EM Emission in pA at Fermilab E706

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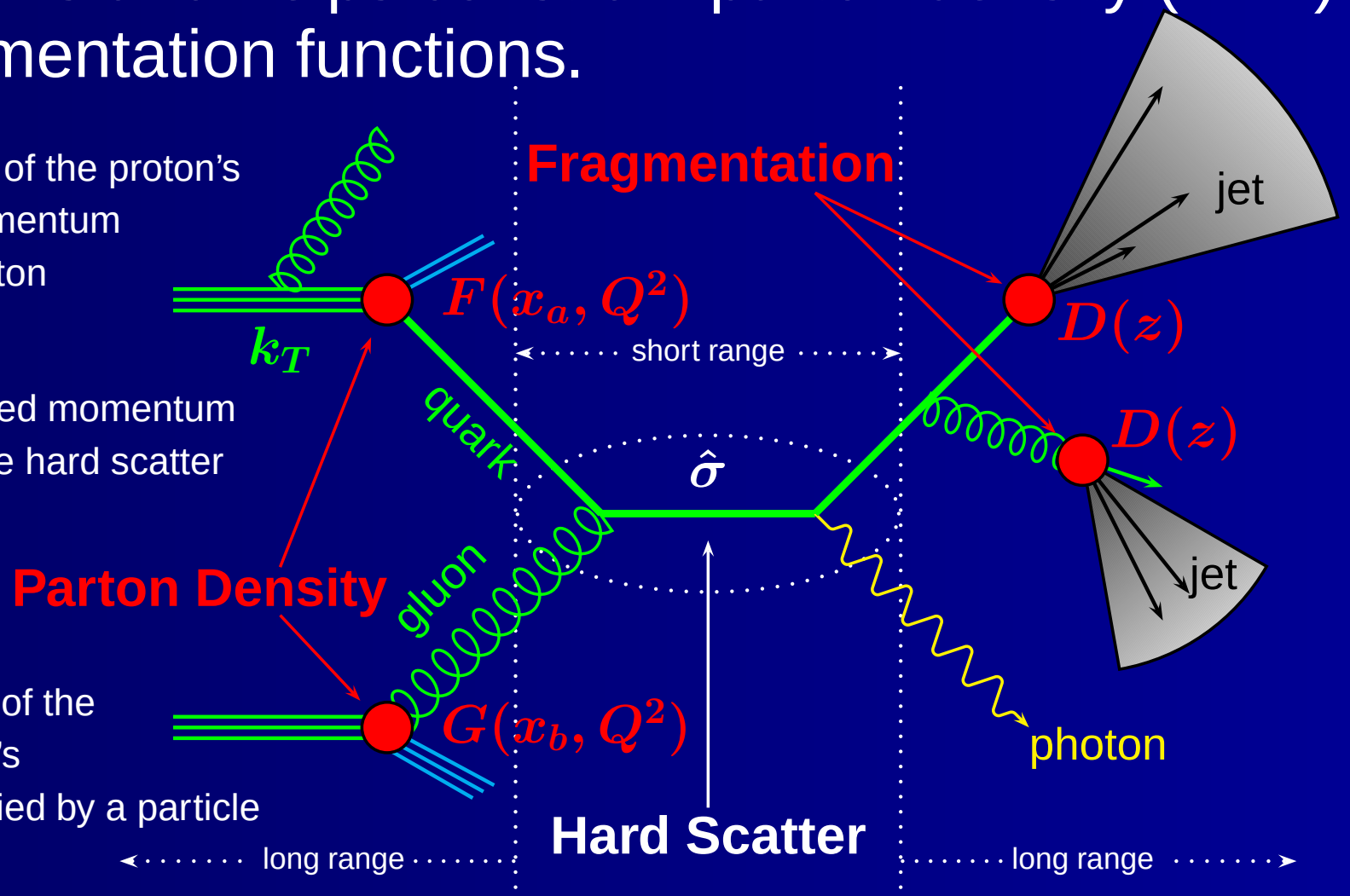
QCD Hard Scatters & Factorization

High p_T particle production tests perturbative QCD calculations and helps constrain parton density (PDF) and fragmentation functions.

x is the fraction of the proton's longitudinal momentum carried by a parton

Q^2 is the squared momentum transferred in the hard scatter

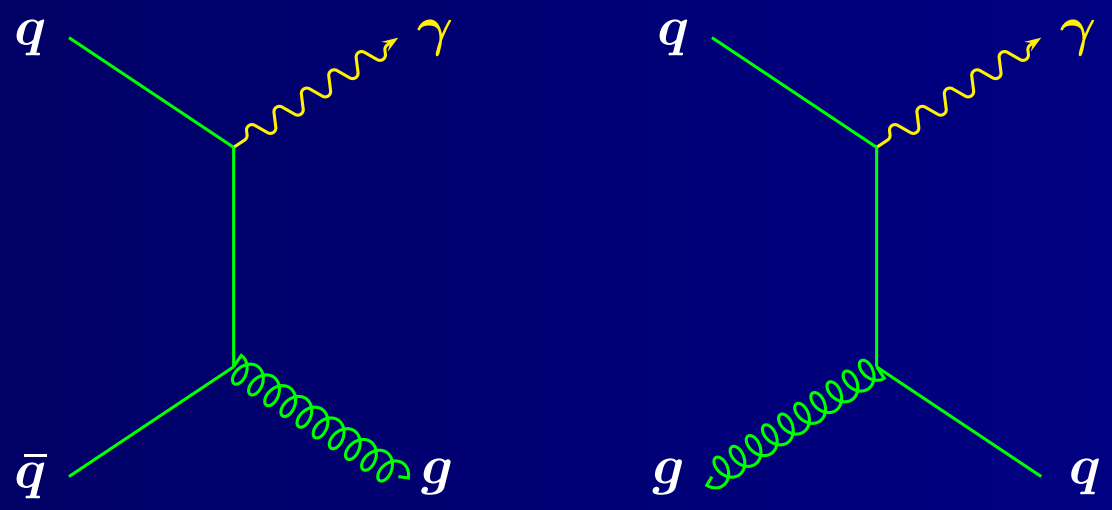
z is the fraction of the outgoing parton's momentum carried by a particle



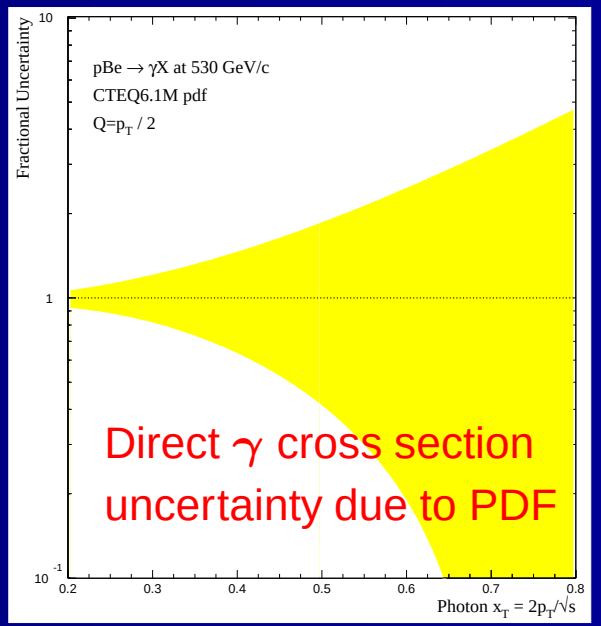
Why Study Direct Photons?

- Photons provide a clean probe of the hard scatter
- Only two processes contribute at leading order to the direct-photon cross section:

  $q\bar{q}$ annihilation and qg Compton scattering

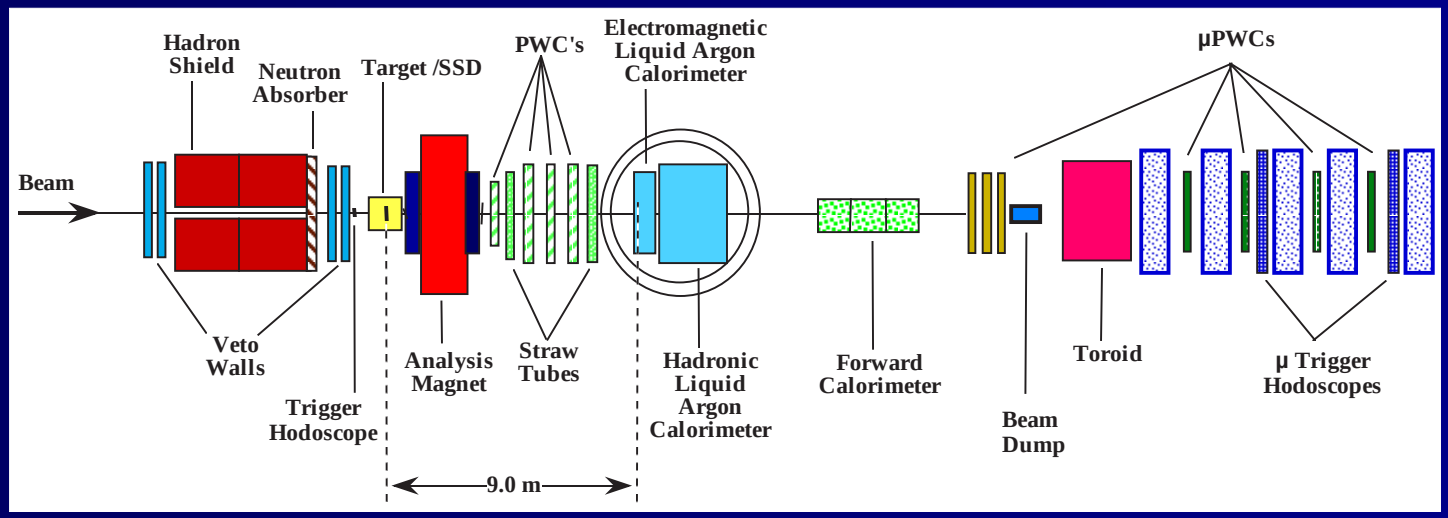


- Direct-photon production is sensitive to the gluon distribution



Meson West Spectrometer

shared with the E672 collaboration



Beams

- 800 GeV p
- 530 GeV p
- 515 GeV π^-

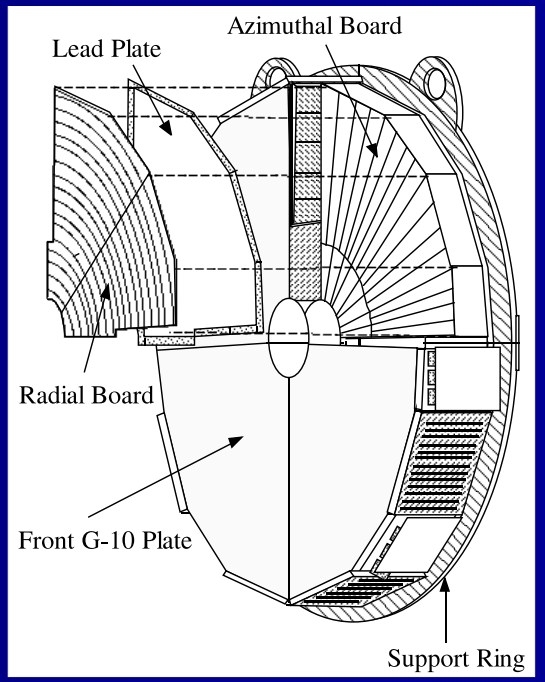
Targets: H_2, Be, Cu

Fermilab E706 Collaboration

UC Davis ★ Delhi ★ Fermilab ★ Michigan State ★ Northeastern
Oklahoma ★ Pennsylvania State ★ Pittsburgh ★ Rochester

Pb–LAr Sampling Electromagnetic Calorimeter

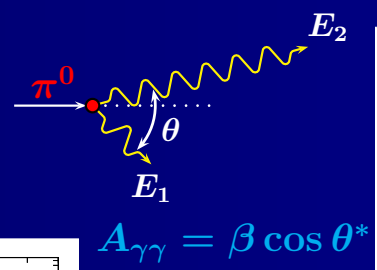
- $8.5\ X_o$ front/$18\ X_o$ back
- Octant-based $R - \phi$ geometry
  - 5.5 mm wide radial strips
  - 16.4 mrad (inner)/8.2 mrad (outer) ϕ strips
- Resolution
  - $\sigma_R(E) = 1.65\ \mathrm{GeV}/E + 0.045\ \mathrm{cm}$
  - $\sigma/E \approx 14.8\%/\sqrt{E} \oplus 0.98\%$

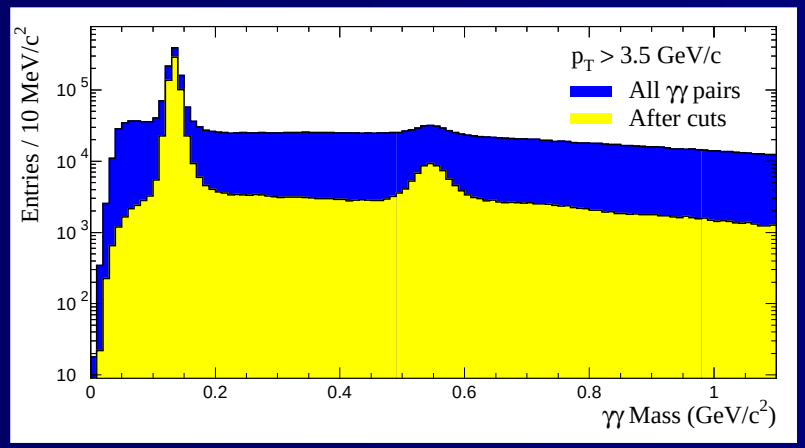


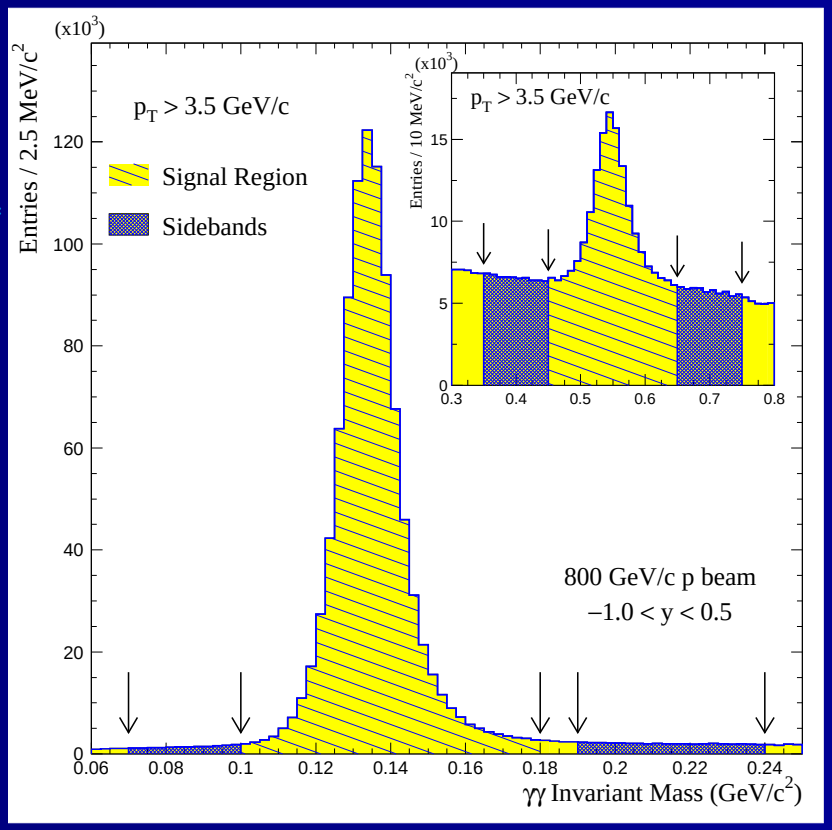
π^0 and η Signal Definitions

π^0 and η mesons are reconstructed via their $\gamma\gamma$ decay modes

$$A_{\gamma\gamma} \equiv \frac{|E_{\gamma_1} - E_{\gamma_2}|}{E_{\gamma_1} + E_{\gamma_2}} < 0.75$$







Photons from π^0 and η meson decays are the leading source of direct-photon background. Reduce this background by identifying these photons.

meson background estimated via sideband subtraction

Direct Photon Candidates

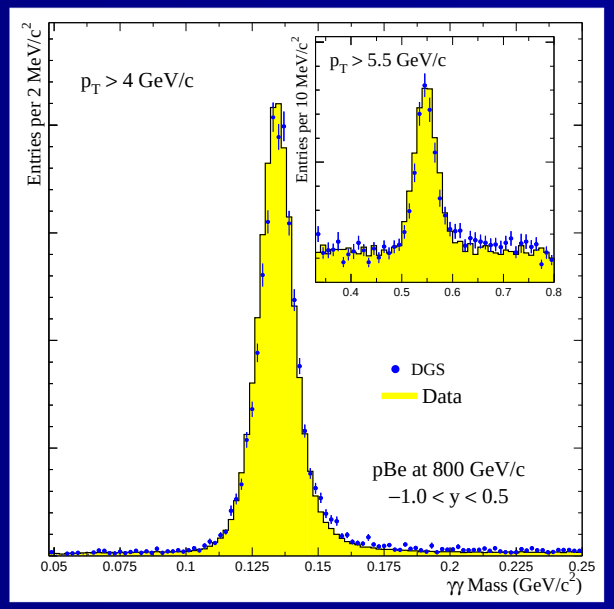
Candidates that formed $\gamma\gamma$ pairs with invariant mass in the π^0 or η peak regions and $A_{\gamma\gamma}$ < 0.9 were rejected

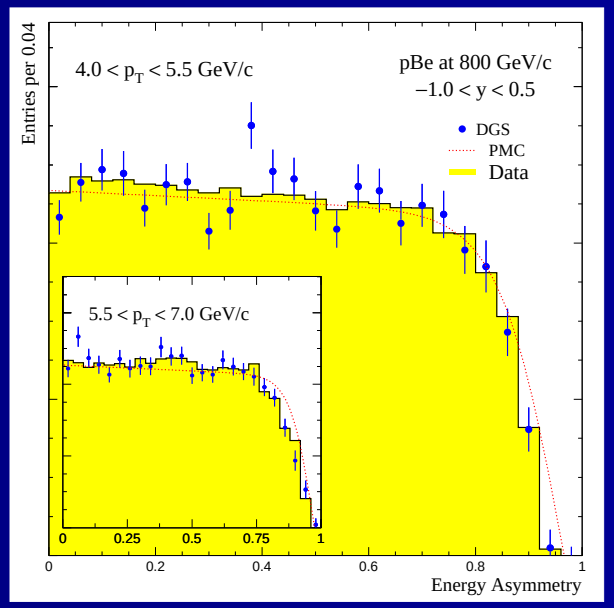
($A_{\gamma\gamma}$ varied for systematic studies)

Backgrounds are still significant even after rejecting most π^0 and η mesons. A properly tuned simulation is necessary to estimate the remaining background.

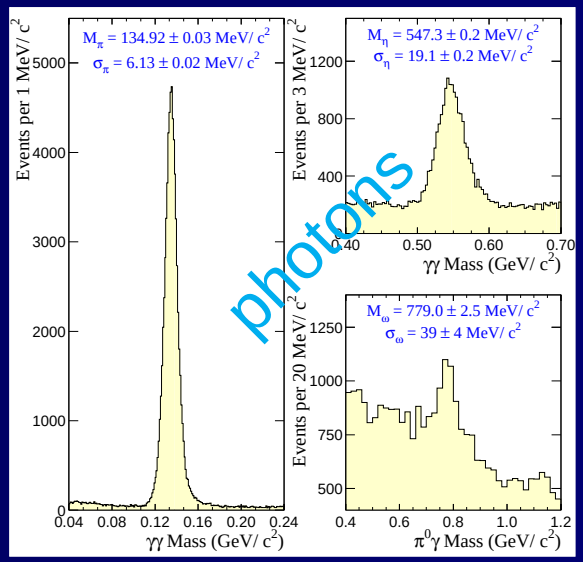
Signal obtained after statistical subtraction of the background

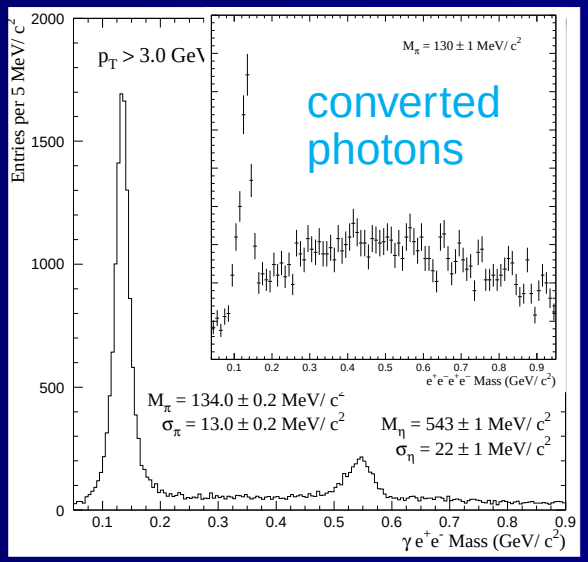
$$\sigma_{\gamma}^{direct} = \sigma_{\gamma}^{single} - (\gamma_b/\pi^0)_{MC} \times \sigma_{\pi^0}$$

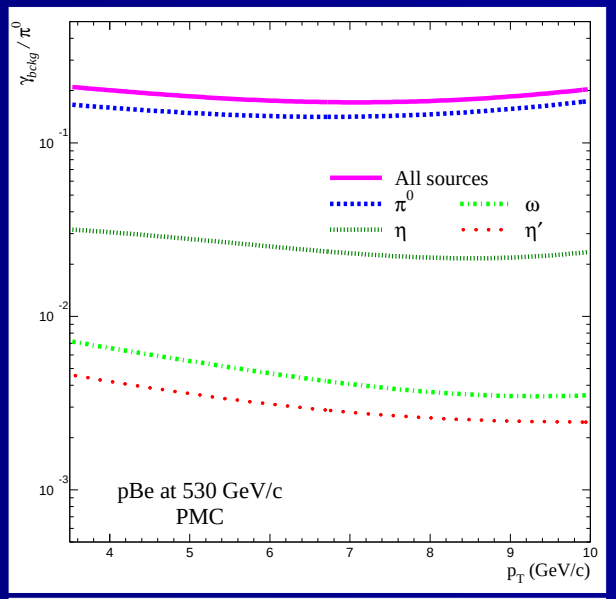


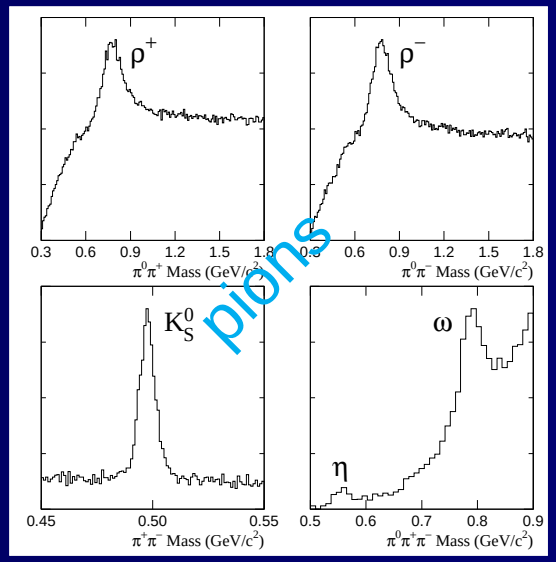


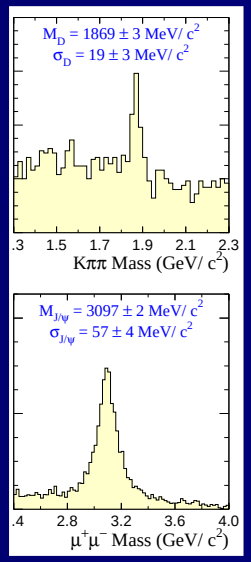
Direct Photon Candidates

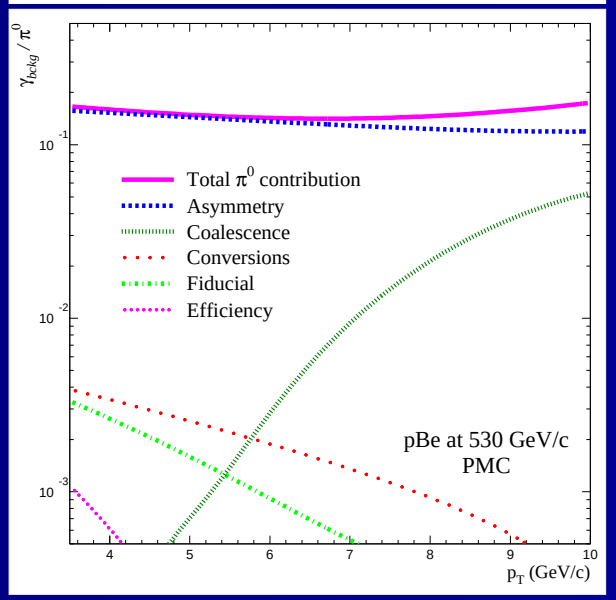




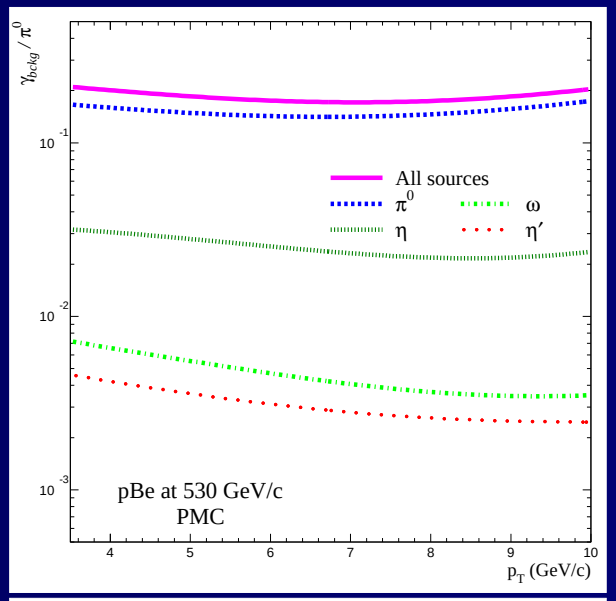


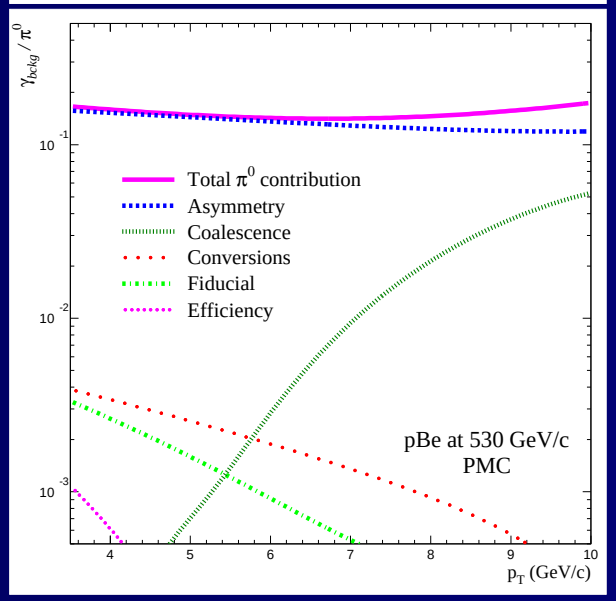


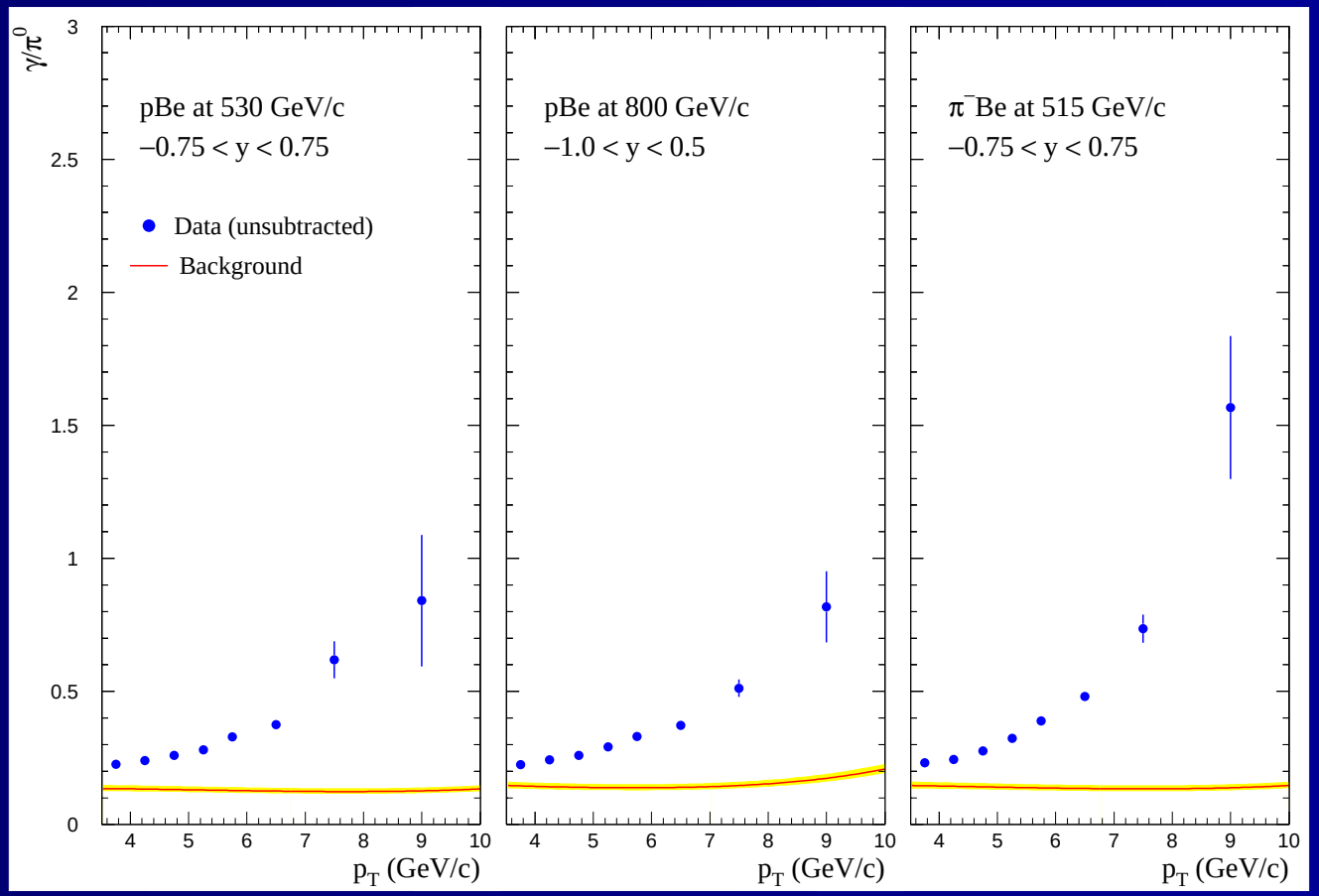




Direct Photon Candidates

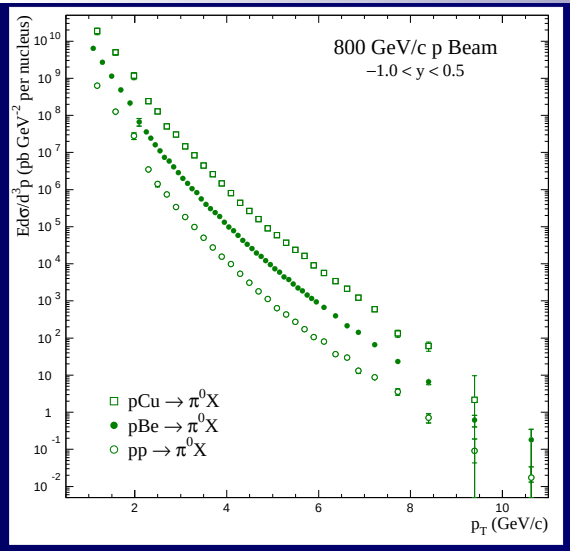


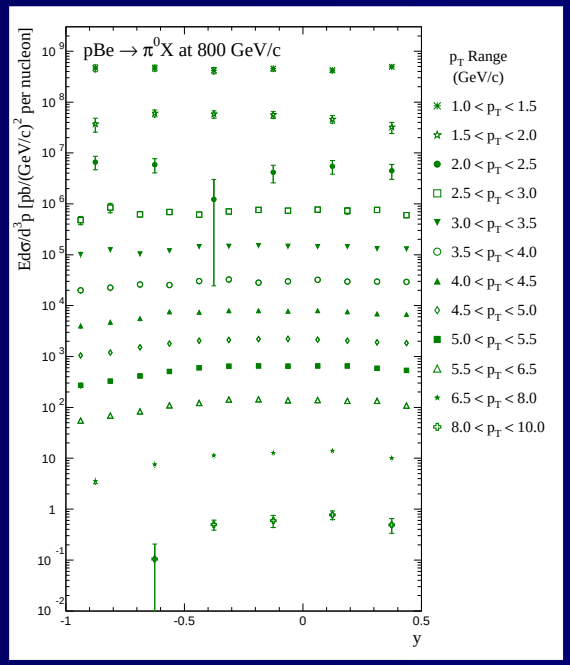




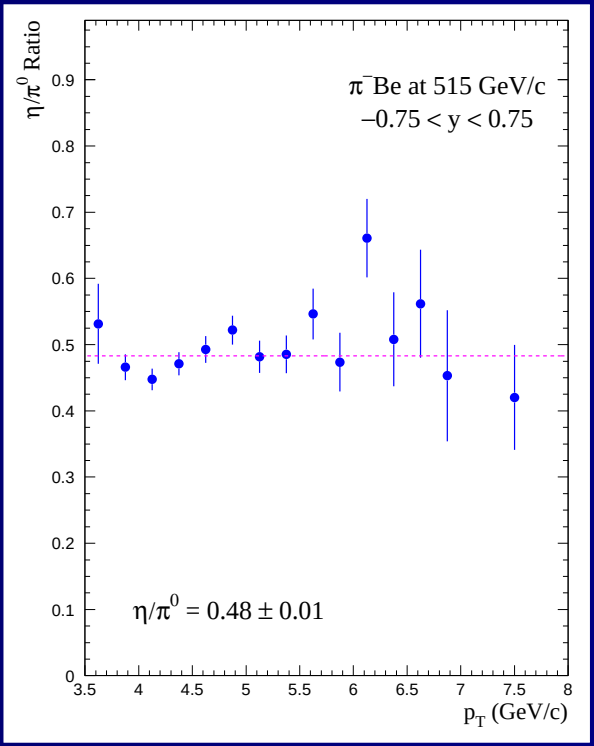
$$\sigma_{\gamma}^{direct} = \sigma_{\gamma}^{single} - (\gamma_b/\pi^0)_{MC} \times \sigma_{\pi^0}$$

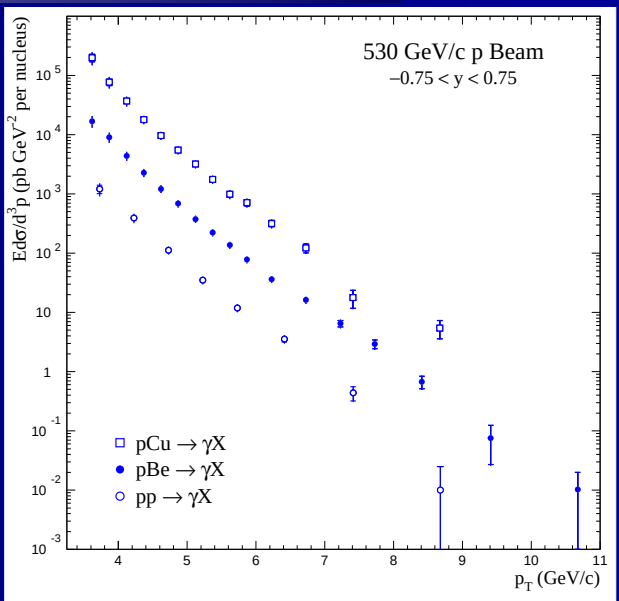
Production Cross Sections

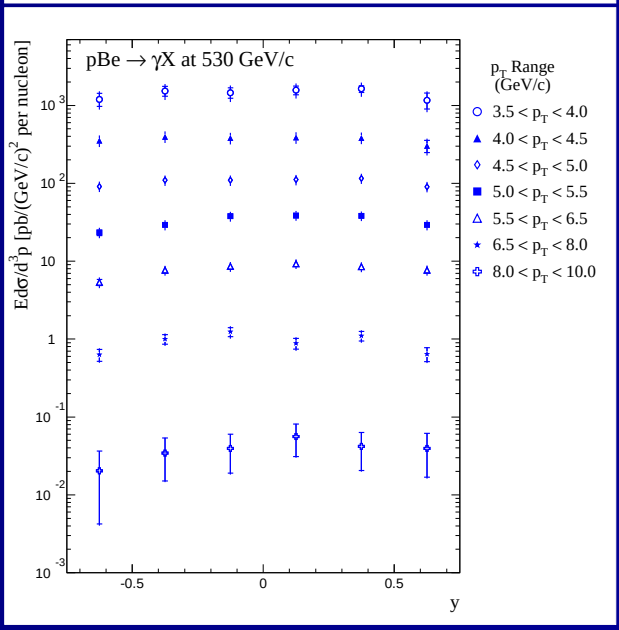




PRL 81, 2642 (1998)
PRD 68, 052001 (2003)
PRD 69, 032003 (2004)
PRD 70, 092009 (2004)
PRD 72, 032003 (2005)





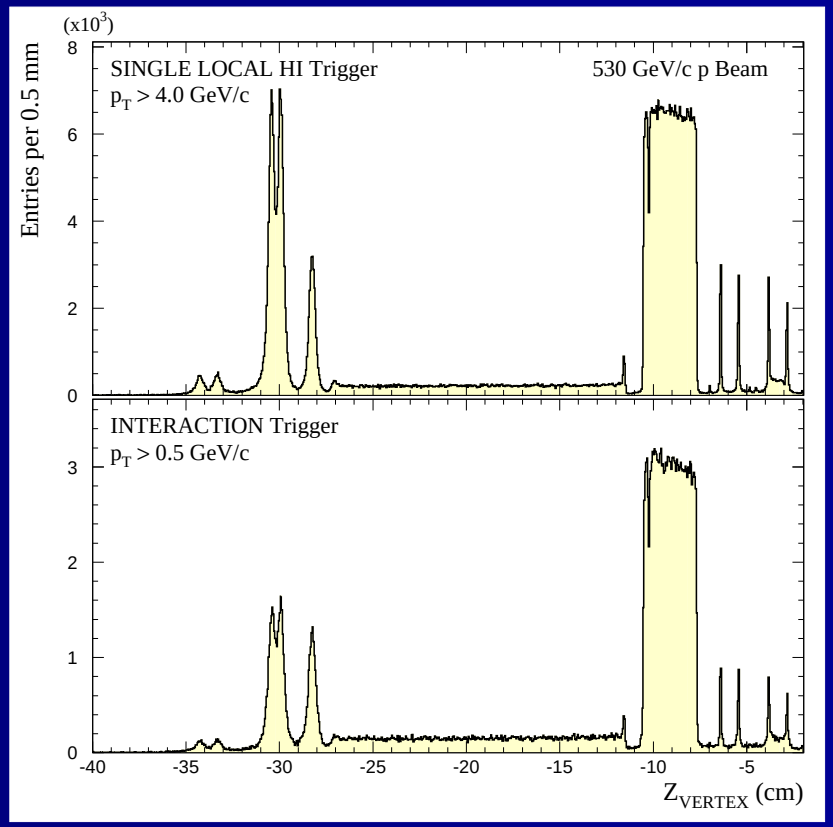


Nuclear Dependence

Large p_T processes on nuclei may be affected by multiple parton scattering or modifications of parton distributions in nuclear matter

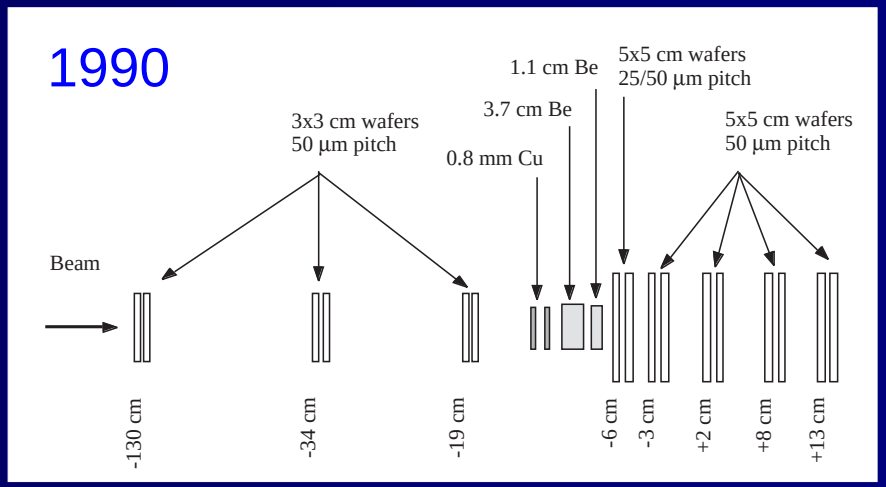
For hadron production by p and π beams,

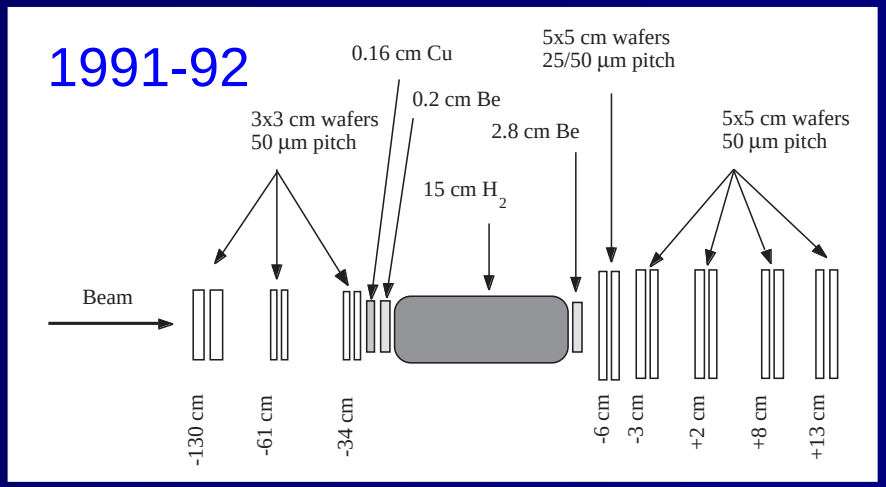
- expect a suppression at low p_T (nuclear disk)
- expect an enhancement at large p_T (scattering)

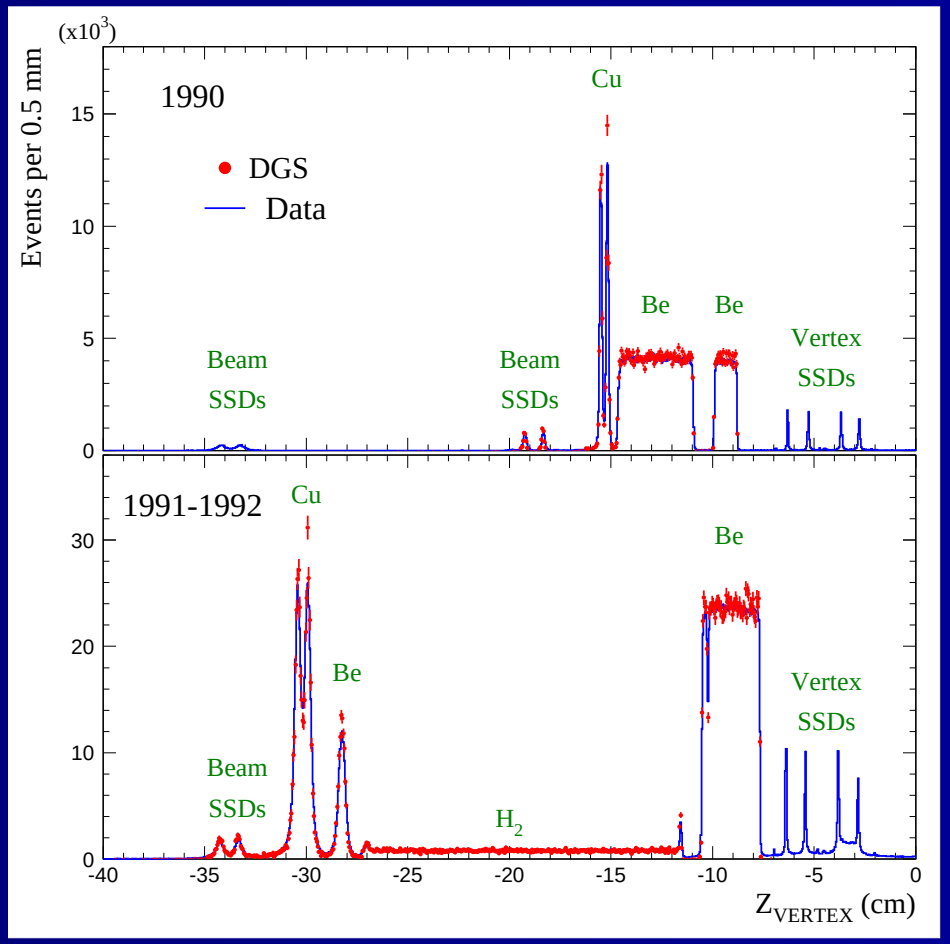


In high p_T hadron production, multiple scattering may occur in the initial and/or final state. In direct photon production, multiple scattering is expected to occur primarily in the initial state.

Target Region

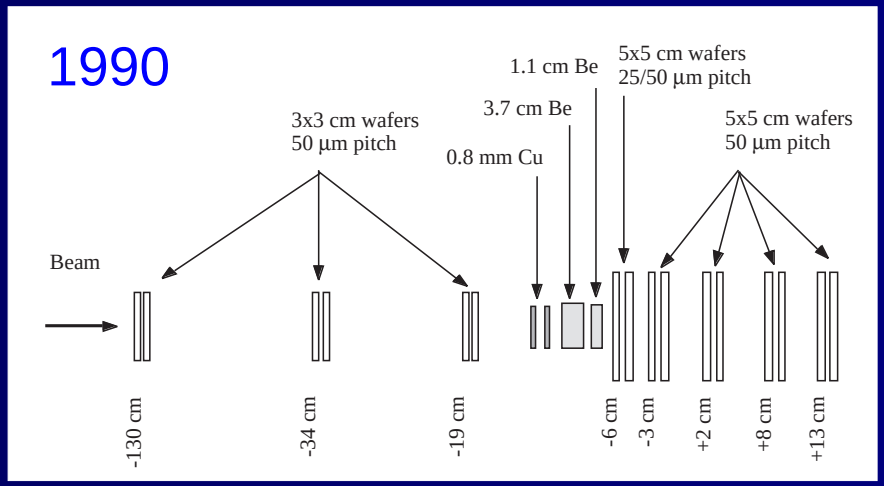


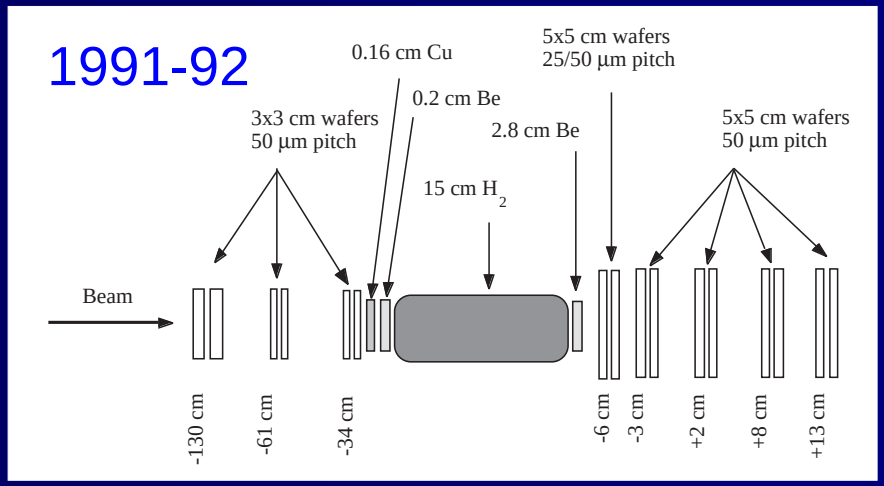


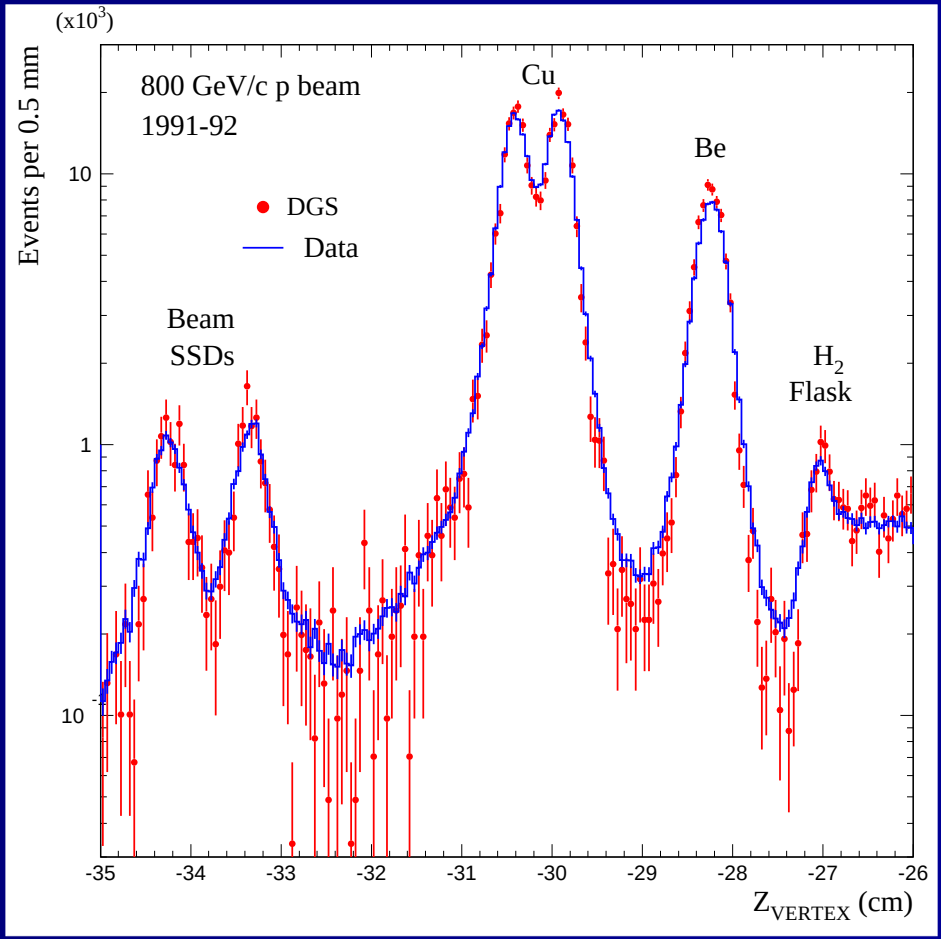


Vertex Distributions

Target Region

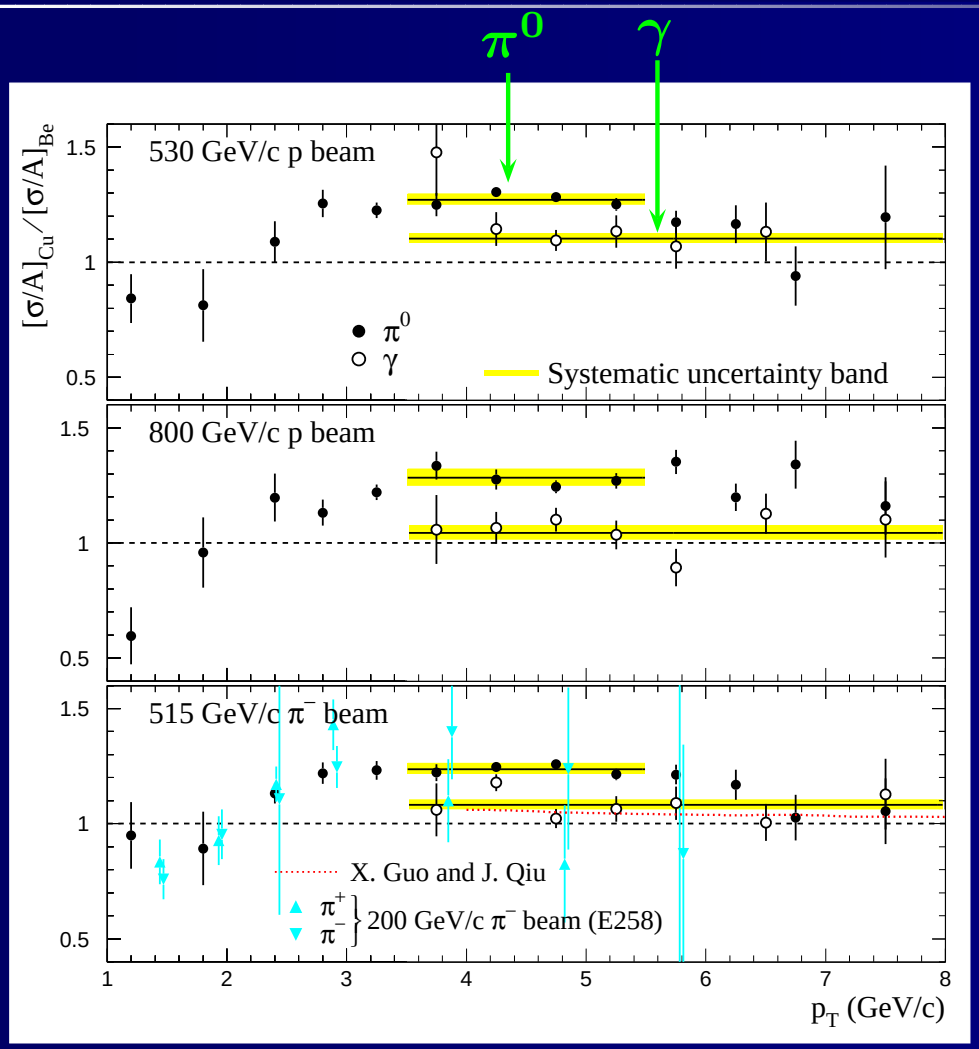






Vertex Distributions

Nuclear Dependence



Cu to Be Ratios

π^0 Production

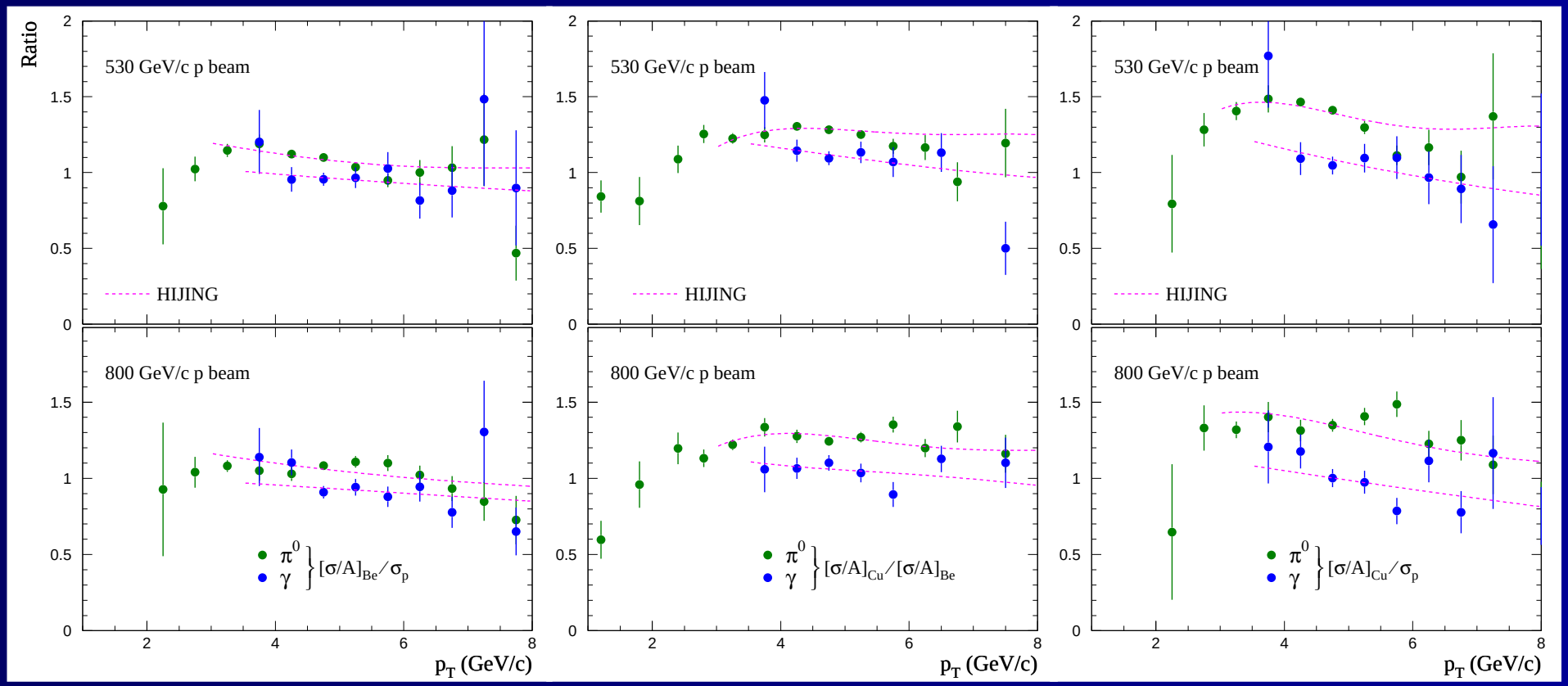
	$3.5 < p_T < 5.5$ GeV/c
530 GeV/c p	$1.271 \pm 0.016 \pm 0.025$
800 GeV/c p	$1.283 \pm 0.025 \pm 0.038$
515 GeV/c π^-	$1.237 \pm 0.015 \pm 0.025$

Direct Photon Production

	$3.5 < p_T < 8.0$ GeV/c
530 GeV/c p	$1.103 \pm 0.032 \pm 0.022$
800 GeV/c p	$1.043 \pm 0.032 \pm 0.031$
515 GeV/c π^-	$1.083 \pm 0.024 \pm 0.022$

Nuclear Dependence

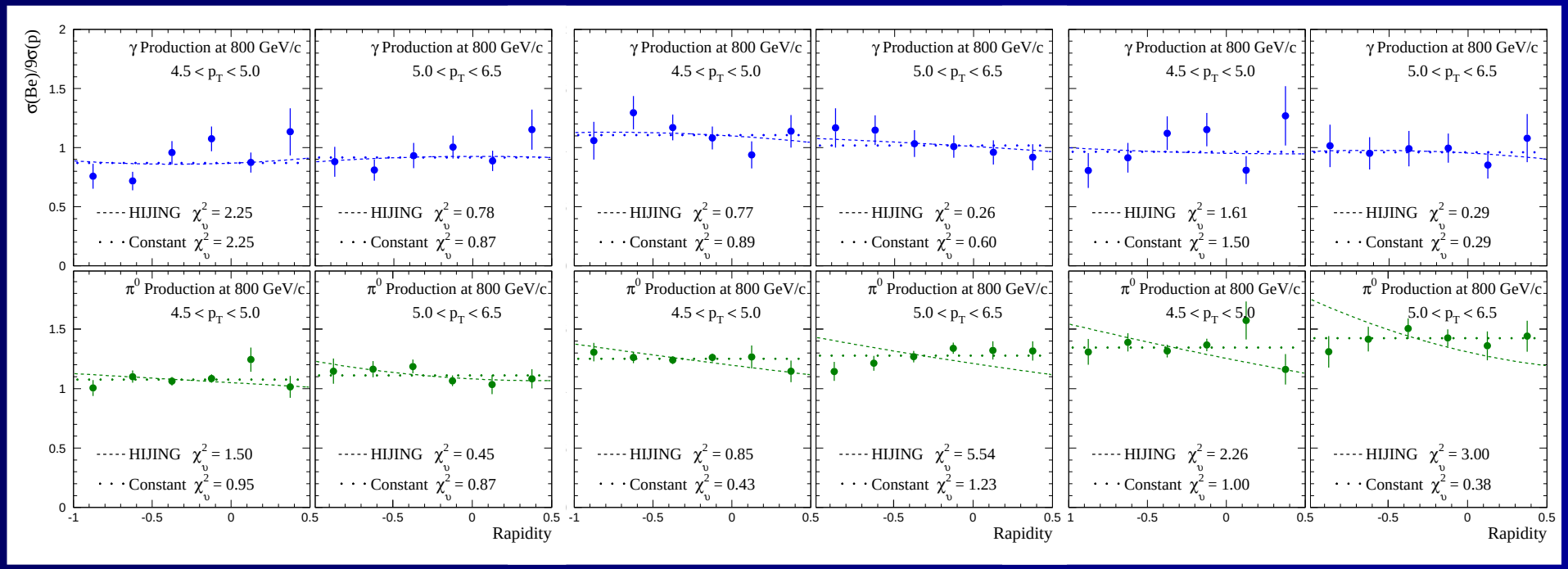
$[\frac{\sigma}{A}]_{Be}/\sigma_p$ $[\frac{\sigma}{A}]_{Cu}/[\frac{\sigma}{A}]_{Be}$ $[\frac{\sigma}{A}]_{Cu}/\sigma_p$



comparison with HIJING

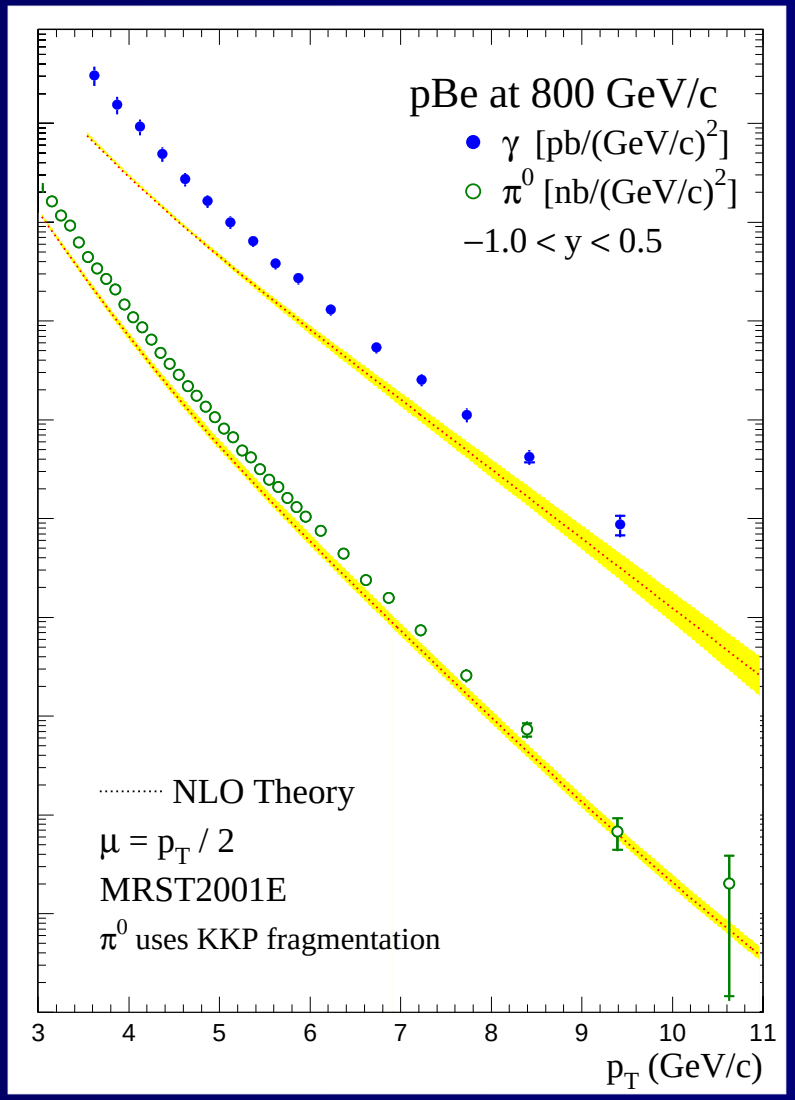
Nuclear Dependence

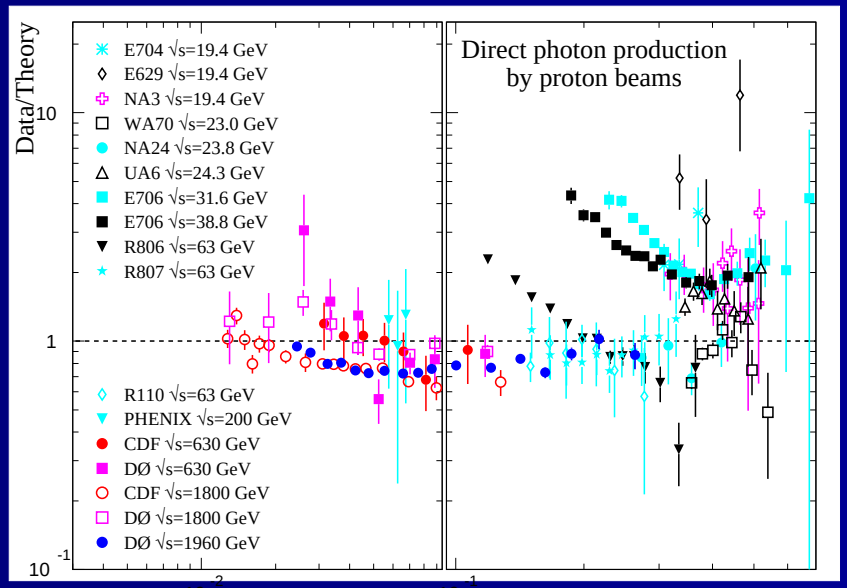
$[\frac{\sigma}{A}]_{Be}/\sigma_p$ $[\frac{\sigma}{A}]_{Cu}/[\frac{\sigma}{A}]_{Be}$ $[\frac{\sigma}{A}]_{Cu}/\sigma_p$

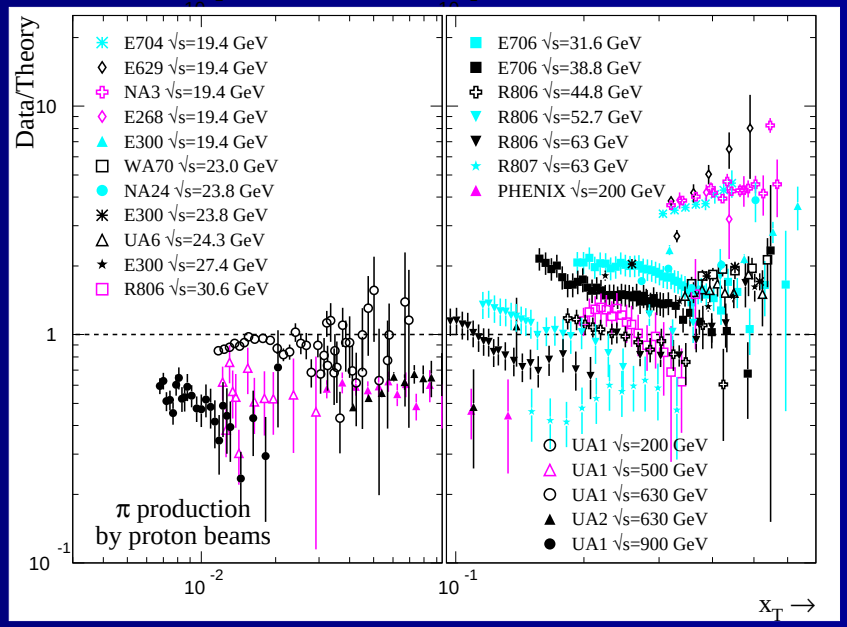


comparison with HIJING

Comparisons with NLO pQCD



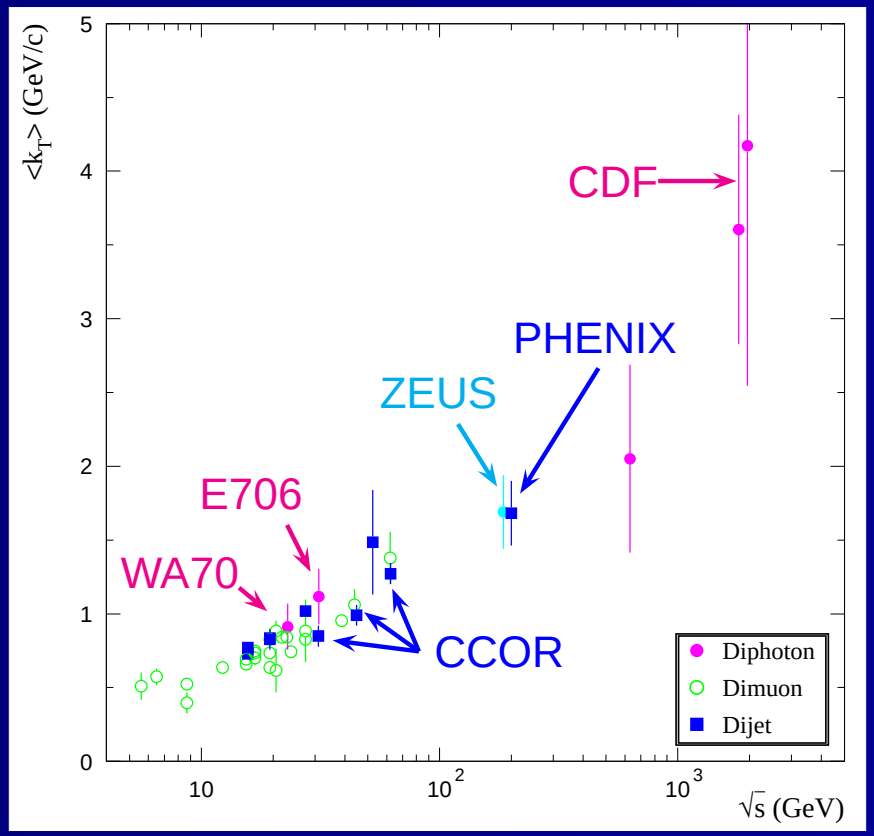


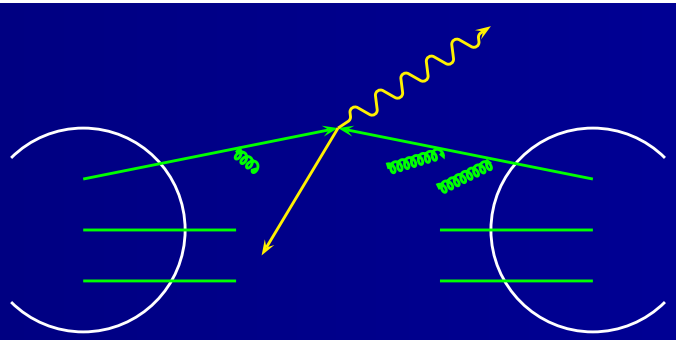


$\mu = p_T/2$ CTEQ5M PDF π^0 uses KKP FF

About k_T Effects

- k_T refers to the magnitude of the effective transverse momentum vector of each of the two colliding partons.
- Average k_T values significantly larger than expected from non-perturbative hardon-size effects have been observed in Drell-Yan, Z, and diphoton production, and have been interpreted as resulting from multiple soft-gluon emissions.

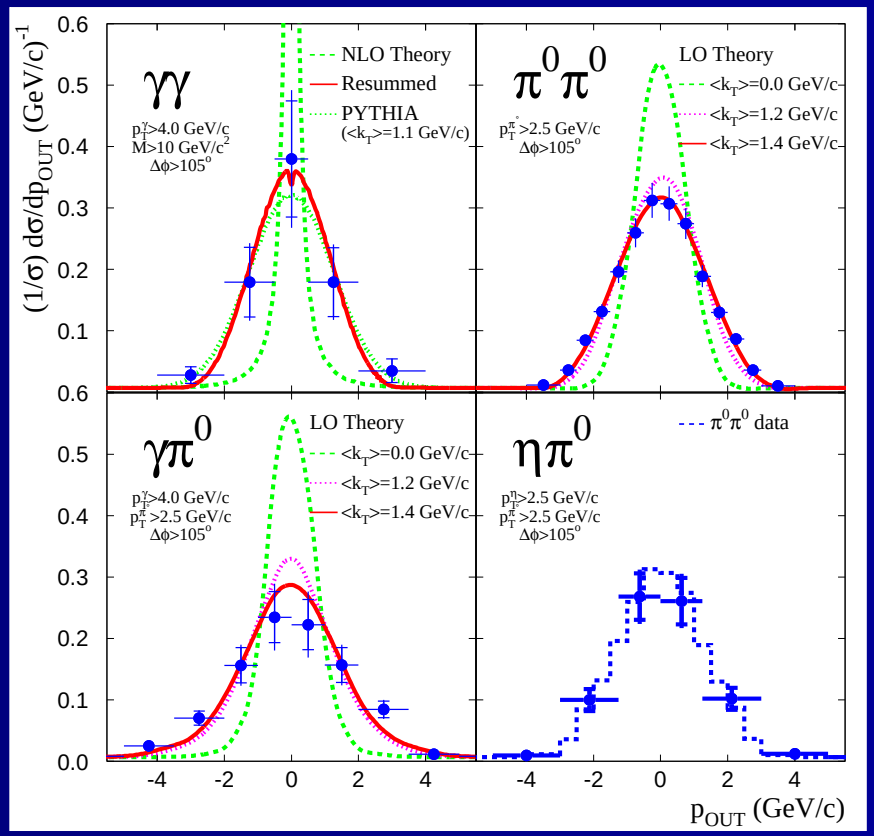


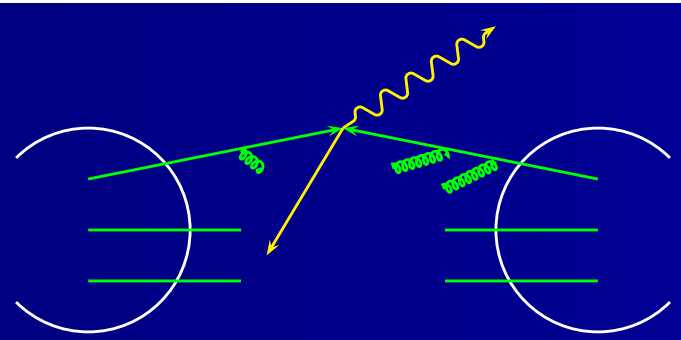


About k_T Effects

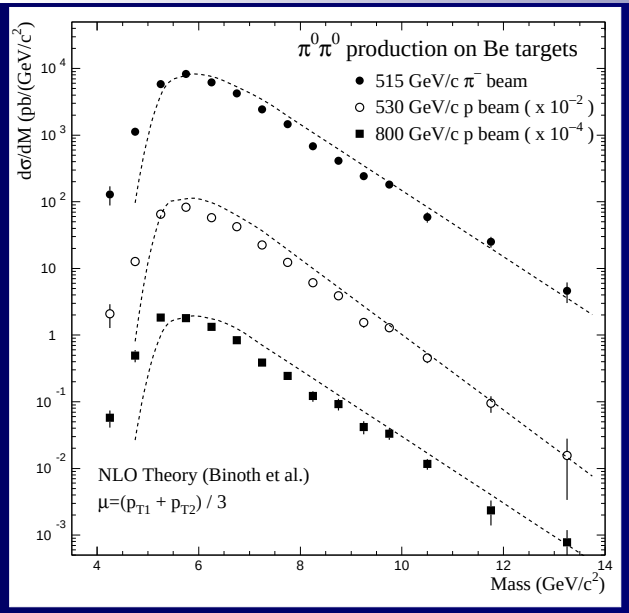
k_T incorporated in LO pQCD via Gaussian smearing

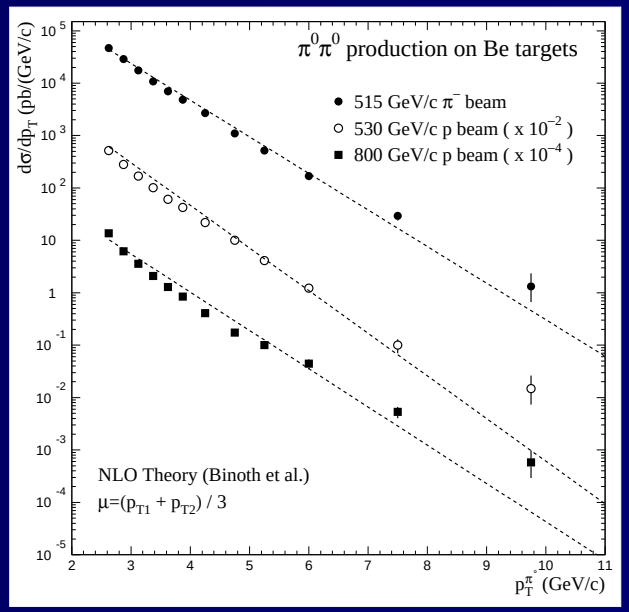
- k_T refers to the magnitude of the effective transverse momentum vector of each of the two colliding partons.
- Average k_T values significantly larger than expected from non-perturbative hardon-size effects have been observed in Drell-Yan, Z, and diphoton production, and have been interpreted as resulting from multiple soft-gluon emissions.
- Fixed-order pQCD calculations partially include this effect through additional diagrams.
- Resummed pQCD calculations should properly include k_T effects.



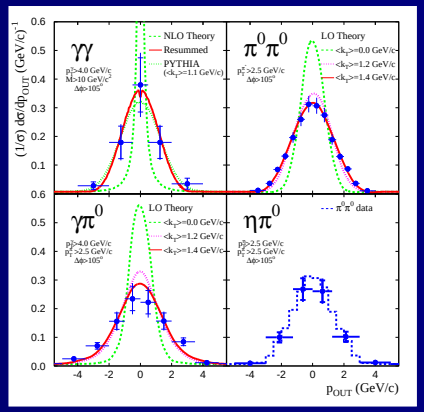


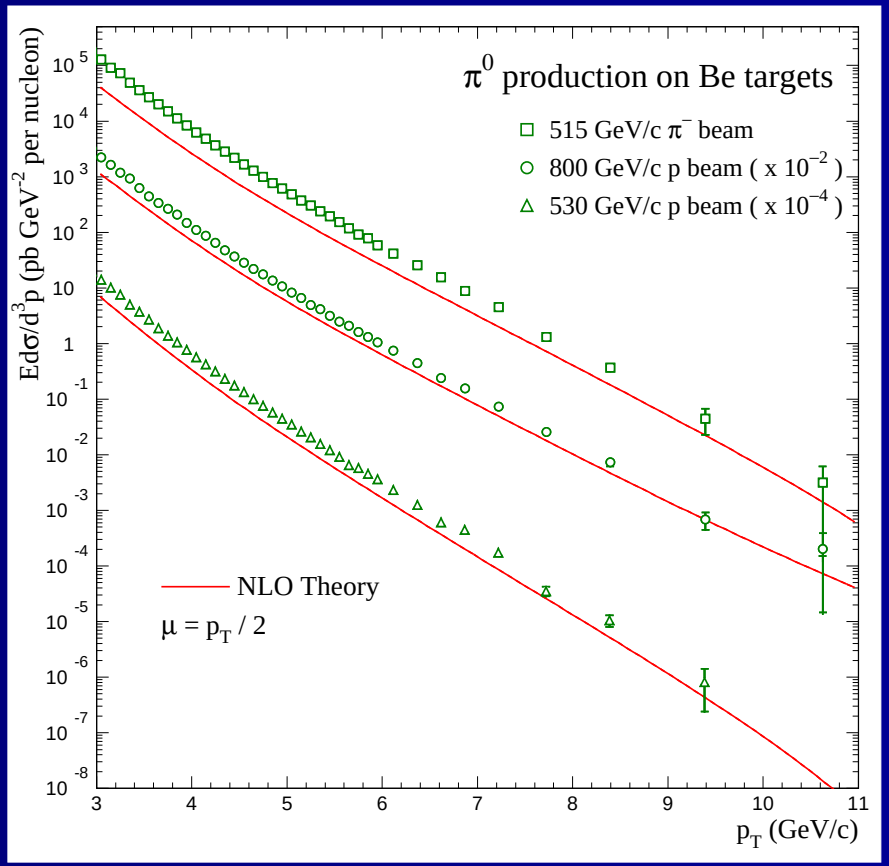
Two Arms are better than One

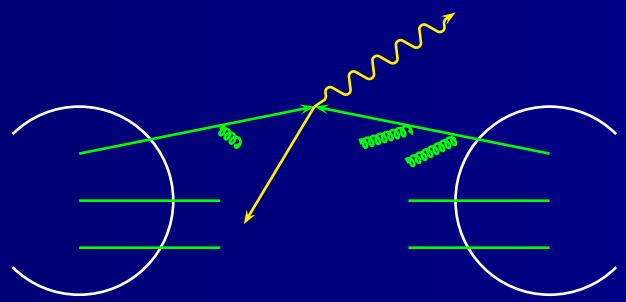


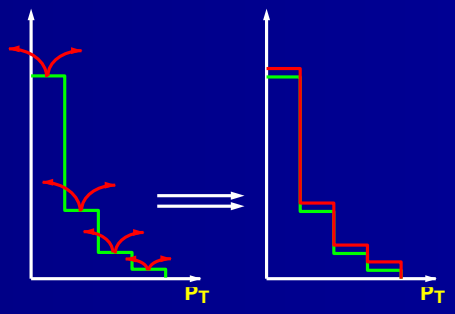


Distributions such as the dipion mass and $p_T^{\pi^0}$ are insensitive to k_T effects.



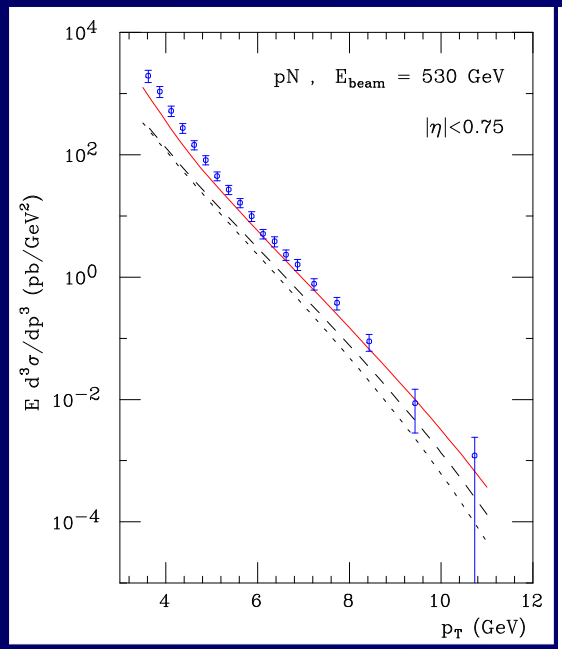




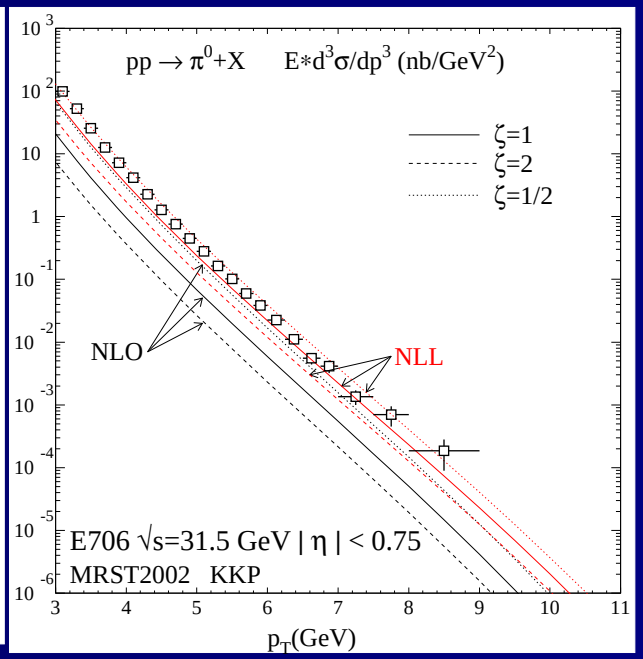


Including Higher Order Effects

There has been significant progress towards developing resummed calculations for inclusive direct photon and π^0 production



E. Laenen, G. Sterman, and W. Vogelsang Phys. Rev. Lett. **84**, 4296 (2000)

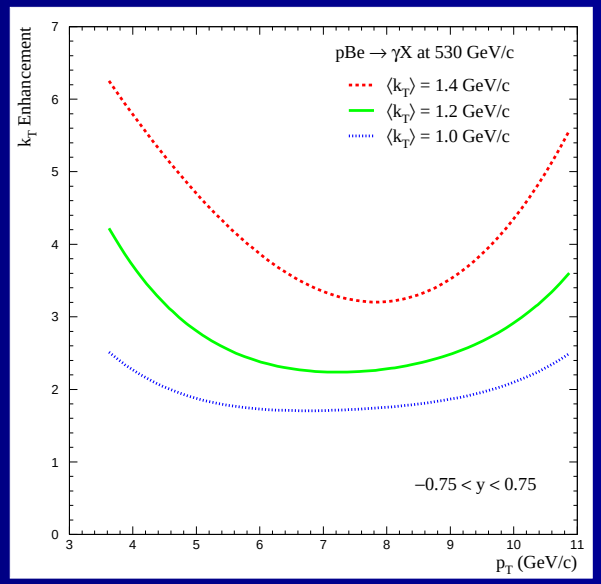


D. Florian and W. Vogelsang Phys. Rev. **D71**, 114004 (2005)

LO pQCD calculations model incident-parton k_T using Gaussian smearing

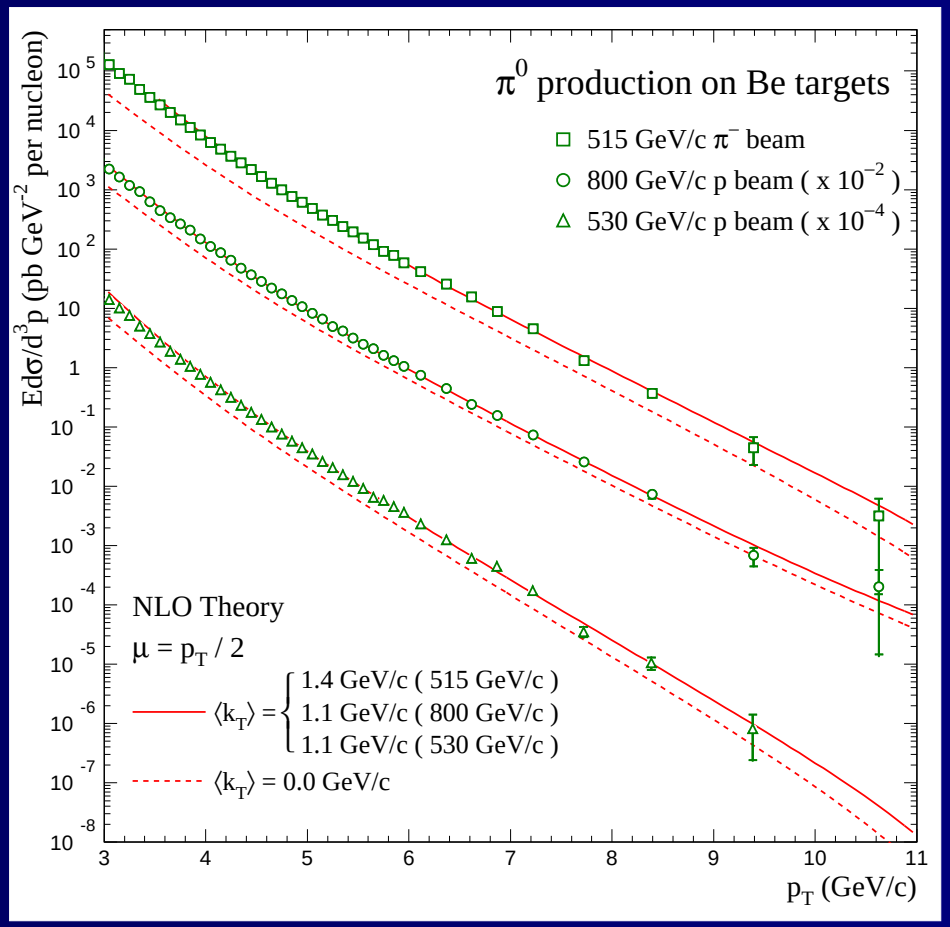
$$\sigma^{\mathrm{NLO}} \times K^{\mathrm{LO}}(p_T)$$

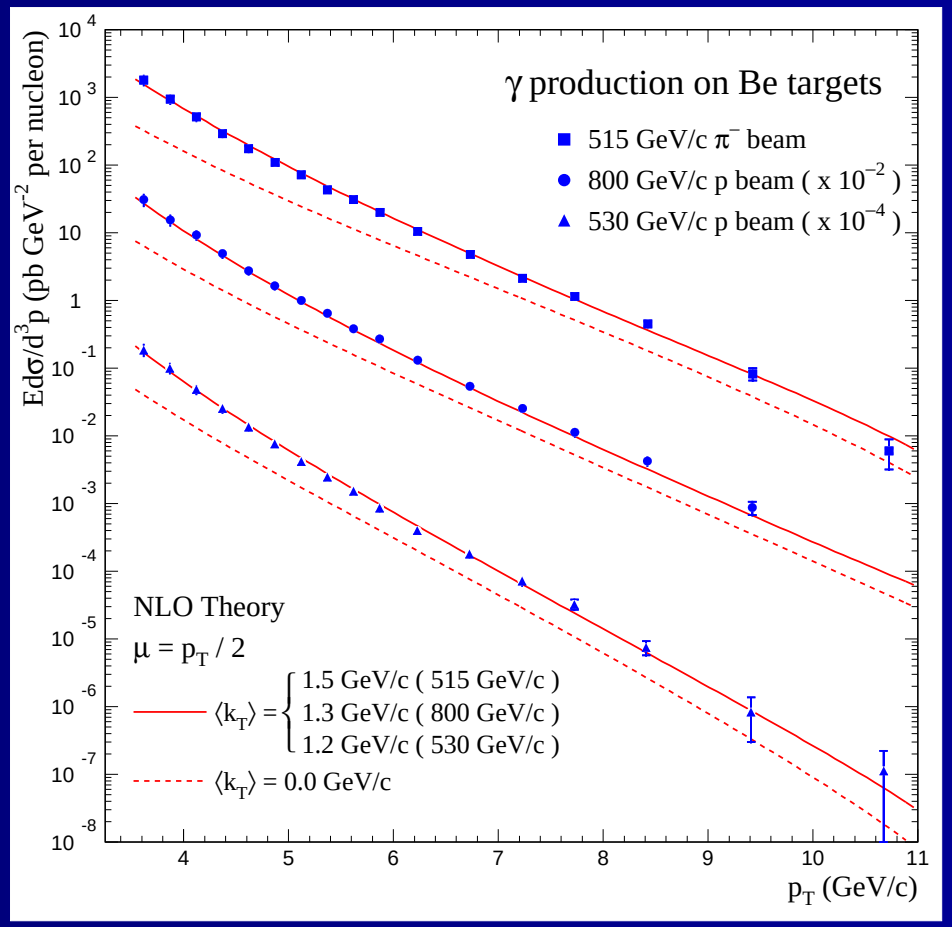
$$K^{\mathrm{LO}}(p_T) = \frac{\sigma^{\mathrm{LO}}\left(\langle k_T \rangle\right)}{\sigma^{\mathrm{LO}}\left(\langle k_T \rangle = 0\right)}$$



$\langle k_T \rangle$ for $K^{\mathrm{LO}}(p_T)$ taken from data (match distributions of high mass pairs to LO calculations)

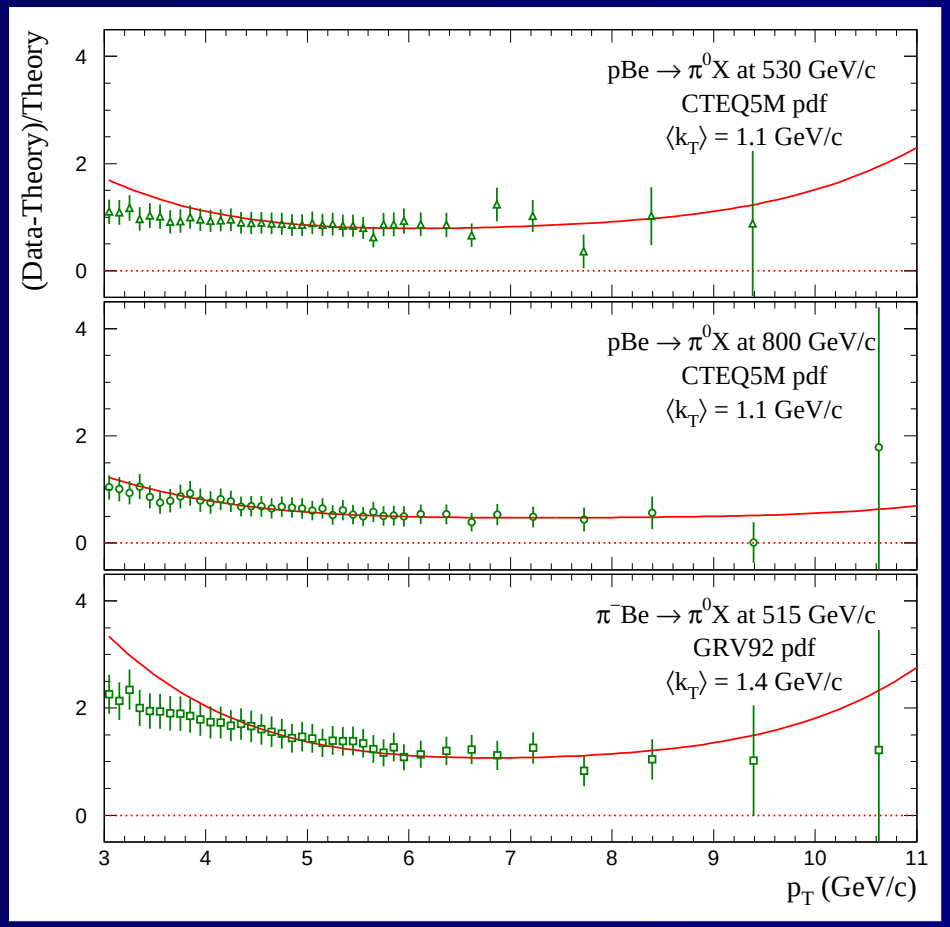
Inclusive Production with k_T

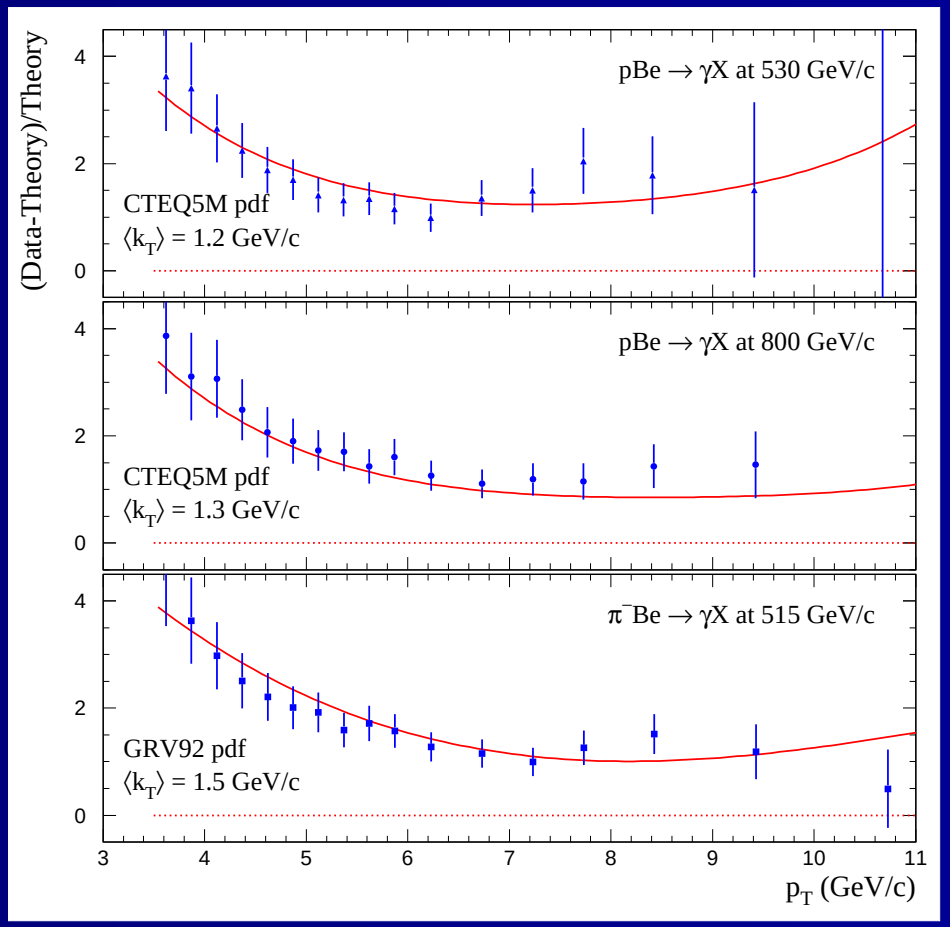




Chosen k_T values were influenced by studies of two particle correlations but are model dependent. This is not a measurement of k_T.

Inclusive Production with k_T

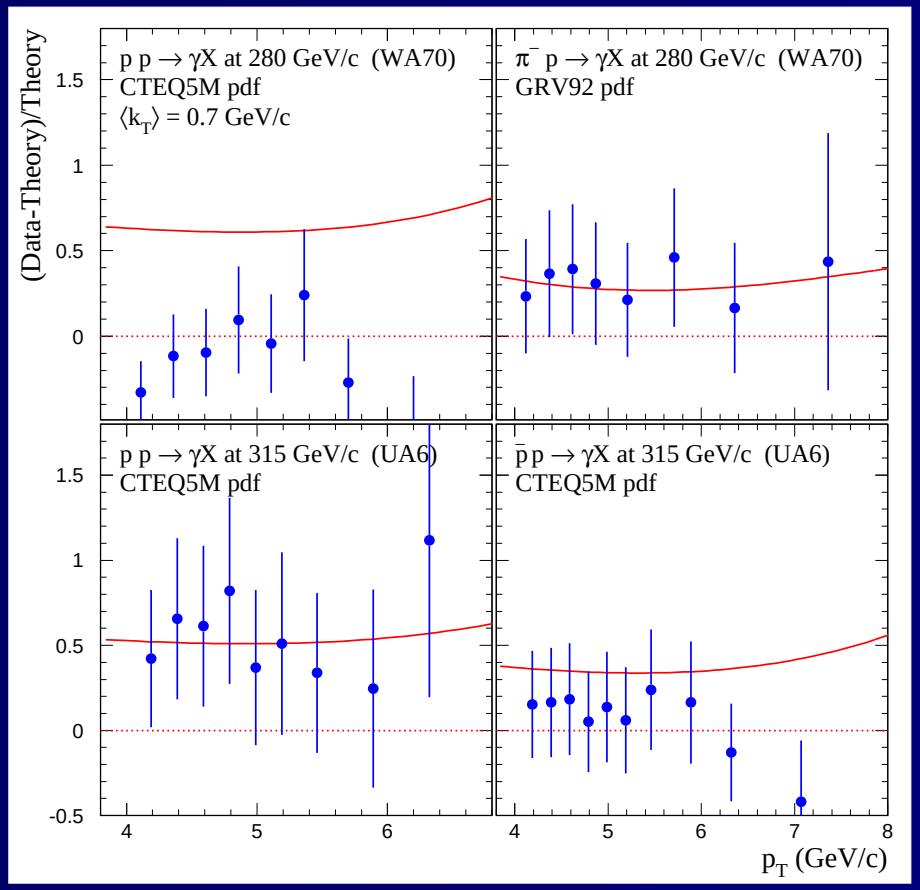


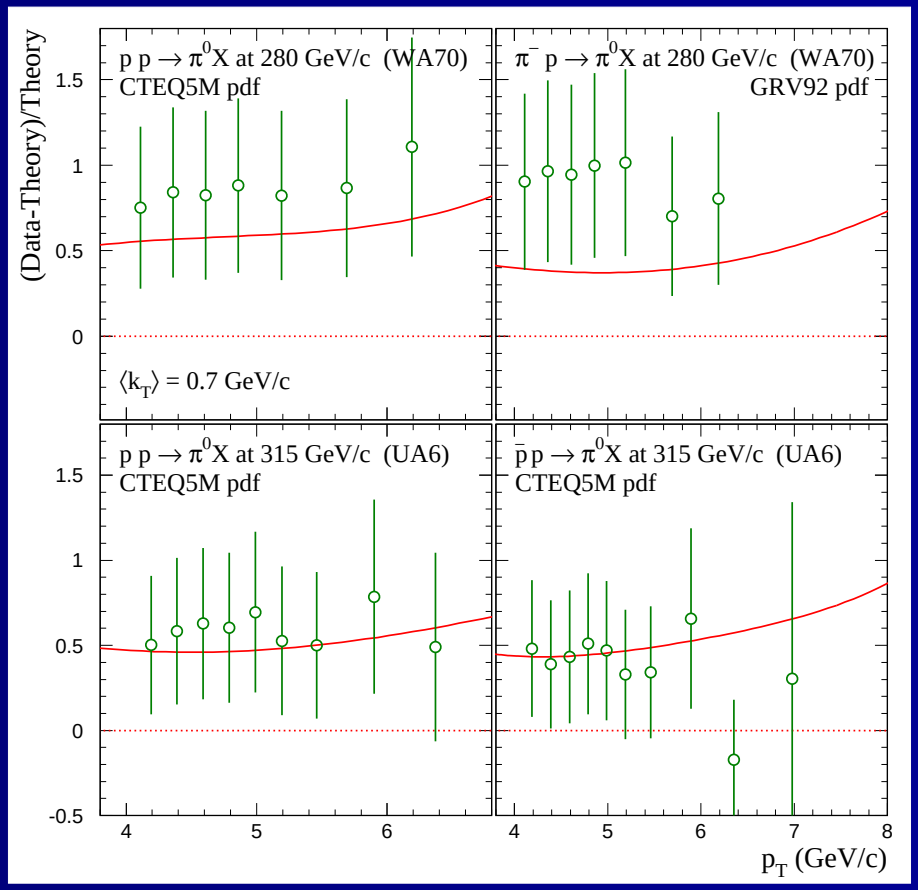


Chosen k_T values were influenced by studies of two particle correlations but are model dependent. This is not a measurement of k_T.

Comparisons with Other Experiments

WA70 and UA6



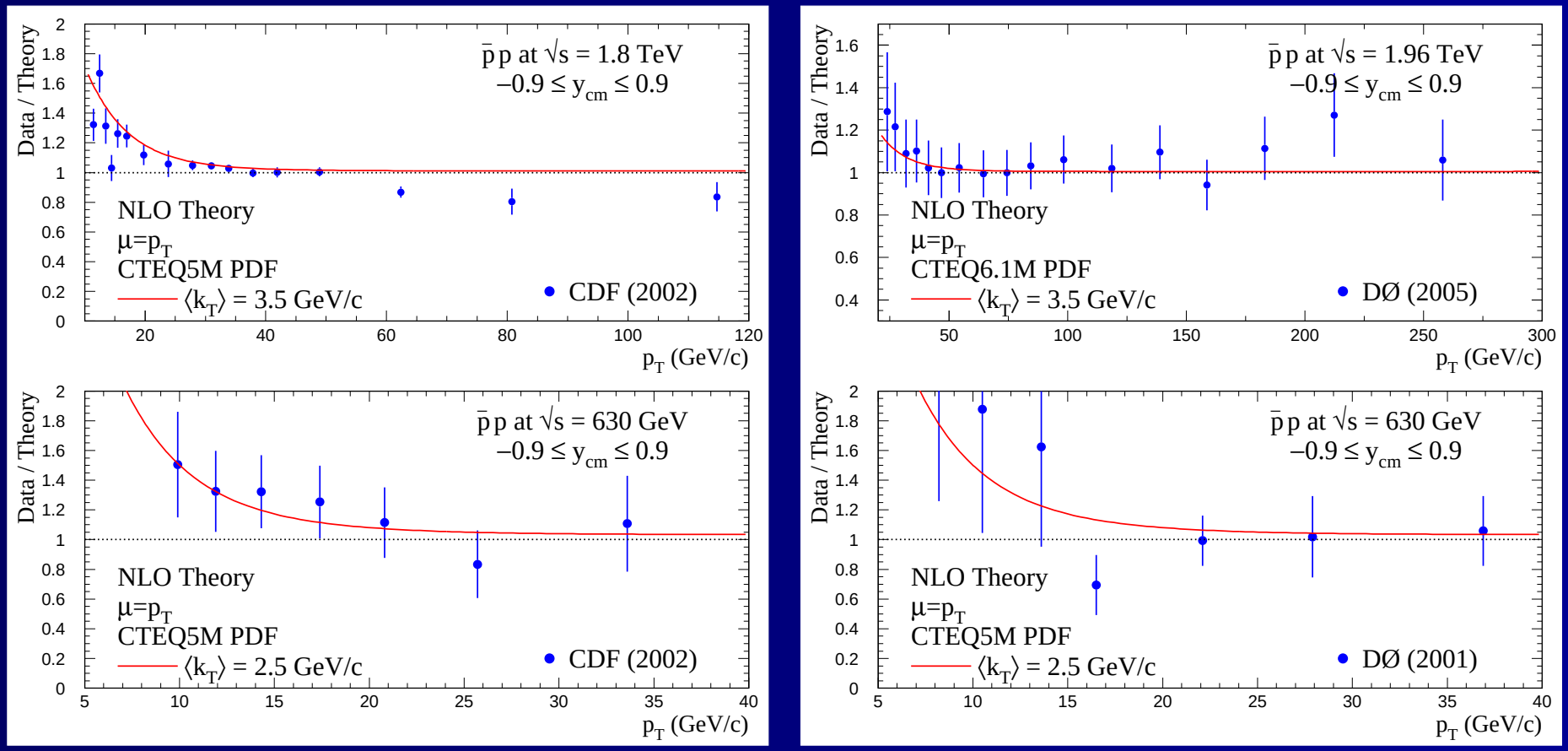


Direct Photon Production

π^0 Production

Comparisons with Other Experiments

CDF and DØ



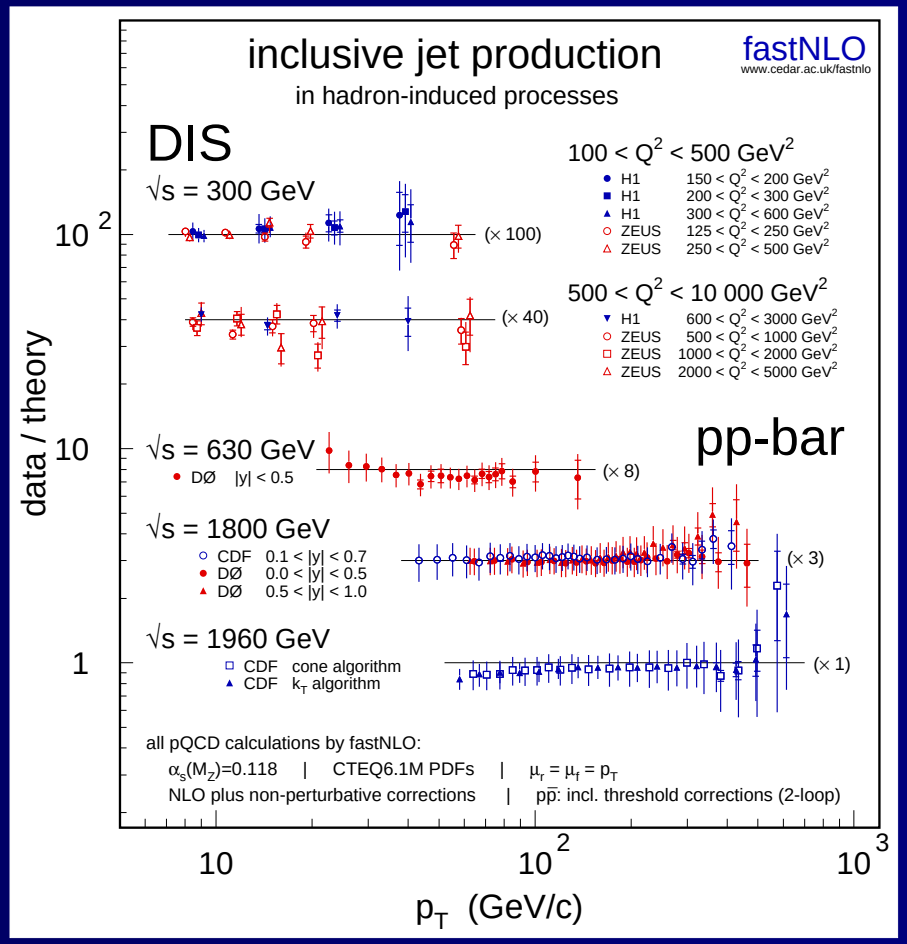
Direct Photon Production

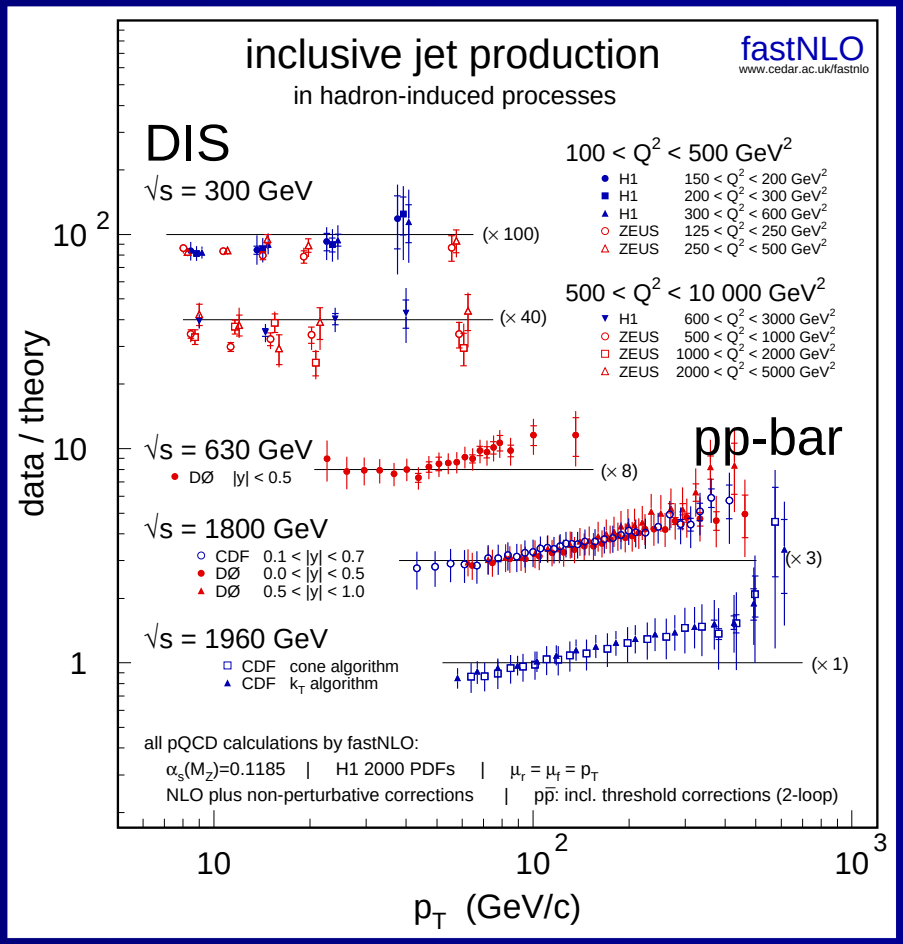
Conclusions

- High-p_T direct-photon and π^0 production has been measured in interactions of 515 GeV/c π^- and 530 GeV/c and 800 GeV/c protons with beryllium, copper, and hydrogen targets.
- The production of direct photons exhibits significantly smaller nuclear enhancement than does high-p_T π^0 production.
- The shape of the rapidity distributions do not exhibit any significant dependence upon the nuclear target over the range covered by the experiment.
- NLO pQCD does not satisfactorily represent the data at our energies.
- The data are described better by k_T-enhanced NLO pQCD calculations using the softer gluons of CTEQ5 and MRST2003 than the harder gluons of CTEQ6.1.
- Inclusion of direct-photon data in global fits would provide additional constraints on the gluon distribution, independent of the Tevatron jet data, thereby enhancing the discovery potential of the jet data being acquired in Tevatron Run II.

Conclusions

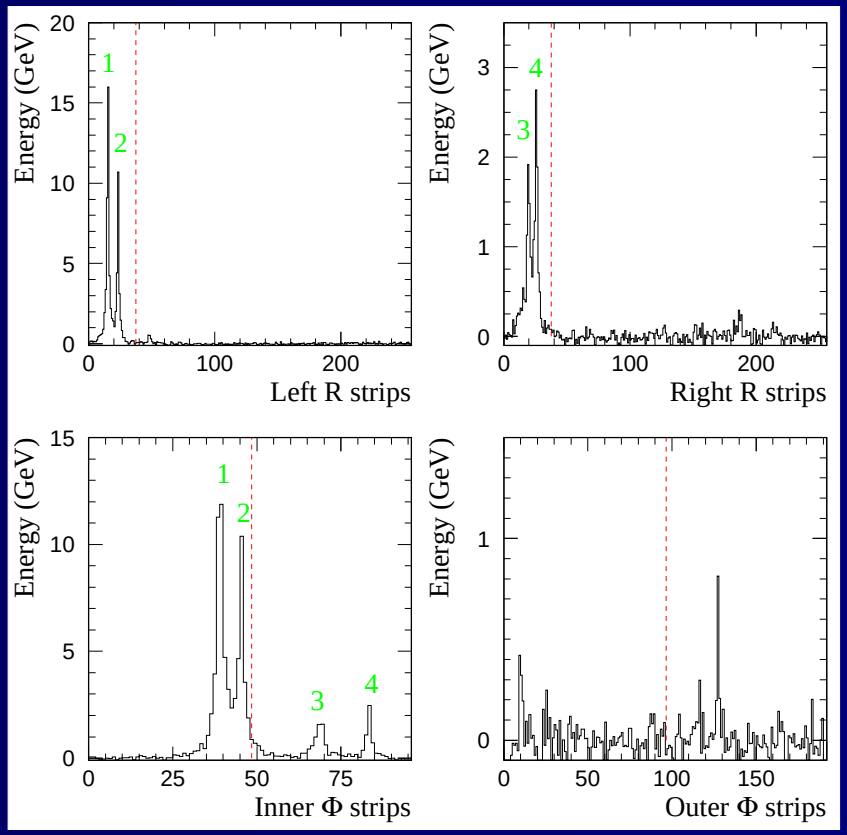
- Inclusion of direct-photon data in global fits would provide additional constraints on the gluon distribution, independent of the Tevatron jet data, thereby enhancing the discovery potential of the jet data being acquired in Tevatron Run II.

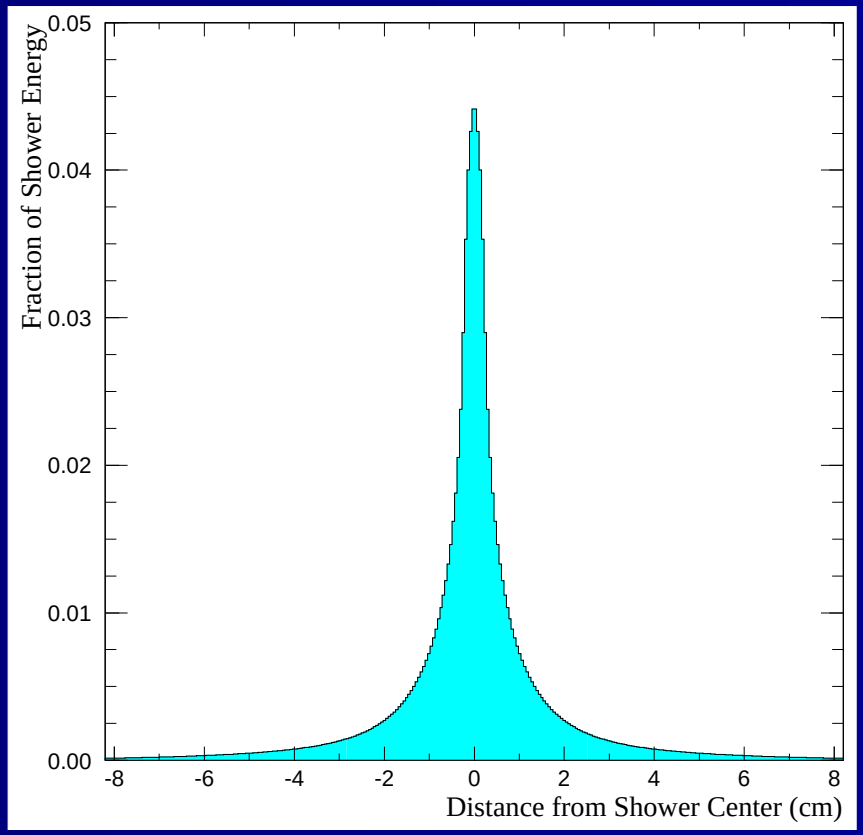




backup

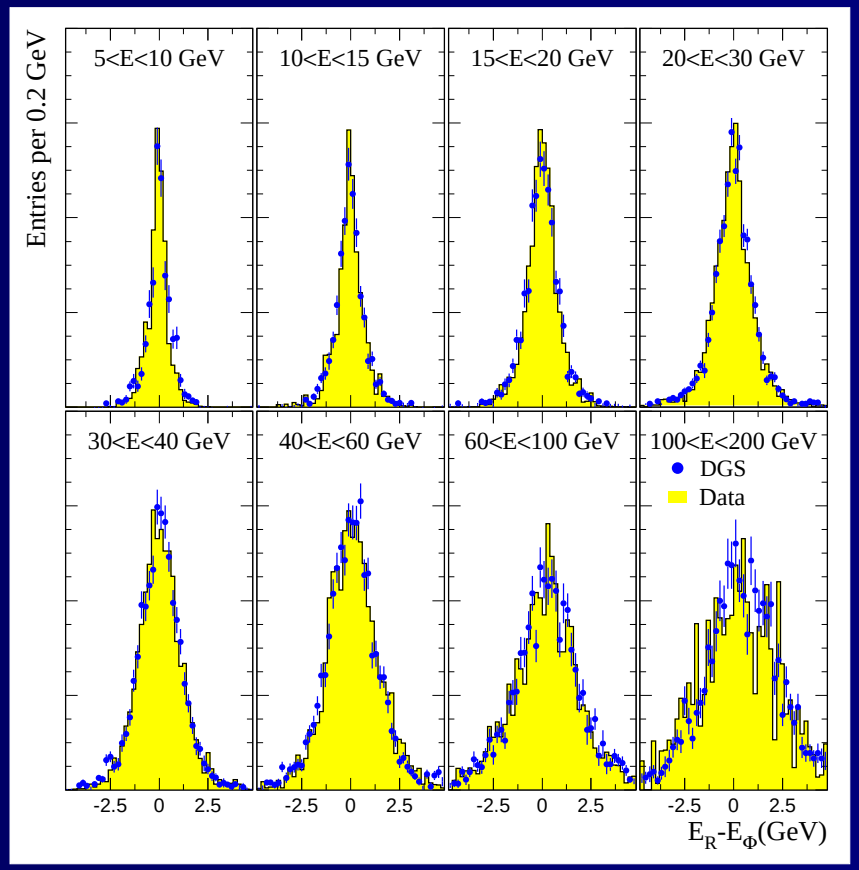
Photon Reconstruction

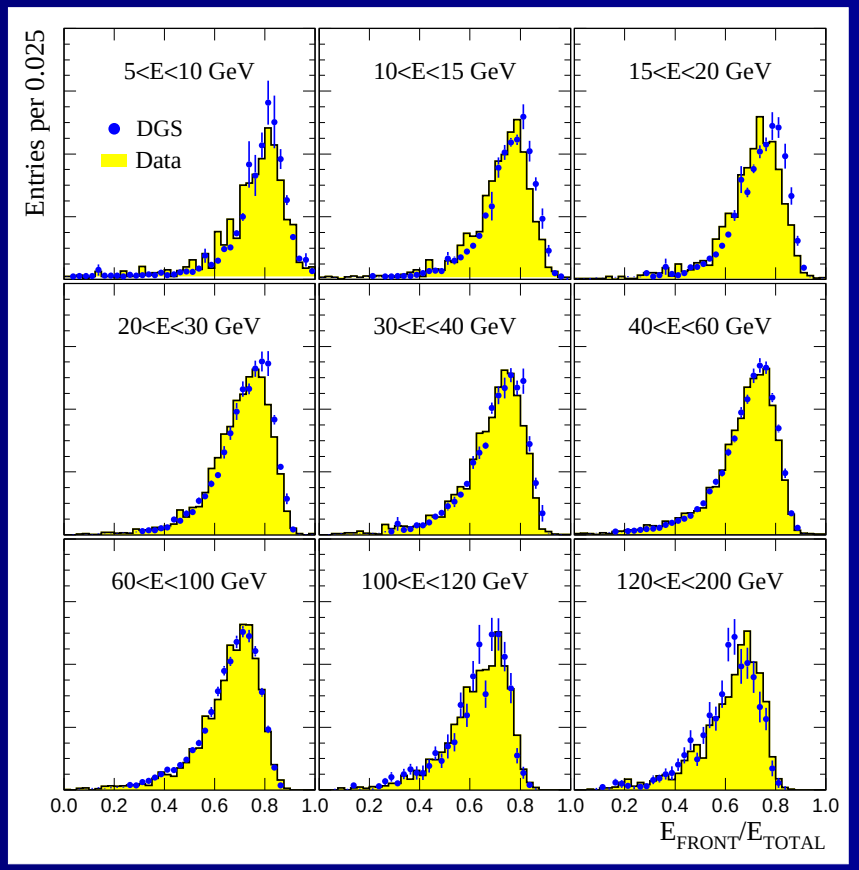




EMLAC Shower Shape

Monte Carlo and Data Comparisons



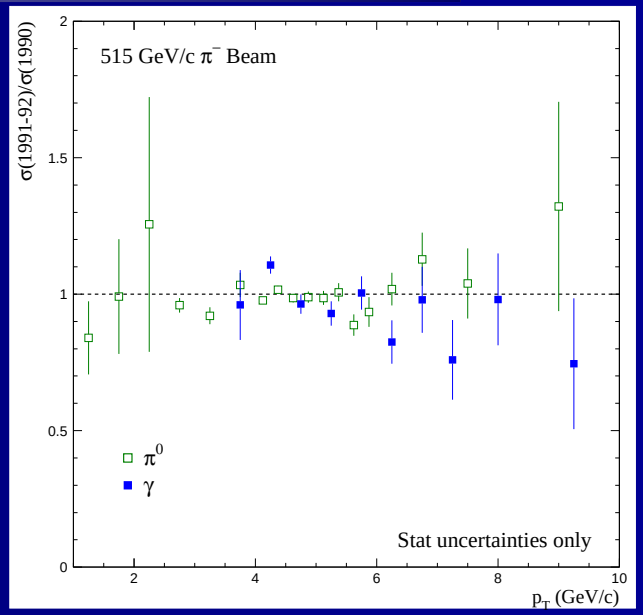


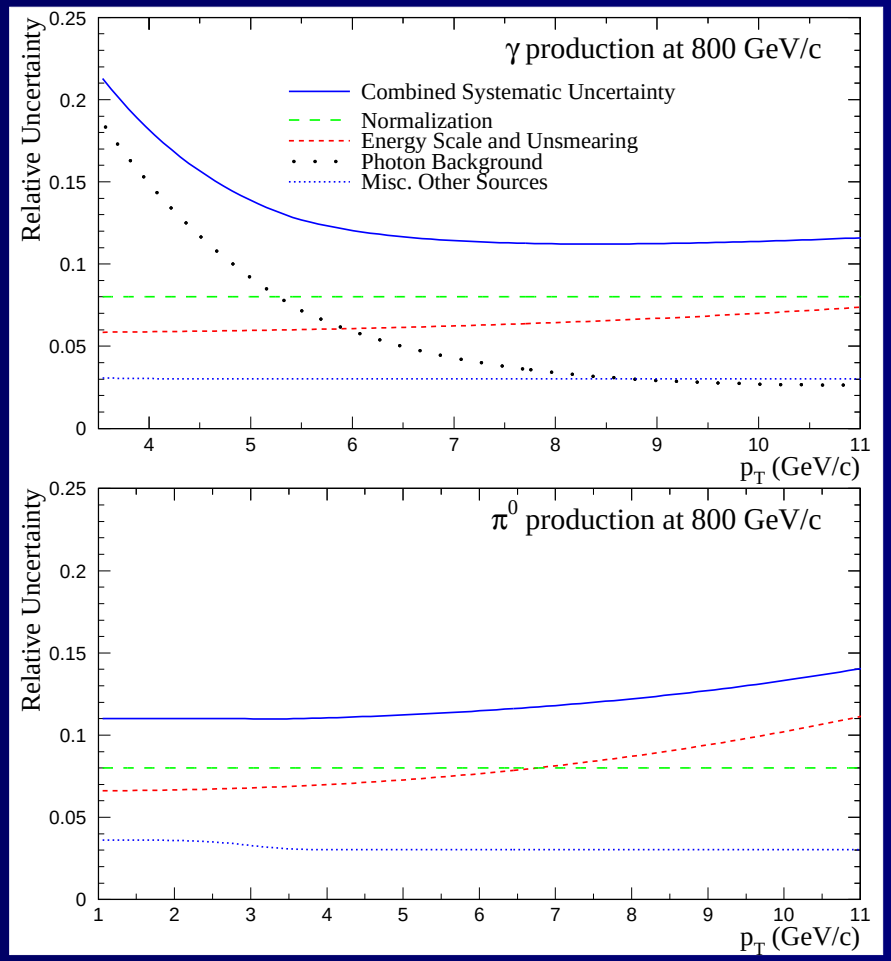
Photon $E_R - E_\phi$

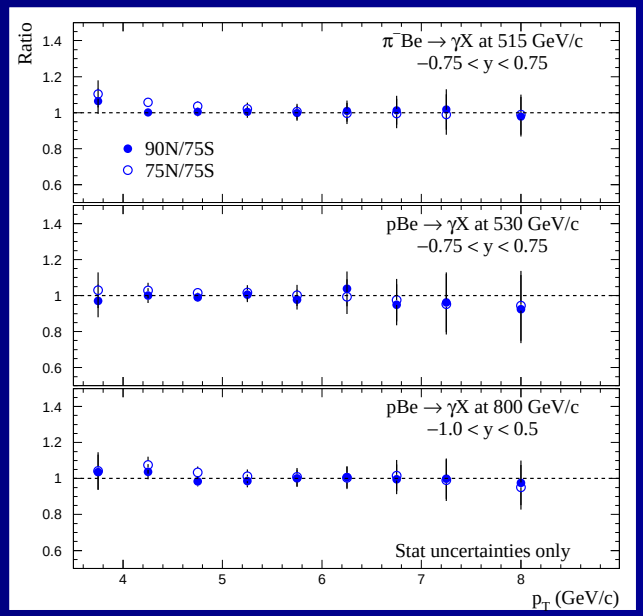
Photon $E_{\mathrm{FRONT}}/E_{\mathrm{TOTAL}}$

Systematic Uncertainties

Comparison of results from the 1991-92 and 1990 runs

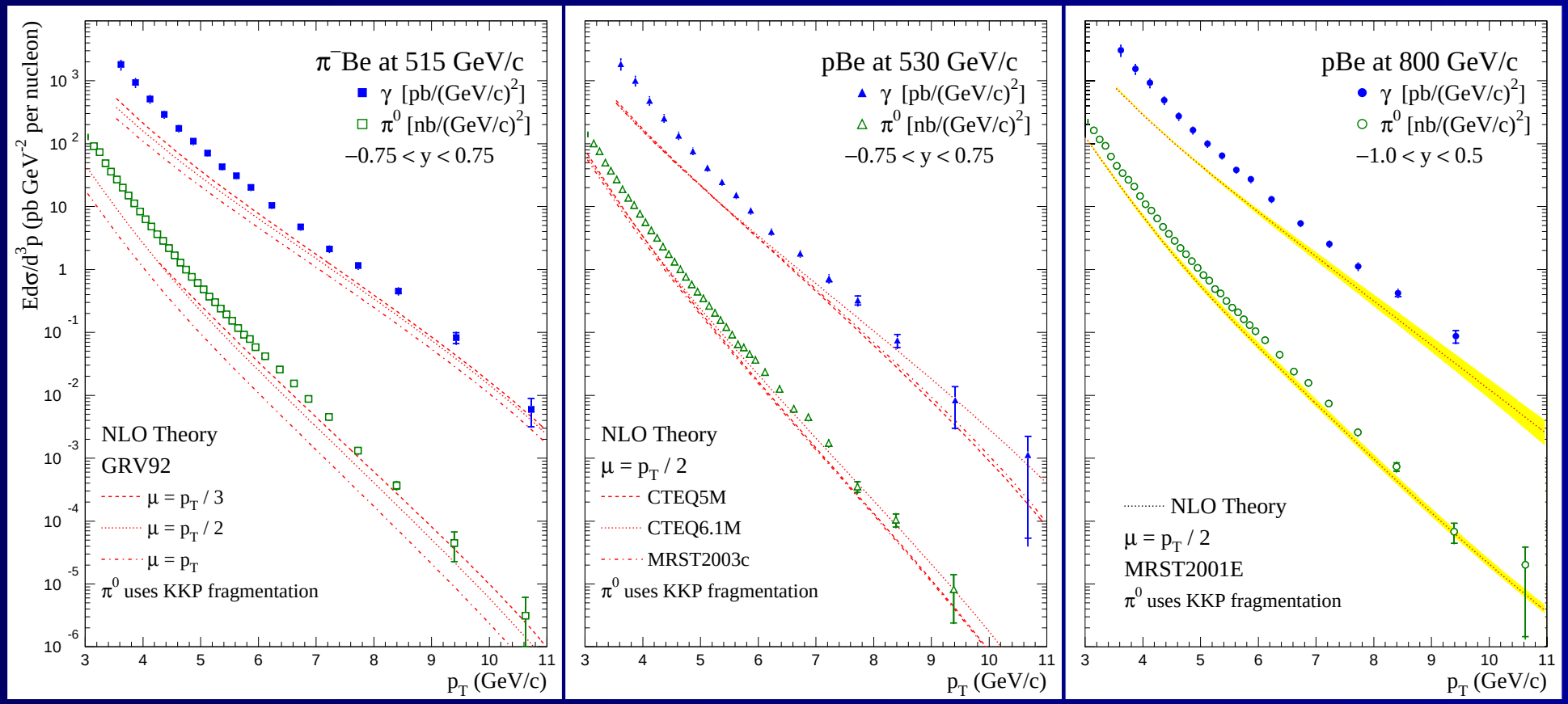






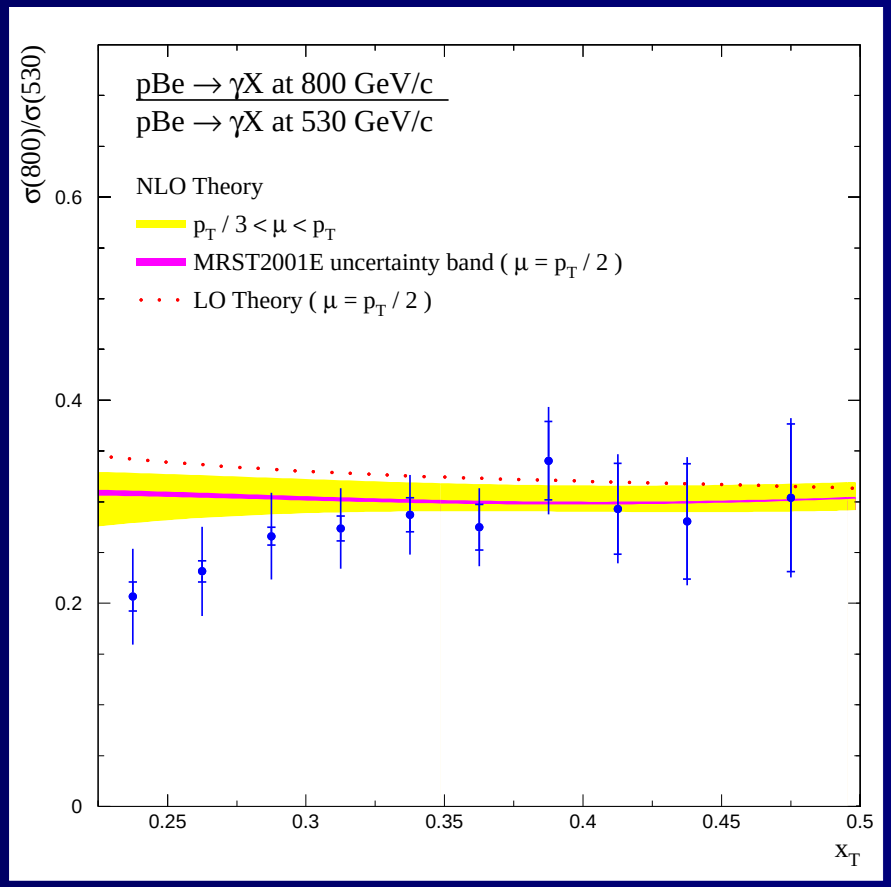
Comparison of direct photon results using 90N, 75N, and 75S definitions

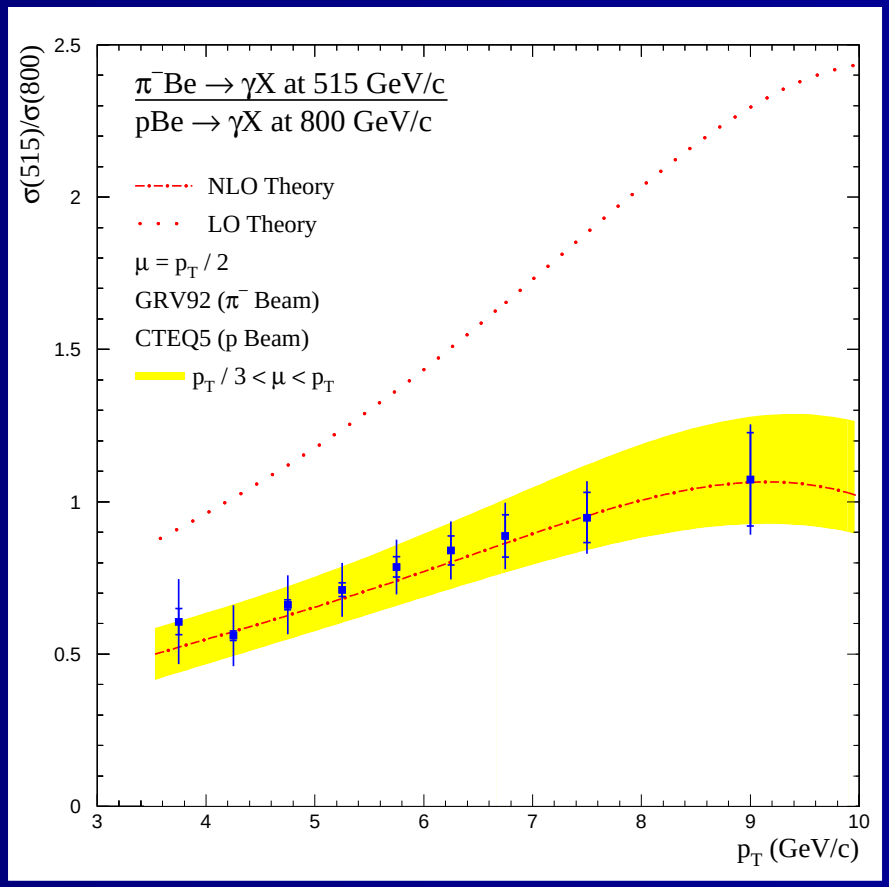
Comparisons with NLO pQCD



Comparisons with pQCD

NLO pQCD has reduced scale dependence and significantly improved agreement when compared to ratios of direct-photon cross sections



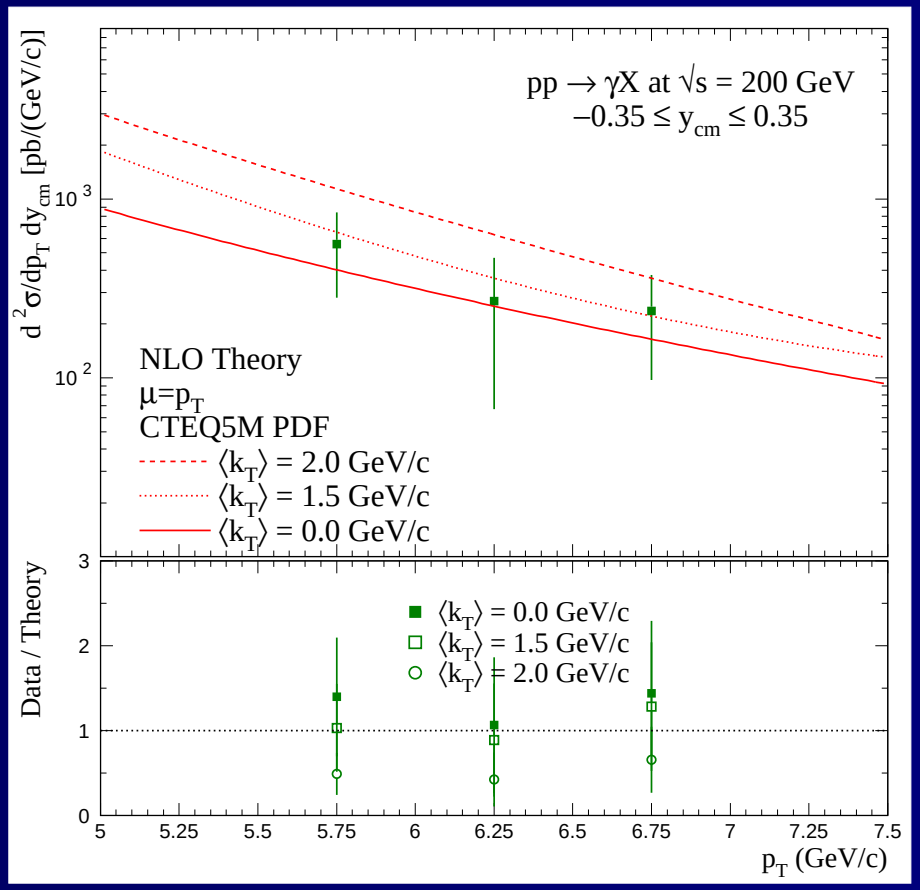


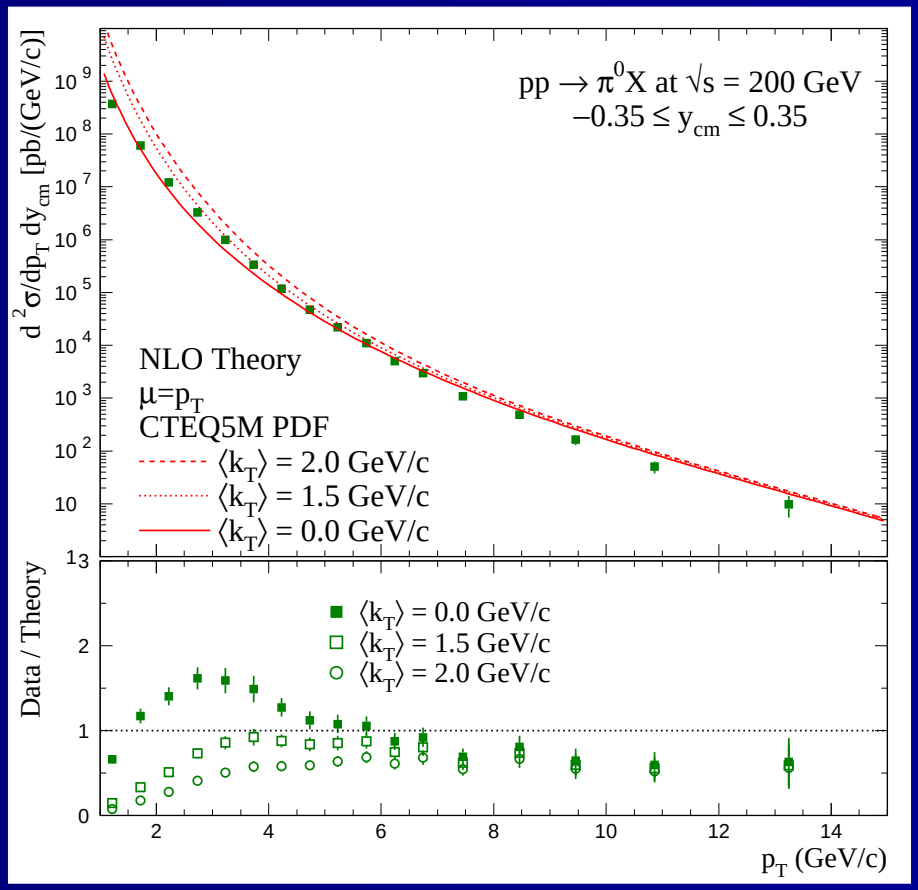
Plotted vs $x_T = 2p_T/\sqrt{s}$ to compensate for different average parton-parton collision energies.

Plotted vs p_T since the average energy per colliding valence quark is similar.

Comparisons with Other Experiments

PHENIX

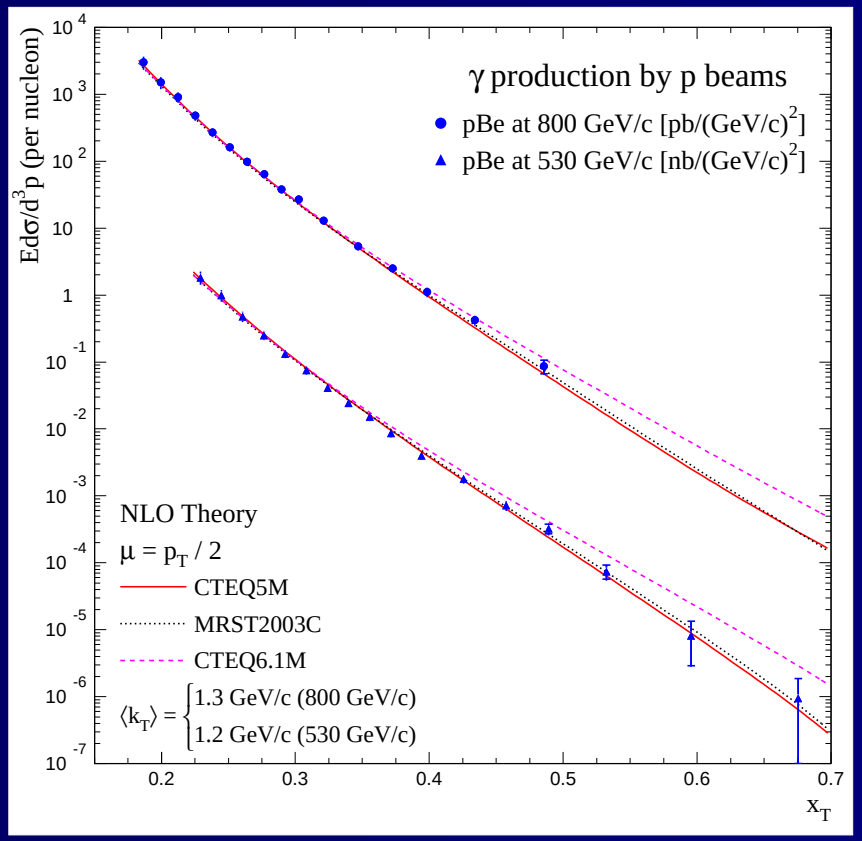


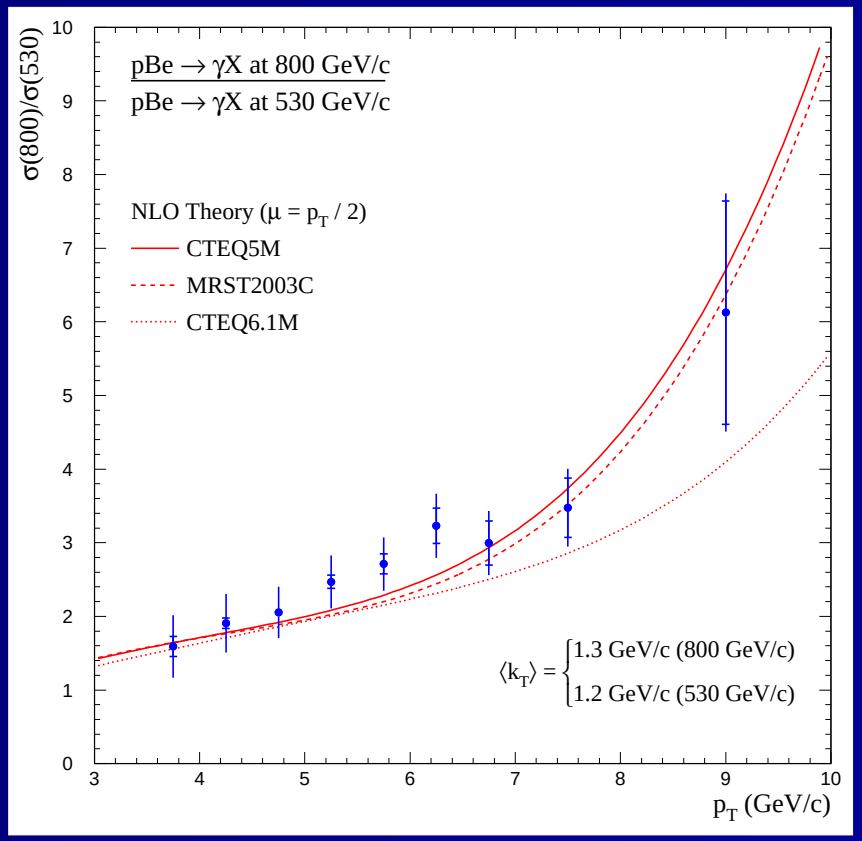


Direct Photon Production

π^0 Production

Sensitivity to the Gluon Distribution





Comparisons between direct-photon data and k_T-enhanced NLO pQCD help us distinguish between various PDF.