High pT Photon Production at Mid and Forward Rapidities in Pb-Pb Collsions at the LHC

SOMNATH DE

Pingla College, Vidyasagar University,W.B.

International Workshop on Forward and Jet Physics at LHC
11-12 February, 2019
Bose Institute, Kolkata

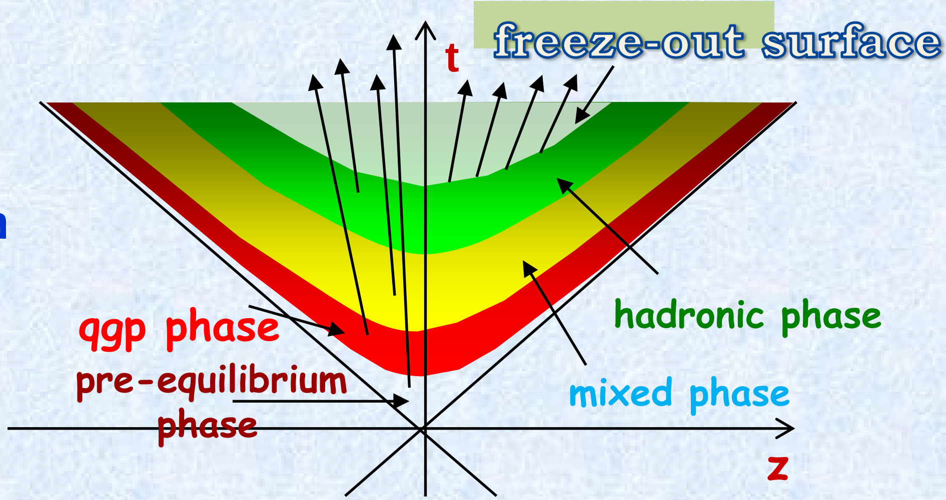
Plan of talk:

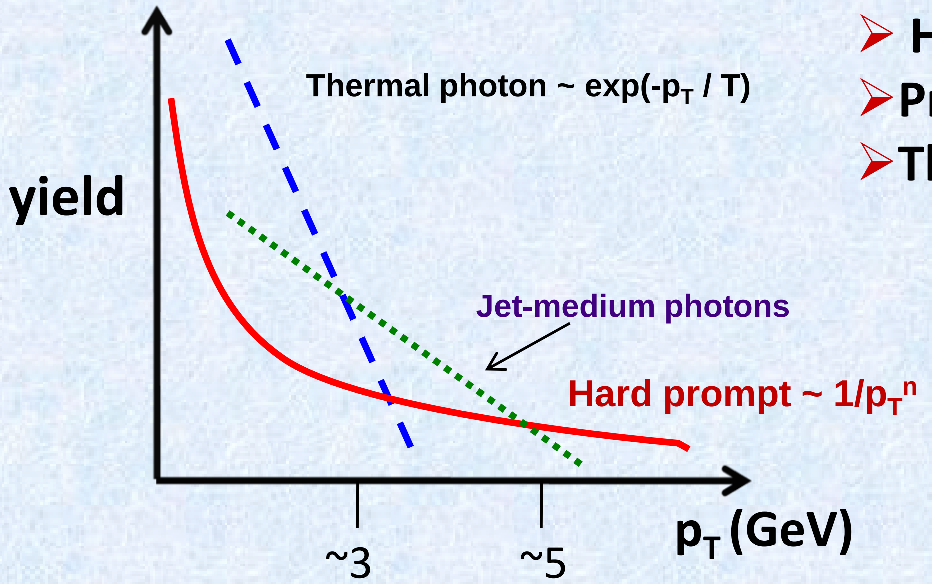
- Introduction: Direct photons in relativistic heavy ion collisions
- Jet triggered back-scattering Photon Production at mid Rapidity at the LHC
- Hard prompt photon production at forward rapidity at the LHC
- Summary and Outlook

Electromagnetic probes in Heavy Ion Collisions:

✓Direct photons are considered as the most cleanest probe in HIC

✓Due to weak coupling ($\alpha_e/\alpha_s \sim 10^{-2}$) with medium, direct photons carry information undistorted from each stages of evolution

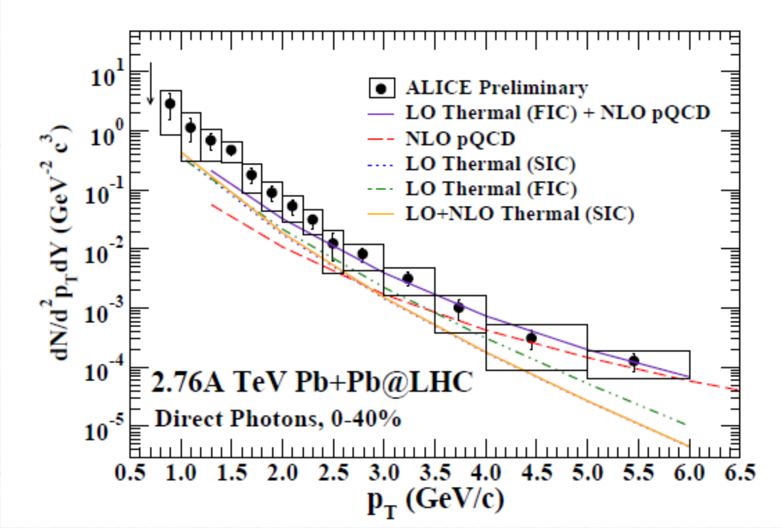




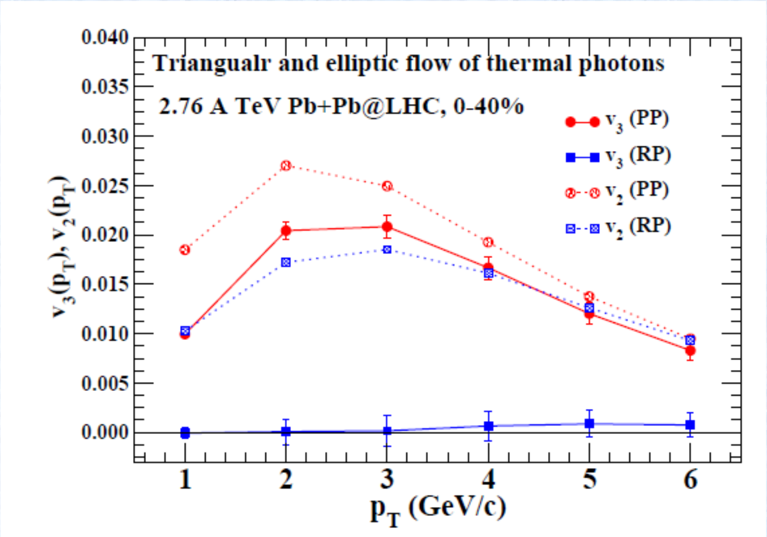
- ➢ Hard photons (Direct + Jet fragment)
- ➢ Pre-equilibrium and jet-medium photons
- ➢ Thermal photons (QGP + Hadron matter)

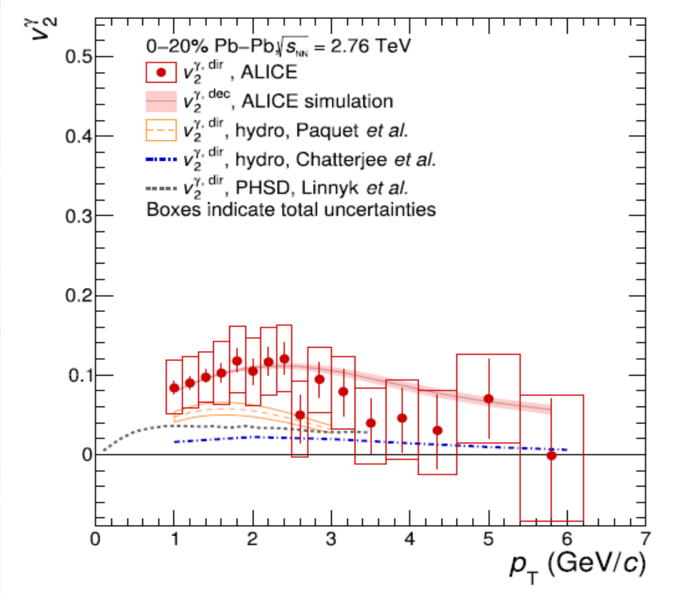
Experimental challenge to separate different sources of direct photon

Thermal photons@ LHC



R. Chatterjee, D.K. Srivastava, and T. Renk
Phys. Rev. C 94, 014903 (2016)





ALICE Coll. PLB 719 (2019) 308

- Thermal photon spectra and flow coefficients are found to be sensitive to the initial state fluctuations

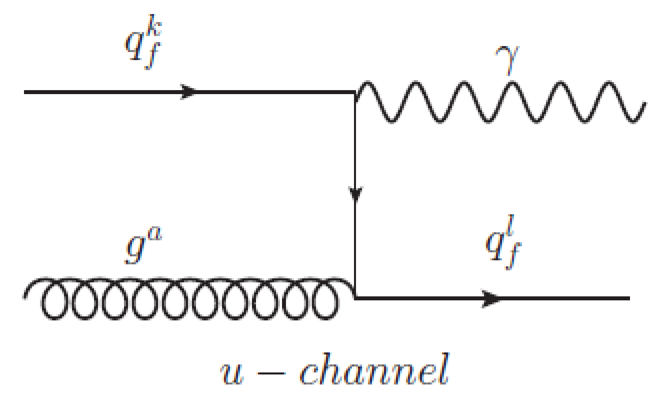
Compton back-scattering photons for QGP tomography

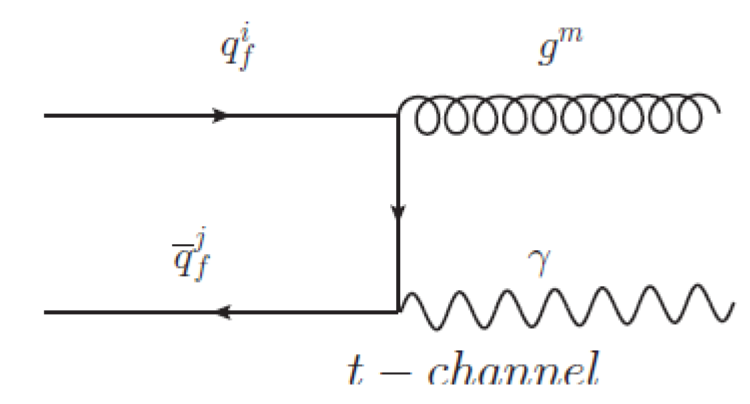
Ref: Phys. Rev. C 90, 034911 (2014)

Collaborators: Dr. Dinesh K Srivastava, VECC, Kolkata
Prof. Rainer J Fries, Texas A & M University

Photons from re-scattering of jets in quark gluon plasma

- QCD Compton and Annihilation process :





$$\frac{d\sigma}{dt} = -\frac{\pi\alpha\alpha_s e_q^2}{3s^2}\left(\frac{u}{s} + \frac{s}{u}\right)$$

$$\frac{d\sigma}{dt} = \frac{8\pi\alpha\alpha_s e_q^2}{9s^2}\left(\frac{u}{t} + \frac{t}{u}\right)$$

Cross sections are maximum for small values of t and u

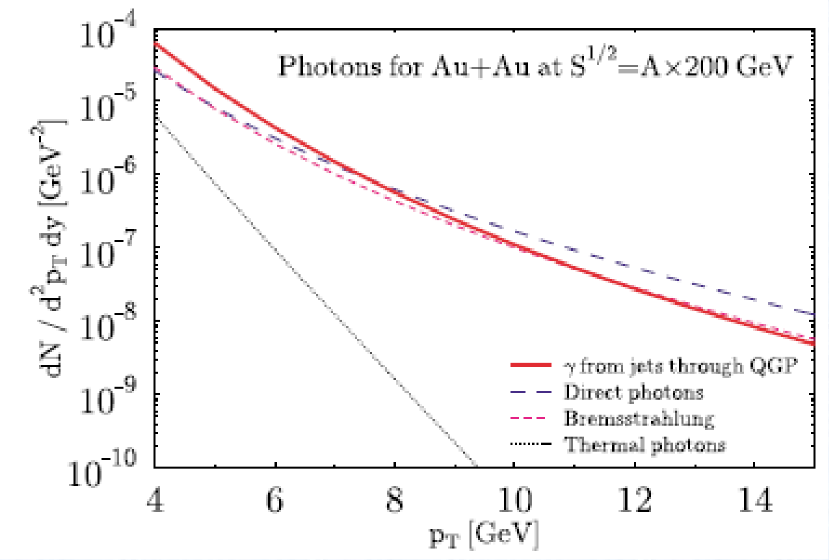
Backward scatt. $\vec{p}_\gamma \approx \vec{p}_q(\vec{p}_{jet})$ $\vec{p}_\gamma \approx \vec{p}_{\bar{q}}(\vec{p}_{jet})$

➢Compton back-scattering is often used for the production of high energy laser beam

Jet-photon contd..

- **Total inclusive yield:**

$$E_\gamma \frac{dN}{d^4x d^3p_\gamma} = \frac{\alpha\alpha_s}{4\pi^2}\sum_f \left(\frac{e_f}{e}\right)^2 [f_q(x,p_\gamma)+f_{\bar{q}}(x,p_\gamma)]T^2[\ln\frac{3E_\gamma}{\alpha_s\pi T}+C]$$



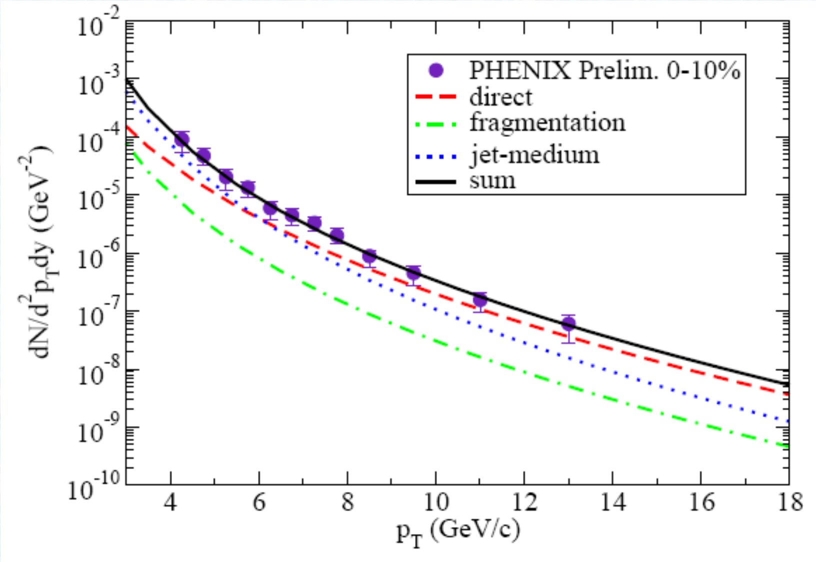
First proposed by : Fries, Muller, Srivastava (PRL,90, 132301 (2003))

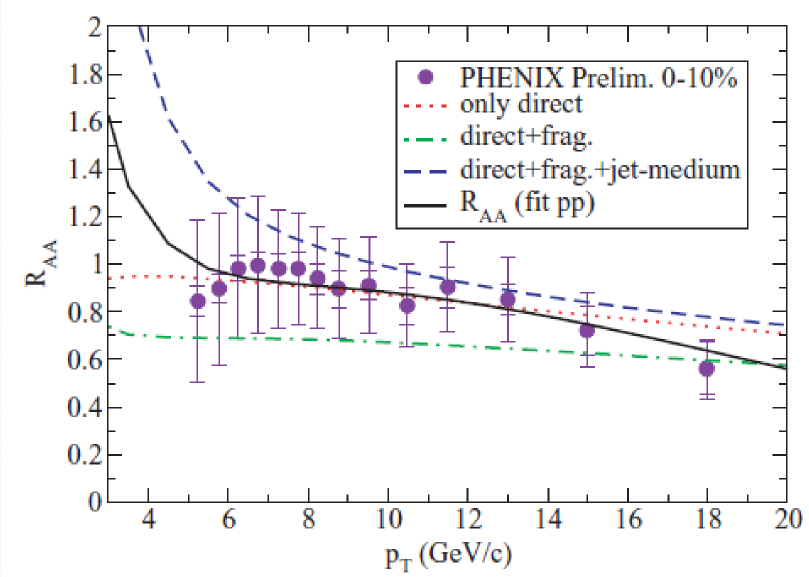
Shows substantial contribution for $p_T \leq 6$ GeV at RHIC energies

Experimental measurement of photons :

- Inclusive yield and Nuclear modification factor of direct photons
- Azimuthal momentum anisotropy coeff. (v_2)

Inclusive yield and R_{AA}:



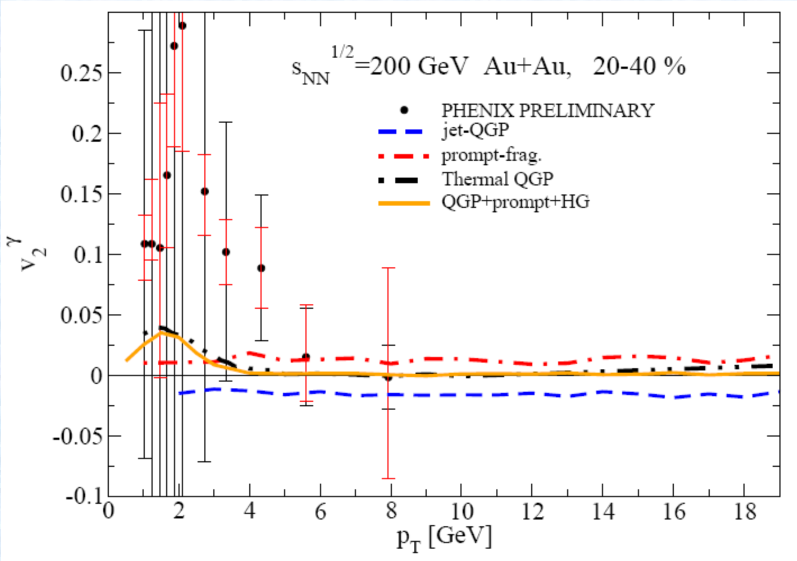


Qin, Ruppert, Gale, Jeon & Moore, PRC 80 (2009)

Azimuthal momentum anisotropy:

- Jet-medium photons shows negative v_2.
- Theoretical predictions are inconclusive.

Chatterjee, Frodermann, Heinz, Srivastava; PRL 96 (2006)
Turbide, Gale, Fries ; PRL 96 (2006)



Turbide et al. PRC 77 (2008)

Not promising, so far…

Jet - tagged photon measurement:

▪**Motivation:**

❖ **The back-scattered photons has strong correlation with the parent jet momentum**

❖ **Jets are produced back-to back in the medium**

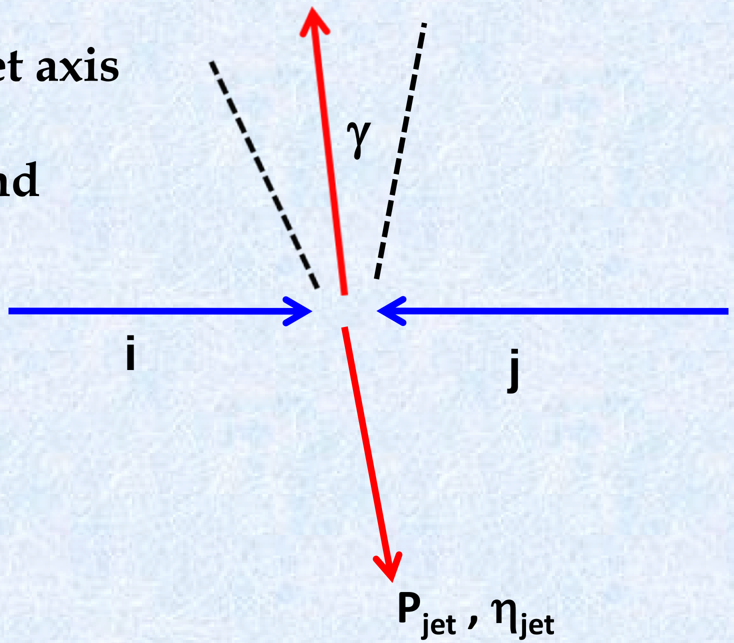
▪**Strategy:**

➢ **Fix the momentum and rapidity of the away-side leading jet**

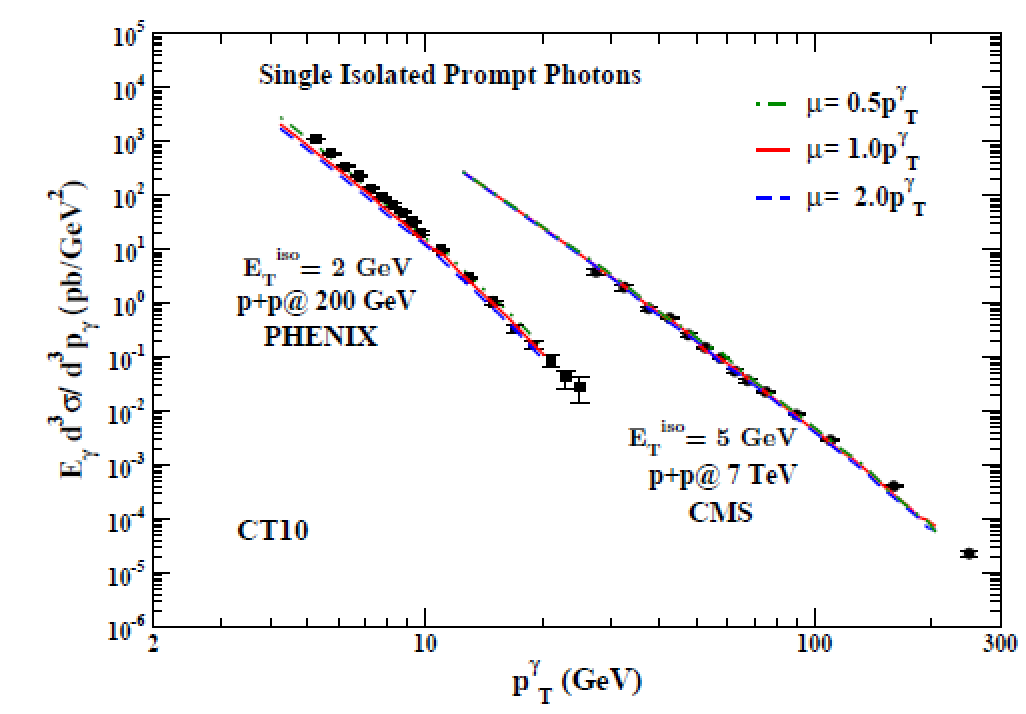
➢ **Study the photons, very close to the away-side jet axis**

➢ **The initial hard photons are treated as background**

➢ **Get rid of thermal and pre-equilibrium photons**



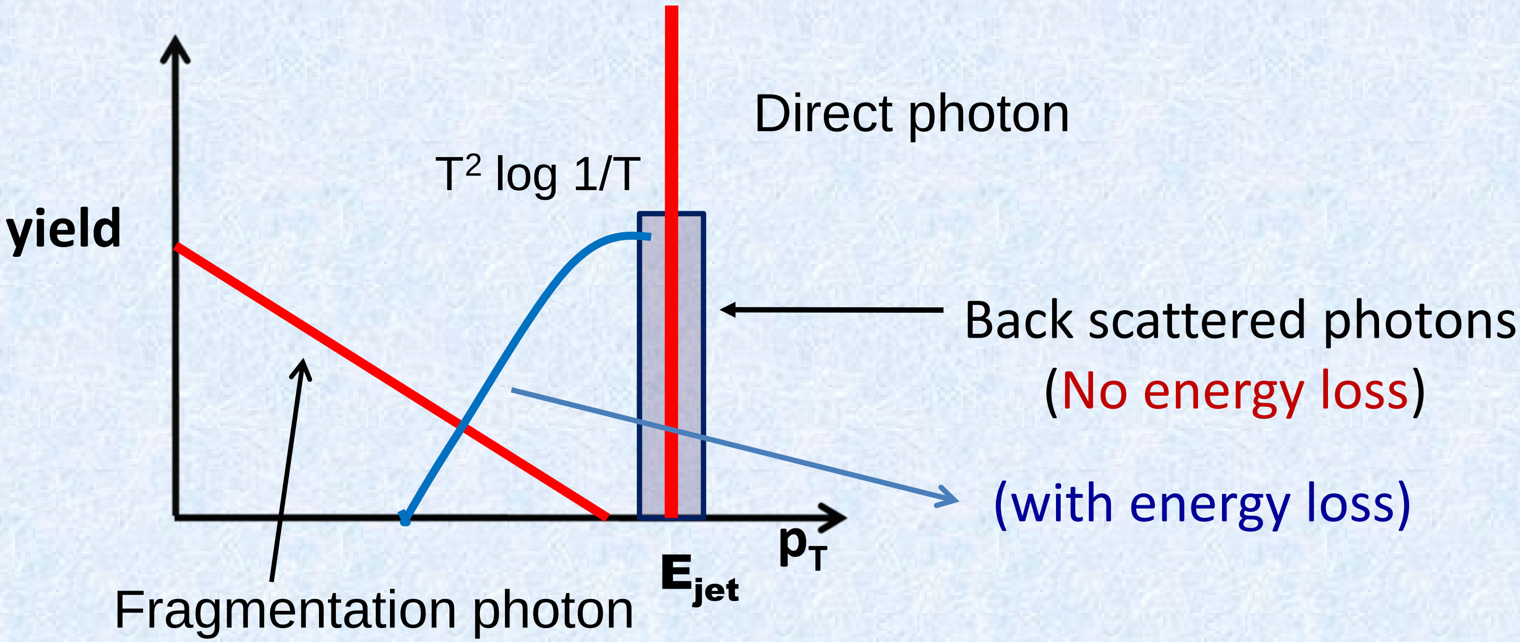
Estimation of Background



SD, Pramana 82 (2014)

- Photons from initial hard collision + Fragmentation of jets
- The background is calculated from the NLO package JETPHOX (Ref: JHEP 05 (2002) 028)
- EPS09 nuclear pdf is used for A+A collisions
- No E_T cut for A+A case

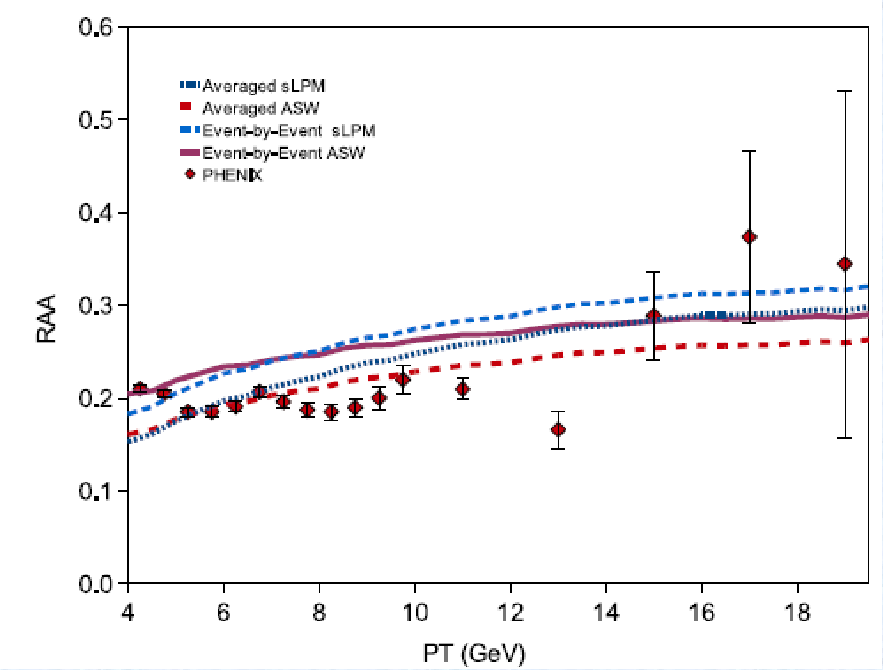
Jet- tagged photons at Leading order: a schematic view



- Important Information: Temperature of the medium
  Energy loss of partons before back-scattering

The energy loss model : ppm

We have used a longitudinally expanding, boost-invariant fireball model by:
Rodriguez, Fries, Ramirez
PLB 693 (2010)



Path travelled by the jet:

$$I_\beta(\vec{r},\varphi) = \int d\tau \tau^\beta \rho(\vec{r} + \tau \vec{e}_\varphi)$$

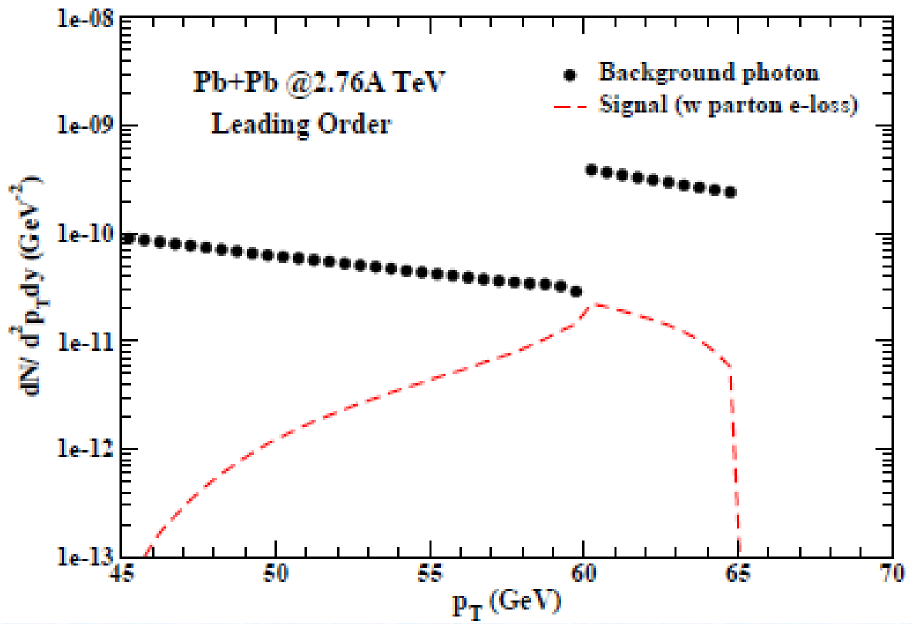
We have used LPM type of energy loss; β=1 $\Delta E = C_{LPM} I_1(r,\varphi)$

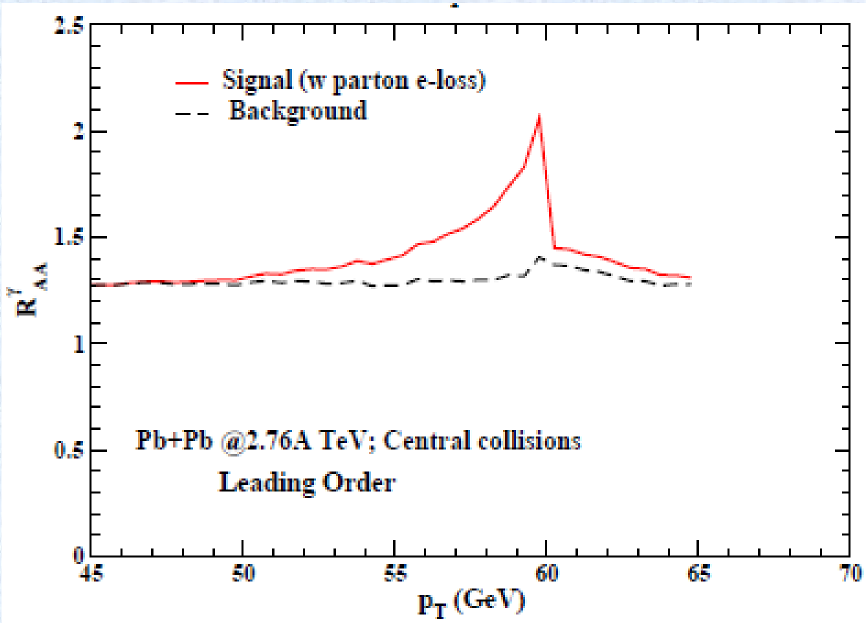
The coeff. C_{LPM} is determined from the fitting of R_{AA} of hadrons

QCD back-scattering photons at LHC : LO

R_{AA} : (Signal + Background)$_{AA}$ / N_{coll} ×(Background)$_{pp}$

- For central Pb+Pb collisions at 2.76 TeV at mid rapidity
- Photons opposite to the 60-65 GeV jet within ± 15 degrees
- The quarks suffer energy loss before conversion

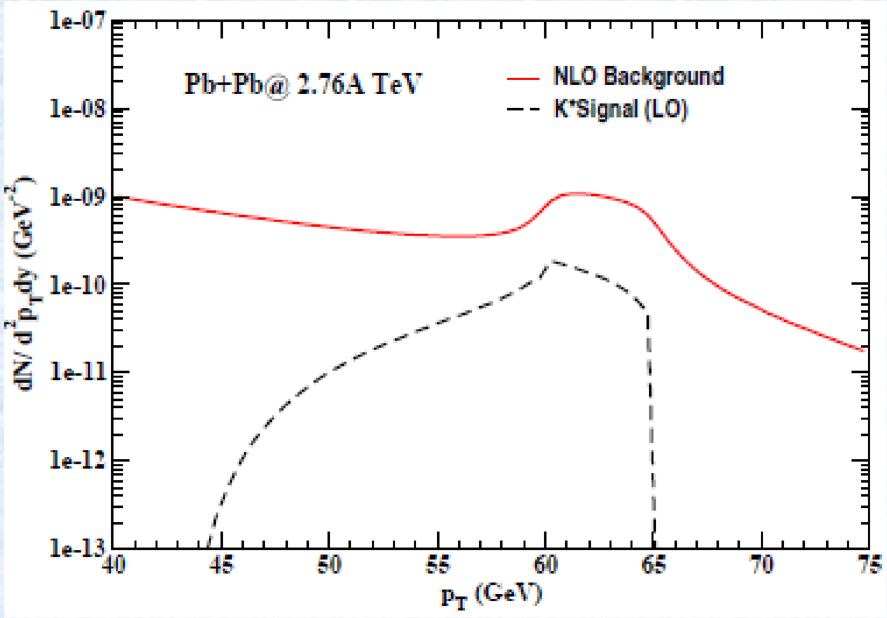


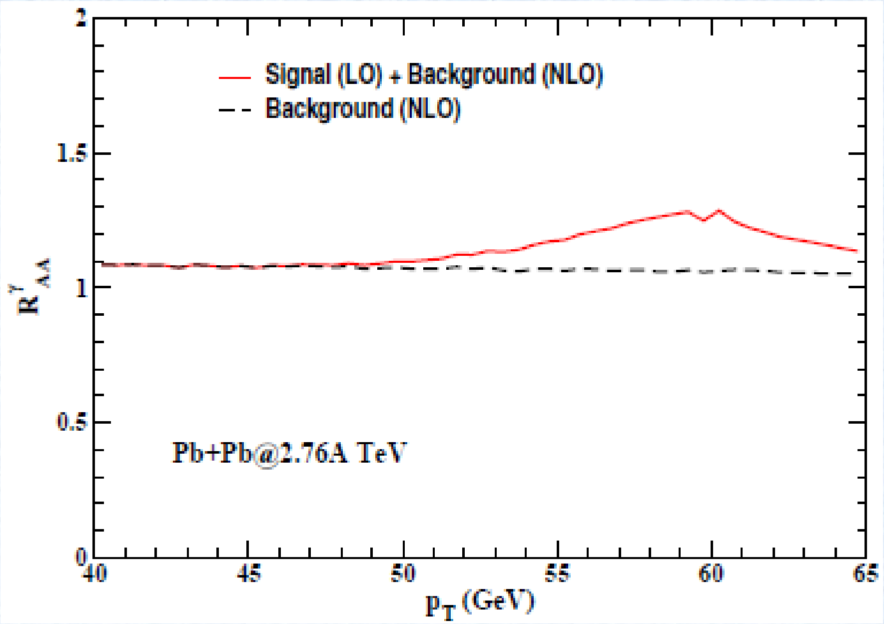


A clear back scattering peak can be seen just below trigger window

QCD back-scattering photons at LHC : NLO

- Back ground is calculated in the Next-to Leading order
- Kinematics of jet-conversion is still leading order
- Parton energy loss is accounted





Signal weakens but survives at NLO

Summary & Outlook-1:

- We propose the use of trigger jet to identify jet-medium re-scattering direct photons.
- Jet-medium photons shows characteristic enhancement in the nuclear modification factor of direct photon production at large momentum.
- The peak is clearly visible in Leading order however weakens when accounting for the radiative corrections and trigger jet energy loss.
- The shift of the peak from the trigger jet window provides complimentary measure of parton energy loss in the medium.
- Separation of this signal from other photon sources depends crucially on the initial trigger jet energy estimation.

Effect of neutron skin thickness on inclusive prompt photon production at LHC

Ref: J. Phys. G 44 (2017) 045104

Motivation-1

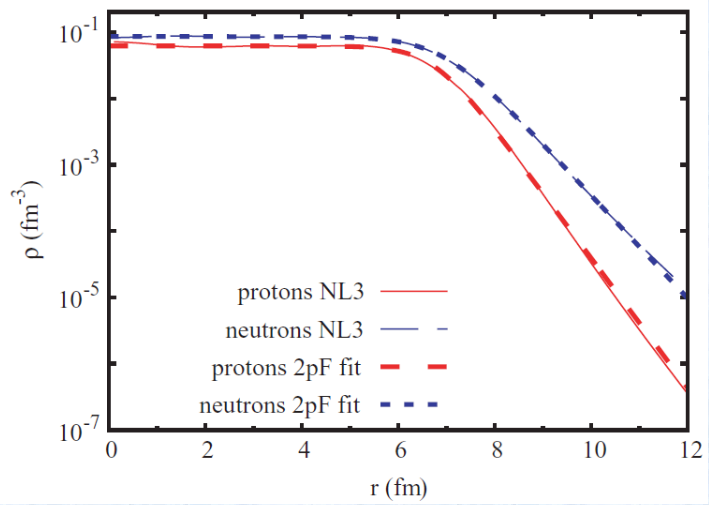
- What is neutron skin-thickness ?

It has been experimentally found in neutron-rich heavy nuclei, the spatial distribution of protons and neutrons are different.
The neutron skin-thickness parameter, generally defined as the rms radius difference of neutron, proton distributions.

$$\Delta R_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$$

- Two recent experiments on Pb^{208} nuclei has reported the positive value of neutron skin-thickness parameter with a very good accuracy. [Ref: PRL 108 (2012) & PRL 112 (2014)]

Outcome: The density of neutrons increases towards the surface than protons in Pb nucleus.



Ref. M. Warda et al., PRC 81 (2010)

Motivation-2

- The skin-thickness parameter is intimately related to nuclear symmetry energy, EoS of pure neutron matter, etc.

- The observation have further implication in the context of heavy ion collisions at relativistic regime.

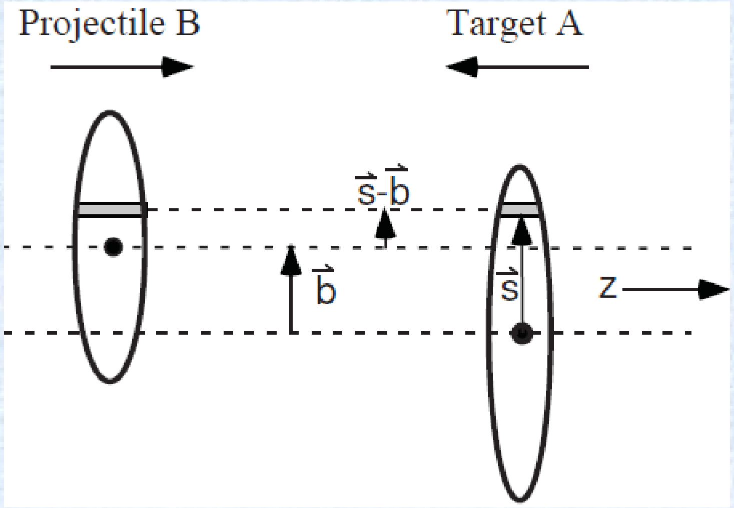
- For ultra-peripheral collisions, more number of neutrons are participating in the reaction than protons in comparison to central collisions.

- We have studied the inclusive prompt photon production for these type of collisions, as the photon production is sensitive to the isospin content of projectile/ target nuclei

- We are particularly interested in the " central-to peripheral ratio: R_{cp} " of prompt photon production which is routinely measured in experiment.

Geometry of high energy nuclear collisions:

The Glauber model has been found very successful in describing the geometry of nuclear collisions. The model views the collision of two nuclei in terms of individual scattering among the constituent nucleons. Nucleons follow independent trajectories. (Ref. Miller et al., Annu. Rev., Vol. 57, 2010)



- The number of wounded nucleons in a collision with impact parameter b:

$$N_{part}(b) = \int d^2s T_A(s_1)\{1-(1-\frac{\sigma T_B(s_2)}{B})^B\} + \int d^2s T_B(s_2)\{1-(1-\frac{\sigma T_A(s_1)}{A})^A\},$$

where T_A (s_1) and T_B (s_2) are the nuclear thickness functions and $s_{1,2} = (x \pm b/2, y)$

- The effective neutron and proton number associated with such collisions

$$\acute{Z} = \frac{Z}{A}\frac{N_{part}(b)}{2}, \quad \acute{N} = \frac{N}{A}\frac{N_{part}(b)}{2}$$

Ref. Chatterjee et al., PRC 79 (2009).

Introducing neutron skin-thickness for Pb nucleus:

The neutron and proton densities are now described by two different Fermi distributions:

$$\rho^{i,A}(\mathbf{r}) = \rho_0^{i,A}/(1 + e^{\frac{|\mathbf{r}|-d_i}{a_i}})$$

Normalization:

$$\int d^3\mathbf{r}\rho^{\mathrm{p},A}(\mathbf{r}) = Z = 82, \qquad \int d^3\mathbf{r}\rho^{\mathrm{n},A}(\mathbf{r}) = N = 126.$$

The parameters of the two distributions are : a_p = 0.447 fm, d_p = 6.680 fm

a_n = 0.55±0.03 fm, d_n = 6.70±0.03 fm

Tarbert et al. PRL 112 (2014)

Thus, we write

$$
\begin{aligned}
\int dz\rho(r) &= \int dz\rho_A^p(r) \ + \ \int dz\rho_A^n(r), \\
T_A(s_1) &= T_A^p(s_1) \ + \ T_A^n(s_1), \\
T_B(s_2) &= T_B^p(s_2) \ + \ T_B^n(s_2).
\end{aligned}
$$

Using these expressions in the formula of N_{part} (b), we get

$$
\begin{aligned}
N_{part}^{AB}(b) = &\int d^2s[T_A^p(s_1) \ + \ T_A^n(s_1)]\{1-(1-\frac{\sigma[T_B^p(s_2)+T_B^n(s_2)]}{B})^B\} \\
&+\int d^2s[T_B^p(s_2) \ + \ T_B^n(s_2)]\{1-(1-\frac{\sigma[T_A^p(s_1) \ + \ T_A^n(s_2)]}{A})^A\}
\end{aligned}
$$

We expand in power series and get

$$
N_{part}^{AB}(b) \approx N_{part}^{pp}(b) \ + \ N_{part}^{nn}(b) \ + \ N_{part}^{pn}(b) \ + \ N_{part}^{np}(b)
$$

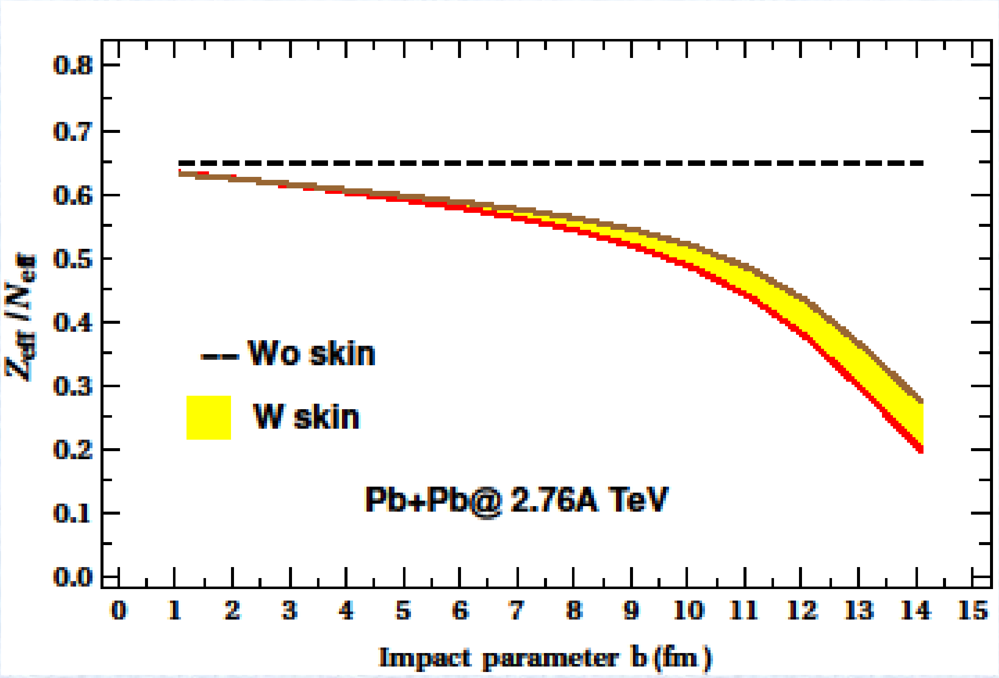
We have considered the following ansatz for symmetric collisions:

$$Z_{eff} = \frac{N^{pp}_{part}(b)}{2}, \quad N_{eff} = \frac{N^{nn}_{part}(b)}{2}$$

Pure events

$$Z_{mix} = \frac{Z_{eff}}{A_{eff}} N^{pn}_{part}(b), \quad N_{mix} = \frac{N_{eff}}{A_{eff}} N^{pn}_{part}(b)$$

Mixed events



Qualitatively agrees with an earlier study by H. Paukkunen, PLB 745(2015) 73

Centrality dependent direct photon production at the LHC:

- Direct photons (those do not come from hadronic decays) are a valuable probe of the strongly interacting matter because of it's large mean free path.

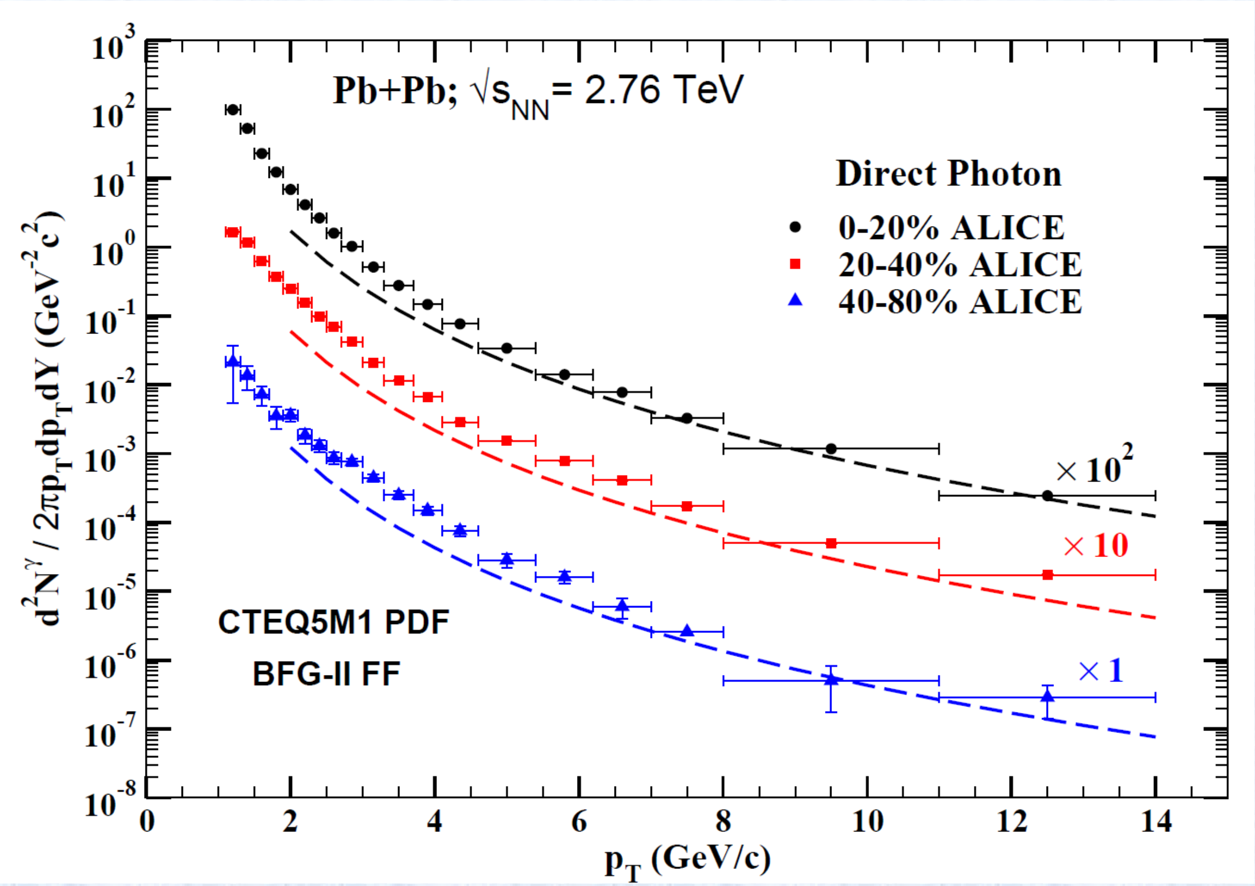
- Different sources of direct photons: Prompt photons from initial scattering, Pre-equilibrium photons, Thermal photons from quark-gluon and hadronic phase, Photons from jet-thermal interaction.

- The production cross-section of prompt photons in hadron-hadron collisions:

$$\frac{d^2\sigma}{d^2p_T^\gamma dy_\gamma} = \sum_{i,j} \int dx_1 f_A^i(x_1, Q_f^2) \int dx_2 f_B^j(x_2, Q_f^2)$$
$$\times \sum_{c=q,g} \int \frac{dz}{z^2} D_{c/\gamma}(z, Q_F^2)\, \frac{d\sigma_{ij\to cX}(x_1, x_2; Q_R^2)}{d^2p_T^c dy_c},$$

- In case of nucleus-nucleus collisions, we replace the free nucleon PDF by isospin averaged nuclear PDF

$$f_A^i(x,Q^2) = R(x,Q^2)\{\frac{Z}{A} f_p^i(x,Q^2) + (1-\frac{Z}{A}) f_n^i(x,Q^2)\}$$



$$Q_f = Q_R = Q_F$$
$$= 1.0\, p_T$$

EKS98 nuclear shadowing

Data Ref: PLB 754 (2016) 235 (ALICE Coll.)

- In order to quantify the effect of neutron skin-thickness on prompt photon production, we have calculated the 'Central-to Peripheral ratio; R_{CP} '

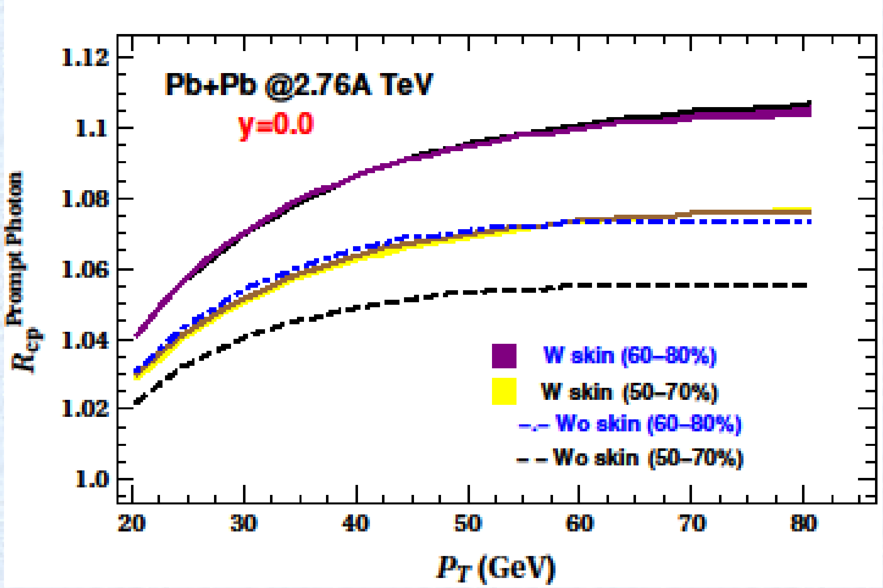
$$R_{CP} = \frac{[d^2N/dp_T dy / N_{coll}(b)]_{Central}}{[d^2N/dp_T dy / N_{coll}(b)]_{Peripheral}}$$

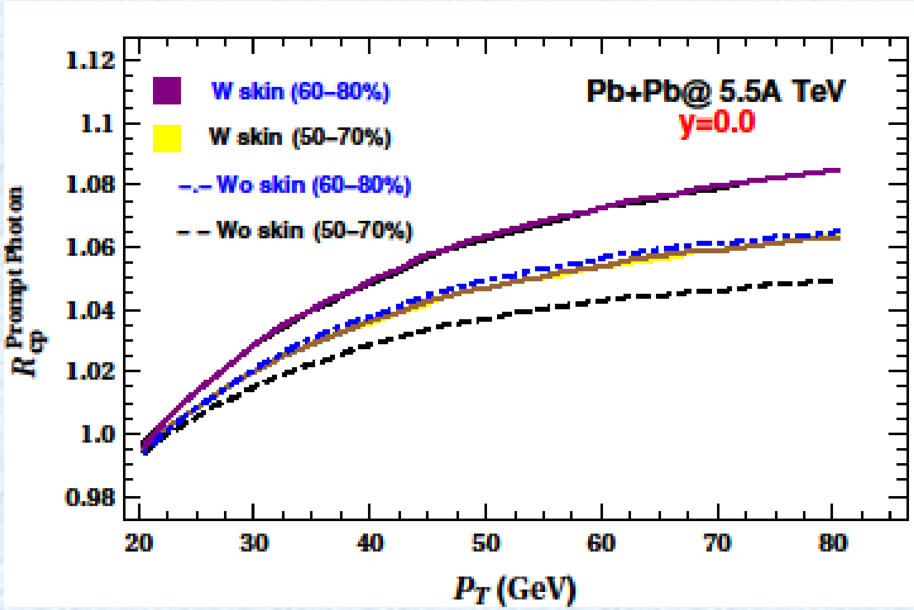
✓ Advantage: The PDF uncertainty, scale uncertainty relatively cancels out.

- We have calculated the above quantity for Pb+Pb collisions at 2.76 TeV and 5.5 TeV per nucleon center of mass energies and at mid and forward rapidities

- We have considered central collisions of 0-10% and peripheral collisions of 50-70% and 60-80% centrality for each cases mentioned above.

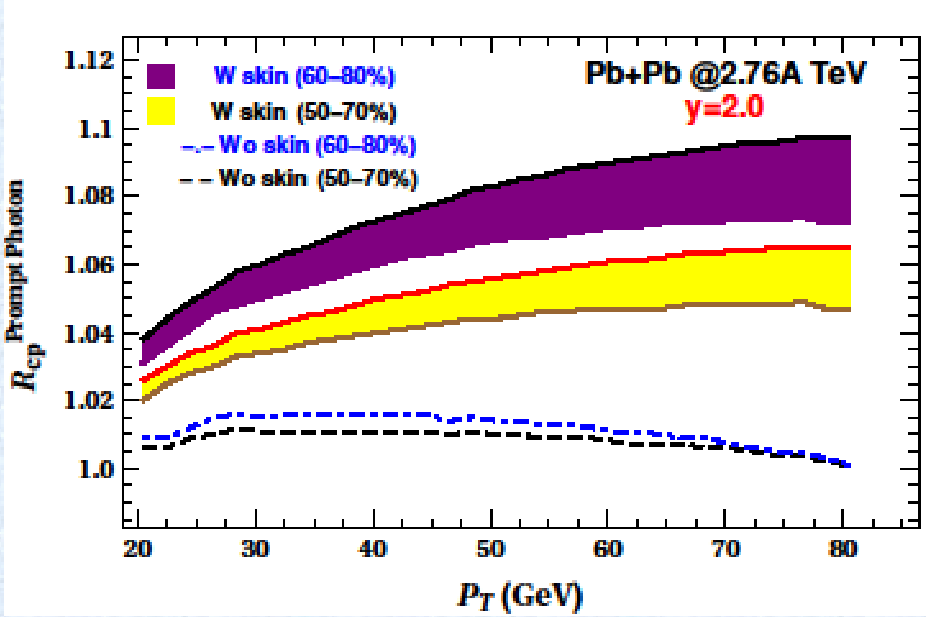
Pb+Pb Collisions @ 2.76A, 5.5A TeV at mid rapidity

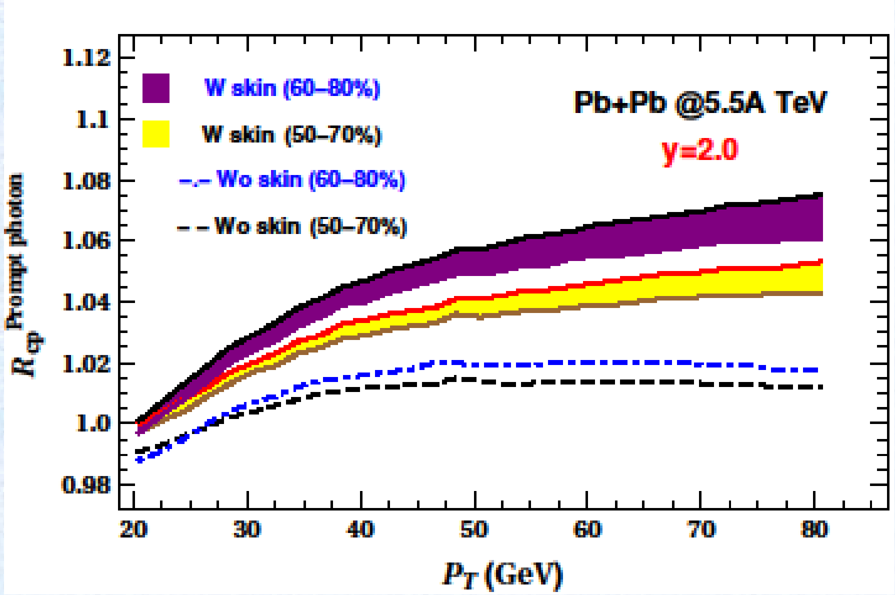




Inclusion of neutron skin enhances R_{cp} by ~2-3%

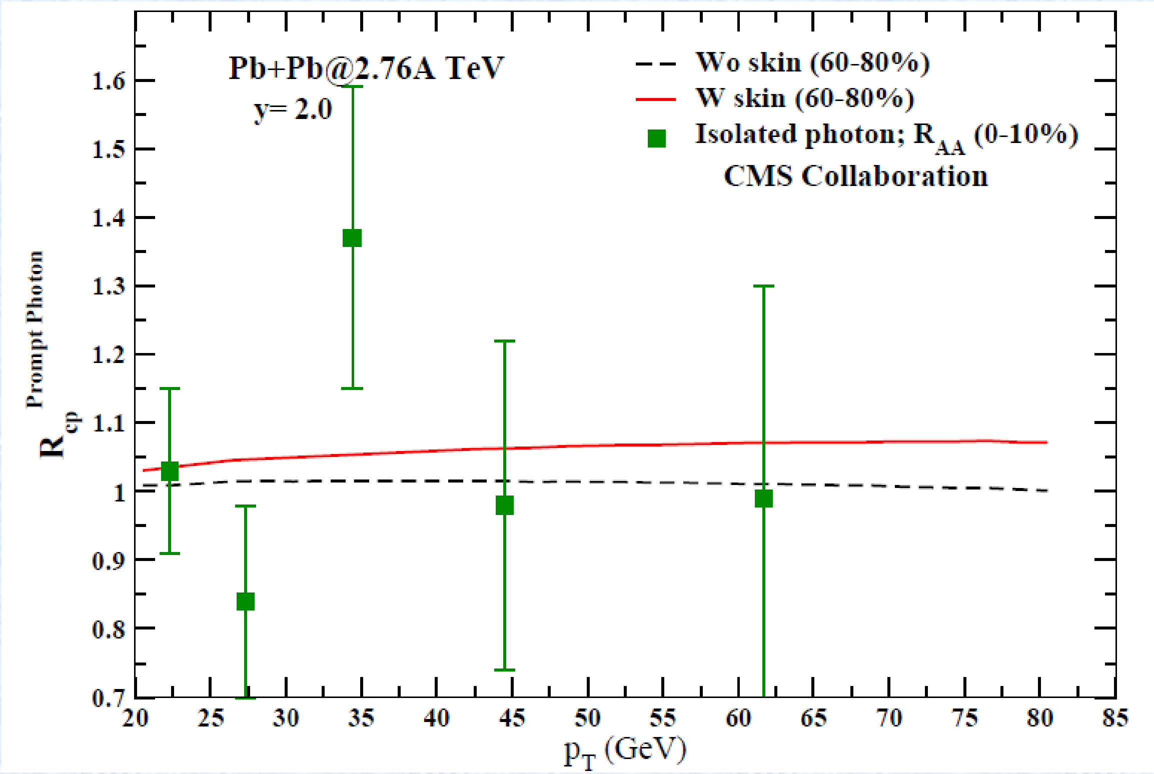
Pb+Pb Collisions@ 2.76A, 5.5A TeV at forward rapidity





Inclusion of neutron skin enhances R_{cp} by ~5-7%

▪A comparison with isolated photon R_{AA} :



Data Ref: PLB 710 (2012) 256 (CMS Coll.)

Summary and Outlook-2:

- The generic effect of neutron skin thickness of Pb nuclei on prompt photon production at LHC energies has been investigated.

- We found effective neutron-to-proton ratio decreases in large impact parameter collisions by including neutron skin thickness.

- The central-to-peripheral ratio "R_{cp}" of inclusive prompt photon production increases by 2-3% at mid-rapidity and by 5-7% at forward rapidity, while accounting for neutron skin thickness.

- The measurement provides a complementary way to constrain the neutron skin thickness parameters.


Thank you
STAR

Jet-Photon Conversion

The rate of production:

$$E_\gamma \frac{dN^{(A)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(p_\gamma)$$

$$\times \int d^3p \, f_{\bar{q}}(p)[1+f_g(p)]\sigma^{(A)}(s) \frac{\sqrt{s(s-4m^2)}}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

$$E_\gamma \frac{dN^{(C)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(p_\gamma)$$

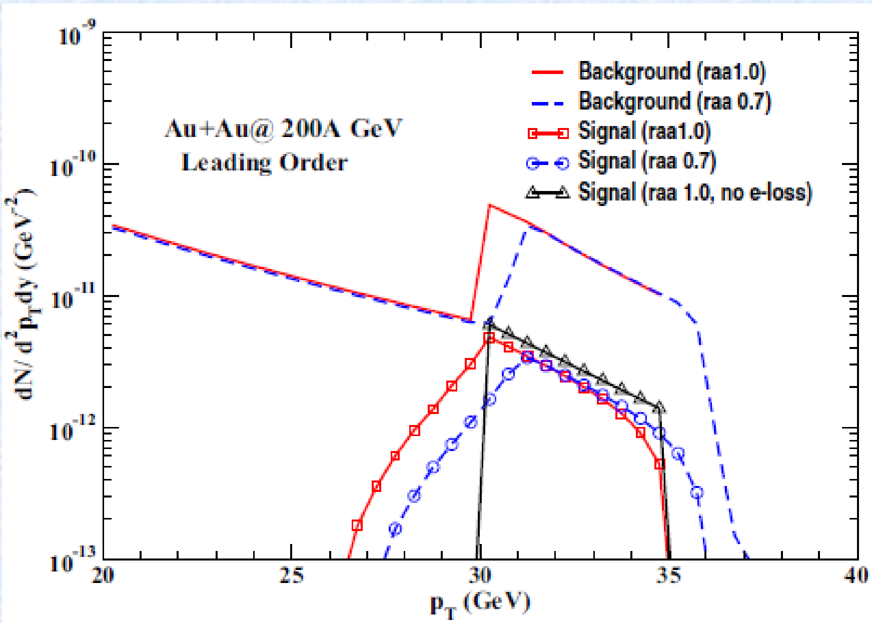
$$\times \int d^3p \, f_g(p)[1-f_q(p)]\sigma^{(C)}(s) \frac{s-m^2}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

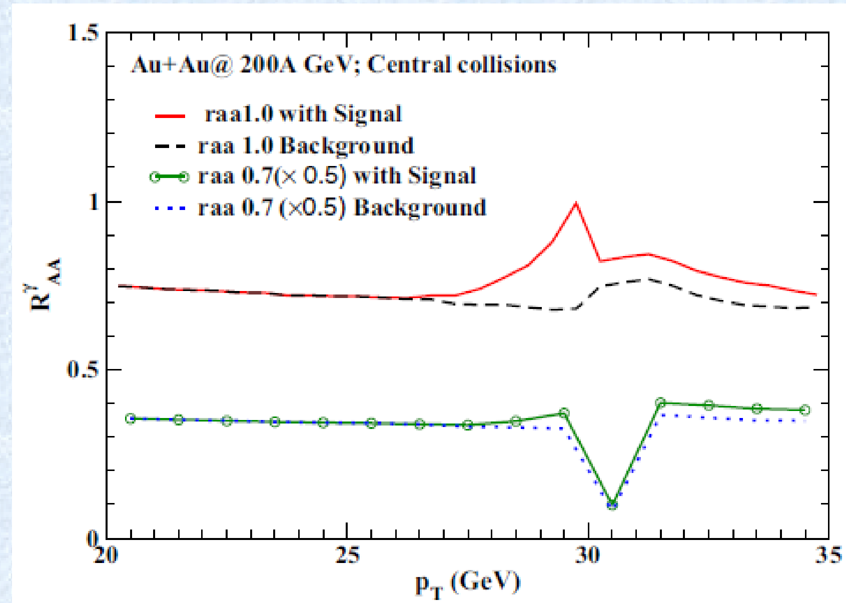
$$f^q(p) = f^{jet}(p) + f^{th}(p)$$

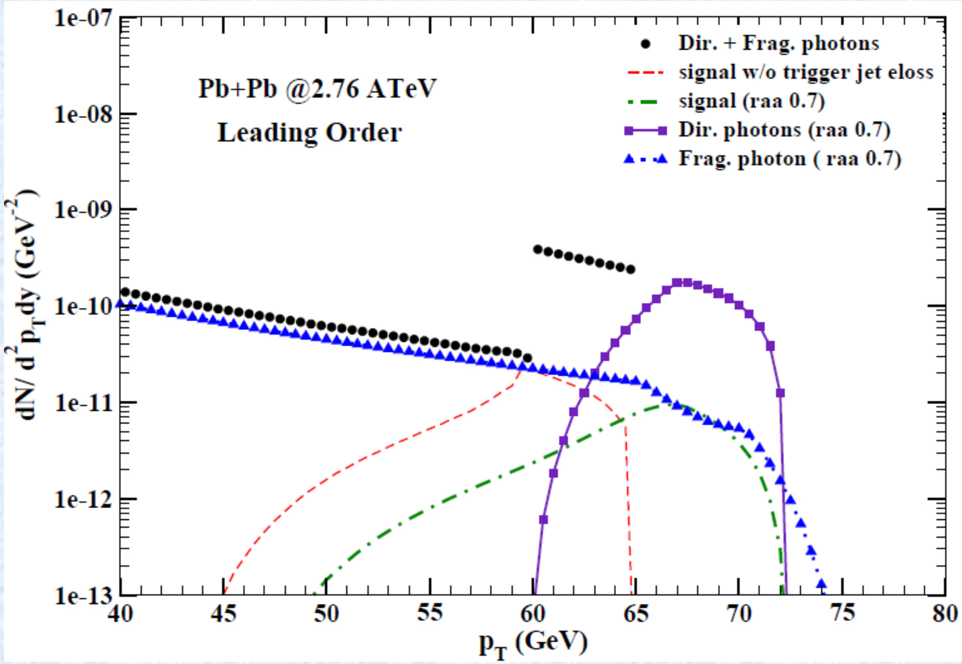
$$dN^\gamma = f_{th} \otimes f_{th} + f_{th} \otimes f_{jet} + \ldots.$$

Jet-converted photons

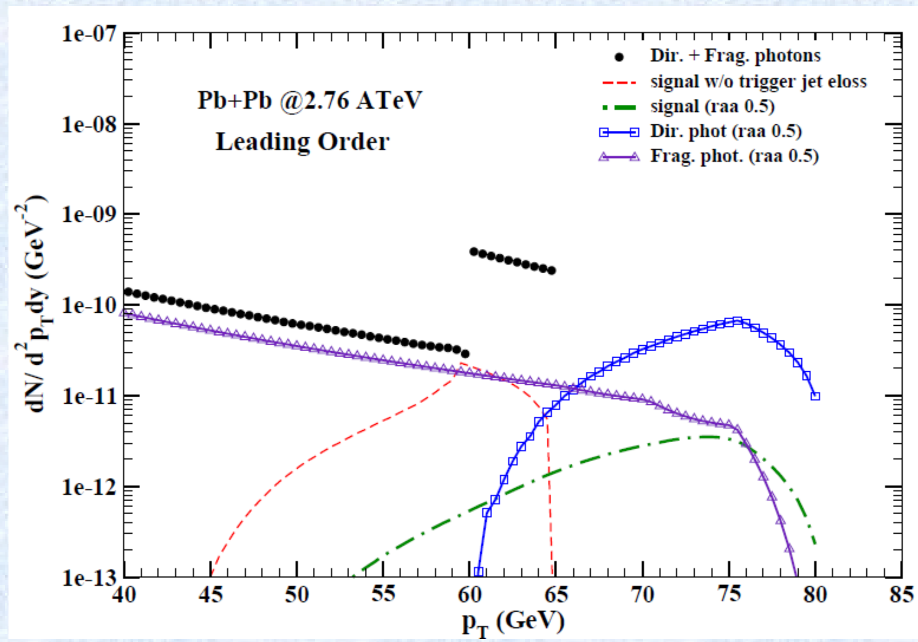
Results at RHIC energy







Dir. + Frag. photons
signal w/o trigger jet eloss
signal (raa 0.7)
Dir. photons (raa 0.7)
Frag. photon (raa 0.7)
Pb+Pb @2.76 ATeV
Leading Order
dN/ d^{2}p$_T$dy (GeV^{-2})
p$_T$ (GeV)



Dir. + Frag. photons
signal w/o trigger jet eloss
signal (raa 0.5)
Dir. phot (raa 0.5)
Frag. phot. (raa 0.5)
Pb+Pb @2.76 ATeV
Leading Order
dN/ d^{2}p$_T$dy (GeV^{-2})
p$_T$ (GeV)

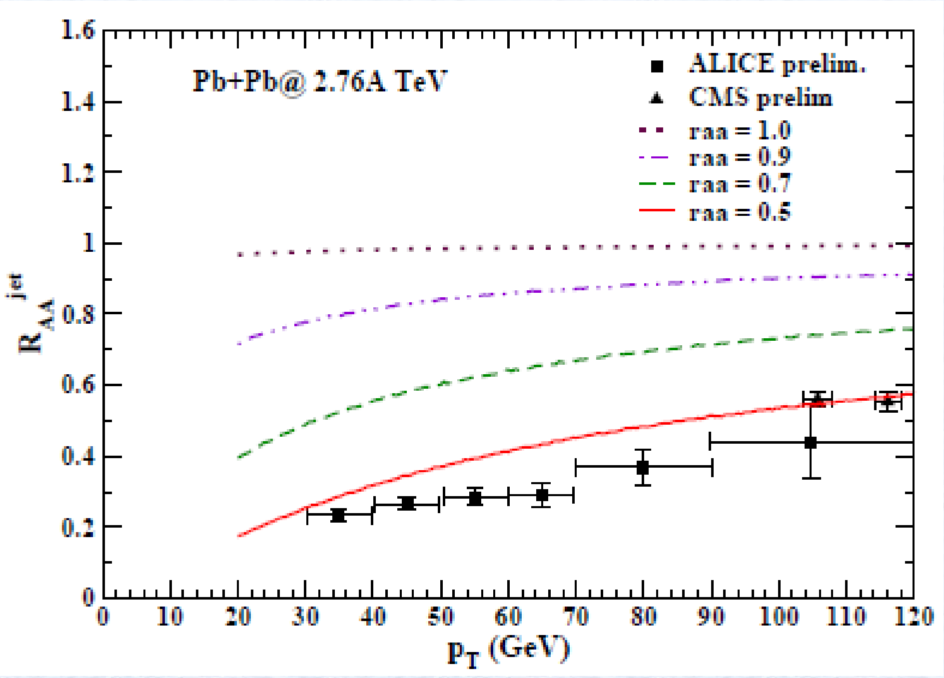
Effect of trigger jet energy loss

❖ Recent measurements at LHC (arXiv:1304.5945, PLB 2015) suggest a strong suppression of trigger jets in central collisions.

We model the trigger jet energy loss as:

$$\frac{dE_T}{d\tau} = -\hat{r}\ln\left(\frac{E_T}{\Lambda}\right)$$

$\hat{r}$ **is proportional to local entropy density, Λ= 0.2 GeV**



SD, R J Fries, D K Srivastava
PRC 90 (2014)

➢ Trigger jet energy loss affects the Background (direct and fragmentation photon) and as well as the Signal

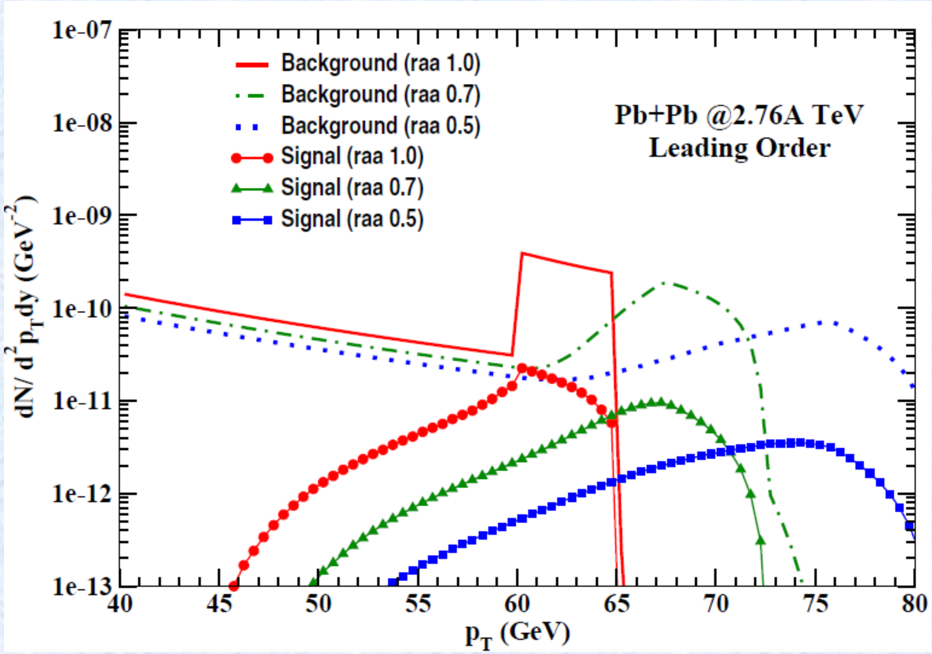
The parton-jet pair distribution:

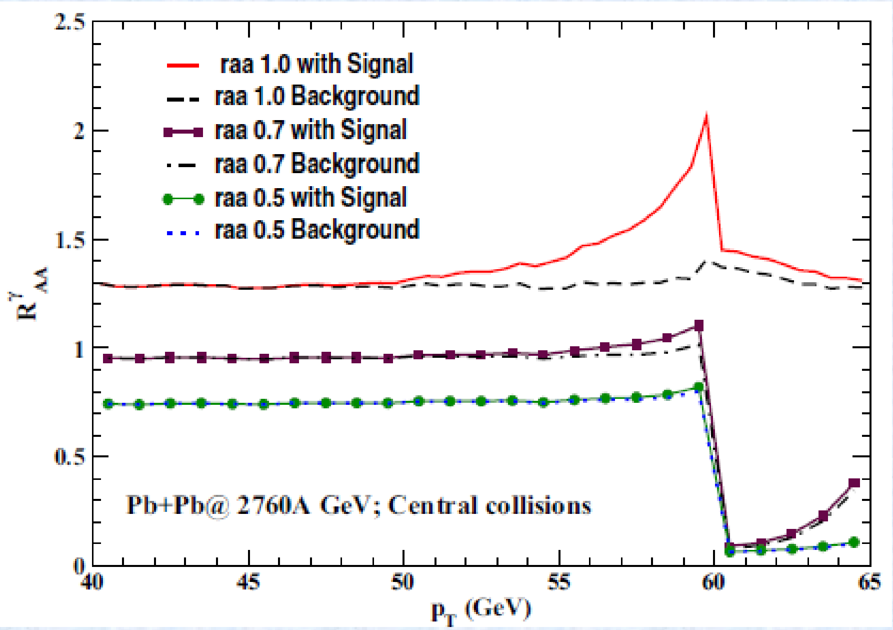
The parton-jet pair distribution integrated over a window Γ in E_T - ϕ-η space

$$f_q^{\mathcal{T}_J}(\mathrm{p}_q, x) = \frac{(2\pi)^3}{g_q \tau p_T}\delta(y-\eta)\rho(\tau, \mathrm{x}_\perp^0) \times \int_{\mathcal{T}_J} dE_T\, dy_j\, d\phi_j\, E_q \frac{dN}{d^3p_q\, dE_T\, dy_j\, d\phi_j}\Bigg|_{\substack{\mathrm{p}_q^0 = \mathrm{p}_q + \Delta \mathrm{p}_q \\ E_T^0 = E_T + \Delta E_T}}$$

- ➢The parton-jet pair are evolved through the medium while their respective energy losses are also accounted.
- ➢The parton back-scattering probability is also computed along the way.

❑Background and Signal: w trigger jet energy loss





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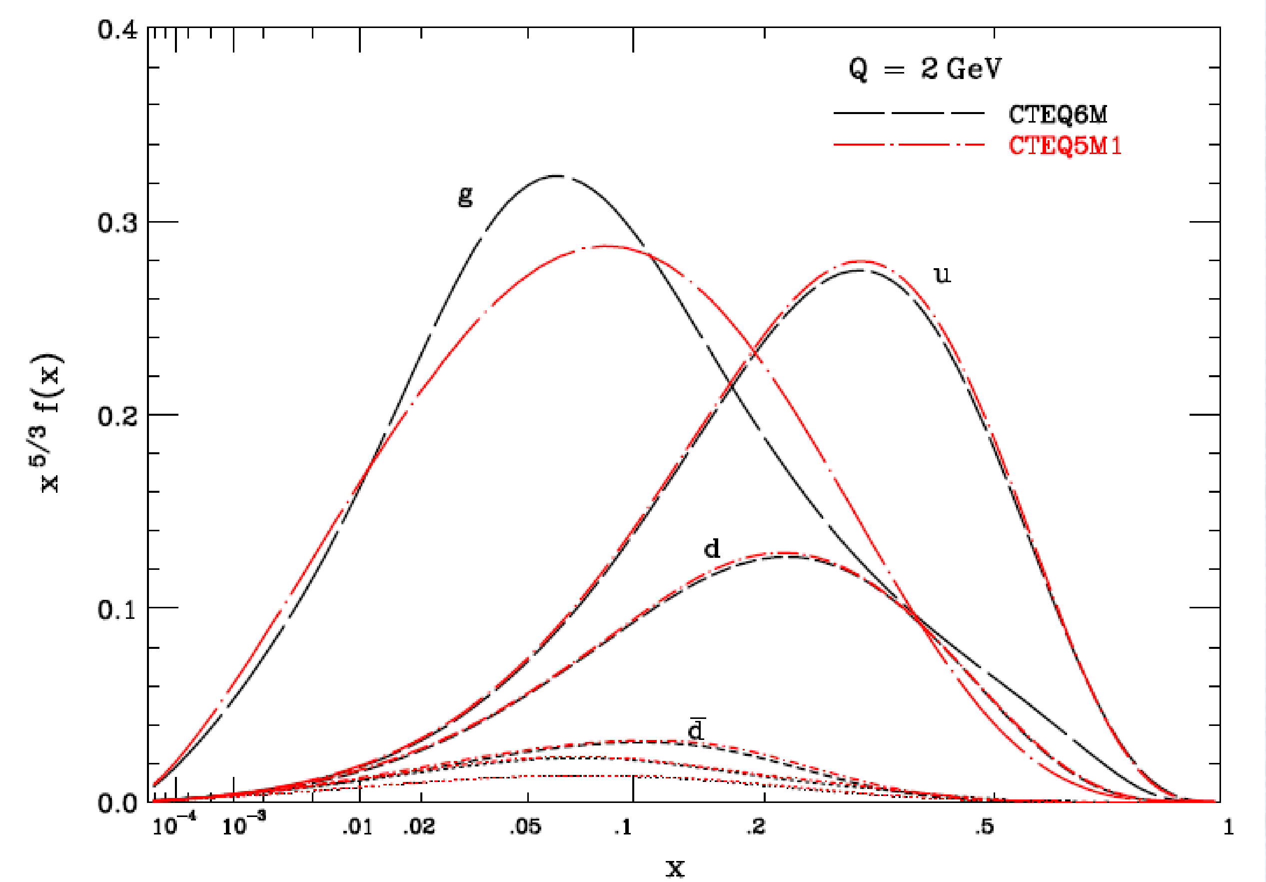
- **Signal and Background are calculated for Leading order kinematics**
- **Both trigger jet and parton energy loss are taken into account**
- **Trigger jet energy loss tends to wash out the strong correlation with parent jet**



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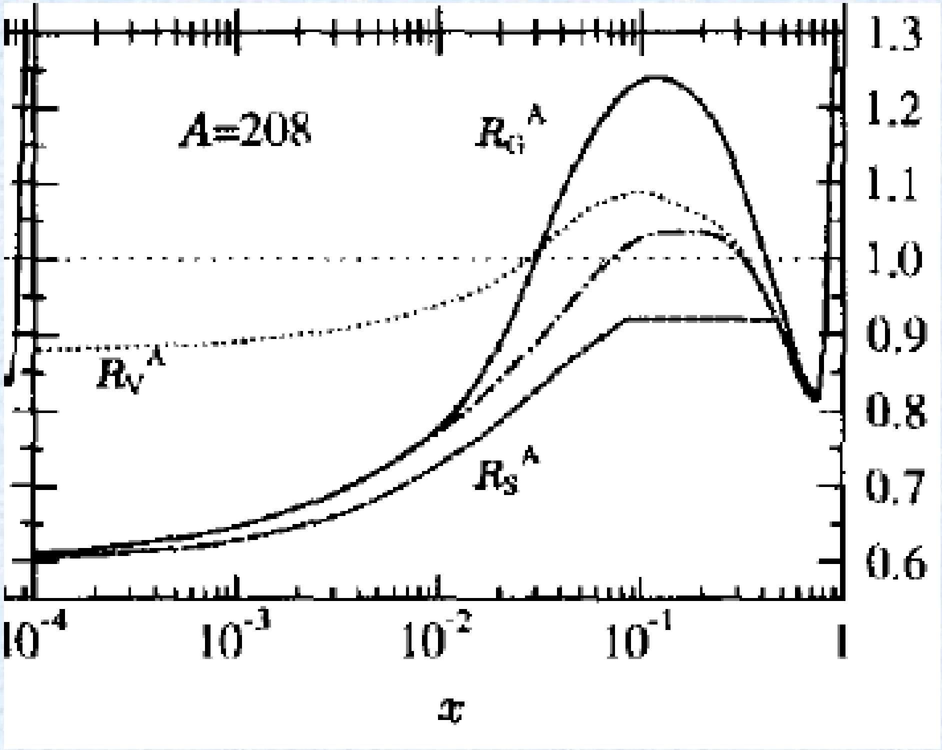

EKS98 Nuclear parton distibution