Theory Predictions in the Precision Era

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MPP Project Review 2021, December 13th 2021

Theory Predictions in the Precision Era

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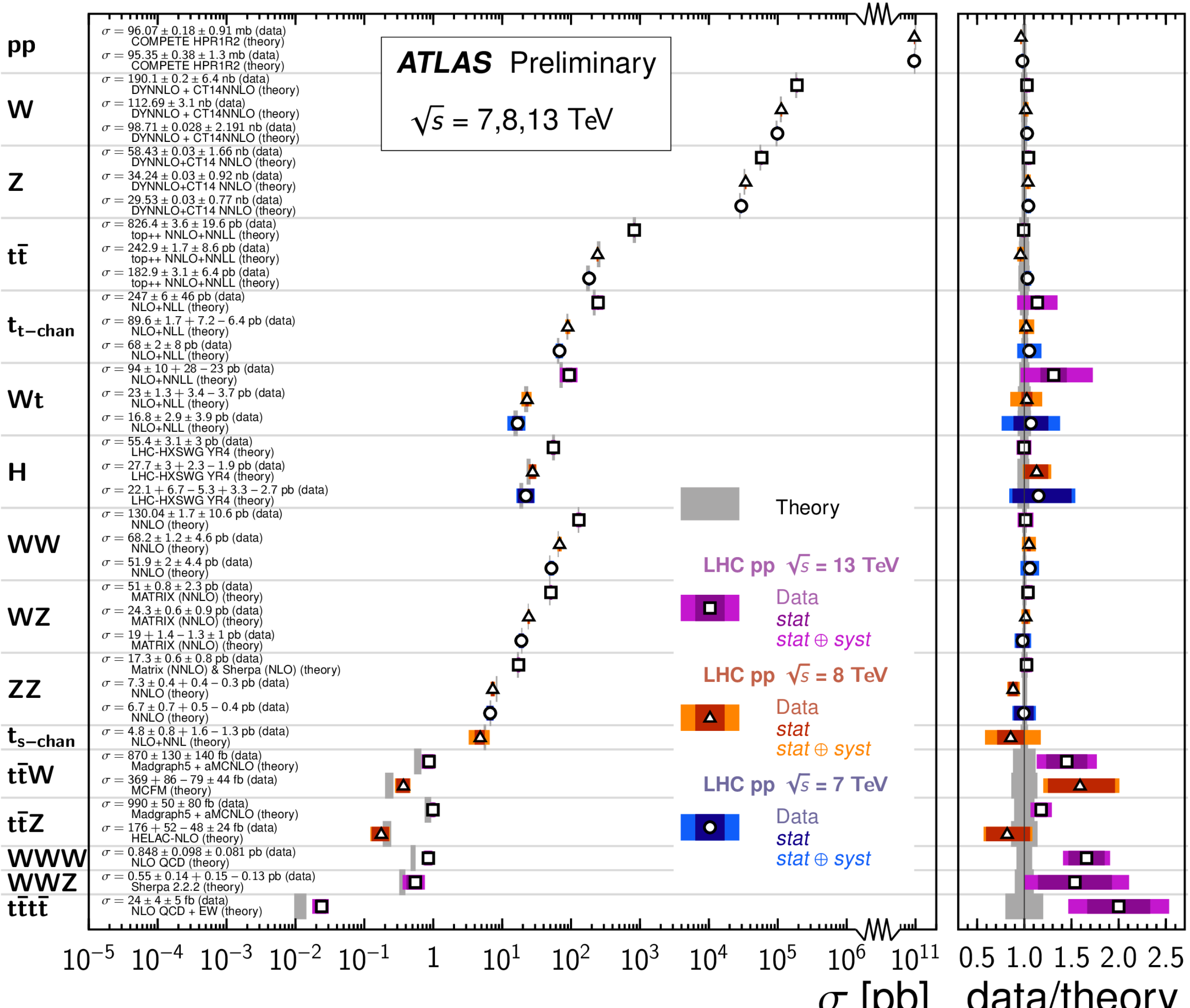
New Physics and Precision Calculations

- **SM** thoroughly tested at the **Large Hadron Collider**
- Higgs boson discovered in 2012
- No other new particles or new physics signals observed so far…
- Main focus is finding small new physics effects

- **Precise predictions** for the SM are always relevant…
- But they are **indispensable** to detect small deviations
- Theory needs at least to match experimental precision

LHC: Present and Future



- Experimental accuracy really impressive!
- W, Z, $t\bar{t}$ at the few percent level
- H and diboson at the 5% level
- Only a small fraction of total integrated luminosity

Current ~150 fb^{-1}

Run3: 300 fb^{-1} (2024)

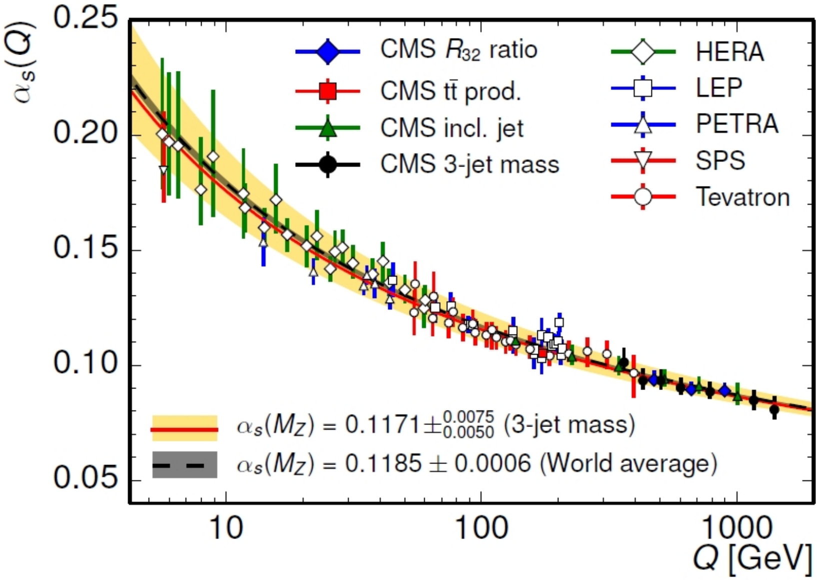
HL-LHC: 3000 fb^{-1} (~2040)

- Experimental precision will only get better!

Demand for precision calculations

Quantum Chromodynamics

- QCD corrections fundamental in hadron collisions, very large corrections due to large value of strong coupling
- Running of α_S → grows at low energies (large distances)
- LHC hard collissions in perturbative regime, but... 🤓
- The physics of the proton (~1GeV) are not! 😢



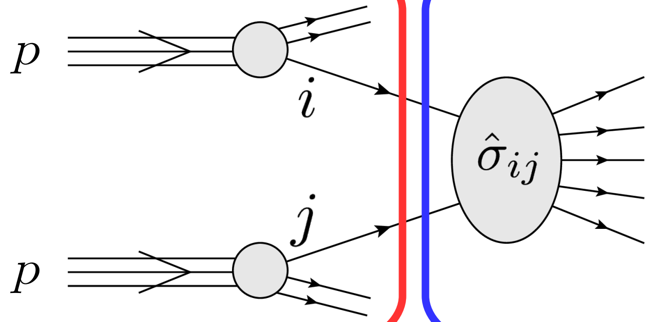
Factorization of long and short distances:

$$\sigma_{pp\to X} = \sum_{ij} \int dx_1 dx_2 f_i(x_1) f_j(x_2)\, \hat{\sigma}_{ij\to X} + \mathcal{O}(\Lambda/Q)$$

Parton Distribution Functions

Partonic cross section (hard process)

- Non perturbative
- Universal
- Extracted from data

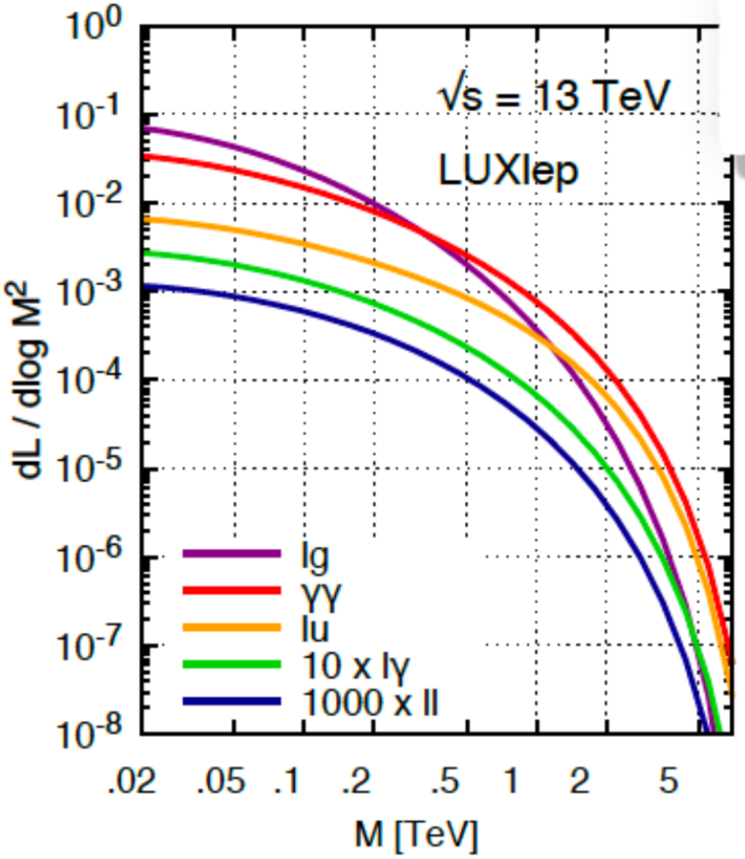


- Perturbative
- Process dependent
- Extracted from theorists

Photon and Lepton Induced Processes at the LHC

- Quarks and gluons inside the proton… and much more!
- At this level of precision or for some rare processes photon and lepton content is relevant

Lepton luminosities



$$\mathcal{L}_{ij} \equiv M^2 \int_0^1 \mathrm{d}z\,\mathrm{d}y\, f_i(z, M^2)\, f_j\,(y, M^2)\,\delta(M^2 - szy)$$

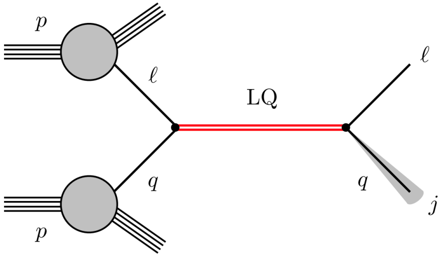
Probability to pick a parton "i" in the proton with momentum fraction z

First precise predictions for photon and lepton induced processes at the LHC:

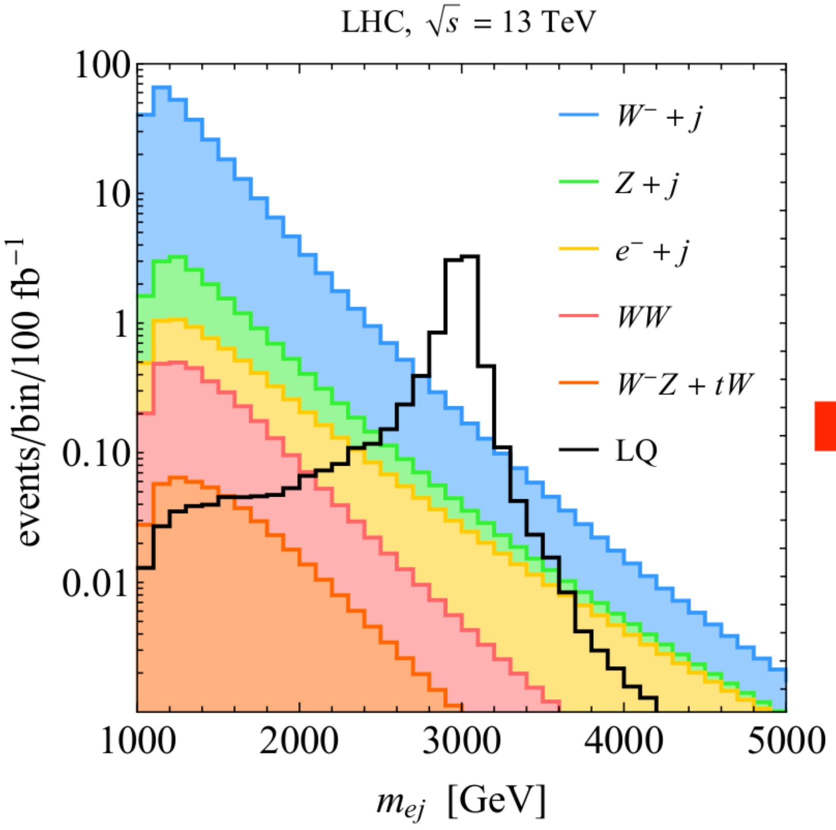
- **opens up possibility to new measurements**
- **backgrounds for BSM searches for rare processes involving leptons/photons**

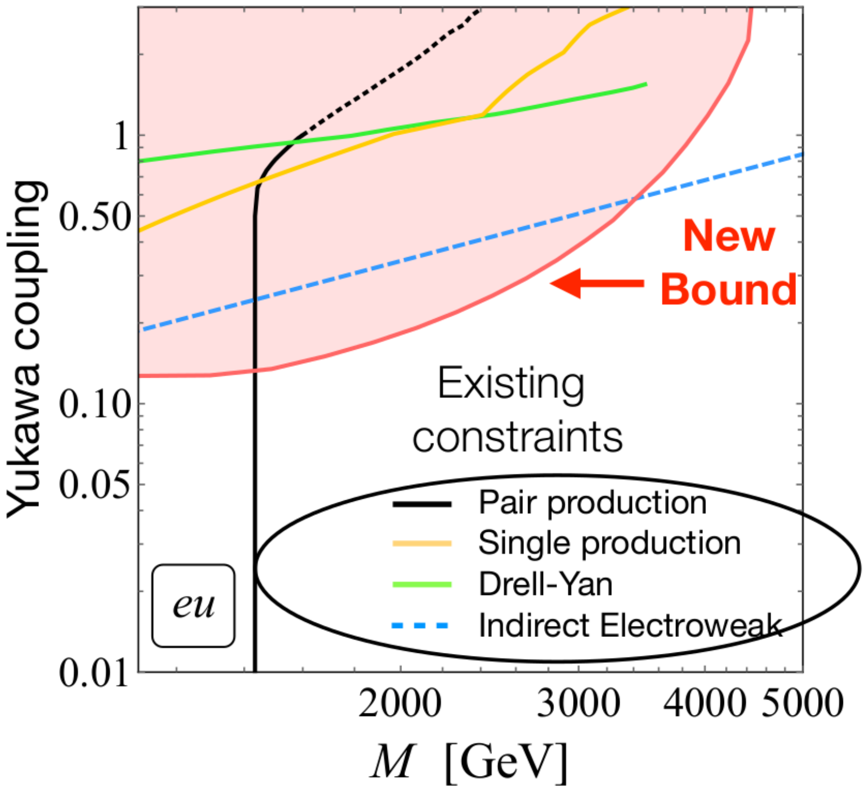
Buonocore, Nason, Tramontano, GZ '20-'21

Resonant Leptoquark Production



- Application: set stringent constraints to Leptoquark production





Buonocore, Haisch, Nason, Tramontano, GZ

Fixed Order Calculations

$$\sigma_{pp\to X} = \sum_{ij} \int dx_1 dx_2 f_i(x_1) f_j(x_2)\, \hat{\sigma}_{ij\to X} + \mathcal{O}(\Lambda/Q)$$

$$\hat{\sigma} = \hat{\sigma}_{\mathrm{LO}}\left(\underbrace{\underbrace{1 + \alpha_S}_{\mathrm{NLO}} + \alpha_S^2}_{\mathrm{NNLO}} + \ldots\right)$$

Uncertainties (indicative!)

$\mathrm{LO} \to \mathcal{O}(100\%)$

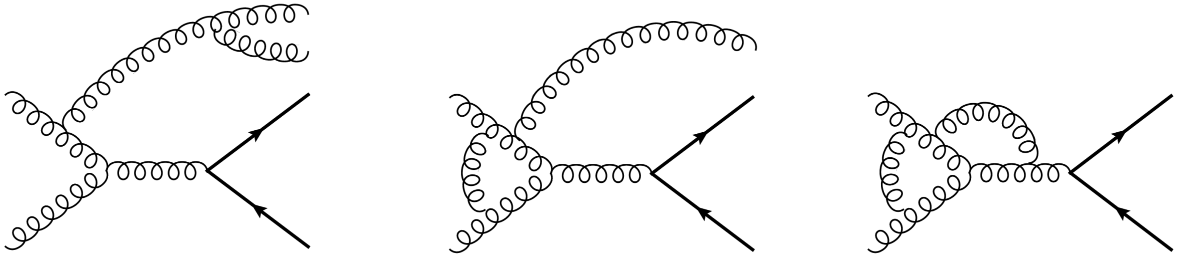
$\mathrm{NLO} \to \mathcal{O}(10\%)$

$\mathrm{NNLO} \to \mathcal{O}(1\%)$

Higher-order calculations are very complex: large number of Feynman diagrams, intermediate divergencies, complicated phase-space integrations, etc… But this is not even the end of the story!

Fixed-order calculations look like this:

E.g.: NNLO $t\bar{t}$

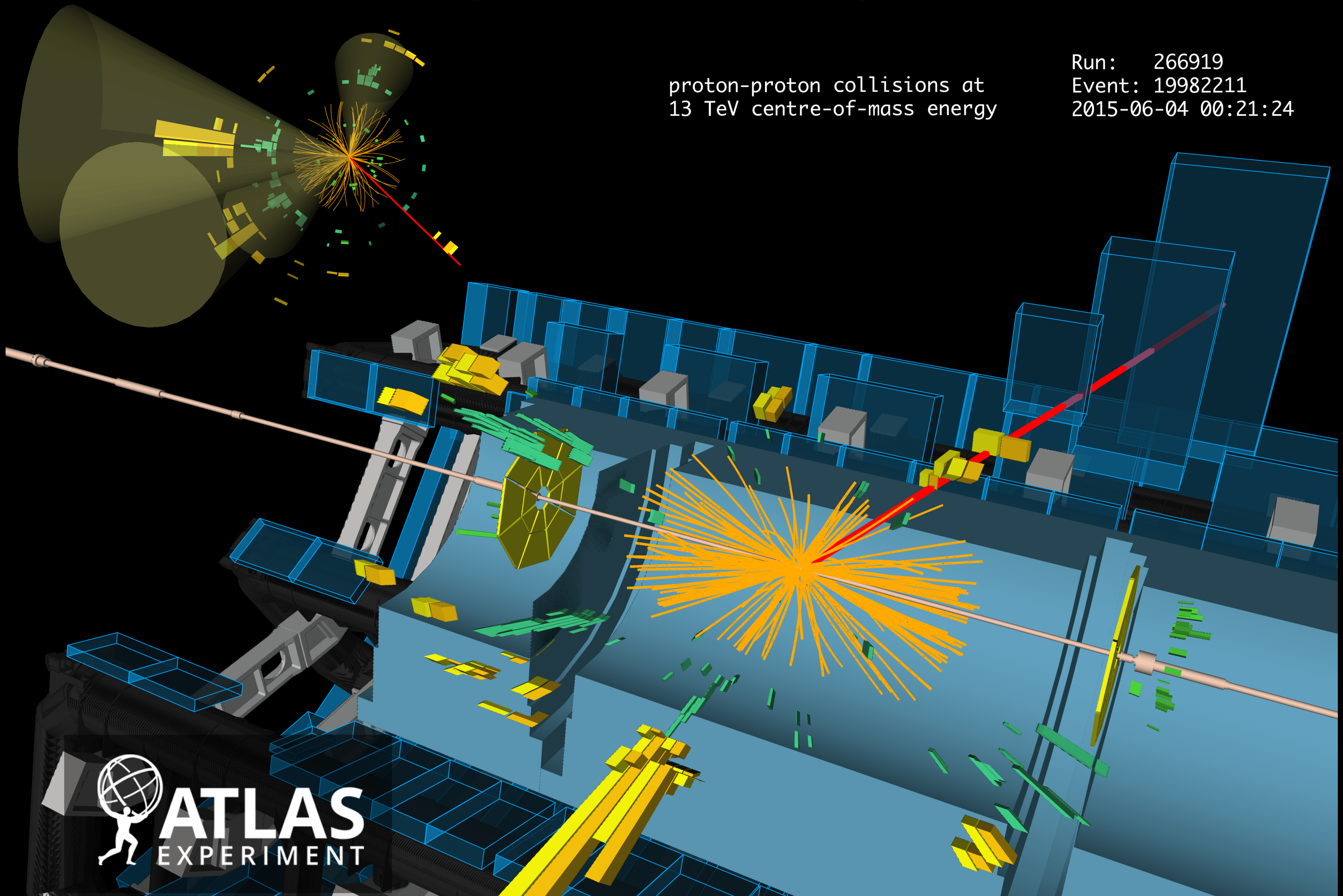


Double real **Real-virtual** **Two-loop virtual**

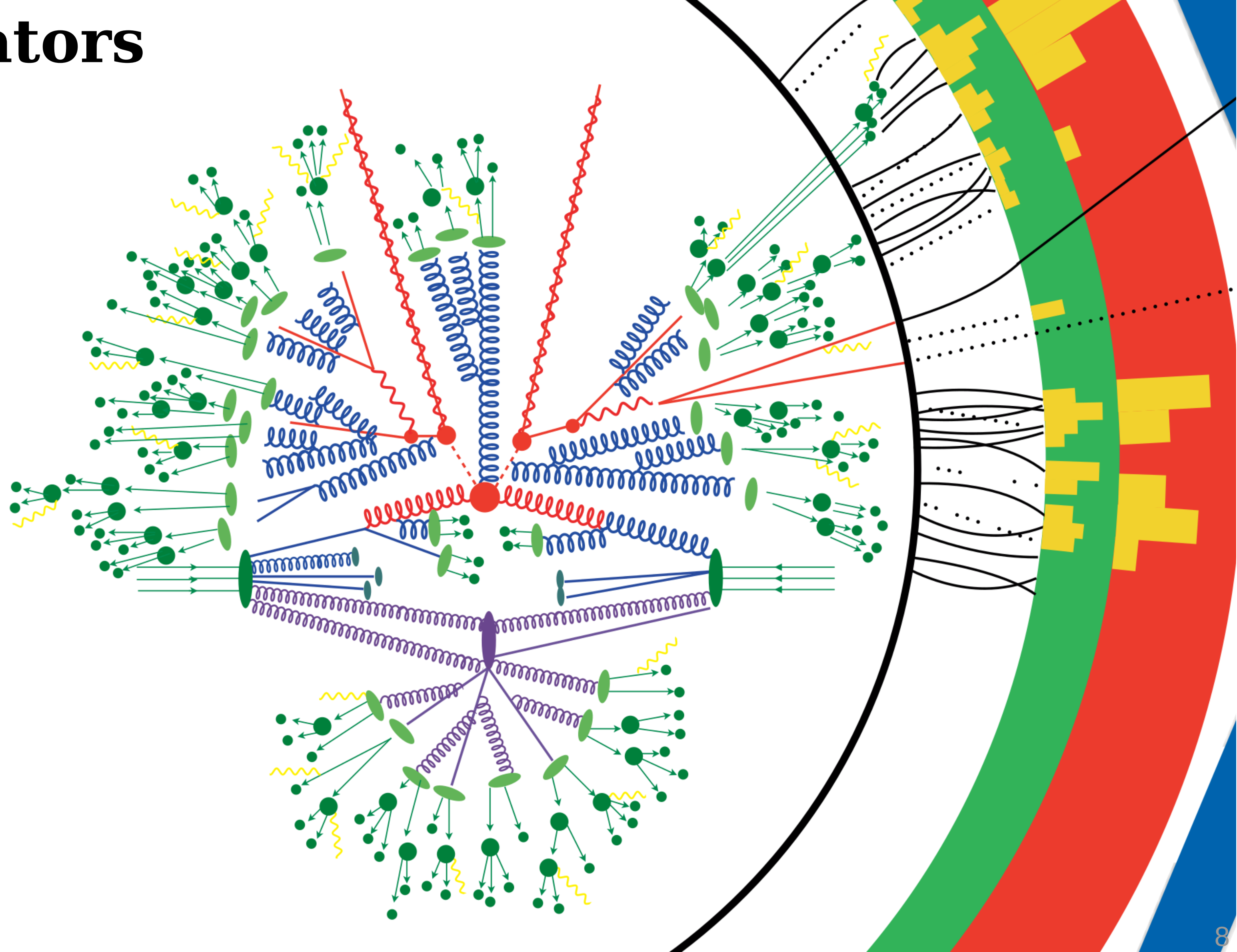
Small number of final-state particles

Free partons in the final state

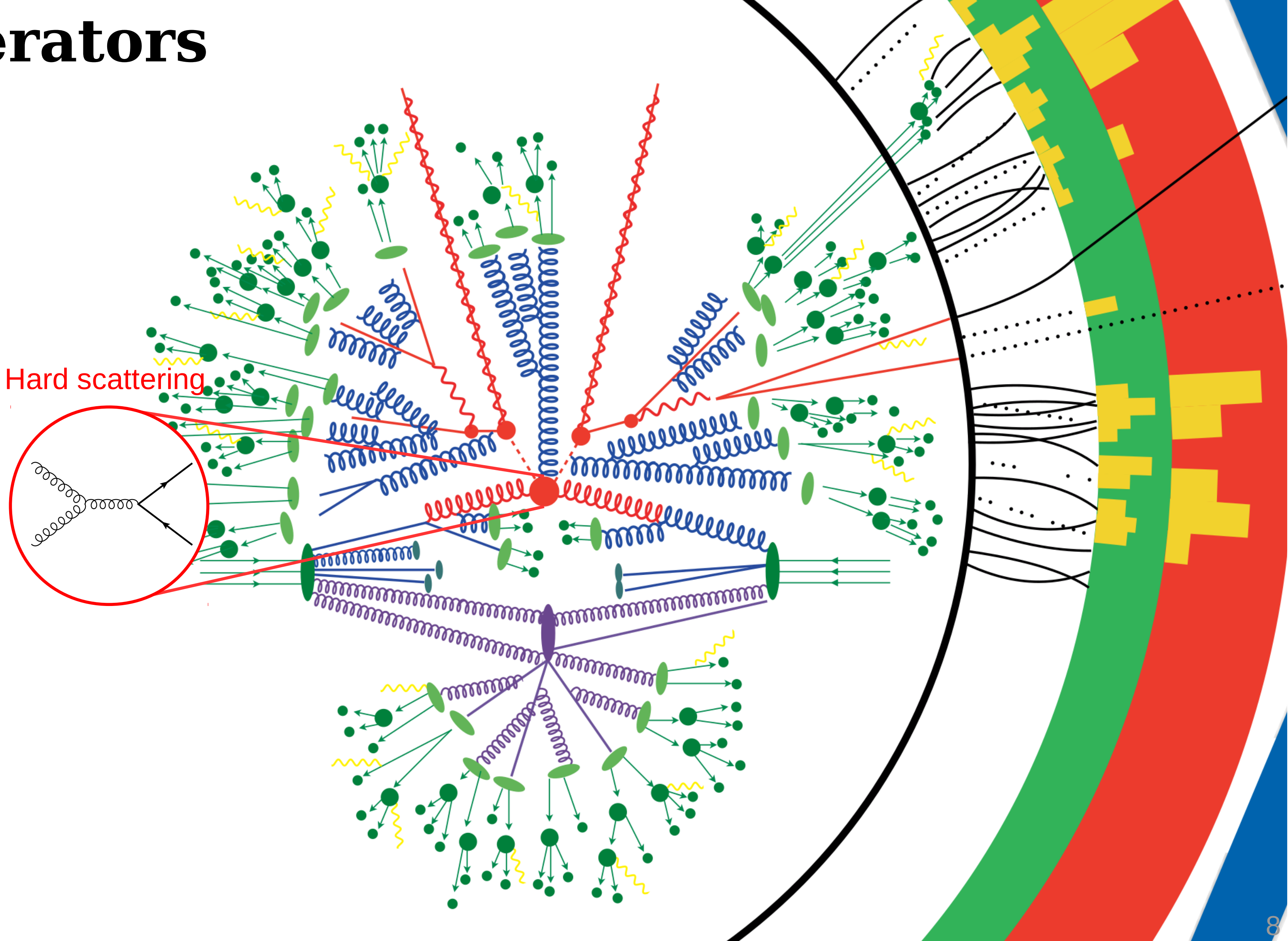
Actual events are more complicated → more complex simulations are needed!



Event Generators



Event Generators



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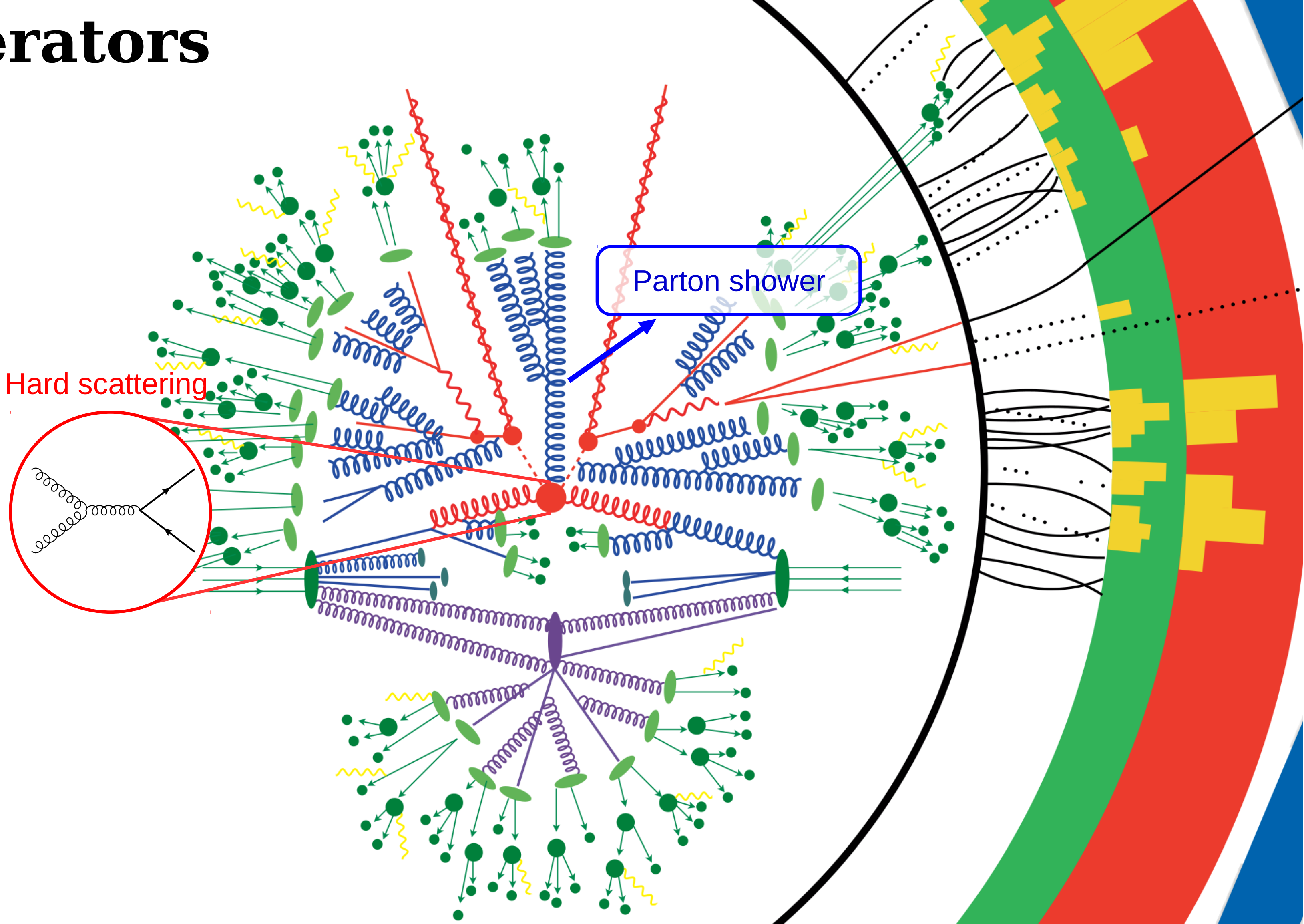

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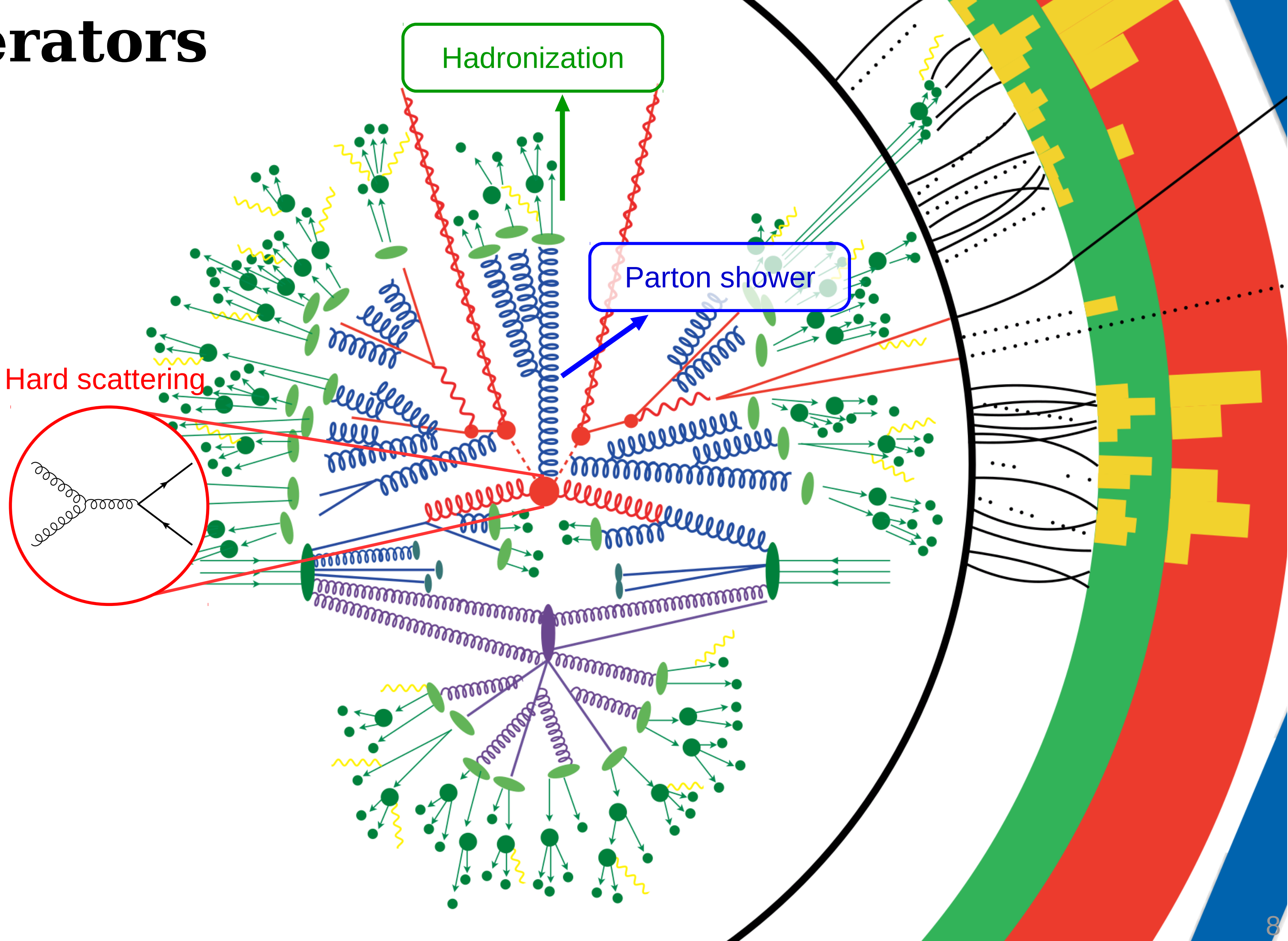
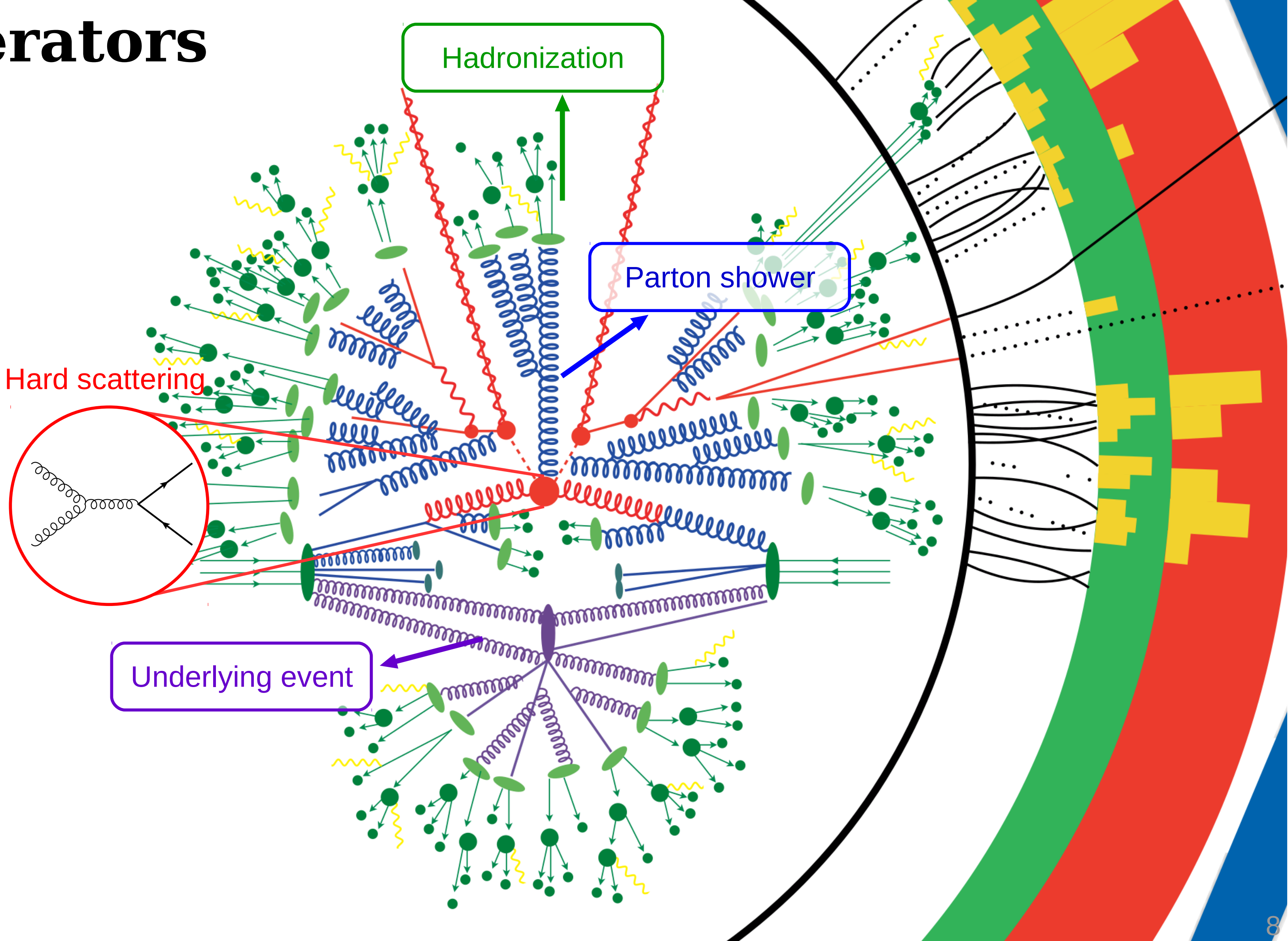
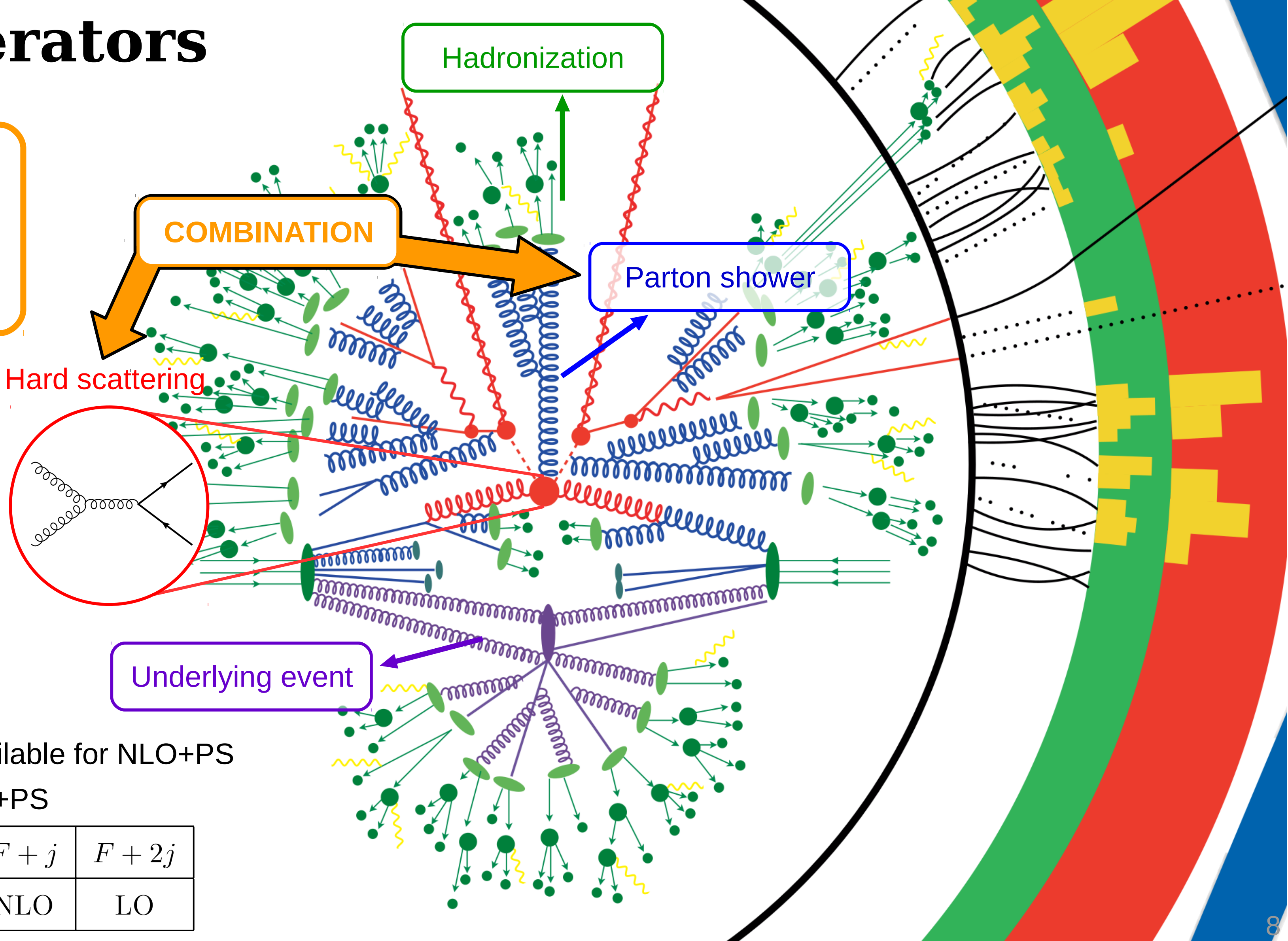


Event Generators



Event Generators

We want to keep the fixed-order accuracy when computing inclusive observables



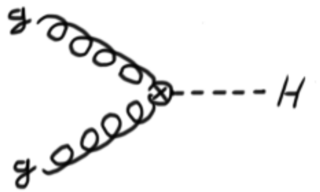
- General approaches available for NLO+PS
- Current frontier is NNLO+PS

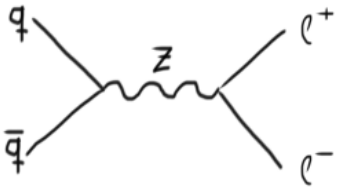
	F	$F+j$	$F+2j$
F@NNLO$_{\text{PS}}$	NNLO	NLO	LO

NNLO+PS

- seminal approaches for NLO+PS many years ago (POWHEG, MC@NLO)

- first NNLO+PS for simple 2→1 processes
  - ***MiNLO+reweighting*** [Hamilton, Nason, Zanderighi '12, + Re '13], [Karlberg, Hamilton, Zanderighi '14]
  - ***Geneva*** [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13], [Alioli, Bauer, Berggren, Tackmann, Walsh '15]
  - ***UNNLOPS*** [Höche, Prestel '14]



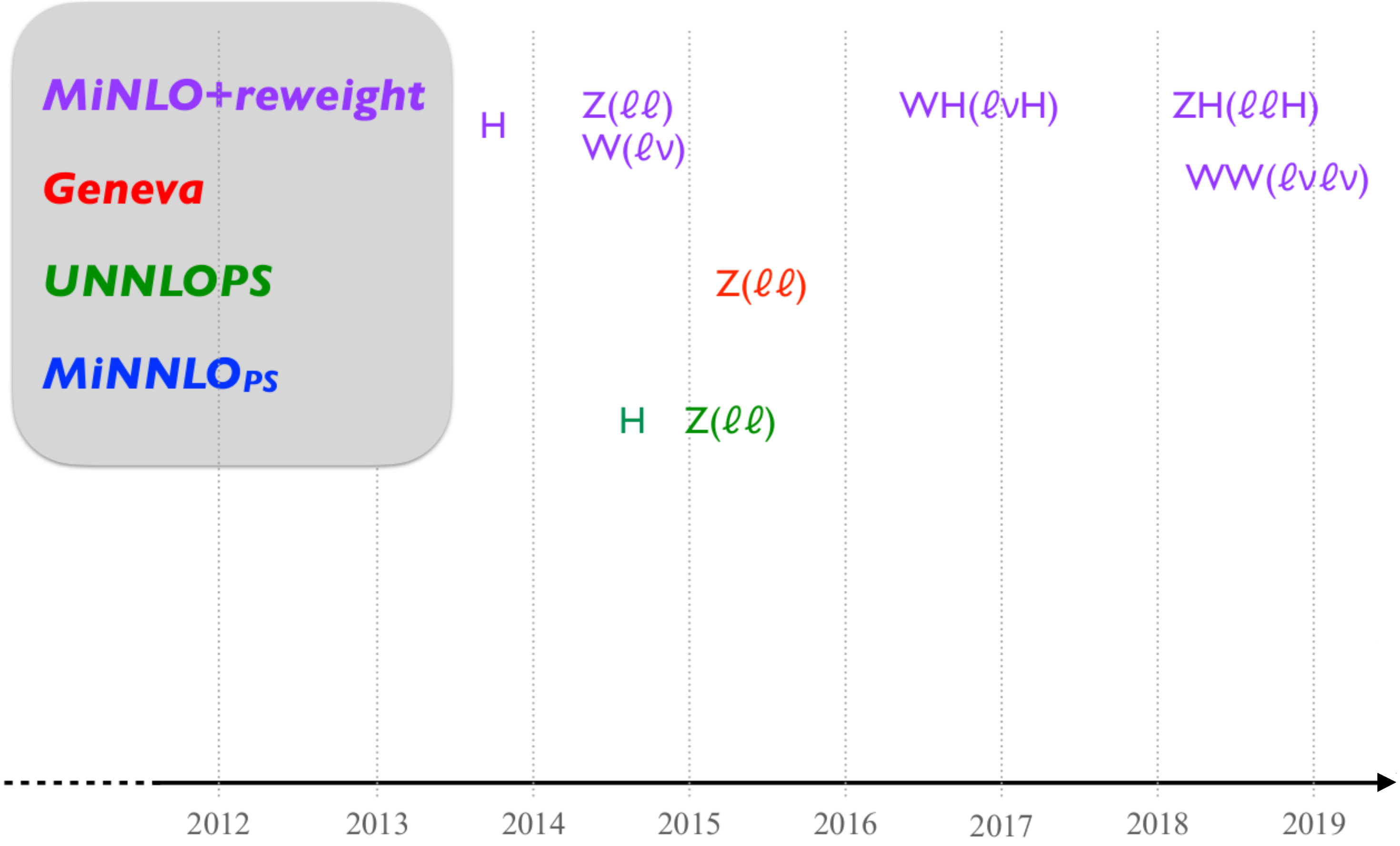


- ***MiNNLOPS***: new approach with enormous potential
  [Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]
  - NNLO corrections extracted from analytic resummation formula

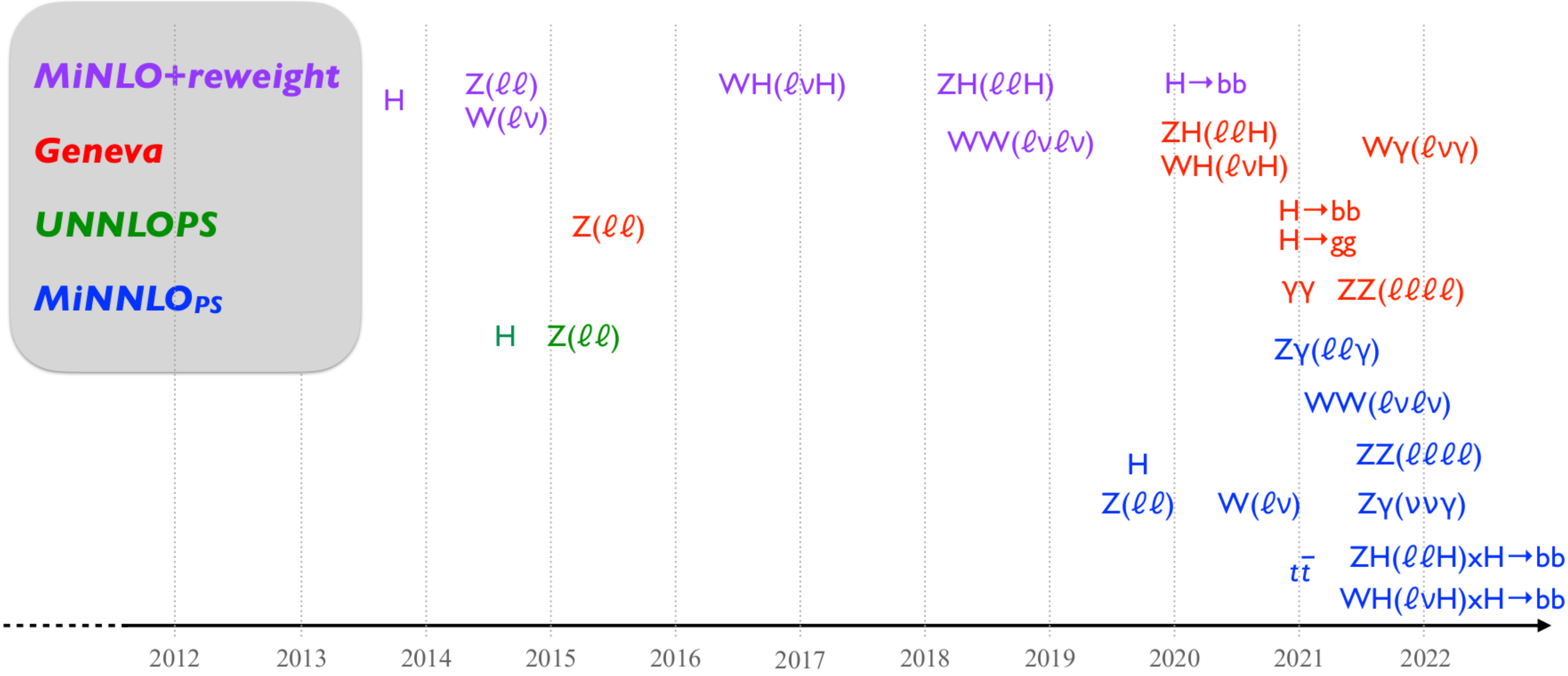
$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[HC_1C_2\right]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$

  - physically sound (no new unphysical scale)
  - applicable beyond 2→1 processes (even beyond colour-singlet)
  - numerically efficient

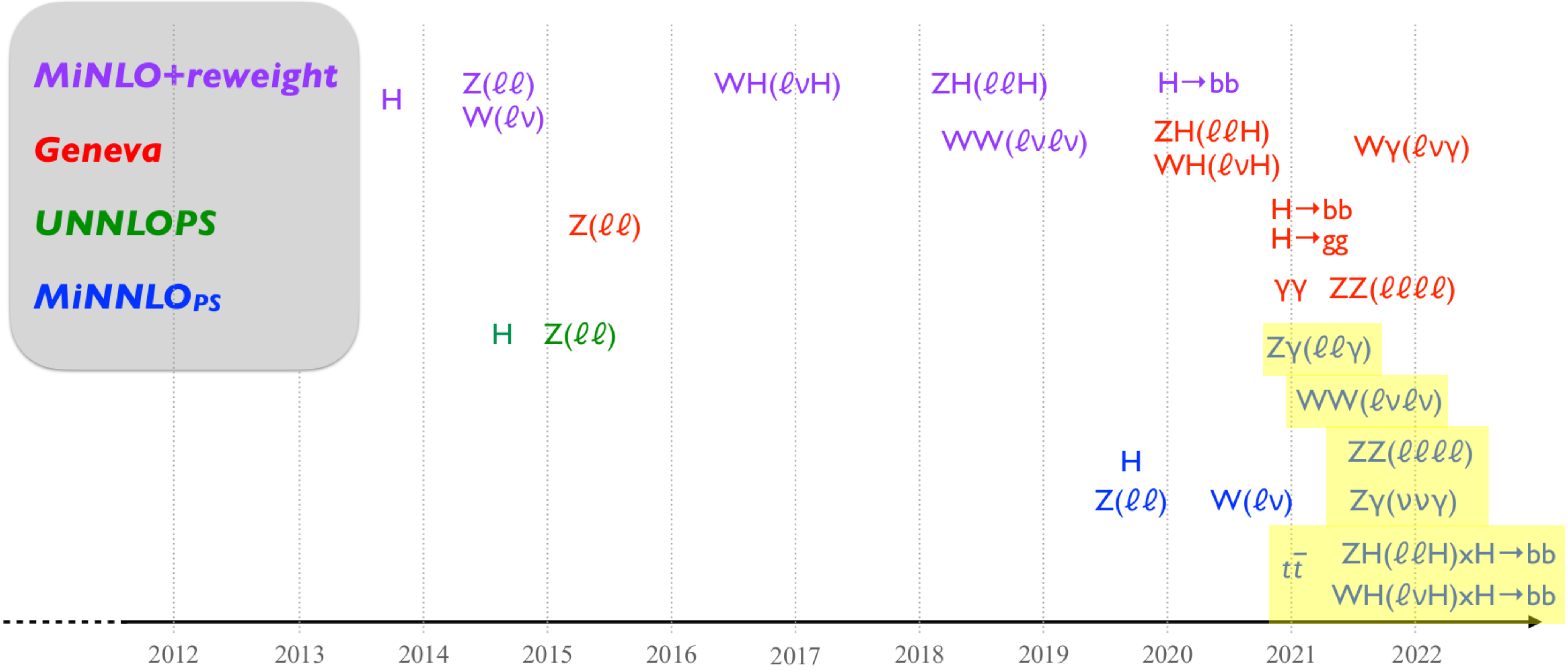
NNLO+PS Timeline



NNLO+PS Timeline



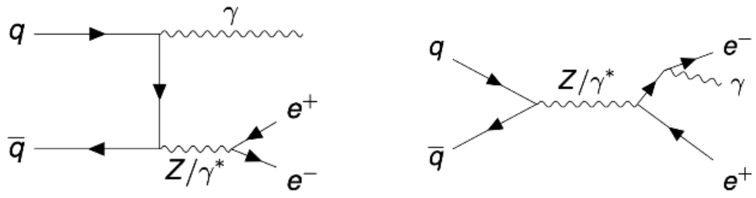
NNLO+PS Timeline



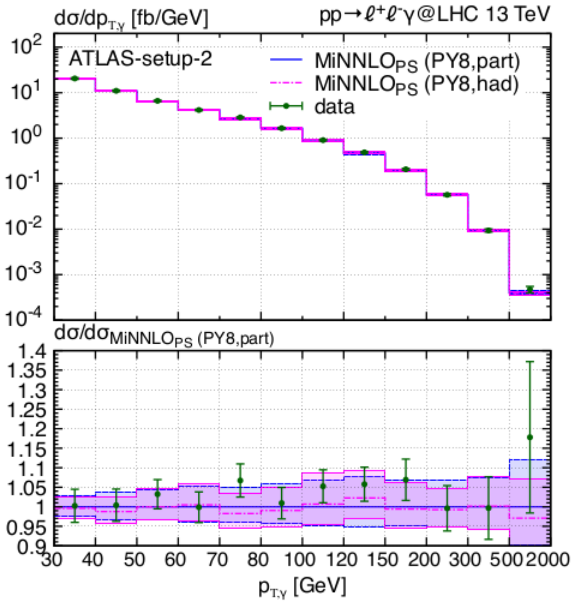
Zγ Phenomenology at the LHC

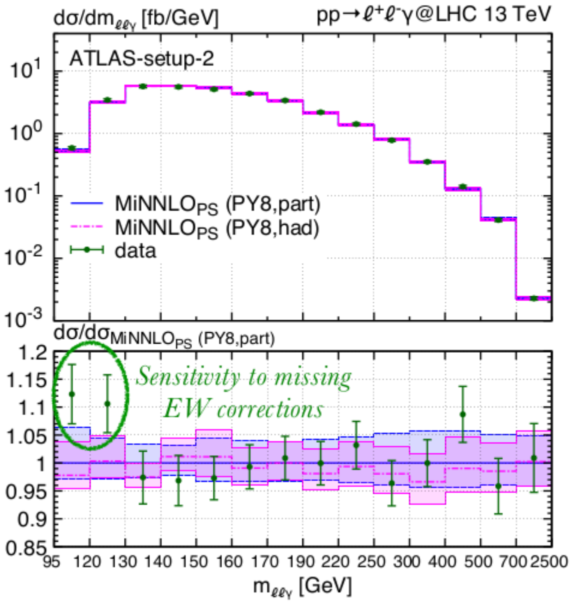
[Lombardi, Wiesemann, Zanderighi '20]

- $Z \to e^+e^-$ *event can be fully reconstructed*
- *presence of* ***isolated photon*** $\to$ *theoretically challenging*
- *highly relevant as a probe for BSM (especially* $Z \to \nu\bar{\nu}$*)*



Very good description of data from ATLAS 139fb⁻¹ analysis!



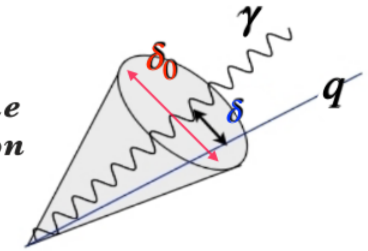


Photon isolation requirement:

- *Experimentally needed to identify hard photons*
- *Theoretically delicate definition of an infrared-safe cross section*

$$\sum_{had/part \in \delta} E_T^{had/part} \leq E_T^{max}(\delta) = E_T^{ref} \cdot \left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)^n, \quad \forall \delta \leq \delta_0$$

Frixione isolation



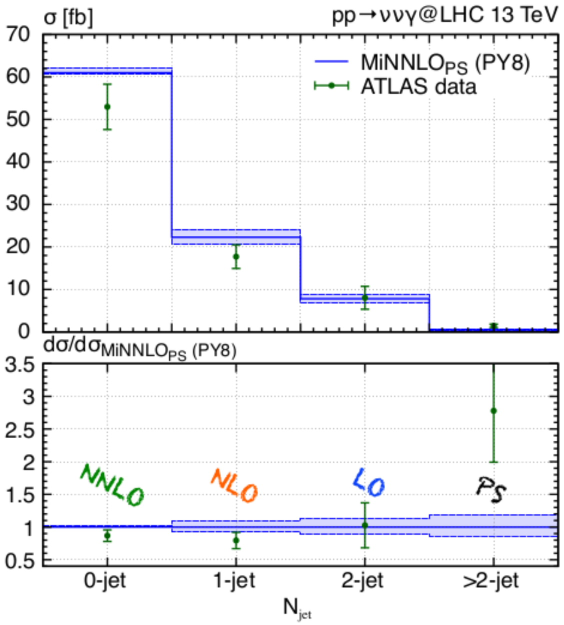
Zγ Phenomenology at the LHC

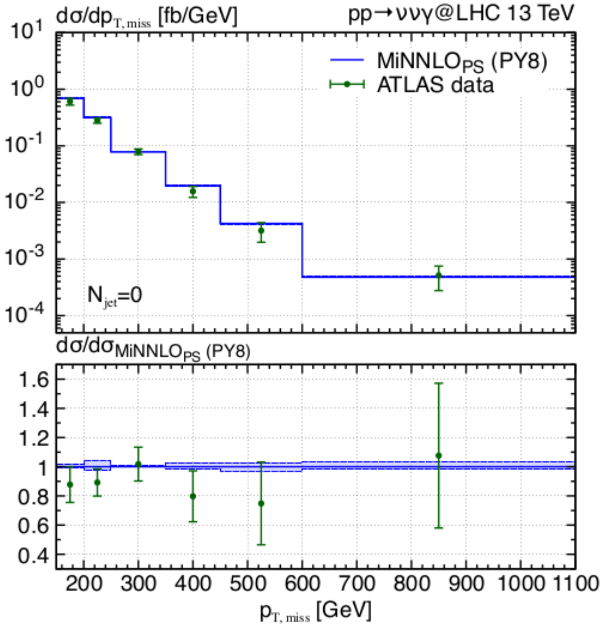
[Lombardi, Wiesemann, Zanderighi ‘21]

$Z \to \nu\bar{\nu}$

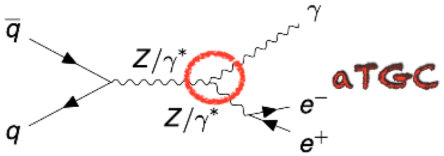
- *$Z \to e^+e^-$ event can be fully reconstructed*
- *presence of isolated photon → theoretically challenging*
- *highly relevant as a* ***probe for BSM*** *(especially $Z \to \nu\bar{\nu}$)*

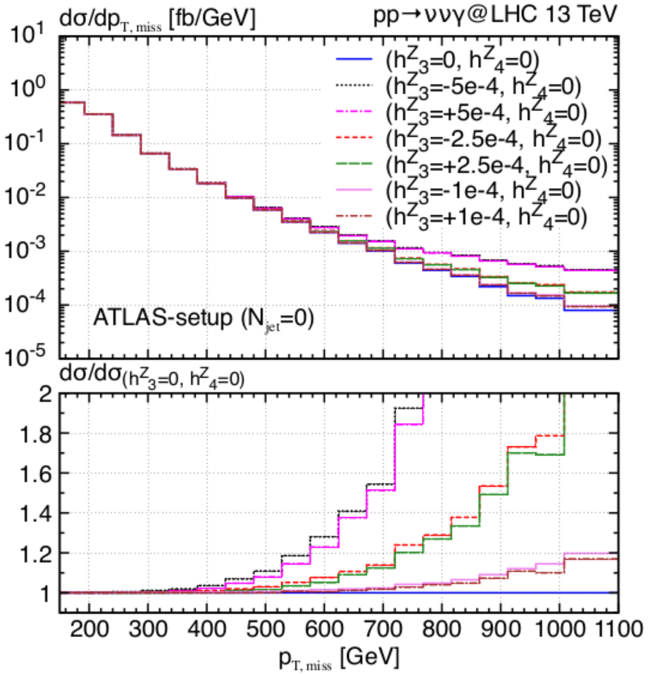
Good agreement with experimental data from ATLAS 36.1fb⁻¹ analysis!





$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,p) = \frac{i(p^2-m_V^2)}{\Lambda^2}\Big(h_1^V \left(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{\Lambda^2} p^\alpha \left(p\cdot q_2\, g^{\mu\beta} - q_2^\mu p^\beta\right) - h_3^V \varepsilon^{\mu\alpha\beta\nu} q_{2\nu} - \frac{h_4^V}{\Lambda^2}\varepsilon^{\mu\beta\nu\sigma}p^\alpha p_\nu q_{2\sigma}\Big)$$

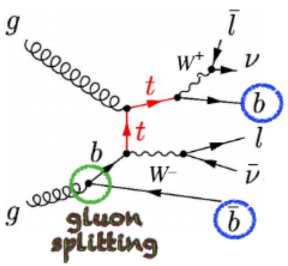




WW Phenomenology at the LHC

[Lombardi, Wiesemann, Zanderighi '21]

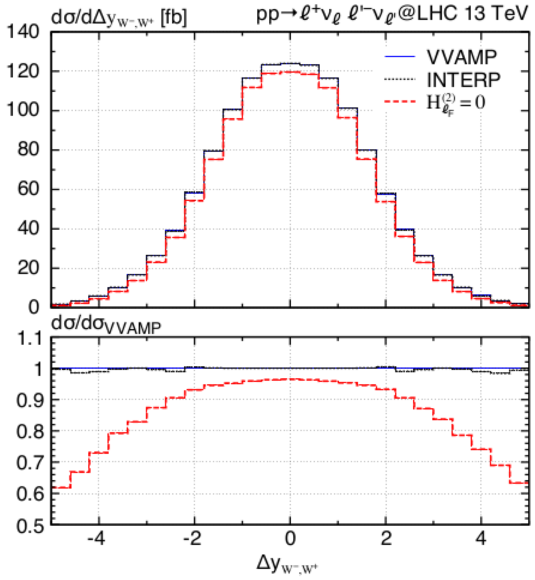
- *largest cross section among massive diboson processes*
- *direct access to anomalous triple gauge couplings*
- *no full event reconstruction due to neutrinos → high-accurate theoretical predictions required*
- *analysis requires a* ***jet-veto*** *→ theoretical modelling important*

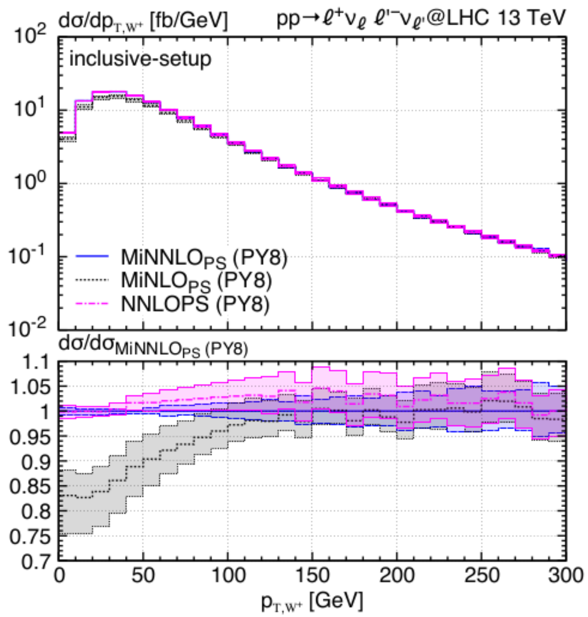


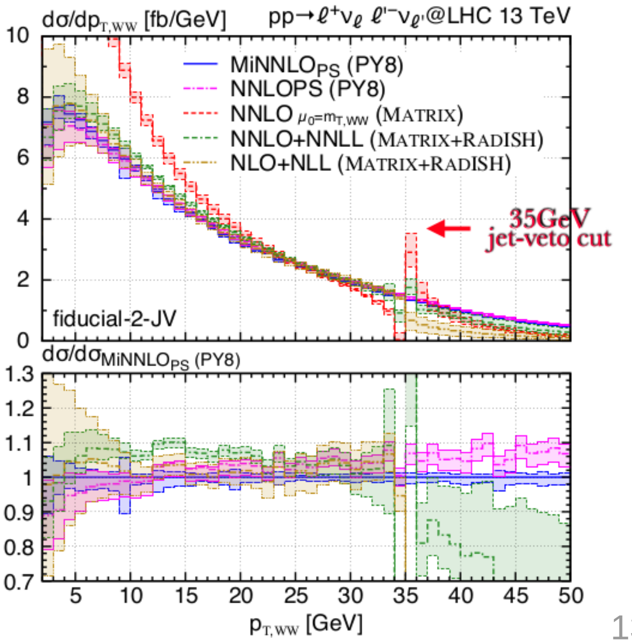
Jet-veto requirement:

- *Experimentally needed to reduce top background*
- *Theoretically involved definition of WW cross section, due to diagrams with resonant top quarks and b final states:*
  - *Interference with double-real diagrams*
  - *Not separately finite for massless b quarks*

Two-loop contributions evaluated with
4D cubic spline interpolation





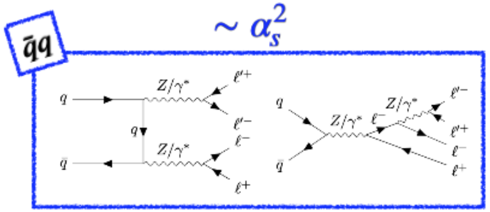


ZZ Phenomenology at the LHC

[Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi '21]

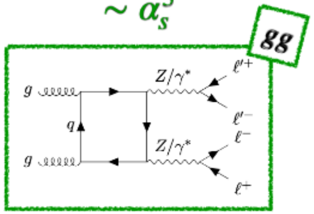
- *smallest cross section among massive diboson processes, but very clean signature*
- *relevant for BSM searches*
- *important for constraining the Higgs width and Higgs couplings*

$\sim \alpha_s^2$



NNLO+PS using MiNNLO$_{PS}$

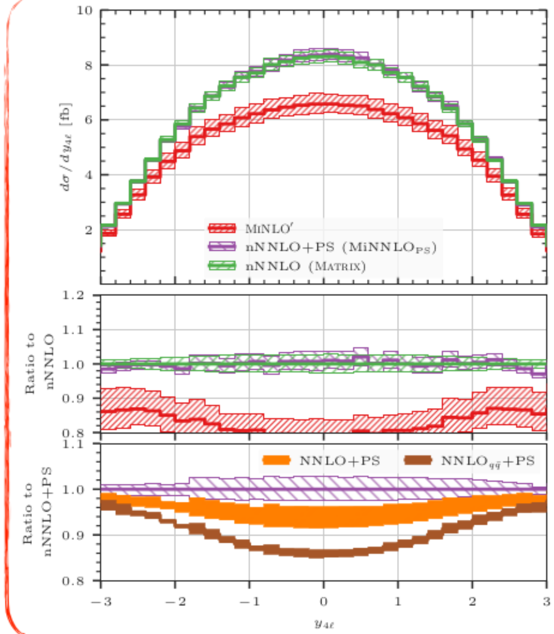
$\sim \alpha_s^3$



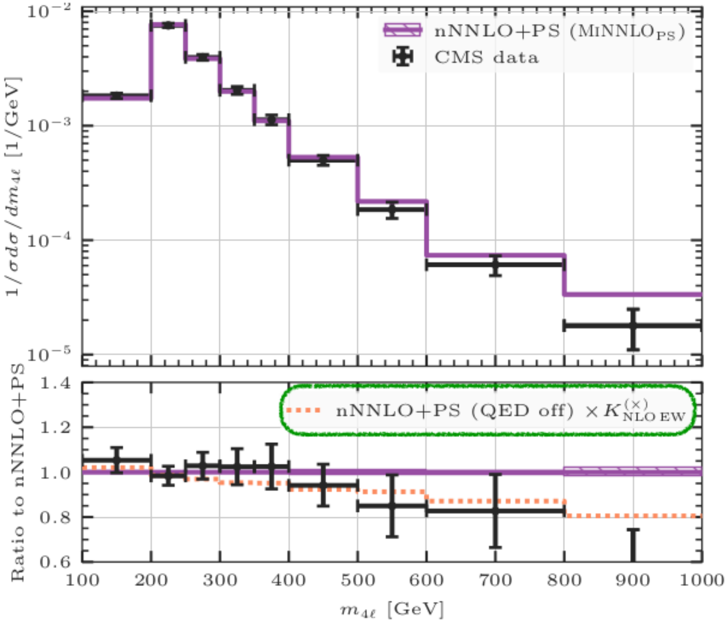
NLO+PS with POWHEG

$$pp \to \ell^+\ell^-\ell^{(\prime)+}\ell^{(\prime)-}$$

Incoherent combination → nNNLO+PS



*Sizeable effects of the **gluon loop-induced** channel at NLO in the bulk regions of distributions!*

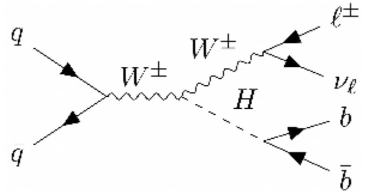


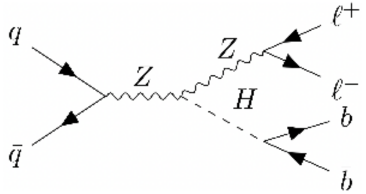
Comparison with CMS 137fb^{-1} analysis!

NLO EW corrections needed for a reliable descriptions of tails of distributions

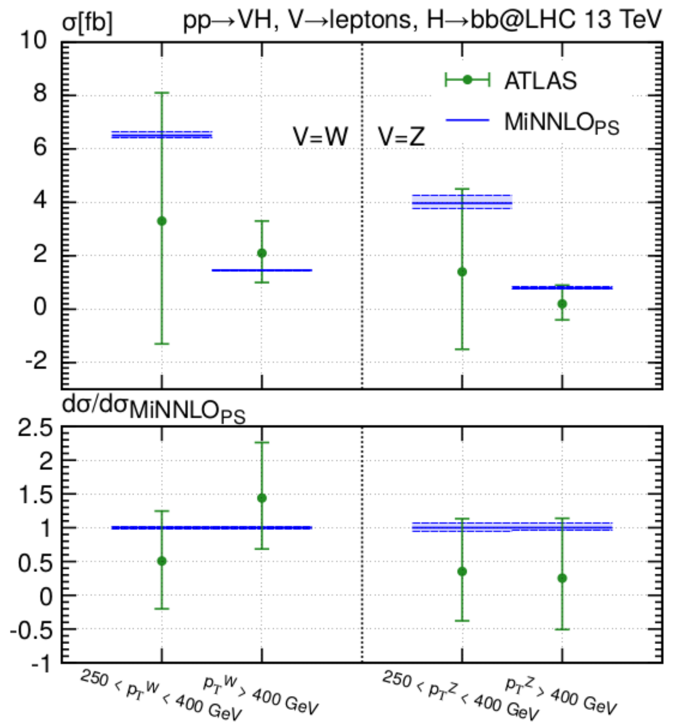
Higgsstrahlung with H→bb decay

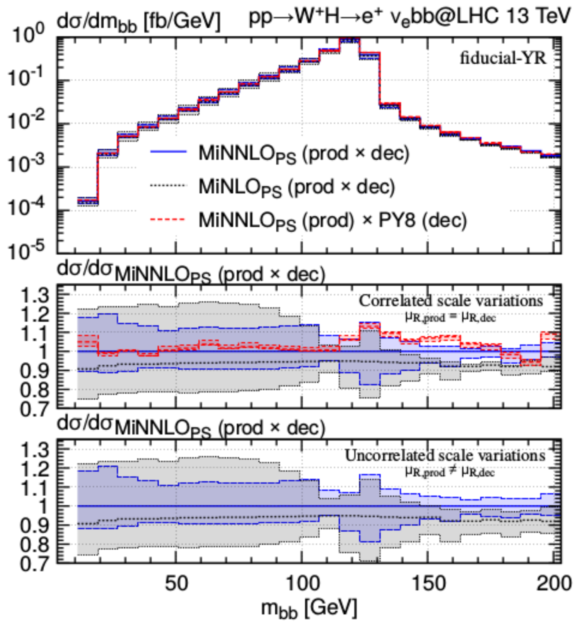
[Zanoli, Chiesa, Re, Wiesemann, Zanderighi '21]

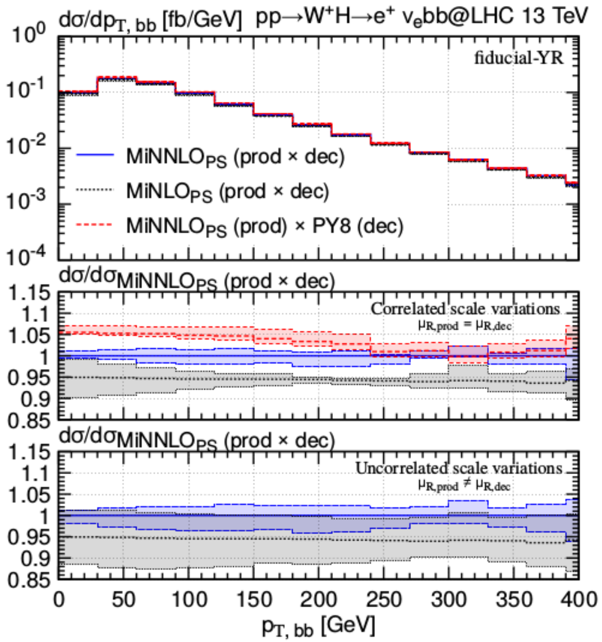




- *Needed for* ***precision measurement*** *in the Higgs sector*
- *One of the main production channels + largest branching fraction in decay*
- ***NNLO+PS*** *accuracy in both* ***production and decay***





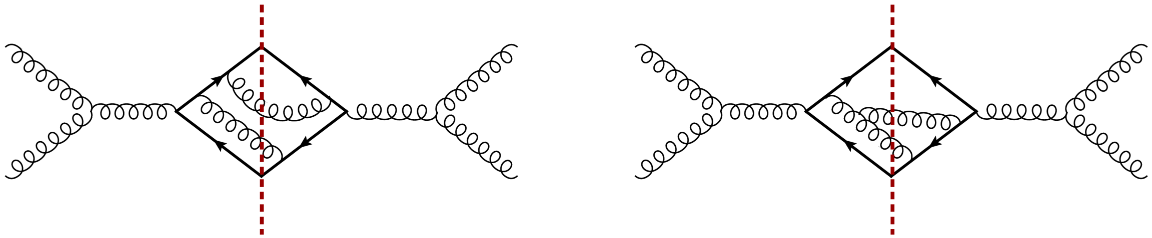


NNLO+PS for Heavy Quarks

[JM, Monni, Nason, Re, Wiesemann, Zanderighi '21]

- MiNNLO$_{PS}$ method recently extended to top-quark pair production
- Qualitative advancement in the NNLO$_{PS}$ field: first method beyond colour singlet
- Paving the way to more complicated processes
- Incredibly relevant for LHC phenomenology → ~40% of analyses using $t\bar{t}$ predictions

More complicated structure due to final-state soft radiation...



… leading to colour interference effects

Colour singlet: $$d\sigma^{(\text{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[H C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

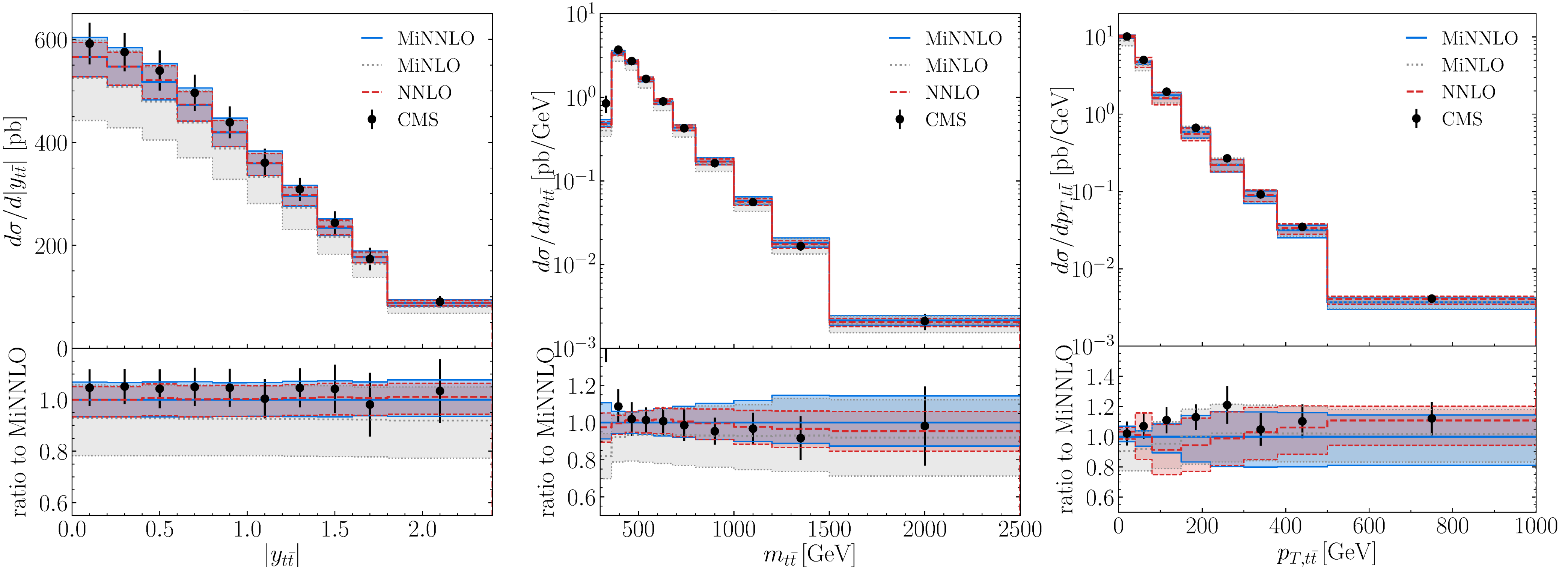
Top-pair production: $$d\sigma^{(\text{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[\text{Tr}(\mathbf{H}\boldsymbol{\Delta}) C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

Effects coming from soft emissions from the FS contained in operator **Δ**

Top-pair Production at NNLOPS

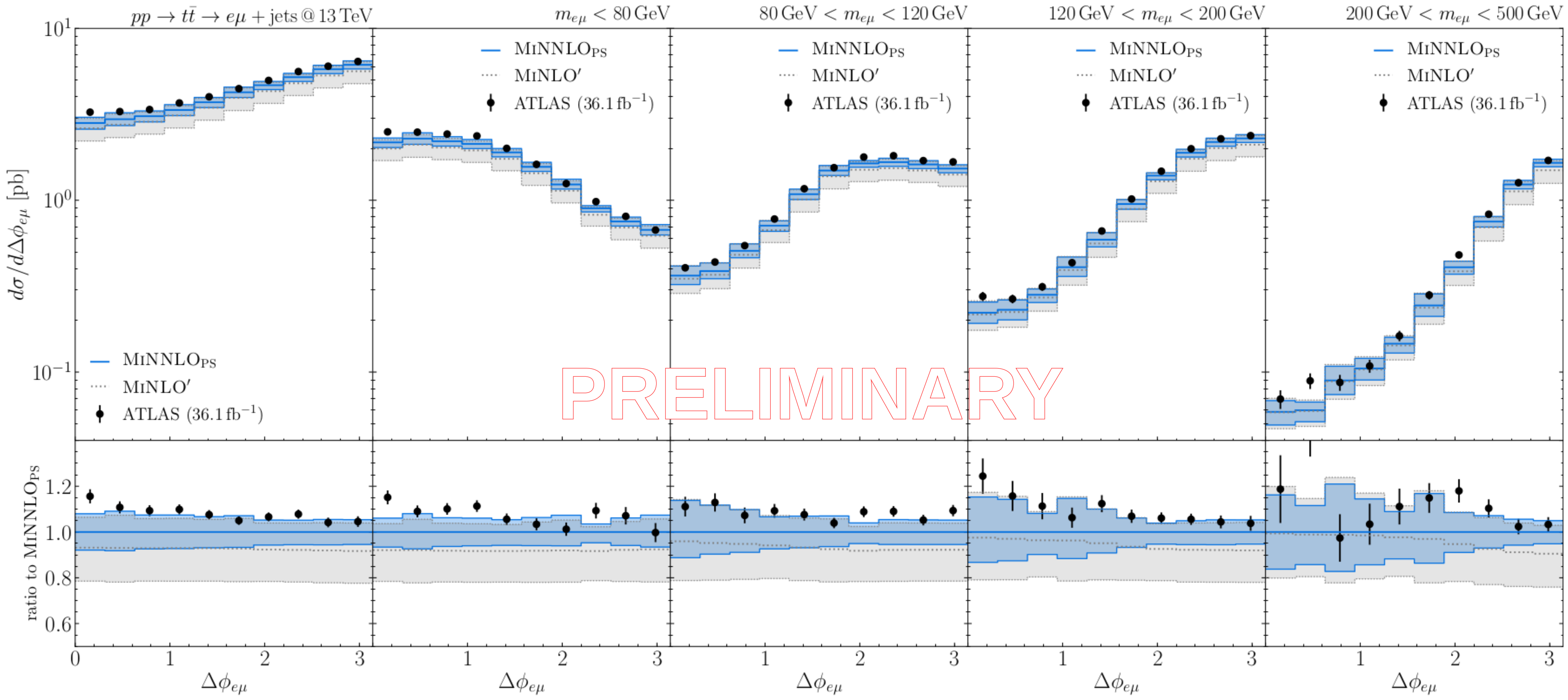
[JM, Monni, Nason, Re, Wiesemann, Zanderighi ‘21]

- Results for stable top quarks:



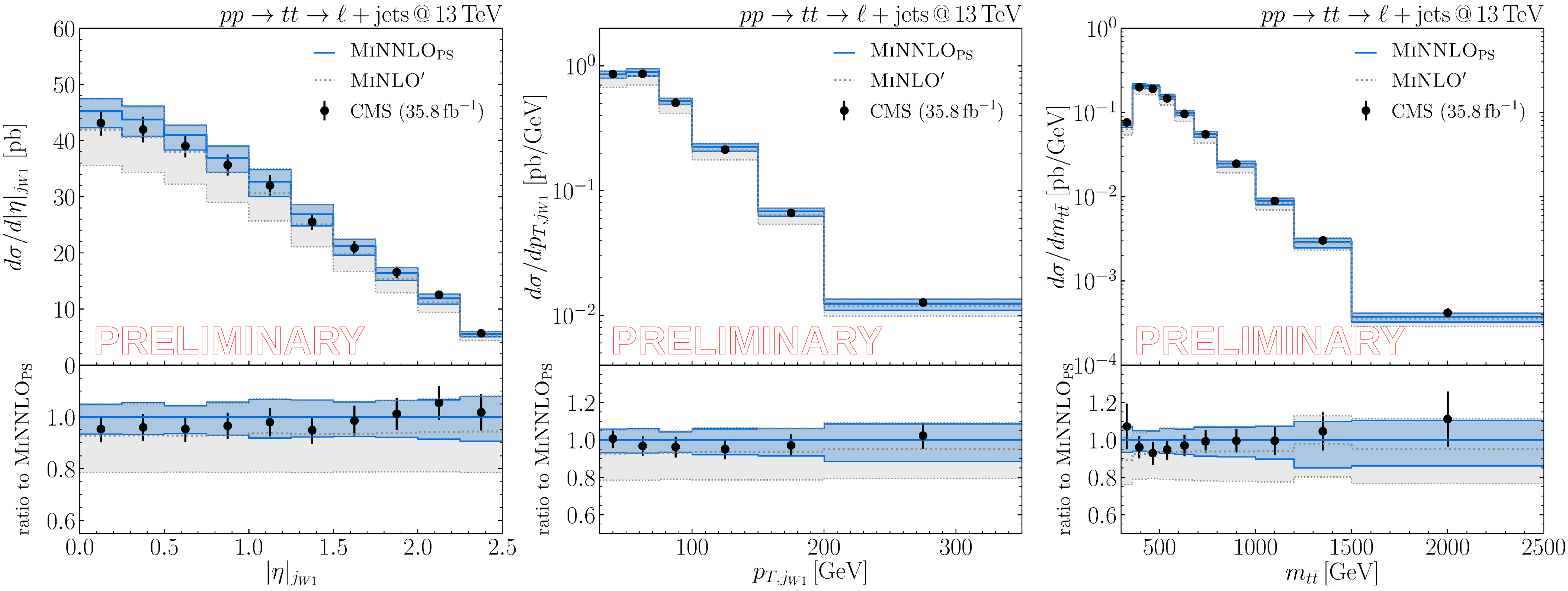
- Excellent agreement with NNLO fixed-order, both in normalization and shape!

- Including top decays using ratio of tree-level decayed and undecayed MEs
- Both W bosons decaying leptonically, comparison to ATLAS analysis:



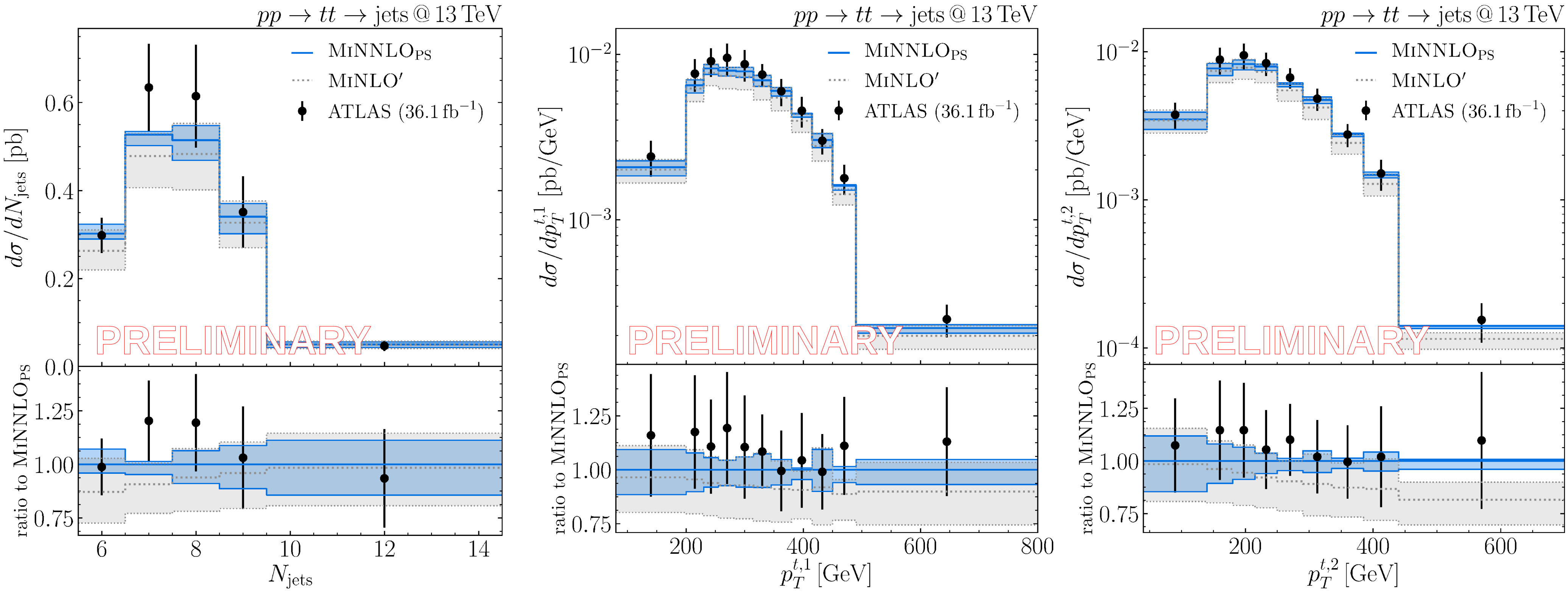
- Azimuthal angle between electron and muon → spin correlations

- Including top decays using ratio of tree-level decayed and undecayed MEs
- W bosons decaying semi-leptonically, comparison to CMS analysis:



- Rapidity and p_T of leading jet coming from reconstructed W, and reconstructed $t\bar{t}$ invariant mass

- Including top decays using ratio of tree-level decayed and undecayed MEs
- Both W bosons decaying hadronically, comparison to ATLAS analysis:



- Rapidity and p_T of leading jet coming from reconstructed W, and reconstructed $t\bar{t}$ invariant mass

[JM, Monni, Nason, Re, Wiesemann, Zanderighi]

- Including top decays using ratio of tree-level decayed and undecayed MEs
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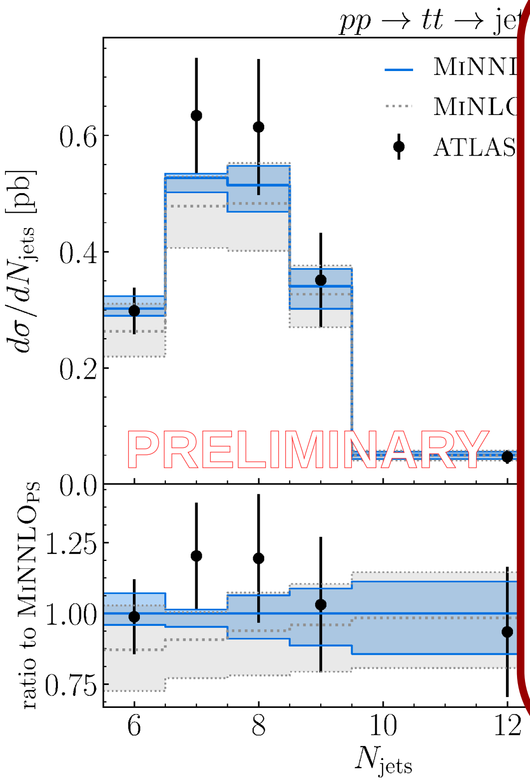
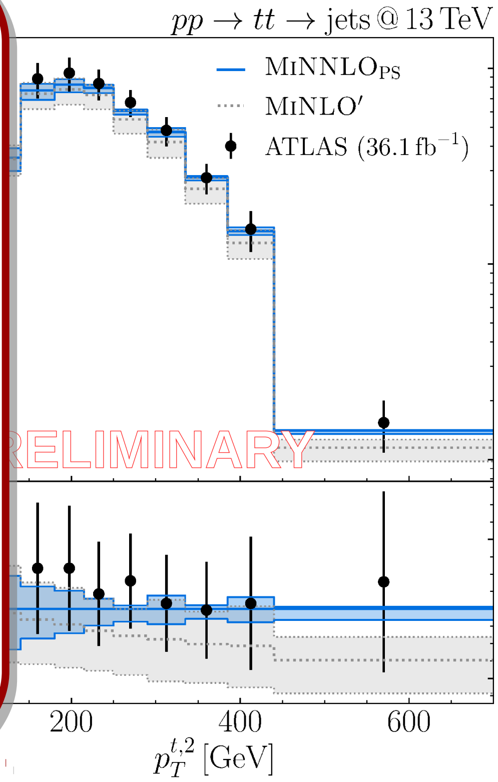


- Great reduction of uncertainties w.r.t. NLOPS
- Excellent agreement with data
- Public code available very soon!
- Further refinements foreseen in future work

Off-shell effects | Higher accuracy in decays | Non-resonant contributions

- Extension to other top-quark processes
- Application to bottom-pair production ongoing

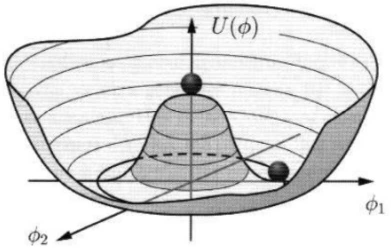
[JM, Ratti, Wiesemann, Zanderighi]



- Rapidity and p_T of leading jet coming from reconstructed W, and reconstructed $t\bar{t}$ invariant mass

The Higgs Potential

- Most of the SM already under scrutiny from LHC searches
- One sector barely explored so far: Higgs boson potential, responsible for EWSB

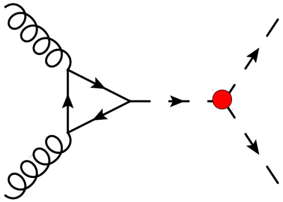


After EWSB, the potential leads to Higgs self interactions

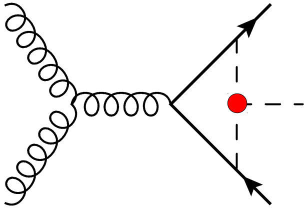
$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

In the SM: $\lambda = \lambda' = M_H^2/(2v^2)$

- Measuring or bounding the trilinear coupling is one of the main tasks of future LHC runs
- Two ways to measure λ



Higgs pair production

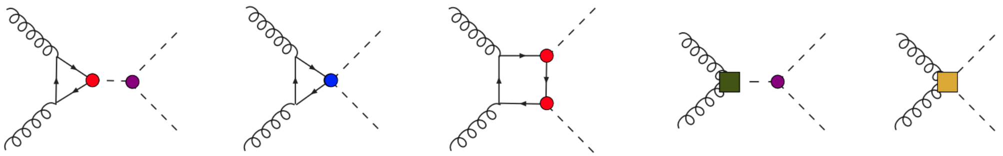


Loop-induced effects in other observables

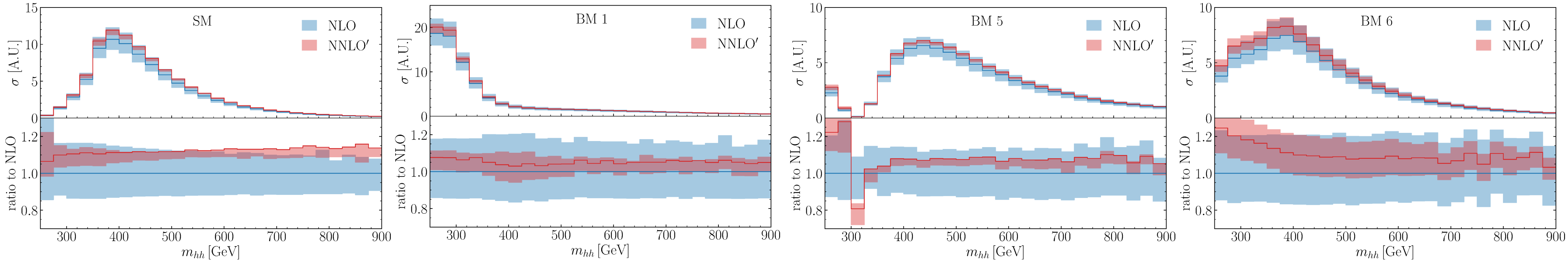
HH at NNLO with Anomalous Couplings

- We consider the HEFT operators affecting HH production

$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$



- NLO corrections → full top mass dependence
  NNLO piece → Born-improved Heavy Top Limit } NNLO'



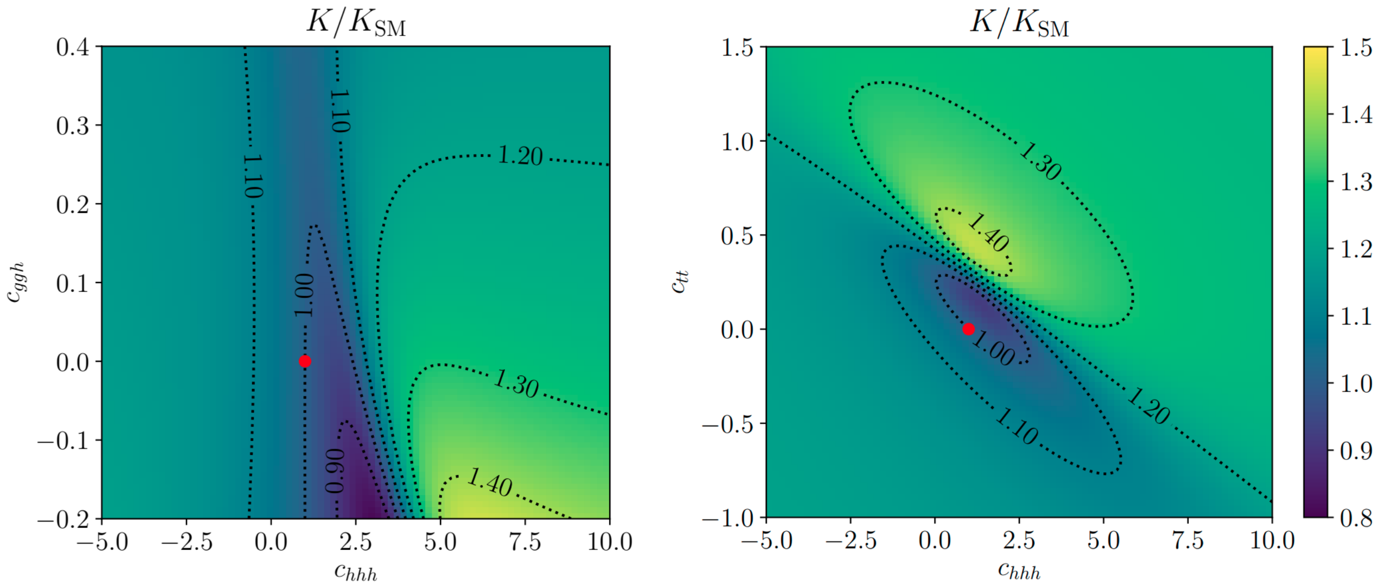
[de Florian, Fabre, Heinrich, JM, Scyboz '21]

HH at NNLO with Anomalous Couplings

- NNLO cross section can be parameterized in terms of anomalous couplings

$$\begin{aligned}\sigma_{\rm BSM}/\sigma_{\rm SM} = &\ a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\ &+ a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh} + a_{11}\, c_t^2 c_{ggh} c_{hhh} + a_{12}\, c_t^2 c_{gghh} \\ &+ a_{13}\, c_t c_{hhh}^2 c_{ggh} + a_{14}\, c_t c_{hhh} c_{gghh} + a_{15}\, c_{ggh} c_{hhh} c_{gghh} + a_{16}\, c_t^3 c_{ggh} \\ &+ a_{17}\, c_t c_{tt} c_{ggh} + a_{18}\, c_t c_{ggh}^2 c_{hhh} + a_{19}\, c_t c_{ggh} c_{gghh} + a_{20}\, c_t^2 c_{ggh}^2 \\ &+ a_{21}\, c_{tt} c_{ggh}^2 + a_{22}\, c_{ggh}^3 c_{hhh} + a_{23}\, c_{ggh}^2 c_{gghh} + a_{24}\, c_{ggh}^4 + a_{25}\, c_{ggh}^3 c_t\end{aligned}$$

- We performed a fit and obtained the values of the a_i coefficients



$$\frac{\sigma^{\rm BSM}_{\rm NNLO}}{\sigma^{\rm BSM}_{\rm LO}} \Big/ \frac{\sigma^{\rm SM}_{\rm NNLO}}{\sigma^{\rm SM}_{\rm LO}}$$

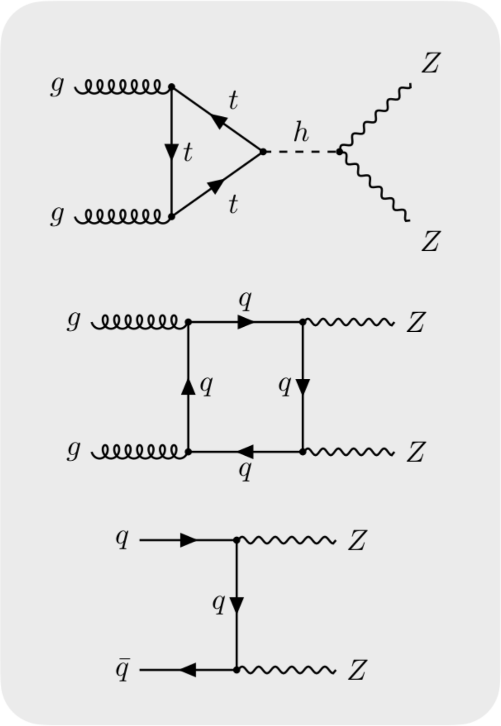
Can present ~40% variations depending on the couplings

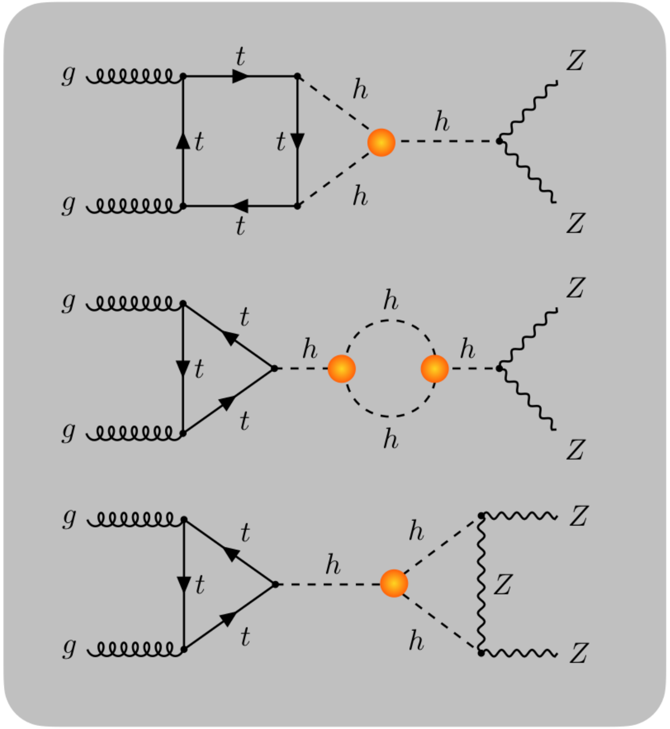
Importance of computing QCD corrections for BSM couplings

[de Florian, Fabre, Heinrich, JM, Scyboz ‘21]

Limits from off-shell H production

[Haisch, Koole ‘21]





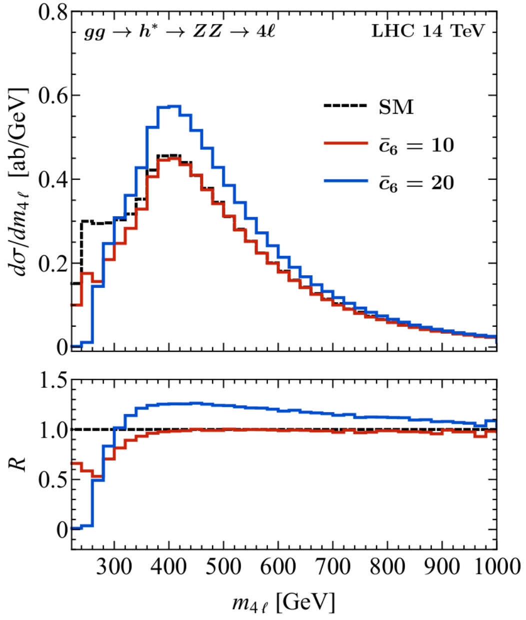
Calculation in SMEFT

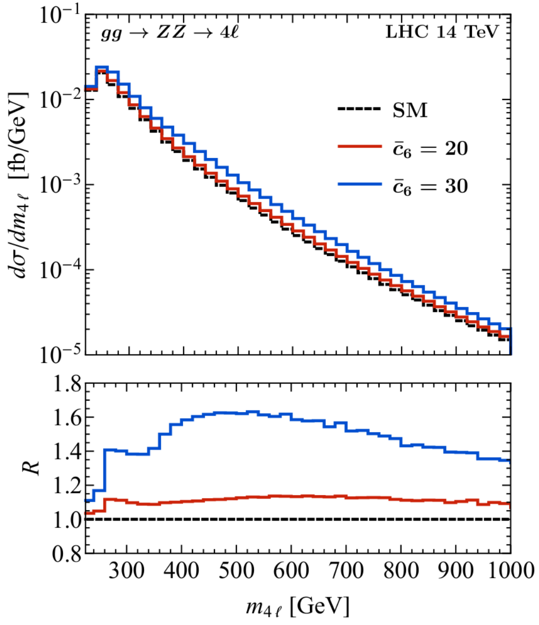
Two operators affecting the trilinear coupling

$\mathcal{O}_6 = -\lambda |H|^6 \,, \qquad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|\right)^2$

$$c_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$

- Both resonant and non-resonant contributions included
- Effect from SMEFT operators O_6 and O_H on self coupling (c_3) via loop corrections





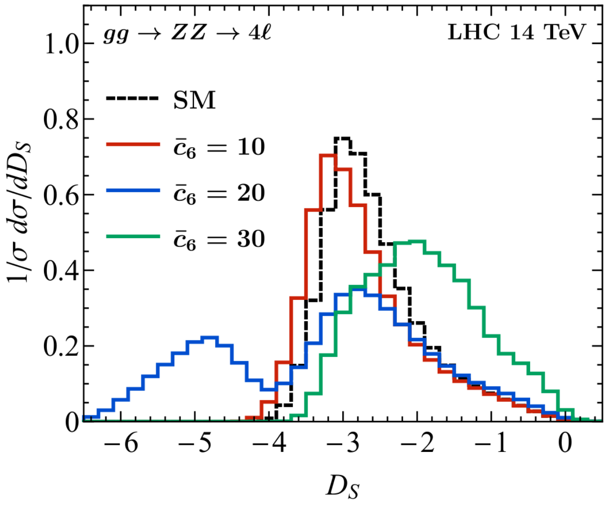
- Four lepton invariant mass and ME-based discriminant D_S have been studied
- Phenomenologically relevant kinematic effects found in both spectra

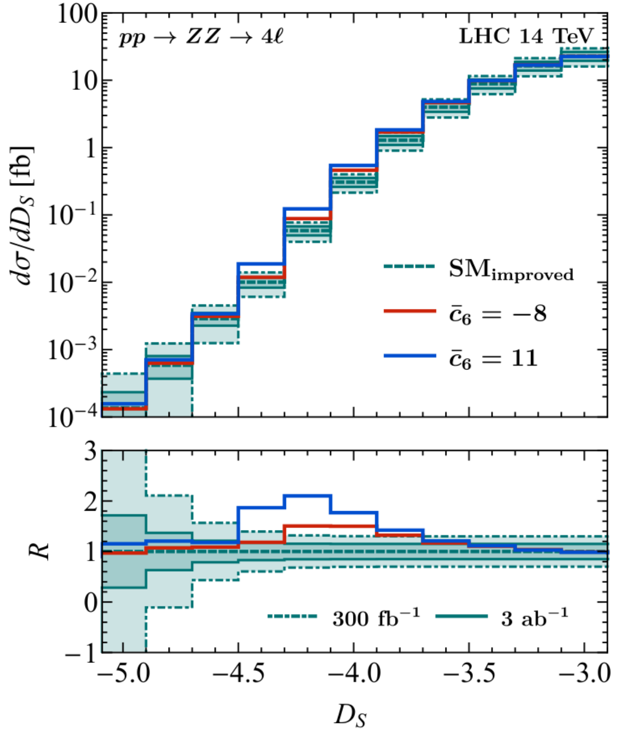
squared matrix element for gg→h*→ZZ→4l

$$D_S = \log_{10}\left(\frac{P_h}{P_{gg} + 0.1 \cdot P_{q\bar{q}}}\right)$$

squared matrix element for gg→ZZ→4l

squared matrix element for q$\bar{q}$→ZZ→4l

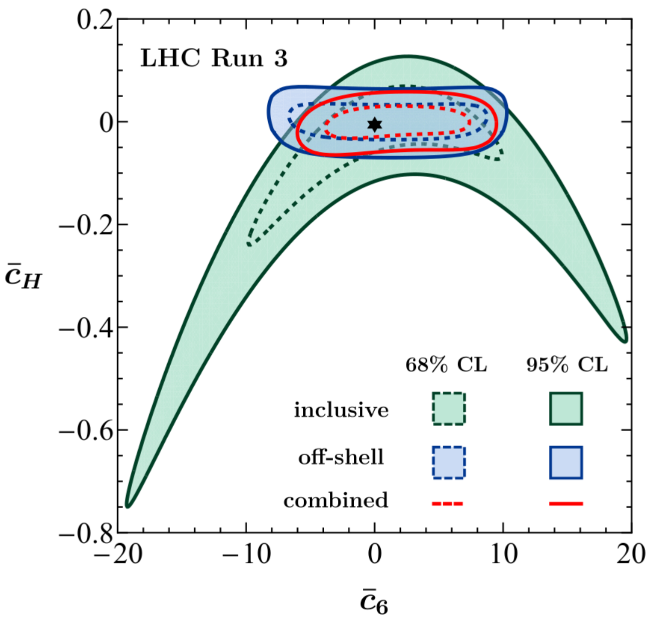


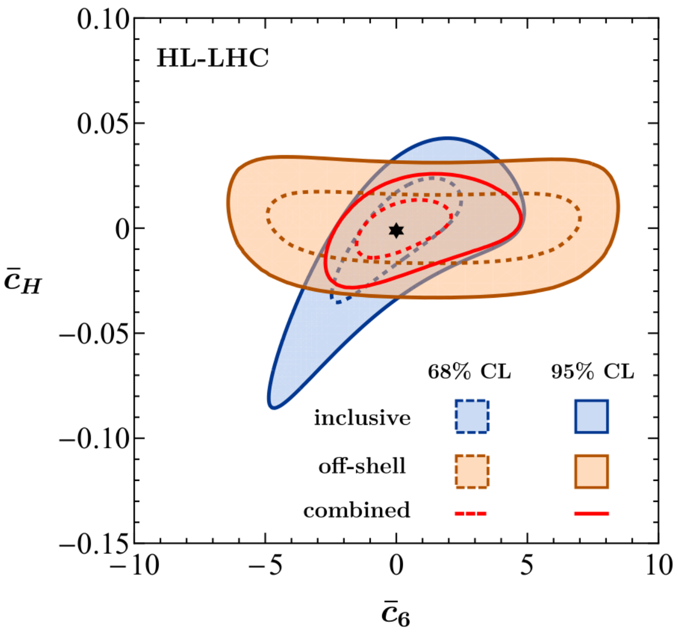


Projected Limits on c_3

[Haisch, Koole '21]

- Projected limits for Run3 and HL-LHC have been derived
- Compared to the projected limits from inclusive single-H production
- Bounds found to be competitive and complementary to the inclusive ones → remove flat directions





Combined 95% C.L. limits: $c_3 \in [-4.0, 6.1]$ $c_3 \in [-1.7, 5.7]$

- Projections from double-Higgs production will strengthen the constraints

Summary

- Without clear NP signals, quest for BSM is focusing more in small deviations
- Precise theory predictions are in this context indispensable
- Big contributions to the field coming from our group in the last year:
    - NNLO_{PS} for diboson production
    - NNLO_{PS} for top-pair production
    - Precise determination of photon and lepton PDFs
    - Studies related to the Higgs self coupling
    - ...
- Promising prospects for the future research activities!

Thanks!