Direct Photon Results from ALICE and the Direct Photon Puzzle

Ab initio approaches in many-body QCD confront heavy-ion experiments
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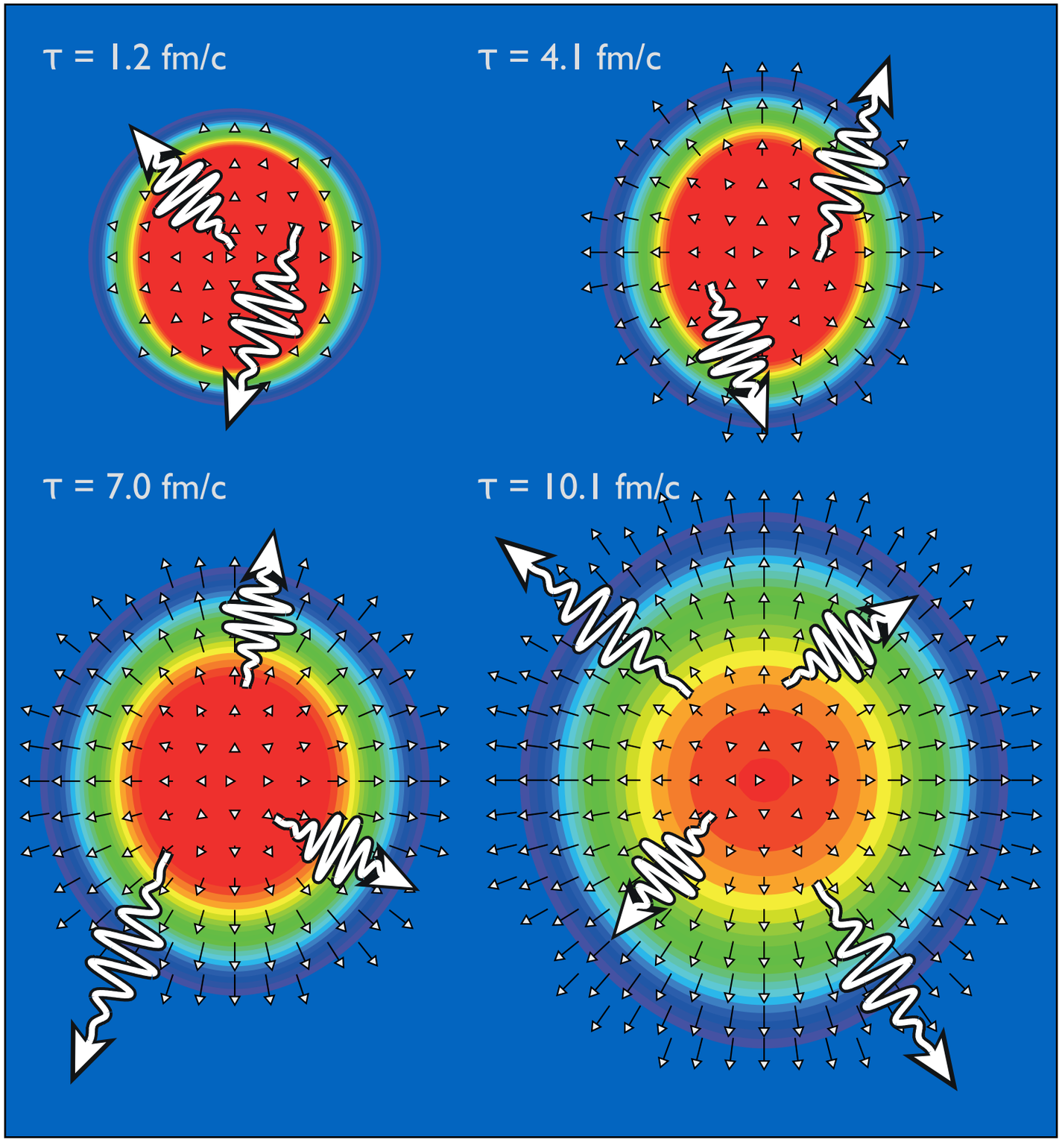
The Role of Direct Photons in Heavy-Ion Physics

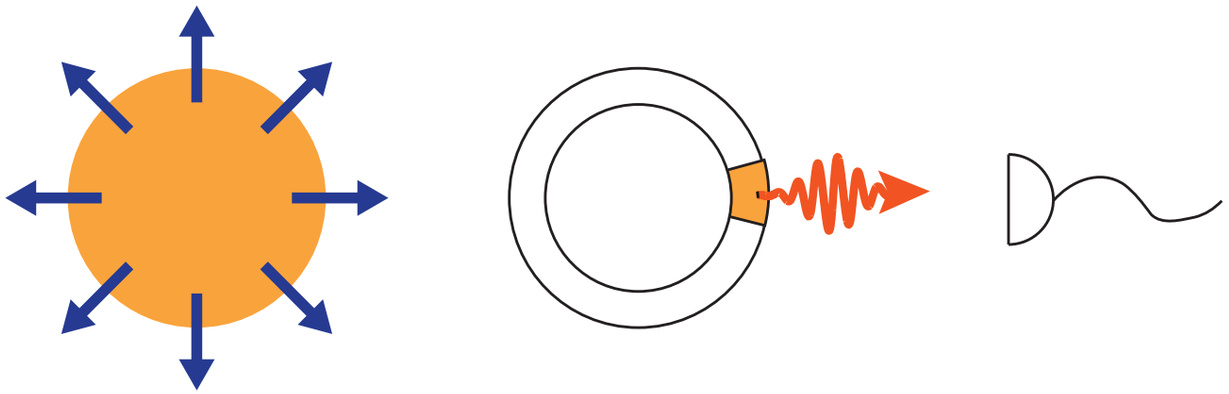


- Escape medium unscathed
- Produced during all stages
  → test of the hydro paradigm
- Experimental access to initial QGP temperature (?)

QGP photon rate (lowest order):

$$E\gamma \frac{dN\gamma}{d^3p} \propto \alpha\alpha_s T^2 e^{-E_\gamma/T} \log \frac{E_\gamma T}{k_c^2}$$

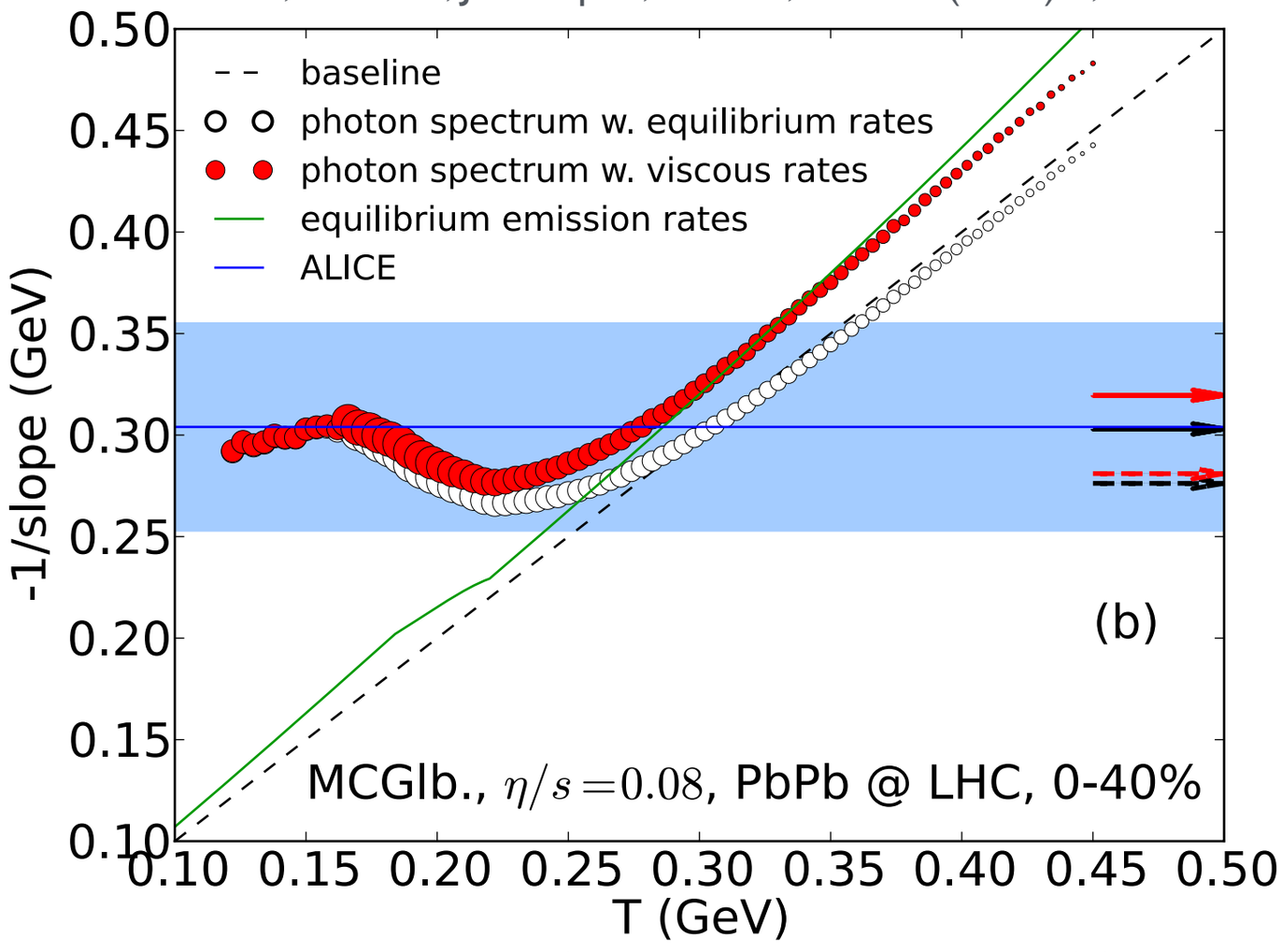
A Complication for the Temperature Measurement: Blueshift due to Radial Flow



$$E_\gamma \frac{\mathrm{d}^3 N_\gamma}{\mathrm{d}^3 p_\gamma} \propto e^{-E_\gamma / T_{\mathrm{eff}}}$$

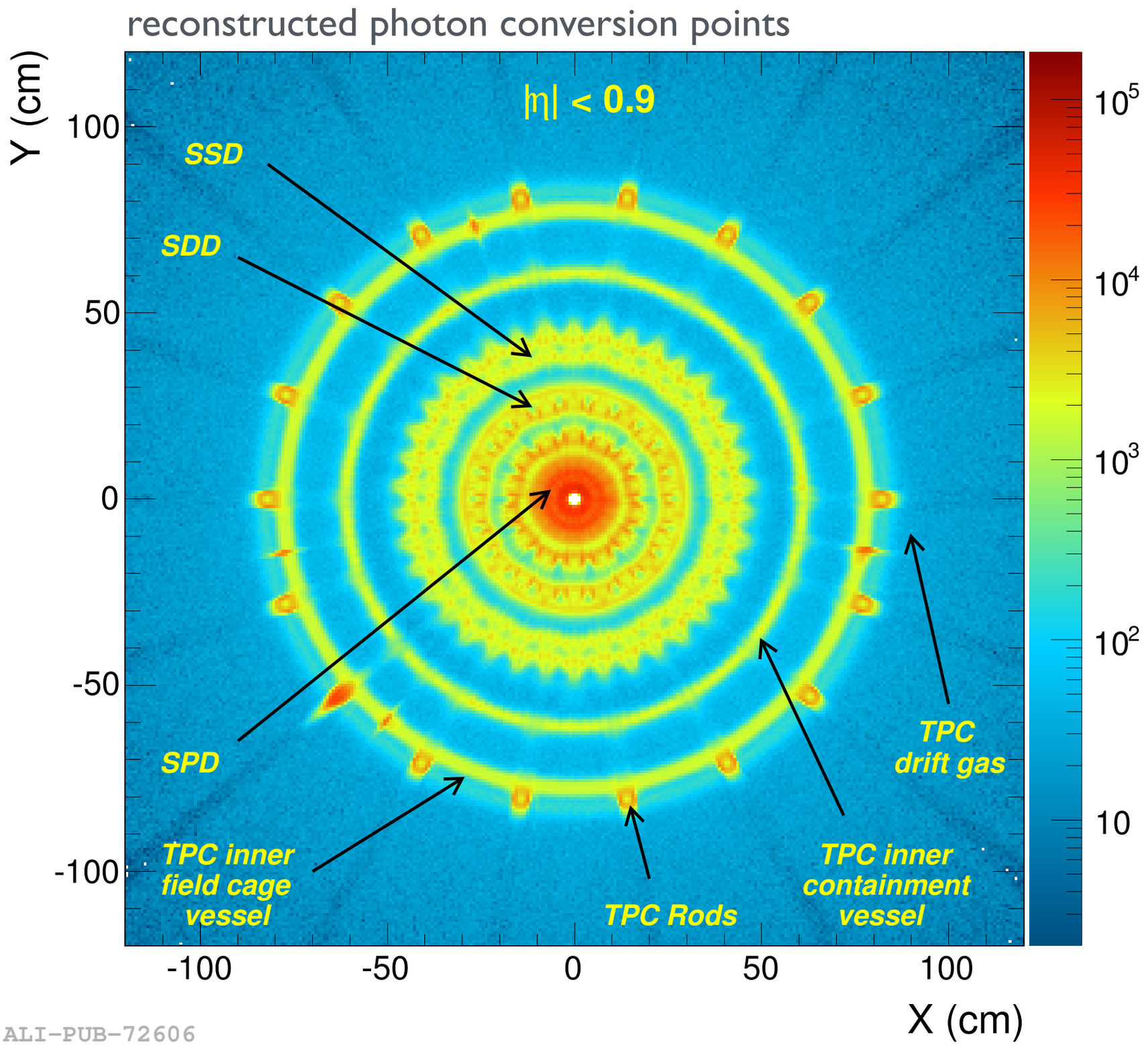
$$T_{\mathrm{eff}} = \underbrace{\sqrt{\frac{1+\beta_{\mathrm{flow}}}{1-\beta_{\mathrm{flow}}}}}_{2 \text{ for } \beta_{\mathrm{flow}}=0.6} \times T$$

C. Shen, U. Heinz, J.-F. Paquet, C. Gale, PRC 89 (2014) 4, 044910



- Large blueshift at late times when $T \approx$ 150 - 200 MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

Photon Conversion Method:
Precise Knowledge of Material Budget is Essential



$X/X_0 = 0.114 \pm 0.005$
($|\eta| < 0.9$, $R < 180$ cm)

→ $p_{conv} \approx 8.5\%$

rel. uncertainty: 4.5%

ALI-PUB-72606

How to Measure Direct Photons?

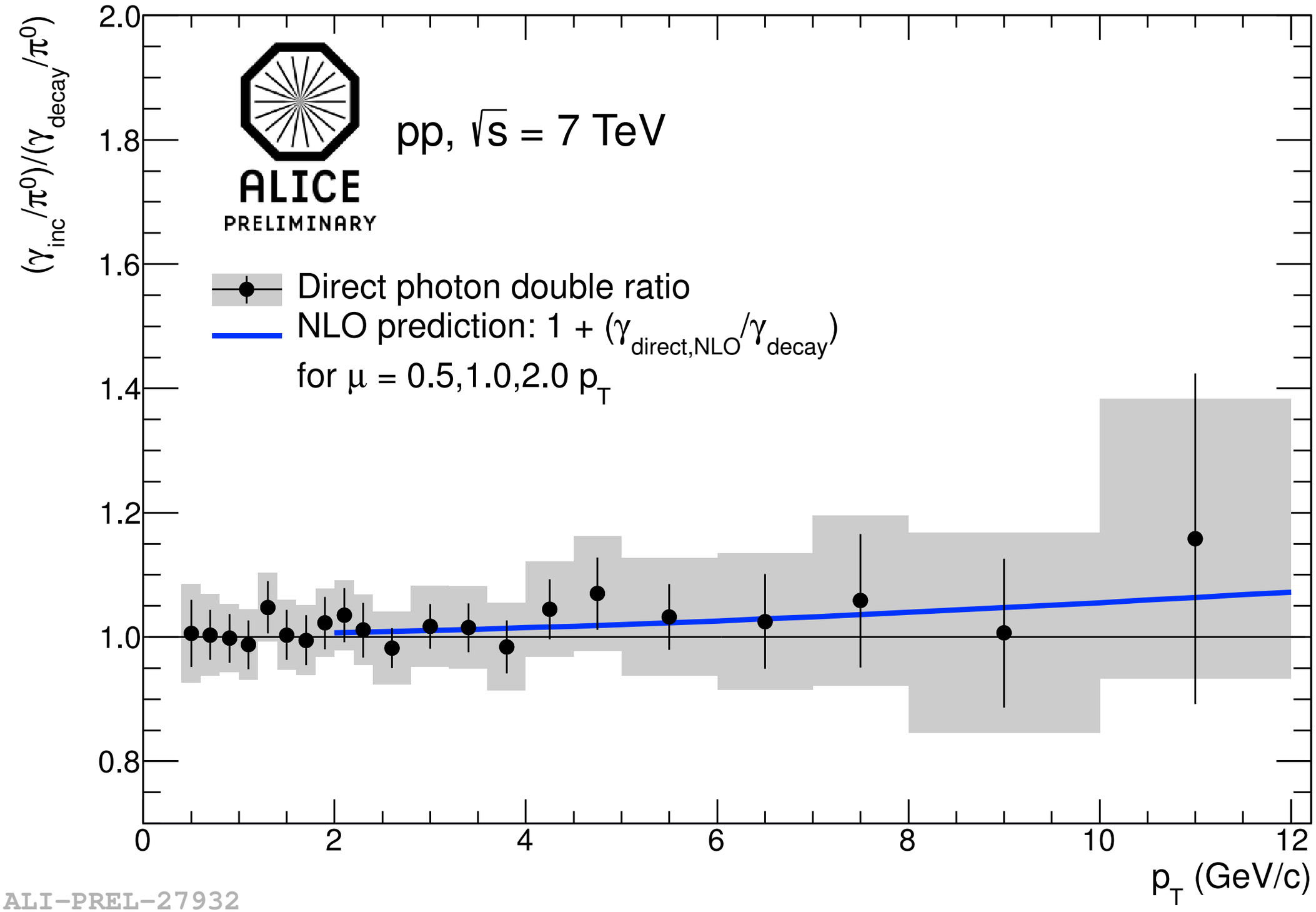
$$\gamma_{\text{direct}} := \gamma_{\text{inclusive}} - \gamma_{\text{decay}} = \left(1 - \frac{1}{R}\right) \gamma_{\text{inclusive}}$$

systematic uncertainties partially cancel in this ratio
(efficiency, energy/momentum scale, material budget ...)

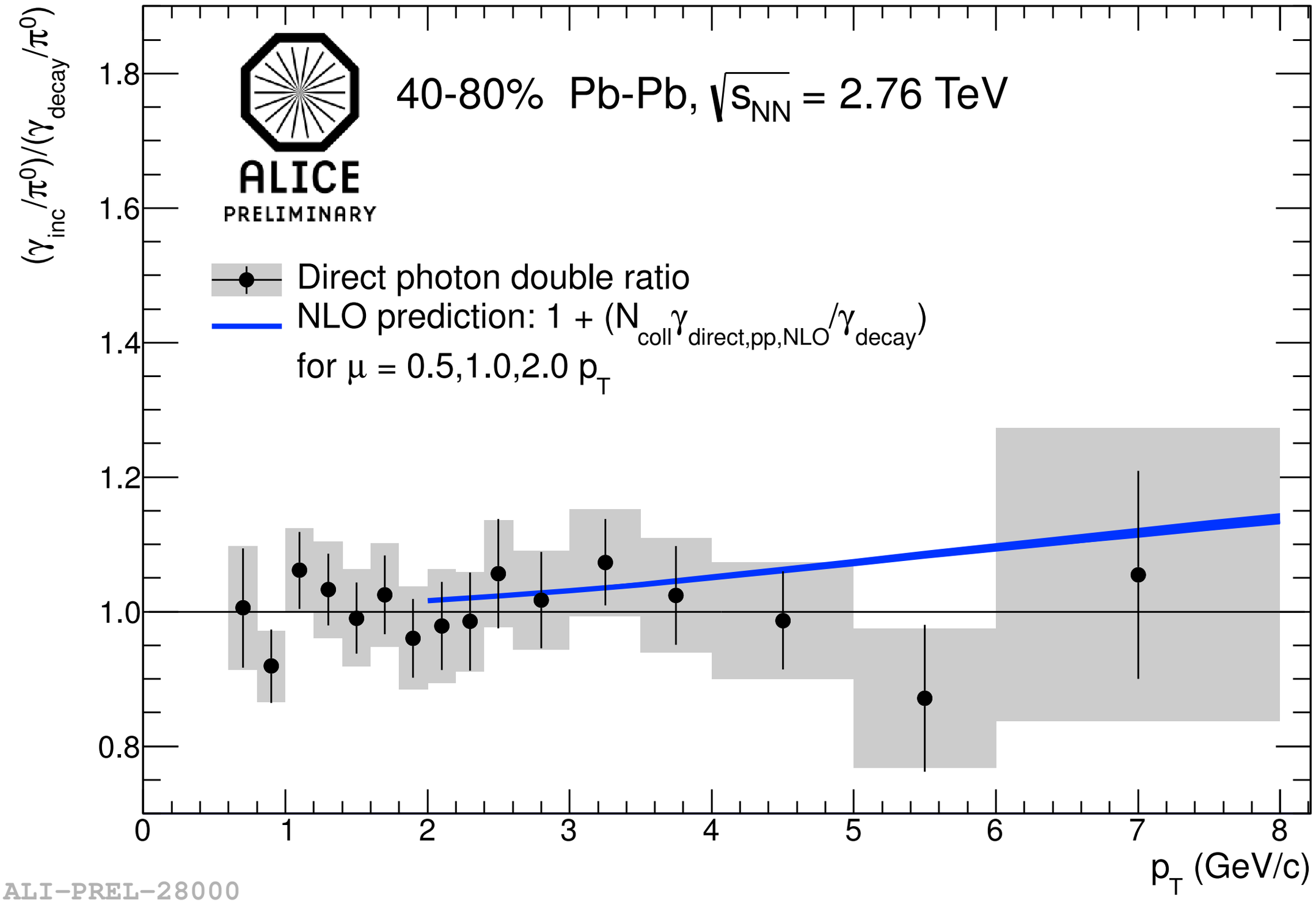
$$\text{with } R = \frac{\left(\gamma_{\text{inclusive}}/\pi^0\right)_{\text{meas}}}{\left(\gamma_{\text{decay}}/\pi^0\right)_{\text{calc}}}$$

Calculated decay photon cocktail (π^0, η, ω, ...),
π^0 measured, other hadrons from m_T scaling so far

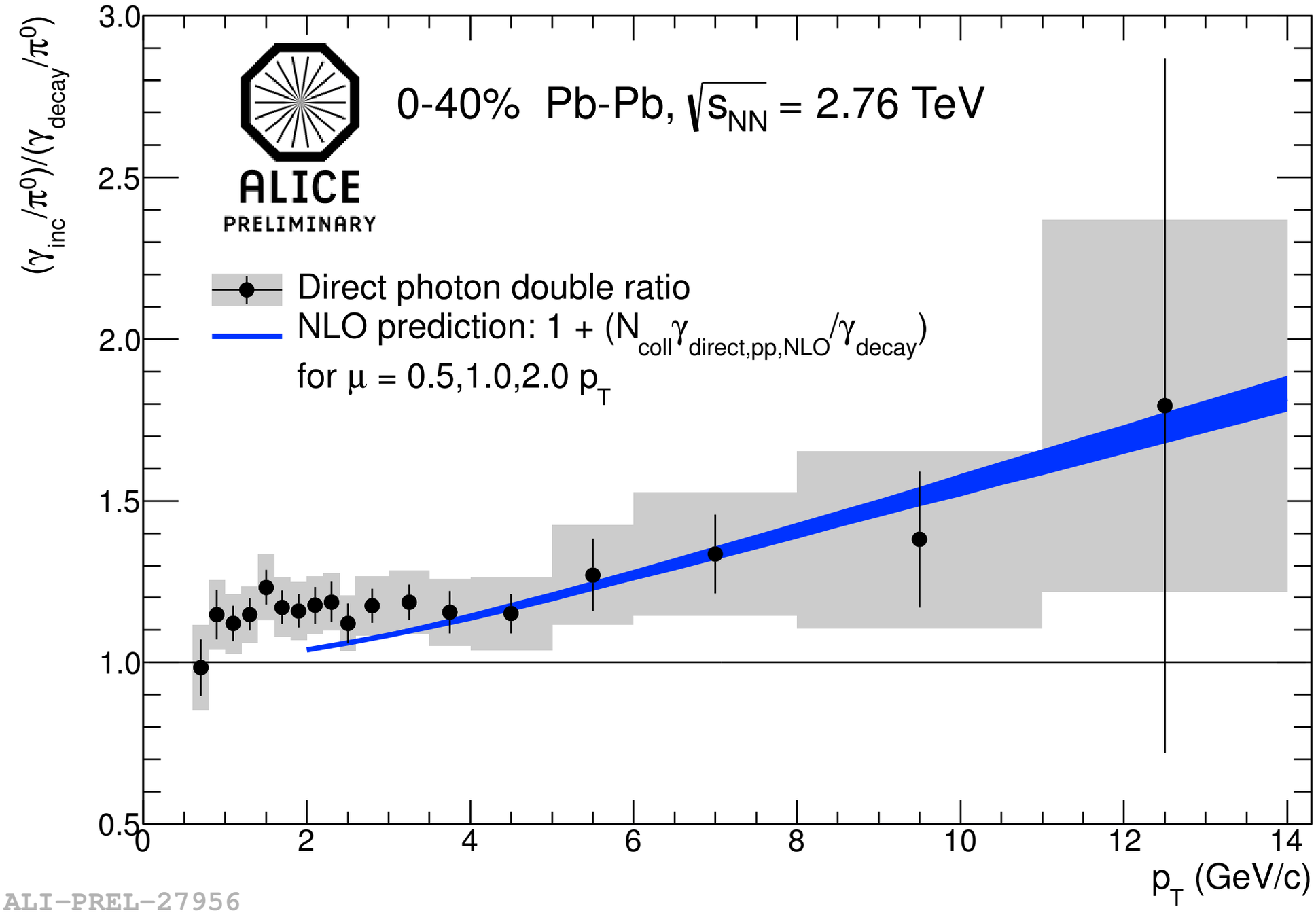
No Significant Direct-Photon Excess in pp at 7 TeV



No Significant Direct-Photon Excess in Peripheral Pb-Pb



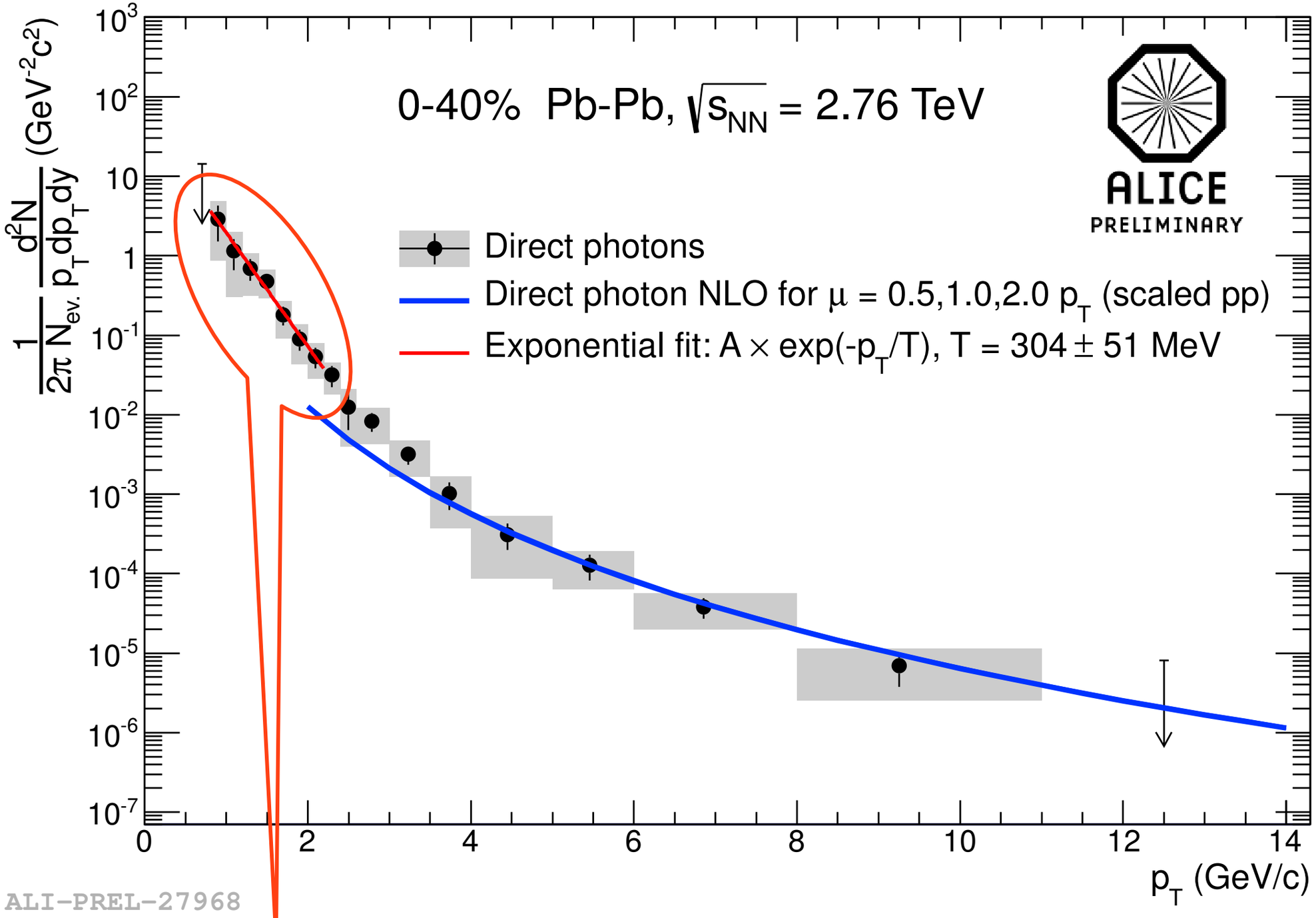
Direct-photon Excess in Central Pb-Pb Collisions



15 - 20% direct-photon excess for $1 < p_T < 2$ GeV/c where contribution from pQCD photons is small

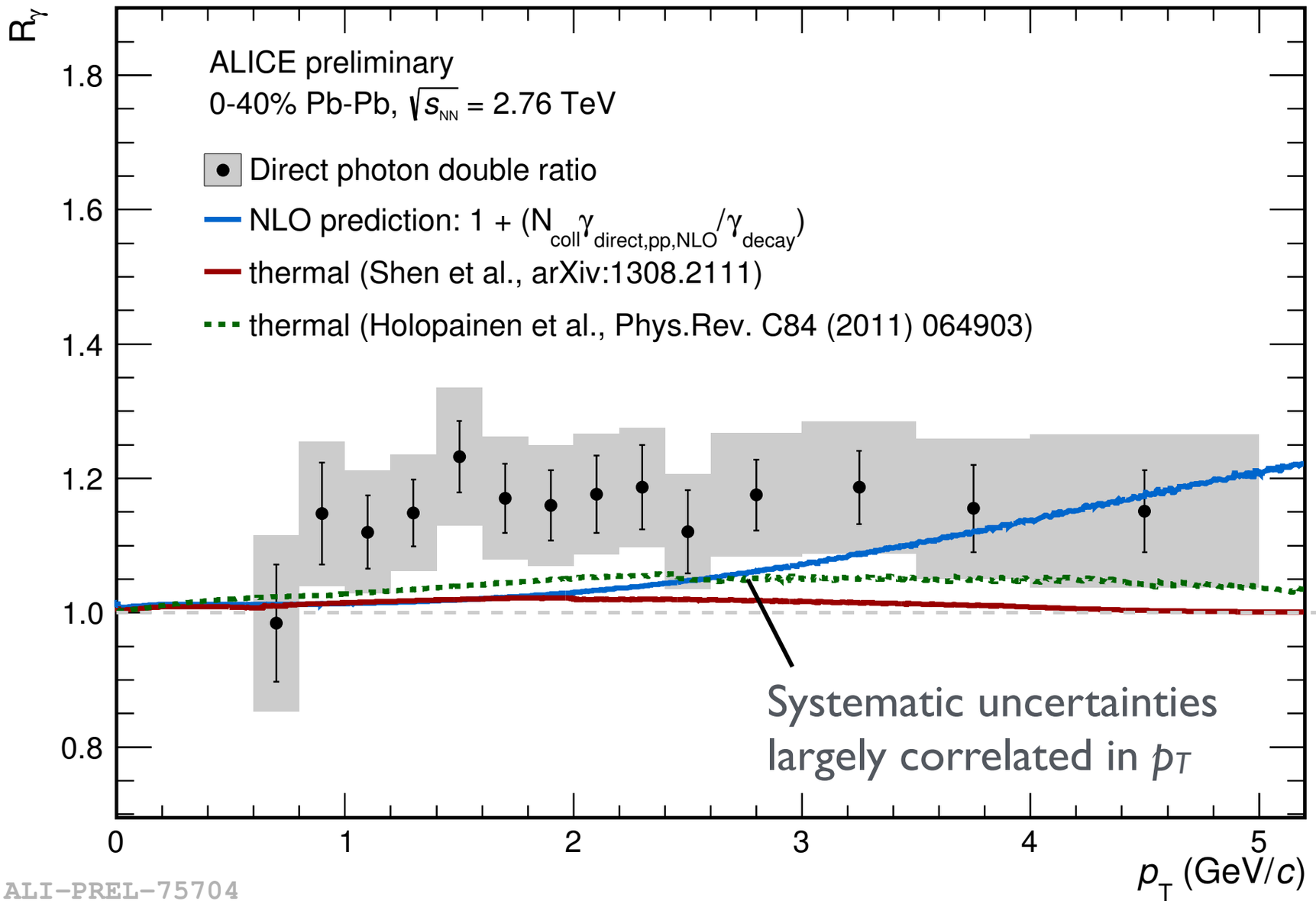
Direct Photon Spectrum in Central Pb-Pb Collisions

($\gamma_{direct} := \gamma_{all} - \gamma_{decay}$)



Low p_T part of the spectrum described by exponential with inverse slope T = 304 ± 51 MeV

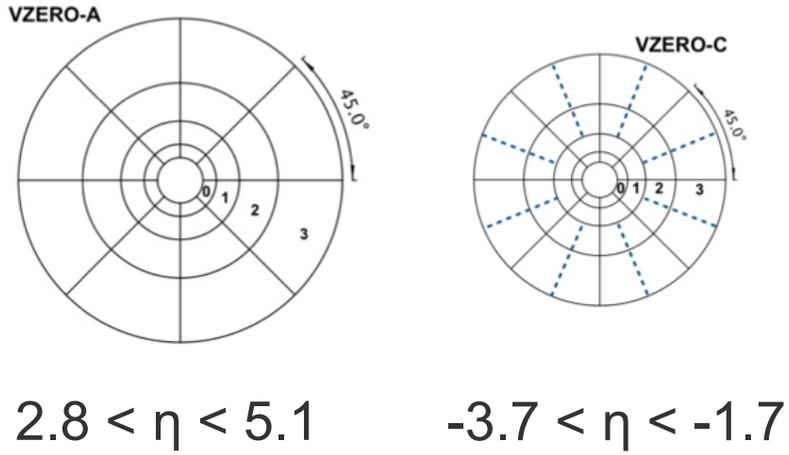
Comparison of the Direct Photon Excess in 0-40% most central Pb-Pb collisions with Hydro Models



- Direct photon excess appears to be larger than expected in hydrodynamic model
- Are we missing an important photon source in these models?

How to Measure the Direct-Photon v_2?

- Reaction plane (RP) from charged particles in forward direction



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

- Inclusive photons (mid-rapidity):

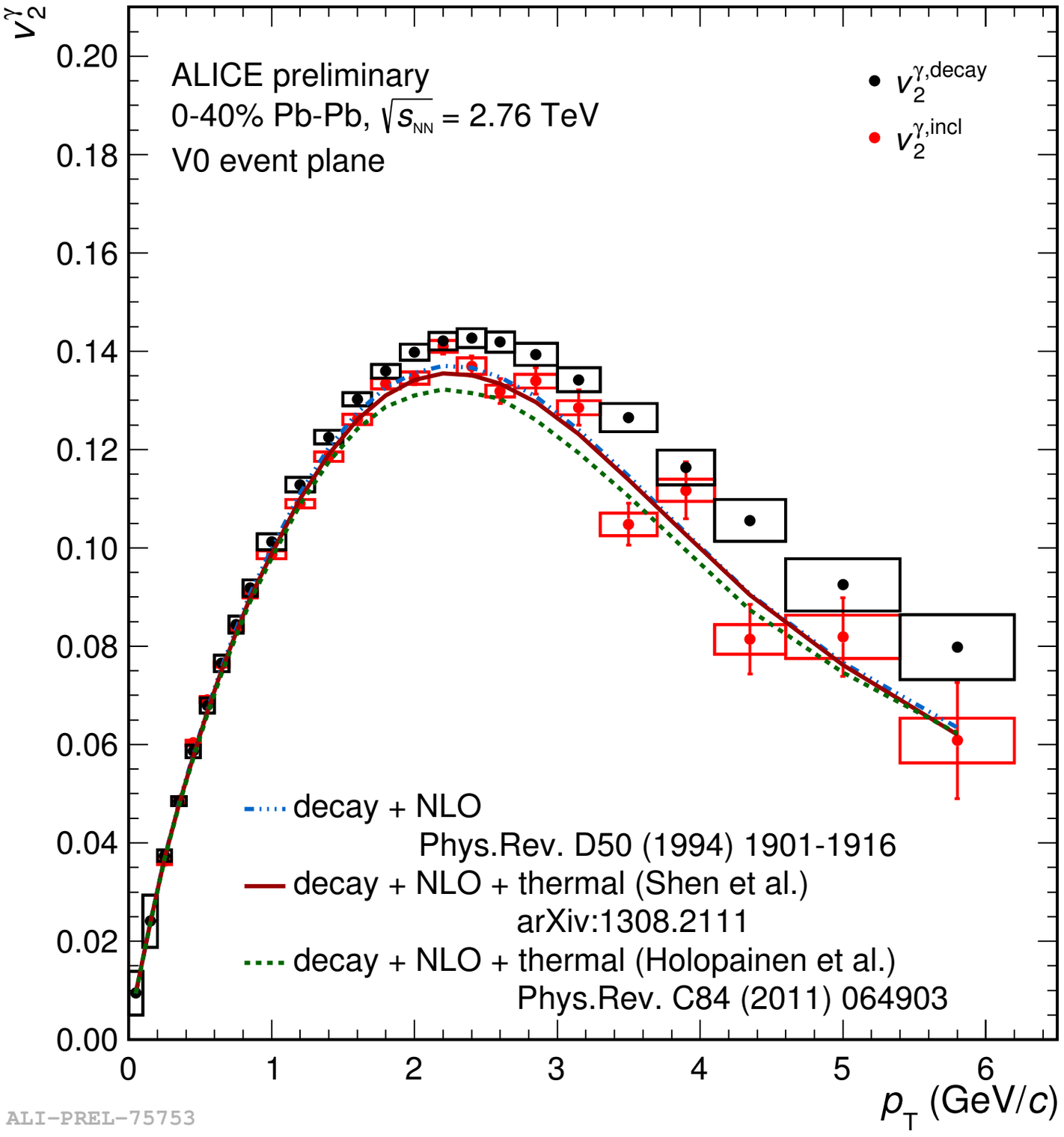
$$v_2^{\gamma,\text{incl}} = \frac{\langle \cos(2(\varphi - \Psi_2^{\text{RP}})) \rangle}{C}, \qquad C = \text{resolution correction}$$

- Decay photon v_2 from cocktail calculation based on measured pion v_2 (+ higher mass hadrons)

- Inclusive photon v_2 is weighted average of decay photon and direct photon v_2. Thus one can calculate the direct-photon v_2 as

$$v_2^{\gamma,\text{direct}} = \frac{R\, v_2^{\gamma,\text{incl}} - v_2^{\gamma,\text{decay}}}{R-1} \quad \text{with} \quad R = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}} = 1 + \frac{\gamma_{\text{direct}}}{\gamma_{\text{decay}}}$$

Measured Inclusive Photon and Calculated Decay Photon v_2



- v_2(incl) < v_2(decay) for p_T > 3 GeV/c
  - expected from v_2 = 0 for prompt photons
- v_2(incl) ≈ v_2(decay) for p_T < 3 GeV/c:
  - If there is a large direct photon component its v_2 must be very similar to the decay photon v_2
  - v_2(incl) described by models with small R_γ predicted by the same models

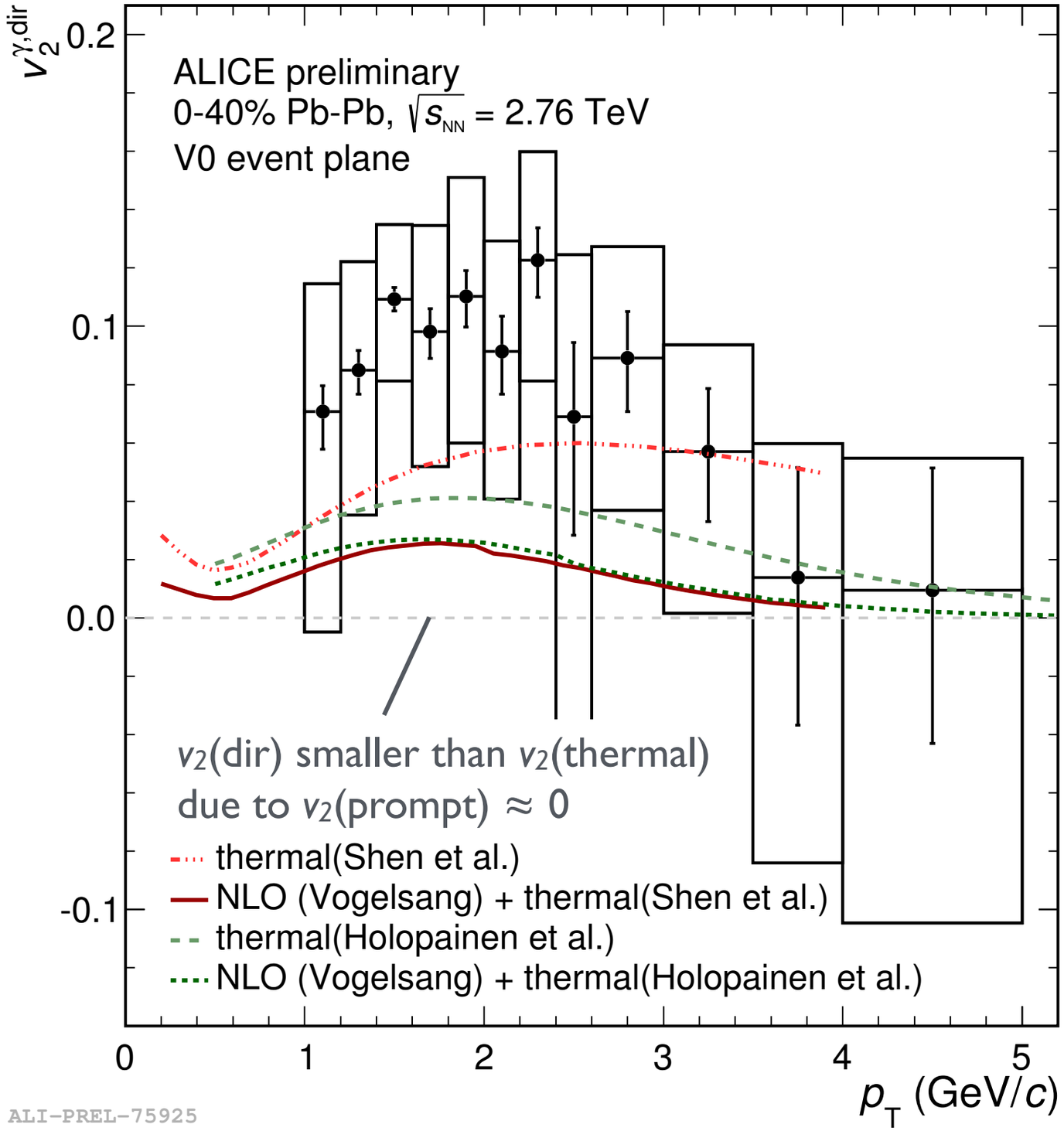
Recap: What to expect for the Direct Photon v_2 ?

- Large inverse slope parameter:
  $T_{slope} \approx 304 \pm 51^{stat+syst}$ MeV (>> T_c = 150 - 160 MeV)

- Could indicate that direct photons mostly come from early hot QGP phase

- Expect then small elliptic flow signal ($v_2 \approx 3\%$ or so at maximum)
  as collective flow needs time to build up

Direct Photon Elliptic Flow Appears to be Larger than Expected in Hydro Models



- Many direct photons from late stage with $T \approx T_c \approx$ 150 - 160 MeV?
- Then large inverse slope parameter due to Doppler blueshift with typical hadronic flow velocity $\beta_{flow} \approx 0.6\ c$?
- However, current systematic uncertainties are sizable so that there is no big puzzle looking at the ALICE data alone

The Direct Photon Puzzle

- The two parts of the puzzle
  - Direct photon yields at low p_T ($1 < p_T < 3$ GeV/c) not described by models
  - Large direct photon v_2, similar in magnitude to pion v_2, not described by hydro models
- Currently mostly in RHIC data, however, similar trend at the LHC
- Challenges …
  - standard (hydro) model of the space-time evolution and/or
  - current photon emission rates for the QGP and the HG

Statistical Significance of the Puzzle: Photon Excess *R* is the Key Quantity

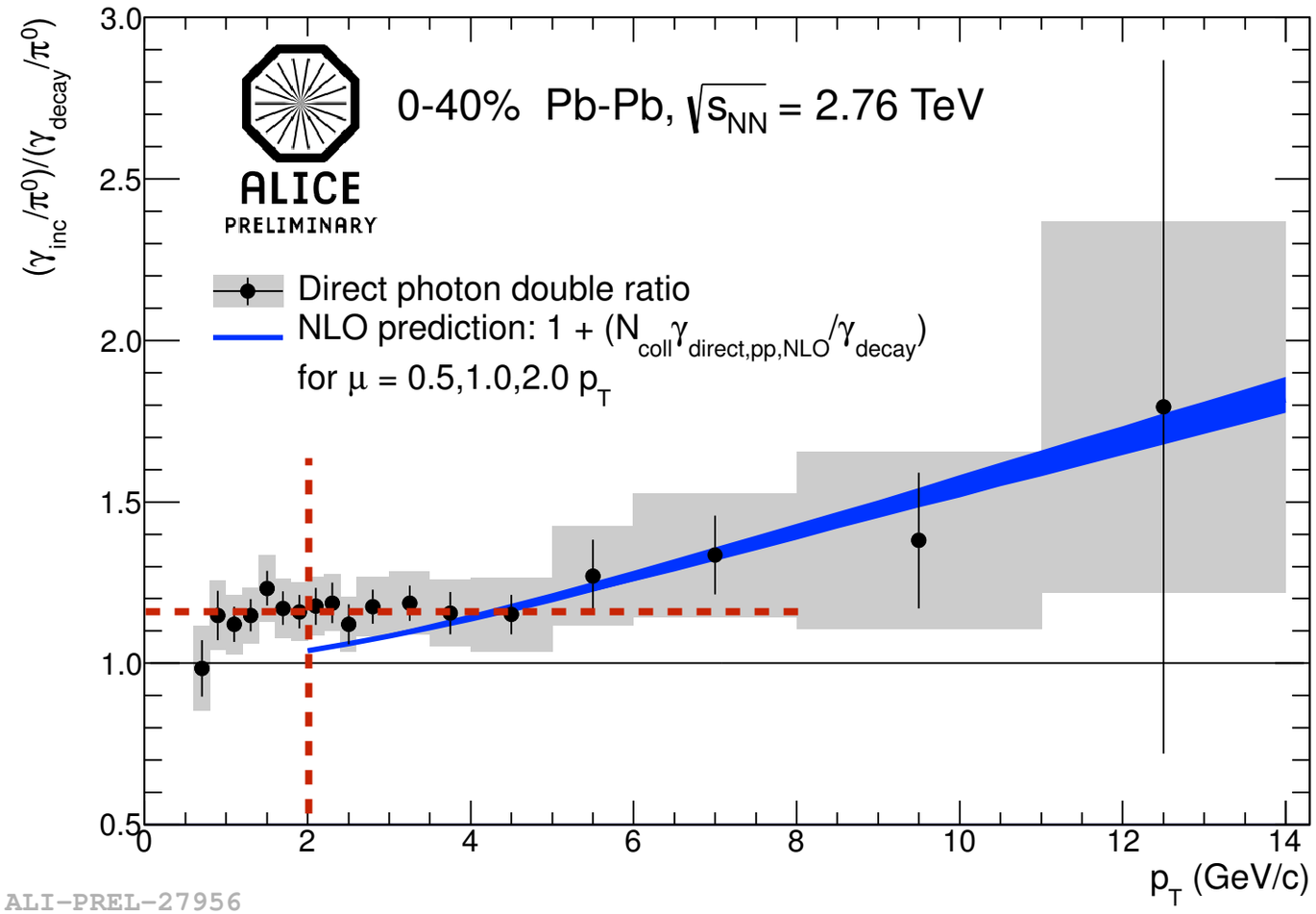
Direct photon excess:

Take one point (e.g. p_T = 2 GeV/*c*):

$R = 1.18 \pm 0.07_{stat} \pm 0.09_{sys}$
$= 1.18 \pm 0.114_{tot}$

The excess for this point is a 1.6 sigma effect

Systematic uncertainties largely correlated in p_T



Direct photon v_2:

$$v_2^{\gamma,\mathrm{dec}} = (1+\varepsilon)v_2^{\gamma,\mathrm{incl}}$$

$$v_2^{\gamma,\mathrm{dir}} = v_2^{\gamma,\mathrm{incl}}\left(1-\frac{\varepsilon}{R-1}\right)$$

$R_{true} < R_{exp,today}$ would solve both parts of the direct photon puzzle …

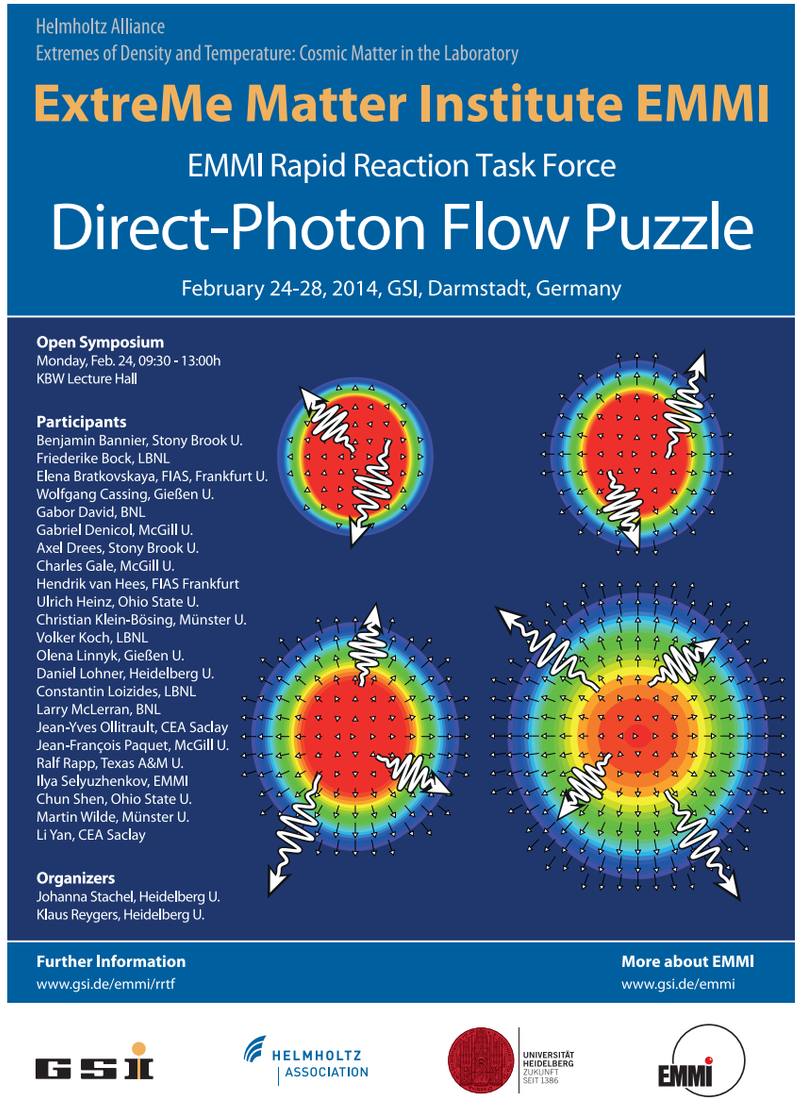
Small but finite chance that this will be the solution of the puzzle

Experimental Prospects of Direct Photon Measurements in ALICE

- Independent measurement with e.m. calorimeters
- Conversions method
  - Use absence of signal in pp to constrain material budget uncertainty
- Use γ_{conv}-γ_{calo} pairs (like PHENIX)
  - Trade material budget uncertainty for calorimeter energy scale uncertainty
  - Very useful as independent method
  - Don’t expect large reduction of systematic uncertainty in ALICE
- Virtual photon method

EMMI Rapid Reaction Task Force on the Direct Photon Flow Puzzle

- Feb. 2014, 25 participants (theory + experiment)
- Open Symposium:
  https://indico.gsi.de/conferenceDisplay.py?confId=2662
- Detailed discussions on
  - Averaging of v_n over large centrality bins, definition of v_n in models
  - Definition of decay photon cocktail in experiment and models, contribution from short-lived resonances
  - Comparison of the space-time evolution (hydro models, PHSD, parameterized fireball evolution)
  - pQCD contribution in various models
  - Initial flow, near T_c enhancement of photon rates, bremsstrahlung photons in the hadrons gas, Glasma photons, role of fragmentation photons, …
- Puzzle remains after checking various aspects of the data/theory comparison



Possible Solutions of the Direct Photon Puzzle

- Maybe many more photons from late stage close to T_c and hadron gas phase (need large increase in HG rates) [van Hees, He, Rapp, arXiv:1404.2846]
  - Theoretical justification?
- Maybe just bremsstrahlung from the HG? (m+m→m+m+γ, m+B→m+B+γ)
  [Linnyk, Cassing, Bratkovskaya, arXiv:1311.0279]
  - Important source in PHSD transport model
- Exotic new photon source, e.g., related to large initial *B* field?
  [Basar, Kharzeev, Skokov., arXiv:1206.1334]
  - seems unlikely to me (centrality dependence, $\sqrt{s}$ dependence, v_3)
- Initial flow before hydro evolution starts, e.g., IPGlasma model?
  - important, but does not address the missing photon yield
- Glasma photons, i.e., large photon production in very early gluon-rich phase?
  [McLerran, Schenke, arXiv:1403.7462], [Klein-Bösing, McLerran, arXiv:1403.1174]
  - promising, but so far based on simplified models
  - calculations from first principles needed

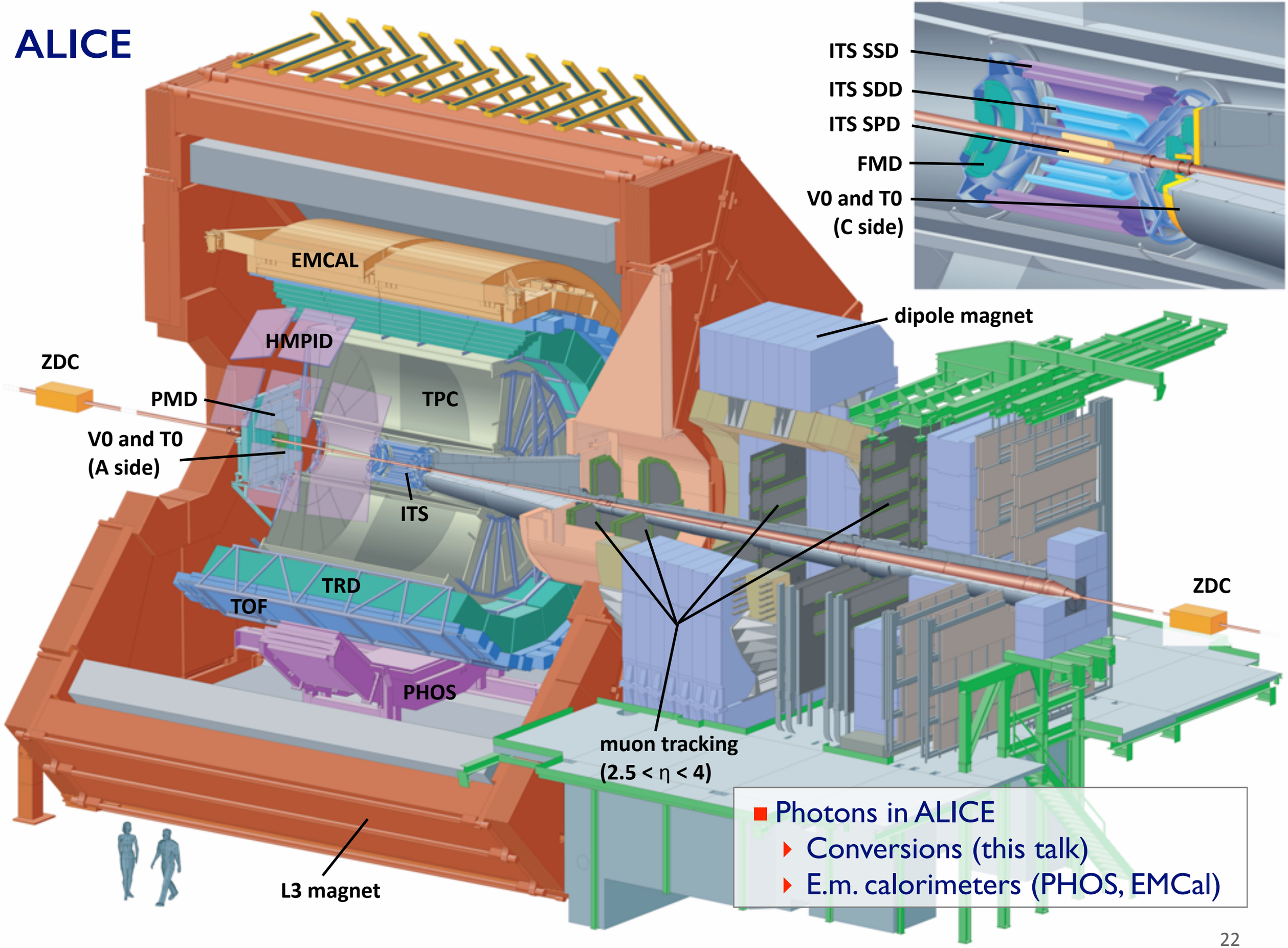
$$\frac{1}{\pi R^2}\frac{dN_\gamma}{dyd^2p_T} = F(Q_{\mathrm{sat}}/p_T)$$

Outlook

- Direct-photon production currently not understood
- Direct photons started out as probe of the early phase
  [Shuryak, PLB 78 (1978) 150]
- Large direct photon v_2:
  Early stage contribution outshined by photons from late phase with $T \approx T_c$ and below?
- Key question: Early or late production?
- Possible paradigm shift in interpretation of direct photons in A+A collisions
- New measurements needed, e.g., direct-photon HBT

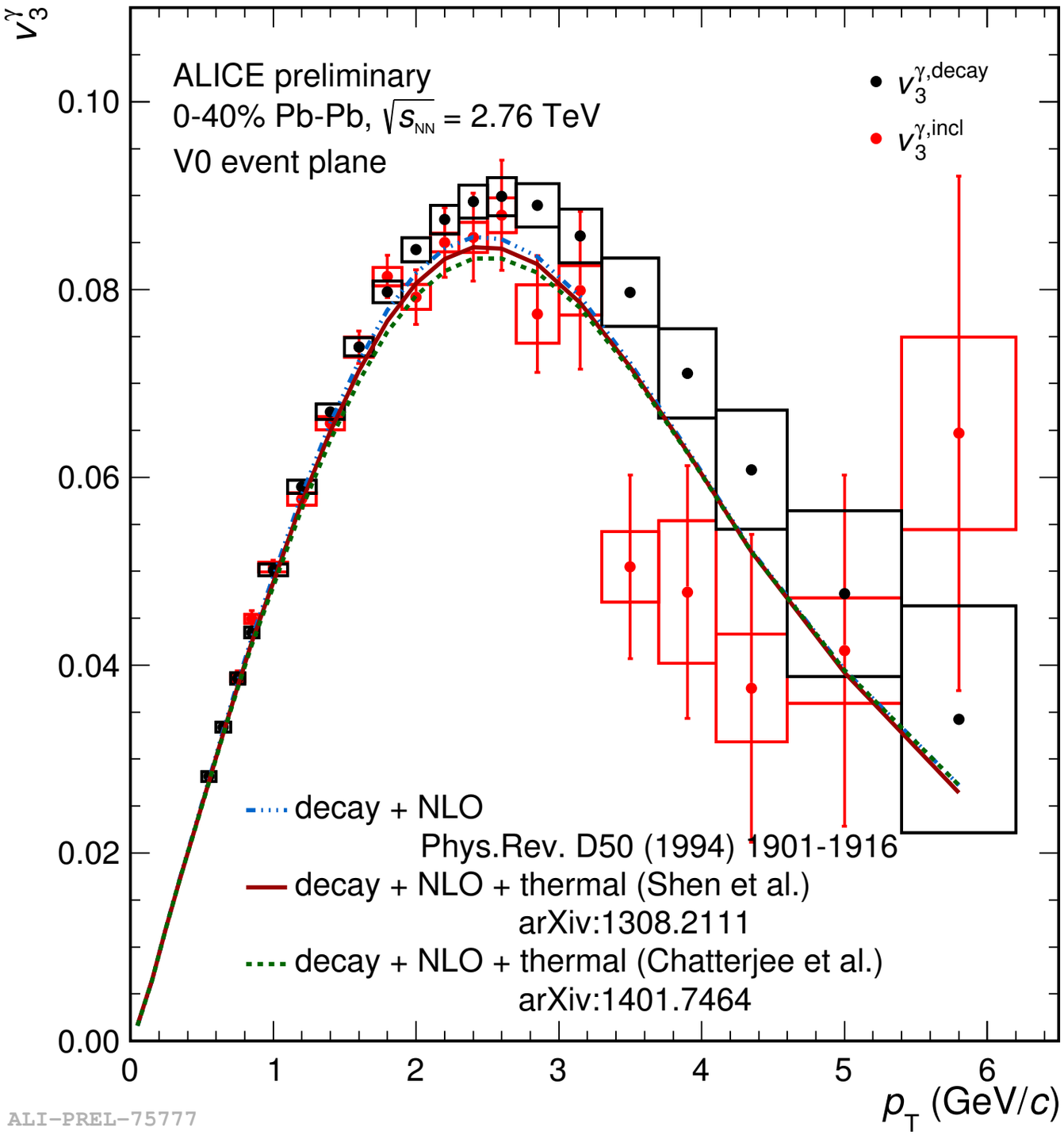
Extra slides

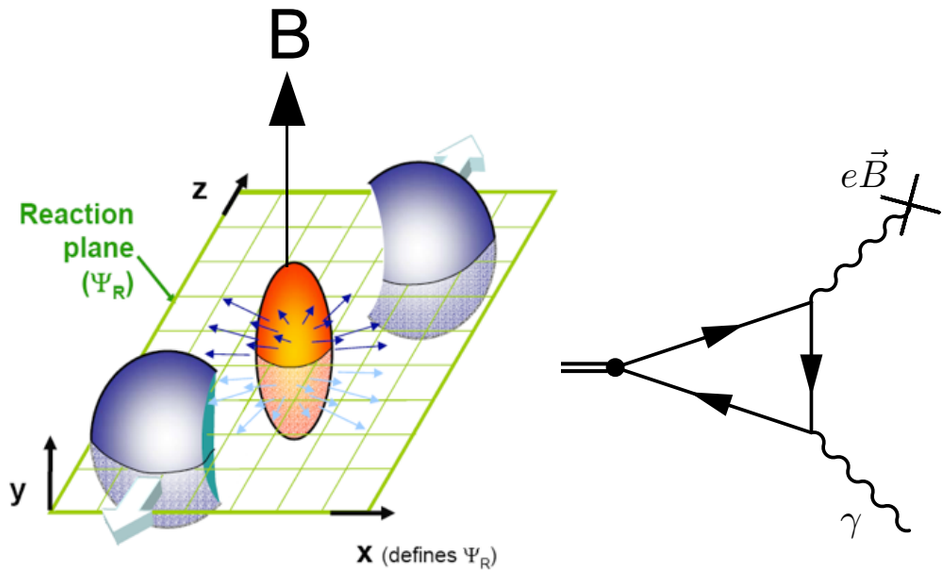
ALICE



- Photons in ALICE
  - Conversions (this talk)
  - E.m. calorimeters (PHOS, EMCal)

Testing "Exotic" Photon Sources By Measuring the Photon v_3

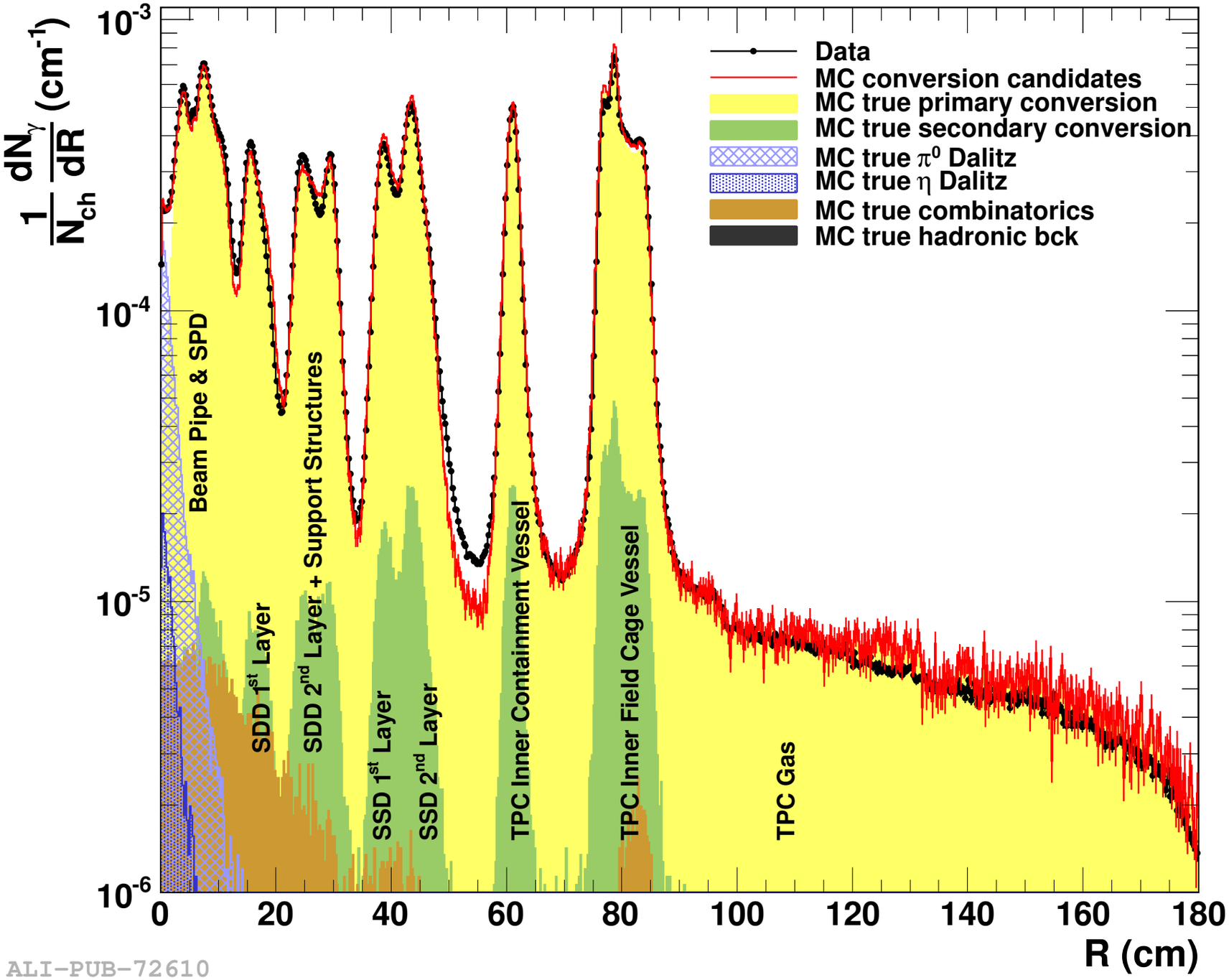




Basar, Kharzeev, Skokov., arXiv:1206.1334

- Photon production resulting from large initial B field?
- Could explain v_2
- Expect small v_3 in these models
- Inclusive photon v_3 measured, not yet conclusive

Photon Conversion Method:
Precise Knowledge of Material Budget Essential



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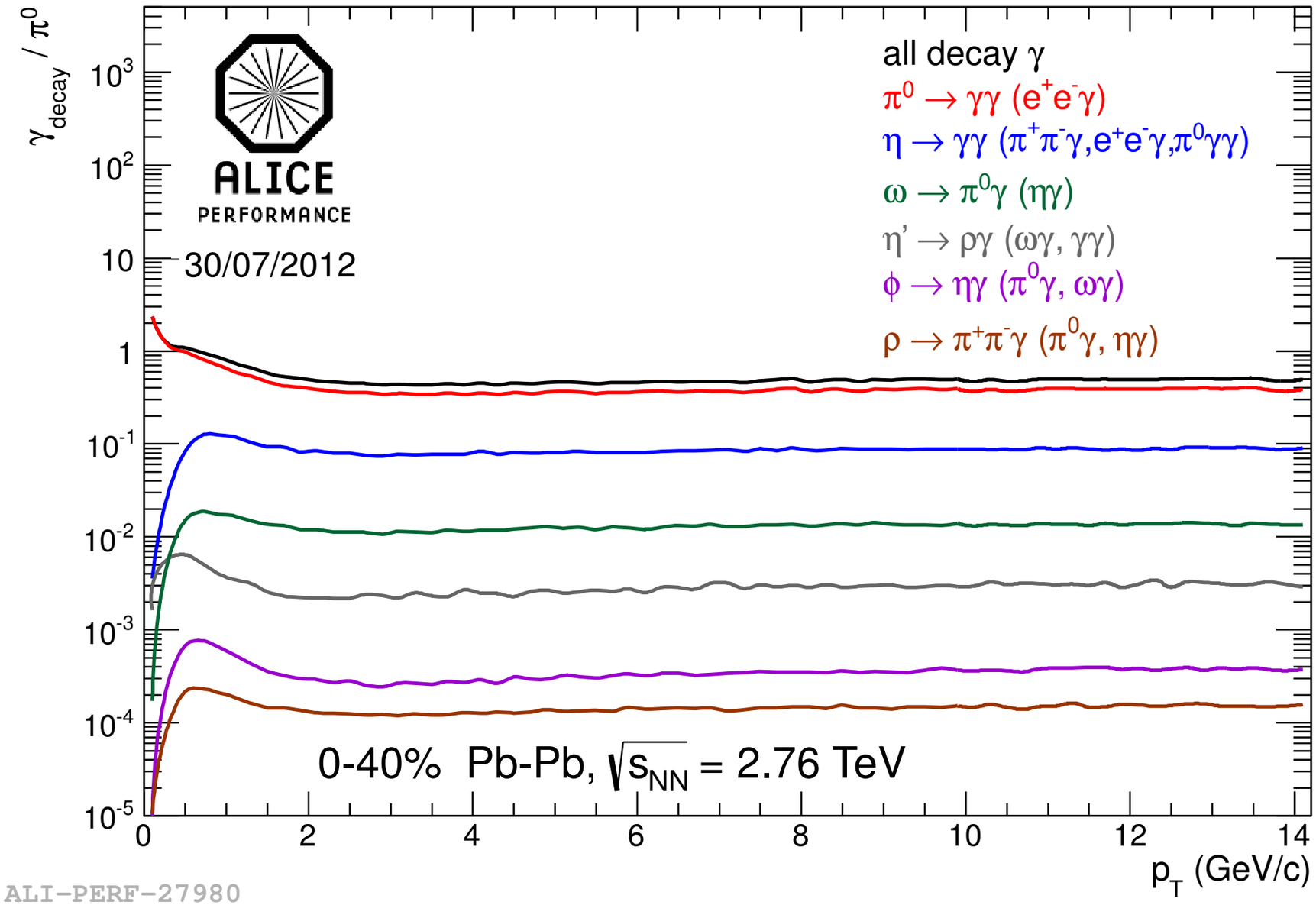
Decay Photon Cocktail from Measured π^0 Spectrum



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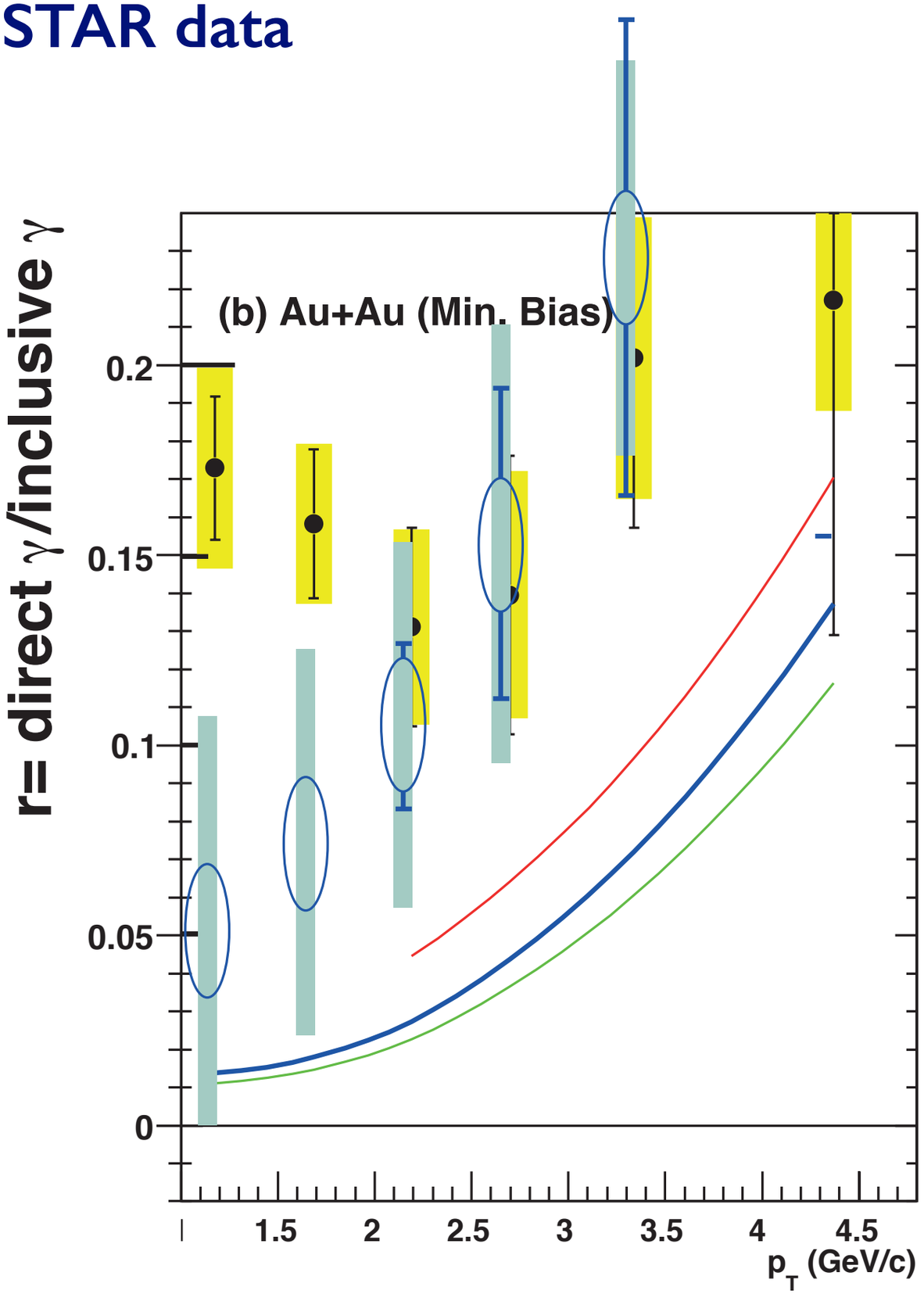
- π^0 spectrum measured, heavier mesons from m_T scaling
- Only π^0, η, ω relevant, the rest is negligible

Direct Photon at RHIC: Comparison of PHENIX data with Preliminary STAR data



STAR, arXiv:1405.3940

PHENIX, arXiv:0912.0244

Direct Photon Spectra at RHIC and the LHC