Precise predictions for photon pair production at the LHC

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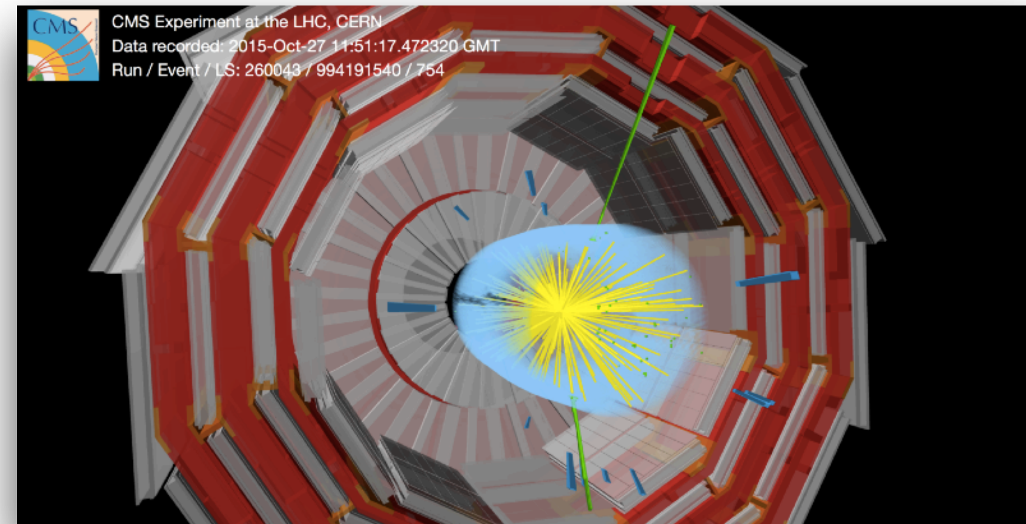
Panic 2021 - 8th September 2021

Photon pair production process

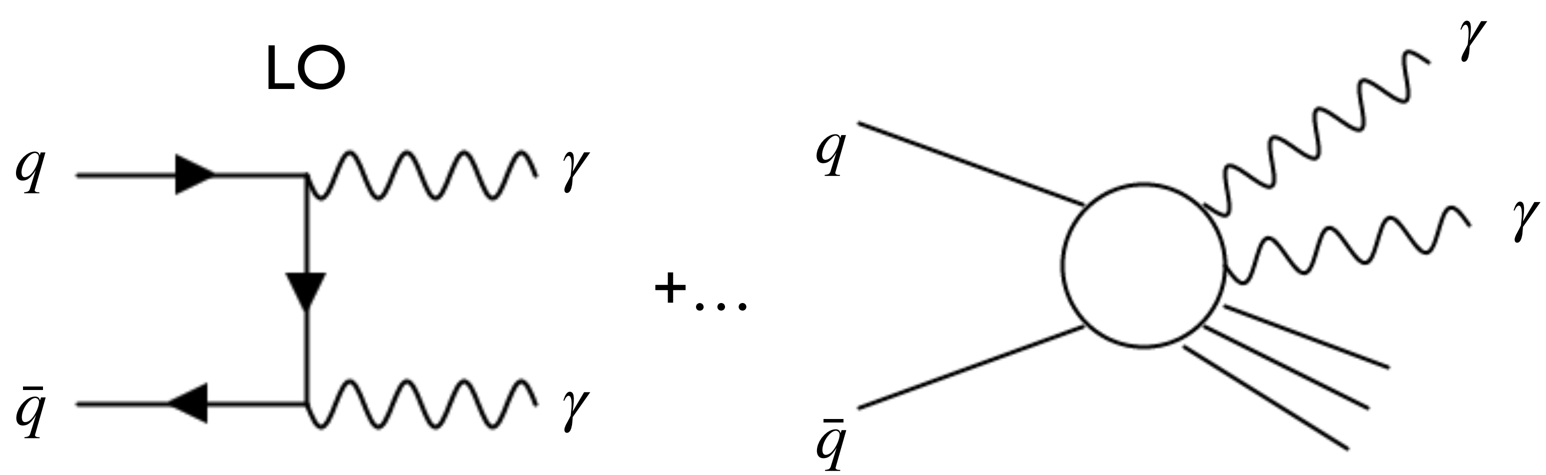
- Production of a pair of "isolated" photons is one of the most interesting processes at the LHC



- Boosted by the discovery of the Higgs boson via its decay mode into two photons
- Experimentally clean final state and high production rate
- Search for new heavy resonances in the diphoton invariant mass spectrum

LO

$$pp \to \gamma\gamma + X$$

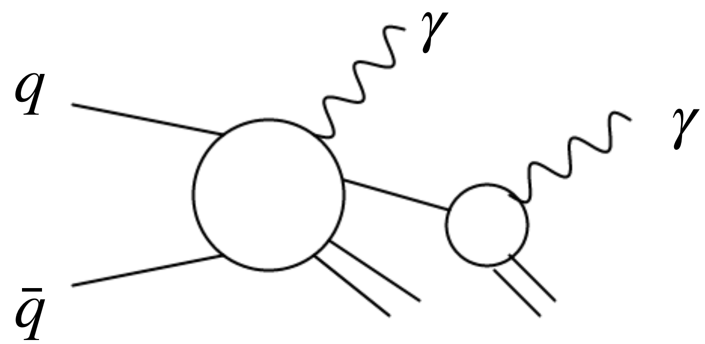


Direct Component

- LO contribution is already divergent due to collinear QED singularities, kinematical cuts are required ($p_T^{\gamma_h} > p_T^{\gamma_h\,\mathrm{cut}}$ and $p_T^{\gamma_s} > p_T^{\gamma_s\,\mathrm{cut}}$)

Photon Isolation

- Second production mechanism: (non perturbative) fragmentation process of a quark or a gluon into a photon. Very different signature compared to direct photon production



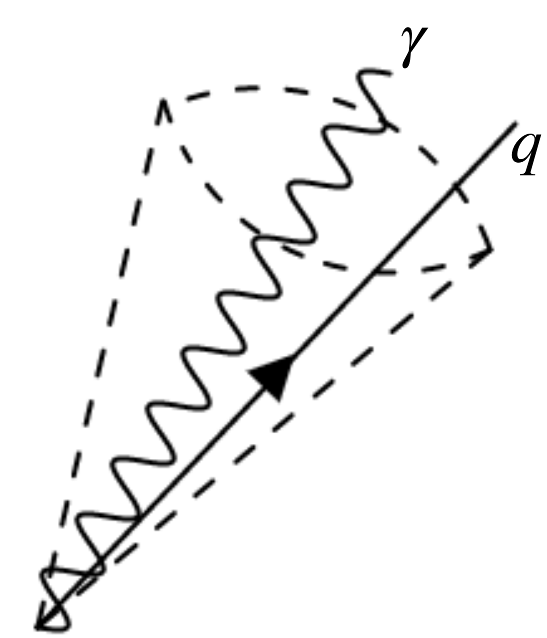
Fragmentation contribution
[Binoth, Guillet, Pilon, Werlen `02]

- Separate direct photons from the rest of the hadrons in the event via Isolation procedures:

  - Fixed-cone and Smooth-Cone isolation [Frixione `98]: initial cone with fixed radius R_{iso} + a series of smaller sub-cones with radius $r \leq R_{\text{iso}}$ are considered $R_{\text{iso}}^2 = (y - y_\gamma)^2 + (\phi - \phi_\gamma)^2$

$$E_T^{\text{had}}(r) \leq E_T^{\max}\,\chi(r; R_{\text{iso}})\,, \quad \text{for all sub-cones with } r \leq R_{\text{iso}}$$

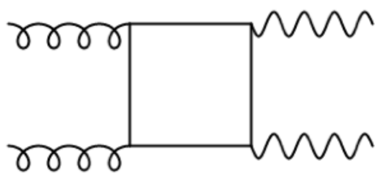
$$\chi(r; R_{\text{iso}}) \to 0, \quad r \to 0 \qquad \chi(r; R_{\text{iso}}) = \left(\frac{1-\cos r}{1-\cos R_{\text{iso}}}\right)^n$$



  - Smooth-cone: removes the fragmentation component and quark-photon collinear QED divergences (direct well defined).
    But ALL experimental analyses use a fixed-cone isolation algorithm! → Hybrid isolation

Available theoretical calculations

- DIPHOX Full NLO for direct and fragmentation contribution + Box contribution [Binoth, Guillet, Pilon, Werlen `02]



- 2γNNLO NNLO with q_T subtraction method [Catani, Cieri, de Florian, Ferrera, Grazzini `12]
  MATRIX NNLO with q_T subtraction method [Grazzini, Kallweit, Wiesemann `17]

- MCFM NNLO with N-jettiness subtraction [Campbell, Ellis, Li, Williams `16]

- NNLOJET NNLO via Antenna subtraction [Gehrmann, Glover, Huss, Whitehead `20]

- Resummation of the small transverse momentum of the photon pair: NNLL RESBOS, 2γRes, reSolve
  N^{3}LL CuTe-MCFM, MATRIX+RadISH

- EW Corrections [A. Bierweiler, T. Kasprzik and J. H. Kuehn `13], [M. Chiesa, N. Greiner, M. Schoenherr and F. Tramontano `17]

- Event generation at NLO matched to PS: SHERPA [Hoeche, Schumann, Siegert `09], HERWIG [Corcella et al. `01], POWHEG [L. D'Errico, P. Richardson `11]

- GENEVA event generation at NNLO+NNLL` accuracy with N-jettiness subtraction matched to PS [S.Alioli, AB, A.Gavardi, S.Kallweit, M.Lim, R.Nagar, D.Napoletano, L.Rottoli `20] JHEP 04 (2021) 041

N-Jettiness and Factorization

- N-jettiness resolution variables: given an M-particle phase space point with $M \geq N$

$$\mathcal{T}_N(\Phi_M) = \sum_k \min\{\hat{q}_a \cdot p_k, \hat{q}_b \cdot p_k, \hat{q}_1 \cdot p_k, \ldots, \hat{q}_N \cdot p_k\}$$

- The limit $\mathcal{T}_N \to 0$ describes a N-jet event where the unresolved emissions can be either soft or collinear to the final state jets or initial state beams

- Color singlet final state, relevant variable is 0-jettiness aka “beam thrust”

$$\mathcal{T}_0 = \sum_k |\vec{p}_{kT}|\, e^{-|\eta_k - Y|}$$

- Cross section factorizes in the limit $\mathcal{T}_0 \to 0$ [Stewart, Tackmann,Waalewijn `09,`10], three different scales arise

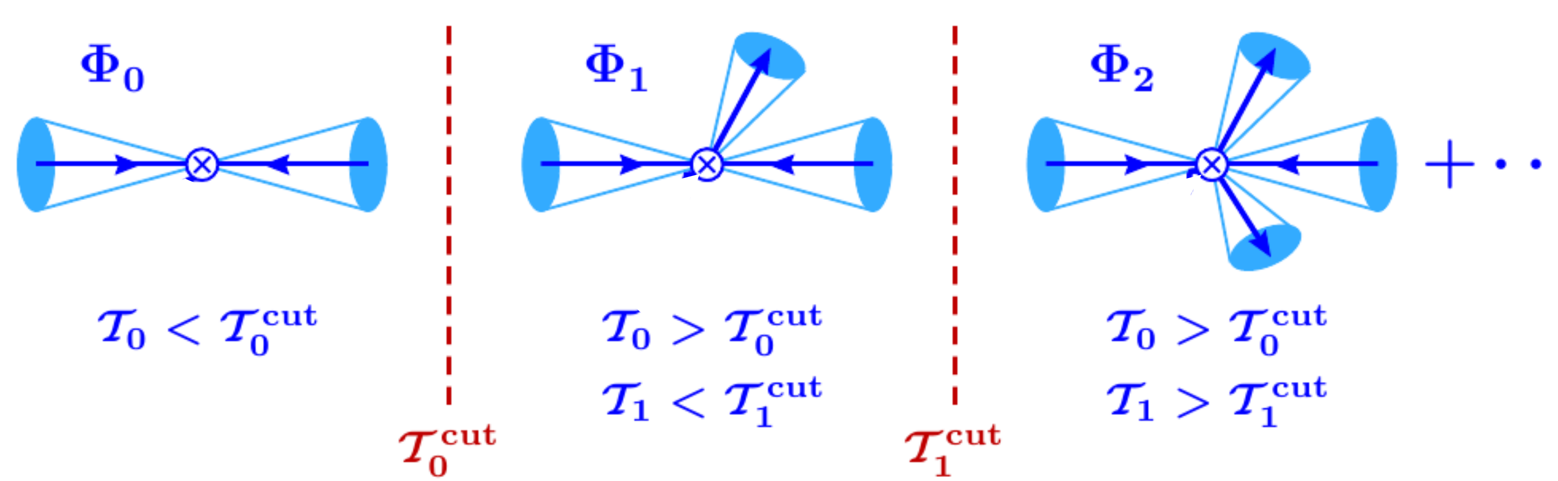
$$\mu_H = Q, \quad \mu_B = \sqrt{Q\mathcal{T}_0}, \quad \mu_S = \mathcal{T}_0$$

$$\begin{aligned}\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0} = \sum_{ij} & \overset{\text{NNLO}}{\boxed{H_{ij}^{\gamma\gamma}(Q^2, t, \mu_H)}} U_H(\mu_H, \mu) \left\{ \left[\overset{\text{NNLO}}{\boxed{B_i(t_a, x_a, \mu_B)}} \otimes U_B(\mu_B, \mu) \right] \right. \\ & \left. \times \left[\boxed{B_j(t_b, x_b, \mu_B)} \otimes U_B(\mu_B, \mu) \right] \right\} \otimes \left[\underset{\text{NNLO}}{\boxed{S(\mu_s)}} \otimes U_S(\mu_S, \mu) \right]\end{aligned}$$

Monte Carlo implementation

- GENEVA [Alioli,Bauer,Berggren,Tackmann, Walsh `15], [Alioli,Bauer,Tackmann,Guns `16], [Alioli,Broggio,Lim, Kallweit,Rottoli `19],[Alioli,Broggio,Gavardi,Lim,Nagar,Napoletano,Kallweit,Rottoli `20] combines 3 theoretical tools that are important for QCD predictions into a single framework
  - fully differential fixed-order calculations, up to NNLO via 0-jettiness subtraction
  - up to NNLL` resummation for 0-jettiness in SCET
  - shower and hadronize events (PYTHIA8)
- IR-finite definition of events based on resolution parameter $\mathcal{T}_0^{\mathrm{cut}}$
- Associate differential cross sections to events such that the 0-jet events are NNLO accurate and 0-jettiness is resummed to NNLL` accuracy

$$
\begin{aligned}
\Phi_0 \text{ events:} \quad & \frac{d\sigma_0^{\mathrm{MC}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\,, \\
\Phi_1 \text{ events:} \quad & \frac{d\sigma_1^{\mathrm{MC}}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}})\,, \\
\Phi_2 \text{ events:} \quad & \frac{d\sigma_{\geq 2}^{\mathrm{MC}}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}})
\end{aligned}
$$



GENEVA http://geneva.physics.lbl.gov

Monte Carlo implementation

0-jet events

$$\frac{\mathrm{d}\sigma_0^{\mathrm{MC}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\,\theta_{\mathrm{iso}}^{\mathrm{PS}}(\Phi_0) + \frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$

$$\frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \left\{\frac{\mathrm{d}\sigma_0^{\mathrm{NNLO}_0}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\right]_{\mathrm{NNLO}_0}\right\}\theta_{\mathrm{iso}}^{\mathrm{PS}}(\Phi_0)$$

At $\mathcal{O}(\alpha_s^2)$ assumed exact cancellation between NNLO and resummed expanded singular contributions

≥ 1-jet events (Split between 1 and ≥ 2 events via $\mathcal{T}_1$ resolution variable)

$$\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}\mathcal{P}(\Phi_1)\theta\left(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}\right)\,\theta_{\mathrm{iso}}^{\mathrm{PS}}(\Phi_1)\theta_{\mathrm{iso}}^{\mathrm{proj}}(\tilde{\Phi}_0) + \frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{nons}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

$$\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{nons}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{NLO}_1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})\,\theta_{\mathrm{iso}}^{\mathrm{PS}}(\Phi_1) - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}\mathcal{P}(\Phi_1)\right]_{\mathrm{NLO}_1}\theta_{\mathrm{iso}}^{\mathrm{PS}}(\Phi_1)\,\theta_{\mathrm{iso}}^{\mathrm{proj}}(\tilde{\Phi}_0)\,\theta\left(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}\right)$$

Diphoton+jet at NLO.
Divergent for
$\mathcal{T}_0 \to 0$

Resummed Expanded
Divergent for
$\mathcal{T}_0 \to 0$

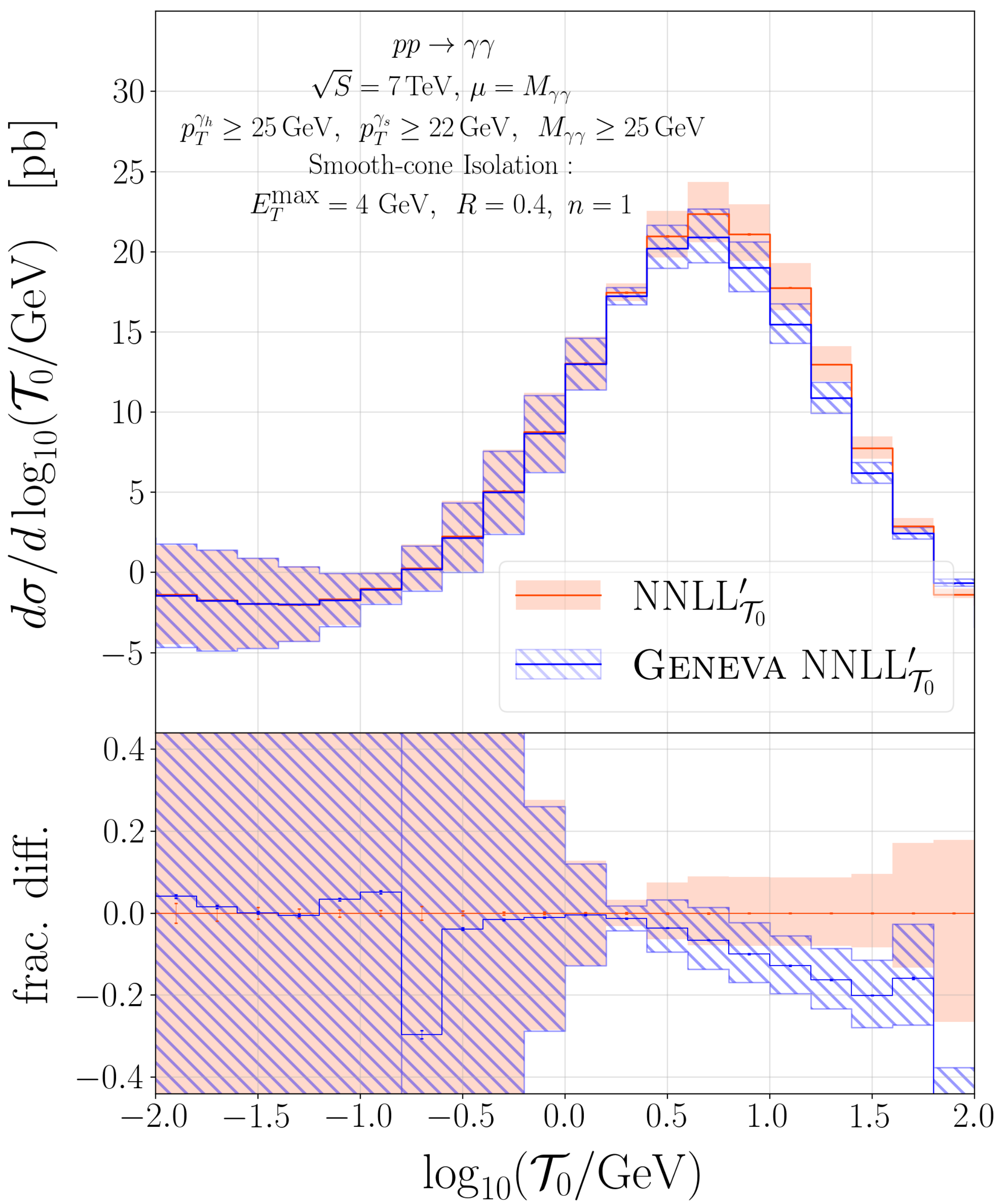
$P(\Phi_1)$ splitting function

$$\int \frac{d\Phi_1}{d\Phi_0 dT_0} P(\Phi_1) = 1$$

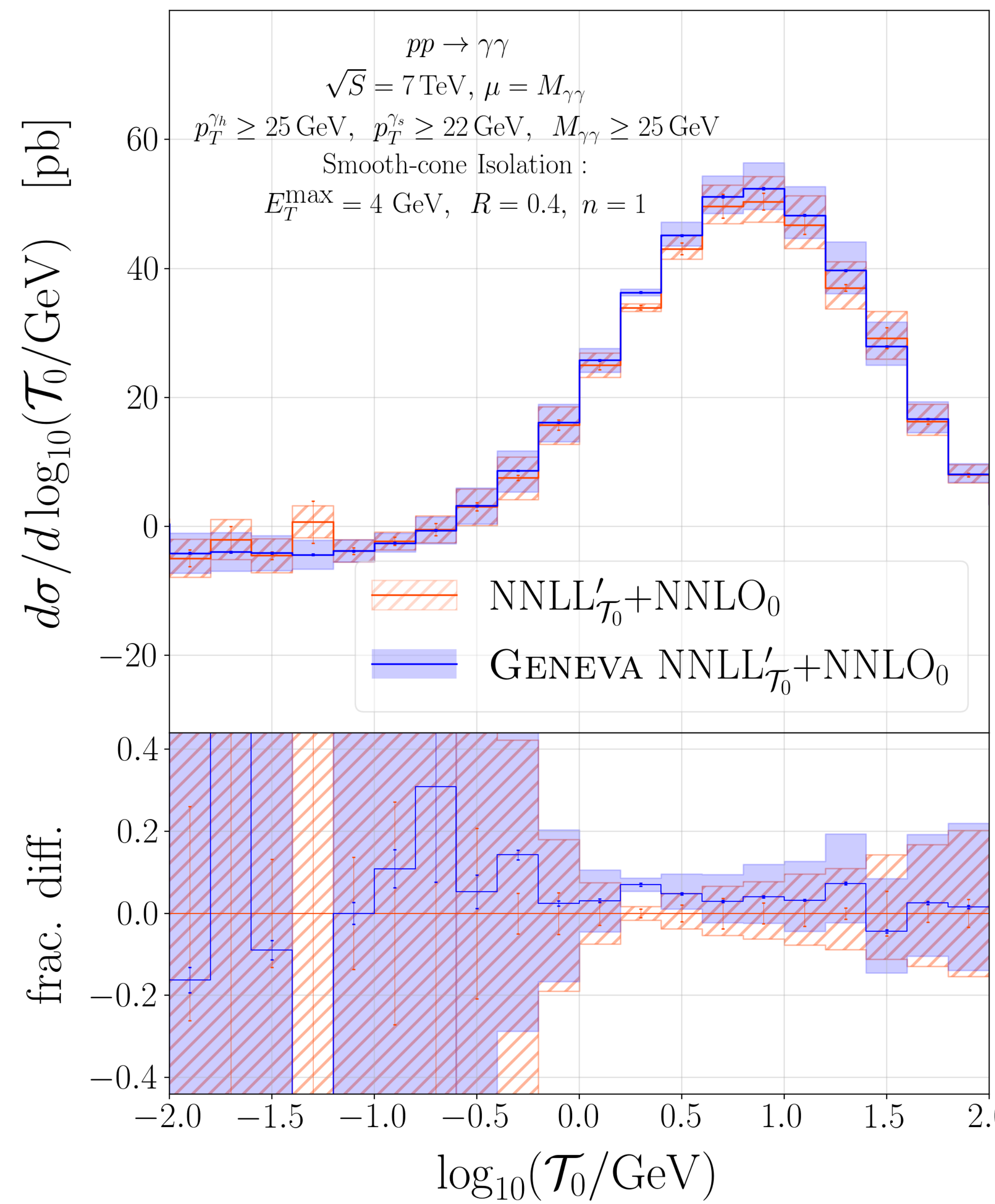
The sum is a non singular contribution

Monte Carlo implementation

Geneva is equivalent to standard resummation only in the $\mathcal{T}_0 \to 0$ limit, away from this limit same result only if one cuts on quantities preserved by $\Phi_1 \to \Phi_0$

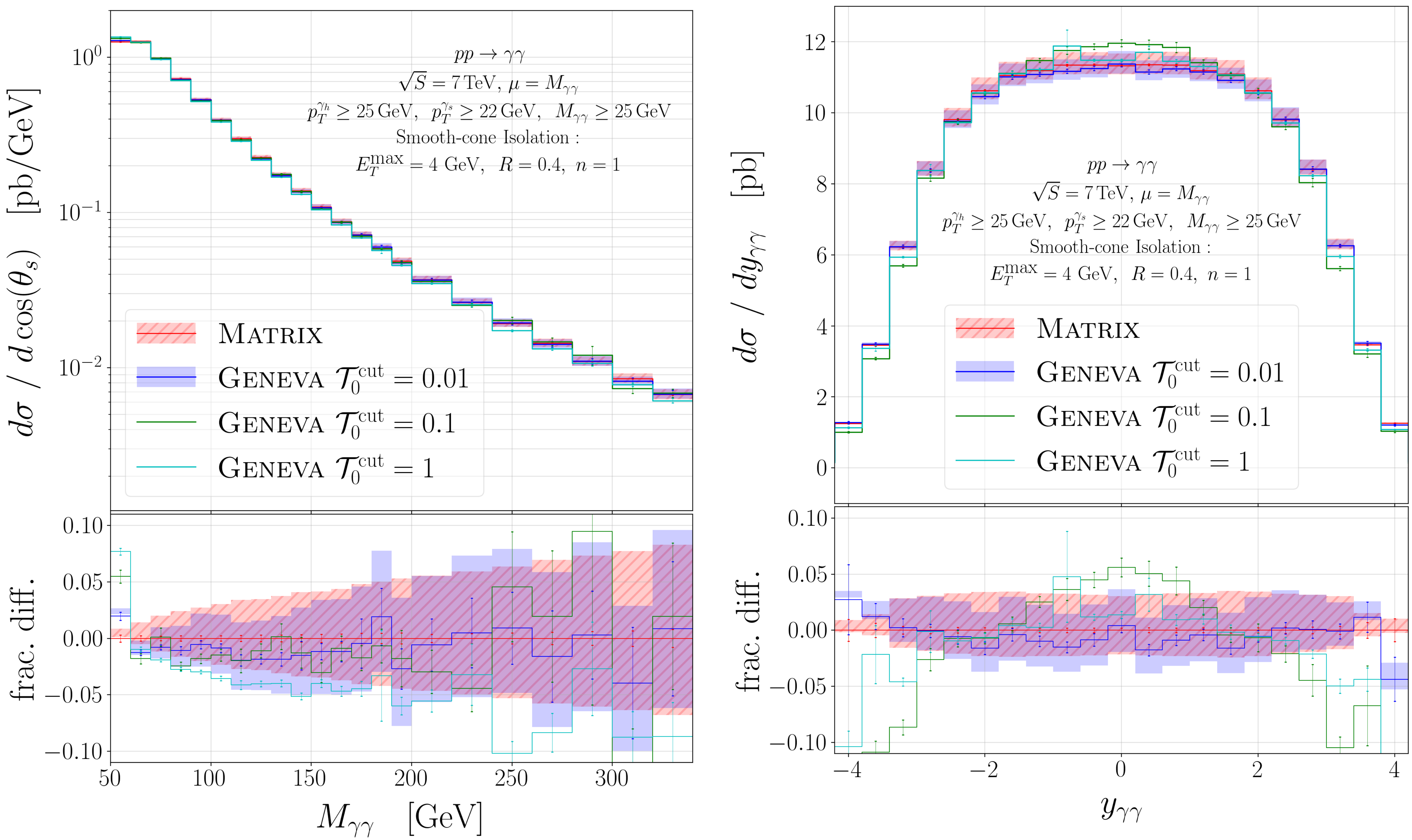


Resummed computation



Matched computation

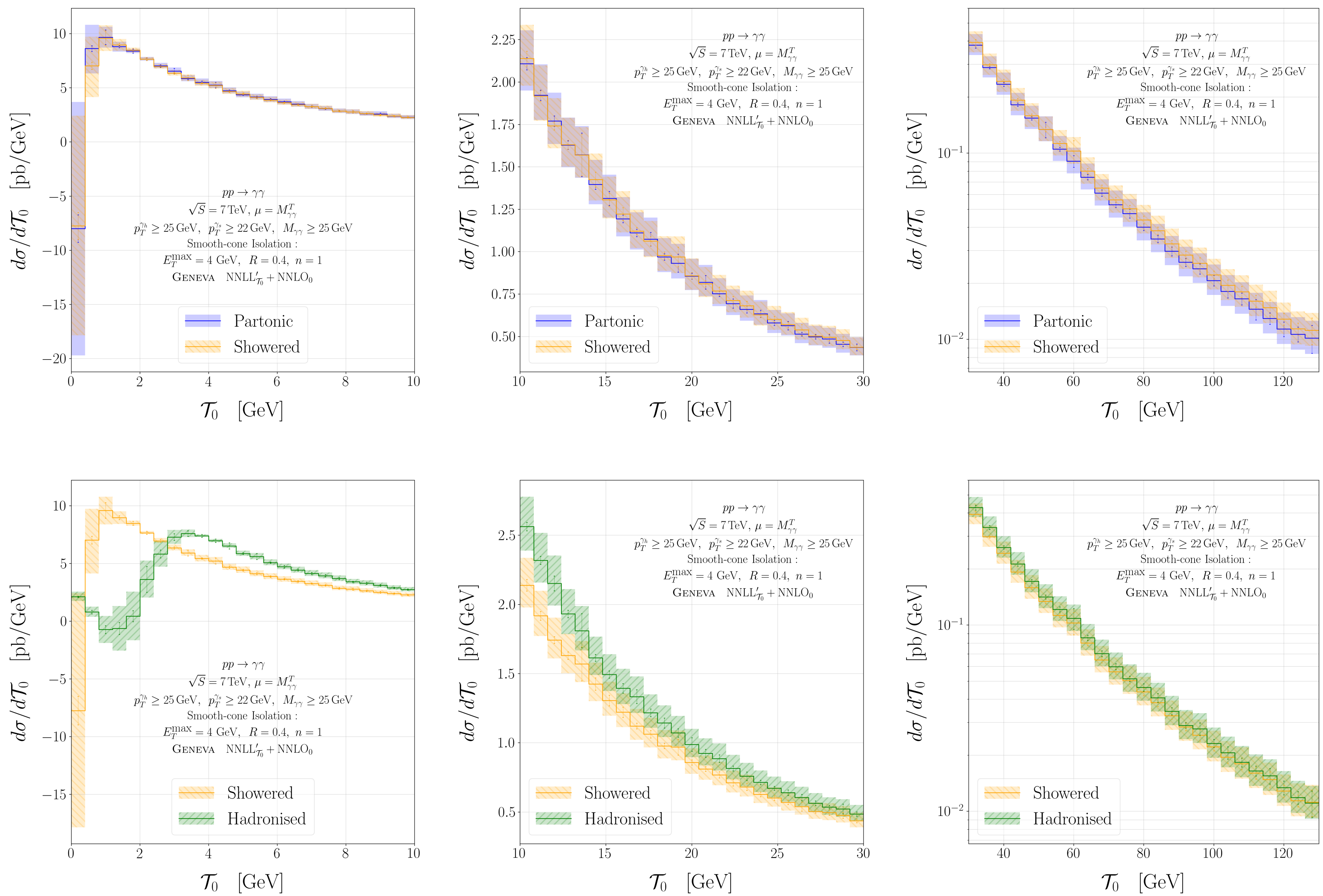
NNLO validation against MATRIX



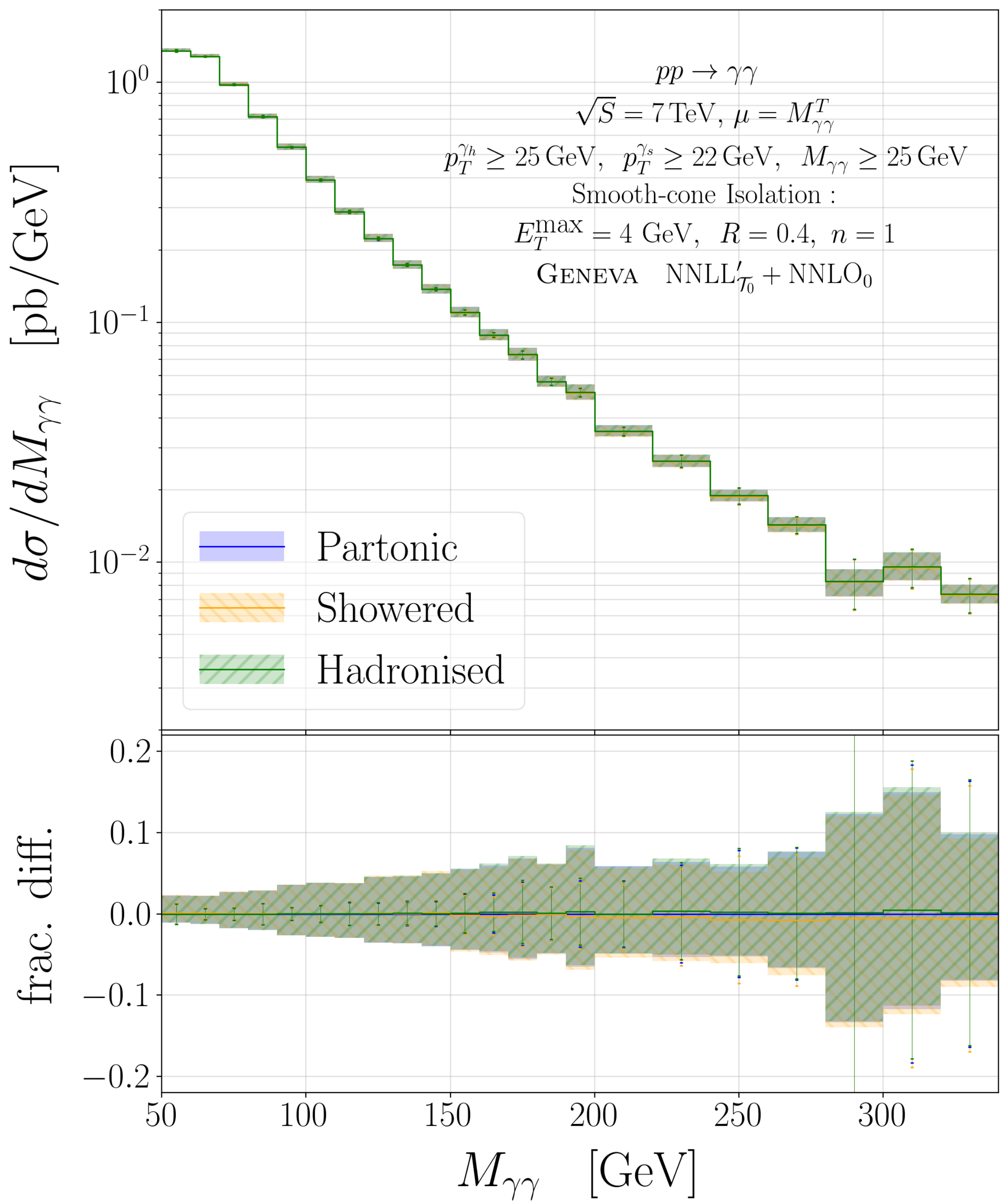
$q\bar{q}$ channel only, good agreement with independent NNLO computation with MATRIX

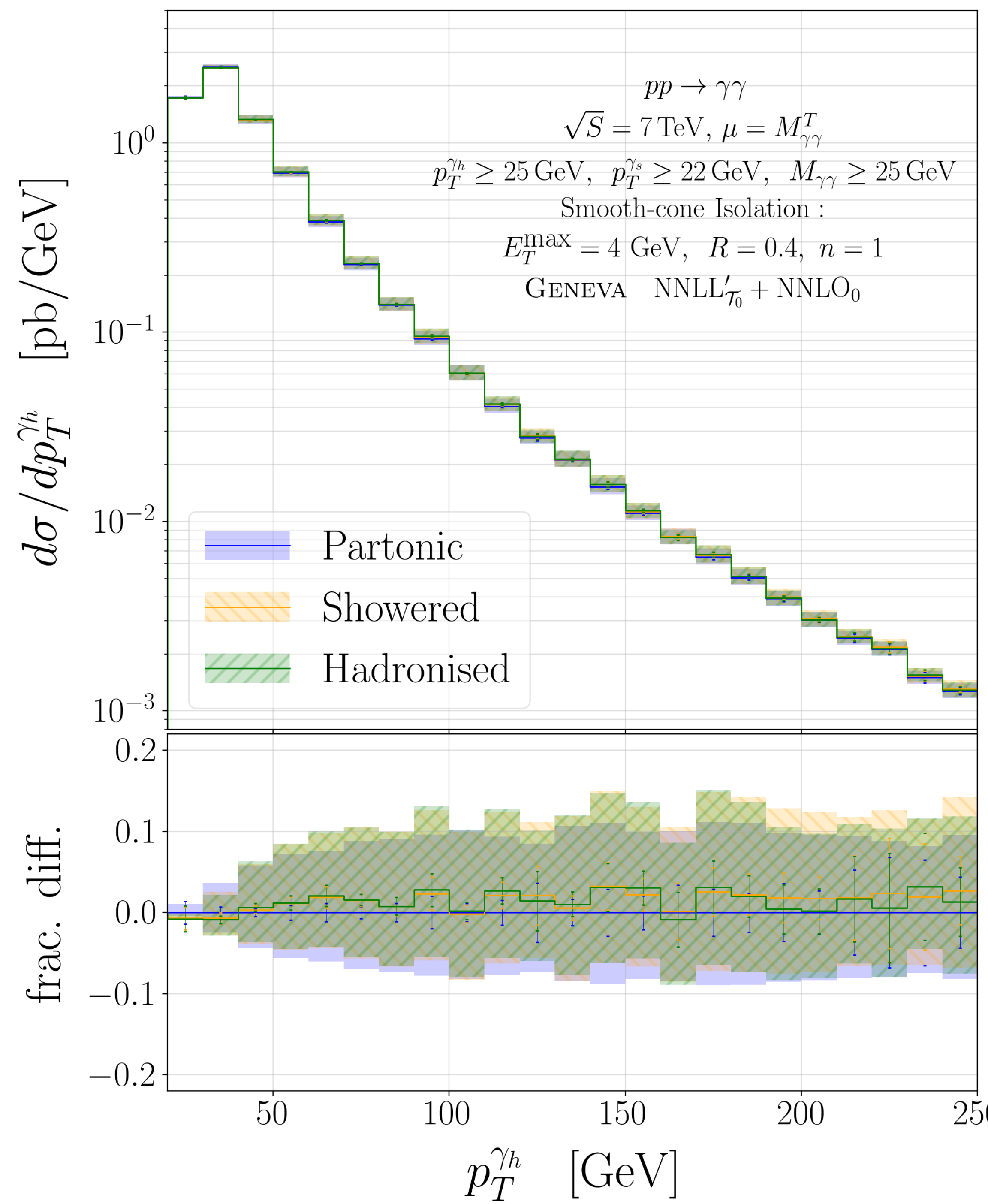
Adding the Shower (PYTHIA8)

- Parton-level result is NNLO+NNLL` accurate
- Parton shower should not affect the accuracy of the cross section reached at partonic level
- Constraints on event definition must be respected
- Accuracy is numerically well-preserved after the shower

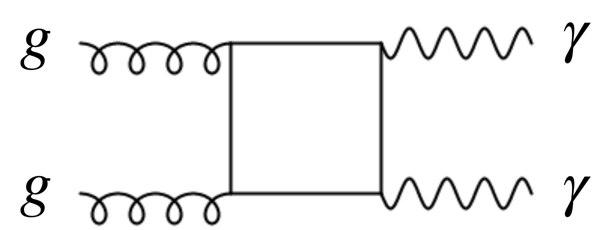


Adding the Shower (PYTHIA8)

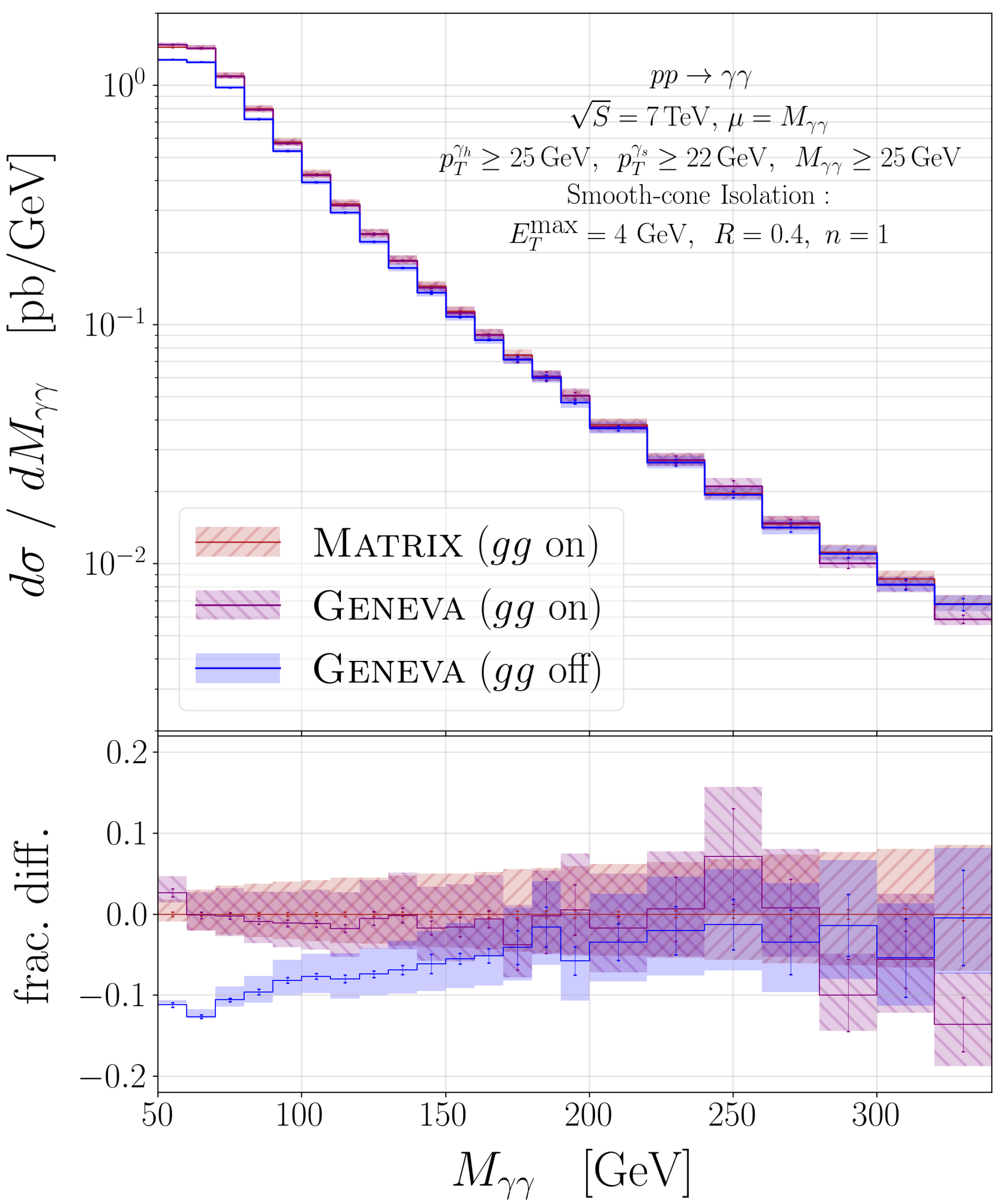


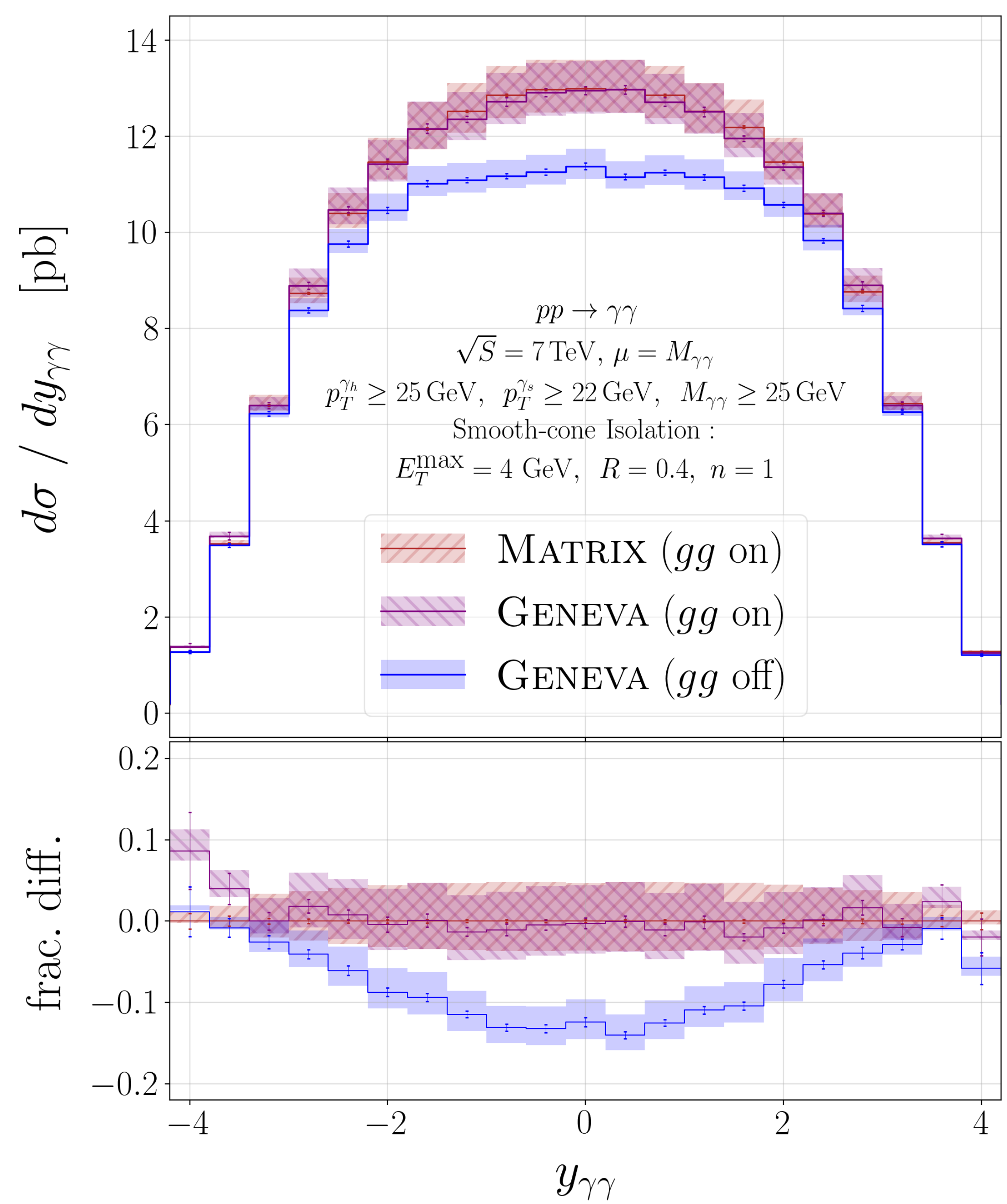


NNLO validation against MATRIX



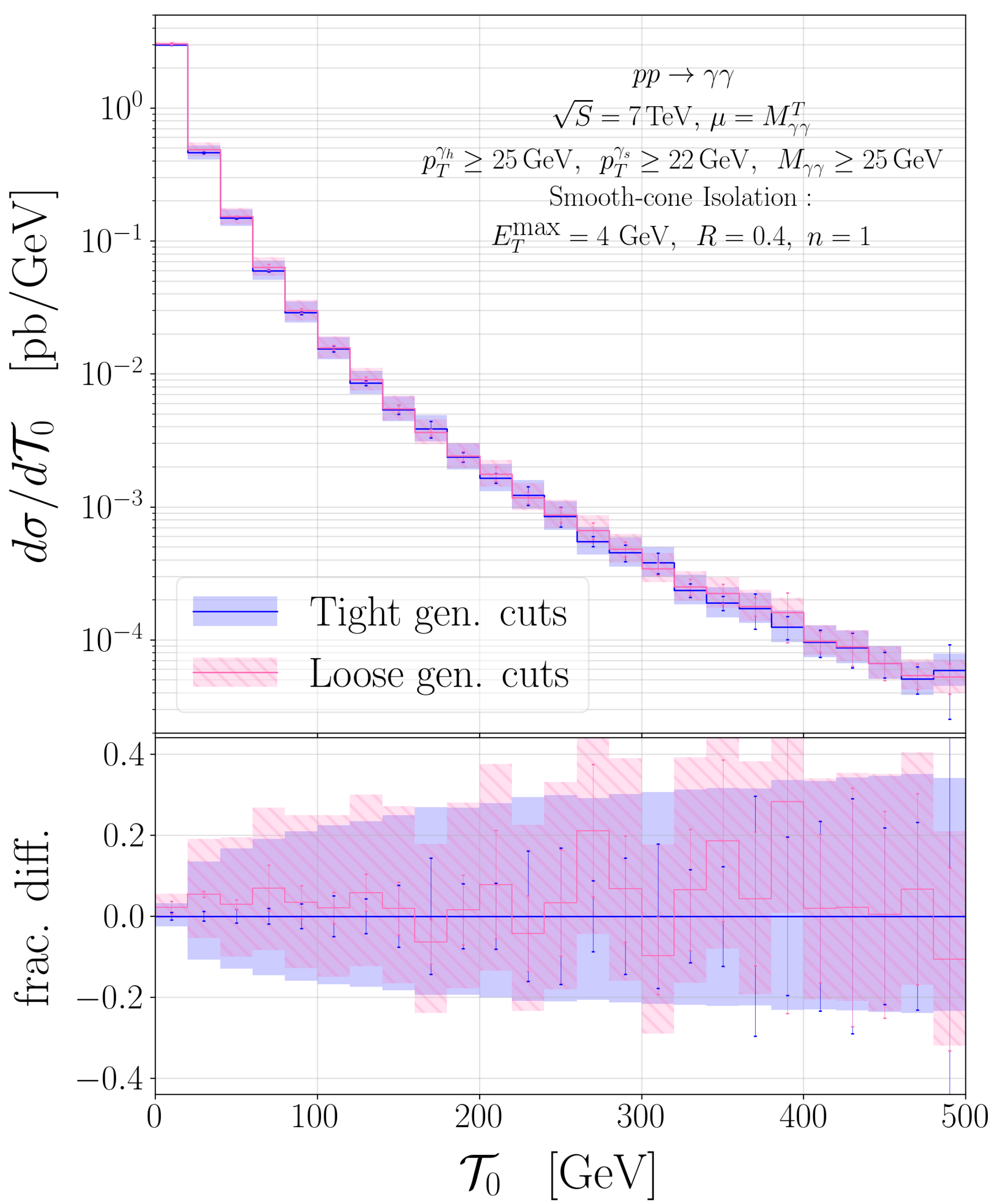
included gg box contribution starts at NNLO, large effect



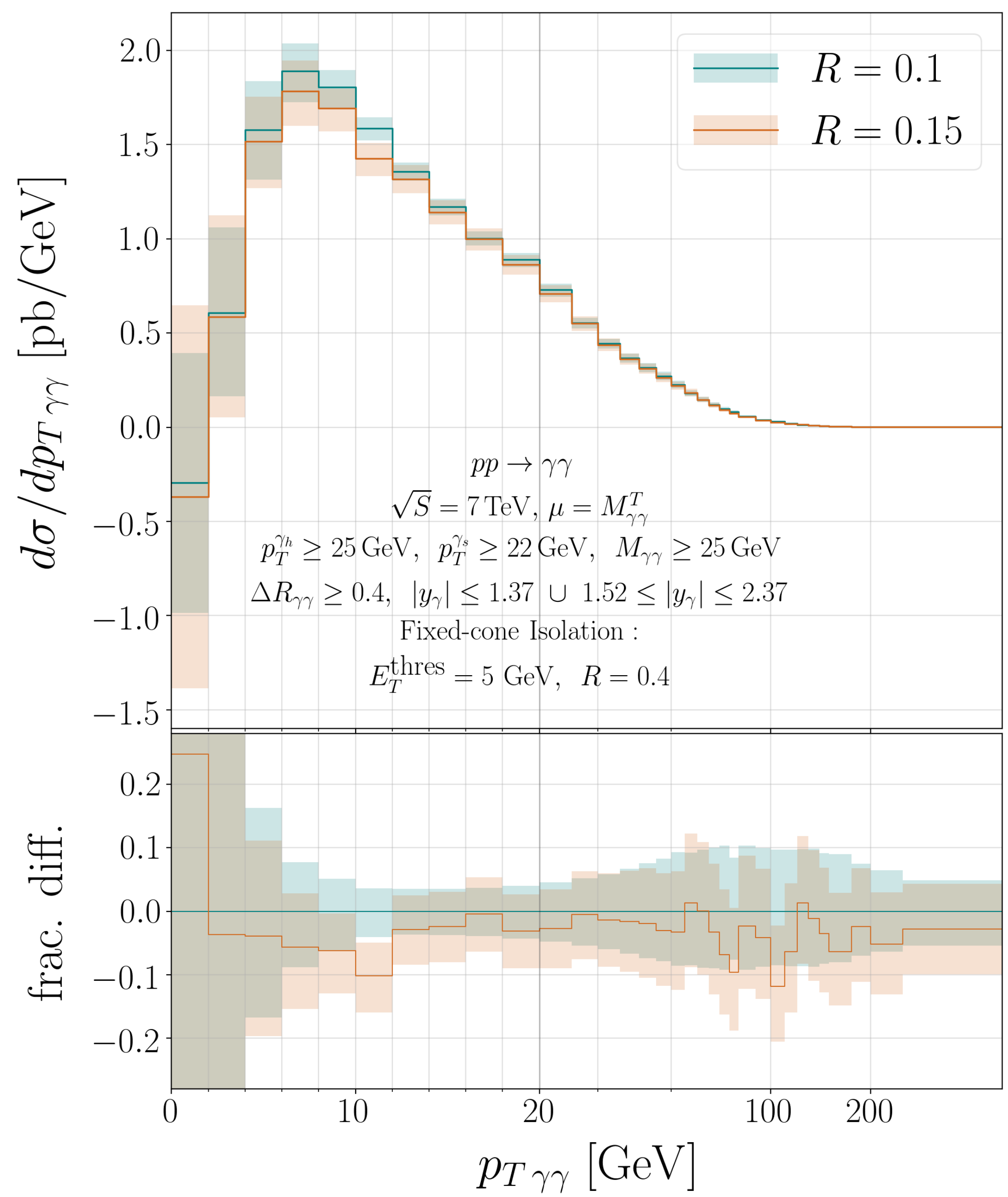


Event Generation and Analysis Cuts

- Study dependence on generation cuts: compare tight generation cuts with loose generation and tight analysis cuts
- Parton level results are not dependent so much on the exact choice
- Shower can reshuffle momenta, larger effects



Partonic

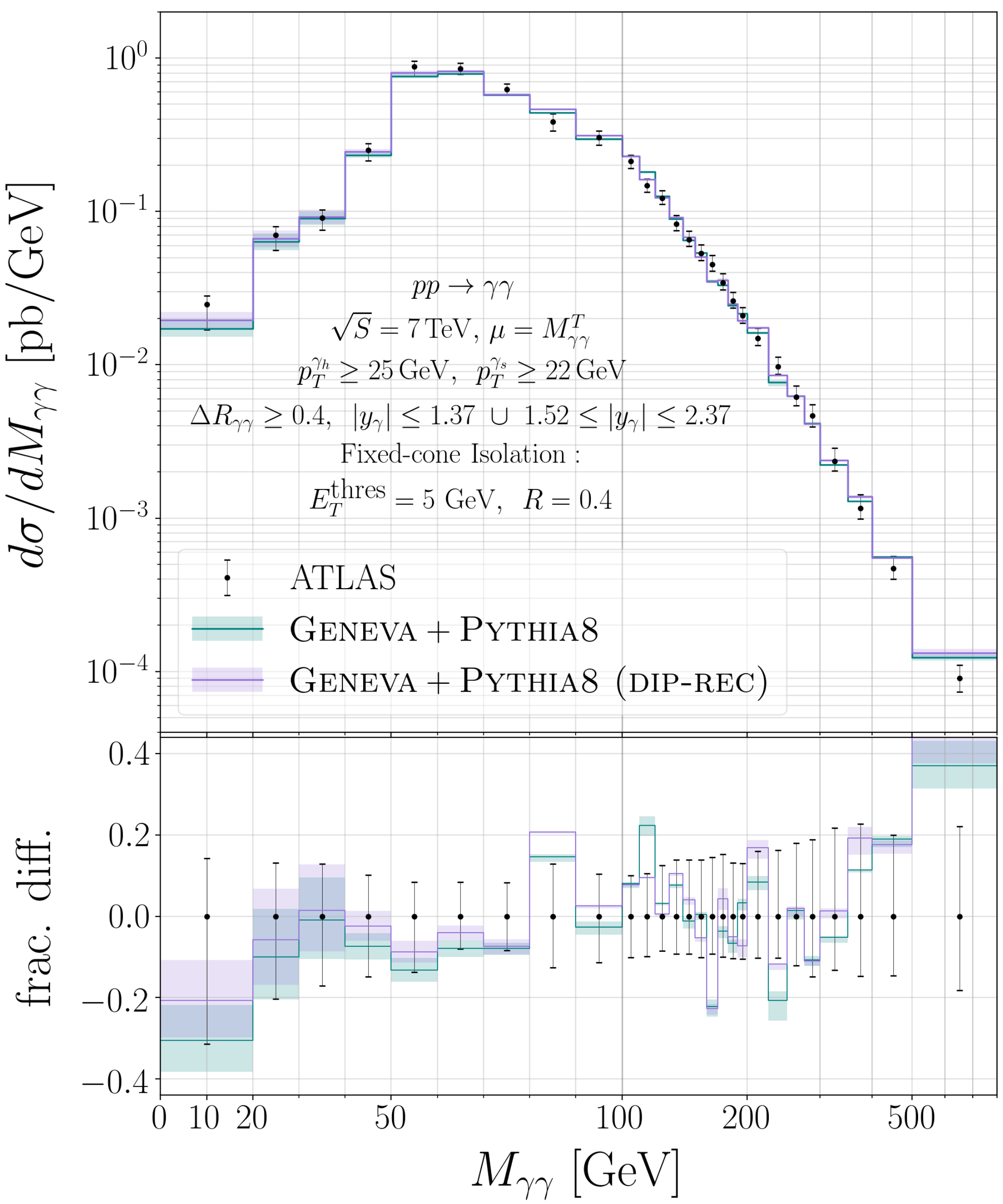


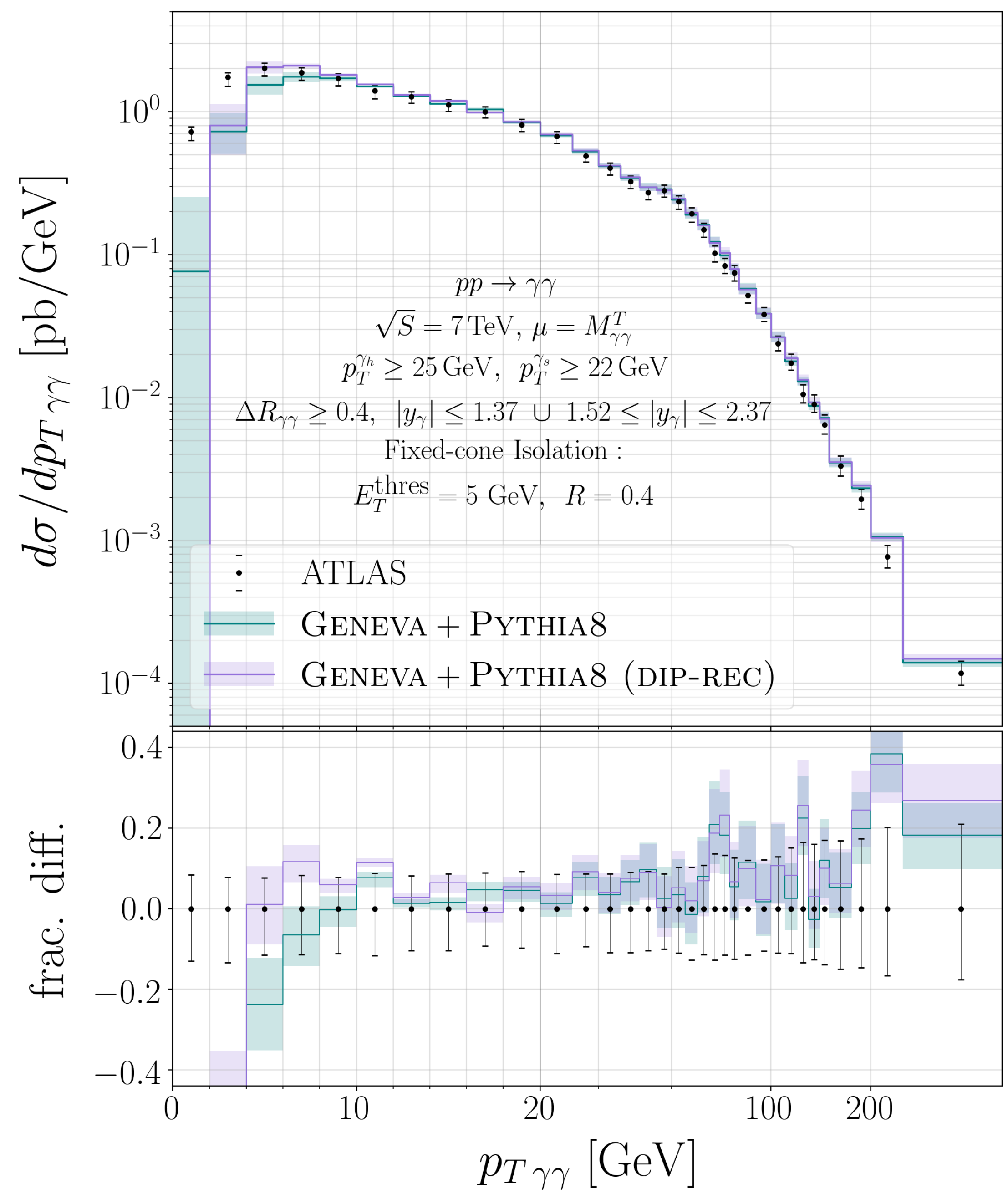
Showered

Comparison to ATLAS data LHC 7 TeV

Hybrid isolation procedure.
Process-defining cuts at generation level

$$p_T^{\gamma_h} \geq 18 \text{ GeV}, \quad p_T^{\gamma_s} \geq 15 \text{ GeV}, \quad M_{\gamma\gamma} \geq 1 \text{ GeV}$$
$$E_T^{\max} = 4 \text{ GeV}, \quad R_{\text{iso}} = 0.1, \quad \text{and} \quad n = 1\,.$$



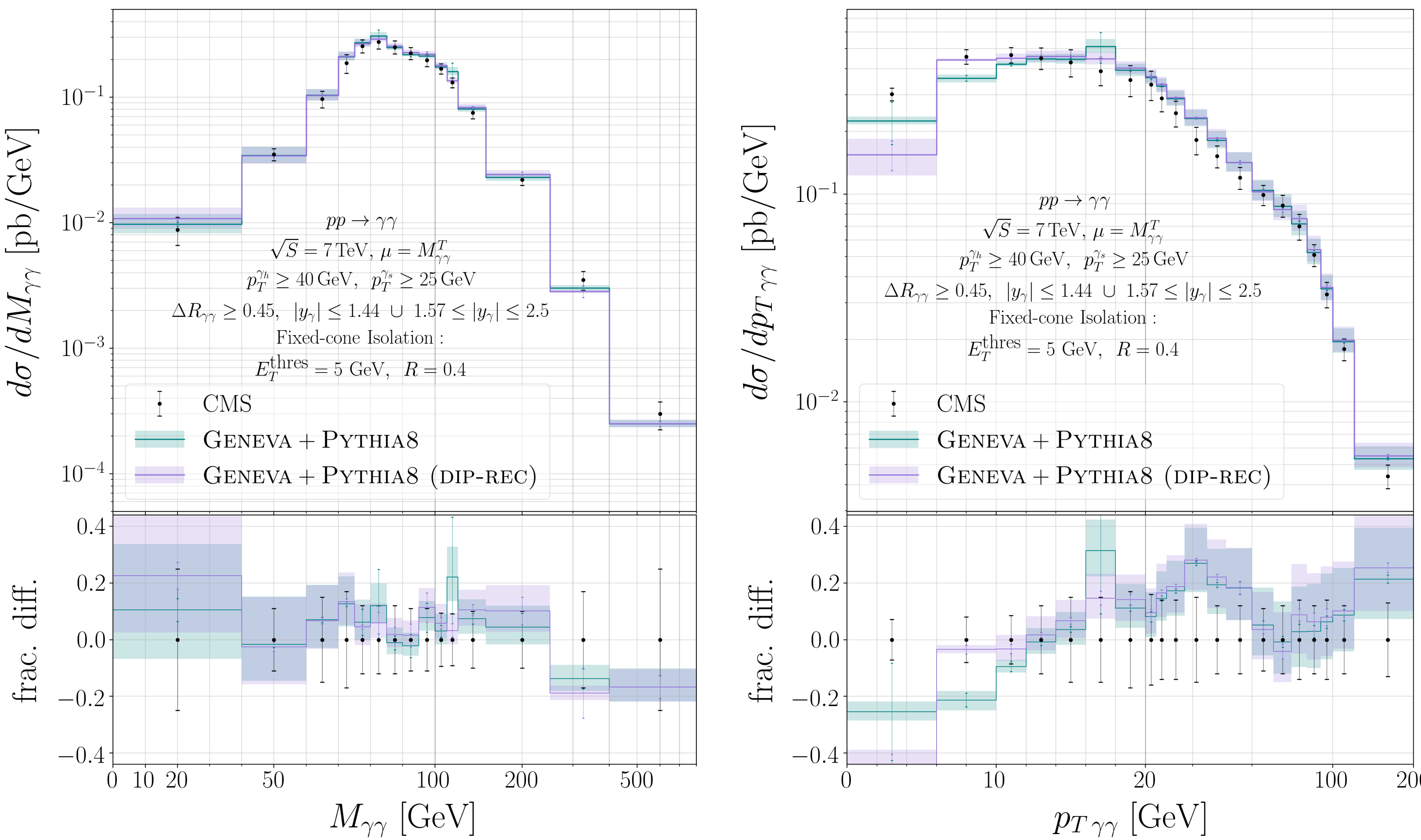


2-loop top massive effects not yet included in qqbar channel. EW effects also important at high $M_{\gamma\gamma}$

ATLAS [arXiv:1211.1913]

Comparison to CMS data LHC 7 TeV

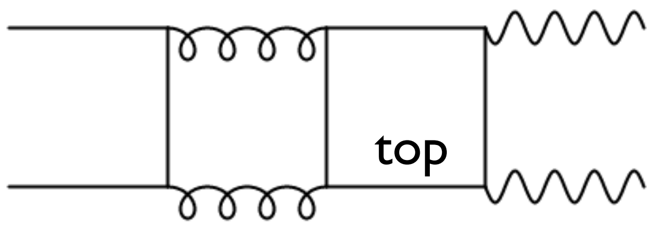
Hybrid isolation procedure (smooth-cone at generation with $R_{\text{iso}} = 0.1$)



CMS [arXiv:1405.7225]

Outlook

- Include massive top quark effects for diphoton production in hard function calculation



- ZZ [arXiv:2103.01214] and $W\gamma$ [arXiv:2105.13214] processes already implemented in GENEVA

- Extend to all diboson (WW, γZ) production processes at the LHC to obtain a better description of exclusive distributions

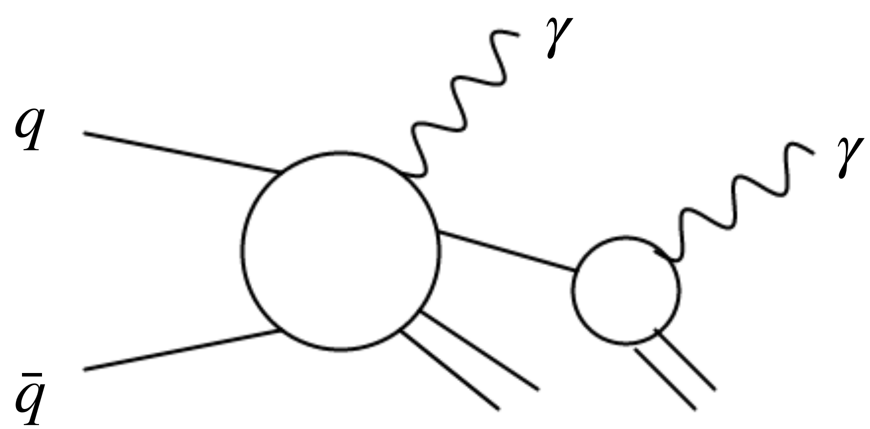
- Inclusion of electroweak corrections

Thank you!

Backup slides

Photon Isolation

- Second production mechanism: (non perturbative) fragmentation process of a quark or a gluon into a photon. Very different signature compared to direct photon production

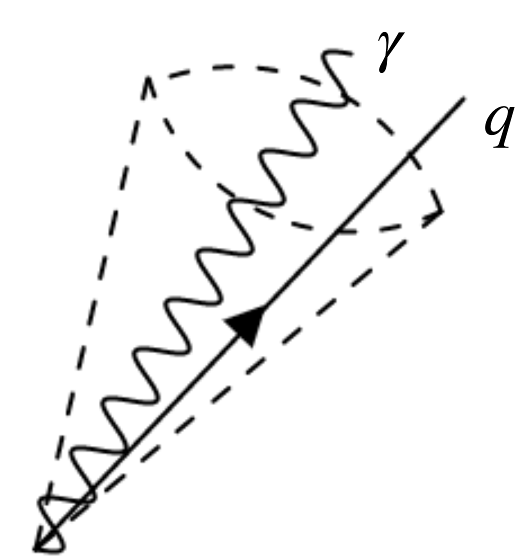


Fragmentation contribution
[Binoth, Guillet, Pilon, Werlen `02]

- Separate direct photons from the rest of the hadrons in the event via Isolation procedures:

  - Fixed-Cone isolation: construct a cone with fixed radius $R_{\rm iso}$ around the photon direction. One then restricts the amount of hadronic energy inside the cone. A photon is considered isolated when $E_T^{\rm had}(R_{\rm iso})$ is smaller than a fixed numerical value $E_T^{\rm thres}$. Sensitive to fragmentation contributions

$$R^2_{\rm iso} = (y - y_\gamma)^2 + (\phi - \phi_\gamma)^2$$



Photon Isolation criteria

- Smooth-Cone isolation [Frixione `98]: initial cone with fixed radius R_{iso} + a series of smaller sub-cones with radius $r \leq R_{\text{iso}}$ are considered

$$E_T^{\text{had}}(r) \leq E_T^{\max}\,\chi(r; R_{\text{iso}})\,, \quad \text{for all sub-cones with } r \leq R_{\text{iso}}$$

isolation function smooth function monotonically decreases and vanishes when the sub-cone radius vanishes

$$\chi(r; R_{\text{iso}}) = \left(\frac{1-\cos r}{1-\cos R_{\text{iso}}}\right)^n$$

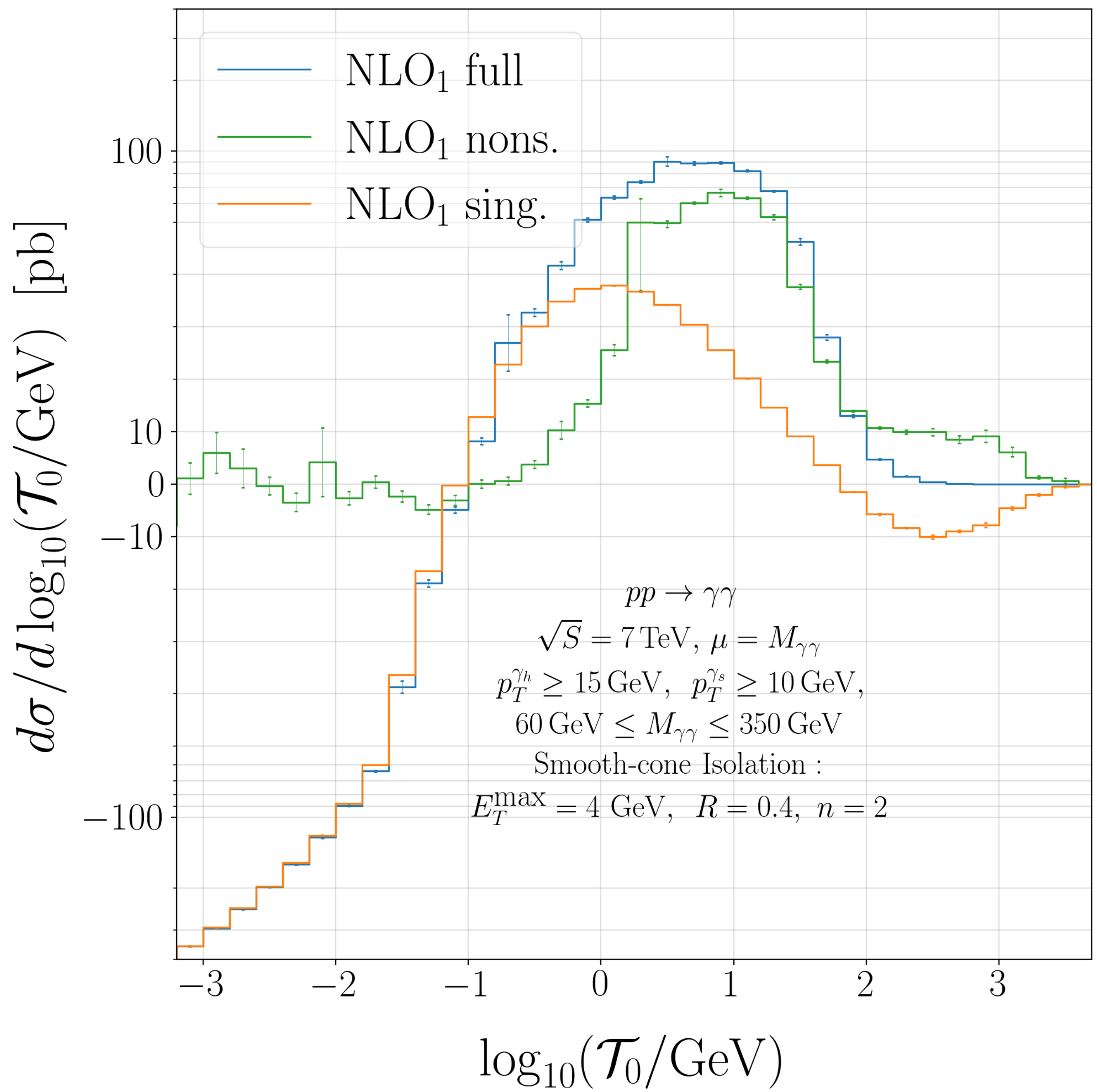
$$\chi(r; R_{\text{iso}}) \to 0, \quad r \to 0$$

- Smooth-cone: removes the fragmentation component and quark-photon collinear QED divergences (direct well defined by itself). But ALL experimental analyses use a fixed-cone isolation algorithm!

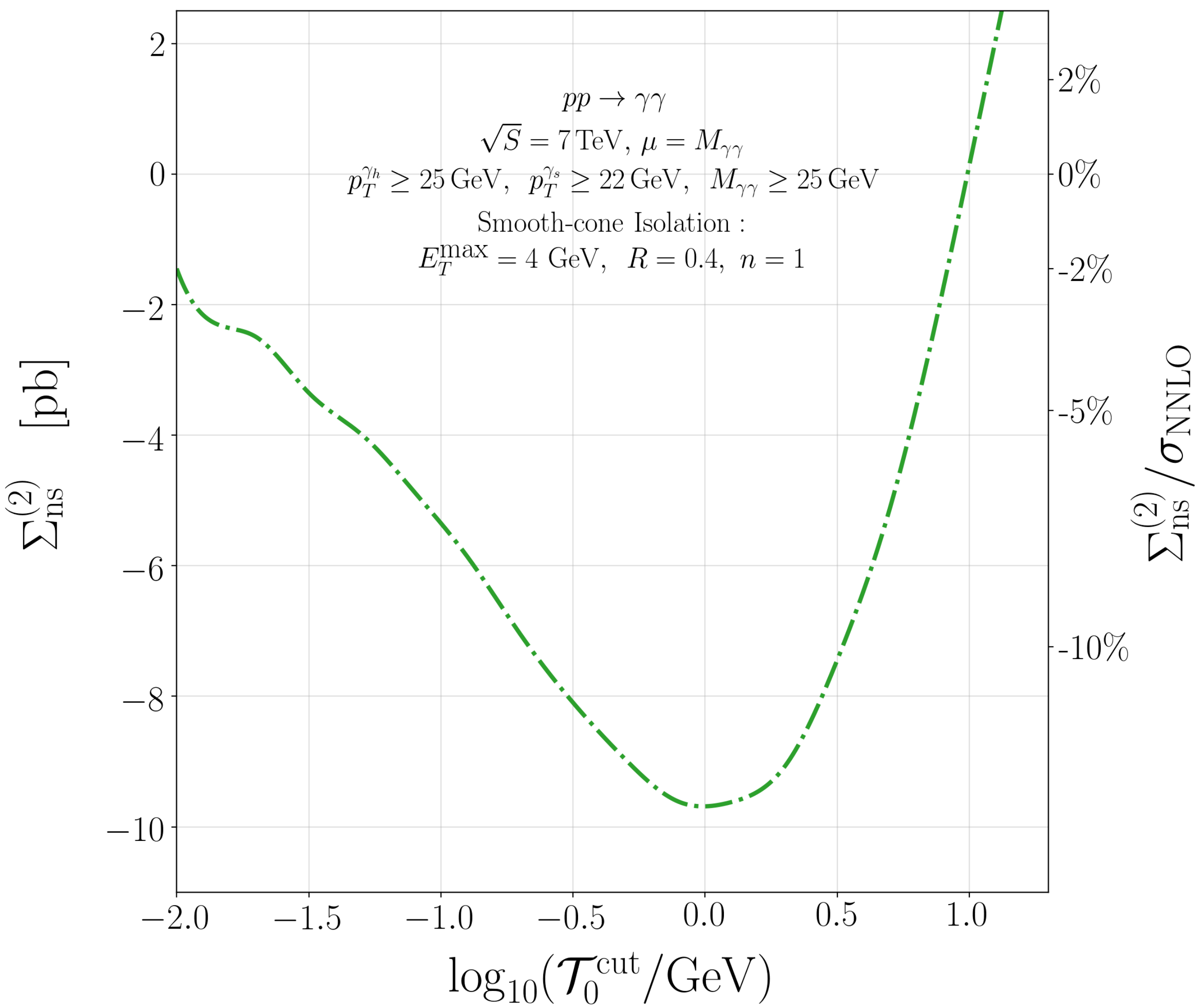
- Hybrid isolation: theoretical calculation is initially carried out using the smooth-cone isolation with a small radius parameter R_{iso}. Second step: the fixed-cone isolation with $R \gg R_{\text{iso}}$ is applied to the events which passed the smooth-cone criterion.

Monte Carlo implementation

NLO_1 vs Resummed expanded



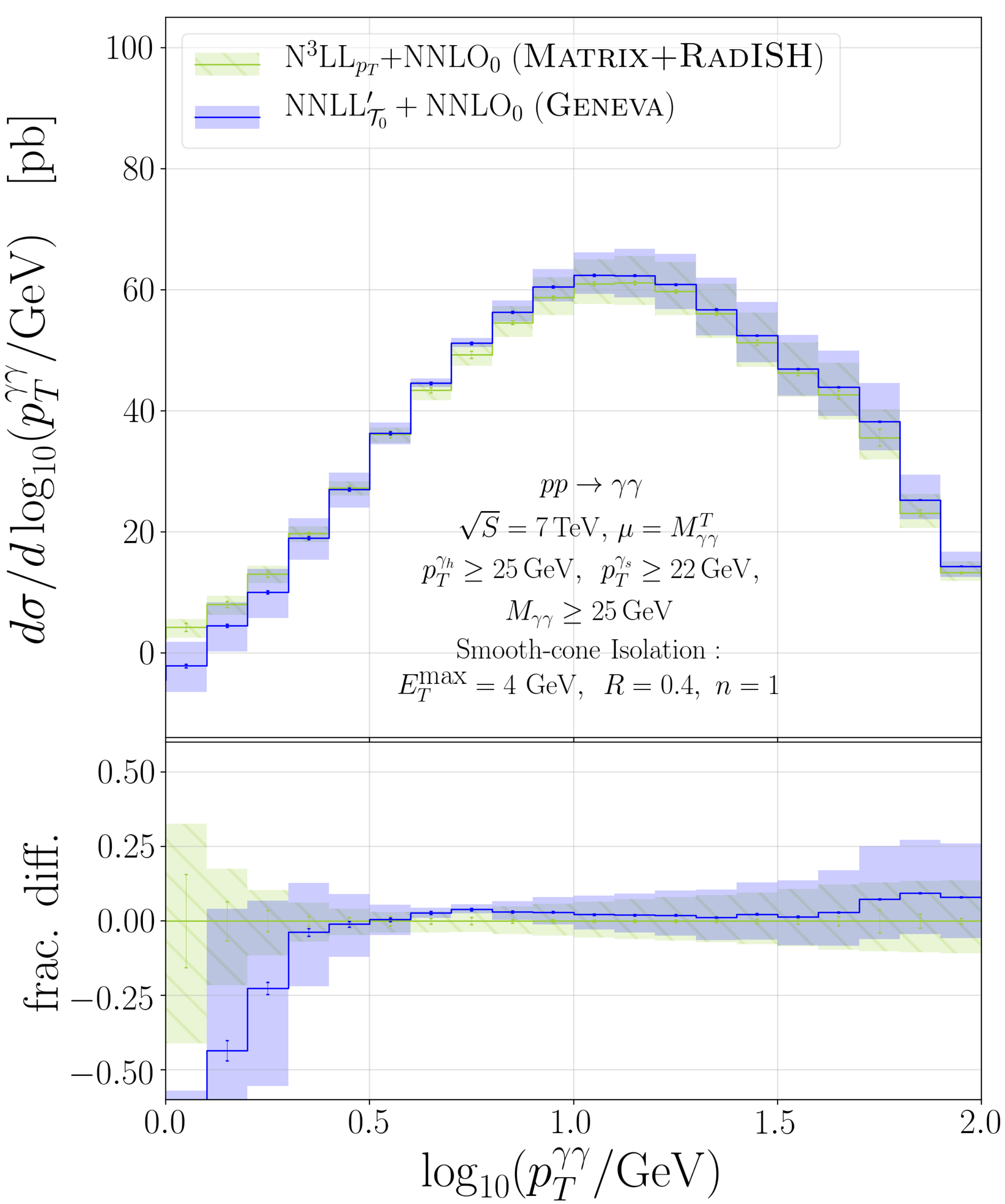
Monte Carlo implementation

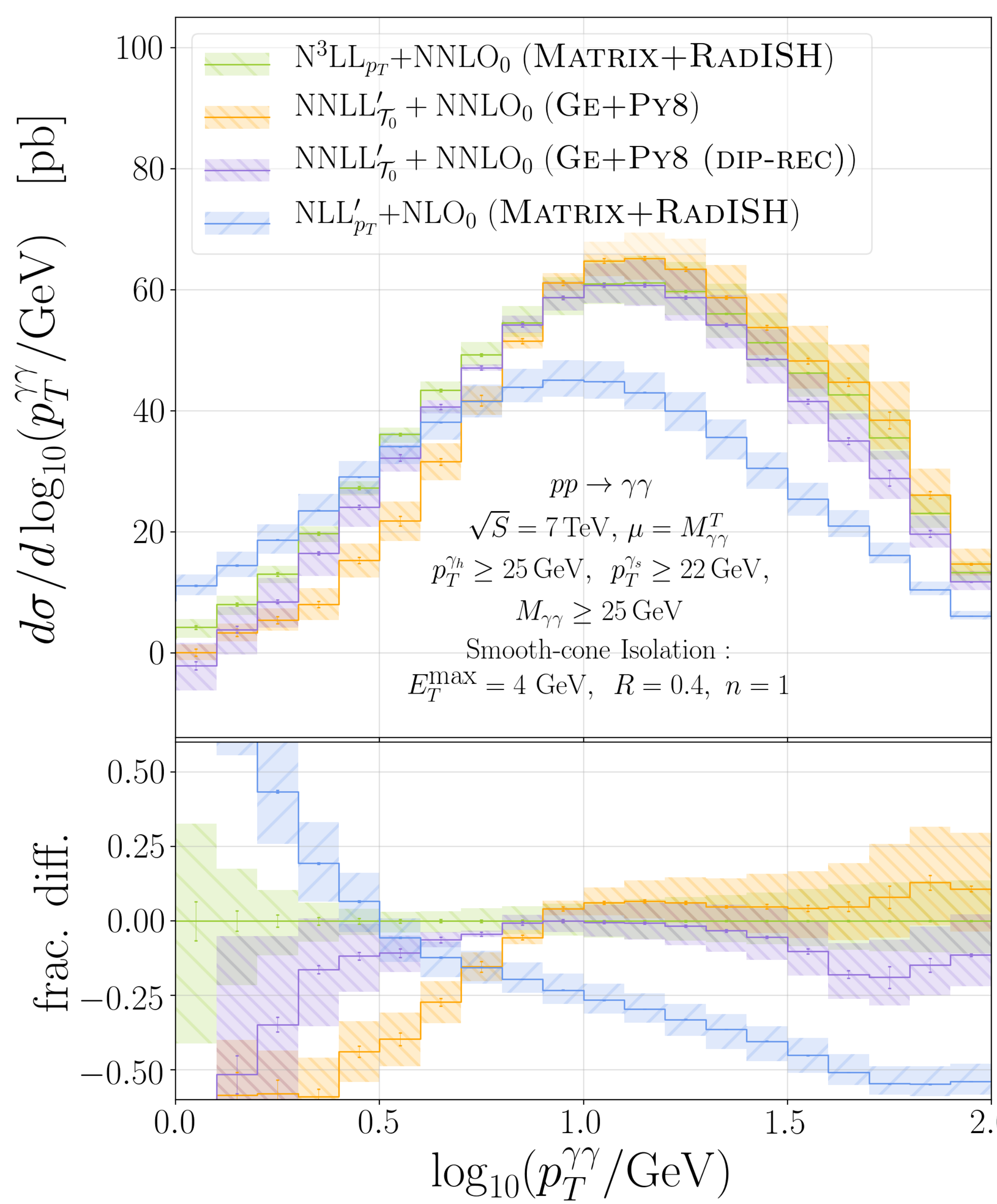


Size of the missing non singular contributions below the cut as a function of $\mathcal{T}_0^{\rm cut}$

$$\Sigma^{\rm NS}_{\mathcal{O}(\alpha_s^2)}(\mathcal{T}_0'^{\rm cut}) = \sigma^{\rm NNLO} - \sigma^{\rm GENEVA}(\mathcal{T}_0^{\rm cut}) + \int_{\mathcal{T}_0^{\rm cut}}^{\mathcal{T}_0'^{\rm cut}} \mathrm{d}\mathcal{T}_0 \left(\frac{\mathrm{d}\sigma^{\rm NLO_1}}{\mathrm{d}\mathcal{T}_0} - \frac{\mathrm{d}\sigma^{\rm NNLL'}}{\mathrm{d}\mathcal{T}_0}\Big|_{\alpha_s^2} \right) - \int_{\mathcal{T}_0^{\rm cut}}^{\mathcal{T}_0'^{\rm cut}} \mathrm{d}\mathcal{T}_0 \left(\frac{\mathrm{d}\sigma^{\rm LO_1}}{\mathrm{d}\mathcal{T}_0} - \frac{\mathrm{d}\sigma^{\rm NNLL'}}{\mathrm{d}\mathcal{T}_0}\Big|_{\alpha_s} \right)$$

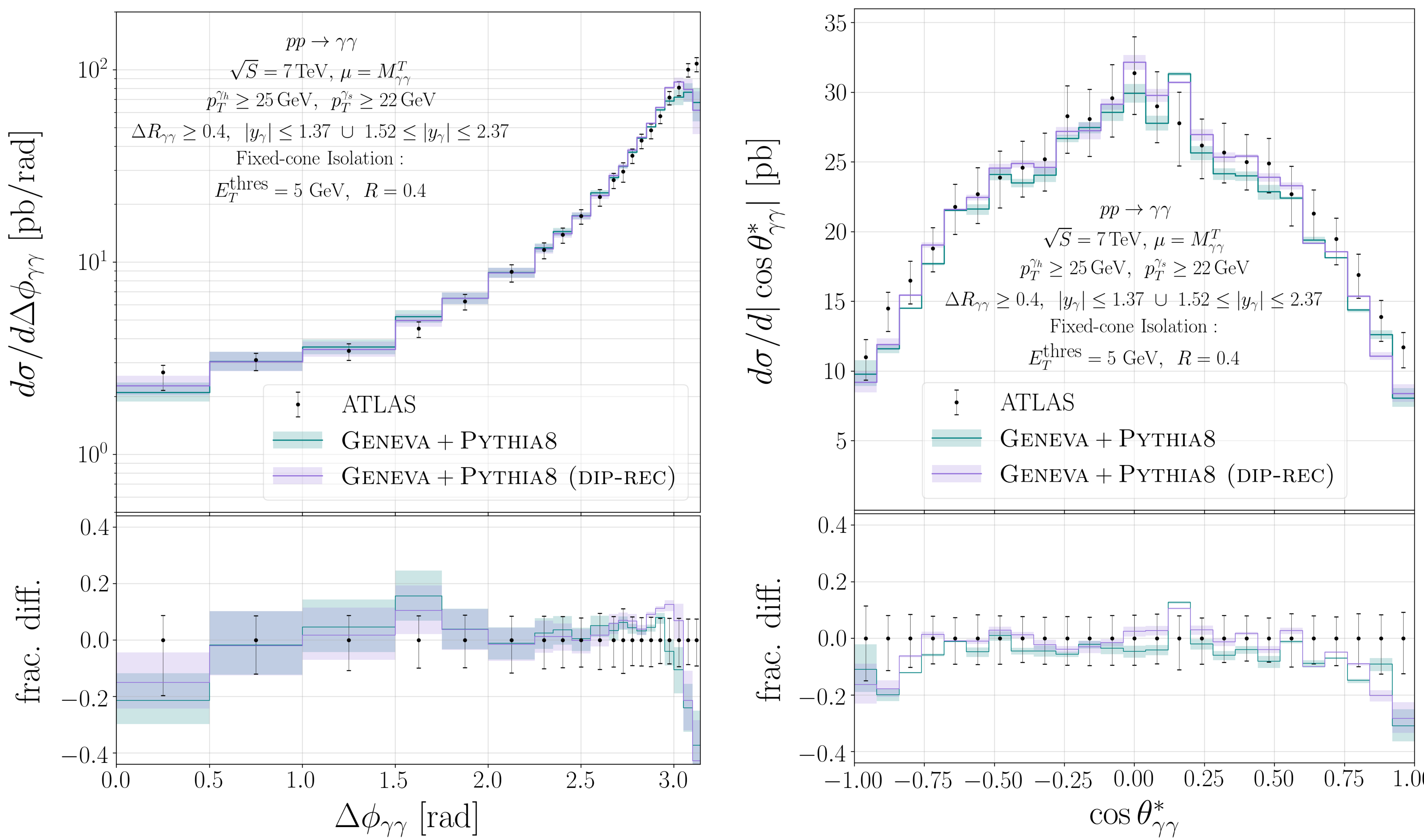
GENEVA vs q_T resummation





Comparison to ATLAS data LHC 7 TeV

Hybrid isolation procedure (initial smooth-cone $R_{\text{iso}} = 0.1$)



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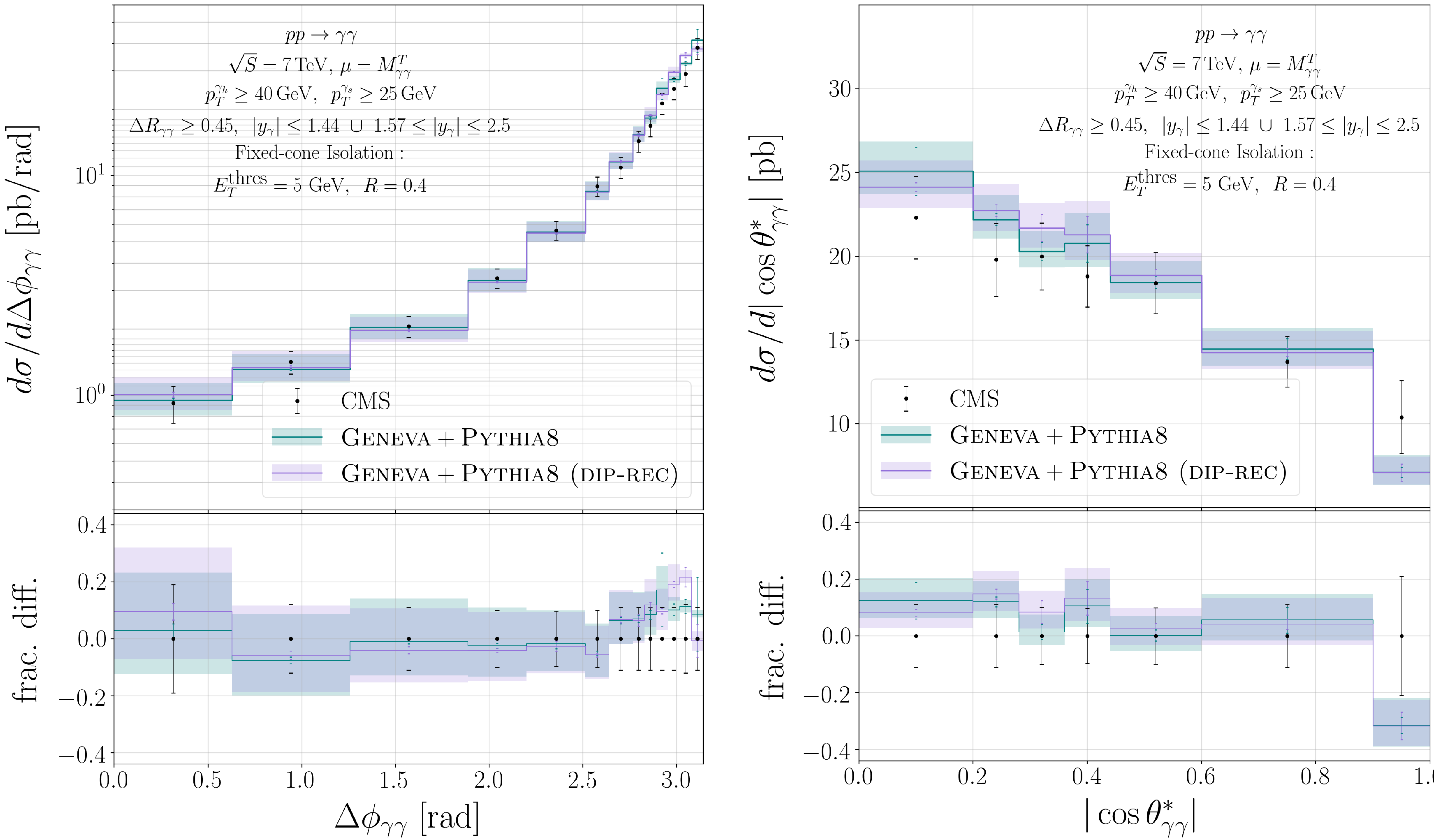

N-Jettiness and Factorization

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$$\mathcal{T}_N(\Phi_M) = \sum_k \min\{\hat{q}_a \cdot p_k, \hat{q}_b \cdot p_k, \hat{q}_1 \cdot p_k, \ldots, \hat{q}_N \cdot p_k\}$$

- The limit $\mathcal{T}_N \to 0$ describes a N-jet event where the unresolved emissions can be either soft or collinear to the final state jets or initial state beams

- Color singlet final state, relevant variable is 0-jettiness

$$\mathcal{T}_0 = \sum_k |\vec{p}_{kT}|\, e^{-|\eta_k - Y|}$$

- Cross section factorizes in the limit $\mathcal{T}_0 \to 0$ [Stewart, Tackmann, Waalewijn `09, `10], three different scales arise

$$\mu_H = Q, \quad \mu_B = \sqrt{Q\mathcal{T}_0}, \quad \mu_S = \mathcal{T}_0$$

$$\frac{d\sigma^{\text{SCET}}}{d\Phi_0 d\mathcal{T}_0} = \sum_{ij} \boxed{H_{ij}^{\gamma\gamma}(Q^2, t, \mu)} \int dt_a\, dt_b \boxed{B_i(t_a, x_a, \mu) B_j(t_b, x_b, \mu)} \boxed{S\left(\mathcal{T}_0 - \frac{t_a + t_b}{Q}, \mu\right)}$$

NNLO NNLO

$$\frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 d\mathcal{T}_0} = \sum_{ij} \boxed{H_{ij}^{\gamma\gamma}(Q^2, t, \mu_H)} U_H(\mu_H, \mu) \left\{ \left[\boxed{B_i(t_a, x_a, \mu_B)} \otimes U_B(\mu_B, \mu)\right] \right.$$
$$\left. \times \left[\boxed{B_j(t_b, x_b, \mu_B)} \otimes U_B(\mu_B, \mu)\right] \right\} \otimes \left[\boxed{S(\mu_s)} \otimes U_S(\mu_S, \mu)\right]$$

NNLO