sys %)
  - $|\eta|<0.9$, $0°<\varphi<360°$.





γ-ray image of ALICE

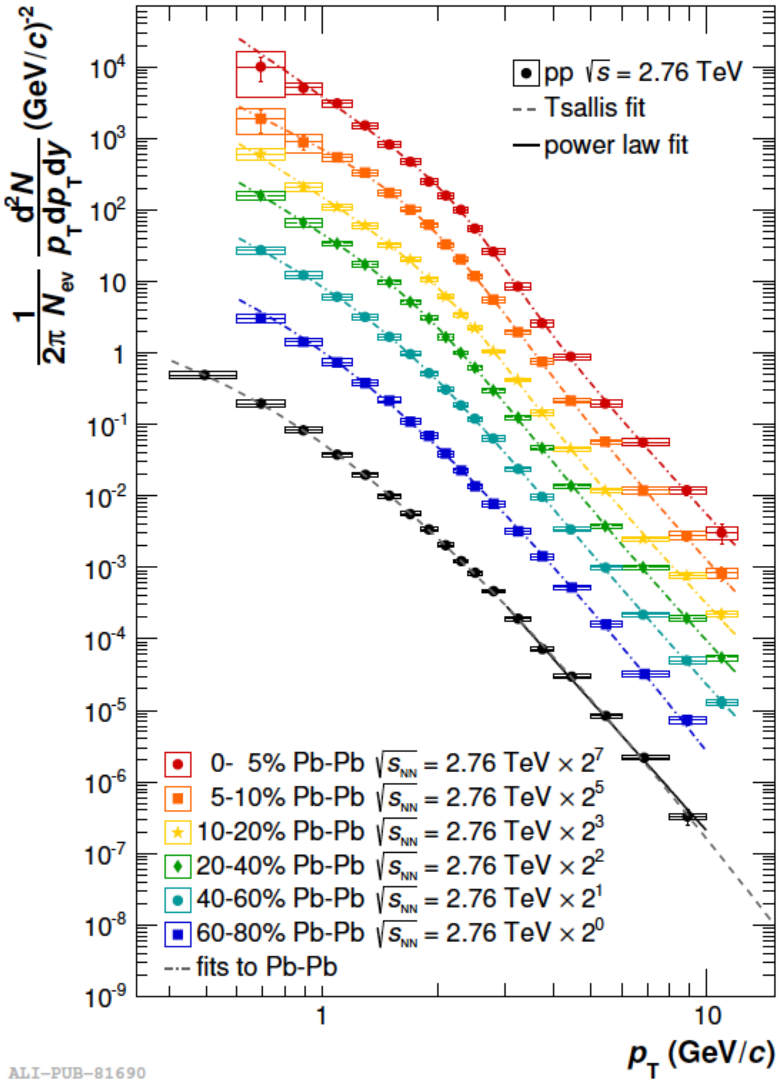




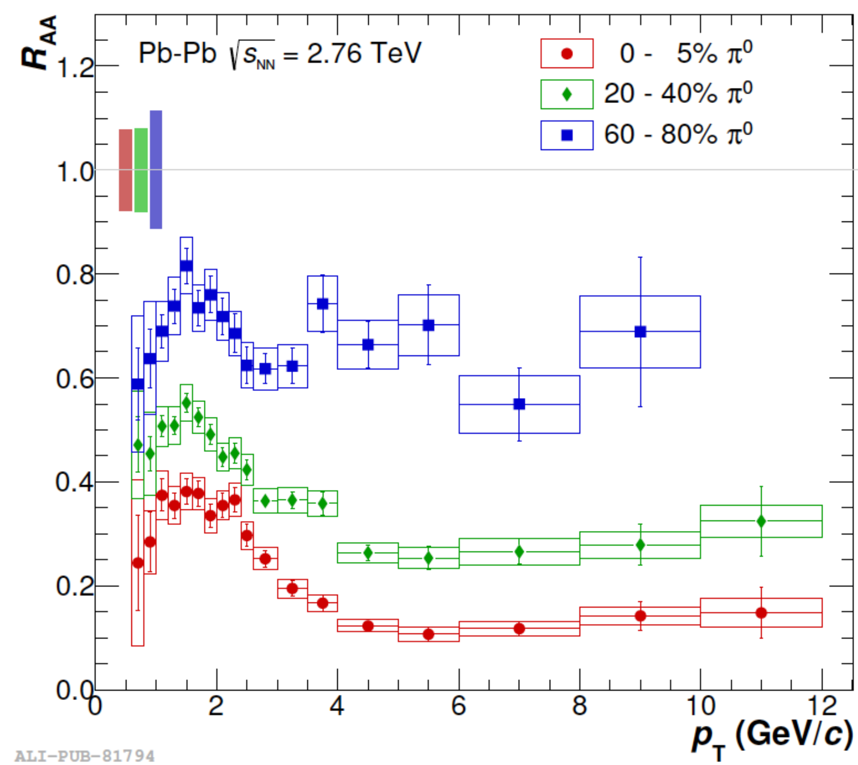
Material thickness is $X/X_0 = 11.4 \pm 0.5_{sys}$ %. ALICE material thickness agrees within ±4.5% with its implementation in GEANT simulations

"ALICE through a gamma-ray looking glass", CERN courier, July 2013
"Performance of the ALICE Experiment at the CERN LHC",
Int.J.Mod.Phys. A29 (2014) 1430044

PbPb@2.76TeV



Eur. Phys. J. C74 no. 10, (2014) 3108

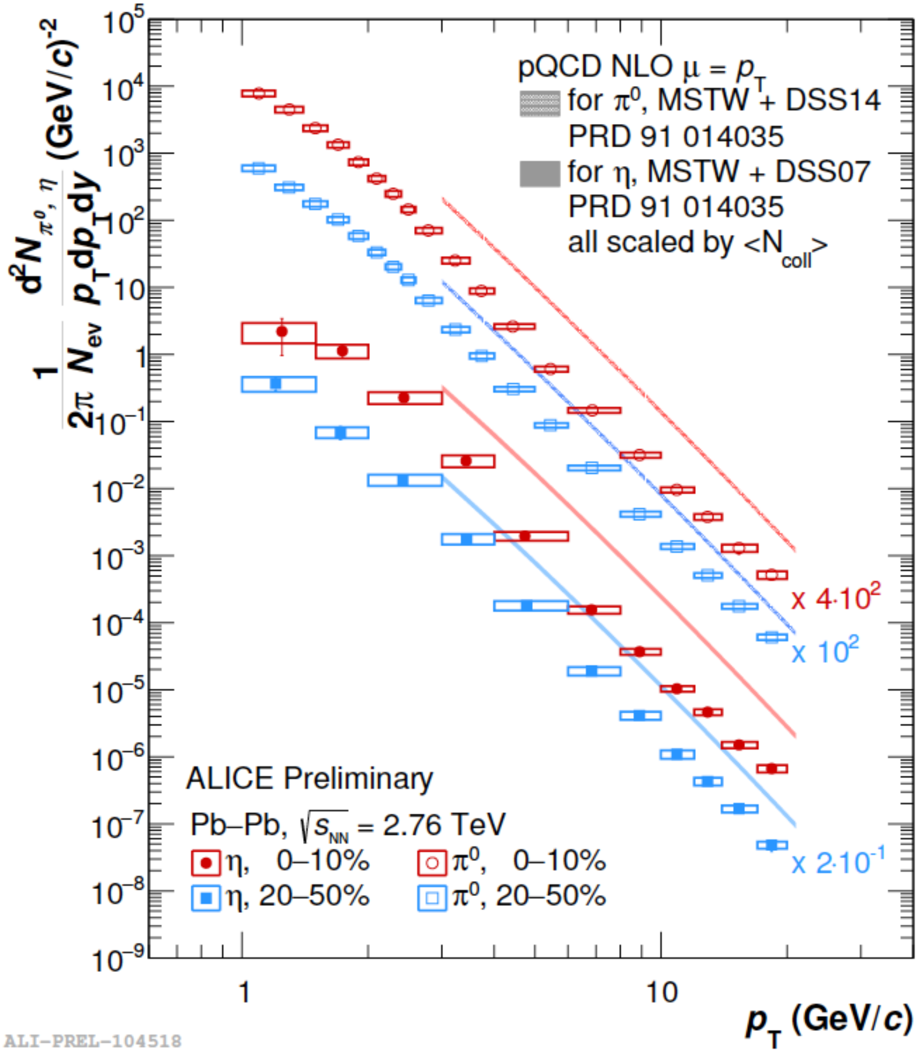


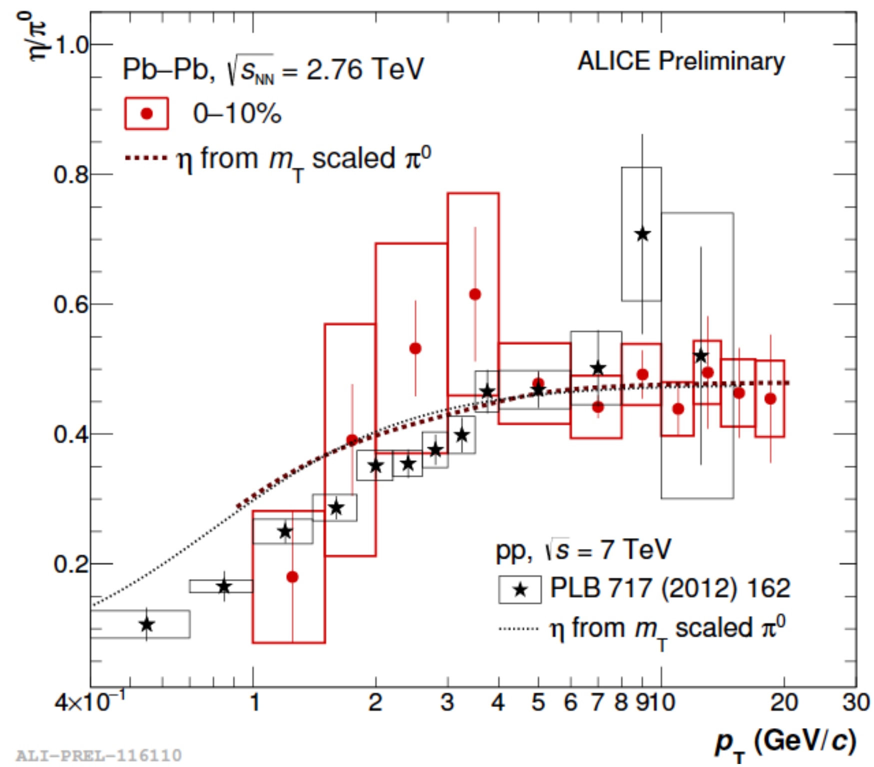
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Large suppression in central collisions

PbPb@2011 Run

Large statistics of 2011 data, makes η measurement possible as well as larger p_T coverage



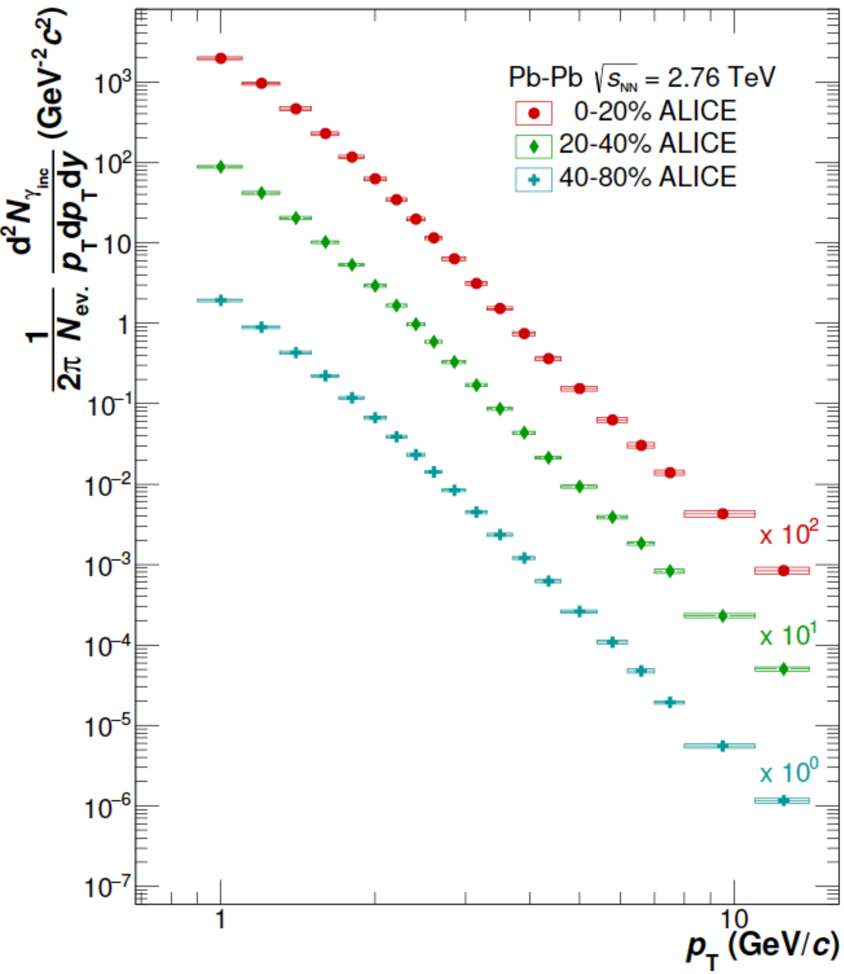


m_T scaling if not measured !

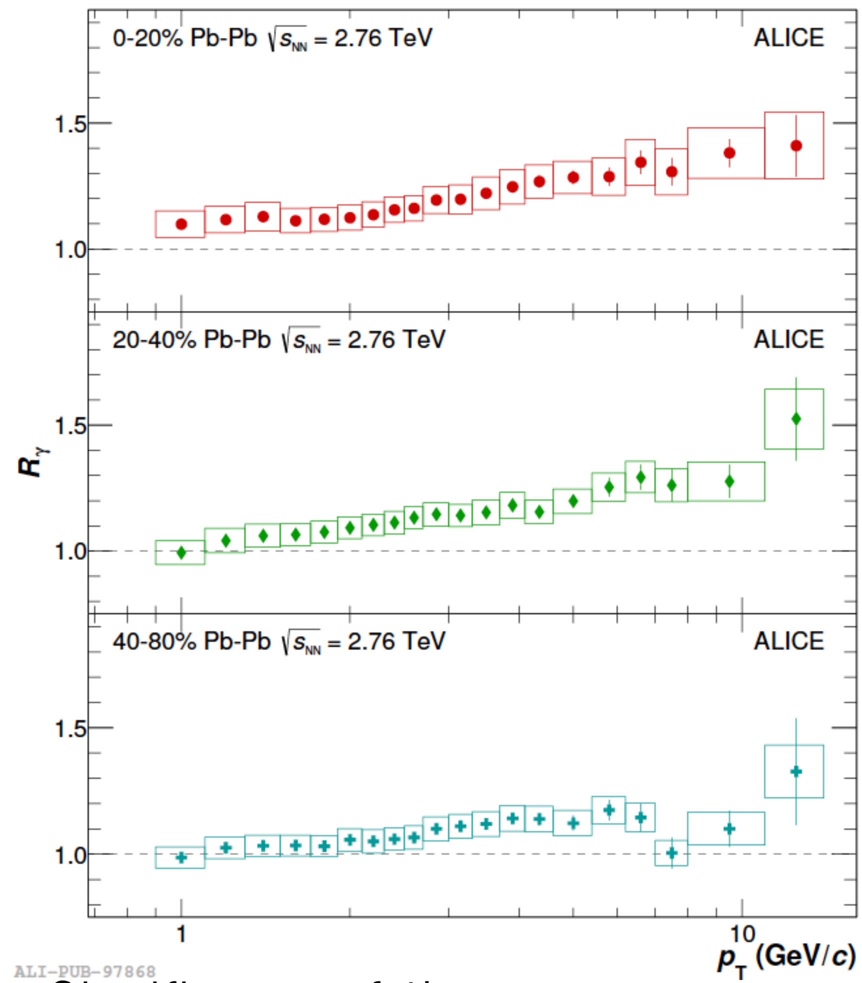
Direct photons @LHC

PLB 754 (2016) 235

Inclusive photon spectrum



Rγ

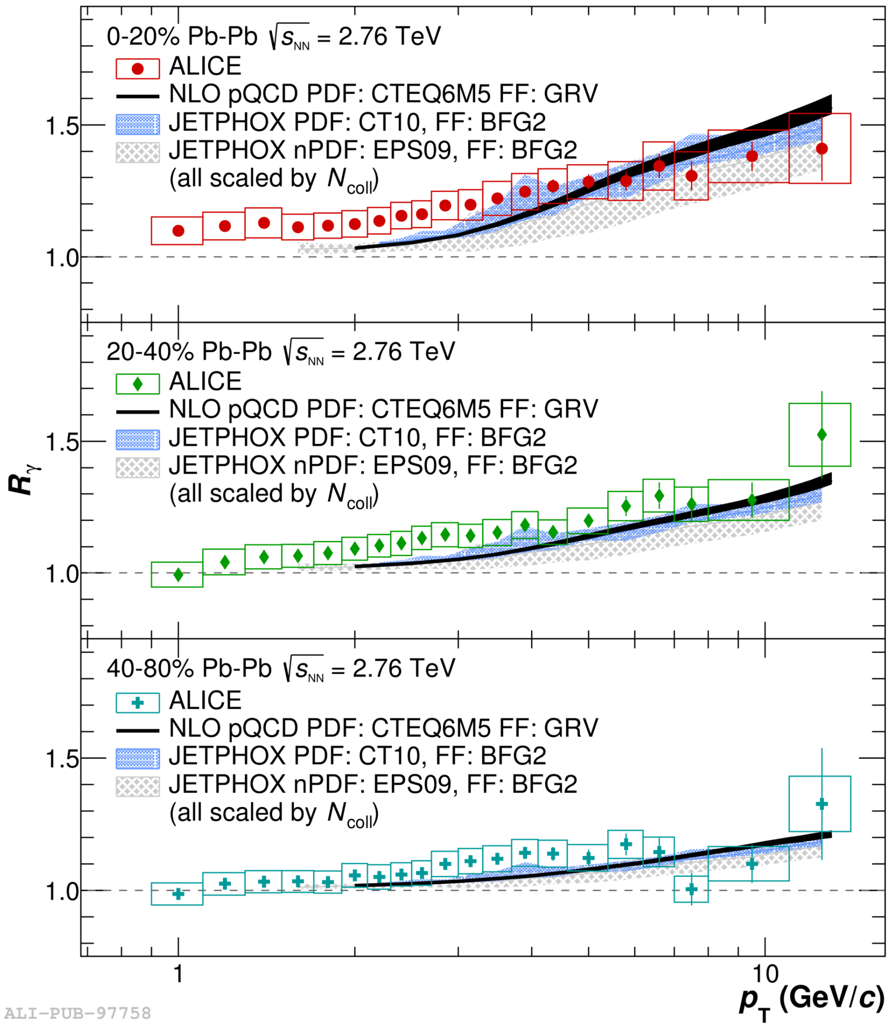


Significance of the excess for $0.9 < p_T < 2.1$ GeV/c:

2.6σ for 0-20%

Direct photons@PbPb

PLB 754 (2016) 235



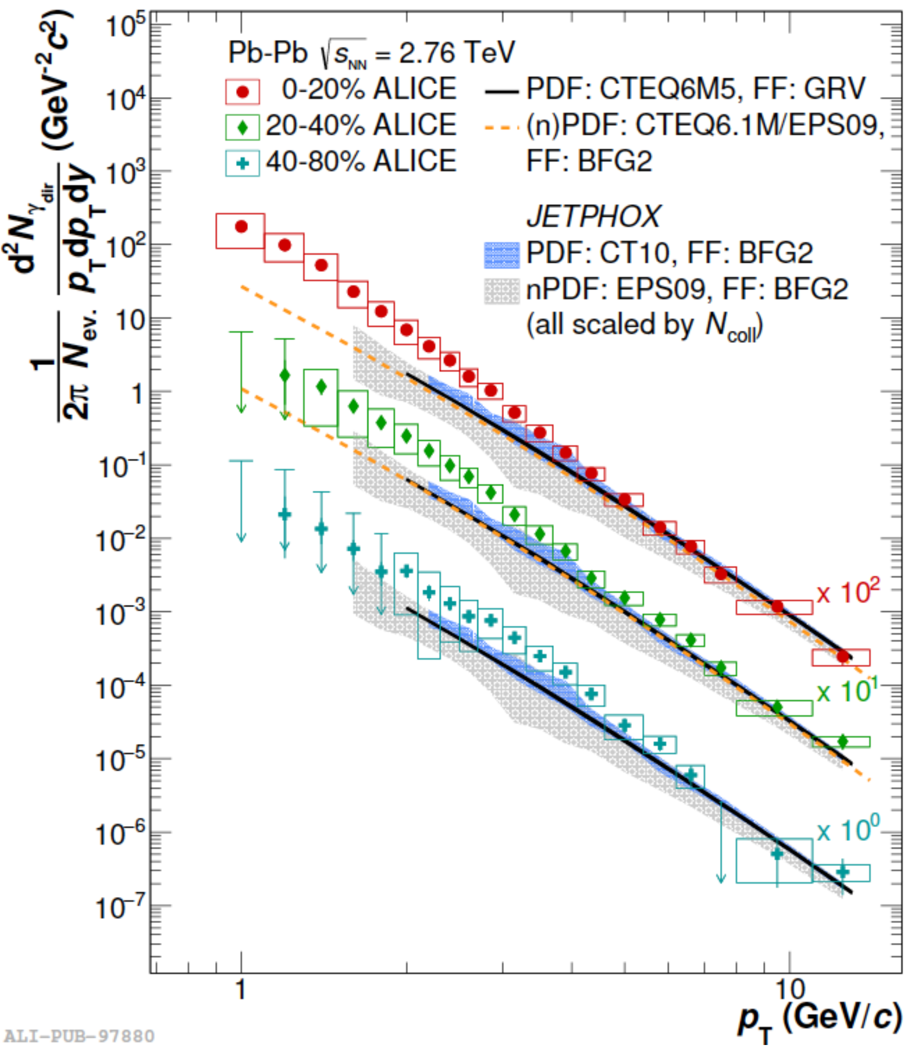
$$R_\gamma^{pQCD} = 1 + N_{coll} \frac{\gamma_{pQCD}}{\gamma_{decay}}$$

pQCD agrees with data for $p_T \gtrsim 5$ GeV/c

Excess beyond known prompt yield $1<p_T<4$ GeV/c:
- Increases for more central collisions
- Consistent with thermal radiation

Comparison to models

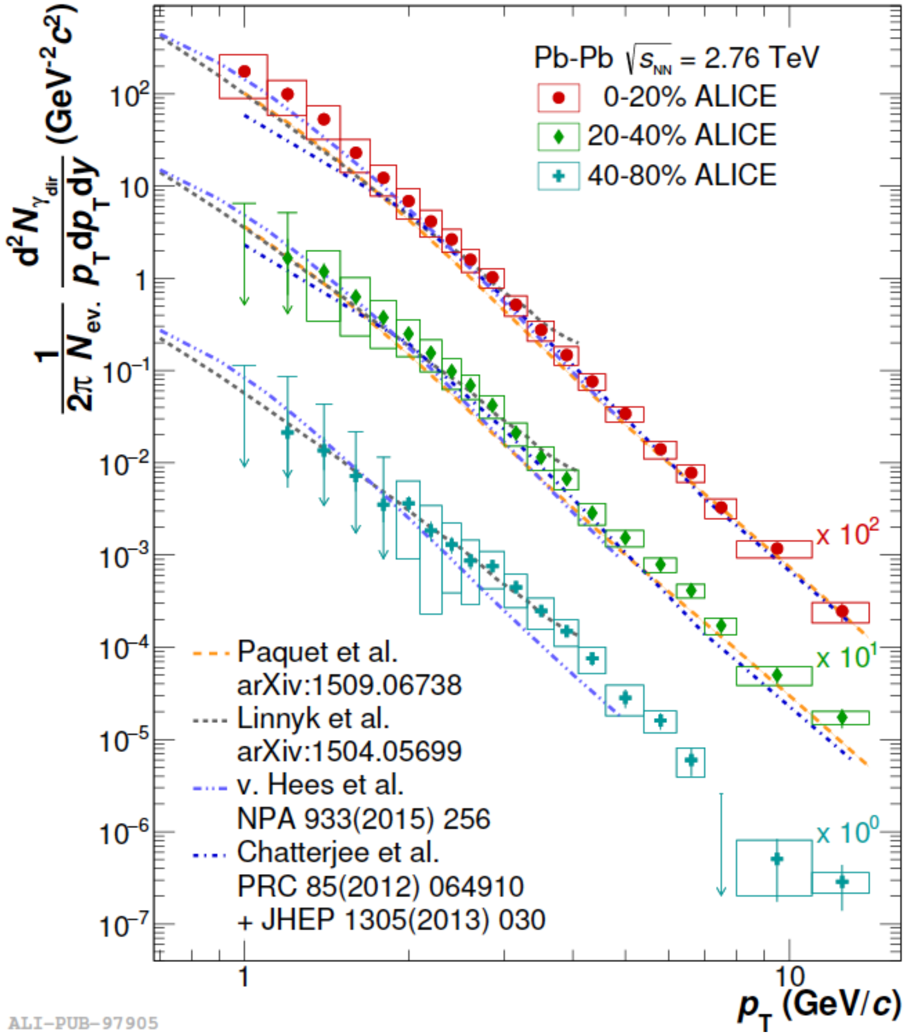
PLB 754 (2016) 235



Approximately exponential spectrum for $p_T \lesssim 3$ GeV/c

Comparison to models

PLB 754 (2016) 235



Models (all with QGP formation)

- Paquet et al.:

2+1 viscous hydro with IP-Glasma initial conditions, (τ = 0.4 fm/c, $T_{0\text{-}20\%}$ = 385 MeV)

- Linnyk et al.:

Off-shell transport, microscopic description of evolution

- v. Hees et al.:

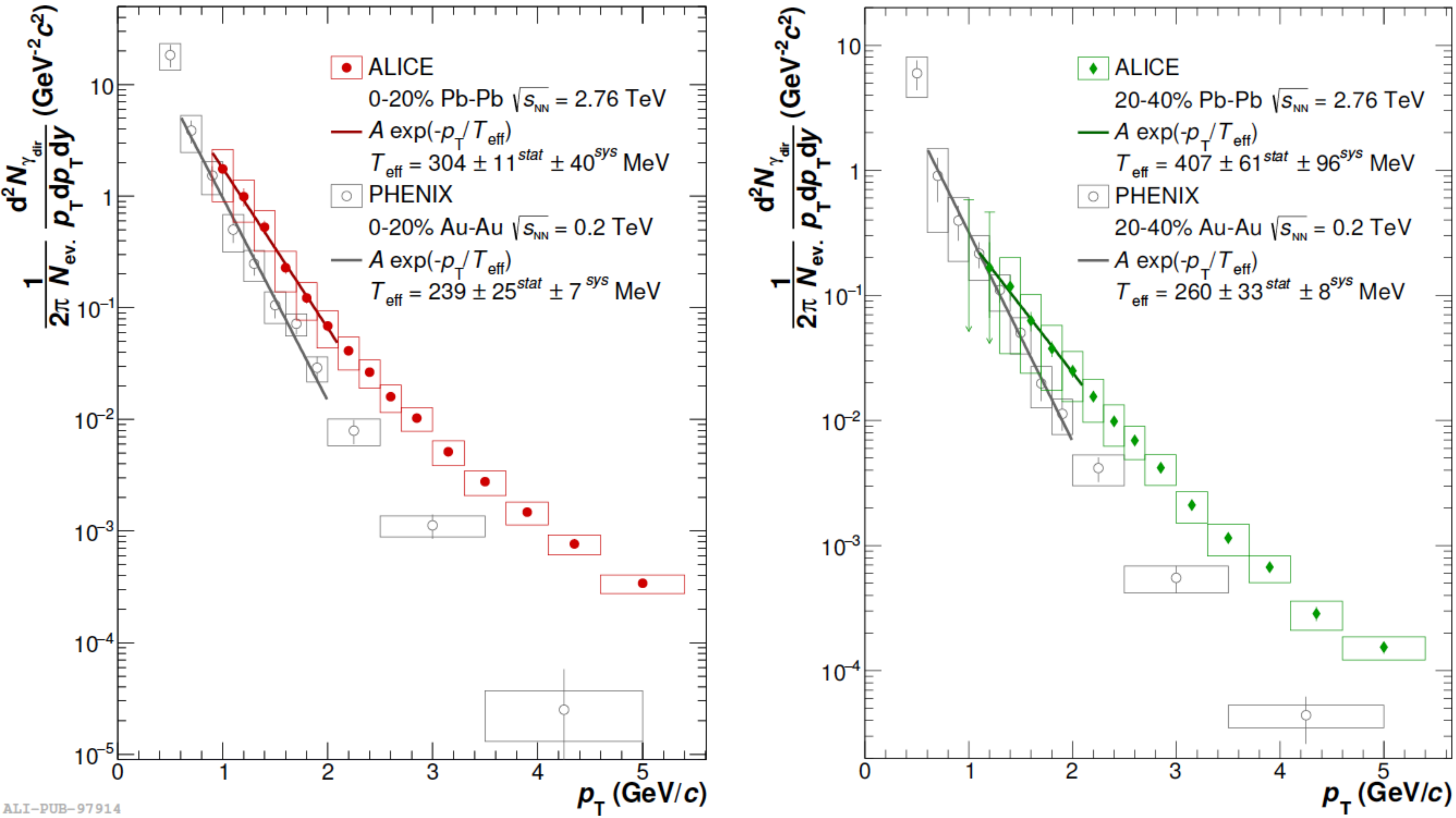
Ideal hydro with initial flow, (τ = 0.2 fm/c, $T_{0\text{-}20\%}$ = 682 MeV)

- Chatterjee et al.:

2+1 hydro, fluctuating initial conditions, (τ = 0.14 fm/c, $T_{0\text{-}20\%}$ ≈ 740 MeV)

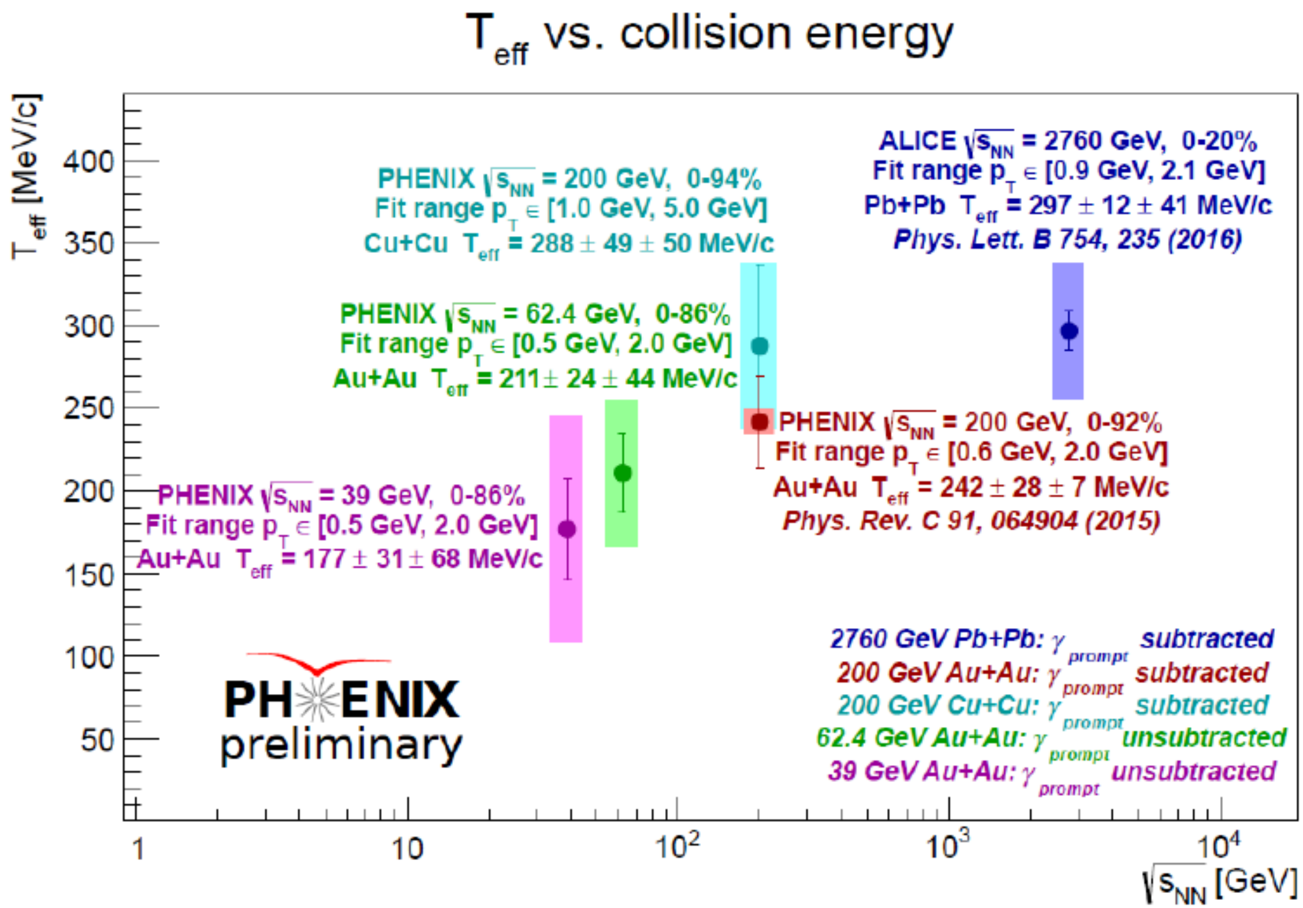
Currently not possible to rule out one or more of these models

Direct photons: LHC vs RHIC



Higher effective temperature at LHC than at RHIC

Teff vs $\sqrt{s}_{NN}$

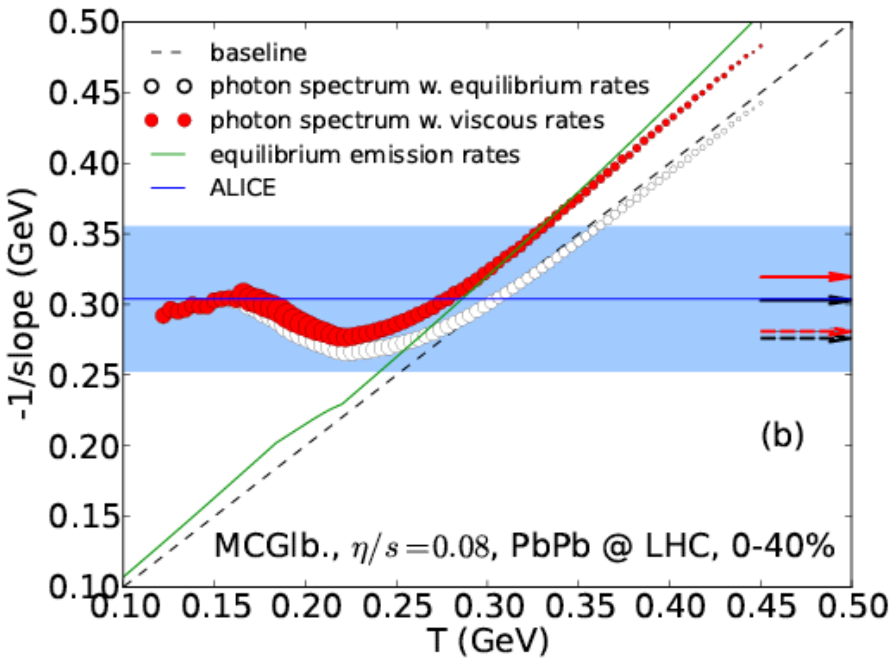


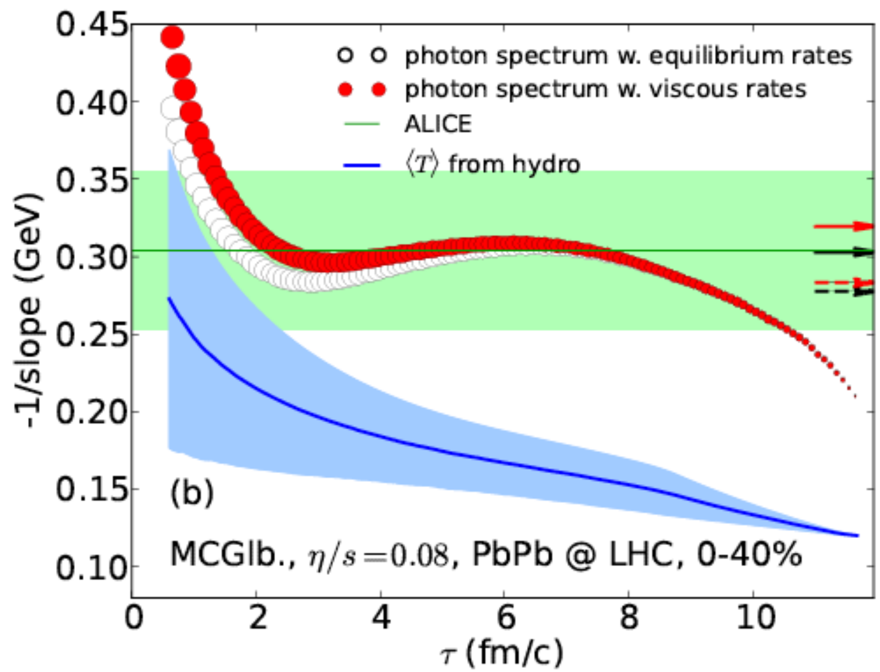
Hint of increase of Teff with √sNN . Also consistent with constant

T_{eff} : blueshift due to radial flow

Phys. Rev. C 89, 044910 (2014)

$$T_{eff} = \sqrt{\frac{1+\beta_{flow}}{1-\beta_{flow}}}T$$

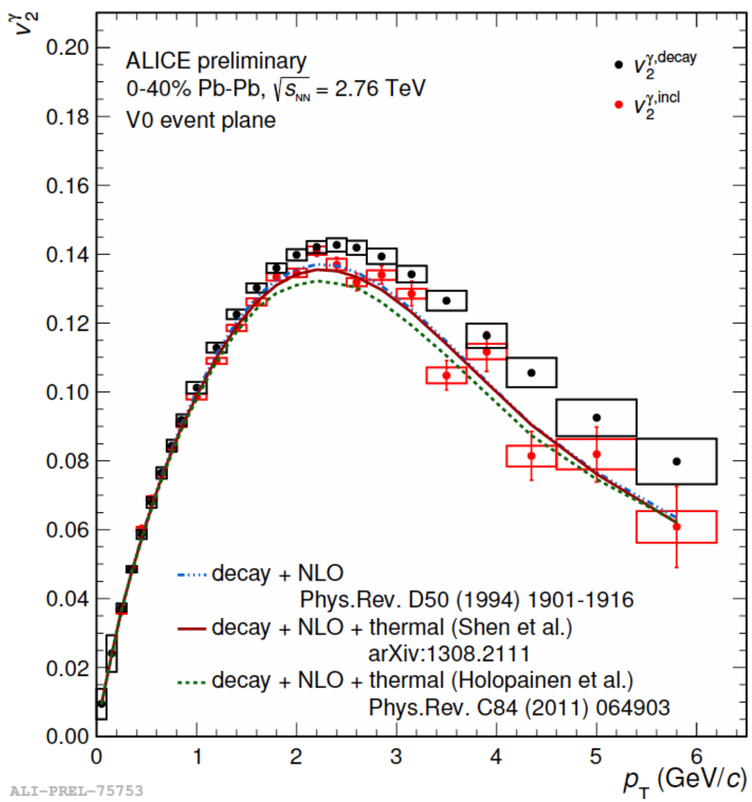




- Large blueshift at late times when T ≈ 150 - 200 MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

Inclusive and decay γ v_2

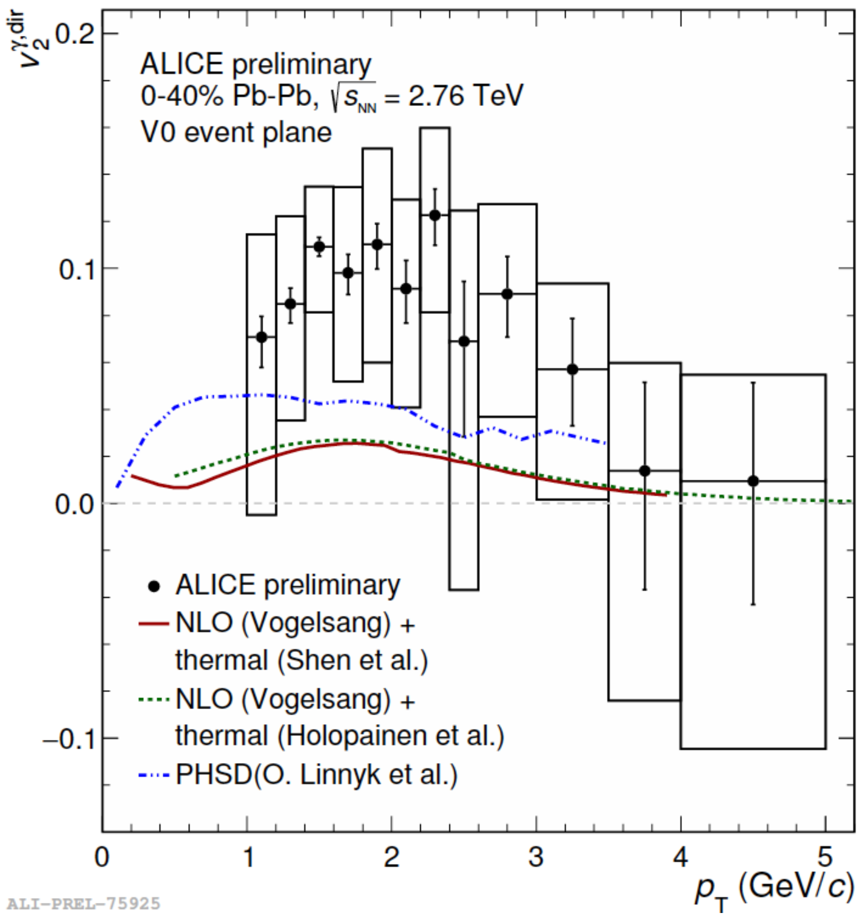
$$v_2^{\text{direct }\gamma} = \frac{R_\gamma \cdot v_2^{\text{inc }\gamma} - v_2^{\text{decay }\gamma}}{R_\gamma - 1}$$



- $v_2^{\text{incl}} < v_2^{\text{decay}}$ for $p_T > 3$ GeV/c
  - Expected from $v_2 = 0$ of prompt photons
- $v_2^{\text{incl}} \approx v_2^{\text{decay}}$ for $p_T < 3$ GeV/c
  - If there is a large direct photon component its v_2 must be very similar to the decay photon v_2
  - v_2^{incl} described by models with small R_γ ($\lesssim 1.05$) predicted by the same models

J. Phys. Conf. Ser. 446 (2013) 012028

Direct γ v_2

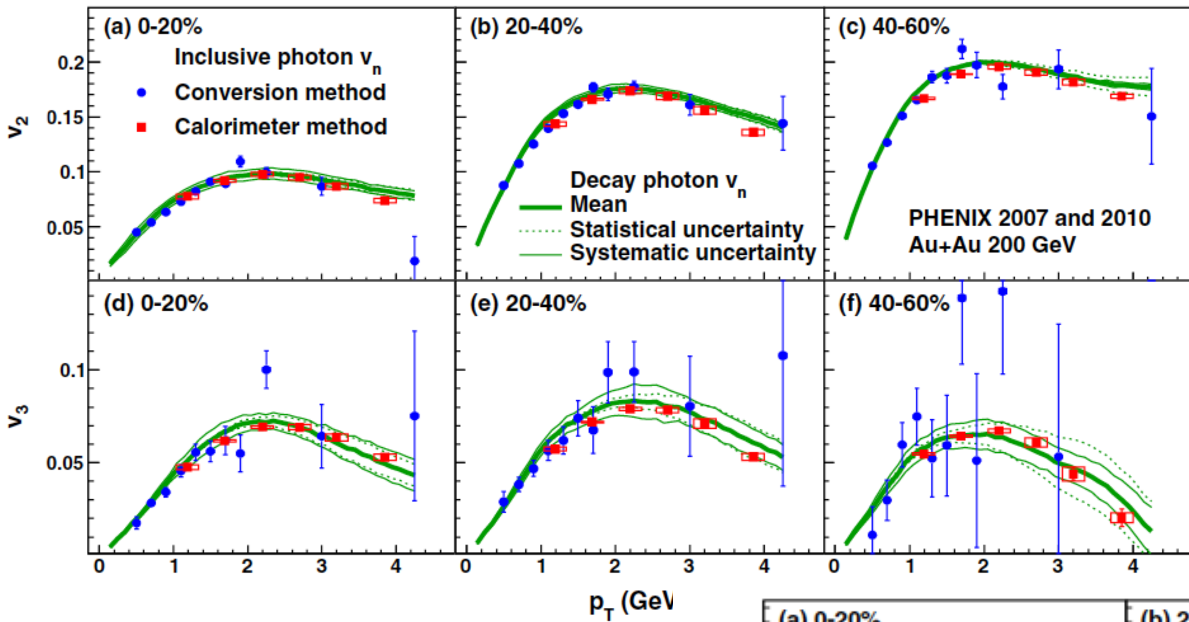


$v_2^{\gamma\,dir}$ only slightly lower than v_2^{incl}

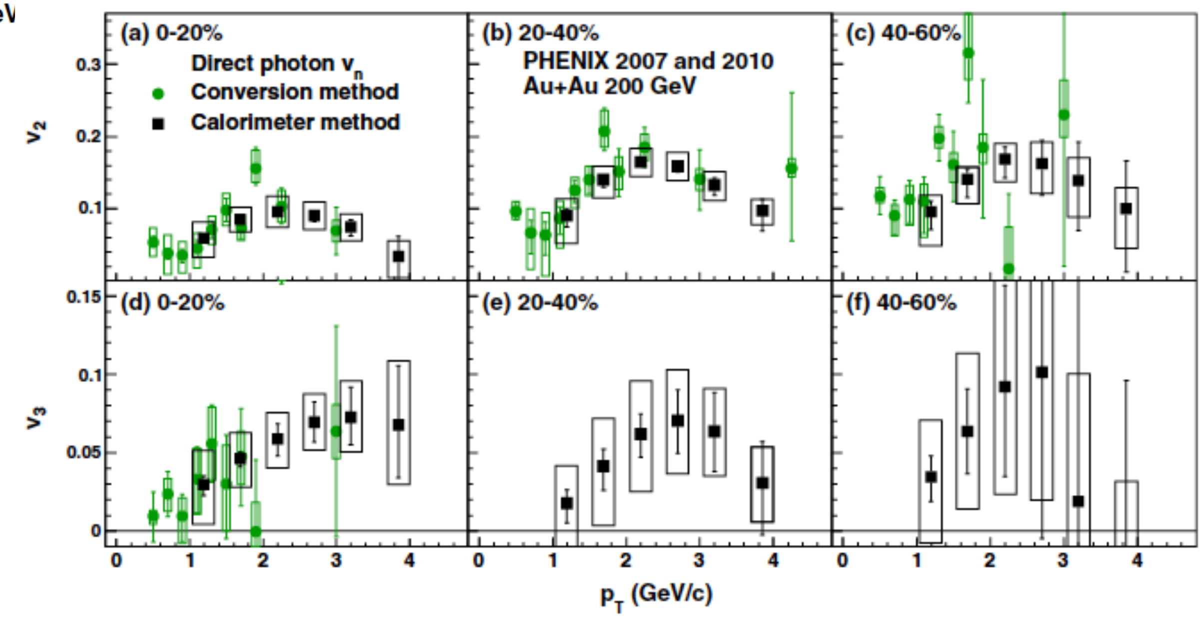
- Many direct photons from late stage with T ≈ Tc ≈ 150 - 160 MeV?
- Then large inverse slope parameter due to Doppler blueshift with typical hadronic flow velocity β flow ≈ 0.6 c?

- However, current systematic uncertainties are sizable so that there is no big puzzle looking at the ALICE data alone

Inclusive, decay and direct γ v_2, v_3



PHENIX

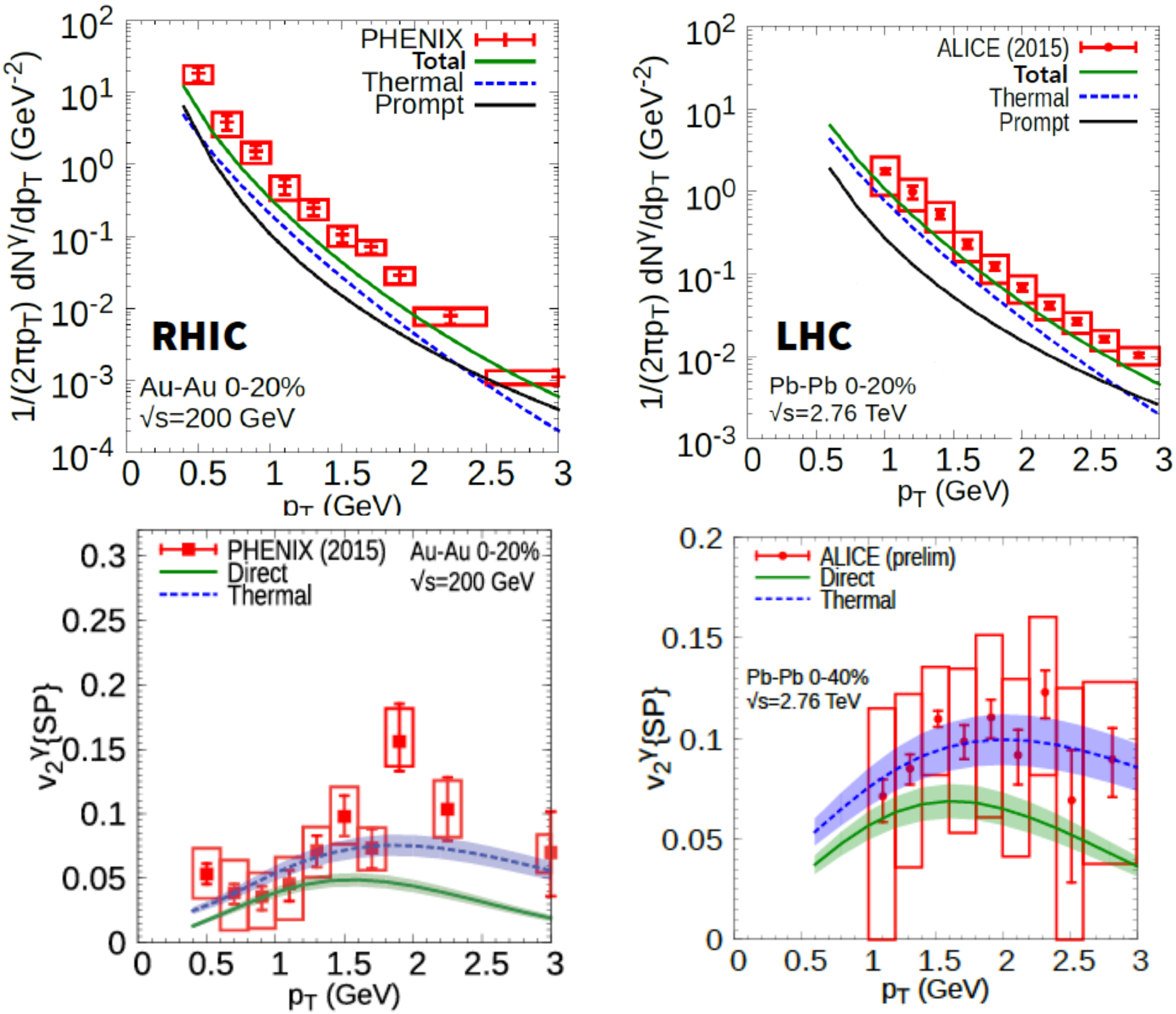


Anisotropic emission of direct photon with large v_2 and v_3

Phys. Rev. C94,064901(2016)

Direct photon puzzle

Phys. Rev. 93,044906 (2016)



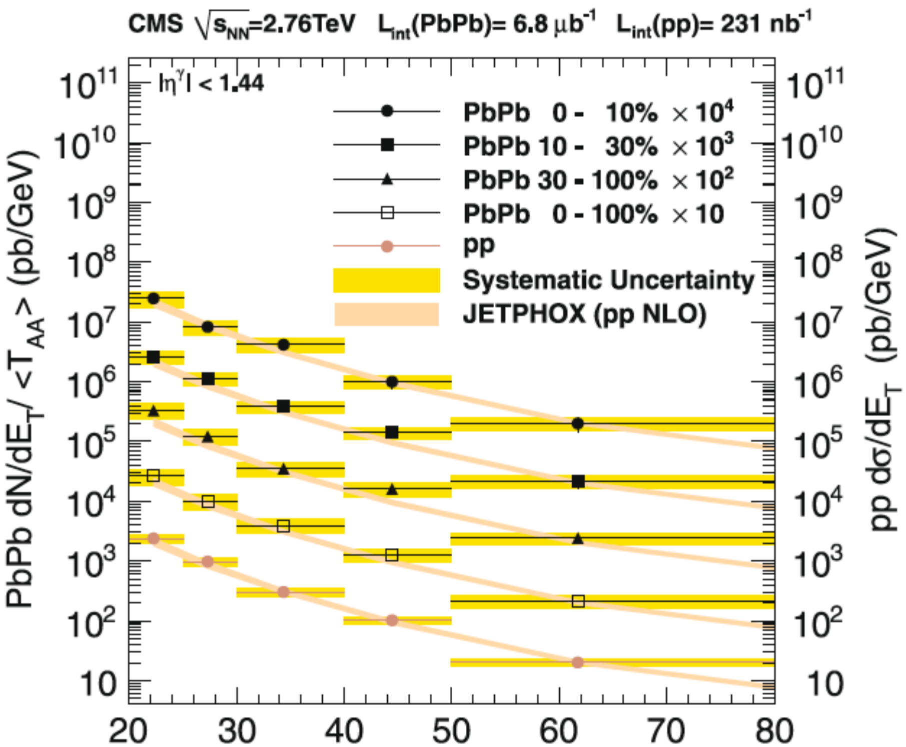
Difficulties for theory to reproduce simultaneously :

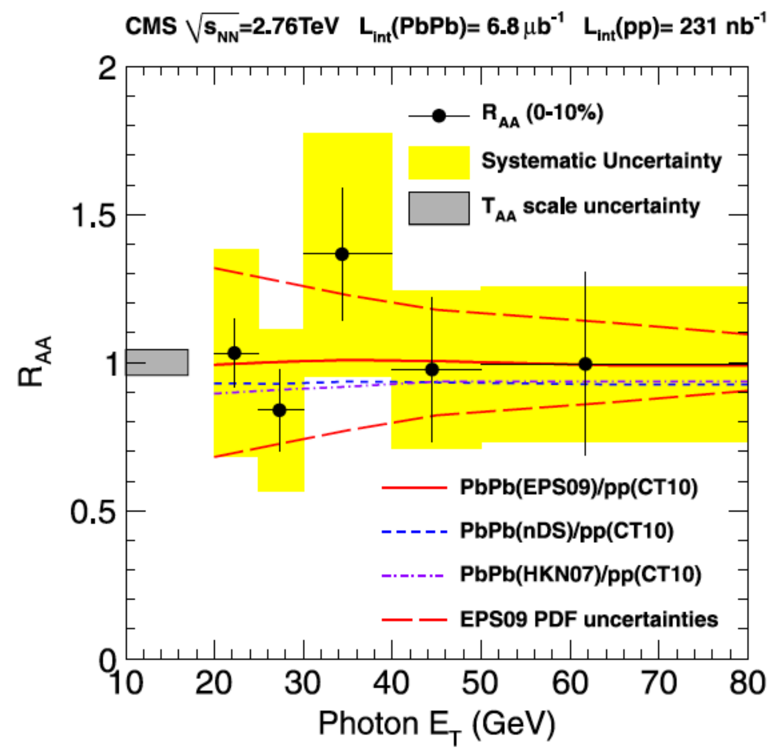
- Large low p_T yields
- large v_2 values

At RHIC

At LHC no puzzle with the current uncertainties

Isolated photon production in PbPb@ 2.76ATeV





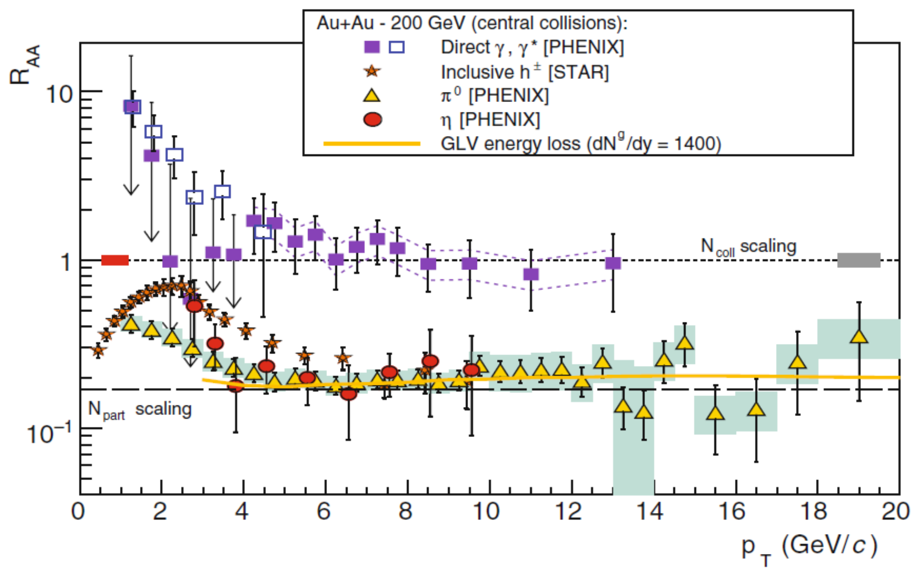
Phys. Lett. B 710 (2012) 256

- The pp and PbPb data are consistent with NLO calculations
- R_{AA}~1 for 0-10% central PbPb collisions. Isolated photons unaffected by the QGP

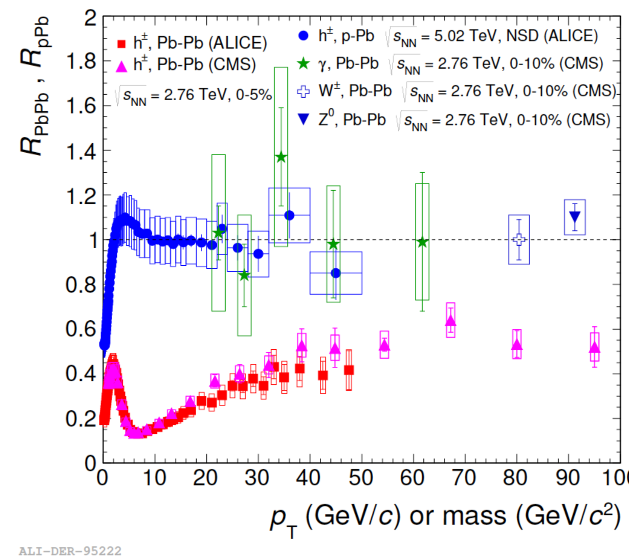
R_{AA}

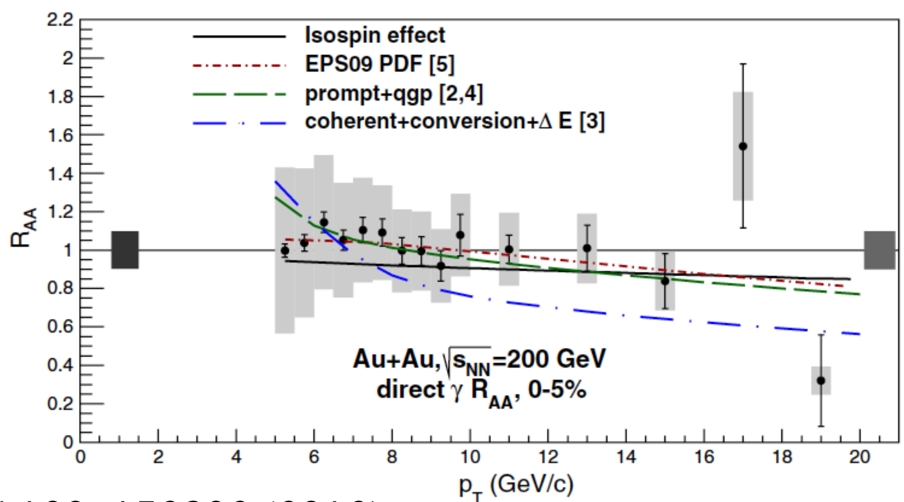
Hadrons are suppressed, direct photons are not

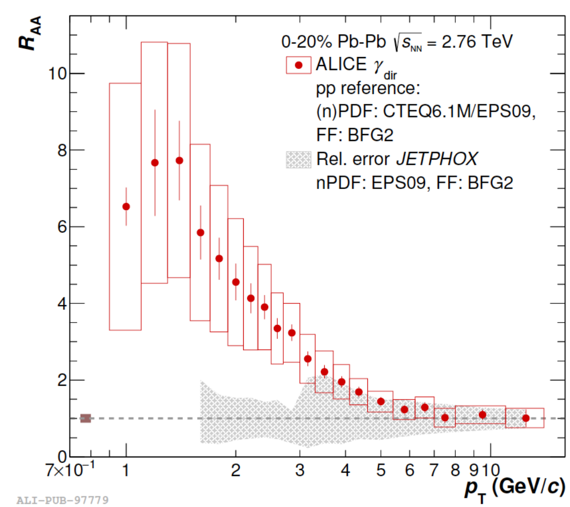
RHIC



LHC







PRL109, 152302 (2012)

DILEPTONS

Dileptons

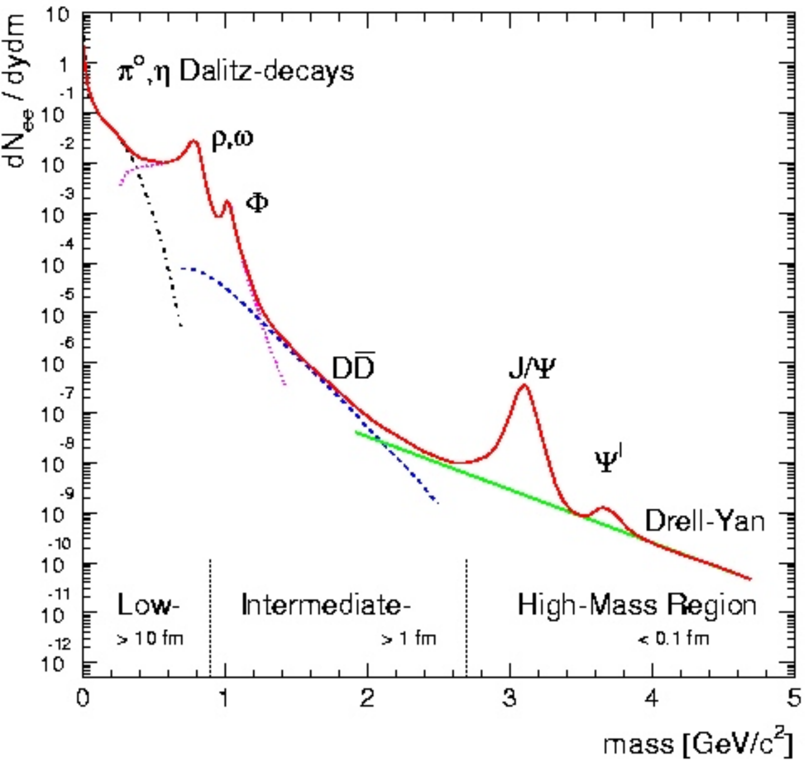
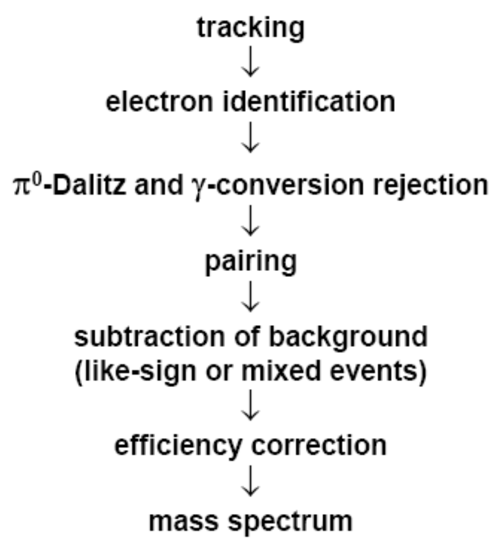


Fig. from A. Drees

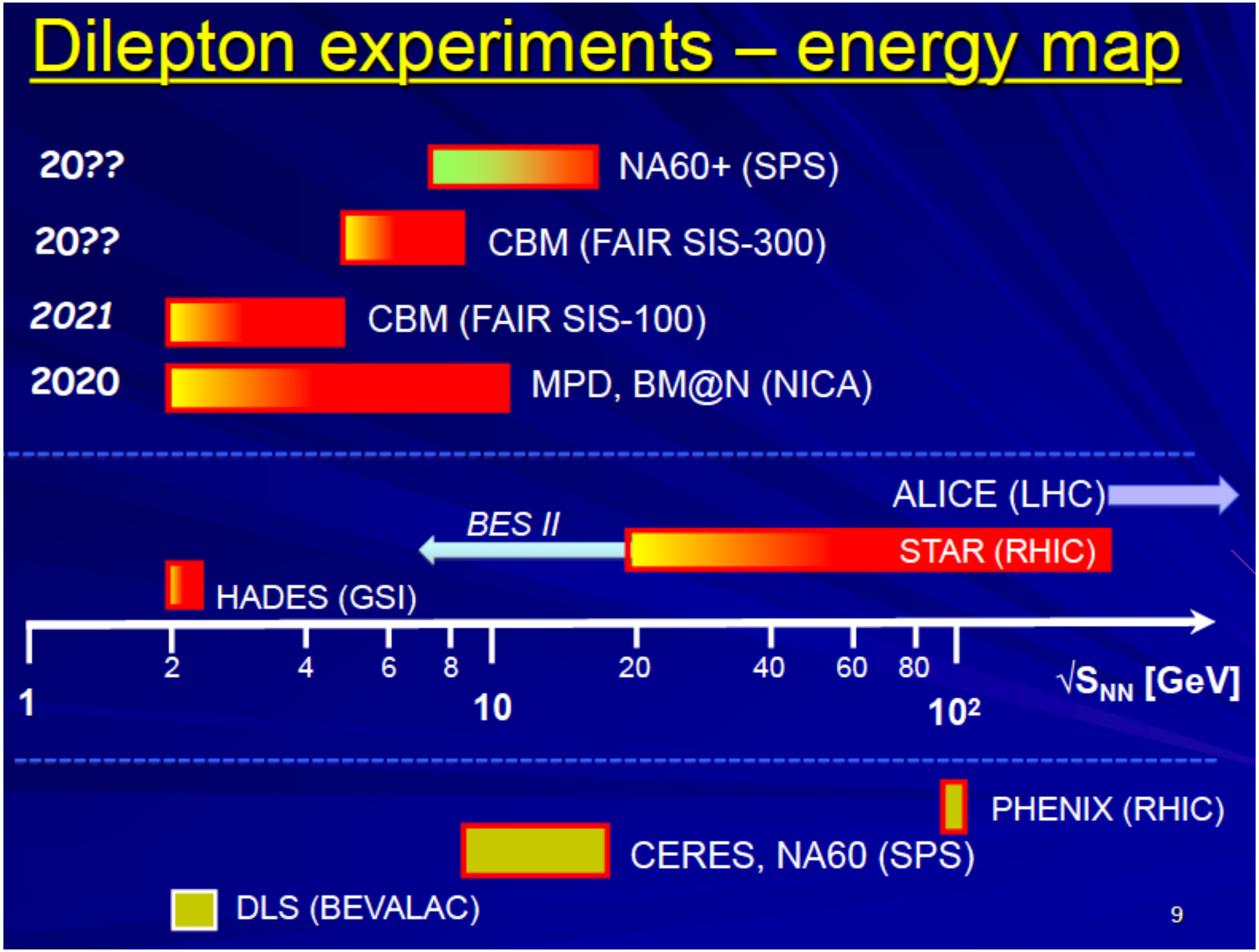
Invariant mass allows separation of different collision stages:

M < 1 GeV: hadronic
hadrons in medium, chiral symmetry restoration
M > 1 GeV: partonic
early temperature, partonic collectivity

Experimental method:



HMR: I. Arsene,
This afternoon



Scheme from I. Tserruya

Dilepton experiments

Nuclear collisions

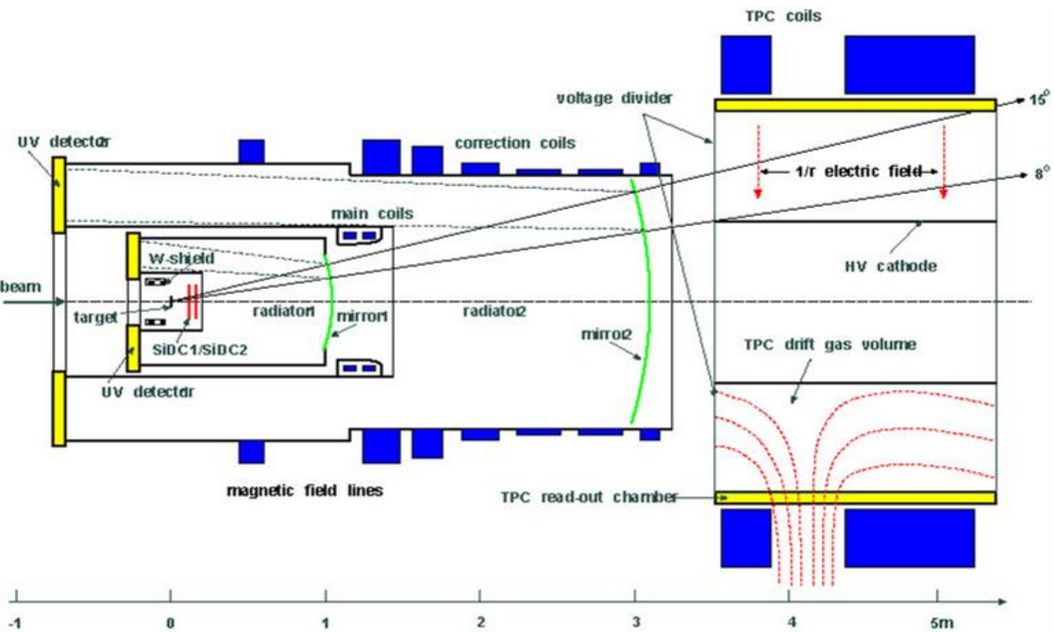
- CERES
- DLS
- HELIOS
- NA38/50
- NA60
- PHENIX
- ALICE
- HADES
- STAR
- BM@N
- CBM
- NA60+
- MPD

Elementary Reactions

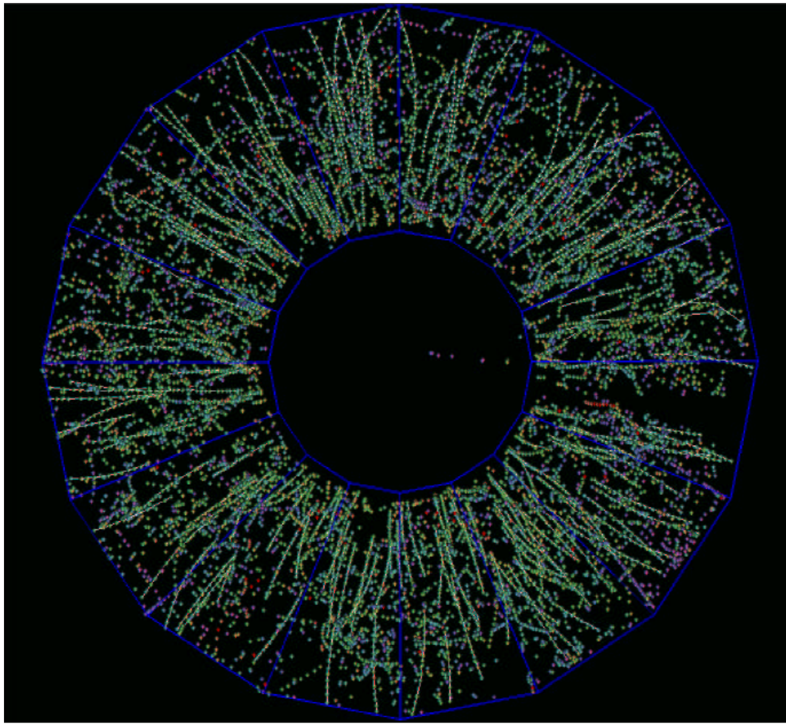
- CLAS
- CBELSA/TAPS
- KEK E235
- TAGX
- JPARC-E16

Completed
Running
Future

The CERES Setup



Pb+Au@$\sqrt{s_{NN}}$=17

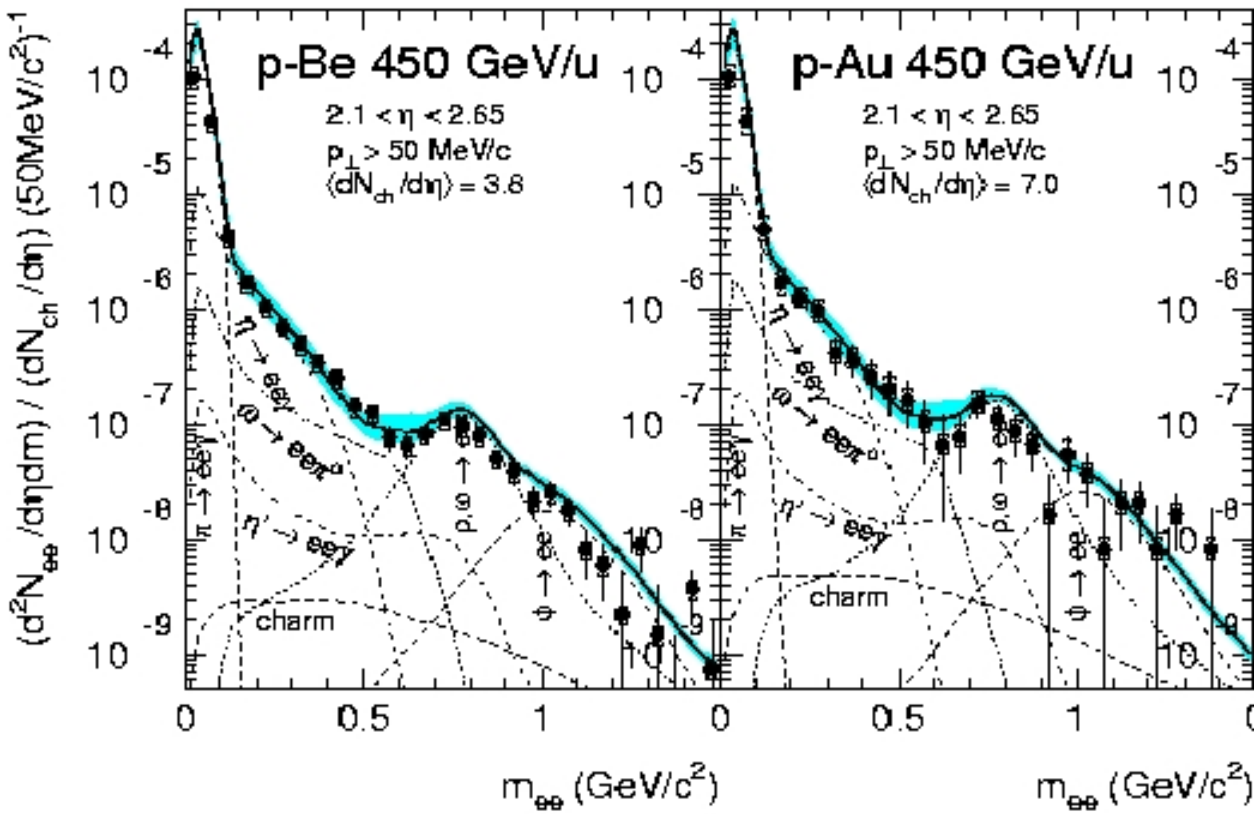


Sidc: vertex reconstruction,
angle measurement
Rich: electron ID
TPC: momentum and
electron-ID (s_{mass}~3.8% at f gee)

Run	p_{beam}		σ/σ_{geo}	Events
92	S+Au	200AGeV	30%	8M
93	p+Be	450 GeV		30M(2 Bill)
93	p+Au	450 GeV		8M(0.3Bill)
95	Pb+Au	158AGeV	35%	8.5M
96	Pb+Au	158AGeV	30%	42M
99	Pb+Au	40AGeV	30%	8M
00	Pb+Au	80AGeV	30%	0.5M
00	Pb+Au	158AGeV	7%	33M

Production of e^+e^- pairs in p+Be(Au) 450GeV

G. Agakichiev et al., Eur. Phys. J. C4 (1998) 231

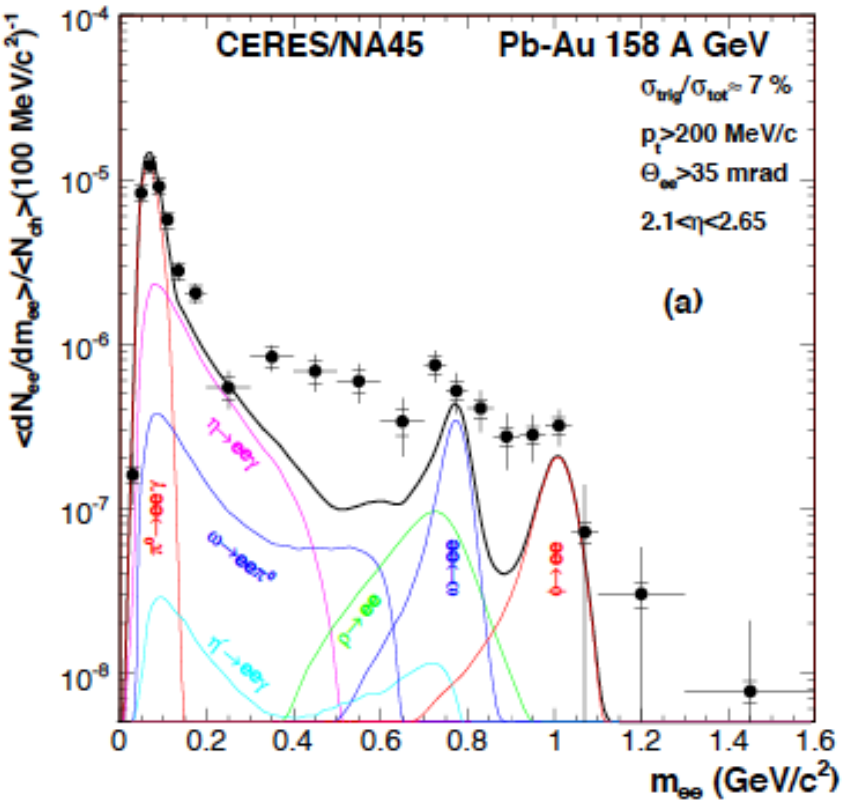


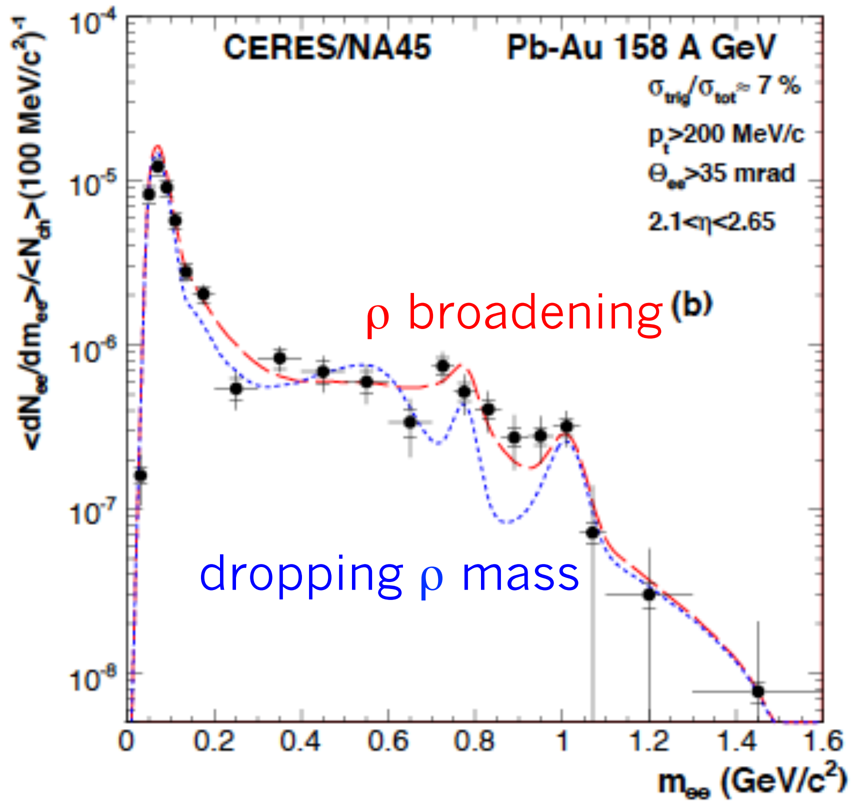
Measured dilepton spectra in good agreement with expectations from hadron decays

CERES dilepton spectrum

Phys. Lett. B666 (2008) 425

mass resolution 3.8%



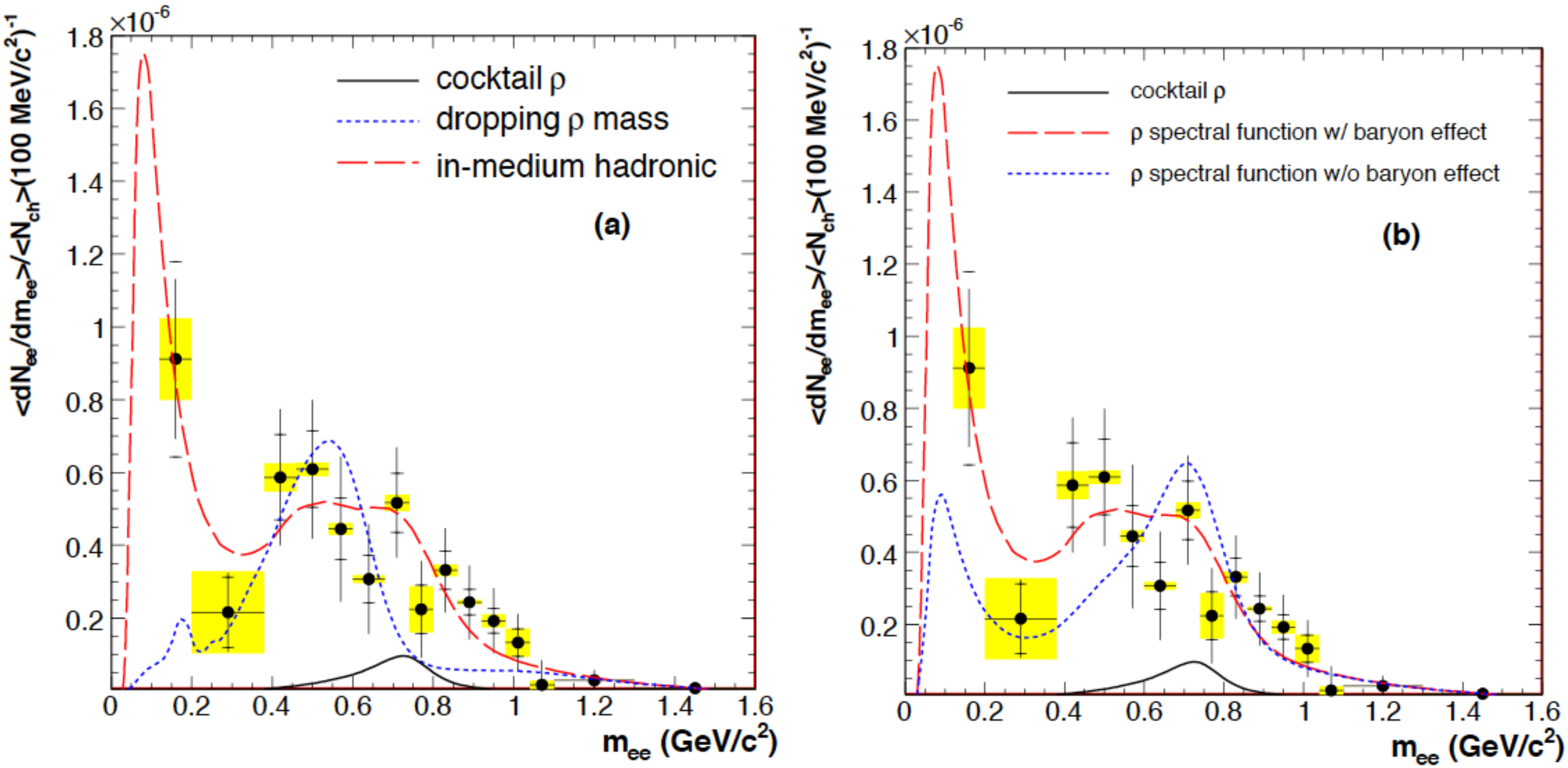


dilepton enhancement at
$0.2<m_{ee}<1.1$ GeV/c^2 :

2.45 ± 0.21 (stat.)
± 0.35 (syst.)
± 0.58 (cocktail)

Data favour ρ broadening
Most evident between ω - ϕ

CERES excess spectrum

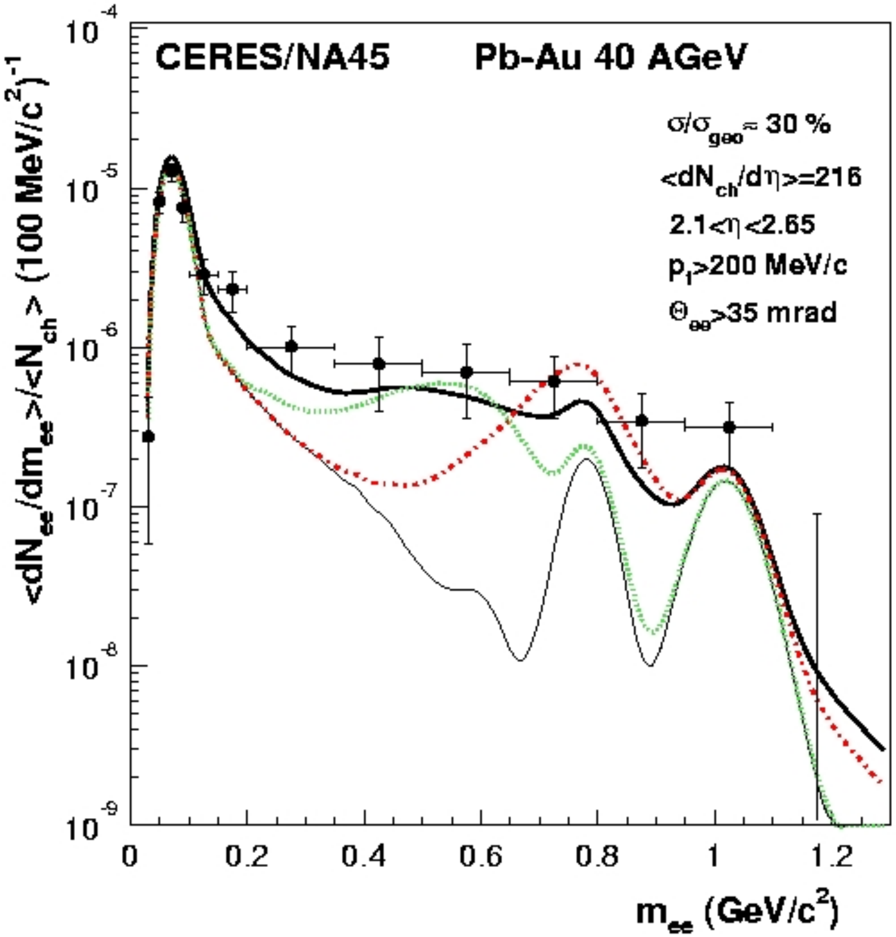


- contribution of ρ at freeze-out totally negligible, medium dominates by more than order of magnitude in central PbPb
- points at 0.7-1 GeV exclude dropping mass

Sensitive to role of baryons in modification

Production of e+e- pairs in Pb+Au 40AGeV

D. Adamova et al., Phys. Rev. Lett. 91(2003) 42301



Calculations Rapp/Wambach

Including pion annihil. only

In-medium ρ modification

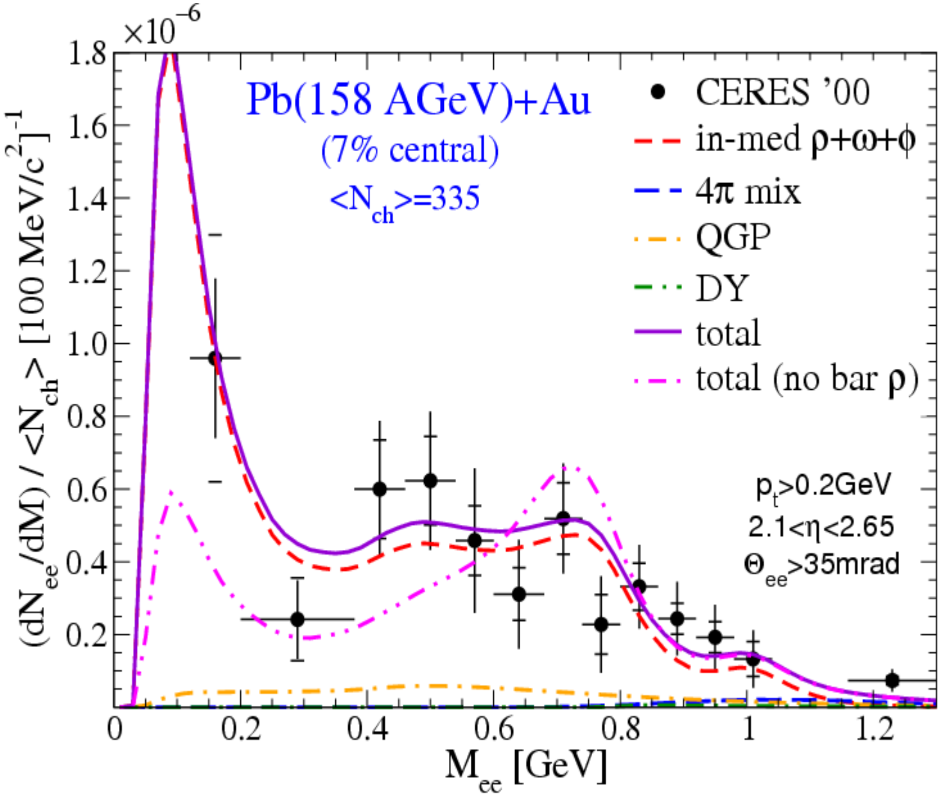
Dropping ρ mass

Enhancement even stronger at lower beam enery
5.9 ± 1.5 (stat) ± 1.2 (syst data) ± 1.8 (decays)
effect of baryon density?

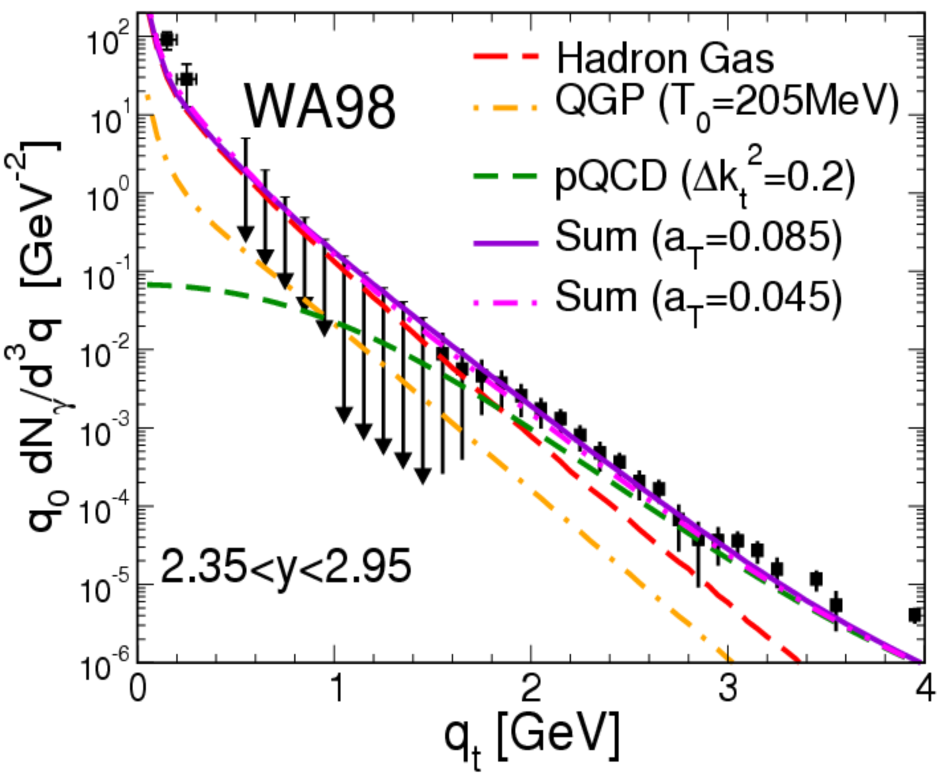
_EM Probes in Central Pb-Au/Pb at SPS

Comparisons with updated calculations

Di-Electrons [CERES/NA45]



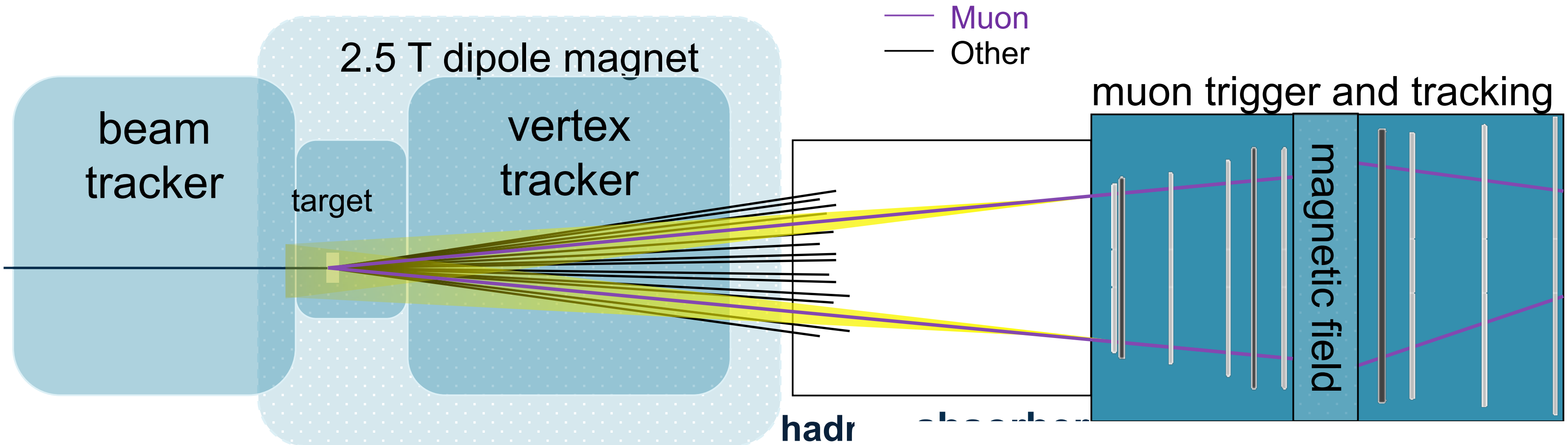
Photons [WA98]

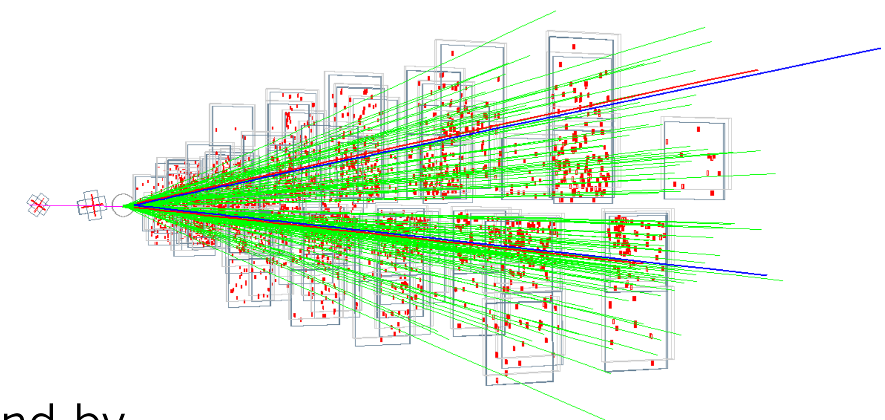


- updated fireball (a_T=0.045→0.085/fm) [van Hees+R.Rapp '07]
- very low-mass di-electrons ↔ (low-energy) photons

[Srivastava et al '05, Liu+R.Rapp '06]

NA60 experiment: $\mu^+\mu^-$





Precision silicon pixel vertex tracker

- tagging of heavy flavor decay muons
- Reduction of combinatorial background by
  - vetoing π, K decay muons

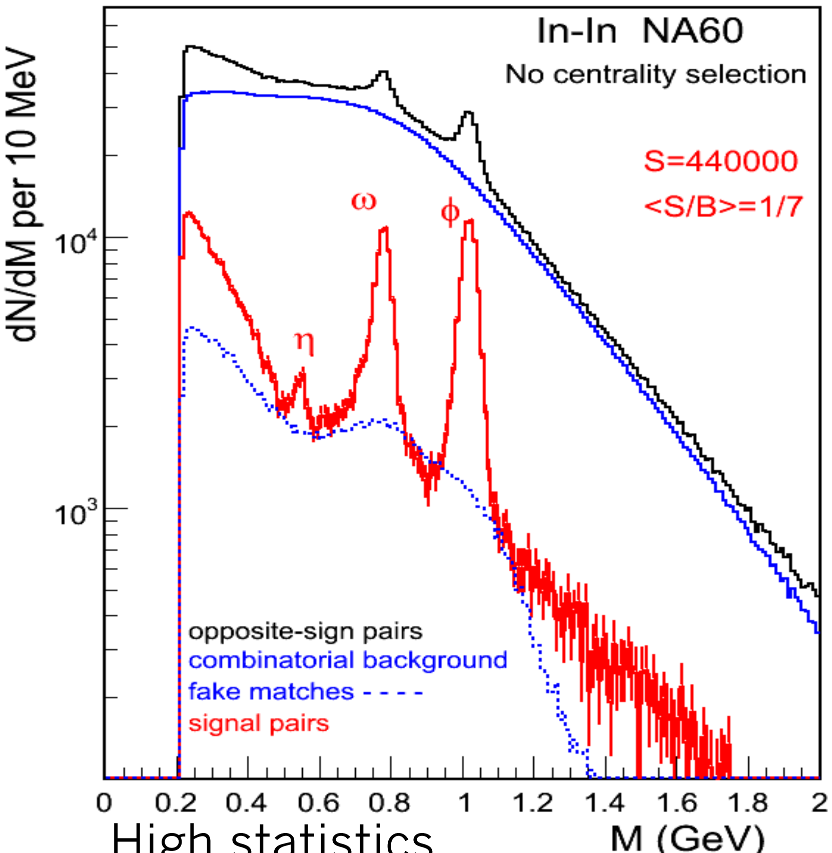
Double dipole for large acceptance (low mass)

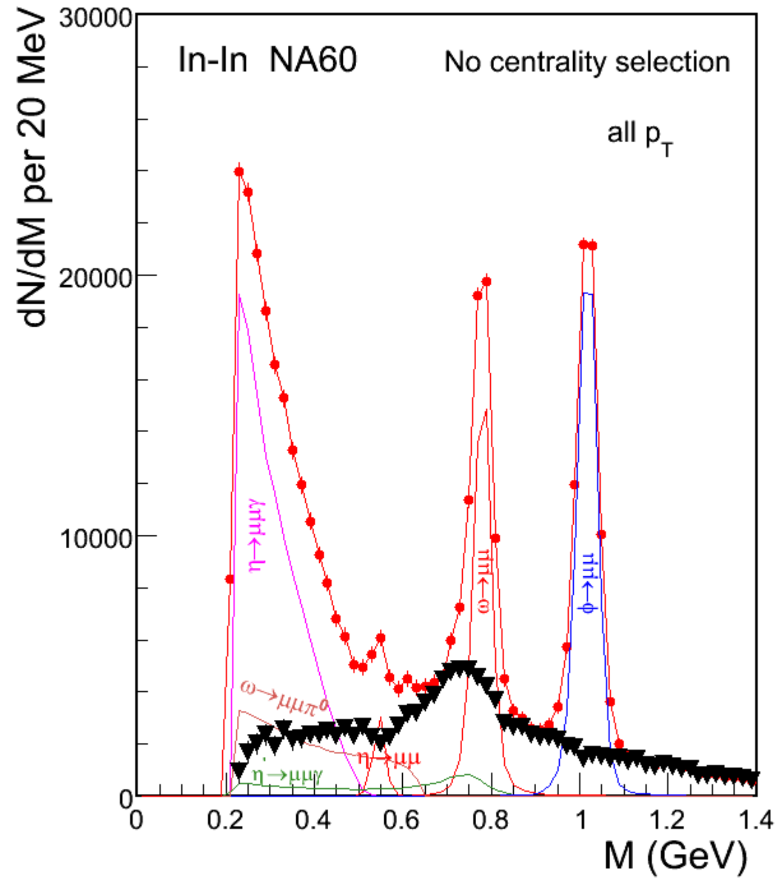
High rate capability

Input from
S. Damjanovic
H. Specht
A. Drees

NA60: In-In

Phys. Rev. Lett. 96 (2006) 162302

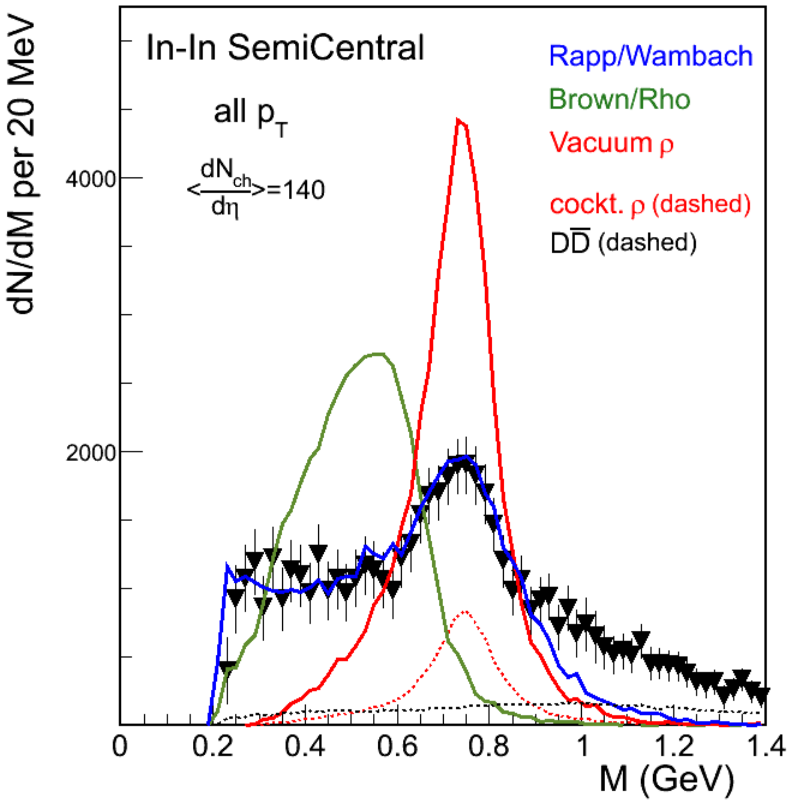


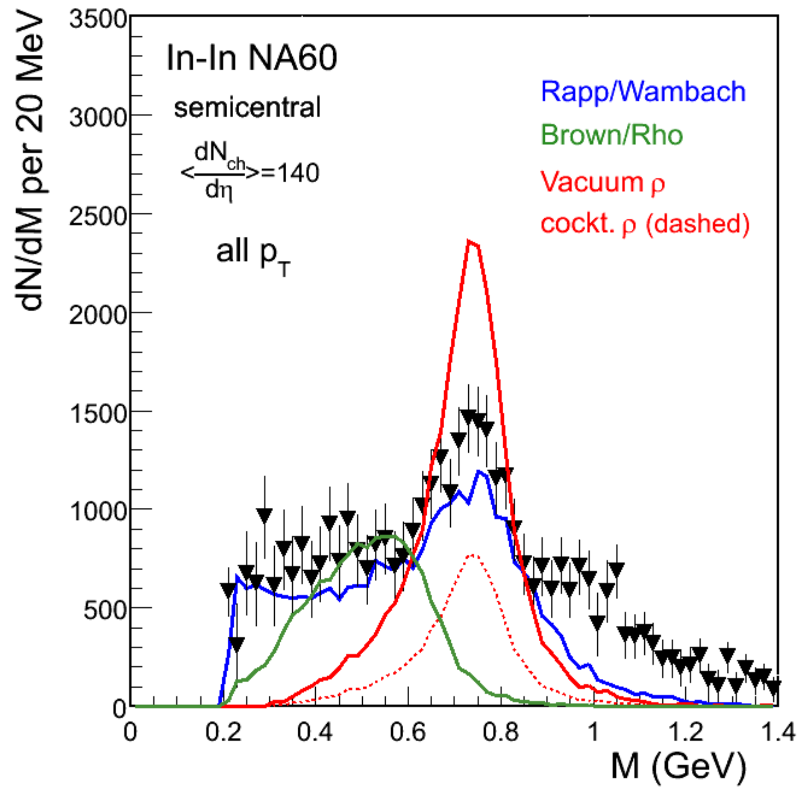


High statistics
Excellent background rejection
Precision control of decay cocktail

Example: NA60 can measure electromagnetic
Transition form factors for of $\eta \rightarrow \mu^+ \mu^- \gamma$ and $\omega \rightarrow \mu^+ \mu^- \pi^0$
removal of the previous 40% error in that hadron cocktail region
Phys. Lett. B 677 (2009) 260

NA60: Excess spectrum





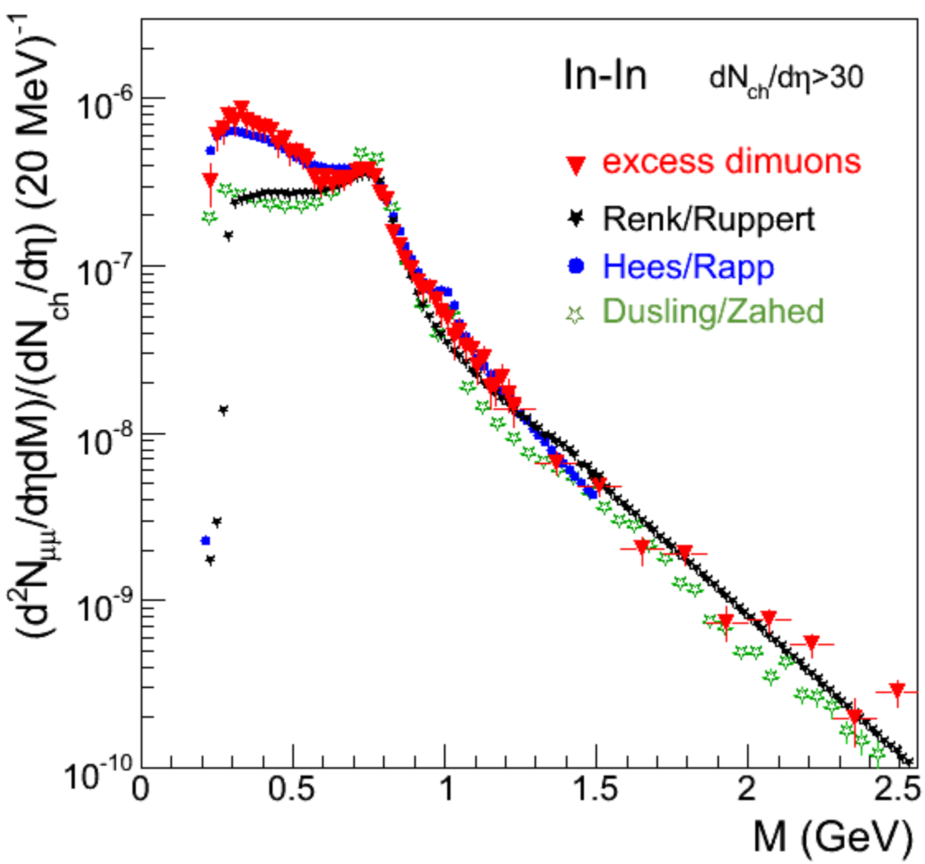
Models for contributions from hot medium (mostly ππ from hadronic phase)

- Vacuum spectral functions
- Dropping mass scenarios
- Broadening of spectral function

Data rule out mass drop of ρ meson

NA60:Inclusive excess mass spectrum

Eur. Phys. J. C 59 (2009) 607-623
CERN Courier 11/ 2009, 31-35
Chiral 2010, AIP Conf.Proc. 1322 (2010) 1-10



all known sources subtracted

integrated over p_T

fully corrected for acceptance

absolutely normalized to $dN_{ch}/d\eta$

M<1 GeV
ρ dominates, 'melts' close to T_c
best described by H/R model

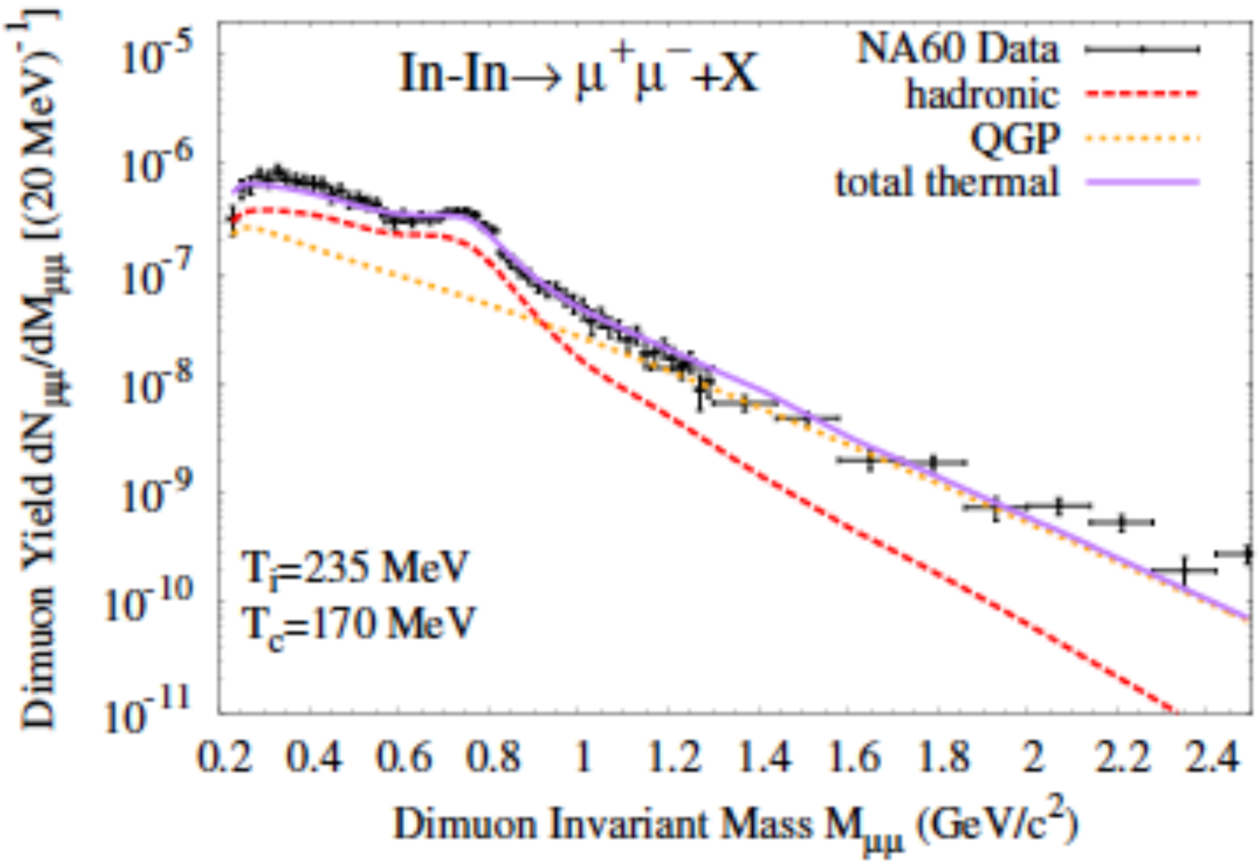
M>1 GeV
~ exponential fall-off

$$dN / dM \propto M^{3/2} \times \exp(-M / T)$$

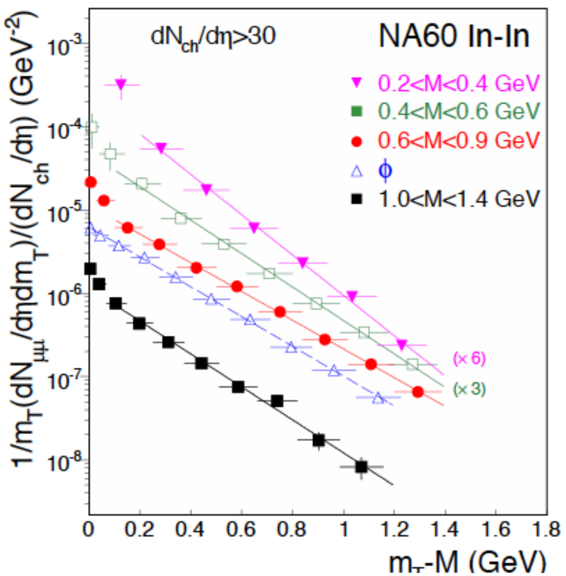
range 1.1-2.0 GeV: T=205±12 MeV
1.1-2.4 GeV: T=230±10 MeV
$T>T_c$: partons dominate
only described by R/R and D/Z models

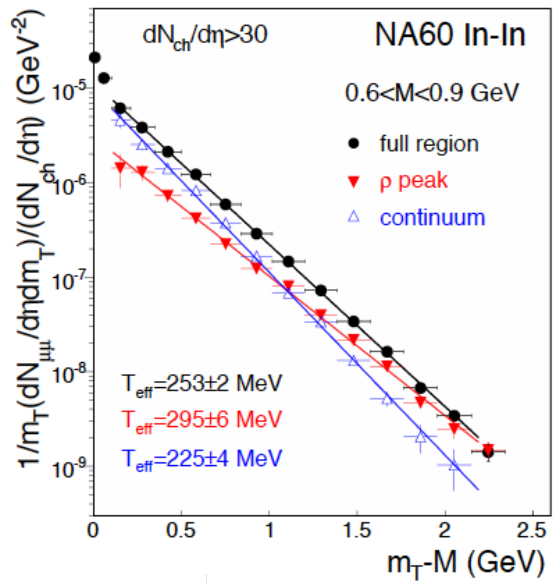
Theoretical interpretation

R.Rapp, v.Hess PLB753, 586 (2016)



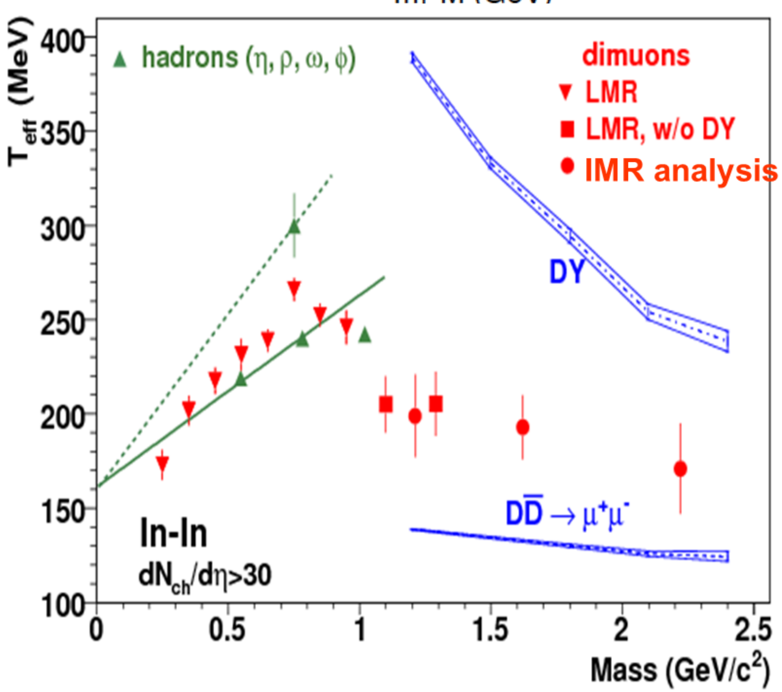
T_{eff} and space time evolution





PRL 100 (2008) 022302
EPJ C 59 (2009) 607
Eur. Phys. J. C 59 (2009) 607

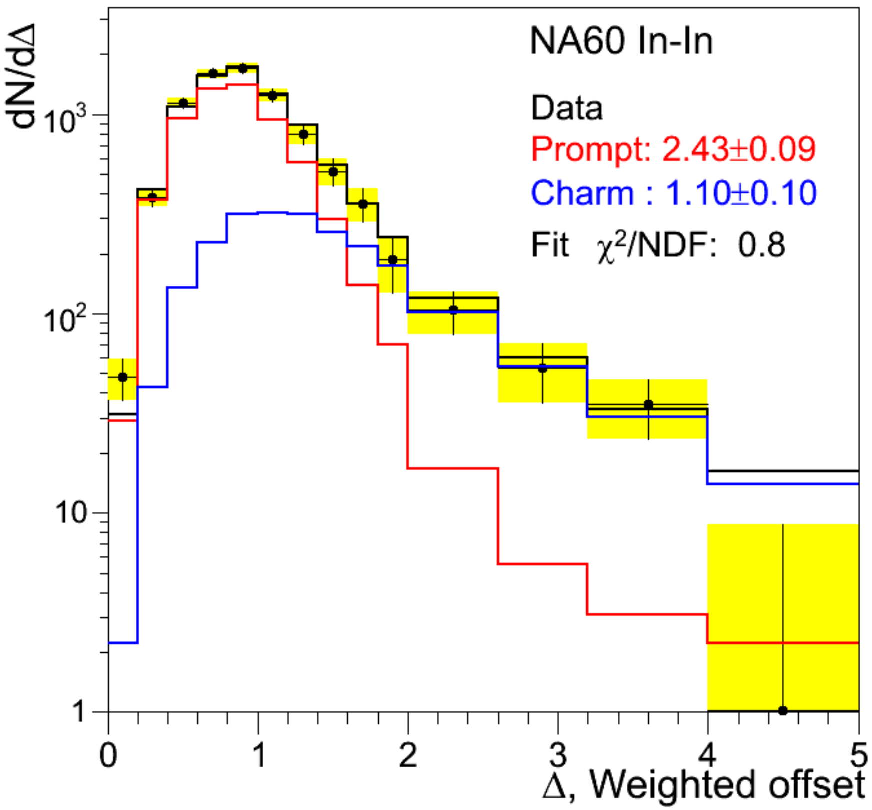
$$dN/dM \propto M^{3/2} \times \exp(-M/T)$$

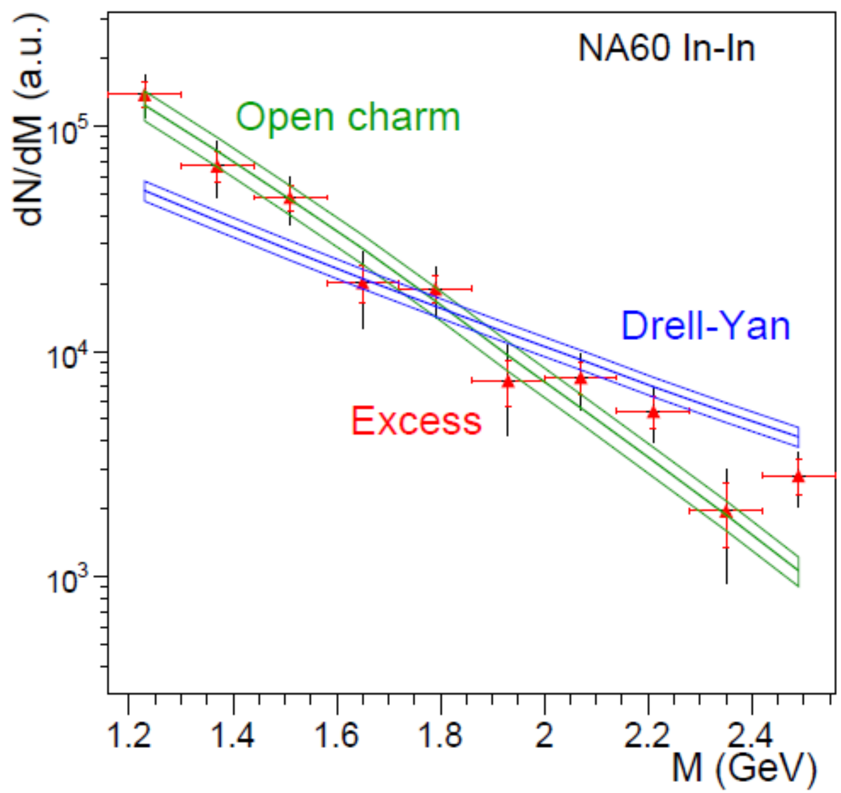


- hadrons (η, ω, ρ, φ)
  - T_{eff} depends on mass
  - T_{eff} smaller for φ, decouples early
  - T_{eff} large for ρ, decouples late
- low mass excess
  - clear flow effect visible
  - follows trend set by hadrons
  - possible late emission
- intermediate mass excess
  - no mass dependence
  - indication for early emission

IMR

excess = signal – [Drell-Yan (1.0 ± 0.1) + Charm (0.7±0.15)]

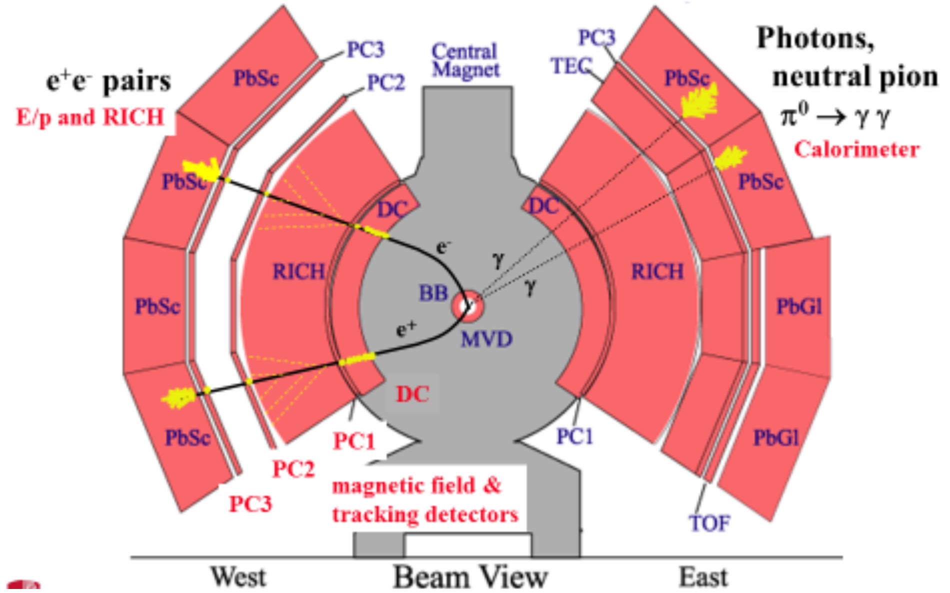




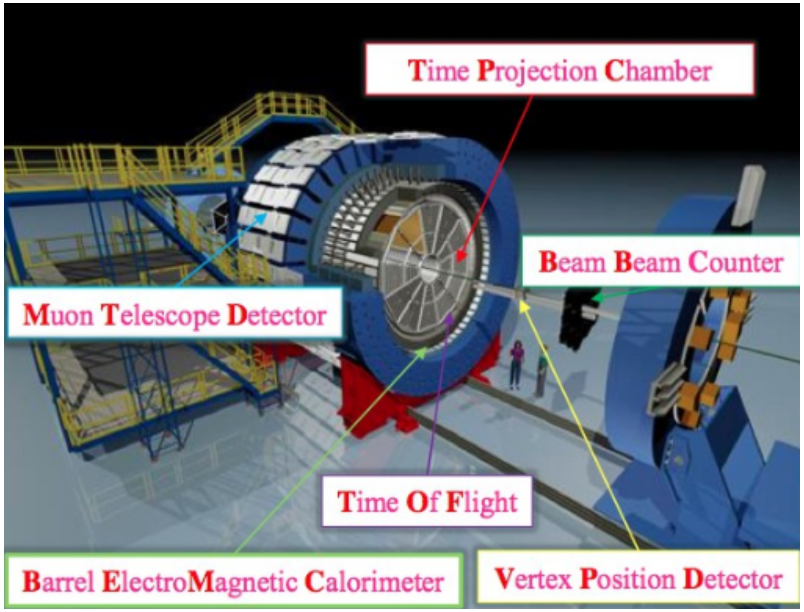
No charm enhancement. IMR dimuon excess is prompt

RHIC: PHENIX and STAR

- PHENIX: $|\eta|<0.35$, $\Delta\phi \sim 2\times\pi/2$
  tracking + RICH + E/p (+ HBD)
  - p+p 200 GeV
  - d+Au 200 GeV
  - Au+Au 200 GeV v/wo HBD

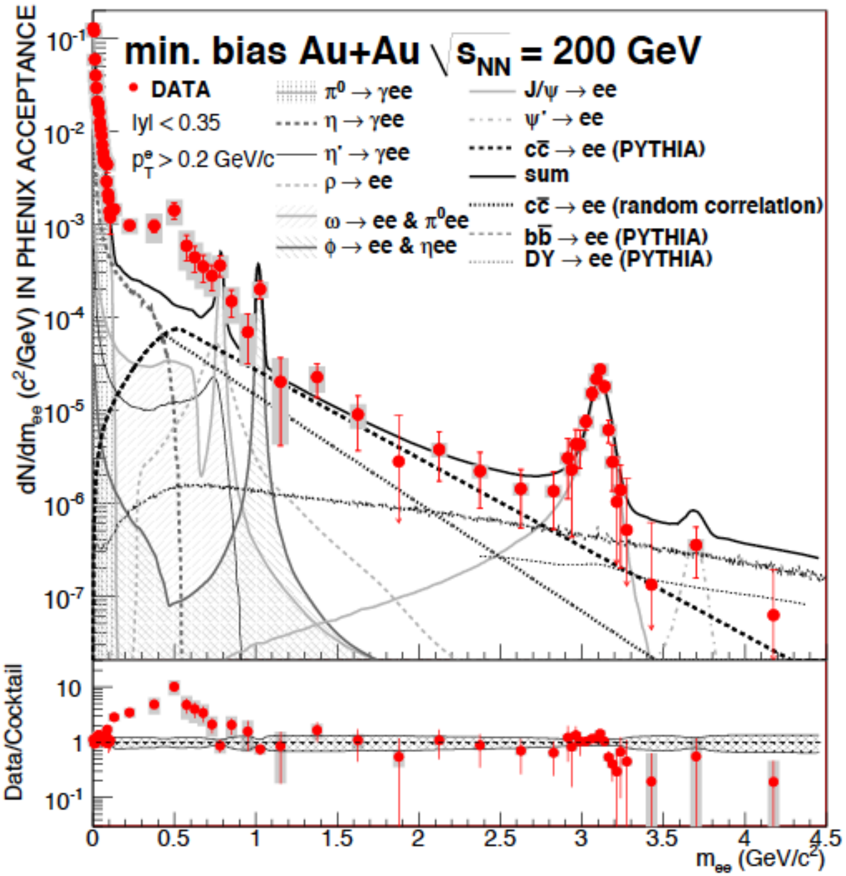


- STAR: $|\eta|< 1$ $\Delta\phi \sim 2\pi$
  tracking + TPC dE/dx + ToF
  - p+p 200 GeV
  - Au+Au 200 GeV
  - Au+Au 19.6, 27, 39, 62.4 GeV
  - U+U 193 GeV

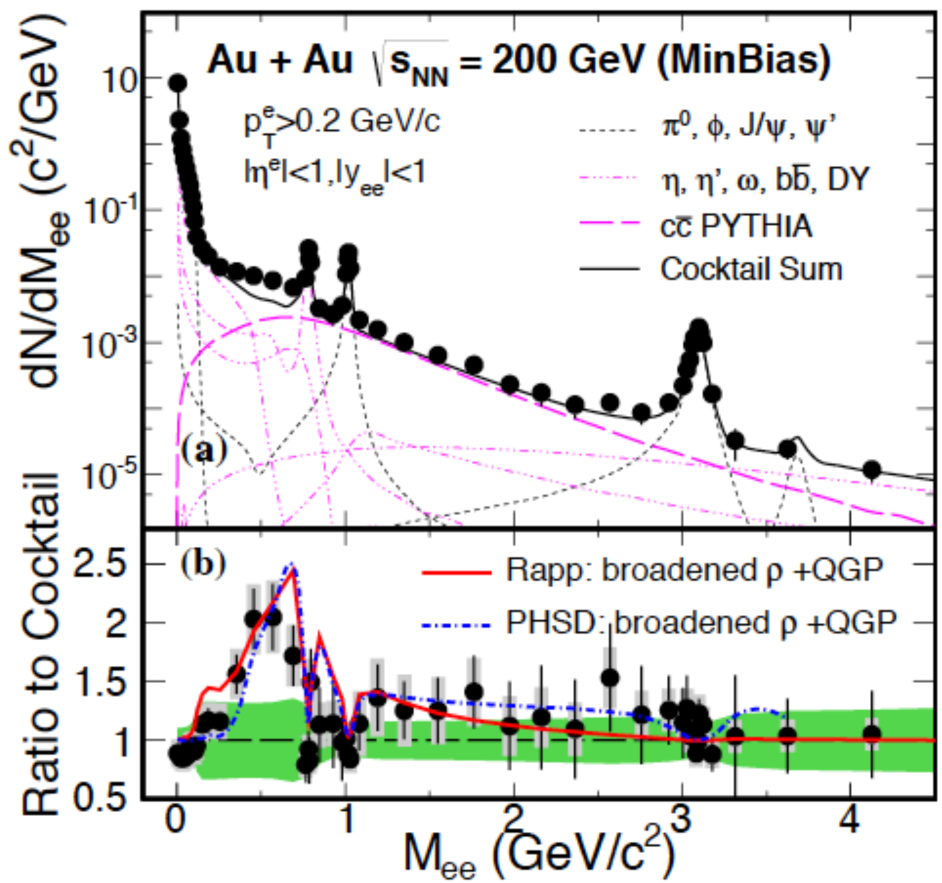


PHENIX vs STAR

Phys. Rev. C 81 (2010) 034911



Phys. Rev. Lett. 113 (2014) 22301



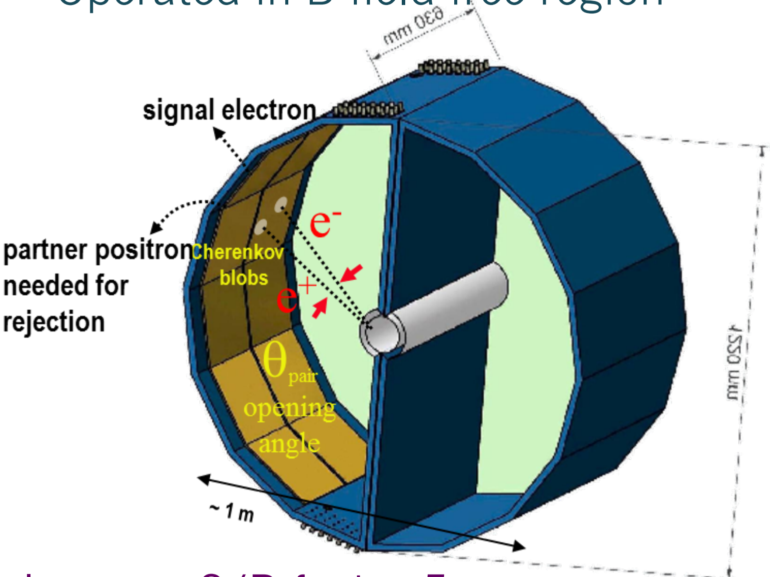
Excess 150 <m_{ee}<750 MeV:
4.7 ± 0.4(stat.) ± 1.5(syst.) ± 0.9(model)

Excess 300 <m_{ee}<760 MeV:
1.77 ± 0.11(stat.) ± 0.24 (syst.) ± 0.41(mod.)

Large quantitative differences in the low-mass region
Difficulties by theory to explain the excess
Precission on the background is crucial.

PHENIX HBD upgrade

Window less CF4 Cherenkov detector
GEM/CSI photo cathode readout
Operated in B-field free region



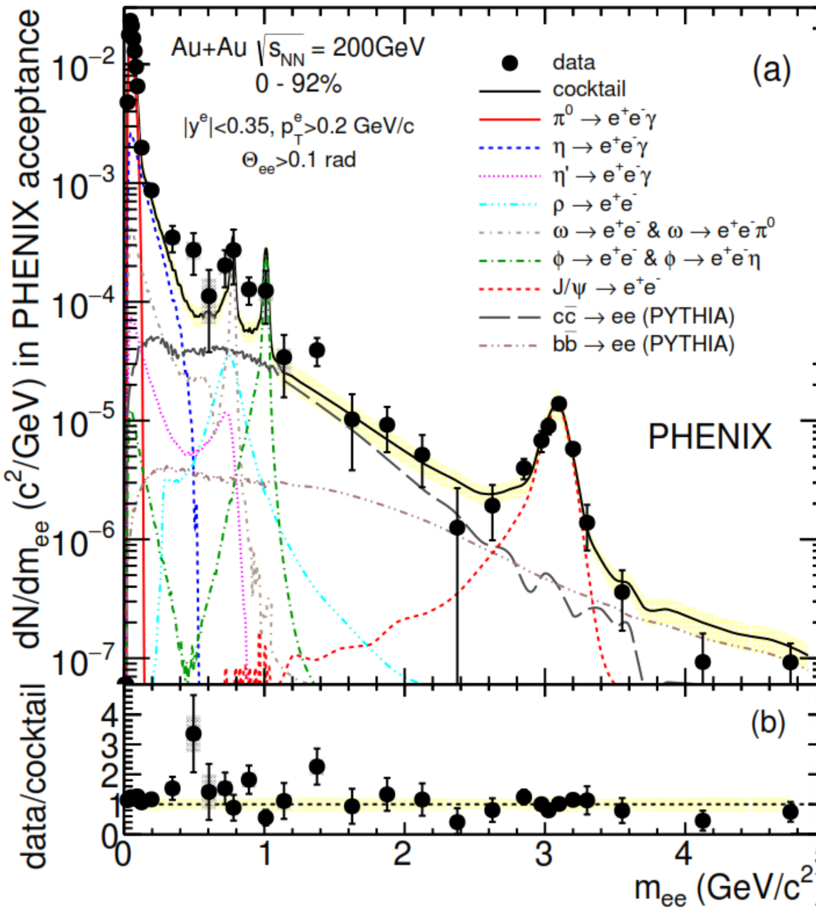
Improve S/B factor 5:

- Veto on double tracks
- Conversion rejection ~ 90%
- Dalitz rejection ~ 80%

Improved analysis:

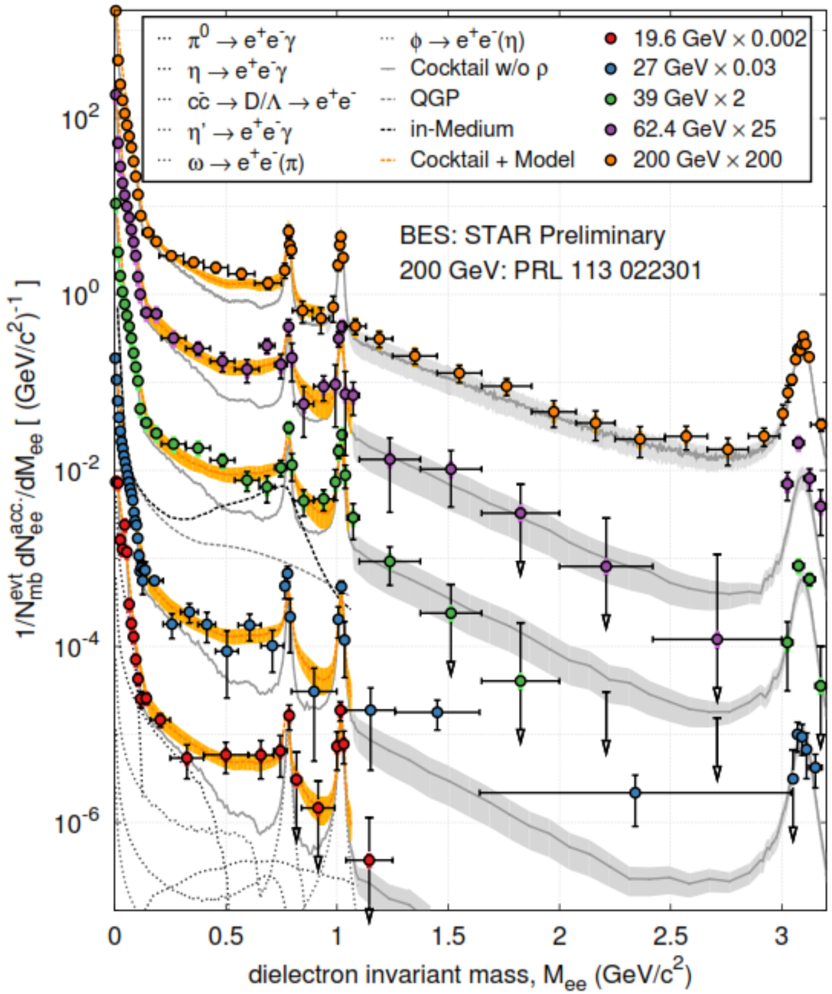
- Neural network for e-id
- Flow modulation incorporated in the Mixed event using an exact analytical method
- Absolutely normalized correlated BG

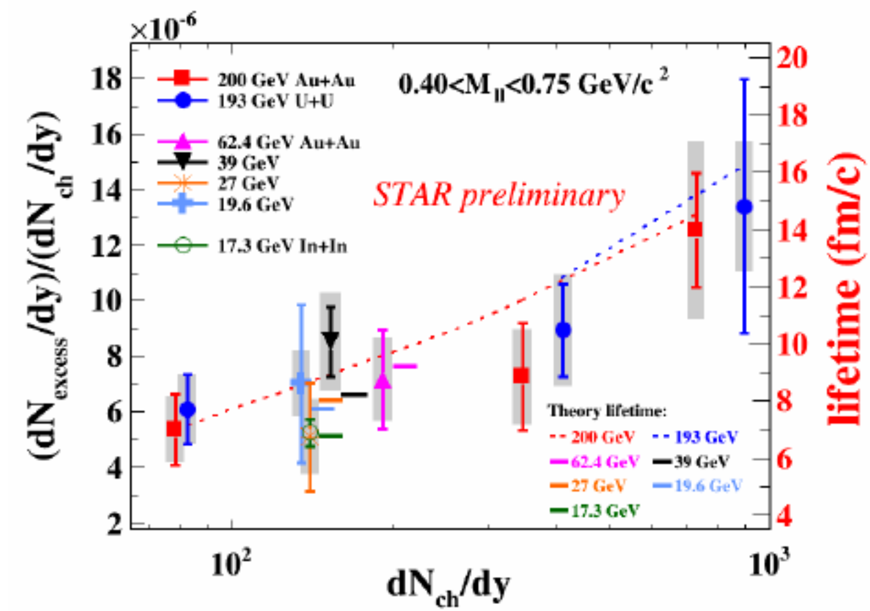
Phys. Rev. C 93,014904 (2016)



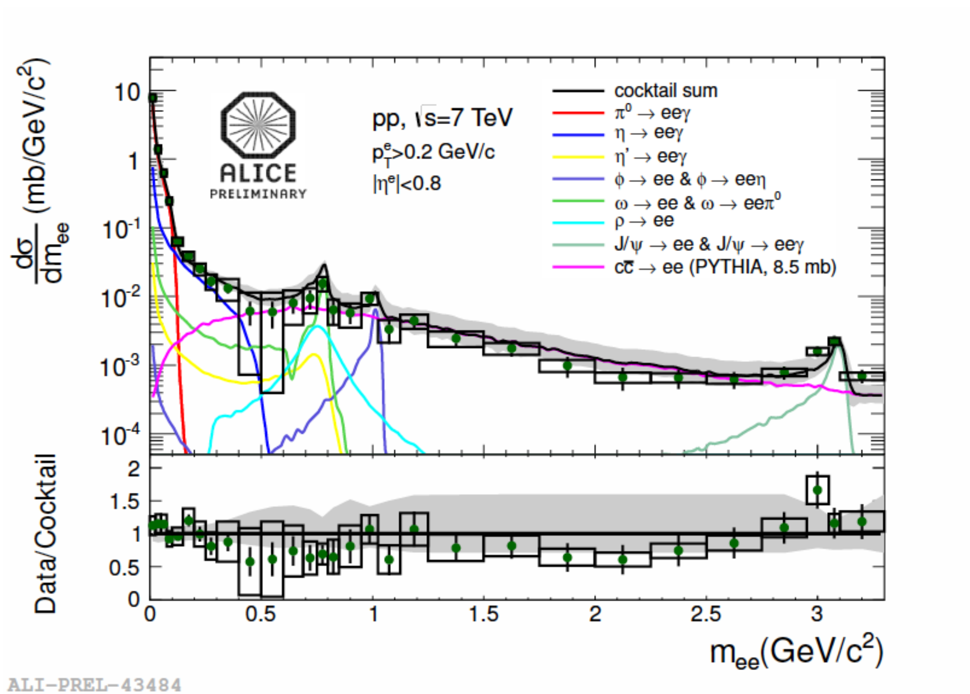
Excess 300 $<m_{ee}<$760 MeV:
2.3 ± 0.4(stat.) ± 0.4 (syst.) ± 0.2(model)

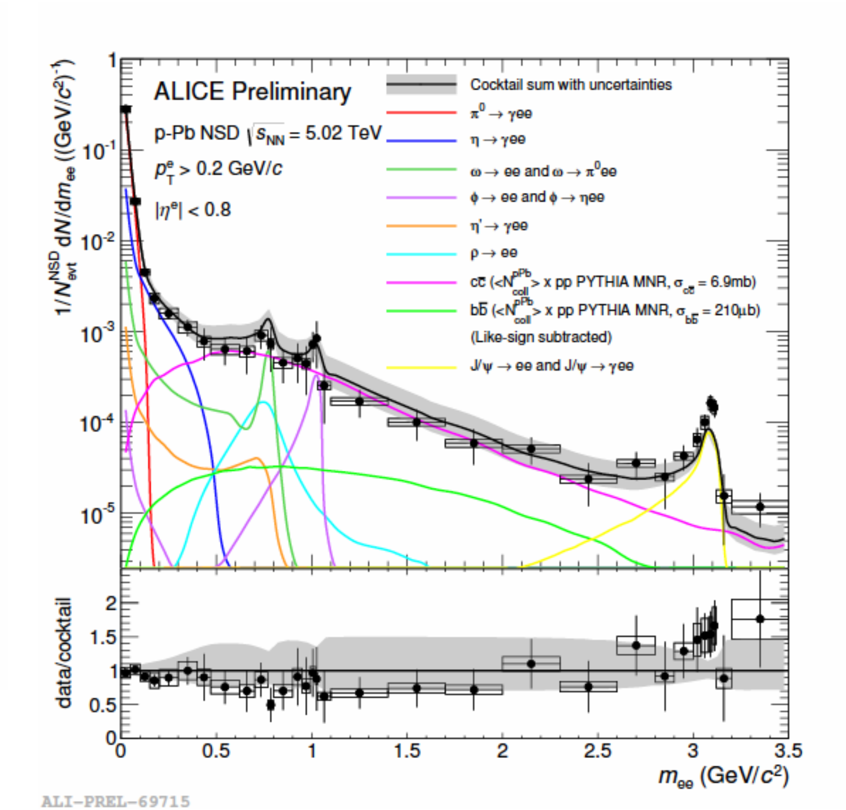
Dileptons:√s dependence





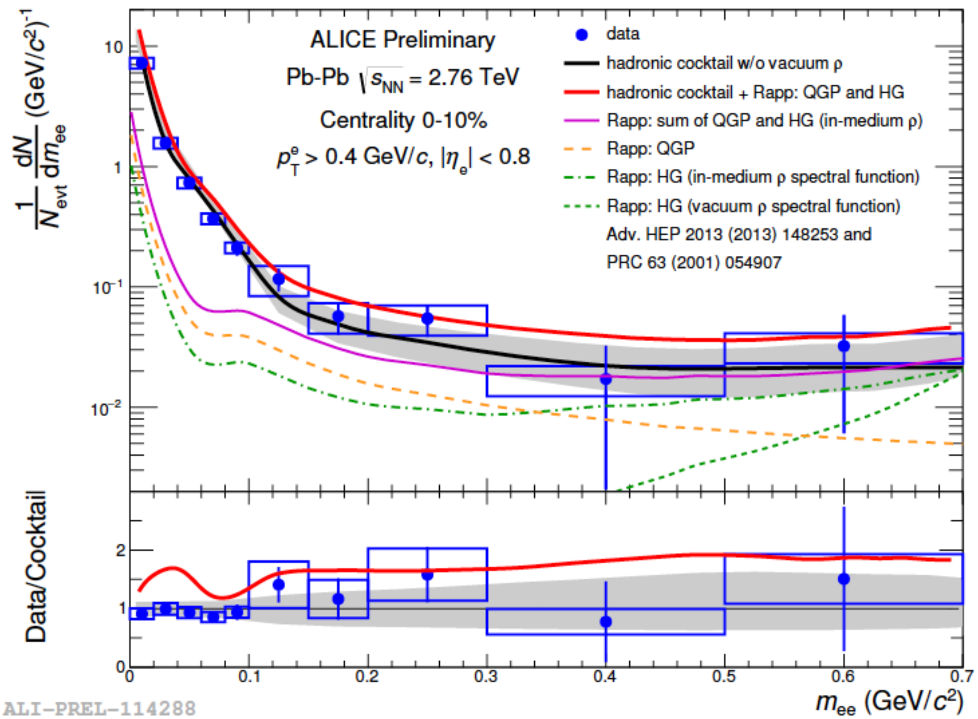
Dileptons at LHC: pp, pPb





Data are in agreement with cocktail within data & cocktail uncertainties

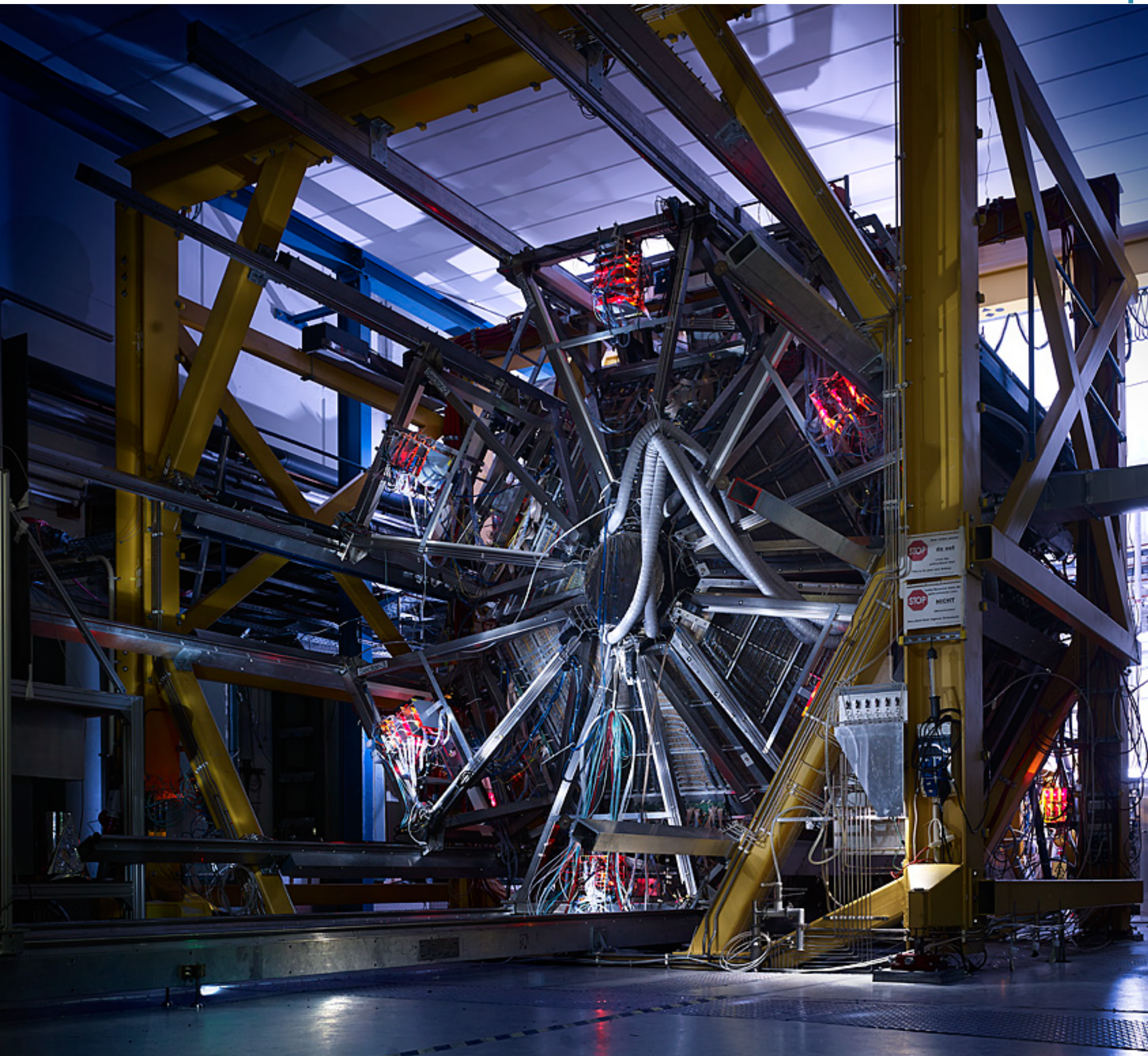
Dileptons at LHC: Run1 PbPb



No enhanced dielectron production in the low-mass region over the cocktail

- Large statistical, systematic uncertainties, cocktail uncertainties

HADES: Au+Au $\sqrt{s_{NN}}$=2.4GeV

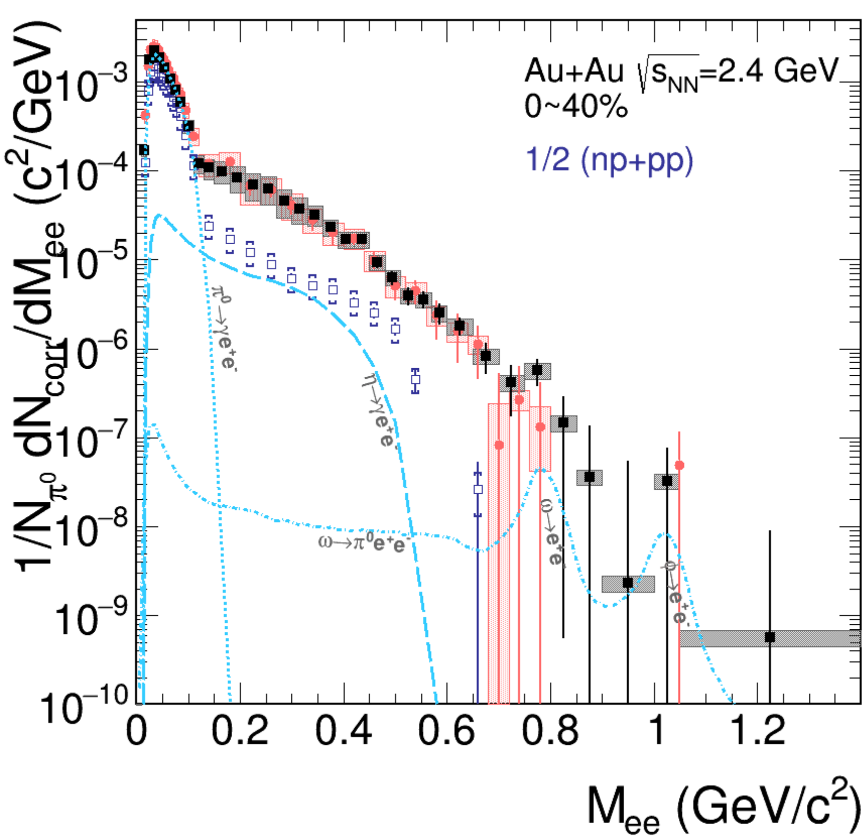


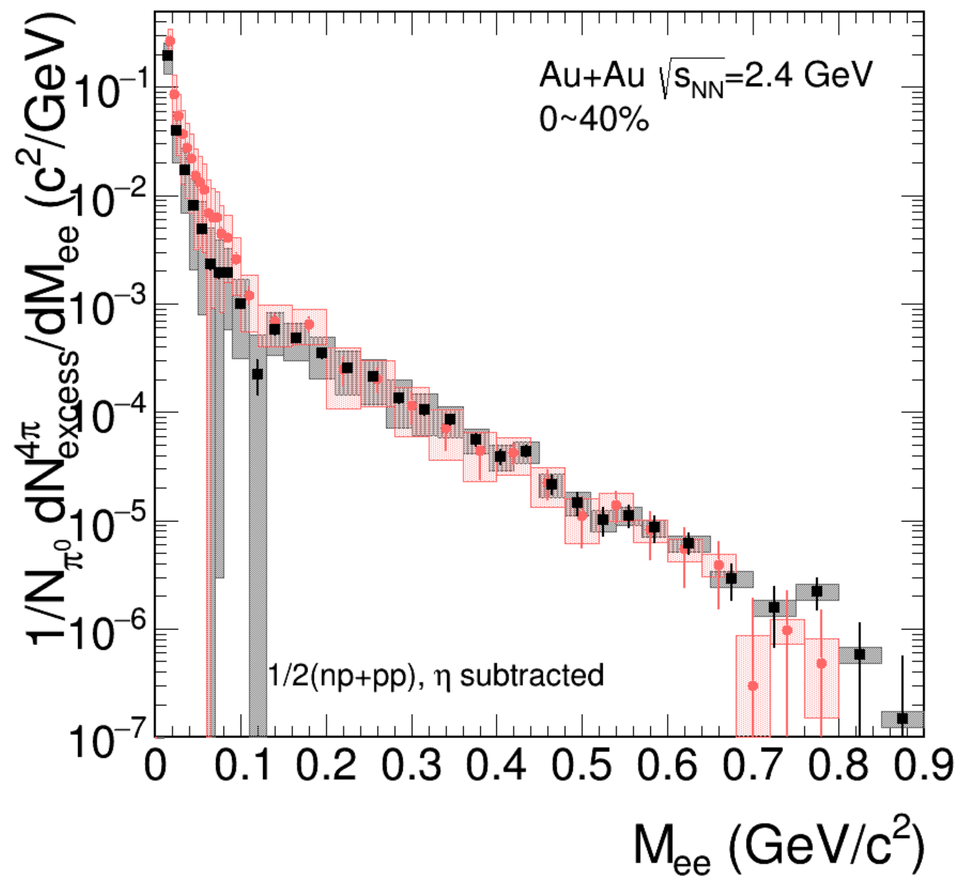
- 2002–2009: light A+A, p+p, n+p, p+A
- 2011–2014: Au+Au, π-induced reactions
- 2018–2020: FAIR Phase-0
  → high-statistics π+p/π+A, p+A and A+A

From T. Galatyuk
QM2017

Dilepton mass spectrum and excess yield

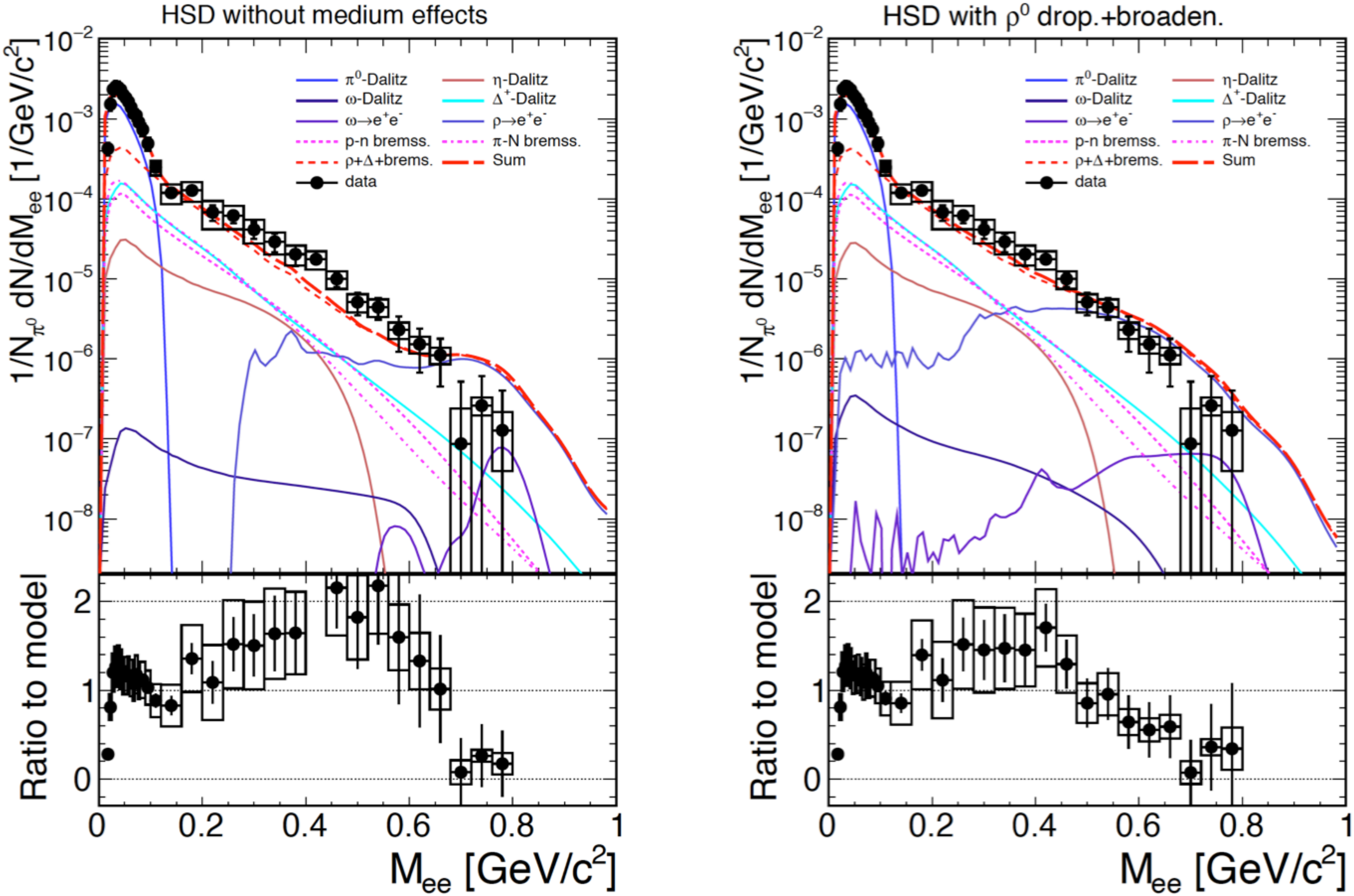
Baryon rich matter





Strong enhancement above the π^0
(In medium radiation, baryons...)
Above scaled NN
Excess is a true in medium effect

NN reference and η contribution subtracted
Acceptance corrected excess yield

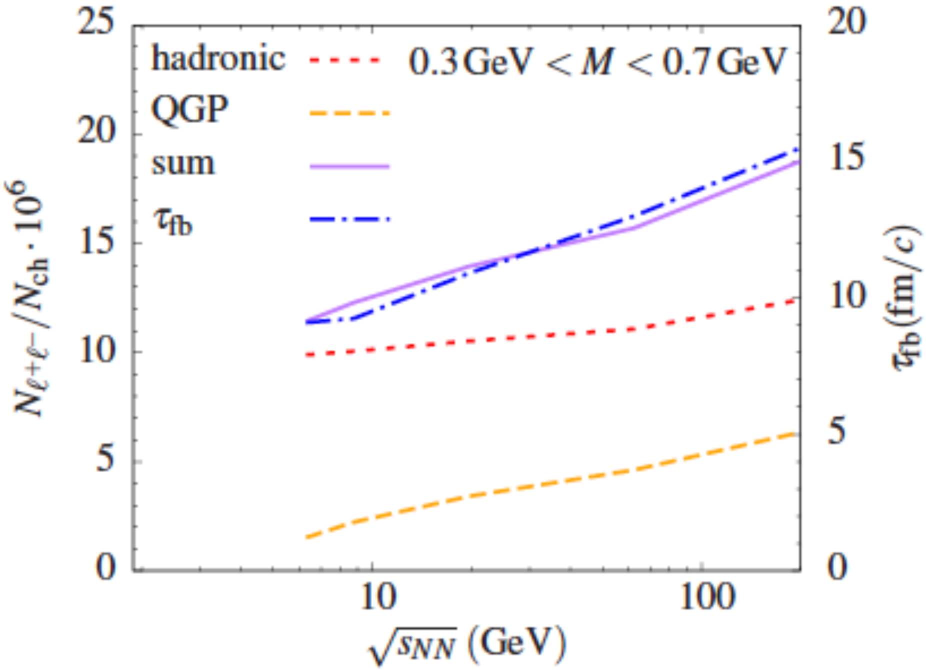


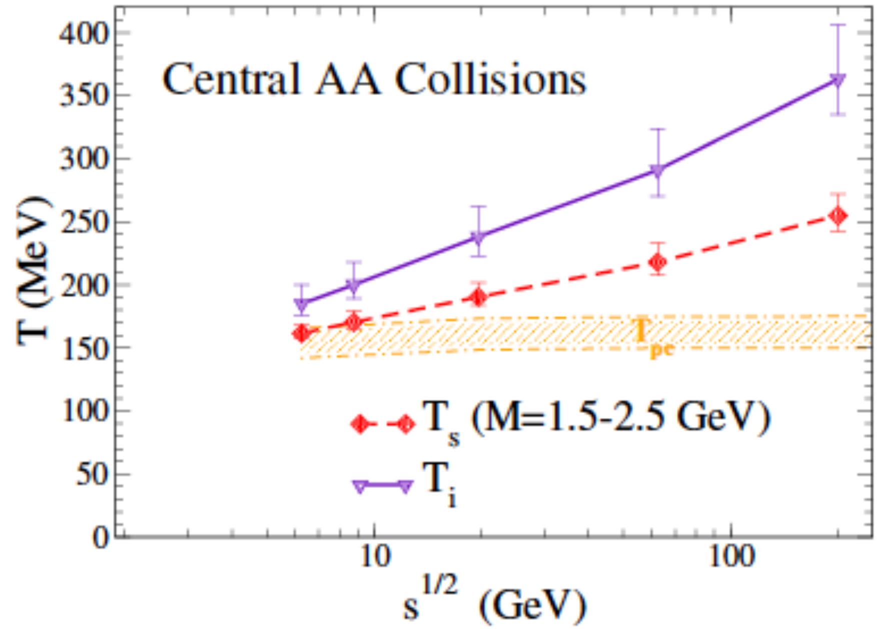
Better agreement when incorporating medium effects

Excess, T , τ :$\sqrt{s_{NN}}$ dependence

PLB 753, 586 (2016)

Theory calculations by R. Rapp, H. van Hees





Conclusion and Outlook

- Direct photons and dileptons are very interesting probes to study the QGP
  - Direct photons:
    - Many new experimental results and theoretical interpretations are available .
    - Photon v2 puzzle at RHIC stays
    - Results at LHC still to come
    - As well as other energies and systems
  - Dileptons:
    - Experimental results available from SIS to RHIC (LHC)
    - ρ broadening explains the excess
    - Gives access to the total life time and early temperature of the fireball

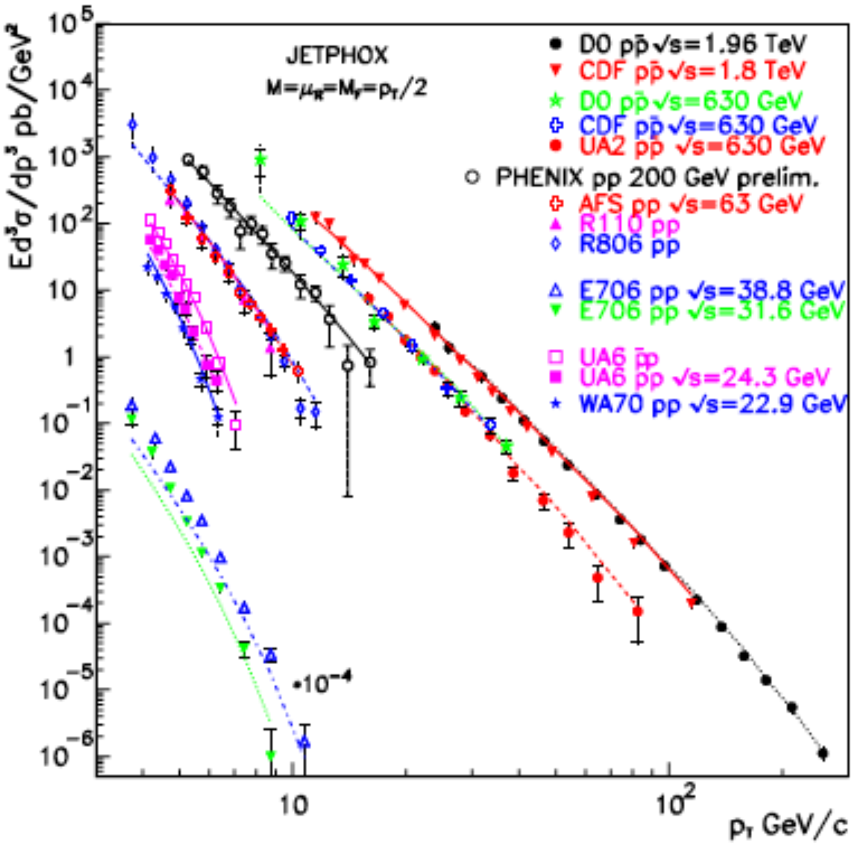
New facilities under development in the near future

THANKS

- CERES, NA60, PHENIX, STAR, HADES collaborations for the plots
- Many plots from theoretical papers
- Some material taken from other talks and lectures:
  - A. Drees, K. Reygers, H. Specht, A. Toia, R. Averbeck, ...

- Models on the market (non-exhaustive list)
  - Thermal photon rate in QGP, hadron gas, prompt production folded with time evolution (viscous/non-viscous hydro, blastwave expansion, etc)
    - H. van Hees, C. Gale, R. Rapp, Phys. Rev. C**84** 054906 (2011)
    - H. van Hees, M. He, R. Rapp, Nucl. Phys. A**933** 256 (2015)
    - C. Shen, U. Heinz, J.F. Paquet, I. Kozlov, C. Gale Phys. Rev. C**91** 024908 (2015)
  - Modifications of formation time and initial conditions
    - R. Chatterjee, H. Holopainen, I. Helenius, T. Renk, K.J. Eskola, Phys. Rev C**88**, 034901 (2013)
    - F.M. Liu, S. X. Liu, Phys. Rev C**89**, 034906 (2014)
    - G. Vujanovic et. al, Nucl. Phys. A**932**, 230 (2014)
  - Enhanced non-equilibrium effects (glasma, etc.)
    - A. Monnai, Phys. Rev. C**90**, 021901 (2014)
    - L. McLerran and B. Schenke, Nucl. Phys. A**929**, 71 (2014)
    - F. Gelis, H. Niemi, P.V. Ruuskanen, S.S. Rasanen, Journal of Physics G30, S1031 (2004)
  - Enhanced early emission from magnetic field
    - B. Mueller, S.Y. Wu, D.L. Yau, Phys. Rev D**89** 026013 (2014)
    - K. Tuchin, Phys. Rev. C**87** 024912 (2013)
    - G. Basar, D. E. Kharzeev, V. Skokov, Phys. Rev. Lett 109 202303 (2012)
  - Microscopic transport (PHSD)
    - O. Linnyk, W. Cassing, E.L. Bratkovskaya, Phys. Rev. C**89**, 034908 (2014)
  - Enhanced emission at hadronization
    - S. Campbell, Phys. Rev. C**92** 014907 (2015)

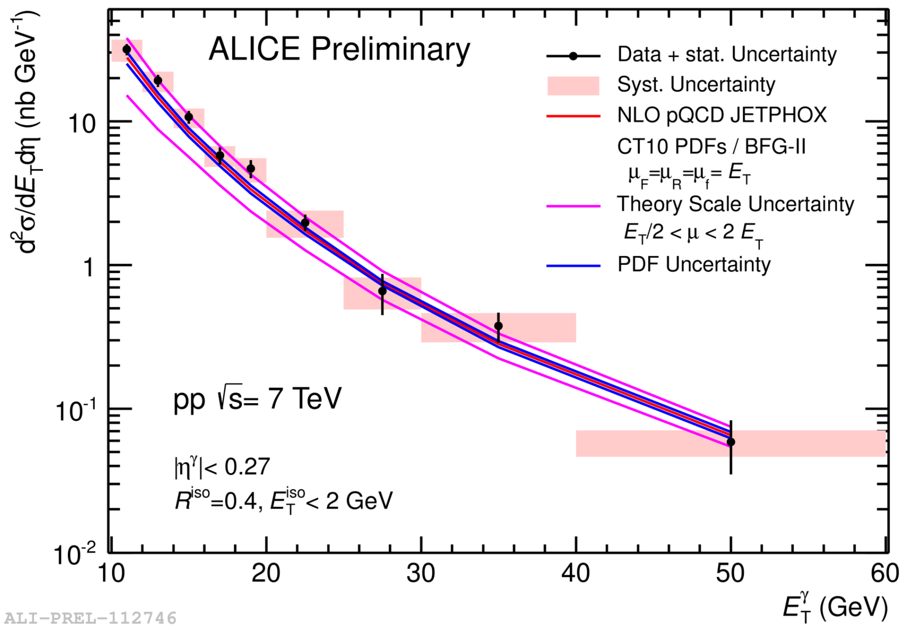
Compilation of direct γ (2006 pre-LHC)

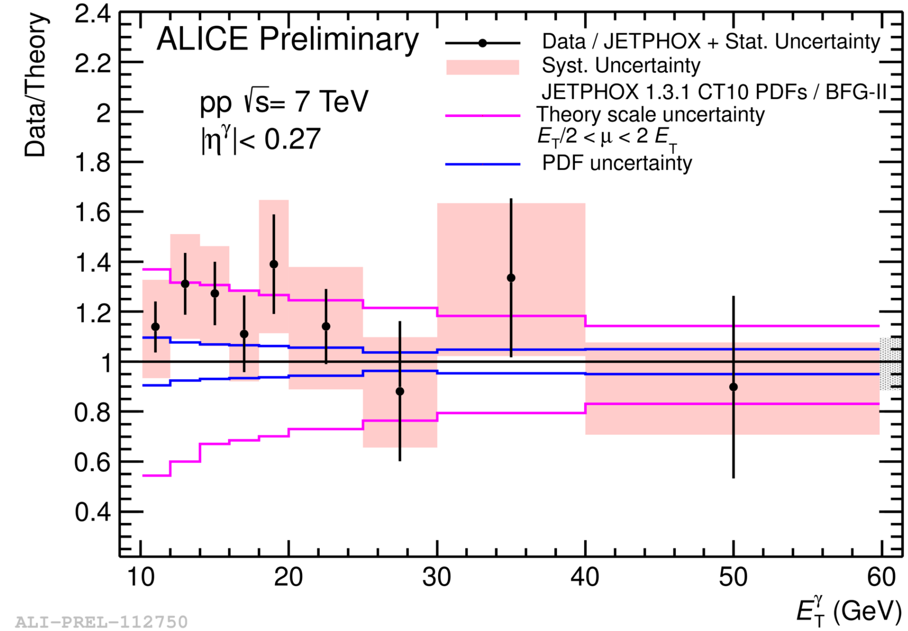


Phys. Rev. D 73 (2006) 094007

World's inclusive and isolated direct photon production cross sections measured in pp and pp collisions compared to JETPHOX NLO predictions, using BFG (CTEQ6M) for fragmentation functions and a common scale p_T

pp collisions@7TeV





Isolated photon cross section measured in 10 GeV $< E_T <$ 60 GeV
Compatible with NLO predictions

Lower E_T reach compared to CMS and ATLAS

Analysis at 8TeV ongoing

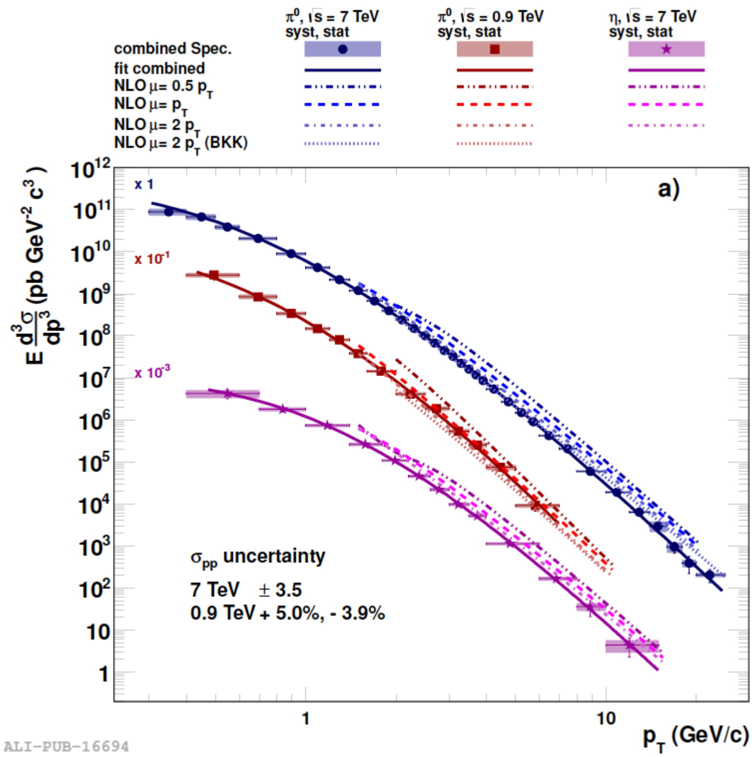
Neutral mesons results

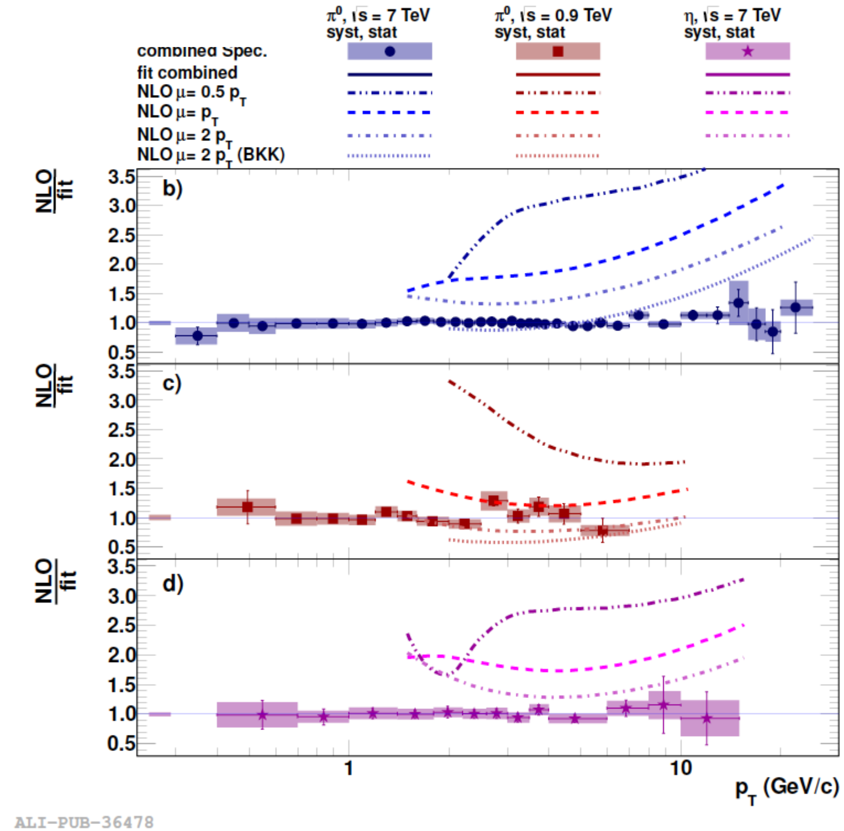
First data: Test of pQCD at high p_T

Neutral pion and η meson production in proton–proton collisions at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV ☆

PLB 717 (2012)162

ALICE Collaboration





DSS FF and CTEQ6M5 PDF

Problem in the set of exiting FF?

Discussion: Nucl. Phys. B883 (2014) 615

Impact: Constraints on gluon to pion fragmentation.

- **Parton-to-Pion Fragmentation Reloaded**

D. de Florian, R. Sassot, M. Epele, R.J. Hernandez-Pinto, M. Stratmann

Phys. Rev. D **91**, (2015) 014035

ArXiv: 1410.6027

DSS14

TABLE II: Data sets used in our NLO global analysis, their optimum normalization shifts N_i, cf. Sec. II C and Eq. (6), the individual χ^2 values (including the χ^2 penalty from the obtained N_i), and the total χ^2 of the fit.

experiment		data type	norm. N_i	# data in fit	χ^2
TPC [48]		incl.	1.043	17	17.3
		uds tag	1.043	9	2.1
		c tag	1.043	9	5.9
		b tag	1.043	9	9.2
TASSO [49]	34 GeV	incl.	1.043	11	30.2
	44 GeV	incl.	1.043	7	22.2
SLD [19]		incl.	0.986	28	15.3
		uds tag	0.986	17	18.5
		c tag	0.986	17	16.1
		b tag	0.986	17	5.8
ALEPH [16]		incl.	1.020	22	22.9
DELPHI [17]		incl.	1.000	17	28.3
		uds tag	1.000	17	33.3
		b tag	1.000	17	10.6
OPAL [18, 20]		incl.	1.000	21	14.0
		u tag	0.786	5	31.6
		d tag	0.786	5	33.0
		s tag	0.786	5	51.3
		c tag	0.786	5	30.4
		b tag	0.786	5	14.6
BABAR [28]		incl.	1.031	45	46.4
BELLE [29]		incl.	1.044	78	44.0
HERMES [30]		π^+ (p)	0.980	32	27.8
		π^- (p)	0.980	32	47.8
		π^+ (d)	0.981	32	40.3
		π^- (d)	0.981	32	59.1
COMPASS [31] prel.		π^+ (d)	0.946	199	174.2
		π^- (d)	0.946	199	229.0
PHENIX [21]		π^0	1.112	15	15.8
STAR [33–36]	$0 \le \eta \le 1$	π^0	1.161	7	5.7
	$0.8 \le \eta \le 2.0$	π^0	0.954	7	2.7
	$\lvert\eta\rvert < 0.5$	$\pi^\pm$	1.071	8	4.3
	$\lvert\eta\rvert < 0.5$	$\pi^+, \pi^-/\pi^+$	1.006	16	17.2
ALICE [32]	7 TeV	π^0	0.766	11	27.7
TOTAL:				973	1154.6

pp@2.76TeV: New NLO pQCD in agreement

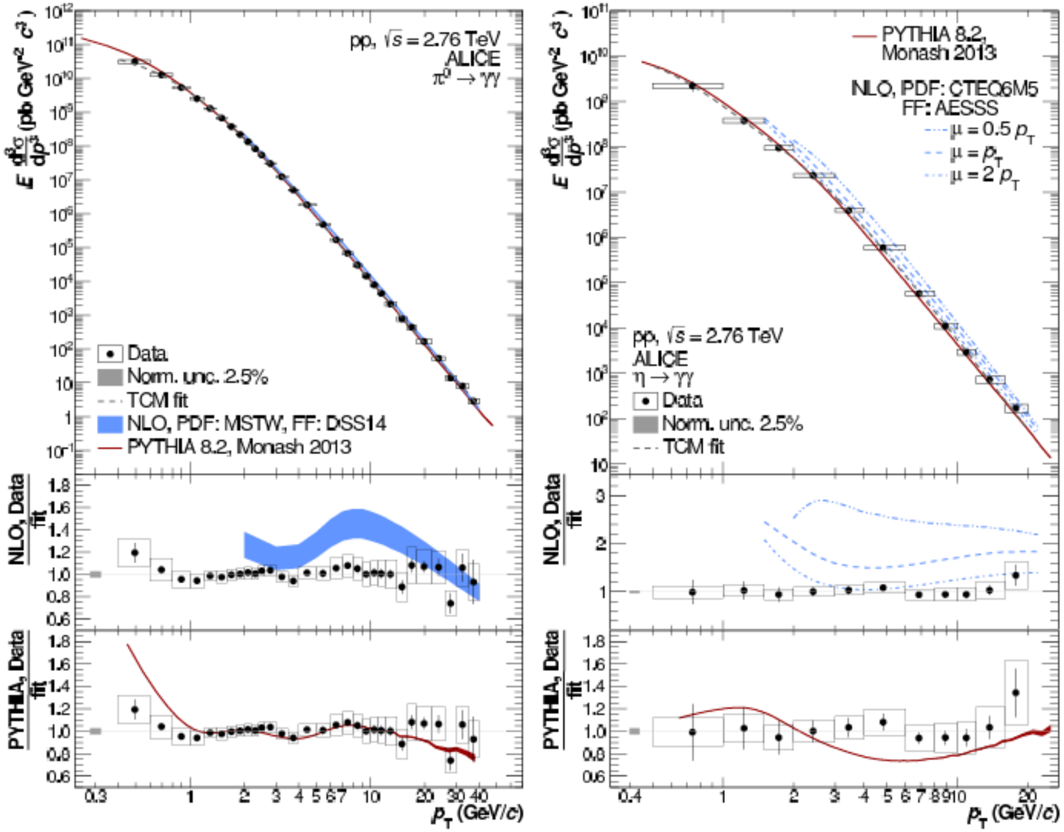


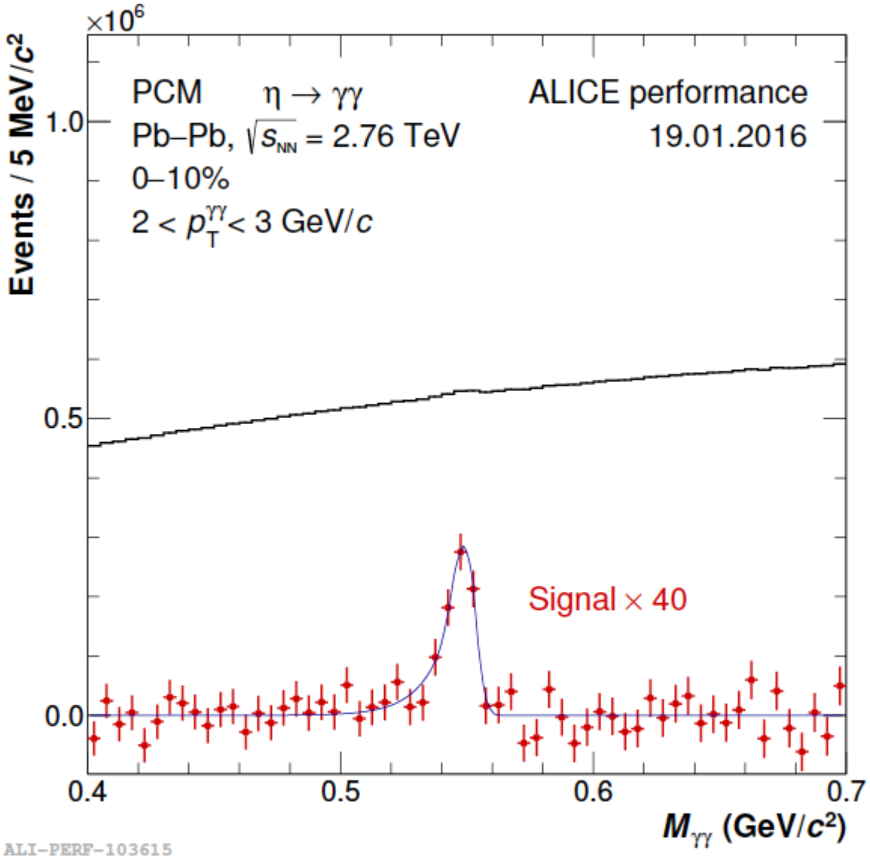
Fig. 9: Invariant differential cross section of the π^0 (left, top panel) and η meson (right, top panel) for pp collisions at $\sqrt{s} = 2.76$ TeV. The data are compared to PYTHIA 8.2 [31] generator-level simulations using the Monash 2013 tune as well as recent NLO pQCD calculations [3, 6]. The ratios of the data and the calculations to the respective two-component model fits [25, 26] to the data are shown in the lower panels. The horizontal error bars denote statistical, the boxes systematic uncertainties.

Arxiv 1702 .00917
EPJC (accepted)

Good description by Pythia

pQCD predictions with new DSS14 describes the π^0

Ongoing:
Study x_T scaling in pp collisions



×10^6
Events / 5 MeV/c²
PCM η → γγ
ALICE performance
Pb–Pb, √s_NN = 2.76 TeV
19.01.2016
0–10%
2 < p_T^γγ < 3 GeV/c
Signal × 40
1.0
0.5
0.0
0.4
0.5
0.6
0.7
M_γγ (GeV/c²)
ALI-PERF-103615

Isolated photons

Interest on High Multiplicity in pp

- **Predictions of thermal photon production in high multiplicity pp collisions .**

Phys. Rev. Lett. 106(2011)242301

Direct photons at low transverse momentum – a QGP signal in pp collisions at LHC

Fu-Ming Liu[1] and Klaus Werner[2]

[1] *Institute of Particle Physics* and Key laboratory of Quark & Lepton Physics (Ministry of Education), Central China Normal University, Wuhan, China

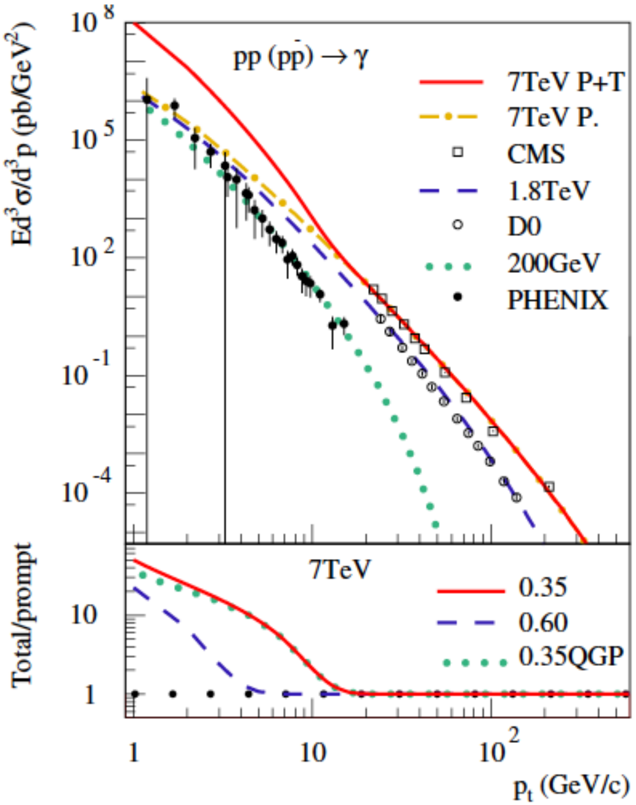
[2] *Laboratoire SUBATECH, University of Nantes - IN2P3/CNRS - Ecole desMines, Nantes, France*

(Dated: May 18, 2011)

We investigate photon production in a scenario of quark-gluon plasma formation in proton-proton scattering at 7 TeV. It is shown that thermal photon yields increase quadratically with the charged particle multiplicity. This gives an enhanced weight to high multiplicity events, and leads to an important photon production even in minimum bias events, where the thermal photons largely dominate over the prompt ones at transverse momentum values smaller than 10 GeV/c.

Direct γ in High-Mult pp

Phys. Rev. Lett. 106(2011)242301



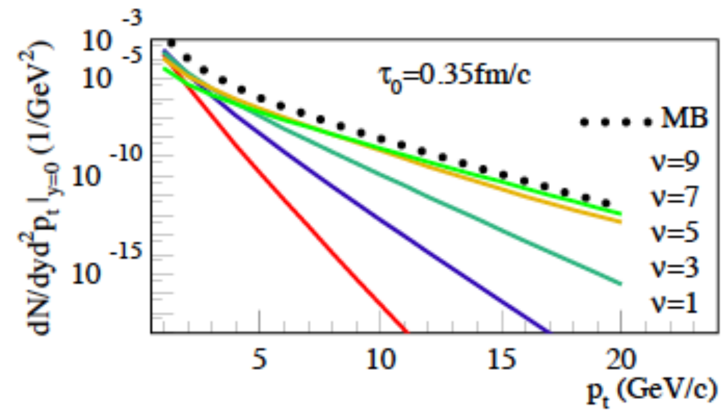


Figure 3: (Color Online) The thermal spectra given ν (solid lines) and the mini-bias case (dotted line). The different solid lines correspond to (from bottom to top) $\nu = 1, 3, 5, 7, 9$.

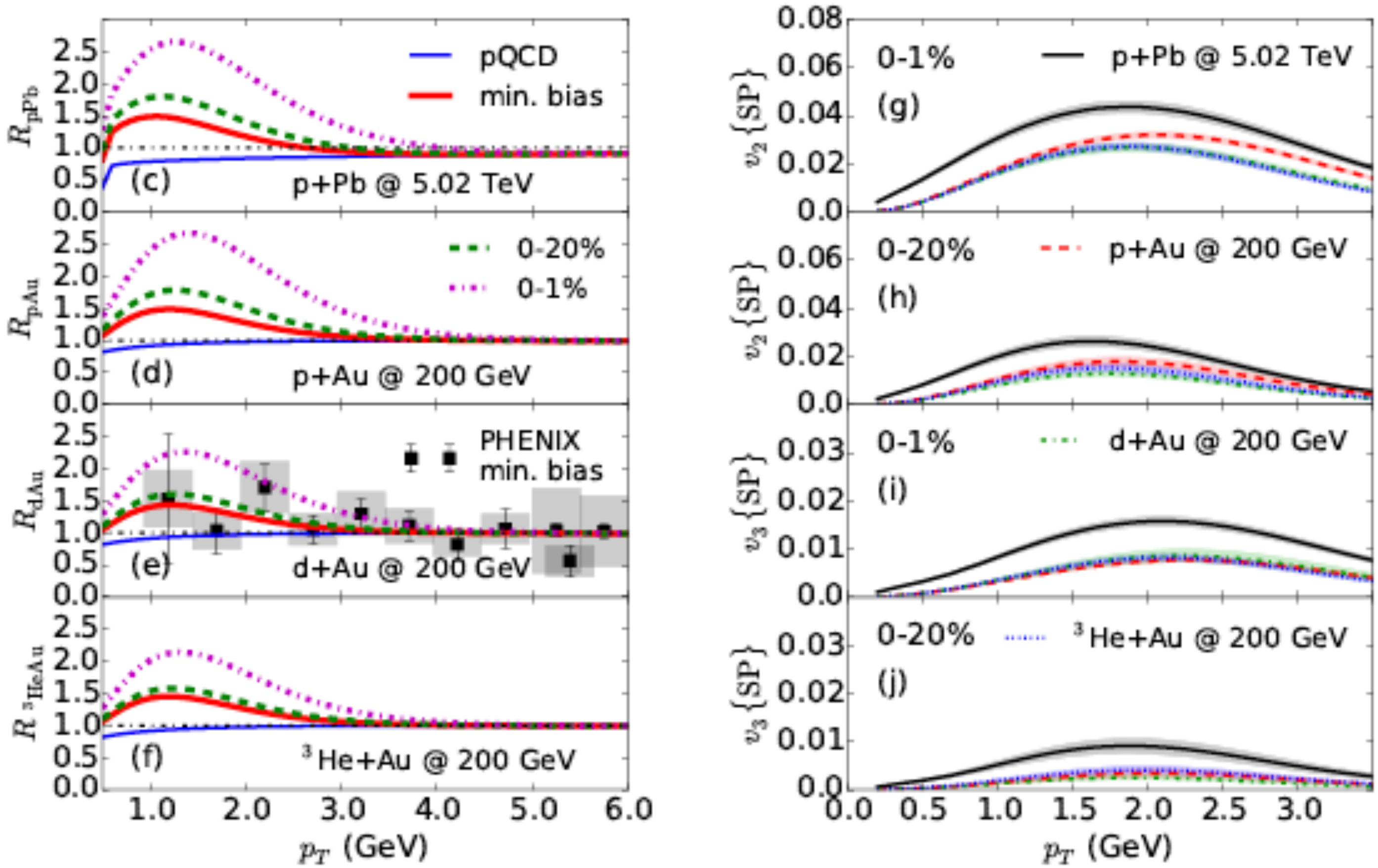
Predictions for 7TeV but should be better for 13 TeV

Direct γ in small systems (pPb)

Direct photon production and jet energy-loss in small systems.

C. Shen, C.Park,J.P. Paquet, G. Denicol, S.Jeon, C.Gale

ArXiv 1601.03070. NPA956(2016)741



Published papers

- ALICE Collaboration, B. B. Abelev et al., “Neutral pion and η meson production in proton-proton collisions at $\sqrt{s}$ = 0.9 TeV and $\sqrt{s}$ = 7 TeV,” Phys. Lett. B717 (2012) 162–172, arXiv:1205.5724
- ALICE Collaboration, B. B. Abelev et al., “Neutral pion production at midrapidity in pp and Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2:76TeV,” Eur. Phys. J. C74 no. 10, (2014) 3108, arXiv:1405.3794
- ALICE Collaboration, S. Acharya et al., “Production of π^0 and η mesons up to high transverse momentum in pp collisions at 2.76 TeV,” arXiv:1702.00917 (accepted)

Analysis steps

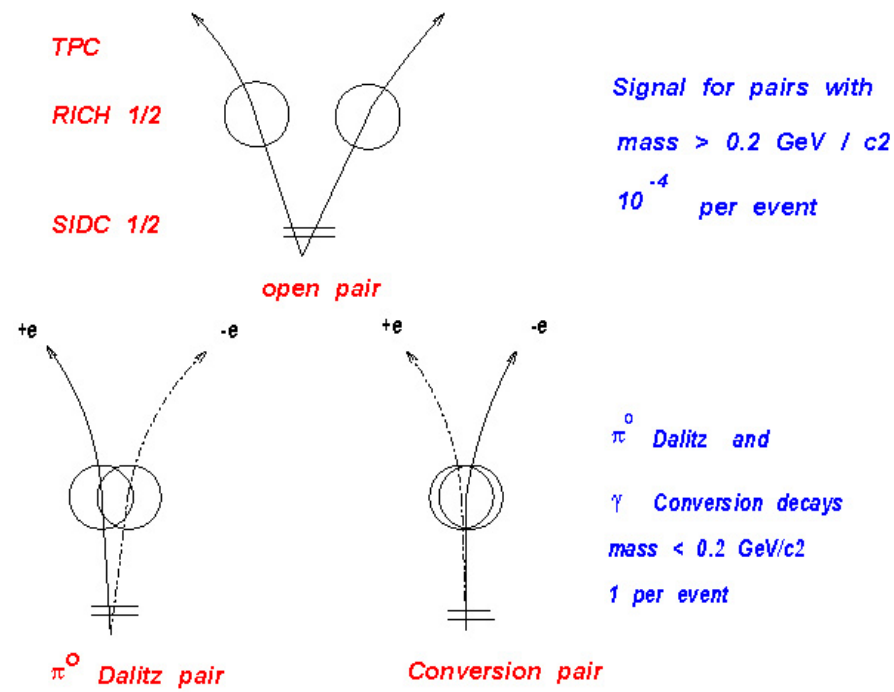
1. Charged particle tracking
2. Electron identification
3. Rejection of combinatorial background

Background rejection

Dominant sources are π^0-Dalitz and γ-conversions

1. Dalitz recognition:

- Rejection of tracks which form a pair $\Theta_{ee} < 35$ mrad
- Tracks which form a pair $m_{ee} < 0.2$ GeV/c^2 excluded
- from further pairing
- ...still a large number of tracks remaining from
- unrecognized π^0-Dalitz pairs and γ-conversions!

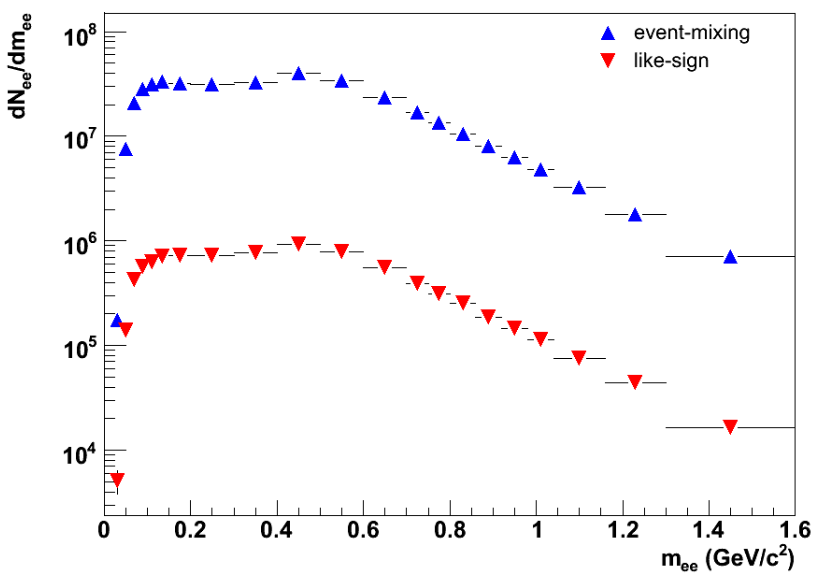


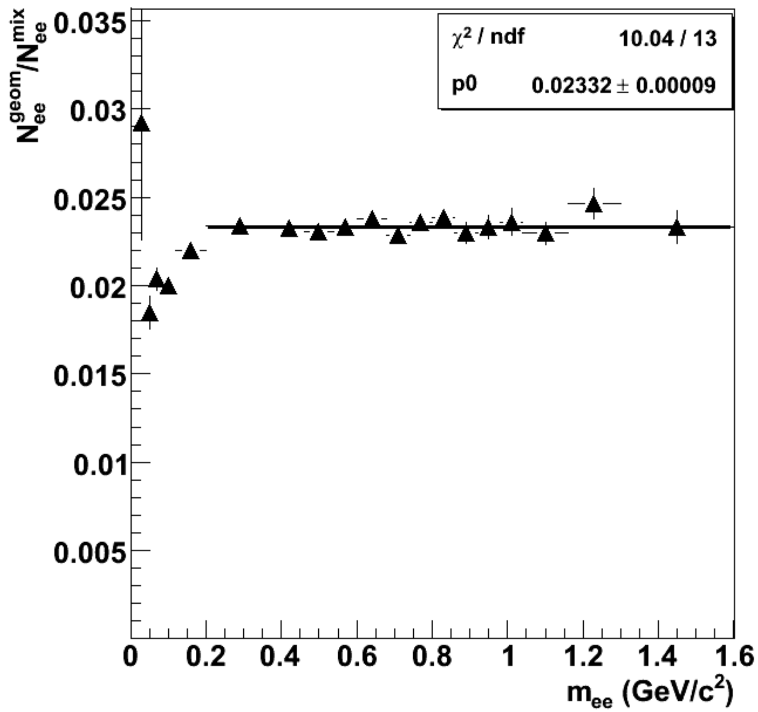
Invariant mass

- Invariant mass for opposite sign pairs with p_t>0.2 GeV/c

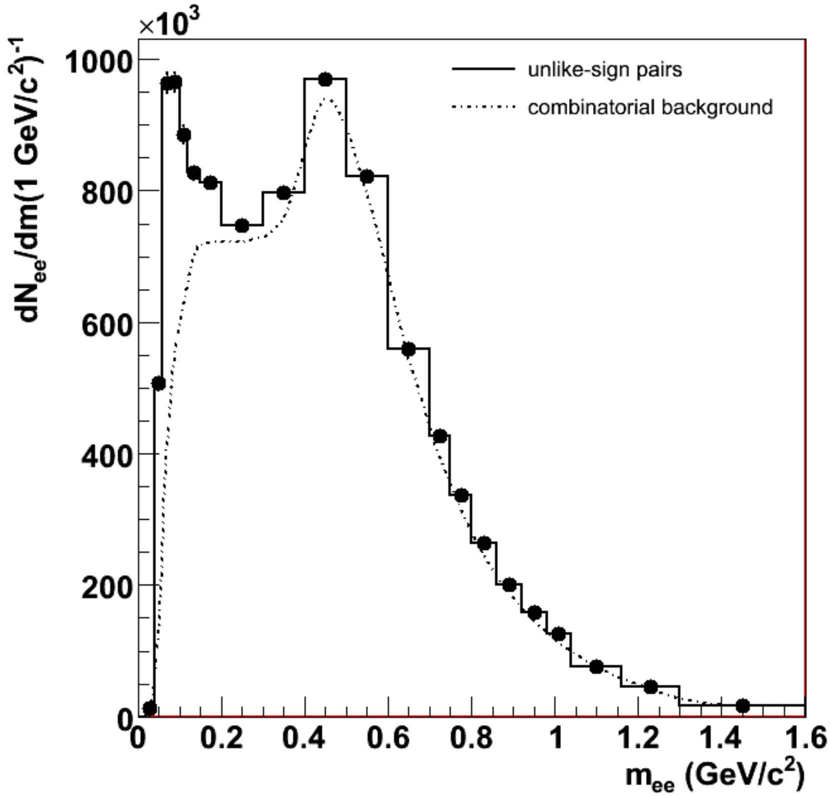
  $$m_{e+e-}^2 = 2 \cdot p_{e+} \cdot p_{e-} (1 - \cos \theta_{e+e-})$$

- Background subtraction using mixed events normalized to like sign background





Invariant mass distribution



<u>for subtraction:</u>

same-event BG for m_{ee}<0.2 GeV/c

normalized mixed-event BG for m_{ee}>0.2 GeV/c

<u>p_t > 0.2 GeV/c</u>

m_{ee}< 0.2 GeV/c²:

S = 6114±176, B/S = 2

m_{ee}> 0.2 GeV/c²:

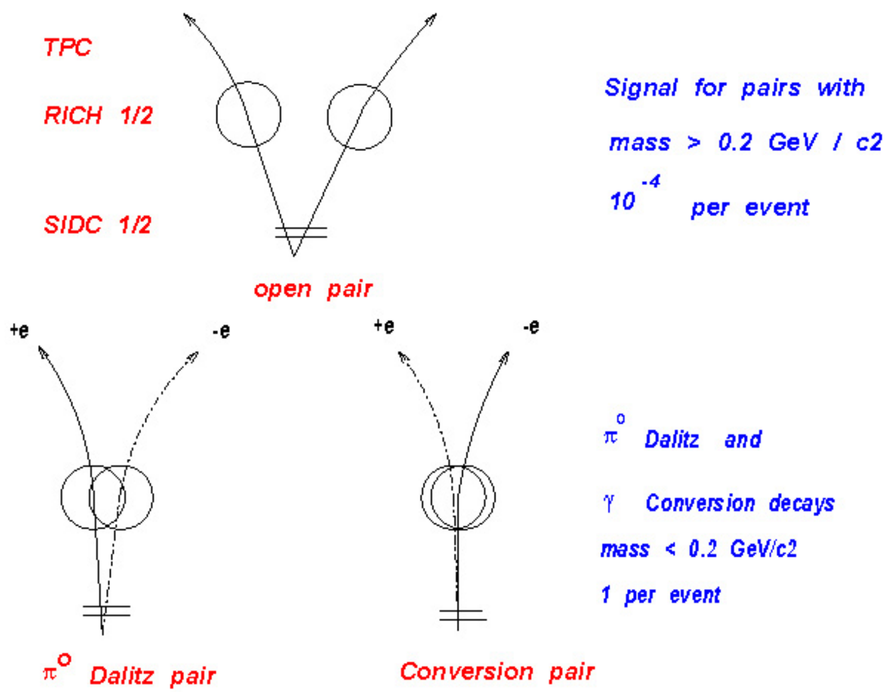
S = 3115±376, B/S = 22

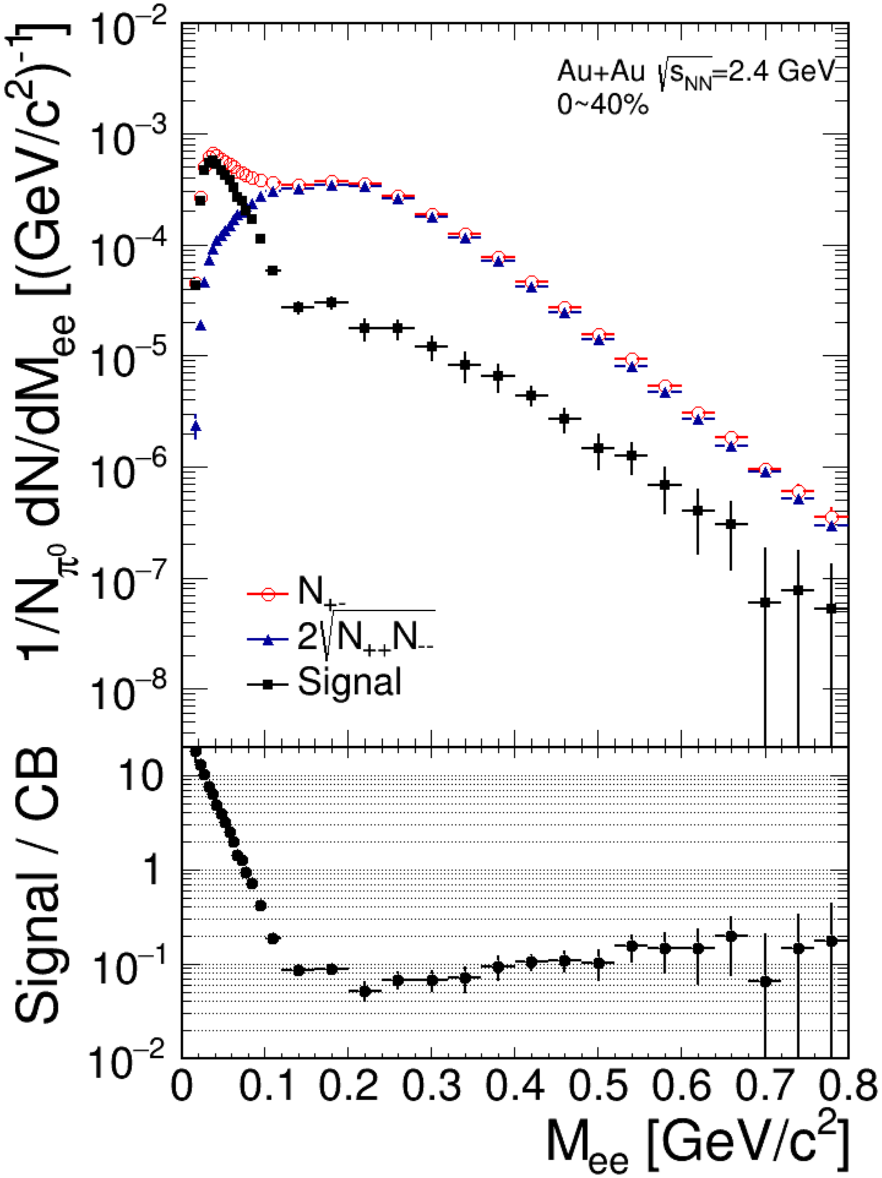
Background rejection

Dominant sources are π^0-Dalitz and γ-conversions

1. Dalitz recognition:

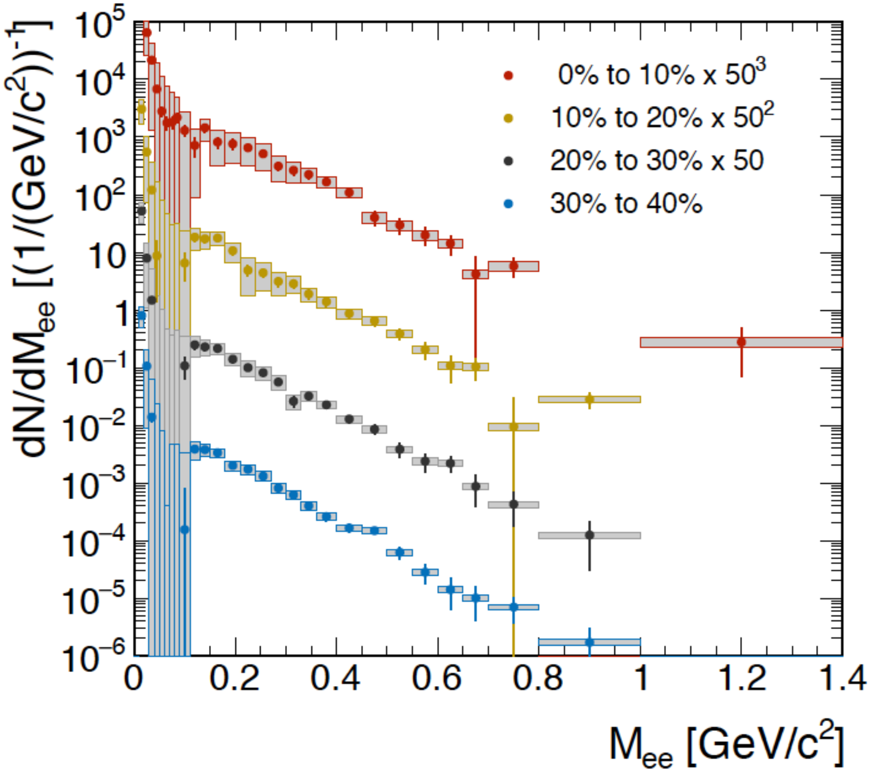
- Rejection of tracks which form a pair Θ_{ee} < 35 mrad
- Tracks which form a pair m_{ee} < 0.2 GeV/c^2 excluded
- from further pairing
- ...still a large number of tracks remaining from
- unrecognized π^0-Dalitz pairs and γ-conversions!

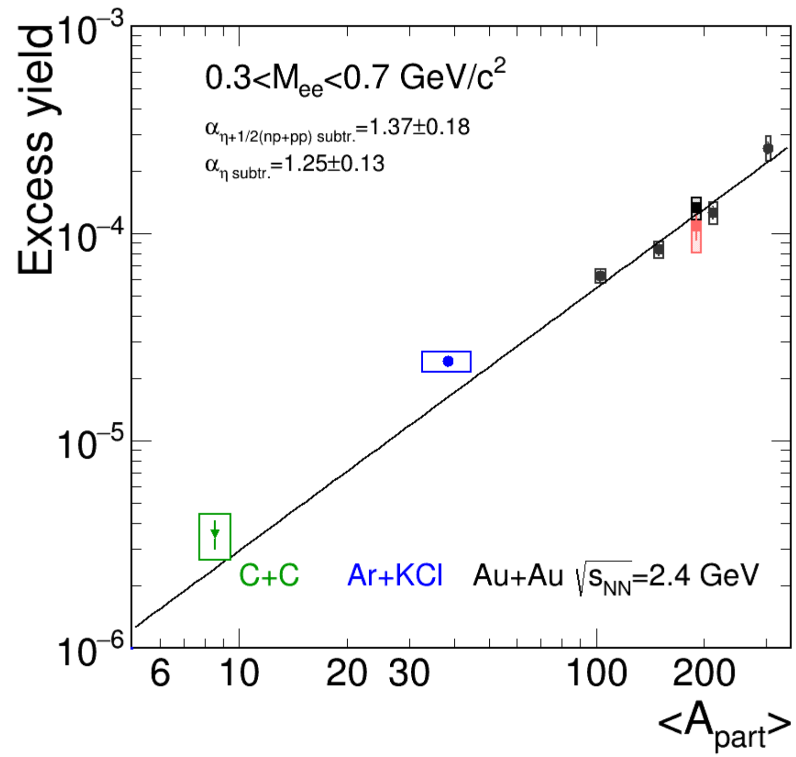


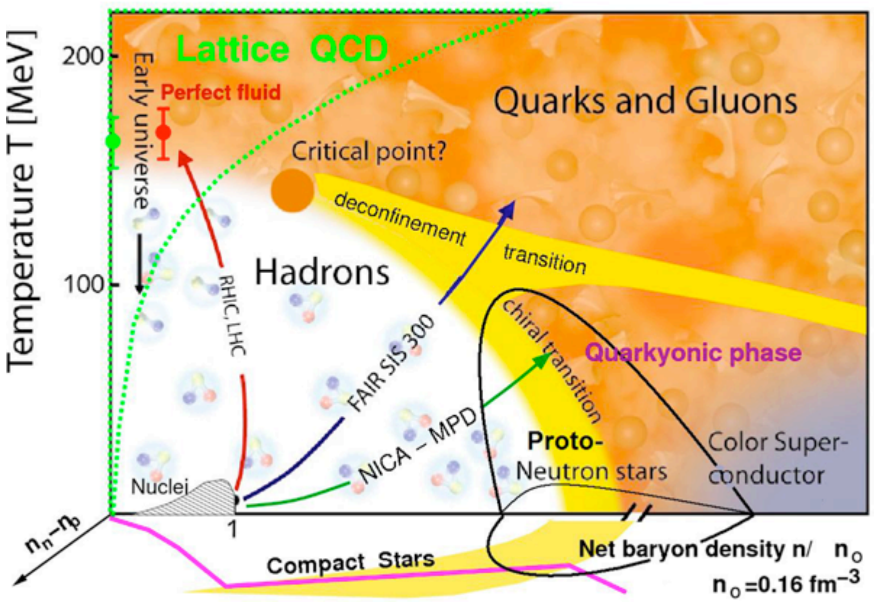


Au+Au $\sqrt{s_{NN}}$=2.4 GeV
0~40%
N_{+-}
$2\sqrt{N_{++}N_{--}}$
Signal
$1/N_{\pi^0}$ dN/dM_{ee} [(GeV/c^2)$^{-1}$]
Signal / CB
M_{ee} [GeV/c^2]

Centrality dependence



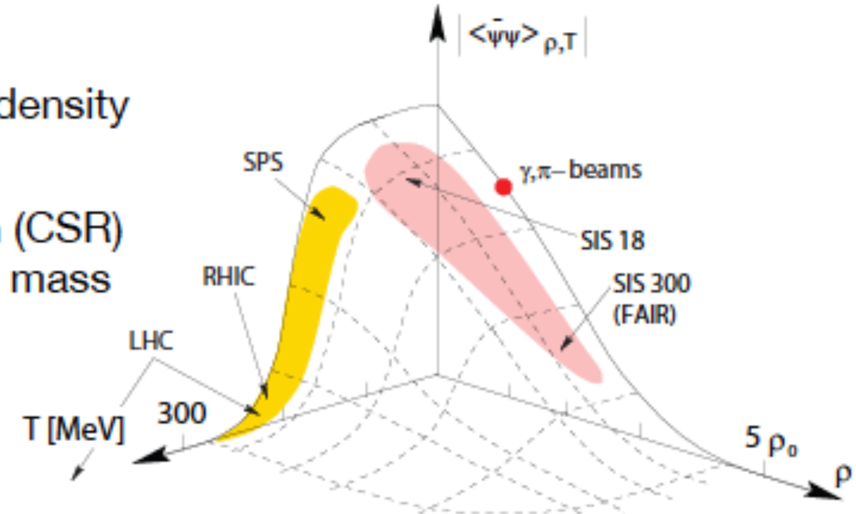




Lattice QCD
Temperature T [MeV]
200
100
Early universe
Perfect fluid
Quarks and Gluons
Critical point?
deconfinement
transition
Hadrons
RHIC, LHC
FAIR SIS 300
chiral transition
Quarkyonic phase
NICA – MPD
Proto-
Neutron stars
Color Super-
conductor
Nuclei
1
$n_n - n_p$
Compact Stars
Net baryon density n/ n_o
n_o=0.16 fm^{-3}

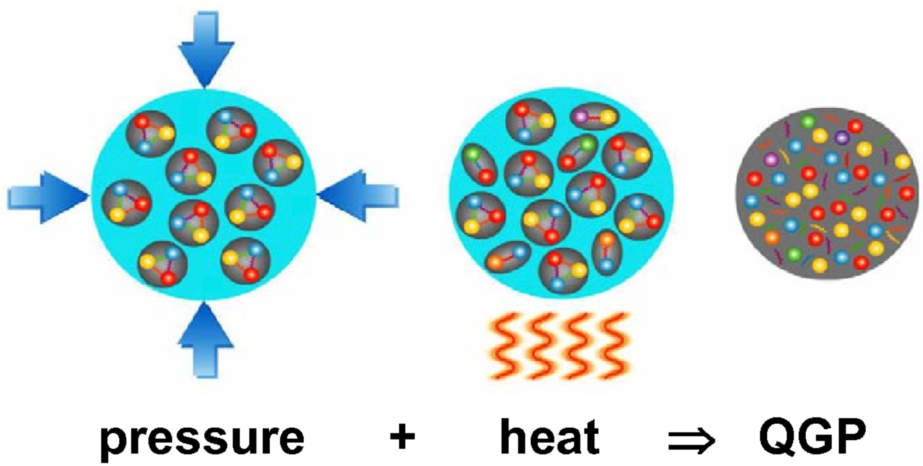
Chiral Symmetry Restoration

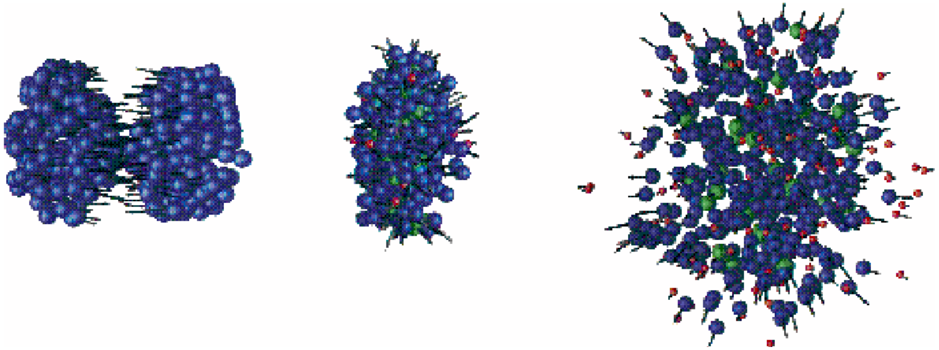
- Spontaneous symmetry breaking gives rise to a nonzero 'order parameter'
  - QCD: quark condensate $\langle\bar{q}q\rangle \approx -250$ MeV^3
  - many models (!): hadron mass and quark condensate are linked
- Numerical QCD calculations
  - at high temperature and/or high baryon density → deconfinement and $\langle\bar{q}q\rangle \to 0$
  - approximate chiral symmetry restoration (CSR) → constituent mass approaches current mass
- Chiral Symmetry Restoration
  - expect modification of hadron spectral properties (mass m, width Γ)



- QCD Lagrangian → parity doublets are degenerate in mass

QGP in the laboratory

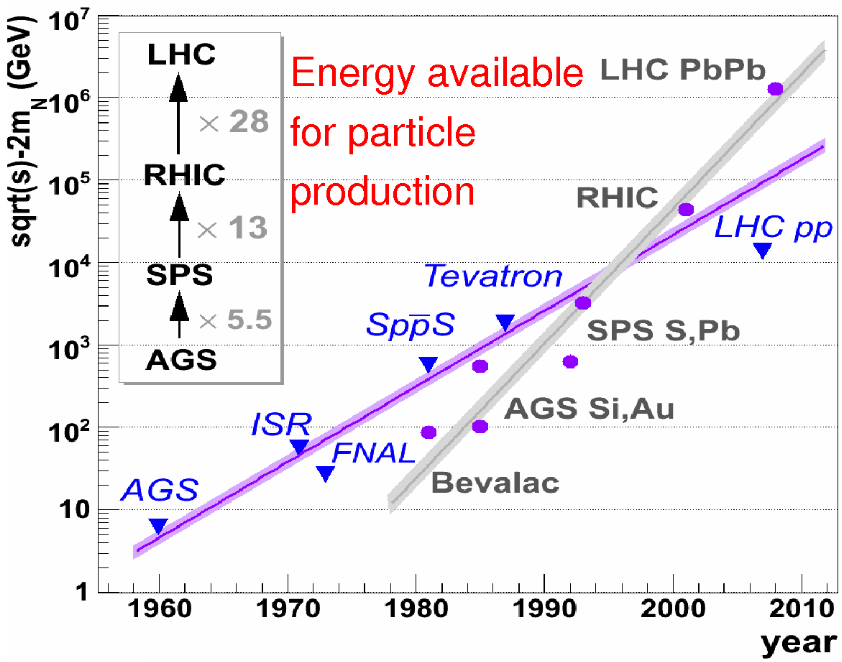




Collisions

- Bevalac (LBL)
  - fixed target (1975-1986) $\sqrt{s}$ <2.4 GeV
- SIS (GSI)
  - fixed target (1989-) $\sqrt{s}$ <2.7 GeV
- AGS (BNL)
  - fixed target (1986-1998) $\sqrt{s}$ <5 GeV
- SPS (CERN)
  - fixed target (1986-2003) $\sqrt{s}$ <20 GeV
- RHIC (BNL)
  - collider (2000-) $\sqrt{s}$ <200 GeV
- LHC (CERN)
  - collider (2008-) $\sqrt{s}$ <5500 GeV
- FAIR (GSI)
  - fixed target (2014-) $\sqrt{s}$ <9 GeV

"Livingston plot"
J. Schukraft nucl-ex/0602014



Energy doubling every ~4 (1.7) years for p (ion) beams.

Heavy ion collisions at LHC

	SPS	RHIC	LHC
$\sqrt{s_{NN}}$ (GeV)	17	200	2760(5500)
dN_{ch}/dy	430	730	1584
τ^0_{QGP} (fm/c)	1	0.2	0.1
T/T_c	1.1	1.9	3.0-4.7
ε (GeV/fm^3)	3	5	>18
τ_{QGP} (fm/c)	≤2	2-4	≥10
τ_f (fm/c)	~10	20-30	15-60
V_f(fm^3)	few 10^3	few 10^4	few 10^5

faster
hotter
denser
longer

bigger

Inclusive, decay and direct γ v_2