Effective Theory applications to precision calculations in Particle Physics

Alessandro Broggio

universität wien

FAKT Workshop 2023, 23-24 February 2023

My scientific trajectory

I am a theoretical particle physicist mostly working on precision calculations for the LHC

- Oct 2009 - Master degree in Physics, University of Padova, Italy
- Feb 2013, PhD, Johannes-Gutenberg University Mainz, Germany
- Jan 2013 - Sept 2015, Postdoctoral fellow, Paul Scherrer Institute (PSI), Switzerland
- Oct 2015 - Sept 2018, Postdoctoral fellow, Technical University of Munich (TUM), Germany
- Oct 2018 - Oct 2022, Senior research fellow, University of Milano-Bicocca, Italy
- Since Oct 2022, University Assistant, University of Vienna, Austria

Overview of the talk

- I will focus on two EFT applications:
  - NNLO Monte Carlo event generators GENEVA http://geneva.physics.lbl.gov
  - Sudakov resummation for WIMP dark matter annihilation processes
- Outlook

Soft-Collinear Effective Theory (SCET)

- A long-standing problem in QCD was how to systematically account for long-distance effects in processes involving for example energetic light particles with momentum p^μ which has some large components but $p^2 \approx 0$. What is there to integrate out?

- One can introduce a small expansion parameter $\lambda \sim m_J/\sqrt{s} \ll 1$ and define two light-like reference vectors along the jet directions $n_-^\mu = (1,0,0,1),\ n_+^\mu = (1,0,0,-1)$ with $n_-^2 = 0, n_+^2 = 0, n_- \cdot n_+ = 2.$

- Decompose 4-vectors in a light-cone basis spanned by n_-^μ, n_+^μ and two perpendicular directions $\quad p^\mu = (n_- \cdot p)\dfrac{n_+^\mu}{2} + (n_+ \cdot p)\dfrac{n_-^\mu}{2} + p_\perp^\mu$

Soft-Collinear Effective Theory (SCET)

- If one considers, for example, two back to back light jets

$$n_- \cdot p_{J_1} = E_1 - \sqrt{E_1^2 - m_{J_1}^2} \simeq \frac{m_{J_1}^2}{2E_1} \simeq \frac{m_{J_1}^2}{\sqrt{s}} \sim \lambda^2 \sqrt{s} \qquad n_+ \cdot p_{J_1} = E_1 + \sqrt{E^2 - m_{J_1}^2} \simeq 2E_1 \simeq \sqrt{s} \qquad p_{J_1}^{\perp} = 0$$

- partons inside jet 1: $(n_- \cdot p_i, n_+ \cdot p_i, p_i^{\perp}) \sim (\lambda^2, 1, \lambda)\sqrt{s}$, collinear (or n-collinear) particles

- partons inside jet 2: $(n_- \cdot p_i, n_+ \cdot p_i, p_i^{\perp}) \sim (1, \lambda^2, \lambda)\sqrt{s}$, anti-collinear (or $\bar{n}$-collinear) particles

- (anti-)collinear particles have virtualities much lower than the hard scale $\sqrt{s}$,

  $$p_i^2 = (n_- \cdot p_i)(n_+ \cdot p_i) + p_{\perp,i}^2 \sim \lambda^2 \sqrt{s}$$

- But in virtual diagrams hard particles can be also exchanged $p_i^{\mu} \sim (1,1,1)\sqrt{s}$

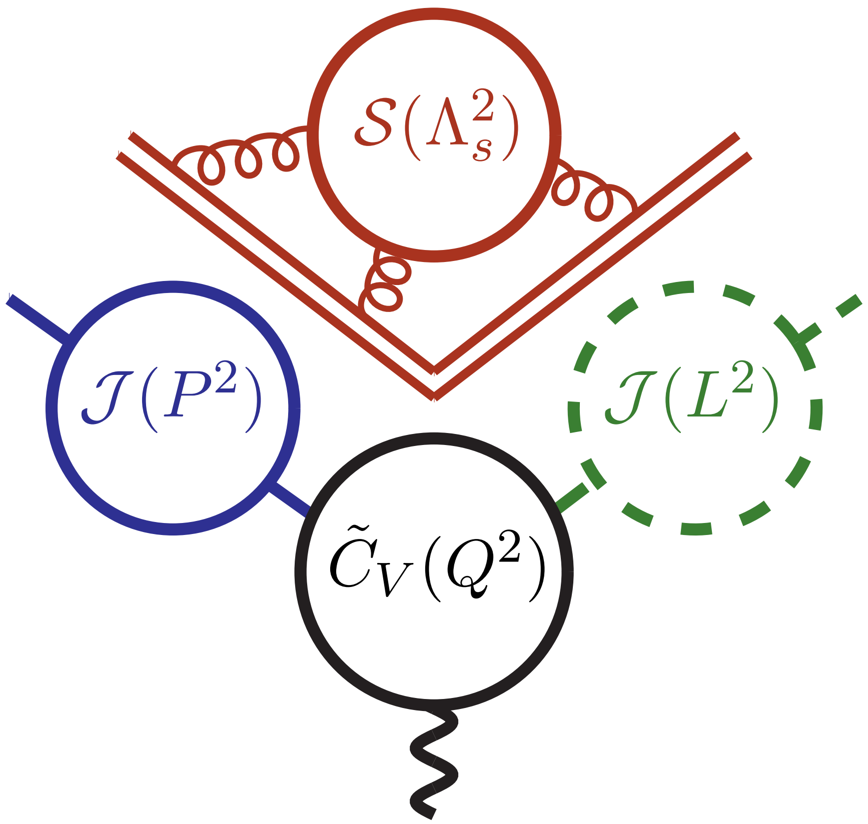
- We can integrate out the hard quantum fluctuations of QCD fields, but this is not the all story, soft modes are also present. Construct an EFT where the hard modes are integrated out, soft and (anti-)collinear modes are present in the theory (introduction to SCET arXiv:1410.1892).

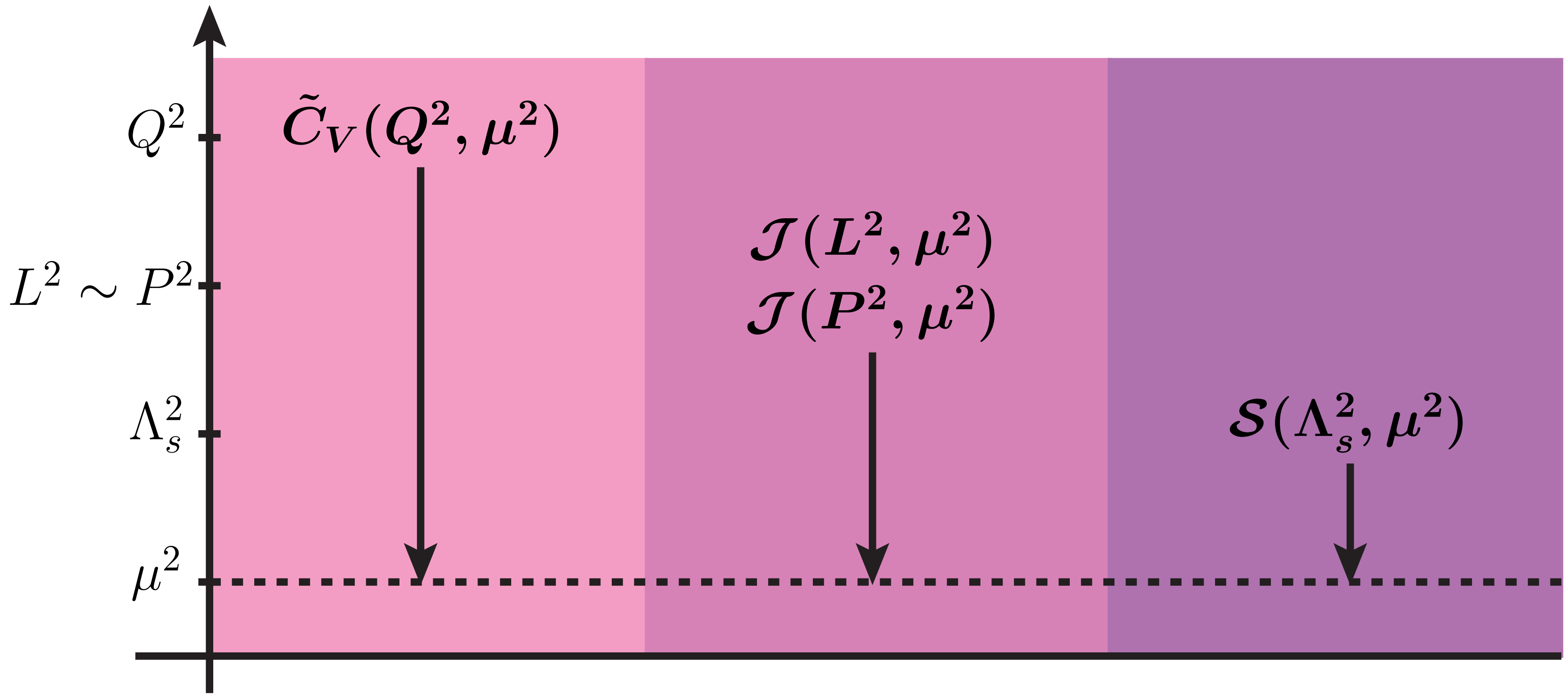
Resummation

- Resummation program in EFT schematically

$$L \equiv \ln\left(\frac{\text{“hard” scale}}{\text{“soft” scale}}\right)$$

  - separation of scales (factorization formula)
  - evaluate each single scale factor in fixed order perturbation theory at a scale for which it is free of large logs
  - use Renormalization Group (RG) equations to evolve the factors to a common scale





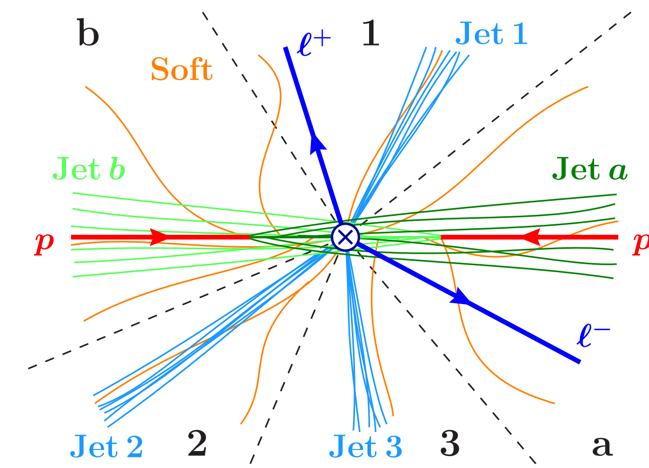
MC event generators

- MC event generators are essential tools for particle physics phenomenology
- They provide realistic simulations: first principles QFT calculations are combined with parton showers and hadronization modelling
- In order to have realistic predictions in all corners of the phase space, resummed calculations (matched to fixed-order predictions) are extremely relevant for MC event generators
- State-of-the-art is the inclusion of partonic NNLO corrections. Several methods are available for colour-singlet processes (UNNLOPS, MiNNLOPS, GENEVA)

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

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

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

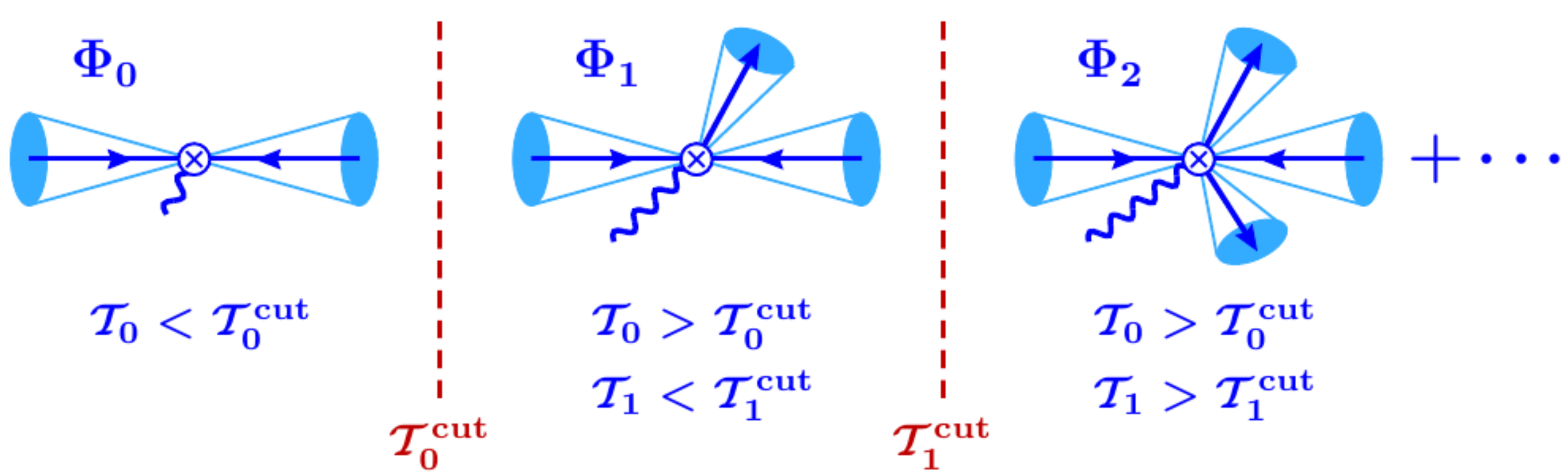
Monte Carlo implementation

- 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-`21] 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 or q_T subtraction
  - up to NNLL` resummation for 0-jettiness in SCET or N^{3}LL for q_T via RadISH for colour singlet processes
  - shower and hadronize events (PYTHIA8)
- IR-finite definition of events based on resolution parameters $\mathcal{T}_0^{\rm cut}$ (or $p_T^{\rm cut}$) and $\mathcal{T}_1^{\rm cut}$

$$\Phi_0 \text{ events:} \quad \frac{d\sigma_0^{\rm MC}}{d\Phi_0}(\mathcal{T}_0^{\rm cut})\,,$$

$$\Phi_1 \text{ events:} \quad \frac{d\sigma_1^{\rm MC}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut})\,,$$

$$\Phi_2 \text{ events:} \quad \frac{d\sigma_{\geq 2}^{\rm MC}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}, \mathcal{T}_1 > \mathcal{T}_1^{\rm cut})$$



Monte Carlo implementation

0-jet events

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

$$\frac{d\sigma_0^{\rm nons}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) = \left\{\frac{d\sigma_0^{\rm NNLO_0}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) - \left[\frac{d\sigma^{\rm NNLL'}}{d\Phi_0}(\mathcal{T}_0^{\rm cut})\right]_{\rm NNLO_0}\right\}\theta_{\rm iso}^{\rm PS}(\Phi_0)$$

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)

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

$$\frac{d\sigma_{\geq 1}^{\rm nons}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) = \boxed{\frac{d\sigma_{\geq 1}^{\rm NLO_1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})\,\theta_{\rm iso}^{\rm PS}(\Phi_1) - \left[\frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0}\mathcal{P}(\Phi_1)\right]_{\rm NLO_1}}\,\theta_{\rm iso}^{\rm PS}(\Phi_1)\,\theta_{\rm iso}^{\rm proj}(\tilde{\Phi}_0)\,\theta\left(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}\right)$$

Colour Singlet + jet at NLO. Divergent for

$\mathcal{T}_0 \to 0$

Resummed Expanded Divergent for

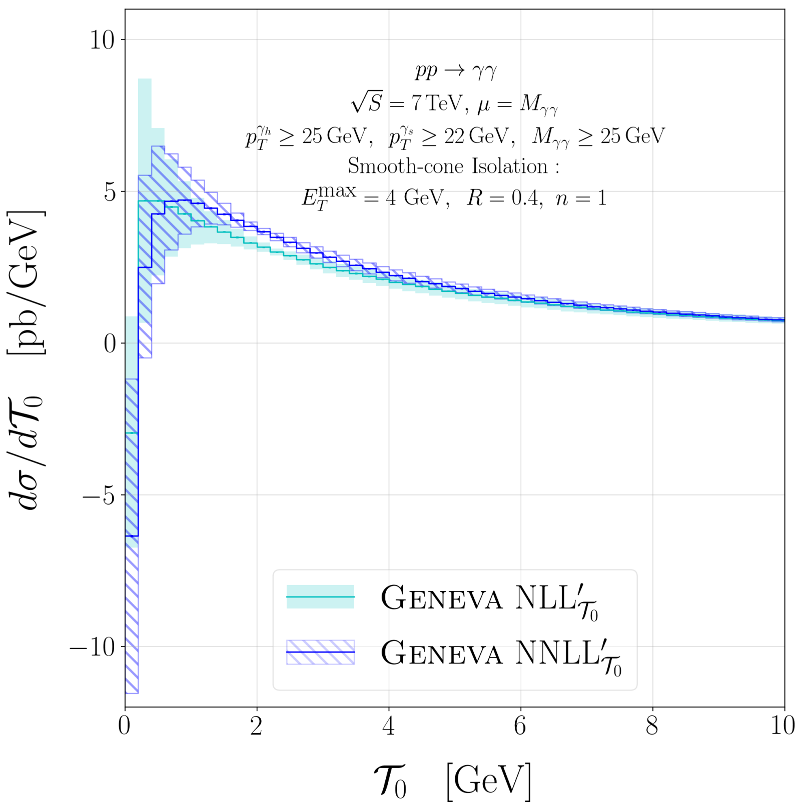
$\mathcal{T}_0 \to 0$

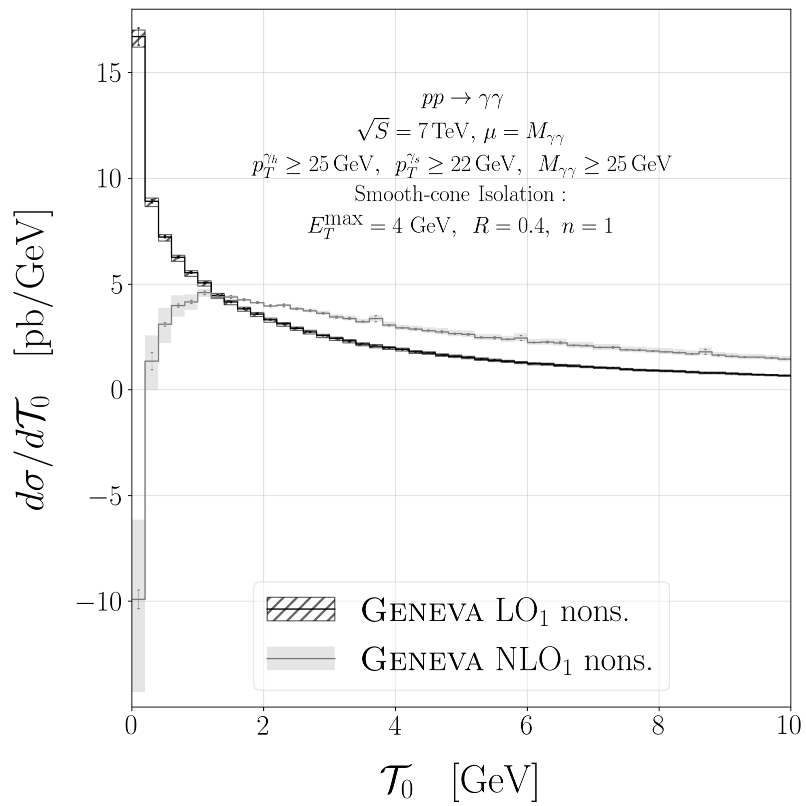
$P(\Phi_1)$ splitting function

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

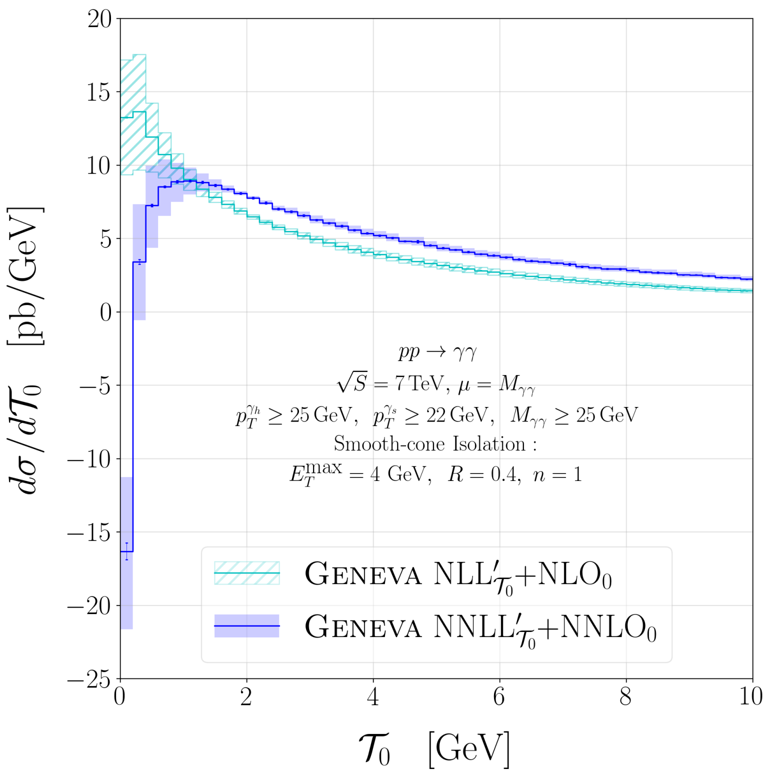
The sum is a non singular contribution

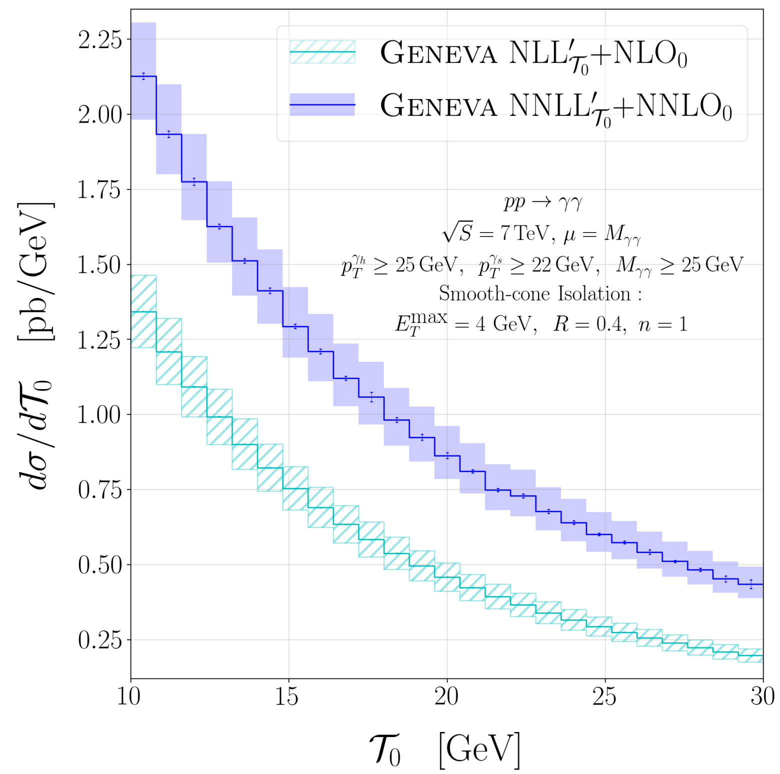
Photon Pair production at the LHC

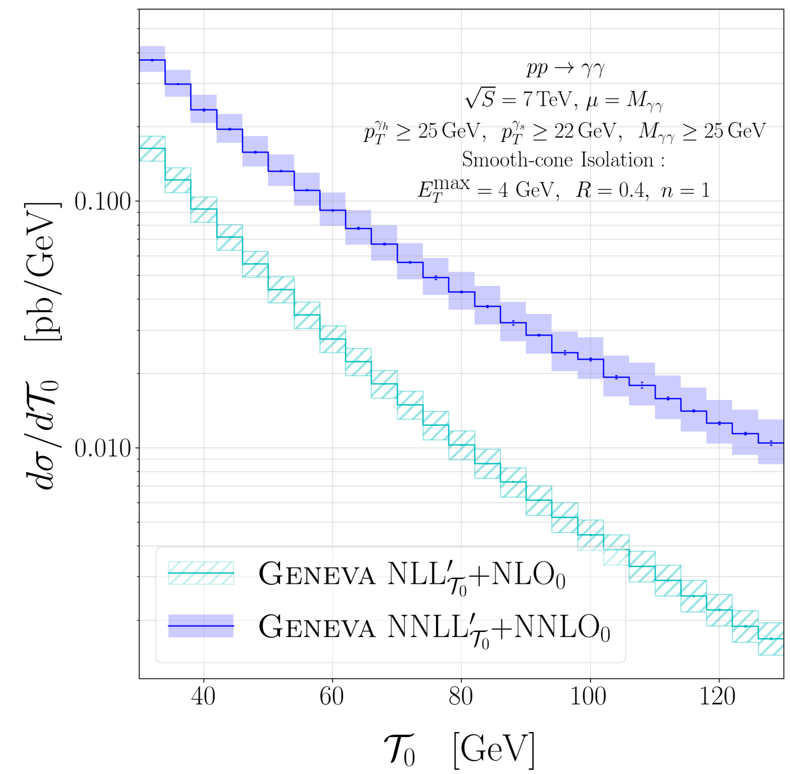




FO and resummation uncertainties combined in quadrature. Resummation uncertainties μ_B and μ_S variations together with variation of profile scale transition points (6 profile functions variations in total)

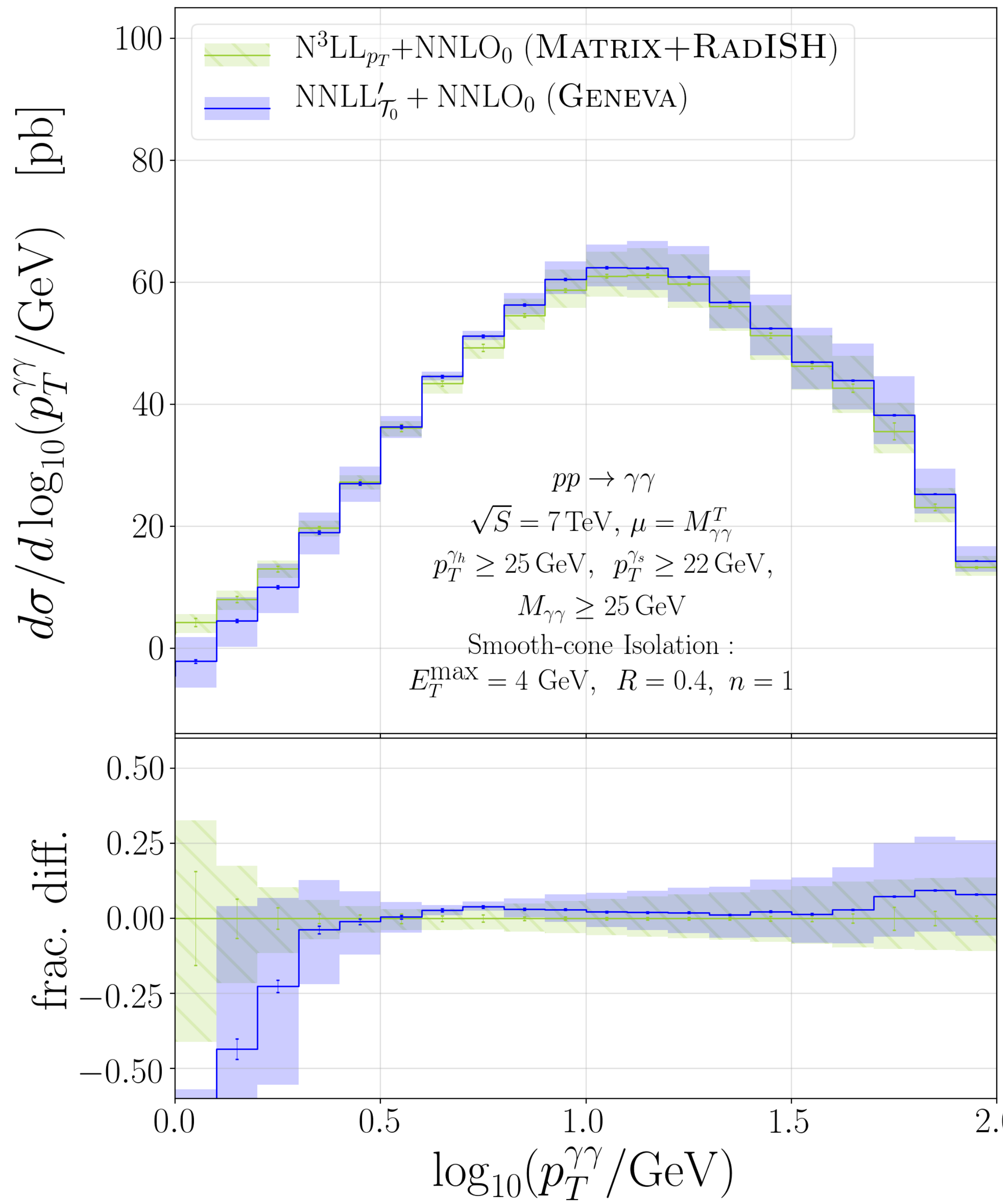


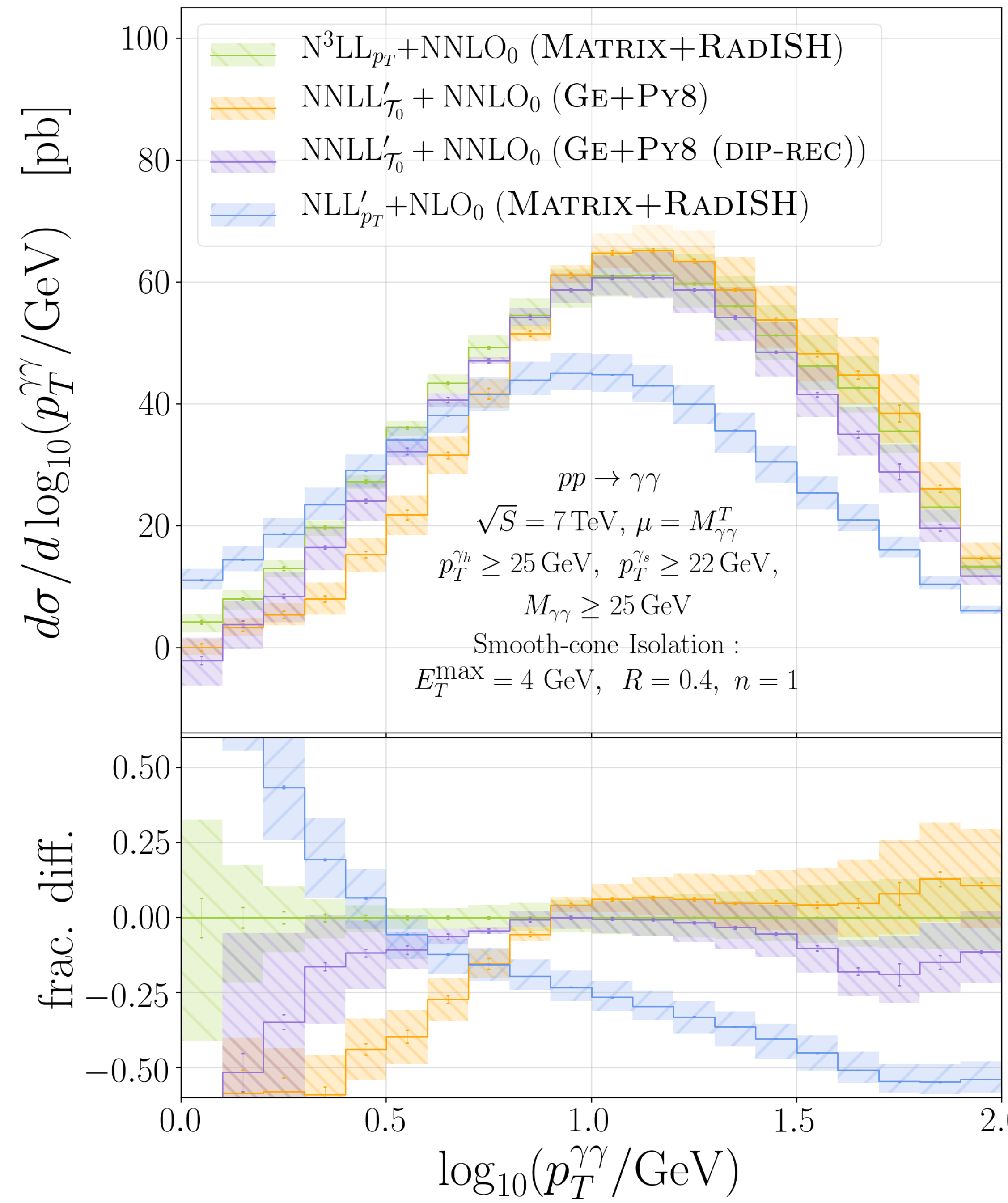




GENEVA vs q_T resummation

- Inclusive quantities are not modified, changes are expected in exclusive observables
- Shower recoil schemes large impact in predictions of colour singlet p_T

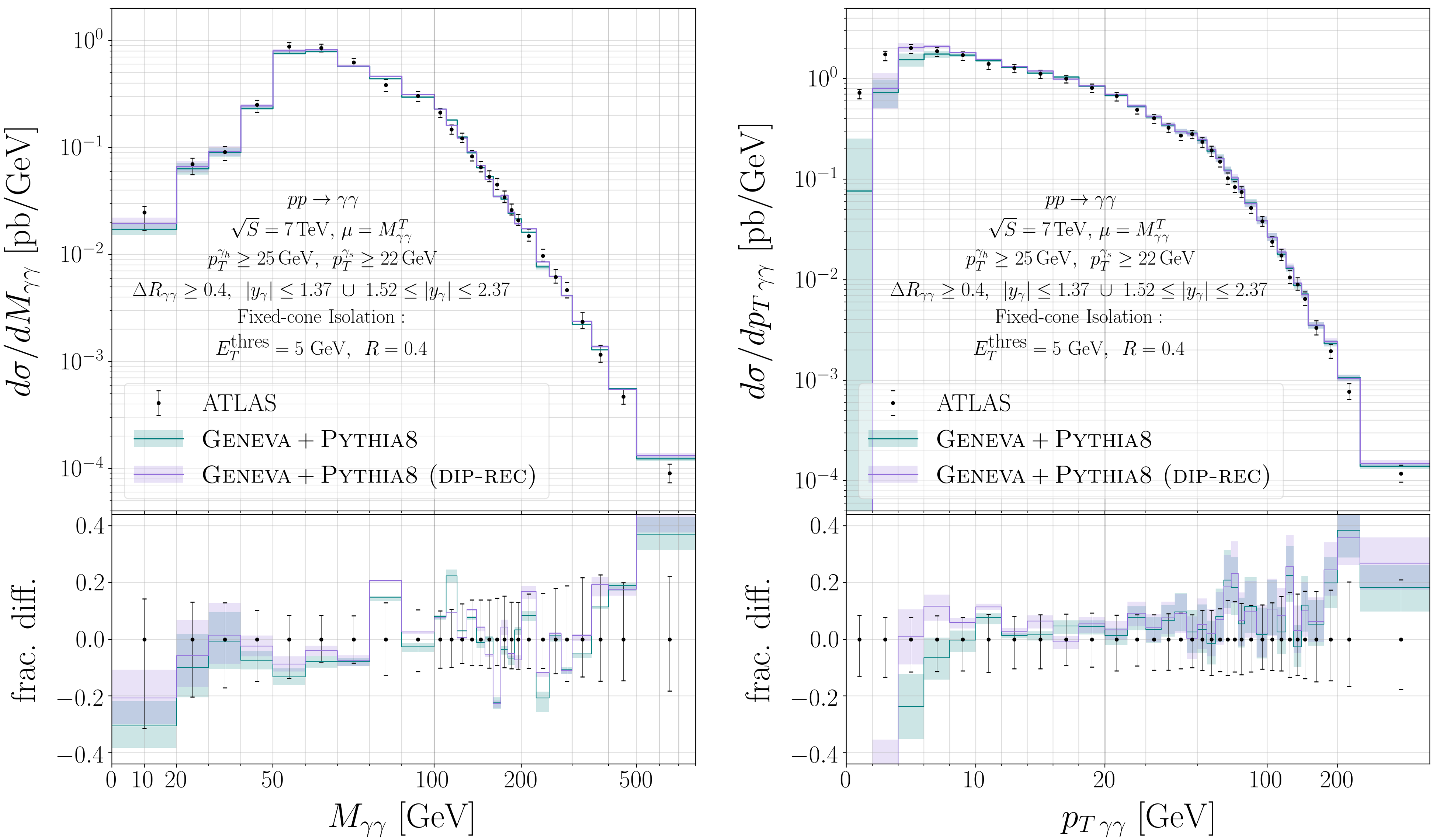




Comparison to ATLAS data LHC 7 TeV

Hybrid isolation procedure.
Process-defining cuts at generation level

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



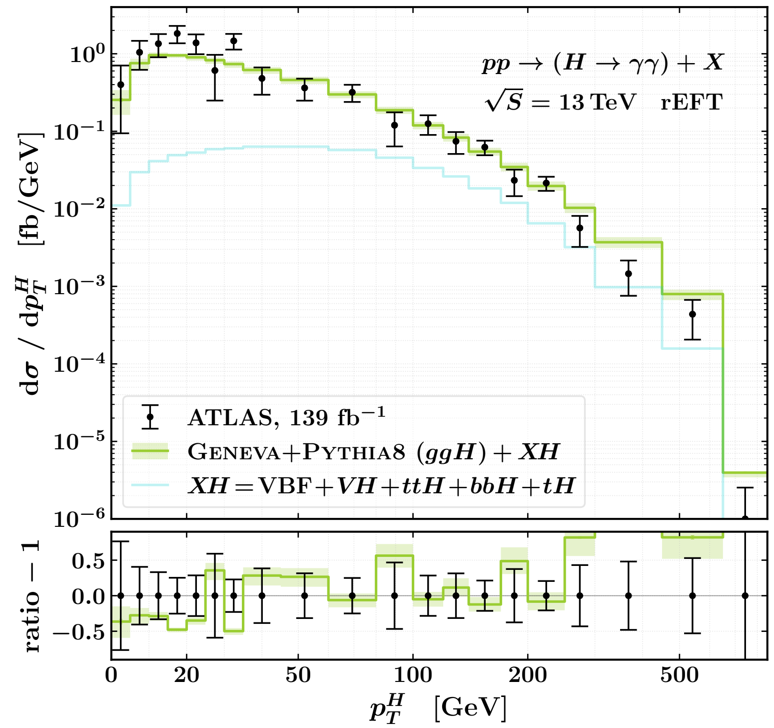
2-loop top massive effects not yet included in qqbar channel. EW effects also important at high $M_{\gamma\gamma}$

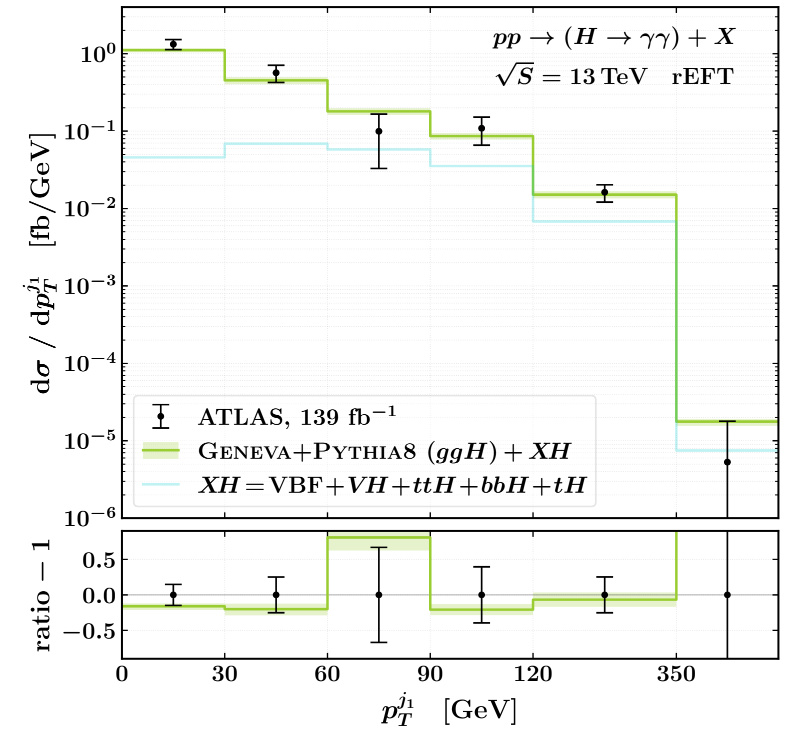
ATLAS [arXiv:1211.1913]

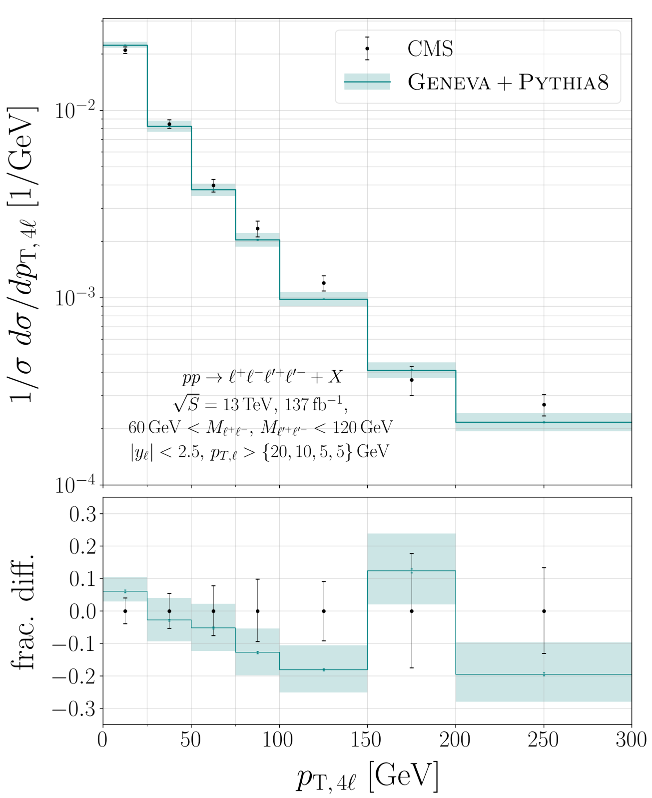
Colour Singlet processes in Geneva

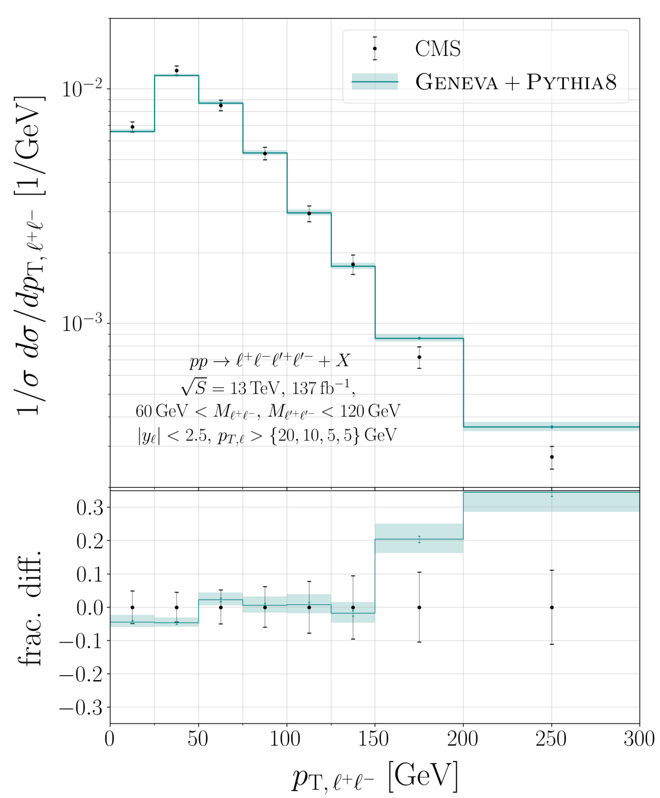
Drell-Yan (1508.01475, 2102.08390), VH (1909.02026), Photon pair (2010.10498), $W\gamma$ (2105.13214), ZZ (2103.01214), single (2301.11875) and double (2212.10489) Higgs production in gluon fusion

$gg \to H$









ZZ production

Top-quark pair production: factorization & resummation

We derived a factorization formula (see 2111.03632 Appendix A) using SCET+HQET in the region where $M_{t\bar{t}} \sim m_t \sim \sqrt{\hat{s}}$ are all hard scales. In case of boosted regime $M_{t\bar{t}} \gg m_t$ situation similar to [Fleming, Hoang,Mantry,Stewart `07][Bachu,Hoang,Mateu,Pathak,Stewart `21]

Hard functions (color matrices)

$$\frac{d\sigma}{d\Phi_0 d\tau_B} = M \sum_{ij=\{q\bar{q},\bar{q}q,gg\}} \int dt_a\, dt_b\, \boxed{B_i(t_a, z_a, \mu)\, B_j(t_b, z_b, \mu)}\, \mathrm{Tr}\left[\boxed{\mathbf{H}_{ij}(\Phi_0, \mu)}\,\boxed{\mathbf{S}_{ij}\left(M\tau_B - \frac{t_a + t_b}{M}, \Phi_0, \mu\right)}\right]$$

Beam functions [Stewart, Tackmann, Waalewijn, [1002.2213], known up to N^3LO

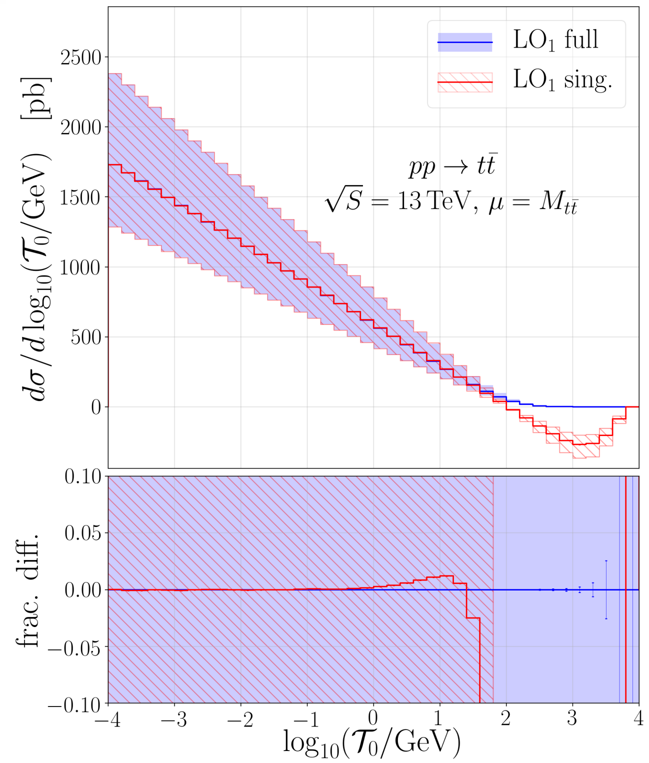
Soft functions (color matrices)

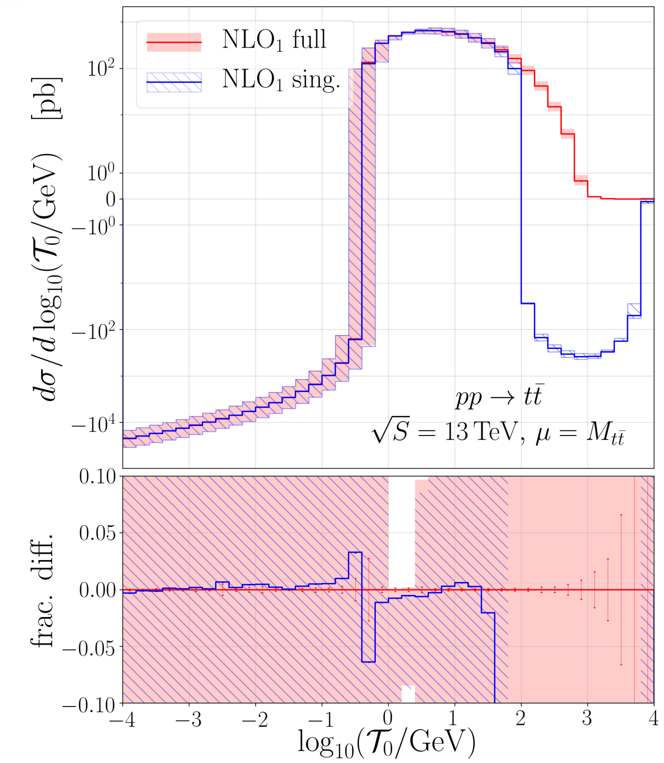
Resummation formula, non-diagonal evolution in colour space

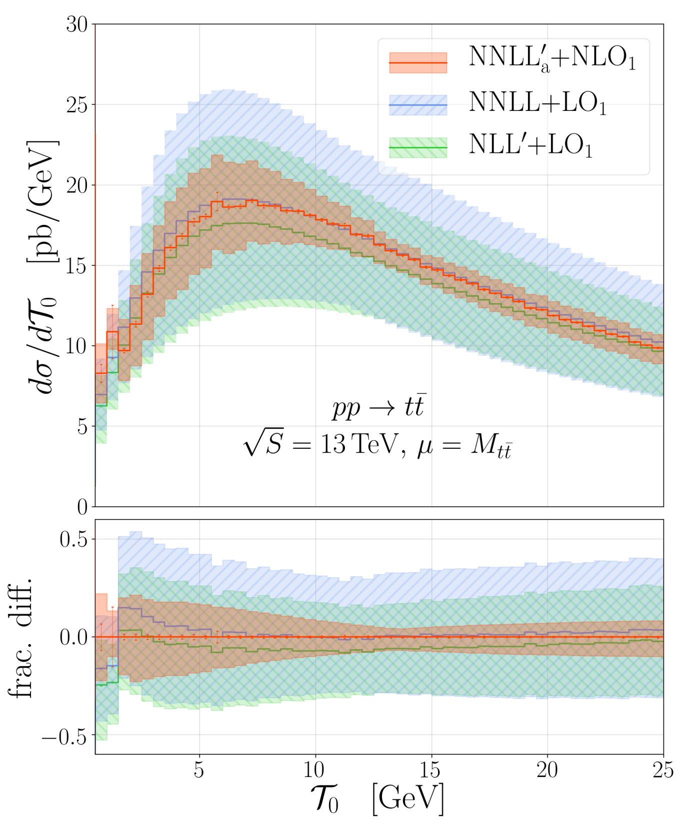
$$\begin{aligned}\frac{d\sigma}{d\Phi_0 d\tau_B} &= U(\mu_h, \mu_B, \mu_s, L_h, L_s) \\ &\times \mathrm{Tr}\left\{\mathbf{u}(\beta_t, \theta, \mu_h, \mu_s)\, \mathbf{H}(M, \beta_t, \theta, \mu_h)\, \mathbf{u}^\dagger(\beta_t, \theta, \mu_h, \mu_s)\, \tilde{\mathbf{S}}_B(\partial_{\eta_s} + L_s, \beta_t, \theta, \mu_s)\right\} \\ &\times \tilde{B}_a(\partial_{\eta_B} + L_B, z_a, \mu_B) \tilde{B}_b(\partial_{\eta'_B} + L_B, z_b, \mu_B) \frac{1}{\tau_B^{1-\eta_{\text{tot}}}} \frac{e^{-\gamma_E \eta_{\text{tot}}}}{\Gamma(\eta_{\text{tot}})}\,. \qquad (3.1)\end{aligned}$$

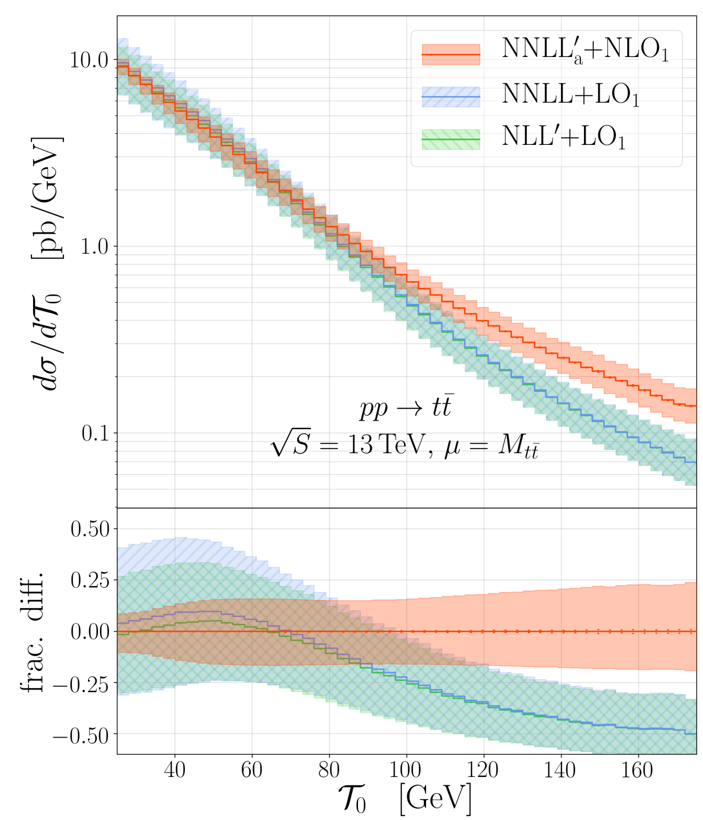
Matched results to fixed-order

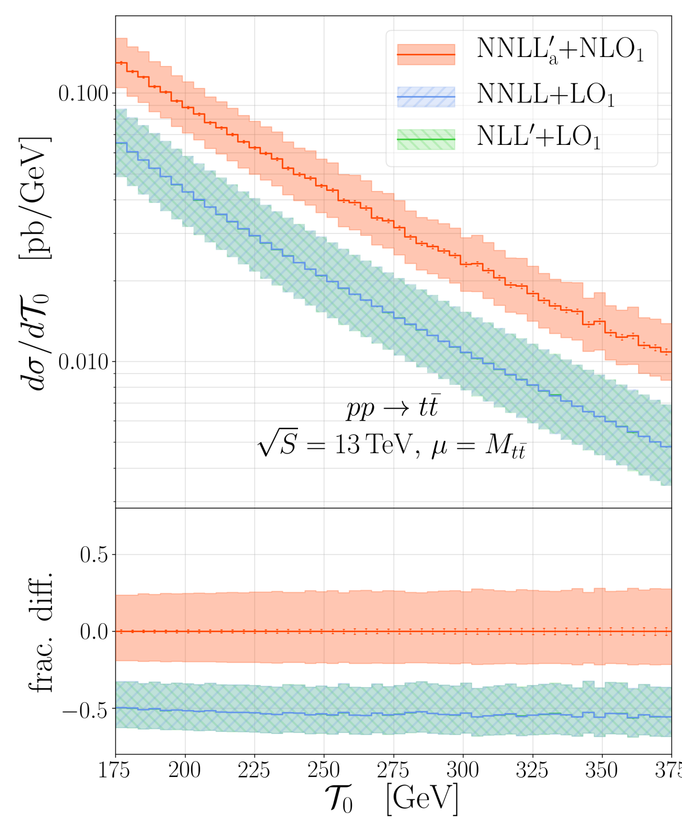
$$\frac{\mathrm{d}\sigma^{\mathrm{match}}}{\mathrm{d}\mathcal{T}_0} = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\mathcal{T}_0} + \boxed{\frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\mathcal{T}_0} - \left[\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\mathcal{T}_0}\right]_{\mathrm{FO}}}$$







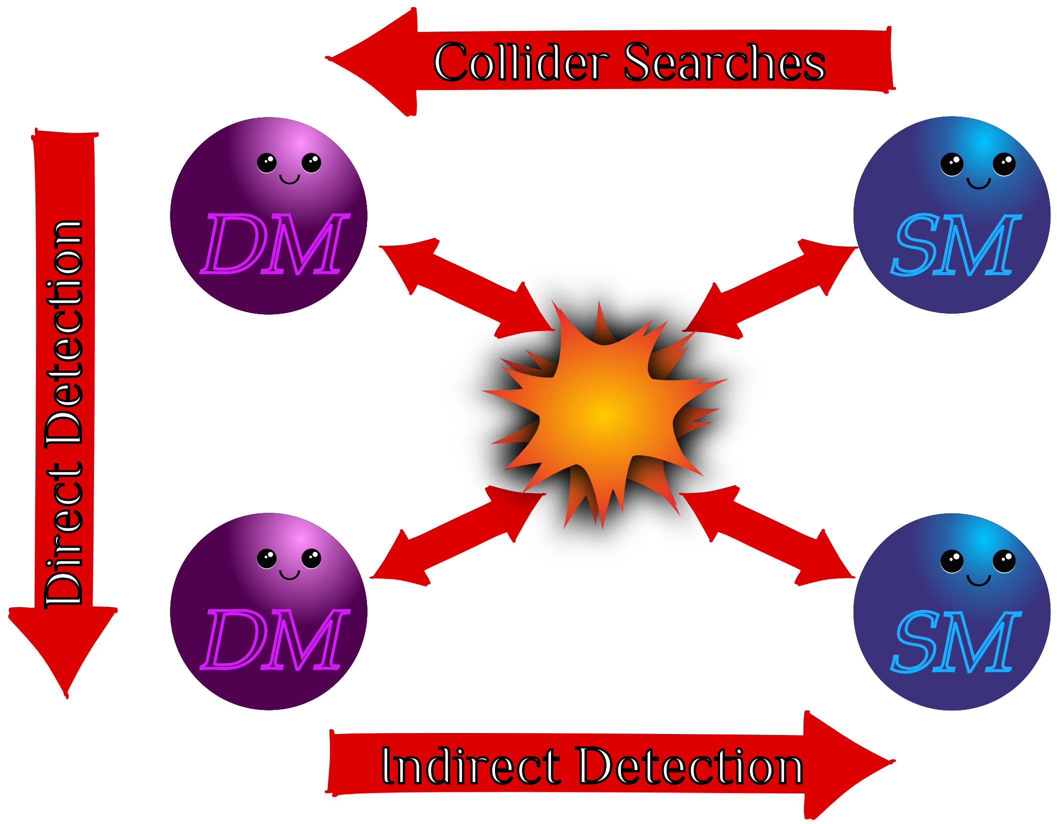




Sudakov resummation for WIMP Dark Matter annihilation

Based on arXiv:1805.07367 (M. Beneke, AB, C. Hasner, M. Vollmann) and arXiv:1903.08702 (M. Beneke, AB, C. Hasner, K. Urban, M. Vollmann)

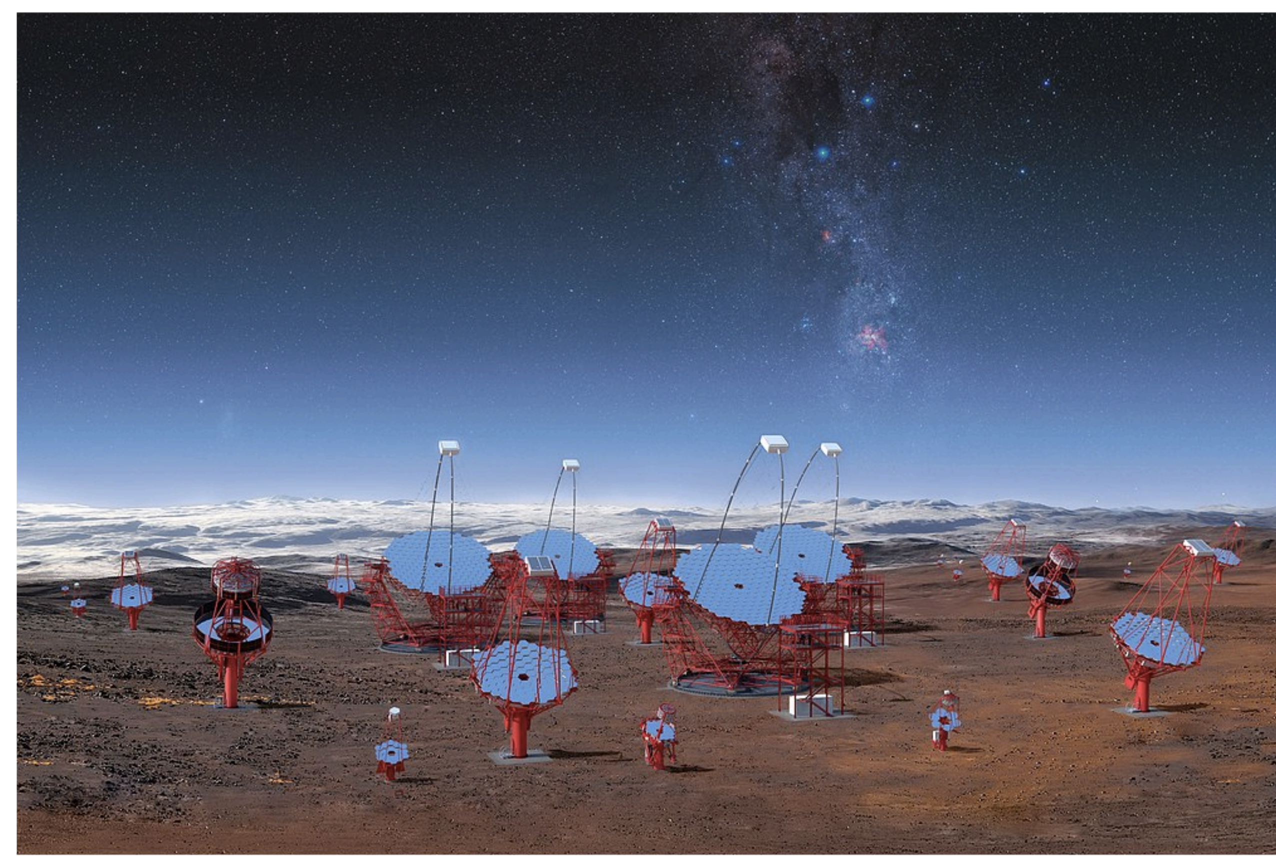
Experimental approaches



- *Indirect searches* detect the final products of dark matter annihilation in our galactic neighbourhood, using different kind of telescopes
- *Direct searches* that look for scattering events of dark matter with heavy nuclei in laboratories
- *Collider searches* that try to identify the traces of direct production of dark matter in particle accelerators (LHC)

Cherenkov Telescope Array (CTA) Experiment

- Ground-based instrument to detect energetic gamma rays
- Photon energy coverage range 20 GeV - 300 TeV
- 2 experimental sites: one in the northern hemisphere (La Palma, Canary Islands, Spain) and one in the south hemisphere (Chile, ESO, Atacama desert)
- CTA will be ten times more sensitive than its predecessors (MAGIC, HESS, VERITAS)



The wino-like triplet model

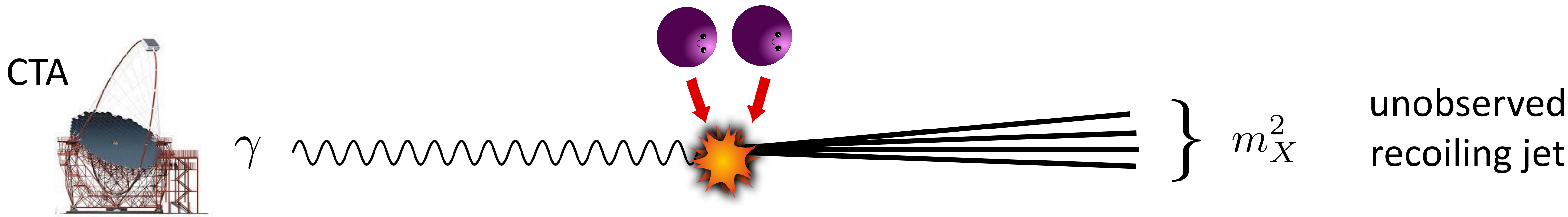
Add to the SM Lagrangian a fermionic multiplet χ (of Majorana or Dirac type) with arbitrary isospin-j representation of the EW SU(2) gauge group and zero hypercharge (Y=0)

Dirac $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}(i\not{D} - m_\chi)\chi \qquad D_\mu = \partial_\mu - i g_2 A_\mu^C T^C$

Minimal DM models [Cirelli,Fornengo,Strumia, arXiv:0512090]

The DM particle is the electrically neutral member of the 2j+1 multiplet

We consider the process $\chi(p_1) + \chi(p_2) \to \gamma(p_\gamma) + X(p_X)$



$$\boxed{\langle \sigma v\rangle(E^\gamma_{\mathrm{res}}) = \int_{m_\chi - E^\gamma_{\mathrm{res}}}^{m_\chi} dE_\gamma \, \frac{d(\sigma v)}{dE_\gamma}}$$

The photon endpoint spectrum depends on 4 different scales: m_χ (hard scale), the small invariant mass $m_X = \sqrt{4 m_\chi E^\gamma_{\mathrm{res}}}$ of the unobserved energetic final state, the EW scale m_W and the energy resolution scale E^γ_{res}

WIMPs

- TeV-scale DM annihilation is NOT accurately described by the leading order rate, modified by the Sommerfeld effect generated by the EW Yukawa force on the DM particles prior to their annihilation

$$\mathcal{O}((m_\chi \alpha_2 / m_W)^n)$$

corresponds to ladder diagrams with W, Z and photon exchange

- In addition to the Sommerfeld effect, large logarithmically enhanced quantum corrections (Sudakov logarithms) arise due to restrictions on the emission of soft radiation

$$\mathcal{O}((\alpha_2 \ln^2(m_\chi / m_W))^n)$$

- EW Sudakov logarithms in DM annihilation into photons have been identified as potential source of large corrections [Hryczuk, Iengo '12] and it was resummed to all orders in perturbation theory [Baumgart, Rothstein, Vaidya '15], [Bauer, Cohen, Hill, Solon '14], [Baumgart, Vaydia '15], [Ovanesyan, Slatyer, Stewart '14], [Ovanesyan, Rodd, Slatyer, Stewart '16], [Baumgart, Cohen, Moult, Rodd, Slatyer, Solon, Stewart, Vaidya '17] [M. Beneke, AB, C. Hasner, M. Vollmann, arXiv:1805.07367], [M. Beneke, AB, C. Hasner, K. Urban, M. Vollmann, arXiv:1903.08702]

Narrow vs Wider resolution

Details of the resummation of EW Sudakov logs differ according to the scaling of E^{γ}_{res} and m_W with respect to each other

Narrow: $E^{\gamma}_{\text{res}} \sim m_W^2/m_\chi$

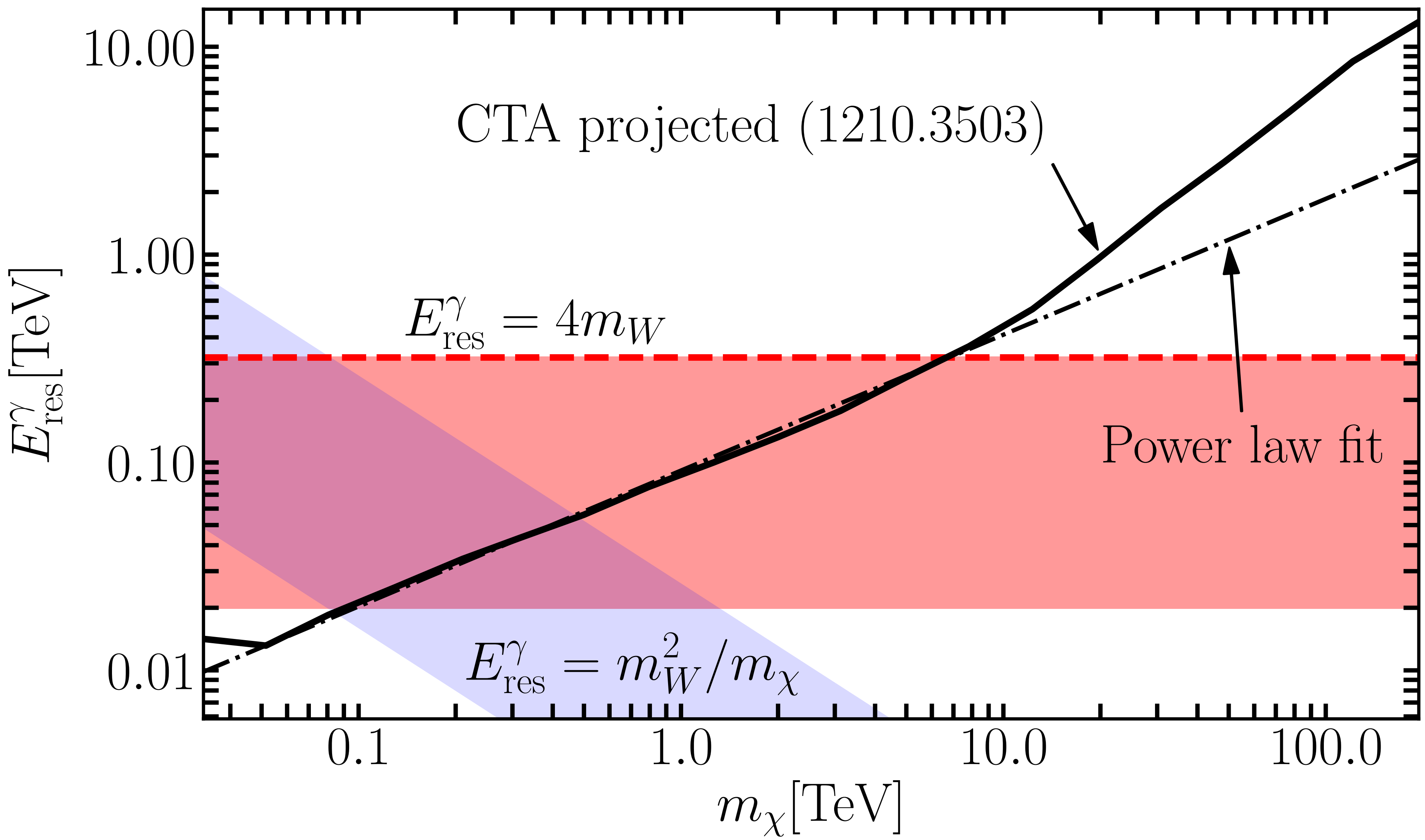
Intermediate: $E^{\gamma}_{\text{res}} \sim m_W$

Wide: $E^{\gamma}_{\text{res}} \gg m_W$

Beneke,AB,Hasner,Vollmann. [arxiv:1805.07367]

Beneke,AB,Hasner,Urban,Vollmann. [arxiv:1903.08702]

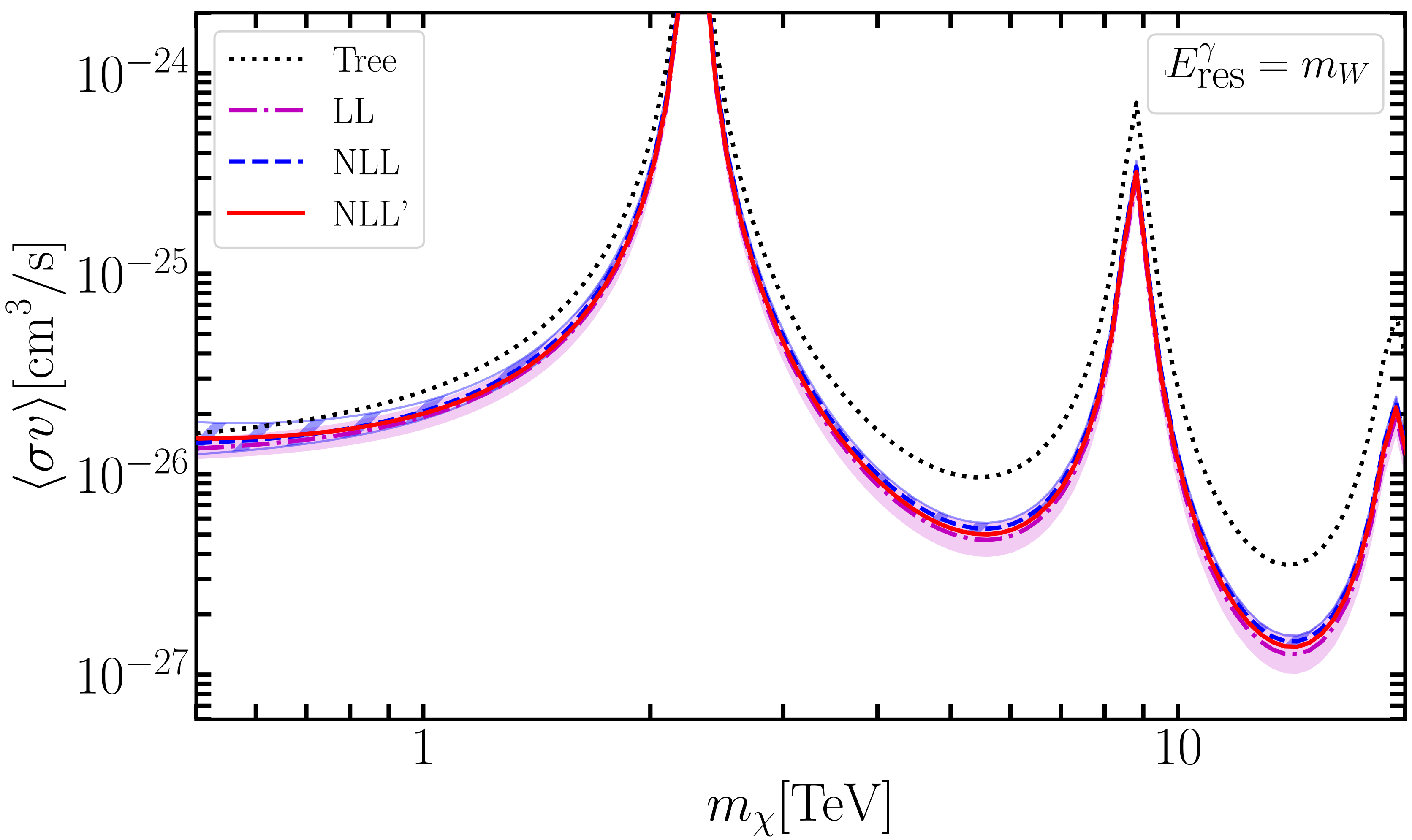
Baumgart et al. [arxiv:1808.08956]



Intermediate resolution

Integrated photon energy spectrum

$$\langle \sigma v \rangle (E^{\gamma}_{\text{res}}) = \int_{m_\chi - E^{\gamma}_{\text{res}}}^{m_\chi} dE_\gamma \frac{d(\sigma v)}{dE_\gamma}$$

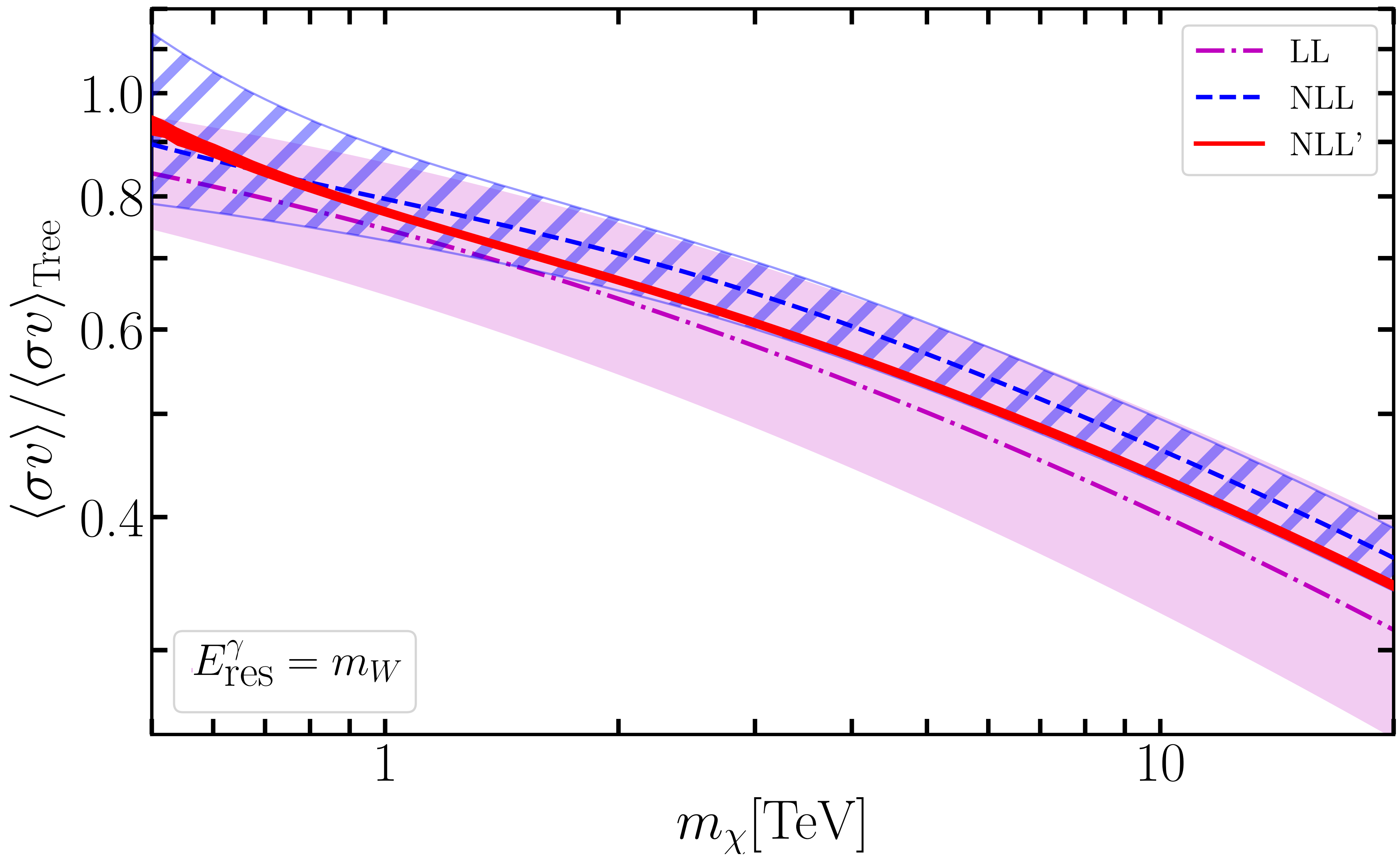


In interesting mass range ≈ 3 TeV where wino DM accounts for observed relic density, the rate is suppressed by about 30-40 %

$$S_{IJ} \sim \frac{1}{E - E_{\text{BS}}}$$

E is the kinetic energy of the two particle state. E_{BS} is the bound state binding energy. At the resonance mass values $E_{BS} \sim 0$ and $S \sim v^{-2}$

Intermediate resolution



- The scale uncertainty reduces from 17% (LL) to 8% (NLL) to 1% (NLL') for $m_\chi = 2$ TeV

- At $m_\chi = 2$ TeV $(10$ TeV$)$ the ratio of the resummed at NLL' to the Sommerfeld-only rate is $0.667^{+0.007}_{-0.006}$ $(0.435^{+0.005}_{-0.004})$

Outlook

- Extract and calculate all the missing ingredients to reach NNLL$'$ accuracy for the top-quark pair production process (hard and soft functions). Implement in GENEVA event generator
- Study processes with jets in the final state. 1-jettiness NNLL' resummation is needed. Combine with parton shower
- Colour singlet processes: multi differential resummation in $\mathcal{T}_0$ and q_T to improve distributions at small q_T
- Extend top-quark pair to study associated production of a top-pair and a heavy boson $t\bar{t}V$ ($V = H, W^{\pm}, Z$) [AB,Ferroglia,Pecjak,Signer, Yang `15], [AB,Ferroglia,Pecjak,Ossola `16],[AB,Ferroglia,Pecjak,Yang `16], [AB,Ferroglia,Pecjak,Ossola,Sameshima `17],[AB,Ferroglia,Frederix, Pagani,Pecjak,Tsinikos `19]
- Develop resummation framework at NLP accuracy for hadron collider processes.

Thank you!