Direct Photon measurements in pp and Pb-Pb collisions with ALICE

M. Germain
on behalf of ALICE Collaboration

Nantes, France

Physics Motivation: Photon production in hadronic collisions

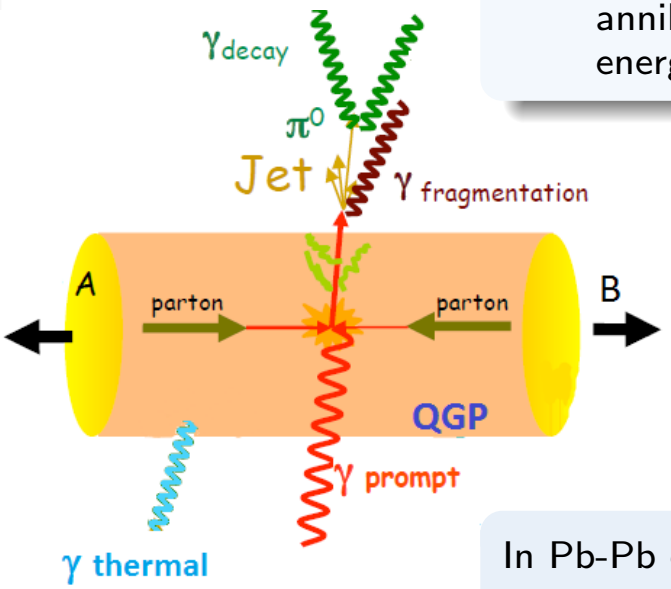
Direct prompt production in pp & Pb-Pb

- Compton scattering
- Annihilation

- Bremsstrahlung & Fragmentation

→

- Rate and cross sections in pQCD @ NLO: constraint on PDF/nPDF
- Direct processes (Compton & annihilation): access to parton energy loss in medium via γ-jet.



Additional direct production in Pb-Pb

- Jet-medium interaction
- Thermal photons

→

In Pb-Pb collisions, access to the medium properties via excess measurement.

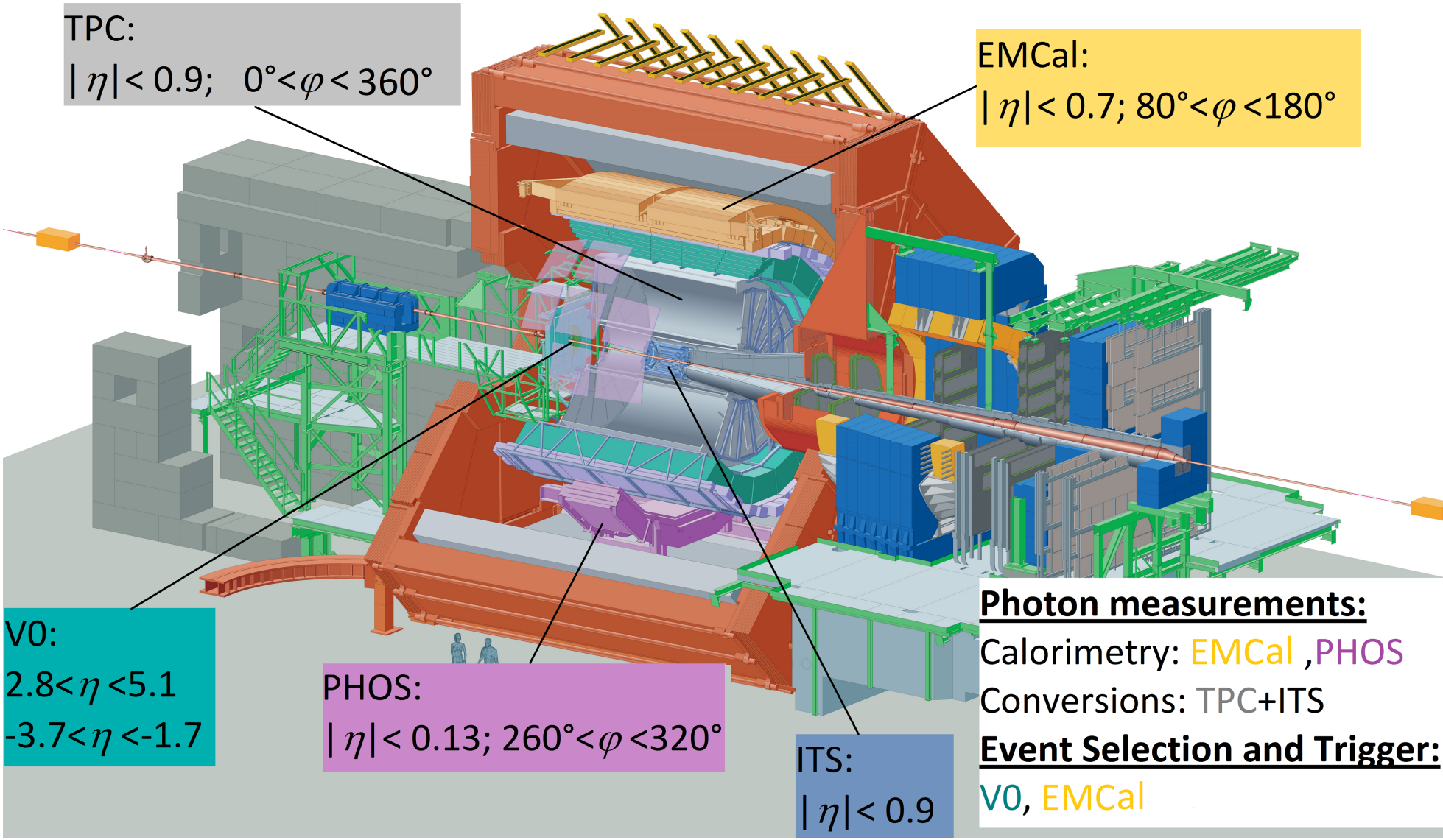
Production in pp & Pb-Pb

Hadronic decays (π^0,η,....$\rightarrow \gamma\gamma$)

→

At high energy mainly from parton fragmentation: jet quenching studies.

ALICE experiment



Photon measurements:

Calorimetry: EMCal ,PHOS

Conversions: TPC+ITS

Event Selection and Trigger:

V0, EMCal

Analysis Strategy

Direct photon at low and intermediate p_T ($\lesssim 10$ GeV/c)

Statistical Subtraction:

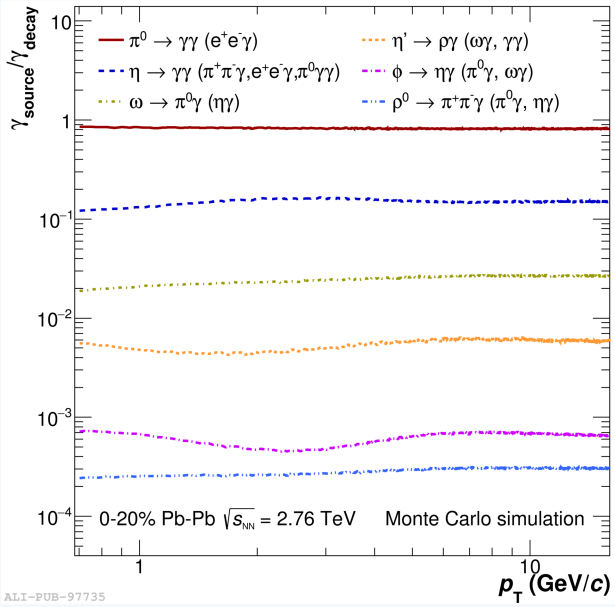
$$\gamma_{direct} = \gamma_{incl} - \gamma_{decay} = (1 - \frac{1}{R_\gamma}).\gamma_{incl}$$

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

γ_{incl}: measured in PHOS,PCM

π^0_{param}: parametrisation of measured π^0 in PHOS,PCM

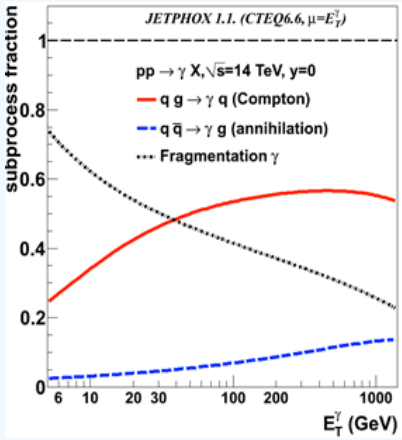
γ_{decay}: from MC simulations

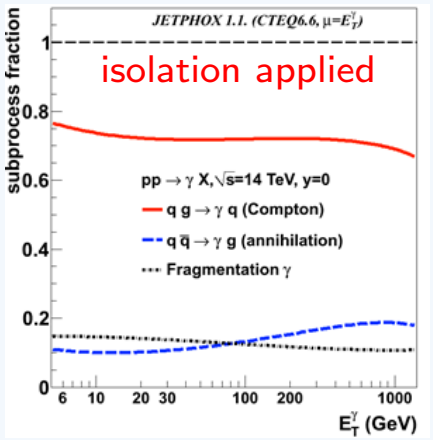


ALICE Phys.Lett.B754 (2016)235-248

Direct photon at high p_T ($\gtrsim 10$ GeV/c)

Isolation:





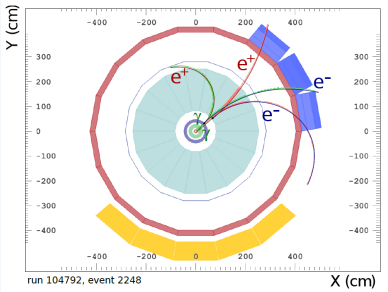
R. Ichou et al., Phys.Rev.D.82(2010)014015

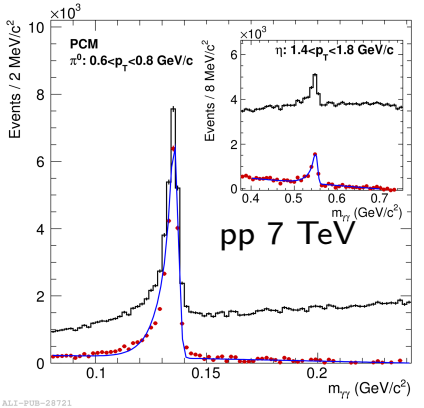
Reduction of fragmentation and decay components (pp 14 TeV but valid at 7 TeV)

Measurement in EMCal

Photons at low and high p_T in ALICE

PCM: Photon Conversion Method

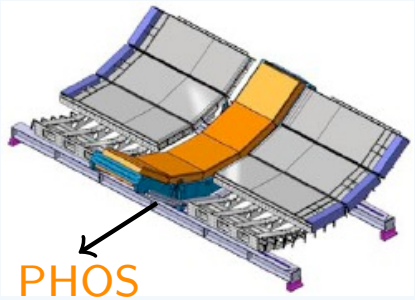


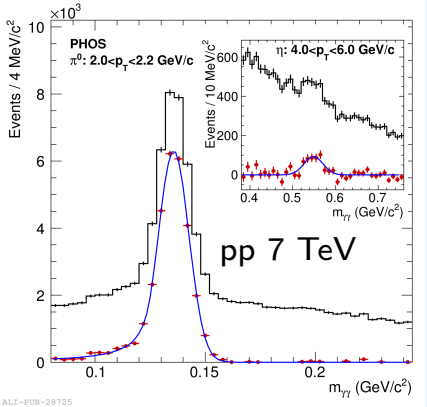


Int.J.Mod.Phys.A29(2014)1430044

- γ by secondary vertex reconstruction
- conversion probability: 8.5%
- π^0 by invariant mass analysis (see D. Muhlheim (id 102), A. Passfeld (id 138), H. Murakami (id 139), M. Danish (id 89))

PHOS

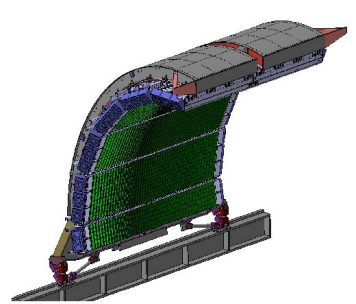


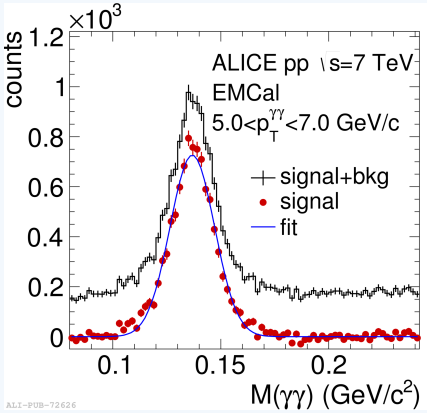


Int.J.Mod.Phys.A29(2014)1430044

- γ measured in calorimeter
- π^0 by invariant mass analysis (see P. Pareek (id 143),D. Sekihata (id 122), S. Yano (id 255))

EMCAL

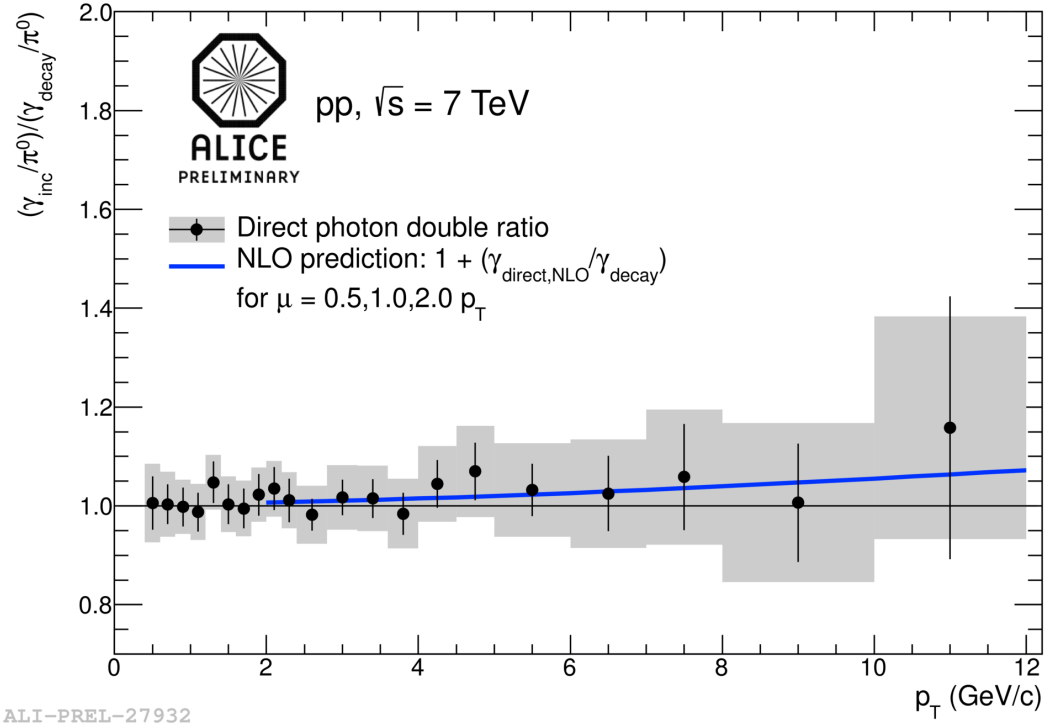




Int.J.Mod.Phys.A29 (2014)1430044

- γ measured in calorimeter
- π^0 by invariant mass analysis (see A. Matyja (id 107))

Direct photon double ratio R_γ: pp at $\sqrt{s}$ =7 TeV



Nucl.Phys.A 904-905(2013)573c-576c
proceeding of QM 2012

PCM only

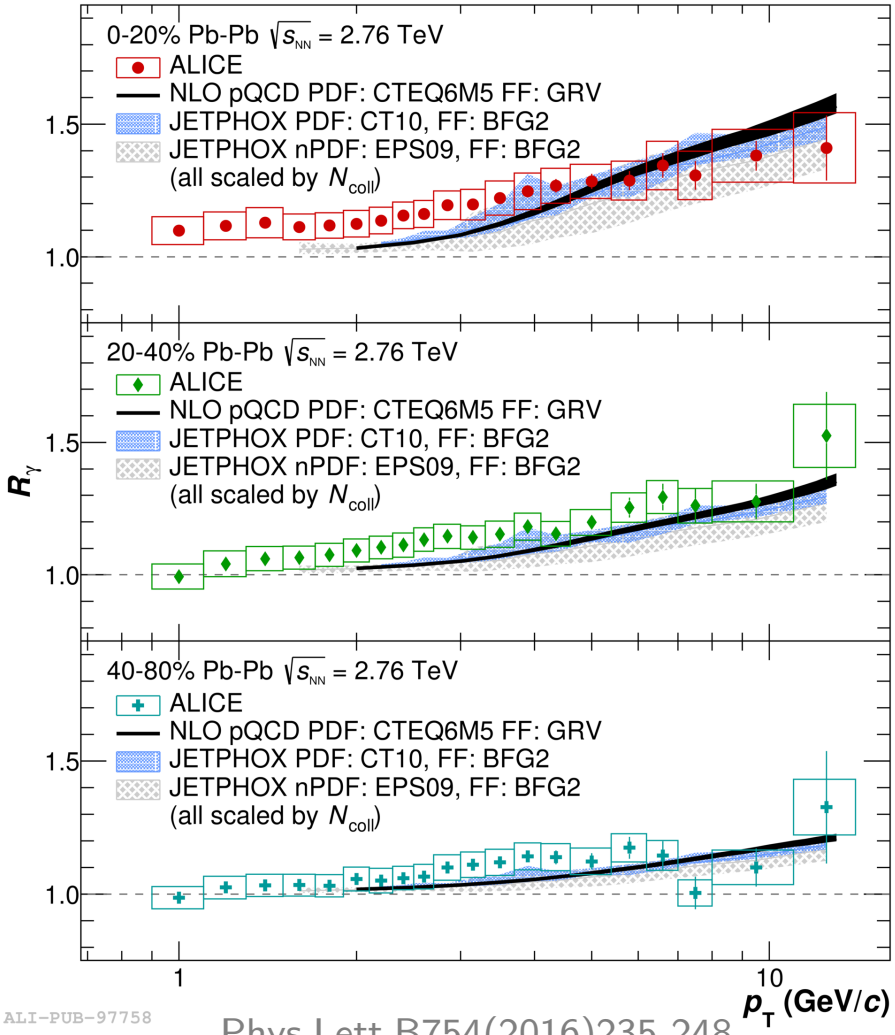
$$R_\gamma = \frac{\gamma_{incl}}{\gamma_{decay}} \equiv \frac{\gamma_{incl}}{\pi^0_{param}} \Big/ \frac{\gamma_{decay}}{\pi^0_{param}}$$

$$R_{NLO} = 1 + \frac{\gamma_{direct,NLO}}{\gamma_{decay}}$$

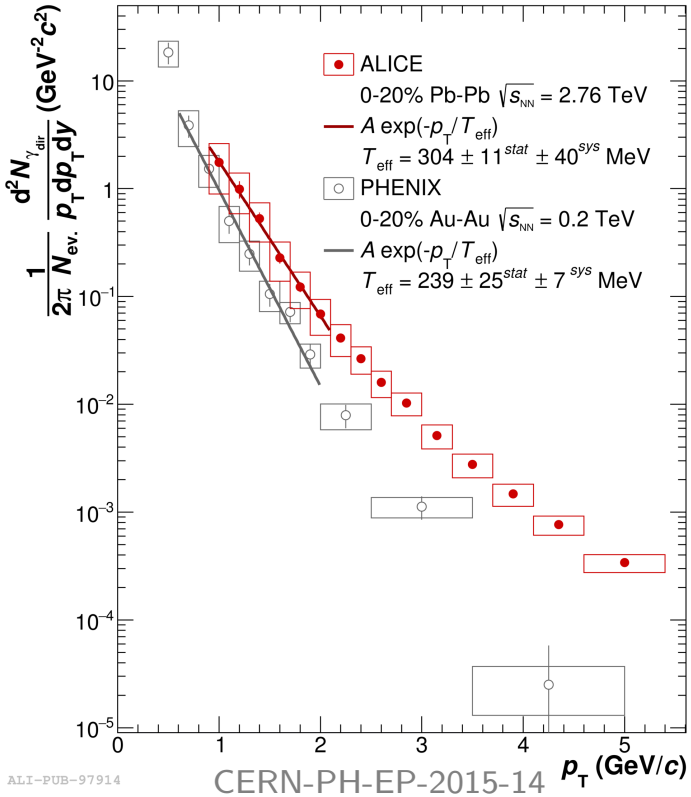
$R_\gamma \simeq 1$

- Consistent with NLO pQCD
- No significant direct photon signal

Direct photon Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV



Phys.Lett.B754(2016)235-248



CERN-PH-EP-2015-14

$R_\gamma > 1$

Intermediate p_T : excess beyond known prompt yield

- increases for more central collisions
- consistent with thermal radiation
- higher effective temperature than at RHIC

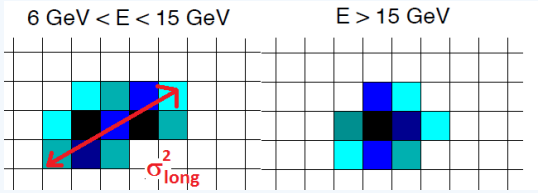
Direct Photon at high p_T: pp at $\sqrt{s}$=7 TeV: Isolation

Analysis: 2011 Data, EMCal L0 trigger at 5.5 GeV NEW

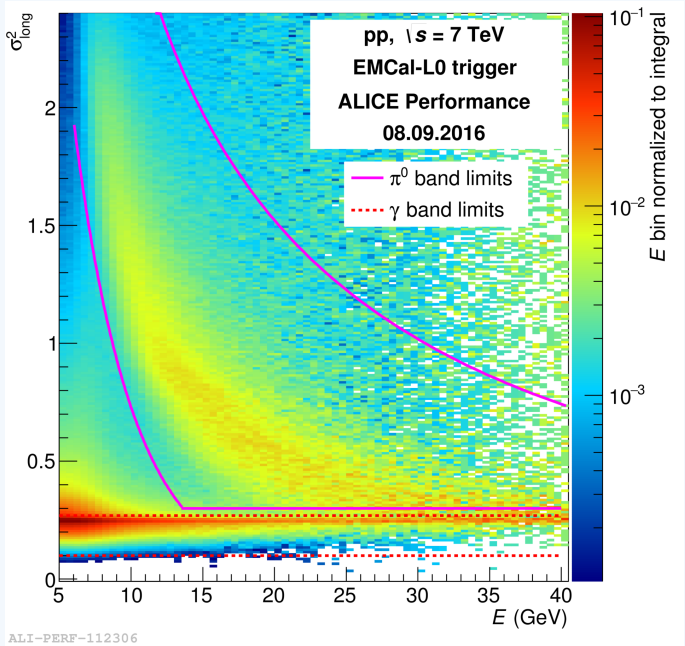
Photon selection: EMCal

- Charge Particle Veto : Cluster-track matching residual: $|\Delta\varphi| > 0.03$, $|\Delta\eta| > 0.025$
- Shower Shape for $\pi^0 \to \gamma\gamma$ rejection:
  $\sigma^2_{\text{long}} = 0.5\left(\sigma^2_{\varphi\varphi} + \sigma^2_{\eta\eta} + \sqrt{(\sigma_{\varphi\varphi} - \sigma_{\eta\eta})^2 + 4\sigma^2_{\eta\varphi}}\right)$

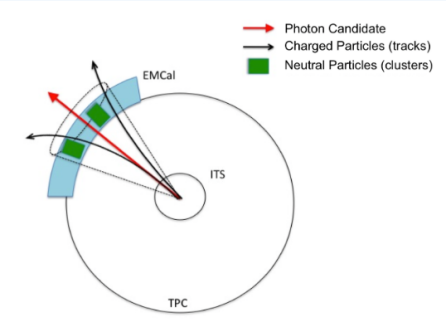
σ^2_{long} larger eigenvalue squared of the cluster's energy decomposition in EMCal $(\eta - \varphi)$ plane:



$0.1 < \sigma^2_{\text{long}} < \sigma^{2,max}_{long}$;
$\sigma^{2,max}_{long}$ energy dependent.



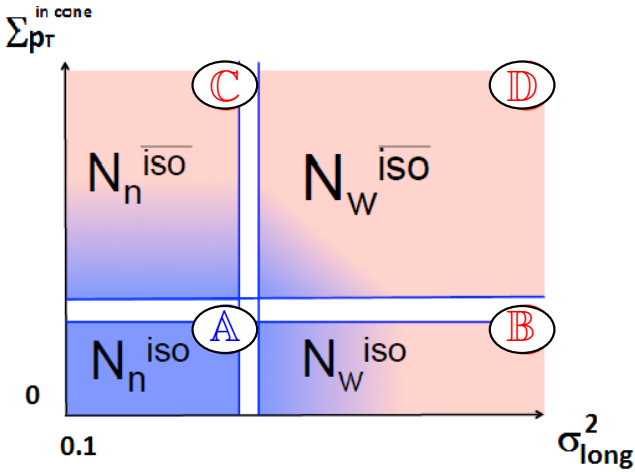
Isolation



cone with radius $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} = 0.4$ around photon candidate
Isolated if: $\sum^{in\ cone}_{charged,neutral} p_T \leq p_T^{thres} = 2$ GeV/c

Isolated Photons in pp at $\sqrt{s} = 7$ TeV: Signal extraction

- The amount of particles is expressed as:
  - S : for direct photons
  - B : for background (π^0, η, decay photons (π^0, η), ...)
  - N : S + B total number of particles
- Dividing Isolation, σ^2_{long}phase space in 4 regions:
  - $\mathbb{A}$: mainly signal region (isolated photons) + background
  - $\mathbb{B}, \mathbb{C}, \mathbb{D}$: mainly background ($\pi^0$) + signal



Purity = number of clusters coming from isolated photons in the N_n^{iso} sample

$$\mathbb{P} = \frac{S_n^{\text{iso}}}{N_n^{\text{iso}}} = 1 - \frac{B_n^{\text{iso}}}{N_n^{\text{iso}}}$$

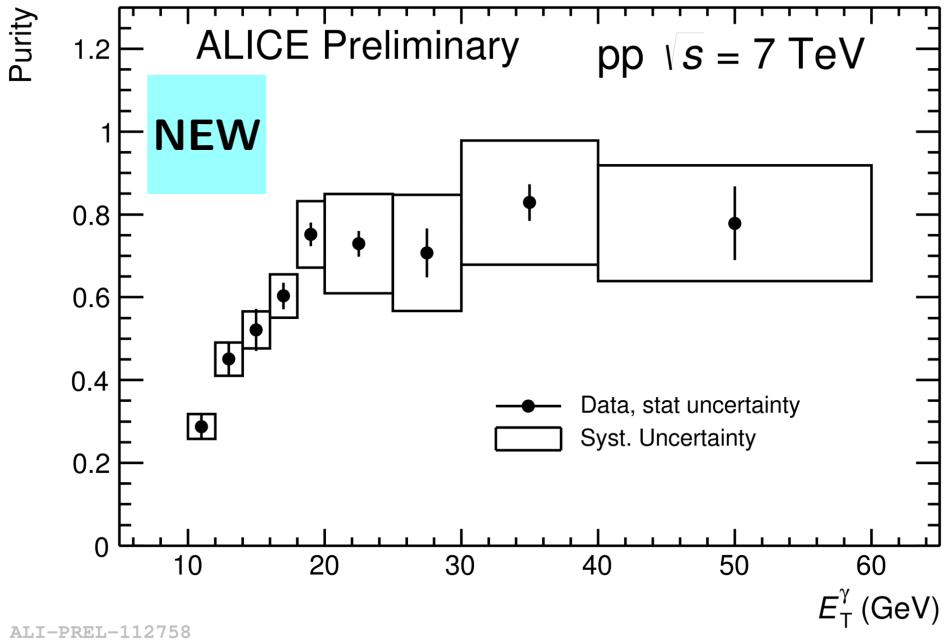
Asuming bkg isolation fractions are the same at low and high σ^2_{long}: $\frac{B_n^{\text{iso}}}{B_n^{\overline{\text{iso}}}} / \frac{B_w^{\text{iso}}}{B_w^{\overline{\text{iso}}}} = 1$

Taking into account signal in background region: $\Leftrightarrow \left(\frac{B_n^{\text{iso}}/N_n^{\overline{\text{iso}}}}{N_w^{\text{iso}}/N_w^{\overline{\text{iso}}}}\right)_{data} = \left(\frac{B_n^{\text{iso}}/N_n^{\overline{\text{iso}}}}{N_w^{\text{iso}}/N_w^{\overline{\text{iso}}}}\right)_{MC(GJ+JJ)^*}$

$$\mathbb{P} = 1 - \left(\frac{N_n^{\overline{\text{iso}}}/N_n^{\text{iso}}}{N_w^{\overline{\text{iso}}}/N_w^{\text{iso}}}\right)_{data} \times \left(\frac{B_n^{\text{iso}}/N_n^{\overline{\text{iso}}}}{N_w^{\text{iso}}/N_w^{\overline{\text{iso}}}}\right)_{MC(GJ+JJ)^*}$$

*MC(GJ+JJ): Pythia pp including processes involving 2 jets (JJ) or a gamma and a jet (GJ) in final state;

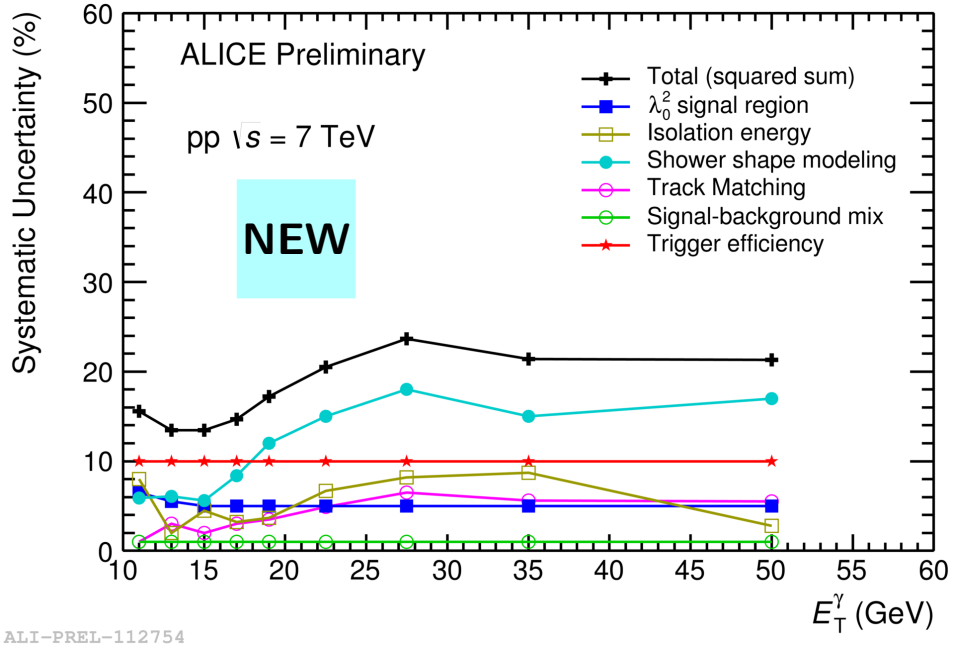
Isolated Photons in pp at $\sqrt{s} = 7$ TeV: Purity and systematics



$$\mathbb{P} = 1 - \left(\frac{N_n^{\overline{iso}}/N_n^{iso}}{N_w^{\overline{iso}}/N_w^{iso}}\right)_{data} \times \left(\frac{B_n^{iso}/N_n^{\overline{iso}}}{N_w^{iso}/N_w^{\overline{iso}}}\right)_{MC(GJ+JJ)}$$

Purity increases with E_T^γ up to 80%

Syst. Uncert. on differential cross section



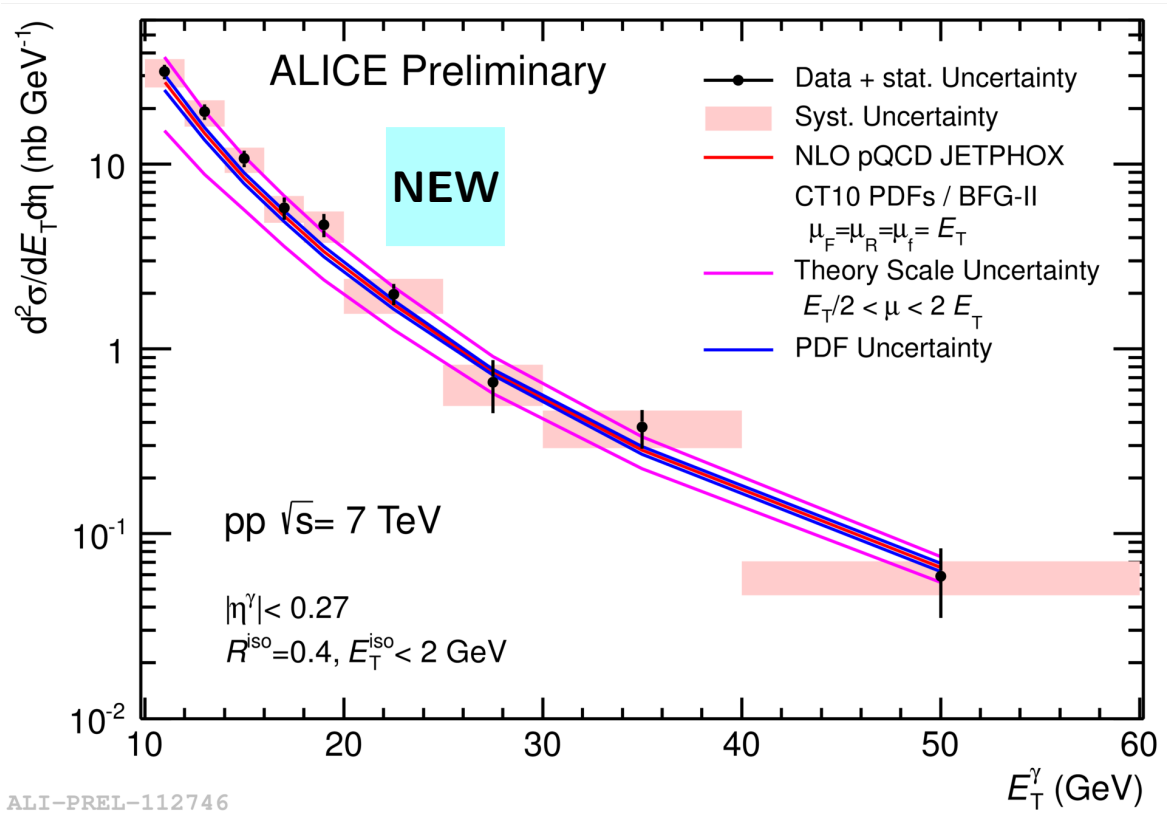
Main systematic error source from MC modelling of shower shape σ^2_{long}

Isolated Photons in pp at $\sqrt{s} = 7$ TeV: Differential cross section

$$\frac{d^2\sigma}{dp_T\,d\eta} = \frac{d^2N}{dp_T\,d\eta} \times \frac{\mathbb{P}}{\epsilon^{reco\&id} \times A_{cc} \times \mathcal{L}_{int}}$$

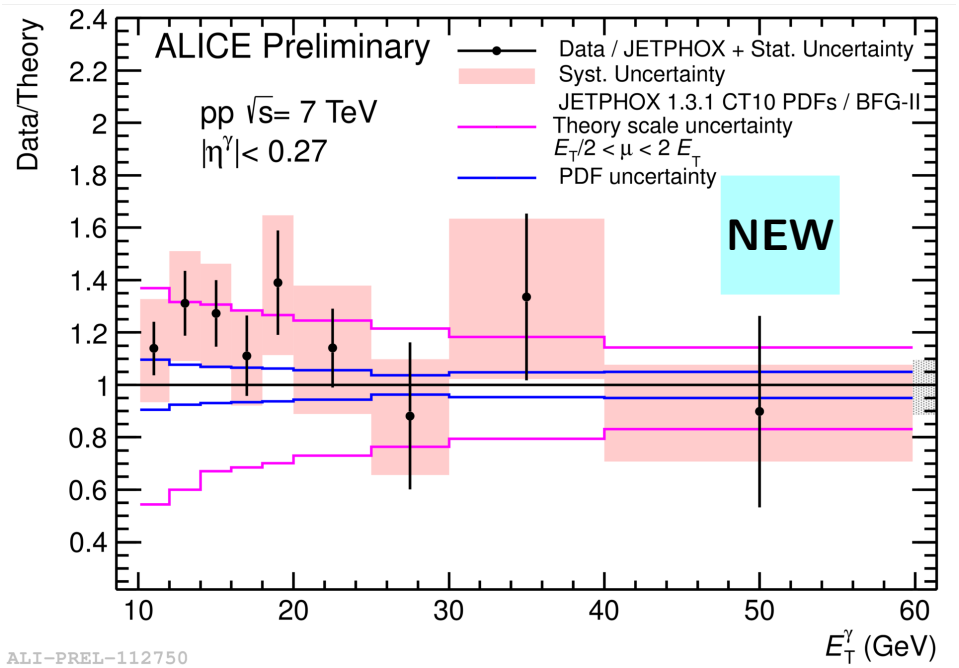
$$\mathcal{L}_{int} = 473 \pm 22^{stat} \pm 17^{syst}\,\mathrm{nb}^{-1}$$

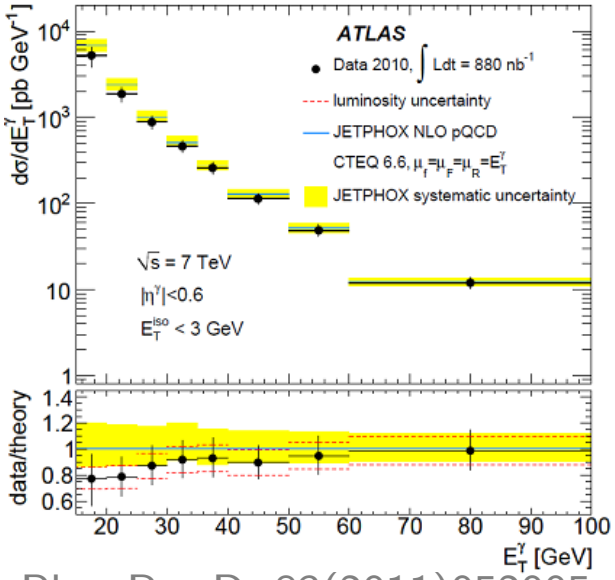
JETPHOX:
JHEP 0205(2002)028, Phys.Rev. D73(2006)094007, Phys.Rev. D79(2009)114024.



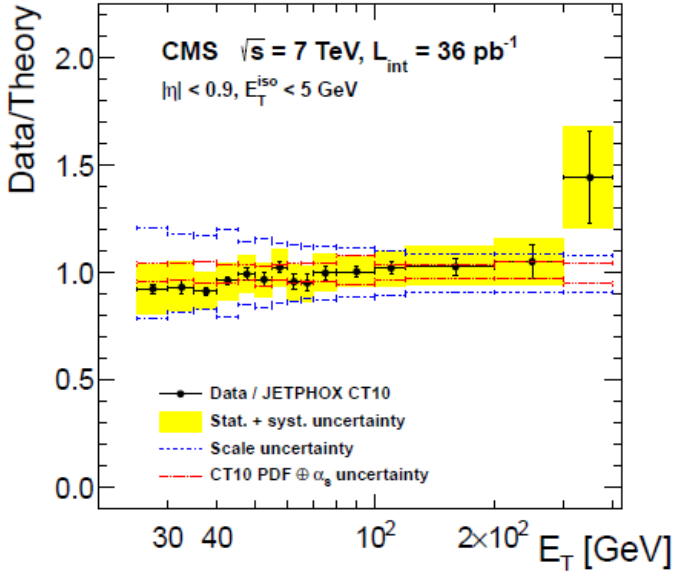
Isolated photon cross section measured in $10\ \mathrm{GeV} \lesssim E_T \lesssim 60\ \mathrm{GeV}$
Compatible with NLO predictions

Isolated Photons: Comparison with CMS, ATLAS





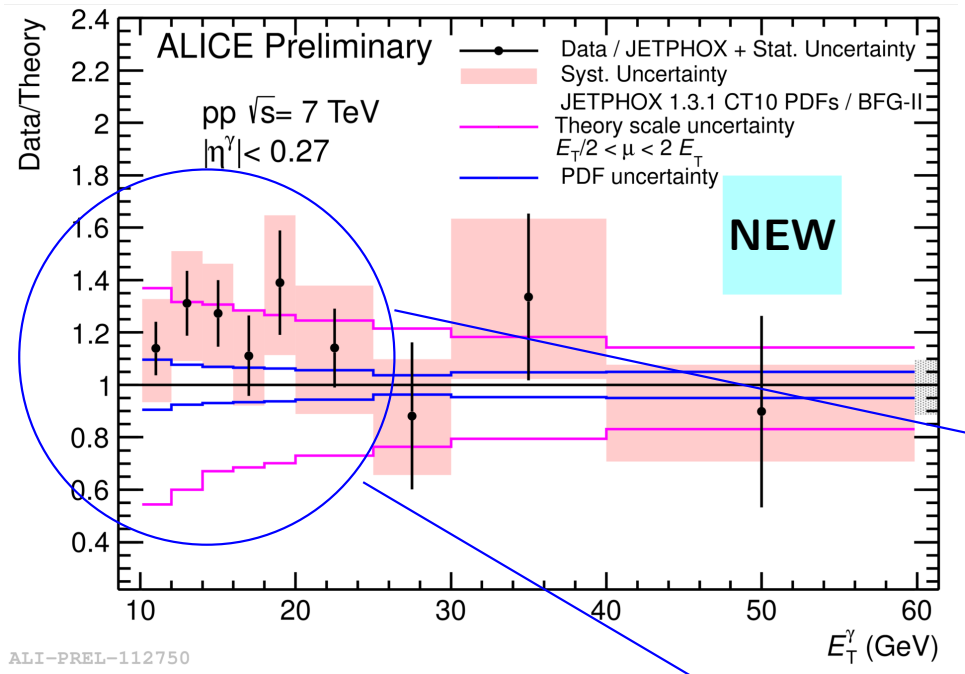
Phys.Rev.D. 83(2011)052005

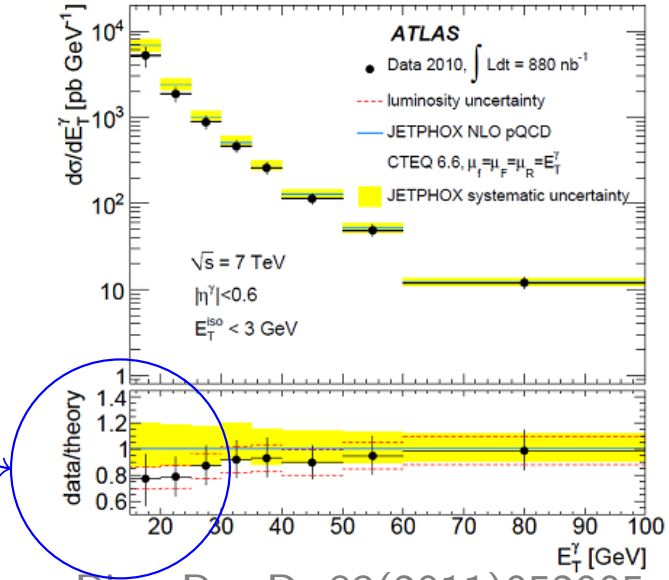


Phys.Rev.D. 84(2011)052011

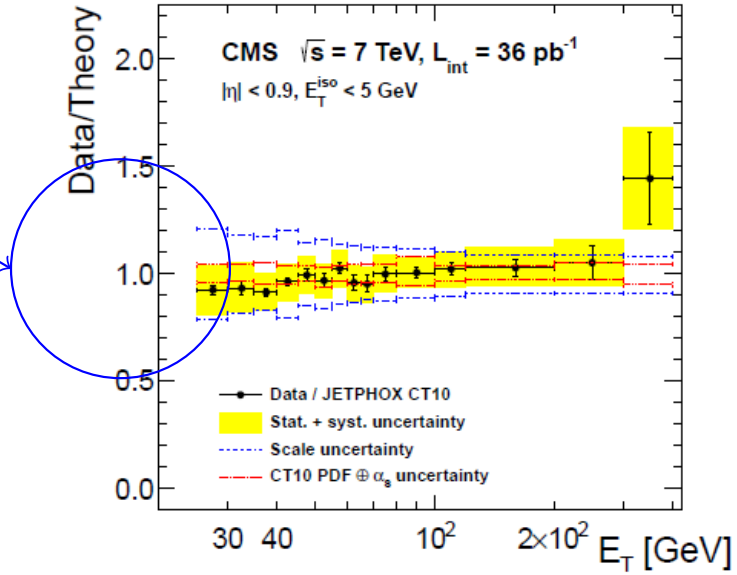
- Reasonable agreement with CMS, ATLAS in overlapping region

Isolated Photons: Comparison with CMS, ATLAS





Phys.Rev.D. 83(2011)052005



Phys.Rev.D. 84(2011)052011

- Reasonable agreement with CMS, ATLAS in overlapping region
- Lower E_T reach
- Constraint error on thermal photons

Summary

Direct photon measurements in ALICE:

- With statistical subtraction:
  - Measurement in pp and Pb-Pb collisions from $p_T \simeq 0.5$ GeV/c to 12 GeV/c
  - Results compatible with NLO pQCD predictions for $p_T \gtrsim 5$ GeV/c.
  - In Pb-Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV low/intermediate p_T excess: consistent with thermal radiation.
- With Isolation in EMCal:
  - Extension of lower p_T reach in ALICE for isolated photons with respect to other LHC experiments;
  - Agreement with NLO pQCD predictions

Outlook:

- Isolated photons in Pb-Pb
- Isolated photons with PHOS
- Isolated photon-hadron correlations to access fragmentation functions

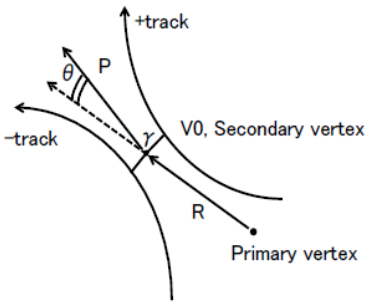
  see E. Epple poster (ID 181), A. Vauthier oral presentation (This morning)
- Direct photon flow measurements in Pb-Pb via statistical subtraction

BACKUP

Photon Reconstruction in PCM analysis

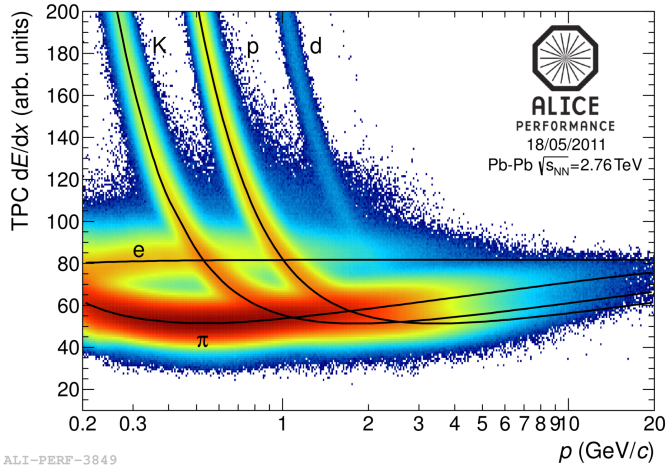
Track selection:

- min track p_T : 50 MeV/c
- dist to primary vertex: R $\in$ [5-180] cm



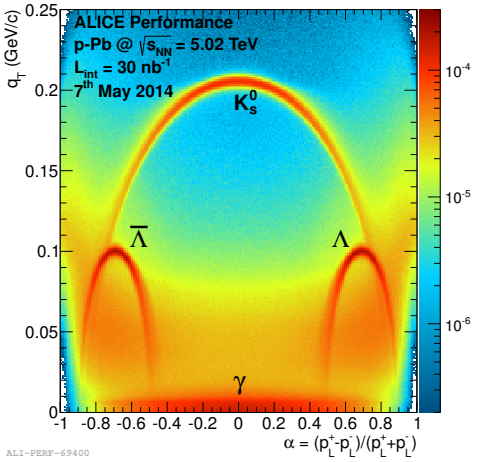
Electron identification:

- TPC dE/dx + TOF nσ if available



Photon Candidates

- Photon χ^2/ndf based on Kalman-Filter
- remaining $V^0(\Lambda, K^0_s ...)$ removed with further selections: $q_T = p \times sin(\theta_{mother-daughter})$



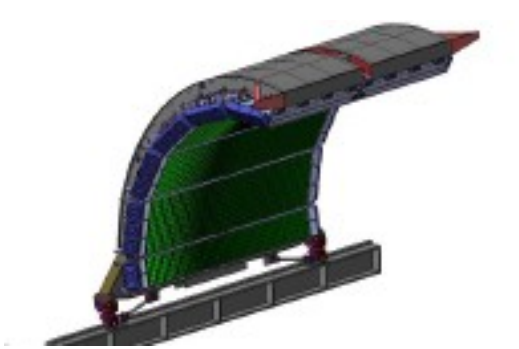
- purity of photon sample for $p_T \lesssim 3$ GeV/c:
  - $\gtrsim$ 98% in periph Pb-Pb
  - $\gtrsim$ 90% in central Pb-Pb
- Energy resolution
  - σ_E/E $\approx$ 1.6% for 1 $\lesssim$ E $\lesssim$ 2 GeV/c

- D. Muhlheim (id 102), A. Passfeld (id 138)
- H. Murakami (id 139), M. Danish (id 89)

Photons in EMCAL

EMCal: Pb-scintillator layers

- 4.28 m from IP
- $|\eta| < 0.7$, $\varphi \in [80^o, 180^o]$
- $\Delta\eta, \Delta\varphi = 0.014$
- $\frac{\sigma_E}{E} = \frac{4.8}{E} \oplus \frac{11.3}{\sqrt{E}} \oplus 1.7$



Photon Identification via Shower shape: σ^2_{long} larger eigenvalue squared of the cluster's energy decomposition in EMCal $(\eta - \varphi)$ plane:

$$\sigma^2_{\text{long}} = 0.5\left(\sigma^2_{\varphi\varphi} + \sigma^2_{\eta\eta} + \sqrt{(\sigma_{\varphi\varphi} - \sigma_{\eta\eta})^2 + 4\sigma^2_{\eta\varphi}}\right)$$

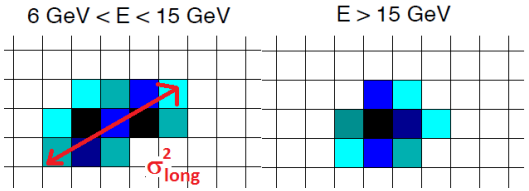
$$\sigma_{\varphi\varphi} = \frac{\sum_i w_i \varphi_i^2}{\sum_i w_i} - \left(\frac{\sum_i w_i \varphi_i}{\sum_i w_i}\right)^2$$

$$\sigma_{\eta\eta} = \frac{\sum_i w_i \eta_i^2}{\sum_i w_i} - \left(\frac{\sum_i w_i \eta_i}{\sum_i w_i}\right)^2$$

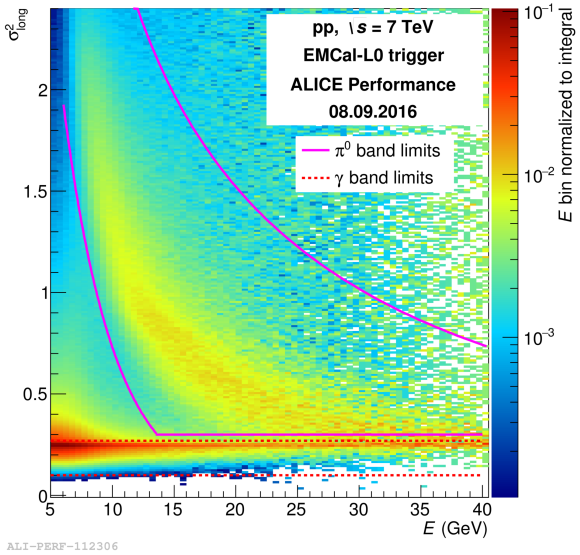
$$\sigma_{\varphi\eta} = \frac{\sum_i w_i \varphi_i \eta_i}{\sum_i w_i} - \left(\frac{\sum_i w_i \eta_i \times \sum_i w_i \varphi_i}{\sum_i w_i}\right)^2$$

$$w_i = max(0, 4.5 + log\frac{E_i}{E})$$

γ from π^0 discrimination



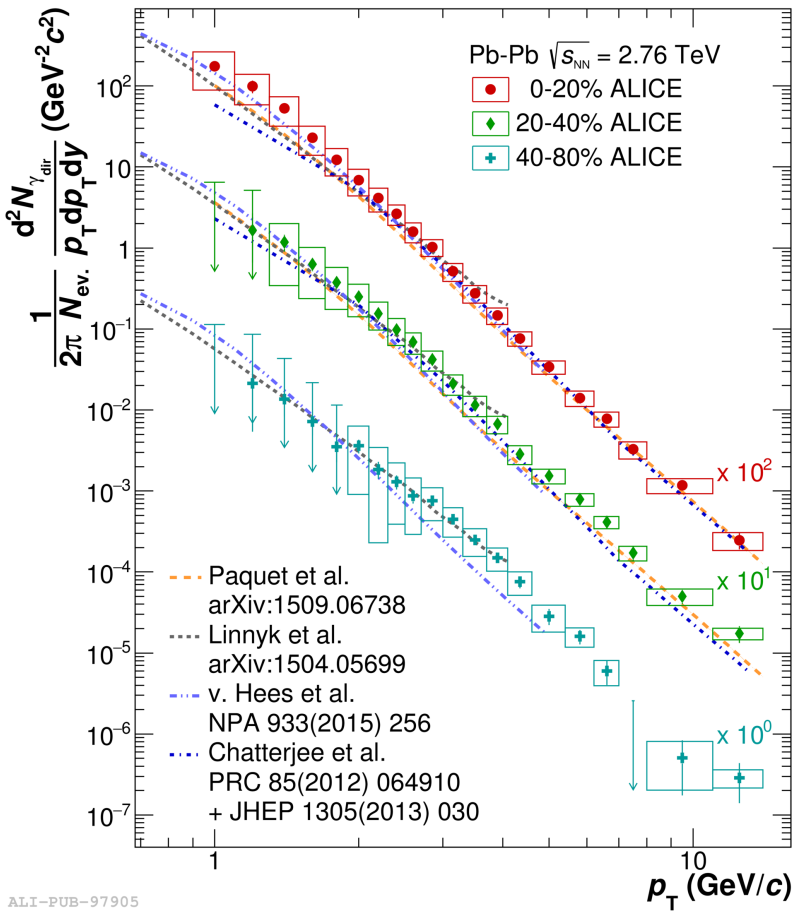
$0.1 < \sigma^2_{\text{long}} < \sigma^{2,max}_{long}$;
$\sigma^{2,max}_{long}$ energy dependent.



Direct Photon Spectra: Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

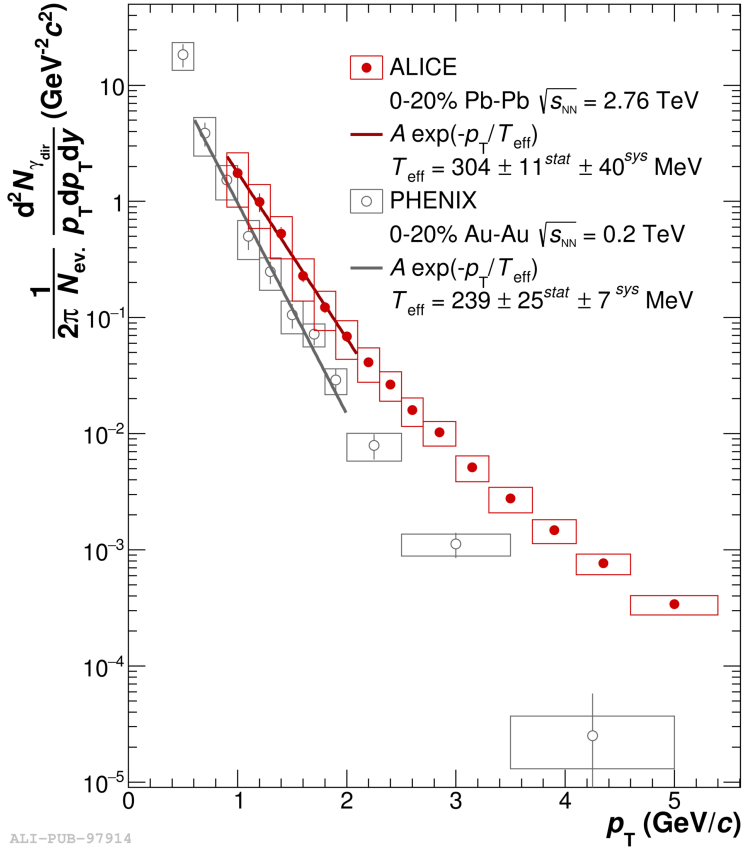
All Models with QGP formation

- **Paquet et al:** 2+1 hydro + IP-Glasma conditions ($\tau = 0.4$ fm/c; $< T_{0-20\%} > \approx 385$ MeV).
- **Linnyck et al:** Off-shell transport, microscopic description of evolution
- **Chatterjee et al:** 2+1 hydro fluctuating initial conditions ($\tau = 0.14$ fm/c; $T_{0-20\%} \approx 740$ MeV).
- **v. Hees et al:** ideal hydro with initial flow, ($\tau = 0.2$ fm/c; $T_{0-20\%} \approx 682$ MeV).

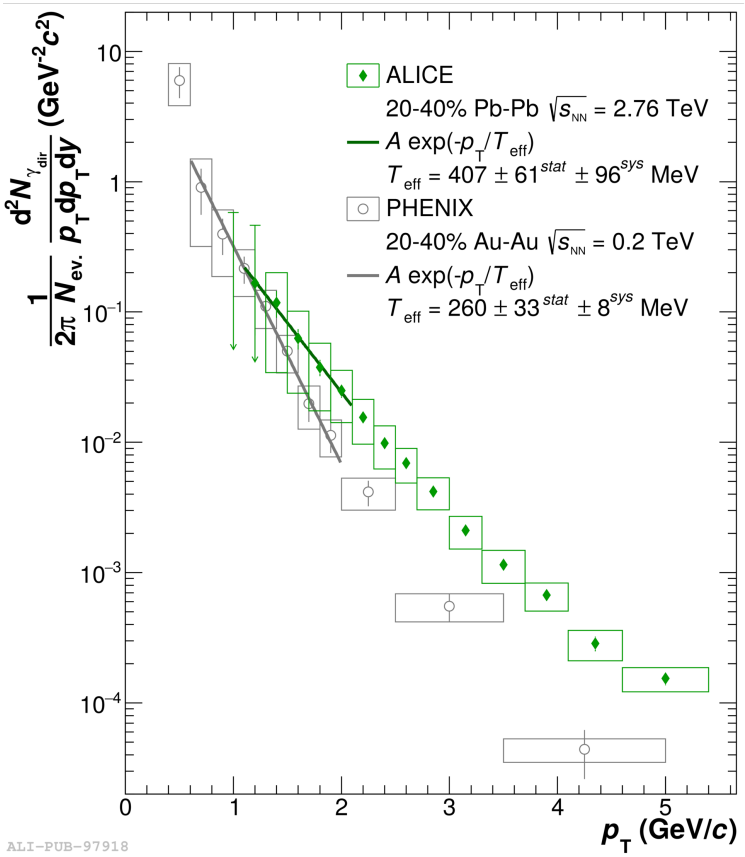


Phys.Lett.B754(2016)235-248

Direct Photon Spectra: Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV



CERN-PH-EP-2015-254



CERN-PH-EP-2015-254

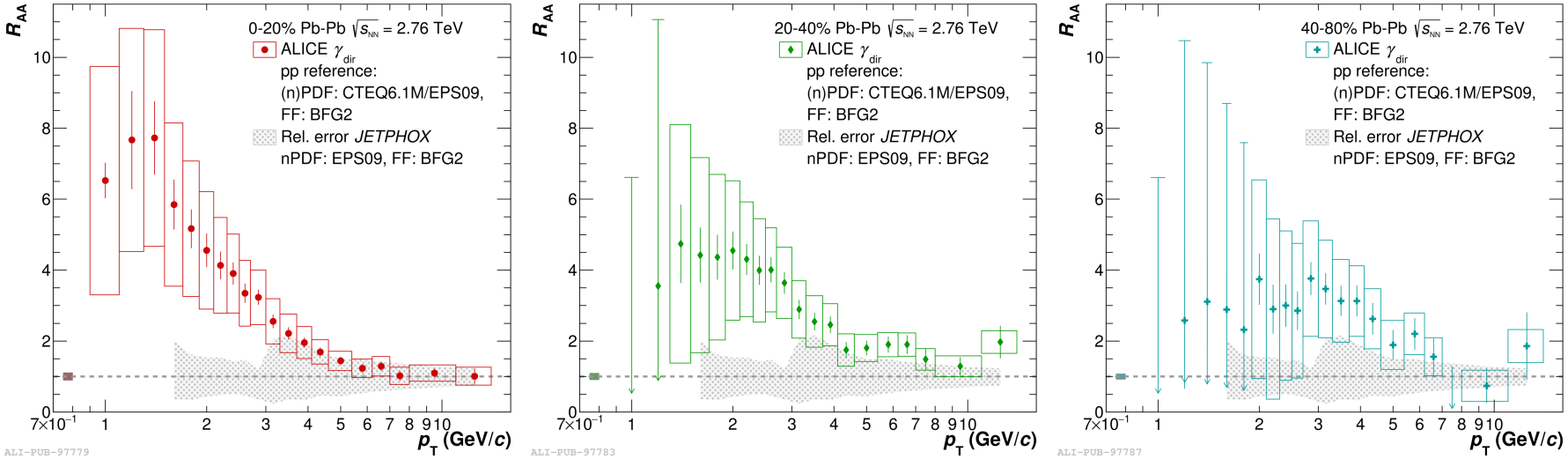
centrality (%)	T_{eff} (MeV)	
	ALICE[1]	PHENIX[2]
0-20%	$304 \mp 11^{stat} \mp 40^{syst}$	$239 \mp 25^{stat} \mp 7^{syst}$
20-40%	$407 \mp 61^{stat} \mp 96^{syst}$	$260 \mp 33^{stat} \mp 8^{syst}$

[1] Phys.Lett.B754(2016)235-248

[2] Phys. Rev. C 91(2015)064904

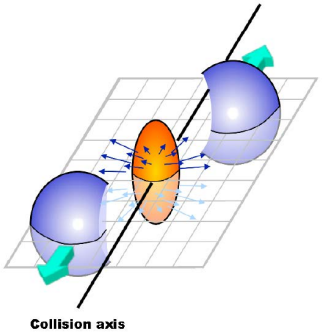
Direct Photon R_{AA}: Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV

ALICE-PUBLIC-2015-007



- Reference: pQCD calculation by the Mc Gill group ArXiv: 1509.06738
- Excesss at low p_T visible in all centrality classes
- confirms N_{coll} scaling of pQCD photons for $p_T \gtrsim 5$ GeV/c

Direct Photon Flow: Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV (1)

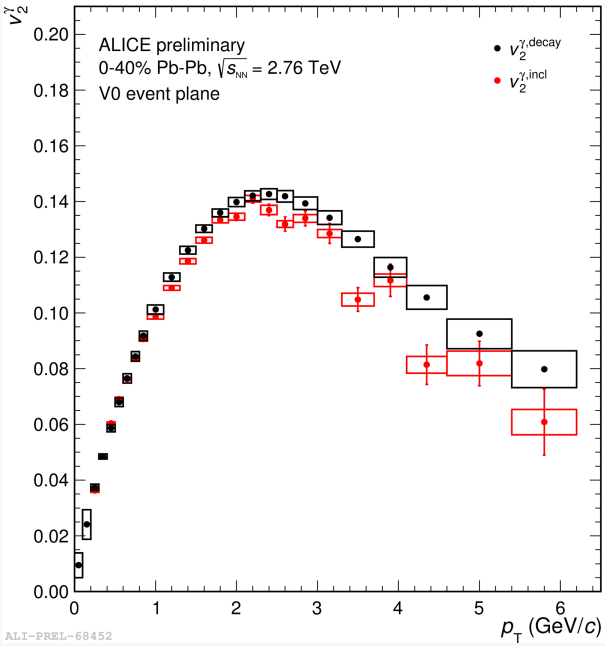


$$\frac{dN}{d\varphi} = \frac{1}{2\pi}(1 + \sum_{n\geq 1} 2v_n cos(n(\varphi - \Psi^{RP})));$$

$$v_n^{incl} = \frac{N_\gamma^{dir}}{N_\gamma^{incl}} v_n^{\gamma,dir} + \frac{N_\gamma^{decay}}{N_\gamma^{incl}} v_n^{\gamma,decay}$$

$$\longrightarrow v_n^{\gamma,dir} = \frac{Rv_n^{\gamma,incl} - v_n^{\gamma,decay}}{1-R}$$

Inclusive photon v_2

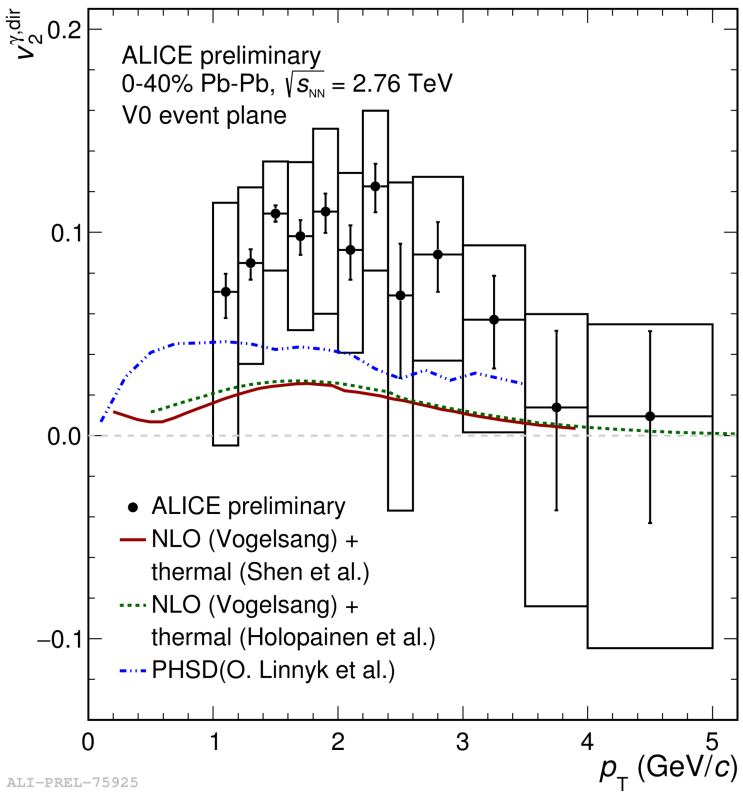


J.Phys.Conf.Ser. 446 (2013) 012028

- Inclusive photons measured via PCM;
- Decay photon v_2 calculated based on measured charged $\pi^{\mp}$ v_2

- inclusive photon v_2 significantly lower than decay photon v_2 for $p_T \geq 3$ GeV/c
- below 3 GeV/c: both consistent within uncertainties
  - similar v_2 or
  - no direct photons

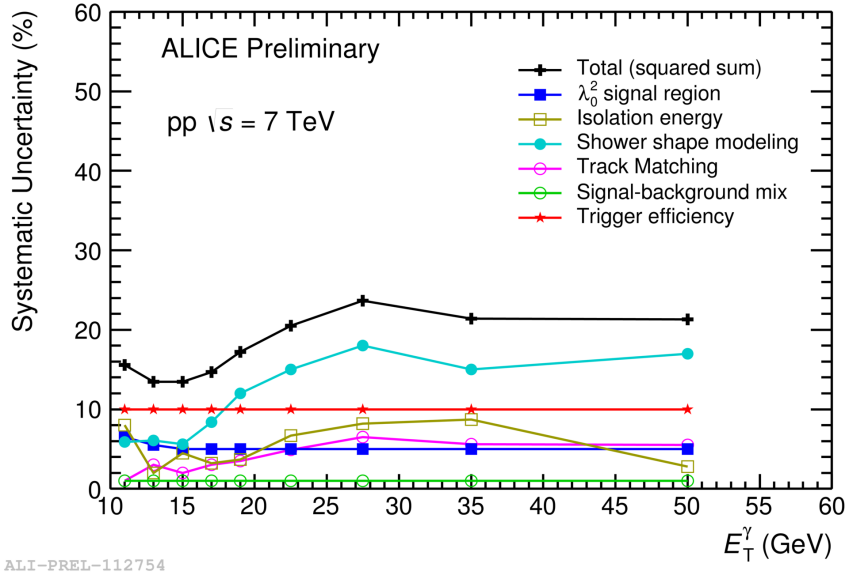
Direct Photon Flow: Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV (2)



- hadron-like v_2
- Different sources in models but no possible discrimination

Isolated photons Systematic Error

systematic error sources	error (%)
Signal σ^2_{long} selection	4-6.5%
Isolation probability	8%-3%
Track-matching	1.%-9%
Monte Carlo (JJ+GJ sample)	1%
Purity: extrapolation of isolation probabilities	5-17%
Efficiency and normalisation	10%
total	13-20%



JETPHOX Direct-Fragmentation contributions

JETPHOX [a], [b] Version 1.3.1

- FF: BFG II (large gluon)
- PDF: CTEQ6M , CT10
- scales: $\mu = 0.5\ E_T^{\gamma}$, E_T^{γ} , $2\ E_T^{\gamma}$
- Isolation criteria: $R = 0.4\ E_T^{iso} < 2$ GeV & R= $0.4\ E_T^{iso} < 5$ GeV