Direct photon and light neutral meson production in the era of precision physics at the LHC

Latest results from Pb–Pb and p–Pb collisions

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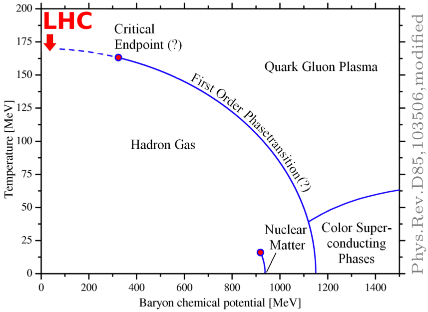
The 18th International Conference on Strangeness in Quark Matter (SQM2019)
10-15 June 2019, Bari
Session: QCD Phase Diagram and Critical Point

Why should you be interested in direct photons?



- We would like to understand the properties of the QGP
- Pb–Pb collisions at the LHC: reach QGP phase at high T and low μ

- **Photons** are created during all stages, not only at freeze-out
- They can leave the medium without further interaction ($\lambda \gg d$) $\Rightarrow$ One can look directly to higher T than with hadrons
- Measured photon p_{T} spectra and v_n are sensitive to the medium **temperature** and **collective flow** at photon production time $\rightsquigarrow$ cross check of space-time evolution and γ emission rates

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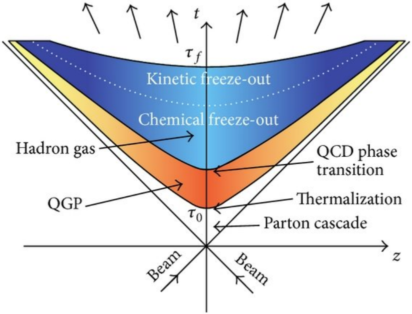


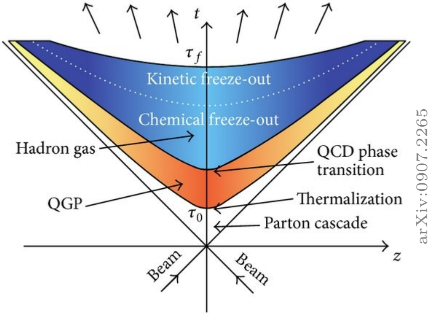
arXiv:0907.2265

Sources in AA:

- prompt photons
- jet-medium interaction ?
- pre-equilibrium photons ?
- thermal photons from QGP and hadron gas ?
- decay photons from π^0, η, ...

Why should you be interested in direct photons?

Prompt and decay photons
also in pp and pA collisions
What about thermal photons?



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Direct photon signal if

$R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} > 1$

Measure γ_{inc}, π^0, η

π^0, η, ... $\Rightarrow$ MC $\Rightarrow$ γ_{decay}

Sources in AA: Direct photons

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Sources dominate in different p_{T} regions:

power-law, $p_{\text{T}} \gtrsim 5\,\text{GeV}/c$ $\rightarrow$
calculable with pQCD

$p_{\text{T}} \lesssim 3\,\text{GeV}/c$ $\rightarrow$

$\approx$ exponential spectral shape $\propto T^2 e^{-E/T}$

Sources in AA: Direct photons

- prompt photons
- jet-medium interaction ?
- pre-equilibrium photons ?
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- decay photons from π^0, η, ...

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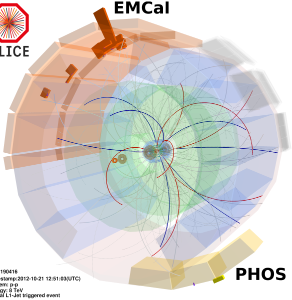
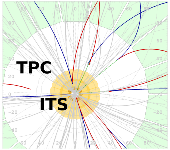
How are inclusive photons measured in ALICE?

EMCal
sampling calorimeter
$\Delta\varphi = 100^\circ$, $|\eta| < 0.7$
cells $\approx 6 \times 6\,\text{cm}^2$ at $R = 4.3\,\text{m}$

PHOS $PbWO_4$ crystals
homogeneous calorimeter
$\Delta\varphi = 60^\circ$, $|\eta| < 0.12$
cells $\approx 2.2 \times 2.2\,\text{cm}^2$, $R = 4.6\,\text{m}$
π^0 up to $p_\text{T} \approx 50\,\text{GeV}/c$





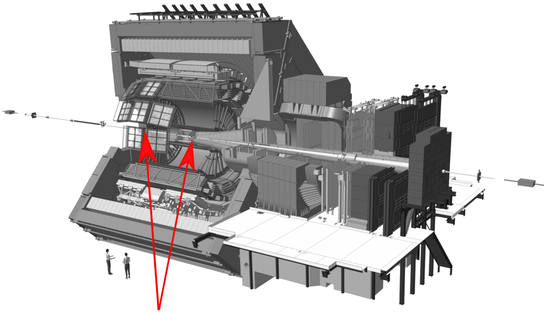
cross section

PCM
photon conversion method
$\gamma\,\text{X} \rightarrow \text{e}^+\text{e}^-\,\text{X}$ with probability $\approx 8\%$ in detector material ($R < 1.8\,\text{m}$)
tracking with ITS ($|\eta| < 2.0$) and TPC ($|\eta| < 0.9$)
π^0 down to $p_\text{T} \approx 0.3\,\text{GeV}/c$

Combination of methods to reduce errors and maximize p_T reach

How do we measure elliptic flow of direct photons?

- Inclusive photon $v_2^{\gamma,\mathrm{inc}}$ with scalar product method
  Reference particles in V0 detectors in forward direction
- Decay photon $v_2^{\gamma,\mathrm{dec}}$ from simulation based on meson v_2 measurements

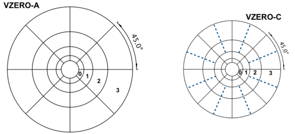


V0 detectors:

$2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$

$$v_2^{\gamma,\mathrm{inc}} = \frac{N_{\gamma,\mathrm{dir}}}{N_{\gamma,\mathrm{inc}}} \cdot v_2^{\gamma,\mathrm{dir}} + \frac{N_{\gamma,\mathrm{dec}}}{N_{\gamma,\mathrm{inc}}} \cdot v_2^{\gamma,\mathrm{dec}}$$

$$\Rightarrow v_2^{\gamma,\mathrm{dir}} = \frac{v_2^{\gamma,\mathrm{inc}} R_\gamma - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}$$

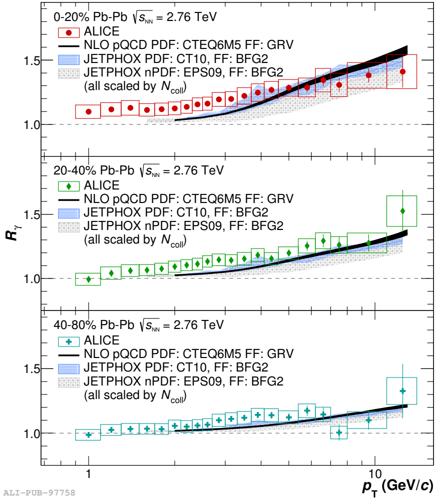


New results: Direct photon elliptic flow in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

Phys.Lett. B789 (2019) 308

Direct photon elliptic flow in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

- Need: R_γ, $v_2^{\gamma,\mathrm{inc}}$, $v_2^{\gamma,\mathrm{dec}}$ for $v_2^{\gamma,\mathrm{dir}}$
- In 0–20% centrality class: $1\,\mathrm{GeV}/c \lesssim p_\mathrm{T} \lesssim 2\,\mathrm{GeV}/c$: $\approx$ 10–15% direct photon signal with $\approx 2\sigma$
- At high p_T: pQCD calculation for prompt photons consistent with data
- $p_\mathrm{T} < 3\,\mathrm{GeV}/c$: Hint of additional photon source $\rightsquigarrow$ **thermal photons**?



Phys.Lett. B754 (2016) 235

$$R_\gamma^{\mathrm{prompt}} = 1 + N_{\mathrm{coll}} \frac{\gamma_{\mathrm{prompt}}^{\mathrm{pp,\ pQCD}}}{\gamma_{\mathrm{decay}}}$$

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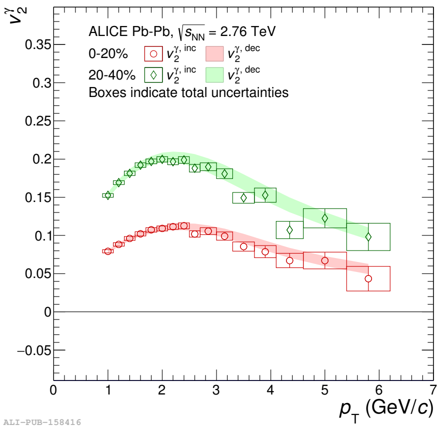
Direct photon elliptic flow in Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV

- Need: R_γ, $v_2^{\gamma,\mathrm{inc}}$, $v_2^{\gamma,\mathrm{dec}}$ for $v_2^{\gamma,\mathrm{dir}}$
- $v_2^{\gamma,0-20\%} < v_2^{\gamma,20-40\%}$
- $v_2^{\gamma,\mathrm{inc}} \approx v_2^{\gamma,\mathrm{dec}}$



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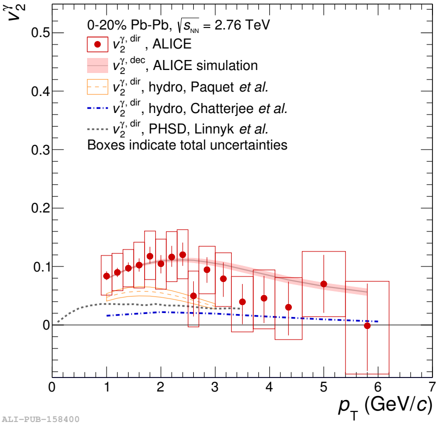
Direct photon elliptic flow in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

- At low $p_{\mathrm{T}} \lesssim 3\,\mathrm{GeV}/c$ expect
  $v_2^{\gamma,\mathrm{dir}} \approx v_2^{\gamma,\mathrm{thermal}} > 0$
- Towards higher p_{T} expect
  $v_2^{\gamma,\mathrm{dir}} \approx v_2^{\gamma,\mathrm{prompt}} = 0$
- In p_{T} region with 2σ $R_\gamma > 1$:
  $v_2^{\gamma,\mathrm{dir}} > 0$ with ≈ 1–2σ
- Models calculate v_2 within hydro or transport approach
- Within current uncertainties, **none of the models can be excluded**, but **predictions are below data**



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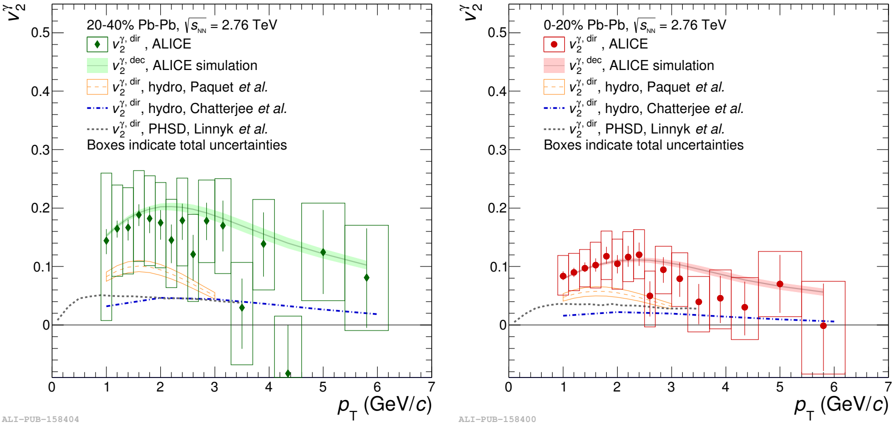
- Difficult to correctly describe direct photon yields and v_2 simultaneously

Direct photon elliptic flow in Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV



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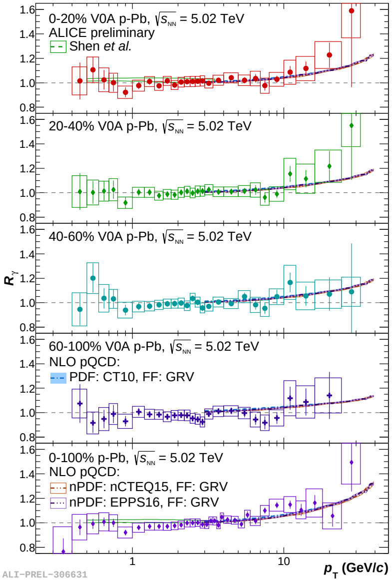
- $v_2^{\gamma,\text{thermal}}$ should be larger in 20–40% than in 0–20%
- R_γ smaller in 20–40% than in 0–20% $\Rightarrow$ larger errors
- **Observed increase of $v_2^{\gamma,\text{dir}}$ is not significant**

New results: Direct photon R_γ in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Direct photon R_γ in p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- Remember question: Do p–Pb collisions show thermal features? Can we observe $R_\gamma > 1$ at low p_T?
- Green band at low p_T: QGP and hadron gas photon thermal rates embedded in hydro model
- Current data **not yet sensitive** to predicted very small **thermal photon signal** of a few percent



Model from Phys. Rev. C 95 (2017) 014906

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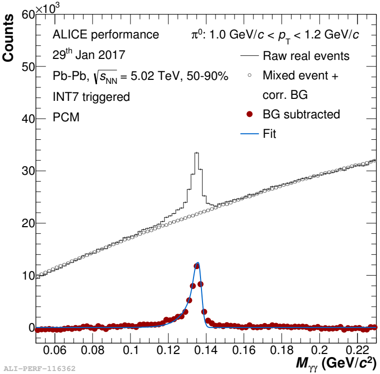
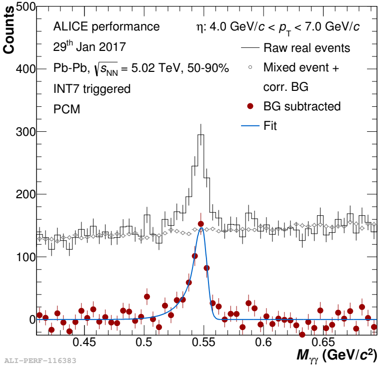
Neutral mesons in Pb–Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV

Neutral mesons in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- Remember goal: precise input for decay photon simulation; Crucial input for direct photons at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
- Measure via π^0, $\eta \to \gamma\gamma$ (invariant mass analysis)

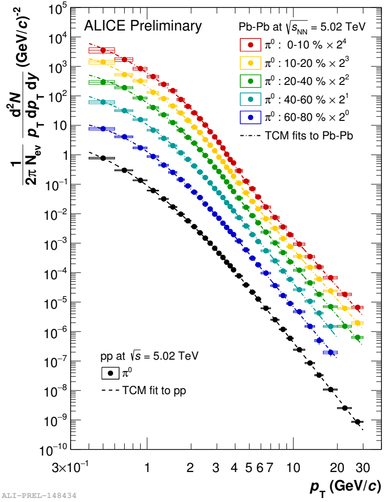


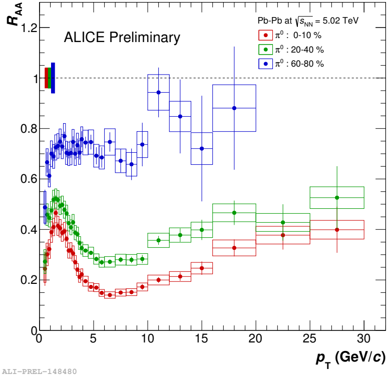
π^0



η

Neutral mesons in Pb–Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV





- Interesting to study jet quenching with identified particles at high $p_{\rm T}$

How can we reach better precision?
Statistics?

we are here ↓ long shutdown 2

LHC Run	**Run I**	**Run II**	**Run III+IV** 2021-29
Pb–Pb $\mathcal{L}_{\text{int}}^{\text{ALICE}} \approx$	$10\ \mu b^{-1}$ (pub. γ)	$1300\ \mu b^{-1}$	$13000\ \mu b^{-1}$
p–Pb $\mathcal{L}_{\text{int}}^{\text{ALICE}} \approx$	$30\ nb^{-1}$ (prel. γ)	$200\ nb^{-1}$	$600\ nb^{-1}$

arXiv:1812.06772

- **Statistical** error will be reduced by a factor ≈ 10
- Need to reduce **systematic uncertainties**
  they already dominate the total error on v_2 and R_γ over parts of the p_{T} range

How can we reach better precision?
Systematics

we are here ↓ long shutdown 2

LHC Run	Run I	Run II	Run III+IV
			2021-29

- The largest systematic uncertainty from PCM is the detector material budget uncertainty (4.5% of total ≈ 6%) which determines the conversion probability in the efficiency
  ⇝ Needs calibration with well-known material
  dedicated photon converter wires in upgraded ITS
  ALICE upgrade will be in place 2021
- Planned Pb–Pb data taking with lower B field will improve quality of low-p_{T} photons from PCM and extend p_{T} reach

Summary and conclusions

- Direct photon **elliptic flow** coefficient v_2 **in Pb–Pb** collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV consistent with current knowledge of **space-time-evolution** and **photon emission rates**
  $\rightsquigarrow$ Smaller errors needed to confirm or exclude model predictions
- **Direct photon** R_γ in **p–Pb** $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  $\rightsquigarrow$ not yet sensitive to predicted very small thermal photon signal
- **Light neutral mesons** were measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  $\rightsquigarrow$ crucial input for direct photon measurement
  $\rightsquigarrow$ study jet quenching with identified particles
- **Statistical errors** will be significantly reduced in Run II measurements (analysis ongoing) and future Run III and IV analyses
- **Systematic errors** need to, and can be reduced (new analysis techniques, ALICE upgrade for LHC Run III)

ALICE

backup

Effective averaged medium temperature

- Production rate depends on the medium temperature:
  $r_\gamma(E,T) \propto T^2 e^{-E/T}$
- blue-shift due to radial flow
  $T_{\text{eff}} = \sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}} \cdot T$
- averaged over time
- Inverse slope $\Rightarrow \langle T_{\text{eff}} \rangle$
- Measurements from ALICE and PHENIX:
  exponential spectral shape with $T_{\text{eff}}^{\text{LHC}} > T_{\text{eff}}^{\text{RHIC}}$
  due to higher T and/or stronger radial flow

Phys.Rev. C 89 (2014) 044910

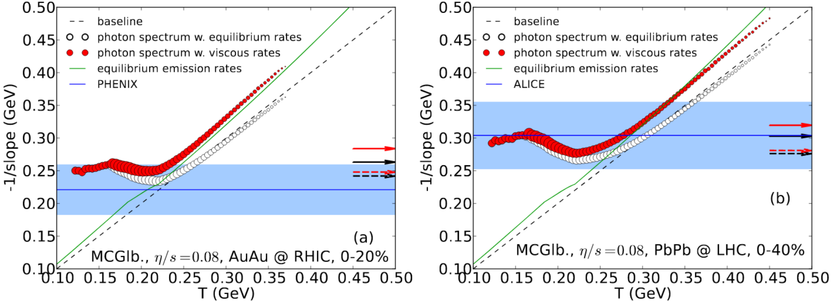
$T_{\text{eff}}^{\text{RHIC}} = (221 \pm 19^{\text{stat}} \pm 19^{\text{syst}})$ MeV

Phys.Rev.Lett. 104 (2010) 132301

$T_{\text{eff}}^{\text{LHC}} = (297 \pm 12^{\text{stat}} \pm 41^{\text{syst}})$ MeV

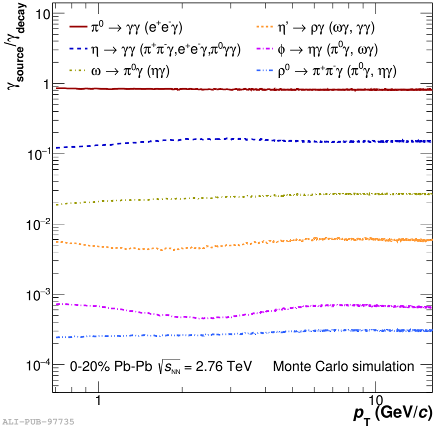
Phys.Lett. B754 (2016) 235

Effective averaged medium temperature



Phys. Rev. C 89, 044910 (2014)

Cocktail simulation



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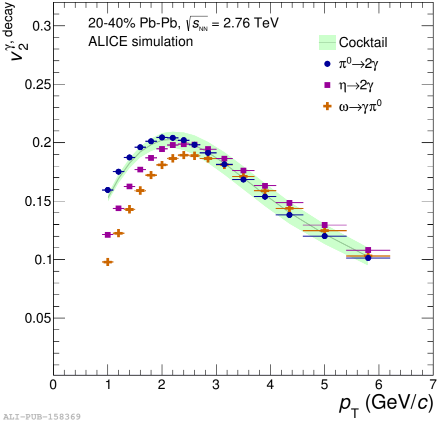


Phys.Lett. B789 (2019) 308

Cocktail simulation

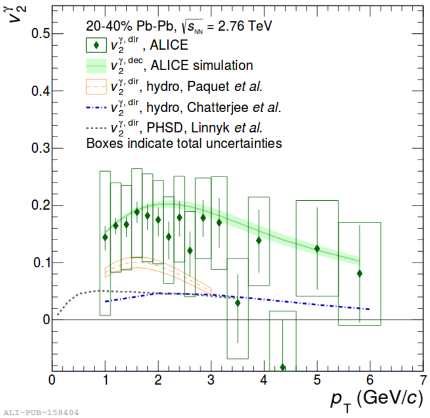
decay photon yields

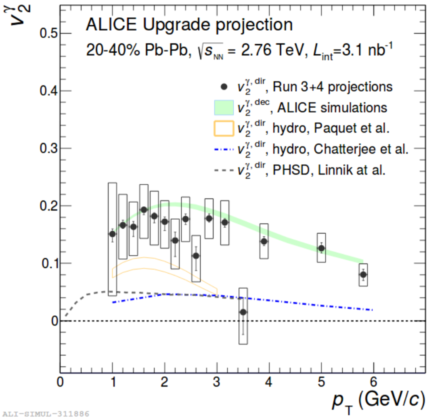
- π^0 measured via $\gamma\gamma$ then parametrized
- measured η in p–Pb, not enough statistics in Pb–Pb
- η from m_T scaling of π^0 from scaling of p_T spectra from K^0_s (similar mass, similar radial flow)
- η/π^0 ratio fixed to reproduce measured value at $p_\mathrm{T} > 5\,\mathrm{GeV}/c$ in $\sqrt{s_\mathrm{NN}} = 200\,\mathrm{GeV}/c$
- ω from m_T scaling of π^0

decay photon v_2

- π^0 v_2 from charged pion v_2 measured under the same conditions
- η and ω from charged and neutral kaons with KE_T scaling

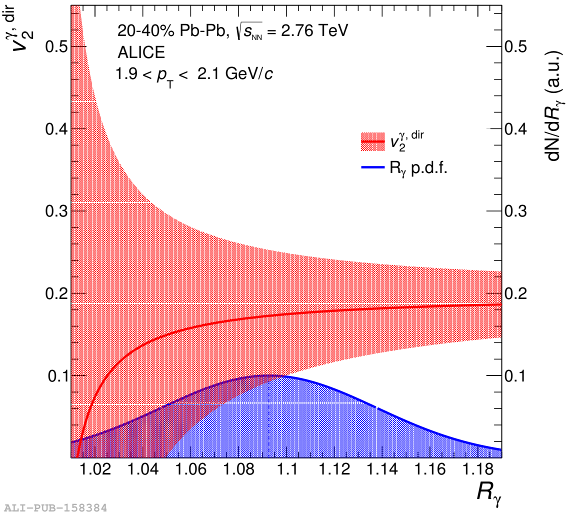
Upgrade projections





arXiv:1812.06772

Elliptic flow uncertainties



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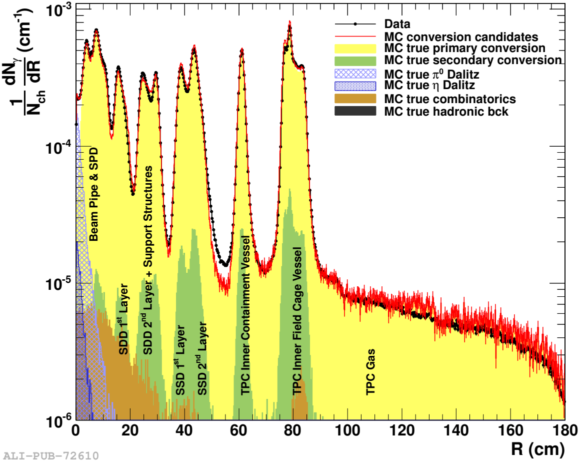
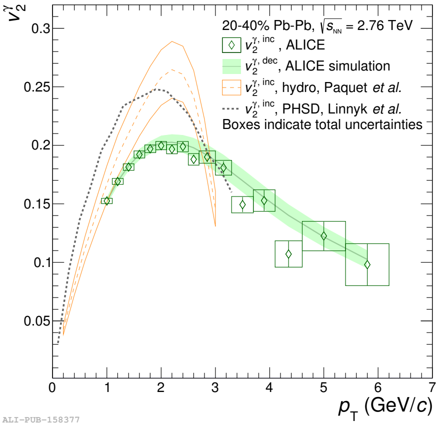
Material budget uncertainty



arXiv:1402.4476

$$v_2 = \sqrt{\frac{\left\langle\left\langle \vec{u}_2 \cdot \frac{\vec{Q}_2^{A*}}{M_A} \right\rangle\right\rangle \left\langle\left\langle \vec{u}_2 \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle\right\rangle}{\left\langle \frac{\vec{Q}_2^{A}}{M_A} \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle}}$$

Inclusive photon v_2



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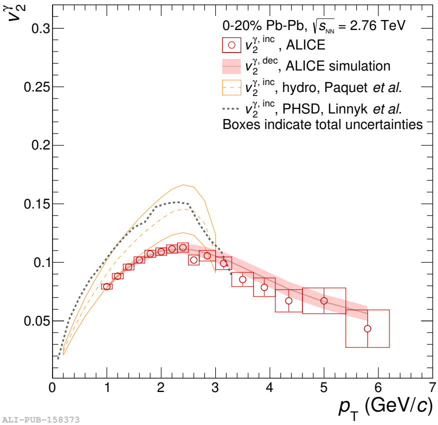

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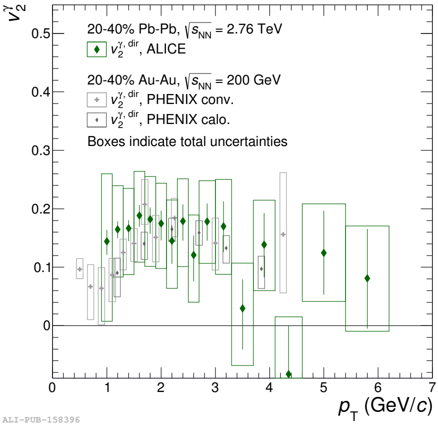
v_2 comparison to PHENIX results



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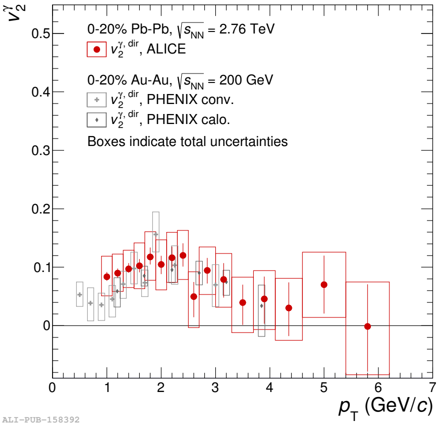

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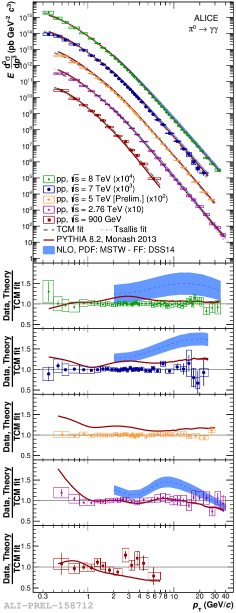
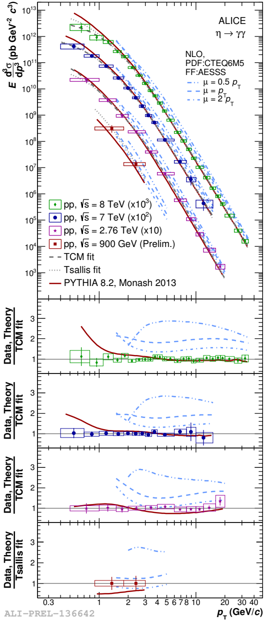

ALICE
$\pi^0 \rightarrow \gamma\gamma$
pp, $\sqrt{s}$ = 8 TeV (x10^4)
pp, $\sqrt{s}$ = 7 TeV (x10^3)
pp, $\sqrt{s}$ = 5 TeV [Prelim.] (x10^2)
pp, $\sqrt{s}$ = 2.76 TeV (x10)
pp, $\sqrt{s}$ = 900 GeV
TCM fit
Tsallis fit
PYTHIA 8.2, Monash 2013
NLO, PDF: MSTW - FF: DSS14
$E\frac{d^3\sigma}{dp^3}$ (pb GeV^{-2} c^3)
Data, Theory / TCM fit
p_T (GeV/c)
ALI-PREL-158712


ALICE
$\eta \rightarrow \gamma\gamma$
NLO,
PDF:CTEQ6M5
FF:AESSS
$\mu = 0.5\ p_T$
$\mu = p_T$
$\mu = 2\ p_T$
pp, $\sqrt{s}$ = 8 TeV (x10^3)
pp, $\sqrt{s}$ = 7 TeV (x10^2)
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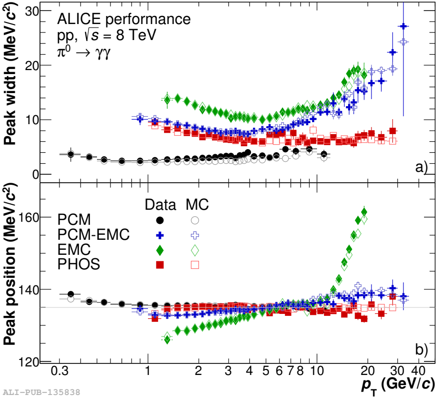
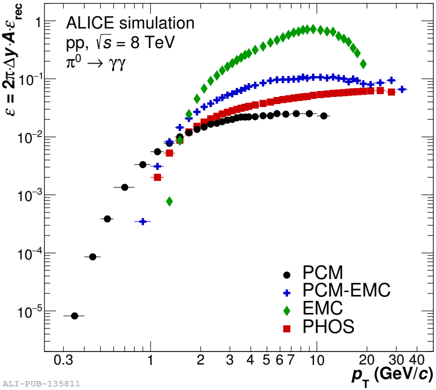
$E\frac{d^3\sigma}{dp^3}$ (pb GeV^{-2} c^3)
Data, Theory / TCM fit
Data, Theory / Tsallis fit
p_T (GeV/c)
ALI-PREL-136642

Complementarity of the methods





Eur. Phys. J. C (2018) 78: 263

Complementarity of the methods