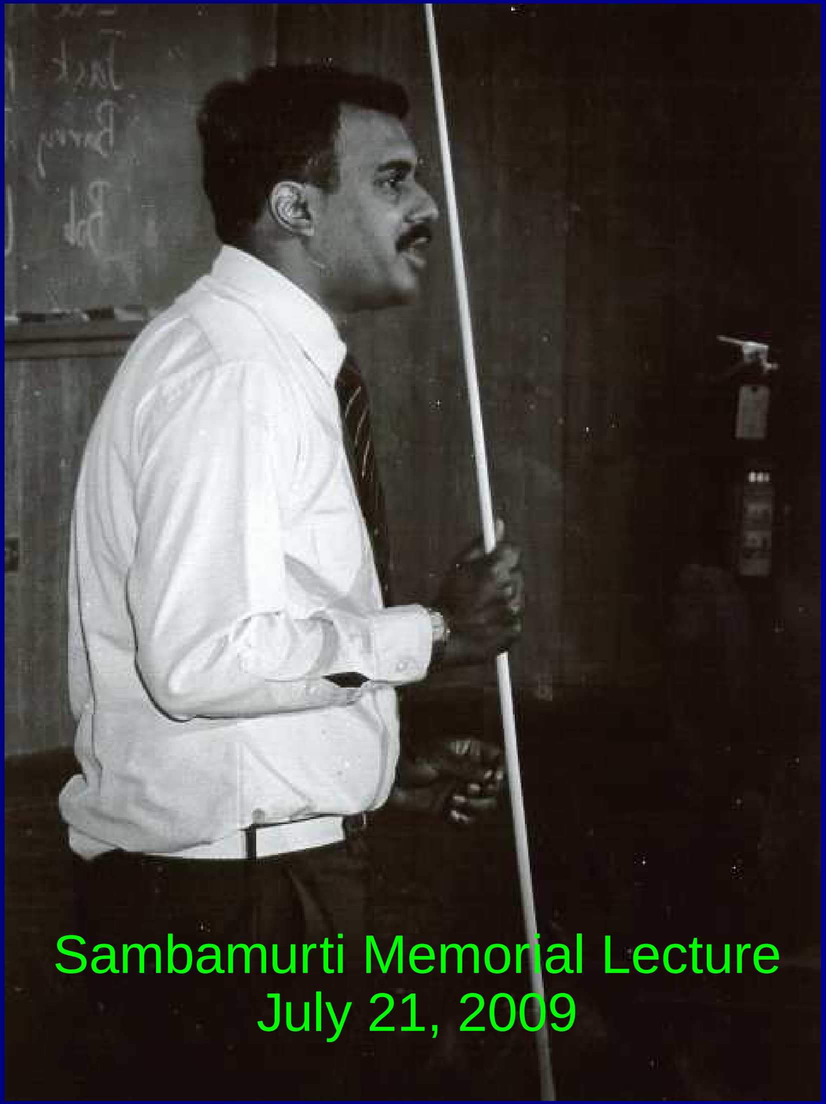
Spotlight on the Gluon

Michael Begel

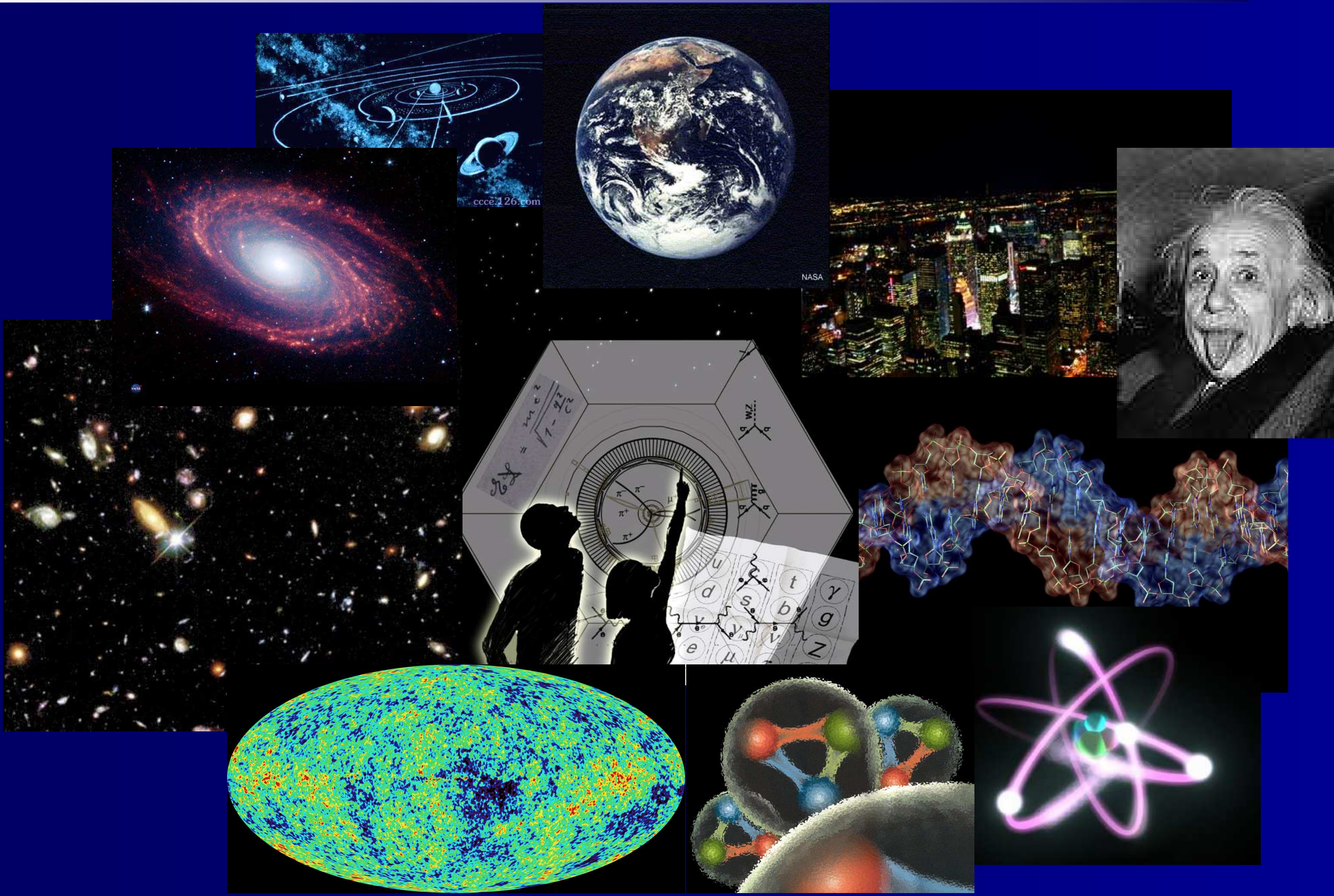
BROOKHAVEN
NATIONAL LABORATORY



The Big Questions

- Why are we here?
- Where did we come from?
- What is the universe made of?
- What is the meaning of life?
- What is the purpose of the universe?
- What holds everything together?
- What time is it?

Searching for Answers



Standard Model

Decades of experimental results and theoretical development have culminated in a theory of matter and forces called the Standard Model of Particle Physics.

quantum field theory describing point-like fermions (quarks and leptons) that interact by exchanging vector bosons (photons, $W^{\pm}$, Z^0, and gluons)

Weak Nuclear: 10^{-6}

Strong Nuclear: 1

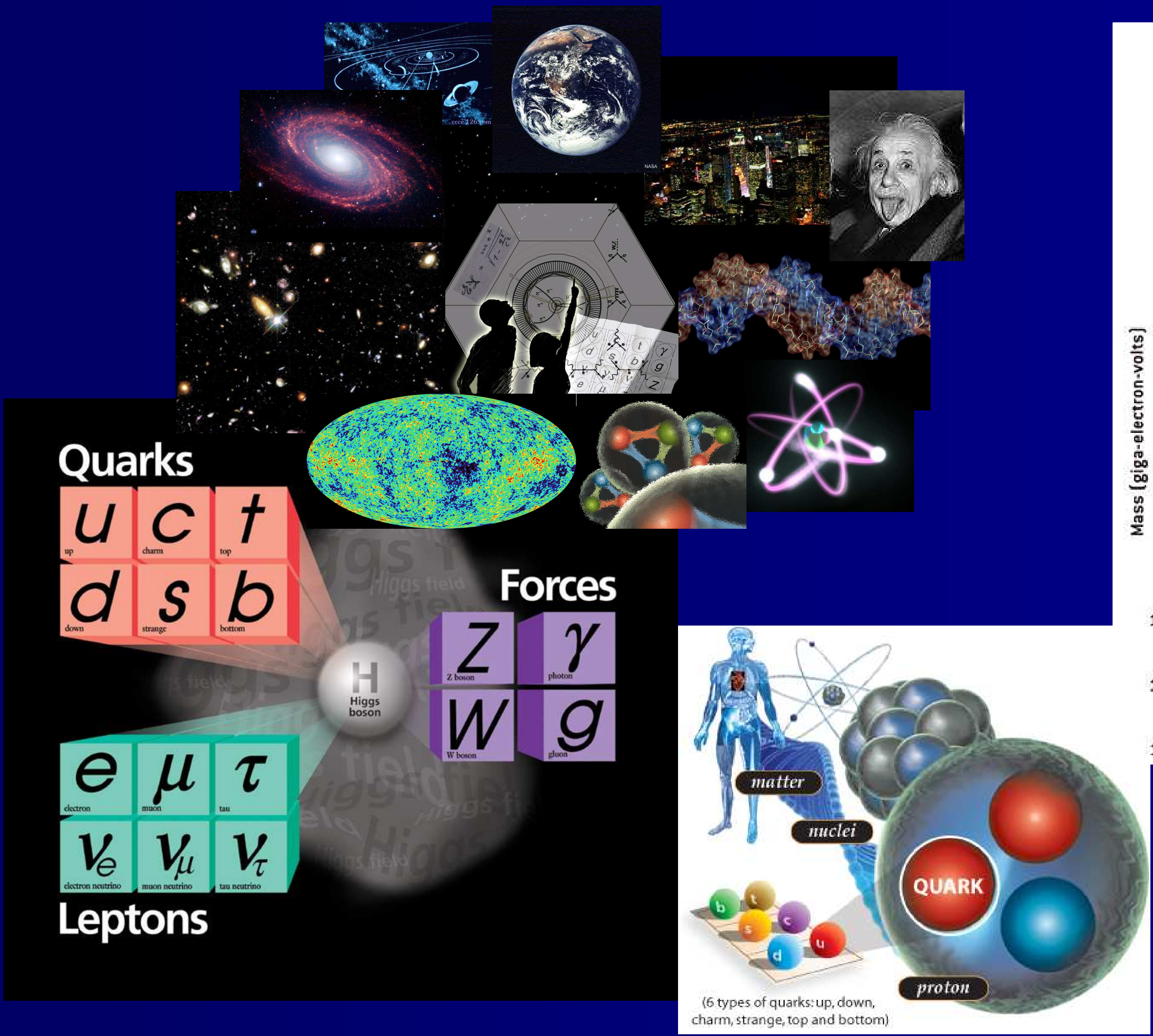
ElectroWeak

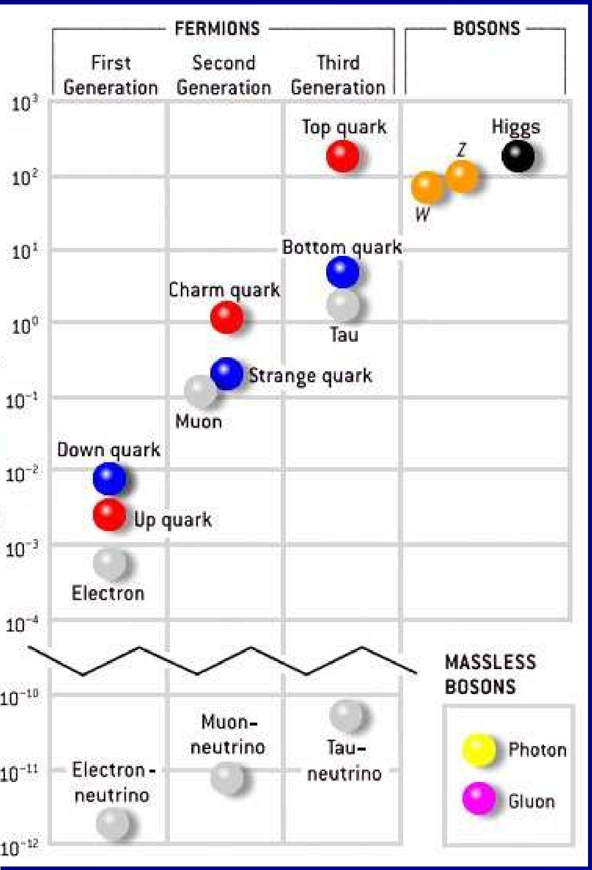
ElectroMagnetism: 10^{-2}

The Standard Model makes precise and accurate predictions and describes a rich panoply of physical phenomena including nucleons, atoms, and stars. Of course, it doesn't explain everything.

Gravity: 10^{-40}
(additional assembly required)

Standard Model

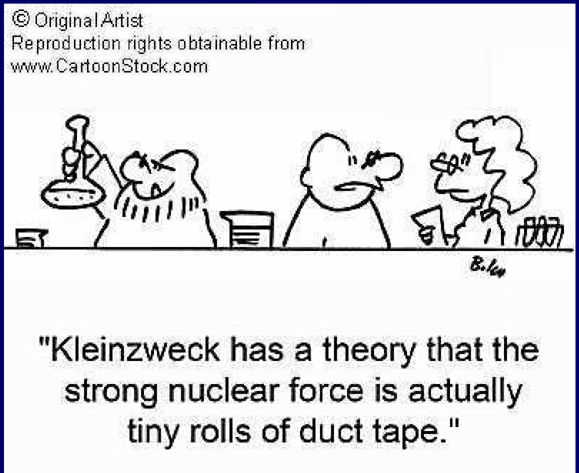


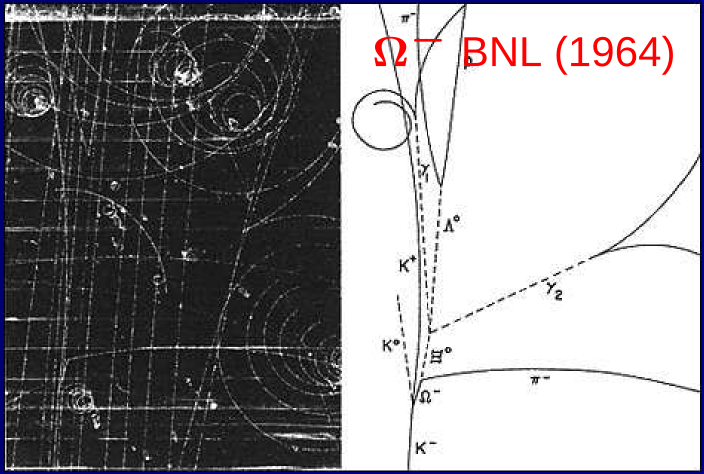


What is the Gluon?

The gluon is the massless spin-1 carrier of the strong force.

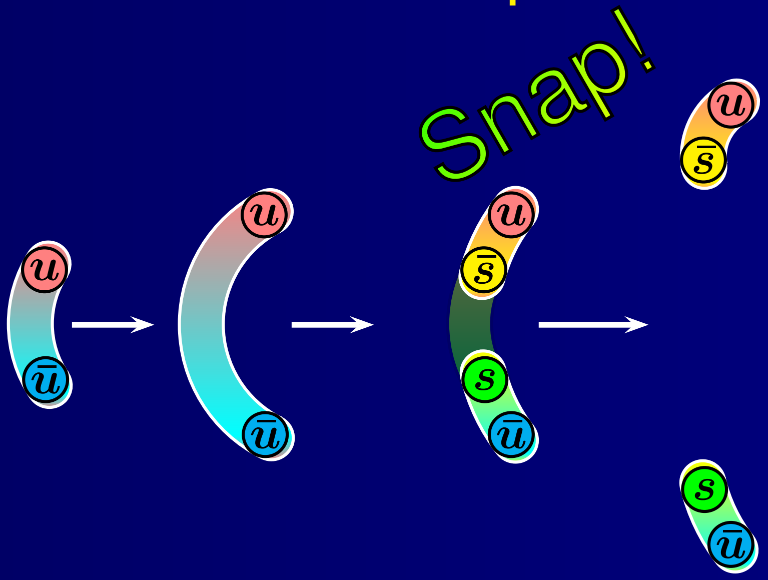
	Electromagnetic	Strong Nuclear
charge	electric	color
number of charges	1 $(+,-)$	3 $(r,g,b,\bar{r},\bar{g},\bar{b})$
force carrier	photon	gluon
carrier charge	none	color + anti-color (8 combinations)
theory	quantum electrodynamics	quantum chromodynamics
relative strength	10^{-2}	1

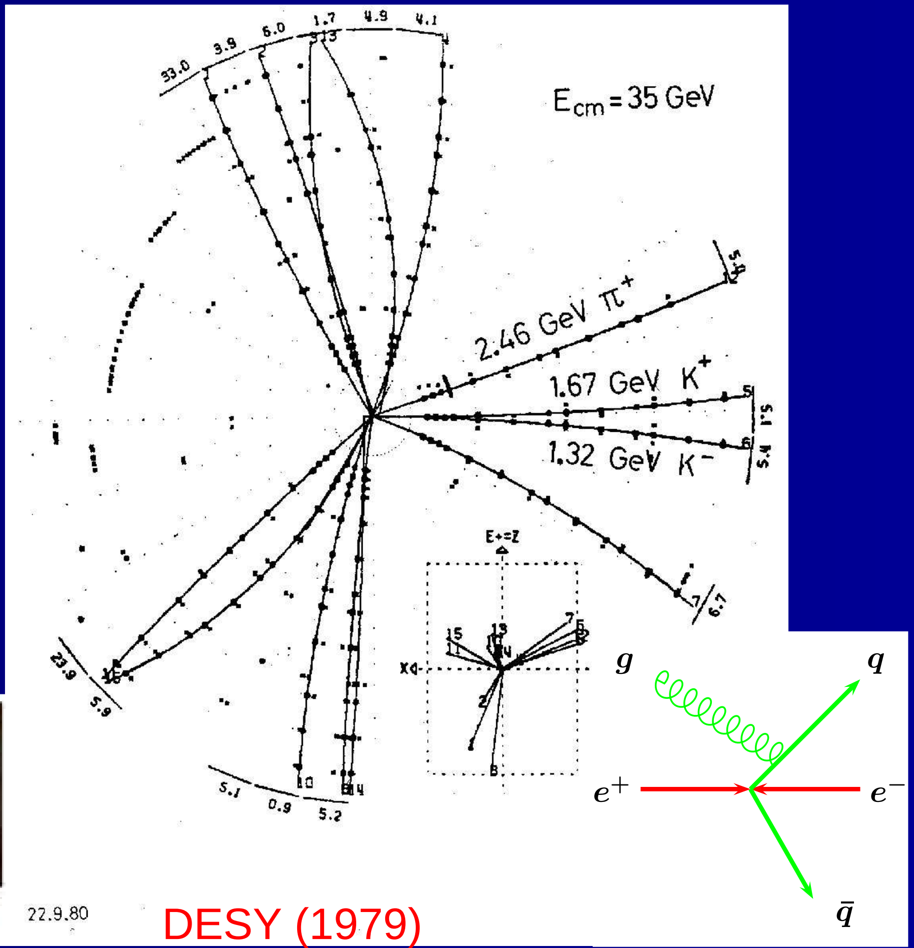




Confinement

The strong force increases in strength as the distance between the quarks increases. There is eventually enough energy to create an additional quark–anti-quark pair from the vacuum.





DESY (1979)

Quarks and gluons can never be directly detected — we only see combinations of quarks and gluons.
Particles are color neutral.

Smashing Protons

Question: How can we study the gluon when it is stuck inside a proton?

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Answer: Hit the proton really hard.

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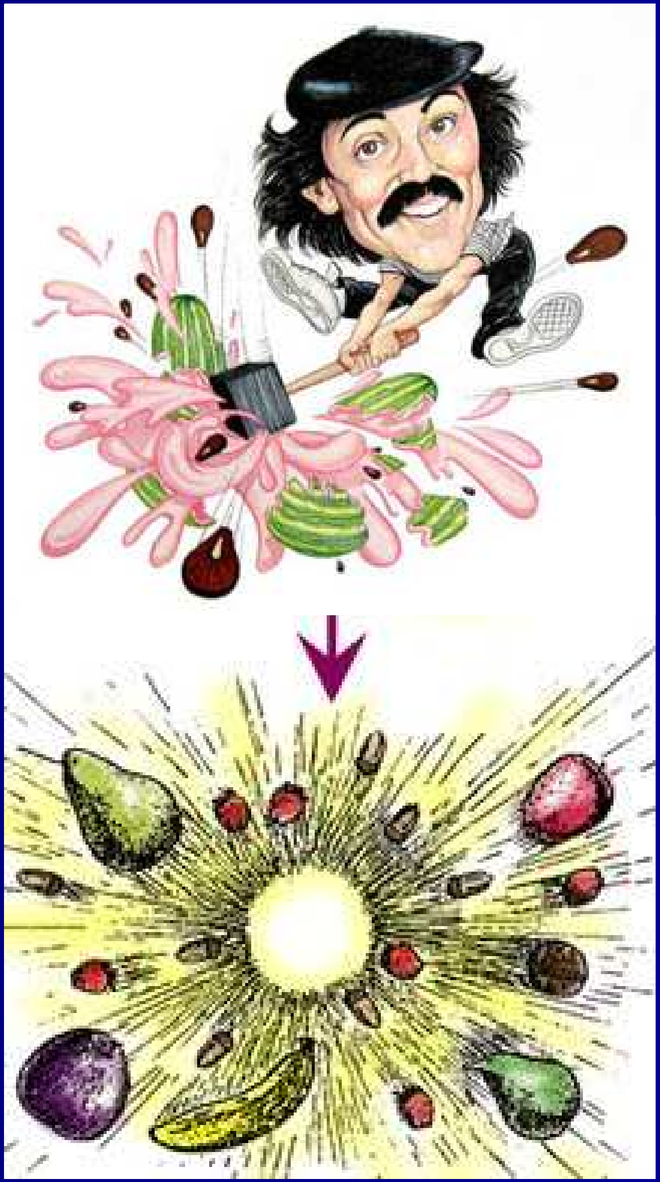
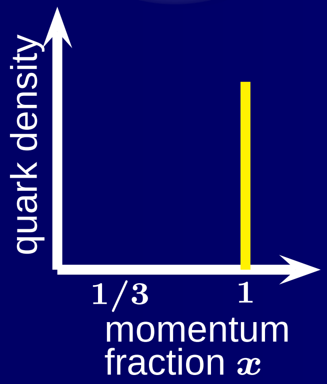


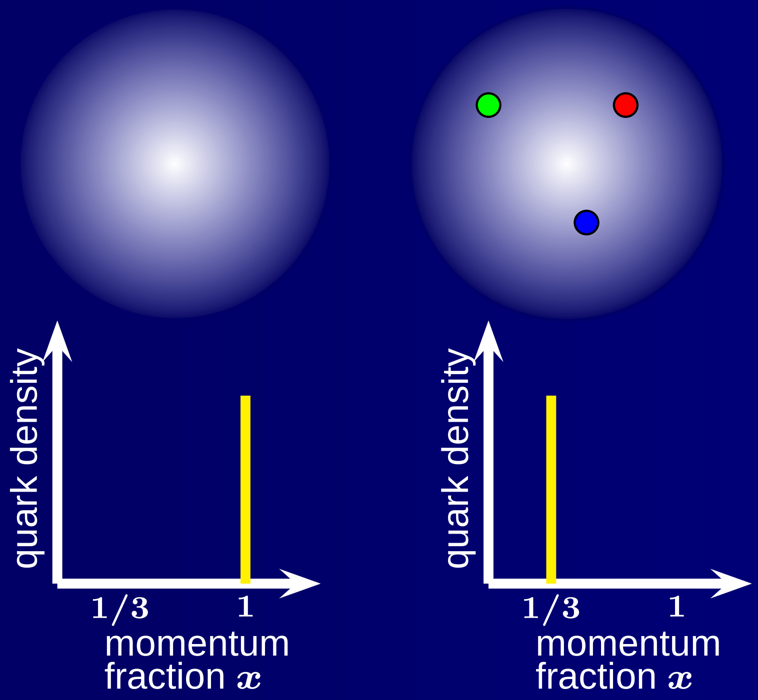
Inside the Proton



increasing resolution (small distance scale) $\Longleftrightarrow$ large momentum transfer (Q^2)

proton as a solid object

Inside the Proton



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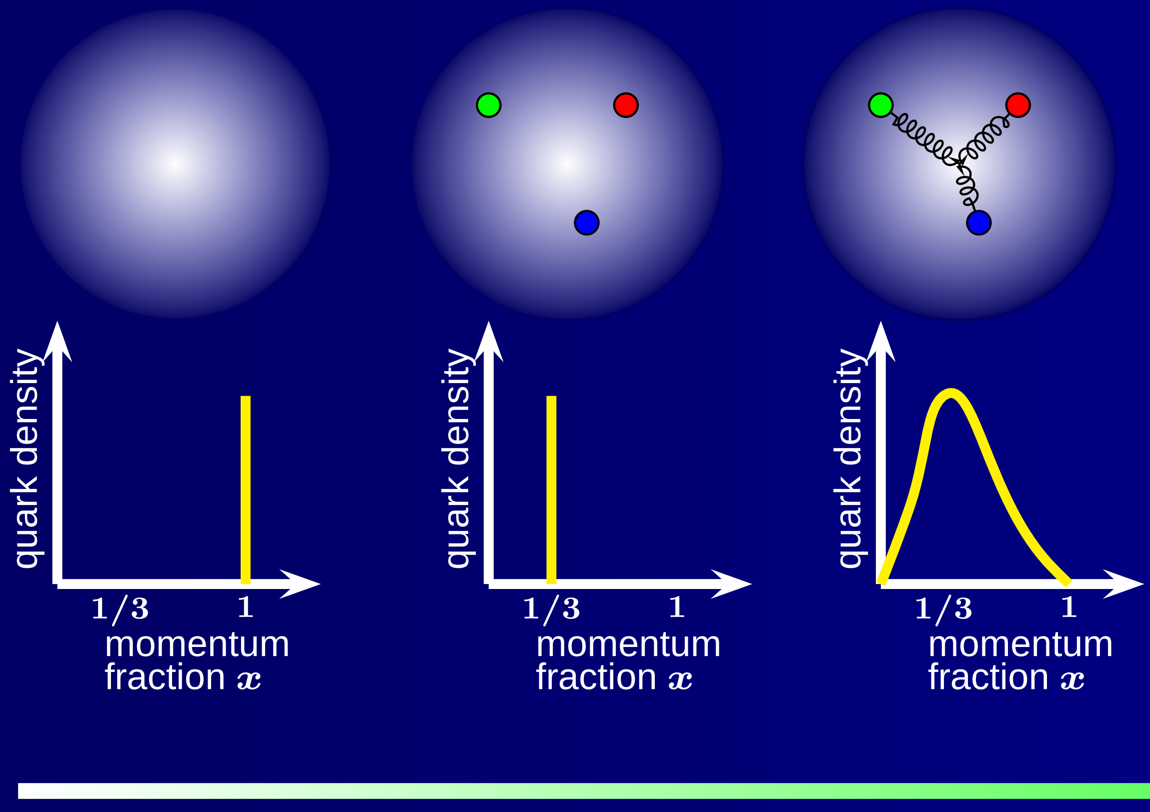
proton made from three quarks

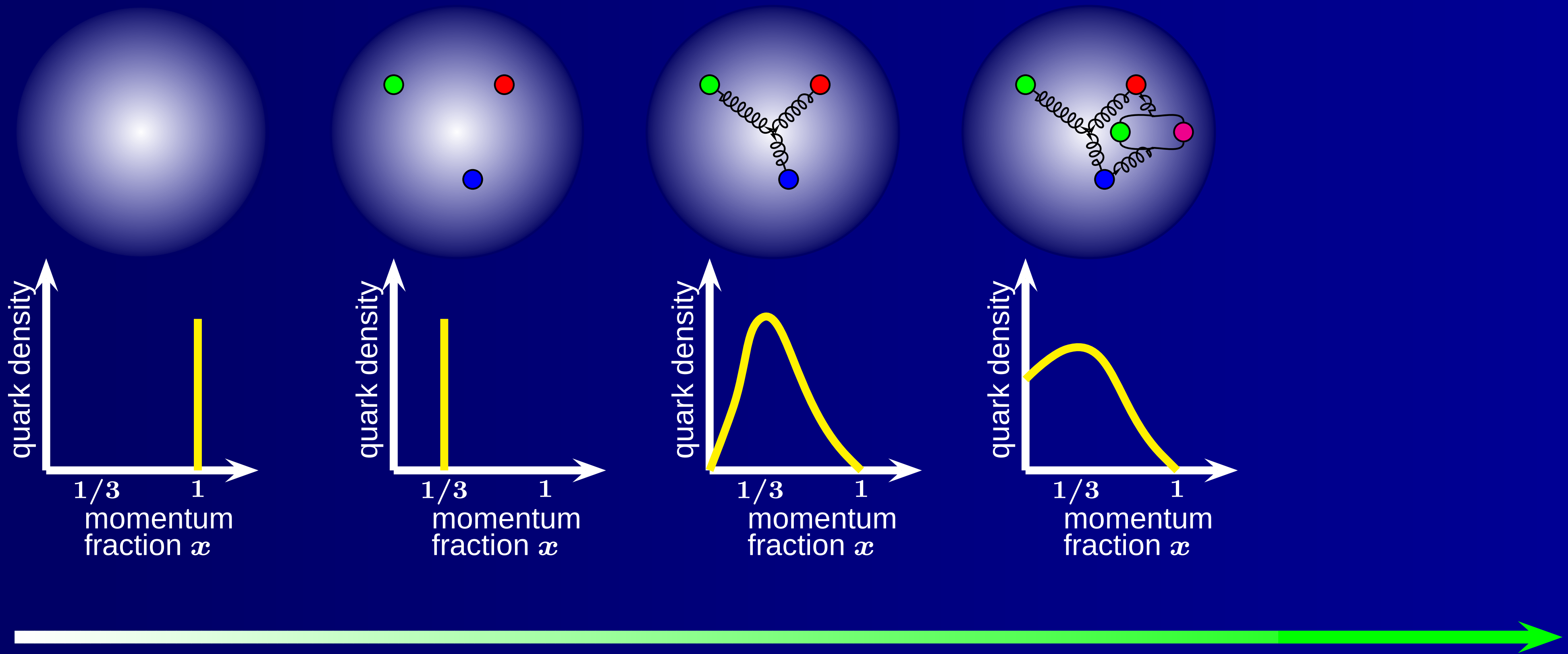
Inside the Proton



increasing resolution (small distance scale) $\Longleftrightarrow$ large momentum transfer (Q^2)

proton made from three valence quarks held together by gluons

Inside the Proton

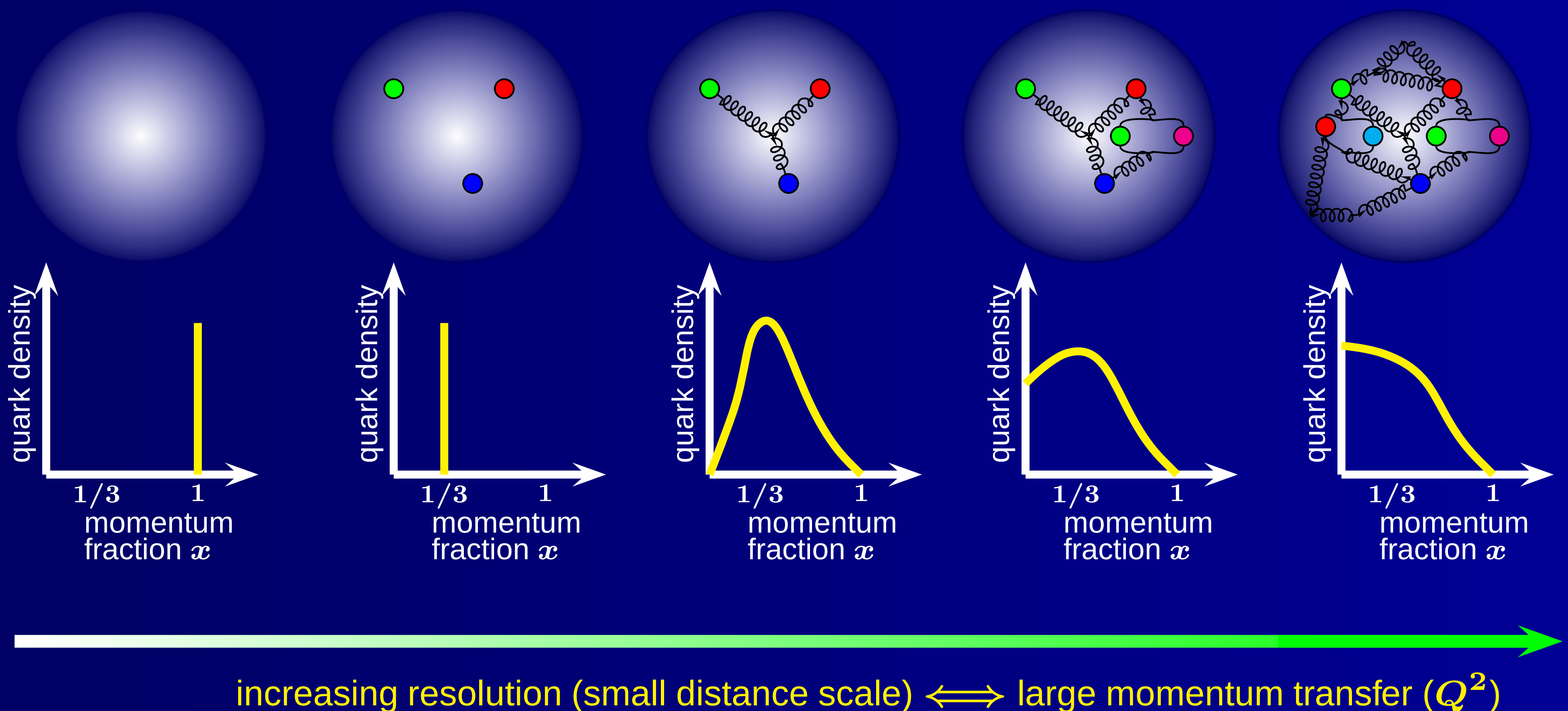


increasing resolution (small distance scale) $\Longleftrightarrow$ large momentum transfer (Q^2)

gluons split into quark–anti-quark pairs $\Rightarrow$ sea quarks

There are more than three quarks inside a proton!

Inside the Proton



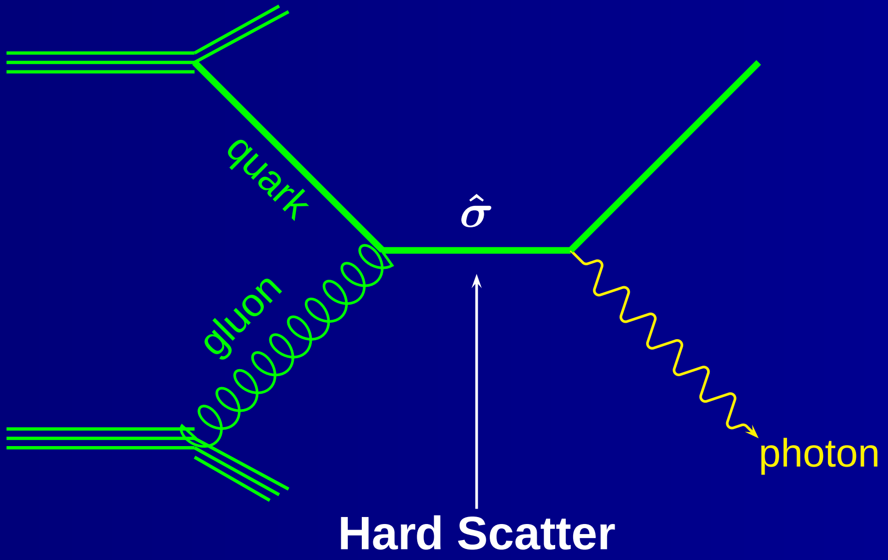
proton is complex object when examined at high resolution

Half the momentum of the proton is carried by gluons!

QCD Hard Scatter

Large p_T processes originate in hard scatters between partons

- allow precision tests of perturbative quantum QCD (pQCD)
- sensitive to presence of new physical phenomena



$$\sigma = \sum_{i,j} \hat{\sigma}_{ij}\left(x_1, x_2, \alpha_s(Q^2)\right)$$

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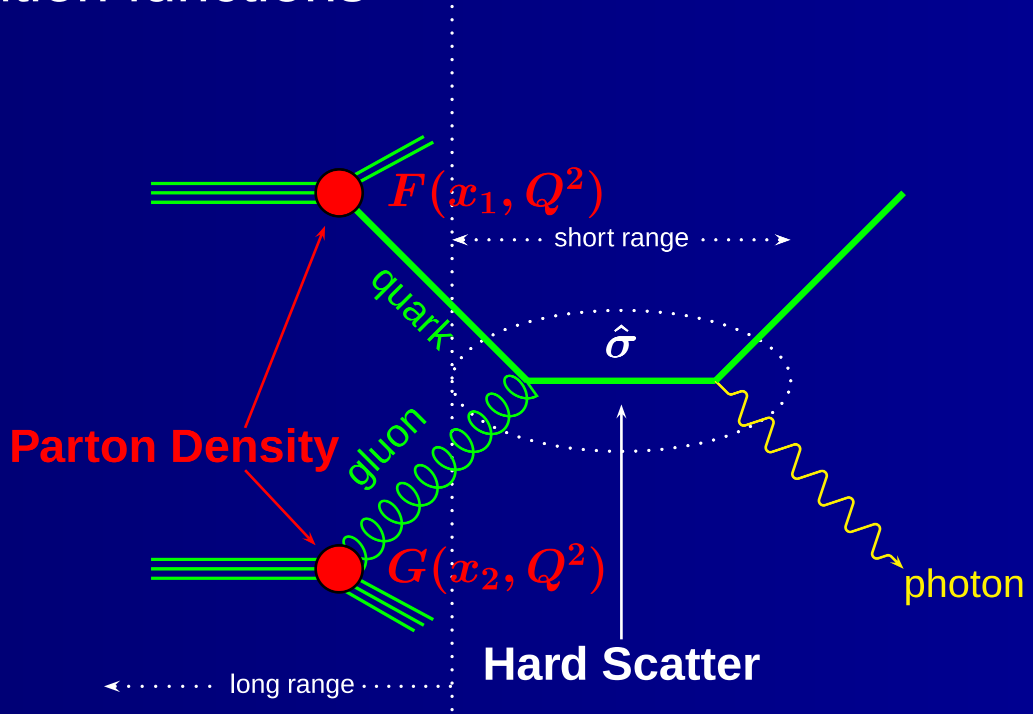
- constrain parton distribution functions

x	fraction of proton's longitudinal momentum carried by parton
Q^2	momentum transferred in hard scatter
α_s	strength of strong force coupling



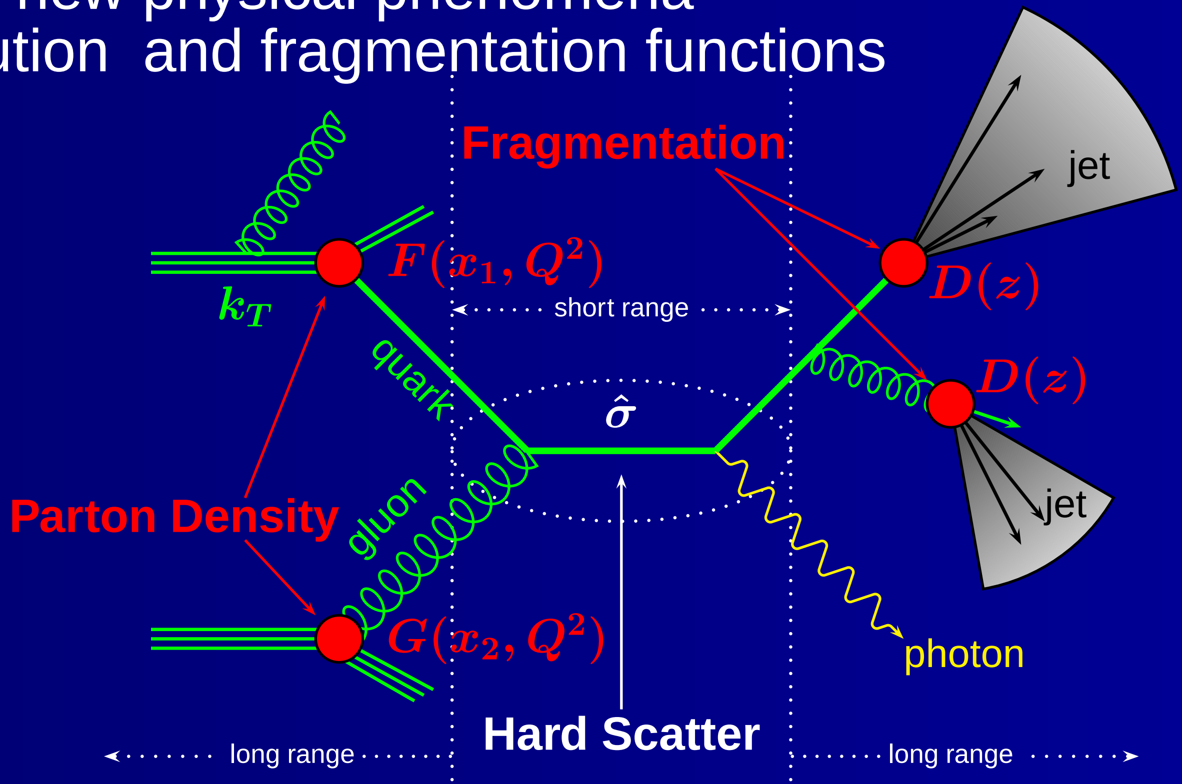
$$\sigma = \sum_{i,j} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \, F_i(x_1, Q^2) \, G_j(x_2, Q^2) \, \hat{\sigma}_{ij}\left(x_1, x_2, \alpha_s(Q^2)\right)$$

QCD Hard Scatter

Large p_T processes originate in hard scatters between partons

- allow precision tests of perturbative quantum QCD (pQCD)
- sensitive to presence of new physical phenomena
- constrain parton distribution and fragmentation functions

x	fraction of proton's longitudinal momentum carried by parton
Q^2	momentum transferred in hard scatter
α_s	strength of strong force coupling
z	fraction of outgoing parton's momentum carried by particle



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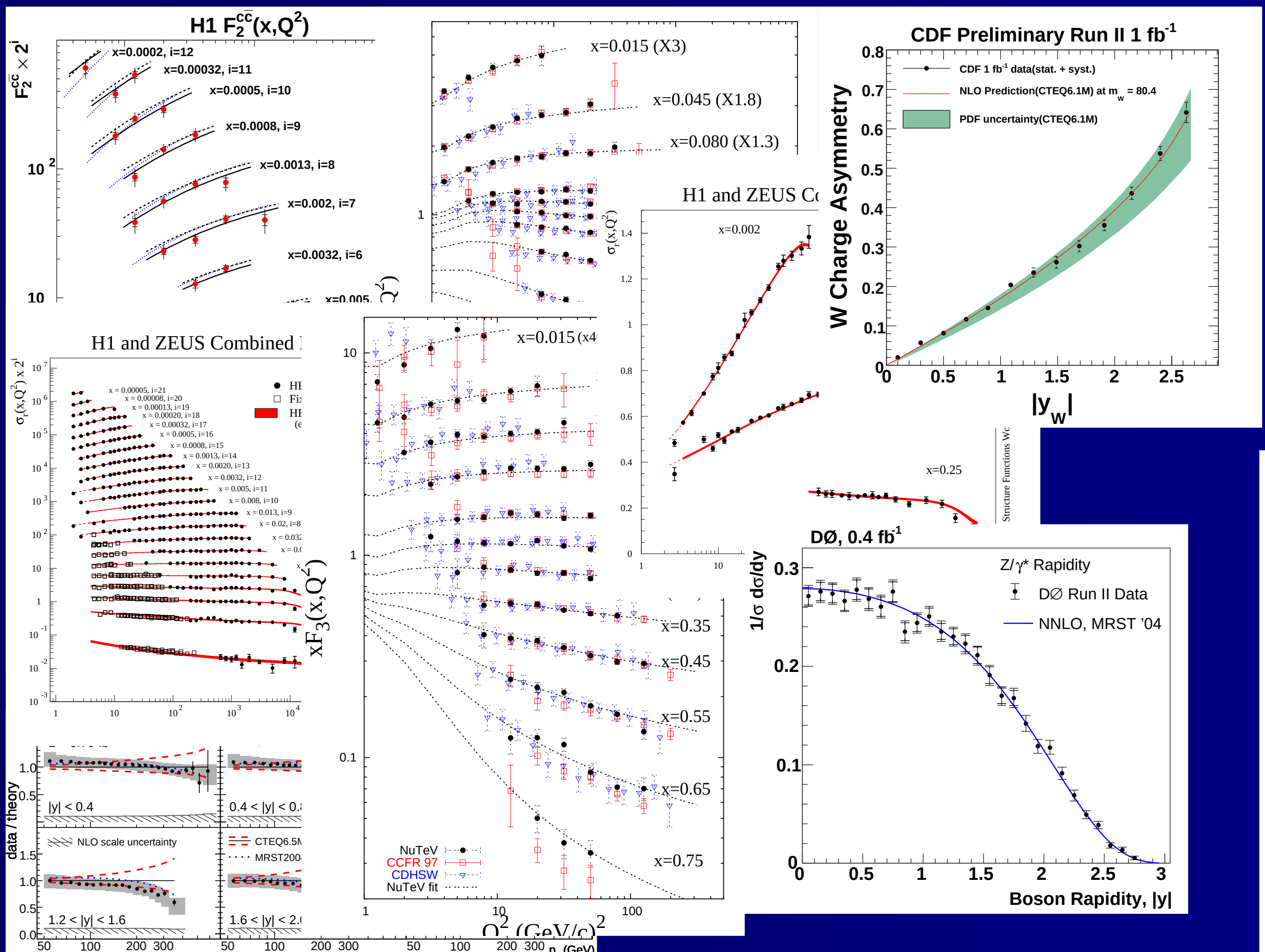
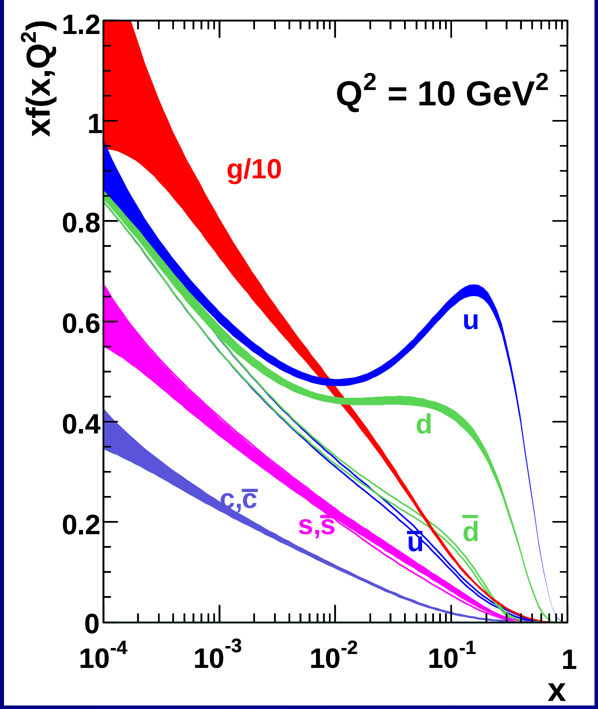
Parton Distribution Functions





+ momentum sum rules (conservation)

Why Photons?

- Photons cleanly probe the hard scatter

	Wavelength	Energy
Green	$\mathbf{520 - 565}$ nm	$\mathbf{2.4 - 2.2}$ eV
X-ray	$\mathbf{10 - 0.01}$ nm	$\mathbf{0.12 - 120}$ keV
Direct γ	$\mathbf{0.35 - 0.0035}$ fm	$\mathbf{3.5 - 350}$ GeV
Proton	radius $\approx \mathbf{1}$ fm	mass $\approx \mathbf{1}$ GeV

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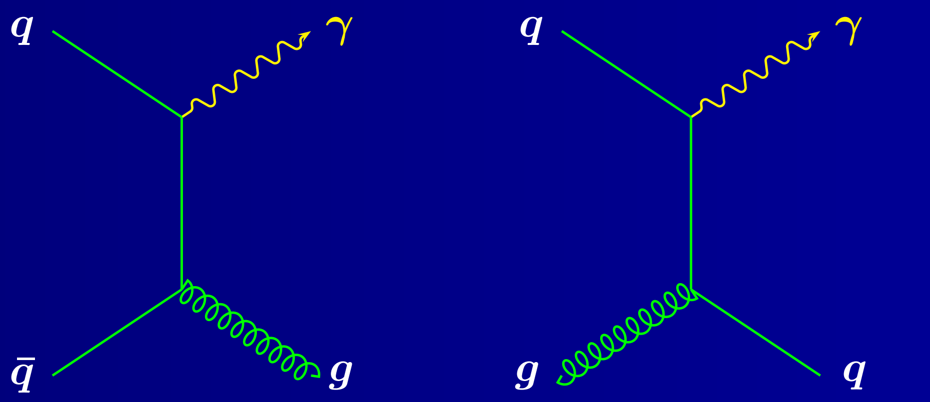
- Production is dominated by two processes

Direct Photons

Annihilation   Compton Scattering



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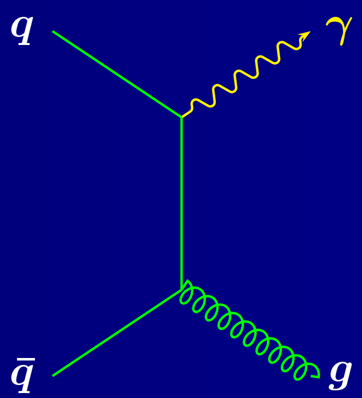
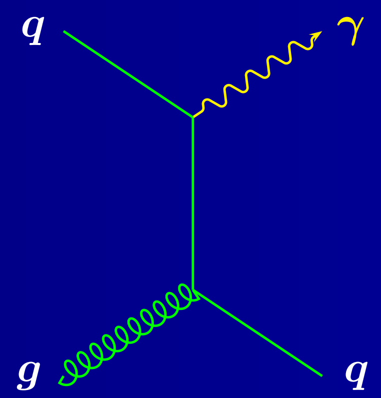
- Production is dominated by two processes
- Important higher-order diagrams include double direct-photon production and fragmentation diagrams ($q \longrightarrow \gamma$)

Direct Photons

Annihilation

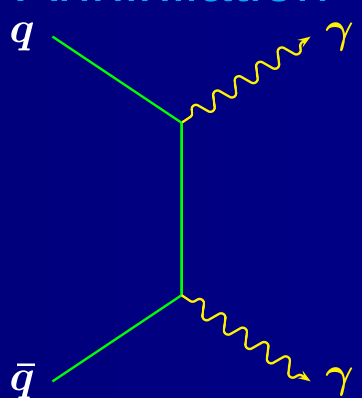


Compton Scattering

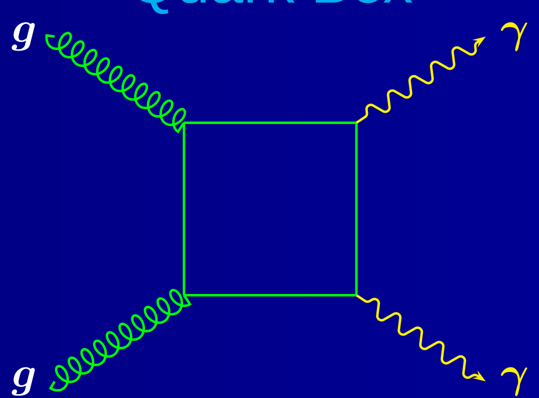


Diphotons

Annihilation

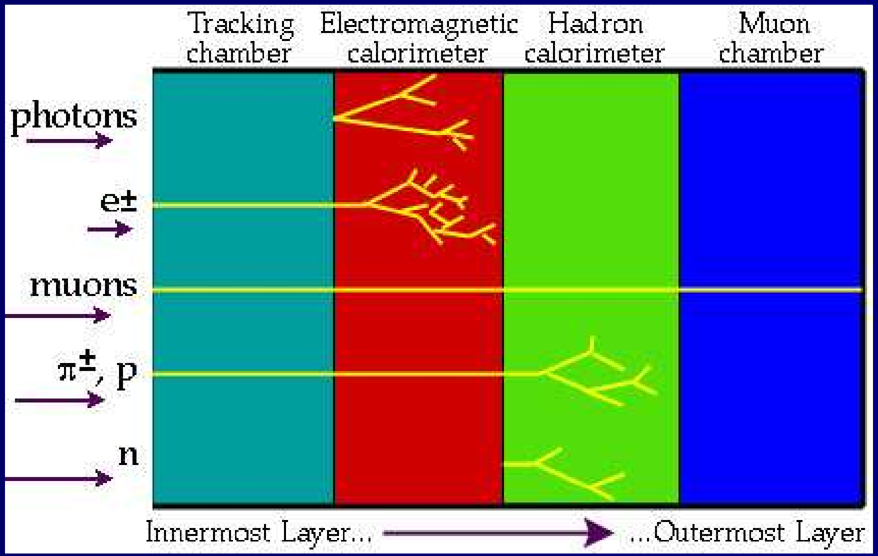


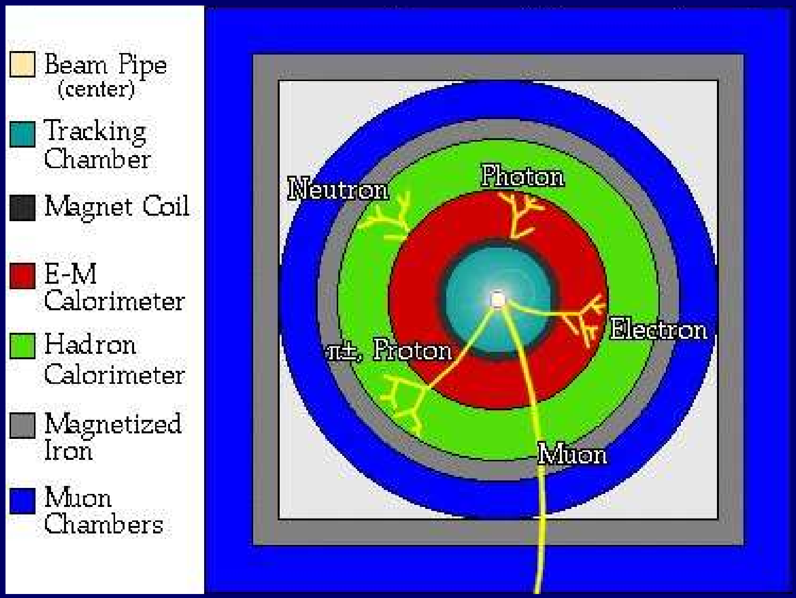
Quark Box



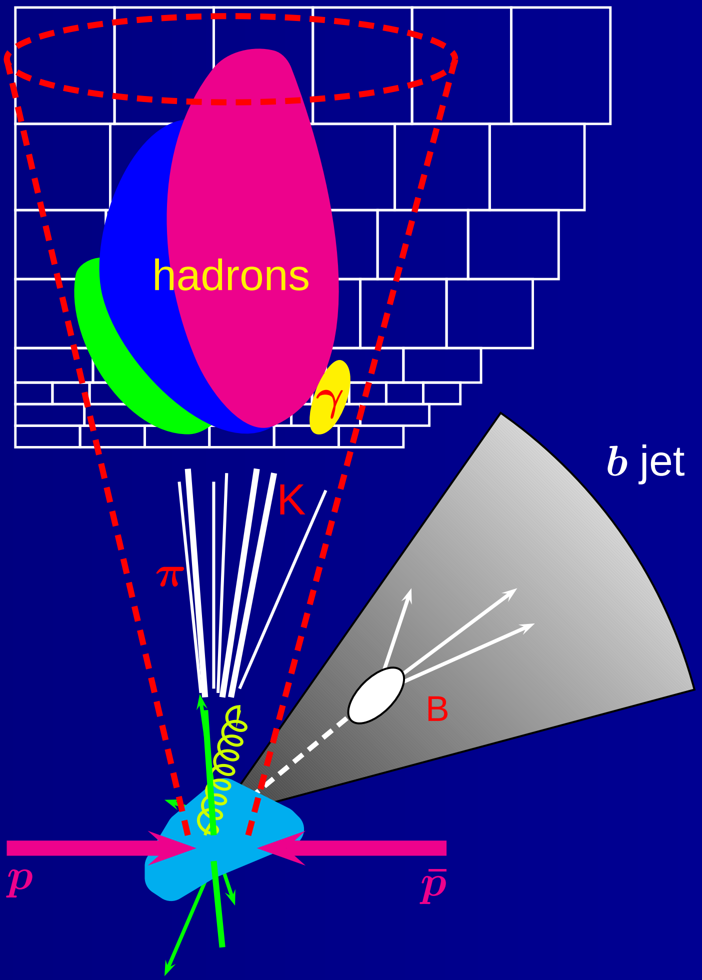
Fermilab Tevatron

High Energy Physics Detectors





Jets are collimated sprays of particles constructed using an iterative cone-based algorithm.

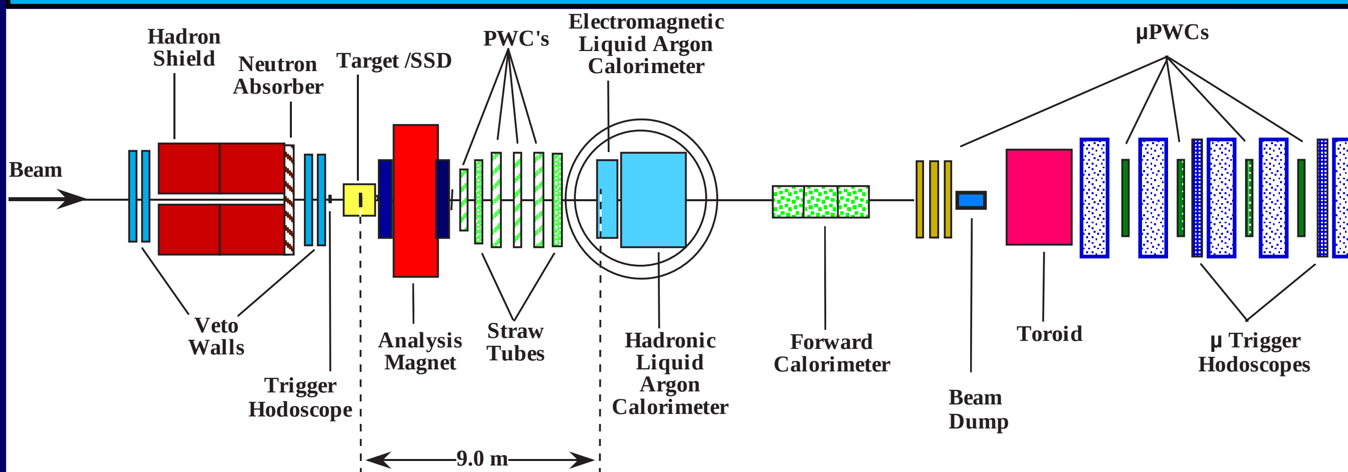


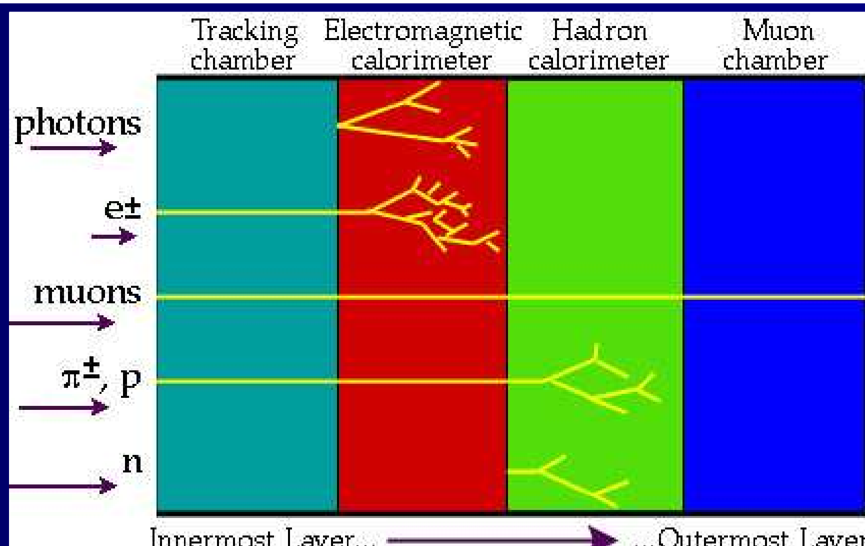
Meson West Spectrometer

shared with the E672 collaboration

Fermilab E706 Collaboration

UC DAVIS ★ DELHI ★ FERMILAB ★ MICHIGAN STATE ★ NORTHEASTERN
OKLAHOMA ★ PENNSYLVANIA STATE ★ PITTSBURGH ★ ROCHESTER

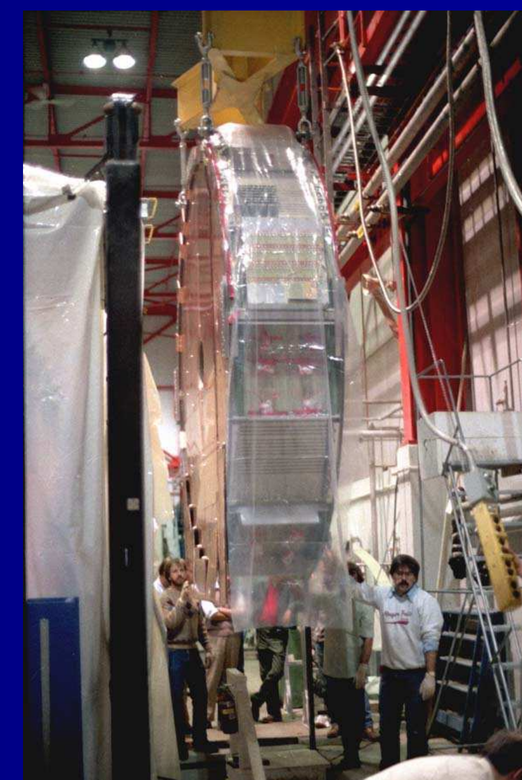




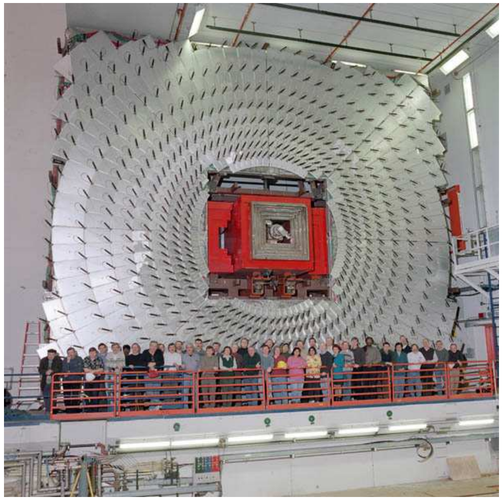
Beams

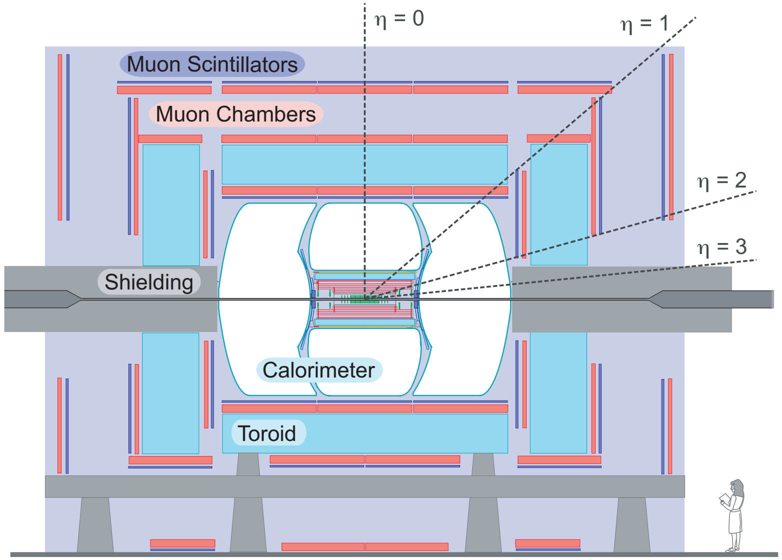
- 800 GeV p
- 530 GeV p
- 515 GeV π^-

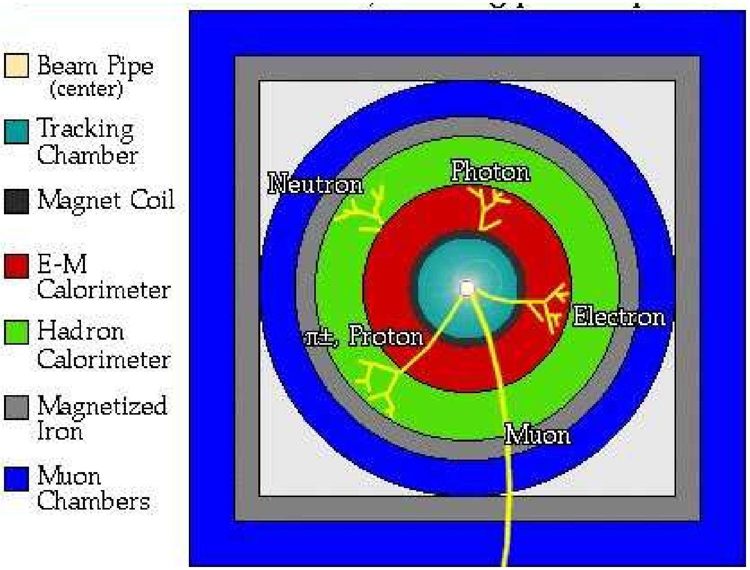
Targets: H_2, Be, Cu

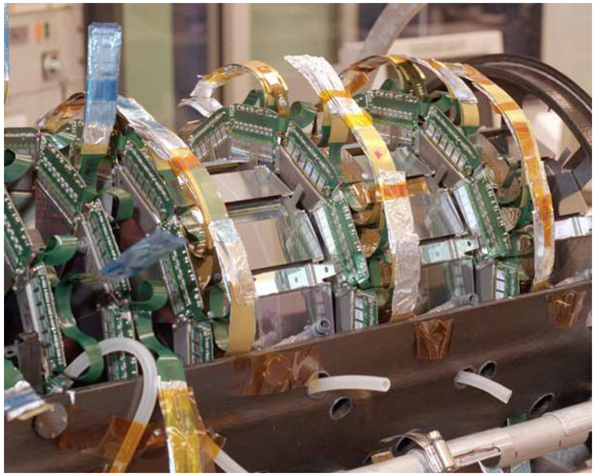


DØ Detector




η = 0
η = 1
η = 2
η = 3
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid


Beam Pipe (center)
Tracking Chamber
Magnet Coil
E-M Calorimeter
Hadron Calorimeter
Magnetized Iron
Muon Chambers
Neutron
Photon
Electron
π±, Proton
Muon



Extracting the Signal

Identifying direct photons is challenging since many particles decay to photons:

- dominant backgrounds are π^0 and η mesons
- $\sigma(\gamma)/\sigma(\text{jet}) \approx 10^{-3}$

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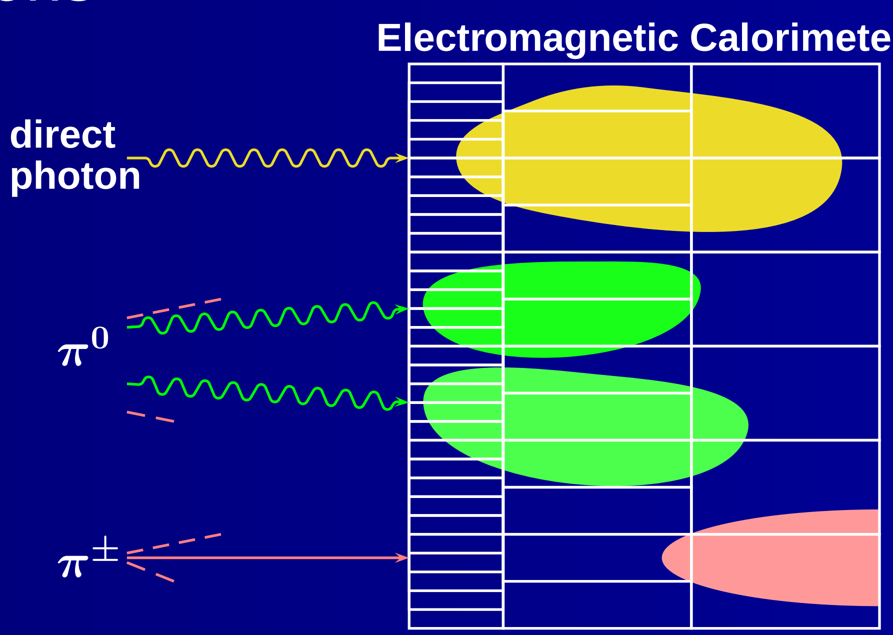
- $\sigma(\gamma)/\sigma(\mathrm{jet}) \approx 10^{-3}$

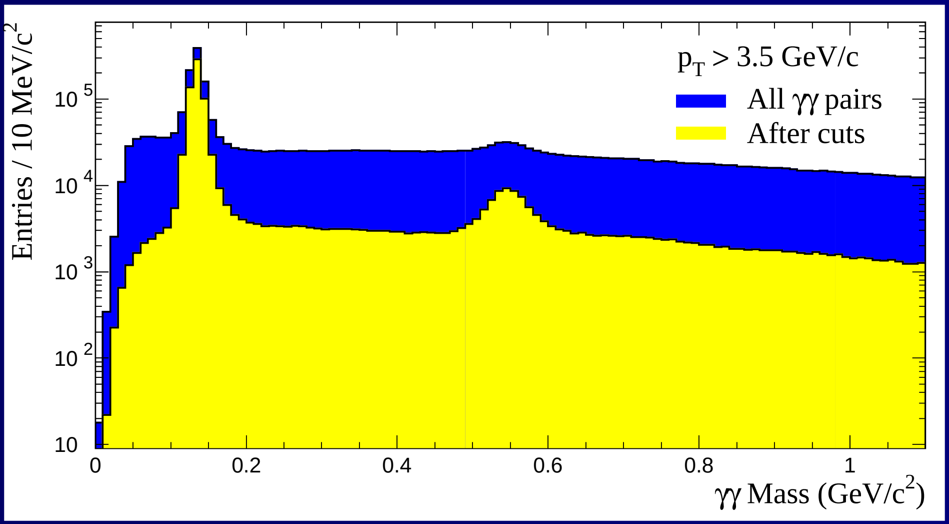
Standard experimental methods:

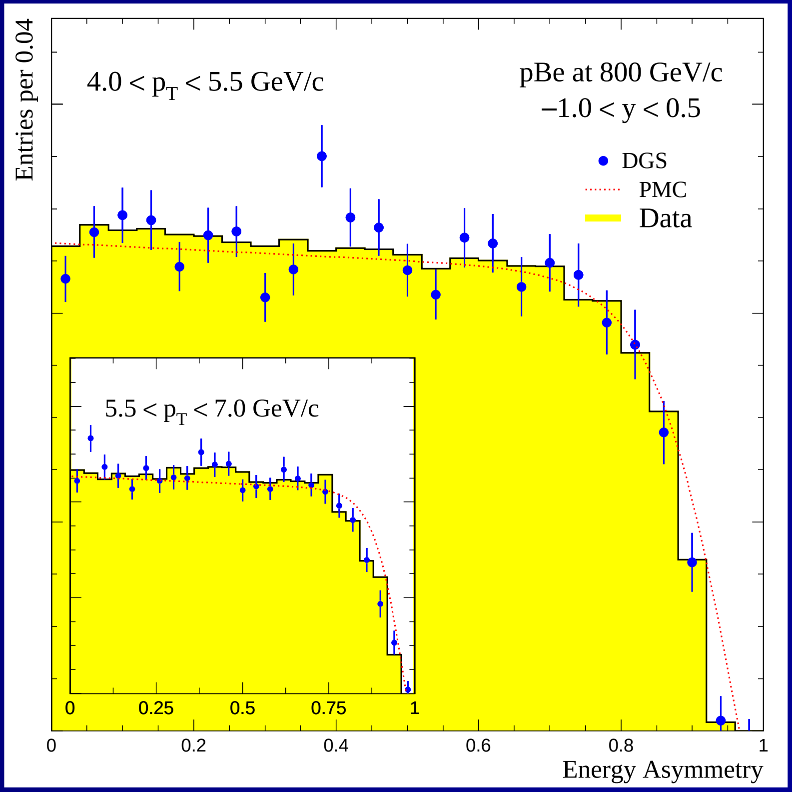
- Detect individual photons and reconstruct neutral mesons
- Statistically separate two photons from a single photon:
  - longitudinal shower profile
  - lateral shower profile
  - conversion probability
- Require isolation from other particles (jets)

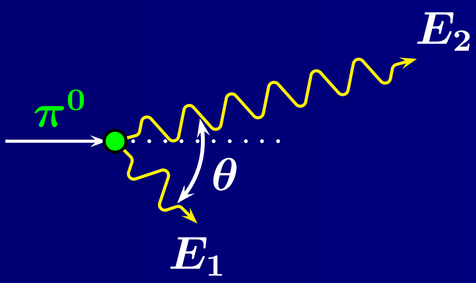


E706 π^0 and η Mesons

Identify photons from π^0 and η meson decays:







$$A_{\gamma\gamma} \equiv \beta \cos\theta^* = \frac{|E_{\gamma 1} - E_{\gamma 2}|}{E_{\gamma 1} + E_{\gamma 2}}$$

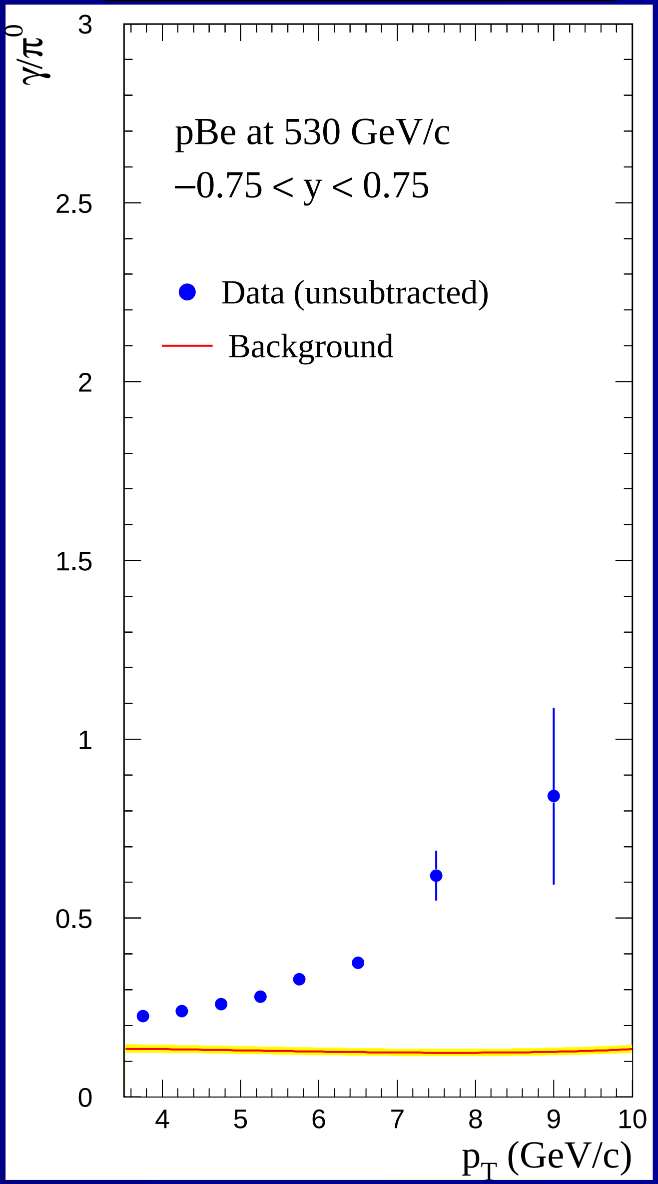
PRD 68:052001 (2003) & 69:032003 (2004) [E706]

E706 Direct Photon Candidates

Backgrounds still significant after rejecting most π^0 and η mesons. Tuned simulation used to estimate remaining background normalized to π^0 cross section.

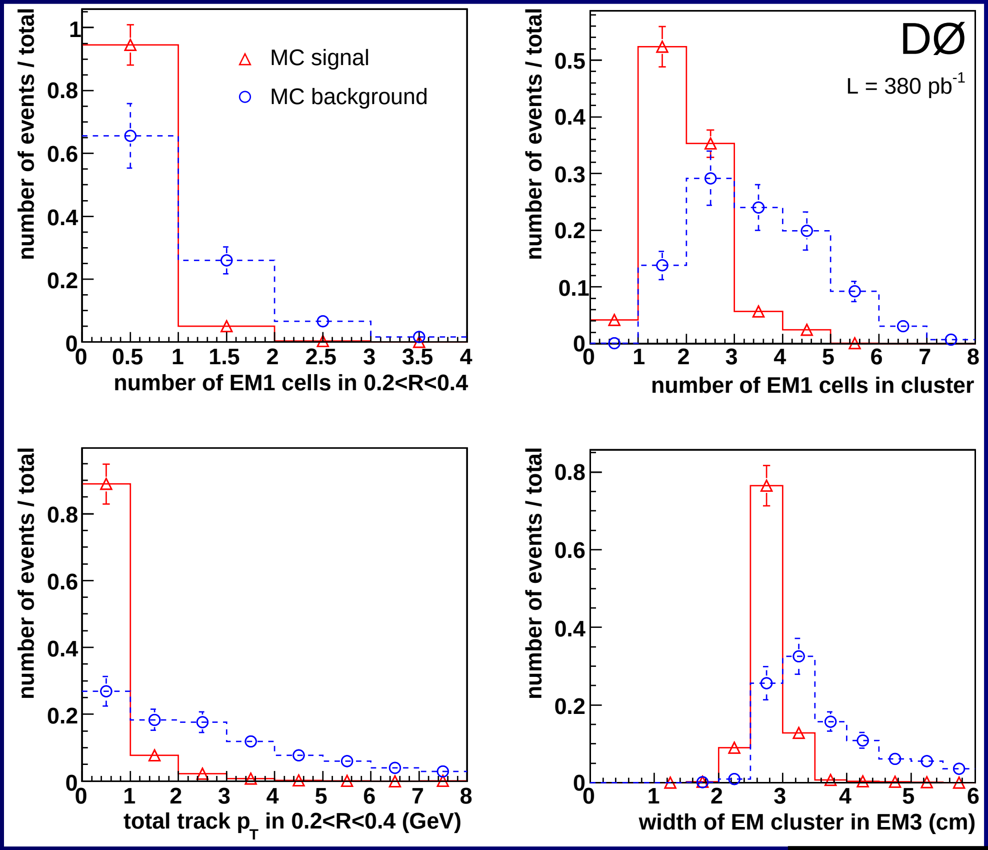
$$\sigma_\gamma^{\text{direct}} = \sigma_\gamma^{\text{single}} - \left.\frac{\gamma_{\text{background}}}{\pi^0}\right|_{MC} \times \sigma_{\pi^0}$$

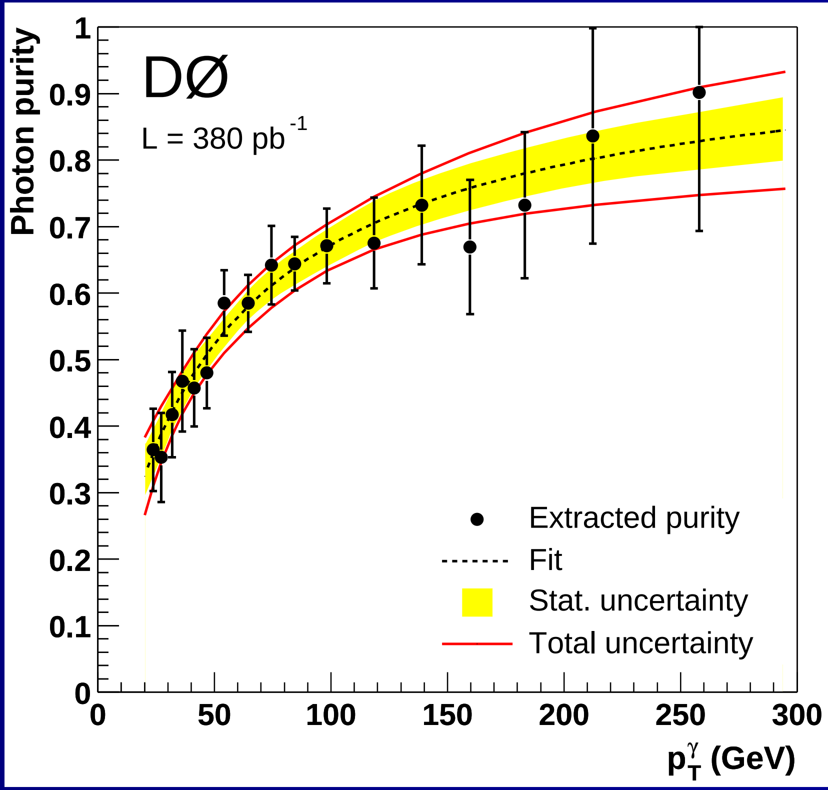
PRD 70:092009 (2004) [E706]



DØ Signal and Background

Photon candidates isolated to suppress background. Discriminate signal from background using shower properties.



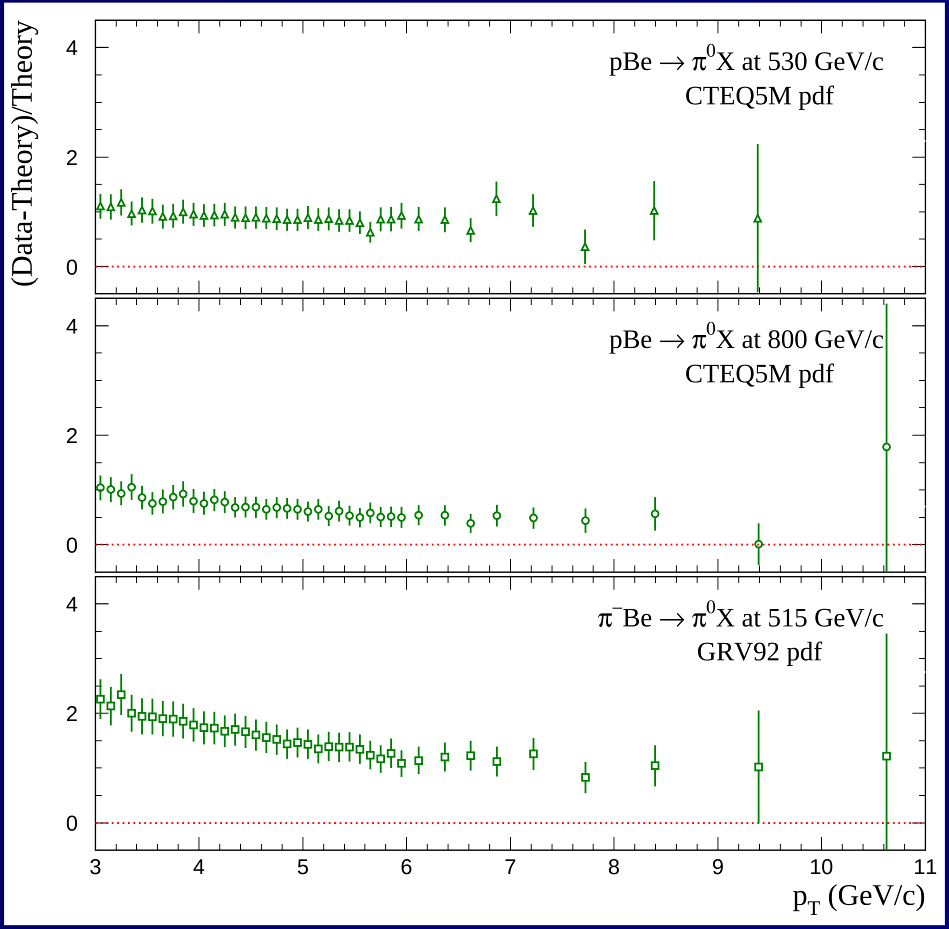


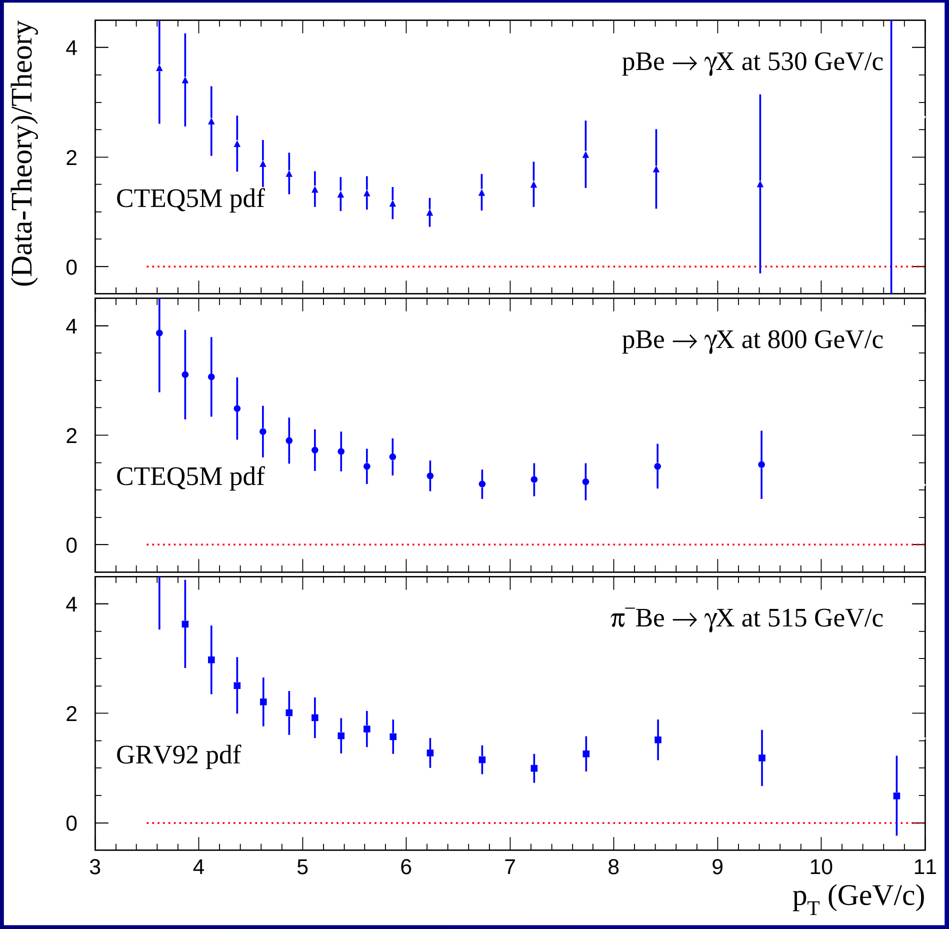
Purity defined as $\mathcal{P} = \frac{\mathcal{S}}{\mathcal{S}+\mathcal{B}}$

PLB 639, 151 (2008) PLB 666, 435 (2008) PRL 102, 192002 (2009) [DØ]

Direct Photon Results

E706 Direct Photon and π^0



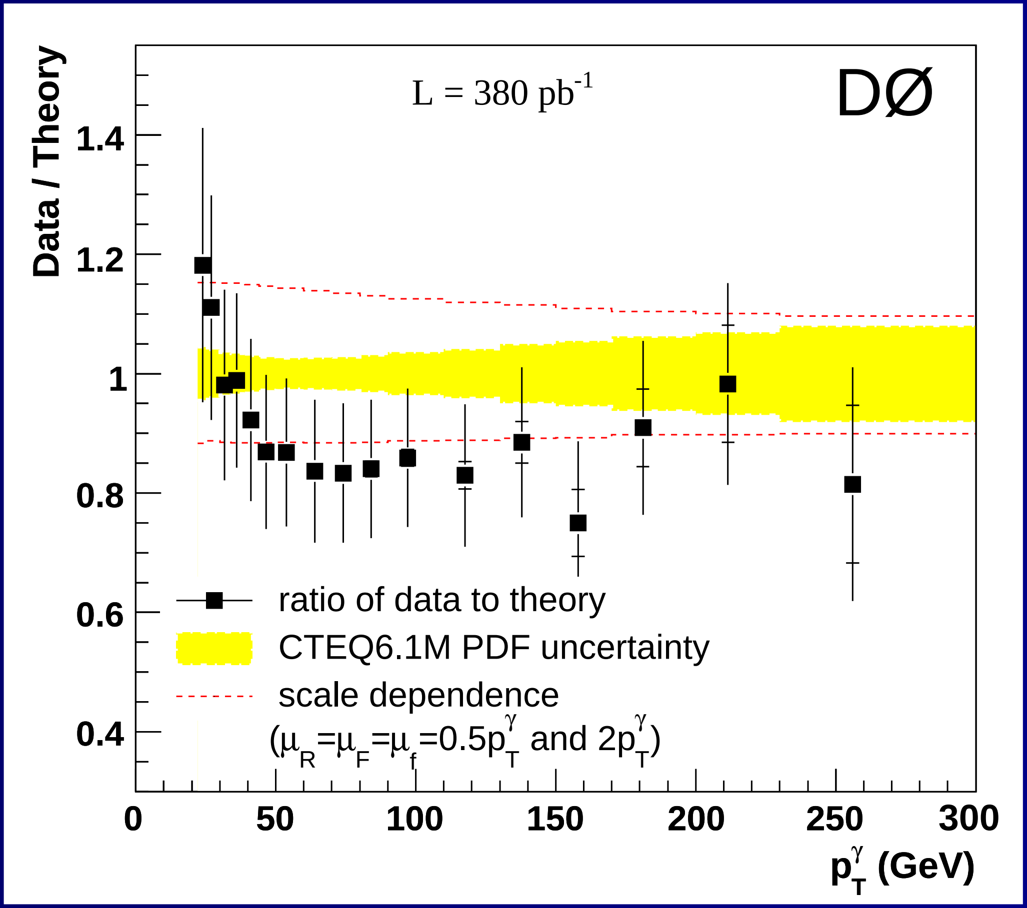


NLO pQCD fails to describe direct photon or π^0 cross sections.

NLO pQCD corrected for small nuclear enhancement. The pp comparisons yield the same conclusions.

PRL 81, 2642 (1998) PRD 68:052001 (2003) PRD 69:032003 (2004) PRD 70:092009 (2004) [E706]

DØ Isolated Photons

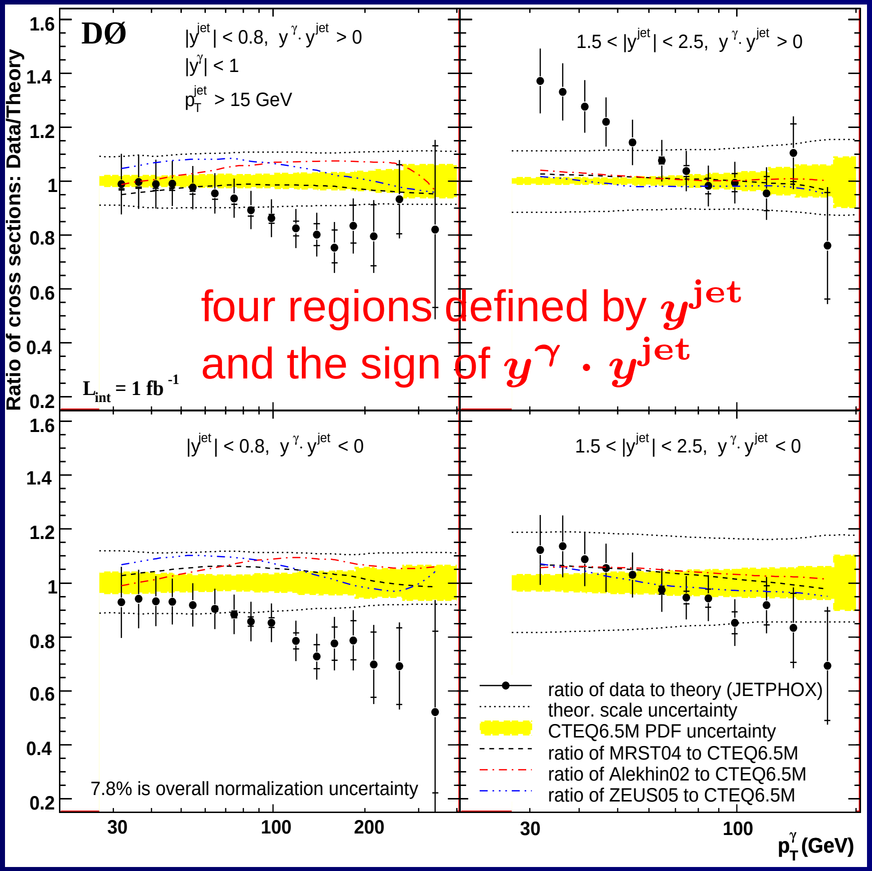


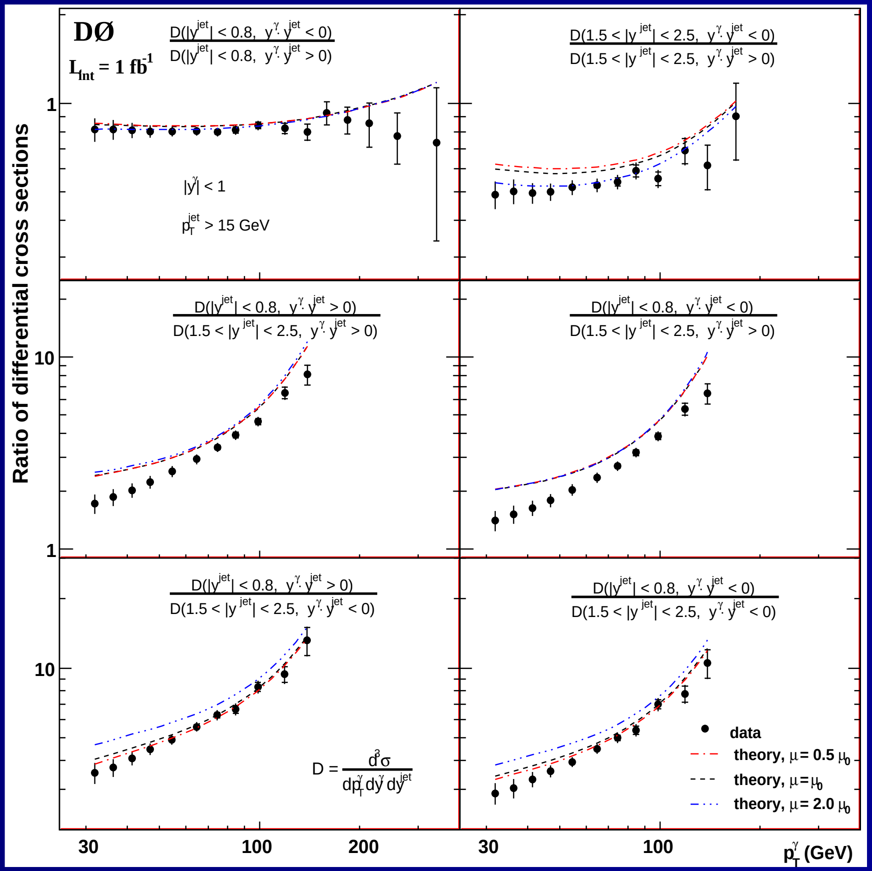
NLO pQCD provides a reasonable description of the experimental measurement except at low p_T.

PLB 639, 151 (2006) [DØ]

DØ Isolated Photon+Jet

Measuring isolated photons with associated jet production increases sensitivity to the gluon distribution.



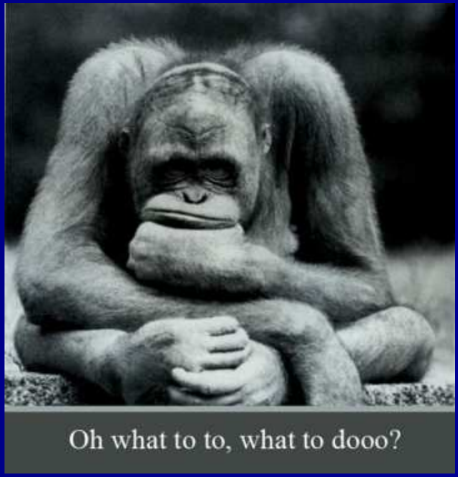


Disagrees in shape like inclusive results; also significant disagreement in ratios of one region to another.

PLB 666, 2435 (2008) [DØ]

Conundrum

- Theory disagrees with E706 measurements in shape and normalization. Why?
  - significant difference for both π^0 and direct-photon production
- Theory differs in shape from DØ data at low p_T. Why?
  - agreement far better than for E706, though shape at low p_T is certainly reminiscent



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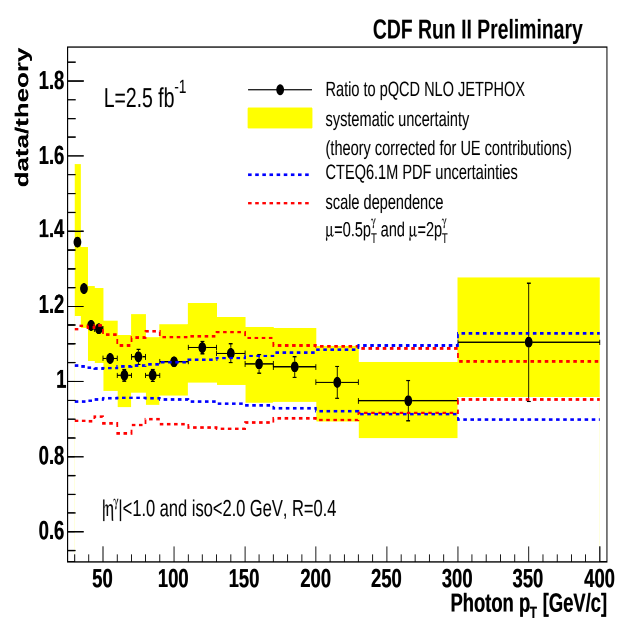
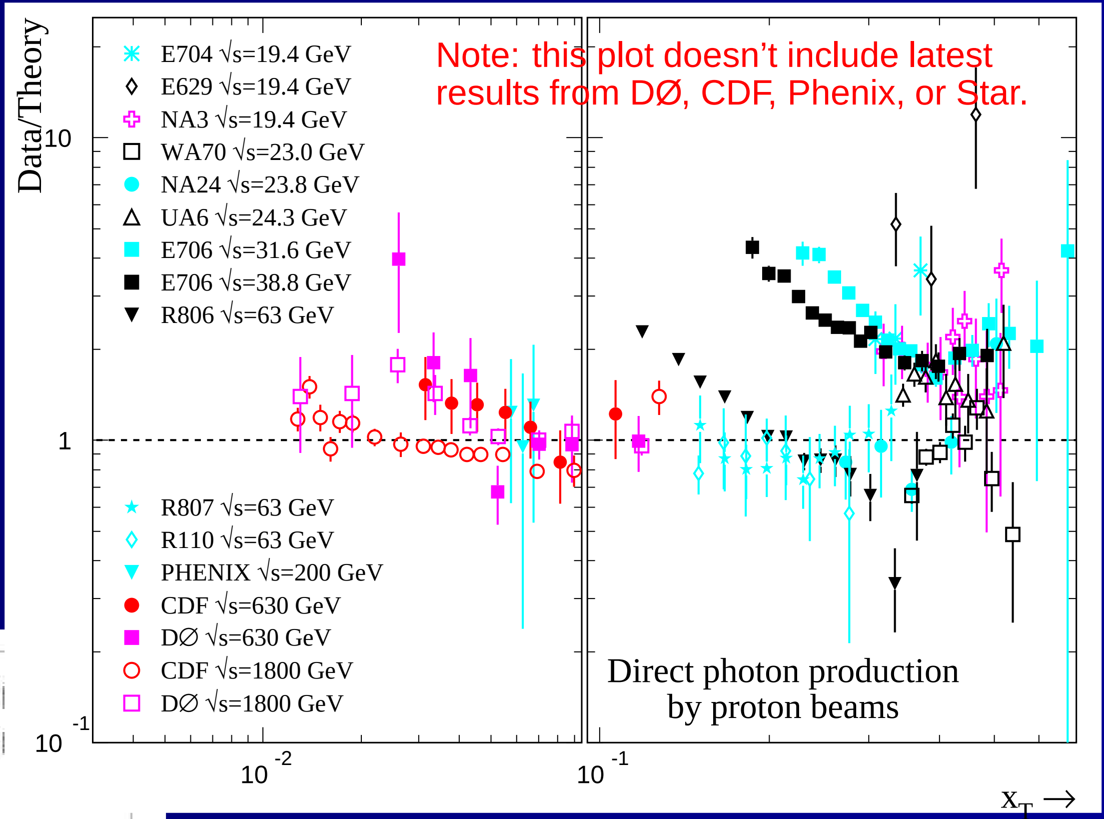
Oh what to to, what to dooo?

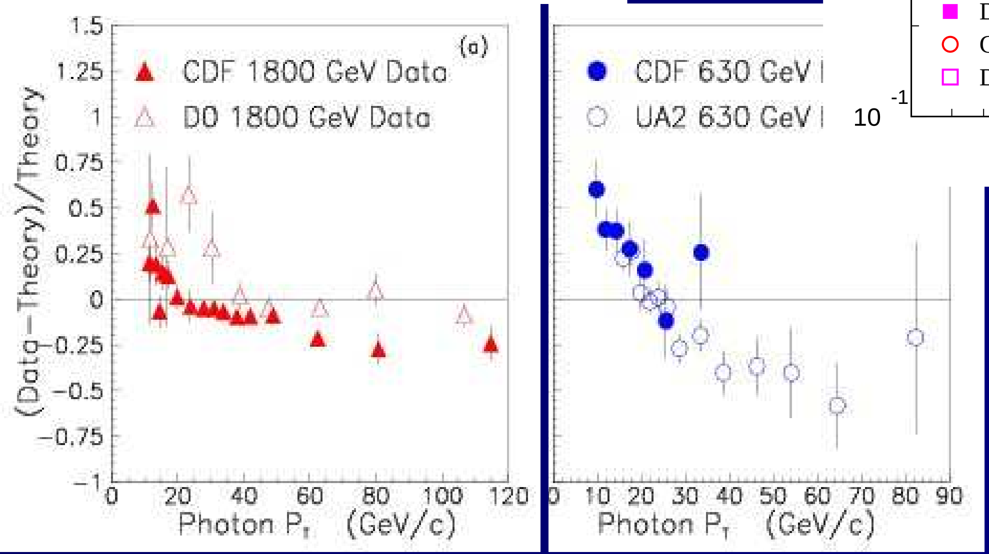
Is there something wrong with the data?
Is there a problem with the methodology?
Is something missing from the theory?

How well does the theory describe everyone else's measurements?

Direct Photon Production





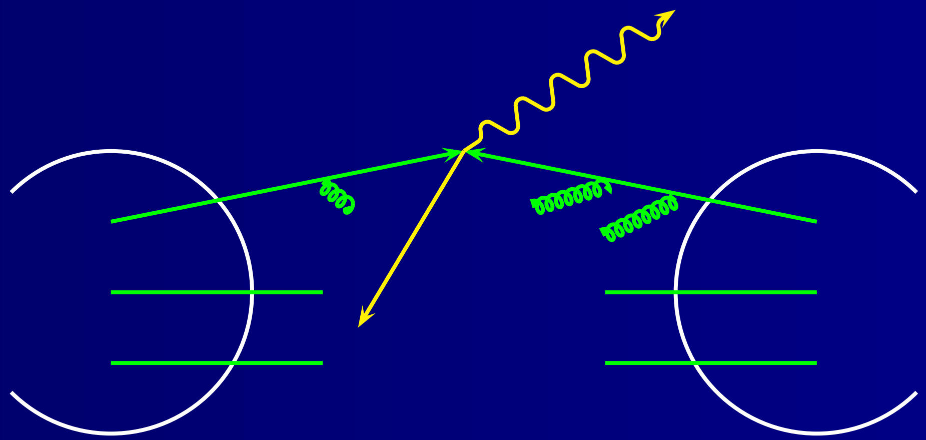


Theory doesn't represent the shape or magnitude of direct photon cross sections over a wide range in $\sqrt{s}$.

Correlations

Question: Can we extract information from our data to better understand the difference between theory and experiment?

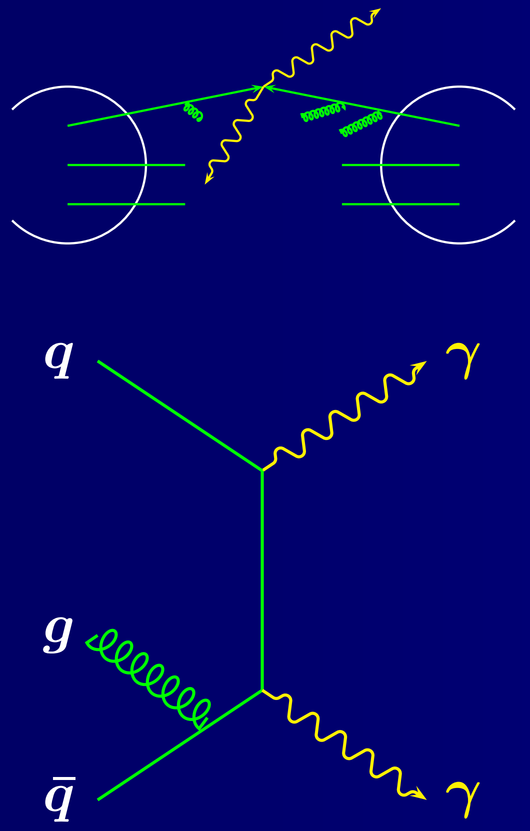
Answer: Correlations between high-p_T particles probe aspects of the hard scatter not easily accessible via studies of inclusive single-particle production.

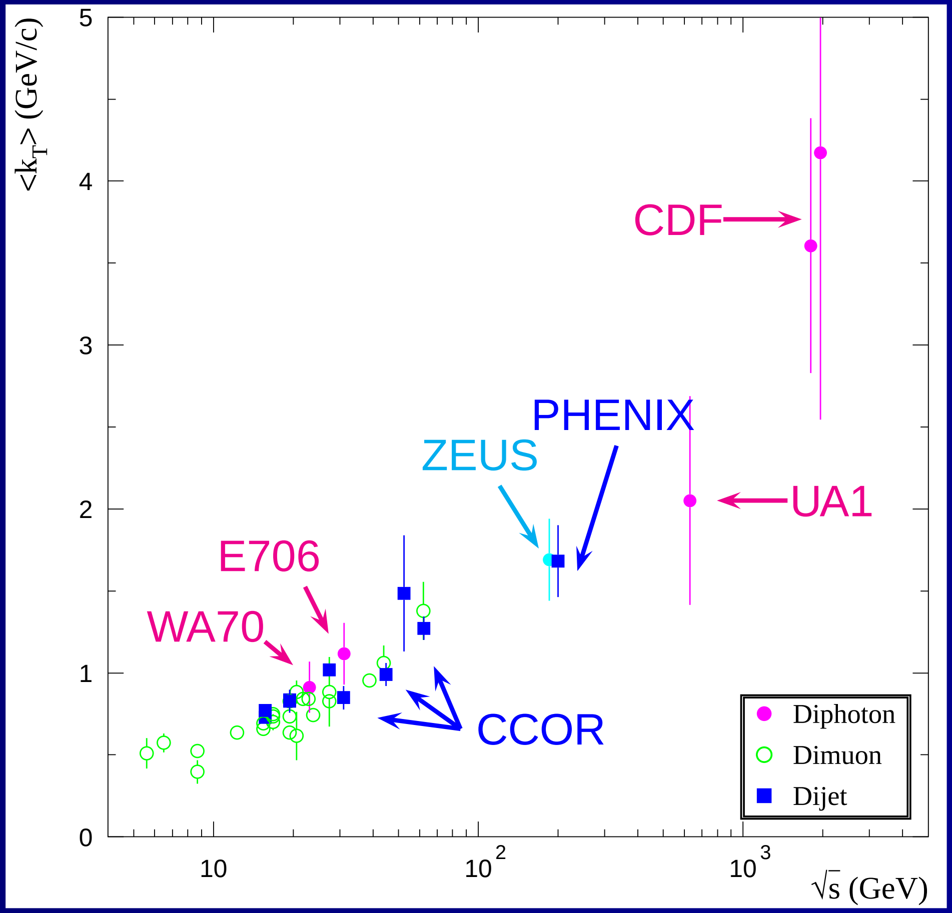


Studies of high-mass pairs of direct photons and π^0's can be used to extract information about the transverse momenta of partons prior to the hard scatter (k_T).

About k_T Effects

Measure $\langle k_T \rangle$ values in Drell-Yan and diphoton production.



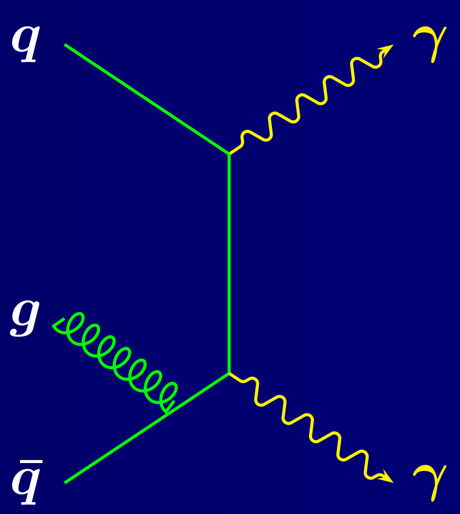


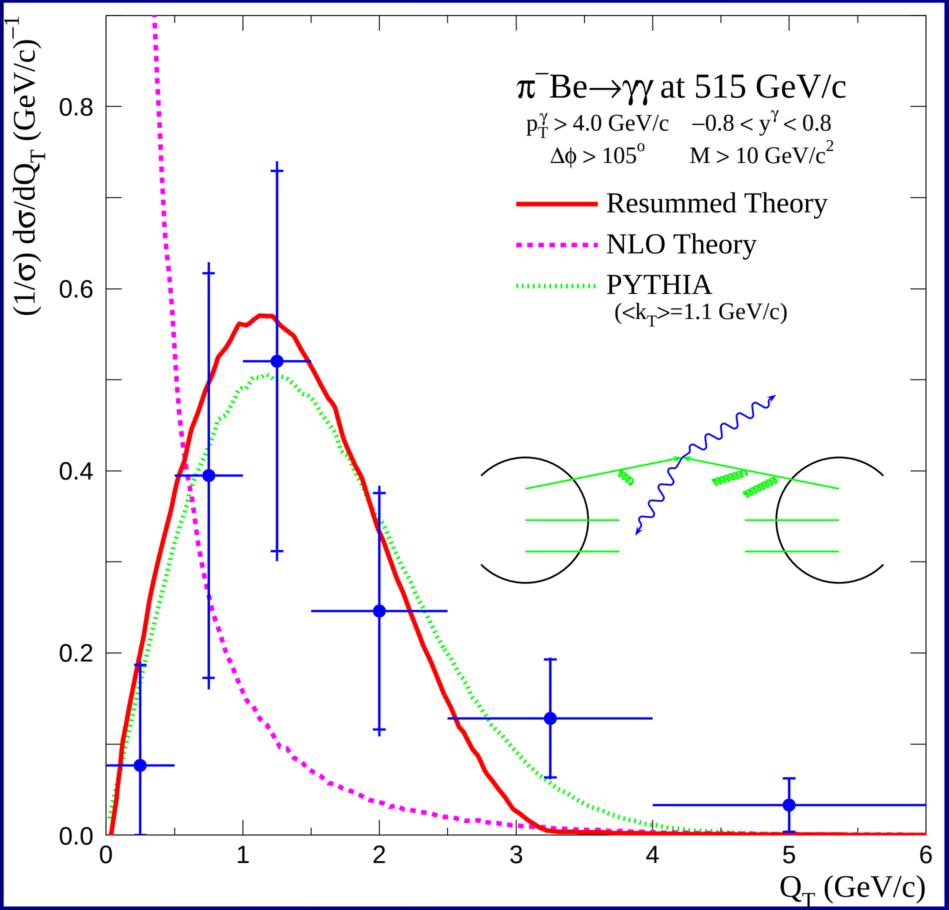
k_T values significantly larger than expected from non-perturbative hadron-size effects interpreted as resulting from multiple soft-gluon emissions.

About k_T Effects

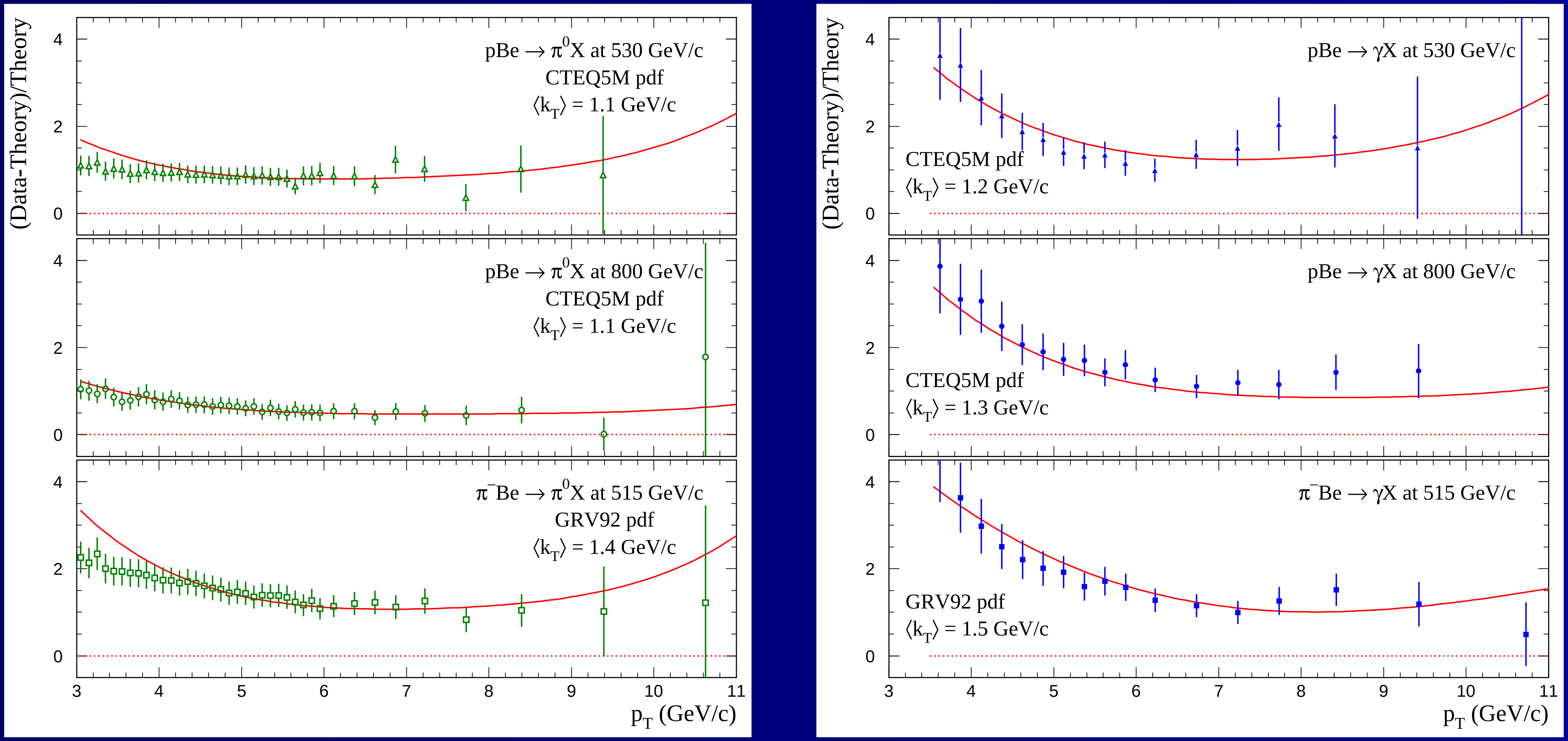
Fixed-order pQCD calculations partially include this effect through additional diagrams.

Resummed calculations can properly include k_T effects.





Inclusive Production with k_T

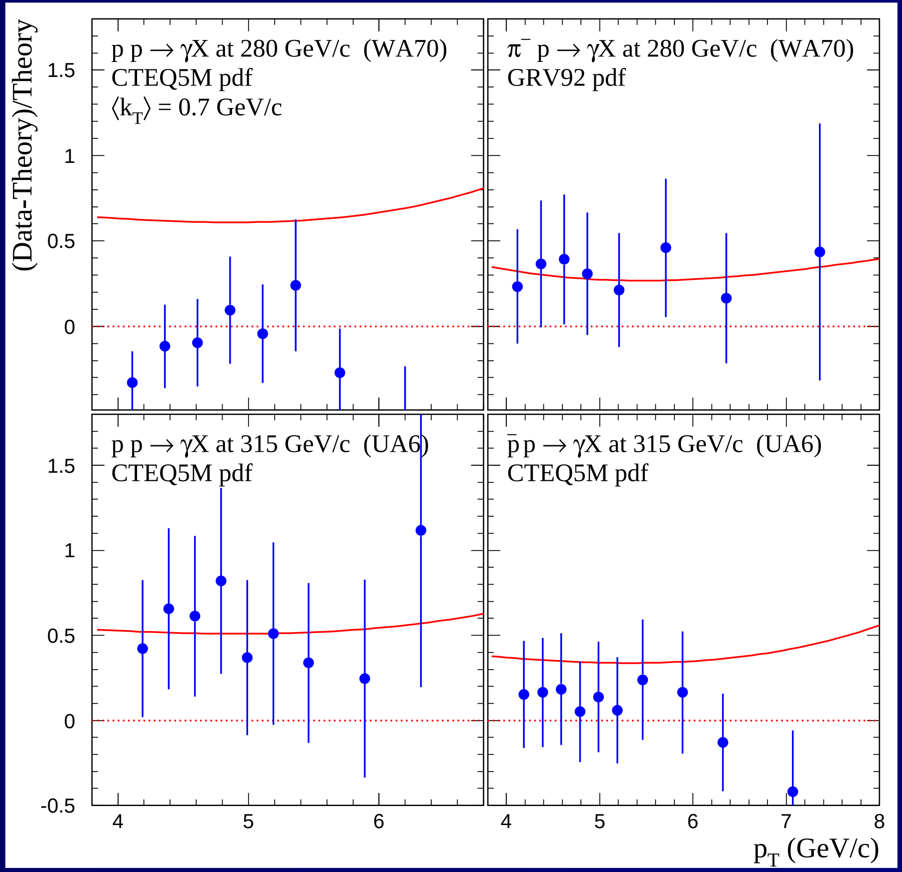


Chosen k_T values were influenced by studies of two particle correlations but are model dependent. This is not a measurement of k_T.

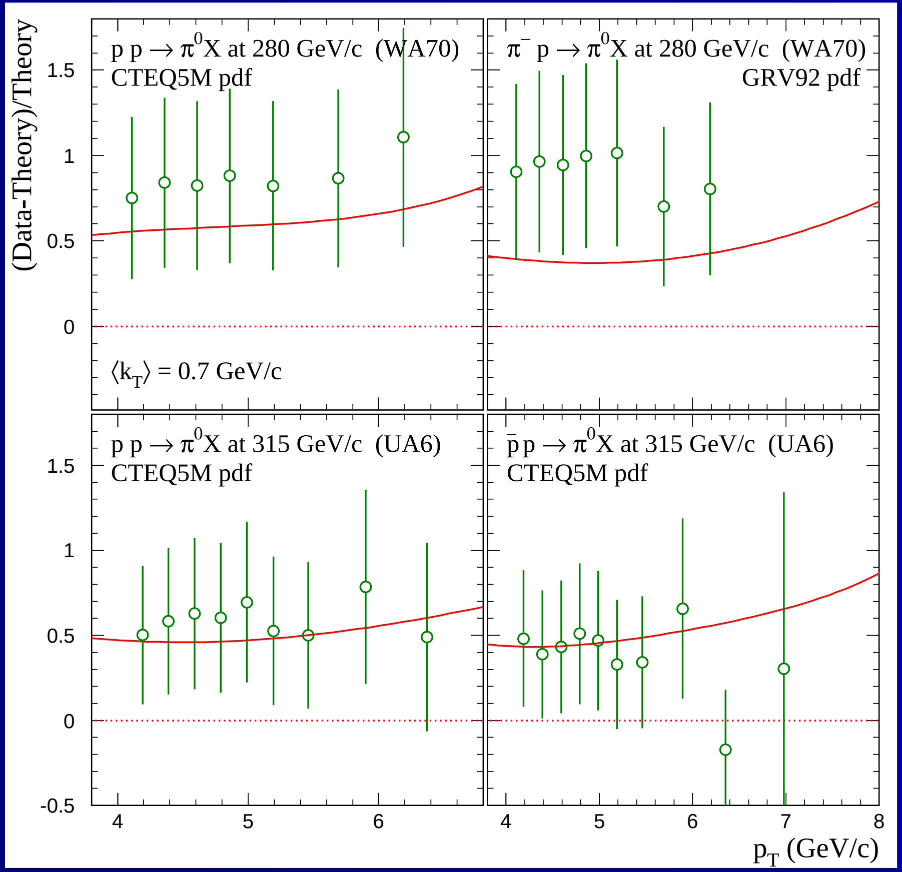
PRL 81, 2642 (1998) [E706] PRD 59:074007 (1999) PRD 63:014009 (2001)

Inclusive Production with k_T

WA70 and UA6



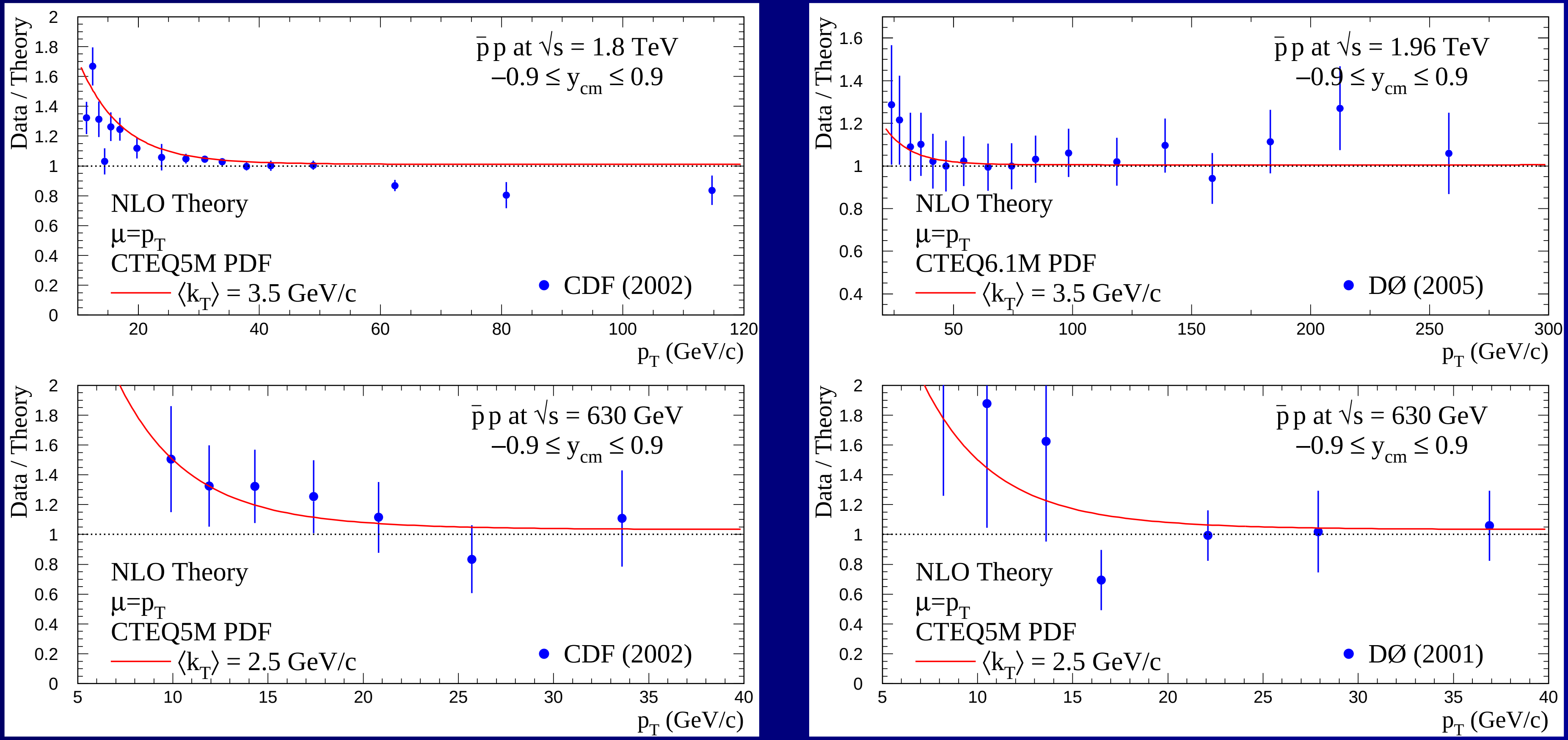
Direct Photon Production



π^0 Production

Inclusive Production with k_T

CDF and DØ

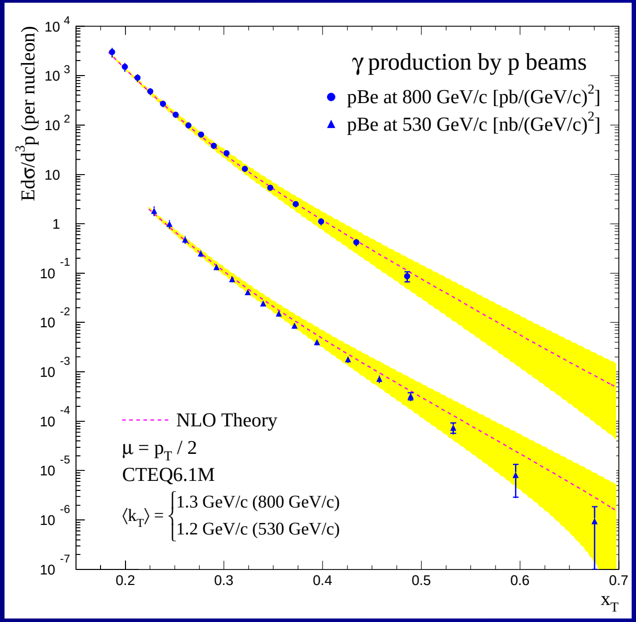


Direct Photon Production

Gluon Distribution Function?

Ad-hoc corrections to theory are not appropriate for use in global PDF fits. Proper calculations that incorporate k_T effects are not yet available.

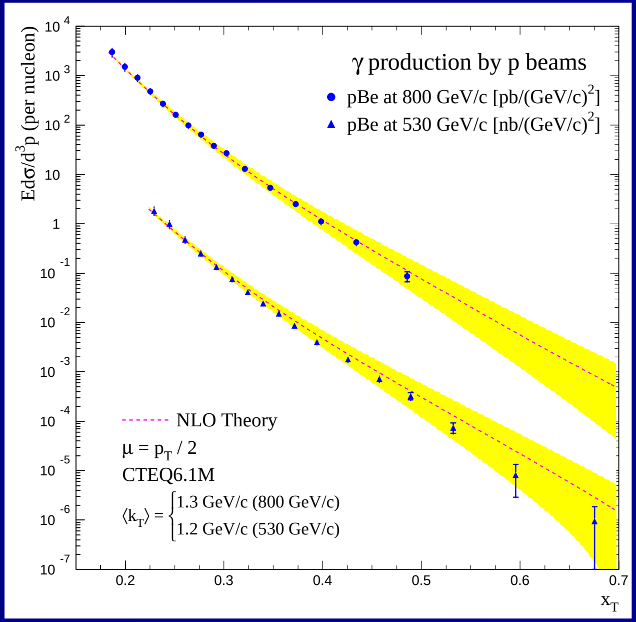
⇒ direct photons removed from fits



Gluon Distribution Function?

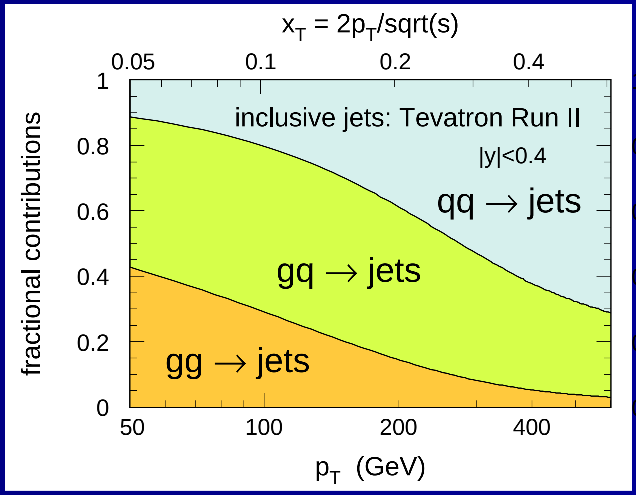
Ad-hoc corrections to theory are not appropriate for use in global PDF fits. Proper calculations that incorporate k_T effects are not yet available.

$\Rightarrow$ direct photons removed from fits



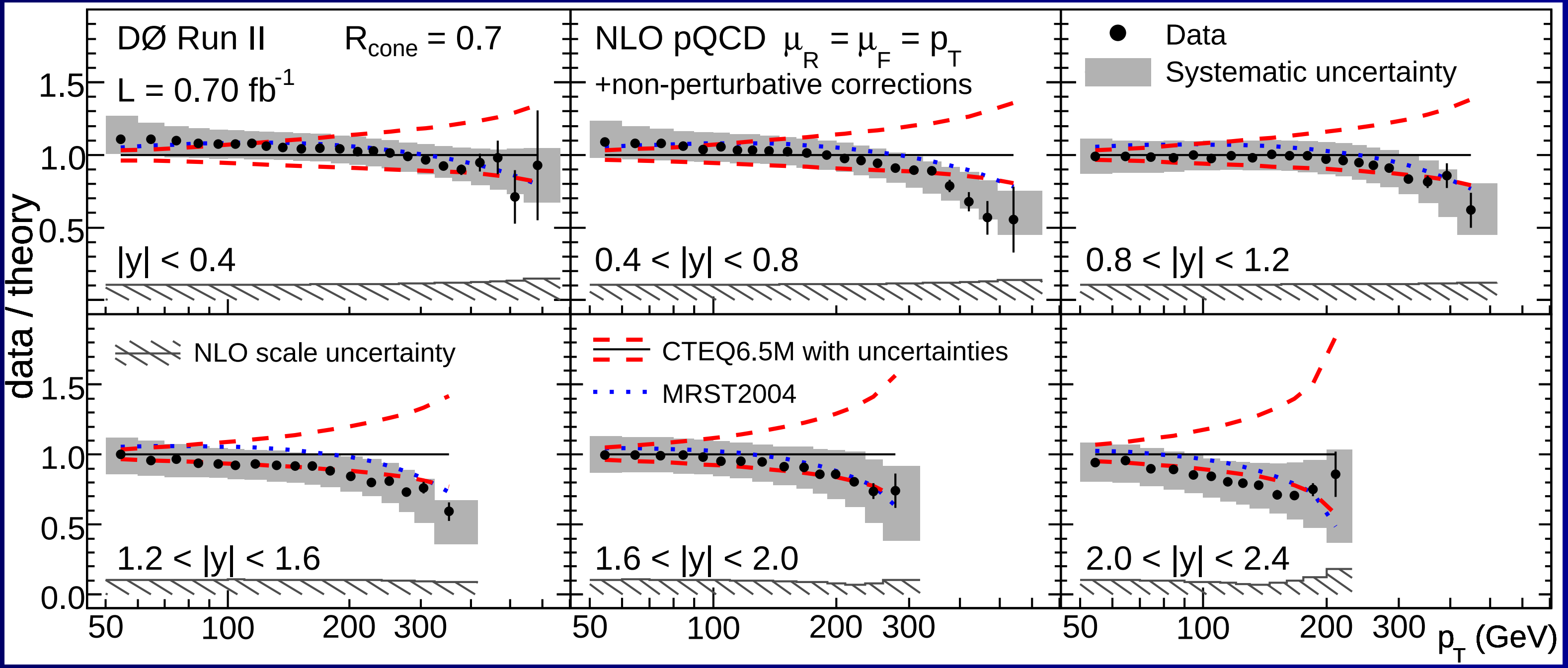
Inclusive jet production is sensitive to the presence of new physical phenomena and also to the gluon distribution.

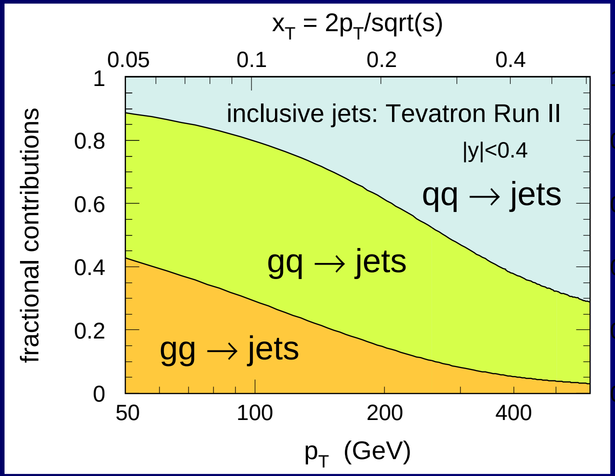
$\Rightarrow$ critical to measure cross section over wide rapidity range to both constrain PDF and maintain sensitivity to new physics

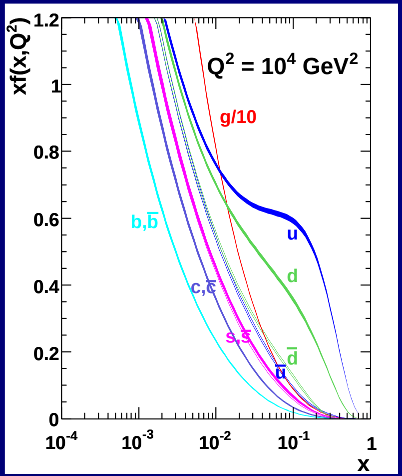


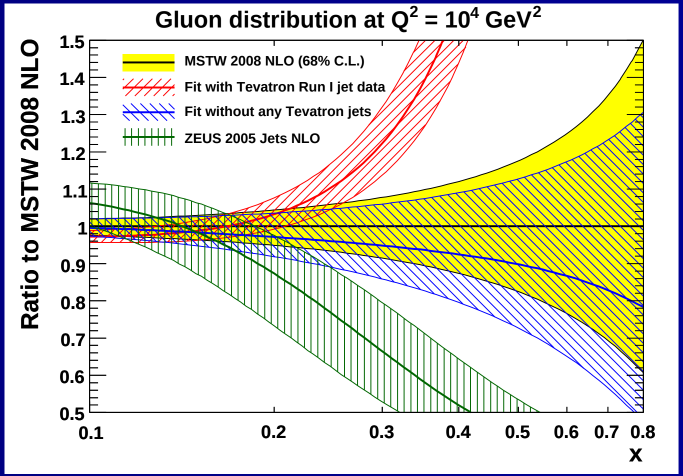
DØ Inclusive Jet Production

PRL 101, 062001 (2008) [DØ]





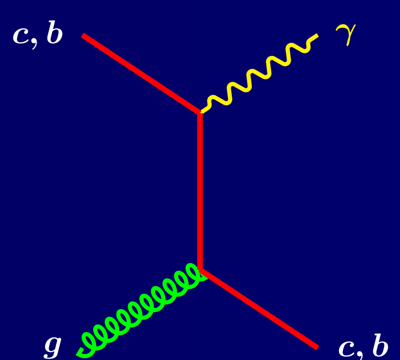


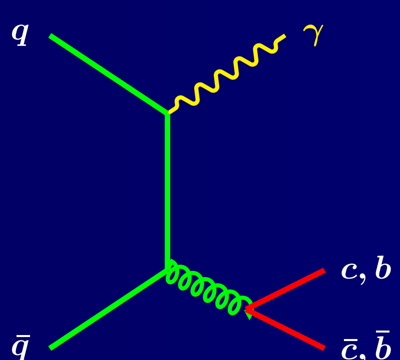


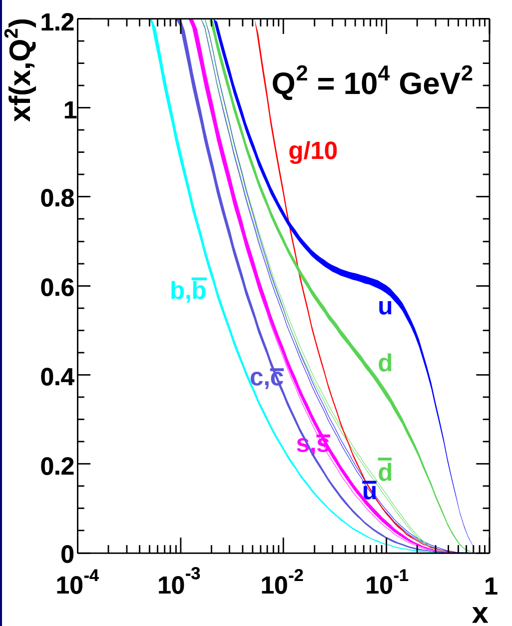
DØ $\gamma + c/b$ Jet

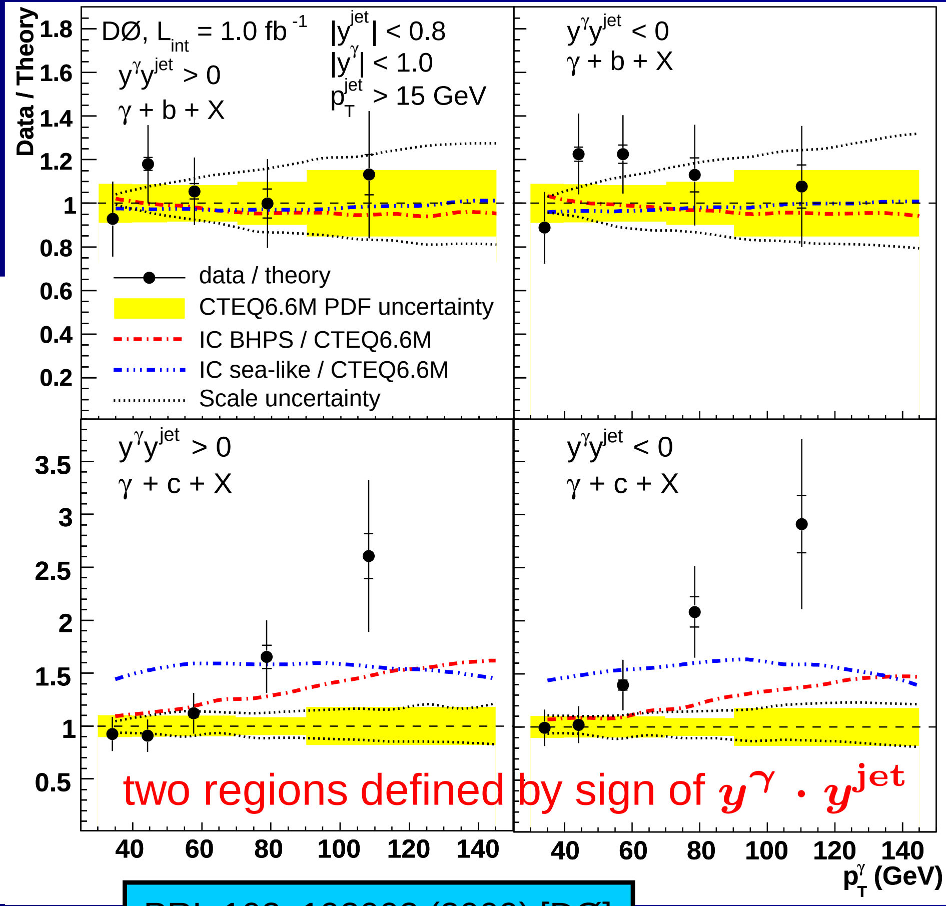
The charm and bottom PDF are derived from the gluon PDF: $g \to c\bar{c}$ and $g \to b\bar{b}$.

The heavy-flavor content of the proton can be probed in γ+jet events where the jets are flavor tagged.









PRL 102, 192002 (2009) [DØ]

NLO pQCD agrees with $\gamma + b$ jet measurements, $\gamma + c$ jet data exceeds expectation at high p_T.

Conclusions

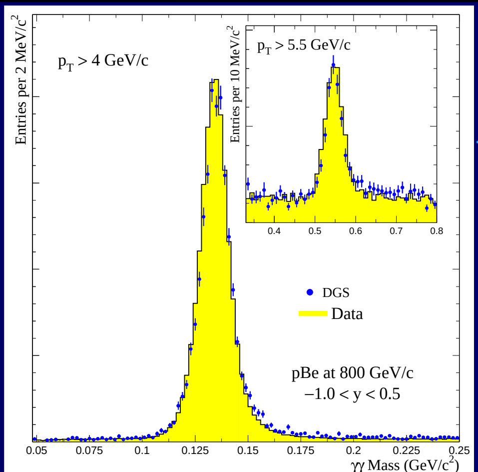
- Direct photons are clean probes of the hard scatter:
  - experimentally challenging
  - theoretically interesting
- Comparisons of pQCD to most of the world's direct photon data at low p_T (not x_T!) are intriguing:
  - somewhat controversial: theory? experiment? is it real?
  - might be explained by including higher order effects (e.g., k_T)
  - still waiting for a definitive answer. . .
- Direct photons were supposed to be the best sample for extracting the gluon distribution at high momentum fraction:
  - now supplanted by jet distributions
  - are we obscuring potential new physics by incorporating it into the gluon distribution?
- Direct photons are a background to many new physical phenomena so precise measurements can be critical to discovery.

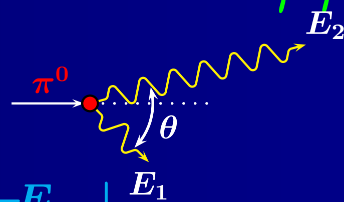
Backup

E706 Direct Photon Candidates

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

PRD 68:052001 (2003) [E706]

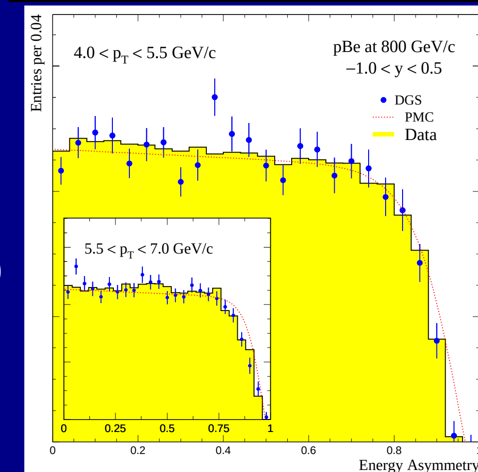


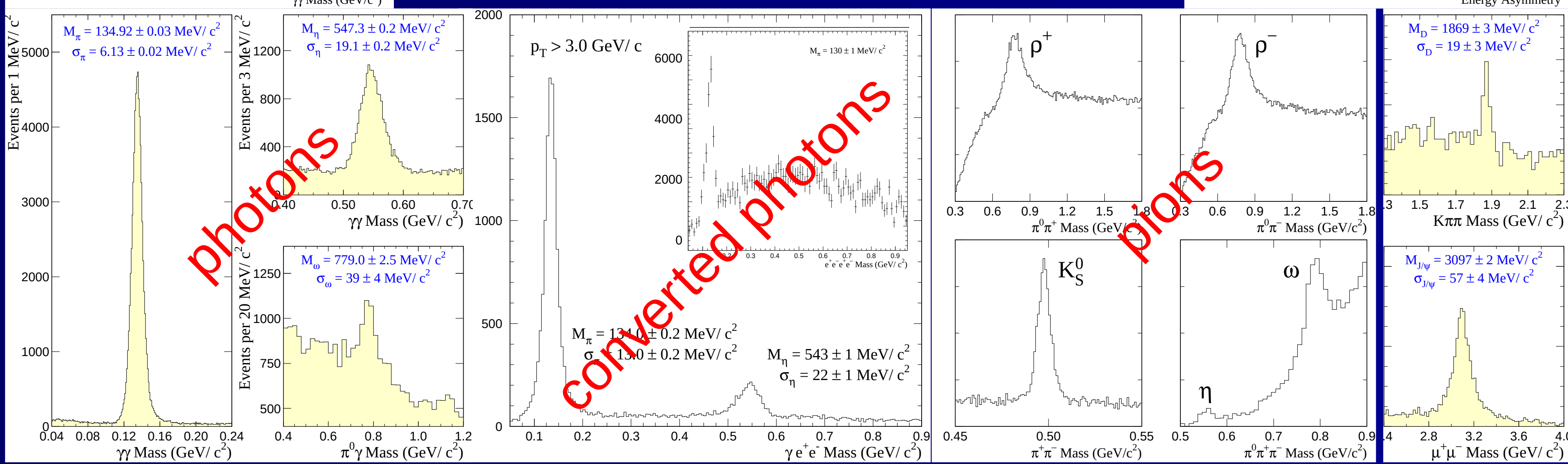


$$A_{\gamma\gamma} \equiv \beta \cos\theta^* = \frac{|E_{\gamma_1} - E_{\gamma_2}|}{E_{\gamma_1} + E_{\gamma_2}}$$

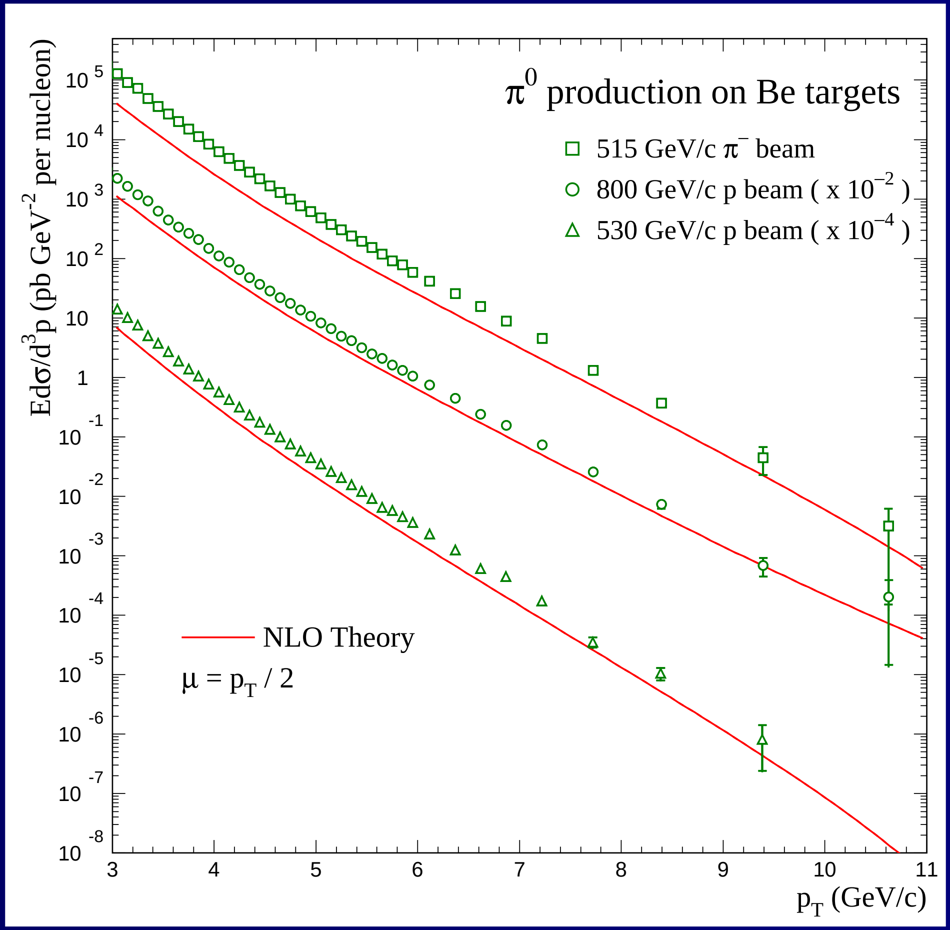
Direct photon candidates that formed $\gamma\gamma$ pairs with invariant mass in the π^0 or η peak regions and $A_{\gamma\gamma} < 0.9$ are rejected ($A_{\gamma\gamma}$ varied for systematic studies)

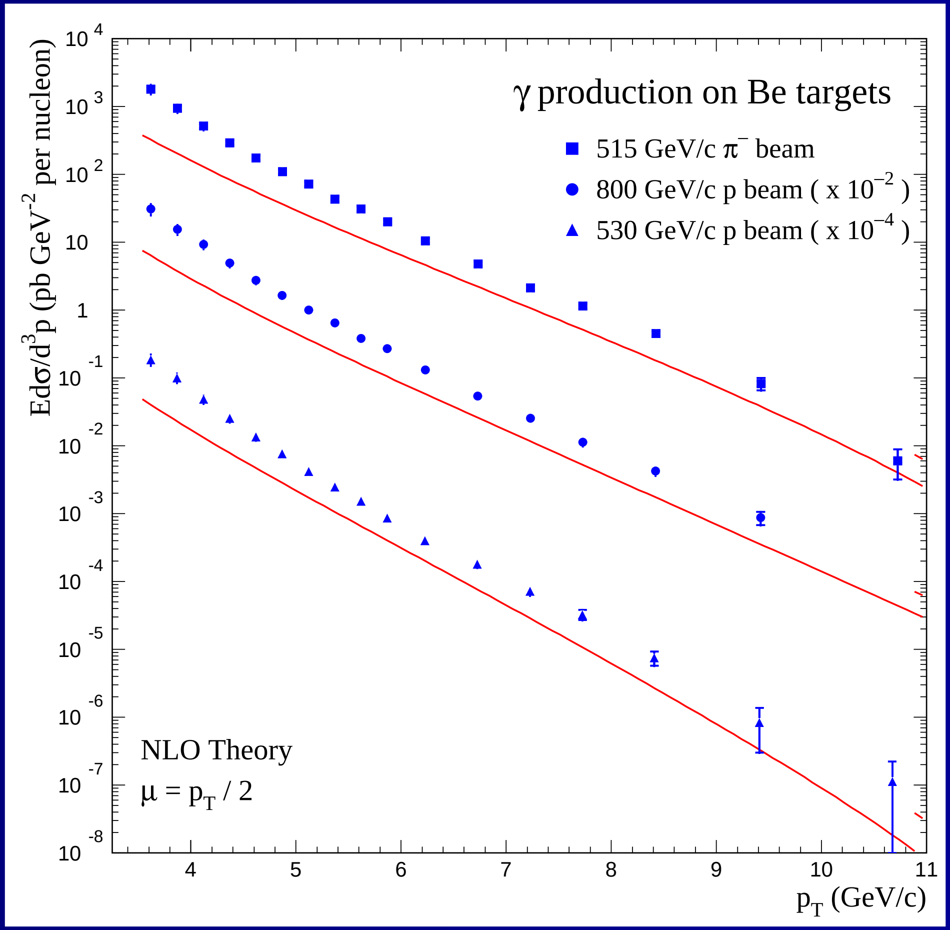
PRD 69:032003 (2004) [E706]





E706 Direct Photon and π^0





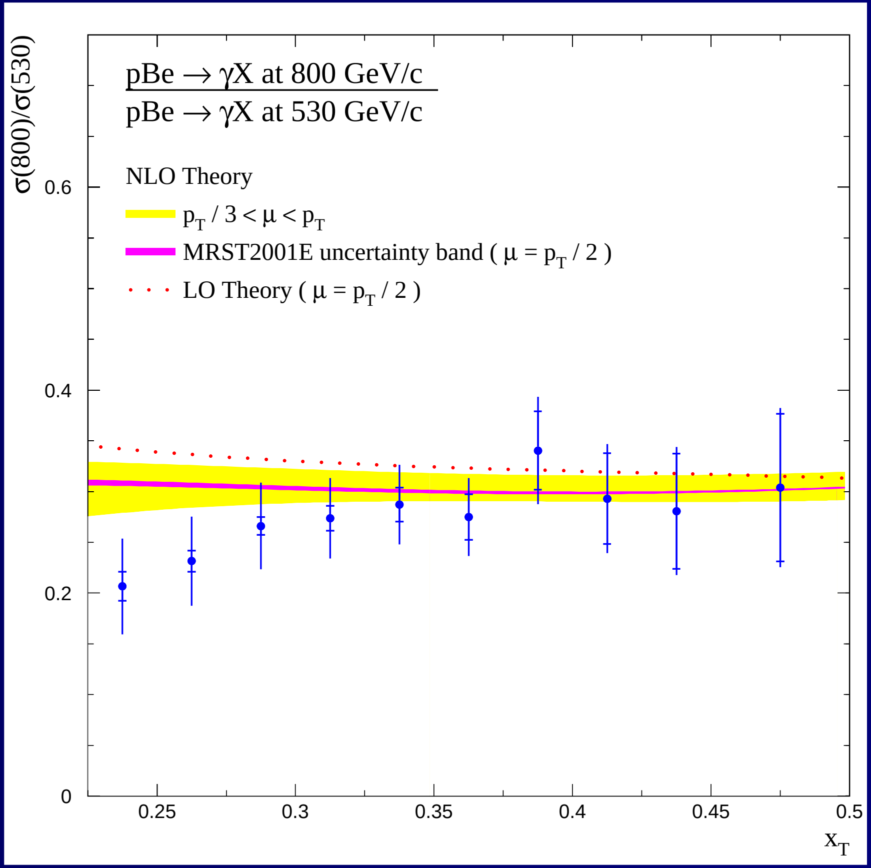
NLO pQCD fails to describe direct photon or π^0 cross sections.

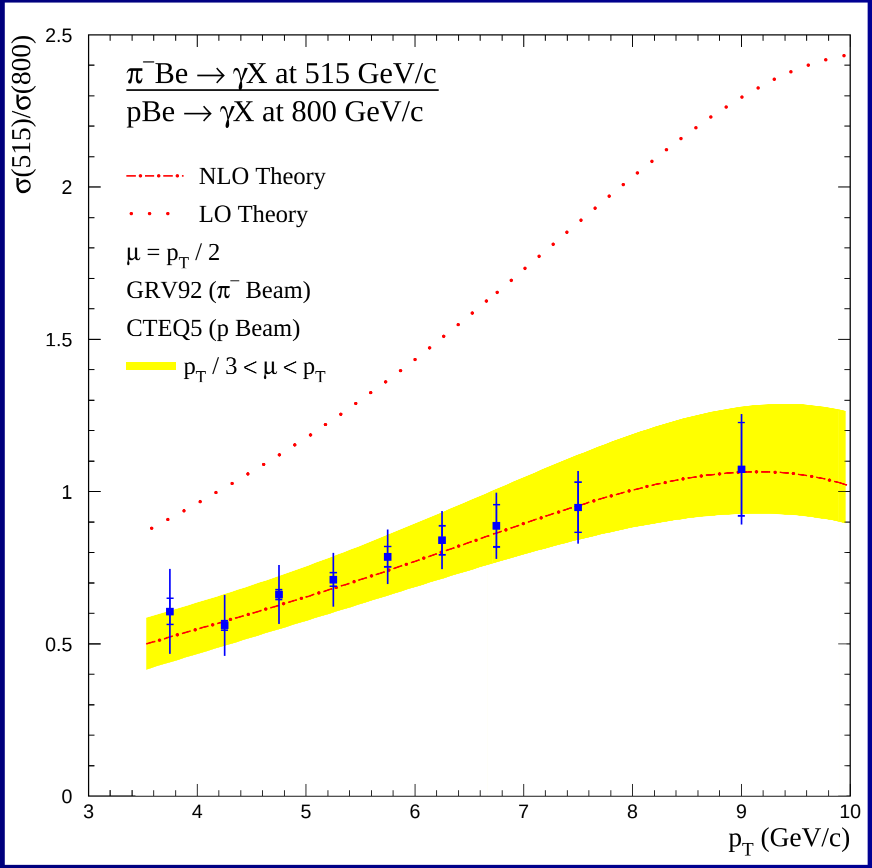
NLO pQCD corrected for small nuclear enhancement. The pp comparisons yield the same conclusions.

PRL 81, 2642 (1998) PRD 68:052001 (2003) PRD 69:032003 (2004) PRD 70:092009 (2004) [E706]

E706 Direct Photon

PRD 70:092009 (2004) [E706]





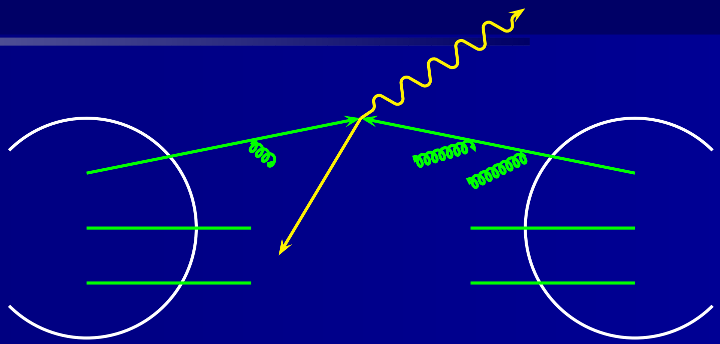
NLO pQCD has reduced scale dependence and significantly improved agreement when compared to ratios of direct-photon cross sections

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.

E706 Pair Production

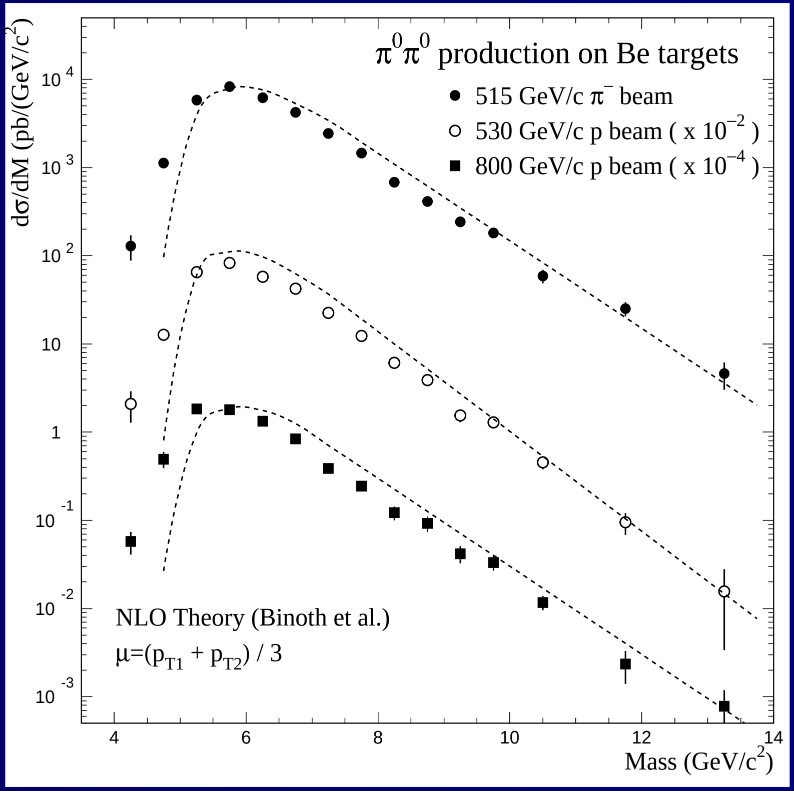
Distributions such as the dipion mass and $p_T^{\pi^0}$ are insensitive to transverse boosts. Topological distributions can be used to investigate the magnitude of k_T.

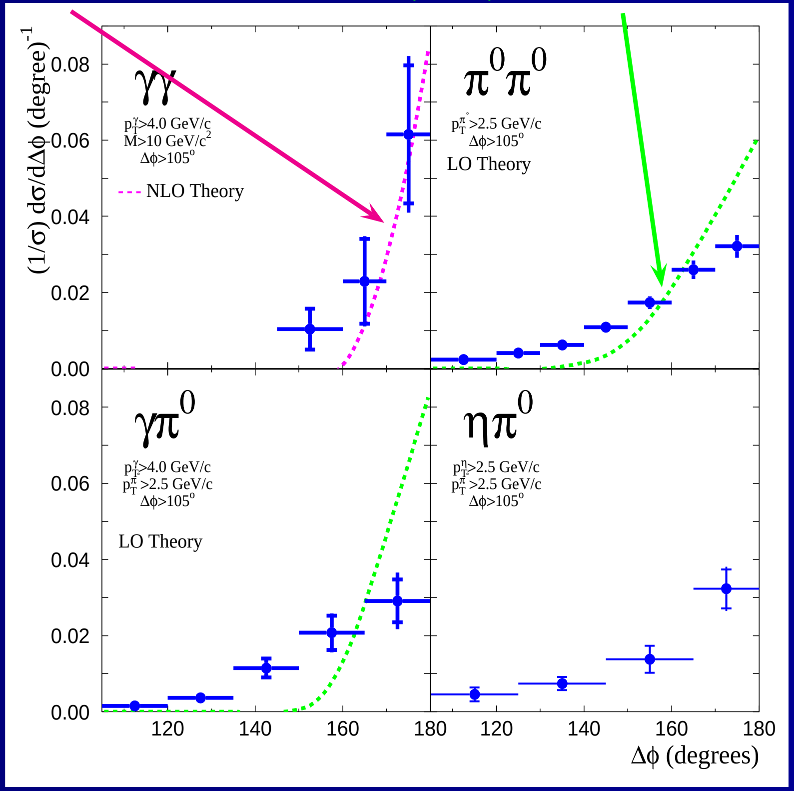


PRL 81, 2642 (1998) [E706]

width from NLO pQCD contributions

width due to fragmentation $\langle q_T \rangle \approx 600$ MeV

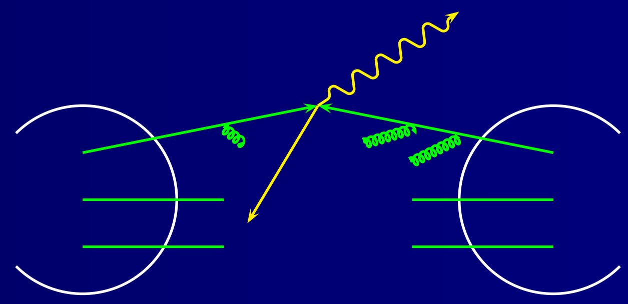


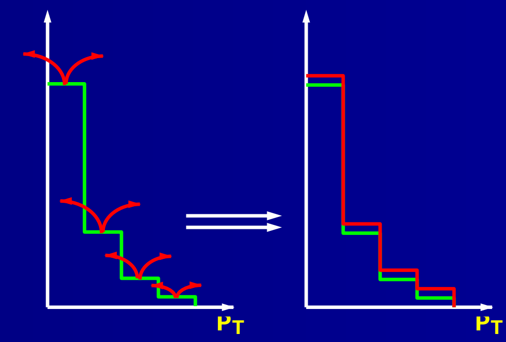


Impact on Inclusive Production

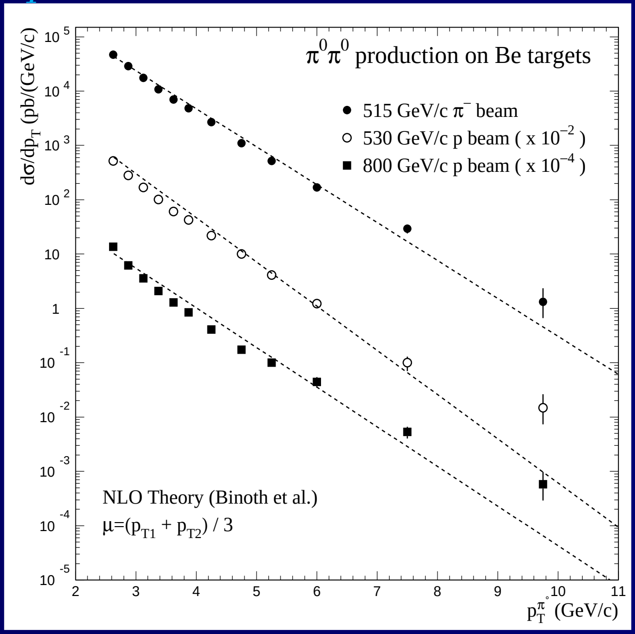
PRL 81, 2642 (1998) [E706]

In many respects, k_T affects single-particle p_T distributions as an additional effective resolution. This can impact $p_T \gg \langle k_T \rangle$.

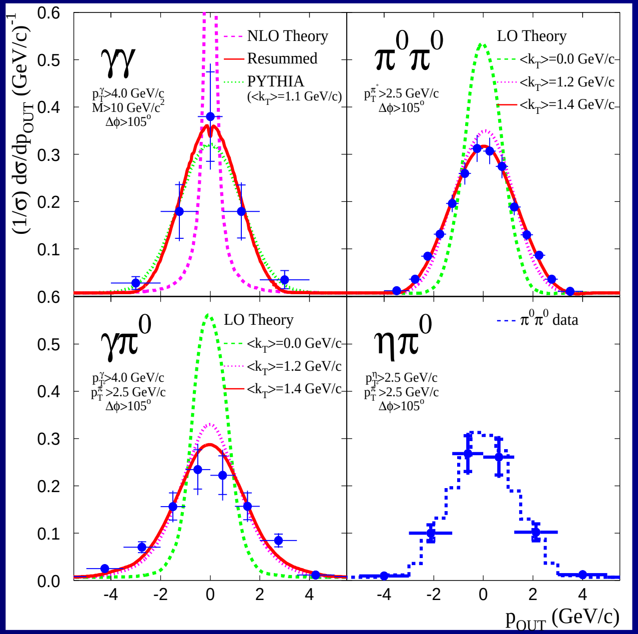




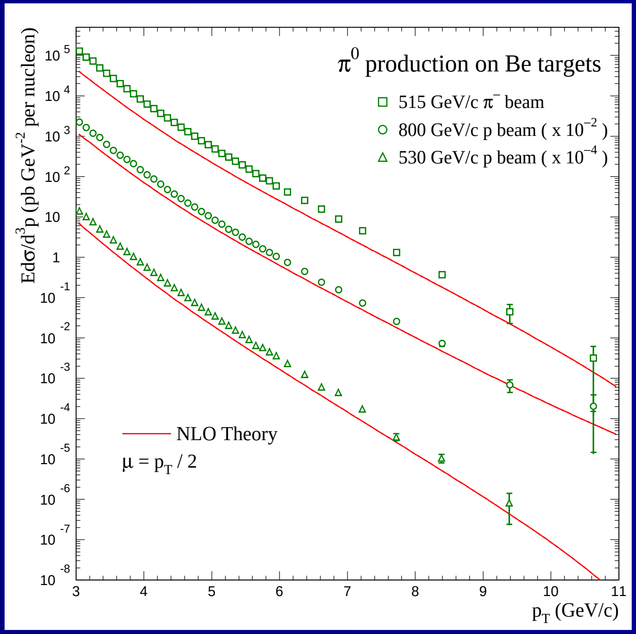
Distributions such as the dipion mass and $p_T^{\pi^0}$ are insensitive to transverse boosts.



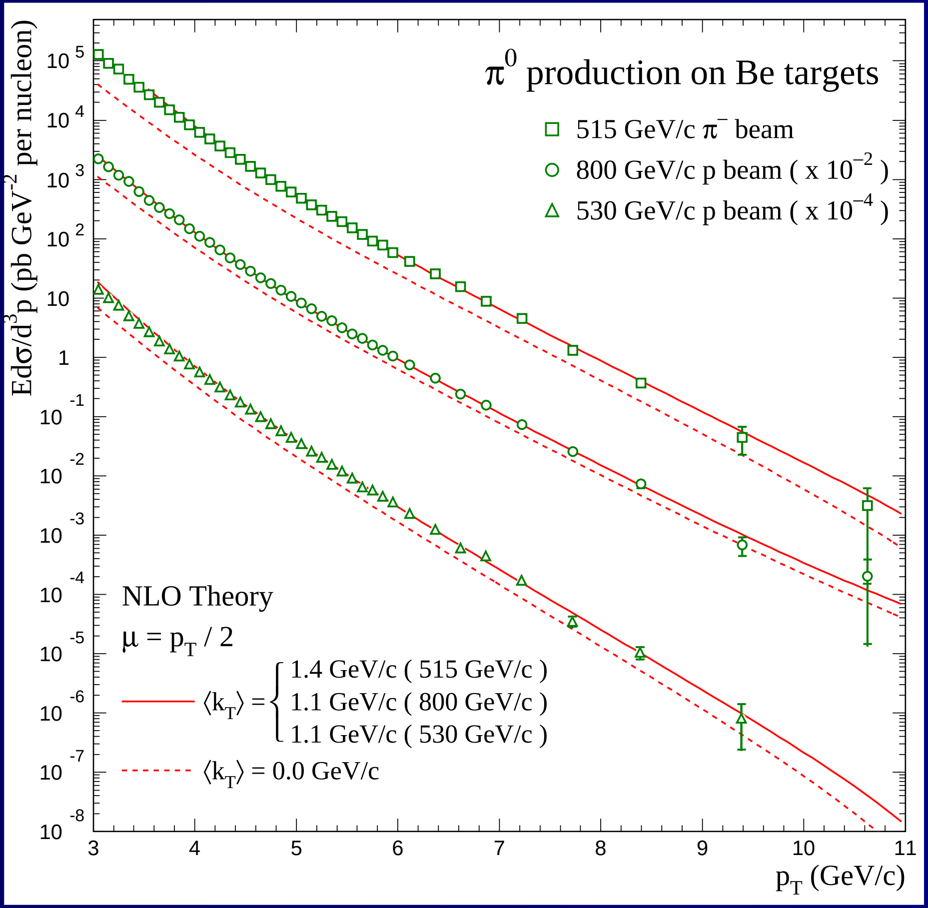
Topological distributions can be used to investigate the magnitude of k_T.

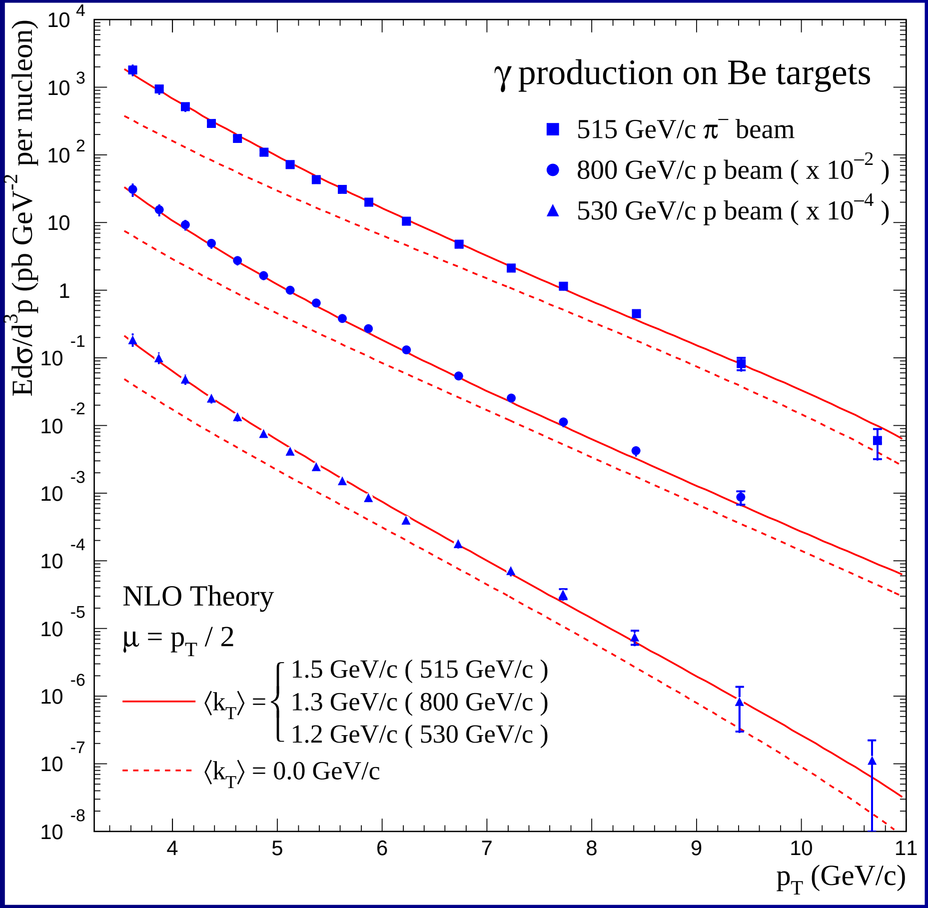


Distributions such as inclusive π^0 and direct photon production are sensitive to k_T effects.



Inclusive Production with k_T





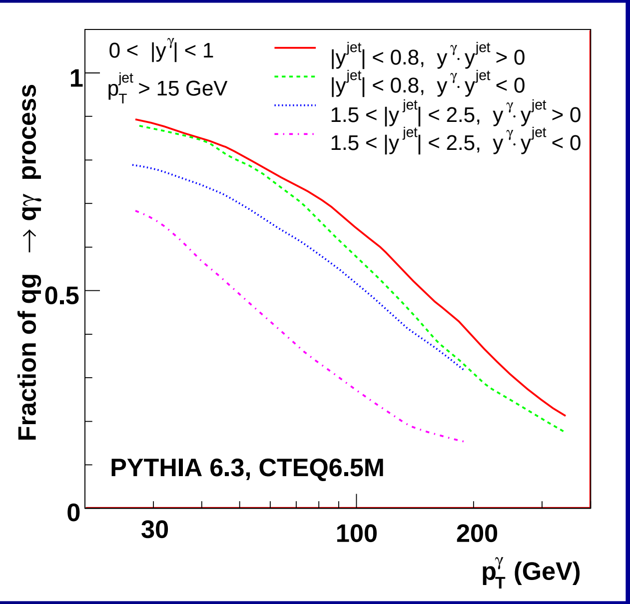
Chosen k_T values were influenced by studies of two particle correlations but are model dependent. This is not a measurement of k_T.

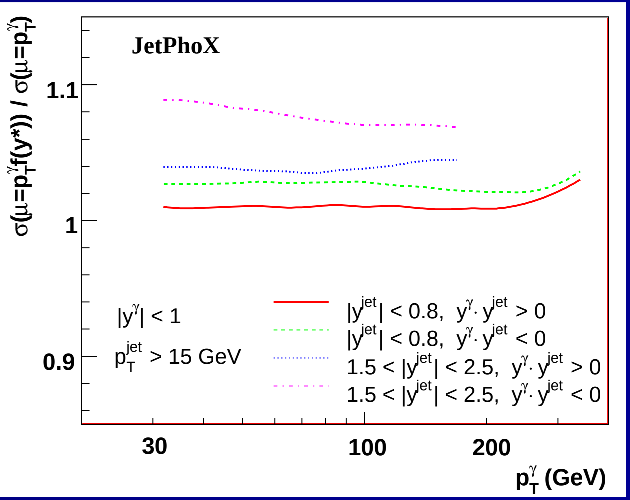
PRL 81, 2642 (1998) [E706] PRD 59:074007 (1999) PRD 63:014009 (2001)

DØ Isolated Photon+Jet

Measuring isolated photons with associated jet production increases sensitivity to the gluon distribution.

$$\frac{d^3\sigma}{dp_T^\gamma \, dy^\gamma \, dy^{jet}}$$





Define four regions based on y^{jet} and the sign of $y^\gamma \cdot y^{jet}$:

- $|y^{jet}| < 0.8,\ y^\gamma \cdot y^{jet} > 0$
  $0.016 \lesssim x_1 \lesssim 0.040$ and $0.040 \lesssim x_2 \lesssim 0.100$
- $|y^{jet}| < 0.8,\ y^\gamma \cdot y^{jet} < 0$
  $0.029 \lesssim x_1 \lesssim 0.074$ and $0.027 \lesssim x_2 \lesssim 0.065$
- $1.5 < |y^{jet}| < 2.5,\ y^\gamma \cdot y^{jet} > 0$
  $0.009 \lesssim x_1 \lesssim 0.024$ and $0.110 \lesssim x_2 \lesssim 0.300$
- $1.5 < |y^{jet}| < 2.5,\ y^\gamma \cdot y^{jet} < 0$
  $0.097 \lesssim x_1 \lesssim 0.264$ and $0.022 \lesssim x_2 \lesssim 0.059$

Define factorization and renormalization scales in terms of both p_T and rapidity: $\mu = p_T^\gamma \sqrt{0.5[1 + \exp(|y^\gamma - y^{jet}|)]}$

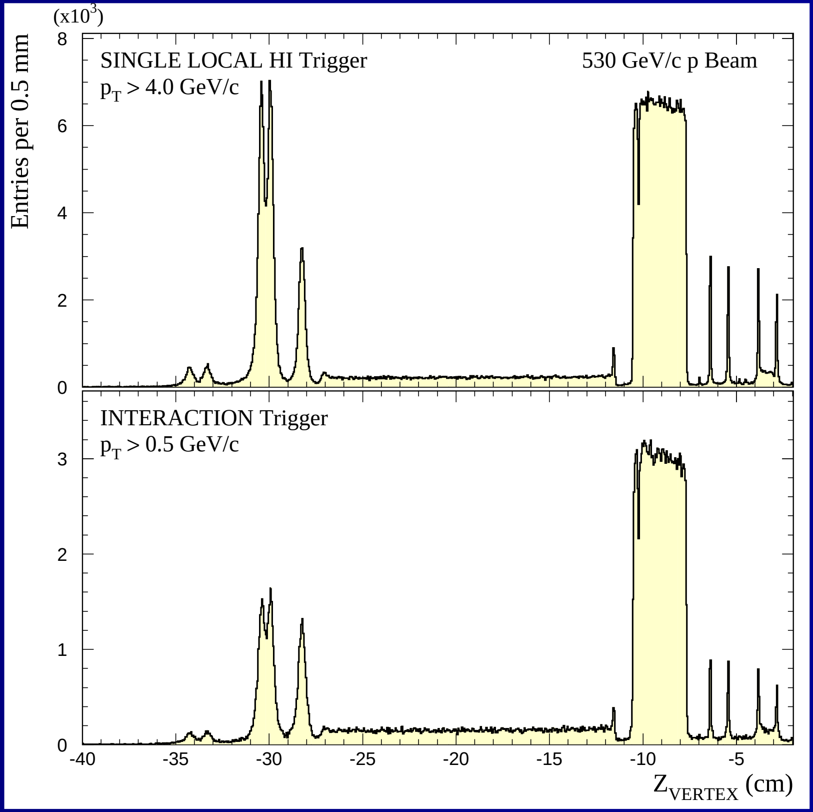
Nuclear Effects from E706

Nuclear Dependence

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

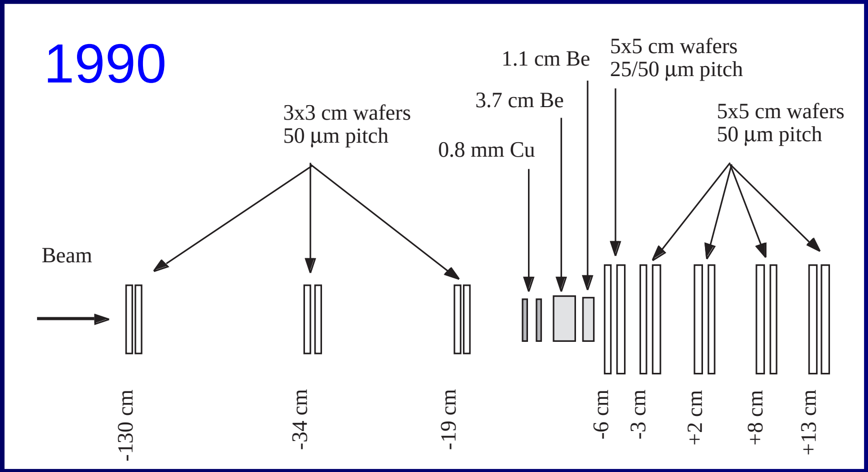
For hadron production by p and π beams,

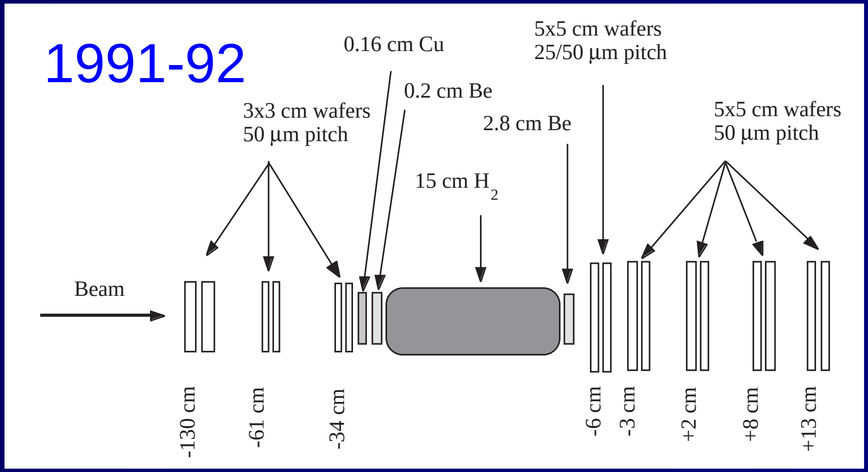
- expect a suppression at low p_T (nuclear disk)
- expect an enhancement at large p_T (scattering)

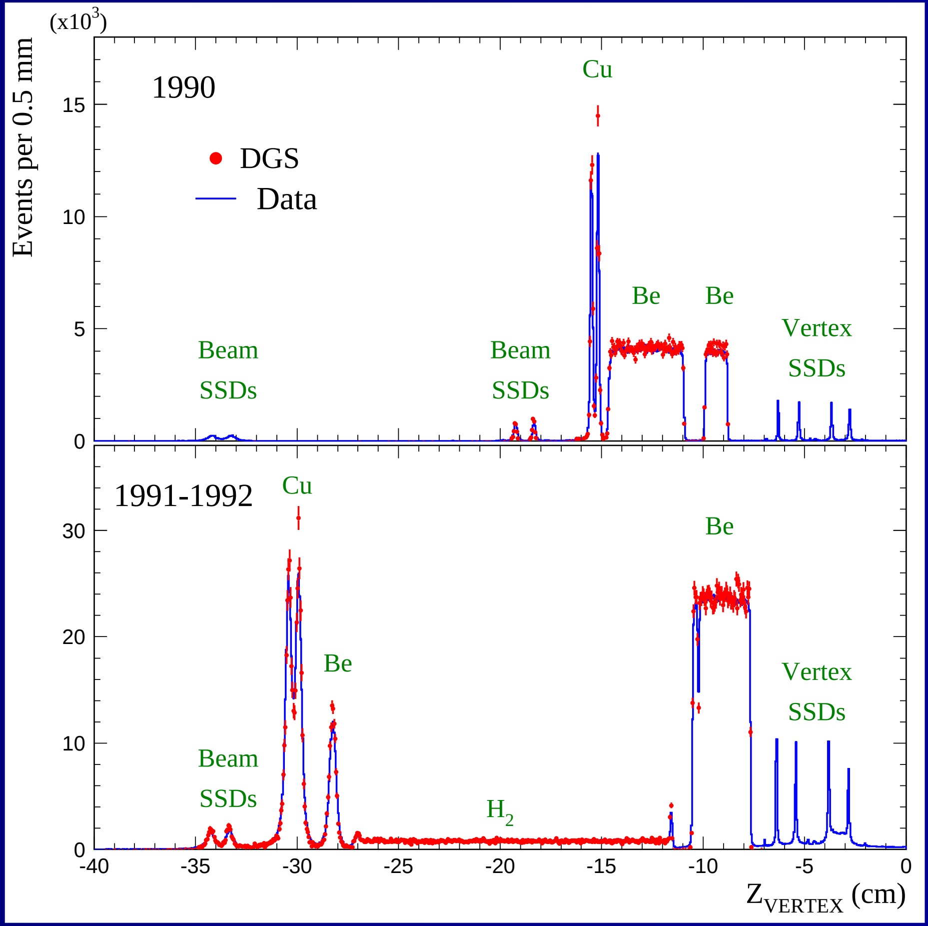


Multiple scattering may occur in the initial and/or final state in high p_T hadron production. Multiple scattering is expected to occur primarily in the initial state in direct photon production.

Target Region

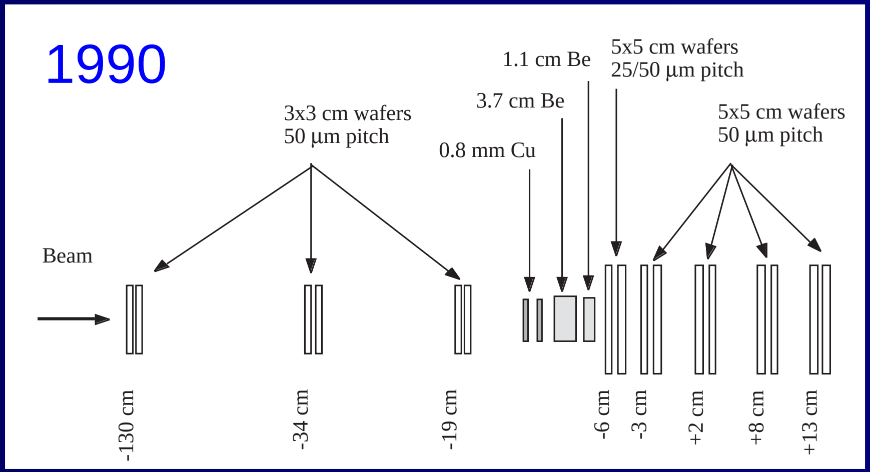


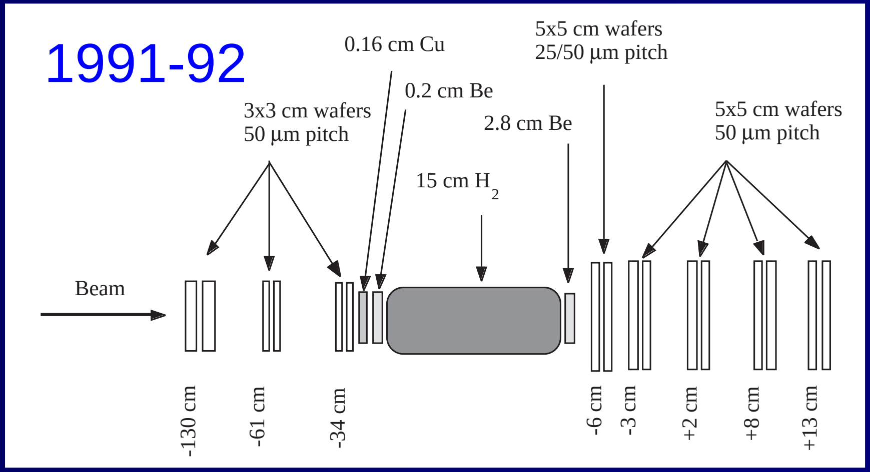


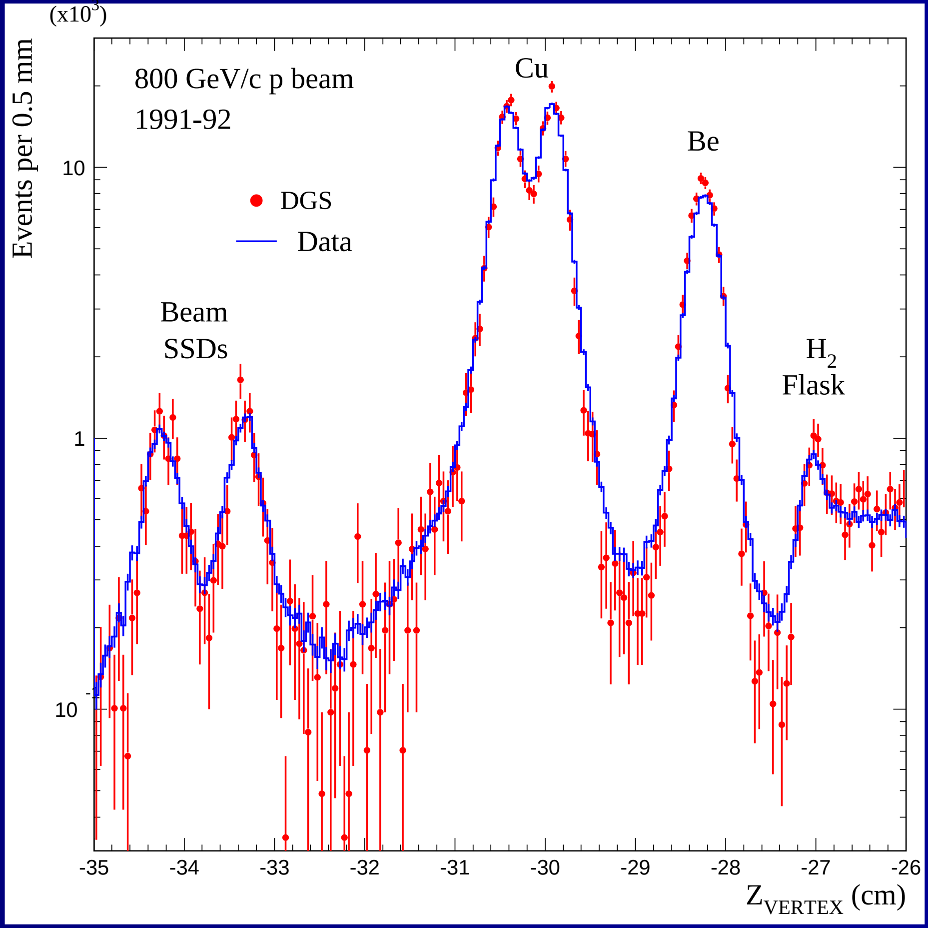


Vertex Distributions

Target Region

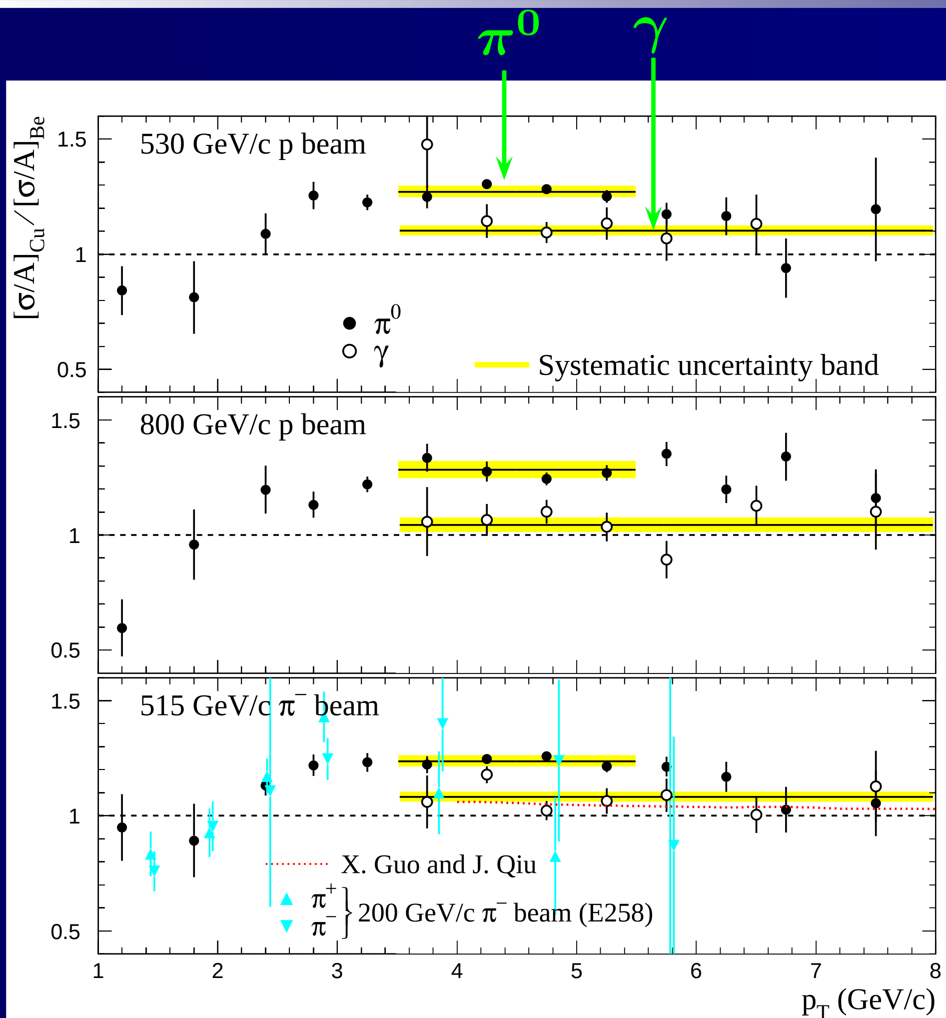






Vertex Distributions

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^-	$1.237 \pm 0.015 \pm 0.025$

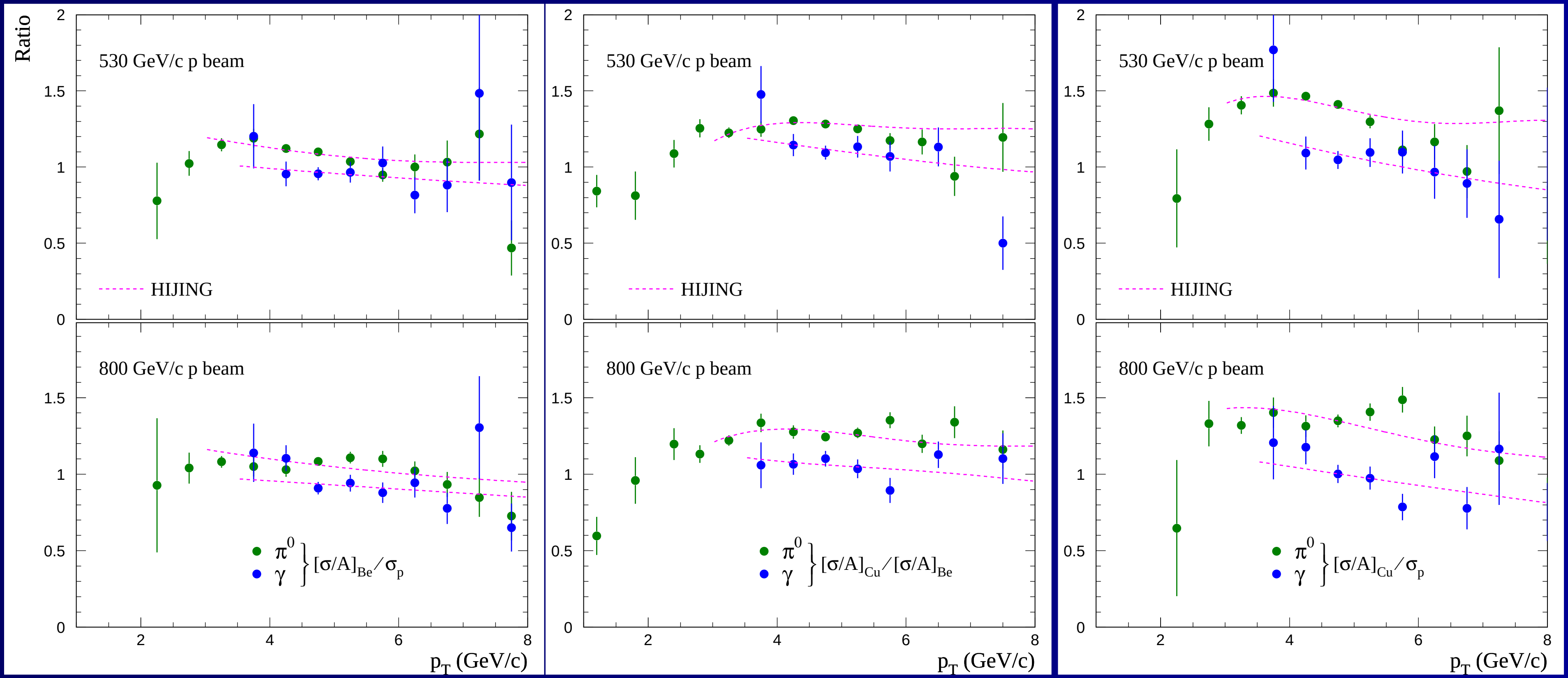
Direct Photon Production

	$3.5 < p_T < 8.0$ 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^-	$1.083 \pm 0.024 \pm 0.022$

PRD 72:032003 (2005) [E706]

Nuclear Dependence

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

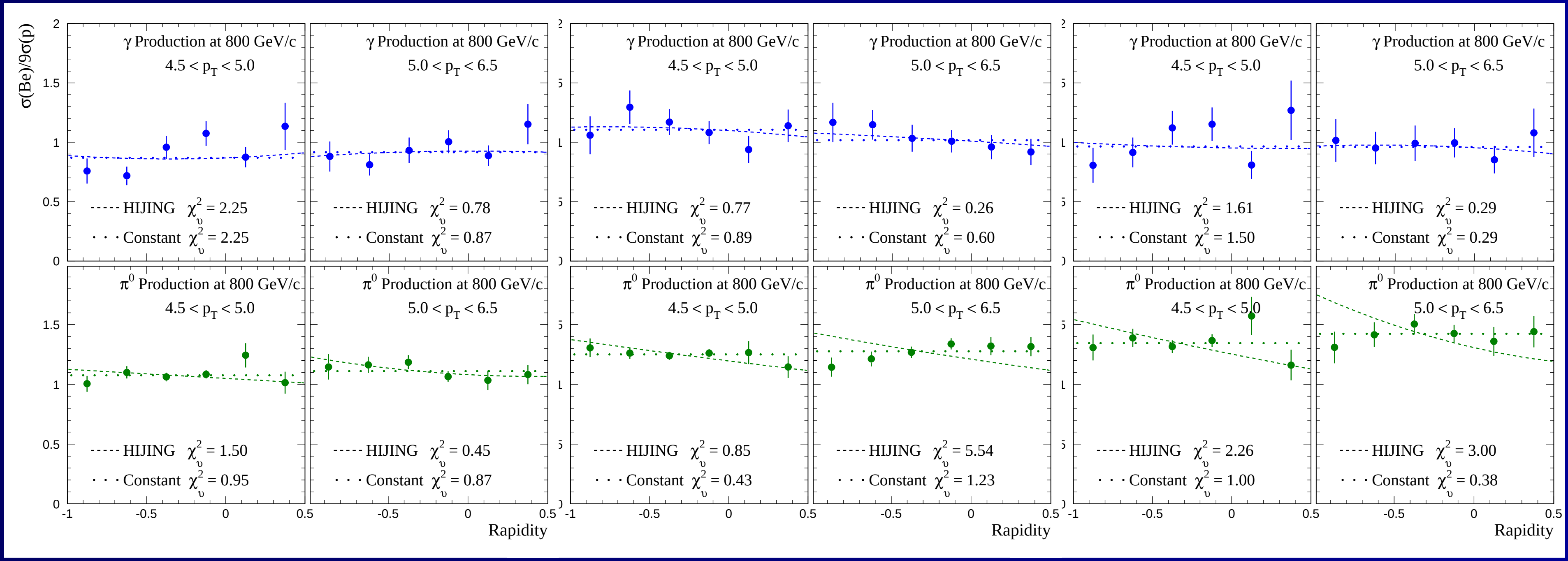


comparison with HIJING

PRD 72:032003 (2005) [E706]

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

PRD 72:032003 (2005) [E706]