

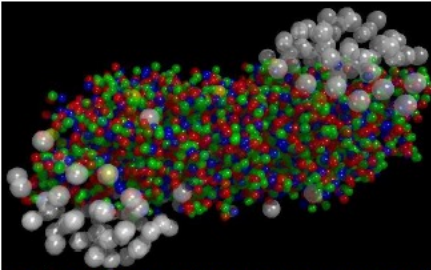
Unlocking the QCD phase diagram – with light.

Photons and mesons as probes of the quark-gluon plasma

A. Marin, Georg-C.-Lichtenberg-Haus, Darmstadt, September 2026

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'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 have 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.phys.uni-helidelberg.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.



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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 ^e, Johanna Stachel ^e

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<https://doi.org/10.1016/j.physrep.2015.12.003>

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The quest for the quark-gluon plasma

Peter Braun-Munzinger¹ & Johanna Stachel²

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.

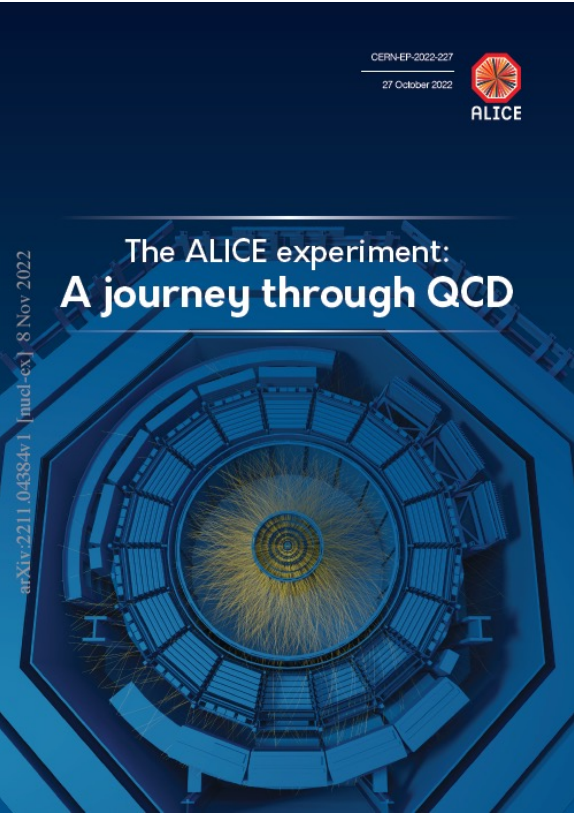
REVIEW

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

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

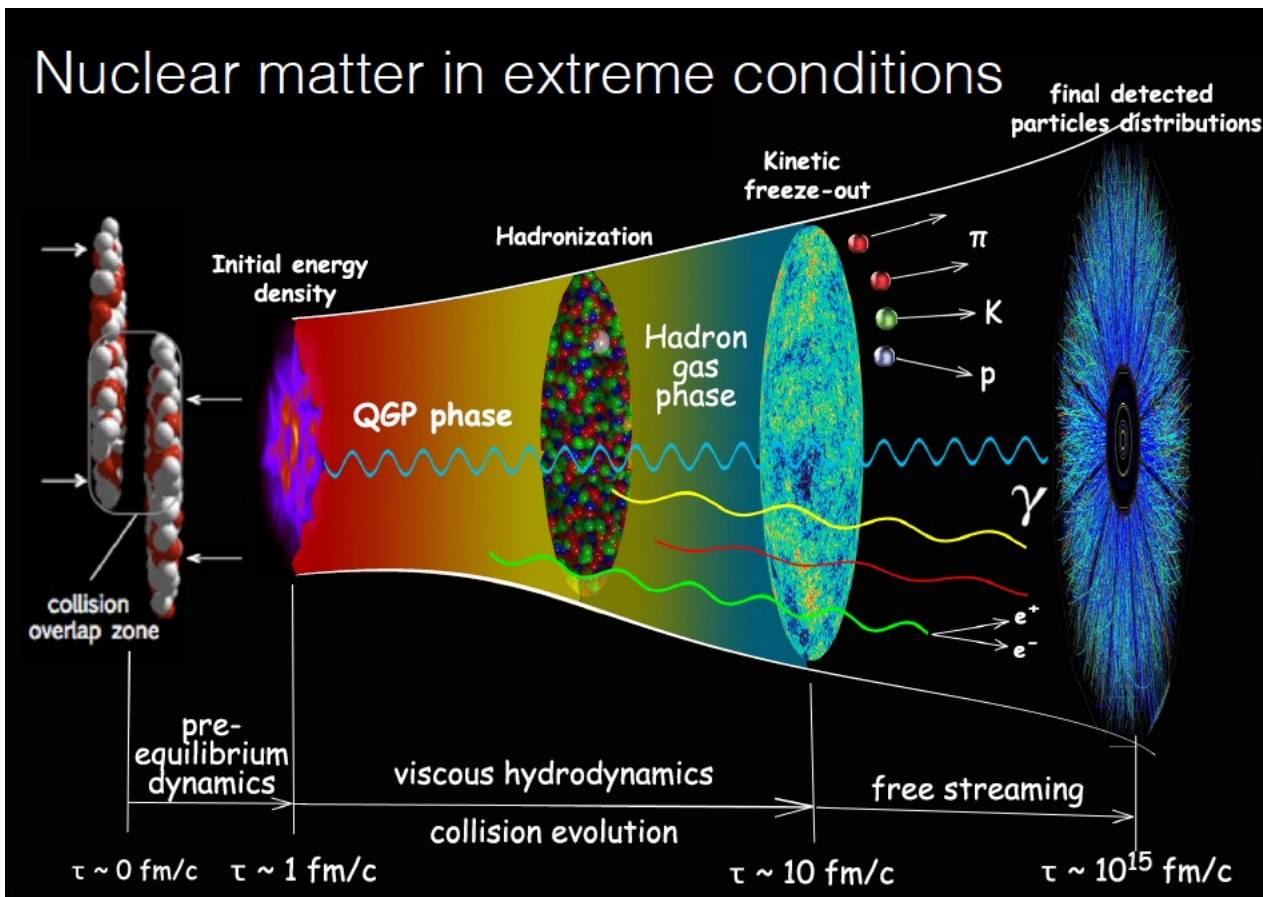
Anton Andronic^{1,2}, Peter Braun-Munzinger^{1,3,4*}, Krzysztof Redlich^{1,5} & Johanna Stachel³

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.



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

Motivation: Direct photons

Colorless objects, scape without interaction

Carry information on the medium's temperature and space-time evolution.

Large background from neutral meson decays (π^0 , η , ω , ...).

Prompt photons:

- Dominant at high p_T ($p_T > \sim 5$ GeV/c), power-law shape
- Initial hard scattering
- Described by NLO pQCD

Pre-equilibrium photons:

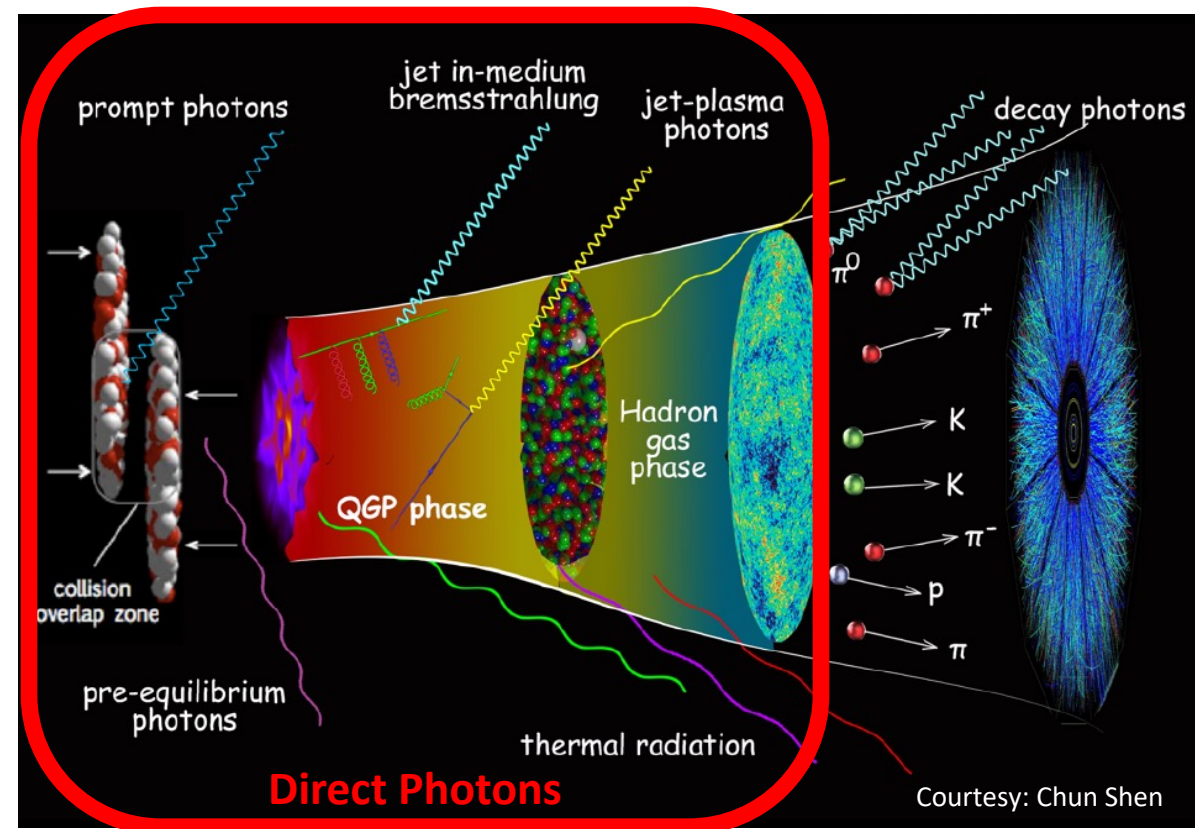
- Sensitive to the saturation momentum

Jet-medium interactions:

- Scattering of hard partons with thermalized partons

Thermal photons:

- Dominant at low p_T ($p_T < \sim 3$ GeV/c) with exponential shape
- Emitted by thermalized medium
- Comparison to models employing hydrodynamics



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:
 - $q_{\text{hard}} + q_{\text{QGP}} \rightarrow \gamma + q$
 - $q_{\text{hard}} + q_{\text{QGP}} \rightarrow \gamma + g$
 - Medium induced γ brems.

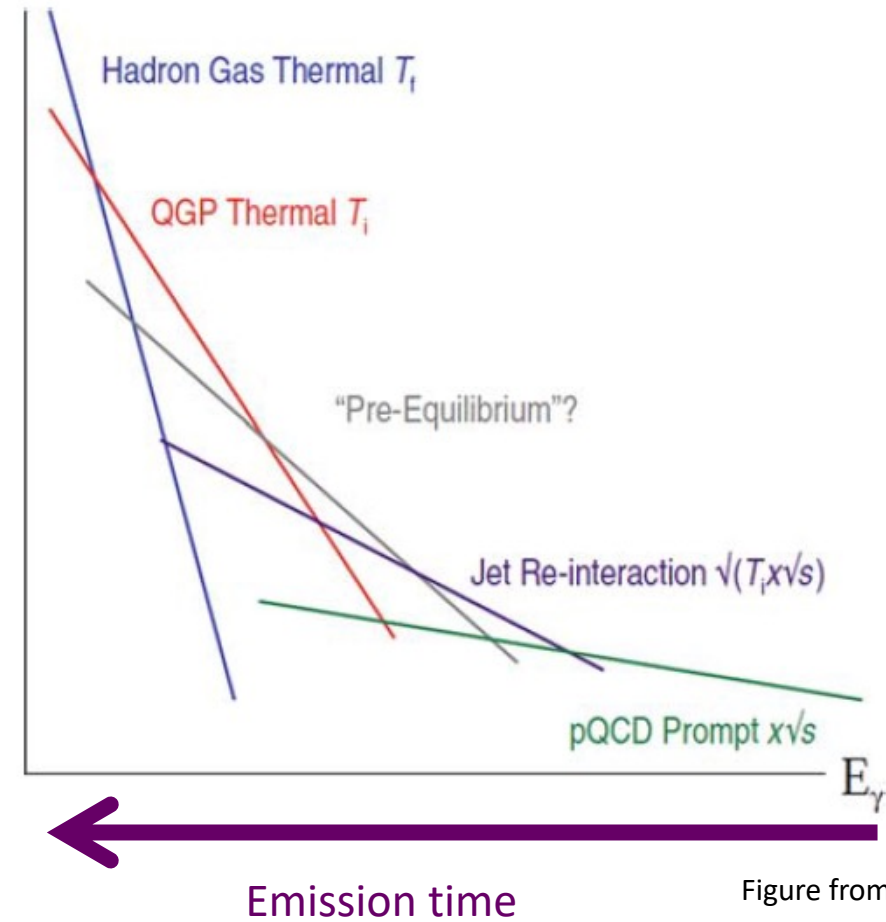
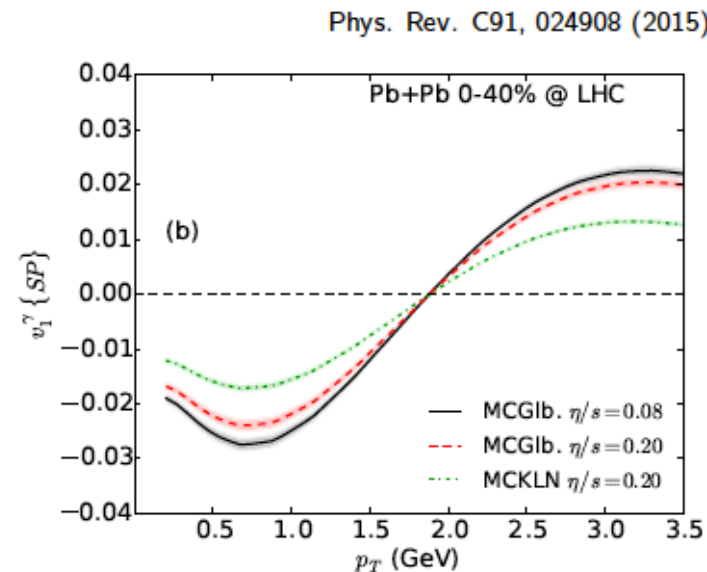
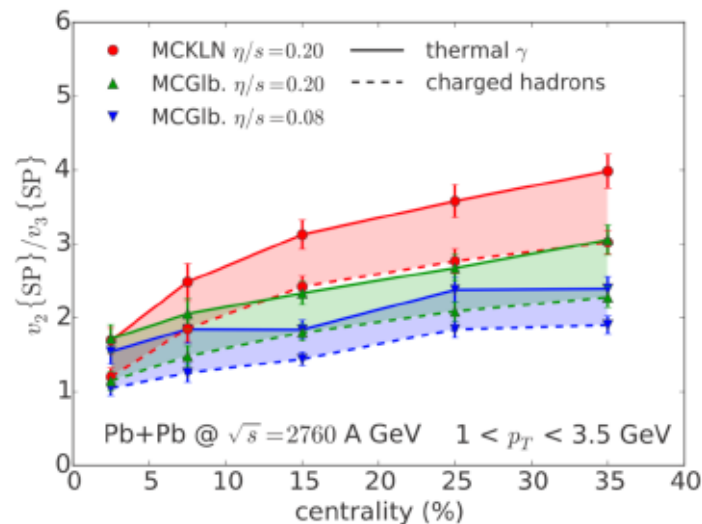


Figure from P. Stankus

**Large background from neutral meson decays.
Difficult measurement**

Motivation: Direct photons

$\gamma, \text{th } p_T$	T , yields
$\gamma, \text{dir elliptic flow } (v_2^{\gamma, \text{dir}})$	emission time
$\gamma, \text{dir triangular flow } (v_3^{\gamma, \text{dir}})$	initial density fluctuations
$v_2^{\gamma, \text{dir}} / v_3^{\gamma, \text{dir}}$	role of initial magnetic field?
$v_1^{\gamma, \text{dir}}$	QGP η/s
HBT	dynamics
	source size



The ALICE detector (version 1: Run 1 + Run 2)

Central barrel | η | < 0.9

Tracking

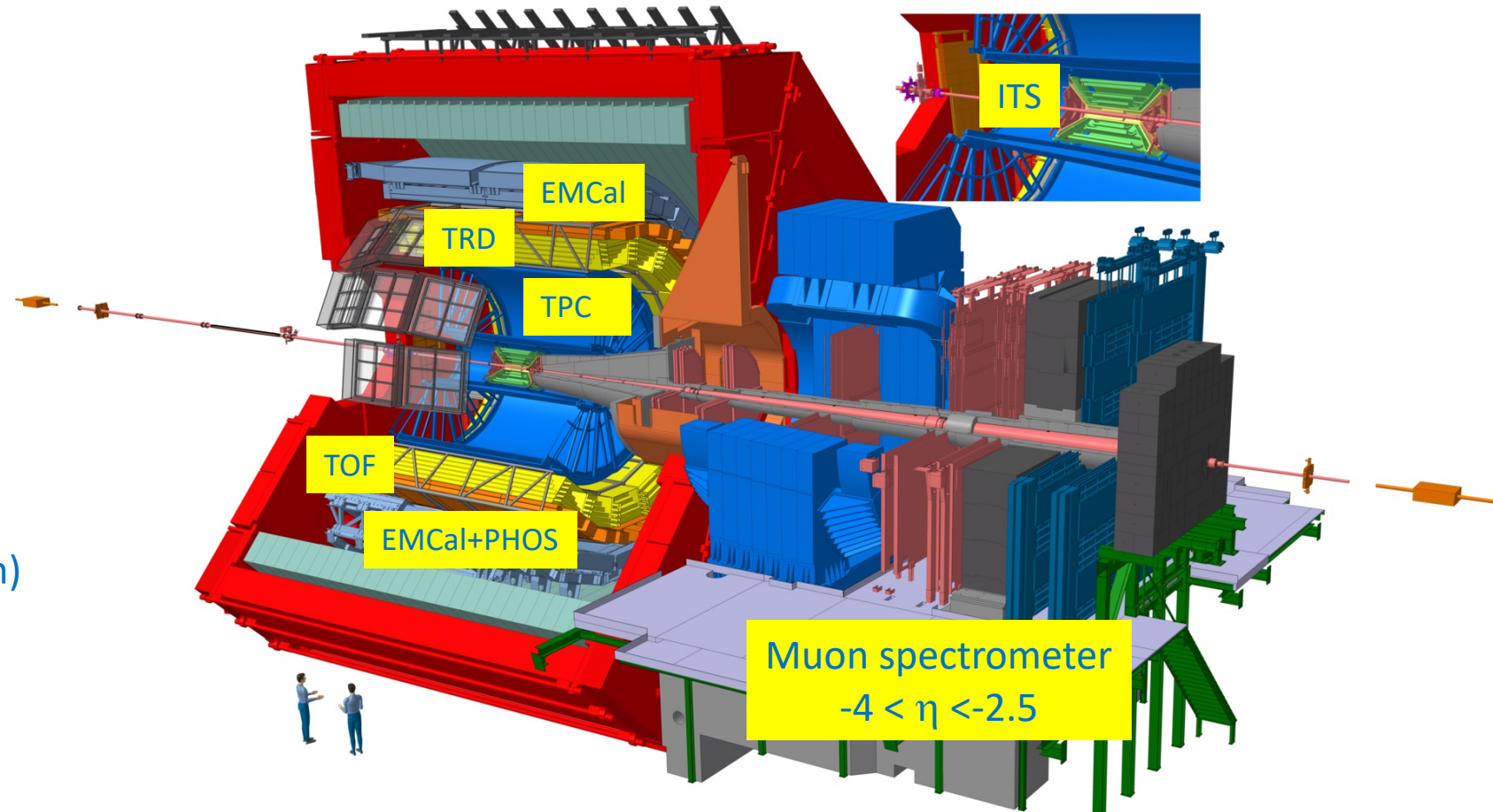
PID

Calorimeters

ACORDE (cosmics)

Forwards detectors:

- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD (N_{γ} , N_{ch})



Size: 16 x 26 meters

Weight: 10,000 tons

Detectors: 18

X- rays

Used commonly in medicine for diagnostics of different diseases

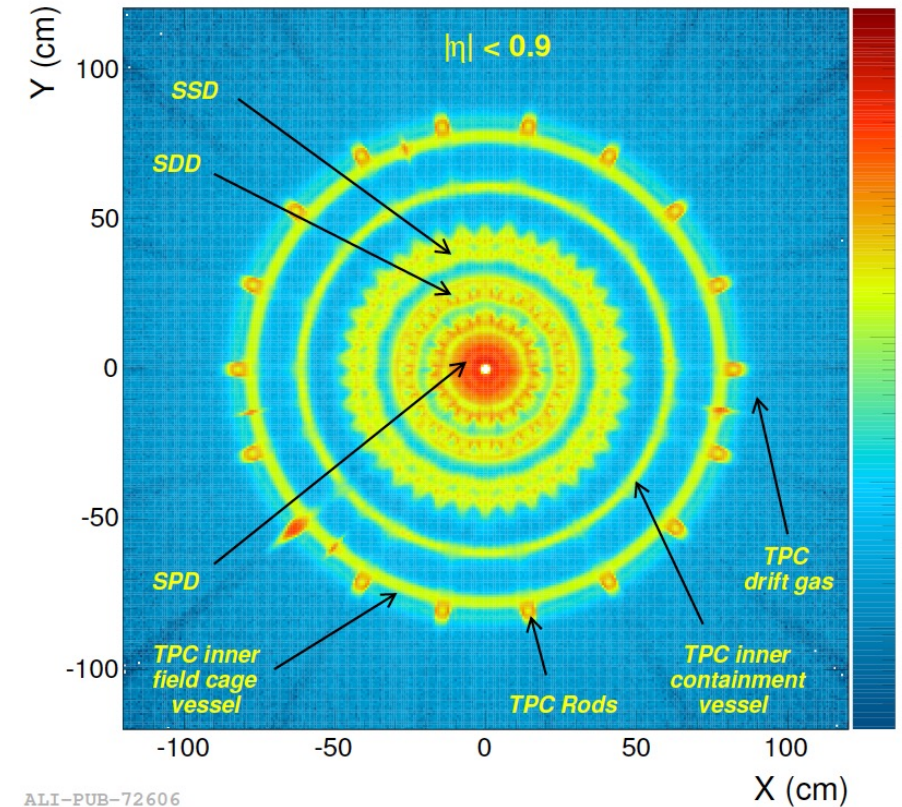
- X-rays tube
- Photographic plate
- Patient



Hand mit Ringen (Hand with Rings): print of Wilhelm Roentgen's first "medical" X-ray, of his wife's hand, taken on 22 December 1895 and presented to Professor Ludwig Zehnder of the Physik Institut, University of Freiburg, on 1 January 1896

a.marin@gsi.de, Georg -C Lichtenberg Haus (2026)

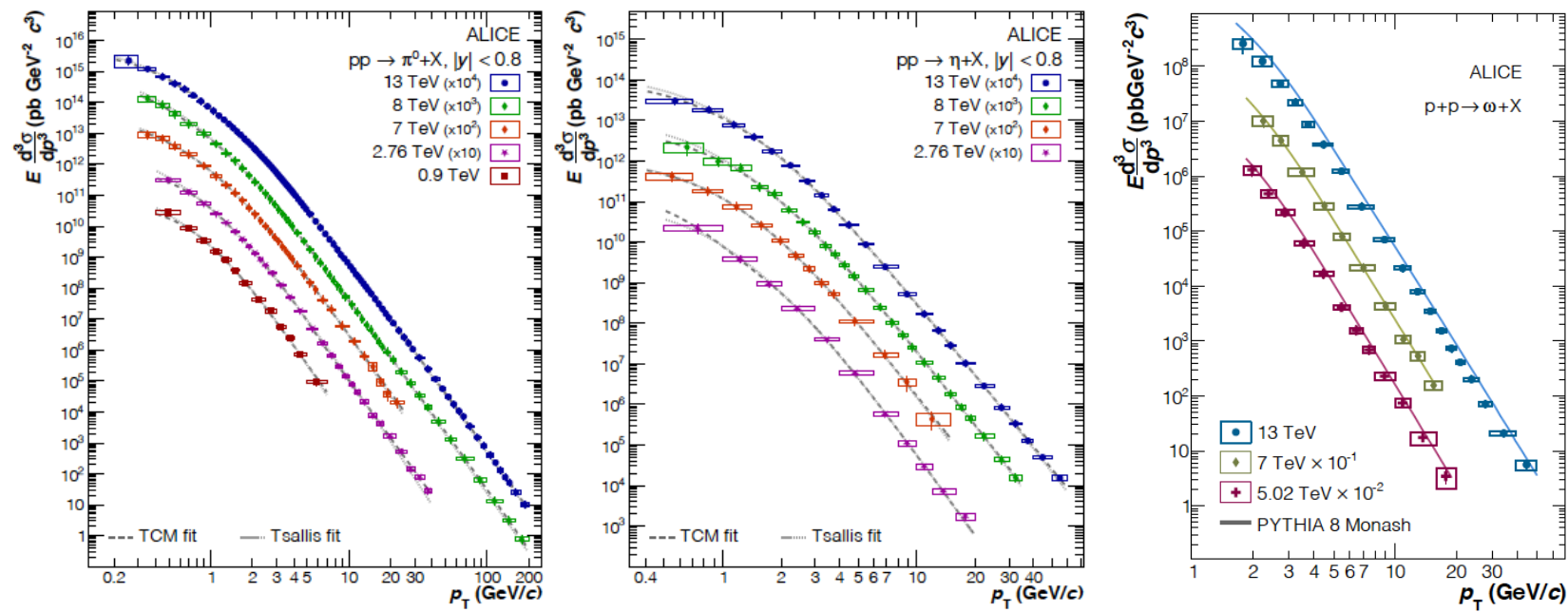
γ -rays



- Material budget of ALICE
- Precise photon measurements

[arxiv: 2303.15317](https://arxiv.org/abs/2303.15317)

Fully developed at GSI-HD (AM, KR, JS + students)

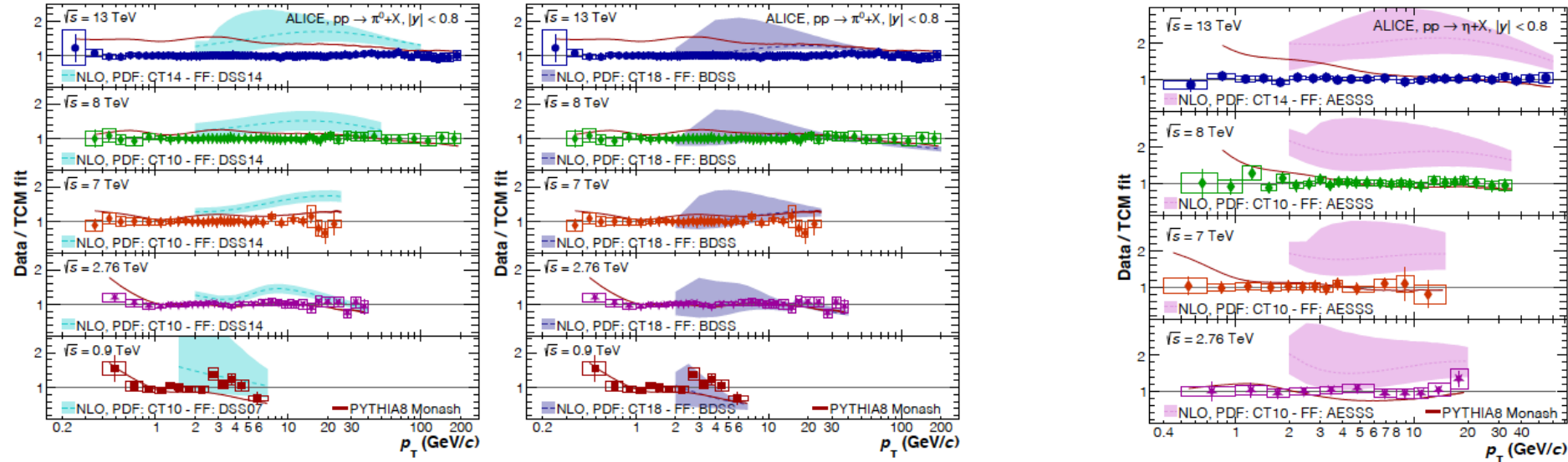


π^0, η, ω :
 $pp \sqrt{s} = 2.76, 7, 8, 13$ TeV

Combination of PCM, EMCal, and PHOS

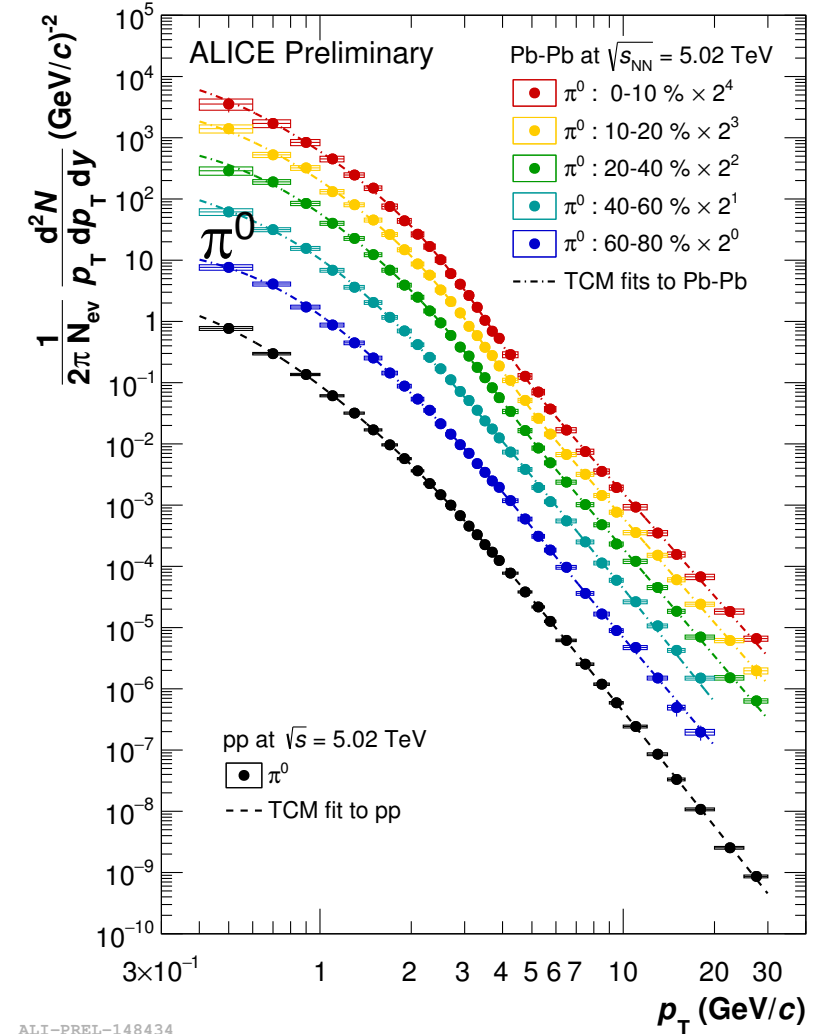
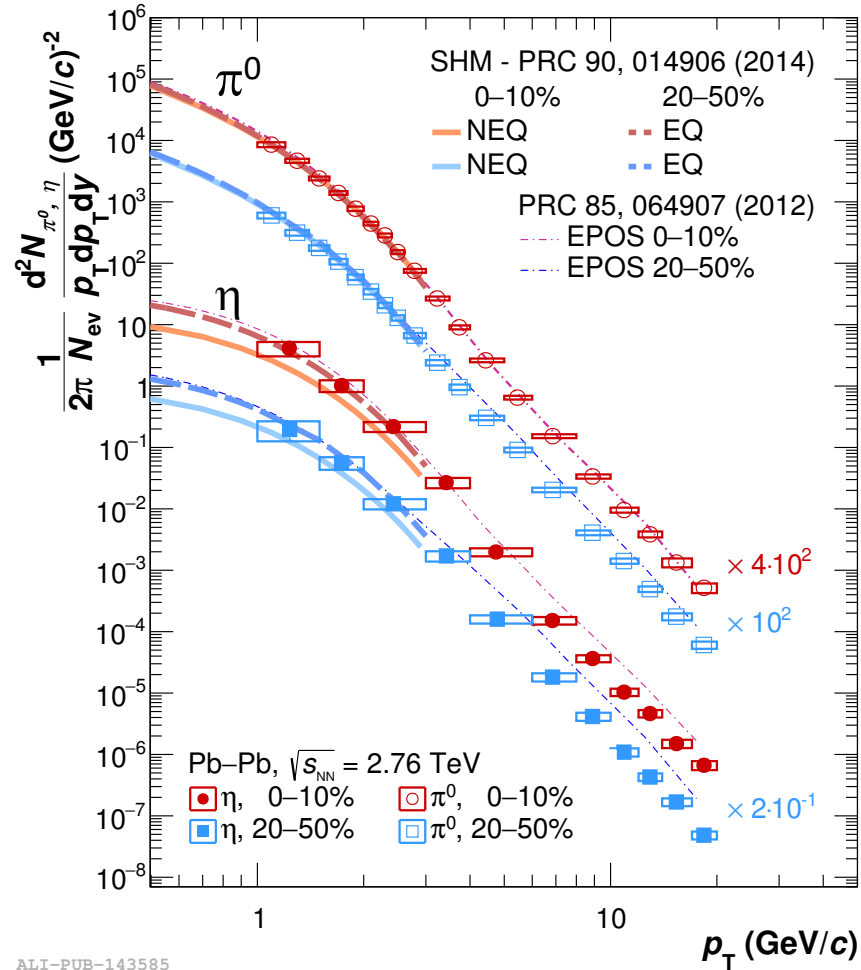
Identified π^0 in broad p_T range:
 0.2-200 GeV/c

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].



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

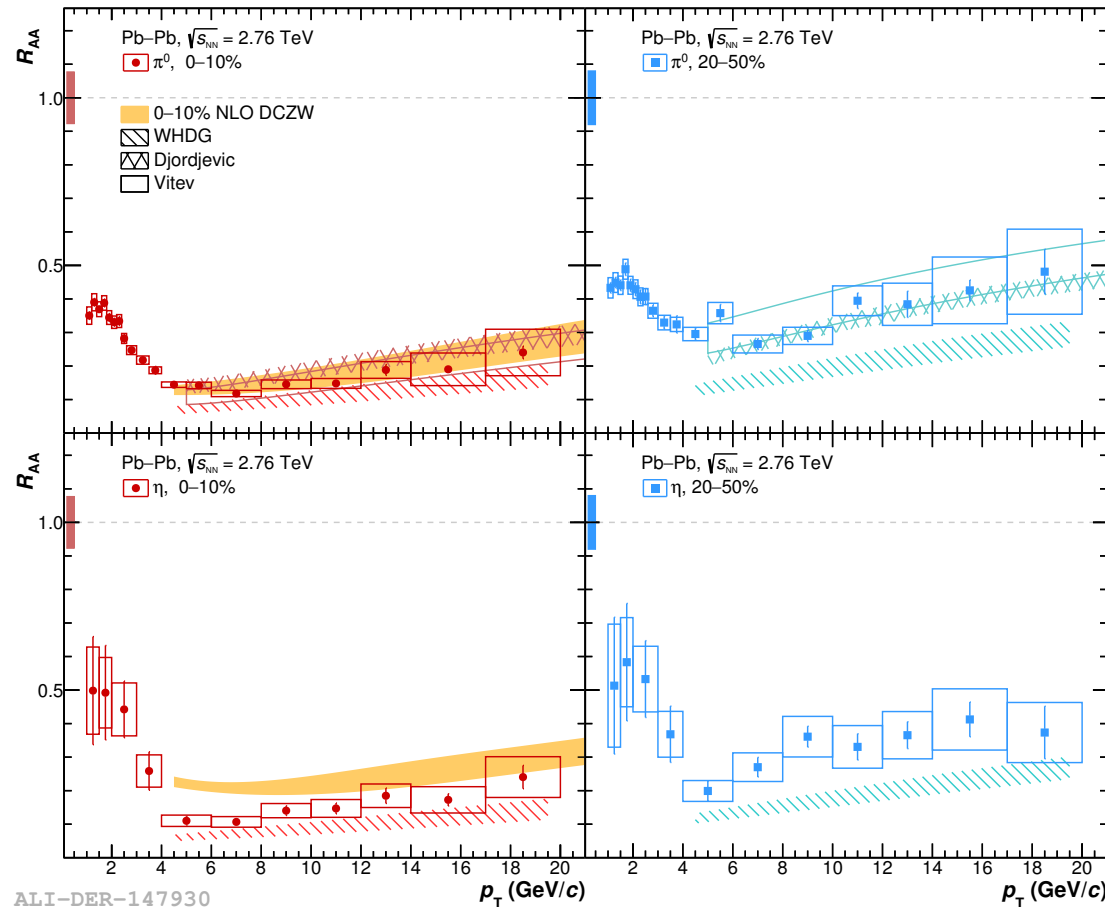
EPJ C 74 (2014); PRC98, 044901 (2018)



First η measurement in Pb-Pb at the LHC

R_{AA} in Pb-Pb collisions

Transport properties of the QGP:
jet transport coefficient $\hat{q}$



$$R_{AA}(p_T) = \frac{d^2 N / d p_T dy|_{AA}}{\langle T_{AA} \rangle \times d^2 \sigma / d p_T dy|_{pp}}$$

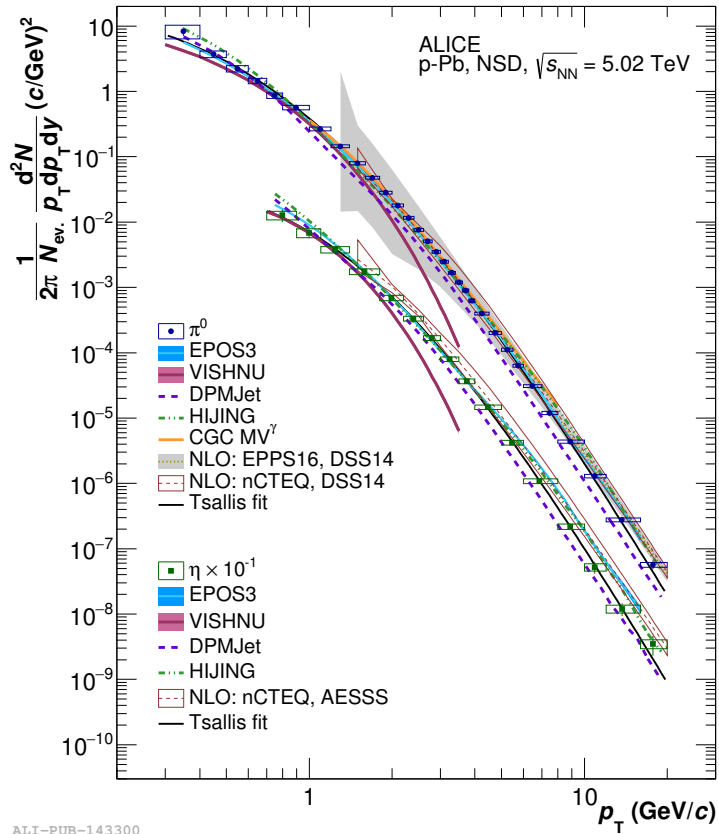
- Suppression depends on centrality
- Same magnitude and p_T dependence of R_{AA} for π^0 and η mesons $p_T > 4$ GeV/c

Model predictions for the η meson are scarce

- Vitev and Djordjevic models reproduce p_T and centrality dependence of $\pi^0 R_{AA}$
- WHDG fails to reproduce centrality dependence of π^0 and ηR_{AA}
- NLO DCZW (central collisions) reproduces p_T dependence of $\pi^0 R_{AA}$ and slightly above measured ηR_{AA} ($p_T \sim 4-12$ GeV/c)

π^0, η in p-Pb collisions

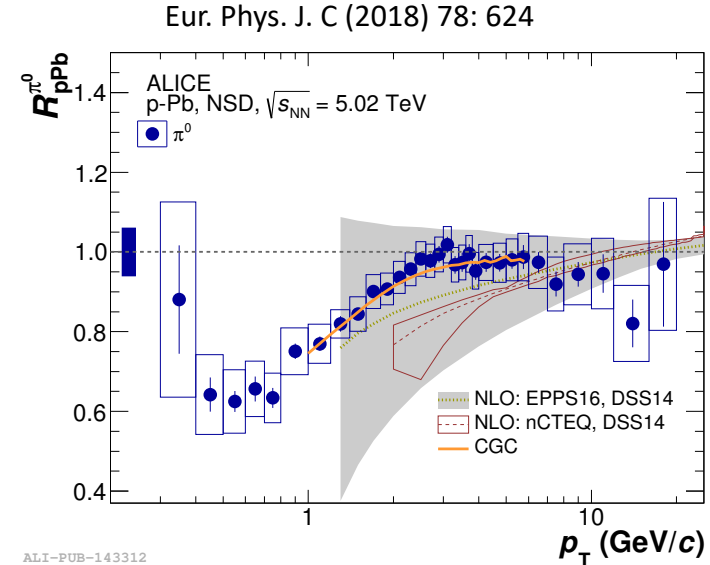
p-Pb collisions: more than a control experiment



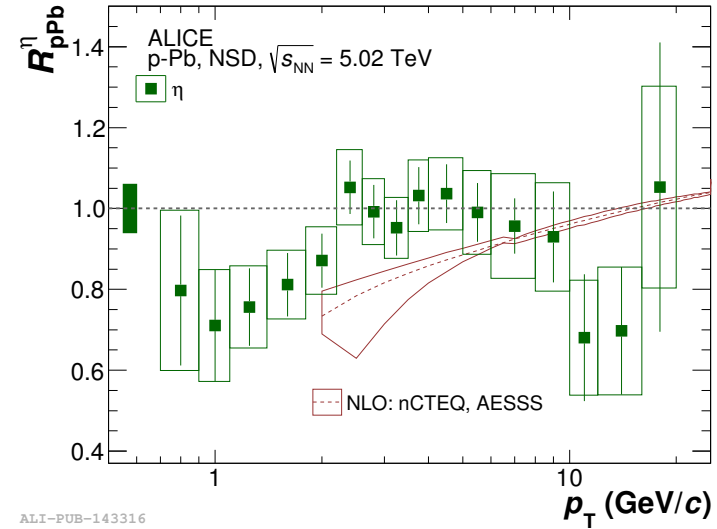
ALI-PUB-143300

To be used in global fits of nPDFs and FFs.

Detailed comparison to theoretical models
 Larger differences observed for the η than for π^0



ALI-PUB-143312



ALI-PUB-143316

R_{pPb} consistent with unity
 for $p_T > 2$ GeV/c

Methods to measure direct photons

- Statistical subtraction method
 - Measure inclusive photons and subtract photons from hadron decays
- Virtual photons ($\gamma^* \rightarrow e^+e^-$)
- 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

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Subtraction method:

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

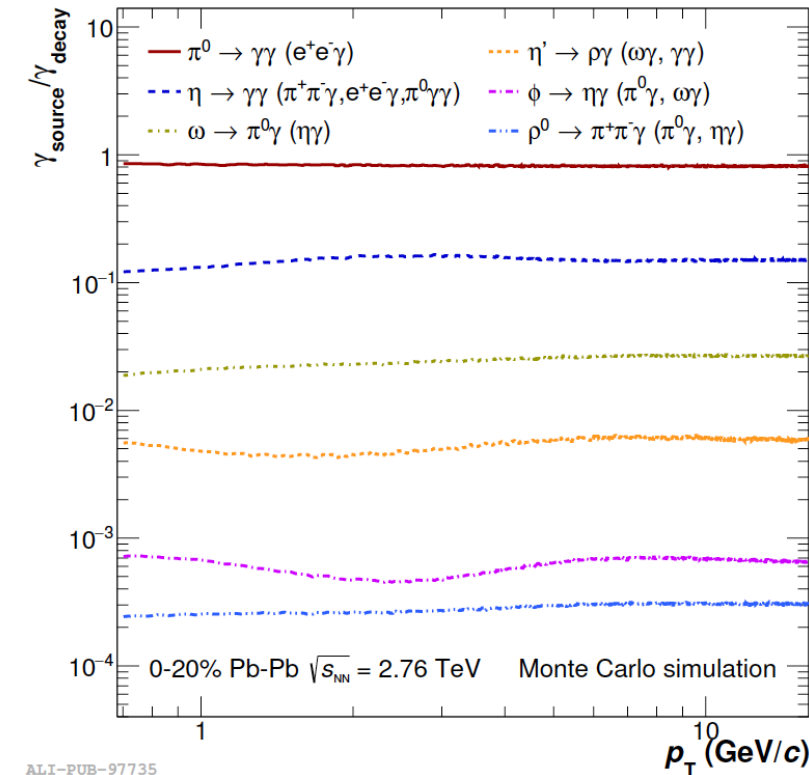
Inclusive photons: All produced photons

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

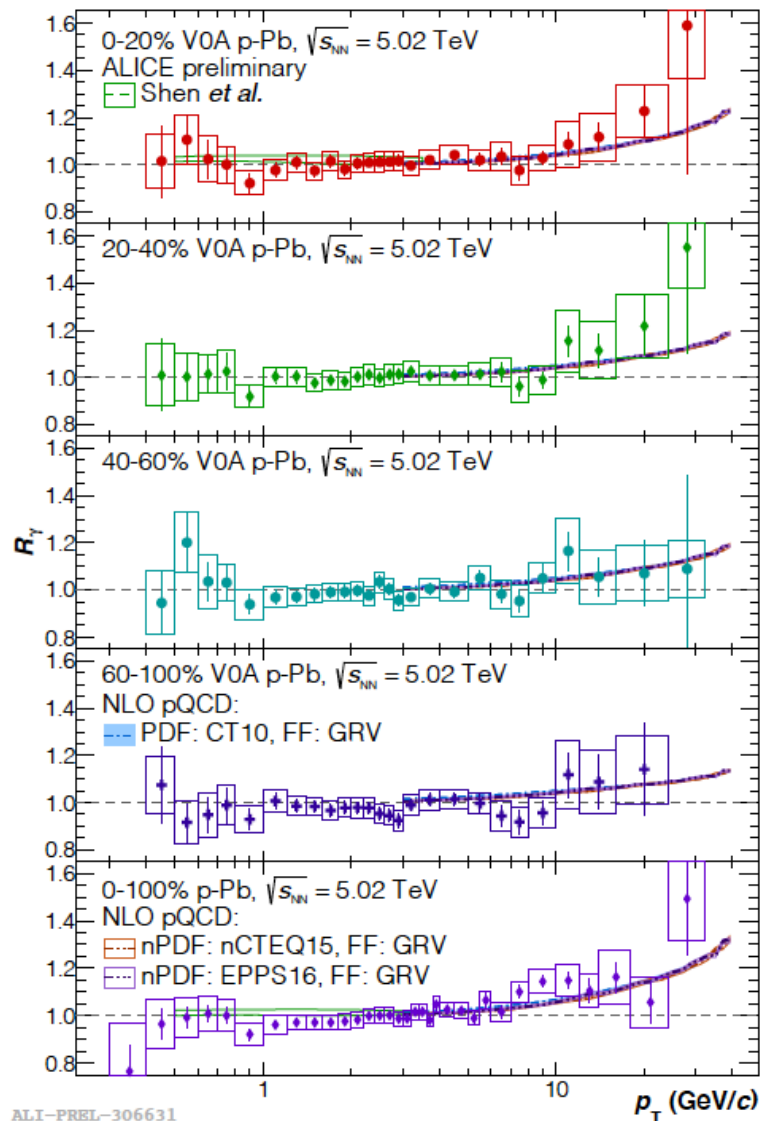
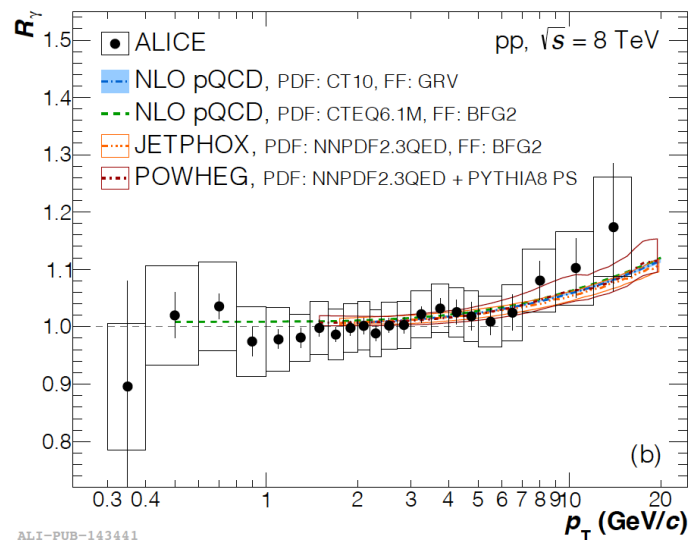
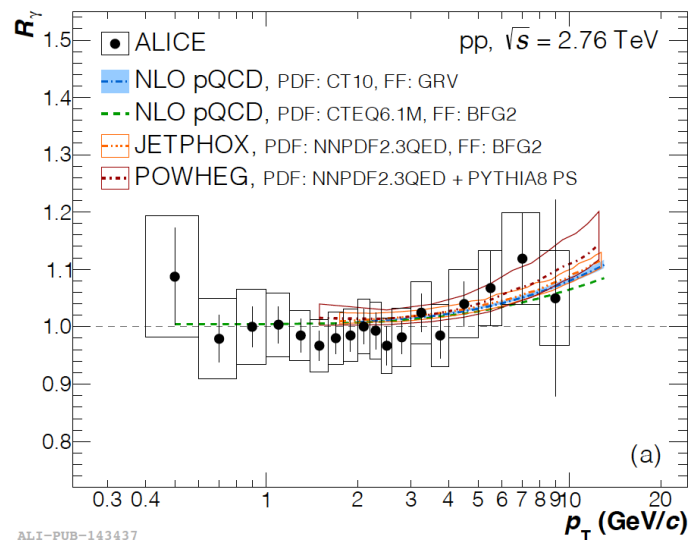
Double ratio:

$$R_{\gamma} = N_{\gamma,\text{inc}}/N_{\gamma,\text{dec}} \approx \left(\frac{N_{\gamma,\text{inc}}}{\pi^0}\right)_{\text{meas}} / \left(\frac{N_{\gamma,\text{dec}}}{\pi^0}\right)_{\text{sim}} \quad >1 \text{ if direct photon signal}$$

Advantage: Cancellation of uncertainties



Direct γ in pp and p-Pb collisions



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

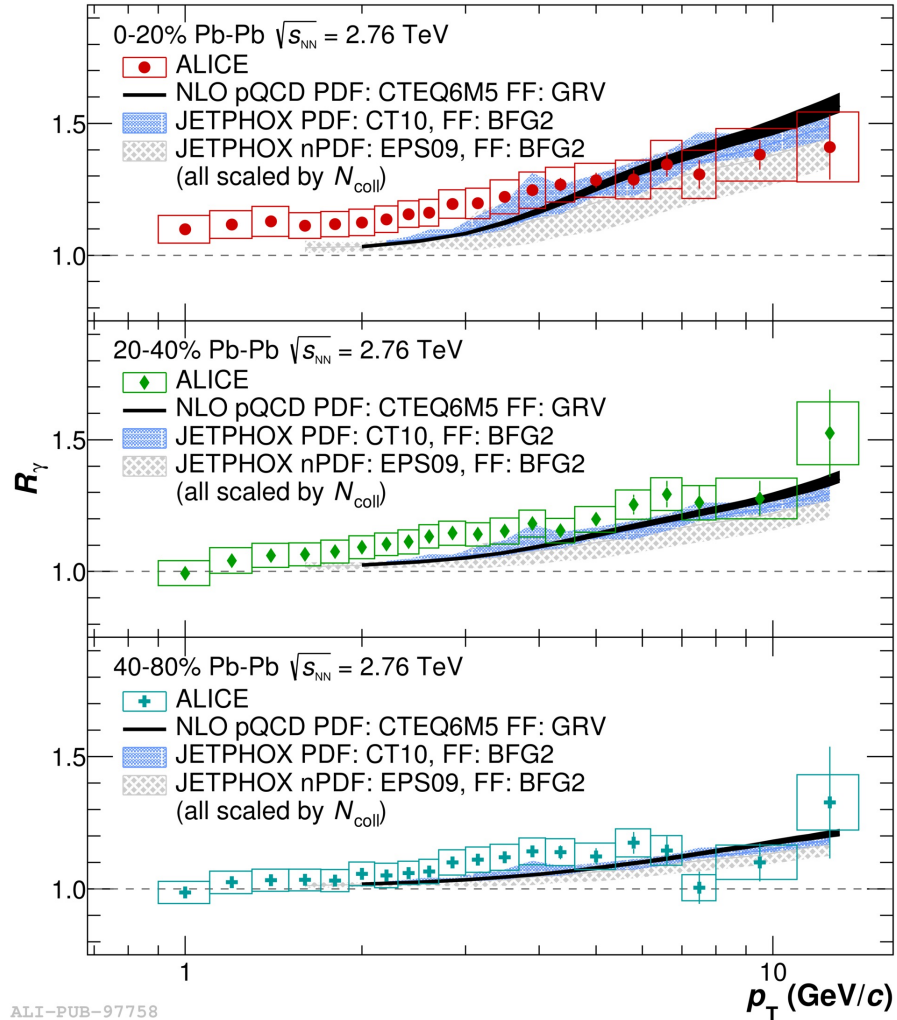
No significant excess observed
at low p_T

For $p_T > 7$ GeV/c:
 $\sim 1\text{-}2 \sigma$ deviation from unity
In agreement with NLO pQCD

γ^{dir} Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

2010 data

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

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

15% excess in 0 – 20%

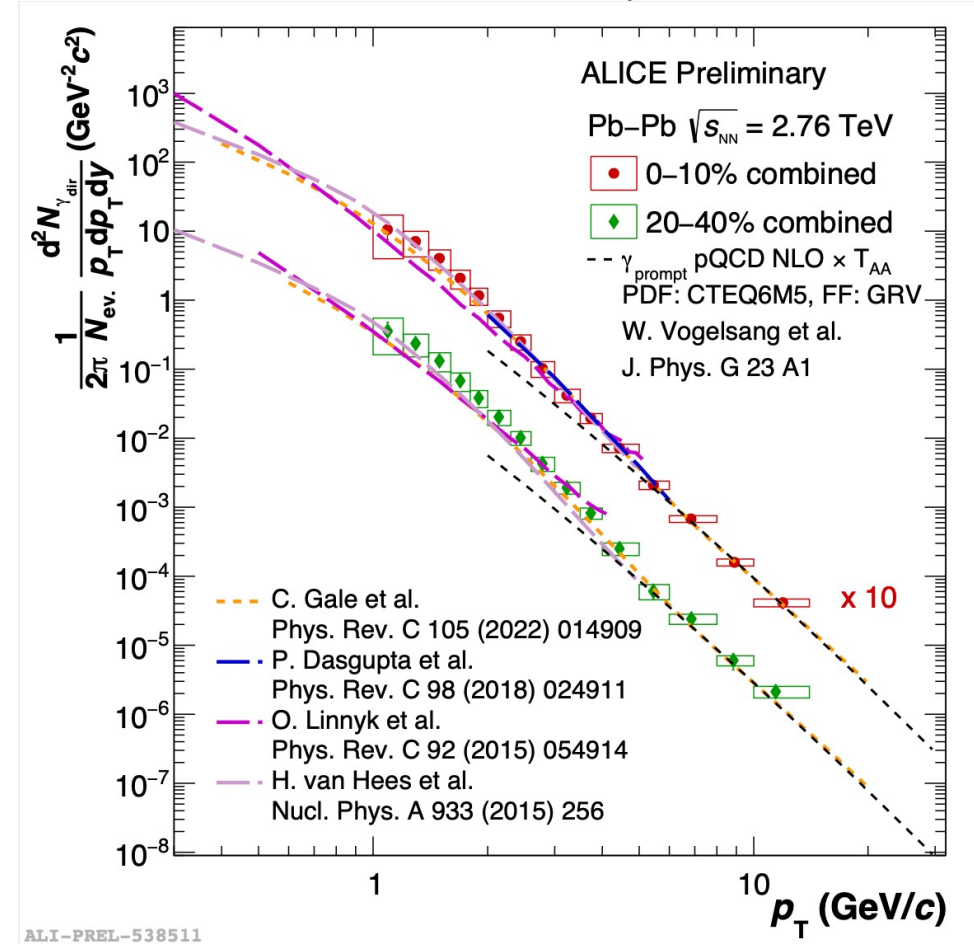
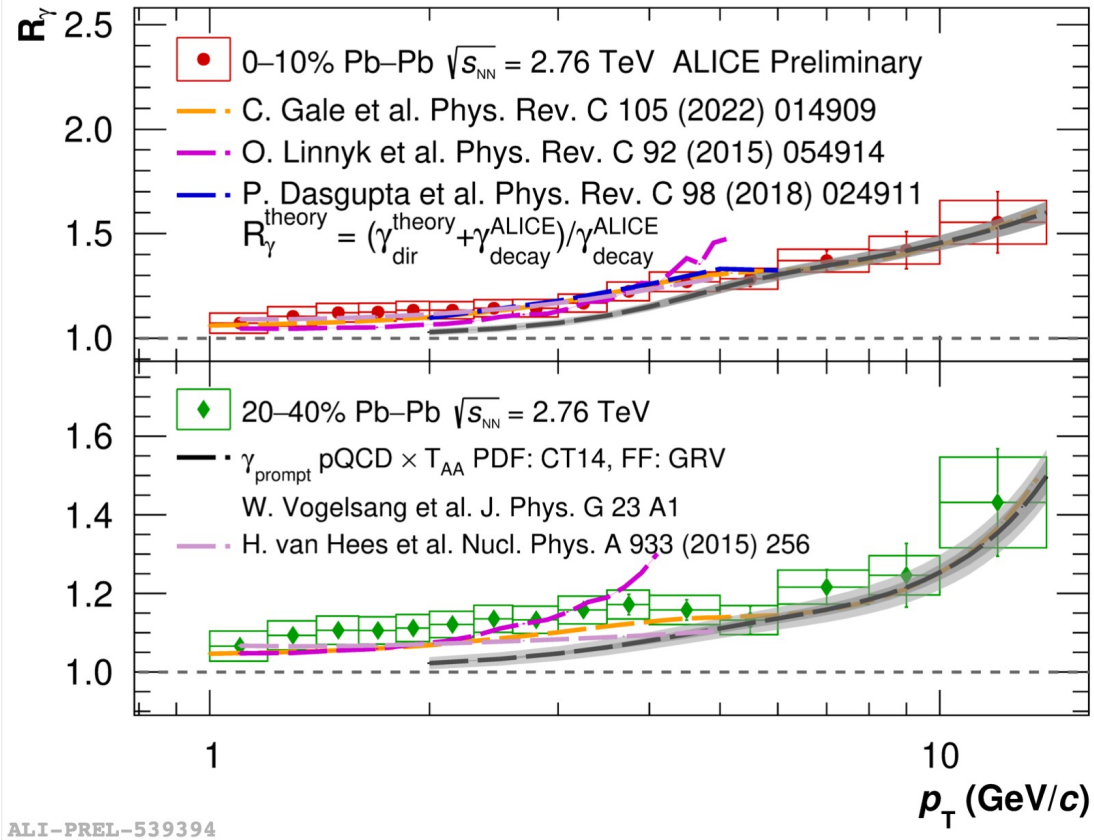
9% in 20 – 40%

Consistent with thermal radiation

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

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

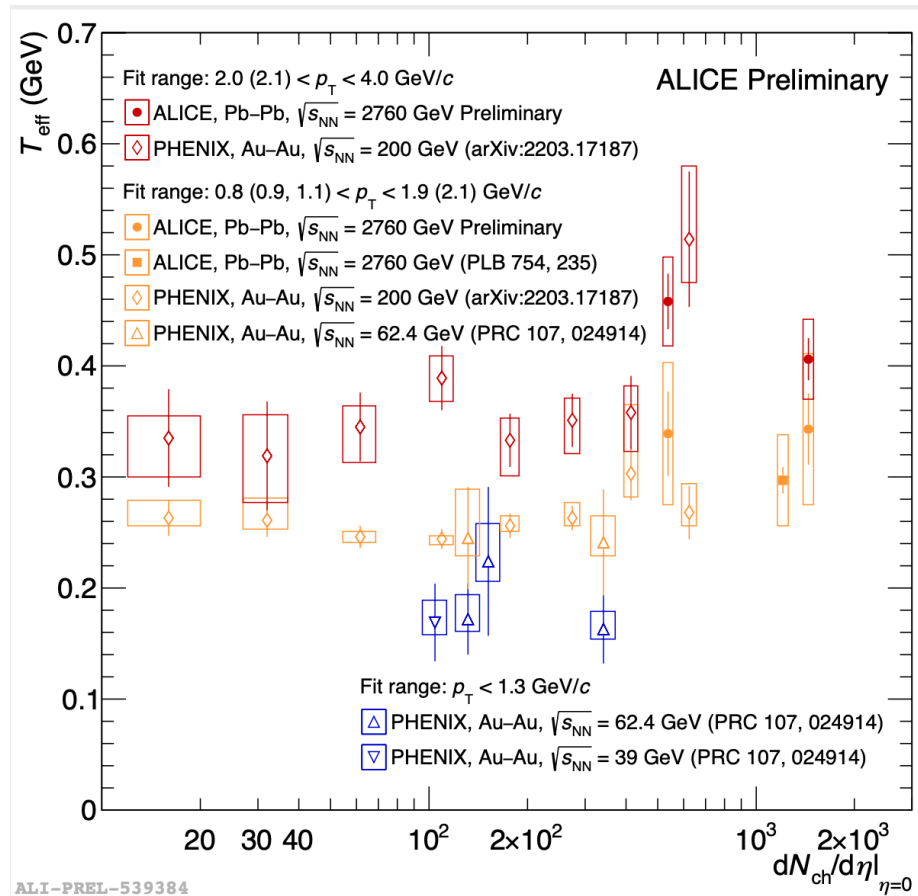
$$N_{\gamma,dir} = \left(1 - \frac{1}{R_\gamma} \right) \cdot N_{\gamma,inc}$$



- 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

T_{eff} non-prompt photons

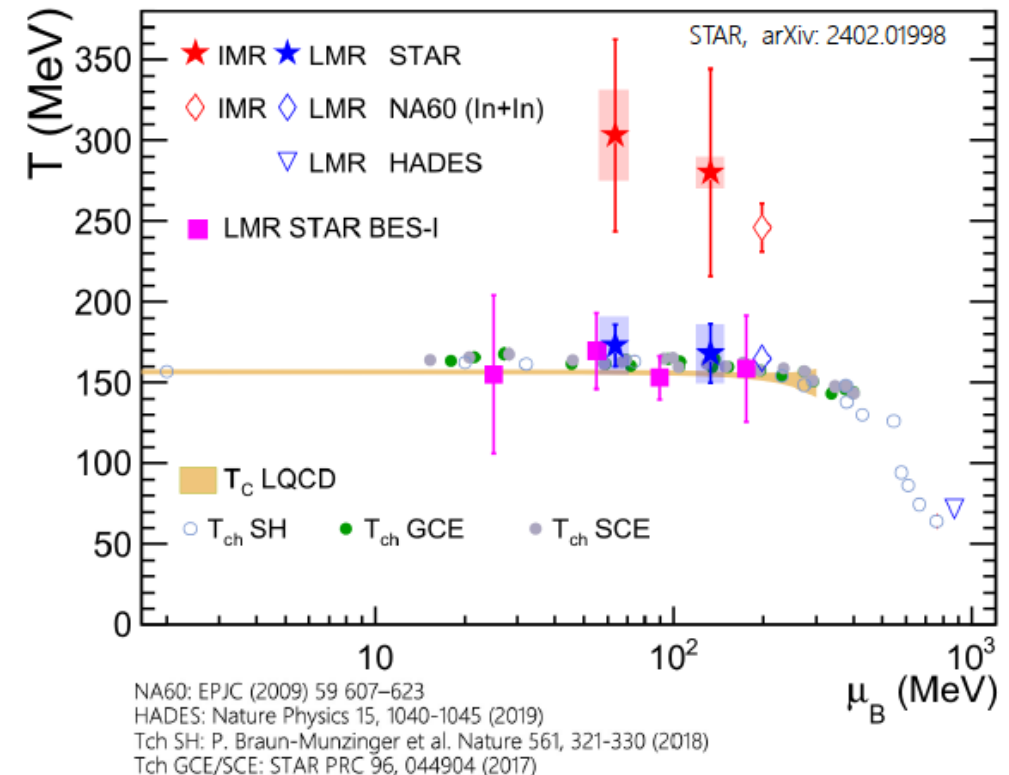
is $T_{\text{eff}} (2.1 < p_T < 4 \text{ GeV}/c) > T_{\text{eff}} (1.1 < p_T < 2.1 \text{ GeV}/c)$?
pre-equilibrium photons? earlier time emission?



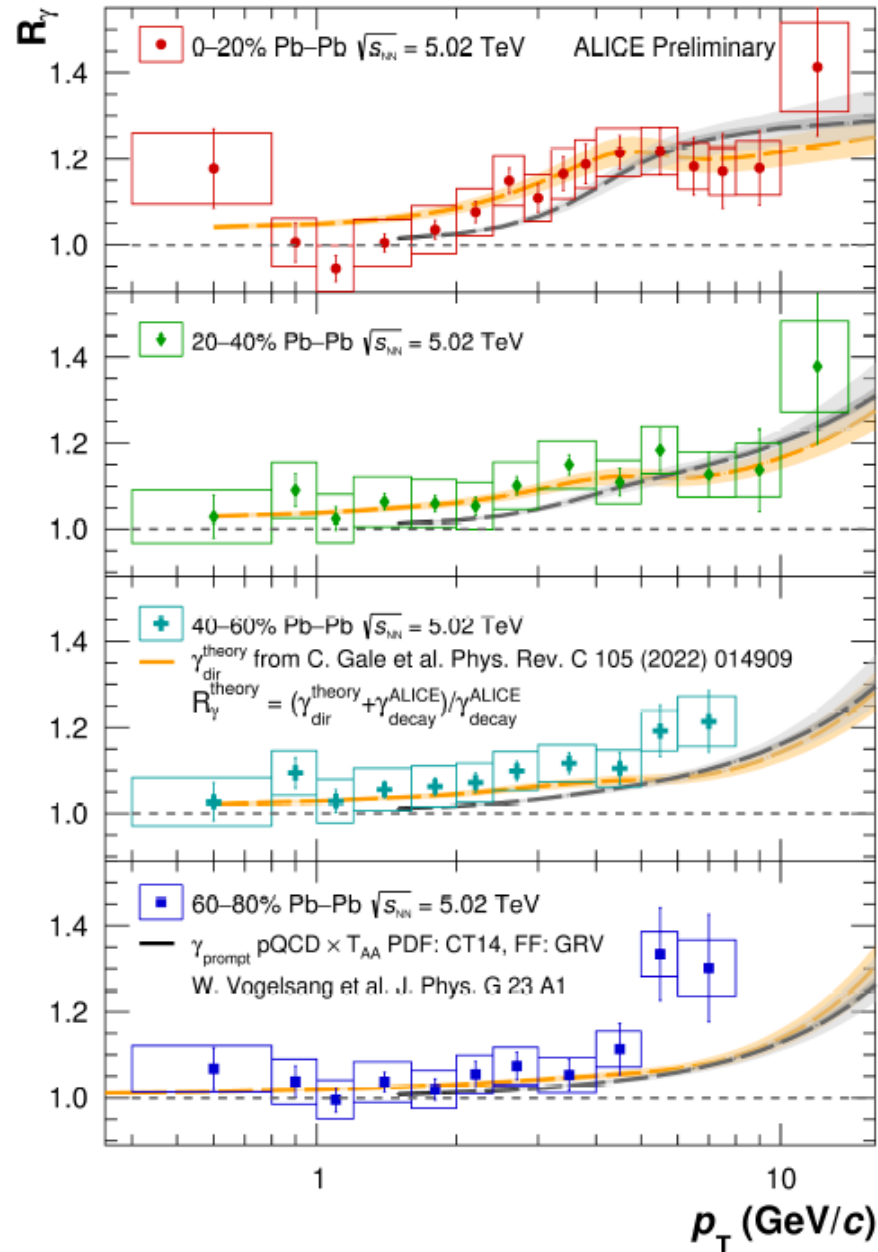
T vs μ_B

Thermal dielectrons in IMR:

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



QGP thermal emission: Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV



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

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

At low p_T :

- thermal radiation should dominate
- R_{γ} is close to 1 $\rightarrow$ 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

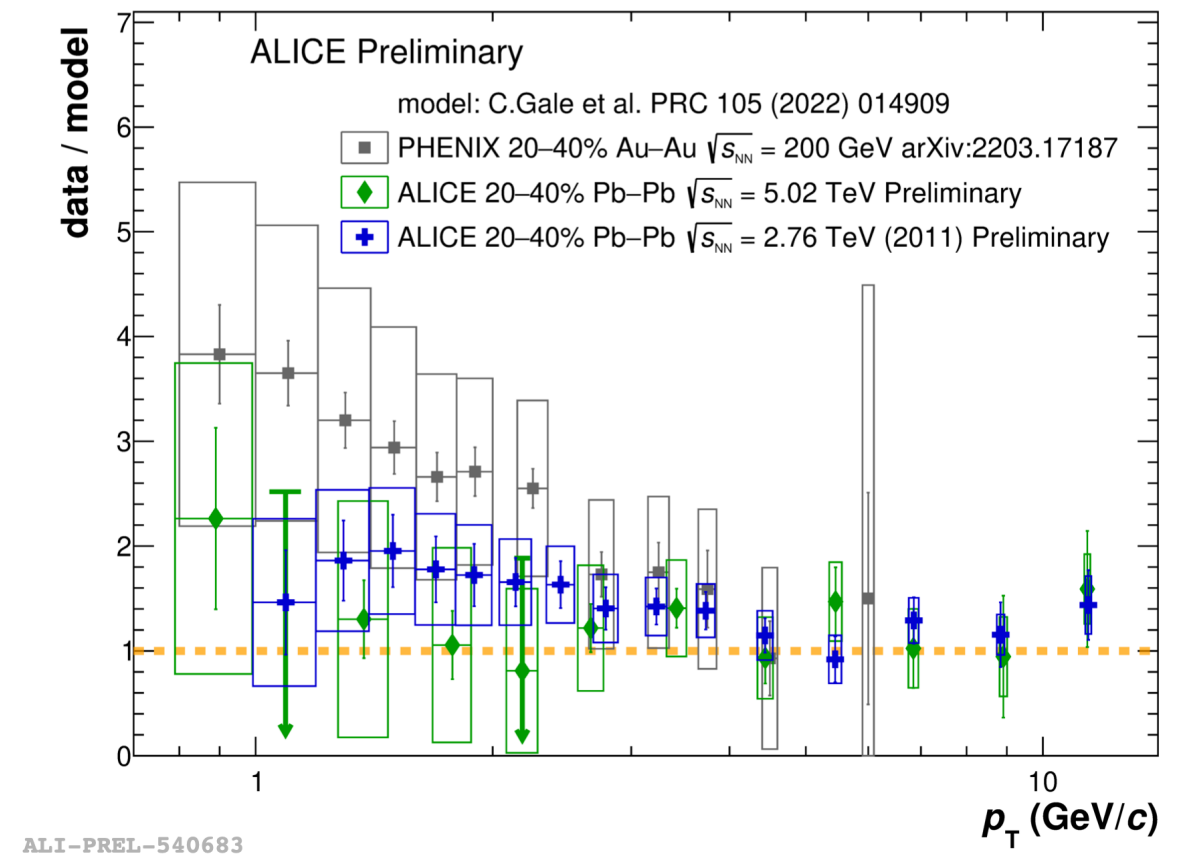
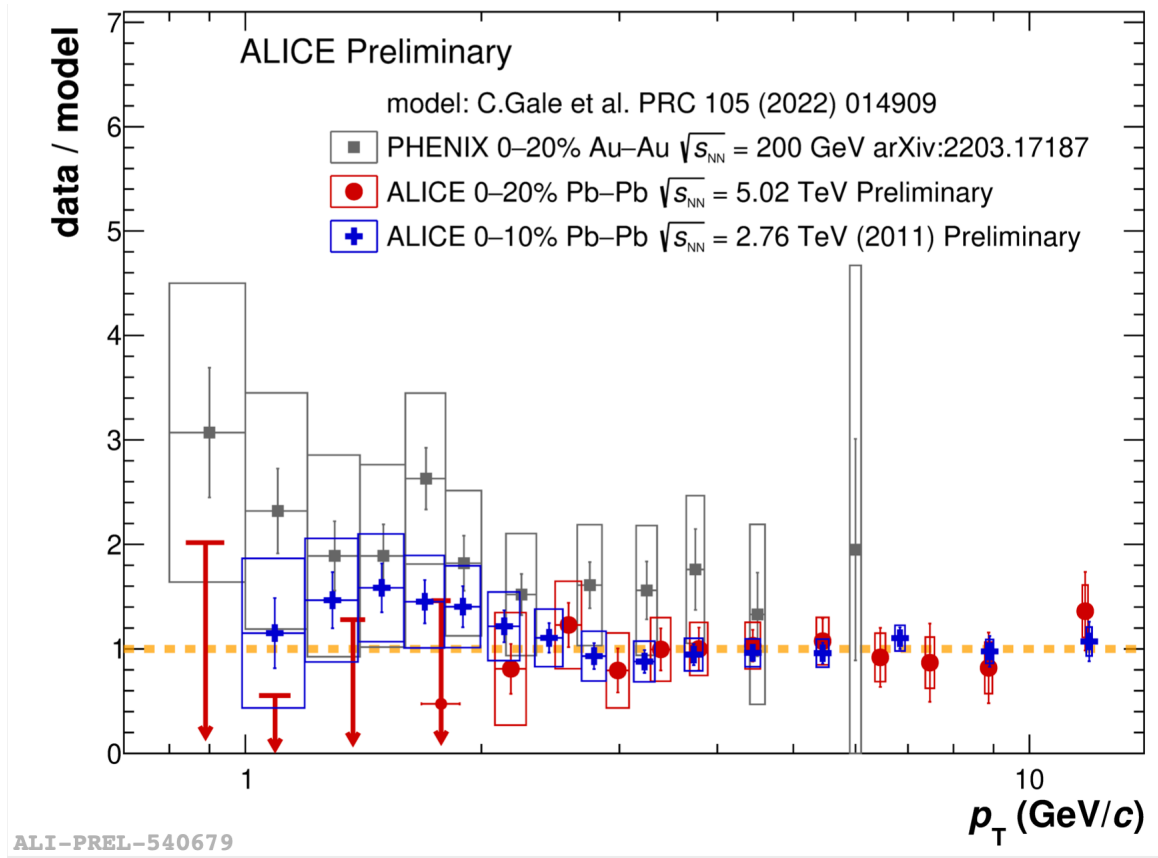
For $p_T > 3$ GeV/c:

- 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

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?

Inclusive and direct γ v_2

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Early emission of photons: high yield $\leftrightarrow$ low v_2

Late emission of photons: low yield $\leftrightarrow$ high v_2

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

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

- 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

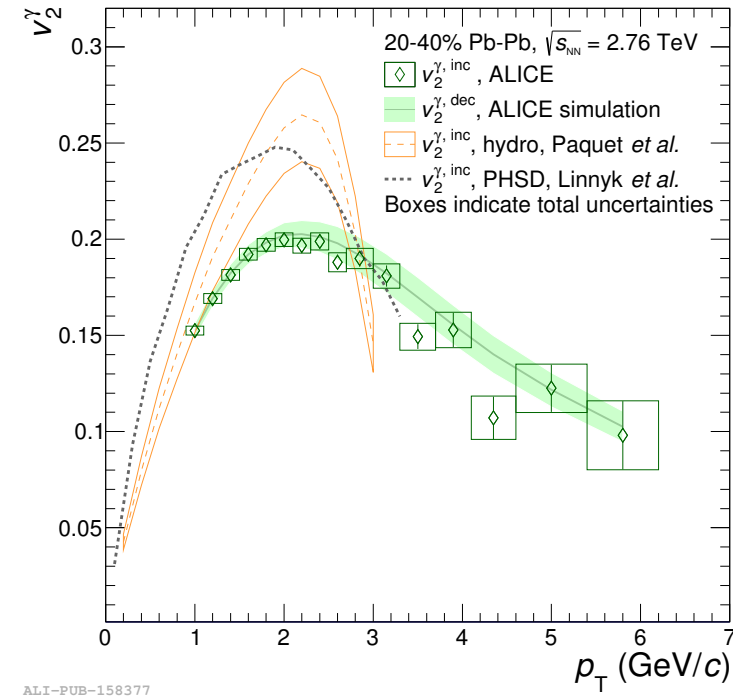
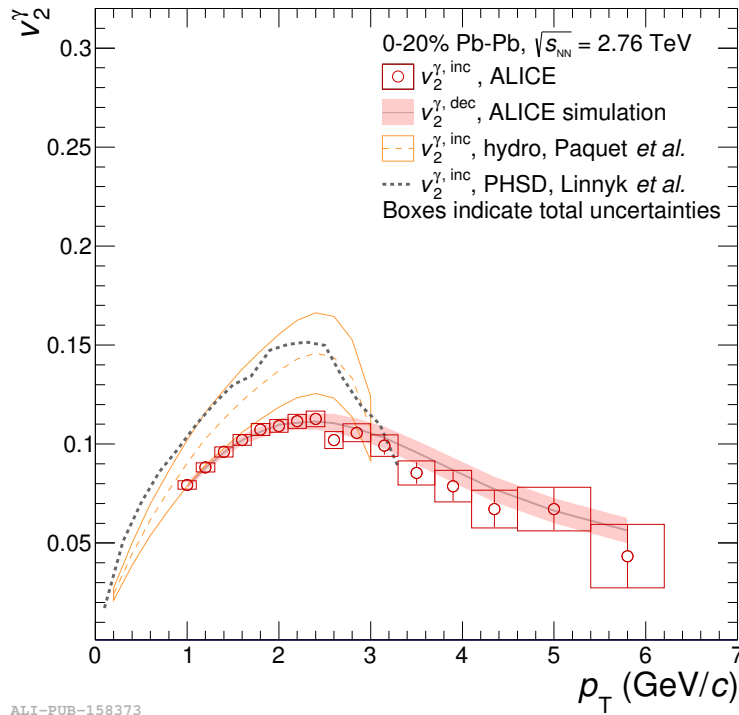
- R_γ from previous measurements:

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

Inclusive γ v_2

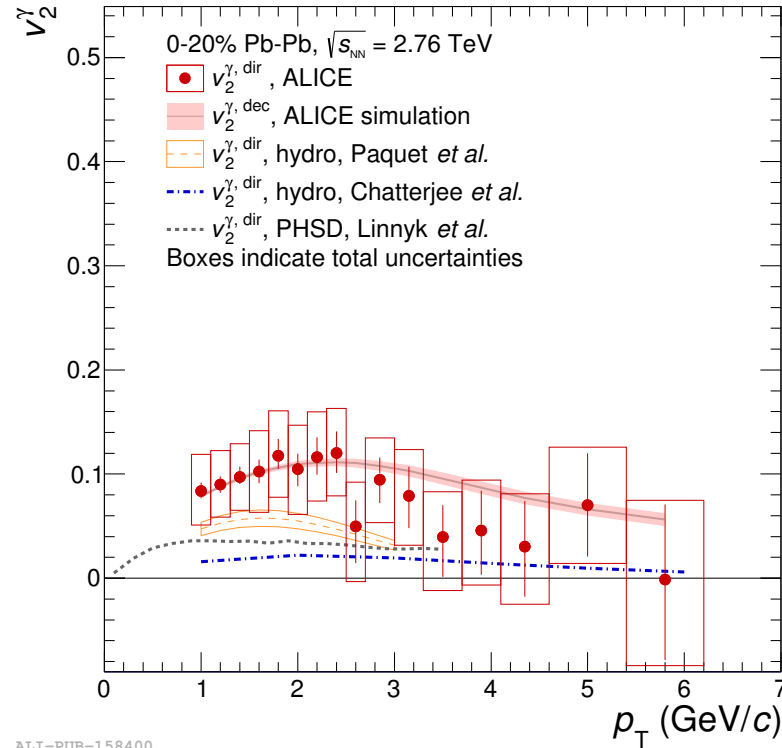
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- $p_T < 3$ GeV/c: $v_2^{\gamma, inc} = v_2^{\gamma, dec}$
 $\Rightarrow$ Either no contribution of γ_{dir} or $v_2^{\gamma, dir} = v_2^{\gamma, dec}$
 Theory $\sim 30 - 40\%$ too high
- $p_T > 3$ GeV/c: $v_2^{\gamma, inc} < v_2^{\gamma, dec}$
 $\rightarrow$ prompt photon contribution

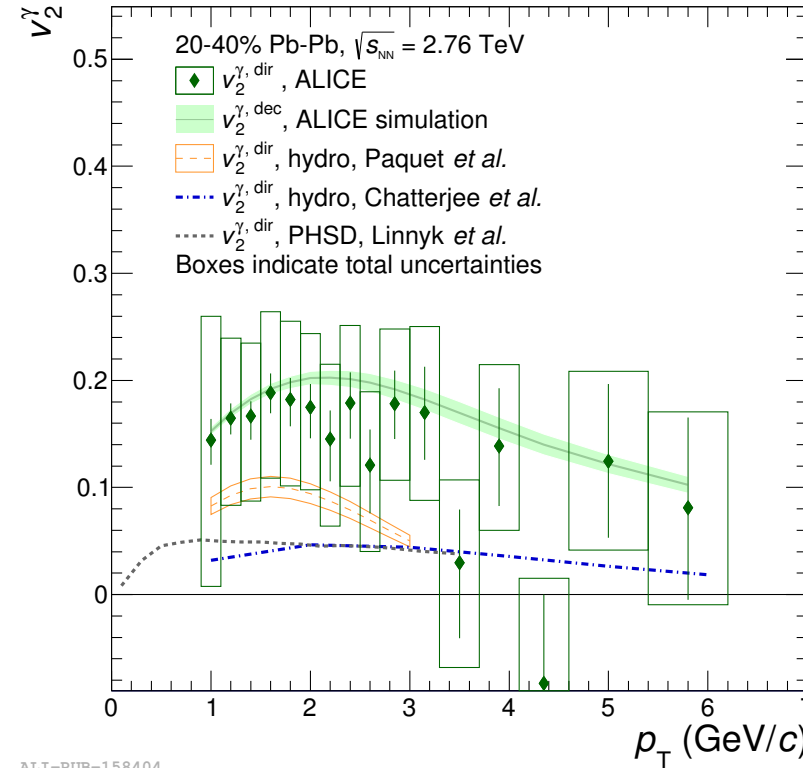
$v_2^{\gamma, \text{dir}}$

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ALI-PUB-158400

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

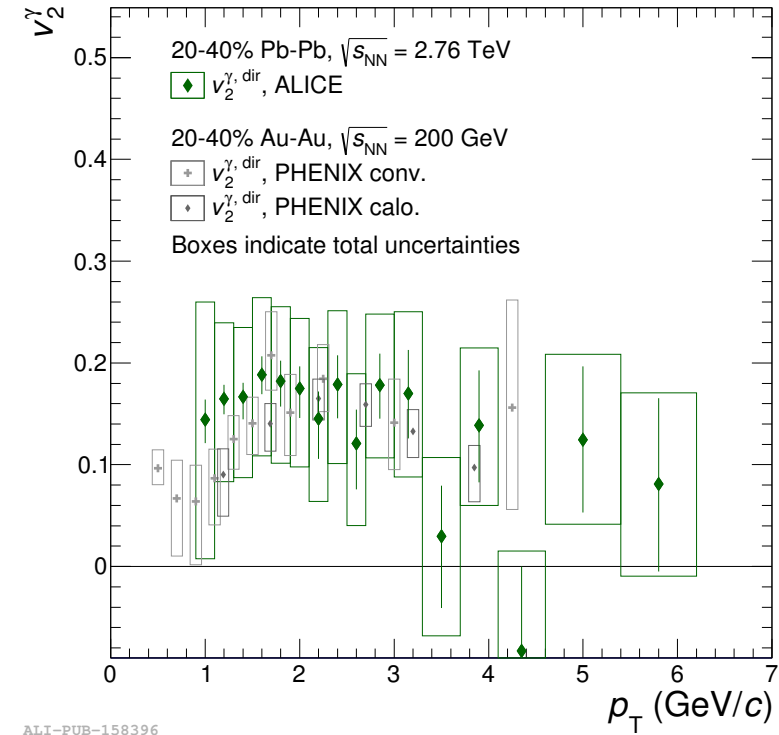
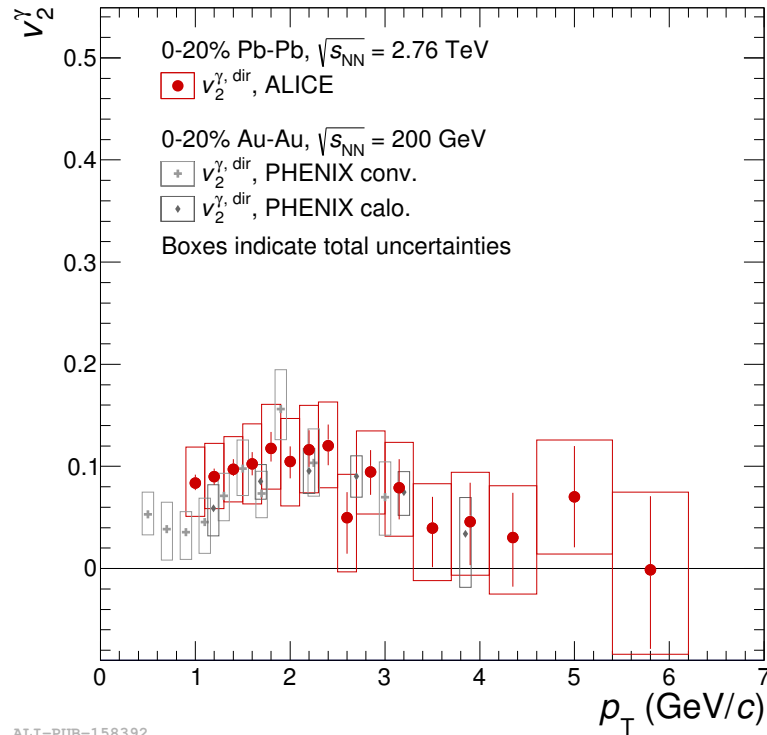


ALI-PUB-158404

- $v_2^{\gamma, \text{dir}}$ larger than models predictions (in qualitative agreement with PHENIX)
- But: null hypothesis $v_2^{\gamma, \text{dir}} = 0$ not inconsistent with the data

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

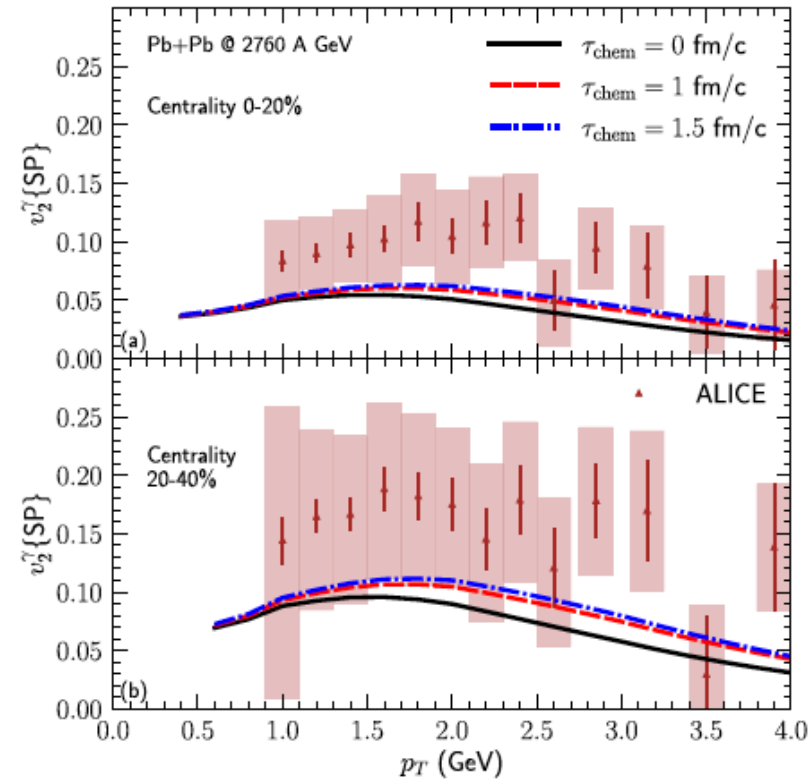
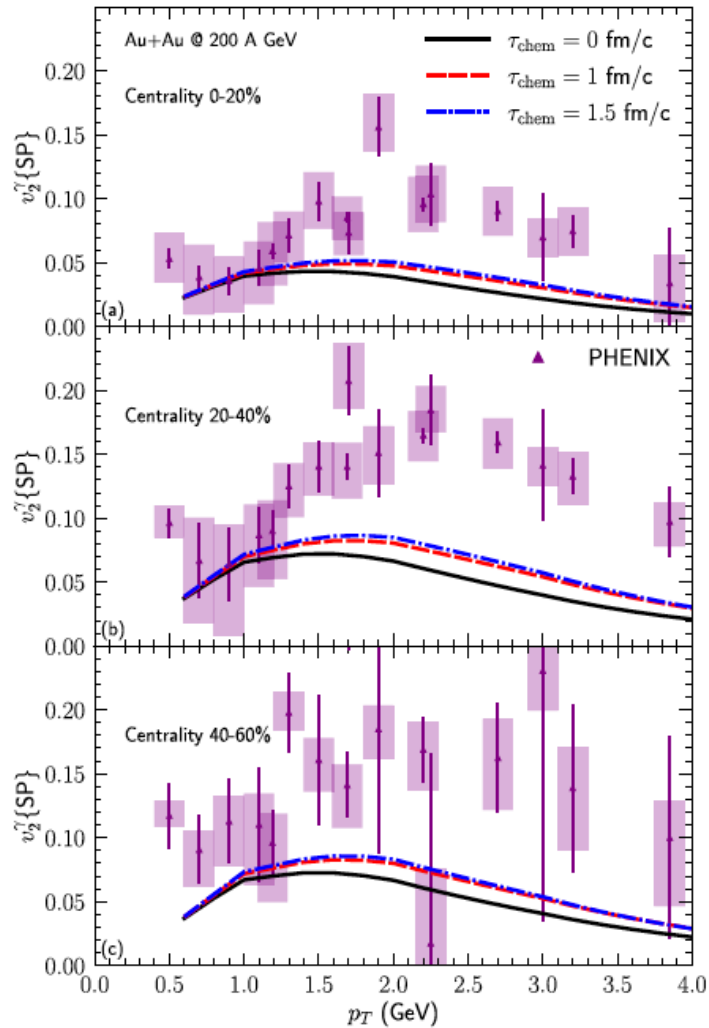
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$$v_2^{\text{dir}}(\text{LHC}) \approx v_2^{\text{dir}}(\text{RHIC})$$

Direct γ v_2 : RHIC, LHC and models

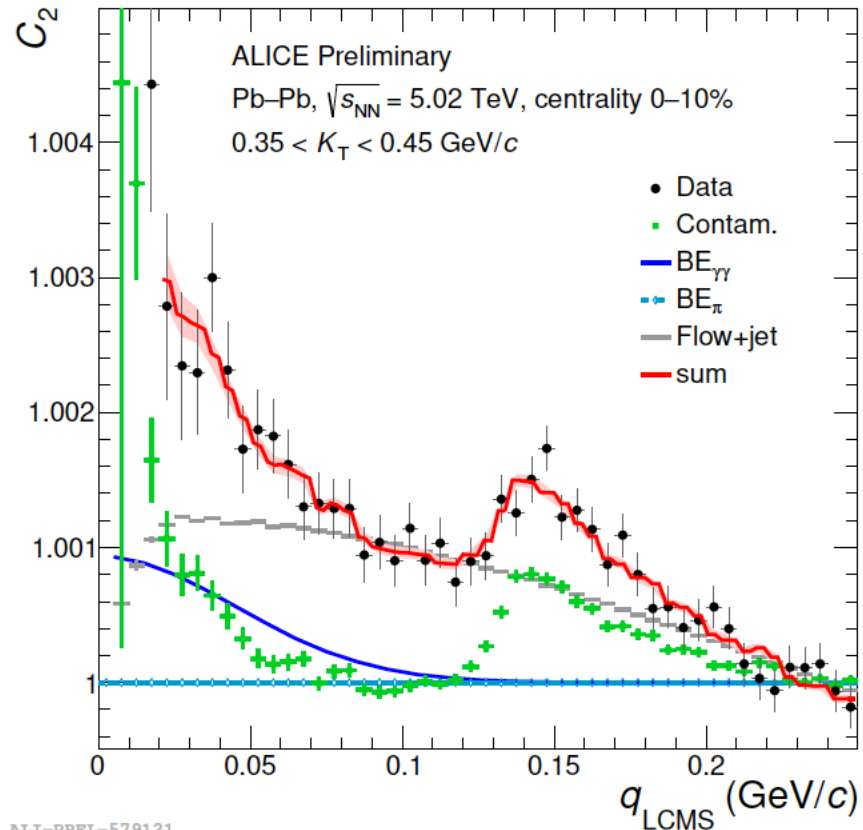
Direct photon puzzle



$v_2^{\text{dir}} \approx v_2^{\pi}$ 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



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

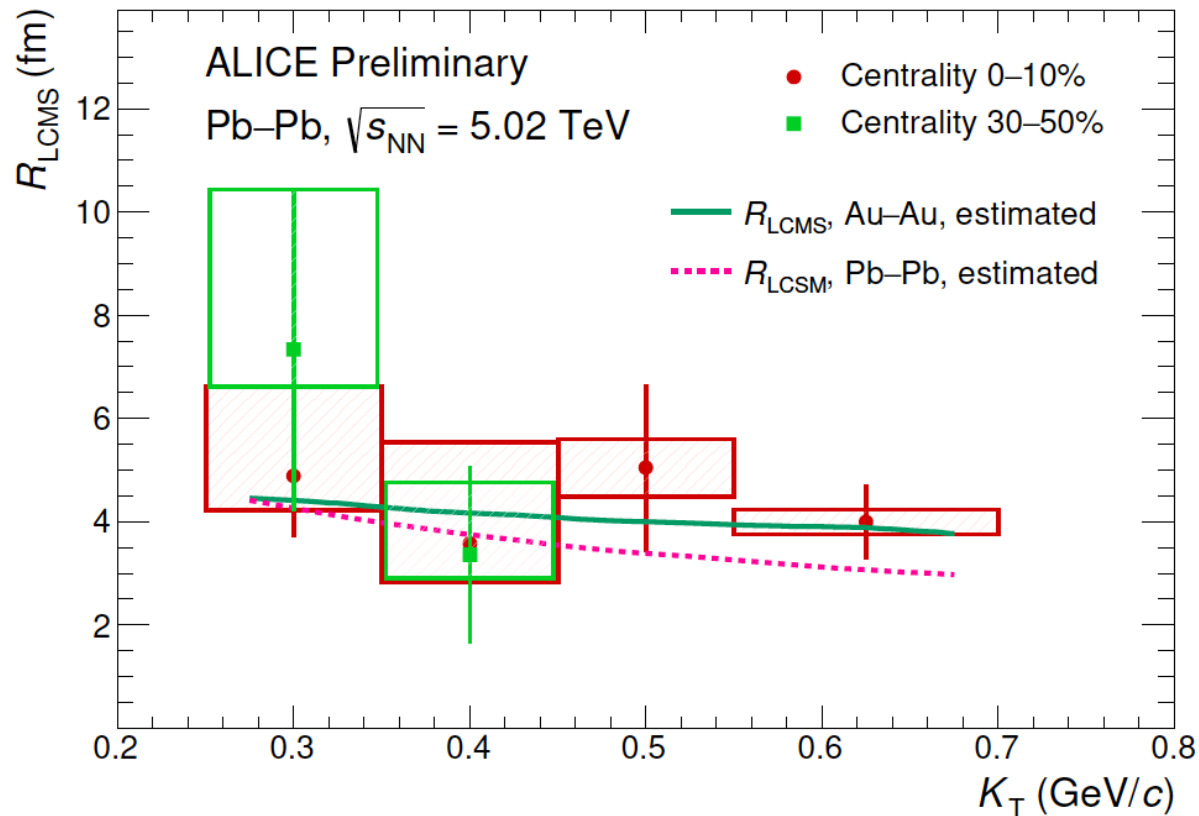
Template fit to the data to extract BE

Correlation Radius

Hydrodynamic calculations:

Pb-Pb: O. Garcia-Montero et al., Phys.Rev.C 102 (2020) 2, 024915

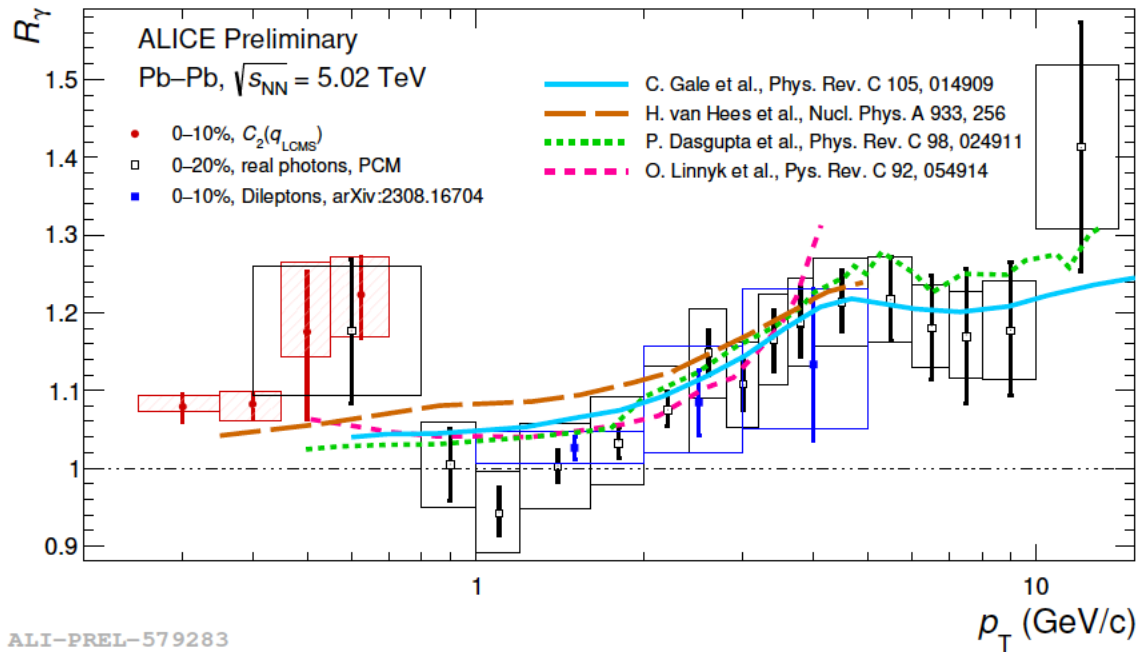
Au-Au: D. Peressounko, Phys.Rev.C 67



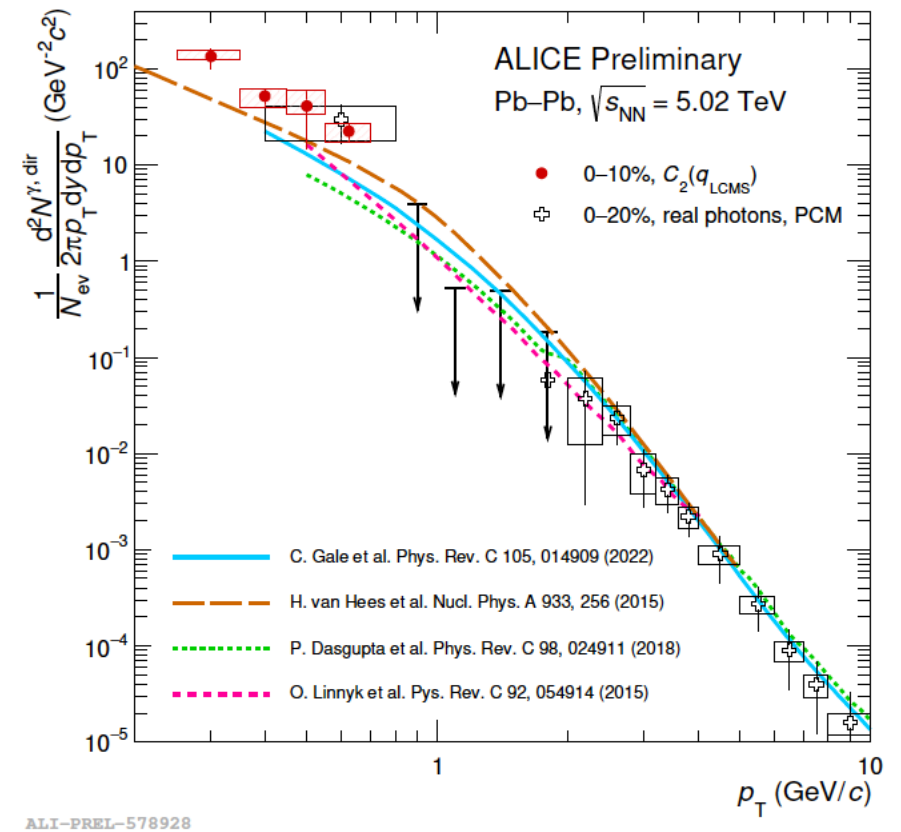
- Correlation radius shows minor K_T dependence
- Agrees with estimated radii from hydro predictions
 - Theoretical curves were estimated by averaging of published R_{out} , R_{side} , R_{long} radii

ALI-PREL-578855

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

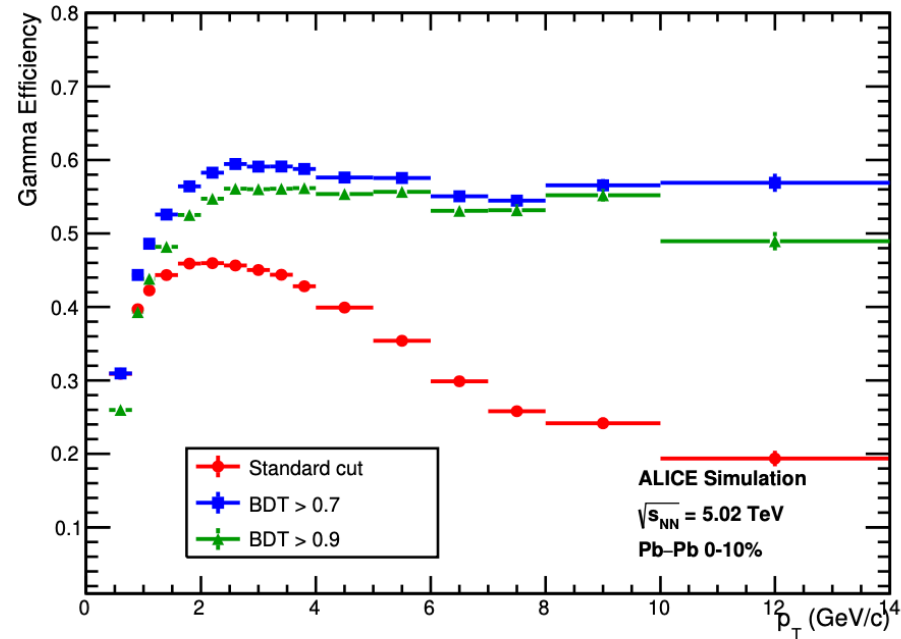


$$\lambda = \frac{1}{2} \left(\frac{N_y^{dir}}{N_y^{incl}} \right)^2 \quad R_y = \frac{N_y^{incl}}{N_y^{decay}} = \frac{1}{1 - \sqrt{2} \lambda}$$

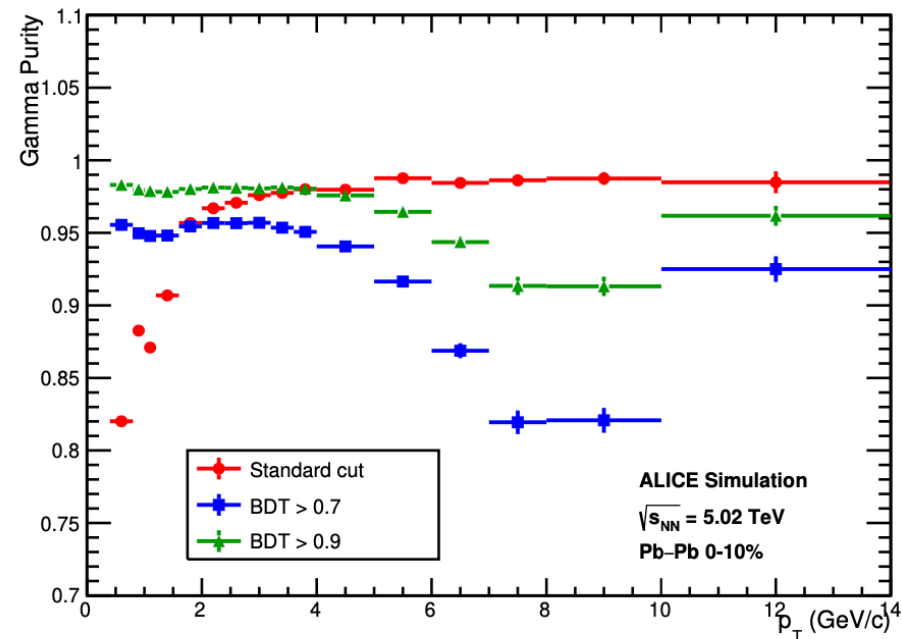


Can ML improve direct photon measurements?

A. Nath, ML - XGBoost



ALI-SIMUL-586280



ALI-SIMUL-586275

Ongoing: Analysis of Pb-Pb 2018 data cut-based (S. Stiefelmaier) + ML simultaneously (A. Nath)

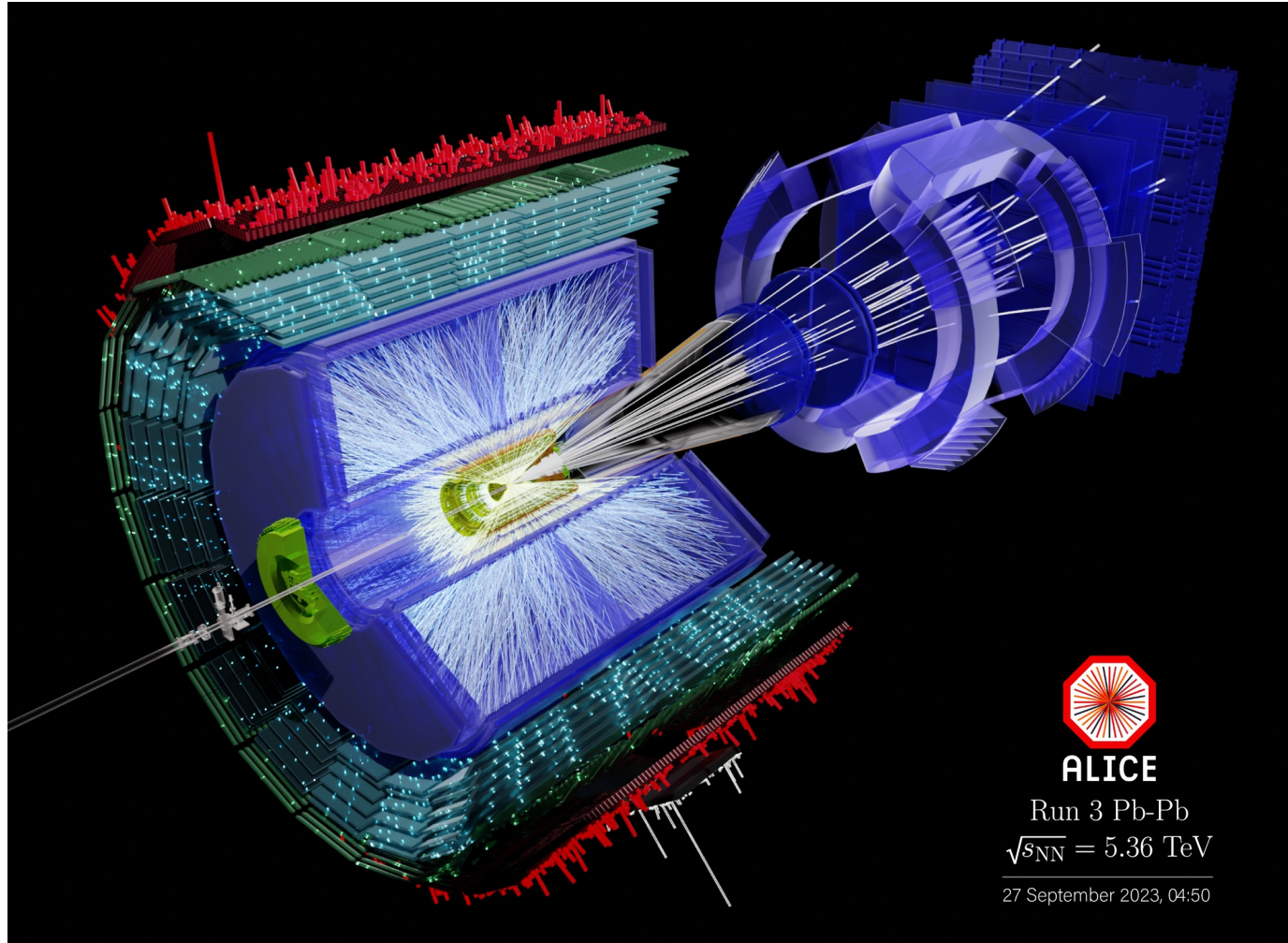
2010-2013

2015-2018

2022-2025

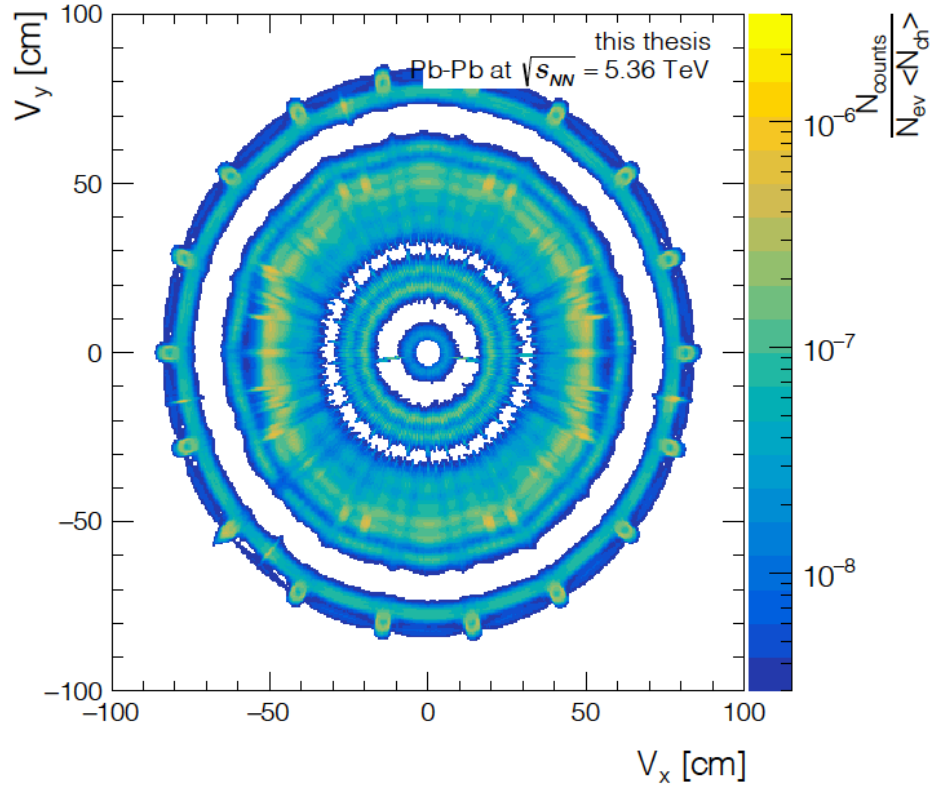
2029-2032

2035-2038



Photons in Run 3 using PCM

Data reconstructed γ (LHC23)



- Challenging measurement for PCM
- Neutral meson measurements with PCM ongoing:
pp, pO, O-O and Pb-Pb

A. Pishchaeva, π^0 and η in Pb-Pb. Master Thesis. To be uploaded

https://www.physi.uni-heidelberg.de/Publications/Masterthesis_Isabel_Kantak.pdf

<https://www.physi.uni-heidelberg.de/Publications/BachelorarbeitLewinDisselmeyer.pdf>

https://physi.uni-heidelberg.de/Publications/Bachelorthesis_Julia_schlaegel_final_qxabv.pdf

https://www.physi.uni-heidelberg.de/Publications/BachelorThesis_AlicaEnderich.pdf

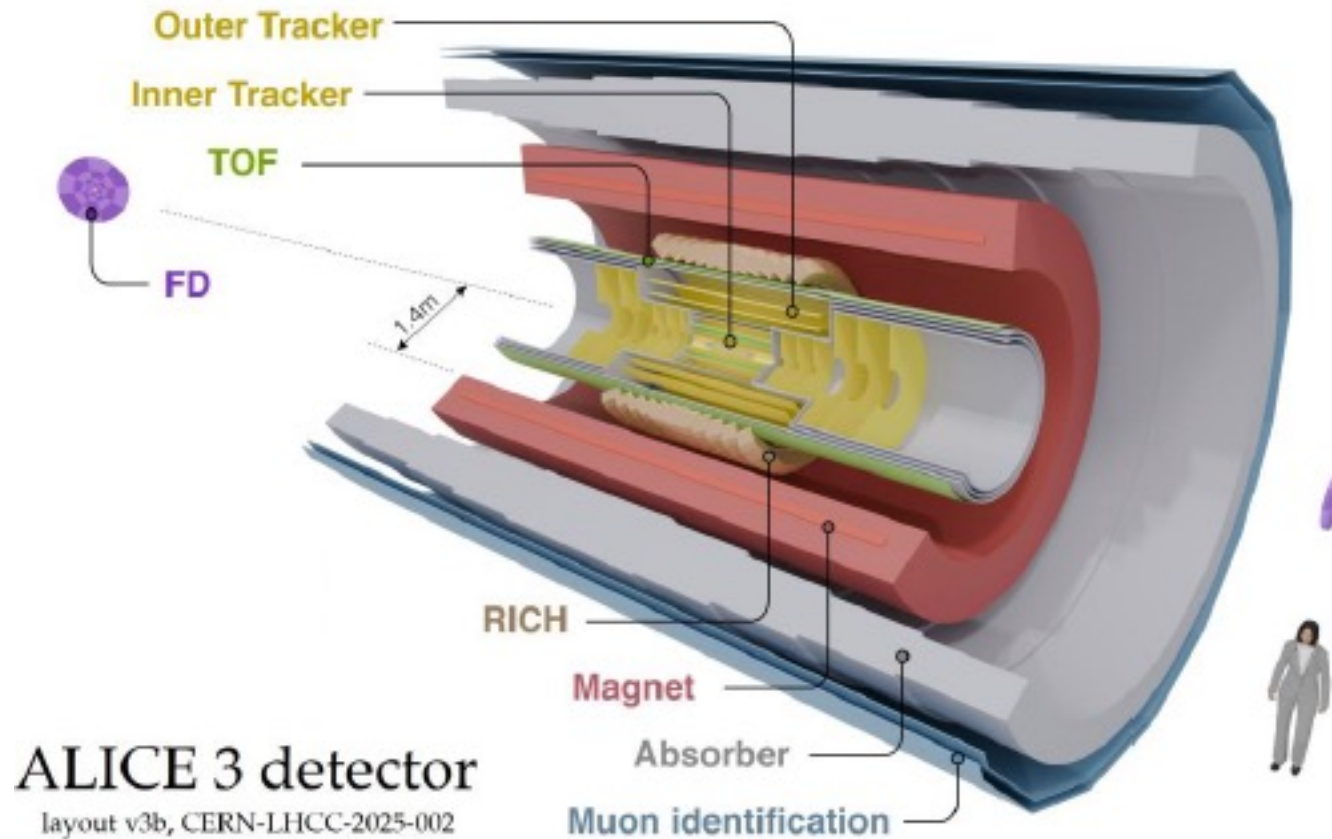
https://www.physi.uni-heidelberg.de/Publications/Bachelorarbeit_Isabel_Kantak_updated.pdf

https://www.physi.uni-heidelberg.de/Publications/Bachelor_Thesis_Nikita_Philip_Tatsch.pdf

What is next after Run 3 + Run 4?

ALICE beyond Run 4

An ultra-light silicon wafer based detector system with very low momentum tracking capabilities for high luminosity collisions



- Heavy-ion Town meeting 2018:
“Next-generation heavy-ion experiment”
[D. Adamova et al. ArXiv: 1902.01211](#)

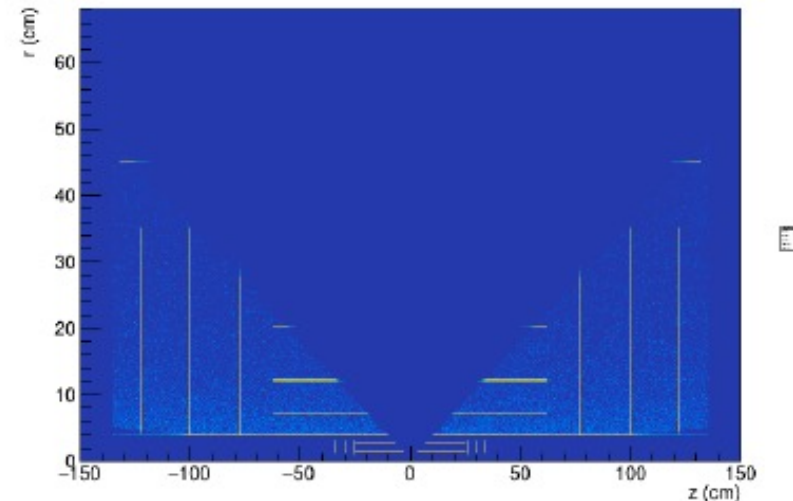
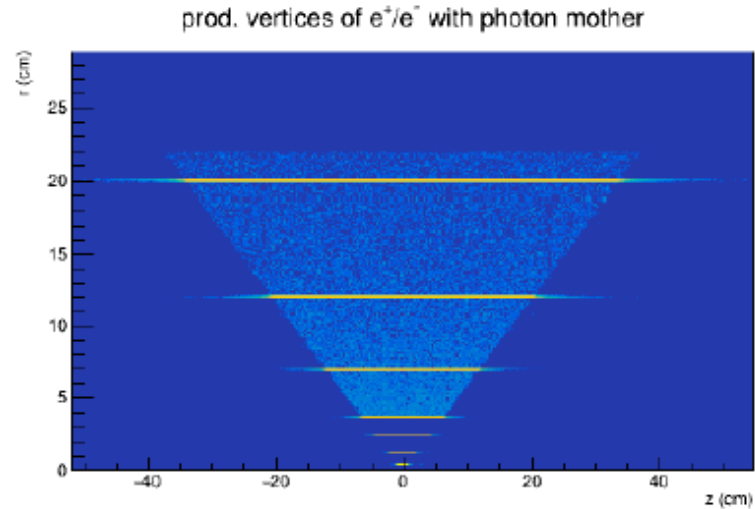
- Letter of Intent for ALICE 3:
[CERN-LHCC-2022-009](#) , arXiv: 2211.02491

[Scoping document](#)

γ -ray tomography of ALICE 3

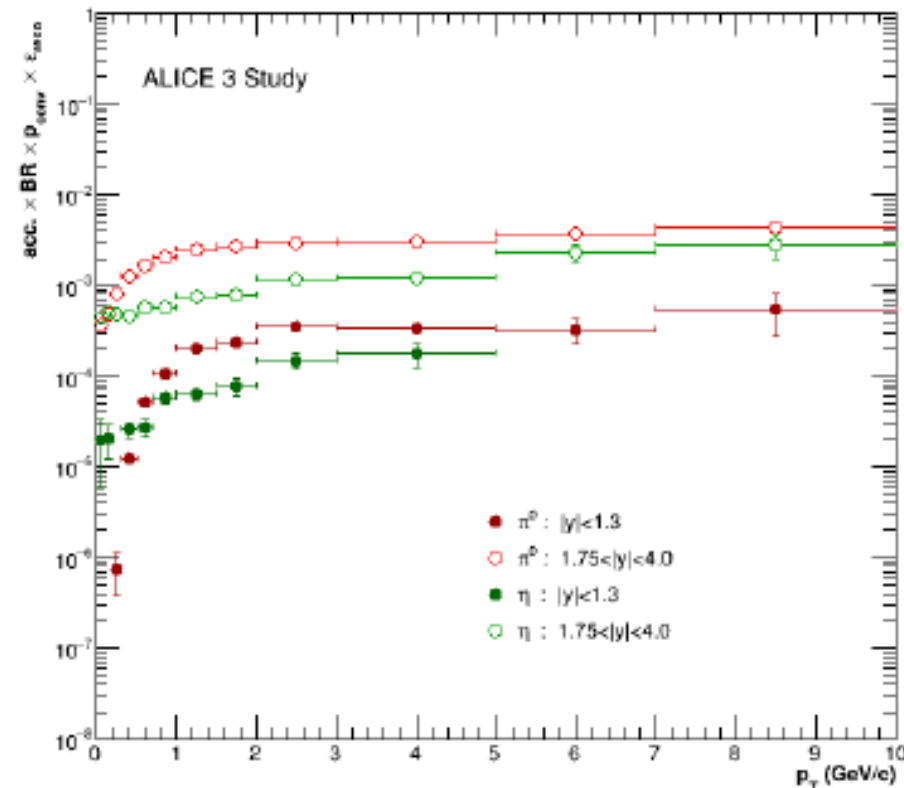
[arxiv2211.02491](https://arxiv.org/abs/2211.02491)

- Estimates of photon efficiency were done for the ALICE 3, LOI



Neutral meson measurements, direct photons

Cannot profit from going forward



PCM in ALICE 3

Central Barrel: $\chi_c \rightarrow J/\psi + \gamma$

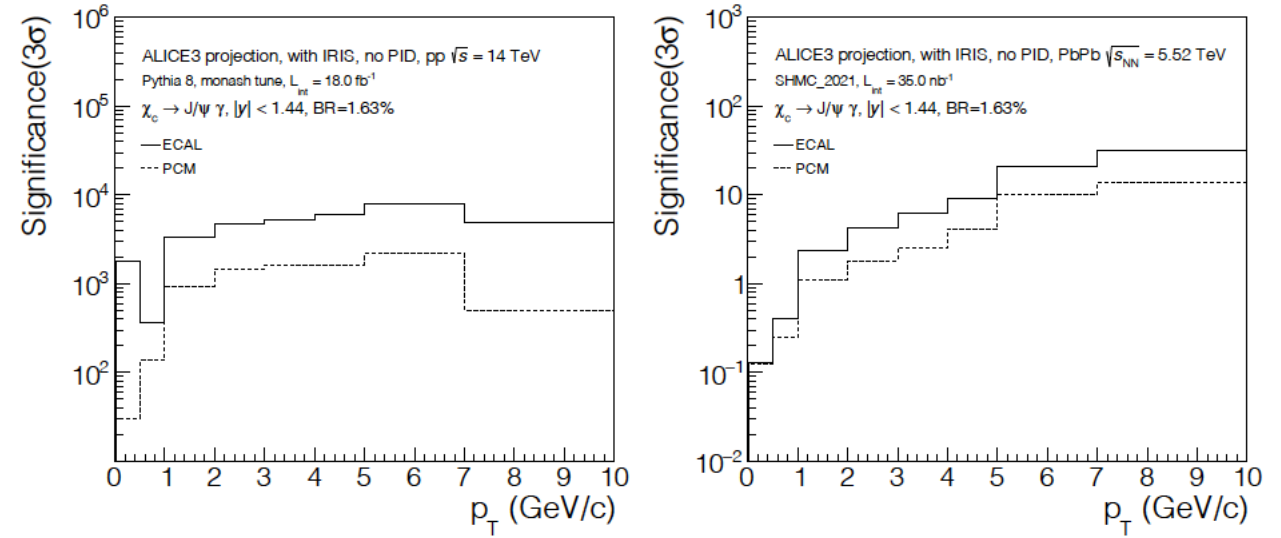
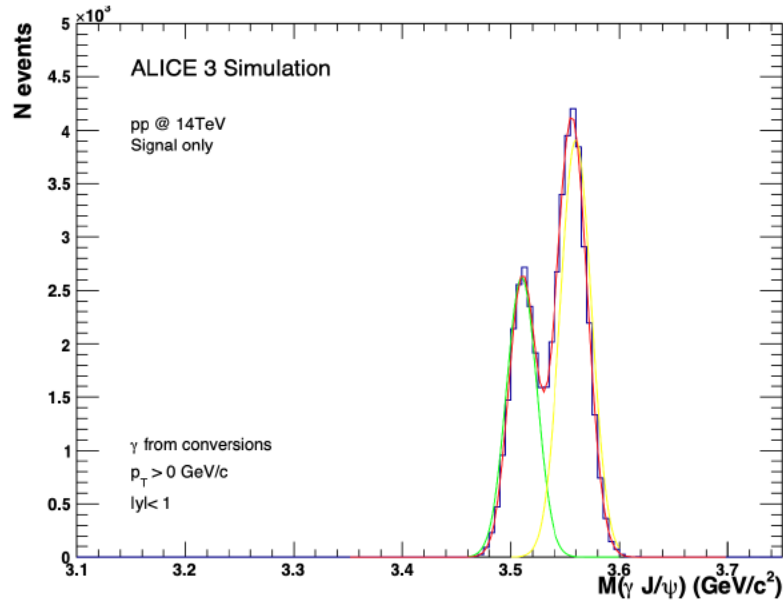
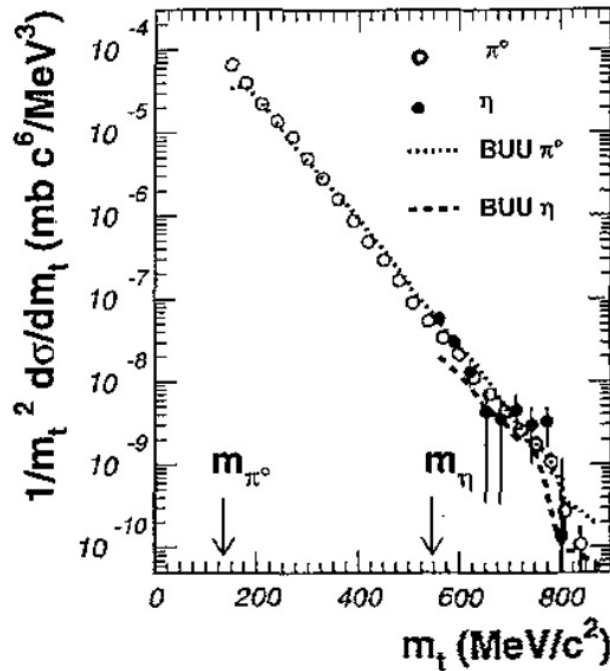


Figure 50: Significance of the χ_c signal (sum of the χ_{c1} and χ_{c2} signals) as a function of transverse momentum in pp collisions at $\sqrt{s} = 14$ TeV ($\mathcal{L}_{int} = 18$ fb⁻¹ using the ECal and the PCM method for photon detection and reconstruction. The fluctuation in the first bins is due to limited Monte Carlo statistics for the background) and in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV ($\mathcal{L}_{int} = 35$ nb⁻¹).

Electromagnetic and Hadronic Probes of Nuclear Matter

Proceedings of the
TAPS Workshop III

September 10-15, 1995
Bosen, Germany



[PLB 409 \(1997\) 77-82](#)

a.marin@gsi.de, Georg -C Lichtenberg Haus (2026)

Monday, September 11

Morning 9:00 – 12:30

V. Metag

Perspectives of a Future Pion-Beam Program at SIS

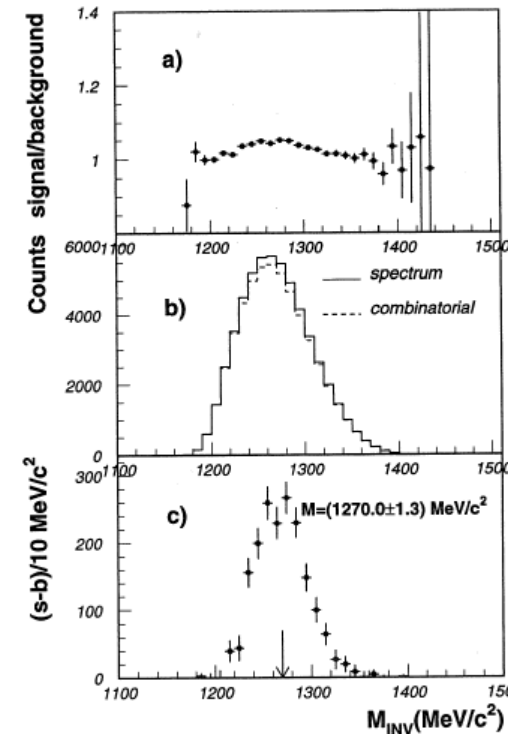
P. Braun-Munzinger *

High-Resolution Electromagnetic Calorimeters for Relativistic Nuclear Collision
Studies

Wednesday, September 13

A. Marin

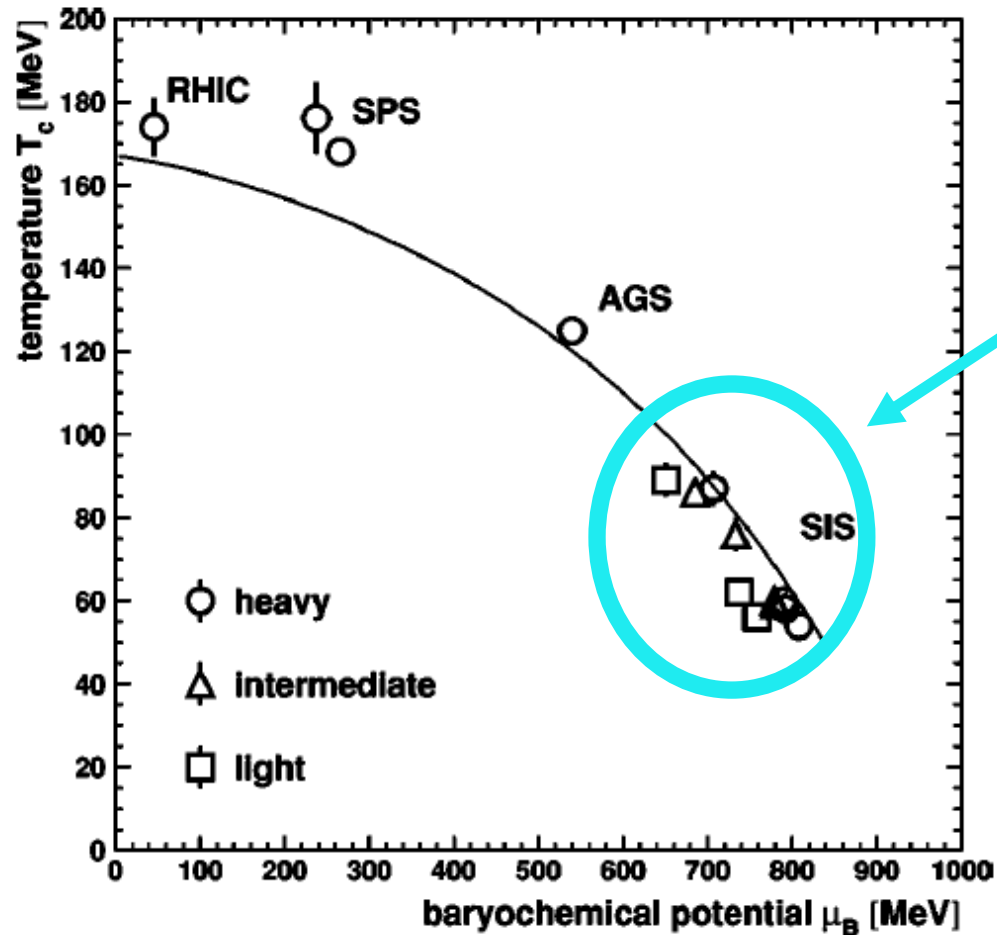
Direct Evidence for the $\Delta(1232)$ Resonance in the System $^{40}\text{Ar} + ^{\text{nat}}\text{Ca}$ at 800 MeV/u



[NIMA 417 \(1998\) 137-149](#)

From the TAPS campaign at GSI

R. Averbeck *et al.*, PRC 67, 024903(2003)



T_c and μ_B obtained from π^0 and η , plus deuteron

- Hadronic fireball in chemical equilibrium
- Freeze-out parameters at SIS are far below the phase boundary between a hadron gas and a quark-gluon plasma

My time at GSI (and HD)

CERES TPC Construction
gas system, slow control

Pb-Au
40A GeV

Pb-Au
158A GeV



CERES data Analysis

ALICE TRD TDR

Power distribution

[PRL96\(2006\)152301](#)

[PLB666\(2008\)425](#)

ALICE TRD Cooling

ALICE PCM

[NIMA593\(2008\)203](#)



[PLB 717\(2012\)162](#)

[EPJC74\(2014\)10,3108](#)

[PLB754\(2016\)235](#)

[EPJC78\(2018\)8,624](#)

pp 7TeV, pp 2.76 TeV, pp 8TeV

[PRC98\(2018\)044901](#)

ALICE Run 1

PbPb 2.76 TeV, pPb 5.02 TeV [cerncourier](#)

ALICE Run 2 PbPb 5.02, pPb 5.02, pPb 8.16



[arXiv:2411.09560](#)

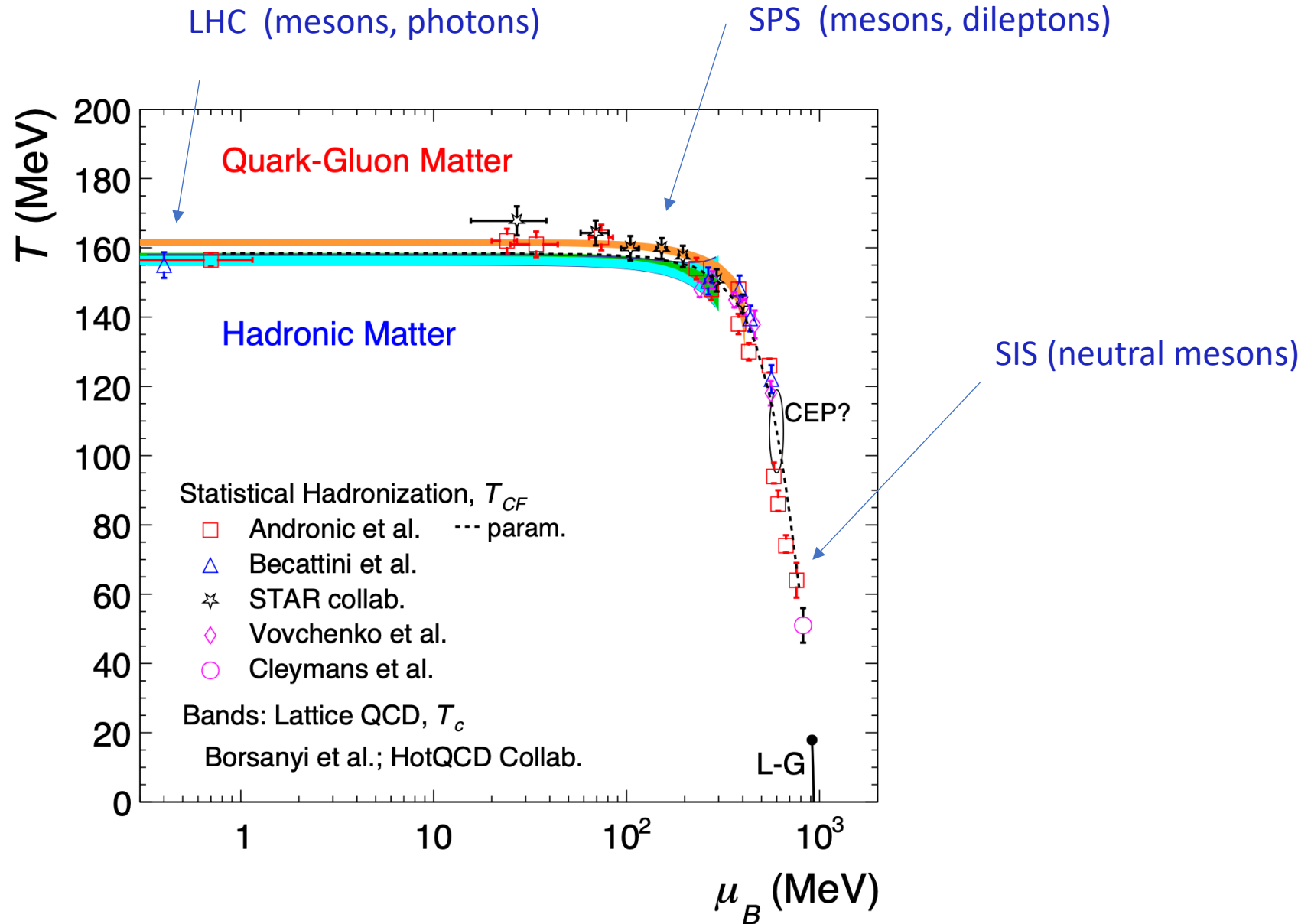
[JINST18 \(2023\)P11032](#)

ALICE3
PCM

ALICE Run 3

pp 13.6 TeV, PbPb 5.36 TeV

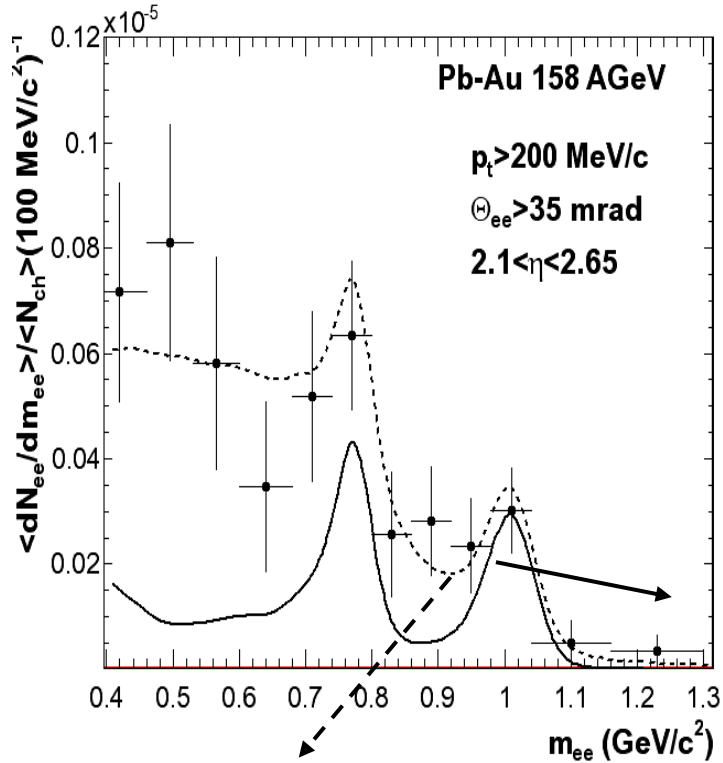




Happy Birthday Peter!

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

[PRL96\(2006\)152301](#)



ϕ : mass 0.9-1.1 GeV/c^2
 229 ± 53 Counts
 $S/B=1/12$

Decay cocktail

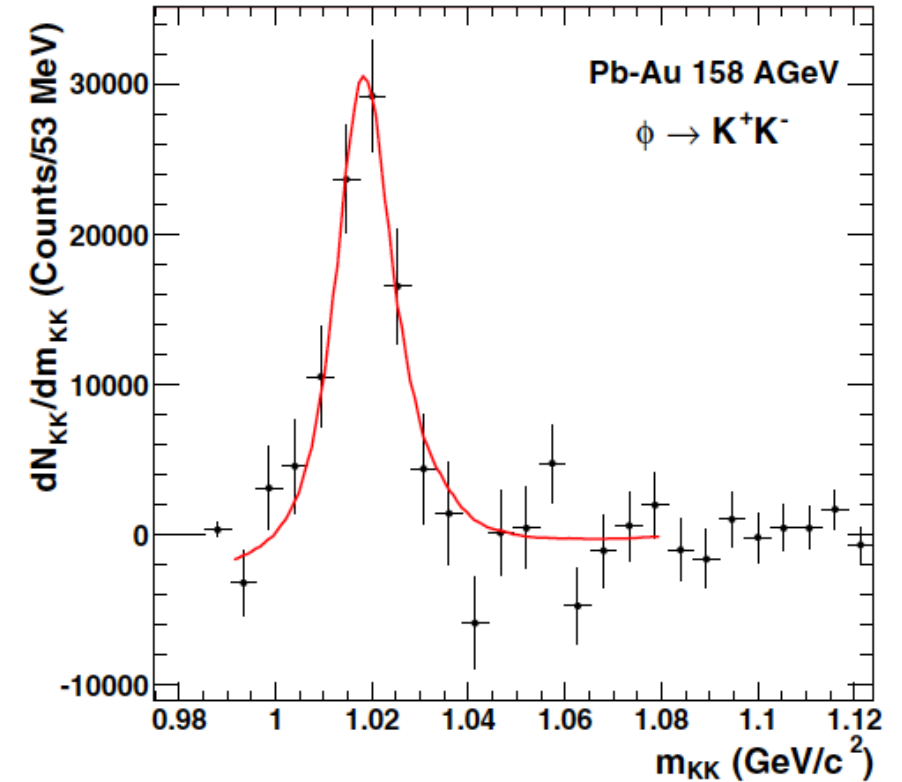
Decay cocktail+rho+QGP

Physics Background:

in-medium modified rho dilepton yield from QGP

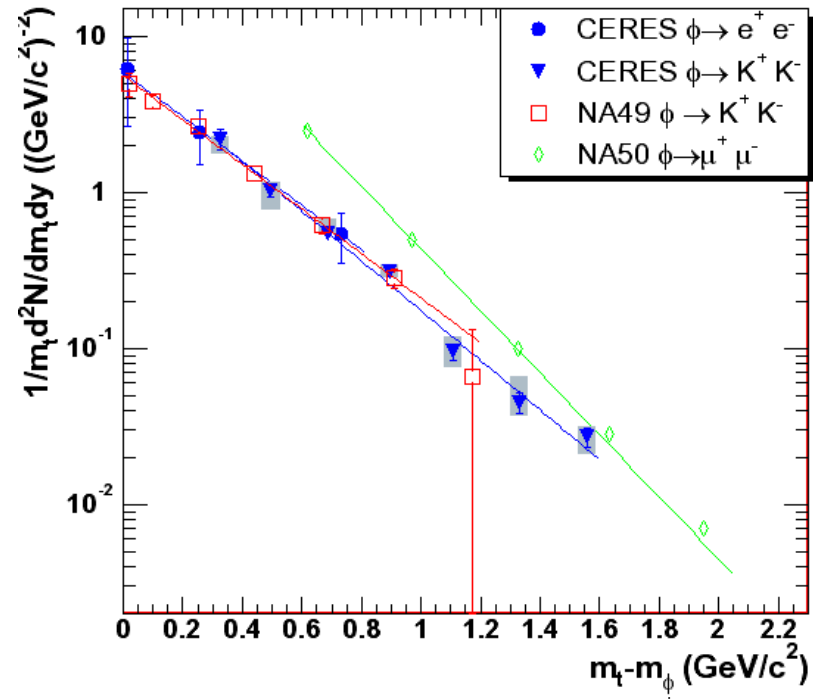
35% contribution in ϕ peak (R. Rapp)

$1.5 \text{ GeV}/c < p_t < 1.75 \text{ GeV}/c$
 $2.2 < \gamma < 2.4$



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

Comparison to NA49/NA50 results



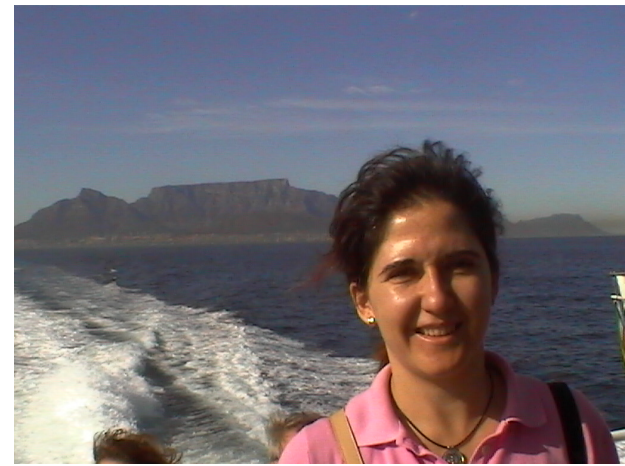
Different measurement conditions:

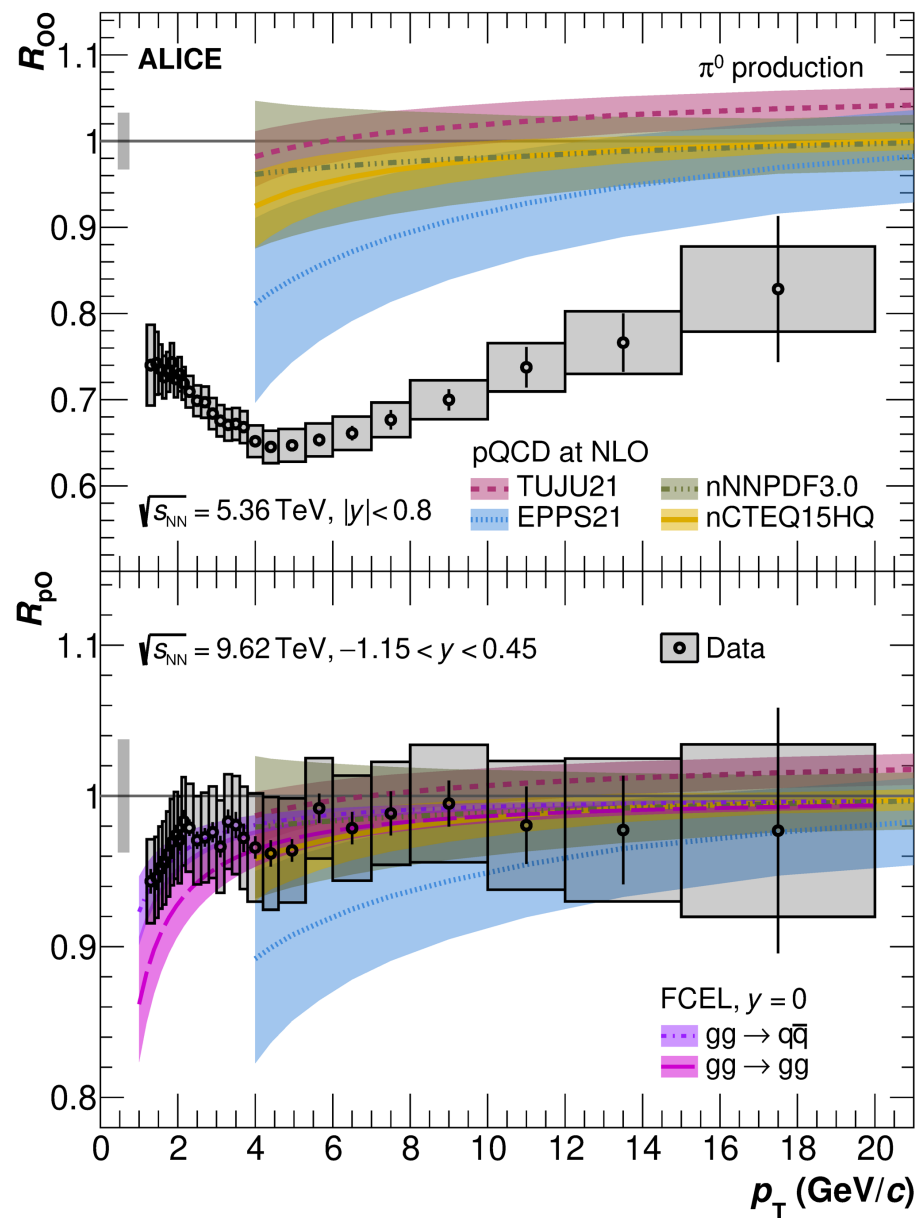
	NA49	CERES	Correction
centrality:	4%	7%	$h_{4\%}^-/h_{7\%}^-$ CERES
rapidity:	3.4	2.2	dN/dy NA49

Scaling factor: $F = 1.17 \pm 0.12$

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

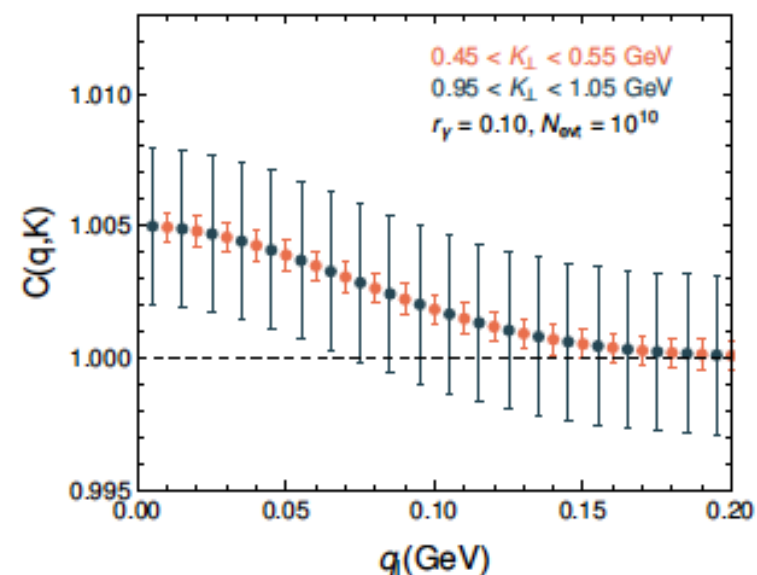
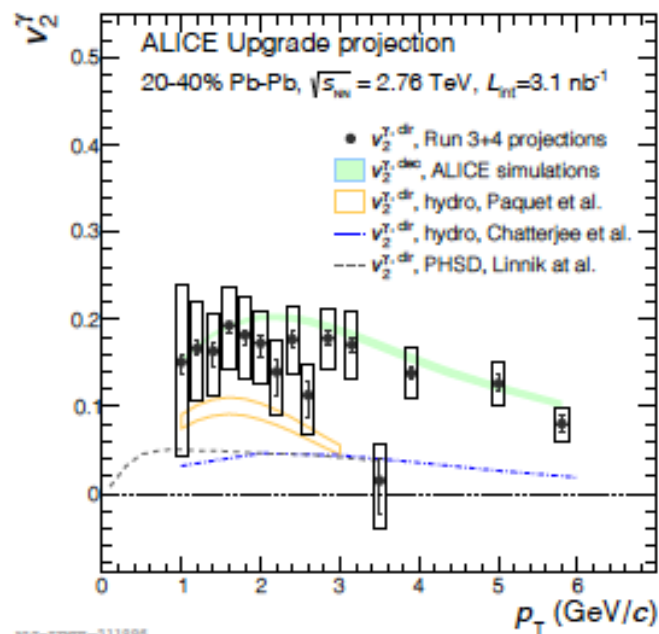
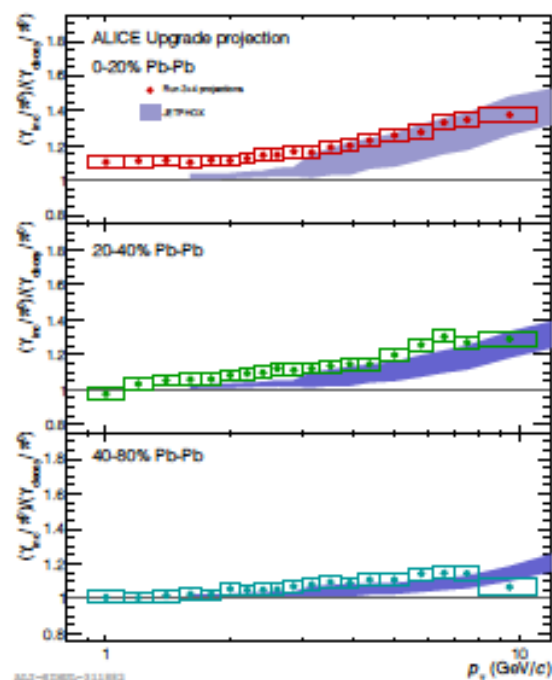




Run 3 + 4 uncertainty projections

[Yellow report](#)

arXiv:1812.06772, Phys. Rev C 102 (2020) 2



Possible open points after Run 3 + 4:
need of lower p_T reach, higher precision, finer centrality bins,

Data-driven precision determination of the material budget in ALICE

RD: Real Data
MC: Monte Carlo

[arxiv: 2303.15317](https://arxiv.org/abs/2303.15317)

ω_i : TPC-gas based calibration weights

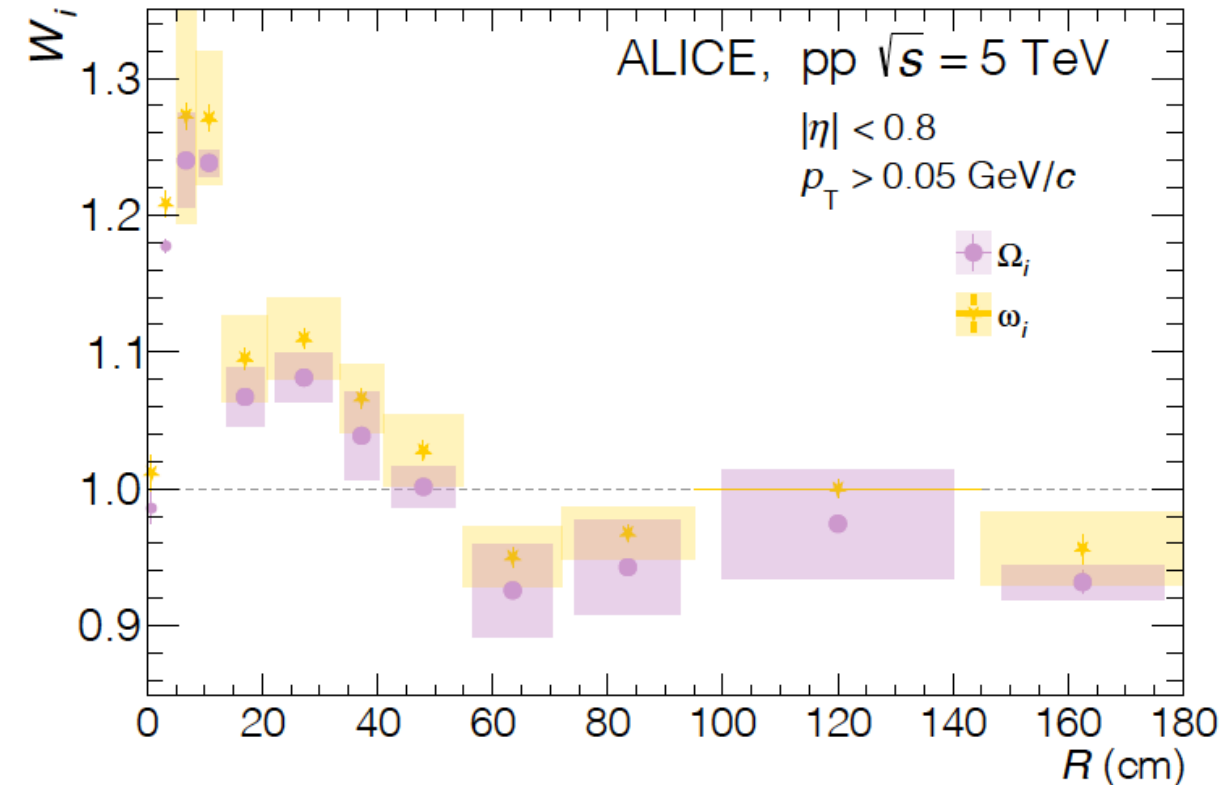
$$\omega_i = \frac{N_{\gamma,i}^{\text{rec,RD}} / N_{\gamma,\text{gas}}^{\text{rec,RD}}}{N_{\gamma,i}'^{\text{rec,MC}} / N_{\gamma,\text{gas}}'^{\text{rec,MC}}}$$

Ω_i : pion-isospin-symmetry

$$\Omega_i = \frac{N_{\gamma,i}^{\text{rec,RD}} / N_{\text{ch}}^{\text{rec,RD}}}{N_{\gamma,i}'^{\text{rec,MC}} / N_{\text{ch}}^{\text{rec,MC}}}$$

Use Ω_i to correct ε_γ :

$$\varepsilon_\gamma^{\text{MC,corr}}(p_T) = \frac{\sum_i \omega_i \times dN_{\gamma,i}^{\text{rec,MC}} / dp_T}{dN_\gamma^{\text{prod}} / dp_T}$$



Reduce X/X_0 systematic uncertainty: 4.5% $\rightarrow$ 2.5%

Mitigate local imperfections in X/X_0 implementation in simulations

QGP thermal emission

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

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

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

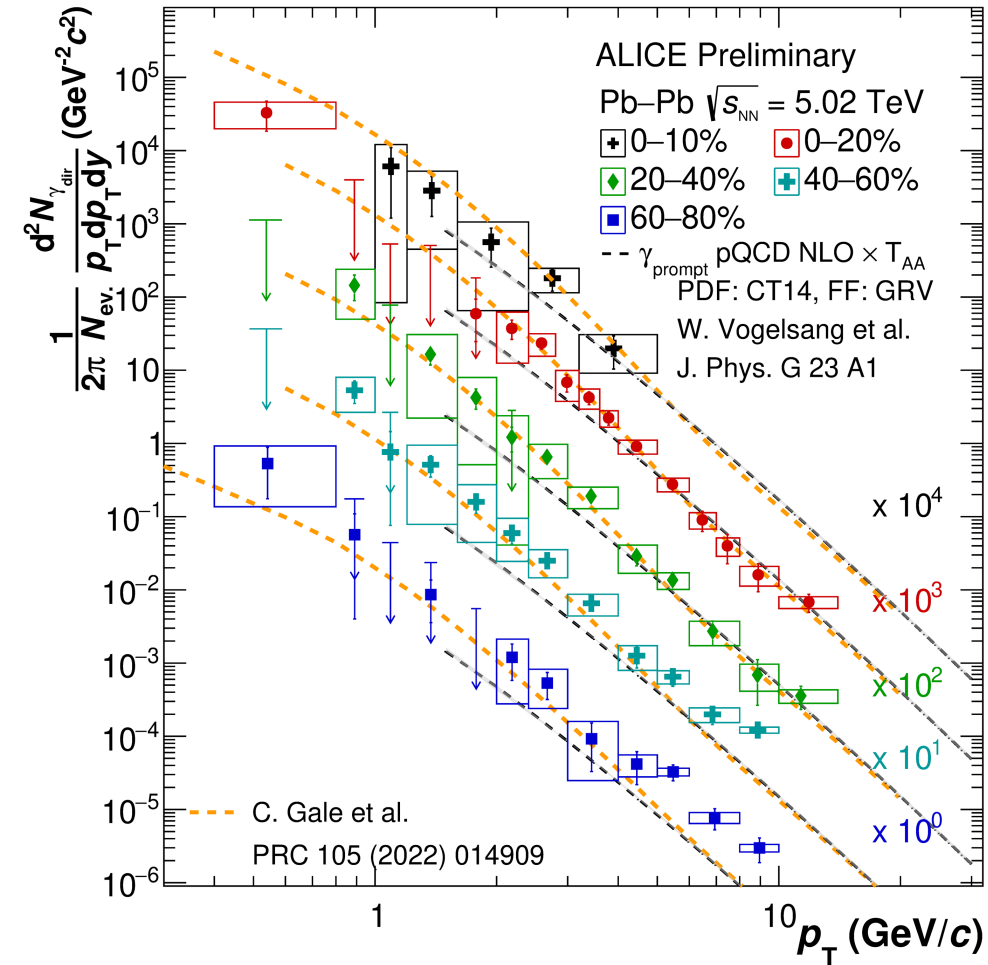
- Virtual γ method, 0-10% centrality
- Real γ (conversion method), other centralities

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

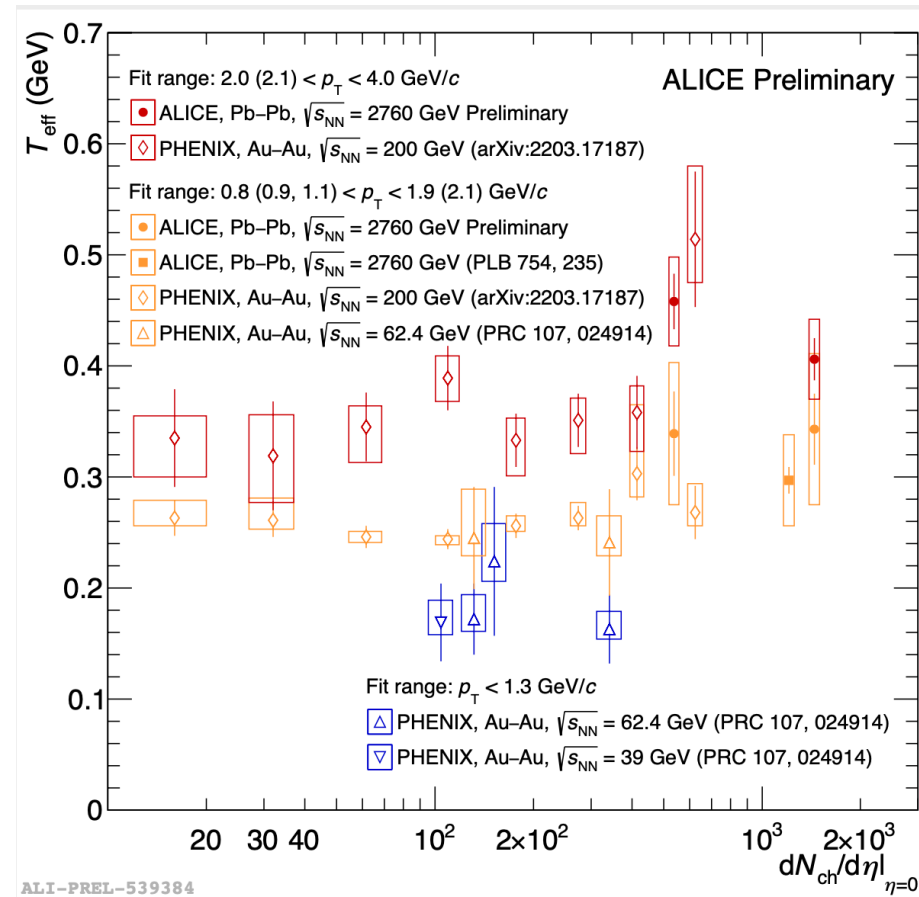
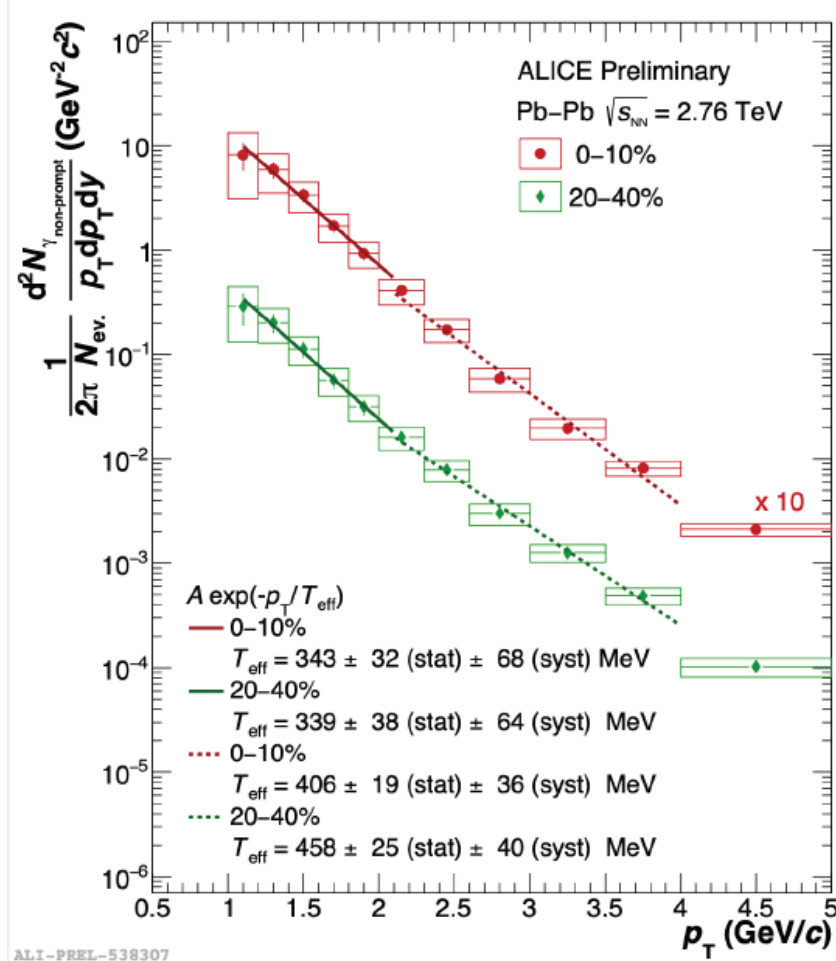
- consistent with pQCD expectations



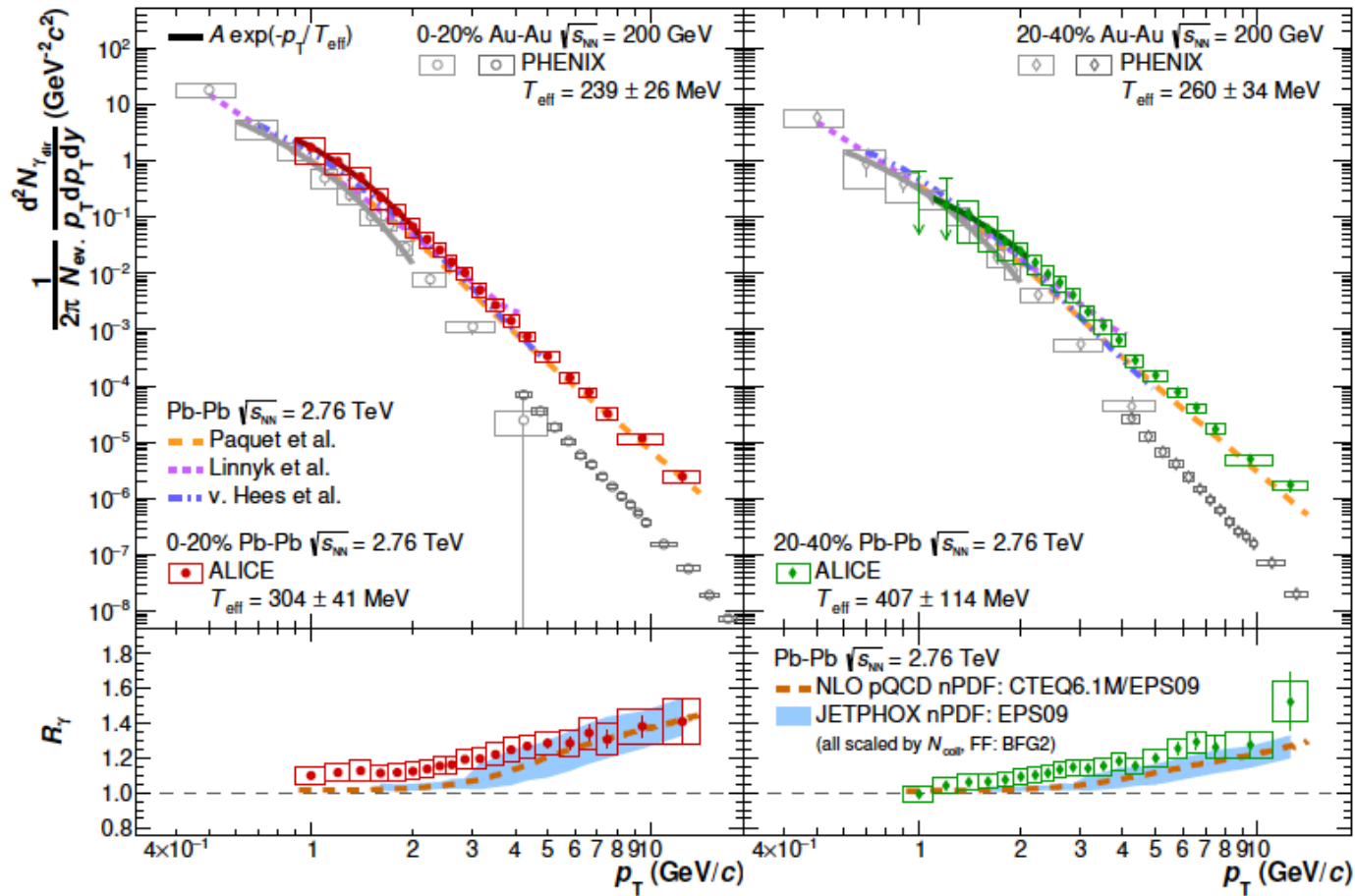
T_{eff} from non-prompt photons

Non-prompt γ = direct γ - T_{AA} · pQCD

is T_{eff} ($2.1 < p_T < 4 \text{ GeV}/c$) $>$ T_{eff} ($1.1 < p_T < 2.1 \text{ GeV}/c$) ?
pre-equilibrium photons? earlier time emission?

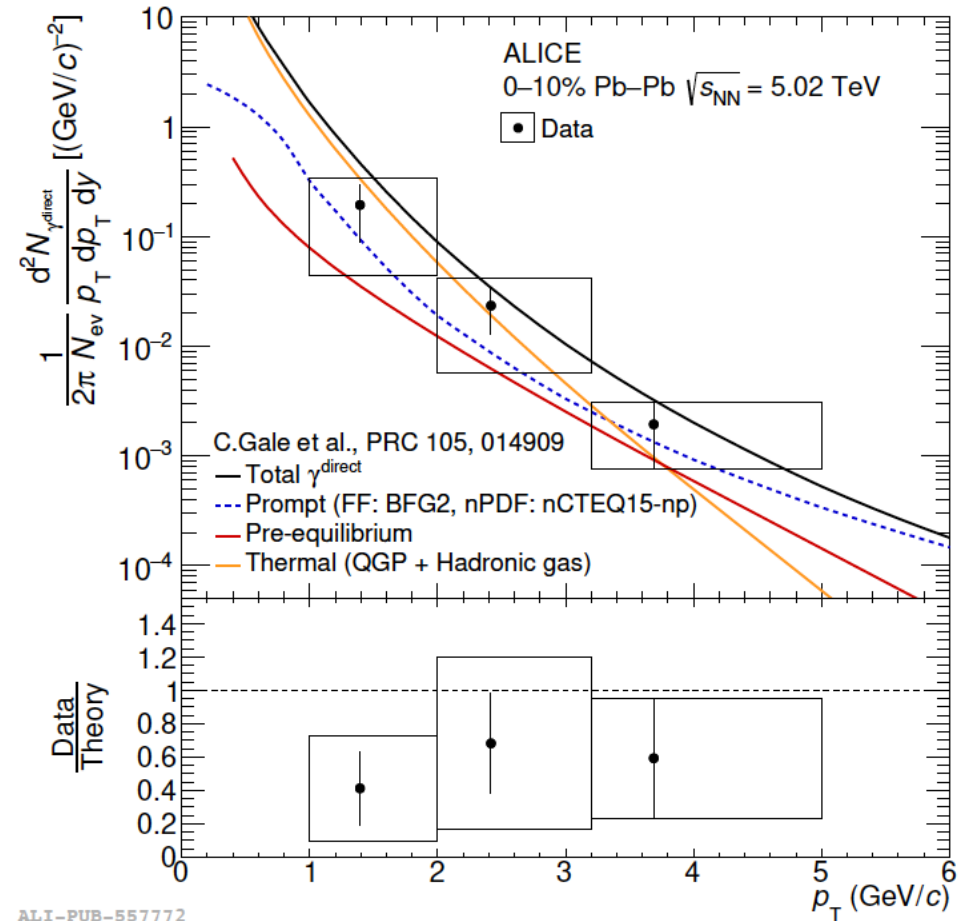
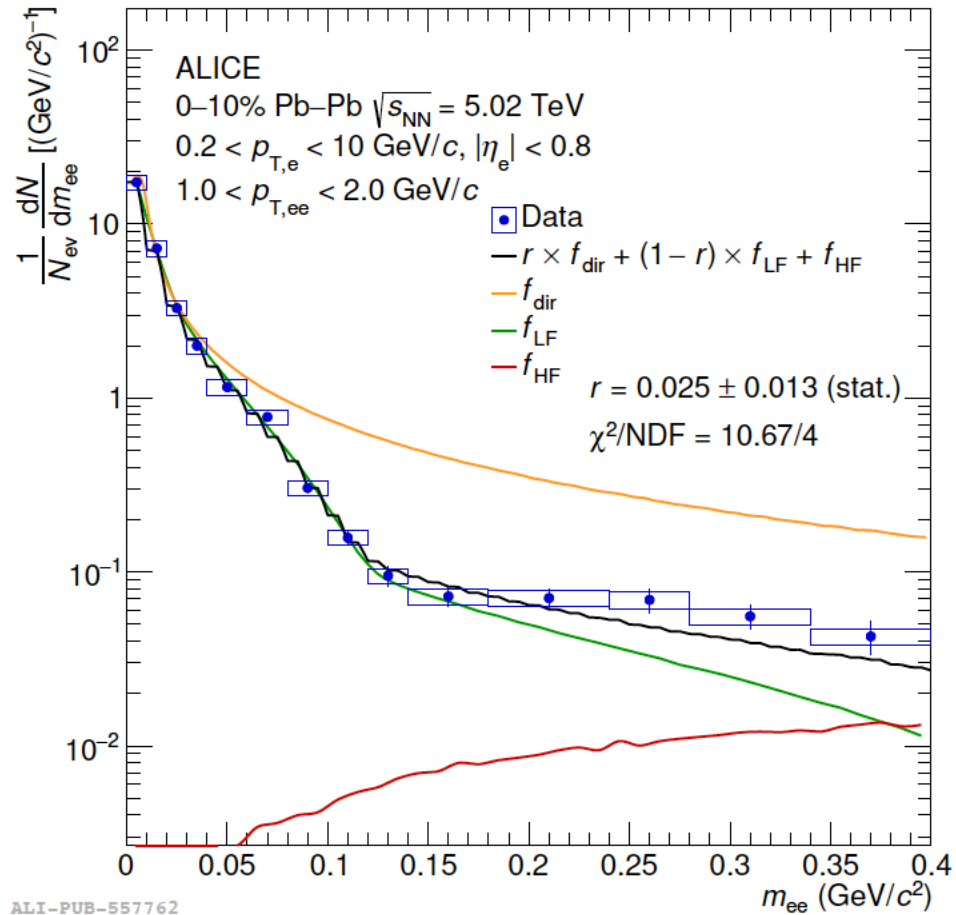


Thermal emission: RHIC and LHC

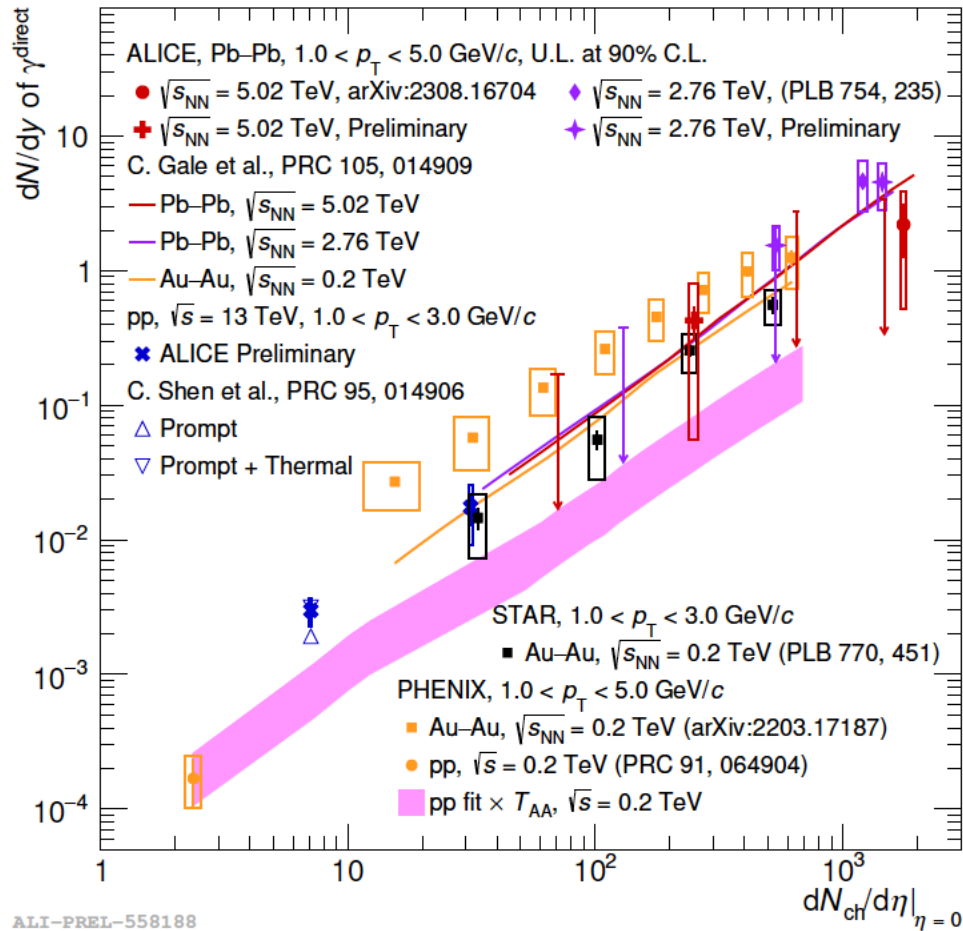


Increase in the effective temperature from RHIC to LHC

Virtual photon method



Integrated direct photon yield vs $dN_{ch}/d\eta$

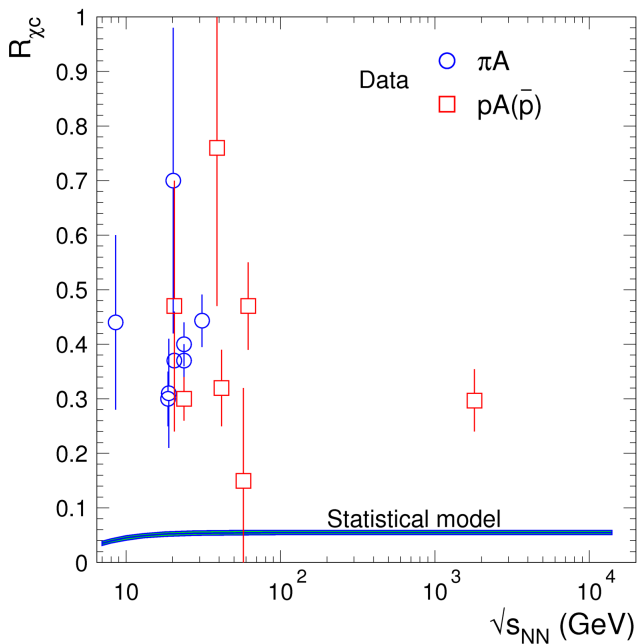


Power-law scaling of direct γ yield vs N_{ch} proposed by PHENIX for different systems and collision energies

- Integrated direct photon yield ($1 < p_T < 5$ GeV/c) vs $dN_{ch}/d\eta$

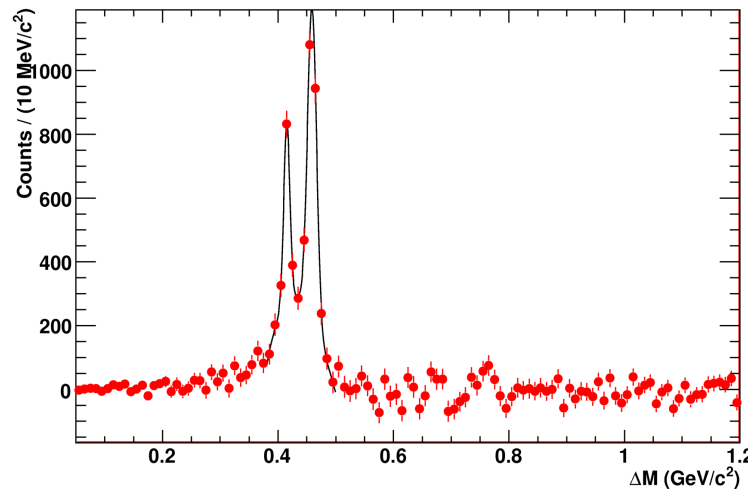
Latest models describe the N_{ch} dependence for ALICE and STAR
Underestimates PHENIX data for semicentral to peripheral collisions

χ_c

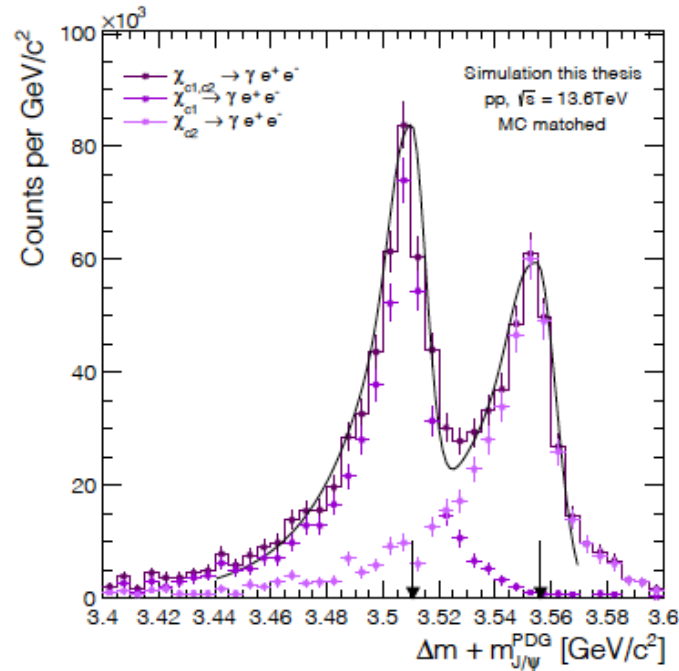


A. Andronic et al.,
Phys.Lett.B 678:350-354(2009)

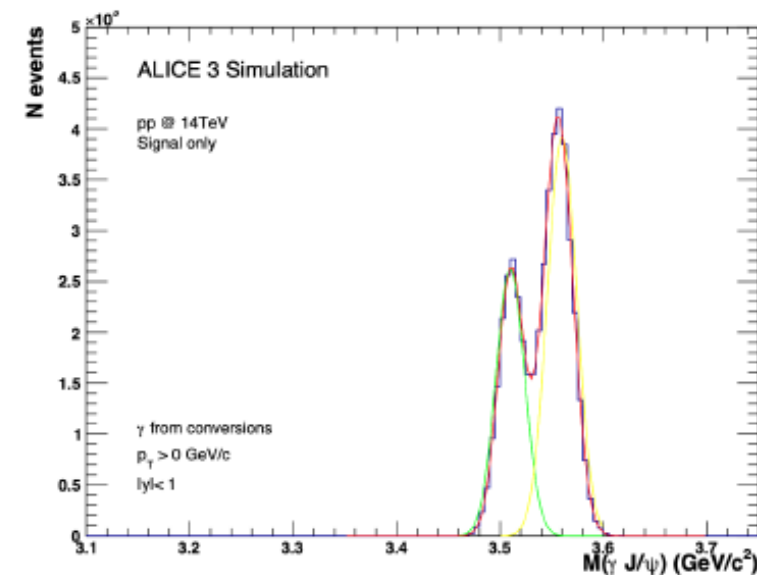
a.marin@gsi.de, Georg -C Lichtenberg Haus (2026)



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



Not yet measured in ALICE

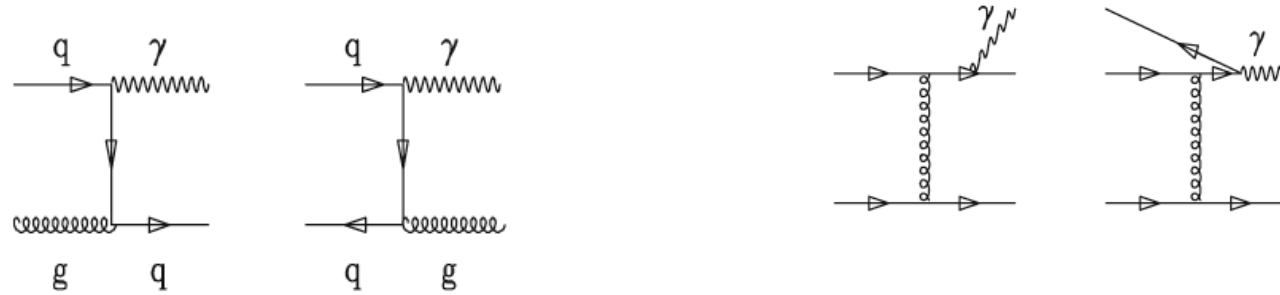


- Letter of Intent for ALICE 3:
[CERN-LHCC-2022-009](https://arxiv.org/abs/2211.02491) , arXiv: 2211.02491

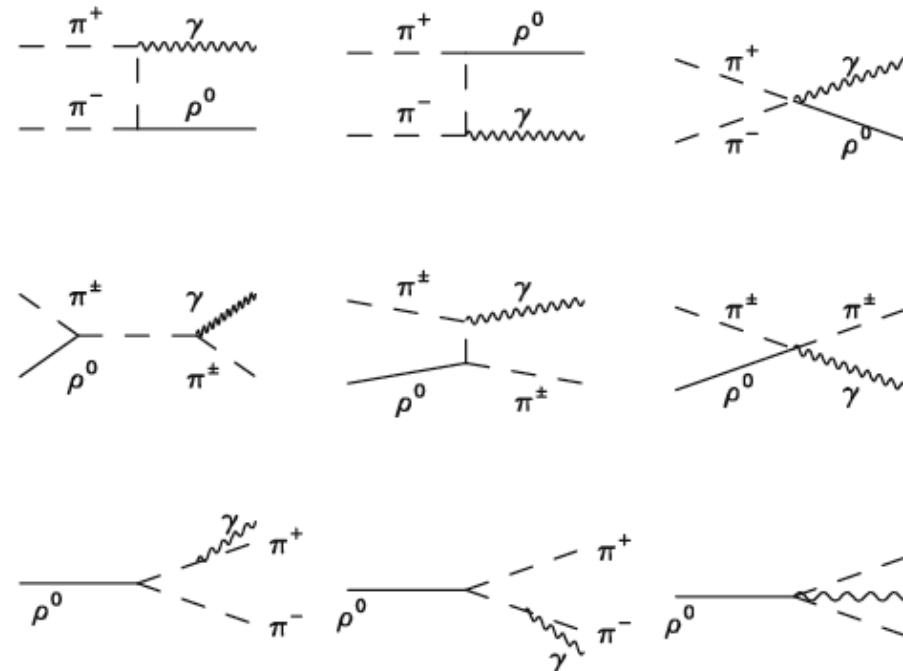
I. Kantak, Bachelor Thesis

Photon production: Feynman diagrams

QGP:

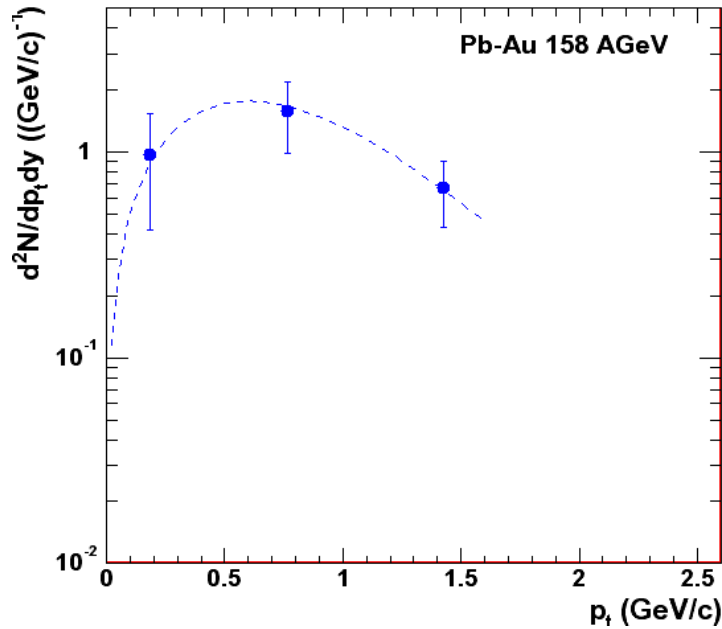


Hadron gas:



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

[PRL96\(2006\)152301](#)

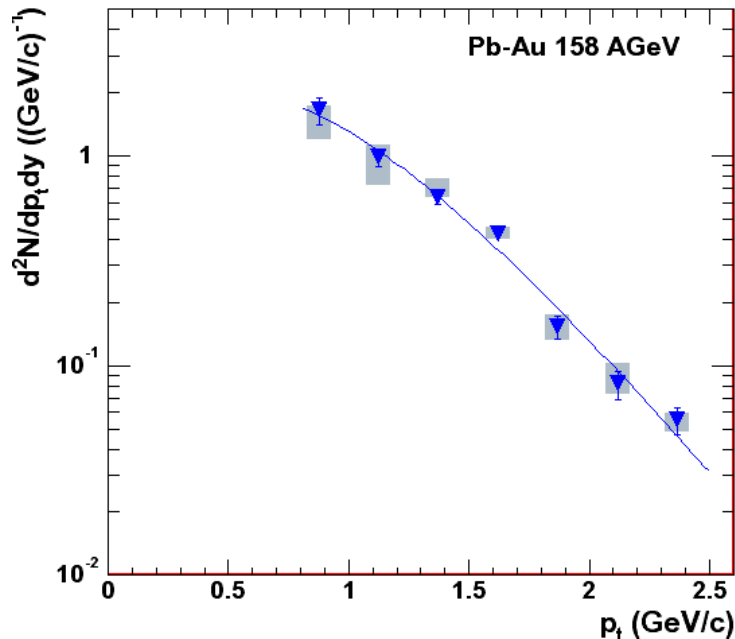


$$\frac{d^2N}{dp_t dy} = \frac{dN/dy}{T(T + m_\phi)} \cdot p_t \cdot e^{-\frac{m_t - m_\phi}{T}}$$

$$T = 306 \pm 82 \text{ (stat) MeV}$$

$$dN/dy = 2.19 \pm 0.52 \text{ (stat)} \pm 0.34 \text{ (syst)}$$

at $2.1 < y < 2.65$



$$T = 273 \pm 9 \text{ (stat)} \pm 10 \text{ (sys) MeV}$$

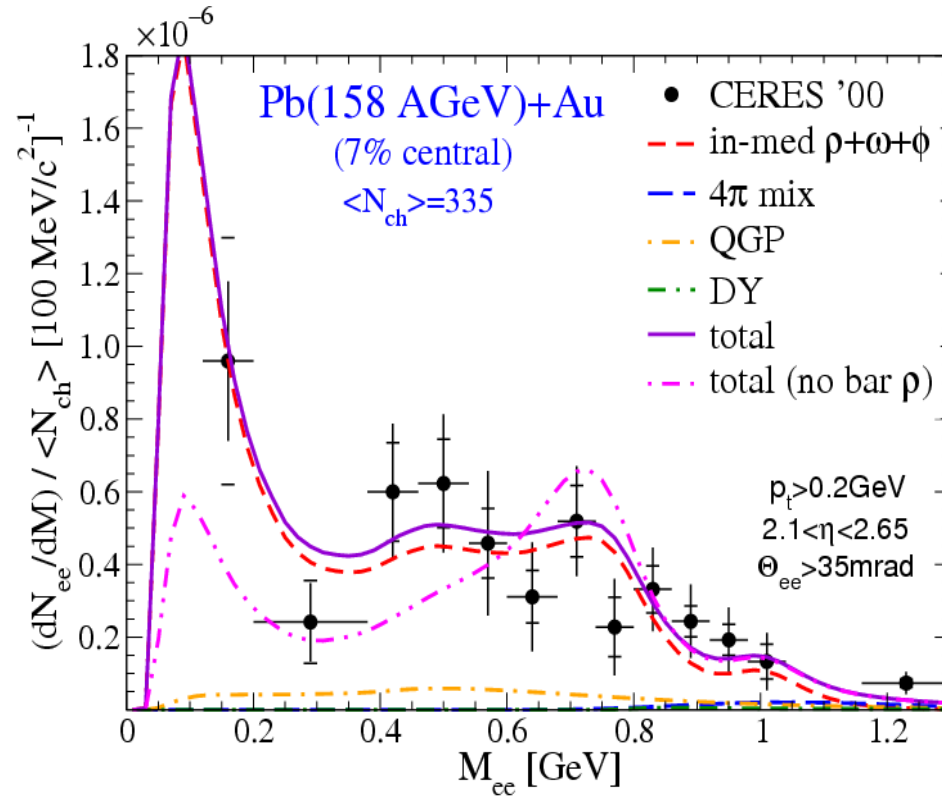
$$dN/dy = 2.05 \pm 0.14 \text{ (stat)} \pm 0.25 \text{ (syst)}$$

at $2.0 < y < 2.4$

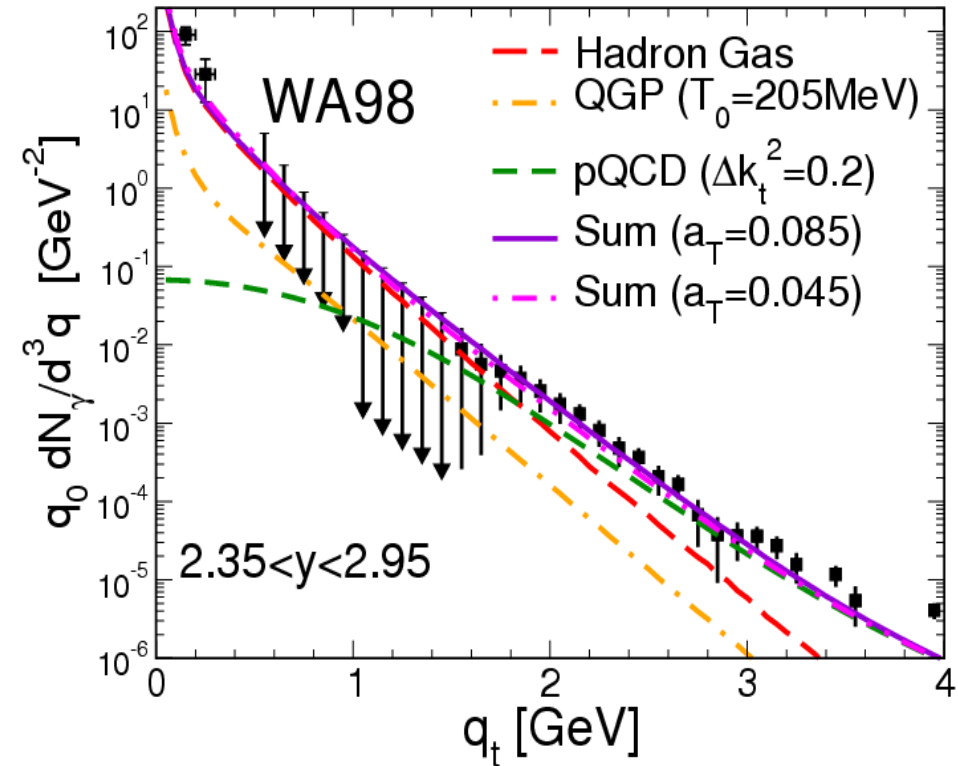
EM Probes in Central Pb-Au/Pb at SPS

Comparisons with updated calculations

Di-Electrons [CERES/NA45]



Photons [WA98]



- updated fireball ($a_T=0.045 \rightarrow 0.085/\text{fm}$)
- very low-mass di-electrons $\leftrightarrow$ (low-energy) photons

[van Hees+R.Rapp '07]

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