Direct photons in high energy proton-proton and nucleus-nucleus collisions

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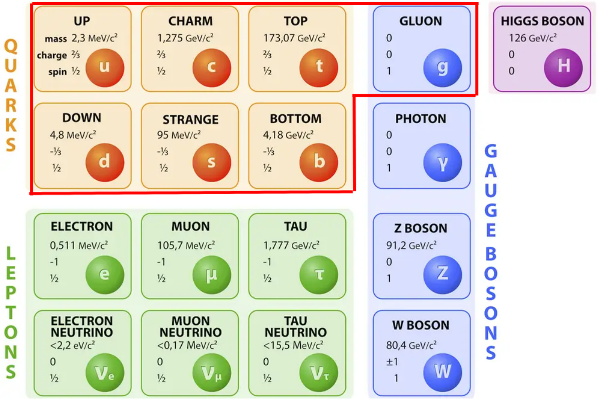
Overview

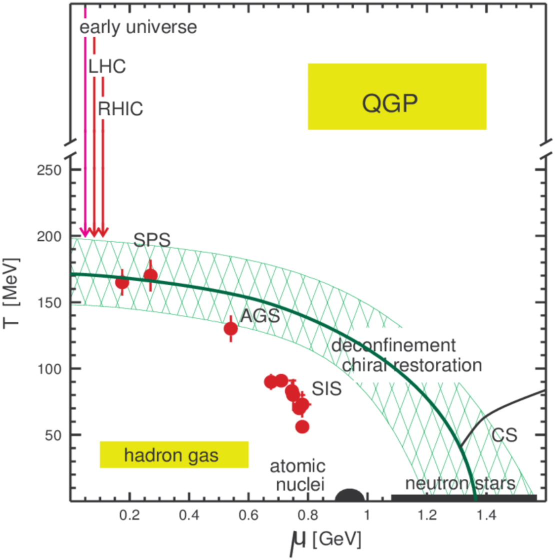
Theoretical introduction

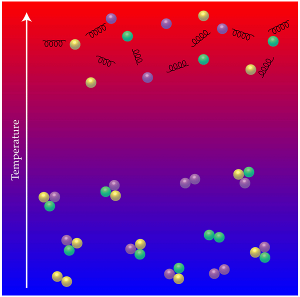
Standard model and strong interaction

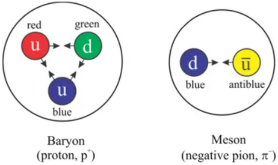


- Quarks and Gluons carry three types of color charges
- Gluons act as mediators between the quarks resulting strong interaction
- Gluons also take part in strong interaction
- Bound states of quarks are formed resulting ordinary matter around us

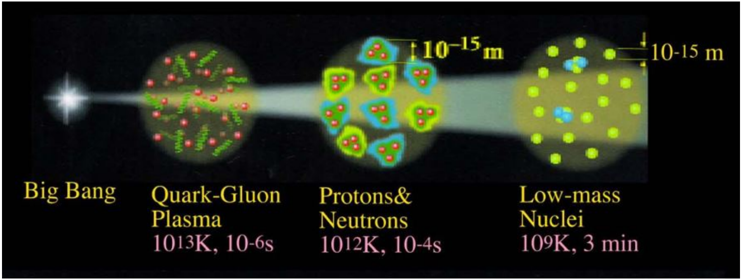
Phase transition in QCD







Early universe and Quark deconfinement



- After big bang (few microseconds old) universe is believed to be filled with deconfined state of quarks and gluons.
- Heavy-ion collisions recreate in the labs, such droplets of matter that filled the universe about 1 microsecond after the big bang
- With heavy-ion collisions we can learn about the properties (Not possible with astronimcal) at very temperature and density and explore QCD phase diagram

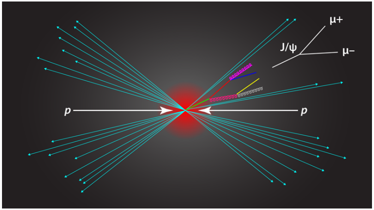
Differences between p-p Collisions and A-A Collisions in QGP Study

- Energy density:
  - p-p collisions: Typically a few GeV/fm^3
  - A-A collisions: 10-20 GeV/fm^3 or higher
- Temperature:
  - A-A collisions: Several hundred MeV to over a trillion degrees Kelvin
- Size and lifetime of the QGP:
  - p-p collisions: Highly transient and smaller in size
  - A-A collisions: Spatial extent of several femtometers, lasting tens to hundreds of femtoseconds
- Particle multiplicity:
  - A-A collisions: Significantly larger number of particles compared to p-p collisions
- Jet quenching:
  - A-A collisions: Much more pronounced, resulting in stronger energy loss and modification of jet-related observables

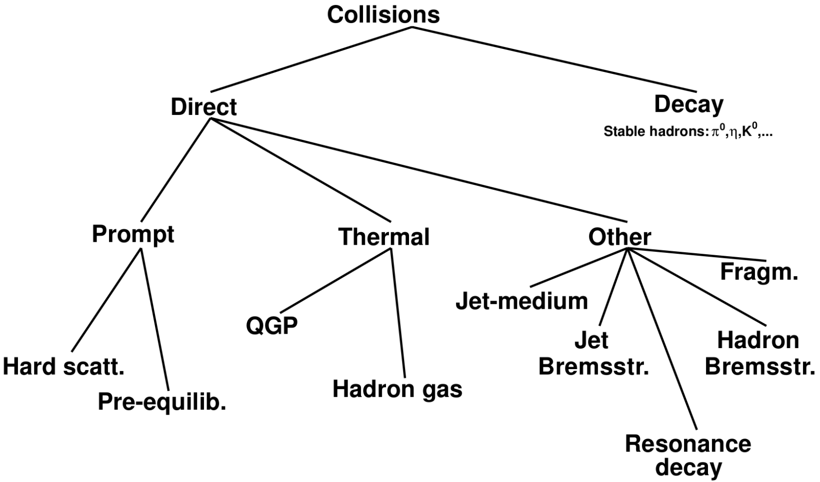
Different ways to study QGP

- $J/\psi(c\bar{c})$ suppression
- Jet quenching
- Direct Photons

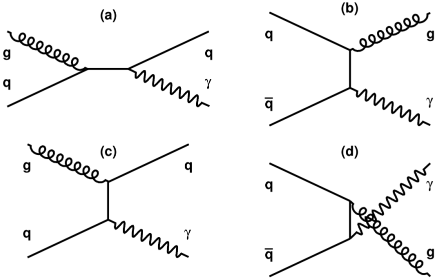
etc.

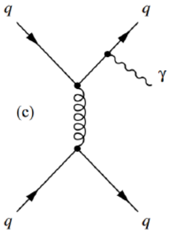


Photons in heavy ion collisions



Feynman diagrams contributing to Direct Photon production





Experimental situation

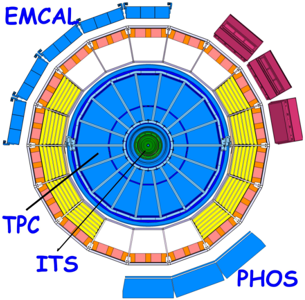


Figure: Photon detection methods at ALICE, LHC

- Photon conversion method:
  - Utilizes the conversion of photons into electron-positron pairs in a detector material
  - Tracks of the converted electrons and positrons are measured to reconstruct the original photon properties
- Calorimetry:
  - Measures the energy of particles by absorbing them in a material and detecting the resulting electromagnetic shower
  - Photon-induced showers are identified and their energy is measured in the calorimeter
  - Provides good energy resolution and allows for the study of high-energy photons in the QGP

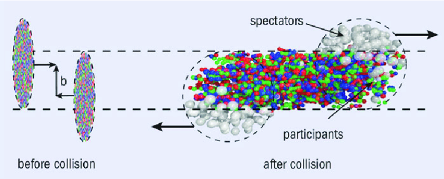
Hadron	Decay
π^0	$\gamma\gamma$
η	$\gamma\gamma$
ω	$\pi^0\gamma$
η'	$\rho\gamma$
ϕ	$\eta\gamma$
ρ^0	$\pi^+\pi^-\gamma$

Table: Hadronic decay to photons

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

Figure: Direct photon yield

- Measurement of inclusive photon spectra
- Determination of decay photon spectra through Monte Carlo simulation as well as neutral meson measurement
- Subtract decay photon yield(γ_{decay}) from inclusive photon yield(γ_{incl})



Collision centrality	Centrality bin nu
0-20%	0
20-40%	1
40-60%	2
60-80%	3
80-100%	4

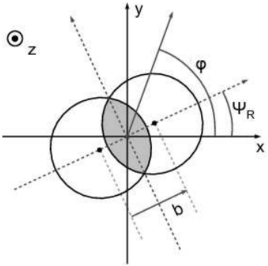
Table: Collision centrality and centrality bins

$$\boxed{\text{Centrality} = \frac{\text{spectator}}{\text{All}}}$$

Anisotropic Collective Flow

The initial spatial anisotropy of non-central ion-ion collision leads to the build-up of collective anisotropic flow, which is described in the distribution of final state particles as a function of azimuthal angle φ:

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{N}{2\pi} \cdot \left(1 + \sum_{\mathrm{n}>1} v_{\mathrm{n}} \cos\left(n[\varphi - \Psi_{\mathrm{R}}]\right)\right), \quad (6)$$



Analysis results from previous experiments

WA98 (West Area experiment)

Super Proton Synchrotron (SPS)

CERN

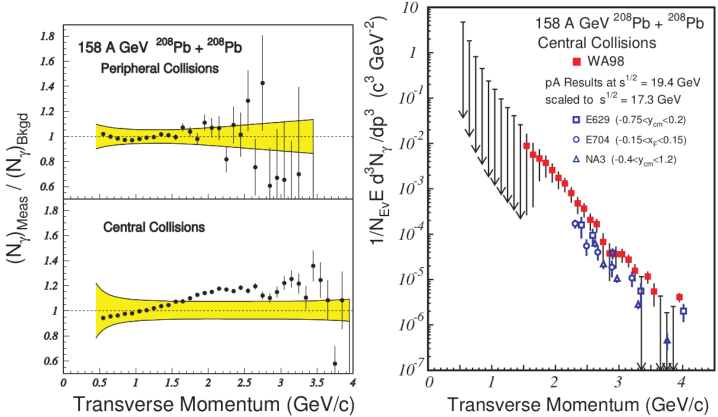
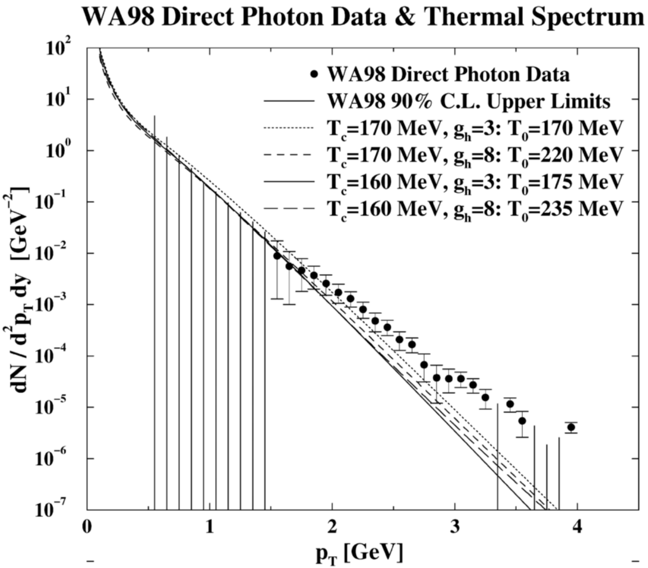


FIG. 18. Direct photon result from the WA98 experiment, 158 AGeV ^{208}Pb + ^{208}Pb collisions [70]. (Left panel) The ratio of measured inclusive photons to calculated decay photons as a function of p_T for peripheral (a) and central (b) collisions. Error bars on the data are statistical only, the p_T-dependent systematic uncertainties are shown as shaded bands. (Right panel) The invariant direct photon yield for central collisions. Error bars indicate combined statistical and systematic uncertainties. Data points with downward arrows indicate 90% C.L. upper limits ($\gamma_{excess} + 1.28\sigma_{upper}$). The data are compared to expected, N_{coll}-scaled pp yields from three earlier experiments (see explanation in the text). (Figures taken from [70].)

Results from WA98, SPS

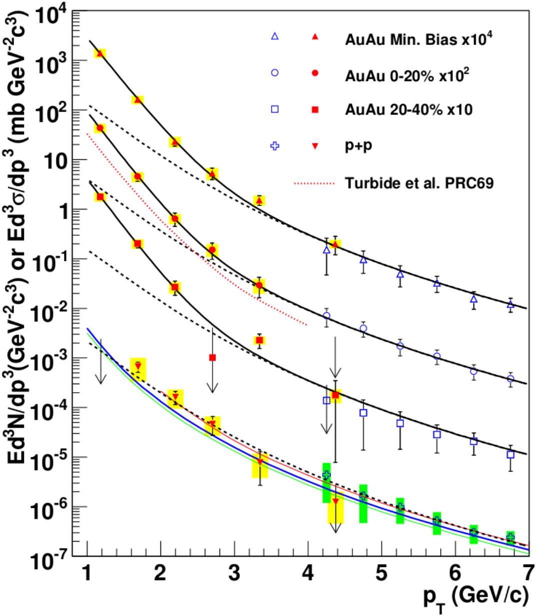


PHENIX (Pioneering High Energy Nuclear Interaction eXperiment)

Relativistic Heavy Ion Collider (RHIC)

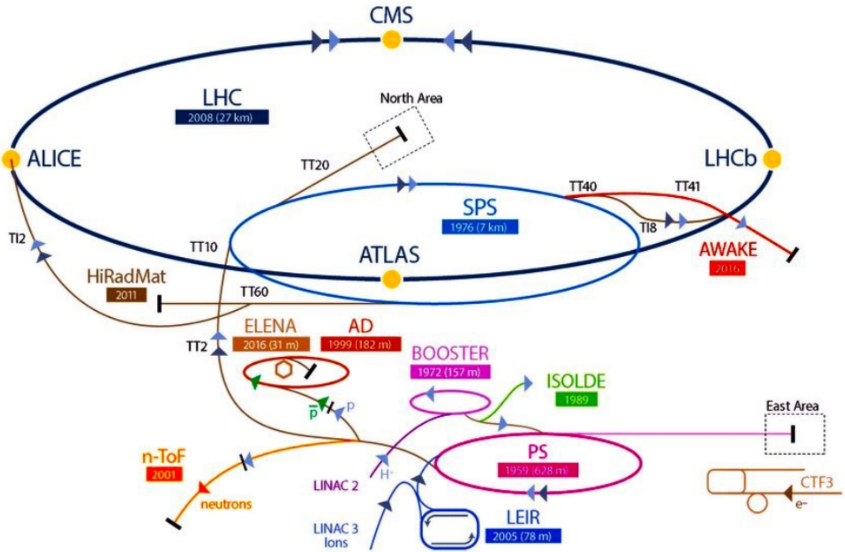
Brookhaven National Laboratory, United States

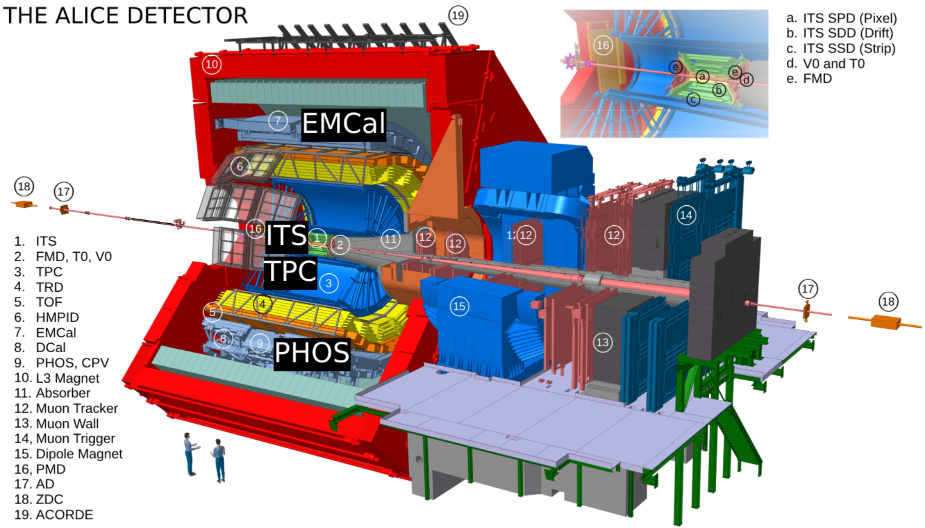
Results from PHENIX, RHIC



LHC and ALICE experiment

LHC schematics during Run2




THE ALICE DETECTOR
a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD
EMCal
ITS
TPC
PHOS
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

ALICE and PHOton Spectrometer(PHOS)

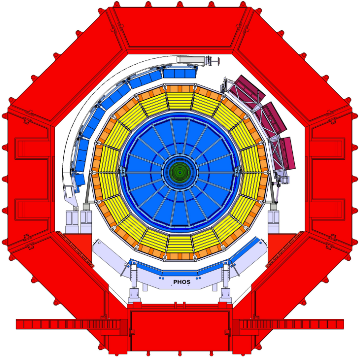


Figure: ALICE cross-sectional view in Run 2

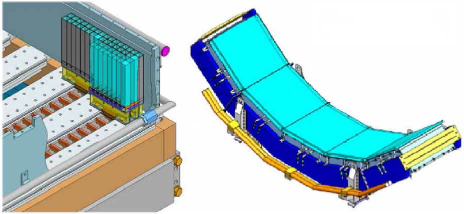


Figure: PHOS modules and its crystals

PHOS hardware

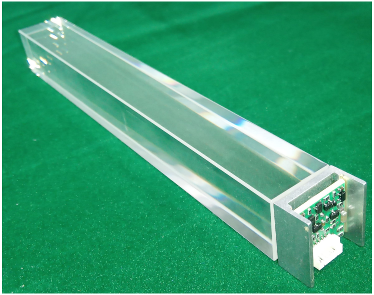


Figure: A detector element consisting $PbWO_4$ crystal, APD(Avalanche Photo Diode) detector and preamplifier

Coverage in pseudo-rapidity	$-0.125 \leq \eta \leq 0.125$
Coverage in azimuthal angle	$\Delta\varphi = 70^\circ$
Distance to interaction point	460 cm
Modularity	Three modules with 3584 and one with 1792 crystals
Material	Lead-tungstate ($PbWO_4$) crystals
Crystal dimensions	$22 \times 22 \times 180$ mm^3
Depth in radiation length	20 X_0
Number of crystals	12 544
Total area	6.0 m^2
Operating temperature	-25° C

PHOS Cluster

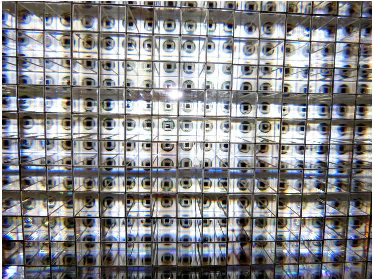


Figure: Part of cell matrix of one module

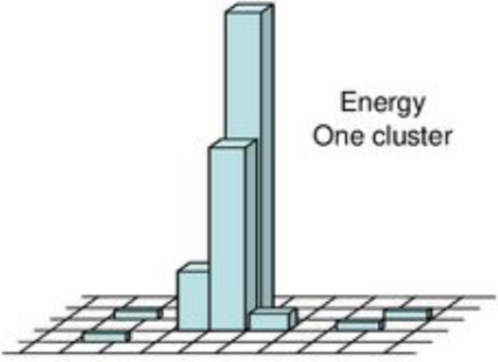


Figure: Cluster created by photon in PHOS cells.
Vertical column represents the amount of energy(not scaled) deposited in a PHOS cell

- With PHOS granularity, the energy deposited in the central cell is around 80% of the total cluster energy

Results from ALICE experiment :

$$\sqrt{S_{NN}} = 2.76\,TeV$$

$\sqrt{S_{NN}} = 2.76\,TeV$ results : Hadronic decays

$$R_\gamma \equiv \frac{\gamma_{\text{incl}}}{\pi^0_{\text{param}}} \Big/ \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}} = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}},$$

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

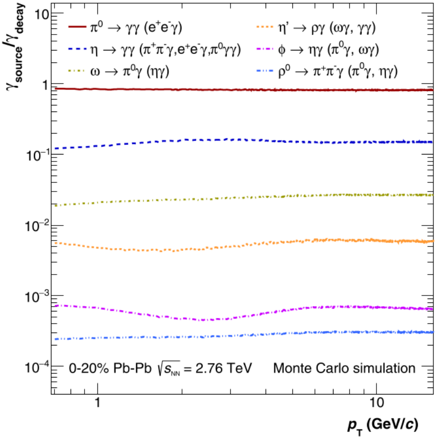
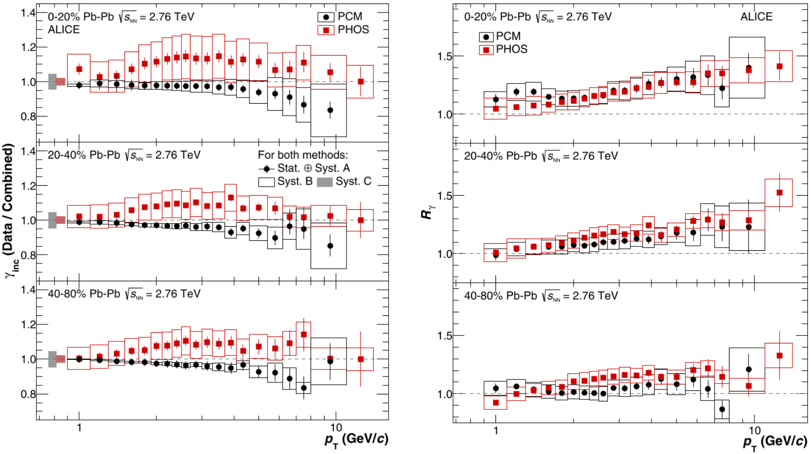
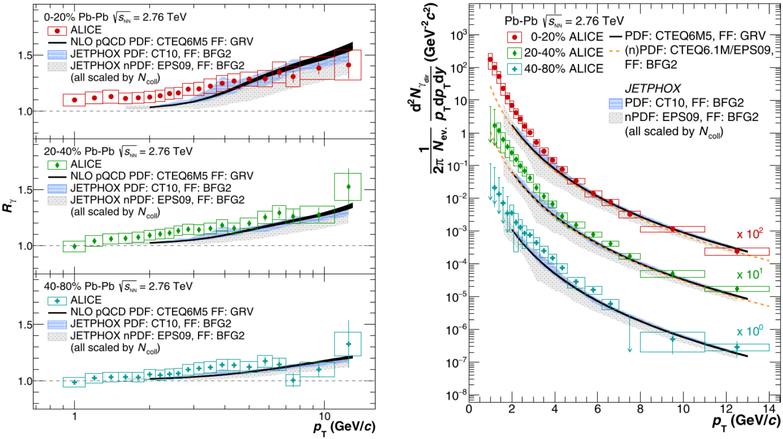


Fig. 1. (Color online.) Relative contributions of different hadrons to the total decay photon spectrum as a function of the decay photon transverse momentum (PCM case).

Inclusive and Direct Photons



Direct Photons



Results from PHENIX and ALICE

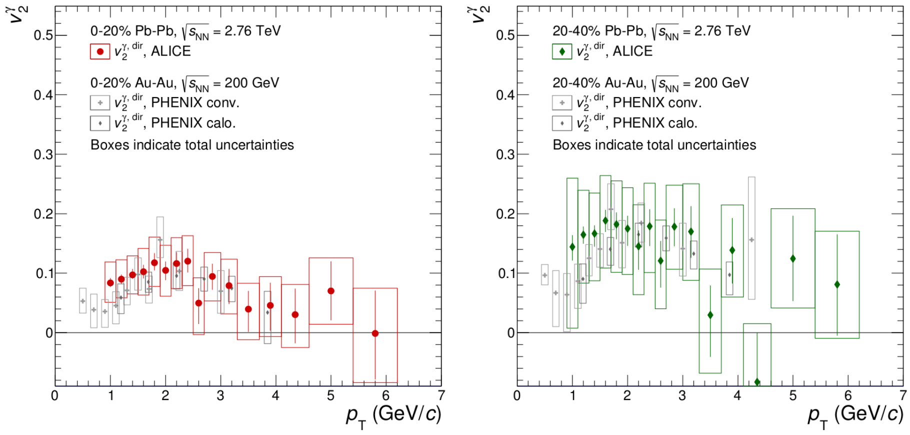
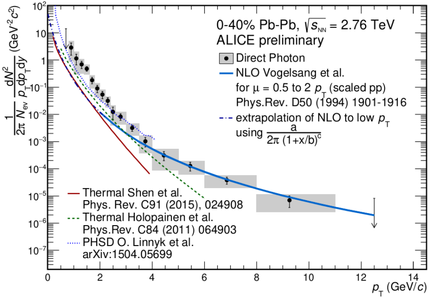


Fig. 5: (Color online) Elliptic flow of direct photons compared with PHENIX results [26] for the 0–20% (left) and 20–40% (right) centrality classes. The vertical bars on each data point indicate the statistical uncertainties and the boxes the total uncertainty.

Temperature estimation



$$A \cdot \exp\left(-\frac{p_T}{T_{\text{eff}}}\right) \text{ for } p_T \leq 2.2\,\text{GeV/c}$$

$$T_{\text{eff}} = 304 \pm 51_{\text{stat+sys}}\,\text{MeV (ALICE, LHC)}$$

$$T_{\text{eff}} = 219 \pm 19_{\text{stat}} \pm 19_{\text{sys}}\,\text{MeV (PHENIX, RHIC)}$$

Advantages of Higher Energy (5.02 TeV)

- Increased energy density of the QGP:
  - Higher collision energy leads to a higher initial energy density of the created QGP. This allows for the formation of a more strongly interacting and longer-lived QGP state.
  - The higher energy density enables the exploration of the QGP phase diagram in more extreme conditions, providing insights into the behavior of matter under more extreme temperatures and densities.
- Enhanced temperature of the QGP:
  - The higher collision energy corresponds to a higher temperature of the QGP, allowing for the study of the QGP in a regime where the QCD coupling constant is small. This facilitates perturbative calculations and theoretical descriptions of the QGP state.
  - The enhanced temperature provides access to higher energy scales and allows for the study of rare processes, such as the production of high-mass resonances and heavy flavor particles, which can provide information about the properties of the QGP.
- QGP phase diagram study in more extreme conditions:
  - By increasing the collision energy, one can explore different regions of the QGP phase diagram, including the search for a possible critical point or the study of the transition from the QGP to hadronic matter.
  - The higher energy allows for measurements of rare phenomena and the investigation of more exotic signatures, such as the search for deconfined quark matter or the formation of exotic states of matter.

Statistics of our analysis

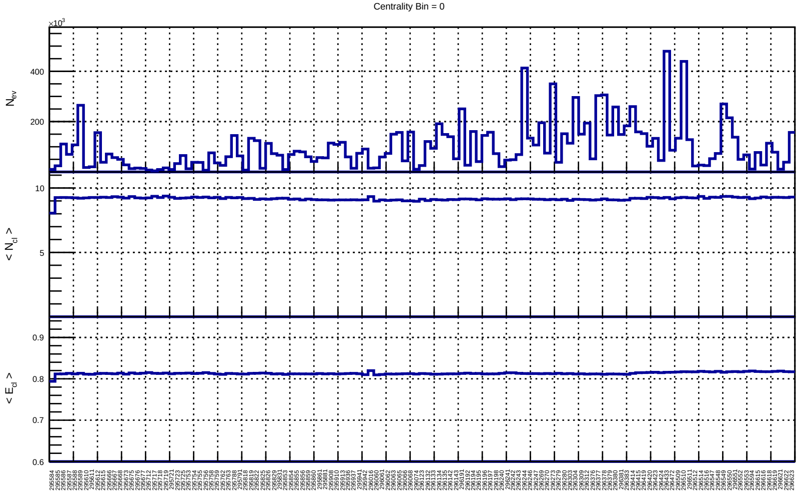
Centrality bin wise event statistics for run period LHC18r and LHC18q

Centrality bin number	Collision centrality	LHC18r	LHC18q
0	0-20%	8.228×10^6	12.97×10^6
1	20-40%	8.268×10^6	13.03×10^6
2	40-60%	8.266×10^6	13.04×10^6
3	60-80%	8.266×10^6	13.04×10^6
4	80-100%	8.206×10^6	12.89×10^6
	Total statistics	41.234×10^6	64.970×10^6

Table: Statistics of events for the run period LHC18r and LHC18q

Run period	Range of run numbers	Number of selected runs
LHC18r	296690-297624	58
LHC18q	295581-296623	131

Table: Selected run number range for our analysis


Centrality Bin = 0
×10^3
400
200
N_ev
10
5
< N_cl >
0.9
0.8
0.7
0.6
< E_cl >

π^0 invariant mass from two photons decay

- $\pi^0 \to \gamma + \gamma$
- $M_{\gamma\gamma} = \sqrt{2E_{\gamma_1} E_{\gamma_2} (1 - \cos\theta)}$
- For signal photons from same event are selected and for background signal from different events are also selected

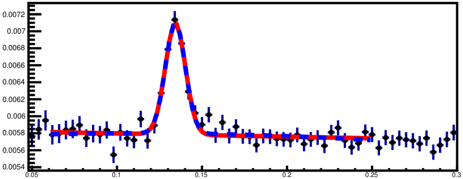
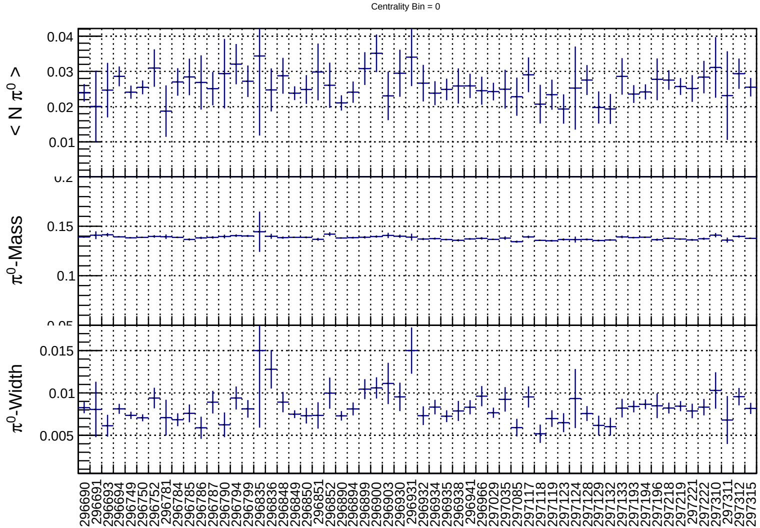
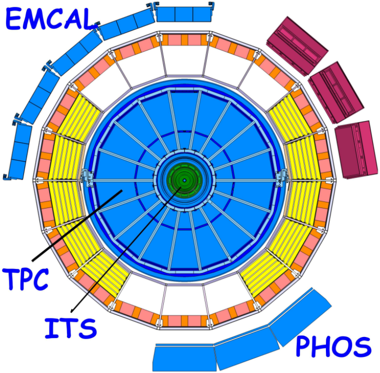


Figure: Gaussian(signal) + second degree polynomial(bkg) fitting

Run-by-run calibration by π^0 invariant mass reconstruction

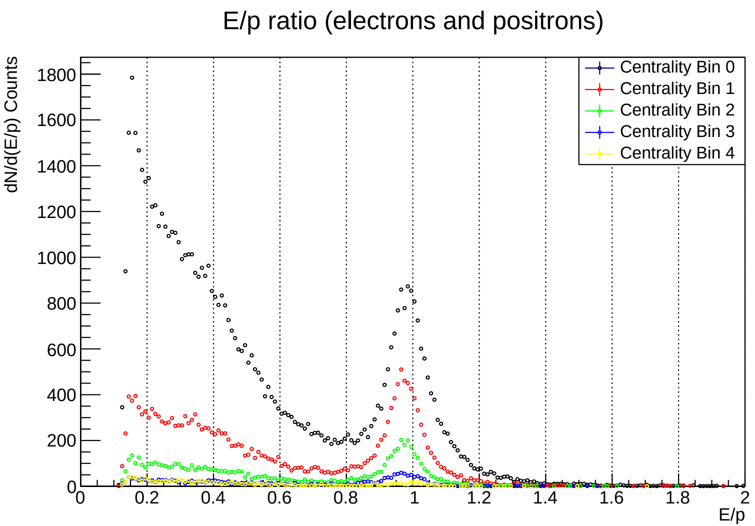


Energy calibration by taking E/p ratio of electrons



- $$E = \sqrt{(p^2 + m_e^2)}$$
- $m_e = 0.0005GeV << p(\sim GeV)$
- E $\approx$ p or, E/p $\approx$ 1
- 'p' is measured by ITS and TPC using curvature of the trajectory whereas 'E' is measured in PHOS

Analysis result: E/p ratio of electrons and positrons



Upcoming work plan

- Photon decay background with Monte-Carlo of neutral mesons (π^0, η, ω...)
- Photon sample purity : (Not all clusters are formed by photon)

$$N_{\text{cluster}} = N_\gamma + N_{e^\pm} + N_{\pi^\pm} + N_{K^\pm} + N_p + N_{\bar{p}} + N_n + N_{\bar{n}} + N_{K_L^0}$$

$$\text{Purity} = \frac{N_\gamma}{N_{\text{cluster}}}$$

- Acceptance and efficiency correction :
  - Not all photons that pass through are detected (dead region, energy threshold, geometric limitations)
  - Trigger efficiency determines how many photons are registered
- Double ratio(R_γ) and elliptic flow analysis
- π^0 transverse momentum distribution for different centralities
  - Centrality dependance of photon production

Final goal

To obtain a physically meaningful results(e.g. yield, elliptic flow etc.) on direct photon production

which is a part of ALICE's effort to reach the following big goals

- To find out whether the QCD transition is of first-order or second order and understanding the formation of QGP and its properties
  in terms of its temperature, shape, viscosity and equation of state
- Testing the predictions of Field QCD and Lattice QCD
- Understanding quark confinement and parton distribution functions within nucleons

Summary

- QCD phase transition and Quark-Gluon Plasma (QGP)
- Advantages of Heavy ion collisions
- Types of direct photons and their measurement
- Previous results demonstrating the presence of direct photons and anisotropic flow
- My analysis of data quality assurance and energy calibration
- Upcoming working plans

THANK YOU FOR LISTENING !