Transverse momentum resummation and diphoton production at LHC

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PART I:
q_T RESUMMATION

Why resummation?

- Let's have a look at the q_T distribution for a generic inclusive $h_1 h_2 \to F$ process (F colorless)
- Standard (collinear) factorization formula gives

$$\frac{d\sigma^F}{dq_T^2} = \int dx_1 dx_2 \, f_{a/h_1}(x_1, \mu_f^2) \, f_{b/h_2}(x_2, \mu_f^2) \, \frac{d\hat{\sigma}^F_{ab}}{dq_T^2}(\hat{s}, q_T, M, \ldots)$$

- Fixed-order (in α_s) perturbative expansion not reliable for $q_T \ll M$

$$\int_0^{q_T^2} d\tilde{q}_T^2 \frac{d\hat{\sigma}^F_{ab}}{dq_T^2} \simeq \hat{\sigma}^{(0)}_{ab} \left[1 + \alpha_s \left(c_{12} \log^2 \frac{M^2}{q_T^2} + c_{11} \log \frac{M^2}{q_T^2} + c_{10} \right) + \ldots \right]$$

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- In general, $\sim \alpha_s^n \log^{2n} \frac{M^2}{q_T^2}$ terms will be present
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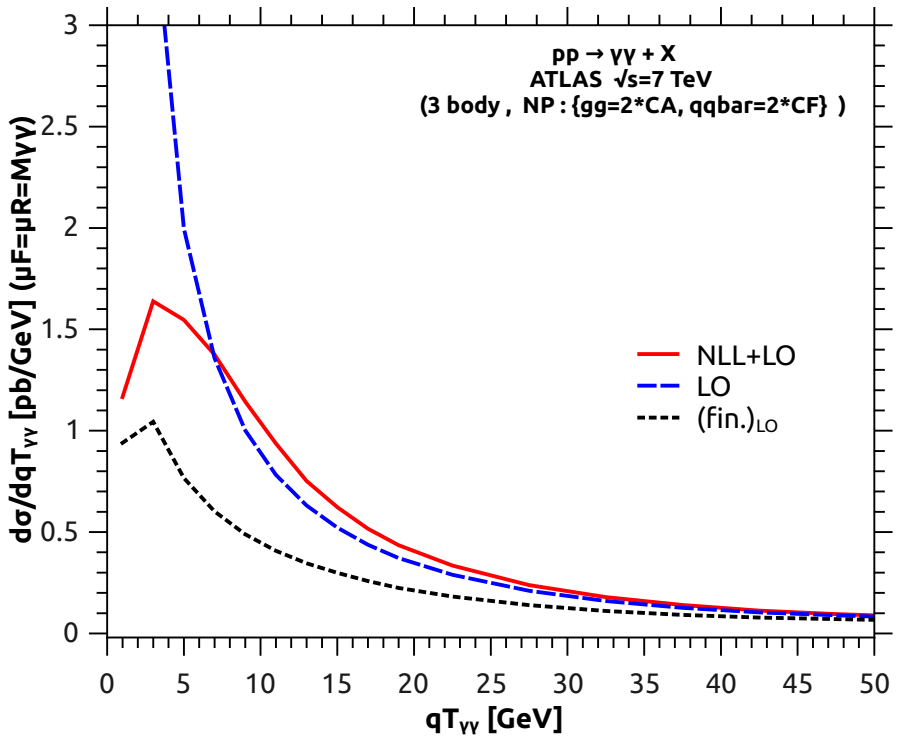

Summing logs to all orders: basic idea

- First ingredient: Sudakov-style exponentiation of soft gluons. Need factorization of both dynamics and kinematics
- Dynamics factorization is a general feature of soft QCD emissions:

$$dw_n(q_1, \ldots, q_n) \simeq \frac{1}{n!} \prod_i dw_i(q_i) \qquad (\to \text{small } q_i)$$

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- In the q_T case, the trick is going to impact parameter space:

$$\int d^2 q_T \exp(-ib \cdot q_T) \delta(q_T - \sum_i q_{iT}) = \prod_i \exp(-ib \cdot q_{iT})$$

- Since exponentiaton holds in b-space, need to F.T. back to physical space. The big logs become

$$\log \frac{M^2}{q_T^2} \leftrightarrow \log M^2 b^2$$

(note the F.T. is rather challenging from a numerical p.o.v. !)

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- The full story is (of course) a bit more complex.

Before going on: q_T resummation has a long history. Some refs:

b-space formalism:
[Dokshitzer,Diakonov,Troian('78)] , [Parisi,Petronzio(79)] , [Kodaira,Trentadue(82)] , [Collins,Soper,Sterman(85)] , [Altarelli et al.(84)] , [Catani,dEmilio,Trentadue(88)] , [Catani,De Florian, Grazzini(01)] , [Catani,Grazzini(10)] , [Catani,Grazzini,Torre(14)] , [Catani,Cieri,De Florian,Ferrera,Grazzini('14)] .

In the framework of Effective Theories:
[Gao,Li,Liu(05)] , [Idilbi,Ji,Yuan(05)] , [Mantry,Petriello(10)] , [Becher, Neubert(10)] , [Echevarria,Idilbi,Scimemi(11)] .

In the context of transverse-momentum dependent factorization:
[DAlesio,Murgia(04)] , [Roger,Mulders(10)] , [Collins(11)] , [DAlesio,Echevarria,Melis,Scimemi(14)] , [Ceccopieri,Trentadue(14)] .

Effective q_T-resummation obtained with Parton Shower algorithms POWHEG/MC@NLO:
[Barzeetal.(12,13)] , [Hoeche,Li,Prestel(14)] , [Karlberg,Re,Zanderighi(14)] .

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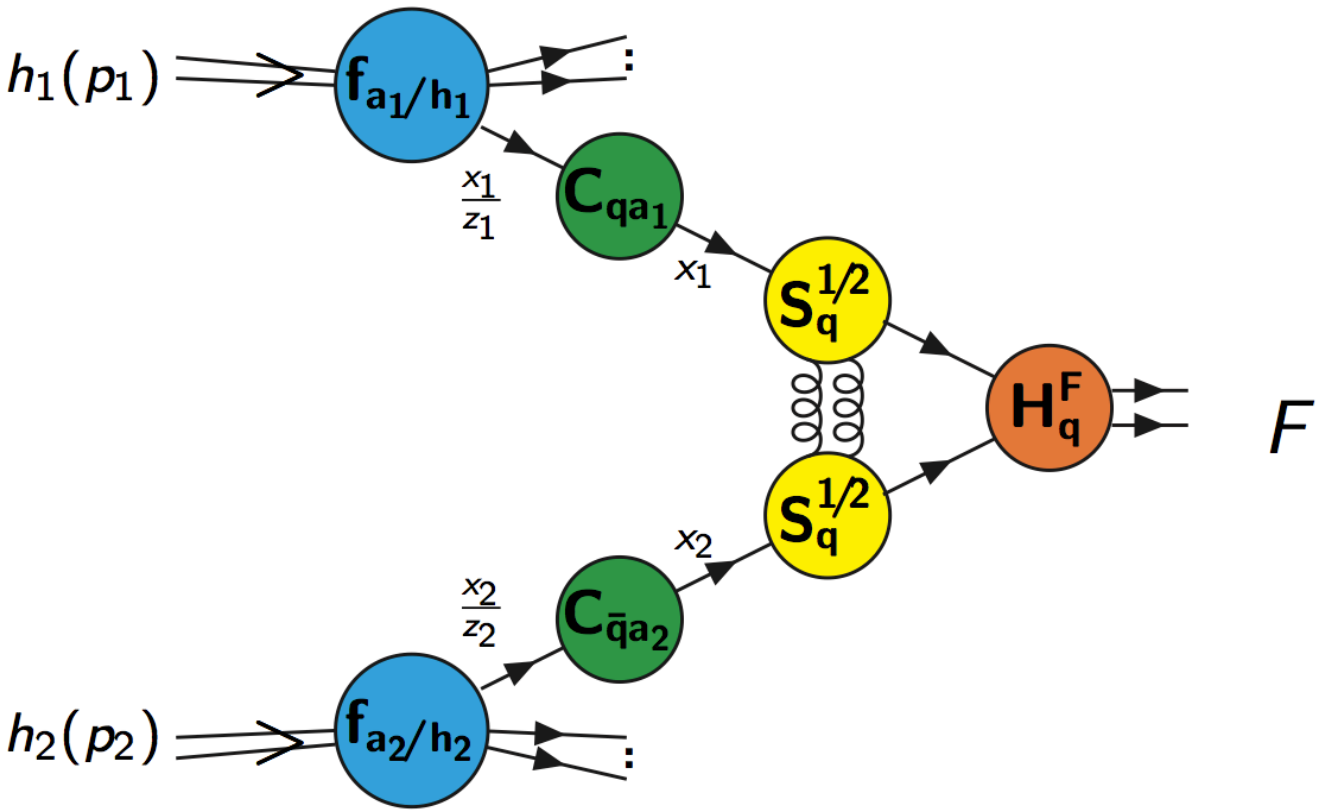
Schematically, the actual full formula looks like (for a $q\bar{q}$-initiated process)[1]



[1] Thanks to Giancarlo for this picture!

The (colorless) q_T resummation formula

The explicit formula is

$$\frac{d\sigma^{F(res)}(s,q_T,M,y,\Omega)}{d^2q_T dM^2 dy d\Omega} = \frac{M^2}{s}\sum_c d\hat{\sigma}^{F(0)}_{c\bar{c}} \int \frac{d^2b}{(2\pi)^2} e^{ib\cdot q_T} S_c(M,b)$$

$$\cdot \sum_{a_1,a_2} \int_{x_1}^1 \frac{dz_1}{z_1} \int_{x_2}^1 \frac{dz_2}{z_2} \left[H^F C_1 C_2\right]_{c\bar{c};a_1a_2} f_{a_1/h_1}\left(\frac{x_1}{z_1},\frac{b_0^2}{b^2}\right) f_{a_2/h_2}\left(\frac{x_2}{z_2},\frac{b_0^2}{b^2}\right)$$

with

$$S_c = \exp\left[-\int_{\frac{b_0^2}{b^2}}^{M^2} \frac{dq^2}{q^2}\left(A_c(\alpha_s(q^2))\log\frac{M^2}{q^2} + B_c(\alpha_s(q^2))\right)\right]$$

$$b_0 = 2e^{-\gamma_E}, \quad x_{1,2} = \frac{M}{\sqrt{s}}e^{\pm y}$$

$$A_c(\alpha_s) = \sum_n \left(\frac{\alpha_s}{\pi}\right)^n A_c^{(n)}, \quad B_c(\alpha_s) = \sum_n \left(\frac{\alpha_s}{\pi}\right)^n B_c^{(n)}$$

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The (colorless) q_T resummation formula

Some comments:

- A_c and B_c in the exponent are evaluated at the scale q^2. They can be evolved using standard α_s evolution, and the q^2 integral can be solved analytically
- The result can be organized in a logarithmic expansion: $A_c^{(1)}$ contributes to Leading Log or LL $\sim \alpha_s(\mu_R)^n L^{n+1}$; $A_c^{(2)}$ and $B_c^{(1)}$ to NLL $\sim \alpha_s(\mu_R)^n L^n$, and so on, with $L = \log(Mb)$.
- The p.d.f. appearing in the formula are evaluated at the relatively soft scale b_0^2/b^2, and have to be evolved to $\sim M^2$ using DGLAP equations.
- The $\left[H^F C_1 C_2\right]_{c\bar{c};a_1 a_2}$ term is the trickiest one, and its actual structure depends on wheter the process is initiated by $q\bar{q}$ or gg at LO.

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q_T resummation in more detail: $q\bar{q}$

The $q\bar{q}$ case is the simplest one

$$\left[H^F C_1 C_2\right]_{q\bar{q};a_1 a_2} = H_q^F(x_1 p_1, x_2 p_2, \Omega; \alpha_s(\mu_R^2)) C_{qa_1}(z_1; \alpha_s(b_0^2/b^2)) C_{\bar{q}a_2}(z_2; \alpha_s(b_0^2/b^2)) \,,$$

$$H_q^F = \sum_n H_q^{F(n)} \,, \quad C_{qa}(z, \alpha_s) = \delta_{qa}\,\delta(1-z) + \sum_{n\geqslant 1} \left(\frac{\alpha_s}{\pi}\right)^n C_{qa}^{(n)} \,,$$

$$C(z, \alpha_s(b_0^2/b^2)) = C(z, \alpha_s(\mu_R^2)) \exp\left[-\int_{\frac{b_0^2}{b^2}}^{M^2} \frac{dq^2}{q^2} \beta(\alpha_s(q^2)) \frac{d\log C(z, \alpha_s(q^2))}{d\log \alpha_s(q^2)}\right] .$$

One can define an "effective p.d.f.":

$$\tilde{F}_{q_f/h}(x, b, \mu) = \sum_a \int_x^1 \frac{dz}{z} \sqrt{S_q(M, b)} C_{q_f a}(z; \alpha_s(b_0^2/b^2)) f_{a/h}(x/z, b_0^2/b^2)$$

q_T resummation in more detail: gg

In the gg case, collinear radiation from gluons leads to spin and azimuthal correlations

$$\left[H^F\, C_1\, C_2\right]_{gg;a_1a_2} = H^F_{g;\mu_1\nu_1\mu_2\nu_2}(x_1p_1, x_2p_2, \Omega; \alpha_s(\mu_R^2)) \\ C^{\mu_1\nu_1}_{ga_1}(z_1; \alpha_s(b_0^2/b^2))\, C^{\mu_2\nu_2}_{ga_2}(z_2; \alpha_s(b_0^2/b^2))\,,$$

$$H^F_{g;\mu_1\nu_1\mu_2\nu_2} = \sum_n H^{F(n)}_{g;\mu_1\nu_1\mu_2\nu_2}\,, \quad C^{\mu\nu}_{ga}(z;\alpha_s) = d^{\mu\nu}\, C_{ga}(z;\alpha_s) + D^{\mu\nu}\, G_{ga}(z;\alpha_s)\,,$$

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- In contrast with the $q\bar{q}$ case, $\left[H^F\, C_1\, C_2\right]_{gg;a_1a_2}$ depends on the azimuth $\phi(b)$.

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q_T resummation: matching

- All of this "just" describes the small q_T cross-section, i.e. it is valid up to power corrections $\mathcal{O}(q_T^2/M^2)$.
- To obtain the complete cross-section, a special matching procedure is used. Namely

$$\frac{d\sigma}{dq_T} = \frac{d\sigma^{(res)}}{dq_T} + \frac{d\sigma^{(fin)}}{dq_T}$$

where $d\sigma^{(fin)}/dq_T$ is defined by subtraction at fixed order and

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q_T resummation: matching

- Finally we have a unitarity constraint

$$\int_0^\infty dq_T^2 \left.\frac{d\sigma^{(res)}}{dq_T}\right|_{l.a.} = \int_0^\infty dq_T^2 \left.\frac{d\sigma^{(res)}}{dq_T}\right|_{f.o.} .$$

- This is implemented by the substitution

$$L \to \tilde{L} = \log\left(M^2 b^2 + 1\right)$$

and besides ensuring that we retain the full perturbative information, also cuts off unwanted Log contributions at small b (large q_T)

q_T resummation: universality

- Process dependence is fully encoded in the "hard-virtual" factor H_c^F (and the Born cross-sec.)
- Even H_c^F has a universal structure; it is related to the IR-subtracted purely virtual amplitude
- Define the UV-finite, IR-divergent renormalized amplitude

$$\mathcal{M}_{c\bar{c}\to F} = \alpha_s^k \sum_n \left(\frac{\alpha_s}{\pi}\right)^n \mathcal{M}^{(n)}_{c\bar{c}\to F}$$

- And the IR-finite subtracted amplitude

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- Then

$$\alpha_s^{2k} H_q^F = \frac{|\tilde{M}_{q\bar{q}\to F}|^2}{|M^{(0)}_{q\bar{q}\to F}|^2}$$

$$\alpha_s^{2k} H_g^{F\mu_1\nu_1\mu_2\nu_2} = \frac{\left(\tilde{M}^{\mu_1\nu_1}_{gg\to F}\right)^\dagger \tilde{M}^{\mu_2\nu_2}_{gg\to F}}{|M^{(0)}_{gg\to F}|^2}$$

- The subtraction operator $\tilde{I}_c$ is universal
- In the end, a couple explicit f.o. calculations are sufficient to fix all resummation coefficients

q_T resummation scheme

- The resummation formula is invariant under the transformations

$$H_c^F(\alpha_s) \to H_c^F(\alpha_s) h(\alpha_s)^{-1}$$

$$B_c(\alpha_s) \to B_c(\alpha_s) - \beta(\alpha_s) \frac{d \log h_c(\alpha_s)}{d \log \alpha_s}$$

$$C_{cb}(z, \alpha_s) \to C_{cb}(z, \alpha_s) \sqrt{h_c(\alpha_s)}$$

  with arbitrary h_c.

- H_c^F, B_c and C_{cb} not unambigously defined

- An explicit choice corresponds to a resummation scheme; the simplest is to set $H_c^F \equiv 1$ for a single specific process, though other possibilities exist.

q_T resummation: other features

- Though the formal b integration extends from 0 to ∞, very small and very large values of b should not play any physical role. The relevant range is

$$M^{-1} \ll b \ll \Lambda_{QCD}^{-1}$$

- The L-dependent exponential does have a singularity at large b, which is related to the Landau pole of α_s; this is regulated by a "minimal prescription" [Catani et al. ('96)] , [Laenen et al. ('00)] .

- The resummation is performed at the partonic level; p.d.f. are evaluated at μ_f and evolved perturbatively to b_0^2/b^2. Uncertainty can be estimated by μ_f and μ_R variation as in f.o. calculations

q_T resummation: other features

- An additional ambiguity in the definition of the logarithms can be accounted for by the introduction of an additional resummation scale Q:

$$\log(M^2 b^2) \to \log(Q^2 b^2) + \log(M^2/Q^2)\,.$$

- An extension to colored final state is possible; the structure is similar with some additional complication
- Finally, the formalism captures the QCD IR structure very well: can also be used for subtraction

PART II:
$\gamma\gamma$ PRODUCTION

Diphoton production: motivations

- Clean experimental channel: good test ground for pQCD
- Irreducible background for the production of a Higgs decaying to two photons
- Also irreducible background for many New Physics models: UED, RS, SUSY, ...

Diphoton production: avaible TH tools

- DIPHOX [T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen]

  Full NLO for direct prod. and fragmentation + Box contribution (part of NNLO)

- gamma2MC [Z. Bern, L. Dixon, and C. Schmidt]

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

- MCFM [J. M. Campbell, R.K. Ellis and C. Williams]

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

- Resbos [C. Balzs, E. L. Berger, P. Nadolsky, and C.-P. Yuan]

  NLL qT resummation for direct (with regulator for collinear singularities)

- 2γNNLO [S. Catani, L. Cieri, D. de Florian, G. Ferrera and M. Grazzini]

  Full NNLO for direct + partial correction to Box contribution (N^3LO)

- 2γRes [L. Cieri, FC and de Florian]

  Incorporates the qT resummation at NNLL+NNLO (direct only)

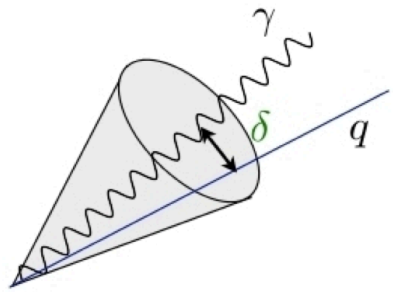
On isolation

- Photons in hadron collisions can be produced directly in the hard scattering or by collinear fragmentation of an emitted parton
- To identify photon experimentally, need an isolation prescription
- In a general prescription, only a combination of the direct + fragmentation components is physically meaningful
- However, fragmentation is nonperturbative (analogous to p.d.f.) $\Rightarrow$ not under theoretical control

On isolation

- Two standard experimental choices: cone isolation

$$\sum_{\delta<R_0} E_T^{had} \leqslant \epsilon p_T^{\gamma} \qquad \sum_{\delta<R_0} E_T^{had} \leqslant E_T^{max}$$



- A better choice from the theory p.o.v.: smooth (Frixione) cone isolation. Well defined with just the direct component!

$$\sum_{\delta<R_0} E_T^{had} \leqslant E_T^{max}\chi(\delta) \qquad \chi(\delta) = \left(\frac{1-\cos\delta}{1-\cos R_0}\right)^n$$

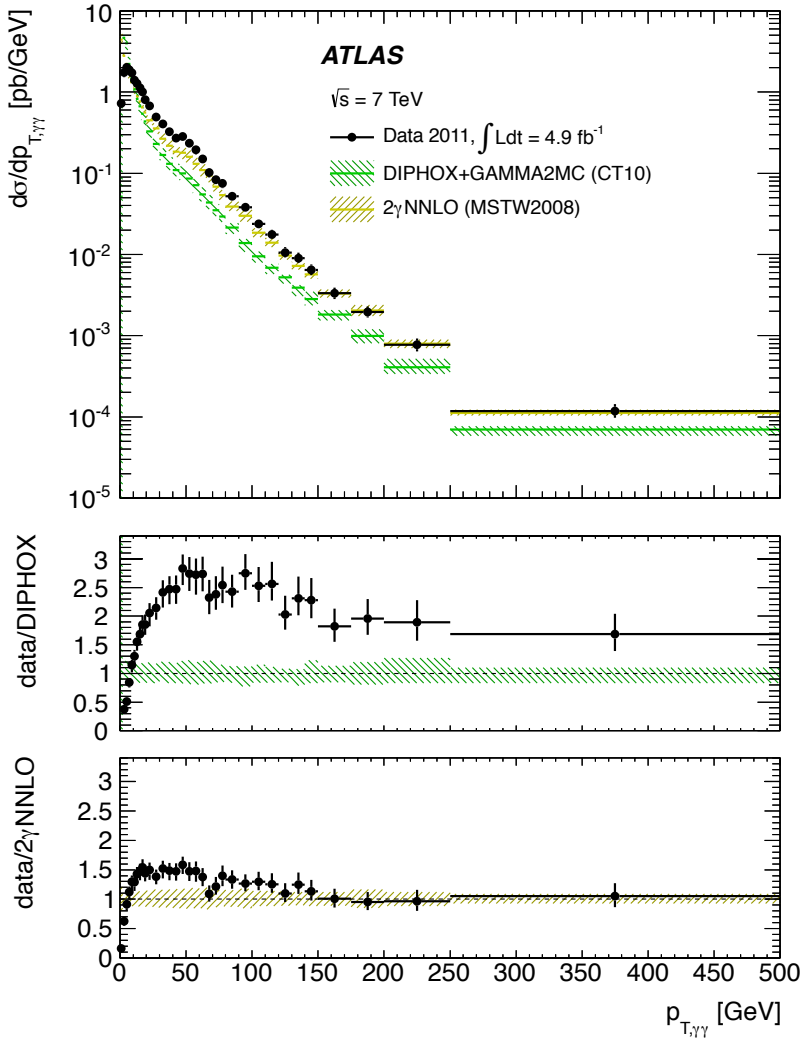
On isolation

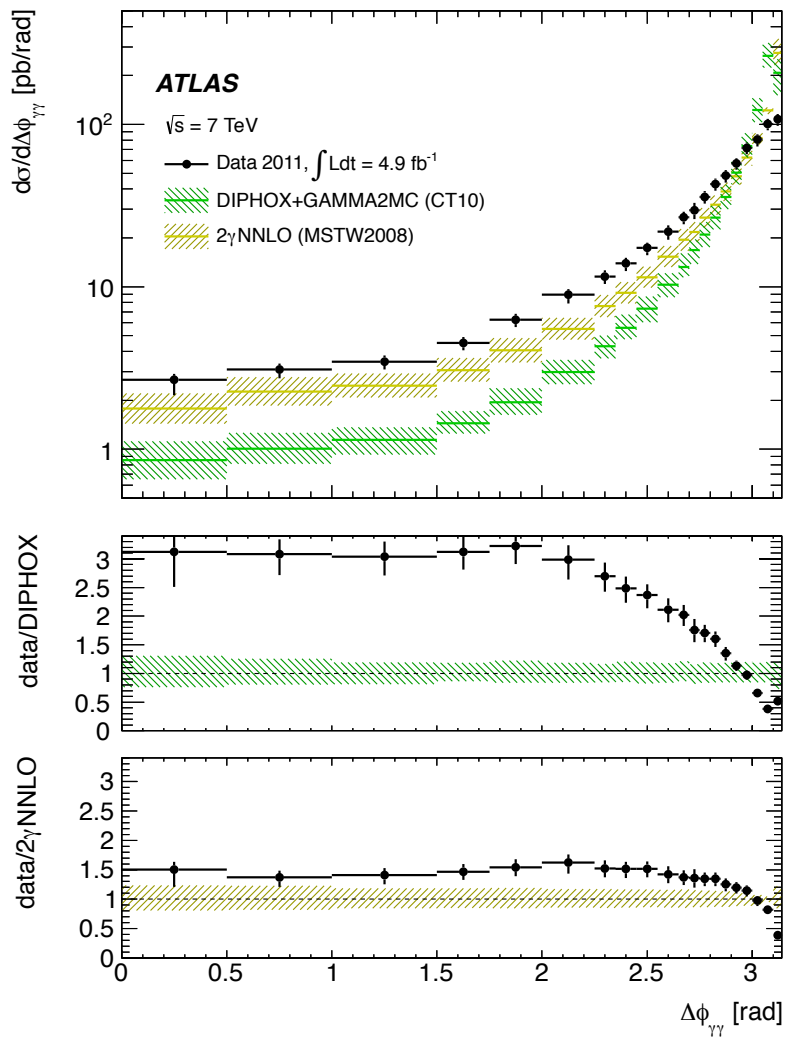
- Not clear how to implement smooth isolation experimentally
- 2013 Les Houces accord goes for a "pragmatic compromise": use cone isolation with tight enough parameters in experiments, use smooth isolation with same R_0 and E_T^{max} in theory calculations
- Estimate a TH uncertainty by using different profiles for the smooth cone

Results: ATLAS comparison

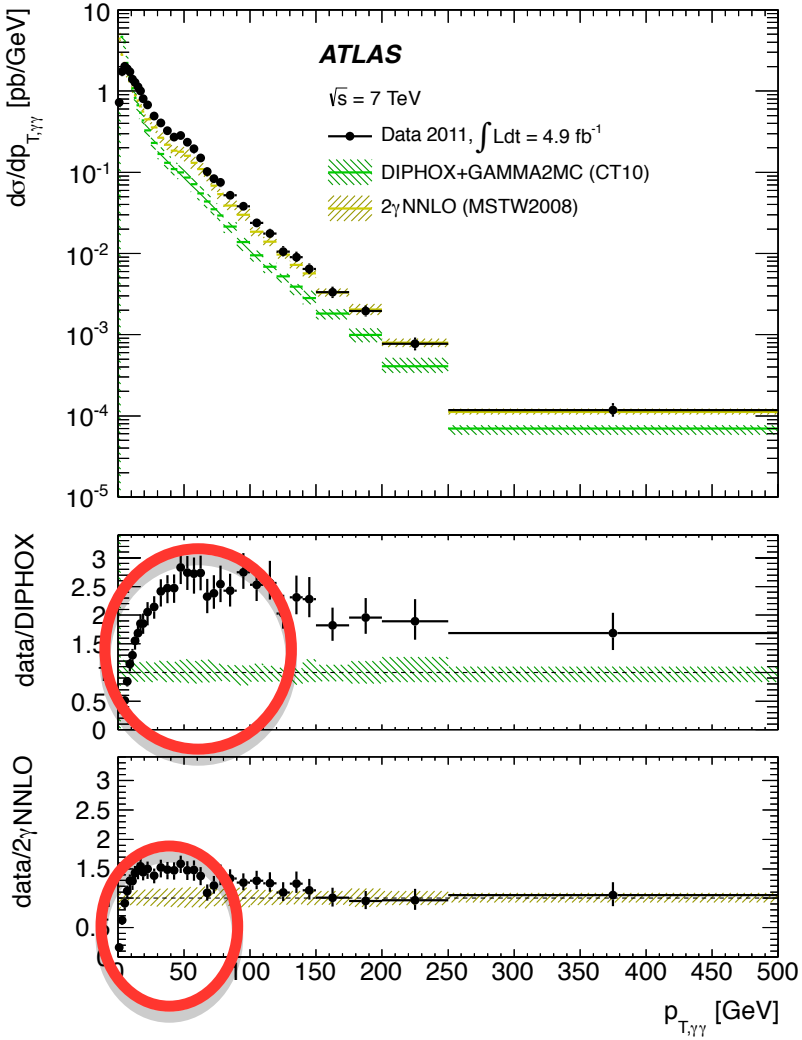
- We use as a test case ATLAS results @ 7 TeV [ATLAS] 1211.1913
- Kinematic cuts are $p_T^{hard} \geqslant 25$ GeV, $p_T^{soft} \geqslant 22$ GeV, $|y_\gamma| \leqslant 1.37 \vee 1.52 \leqslant |y_\gamma| \leqslant 2.37$ for both photons, $R_{\gamma\gamma} \geqslant 0.4$
- Isolation parameters are $E_T^{max} = 4$ GeV, $R_0 = 0.4$, $n = 1$
- Theory uncertainty is around $6 - 8\%$, mainly due to gg contribution which is effectively LO at $\mathcal{O}(\alpha_s^2)$

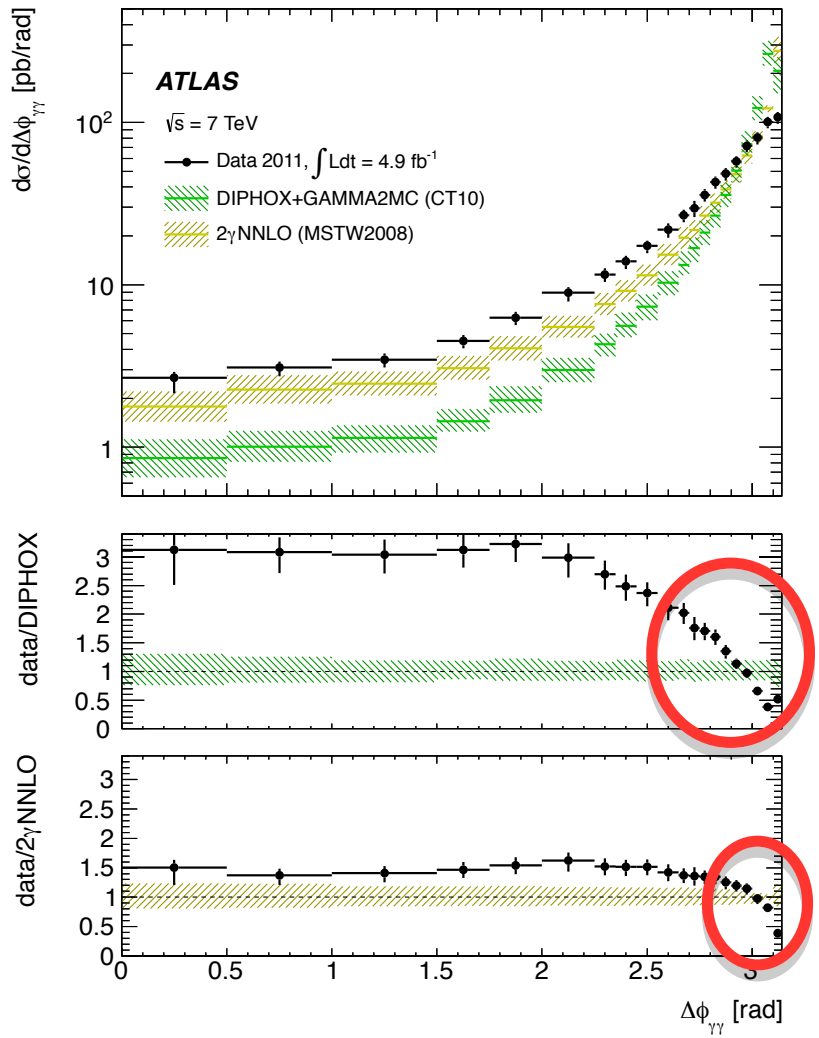
Results: ATLAS comparison - fixed order



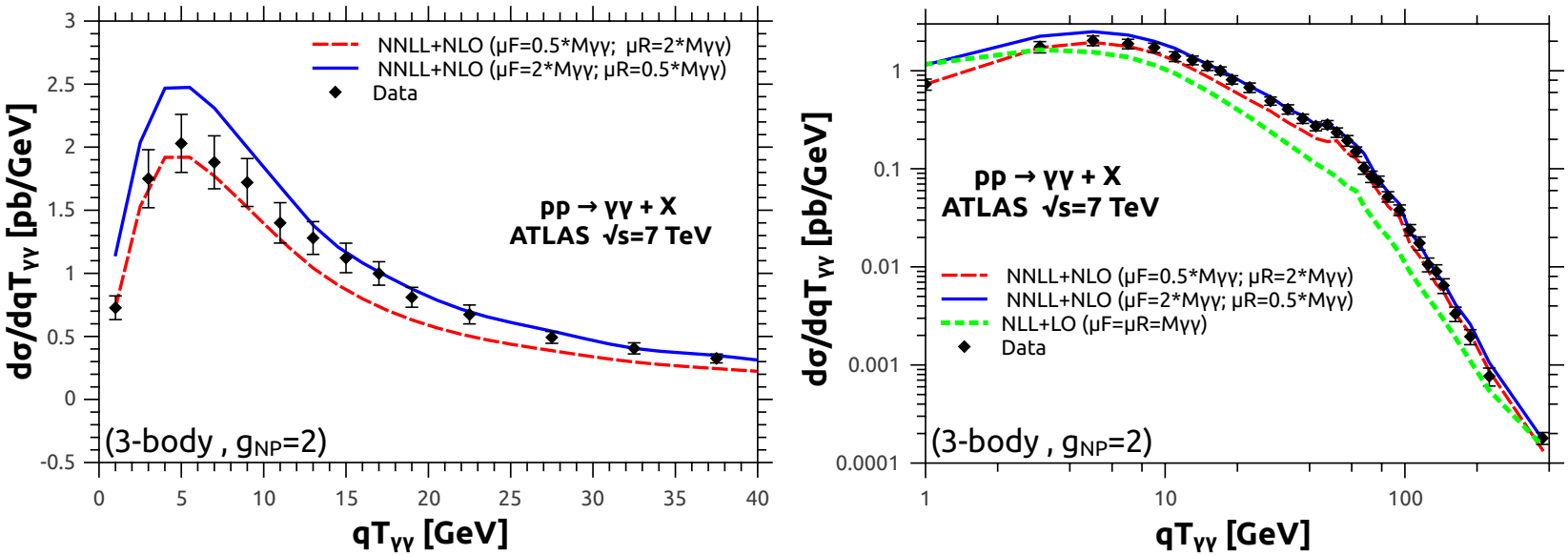


Results: ATLAS comparison - fixed order



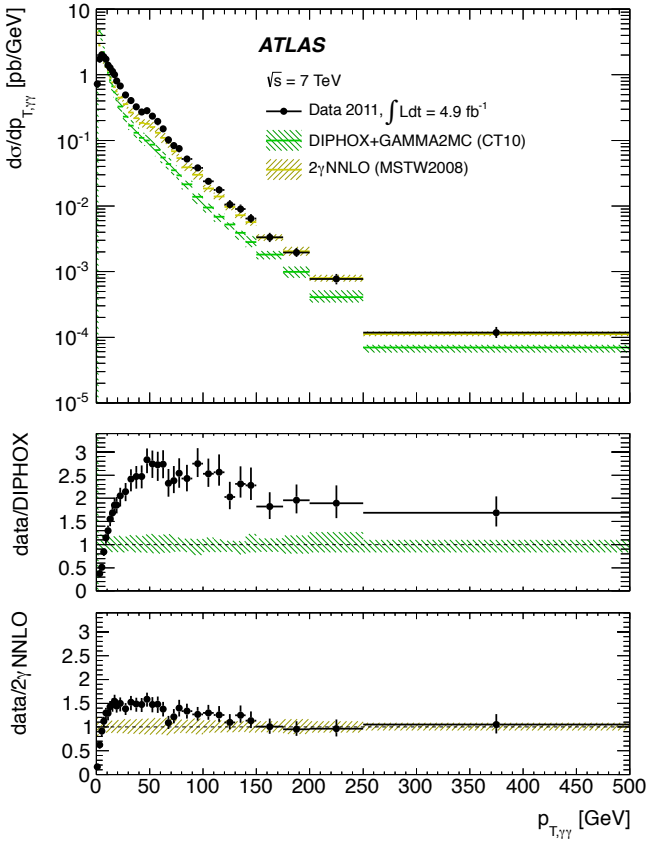


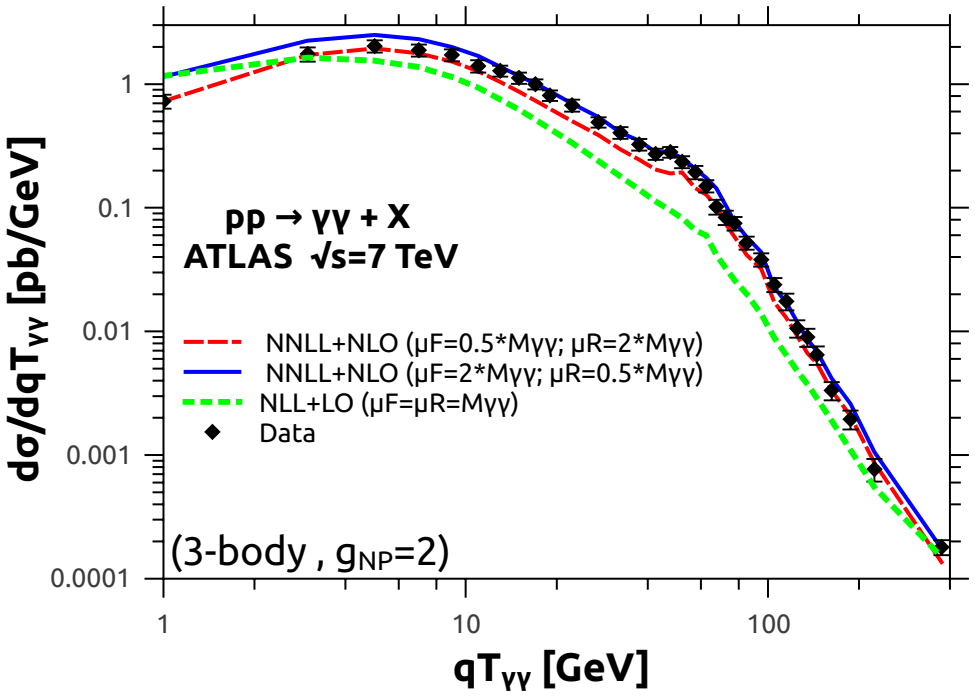
Results: ATLAS comparison - resummation [Cieri,FC,De Florian] 1505.03162



- Resummation spreads the uncertainties due to the gg channel over the whole q_T range

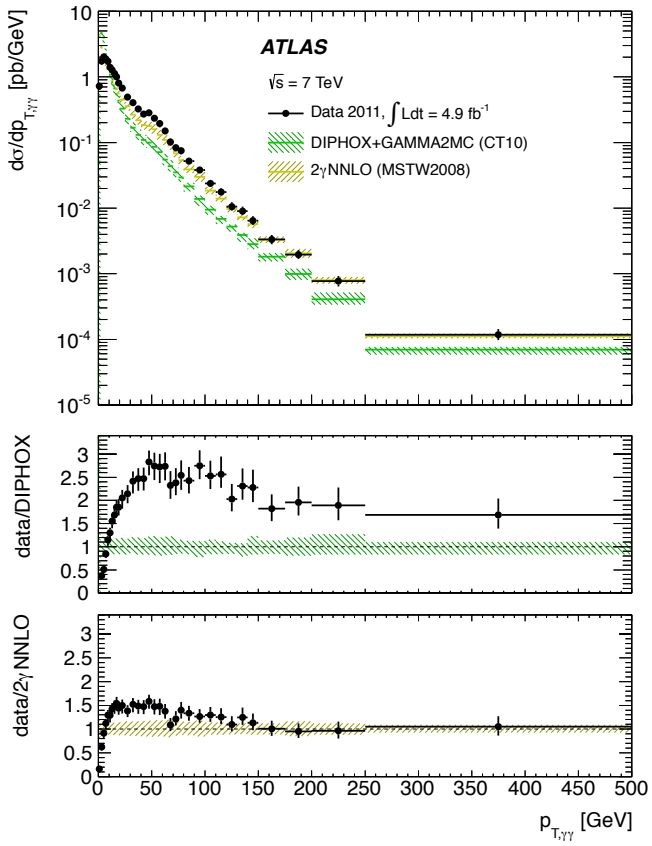
Results: ATLAS comparison - resummation

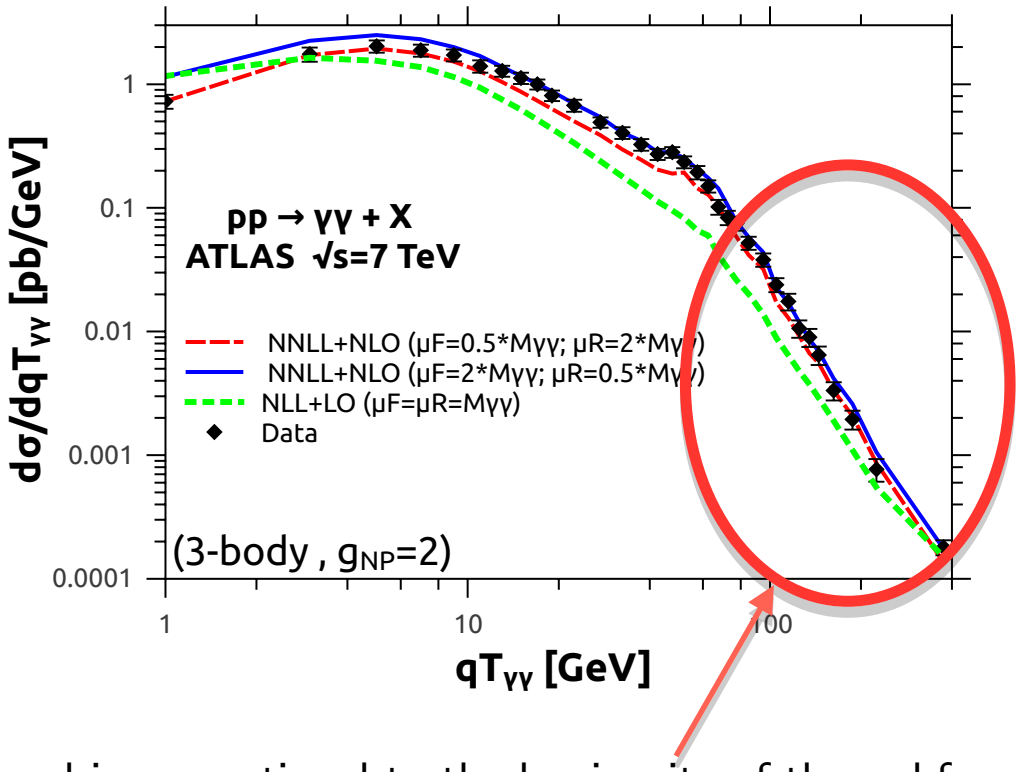




- Very good agreement between theory and experiment over the whole q_T range.

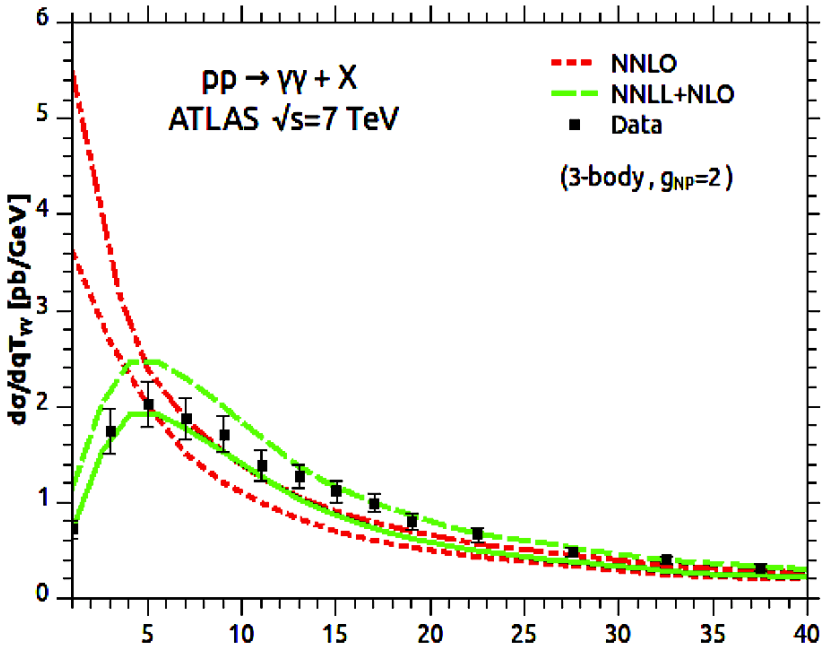
Results: ATLAS comparison - resummation

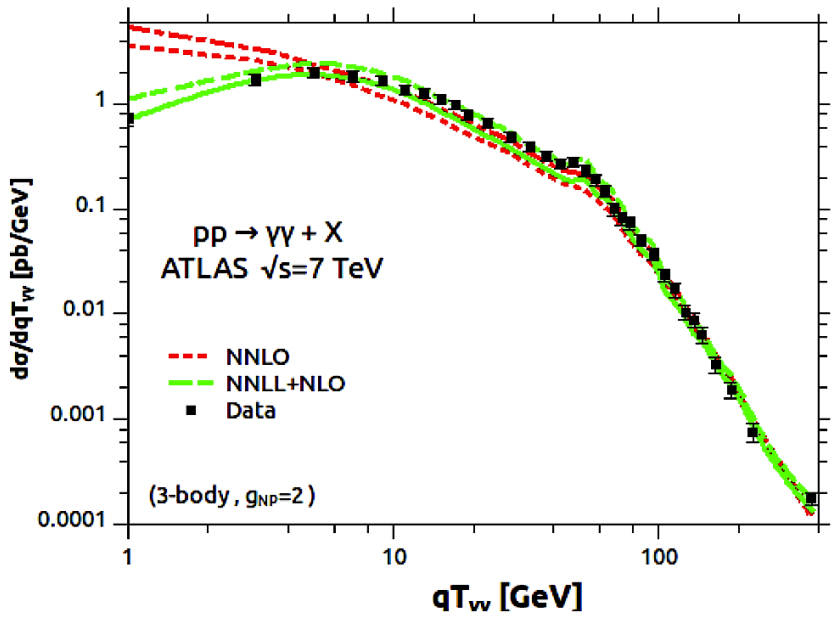




- The size of the uncertainty band is proportional to the luminosity of the p.d.f. of the gluon

Results: ATLAS comparison - resummation





- Description of the data better with respect to f.o.
- Correct physical behaviour at small q_T recovered

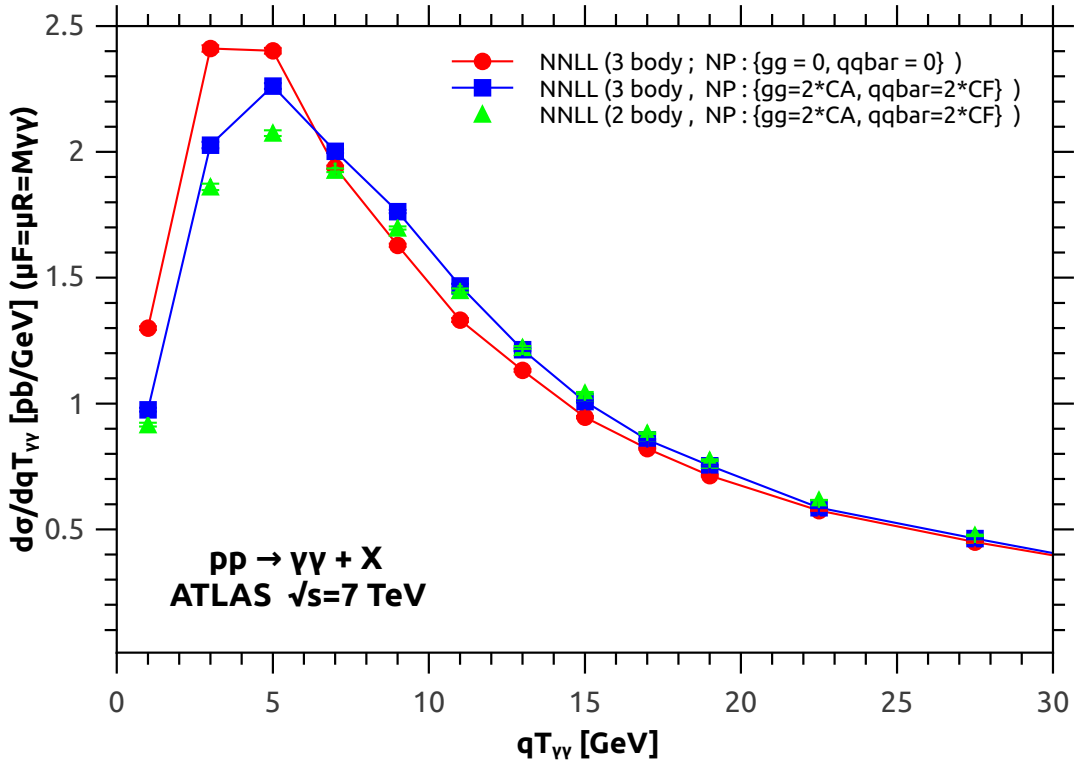
Results: ATLAS comparison - resummation

- We estimated the impact of a possible NP contribution by using a simple parametrization

$$S^a_{NP} = \exp(-C_a g_{NP} b^2)$$
$$a = q, g, \;\; C_q \equiv C_F, \;\; C_g \equiv C_A$$

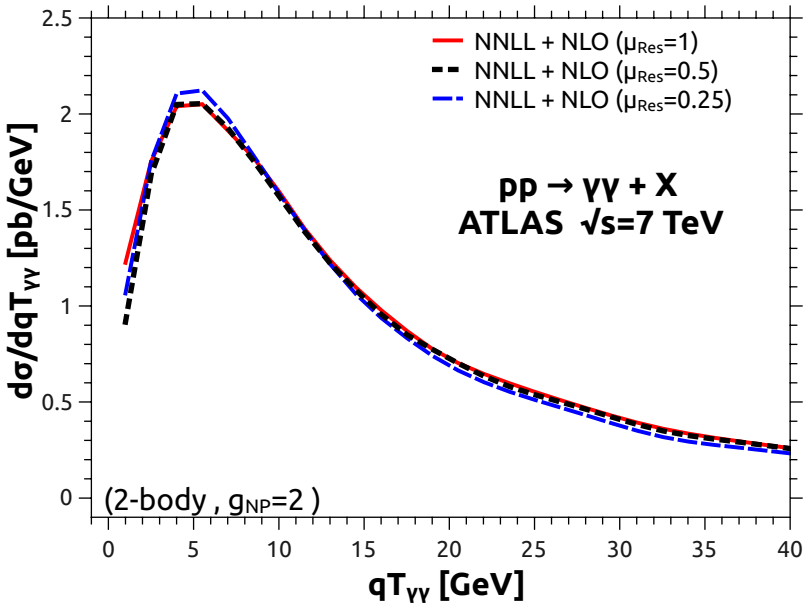
- The resummation formula is fully differential in the final partons phase space Ω. Can be used to make prediction for different distributions, not just q_T (accuracy is no longer formally NNLL).
- Describing the photon phase space presents an ambiguity due to a kinematic mismatch (H_c^F has Born kinematics). This can be parametrized [Catani,De Florian,Ferrera,Grazzini] 1507.06937 and is an additional source of TH error

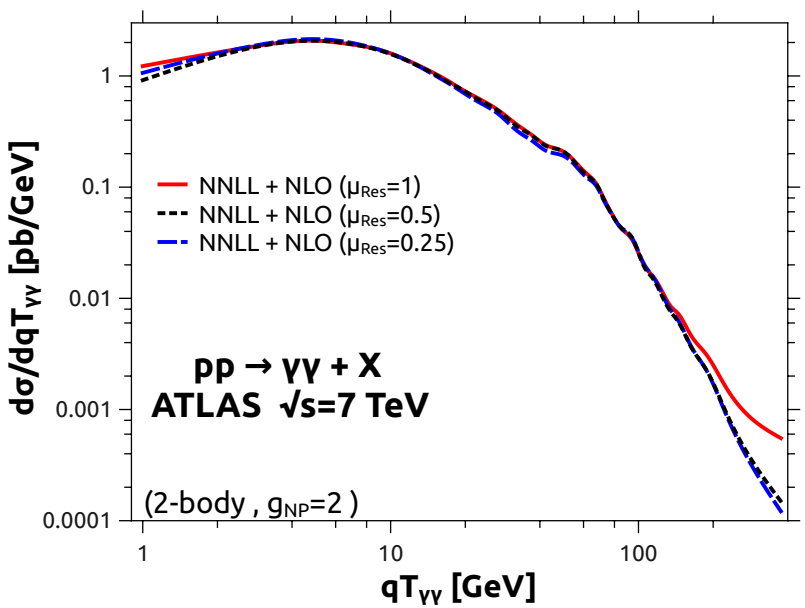
Results: ATLAS comparison - resummation



- Uncertainty due to NP and phase space parametrization. As expected, they are subdominant with respect to scale variation (comparable for very small q_T)

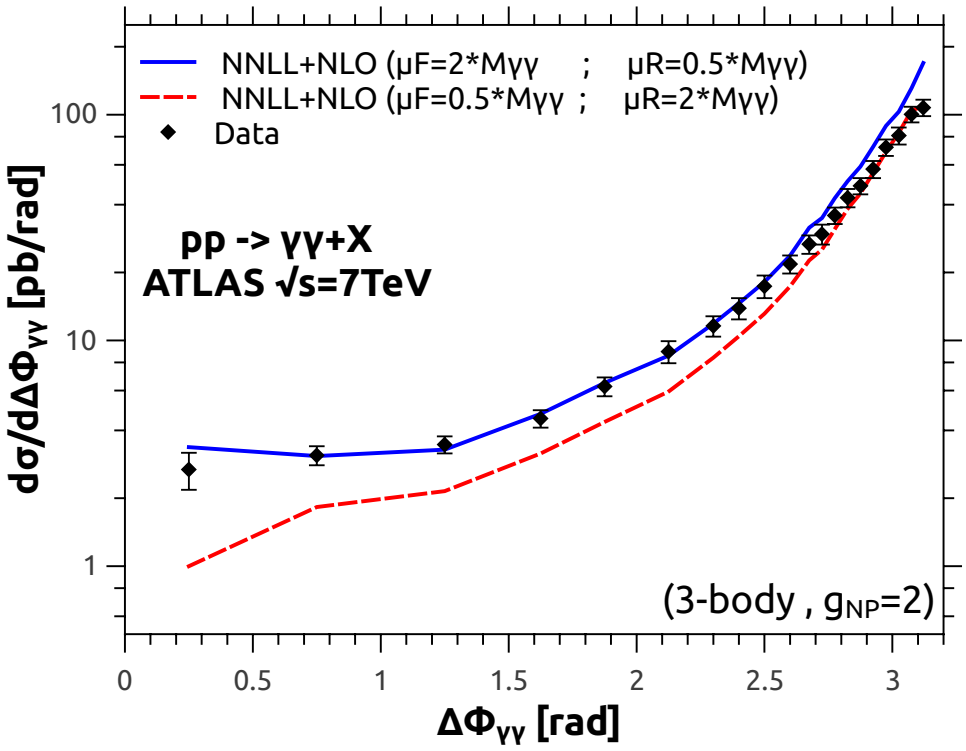
Results: ATLAS comparison - resummation

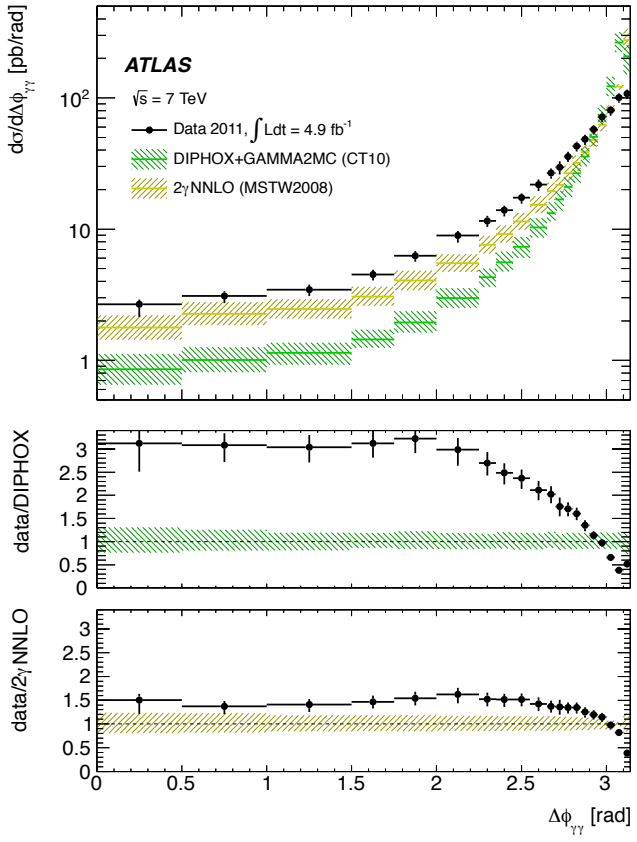




- Uncertainty due to resummation scale Q variation; very much subdominant with respect to μ_R and μ_f.

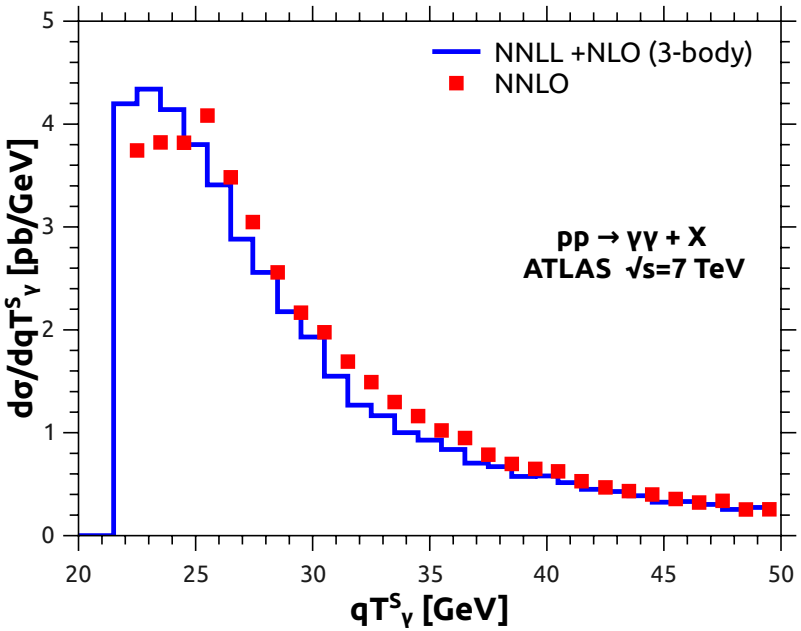
Results: ATLAS comparison - resummation

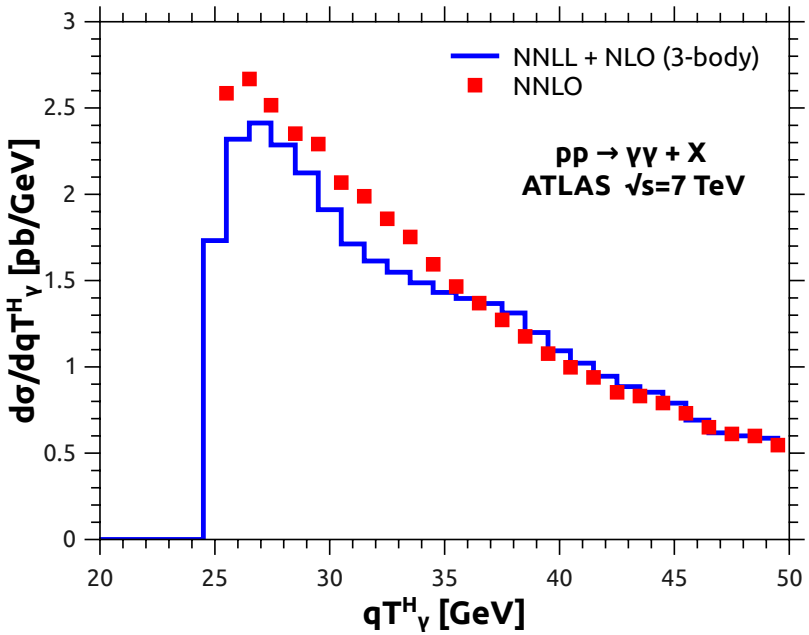




- The data-theory agreement is improved also for non-q_T observables

Results: resummation





- More exclusive observables: individual photon q_T (without data).

Conclusions

- q_T resummation is a powerful tool for making accurate pQCD predictions for multi-scale observables
- The formalism is well-developed, flexible and mostly process-independet
- Sources of theoretical error are understood and under control
- For diphoton production, resummation improves agreement with experimental data over the whole q_T range
- The same set-up can be used to make predictions for different observables