Performance and upgrade plans of the ALICE Photon Spectrometer

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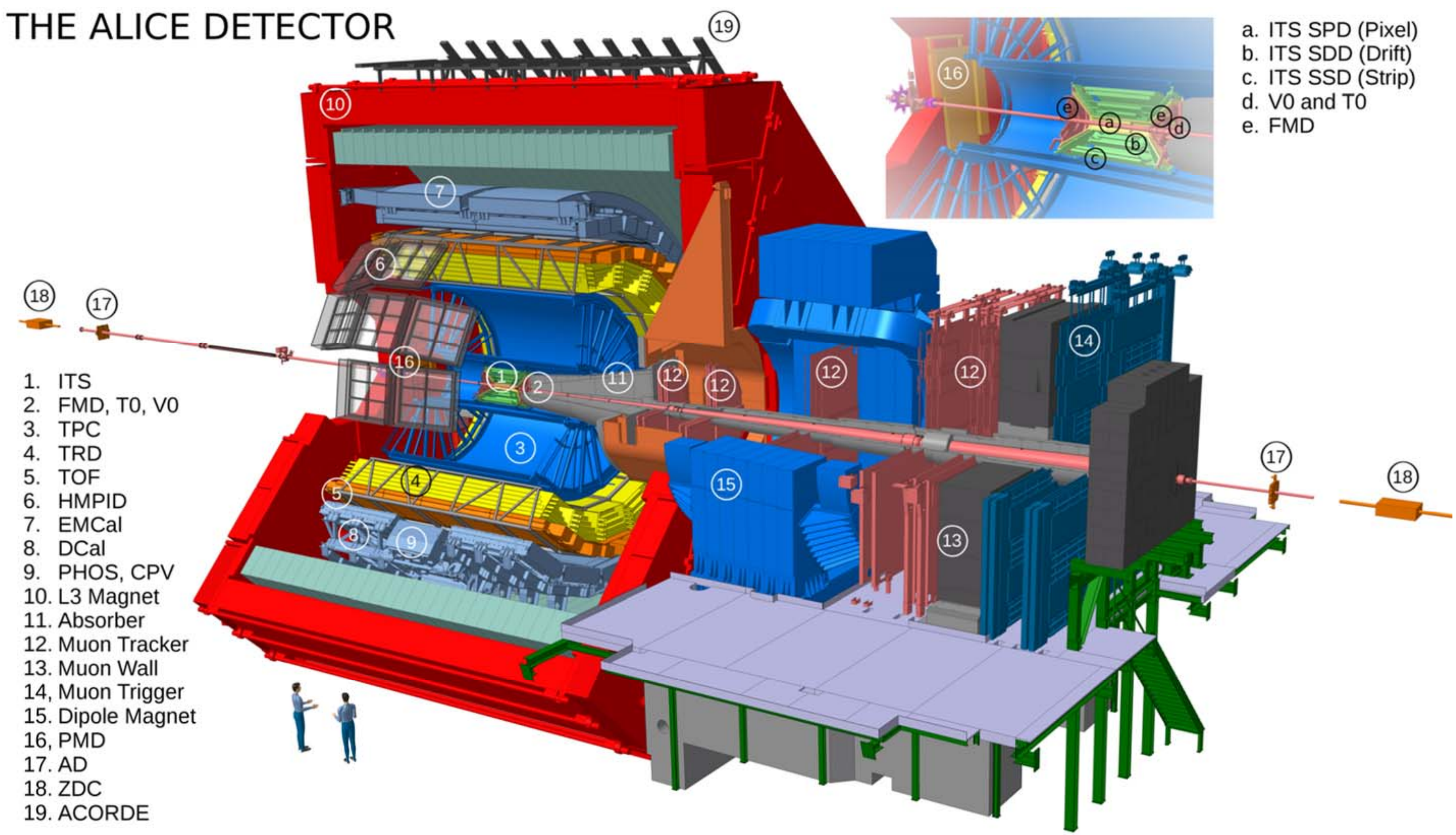
NRC “Kurchatov Institute”

The ALICE experiment at the LHC



- ALICE is designed to study the quark-gluon plasma (QGP)
- Good tracking and PID capabilities are supplemented with electromagnetic-probe measurements with the help of EMCal and PHOS
- Two long data taking periods: 2010-2013 (Run 1) and 2015-2018 (Run 2). Comprehensive studies on hot QCD matter in pp, p-A and A-A collisions at LHC energies

ALICE detector setup from 2011-2013

EMCal calorimeter
Pb/scintillator
Sampling calorimeter
distance to interaction point (IP): 4.28 m
cell size 6×6 cm^2

$|\eta| < 0.7,$
$80° < \varphi < 180°$

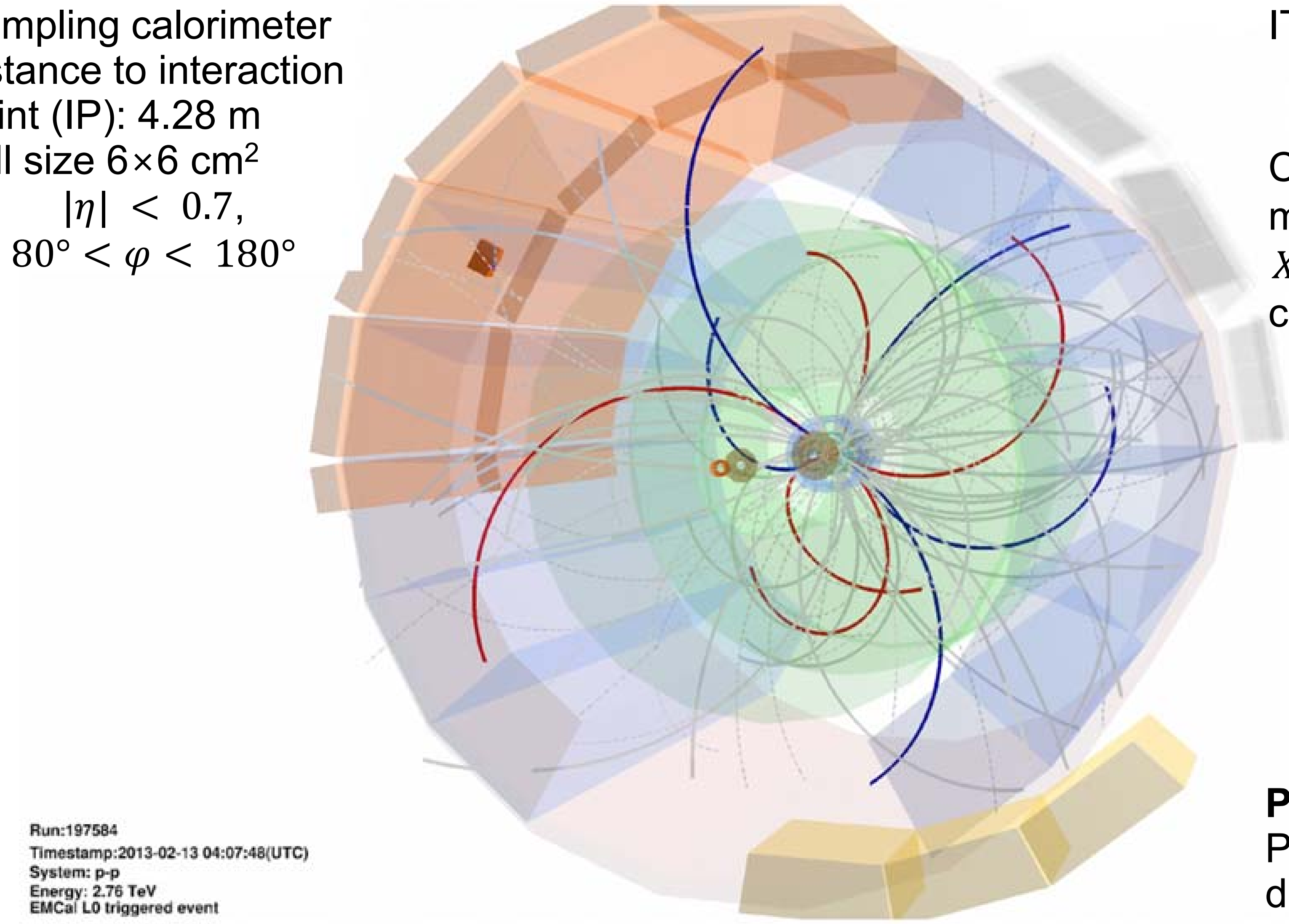
Photon conversion method (PCM)
ITS and TPC

$|\eta| < 0.9,$
$0° < \varphi < 360°$

Conversion in detector material

$X/X_0 = (11.4 \pm 0.5)\%$

conv. Probability ~ 8%

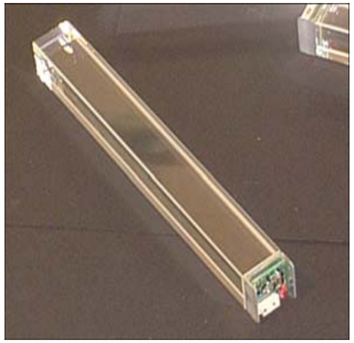


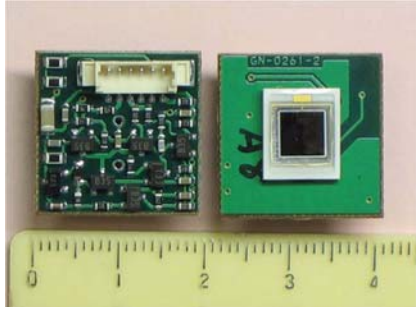
PHOS calorimeter
$PbWO_4$ crystals
distance to IP: 4.6 m
cell size 2.2×2.2 cm^2

$|\eta| < 0.12,$
$260° < \varphi < 320°$

Properties of PHOS

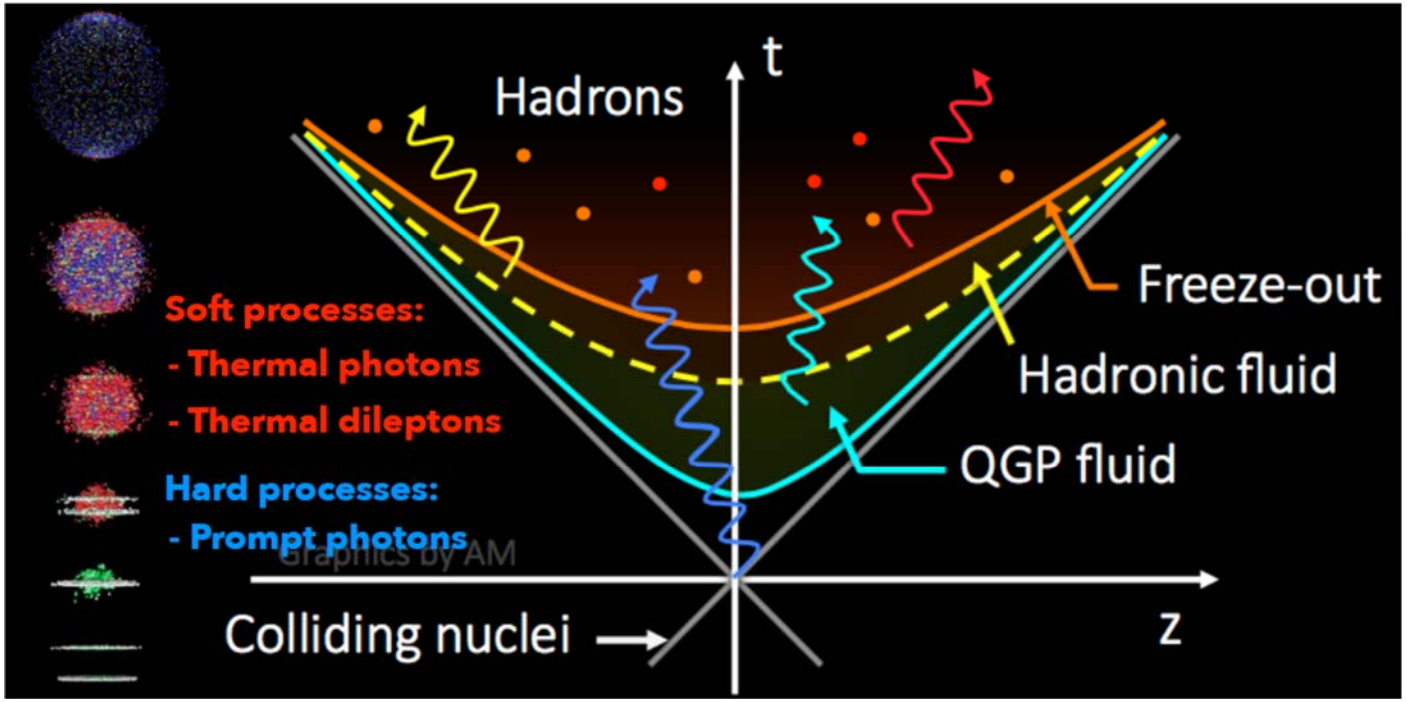
Active element	Homogeneous crystals $PbWO_4$
Molière radius	2.0 cm
Photodetector	Avalanche Photodiode (APD) 5×5 mm^2
Depth	20 X_0
Acceptance	Run 1: $\lvert\eta\rvert<0.12$, $260 < \varphi < 320°$ Run 2: $\lvert\eta\rvert<0.12$, $250 < \varphi < 320°$
Granularity	Cell 2×2 cm^2 $\Delta\varphi\cdot\Delta\eta = 0.0048\cdot0.0048$ rad
Modularity	3+1/2 modules 12544 cells
Dynamic range	0-100 GeV
Energy resolution	$\sigma_E/E = 1.8\%/E \oplus 3.3\%/\sqrt{E} \oplus 1.1\%$
Distance from IP	460 cm, 0.2 X_0





PHOS physics tasks

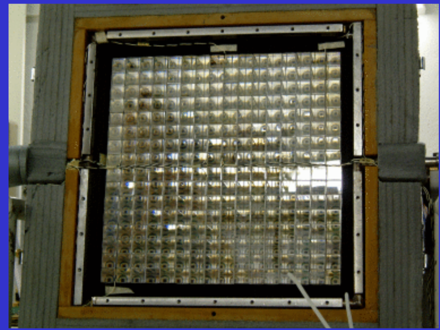
- Main goal: study thermal properties of the QGP through direct photon measurements
- Other subjects: precise neutral meson and direct photon spectra, flow and HBT correlations in pp, p-A and A-A collisions
- Complementary to other neutral meson / direct photon measurements with ALICE (Photon conversion, EMCal).



PHOS yesterday and today

- PHOS has excellent energy and position resolution. But cost is very high. Price in 2000 (ALICE MoU) – 10.5 MCHF (CORE).
- Constant cooling of the whole detector down to -25 °C.
- 8 ALICE collaboration papers utilized data from PHOS.
- PHOS is competitive w.r.t. other e.m. calorimeters at LHC at moderate and low p_T (~$0.1 < p_T < 50$ GeV/c).
- With data from Run 1-3 main limitation for obtaining new physics results will not be statistics, but systematics.
- Ageing of electronics and challenges of achieving better accuracy requires PHOS upgrade beyond Run 3.

2000



PHOS prototype (2003)

2005

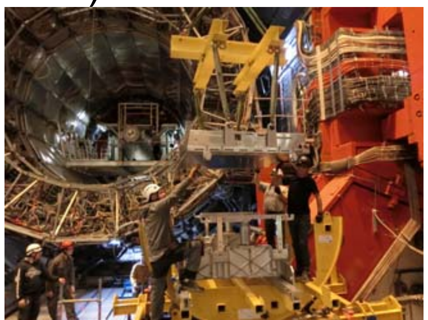
Installation of PHOS (2009)

2010

First LHC HI Run (2010)

2015

Installation of PHOS CPV modules (2013-2019)



Repair and re-installation in ALICE (2019)

2020

2025

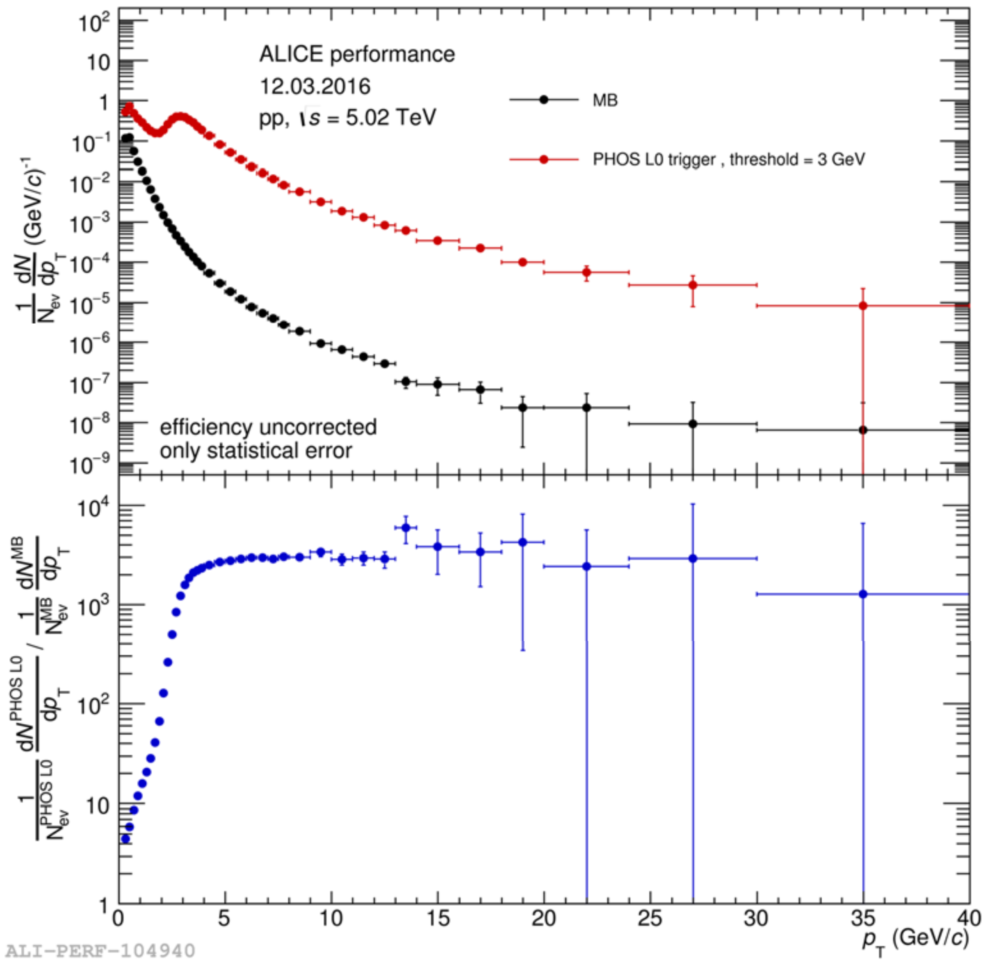
Major upgrade of PHOS (~2025)

Trigger performance

- ALICE calorimeters provide triggers at levels L0 (1.2 μs) and L1 (7 μs)
  - PHOS L0: trigger on energy sum of 4×4 cells within area covered by trigger region units (TRUs) above a threshold
  - PHOS L1: trigger on photons with 3 thresholds

- Thresholds are adjustable depending on collision rate, trigger rejection factor, readout time. Typical threshold: 4 GeV

- ✓ pp collisions: low trigger rate → only PHOS L0 trigger is required
- ✓ Pb-Pb collisions: L1 triggers become effective



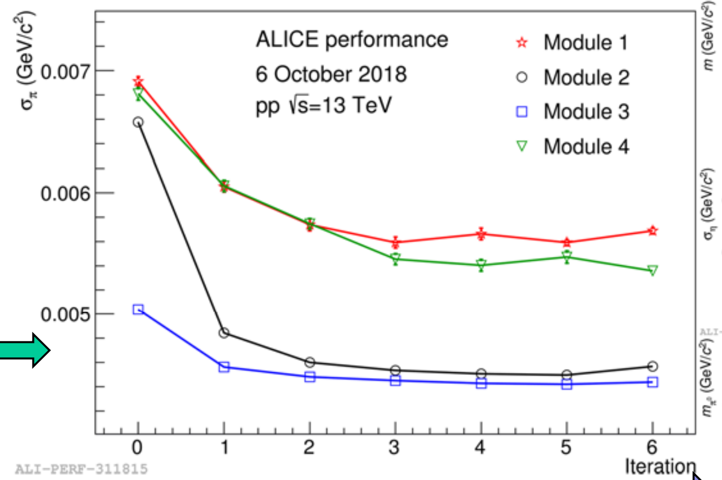
More details about trigger electronics in:
J.Kral et al., L0 trigger for the EMCal detector of the ALICE experiment, NIM. A693 (2012) 261-267

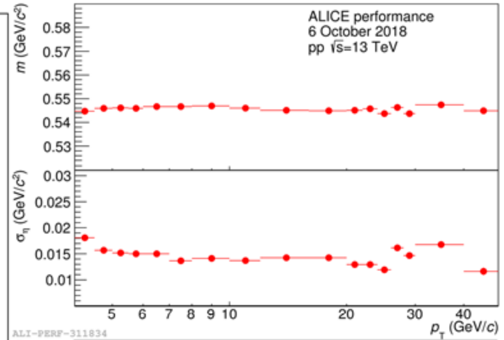
PHOS calibration

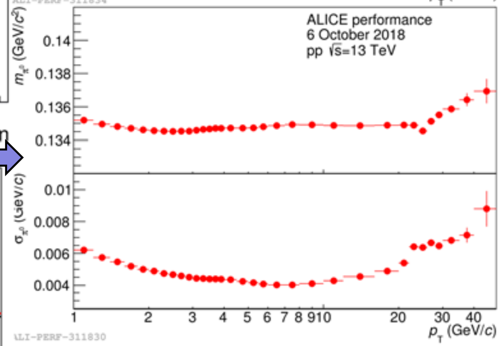
- Energy calibration

  - Pre-calibration based on APD gain equalization and fine energy calibration based on $\pi 0$ peak position equalization

  - Optimized for number of iterations in MC study

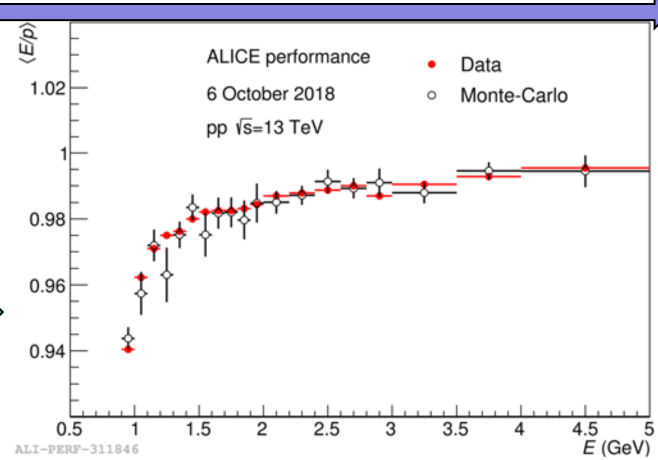






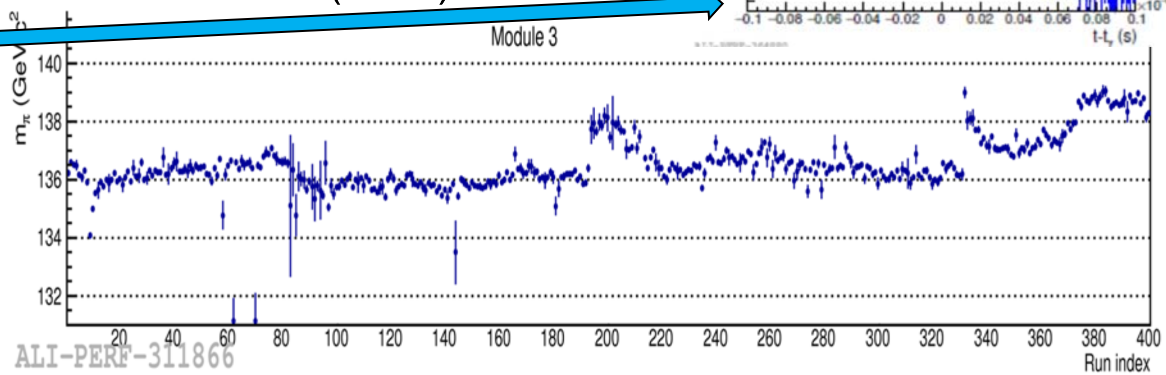
  - π^0 and η peaks are at their PDG positions over a wide p_{T} range
  - Peak widths are close to ideal values ($\sim 4.56\ \mathrm{MeV}/c^2$ for π^0 and $15.3\ \mathrm{MeV}/c^2$ for η)

  - Absolute energy scale was checked with electrons E/p



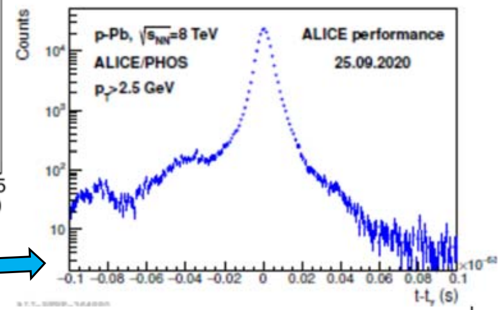
  - Run-by-run correction of π^0 peak position is important for good performance

JINST 14 P05025 (2019)



- Timing calibration

  - Good timing calibration is important to discriminate bunch crossings (25 ns minimum at LHC). Timing calibration is obtained from physical data



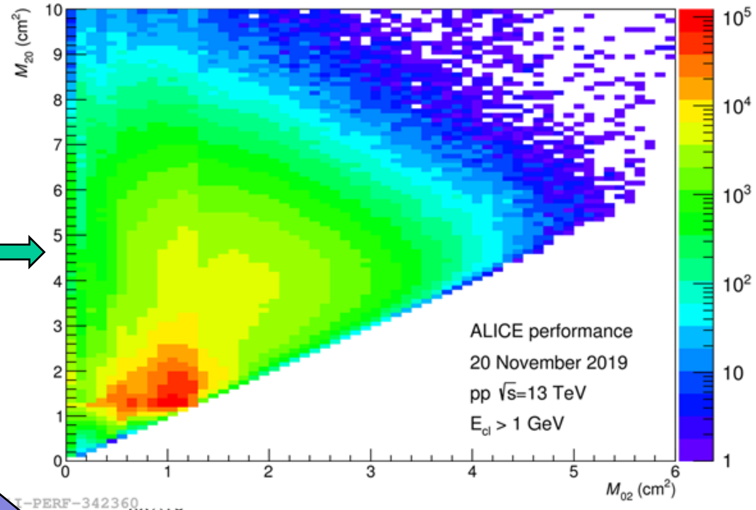
Photon identification

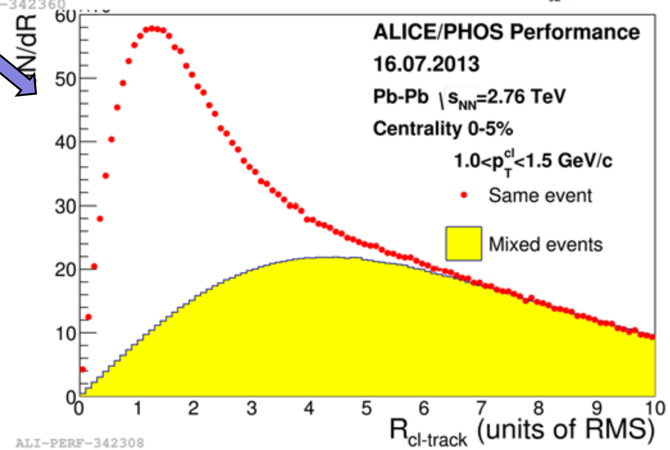
- Criteria of identification: shower shape and charged particle track vetoing (CPV)

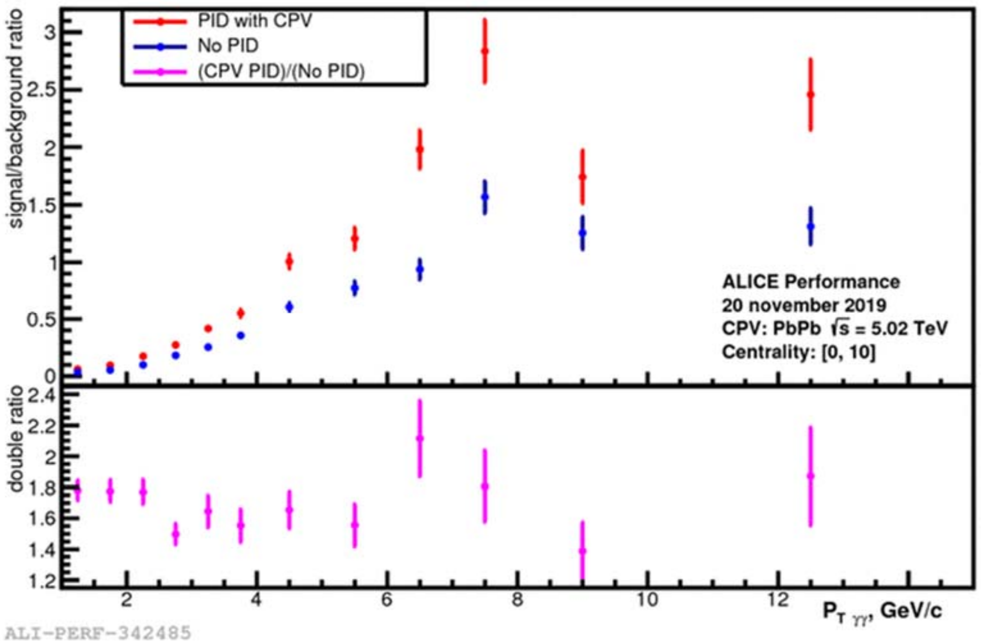
- Shower shape cut is based on 2-dimensional dispersion of clusters

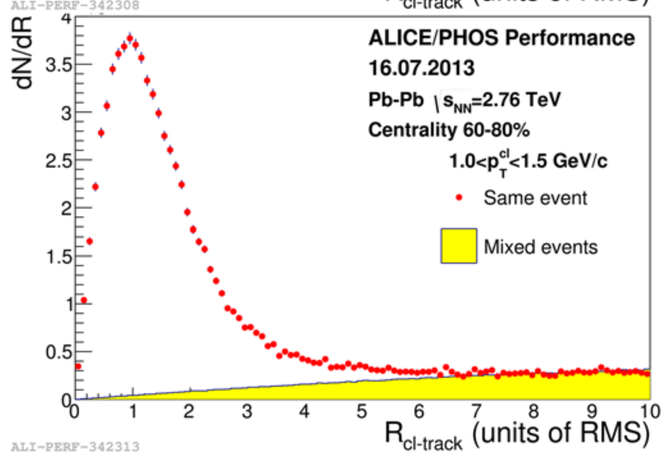
- CPV cut is based on distance to the closest extrapolated track from the ALICE central tracking system

- CPV detector in front of PHOS can further improve efficiency of this cut. In Run 2: 1 CPV module in front of PHOS module #3; **in Run 3: 3 CPV modules.**





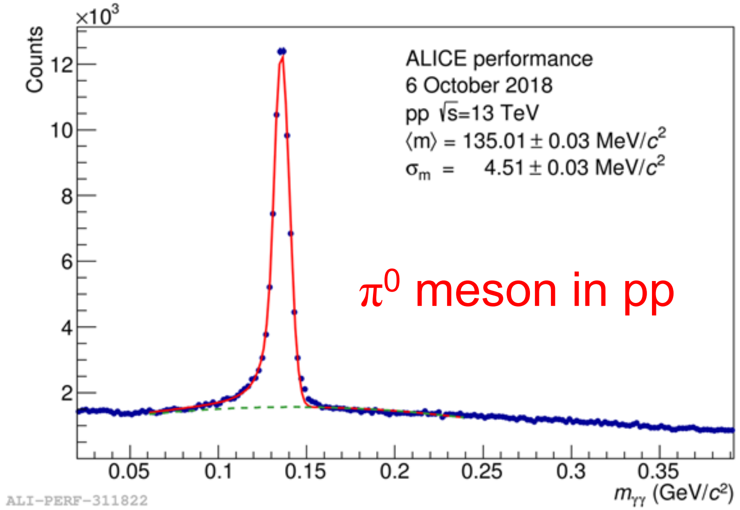




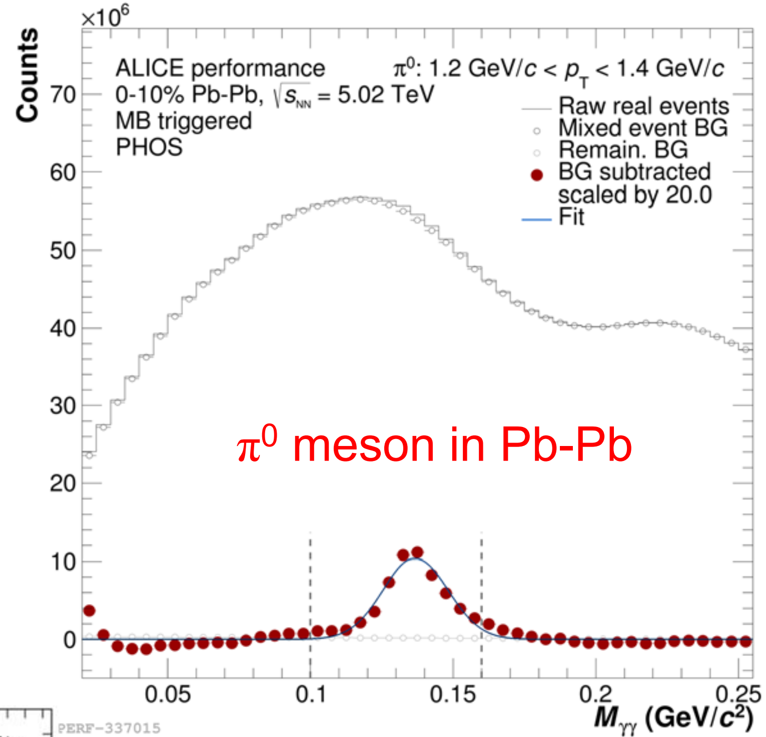
JINST 15 C04047 (2020), JINST 15 C03025 (2020)

Physics performance: neutral meson measurements

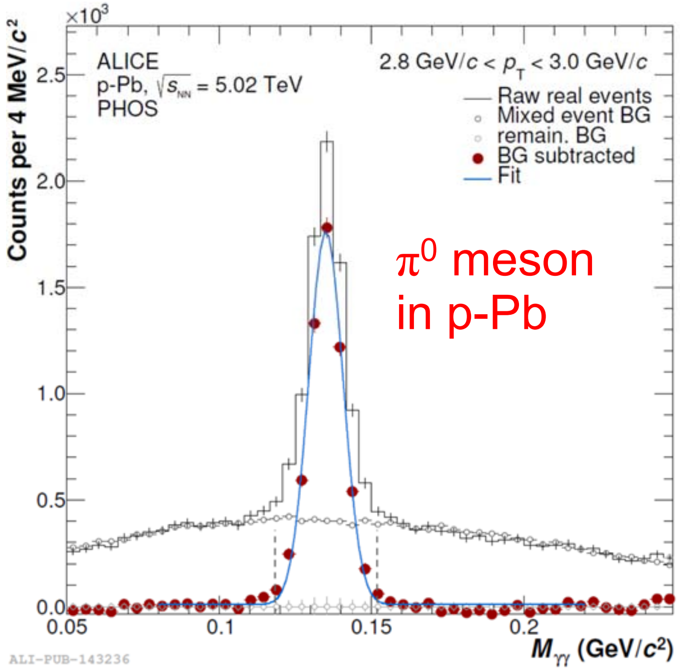
- PHOS reconstructs neutral mesons in low and high multiplicity environments down to low p_{T}

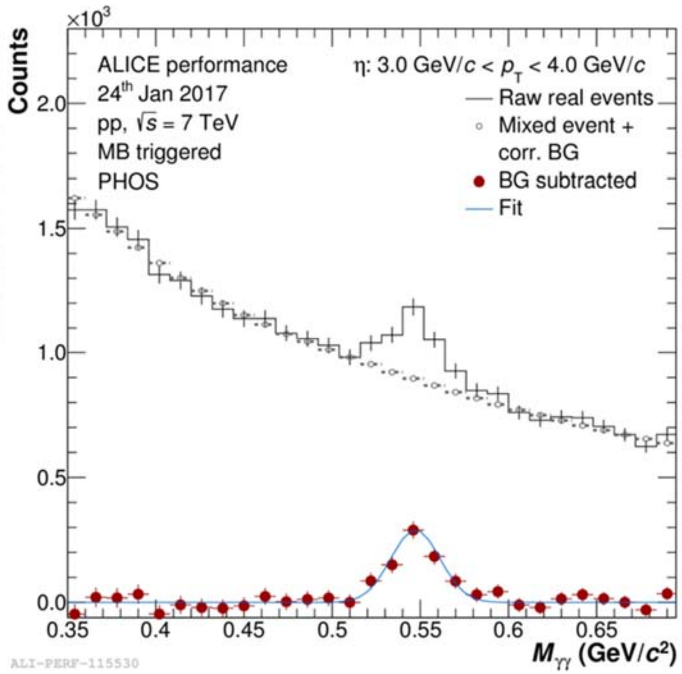


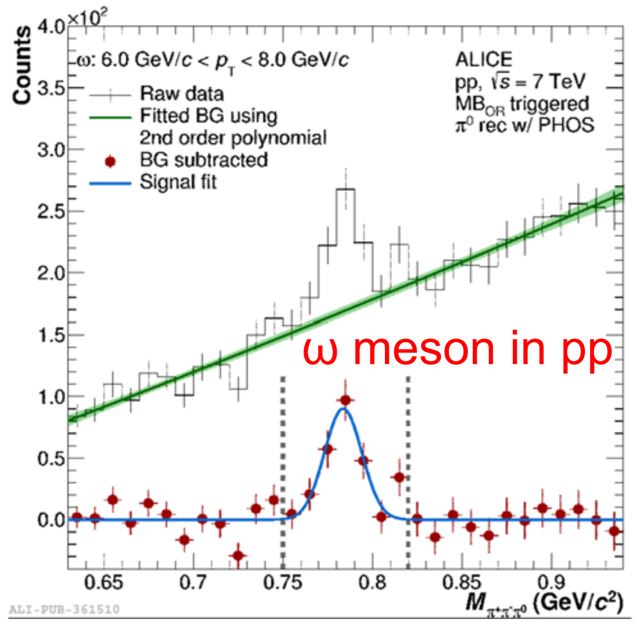
arXiv:2007.02208 [nucl-ex]
New ω-meson production results



η meson in pp

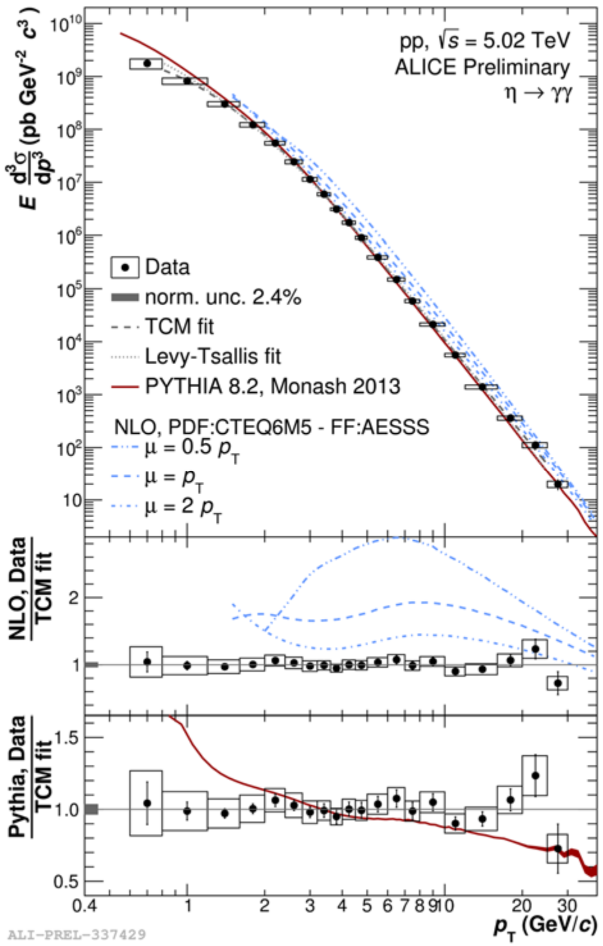


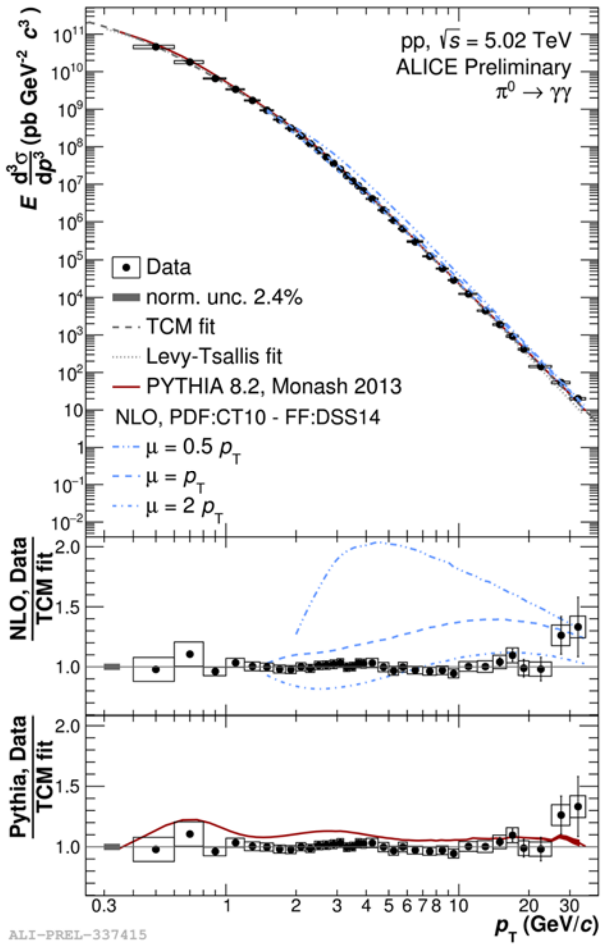


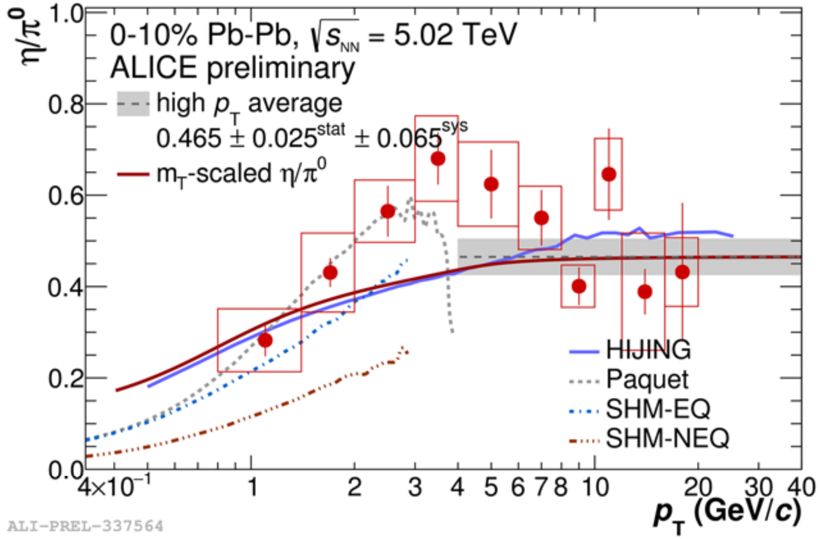


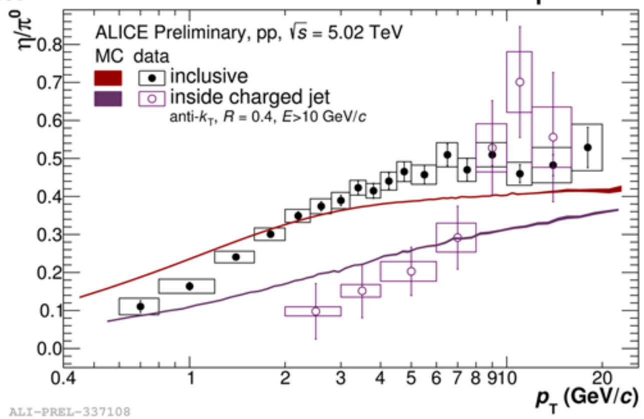
Physics performance: neutral meson measurements in pp

- Neutral meson measurements over wide p_T range provide important data for fragmentation functions (FF) and PDF global fits, and are also needed for direct photon measurements
- Study of strangeness production through η/π^0 ratio measurements:
  - ✓ Modification of η/π^0 ratio in most central Pb-Pb collisions due to radial flow (and probably other effects)
  - ✓ Strong modification of η/π^0 ratio in jets (probably just kinematical effect)



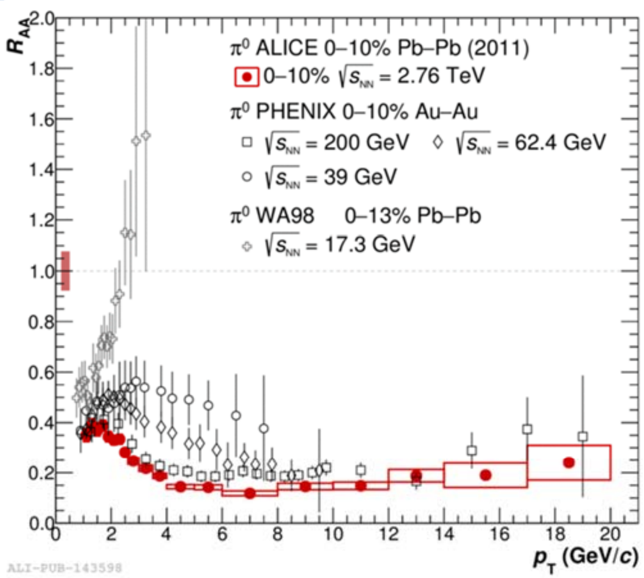


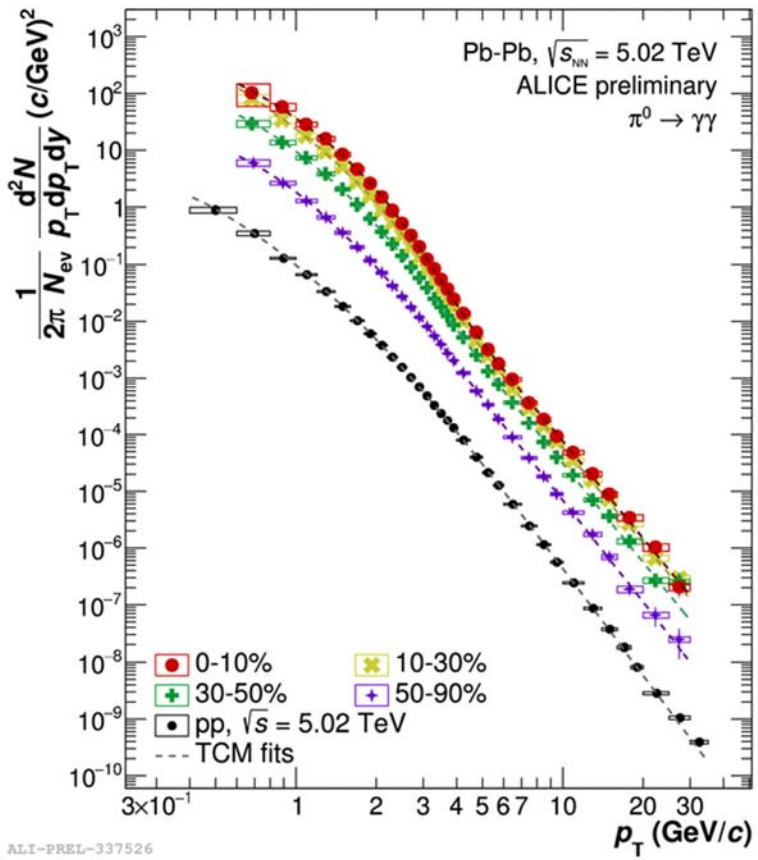


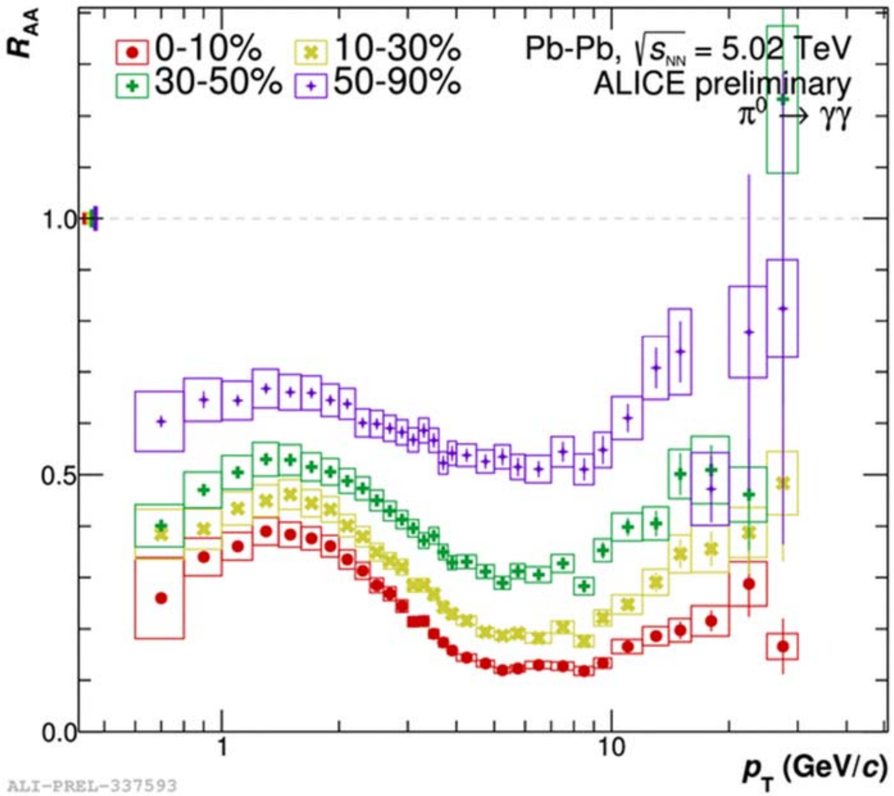


Physics performance: neutral meson measurements in Pb-Pb

- Study parton energy loss in hot medium via π^0 and η spectra modification relative to pp collisions (R_{AA})
- New results on π^0 R_{AA} from Run 2 Pb-Pb collisions at 5.02 TeV:
  - ✓ Similar magnitude of suppression as at 2.76 TeV
  - ✓ p_T range from 0.4 to 35 GeV/c (pp) and 0.6 to 30 GeV/c (Pb-Pb).







Physics performance: direct photon measurements

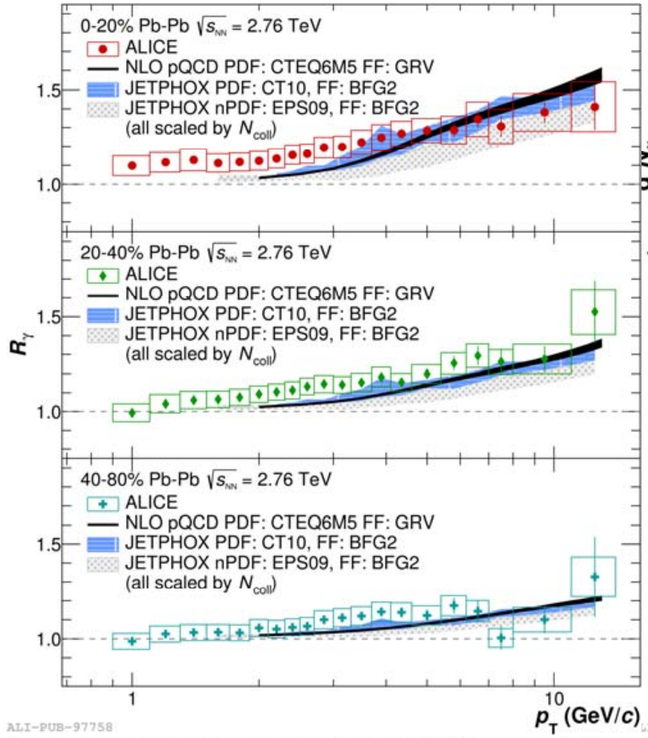
$$R_\gamma = {\gamma_{\rm inc}}/{\gamma_{\rm decay}} \approx {\gamma_{\rm inc}/\pi^0}/{\gamma_{\rm decay}/\pi^0}_{\rm param}$$

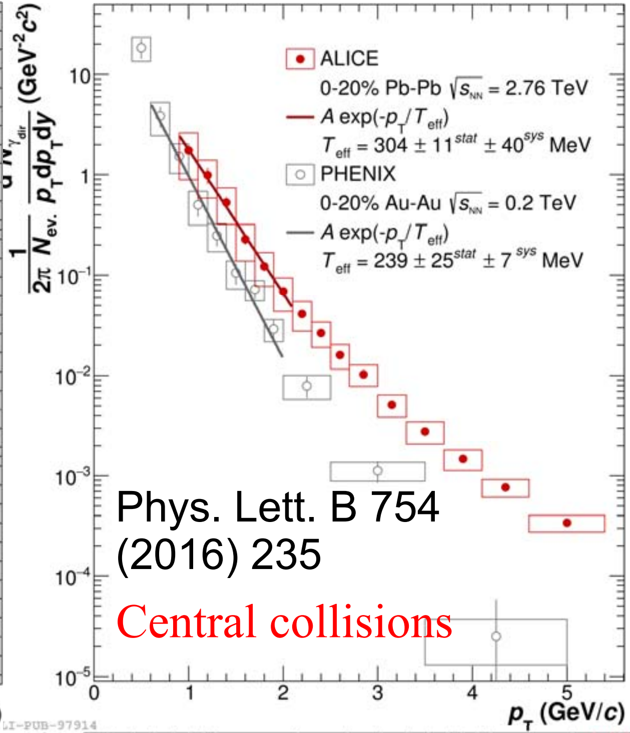
$$\gamma_{\rm dir} = \gamma_{\rm inc} - \gamma_{\rm decay} = \left(1 - \frac{1}{R_\gamma}\right)\gamma_{\rm inc}$$

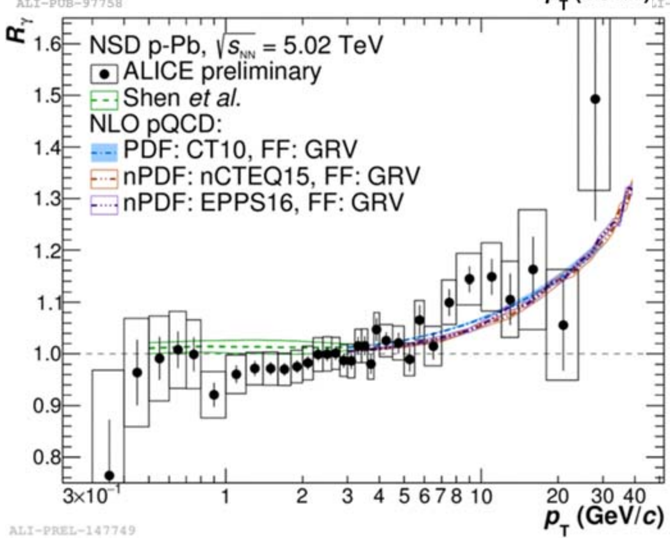
- Photons don't interact strongly and therefore carry information about e-m interactions of particles over the whole evolution of hot QCD matter
  - High $p_{\rm T}$: test of initial conditions
  - Low $p_{\rm T}$: test of hot matter evolution

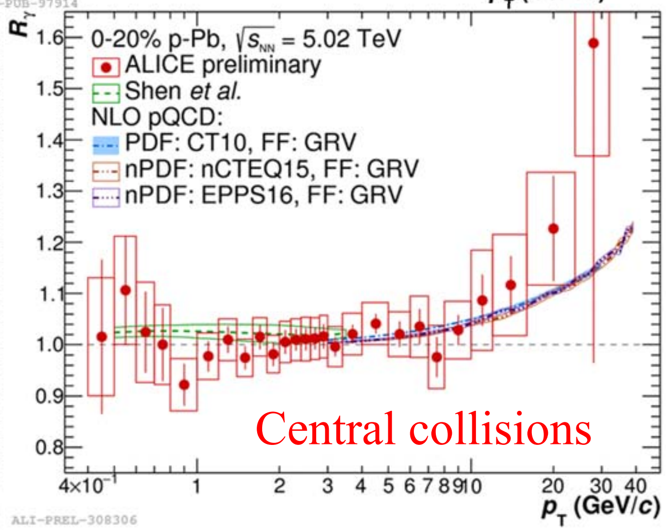
- Direct photon measurements in Pb-Pb collisions:
  - ✓ At low $p_{\rm T}$ (<2-3 GeV/c) agreement with hydro predictions. Inverse slope parameter of about 300 MeV is obtained.
  - ✓ At high $p_{\rm T}$ (above ~5 GeV/c) in agreement with NLO pQCD and JETPHOX

- Direct photon measurements in p-Pb collisions:
  - ✓ At low $p_{\rm T}$ no thermal photon excess
  - ✓ At high $p_{\rm T}$ consistent with pQCD calculations



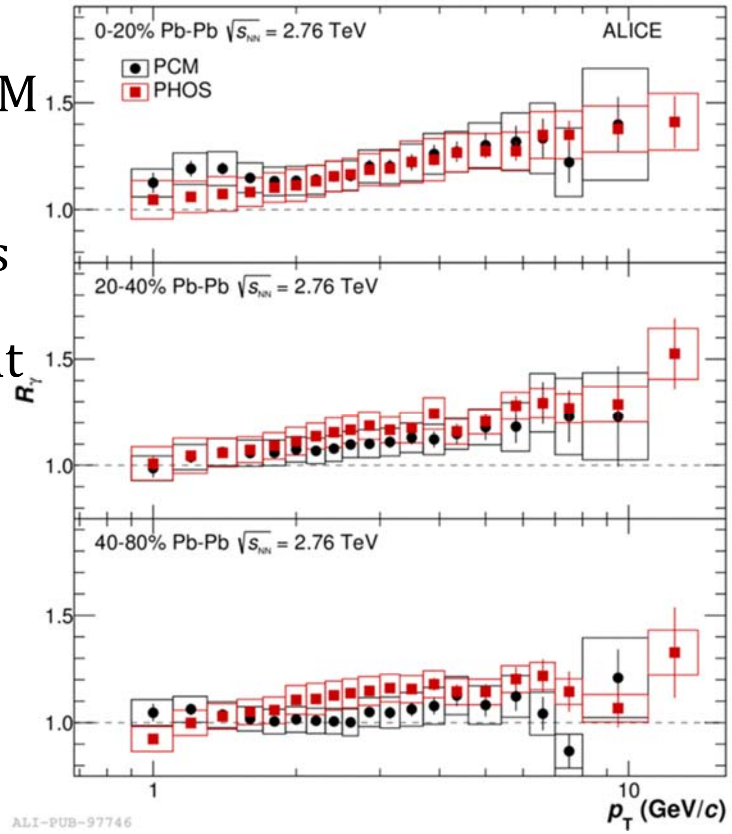






PHOS Upgrade motivation

- Direct photon and neutral meson measurements have about the same systematic uncertainties for PHOS and PCM in the low- and mid-p_T range.
- Main systematic uncertainty for PHOS at low p_T originates from raw yield extraction. This uncertainty is decreasing with accumulation of data. Run 3 is expected to have about 100 times more statistics than Run 1 and 2 thanks to upgrade of ALICE trigger and readout system.



PHOS

Centrality	0–20%	
p_T (GeV/c)	2	10
γ_{incl} yield		
Efficiency (B)	3.0	3.0
Contamination (B)	2.0	2.0
Conversion (C)	1.7	1.7
Acceptance (C)	1.0	1.0
*Global E scale (B)	9.6	9.0
*Non-linearity (B)	2.2	0.1
π^0 yield		
Yield extraction (A)	2.7	4.0
Efficiency (B)	1.8	1.8
Acceptance (C)	1.0	1.0
Pileup (C)	1.0	1.0
Feed-down (B)	2.0	2.0
γ_{decay}/π^0		
π^0 spectrum (B)	1.3	4.3
η contribution (B)	2.2	1.7
Total R_γ	6.8	7.9
Total γ_{incl}	12.4	12.7

Photon Conversion (PCM)

Centrality	0–20%	
p_T (GeV/c)	1.2	5.0
γ_{incl} yield		
Track quality (A)	0.6	0.6
Electron PID (A, B)	1.5	6.9
Photon selection (A, B)	4.0	1.8
Material (C)	4.5	4.5
γ_{incl}/π^0		
Track quality (A)	0.7	1.7
Electron PID (A, B)	1.2	4.8
Photon selection (A, B)	3.2	3.2
π^0 yield (A)	1.6	2.9
Material (C)	4.5	4.5
γ_{decay}/π^0		
π^0 spectrum (B)	0.5	1.2
η yield (C)	1.4	1.4
η shape (B)	1.6	0.5
Total R_γ	6.2	8.1
Total γ_{incl}	6.2	8.5

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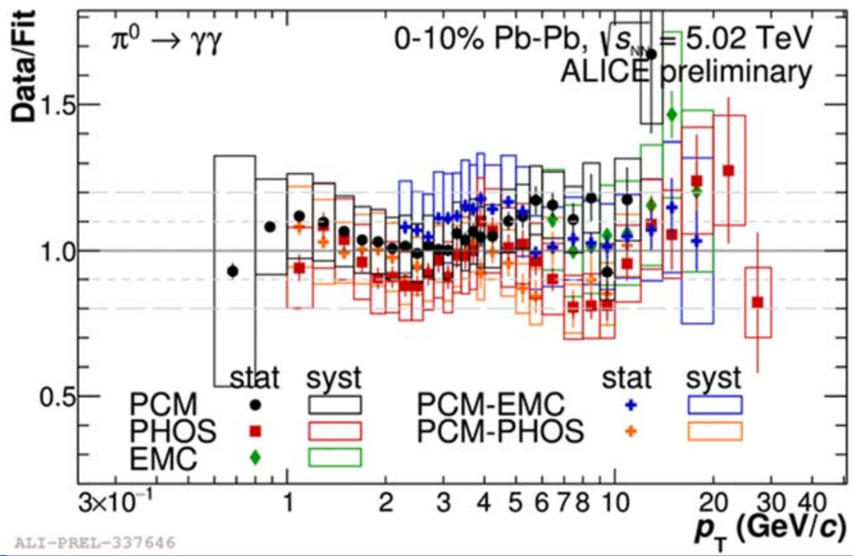
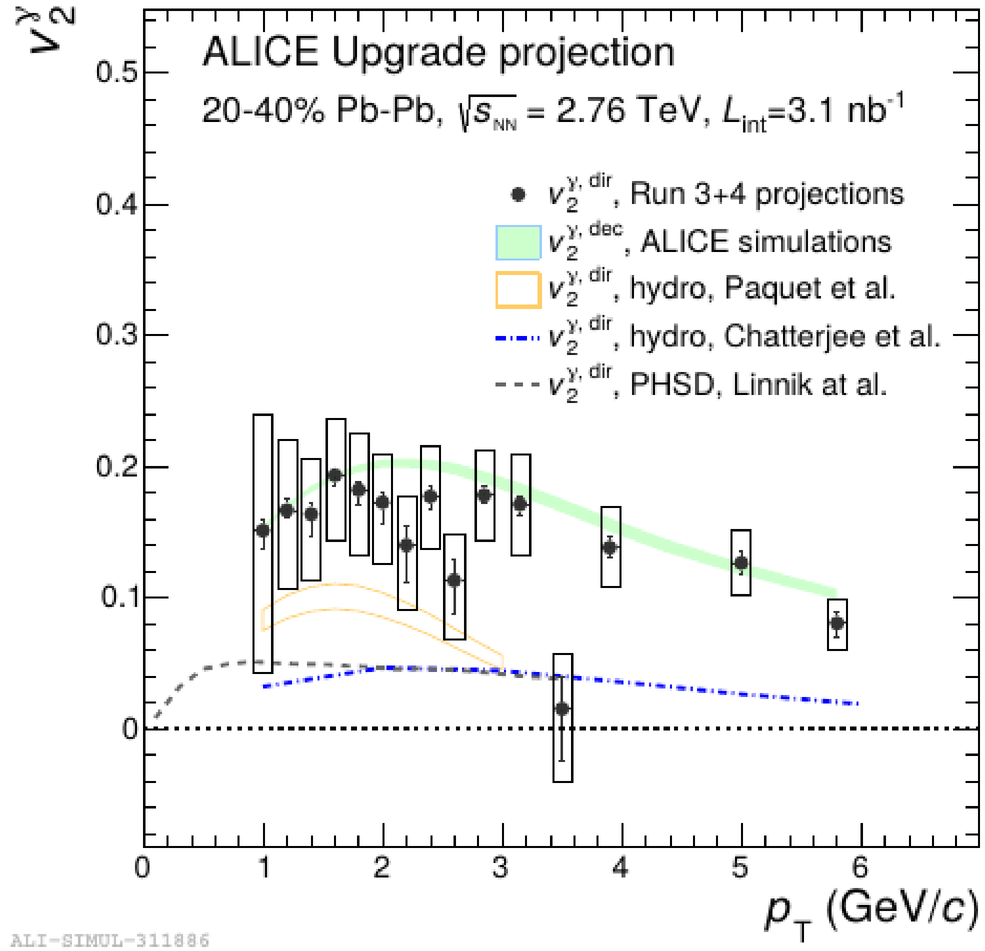
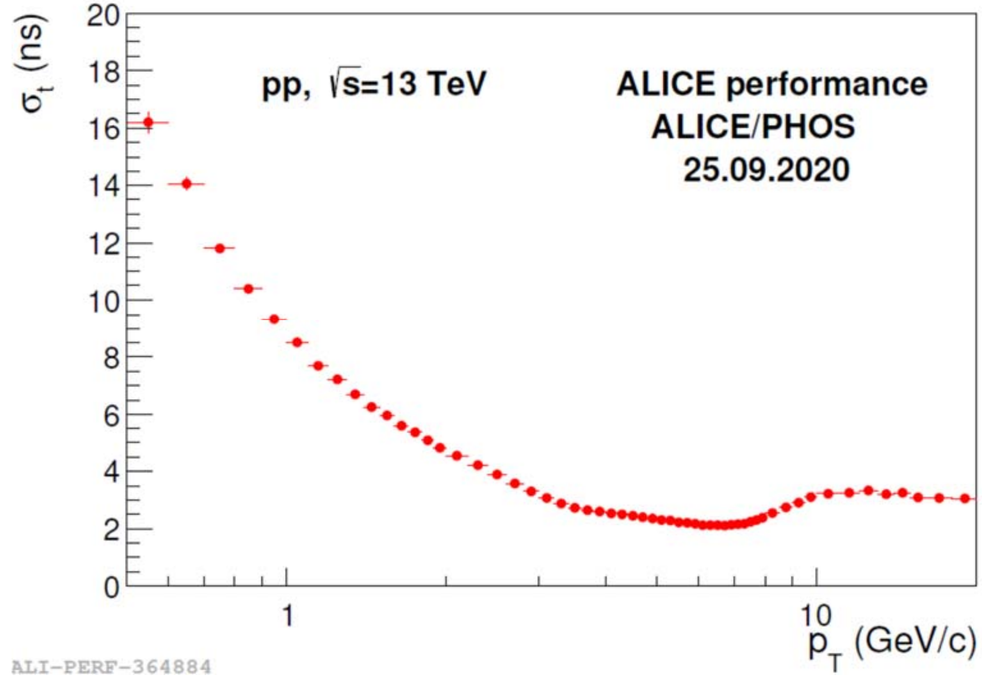


PHOS Upgrade motivation

- Photon identification at low p_T require timing information (CPV and shower shape criteria are not effective)
- Current timing resolution is not enough
- Goal: improve timing resolution to 500 ns to reduce contamination





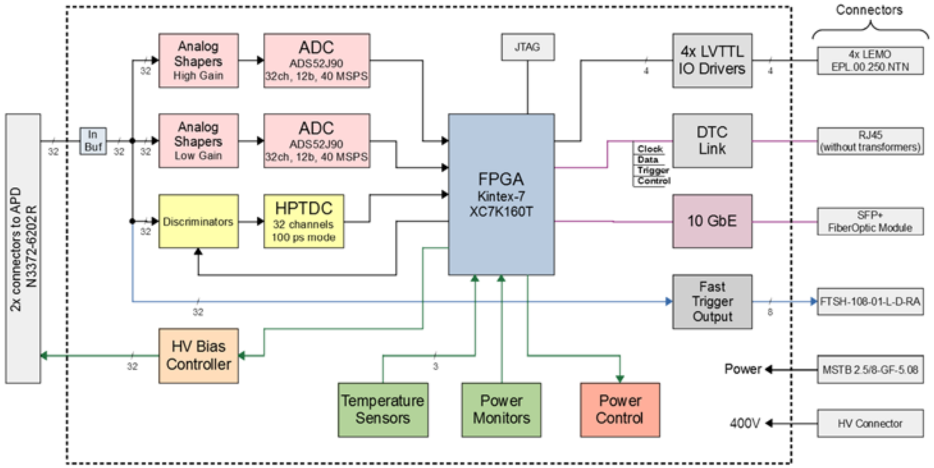
CERN Yellow Rep.Monogr. 7 (2019)
1159-1411812.06772 [hep-ph]

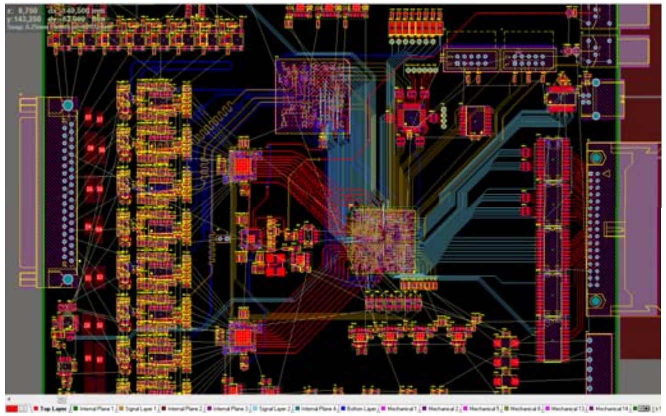
PHOS tomorrow

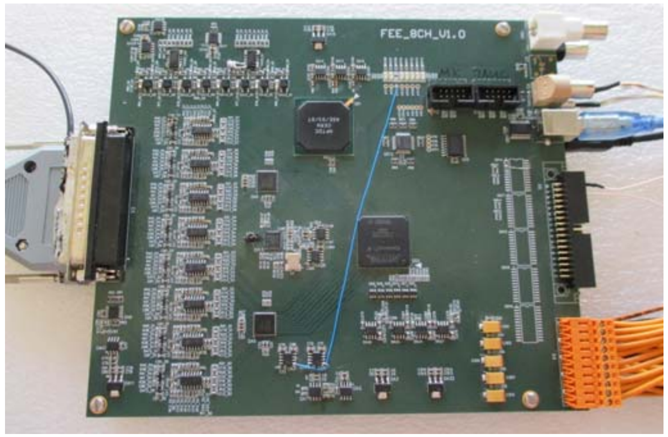
- Run 3: upgrade of current FEE firmware and reconstruction software to comply with O^2.
- Run 4: consider upgrade of PHOS to improve energy and time resolution
  - ✓ upgrade FEC using modern components to improve timing resolution and operation reliability
  - ✓ upgrade photodetectors to increase sensitivity for low-energy photons and to improve timing resolution
  - ✓ upgrade module structure to ease access to FEC and improve operation reliability

Upgrade of FEE

- Why do we need it?
  - ✓ Spare parts of current FECs become obsolete and no longer produced.
  - ✓ Possibility to reduce noise.
  - ✓ New picoTDC chip is state-of-the art technology which will provide best possible timing capabilities of new cards.
- FEC 8 channel prototype is ready and tested with beam at CERN. FEC 32 channel prototype will be ready by 2021.
- New readout units:
  - Designed for upgraded ITS. Will have bandwidth up to 200 MHz.

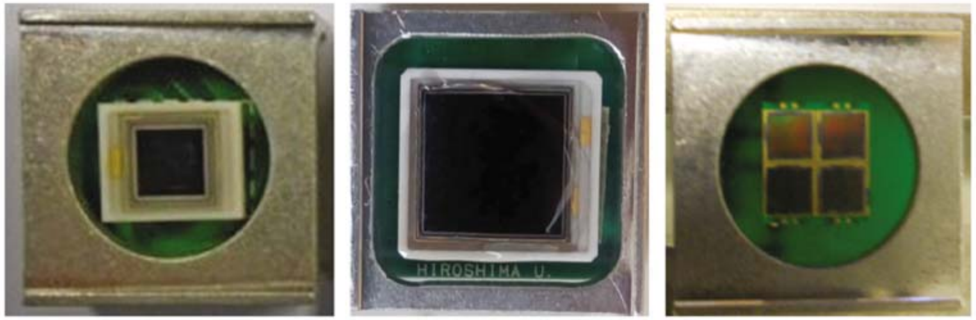




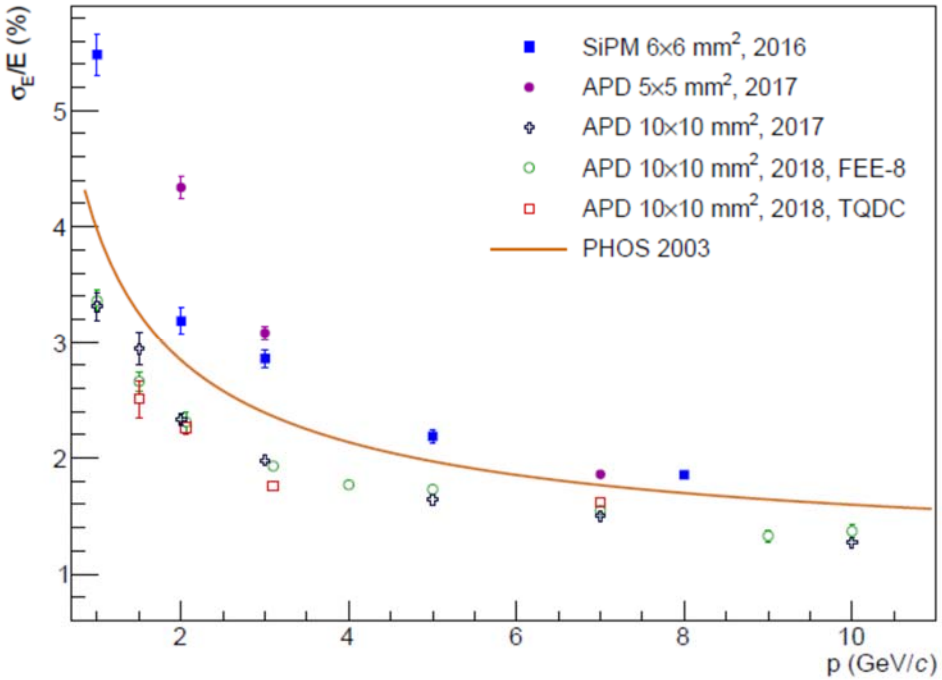


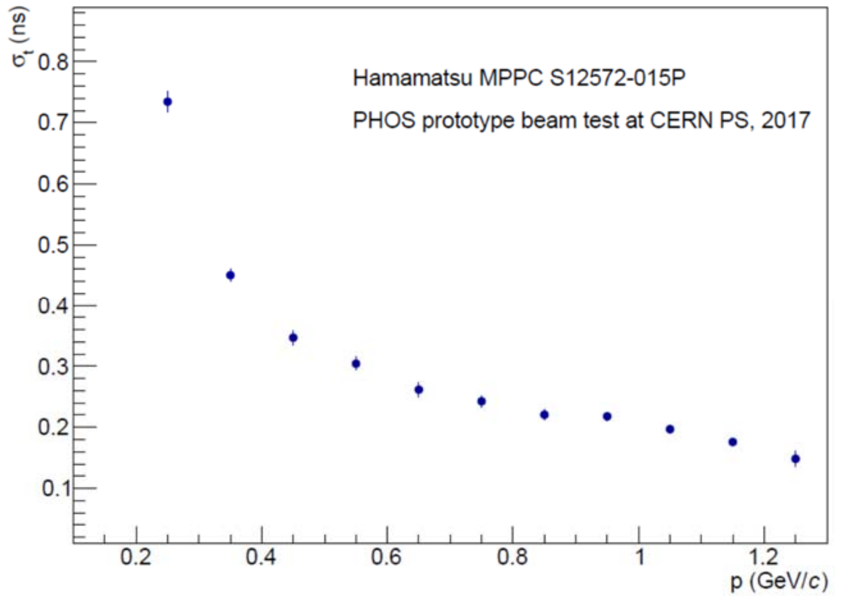
Upgrade of photodetectors

Details in: Instrum. Exp. Tech. **61** (2018) 639



Left to right: APD 5×5, APD 10×10, SiPM array





- Why do we need it?
  - ✓ Provide the best possible energy and timing resolution for low-p_T measurements
- Beam tests showed that APD 10×10 mm^2 and SIPM arrays 6×6 mm^2 provide similar energy resolution without cooling (+17.5 °C) as the current APD 5×5 mm^2 with cooling down to -25 °C.
- Estimations showed that below 1 GeV energy resolution can be improved by a factor of about 2 if we keep cooling.
- Time resolution: with SiPM 200 ps at 1 GeV can be achieved. With APD only about 500 ps.

Conclusions

- PHOS contributes to ALICE physics program with photon and neutral meson measurements in pp, p-A and A-A collisions
- Trigger system of PHOS allows ALICE to enhance collected data of event samples with high-p_{T} photons
- PHOS is calibrated using the collision data
- Continuously improving techniques of photon and neutral meson identification
- Preparation of the Upgrade program is ongoing including upgrade of the readout system, installation of the new photodetectors and change of mechanical construction during LHC LS3

This work was supported by the Russian Science Foundation grant 17-72-20234