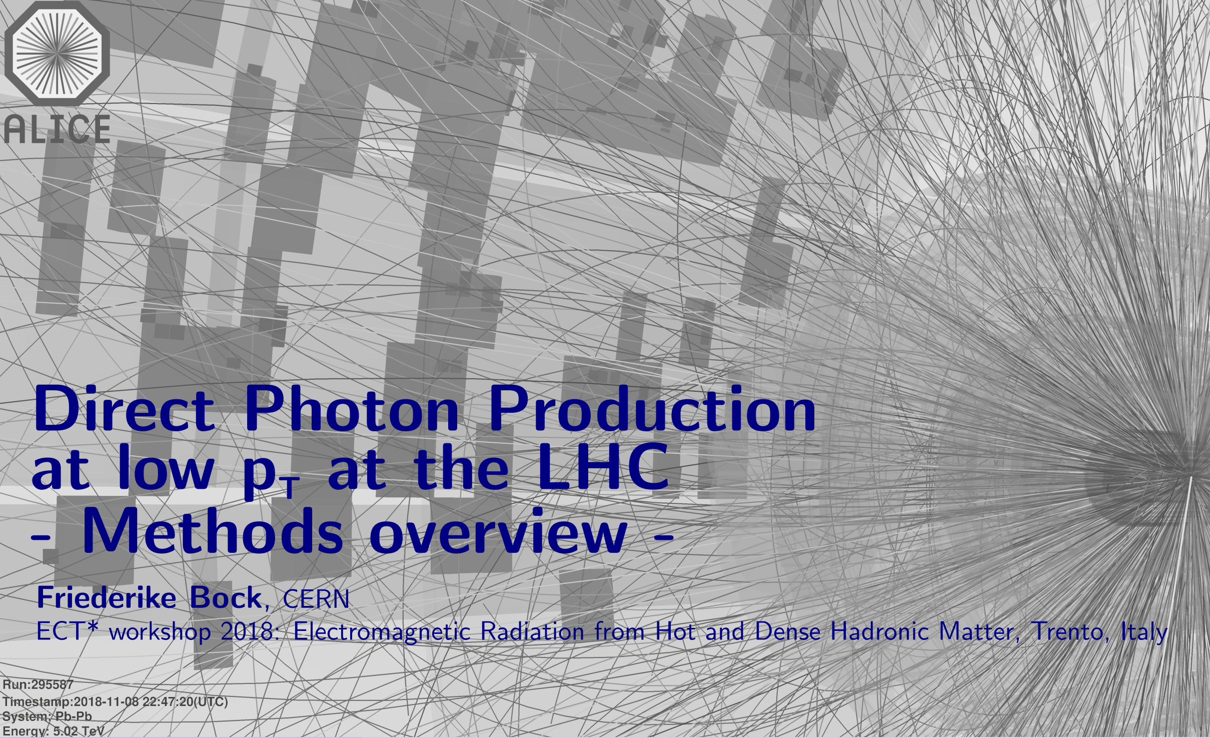


Direct Photon Production at low p_T at the LHC - Methods overview -

Friederike Bock, CERN

ECT* workshop 2018: Electromagnetic Radiation from Hot and Dense Hadronic Matter, Trento, Italy

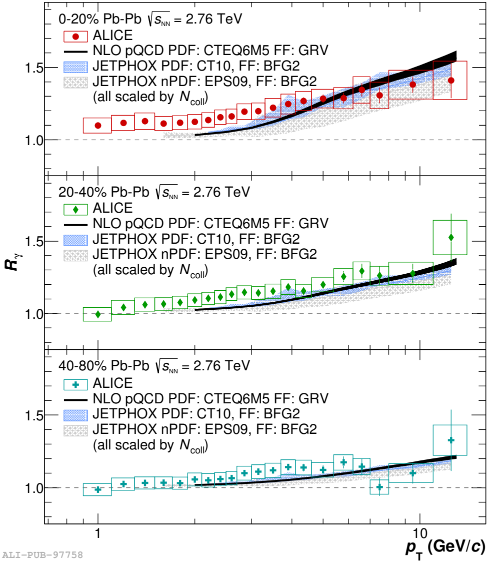
Experimental Definition of Photon Excess in ALICE

Experimental definition of Direct Photons:

- Every photon which is not directly produced by: π^0, η, ω, η', ϕ, $\rho^{0,\pm}$ and Σ^0, Δ, Λ
- Decay photons simulated via a cocktail calculation based on measured yield of π^0 (Pb–Pb, p-Pb, pp) and η (p-Pb, pp), remaining spectra are obtained from m_T scaling of measured π^0, K, p etc. (if not measured)

Experimental measurement of π^0:

- Published π^0 measurements contain feed-down from higher mass particles going to π^0, except π^0 from K^0_s & Λ
- Measured spectra are taken as input for cocktail calculation



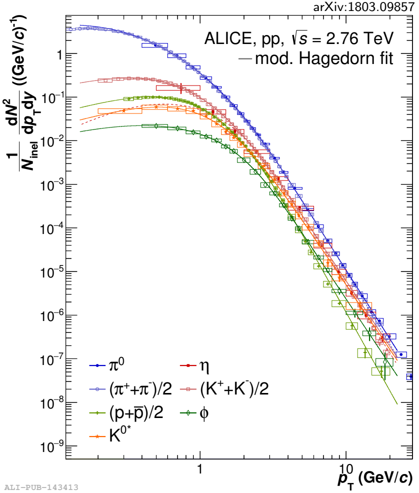
Direct Photon Extraction

Subtraction Method:

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

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

- Inclusive photons: measure all photons that are produced
- Decay photons: calculated by decay simulation from measured or m_T scaled particle spectra



Double Ratio:

$$R_\gamma = \frac{\gamma_{\text{inc}}}{\pi^0} \bigg/ \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}} \quad \text{if } > 1 \text{ direct photon signal}$$

Numerator: Measured inclusive γ spectrum per π^0 Denominator: Estimated sum of all decay photons per π^0

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

Cocktail Generation

Decay photon spectra are obtained via calculation

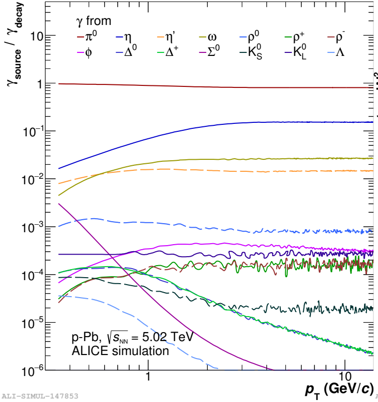
- Based on a fit to measured π^0 (Pb–Pb, pp) and η (pp)
- Other particle spectra obtained via m_{T}-scaling of measured π^0, K, p
- Incorporated mesons: π^0, η, η', ω, ϕ, ρ_0, $\rho_{\pm}$, (K^0_S, K^0_L) and baryons: Σ^0, $\Delta^{0,+}$, (Λ)

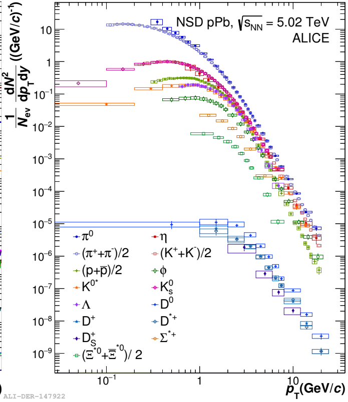
m_T-Scaling:

arXiv:1710.01933

Same shape of cross sections, $f(m_{\mathrm{T}})$, of various mesons

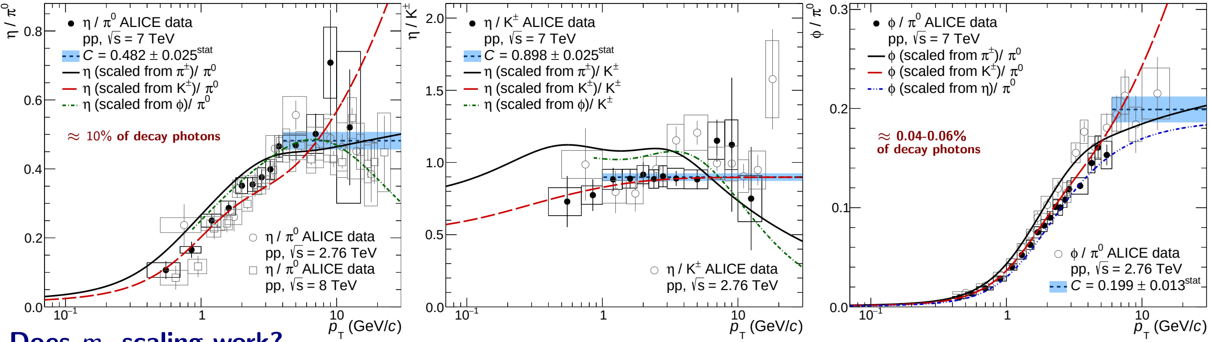
$$E\frac{d^3\sigma_m}{dp^3} = C_m \cdot f(m_{\mathrm{T}})$$





Meson (C_m)	meas.	Mass	Decay Branch	B. Ratio
π^0	pp, p–Pb Pb–Pb	134.98	$\gamma\gamma$ $e^+e^-\gamma$	98.82% 1.174%
η (0.48)	pp, p–Pb Pb–Pb	547.3	$\gamma\gamma$ $\pi^+\pi^-\gamma$ $e^+e^-\gamma$	39.21% 4.22% 0.69%
ρ^0 (1.0)	pp	770.0	$\pi^+\pi^-\gamma$ $\pi^0\gamma$ $\eta\gamma$	0.99% 0.06% 0.03%
$\rho^{\pm}$ (1.0)		775.49	$\pi^{\pm}\gamma$	0.045%
ω (0.9)	pp	781.9	$\pi^0\gamma$ $\eta\gamma$	8.5% 0.46%
η' (0.25)		957.8	$\rho^0\gamma$ $\omega\gamma$ $\gamma\gamma$	29.08% 2.75% 2.20%
ϕ (0.35)	pp, p–Pb Pb–Pb	1019.5	$\eta\gamma$ $\pi^0\gamma$ $\pi^0\pi^0\gamma$	1.31% 0.125% 0.013%
Λ (1.0)		1115.68	$n\gamma$	0.084%
Σ^0 (1.0)		1192.6	$\Lambda\gamma$	100%
Δ^0 (1.0)		1232.0	$n\gamma$	0.6%
Δ^+ (1.0)		1232.0	$n\gamma$	0.6%

Test of Assumptions for Cocktail



arXiv:1710.01933

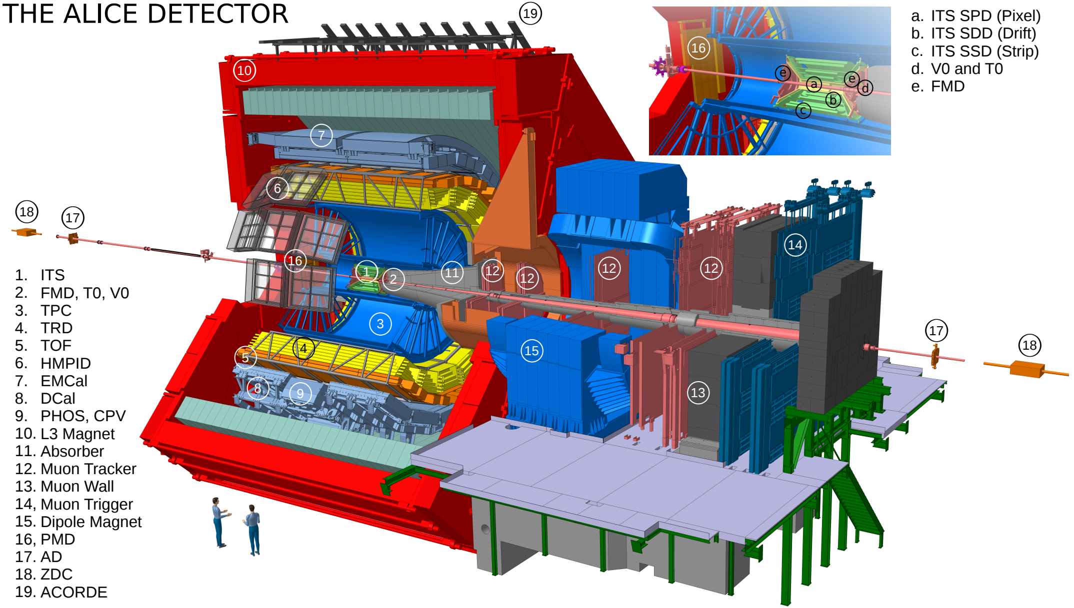
Does m_T-scaling work?

- For many collision systems and energies only π^0 spectrum measured, is this a good baseline?
  $\rightarrow$ Probably not.
- m_T-scaling from π^0 overestimates yield at low p_T due to resonance contributions in π^0 spectrum,
- Collective flow in Pb–Pb collisions modifies shape of spectra additionally $\rightarrow$ stronger deviation at low p_T

What can we improve?

- Check ratio's (η/π^0, ω/π^0, ϕ/π^0, ...) in which p_T-regime m_T-scaling from π^0 is applicable
- Never use mesonic baseline to obtain baryon spectra
- Find measured meson with less affected by feed down to use as scaling baseline

THE ALICE DETECTOR

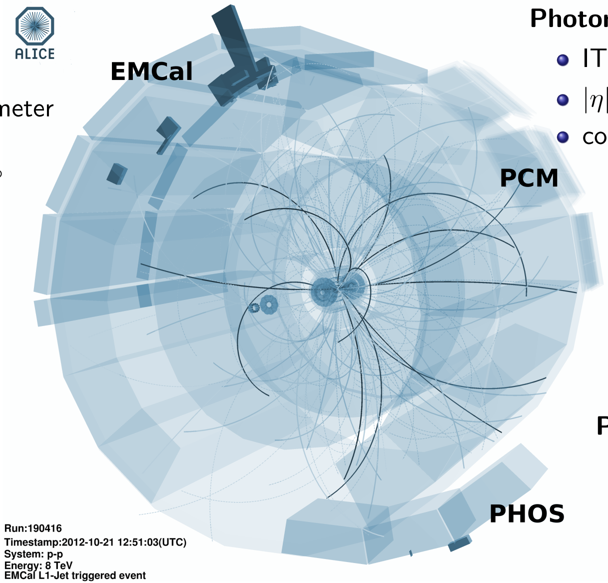


a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

EMCal calorimeter

- Pb/scintillator sampling calorimeter
- $|\eta| < 0.7$, $80° < \varphi < 180°$



Photon Conversion Method (PCM)

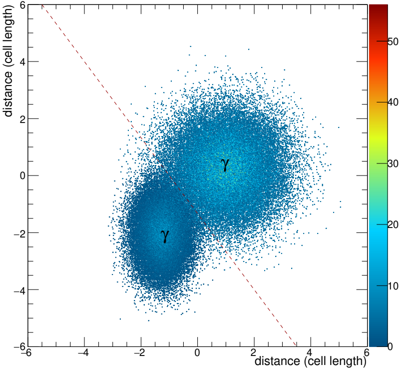
- ITS and TPC
- $|\eta| < 0.9$, $0° < \varphi < 360°$
- conversion in detector material
  - $X/X_0 = (11.4 \pm 0.5)\%$
  - conv. probability $\sim 8\%$

PHOS calorimeter

- $PbWO_4$ crystals
- $|\eta| < 0.12$, $260° < \varphi < 320°$ (2009-2013)

Calorimetric Photon Reconstruction

- Energy deposit in calorimeter reconstructed in clusters
- Basic cluster quality selections (N_{cells}, timing, minimum E deposit)
- Limited hadron vs. electron vs. photon discrimination possible via
  - Shower Shape (elongation along long σ^2_{long} or short axis σ^2_{short})
  - Energy Dispersion
  - Charged particle track veto or matching (E/p)
- Purity and type of contamination strongly dependent on selection criteria & granularity of calorimeter and cluster energy



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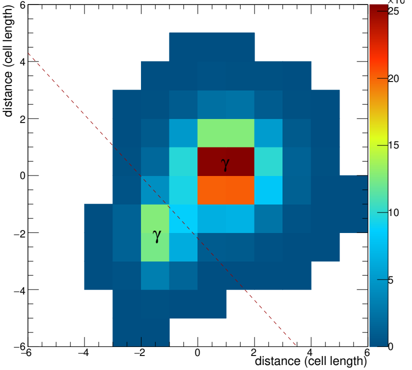

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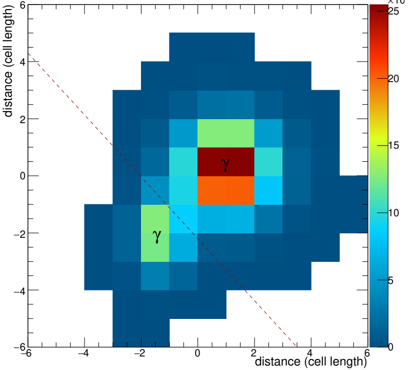
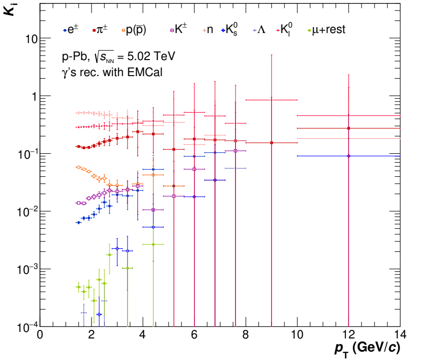
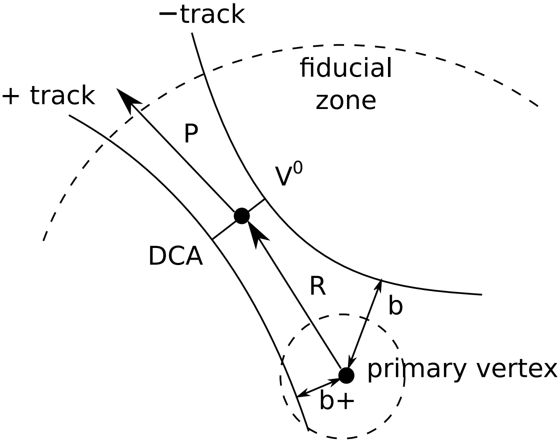




Conversion Photon Reconstruction I

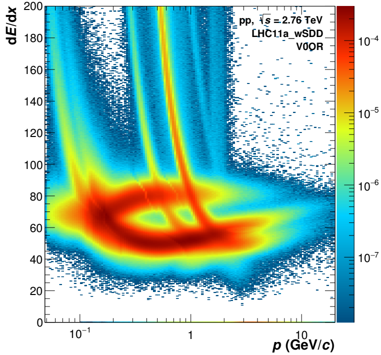
Secondary Vertex Algorithm - V0 Particles

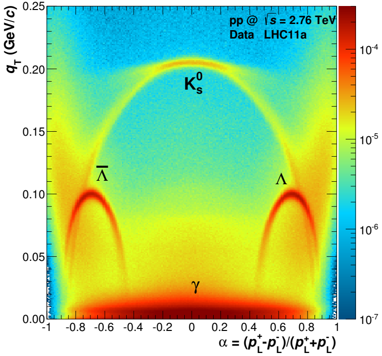
- Charged tracks with large impact parameter are paired
- Candidates with a small DCA (distance of closest approach) $\rightarrow$ V0 candidate
- Most abundant particle species: K^0_s, Λ, $\bar{\Lambda}$ or γ
- Photon conversion probability in $|\eta| < 0.9$ up to $R = 180\,\mathrm{cm}$ saturates at $\approx 8\%$



Conversion Photon Reconstruction II

How do you select photons when working with conversions?



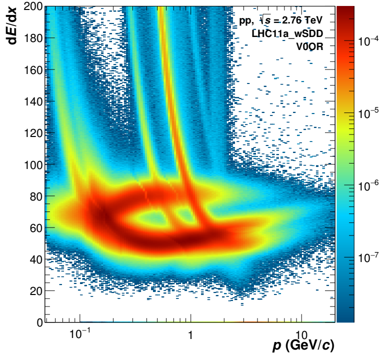


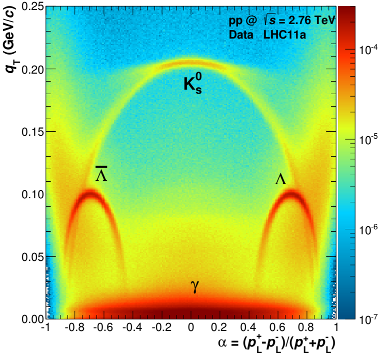
Conversion Photon Reconstruction II

How do you select photons when working with conversions?

Depends on detector capabilities

- PID to select electrons (dE/dx, time of flight, transition radiation, energy deposit in the calorimeter)
- Properties of the rec. photon (χ^2, angles between electrons and photon and beam)





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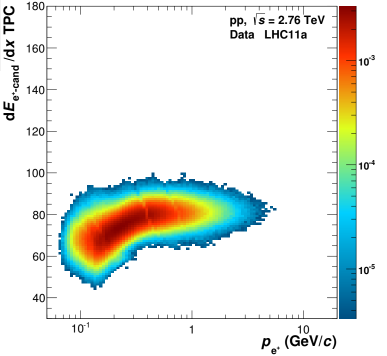
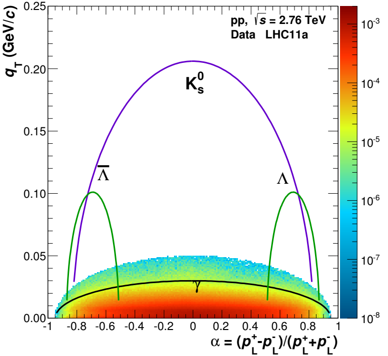


How clean do you have to be?



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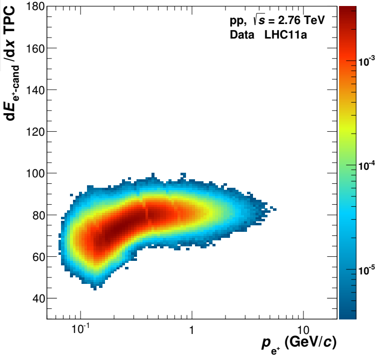
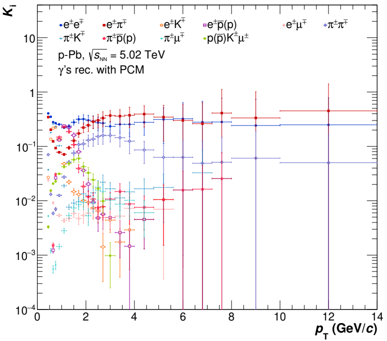
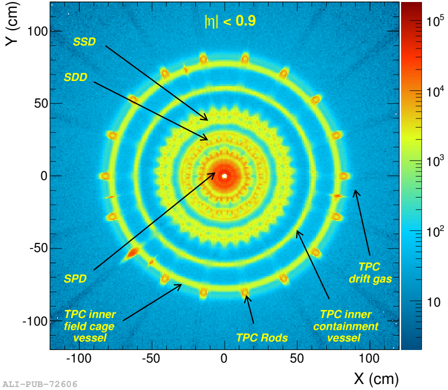


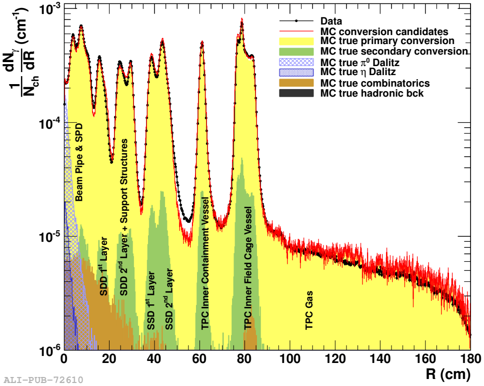


How clean do you have to be?

Depends on property you want to measure & signal strength!

γ - Ray Tomography of ALICE



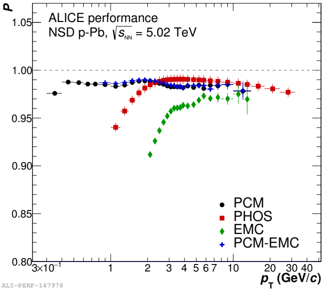


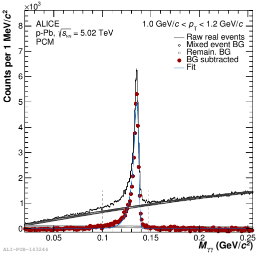
Performance of the ALICE Experiment at the CERN LHC
arXiv:1402.4476 [nucl-ex]

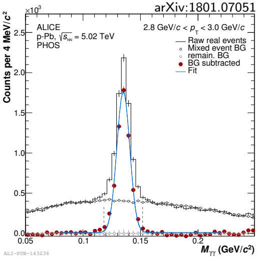
- Cuts on the decay topology of photons and electron track properties
- Background is mainly combinatorial - Strange particle contribution negligible

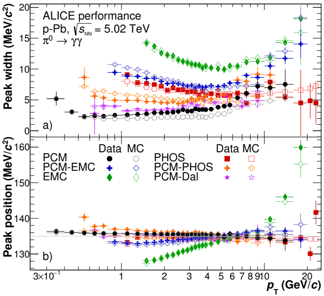
- Very useful tool to check the material budget:
  - Effective radiation length: $X/X_0 = 0.114 \pm 0.005$ $(|\eta| < 0.9, R < 180\ \mathrm{cm})$
  - Current systematic error is $\sim 4.5\%$

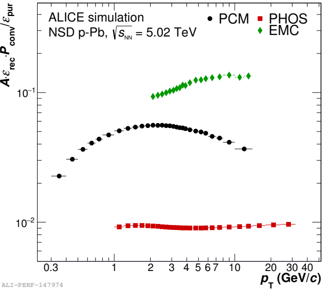
Measuring Photons, π^0 and η Mesons: Example MB p-Pb

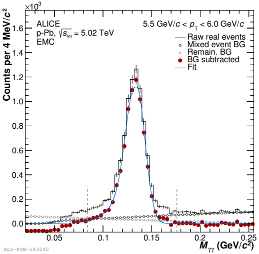


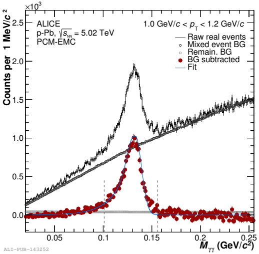


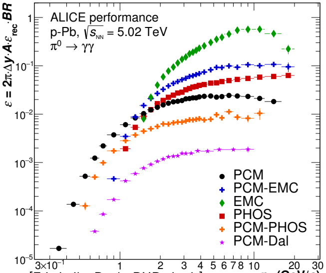












[Friederike Bock, PHD thesis]

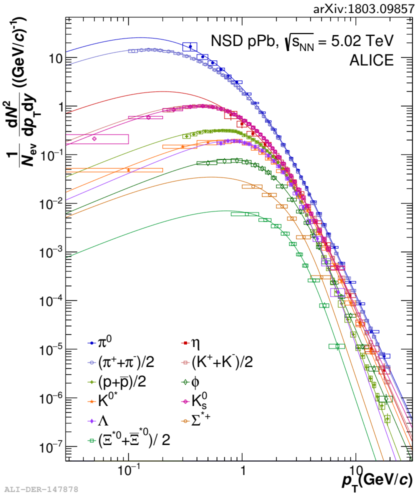
Direct Photon Extraction - Reminder

Subtraction Method:

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

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

- Inclusive photons: measure all photons that are produced
- Decay photons: calculated by decay simulation from measured or m_{T} scaled particle spectra



Double Ratio:

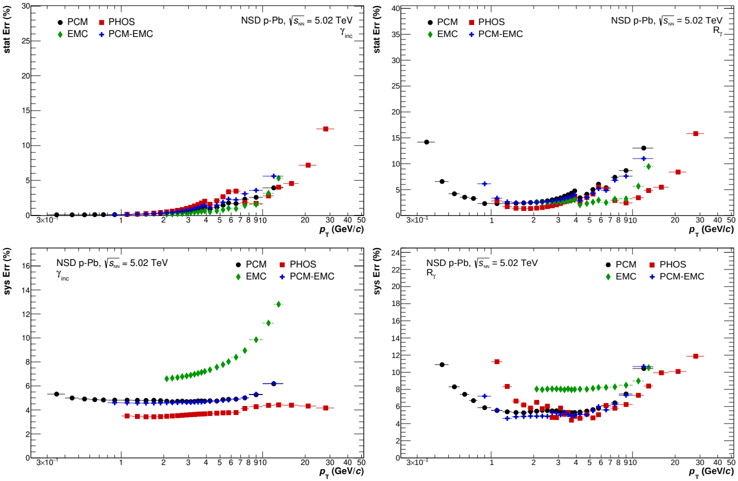
$$R_\gamma = \frac{\gamma_{\text{inc}}}{\pi^0} \Big/ \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}} \quad \text{if} > 1 \text{ direct photon signal}$$

Numerator: Measured inclusive γ spectrum per π^0 Denominator: Estimated sum of all decay photons per π^0

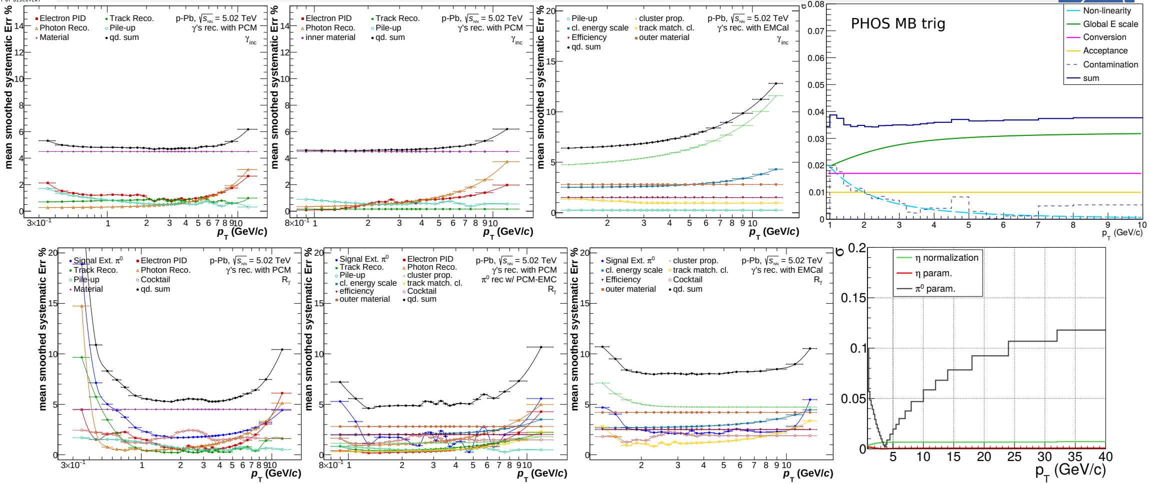
$\rightarrow$ advantage of ratio method: cancellation of some large uncertainties

Systematic and Statistical uncertainties

- Systematics evaluated on corrected γ_{inc} yield or R_γ directly
- Evaluation done via cut variations on analysis cuts (always at least one tighter and one more open cut) and comparison of variation to standard cut
- Systematics were smoothed to remove unwanted statistical fluctuations
- Material budget uncertainties for PCM and EMCal are 4.5% and 2.8% respectively and therefore dominant contributors



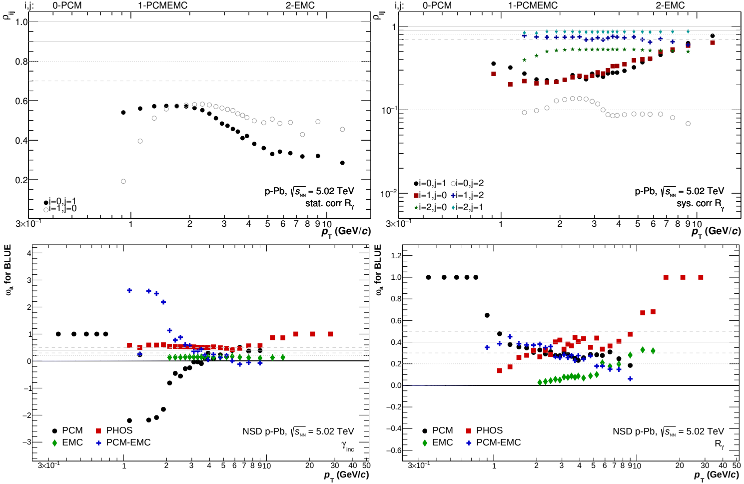
Detailed Systematics p-Pb MB



PCM	PCM-EMC	EMC	PHOS
inner mat. budget: 4.5%, pile-up: 3-4%, π^0 yield: 1.5-2.5%, $e^{\pm}$&γ PID: 1-2%	pile-up: 3-4%, outer mat. budget: 2.0%, cl. properties: 2.5%, π^0 yield: 2%, cl. energy scale: 2%	outer mat. budget: 3.0%, efficiency: 2.6%, cl. energy scale: 2%, π^0 yield: 1.4%, cl. properties: 1.3%	cl. energy scale: 3.0%, outer mat. budget: 1.8%, MC-corrections: 1%, π^0 yield: 1-5%, cl. properties: 1%

Combination of Results in p-Pb MB

- For the combination not only systematic correlation but also statistical correlations among measurements need to be taken into account
- Correlation factors for both have been calculated and then results are combined using BLUE-method, where the binning agrees with the chosen common binning



1 L. Lyons, D. Gibaut, and P. Clifford, *How to Combine Correlated Estimates of a Single Physical Quantity*, Nucl.Instrum.Meth. A270 (1988) 110.

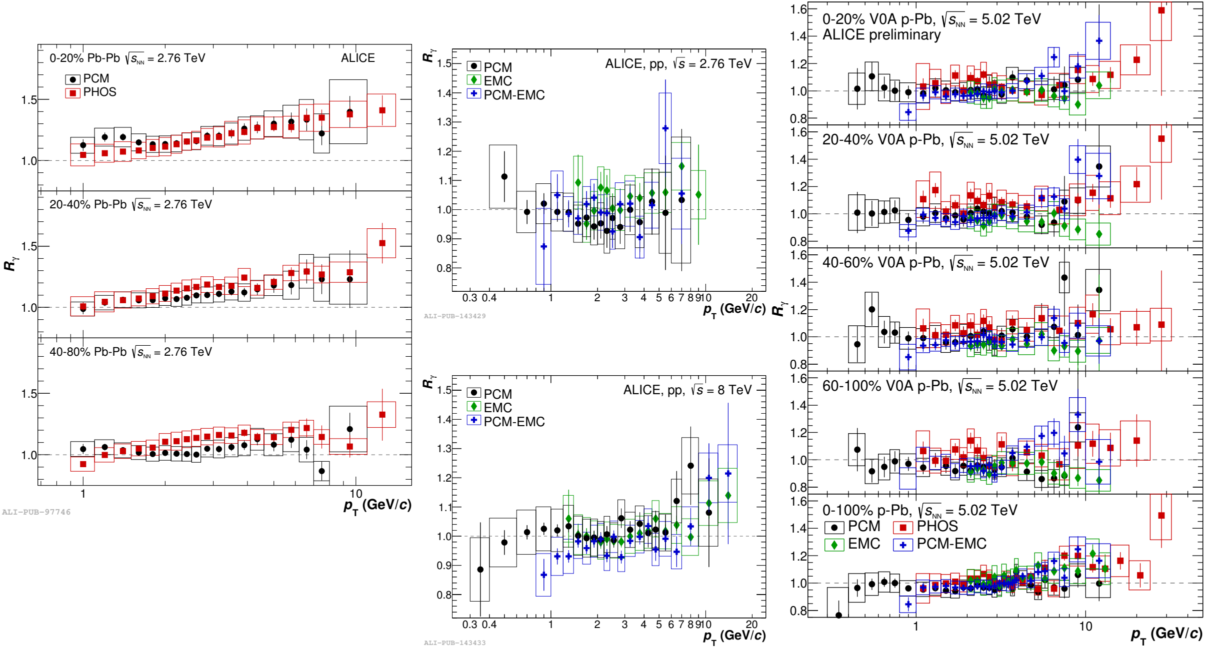
2 A. Valassi, *Combining correlated measurements of several different physical quantities*, Nucl.Instrum.Meth. A500 (2003) 391–405.

3 L. Lyons, *Statistics for nuclear and particle physicists*, Cambridge, Uk: Univ. Pr., 1986.

4 R. J. Barlow, *Statistics: a guide to the use of statistical methods in the physical sciences*, John Wiley & Sons, 1989.

5 A. Valassi and R. Chierici, *Information and treatment of unknown correlations in the combination of measurements using the BLUE method*, Eur.Phys.J. C74 (2014) 2717, arXiv:1307.4003.

Compilation of Different Individual Measurements



Direct Photon Flow

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

- $R_\gamma \cdot v_2^{\text{inc }\gamma}$: 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 Method

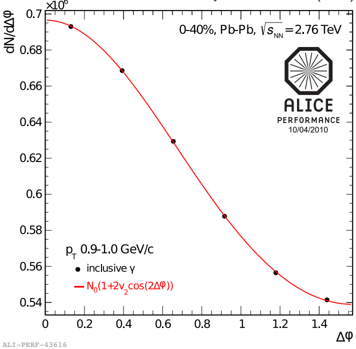
Initial azimuthal asymmetry in coordinate space in non-central A+A
$\Rightarrow$ asymmetry in momentum space

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

v_2 given by photon production with respect to event plane

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

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



Event Plane Method (prel.):

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

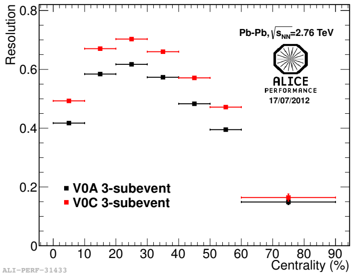
Resolution correction for EP:

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

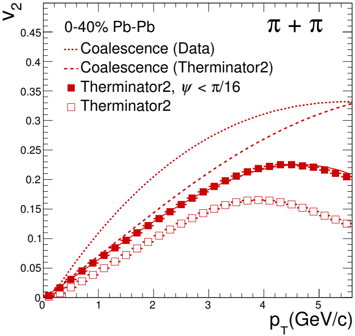
Scalar Product Method (publ.):

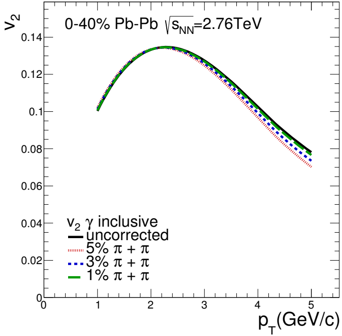
$$\vec{Q}_n = \sum_{i=1}^{N} w_i e^{ni\varphi_i},$$

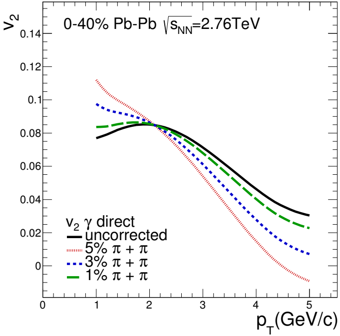
$$v_n = \sqrt{\frac{\langle \vec{u}_n^{\,A} \cdot \frac{\vec{Q}_n^{B}}{M_B}\rangle \langle \vec{u}_n^{\,A} \cdot \frac{\vec{Q}_n^{C}}{M_C}\rangle}{\langle \frac{\vec{Q}_n^{B}}{M_B} \cdot \frac{\vec{Q}_n^{C}}{M_C}\rangle}}$$

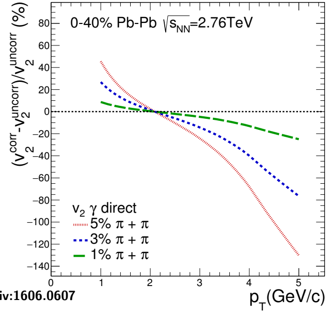


Impact of non photonic backgrounds on $\nu_{2,\gamma_{dir}}$





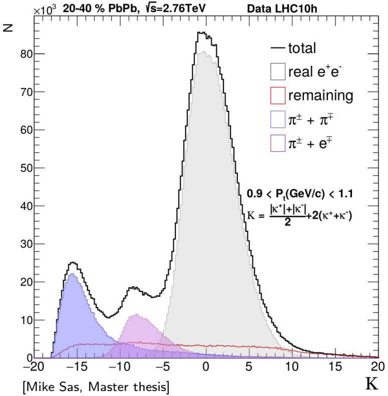




arXiv:1606.0607

- Impurities in PCM photons could cause strong biases
- Simple requirement of $\pi^+\pi^-$ in Therminator creates huge ν_2
- What's the ν_2 of $\pi^\pm e^\mp$, $\pi^+\pi^-$, ... in real data?
- How good are our purity estimates from the MC ?

A Data-Driven Purity Estimate



[Mike Sas, Master thesis]

- Combine σ to electron dE/dx expectation ($\kappa^{\pm}$) on both legs to one discriminator (**K**)

$$\mathbf{K} = \frac{|\kappa^{+}| + |\kappa^{-}|}{2} + 2(\kappa^{+} + \kappa^{-})$$

- Data and simulation don't show same purity
  Different combinatorics in MC and data, need to correct for that
- Possibility to measure ν_2 in different regions of **K** and construct BG ν_2 from separate components

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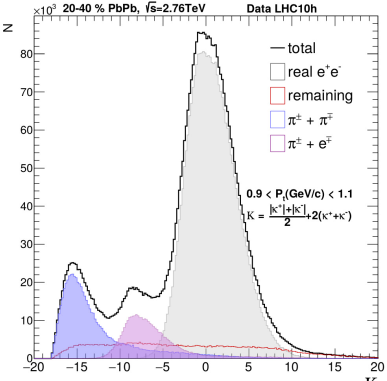

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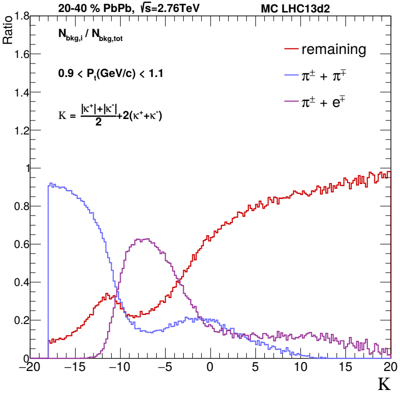

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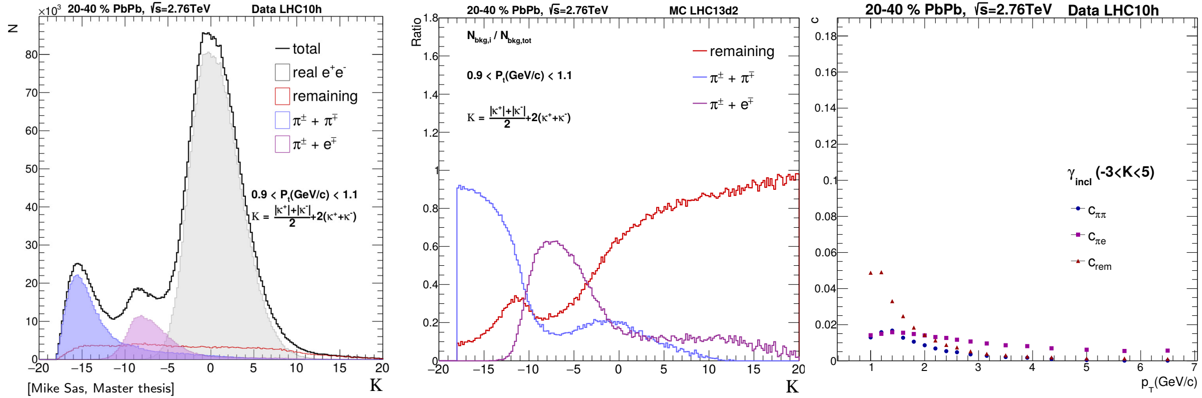

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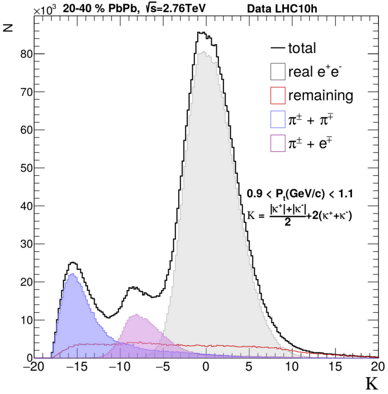
Non Photonic Background Flow

[Mike Sas, Master thesis]



- Assumption: ν_2 independent of **K** for single component (i.e. $\nu_2^{\pi\pi}$)
- Use different **K** regions to measure single components
- Construct non photonic BG flow in signal region from respective fractions and ν_2 of components
- Significant non photonic BG flow seen, similar or larger than single hadron flow
  $\Rightarrow$ correction needed to $v_2^{\gamma^{\rm inc}}$ taking into account c_i

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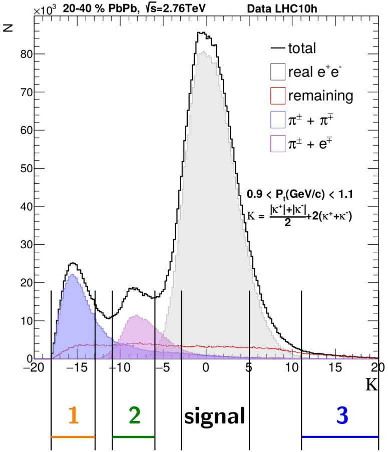
[Mike Sas, Master thesis]



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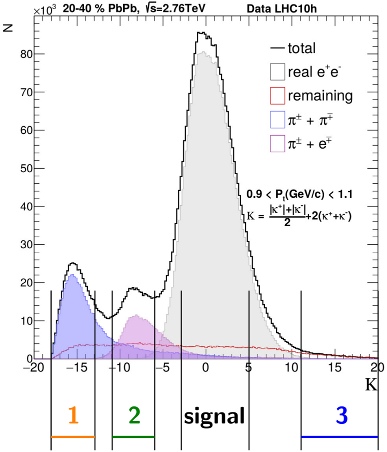

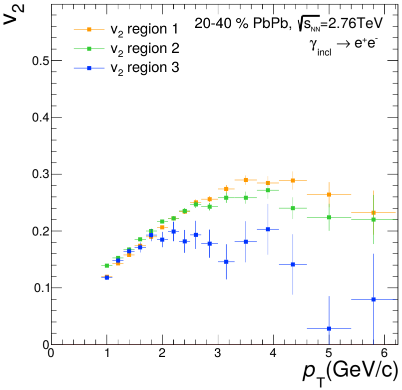

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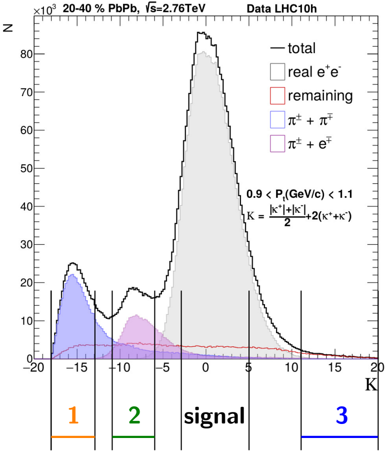

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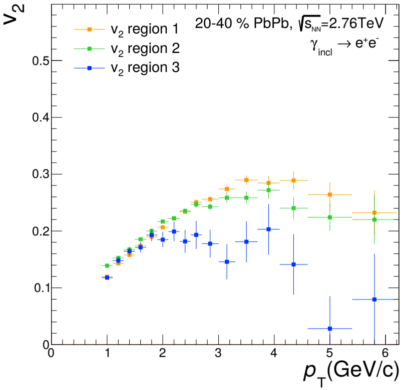

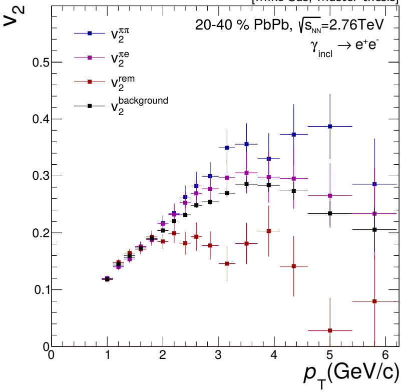

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Backup Slides

Decay photon v_2:

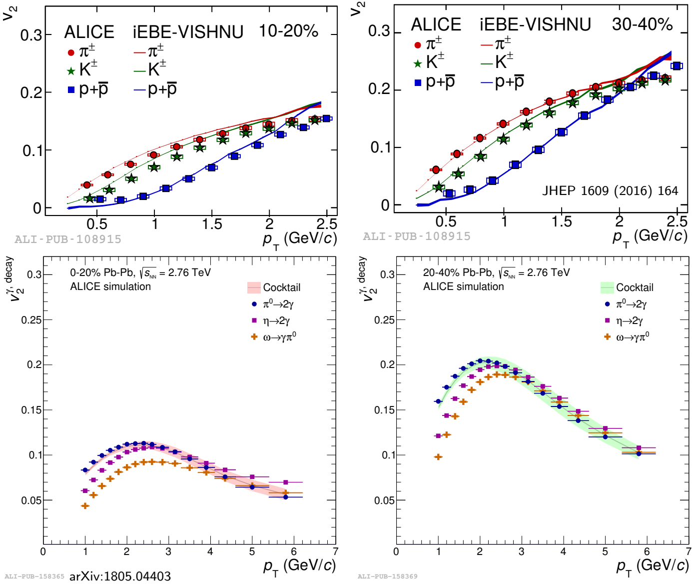
- KE_T scaling: v_2 of mesons scales with KE_T
  $KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$

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

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

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

- Decay photon v_2 from different mesons obtained from cocktail calculation



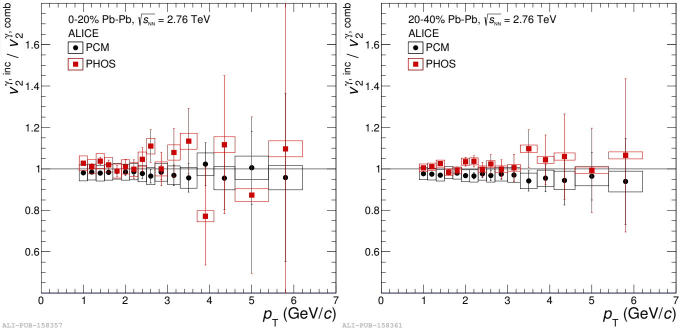
v_2^{γ} Inclusive and Decay

- $v_2^{\gamma,\mathrm{inc}}$ measured with PCM & PHOS

$\rightarrow$ Corrected for BG flow from impurities
[JPG 44 (2917) no. 2, 025106]

$\rightarrow$ Assumed to be independent

$\rightarrow$ Consistent, p-values of
0.93 (0-20%) & 0.43 (20-40%)



arXiv:1805.04403

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- $\mathbf{p_T < 3\ GeV/}c\mathbf{:\ v_2^{\gamma,inc} = v_2^{\gamma,dec}}$

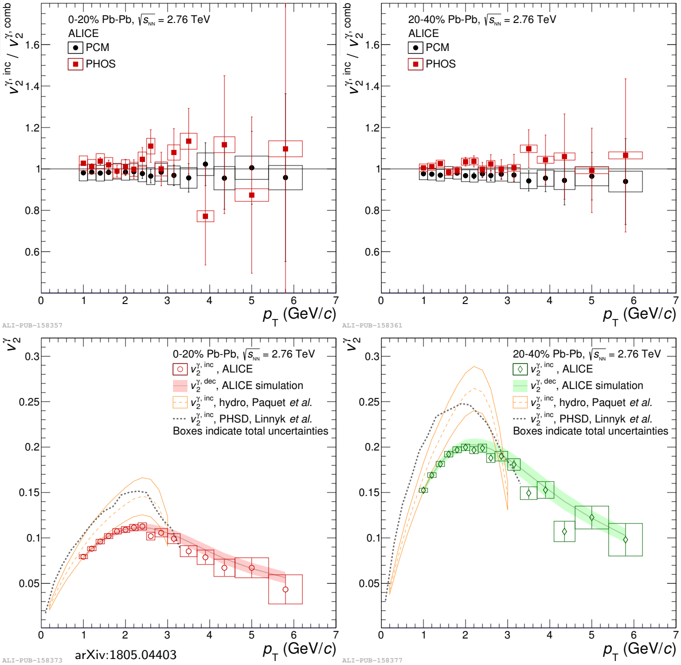
$\Rightarrow$ Either no contribution of γ_{dir}
or $v_2^{\gamma,\mathrm{inc}} \approx v_2^{\gamma,\mathrm{dec}}$

$\rightarrow$ Theory $\sim 30-40\%$ too high

- $\mathbf{p_T > 3\ GeV/}c\mathbf{:\ v_2^{\gamma,inc} < v_2^{\gamma,dec}}$

$\rightarrow$ Direct photon v_2 contribution with
$v_2^{\mathrm{direct}} < v_2^{\mathrm{decay}}$

$\rightarrow$ Mainly prompt photons



Direct Photon v_2 0-20 & 20-40

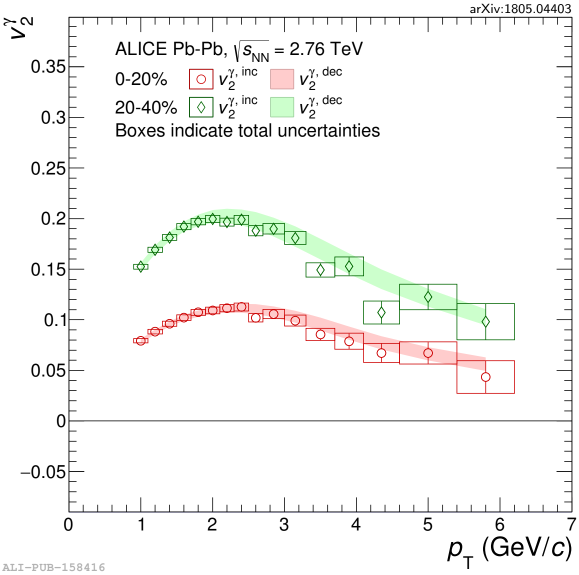
Direct photon v_2:

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

- Measured R_γ often less than $2\sigma_{\mathrm{sys}}$ deviation from 1

⇒ Central value & unc. calculated using MC simulation following Bayesian approach with probability distributions of true values of $R^{\mathrm{t}}_\gamma(p_\mathrm{T})$, $v_2^{\gamma,\mathrm{dec,t}}(p_\mathrm{T})$, $v_2^{\gamma,\mathrm{inc,t}}(p_\mathrm{T})$ assuming R_γ can't be smaller unity & partially $p_\mathrm{T}$correlated unc.

- Large direct photon v_2 for $p_\mathrm{T} < 3$ GeV/c measured
- Magnitude of $v_2^{\gamma,\mathrm{dir}}$ comparable to hadrons
- Result points to late production times of direct photons after flow is established



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