Universität Regensburg

Anomalous Higgs boson couplings in WBF Higgs boson production

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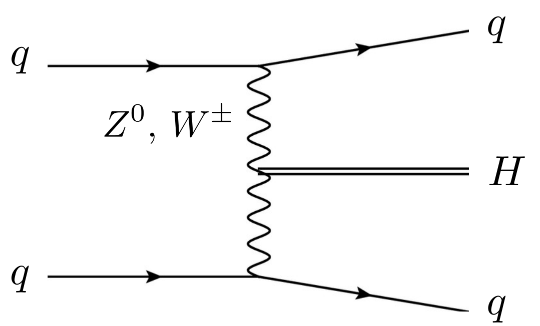
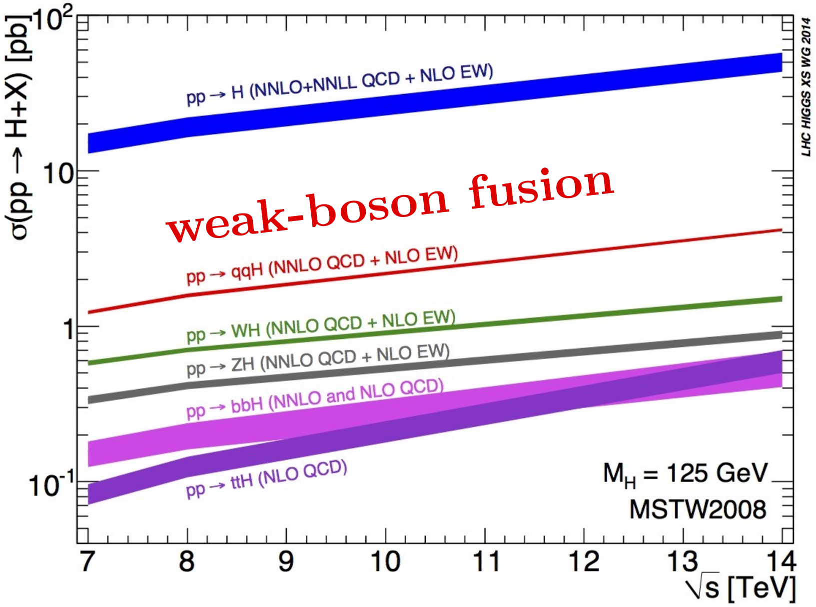
For more details see Phys. Rev. D 107 (2023) 3, 034034.
Work done at BNL in collaboration with Fabrizio Caola, Kirill Melnikov and Raoul Röntsch.

Higgs-boson production in weak-boson fusion (WBF)

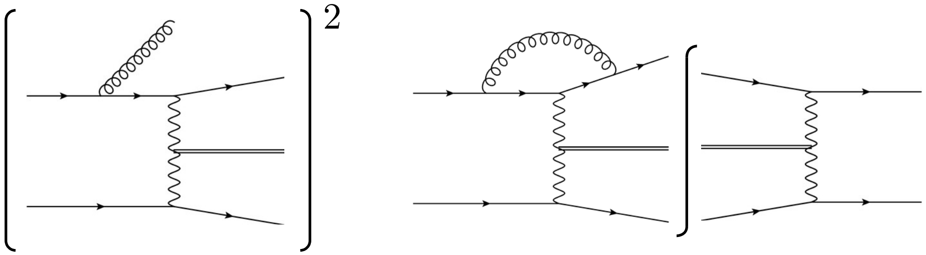




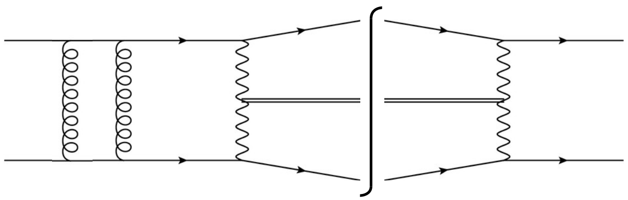
- Important production channel of Higgs boson @LHC (second highest cross section @14TeV)
- Probes electro-weak sector
- Very distinct signature

Higher order QCD correction to vector-boson fusion

- 2 classes of corrections to the amplitude squared:



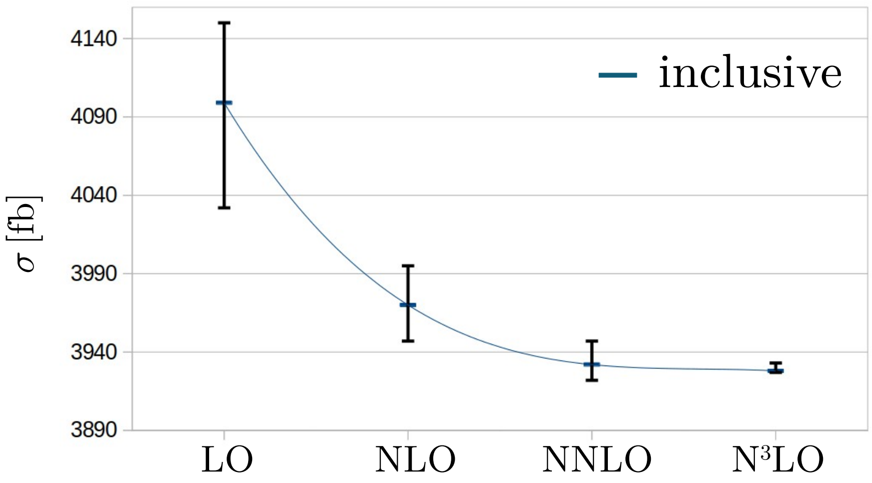
factorizable **(in the following)**



non-factorizable

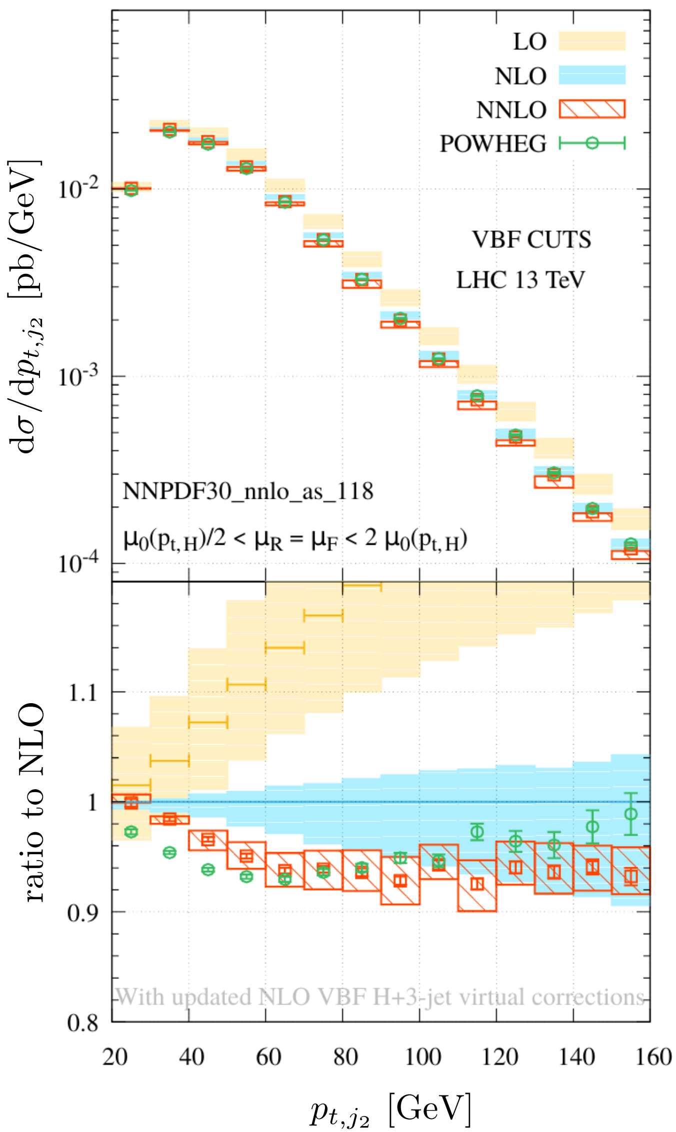
- **Inclusive** known till **N³LO** [Dreyer, Karlberg '16]
  → Nicely converging, N³LO within residual scale uncertainties

- **Fully differential known till NNLO** [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15; Cruz-Martinez, Glover, Gehrmann, Huss '18]
  → **Fiducial cuts:** NNLO corrections outside of residual NLO scale uncertainties

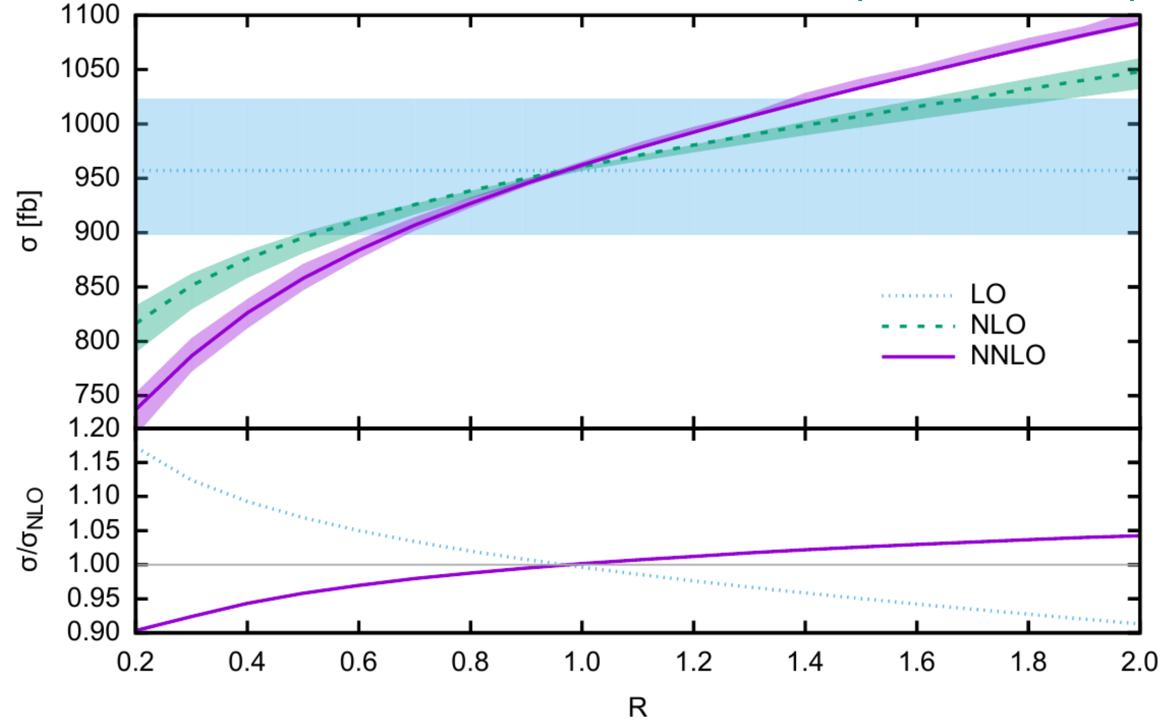


Effect of fiducial cuts

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]



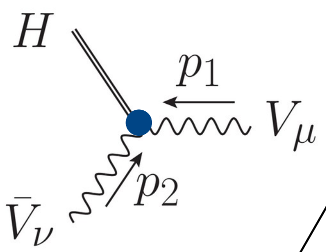
[Rauch, Zeppenfeld '17]



- **Non-trivial jet dynamics in WBF Higgs boson poduction**
- **New Physics:**
  - New operators → New tensor structures
  - Studied at NLO QCD [Hankele, Klämke, Zeppenfeld '06]
    → Potential interplay with real radiation at higher orders
    → Can we trust NLO analysis?
  - Higgs coupling to weak bosons measured to O(30%)

Anomalous HVV interactions

- Most general tensor structure of the HVV vertex (Lorentz invariance / Bose symmetry)



$$= i\Big[g^{\mu\nu} A(p_1^2, p_2^2, p_1\cdot p_2) + p_1^\nu p_2^\mu\, B(p_1^2, p_2^2, p_1\cdot p_2) + i\epsilon^{\mu\nu\rho\sigma} p_{1,\rho} p_{2,\sigma}\, C(p_1^2, p_2^2, p_1\cdot p_2)\Big]$$

only dimension 6 SMEFT [Helset, Martin, Trott '20]

$$= i g_{HVV}^{(SM)} \left[g^{\mu\nu} \left(1 + \frac{m_H^2}{\Lambda^2}\, c_{HVV}^{(2)} + \frac{p_1^2 + p_2^2}{\Lambda^2}\, c_{HVV}^{(1)} \right) + \frac{2 p_1^\nu p_2^\mu}{\Lambda^2} c_{HVV}^{(1)} - \tilde{c}_{HVV} (6\pi) \epsilon^{\mu\nu\rho\sigma} \frac{p_{1,\rho} p_{2,\sigma}}{\Lambda^2} \right]$$

"rescaling" of SM — CP-even coupling — CP-odd coupling

- (6π) in CP-odd contribution such that $\tilde{c}_{\mathrm{HVV}} = 1 \to O(1\%)$ deviation of the LO fiducial cross section

- Consider "symmetric" model where non-SM couplings to W and Z are identical (main difference accounted for via factoring out SM coupling)

Fiducial cross section at any order

$$\sigma_{\text{fid}} = \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right)^2 X_1 + \left(c_{HVV}^{(1)}\right)^2 X_2 + \left(\tilde{c}_{HVV}\right)^2 X_3 + \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) c_{HVV}^{(1)} X_4$$
$$+ \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) \tilde{c}_{HVV} X_5 + c_{HVV}^{(1)} \tilde{c}_{HVV} X_6 \,.$$

where

$$X_i = X_i^{\text{LO}} + \frac{\alpha_s}{4\pi} X_i^{\text{NLO}} + \left(\frac{\alpha_s}{4\pi}\right)^2 X_i^{\text{NNLO}} + \mathcal{O}(\alpha_s^3)$$

- $X_5 = X_6 = 0$ for fiducial cross sections because it is integrate over the full angular phase space
- Compute $X_{1,2,3,4}$ individually

Fiducial cross section at any order

$$\sigma_{\text{fid}} = \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right)^2 X_1 + \left(c_{HVV}^{(1)}\right)^2 X_2 + \left(\tilde{c}_{HVV}\right)^2 X_3 + \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) c_{HVV}^{(1)} X_4$$

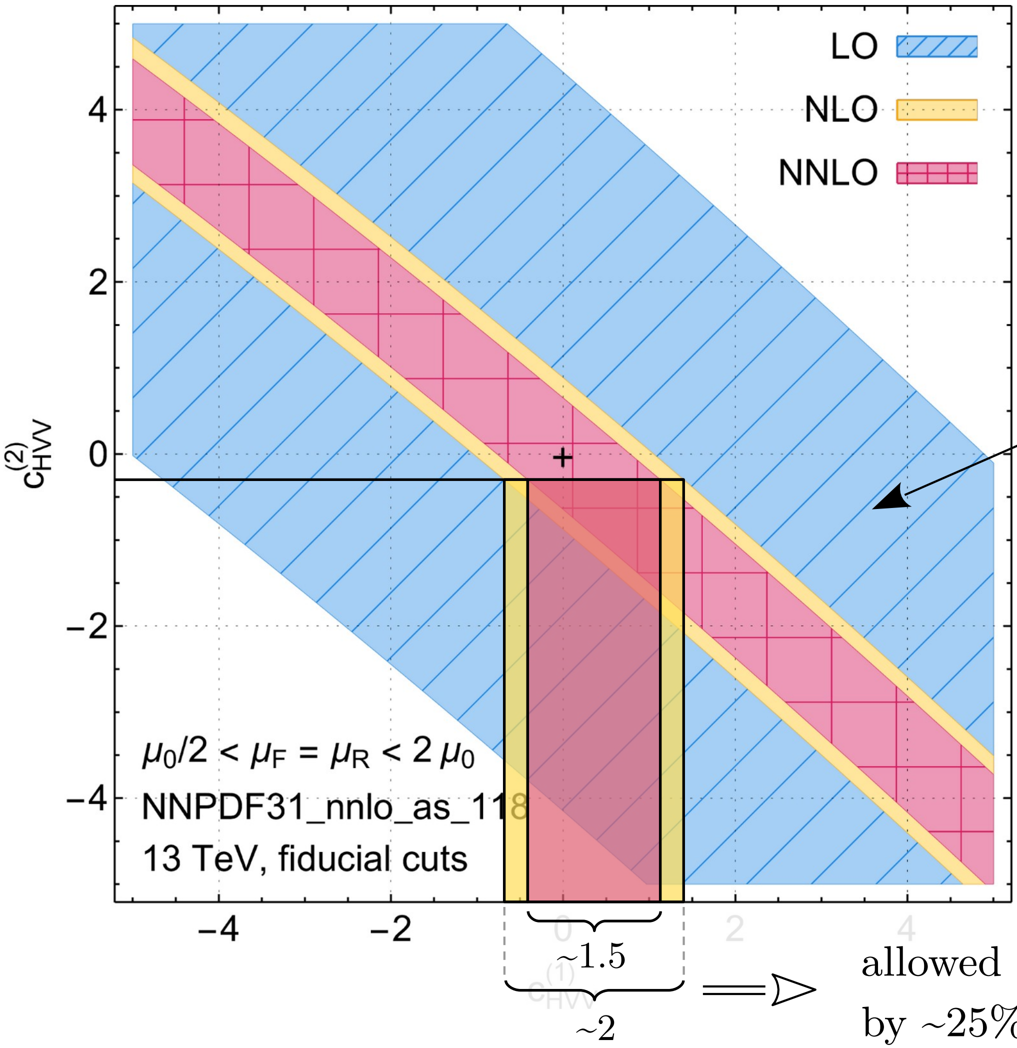
$$+ \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) \tilde{c}_{HVV} X_5 + c_{HVV}^{(1)} \tilde{c}_{HVV} X_6 \,.$$

- Results

σ_{fid} (fb)	LO	NLO	NNLO
X_1	971^{-61}_{+69}	890^{+8}_{-18}	859^{+8}_{-10}
X_2	$0.413^{-0.033}_{+0.039}$	$0.398^{-0.001}_{-0.005}$	$0.383^{+0.004}_{-0.005}$
X_3	$19.57^{-1.84}_{+2.22}$	$19.64^{-0.25}_{-0.07}$	$19.25^{+0.08}_{-0.18}$
X_4	$26.43^{-1.61}_{+1.80}$	$23.45^{+0.35}_{-0.66}$	$22.53^{+0.39}_{-0.42}$

- X_1 largest (by construction since it corresponds to the SM contribution)
- Large scale uncertainty decrease from LO → NLO; only ~20% from NLO → NNLO
- Similar k-factors for all $X_{1,2,3,4}$ (~ -4% from NLO → NNLO)
- Having $X_{1,2,3,4}$ available allows to study the allowed parameter space

Allowed parameter space: fiducial cross section



parameter points are accepted if residual scale uncertainty band overlaps with SM residual scale uncertainty band

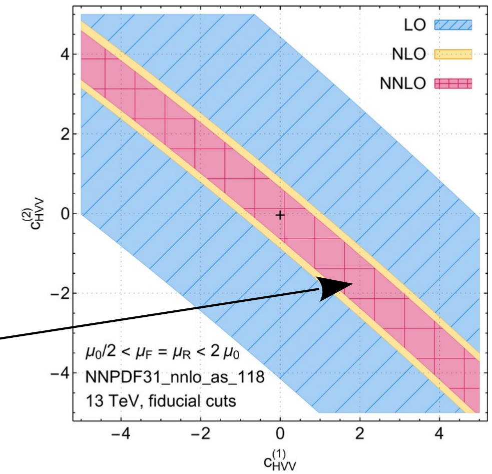
⟹ allowed parameter space shrinks by ~25% (significant impact)

- Similar results for all pairs of anomalous couplings

Differential distributions

- Computing differential distributions is numerically expensive
- Hence instead of computing differential coefficients $X_{1,2,3,4,5,6}$ we consider two fixed scenarios

$$\text{Sce. A:}\quad c^{(1)}_{HVV} = +1.5\,,\ \ c^{(2)}_{HVV} = -1.9\,,\ \ \tilde{c}_{HVV} = +0.6$$
$$\text{Sce. B:}\quad c^{(1)}_{HVV} = -1.8\,,\ \ c^{(2)}_{HVV} = -0.1\,,\ \ \tilde{c}_{HVV} = -1.5$$



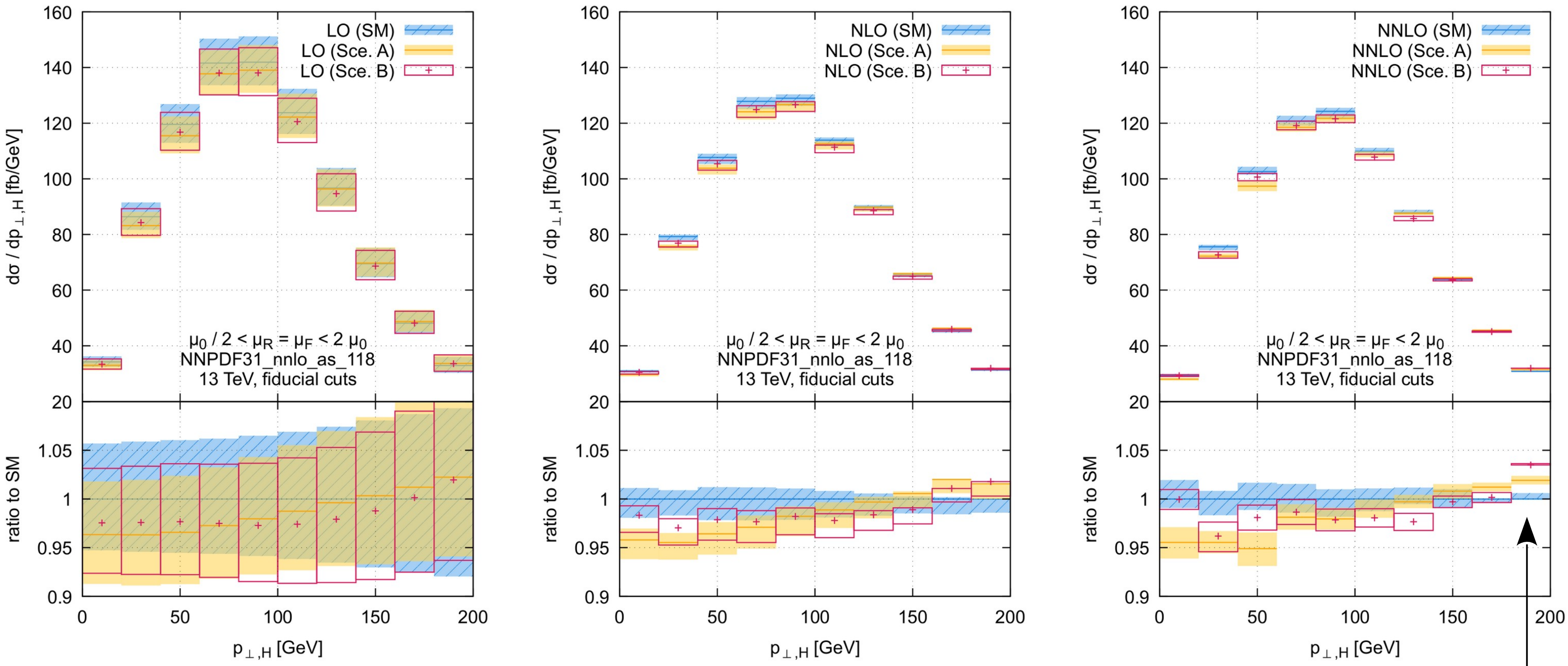
- They are chosen such that fiducial cross section are indistinguishable

σ_{fid} (fb)	SM	Sce. A	Sce. B
LO	971^{-61}_{+69}	960^{-61}_{+68}	965^{-63}_{+71}
NLO	890^{+8}_{-18}	882^{+7}_{-17}	890^{+6}_{-17}
NNLO	859^{+8}_{-10}	851^{+9}_{-8}	860^{+8}_{-8}

$\leq$ 1% and covered by residual scale uncertainties

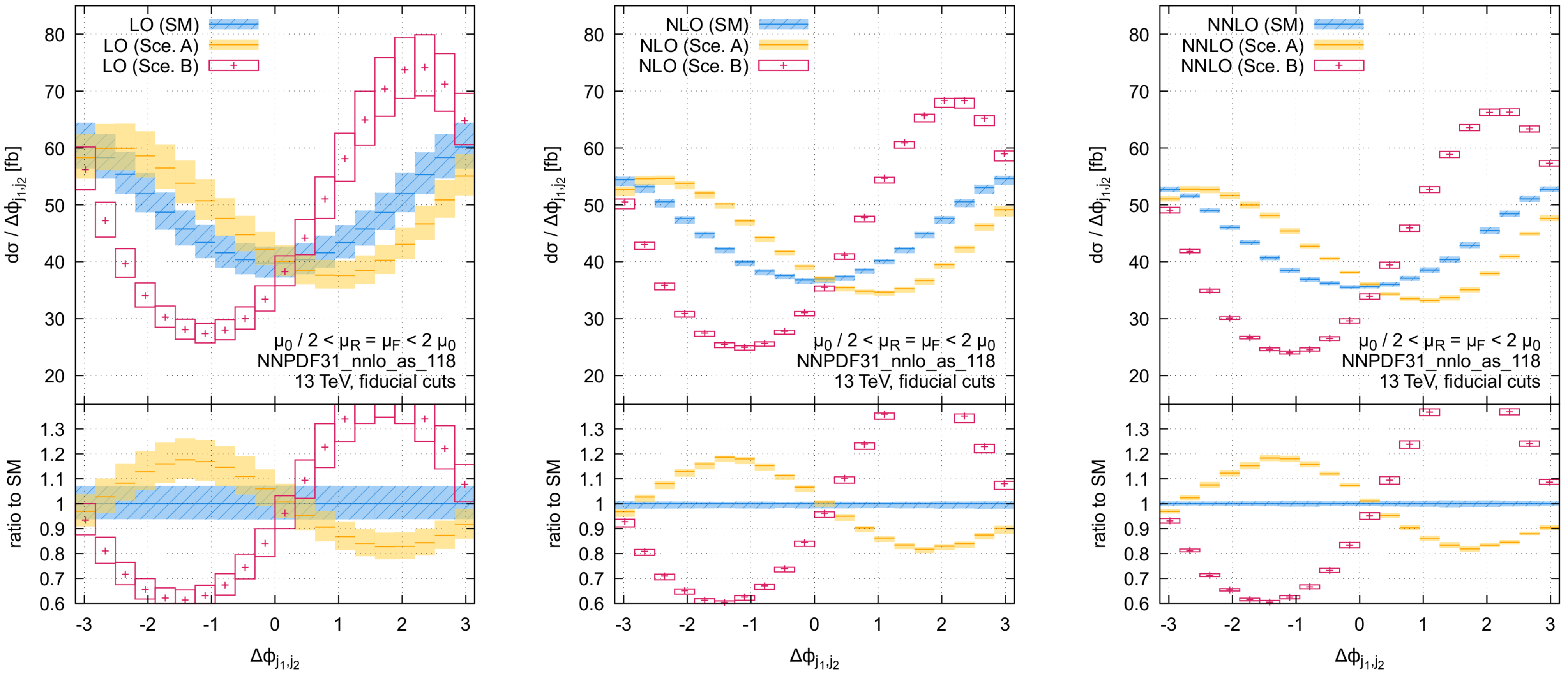
Differential distributions

- Most distributions are **NOT** sensitive to anomalous couplings [Hankele, Klämke, Zeppenfeld '06]
- For example consider Higgs transverse momentum distribution



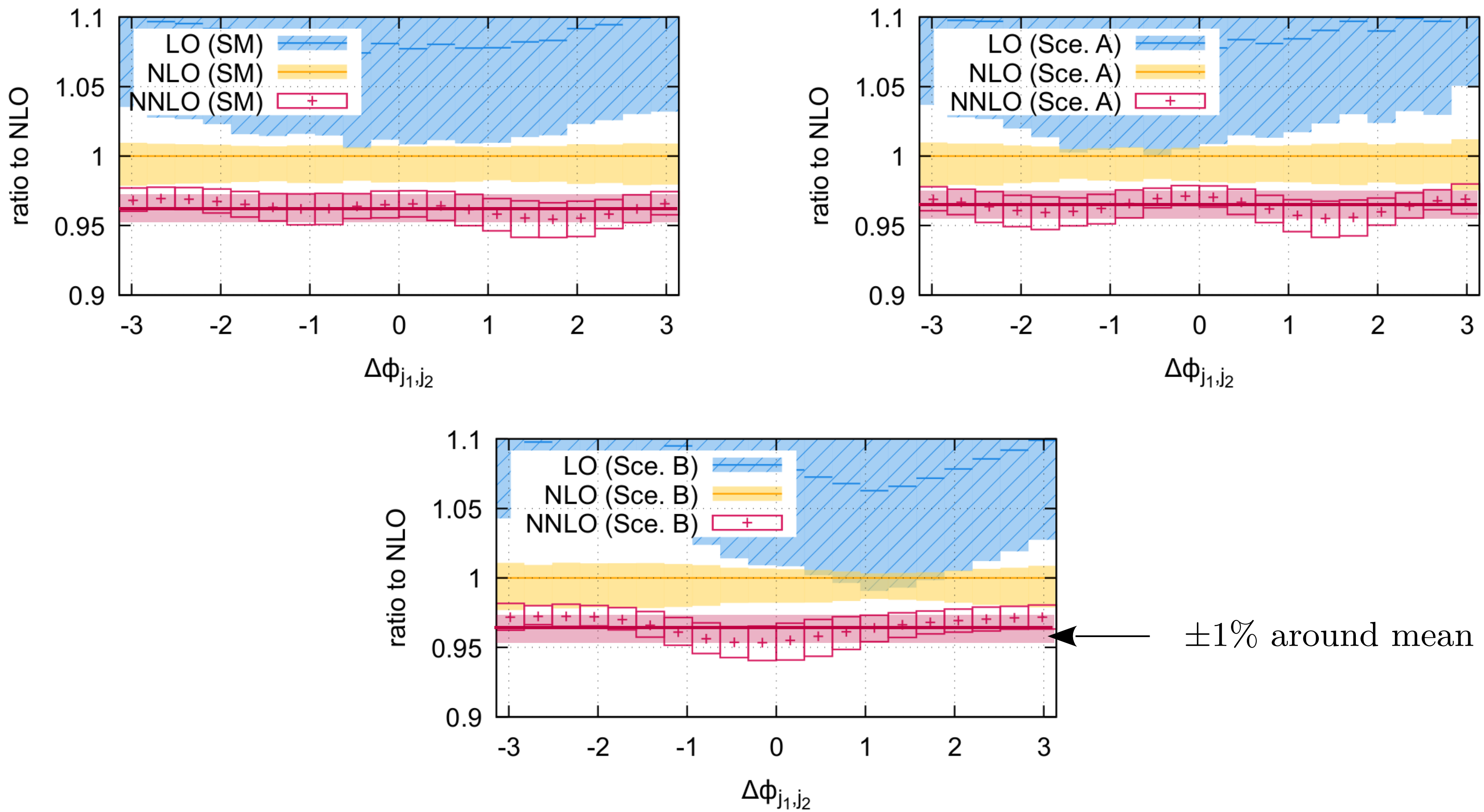
start of diverging distributions, expected
but cross section already down by an order

$\Delta\varphi$ a CP sensitive observable



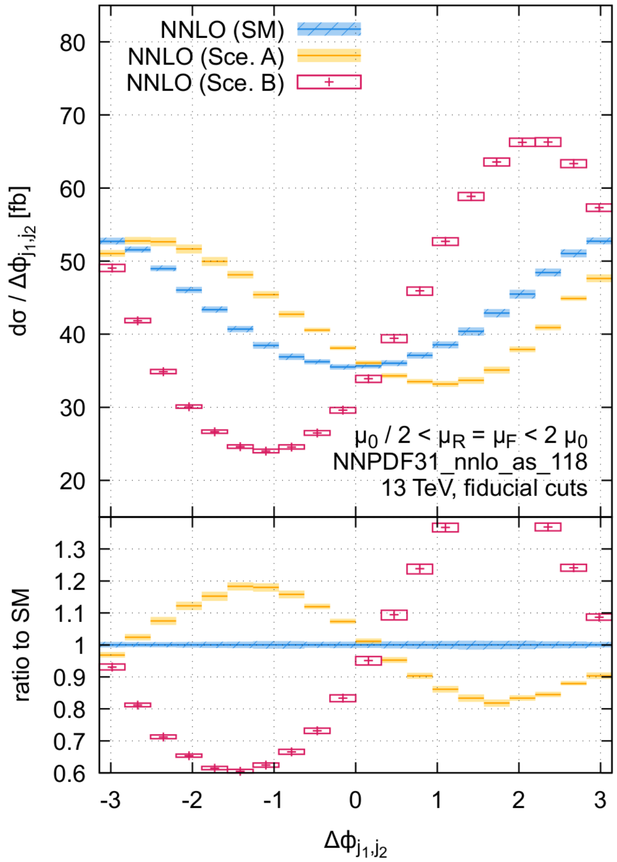
- At LO: Sce. B and SM distinguishable, Sce. A and SM just covered by scale variation
- Similar to fiducial cross section: no significant reduction of scale uncertainties from NLO → NNLO

$\Delta\varphi$ a CP sensitive observable



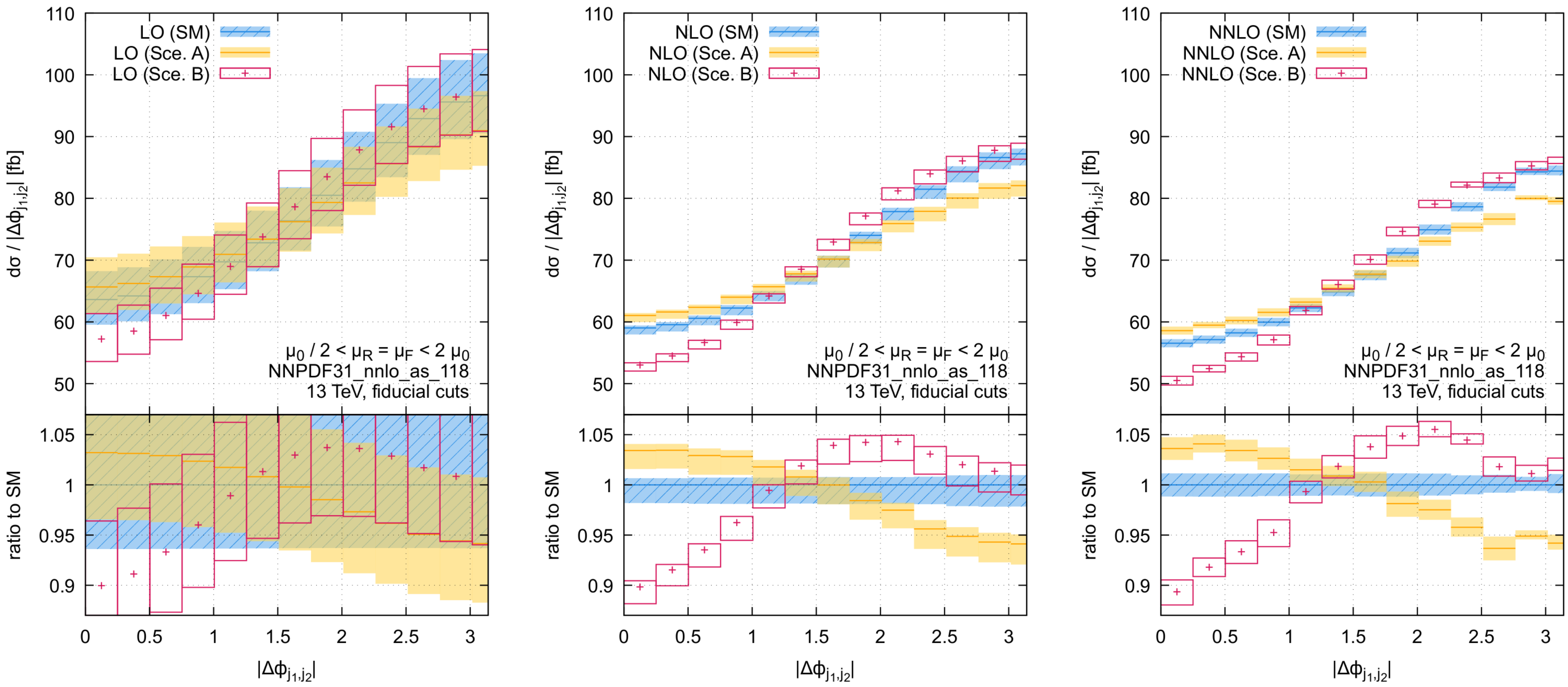
- K-factor rather flat and almost independent of anomalous couplings
- K-factors rather flat $\rightarrow$ global rescaling from NLO to NNLO should be sufficient for O(1%)

$\Delta\varphi$ a CP sensitive observable



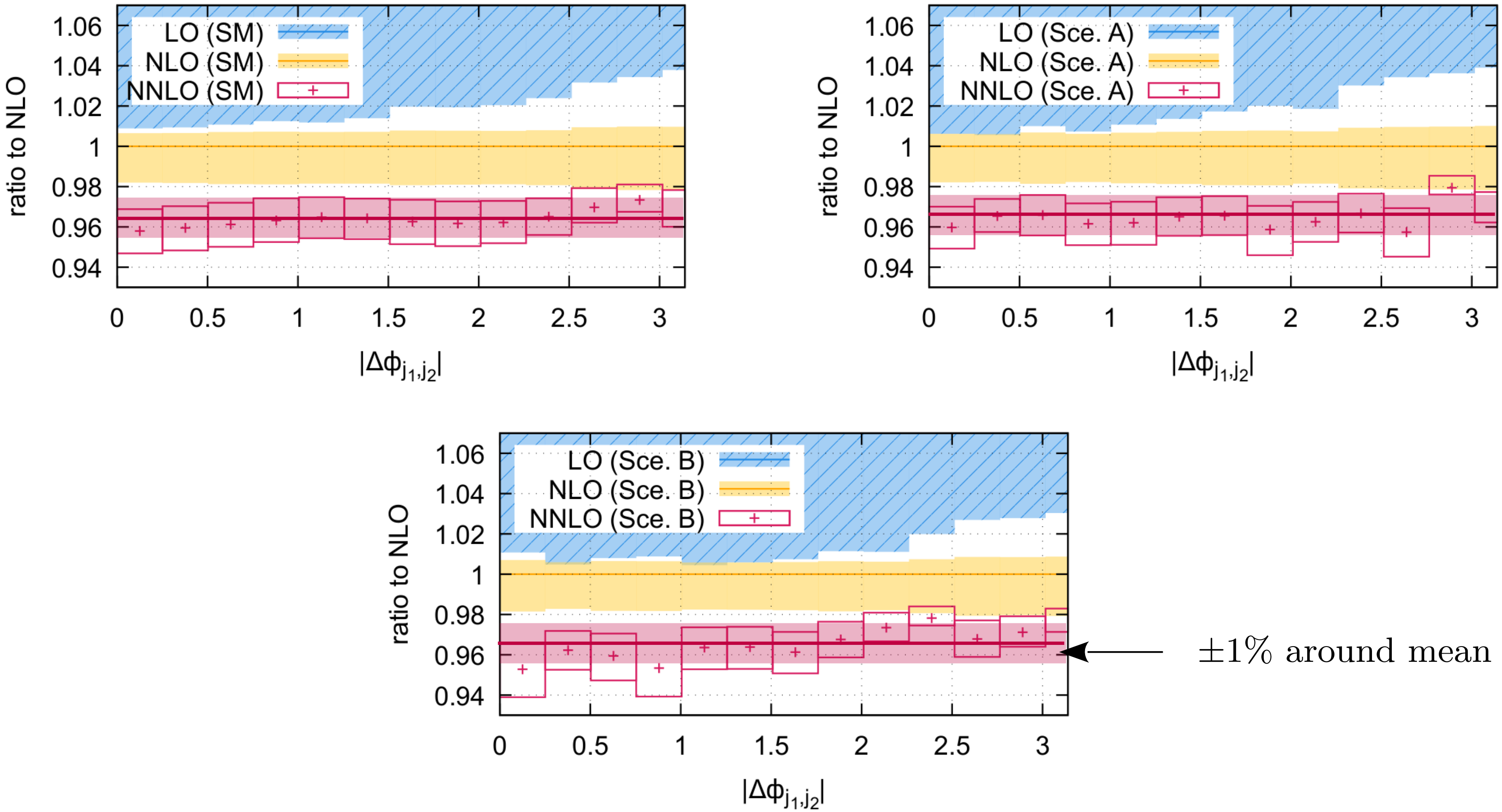
- Deviation(s) from SM dominated by antisymetric contributions $\rightarrow$ CP-odd / CP-even interference
- Ratio of events with $\Delta\varphi < 0$ and $\Delta\varphi > 0$ might be useful to include differential data in exclusion plots in a efficient way (cut-and-count approach)
- To study CP-even couplings, consider absolute value of $\Delta\varphi$ where CP-odd / CP-even interference again drops out

$|\Delta\varphi|$ a CP insensitive observable



- At LO differences are swamped by scale uncertainty
- Starting from NLO scale uncertainties sufficiently reduced to distinguish between different scenarios and SM; NNLO might help to distinguish from SM
- Ratio of events with $|\Delta\varphi| < \pi/2$ and $|\Delta\varphi| > \pi/2$ might be useful to include differential data in exclusion plots in a efficient way (cut-and-count approach)

$|\Delta\varphi|$ a CP insensitive observable



- K-factor rather flat and almost independent of anomalous couplings
- K-factors rather flat $\rightarrow$ global rescaling from NLO to NNLO should be sufficient for O(1%)

Conclusion and Outlook

- Higher order QCD corrections in New Physics scenarios similar to SM

  $\rightarrow$ No significant shape change from NLO $\rightarrow$ NNLO

  $\rightarrow$ May be captured with global K-factor

- NLO and NNLO have similar "discriminating power"

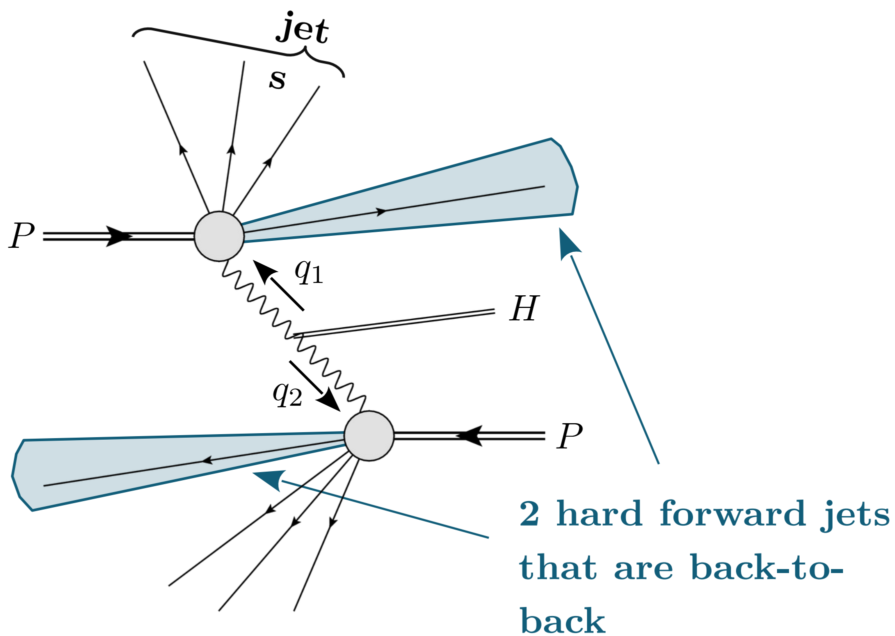
  $\rightarrow$ NNLO study indicates analysis at NLO is robust

- **Future work:** Include differential data into exclusion plots

- **Future work:** Include higher order operators (In particular once that are directly affected by QCD) radiation; allow for different HZZ and HWW couplings

Miscellaneous

$\Delta\varphi$ a CP sensitive observable

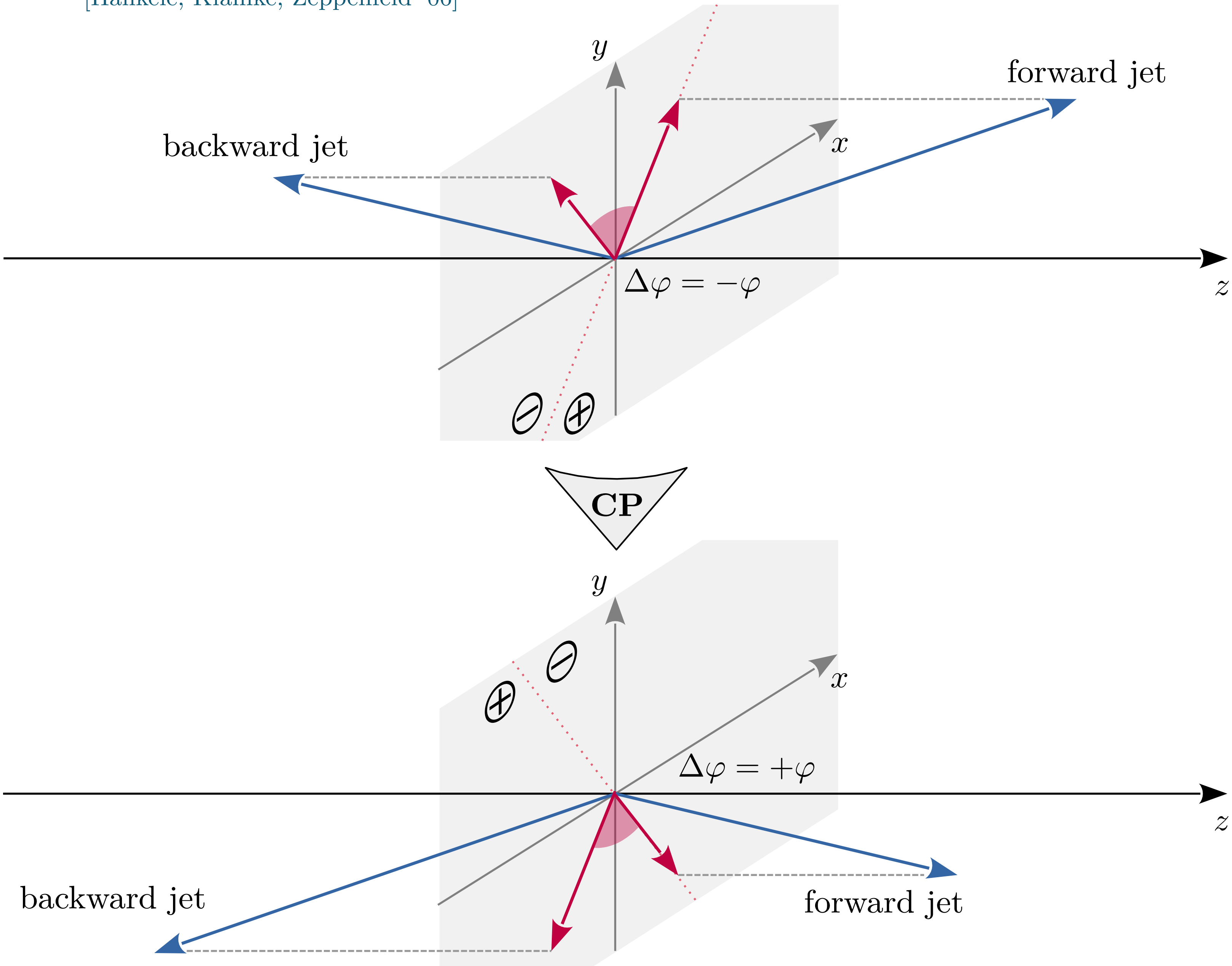


Typical VBF cuts:

- At least 2 resolved "tag" jets with $p_{\perp,j} > 25\,\text{GeV}$ and $-4.5 < y_j < 4.5$
- Separated in rapidity $|y_{j_1} - y_{j_2}| > 4.5$ and in different hemispheres $y_{j_1} \times y_{j_2} < 0$
- Invariant mass $\sqrt{(p_{j_1} + p_{j_2})^2} > 600\,\text{GeV}$
- Jets identified using anti-kt jet-algorithm with $R = 0.4$

$\Delta\varphi$ a CP sensitive observable

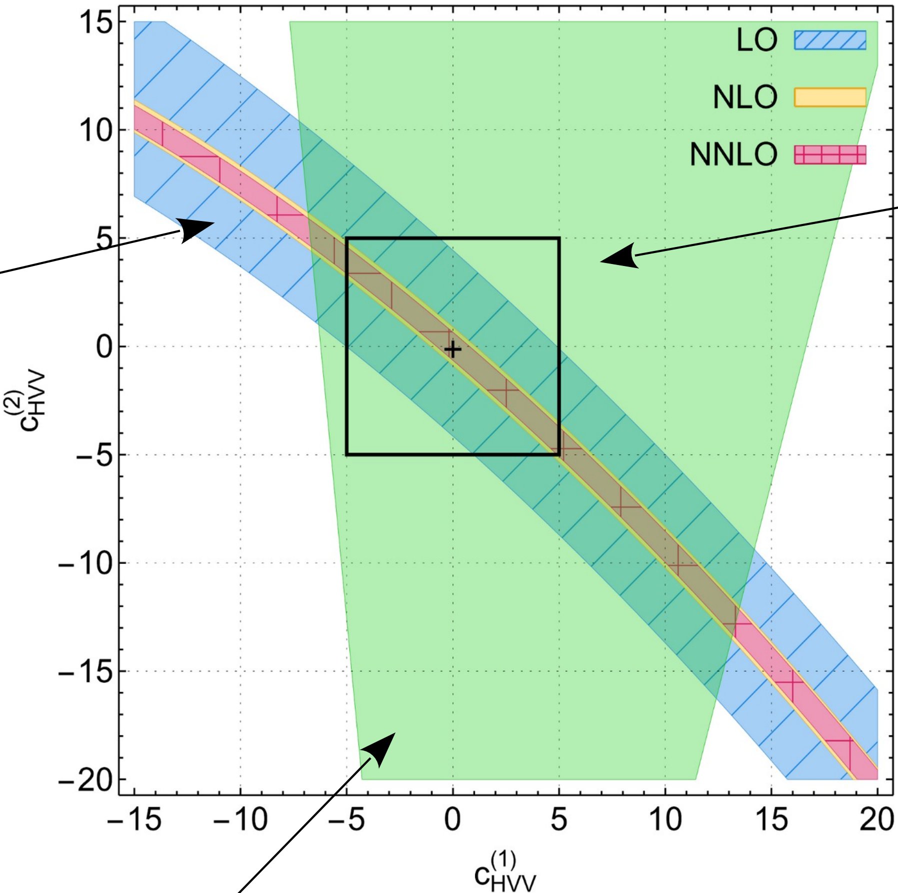
[Hankele, Klämke, Zeppenfeld '06]



Numerical control and extrapolation to parameter space

- **Area** where numerical error is *smaller-equal* then the residual scale uncertainty

needs to be recomputed for each parameter point



"original" parameter space

Is this enough? Yes! (c.f. differential distributions later)

Connection to SMEFT Wilson coefficients in Warsaw basis

$$c^{(1)}_{HWW} = \frac{C_{\varphi W}}{\sqrt{2} G_f M_W^2},$$

$$c^{(2)}_{HWW} = -\frac{1}{\sqrt{2} G_f}\left[\frac{C_{\varphi W}}{M_W^2} + \frac{2C^{(3)}_{\varphi l} - C_{ll}}{2m_H^2} - \frac{4C_{\varphi\Box} - C_{\varphi D}}{4m_H^2}\right],$$

$$\tilde{c}_{HWW} = -\frac{2C_{\varphi\tilde{W}}}{(6\pi)\sqrt{2} G_f M_W^2},$$

$$c^{(1)}_{HZZ} = \frac{1}{\sqrt{2} G_f M_Z^4}\Big[C_{\varphi B}(M_Z^2 - M_W^2) + C_{\varphi W} M_W^2 + C_{\varphi WB} M_W \sqrt{M_Z^2 - M_W^2}\Big],$$

$$c^{(2)}_{HZZ} = -\frac{1}{\sqrt{2} G_f}\left[\frac{C_{\varphi B}(M_Z^2 - M_W^2)}{M_Z^4} + \frac{C_{\varphi W} M_W^2}{M_Z^4} + \frac{C_{\varphi WB} M_W \sqrt{M_Z^2 - M_W^2}}{M_Z^4} + \frac{2C^{(3)}_{\varphi l} - C_{ll}}{2m_H^2} - \frac{4C_{\varphi\Box} + C_{\varphi D}}{4m_H^2}\right],$$

$$\tilde{c}_{HZZ} = -\frac{2}{(6\pi)\sqrt{2} G_f M_Z^4}\Big[C_{\varphi\tilde{B}}(M_Z^2 - M_W^2) + C_{\varphi\tilde{W}} M_W^2 + C_{\varphi\tilde{W}B} M_W \sqrt{M_Z^2 - M_W^2}\Big],$$

For more details see Phys. Rev. D 107 (2023) 3, 034034.