Precision predictions in multi-boson production

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Goal of COMETA:

provide global understanding of electroweak symmetry breaking

↓

precise determination of multi-boson interactions

- HVV couplings determined at 10% level
- HHH coupling: $-0.4 < \kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{SM} < 6.3$ [ATLAS 2022]
- HHVV coupling: $0 < \kappa_{HHVV} < 2.1$ [ATLAS 2023]
- VVV and VVVV couplings: e.g $-0.4 \lesssim C_{3W} \lesssim 0.2$ [CMS 2022] in $W^\pm\gamma$ search

↓

requires precise predictions for multi-boson processes

Les Houches wishlist 2021

	known	desired
$pp \to VH$	$\mathrm{NNLO}_{\mathrm{QCD}} + \mathrm{NLO}_{\mathrm{EW}}$ $\mathrm{NLO}^{(t,b)}_{gg\to HZ}$	
$pp \to VH + j$	$\mathrm{NNLO}_{\mathrm{QCD}}$ $\mathrm{NLO}_{\mathrm{QCD}} + \mathrm{NLO}_{\mathrm{EW}}$	$\mathrm{NNLO}_{\mathrm{QCD}} + \mathrm{NLO}_{\mathrm{EW}}$
$pp \to HH$	$\mathrm{N}^3\mathrm{LO}_{\mathrm{HTL}} \otimes \mathrm{NLO}_{\mathrm{QCD}}$	$\mathrm{NLO}_{\mathrm{EW}}$
$pp \to HH + 2j$	$\mathrm{N}^3\mathrm{LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ (incl.) $\mathrm{NNLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{EW}}$	
$pp \to HHH$	$\mathrm{NNLO}_{\mathrm{HTL}}$	

Status

Les Houches wishlist 2021

	known	desired
$pp \to V$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD} + N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $+\mathrm{NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

Status

Les Houches wishlist 2021

	known	desired
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^\pm W^+ W^-$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	

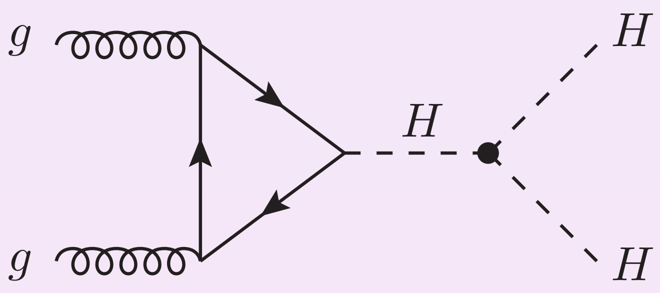
Gluon fusion processes

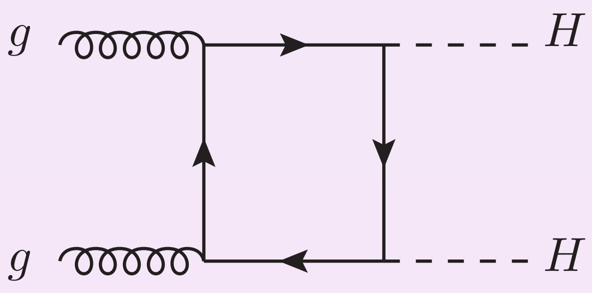
COMETA wants to advocate networking among the precision experts

We can learn from the methods applied to the various multi-boson processes

Example: Gluon fusion processes

in Higgs production processes gluon fusion dominant





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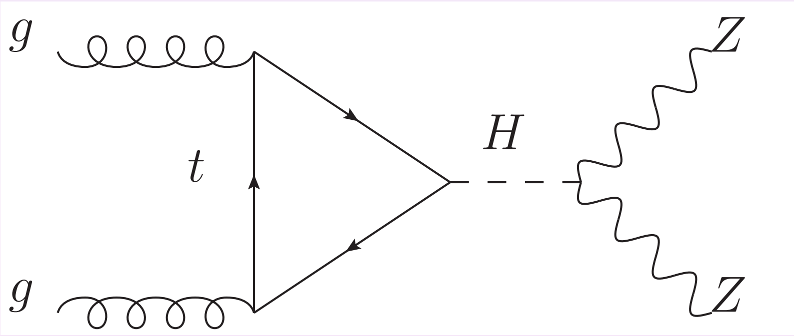
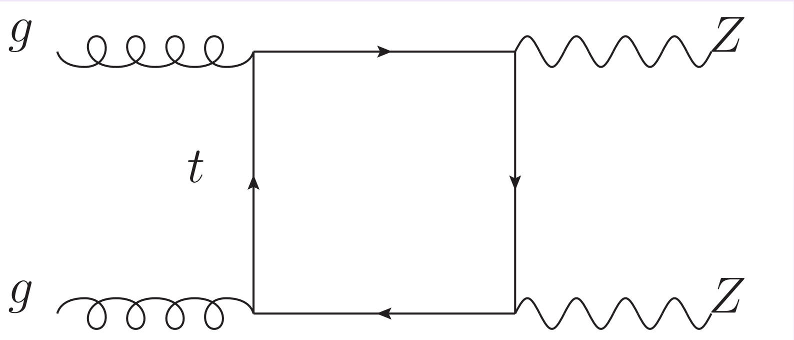
vector boson dominantly produced from quarks, but gluon fusion relevant at higher orders in QCD





Higgs pair production

Up to NLO in full top mass dependence [Borowka et al '16, Baglio et al '18]

combination of expansion in p_T and high energy [Bellafronte, Degrassi, Giardino, RG, Vitti '22, Davies, Mishima, Schönwald, Steinhauser '23]

@ NNLO in heavy top mass limit [de Florian, Mazzitelli '13, Grigo, Melnikov, Steinhauser '14]
(mass effects incorporated for double-real radiation or in asymptotic expansion in heavy top mass) [Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli '18, Grigo Hoff, Steinhauser '15]

N³LO in heavy top mass limit [L.B.Chen, H. T. Li, H.-S. Shao and J.Wang'19]

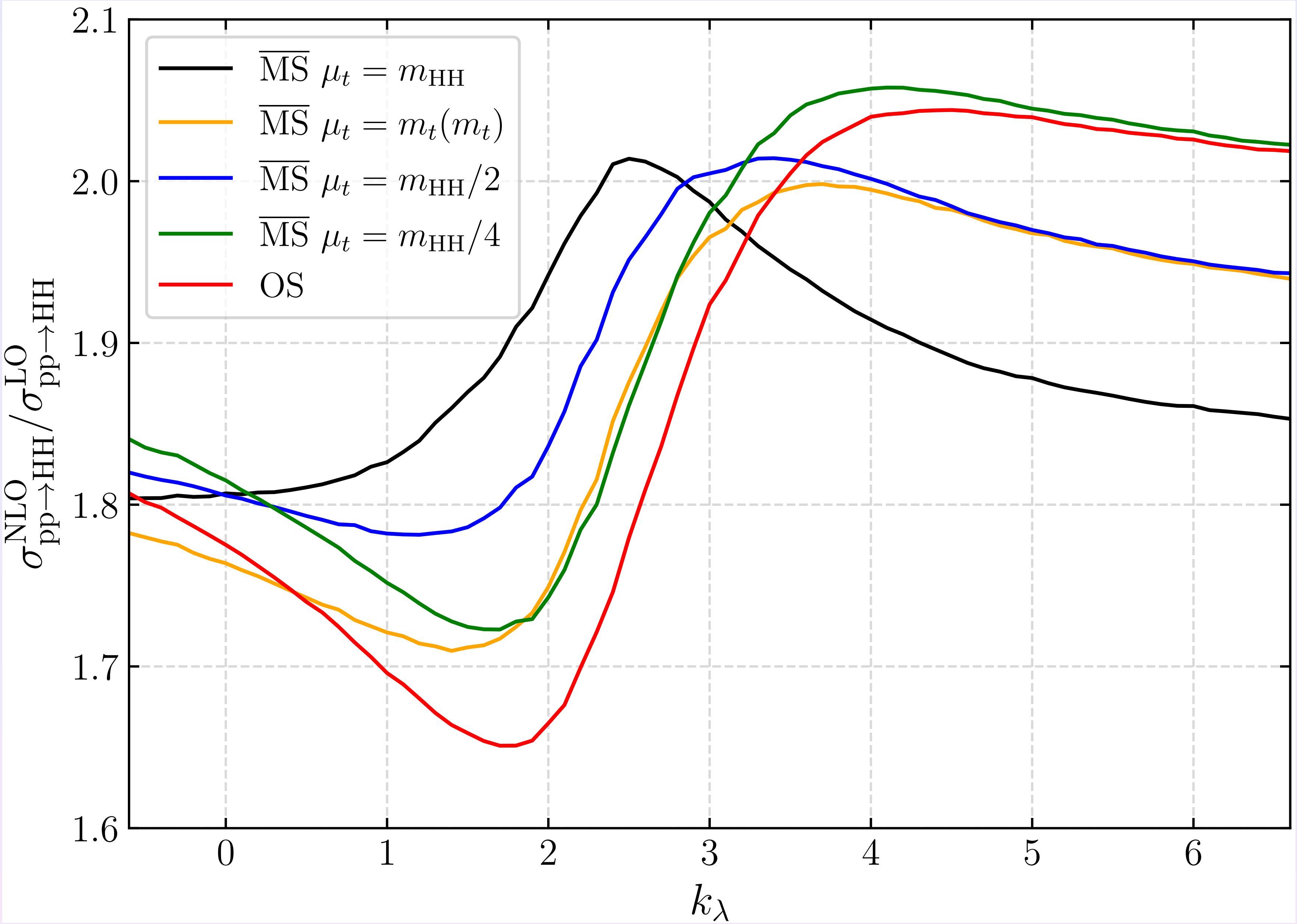
$$\sigma(13.6\ \text{TeV}) = 34.43^{6\%}_{-23\%}\ \text{fb}$$

[Baglio et al '18 '20]

large uncertainty mainly due to top mass renormalisation scheme

Higgs pair production

[Bagnaschi, Degrassi, RG '23]



top renormalisation scheme dependence uncertainty depends on value of trilinear Higgs self-coupling

What can we learn for other processes?

$gg \to ZH$

at NLO QCD

top renormalisation scheme uncertainty $^{+0\%}_{-12.9\%}$

of similar size

than scale uncertainty $^{+16.7\%}_{-14.1\%}$ [Degrassi, RG, Vitti, Zhao '22]

reduction from LO to NLO in ZH though smaller compared to HH due to different logarithmic structure in high-energy limit

[Chen et al. '22]

$gg \to ZZ$

$gg \to W^+W^-$

results available at NLO QCD do not allow to compute the uncertainty

similar behaviour to HH though expected for top loops

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similar behaviour to HH though expected

Shrinking the top renormalisation scheme dependence requires NNLO QCD corrections in full mass dependence → beyond state of the art

can we learn more about them by making use of expansions?

BSM precision

Is it sufficient to have a precise SM result?

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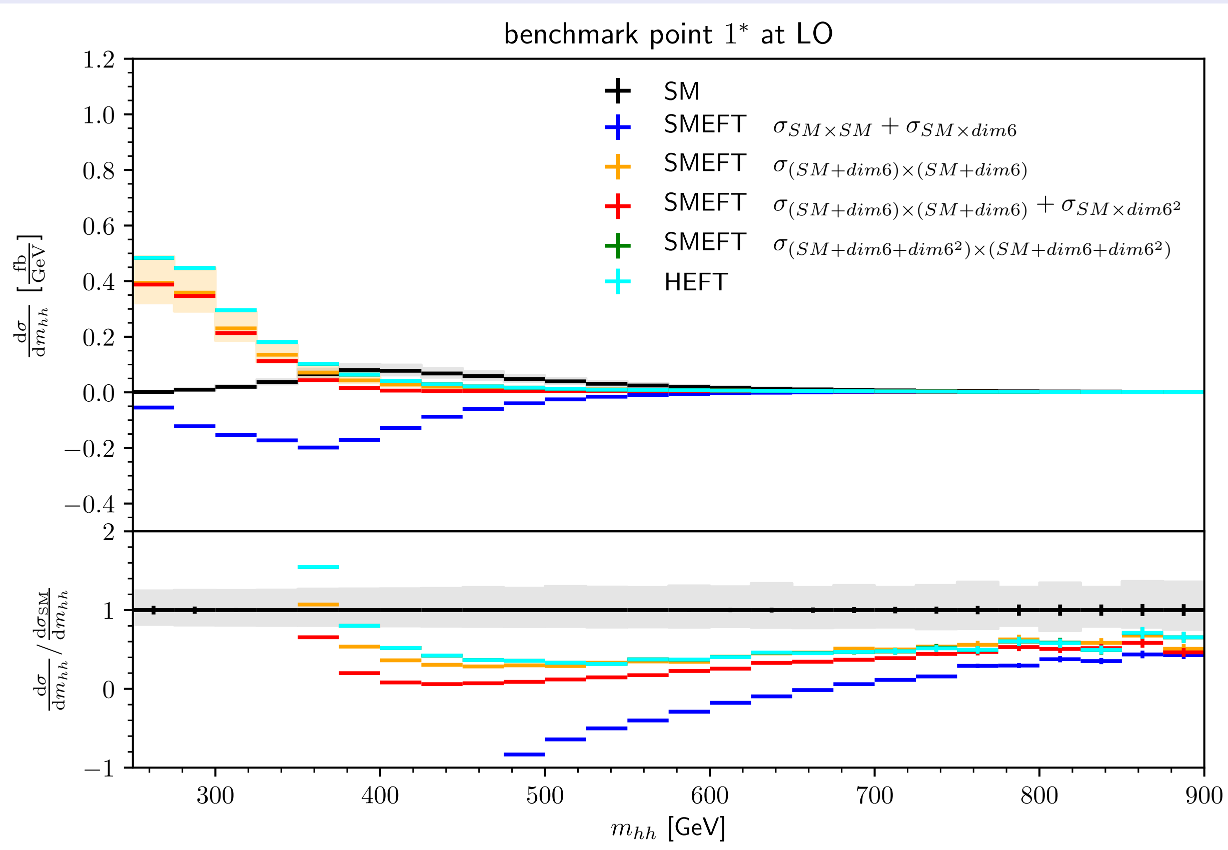
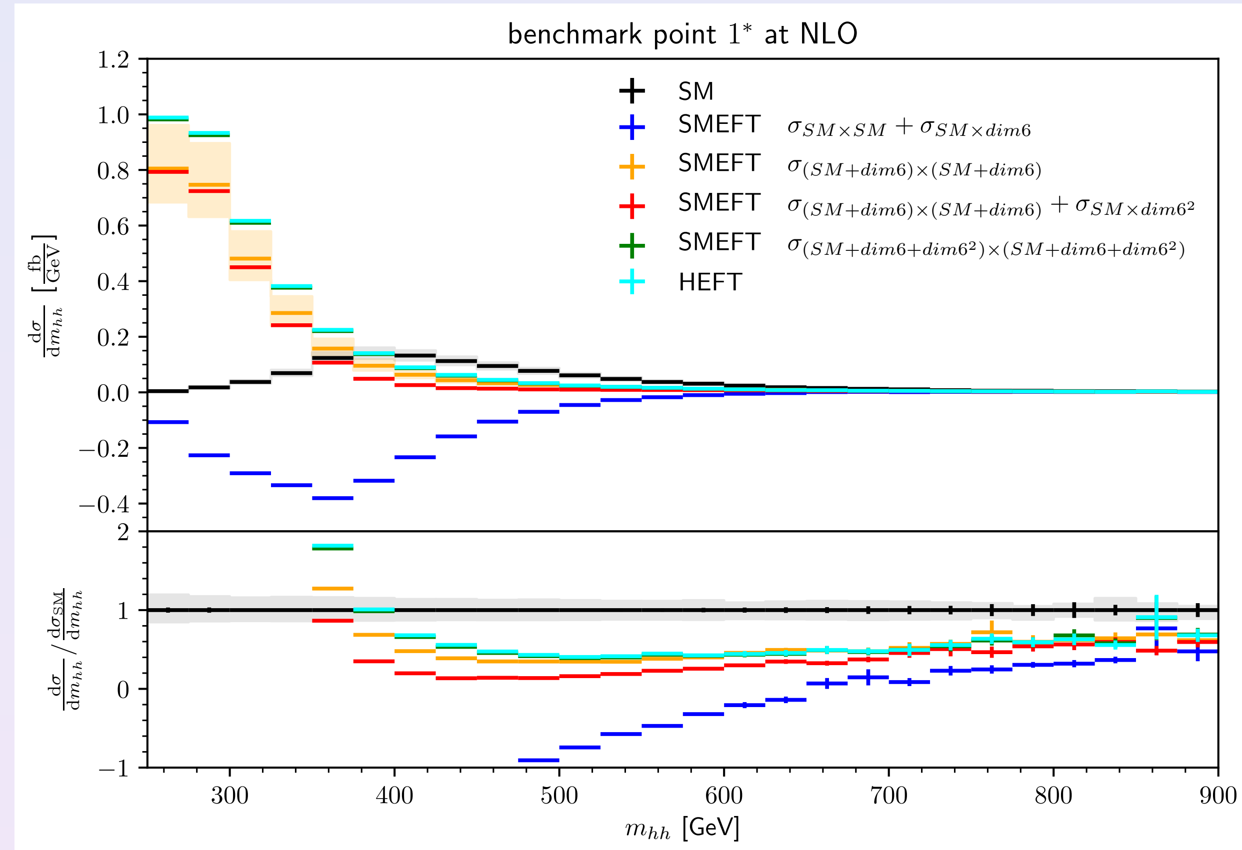
HH production





[Heinrich, Lang Scyboz '22]

benchmark	σ_{NLO}[fb] option (b)	K-factor option (b)
SM	$27.94^{+13.7\%}_{-12.8\%}$	1.67
$1^\star$	$71.95^{+20.1\%}_{-15.7\%}$	2.06
$3^\star$	$68.69^{+9.4\%}_{-9.5\%}$	1.80
$6^\star$	$70.18^{+18.8\%}_{-15.5\%}$	1.83

→ no, SMEFT operators change shape at NLO, multiplication with SM K-factor not sufficient

(see [Haisch, Scott, Wiesemann, Zanderighi, Zanoli '22] for ZH)

BSM precision

For other processes urgently needed!

i.e. VBF HH known to N³LO QCD and N²LO QCD + NLO EW

[Dreyer, Karlberg, Lang, Pellen '22]

[Dreyer, Karlberg, Tancredi '20]

[Dreyer, Karlberg, Tancredi '18]

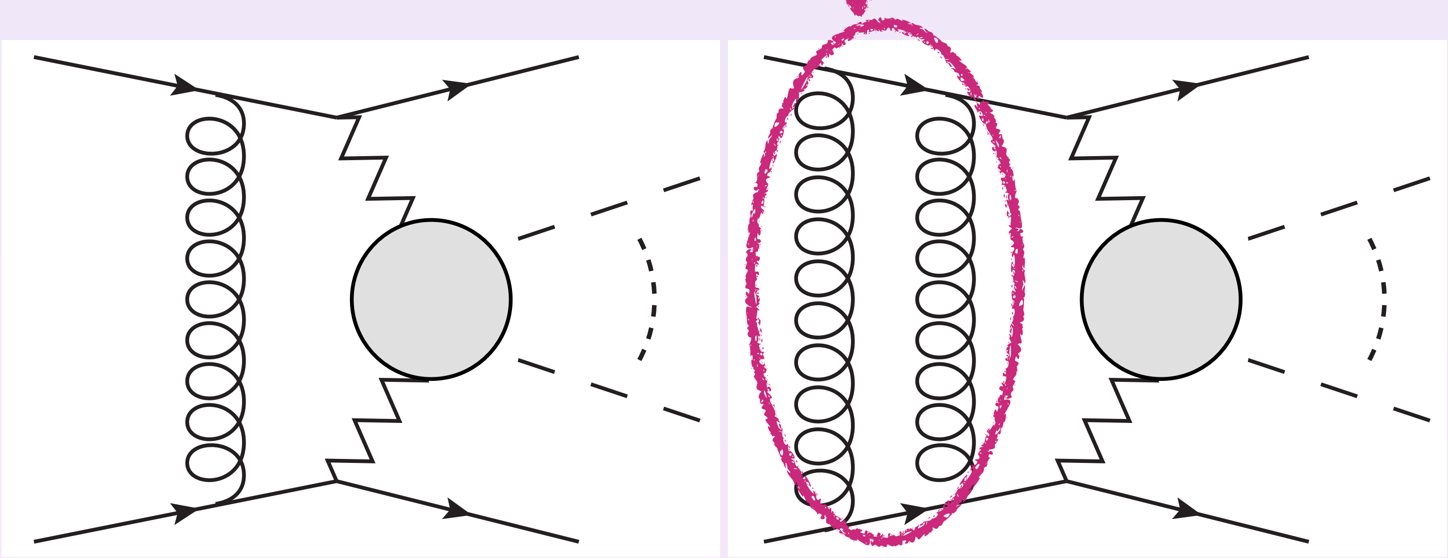
Used to constrain κ_{VVHH}

at NLO QCD the LO factorises

at NNLO QCD this no longer holds true

→ dependence on HEFT coefficients beyond LO needed

color singlet possible



(a) (b)

Rare Multi-Boson Production

COMETA advocates the study of rare multi-boson processes

such as triboson production, triple Higgs production, VHH, VVH, VBF VH or VVV production

Allow to measure HHHH, VVVV, VHHH, VVVH, VVVVV, ... couplings

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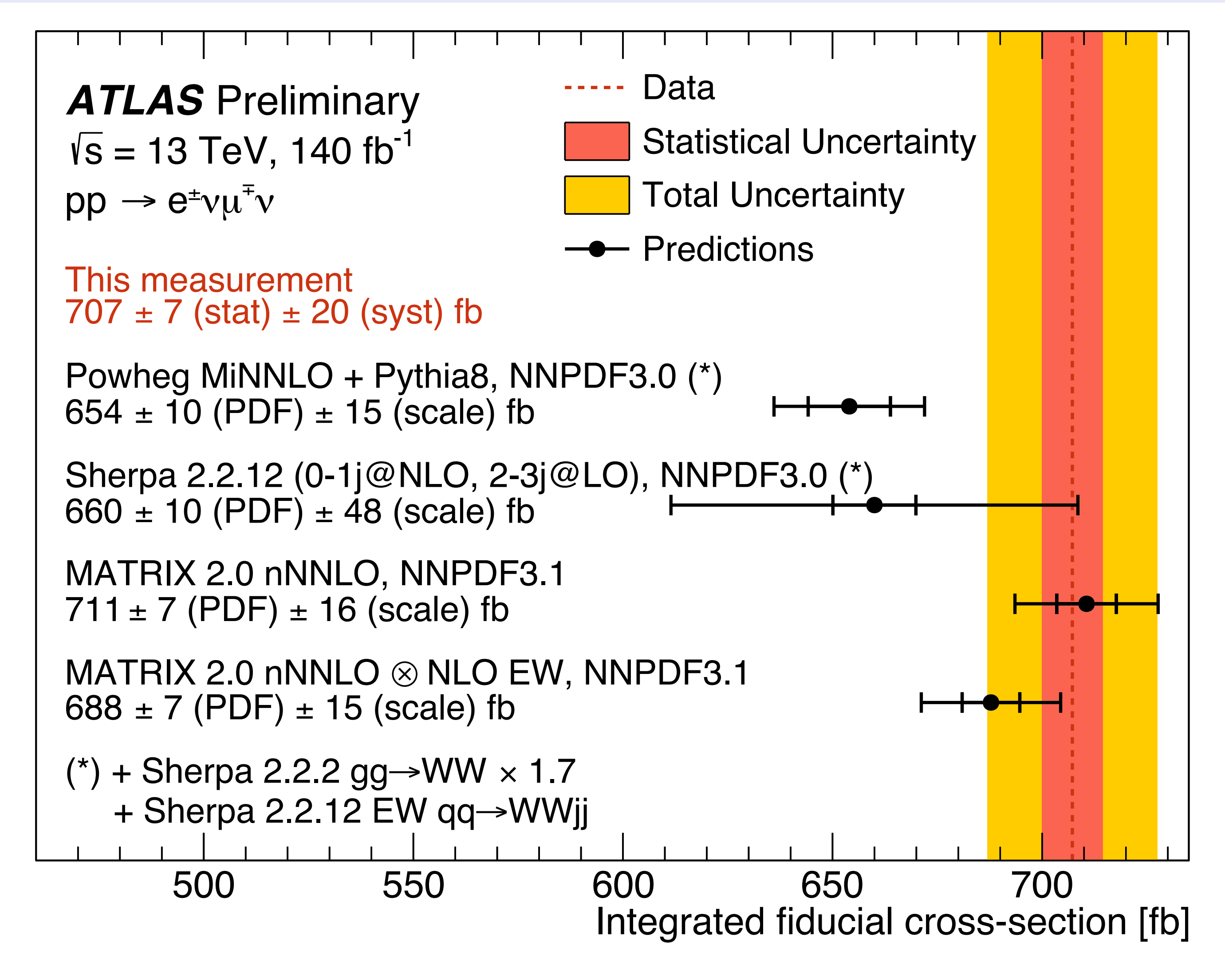
Precision needed?

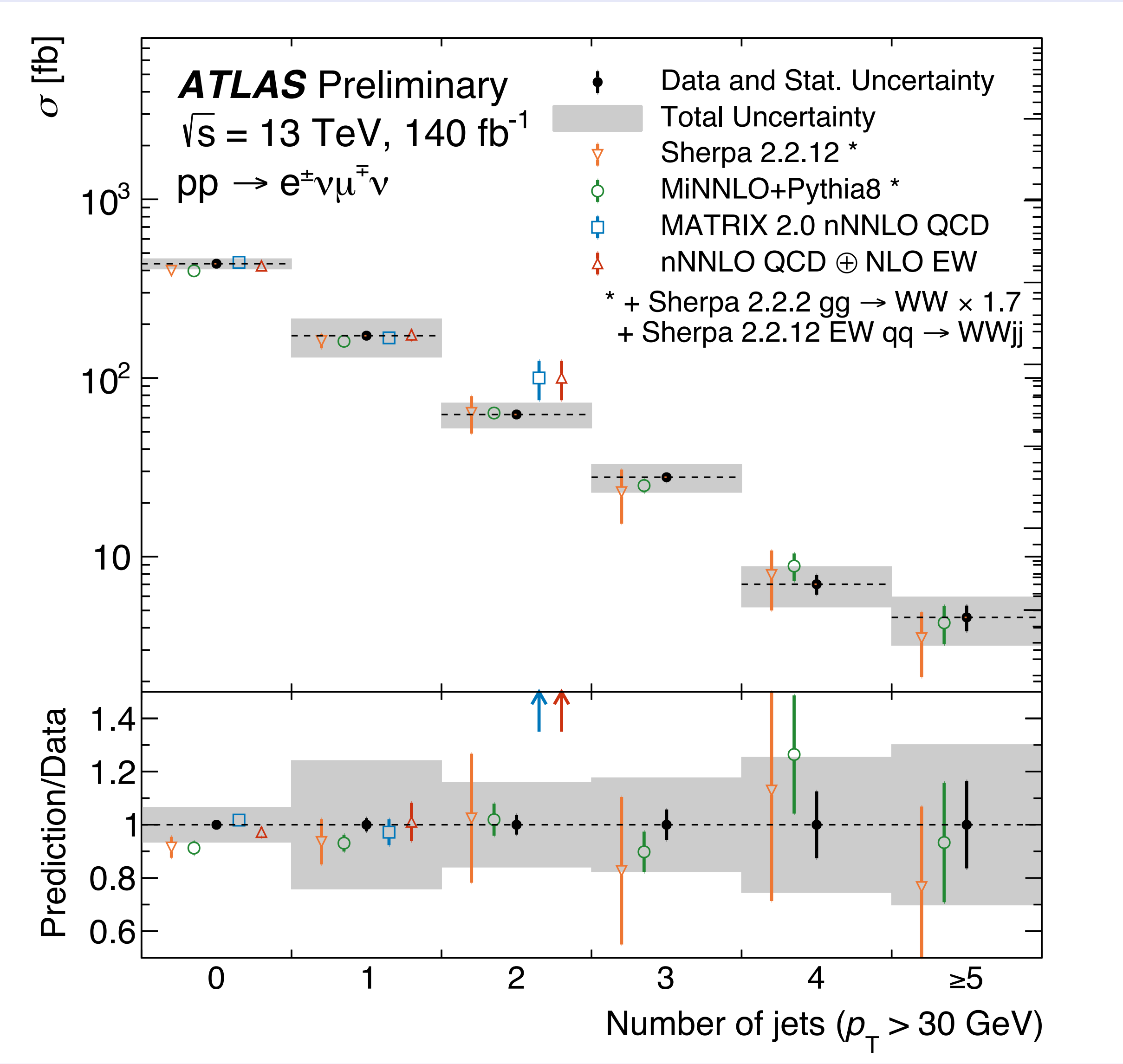
tri-boson studies started at LHC Run 2, e.g. NLO QCD + EW corrections in WWZ of $\mathcal{O}(30\%)$ [Yong-Bai, Ren-You, Wen-Gan, Xiao-Zhu, Yu, Lei '15]

feasibility studies of HHH production started, NLO QCD corrections in top mass dependence not available, [HHH workshop @ Dubrovnik '23]
NLO QCD corrections expected to be $\mathcal{O}(100\%)$

Matching to Parton Shower

Needed to allow experimentalists to use the precise predictions provided by the theory community





- MATRIX includes NNLO QCD + $gg \to W^+W^-(massless)$ +photon induced at NLO QCD and is fixed order
- MiNNLO lacks photon induced and NLO QCD to $gg \to W^+W^-$
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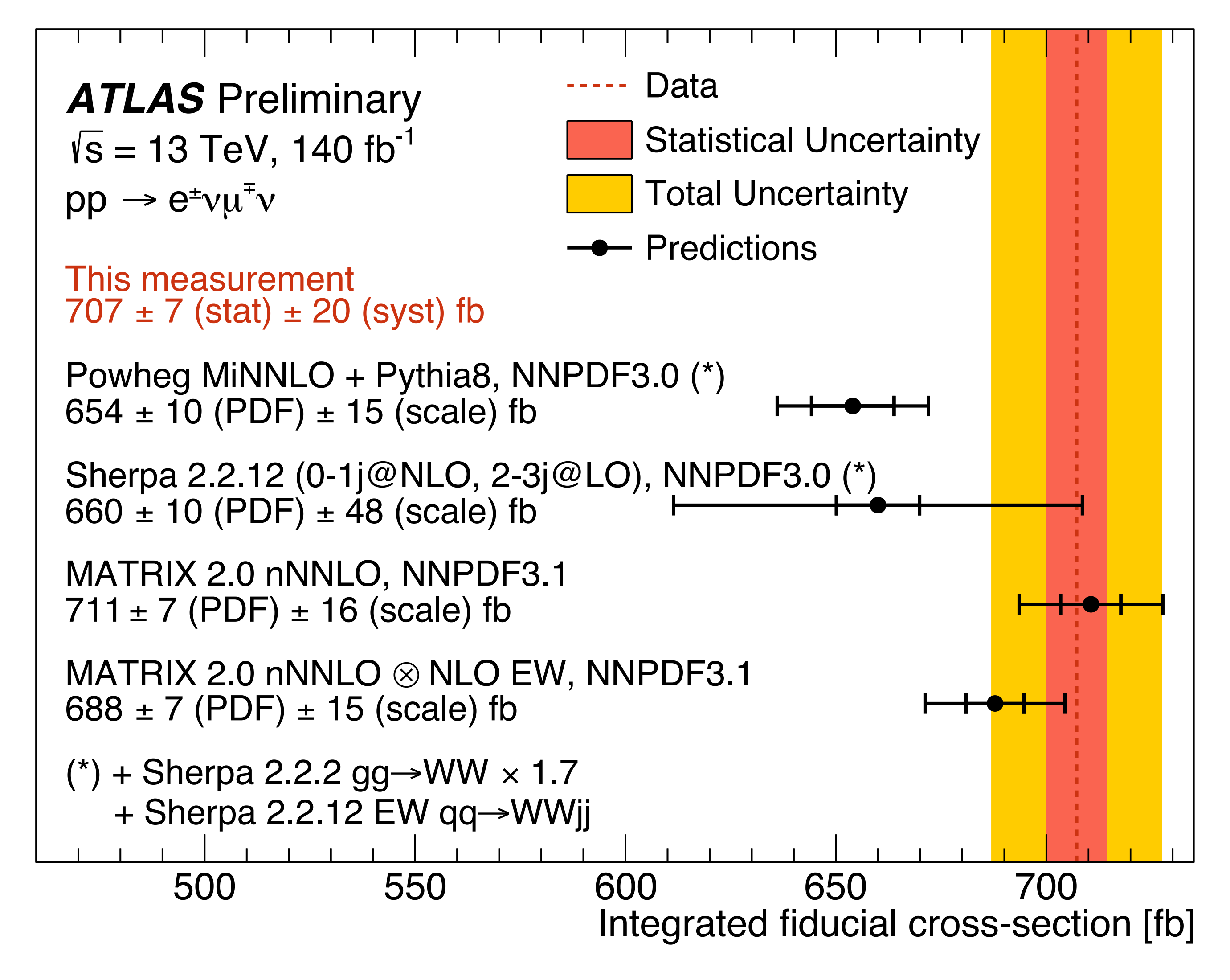

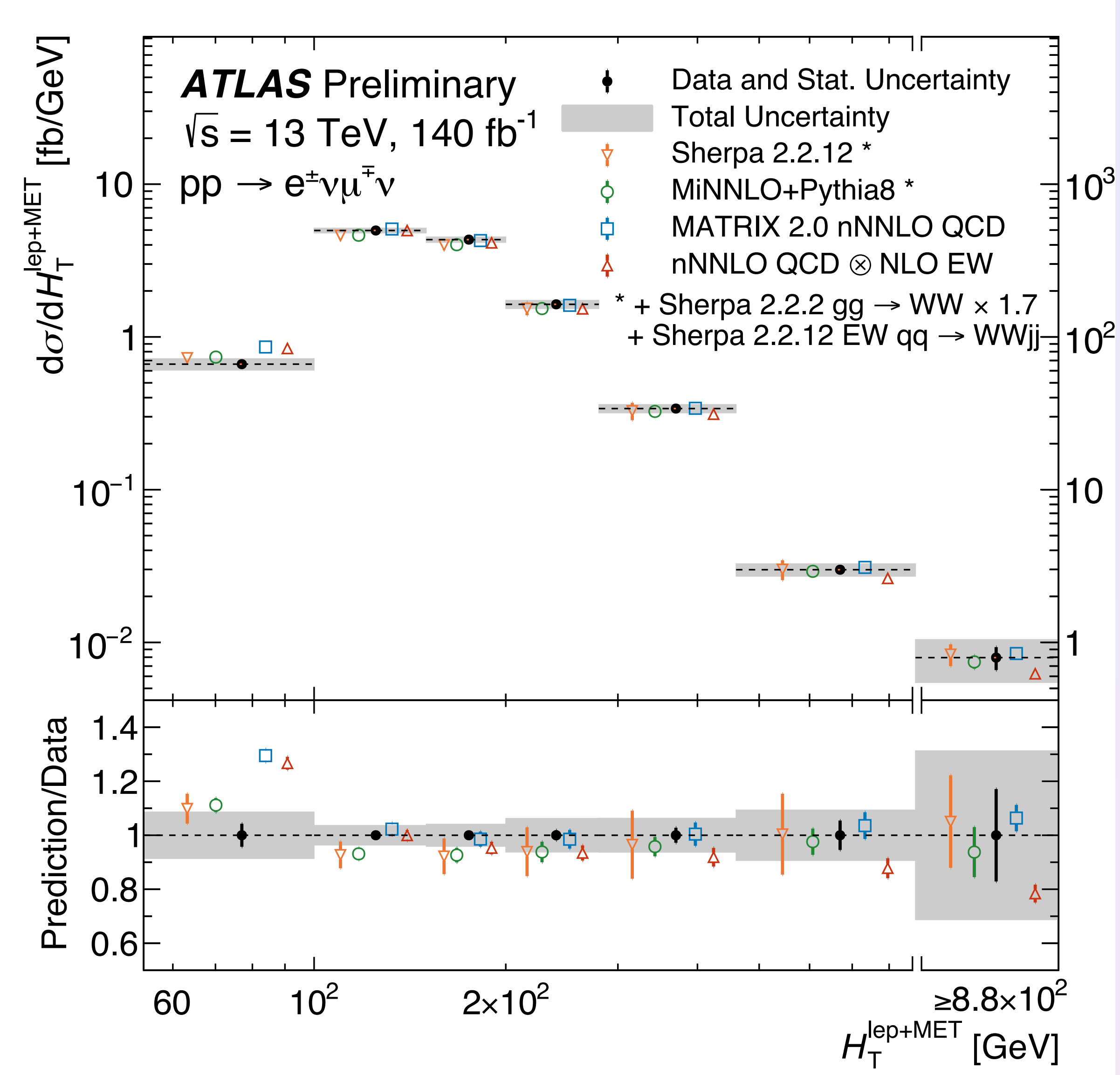

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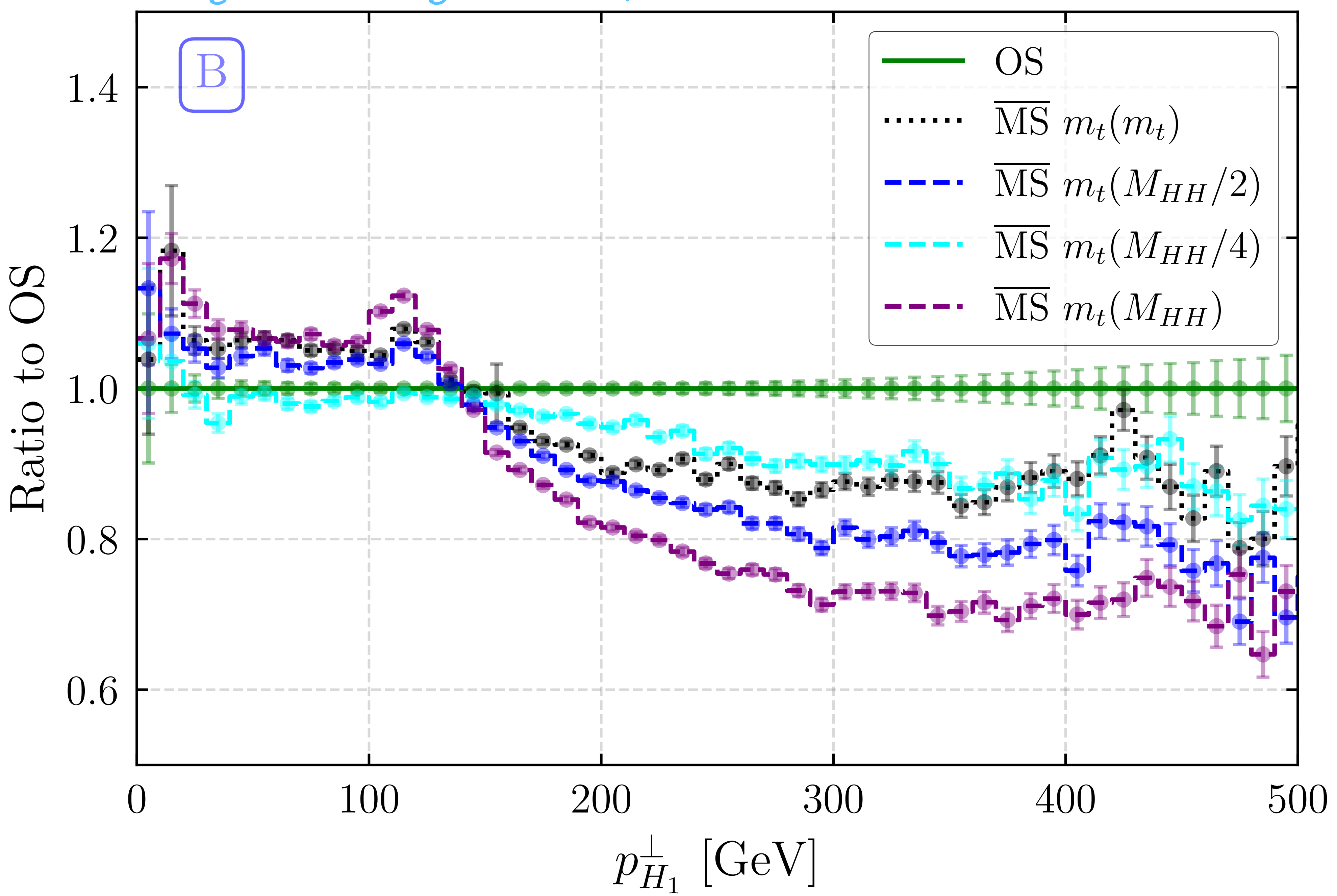
Parton Shower for HH

[Bagnaschi, Degrassi, RG '23]



Matching to Parton Shower

COMETA intends to bring together experts in precision computations, Monte Carlo simulations and Parton showers as well as experimentalists together

- integrating the precision predictions (NLO and NNLO) in MC codes including BSM
- uncertainty estimates with PS effects
- spin-correlations, EW effects at high energies

see also talk by Giovanni

Conclusion

still lots to do what regards precision in multi-boson production

- understanding of top mass renormalisation scheme uncertainty
- inclusion of BSM in VBF precision predictions
- networking among precision experts, MC+PS experts, experimentalists to include all of these in tools used by the experimentalists
- which precision will be needed for the rare multi-boson processes?