NNLO QCD results for diphoton production at the LHC and the Tevatron

Leandro Cieri

La Sapienza - Università di Roma

Spring Institute 2014: High-energy physics after LHC Run I
Frascati
Wednesday, 12 March 2014

Outline

- Introduction
- Isolation
- Available theoretical tools (NLO)
- Diphoton production with **2γNNLO**
- Summary

In collaboration with S. Catani, D. de Florian, G. Ferrera and M. Grazzini

Outline

- Introduction
  - Why is diphoton production important?
  - Photon production mechanisms
- Isolation
- Available theoretical tools (NLO)
- Diphoton production with **2γNNLO**
- Summary

Outline

- Introduction
- Isolation
  - “Tight isolation” accord
- Available theoretical tools (NLO)
- Diphoton production with **2γNNLO**
- Summary

Outline

- Introduction
- Isolation
- Available theoretical tools (NLO)
  - Comparison theory vs. data
  - Some discrepancies (theory ↔ data)
- Diphoton production with **2γNNLO**
- Summary

Outline

- Introduction
- Isolation
- Available theoretical tools (NLO)
- Diphoton production with **2γNNLO**
    - Features of the code
    - Results
- Summary

Why is diphoton production important?

- **It is a channel that we can use to check the validity of perturbative Quantum Chromodynamics (pQCD)**
  - Collinear factorization approach
  - K_T factorization approach
  - Soft gluon logarithmic resummation techniques

- **It constitutes an irreducible background for new physics searches**
  - Universal Extra Dimensions
  - Randall-Sundrum ED
  - Supersymmetry
  - New heavy resonances

Why is diphoton production important?

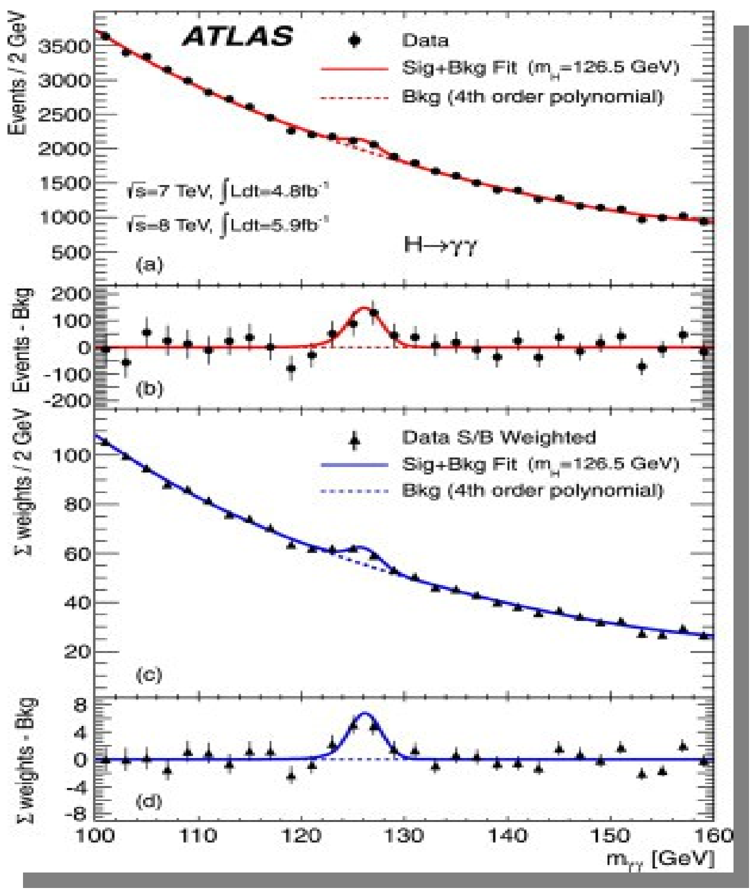
- **It is a channel that we can use to check the validity of perturbative Quantum Chromodynamics (pQCD)**
  - Collinear factorization approach
  - K_T factorization approach
  - Soft gluon logarithmic resummation techniques

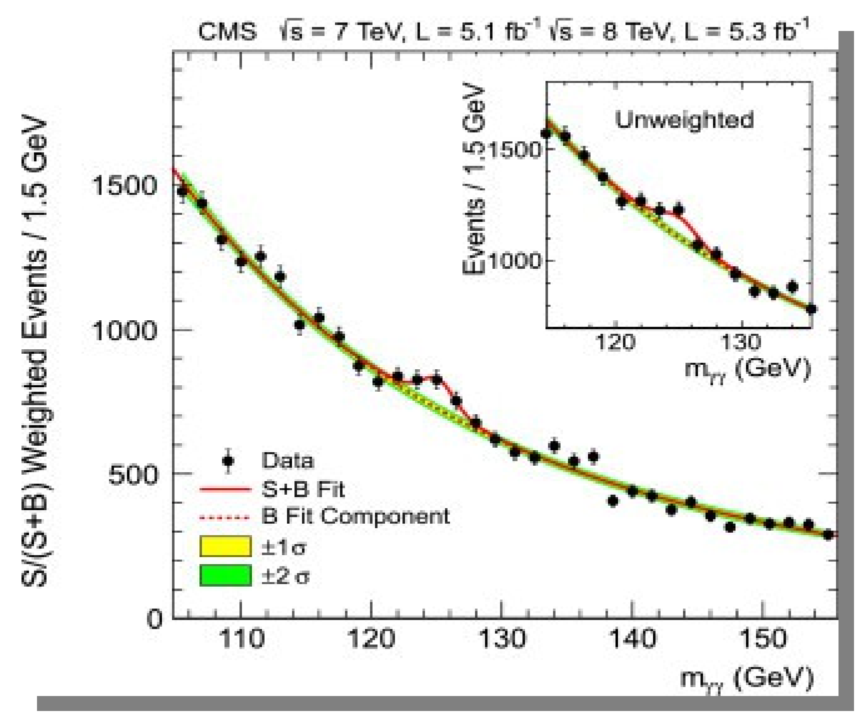
- **It constitutes an irreducible background for new physics searches**

- **Irreducible background**
  - **In studies and searches for a low mass Higgs boson decaying into photon pairs**

The search for the SM Higgs boson

All these motivations are strengthened by the spectacular observation of a new neutral boson (M~125 GeV)

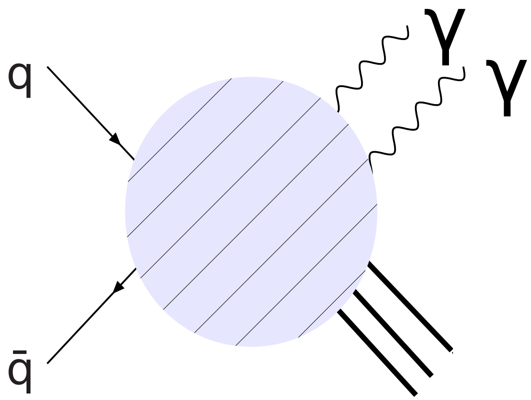




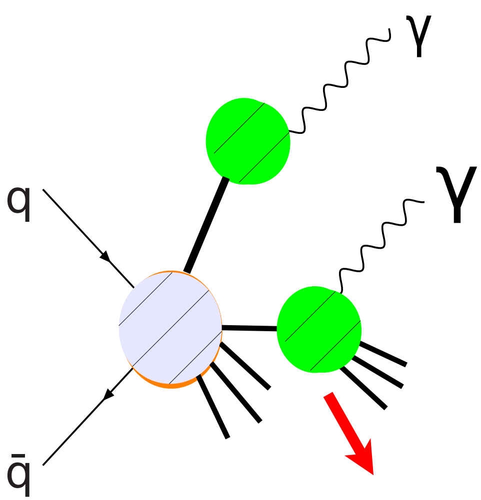
Phys.Lett. B716 (2012) 1-29 (ATLAS)
Phys.Lett. B716 (2012) 30-61 (CMS)

Photon production

When we dealing with the production of photons we have to consider two production mechanisms:



Direct component: photon directly produced through the hard interaction



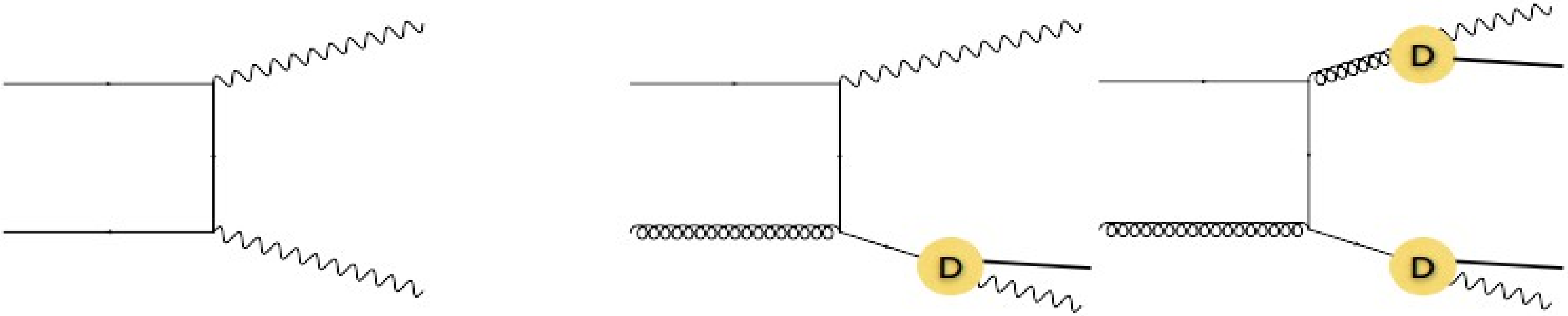
Fragmentation component: photon produced from non-perturbative fragmentation of a hard parton (analogously to a hadron)

Calculations of cross sections with photons have additional singularities in the presence of QCD radiation.
(i.e. When we go beyond LO)

Fragmentation function:
to be fitted from data

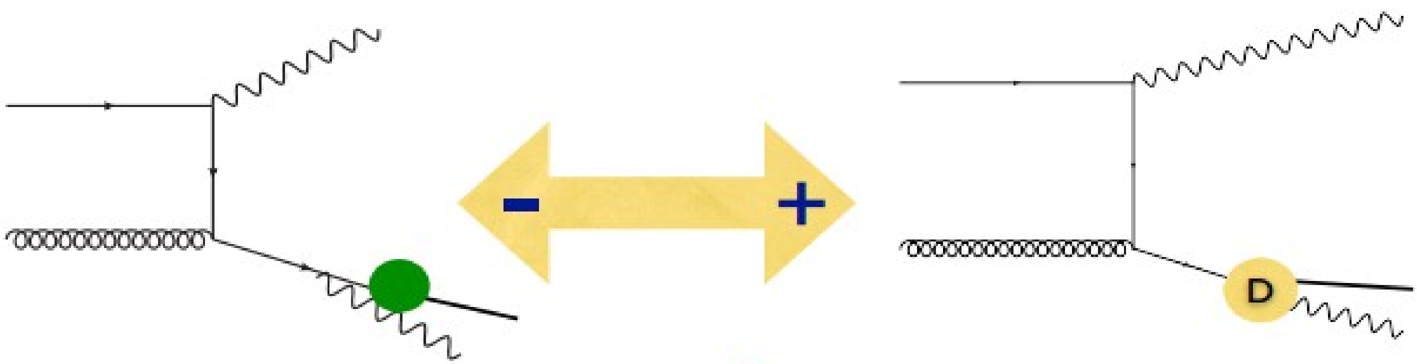
Photon production

Two mechanisms for photon production



Direct (point-like) Single and double resolved (collinear fragmentation)

Separation between them NOT physical in general (beyond LO)

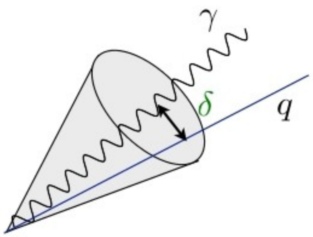


collinear divergence → Cancelled by fragmentation

Photon production

- Experimentally photons must be isolated
- Isolation reduces fragmentation component
- Experimentalist may choose:

$$\sum_{\delta<R_0} E_T^{had} \leq \varepsilon_\gamma p_T^\gamma$$



$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max}$$

Using conventional isolation, only the sum of the direct and fragmentation contributions is meaningful.

But there is a way to isolate and make the direct cross section physical

Smooth cone Isolation

(Infrared safe)

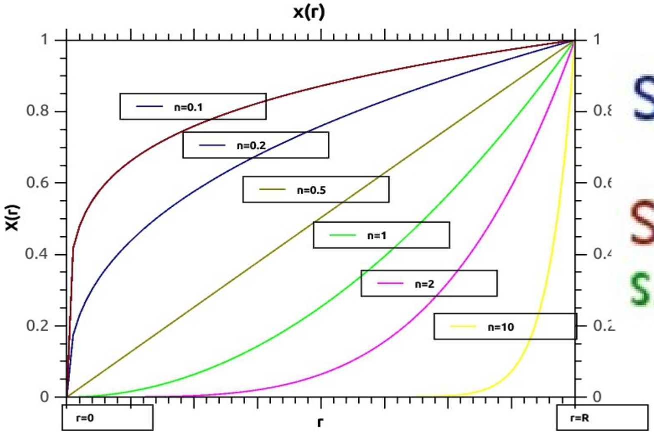
Soft emission allowed arbitrarily close to the photon

$$\chi(\delta) = \epsilon_\gamma E_T^\gamma \left(\frac{1-\cos(\delta)}{1-\cos(R_0)} \right)^n$$

$E_T^{had}(\delta) \leq \chi(\delta)$ such that $\lim_{\delta \to 0} \chi(\delta) = 0$

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- direct well defined by itself

S. Frixione, Phys.Lett. B429 (1998) 369–374,



Standard Photon Isolation

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}$$

Smooth Photon Isolation

S.Frixione

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$$

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

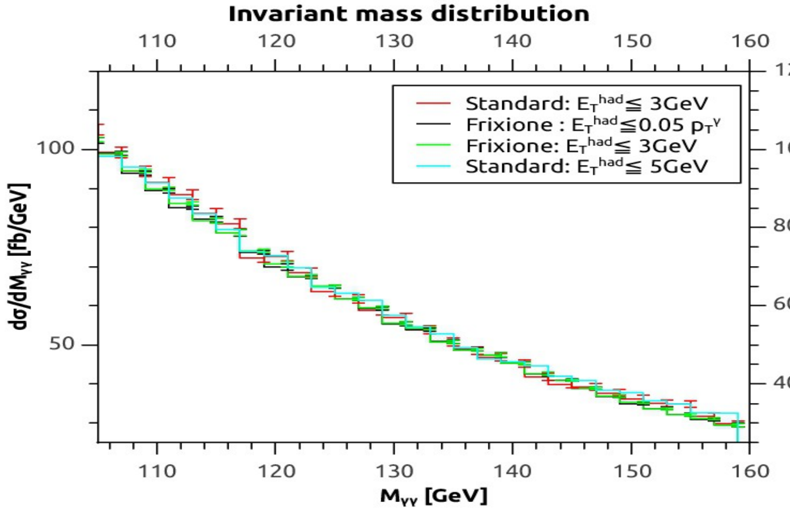
More restrictive than usual cone : lower limit on cross section (close for small R)

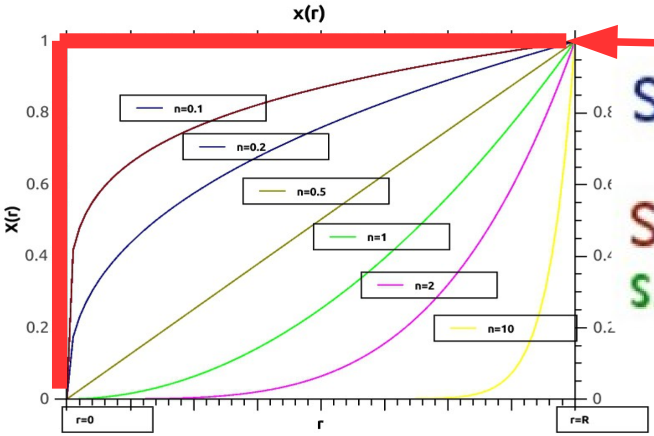
In real (TH)life... how much different? NLO comparison $R_0 = 0.4 \quad n = 1$

CMS Higgs cuts at 7 TeV

$E_{T\,max}^{had}$	standard/smooth
2 GeV	< 1%
3 GeV	< 1%
4 GeV	1%
5 GeV	3%
0.05 p_T	< 1%
0.5 p_T	11%

Standard: direct+fragmentation (Diphox)





Standard Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}$

Smooth Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$

S.Frixione

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

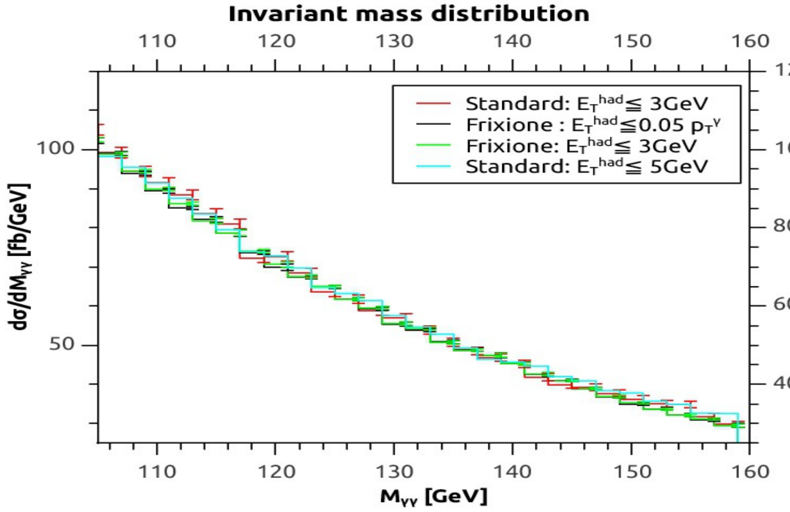
More restrictive than usual cone : lower limit on cross section (close for small R)

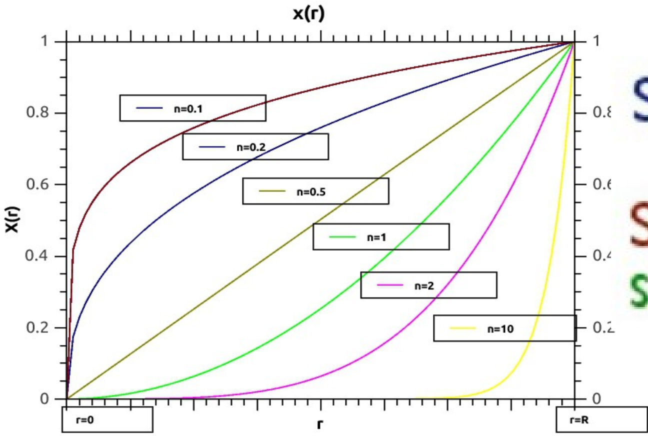
In real (TH)life... how much different? NLO comparison $R_0 = 0.4 \quad n = 1$

CMS Higgs cuts at 7 TeV

Standard: direct+fragmentation (Diphox)

$E_{T\,max}^{had}$	standard/smooth
2 GeV	< 1%
3 GeV	< 1%
4 GeV	1%
5 GeV	3%
0.05 p_T	< 1%
0.5 p_T	11%





Standard Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}$

Smooth Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$

S.Frixione

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

More restrictive than usual cone : lower limit on cross section (close for small R)

In real (TH)life... how much different? NLO comparison $R_0 = 0.4 \quad n = 1$

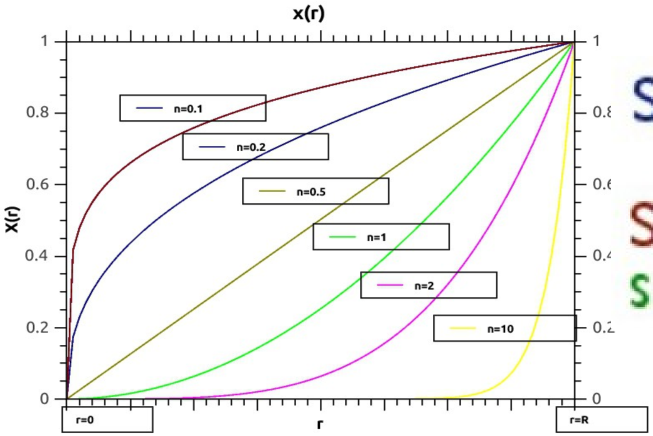
CMS Higgs cuts at 7 TeV

Standard: direct+fragmentation (Diphox)

Invariant mass distribution

- **The smooth cone isolation criterion is more restrictive than the standard one**
- $$\sigma_{Frix}\{R, E_{T\ max}\} \leq \sigma_{Stand}\{R, E_{T\ max}\}$$

(both theoretically and experimentally)



Standard Photon Isolation

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}$$

Smooth Photon Isolation

S.Frixione

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$$

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

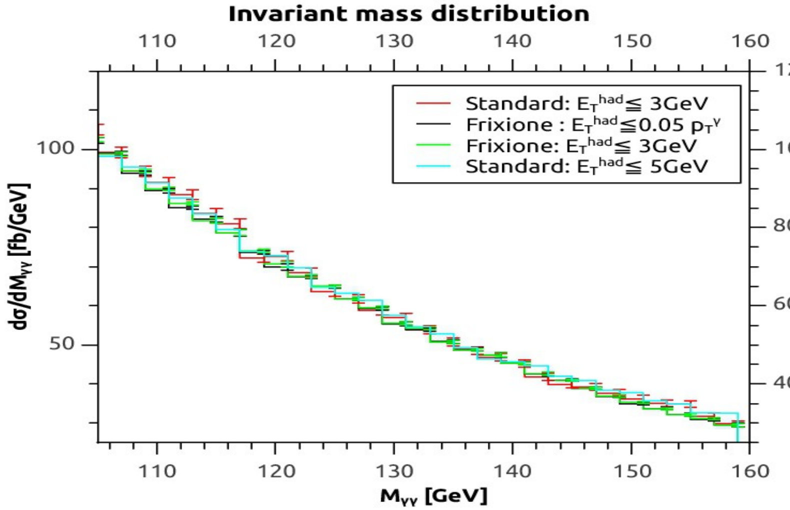
More restrictive than usual cone : lower limit on cross section (close for small R)

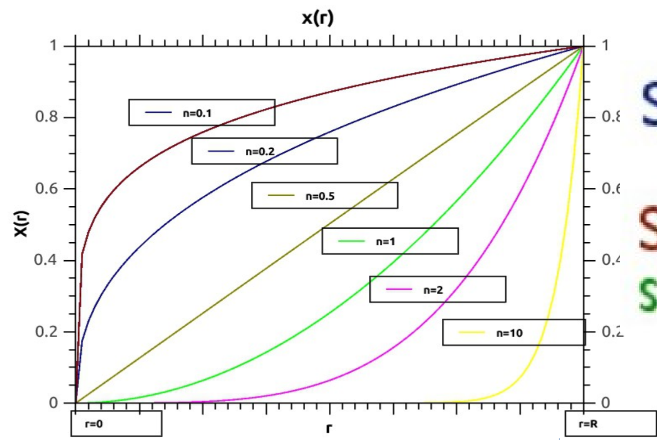
In real (TH)life… how much different? NLO comparison $R_0 = 0.4 \quad n = 1$

CMS Higgs cuts at 7 TeV

Standard: direct+fragmentation (Diphox)

$E_{T\,max}^{had}$	standard/smooth
2 GeV	< 1%
3 GeV	< 1%
4 GeV	1%
5 GeV	3%
0.05 p_T	< 1%
0.5 p_T	11%





Standard Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}$

Smooth Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$

S.Frixione

no quark-photon collinear divergences

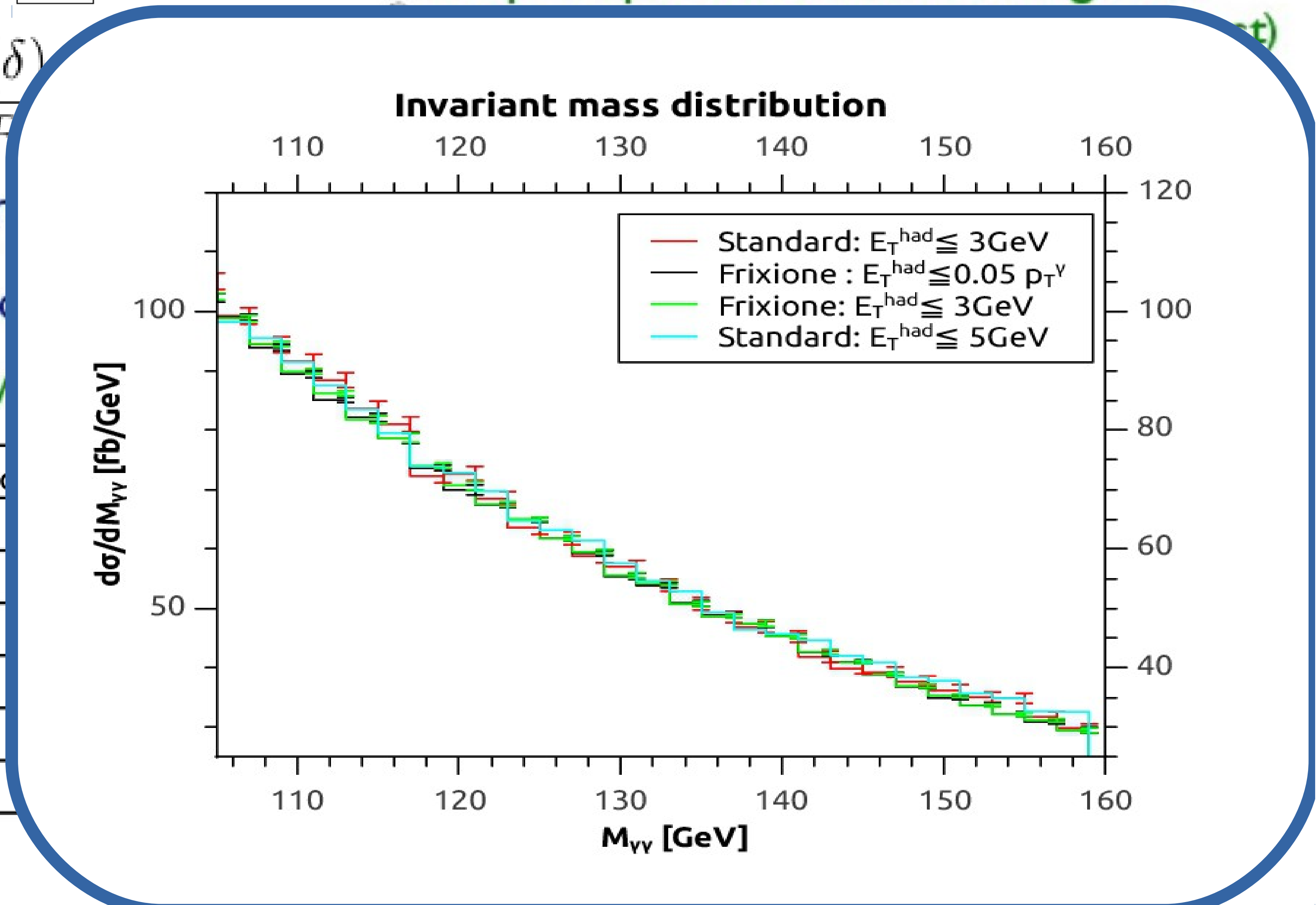
$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R}\right.$$

More restrictive thar

In real (TH)life... hc

CMS Higgs cuts at 7 TeV

$E_{T\,max}^{had}$	stanc
2 GeV	
3 GeV	
4 GeV	
5 GeV	
0.05 p_T	
0.5 p_T	



But the effects of the fragmentantion could appear strongly in kinematical regions far away from the back-to-back configuration.....

The calculation of fragmentation contributions is very difficult:

We can find calculations in which the fragmentation component is considered at one perturbative level less, than the direct component.

For the next slides:

Xsection [NLO] = **Direct [NLO] + Frag [NLO]** (Isolation Criterion: Standard, Democratic, Frixione, etc.)

Xsection [NLO] = Direct [NLO] ~~+ Frag [NLO]~~ (Isolation Criterion: Frixione)

Xsection [NLO] = Direct [NLO] + **Frag [LO]** (Isolation Criterion: Standard, Democratic, Frixione, etc.)

Check less inclusive observables: any significant difference?

new at LH

Diphoton production $\sqrt{s} = 8\,\mathrm{TeV}$ **CTEQ6M** $\mu_F = \mu_R = M_{\gamma\gamma}$

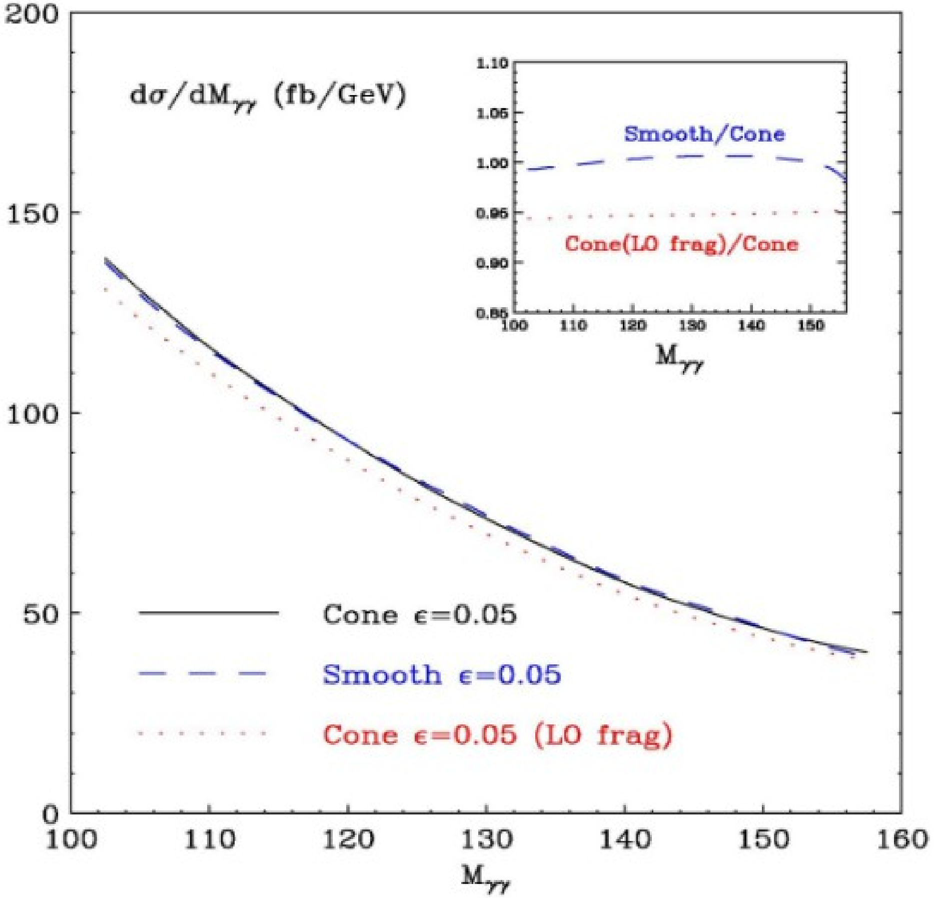
$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$

$p_T^{\gamma\, soft} \geq 30\,\mathrm{GeV}$

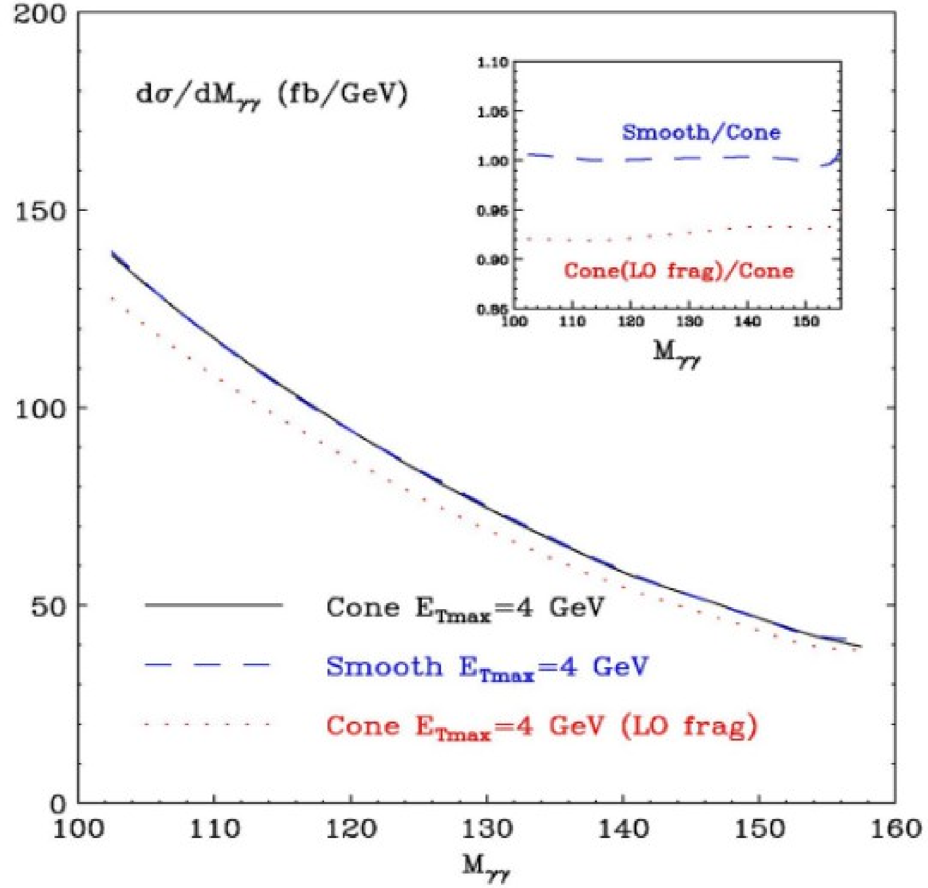
$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$ $|\eta^\gamma| \leq 2.5$ $R_{\gamma\gamma} \geq 0.45$

full NLO Cone (DIPHOX) vs Cone with LO fragmentation vs NLO Smooth

$E_{T\,max}^{had} = \epsilon\, p_T^\gamma$ $\epsilon = 0.05$



$E_{T\,max}^{had} = 4\,\mathrm{GeV}$



L.C , D. de Florian 2013

Check less inclusive observables: any significant difference?

new at LH

Diphoton production $\sqrt{s} = 8\,\mathrm{TeV}$ **CTEQ6M** $\mu_F = \mu_R = M_{\gamma\gamma}$

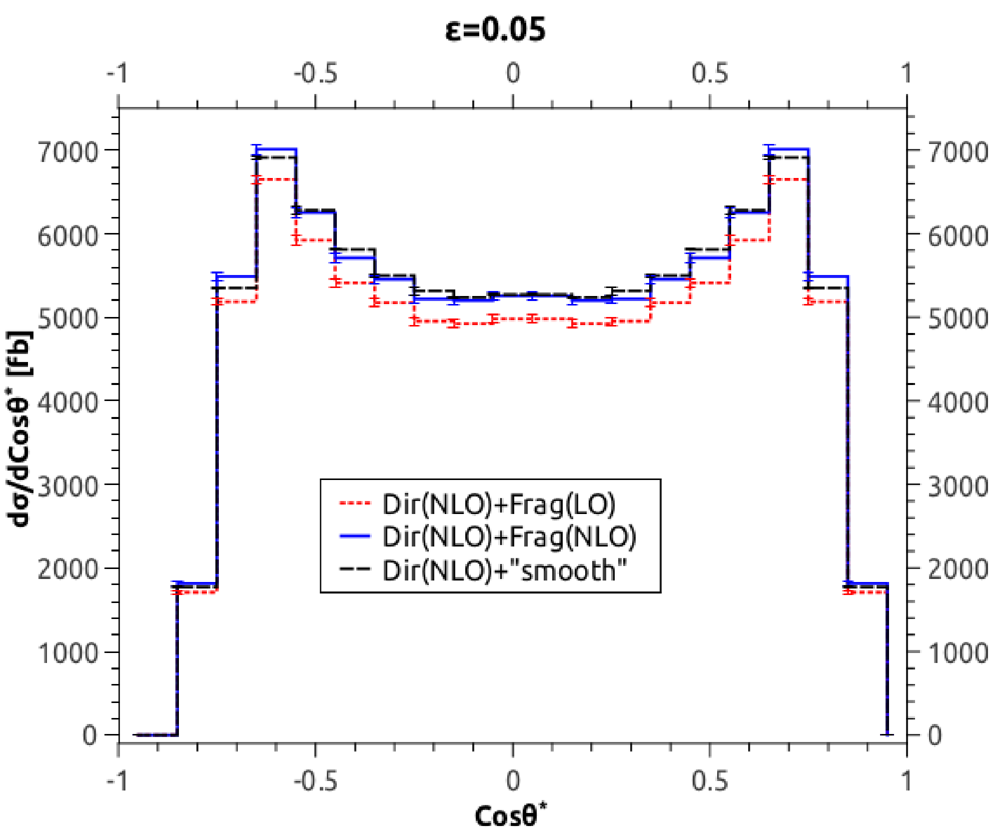
$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$

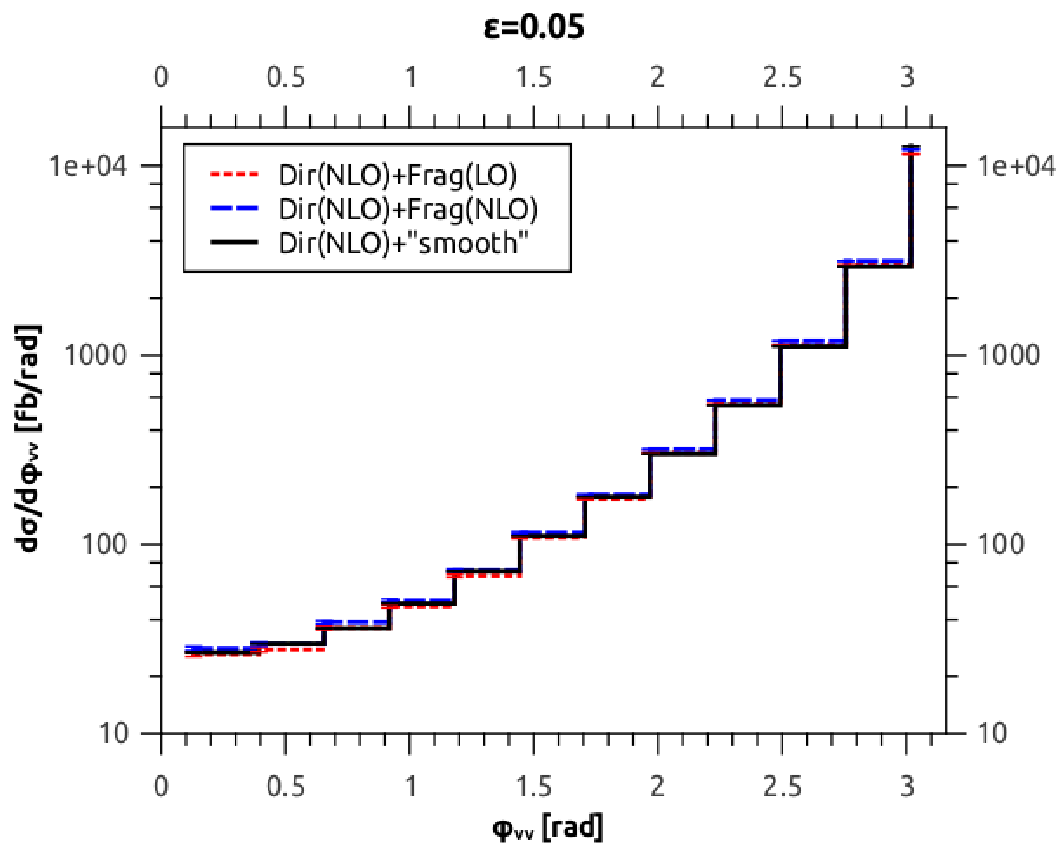
$p_T^{\gamma\, soft} \geq 30\,\mathrm{GeV}$

$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$ $|\eta^\gamma| \leq 2.5$ $R_{\gamma\gamma} \geq 0.45$

full NLO Cone (DIPHOX) vs Cone with LO fragmentation vs NLO Smooth

$E_{T\,max}^{had} = \epsilon\, p_T^\gamma \quad \epsilon = 0.05$ $E_{T\,max}^{had} = 4\,\mathrm{GeV}$



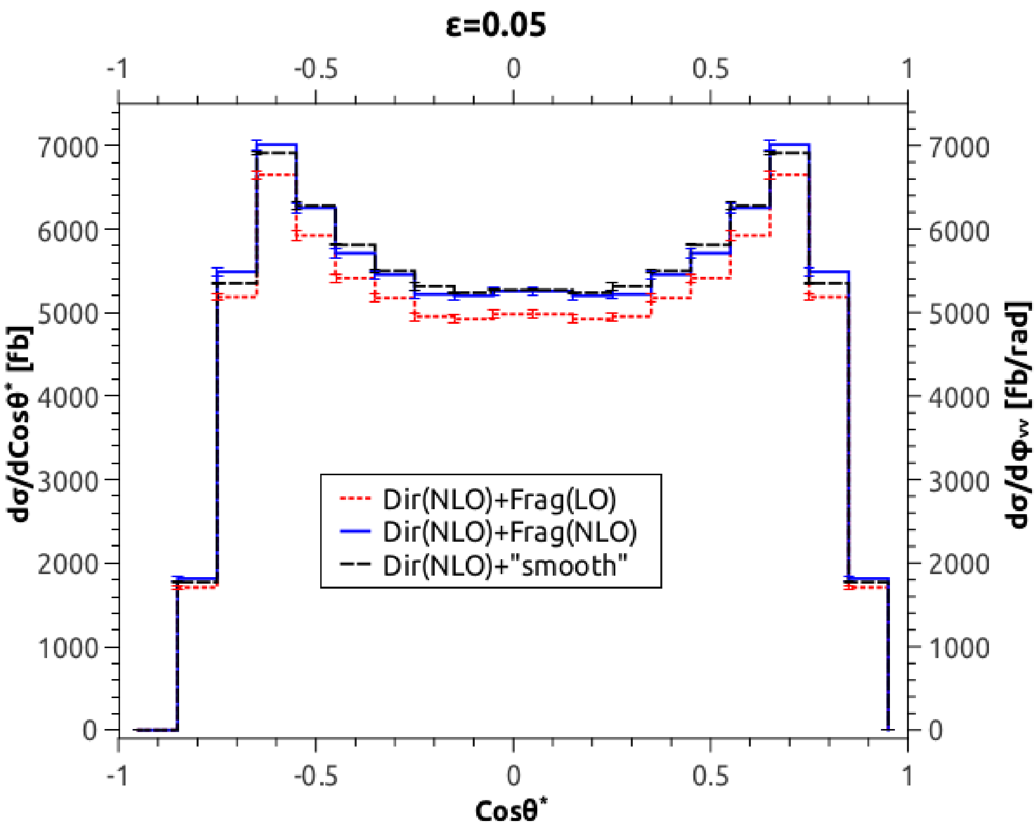


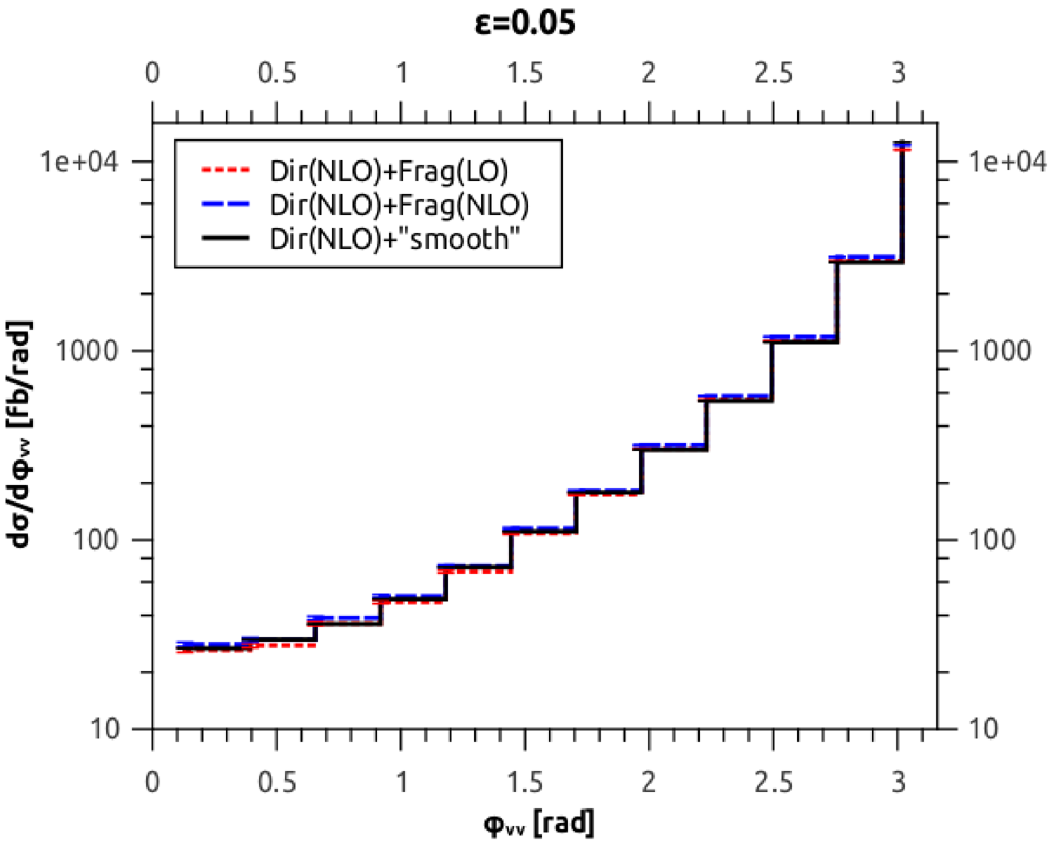
L.C , D. de Florian 2013

Same feature for all distributions

Smooth cone @NLO ~ Cone @ NLO 1-2% level

Cone + LO fragmentation component worse than 5%

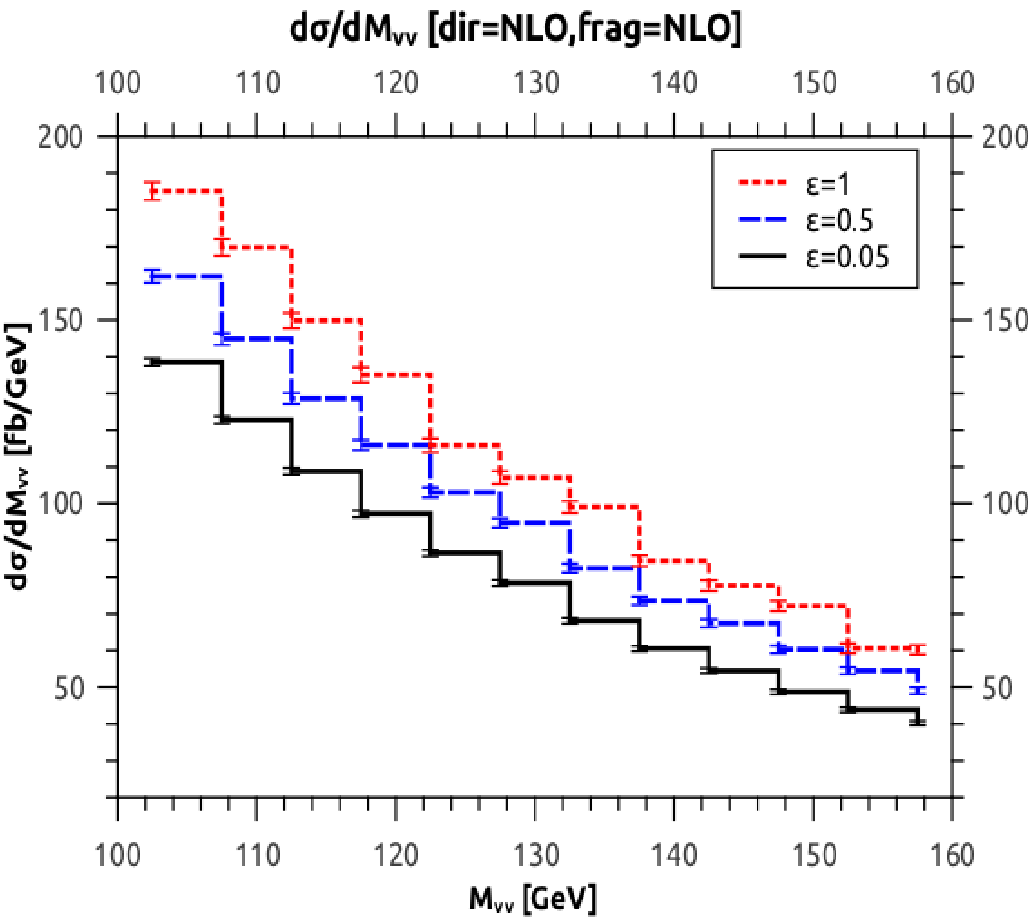


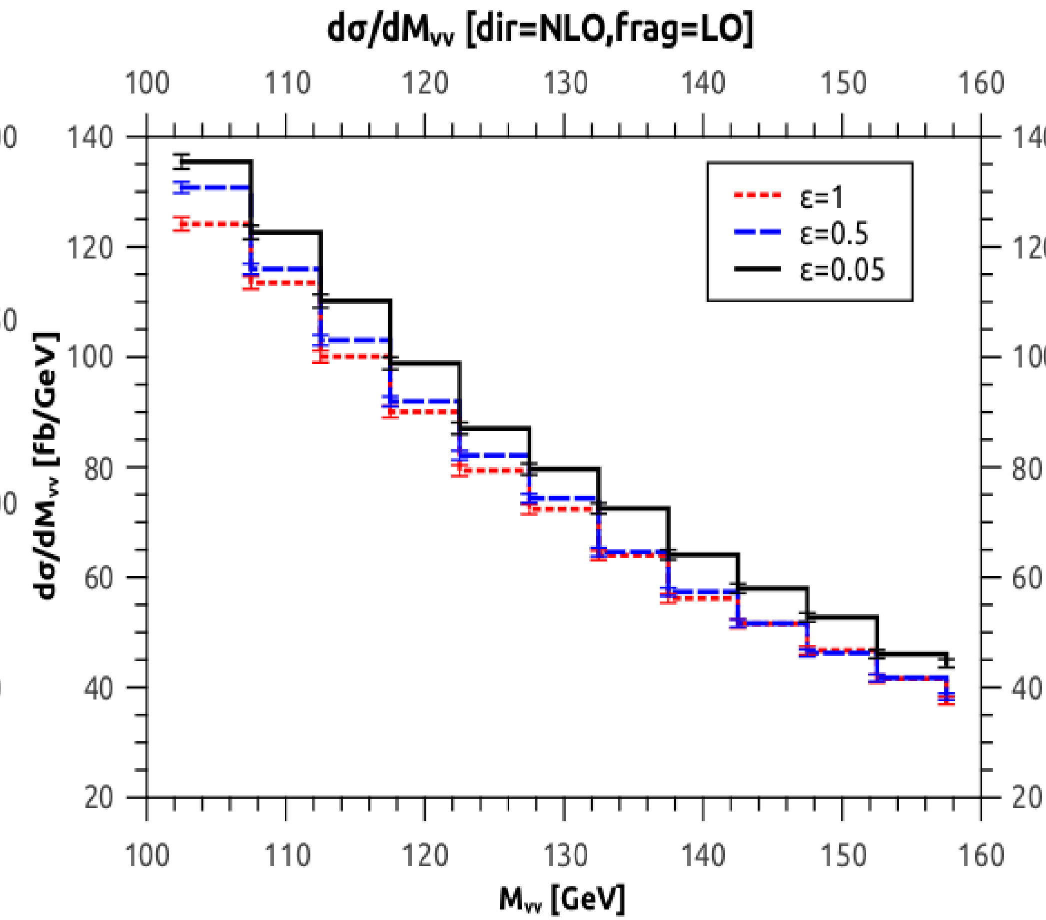


L.C , D. de Florian 2013

In cases, using LO fragmentation component can make things look very strange…

Cone isolation (DIPHOX)





L.C , D. de Florian 2013

In cases, using LO fragmentation component can make things look very strange...

Cone isolation (DIPHOX)

CMS [7 TeV]

	Code	$\sum E_T^{had} \leq$	σ^{NLO}_{total}(fb)	σ^{NLO}_{dir}(fb)	σ^{NLO}_{onef}(fb)	σ^{NLO}_{twof}(fb)	Isolation
a	DIPHOX	2 GeV	3746	3504	239	2.6	Standard
b	DIPHOX	3 GeV	3776	3396	374	6	Standard
c	DIPHOX	4 GeV	3796	3296	488	12	Standard
d	DIPHOX	5 GeV	3825	3201	607	17	Standard
e	DIPHOX	$0.05\ p_T^\gamma$	3770	3446	320	4	Standard
f	DIPHOX	$0.5\ p_T^\gamma$	4474	2144	2104	226	Standard
g	DIPHOX	*incl*	6584	1186	3930	1468	none
h	2γNNLO	$0.05\ p_T^\gamma\ \chi(r)$	3768	3768	0	0	Smooth
i	2γNNLO	$0.5\ p_T^\gamma\ \chi(r)$	4074	4074	0	0	Smooth
j	2γNNLO	2 GeV $\chi(r)$	3743	3743	0	0	Smooth
k	2γNNLO	3 GeV $\chi(r)$	3776	3776	0	0	Smooth
l	2γNNLO	4 GeV $\chi(r)$	3795	3795	0	0	Smooth
m	2γNNLO	5 GeV $\chi(r)$	3814	3814	0	0	Smooth

new at LH

L.C , D. de Florian 2013

In cases, using LO fragmentation component can make things look very strange...

Cone isolation (DIPHOX)

CMS [7 TeV]

	Code	$\sum E_T^{had} \leq$	σ_{total}^{NLO}(fb)	σ_{dir}^{NLO}(fb)	σ_{onef}^{NLO}(fb)	σ_{twof}^{NLO}(fb)	Isolation
a	DIPHOX	2 GeV	3746	3504	239	2.6	Standard
b	DIPHOX	3 GeV	3776	3396	374	6	Standard
c	DIPHOX	4 GeV	3796	3296	488	12	Standard
d	DIPHOX	5 GeV	3825	3201	607	17	Standard
e	DIPHOX	$0.05\ p_T^\gamma$	3770	3446	320	4	Standard
f	DIPHOX	$0.5\ p_T^\gamma$	4474	2144	2104	226	Standard
g	DIPHOX	*incl*	6584	1186	3930	1468	none
h	2γNNLO	$0.05\ p_T^\gamma\ \chi(r)$	3768	3768	0	0	Smooth
i	2γNNLO	$0.5\ p_T^\gamma\ \chi(r)$	4074	4074	0	0	Smooth
j	2γNNLO	2 GeV $\chi(r)$	3743	3743	0	0	Smooth
k	2γNNLO	3 GeV $\chi(r)$	3776	3776	0	0	Smooth
l	2γNNLO	4 GeV $\chi(r)$	3795	3795	0	0	Smooth
m	2γNNLO	5 GeV $\chi(r)$	3814	3814	0	0	Smooth

Tighter criteria

Direct component increasing

new at LH

Les Houches accord 2013

"LH tight photon isolation accord"

- EXP: use (tight) Cone isolation — solid and well understood
- TH: use smooth cone with same R and E_{Tmax} — accurate, better than using cone with LO fragmentation

Estimate TH isolation uncertainties using different profiles in smooth cone

While the definition of "tight enough" might slightly depend on the particular observable (that can always be checked by a lowest order calculation), our analysis shows that at the LHC isolation parameters as $E_T^{max} \leq 5$ GeV (or $\epsilon < 0.1$), $R \sim 0.4$ and $R_{\gamma\gamma} \sim 0.4$ are safe enough to proceeed.

This procedure would allow to extend available NLO calculations to one order higher (NNLO) for a number of observables, since the direct component is always much simpler to evaluate than the fragmentation part, which identically vanishes under the smooth cone isolation.

Les Houches accord 2013

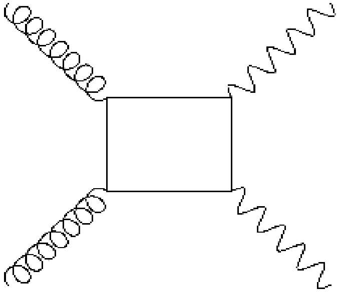
"LH tight photon isolation accord"

- EXP: use (tight) Cone isolation — solid and well understood
- TH: use smooth cone with same R and E_{Tmax} — accurate, better than using cone with LO fragmentation

Estimate TH isolation uncertainties using different profiles in smooth cone

Considering that NNLO corrections are of the order of 50% for diphoton cross sections and a few 100% for some distributions in extreme kinematical configurations, it is far better accepting a few % error arising from the isolation (less than the size of the expected NNNLO corrections and within any estimate of TH uncertainties!) than neglecting those huge QCD effects towards some "more pure implementation" of the isolation prescription.

Available NLO theoretical tools

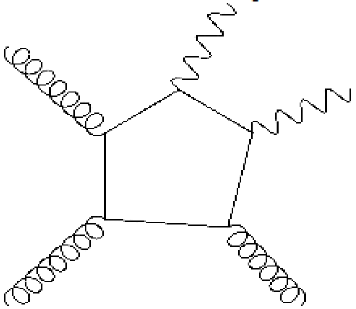


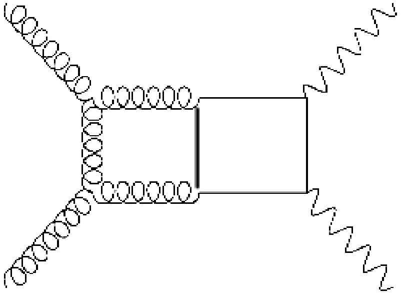
DIPHOX Full NLO for direct and fragmentation
+ Box contribution (one piece of NNLO)

T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen

gamma2MC Full NLO (direct only) + Box
+ correction to Box contribution partial N^3LO term

Zvi Bern, Lance Dixon, and Carl Schmidt





MCFM Full NLO for direct, but only LO for fragmentation
+ correction to Box contribution partial N^3LO term

John M. Campbell, R.Keith Ellis, Ciaran Williams

Resbos NLL q_T resummation for direct (with regulator for collinear singularities)
+ correction to Box contribution partial N^3LO term

C. Balázs, E. L. Berger, P. Nadolsky, and C.-P. Yuan

+ MC generators : Herwig, Pythia, SHERPA

Available NLO theoretical tools

DIPHOX Full NLO for direct and fragmentation
+ Box contribution (one piece of NNLO)

T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen

gamma2MC Full NLO (direct only) + Box
+ correction to Box contribution partial N^3LO term

Zvi Bern, Lance Dixon, and Carl Schmidt

MCFM Full NLO for direct, but only LO for fragmentation
+ correction to Box contribution partial N^3LO term

John M. Campbell, R.Keith Ellis, Ciaran Williams

Resbos NLL q_T resummation for direct (with regulator for collinear singularities)
+ correction to Box contribution partial N^3LO term

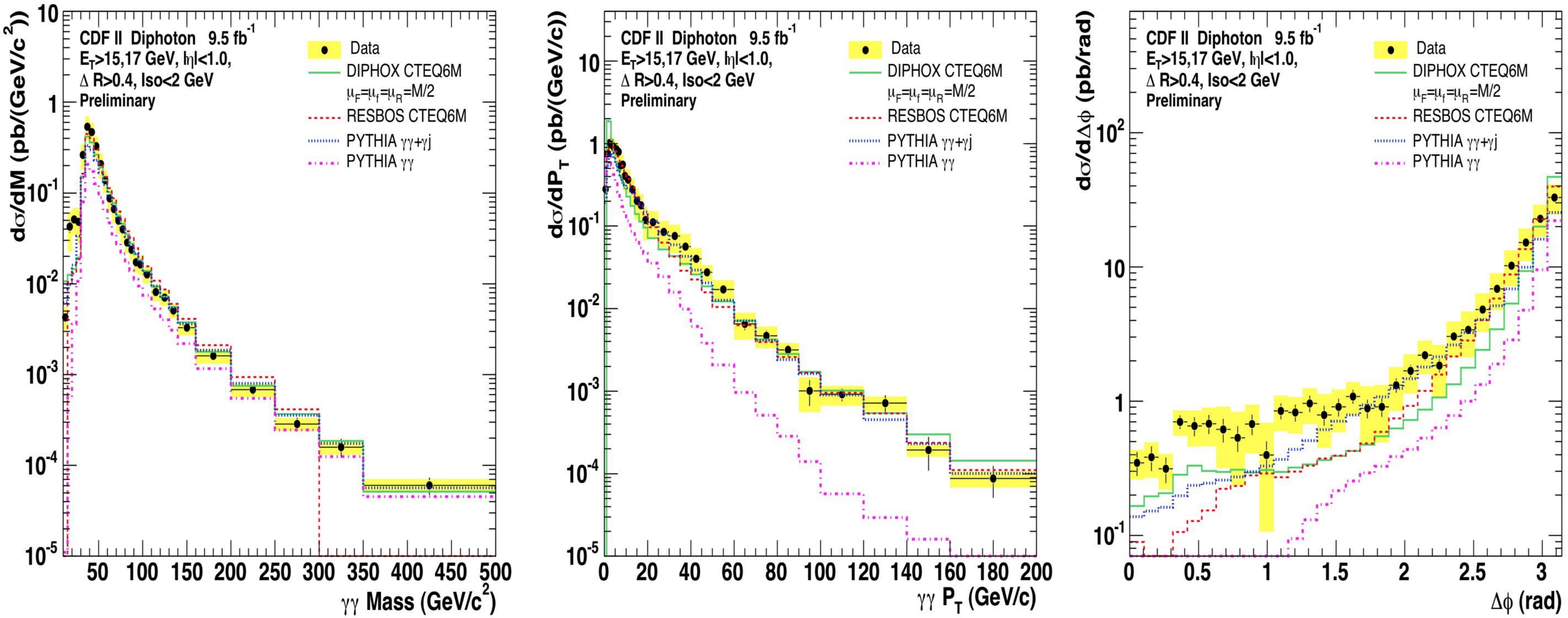
C. Balázs, E. L. Berger, P. Nadolsky, and C.-P. Yuan

Results tipically in good agreement with data, but some differences observed:

- **Azimuth separation for diphoton production**
- **Low mass region of the invariant mass distribution**

It is desireable to count on a NNLO description of the phenomenology of diphoton production

Differential cross sections: CDF

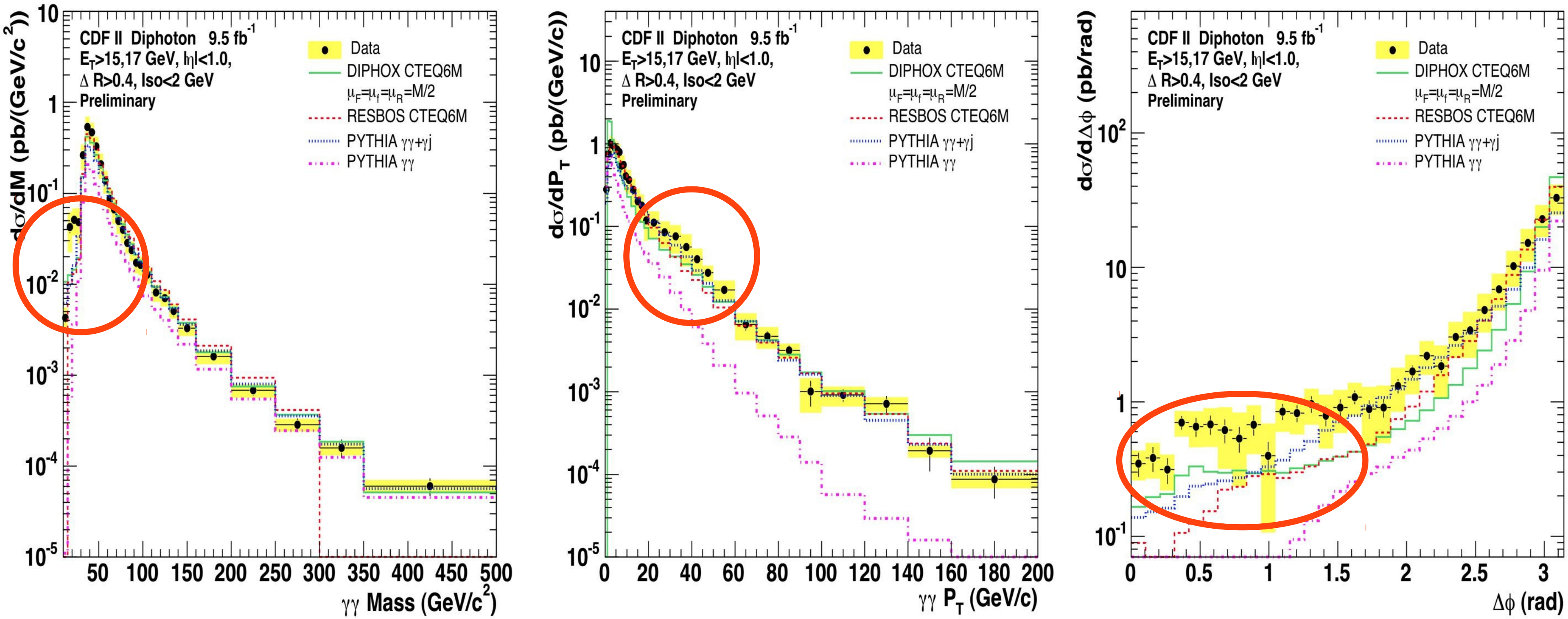


- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c²

- Resummation important
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the "Guillet shoulder")

- Resummation important for $\Delta\phi_{\gamma\gamma}$ > 2.2 rad
- Data spectrum harder than predicted

Differential cross sections: CDF



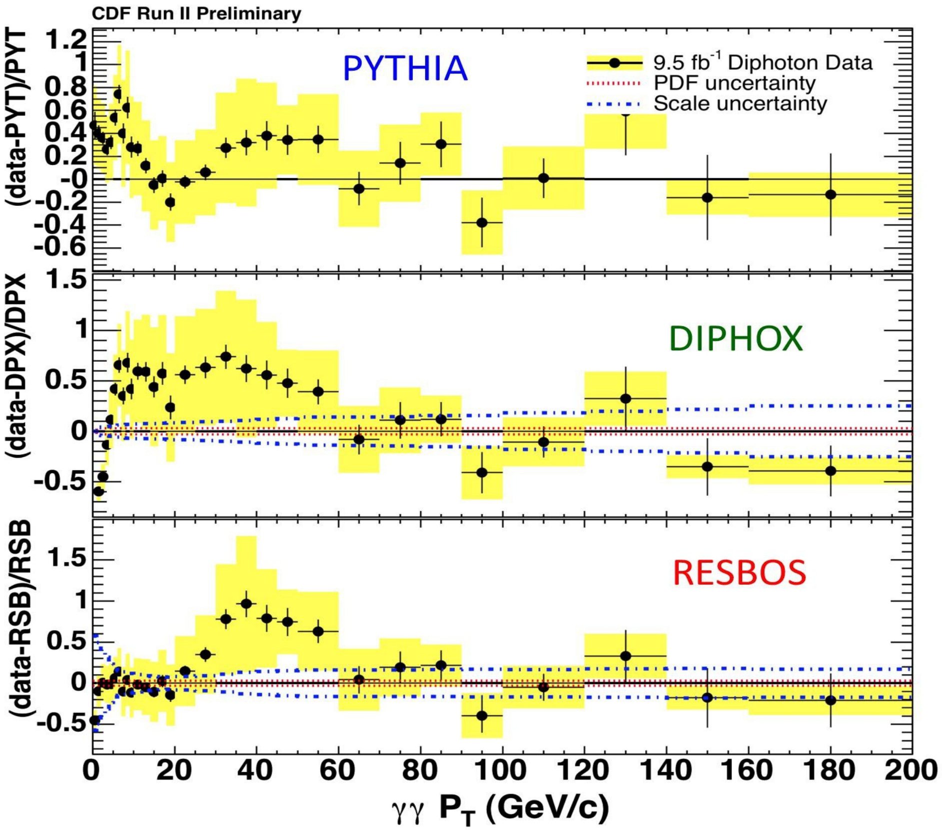
- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2

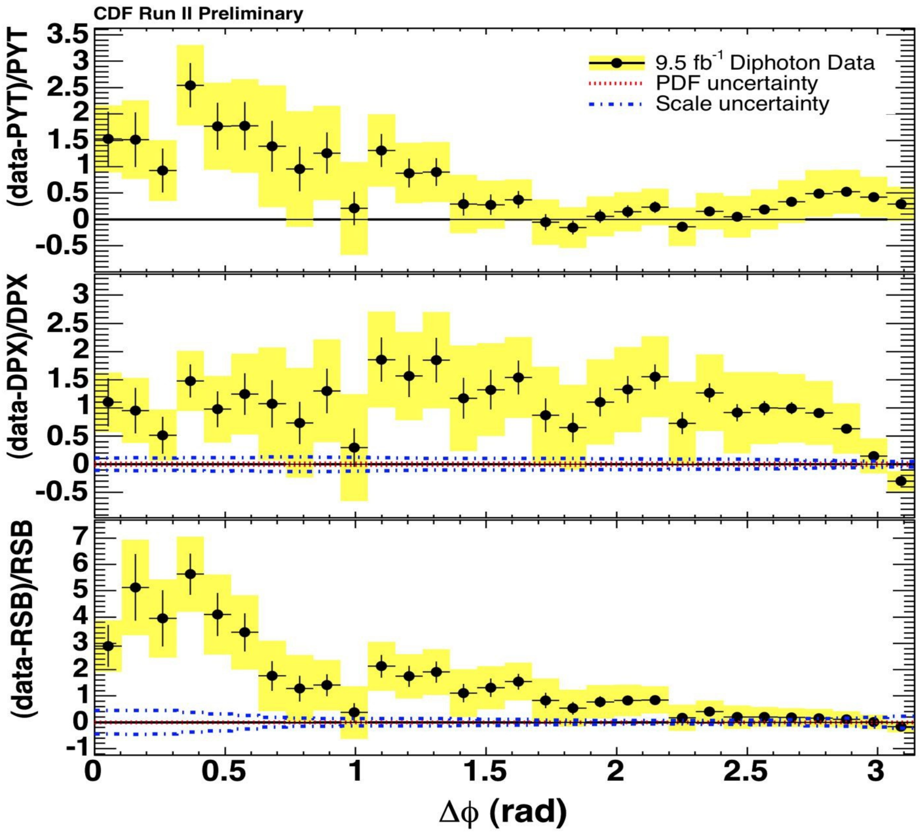
- Resummation important
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the "Guillet shoulder")

- Resummation important for $\Delta\phi_{\gamma\gamma}$ > 2.2 rad
- Data spectrum harder than predicted

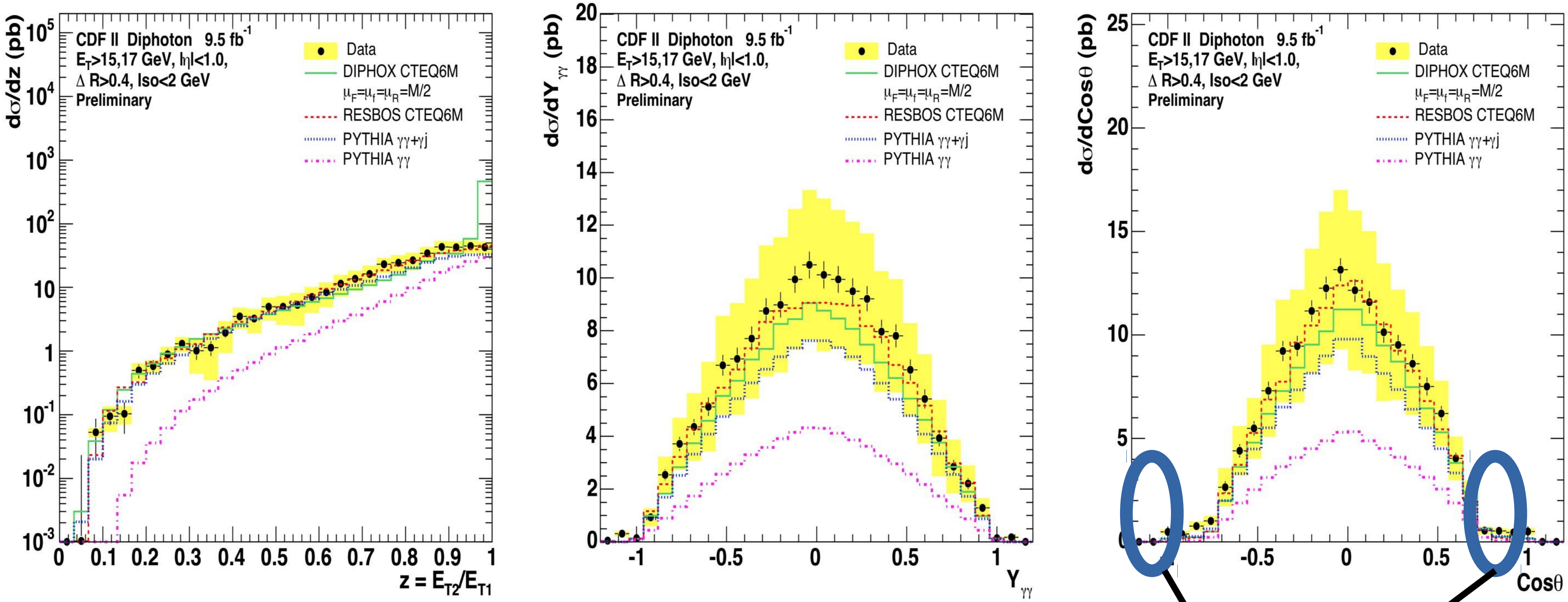
Data-to-theory cross section ratios: CDF

NB: Vertical axis scales are not the same





Differential cross sections: CDF



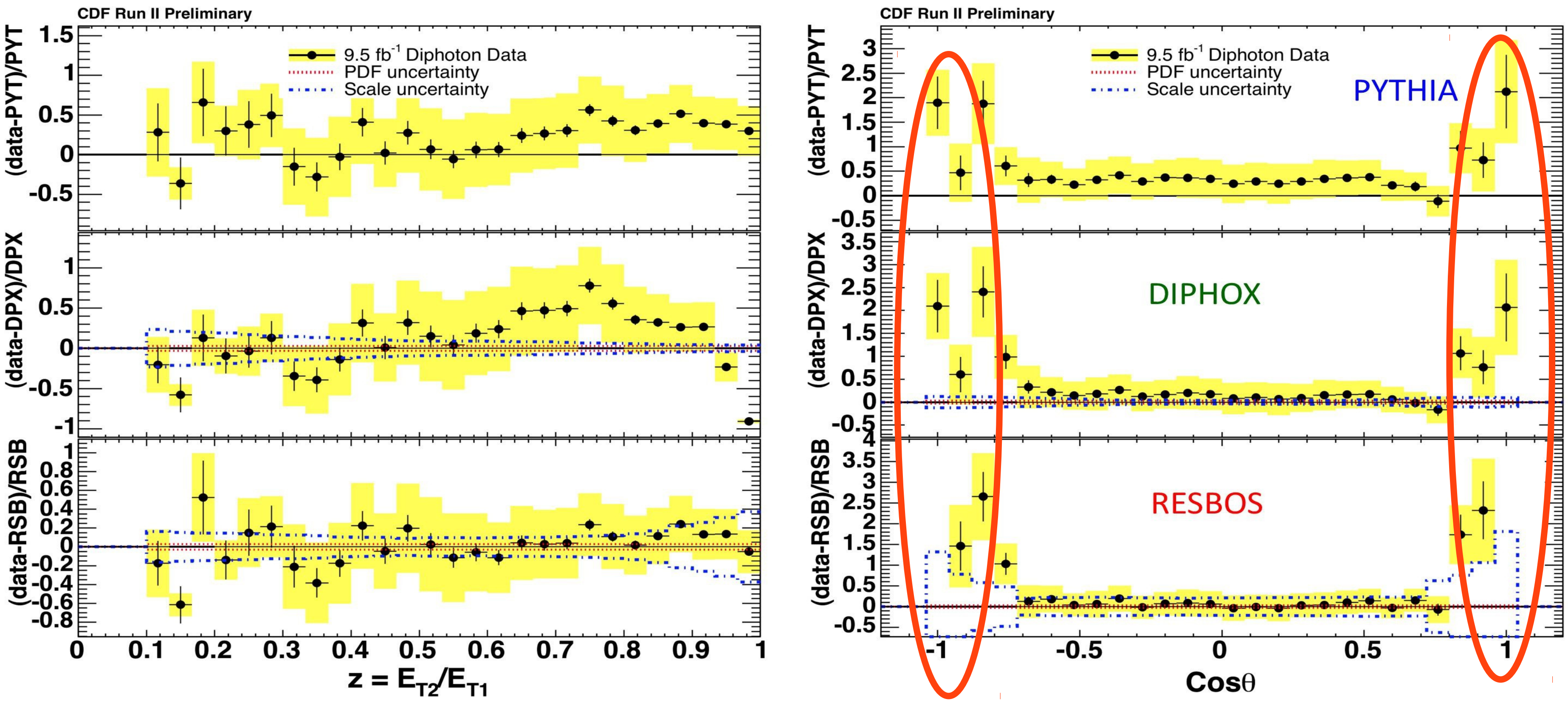
- Good agreement between data and RESBOS
- Good agreement between data and DIPHOX, except for 0.7<z<0.8

- Good agreement between data and theory

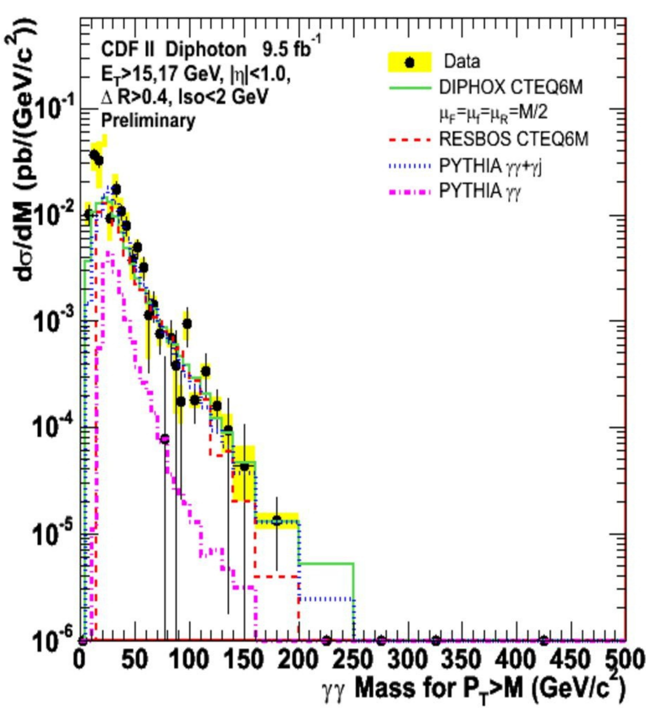
- Good agreement between data and theory, except for |cosθ|→1

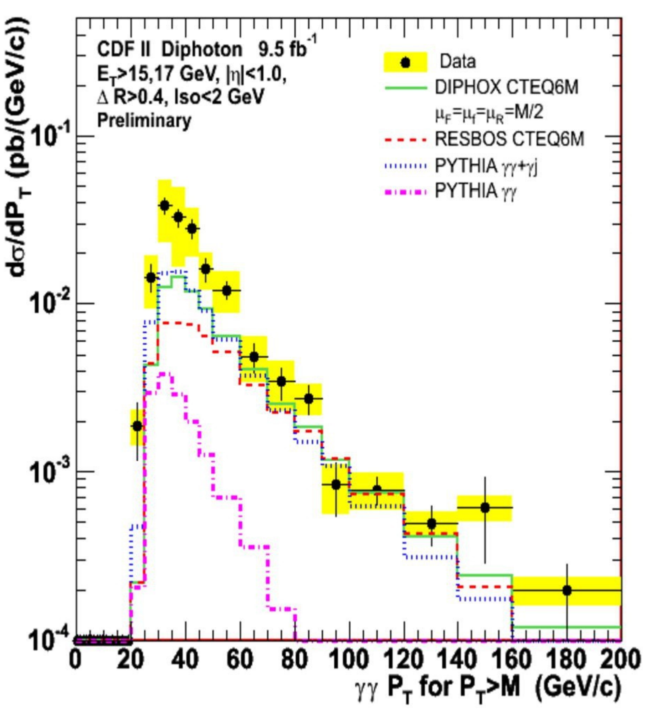
Data-to-theory cross section ratios: CDF

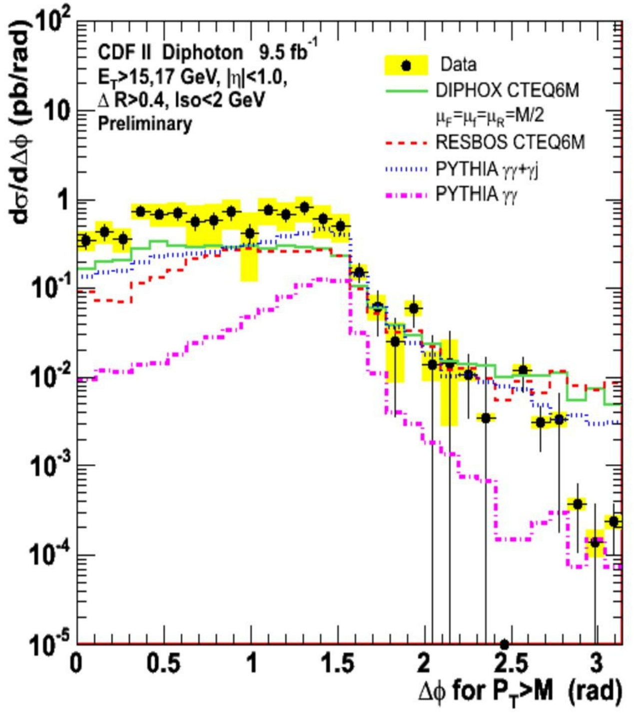
NB: Vertical axis scales are not the same



Differential cross sections for $P_T(\gamma\gamma)>M_{\gamma\gamma}$: CDF





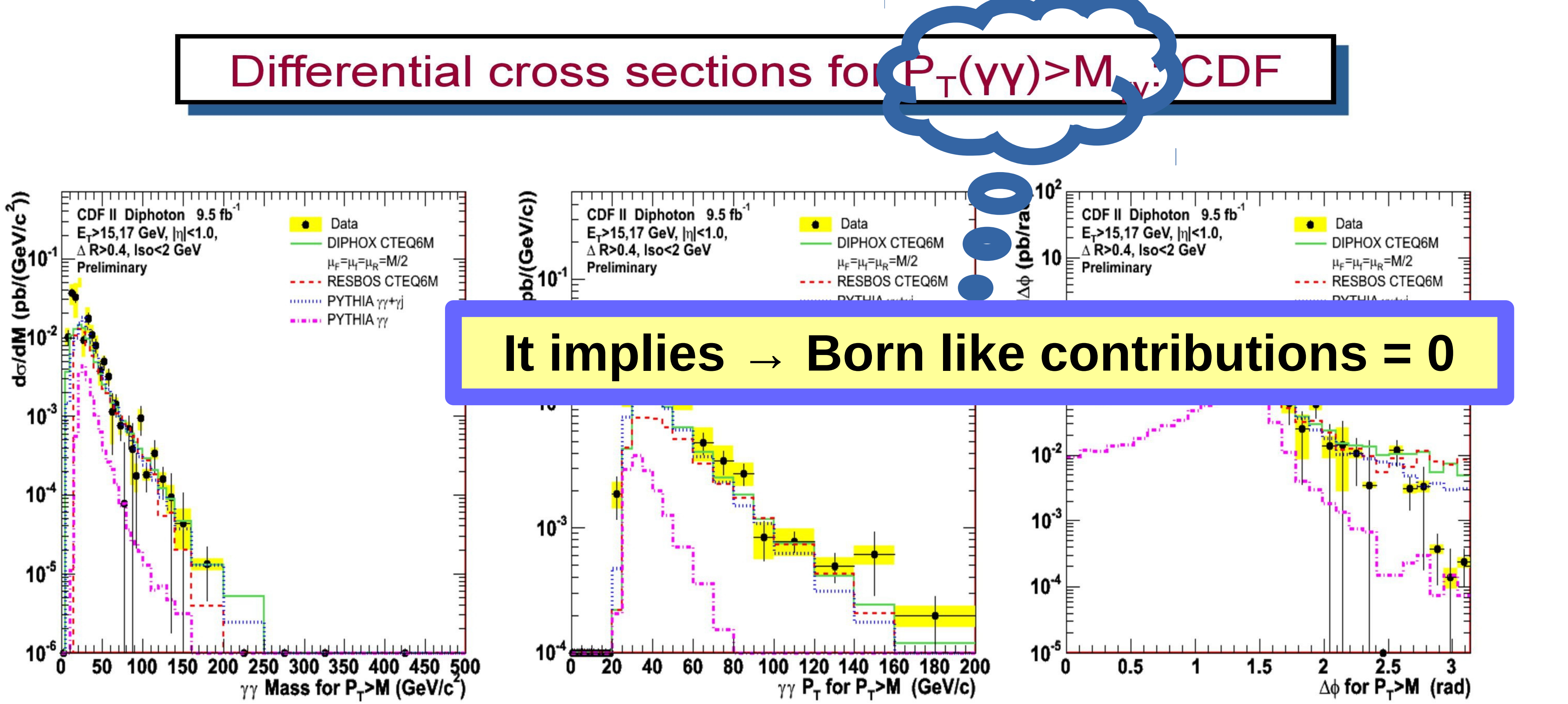


- Low statistics
- Excess of data over theory for $M_{\gamma\gamma}$<30 GeV/c^2

- Low statistics
- No events below $P_T(\gamma\gamma)$ = 20 GeV/c
- Excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the “Guillet shoulder”)

- Low statistics
- Data spectrum harder than predicted for $\Delta\phi$<1.5 rad
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma}$>1.5 rad

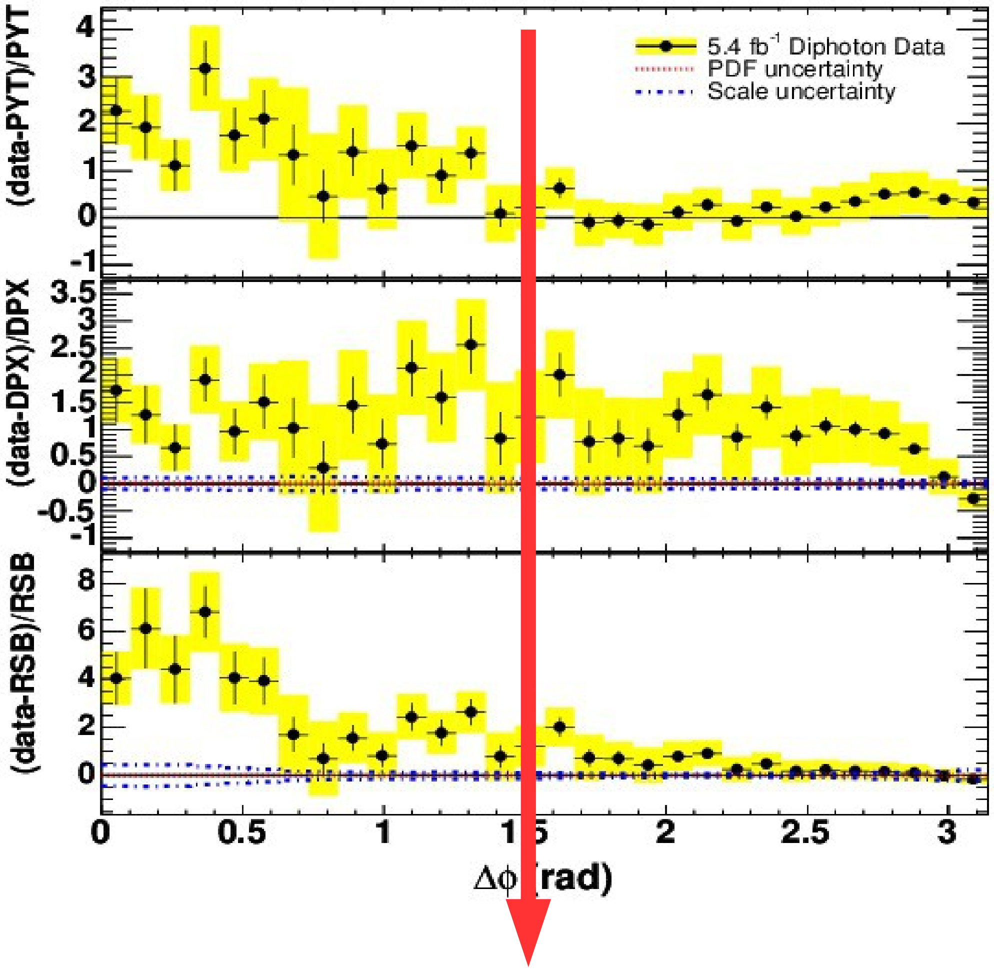
Differential cross sections for $P_T(\gamma\gamma)>M_{\gamma\gamma}$: CDF

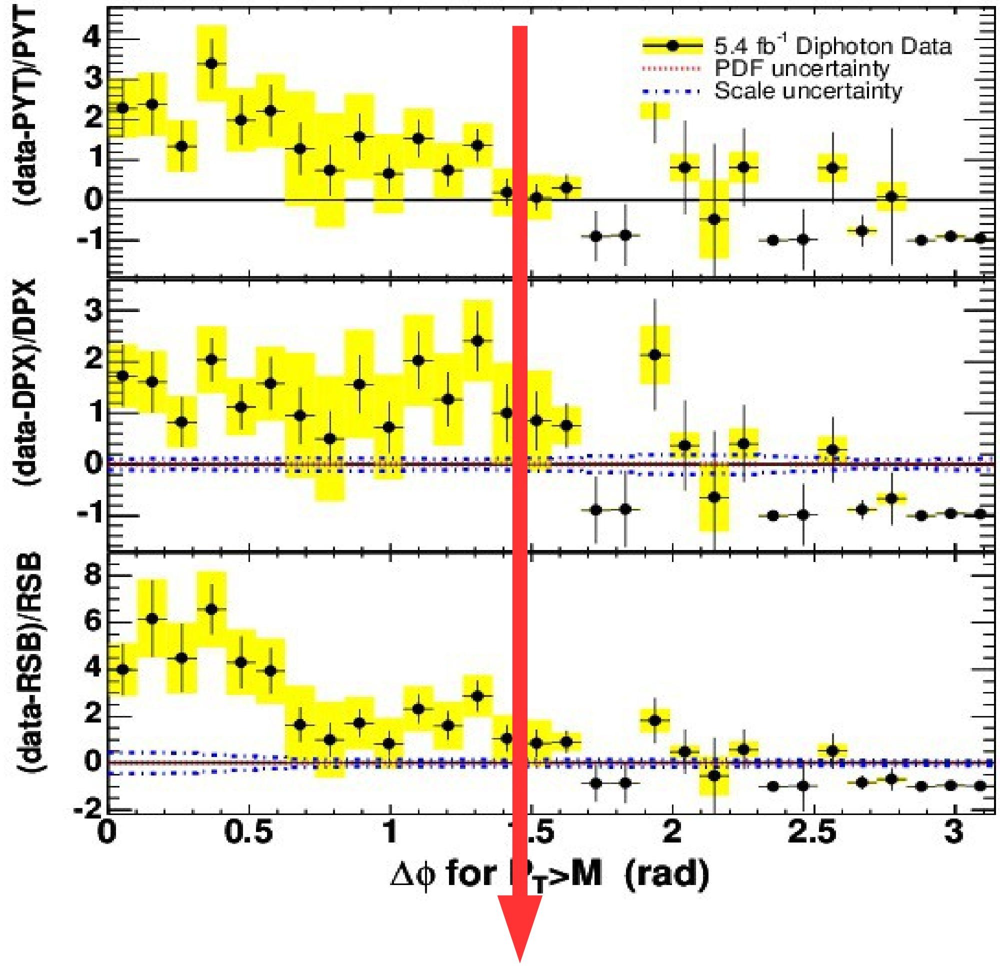


- Low statistics
- Excess of data over theory for $M_{\gamma\gamma}$<30 GeV/c²

- Low statistics
- No events below $P_T(\gamma\gamma)$ = 20 GeV/c
- Excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the "Guillet shoulder")

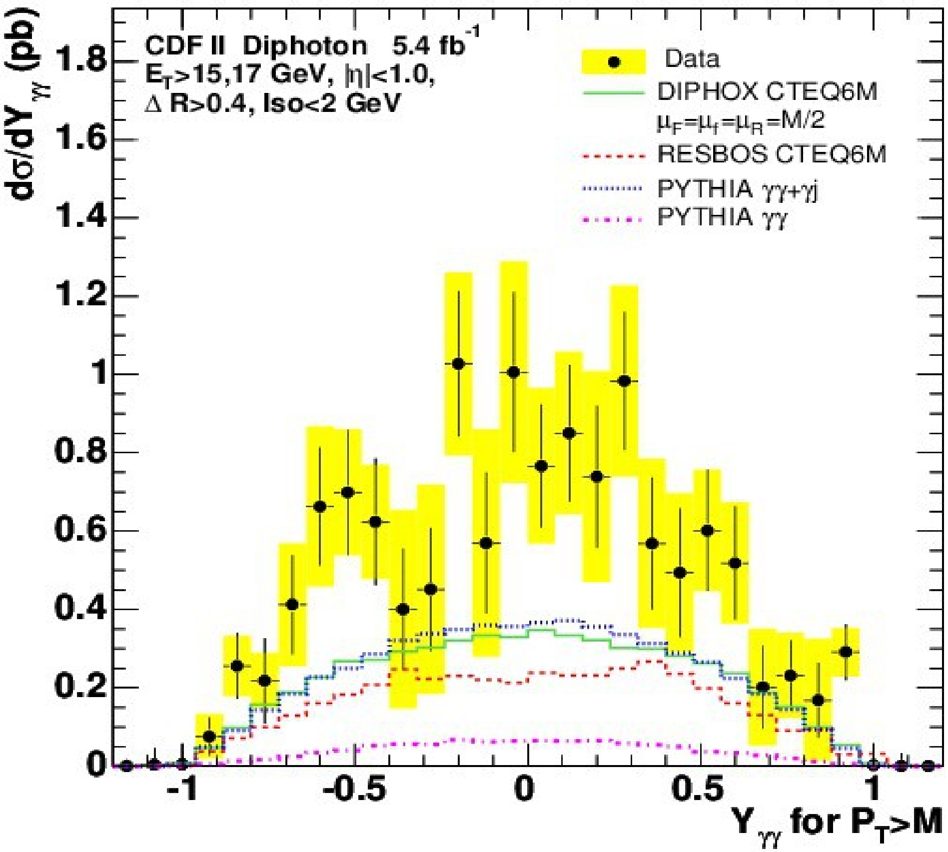
- Low statistics
- Data spectrum harder than predicted for $\Delta\phi$<1.5 rad
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma}$>1.5 rad

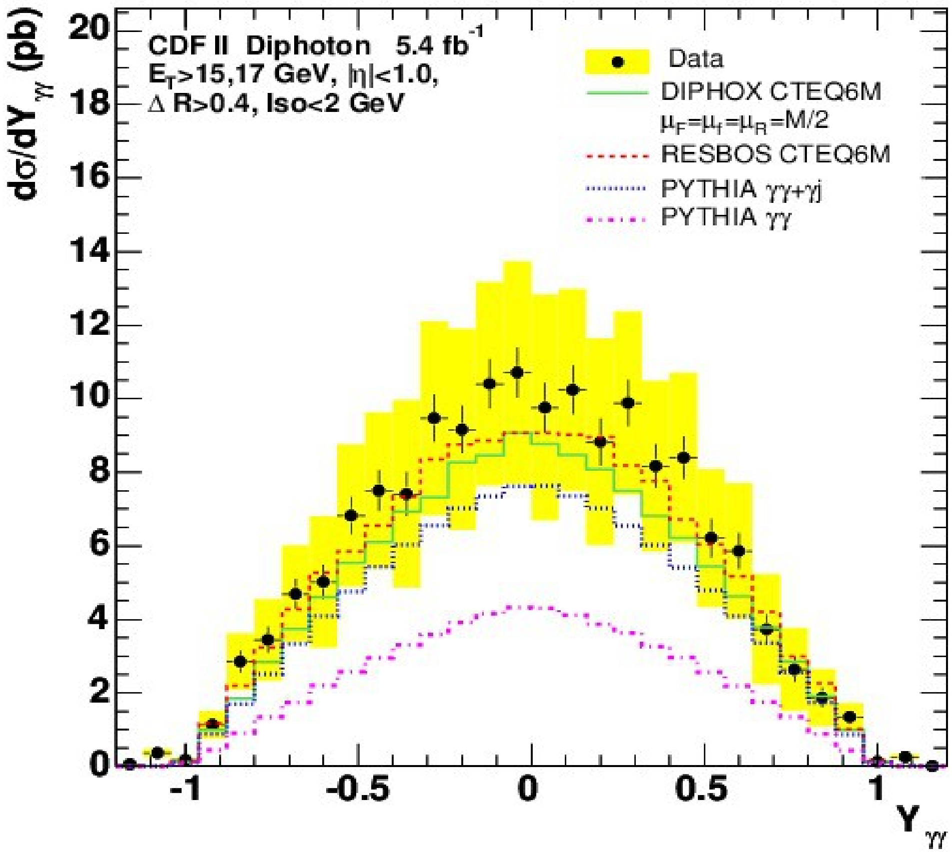




Full Xsection (NLO)

Only real corrections (NLO)



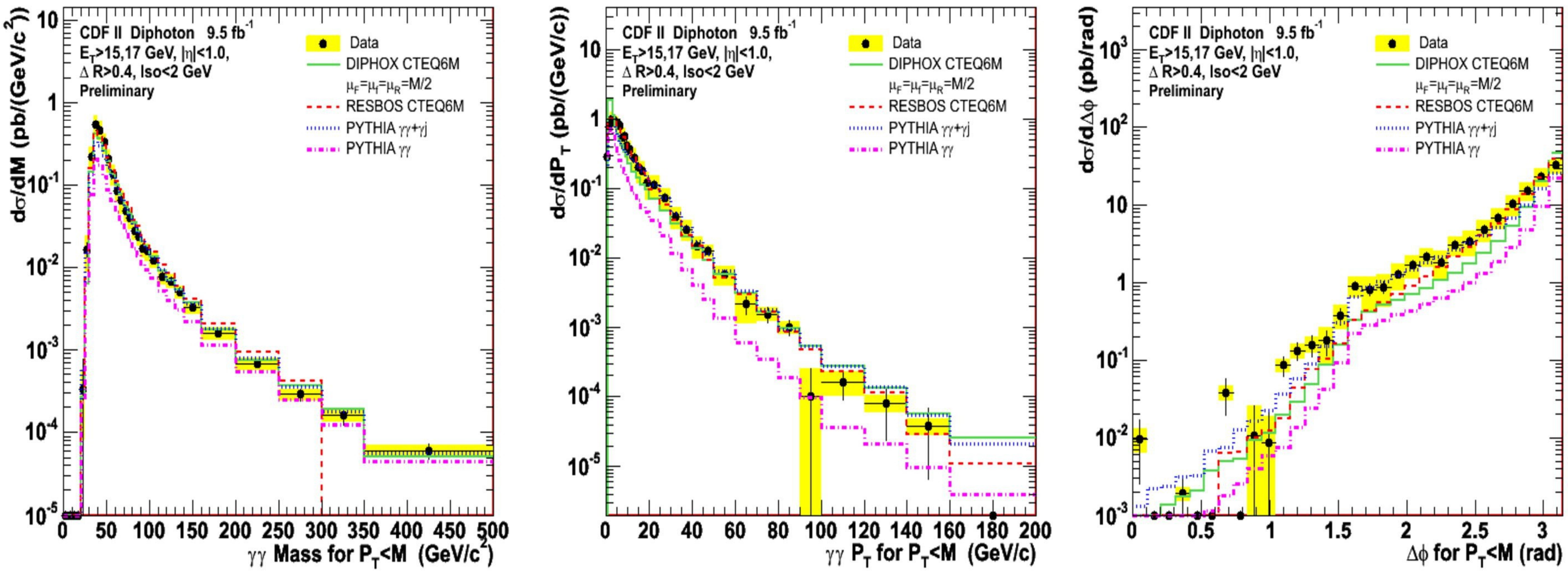


Only real corrections (NLO)

Full Xsection (NLO)

$$q_T^{\gamma\gamma} > M_{\gamma\gamma} \rightarrow \text{NLO} = \text{“LO”}$$

Differential cross sections for $P_T(\gamma\gamma)<M_{\gamma\gamma}$: CDF



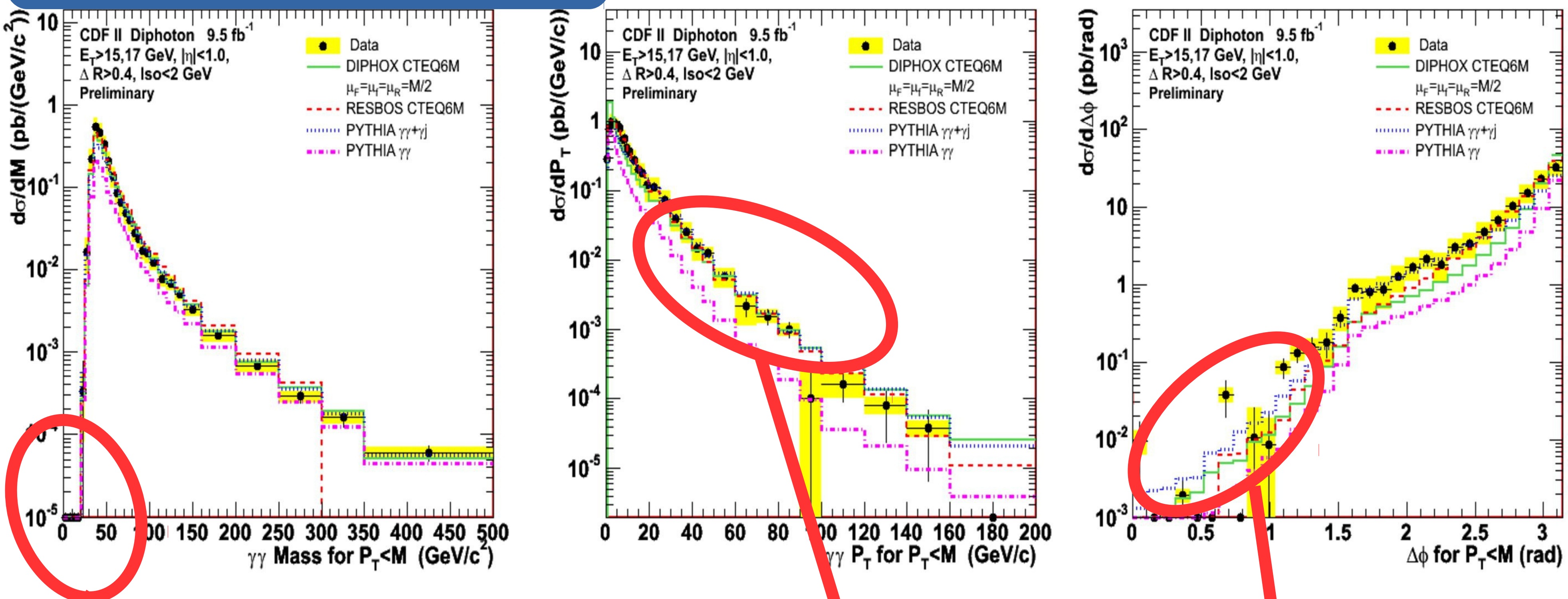
- Good agreement between data and theory
- No events for $M_{\gamma\gamma}<30$ GeV/c^2

- Good agreement between data and theory
- No excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the “Guillet shoulder”)

- Good agreement between data and theory
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma}<1.5$ rad

Differential cross sections for $P_T(\gamma\gamma)<M_{\gamma\gamma}$: CDF

Real radiation suppressed (NLO)



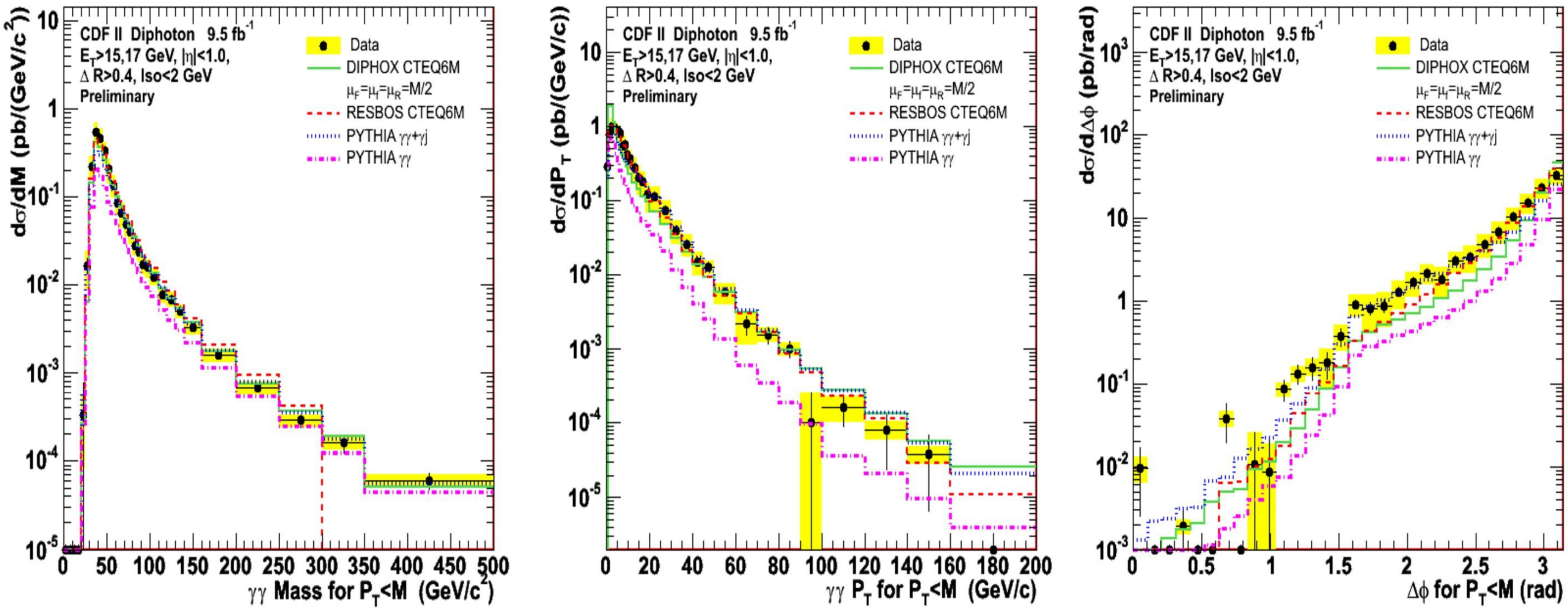
- Good agreement between data and theory
- No events for $M_{\gamma\gamma}$<30 GeV/c²

- Good agreement between data and theory
- No excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the "Guillet shoulder")

- Good agreement between data and theory
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma}$<1.5 rad

Real radiation suppressed (NLO)

Differential cross sections for $P_T(\gamma\gamma)<M_{\gamma\gamma}$: CDF



The discrepancies appear due to missing higher order correction terms (real radiation terms)

Diphoton production with 2γNNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

- Based on the q_T subtraction formalism

S. Catani, M. Grazzini

- Fully exclusive NNLO description(direct contribution) for $pp(\bar{p}) \rightarrow \gamma\gamma$
- No fragmentation contribution

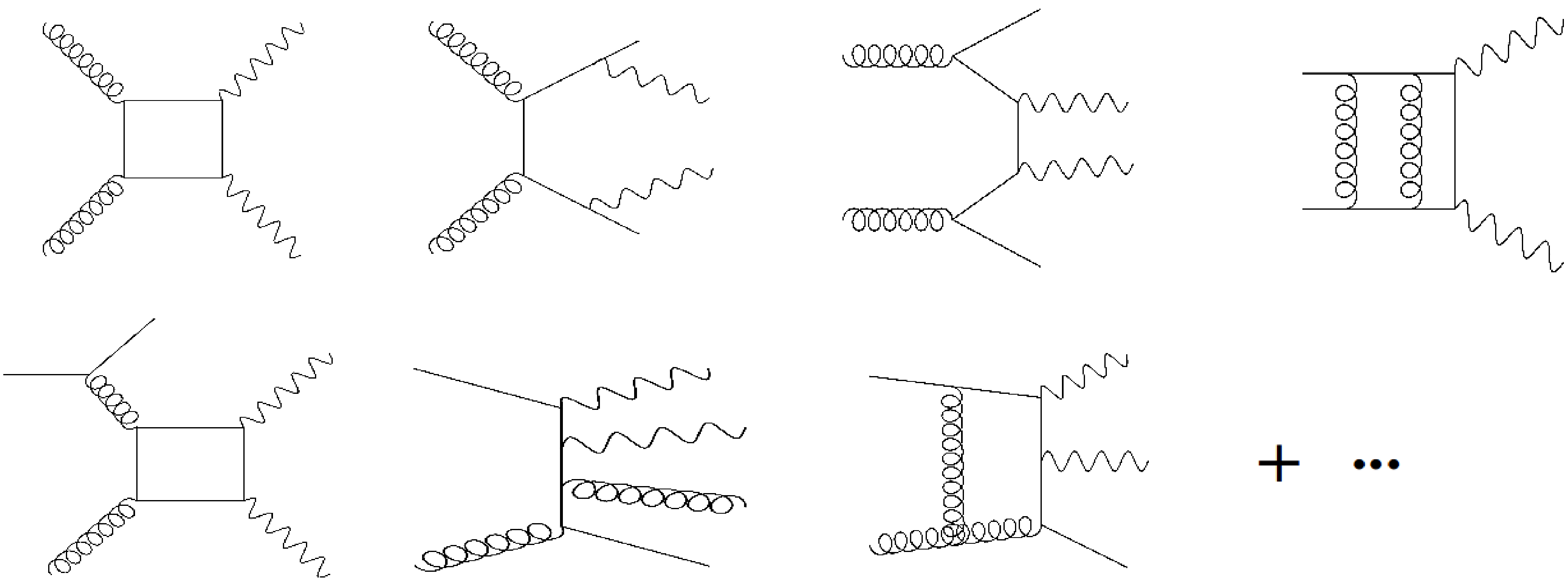
Frixione Isolation

- Also corrections to Box contribution, partial N^3LO terms available

Zvi Bern, Lance Dixon, and Carl Schmidt

(Available, but not present in the following analysis)

Full NNLO means full control of the $\mathcal{O}(\alpha_s^2)$ diagrams:



Diphoton production with 2γNNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

- Based on the q_T subtraction formalism

S. Catani, M. Grazzini

- Fully exclusive NNLO description(direct contribution) for $pp(\bar{p}) \to \gamma\gamma$
- No fragmentation contribution

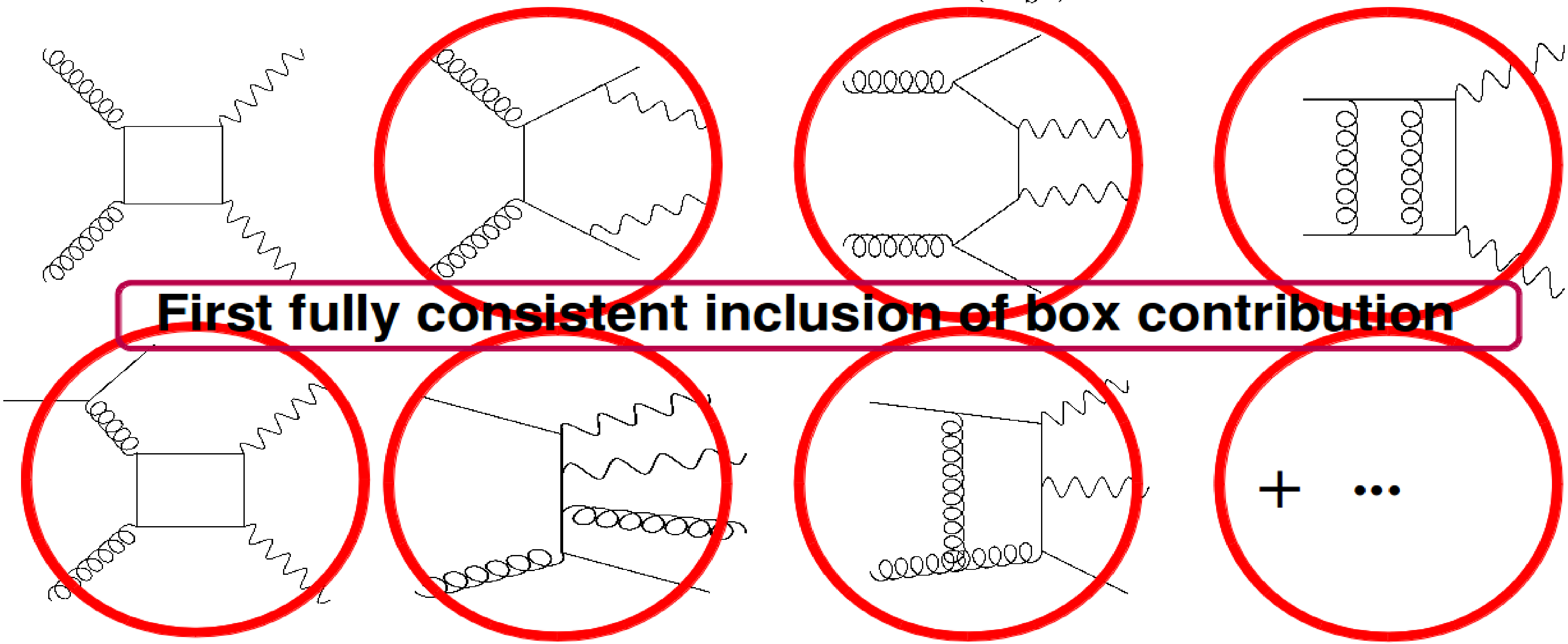
Frixione Isolation

- Also corrections to Box contribution, partial N^3LO terms available

Zvi Bern, Lance Dixon, and Carl Schmidt

(Available, but not present in the following analysis)

Full NNLO means full control of the $\mathcal{O}(\alpha_s^2)$ diagrams:

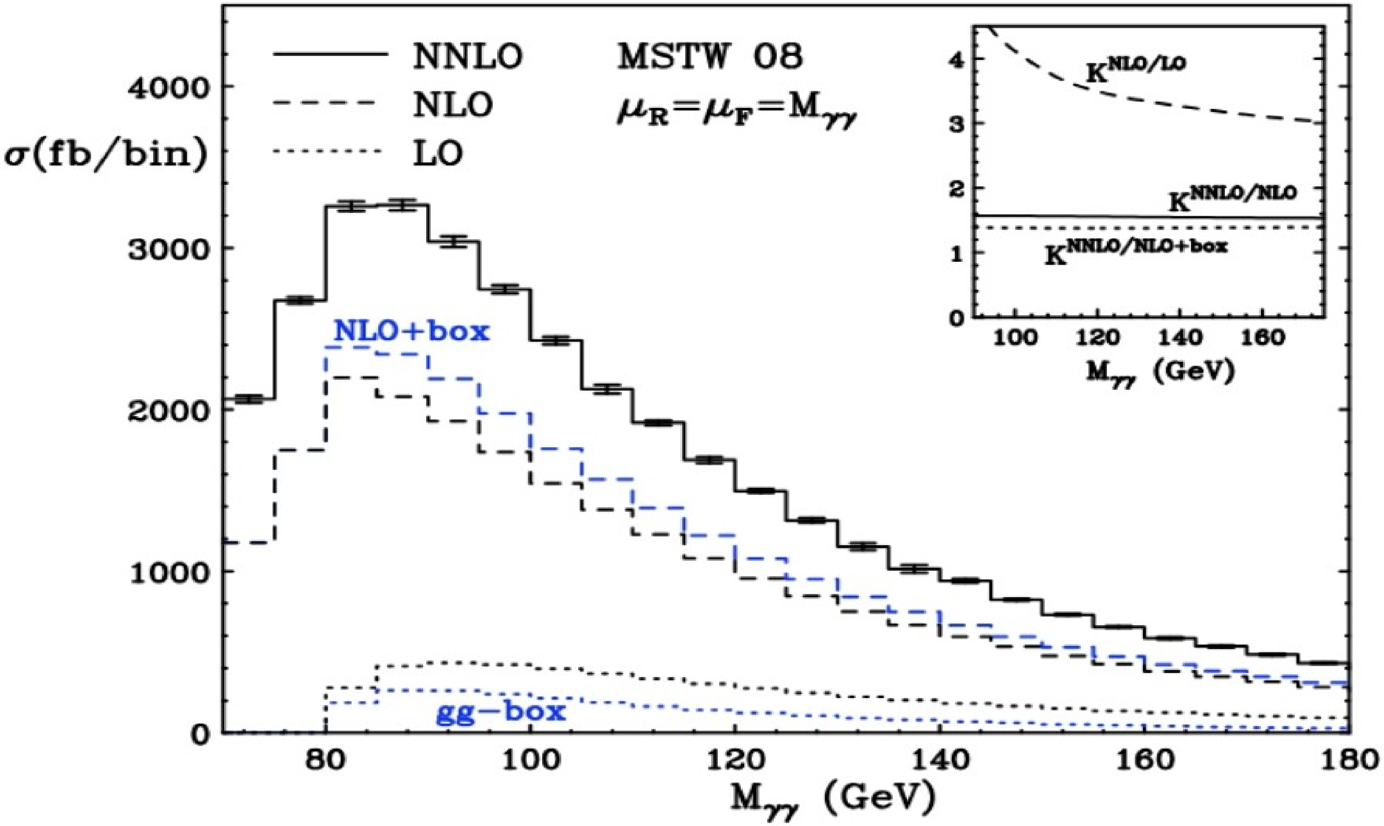


Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

First results using $2\gamma\mathrm{NNLO}$



$$\sqrt{S} = 14\,\mathrm{TeV}$$

$$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$$

$$p_T^{\gamma\, soft} \geq 25\,\mathrm{GeV}$$

$$|\eta^\gamma| \leq 2.5$$

$$20\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 250\,\mathrm{GeV}$$

$$\mu_R = \mu_F = M_{\gamma\gamma}$$

NNLO effect about +50 % in the peak region

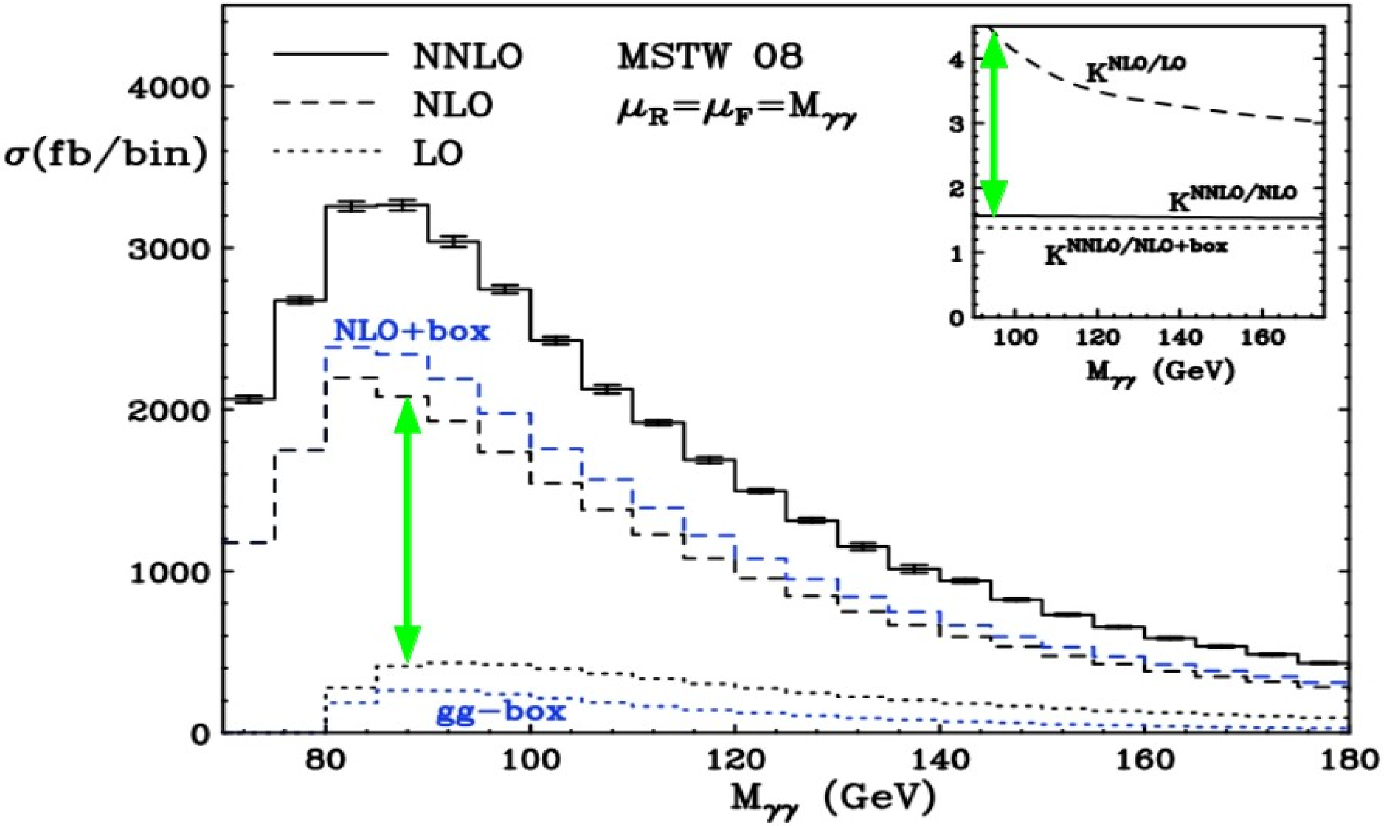
Box only ~22% of NNLO correction

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

First results using $2\gamma\mathrm{NNLO}$



$$\sqrt{S} = 14\,\mathrm{TeV}$$

$$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$$

$$p_T^{\gamma\,soft} \geq 25\,\mathrm{GeV}$$

$$|\eta^\gamma| \leq 2.5$$

$$20\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 250\,\mathrm{GeV}$$

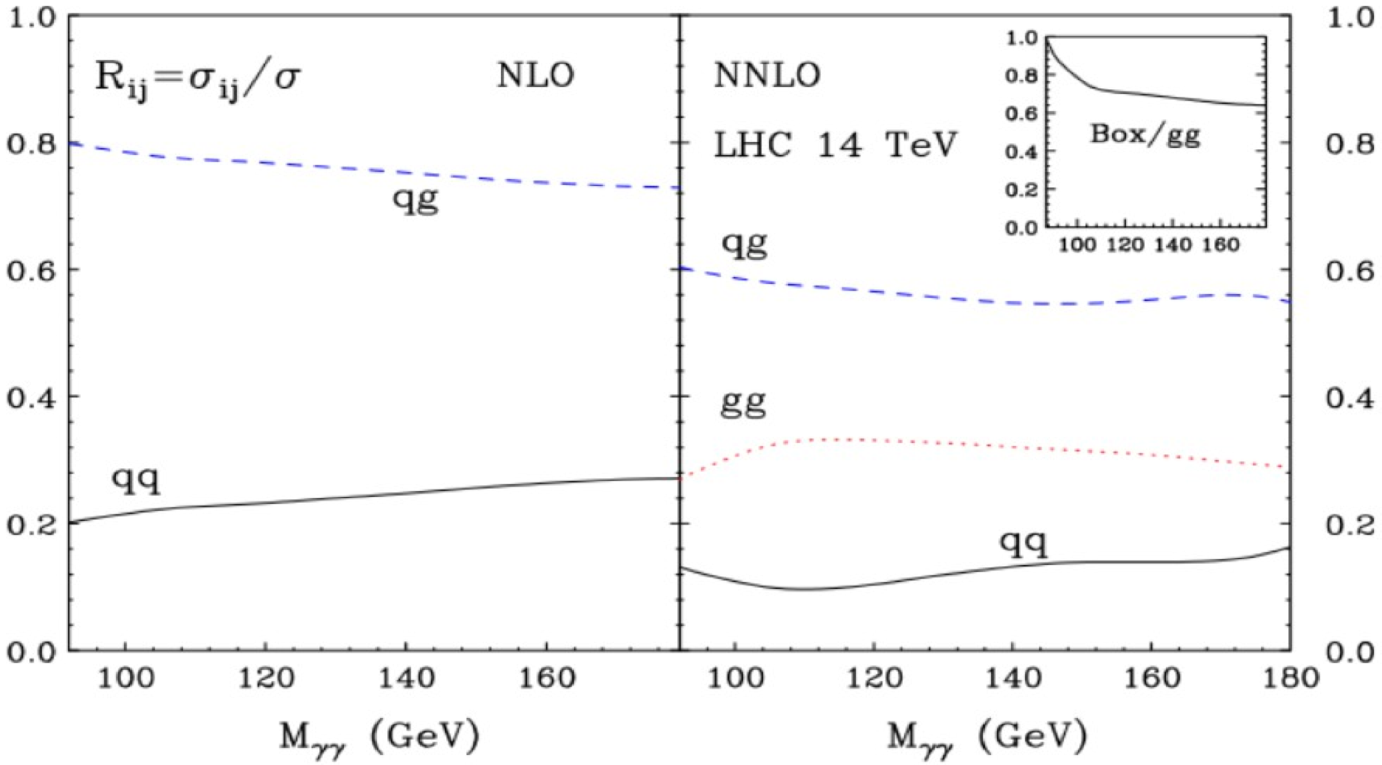
$$\mu_R = \mu_F = M_{\gamma\gamma}$$

$$\frac{\sigma^{NNLO}}{\sigma^{NLO+Box}} \sim 1.35$$

$$\frac{\sigma^{NNLO}}{\sigma^{NLO}} \sim 1.55$$

Huge corrections 1 : new channels

Channels @ 14 TeV



Box only ~22% of NNLO correction

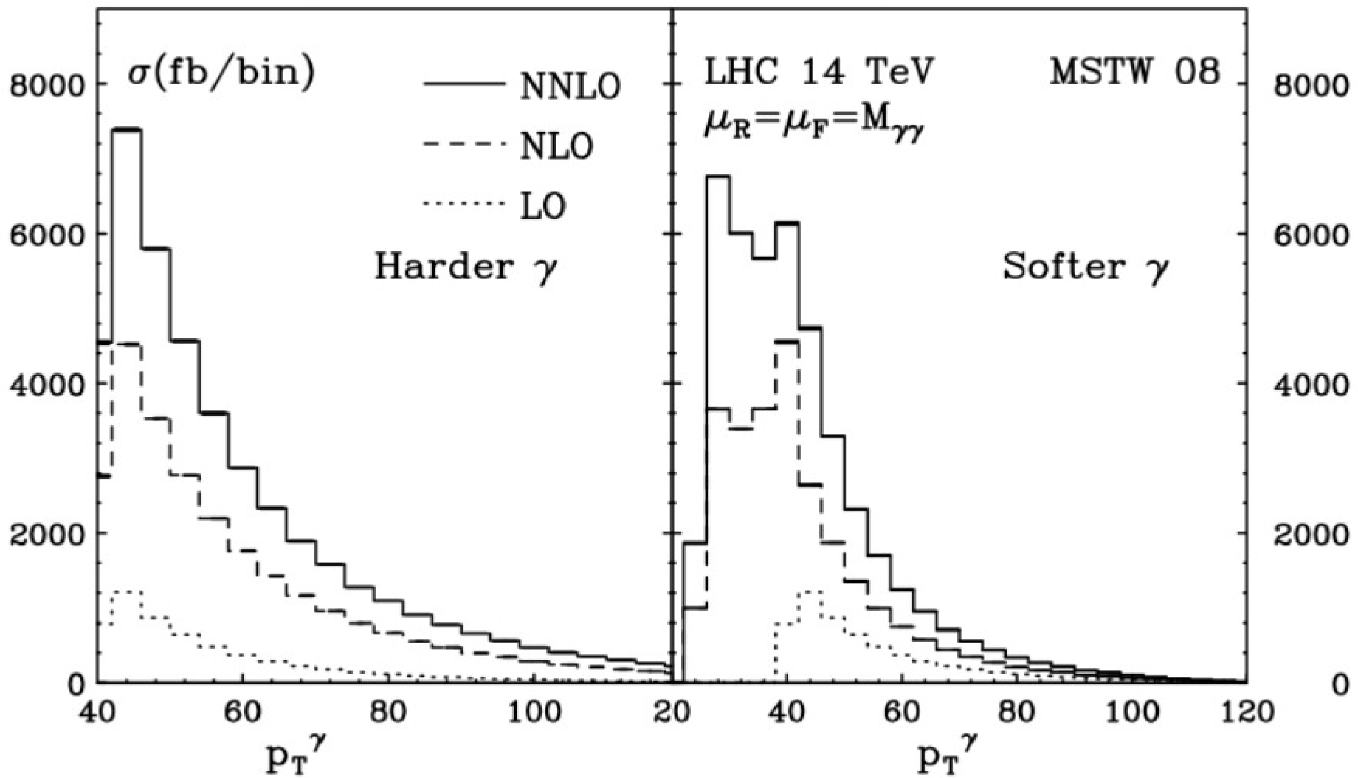
Main contribution from qg channel
(corrections to NLO dominant channel)

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

p_T of harder and softer photon



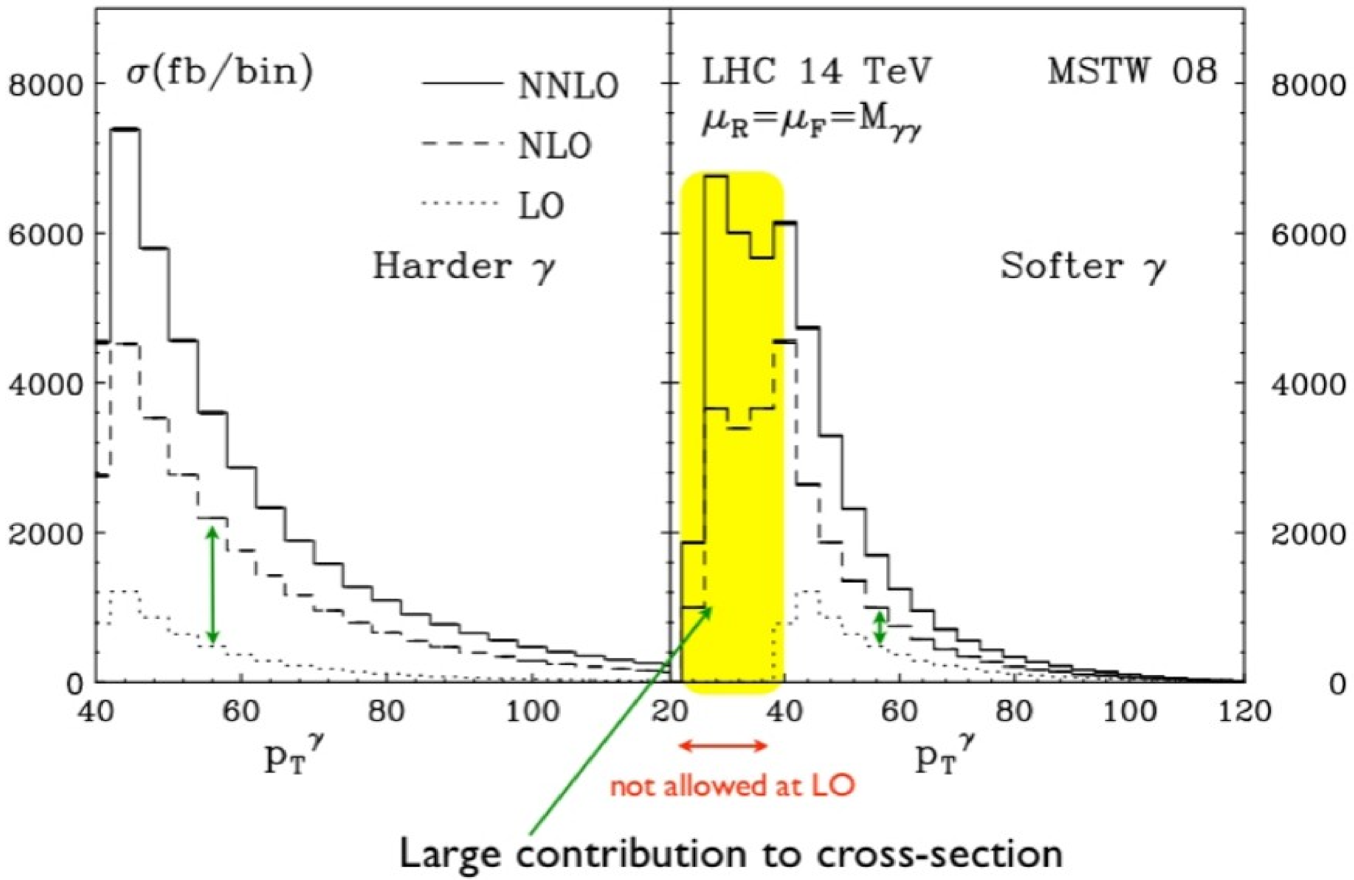
The requirement $p^{\gamma}_{T1} \geq 40$ GeV implies that at LO also the softer photon must have $p^{\gamma}_{T} \geq 40$ GeV

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

p_T of harder and softer photon



The requirement $p^\gamma_{T1} \geq 40$ GeV implies that at LO also the softer photon must have $p^\gamma_T \geq 40$ GeV

- Substantial contribution from radiation in the region 25 GeV < pT < 40 GeV
- Unphysical peak in $\mathbf{p}^\gamma_{T2}$ at $\mathbf{p}^\gamma_T$ =40 GeV

S. Catani, M. Fontannaz, J.P. Guillet, E. Pilon. JHEP 0205 (2002) 028

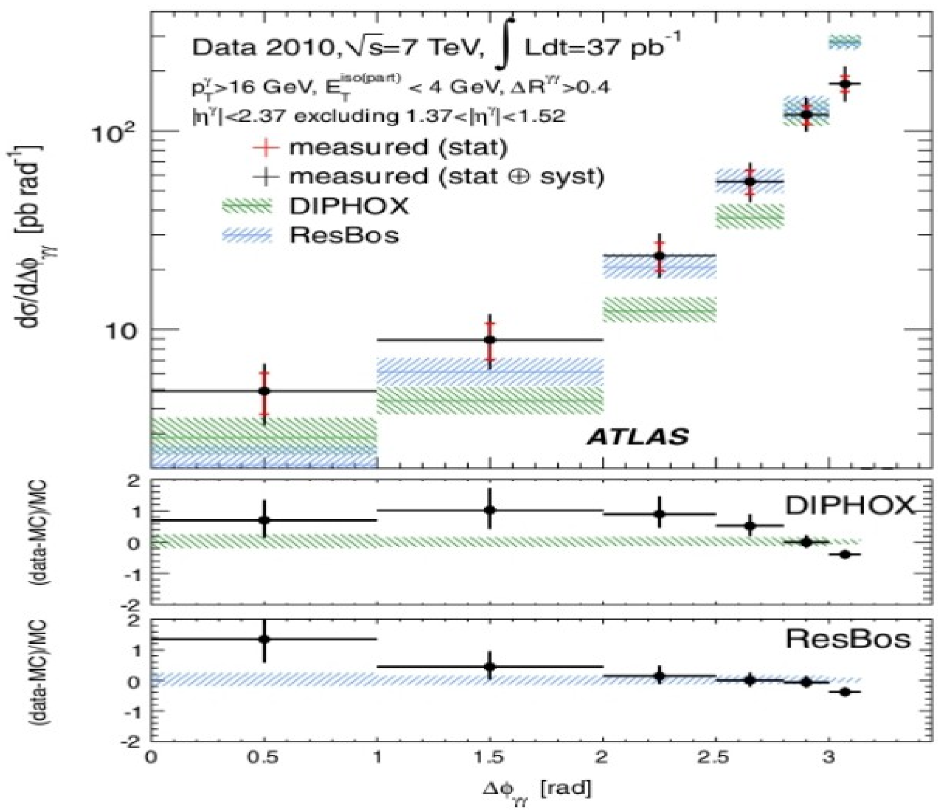
Catani, Webber. JHEP 9710 (1997) 005

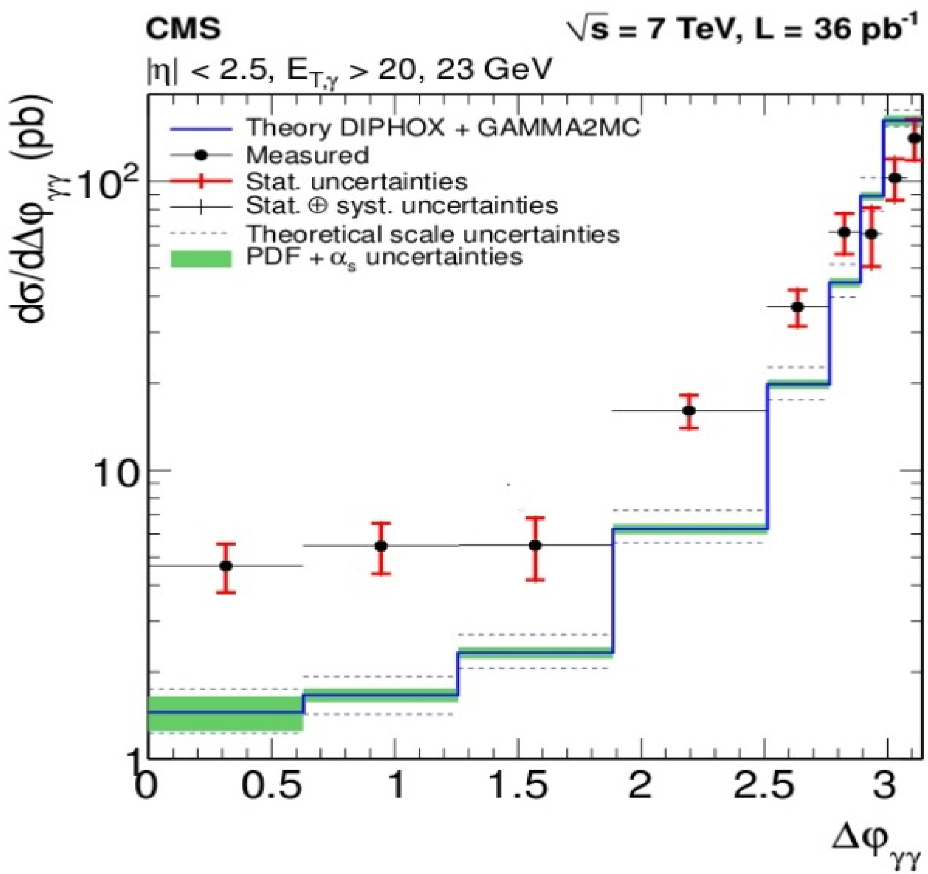
Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data





PRD 85, 012003 (2012)

JHEP 01(2012)133

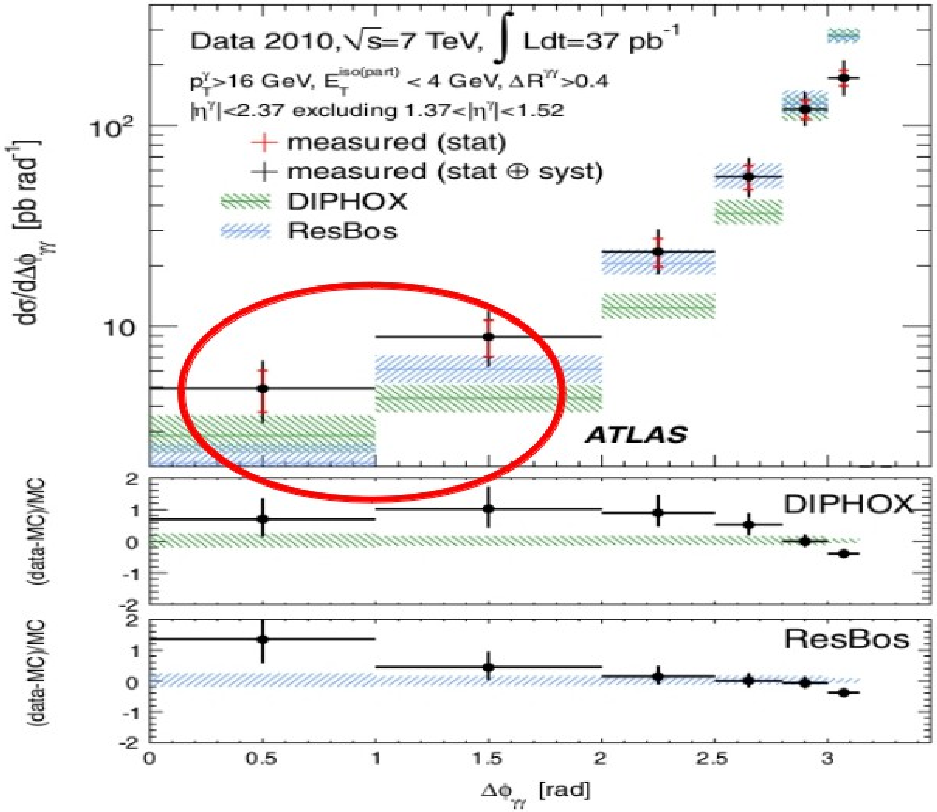
Same discrepancies found by CDF: Phys.Rev.Lett.107:102003,2011.

Diphoton production at NNLO

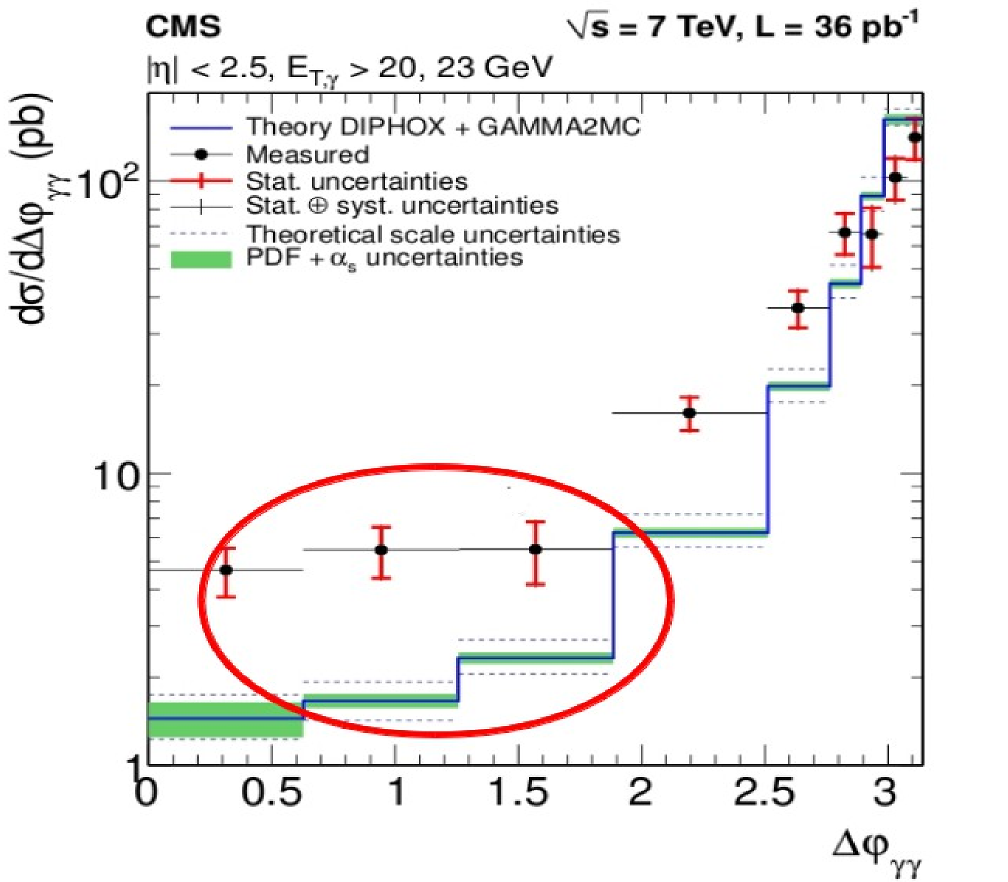
S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data



PRD 85, 012003 (2012)



JHEP 01(2012)133

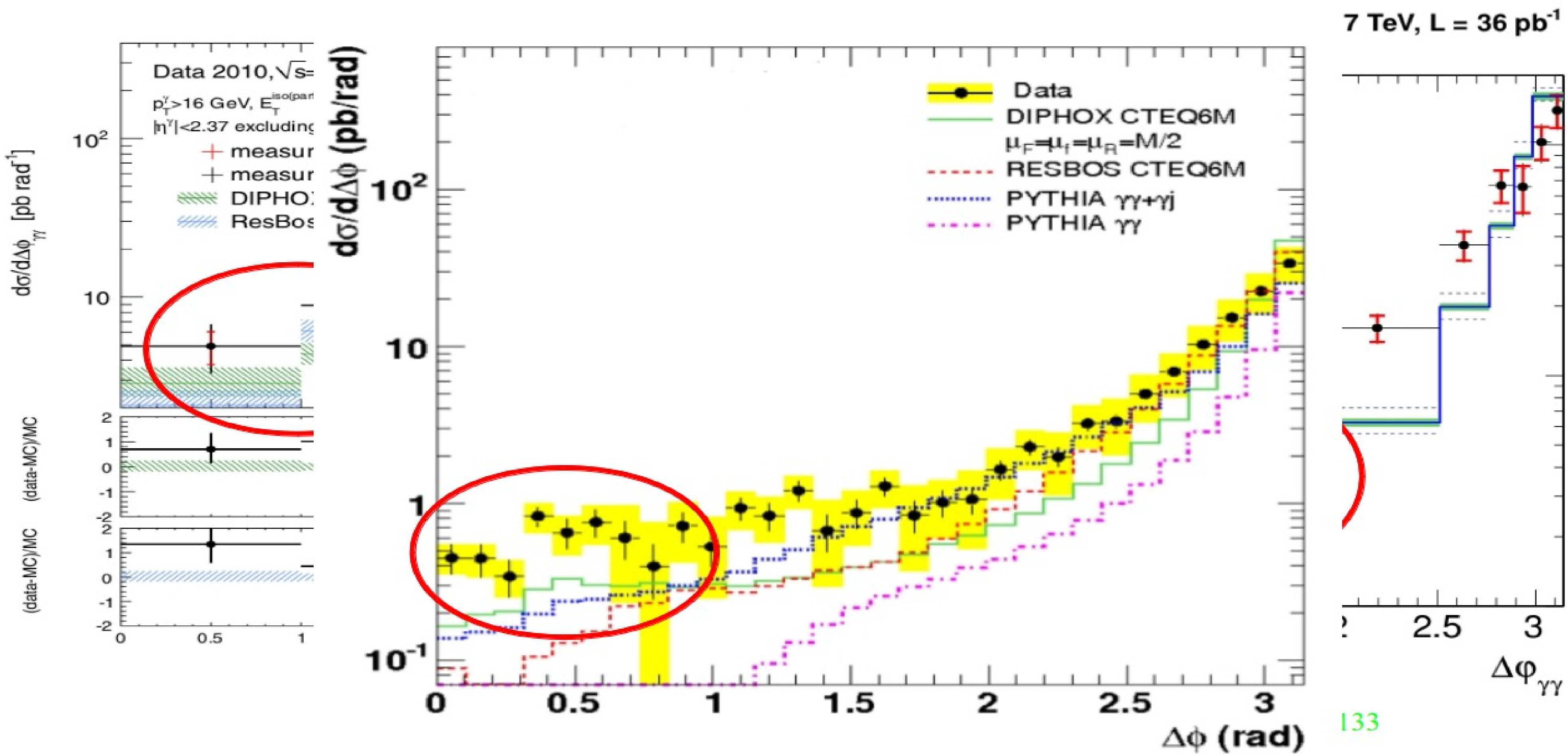
Same discrepancies found by CDF: Phys.Rev.Lett.107:102003,2011.

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data



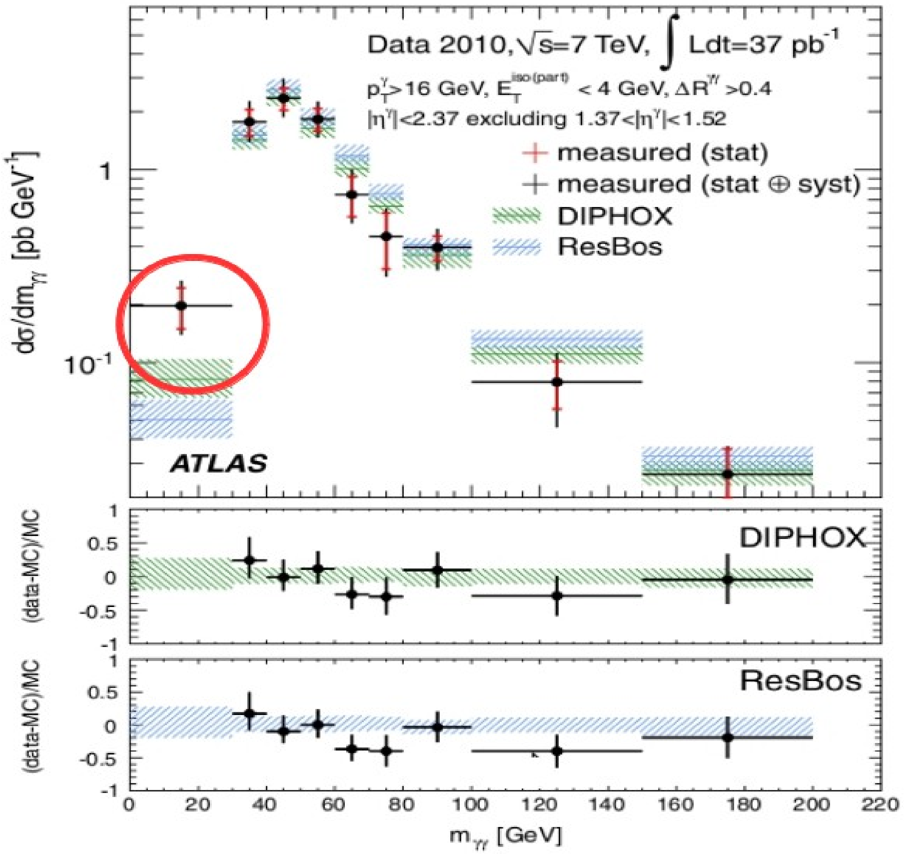
Same discrepancies found by CDF: Phys.Rev.Lett.107:102003,2011.

Diphoton production at NNLO

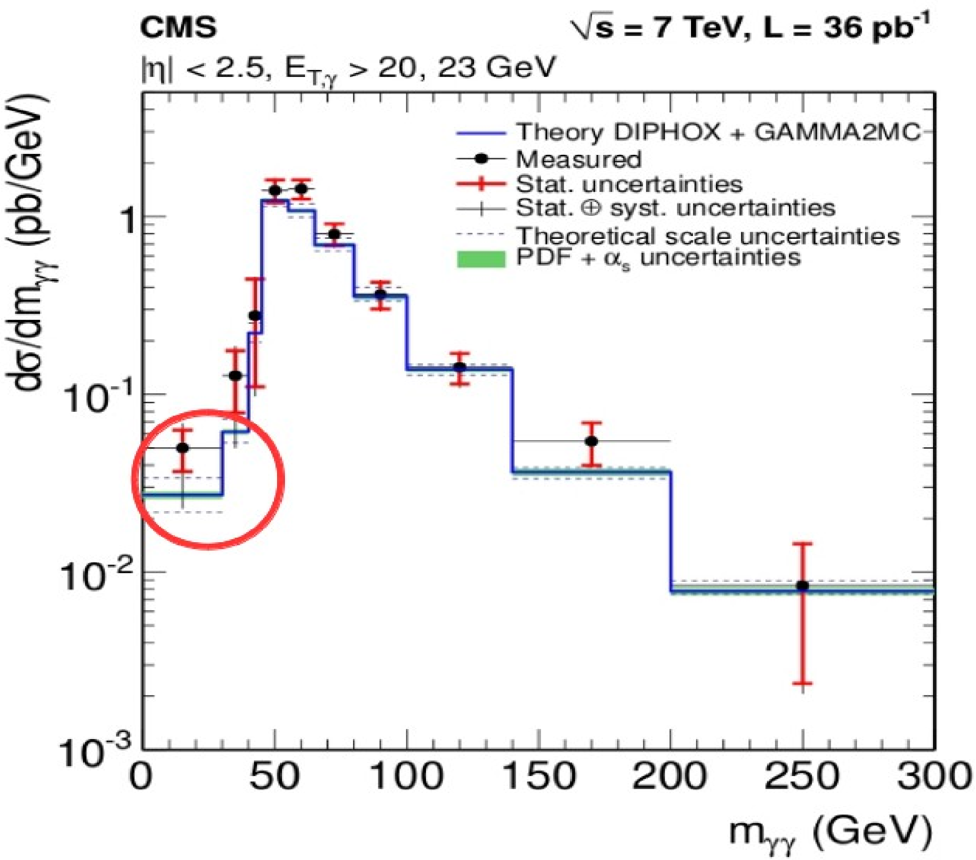
S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data



PRD 85, 012003 (2012)



JHEP 01(2012)133

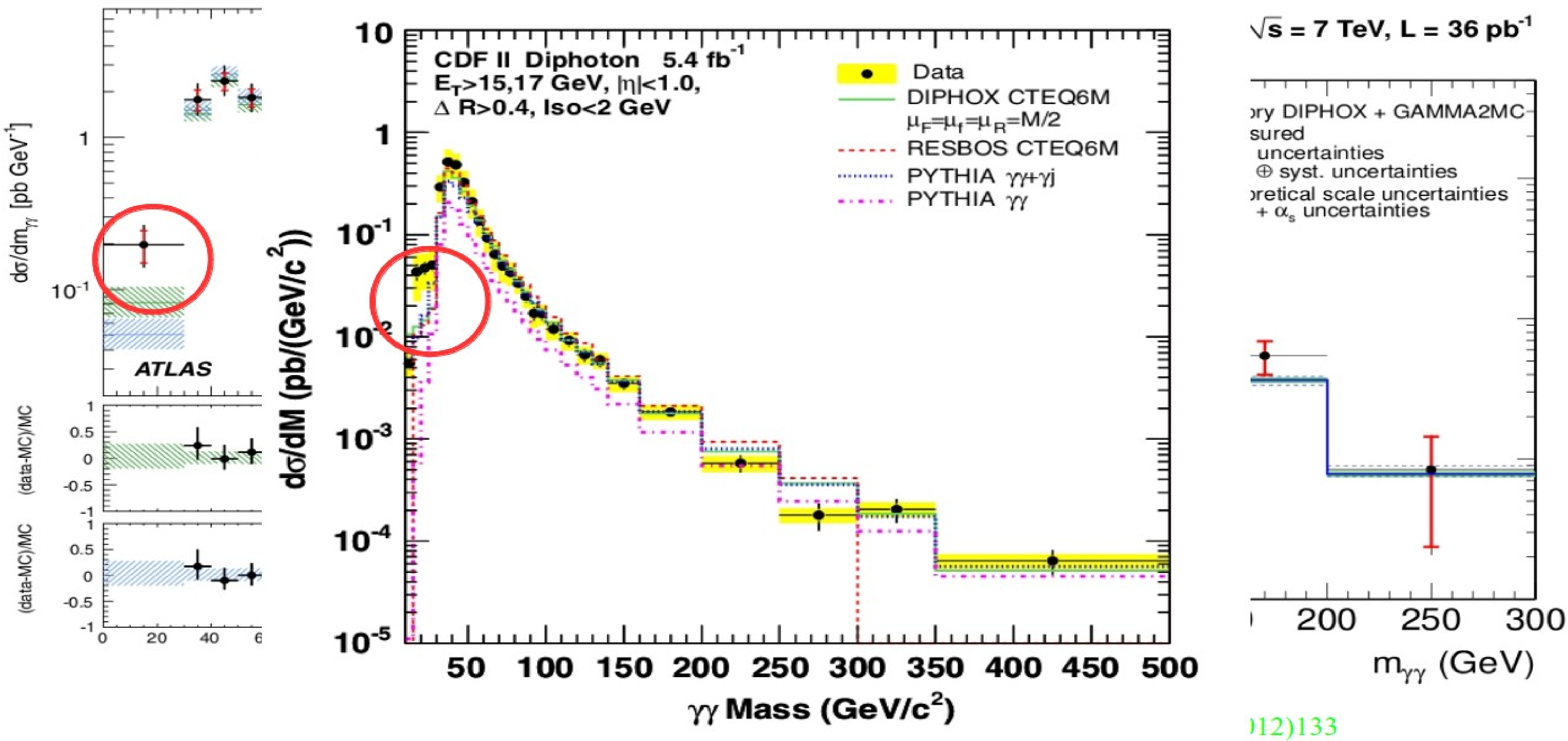
Same discrepancies found by CDF: Phys.Rev.Lett.107:102003,2011.

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data



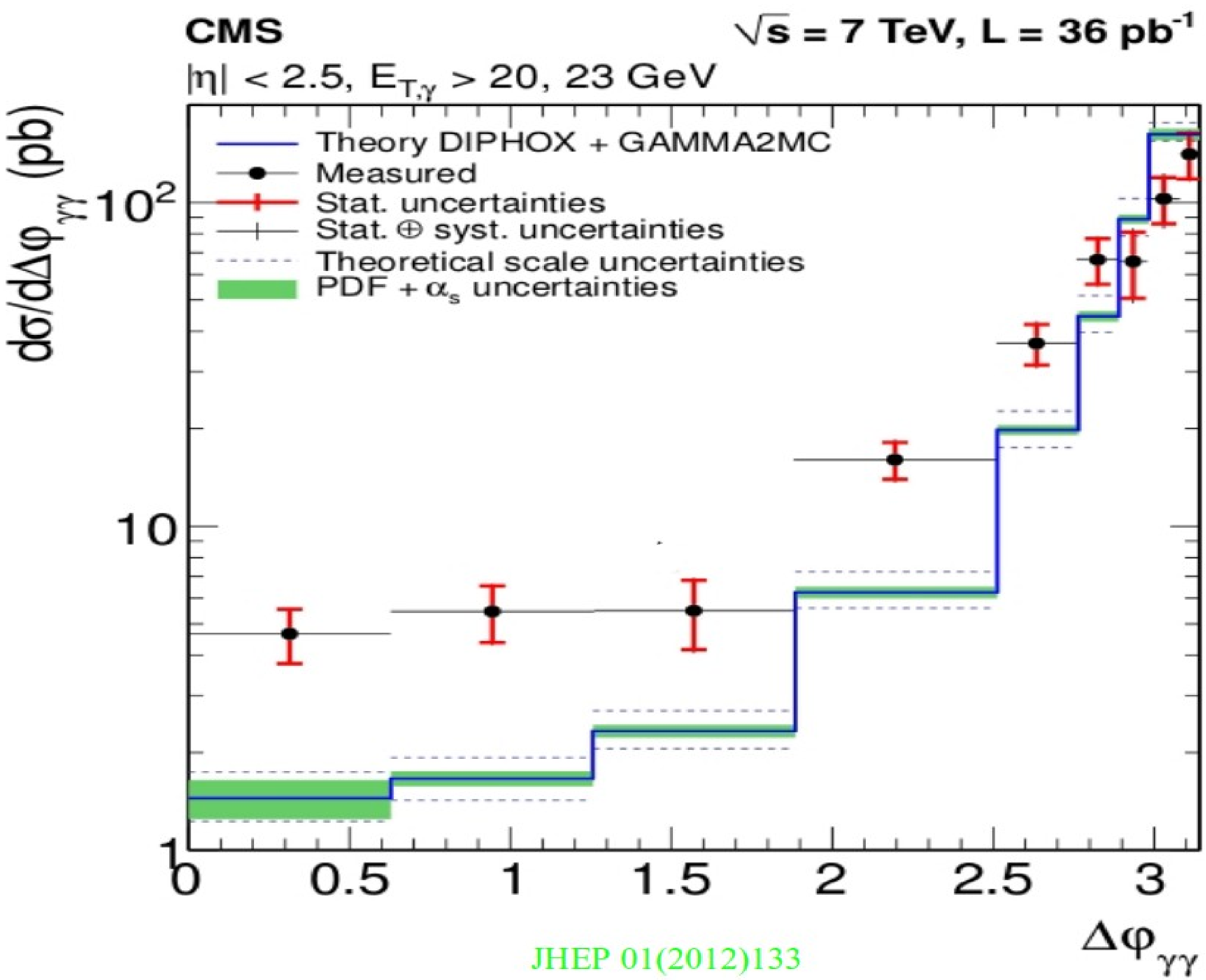
Same discrepancies found by CDF: Phys.Rev.Lett.107:102003,2011.

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data at low $\Delta\varphi$



JHEP 01(2012)133

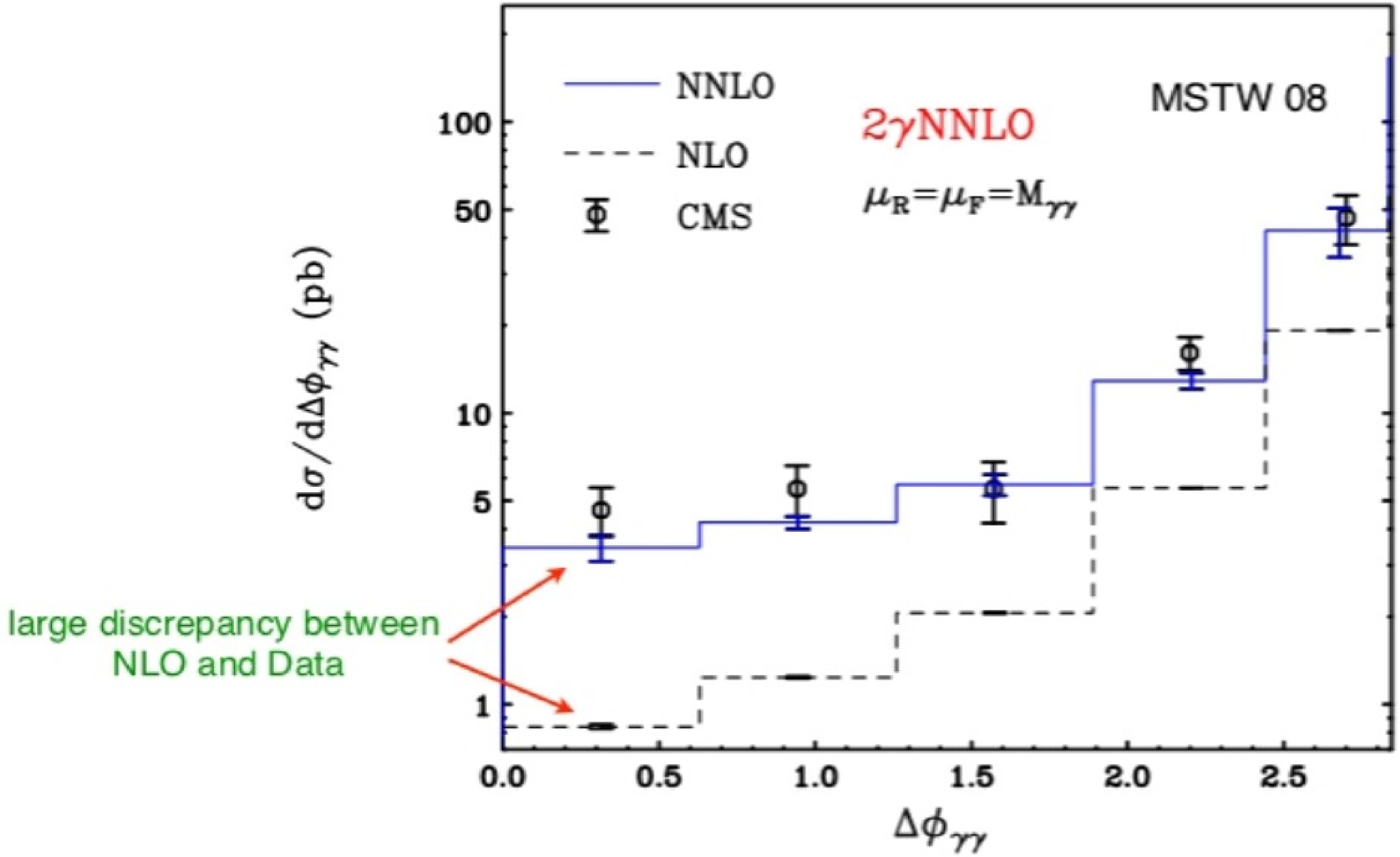
Diphoton production at NNLO

Preliminary results

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

NNLO Corrections much larger in some kinematical regions
NLO effectively lowest order

"away from back-to-back configuration"



$\sqrt{S} = 7\,\text{TeV}$

CMS diphoton cuts

$p_T^{\gamma\,hard} \geq 23\,\text{GeV}$

$p_T^{\gamma\,soft} \geq 20\,\text{GeV}$

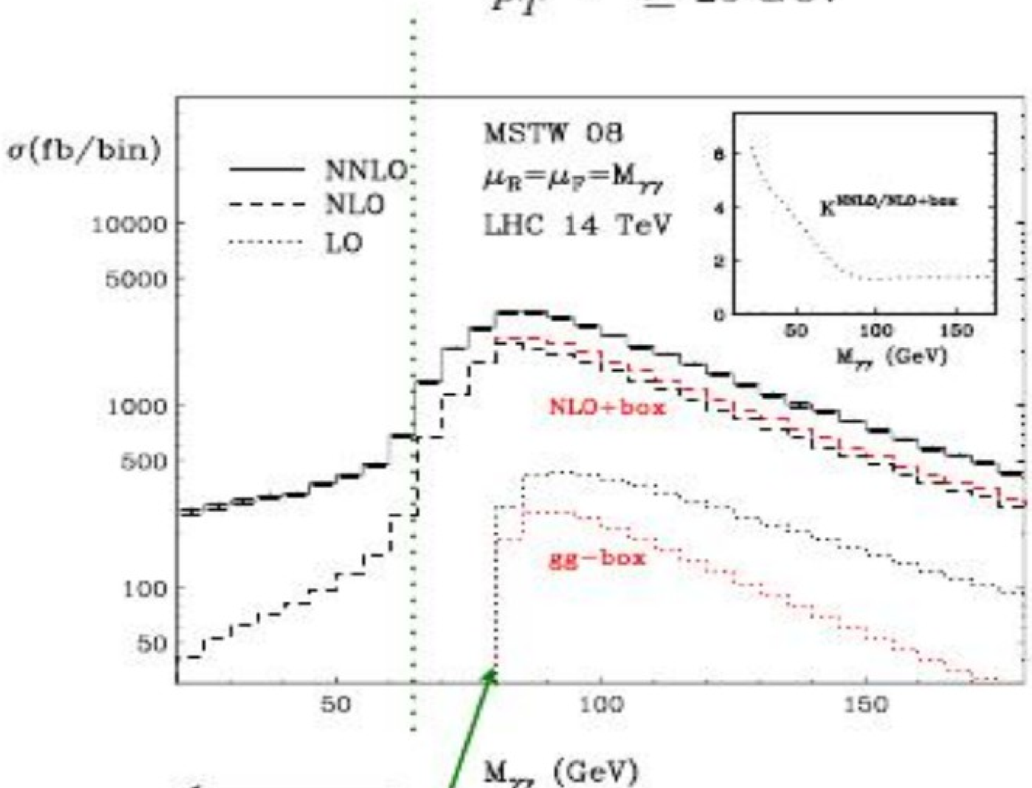
$|\eta^\gamma| \leq 2.5$

$R_{\gamma\gamma} > 0.45$

smooth cone isolation

NNLO corrections essential to understand the background invariant mass below the LO threshold

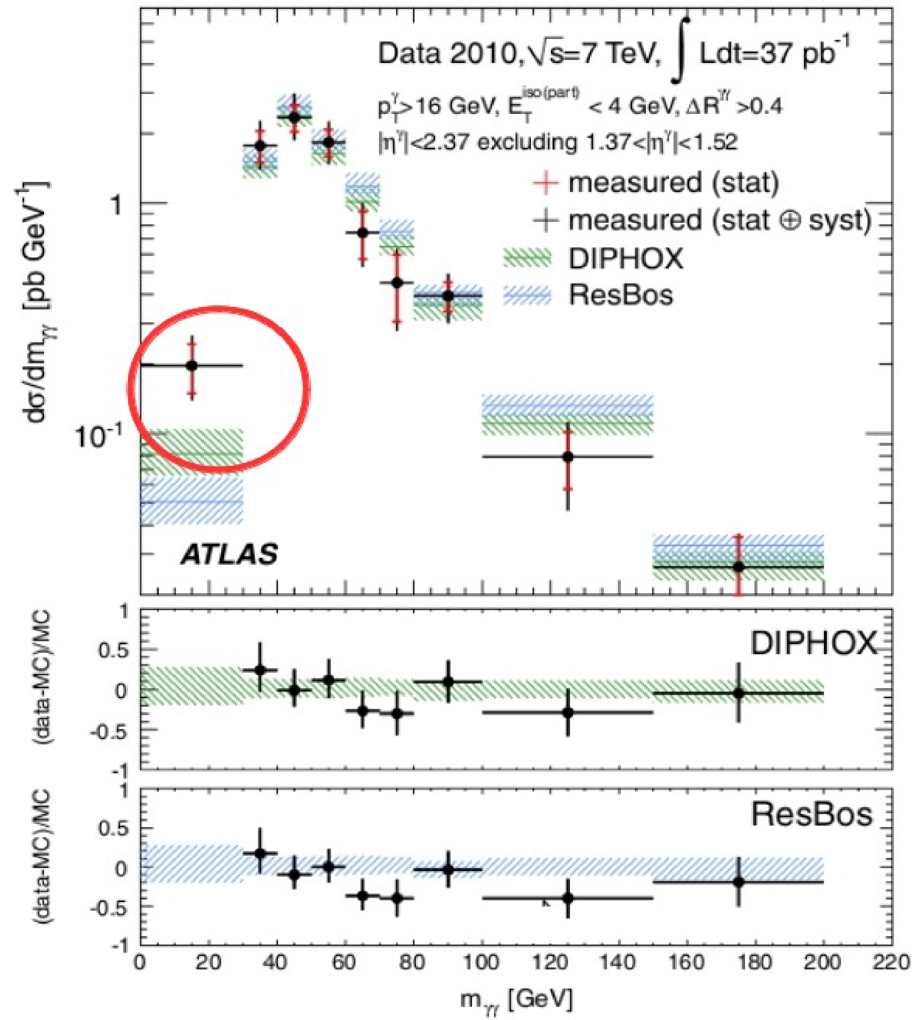
$$\sqrt{S} = 14\,\mathrm{TeV} \qquad p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV} \qquad p_T^{\gamma\,soft} \geq 25\,\mathrm{GeV}$$



~"collinear"

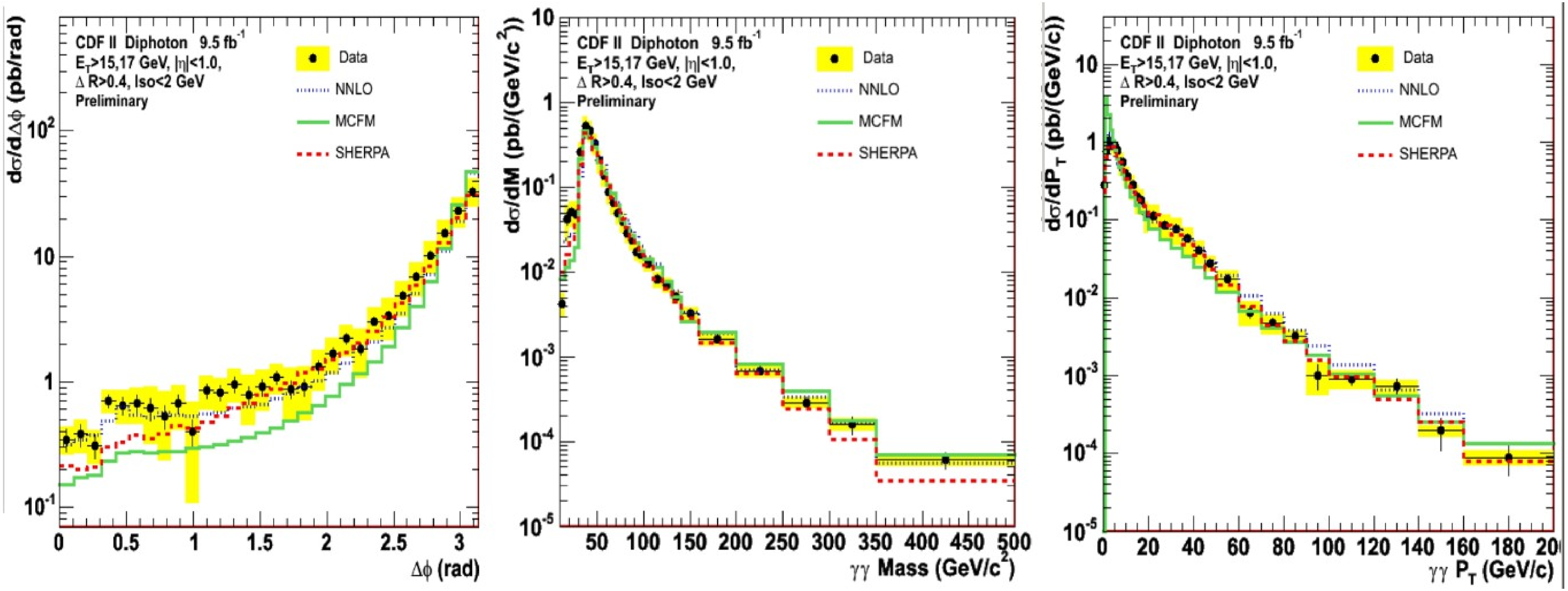
LO threshold at 80 GeV

"No back-to-back"



This discrepancy can be related to the discrepancy observed in the $\Delta\varphi$ distribution.

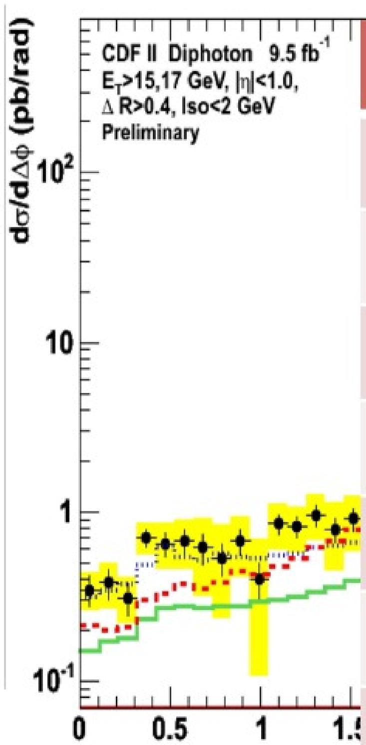
Preliminary comparison CDF 9.5 fb^{-1} results



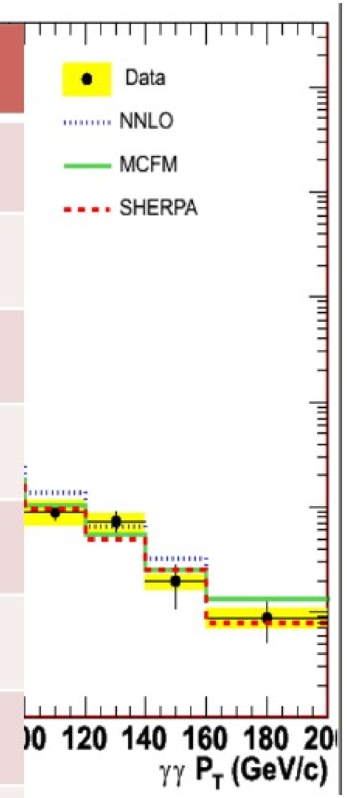
$P^{\gamma}_{T\,harder} \geq 17GeV$ $P^{\gamma}_{T\,softer} \geq 15GeV$ Isolation(Parameters): R=0.4 ; $E_{t\,max}$ = 2 GeV

$|\eta| \leq 1$ $R_{\gamma\gamma} \geq 0.4$

Preliminary comparison CDF 9.5 fb^{-1} results



	Total cross section (pb)
Data (CDF)	$12.3 \pm 0.2_{stat} \pm 3.5_{syst}$
RESBOS	11.3 ± 2.4
DIPHOX	10.6 ± 0.6
MCFM	11.6 ± 0.3
SHERPA	10.9
PYTHIA γγ+γj	9.2
PYTHIA γγ	5.0
NNLO	11.8 + 1.7 – 0.6

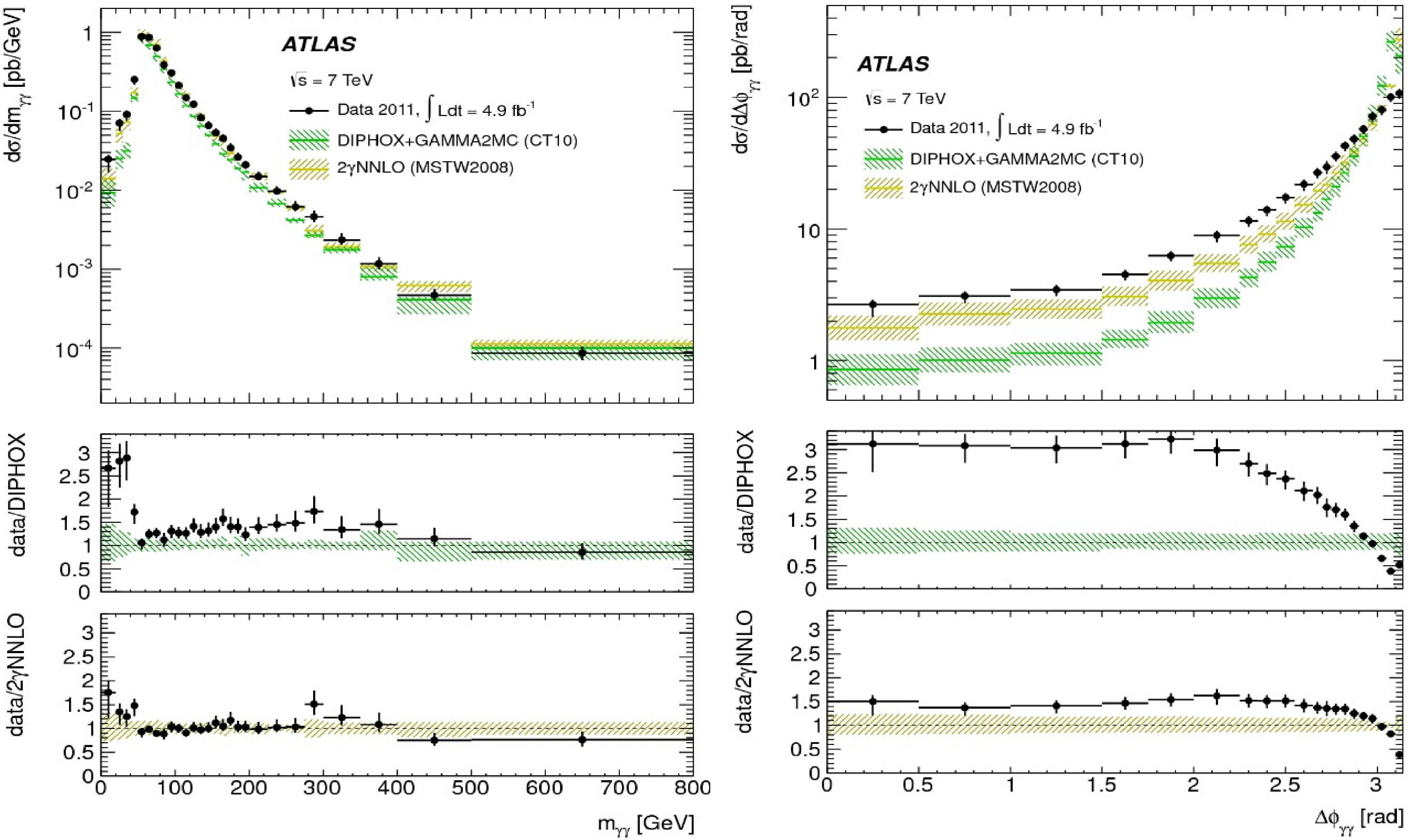


$P^{\gamma}_{T\,harder} \geq 17$ GeV $P^{\gamma}_{T\,softer} \geq 15$ GeV Isolation(Parameters): R=0.4 ; $E_{t\,max} = 2$ GeV

$|\eta| \leq 1$ $R_{\gamma\gamma} \geq 0.4$

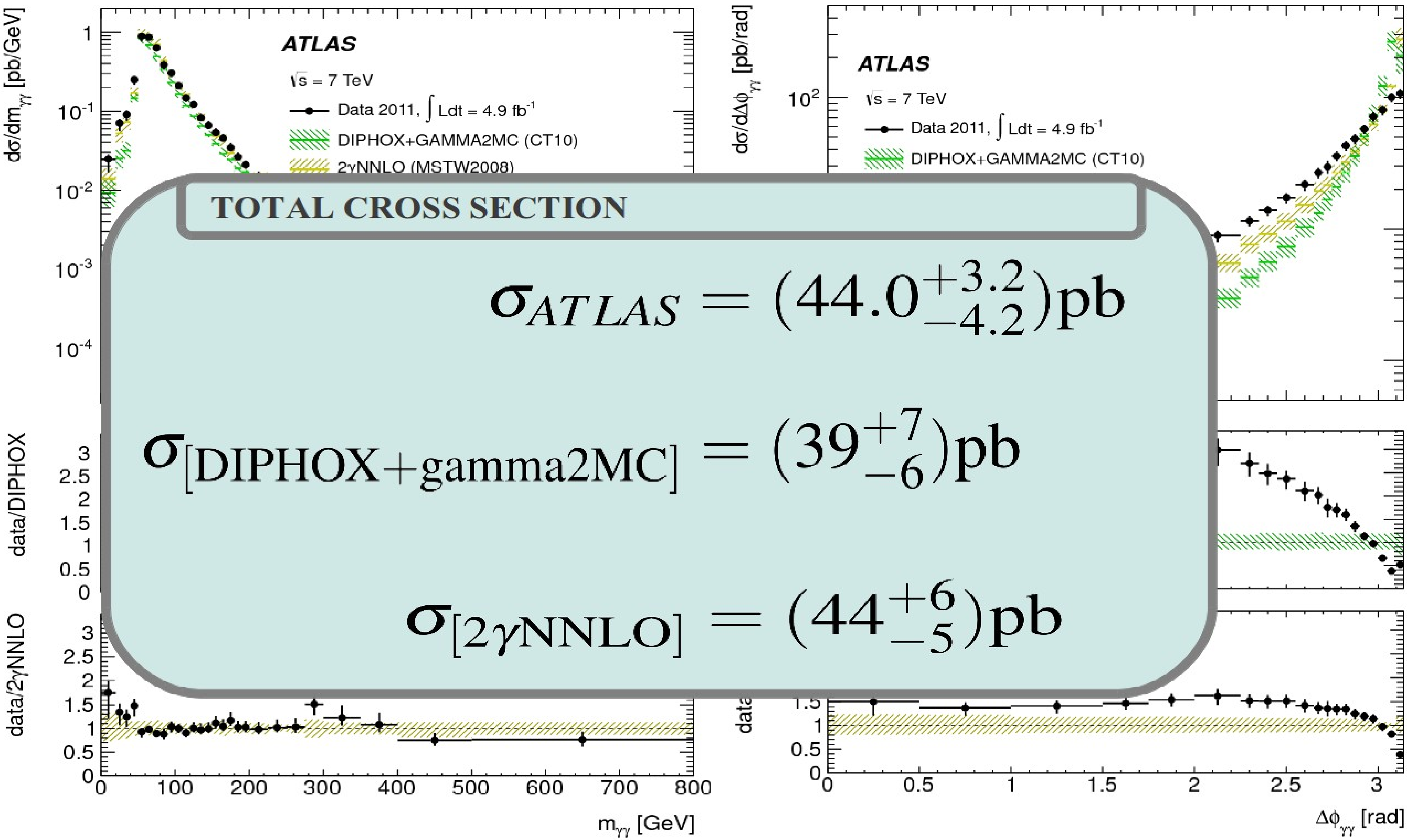
ATLAS results

arXiv:1211.1913 [hep-ex].



ATLAS results

arXiv:1211.1913 [hep-ex].



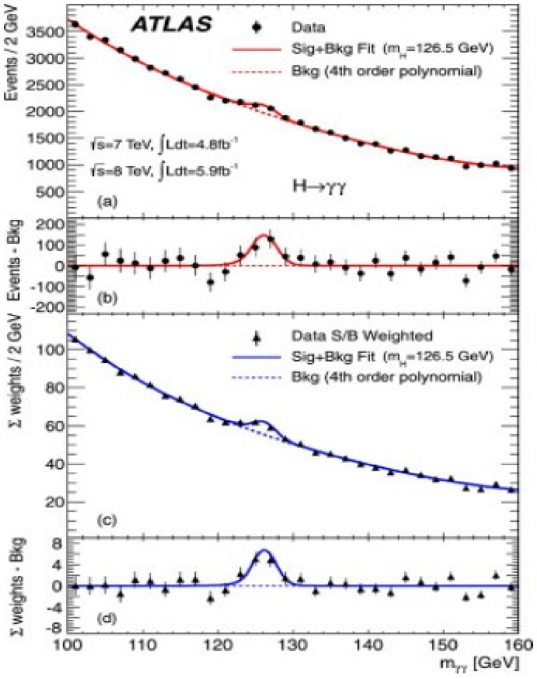
TOTAL CROSS SECTION

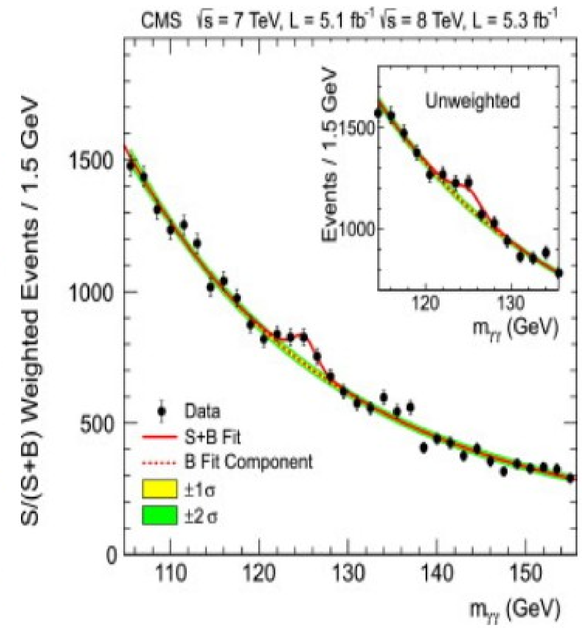
$$\sigma_{ATLAS} = (44.0^{+3.2}_{-4.2})\mathrm{pb}$$

$$\sigma_{[\mathrm{DIPHOX+gamma2MC}]} = (39^{+7}_{-6})\mathrm{pb}$$

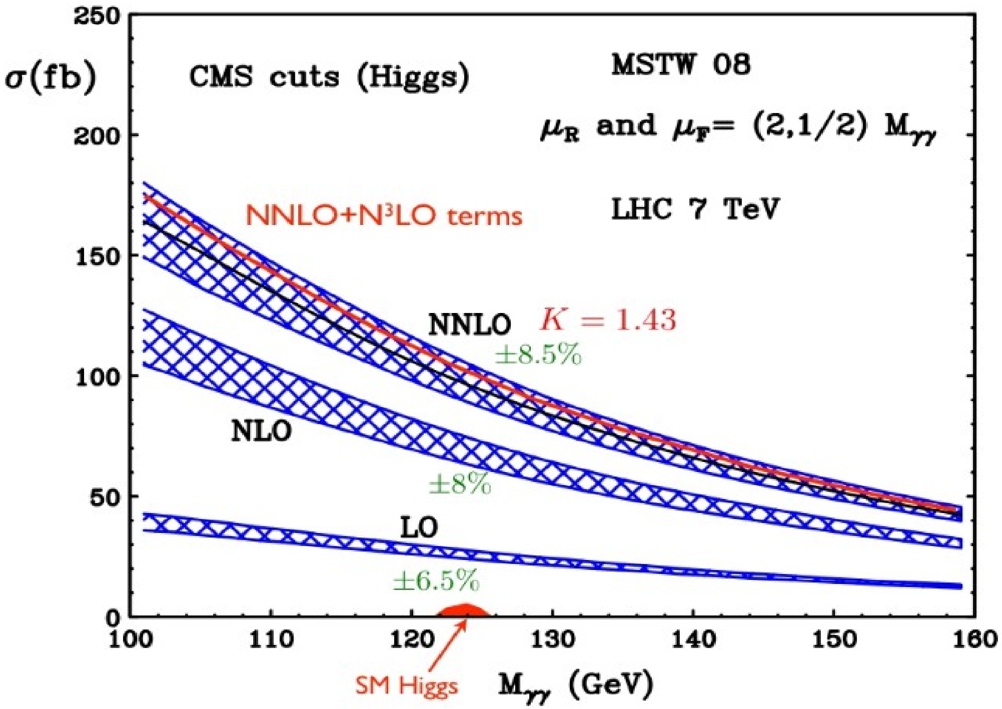
$$\sigma_{[2\gamma\mathrm{NNLO}]} = (44^{+6}_{-5})\mathrm{pb}$$

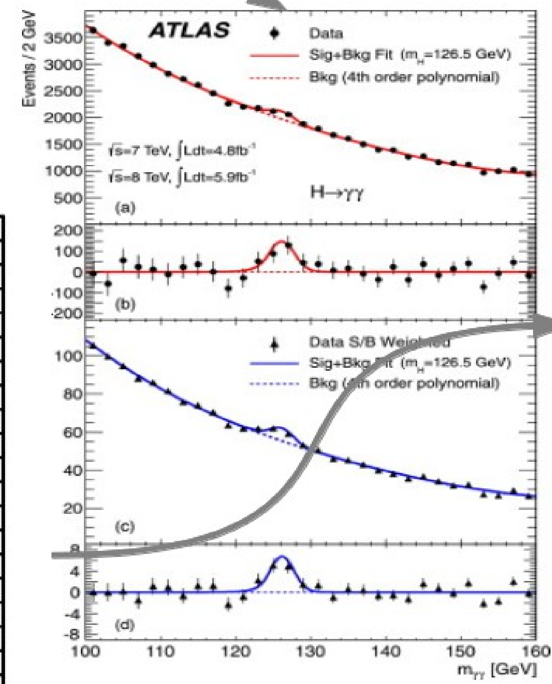
Higgs boson searches

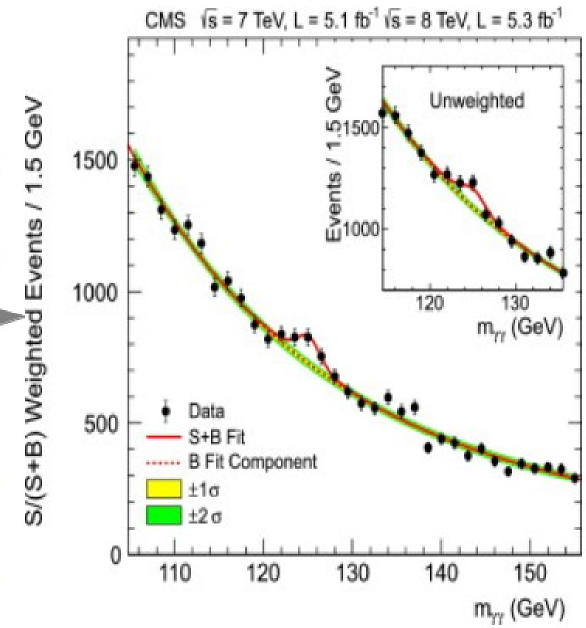




Higgs boson searches







$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$

$p_T^{\gamma\, soft} \geq 30\,\mathrm{GeV}$

$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$

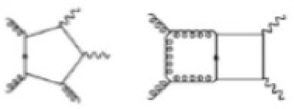
$|\eta^\gamma| \leq 2.5$

excluding $1.4442 \leq |\eta^\gamma| \leq 1.566$

$\epsilon = 0.05$

- Scale does not represent TH uncertainties at LO and NLO → new channels
- All channels open at NNLO → estimate of TH uncertainties

α_s^3 Bern, Dixon, Schmidt (2002)



Some N³LO terms known to contribute ~5%

Summary

- Cross section with “smooth” isolation, is a lower bound for cross section with standard isolation.
- Sizeable NNLO corrections to the $\gamma\gamma$ mass distribution in kinematical regions related to Higgs boson searches

  40-55% effect over NLO

- NNLO very large away from back-to-back configuration (effectively NLO)

  needed to understand LHC data

- At NNLO starts to reliably predict values of cross sections in all kinematical regions (with very few exceptions; e.g $p_{T\gamma\gamma} \rightarrow 0$)

Thank you!!!

Backup slides

q_T subtraction method

S. Catani, M. Grazzini (2007)

For a generic $pp \to F + X$ process:
[colorless]

- At NLO we need a LO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{LO}$ and $\mathcal{H}^{F(1)}$

D. de Florian, M. Grazzini (2000)

G. Bozzi, S. Catani, D. de Florian, M.Grazzini (2005)

- At NNLO we need a NLO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$

S. Catani, M. Grazzini (2007)

S. Catani, L. C, G.Ferrera, D. de Florian, M. Grazzini (2009)

S. Catani, L. C, G.Ferrera, D. de Florian, M. Grazzini (2009)

$$d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\mathrm{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

q_T subtraction method

S. Catani, M. Grazzini (2007)

For a generic $pp \to F + X$ process:
[colorless]

- At NLO we need a LO calculation of $d\sigma^{F+\mathrm{jet(s)}}$
 plus the knowledge of $d\sigma^{CT}_{LO}$ and $\mathcal{H}^{F(1)}$

D. de Florian, M. Grazzini (2000)

G. Bozzi, S. Catani, D. de Florian, M.Grazzini (2005)

- At NNLO we need a NLO calculation of $d\sigma^{F+\mathrm{jet(s)}}$
 plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$

S. Catani, M. Grazzini (2007)

S. Catani, L. C, G.Ferrera, D. de Florian, M. Grazzini (2009)

S. Catani, L. C, G.Ferrera, D. de Florian, M. Grazzini (2009)

This is enough to compute NNLO corrections for *any* process in this class provided that F+jet is known up to NLO and the two loop amplitude for $c\bar{c} \to F$ is known

q_T subtraction method

S. Catani, M. Grazzini (2007)

In our case

DiPhoton production at NNLO

Two-loop amplitudes available C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans

Di-photon + jet at NLO computed V.Del Duca, F.Maltoni, Z.Nagy, Z.Trocsanyi

implemented in NLOJet++

Z. Bern, L. J. Dixon and D. A. Kosower (1995)
A. Signer (1995)
V. D. Barger, T. Han, J. Ohnemus and D. Zeppenfeld (1990)
V. Del Duca, W. B. Kilgore and F. Maltoni (2000)

q_T subtraction method

S. Catani, M. Grazzini (2007)

In our case

DiPhoton production at NNLO → $\mathcal{H}^{F(2)}$

Two-loop amplitudes available • C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans

Di-photon + jet at NLO computed V.Del Duca, F.Maltoni, Z.Nagy, Z.Trocsanyi

implemented in NLOJet++

Z. Bern, L. J. Dixon and D. A. Kosower (1995)
A. Signer (1995)
V. D. Barger, T. Han, J. Ohnemus and D. Zeppenfeld (1990)
V. Del Duca, W. B. Kilgore and F. Maltoni (2000)

q_T subtraction method

S. Catani, M. Grazzini (2007)

In our case

DiPhoton production at NNLO

$\mathcal{H}^{F(2)}$

$d\sigma^{F+\mathrm{jet(s)}}$

Two-loop amplitudes available • C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans

Di-photon + jet at NLO computed • V.Del Duca, F.Maltoni, Z.Nagy, Z.Trocsanyi

implemented in NLOJet++

Z. Bern, L. J. Dixon and D. A. Kosower (1995)
A. Signer (1995)
V. D. Barger, T. Han, J. Ohnemus and D. Zeppenfeld (1990)
V. Del Duca, W. B. Kilgore and F. Maltoni (2000)

q_T subtraction method

S. Catani, M. Grazzini (2007)

In our case

DiPhoton production at NNLO

Two-loop amplitudes available • C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans → $\mathcal{H}^{F(2)}$

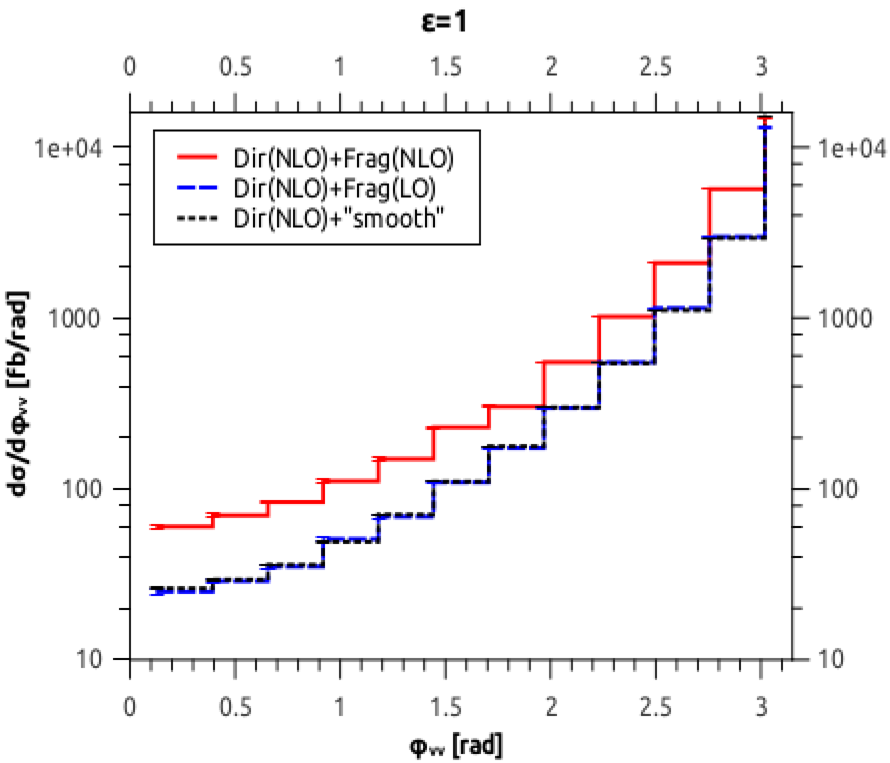
Di-photon + jet at NLO computed • V.Del Duca, F.Maltoni, Z.Nagy, Z.Trocsanyi → $d\sigma^{F+\mathrm{jet(s)}}$

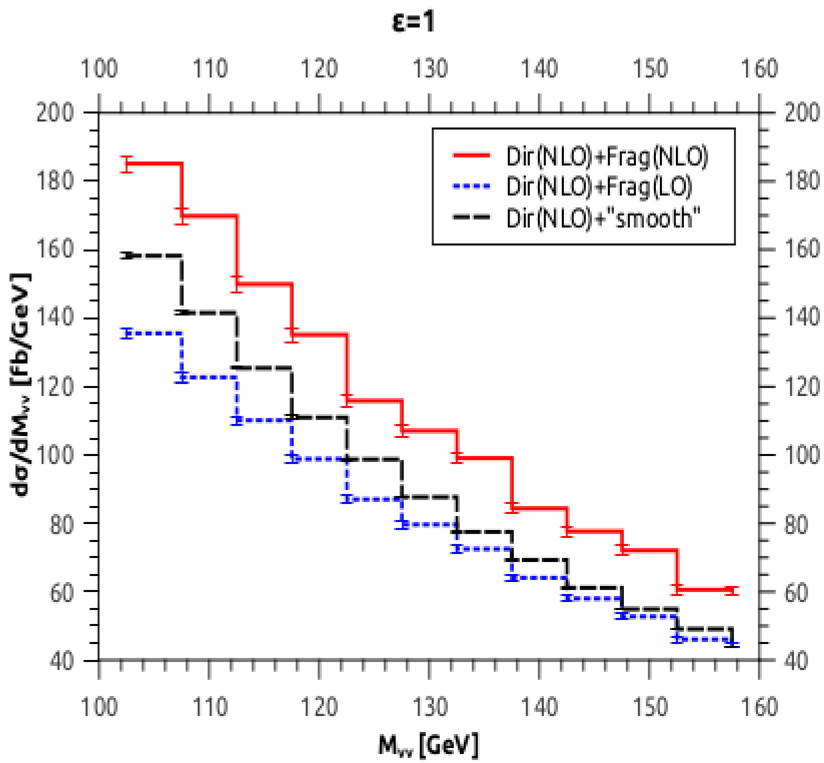
implemented in NLOJet++

Fully exclusive NNLO code for $pp \to F$

2γNNLO

First exclusive NNLO in pp collisions with two final state particles
S.Catani, L.Cieri, D.de Florian, G.Ferrera, M.Grazzini (2011)


ε=1
Dir(NLO)+Frag(NLO)
Dir(NLO)+Frag(LO)
Dir(NLO)+"smooth"
dσ/dφγγ [fb/rad]
φγγ [rad]


ε=1
Dir(NLO)+Frag(NLO)
Dir(NLO)+Frag(LO)
Dir(NLO)+"smooth"
dσ/dMγγ [fb/GeV]
Mγγ [GeV]

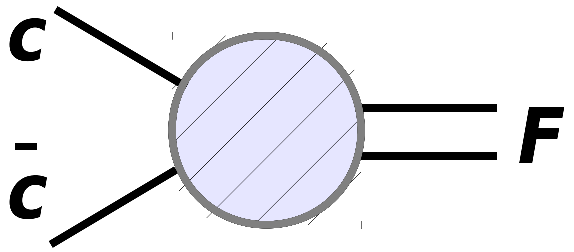
q_T subtraction method

S. Catani, M. Grazzini (2007)

Let us consider a specific, though important class of processes: the production of colourless high-mass systems ***F*** in hadron collisions

(***F*** may consist of lepton pairs, vector bosons, Higgs bosons......)

At LO it starts with $c\bar{c} \rightarrow F$



Strategy: start from NLO calculation of ***F+jet(s)*** and observe that as soon as the transverse momentum of the ***F***, $q_T \neq 0$, on can write:

$$d\sigma^{F}_{(N)NLO}\big|_{q_T \neq 0} = d\sigma^{F+\text{jets}}_{(N)LO}$$

Define a counterterm to deal with singular behaviour at $q_T \rightarrow 0$

But.....

the singular behaviour of $d\sigma^{F+\text{jets}}_{(N)LO}$ is well known from the resummation program of large logarithmic contributions at small transverse momenta

G. Parisi, R. Petronzio (1979)
J. Collins, D.E. Soper, G. Sterman (1985)
S. Catani, D. de Florian, M.Grazzini (2000)

q_T subtraction method

S. Catani, M. Grazzini (2007)

choose
$$d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$$

where
$$\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}\right]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + ...$$

q_T subtraction method

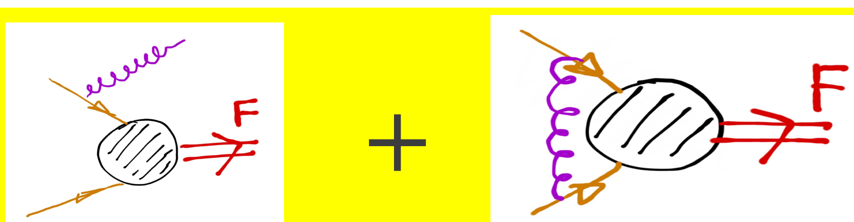
S. Catani, M. Grazzini (2007)

choose $$d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$$

where $$\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$



...ation of the counterterm at (N)LO and
... to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

[Real + Virtual]$_{\text{Contributions}}$ $+ \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots$

q_T subtraction method

S. Catani, M. Grazzini (2007)

choose
$$d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$$

where
$$\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots$$

σ^F_{LO} (Born)

q_T subtraction method

S. Catani, M. Grazzini (2007)

choose $$d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$$

where $$\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

Then the calculation can be extended to include the $q_T = 0$ contribution:

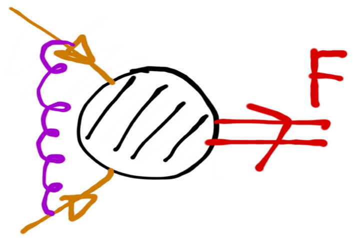
$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}\right]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots.$$

Finite (NLO)



q_T subtraction method

S. Catani, M. Grazzini (2007)

choose $$d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$$

where $$\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

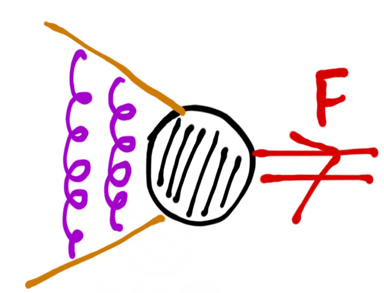
Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots$$



Finite (NNLO)

The Normalization H

Expand to the fixed order in α_s

$$\mathcal{H}^F = 1 + \frac{\alpha_S}{\pi}\mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots \qquad \sim \delta(q_T^2)$$

LO NLO NNLO

Normalization of $\sigma_{tot}^{(N)NLO}$ → computational effort comparable to $\sigma_{tot}^{(N)NLO}$

$$p_T^2 \ll Q^2 \qquad \int_0^{p_T^2} dq_T^2 \, \frac{d\sigma^F}{dq_T^2} \equiv \sigma_{LO}^F \, R^F(p_T/Q)$$

The coefficients appear in the constant term

$$R^{F(1)} = l_0^2 \, \Sigma^{F(1;2)} + l_0 \, \Sigma^{F(1;1)} + \mathcal{H}^{F(1)} + \mathcal{O}(p_T^2/Q^2)$$

$$l_0 = \ln \frac{Q^2}{p_T^2}$$

$$R^{F(2)} = l_0^4 \, \Sigma^{F(2;4)} + l_0^3 \, \Sigma^{F(2;3)} + l_0^2 \, \Sigma^{F(2;2)}$$
$$+ l_0 \left(\Sigma^{F(2;1)} - 16\zeta_3 \Sigma^{F(2;4)}\right) + \mathcal{H}^{F(2)} - 4\zeta_3 \Sigma^{F(2;3)} + \mathcal{O}(p_T^2/Q^2)$$

Very hard to reach that accuracy... but...

$$\int_0^{p_T^2} dq_T^2 \, \frac{d\sigma^F}{dq_T^2} \equiv \sigma_{tot}^{(N)NLO} - \int_{p_T^2}^{\infty} dq_T^2 \, \frac{d\sigma^{F+jet(N)LO}}{dq_T^2}$$

Inclusive

(analytic) distribution

known for Drell-Yan and Higgs!

Integral can be carried out in 4-dimensions

Method used to obtain $\mathcal{H}^{F(2)}$ for Higgs and Drell-Yan

In this requirement is manifested its weakness

$$\int_0^{p_T^2} dq_T^2 \, \frac{d\sigma^F}{dq_T^2} \equiv \sigma_{tot}^{(N)NLO} - \int_{p_T^2}^{\infty} dq_T^2 \, \frac{d\sigma^{F+jet(N)LO}}{dq_T^2}$$

Inclusive   (analytic) distribution

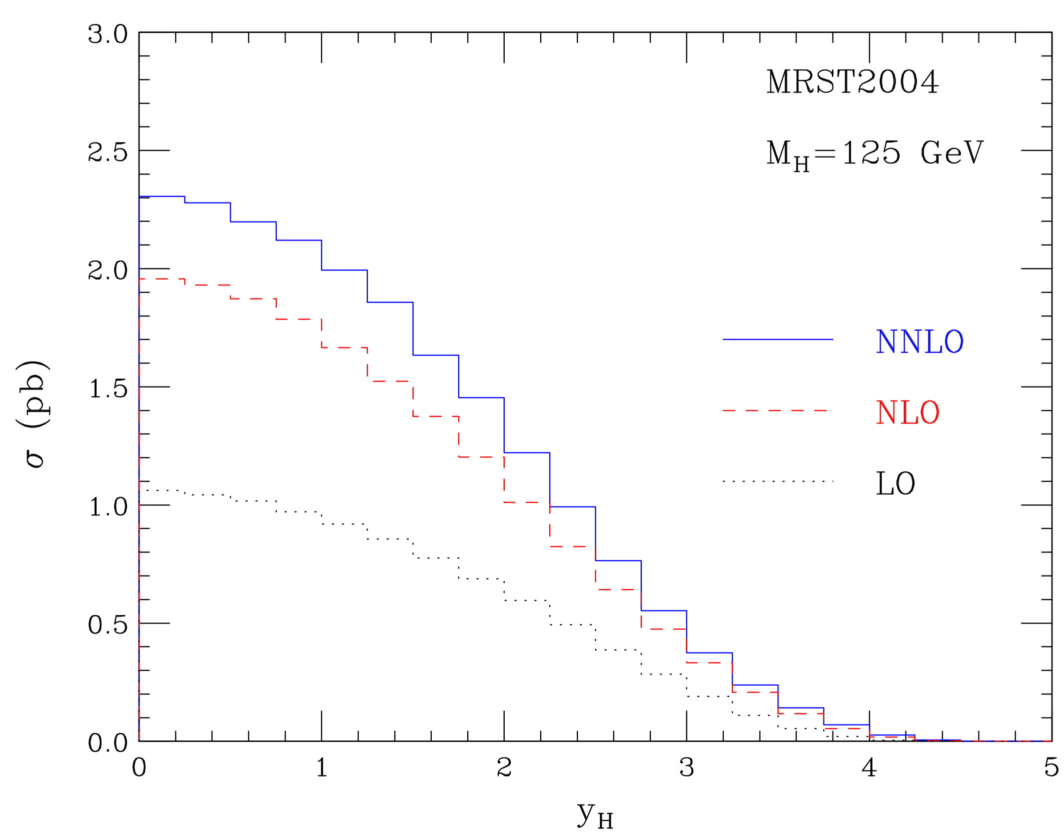
known for Drell-Yan and Higgs!

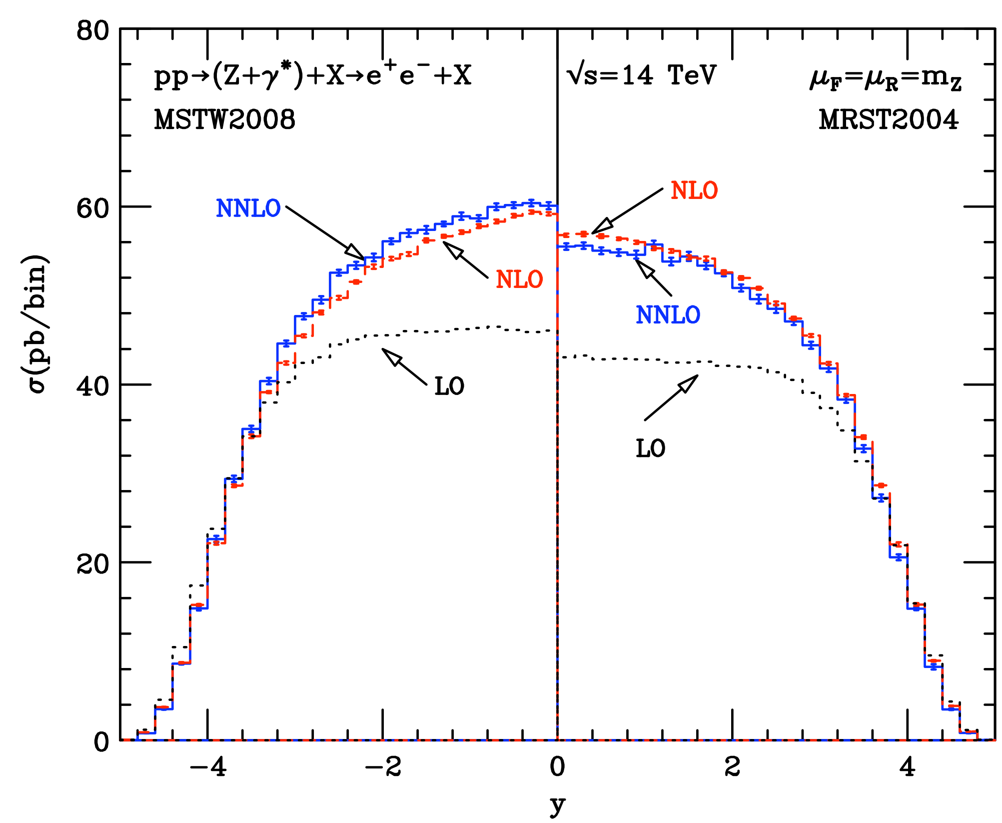
Integral can be carried out in 4-dimensions

Method used to obtain $\mathcal{H}^{F(2)}$ for Higgs and Drell-Yan

HNNLO S.Catani, M.Grazzini

DYNNLO S.Catani, L.Cieri, DdeF, G.Ferrera, M.Grazzini





Up to now, Inclusive and analytical Momentum Distribution needed for Exclusive

q_T *subtraction method* S. Catani, M. Grazzini (2007)

- Why we used a “subtraction” method for $H^{F(2)}$?
  - We didn't know the “internal” estructure of $H^{F(2)}$

Before 2γNNLO

q_T subtraction method

S. Catani, M. Grazzini (2007)

- Why we used a “subtraction” method for $H^{F(2)}$?
  - We didn't know the “internal” estructure of $H^{F(2)}$ — Before 2γNNLO
  - We dind't know how to relate $H^{F(2)}$ and the finite component of the two-loops virtual matrix elements. — Before 2γNNLO

q_T subtraction method

S. Catani, M. Grazzini (2007)

- Why we used a “subtraction” method for $H^{F(2)}$?
  - We didn't know the “internal” estructure of $H^{F(2)}$

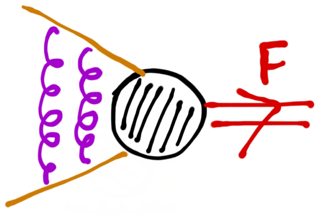
    Before 2γNNLO

  - We dind't know how to relate $H^{F(2)}$ and the finite component of the two-loops virtual matrix elements.

    Before 2γNNLO

  - The generalization of the precedent method implies to find the universal terms contained in $H^{F(2)}$

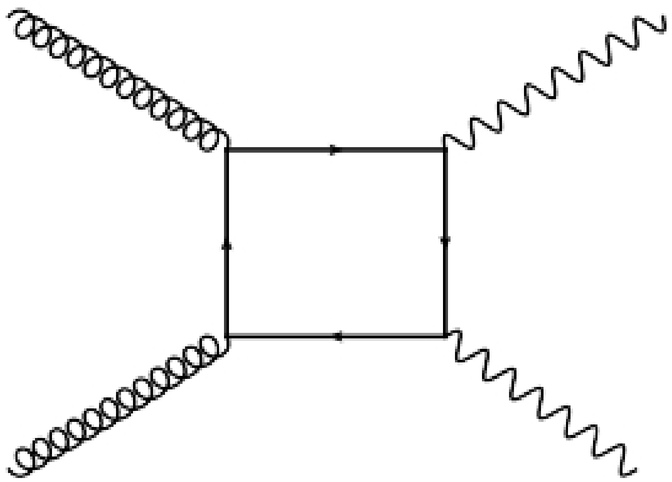
$$H^{F(2)} = H^{F(2)}_{\text{Universal}} + \text{Finite}^{(2X0)}$$



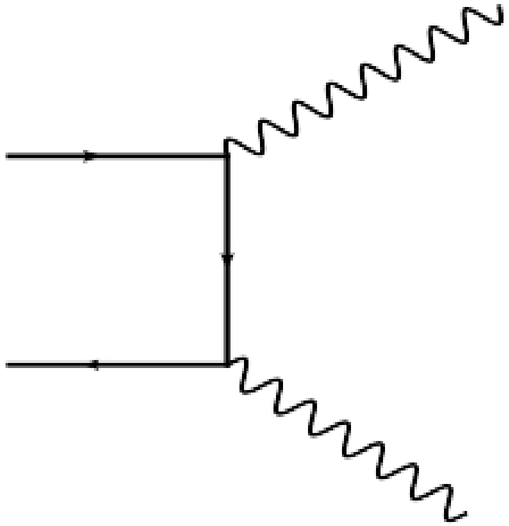
Why do we need NNLO corrections?

NNLO QCD corrections in diphoton production

$\gamma\gamma$ production → some NNLO terms known to be as large as Born!



$O(\alpha_s^2)$ but gg Luminosity



$O(\alpha_s^0)$ but $q\bar{q}$ Luminosity

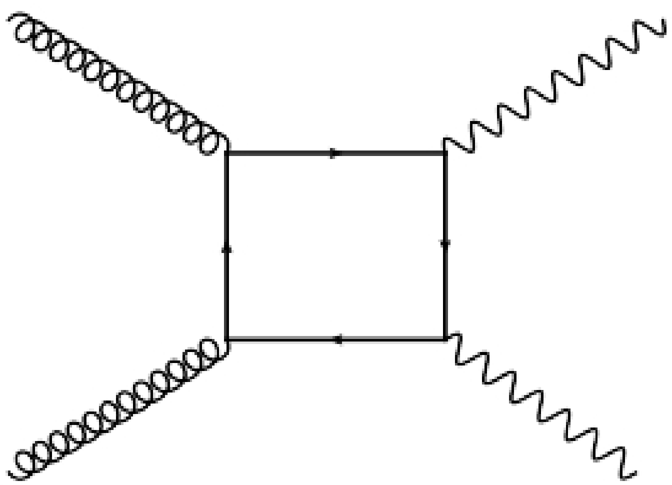
- Box contribution already included in NLO calculation

DIPHOX: T.Binoth, J.P.Guillet, E.Pilon, M.Werlen

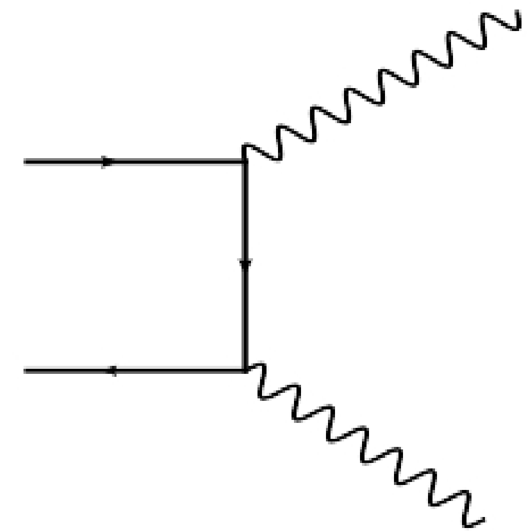
Why do we need NNLO corrections?

NNLO QCD corrections in diphoton production

$\gamma\gamma$ production → some NNLO terms known to be as large as Born!



$O(\alpha_s^2)$ but gg Luminosity



$O(\alpha_s^0)$ but $q\bar{q}$ Luminosity

- Box contribution already included in NLO calculation

DIPHOX: T.Binoth, J.P.Guillet, E.Pilon, M.Werlen

- Full NNLO control of Di-photon production is desired (main light Higgs bkg)

Kinematic variables

$$M = \sqrt{\left(p^{\mu}_{\gamma 1} + p^{\mu}_{\gamma 2}\right)^2}$$

$$P_{\mathrm{T}} = \left| \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) - \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) \cdot \hat{\mathrm{z}} \right|$$

$$\Delta\phi = \left|\phi_{\gamma 1} - \phi_{\gamma 2}\right| \bmod \pi$$

$$Y_{\gamma\gamma} = \tanh^{-1} \frac{\left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) \cdot \hat{\mathrm{z}}}{\left|\vec{p}_{\gamma 1}\right| + \left|\vec{p}_{\gamma 1}\right|}$$

$$z = \frac{p^{<}_{\mathrm{T}\gamma}}{p^{>}_{\mathrm{T}\gamma}}$$

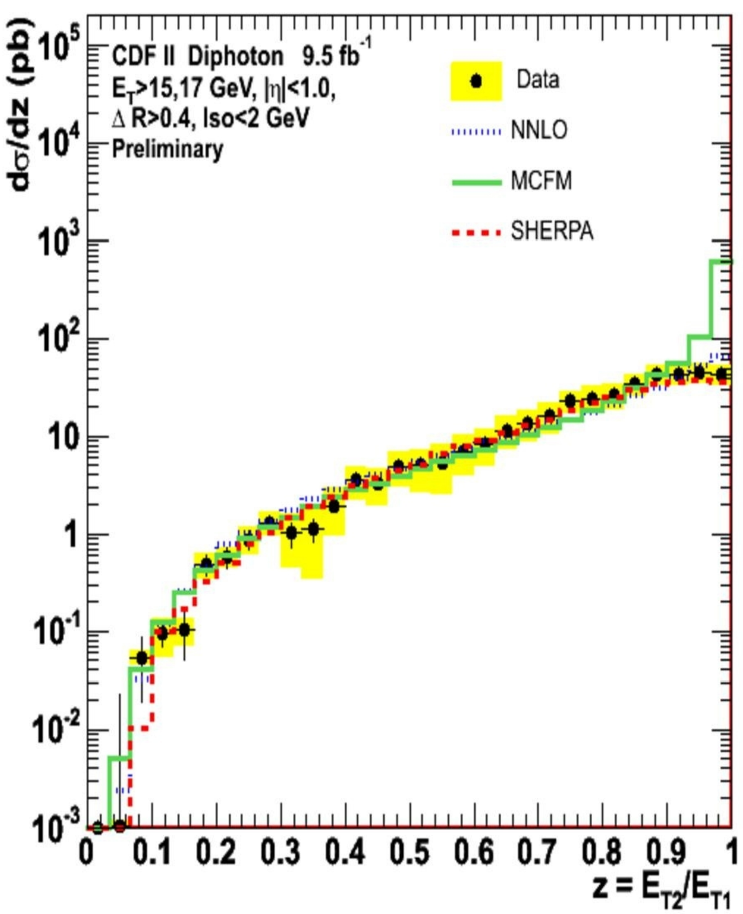
Low-p_{T}/high-p_{T} ratio of the photon pair ($z<1$)

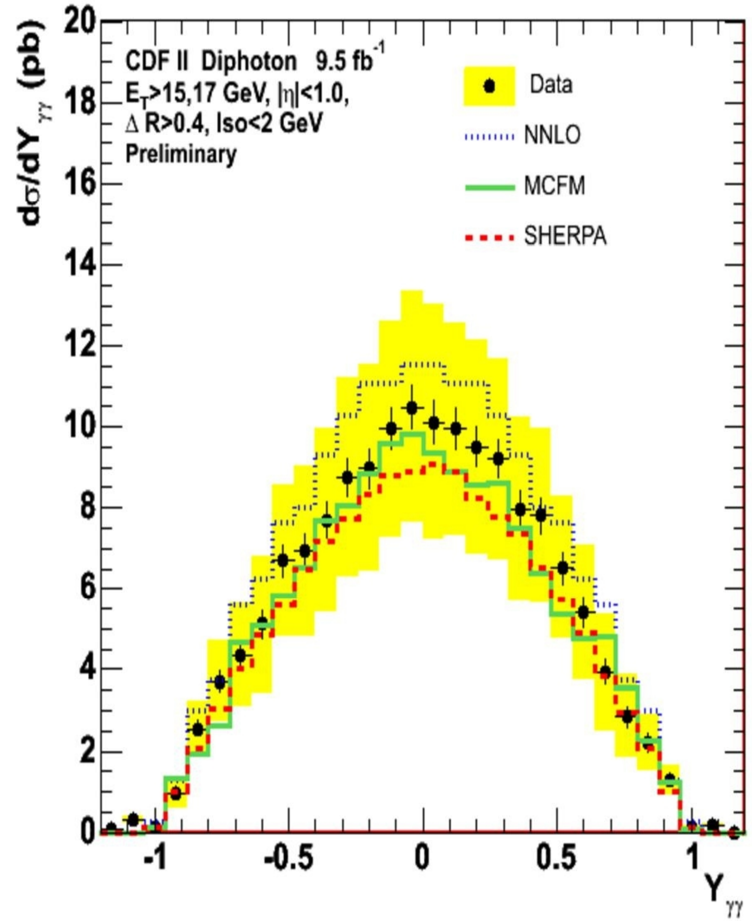
$$\cos\theta = \frac{2 p_{\mathrm{T}\gamma 1} p_{\mathrm{T}\gamma 2} \sinh\left(y_{\gamma 1} - y_{\gamma 2}\right)}{M\sqrt{M^2 + P_{\mathrm{T}}^2}}$$

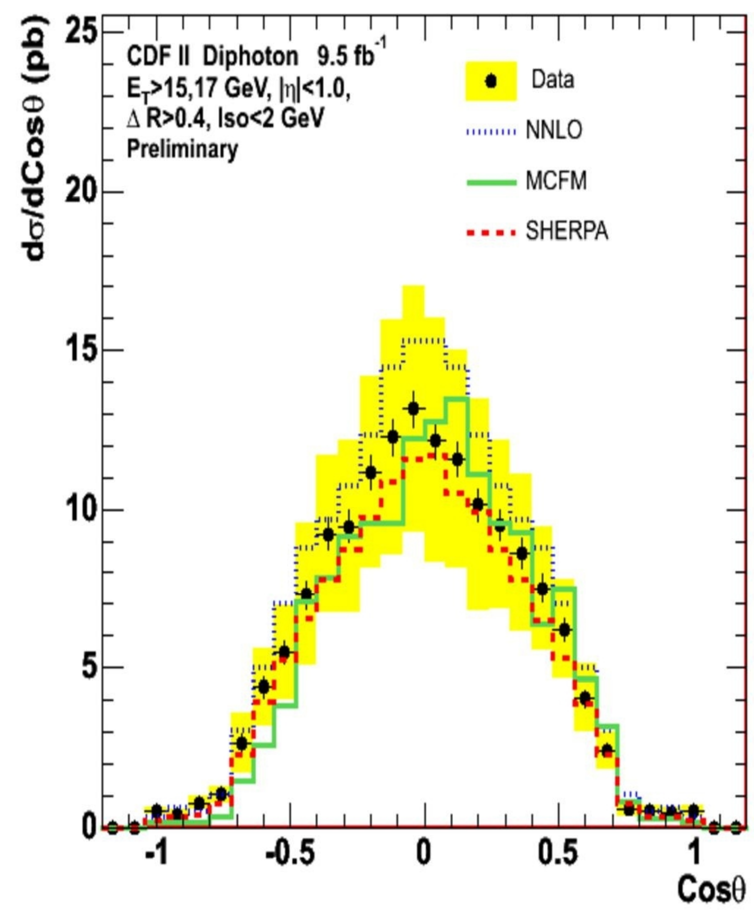
$$\begin{cases} \cos\theta \to \tanh \dfrac{y_{\gamma 1} - y_{\gamma 2}}{2} \approx 0 \quad \left(P_{\mathrm{T}} << M\right) \\ \cos^2\theta \to \dfrac{4 p_{\mathrm{T}\gamma 1} p_{\mathrm{T}\gamma 2}}{\left(p_{\mathrm{T}\gamma 1} + p_{\mathrm{T}\gamma 2}\right)^2} \approx 1 \quad \left(P_{\mathrm{T}} >> M\right) \end{cases}$$

Cosine of the leading photon polar angle in the **Collins-Soper frame** (γγ rest frame with the polar axis bisecting the angle between the colliding hadrons)

Differential cross sections: CDF





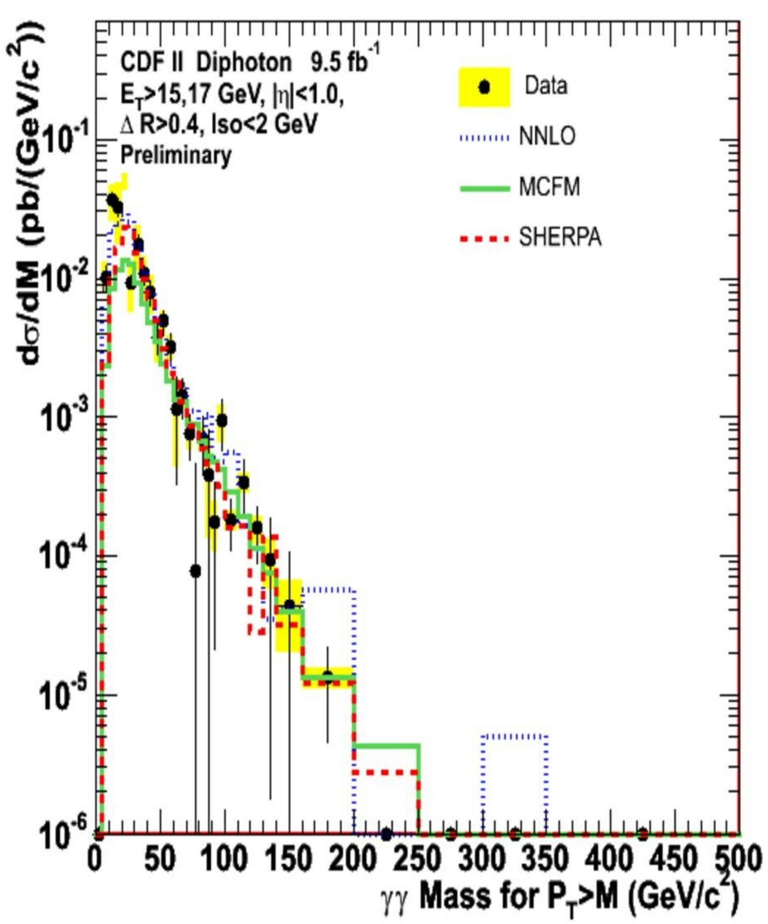


- Good agreement between data and theory

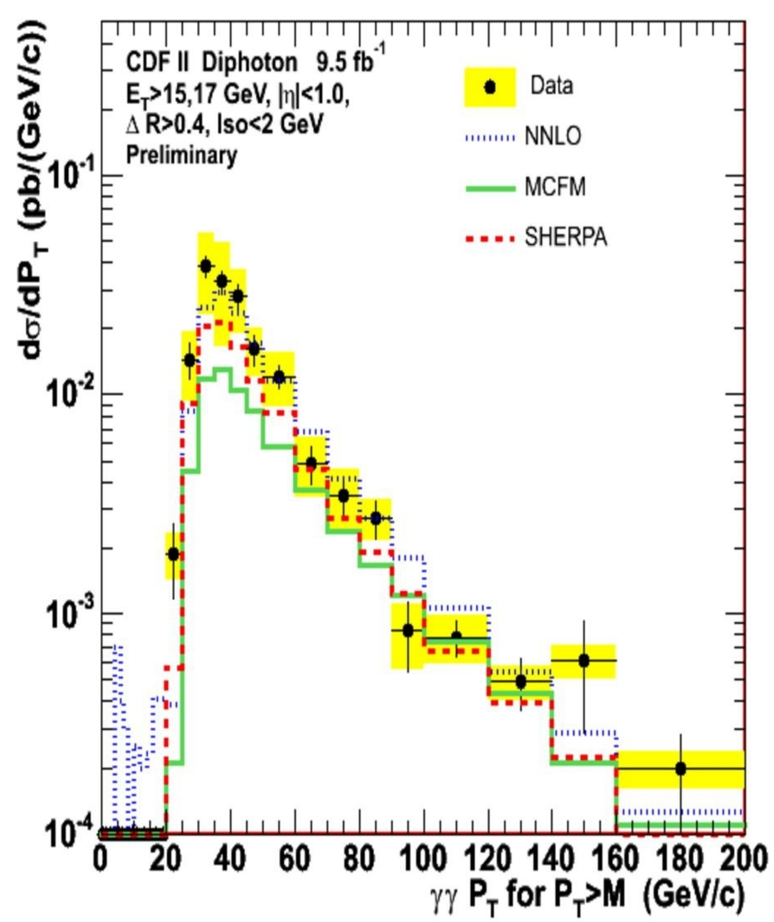
- Good agreement between data and theory

- Good agreement between data and theory

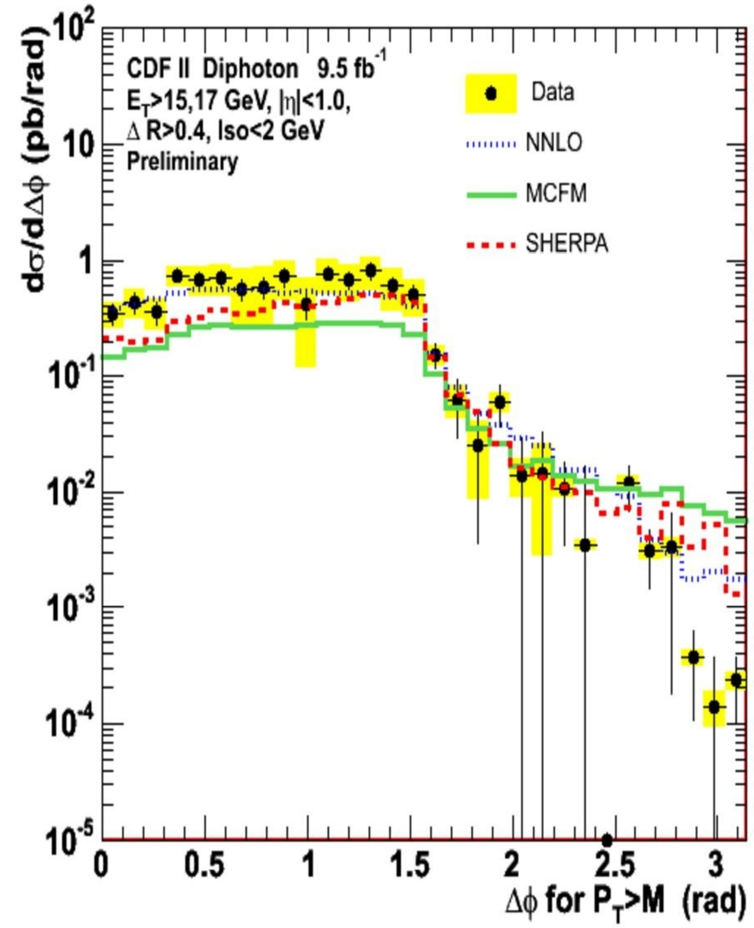
Differential cross sections for $P_T(\gamma\gamma) > M_{\gamma\gamma}$: CDF



- Low statistics

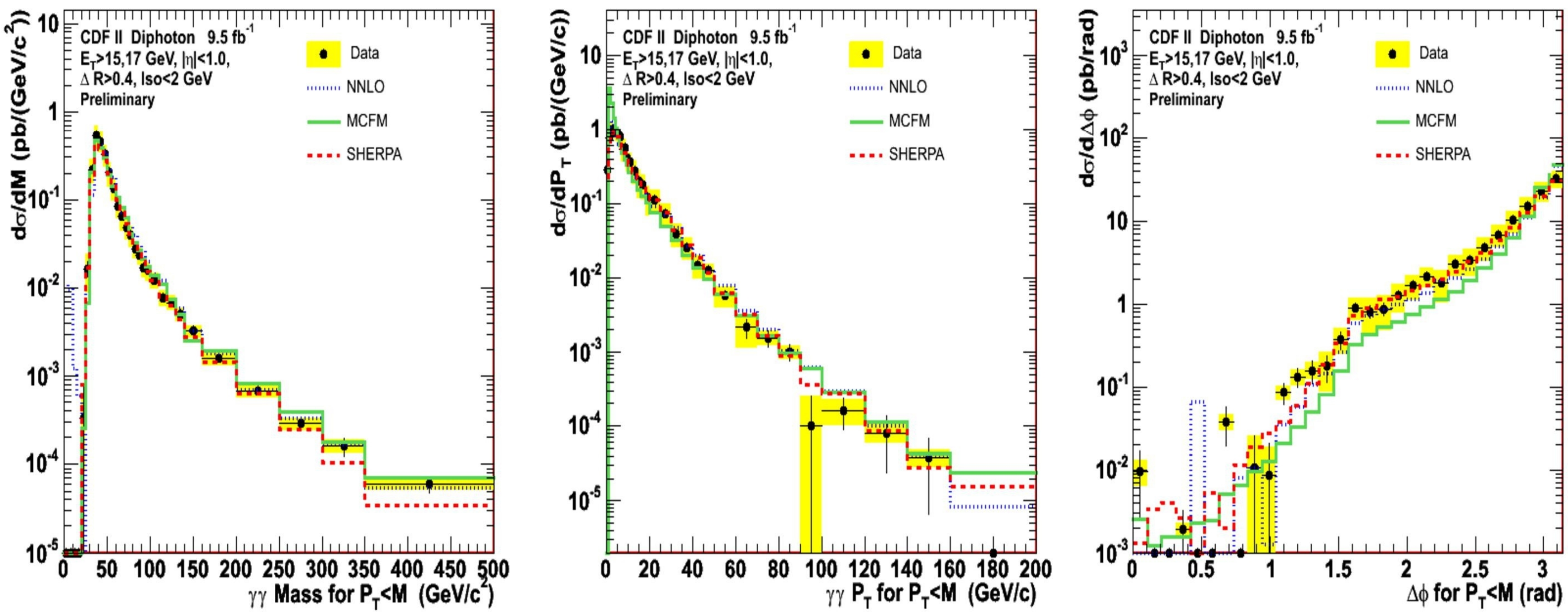


- Low statistics
- No events below $P_T(\gamma\gamma)$ = 20 GeV/c



- Low statistics
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma}$>1.5 rad

Differential cross sections for $P_T(\gamma\gamma)<M_{\gamma\gamma}$: CDF

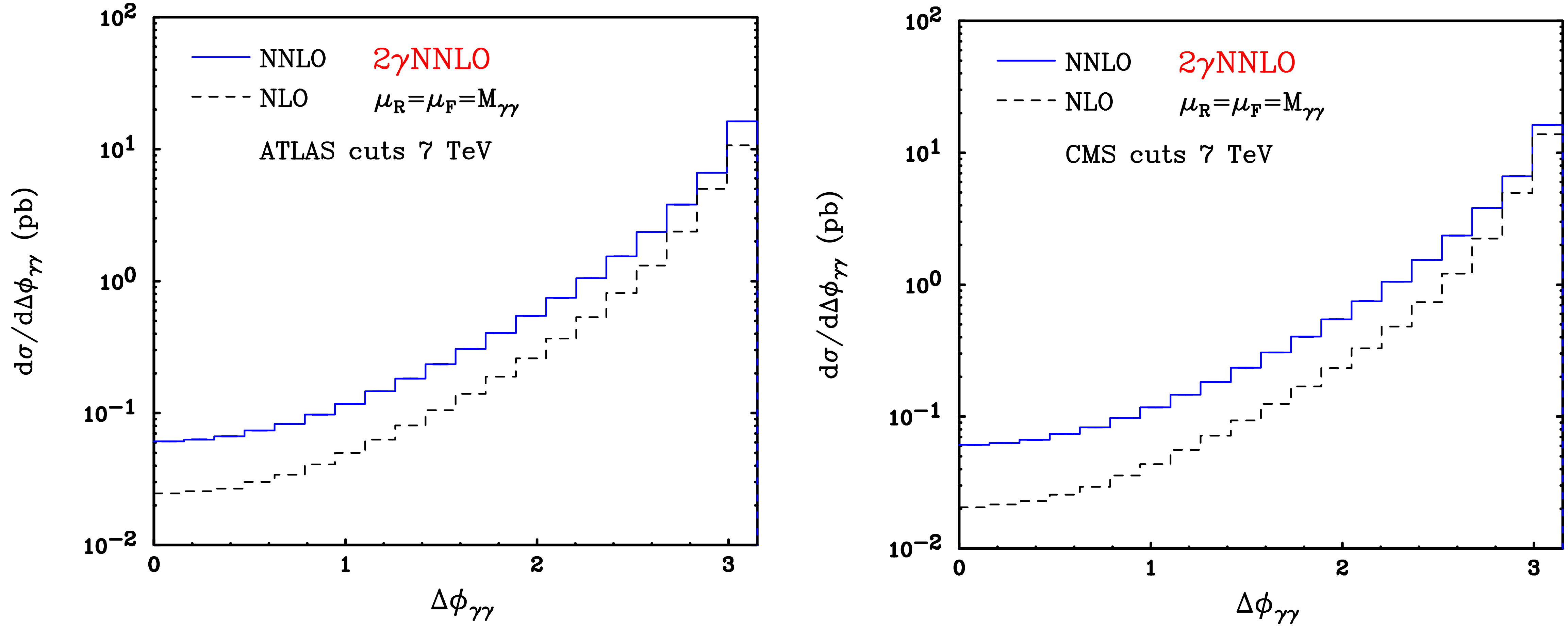


- Good agreement between data and theory
- No events for $M_{\gamma\gamma}$<30 GeV/c^2

- Good agreement between data and theory
- No excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the “Guillet shoulder”)

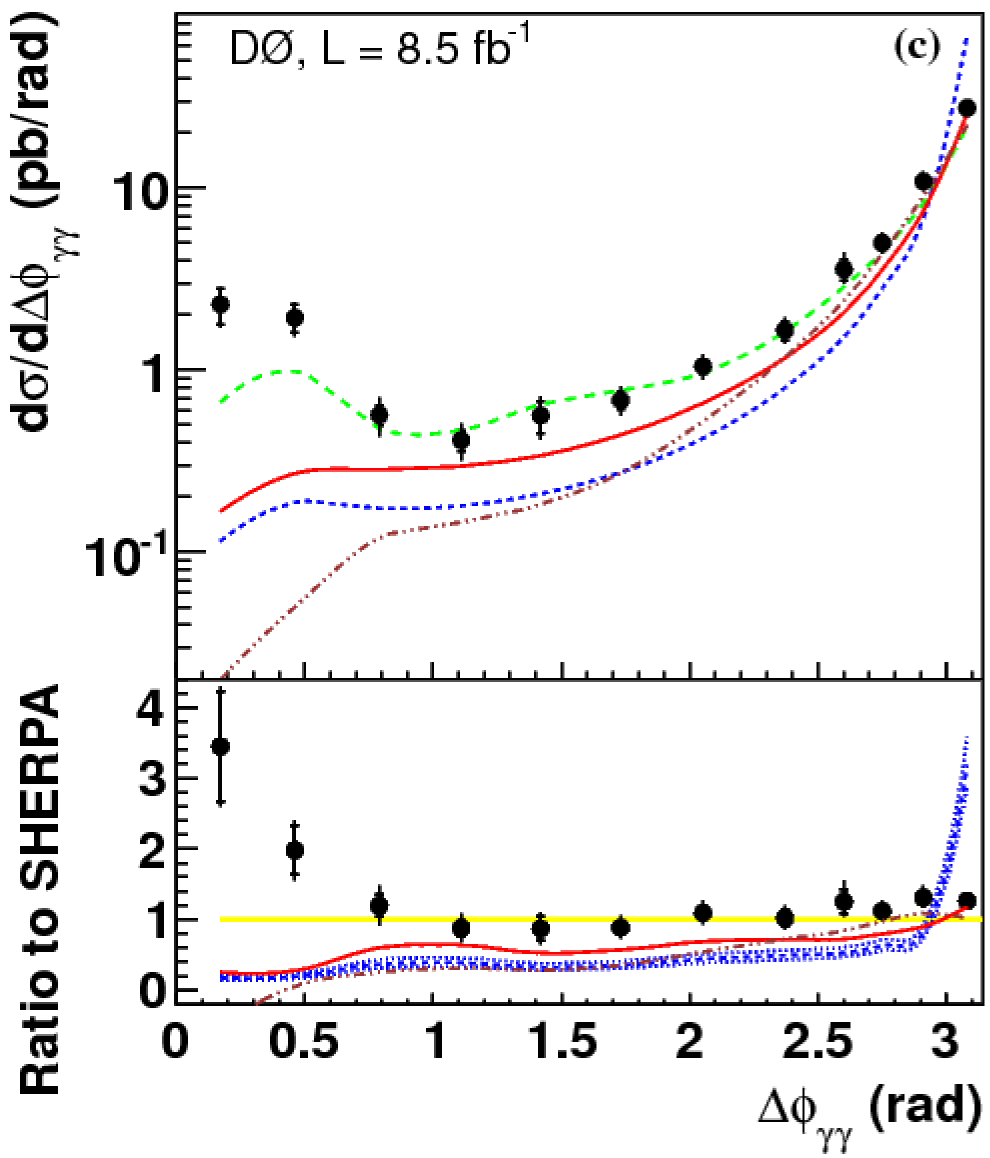
- Good agreement between data and theory
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma}$<1.5 rad

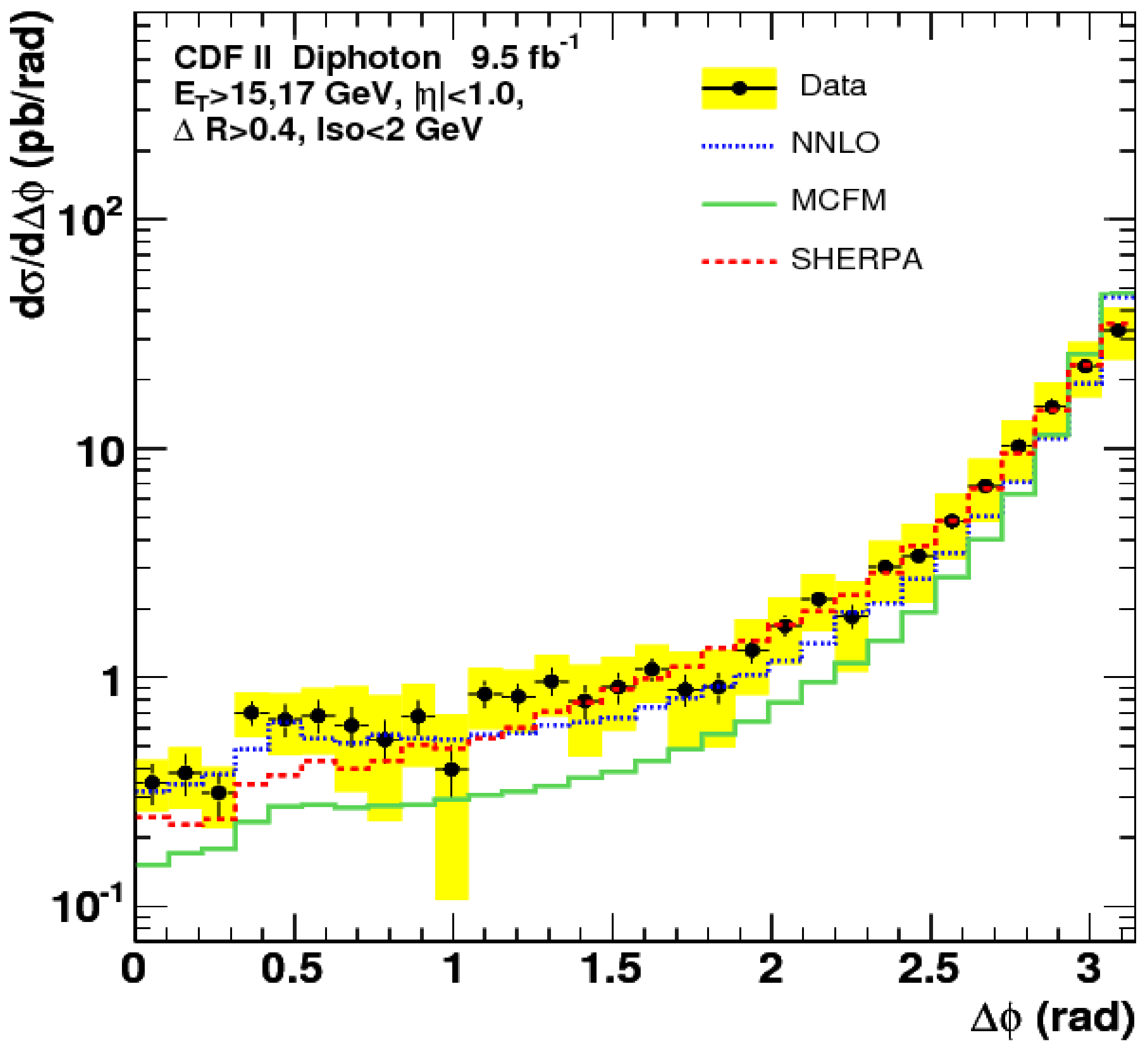
With Higgs search cuts at 7 TeV



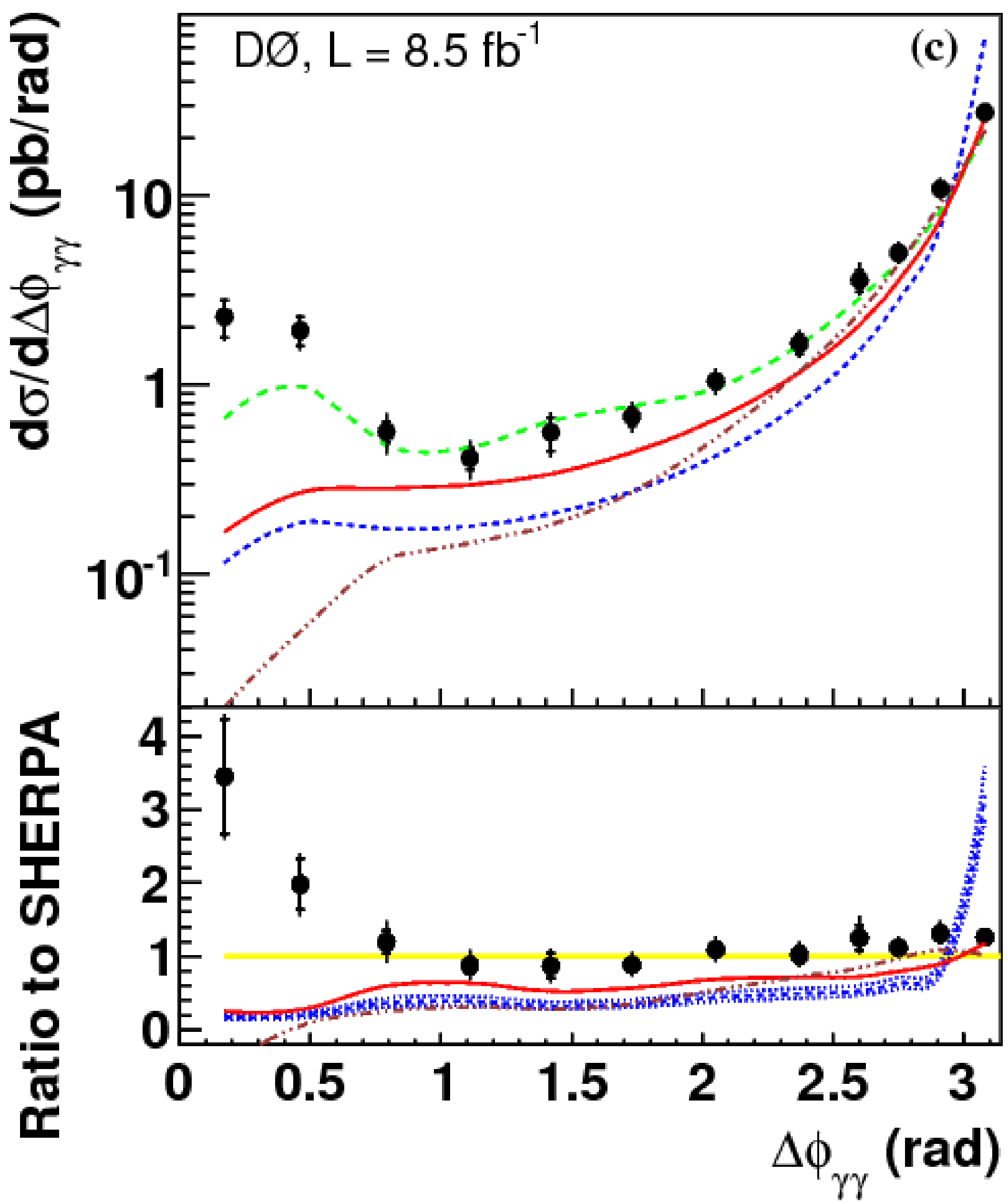
$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$	$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$
$p_T^{\gamma\, soft} \geq 25\,\mathrm{GeV}$	$p_T^{\gamma\, soft} \geq 30\,\mathrm{GeV}$
$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$	$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$
$\lvert\eta^\gamma\rvert \leq 2.37$	$\lvert\eta^\gamma\rvert \leq 2.5$
excluding $1.37 \leq \lvert\eta^\gamma\rvert \leq 1.52$	excluding $1.4442 \leq \lvert\eta^\gamma\rvert \leq 1.566$
$\epsilon = 0.05$	$\epsilon = 0.05$

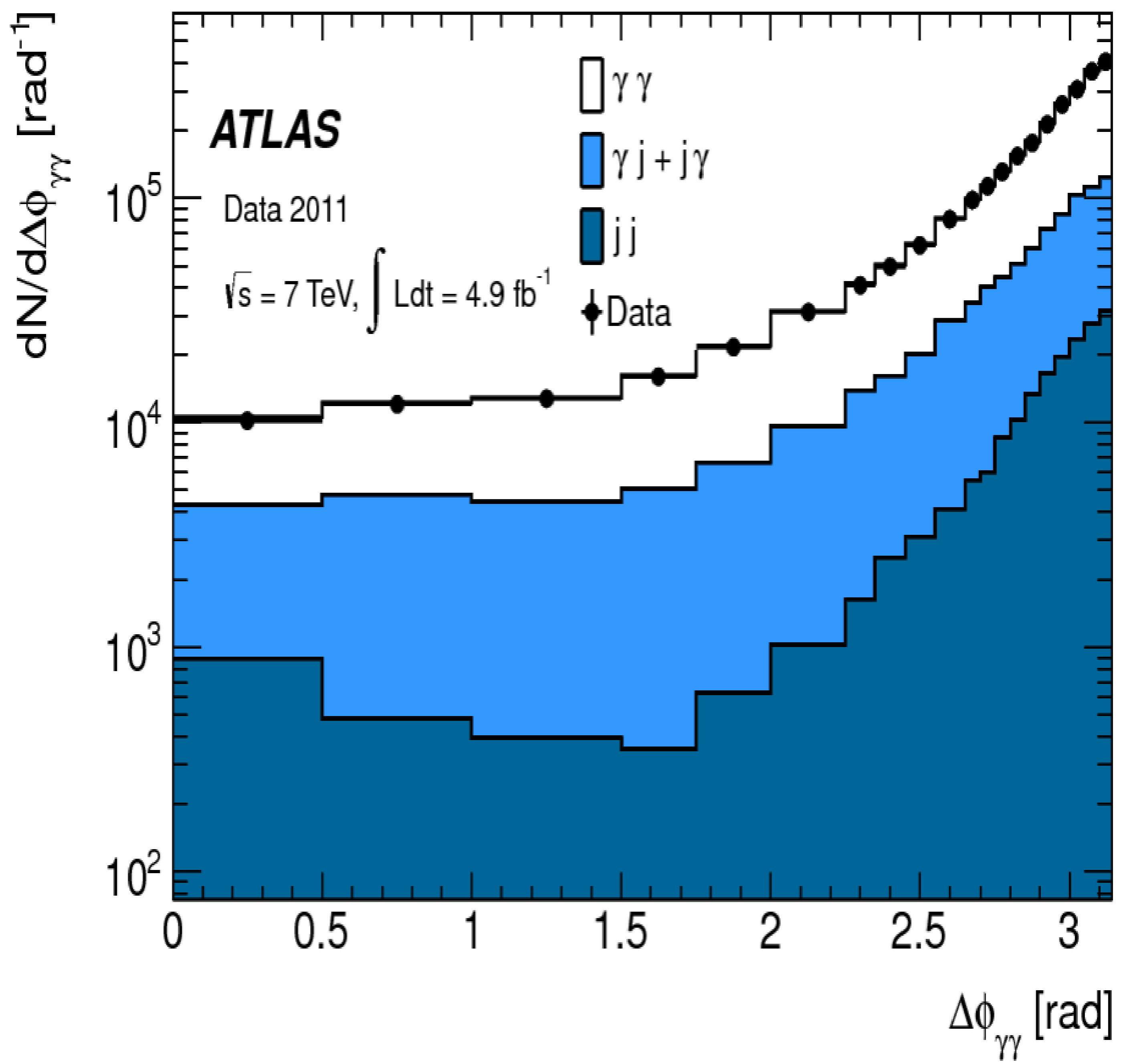
D0 vs CDF diphoton studies



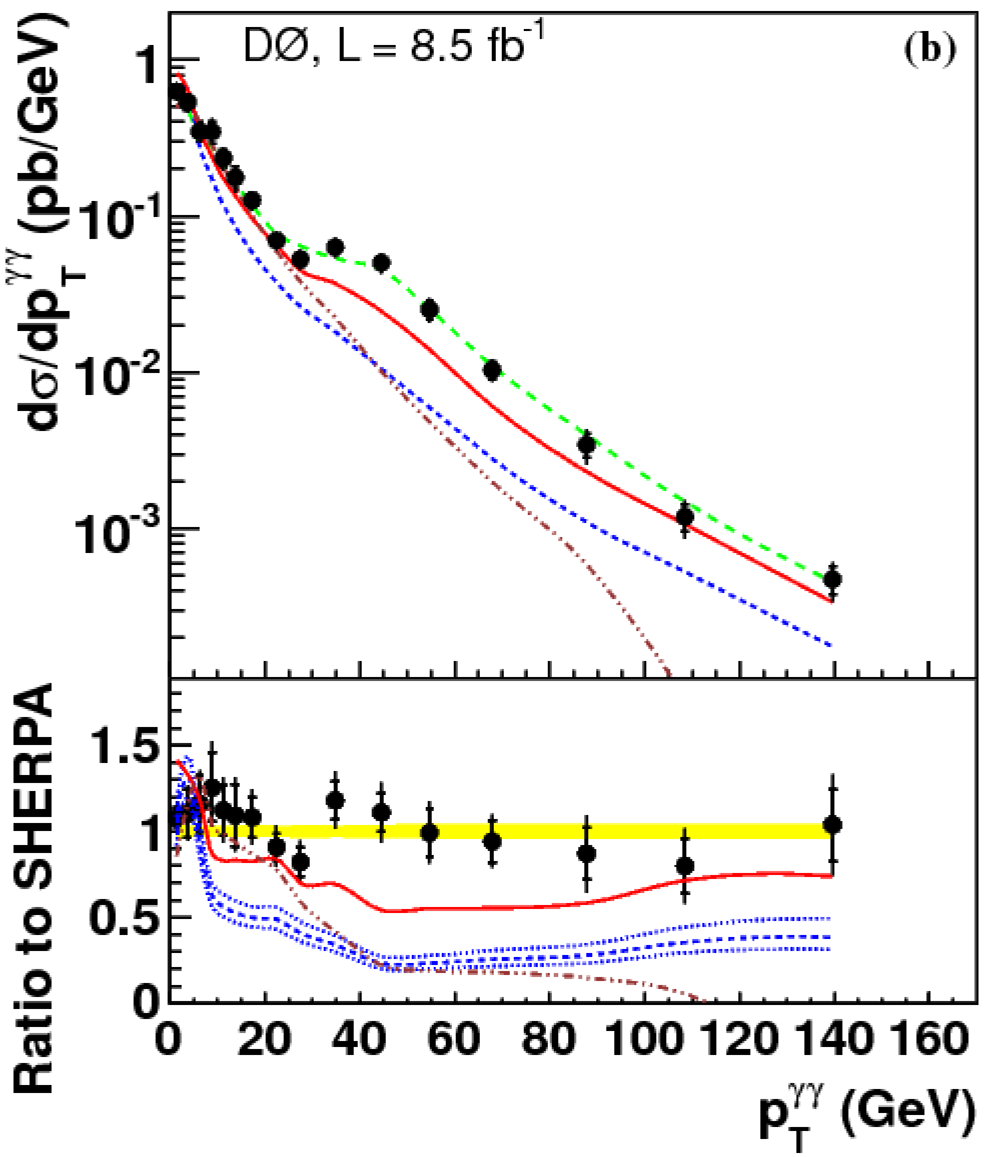


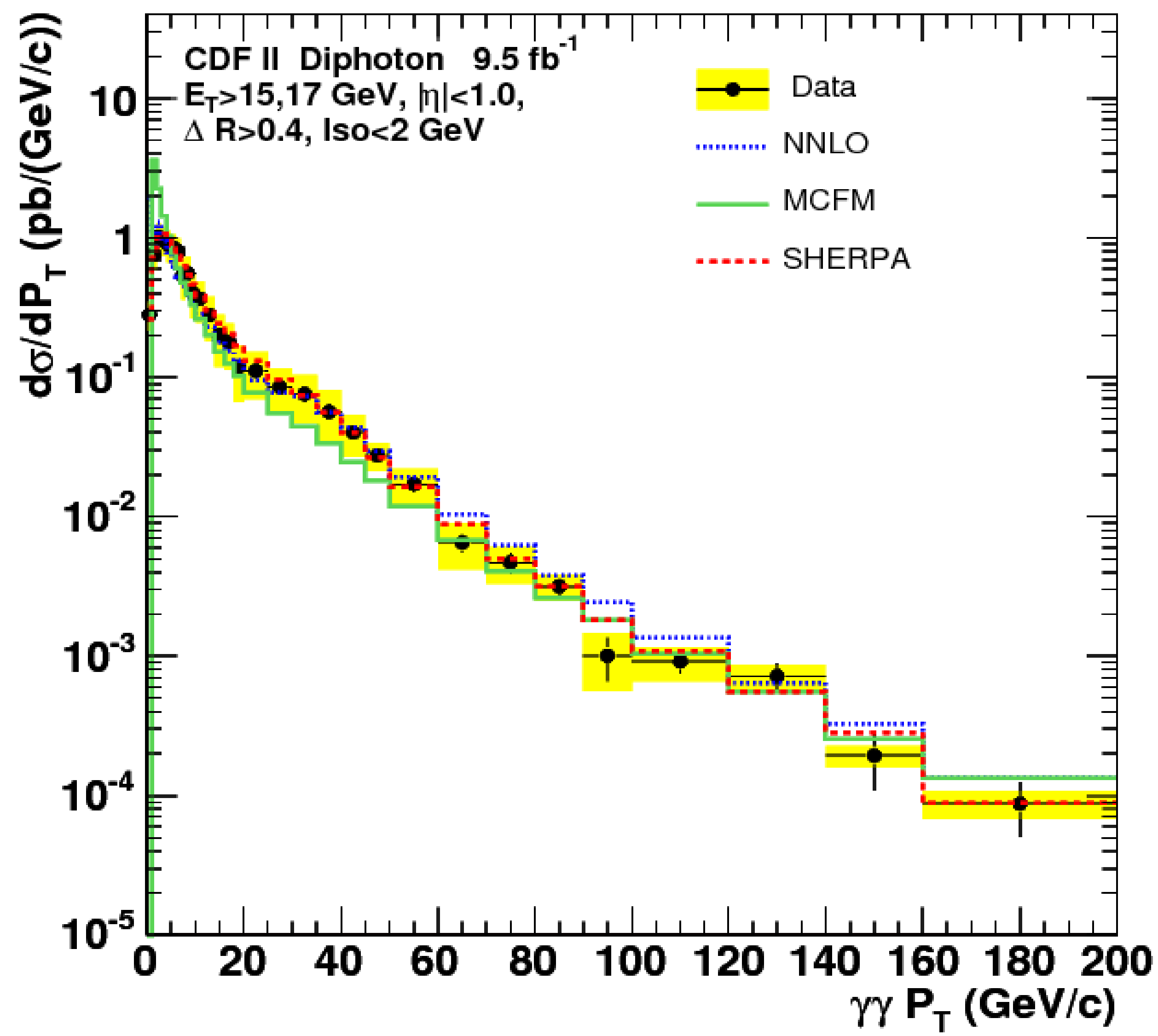
D0 vs ATLAS diphoton studies



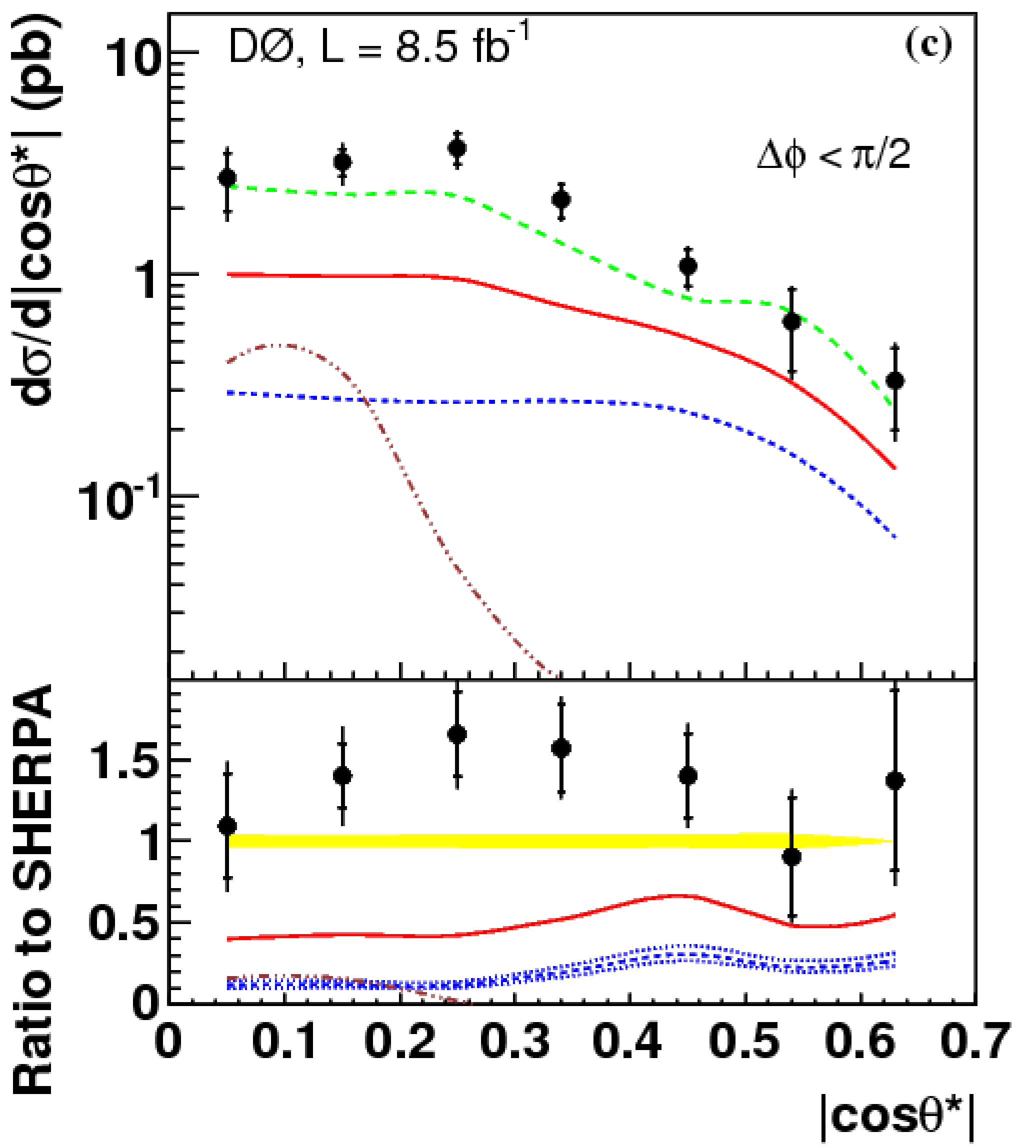


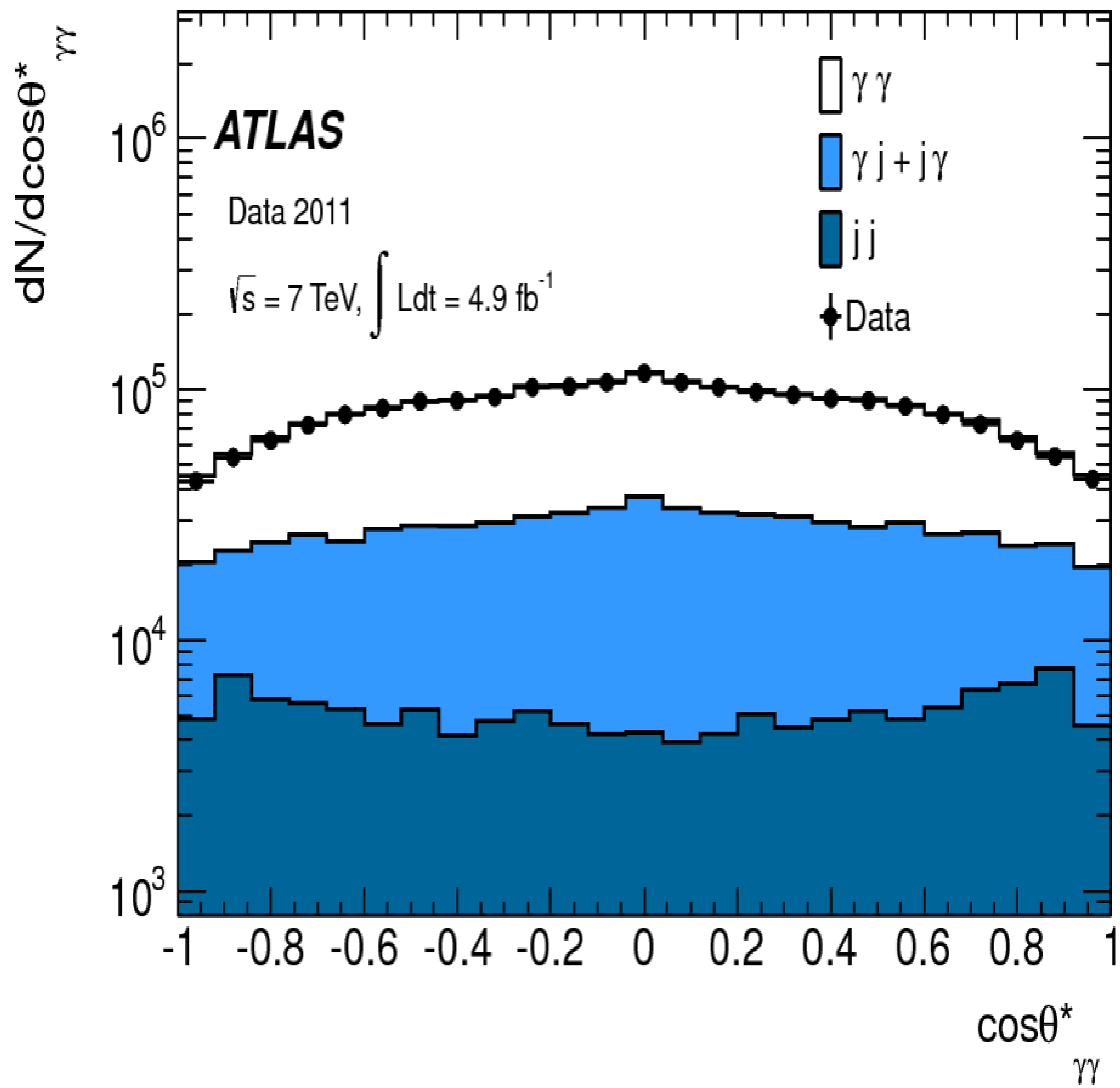
D0 vs CDF diphoton studies





D0 vs ATLAS diphoton studies





D0 vs ATLAS diphoton studies