Parton distribution functions, isolated-photons and AFTER

Physics at fixed-target energies using the LHC beams

ECT*, Trento, 5th February 2013

David d'Enterria

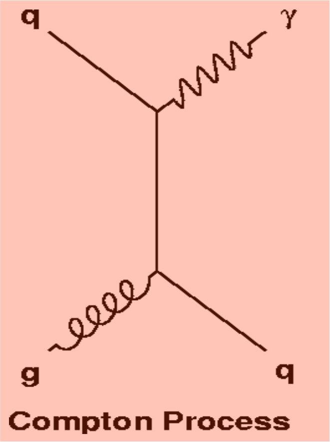
CERN

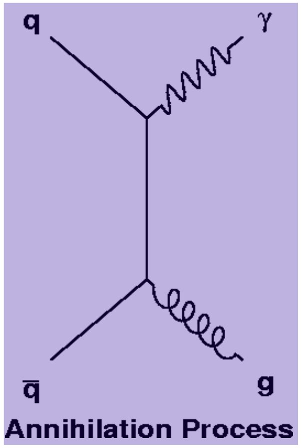
Outline

- Introduction:
  - Prompt & isolated photon production in hadronic collisions
- Isolated-γ at colliders (RHIC, SppS, Tevatron, LHC):
  - World $d\sigma_\gamma/dp_T$ data: 35 measurements, (x,Q^2) map, x_T scaling
  - PDF reweighting setup: JETPHOX NLO + NNPDF2.1 (100 replicas)
  - Quantitative impact on gluon PDF
  - Other LHC measurements: isolated-γ+jet in p-p, isolated-γ in Pb-Pb
- Isolated-γ predictions for AFTER:
  - (x,Q^2) map, uncertainties in p and Pb PDFs at high-x
  - NLO predictions for p-p and Pb-Pb: uncertainties, expected yields.
- Summary

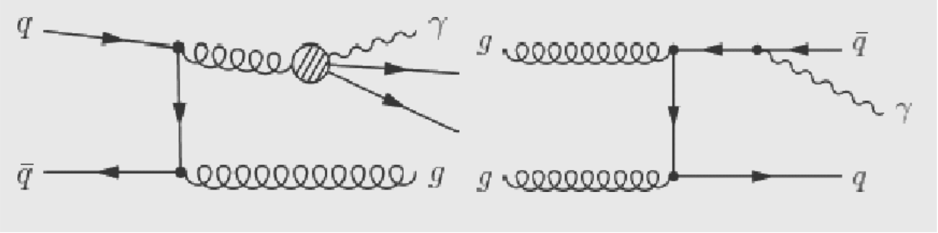
Prompt-γ production in hadronic collisions

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

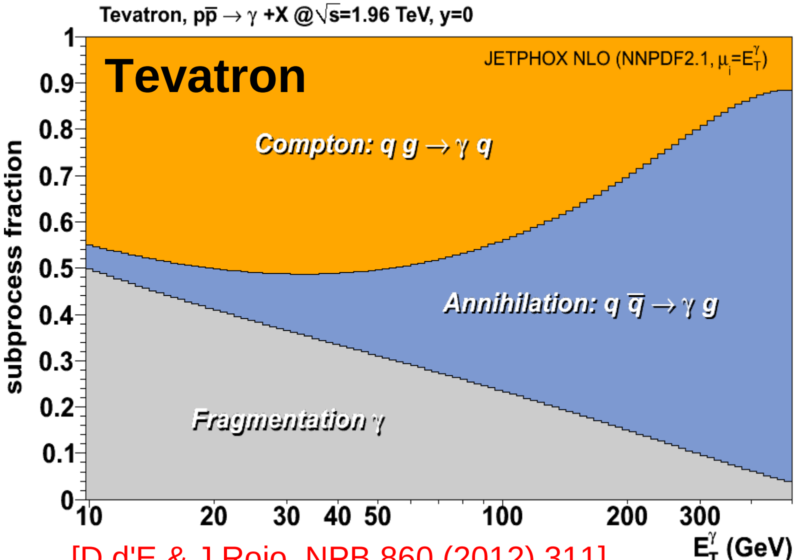


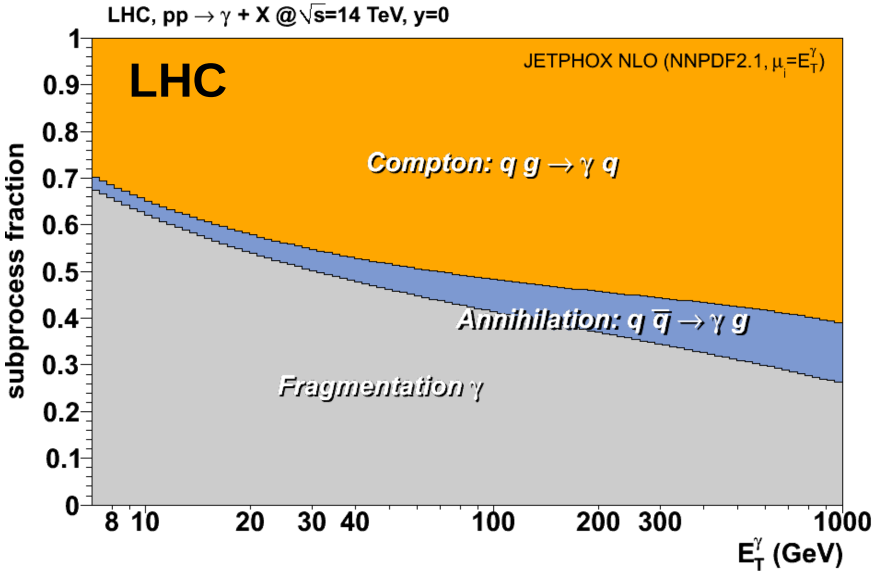


+ parton-to-photon fragmentation:



- Relative subprocess fractions (NLO): Important fragmentation contribution

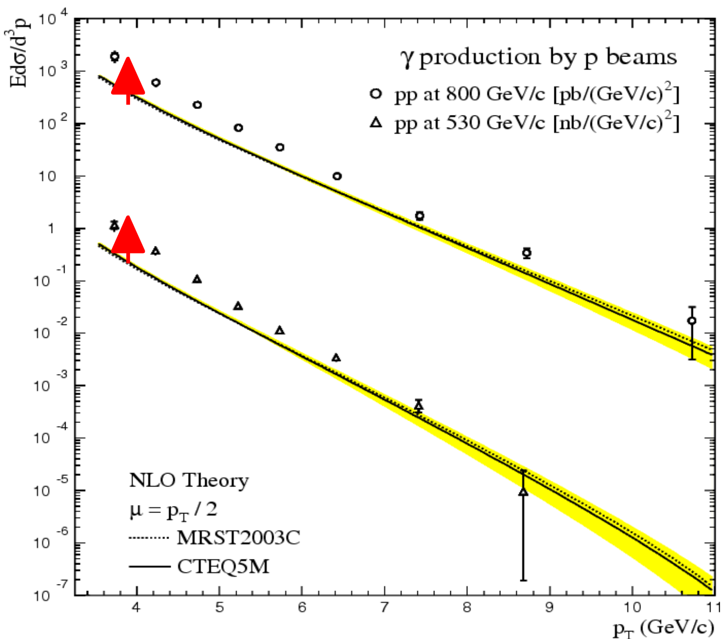




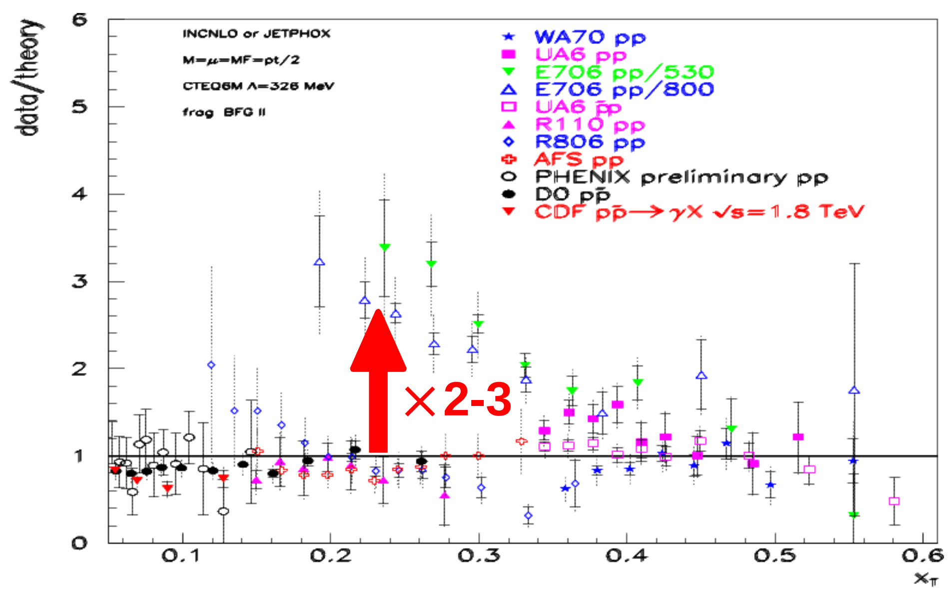
[D.d'E & J.Rojo, NPB 860 (2012) 311]

Prompt-γ production in hadronic collisions

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



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



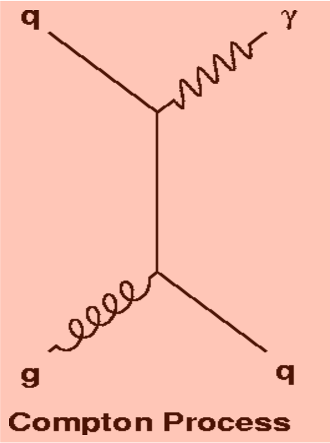
[P.Aurenche et al.'06]
[Also Owens, Vogelsang, ...]

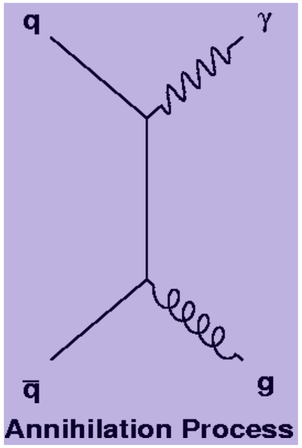
- Not solved by N^{2,3}LL soft-gluon threshold & recoil resummations:
  Low p_T dominated by intrinsic-k_T ? parton-to-γ FF ? nuclear target effects ?

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

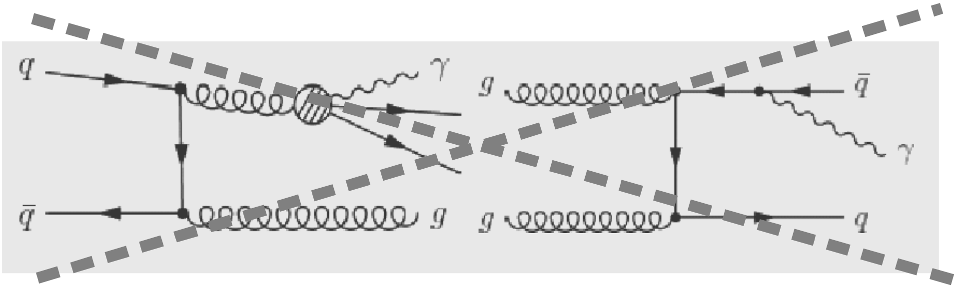
Isolated-γ production in hadronic collisions

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



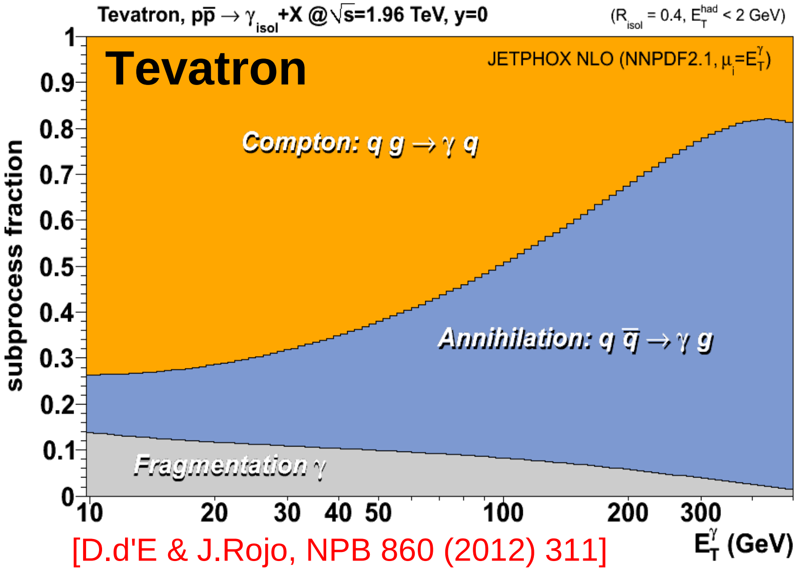


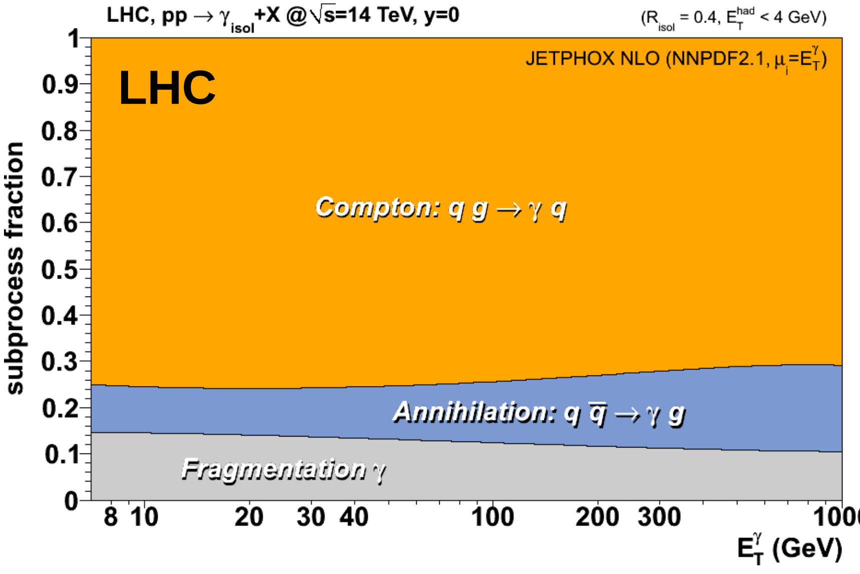
+ parton-to-photon fragmentation:



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

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





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

Redeeming γ data for PDF global fits

- Does NLO reproduce the existing photon data ... ? Yes !
  - ✔ Applying isolation cuts: Removing 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

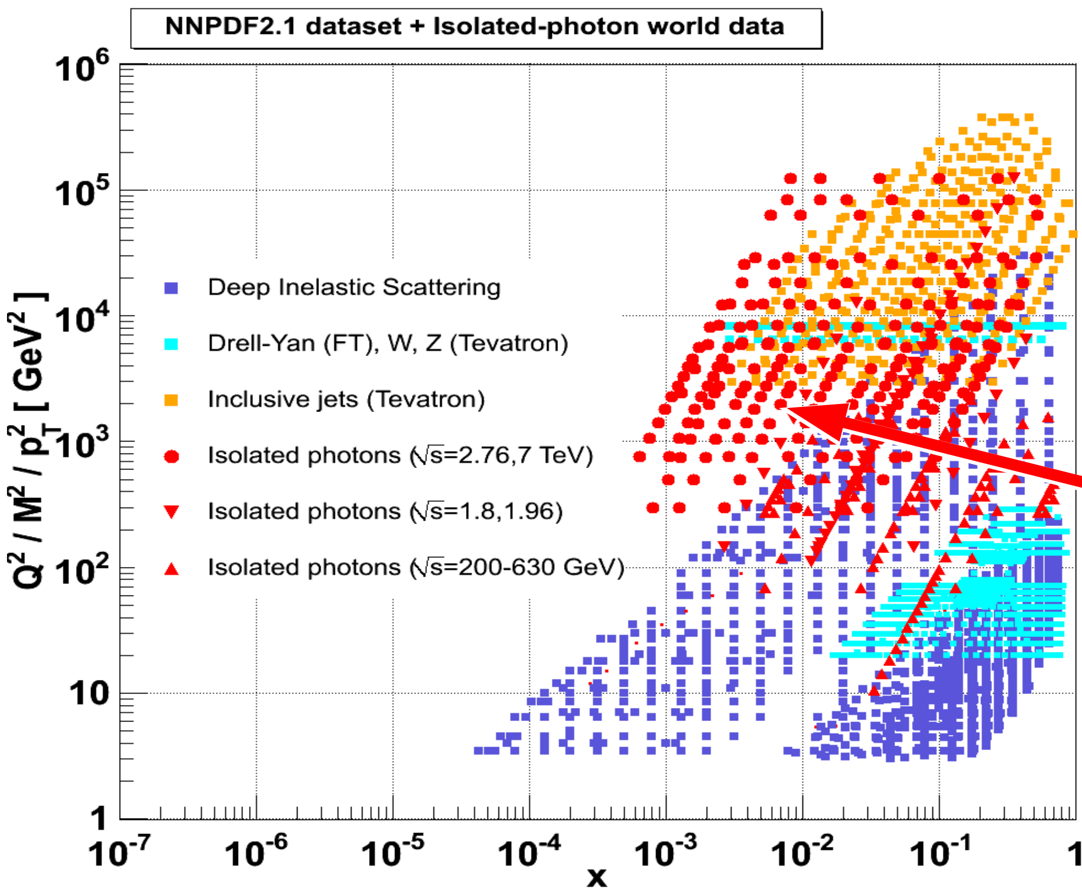
(3) Using NNPDF Bayesian reweighting technique ✔

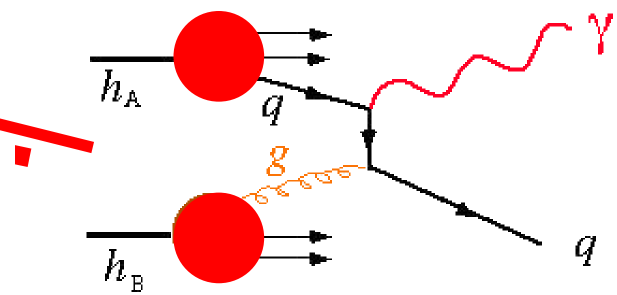
Isolated-photons at p-p colliders

(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,Q²) domain

[xG(x,Q²) 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/S$p\bar{p}$S/RHIC & increasing ...

LHC: ~135 data points

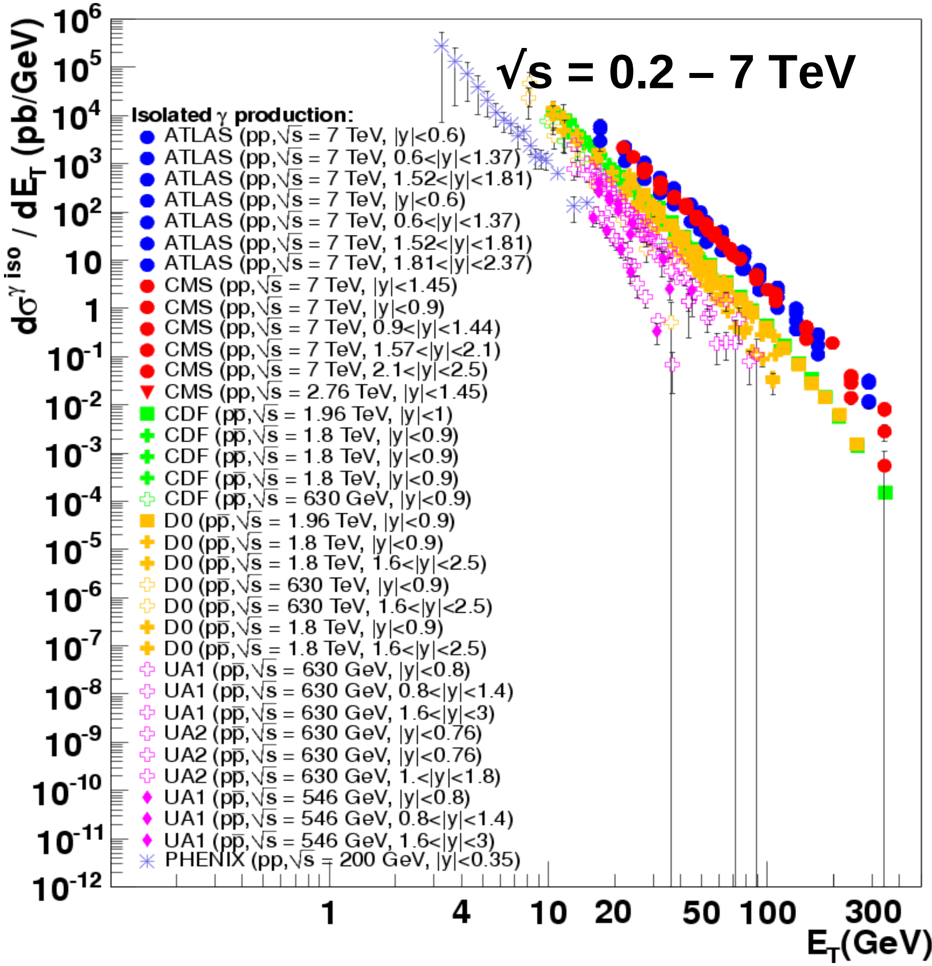
System	Collab./experiment (collider) [Ref.]	$\sqrt{s}$ (TeV)	$\lvert y_\gamma \rvert$ range	E_T^γ range (GeV)	x range	Data points	Isolation radius, had. energy
p–p	ATLAS (LHC) [34]	7.	<0.6	15–100	5×10^{-3}–0.05	8	$R=0.4$, $E_h<5$ GeV
p–p	ATLAS (LHC) [34]	7.	0.6–1.37	15–100	3×10^{-3}–0.1	8	$R=0.4$, $E_h<5$ 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 (S$p\bar{p}$S) [52]	0.63	<0.8	16–100	0.03–0.3	16	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (S$p\bar{p}$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 (S$p\bar{p}$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 (S$p\bar{p}$S) [53]	0.63	<0.76	14–92	0.03–0.3	13	$R=0.265$, $\varepsilon_h<0.25$
p–$\bar{p}$	UA2 (S$p\bar{p}$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 (S$p\bar{p}$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 (S$p\bar{p}$S) [52]	0.546	<0.8	16–51	0.03–0.2	6	$R=0.7$, $E_h<2$ GeV
p–$\bar{p}$	UA1 (S$p\bar{p}$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 (S$p\bar{p}$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	$R=0.5$, $\varepsilon_h<0.1$

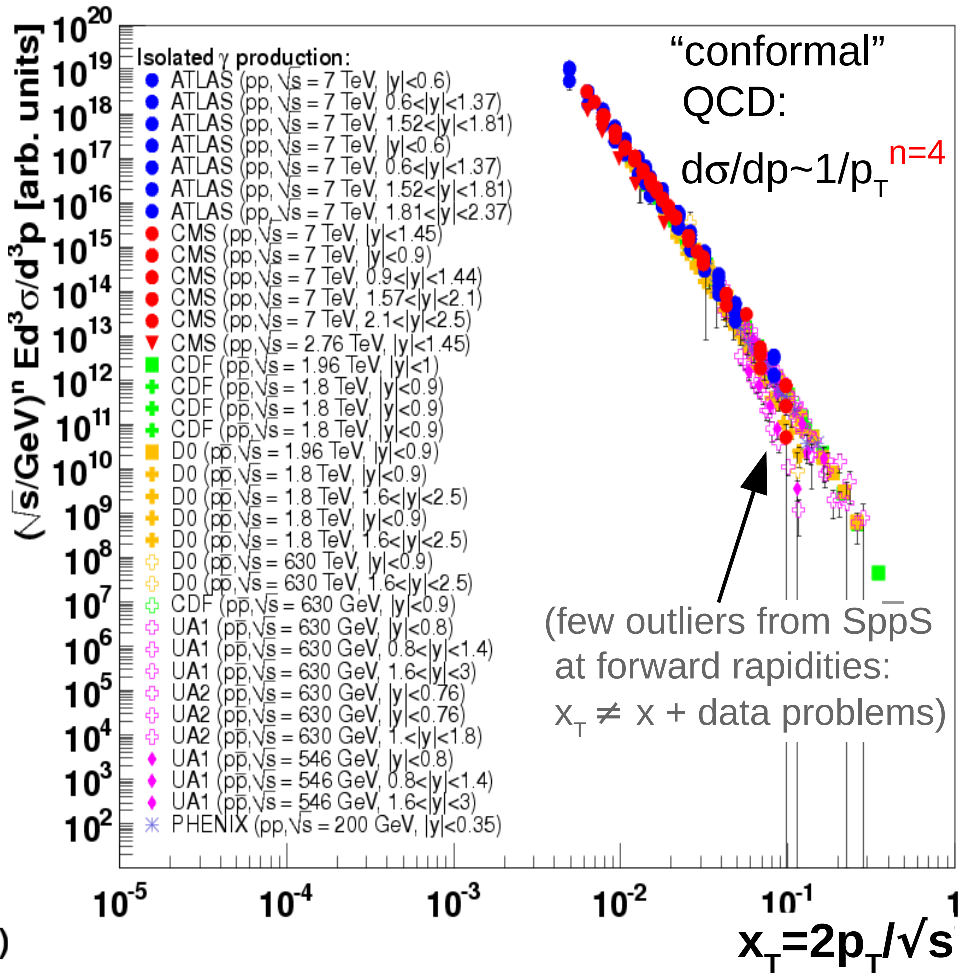
Isolated-γ collider world-data (II)

[D.d'E & R.Ichou, PoS EPS-HEP(2011) 291]

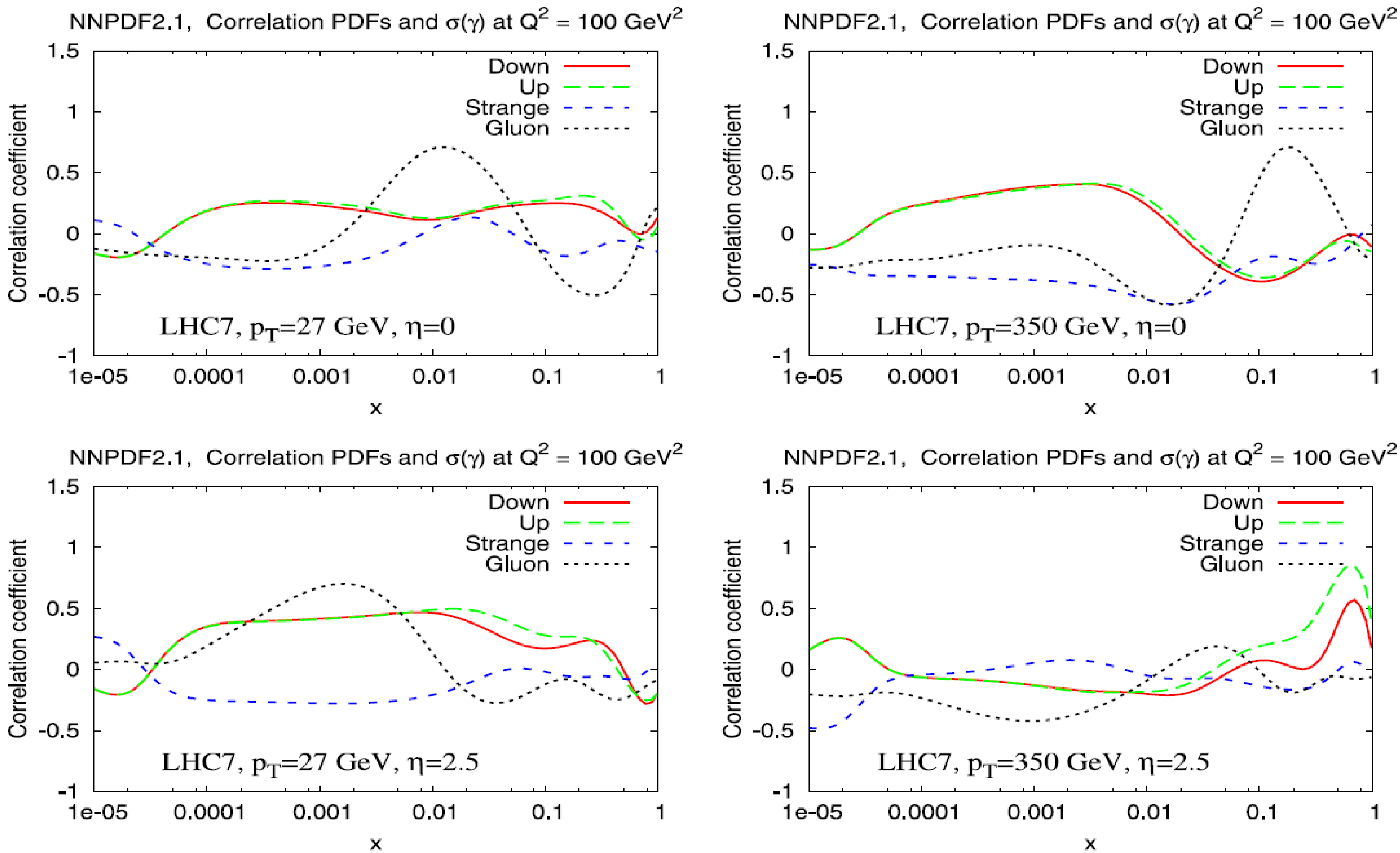
- LHC/Tevatron/Sp$\bar{p}$S/RHIC
  power-law p_T spectra
  within ~4 – 400 GeV/c

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





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.

PDF reweighting via JETPHOX + NNPDF2.1

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

- 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 !)

  ×35 !

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

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

(2) χ^2 $d\sigma_{EXP}/dp_T$ (syst.⊕stat. uncert., no cov.matrices) vs $d\sigma_{NLO}/dp_T$ per replica.

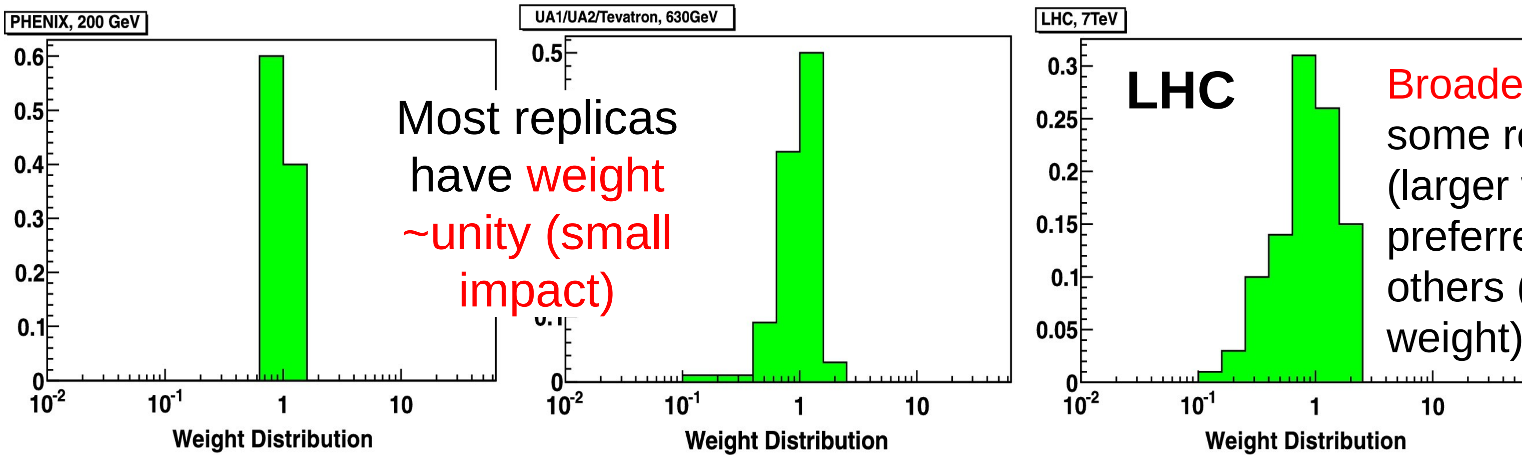
(3) Obtain associated "weight" for each replica: $$w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}{\frac{1}{N}\sum_{k=1}^N (\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}$$

(4) Obtain effective old+new 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: $$\langle \mathcal{O}\rangle_{\rm new} = \frac{1}{N}\sum_{k=1}^N w_k \mathcal{O}[f_k]$$

NNPDF reweighting results

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

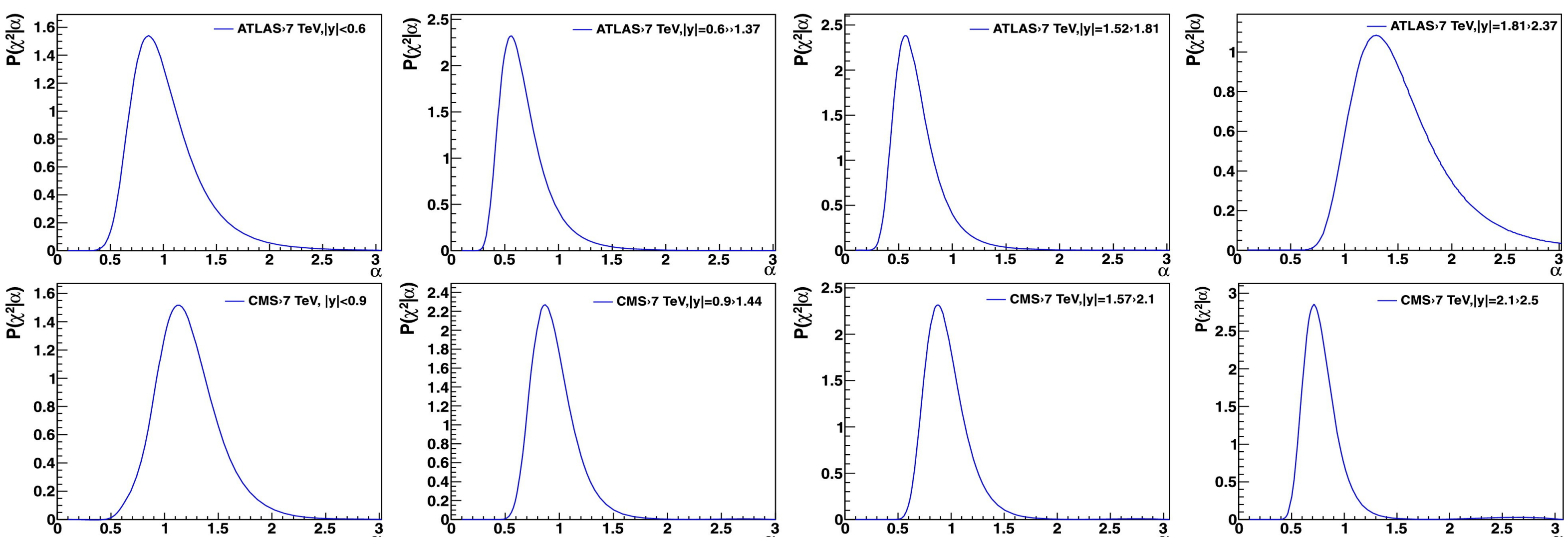


Most replicas have weight ~unity (small impact)

LHC

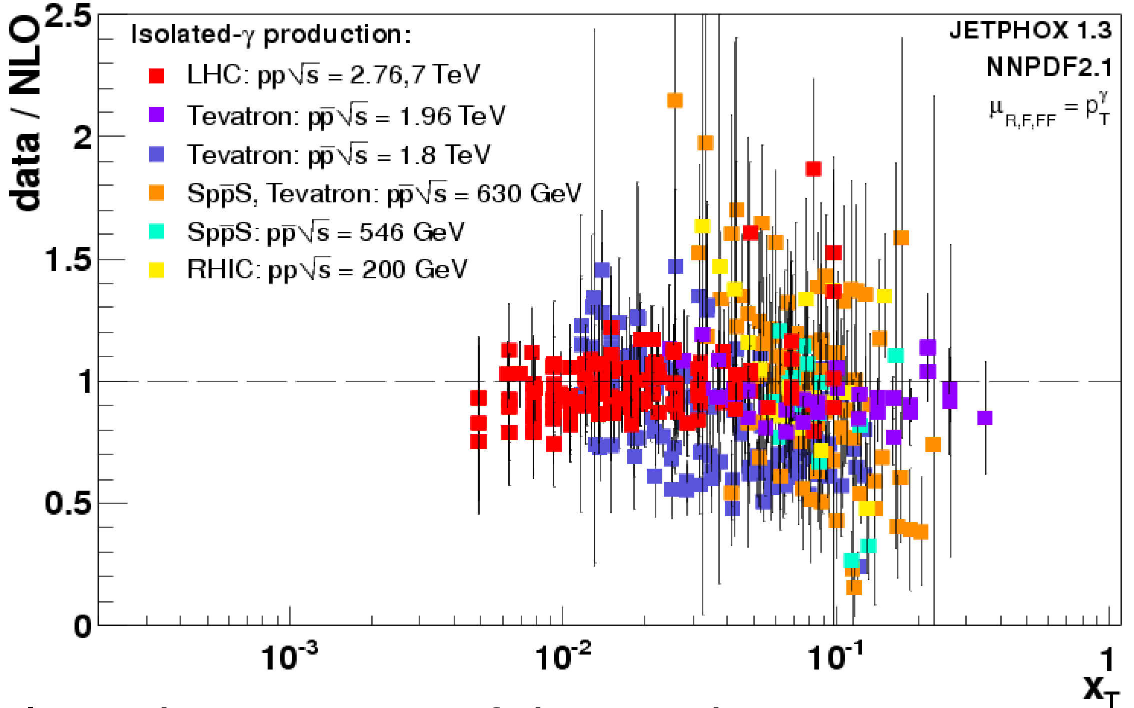
Broader distribution: some replicas (larger weight) preferred over others (smaller weight)

- 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]



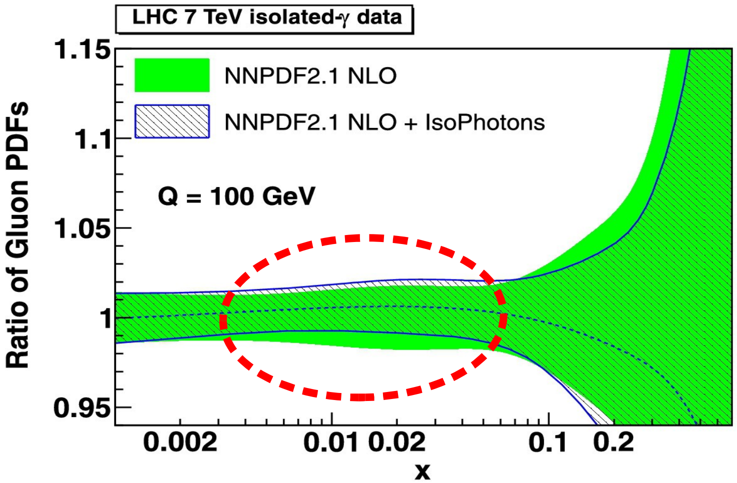
- General good agreement of data and NLO.
- 6 systems (older measurements) with χ^2/ndf>3 removed:
  - large P(χ^2|α): syst. uncertainties underestimated in a few bins.
  - Inconsistent with other measurements at same √s, η.
- Effective number of replicas after reweighting (Shannon entropy):

$\sqrt{s}$ (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

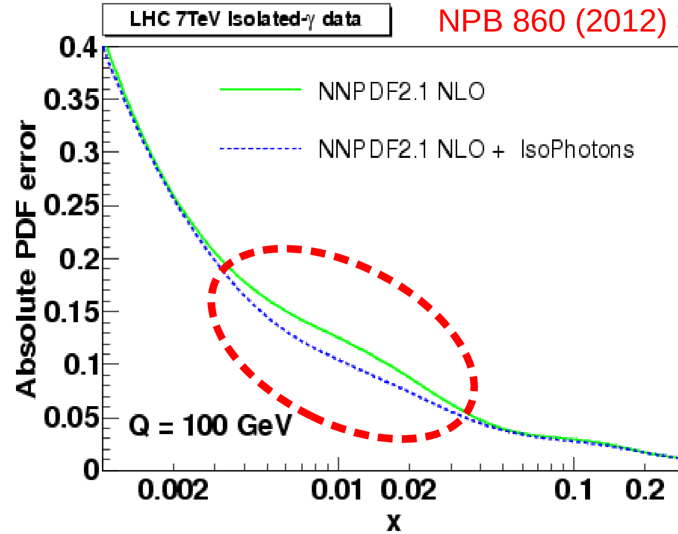
LHC γ_{isol} data: Impact on gluon PDF

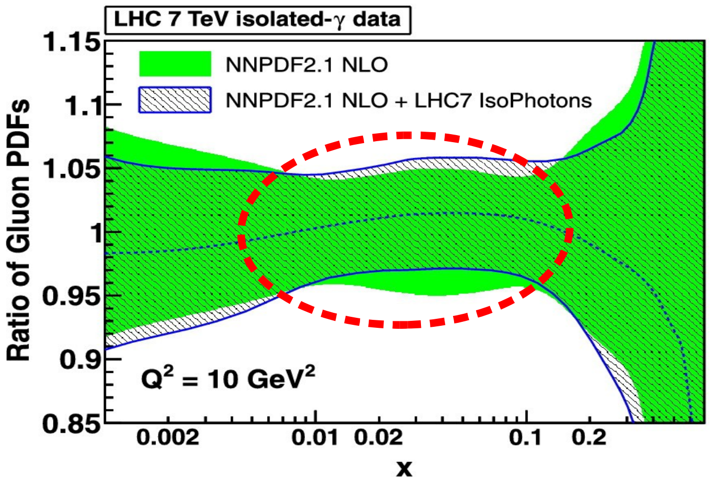
Reweighted-gluon / NNPDF2.1-gluon

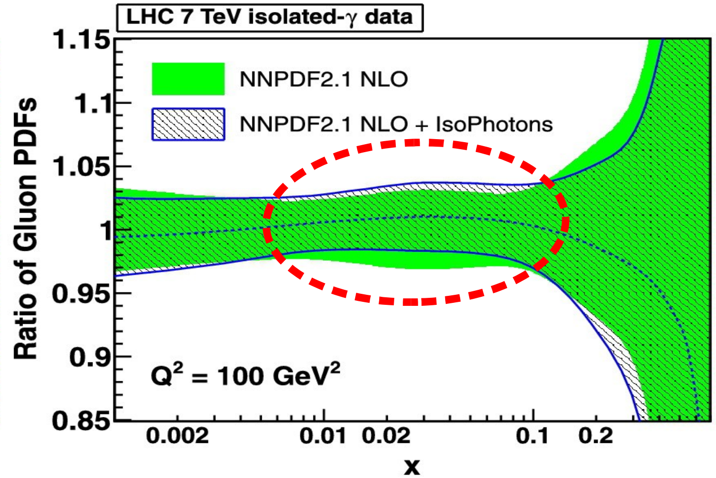


Abs. Gluon errors

NPB 860 (2012) 311]



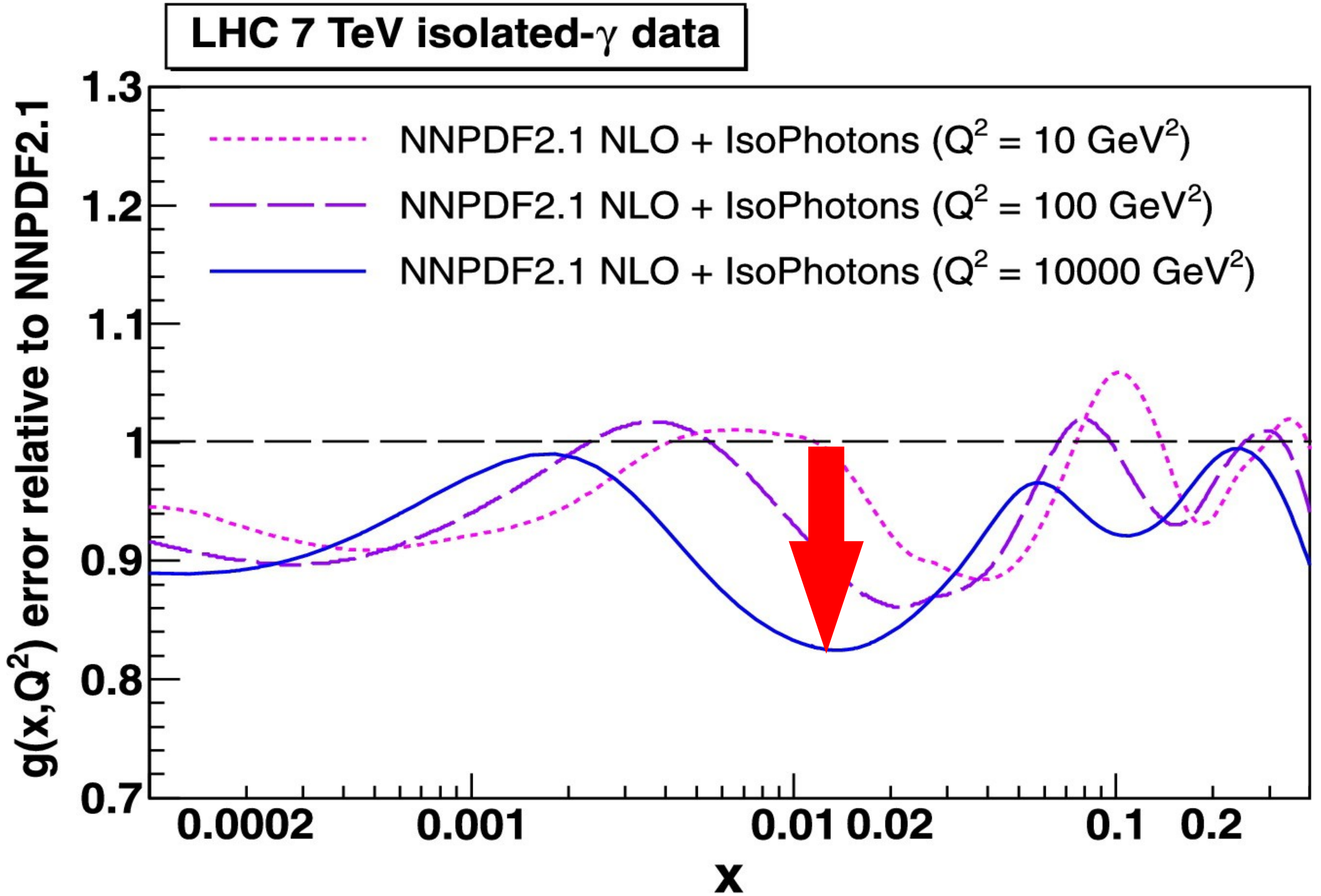




- LHC-7 TeV isolated-photons have impact for $5\cdot10^{-3} < x < 0.1$, all Q^2
- Gluon NLO PDF uncertainty reduced by up to ~20%
- Tevatron, $Sp\bar{p}S$, RHIC measurements have negligible impact ...

LHC γ_{isol} data: Impact on gluon PDF

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



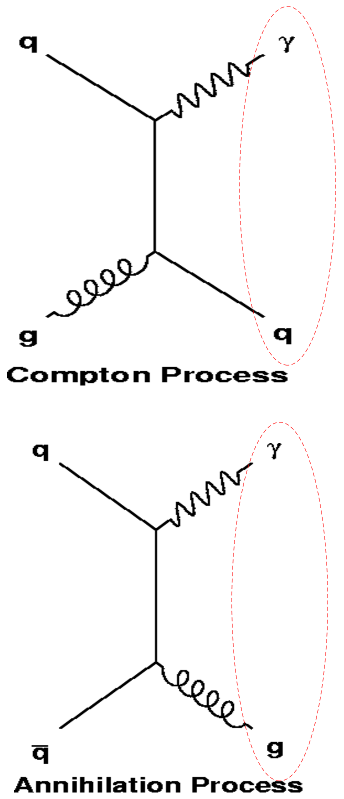
- LHC-7 TeV isolated-photons have impact for $5\cdot10^{-3} < x < 0.1$, all Q^2
- Gluon NLO PDF uncertainty reduced by up to ~20%

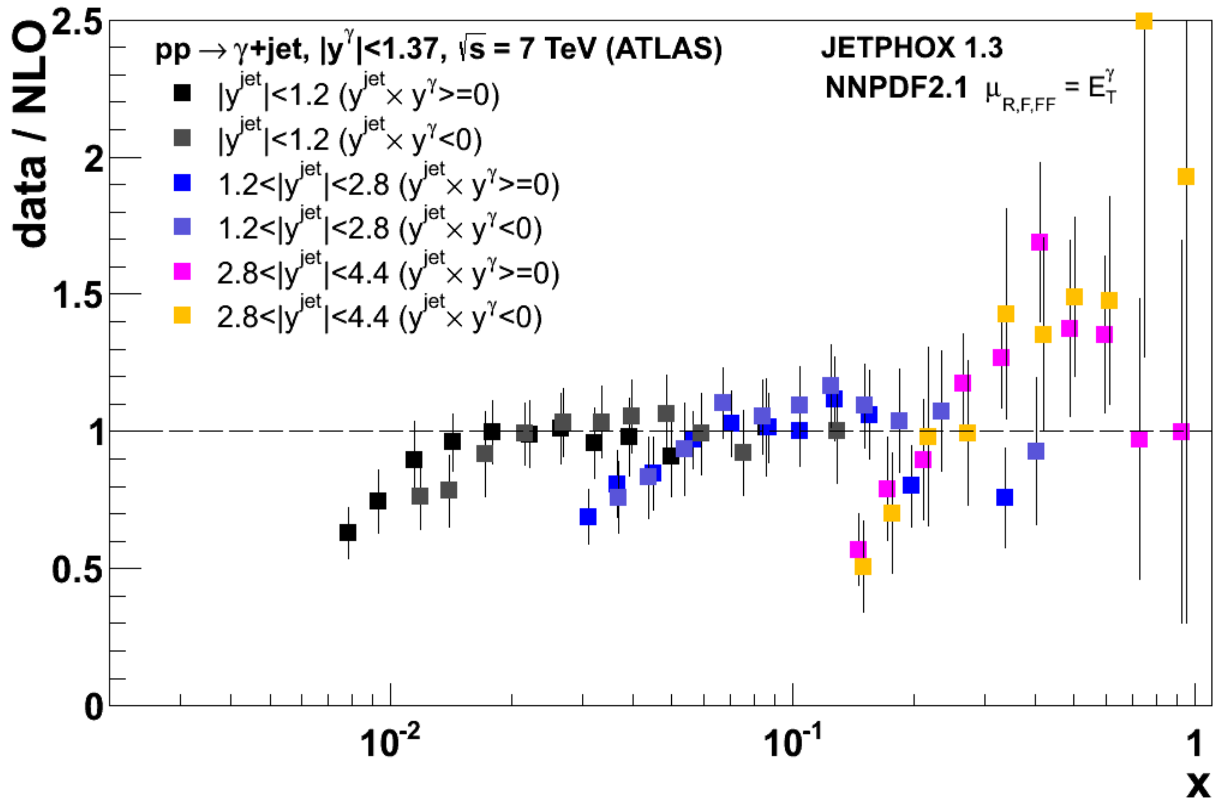
γ_{isol}-jet at 7 TeV: data vs JETPHOX+NNPDF2.1

[Carminati,D.d'E,J.Rojo, et al. arXiv:1212.5511]

- 6 data sets: $|y^{\gamma}|<1.37$, $p_T^{photon}, p_T^{jet}>20$ GeV

  [$|y^{jet}| < 1.2$, $1.2 < |y^{jet}| < 2.8$, $2.8 < |y^{jet}| < 4.4$] for $y^{\gamma} \times y^{jet} < 0$, $y^{\gamma} \times y^{jet} > 0$





- Good data-NLO agreement for the 6 data-sets ($\chi^2 \sim 1$)

  except for events with most fwd-jets: $\chi^2 \sim 2.6$ (physics ? experimental ?)

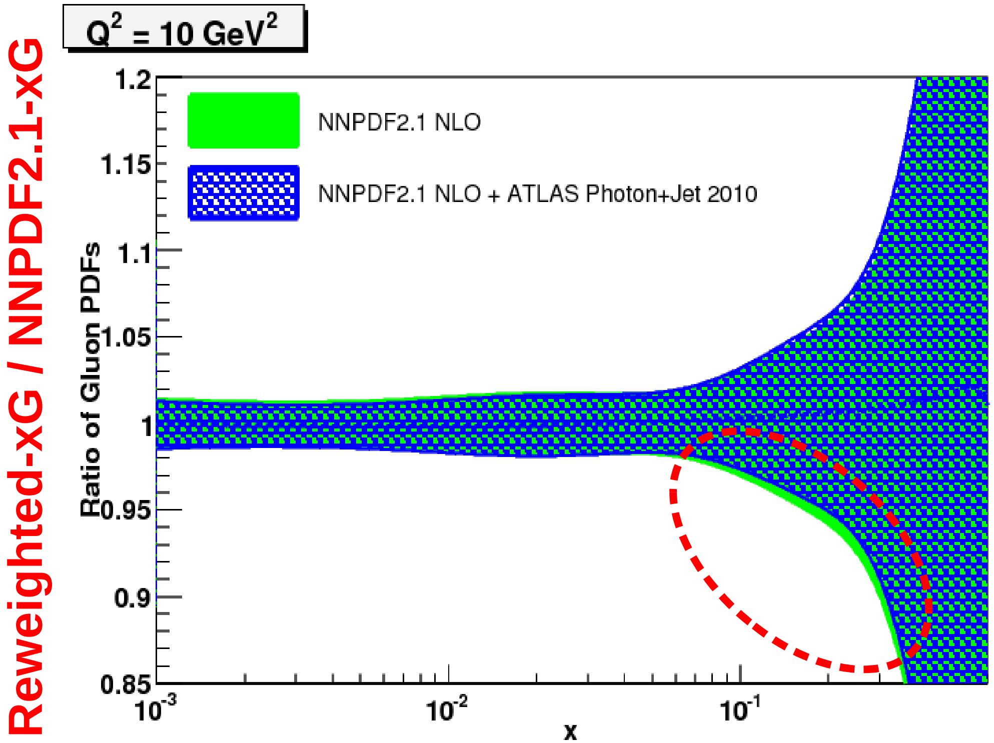
γ_{isol}-jet at 7 TeV: Impact on gluon PDF

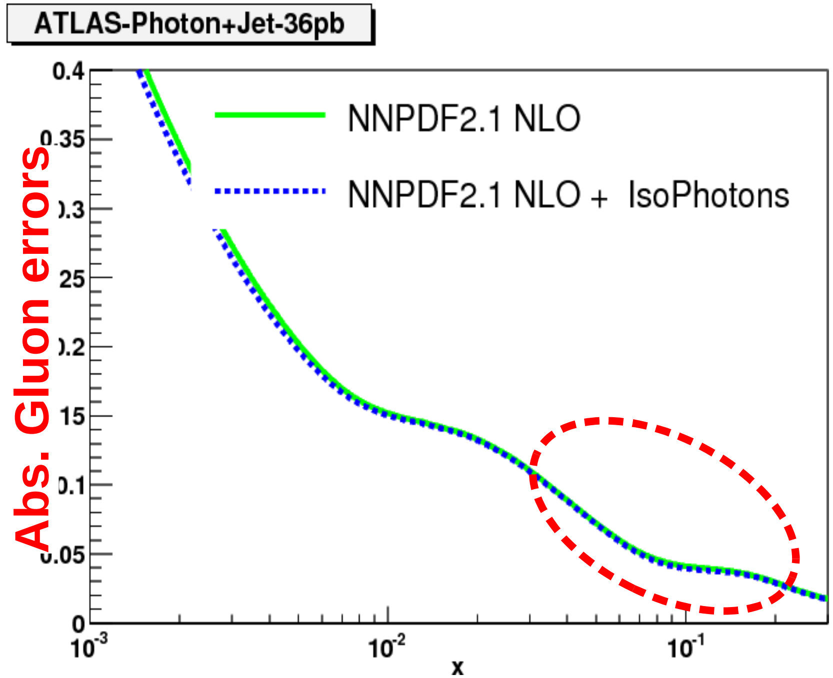
[Carminati,D.d'E,J.Rojo, et al. arXiv:1212.5511]

- Effective # of replicas after reweighting (Shannon entropy): 98.7/100

$$N_{\rm eff} \equiv \exp\left\{\frac{1}{N}\sum_{k=1}^{N} w_k \ln(N/w_k)\right\}$$

- Very small impact on gluon density:



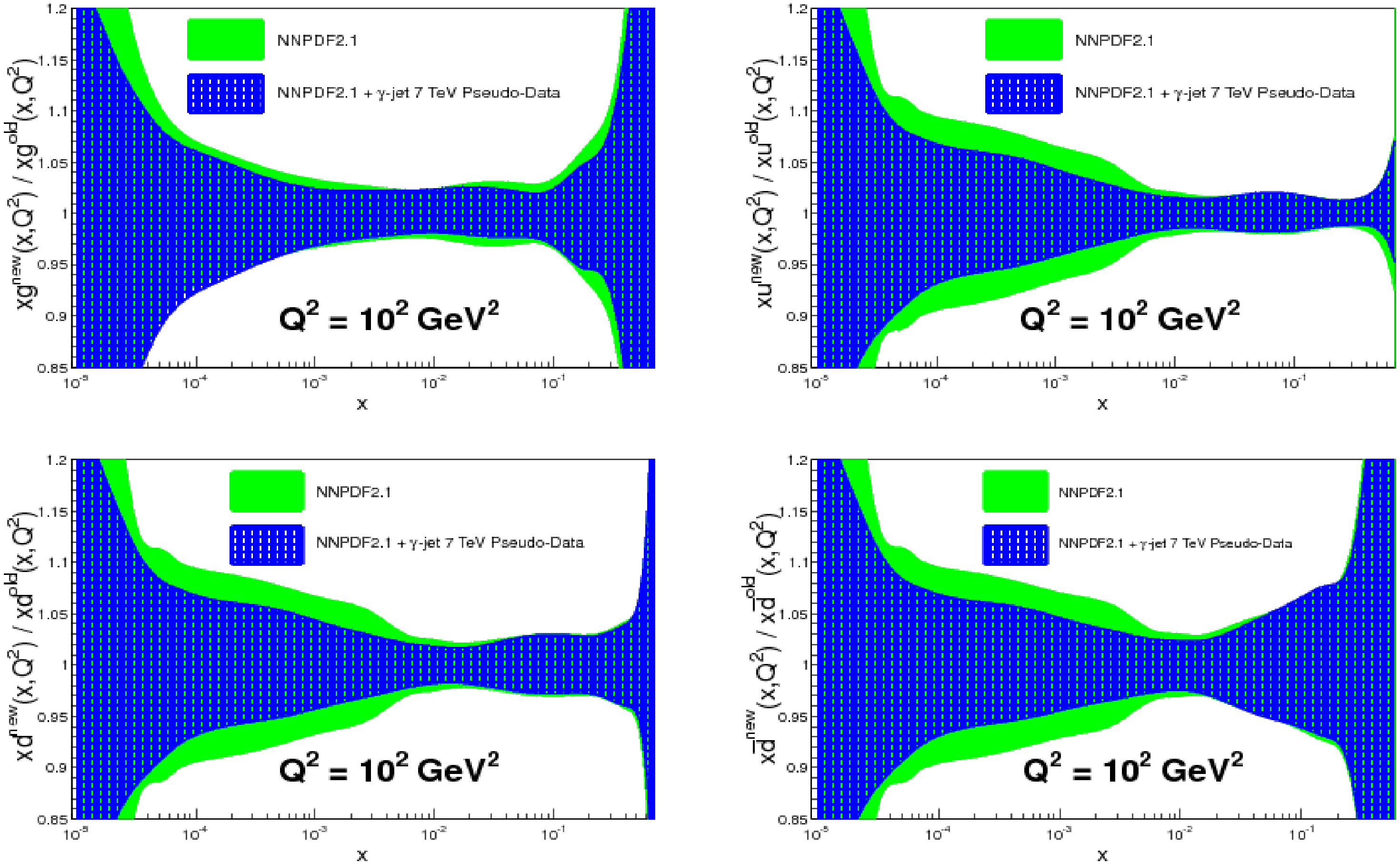


- Gluon NLO PDF central PDF unchanged, uncertainty reduced by about ~5% for 0.05 < x < 0.3

γ_{isol}-jet at 7 TeV with reduced errors: PDFs impact

[Carminati,D.d'E,J.Rojo, et al. arXiv:1212.5511]

- γ-jet impact on PDFs with twice smaller exp. uncertainties:

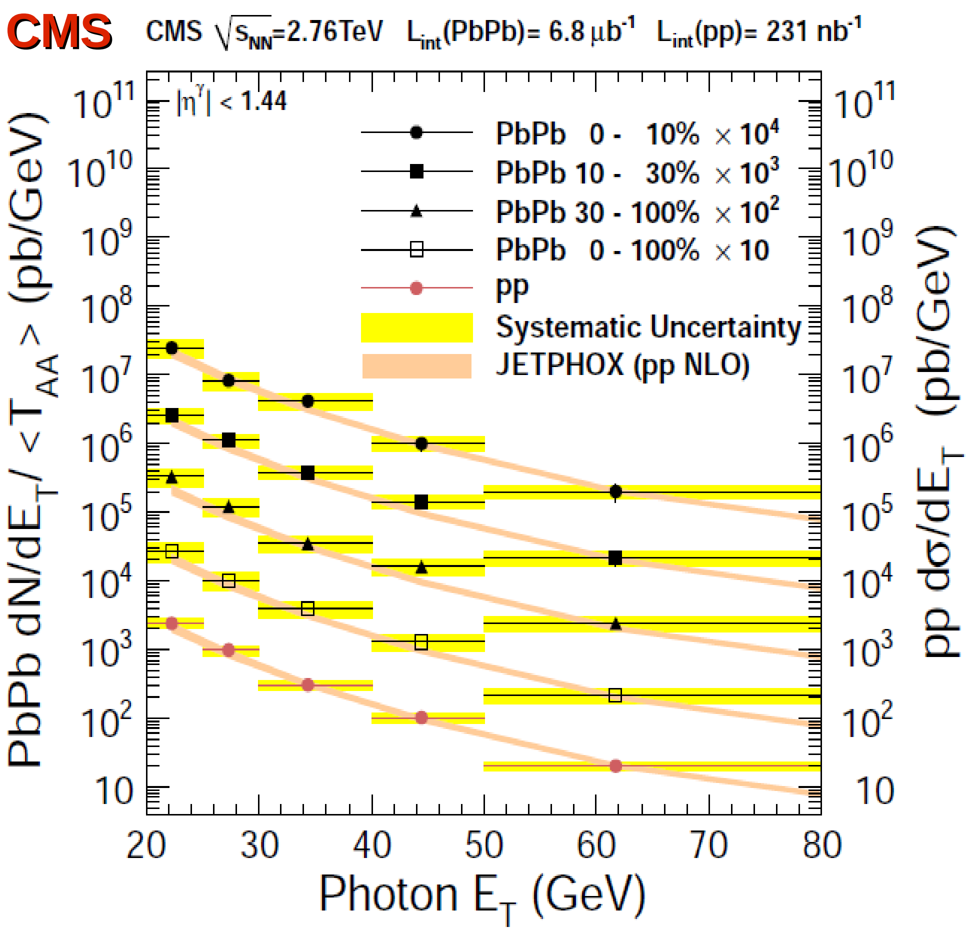


- Gluon NLO PDF uncertainty reduced by ~15% at high x
- Sea-quark NLO PDF uncertainty reduced by ~40% at low x

Nuclear PDFs: PbPb → γ_{iso}+X at 2.76 TeV vs NLO

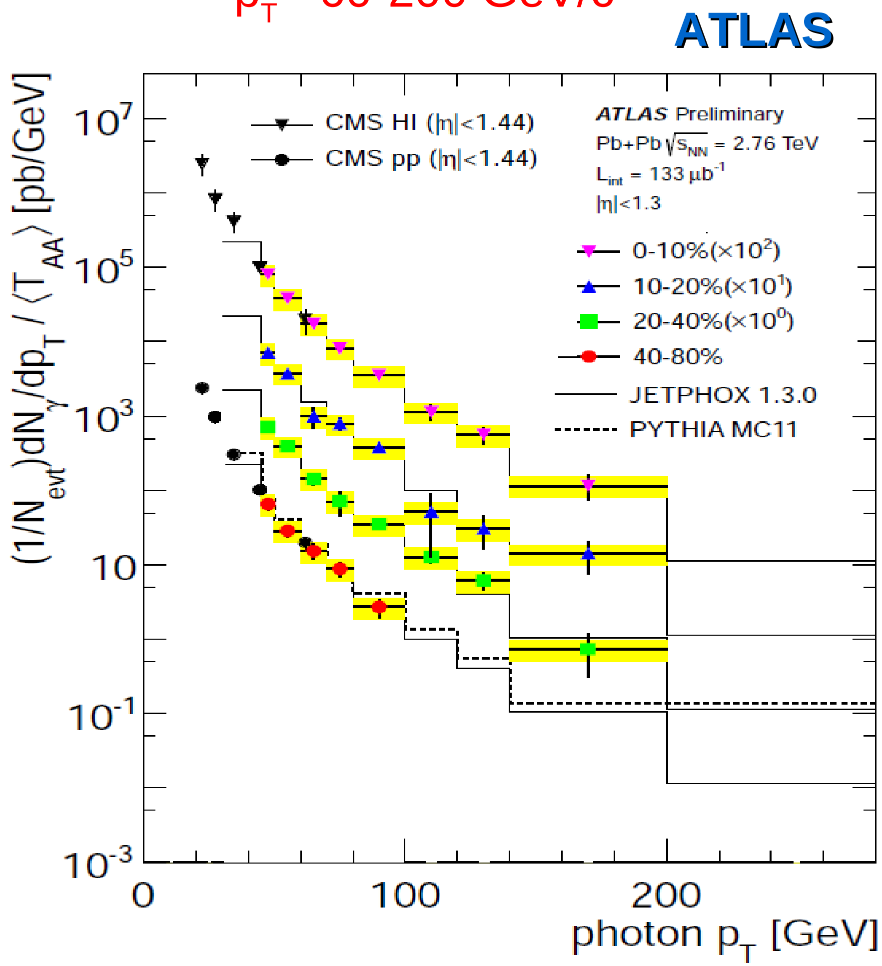
- Good agreement data – NLO for both pp & PbPb (all centralities).

p_T~ 20-80 GeV/c



[CMS, PLB710 (2012) 256]

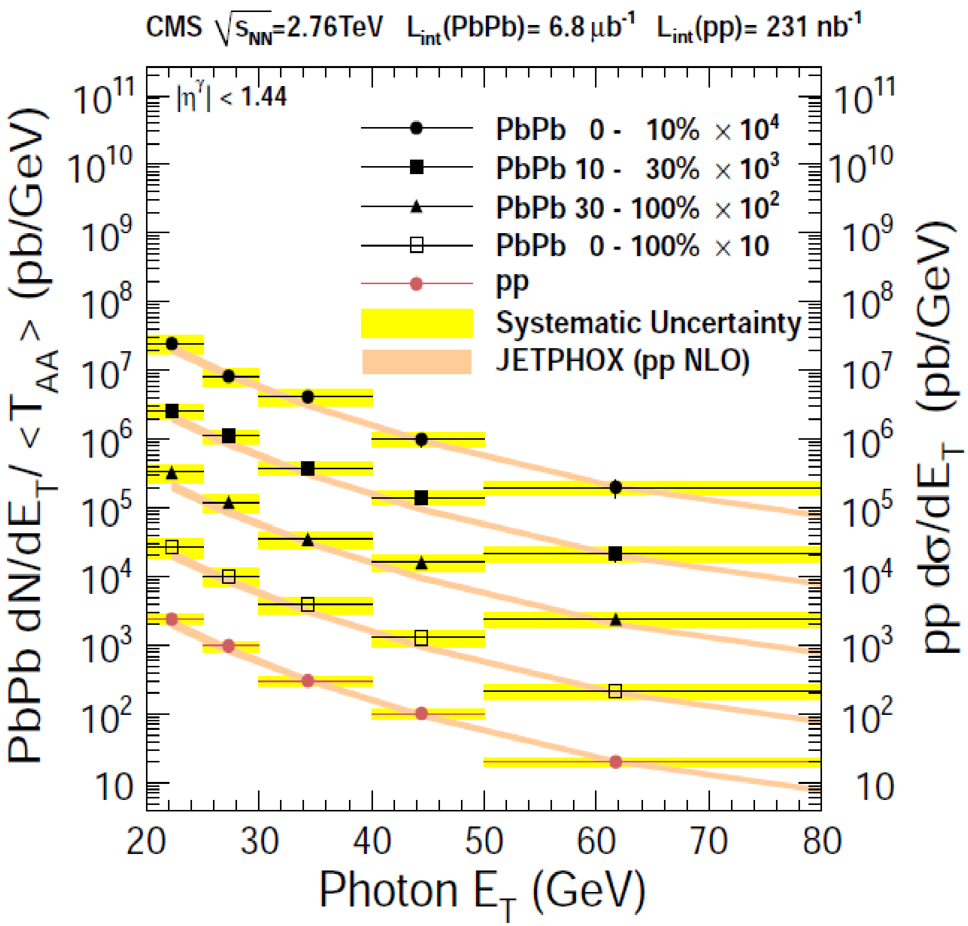
p_T~ 60-200 GeV/c



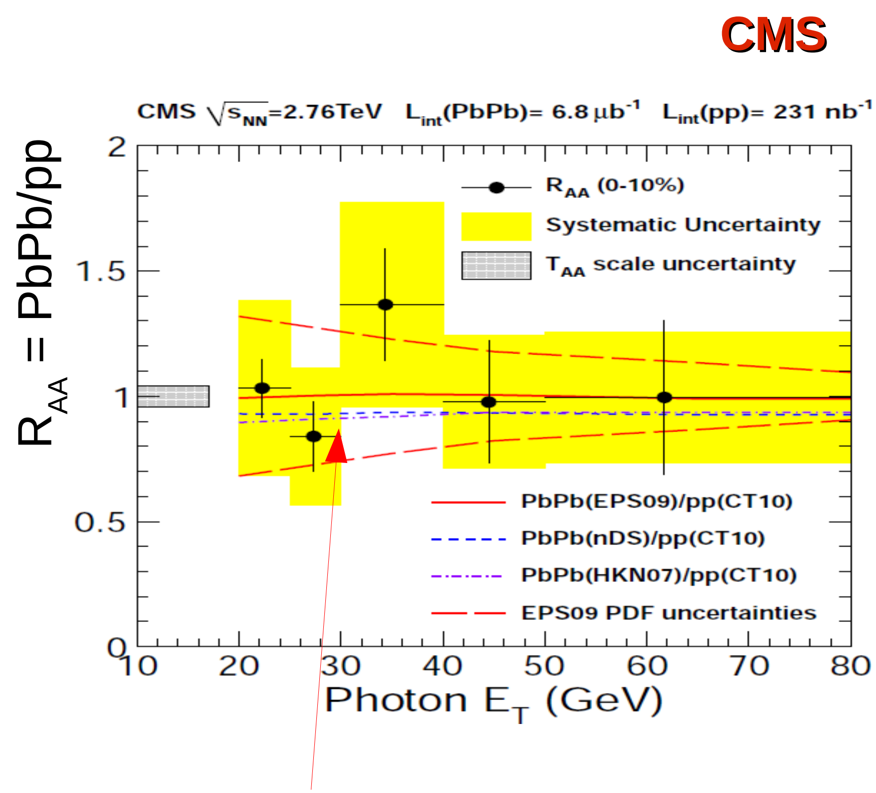
[ATLAS-CONF-2012-051]

Nuclear PDFs: PbPb → γ_{iso}+X at 2.76 TeV vs NLO

- 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



[CMS, PLB710 (2012) 256]



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

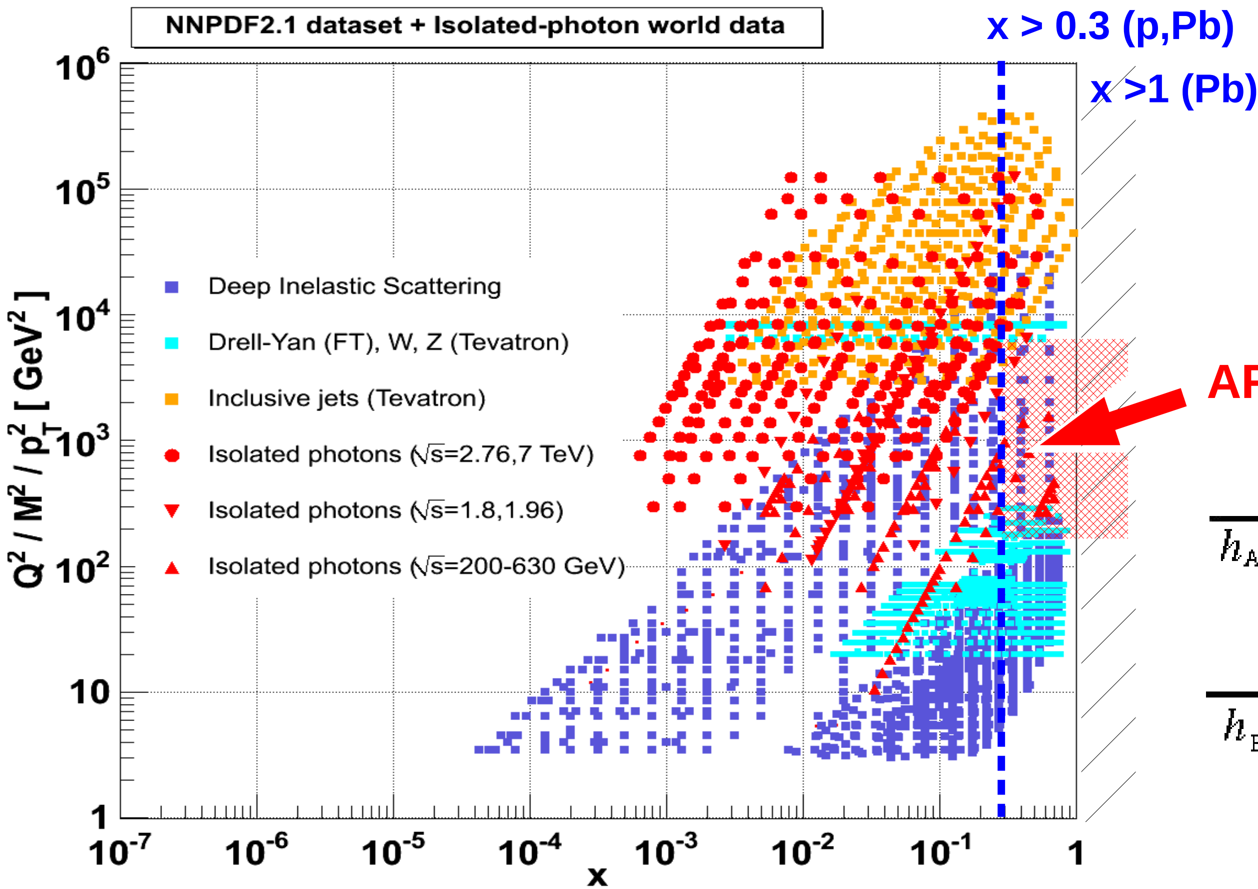
Isolated-photons at AFTER

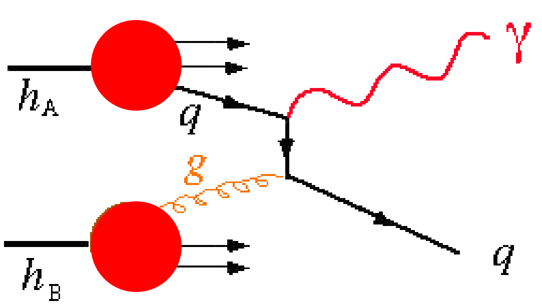
(x,Q^2) map of AFTER isolated-γ

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

- p-p kinematics at fixed-target LHC:

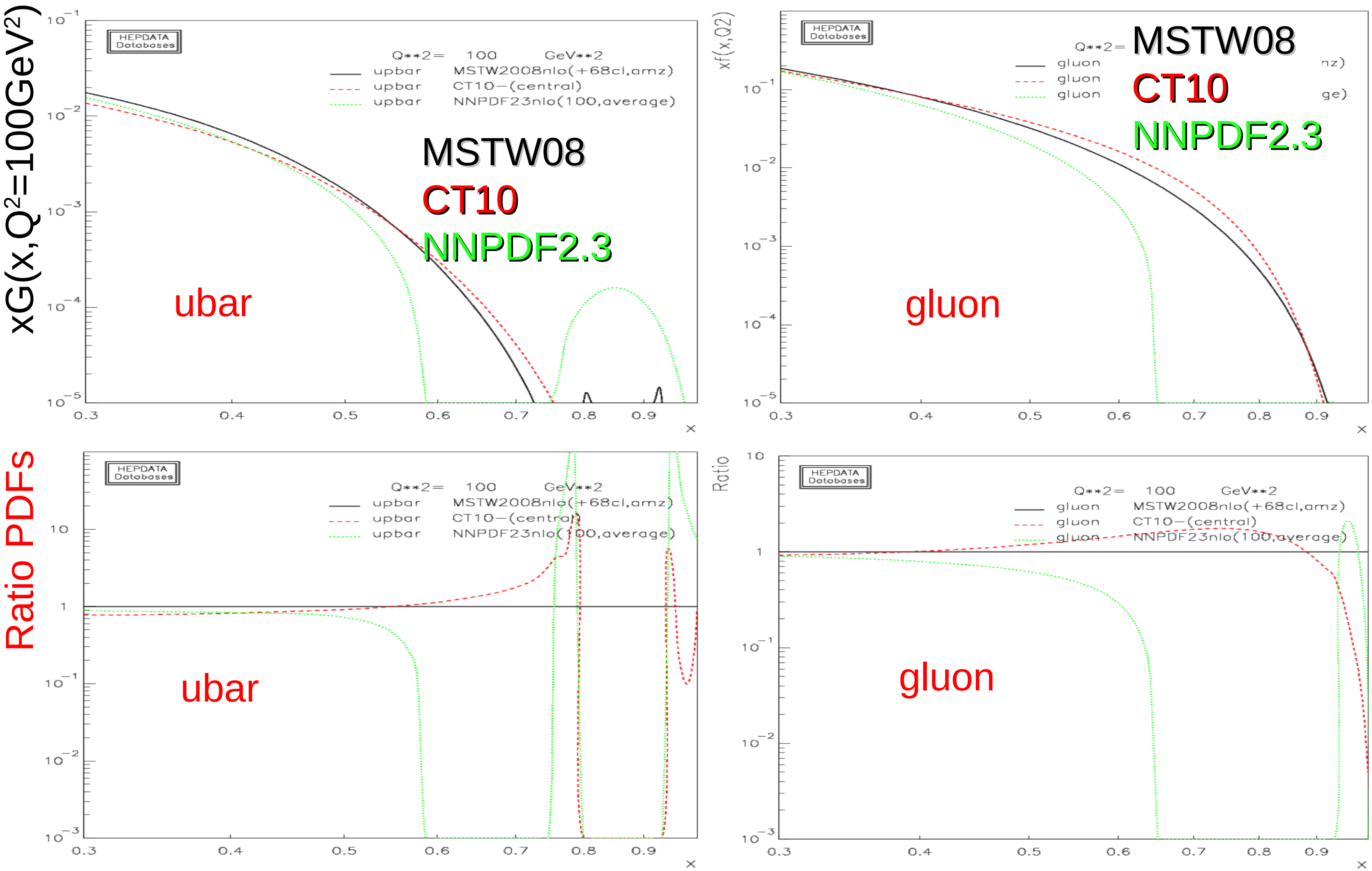
  To access $x > 0.3$ one needs isolated-γ with: $p_T = x_T\sqrt{s}/2 > 10\text{-}20$ GeV/c





Uncertainties in proton PDFs at high-x

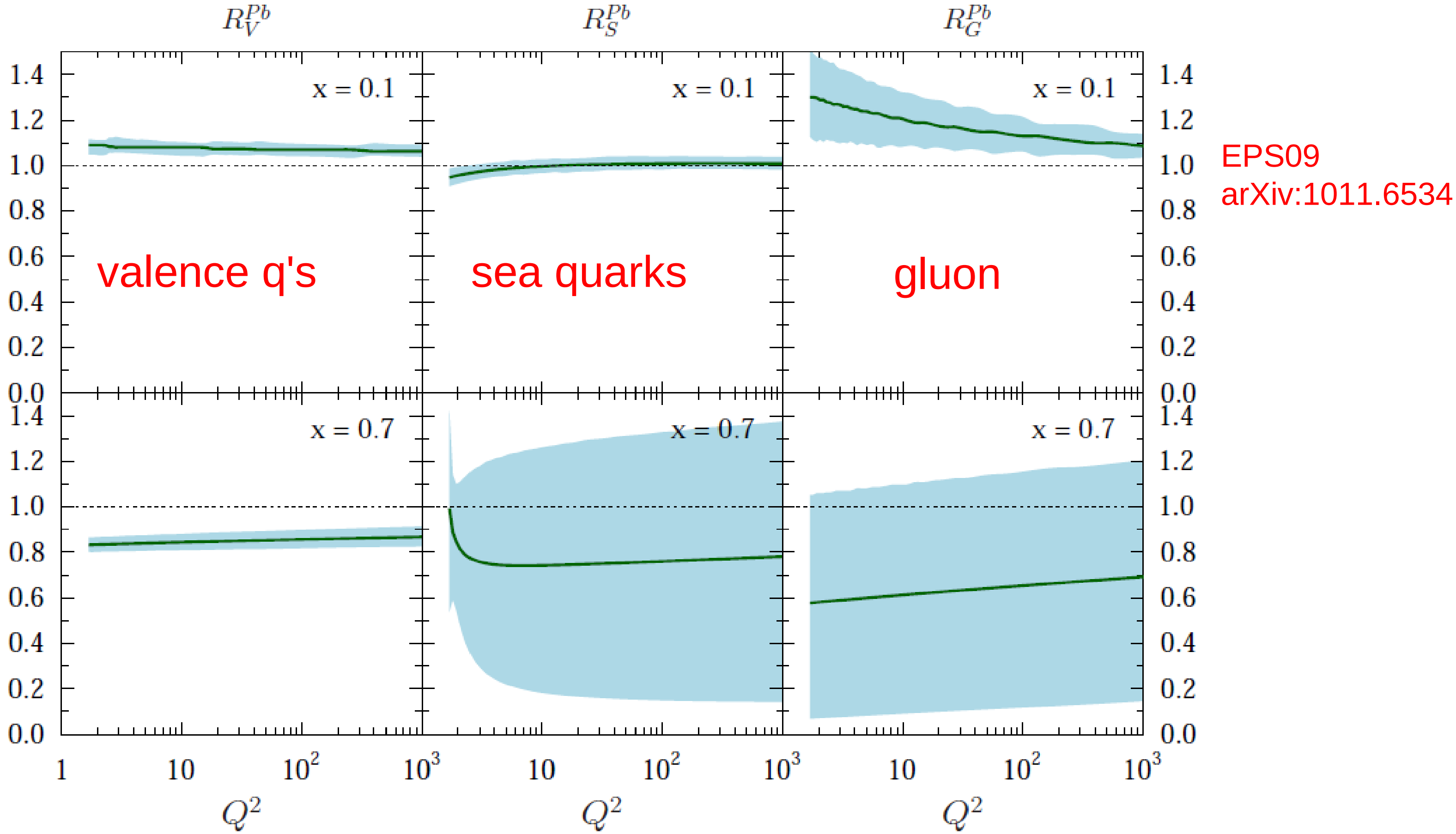
- Isolated-γ at “low”-√s & high-p_T are sentitive to high-x gluons & sea:



Very large uncertainties above x~0.3, at all (including large) Q² !

Uncertainties in nuclear PDFs at high-x

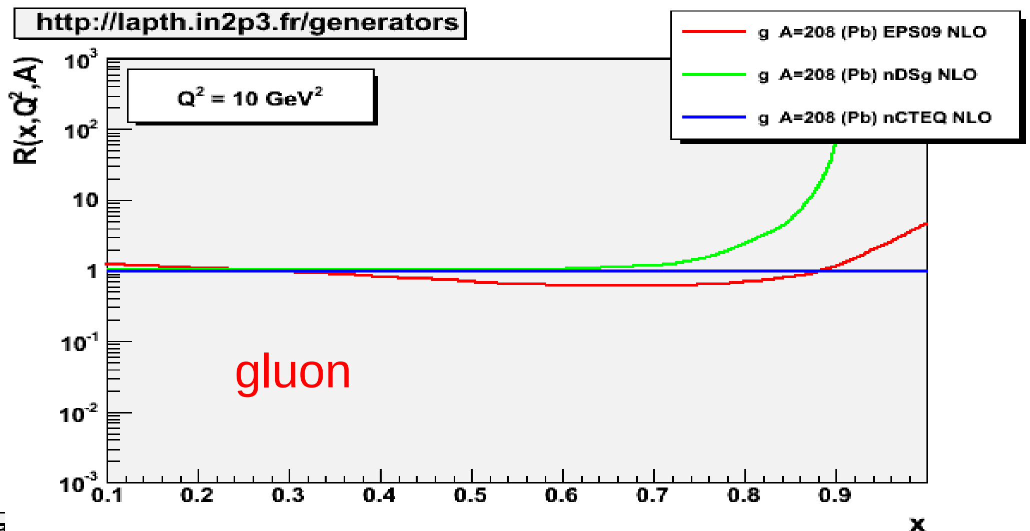
- Even larger uncertainties for nuclear high-x sea & gluon PDFs:



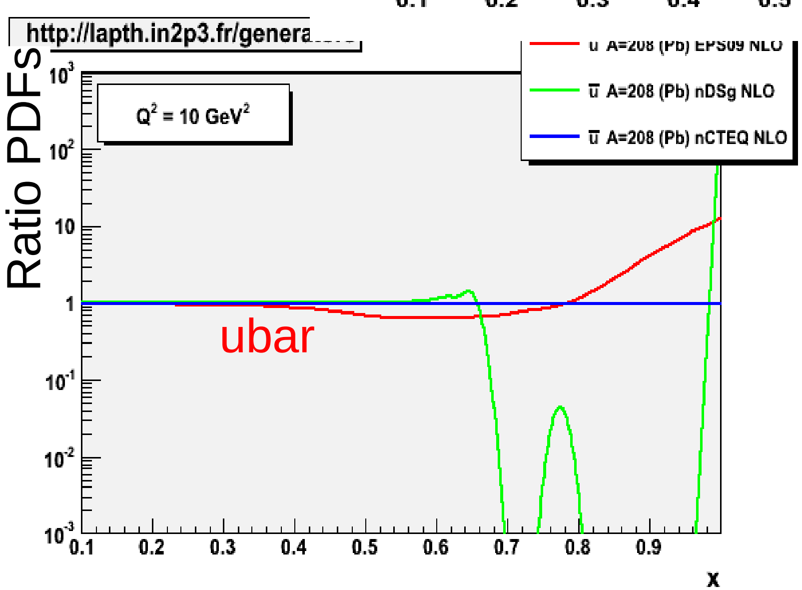
Sea-quarks & gluons are virtually unknown in EMC & Fermi regions
At all virtualities (including large) Q^2

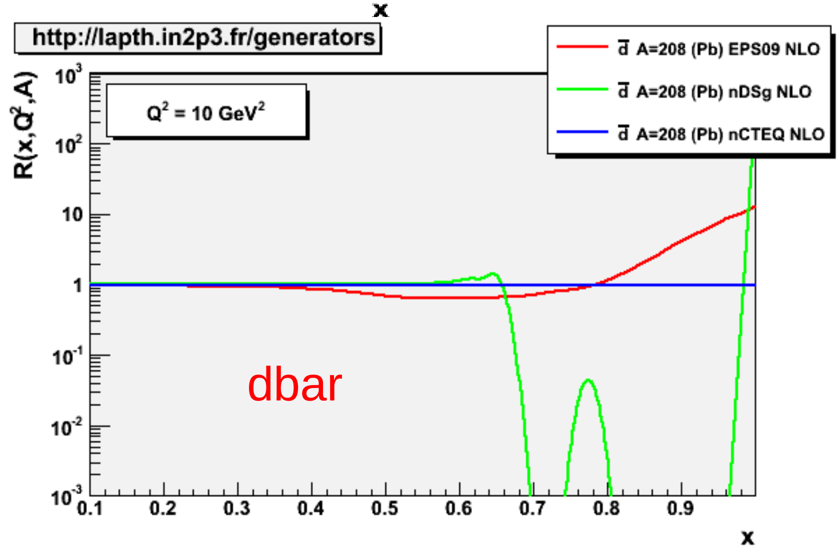
Uncertainties in nuclear PDFs at high-x

- Isolated-γ at “low”-$\sqrt{s}$ & high-p_T are sentitive to high-x gluons & sea:



EPS09 NLO
nCTEQ NLO
nDSGg NLO





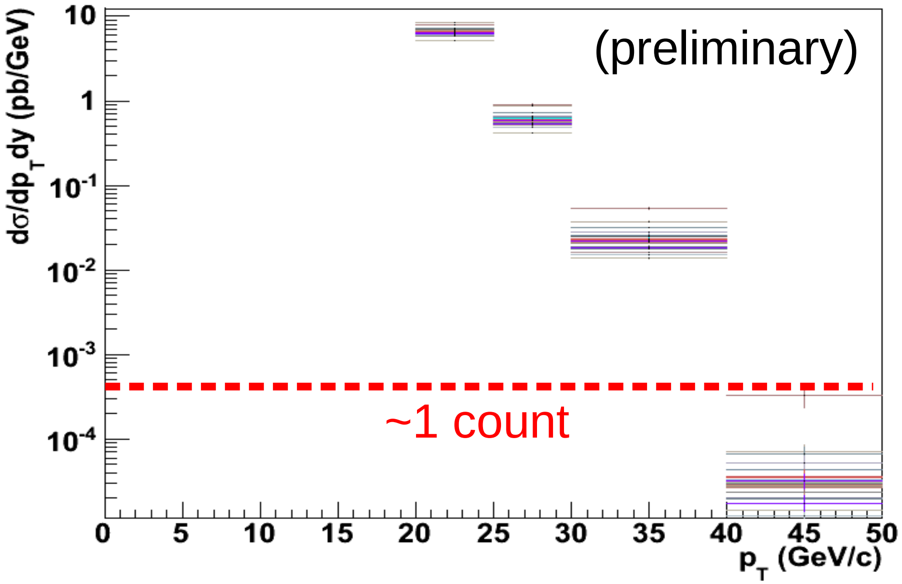
Very large uncertainties above x~0.3, at all (including large) Q^2 !

Isolated-γ in p(7 TeV)-p(rest): $\sqrt{s}$ ~ 115 GeV

- p-p photon kinematics at fixed-target LHC (central rapidities):
  To access x > 0.3 one needs isolated-γ at: $p_T = x_T\sqrt{s}/2 > 20$ GeV/c
- JETPHOX NLO pQCD calculations:

  p-p at $\sqrt{s}$=115 GeV
  |y|<0.5, p_T>20 GeV/c
  Isolation: R=0.4, E_T^{had}<5 GeV

  $\mathcal{L}$(10 cm H_2-target) ~ $2 \bullet 10^3$ pb^{-1}/year



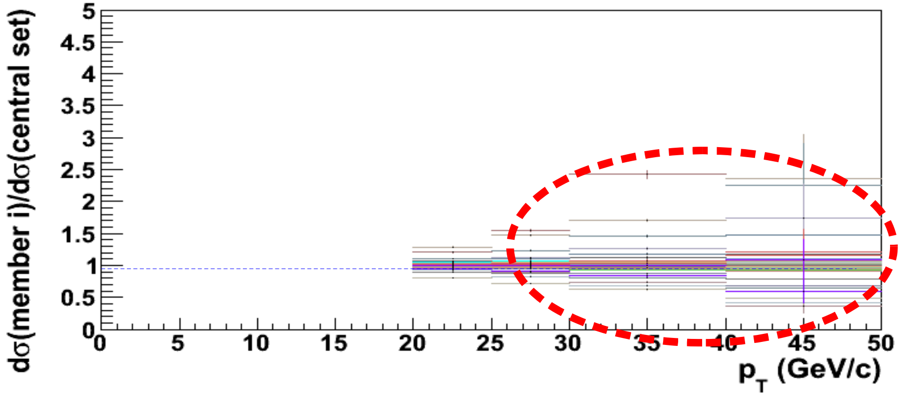
PDF: CT10 52 eigenval. (90% CL)

Scales: $\mu_i = p_T$

FF = BFG-II

x-section uncertainties(*) of ±150%

(*) (68%CL)/(90% CL) ~ 1.65



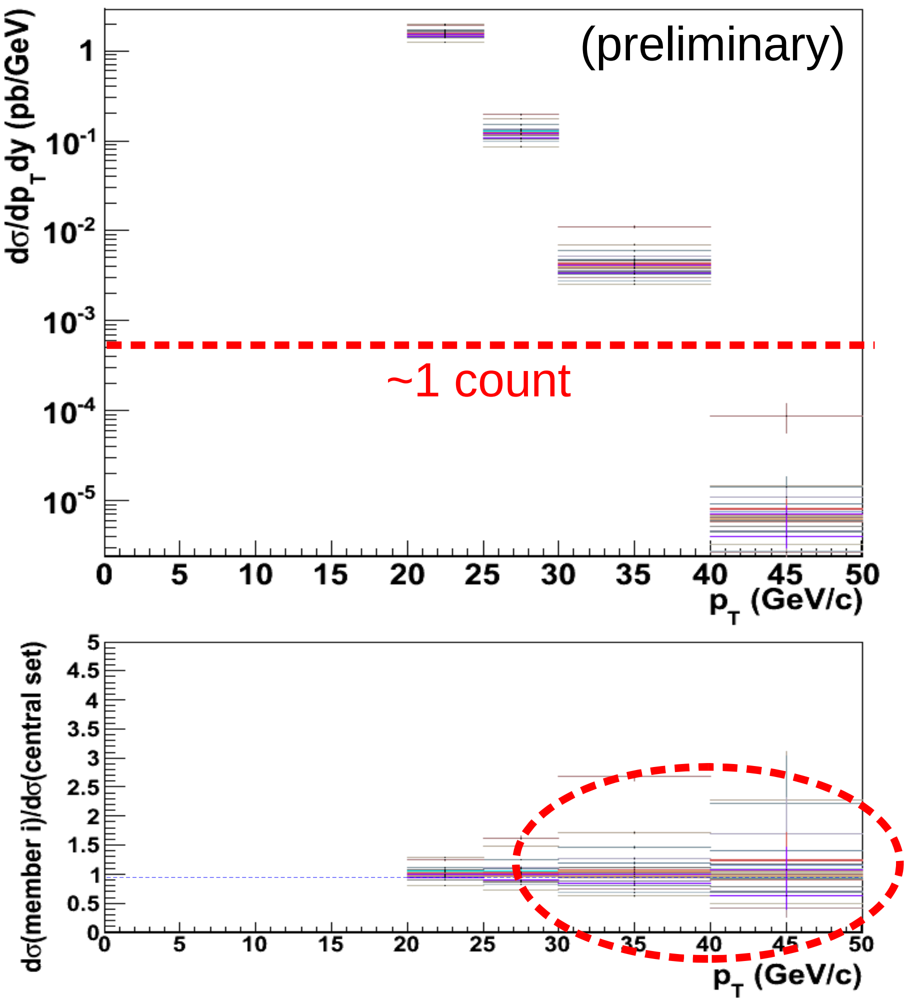
Isolated-γ in p(7 TeV)-p(rest): √s ~ 115 GeV

- p-p photon kinematics at fixed-target LHC (backwards rapidities):
  To access x > 0.3 one needs isolated-γ at: $p_T = x_T\sqrt{s}/2e^{-y} > 10$ GeV/c

- JETPHOX NLO pQCD calculations:

  p-p at √s=115 GeV
  $0<y<-3.$, $p_T>20$ GeV/c
  Isolation: R=0.4, $E_T^{had}<5$ GeV

$\mathcal{L}$(10 cm H_2-target) ~ $2\bullet10^3$ pb^{-1}/year



PDF: CT10 52 eigenval. (90% CL)
Scales: $\mu_i = p_T$
FF = BFG-II
x-section uncertainties(*) of ±170%

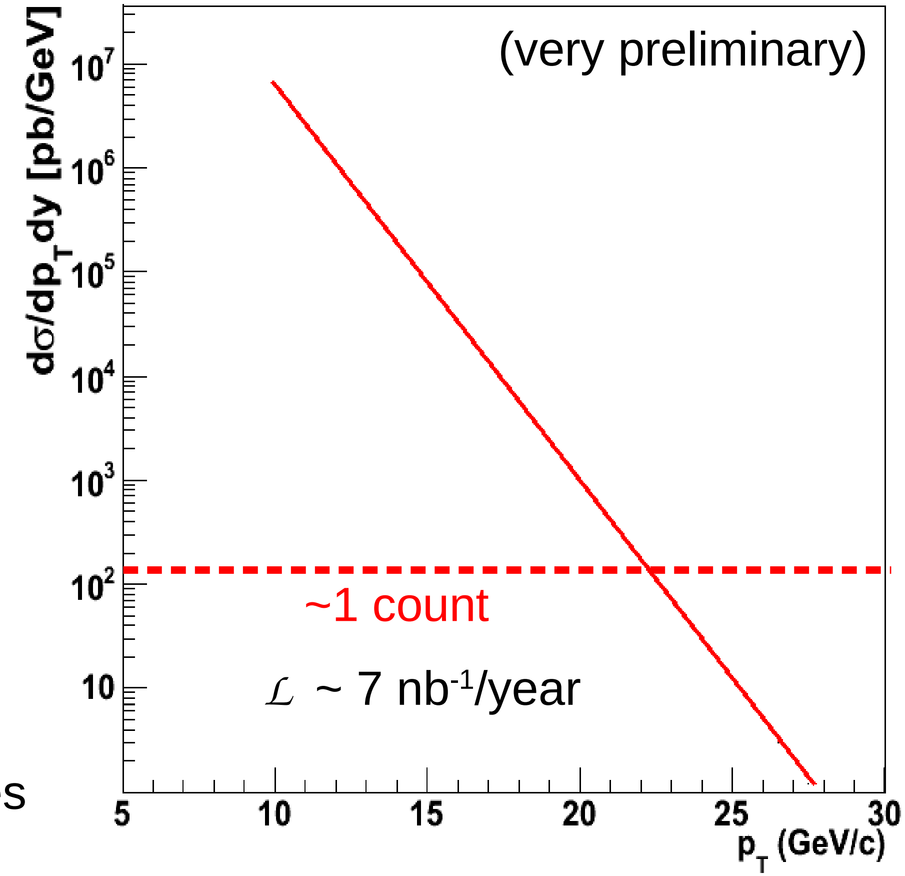
(*) (68%CL)/(90% CL) ~ 1.65

Isolated-γ in Pb(2.76 TeV)-Pb(rest): $\sqrt{s_{NN}}$~72 GeV

- Pb-Pb photon kinematics at fixed-target LHC:
  To access x > 0.3 one needs isolated-γ at: $p_T = x_T\sqrt{s}/2 > 10$ GeV/c
- JETPHOX NLO
  pQCD calculations:

  Pb-Pb at $\sqrt{s_{NN}}$=72 GeV
  |y|<0.5, p_T>20 GeV/c
  Isolation: R=0.4, E_T^{had}<5 GeV

  PDF: EPS09
  Scales: $\mu_i = p_T$
  FF = BFG-II



(Ongoing determination of uncertainties with 40 EPS09 eigenvalues ...)

Conclusions (LHC γ_{isol})

- 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} ~ 87/100. 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 uncertainty
  - ✔ LHC-7 TeV isolated-γ +jet have impact on wide x-range for g,u,d PDF only if exp. uncertainties reduced.

Conclusions (AFTER γ_{isol})

- Photons at AFTER (p-p, Pb-Pb at $\sqrt{s}$ = 72 – 115 GeV):
  - ✔ Directly sensitive to high-x PDFs (x > 0.3 – 1)
  - ✔ Very uncertain valence gluon and anti-quarks in p and Pb PDFs
  - ✔ NLO predictions for isolated-photon x-sections:
    - Expected yields up to p_T= 25, 40 GeV/c
    - CT10 uncertainties in NLO:
      p-p: ~150% for y=0, ~170% for y<0
      Pb-Pb (EPS09): much larger (to be quantified ...)
    - Outlook: NNPDF-reweighting study would be useful

Backup slides

Typical NLO scale uncertainties

- Scales variations: $(\mu_R,\mu_F)=(1,1),(1/2,1),(1,1/2),(1/2,1/2),(2,1),(1,2),(2,2)\times E_{T,\gamma}$