Direct Photon Production in Hadronic Collisions

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Invited talk at CALC 2009
JINR, Dubna, 18.07.2009

Outline:

- SANC Motivation: to implement a new class of processes in SANC
- Direct photon production: definition
- Motivation for studying dpp in hadronic collisions
- Review of dpp experiments; x_T scaling
- π^0 background; photon isolation
- The hard subprocesses of dpp in LO
- Kinematics of dpp; event reconstruction
- Observable: invariant differential cross section
- NLO amplitudes of dpp
- JETPHOX: state-of-the-art QCD NLO program of dpp; comparison with data
- Summary and conclusions

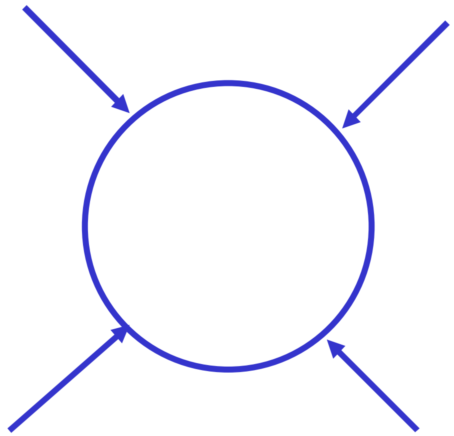
SANC Motivation:
to implement a new class of processes in SANC

Within the framework of SANC it is intended to develop the formalism for a new class of reactions

in SANC notation : $2f2b \to 0$ (all incoming 4-momenta)

here f = any fermion

b = any boson



Examples of *2f 2b* --> 0 Processes:

- $2\,fbb \to 0, \quad b = \gamma, Z, W, H, \, not \; g$

- $2\,fgb \to 0, \quad b = \gamma, Z, W, H, \, not \; g$

and in particular single top production in b-quark gluon collisions (see V. Kolesnikov in this Workshop):

$$g\mathrm{b} \to \mathrm{t}W$$

(*here* b *is the bottom quark and* t *is the top quark*)

Direct photon production also belongs to this class of processes:

$$qg \to q\gamma \;(or\; \bar{q}g \to \bar{q}\gamma)\; and\; q\bar{q} \to g\gamma$$

Implementation within SANC means calculation of the complete EW and QCD NLO corrections

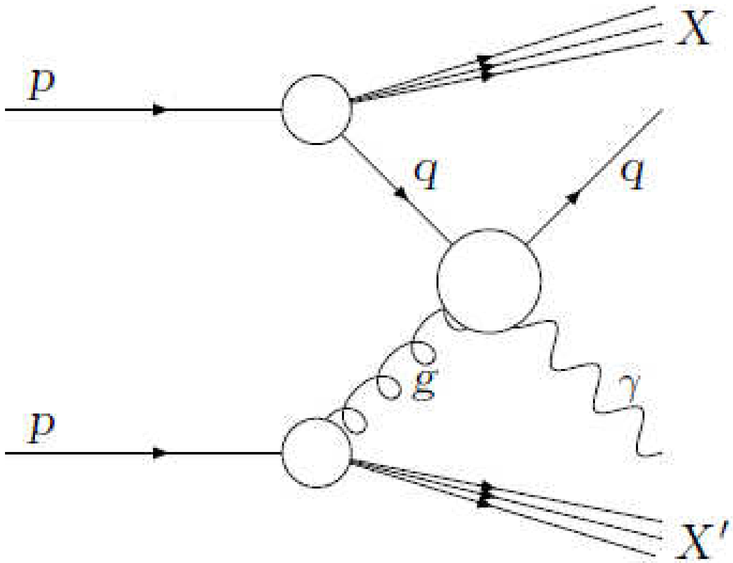
QCD NLO for dpp has a long history; see *e.g.*:

- T. Binot, J.P. Guillet, E. Pilon and M. Werlen, Eur. Phys. J. C16 (2000) 311.
- S. Catani, M. Fontannaz, J.-Ph. Guillet, and E. Pilon, JHEP 0205 (2002) 028
- P.Aurenche, M. Fontannez, J.-Ph. Guillet, E. Pilon, and M. Werlen, Phys. Rev. D73 (2006) 094007.

and references therein

As far as we know, the EW NLO formulas for this class of processes have not yet been derived (*please tell me if I am wrong*!)

• Direct Photon Production in hadronic collisions: Definition



Prompt Photon Production

the hard subprocess shown is QCD Compton scattering:
$qg \to q\gamma$

by crossing we get the subprocess $q\bar{q} \to \gamma g$

• Motivation for studying direct photon production in hadronic collisions

Original motivation

H. Fritzsch and P. Minkowski, PL 69B(1977) 316: test of QCD

Today:

- precision test of pQCD;
- dpp is complementary to DIS, Drell-Yan and pure QCD processes, such as production of jets or heavy flavours;
- dpp contributes significantly to the measurement of the gluon distribution in hadrons;
- serves to calibrate jet energy – *a serious experimental consideration.*

• A Historical Review of dpp Experiments

Direct photon production was first seen in *pp* collisions
in 1980 by the CERN ISR*) experiment R108
at a CMS energy of 62.4 GeV

*) ISR = I*ntersecting* S*torage* R*ings: the world's first pp collider*

The current status of experiments in proton-proton and proton - antiproton collisions is shown in the next two tables

Direct Photon Production in *pp* Collisions

1980	R108	E_{CMS}=62.4 GeV	Angelis 80
1982	R806	E_{CMS}=63 GeV	Anassontis 82
1987	NA24	E_{LAB}=300 GeV	De Marzo 87
1988	WA70	E_{LAB}=280 GeV	Bonesini 88
1989	R110	E_{CMS}=63 GeV	Angelis 89
1989	R807	E_{CMS}=63 GeV	Akesson 89
1993	UA6	E_{LAB}=315 GeV	Ballochi 93
1995	E704	E_{LAB}=200 GeV	Adams 95
1998	UA6	E_{LAB}=315 GeV	Ballochi 98
2006	PHENIX	E_{CMS}=200 GeV	Adler 06

Direct Photon Production in *p*-anti *p* Collisions

1988	UA1	E_{CMS}=546; 630	Albajar 88
1988	UA2	E_{CMS}=630 GeV	Ansari 88
1992	UA2	E_{CMS}=630 GeV	Alitti 92
1993	UA6	E_{LAB}=315 GeV	Ballochi 93
1994	CDF	E_{CMS}=1800 GeV	Abe 94
1996	D0	E_{CMS}=1800 GeV	Abachi 96
1998	UA6	E_{LAB}=315 GeV	Ballochi 98
2000	D0	E_{CMS}=1800 GeV	Abbott 00
2002	CDF	E_{CMS}=1800 GeV	Acosta 02
2006	D0	E_{CMS}=1960 GeV	Abazov 06

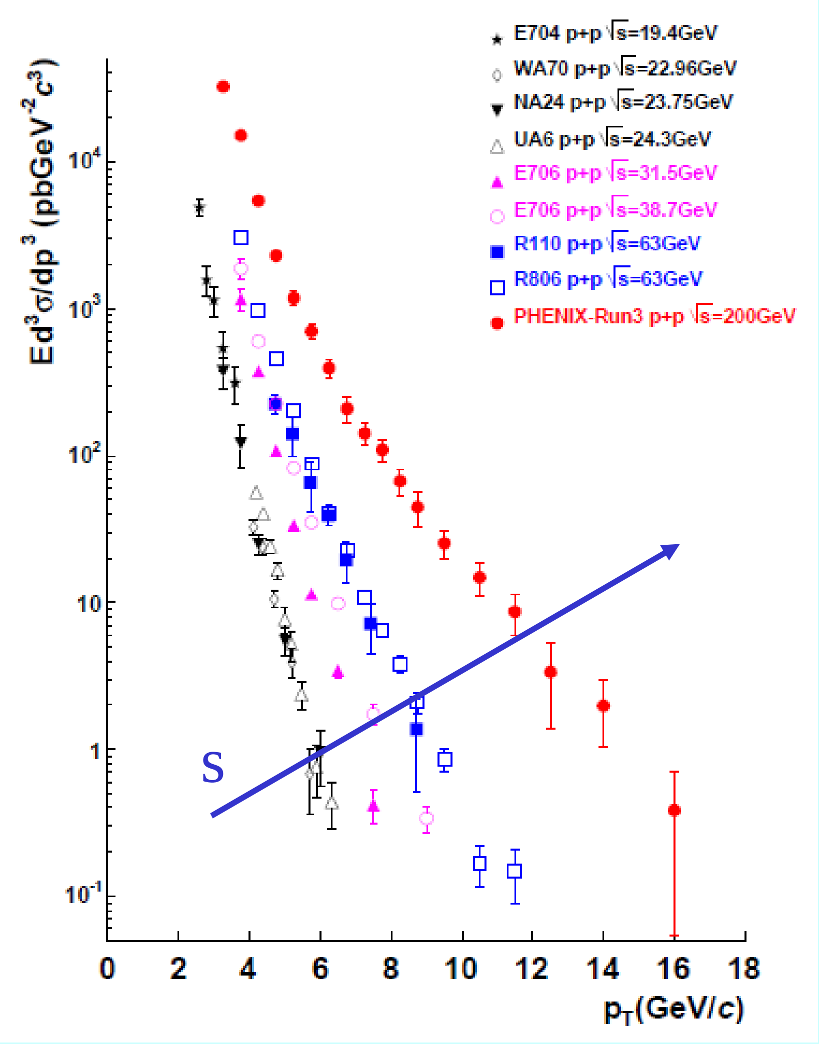
Direct Photon Production in Other Reactions:

Direct photon production has also been studied in
pion-proton,
pion-nucleus,
proton-nucleus
and in
heavy ion collisions,
also at LEP in ***$\gamma^*\gamma^*$*** collisions
and at HERA,
but these will not be reviewed in this talk.

• Experimental Data

- In the next few slides a selection of experimental data of direct photon production in $p - p$ and *anti* $p - p$ collisions are shown.

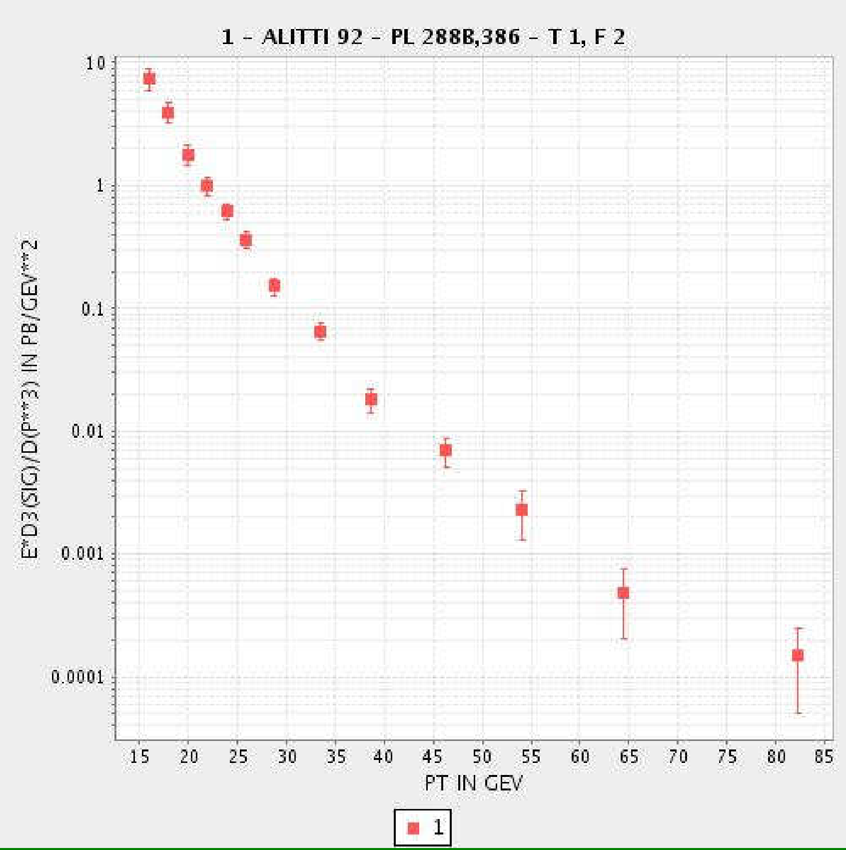
Prompt Photon Production in pp Collisions



source: T. Horaguchi, PHENIX PhD Thesis 2006

CERN UA2 1992

$$\bar{p}p \to \gamma X \quad \sqrt{s} = 630\ \text{GeV}; \quad L = 13.2\ \text{pb}^{-1}; \quad |\eta| = 0$$



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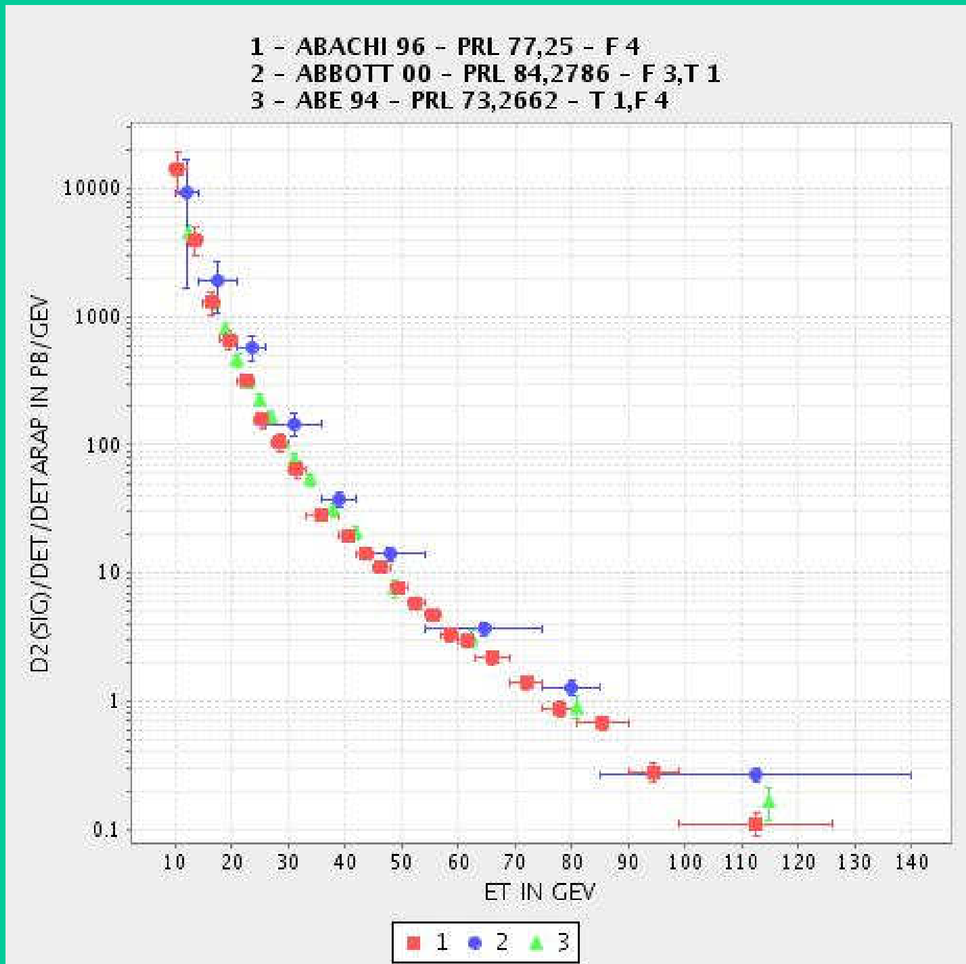
Tevatron Results Run I: $\sqrt{s}$ = 1800 GeV



- CDF 1994
- D0 1996

- D0 2000; Ecm=1.8 TeV L=107.6 pb^{-1}

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Direct Photon Production in pbar-p Collisions

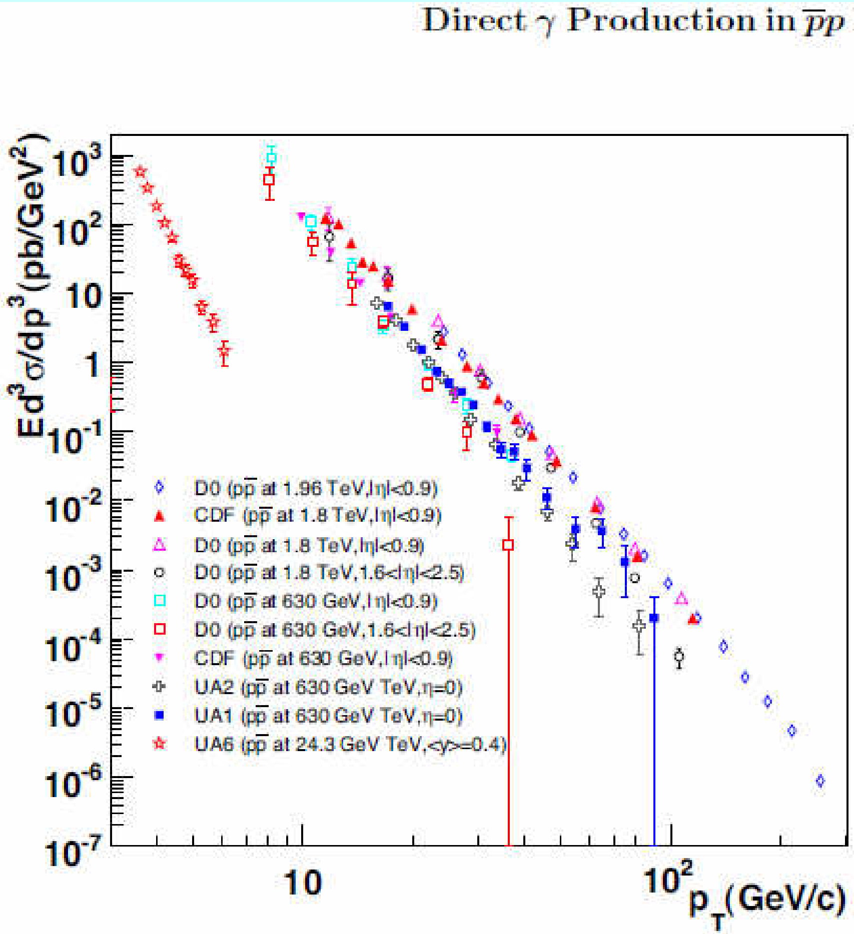


Figure 40.2: Isolated photon cross sections plotted as a function of the photon transverse momentum. The errors are either statistical only (CDF, D0 (1.96 TeV), UA1, UA2, UA6) or uncorrelated (D0 1.8 TeV, 630 GeV). The data are generally in good agreement with NLO QCD predictions, albeit with a tendency for the data to be above (below) the theory for lower (large) transverse momenta, Phys. Rev. **D59**, 074007 (1999). **D0**: Phys. Lett. **B639**, 151 (2006), Phys. Rev. Lett. **87**, 251805 (2001); **CDF**: Phys. Rev. **D65**, 112003 (2002); **UA6**: Phys. Lett. **B206**, 163 (1988); **UA1**: Phys. Lett. **B209**, 385 (1988); **UA2**: Phys. Lett. **B288**, 386 (1992). (Courtesy of J. Huston, Michigan State University, 2007)

source PDT rev 2009

• *A remarkable property:* x_T scaling

RF Cahalan, KA Geer,
JB Kogut and L Susskind,
Phys. Rev. **D11** (1975) 1199

$$E\frac{d^3\sigma}{dp^3} \approx \left(\sqrt{s}\right)^{-n} \times F\left(x_T\right)$$

where $$x_T = 2p_T/\sqrt{s}$$

shown in the figure is

$$\left(\sqrt{s}\right)^5 E\frac{d^3\sigma}{dp^3} \quad vs \quad x_T$$

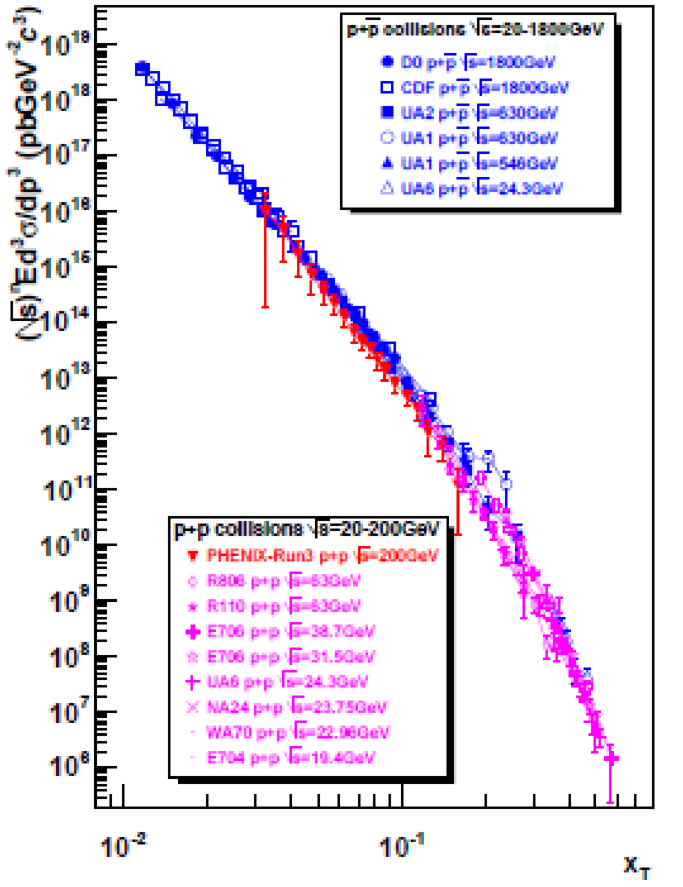
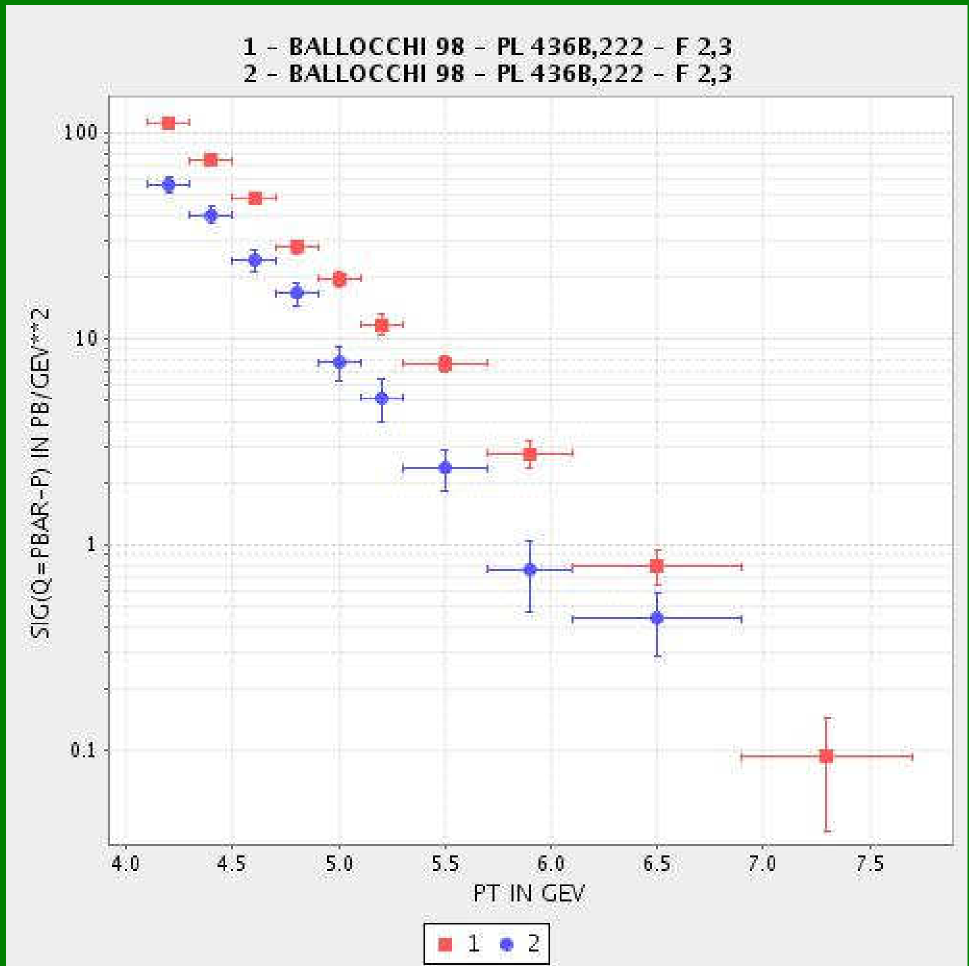


Figure 5.4: Cross section for prompt photon production $(\sqrt{s})^{5.0} \times E\frac{d^3\sigma}{dp^3}$ at $\sqrt{s}$ between 19.4 and 1800 GeV.

from Takuma Horaguchi, Thesis - PHENIX experiment

UA6 Ballochi 98 E_{LAB}=315 GeV ($\sqrt{s}$ = 24.3 GeV)



- $\bar{p}p \rightarrow \gamma X$
- $pp \rightarrow \gamma X$

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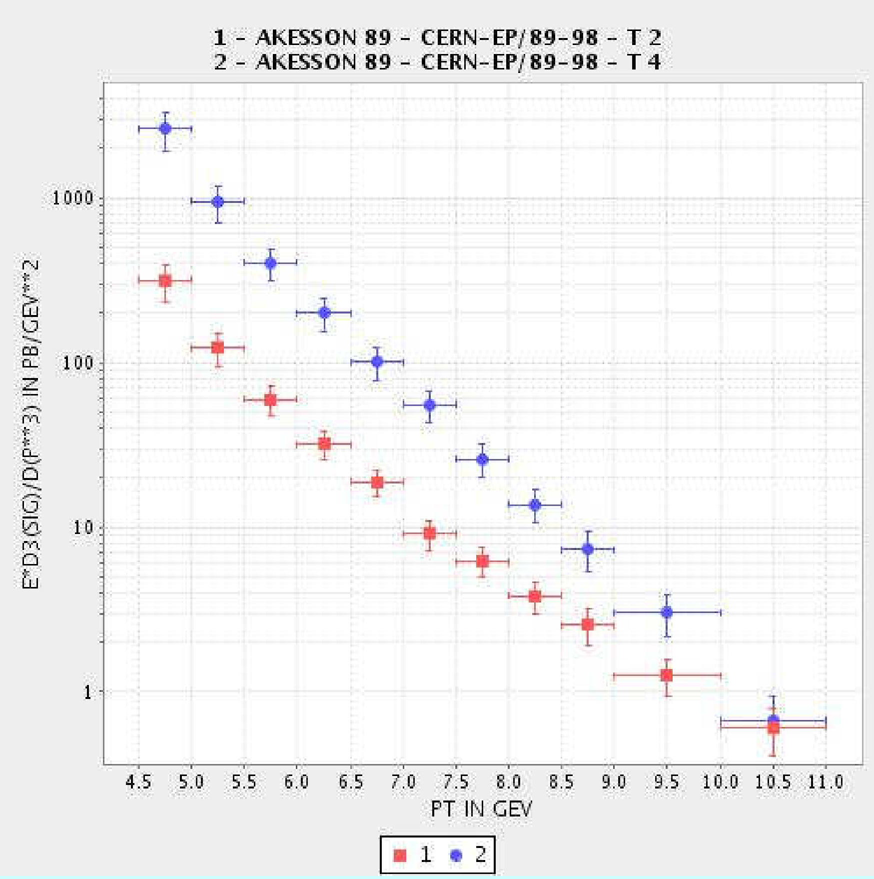
CERN ISR Experiment R807 (AFS)



- $pp \to \pi^0 X$
- $pp \to \gamma X$

this shows that there is an overwhelming background of π^0 production

Ref: Anassontzis et al. (AFS Coll.), Yad. Fiz. **51**(1990)1314 [Sov. J. Nucl. Phys. **51** (1990) 836]

source HEPDATA

• Photon isolation

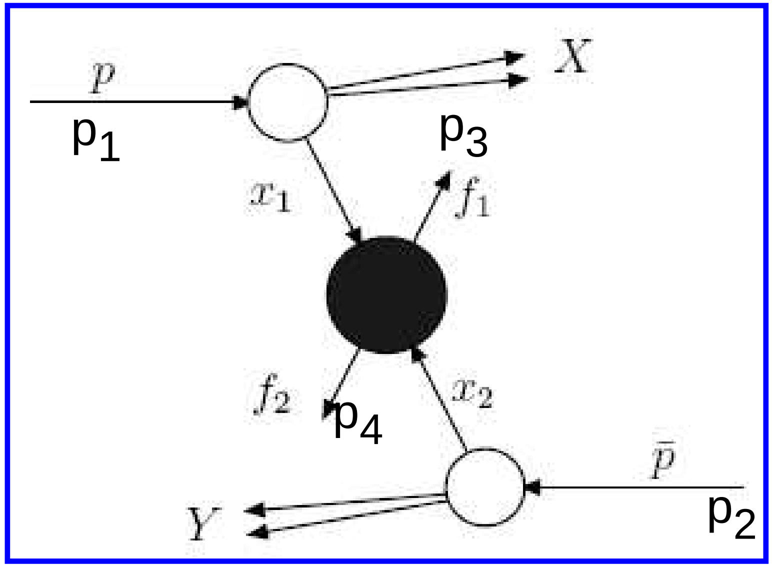
To suppress the background of unresolved photons from π^0 and η decay one applies an isolation condition in the event selection:

> the hadronic energy in a cone about the photon of half-opening angle δ in (φ,η) space should be less than a fraction ε of the photon energy.

The precise values of δ and ε are chosen by the experimentalists specifically for their experiment, but typically they are

$$\delta = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} \approx 0.5; \quad \varepsilon \approx 0.1$$

• Kinematics; I: basic definitions



$$s = (p_1 + p_2)^2 = (2E_{beam}^{CMS})^2$$

$$\hat{p}_1 = x_1 p_1; \qquad \hat{p}_2 = x_2 p_2$$

$$\hat{s} = (\hat{p}_1 + \hat{p}_2)^2 = x_1 x_2 s$$

$$= (\hat{p}_3 + \hat{p}_4)^2$$

$$\hat{t} = (\hat{p}_1 - \hat{p}_3)^2$$

$$\hat{u} = (\hat{p}_1 - \hat{p}_4)^2$$

$$massless\ quarks: \quad \hat{s} + \hat{t} + \hat{u} = 0$$

Kinematics; II: Rapidity and Pseudorapidity

Definition of rapidity:

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

$$for \quad p \gg m \quad and \quad \theta \gg m/E:$$

$$y = \frac{1}{2}\ln\frac{1+\cos\theta + m^2/4p^2 + \dots}{1-\cos\theta + m^2/4p^2 + \dots} \approx -\ln\tan\frac{\theta}{2} \equiv \eta$$

η **-** *pseudorapidity*

for LHC beam protons, neglecting terms of order (m/E)^4**,** we have:

$$y = \ln\frac{2E_{beam}}{m} = 9.6$$

(*cf*. Tevatron Run II (E_{beam}=0.98 TeV): y_{beam} = 7.6)

Feynman x

In colliders, the CMS four-momenta of incoming hadrons A and B are

$$p_A = (E, 0, 0, E), \quad p_B = (E, 0, 0, -E)$$ (E is beam energy)

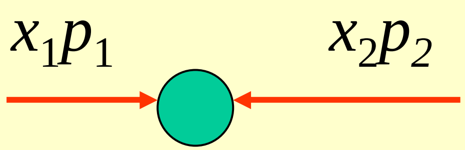
Total CMS energy squared: $$S = (p_A + p_B)^2 = 4E^2$$

incoming parton four-momenta: $$\hat{p}_1 = x_1 p_A,\ \hat{p}_2 = x_2 p_B; \quad x_{1,2} \in [0,1]$$

Longitudinal momentum of the parton pair: $$\hat{p}_z = \hat{p}_{1z} + \hat{p}_{2z} = (x_1 - x_2) E$$

Feynman x $$x_F \equiv \hat{p}_z / E = (x_1 - x_2) \in [-1,1]$$

• Reconstruction of Event Kinematics



$$\hat{p} \equiv x_1 p_1 + x_2 p_2$$
$$= x_1 (E, 0, 0, E) + x_2 (E, 0, 0, -E)$$
$$= E (x_1 + x_2, 0, 0, x_1 - x_2)$$

rapidity of the intermediate state:

$$y = \frac{1}{2} \ln \frac{x_1}{x_2}, \quad \therefore \; \frac{x_1}{x_2} = e^{2y}$$

and hence with

$$x_1 x_2 = \hat{s}/s$$

we get

$$x_{1,2} = \sqrt{\hat{s}/s}\; e^{\pm y}$$

from the measured four-momenta of the prompt photon and associated jet we get

$$\hat{s} \quad and \quad x_F$$

and hence using

$$\tau \equiv \hat{s}/s = x_1 x_2; \qquad x_F \equiv \hat{p}_z/E = x_1 - x_2$$

we get x_1 and x_2:

$$x_1 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\tau} + x_F\right), \qquad x_2 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\tau} - x_F\right)$$

• Observable: invariant cross section

hadronic process: $A+B \to \gamma + X$

partonic (hard) subprocess: $a+b \to \gamma + c$

then the invariant cross section is

$$E\frac{d^3\sigma}{dp^3} = \frac{4}{\pi}\sum_a \int_{x_1}^{1} \frac{dx_a}{2x_a - x_T} F_{a/A}\left(x_a, Q^2\right) F_{b/B}\left(x_b, Q^2\right) \frac{d\hat{\sigma}\left(ab \to c\gamma\right)}{d\hat{t}}$$

where

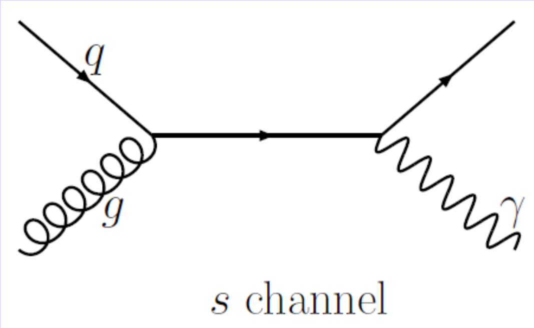
$$x_T = \frac{2p_T}{\sqrt{s}}, \quad x_b = x_T \frac{x_a}{2x_a - x_T}, \quad x_1 \equiv x_a^{\min} = \frac{x_T}{2 - x_T}$$

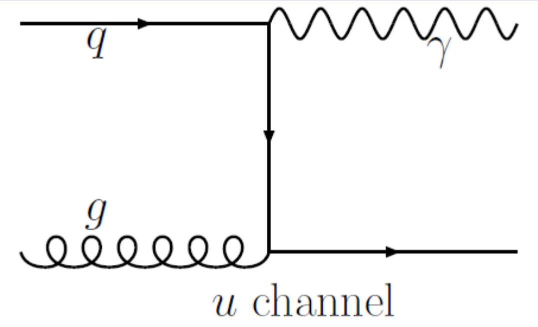
and

$$\hat{s} = x_a x_b s, \quad \hat{t} = -\frac{1}{2} x_a x_T s, \quad \hat{u} = -\frac{1}{2} x_b x_T s,$$

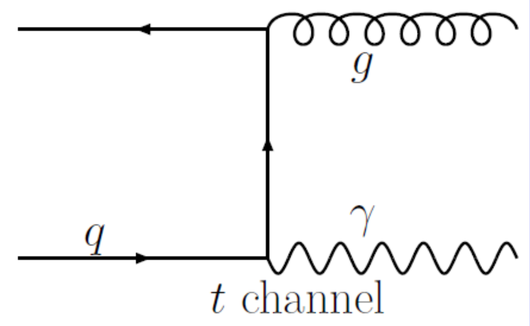
• The Hard Subprocesses of dpp in LO

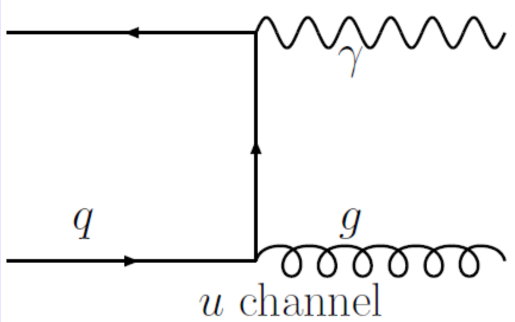
QCD Compton effect:





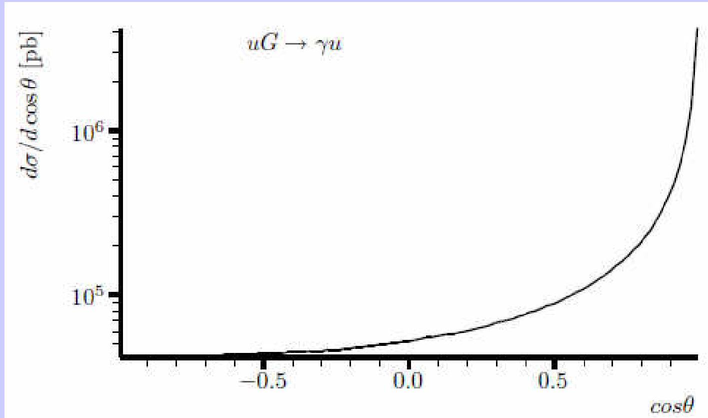
$q\bar{q}$ annihilation:



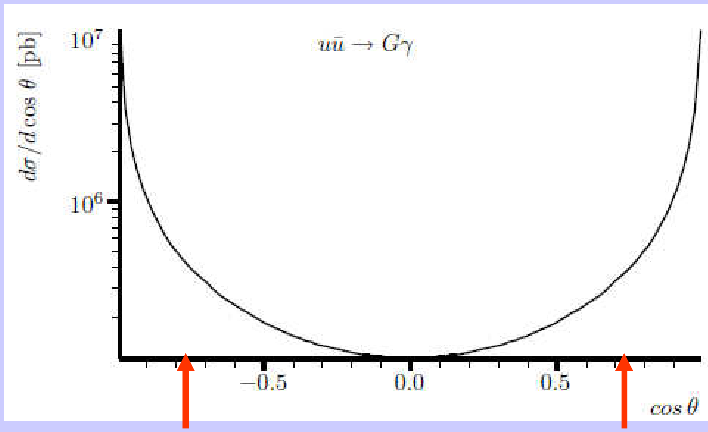


Formulas and plots of direct photon production differential cross sections in LO
(the plots were produced using CompHEP)

$$qg \rightarrow q\gamma: \quad \frac{1}{3} e_q^2 \left(\frac{-u}{s} + \frac{s}{-u} \right)$$



$$q\bar{q} \rightarrow g\gamma: \quad \frac{8}{9} e_q^2 \left(\frac{u}{t} + \frac{t}{u} \right)$$



Note: cosθ=0.76 corresponds to η=1
and cosθ=0.96 to η=2

the complete expressions for the differential cross sections of the hard subprocesses are

$$\frac{d\hat{\sigma}(qg \to \gamma q)}{d\hat{t}} = e_q^2 \frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2} \frac{\hat{s}^2 + \hat{u}^2}{-\hat{s}\hat{u}}$$

$$\frac{d\hat{\sigma}(q\bar{q} \to \gamma g)}{d\hat{t}} = e_q^2 \frac{8\pi\alpha\alpha_s(Q^2)}{9\hat{s}^2} \frac{\hat{t}^2 + \hat{u}^2}{\hat{t}\hat{u}}$$

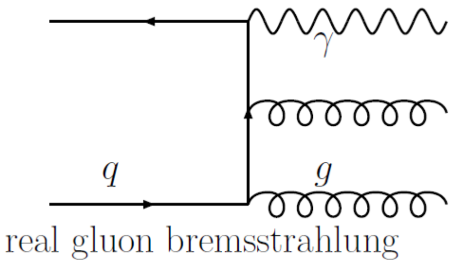
fn of cosθ

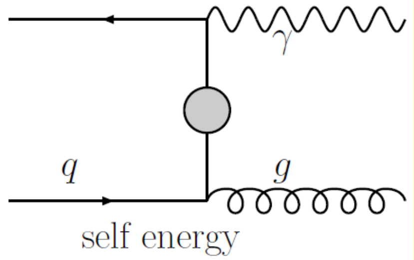
There is a famous ambiguity in the definition of Q^2:

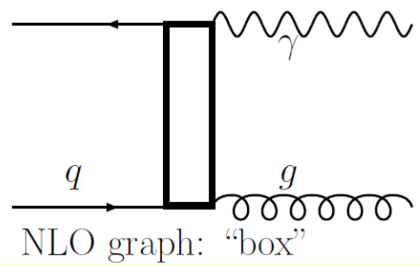
$$(i)\, Q^2 = -\hat{t}, \quad (ii)\, Q^2 = 2\hat{s}\hat{t}\hat{u}\big/\left(\hat{s}^2 + \hat{t}^2 + \hat{u}^2\right), \quad (iii)\, Q^2 = 2p_T^2$$

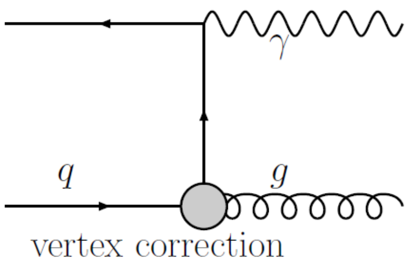
((*ii*) was favoured by Feynman)

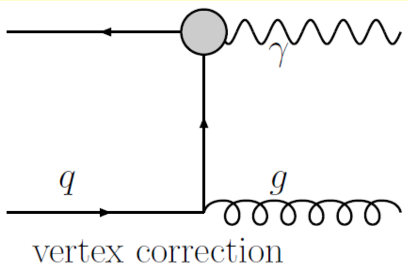
• NLO amplitudes of direct photon production











and similar NLO graphs in QCD Compton scattering

Real gluon bremsstrahlung gives rise to an experimental difficulty:

kinematically it is possible for the additional gluon to travel close to the photon and thereby violate the isolation criterion

hence we lose a good direct photon!

there is an obvious need to control this difficulty theoretically.

•JETPHOX: the state-of-the-art program of dpp

JETPHOX is a program to calculate direct photon (or hadron) + jet production cross sections in NLO (*JHEP 0205:028*, *2002*)

Authors: P. Aurenche, T. Binot, M. Fontannaz, J.-Ph. Guillet, G. Heinrich, E. Pilon, and M. Werlen

http://wwwlapp.in2p3.fr/lapth/PHOX-FAMILY/main.html the inclusive direct photon production cross section can be obtained within JETPHOX by integrating over the jet.

you can choose any set of parton density functions from PDFLIB

(by default: MRST99, MRST01, CTEQ5 and CTEQ6)

to date JETPHOX is probably the most advanced program of its kind

it is widely used by experimentalists to compare data with theory.

but do NOT use it blindly: read the **WARNINGS** supplied on their web site!

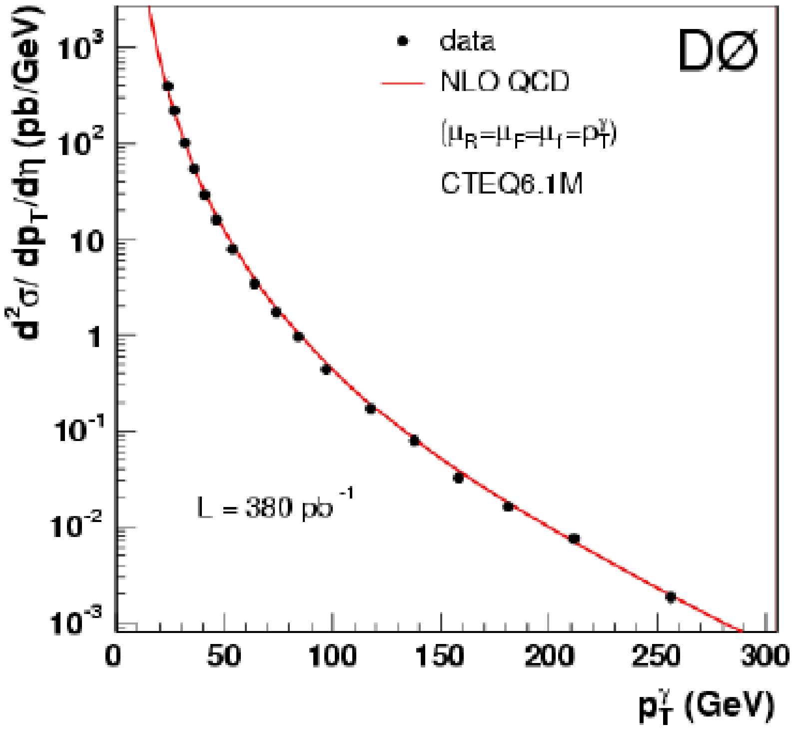
PHOX Warnings

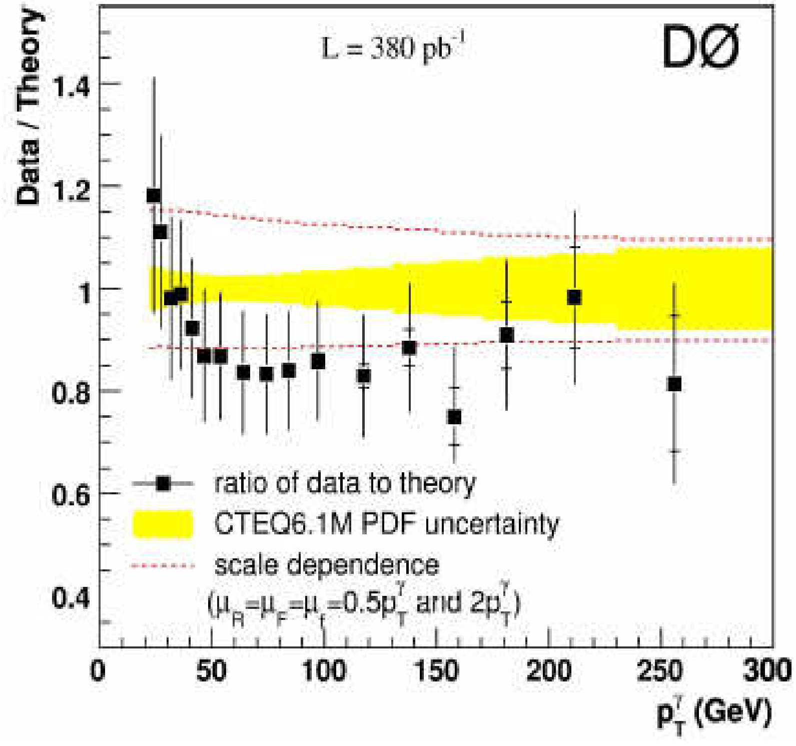
- “The PHOX codes ARE NOT FULL EVENT GENERATORS”.

- “The PHOX codes do not provide a full, exclusive portrait of events which could for example be further processed through a detector simulation”.

• Comparison of D0 data with JETPHOX calculation

from “Photon + jet measurements at D0”
(D. Bandurin, Talk on behalf of D0 Collaboration at CIPAND 2009)





Conclusions to draw from D0 data vs. JETPHOX

- There is a systematic discrepancy between data and JETPHOX
- Experiment is faulty?

  no, I think they are too smart

- JETPHOX is still rather less than perfect?

  no, I think they are too good

- New physics?

  that's not where we'd look for it

- The WARNINGS of the JETPHOX authors were not heeded?

  *well, can **you** think of an alternative?*

- Take your pick, BUT

  whichever it is: there is room for improvement.

• Relative contributions of QCD Compton and quark-antiquark annihilation

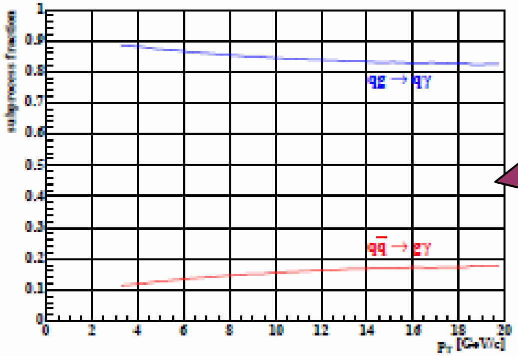


Figure 2.10: The fraction of $gq \to \gamma q$ and $q\bar{q} \to \gamma g$ as function of p_T in $p+p$ at $\sqrt{s} = 200$GeV.

fraction of $qg \to \gamma q$ and $q\bar{q} \to \gamma g$
in pp collisions at $\sqrt{s} = 200\,GeV$

fraction of $qg \to \gamma q$ and $q\bar{q} \to \gamma g$
in $\bar{p}p$ *collisions at* $\sqrt{s} = 200\,GeV\,(left)$
and $\sqrt{s} = 1800\,GeV\,(right)$

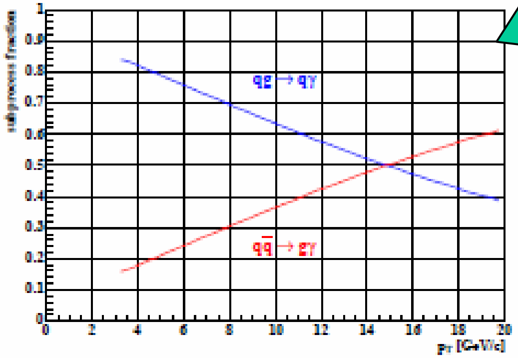


Figure 2.11: The fraction of $gq \to \gamma q$ and $q\bar{q} \to \gamma g$ as function of p_T in $p+\bar{p}$ at $\sqrt{s} = 200$GeV.

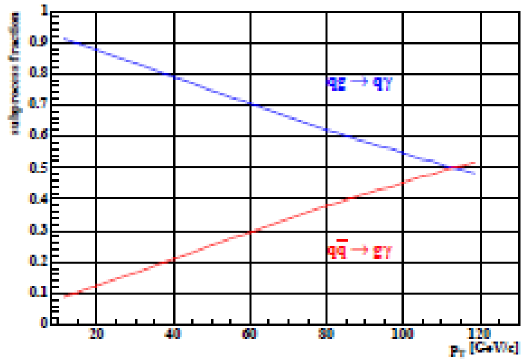
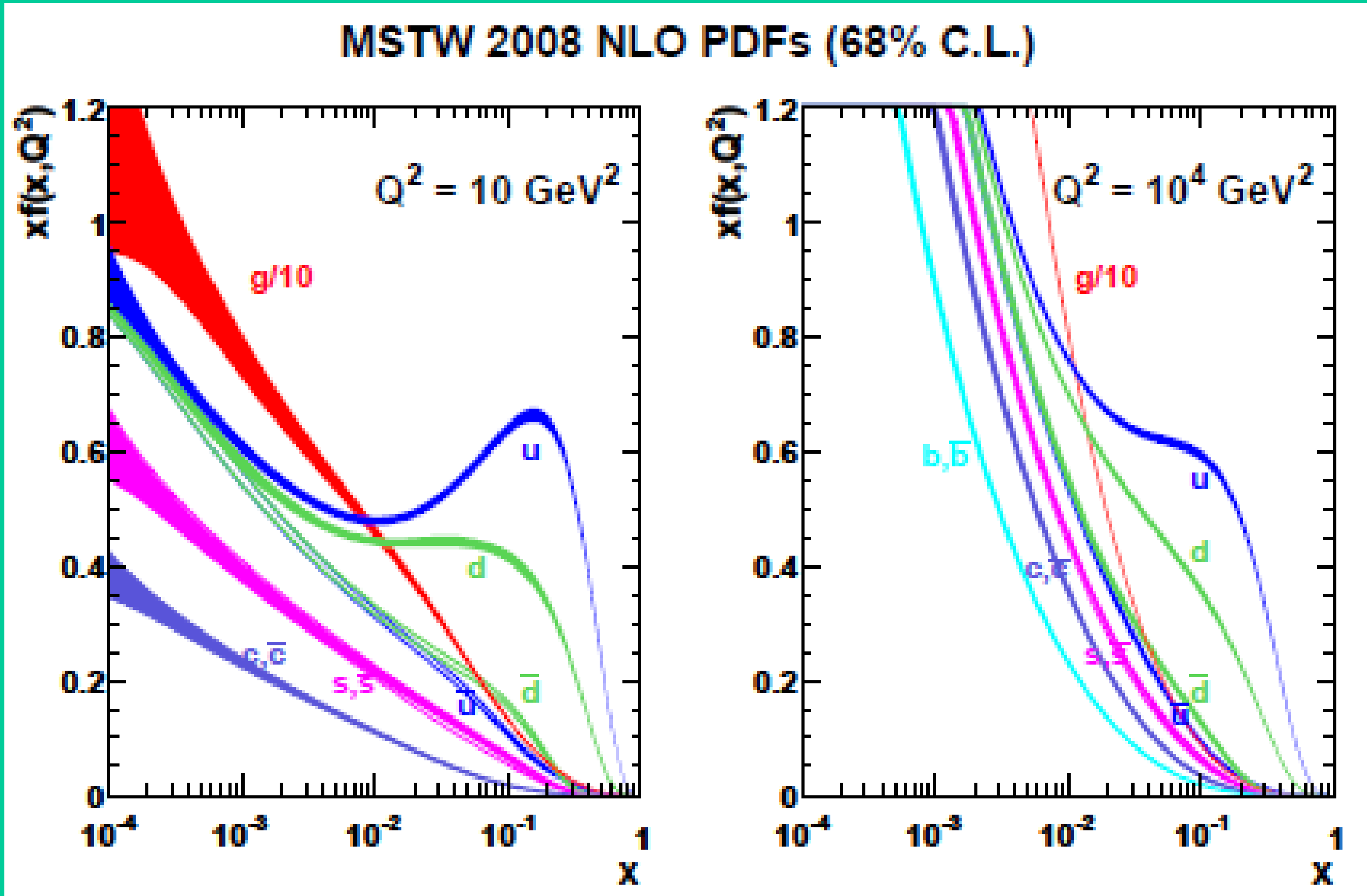


Figure 2.12: The fraction of $gq \to \gamma q$ and $q\bar{q} \to \gamma g$ as function of p_T in $p+\bar{p}$ at $\sqrt{s} = 1800$GeV.

from Takuma Horaguchi (Thesis - PHENIX experiment)

• Parton Density Functions



from HEPDATA

Summary and Conclusions

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