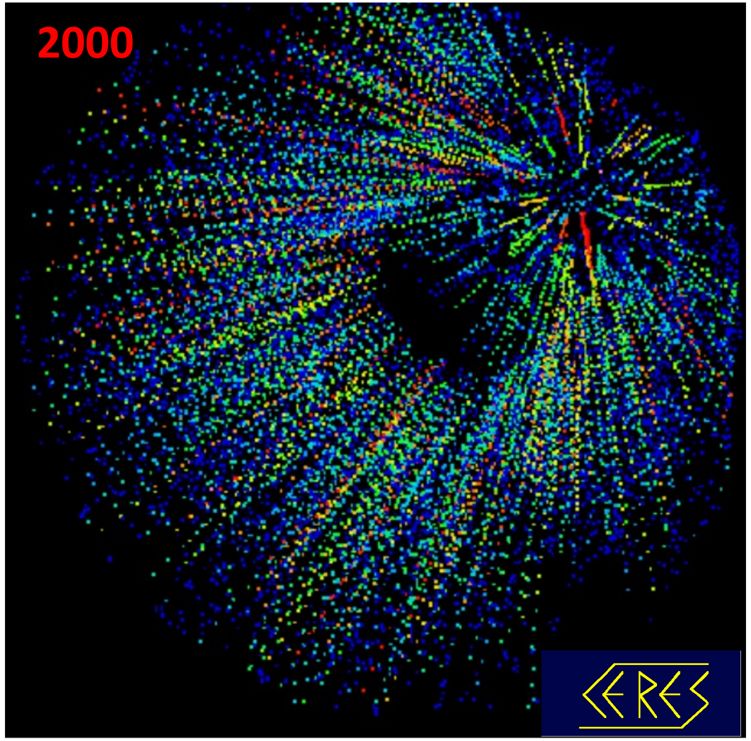
From the *Heart* of the QGP: Probing the Early Universe with Photons and Dileptons

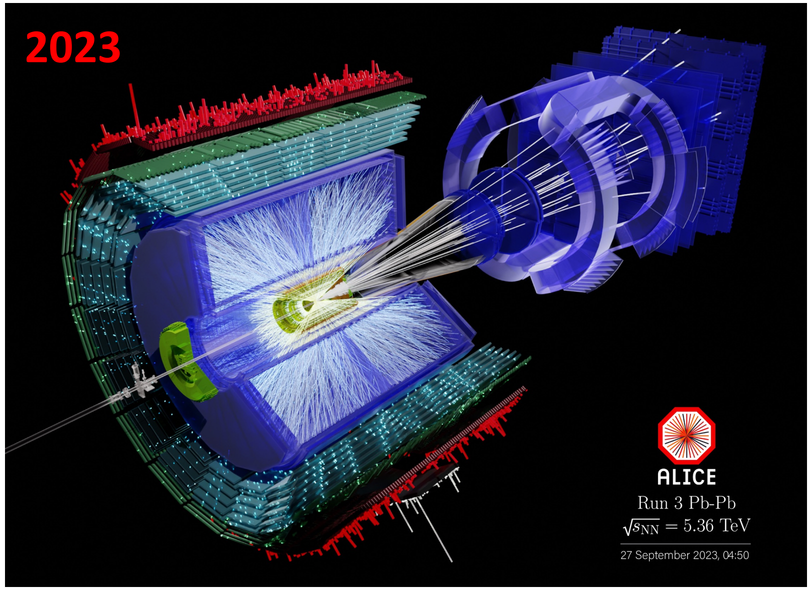
A. Marin, Bad Honnef, February 2025

Never at Rest: A Lifetime Inquiry of QGP

Heavy-ion collisions



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



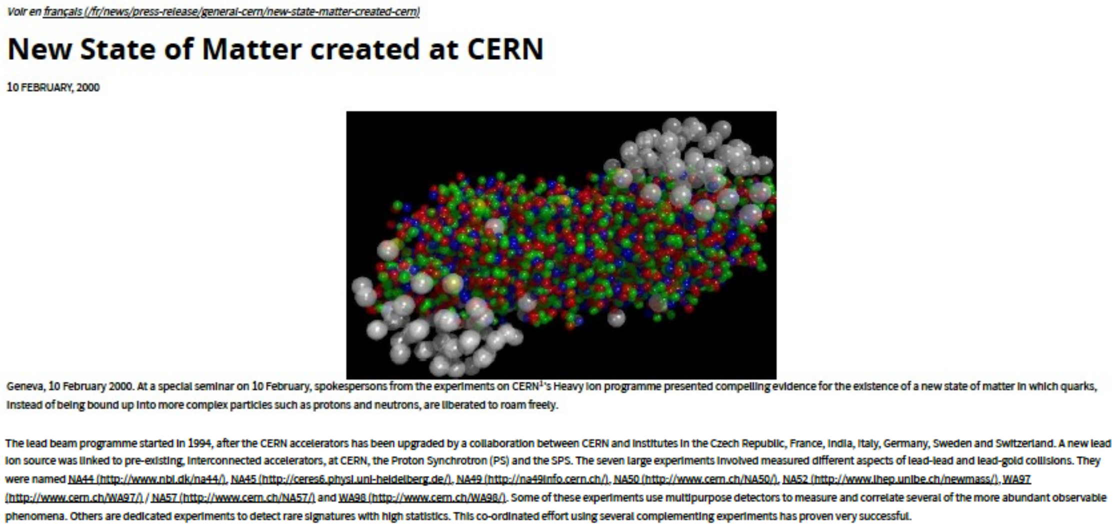
Pb-Pb $\sqrt{s_{NN}}$= 5.36 TeV

	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

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)



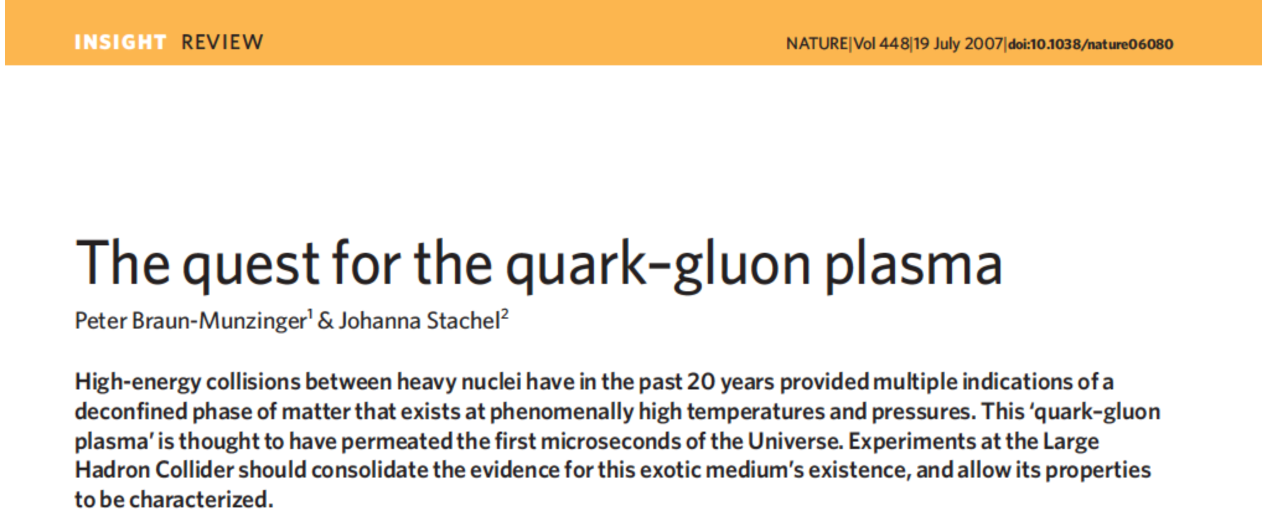
Voir en *français (/fr/news/press-release/general-cern/new-state-matter-created-cern)*

New State of Matter created at CERN

10 FEBRUARY, 2000

Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

The lead beam programme started in 1994, after the CERN accelerators has been upgraded by a collaboration between CERN and institutes in the Czech Republic, France, India, Italy, Germany, Sweden and Switzerland. A new lead ion source was linked to pre-existing, interconnected accelerators, at CERN, the Proton Synchrotron (PS) and the SPS. The seven large experiments involved measured different aspects of lead-lead and lead-gold collisions. They were named NA44 (http://www.nbi.dk/na44/), NA45 (http://ceres6.physi.uni-heidelberg.de/), NA49 (http://na49info.cern.ch/), NA50 (http://www.cern.ch/NA50/), NA52 (http://www.lhep.unibe.ch/newmass/), WA97 (http://www.cern.ch/WA97/) / NA57 (http://www.cern.ch/NA57/) and WA98 (http://www.cern.ch/WA98/). Some of these experiments use multipurpose detectors to measure and correlate several of the more abundant observable phenomena. Others are dedicated experiments to detect rare signatures with high statistics. This co-ordinated effort using several complementing experiments has proven very successful.

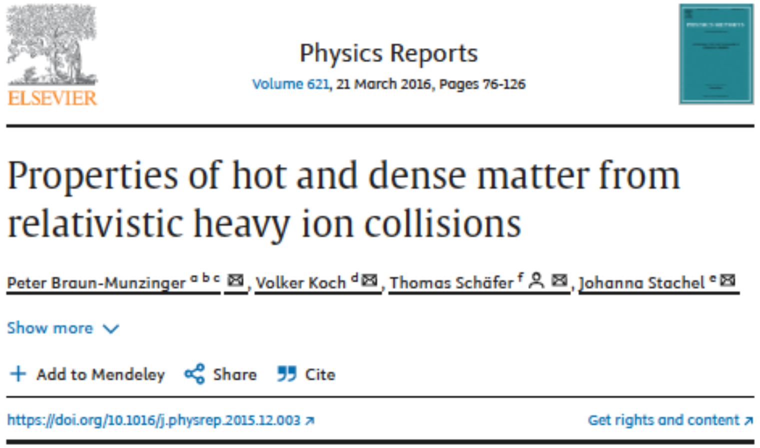


INSIGHT REVIEW NATURE|Vol 448|19 July 2007|doi:10.1038/nature06080

The quest for the quark–gluon plasma

Peter Braun-Munzinger[1] & Johanna Stachel[2]

High-energy collisions between heavy nuclei have in the past 20 years provided multiple indications of a deconfined phase of matter that exists at phenomenally high temperatures and pressures. This 'quark–gluon plasma' is thought to have permeated the first microseconds of the Universe. Experiments at the Large Hadron Collider should consolidate the evidence for this exotic medium's existence, and allow its properties to be characterized.



ELSEVIER
Physics Reports
Volume 621, 21 March 2016, Pages 76-126

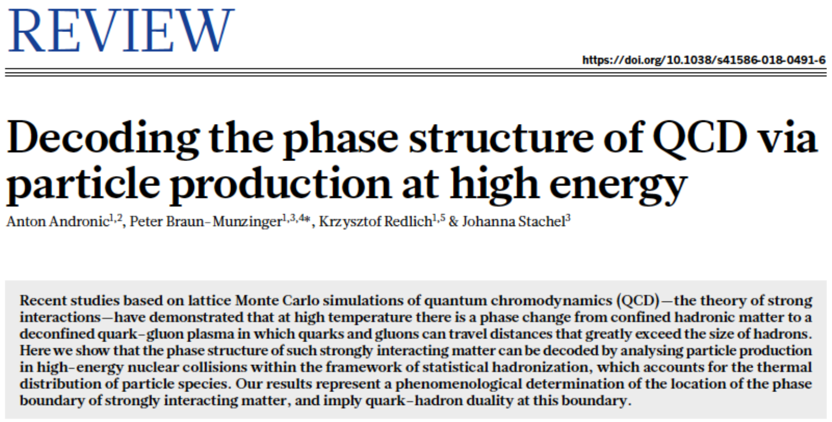
Properties of hot and dense matter from relativistic heavy ion collisions

Peter Braun-Munzinger [a,b,c], Volker Koch [d], Thomas Schäfer [f], Johanna Stachel [e]

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.physrep.2015.12.003
Get rights and content



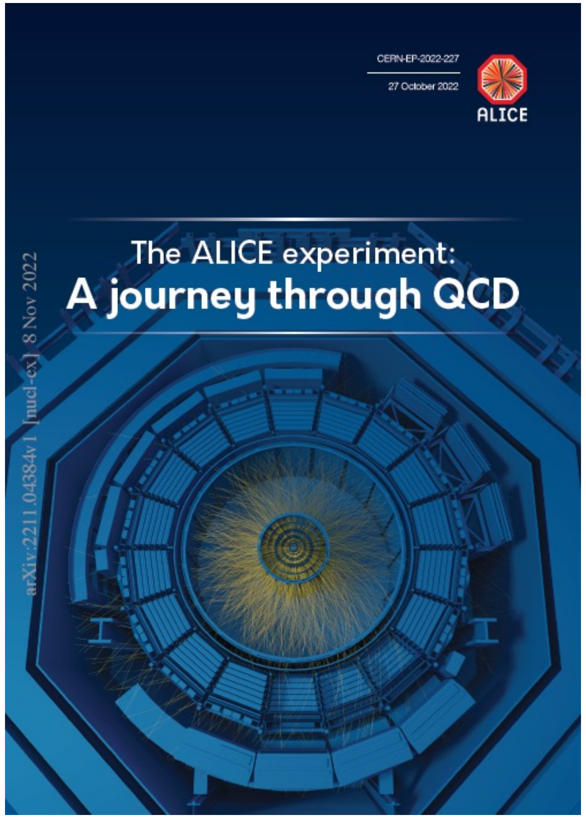
REVIEW

https://doi.org/10.1038/s41586-018-0491-6

Decoding the phase structure of QCD via particle production at high energy

Anton Andronic[1,2], Peter Braun-Munzinger[1,3,4]*, Krzysztof Redlich[1,5] & Johanna Stachel[3]

Recent studies based on lattice Monte Carlo simulations of quantum chromodynamics (QCD)—the theory of strong interactions—have demonstrated that at high temperature there is a phase change from confined hadronic matter to a deconfined quark–gluon plasma in which quarks and gluons can travel distances that greatly exceed the size of hadrons. Here we show that the phase structure of such strongly interacting matter can be decoded by analysing particle production in high-energy nuclear collisions within the framework of statistical hadronization, which accounts for the thermal distribution of particle species. Our results represent a phenomenological determination of the location of the phase boundary of strongly interacting matter, and imply quark–hadron duality at this boundary.



CERN-EP-2022-227
27 October 2022

ALICE

The ALICE experiment: A journey through QCD

arXiv:2211.04384v1 [nucl-ex] 8 Nov 2022

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

My time with Johanna from HD and GSI

CERES TPC Construction
gas system, slow control

Pb-Au
40AGeV

Pb-Au
158AGeV

1997 1998 1999 2000

CERES data Analysis
ALICE TRD TDR
Power distribution

ALICE TRD Cooling

PRL96(2006)152301

ALICE PCM

PLB666(2008)425

NIMA593(2008)203

2001 2002 2003 2004 2005 2006 2007 2008 2009

ALICE Run 1

PLB 717(2012)162

pp 7TeV, pp 2.76 TeV, pp 8TeV
PbPb2.76TeV, pPb 5.02TeV cerncourier

EPJC74(2014)10,3108

ALICE Run 2

PLB754(2016)235

PbPb 5.02, pPb5.02, pPb 8.16

EPJC78(2018)8,624
PRC98(2018)044901

2010 2011 2012 2013 2014 2015 2016 2017 2018

ALICE3
PCM

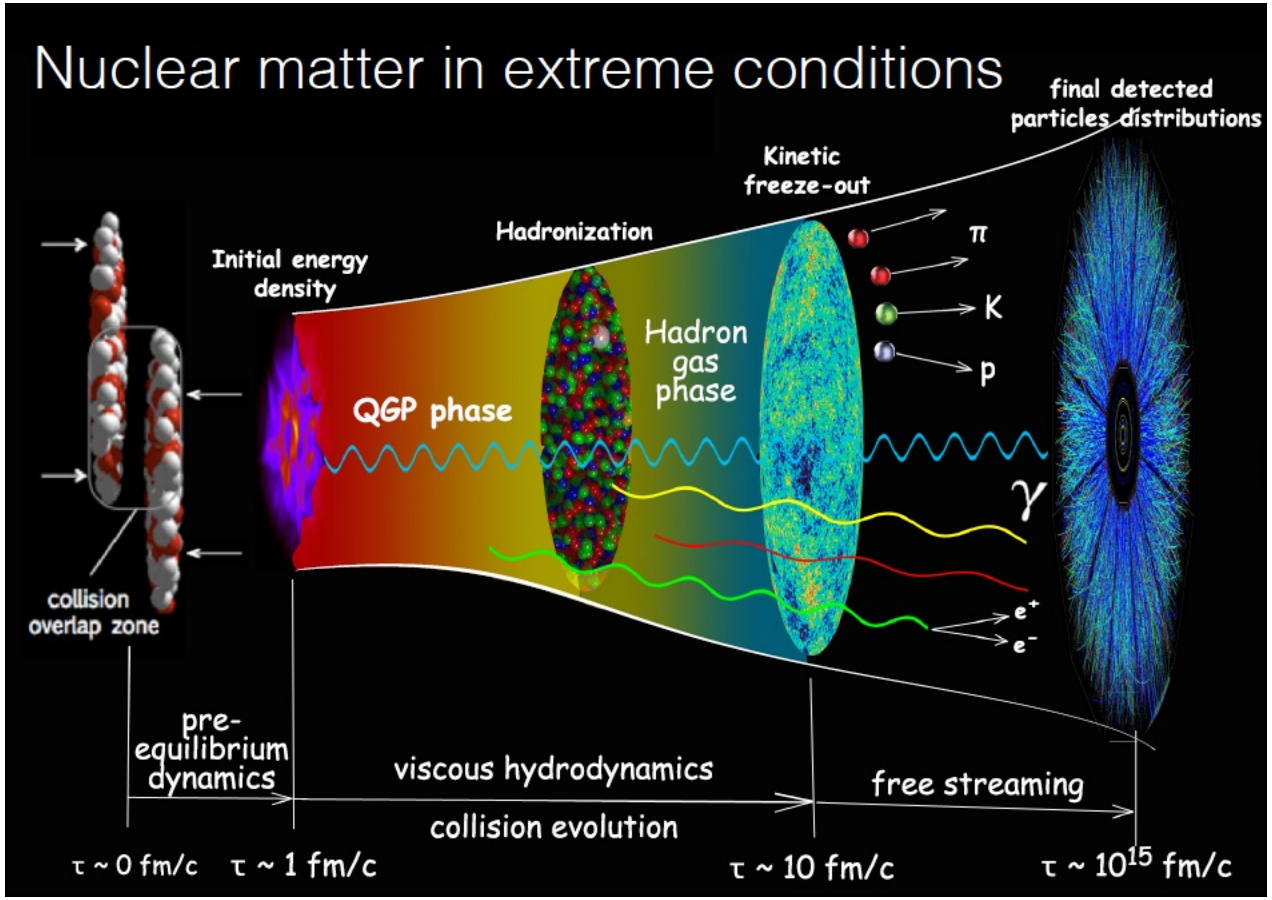
ALICE Run 3

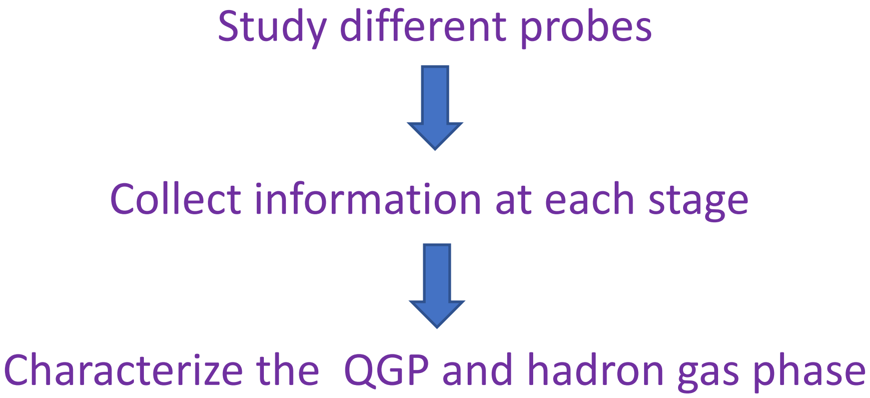
arXiv:2411.09560
JINST18 (2023)P11032
pp 13.6 TeV, PbPb 5.36 TeV

2020 2021 2022 2023 2024 2025

Heavy-ion collisions

Courtesy C. Shen





Study different probes

Collect information at each stage

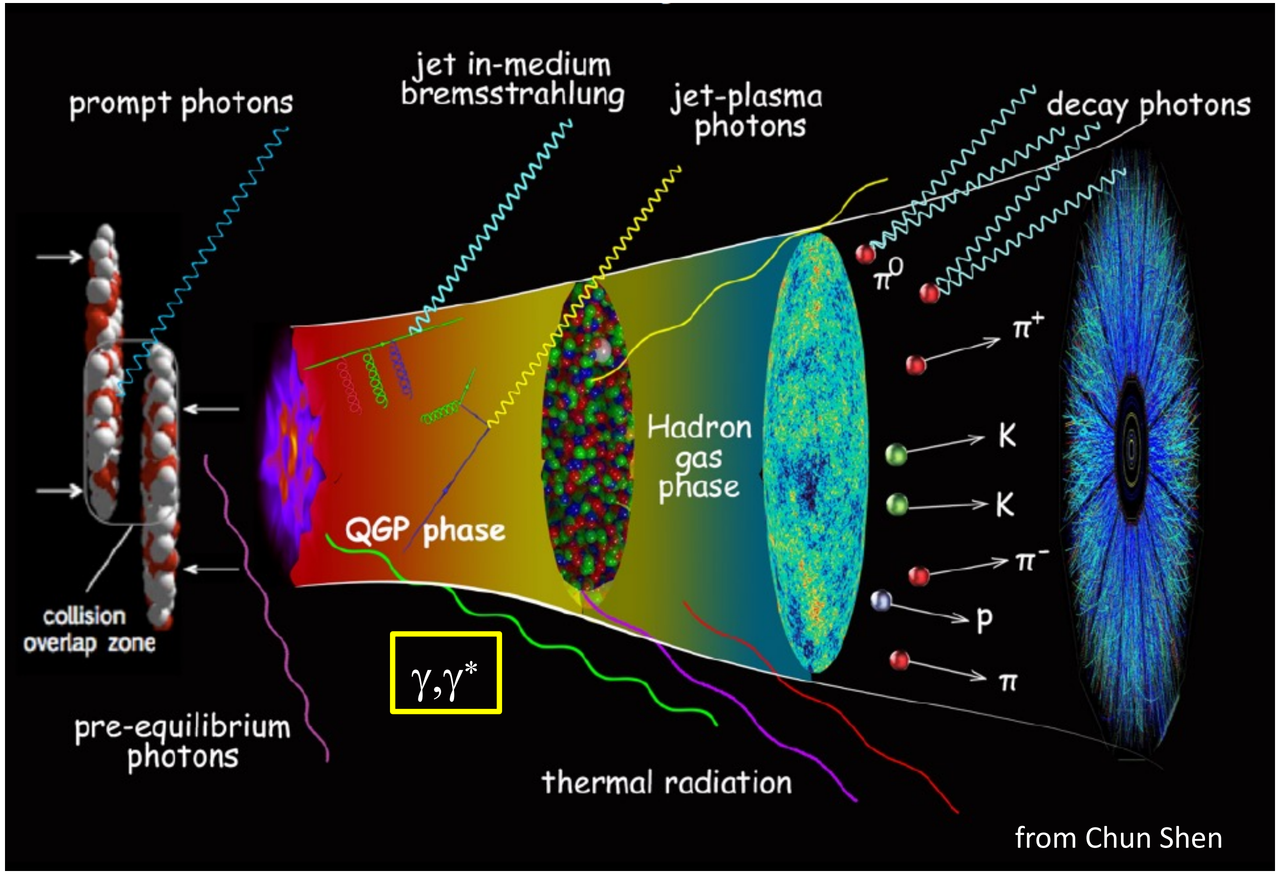
Characterize the QGP and hadron gas phase

AA collisions
pA and pp : control and reference systems

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Electromagnetic Probes

Courtesy C. Shen



from Chun Shen

EM

- Photons: prompt and thermal
- Dileptons: e^+e^-,$\mu^+\mu^-$

Produced at several stages of the collision
Colorless objects, scape without interaction

Directly probe the entire evolution of the fireball

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

Measure (effective) temperature
Test chiral symmetry restoration

Thermal electromagnetic radiation

Thermal emission rates:

Dileptons: $\frac{dR_{ee}}{d^4p} = \frac{-\alpha^2}{\pi^3 M^2} f^B(p_0;T)\, \rho_{em}(M,p;\mu_B,T)$

Depends on the mass and on p

Photons: $p_0\frac{dR_\gamma}{d^3p} = \frac{-\alpha}{\pi^2} f^B(p_0;T)\, \rho_{em}(M=0,p;\mu_B,T)$

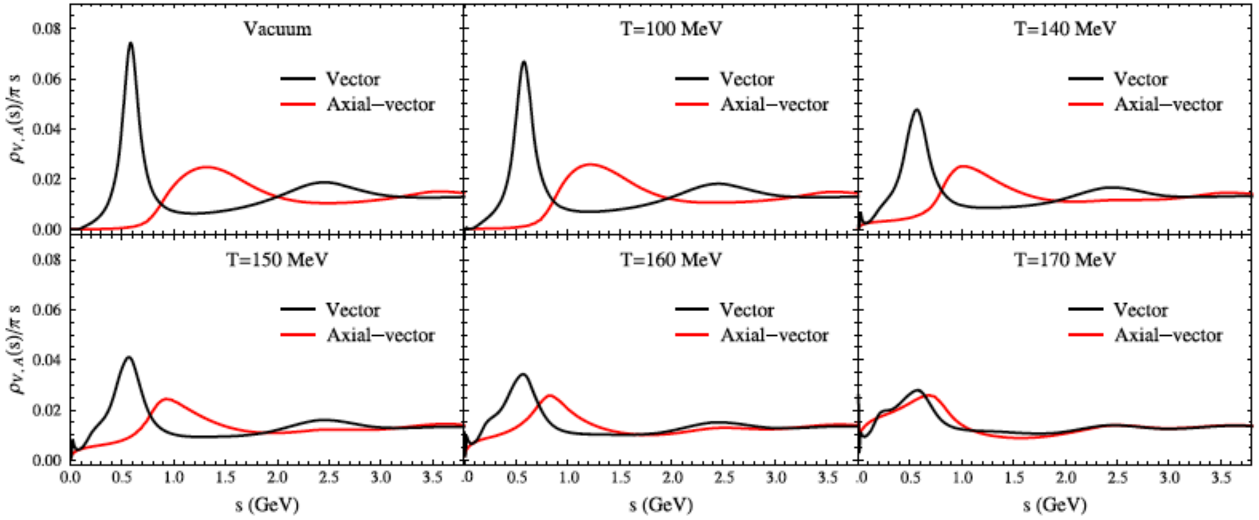
M→0, depends only on p

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

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)



Access to Chiral symmetry restoration ρ -a_1 mixing

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

(Dilepton) experiments

Nucl. Phys. A 982 (2018) 163

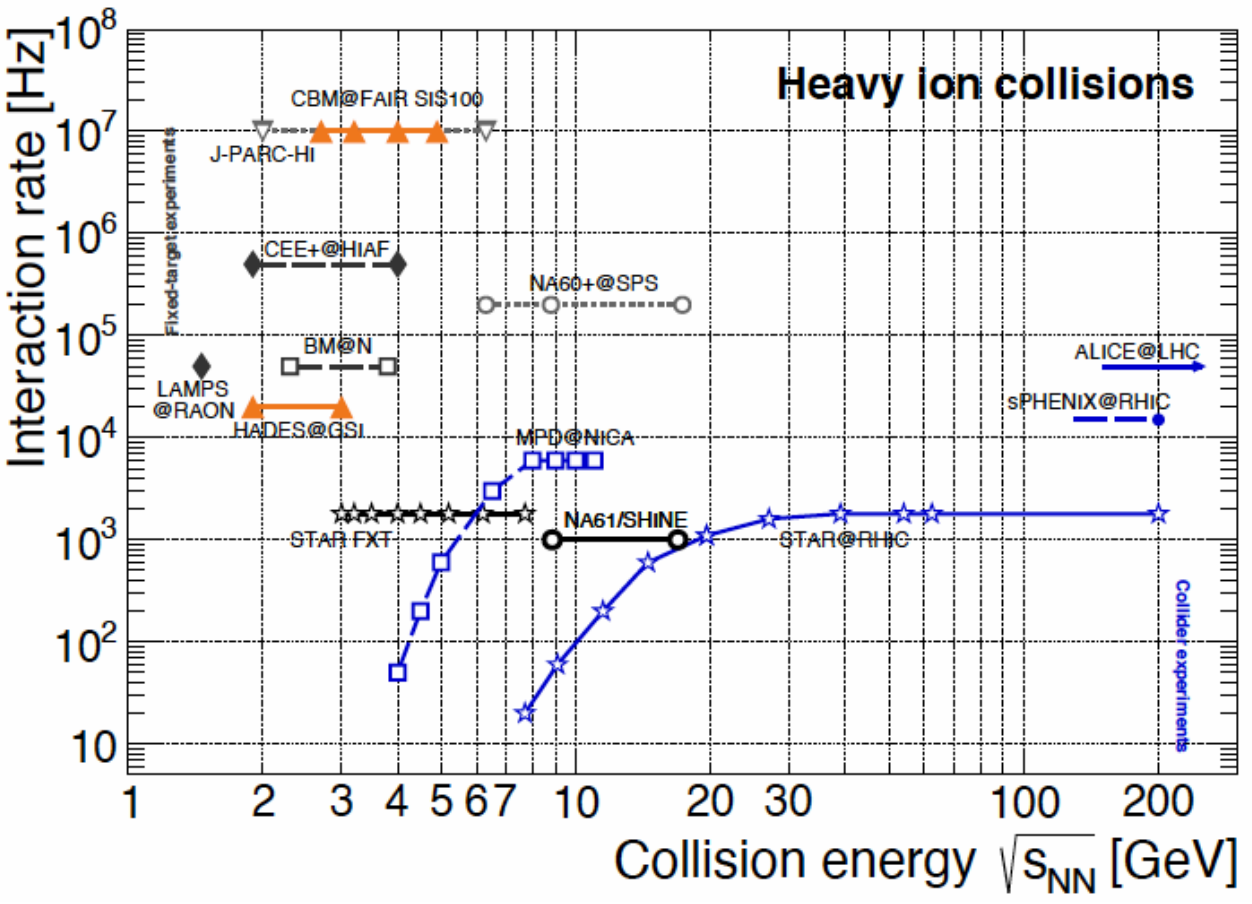
Nuclear collisions

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

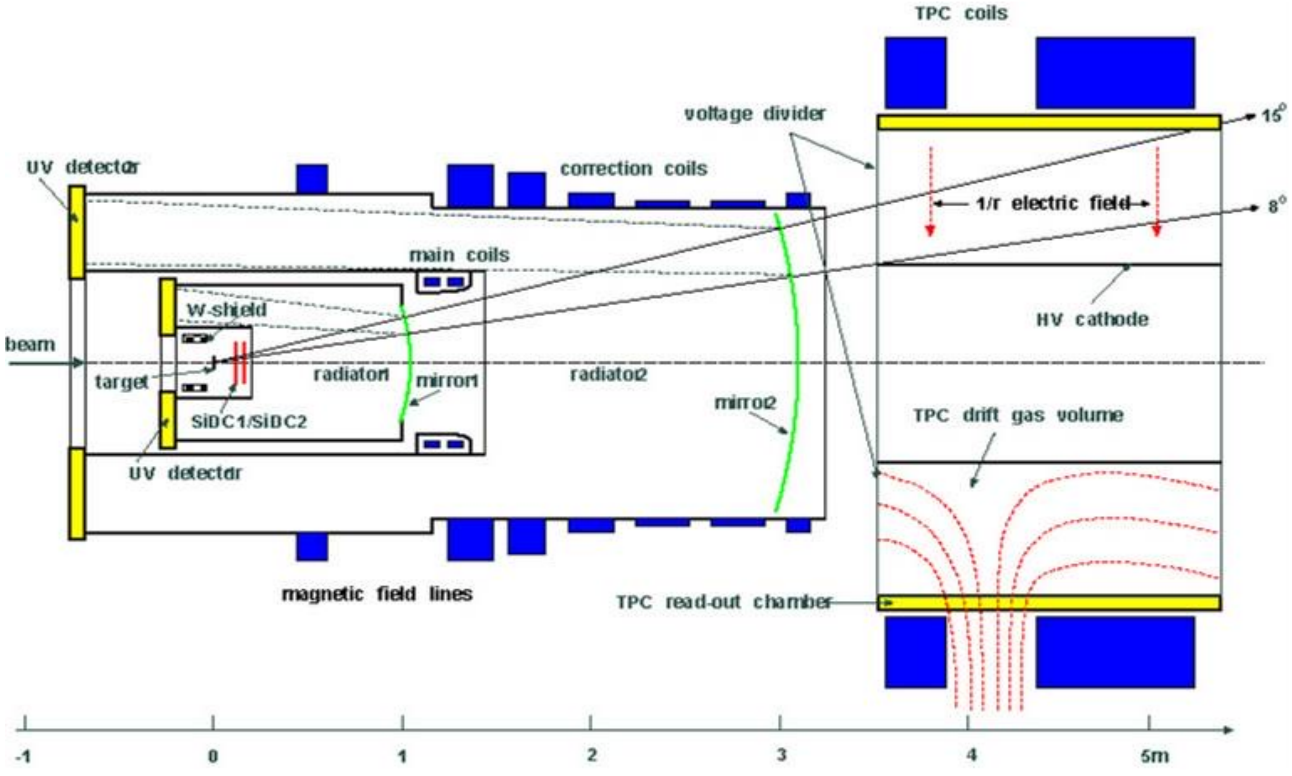
Elementary Reactions

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

Completed
Running
Future



The CERES Setup



1999 Run:

- Pb+Au 40 AGeV

$8x10^6$ events

$\sigma/\sigma_{geo}=30\%$

2000 Run:

- Pb+Au 80 AGeV

0.5 x 10^6 events

$\sigma/\sigma_{geo}=30\%$

- Pb+Au 158 AGeV

$30x10^6$ events

$\sigma/\sigma_{geo}=7\%$

$3x10^6$ events

$\sigma/\sigma_{geo}=20\%$

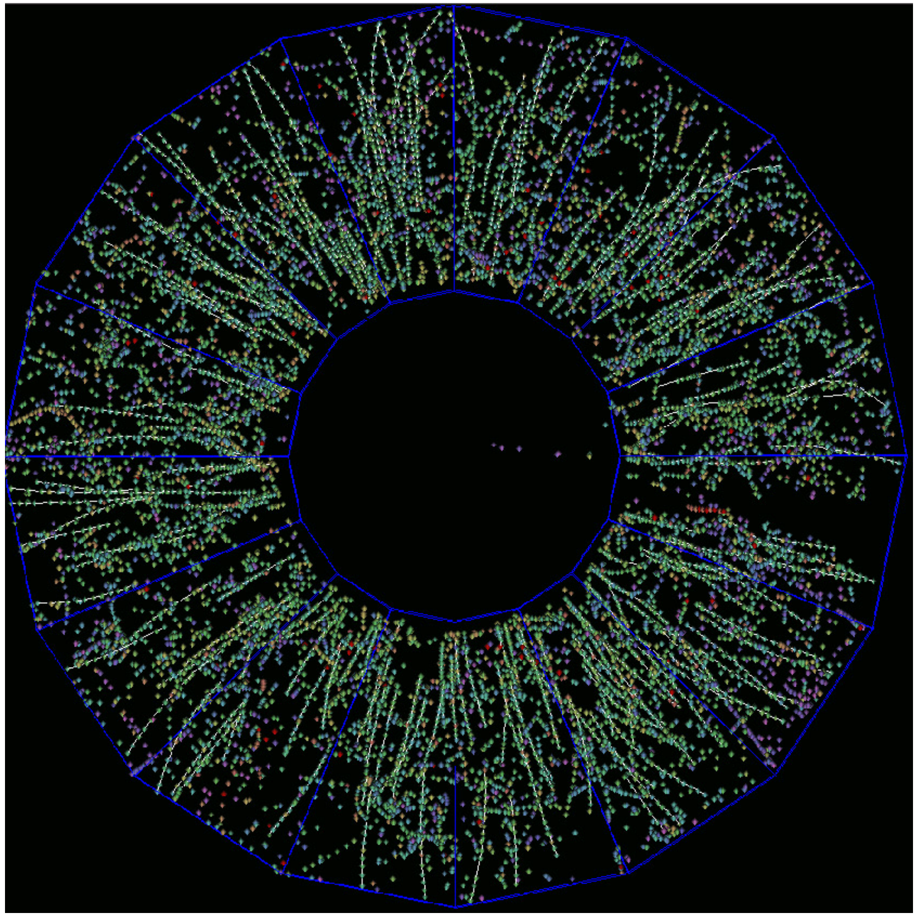
Sidc: vertex reconstruction, angle measurement

Rich: electron ID

TPC: momentum and electron-ID (σ_{mass}~3.8% at $\phi \rightarrow ee$)

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

The CERES TPC

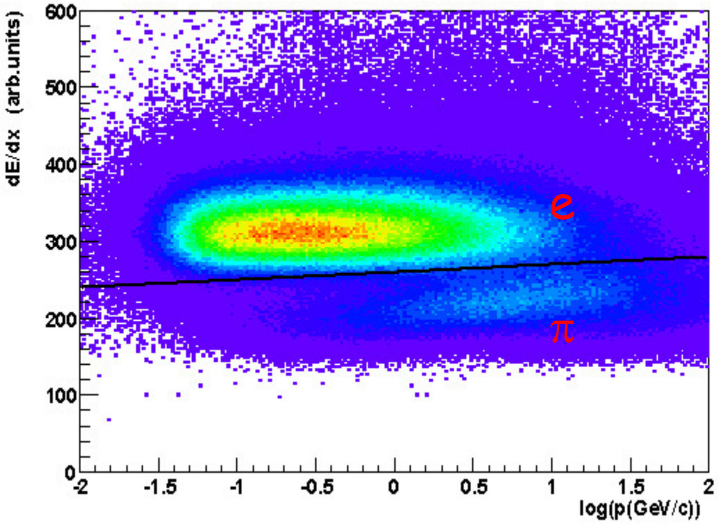


radial-drift TPC:

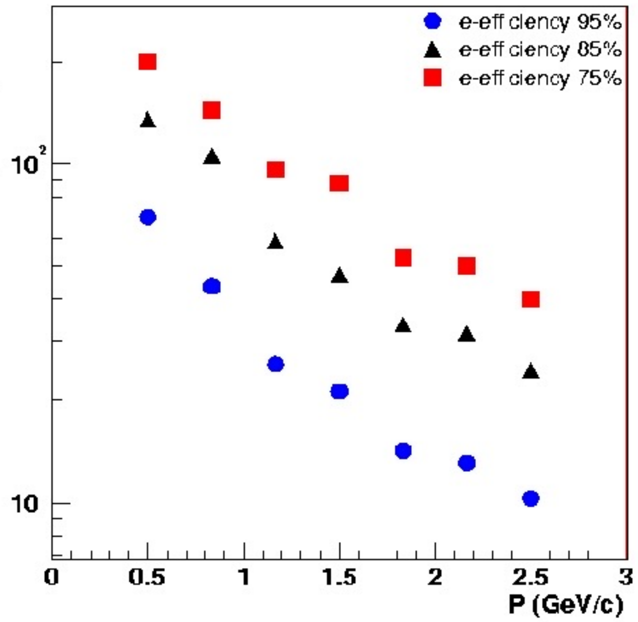
- charged particle tracking
- momentum determination
- electron ID via dE/dx

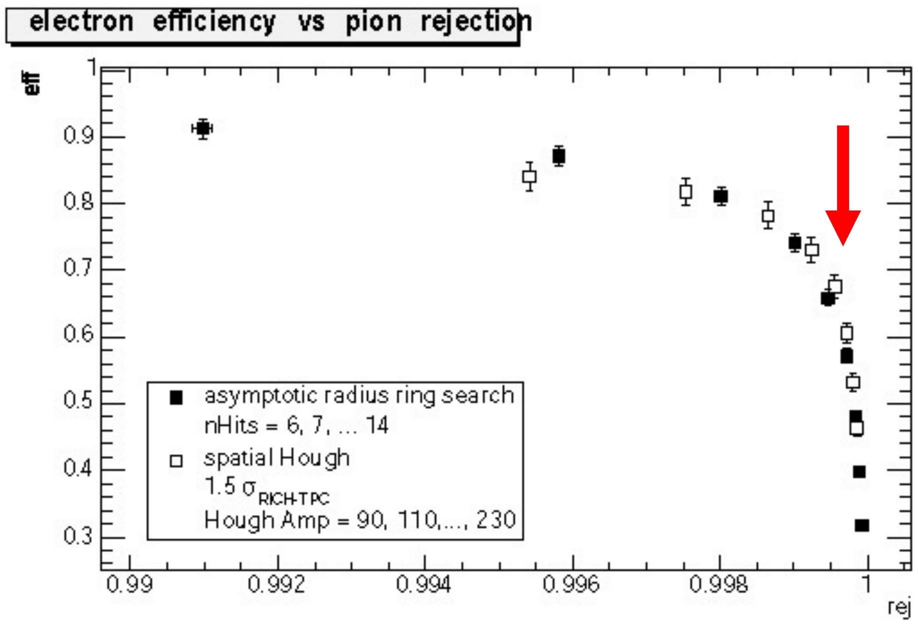
a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Electron identification: TPC and RICH



Energy loss dE/dx
in TPC





e.g. at 1.0 GeV/c:
4×10^4 π-rejection factor
68% e-efficiency

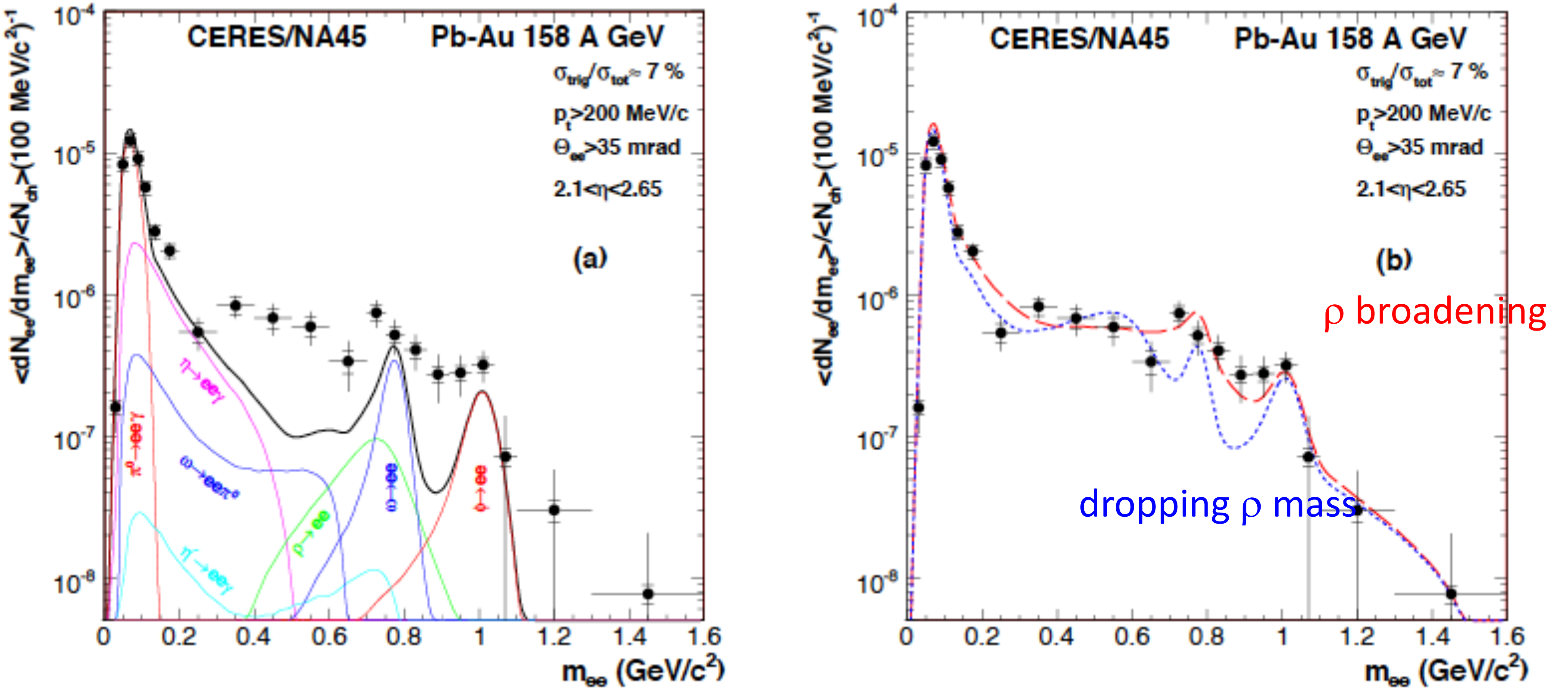
a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

CERES dilepton spectrum

Phys. Lett. B666 (2008) 425

mass resolution 3.8%



ρ broadening

dropping ρ mass

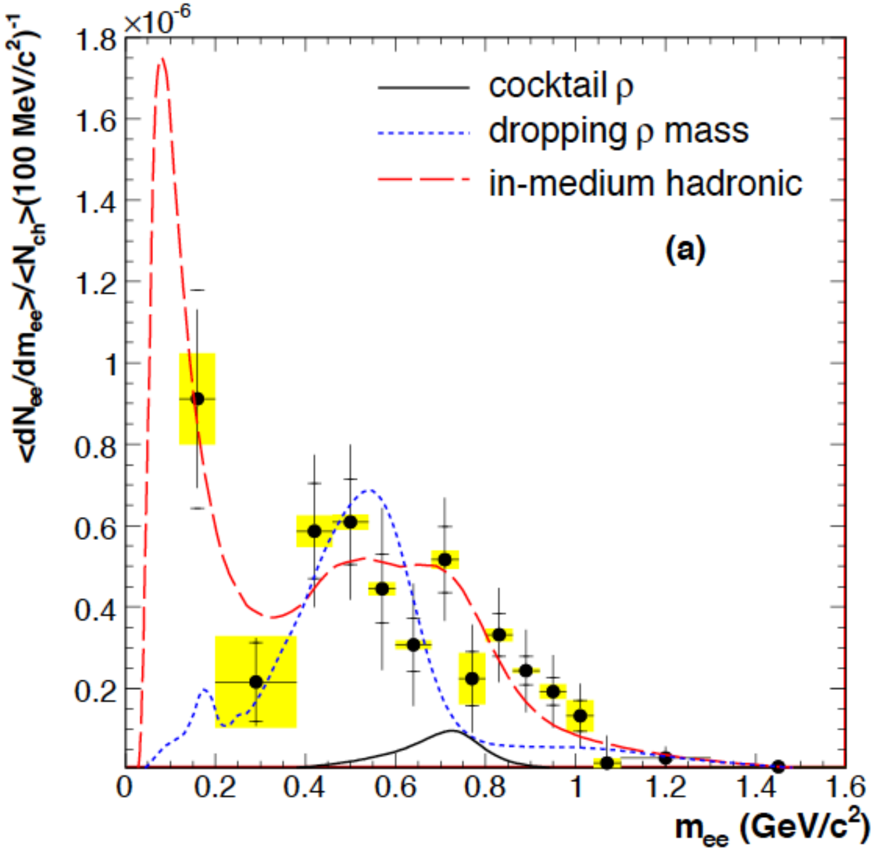
dilepton enhancement at $0.2<m_{ee}<1.1$ GeV/c^2 :

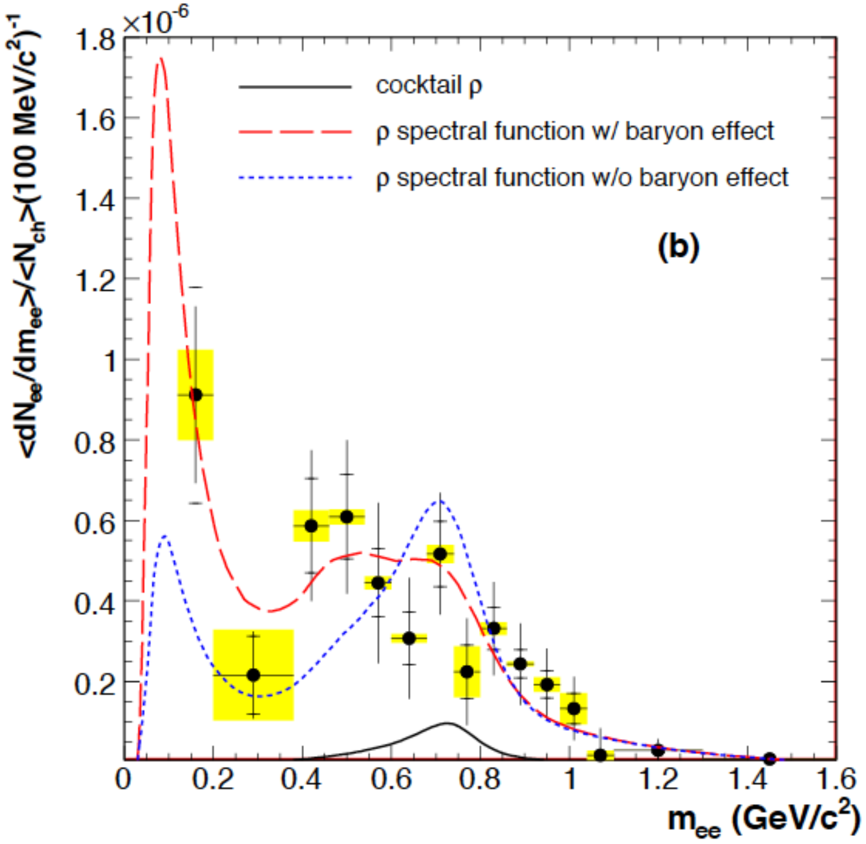
2.45 ± 0.21 (stat.)± 0.35 (syst.)± 0.58 (cocktail)

Data favour ρ broadening

Most evident between ω - ϕ

CERES excess spectrum



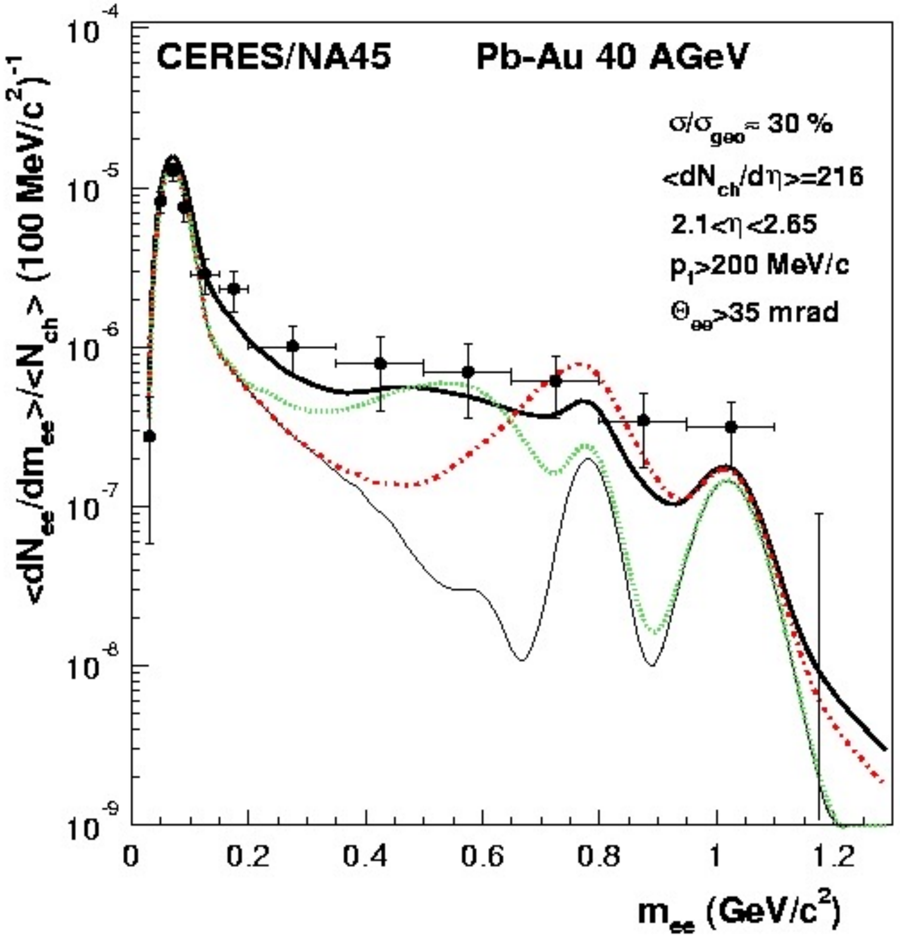


- contribution of ρ at freeze-out totally negligible, medium dominates by more than order of magnitude in central PbAu
- points at 0.7-1 GeV exclude dropping mass

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 energy

5.9 ±1.5 (stat) ±1.2 (syst data) ± 1.8 (decays)

effect of baryon density?

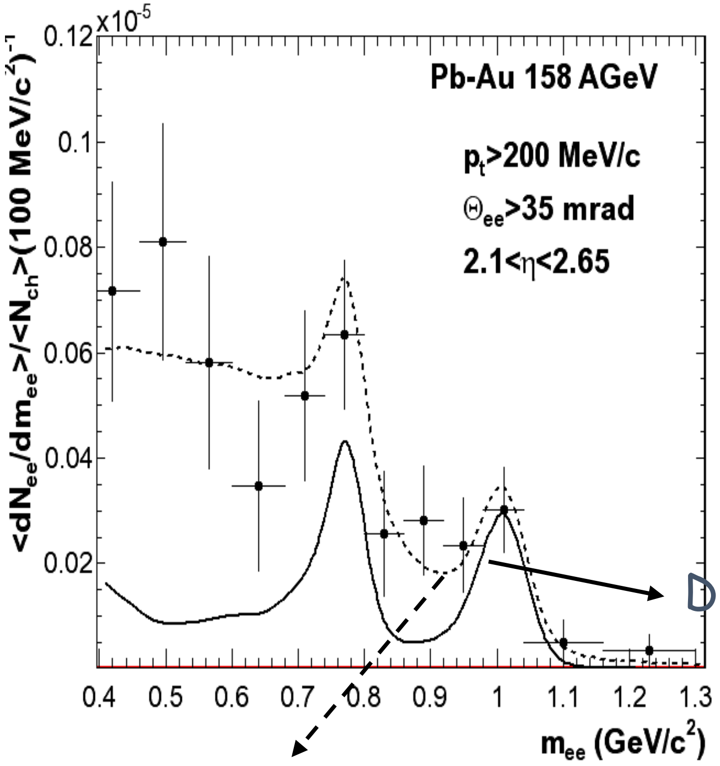
a.marin@gsi.de, Physikzentrum Bad Honnef (2025)


10 4:54PM


10 5:21PM

Invariant mass: $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$

PRL96(2006)152301



Decay cocktail

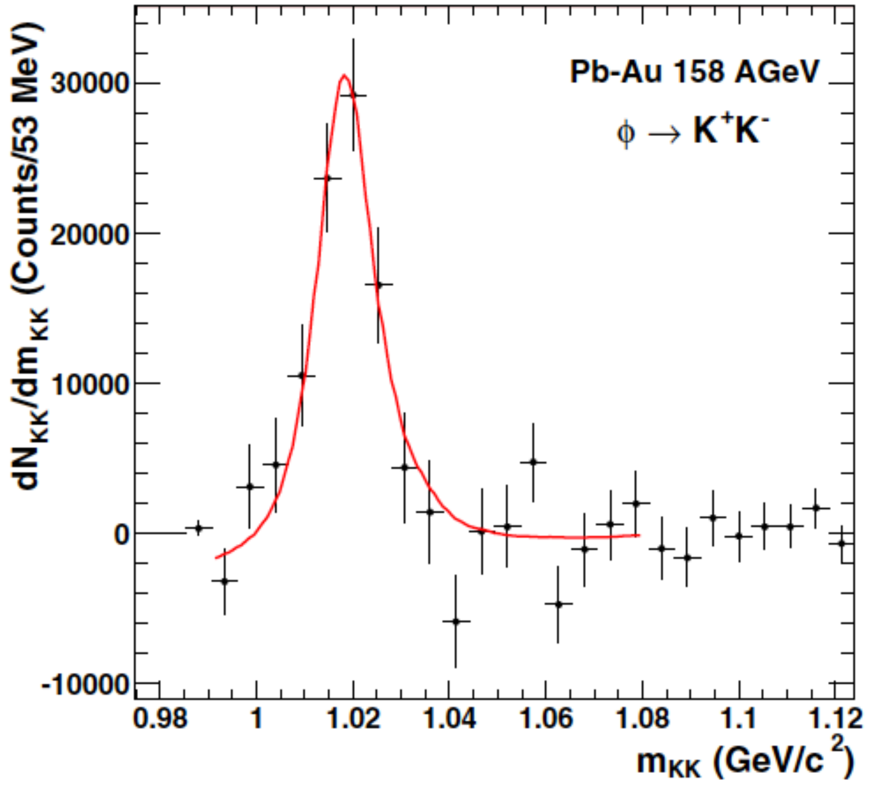
Decay cocktail+rho+QGP

ϕ : mass 0.9-1.1 GeV/c^2

229 ± 53 Counts

S/B=1/12

1.5 GeV/c < p_t < 1.75 GeV/c
2.2<y<2.4



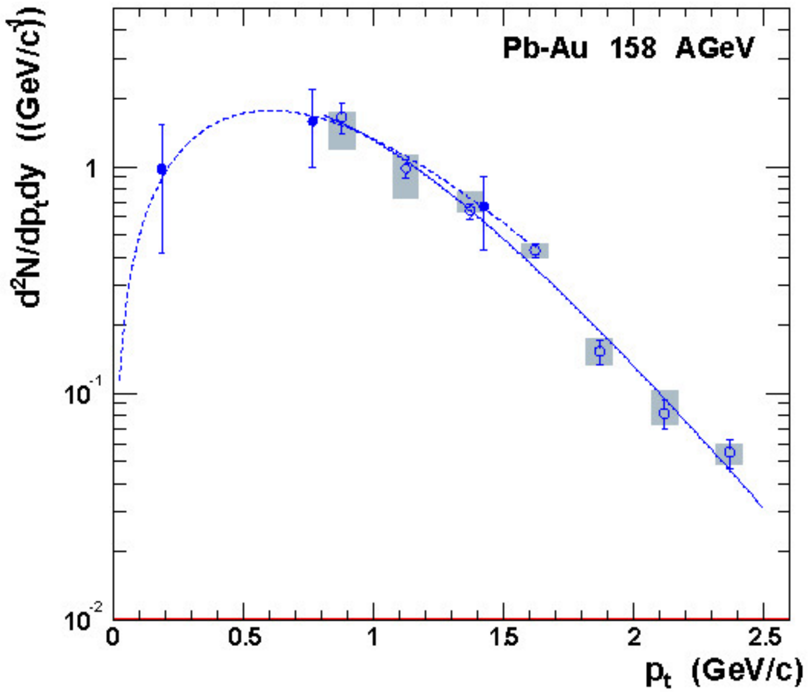
Physics Background:

in-medium modified rho dilepton yield from QGP

35% contribution in ϕ peak (R. Rapp)

- All charged particles asigned the Kaon mass (no PID)
- Selection of target tracks with matched SDD-TPC tracks
- Single track cuts: $0.13<\theta<0.24$ rad, $p_t>0.250$ GeV/c
- Opening angle vs pt cut following the ϕ , Armenteros cut

Comparison between two decay channels



Different rapidity

$dN_f/dy^{\,2-2.4} = 0.93.(dN_f/dy)^{2.1-2.65}$
(from NA49, PLB 491(2000) 59)

K^+K^-:
dN/dy=2.05±0.14(stat)±0.25(syst)
T = 273± 9(stat)±10(sys) MeV
e^+e^- :
dN/dy=2.04±0.49(stat)±0.32(syst)
T = 306 ± 82(stat) MeV

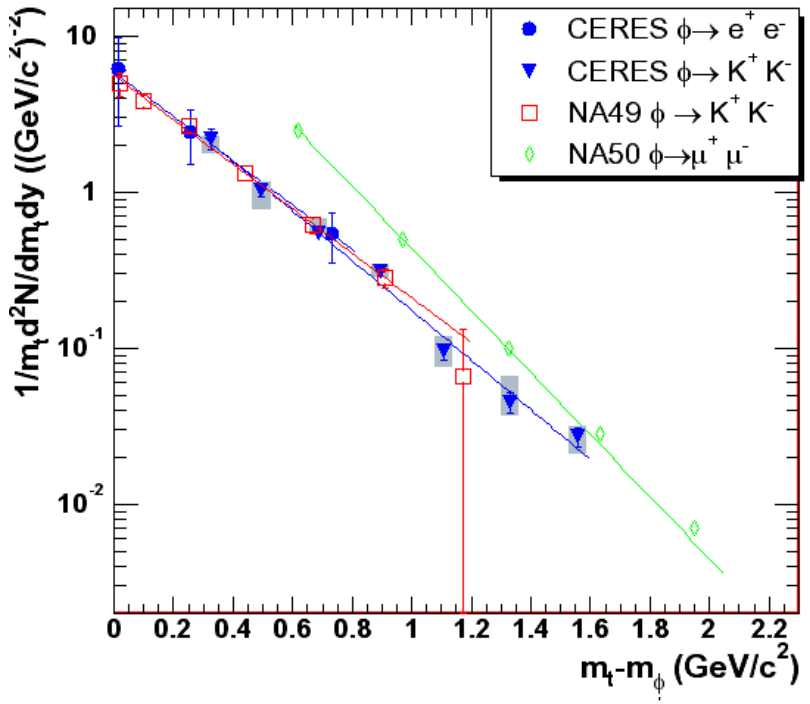
Results in both channels in close agreement

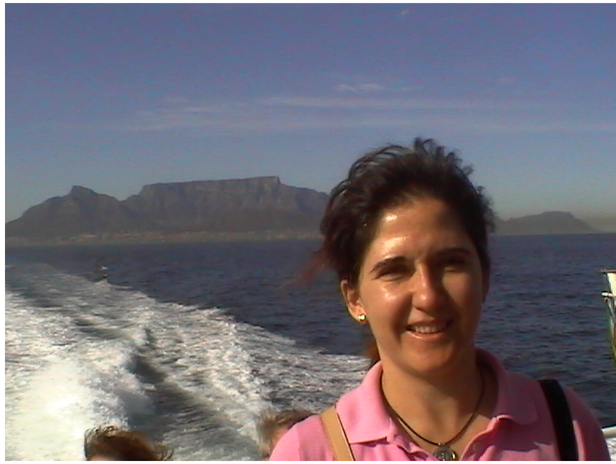
$dN/dy\ (\phi \rightarrow e^+e^-)/dN/dy(\phi \rightarrow K^+\ K^-) < 1.6$ at 95% CL

Ceres Collaboration: nucl-ex/0512007 PRL96(2006)152301

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Comparison to NA49/NA50 results





Different measurement conditions:

	NA49	CERES	Correction
centrality:	4%	7%	$h^-_{4\%}/h^-_{7\%}$ CERES
rapidity:	3.4	2.2	dN/dy NA49

Scaling factor: F =1.17 ± 0.12

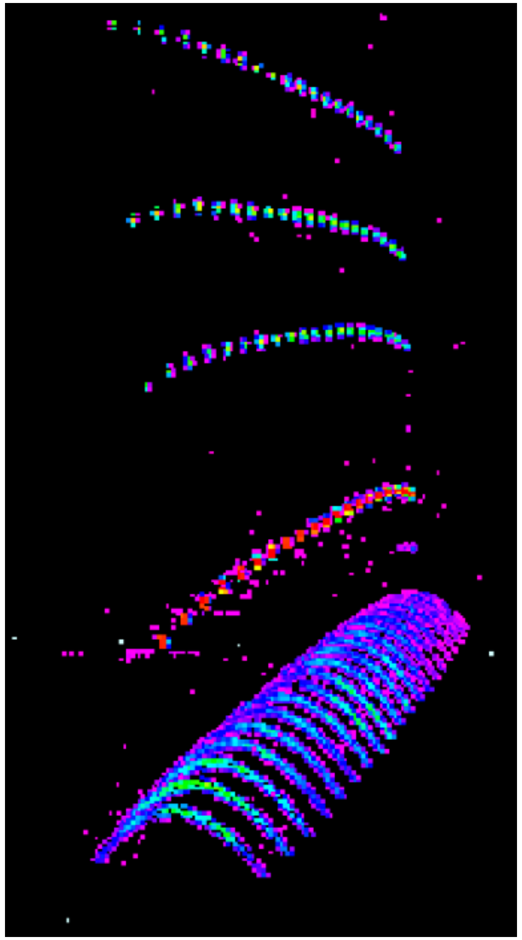
NA49 and NA50:D.Röhrich, J.Phys.G.27(2001)355
CERES: nucl-ex/0512007

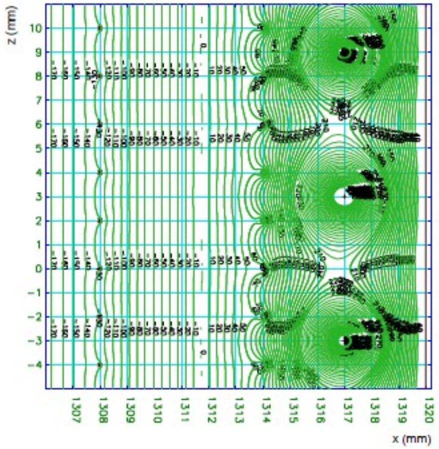
CERES results in K^+K^- and e^+e^- decay channels agree with NA49 results

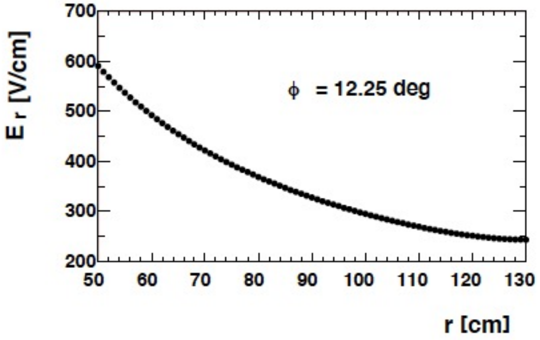

12 3:19PM

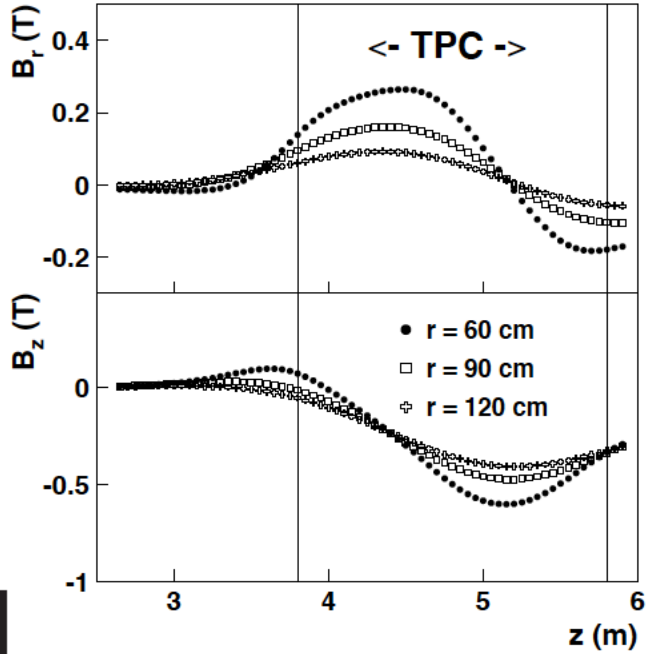

12 3:20PM

From Challenges to Results

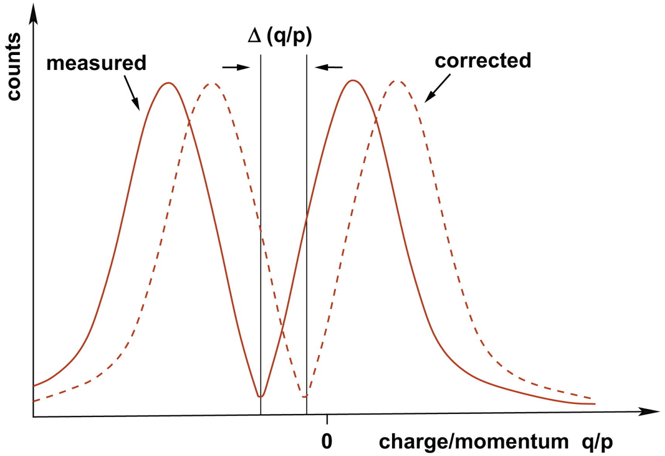


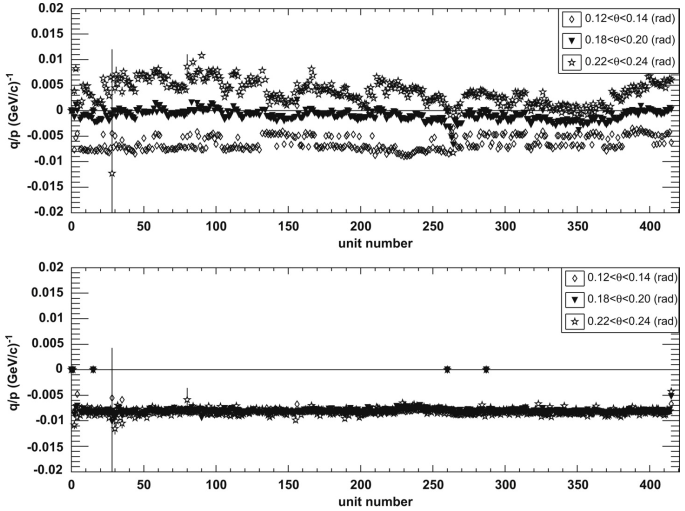






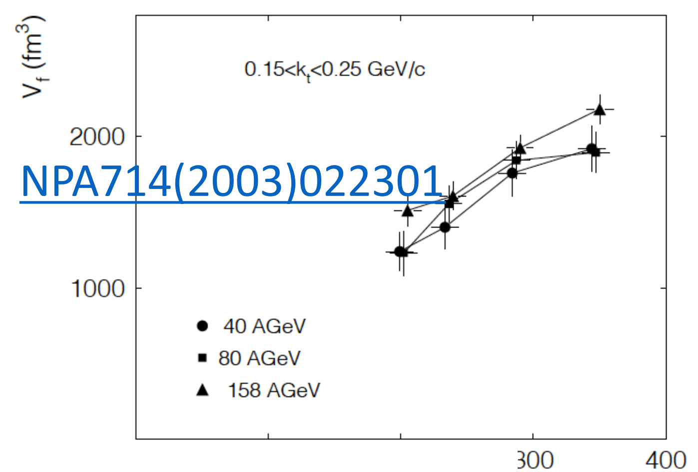
$$\vec{v}_D = \mu \frac{1}{1+(\mu|B|)^2}(\vec{E} + \mu(\vec{E}\times\vec{B}) + \mu^2(\vec{E}\cdot\vec{B})\vec{B})$$





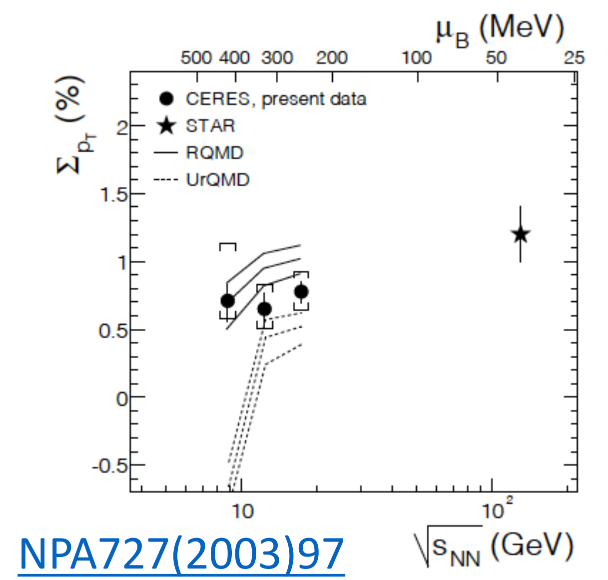
NIMA593(2008)203

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)



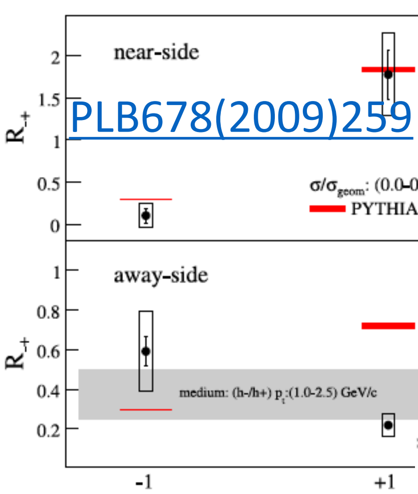
NPA714(2003)022301

GeV/c (see text) as
ber of participants at

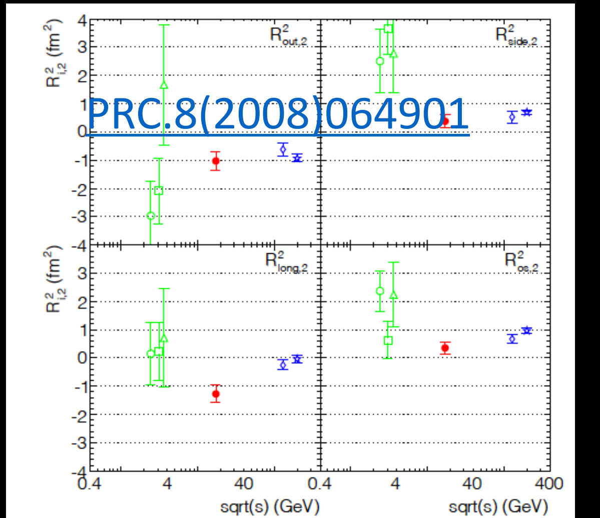


NPA727(2003)97

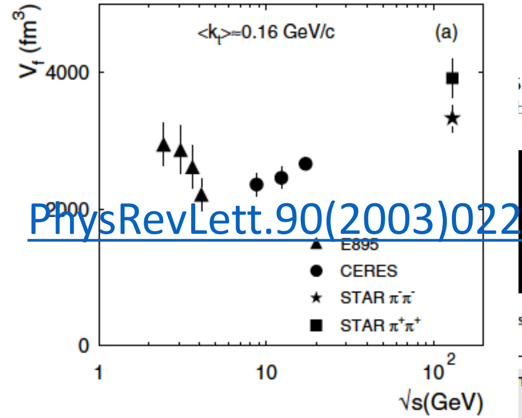
Fig. 10. The fluctuation measure Σ_{p_T} as function of $\sqrt{s_{NN}}$ and of μ
freeze-out [30]. The full circles show CERES results (after SRC remov
events at 40, 80, and 158 A GeV/c. The brackets indicate the syste
Also shown is the STAR result [31] at $\sqrt{s_{NN}}$ = 130 GeV which is
for SRC. Results and statistical errors from RQMD and URQMD calcu
rescattering) are indicated as solid and dashed lines, respectively.



PLB678(2009)259

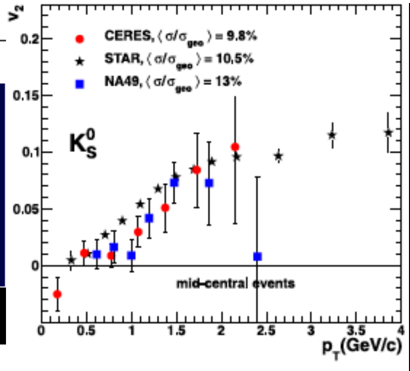


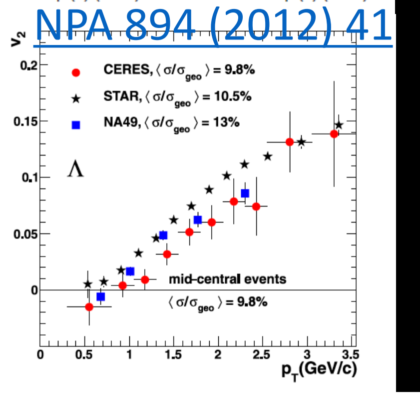
PRC.8(2008)064901



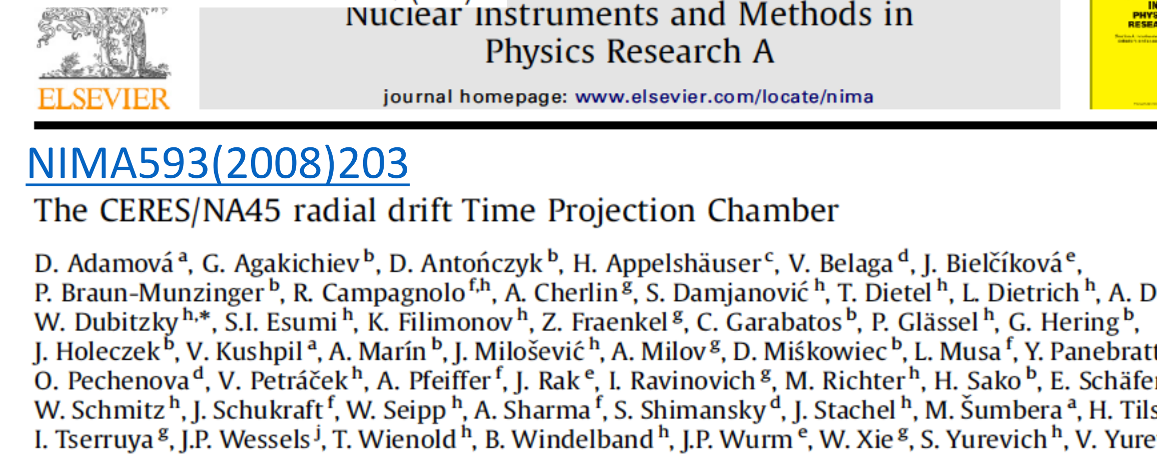
PhysRevLett.90(2003)022301

CERES





NPA 894 (2012) 41



s and Methods in Physics Research A 593 (2008) 203–231

nts lists available at ScienceDirect

ELSEVIER

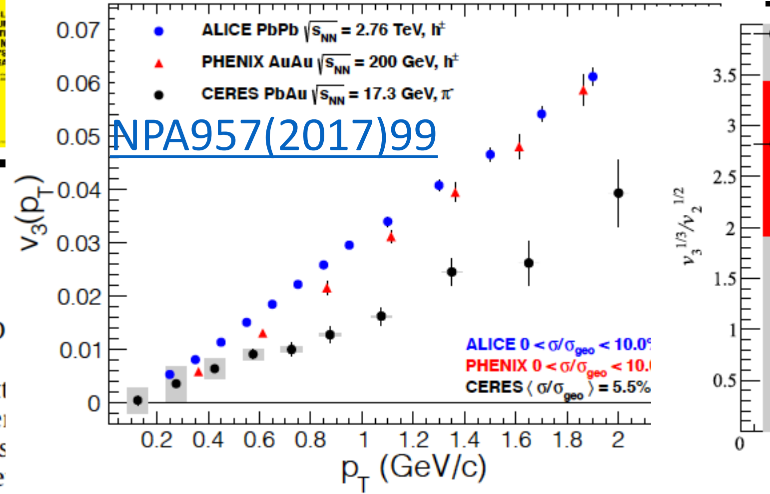
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

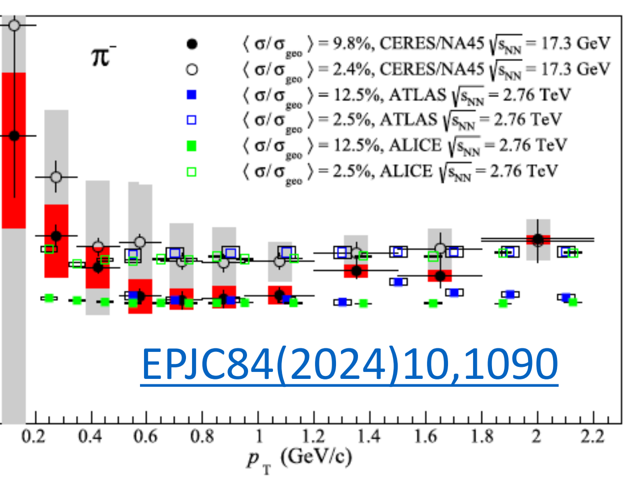
NIMA593(2008)203

The CERES/NA45 radial drift Time Projection Chamber

D. Adamová[a], G. Agakichiev[b], D. Antończyk[b], H. Appelshäuser[c], V. Belaga[d], J. Bielčíková[e],
P. Braun-Munzinger[b], R. Campagnolo[f,h], A. Cherlin[g], S. Damjanović[h], T. Dietel[h], L. Dietrich[h], A. D
W. Dubitzky[h,*], S.I. Esumi[h], K. Filimonov[h], Z. Fraenkel[g], C. Garabatos[b], P. Glässel[h], G. Hering[b],
J. Holeczek[b], V. Kushpil[a], A. Marín[b], J. Milošević[h], A. Milov[g], D. Miśkowiec[b], L. Musa[f], Y. Panebratt
O. Pechenova[d], V. Petráček[h], A. Pfeiffer[f], J. Rak[e], I. Ravinovich[g], M. Richter[h], H. Sako[b], E. Schäfe
W. Schmitz[h], J. Schukraft[f], W. Seipp[h], A. Sharma[f], S. Shimansky[d], J. Stachel[h], M. Šumbera[a], H. Tils
I. Tserruya[g], J.P. Wessels[j], T. Wienold[h], B. Windelband[h], J.P. Wurm[e], W. Xie[g], S. Yurevich[h], V. Yure



NPA957(2017)99



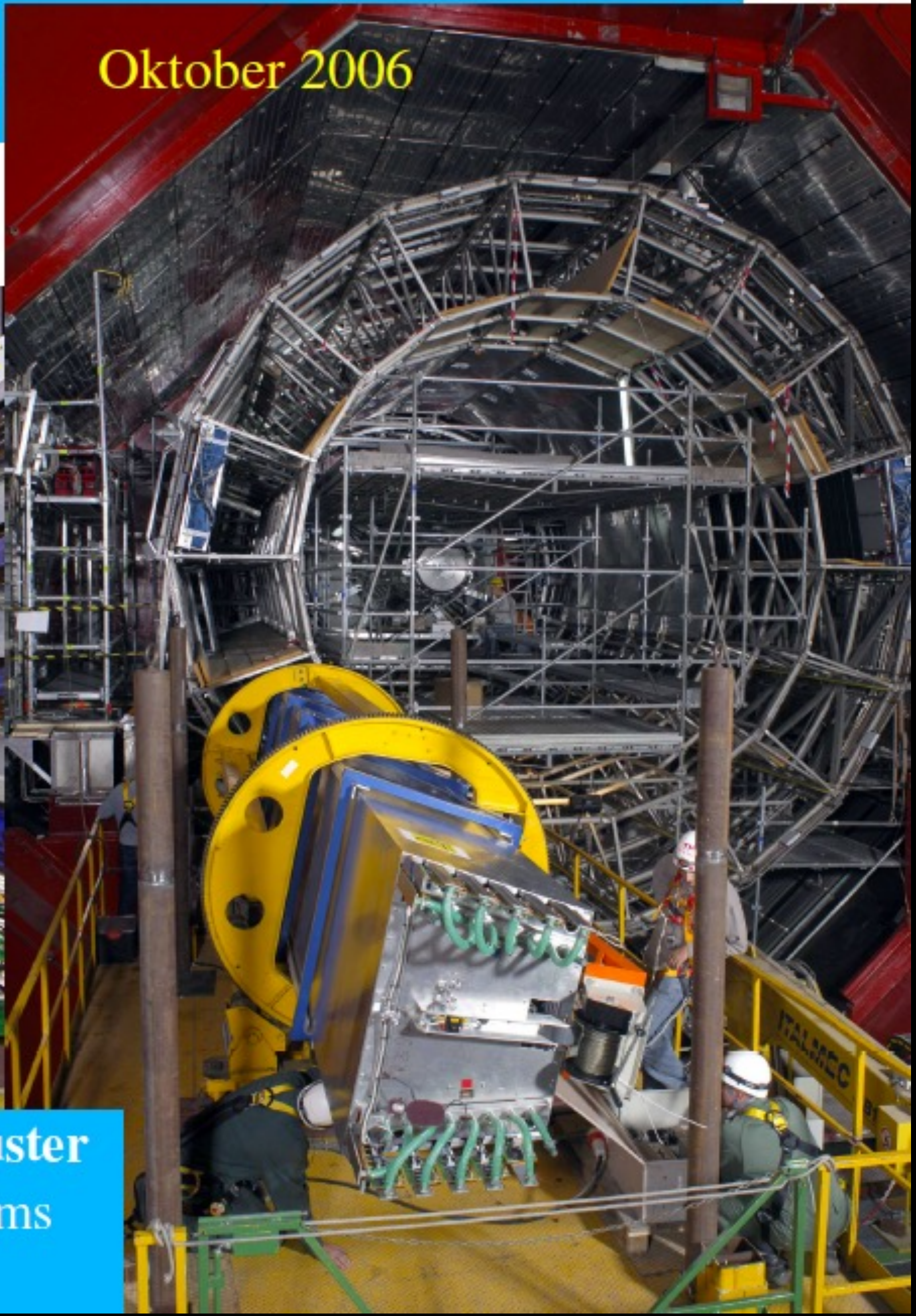
EPJC84(2024)10,1090

TRD

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Aufbau u. Einbau des ersten TRD Supermoduls

zweite Lage von Kammern komplett mit Elektronik im Supermodul



Oktober 2006

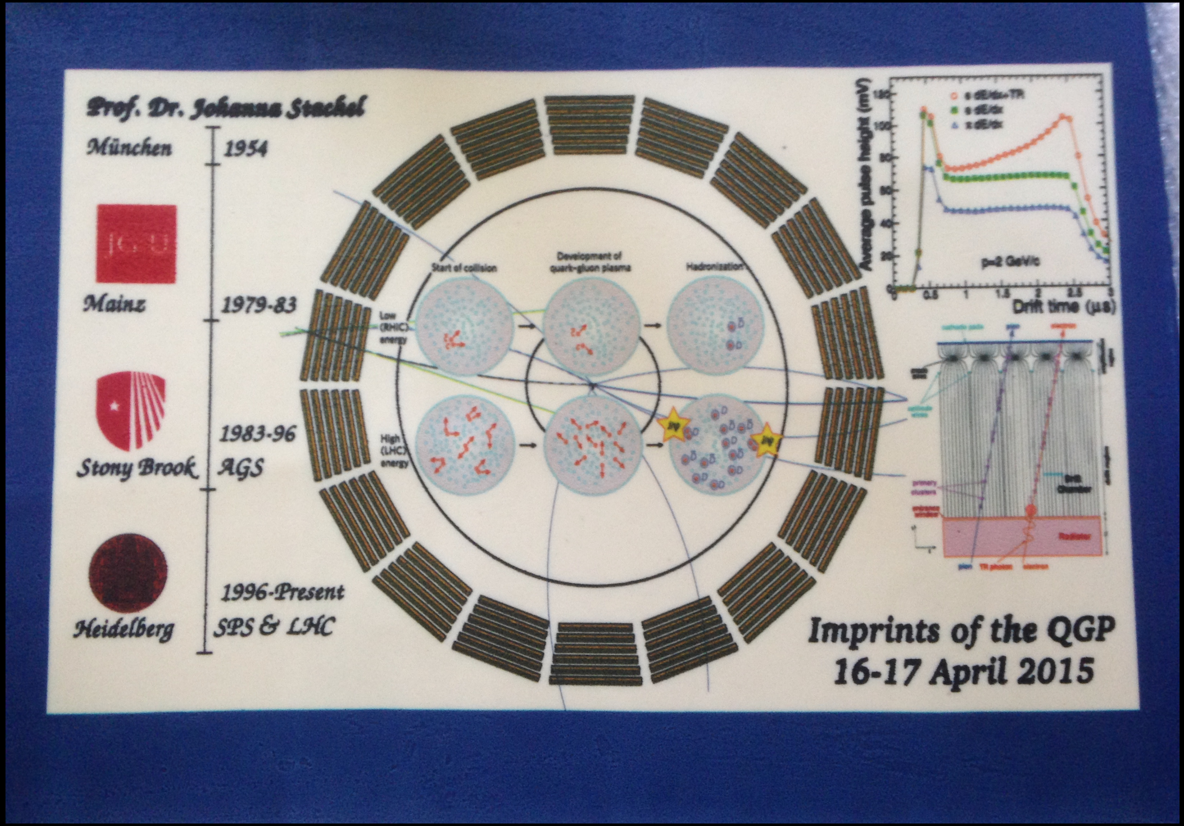
Kontrolle des Detektors: **540 CPU Linux Cluster**
PI und KIP U. Heidelberg, FH Köln, FH Worms
U. Münster, GSI


22 5:17PM


22 7:33PM


22 7:37PM


22 7:35PM



Prof. Dr. Johanna Stachel

München	1954
Mainz	1979-83
Stony Brook	1983-96 AGS
Heidelberg	1996-Present SPS & LHC

Imprints of the QGP
16-17 April 2015

Photon sources

- **Decay photons:**
  - π^0, η, ω
- **Direct photons:**
  - Hard:
    - Direct:
      - qg Compton Scattering
      - qq 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.

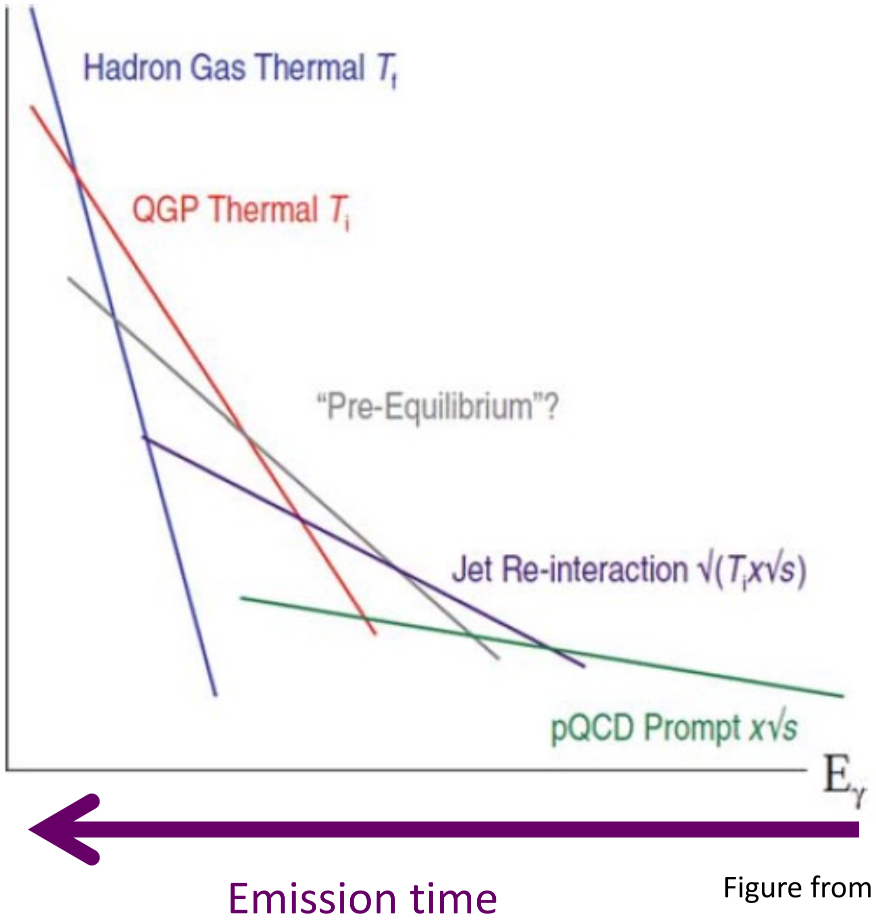


Figure from P. Stankus

Large background from neutral meson decays.
Difficult measurement

π^0,η: pp √s = 2.76, 7, 8, 13 TeV

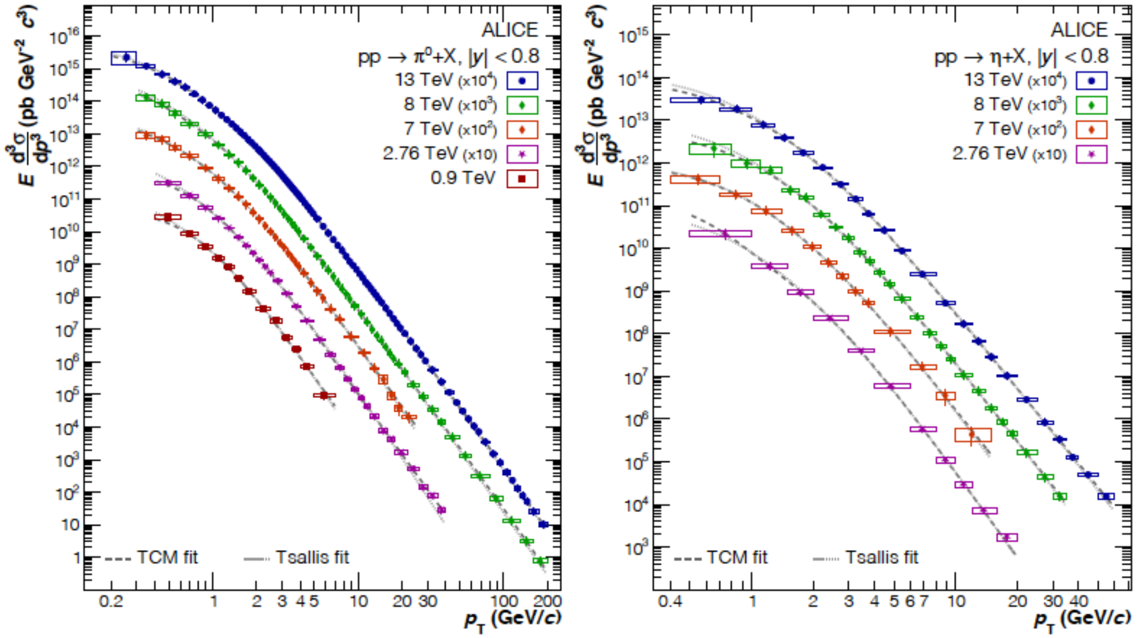
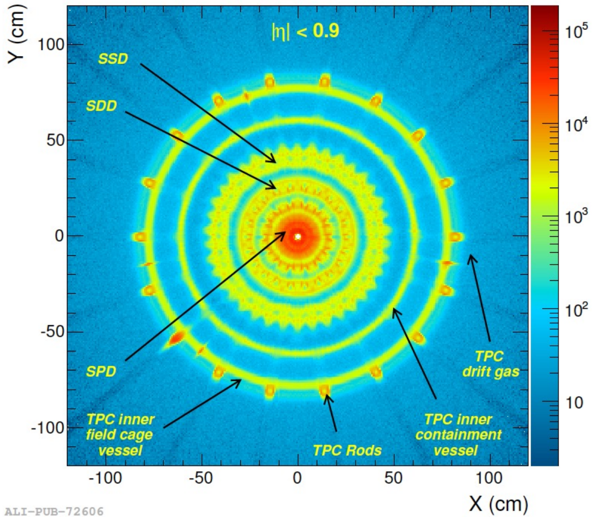
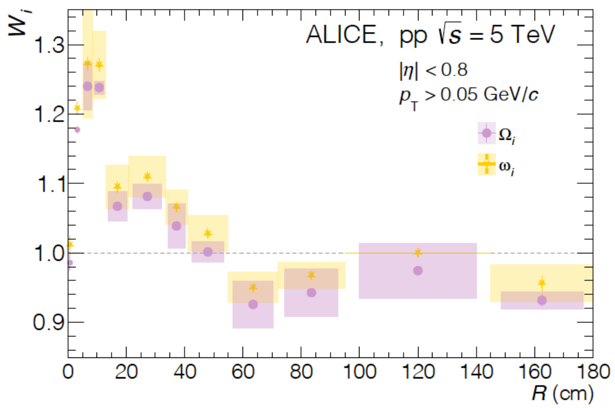
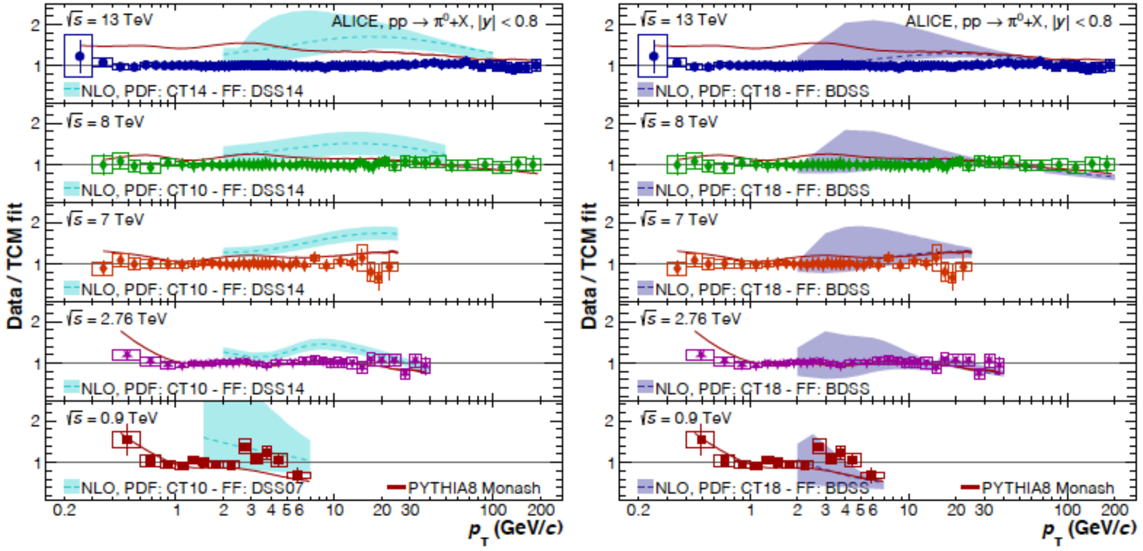


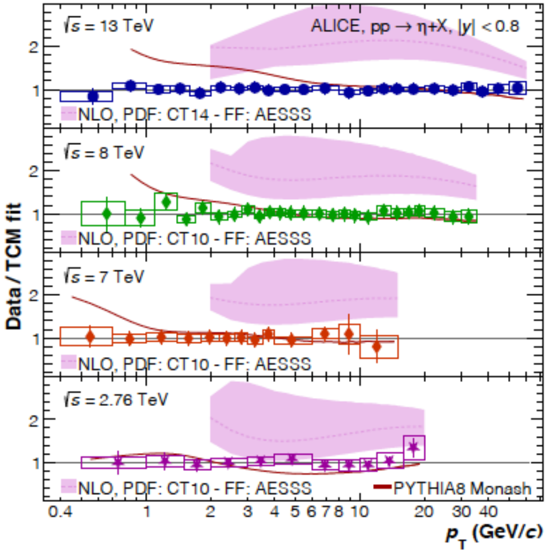
Figure 11: Compilation of π^0 (left) and η meson (right) invariant cross sections in pp collisions at $\sqrt{s} = 0.9$, 2.76, 7, 8 and 13 TeV [2–4].



JINST18 (2023)P11032

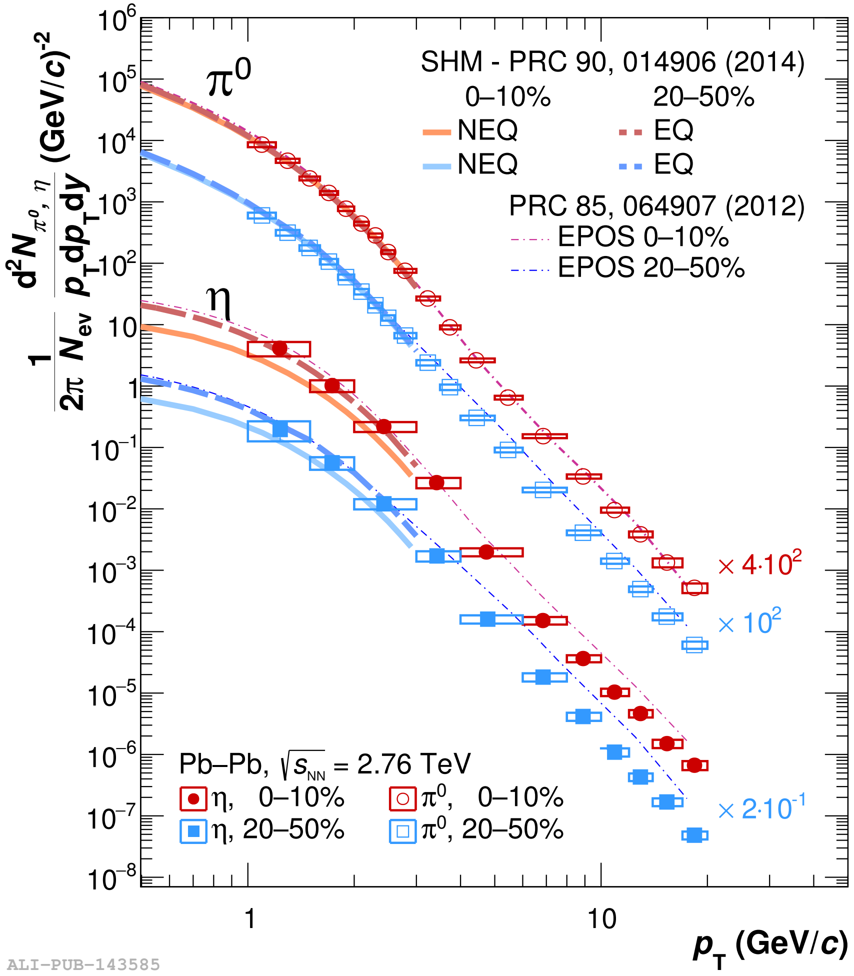


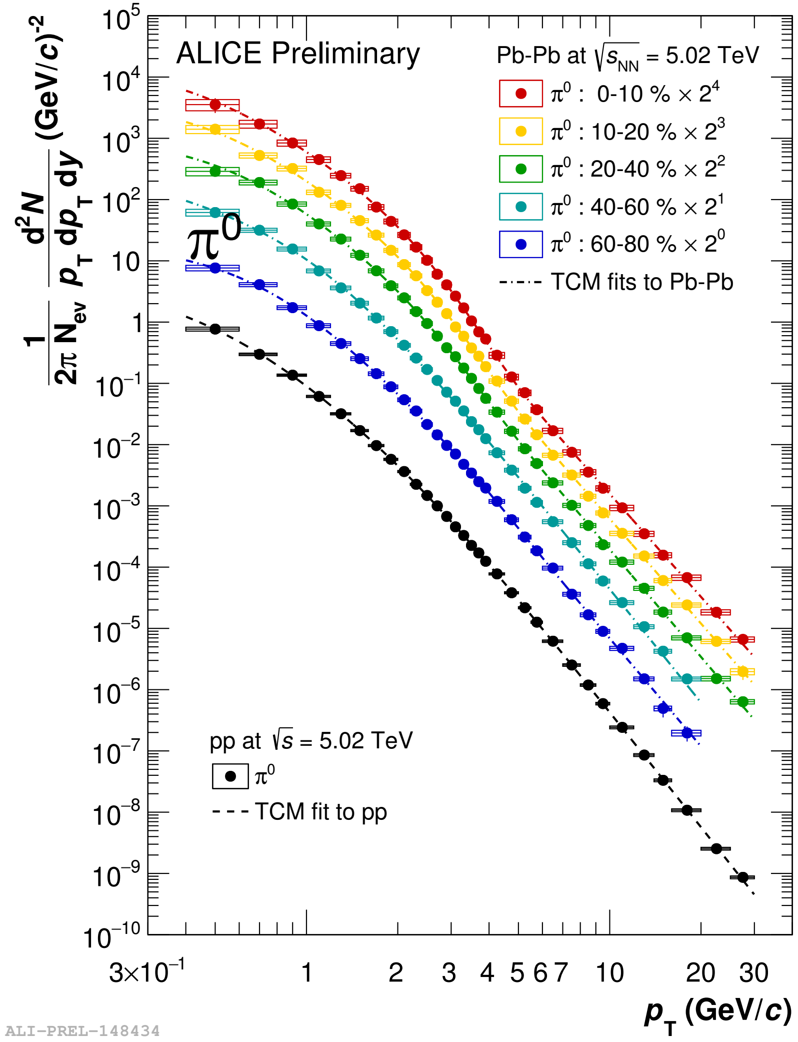




π^0,η: Pb-Pb at $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

EPJ C 74 (2014); PRC98, 044901 (2018)



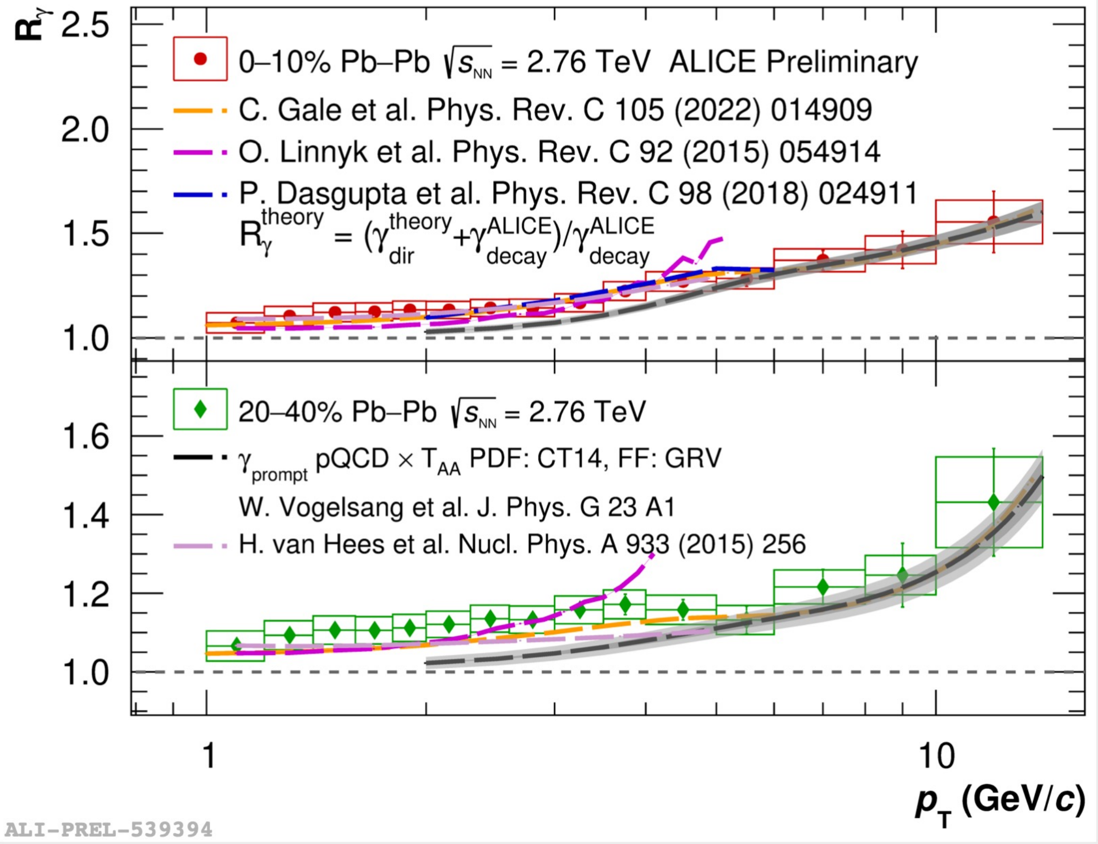


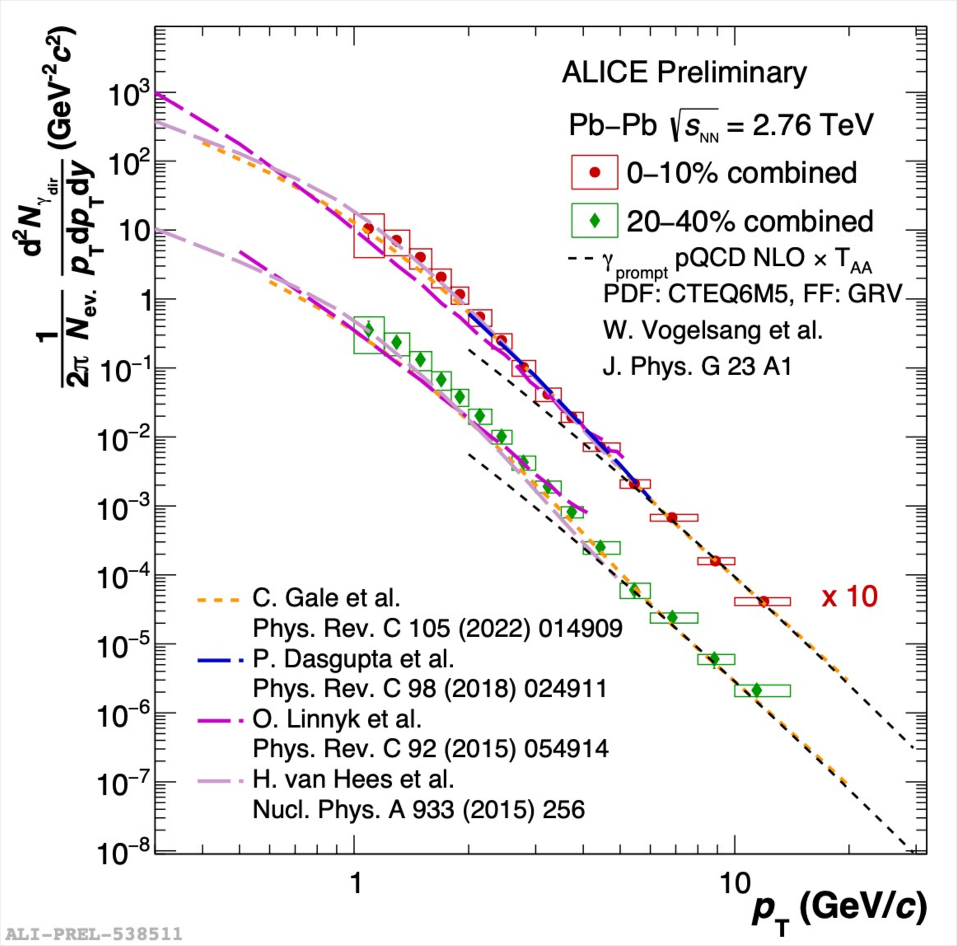
First η measurement in Pb-Pb at the LHC

QGP thermal emission: Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

$$R_\gamma = N_{\gamma,\mathrm{inc}}/N_{\gamma,\mathrm{dec}} \approx \left(\frac{N_{\gamma,\mathrm{inc}}}{\pi^0}\right)_{\mathrm{meas}} \Big/ \left(\frac{N_{\gamma,\mathrm{dec}}}{\pi^0}\right)_{\mathrm{sim}}$$

$$N_{\gamma,\mathrm{dir}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot N_{\gamma,\mathrm{inc}}$$



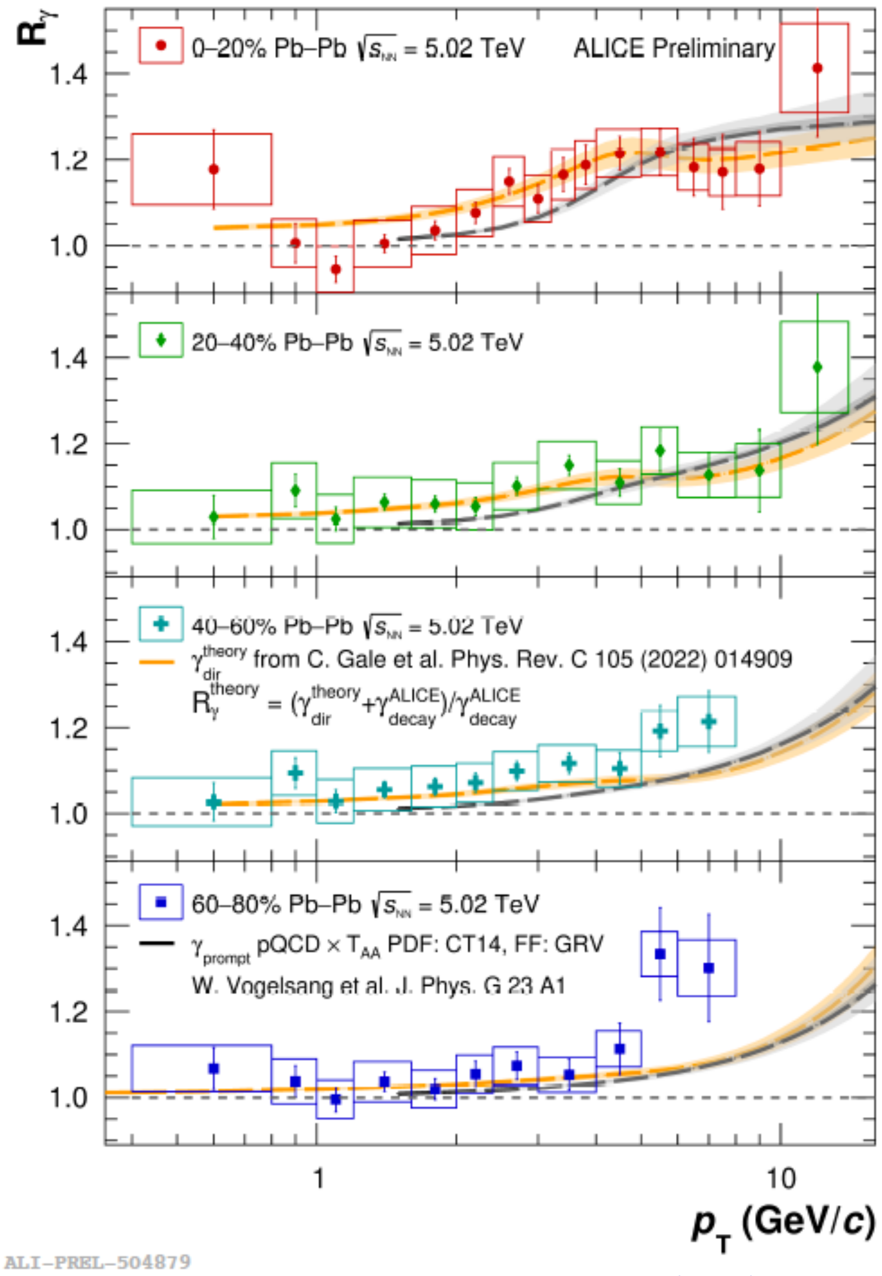


- Excess beyond known prompt yield 1 < p_T < 4 GeV/c
- Models that include thermal +(pre-equilibrium) + prompt photons are able to describe the data
- Not yet possible to discriminate among different models

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

HP2023, improved material budget

QGP thermal emission



$$R_\gamma = N_{\gamma,\mathrm{inc}}/N_{\gamma,\mathrm{dec}} \approx \left(\frac{N_{\gamma,\mathrm{inc}}}{\pi^0}\right)_{\mathrm{meas}} / \left(\frac{N_{\gamma,\mathrm{dec}}}{\pi^0}\right)_{\mathrm{sim}}$$

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

At low p_T :

- thermal radiation should dominate
- R_γ is close to 1 → small thermal and pre-equilibrium photon contribution
- Models with thermal and pre-equilibrium photons, can describe the data better than the calculation including only prompt photons

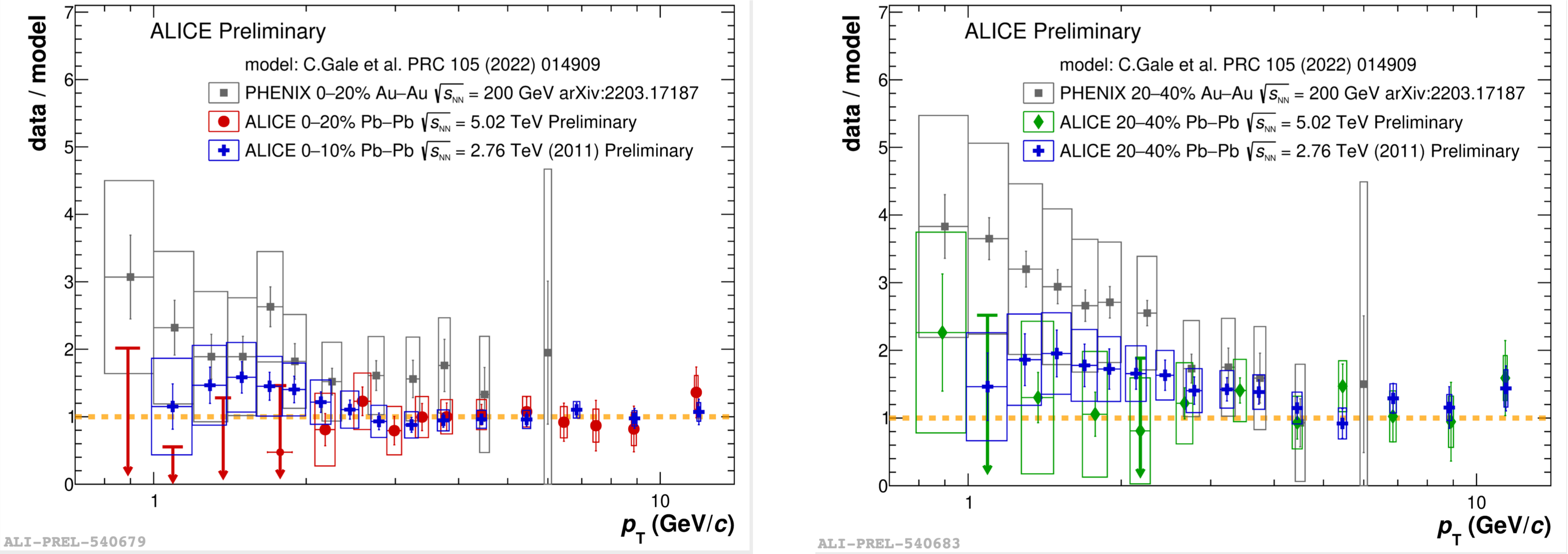
For p_T > 3 GeV/c:

- can be attributed to prompt (hard scattering) photons
- data is consistent with NLO pQCD calculation of prompt photons in pp collisions, scaled with T_{AA}
  Calculation by W. Vogelsang, using PDF: CT14, FF: GRV

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Direct photon puzzle in yields?

Ratio between direct photon production and their respective state-of the-art model calculation



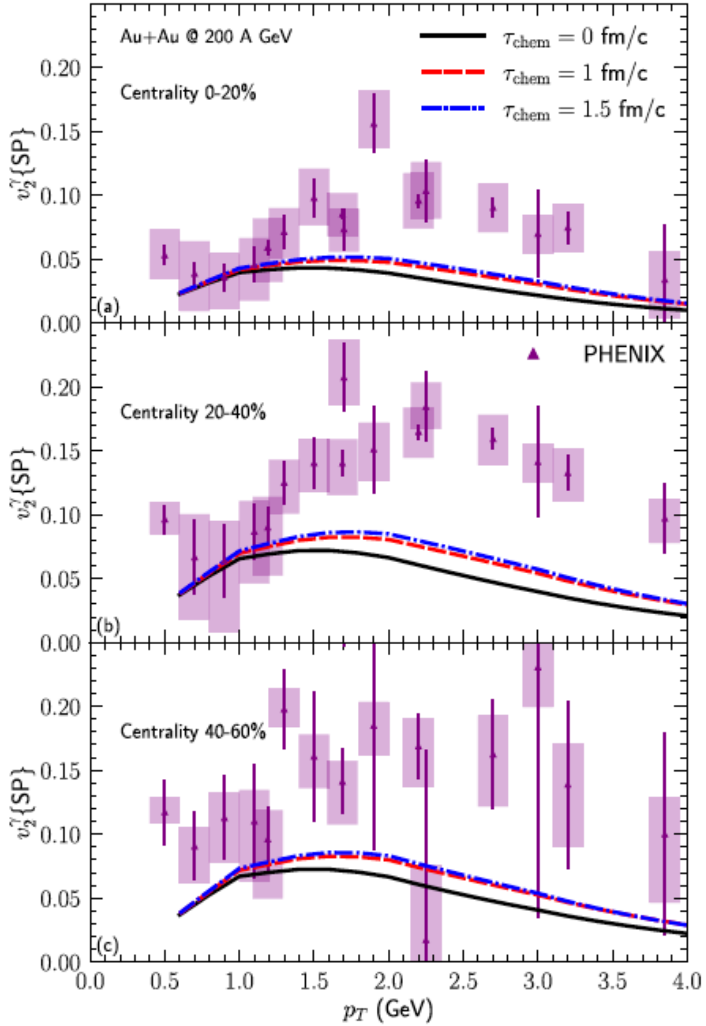
Good agreement between ALICE data and model predictions

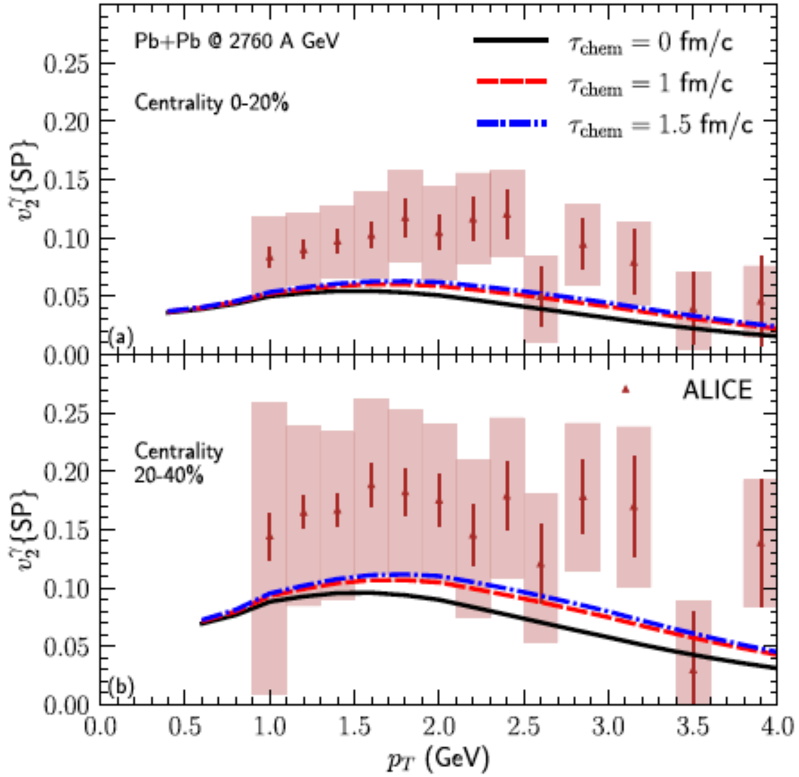
Slight tension at low p_T for the PHENIX data

Future: puzzle involving direct photon flow?

Direct γ $v_{2:}$ RHIC, LHC and models

Direct photon puzzle

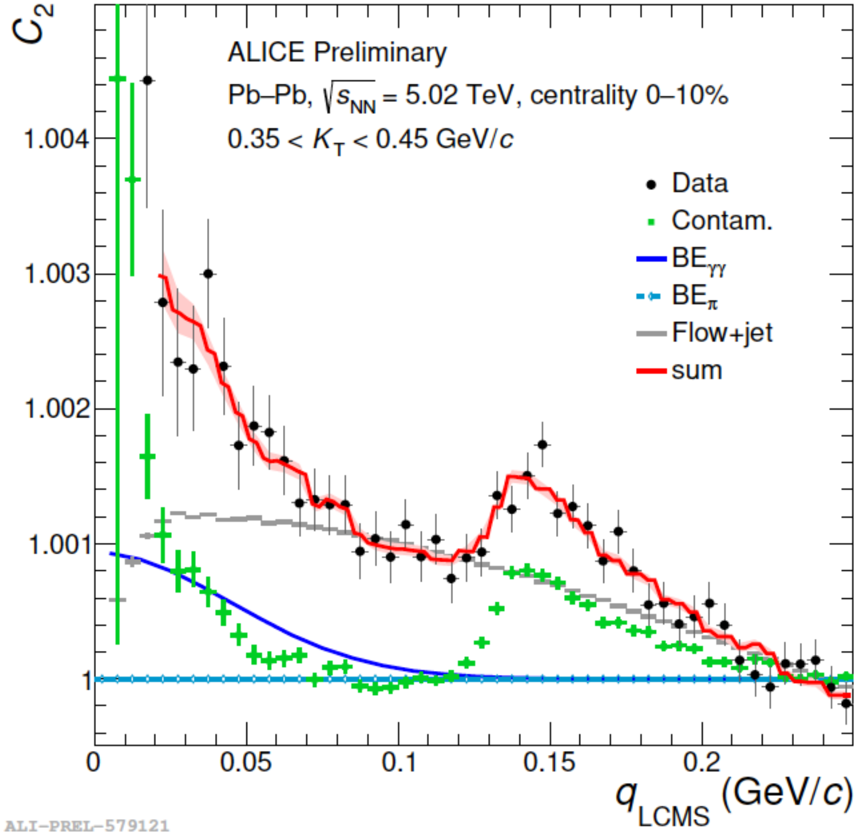




$v_2^{dir} \approx v_2^{\pi}$ but not puzzle within exp. uncertainties

large v_2 values not reproduced by models

Bose-Einstein $\gamma\gamma$ correlations in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



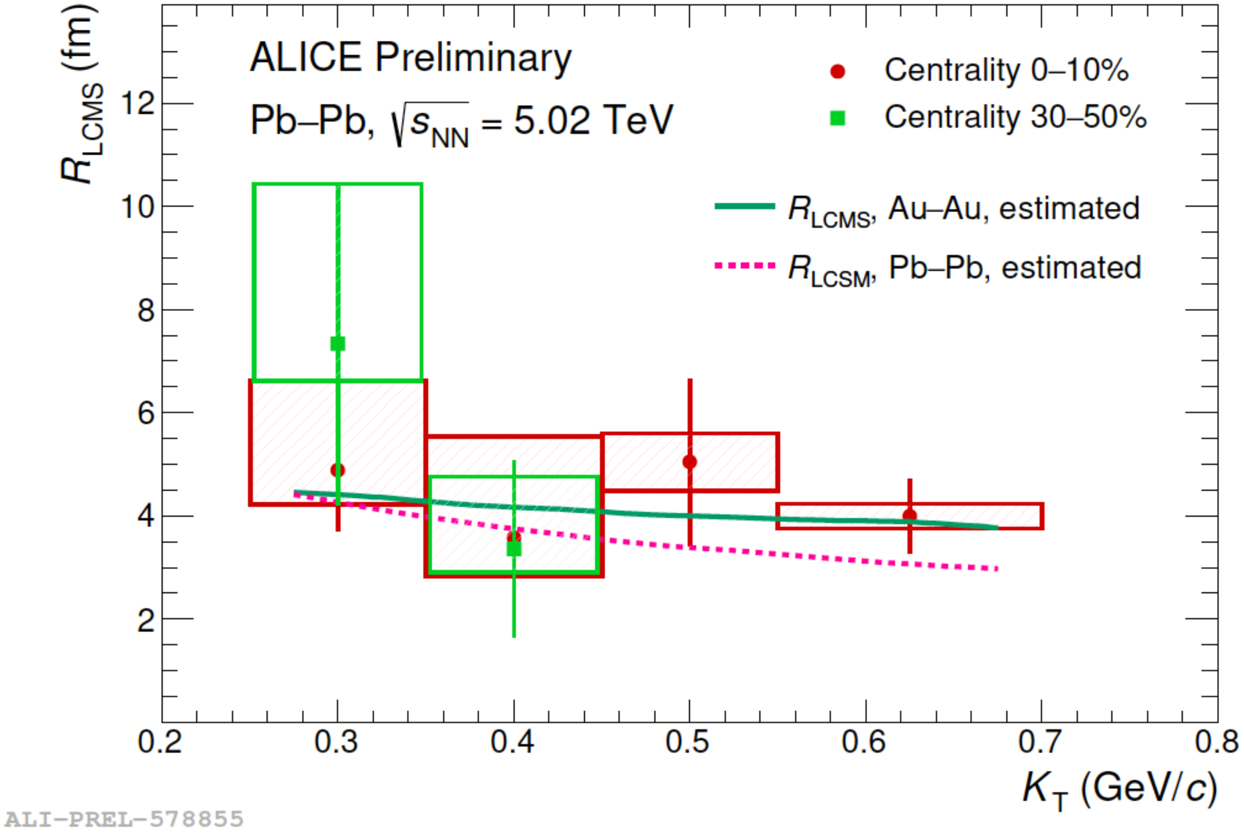
$$A\left(1+\lambda\exp\left(-q^2R^2\right)+a_{contam}Cont+a_{BE\,\pi\pi}\left(C_2^{BE\,\pi\pi}-1\right)+a_{Flow}\left(C_2^{Flow}-1\right)\right)$$

Template fit to the data to extract BE

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

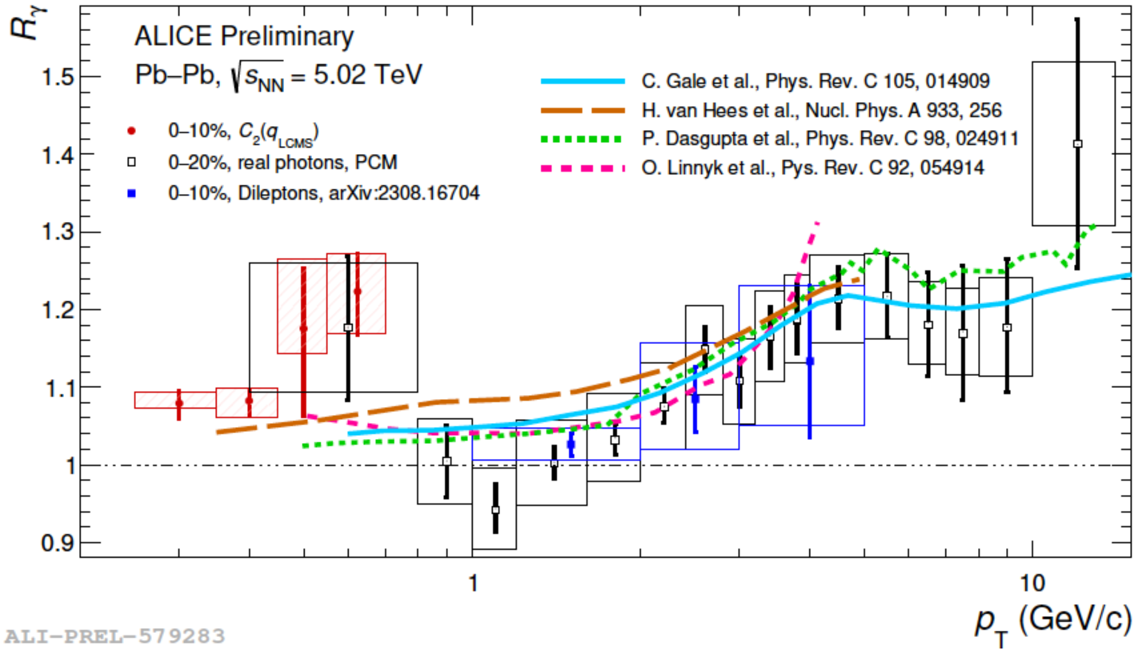
Correlation Radius

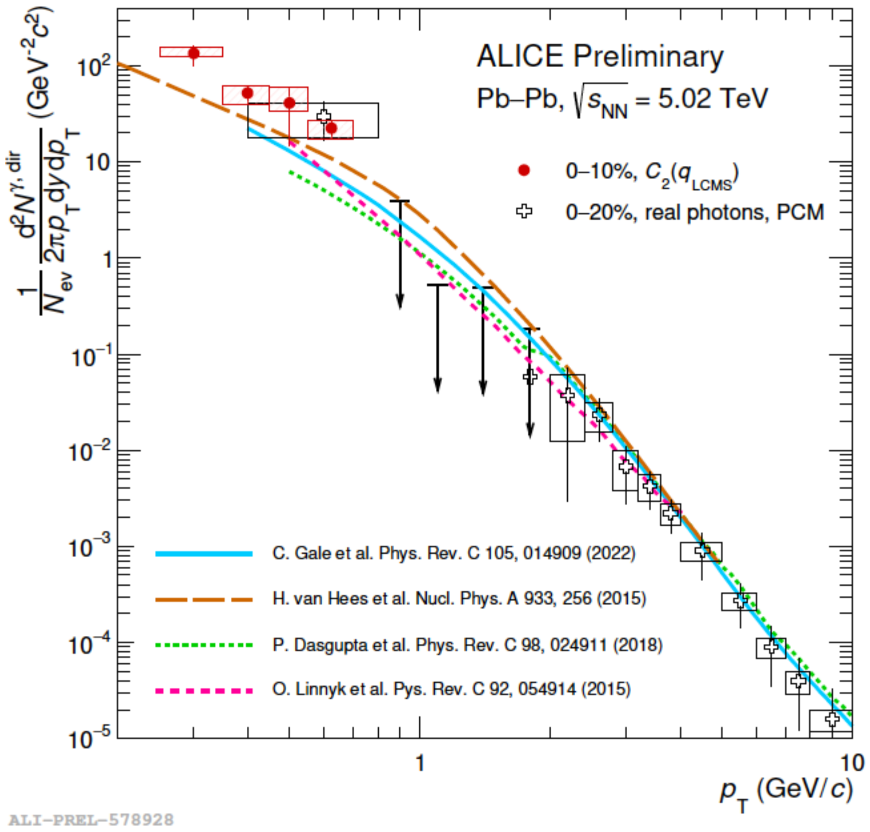
Hydrodynamic calculations:
Pb-Pb: O. Garcia-Montero et al., Phys.Rev.C 102 (2020) 2, 024915
Au-Au: D. Peressounko, Phys.Rev.C 67



- Correlation radius shows minor K_T dependence
- Agrees with estimated radii from hydro predictions
  - Theoretical curves were estimated by averaging of published R_{out}, R_{side}, R_{long} radii

Direct photon excess Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV





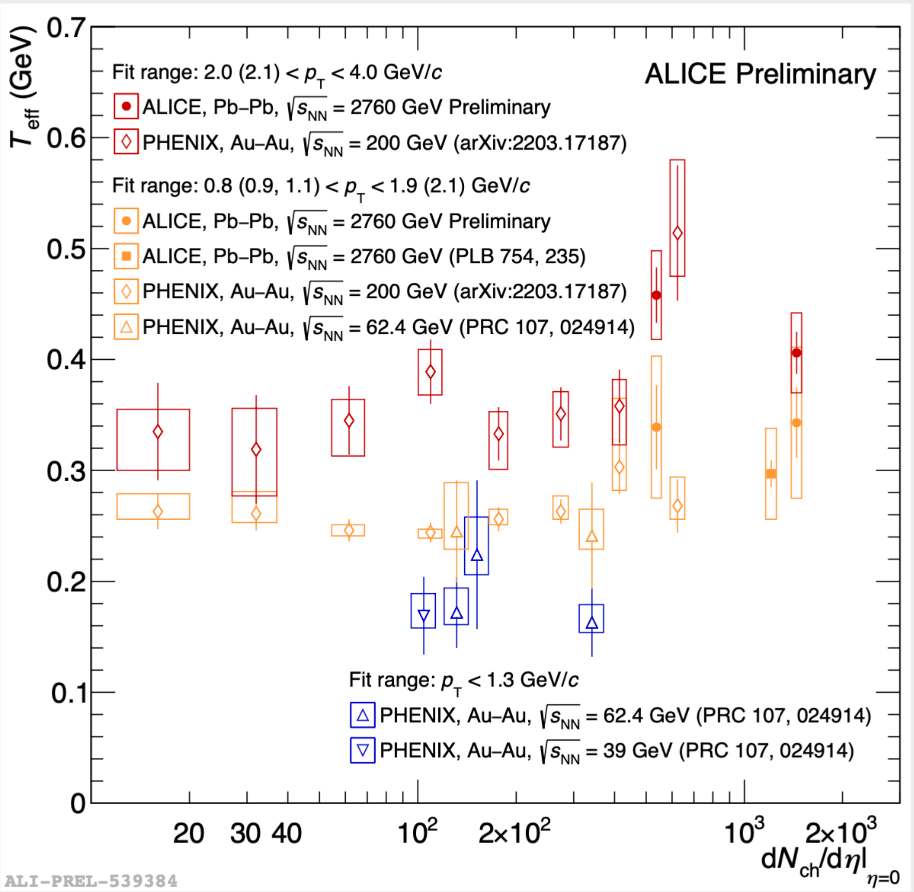
$$\lambda = \frac{1}{2}\left(\frac{N_\gamma^{dir}}{N_\gamma^{incl}}\right)^2 \qquad R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{decay}} = \frac{1}{1-\sqrt{2\lambda}}$$

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

T_{eff} non-prompt photons

is T_{eff} ($2.1 < p_T < 4$ GeV/c) > T_{eff} ($1.1 < p_T < 2.1$ GeV/c) ?

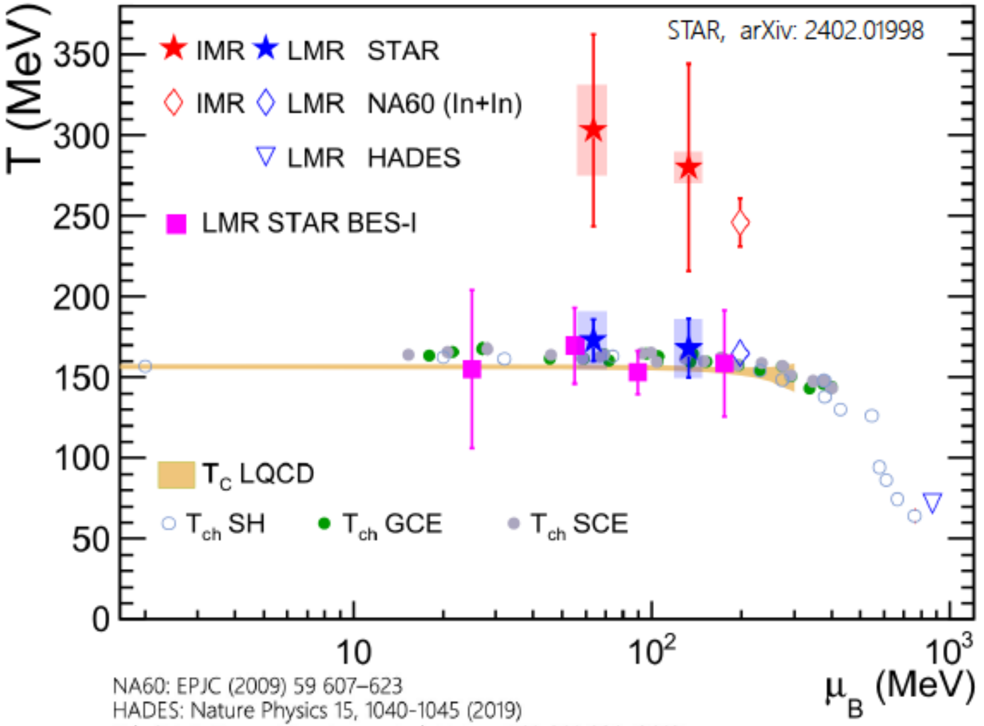
pre-equilibrium photons? earlier time emission?



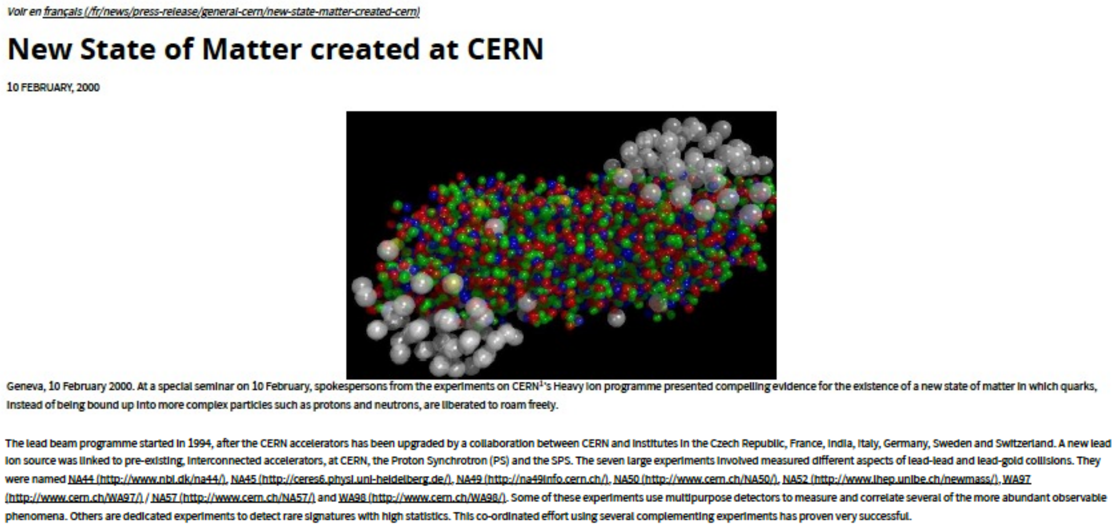
T vs μ_B

Thermal dielectrons in IMR:

- T_{IMR} is higher than T_{LMR} ,T_{pc} and T_{ch}
- Emitted from the partonic phase



NA60: EPJC (2009) 59 607–623
HADES: Nature Physics 15, 1040-1045 (2019)
Tch SH: P. Braun-Munzinger et al. Nature 561, 321-330 (2018)
Tch GCE/SCE: STAR PRC 96, 044904 (2017)



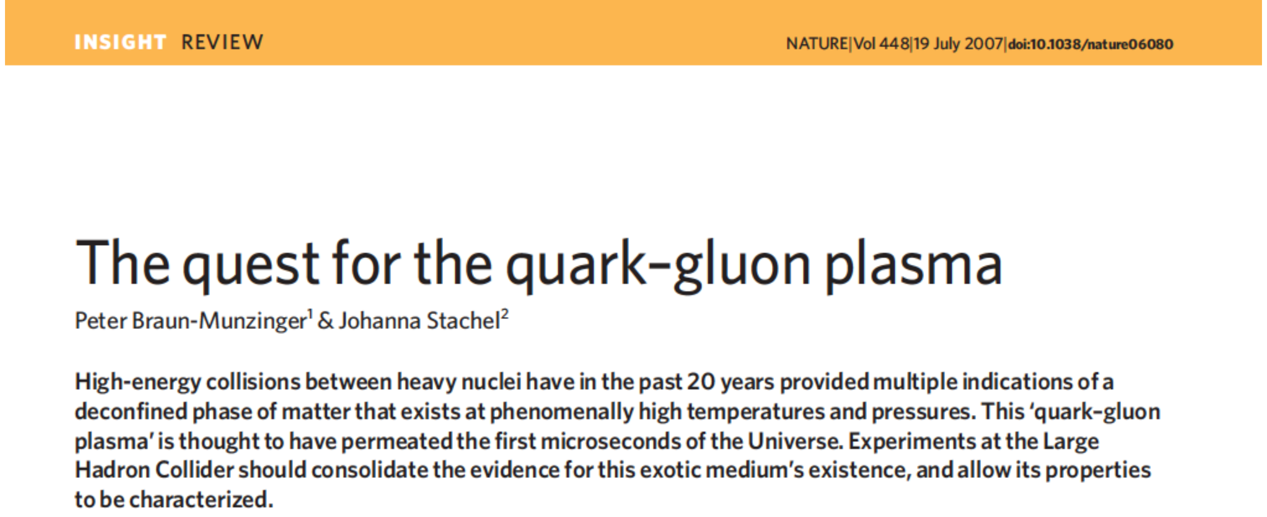
Voir en français (/fr/news/press-release/general-cern/new-state-matter-created-cern)

New State of Matter created at CERN

10 FEBRUARY, 2000

Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

The lead beam programme started in 1994, after the CERN accelerators has been upgraded by a collaboration between CERN and institutes in the Czech Republic, France, India, Italy, Germany, Sweden and Switzerland. A new lead ion source was linked to pre-existing, interconnected accelerators, at CERN, the Proton Synchrotron (PS) and the SPS. The seven large experiments involved measured different aspects of lead-lead and lead-gold collisions. They were named NA44 (http://www.nbi.dk/na44/), NA45 (http://ceres6.physi.uni-heidelberg.de/), NA49 (http://na49info.cern.ch/), NA50 (http://www.cern.ch/NA50/), NA52 (http://www.lhep.unibe.ch/newmass/), WA97 (http://www.cern.ch/WA97/) / NA57 (http://www.cern.ch/NA57/) and WA98 (http://www.cern.ch/WA98/). Some of these experiments use multipurpose detectors to measure and correlate several of the more abundant observable phenomena. Others are dedicated experiments to detect rare signatures with high statistics. This co-ordinated effort using several complementing experiments has proven very successful.

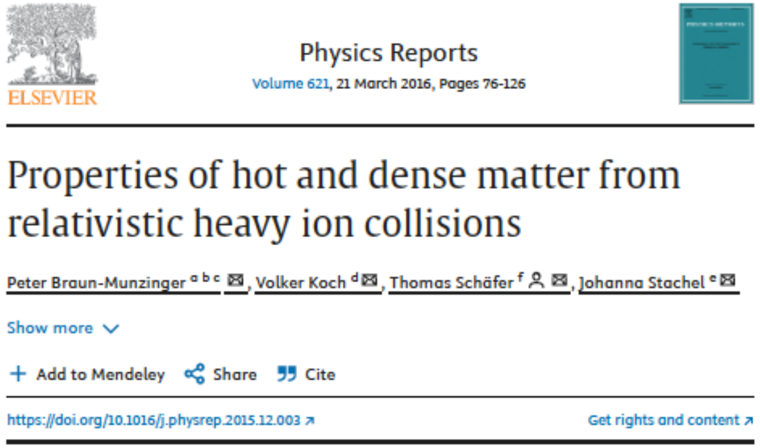


INSIGHT REVIEW NATURE|Vol 448|19 July 2007|doi:10.1038/nature06080

The quest for the quark–gluon plasma

Peter Braun-Munzinger[1] & Johanna Stachel[2]

High-energy collisions between heavy nuclei have in the past 20 years provided multiple indications of a deconfined phase of matter that exists at phenomenally high temperatures and pressures. This 'quark–gluon plasma' is thought to have permeated the first microseconds of the Universe. Experiments at the Large Hadron Collider should consolidate the evidence for this exotic medium's existence, and allow its properties to be characterized.



Physics Reports
Volume 621, 21 March 2016, Pages 76-126

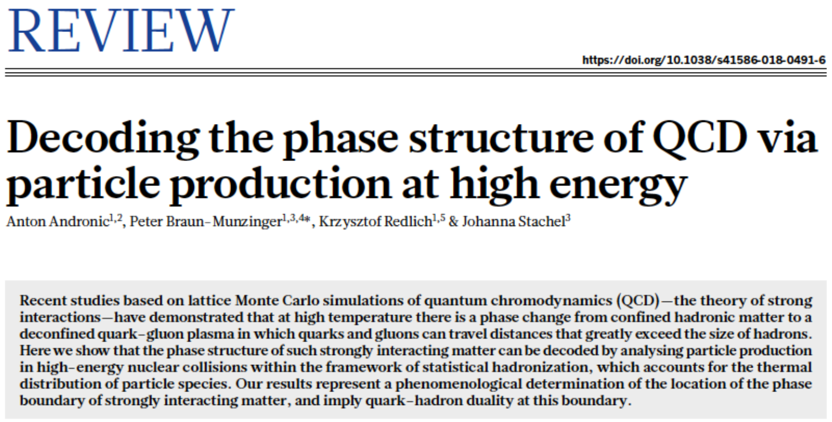
Properties of hot and dense matter from relativistic heavy ion collisions

Peter Braun-Munzinger [a b c], Volker Koch [d], Thomas Schäfer [f], Johanna Stachel [e]

Show more

+ Add to Mendeley Share Cite

https://doi.org/10.1016/j.physrep.2015.12.003 ↗ Get rights and content ↗



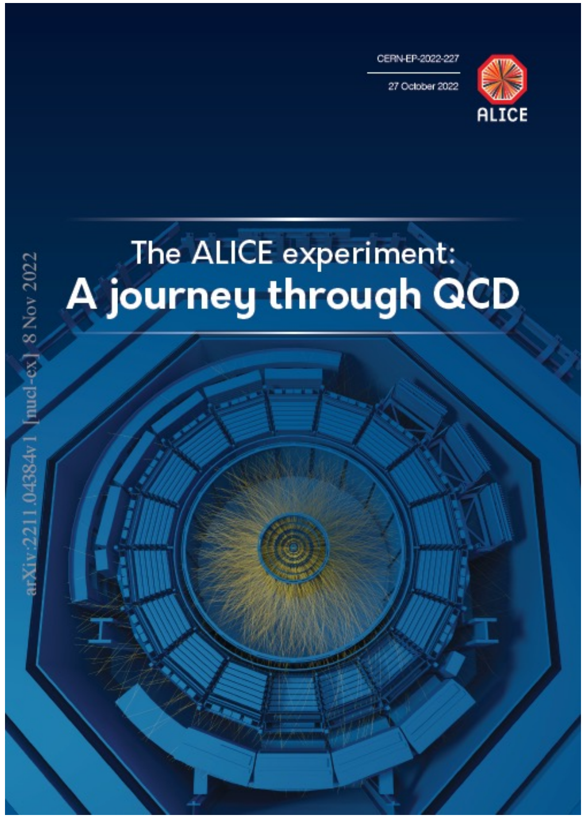
REVIEW

https://doi.org/10.1038/s41586-018-0491-6

Decoding the phase structure of QCD via particle production at high energy

Anton Andronic[1,2], Peter Braun-Munzinger[1,3,4*], Krzysztof Redlich[1,5] & Johanna Stachel[3]

Recent studies based on lattice Monte Carlo simulations of quantum chromodynamics (QCD)—the theory of strong interactions—have demonstrated that at high temperature there is a phase change from confined hadronic matter to a deconfined quark–gluon plasma in which quarks and gluons can travel distances that greatly exceed the size of hadrons. Here we show that the phase structure of such strongly interacting matter can be decoded by analysing particle production in high-energy nuclear collisions within the framework of statistical hadronization, which accounts for the thermal distribution of particle species. Our results represent a phenomenological determination of the location of the phase boundary of strongly interacting matter, and imply quark–hadron duality at this boundary.



CERN-EP-2022-227
27 October 2022
ALICE

arXiv:2211.04384v1 [nucl-ex] 8 Nov 2022

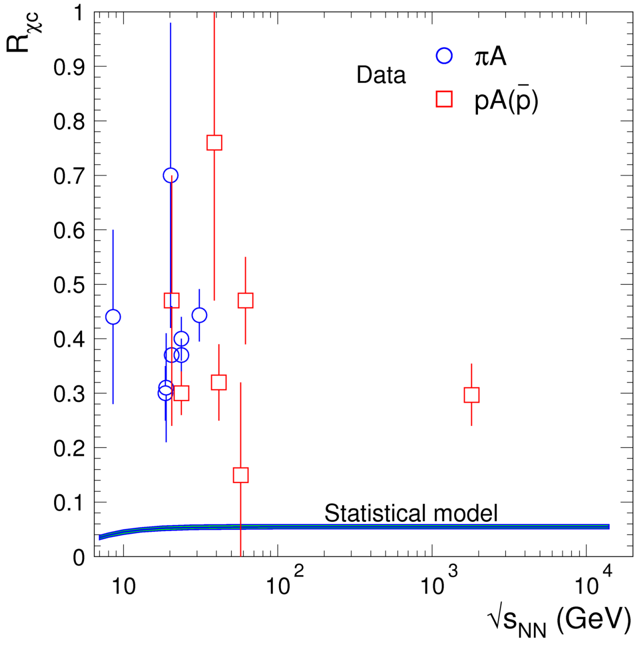
The ALICE experiment:
A journey through QCD

Back up

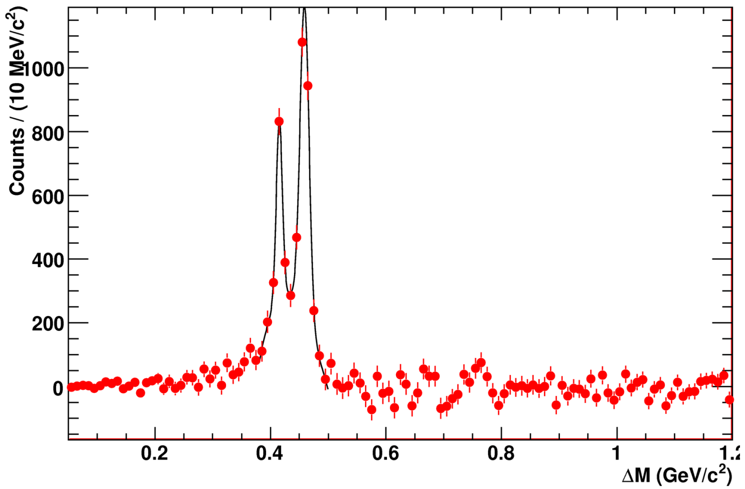
a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

χ_c

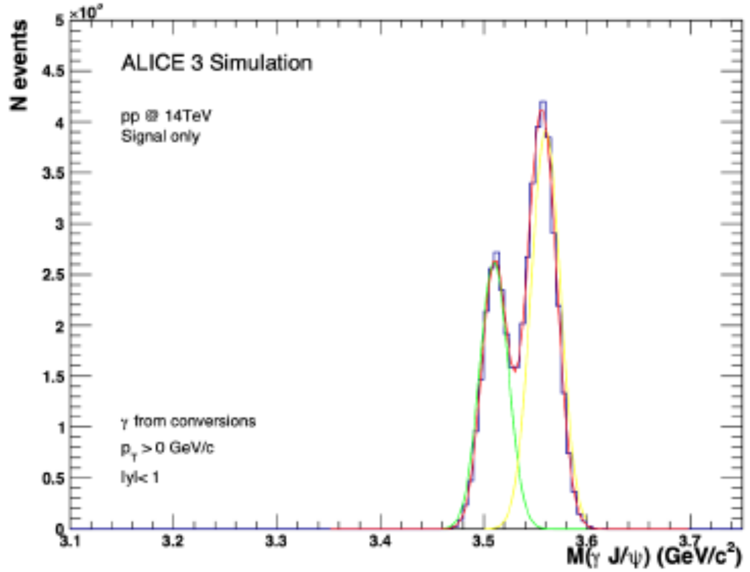
Not yet measured in ALICE



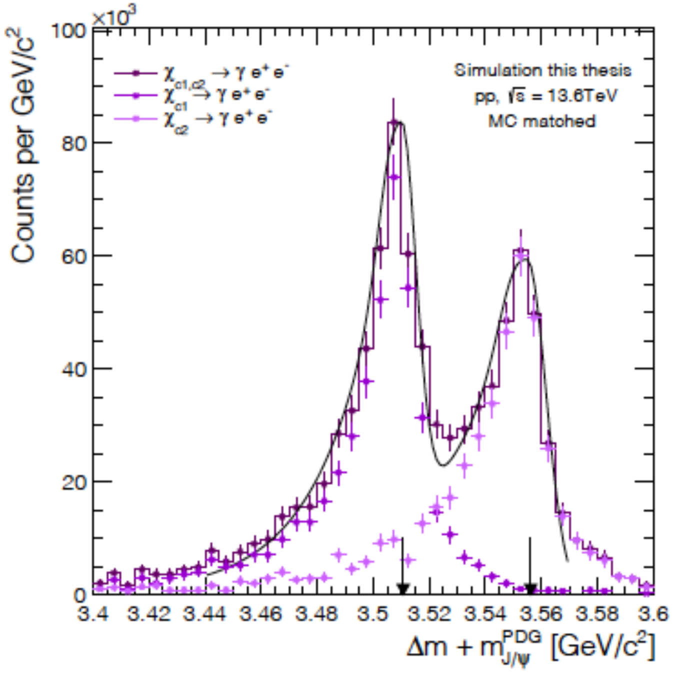
A. Andronic et al.,
Phys.Lett.B 678:350-354(2009)



P. Gonzalez et at., EPJC 61 (2009) 899
Erratum-ibid.C61:915,2009.

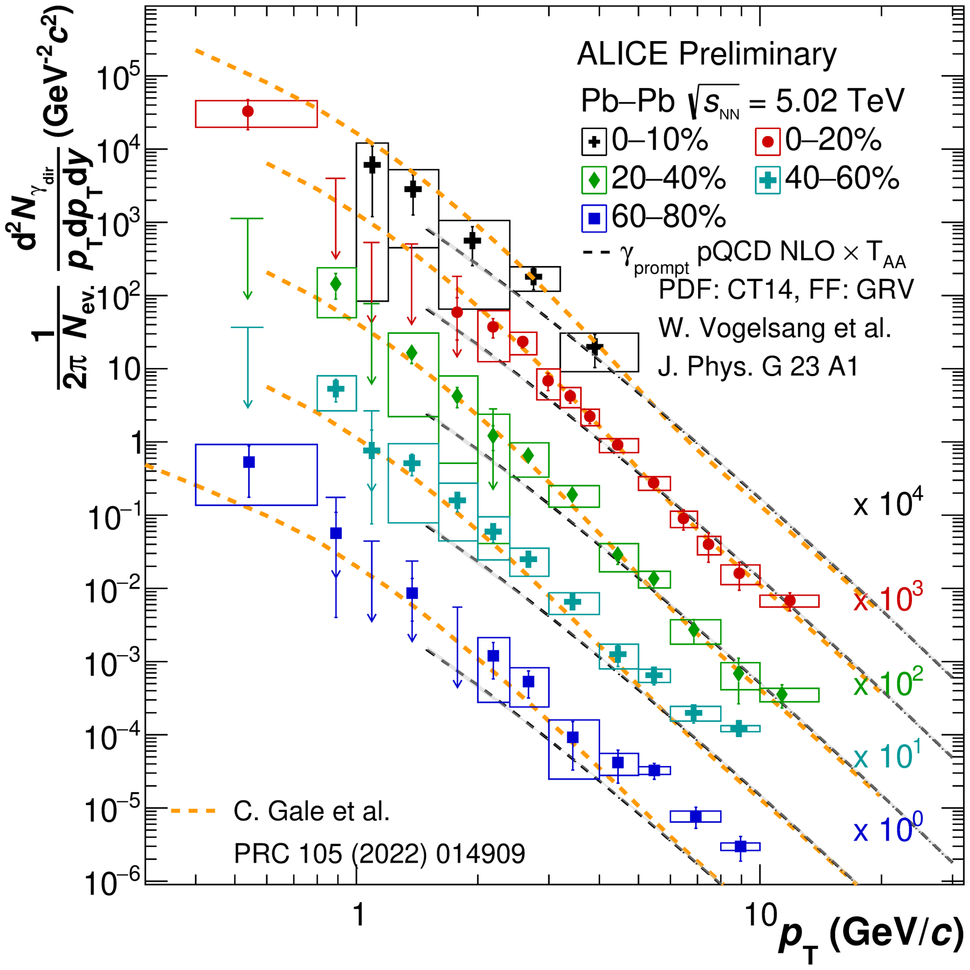


- Letter of Intent for ALICE 3: CERN-LHCC-2022-009 , arXiv: 2211.02491



I. Kantak, Bachelor Thesis

QGP thermal emission



$$N_{\gamma,\mathrm{dir}} = N_{\gamma,\mathrm{inc}} - N_{\gamma,\mathrm{dec}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot N_{\gamma,\mathrm{inc}}$$

$$\gamma_{\mathrm{dir}} = \frac{\gamma^*_{\mathrm{dir}}}{\gamma^*_{\mathrm{incl}}} \cdot (\gamma_{\mathrm{incl}})_{\mathrm{real}}$$

New measurement of direct γ in Pb-Pb at 5.02 TeV

- Virtual γ method, 0-10% centrality
- Real γ (conversion method), other centralities

Low p_T ($p_T \lesssim 3$ GeV/c) – “thermal” photons

- consistent with model with pre-equilibrium and thermal photons

High p_T ($p_T \gtrsim 3$ GeV/c) – prompt photons

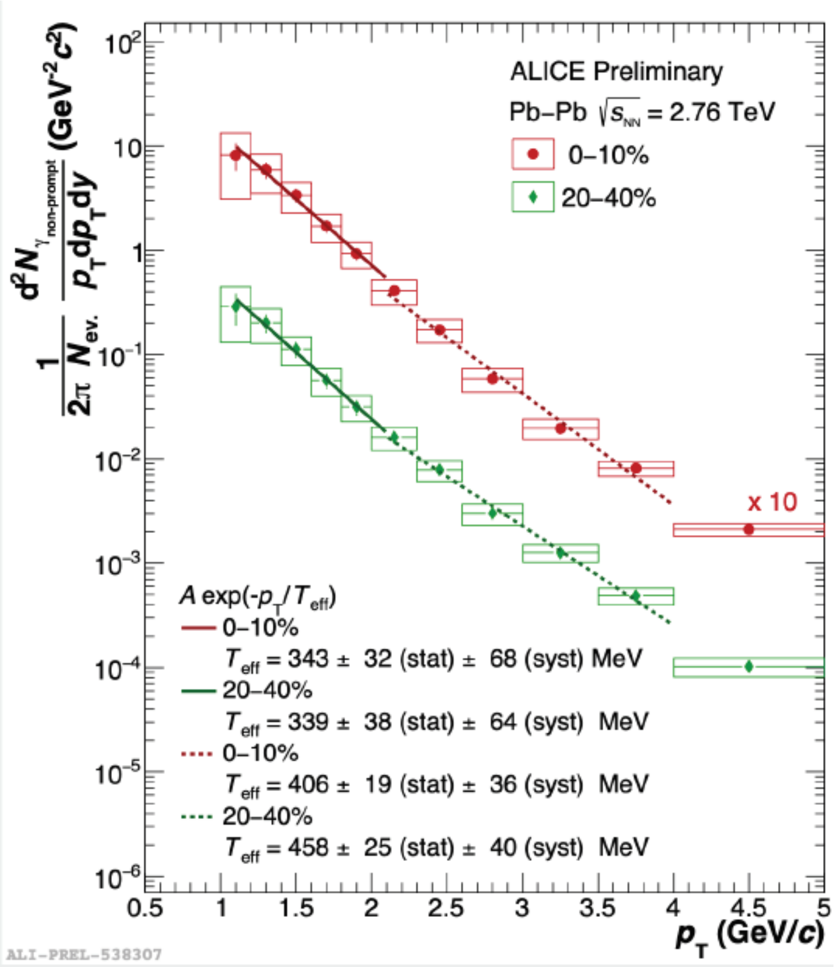
- consistent with pQCD expectations

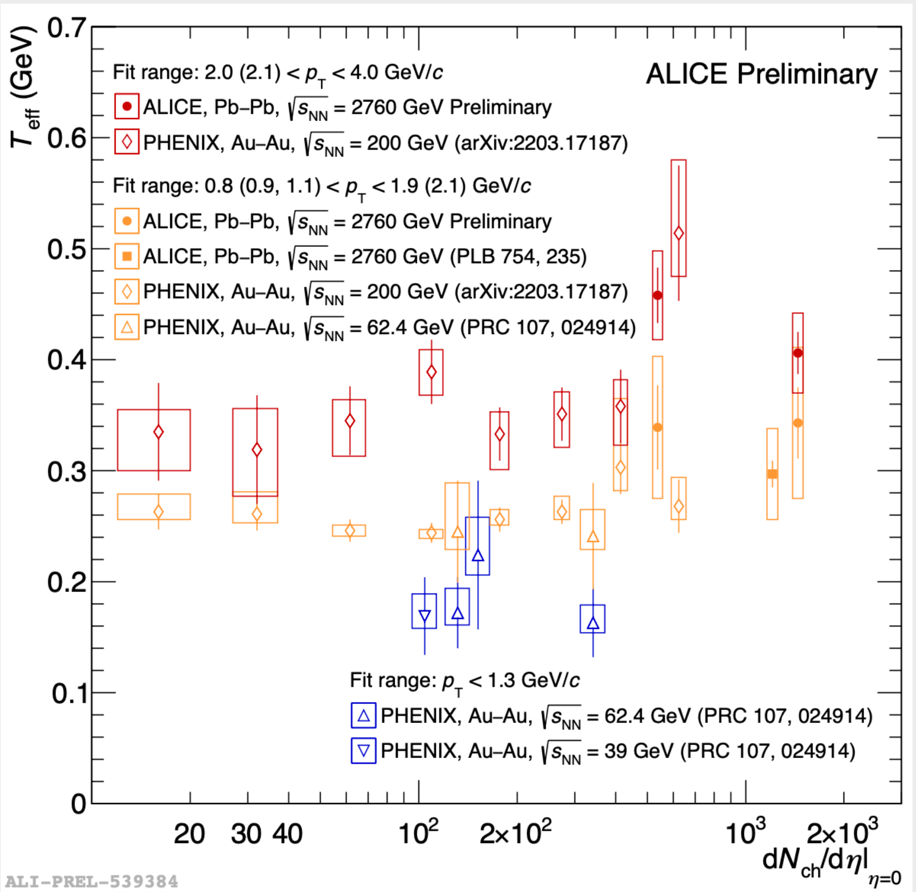
T_{eff} from non-prompt photons

Non-prompt γ = direct γ – T_{AA} . pQCD

is T_{eff} ($2.1 < p_T < 4$ GeV/*c*) > T_{eff} ($1.1 < p_T < 2.1$ GeV/*c*) ?

pre-equilibrium photons? earlier time emission?

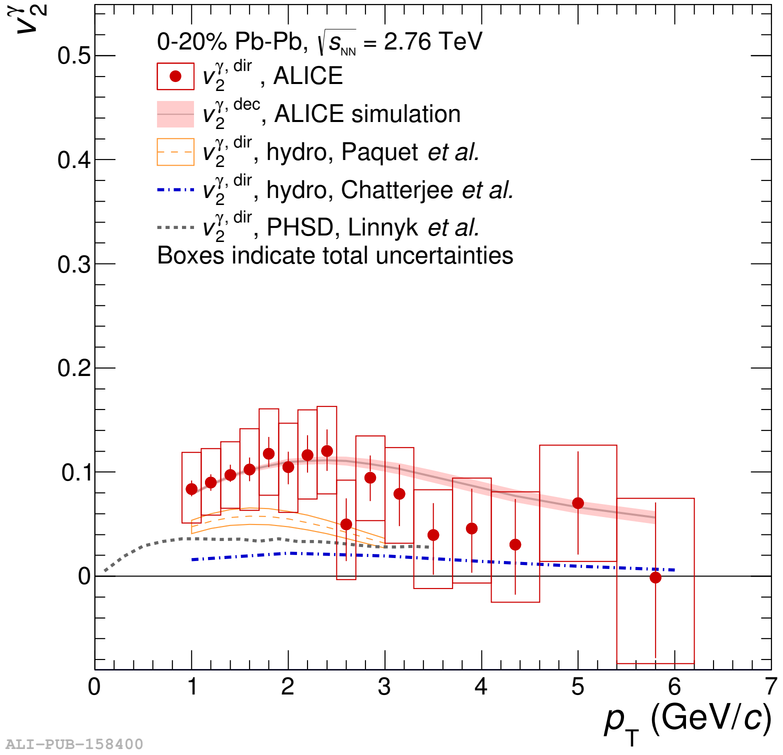


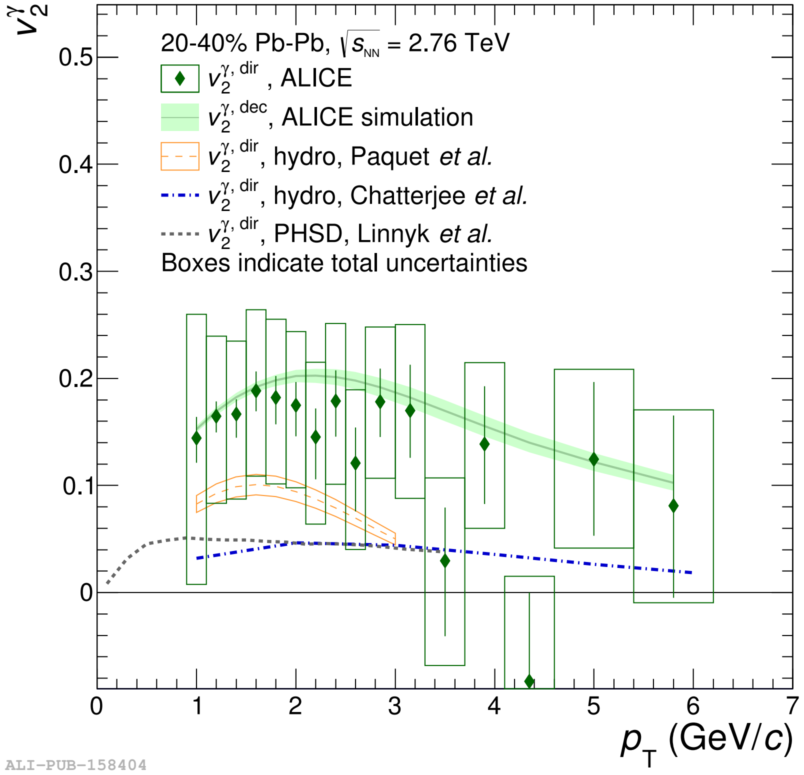


a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

$v_2^{\gamma,\mathrm{dir}}$

PLB 789 (2019) 308





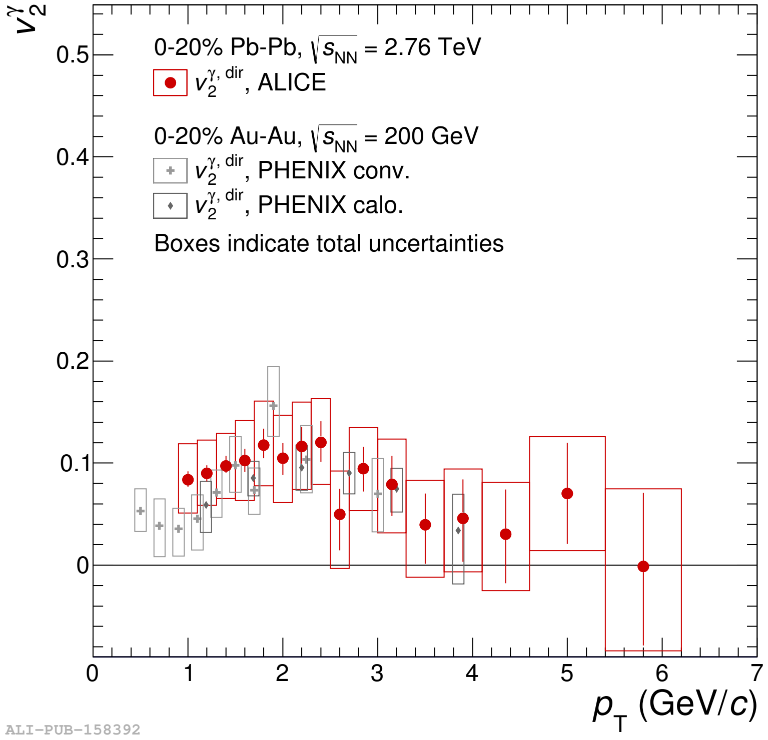
- Large direct photon v_2 for $p_T < 3$ GeV/c
- Measured magnitude of $v_2^{\gamma,\mathrm{dir}}$ comparable to hadrons
- Result points to late production times of direct photons after flow is established

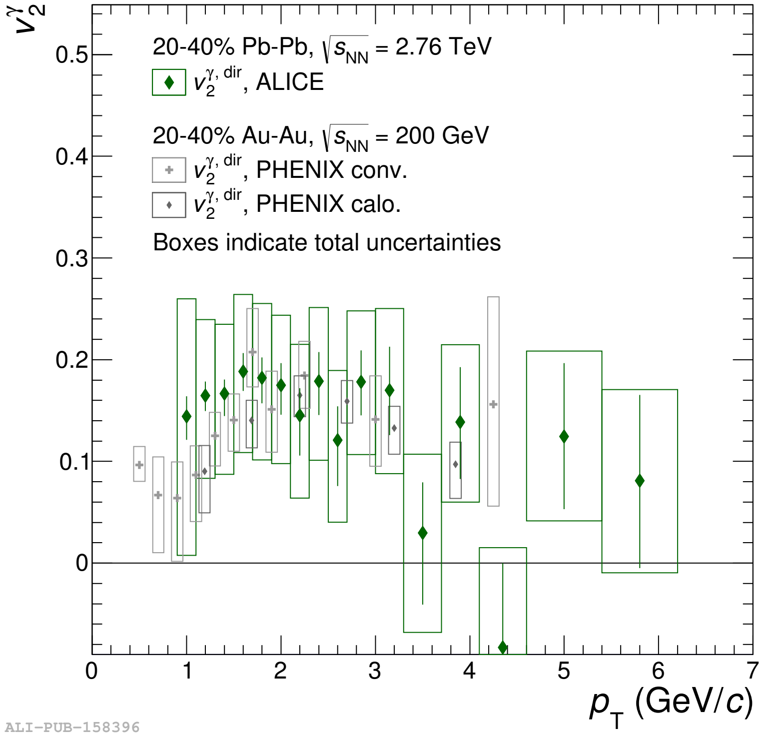
- v_2^{dir} larger than models predictions (in qualitative agreement with PHENIX)

- But: null hypothesis $v_2^{\mathrm{dir}} = 0$ not inconsistent with the data

$v_2^{\gamma,dir}$: RHIC vs LHC

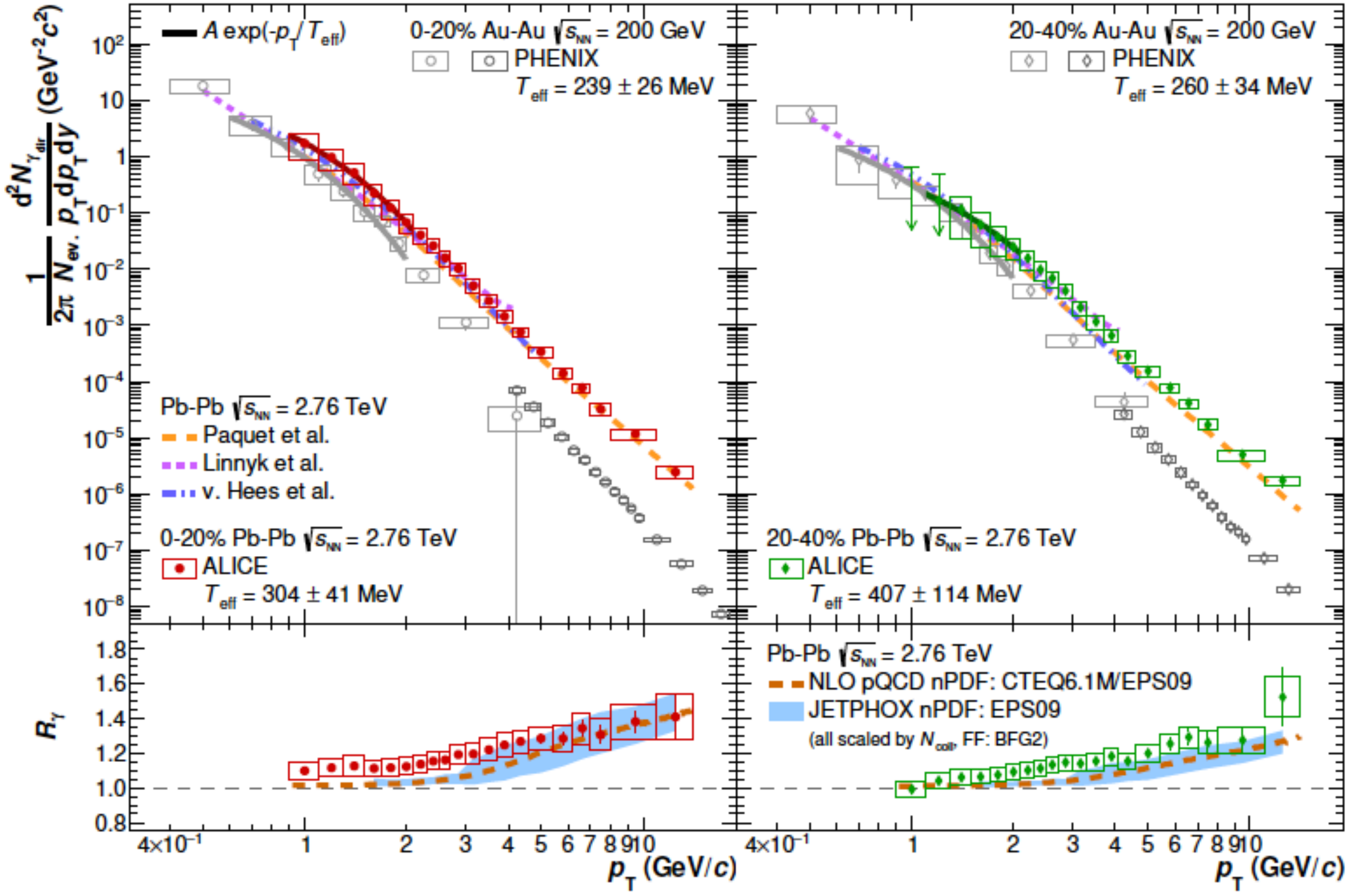
PLB 789 (2019) 308





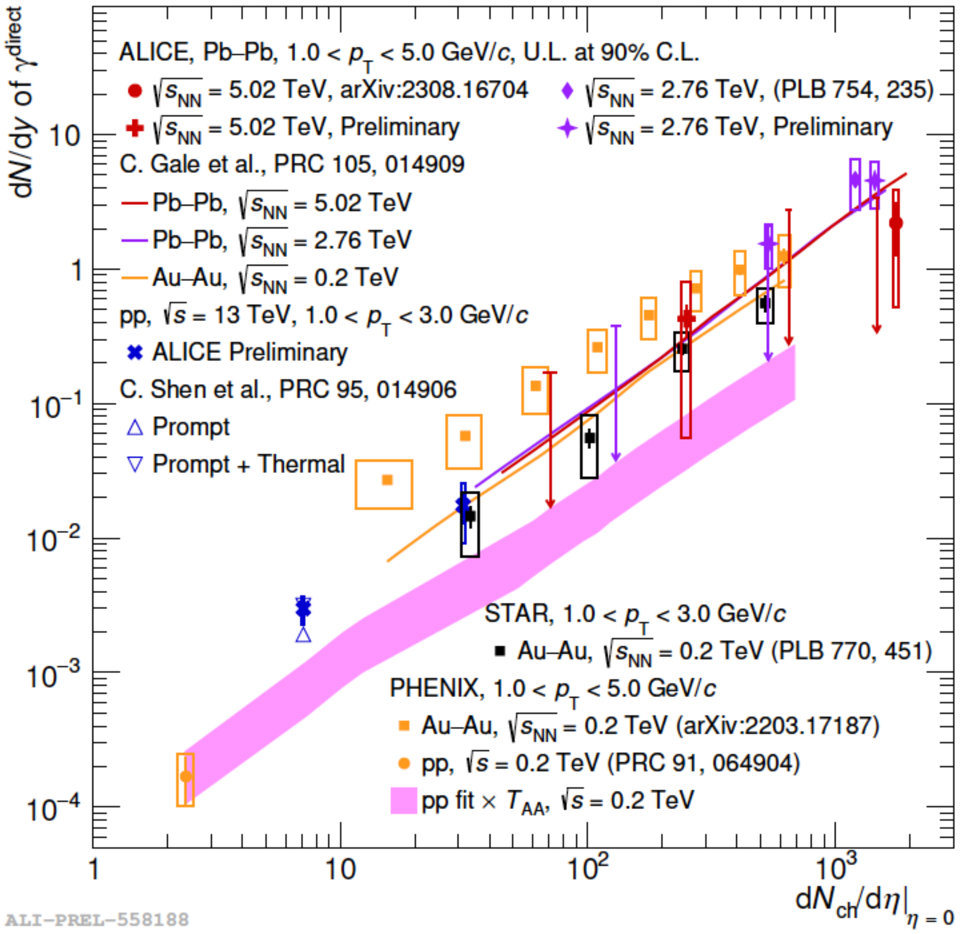
$v_2^{dir}(\mathrm{LHC}) \approx v_2^{dir}(\mathrm{RHIC})$

Thermal emission: RHIC and LHC



Increase in the effective temperature from RHIC to LHC

Integrated direct photon yield vs dN_{ch}/dη



Power-law scaling of direct γ yield vs N_{ch} proposed by PHENIX for different systems and collision energies

- Integrated direct photon yield (1 < p_T < 5 GeV/c) vs dN_{ch}/dη

Latest models describe the N_{ch} dependence for ALICE and STAR
Underestimates PHENIX data for semicentral to peripheral collisions

Inclusive and direct γ v_2

PLB 789 (2019) 308

Early emission of photons: high yield ↔ low v_2

Late emission of photons: low yield ↔ high v_2

$$E\frac{dR}{d^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}T^2e^{-E/T}\ln\left(\frac{2.912}{g^2}\frac{E}{T}\right)$$

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

- Inclusive photon v_2 via scalar product:

$$v_2 = \sqrt{\frac{\langle\langle \vec{u}_2 \cdot \frac{\vec{Q}_2^{A*}}{M_A}\rangle\rangle\langle\langle \vec{u}_2 \cdot \frac{\vec{Q}_2^{C*}}{M_C}\rangle\rangle}{\langle \frac{\vec{Q}_2^{A}}{M_A} \cdot \frac{\vec{Q}_2^{C*}}{M_C}\rangle}}$$

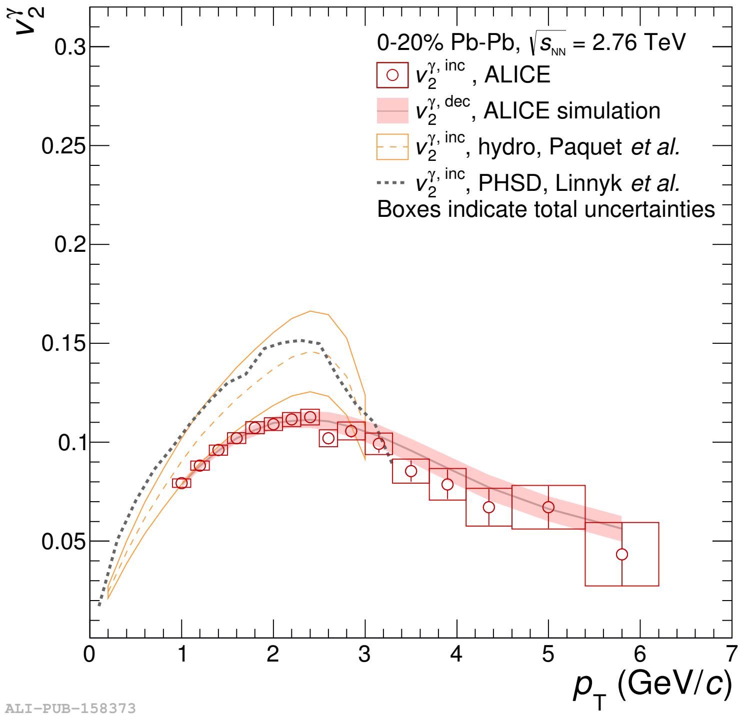
- Reference particles:
  charged hadrons in V0-A , V0-C
- Particles of interest:
  photons

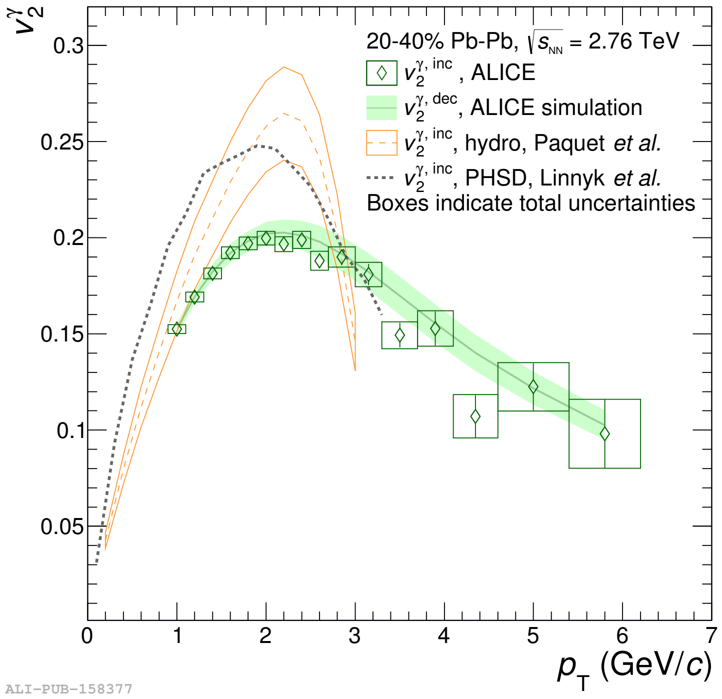
- Decay γ v_2 from simulation based on measured meson v_2
- R_γ from previous measurements:
  PLB 754 (2016) 235

$$R_\gamma = \frac{Y_{\gamma_{\mathrm{incl}}}}{Y_{\gamma_{\mathrm{decay}}}} \approx \left(\frac{Y_{\gamma_{\mathrm{incl}}}}{Y_{\pi^0}}\right)_{\mathrm{meas}} \Big/ \left(\frac{Y_{\gamma_{\mathrm{decay}}}}{Y_{\pi^0}}\right)_{\mathrm{sim}}$$

Inclusive γ v_2

PLB 789 (2019) 308





- **p_T < 3 GeV/c: $v_2^{\gamma,inc} = v_2^{\gamma,dec}$**

⇒ Either no contribution ofγ,dir or $v_2^{\gamma,dir} = v_2^{\gamma,dec}$

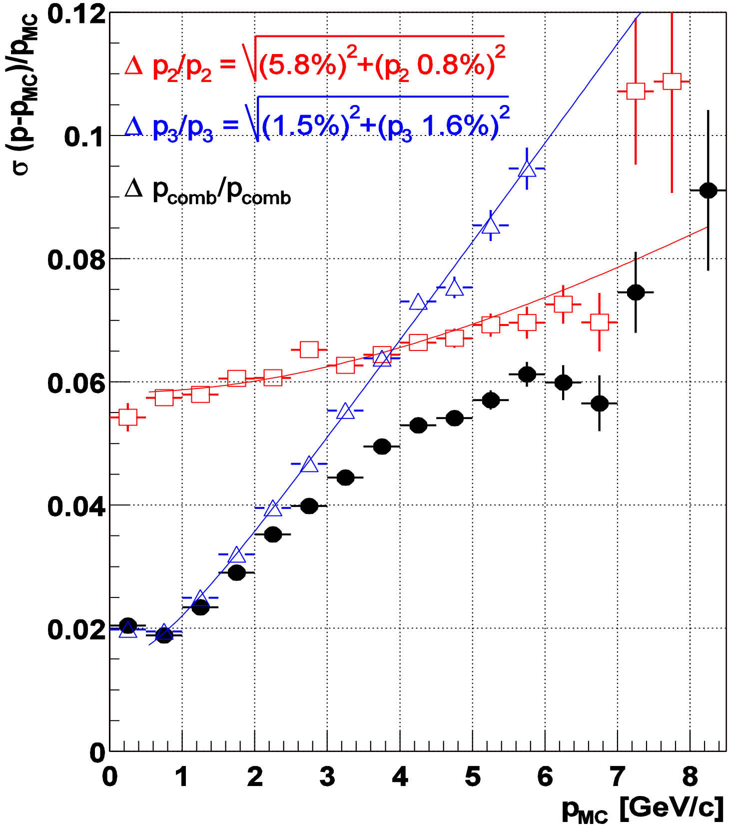
Theory ~ 30 – 40% too high

- **p_T> 3 GeV/c: $v_2^{\gamma,inc} < v_2^{\gamma,dec}$**

→ prompt photon contribution

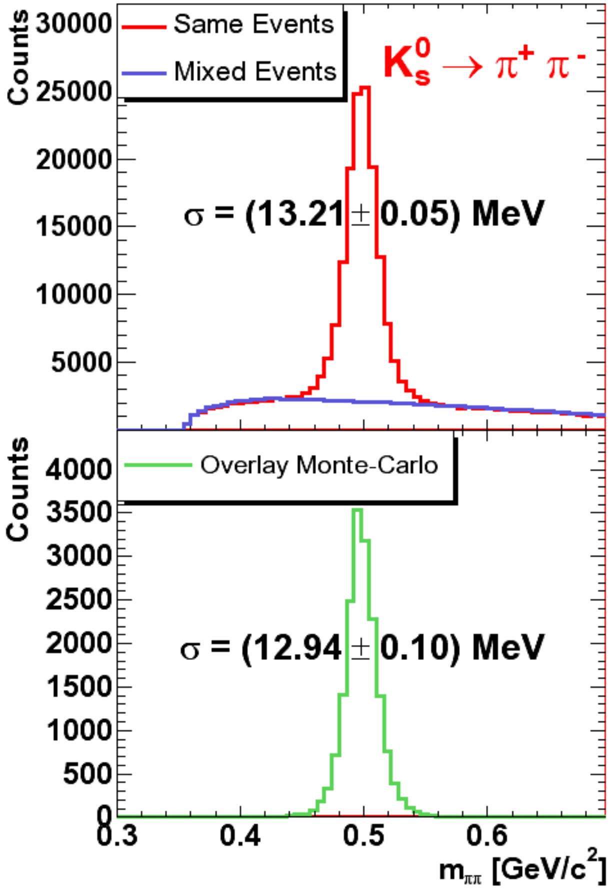
a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Momentum and mass resolution



$\sigma_p/p=2\% \oplus 1\%.p(\mathrm{GeV})$

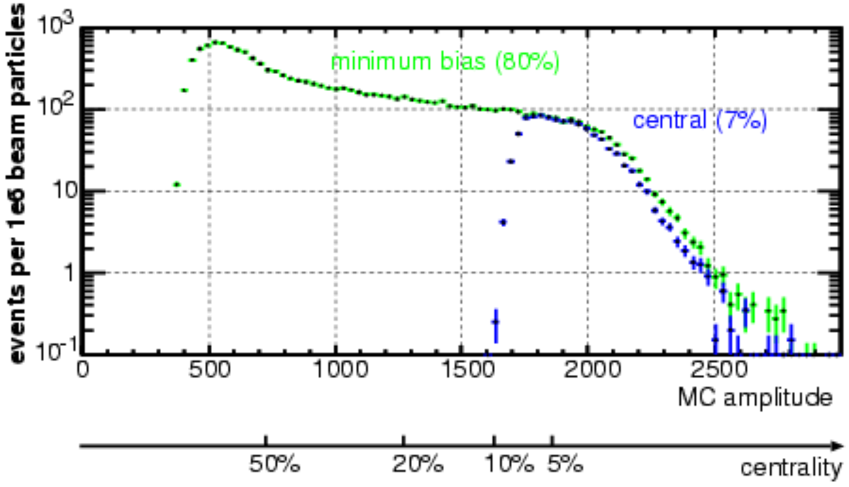
mass resolution ~3.8% at ϕ (includes bremsstrahlung contribution)

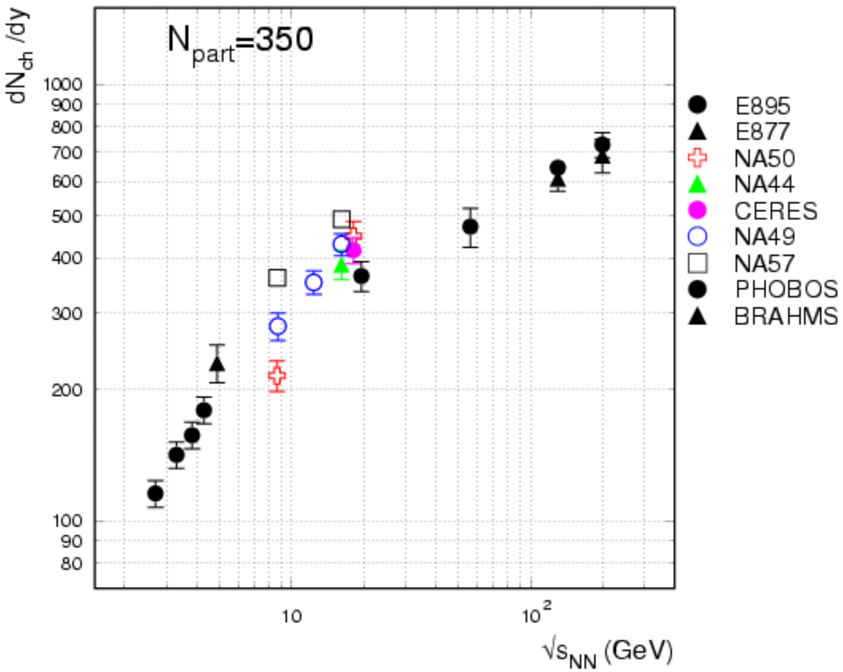


a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Centrality and N_{charge} of 2000 data

D.Miskowiec, nucl-ex/0511010





Measurement done at 7% centrality

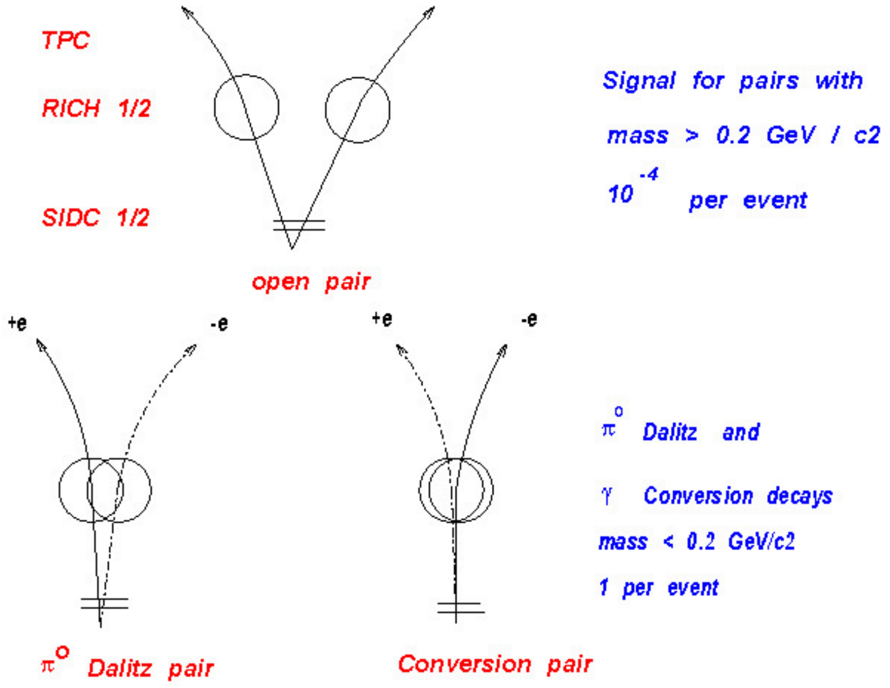
Background rejection

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

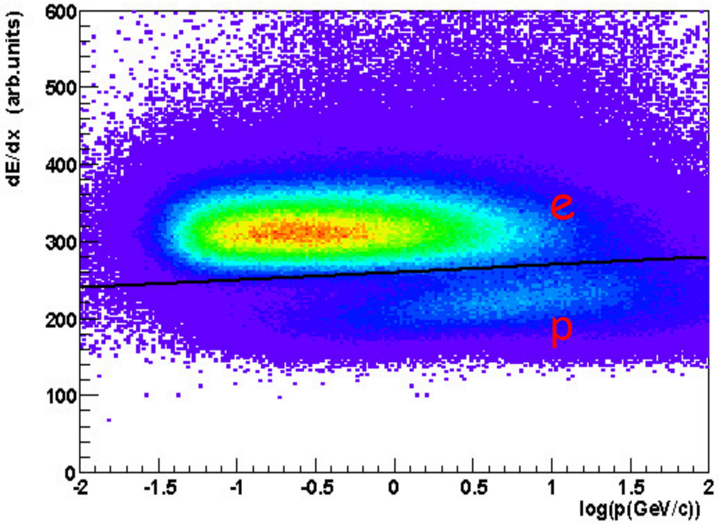
1. Dalitz recognition:

- 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!

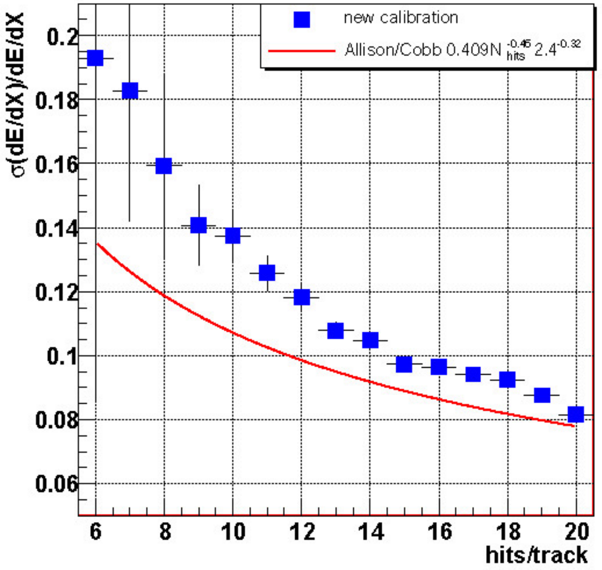


Electron identification with TPC dE/dx



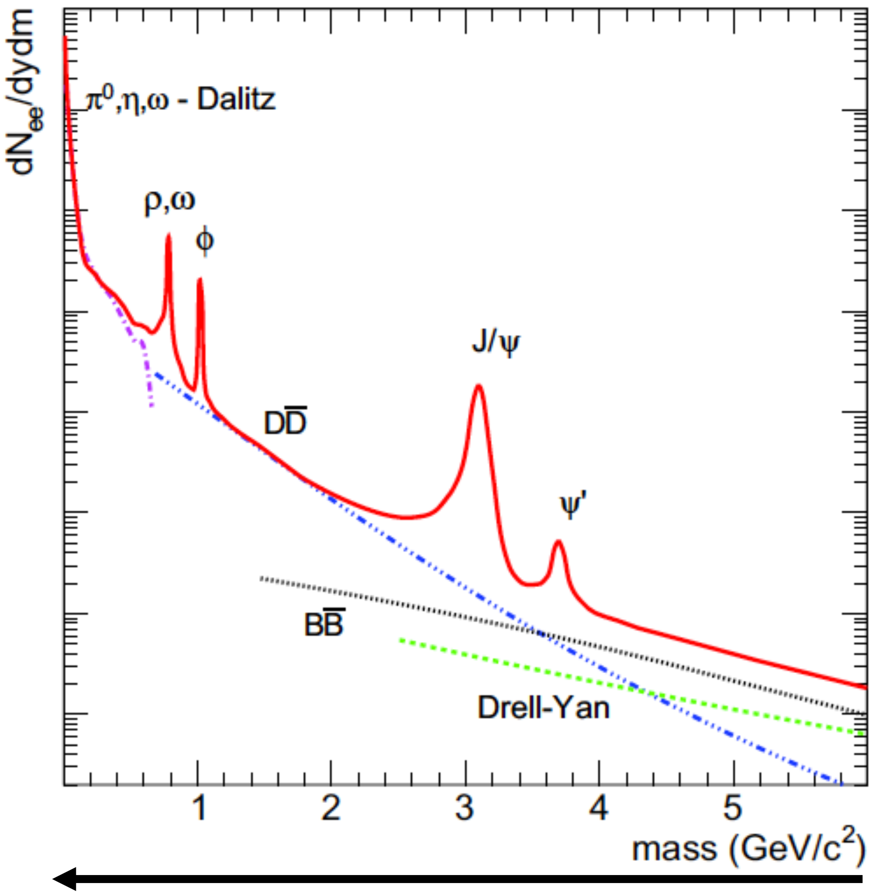
Energy loss dE/dx
in TPC

σ(dE/dx)/(dE/dx)<10%
for all tracks used

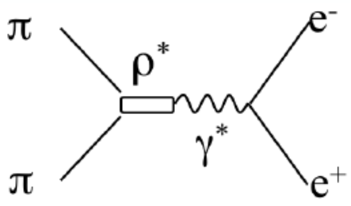


Dileptons

A. Drees [Nucl. Phys. A830 (2009) 435]



Late Probed time scale Early


hadron gas


quark-gluon plasma

Invariant mass allows separation of different collision stages:

- **M < 1 GeV:** hadronic

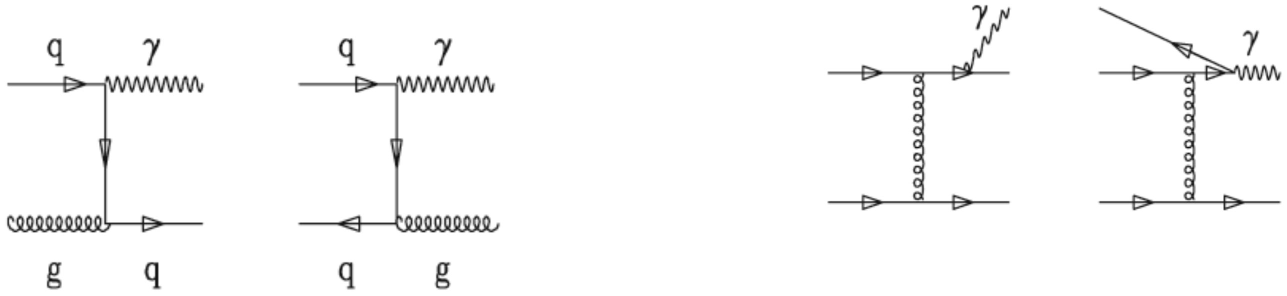
hadrons in medium, in medium modifications of vector mesons, chiral symmetry restoration

- **M > 1 GeV:** partonic

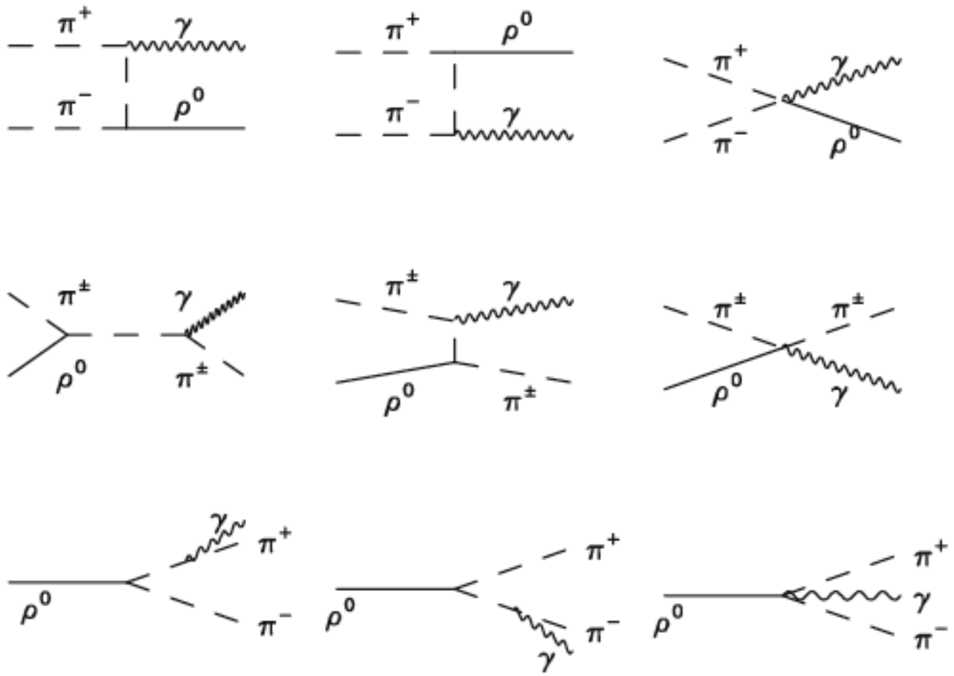
early temperature, partonic collectivity, thermal radiation

Photon production: Feynman diagrams

QGP:



Hadron gas:



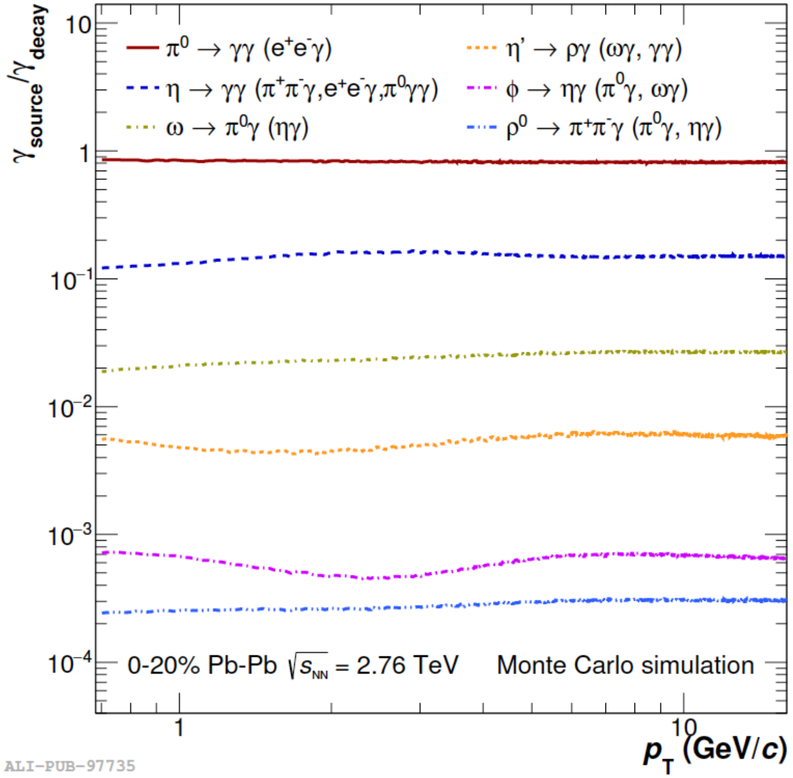
Methods to measure direct photons

- 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

a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Direct photons: statistical subtraction method and double ratio

PLB 754 (2016) 235



Subtraction method:

$$N_{\gamma,\mathrm{dir}} = N_{\gamma,\mathrm{inc}} - N_{\gamma,\mathrm{dec}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot N_{\gamma,\mathrm{inc}}$$

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

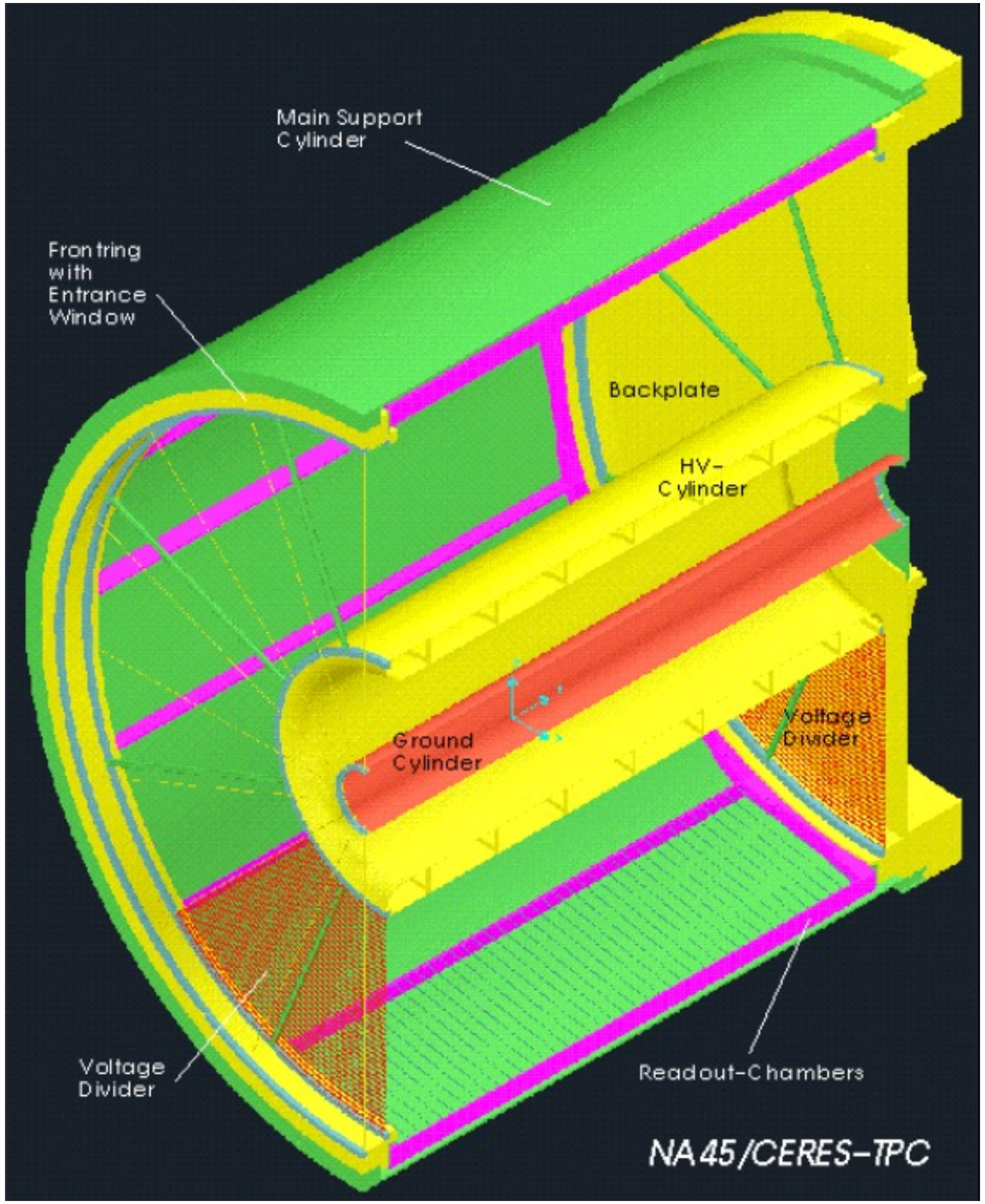
Double ratio:

$$R_\gamma = N_{\gamma,\mathrm{inc}}/N_{\gamma,\mathrm{dec}} \approx \left(\frac{N_{\gamma,\mathrm{inc}}}{\pi^0}\right)_{\mathrm{meas}} \Big/ \left(\frac{N_{\gamma,\mathrm{dec}}}{\pi^0}\right)_{\mathrm{sim}}$$

>1 if direct photon signal

Advantage: Cancellation of uncertainties

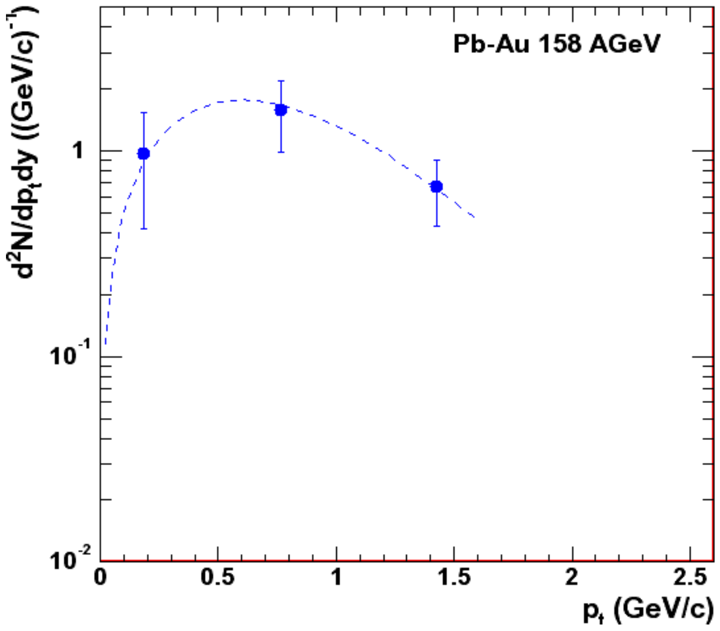
To obtain γ direct spectrum add systematic uncertainties of the inclusive photon spectrum which canceled in the double ratio



a.marin@gsi.de, Physikzentrum Bad Honnef (2025)

Transverse Momentum Distribution $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$

PRL96(2006)152301

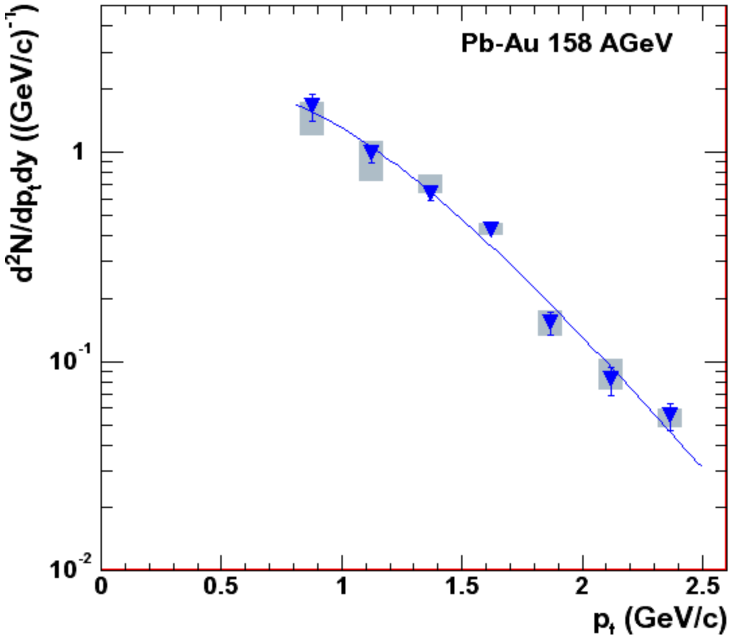


$$\frac{d^2N}{dp_t dy} = \frac{dN/dy}{T(T+m_\phi)} \bullet pt \bullet e^{-\frac{m_t - m_\phi}{T}}$$

T = 306 ± 82 (stat) MeV

dN/dy=2.19±0.52(stat)±0.34(syst)

at 2.1<y<2.65

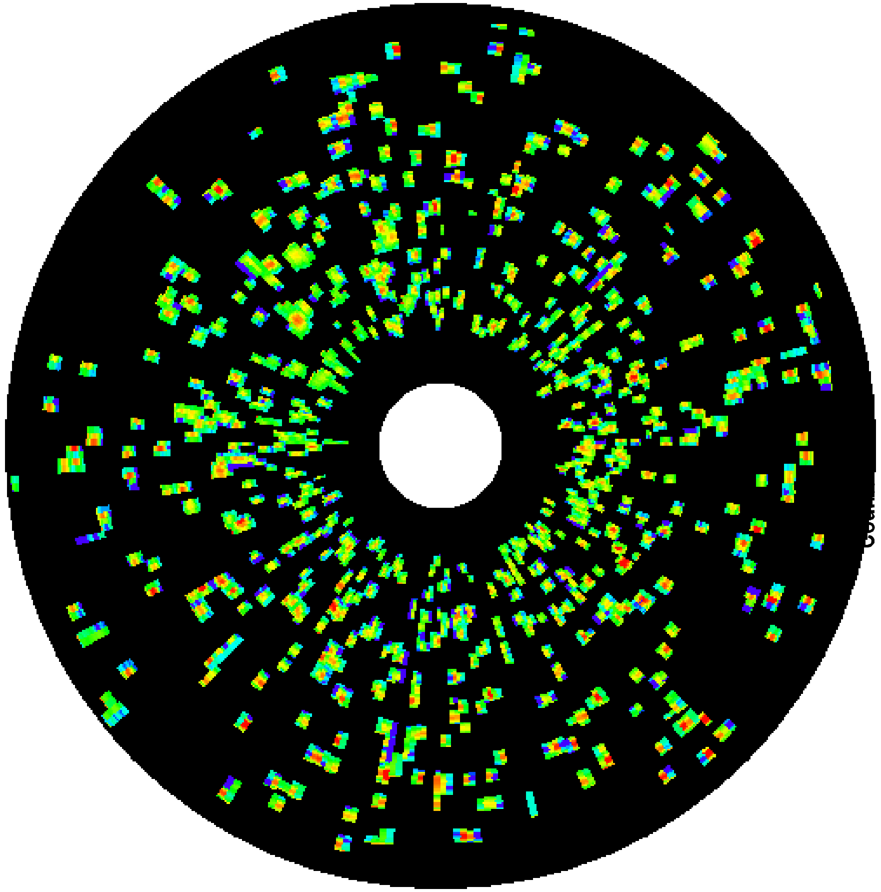


T = 273 ± 9(stat) ± 10(sys) MeV

dN/dy = 2.05 ± 0.14(stat) ± 0.25(syst)

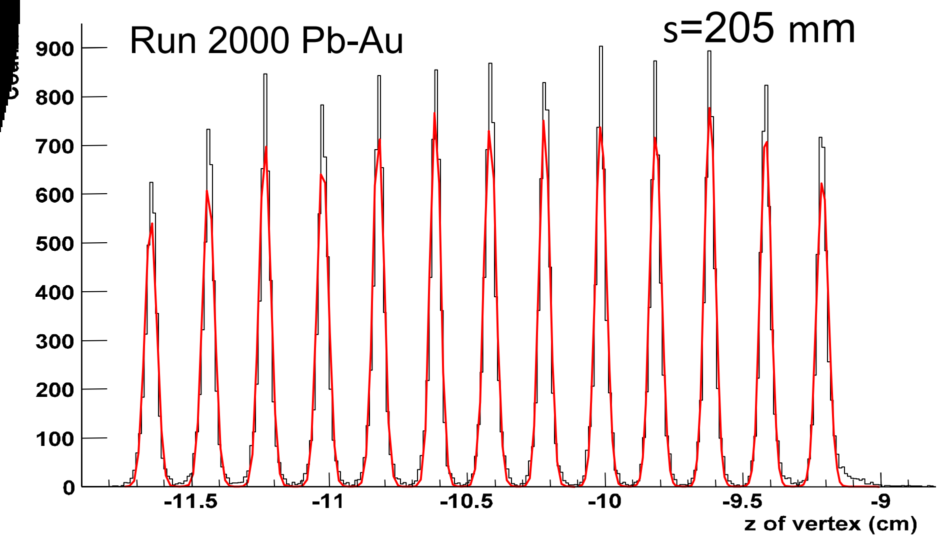
at 2.0<y<2.4

The Sidc detectors

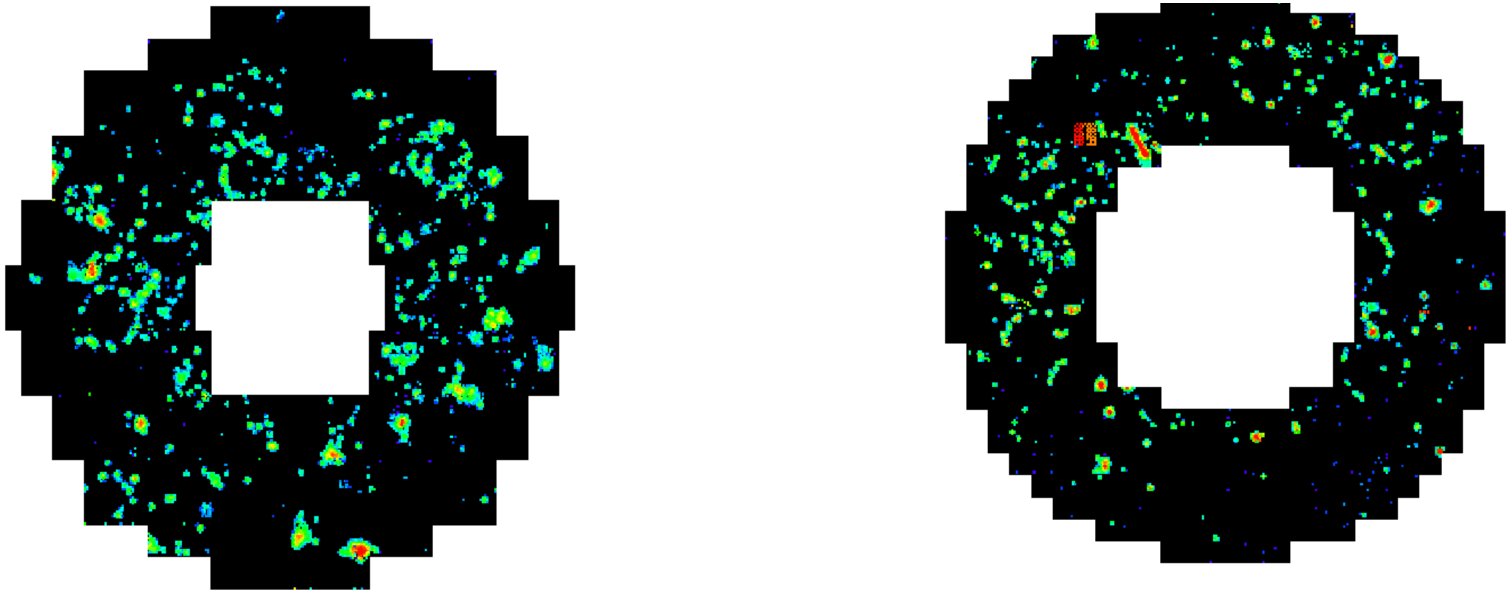


Two 4" silicon wafers

- Charged particle tracking
- Vertex reconstruction
- Angle measurement



The RICH detectors


Rich1

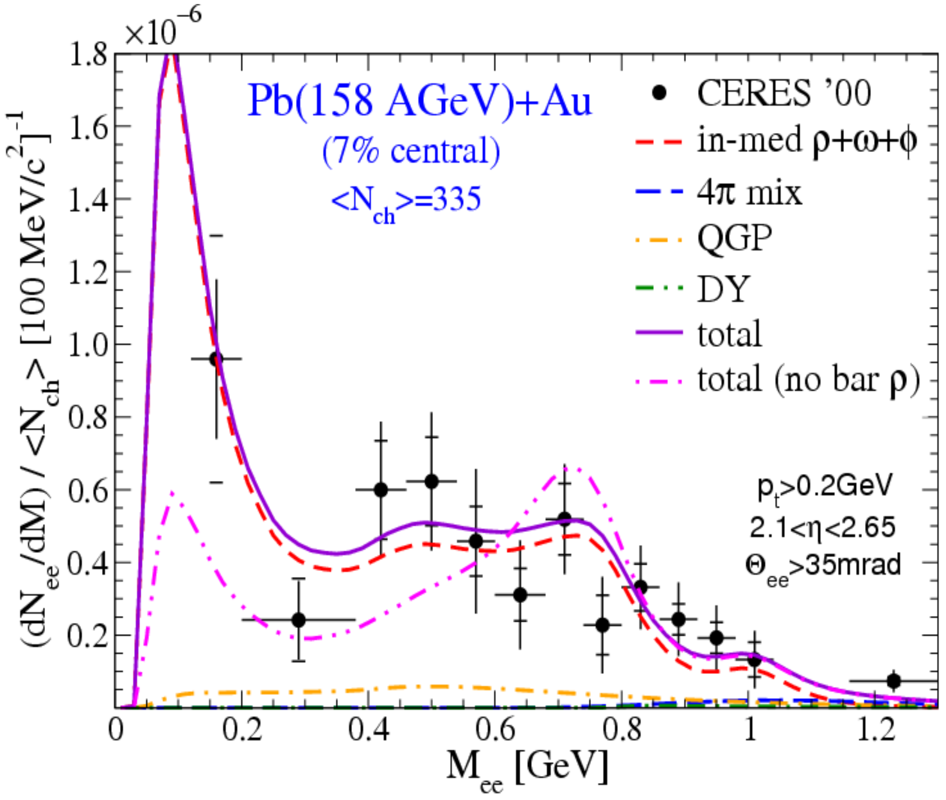
Rich2

- Electron identification
- Hough transformation algorithm for ring recognition
- Use of Rich1/2 in combined mode (no Bfield)

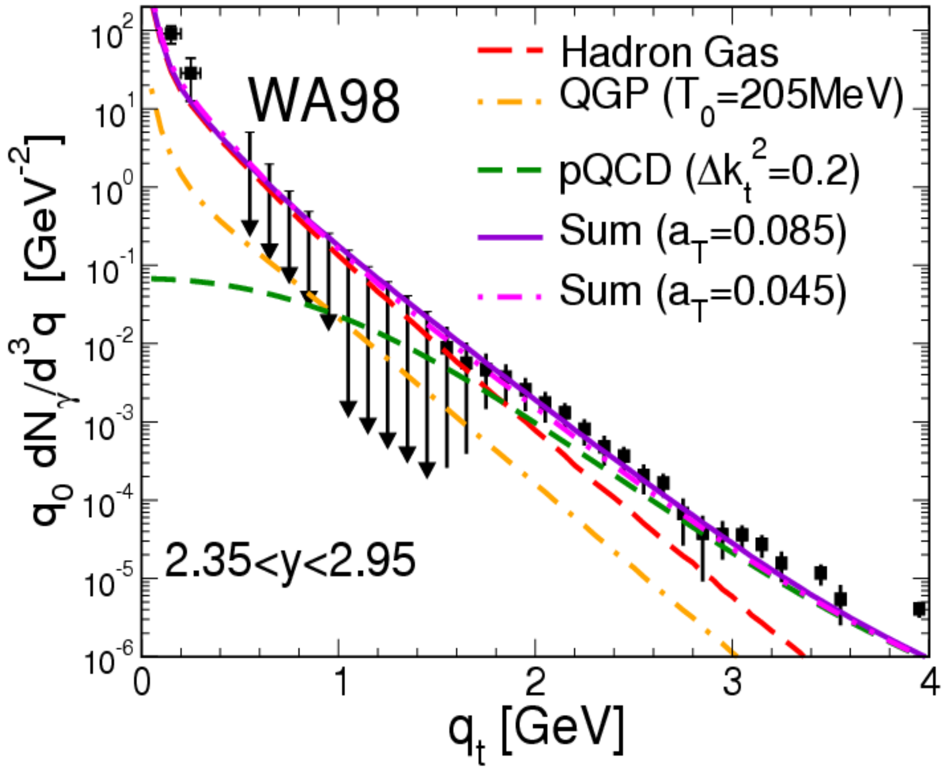
EM Probes in Central Pb-Au/Pb at SPS

Comparisons with updated calculations

Di-Electrons [CERES/NA45]



Photons [WA98]



- updated fireball (a_T=0.045→0.085/fm)
- very low-mass di-electrons ↔ (low-energy) photons

[van Hees+R.Rapp '07]

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