Photon studies update for ALICE 3

HighRR meeting

Abhishek Nath

Physikalisches Institut
Heidelberg University

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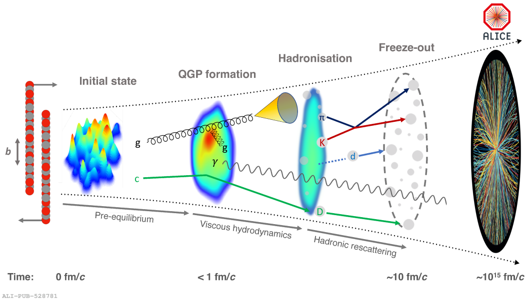
1. Introduction
2. Pre-shower detector
3. Neutral meson and direct photons
4. Summary and outlook

Introduction: QCD interaction and ALICE



- Quantum Chromodynamics: gauge field theory describing the strong interaction
- QUESTIONS:
  → What are the thermodynamic and global properties the QGP produced at the LHC?
  → How does the QGP affect the formation of hadrons?
  → What is the nature of the initial state of heavy-ion collisions?
  → How chiral symmetry is restored in QGP?

Introduction: A Large Ion Collider Experiment

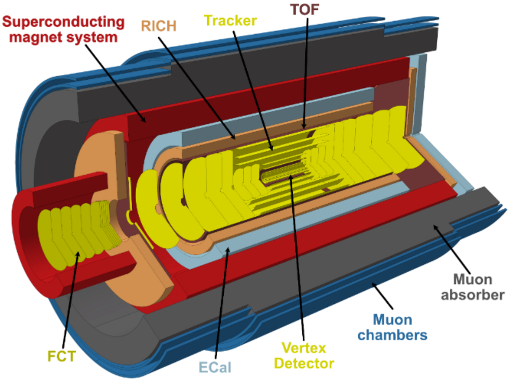
Observables	Kinematic range
Heavy-flavour hadrons	$p_T \to 0$, $\lvert\eta\rvert < 4$
Dielectrons	$p_T \approx 0.05$ to $3\,\mathrm{GeV}/c$, $M_{ee} \approx 0.05$ to $4\,\mathrm{GeV}/c^2$
Photons	$p_T \approx 0.1$ to $50\,\mathrm{GeV}/c$, $-2 < \eta < 4$
Quarkonia and exotica	$p_T \to 0$, $\lvert\eta\rvert < 1.75$
Ultrasoft photons	$p_T \approx 1$ to $50\,\mathrm{MeV}/c$, $3 < \eta < 5$
Nuclei	$p_T \to 0$, $\lvert\eta\rvert < 4$

- ALICE: detector system to study heavy-ion collision focusing on strong interaction and its properties (like QGP)
- Scope of improvements:
  $\rightarrow$ charm and beauty hadrons measurements and their correlations across wide rapidity
  $\rightarrow$ High-precision electromagnetic radiation down to very low p_T
  $\rightarrow$ measurements of net-quantum number fluctuations over a wide rapidity range

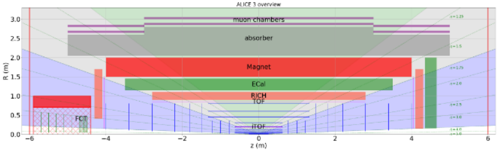
Need for a novel detector with a high read-out rate, superb pointing resolution, and excellent tracking and particle identification over a large acceptance

Introduction: ALICE 3

- ALICE 3: An ultra-light silicon wafer-based detector system with very low momentum tracking capabilities for high luminosity collisions
- bent cylindrical wafer-scale CMOS Active Pixel Sensors thinned to 30 μm
- Better pointing resolution: first tracking layer closest to the interaction point till date
- Retractable vertex detector: large aperture for beams at injection energy
- Wide rapidity range ($|y| < 4$)
- Photons: FCT, ECAL (1 MeV/c - 50 GeV/c) and PCM



Inner Tracker



Layer	Material thickness (% X_0)	Intrinsic resolution (μm)	Barrel layers: Length ($\pm z$) (cm)	Barrel layers: Radius (r) (cm)	Forward discs: Position ($\|z\|$) (cm)	Forward discs: R_{in} (cm)	Forward discs: R_{out} (cm)
0	0.1	2.5	50	0.50	26	0.50	3
1	0.1	2.5	50	1.20	30	0.50	3
2	0.1	2.5	50	2.50	34	0.50	3
3	1	10	124	3.75	77	5	35
4	1	10	124	7	100	5	35
5	1	10	124	12	122	5	35
6	1	10	124	20	150	5	80
7	1	10	124	30	180	5	80
8	1	10	264	45	220	5	80
9	1	10	264	60	279	5	80
10	1	10	264	80	340	5	80
11	1				400	5	80

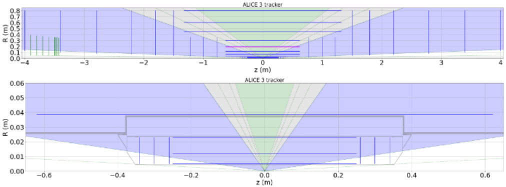
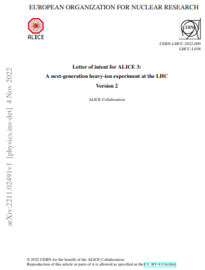


Figure 81: Schematic $R-z$ view of the full tracker (top) and of the vertex detector separately (bottom). The blue lines represent the tracking layers. The FCT disks are marked in green. In addition, the beampipe and vacuum vessel of the vertex detector are shown in grey.

Detector systems

Component	Observables	Barrel ($|\eta| < 1.75$)	Forward ($1.75 < |\eta| < 4$)	Detectors
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\mu m$ at $p_T = 200 MeV/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{DCA} \approx 30\mu m$ at $p_T = 200 MeV/c$, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\mu m$, $R_{in} \approx 5 mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	(Multi-)charm baryons, dielectrons, photons ...	$\sigma_{p_T}/p_T \approx 1--2\,\%$		Silicon pixel tracker: $\sigma_{pos} \approx 10\mu m$, $R_{out} \approx 80 cm$, $L \approx \pm 4 m$, $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{tof} \approx 20 ps$, RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5 mrad$
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{tof} \approx 20 ps$, RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5 mrad$
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_T \sim 1.5$ GeV/c at $\eta = 0$		steel absorber: $L \approx 70 cm$ muon detectors
ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
ECal	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Soft photon detection	Ultra-soft photons		measurement of photons in p_T range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

Table 4: Detector requirements


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN-LHCC-2022-009
LHCC-I-038

arXiv:2211.02491v1 [physics.ins-det] 4 Nov 2022

Letter of intent for ALICE 3:
A next-generation heavy-ion experiment at the LHC
Version 2

ALICE Collaboration

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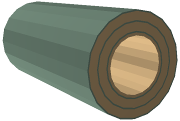
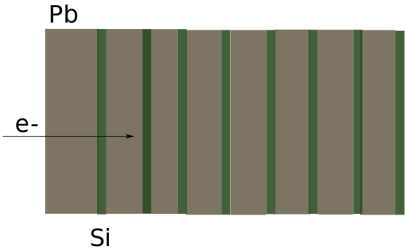
Letter of intent for ALICE 3:
https://arxiv.org/abs/2211.02491

Introduction: Pre-shower detector



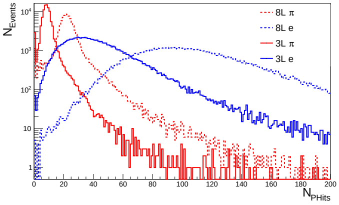


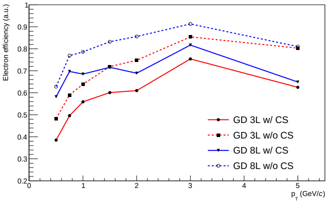
Aim: electron efficiency over 50% and a pion rejection factor of 1000 for all pT bins

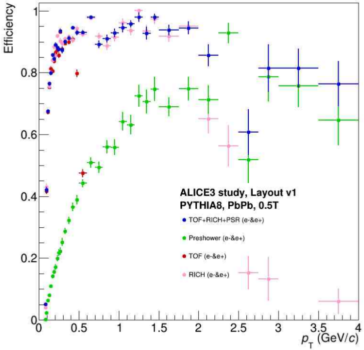
- GEANT4 simulation
- Successive shower and detection layers (8)
- Shower layer: 0.5 cm Pb
- Detector layer: 50 μm Si
- Length in z: 400 cm
- Overlay the detection layers with an Alpide pixel grid
  → Pixels have binary readouts
  → Pixels have a finite size
  → Y(Col): 29.24 microns
  → Z(Row): 26.88 microns
  → X(depth): 45 microns
- Electron gun perpendicular to the detector

Manual optimization of a 3-layer setup

Based on the distribution of the hits, a 3-layer setup is considered with and without charge sharing.
The final result is parametrized and implemented in DelphesO2





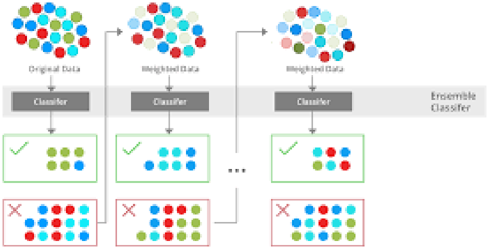


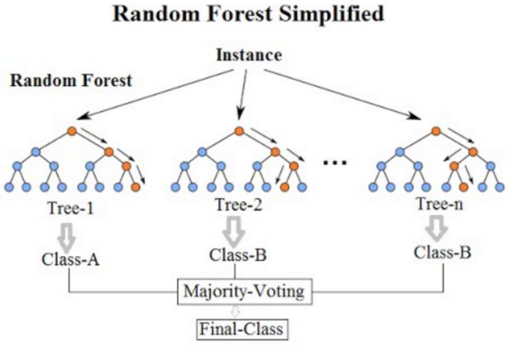
Both RICH and TOF detectors lose efficiency above 2.5 GeV/c.
As can be seen, the addition of a shower detector improves the performances above 2 GeV/c

Layer optimisation with machine learning

Needed an optimization to read out certain layers to reduce cost. Two methods are compared :

XGBoost

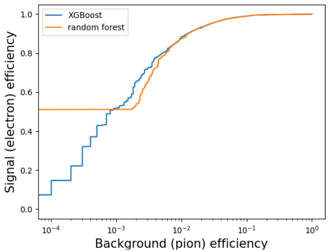


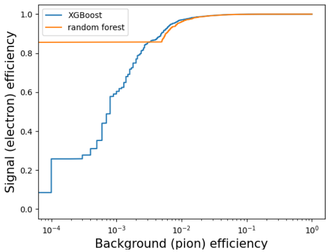


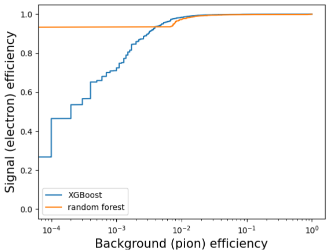
Here the data for hits were taken and were varied wrt the number of layers

choosing ML algorithm

Two algorithms were compared for different p_T (0.5, 0.75 and 1 GeV/c) with no charge-sharing data



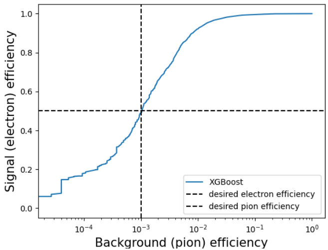


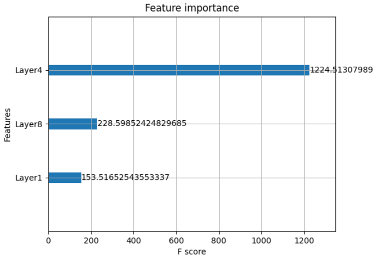


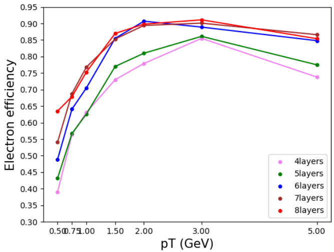
XGBoost gave better results for electron identification on these scenarios and was chosen for further analysis

minimising layers

With XGBoost, the next task was to determine which layers contributed most to electron identification and optimize the number of layers
we took data hits of various layers and also their summed contributions.



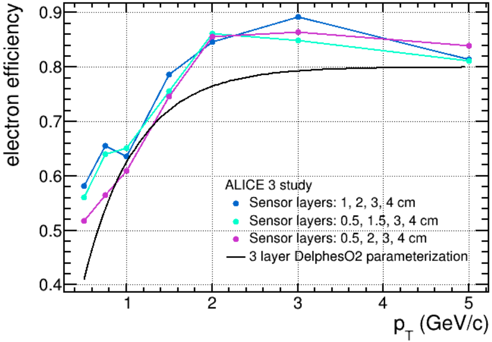




An efficiency of at most 65% is reached at low p_T (0.5 GeV/c) with all layers. However, an efficiency of over 80% can be reached even with 4 layers past 1.5 GeV/c all at 1000 pion rejection factor

4 layer setup comparison

A combination of 4 layers gave the best results. So various combinations of 4-layer detector systems were tried out



- Using all to least layers, finally 4 layers setup was found optimal especially combination (3,6,7,8) and combination (4,6,7,8)
- This is expected as the initial layers deposited energy from electrons and the later layers separated it from pions
- The 4-layer setup gave an optimal efficiency of 60% at lower p_T
- To reduce very high costs, a two-layer setup was tried but it didn't achieve a 50% efficiency at all p_T
- Currently a sampling calorimeter is being considered

The 4 layered versions of the pre-shower detector gave better efficiency than the DelphesO2 implementation and are the optimal outcome. Due to high-cost estimates, it has been excluded from LOI

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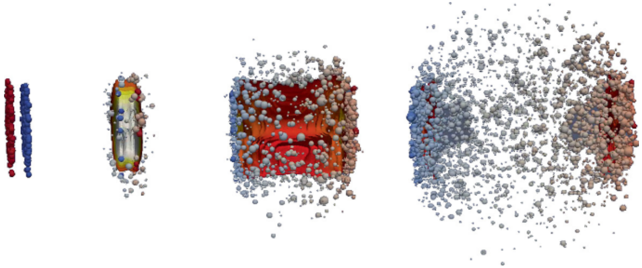
2. Pre-shower detector
3. **Neutral meson and direct photons**
4. Summary and outlook

Photons as probe

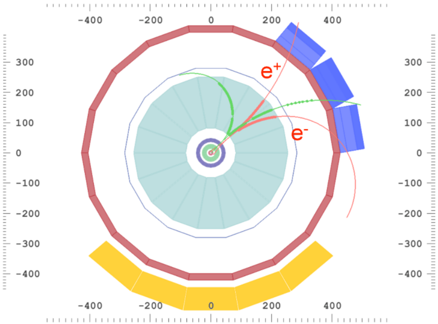


- **Inclusive photons**: photons from all sources
- Can escape QCD medium without being affected
- Carry information on the medium's space-time expansion and temperature

- **Decay photons**: photons from hadronic decays
- Main contributions from π^0 and η mesons
- High precision decay photon measurement necessary

For our study, we focus on neutral mesons and direct photons using the conversion method

Introduction: Photon Conversion Method



- Photon Conversion Method (PCM): Converted photons measured by reconstructing e^+e^- pairs

  —> Photon momentum resolution linked to charged particle momentum resolution.

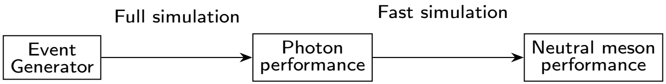
  —> Good reconstruction at low p_T compared to calorimeter

- π^0 and η are reconstructed in their respective 2 γ decay channel

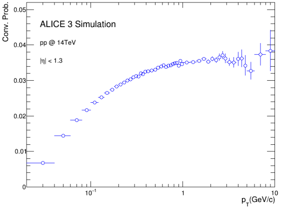
Neutral meson Monte-Carlo performance studies using PCM

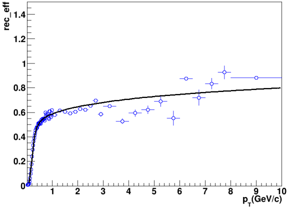
	Barrel	Forward
Rapidity	0<|y|<1.3	1.75<|y|<4.0
Conversion	r<22 cm	0<|z| <135 cm
Reconstruction	5 layers 22 <r <100 cm	5 disks 135 <|z| <200 cm

- Full simulations of pp $\sqrt{s} = 14$ (PbPb $\sqrt{s} = 5.52$)TeV using PYTHIA 8.2 (pp: 9.6∗10^6 ; PbPb: 1.1∗10^6 events)
- Results are scaled to expected ALICE 3 luminosity
- Integrated Luminosity = 33.6 nb^{-1} (PbPb)
- **Full simulation**: Get photon conversion and photon reconstruction efficiencies
- **Fast simulation**: Use the parameterised curves to get photon samples



Full simulation: Single photon results





- No particle tracking available at the forward rapidity
- Barrel $\rightarrow$ Photon conversion probability and reconstruction efficiencies
- parameterized and extended to forward rapidities $\rightarrow$ used as input to select photon pairs for meson analysis

Conversion probability (Barrel):

Barrel: $$\frac{0.0354334 * p_T^{1.47512}}{(0.0156461 + p_T^{1.43599})}$$

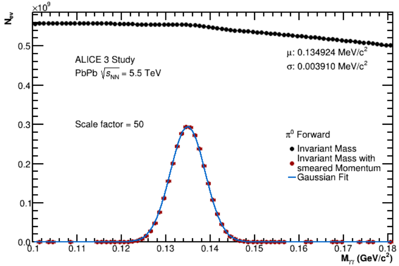
Reconstruction efficiency (Barrel):

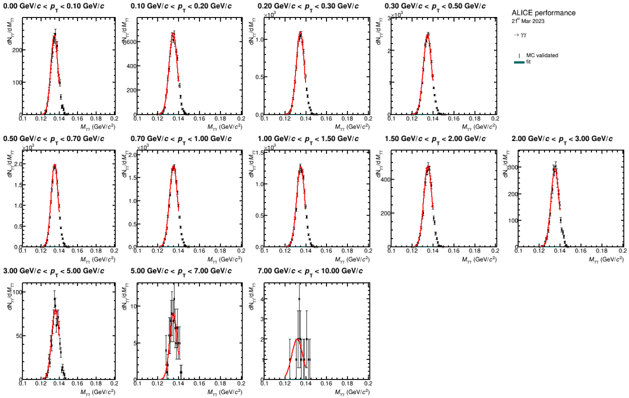
$$\frac{0.589182 * p_T^{3.85834}}{(0.00296558 + p_T^{3.72573})}$$

Conversion probability: (Forward)

$$\frac{-0.00824825 * (p^{-0.503182} - 11.3113 * p)}{(0.223495 + p^{1.08338})}$$

All photons → photons pairs → Meson invariant mass reconstruction
PbPb events: $1.1*10^6$



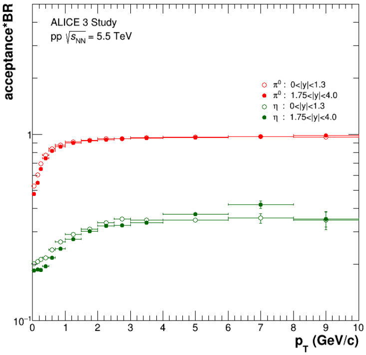


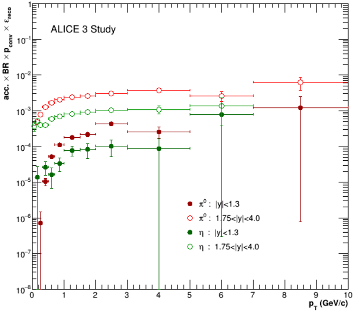
$$p_T = 2GeV/c,$$

Black = signal+ combinatorial background
Blue = Gaussian fits

$$M_{\gamma\gamma} = \sqrt{2E_{\gamma1}E_{\gamma2}(1-\cos\theta_{12})}$$

Results: acceptance and net efficiency





$$A_{\pi^0(\eta)}(p_{\mathrm{T}}) = \left. \frac{N^{\text{daughters in acceptance}}_{\pi^0(\eta)}(p_{\mathrm{T}})}{N^{\text{all}}_{\pi^0(\eta)}(p_{\mathrm{T}})} \right|_{|y|<y_{\max}}$$

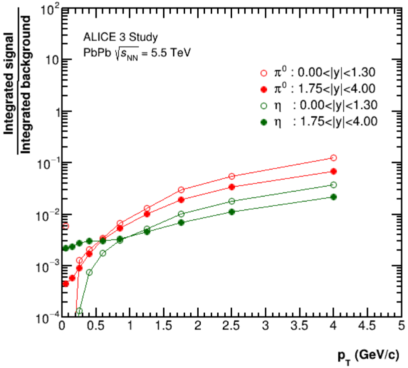
$$\epsilon_{\pi^0(\eta)}(p_{\mathrm{T}}) = \frac{N^{\text{validated}}_{\pi^0(\eta)}(p_{\mathrm{T}})}{N^{\text{daughters in acceptance }(\eta)}_{\pi^0(\eta)}(p_{\mathrm{T}})}$$

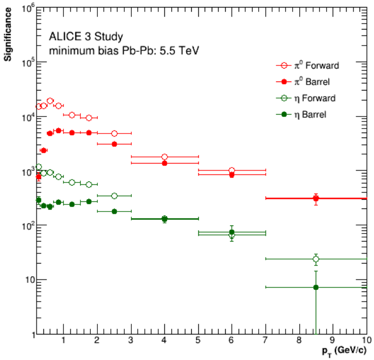
PbPb: meson signal and background

- Signal : S = Parameters * Acceptance * Branching ratio* Reconstruction efficiency * Meson production per event per bin width[1]
- Background : B = Parameters * Background count per event per bin width
- Significance : $\frac{S}{\sqrt{S+B}}$
- Parameters
  - Collision cross-section : 7.8b
  - Luminosity for Run 5+6: pp->$18 * 10^{6}$ nb^{-1} PbPb->35 nb^{-1}
- Integral range:
  Meson mass $+/-0.05$ (η) or $+/-0.01$ (π^{0}) (GeV/c^{2})

[1] From pythia

Result: meson significance



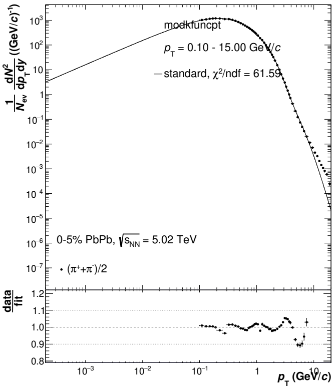


- Higher significance at forward rapidity
- Significance quite high till very low p_T with nearly no drop in y

Large statistics → negligible statistical uncertainties → focus on systematic uncertainties projections

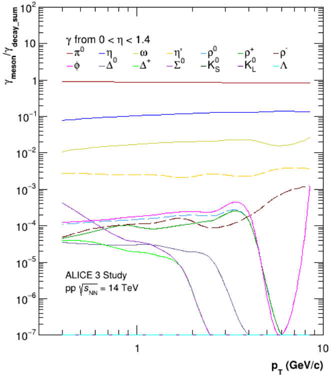
Cocktail simulation from charged pions

A detailed photon contribution from electromagnetic meson decay is needed as an input for direct photons. This is done by cocktail simulation:



- Decay Photons
  $\rightarrow$ cocktail simulation
- low centrality
  $\rightarrow$ charged pion as proxy for π^0
- spectra is parameterized
- m_T scaling is applied to calculate the contribution of other decay mesons

——————————————->



Photon projections for ALICE 3

Direct photons: Inclusive - Decay $=$ **Thermal** ($<$ 3 GeV), **Prompt** ($>$ 5 GeV),**pQCD**

$R_\gamma = \frac{\gamma_{Inclusive}}{\gamma_{Decay}}$

$\gamma_{Direct} = \gamma_{Inclusive} * (1 - \frac{1}{R_\gamma})$

Direct Photons —> Using hydrodynamics model[a]

Systematic uncertainties(%) from tables

x « 1

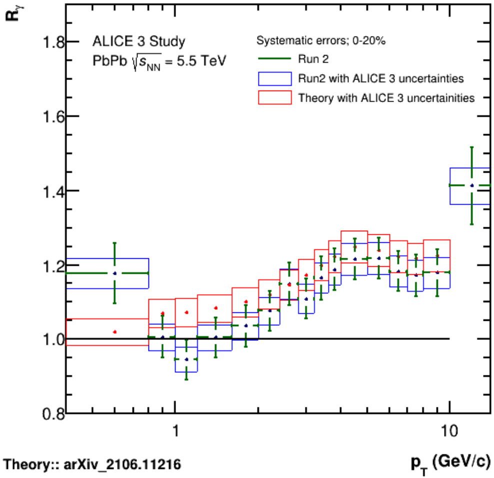
γ_{Direct} pub. : arXiv:1811.02220

[a]Multimessenger heavy-ion collision physics, Charles Gale et al. arXiv:2106.11216 .

Invariant yield	γ_{Direct} pub.	PbPb run 2	ALICE 3
Track quality	0.6	x	x
Electron PID	1.5	∼(3+1+1+1)	∼(1.5+1)
Photon selection	4	∼(0.5+0.5+x)	x
Material budget	4.5	2	∼ 1
Others:	-	x	x
Quad sum:	**6.23**	**6**	**3**

R_γ	γ_{Direct} pub	PbPb run 2	ALICE 3
Track quality	0.7	<1	<1
Electron PID	1.2	∼ (2+2+1+1)	∼(1.5+2+1)
Photon selection	3.2	∼(0.5+0.5+0.5)	∼ 1
Material budget	4.5	2	∼ 1
0 yield	1.6	2	-
0 spectrum	0.5	-	-
yield	1.4	-	-
shape	1.6	-	-
Others:	-	2	x
Quad sum:	**6.3**	**6**	**3.5**

Double ratio run 2 vs Projections



Theory:: arXiv_2106.11216

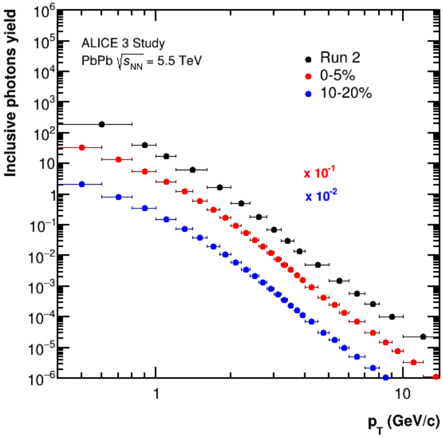
- Hydrodynamical model (thermal, pre-equilibrium and prompt photons)

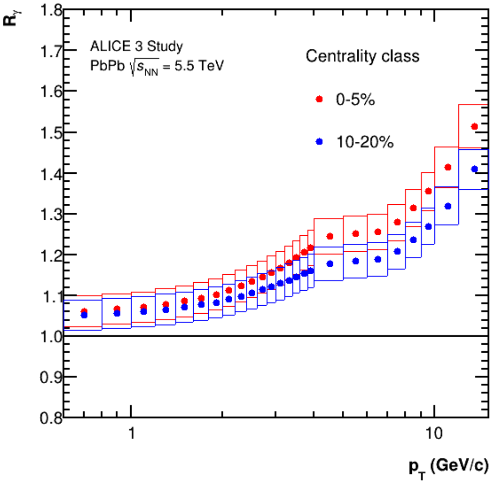
  —> R_γ is > 1 across all p_T bins

- Trying more central collisions

  —> 0-5% and 10-20% centrality class

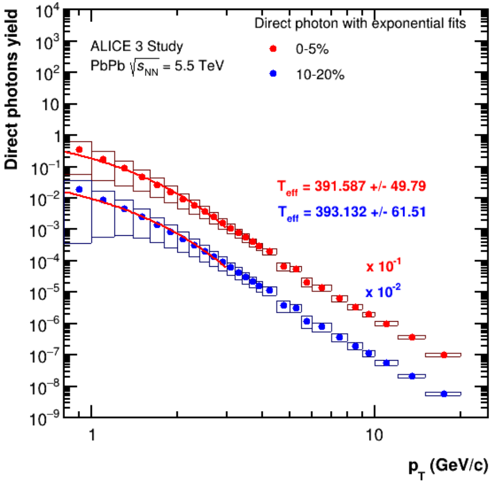
Inclusive photon and decay photons yields across centralities





The same uncertainties from the table across all centrality —> propagated to the direct photons yield

Direct photons across centrality



- At a similar scale, improvement in the uncertainty is noticed
- Other sources of uncertainties needed to be reduced

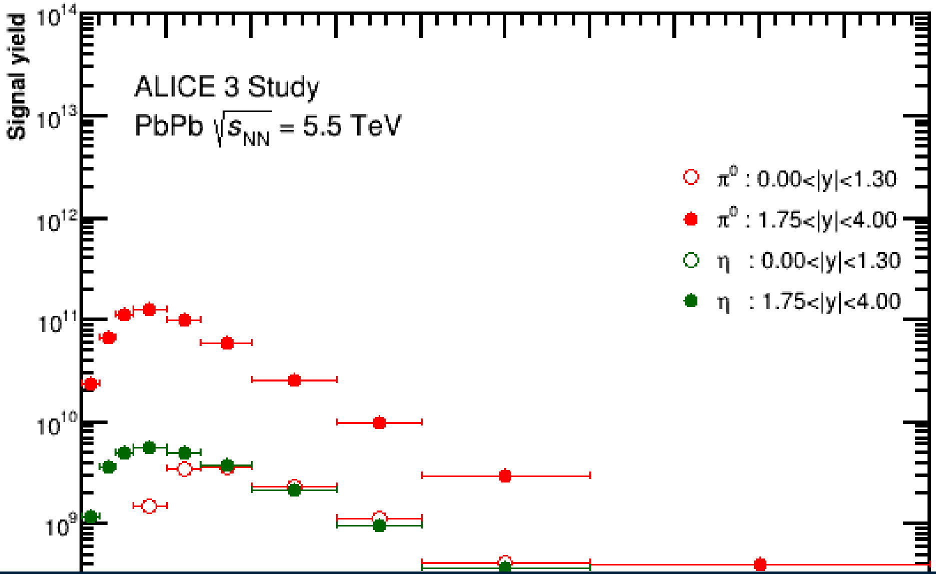
Summary and outlook

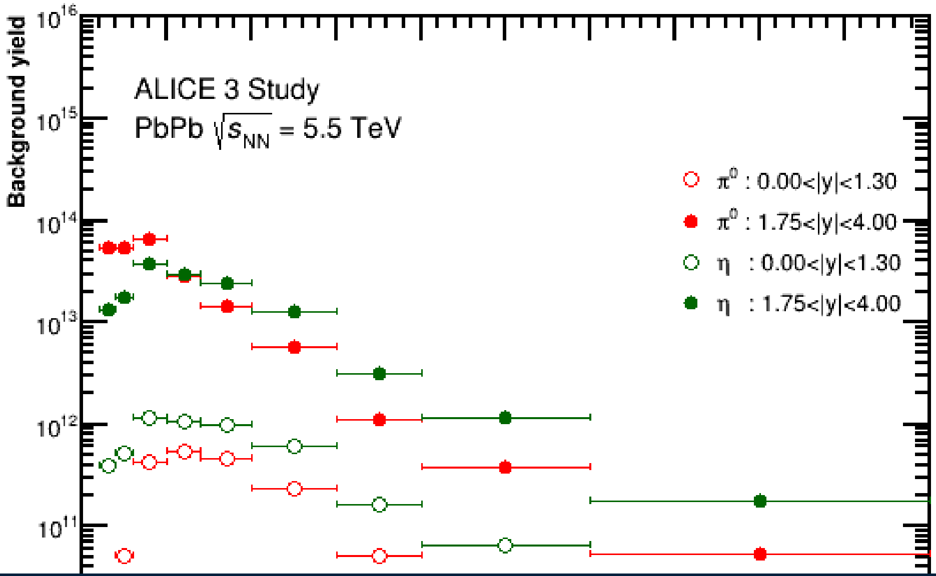
- A 4-layered Preshower detector is found to be optimum for di-electron and photon studies providing at least 50% efficiency with a 1000 pion rejection factor. Currently, possibilities for a cost-effective ECal are being checked

- An initial study on direct photon for ALICE 3 is presented
  → Neutral meson measurement: Extended rapidity (along with boost) would significantly increase the precision of the measurements
  → Direct photons: An estimate of systematic uncertainties is done. Both upper and lower bound is obtained even at low p_T
  → More efforts on reducing uncertainties in material budgets/ other sources are needed. Studies from ECal results will also improve uncertainty estimates
  → with the inclusion of extended rapidity, improvement is expected

- Outlook: A performance study with PbPb dataset for both neutral meson and direct photons is presented. Progress toward the direction of photon flow is next in line

Thank you


Signal yield
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
ALICE 3 Study
PbPb $\sqrt{s_{NN}}$ = 5.5 TeV
π^0 : 0.00<|y|<1.30
π^0 : 1.75<|y|<4.00
η : 0.00<|y|<1.30
η : 1.75<|y|<4.00


Background yield
ALICE 3 Study
PbPb $\sqrt{s_{NN}}$ = 5.5 TeV
π^0 : 0.00<|y|<1.30
π^0 : 1.75<|y|<4.00
η : 0.00<|y|<1.30
η : 1.75<|y|<4.00
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}

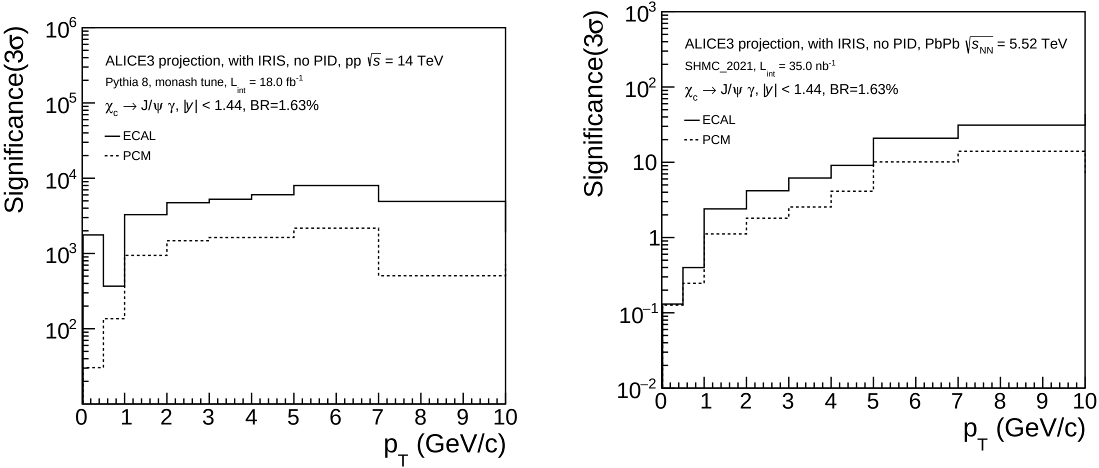
Motivation: Quarkonium states

- Explore new states: P-wave and pseudoscalars
- Test theoretical predictions
- χ_c and χ_b decay to $J/\psi + \gamma$ and $\Upsilon + \gamma$ respectively
- Possibility of J/ψ and Υ and γ reconstruction down to low p_T

Procedure:

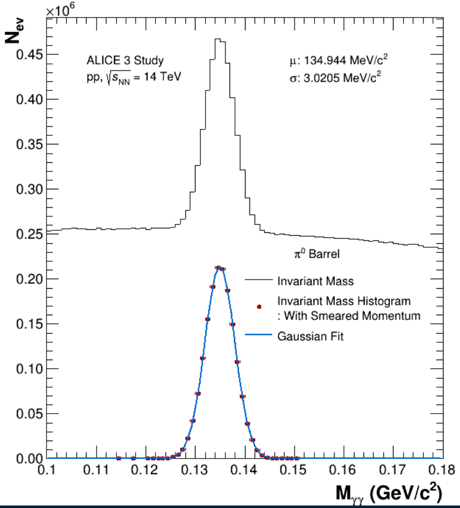
Electron pair —> Invariant mass —> Peak (signal) and background extraction —> Significance

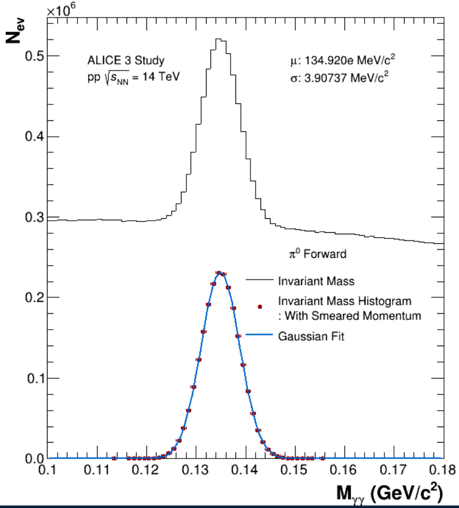
Results: Significance : Barrel



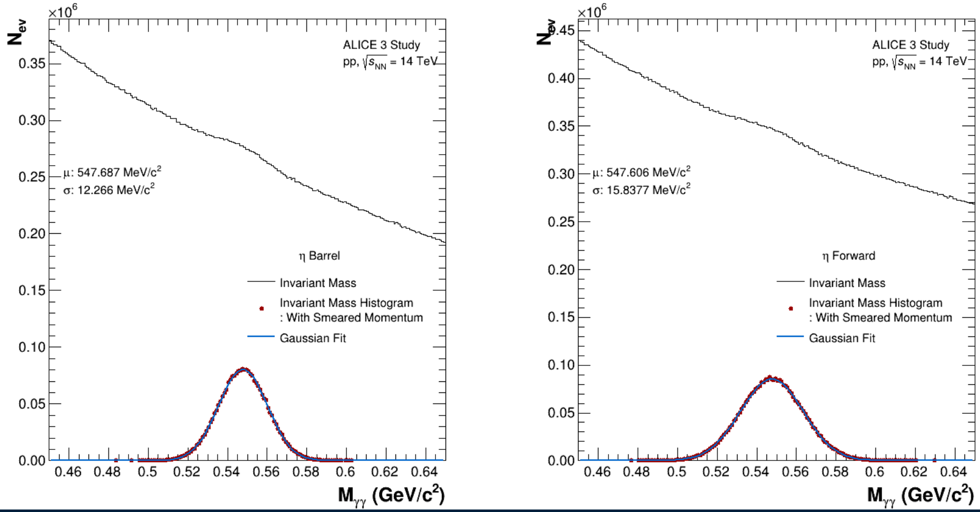
Plots added to LoI

Results: π^0 mass resolution

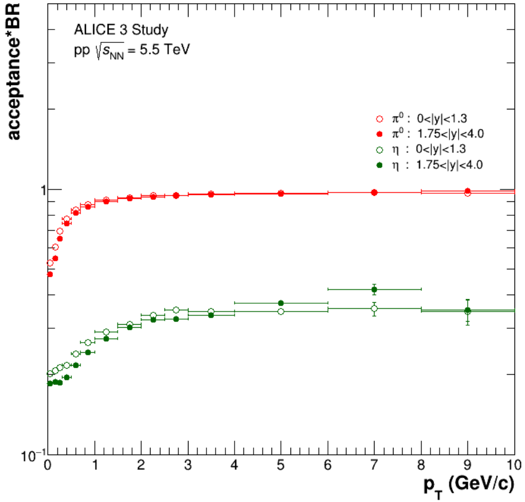


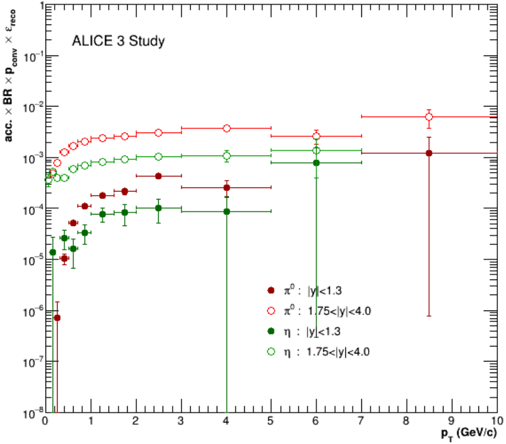


Backup: Results: η mass resolution

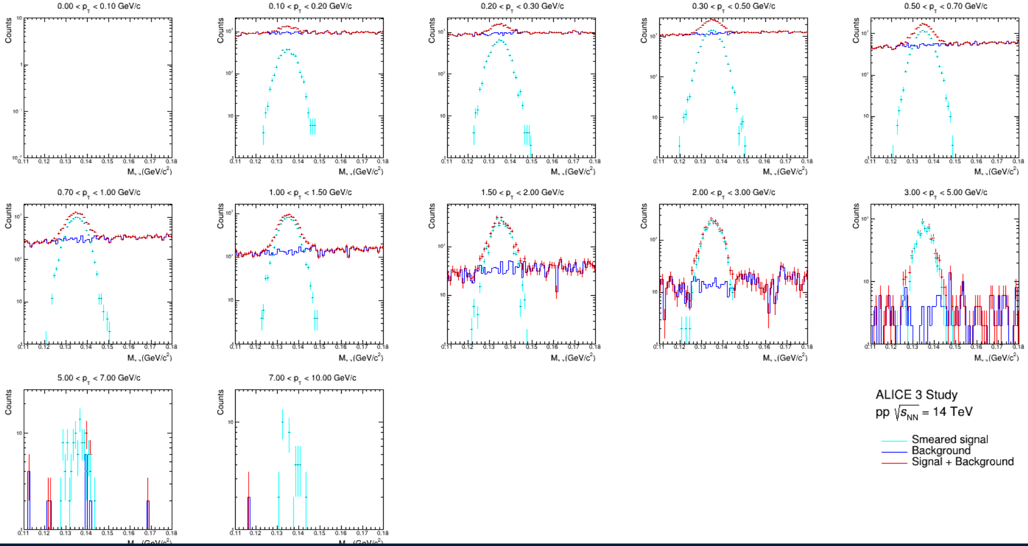


Backup: π^0 and η acceptance and efficiency: PbPb

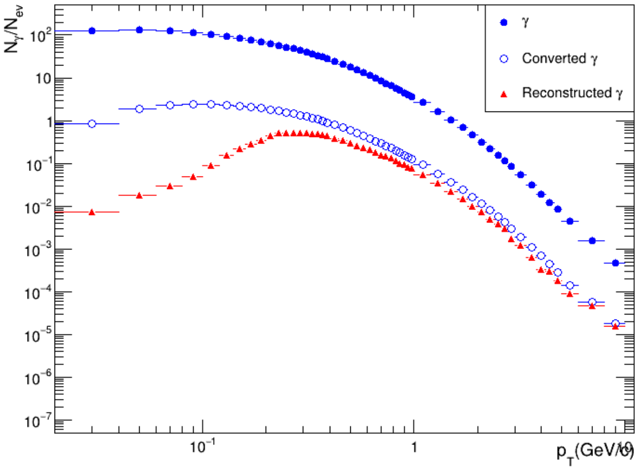




Results: π^0 mass resolution across p_T bins



Backup 3: Results: reconstructed γ



Backup 4: Peak separation with Ecal