Direct Photon Spectra and Elliptic Flow in 2.76 TeV Pb-Pb Collisions from ALICE

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H-QM | Helmholtz Research School Quark Matter Studies

EMMI

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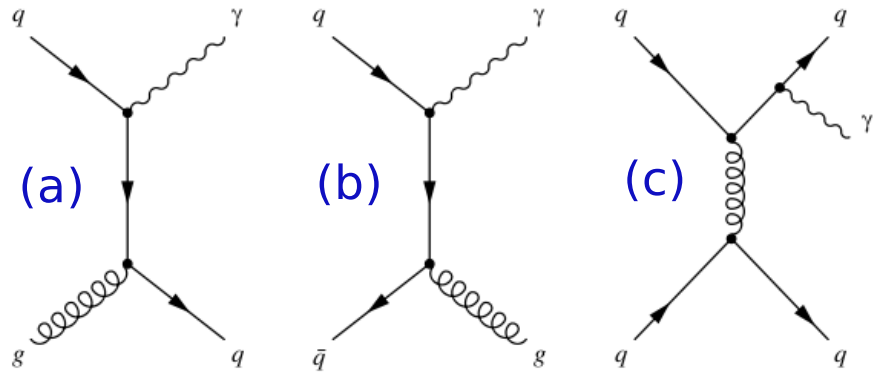
Direct Photons in pp and Pb-Pb Collisions

Direct Photons - Definition

Photons that are not produced by particle decays



Prompt Photons: In pp and Pb-Pb

- Calculable within NLO pQCD
- Predominant source in pp
- Signal expected to scale with number of binary collisions in Pb-Pb
- Fragmentation photons may be modified by parton energy loss in the medium

(a) Quark-gluon Compton scattering

(b) Quark-Anti-quark annihilation

(c) Fragmentation photons (bremsstrahlung)

Measurement of direct photons in pp is an ideal test for pQCD

Direct Photons in Pb-Pb Collisions

Additional sources of direct photons in Pb-Pb collisions

Jet-Medium Interactions:

- Scattering of hard partons with thermalized partons
- In medium (photon) bremsstrahlung emitted by quarks

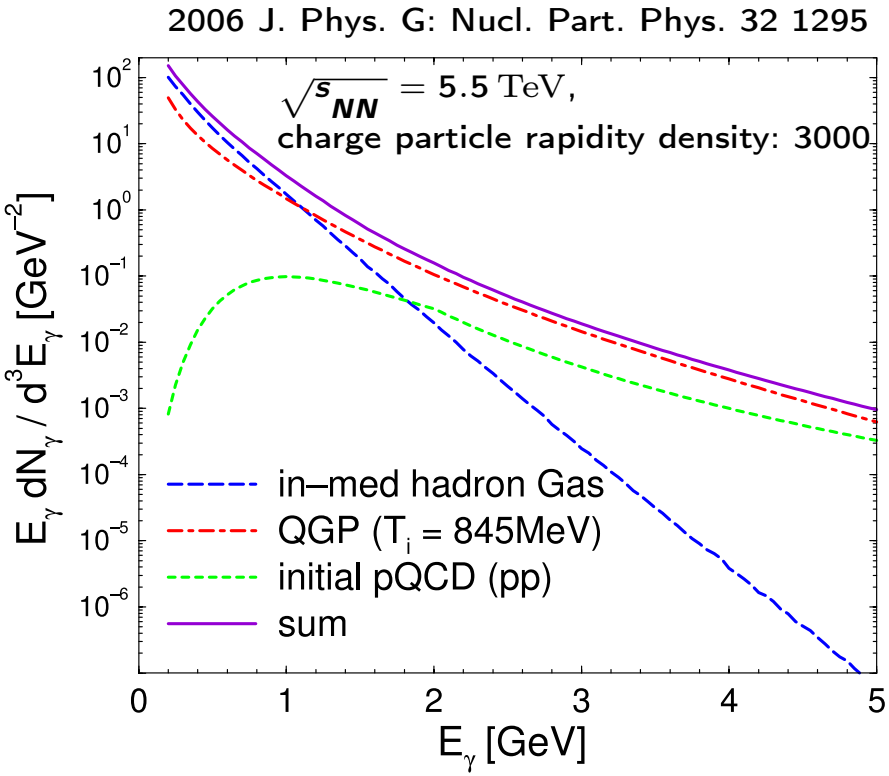
Thermal Photons:

- Scattering of thermalized particles

  QGP: $q\bar{q} \rightarrow g\gamma$ and $qg \rightarrow q\gamma$ (+NLO)

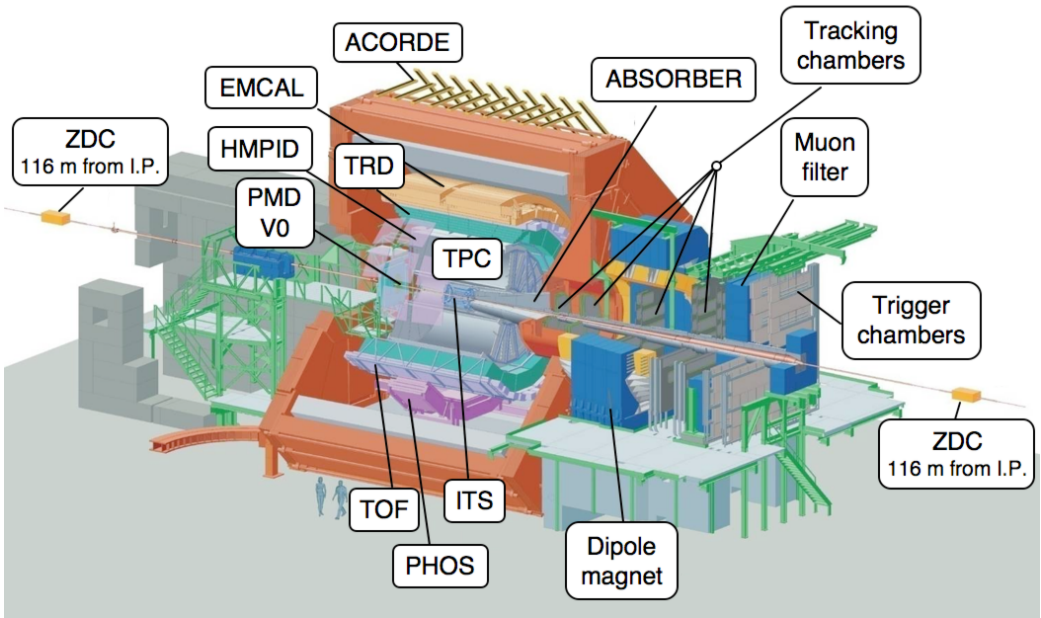
  HHG (hot hadronic gas): Hadronic interactions (e.g. $\pi^+\pi^- \rightarrow \gamma\rho_0$)

- Exponentially decreasing but dominant at low p_T



Photons leave medium unaffected, an ideal probe to study HI collisions

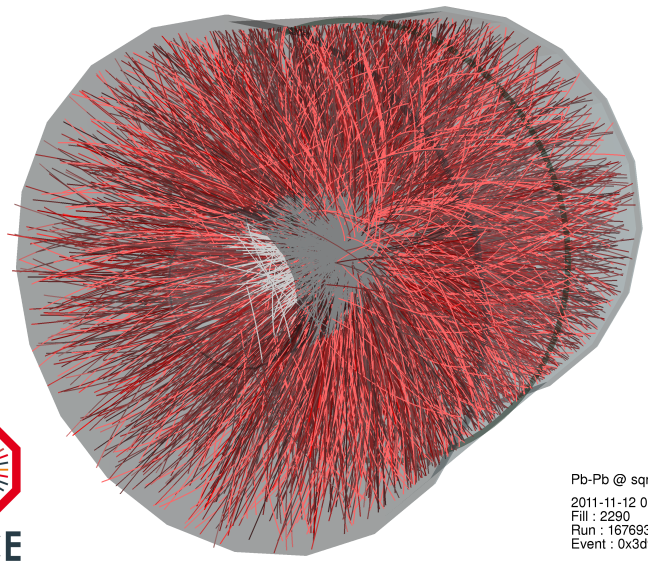
The ALICE Detector and Data Sample



pp, $\sqrt{s} = 7\,\mathrm{TeV}$:

- Data sample: 3.54×10^8 events (min. bias)
- Monte Carlo: Pythia-Perugia0 and Phojet

Pb-Pb, $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$:



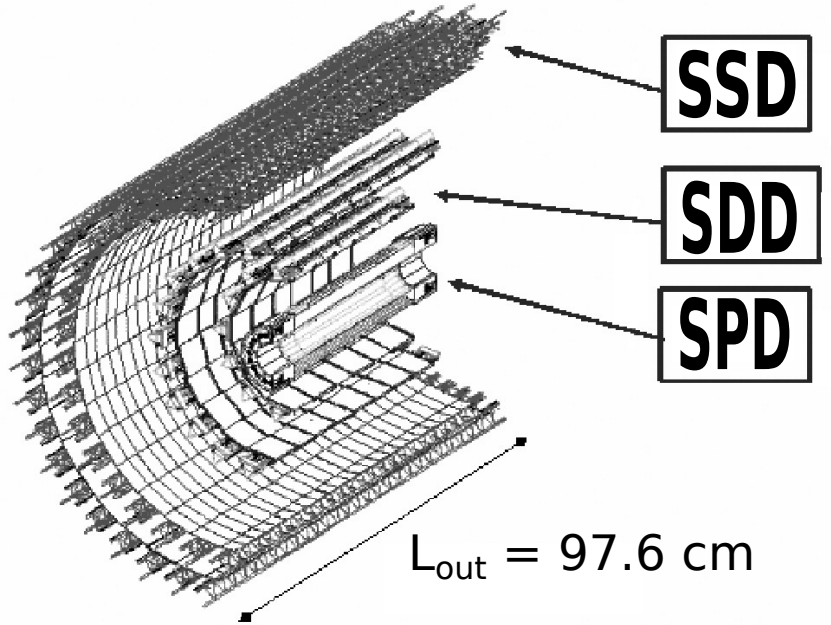
- Data sample: 17×10^6 min. bias events
- Monte Carlo: Hijing (min. bias plus enriched events with high p_T π^0s)

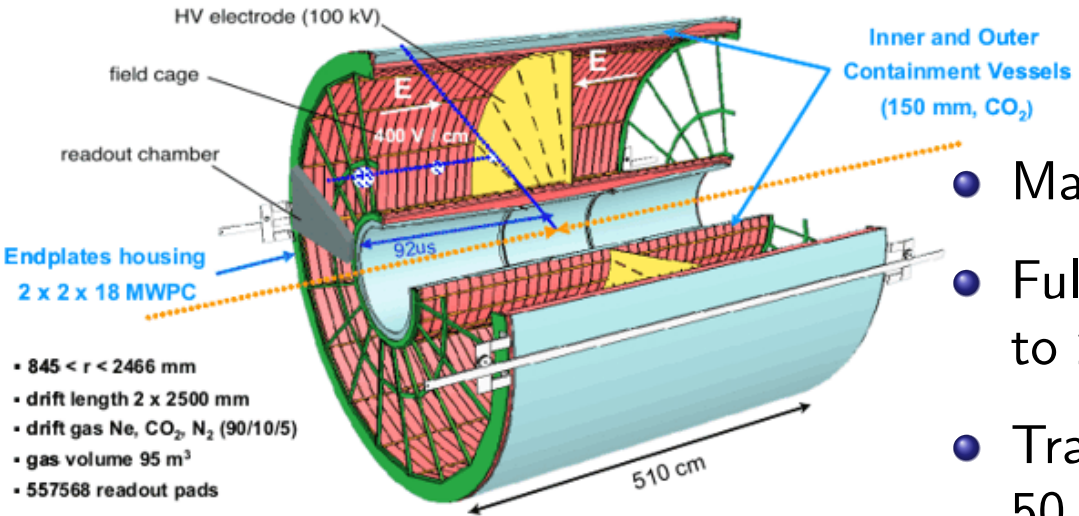
Photons are measured via their conversion products in ITS and TPC

Closer Look at the Central Barrel - ITS and TPC

Inner Tracking System - ITS

- Full azimuth coverage, six cylindrical layers
- Three different detector types: silicon pixel / drift / stripes
- Designed for primary / secondary vertex finding (inner radius $R_{BP} = 2.94\,\mathrm{cm}$)
- Tracks charged particles down to $p_T = 100\,\mathrm{MeV/c}$





Time Projection Chamber - TPC

- Main tracking and PID detector
- Full azimuth coverage, $R = 84.8\,\mathrm{cm}$ up to $246.6\,\mathrm{cm}$
- Tracking: 100 MeV/c (primary) or 50 MeV/c (secondary) up to 100 GeV/c

Part I: Direct Photon Spectra

General Strategy of the Analysis

Subtraction Method

$$\gamma_{\text{direct}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = \left(1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}}\right) \cdot \gamma_{\text{inc}}$$

- Inclusive photons: measure all photons that are produced
- Decay photons: calculated from measured particle spectra with photon decay branches (π^0, η, ...)

Double Ratio

$$\frac{\gamma_{\text{inc}}}{\pi^0} \Big/ \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}} \approx \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} \qquad \text{if} > 1 \text{ direct photon signal}$$

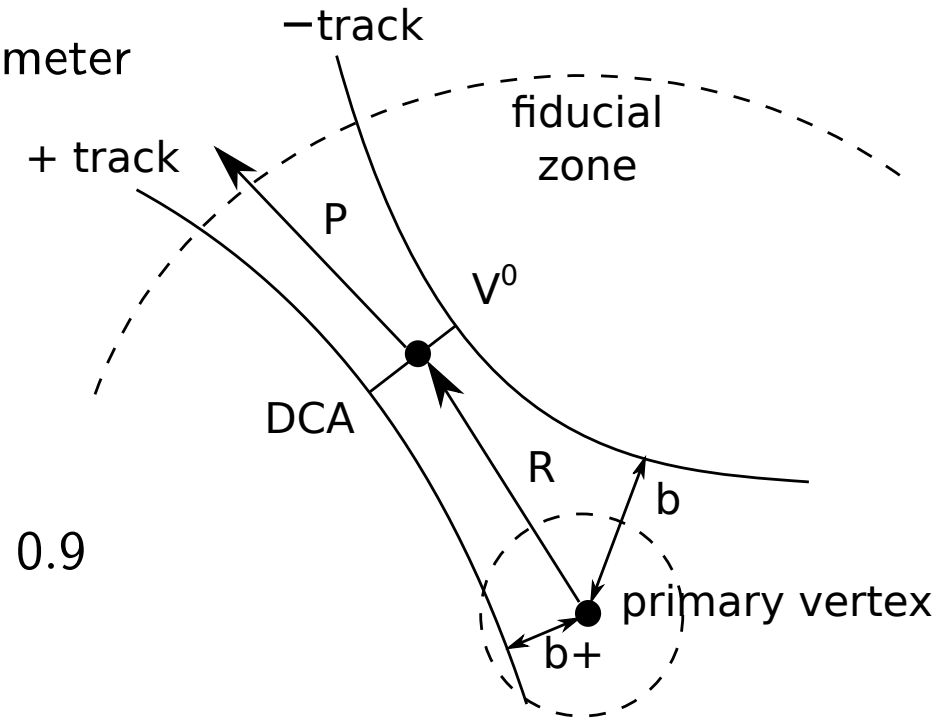
$\rightarrow$ advantage of ratio method: cancellation of uncertainties

- Photons and π^0s (and η) are measured via conversion method $\pi^0 \rightarrow \gamma\gamma$, $\gamma \rightarrow e^+e^-$

Photon Reconstruction with ITS and TPC

Secondary Vertex Algorithm - V0 Particles

- Charged tracks with large impact parameter are paired
- Candidates with a small DCA
  $\rightarrow$ V0 candidate
- Most abundant particle species:
  K^0_s, Λ, $\bar{\Lambda}$ or γ
- Photon conversion probability in $|\eta| < 0.9$ up to $R = 180\,\mathrm{cm}$ saturates at 8.5%



- Cuts on the decay topology of photons and electron track properties
  $\rightarrow$ Purity at 90% at $2\,\mathrm{GeV/c}$ for 0-40% Pb-Pb events
- Background is mainly combinatorial - Strange particle contribution negligible

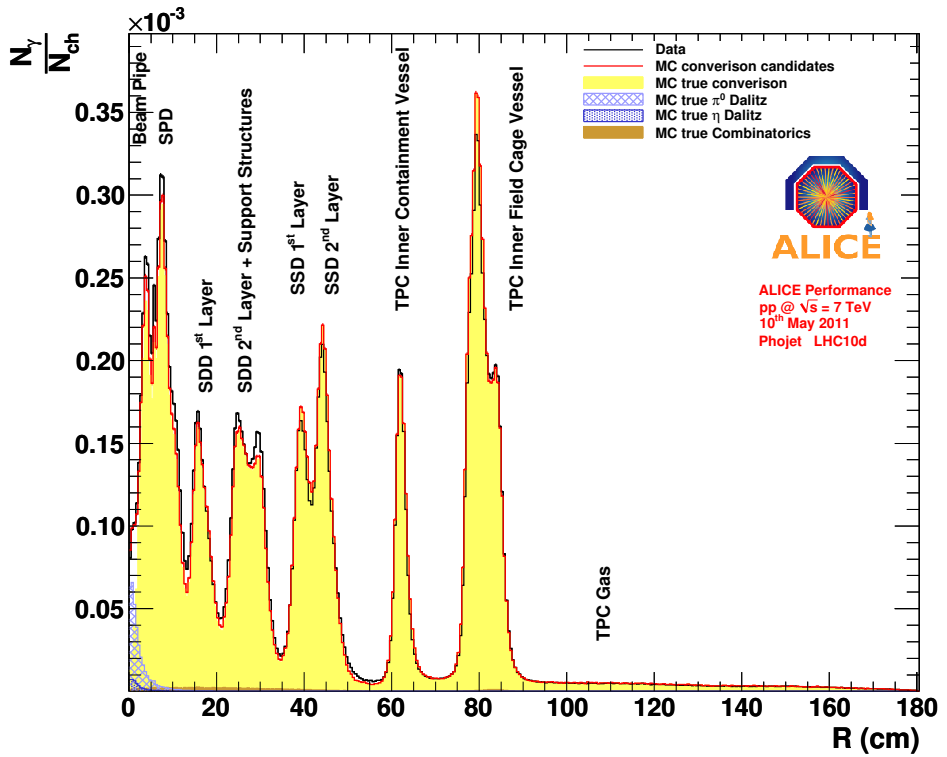
Material Budget of the ALICE Detector

Material budget is the largest contribution to the systematic uncertainty

- Effects MC simulations and track reconstruction (e.g. conversion probability, energy loss, etc.)
- Material contributing to the analysis: beam pipe, 6 layers of the ITS detector, the TPC vessels (+ drift gas)

$\rightarrow$ Comparison of normalized amount of photon conversions in data and MC for $|\eta| < 0.9$

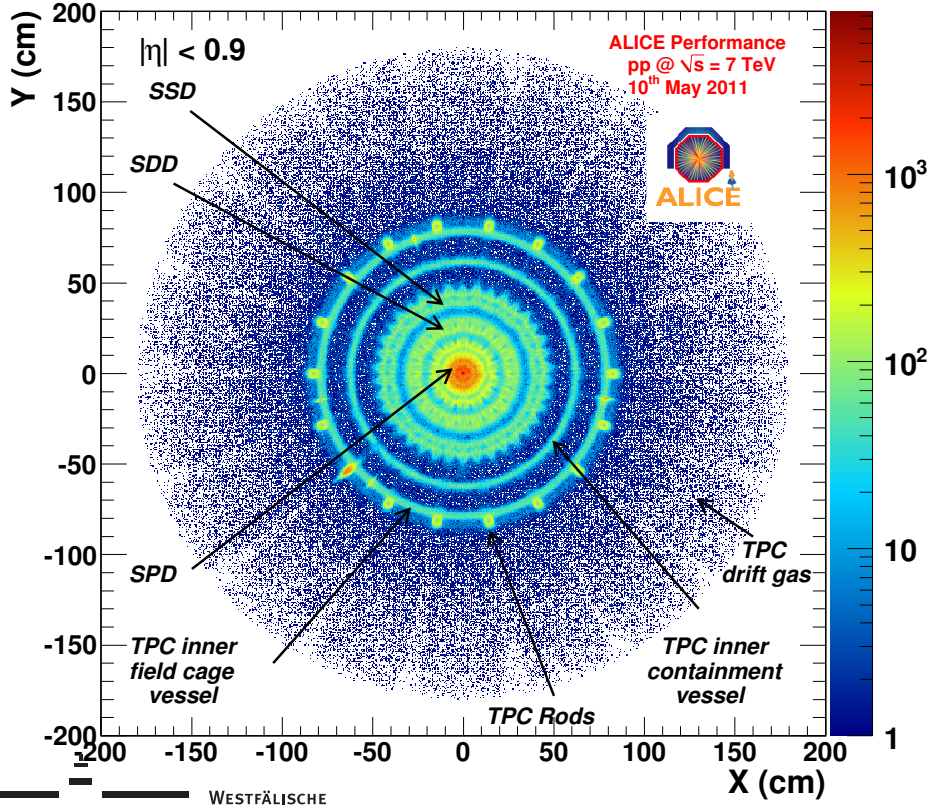
- Differences are given by the integral of the distributions (red, black)
- Systematics are calculated by varying MC generator, p_T range and V0 finder
- Effective radiation lenght: $X/X_0 = 0.1114$ $(|\eta| < 0.9, R < 180\,\mathrm{cm})$
- Final systematic error is $\sim 4.5\%$

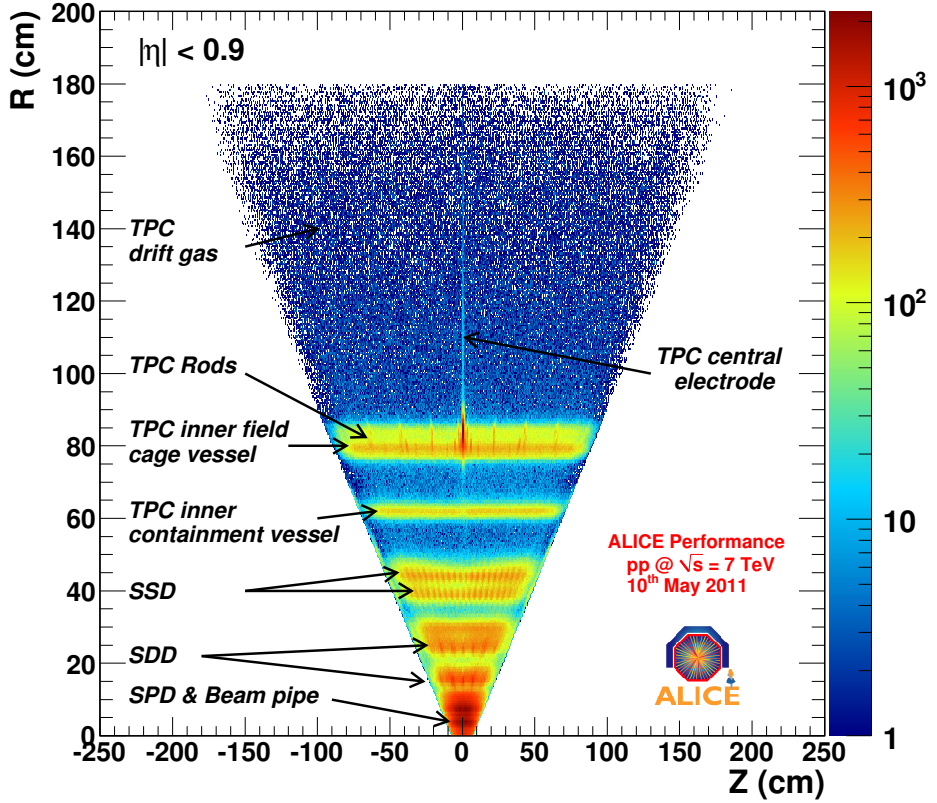


Material Budget and Conversion Point Resolution

γ-Ray Tomography of the ALICE Detector

- Very good conversion point resolution with ALICE
  $\rightarrow$ even smallest structures clearly visible
  $\rightarrow$ direct comparison between MC and data material budget
- R resolution 1.3 cm; Z resolution 0.8 cm; ϕ resolution 3 μrad (in $|\eta| < 0.9$)





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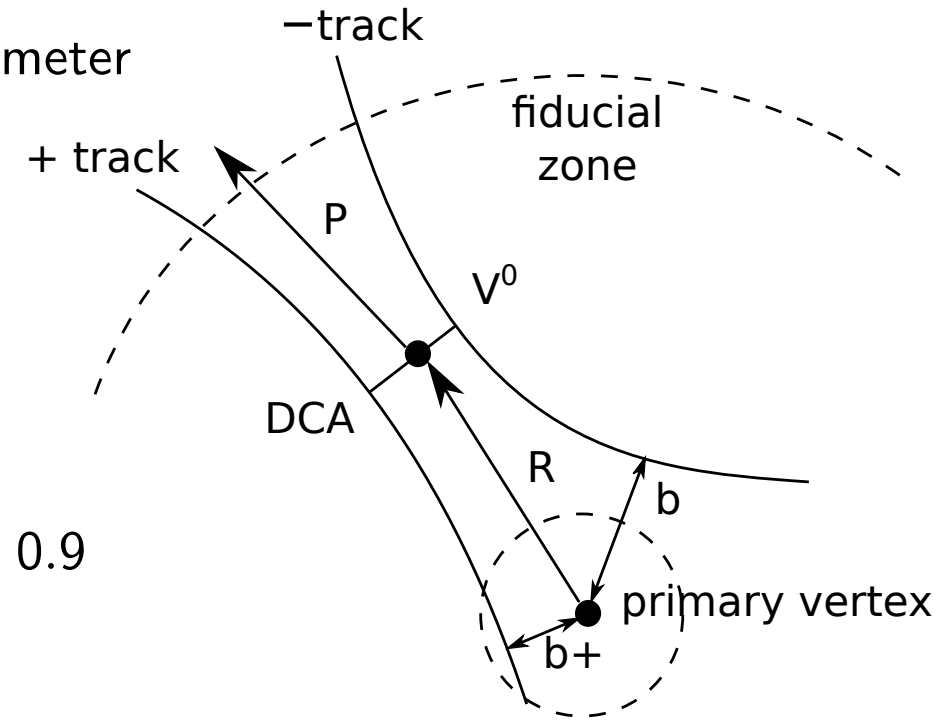
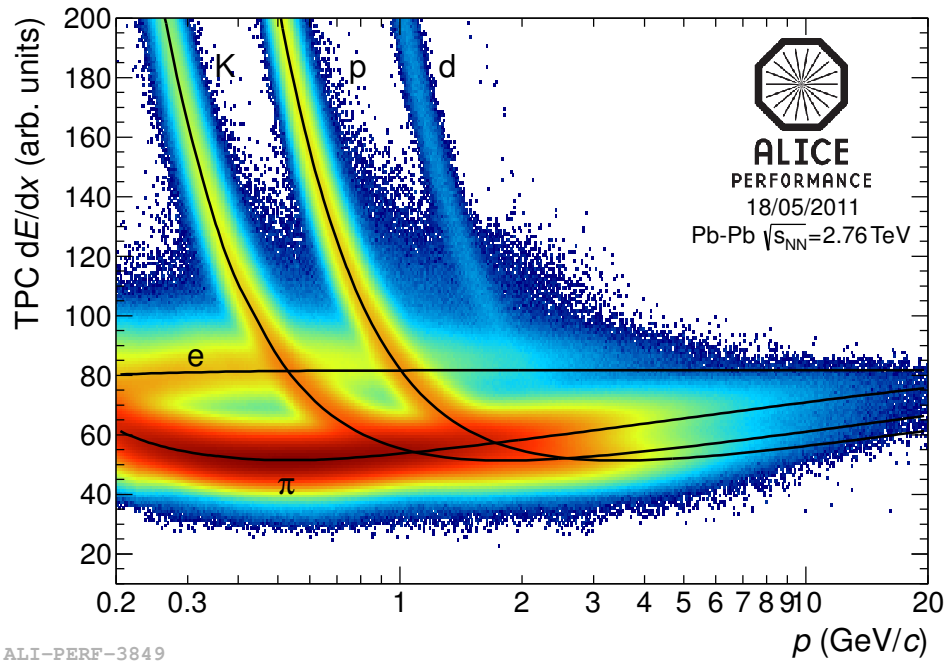


- Cuts on the decay topology of photons and electron track properties
  $\rightarrow$ Purity at 90% at $2\,\mathrm{GeV/c}$ for 0-40% Pb-Pb events
- Background is mainly combinatorial - Strange particle contribution negligible

Electron Selection Criteria

Global Electron Selection Criteria

- Both tracks originate from the same V0 candidate
- No kinks
- Opposite charge
- Small R cut ($R < 5\,\mathrm{cm}$)
- TPC refit condition
- Minimum momentum of 50 MeV/c
- Minimum fraction of the TPC clusters



PID Based Selection Criteria

- nσ around electron energy loss hypothesis in the TPC $\mathrm{d}E/\mathrm{d}x$
- Pion, kaon, proton rejection optional
- TOF electron nσ selection

  (if information available)
- After PID $\sim$ 80% pure photon sample

Photon Selection Criteria

Photon χ^2/ndf:

- Based on a Kalman-Filter
  (AliKFParticle package)
- Measure for conversion likelihood:
  includes: zero V0 mass, pointing to primary vertex, correct electron mass, mutual secondary vertex

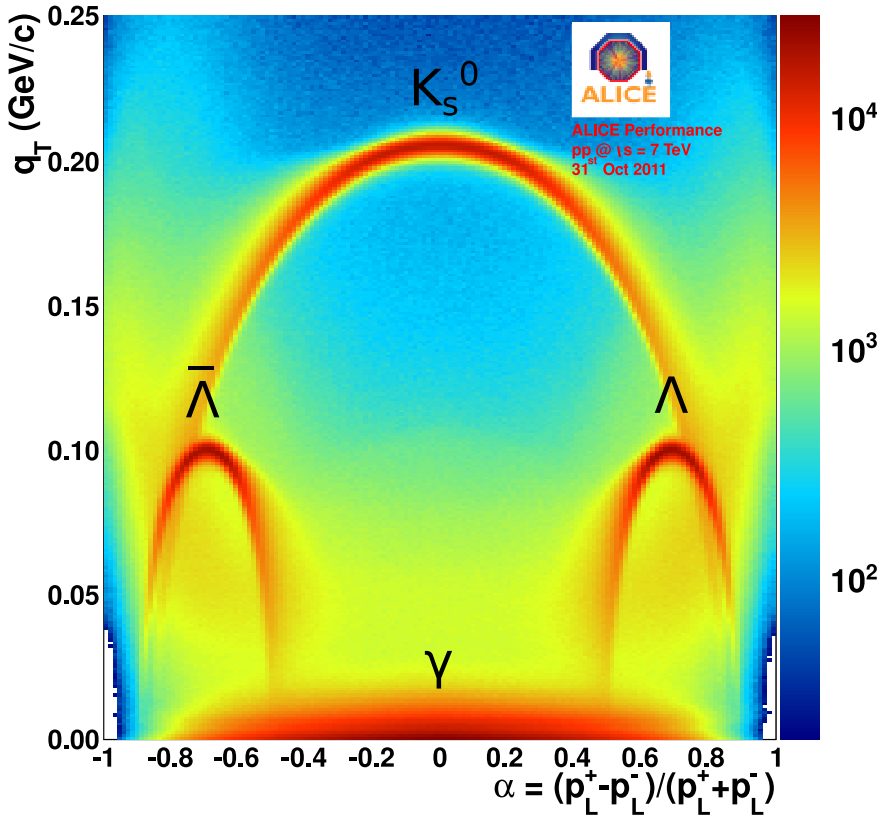
Further Photon Selection Criteria:

- Crosschecks for std. photon criteria
- Psi-Pair angle
  opening angle perpendicular to B field
- Cosine of pointing angle
  pointing to the primary vertex

Photon q_T:

- Transv. mom. component of daughter relative to the V0

  $q_T = p \times \sin(\Theta_{\mathrm{mother-daughter}})$
- Clear separation of γ, Λ and K^0_s



Photon Corrections and Invariant Cross Section for pp

- Raw γ spectrum in pp and Pb-Pb corrected for:
  - purity ($\mathcal{P}$)
  - efficiency ($\mathcal{E}$)
  - conversion probability ($\mathcal{C}$)

  and secondary photon candidates subtracted

- Inc. photon cross section in pp: $$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = \frac{1}{2\pi}\frac{\sigma^{MB_{OR}}}{N_{events}}\frac{1}{p_T}\frac{\mathcal{P}}{\mathcal{C}\mathcal{E}}\frac{N^{\gamma\,prim}}{\Delta y \Delta p_T}, \quad \frac{\sigma^{MB_{OR}}}{\sigma_{inel}} = 0.85^{+0.03}_{-0.13}$$

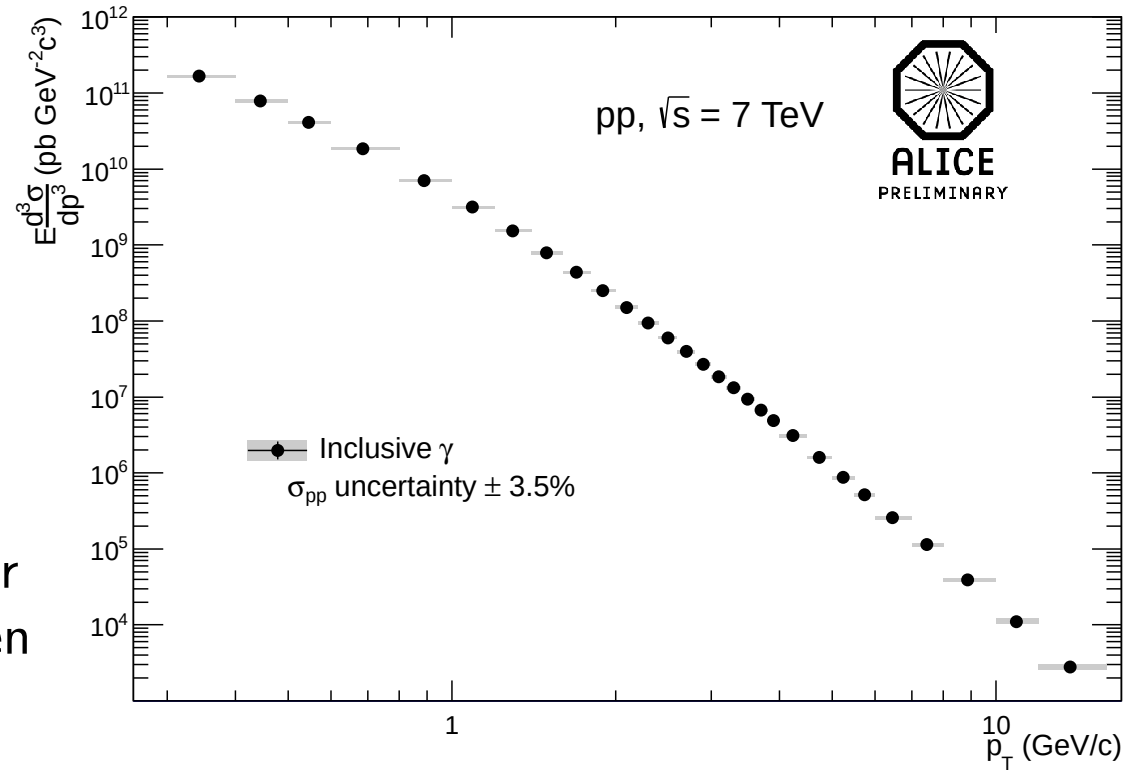
Main sources of uncertainty:

- Material budget of the detector $\sim$ 4.5%
- Efficiency estimation by cut variations

  $p_T < 5\,\mathrm{GeV}$: pp $\sim$ 3%, Pb-Pb $\sim$ 6%

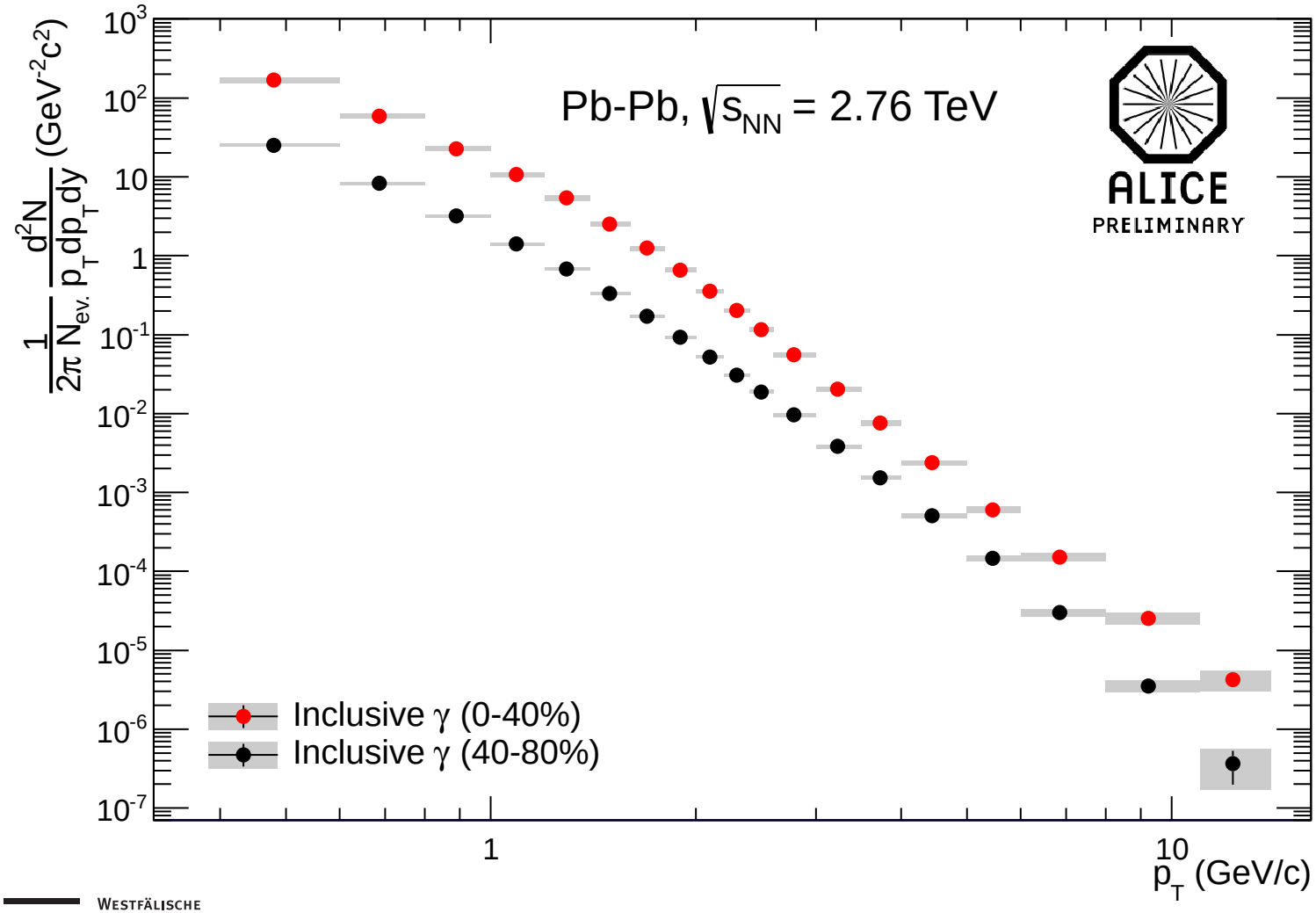
  $p_T > 5\,\mathrm{GeV}$: pp $\sim$ 6%, Pb-Pb $\sim$ 15%

  e.g. geometrical cuts, detector PID, sharing of tracks between sec. vertices



Inclusive Photon Invariant Yield in Pb-Pb

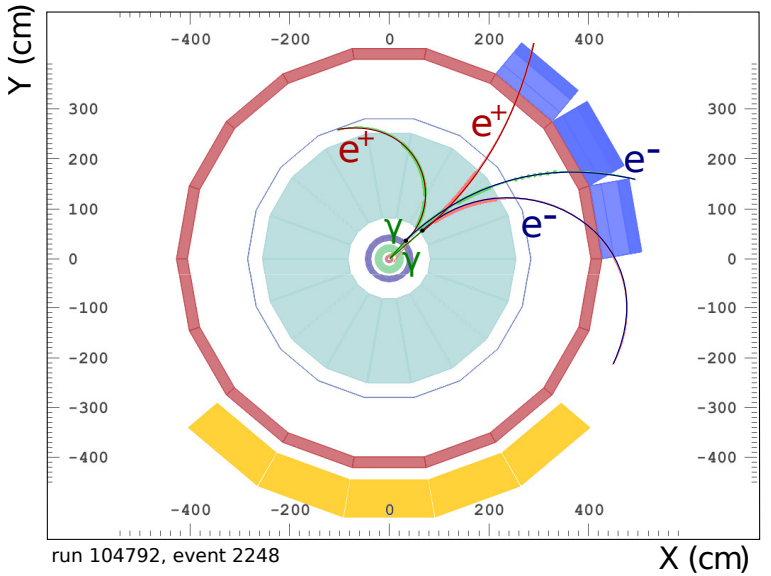
- Two centrality selections: 0-40% and 40-80% (central and peripheral)

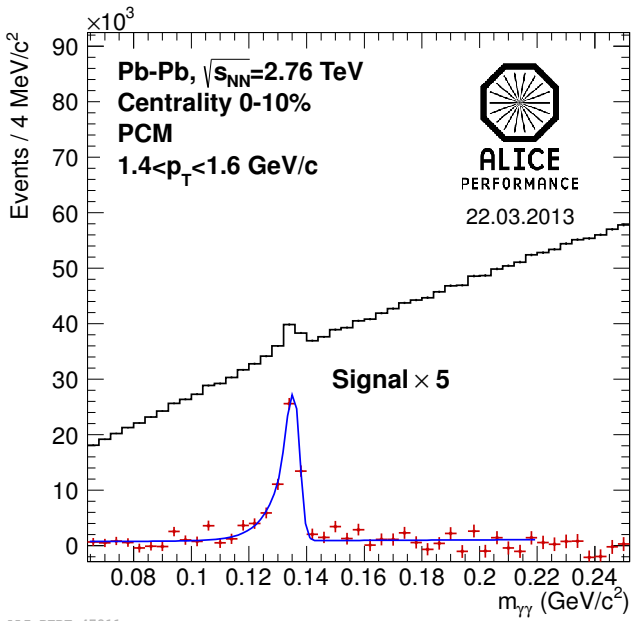


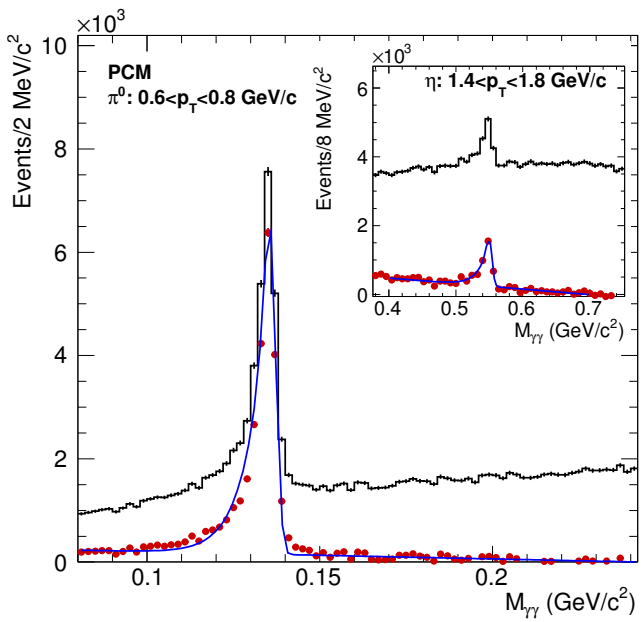
π^0 and η Reconstruction via Conversion

Neutral pion and η (pp only), based on identical set of converted photons

- Inv. mass calculated for all photon pairs in an event
- Combinatorial background obtained via mixed event technique
- Raw π^0 spectrum obtained by peak integration
- Efficiency and acceptance estimated with MC simulations







For more details see:

- pp at TeV: Phys. Lett. B 717, 162 (arXiv:1205.5724)
- Pb-Pb and pp at 2.76TeV: published soon, similar method

Cocktail Generator

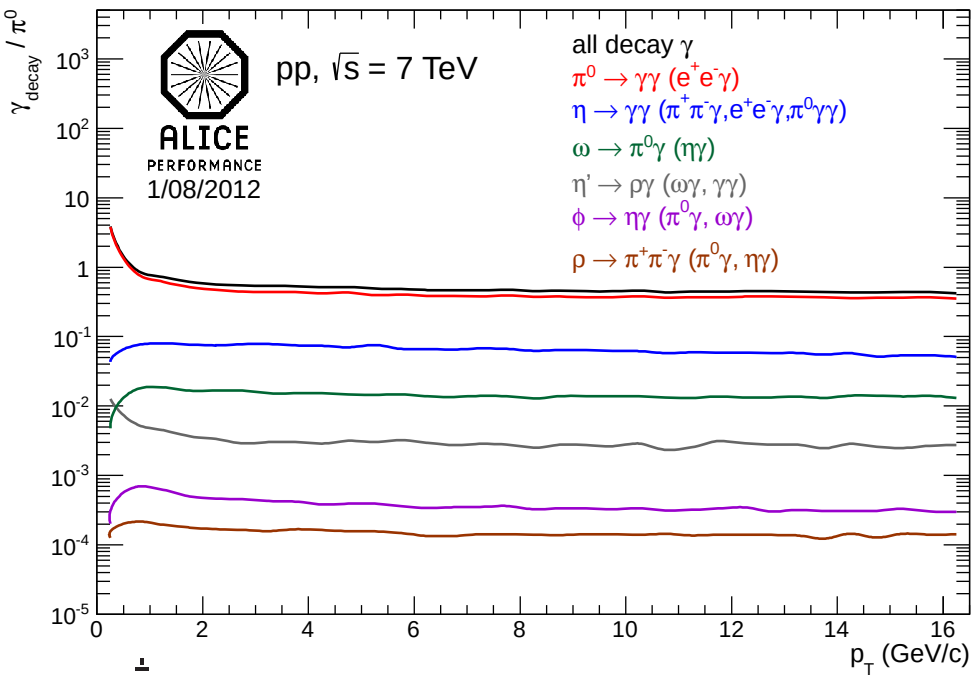
Decay photon spectra are obtained via calculation

- Based on a fit to measured π^0 and η (in pp)
- Other particle spectra obtained via m_T-scaling
- Incorporated mesons: π^0, η, η', ω, ϕ, ρ_0 and the Σ^0 baryon

m_T-Scaling:

Same shape of cross sections, $f(m_T)$, of various mesons

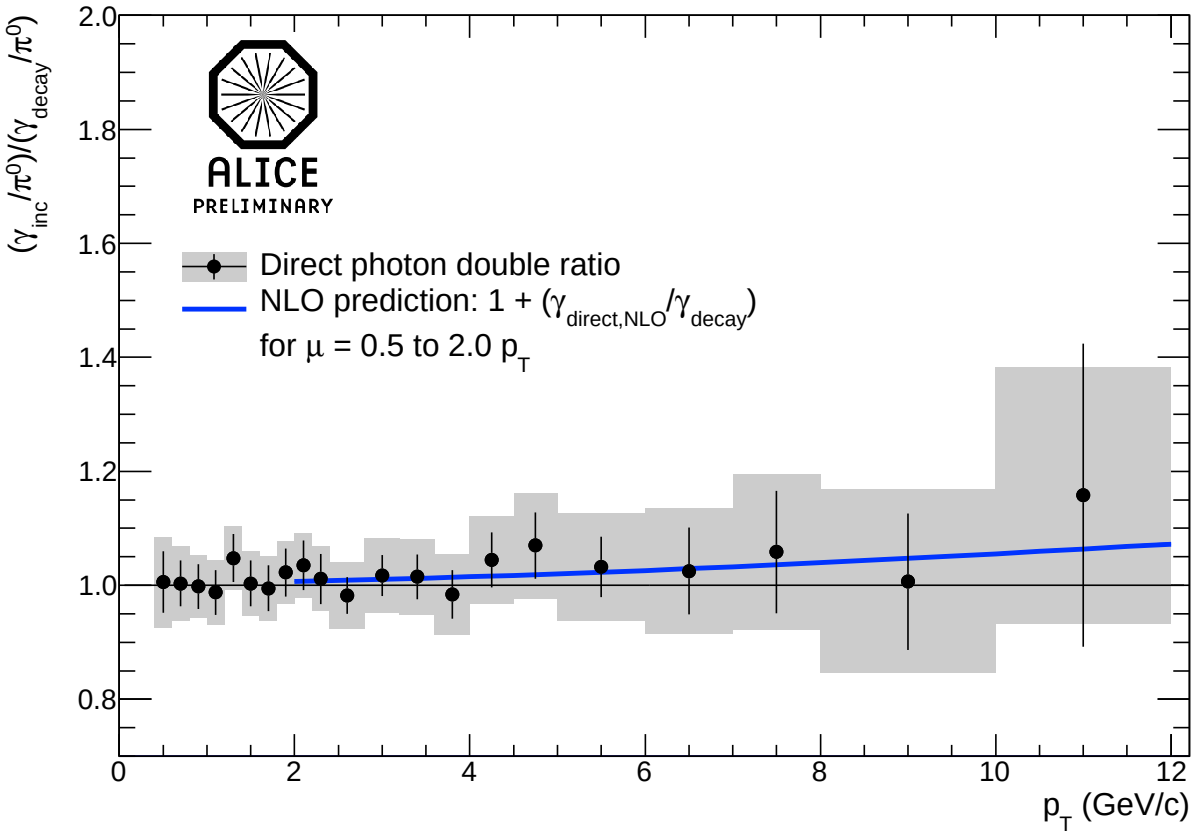
$$E\frac{d^3\sigma_m}{dp^3} = C_m \cdot f(m_T)$$



Meson (C_m)	Mass	Decay Branch	B. Ratio
π^0	134.98	$\gamma\gamma$	98.789%
		$e^+e^-\gamma$	1.198%
η	547.3	$\gamma\gamma$	39.21%
		$\pi^+\pi^-\gamma$	4.77%
(0.48)		$e^+e^-\gamma$	$4.9 \cdot 10^{-3}$
ρ_0	770.0	$\pi^+\pi^-\gamma$	$9.9 \cdot 10^{-3}$
(1.0)		$\pi^0\gamma$	$7.9 \cdot 10^{-4}$
ω	781.9	$\pi^0\gamma$	8.5%
(0.9)		$\eta\gamma$	$6.5 \cdot 10^{-4}$
η'	957.8	$\rho^0\gamma$	30.2%
		$\omega\gamma$	3.01%
(0.25)		$\gamma\gamma$	2.11%
ϕ	1019.5	$\eta\gamma$	1.3%
		$\pi^0\gamma$	$1.25 \cdot 10-3$
(0.35)		$\omega\gamma$	$< 5\%$
Σ^0 (1.0)	1192.6	$\Lambda\gamma$	100%

Phys. Rev. C (arXiv:1110.3929)

Direct Photons in pp Collisions at 7 TeV



In the ratio uncertainties related to:

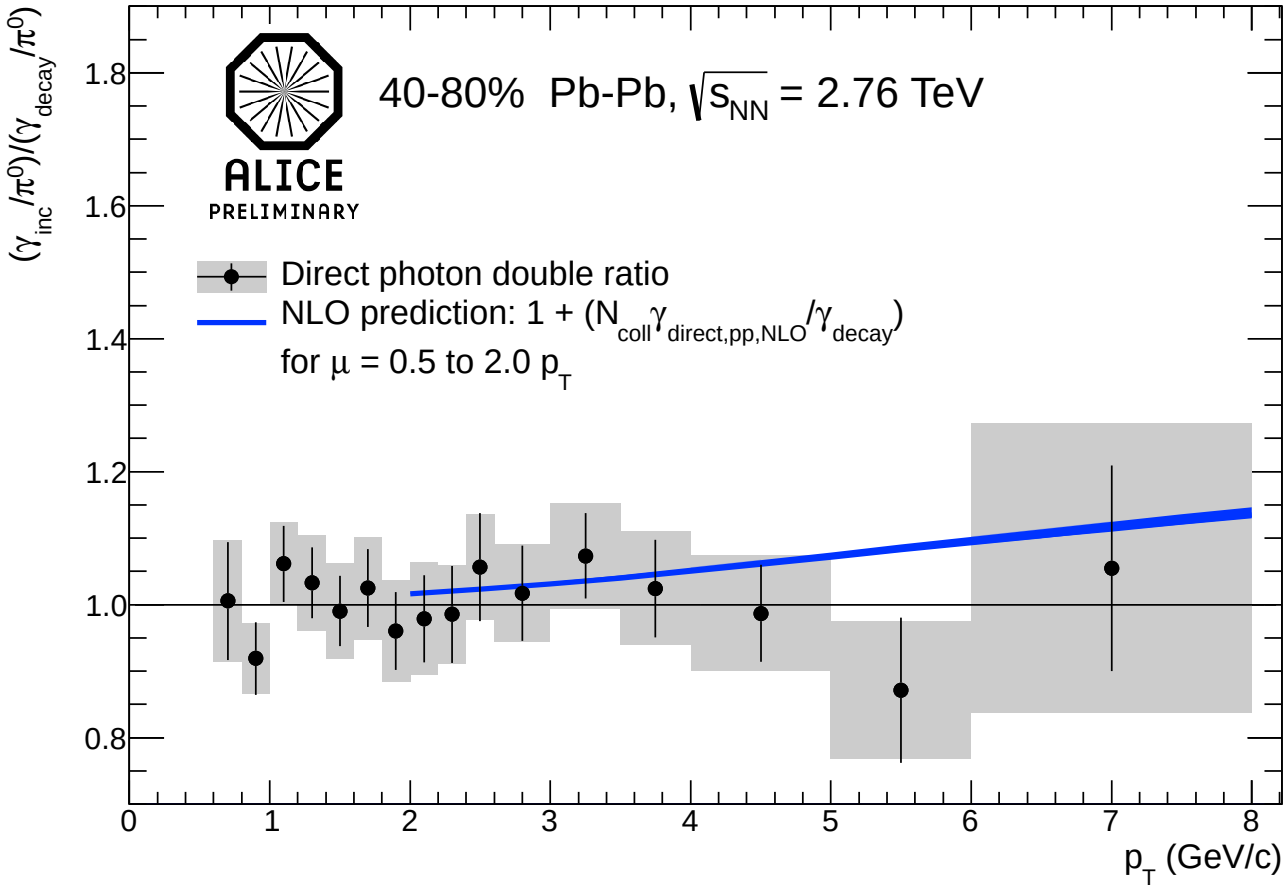
- normalization
- π^0 measurement
- rec. efficiency

partially or exactly canceled

Direct photon signal in pp at 7 TeV is consistent with zero

- The NLO double ratio prediction is plotted as $\mathcal{R}_{NLO} = 1 + \frac{\gamma^{direct,NLO}}{\gamma^{decay}_{cocktail}}$
- Measurement is consistent with the expected direct photon signal

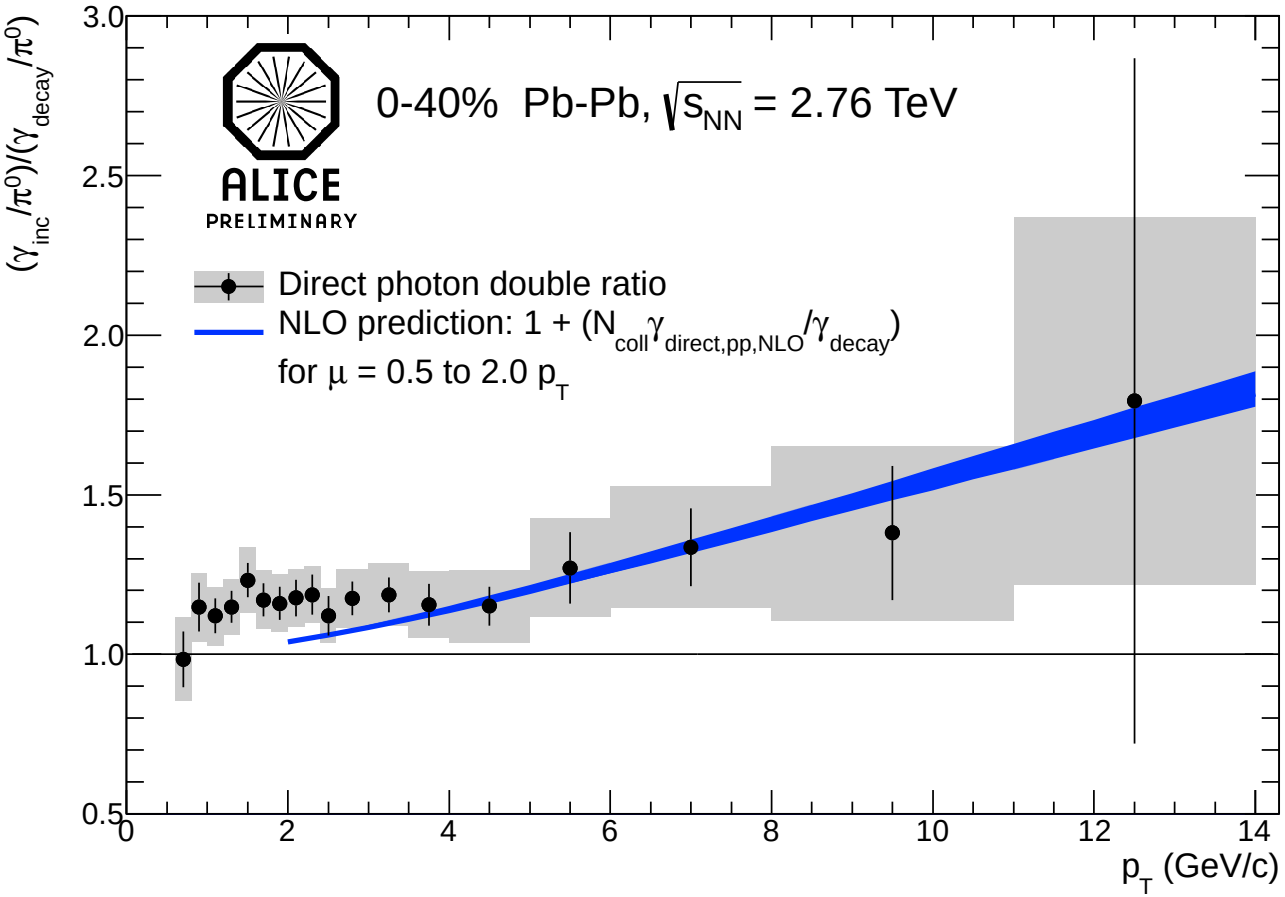
Double Ratio - Pb-Pb 2.76 TeV - peripheral



Double ratio for peripheral events shows no excess at any value of p_T

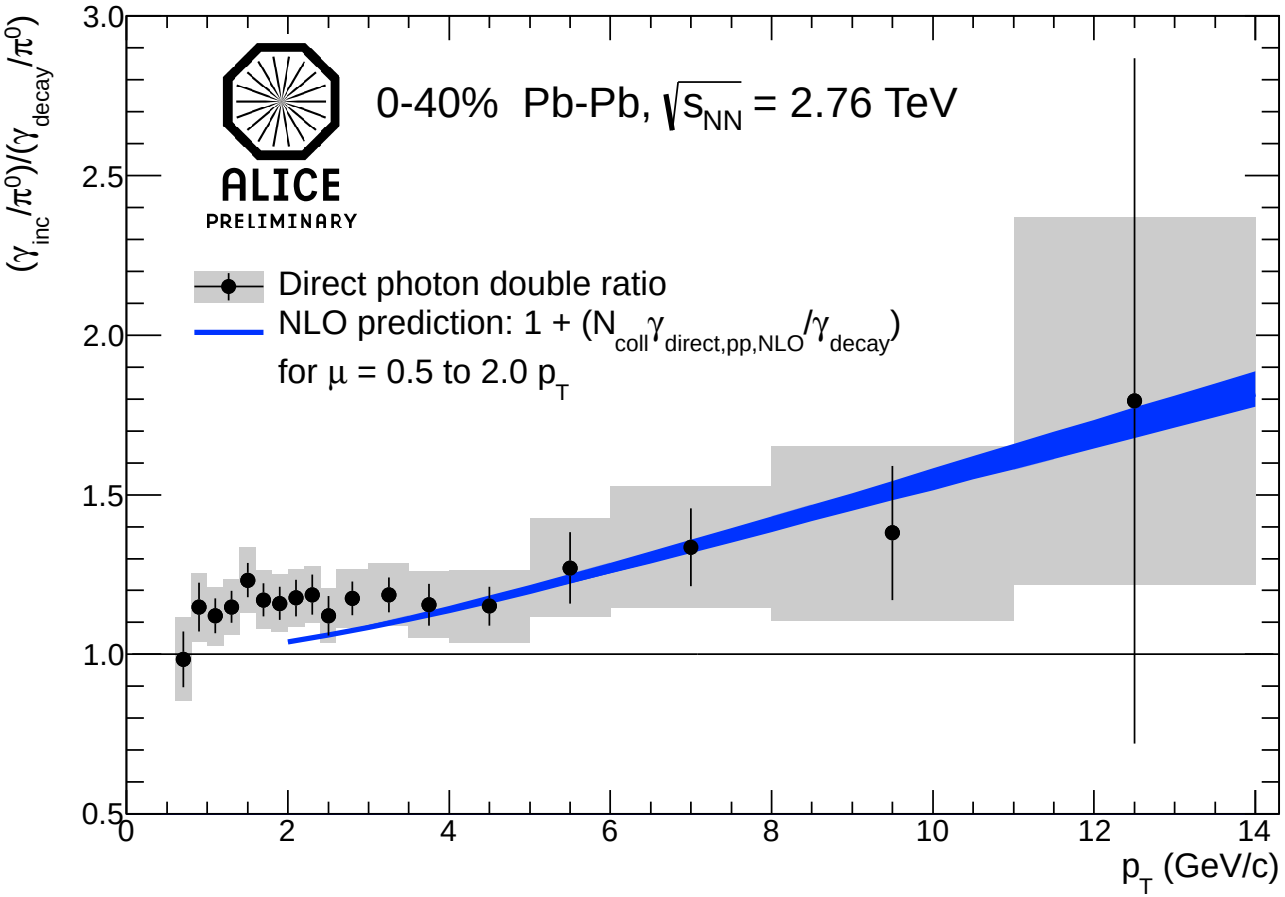
- Measurement is consistent with the expected direct photon signal
- pp NLO predictions scaled with N_{coll}

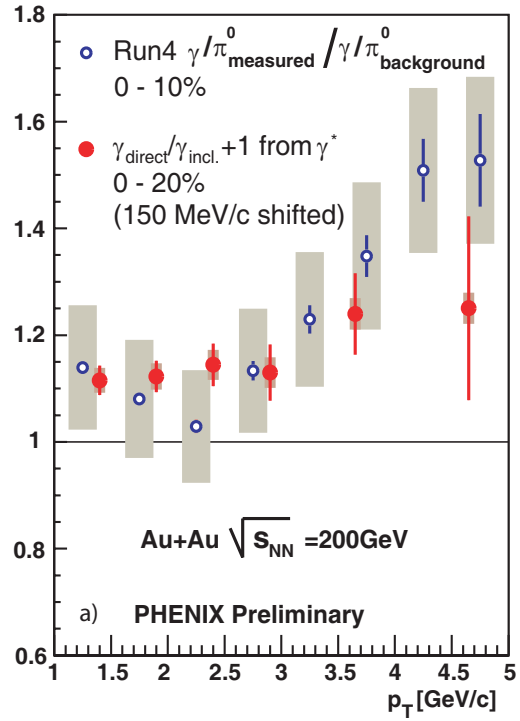
Double Ratio - Pb-Pb 2.76 TeV - central



Clear extra yield of 20% for $p_T < 2\,\mathrm{GeV/c}$
N_{coll} scaled pp NLO in agreement with high p_T direct photons

Double Ratio - Pb-Pb 2.76 TeV - central

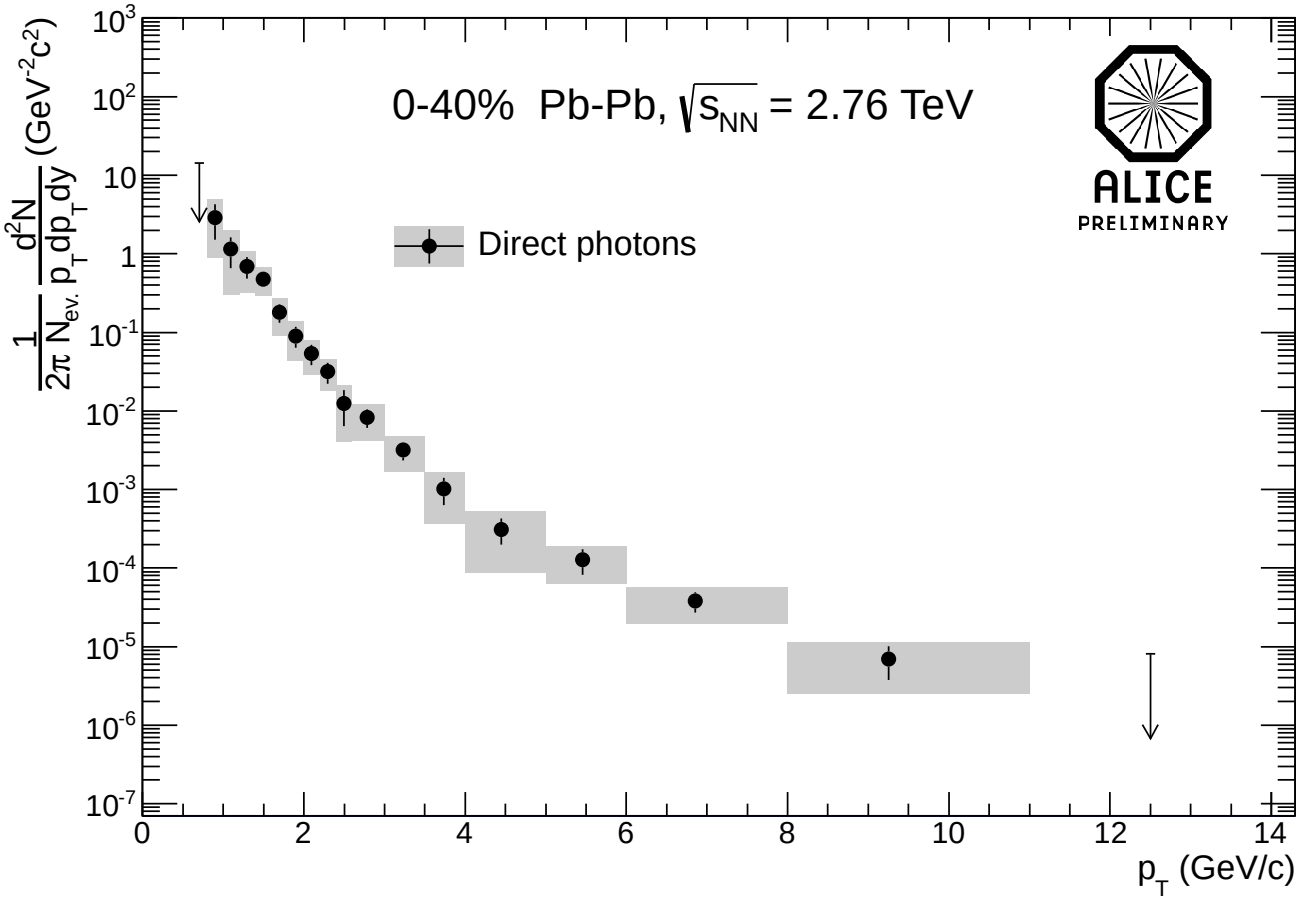




Clear extra yield of 20% for $p_T < 2\,\mathrm{GeV/c}$
N_{coll} scaled pp NLO in agreement with high p_T direct photons

- Similar to low p_T direct photon observation by PHENIX

Results of Pb-Pb Direct Photons at 2.76 TeV

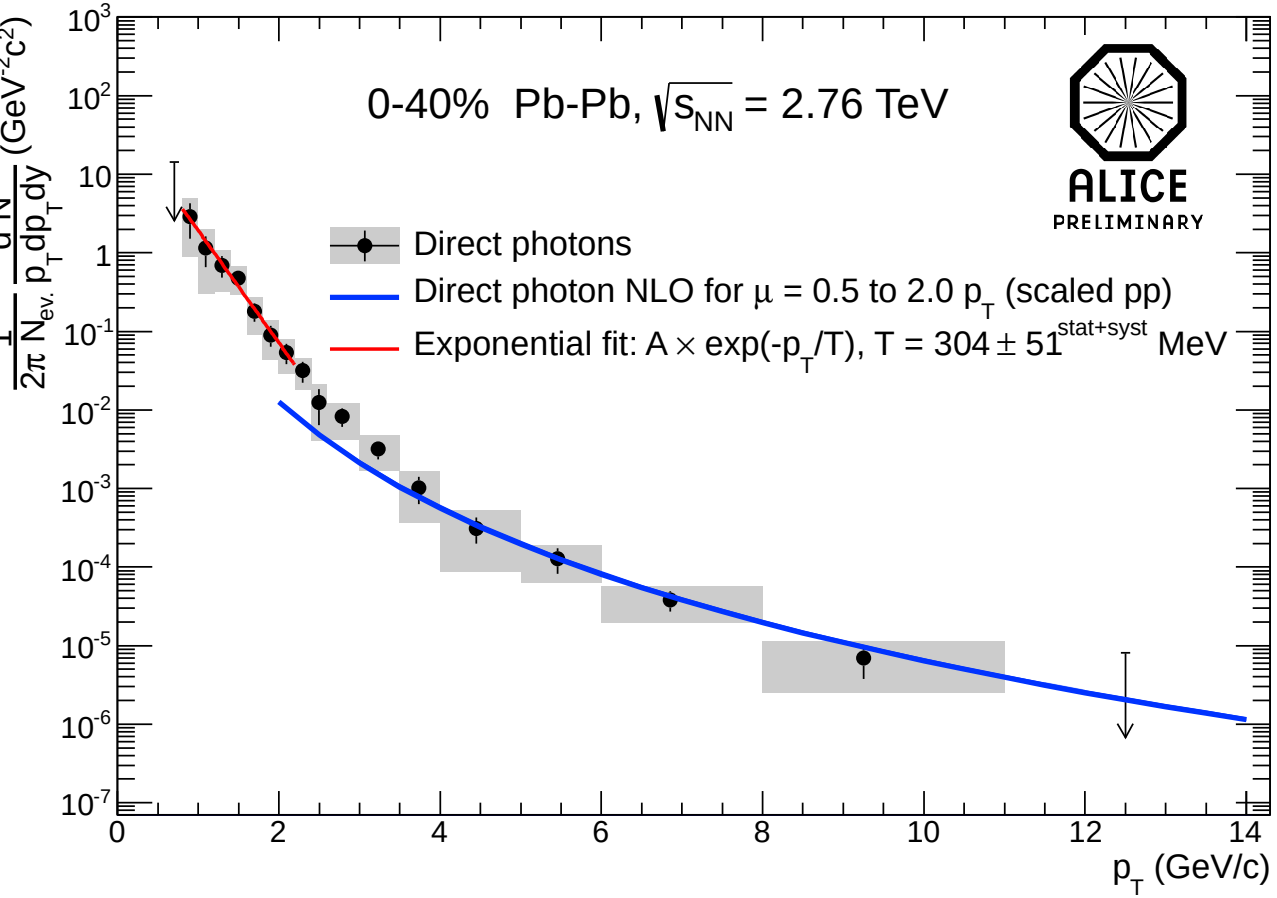


Direct Photon Spectrum for central Pb-Pb events

Spectrum derived from double ratio by:

$$\gamma_{direct} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}) \cdot \gamma_{inc}$$

Results of Pb-Pb Direct Photons at 2.76 TeV



Direct Photon Spectrum for central Pb-Pb events

Spectrum derived from double ratio by:

$$\gamma_{direct} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}) \cdot \gamma_{inc}$$

- NLO predictions in agreement with spectrum ($p_T > 4\,\mathrm{GeV/c}$)
- At low p_T ($< 2.2\,\mathrm{GeV/c}$) spectrum fitted with an exponential
  $\rightarrow$ slope parameter $T = 304 \pm 51^{\mathrm{stat+syst}}\,\mathrm{MeV}$
- Intermediate region: superposition of low and high p_T direct photons

Conclusions I: Direct Photon Spectra

- Statistical analysis of direct photons based on converted photons via double ratio
- With current uncertainties no significant direct photon signal in pp and peripheral Pb-Pb
- Direct photon signal is consistent with expectation from NLO pQCD

- In central Pb-Pb:
  Low p_T direct photon signal, exponential in shape
- Similar excess measured at RHIC interpreted as thermal signal

  Slope parameter:
  - $T_{ALICE} = 304 \pm 51^{\mathrm{stat+syst}}\ \mathrm{MeV}$ (0-40%)
  - $T_{PHENIX} = 221 \pm 19^{\mathrm{stat}} \pm 19^{\mathrm{syst}}\ \mathrm{MeV}$ (0-20%)

  arxiv:0804.4168 PRL 104 (132301) 2010

Part II: Direct Photon v_2

What can we learn from direct photon v_2?

Initial azimuthal asymmetry in coordinate space in non-central A+A
$\Rightarrow$ asymmetry in momentum space

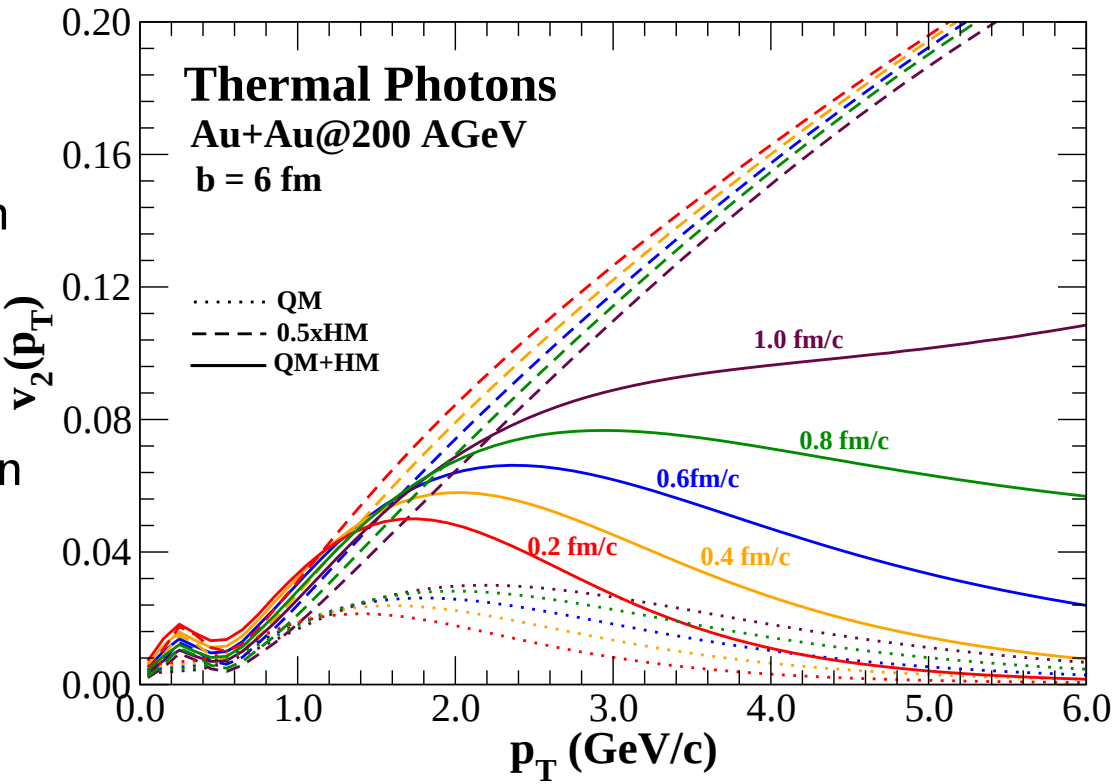
$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos(n(\phi - \Psi_n^{RP}))\right)$$

- v_2: elliptic flow, collective expansion at low p_T
- v_2 at high p_T: path length dependence of in-medium parton energy loss

Thermal Photon v_2

- Constrains onset of direct photon production
  - Early production $\rightarrow$ small flow
  - Late production $\rightarrow$ hadron-like flow

ideal hydro th. photon v_2 for different QGP formation times τ_0



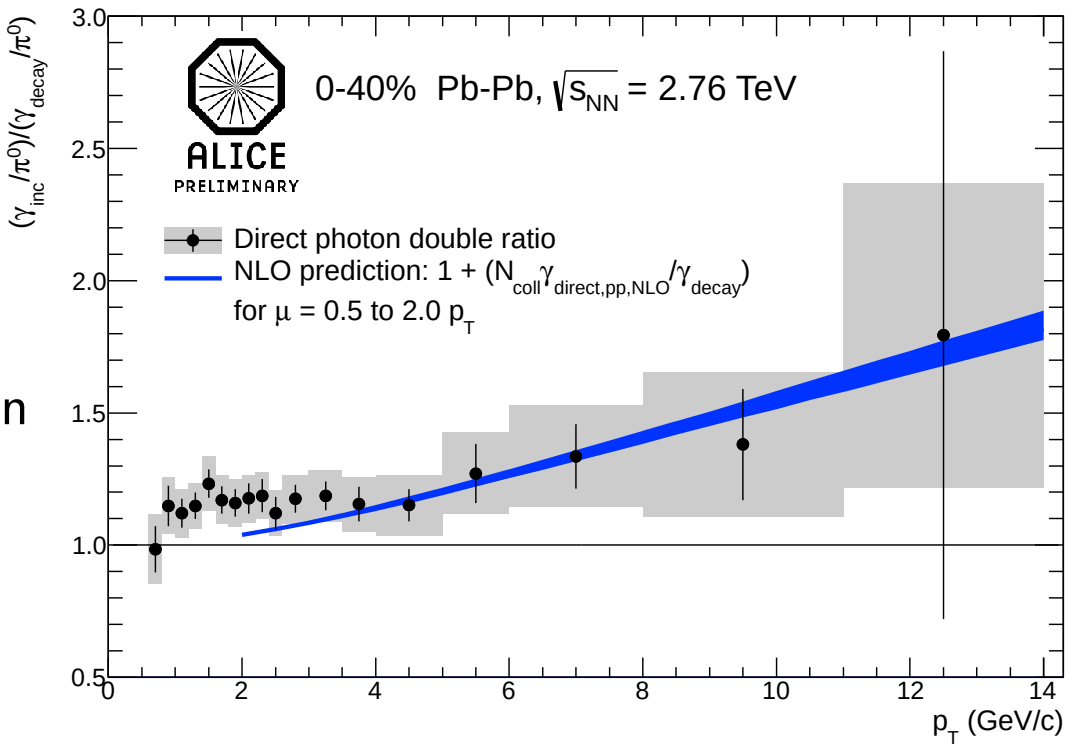
arXiv:0809.0548 [nucl-th]

General Strategy of the v_2 Analysis

Direct photon v_2 obtained via comparison between measured and calculated decay photon v_2

$$v_2^{\text{direct }\gamma} = \frac{R \cdot v_2^{\text{inc }\gamma} - v_2^{\text{decay }\gamma}}{R-1}$$

Factor R represents the direct photon double ratio



- $R \cdot v_2^{\text{inc }\gamma}$: weighted inclusive photon v_2 due to extra photons compared to background
- $v_2^{\text{decay }\gamma}$: calculated decay photon v_2 from cocktail calculation

Inclusive Photon v_2 Analysis

v_2 given by the event plane

$$v_2 = \langle \cos(2(\phi - \Psi_2^{RP})) \rangle$$

Extracted via this formula or by a fit

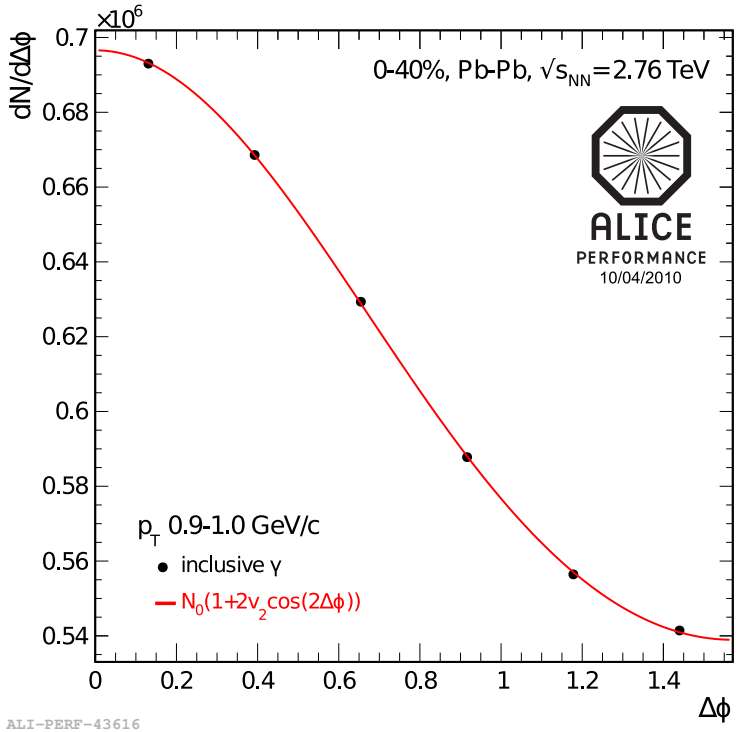
Event Plane angle determined by using the VZERO detector

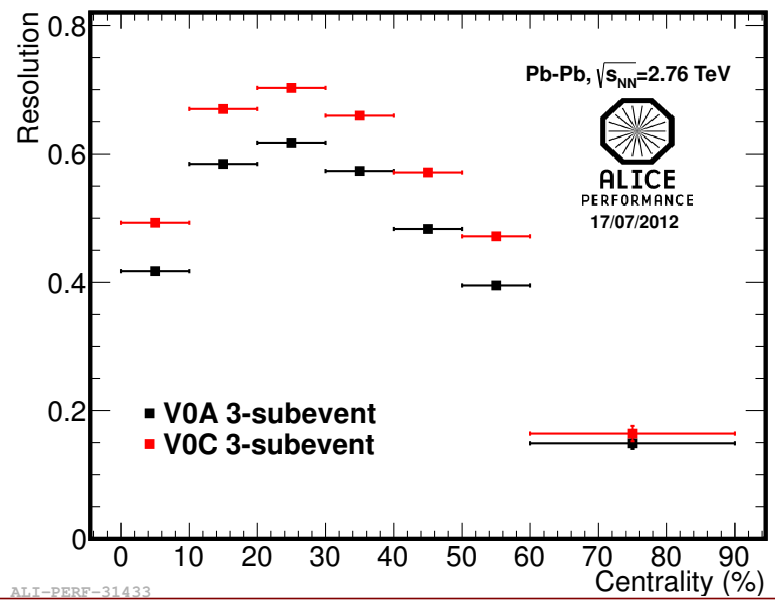
- VZEROA: $2.8 < \eta < 5.1$
- VZEROC: $-3.7 < \eta < -1.7$

Reaction plane resolution obtained by the three sub-event method

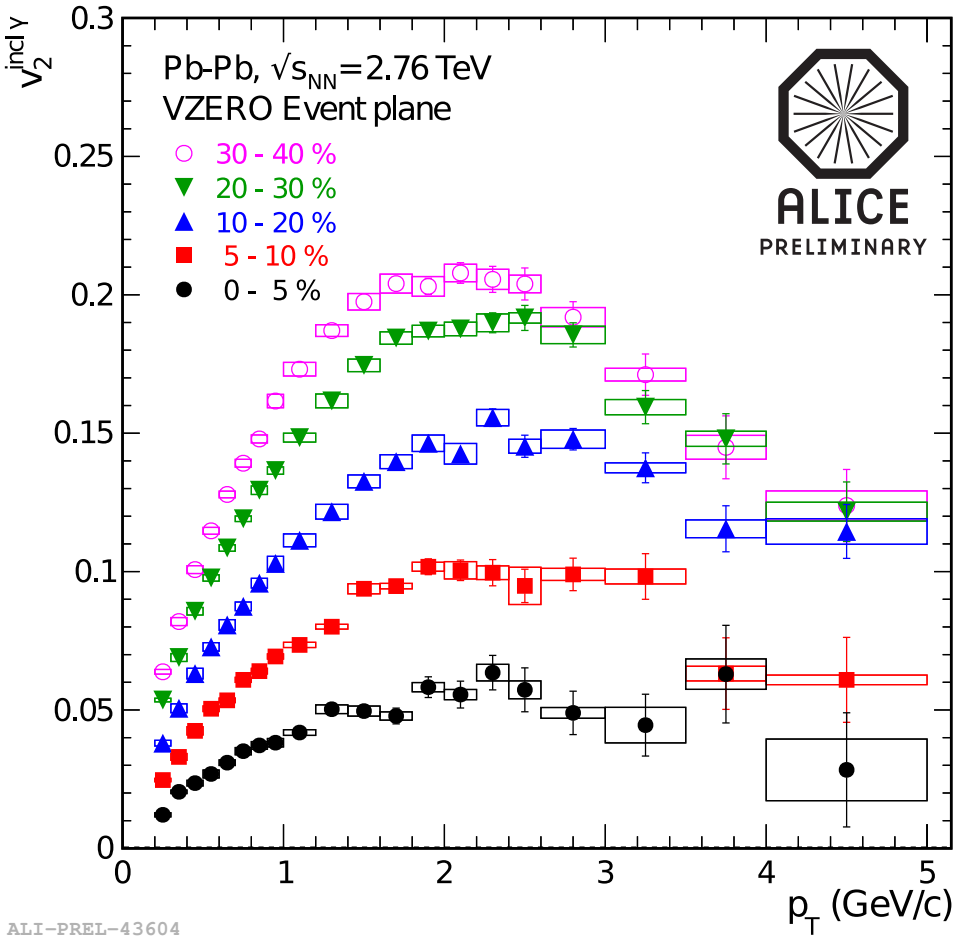
Resolution correction for EP:

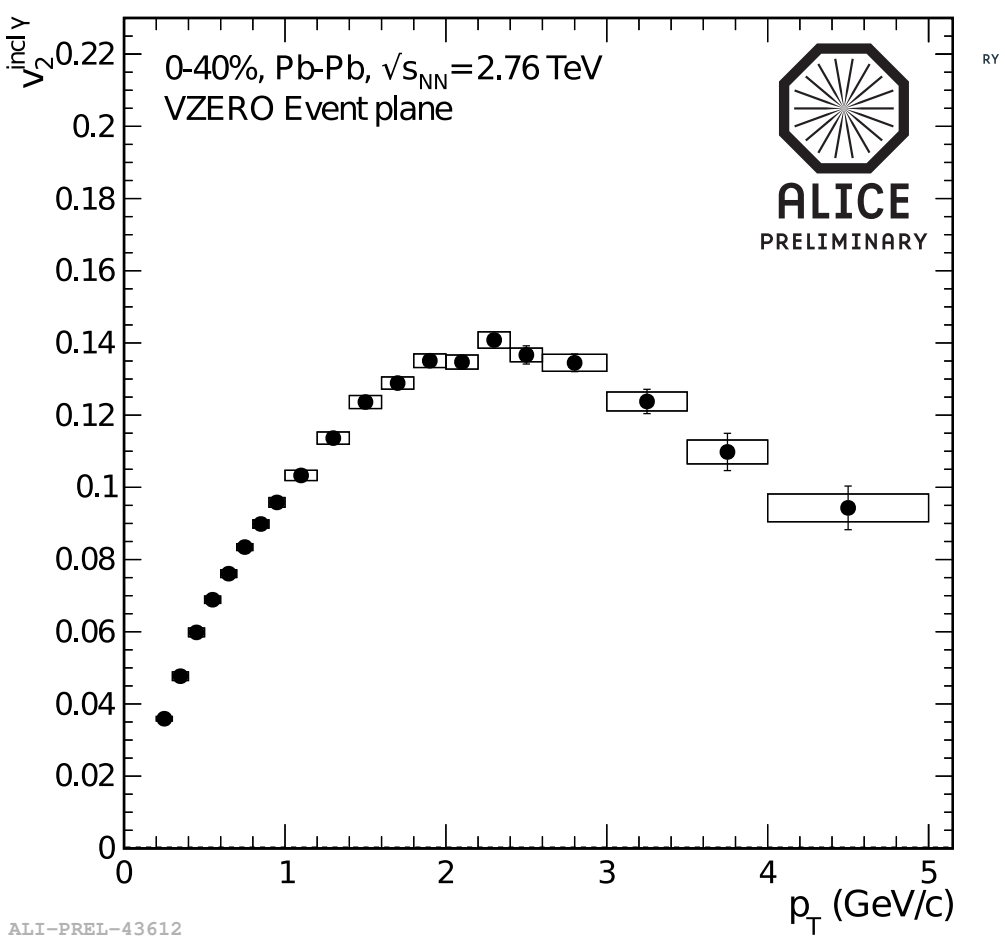
$$v_2 = \frac{v_2^{EP}}{\langle \cos(2\Psi_2^{EP} - \Psi_2^{RP}) \rangle} = \frac{v_2^{\mathrm{raw}}}{\text{resolution}}$$





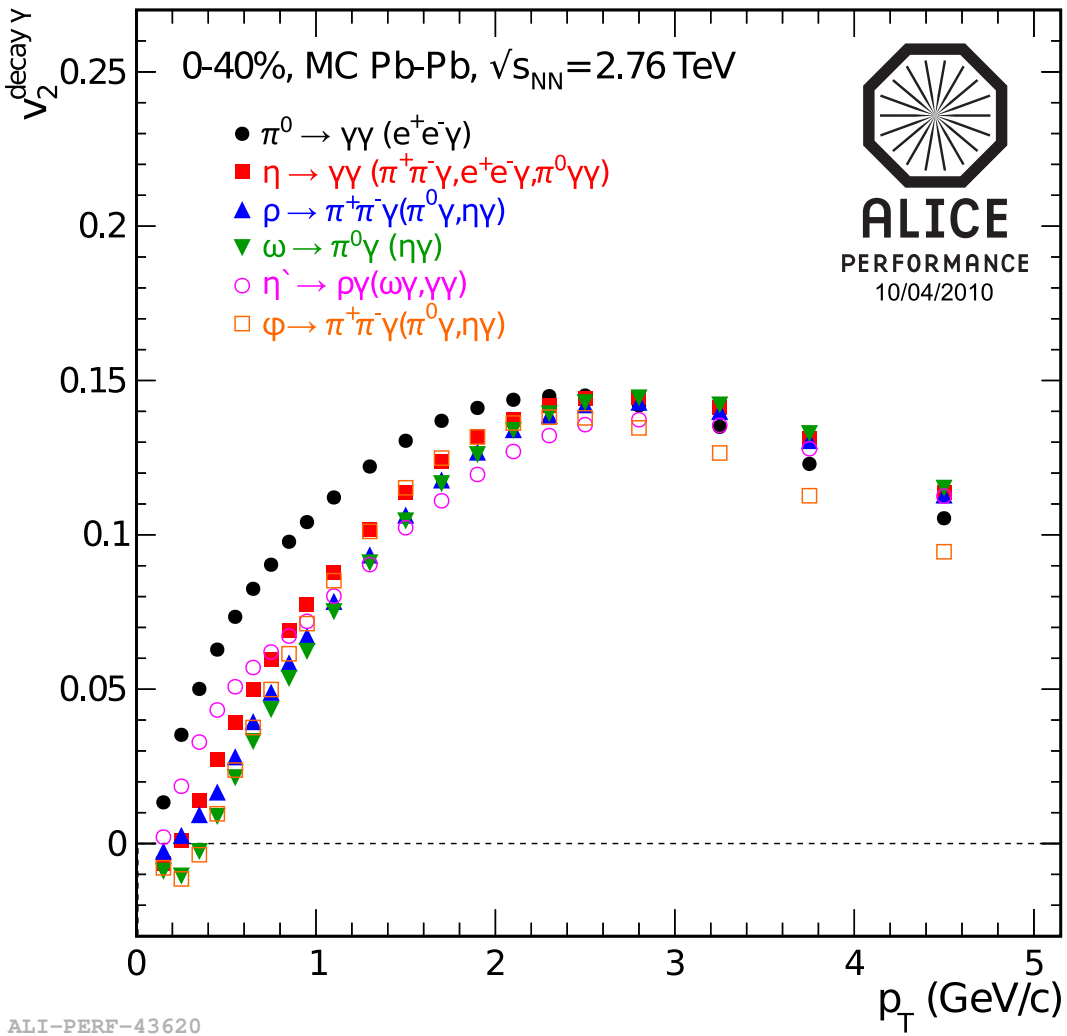
Inclusive Photon v_2 Results 0-40%





- Magnitude of v_2 increases with decreasing centrality
- Similar v_2 to hadrons
- Expected behavior, main contributions are decay photons

Cocktail Simulation and Decay Photon v_2



- KE_T scaling: v_2 of mesons scales with KE_T

$\Rightarrow$ $v_2^{\pi^0} \approx v_2^{\pi^\pm}$ $(m^{\pi^0} \approx m^{\pi^\pm})$

$\rightarrow$ v_2 of various mesons (X) calculated via KE_T (quark number) scaling from $v_2^{\pi^\pm}$

$$v_2^X(p_T^X) = v_2^{\pi^\pm}\left(\sqrt{(KE_T^X + m^{\pi^\pm})^2 - (m^{\pi^\pm})^2}\right)$$

with:

$$KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$

- Decay photon v_2 from different mesons obtained from cocktail calculation

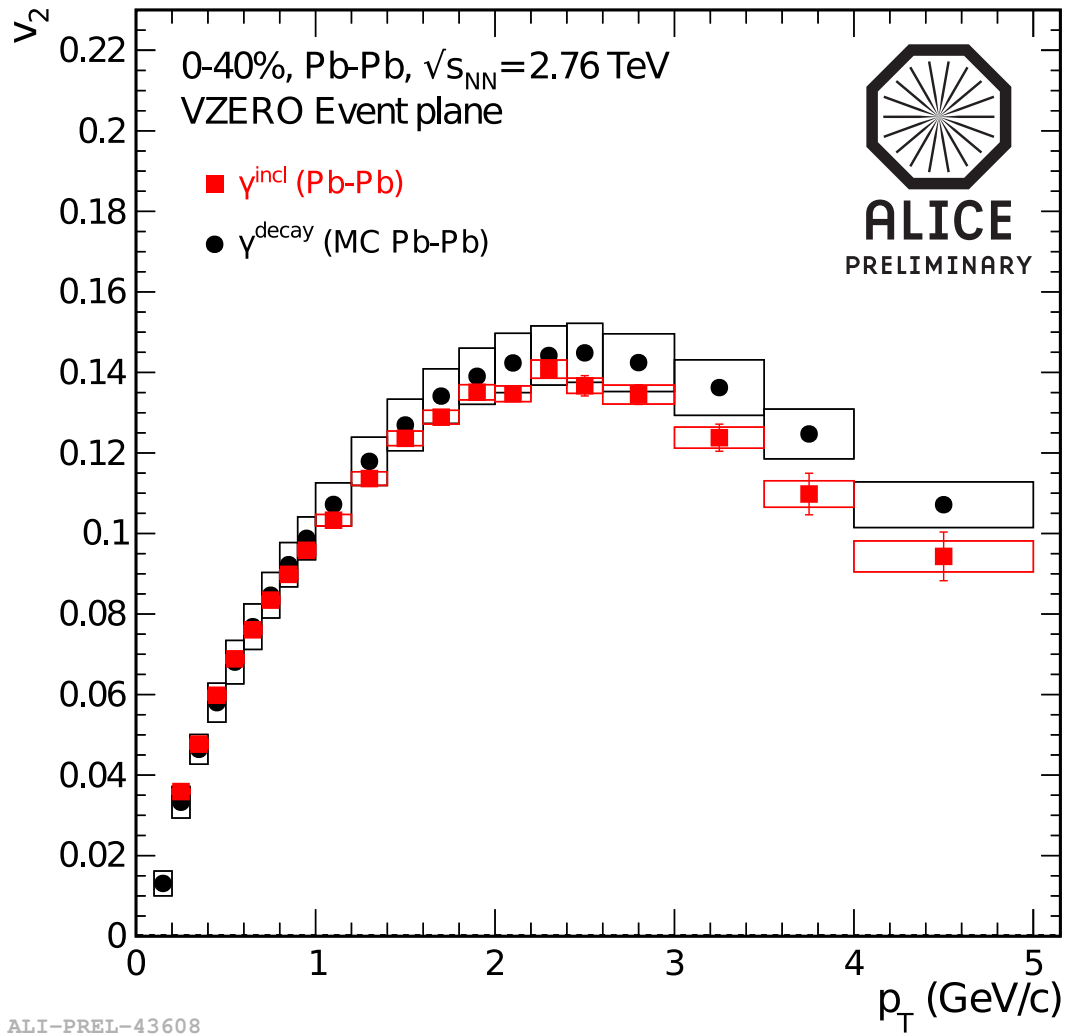
Comparison of Inclusive and Decay v_2

- Above 3 GeV/c inclusive photons significantly smaller than decay photons

→ Direct photon v_2 contribution with $v_2^{\text{direct}} < v_2^{\text{inc}}$

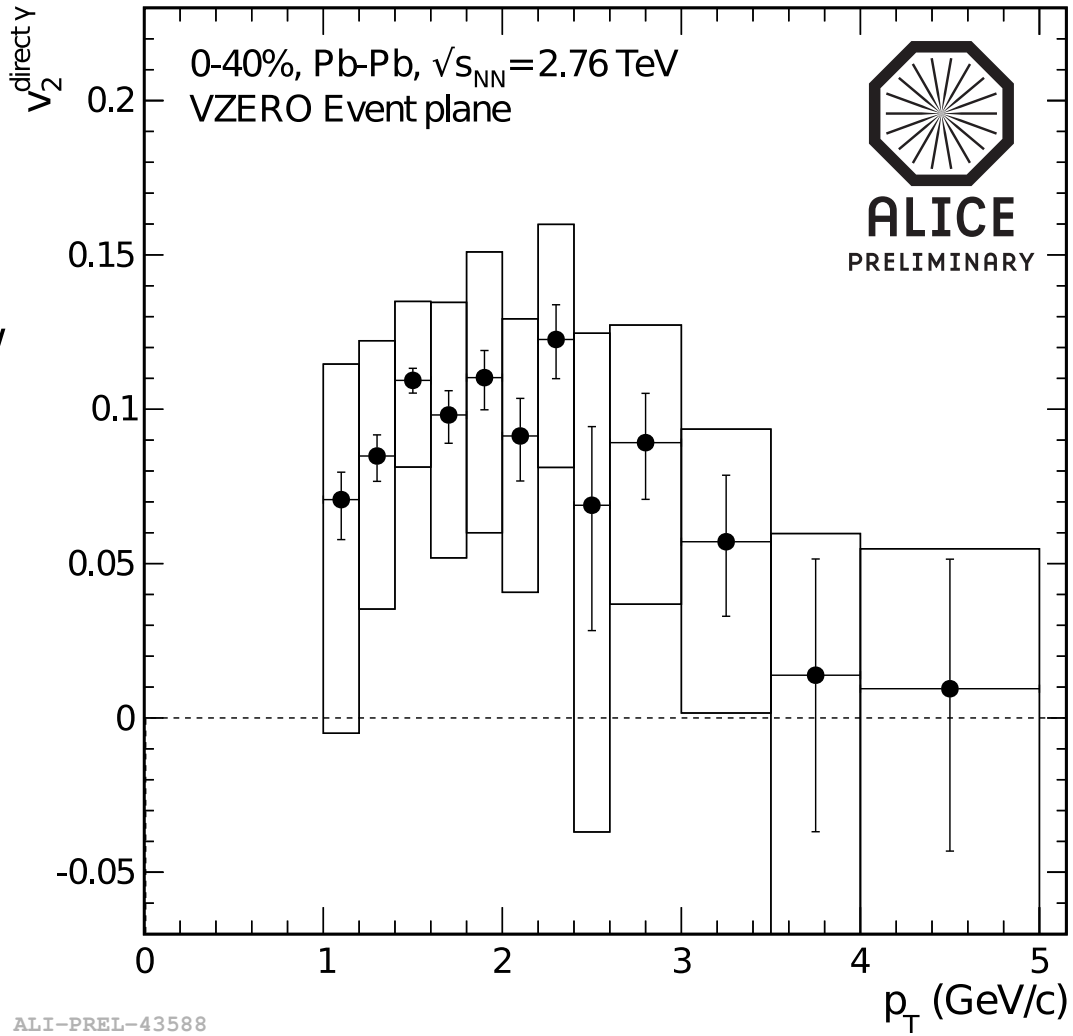
- Below 3 GeV/c consistent within uncertainties

→ Either contribution of direct photons with similar v_2 or no direct photons



Direct Photon v_2 0-40% and Conclusions II

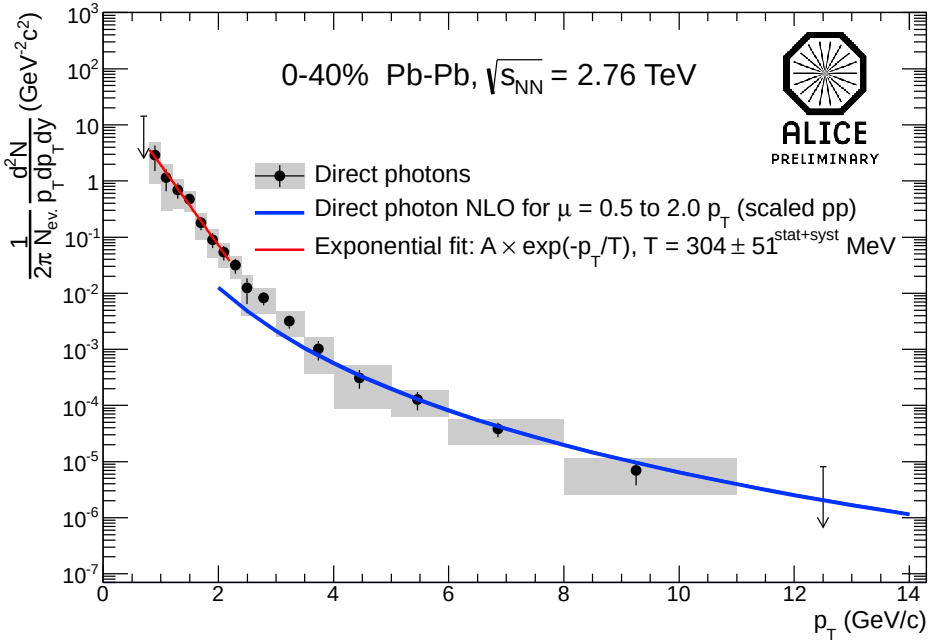
- Significant direct photon v_2 for $p_T < 3\,\mathrm{GeV/c}$ measured
- Magnitude of v_2 comparable to hadrons
- Result points to late production times of direct photons after flow is established
- Large inverse slope parameter of low p_T direct photon spectrum favours earlier production times
- Spectrum might be softer after blue-shift corrections
- Similar direct photon v_2 results seen by PHENIX

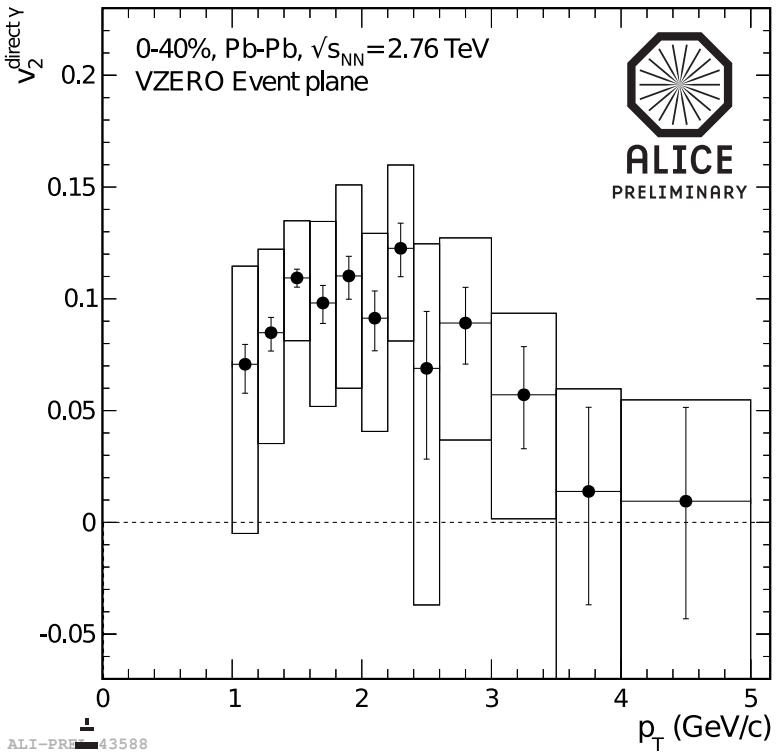


Summary - Photons and Flow

- Low p_T direct photon signal measured, exponential in shape
- $T_{ALICE} = 304 \pm 51^{\mathrm{stat+syst}}\ \mathrm{MeV}$

Measurement of Direct Photons in pp and Pb-Pb Collisions with ALICE
Nuclear Physics, Section A (2013) pp. 573-576, arXiv:1210.5958v2 [hep-ex]



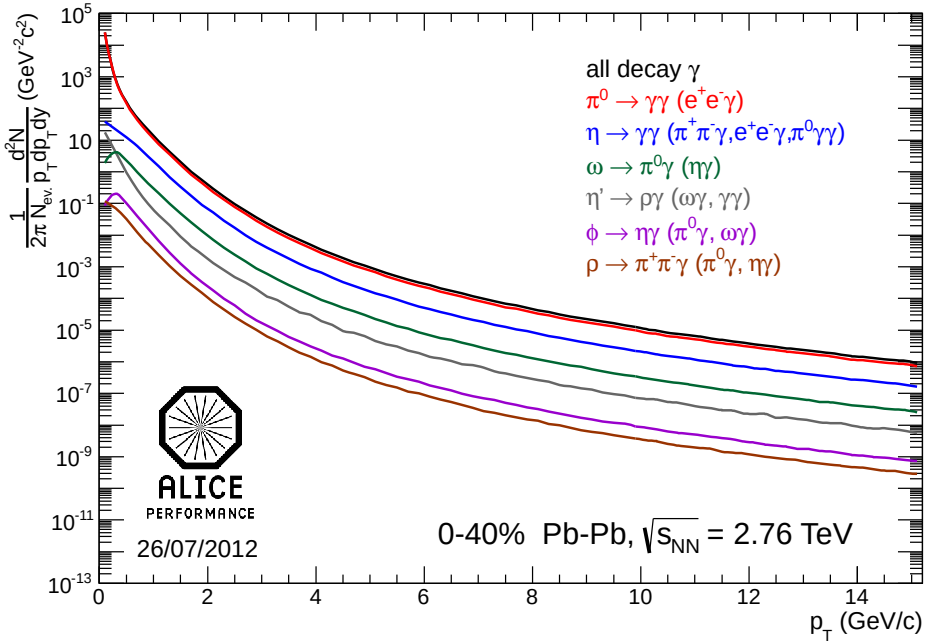


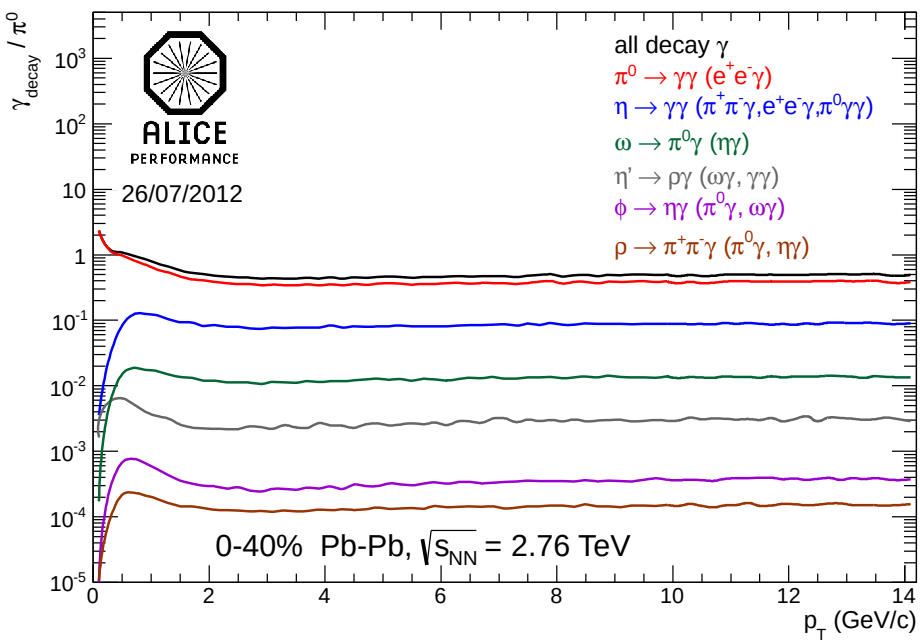
- Significant, hadron-like, direct photon v_2 for $p_T < 3\,\mathrm{GeV/c}$
- Points to late production times

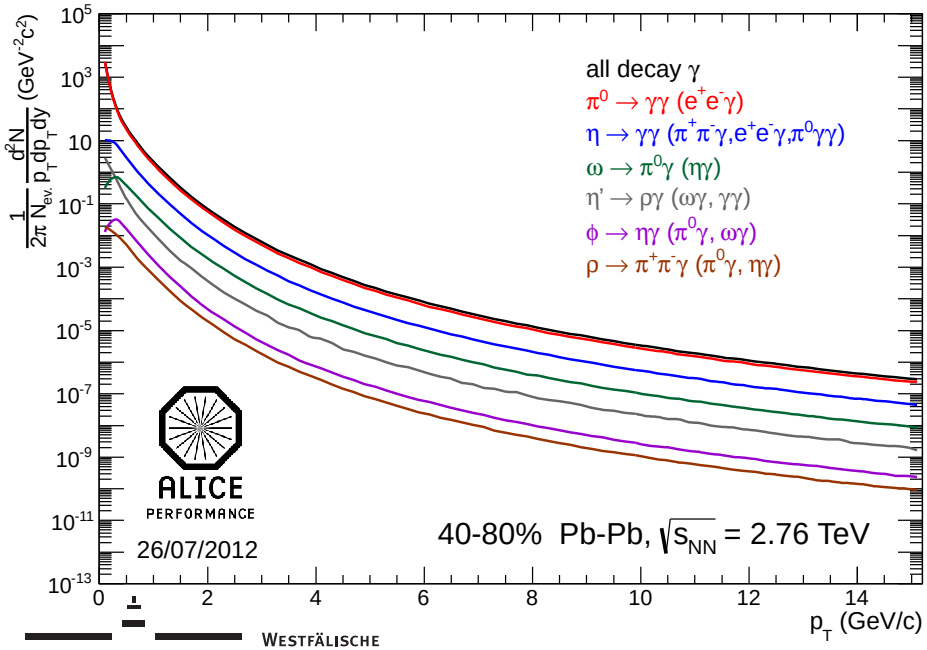
Measurement of Direct-Photon Elliptic Flow in Pb-Pb Collisions at sqrt(NN) = 2.76 TeV
arXiv:1212.3995v2 [hep-ex]

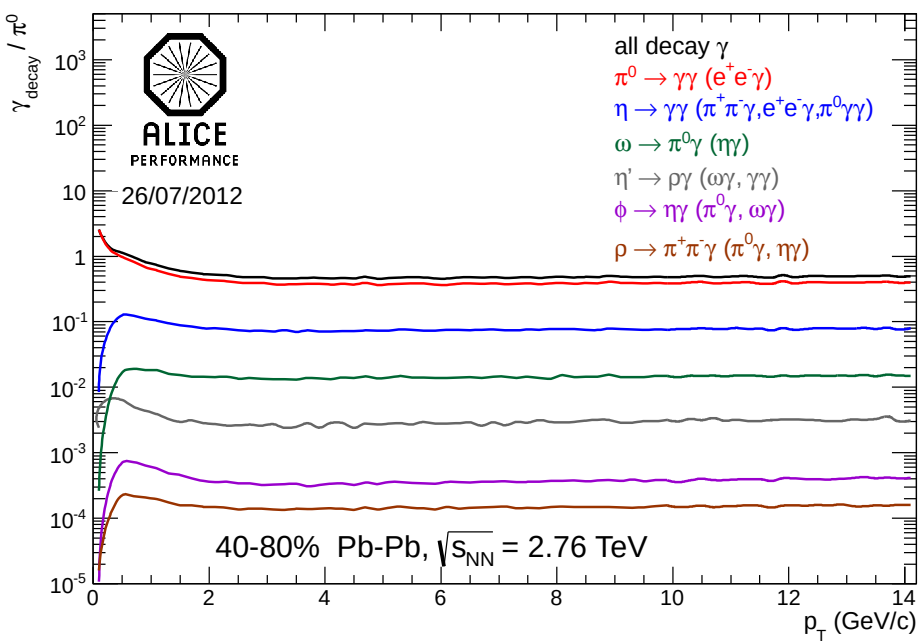
Backup Slides

Denominator Ratio: Cocktail Generator Pb-Pb Results

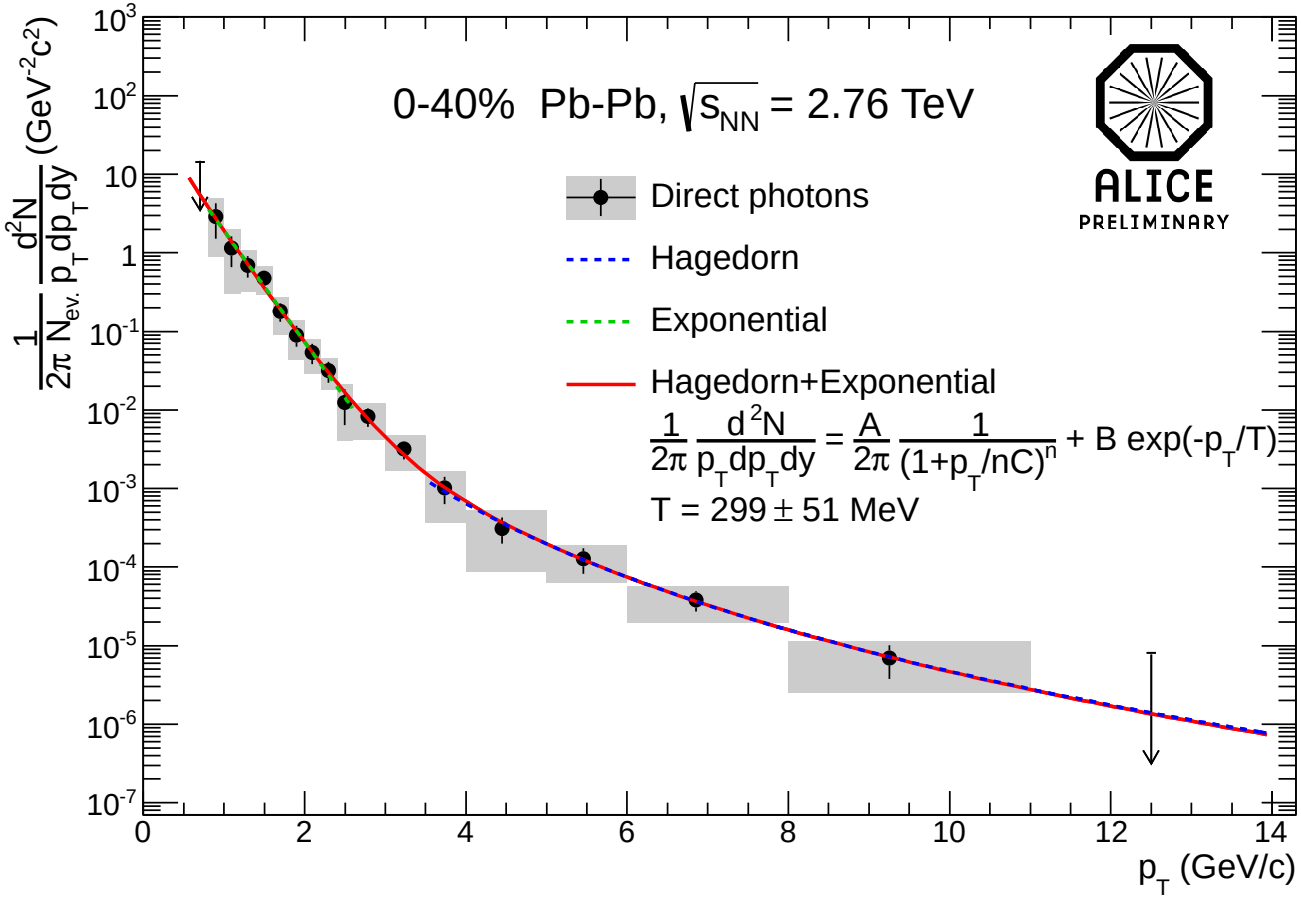








Combined Fit for Direct Photons



Combined fit (Hagedorn + Exponential) gives similar result for the inverse slope parameter T as for the exponential only fit

Systematic Cut Studies pp

- Cut Variations for γ and π^0:

Cut Name	Std. value	Variation 1	Variation 2	Variation 3
Electron dEdx	-4,5σ	-4,4σ	-3,4σ	-
Pion dEdx	1,-10σ	2,1σ	2,0.5σ	2,0.5σ
Min. p e^+/e^-	0.4 GeV/c	0.4 GeV/c	0.4 GeV/c	0.3 GeV/c
Find. Cls. TPC	0.35	0.6	-	-
Photon χ^2	20	30	10	-
q_t	0.05	0.07	0.03	-
min. p_t e^+/e^-	50 MeV/c	75 MeV/c	100 MeV/c	-
photon η, π^0 y	0.9, 0.8	0.8, 0.7	1.2, 0.9	-
min. R	5 cm - 180 cm	2.8 cm - 180 cm	10 cm - 180 cm	-

  - V0s with shared electrons rejected
  - Purity for different centralities used
  - TOF and α cut not used for pp
  - R cut already considered for material budget

- π^0 yield extraction:
  - Three different integration windows
  - Different Numbers of mixed events for bg, different mixed event bins (n V0s, n tracks)

- Cocktail simulation:
  - Two different fits
  - Variation of the m_t scaling factors (η measured)

Systematic Cut Studies Pb-Pb

- Cut Variations for γ and π^0:

Cut Name	Std. value	Variation 1	Variation 2	Variation 3
Electron dEdx	-3,5σ	-4,5σ	-2.5,4σ	-
Pion dEdx	3,-10σ	2.5,-10σ	3.5,-10σ	3,-10σ
Min. p e^+/e^-	0.4 GeV/c	0.4 GeV/c	0.4 GeV/c	0.3 GeV/c
Find. Cls. TPC	0.6	0.7	0.35	-
Photon χ^2	10	5	20	-
q_t	0.05	0.03	0.07	-
min. p_t e^+/e^-	50 MeV/c	75 MeV/c	100 MeV/c	-
photon η, π^0 y	0.75, 0.7	0.9, 0.8	0.8, 0.7	-
min. R	5 cm - 180 cm	2.8 cm - 180 cm	10 cm - 180 cm	-
α meson central	0.65	1.00	-	-
α meson peripheral	0.8	1.00	-	-
TOF	-5,-5σ	-3,-5σ	-2,-5σ	-

  - V0s with shared electrons rejected
  - Purity for different centralities used

- π^0 yield extraction:
  - Three different integration windows
  - Different Numbers of mixed events for bg, different mixed event bins (n V0s, n tracks)

- Cocktail simulation:
  - Two different fits, with and without blast wave
  - Variation of the m_t scaling factors

PHENIX Direct Photon v_2 Results