Constraints on the gluon from collider isolated photons(*)

Workshop on photon physics at colliders

Jussieu (Paris), 30th March 2012

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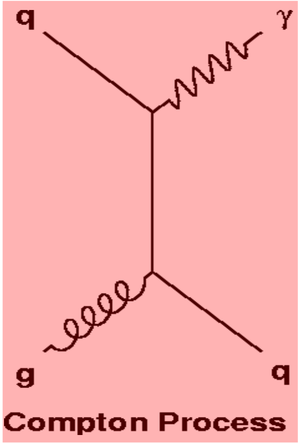
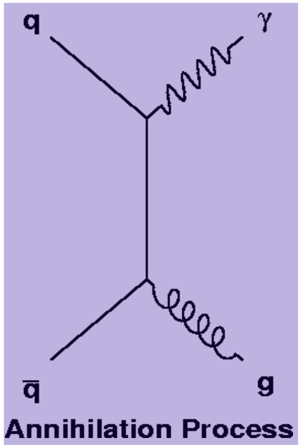
CERN

(*) Based mostly on: DdE & J. Rojo, arXiv:1202.1762, NPB 860 (2012) 311

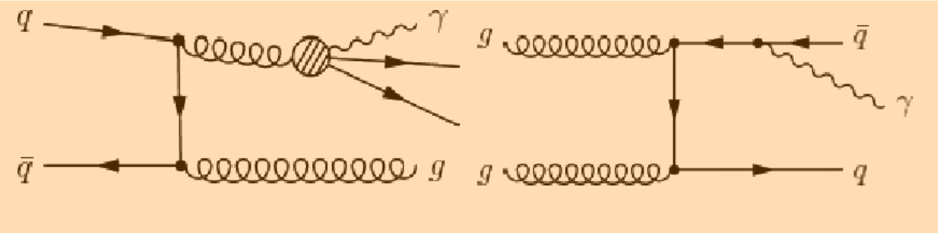
Prompt-γ production in hadronic collisions

- Leading partonic production processes in p-p, p-$\bar{p}$ collisions :

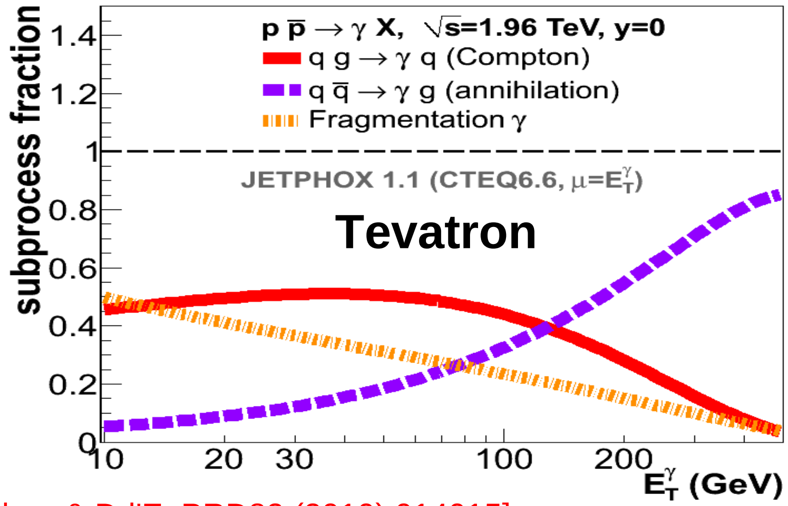


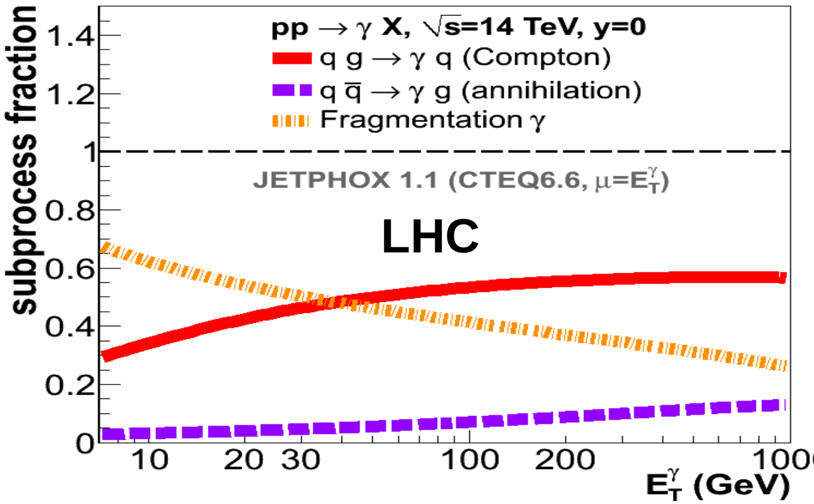


+ parton-to-photon fragmentation:



- Relative subprocess fractions (NLO): Important fragmentation contribution

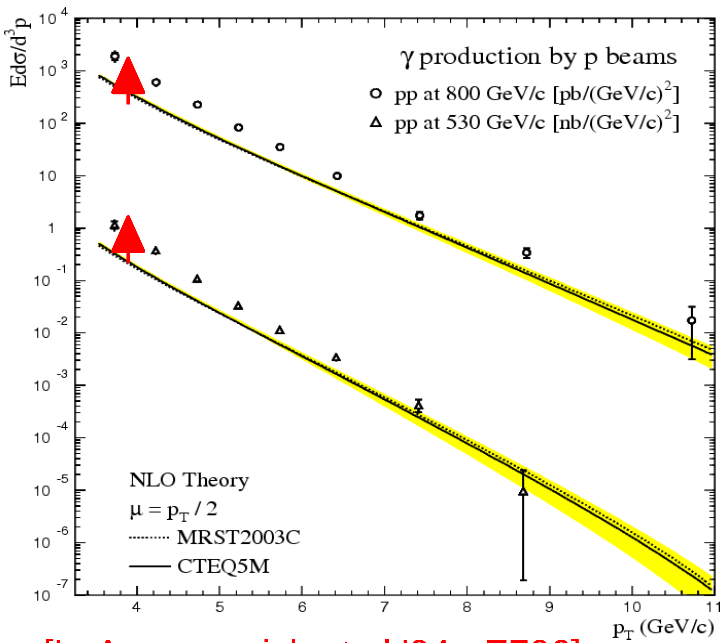




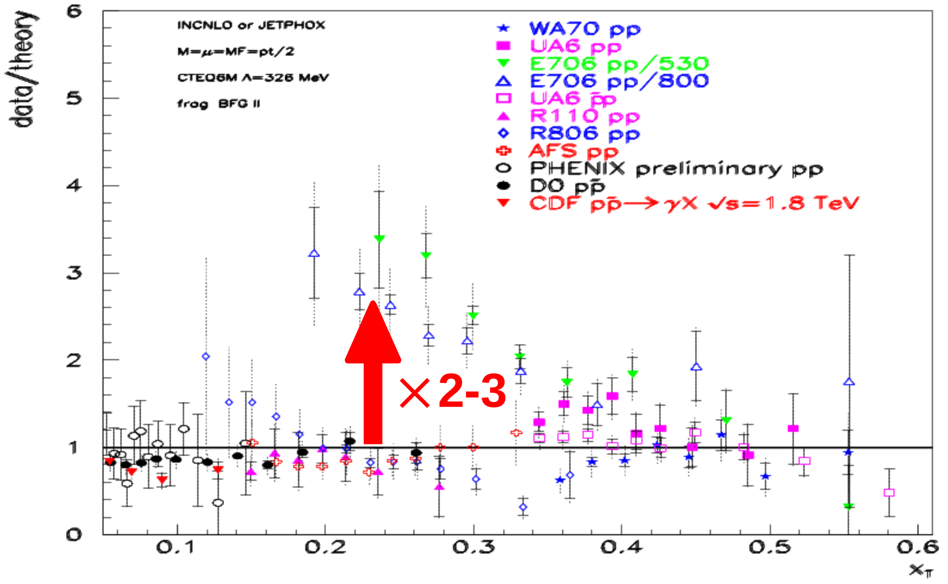
[R.Ichou & Dd'E, PRD82 (2010) 014015]

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: Larger pQCD scales

- Are they useful for PDF constraints ... ? Yes !
  - ✔ 35+ meas., 400+ 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 ?

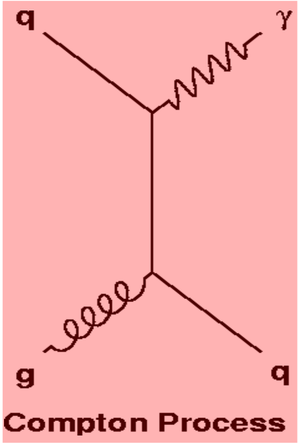
(1) Including γ data & full refitting all data-sets: (very) slow NLO code ...

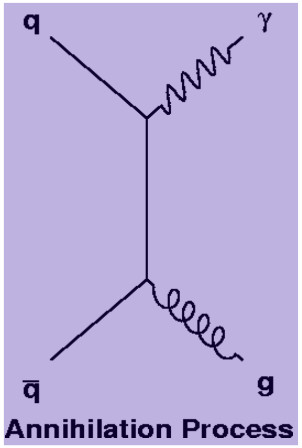
(2) “A posteriori” inclusion via fastNLO or ApplGrid: not implemented yet

(3) Using NNPDF Bayesian reweighting technique ✔

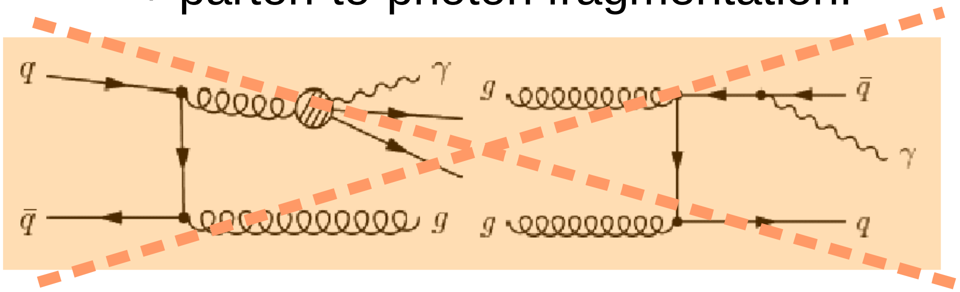
Isolated γ production in hadronic collisions

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



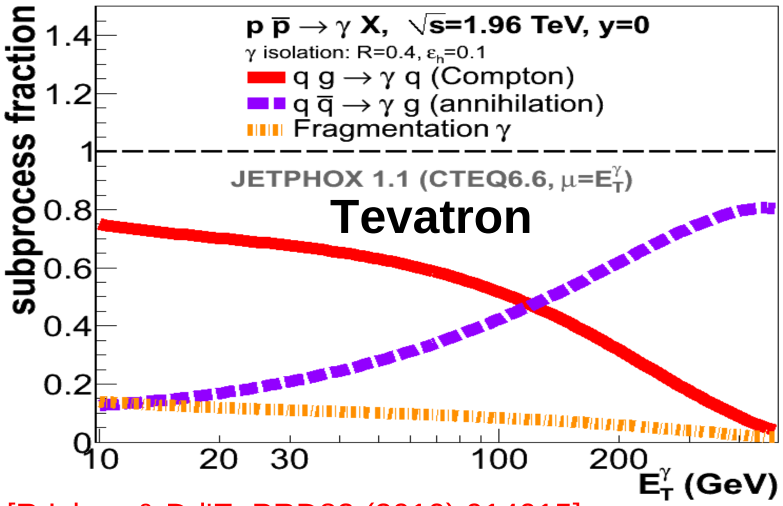


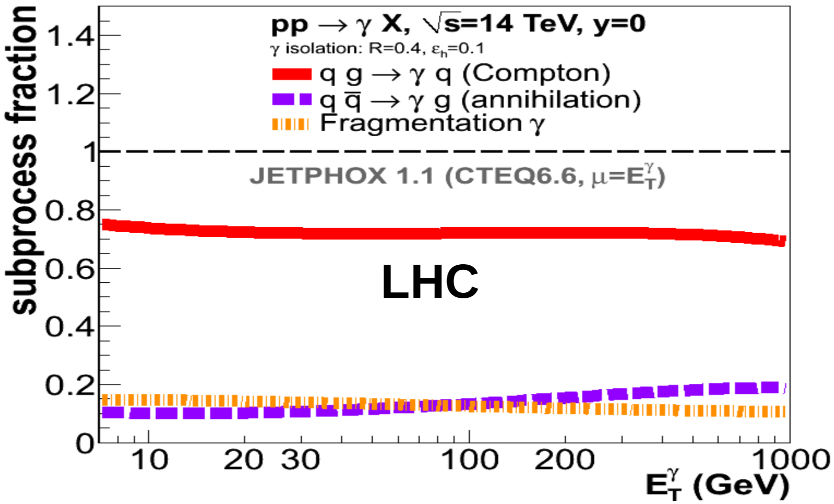
+ parton-to-photon fragmentation:



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

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



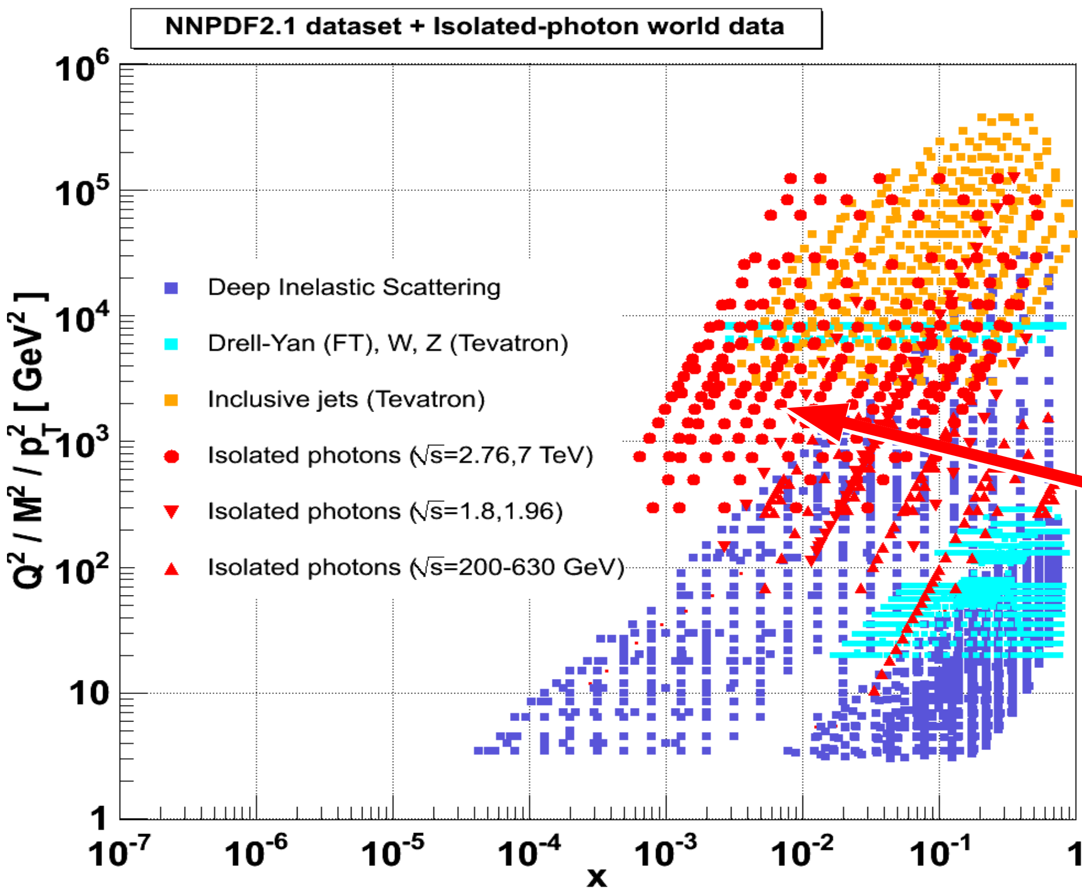


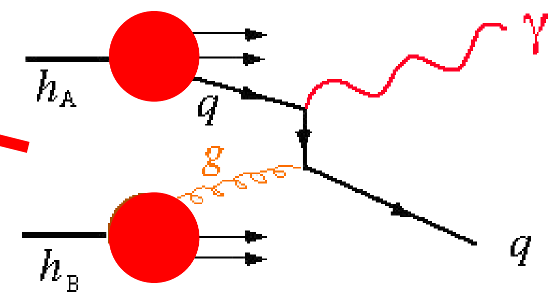
[R.Ichou & Dd'E, PRD82 (2010) 014015]

(x,Q²) map of collider isolated-γ datasets

[D.d'E & J.Rojo, NPB 860 (2012) 311]

- 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 by p-p jets at high-x]

Isolated-γ collider world-data (I)

- 35 meas. (~400 data points) at LHC/Tevatron/Sp$\bar{p}$S/RHIC & increasing ...

LHC: ~135 data points

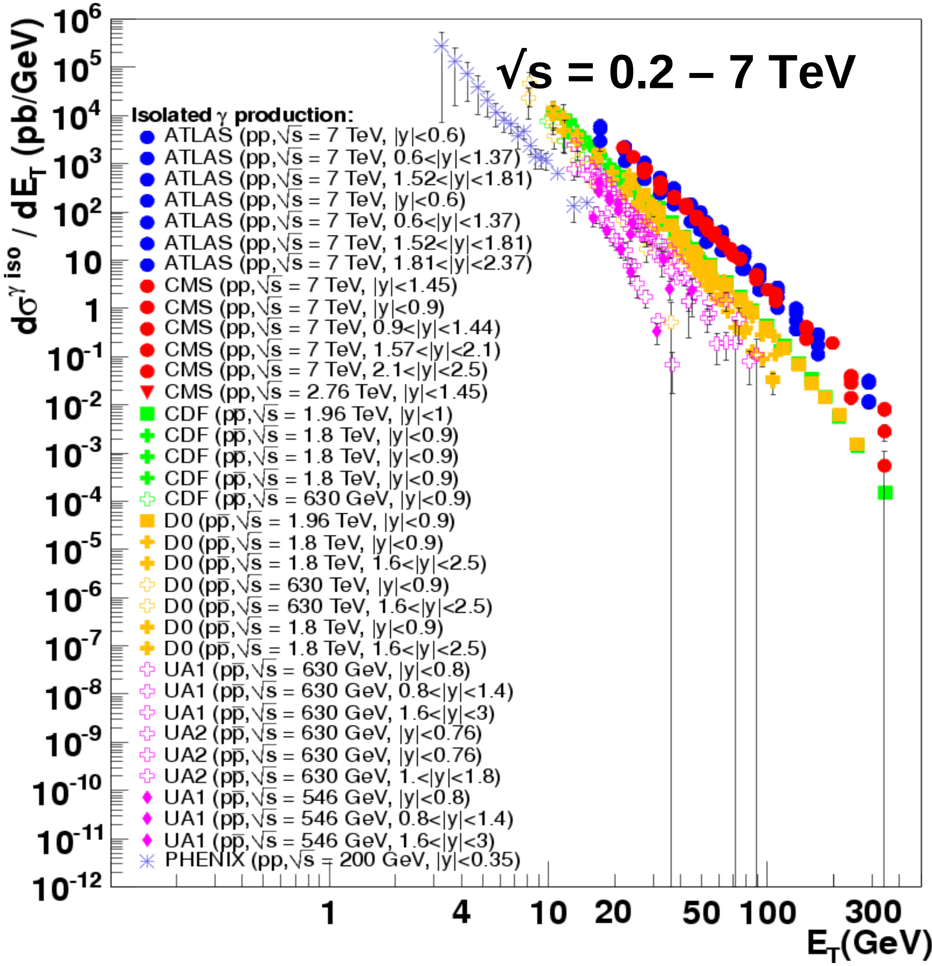
System	Collab./experiment (collider) [Ref.]	$\sqrt{s}$ (TeV)	$\lvert y_\gamma \rvert$ range	E_T^γ range (GeV)	x range	Data points	Isolation radius, had. energy
p–p	ATLAS (LHC) [34]	7.	<0.6	15–100	5×10^{-3}–0.05	8	$R=0.4$, $E_h<5$ GeV
p–p	ATLAS (LHC) [34]	7.	0.6–1.37	15–100	3×10^{-3}–0.1	8	$R=0.4$, $E_h<5$ GeV
p–p	ATLAS (LHC) [34]	7.	1.52–1.81	15–100	2×10^{-3}–0.1	8	$R=0.4$, $E_h<5$ GeV
p–p	ATLAS (LHC) [35]	7.	<0.6	45–400	5×10^{-3}–0.1	8	$R=0.4$, $E_h<4$ GeV
p–p	ATLAS (LHC) [35]	7.	0.6–1.37	45–400	5×10^{-3}–0.2	8	$R=0.4$, $E_h<4$ GeV
p–p	ATLAS (LHC) [35]	7.	1.52–1.81	45–400	2×10^{-3}–0.3	8	$R=0.4$, $E_h<4$ GeV
p–p	ATLAS (LHC) [35]	7.	1.81–2.37	45–400	2×10^{-3}–0.5	8	$R=0.4$, $E_h<4$ GeV
p–p	CMS (LHC) [37]	7.	<1.45	21–300	5×10^{-3}–0.1	11	$R=0.4$, $E_h<5$ GeV
p–p	CMS (LHC) [36]	7.	<0.9	25–400	5×10^{-3}–0.2	15	$R=0.4$, $E_h<5$ GeV
p–p	CMS (LHC) [36]	7.	0.9–1.44	25–400	2×10^{-3}–0.3	15	$R=0.4$, $E_h<5$ GeV
p–p	CMS (LHC) [36]	7.	1.57–2.1	25–400	10^{-3}–0.4	15	$R=0.4$, $E_h<5$ GeV
p–p	CMS (LHC) [36]	7.	2.1–2.5	25–400	10^{-3}–0.5	15	$R=0.4$, $E_h<5$ GeV
p–p	CMS (LHC) [38]	2.76	<1.45	20–80	10^{-3}–0.05	6	$R=0.4$, $E_h<5$ GeV
p–$\bar{p}$	CDF (Tevatron) [44]	1.96	<1.0	30–400	0.01–0.4	16	$R=0.4$, $\varepsilon_h<0.1$
p–$\bar{p}$	D0 (Tevatron) [45]	1.96	<0.9	23–300	0.01–0.3	17	$R=0.4$, $E_h<2$ GeV
p–$\bar{p}$	CDF (Tevatron) [46]	1.8	<0.9	11–132	5×10^{-3}–0.2	17	$R=0.4$, $E_h<4$ GeV
p–$\bar{p}$	CDF (Tevatron) [47]	1.8	<0.9	10–65	5×10^{-3}–0.1	17	$R=0.4$, $E_h<1$ GeV
p–$\bar{p}$	CDF (Tevatron) [48]	1.8	<0.9	8–132	5×10^{-3}–0.2	16	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	D0 (Tevatron) [49]	1.8	<0.9	10–140	5×10^{-3}–0.2	9	$R=0.4$, $E_h<2$ GeV
p–$\bar{p}$	D0 (Tevatron) [49]	1.8	1.6–2.5	10–140	10^{-3}–0.4	9	$R=0.4$, $E_h<2$ GeV
p–$\bar{p}$	D0 (Tevatron) [50]	1.8	<0.9	9–126	5×10^{-3}–0.2	23	$R=0.4$, $E_h<2$ GeV
p–$\bar{p}$	D0 (Tevatron) [50]	1.8	1.6–2.5	9–126	10^{-3}–0.4	23	$R=0.4$ $E_h<2$ GeV
p–$\bar{p}$	CDF (Tevatron) [46]	0.63	<0.9	8–38	0.01–0.2	7	$R=0.4$, $E_h<4$ GeV
p–$\bar{p}$	D0 (Tevatron) [51]	0.63	<0.9	7–50	0.01–0.3	7	$R=0.4$, $E_h<2$ GeV
p–$\bar{p}$	D0 (Tevatron) [51]	0.63	1.6–2.5	7–50	10^{-3}–0.4	7	$R=0.4$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (Sp$\bar{p}$S) [52]	0.63	<0.8	16–100	0.03–0.3	16	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (Sp$\bar{p}$S) [52]	0.63	0.8–1.4	16–70	0.01–0.4	10	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (Sp$\bar{p}$S) [52]	0.63	1.6–3.0	16–70	0.01–0.5	13	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	UA2 (Sp$\bar{p}$S) [53]	0.63	<0.76	14–92	0.03–0.3	13	$R=0.265$, $\varepsilon_h<0.25$
p–$\bar{p}$	UA2 (Sp$\bar{p}$S) [54]	0.63	<0.76	12–83	0.03–0.3	14	$R=0.25$, $E_h<0.1$ GeV
p–$\bar{p}$	UA2 (Sp$\bar{p}$S) [54]	0.63	1.0–1.8	12–51	0.01–0.4	8	$R=0.53$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (Sp$\bar{p}$S) [52]	0.546	<0.8	16–51	0.03–0.2	6	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (Sp$\bar{p}$S) [52]	0.546	0.8–1.4	16–46	0.02–0.4	5	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (Sp$\bar{p}$S) [52]	0.546	1.6–3.0	16–38	0.01–0.5	5	$R=0.7$, $E_h<2$ GeV
p–p	PHENIX (RHIC) [55]	0.2	<0.35	3–16	0.03–0.2	17	$R=0.5$, $\varepsilon_h<0.1$

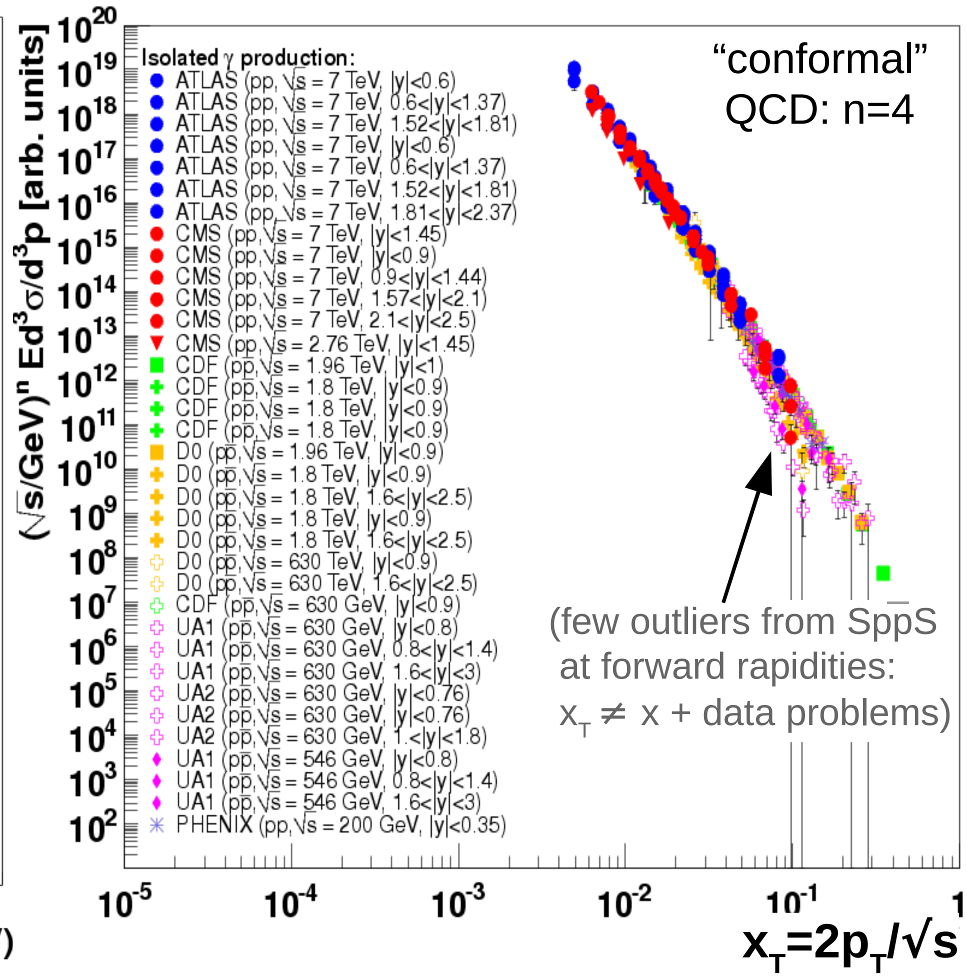
Isolated-γ collider world-data (II)

[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)





PDF reweighting via JETPHOX + 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 !)

  $\times$30 !

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

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

(2) χ^2 (syst.⊕stat. uncert., no err. matrices) per replica: $\chi_k^2 = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} \frac{(\sigma_i^{({\rm th}),(k)} - \sigma_i^{({\rm exp})})^2}{\Delta_{\rm tot}^2}$

(3) Obtain associated "weight" for each replica: $w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}{\frac{1}{N}\sum_{k=1}^{N}(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}$

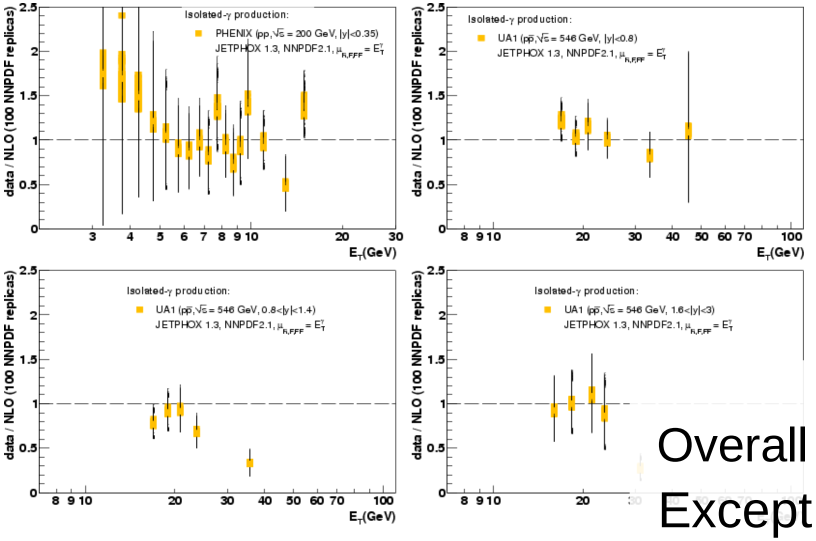
(4) Obtain new effective number of replicas: $N_{\rm eff} \equiv \exp\left\{\frac{1}{N}\sum_{k=1}^{N} w_k \ln(N/w_k)\right\}$

(5) Obtain reweighted PDF replicas: $\langle \mathcal{O} \rangle_{\rm new} = \frac{1}{N}\sum_{k=1}^{N} w_k \mathcal{O}[f_k]$

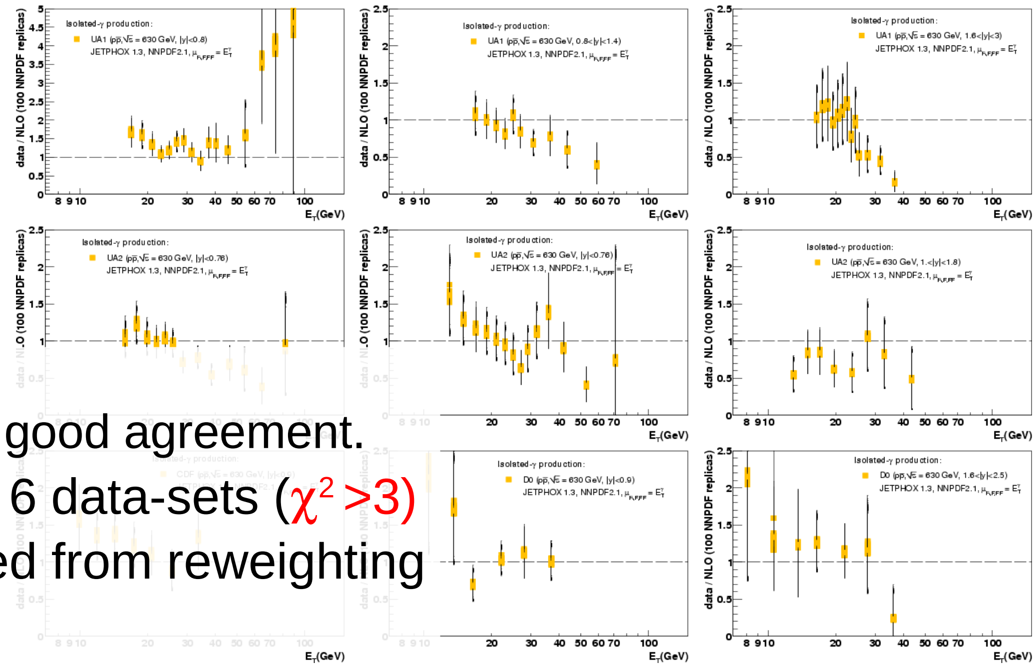
PDF reweighting: γ_{isol} data/NLO ratios

[D.d'E & J.Rojo, NPB 860 (2012) 311]

√s =200,546 GeV

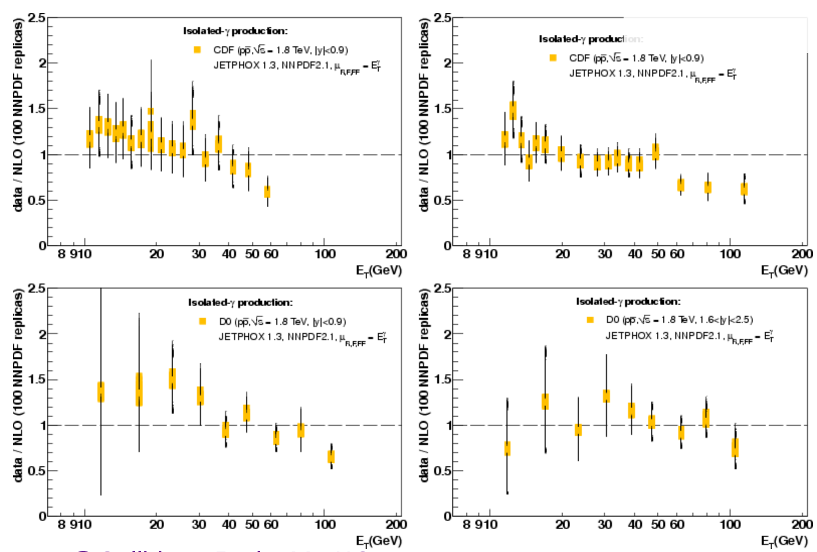


√s =630 GeV

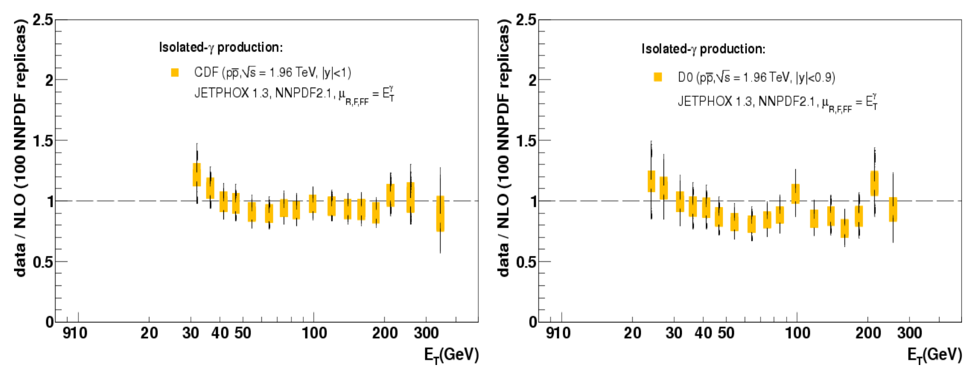


Overall good agreement.
Except 6 data-sets (χ^2 >3)
removed from reweighting

√s =1800 GeV



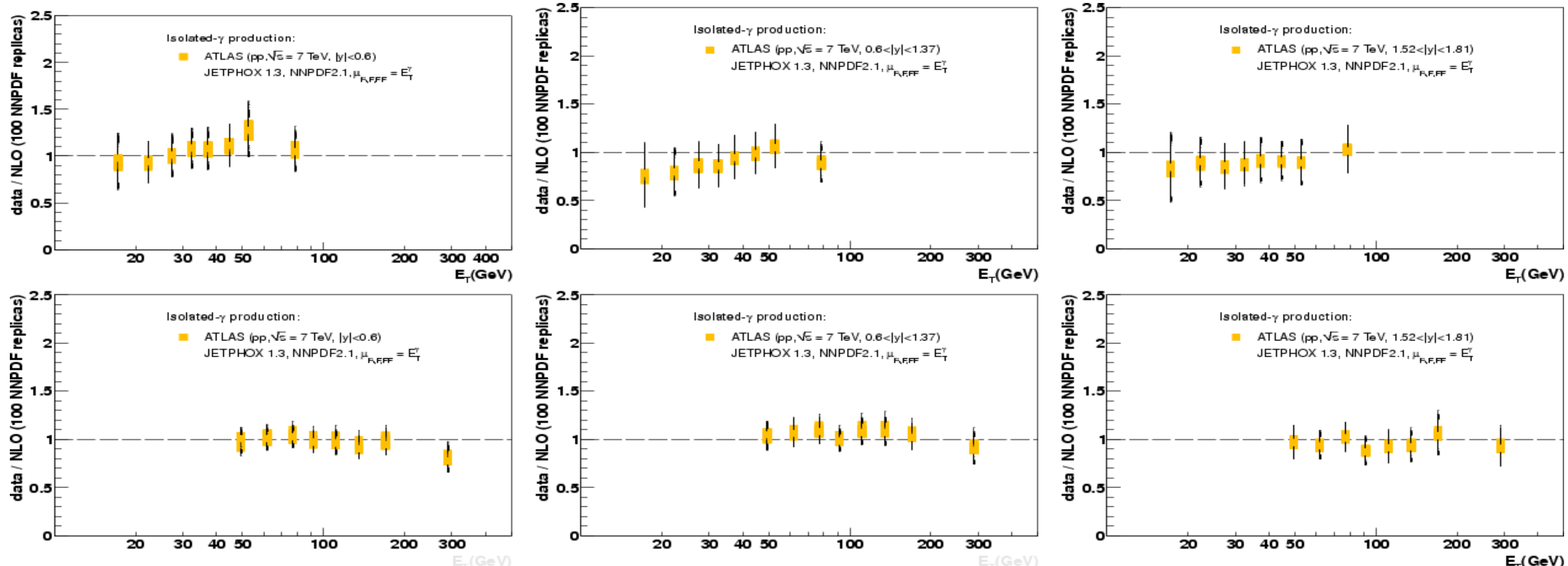
√s =1960 GeV



PDF reweighting: LHC γ_{isol} data/NLO ratios

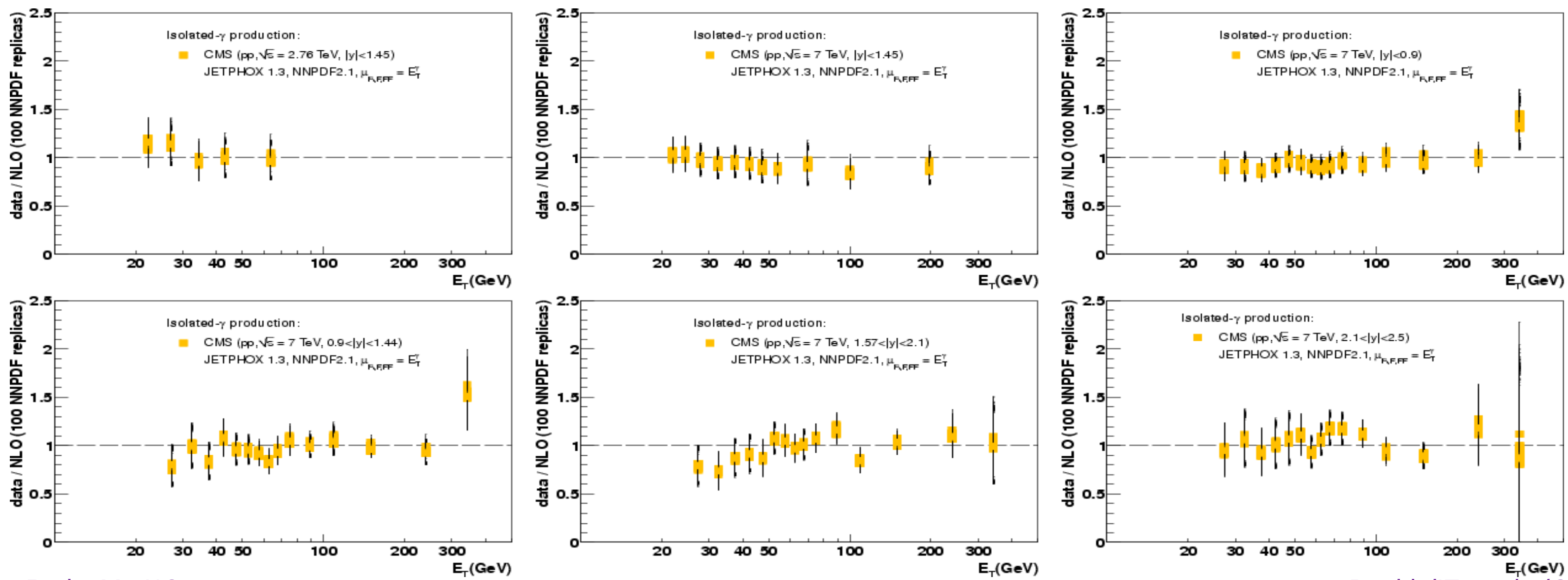
[D.d'E & J.Rojo, NPB 860 (2012) 311]

ATLAS



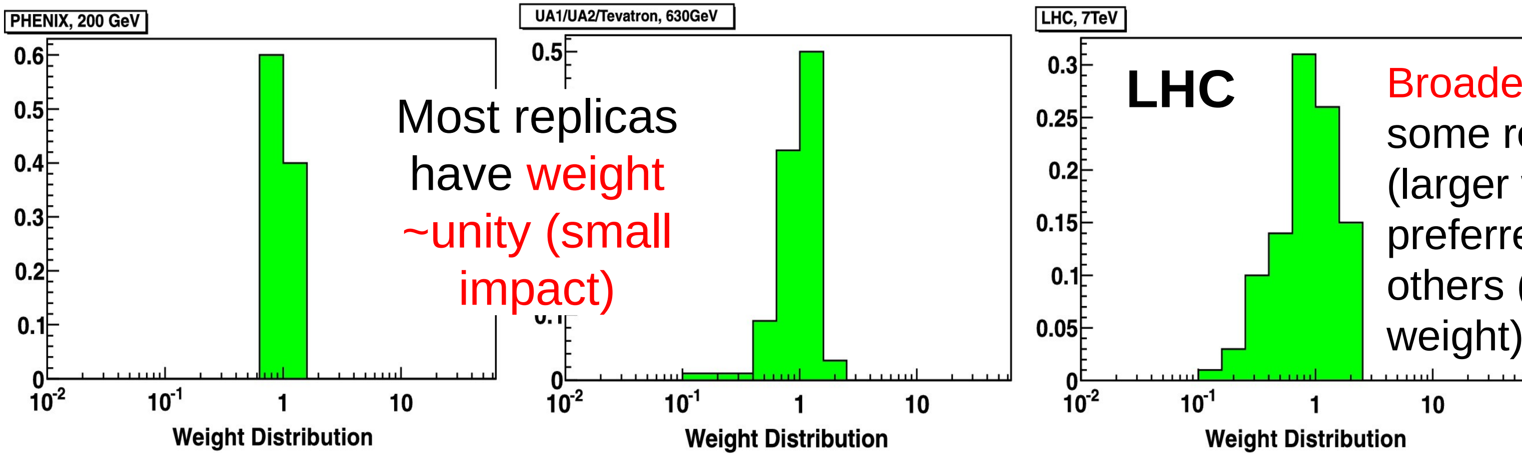
Very good agreement : $\chi^2 \sim 1$!

CMS



PDF reweighting results

- Typical distributions of replicas-weights for RHIC, Sp$\bar{p}$S, LHC:

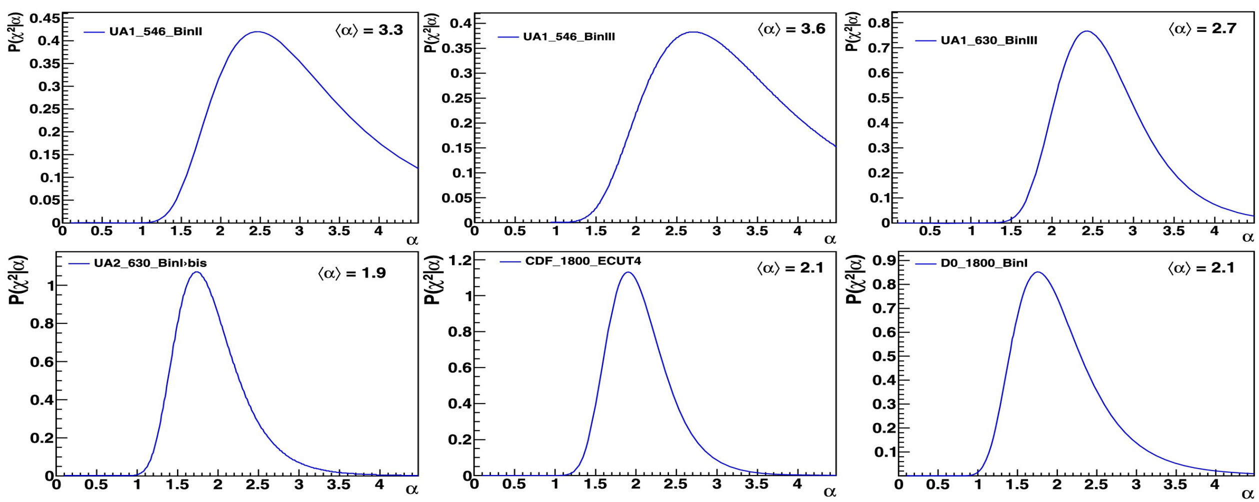


Most replicas have weight ~unity (small impact)

LHC

Broader distribution: some replicas (larger weight) preferred over others (smaller weight)

- 6 datasets (UA1/2 fwd-rapidities & older CDF/D0) have $\chi^2 > 3$:
Underestimated exp. uncertainties as indicated by α rescaling factor:

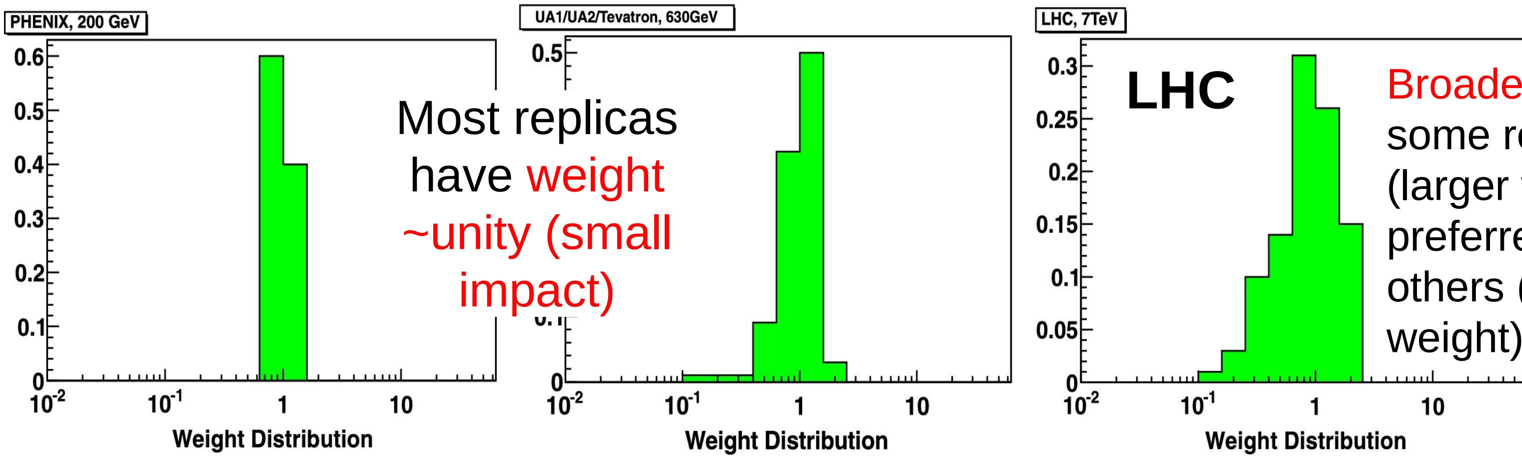


$$\mathcal{P}(\alpha) \propto \frac{1}{\alpha} \sum_{k=1}^{N_{\rm rep}} w_k(\alpha)$$

χ^2 should be rescaled by $\alpha \sim 2$–3 to get good data-NLO agreement

PDF reweighting results

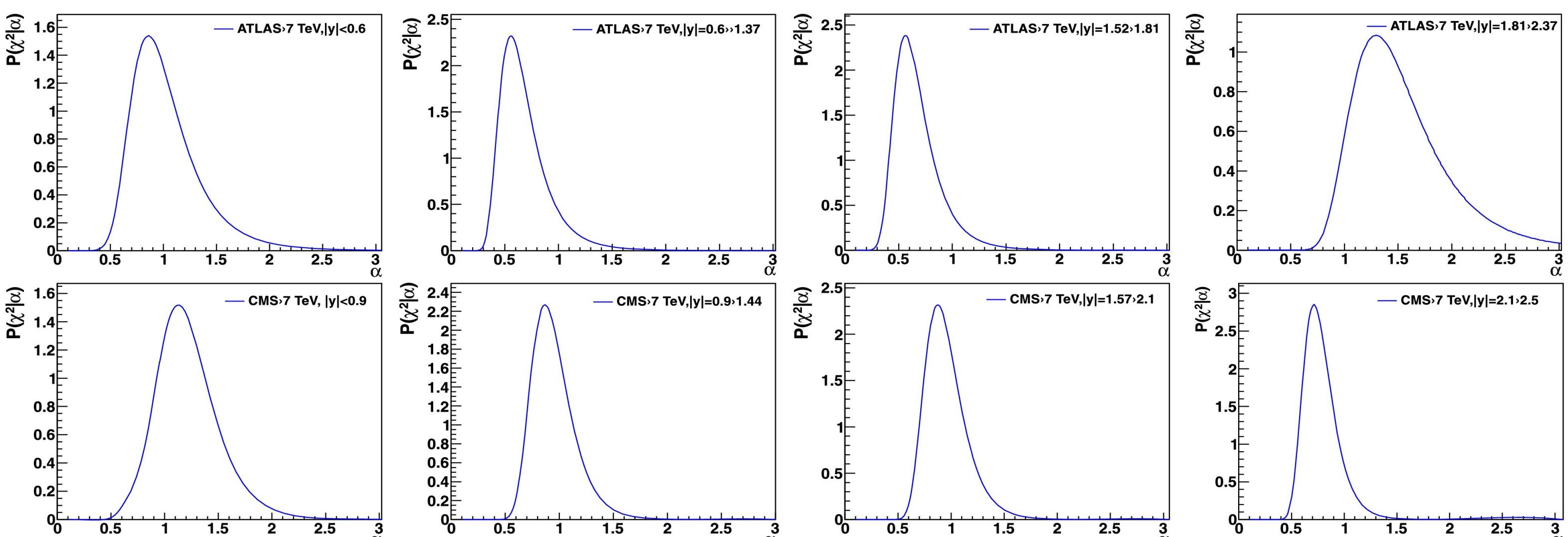
- Typical distributions of replicas-weights for RHIC, Sp$\bar{p}$S, LHC:



Most replicas have weight ~unity (small impact)

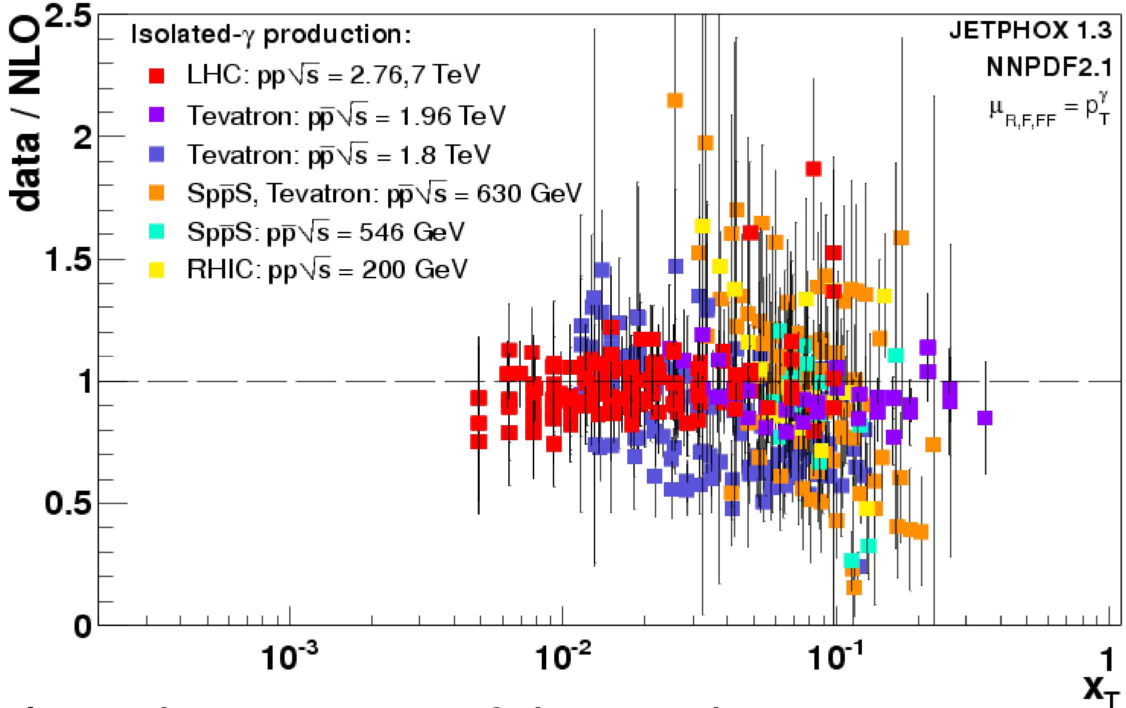
Broader distribution: some replicas (larger weight) preferred over others (smaller weight)

- LHC rescaling-factors ~1. Experimental uncertainties well determined.



World γ_{isol}-data vs JETPHOX-NNPDF2.1

[D.d'E & J.Rojo, NPB 860 (2012) 311]

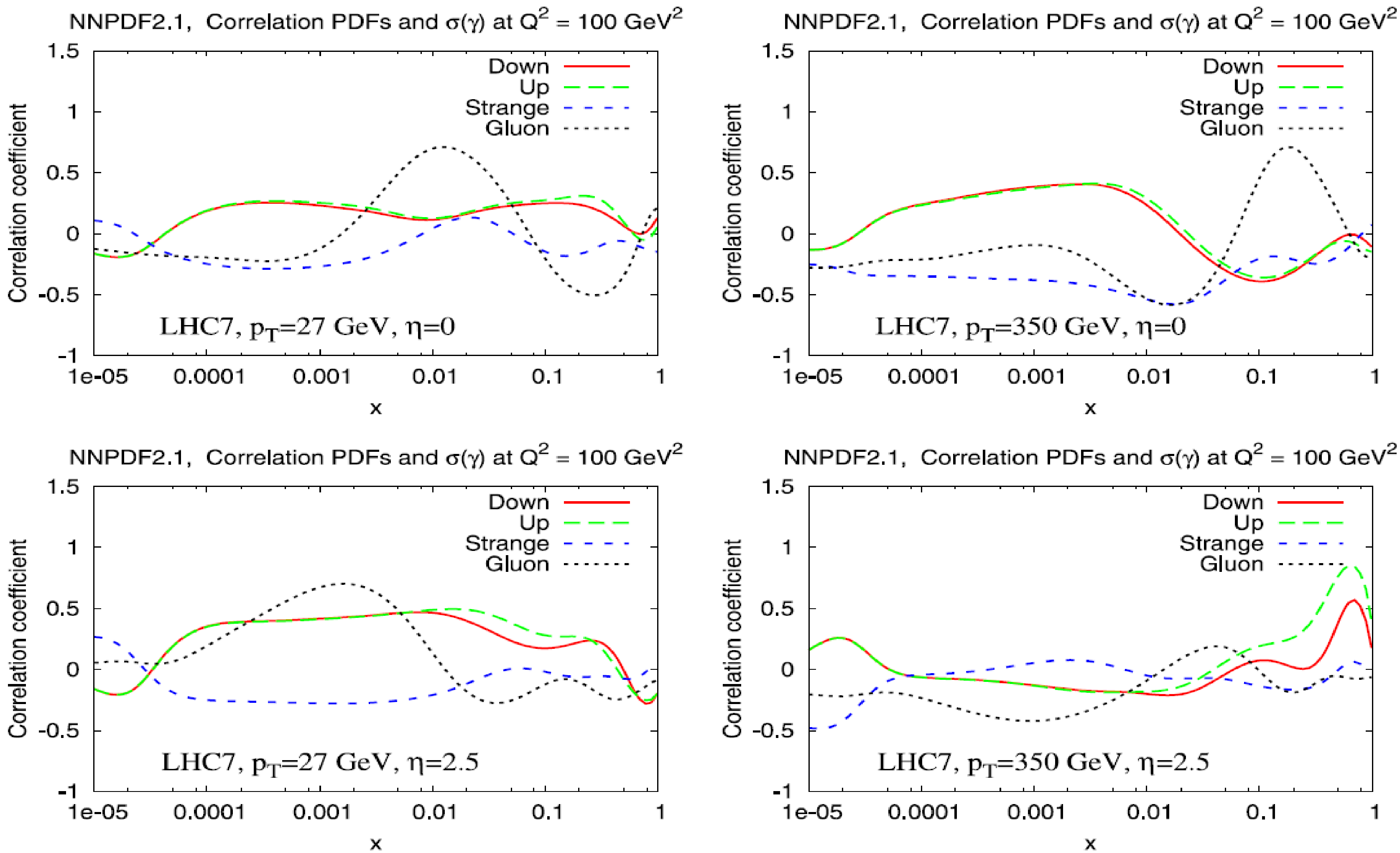


- General good agreement of data and NLO.
- 6 systems (older measurements) with $\chi^2 > 3$ removed:
  - large $P(\chi^2|\alpha)$: syst. uncertainties underestimated in a few bins.
  - Inconsistent with other measurements at same √s, η.
- Effective number of replicas after reweighting (Shannon entropy):

$\sqrt{s}$ (TeV)	0.2	0.546	0.630	1.8	1.96	2.76	7
$N_{\rm eff}$	99.6	99	95	99.8	96	96	87

LHC data are most constraining

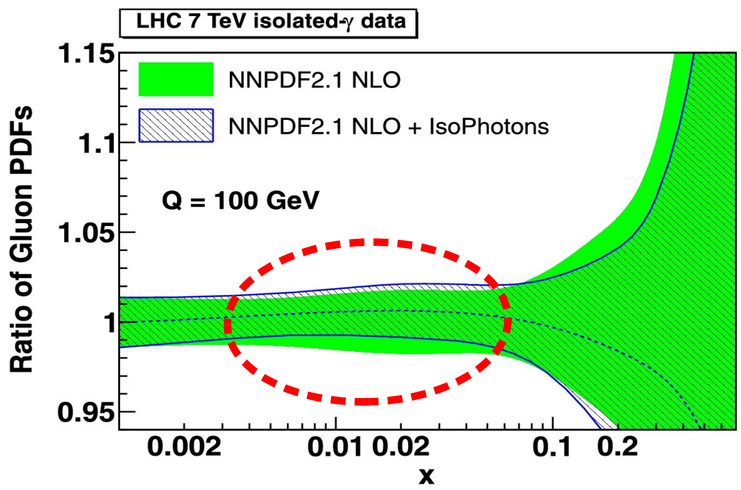
LHC γ_{isol}-data: PDF flavours and x range



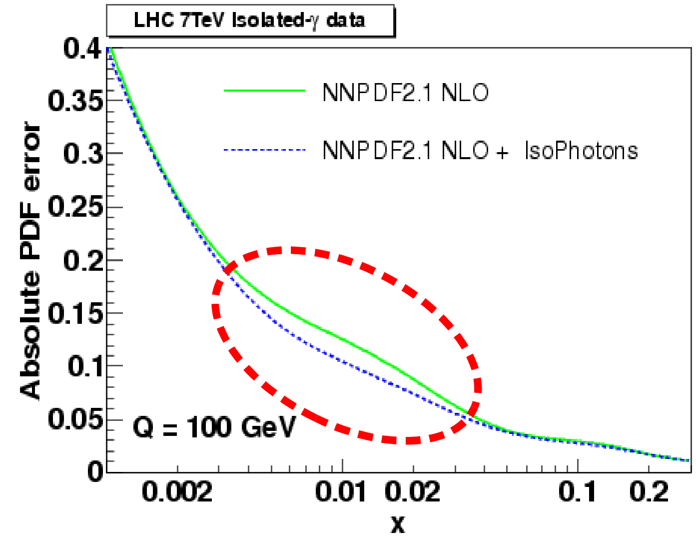
- LHC-7 TeV isolated-photons: at y = 0 probe gluon x ~ 0.01 – 0.1
  at y = 2.5 probe gluon x ~ 10^{-3} – 0.01
- Sensitivity to other partons (u-,d-quarks) less important.

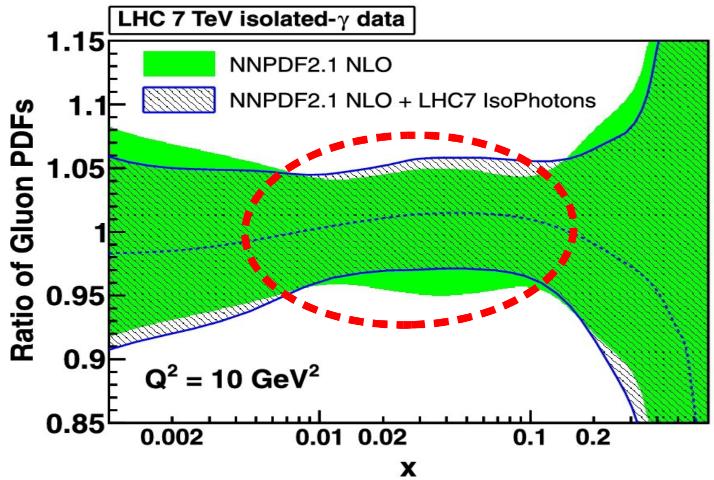
LHC γ_{isol}-data: Impact on gluon PDF

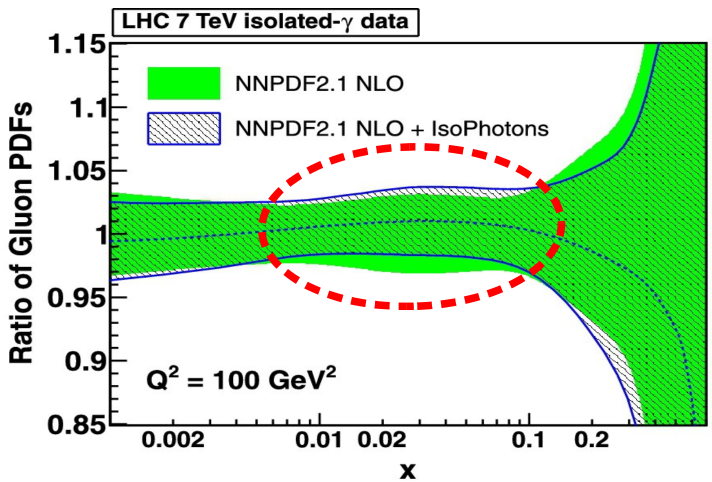
Reweighted-gluon / NNPDF2.1-gluon



Abs. Gluon errors



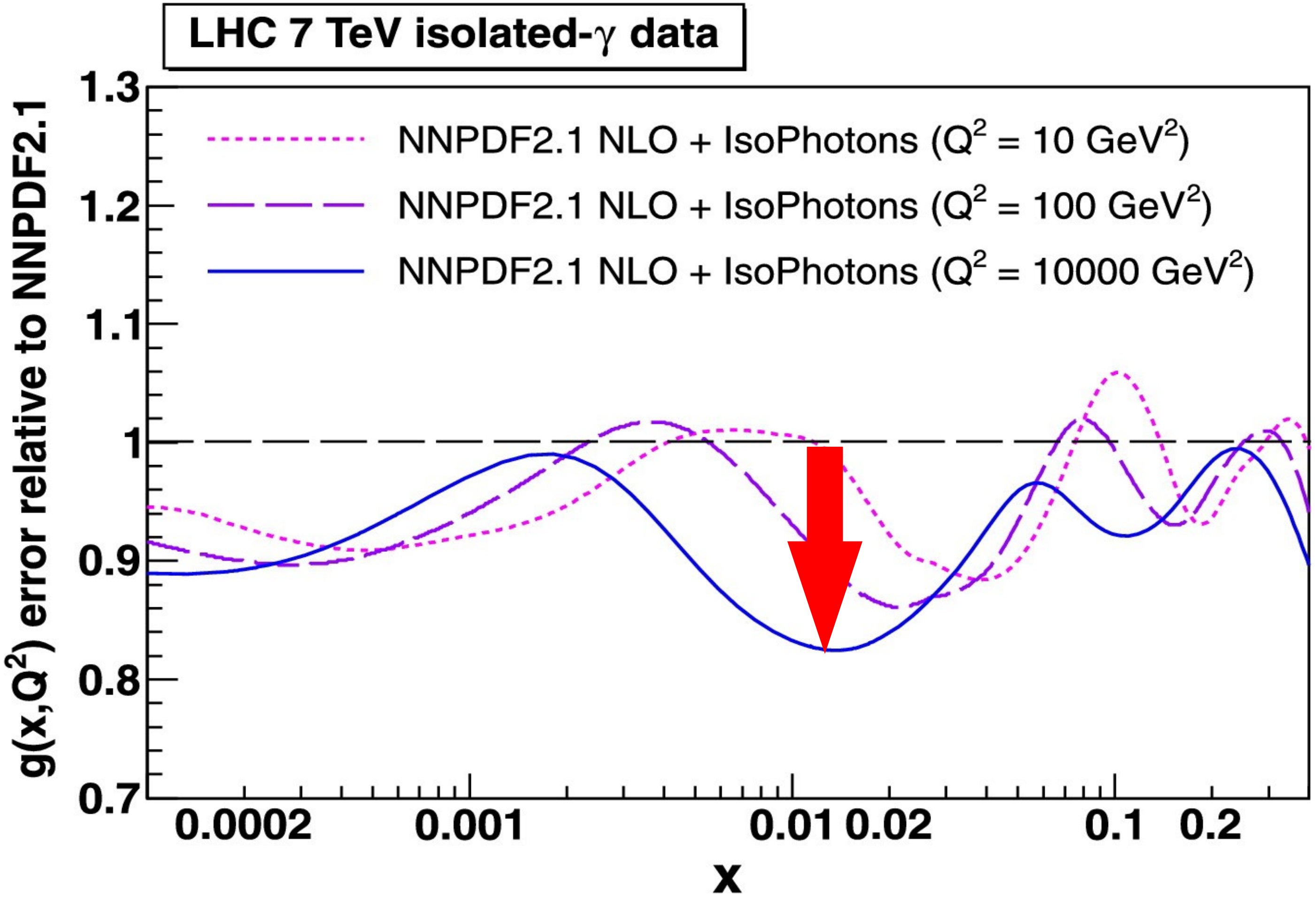




- LHC-7 TeV isolated-photons have impact for $5 \cdot 10^{-3} < x < 0.1$, all Q^2
- Gluon NLO PDF uncertainty reduced by up to ~20%
- Tevatron, Sp$\bar{p}$S, RHIC measurements have negligible impact ...

LHC γ_{isol}-data: Impact on gluon PDF

[D.d'E & J.Rojo, NPB 860 (2012) 311]

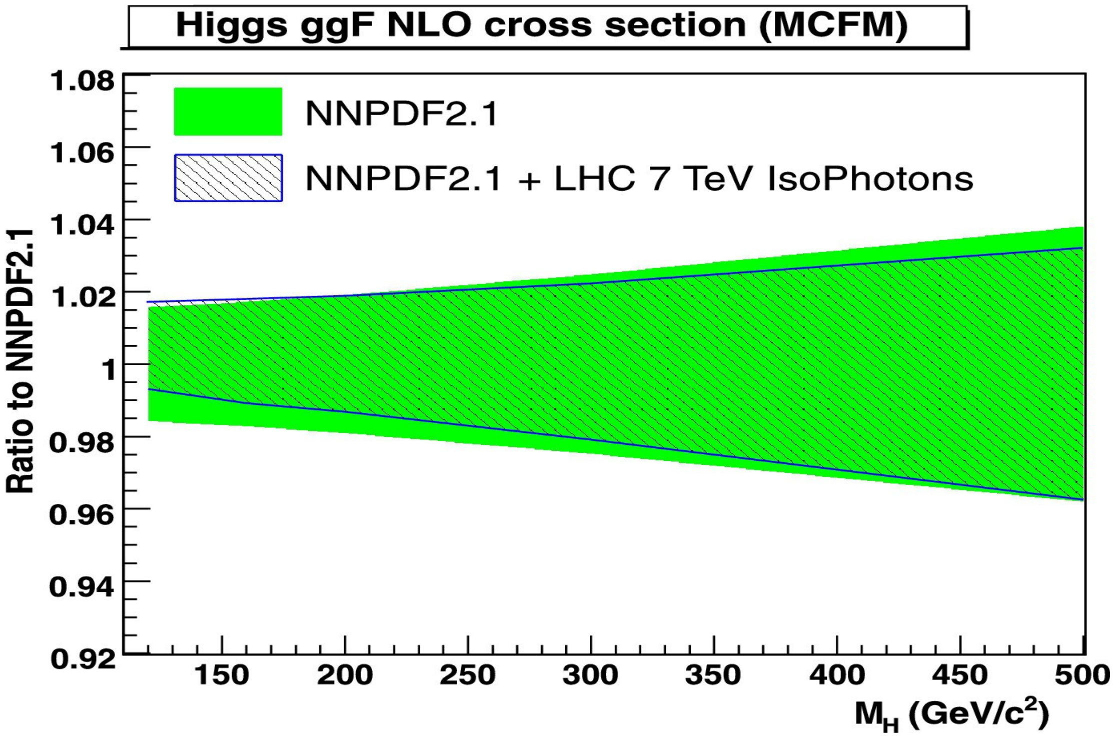


- LHC-7 TeV isolated-photons have impact for $5{\cdot}10^{-3} < x < 0.1$, all Q^2
- Gluon NLO PDF uncertainty reduced by up to ~20%

Example of reweighted gluon: Impact on gg → H

[D.d'E & J.Rojo, NPB 860 (2012) 311]

- Reweighted $g_{NLO}(x,Q^2)$ reduces by ~20% the theoretical (PDF) uncertainty on σ(gg → H):



- σ(gg → H) & other processes:

Process/cross section	$gg \to H(120)$	$gg \to H(160)$	$gg \to H(200)$	$gg \to H(500)$
NNPDF2.1	11640 ± 181 fb	6052 ± 103 fb	3494 ± 66 fb	219.3 ± 8.3 fb
NNPDF2.1 + LHC IsoPhotons	11701 ± 140 fb	6073 ± 86 fb	3504 ± 56 fb	218.4 ± 7.6 fb

Process/cross section	$t\bar{t}$	$t\bar{t}H(120)$	$WH(120)$	$ZH(120)$
NNPDF2.1	162 ± 51 pb	114 ± 5 fb	447 ± 9 fb	364 ± 6 fb
NNPDF2.1 + LHC IsoPhotons	162 ± 47 pb	113 ± 4 fb	448 ± 9 fb	365 ± 6 fb

Conclusions

- There exists 40+ measurements of isolated-photons at collider energies ($\sqrt{s}$ = 0.2 – 7 TeV):
  - ✔ Directly sensitive to gluon density: quark-gluon Compton scattering dominates x-sections (fragmentation-γ much reduced).
  - ✔ Follow "x_T scaling" with quasi-conformal n~4 power-law.
  - ✔ Corresponding 400+ data points (~135 from LHC) can be used to add direct constraints to the gluon PDF.

- NNPDF reweighting technique used with NLO JETPHOX:
  - ✔ Good agreement data vs 100 replicas (only 6 datasets with $\chi^2 > 3$).
  - ✔ Effective # of replicas reduced for LHC-7 TeV: N_{eff} ~ 89/100.
    For other c.m. energies: $N_{eff} \sim N_{old}$
  - ✔ LHC-7 TeV isolated-γ's have impact on $xG(x,Q^2)$ for $5\cdot10^{-3} < x < 0.1$: reduction of ~20% of gluon PDF (and gg-H x-section) uncertainty

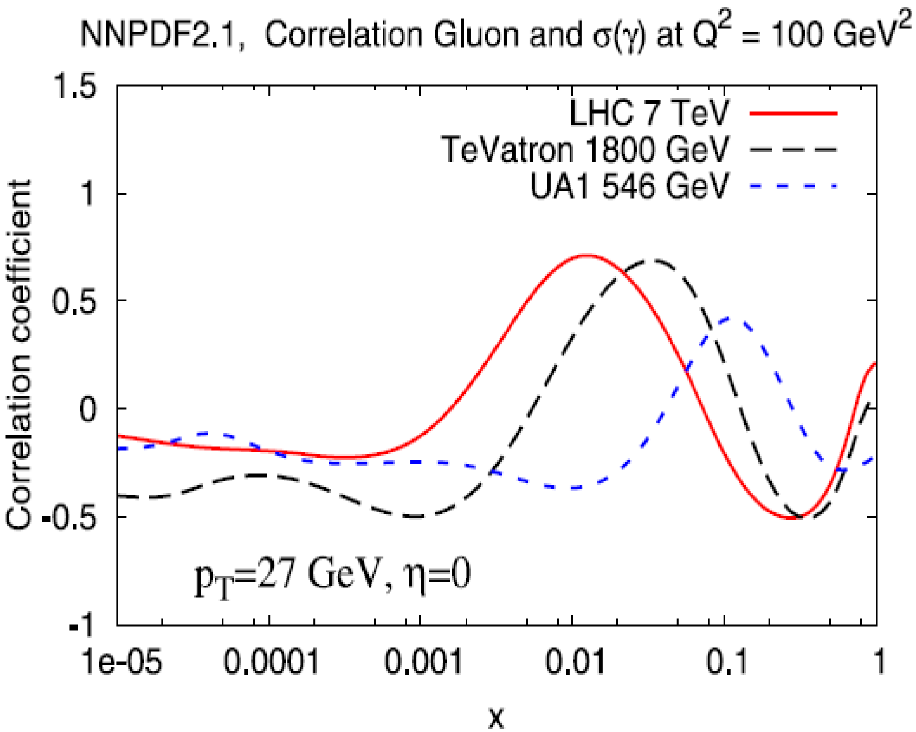
Outlook

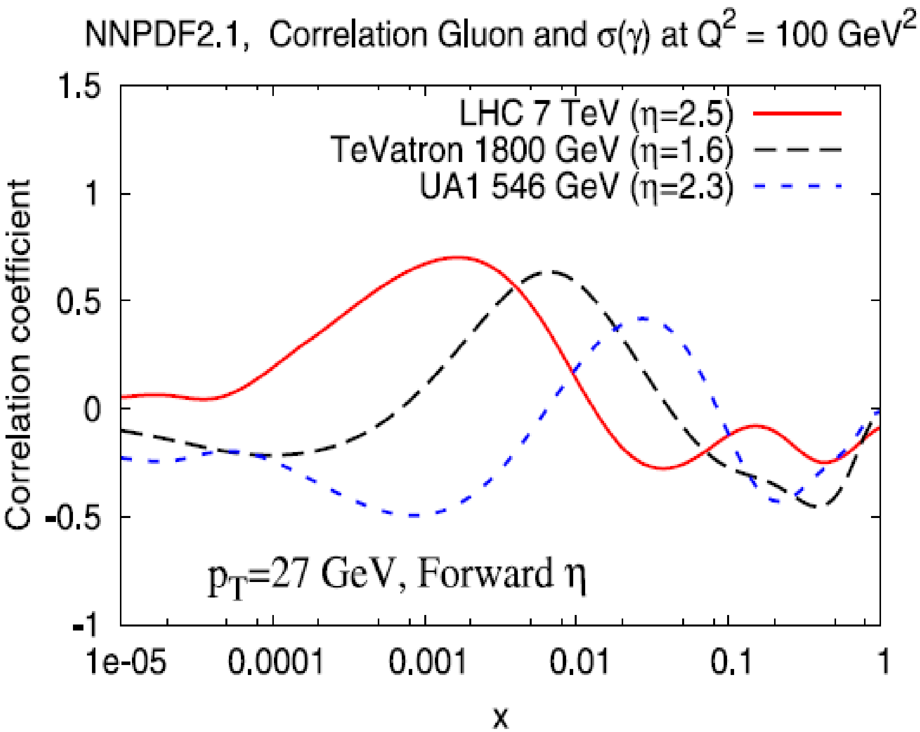
- Potentially interesting experimental developments:
  - Measurement of γ_{isol}(8 TeV)/γ_{isol}(7 TeV)
  - Measurement of γ_{isol}-jet
  - Meas. of γ_{isol} at higher y (LHCb?), lower p_T (ALICE?), lower $\sqrt{s}$ (RHIC?)
  - Use of Frixione's smooth cone ?
  - Provide full covariance matrix for uncertainties
  - ...

- Potentially interesting theoretical developments:
  - NLO + logs-resummations ? (also for jets)
  - Consistent determination of α_s coupling ?
  - Direct inclusion of γ_{isol} data in global fits (ApplGrid, fastNLO) ?
  - ...

Backup slides

World γ_{isol}-data: PDF flavours and x range

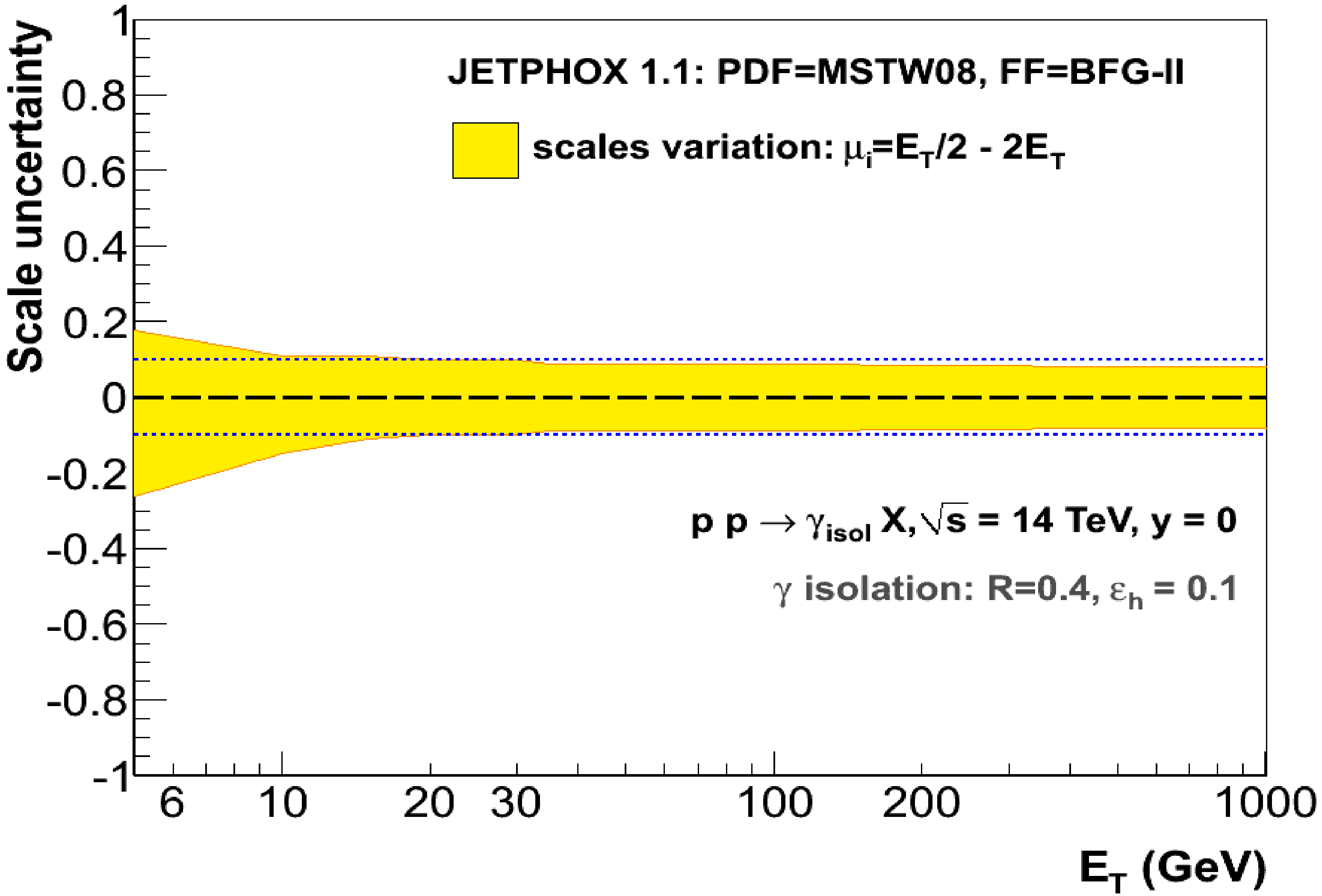




- LHC-7 TeV isolated-photons: at $y = 0$ probe gluon $x \sim 0.01 - 0.1$
  at $y = 2.5$ probe gluon $x \sim 10^{-3}$
- Tevatron & SppS: gluon probed at $x \sim 0.01 - 0.1$

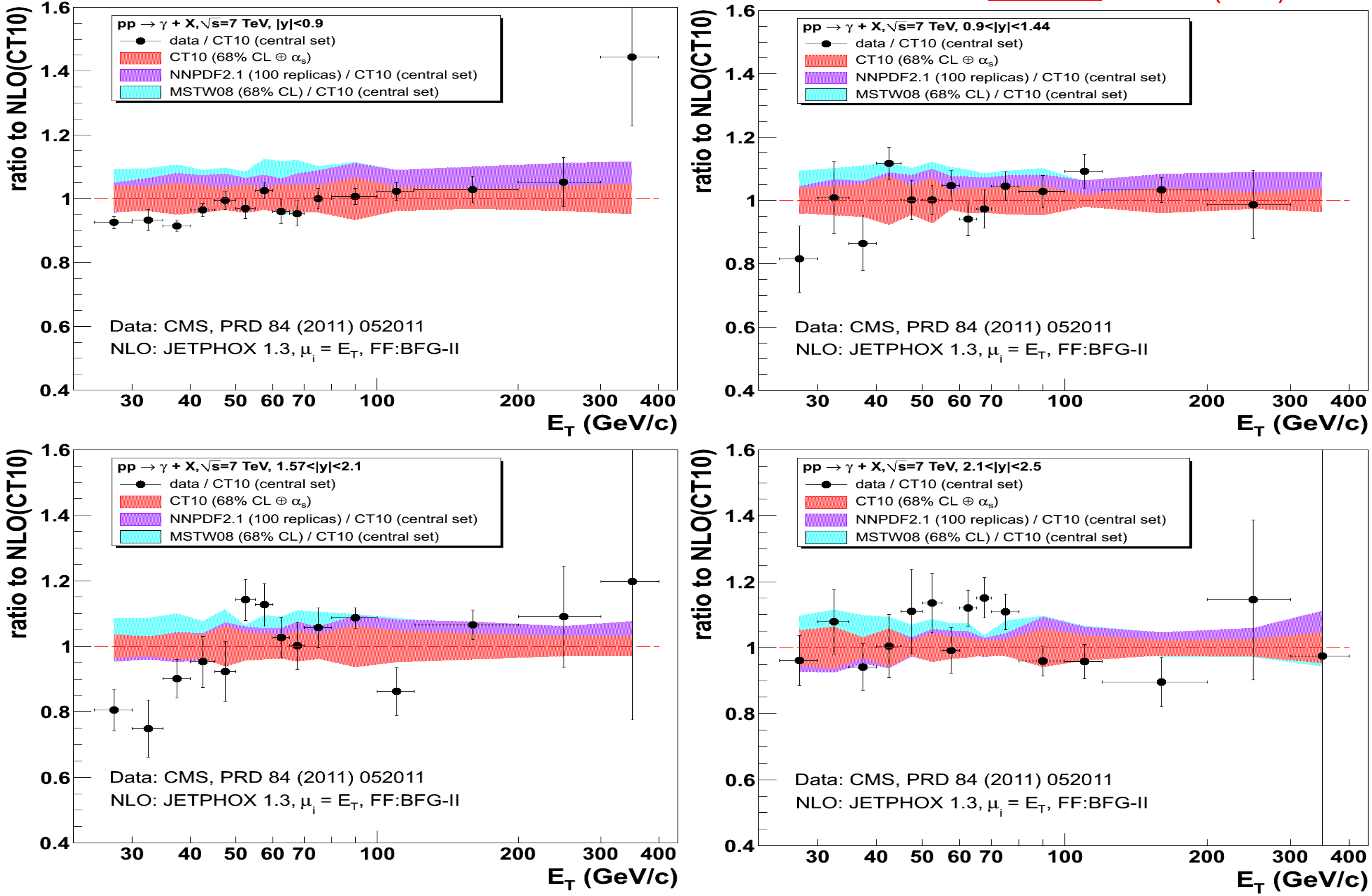
Scale uncertainty (NLO)

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



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

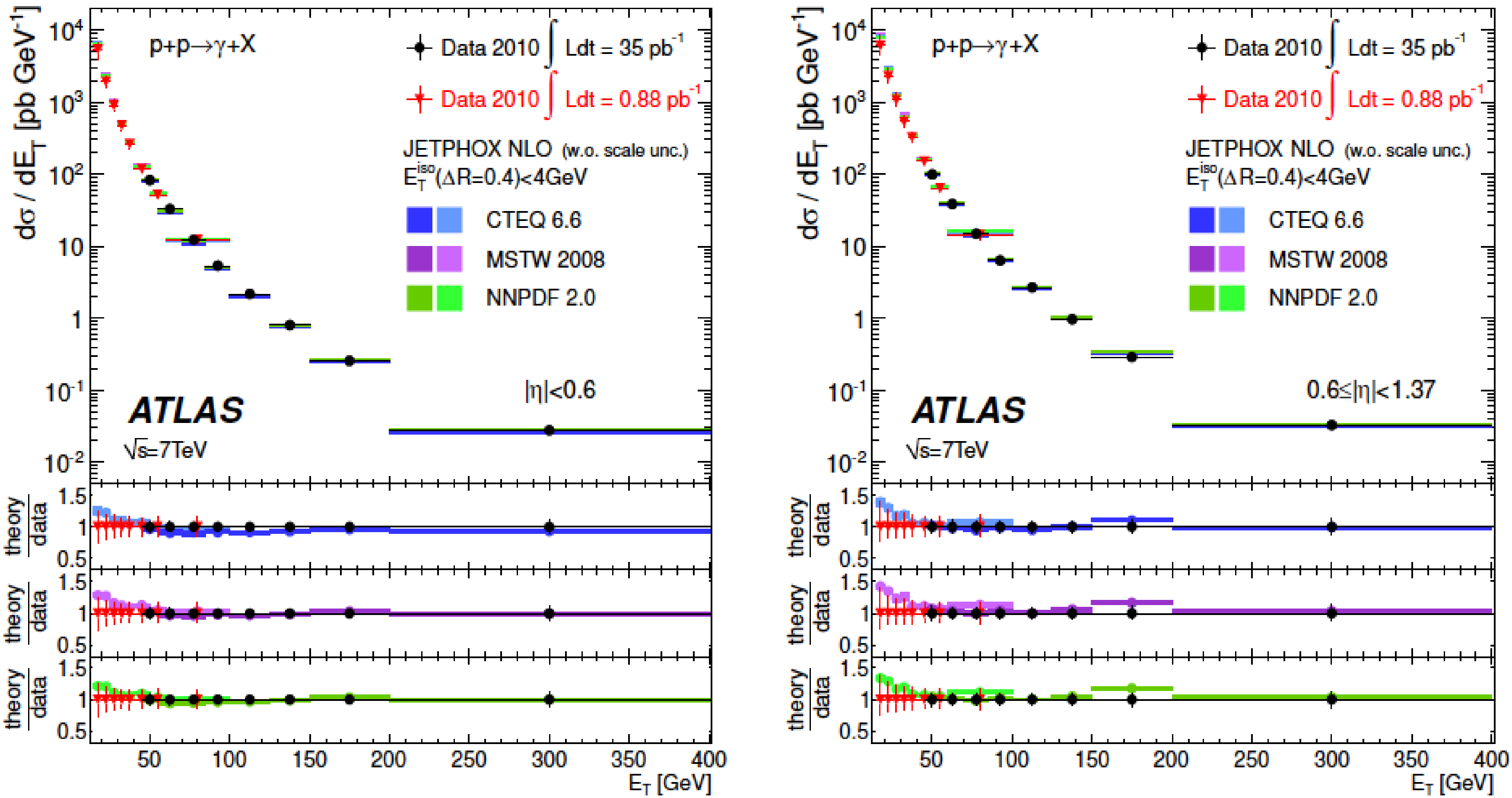
CMS data: PRD 84 (2011) 052011



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

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

ATL-PHYS-PUB-2011-013



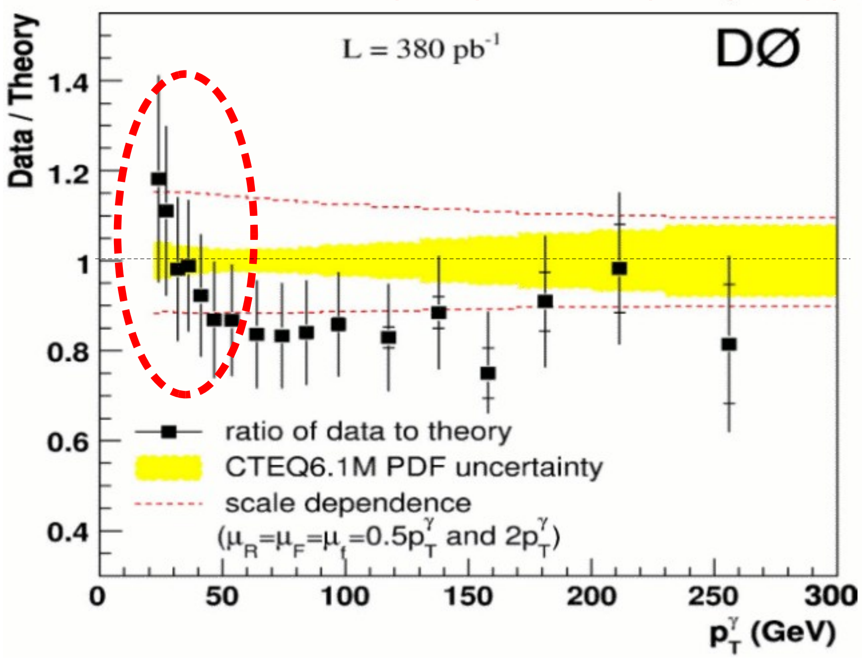
- Very good agreement data-NLO (slight overprediction at E_T<50 GeV/c ?)
  - Typical systematic uncertainties: ~20 – 7%
  - Theory uncertainties: Scales = 15 – 10%; PDF diffs. = 5 – 10%

pp → γ_{iso}+X at 1.96 TeV vs NLO

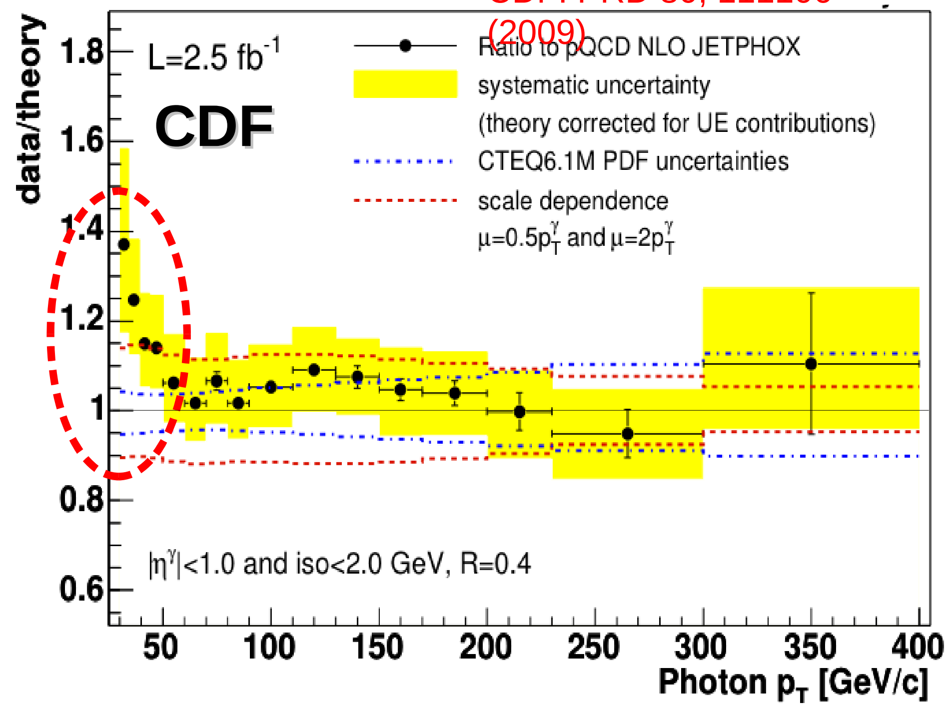
- D0 syst. uncertainty: ~20%
- CDF syst. uncertainty: 15 – 10%

(Tevatron uncertainties dominated by photon energy scale)

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



CDF: PRD 80, 111106 (2009)



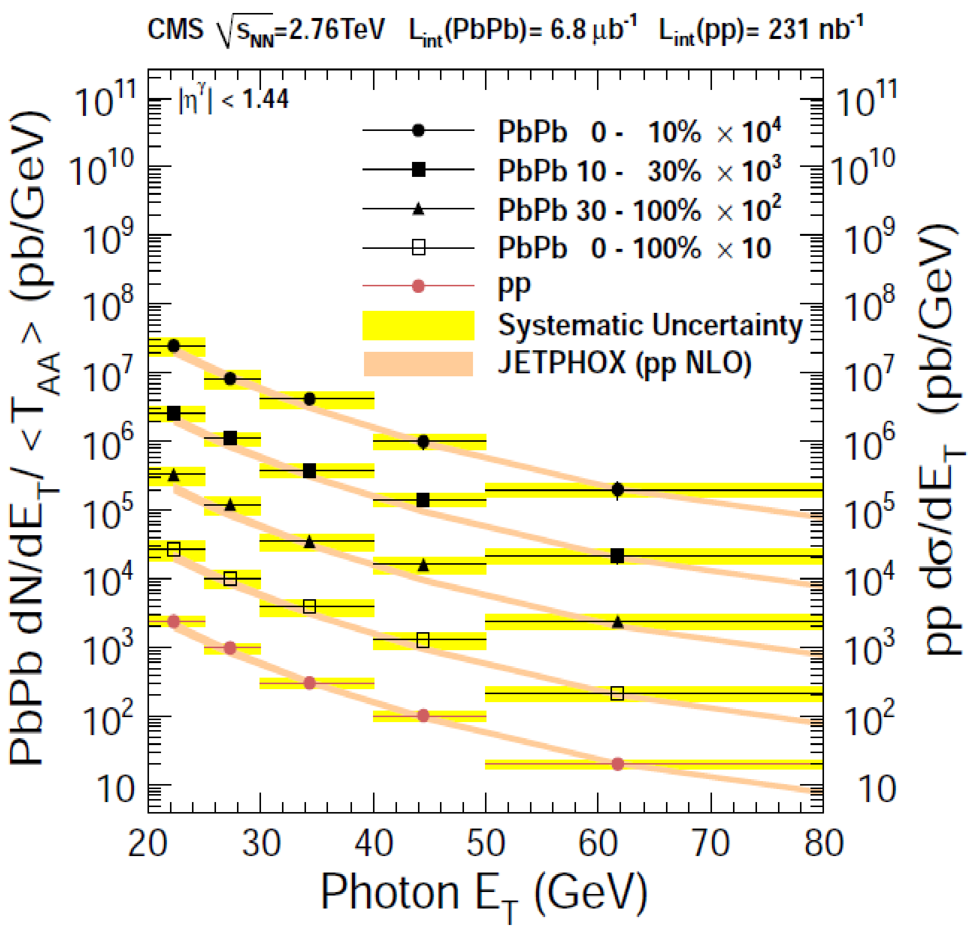
- NLO tends to underpredict data at p_T < 50 GeV/c (still OK within errors)
  - Theory scale uncertainty: 15 – 10%
  - Theory PDF uncertainty: 5 – 10%

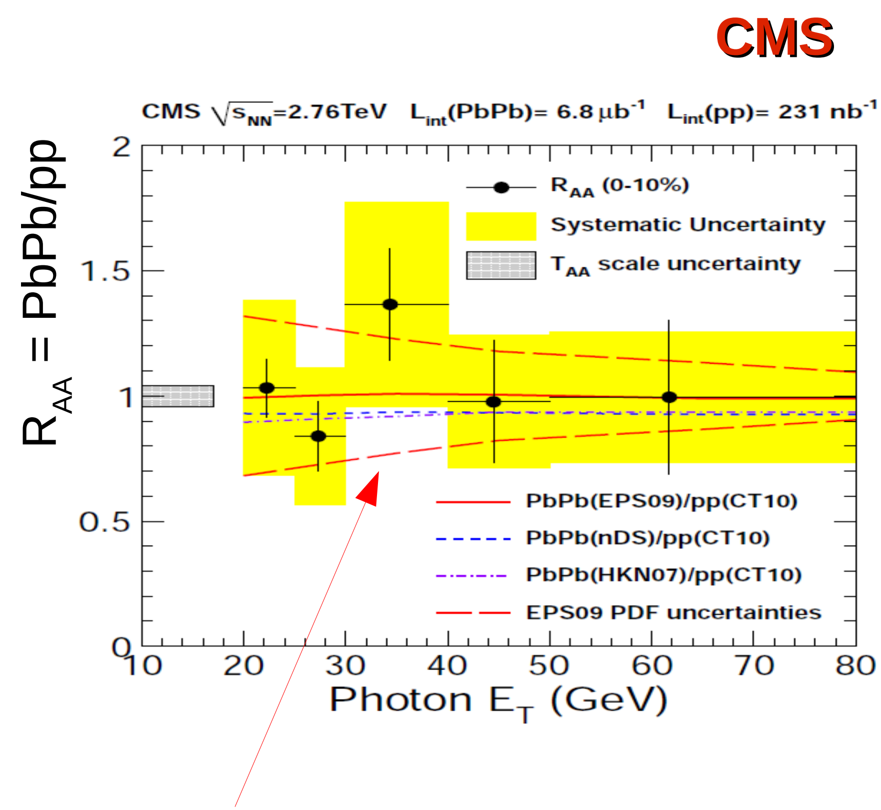
[See R.Ichou & D.d'E, PRD82 (2010) 014015]

PbPb,pp → γ_{iso}+X at 2.76 TeV vs NLO

[CMS, arXiv:1201.3093]

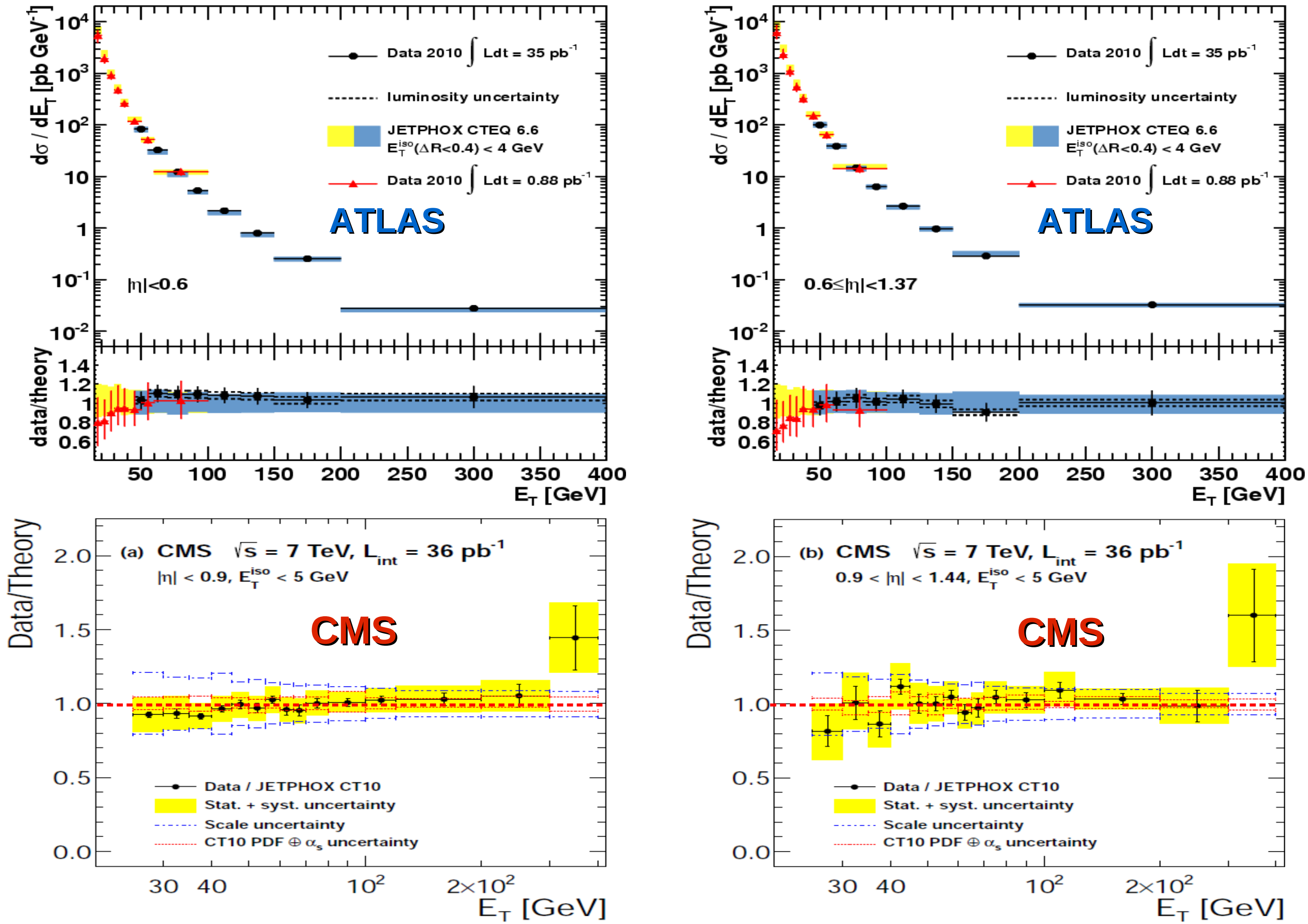
- Good agreement data – NLO for both pp & PbPb systems.
- R_{AA} = Pb-Pb/p-p~1 ⇒ small nuclear PDF modifications in probed x,Q^2





Current nuclear PDF (NLO) uncertainties: ±30-5%

pp → γ_{iso}+X at 7 TeV (barrel) vs NLO

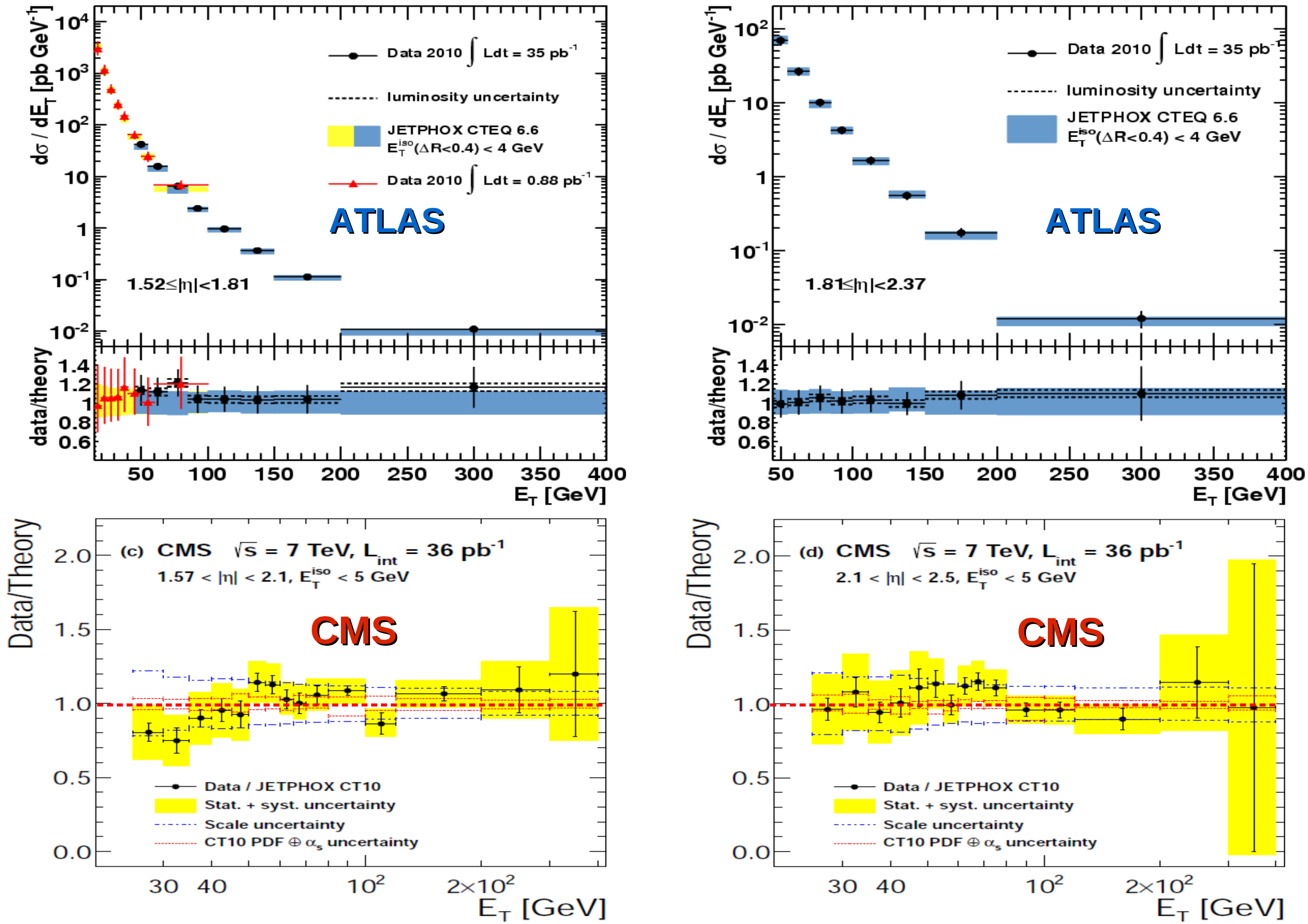


PRD 83 (2011) 052005
arXiv:1108.0253

PRL 106 (2011) 082001
PRD84 (2011) 052011

- Very good agreement data-NLO (slight overprediction at E_T<50 GeV/c ?)

pp → γ_{iso}+X at 7 TeV (endcap) vs NLO



PRD 83 (2011) 052005
arXiv:1108.0253

PRL 106 (2011) 082001
PRD84 (2011) 052011

- Very good agreement data-NLO at more forward rapidities