Direct Photon Production

Jianwei Qiu
Brookhaven National Laboratory

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Outline of the lecture

- Why photons?
- Photon production at large transverse momentum
- Direct vs fragmentation contribution
- Isolation cut
- From fixed target to collider energies
- Summary

Why photons?

- Photon is a EM probe:

  It can be produced at any stage of the collision

  It does not interact strongly once produced

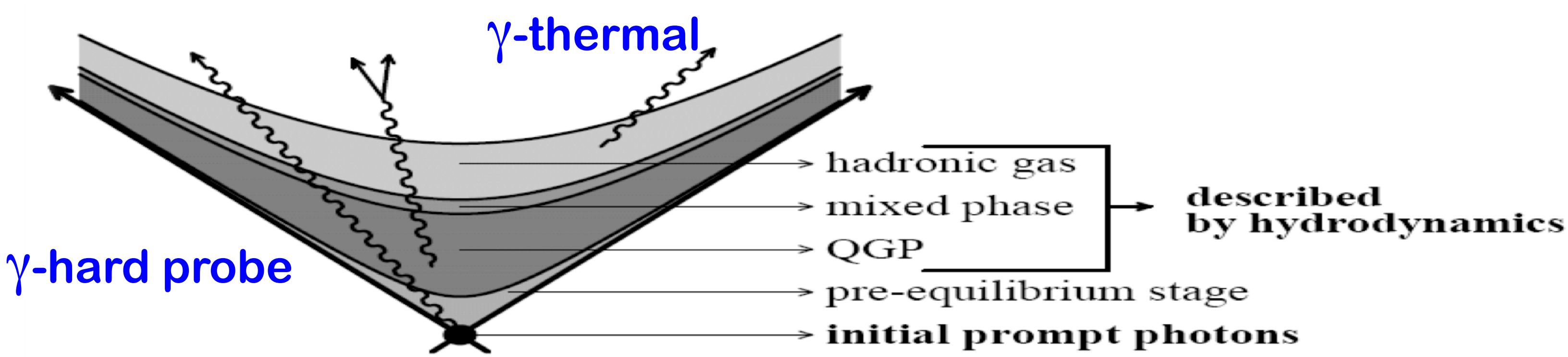
- Good probe of short-distance strong interaction:

  Isolated or "direct" photon is produced at a distance $1/p_T << \text{fm}$

  "snap shot" of what happened at the distance scale $1/p_T$

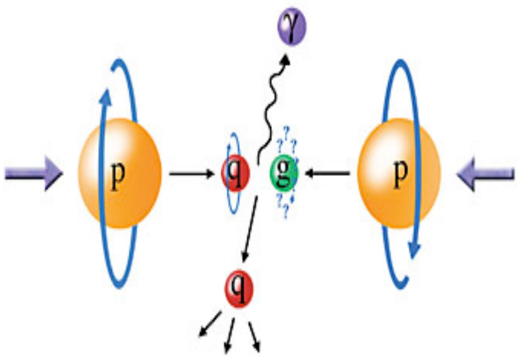
  Key background of Higgs production if $M_H < 2\,M_W$: $H^0 \rightarrow \gamma + \gamma$

- Photon can tell the full history of heavy ion collision



Theory behind the high p_T photon

❑ **Production mechanism – leading power factorization:**



$$\frac{d\sigma_{AB}}{dy dp_T^2} = \int dx f_{a/A}(x,\mu) \int dx' f_{b/B}(x',\mu) \frac{d\hat{\sigma}_{ab}(\alpha_s(\mu))}{dy dp_T^2}$$
$$+ \text{ frag contribution} + \mathcal{O}\left(\frac{1}{p_T^n}\right)$$

Hard part: $\hat{\sigma}_{ab}(\alpha_s(\mu)) = \hat{\sigma}^0_{ab}\alpha_s^m(\mu) + \hat{\sigma}^1_{ab}(\log(\mu))\alpha_s^{m+1}(\mu) + \ldots$

❑ **Predictive power:**

✧ **Short-distance part is Infrared-Safe, and calculable**

✧ **Long-distance part can be defined to be Universal - PDFs**

❑ **Factorization and renormalization scale dependence:**

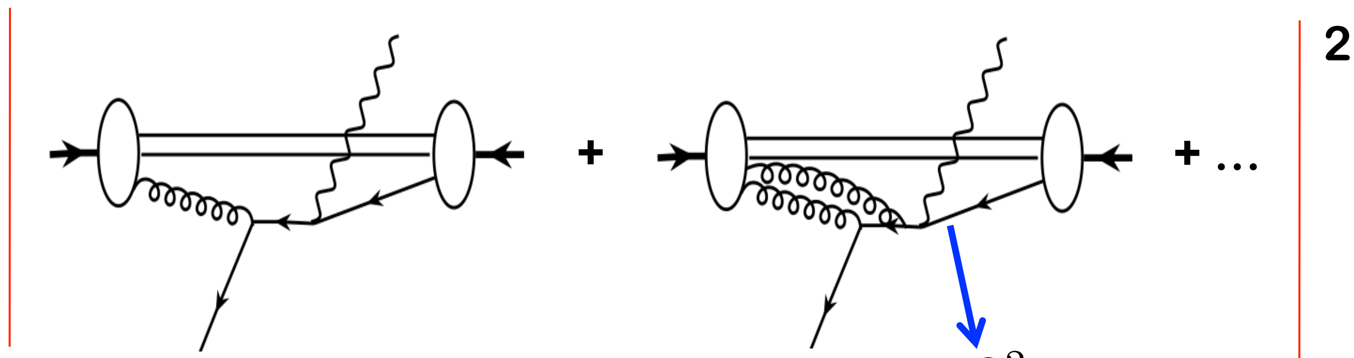
✧ **NLO is necessary**

❑ **Power correction could be important at low p_T**

Factorization is an approximation

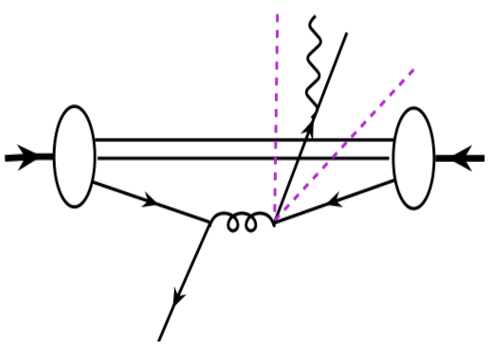
- **Multiple scattering and power correction:**

$\sigma(P_T) \sim$



$$\propto \hat{\sigma}(P_T, x_1, x_2, \mu) \otimes \phi(x_1, \mu) \otimes \phi(x_2, \mu) + \mathcal{O}(\frac{Q_s^2}{p_T^2})$$

- **Fragmentation function and isolation cut:**



$$\sigma(P_T) \propto \hat{\sigma}(P_T, x_1, x_2, \mu) \otimes \phi(x_1, \mu) \otimes \phi(x_2, \mu) \otimes D(z) + \mathcal{O}(\frac{Q_s^2}{p_T^2})$$

Note: $\ln(R)$ **Cone size cannot be too small**

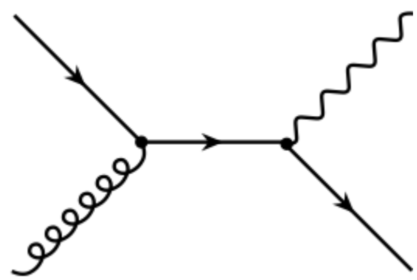
$\ln(E_h/E_\gamma)$ → E_h/E_γ **Not too small**

Direct photon is sensitive to gluon

- Sensitive to gluon at the leading order – hadronic collision:

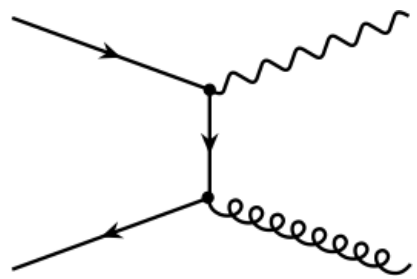
  ✧ Lowest order direct $\mathcal{O}(\alpha_{em}\alpha_s)$:

  Compton: $q(\bar{q}) + g \to \gamma + q(\bar{q})$



+ …

  Annihilation: $q + \bar{q} \to \gamma + g$



+ …

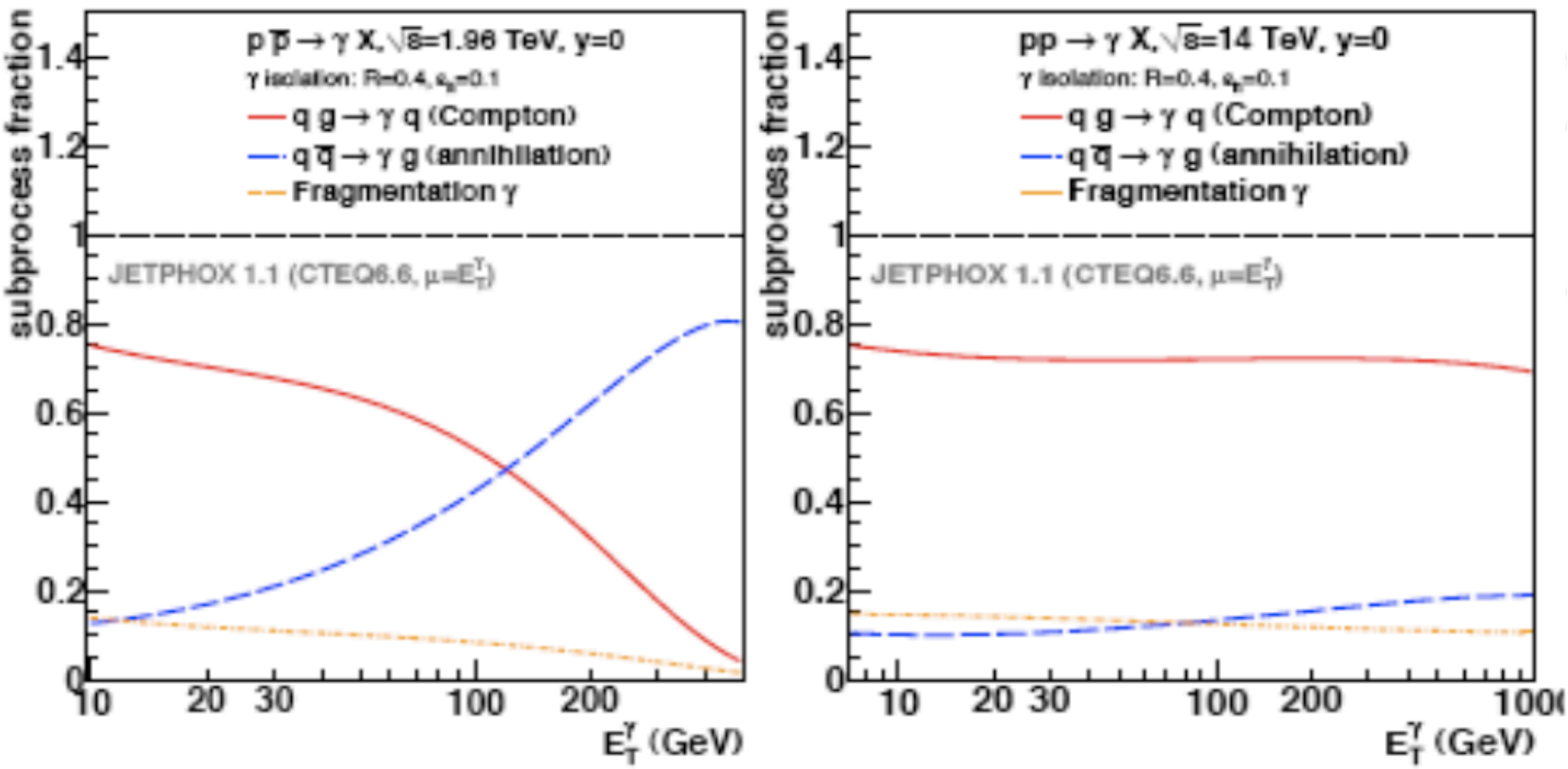
  ✧ Compton dominates in pp collision:

  $f_{g/p}(x,\mu^2) \gg f_{\bar{q}/p}(x,\mu^2)$ for all x

Direct photon production could be a good probe of gluon distribution

Role of gluon in pp collision

❑ pp vs p$\bar{p}$ – dominance of gluon in pp:

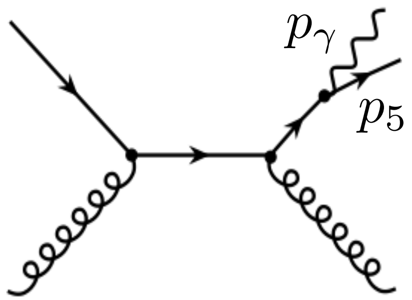


✧ Isolation cut removes the most of fragmentation contribution!

✧ More dominance in the forward region!

Complication from high orders

- **Final-state collinear singularity:**



$$\overline{\sum}|M(qg\to\gamma qg)|^2 \approx \frac{\alpha_{em}}{2\pi}\mathcal{P}^{(0)}_{q\to\gamma}(z)\,\frac{1}{s_{\gamma q}}\,\overline{\sum}|M(qg\to qg)|^2$$

$$\mathcal{P}^{(0)}_{q\to\gamma}(z) = \frac{1+(1-z)^2}{z}$$

$$s_{\gamma q} = (p_\gamma + p_5)^2 \to 0 \qquad \textbf{when} \quad p_\gamma \parallel p_5$$

An internal quark line goes on-shell signaling long-distance physics

- **Fragmentation contribution:**

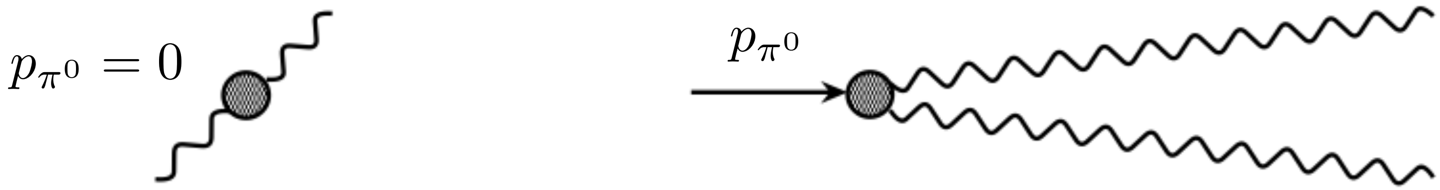
$$\frac{d\sigma^{\rm Frag}_{AB\to\gamma}}{dy\,dp_T^2} = \sum_{abc}\int \frac{dz}{z^2}D_{c\to\gamma}(z,\mu)\int dx\, f_{a/A}(x,\mu)\int dx'\, f_{b/B}(x',\mu)\,\frac{d\hat{\sigma}^{\rm Frag}_{ab\to c}}{dy\,dp_T^2}$$

- **Photon fragmentation functions – inhomogeneous evolution:**

$$\frac{\partial D_{c\to\gamma}(z,\mu)}{\partial\log(\mu)} = \frac{\alpha_{em}}{2\pi}\mathcal{P}_{c\to\gamma}(z) + \sum_{a=q\bar{q}g}\frac{\alpha_s}{2\pi}P_{ac}(z)\otimes D_{a\to\gamma}(z,\mu)$$

Complication from the measurement

- Separation the signal photon from $\pi^0 \to \gamma\gamma$:



  - ✧ When $p_{\pi 0}$ increases, the opening angle between two photons decreases
  - ✧ Two photons can be mis-identified as one photon at high p_T

- Isolation cut – algorithms:
  - ✧ CDF cone algorithm - reduction of fragmentation contribution

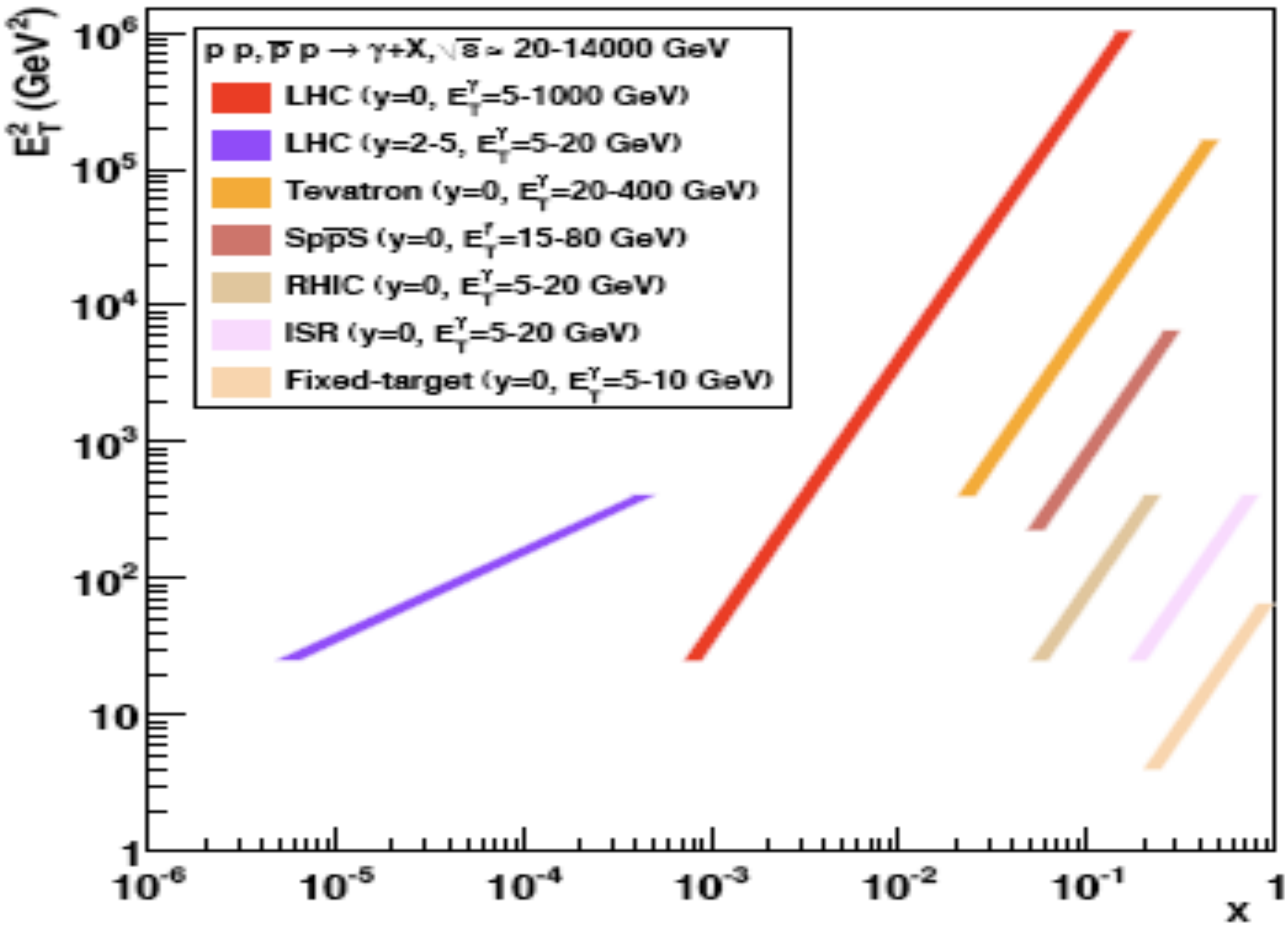
    Require that there is less then 1 GeV hadronic transverse energy in a cone of radius: $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \sim 0.7$

  - ✧ Modified cone algorithm – NO fragmentation contribution

    S. Frixione, Phys.Lett. B429 (1998) 369

Direct photon covers a wide range of x and Q^2

- Photon energy vs gluon momentum fraction x:



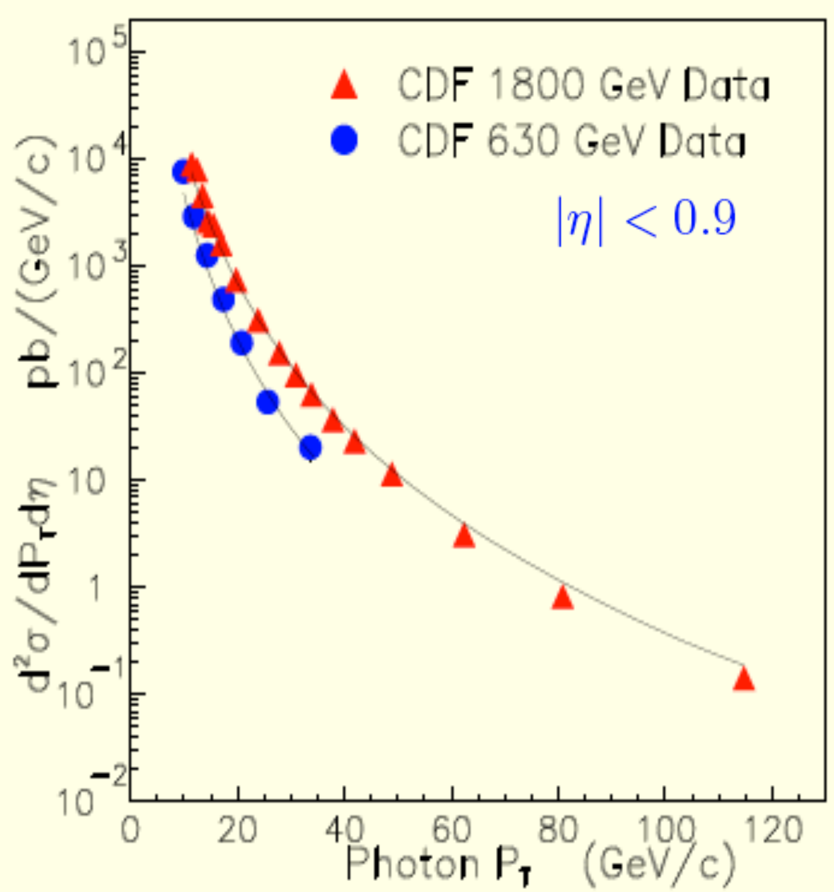
Ichou and D'Enterria, arXiv:1005.4529

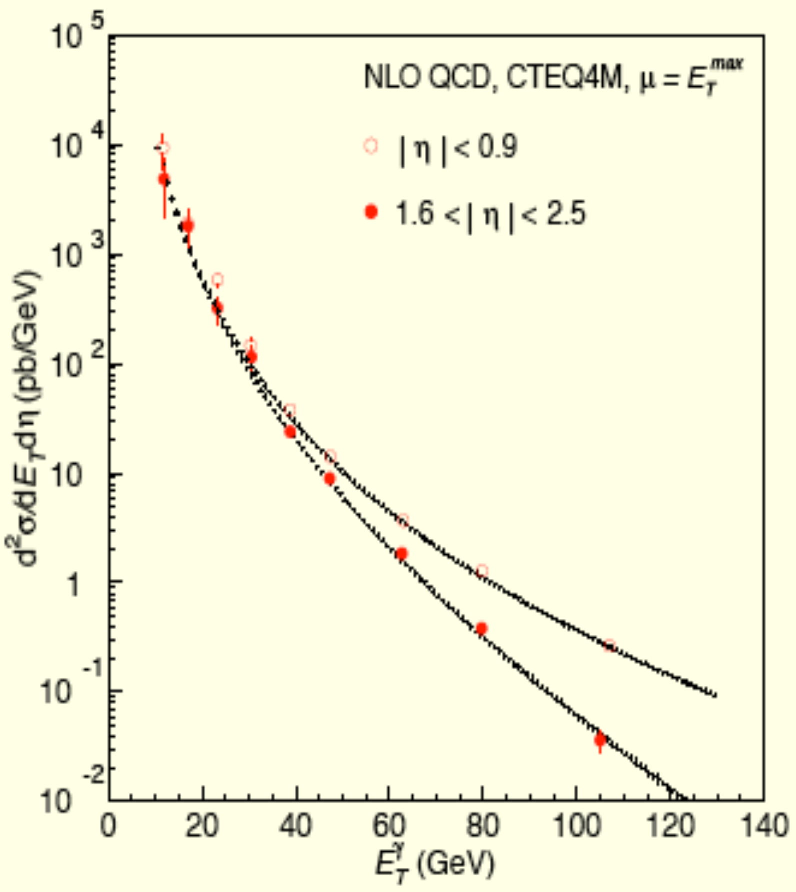
Direct photon data

- ❑ **Fixed target energies** $\sqrt{s} = 20 - 40 \text{ GeV}$:
  - ✧ With p_T = 3-10 GeV, data have high $x_T = \frac{2p_T}{\sqrt{s}}$
  - ✧ Challenge for NLO theory to fit data – wrong shape!
- ❑ **Collider energies:**
  - ✧ pp at ISR with $\sqrt{s} = 44 - 62 \text{ GeV}$
  - ✧ pp at CERN and Fermilab with $\sqrt{s} = 540 - 1960 \text{ GeV}$
  - ✧ $p\bar{p}$ at RHIC with $\sqrt{s} = 200 - 500 \text{ GeV}$, dA and AA as well
  - ✧ pp at LHC with $\sqrt{s} = 7 - 14 \text{ TeV}$, and PbPb as well
- ❑ **Data sources:**
  - ✧ Data review by W. Vogelsang and M.R. Whalley, J. Phys. G23, Suppl. 7A, A1 (1997)
  - ✧ Online database at http://durpdg.dur.ac.uk/HEPDATA

Theory vs experimental data

❑ Tevatron data





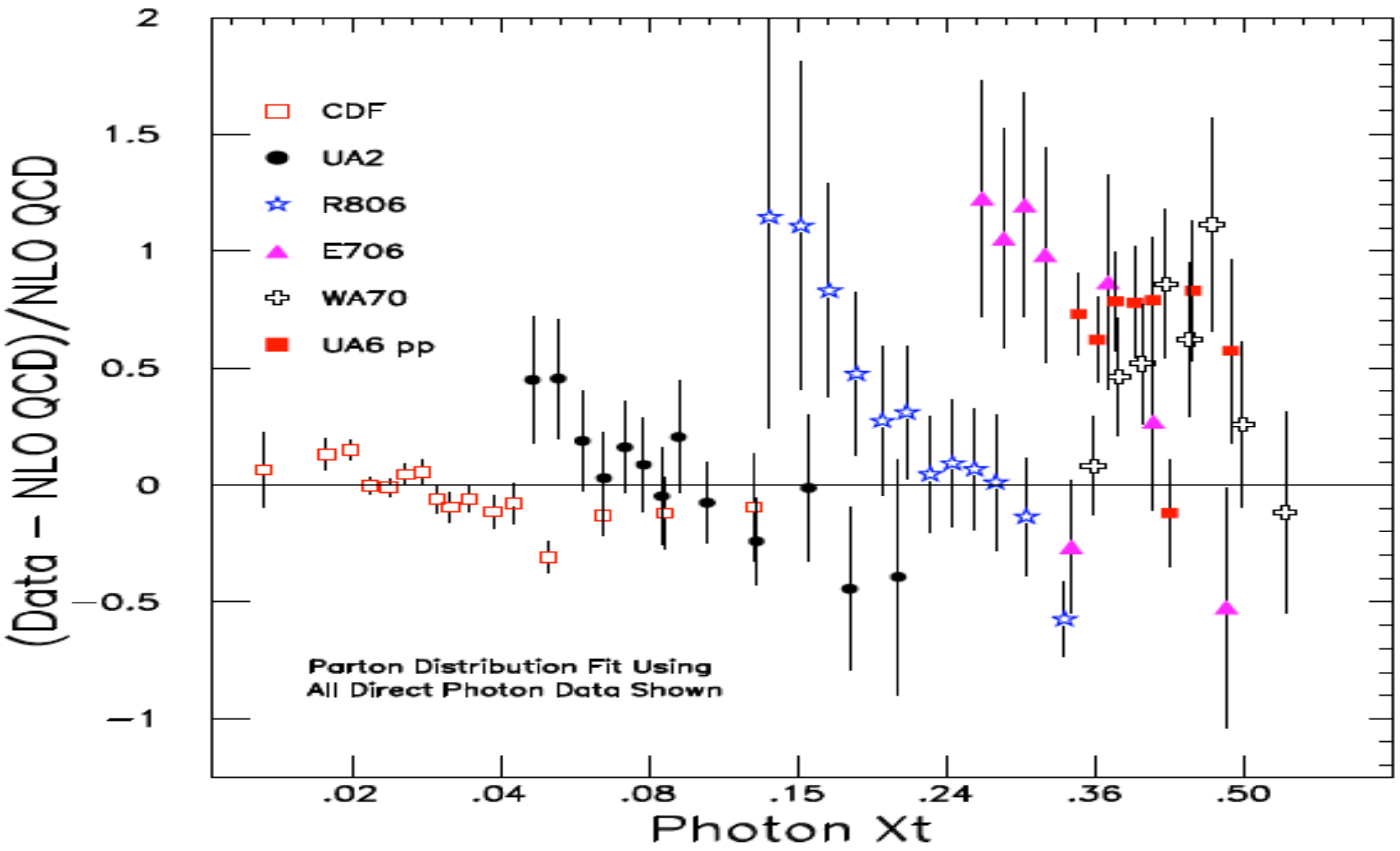
✧ **Agreement looks good when plotted on a logarithmic scale**

✧ **QCD description of direct photon production works**

Compare with data from different expt's

❑ **CTEQ global analysis:**

CTEQ Huston et al.



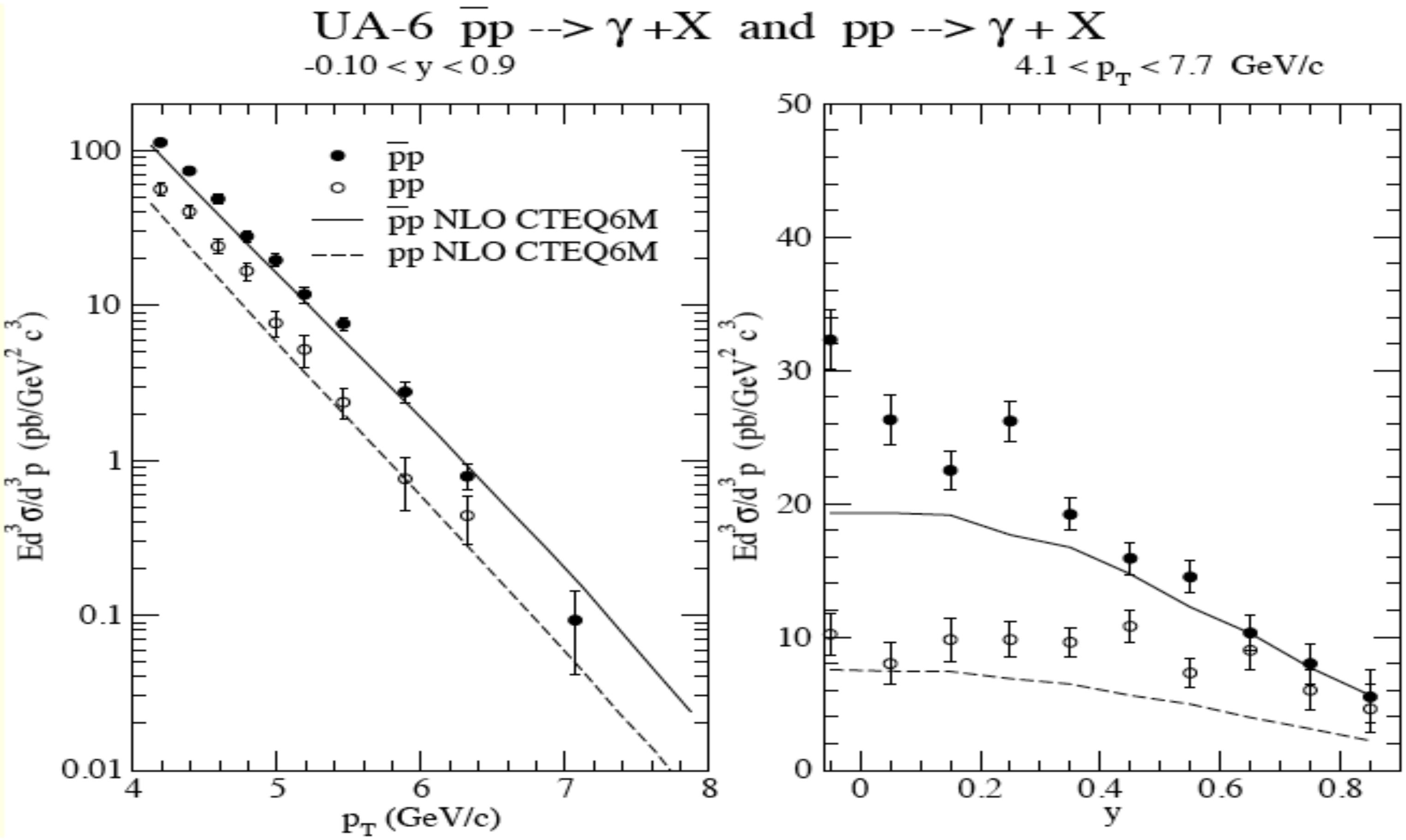
$$x_T = \frac{2p_T}{\sqrt{s}}$$

✧ **Neither PDFs nor photon FFs can significantly improve the shape**

✧ **Direct photon data were NOT in recent global fits**

Experiments with both pp and p$\bar{\text{p}}$

❑ **UA6:** both pp and $\bar{p}p$ at $\sqrt{s} = 24.3$ GeV

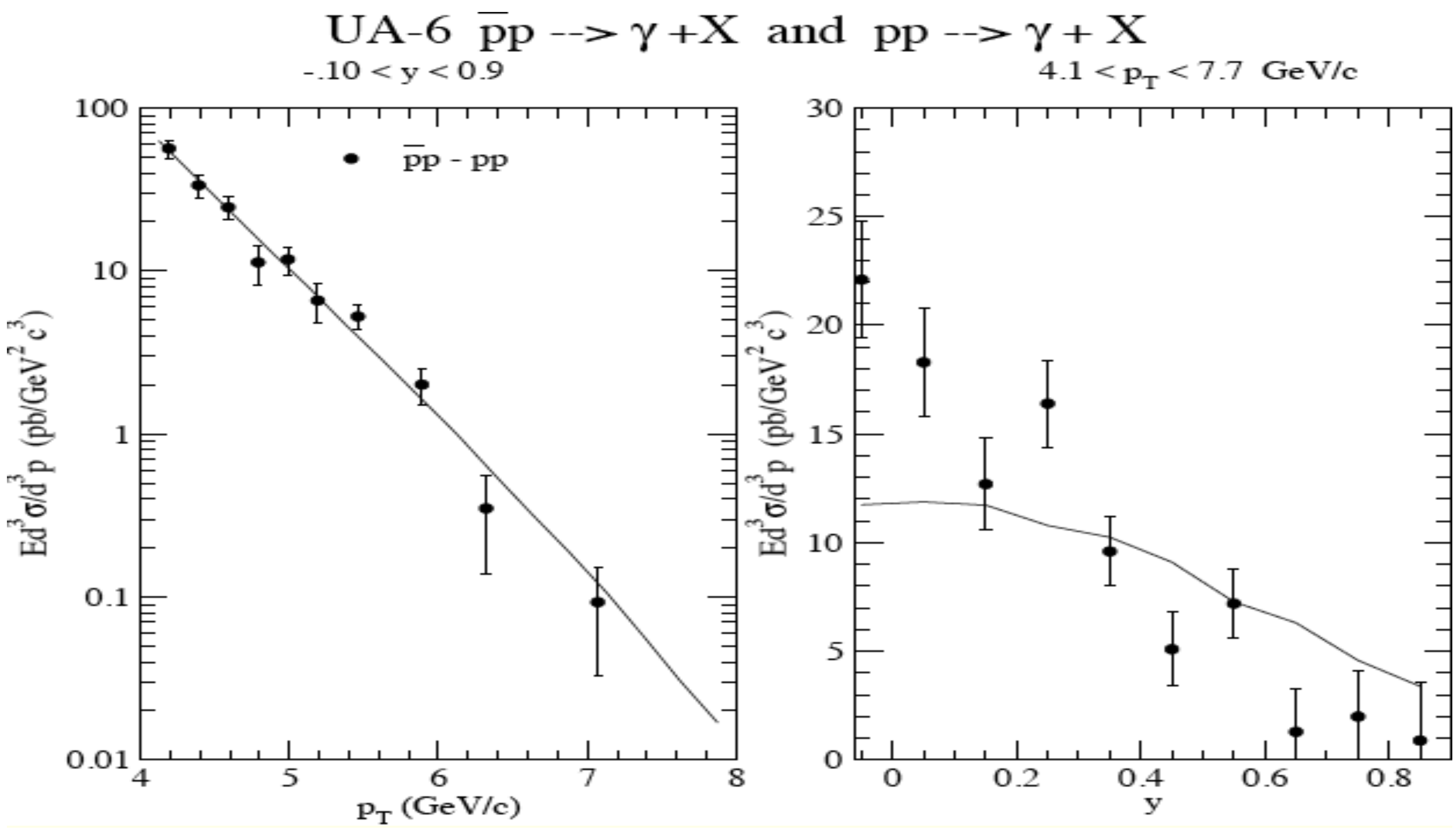


✧ **Theory curves are below the data**

✧ **Rapidity curves are flatter**

Role of gluon distribution?

❑ **UA6: $\bar{p}p$ - pp** both pp and $\bar{p}p$ at $\sqrt{s} = 24.3$ GeV

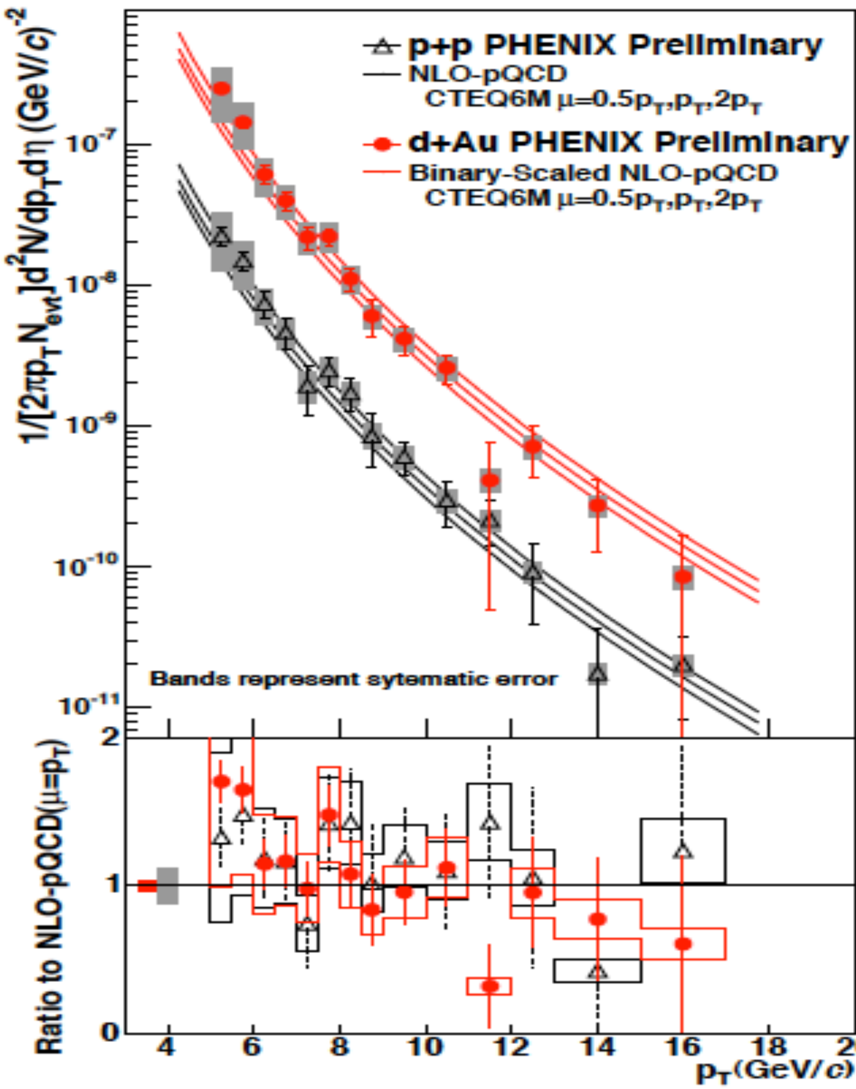


✧ **NO gluon contribution to the difference!**

✧ **Theory matches the data better – role of gluon?**

Theory works well at RHIC energy

PHENIX



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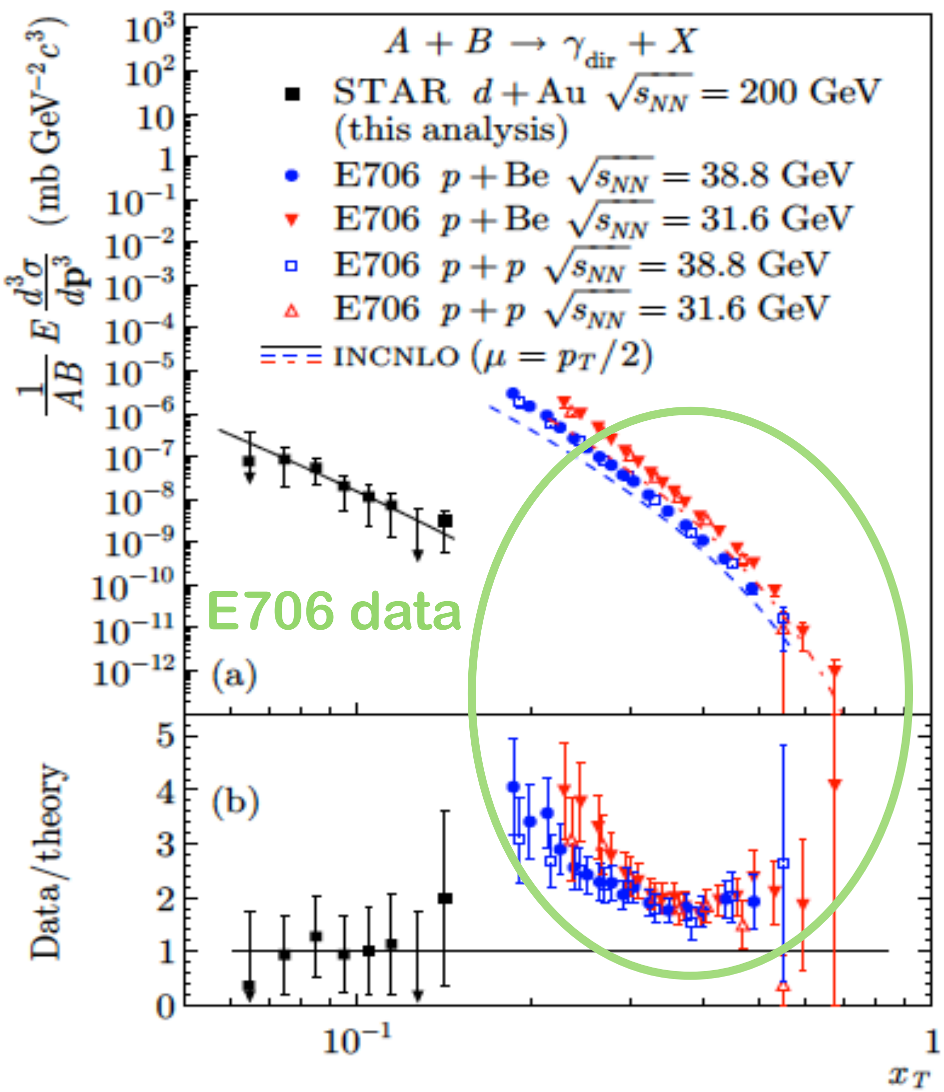
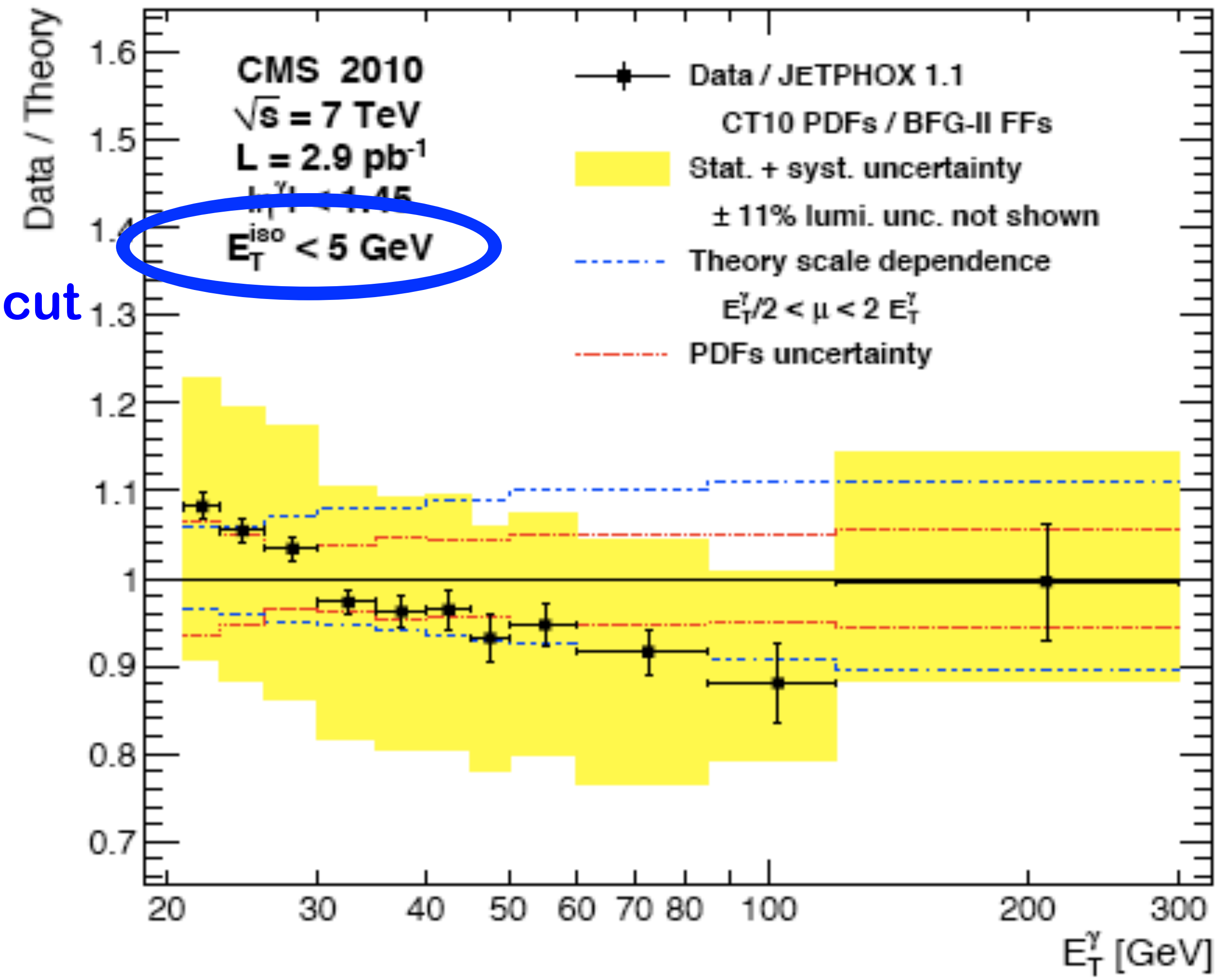


How about at the LHC?

- CMS:

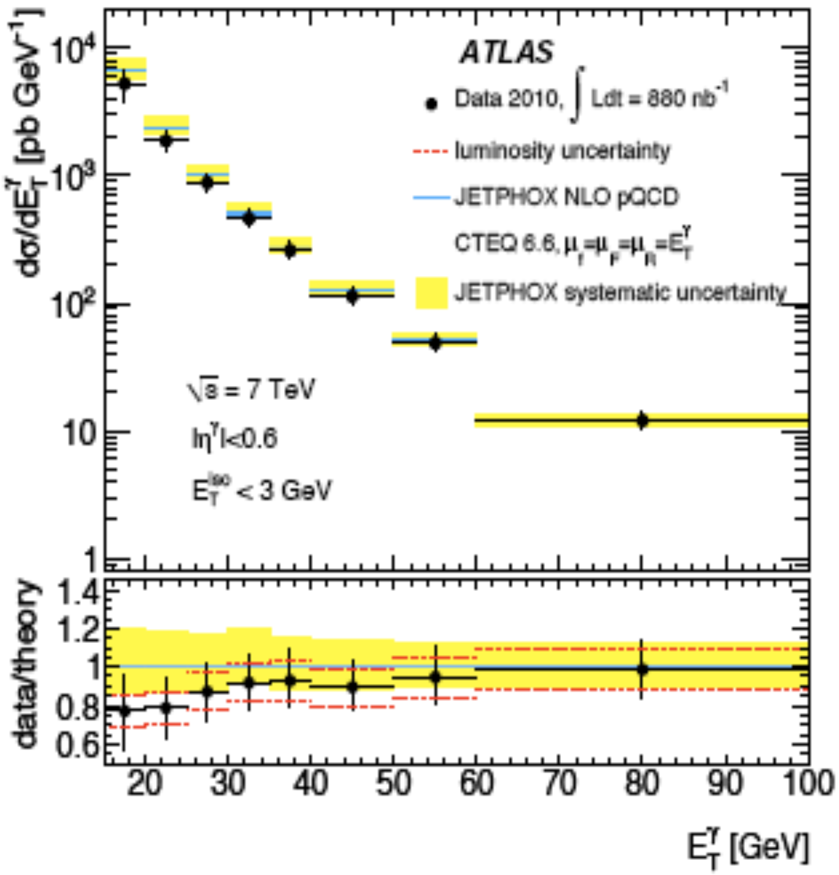
Isolation cut

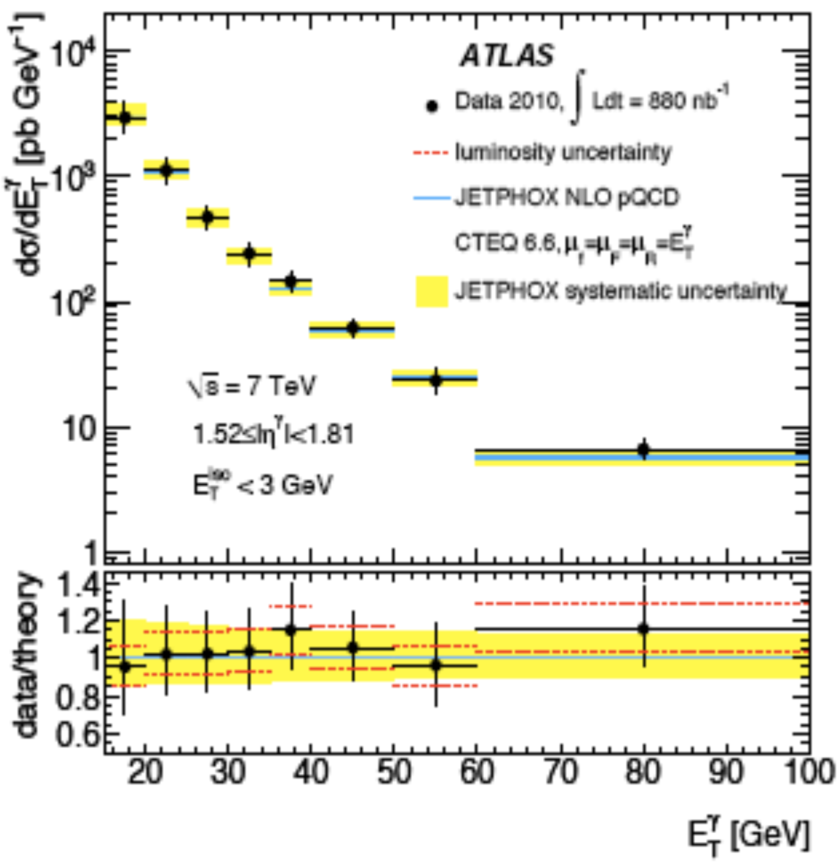


✧ Shape in x_T – within the PDF uncertainty?

Rapidity dependence at the LHC

❑ **ATLAS:**

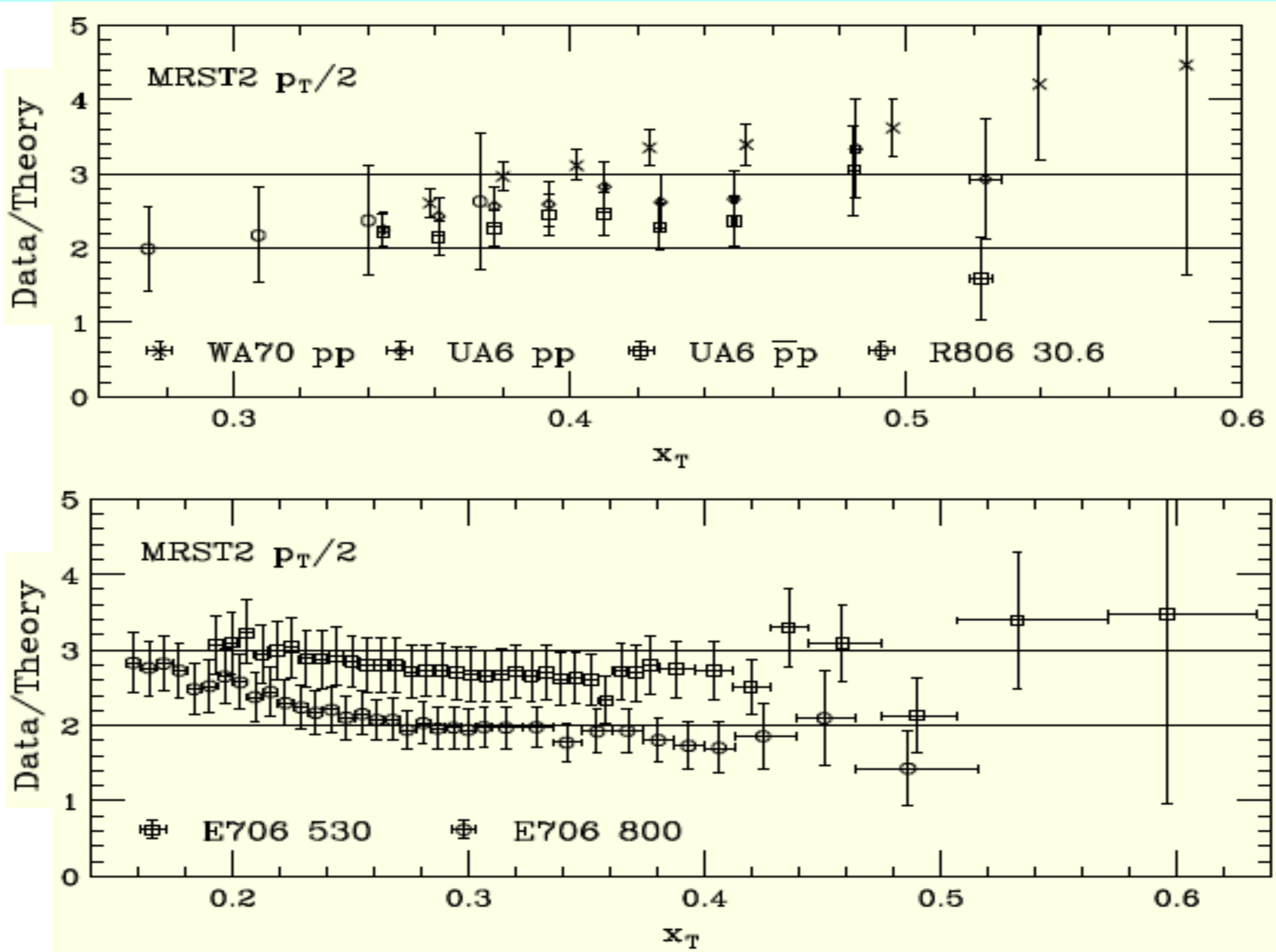




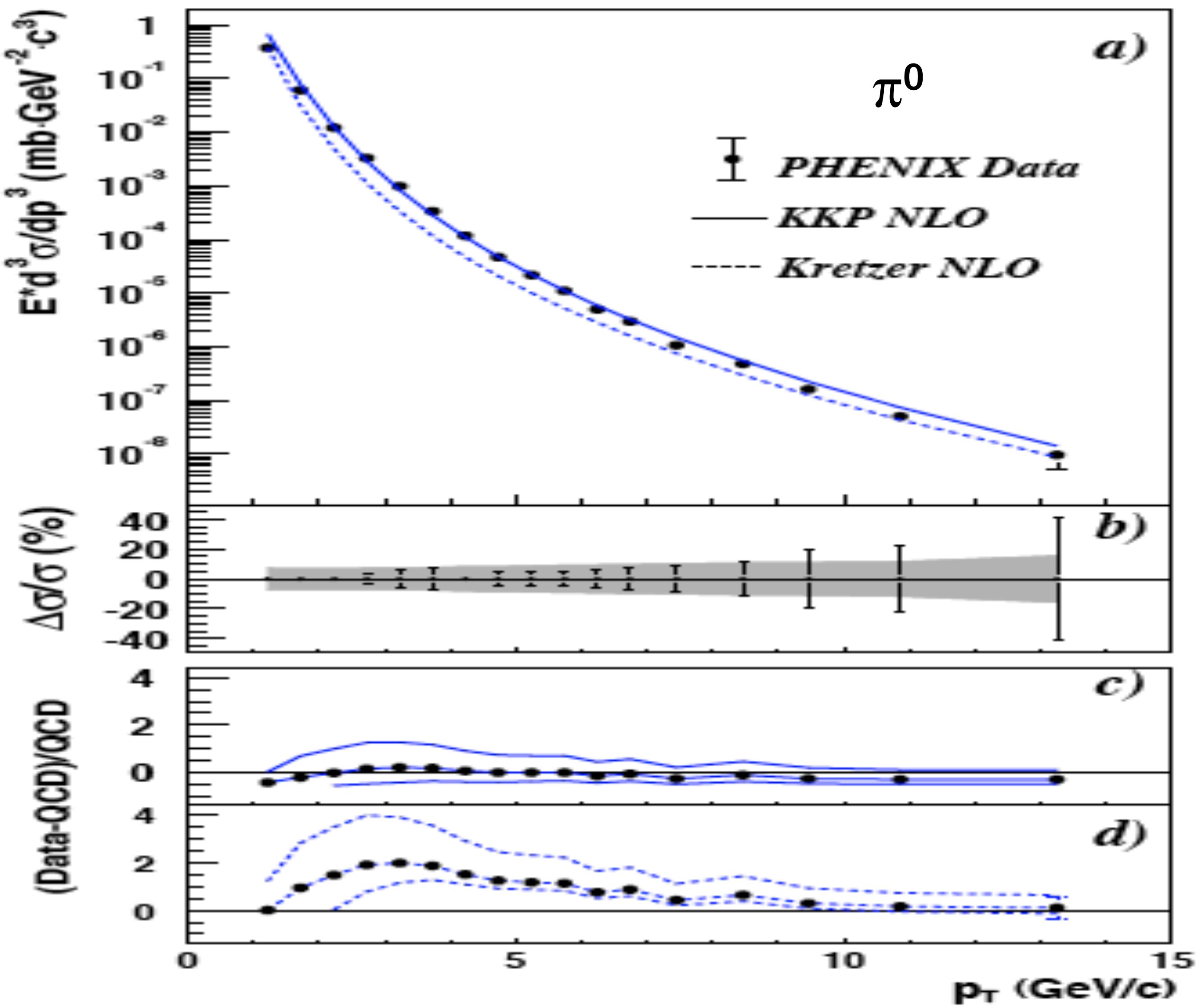
✧ **Data is systematically lower than theory at central** η^γ **and small** E_T^γ

✧ **small** $E_T^{\rm iso} < 3\ {\rm GeV}$, **NOTE: CMS has** $E_T^{\rm iso} < 5\ {\rm GeV}$

Same excess seen in π^0 production



But, works at RHIC energy



Where do we stand?

- ❑ Agreement between theory and data improves with increasing energy and is excellent by $\sqrt{s}$ = 200 GeV

- ❑ Situation with fixed target direct photon data is confusing:
  - ✧ Disagreement between experiments

    See Apanasevich et al., hep-ph/0007191 for a discussion of the systematics of γ/π^0 ratios and consistency between experiments

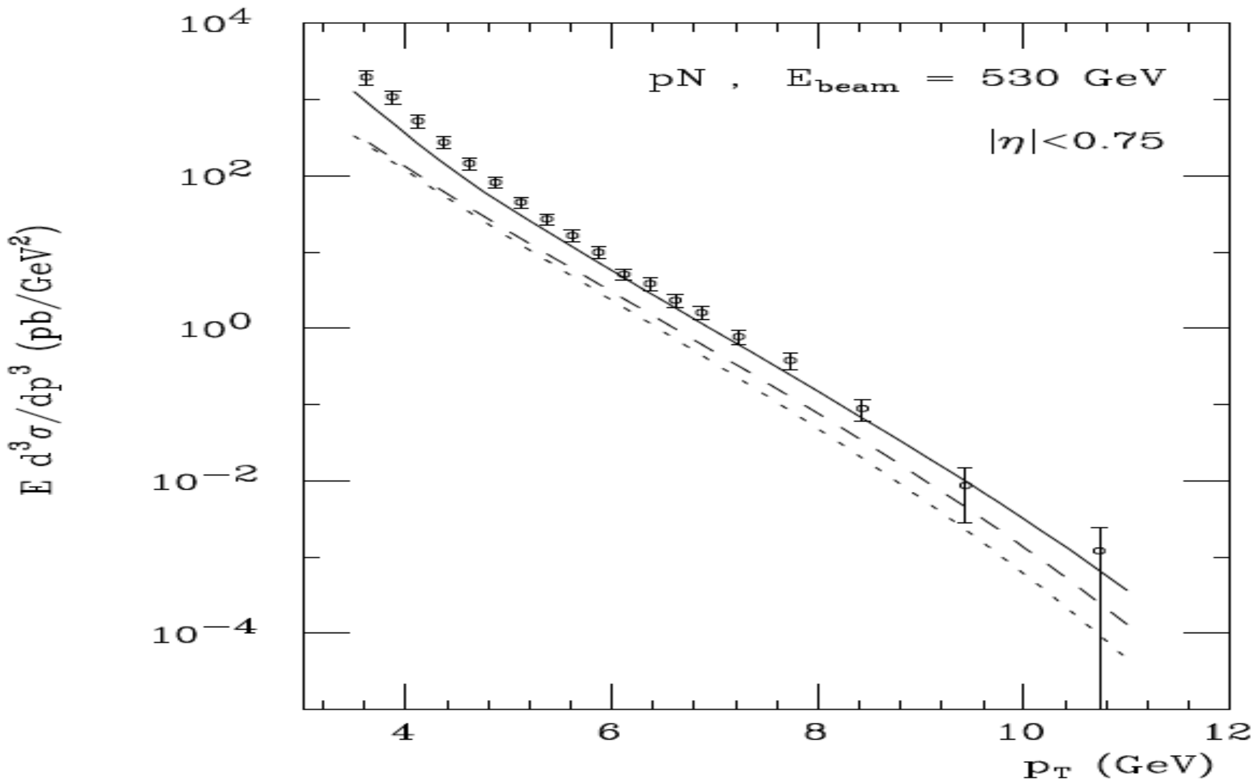
  - ✧ A reassessment of systematic errors on the existing fixed target photon experiments might help resolve the discrepancies

- ❑ All experiments see an excess of data over theory at fixed target energies

- ❑ We need an improved method of calculating single particle inclusive cross sections in the fixed target energy
  – to improve agreement for both photon and π^0 production

Threshold resummation could help

- ❑ Threshold resummation – rate at fixed target energy:

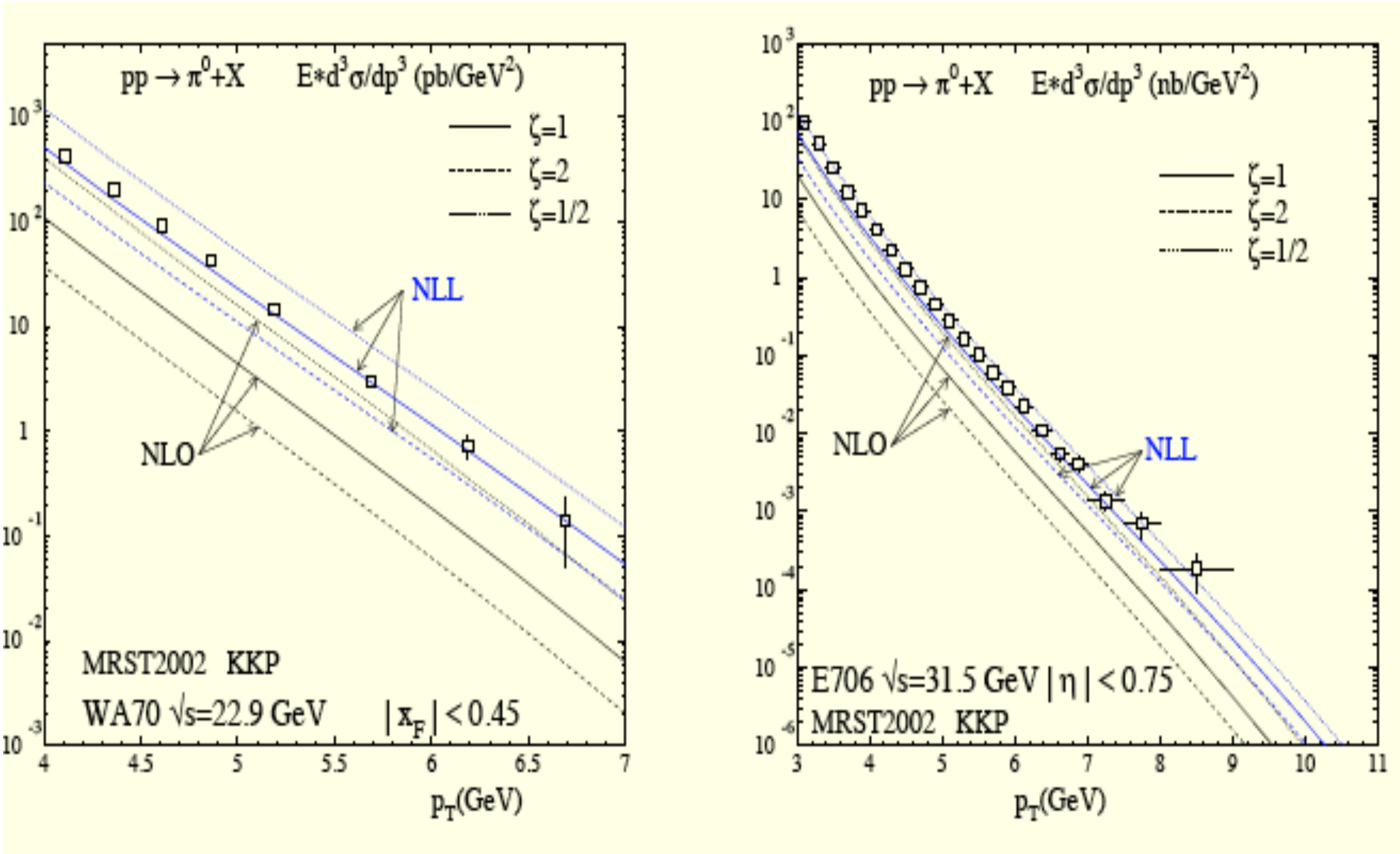


Laenen, Sterman, Vogelsang, 2008

CTEQ Huston et al.

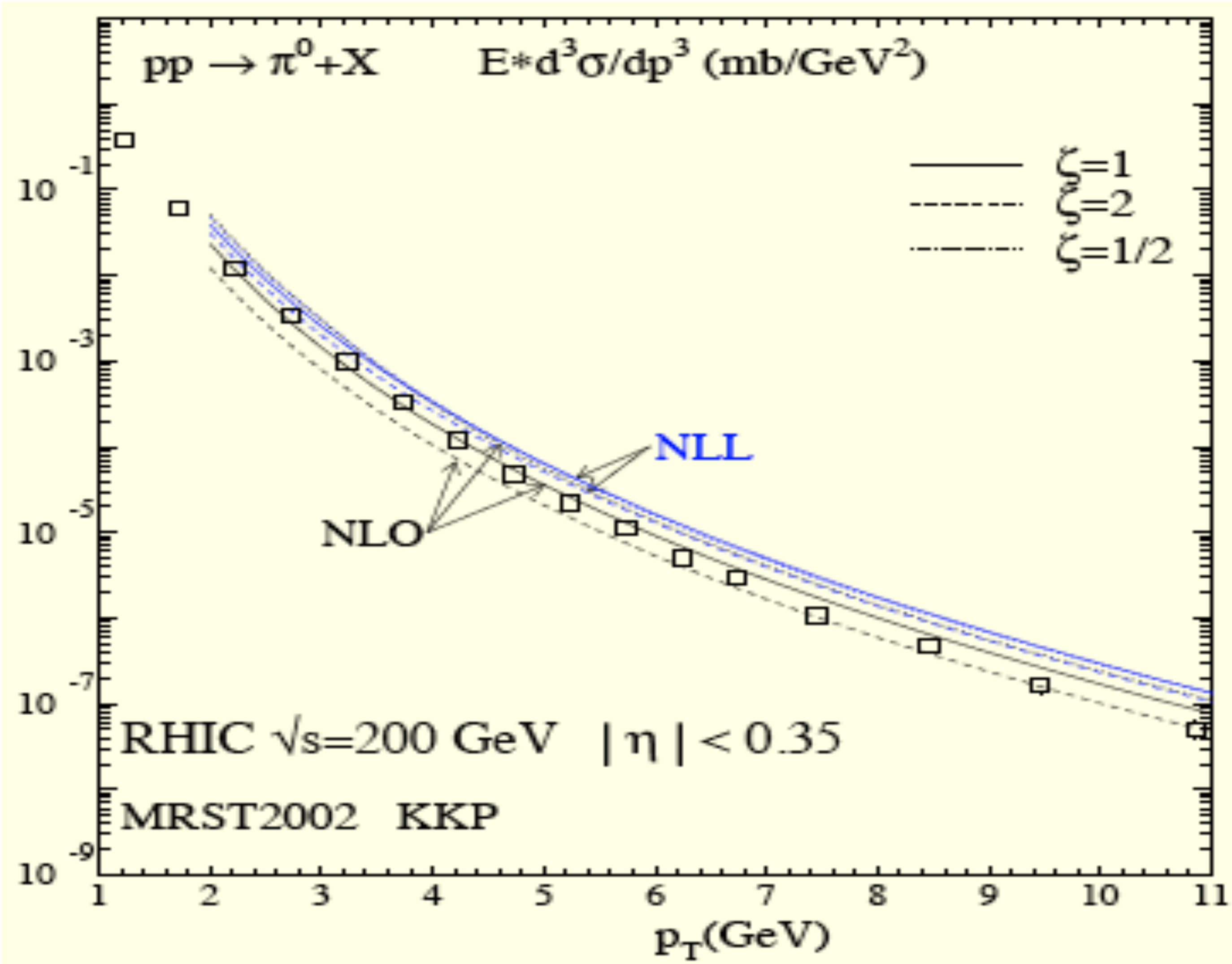
- ❑ Intrinsic k_T – x_T dependence at fixed target energy:
  - ✧ Mimic the resummation of initial-state gluon shower
  - ✧ Large effect on a steep falling P_T distribution

Resummation helps π^0 cross section too



de Florian and Vogelsang, hep-ph/0501258

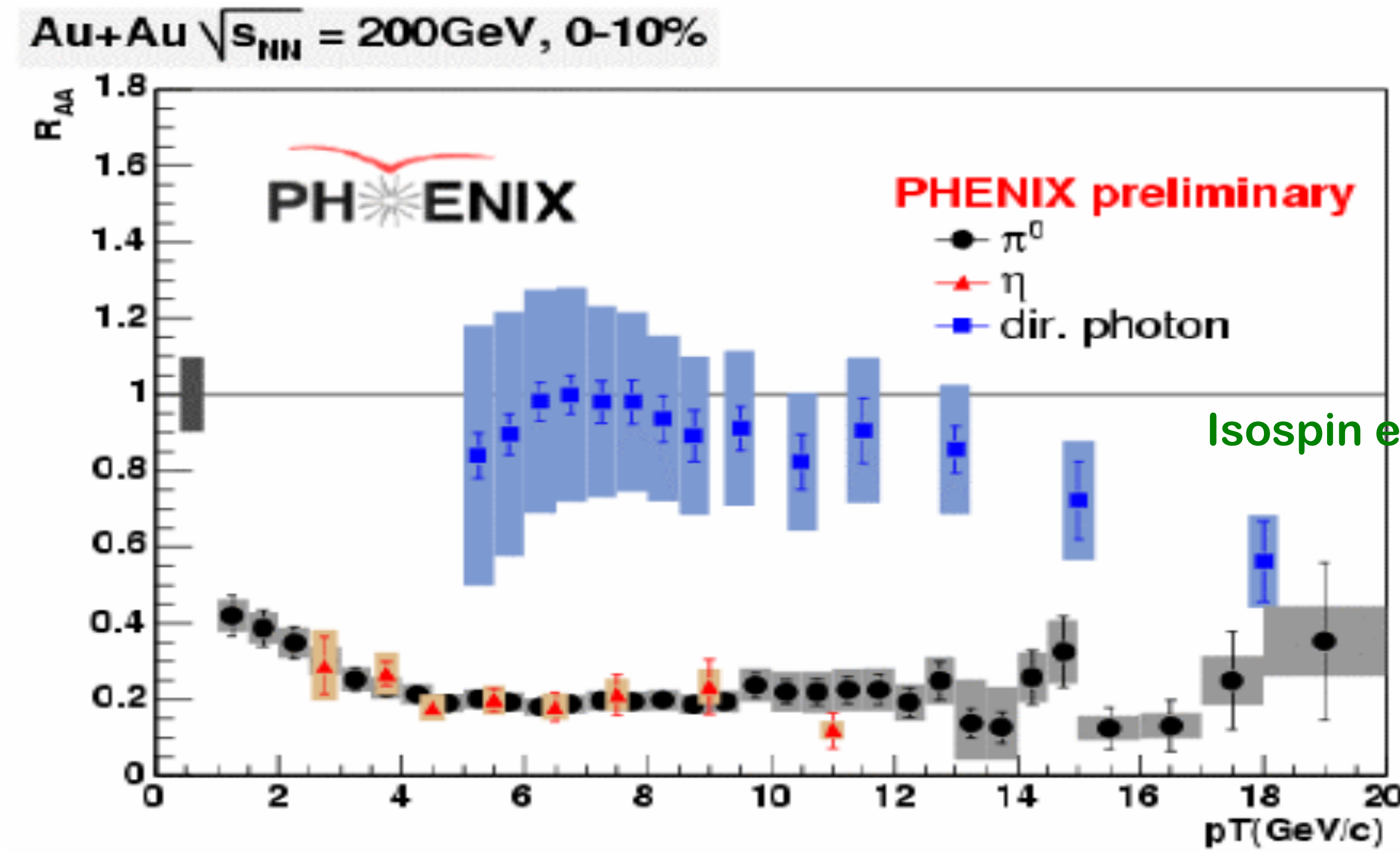
What happens at RHIC energy?



Reduced enhancement at RHIC energies than fixed target energies

Photon can penetrate the medium

- Photon tells the history:



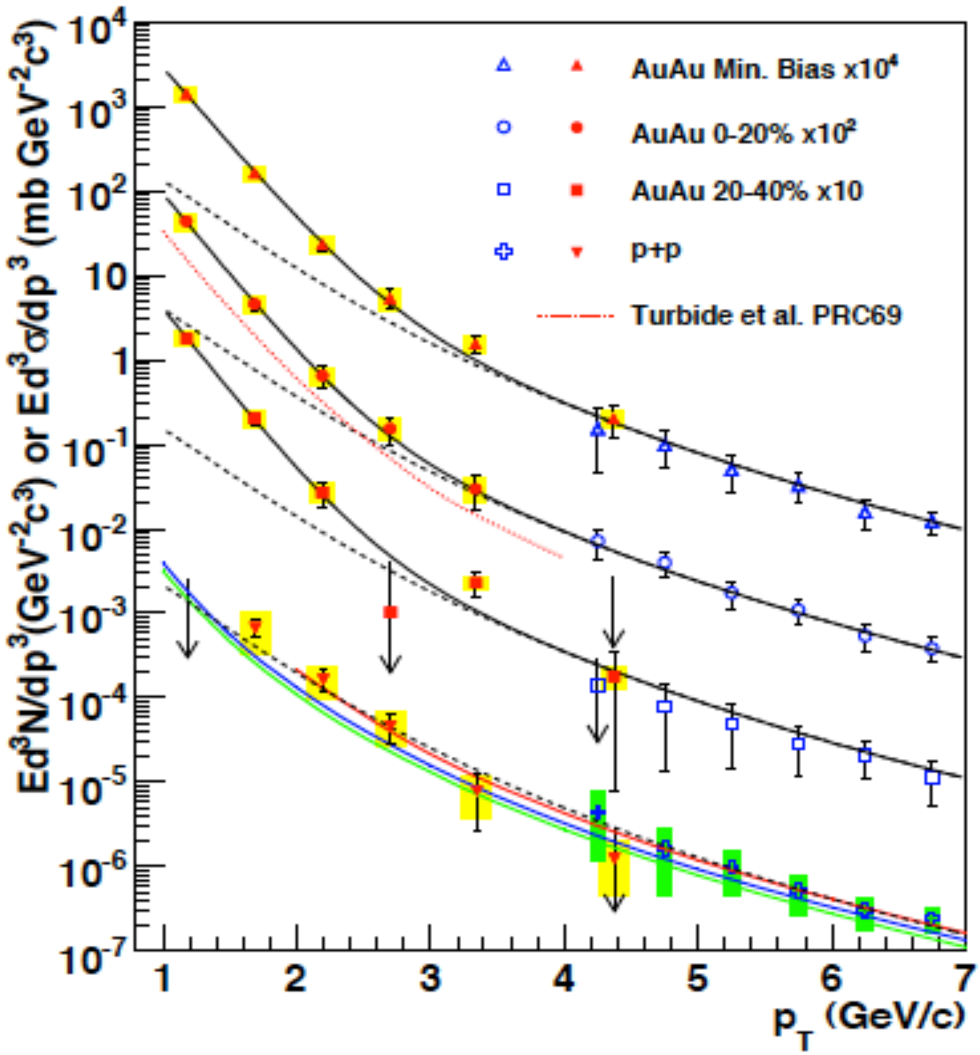
Isospin effect

High P_T photon penetrates the medium without suppression

“Photon” at low p_T in Au-Au collisions

- Low mass e^+e^- pairs ⟶ direct photon production:

arXiv:0804.4168 (PRL in press)



$$\frac{d^2 n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S dn_\gamma$$

S : process dependent factor

$$\sqrt{s} = 200 \text{ GeV}$$

$$m_{ee} < 0.3 \text{ GeV}/c$$

$$1 < p_T < 5 \text{ GeV}/c$$

Difference pp vs AA – thermal photon

➡ **Temperature**

$$T = 221 \pm 19^{\text{stat}} \pm 19^{\text{syst}} \text{ MeV}$$

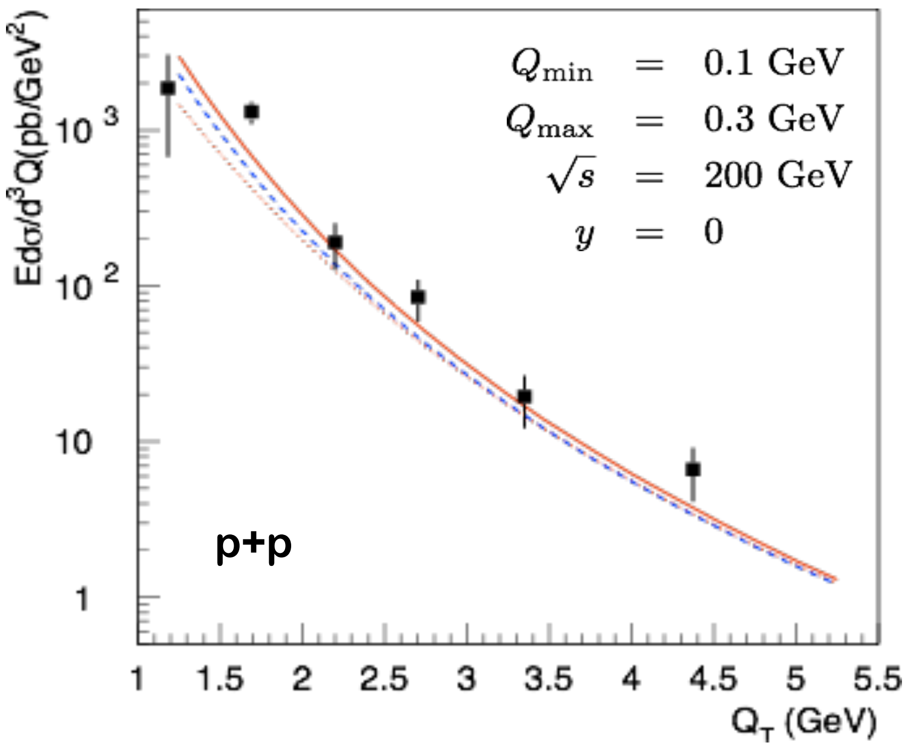
Invariant cross section in pp collision

Kang, Qiu, Vogelsang, PRD 2009

❑ **Definition:**

$$E\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{d^3Q} \equiv \int_{Q^2_{\rm min}}^{Q^2_{\rm max}} dQ^2\,\frac{1}{\pi}\,\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy}$$

❑ **Role of non-perturbative fragmentation function:**



Data from PHENIX: arXiv:0804.4168

✧ **Input FF:**

$$D(z,\mu_0) = D^{\rm QED}(z) + \kappa\, D^{\rm NP}(z)$$

✧ **QED alone (dotted):**

$\kappa = 0$ at $\mu_0 = 1$ GeV

✧ **QED + hadronic input (solid):**

$\kappa = 1$ at $\mu_0 = 1$ GeV

Hadronic component of fragmentation is very important at low Q_T

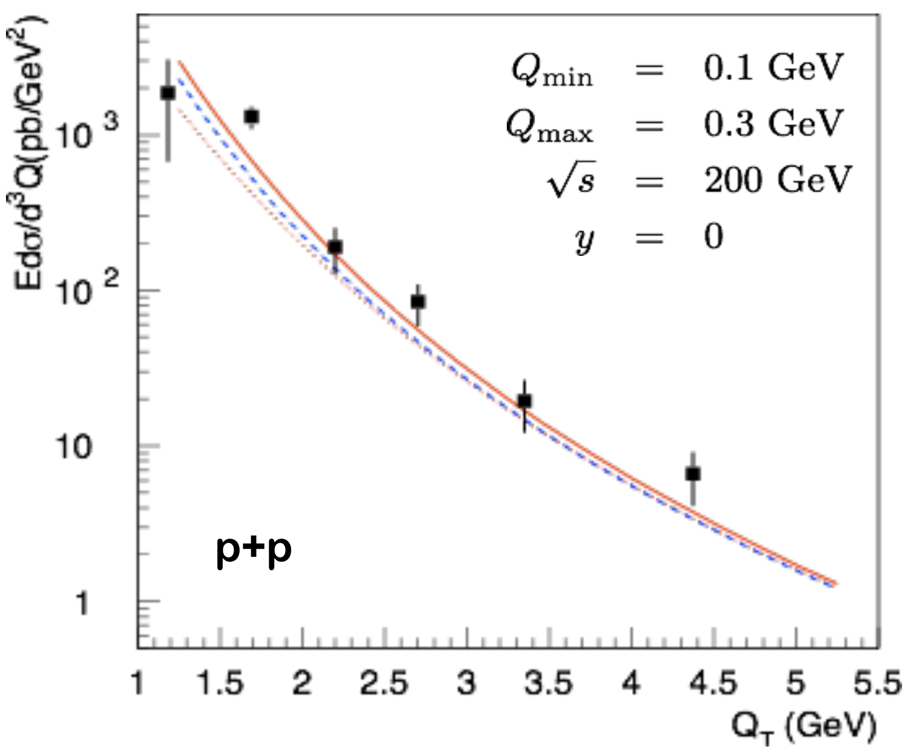
"Direct photon" approximation

- **Dilepton production vs direct photon production:**

$$E\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{d^3Q} \approx \frac{d\sigma_{AB\to\gamma(\hat{Q})X}}{dQ_T^2dy}\int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2\left(\frac{\alpha_{em}}{3\pi^2Q^2}\right)\sqrt{1-\frac{4m_\ell^2}{Q^2}}\left(1+\frac{2m_\ell^2}{Q^2}\right)$$

$$\approx \frac{\alpha_{em}}{3\pi}\ln\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right)E_\gamma\frac{d\sigma_{AB\to\gamma(\hat{Q})X}}{d^3Q}$$

← Direct photon cross section



Data from PHENIX: arXiv:0804.4168

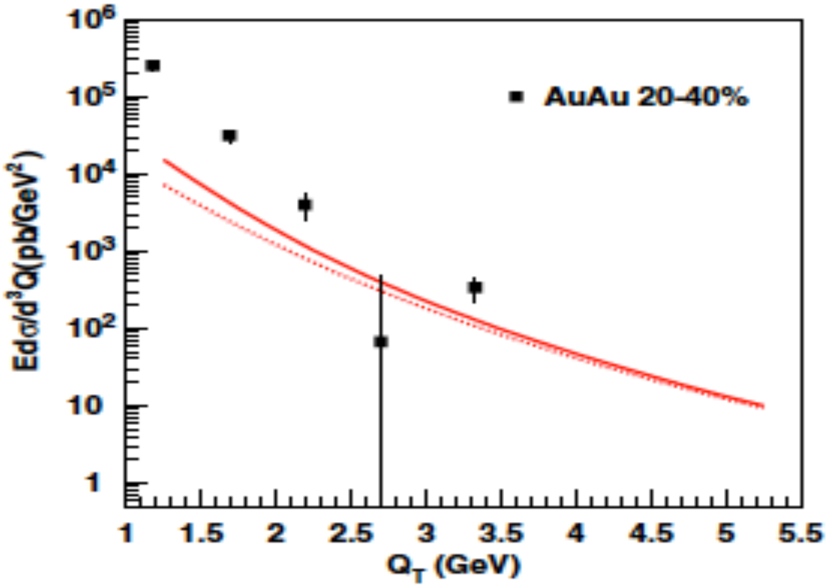
✧ **Inclusive NLO direct photon (blue-dashed)**

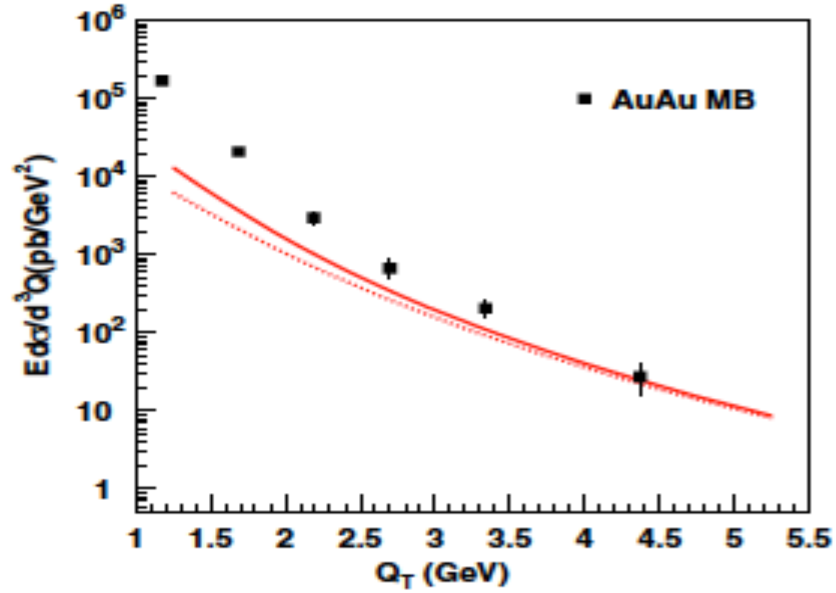
Gordon, Vogelsang, 1993

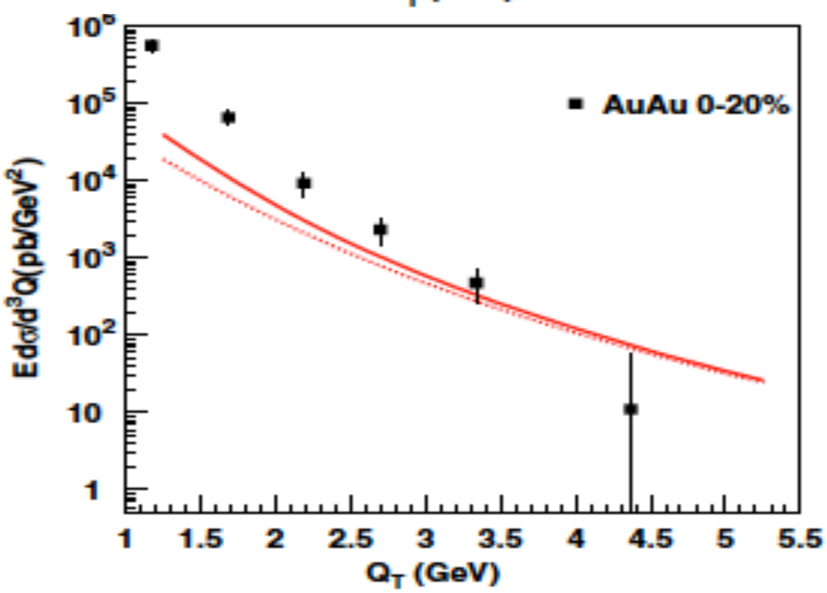
✧ **Direct photon code has similar non-perturbative fragmentation functions**

✧ **Low mass dilepton ~ inclusive photon production**

Au-Au data: beyond shadowing + isospin







Data from PHENIX: arXiv:0804.4168

- ✧ **EPS08 nPDFs**

$$\kappa = 1(\text{solid}),\ \kappa = 0(\text{dotted})$$

- ✧ **Clear enhancement at low Q_T**

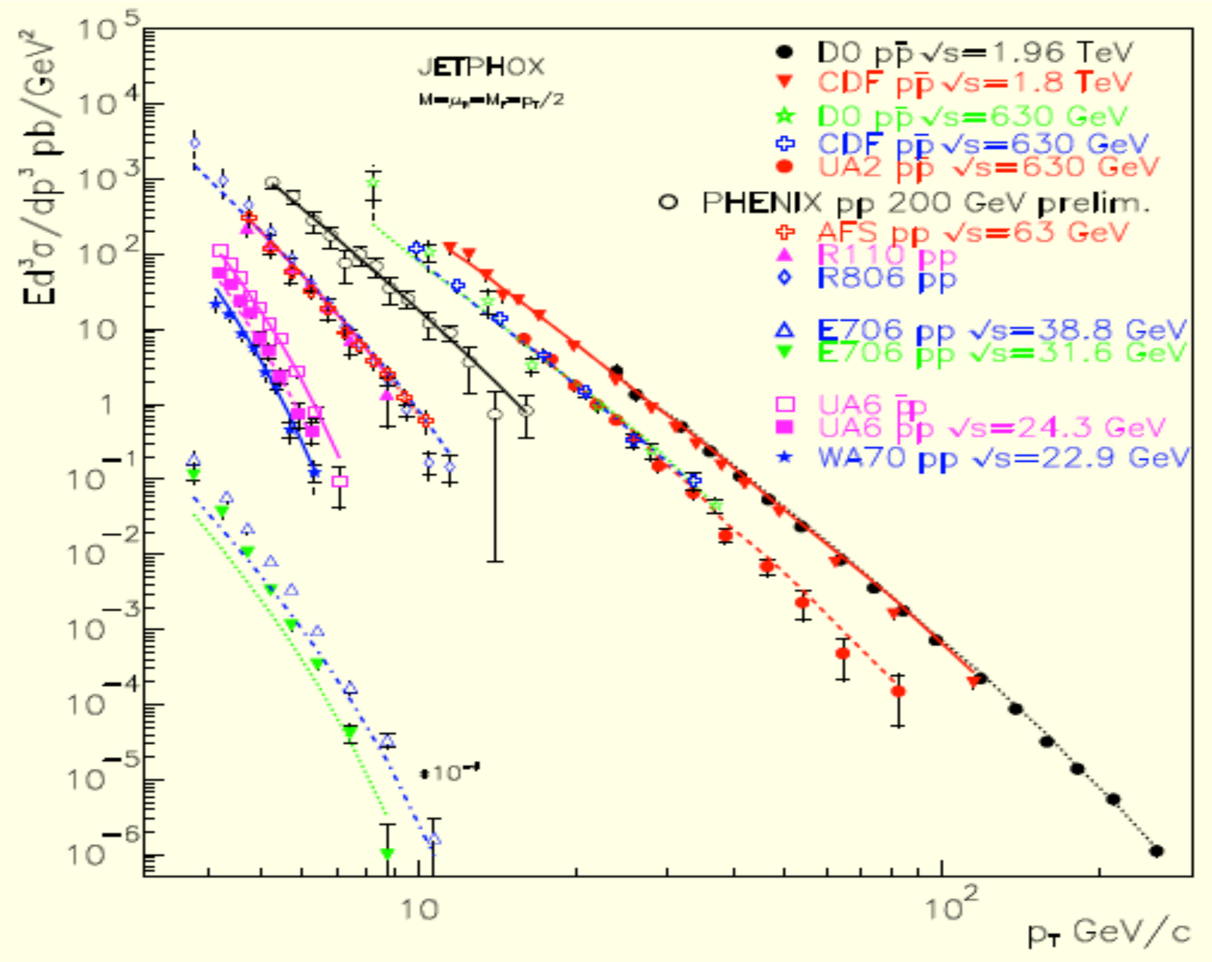
Hot medium effect?

$$T = 221 \pm 19^{\text{stat}} \pm 19^{\text{syst}}\ \text{MeV}$$

Kang, Qiu, Vogelsang, PRD 2009

Summary

- ❑ World data:



- ❑ Reasonably consistent picture covering 9 orders of magnitude

- ❑ Threshold resummation helps improve theory at fixed target energy

Thank you!

Backup slices

PDF uncertainties

- CMS and ATLAS use different PDFs: