"High-pT Probes of High-Density QCD at the LHC"
Paris, 30 May- 1 June 2011

Photon physics with the ALICE experiment

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For the ALICE collaboration

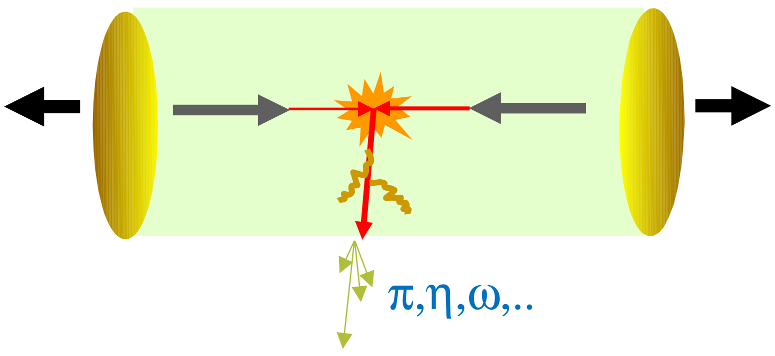
Outline

- Photon physics scope
- ALICE setup
- π^0 and η spectra
- η to π^0 ratio
- Azimuthal anisotropy v_2
- Calorimeter performance in heavy ion collisions
- Nuclear modification factor R_{AA} of π^0
- Direct photons
- Photon-hadron correlations
- Summary

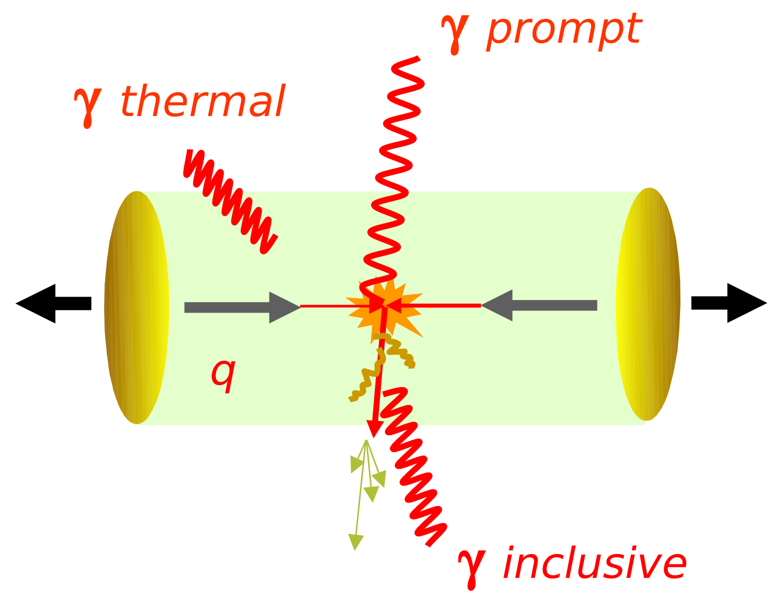
Why measure photons?

- Photons, having negligible final state interaction, carry undistorted information about various stages of the nuclear matter evolution.
- Direct photons are produced in:
  - photons emission from QGP (qq–annihilation and Compton scattering, etc)
  - photons emission from hadron gas ($\pi\rho\to\pi\gamma$, $\pi\pi\to\rho\gamma$, $\omega\to\pi^0\gamma$)
  - ***prompt photons***, produced directly in hard scatterings of partons of colliding nuclei, dominate at high p_T
  - this also includes ***fragmentation photons***, produced in hard processes
  - ***thermal photons***, produced in thermalized nuclear matter radiation at low and intermediate p_T.
  - ***hard medium-induced photons*** can be produced in:
    - jet-photon conversion (annihilation and Compton scattering of hard and thermal partons)
    - bremsstrahlung of hard partons in the medium
- Decay photons reveal medium-induced modifications of hadron properties.
- Interferometry of photons can be used as a tool to measure space-time dimensions of the source.

Photon Physics



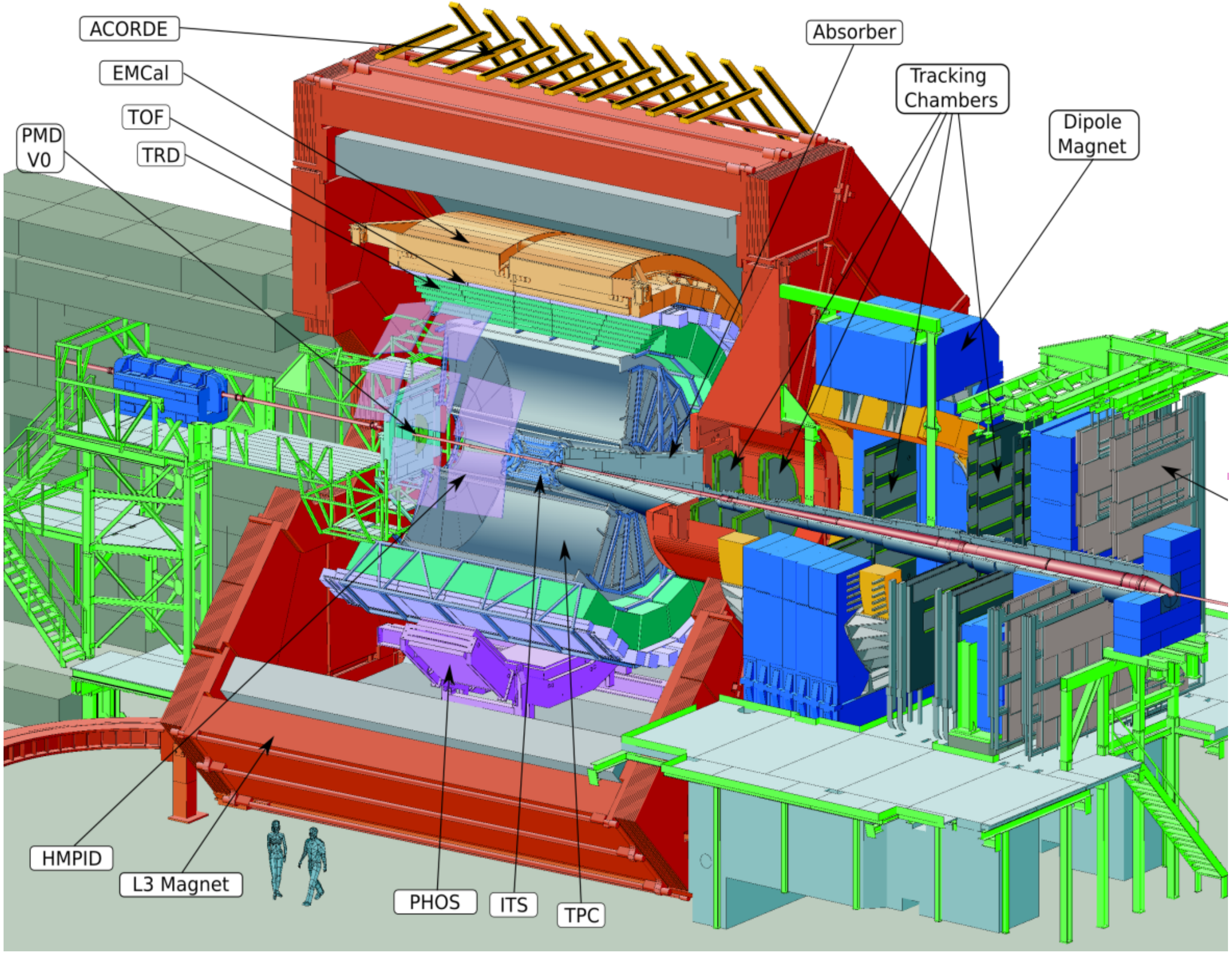
Decay photons:
Neutral meson spectra, R_{AA}, v_2…
Chemical composition: π^0,η, ω



Direct photons:
Spectra, R_{AA}, v_2…
Inclusive, Prompt, Thermal

Direct photon – jet correlations

ALICE setup

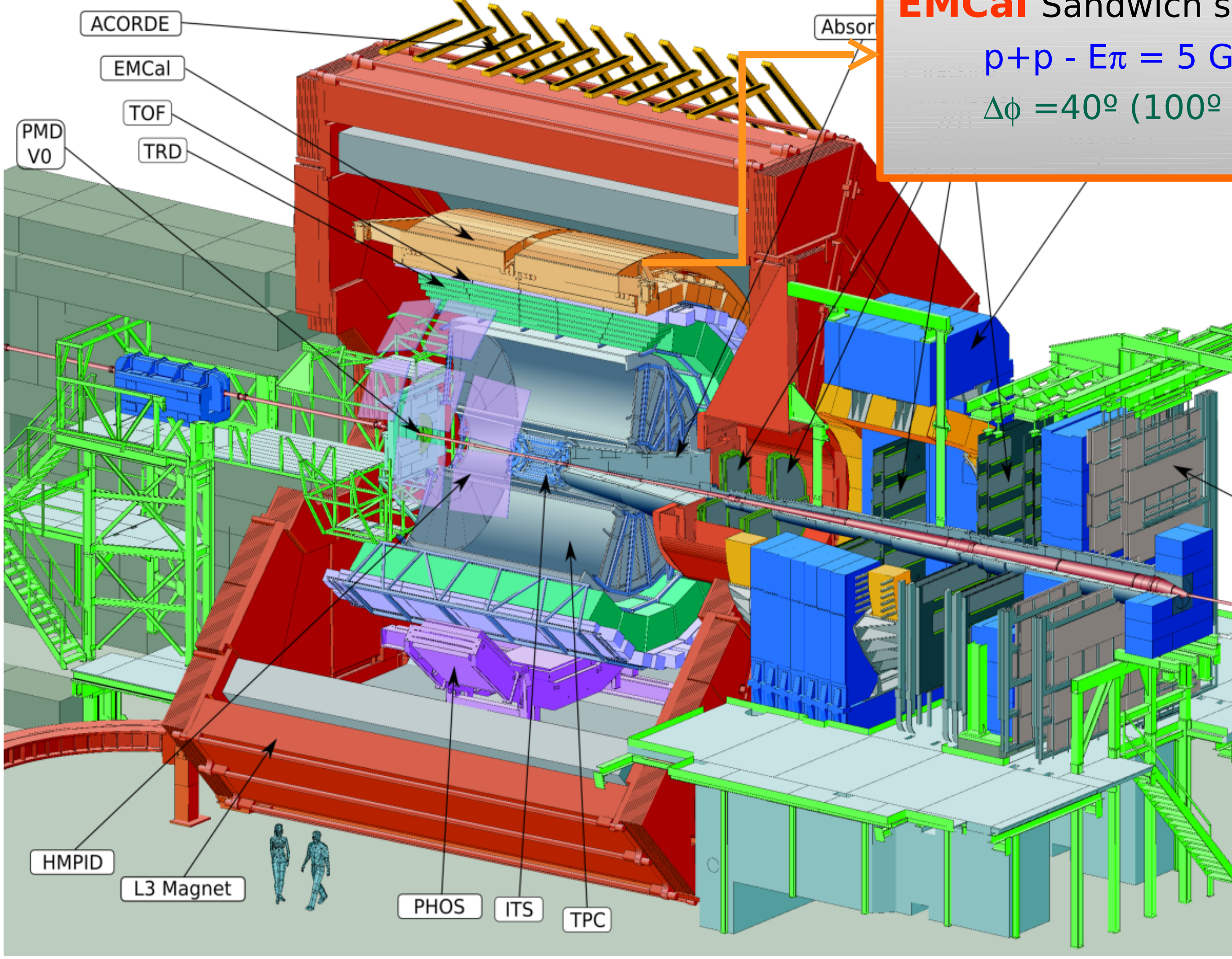

ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking
Chambers
Dipole
Magnet
HMPID
L3 Magnet
PHOS
ITS
TPC

ALICE setup

EMCal Sandwich scintillator-Pb

$p+p$ - $E_\pi = 5$ GeV $\rightarrow \sigma \approx 10$ MeV/c2

$\Delta\phi = 40º$ (100º in 2011) $|\eta| < 0.7$



ALICE setup

EMCal Sandwich scintillator-Pb

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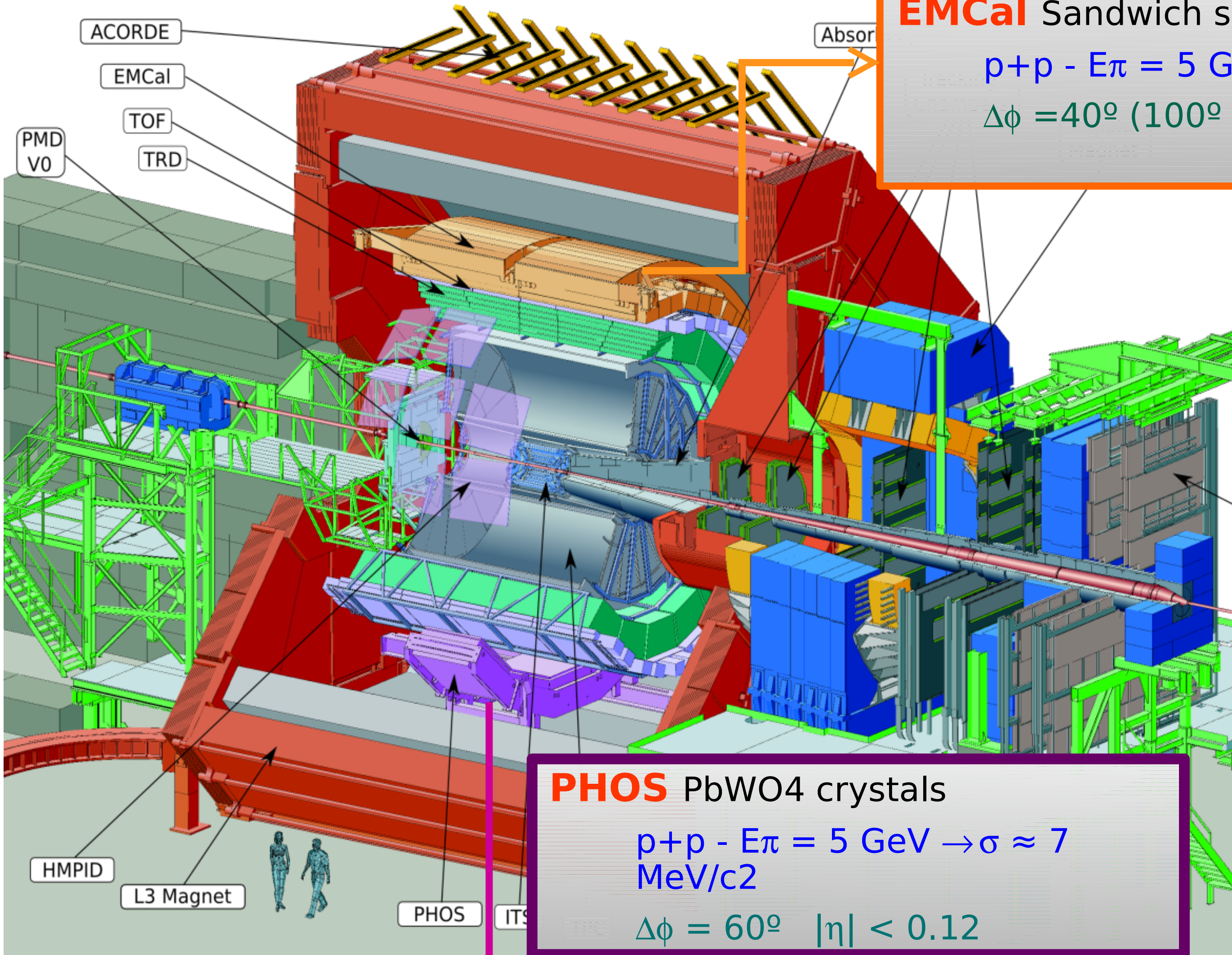
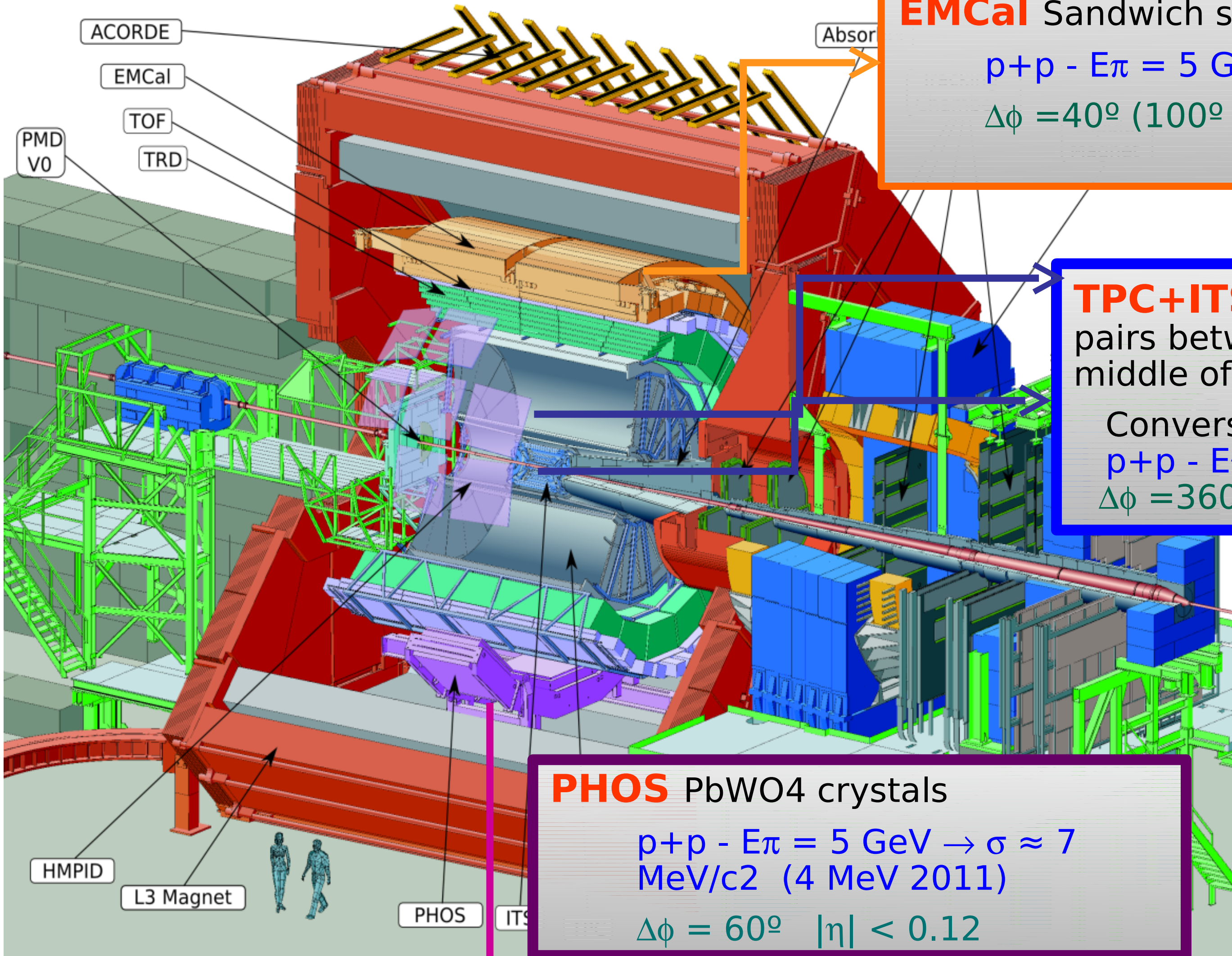


PHOS PbWO4 crystals

p+p - E_π = 5 GeV →σ ≈ 7 MeV/c2

Δϕ = 60º |η| < 0.12

ALICE setup



EMCal Sandwich scintillator-Pb

p+p - $E\pi$ = 5 GeV $\rightarrow \sigma \approx$10 MeV/c2

$\Delta\phi$ =40º (100º in 2011) $|\eta| < 0.7$

TPC+ITS γ's converted into $e^{\pm}$ pairs between beam pipe and middle of TPC can be detected

Conversion *probability* $\approx$ 9%

p+p - $E\pi$ = 5 GeV $\rightarrow \sigma \approx$4 MeV/c2

$\Delta\phi$ =360º $|\eta| < 0.9$

PHOS PbWO4 crystals

p+p - $E\pi$ = 5 GeV $\rightarrow \sigma \approx$ 7 MeV/c2 (4 MeV 2011)

$\Delta\phi$ = 60º $|\eta| < 0.12$

ALICE calorimeters

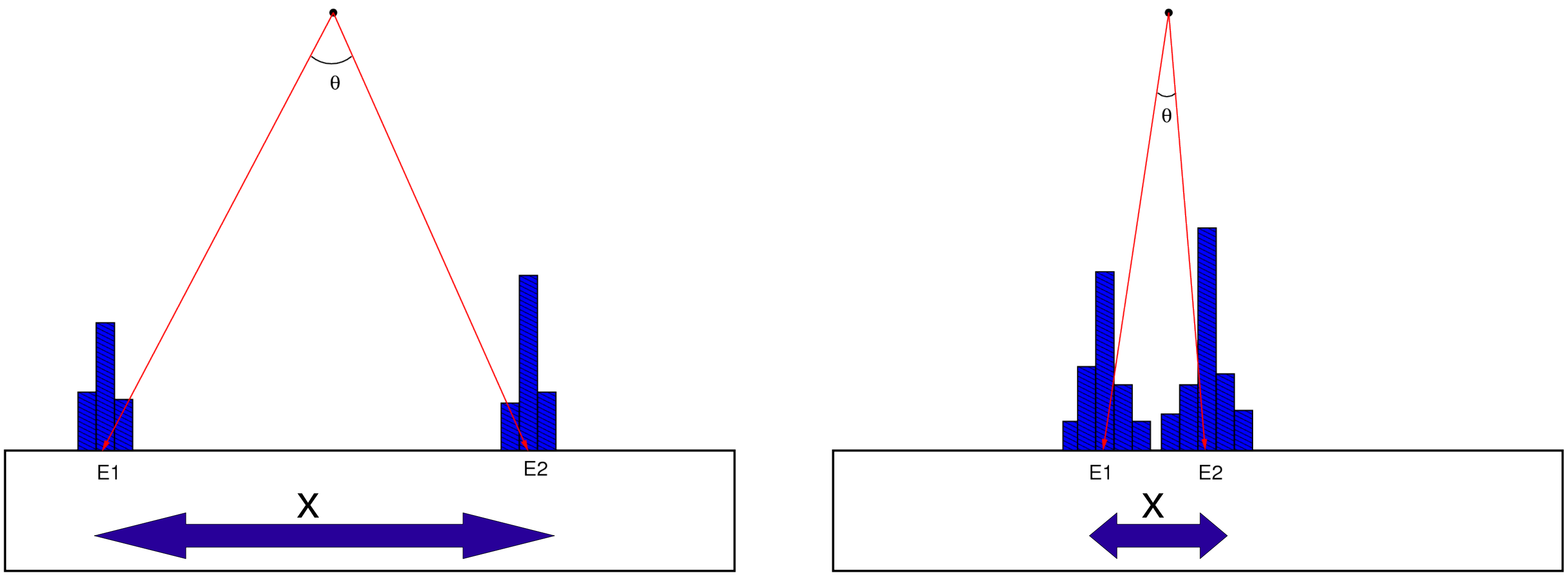
PHOS

- **Active element**: crystal of lead tungstate $2.2 \times 2.2 \times 18$ cm^3.
- **Geometry 2010**: 3 modules 64×56 crystals each; distance from IP to active surface: 460 cm
- **Aperture**: $|\eta|<0.13$, $\Delta\varphi = 60°$
- **Energy range**: 0<E<100 GeV
- **Material budget** from IP to PHOS: $0.2X_0$.

EMCAL

- **Active element**: tower of 77 layers (1.4mm lead + 1.7 mm scintillator) $6 \times 6 \times 25 cm^3$.
- **Geo 2010**: 4 super modules 24×48 towers each; distance from IP to active surface: 430 cm
- **Aperture**: $|\eta|<0.7$, $\Delta\varphi = 40°$ (2010); $\Delta\varphi = 100°$ (2011).
- **Energy range**: 0<E<250 GeV
- **Material budget** from IP to EMCAL: $0.5X_0$ (2010), 0.5-0.8X_0 (2011)

Neutral meson mass resolution



$$M = \sqrt{(2 E_1 E_2 (1 - \cos(\theta_{12})))}$$

Energy resolution in PHOS

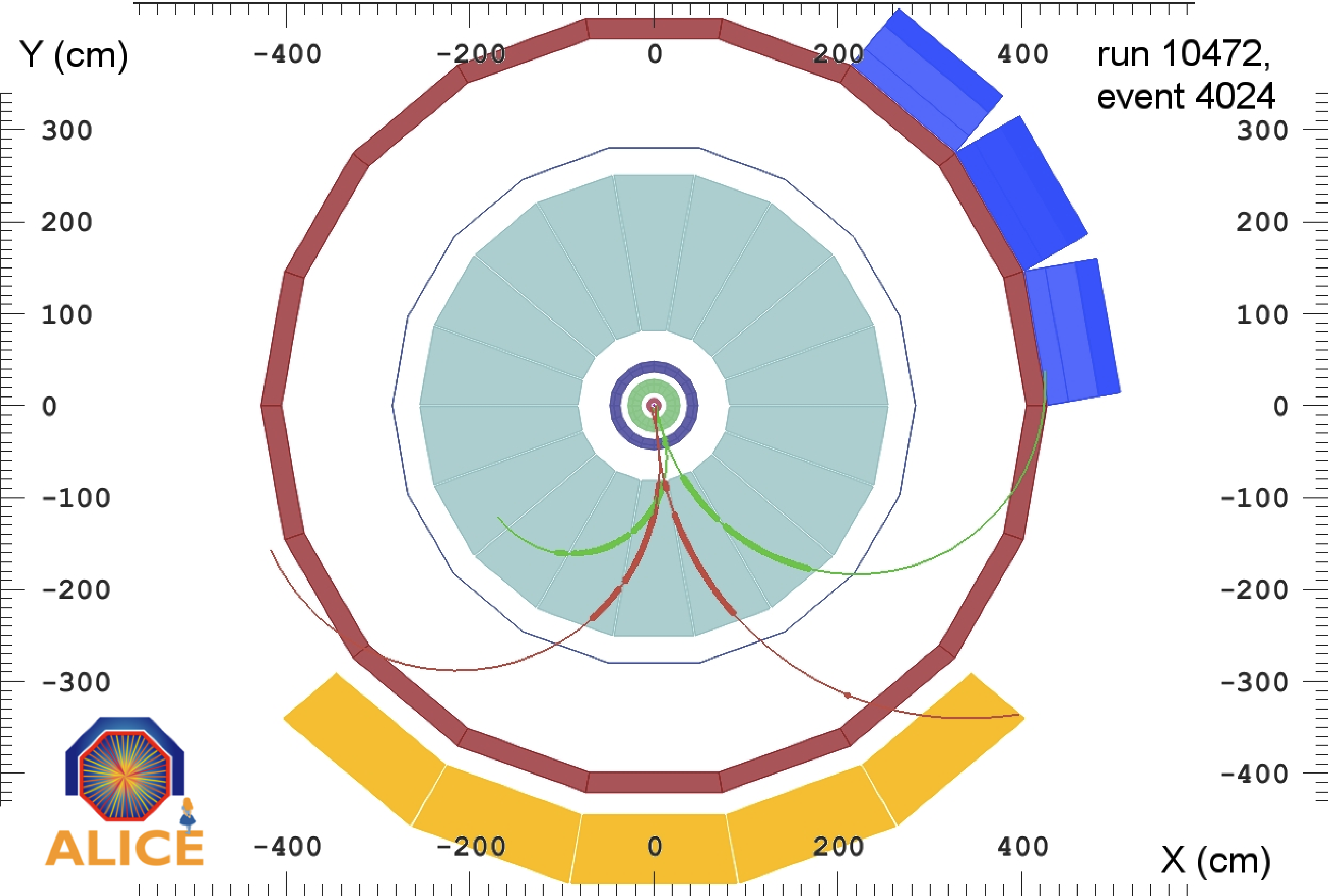
$$\frac{\Delta E}{E} = \frac{1.3\%}{E\ (\mathrm{GeV})} \oplus \frac{3.3\%}{\sqrt{E\ (\mathrm{GeV})}} \oplus 1.12\%$$

Energy resolution in EMCAL

$$\frac{\Delta E}{E} = \frac{4.8\%}{E\ (\mathrm{GeV})} \oplus \frac{11.3\%}{\sqrt{E\ (\mathrm{GeV})}} \oplus 1.7\%$$

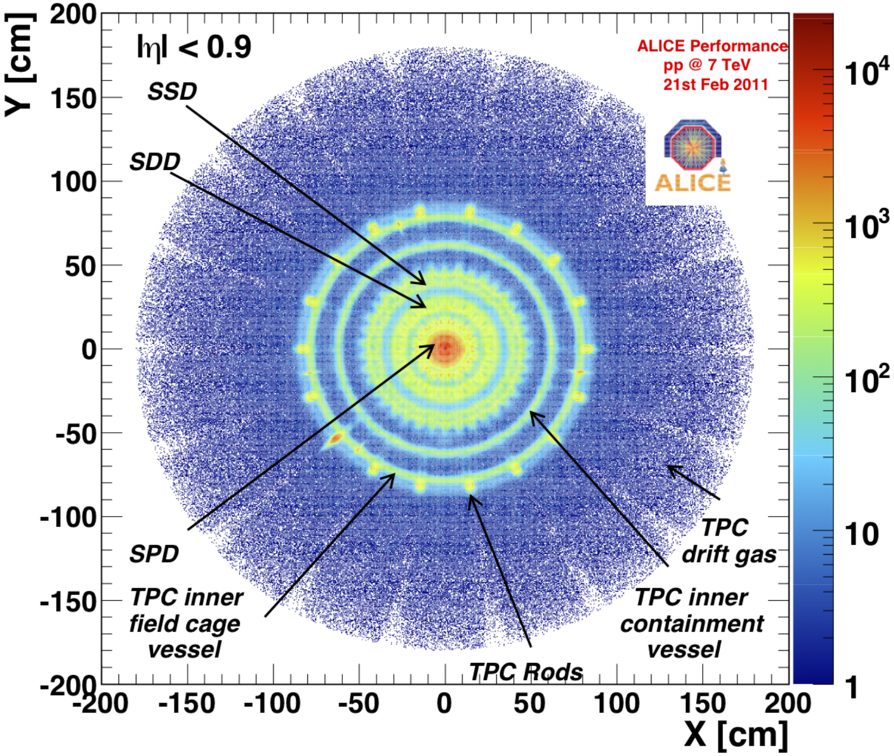
- Position resolution (δx/x) (where δx is your precision) is better at low p_T
- Energy resolution is better at high p_T

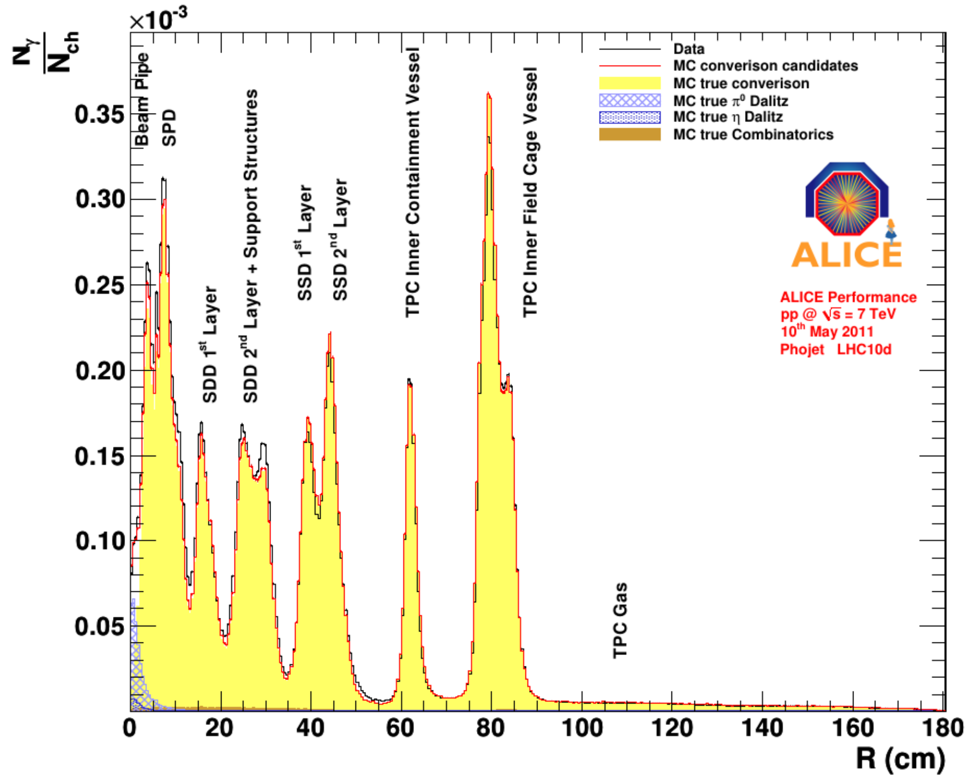
Photon conversion



ALICE tomography with conversions

Measurements of the conversion vertex is a powerful tool to x-ray ALICE up from beam pipe to up to the middle of TPC.





ALICE material budget, 11.4 % X_0 up to half TPC agrees within 3.4%-6% with its implementation in GEANT.

Neutral mesons

•Neutral mesons are reconstructed via two-photon invariant mass spectra
•Background subtraction using mixed events
•Bin counting for signal subtraction
•Additional cuts:

-PHOS:

- $E_{cluster}$ > 300 MeV
- more than 3 cells in a cluster (to suppress hadronic background)

-EMCAL:

$E_{cluster}$ > 500 MeV

-Conversion:

- 2 e^+e^- track produced from the same secondary vertex
- e^+e^- identified in TPC by dE/dx
- min. opening angle gamma-gamma: 5 mrad
- $p_T(e^+)$, $p_T(e^-)$>50 MeV/c

Main systematic uncertainties

Calorimeters

-Energy irresolution and

residual miscalibration

-energy scale nonlinearity

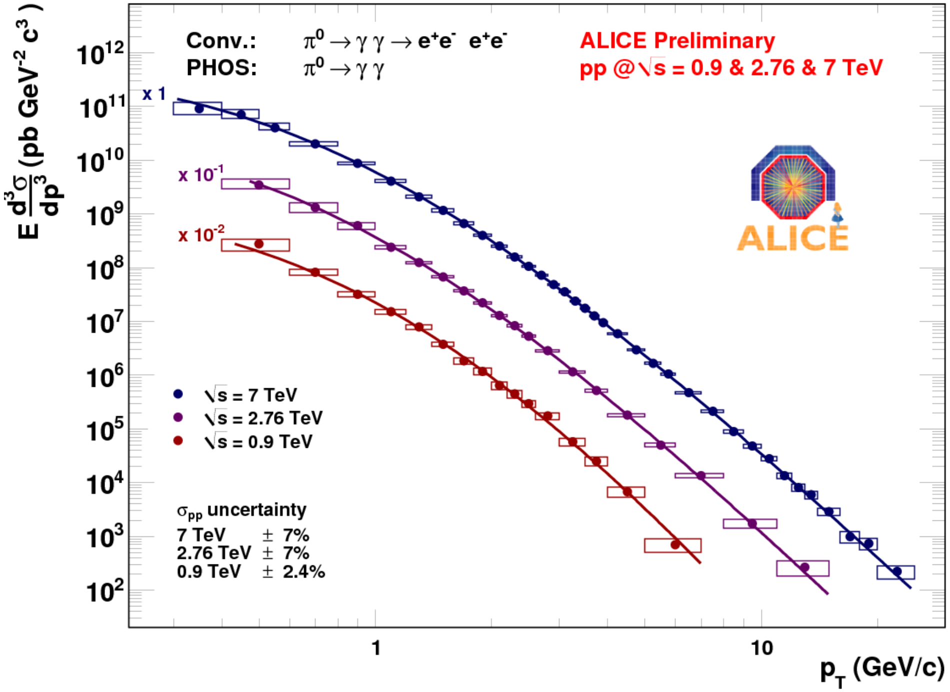
-pi0 loss due to photon conversion in the ALICE medium

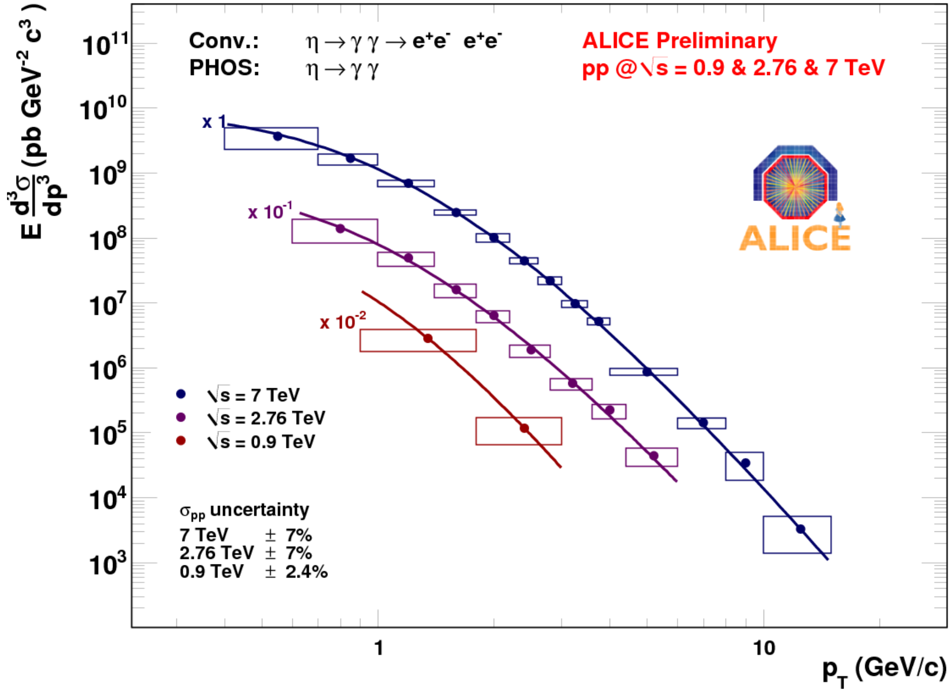
-signal extraction

Conversions

- Material budget
- signal extraction
- background estimation
- e+e- identification
- track selection

π^0 and η production spectra in pp @ 0.9, 2.76 and 7TeV



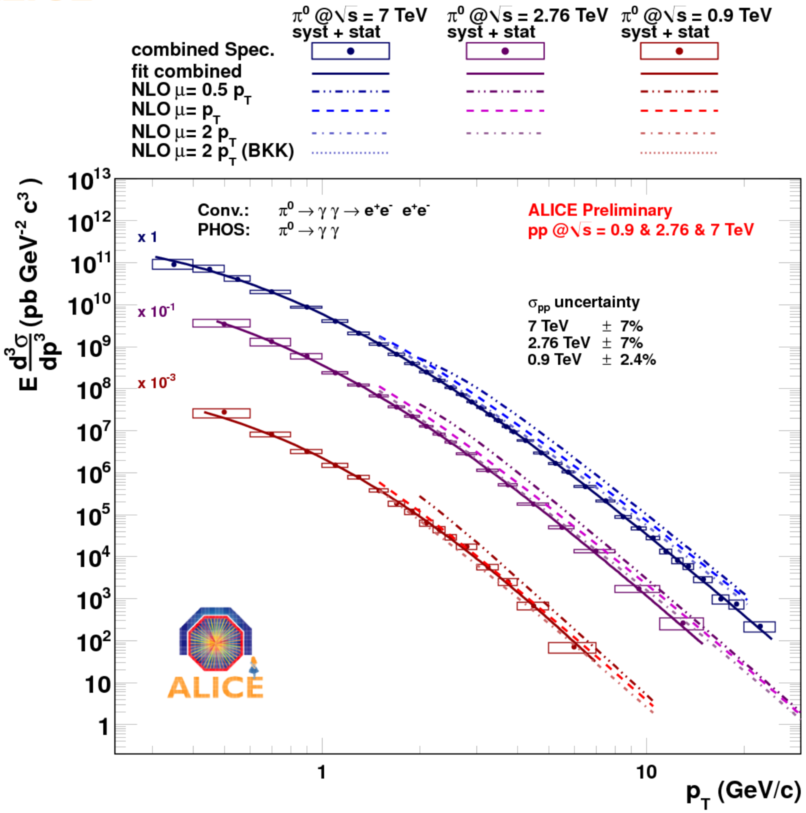


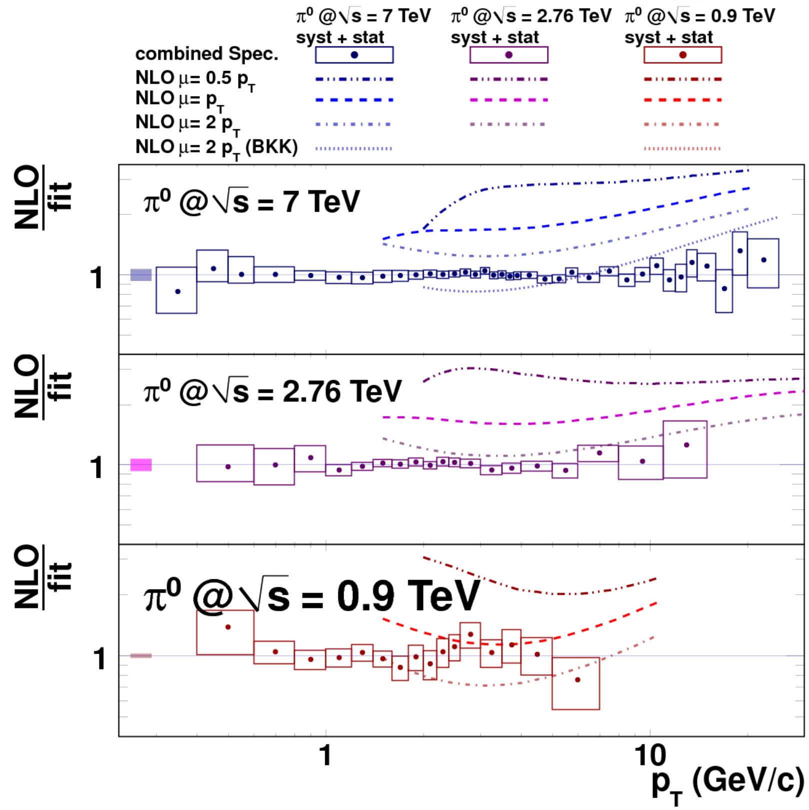
π^0 and η spectra measured at 3 energies by PHOS and conversions methods and fitted by Tsalis function.

Tsallis function:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi}\frac{d\sigma}{dy}\frac{(n-1)(n-2)}{nT(nT+m(n-2))}\left(1+\frac{m_T-m}{nT}\right)^{-n}$$

π^0 meson: ALICE data vs NLO





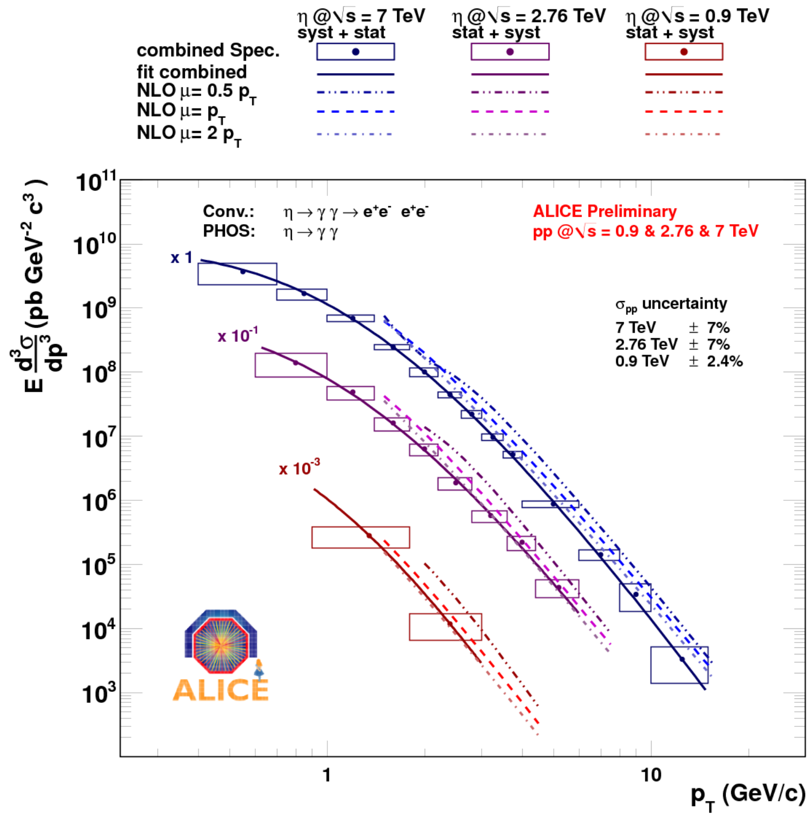
DSS FF's Phys. Rev. D75 114010 (2007)

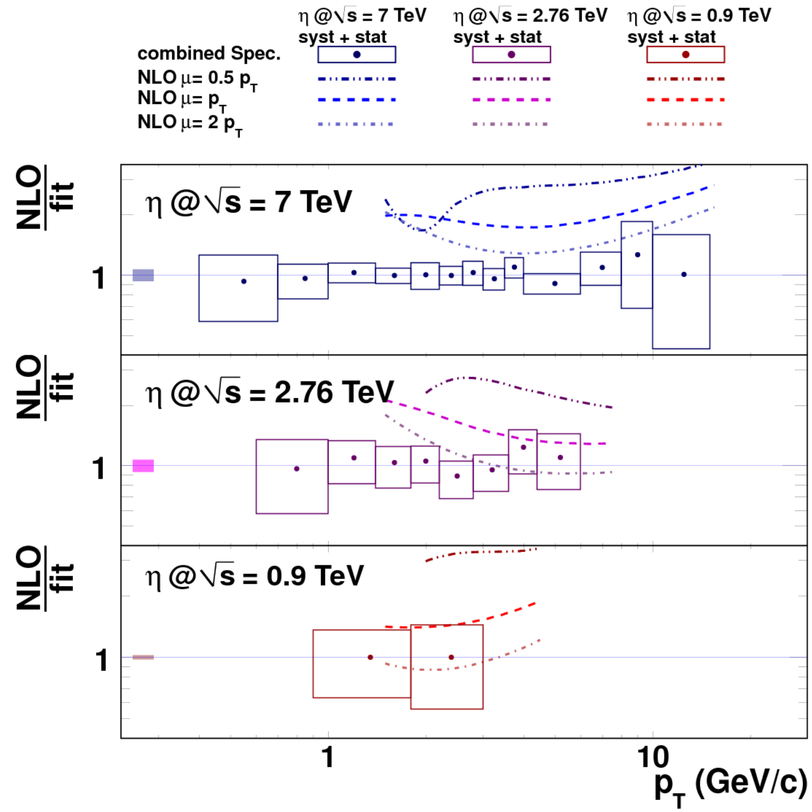
One common set of NLO parameters cannot describe data both at 900 GeV and 7 TeV

NLO pQCD (W. Vogelsang; F. Arleo et al)
PDF: CTEQ6M5, FF: DSS,
μ=0.5p_T, p_T, 2p_T

NLO predictions with DSS FF:
-agree with ALICE data at 900 GeV
-overestimates cross-section for 2.76 and 7 TeV for all scales
-the slope of data and NLO are slightly different
-BKK FF gives better agreement at 7 TeV data

η meson: ALICE data vs NLO





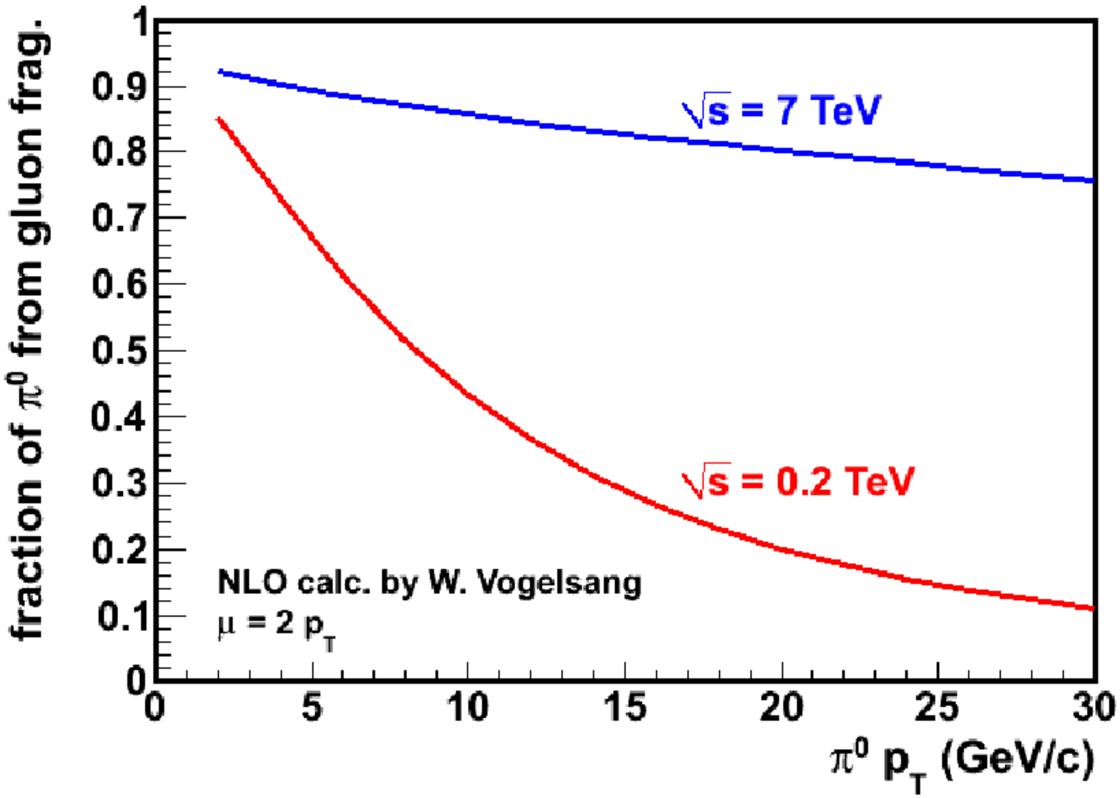
AESSS FF's Phys. Rev. D83 034002 (2011)

One common set of NLO parameters cannot describe data both at 900 GeV and 7 TeV

NLO pQCD (W. Vogelsang; F. Arleo et al)
PDF: CTEQ6M5, FF: AESSS,
$\mu=0.5p_T$, p_T, $2p_T$

NLO predictions with AESSS FF (same trend as for π^0)
- agree with ALICE data at 900 GeV and for p_T>3 GeV at 2.76 TeV
- overestimates cross-section 7 TeV for all scales
- the slope of data and NLO are slightly different

Uncertainties of NLO predictions



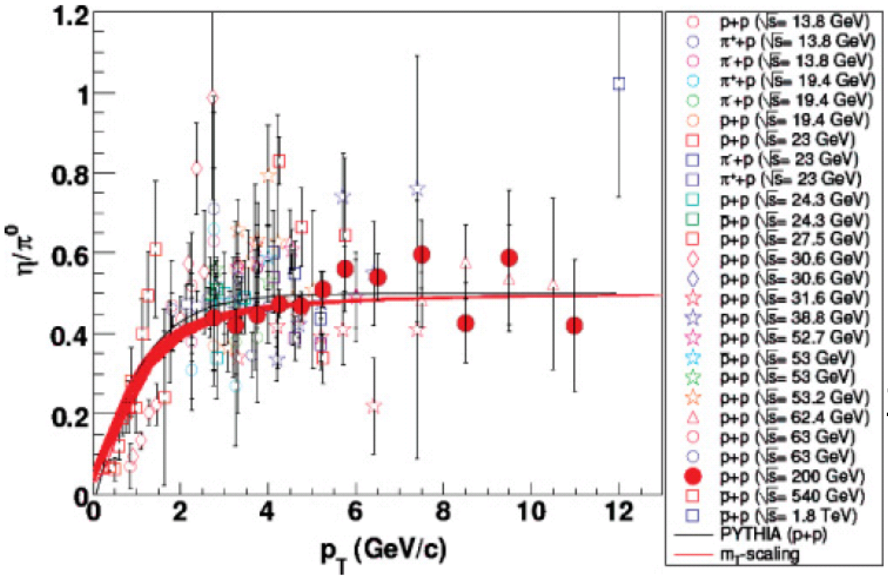
NLO pQCD cross-section factorizes into 3 parts:

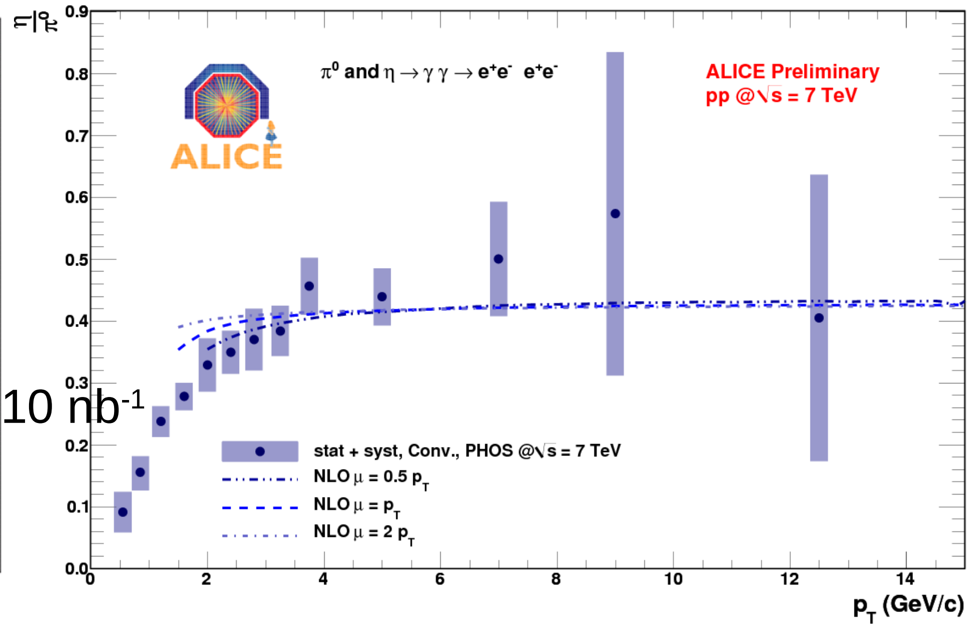
•Parton distribution function (PDF)
•matrix element of the parton level subprocesses and
• Fragmentation function (FF).

•Gluon Fragmentation function is not well constrained.
•Gluon FF is more important at LHC than at RHIC.

η/π^0 ratio: world data compilation

PHENIX PRC 75, 024909 (2007)





- Ratio of neutral meson yields to π^0 is universal for a wide energy range. Precise measurements of neutral meson spectra is necessary for direct photon search. Ratio of spectra are needed for nuclear transport models.
- η/π^0 ratio follows the trend observed at lower energies.
- η/π^0 ratio is consistent with NLO pQCD calculations

η/π^0 ratio: world data compilation

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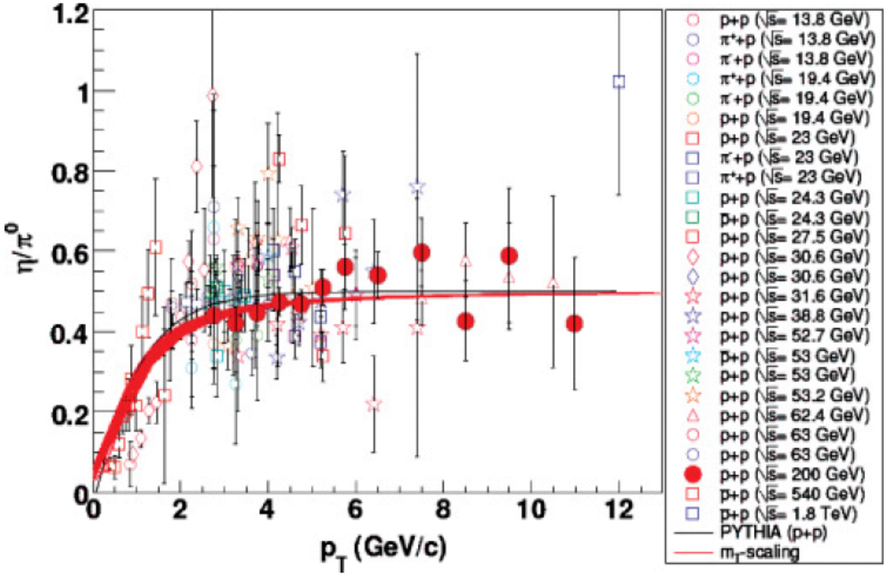
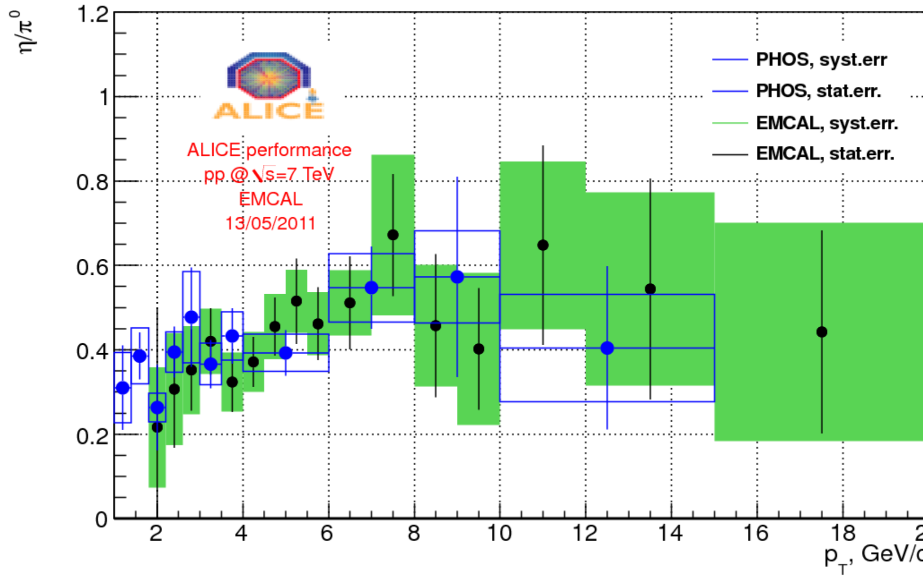


EMCAL enters the stage



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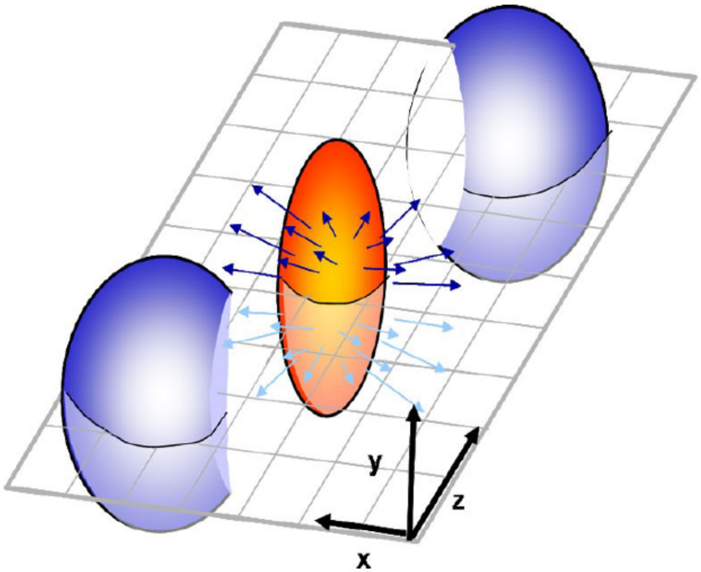
Flow and non-flow



•Particle azimuthal distribution measured with respect to the reaction plane is not isotropic.

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t\, dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\varphi-\Psi_{RP}\right)\right)\right)$$

$$v_n=\langle\cos\left(n\left(\varphi_i-\Psi_{RP}\right)\right)\rangle$$

•v_n quantify the event anisotropy

•Ψ_{RP} can be estimated from the particle azimuthal distribution

Problems:

•Non-flow (other sources of azimuthal correlations) quantified by δ_n:

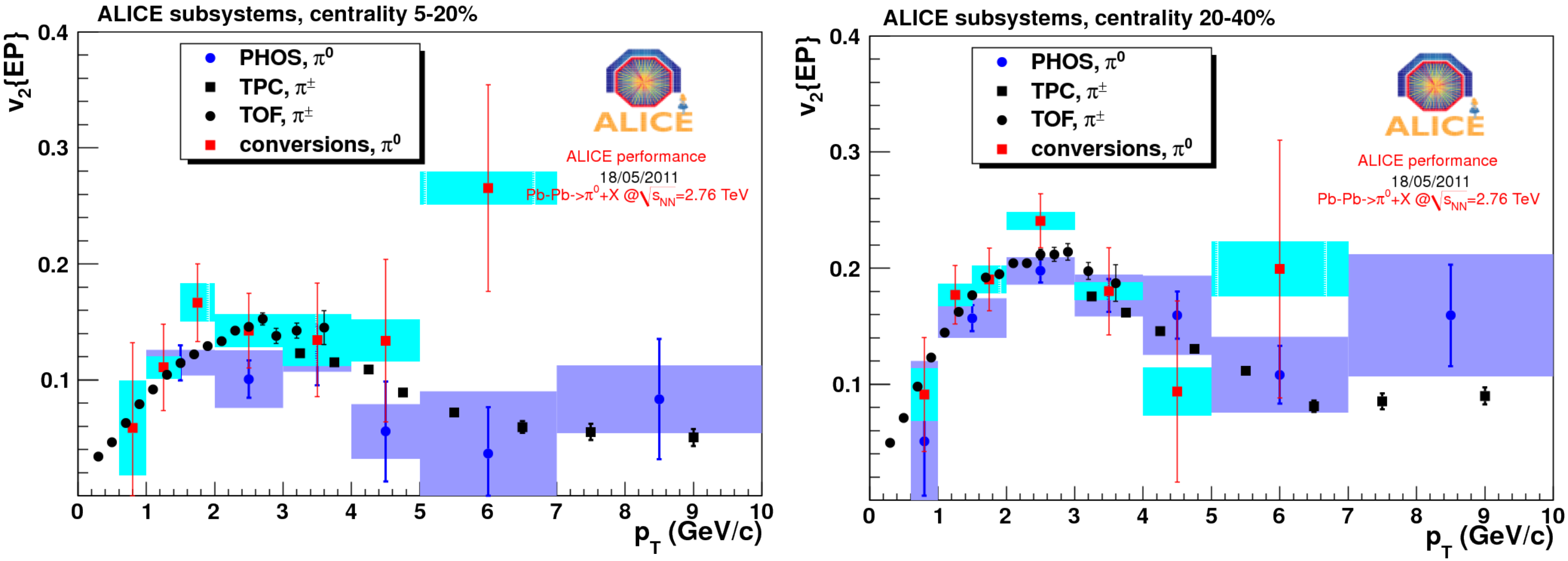
$$\langle\cos\left(n\left(\varphi_i-\varphi_j\right)\right)\rangle=\langle v_n^2\rangle+\delta_n$$

•Flow fluctuations:

$$\langle v_n^2\rangle=\langle v_n\rangle^2+\sigma_{vn}^2$$

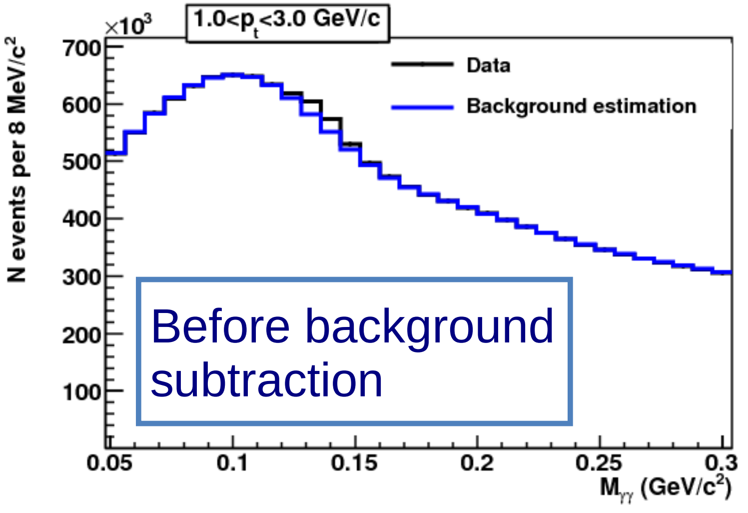
Azimuthal anisotropy of π^0: v_2

ALICE studies azimuthal anisotropy in production of many identified hadrons. π^0 mesons is not an exclusion



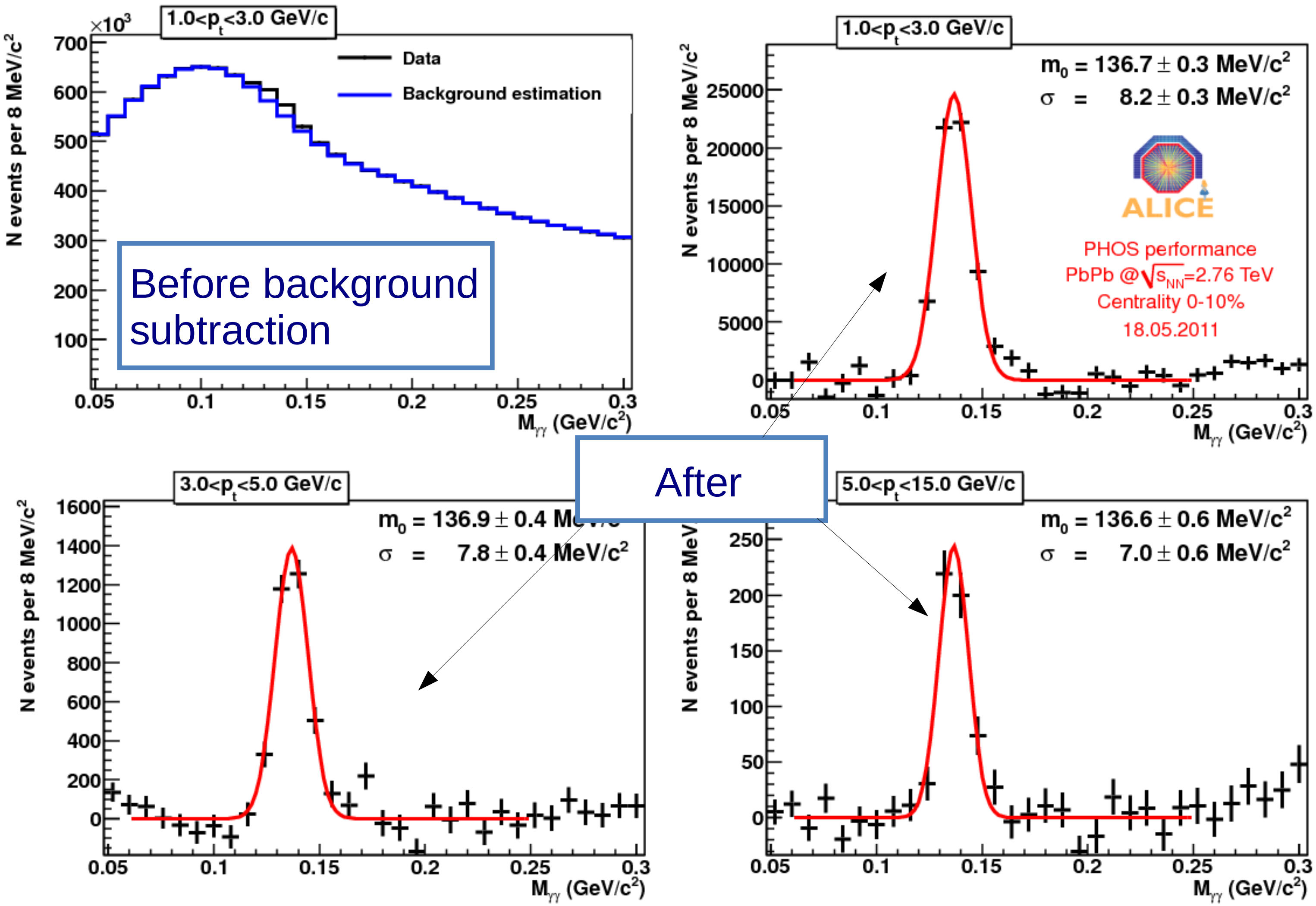
– π^0 v_2 is in agreement with charged pions measurements
- sufficient statistics is needed in order to reduce the error bars

Calorimeter performance in HIC



Calorimeter performance in HIC

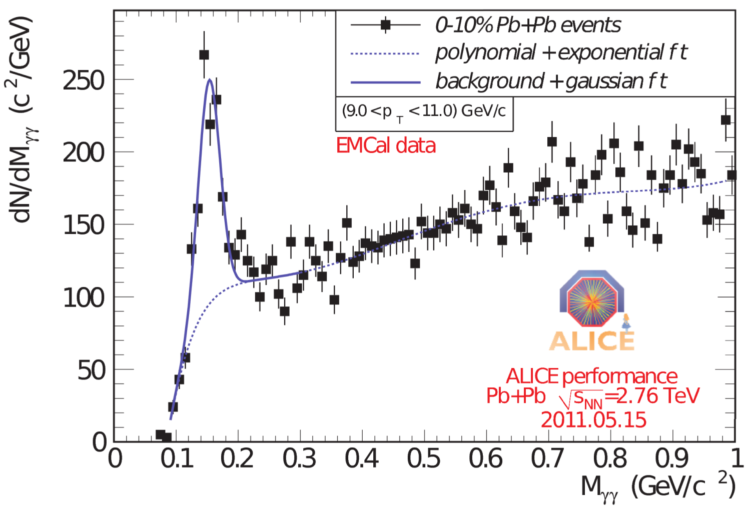
PHOS

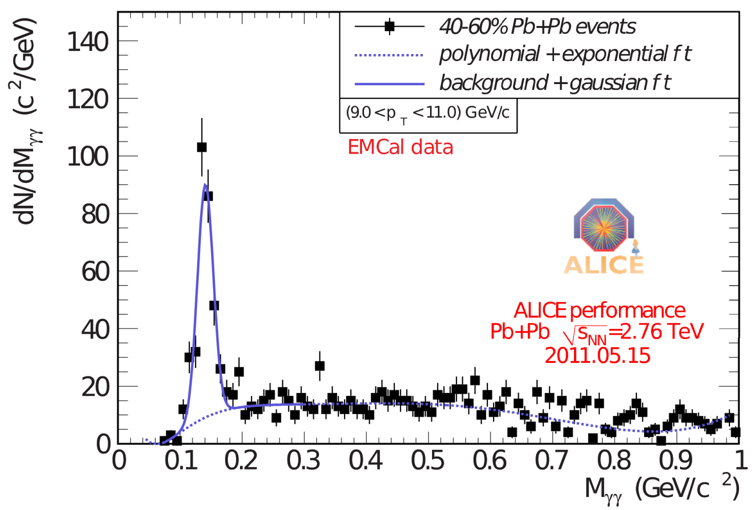


Pi0 peak in the most central collisions.

Calorimeter performance in HIC

EMCAL enters the stage

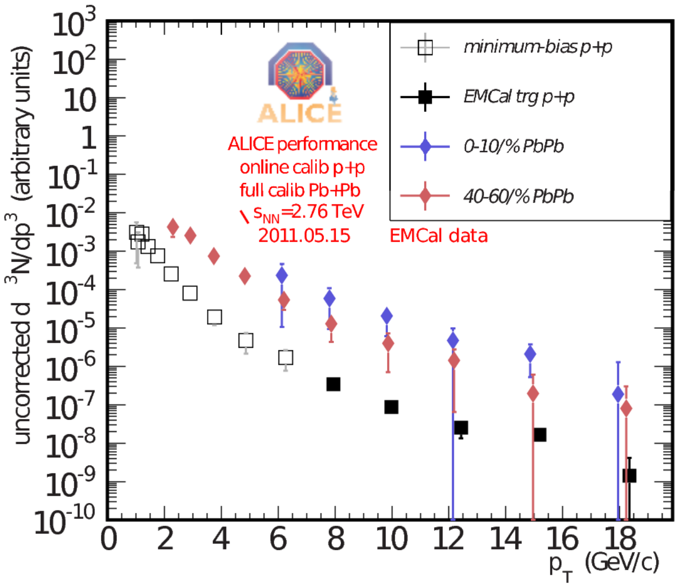


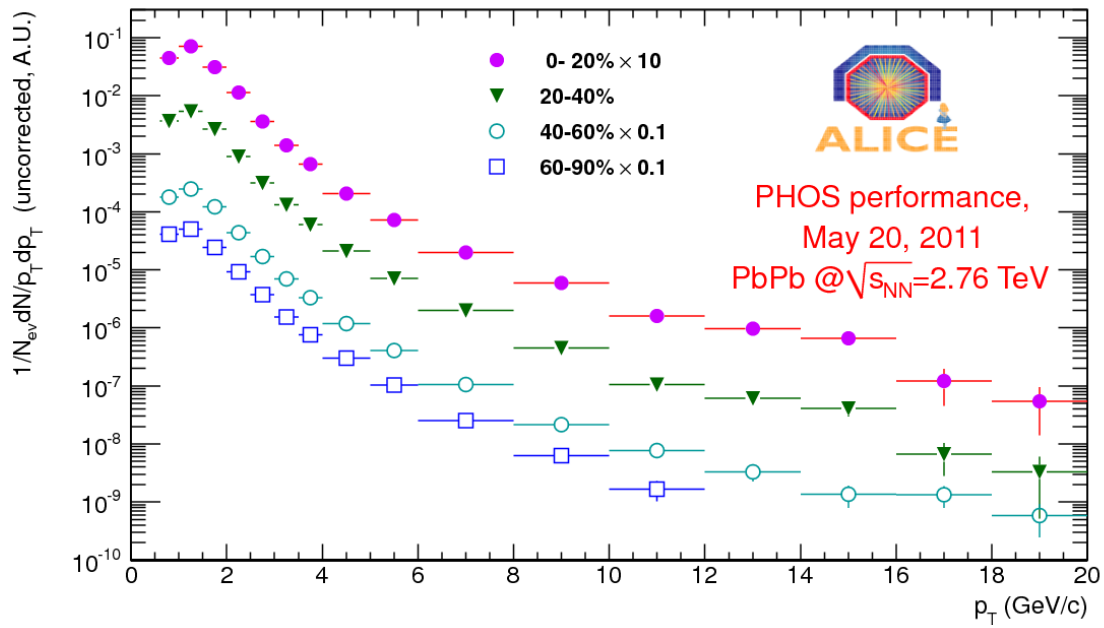


EMCAL

Pi0 peak in the most central collisions.

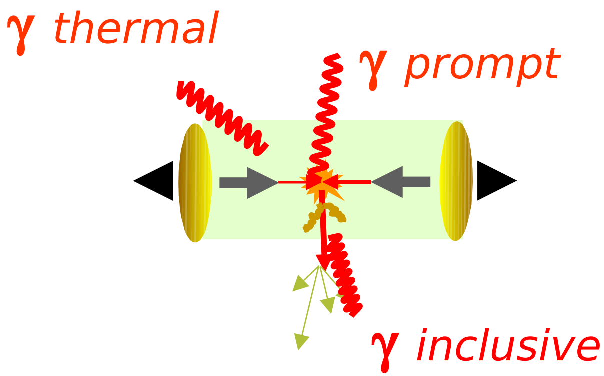
Calorimeter PbPb performance





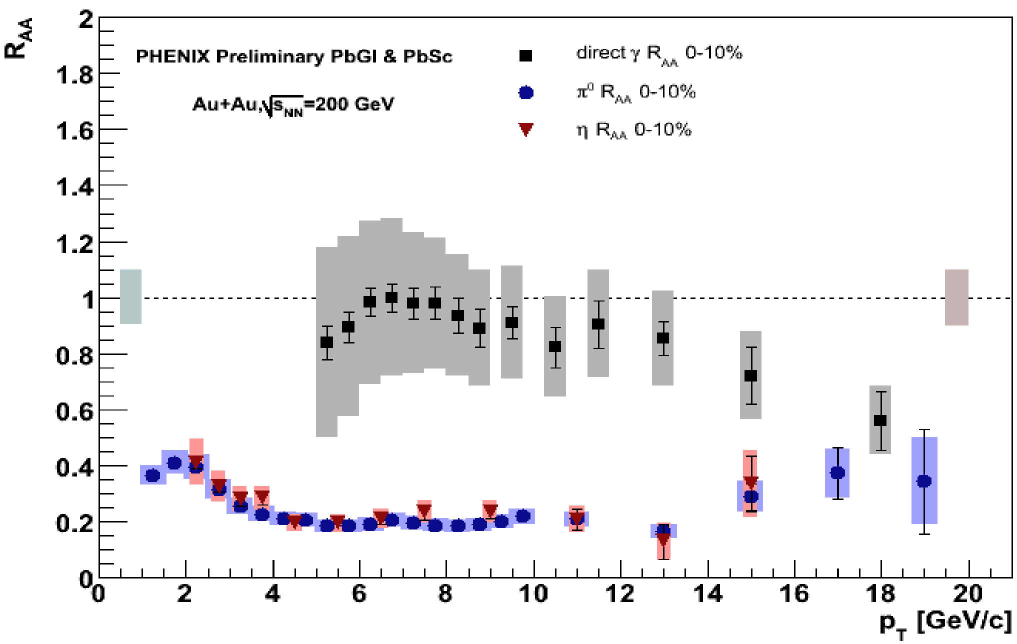
- Uncorrected spectra of reconstructed π^0s in different centralities normalized by number of PbPb collisions in a given centrality.
- Efficiency calculation is a challenging task, as it drops dramatically in the high detector occupancy environment.
- Uncorrected π^0 spectra give us an idea of the accessible range for R_{aa} $1 < p_t < 20$ GeV

Direct photons and π^0 R_{AA}

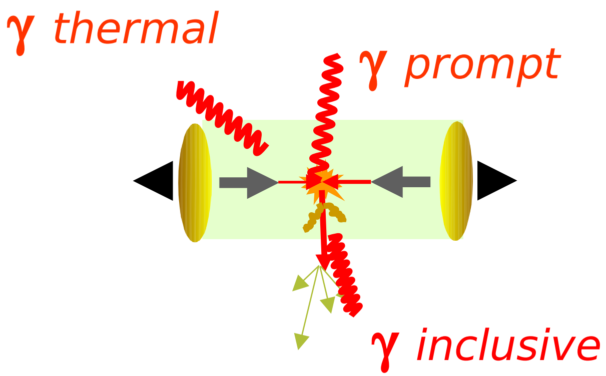


- Hard partons lose energy in the hot medium.
- π^0 R_{AA} suppression at high p_T.

prompt+thermal=direct



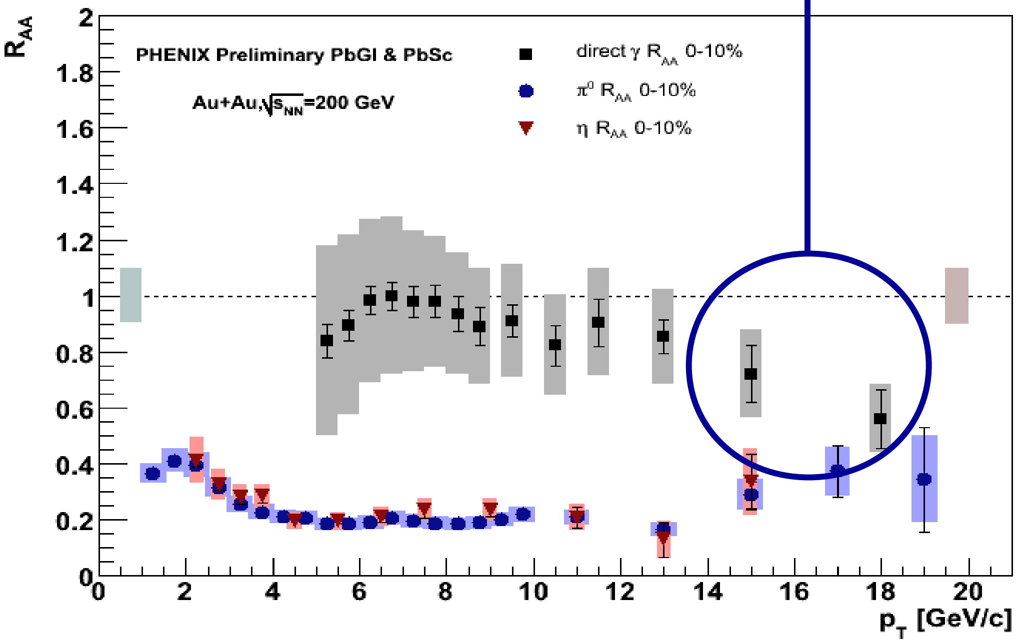
Direct photons and π^0 R_{AA}



- Hard partons lose energy in the hot medium.
- π^0 R_{AA} suppression at high p_T.
- direct photons R_{AA}: deviation from 1

[http://arxiv.org/abs/0908.2382]

prompt+thermal=direct



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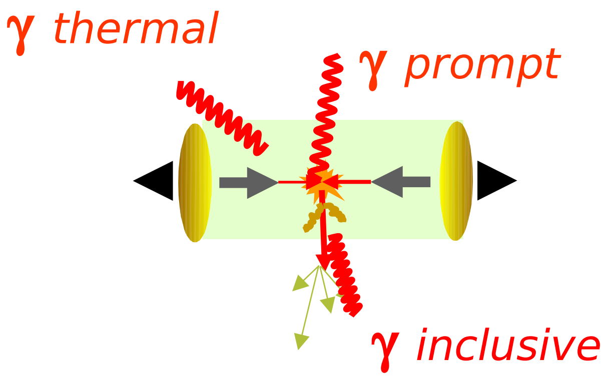

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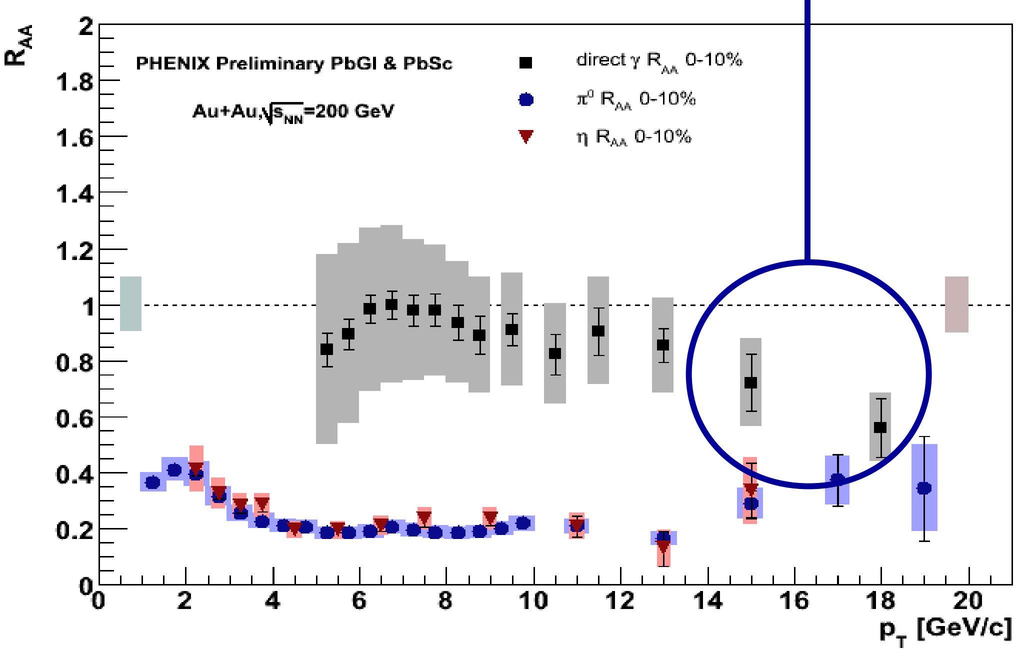

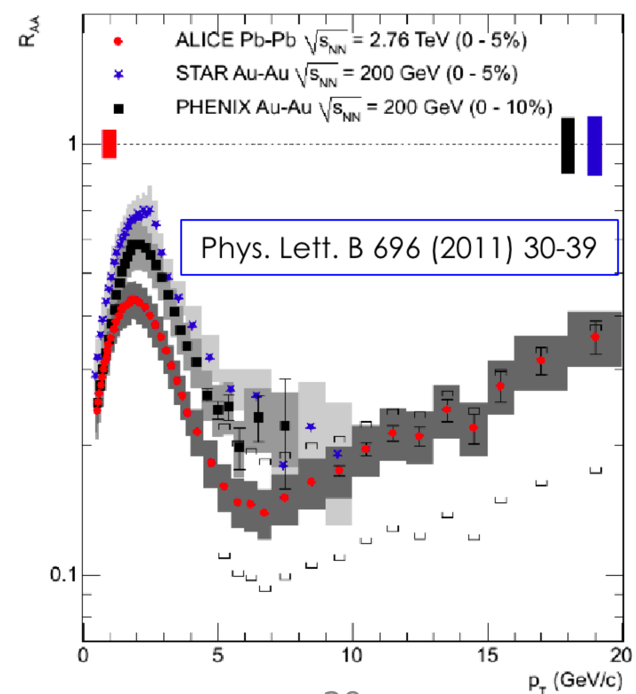

R_{AA} η in PHENIX: PHYS.REV. C 82, 011902(R) (2010)

R_{AA} π^0, η, direct photons: arXiv:0908.2382v1 [nucl-ex]

R_{AA} π^0 in PHENIX: PRL 101, 232301 (2008)

Direct photons and π^0 R_{AA}

-Hard partons lose energy in the hot medium.
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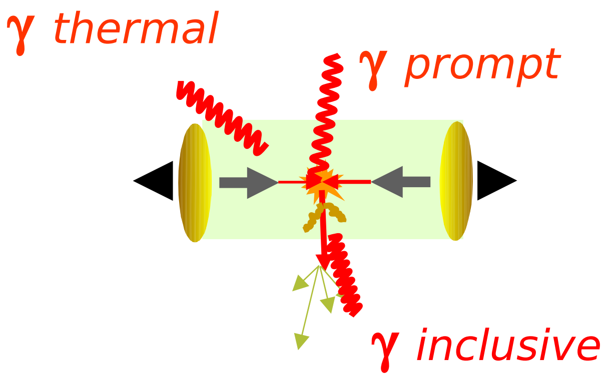
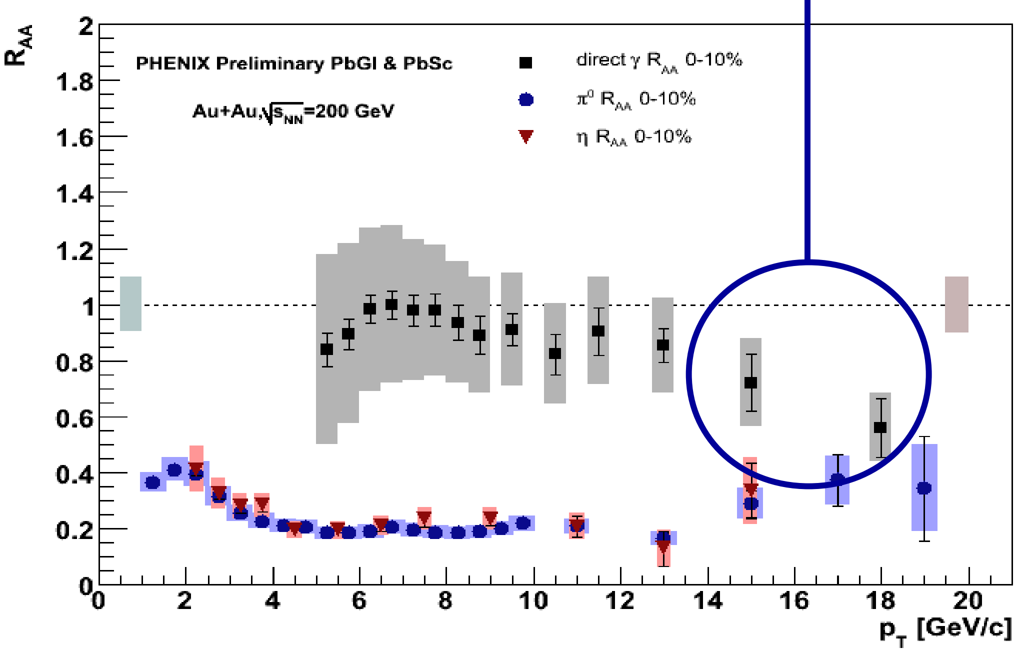
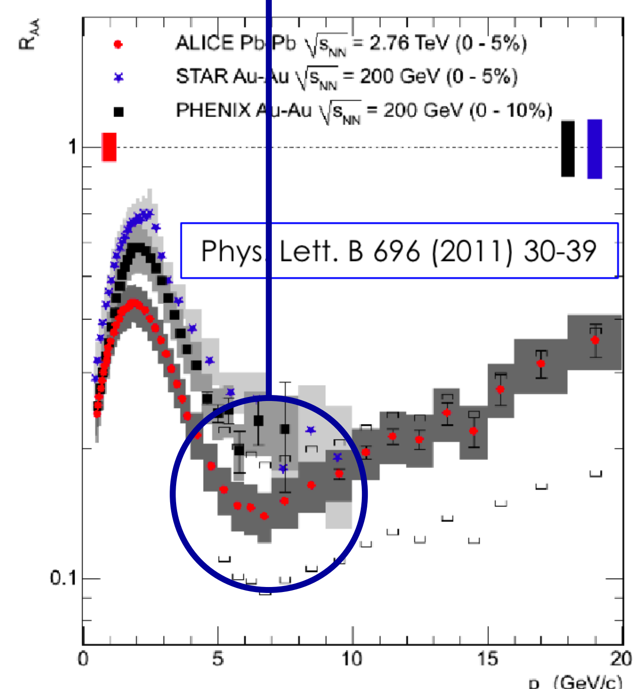


prompt+thermal=direct

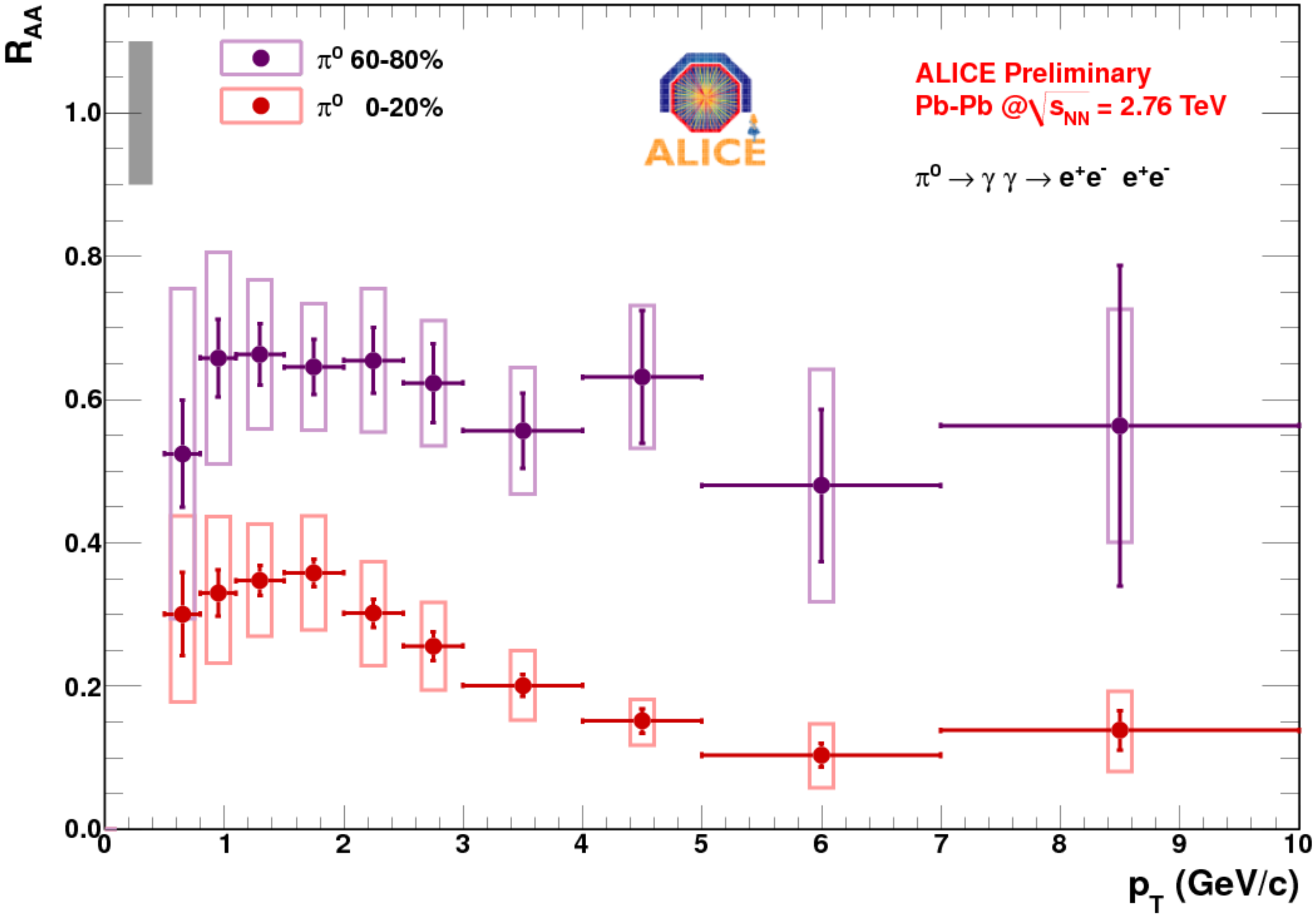


-R_{AA} in ALICE show stronger suppression than at RHIC energies
-R_{AA} of identified particles?



R_{AA} η in PHENIX: PHYS.REV. C 82, 011902(R) (2010)
R_{AA} π^0, η, direct photons: arXiv:0908.2382v1 [nucl-ex]
R_{AA} π^0 in PHENIX: PRL 101, 232301 (2008)

π^0 R_{AA} with conversions

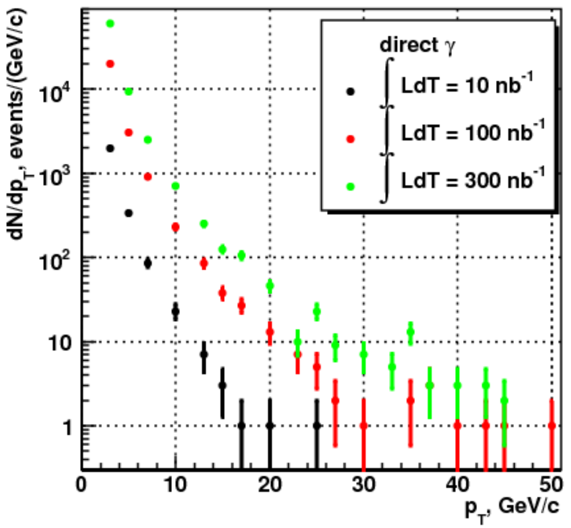


Strong suppression in the central events, R_{AA} =0.15 at high p_T

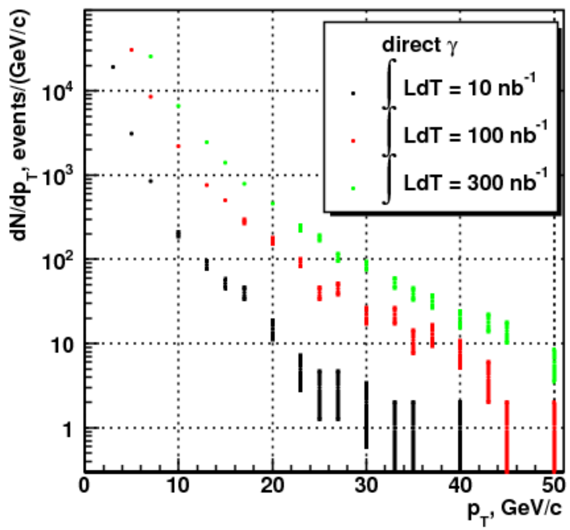
Predicted rates for direct photons

$$pp \to \gamma_{direct} X$$

PHOS



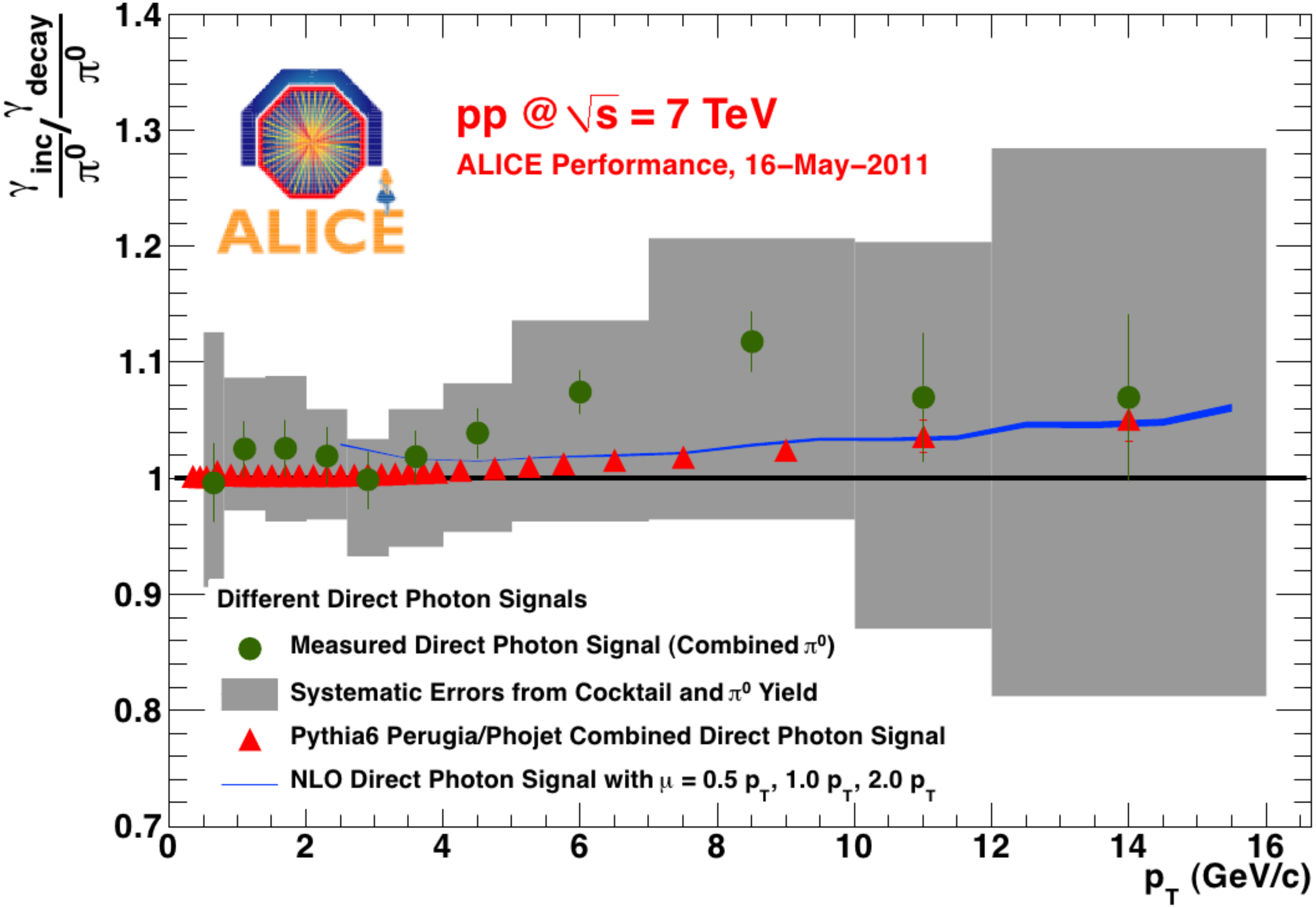
EMCAL



- The first year of LHC with pp@7 TeV delivered 10 nb^{-1} to ALICE.
- Expected p_T ranges for direct photon spectra are
  - in PHOS p_T<8 GeV/c
  - in EMCAL p_T<12 GeV/c
- Rates were calculated using INCNLO[1] program (pQCD NLO).

[1] P. Aurenche, et al., Eur. Phys. J. C 13,347 (2000)

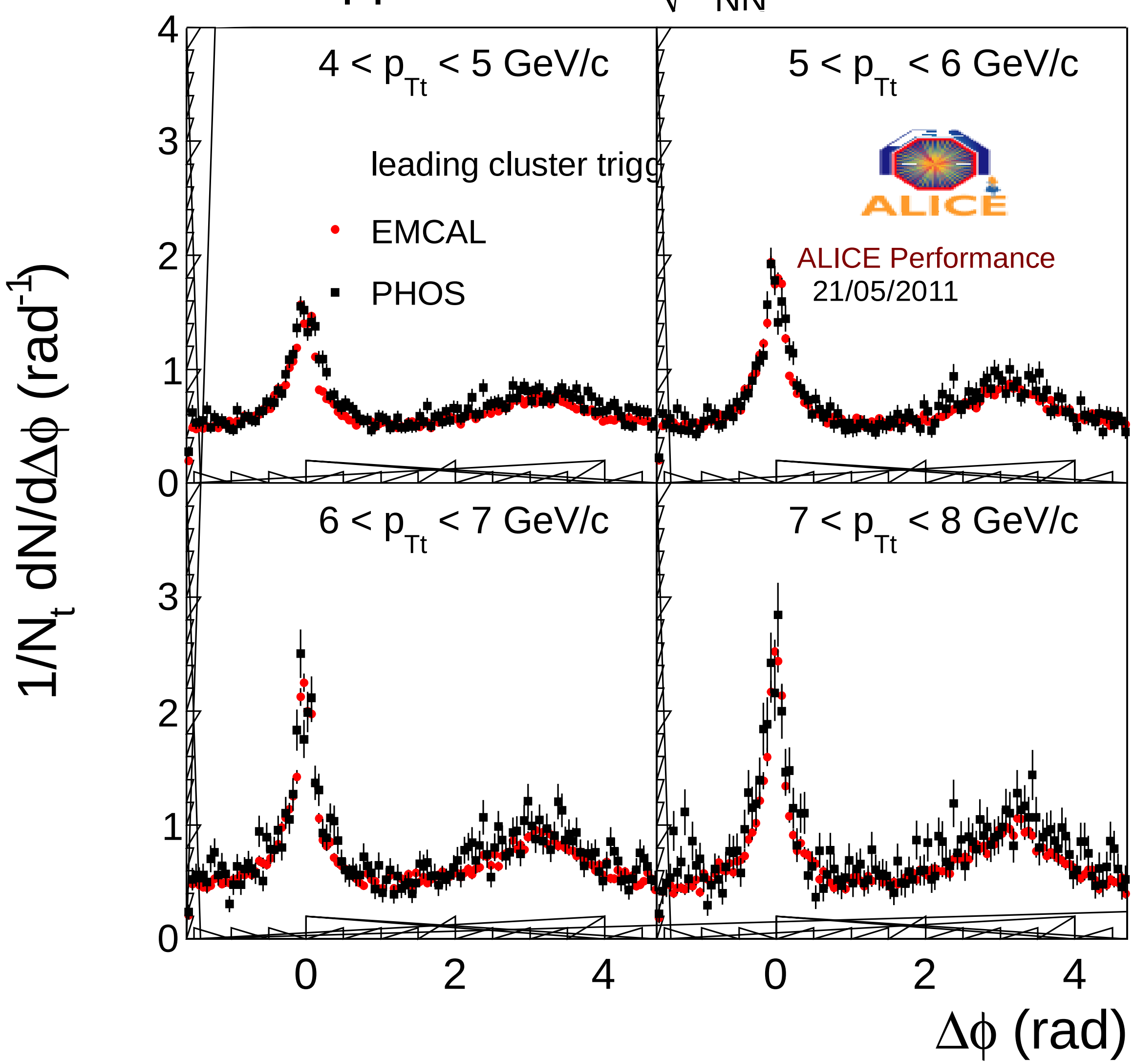
Direct photons



First attempt to measure direct photons in ALICE.

Photon-hadron correlations

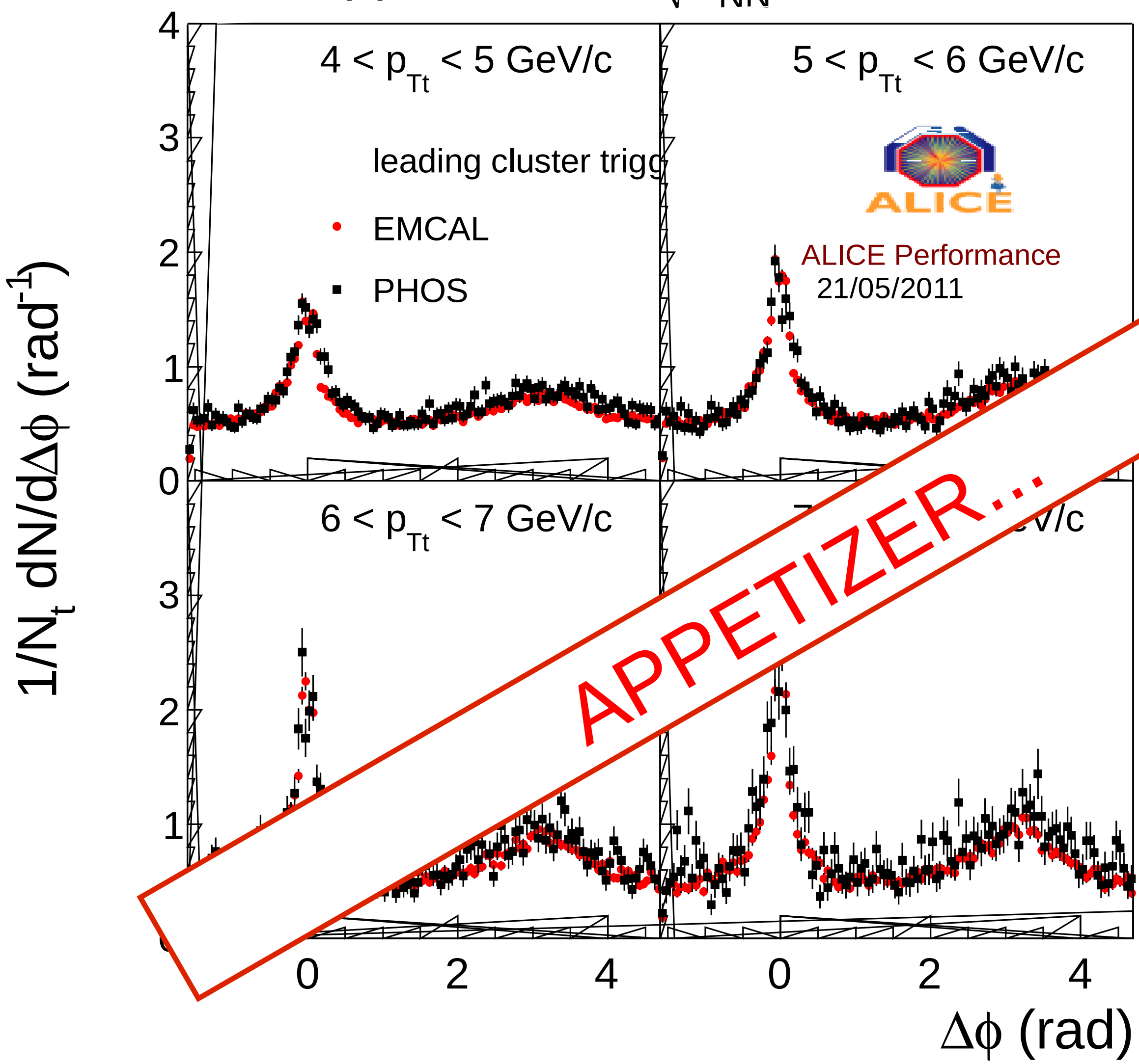
pp events at $\sqrt{s_{NN}}$ = 7 TeV



ALICE performance in pp already illustrates near- and away- side peaks.

Photon-hadron correlations

pp events at $\sqrt{s_{NN}} = 7$ TeV



CE performance in
eady illustrates
ear- and away- side
peaks.

Looking forward to PbPb results!

Summary

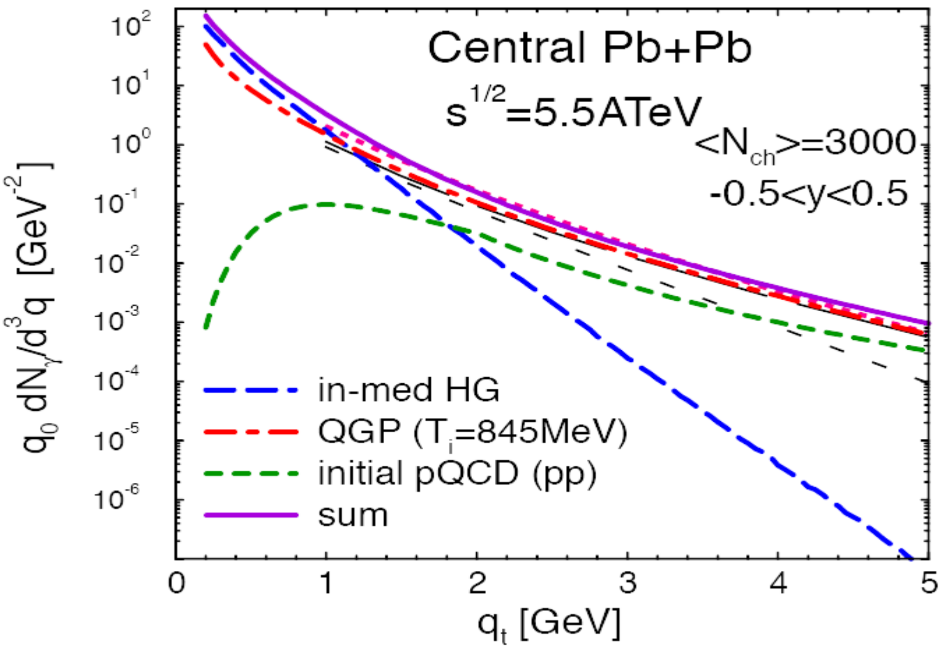
- ALICE is well equipped by photon detectors: PHOS and EMCAL
- ALICE will measure direct photon, neutral meson spectra, γ-hadron and γ-jet correlations, jet fragmentation functions.
- The first year LHC run with pp@7 TeV has brought results on π^0 spectrum at p_T<25 GeV/c, η meson spectrum at p_T<20 GeV/c, η to π^0 ratio at p_T<20 GeV/c.
- In a first year heavy-ion run PbPb@2.76 ATeV at LHC calorimeters can measure π^0 spectrum and R_{AA} up to p_T<20 GeV/c depending on centrality.
- Azimuthal anisotropy v_2 of π^0 production was measured in ALICE.
- π^0 R_{AA} observed with conversion method show strong suppression at high p_T.

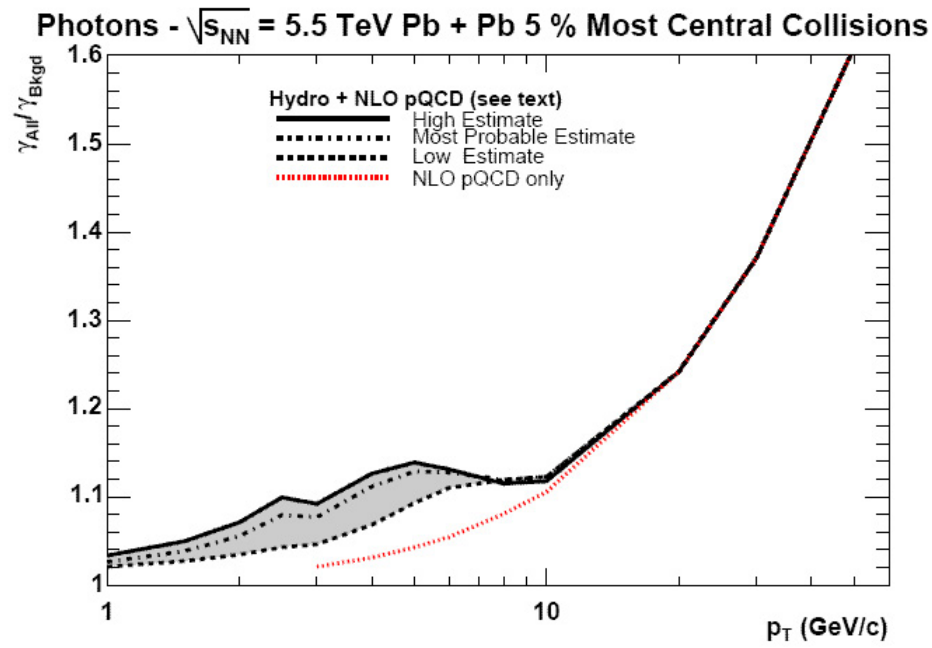
Thank you for attention!

Backup

Physics observables

Thermal photons





F.Arleo et al., arXiv:hep-ph/0311131

- Thermal photon from hadron gas contribute at low p_t>2 GeV.
- Prompt photons contribute at p_t>3 GeV.
- Thermal photons from QGP radiation (up to 10% of inclusive photons) contribute at p_t>10 GeV.
- Thermal photons have large theoretical uncertainties.

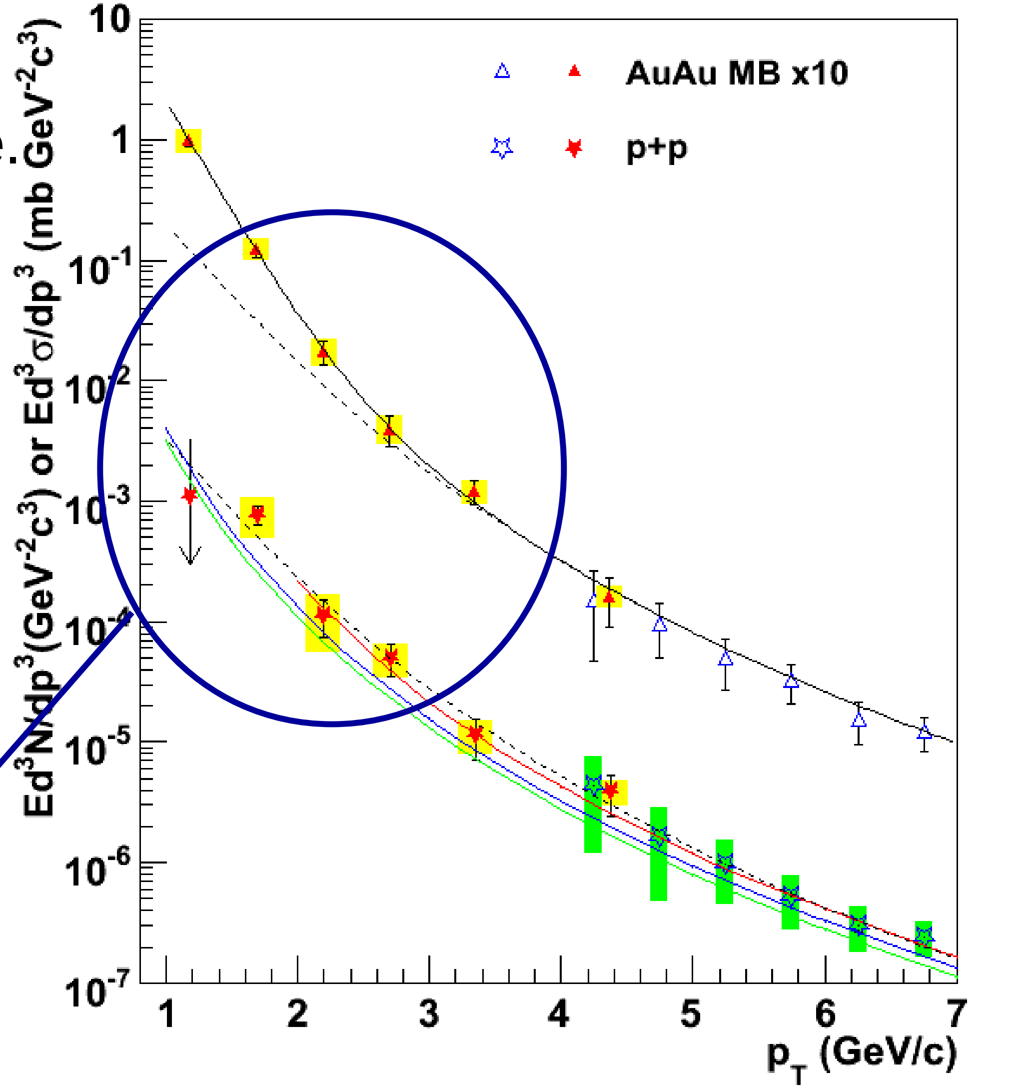
Thermal photons

PHENIX p+p: PRL 104, 132301(2010)

Hot quark-gluon matter radiates photons which escape.

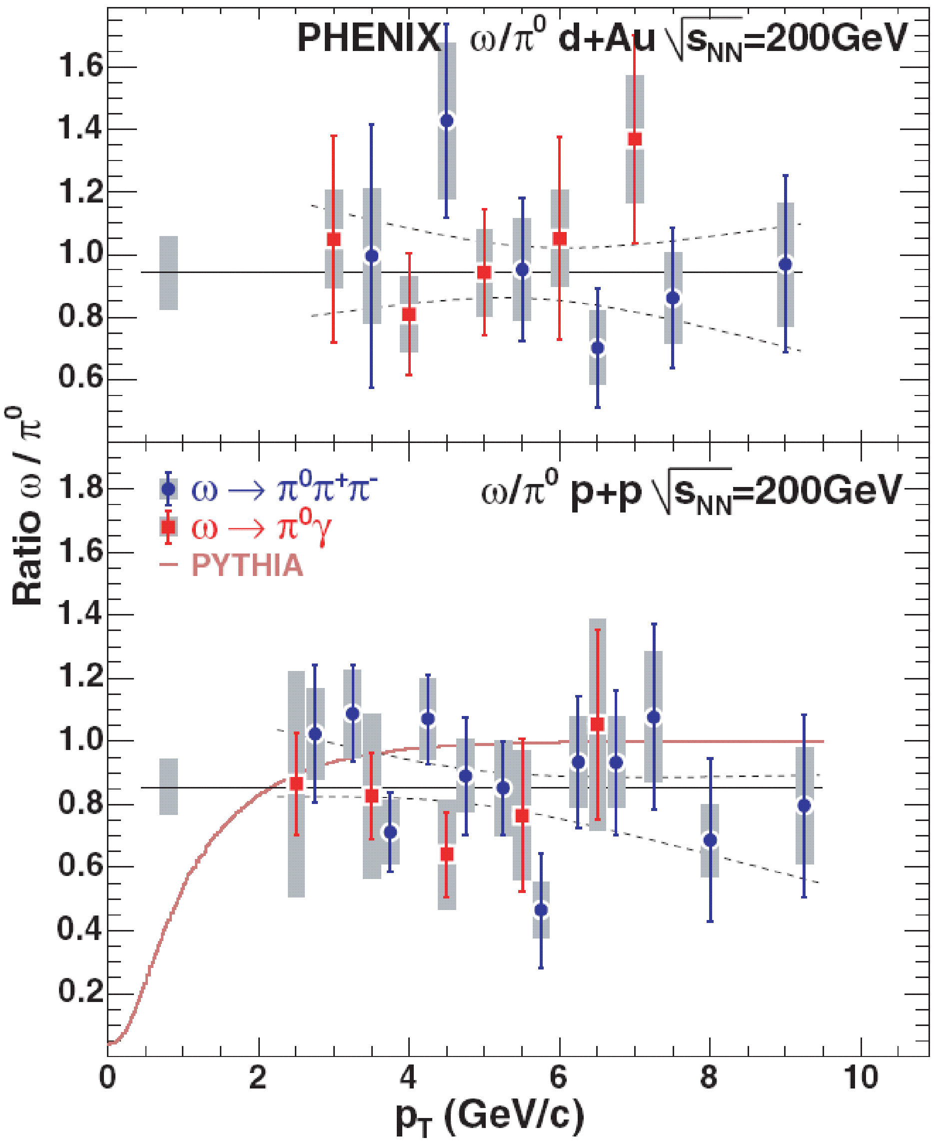
Difficult measurement:

- Large background $\pi^0 \rightarrow \gamma\gamma$
- Thermal photons at low p_T



Excess of direct photons seen at RHIC above *p+p* spectrum.

ω/π^0 ratio: world data compilation



PHENIX, PRC 75, 051902(R) (2007)

What is expected at LHC scale?

ALICE

ALICE calorimeters

PHOS

- **Active element**: crystal of lead tungstate $2.2 \times 2.2 \times 18$ cm^3.
- **Geometry 2010**: 3 modules 64×56 crystals each; distance from IP to active surface: 460 cm
- **Aperture**: $|\eta|<0.13$, $\Delta\varphi = 60°$
- **Energy range**: 0<E<100 GeV
- **Material budget** from IP to PHOS: $0.2X_0$.
- **Energy resolution**:

$$\frac{\Delta E}{E} = \frac{1.3\%}{E\,(\mathrm{GeV})} \oplus \frac{3.3\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus 1.12\%$$

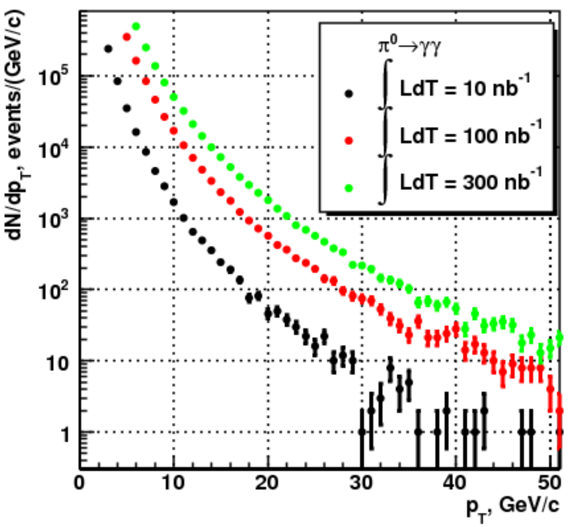
EMCAL

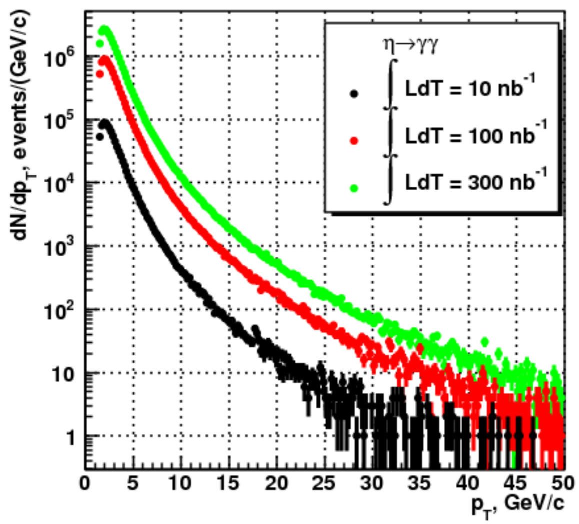
- **Active element**: tower of 77 layers (1.4mm lead + 1.7 mm scintillator) $6 \times 6 \times 25$cm^3.
- **Geo 2010**: 4 super modules 24×48 towers each; distance from IP to active surface: 430 cm
- **Aperture**: $|\eta|<0.7$, $\Delta\varphi = 40°$ (2010); $\Delta\varphi = 100°$ (2011).
- **Energy range**: 0<E<250 GeV
- **Material budget** from IP to EMCAL: $0.5X_0$ (2010), $0.5\text{-}0.8X_0$ (2011)
- **Energy resolution**:

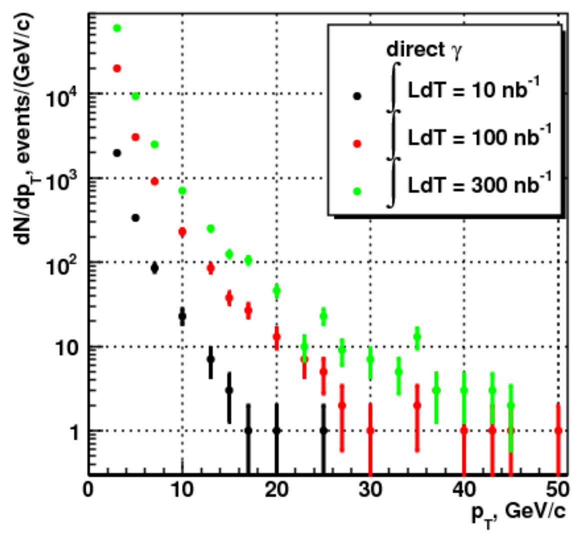
$$\frac{\Delta E}{E} = \frac{4.8\%}{E\,(\mathrm{GeV})} \oplus \frac{11.3\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus 1.7\%$$

Expected event rates in ALICE PHOS in pp

$pp \to \pi^0 X,\ \pi^0 \to \gamma\gamma$ $pp \to \eta X,\ \eta \to \gamma\gamma$ $pp \to \gamma_{direct} X$







The first year of LHC with pp@7 TeV delivered 10 nb^{-1} to ALICE.
Expected p_T ranges for spectra in PHOS:

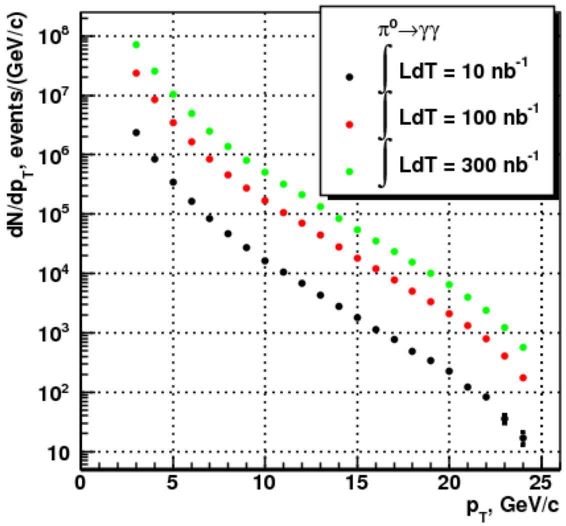
- π^0: p_T<25 GeV/c
- η: p_T<20 GeV/c
- γ : p_T<8 GeV/c

Cross-sections were calculated by INCNLO[1] for π^0 and direct photons and by Pythia 6 for η.

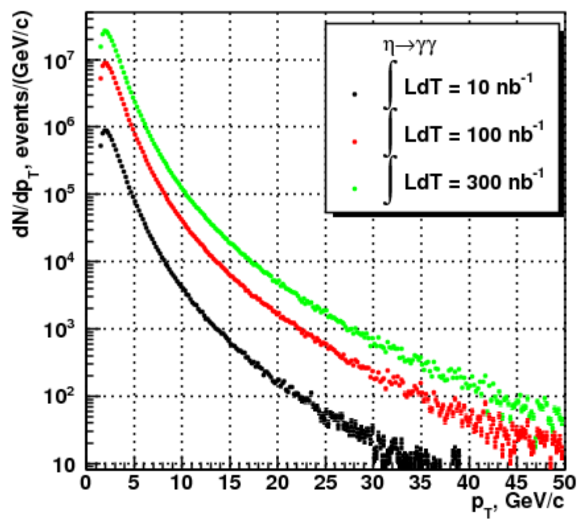
[1] P. Aurenche, et al., Eur. Phys. J. C 13,347 (2000)

Expected event rates in ALICE EMCAL in pp

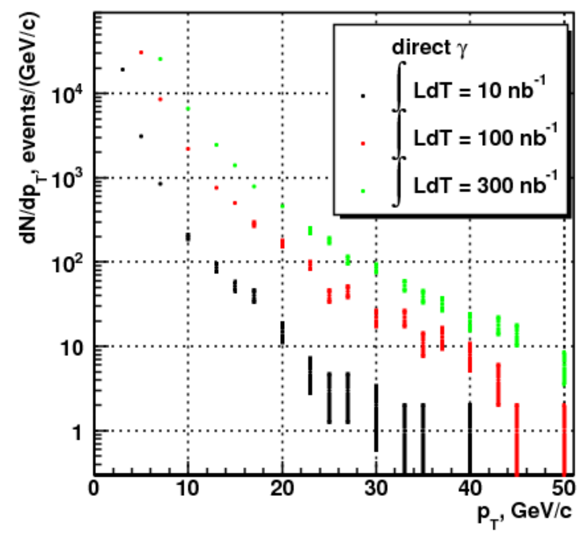
$pp \rightarrow \pi^0 X,\ \pi^0 \rightarrow \gamma\gamma$



$pp \rightarrow \eta X,\ \eta \rightarrow \gamma\gamma$



$pp \rightarrow \gamma_{direct} X$



In december 2010 EMCAL was fully installed, $\Delta\varphi = 100°$

Expected p_T ranges for spectra in EMCAL at L=10 nb^{-1}

- π^0: p_T<25 GeV/c
- η: p_T<25 GeV/c
- γ : p_T<12 GeV/c

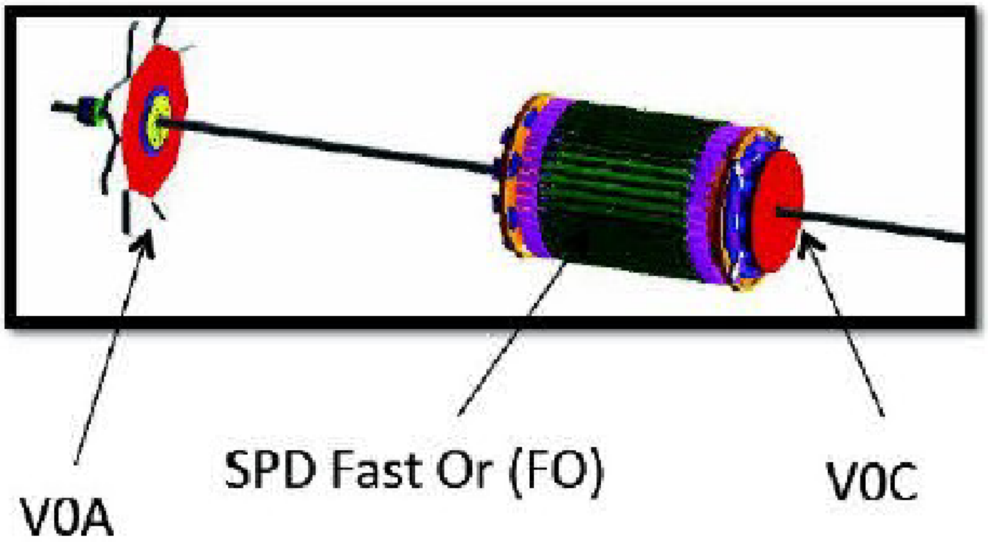
Cross-sections were calculated by INCNLO[1] for π^0 and direct photons and by Pythia 6 for η.

[1] P. Aurenche, et al., Eur. Phys. J. C 13,347 (2000)

Event selection

ALICE trigger detectors:

•Silicon Pixel Detector (SPD) |η|<2
•Scintillator hodoscopes
V0A (2.8<η<5.1)
V0C (-3.7<η<-1.7)



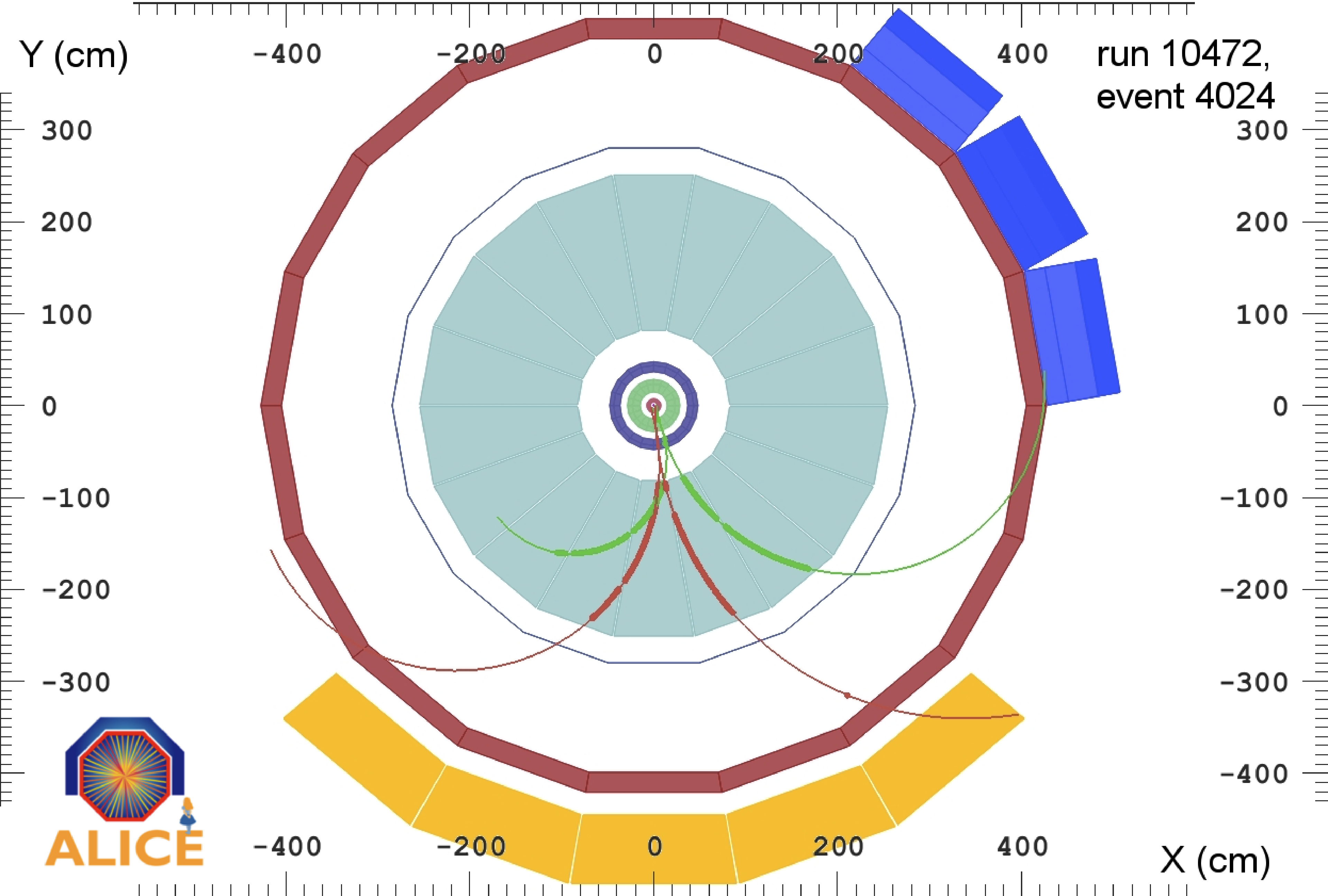
Minimum bias trigger:

•Minimum bias event is selected by the coincidence of the bunch crossing signal and the condition:

SPD|V0A|V0C

•Not a beam-gas event type calculated offline by V0A or V0C
•Efficiency of selecting inelastic pp events is ~90%.

Conversion method

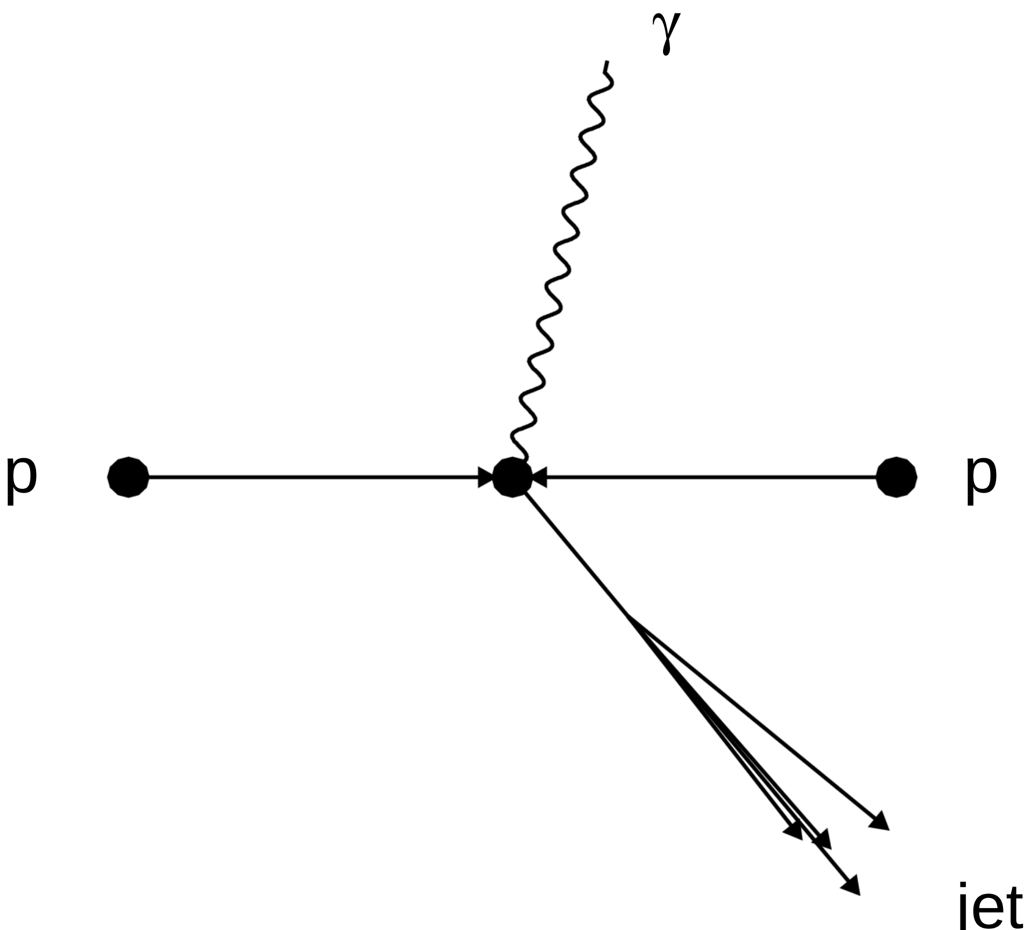


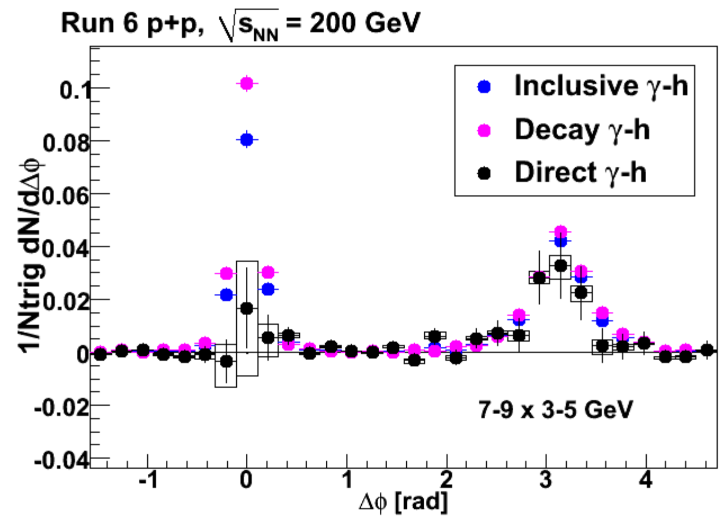
Tsallis fit parameters

	Fit	value	sys Error	χ^2	ndf	χ^2/ndf
7 TeV:	$d\sigma^{\pi^0}/dy$ (pb)	$1.72 \cdot 10^{11}$	$0.096 \cdot 10^{11}$	12.8	33.00	0.39
	n	6.79	0.06			
	$T_{Tsallis}$ (GeV/c)	0.140	0.004			
2.76 TeV:	$d\sigma^{\pi^0}/dy$ (pb)	$1.24 \cdot 10^{11}$	$0.16 \cdot 10^{11}$	7.9	16.00	0.49
	n	7.05	0.18			
	$T_{Tsallis}$ (GeV/c)	0.130	0.008			
0.9 TeV:	$d\sigma^{\pi^0}/dy$ (pb)	$6.51 \cdot 10^{10}$	$1.12 \cdot 10^{10}$	7.5	13.00	0.57
	n	8.4	0.6			
	$T_{Tsallis}$ (GeV/c)	0.151	0.015			

	Fit	value	sys Error	χ^2	ndf	χ^2/ndf
7 TeV:	$d\sigma^{\eta}/dy$ (pb)	$1.48 \cdot 10^{10}$	$0.17 \cdot 10^{10}$	2.0	10.00	0.2
	n	7.2	0.5			
	$T_{Tsallis}$ (GeV/c)	0.239	0.021			
2.76 TeV:	$d\sigma^{\eta}/dy$ (pb)	$1.08 \cdot 10^{10}$	$0.3 \cdot 10^{10}$	1.31	6.00	0.22
	n	7.05	fixed as π^0			
	$T_{Tsallis}$ (GeV/c)	0.215	0.020			
0.9 TeV:	$d\sigma^{\eta}/dy$ (pb)	$2.1 \cdot 10^{10}$	$2.3 \cdot 10^{10}$	-	-	-
	n	8.4	fixed as π^0			
	$T_{Tsallis}$ (GeV/c)	0.152	0.057			

Jet tagging by prompt photons



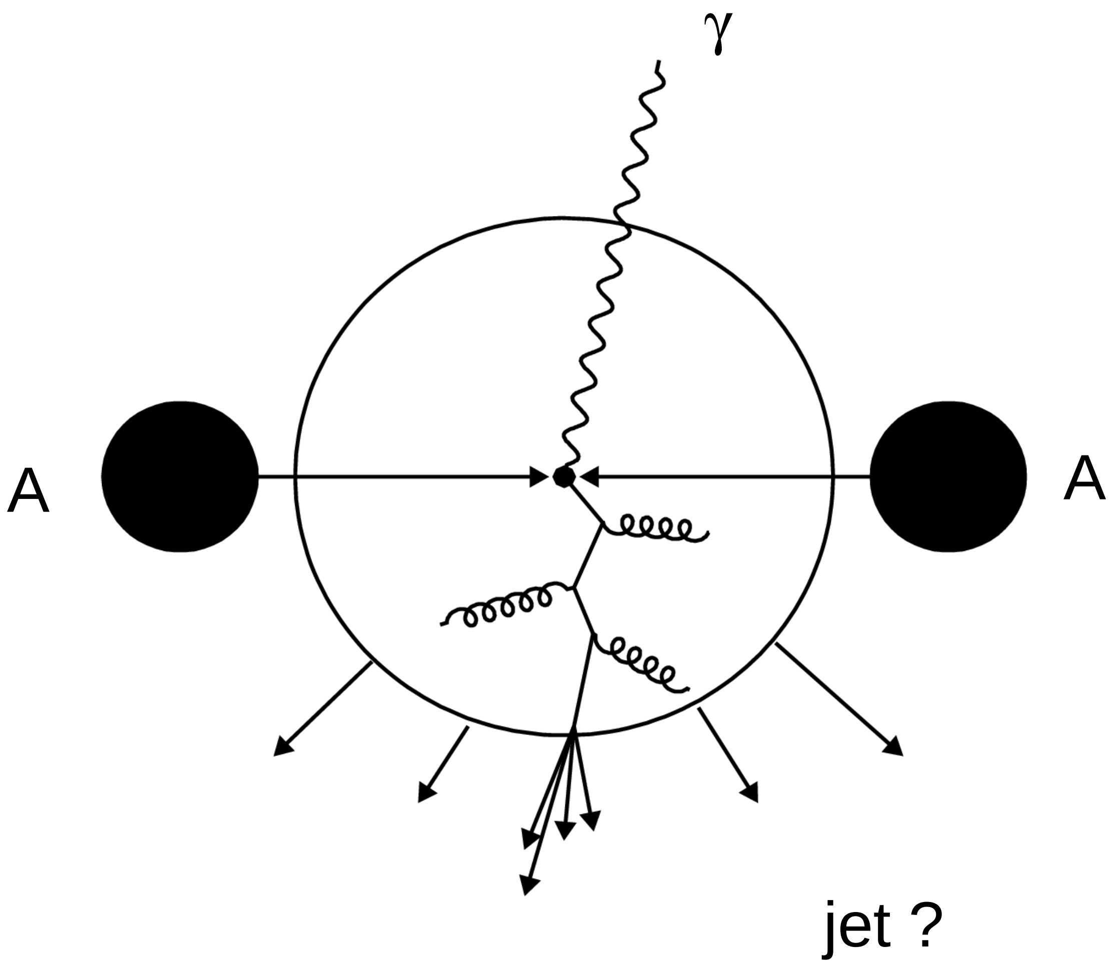


pp: $p_T^{gamma} \sim p_T^{jet}$

When tagging jet with:

- inclusive photon – near side peak is pronounced.
- Decay photons – near side peak is well seen.
- direct photon - near side peak is not visible.

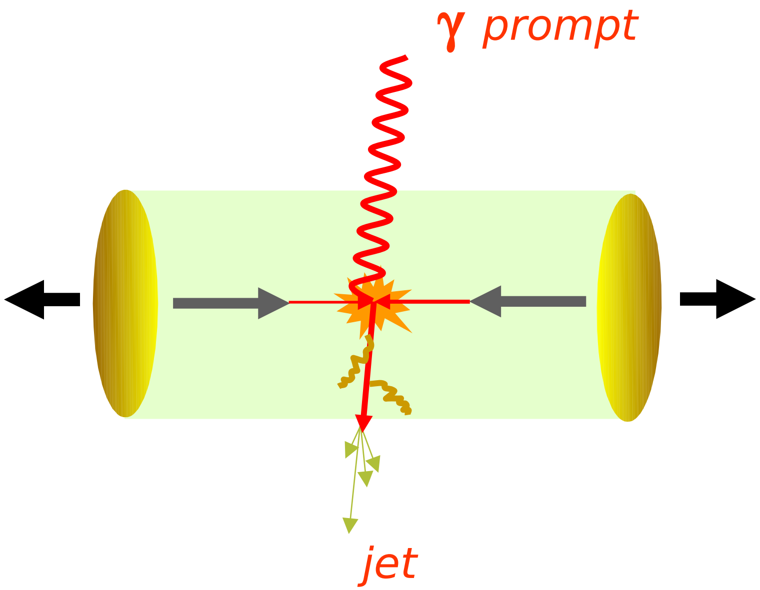
Jet tagging by prompt photons



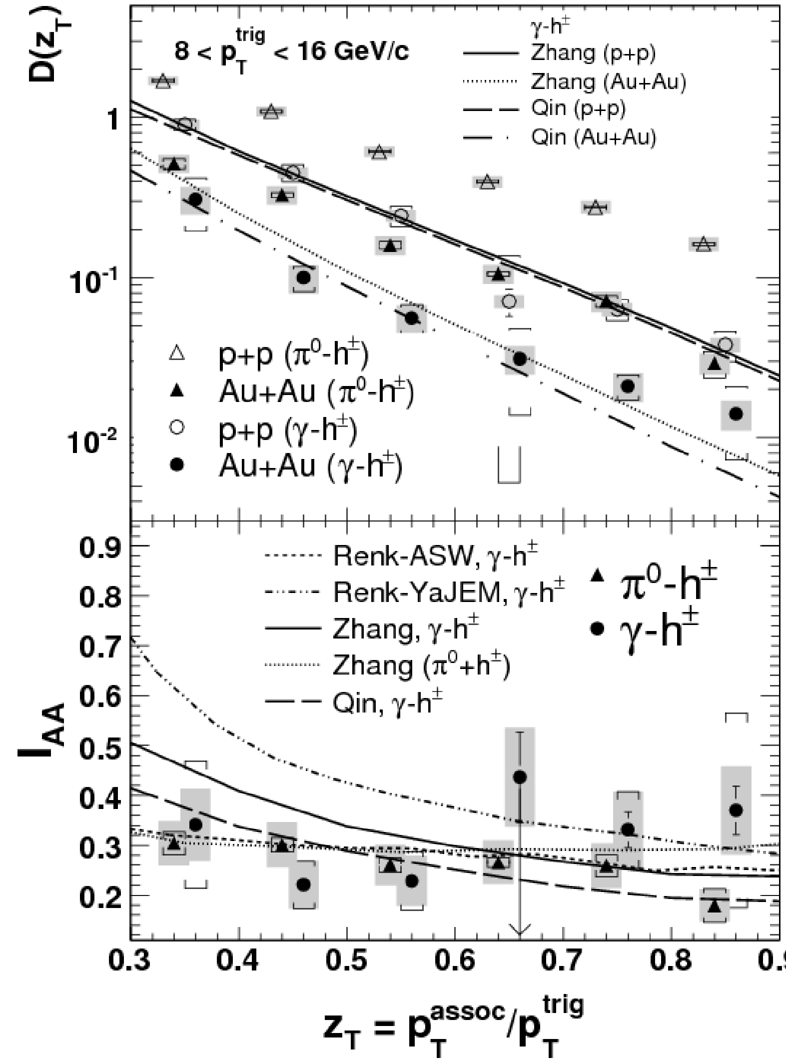
AA: $p_T^{gamma} > p_T^{jet}$

When tagging jet with direct photon - away side peak is being dissolved.

Direct γ–recoil hadron suppression



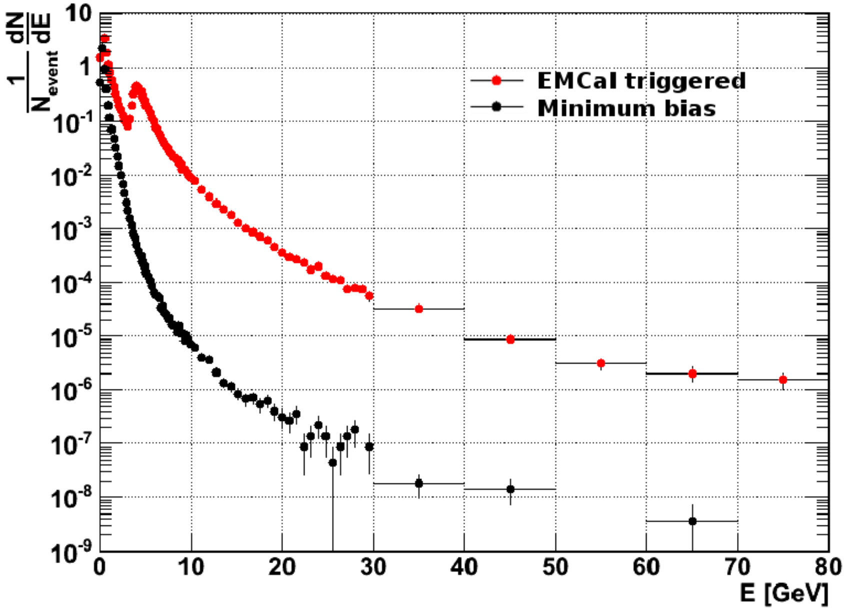
$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$

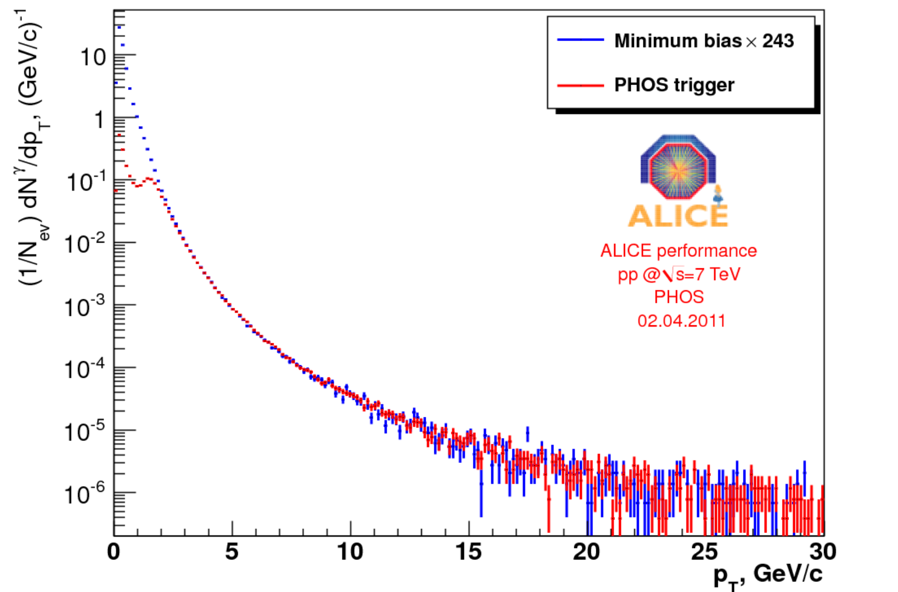


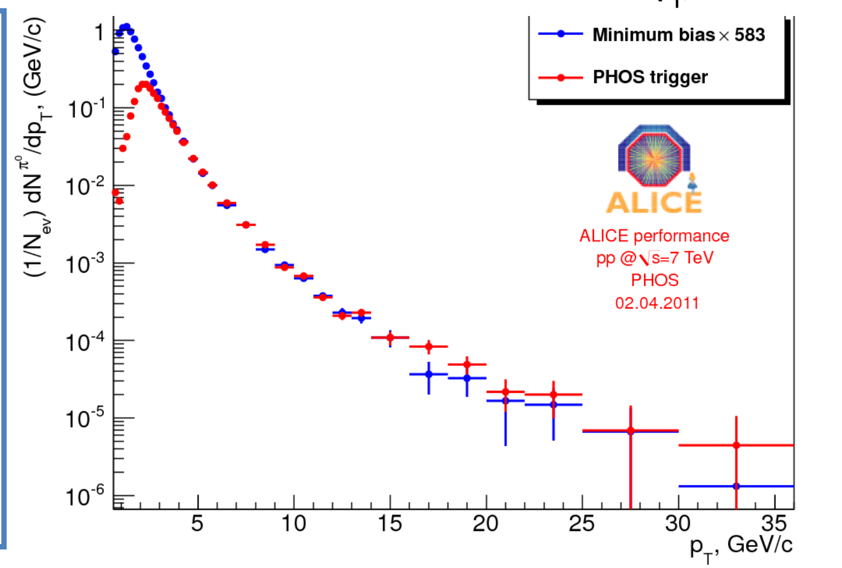
STAR, arxiv: 0912.1871

Large suppression for away-side: factor 3-5

Trigger L0 in calorimeters





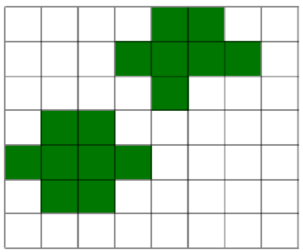


- Trigger system L0 aims to enhance selection of hard QCD events containing high pT neutral particles and jets to be recordered.
- Will allow to use of the full luminosity in ALICE
- Moderate p_T threshold allows to suppress minimum bias events and enrich events with high pt clusters in PHOS and EMCAL.

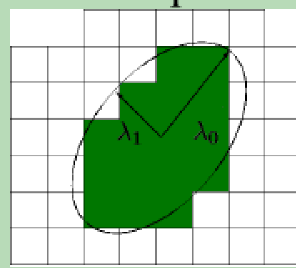
Methods of photon measurements

p_T< ~ 10 GeV/c | **10 ~ < p_T< ~ 45 GeV/c** | **p_T > 30 GeV/c (EMCal)**

resolved clusters
→ invariant mass analysis



merged cluster
→ shower shape analysis



small aperture angle
isolation cuts needed!