Photons and the PDFs

Confronting Theory with Experiment: Puzzles, Challenges & Opportunities in the LHC Era

Fermilab, 17-18th November 2011

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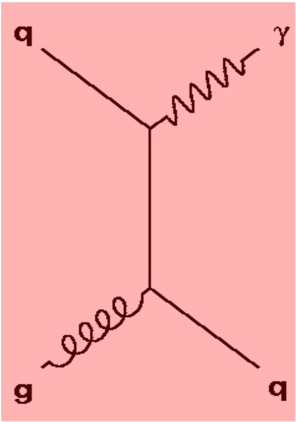
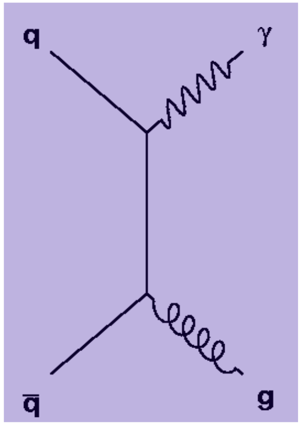
CERN

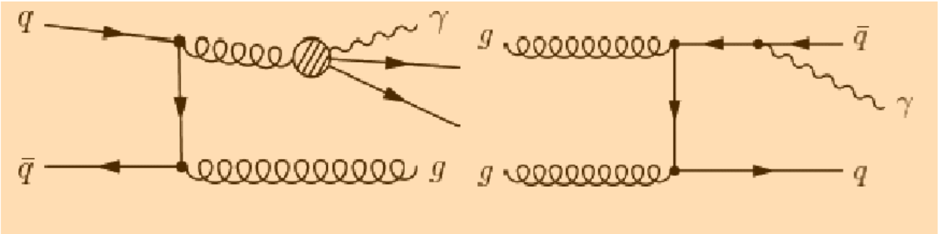
Prompt γ production in hadronic collisions

- Leading-order partonic production processes in p-p, p-p̄ collisions :

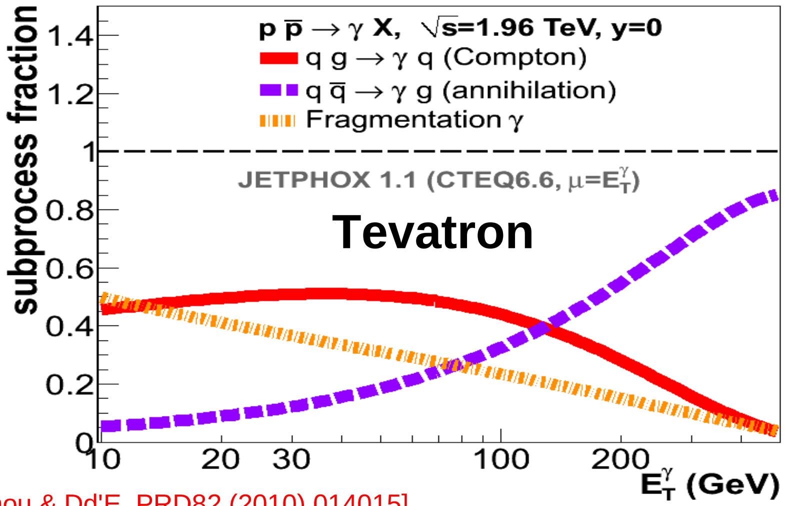


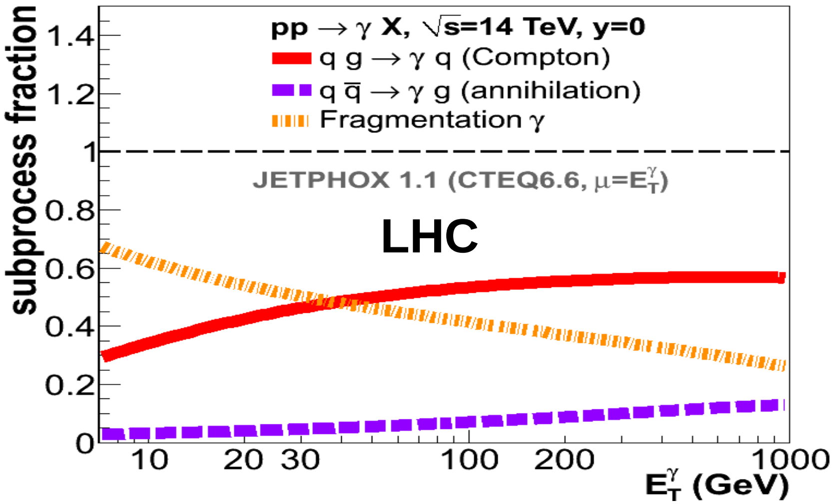


+ parton-to-photon fragmentation:



- Relative subprocess fractions (NLO): Important fragmentation contribution

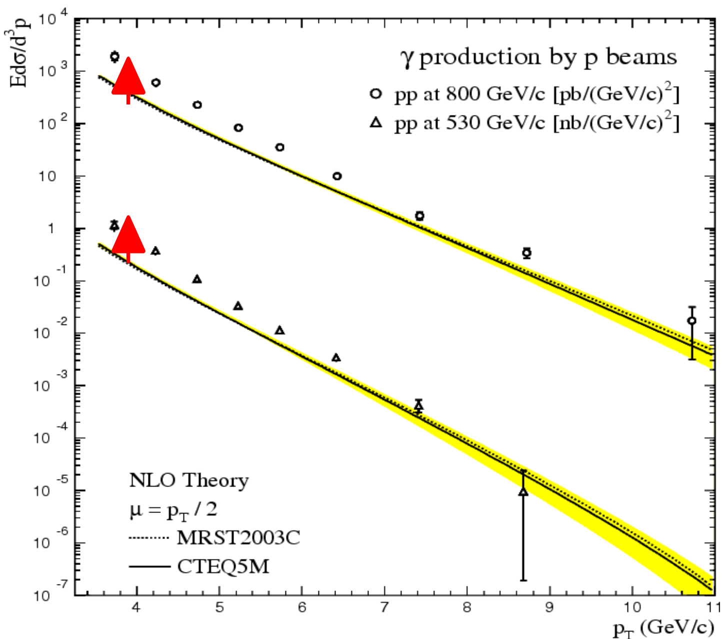




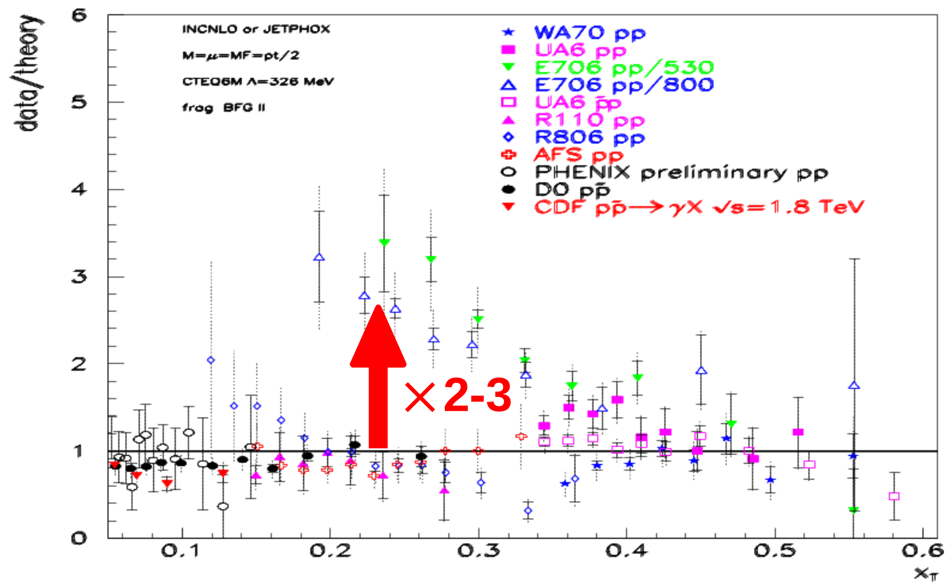
[R.Ichou & Dd'E, PRD82 (2010) 014015]

Prompt γ production in hadronic collisions

- Long-standing disagreement between NLO pQCD & fixed-target inclusive photon data (p-p, p-A @ √s~20-40 GeV):



[L. Apanasevich et al.'04 - E706]



[P.Aurenche et al.'06]
[Also Owens, Vogelsang, ...]

- Not solved by (N)NNL soft-gluon threshold & recoil resummations:
  Low p_T dominated by intrinsic-k_T ? parton-to-γ FF ? nuclear target effects ?

- "Conclusion": Photons removed from global PDF fits (used to constrain high-x gluon) since MRST99 !

Redeeming γ data for PDF global fits

- Does NLO reproduce the existing photon data ... ? Yes !

  ✔ Applying isolation cuts: remove most fragmentation γ 's

  ✔ Moving to collider energies: higher pQCD scales

- Are they useful for PDF constraints ... ? Yes !

  ✔ 30+ meas., 350+ data points = direct access to gluon PDF !

  [$xg(x,Q^2)$ only indirectly constrained by F_2 scaling violations & directly at large-x by Tevatron jets]

- How can one quantify the inclusion of isolated-γ into PDF fits ?

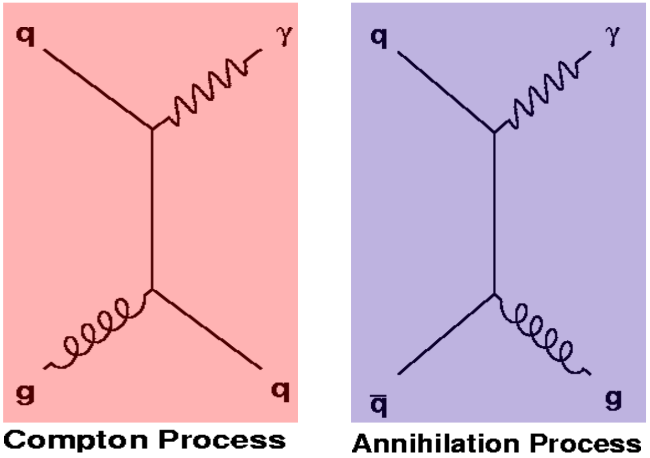
(1) Including γ data & full refitting all data-sets: (very) slow NLO code ...

(2) "A posteriori" inclusion via fastNLO or ApplGrid: not implemented yet

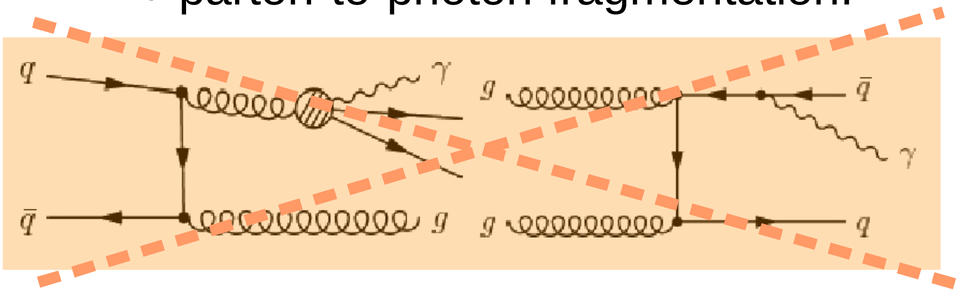
(3) Using NNPDF "reweighting" technique ✔

Isolated γ production in hadronic collisions

- Leading partonic production processes in p-p, p-p collisions :

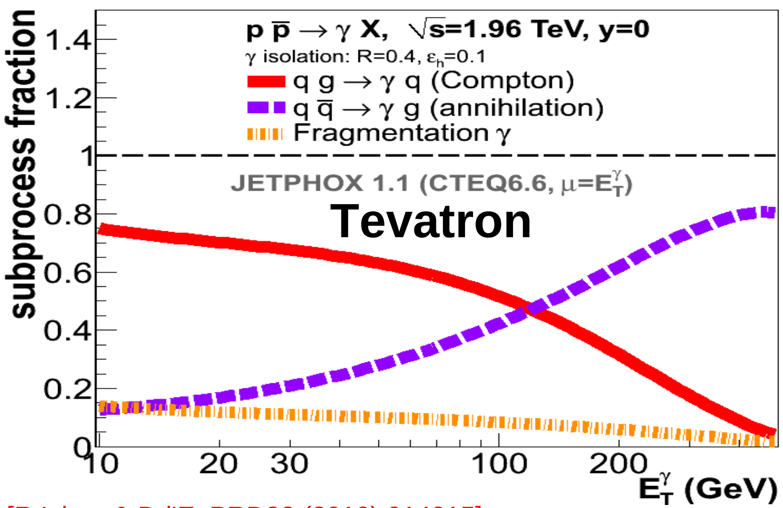


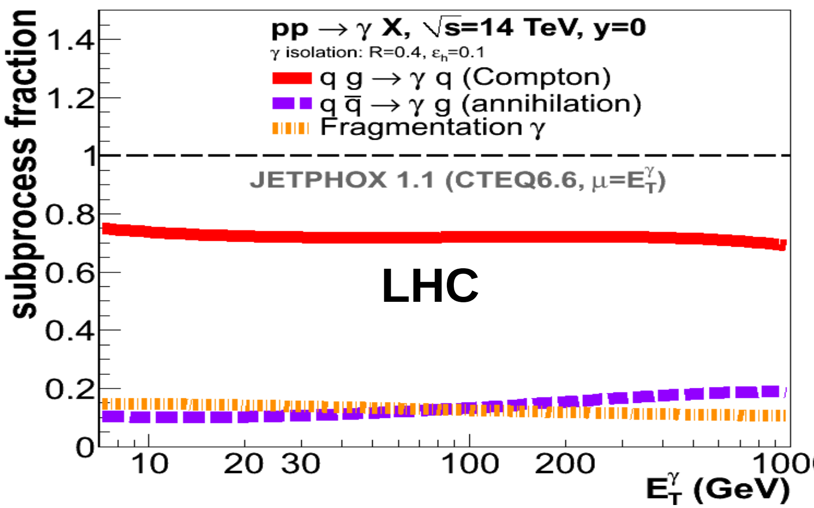
+ parton-to-photon fragmentation:



Isolation cuts (e.g. R=0.4, $E_{T,had}$<5 GeV)

- Quark-gluon Compton scattering dominates now (~80%) x-sections:



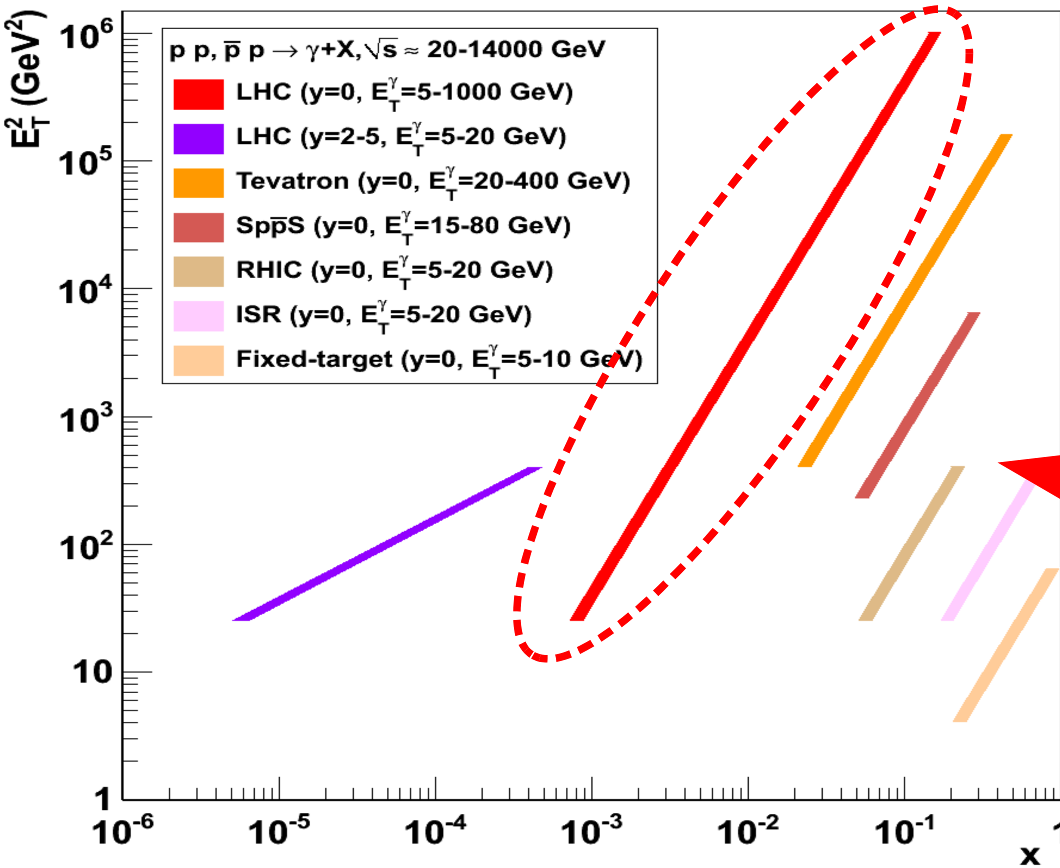


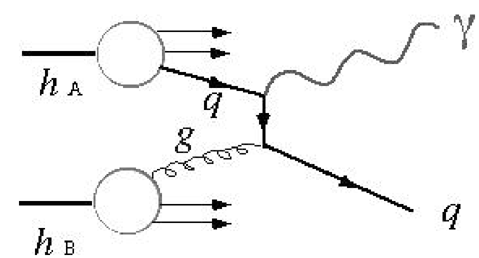
[R.Ichou & Dd'E, PRD82 (2010) 014015]

(x,Q^2) map of collider isolated- γ data-sets

[R.Ichou & D.d'E, PRD82 (2010) 014015]

- Kinematical range of LHC, Tevatron, Sp$\bar{p}$S & RHIC γ_{isol} data:

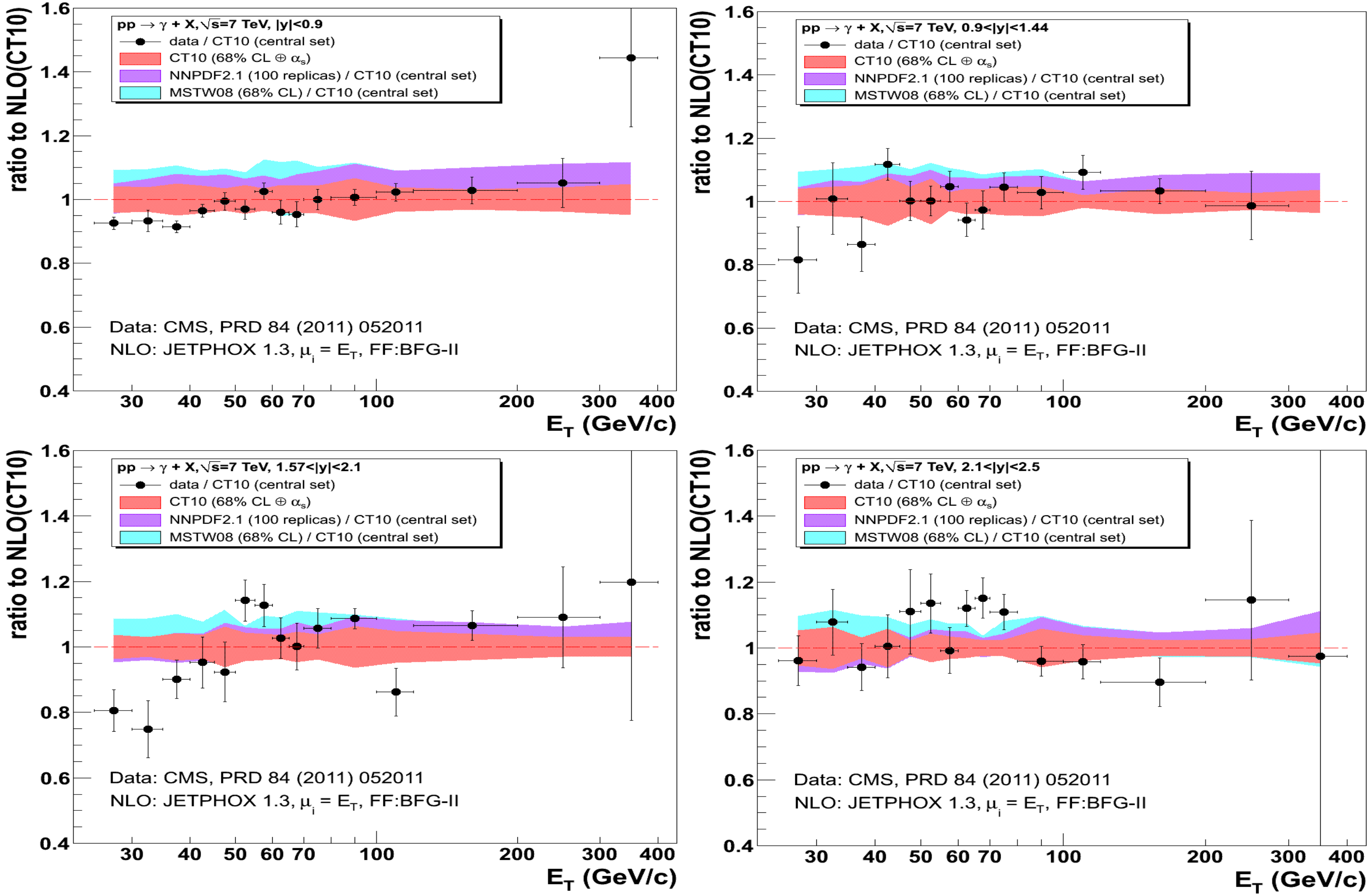




- Direct sensitivity to gluon PDF over wide (x,Q^2) domain

[$xG(x,Q^2)$ only constrained indirectly by DIS & directly at large-x by Tevatron jets]

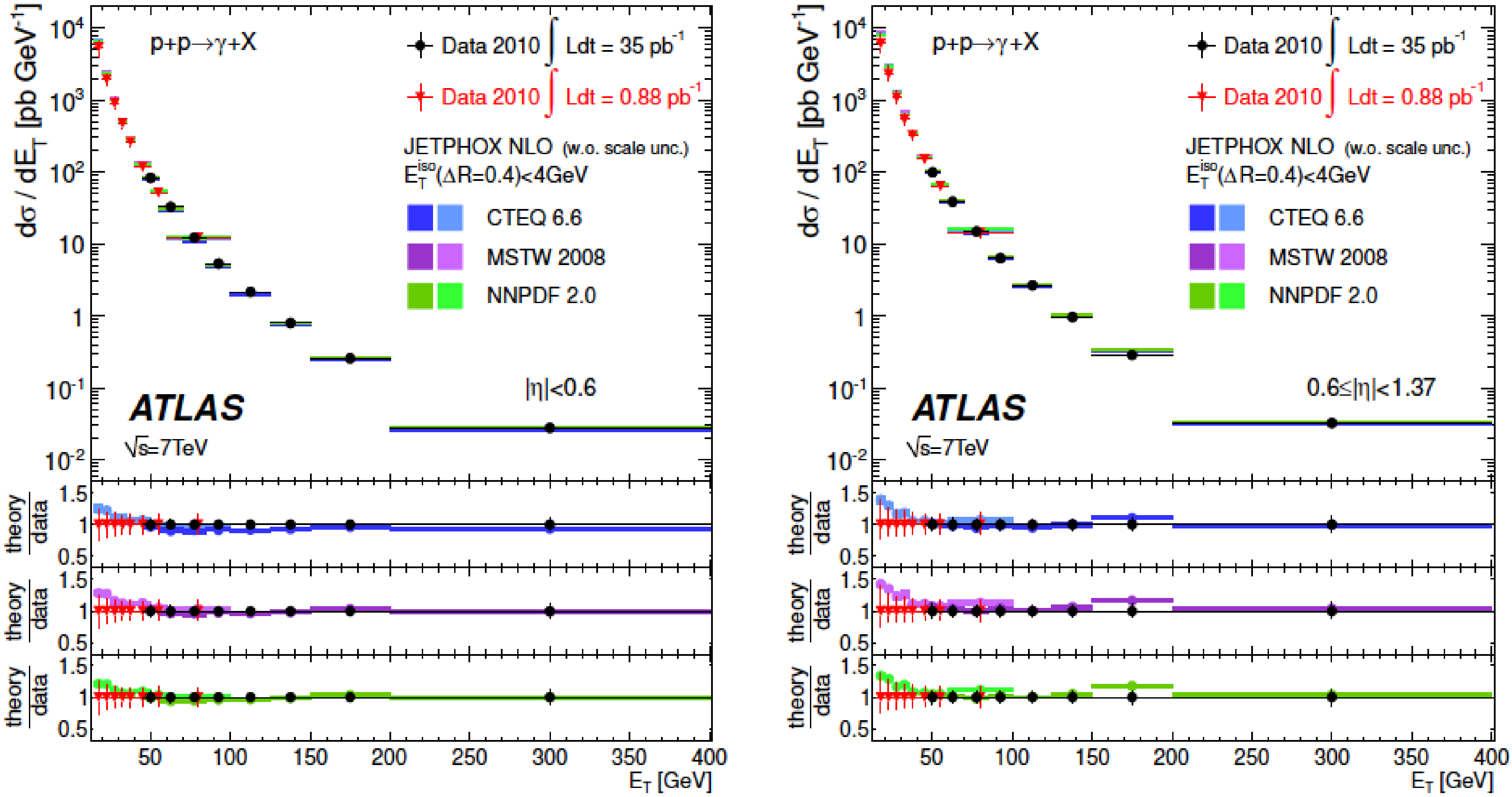
$pp \rightarrow \gamma_{iso}$+X at 7 TeV (CMS) vs NLO (3 PDFs)



- Very good agreement data-NLO at barrel & endcap rapidities.

pp → γ_{iso}+X at 7 TeV (ATLAS) vs NLO (3 PDFs)

ATLAS data: PRD 83 (2011) 052005
arXiv:1108.0253



- Very good agreement data-NLO (slight overprediction at E_T<50 GeV/c ?)
  - Typical systematic uncertainties: ~20 – 7%
  - Theory uncertainties: Scales = 15 – 10%; PDF diffs. = 5 – 10%

Isolated- γ collider world-data (I)

- 30 meas. (350 data points) at LHC/Tevatron/SppS/RHIC & increasing ...

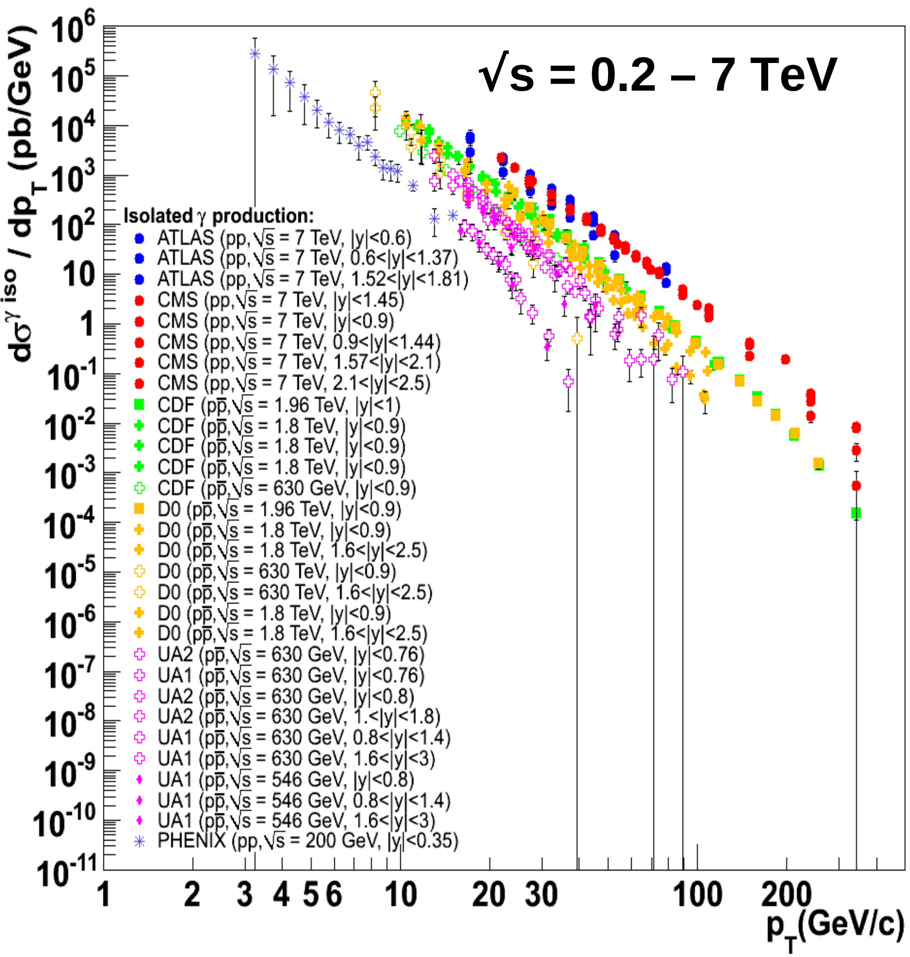
System	Collab./Exp. (collider)	$\sqrt{s}$ (GeV)	Ref.	y (c.m.)	p_T range (GeV/c)	Number of points	Isolation
p-$p \to \gamma_{isol} + X$	ATLAS (LHC)	7000.	(Aad *et al.*, 2010) [3]	-0.6 – 0.6	15. – 100.	8	$R = 0.4$, $E_h < 5$ GeV
p-$p \to \gamma_{isol} + X$	ATLAS (LHC)	7000.	(Aad *et al.*, 2010) [3]	0.6 – 1.37	15. – 100.	8	$R = 0.4$, $E_h < 5$ GeV
p-$p \to \gamma_{isol} + X$	ATLAS (LHC)	7000.	(Aad *et al.*, 2010) [3]	1.52 – 1.81	15. – 100.	8	$R = 0.4$, $E_h < 5$ GeV
p-$p \to \gamma_{isol} + X$	CMS (LHC)	7000.	(Khatrchyan *et al.*, 2010) [1]	-1.45 – 1.45	21. – 300.	11	$R = 0.4$, $E_h < 5$ GeV
p-$p \to \gamma_{isol} + X$	CMS (LHC)	7000.	(Khatrchyan *et al.*, 2011) [2]	-0.9 – 0.9	25. – 400.	15	$R = 0.4$, $E_h < 5$ GeV
p-$p \to \gamma_{isol} + X$	CMS (LHC)	7000.	(Khatrchyan *et al.*, 2011) [2]	0.9 – 1.44	25. – 400.	15	$R = 0.4$, $E_h < 5$ GeV
p-$p \to \gamma_{isol} + X$	CMS (LHC)	7000.	(Khatrchyan *et al.*, 2011) [2]	1.57 – 2.1	25. – 400.	15	$R = 0.4$, $E_h < 5$ GeV
p-$p \to \gamma_{isol} + X$	CMS (LHC)	7000.	(Khatrchyan *et al.*, 2011) [2]	2.1 – 2.5	25. – 400.	15	$R = 0.4$, $E_h < 5$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	CDF (Tevatron)	1960.	(Aaltonen *et al.*, 2009) [4]	-1.0 – 1.0	30. – 400.	16	$R = 0.4$, $\varepsilon_h = 0.1$
p-$\bar{p} \to \gamma_{isol} + X$	D0 (Tevatron)	1960.	(Abazov *et al.*, 2005) [5]	-0.9 – 0.9	23. – 300.	17	$R = 0.4$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	CDF (Tevatron)	1800.	(Abe *et al.*, 1994) [6]	-0.9 – 0.9	8. – 132.	16	$R = 0.7$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	CDF (Tevatron)	1800	(Acosta *et al.*, 2002) [7]	-0.9 – 0.9	11. – 132.	17	$R = 0.4$, $E_h < 4$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	CDF (Tevatron)	1800	(Acosta *et al.*, 2004) [8]	-0.9 – 0.9	10. – 65.	17	$R = 0.4$, $E_h < 1$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	D0 (Tevatron)	1800.	(Abachi *et al.*, 1996) [9]	-0.9 – 0.9	9.0 – 126.	23	$R = 0.4$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	D0 (Tevatron)	1800.	(Abachi *et al.*, 1996) [9]	1.6 – 2.5	9.0 – 126.	23	$R = 0.4$ $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	D0 (Tevatron)	1800.	(Abbott *et al.*, 1999) [10]	-0.9 – 0.9	10. – 140.	9	$R = 0.4$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	D0 (Tevatron)	1800.	(Abbott *et al.*, 1999) [10]	1.6 – 2.5	10. – 140.	9	$R = 0.4$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	CDF (Tevatron)	630	(Acosta *et al.*, 2002) [7]	-0.9 – 0.9	8. – 38.	7	$R = 0.4$, $E_h < 4$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	D0 (Tevatron)	630	(Abazov *et al.*, 2001) [11]	-0.9 – 0.9	7.0 – 50.	7	$R = 0.4$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	D0 (Tevatron)	630	(Abazov *et al.*, 2001) [11]	1.6 – 2.5	7.0 – 50.	7	$R = 0.4$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA1 (Sp$\bar{p}$S)	630.	(Albajar *et al.*, 1988) [12]	-0.8 – 0.8	16. – 100.	16	$R = 0.7$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA1 (Sp$\bar{p}$S)	630.	(Albajar *et al.*, 1988) [12]	0.8 – 1.4	16. – 70.	10	$R = 0.7$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA1 (Sp$\bar{p}$S)	630.	(Albajar *et al.*, 1988) [12]	1.6 – 3.	16. – 70.	13	$R = 0.7$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA2 (Sp$\bar{p}$S)	630.	(Alitti *et al.*, 1992) [14]	-0.76 – 0.76	14. – 92.	13	$R = 0.265$, $\varepsilon_h = 0.25$
p-$\bar{p} \to \gamma_{isol} + X$	UA2 (Sp$\bar{p}$S)	630.	(Ansari *et al.*, 1988) [13]	-0.76 – 0.76	12. – 83.0	14	$R = 0.25$, $E_h < 0.1$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA2 (Sp$\bar{p}$S)	630.	(Ansari *et al.*, 1988) [13]	1.0 – 1.8	12. – 51.	8	$R = 0.53$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA1 (Sp$\bar{p}$S)	546.	(Albajar *et al.*, 1988) [12]	-0.8 – 0.8	16. – 51.	6	$R = 0.7$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA1 (Sp$\bar{p}$S)	546.	(Albajar *et al.*, 1988) [12]	0.8 – 1.4	16. – 46.	5	$R = 0.7$, $E_h < 2$ GeV
p-$\bar{p} \to \gamma_{isol} + X$	UA1 (Sp$\bar{p}$S)	546.	(Albajar *et al.*, 1988) [12]	1.6 – 3.	16. – 38.	5	$R = 0.7$, $E_h < 2$ GeV
p-$p \to \gamma_{isol} + X$	PHENIX (RHIC)	200.	(Adler *et al.*, 2006) [15]	-0.35 – 0.35	3.0 – 16.0	17	$R = 0.5$, $\varepsilon_h = 0.1$

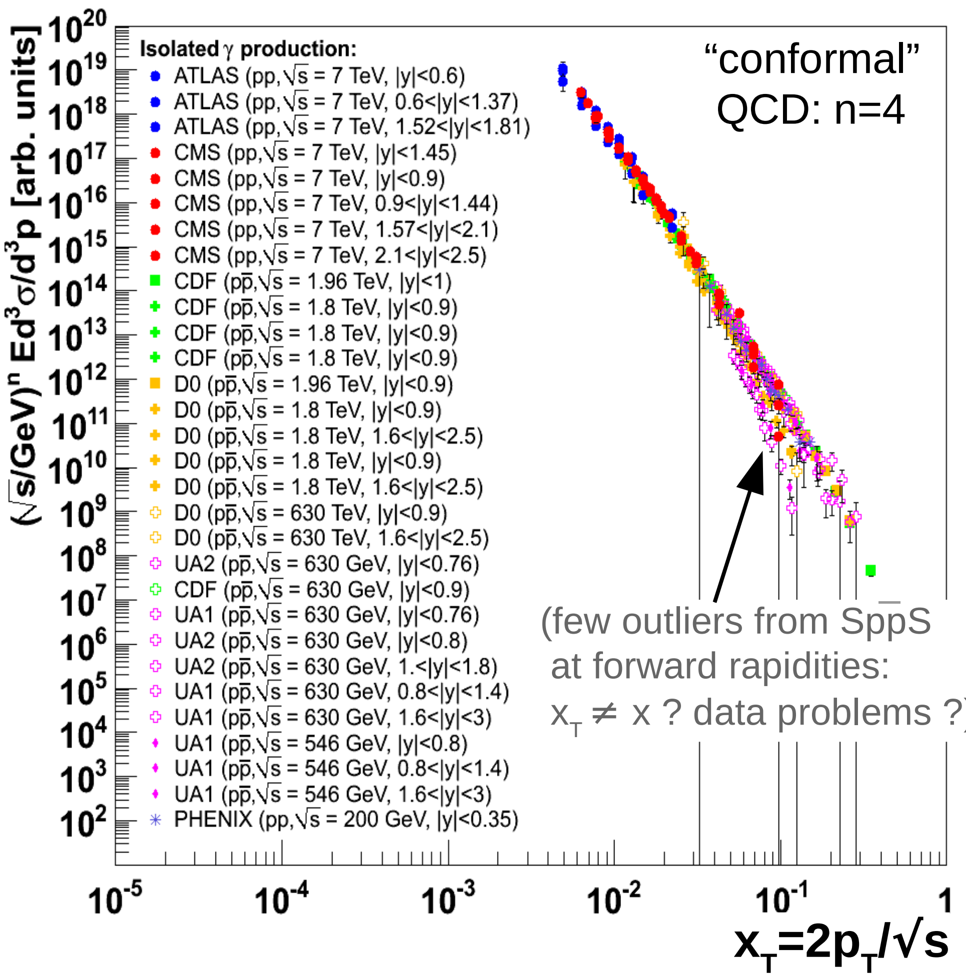
Isolated-γ collider world-data (II)

[D.d'E & R.Ichou, HEP-EPS'11 Proceeds.]

- LHC/Tevatron/Sp$\bar{p}$S/RHIC
  power-law p_T spectra
  within ~4 – 400 GeV/c

- x_T-scaled cross sections:
  power slope n=4.5
  (pQCD tell-tale behaviour)





Theoretical setup: JETPHOX NLO + NNPDF2.1

- JETPHOX 1.3.0 NLO pQCD code.
- NNPDF21_100.LHgrid (100 replicas) interfaced via LHAPDF5.8.5
- BFG-II parton-to-photon FFs (but suppressed by isolation cuts).
- All scales set to default: $\mu_R = \mu_F = \mu_{FF} = E_T^\gamma$
- Exp. kinematics+isolation cuts & p_T binnings for 30+ systems:

  100 replicas direct-γ NLO: ~ 7h CPU / 1M evts (~5 days for 20 Mevts !)

  100 replicas frag-γ NLO: ~10h CPU / 1M evts (~1 week for 20 Mevts !)

  ×30 !

- NNPDF2.1 "reweighting technique": **[R.D.Ball et al. NPB 849 (2011) 112]**

(1) Compute $d\sigma_{NLO}/dp_T$ for 100 replicas

(2) Perform χ^2 analysis $d\sigma_{EXP}/dp_T$ vs $d\sigma_{NLO}/dp_T$ for each replica.

(3) Obtain associated "weight" for each replica:

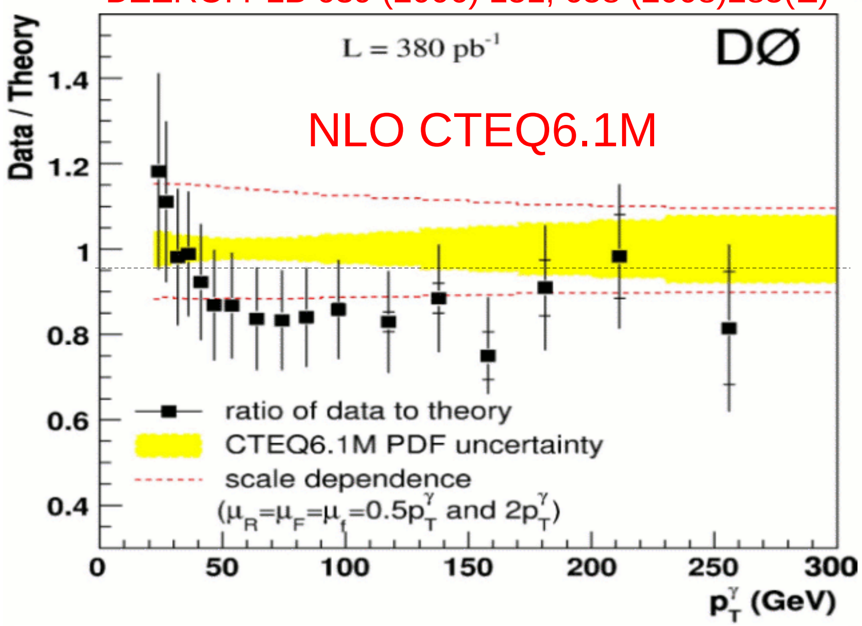
$$w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}{\frac{1}{N}\sum_{k=1}^{N}(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}$$

(4) Obtain reweighted PDF replicas:

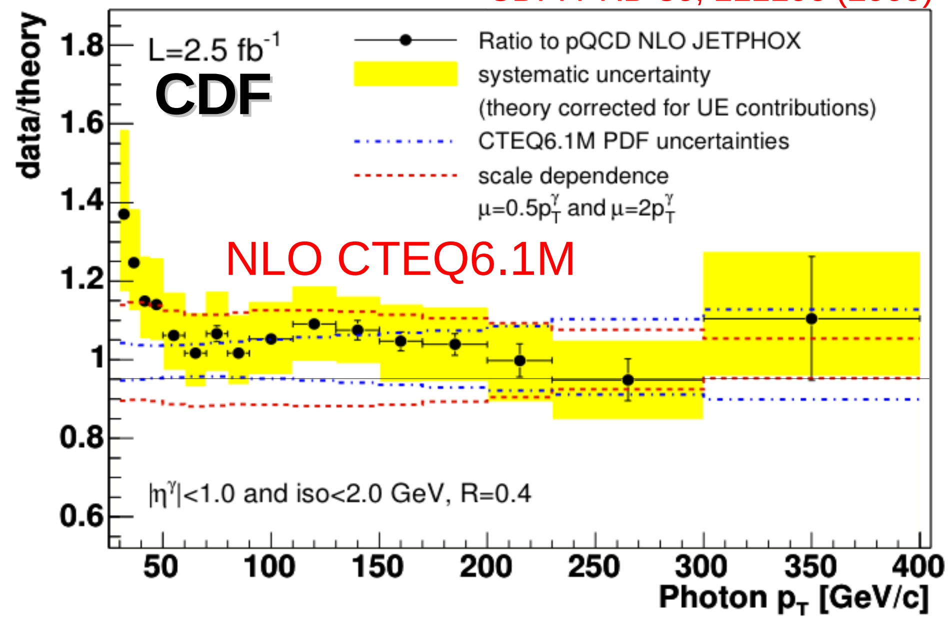
$$\langle \mathcal{O} \rangle_{\mathrm{new}} = \frac{1}{N}\sum_{k=1}^{N} w_k \mathcal{O}[f_k]$$

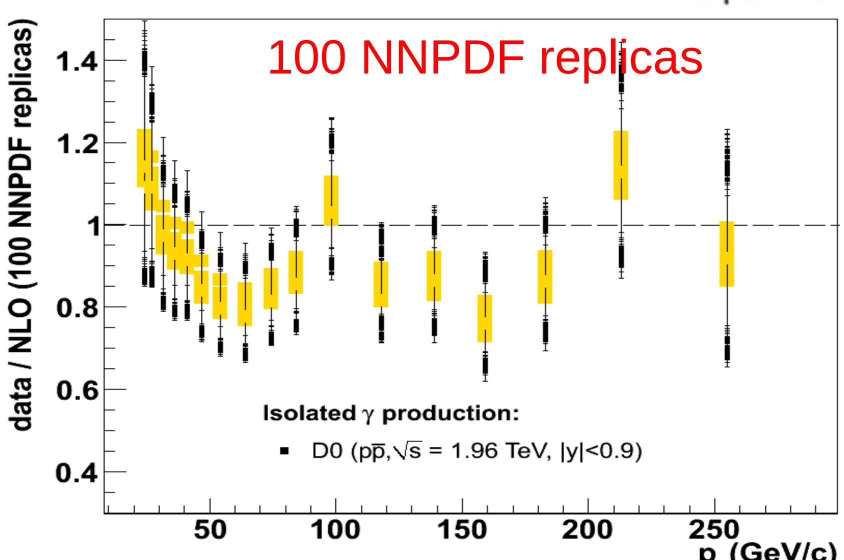
Example: Tevatron vs JETPHOX-NNPDF2.1 (I)

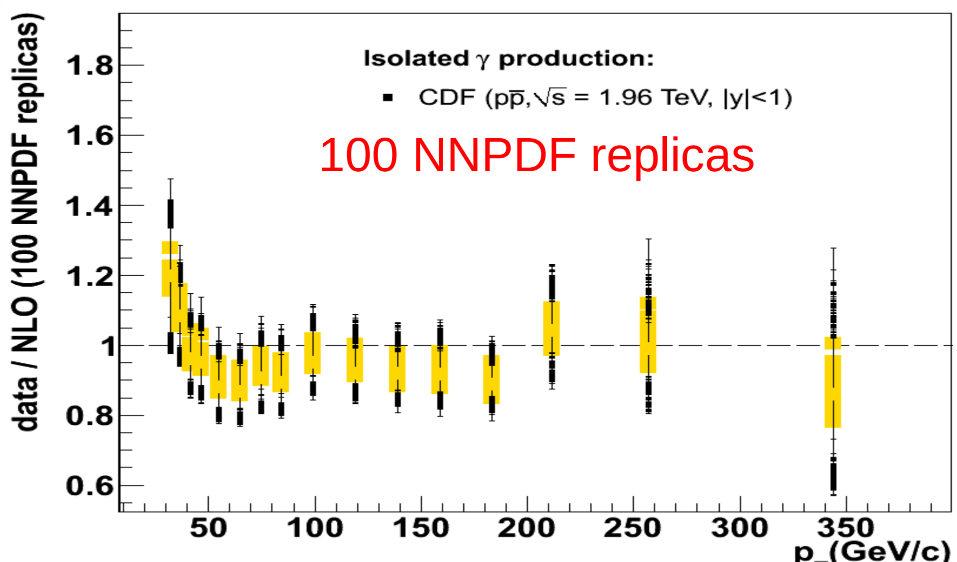
DZERO: PLB 639 (2006) 151; 658 (2008)285(E)



CDF: PRD 80, 111106 (2009)

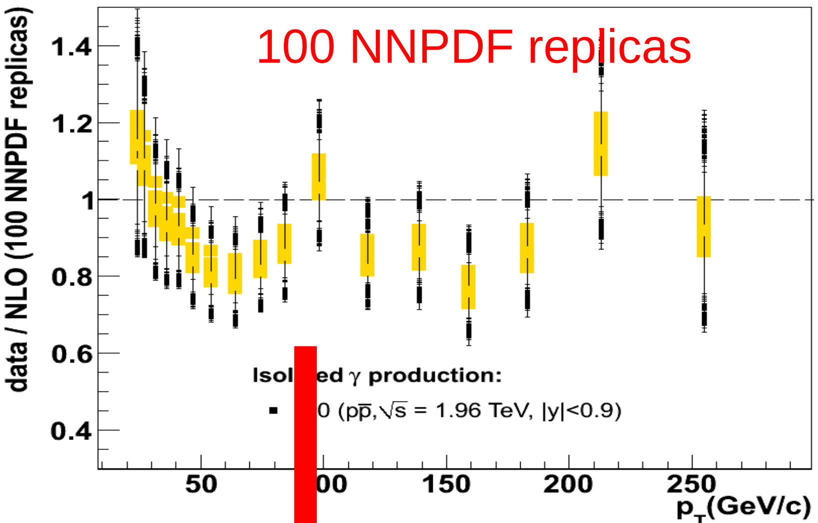


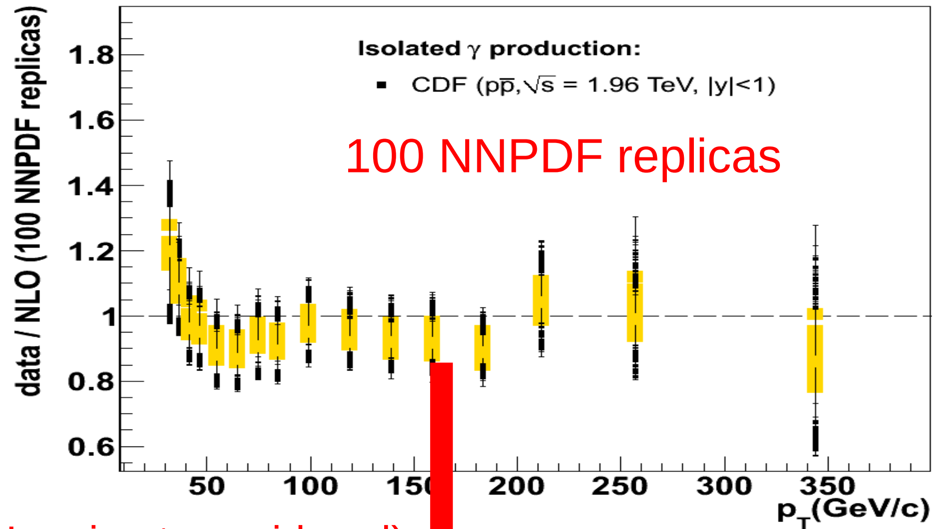




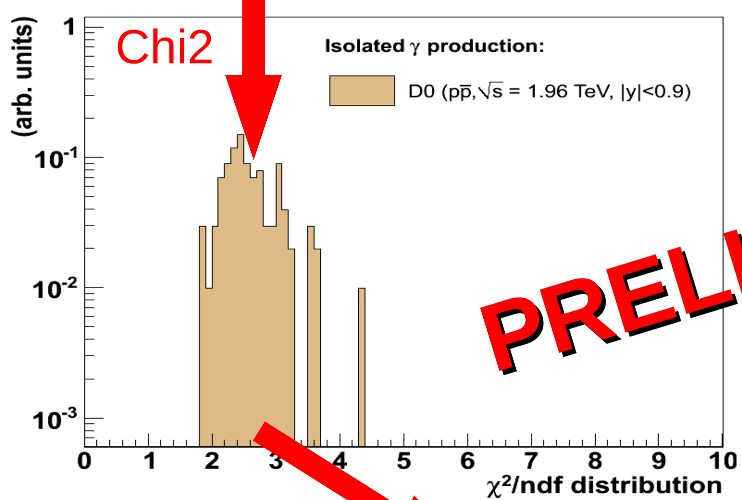
Example: Tevatron vs JETPHOX-NNPDF2.1 (II)

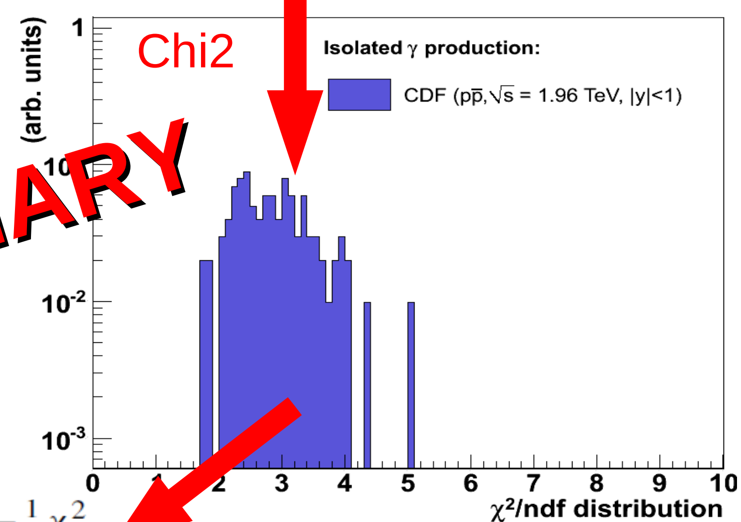
[D.d'E & J.Rojo, in preparation]





(syst.⊕stat. uncertainties. Lumi not considered)



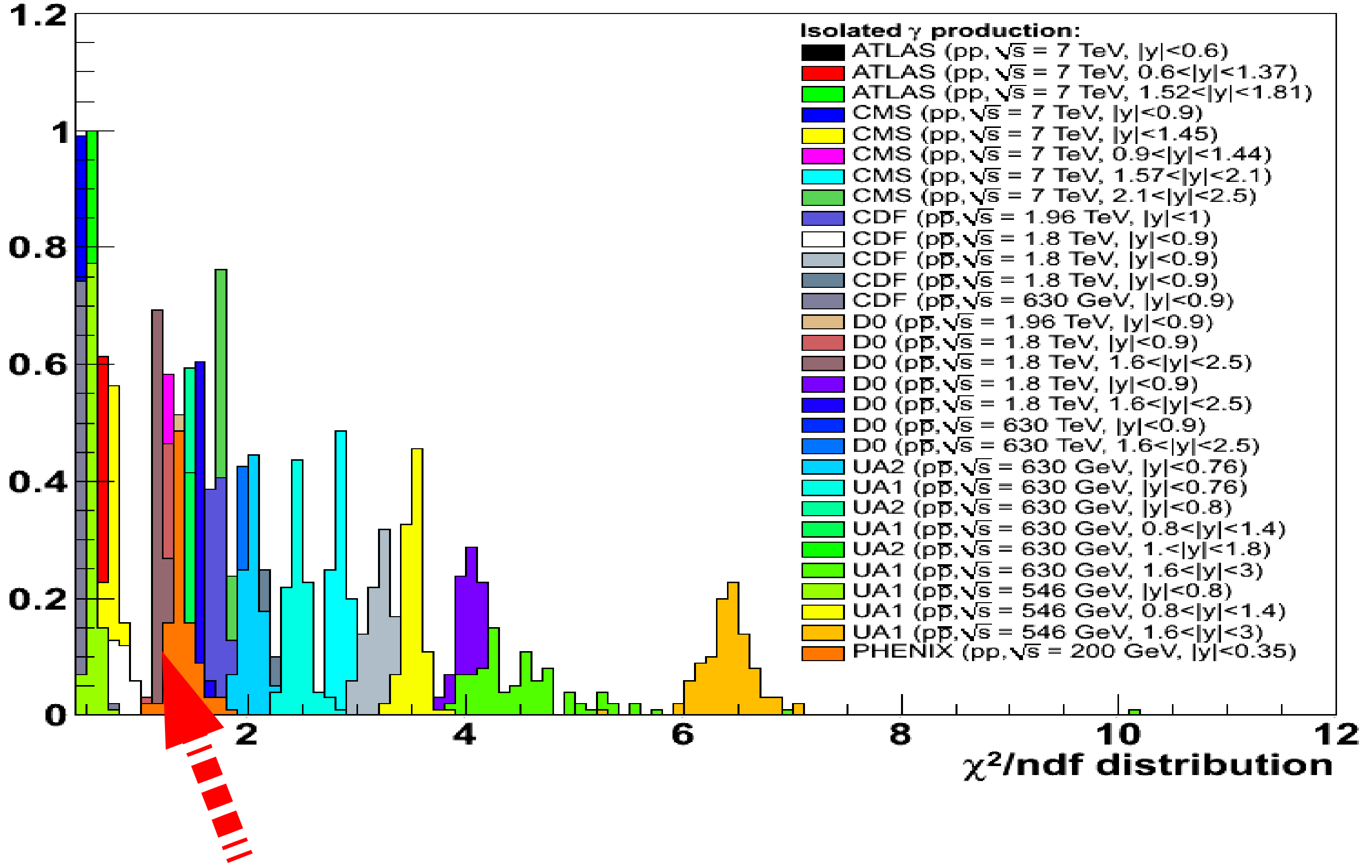


PRELIMINARY

$$w_k = \frac{(\chi^2_k)^{n/2-1} e^{-\frac{1}{2}\chi^2_k}}{\frac{1}{N}\sum_{k=1}^{N}(\chi^2_k)^{n/2-1} e^{-\frac{1}{2}\chi^2_k}}.$$: Replicas weights

χ^2 world γ-data vs NNPDF replicas (preliminary)

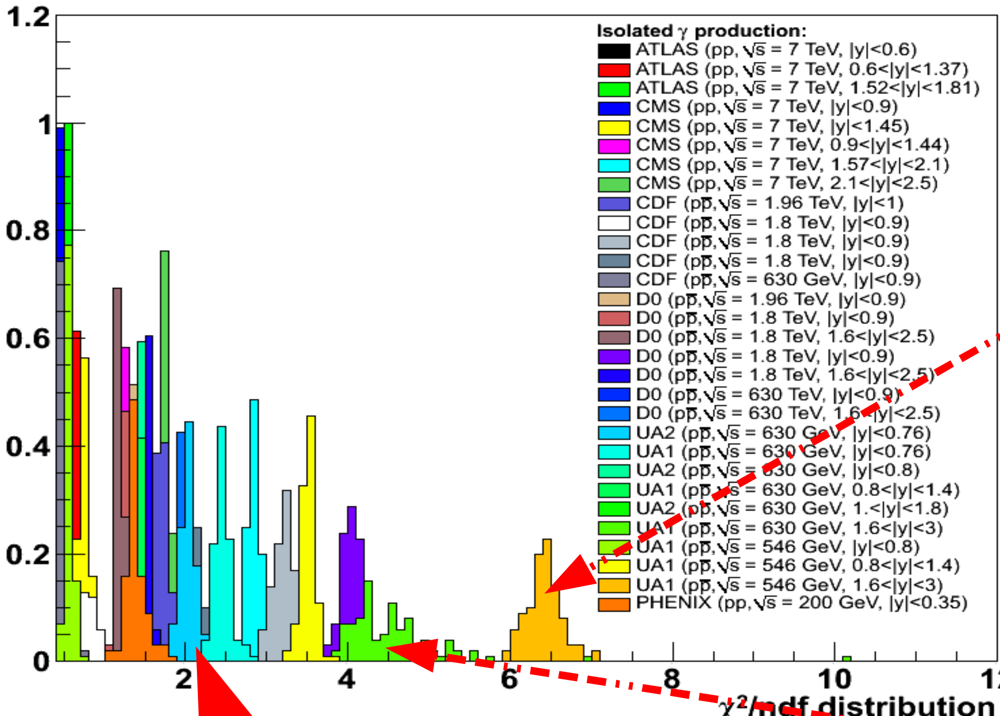
- χ^2/ndf distribution of 100 replicas for each one of 30 systems:
  (syst.+stat. uncertainties in quadrature. Lumi not considered)

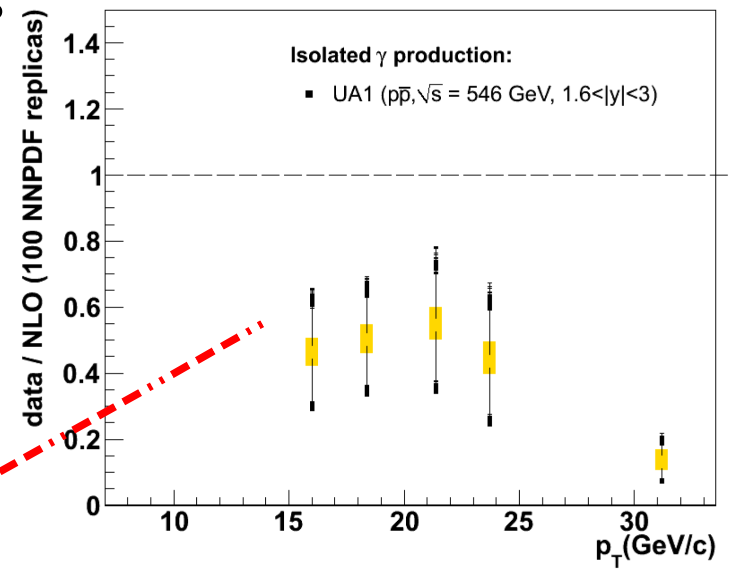


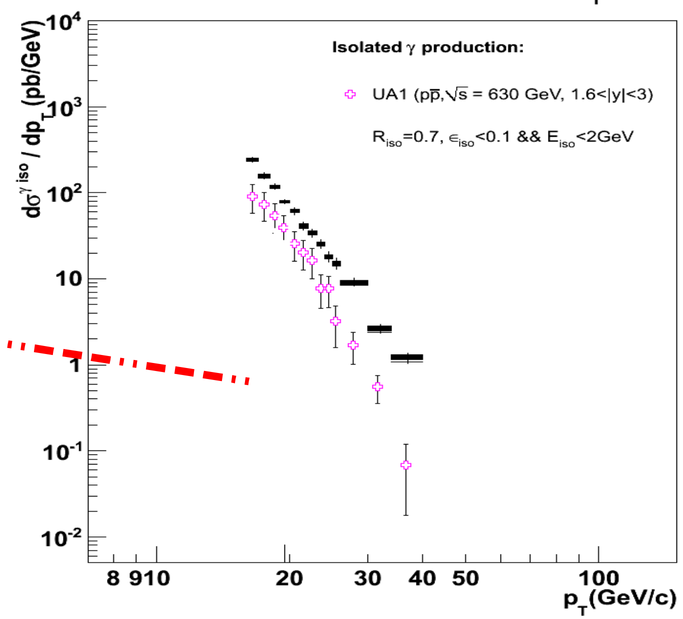
- ~2/3 of measurements have all replicas with χ^2/ndf<2.
  Possible impact on PDFs if included in global-fit

χ^2 world γ-data vs NNPDF replicas (preliminary)

- A few outliers from $Sp\bar{p}S$ at fwd rapidities (likely not "physics". Being checked ...):







- Other measurements with $\chi^2/ndf \sim 2\text{-}4$
Possibly larger impact on global PDF fits

Conclusion & Outlook

- There exists 30+ measurements of isolated-photons at collider energies ($\sqrt{s}$ = 0.2 – 7 TeV):
  - ✔ Directly sensitive to gluon density: quark-gluon Compton scatt. dominates x-sections (fragmentation γ much reduced).
  - ✔ Follow "x_T scaling". Reproduced by NLO pQCD calculations.
  - ✔ Corresponding 350+ data points (+100's more from the LHC ?) can be used to add direct constraints to the gluon PDF.

- NNPDF "reweighting" technique tested with NLO JETPHOX:
  - ✔ 2/3 of data-sets have all 100 replicas with χ^2/ndf<2.
  - ✔ Few outliers (physics ? instrumental ?) & data-sets with χ^2/ndf>~2.
  - ✔ Coming steps:
    - Reweighting of replicas.
    - Quantitative determination of impact on global PDF fits.

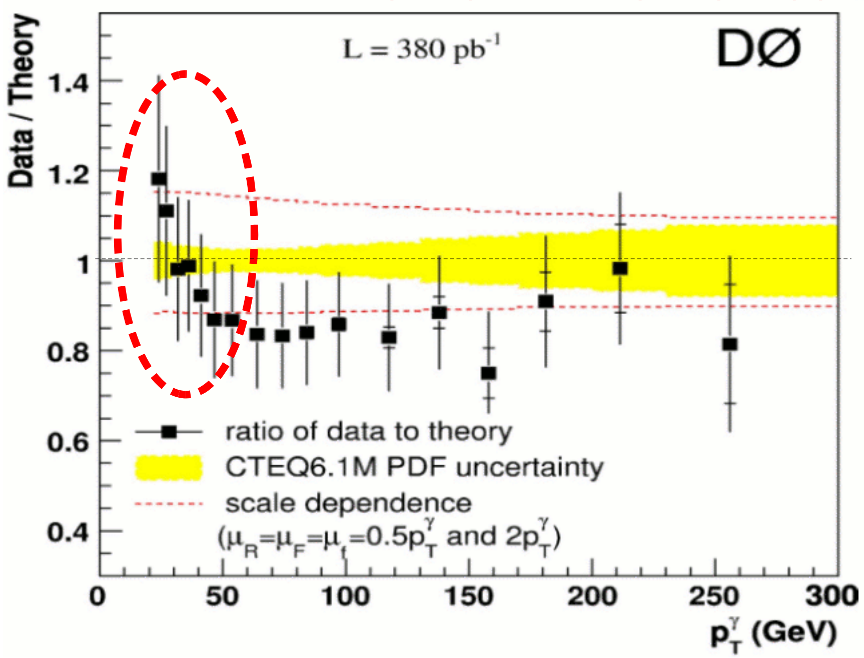
Backup slides

Compare to ... $pp \to \gamma_{iso}$+X at 1.96 TeV vs NLO

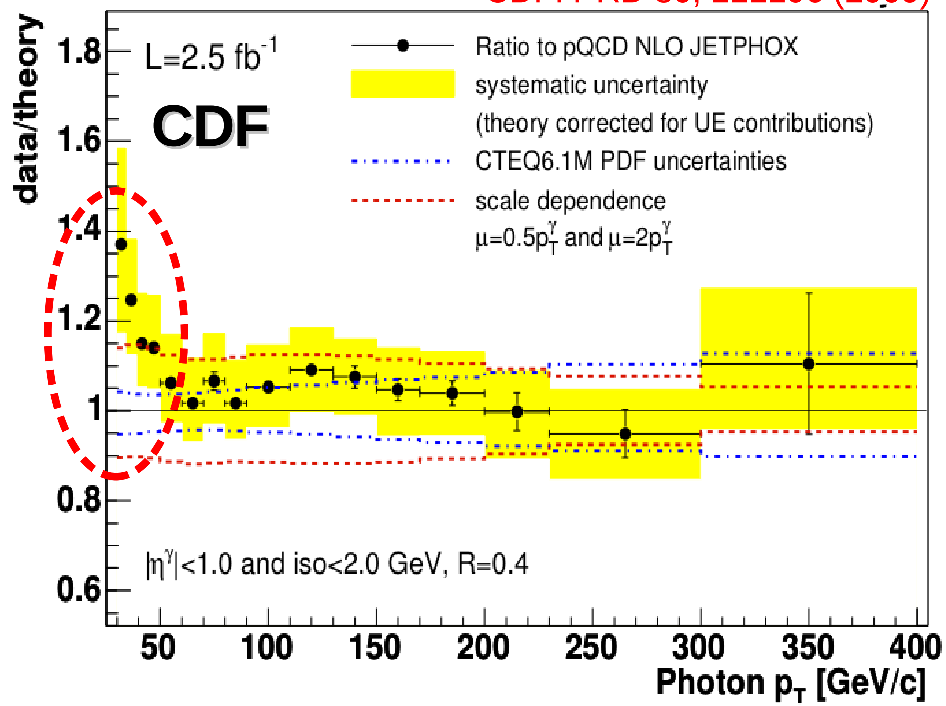
- D0 syst. uncertainty: ~20%
- CDF syst. uncertainty: 15 – 10%

(Tevatron uncertainties dominated by photon energy scale)

DZERO: PLB 639 (2006) 151; 658 (2008) 285(E)



CDF: PRD 80, 111106 (2009)

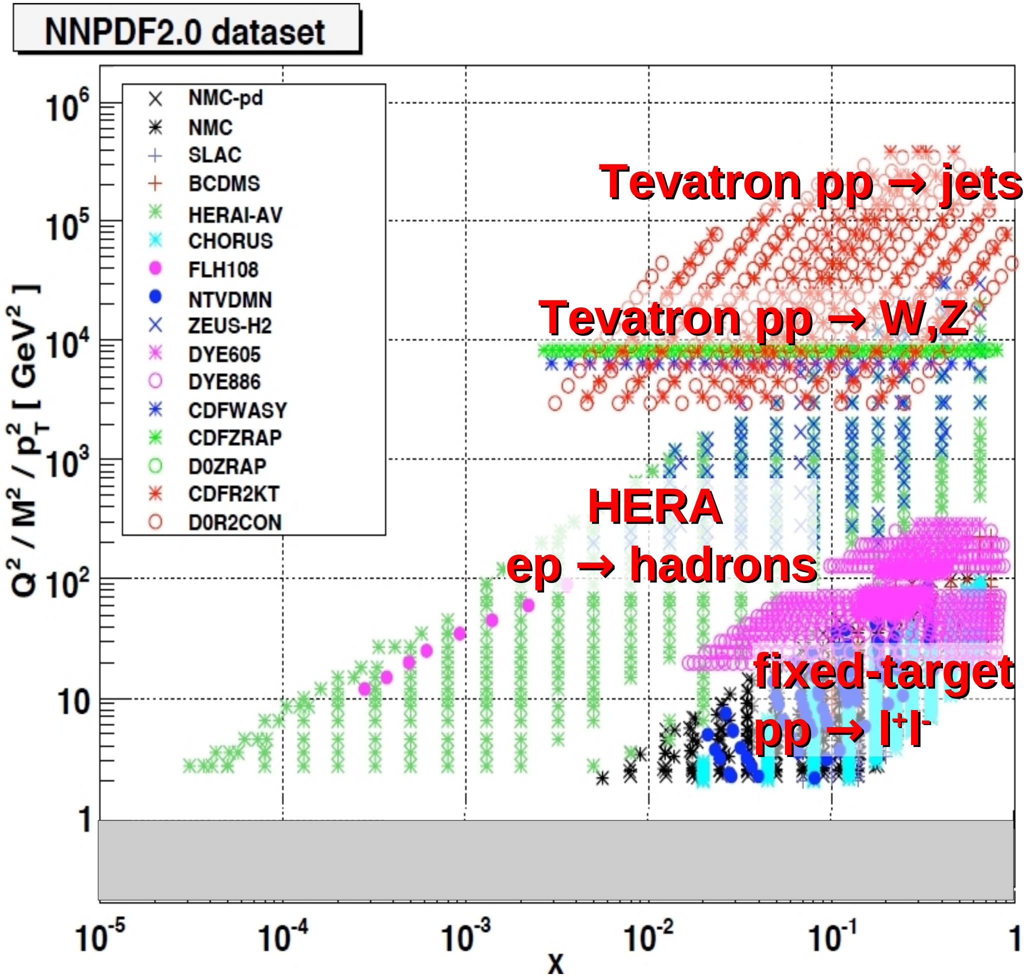


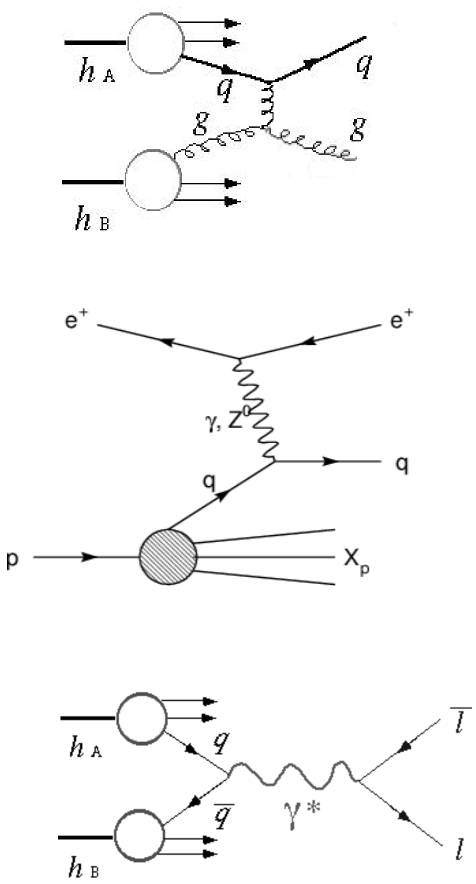
- NLO tends to underpredict data at $p_T < 50$ GeV/c (still OK within errors)
  - Theory scale uncertainty: 15 – 10%
  - Theory PDF uncertainty: 5 – 10%

[See also: R.Ichou & D.d'E, PRD82 (2010) 014015]

(x,Q^2) map of data-sets used in PDF global fits

- ~3500 data points from DIS, fixed-target & collider data:

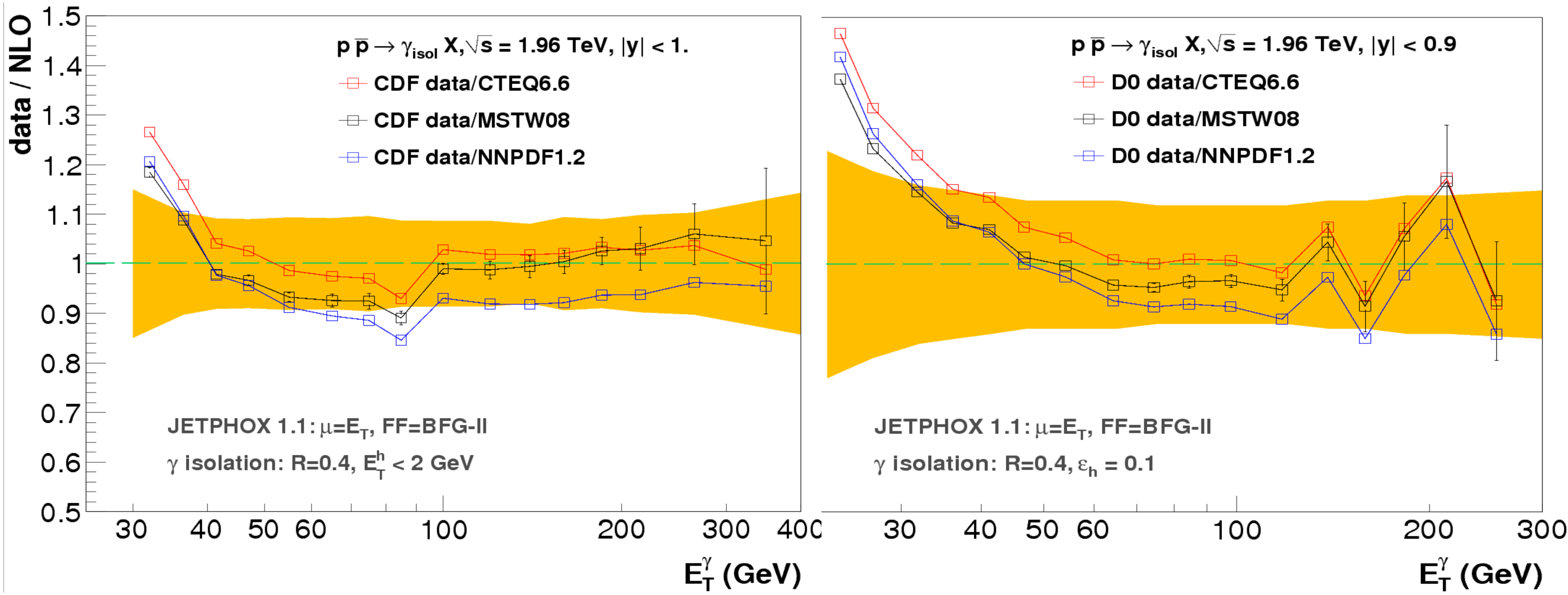




- Gluon: indirectly via $\partial F_2/\partial \log Q^2$ & directly at large-x via Tevatron jets

Tevatron isolated-γ vs NLO (3 PDFs)

[R.Ichou & Dd'E, PRD82 (2010) 014015]



- Good overall agreement data-NLO in pp → γ_{isol}+X at 1.96 TeV.
- Excess at p_T<30 GeV/c (still within exp. uncertainties):
  physics ? Instrumental ?