NNLO+PS predictions for diboson processes in MiNNLOps

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Workshop on Tools for High Precision LHC simulations

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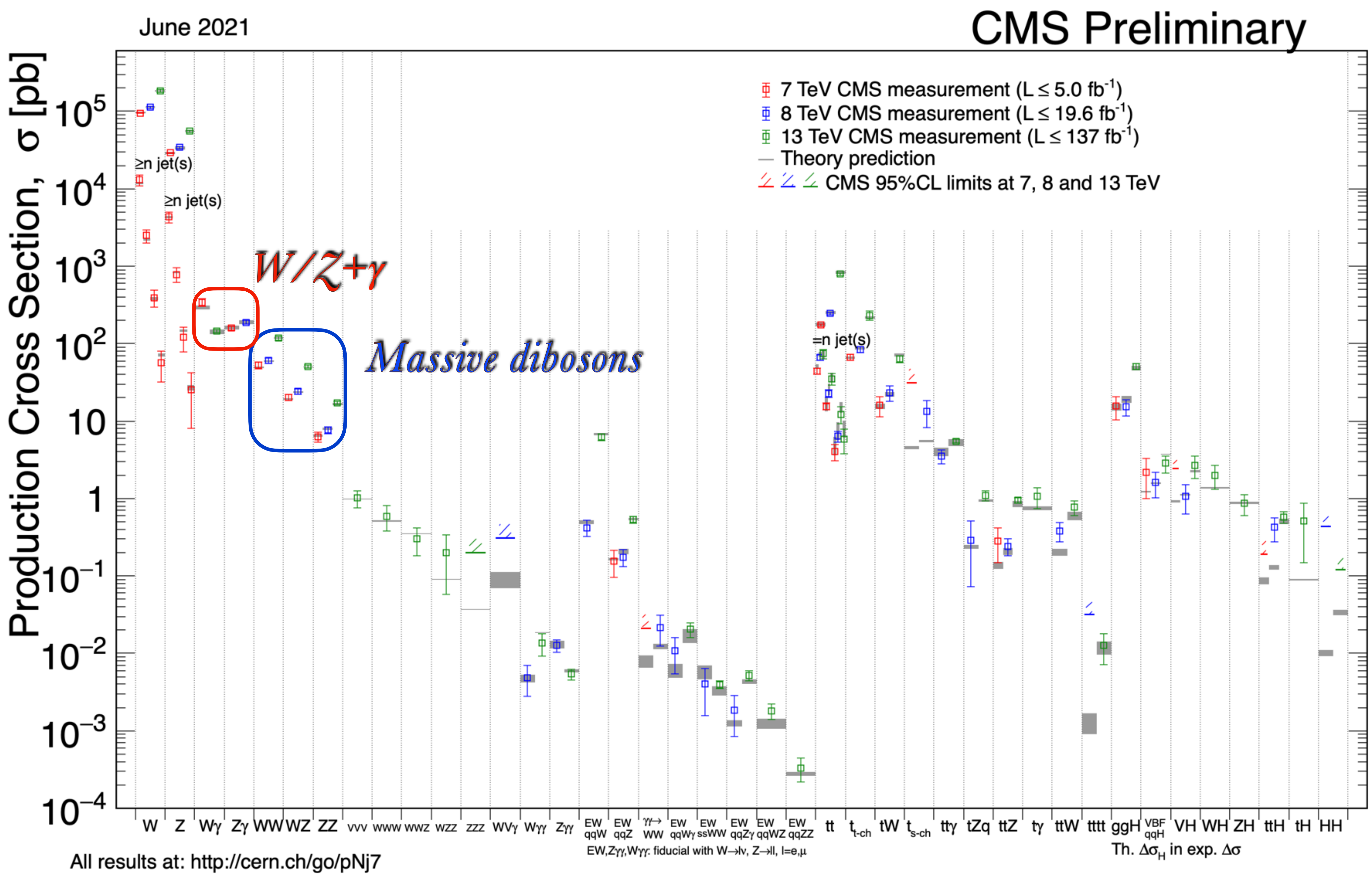
MAX-PLANCK-GESELLSCHAFT

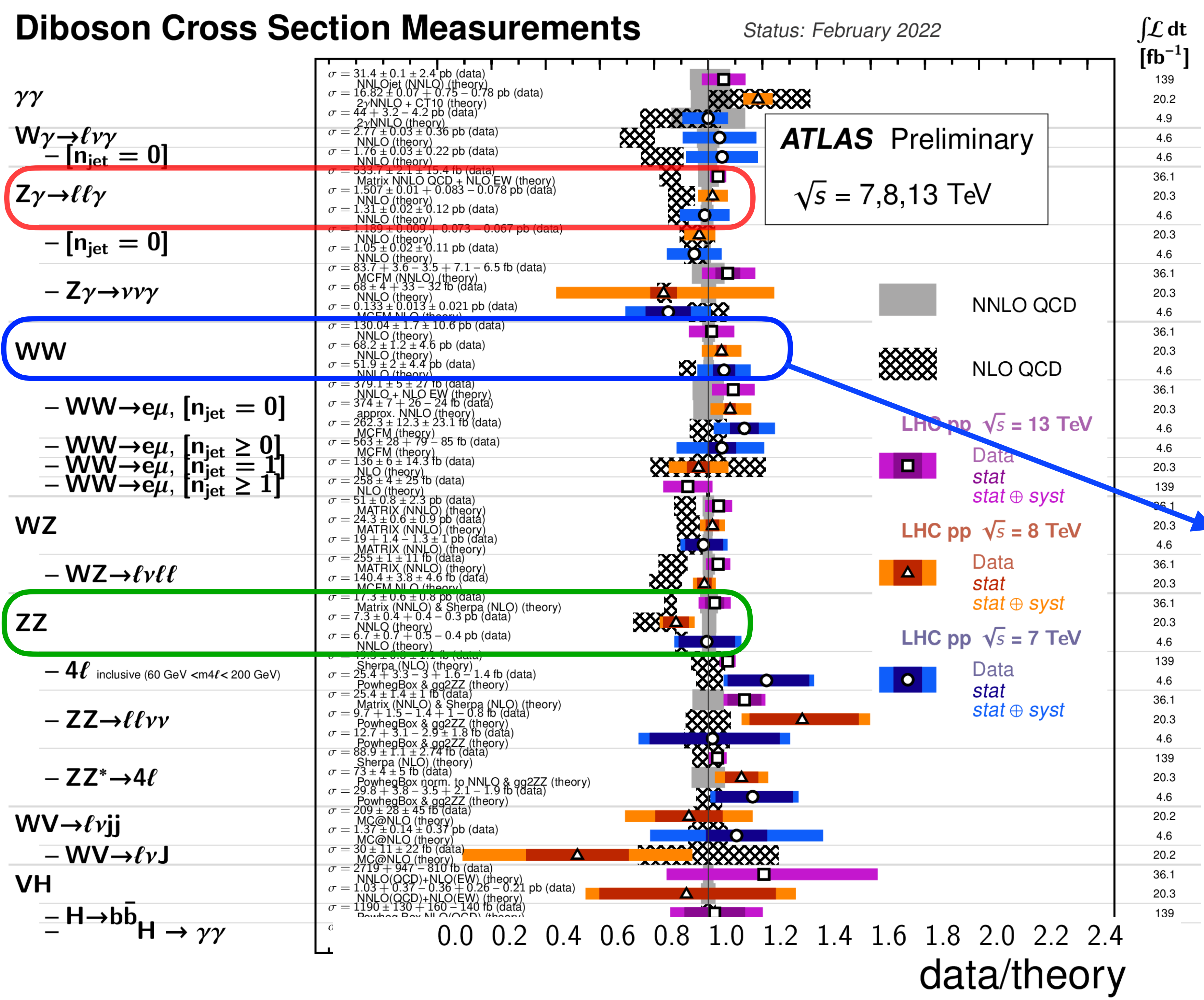
Max-Planck-Institut für Physik

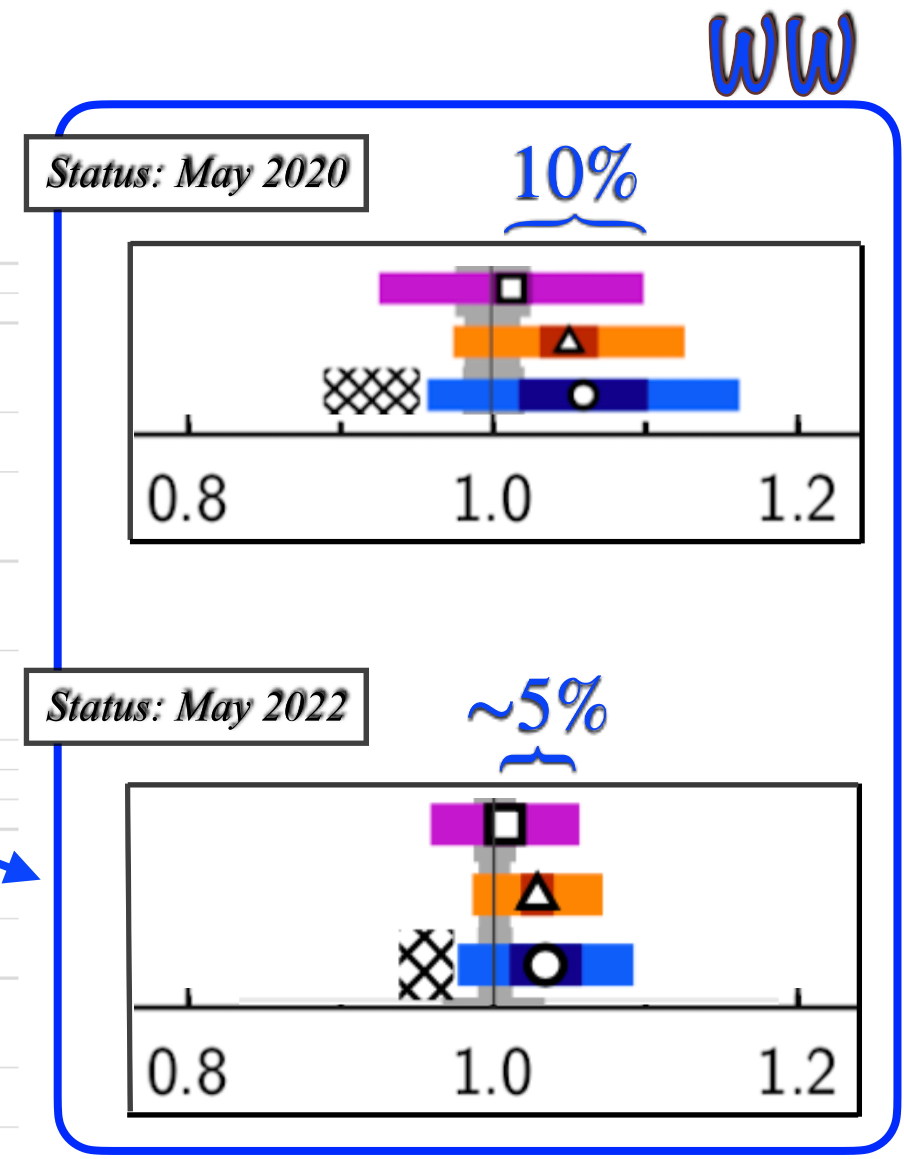
Importance of diboson processes at LHC

- *They can be measured very accurately (SM candle processes)*
- *Background to Higgs measurements and direct new-physics searches*
- *Important for indirect BSM searches (anomalous couplings/EFT)*



The need for high accuracy ...

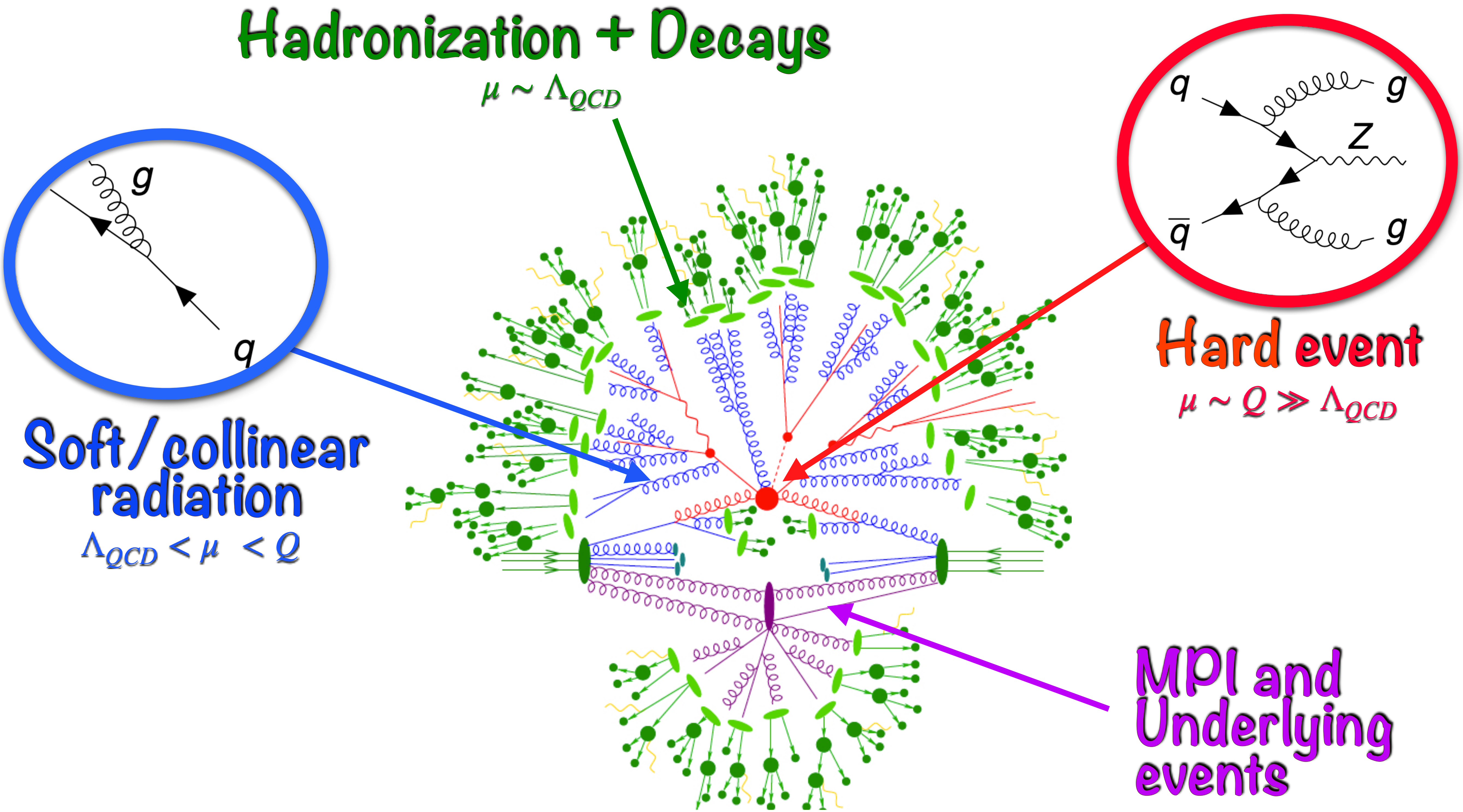




Experiments demand $\mathcal{O}(1\%)$ theoretical precision

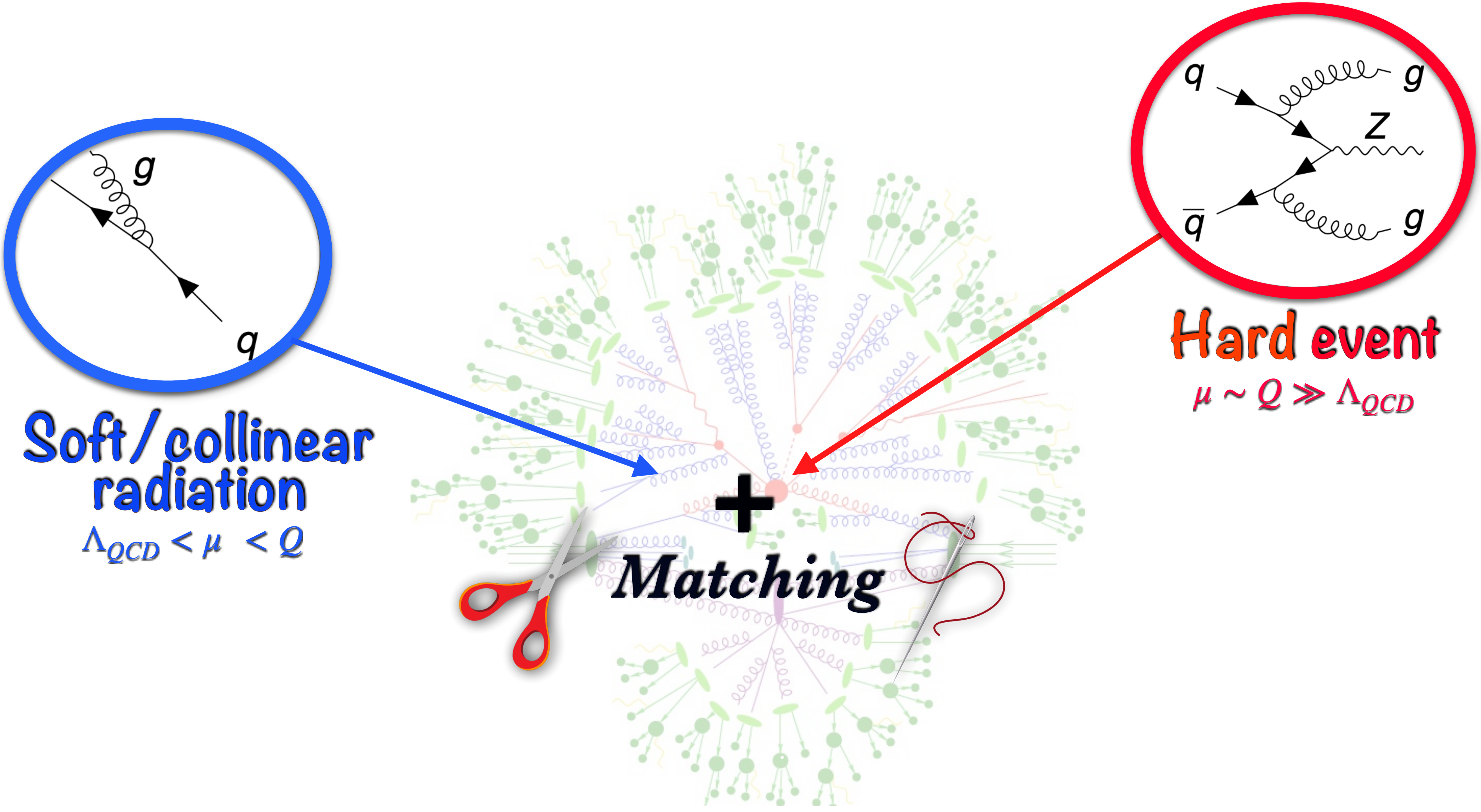
The need for MC event generators

Precise and realistic LHC phenomenology requires full-fledged event simulations.



Fixed-order + PS accuracy

- ***NLO+PS (~10%)***: *long-standing issue → standard today*
- ***NNLO+PS (~1%)***: *extremely challenging → no general approach for involved processes*



NNLO+PS generator

- *NNLO accuracy for observables inclusive over QCD radiation*
- *NLO(LO) accuracy for VV+1(2)jets observables*
- *Resummation obtained by preserving the logarithmic accuracy of the PS*

F	***F+1 jet***	***F+ 2jets***	***F + ≥3jets***
NNLO	NLO	LO	PS

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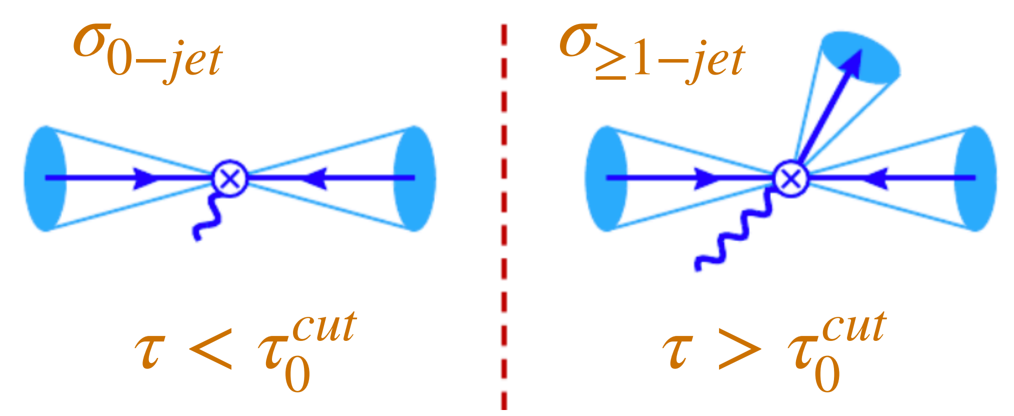
NLO Merging:

- *FxFx [Frixione, Frederix '12]*
- *MEPS@NLO [Höche, Krauss, Schönherr, Siegert '13]*
- *UNLOPS [Lönnblad, Prestel '12]*
- *MiNLO' [Hamilton, Nason, Oleari, Zanderighi '12]*
- *GENEVA [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13], [Alioli, Bauer, Berggren, Tackmann, Walsh '15]*
- ...

Inclusive 0-jet cross section



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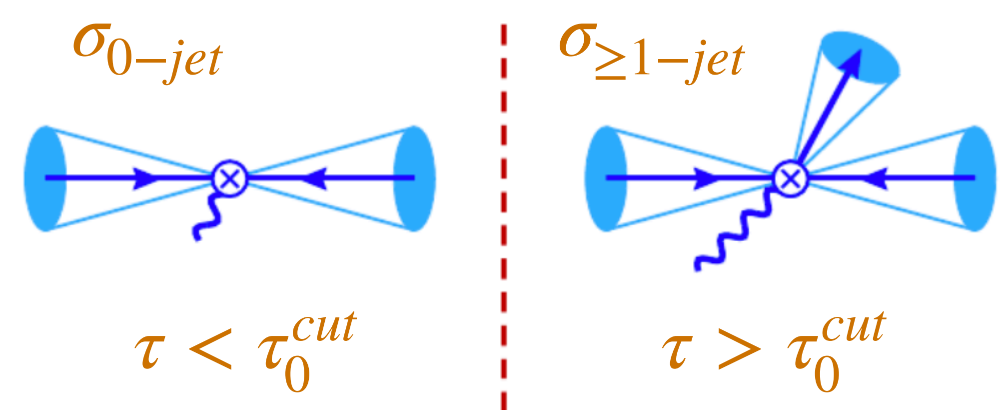
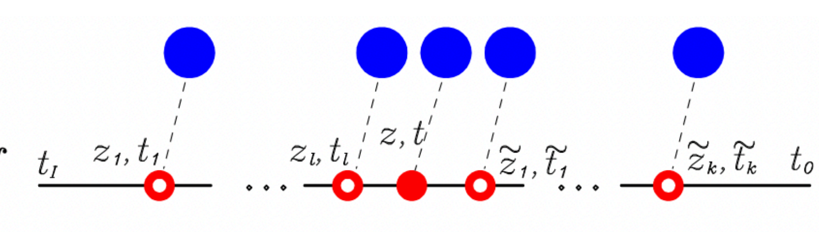


NLO Matching:

- *MC@NLO [Frixione, Weber '02]*
- *POWHEG [Nason '04]*
- *KrkNLO [Jadach, Płaczek, Sapeta, Siódmok, Skrzypek '15]*
- *MAcNLOPS [Nason, Salam '21]*

$$\mathbb{S}(t_I) = \Delta(t_I, t_0)\langle \mathbb{I}| + \sum_{l,k=0}^{\infty} \int$$



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↓

Issue: interface NNLO calculations to PS by preserving the accuracy of the latter

Solution: different methods available (for colour singlets)

- *MiNLO'+reweighting [Hamilton, Nason, Oleari, 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]*
- *VINCIA sector shower [Campbell, Höche, Li, Preuss, Skands '21]*

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- *MiNLO'+~~reweighting~~ [Hamilton, Nason, Oleari, Zanderighi '12,+Re '13], [Karlberg, Hamilton, Zanderighi '14]* → **MiNNLOps:**
  - $2\to1$ *[Monni, Nason, Re, Wiesemann, Zanderighi '19], [Monni, Re, Wiesemann '20]*
  - $2\to2$ extension *[Lombardi, Wiesemann, Zanderighi '20]*
  - $t\bar{t}$ *[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '21, '22]*
- *GENEVA [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13], [Alioli, Bauer, Berggren, Tackmann, Walsh '15]*
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MiNNLOPS

[Monni, Nason, Re, Wiesemann, Zanderighi '19], [Monni, Re, Wiesemann '20]

NNLO accuracy obtained by connecting MiNLO′ with transverse-momentum resummation formulae.

$$\underbrace{\frac{d\sigma_F^{\rm res}}{dp_T\, d\Phi_B}} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{\mathscr{L}' - S'\mathscr{L}\right\}}_{\equiv D} \quad \to \mathscr{L} \sim H(C\otimes f)(C\otimes f)$$

luminosity

$$\bar{B}(\Phi_{FJ}) = d\sigma_F^{\rm res} + [d\sigma_{FJ}]_{\rm f.o.} - [d\sigma_F^{\rm res}]_{\rm f.o.} = e^{-S}\left\{D + \underbrace{\frac{[d\sigma_{FJ}]_{\rm f.o.}}{[e^{-S}]_{\rm f.o.}}}_{1-S^{(1)}\dots} \underbrace{- \frac{[d\sigma_F^{\rm res}]_{\rm f.o.}}{[e^{-S}]_{\rm f.o.}}}_{-D^{(1)}-D^{(2)}\dots}\right\} \to \mu_R \sim \mu_F \sim p_T$$

resummation scheme

F : *generic colour-singlet system*

Expand up to $\mathscr{O}(\alpha_s^3)$: $\int \frac{dp_T}{p_T} e^{-S}\alpha_s^n(p_T)\log^m\frac{Q}{p_T} \sim \mathscr{O}\left(\alpha_s^{n-\frac{m+1}{2}}(Q)\right)$

$$\bar{B}_{\rm MiNNLO_{PS}}(\Phi_{FJ}) \sim e^{-S}\left\{\underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\underbrace{\left(1+S^{(1)}\right) + d\sigma_{FJ}^{(2),sing}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)} + \text{regular}\right\}$$

MiNNLOps

[Monni, Nason, Re, Wiesemann, Zanderighi '19], [Monni, Re, Wiesemann '20]

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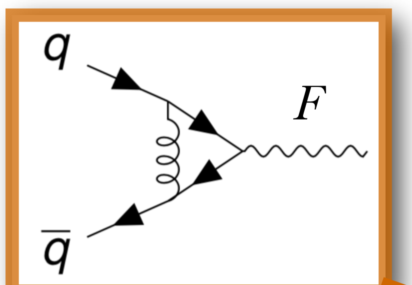

Include NLO corrections for unresolved radiation

MiNLO′

$$\bar{B}_{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) \sim e^{-S}\left\{\underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\underbrace{\left(1 + S^{(1)}\right) + d\sigma_{FJ}^{(2),sing}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)} + \mathrm{regular}\right\}$$

Preserve original F+1jet accuracy

MiNNLOPS

[Monni, Nason, Re, Wiesemann, Zanderighi '19], [Monni, Re, Wiesemann '20]

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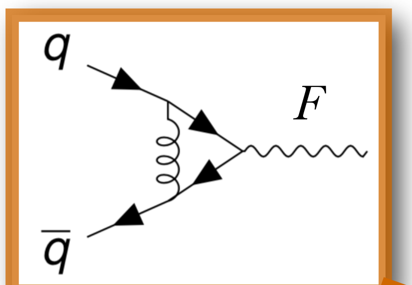


Include NLO corrections for unresolved radiation

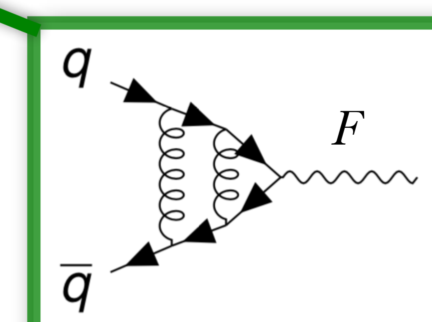
Beyond accuracy

MiNLO′ MiNNLOPS

$$\bar{B}_{\rm MiNNLO_{PS}}(\Phi_{FJ}) \sim e^{-S}\Big\{ \underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)} \underbrace{\big(1+S^{(1)}\big) + d\sigma_{FJ}^{(2),sing}}_{\sim\alpha_s^2(p_T)} + \underbrace{\big(D - D^{(1)} - D^{(2)}\big)}_{\sim\alpha_s^3(p_T)} + \text{regular}\Big\}$$

Preserve original F+1jet accuracy

Include missing NNLO ingredients



MiNNLOps: 2→2 extension

[Lombardi, Wiesemann, Zanderighi '20]

NNLO accuracy obtained by connecting MiNLO′ with transverse-momentum resummation formulae.

$$\frac{\mathrm{d}\sigma_F^{\mathrm{res}}}{\mathrm{d}p_T\,\mathrm{d}\Phi_{\mathrm{B}}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{\mathscr{L}' - S'\mathscr{L}\right\}}_{\equiv D} \quad \to \mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

luminosity

Hard function

$H^{(1)}$ and $H^{(2)}$ generally flavour and kinematic dependent

$$\bar{B}(\Phi_{FJ}) = \mathrm{d}\sigma_F^{\mathrm{res}} + [\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}} - [\mathrm{d}\sigma_F^{\mathrm{res}}]_{\mathrm{f.o.}} = e^{-S}\left\{ D + \underbrace{\frac{[\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}}}{[e^{-S}]_{\mathrm{f.o.}}}}_{1-S^{(1)}\ldots} \underbrace{-\frac{[\mathrm{d}\sigma_F^{\mathrm{res}}]_{\mathrm{f.o.}}}{[e^{-S}]_{\mathrm{f.o.}}}}_{-D^{(1)}-D^{(2)}\ldots} \right\}$$

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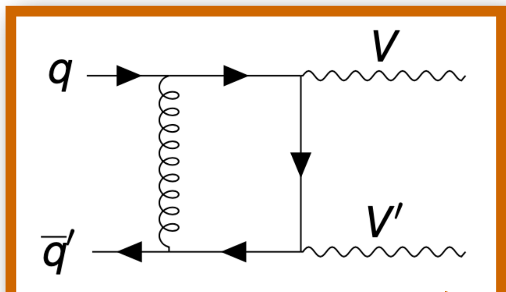


Include NLO corrections for unresolved radiation

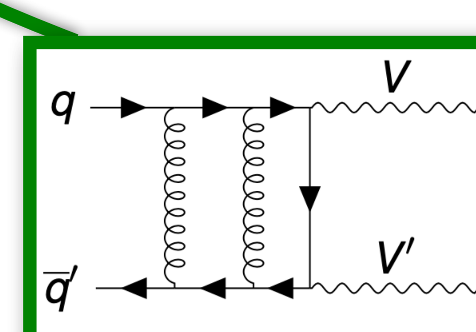
MiNLO′ **MiNNLOps**

Beyond accuracy

$$\bar{B}_{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) \sim e^{-S}\left\{ \underbrace{\mathrm{d}\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\underbrace{\left(1 + S^{(1)}\right) + \mathrm{d}\sigma_{FJ}^{(2),sing}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)} + \text{regular} \right\}$$

Preserve original F+1jet accuracy

Include missing NNLO ingredients



MiNNLOPS: matching to Parton shower

- ***Merging*** *without unphysical merging scale*

$$\bar{B}_{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) \sim e^{-S}\left\{ \mathrm{d}\sigma_{FJ}^{(1)}\left(1+S^{(1)}\right) + \mathrm{d}\sigma_{FJ}^{(2),sing} + \left(D - D^{(1)} - D^{(2)}\right)(p_T) \cdot F^{\mathrm{corr}}(\Phi_{FJ}) + \text{regular} \right\}$$

NNLO corrections are:

❖ *spread over the F+1jet phase space* →

$$F^{\mathrm{corr}}(\Phi_{FJ}) = \frac{J(\Phi_{FJ})}{\int d\Phi'_{FJ}\, J(\Phi'_{FJ})\, \delta(p_T - p'_T)\, \delta(\Phi_F - \Phi'_F)}$$

❖ *switched off at high transverse momentum* $p_T \geq Q$

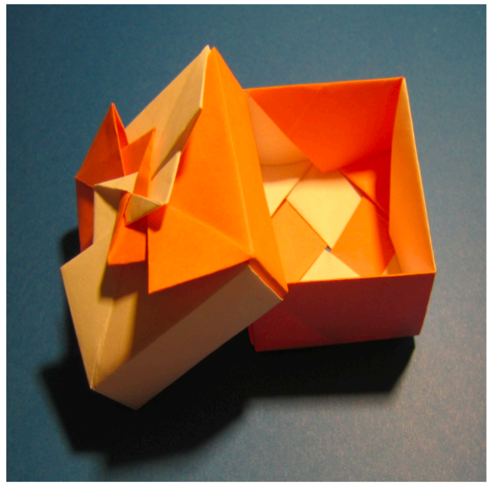
↓

- ***Matching*** *(NNLO+PS accuracy) obtained using POWHEG method*

$$d\sigma_{\mathrm{MiNNLO_{PS}}} = \bar{B}_{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ})\, d\Phi_{FJ} \cdot \left\{ \Delta_{pwg}(\Lambda_{QCD}) + \Delta_{pwg}(p_{T,rad}) \frac{R_s(\Phi_{FJJ})}{B(\Phi_{FJ})}\, d\Phi_{rad} \right\}$$

NNLO+PS generators for Dibosons

The POWHEG BOX



Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Available Processes

- Higgs boson production in gluon fusion, P. Monni, P. Nason, E. Re, M. Wiesemann and G. Zanderighi, *JHEP* **05** (2020) 143, arXiv:1908.06987 [paper], P. Monni, E. Re and M. Wiesemann, *Eur. Phys. J.* **C80** (2020), no.11, 1075, arXiv:2006.04133 [paper]

POWHEG-BOX-V2/HJ (inside HJMiNNLO subfolder)

- Next-to-Next-to-Leading Order Event Generation for Top-Quark Pair Production, J. Mazzitelli, P. Monni, P. Nason, E. Re, M. Wiesemann and G. Zanderighi, *Phys.Rev.Lett.* **127** (2021) 062001, arXiv:2012.14267 [paper], Top-pair production at the LHC with MiNNLO$_{PS}$, J. Mazzitelli, P. Monni, P. Nason, E. Re, M. Wiesemann and G. Zanderighi, arXiv:2112.XXXXX [paper]

POWHEG-BOX-V2/ttJ_MiNNLO

- Advancing MiNNLO$_{PS}$ to diboson processes: Zγ production at NNLO+PS, D. Lombardi, M. Wiesemann and G. Zanderighi, *JHEP* **2106** (2021) 095, arXiv:2010.10478 [paper], Anomalous couplings in Zγ events at NNLO+PS and improving ννγ backgrounds in dark-matter searches, D. Lombardi, M. Wiesemann and G. Zanderighi, *Phys.Lett. B* **XX** (2021) XXX, arXiv:2108.11315 [paper]

POWHEG-BOX-RES/ZgamJ

- W^+W^- production at NNLO+PS with MINNLO$_{PS}$, D. Lombardi, M. Wiesemann and G. Zanderighi, *JHEP* **2111** (2021) 230, 2103.12077 [paper]

POWHEG-BOX-RES/WWJ

- ZZ production at nNNLO+PS with MINNLO$_{PS}$, L. Buonocore, G. Koole, D. Lombardi, L. Rottoli, M. Wiesemann, G. Zanderighi, arXiv:2108.05337 [paper]

POWHEG-BOX-RES/ZZJ

MiNNLO$_{PS}$ has been extended to $2 \to 2$ colour-singlet processes (built in POWHEG-BOX-RES).

NEW — *First implementation of* ***Zγ*** *generator (both $Z \to \ell^+\ell^-$ and $Z \to \bar{\nu}\nu$ + aTGC @NNLO)* [Lombardi, Wiesemann, Zanderighi '20, '21]

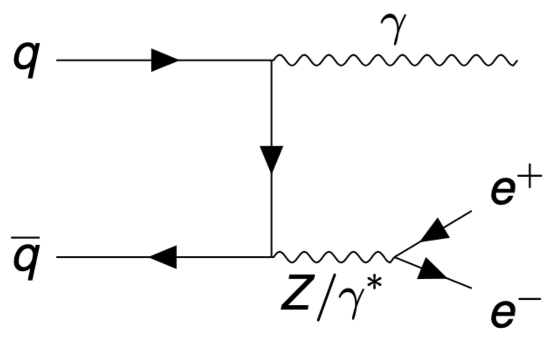
NEW — *New approach to the existing* ***WW*** *generator* [Lombardi, Wiesemann, Zanderighi '21]

NEW — ***ZZ*** *generator with incoherent combination of $\bar{q}q$ and gg channels* [Buonocre, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi '21]

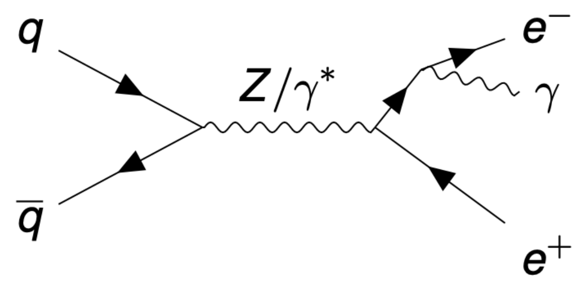
NEW — ***γγ*** *generator* [Gavardi, Oleari, Re '22]

NEW — ***WZ*** *generator including NLO EW corrections and QED PS effects* [Lindert, Lombardi, Wiesemann, Zanderighi, Zanoli '22]

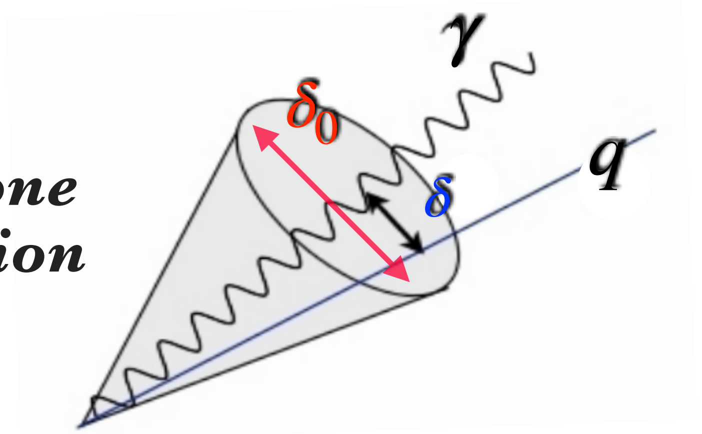
$Z\gamma$ phenomenology at the LHC *[Lombardi, Wiesemann, Zanderighi '20]*



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



Frixione isolation



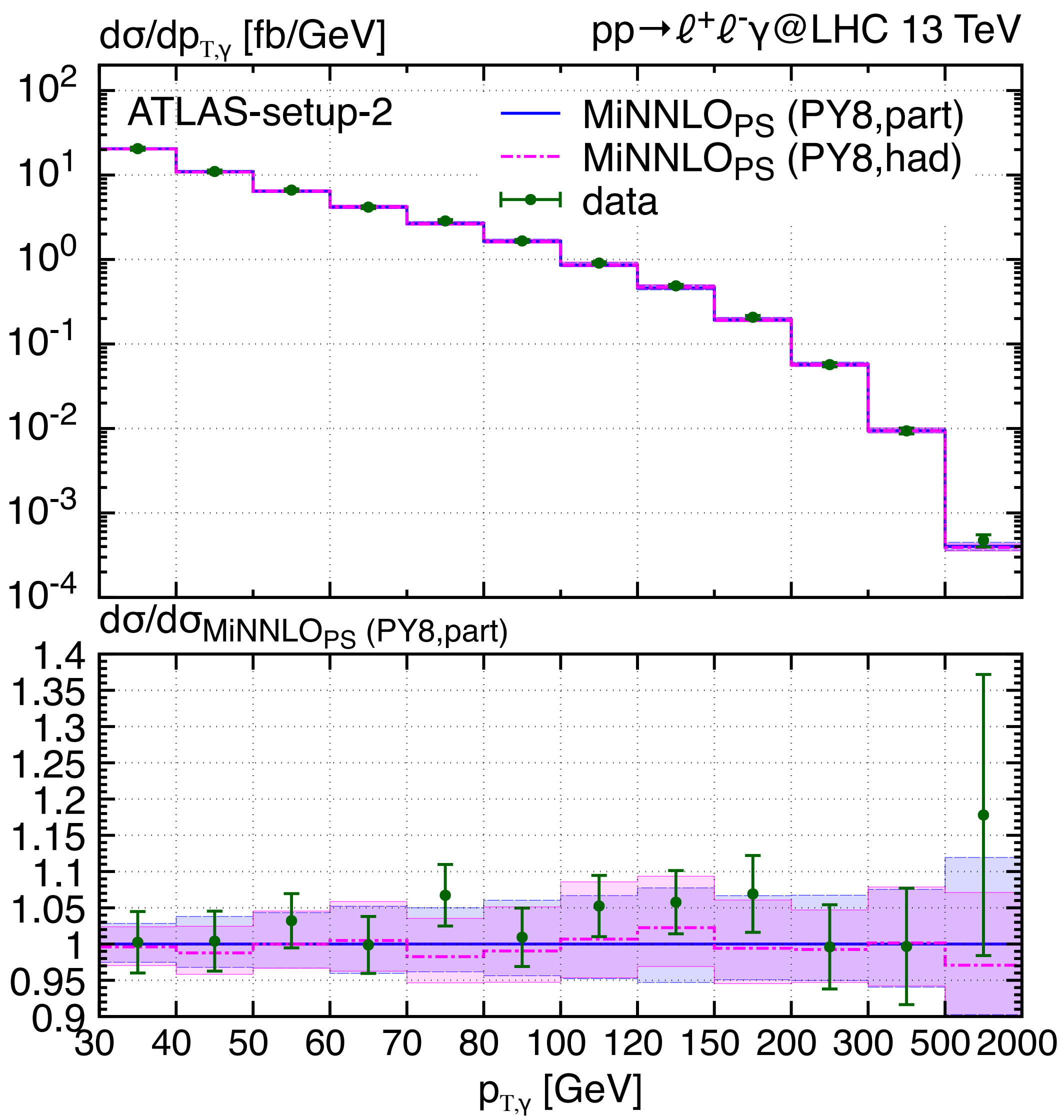
Photon isolation requirement:

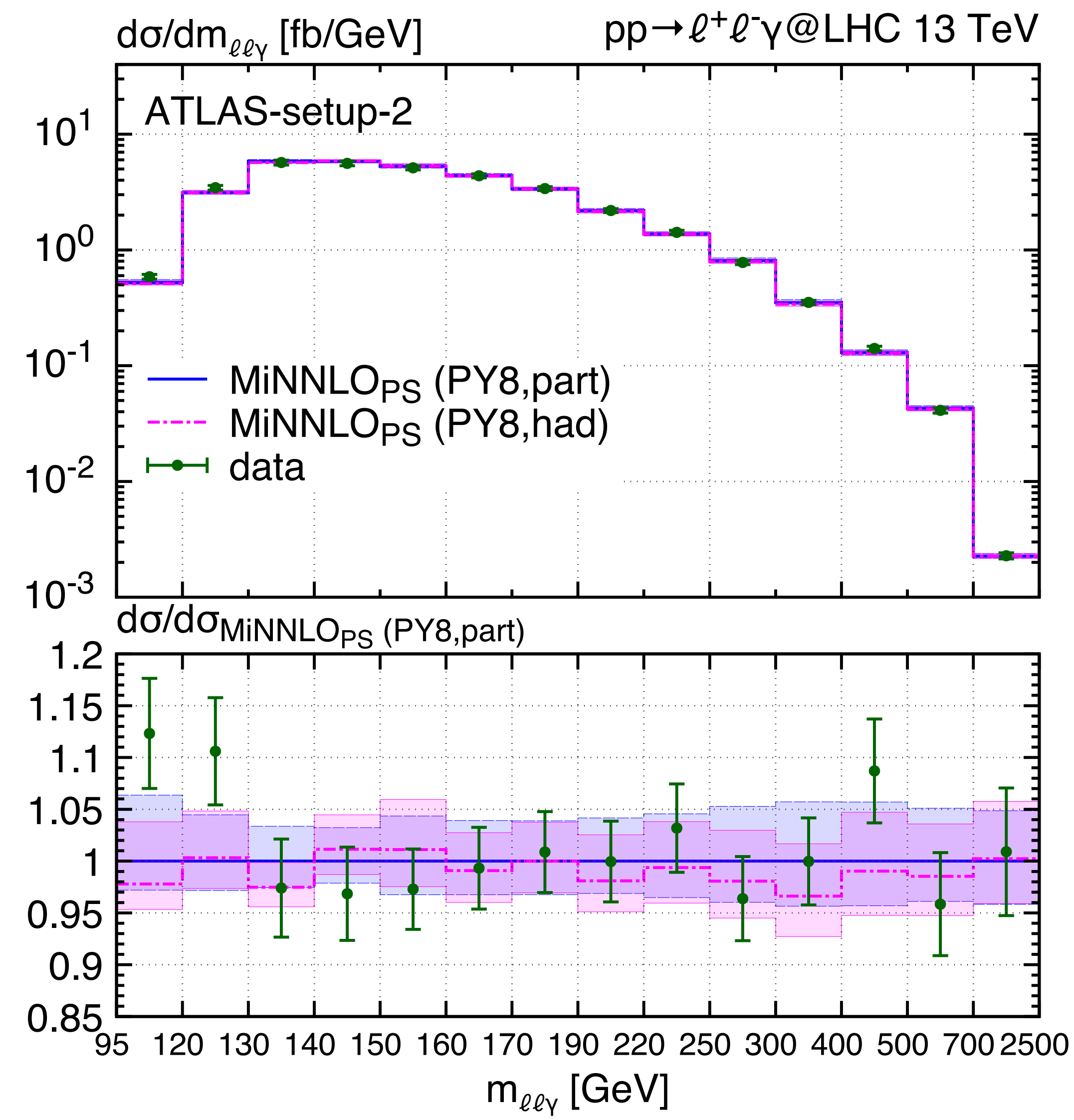
- *Experimentally needed to identify hard photons*
- *Theoretically delicate definition of an infrared-safe cross section*

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

NNLO+PS for Zγ: Phenomenological results

Comparison to data: ATLAS 13TeV analysis





✓ *MiNNLO$_{PS}$ predictions in very good agreement with ATLAS 13TeV results, based on the full 139fb^{-1} Run-2 data ([arXiv:1911.04813])!*

NNLO+PS for Zγ: Phenomenological results

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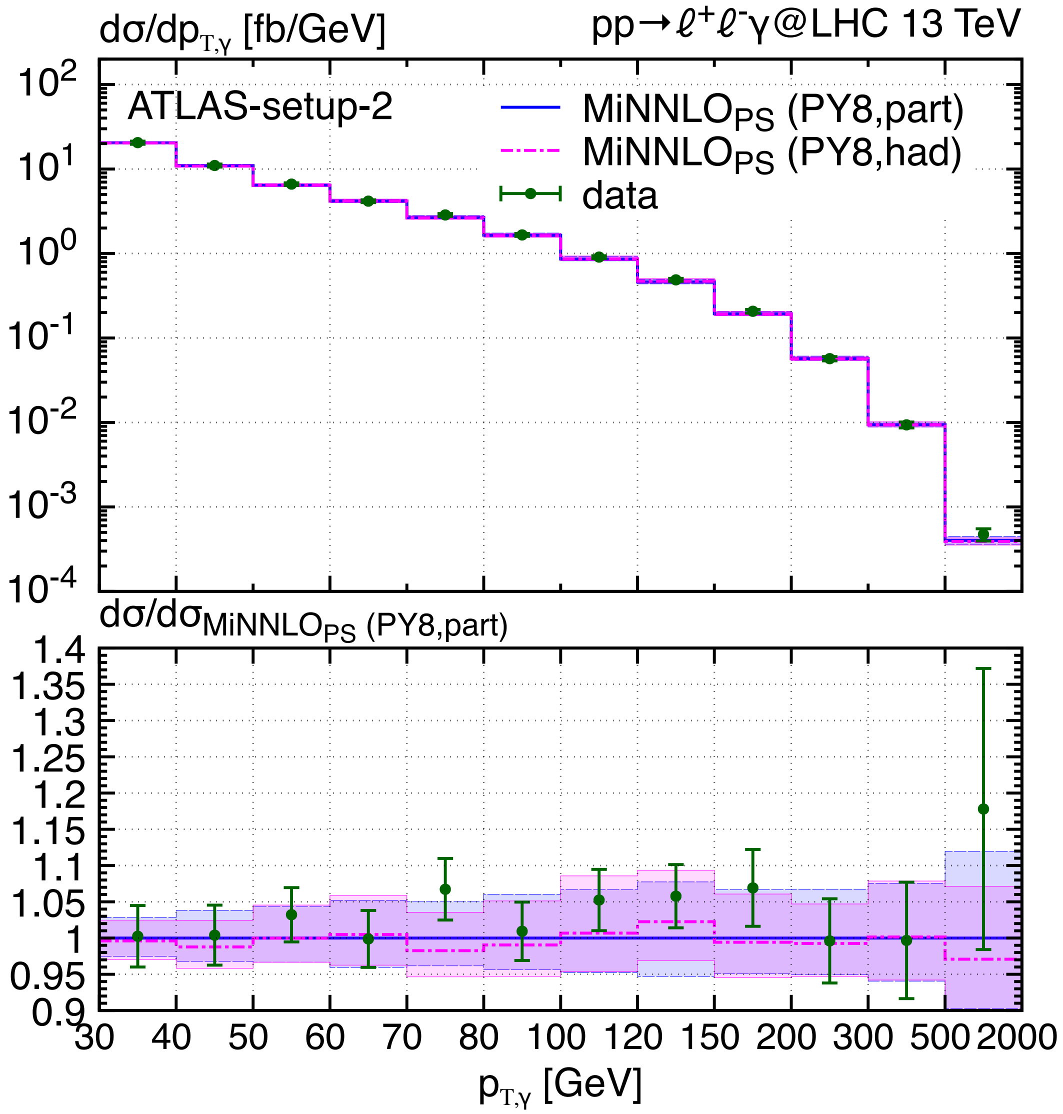
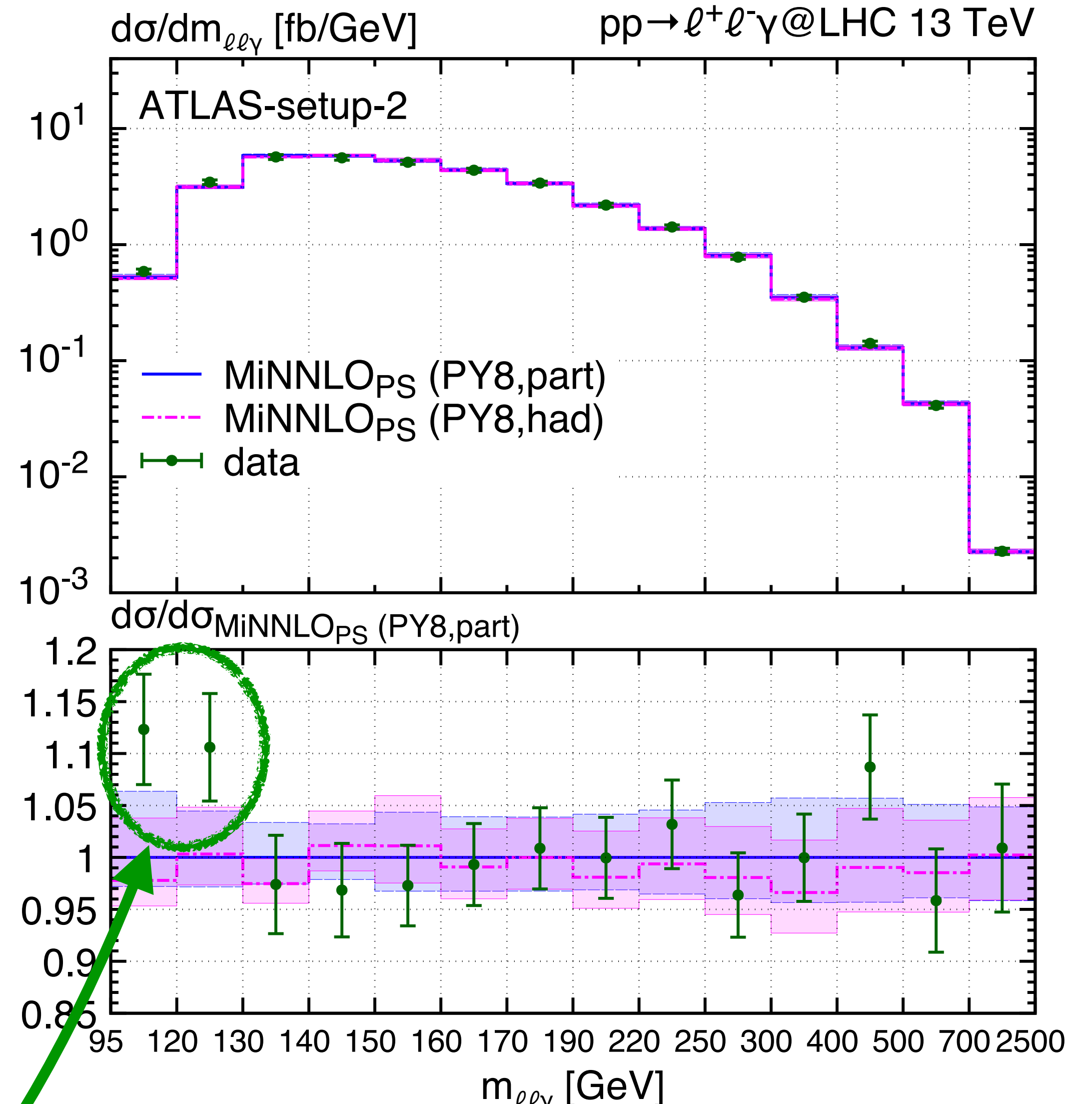


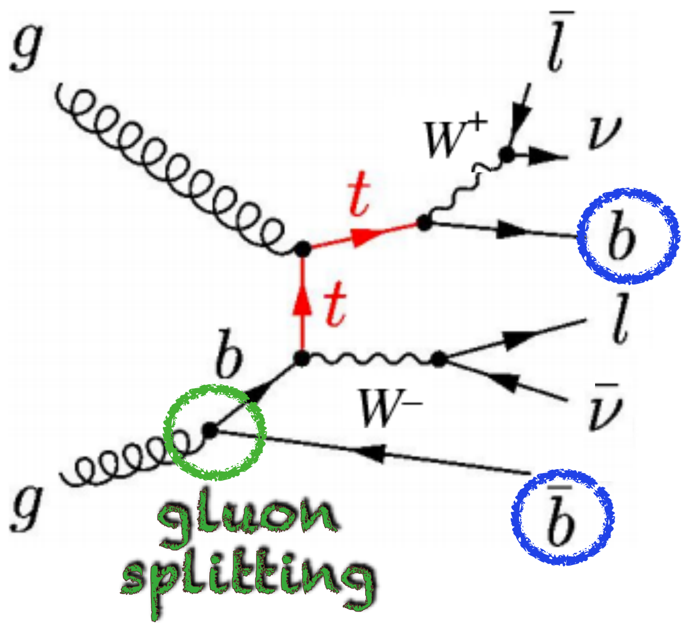


- ✓ *MiNNLO$_{PS}$ predictions in very good agreement with ATLAS 13TeV results, based on the full 139fb^{-1} Run-2 data ([arXiv:1911.04813])!*
- ✓ *Sensitivity to QED radiation*

WW phenomenology at 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:

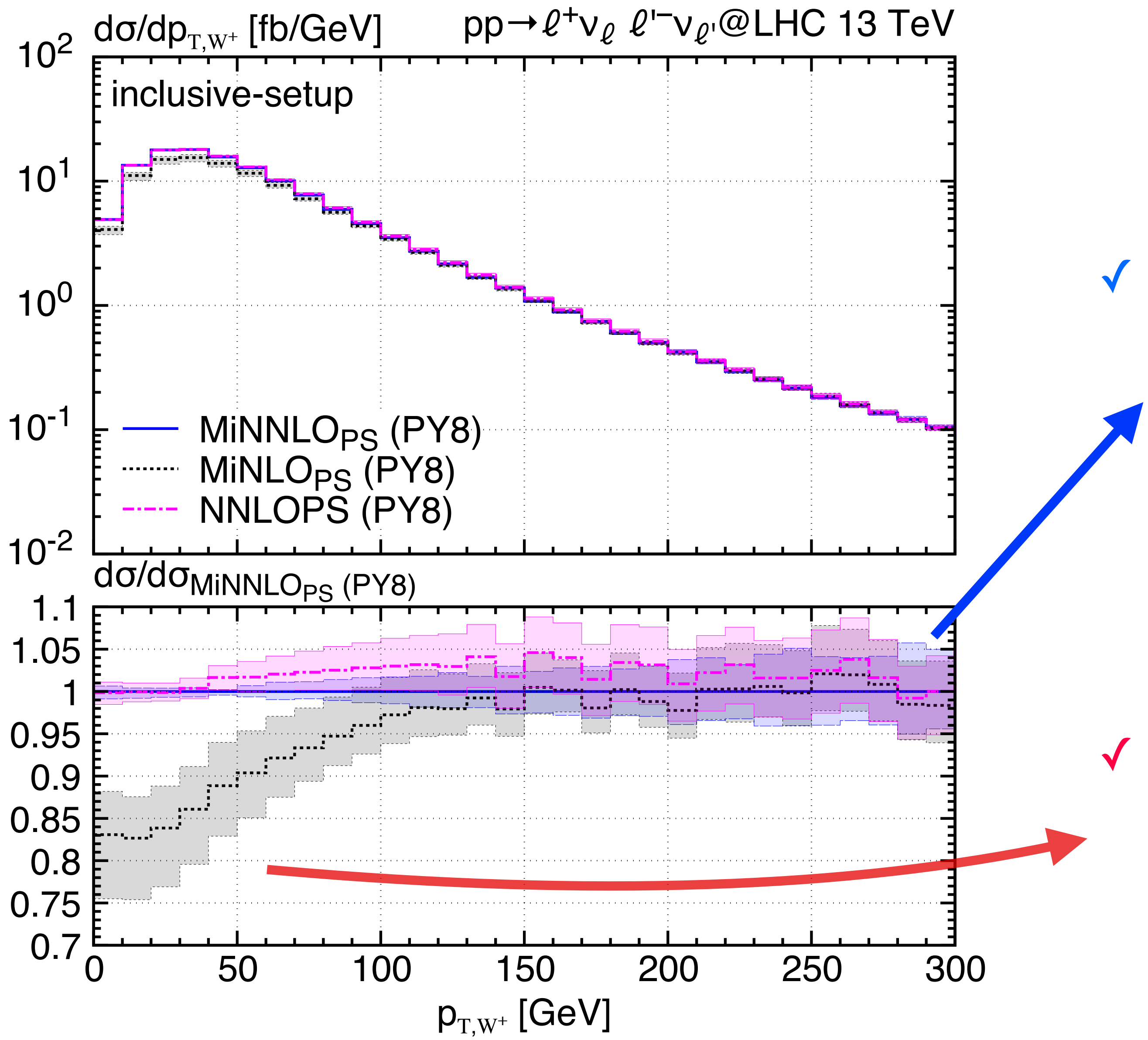
- *Experimentally needed to reduce top background*
- *Theoretically involved definition of WW cross section, due to diagrams with resonant top quarks and b final states:*
  - *Interference with double-real diagrams*
  - *Not separately finite for massless b quarks*

↓

4 flavour scheme (4FS) adopted (in good agreement with top-free 5FS [Grazzini, Kallweit, Pozzorini, Rathlev, Wiesemann '17])

NNLO+PS for WW: Phenomenological results

Theoretical studies: inclusive phase space

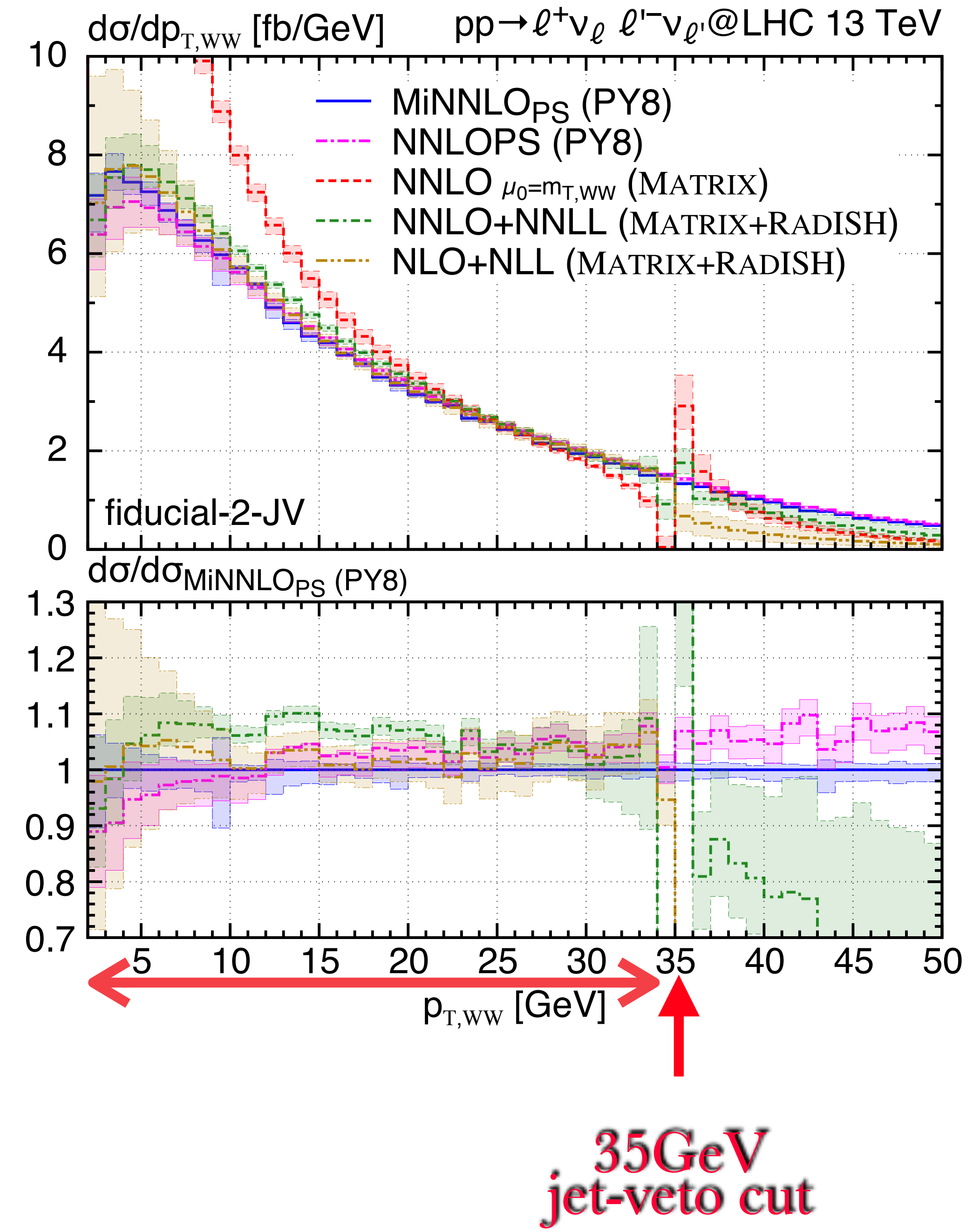


- ✓ *At high $p_{T,W+}$ NNLO+PS and MiNLO′ predictions agree*
- ✓ *Improved description in the low $p_{T,W+}$ region (both normalisation and accuracy)*

NNLO+PS for WW: Phenomenological results

Comparison with resummation: jet-vetoed $p_{T,WW}$ spectrum

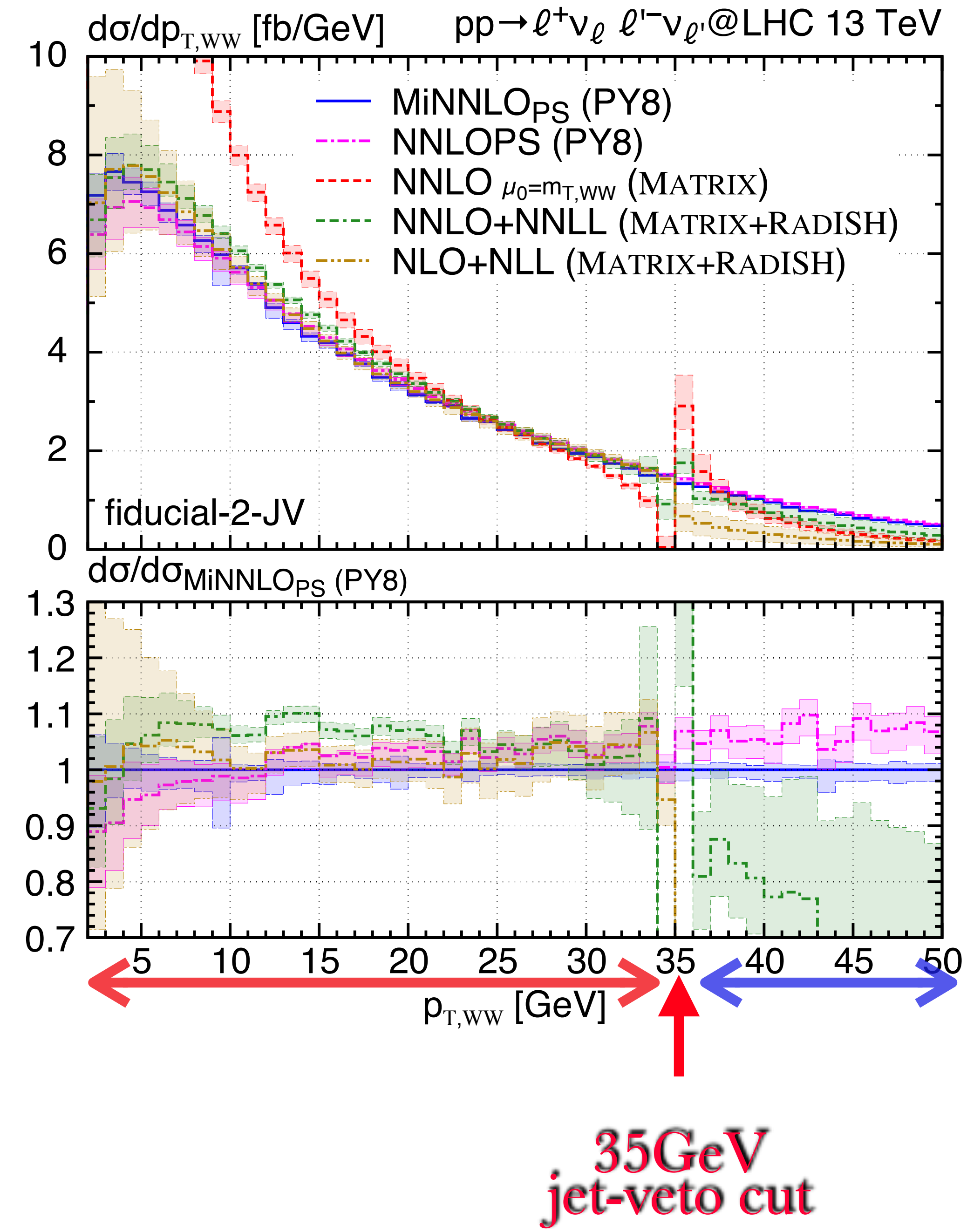
- ✓ *Fixed-order becomes unphysical at* ***low p_T*** *and at the* ***jet-veto threshold***
- ✓ *Analytic resummation only partially cures problems at low p_T, not* ***above jet-veto cut***



NNLO+PS for WW: Phenomenological results

Comparison with resummation: jet-vetoed $p_{T,WW}$ spectrum

- ✓ *Fixed-order becomes unphysical at **low p_T** and at the **jet-veto threshold***
- ✓ *Analytic resummation only partially cures problems at low p_T, not **above jet-veto cut***
- ✓ *NNLO+PS results provide a more physical description also above jet-veto threshold*

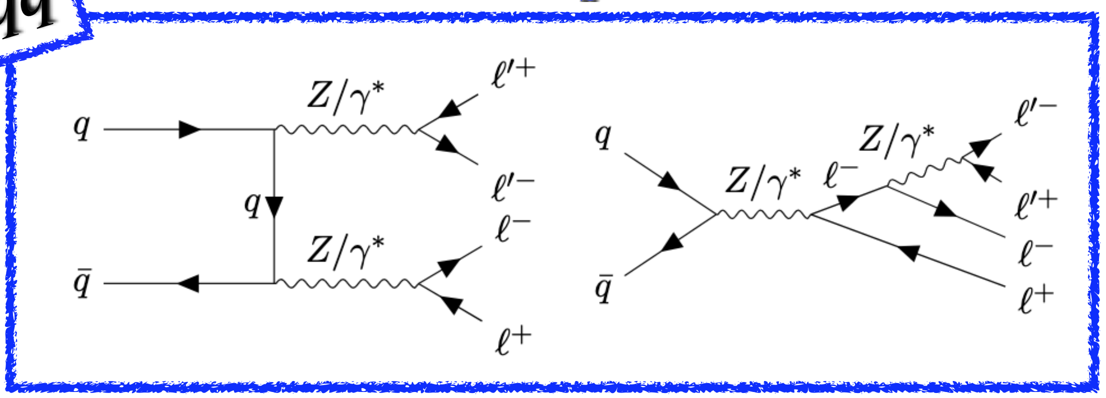


ZZ phenomenology at LHC

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

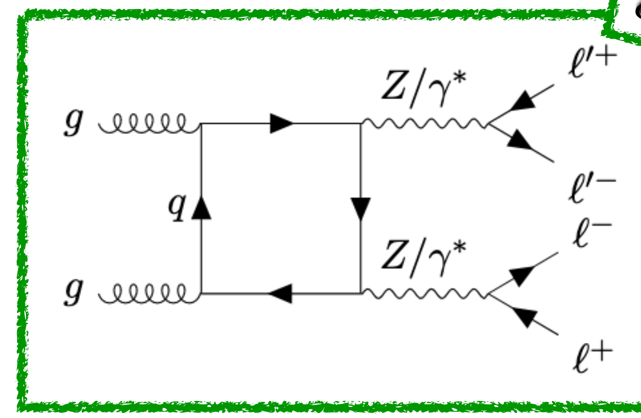
- *smallest cross section among massive diboson processes, but very clean signature*
- *relevant for BSM searches*
- *important for constraining the Higgs width and Higgs couplings*

$\bar{q}q$ $\sim \alpha_s^2$



NNLO+PS using MiNNLOPS *

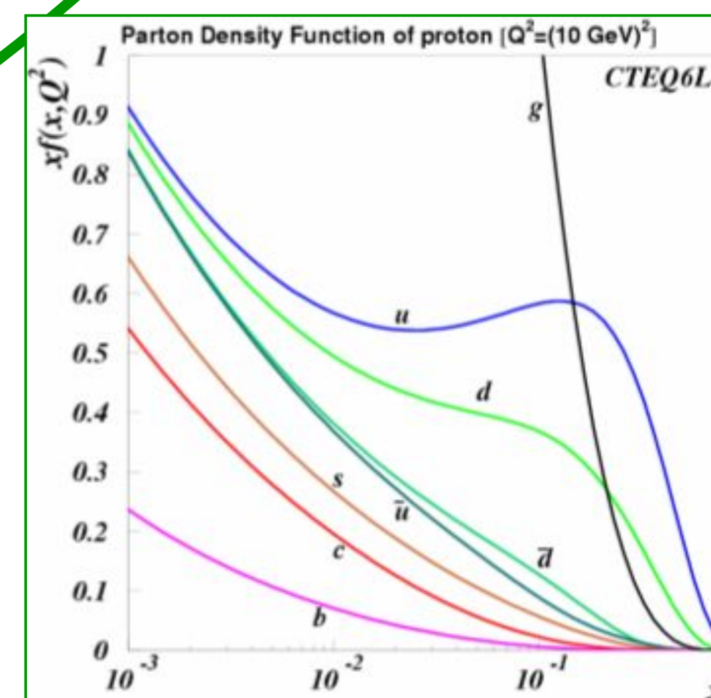
gg $\sim \alpha_s^3$



NLO+PS with POWHEG *

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

Incoherent combination ⟶ nNNLO+PS

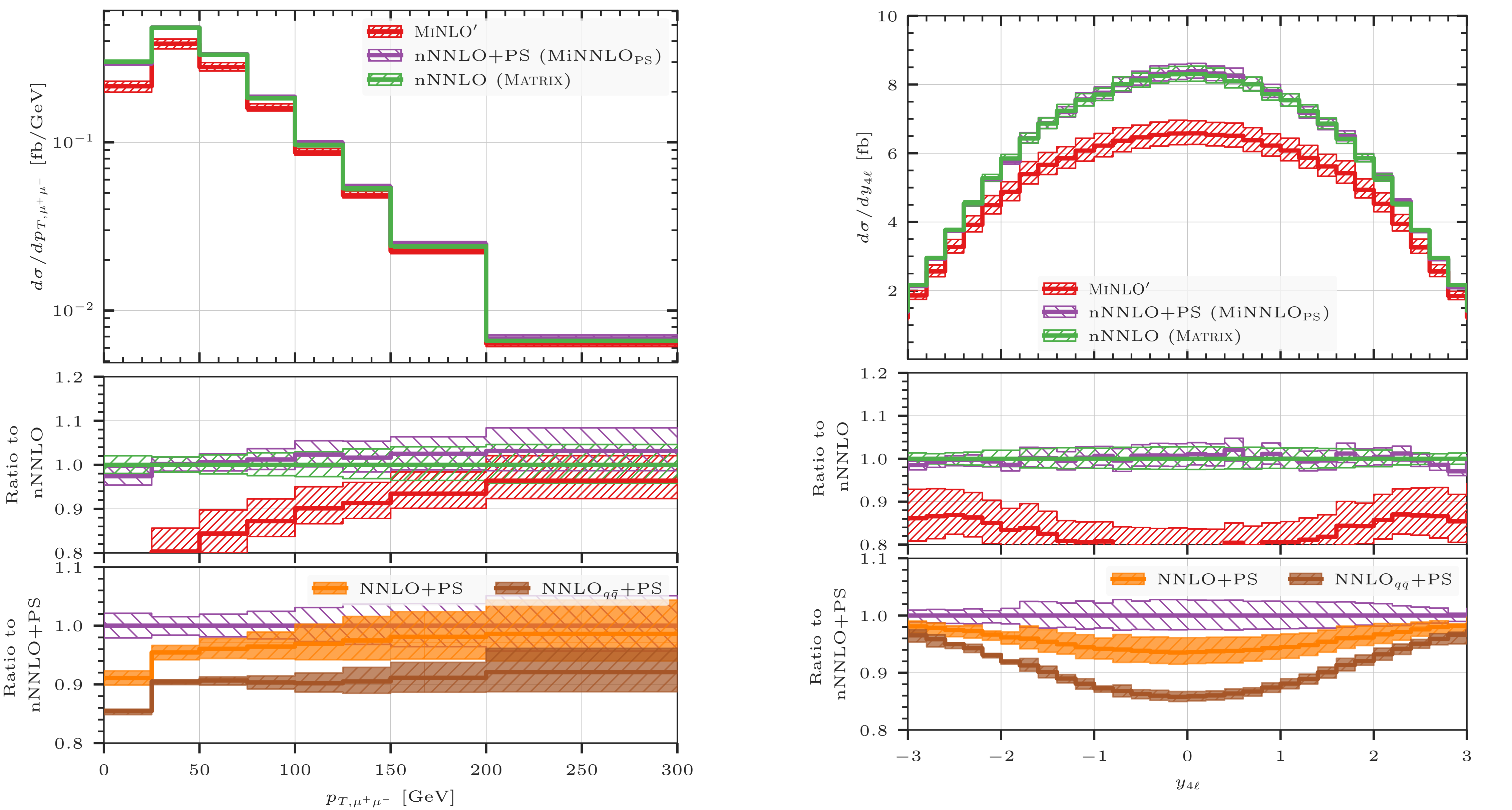


* *also done in GENEVA framework* [Alioli, Broggio, Gavardi, Kallweit, Lim '21]

* *first independent implementation in* [Alioli, Ferrario Ravasio, Lindert, Röntsch '21]

nNNLO+PS for ZZ: Phenomenological results

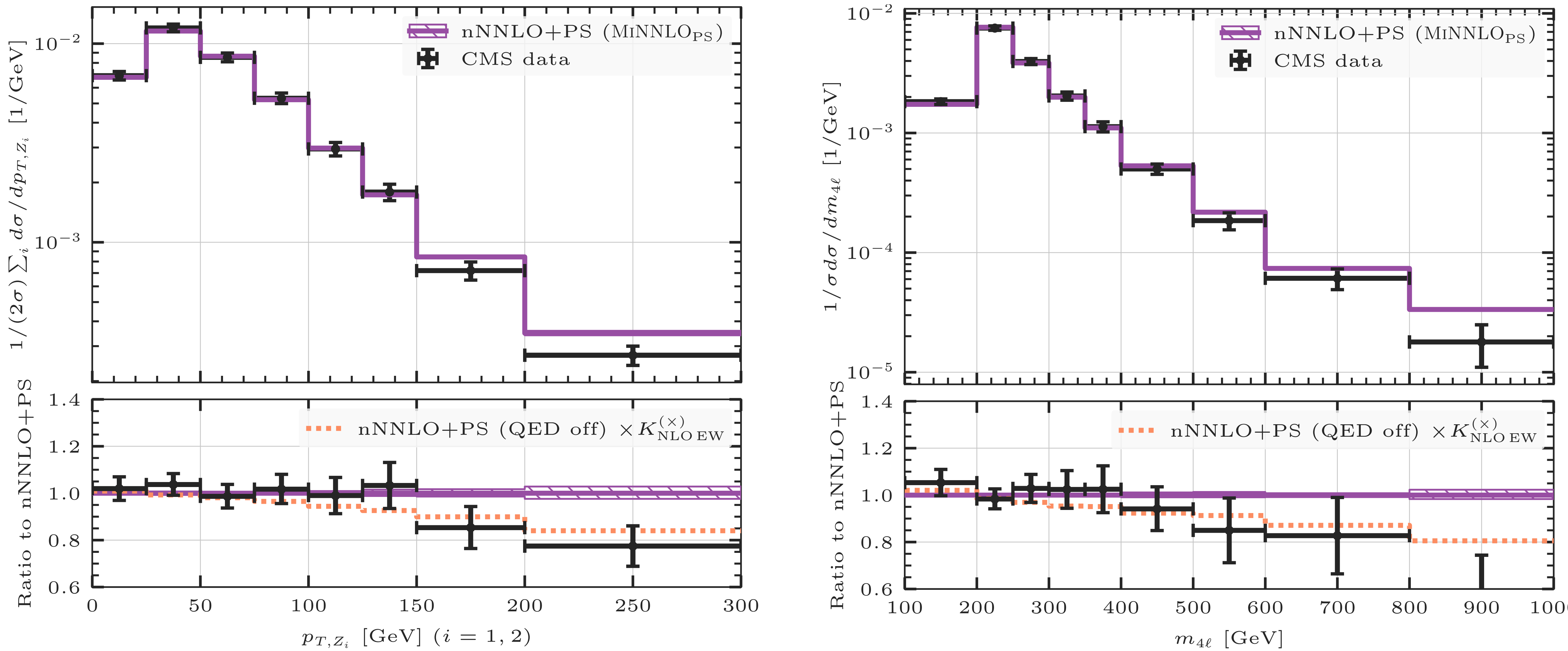
Differential distributions



✓ *Sizeable effects from the inclusion of gg contributions in bulk regions*

nNNLO+PS for ZZ: Phenomenological results

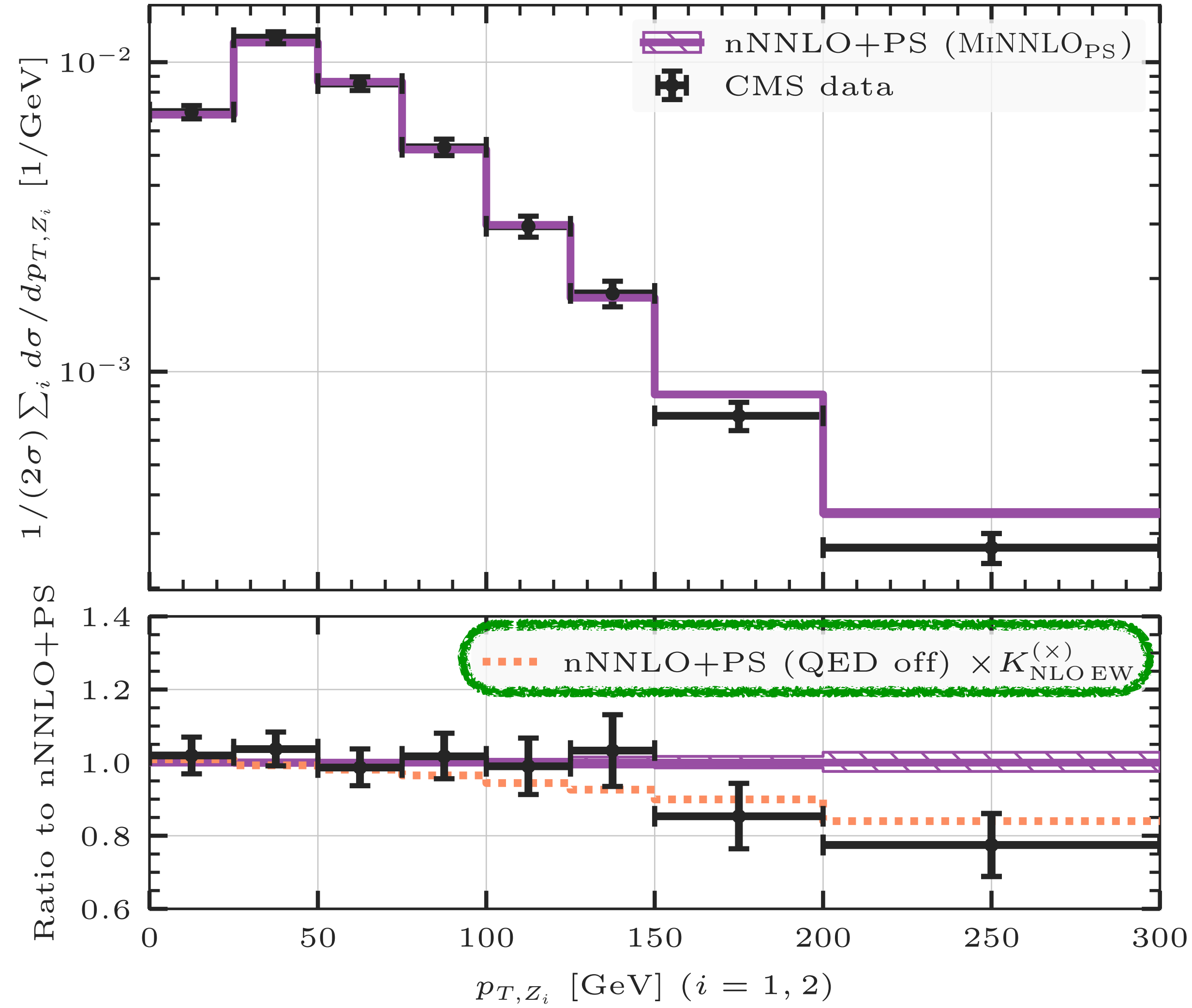
Comparison to data: CMS 13TeV analysis

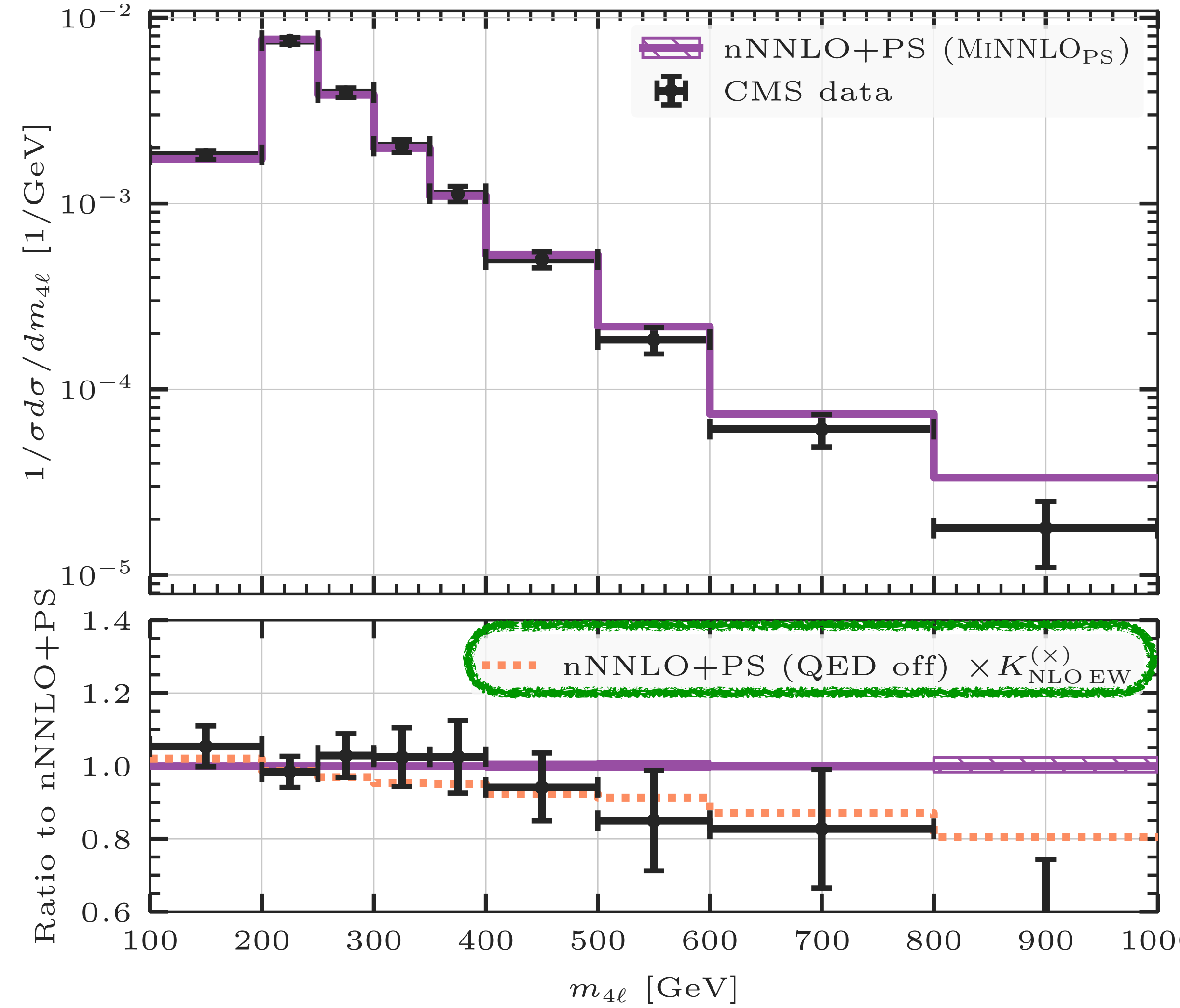


✓ *nNNLO+PS predictions in good agreement with CMS results, based on the a137fb*$^{-1}$ *13TeV analysis ([arXiv:2009.01186])!*

nNNLO+PS for ZZ: Phenomenological results

Comparison to data: CMS 13TeV analysis





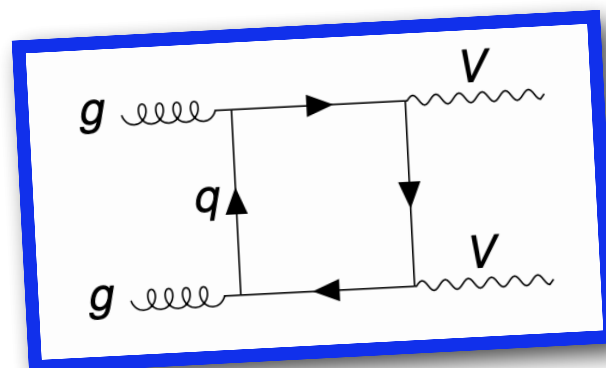
- ✓ *nNNLO+PS predictions in good agreement with CMS results, based on the a137fb^{-1} 13TeV analysis ([arXiv:2009.01186])!*
- ✓ *Consistent inclusion of EW corrections to describe tails of distributions*

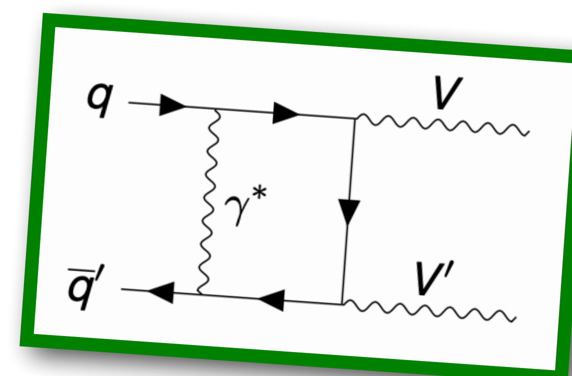
$$K^{(\times)}_{NLO\,EW} = \frac{\sigma_{nNNLO\,QCD} + \sigma^{\bar{q}q}_{LO}\cdot(\delta_{EW} + \delta_{QCD}\delta_{EW})}{\sigma_{nNNLO\,QCD}}$$

Summary:

- ✓ *NNLO+PS accuracy crucial for realistic and precise LHC phenomenology*
- ✓ *Very good description of data by* ***Zγ*** *MiNNLO$_{PS}$ predictions*
- ✓ ***WW*** *NNLO corrections efficiently included by MiNNLO$_{PS}$ without any a-posteriori reweighting*
- ✓ *nNNLO+PS predictions in* ***ZZ*** *crucial for a physical description of data*

Outlook:





- ✓ *MiNNLO$_{PS}$ to all other diboson processes in the pipeline*
- ✓ *Inclusion of* ***gg@NLO+PS*** *and* ***NLO EW*** *corrections*
- ✓ *Systematically accounting for <u>BSM effects</u> (i.e with EFT approach)*

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✓ *NNLO+PS accuracy crucial for realistic and precise LHC phenomenology*

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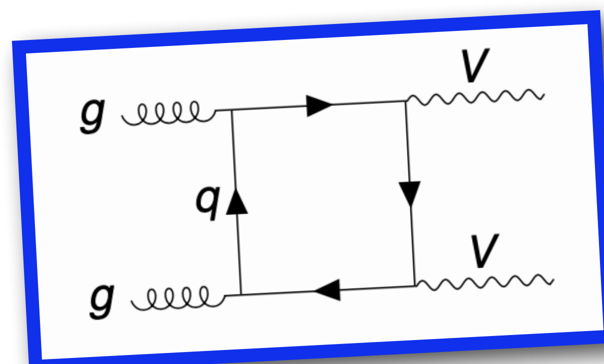

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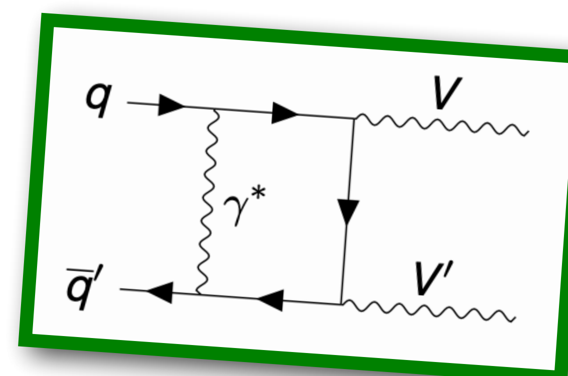

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Thank you for your attention