NNLO+PS ACCURACY USING THE MiNNLO$_{PS}$ METHOD

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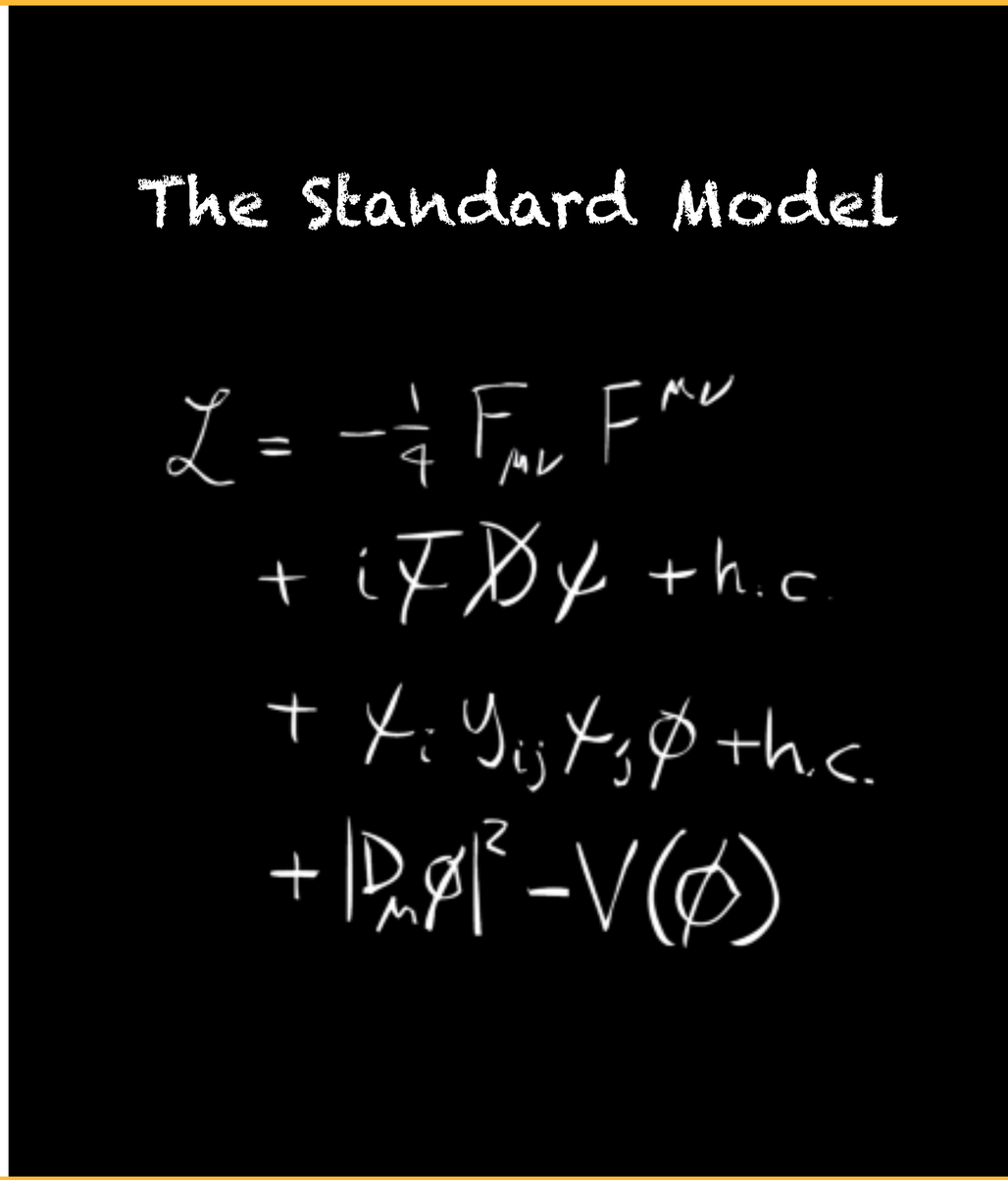
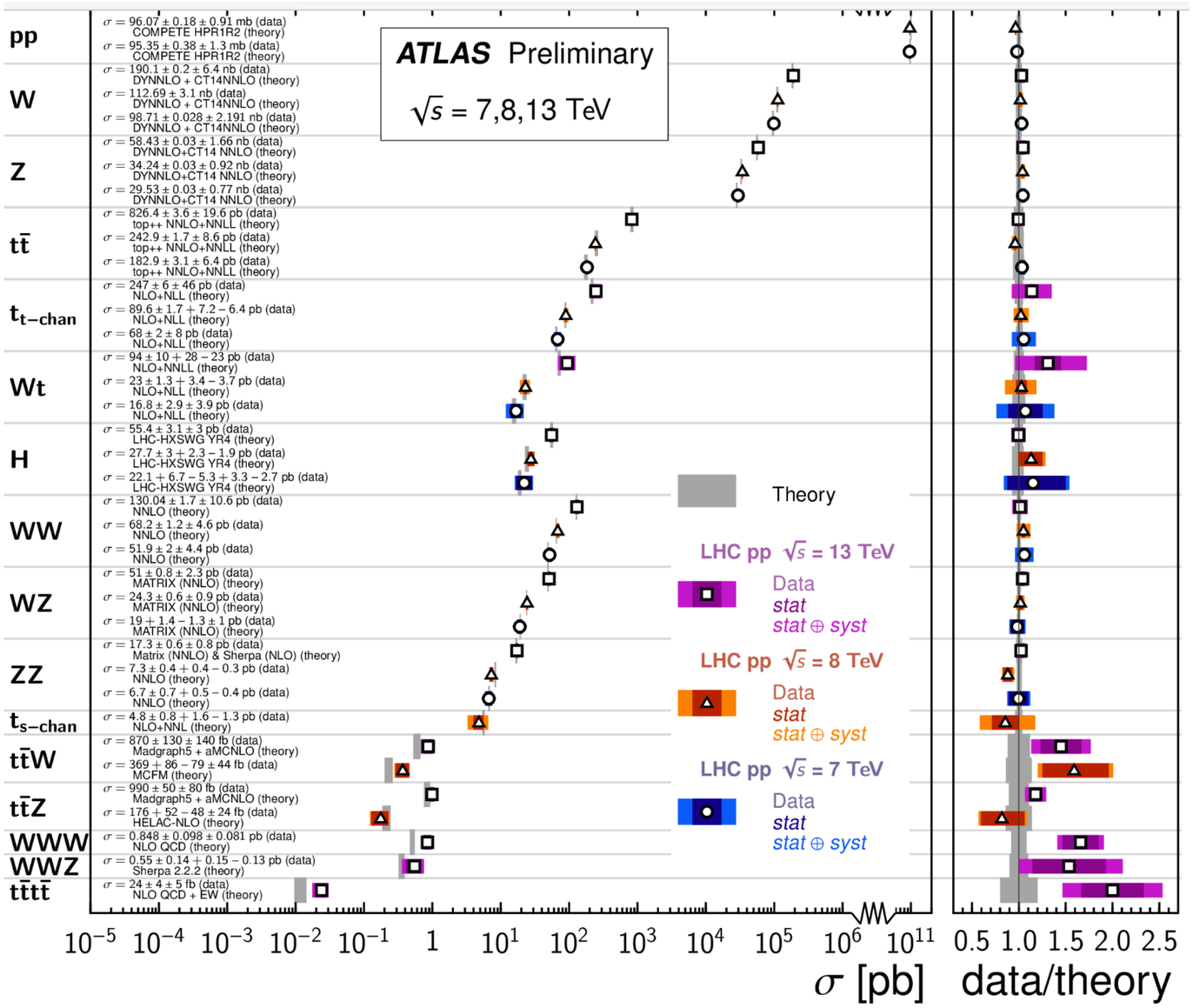
Precision Physics: why?

- The SM is a beautiful theory… but it's **not complete**!
- It has been thoroughly tested at the Large Hadron Collider, but **no new physics signal has been observed so far**.
- **Precise predictions** are needed for detecting small deviations from the SM.
- Theory needs to match at least the experimental precision.

Precise predictions are mandatory!



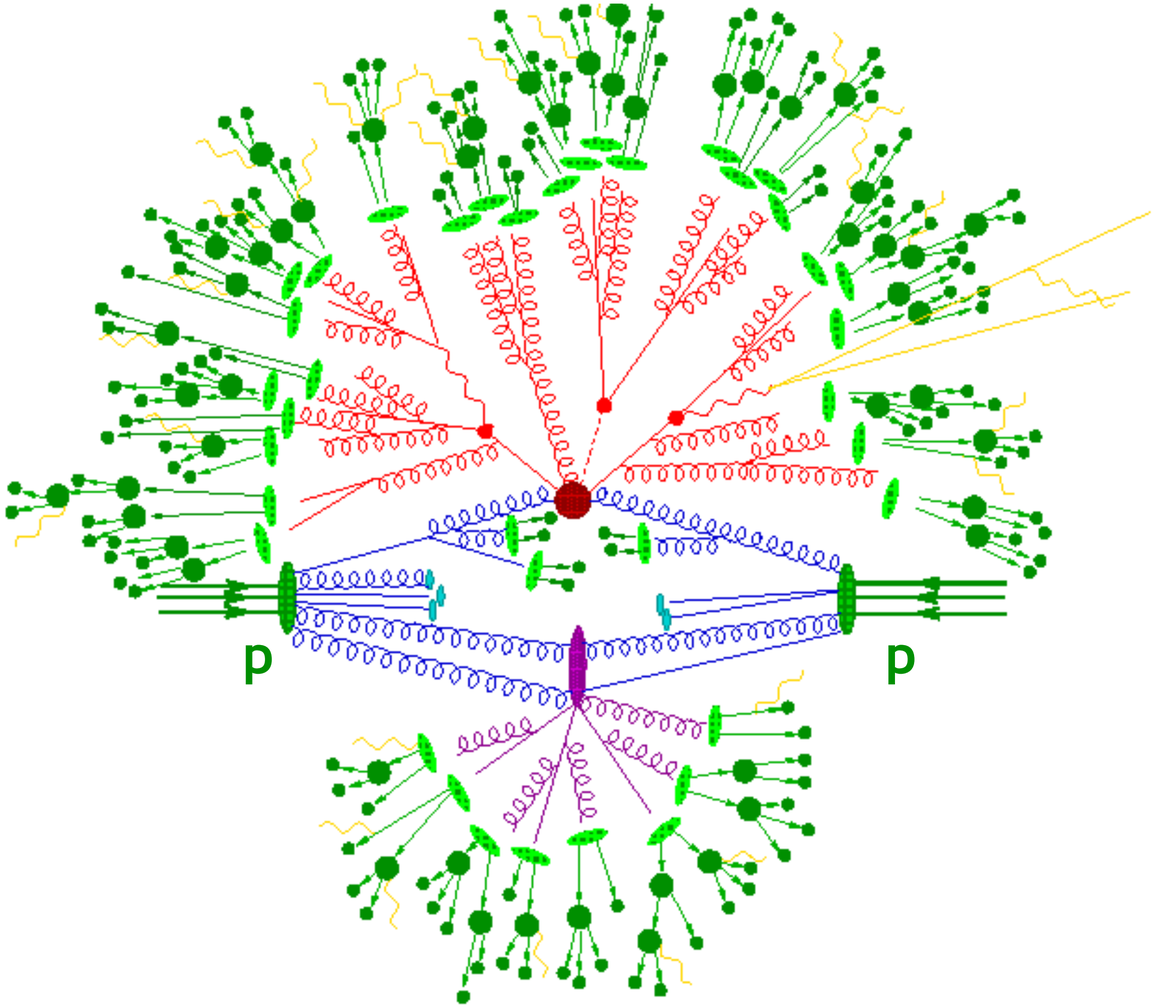
Precision Physics: why?



Impressive experimental accuracy

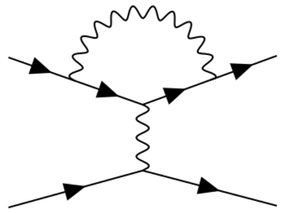
- Most measurements have few % error bars.
- Improvements in detectors + increased luminosity (Hi-Lumi) → the experimental accuracy will become even better!

Event Generators



Event Generators

Hard Scattering

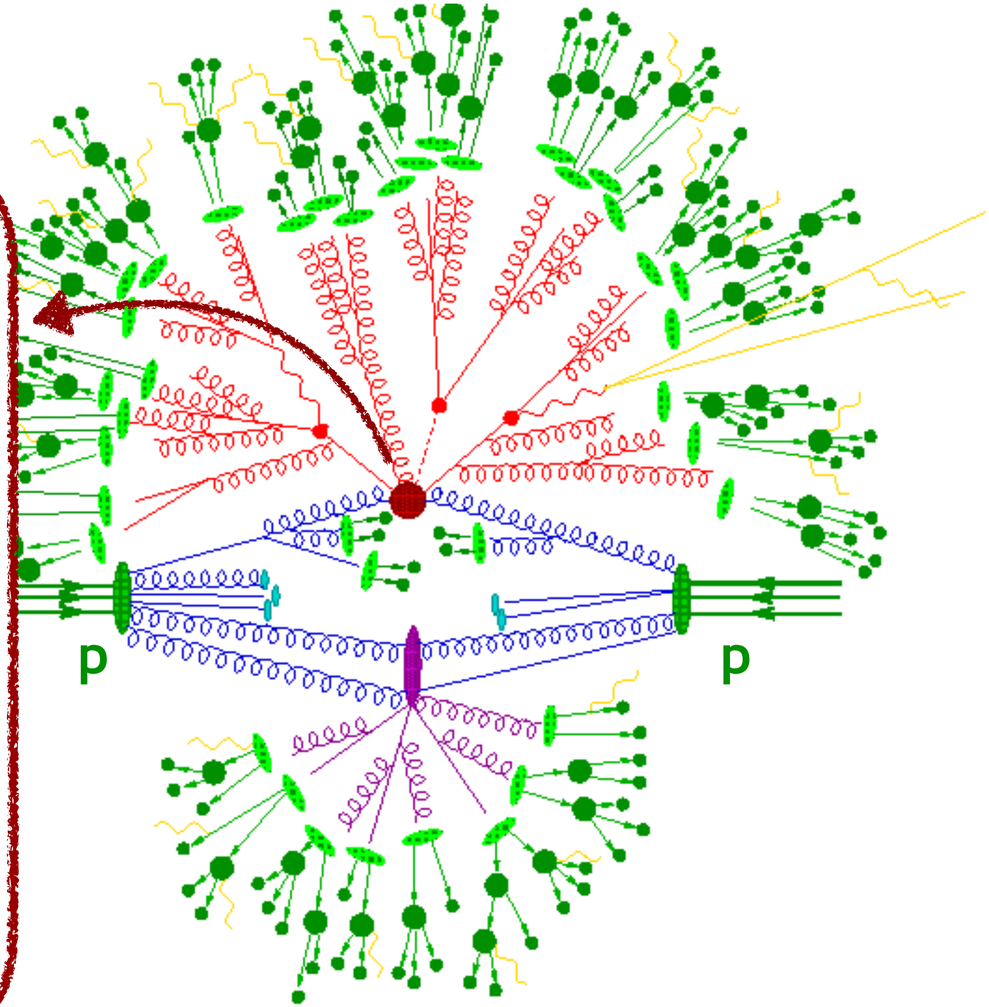


$$\hat{\sigma} = \hat{\sigma}_{LO}\left(1 + \alpha_s \delta_{NLO} + \alpha_s^2 \delta_{NNLO} + \mathcal{O}(\alpha_s^3)\right)$$

LO → $\mathcal{O}$(100 %)

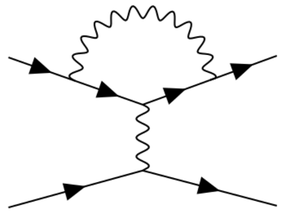
NLO → $\mathcal{O}$(10 %)

NNLO → $\mathcal{O}$(1 %)



Event Generators

Hard Scattering



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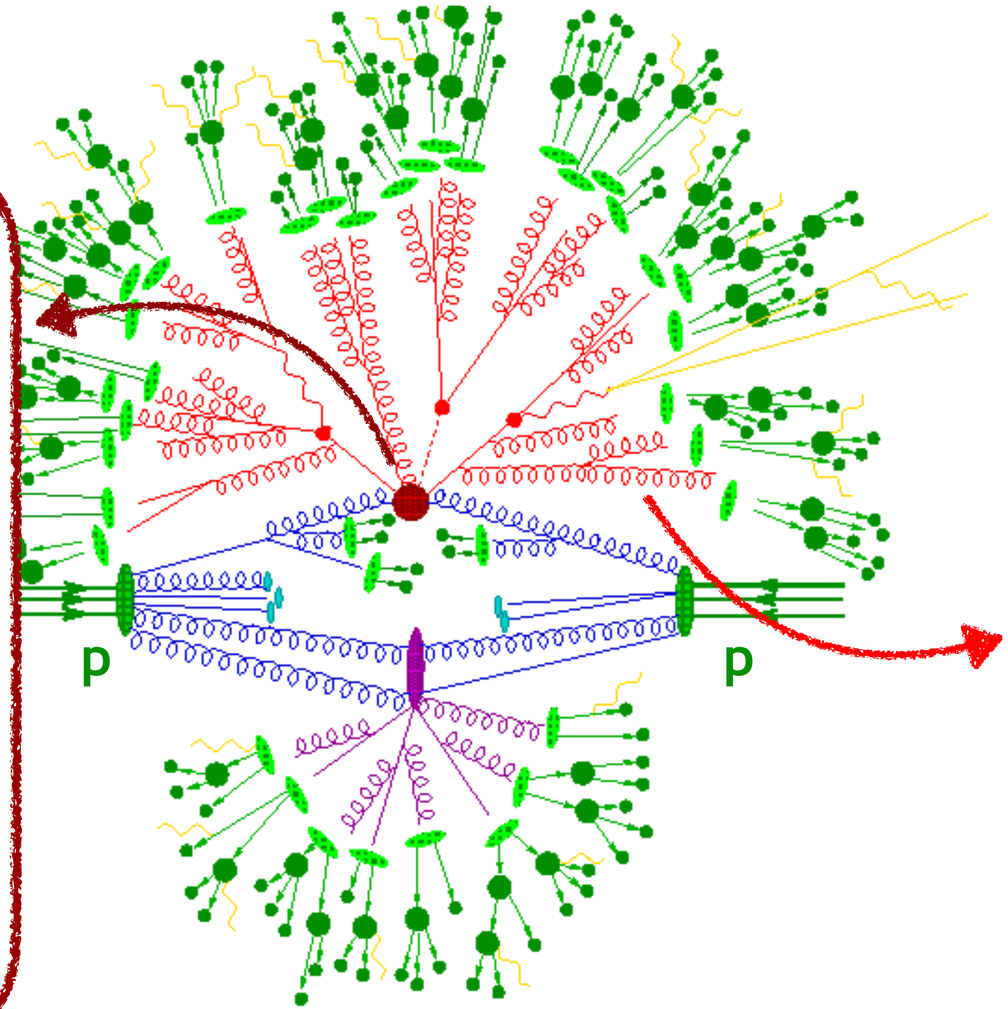
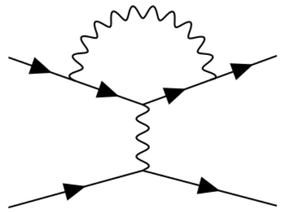


Parton Shower (PS)

Description of soft and collinear emissions from the high-energy limit down to the QCD cutoff. Accuracy is low, usually only LL.

Event Generators

Hard Scattering



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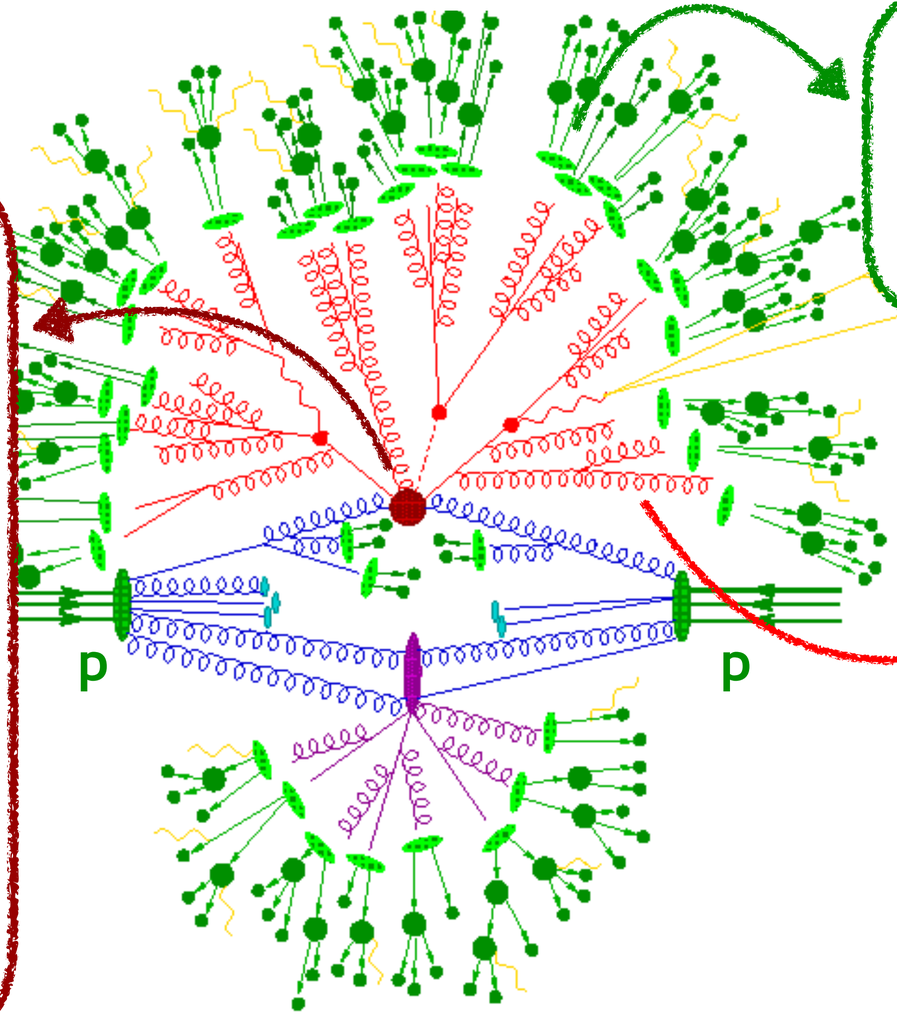


Hadronization + decay

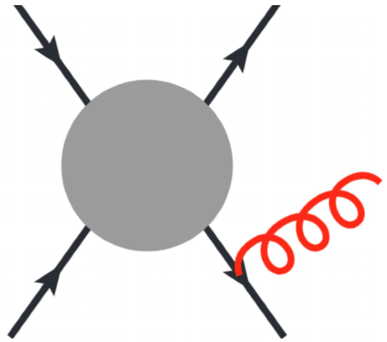
Tuned to phenomenological models.

Parton Shower (PS)

Description of soft and collinear emissions from the high-energy limit down to the QCD cutoff. Accuracy is low, usually only LL.

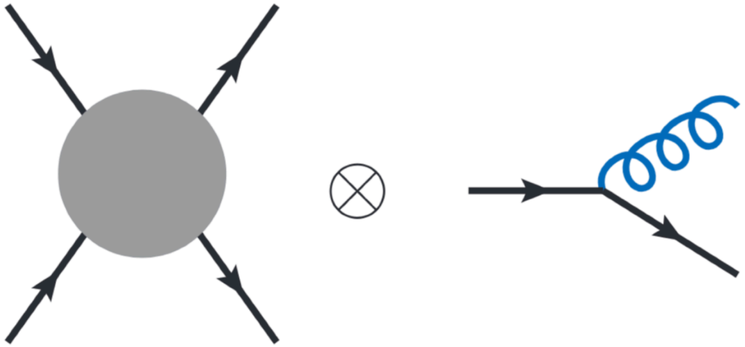
NNLO+PS

Hard Scattering



Correct Real Emission

Parton Shower (PS)



Approx Real Emission

Combination: NNLO+PS

MiNNLOPS

- **No** computationally intense **reweighting**.
- **No unphysical merging scale**.
- **LL** accuracy of the shower **preserved** (MiNNLOPS is based on the POWHEG framework).
- Numerically **efficient**.

	F	F+J	F+JJ
F@MiNNLOPS	**NNLO**	NLO	LO

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

Master Formula ($\bar{B}$ function in POWHEG):

$$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d}{dp_T}\left\{ e^{-\tilde{S}(p_T)} \mathscr{L}(p_T) \right\} + R_f(p_T) = e^{-\tilde{S}(p_T)} \left[D(p_T) + \frac{R_f(p_T)}{e^{-\tilde{S}(p_T)}} \right] = \ldots =$$

$$= e^{-\tilde{S}(p_T)} \left\{ \frac{\alpha_s(p_T)}{2\pi} \left[\frac{d\sigma_{FJ}}{d\Phi_{FJ} dp_T} \right]^{(1)} \left(1 + \frac{\alpha_s(p_T)}{2\pi} [\tilde{S}]^{(1)} \right) + \left(\frac{\alpha_s(p_T)}{2\pi} \right)^2 \left[\frac{d\sigma_{FJ}}{d\Phi_{FJ} dp_T} \right]^{(2)} + \left(\frac{\alpha_s(p_T)}{2\pi} \right)^3 [D(p_T)]^{(3)} + regular \right\}$$

Higgstrahlung with H→bb decay

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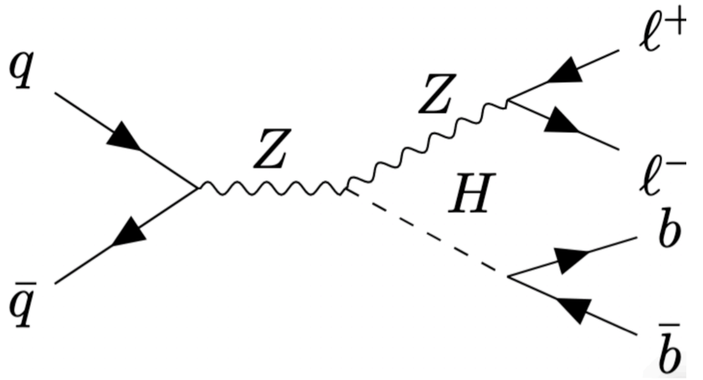
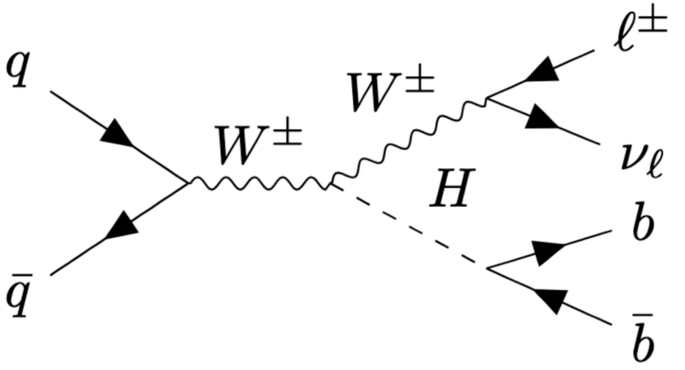
- One of the **main production channels**.
- **Largest branching fraction** in decay (≈60%).
- Needed for **precision measurements** in the Higgs sector.
- Separate study of production and decay.

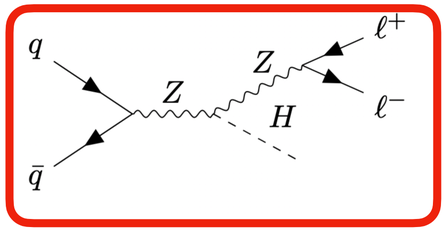


NNLO+PS accuracy in both **production and decay**



Generation of events

PRODUCTION:

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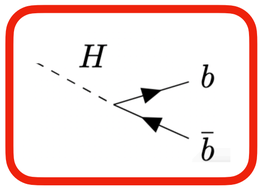
      2     -1     0     0   501     0  0.000000000E+00  0.000000000E+00 -1.149726029E+03  1.149726029E+03  0.000000000E+00  0.00000E+00  9.000E+00
     24      2     1     2     0     0  5.211805348E-01  7.118662673E-01 -9.897030656E+02  1.097861941E+03  4.751714489E+02  0.00000E+00  9.000E+00
     24      2     3     3     0     0  7.098090236E+01 -1.423395610E+02 -8.031126759E+02  8.223773332E+02  7.756074276E+01  0.00000E+00  9.000E+00
     25      1     3     3     0     0 -7.045972182E+01  1.430514272E+02 -1.865903897E+02  2.754846082E+02  1.250900180E+02  0.00000E+00  9.000E+00
    -11      1     4     4     0     0  6.342590728E+01 -4.142757742E+01 -3.399963187E+02  3.483340159E+02  5.110000000E-04  0.00000E+00  9.000E+00
     12      1     4     4     0     0  7.554995079E+00 -1.009119835E+02 -4.631163572E+02  4.740433173E+02  5.394796609E-06  0.00000E+00  9.000E+00
     21      1     1     2   501   502 -1.890605848E+00  4.823555713E-02 -1.059077847E+02  1.059246694E+02  5.046370146E-06  0.00000E+00  9.000E+00
     21      1     1     2   502   511  1.369425313E+00 -7.601018244E-01  2.243777045E+01  2.249236811E+01  8.920806376E-07  0.00000E+00  9.000E+00
```

DECAY:




```
<event>
      7  10001  4.49807E-03  1.06934E+01 -1.00000E+00  1.92716E-01
     12     -1     0     0     0     0  0.000000000E+00  0.000000000E+00  6.254500000E+01  6.254500000E+01  0.000000000E+00  0.00000E+00  9.000E+00
    -12     -1     0     0     0     0  0.000000000E+00  0.000000000E+00 -6.254500000E+01  6.254500000E+01  0.000000000E+00  0.00000E+00  9.000E+00
     25      2     1     2     0     0  0.000000000E+00  0.000000000E+00  0.000000000E+00  1.250900000E+02  1.250900000E+02  0.00000E+00  9.000E+00
      5      1     3     3   502     0 -3.482558088E+01 -3.087472611E+01  1.355053755E+01  4.870867750E+01  4.780000000E+00  0.00000E+00  9.000E+00
     -5      1     3     3     0   511  2.523902727E+01  4.214457839E+01 -1.662090492E+01  5.207952443E+01  4.780000000E+00  0.00000E+00  9.000E+00
     21      1     3     3   501   502 -1.784543959E+00 -1.199533279E+01  4.241201676E+00  1.284758334E+01  2.308477966E-07  0.00000E+00  9.000E+00
     21      1     3     3   511   501  1.137109758E+01  7.254805161E-01 -1.170834306E+00  1.145421473E+01  1.255594160E-07  0.00000E+00  9.000E+00
```

Higgstrahlung with H→bb decay

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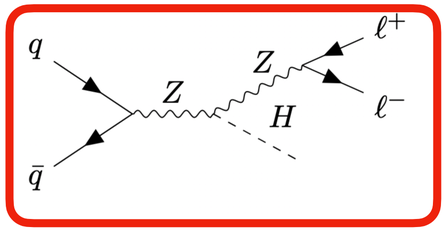
PRODUCTION:

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     -1     -1     0     0     0   511  0.000000000E+00  0.000000000E+00  7.655294950E+01  7.655294950E+01  0.000000000E+00  0.00000E+00  9.000E+00
      2     -1     0     0   501     0  0.000000000E+00  0.000000000E+00 -1.149726029E+03  1.149726029E+03  0.000000000E+00  0.00000E+00  9.000E+00
     24      2     1     2     0     0  5.211805348E-01  7.118662673E-01 -9.897030656E+02  1.097861941E+03  4.751714489E+02  0.00000E+00  9.000E+00
     24      2     3     3     0     0  7.098090236E+01 -1.423395610E+02 -8.031126759E+02  8.223773332E+02  7.756074276E+01  0.00000E+00  9.000E+00
Higgs
     25      1     3     3     0     0 -7.045972182E+01  1.430514272E+02 -1.865903897E+02  2.754846082E+02  1.250900180E+02  0.00000E+00  9.000E+00
    -11      1     4     4     0     0  6.342590728E+01 -4.142757742E+01 -3.399963187E+02  3.483340159E+02  5.110000000E-04  0.00000E+00  9.000E+00
     12      1     4     4     0     0  7.554995079E+00 -1.009119835E+02 -4.631163572E+02  4.740433173E+02  5.394796609E-06  0.00000E+00  9.000E+00
     21      1     1     2   501   502 -1.890605848E+00  4.823555713E-02 -1.059077847E+02  1.059246694E+02  5.046370146E-06  0.00000E+00  9.000E+00
     21      1     1     2   502   511  1.369425313E+00 -7.601018244E-01  2.243777045E+01  2.249236811E+01  8.920806376E-07  0.00000E+00  9.000E+00
```
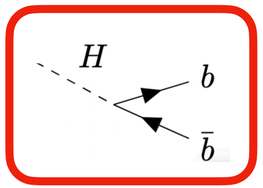

DECAY:




```
<event>
      7  10001  4.49807E-03  1.06934E+01 -1.00000E+00  1.92716E-01
     12     -1     0     0     0     0  0.000000000E+00  0.000000000E+00  6.254500000E+01  6.254500000E+01  0.000000000E+00  0.00000E+00  9.000E+00
    -12     -1     0     0     0     0  0.000000000E+00  0.000000000E+00 -6.254500000E+01  6.254500000E+01  0.000000000E+00  0.00000E+00  9.000E+00
     25      2     1     2     0     0  0.000000000E+00  0.000000000E+00  0.000000000E+00  1.250900000E+02  1.250900000E+02  0.00000E+00  9.000E+00
Higgs +
Decay
Products
      5      1     3     3   502     0 -3.482558088E+01 -3.087472611E+01  1.355053755E+01  4.870867750E+01  4.780000000E+00  0.00000E+00  9.000E+00
     -5      1     3     3     0   511  2.523902727E+01  4.214457839E+01 -1.662090492E+01  5.207952443E+01  4.780000000E+00  0.00000E+00  9.000E+00
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```
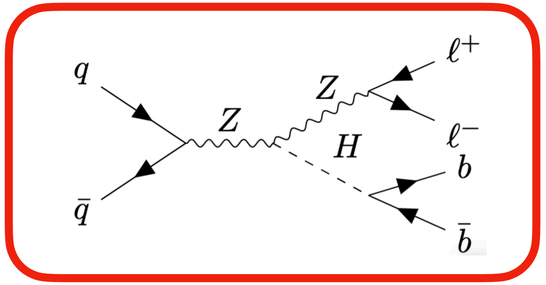

Higgstrahlung with H→bb decay



FULL EVENT:

```
<event>
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     -1     -1     0     0     0   511  0.000000000E+00  0.000000000E+00  7.655294950E+01  7.655294950E+01  0.000000000E+00  0.00000E+00  9.000E+00
      2     -1     0     0   501     0  0.000000000E+00  0.000000000E+00 -1.149726029E+03  1.149726029E+03  0.000000000E+00  0.00000E+00  9.000E+00
     24      2     1     2     0     0  5.211805348E-01  7.118662673E-01 -9.897030656E+02  1.097861941E+03  4.751714489E+02  0.00000E+00  9.000E+00
     24      2     3     3     0     0  7.098090236E+01 -1.423395610E+02 -8.031126759E+02  8.223773332E+02  7.756074276E+01  0.00000E+00  9.000E+00
     25      2     3     3     0     0 -7.045972182E+01  1.430514272E+02 -1.865903897E+02  2.754846082E+02  1.250900180E+02  0.00000E+00  9.000E+00
    -11      1     4     4     0     0  6.342590728E+01 -4.142757742E+01 -3.399963187E+02  3.483340159E+02  5.110000000E-04  0.00000E+00  9.000E+00
     12      1     4     4     0     0  7.554995079E+00 -1.009119835E+02 -4.631163572E+02  4.740433173E+02  5.394796609E-06  0.00000E+00  9.000E+00
     21      1     1     2   501   502 -1.890605848E+00  4.823555713E-02 -1.059077847E+02  1.059246694E+02  5.046370146E-06  0.00000E+00  9.000E+00
     21      1     1     2   502   511  1.369425313E+00 -7.601018244E-01  2.243777045E+01  2.249236811E+01  8.920806376E-07  0.00000E+00  9.000E+00
      5      1     5     5   702     0 -7.654277374E+01  9.828619533E+01 -1.413293817E+02  1.884564006E+02  4.780000000E+00  0.00000E+00  9.000E+00
     -5      1     5     5     0   711  1.308120069E+01  4.864606448E+00  8.538335619E+00  1.704505155E+01  4.780000000E+00  0.00000E+00  9.000E+00
     21      1     5     5   701   702 -1.334729692E+01  2.944741792E+01 -4.185354346E+01  5.288685902E+01  0.000000000E+00  0.00000E+00  9.000E+00
     21      1     5     5   711   701  6.349148171E+00  1.045320749E+01 -1.194580015E+01  1.709629699E+01  0.000000000E+00  0.00000E+00  9.000E+00
#rwgt            1           1   5.3448772136252189E-002           1         156           0           1           0
```

Higgs

H Decay Products

We can now interface the full event with the shower and obtain a realistic result!

Results: cross sections

[2112.04168]

$pp \to W^+H \to e^+\nu_e b\bar{b}$		
σ [fb]	`inclusive`	`fiducial-YR`
MiNLO′	$54.04^{+6.6\%}_{-3.6\%}$	$20.13^{+2.3\%}_{-3.1\%}$
MiNNLO$_{\rm PS}$	$57.44^{+1.7\%}_{-0.8\%}$	$21.27^{+1.3\%}_{-1.3\%}$
$pp \to W^-H \to e^-\bar{\nu}_e b\bar{b}$		
σ [fb]	`inclusive`	`fiducial-YR`
MiNLO′	$33.82^{+6.6\%}_{-3.6\%}$	$13.07^{+2.4\%}_{-3.3\%}$
MiNNLO$_{\rm PS}$	$35.87^{+1.5\%}_{-0.7\%}$	$13.77^{+1.5\%}_{-1.6\%}$
$pp \to ZH \to e^+e^- b\bar{b}$		
σ [fb]	`inclusive`	`fiducial-YR`
MiNLO′	$14.88^{+6.7\%}_{-3.7\%}$	$5.21^{+2.2\%}_{-3.0\%}$
MiNNLO$_{\rm PS}$ (no $gg \to ZH$)	$15.79^{+1.8\%}_{-0.9\%}$	$5.48^{+1.2\%}_{-1.2\%}$
MiNNLO$_{\rm PS}$ (with $gg \to ZH$)	$16.99^{+3.6\%}_{-2.3\%}$	$6.07^{+3.4\%}_{-2.9\%}$

[Yellow Report (YR) 1610.07922]

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[2112.04168]

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σ [fb]	inclusive	fiducial-YR
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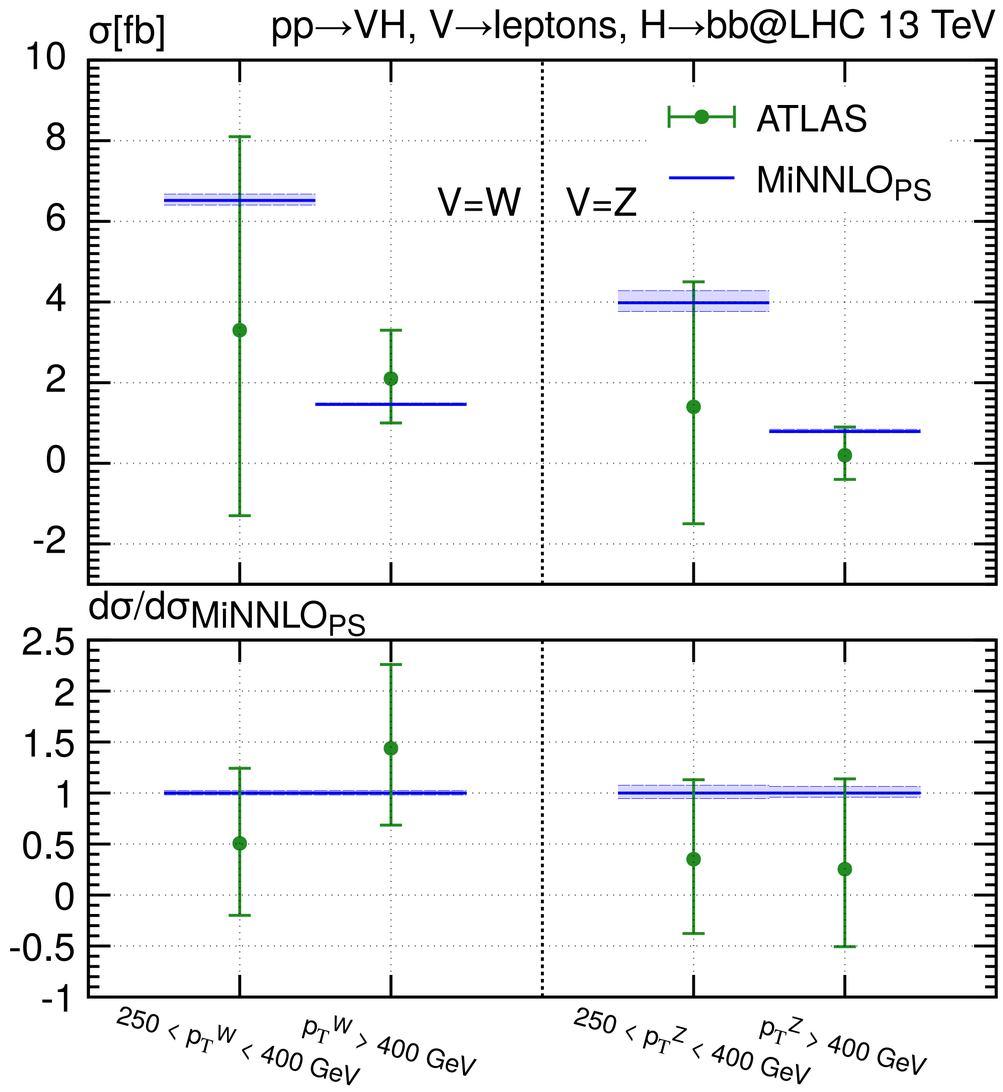
MiNNLO$_{\rm PS}$	$35.87^{+1.5\%}_{-0.7\%}$	$13.77^{+1.5\%}_{-1.6\%}$
$pp \to ZH \to e^+e^- b\bar{b}$		
σ [fb]	inclusive	fiducial-YR
MiNLO′	$14.88^{+6.7\%}_{-3.7\%}$	$5.21^{+2.2\%}_{-3.0\%}$
MiNNLO$_{\rm PS}$ (no $gg \to ZH$)	$15.79^{+1.8\%}_{-0.9\%}$	$5.48^{+1.2\%}_{-1.2\%}$
MiNNLO$_{\rm PS}$ (with $gg \to ZH$)	$16.99^{+3.6\%}_{-2.3\%}$	$6.07^{+3.4\%}_{-2.9\%}$ ← Included at LO only!

[Yellow Report (YR) 1610.07922]

Results: comparison with data



[2112.04168]

$pp \to W^{\pm}H \to \ell^{\pm}\nu_\ell b\bar{b}$		
σ [fb]	$p_T^W \in [250,400]$ GeV	$p_T^W \in [400, \infty]$ GeV
MiNNLOPS	$6.52^{+2.4\%}_{-1.8\%}$	$1.46^{+2.5\%}_{-1.9\%}$
ATLAS [130]	$3.3^{+3.6(\text{Stat.})+3.2(\text{Syst.})}_{-3.4(\text{Stat.})-3.0(\text{Syst.})}$	$2.1^{+1.0(\text{Stat.})+0.6(\text{Syst.})}_{-0.9(\text{Stat.})-0.5(\text{Syst.})}$
$pp \to ZH \to (\ell^+\ell^-, \nu_\ell\bar{\nu}_\ell)b\bar{b}$		
σ [fb]	$p_T^Z \in [250,400]$ GeV	$p_T^Z \in [400, \infty]$ GeV
MiNNLOPS	$3.98^{+7.6\%}_{-5.4\%}$	$0.79^{+6.5\%}_{-4.2\%}$
ATLAS [130]	$1.4^{+2.4(\text{Stat.})+1.9(\text{Syst.})}_{-2.3(\text{Stat.})-1.7(\text{Syst.})}$	$0.2^{+0.6(\text{Stat.})+0.3(\text{Syst.})}_{-0.5(\text{Stat.})-0.3(\text{Syst.})}$

[ATLAS data taken from 2008.02508]

Results: fiducial distributions

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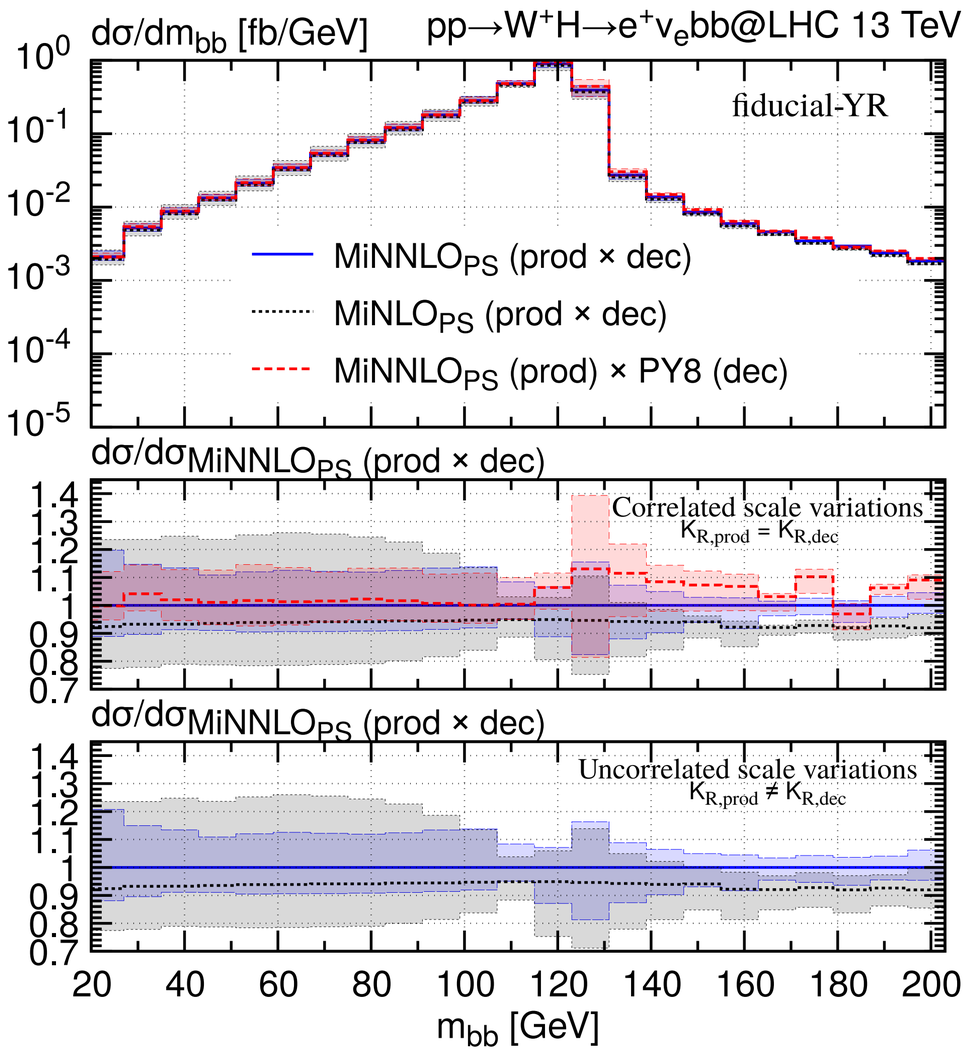
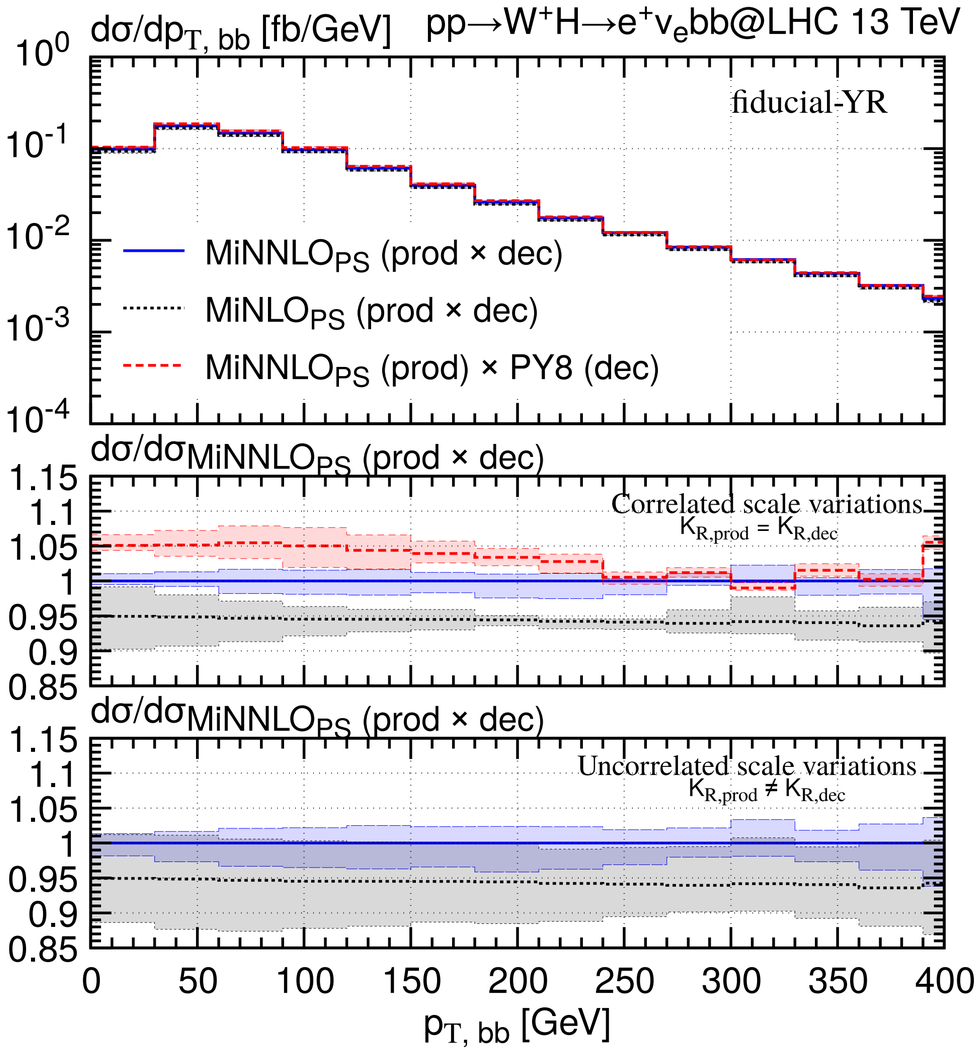
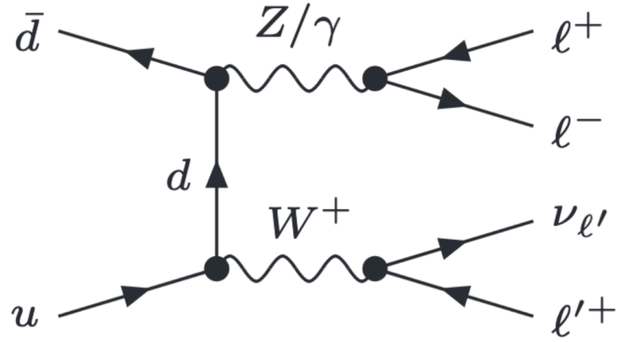
[2112.04168]

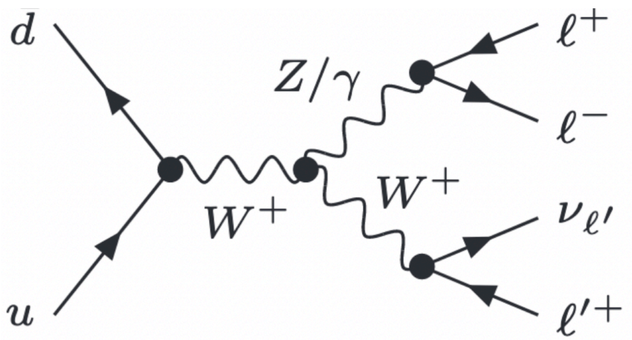




WZ production

- Interesting for **testing** the **gauge structure** of the EW sector.
- **Background** in many **BSM studies**.
- Different possibilities when **matching QCD and EW corrections** and **QCD and QED showers**.





NNLO+PS QCD accuracy
+
NLO+PS EW accuracy

Validation

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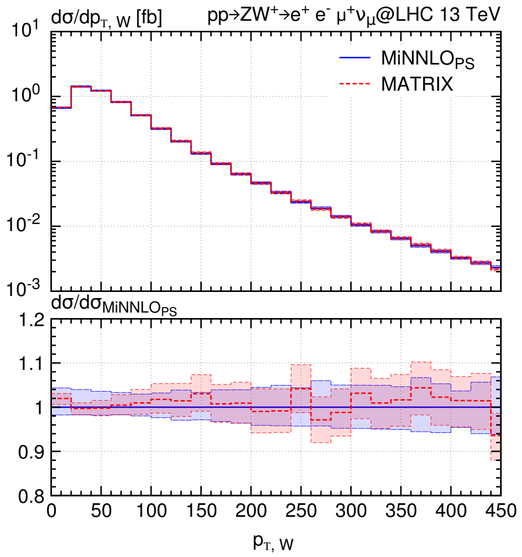
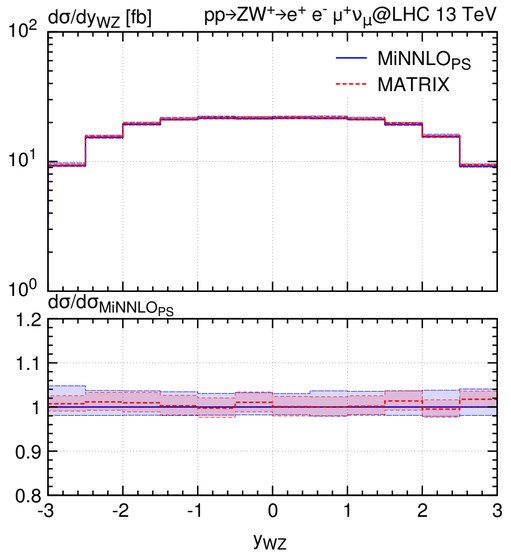
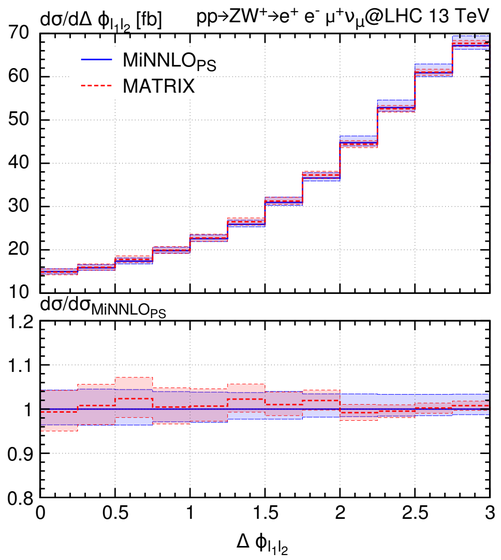
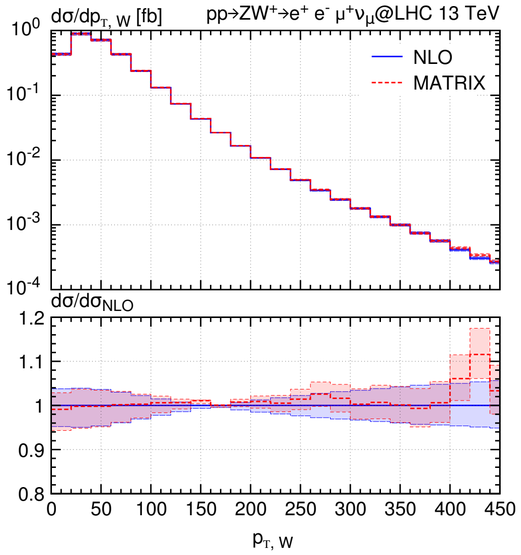
NNLO QCD:

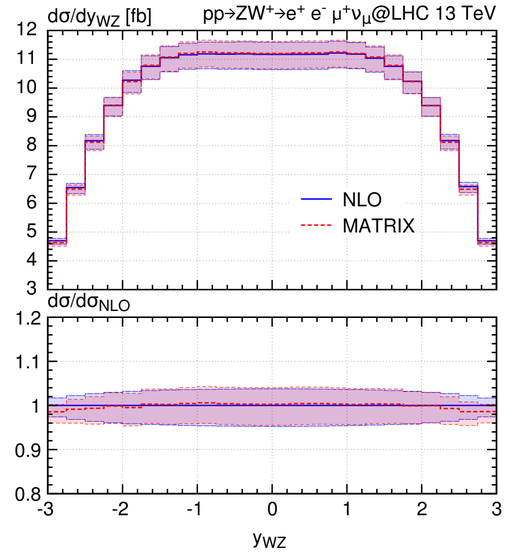


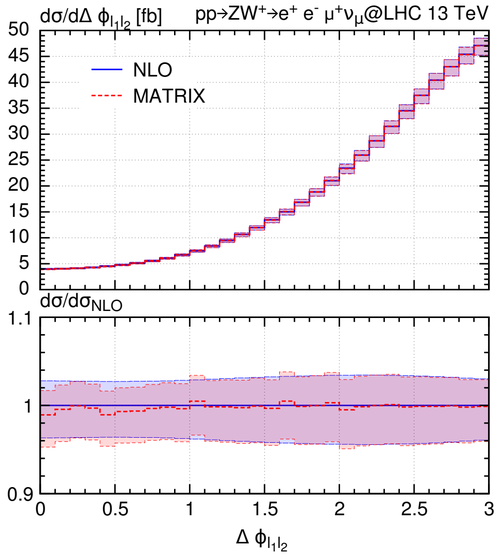




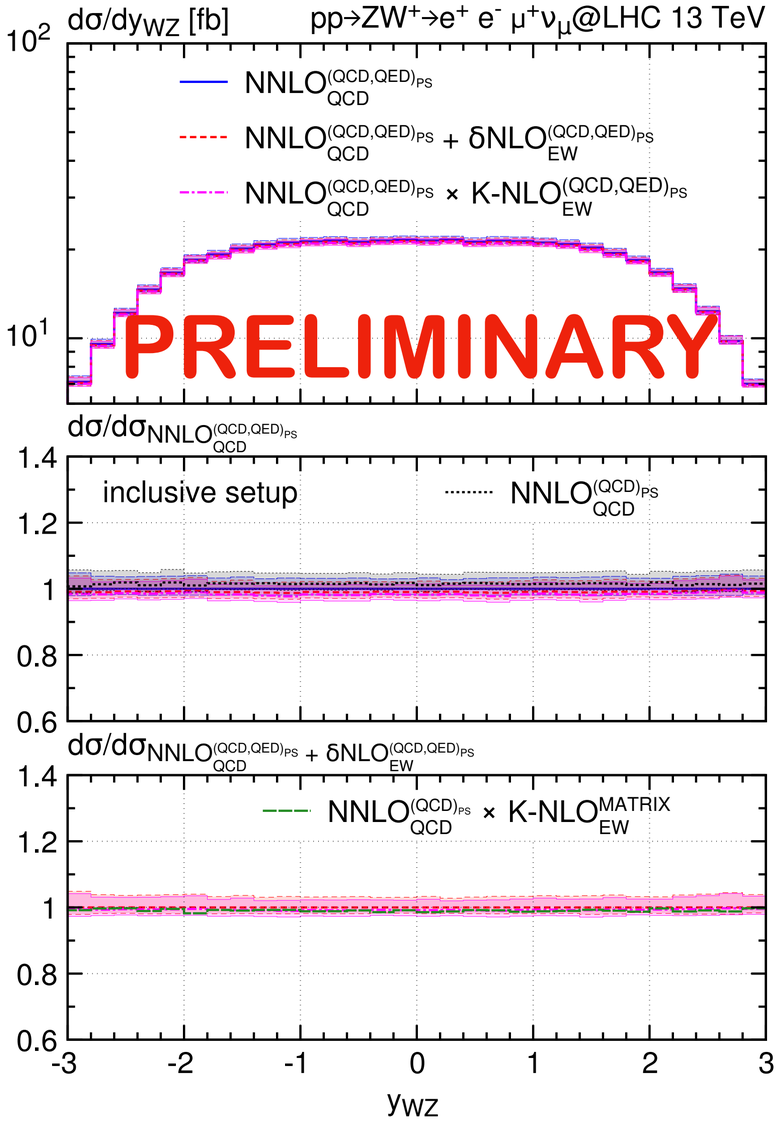
NLO EW:

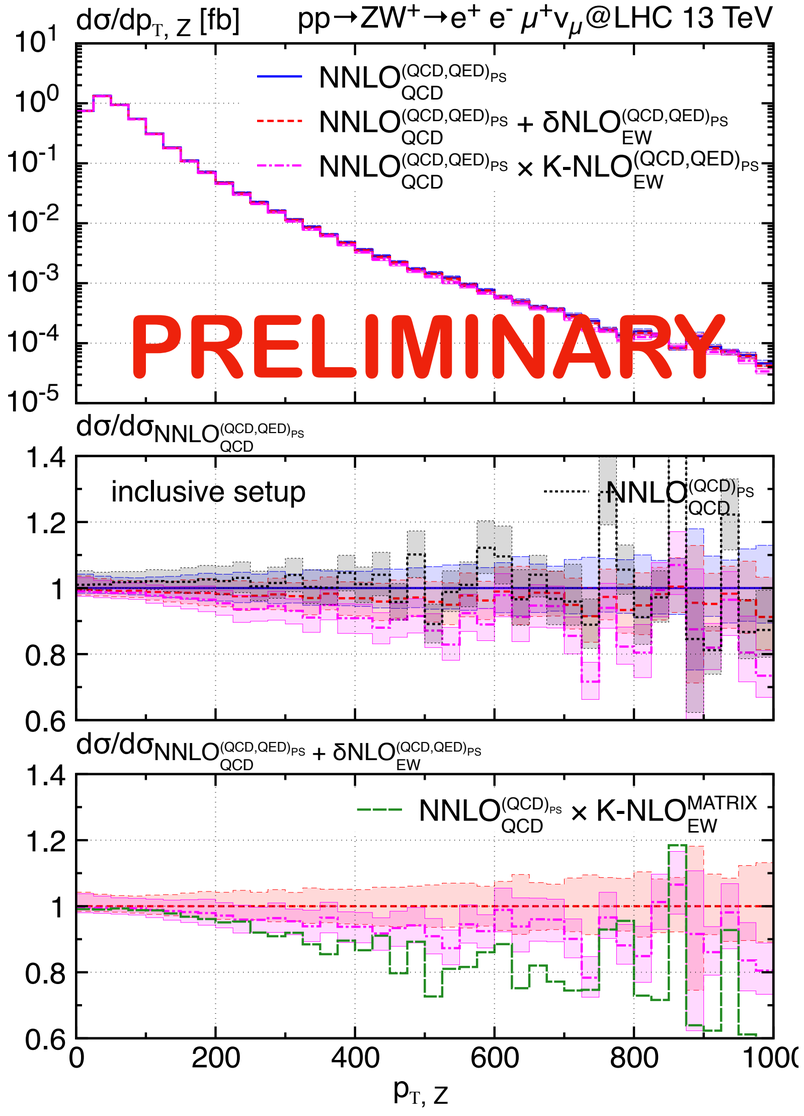


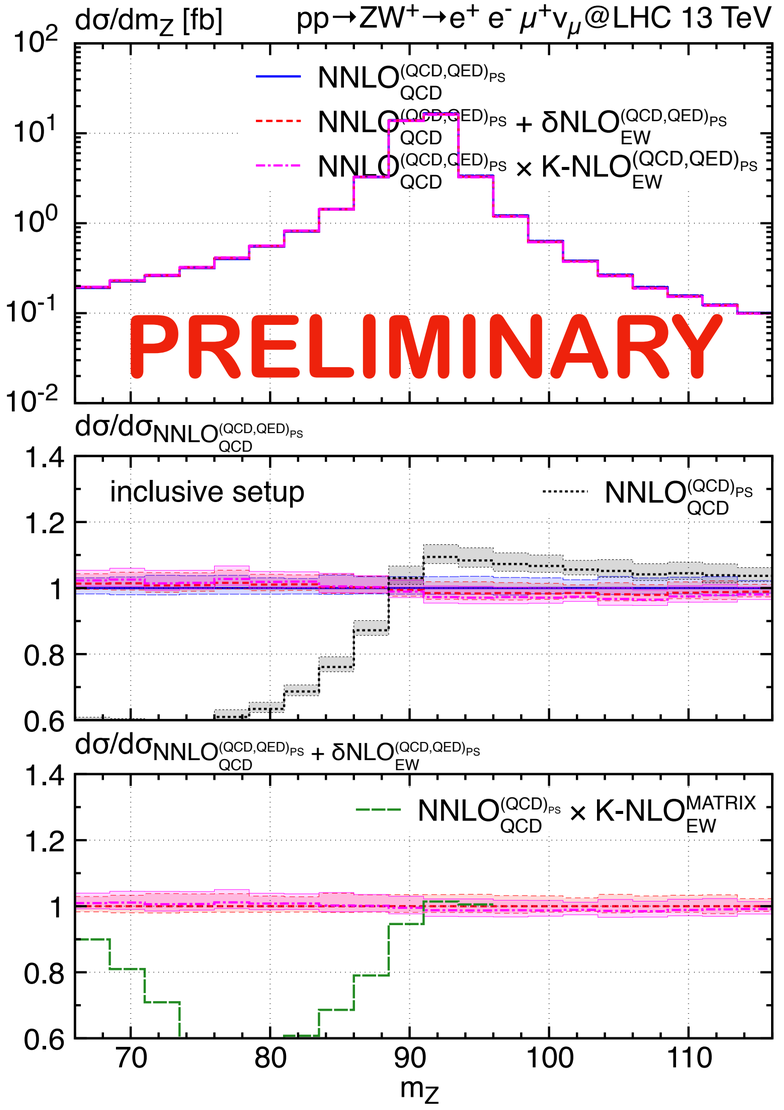




Results: fiducial distributions







Conclusions

- **NNLO+PS** predictions are **strongly needed** for a realistic description of LHC events.
- **MiNNLO$_{PS}$** is a **powerful tool** for reaching this accuracy.
- I showed and discussed results for **Higgstrahlung with H→bb decay**, which is needed for precision measurements in the Higgs sector.
- I showed and discussed results for **WZ production**, which is needed for testing the gauge structure of the EW sector.

Thank you for your attention!