HH

report and plans

Sally Dawson, Christoph Englert,
Maxime Gouzevitch, Roberto Salerno,
Magdalena Sławińska

LHCHXSWG meeting, October 2016

HH in YR4

- recommendations for total rates in the SM (gluon fusion and rare channels)
- estimation of th. uncertainties in gluon fusion

- comparisons of available differential distributions

- recommendations for BSM benchmarks
  (EW singlet, 2HDM, effective Lagrangian)

SM rates – a quick dictionary

from S. Jones

	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)
HEFT	$17.07^{+30.9\%}_{-22.2\%}$	$31.93^{+17.6\%}_{-15.2\%}$	$37.52^{+5.2\%}_{-7.6\%}$
B.I. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$43.63^{+5.2\%}_{-7.6\%}$ *
FTapprox	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$	–
Full Theory	$19.85^{+27.6\%}_{-20.5\%}$	$32.91^{+13.6\%}_{-12.6\%}$	–
N.I. HEFT	–	$32.91^{+13.6\%}_{-12.6\%}$	$38.67^{+5.2\%}_{-7.6\%}$ *

(Born/NLO Improved) Higgs Effective Field Theory - $m_t \to \infty$ (finite at LO/NLO)

FTapprox. – complete NLO real emissions, approx. virtual contributions

* reweighted to full NLO

Glover, van der Bij 88, Dawson, Dittmaier, Spira 98
Maltoni, Vryonidou, Zaro 14 ,
de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16
Borowka, Greiner, Heinrich, Kerner, Schlenk, Schubert, Zirke 16

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LHCHXSWG recommendations for $\sqrt{s}$= 14 TeV, m_h=125 GeV, μ_R=μ_F = $m_{hh}/2$

$$\sigma_{NNLO+NNLL} = 39.56^{+4.4\%}_{-6.0\%}\ \text{fb}$$

Gluon fusion cross-sections

NNLL+NNLO with top mass effects at NLO

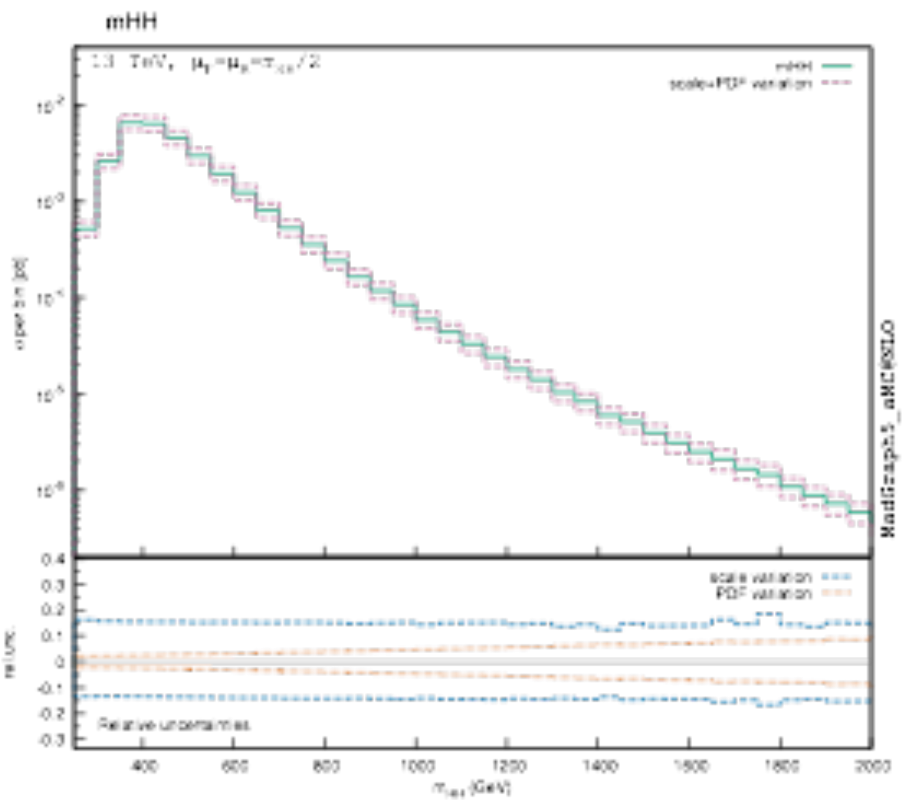
arXiv:1604.06447
arXiv:1505.07122

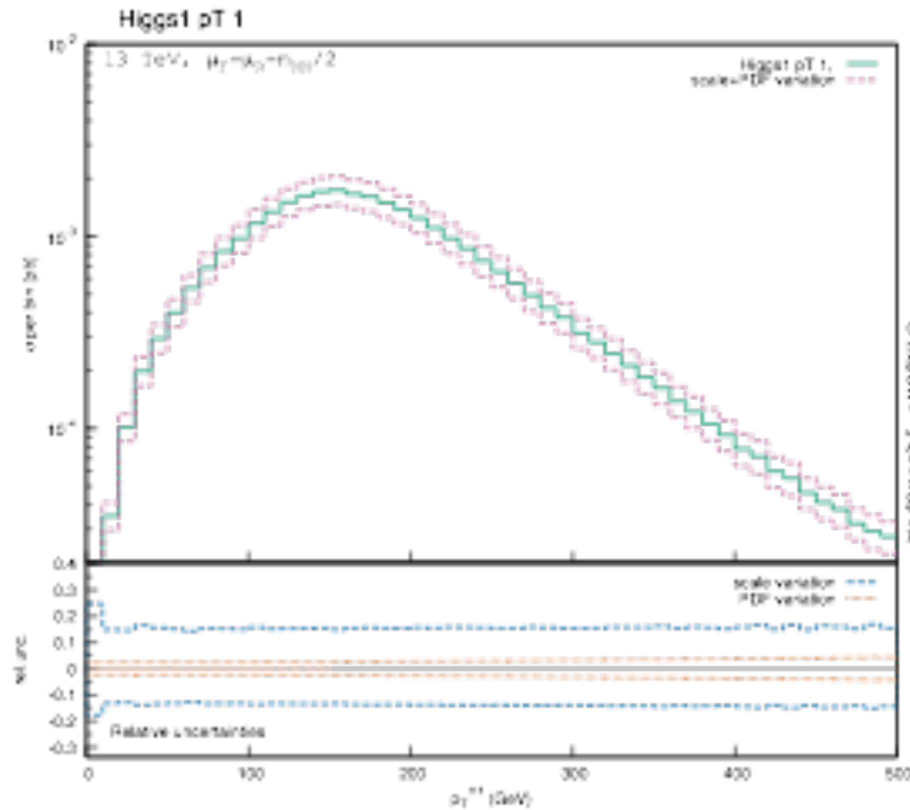
$m_h = 124.5$ GeV	$\sigma'_{\rm NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.132	$+4.0-5.7$	±3.4	±2.8
$\sqrt{s} = 8$ TeV	10.24	$+4.1-5.7$	±3.0	±2.6
$\sqrt{s} = 13$ TeV	33.70	$+4.3-6.0$	±2.1	±2.3
$\sqrt{s} = 14$ TeV	39.85	$+4.4-6.0$	±2.1	±2.2
$m_h = 125$ GeV	$\sigma'_{\rm NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.078	$+4.0-5.7$	±3.4	±2.8
$\sqrt{s} = 8$ TeV	10.16	$+4.1-5.7$	±3.1	±2.6
$\sqrt{s} = 13$ TeV	33.45	$+4.3-6.0$	±2.1	±2.3
$\sqrt{s} = 14$ TeV	39.56	$+4.4-6.0$	±2.1	±2.2
$m_h = 125.09$ GeV	$\sigma'_{\rm NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.068	$+4.0-5.7$	±3.4	±2.8
$\sqrt{s} = 8$ TeV	10.15	$+4.1-5.7$	±3.1	±2.6
$\sqrt{s} = 13$ TeV	33.41	$+4.3-6.0$	±2.1	±2.3
$\sqrt{s} = 14$ TeV	39.51	$+4.4-6.0$	±2.1	±2.2
$m_h = 125.5$ GeV	$\sigma'_{\rm NNLL}(fb)$	Scale Unc. (%)	PDF Unc. (%)	α_s Unc. (%)
$\sqrt{s} = 7$ TeV	7.023	$+4.0-5.7$	±3.4	±2.8
$\sqrt{s} = 8$ TeV	10.09	$+4.1-5.7$	±3.1	±2.6
$\sqrt{s} = 13$ TeV	33.21	$+4.3-6.0$	±2.1	±2.3
$\sqrt{s} = 14$ TeV	39.27	$+4.4-5.9$	±2.1	±2.2

5% th. uncertainties

Differential distributions

FTapprox from Madgraph5_aMC@NLO matched to Pythia 8

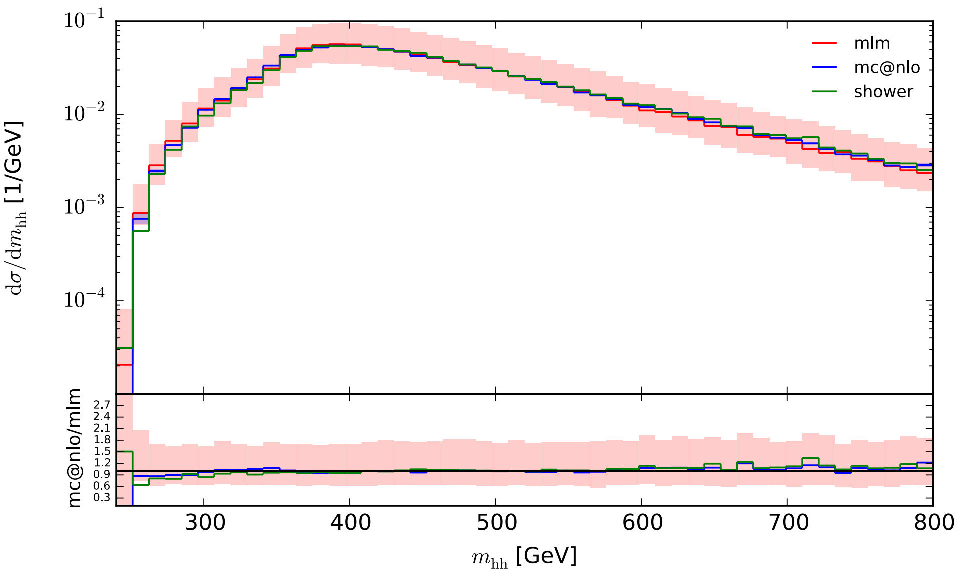




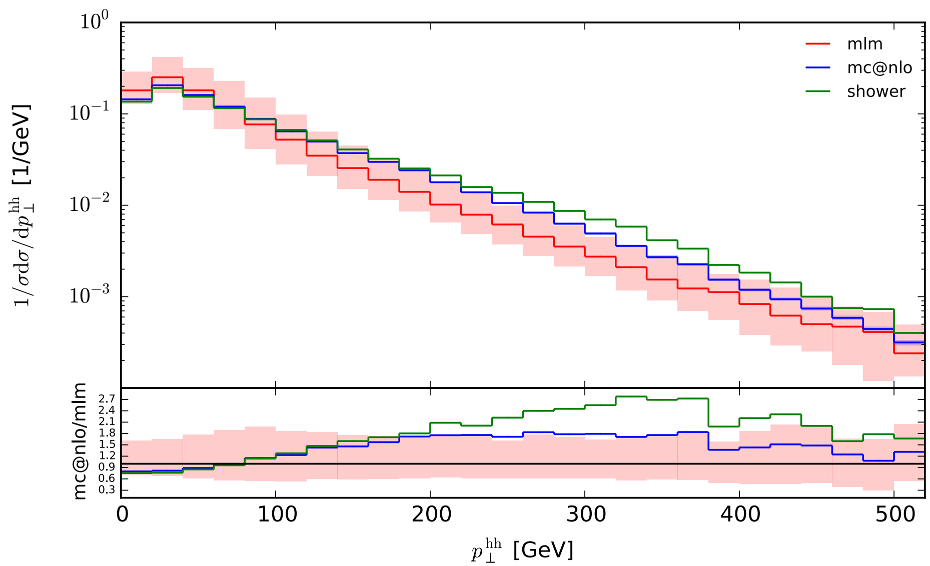
Towards estimating shower uncertainties

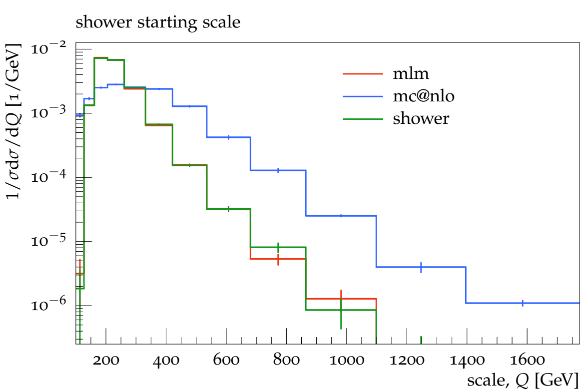
from A. Papaefstathiou

diHiggs invariant mass



diHiggs $p_\perp$





- "mc@nlo" (blue): MG5_aMC@NLO samples,
- "mlm" (red): MLM-merged HERWIG samples,
- "shower" (green): LO+HERWIG parton shower samples.

BSM resonant benchmarks

- Singlet model

$$V = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3\Phi^\dagger\Phi S^2$$

- input parameters: $m_h = 125$ GeV, M_H, $\cos\alpha$, v, $\tan\beta = v/\langle s\rangle$

cross-section tables included in the Report

- 2HDM

	$\tan\beta$	α	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.5881	300	441	442	38300
B2	1.50	-0.6792	700	701	670	180000
B7	10.00	0.1015	500	500	500	24746

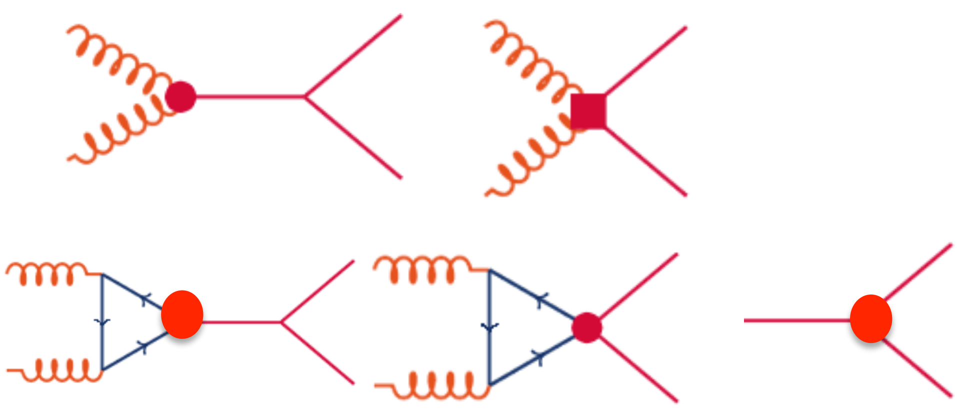
EFT benchmarks

Effective Lagrangian for a CP even Higgs

$$L = L_{SM} + \left(c_g\frac{h}{v} + c_{gg}\frac{h^2}{2v^2}\right)\frac{g_s^2}{4}G^A_{\mu\nu}G^{A,\mu\nu} - \frac{h}{v}\Sigma_f\Sigma_i m_{f_i}[\delta y_f]_i\bar{f}_i f_i$$
$$-\frac{h^2}{2v^2}\Sigma_f\Sigma_i m_{f_i}[y_f^{(2)}]_i\bar{f}_i f_i + \delta\lambda_3 h^3 \,.$$

5 BSM parameters relevant for di-Higgs production:

$$c_g,\ c_{gg},\ \delta y_t,\ y_t^{(2)},\ \delta\lambda_3$$



Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.55	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

Many thanks for contributions to YR4!

J. Adelman, A. Apyan, J. Baglio, A. Carvalho, D. de Florian, M. Dall'Osso, T. Dorigo, F. Goertz, C. Gottardo, J. Grigo, R. Gröber, P. Hebda, G. Heinrich, B. Hespel, N. Konstantinidis, I. Lewis, J. Mazzitelli, M. Mühlleitner, N. Styles, A. Papaefstathiou, J. Rojo, M. Spannowsky, M. Spira, M. Tosi, C. Vernieri, E. Vryonidou, M. Zaro, T. Zirke.

Now we are before YR5...

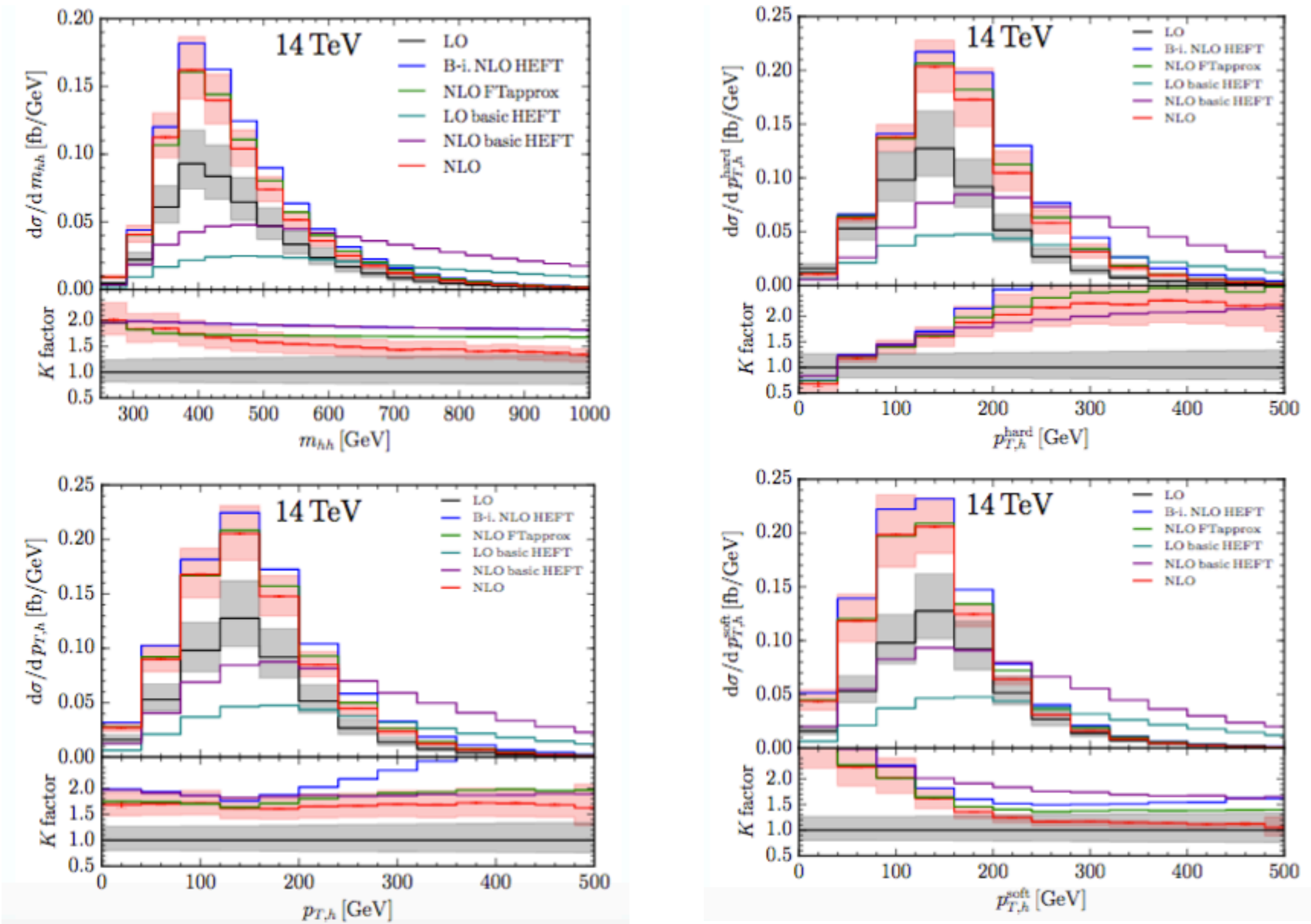
Future plans

- 1. distributions at NLO (finite top mass effects)
- 2. distributions at NNLO (HEFT)
- 3. bridging parton level to hadron level
- 4. general directions for BSM
- 5. additional processes? GF+2j, more WBF, VVHH?

based on contributions and discussions during the meeting
https://indico.cern.ch/event/573916/

NLO distributions

from S. Jones



Phase space sampling for NLO calculations

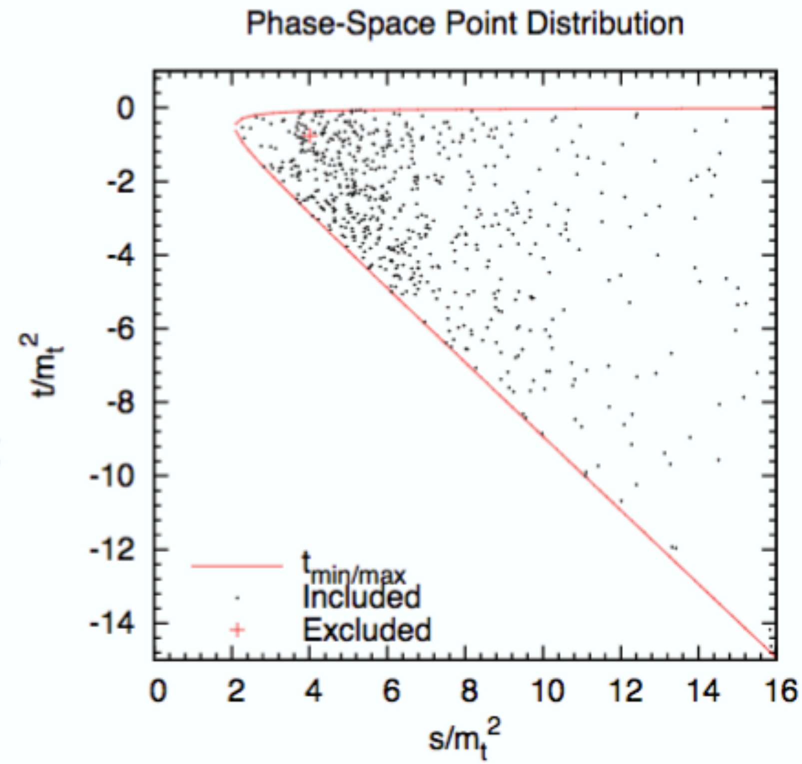
from S. Jones

Events for virtual:

1) VEGAS algorithm applied to LO matrix element $\mathcal{O}(100k)$ events computed

2) Using LO events unweighted events generated using accept/reject method $\mathcal{O}(30k)$ events remain

3) Randomly select 665 Events, compute at NLO



Median GPU time per PS point: 2 hours

Total compute time used: 4680 GPU Hours

Wall time: **6 days**

Possible future improvements

- Differential distributions are a bottle neck since much CPU needed for phase space sampling
- Cannot be matched to PS and used out-of-the-box
- Investigating the use of the Grid infrastructure
- PS matching (in progress, may need grid)
- Improving N.I. HEFT for fully differential distributions (see later)

Towards differential distributions at NNLO HEFT

- NNLO + threshold resummation at NNLL available → Large increase (~20%) w.r.t. NLO

  → Substantial reduction of scale uncertainty (~±5%)

  [D. de Florian and JM, arXiv:1505.07122]

  ↓ BSM: NNLO including dim 6 operators in progress [de Florian, Fabre, Mazzitelli]

- Fully differential calculation at NNLO in QCD is desirable

  [de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhoefer, JM and Rathlev, arXiv:1606.09519]

NNLO HEFT - technicalities

from J. Mazzitelli

Amplitudes
- → Double real
- → Real-virtual
- → Two-loop virtual

Double real, Real-virtual: OpenLoops [Cascioli, Lindert, Maierhöfer and Pozzorini]

Two-loop virtual → Available from the inclusive NNLO calculation [D. de Florian and JM, arXiv:1305.5206 and 1309.6594]

Subtraction formalism → qT subtraction

explicit separation of NNLO singularities from qTHH→0 from NLO HH+j contribution

Proc. indep. CT from qT resummation

$$d\sigma^{HH}_{\mathrm{NNLO}} = \mathcal{H}^{HH}_{\mathrm{NNLO}} \otimes d\sigma^{HH}_{\mathrm{LO}} + \left[d\sigma^{HH+\mathrm{jet}}_{\mathrm{NLO}} - d\sigma^{\mathrm{CT}}_{\mathrm{NNLO}} \right]$$

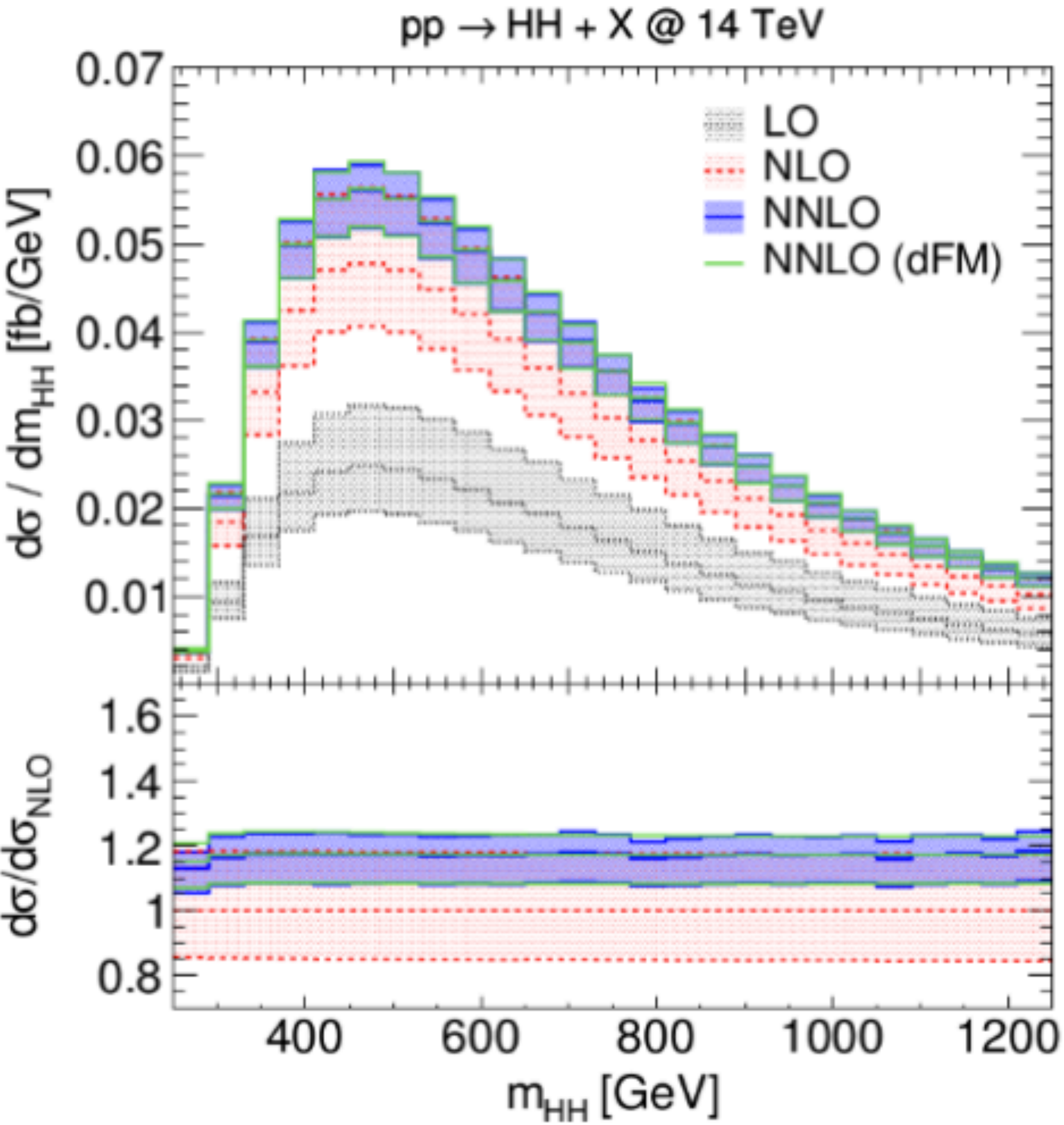
Hard-virtual coeff. Includes virtuals

Finite for qT → 0

[Catani, Grazzini, hep-ph/0703012]

Results of NLO reweighting - m_{hh}

from J. Mazzitelli



NNLO corrections:

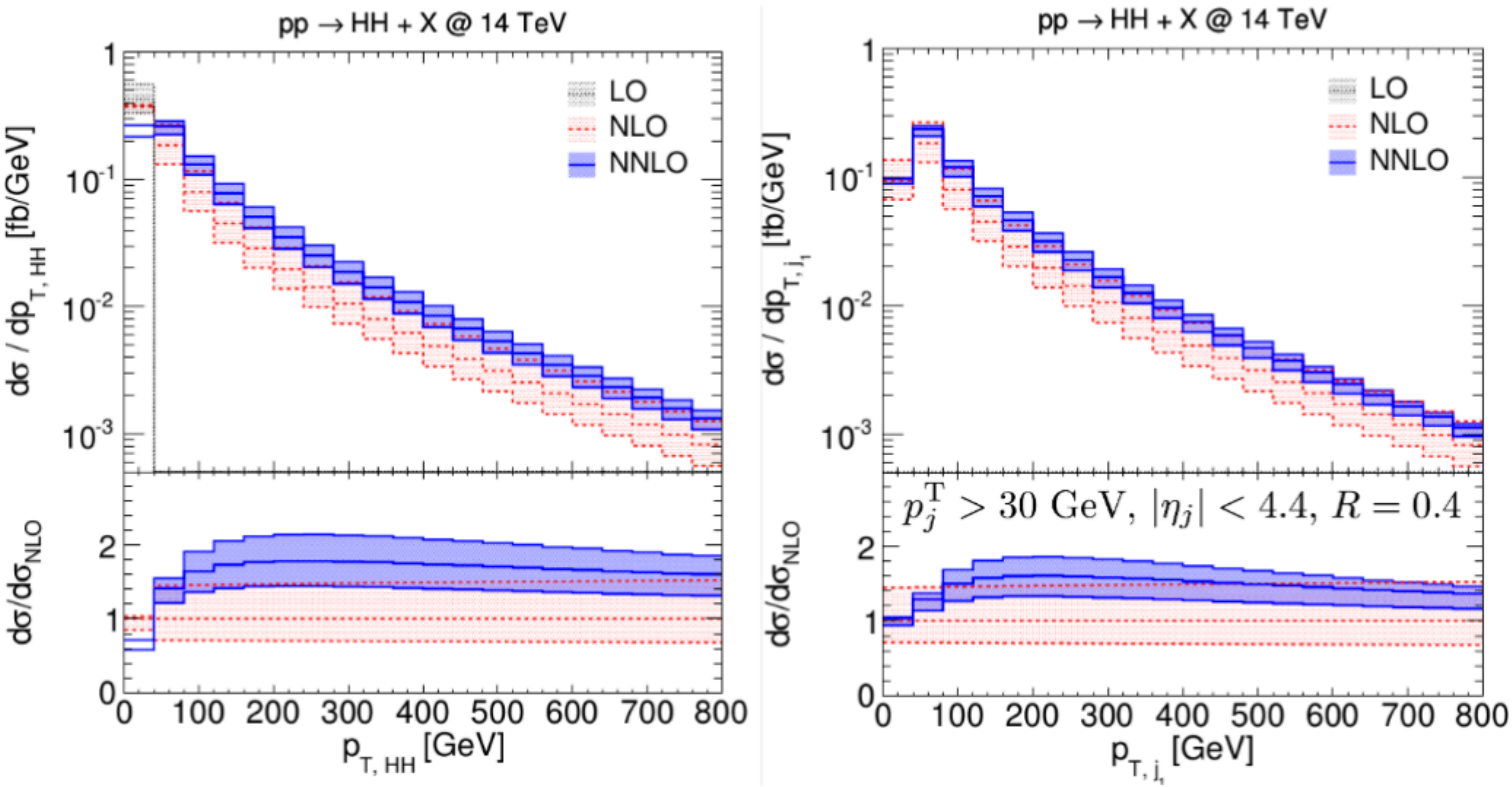
- Almost flat in m_{HH}
- About 18% increase w.r.t. NLO
- Scale uncertainties: ~ ±6.5%
- Overlap with NLO band

Perfect agreement with the analytical NNLO result

exact LO reweighting in progress

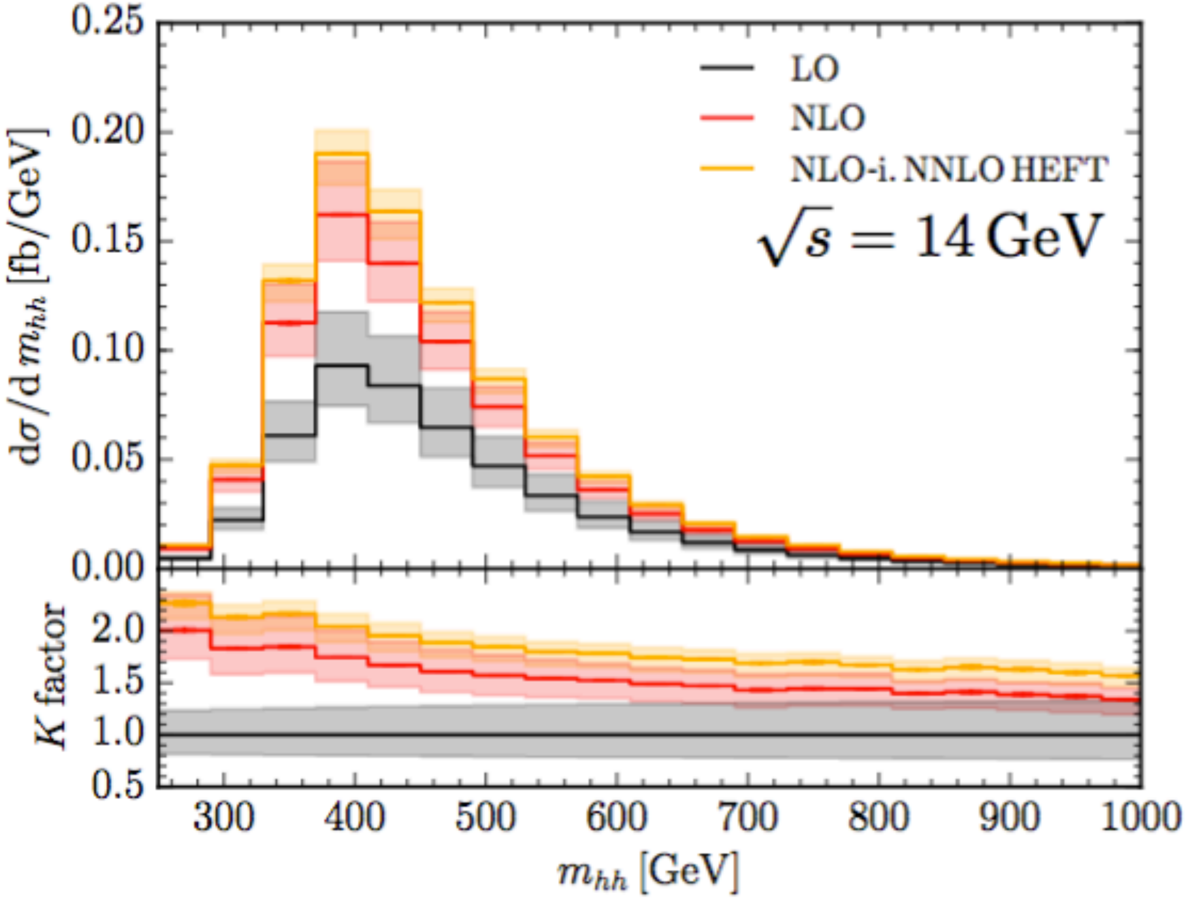
Results of NLO reweighting - p_h^T

from J. Mazzitelli



NNLO corrections up to 80-60%, scale uncertainties ~30-40%

Combining the two improvements



First attempt to combine full NLO

Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16

+

NNLO HEFT (Differential)

de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16

$$\frac{\mathrm{d}\sigma^{\mathrm{approx.}}}{\mathrm{d}m_{hh}} \equiv \frac{\mathrm{d}\sigma_{\mathrm{NLO}}}{\mathrm{d}m_{hh}} \times \frac{\mathrm{d}\sigma^{\mathrm{HEFT}}_{\mathrm{NNLO}}/\mathrm{d}m_{hh}}{\mathrm{d}\sigma^{\mathrm{HEFT}}_{\mathrm{NLO}}/\mathrm{d}m_{hh}}$$

Bin-by-bin rescaling of NLO by NNLO HEFT K-factor

Plans for improving the combination

- Combining $NNLO_{mt\rightarrow\infty}$ with $NLO_{finite\ mt}$:

  - Reweighting NNLO with the exact LO
  - With 1D NLO K-factors reweight m_{hh} distribution and apply the correction to others

- Different procedures → estimation of the HEFT uncertainty for NNLO distributions

- Inclusion of Higgs decays

Parton to hadron level

from A. Papaefstathiou

- Current state-of-the art of HH Monte Carlo

simulations relies on full LO + full hard radiation + virtual corrections from HEFT.

- LO+PS vs. PS+full real radiation efficiencies can vary up to 20% in an LHC analysis.
- Differences between merged and matched samples due to uncertainties related to the shower starting scale.

MC outlook

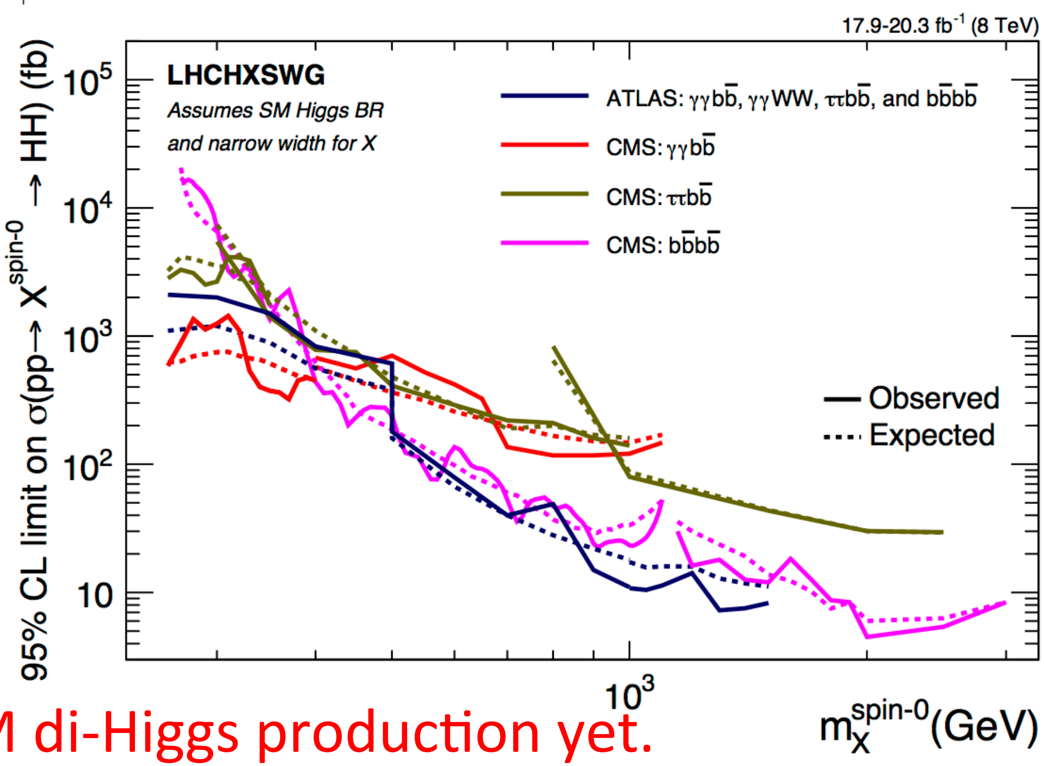
- Use the same inputs
- Discuss with experiments which MC generators and settings are used to include them in the comparison
- Can we gain in efficiency of signal selection with better MC modeling?

Experimental searches

Run 1 limits on non resonant SM-like cross-sections

Channel	Experiment	Observed (pb)	Expected (pb)
$\gamma\gamma b\bar{b}$	ATLAS	2.2	1.0
$\gamma\gamma b\bar{b}$	CMS	0.71	0.60
$\tau\tau b\bar{b}$	ATLAS	1.6	1.3
$\tau\tau b\bar{b}$	CMS	0.59	0.94
$b\bar{b}b\bar{b}$	ATLAS	0.62	0.62
$\gamma\gamma WW^*$	ATLAS	11.0	6.7
Combination	ATLAS	0.69	0.47

Run 1 limits on resonant cross-sections



Searches not sensitive to the SM di-Higgs production yet.

→ need to develop reasonable BSM benchmark models

BSM models

- Inherit SM improvements in BSM benchmarks

- open questions about the progress:
  - new resonant models? need to work with other groups on 2HDM, MSSM, NMSSM benchmarks relevant for HH
  - more EFT operators? (CP violation?)
  - EFT operators in other production channels? (VVhh, tthh,...)

Thoughts for general consideration before YR5

- harmonise BSM activities with WG2 and WG3 to make sure our benchmarks are not excluded already by single Higgs processes

- the necessity for providing recommendations for 4 mass points for rare processes (non-integer values a bottleneck for NLO computations)

Conclusions

- Many theory developments already in YR4!
- Ongoing efforts in improving predictions for SM gluon fusion production
- Works towards estimating shower systematic
- Plans to improve BSM benchmarks with SM developments
- More discussions needed for BSM directions