Higher order and top quark mass effects in Higgs boson pair production
within and beyond the SM

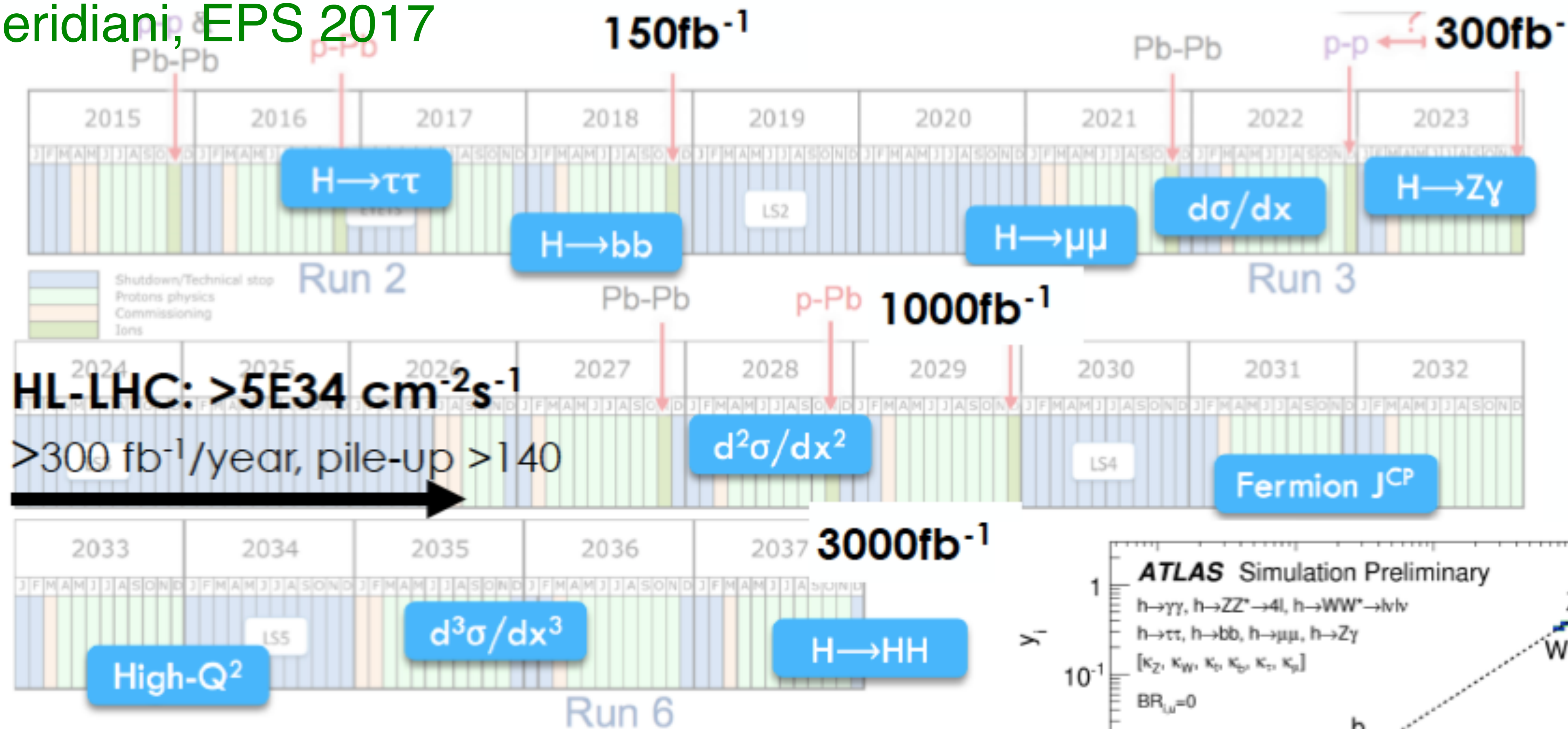
Gudrun Heinrich
Max Planck Institute for Physics, Munich

Loops & Legs in Quantum Field Theory
St. Goar, May 4, 2018

TIMELINE BEYOND RUN2

Credits: A. David @ GRC 2017

P.Meridiani, EPS 2017

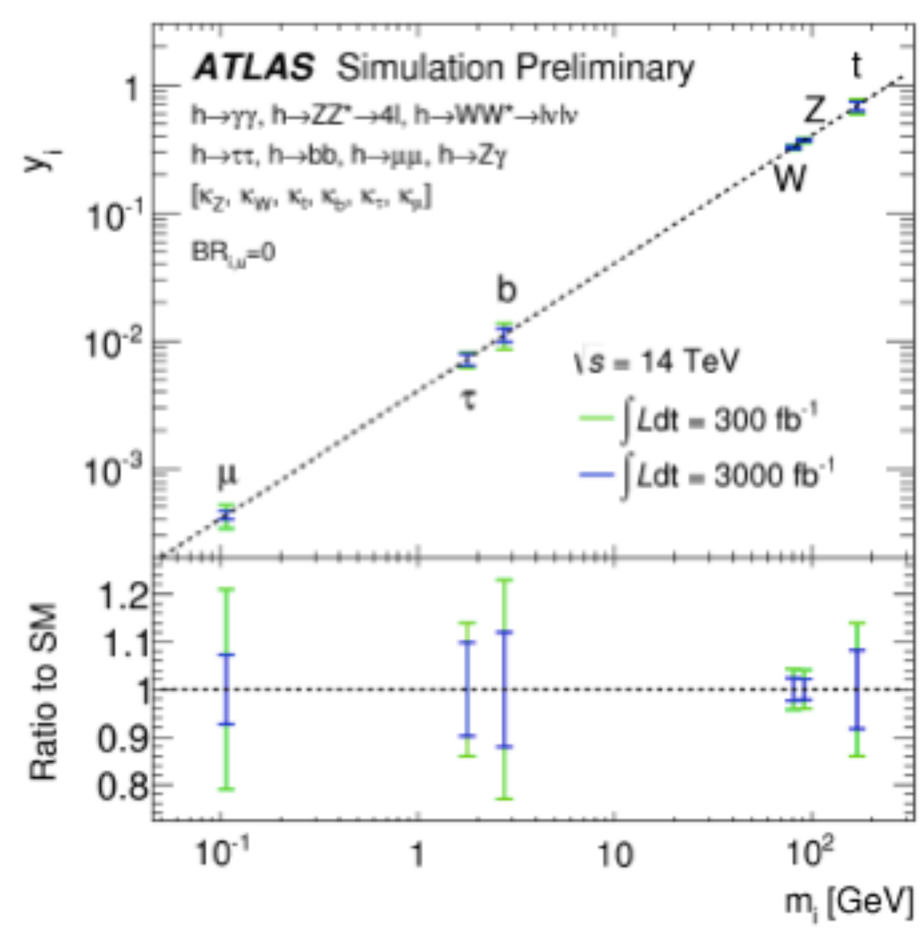


HL-LHC: >5E34 cm^{-2}s^{-1}

>300 fb^{-1}/year, pile-up >140

Higgs boson self-coupling:

prime candidate for
New Physics to show up



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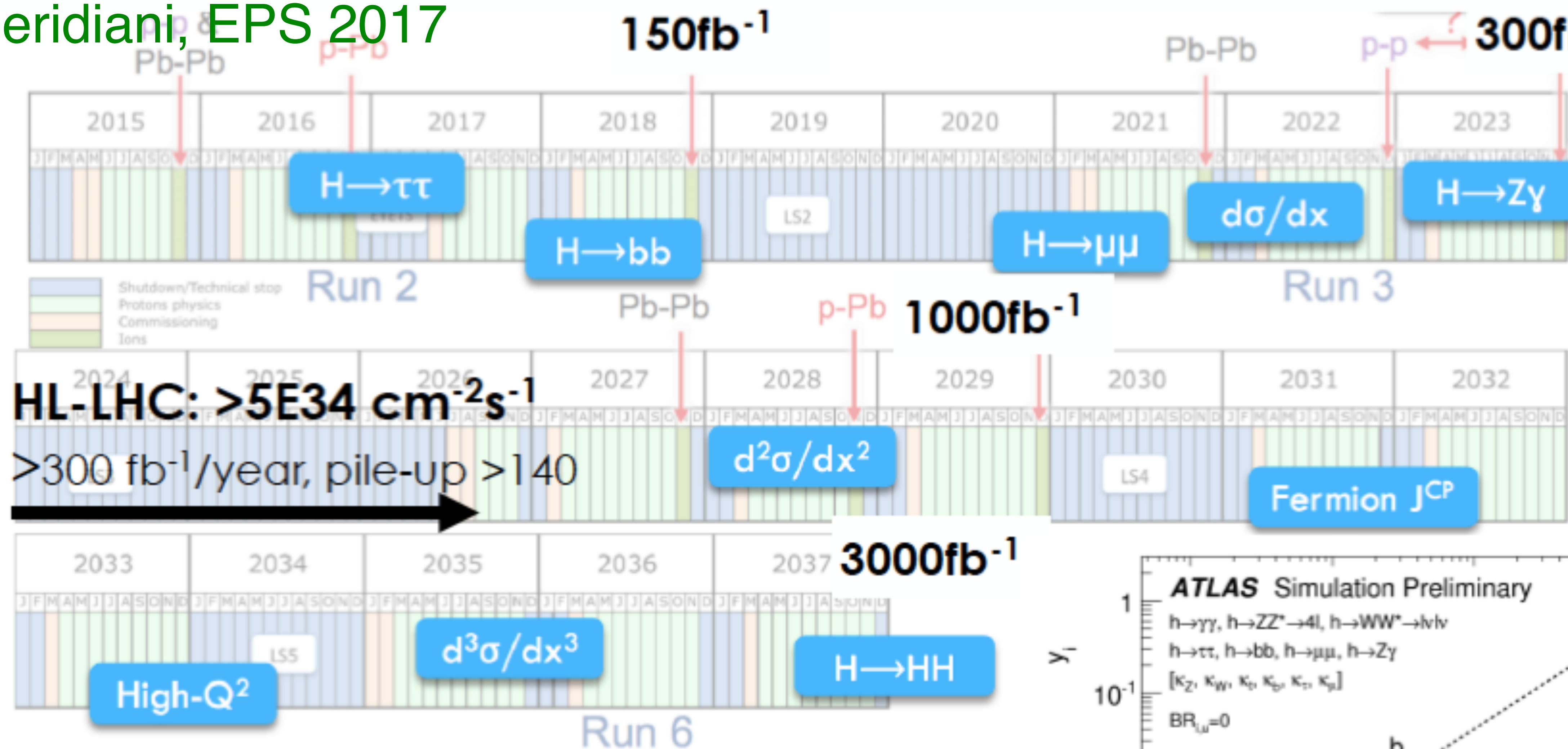

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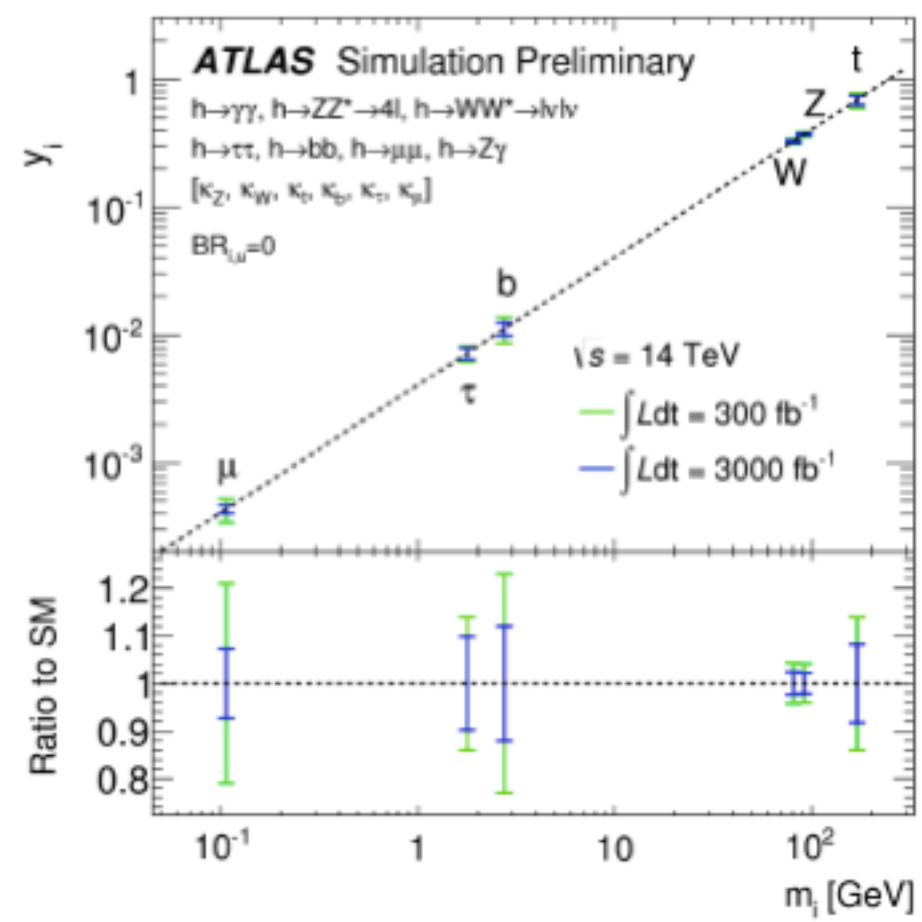

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Exploring the Higgs sector

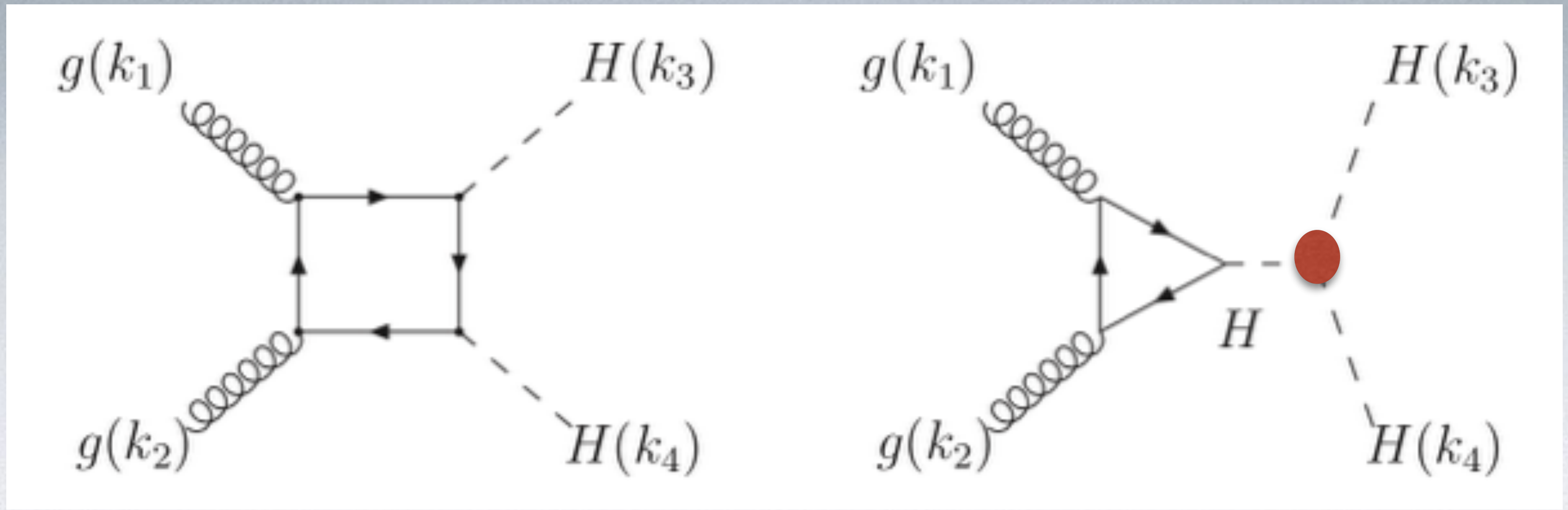
SM: $V(\Phi) = -\frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$

↓ EW symmetry breaking

$$\frac{m_h^2}{2}\,h^2 + \frac{m_h^2}{2v}\,h^3 + \frac{m_h^2}{8v^2}\,h^4$$

λ_{3h} completely determined in the SM

can be measured e.g. in Higgs boson pair production



current best limit $\sigma_{HH} \leq 19\,\sigma_{HH}^{SM}$ ($b\bar{b}\gamma\gamma$ channel)

theoretical constraints on λ_{3h} rather model dependent

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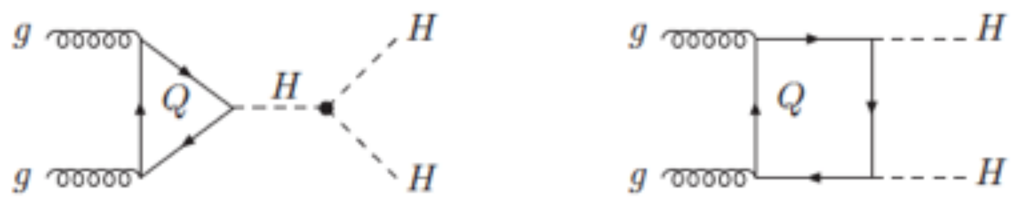
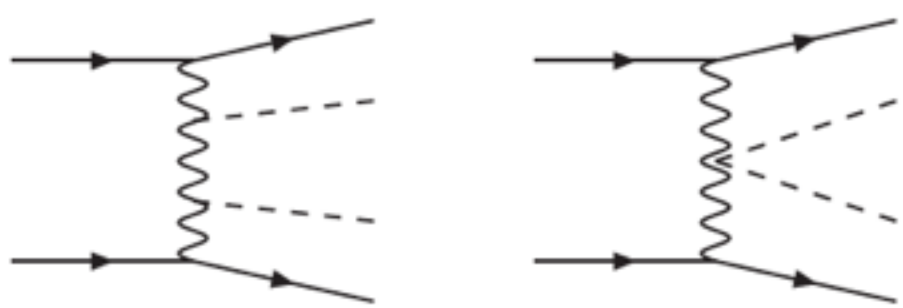
Higgs boson pair production channels

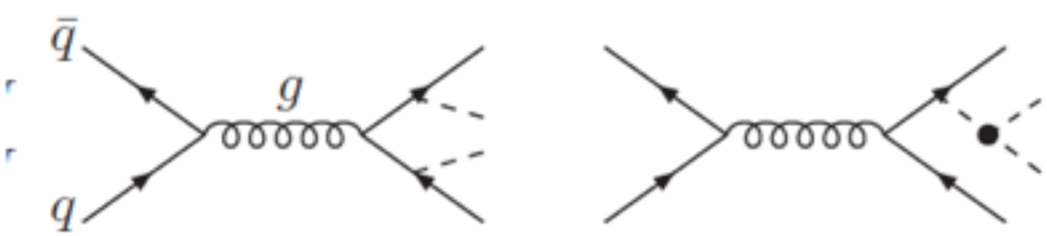
- gluon fusion



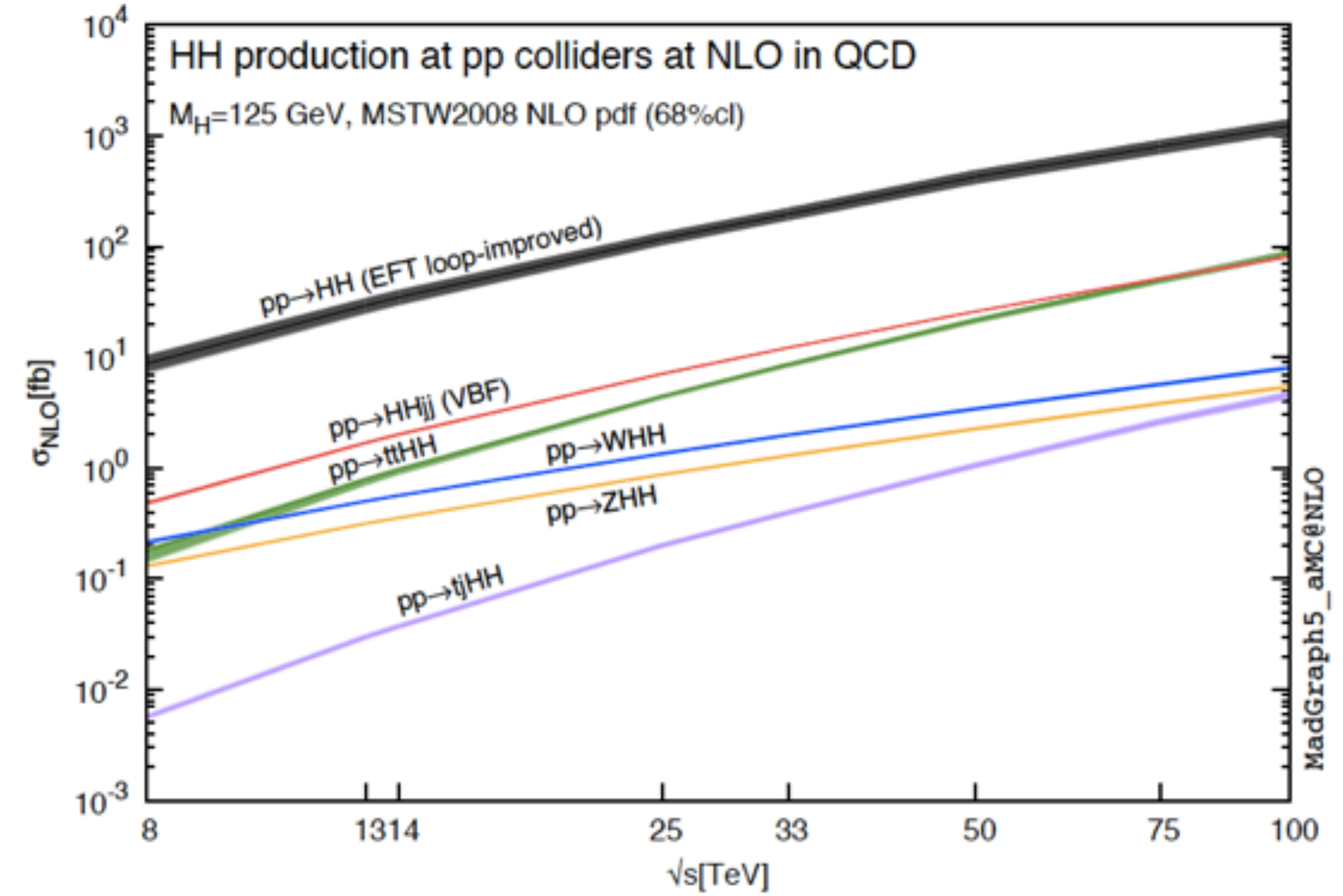
- vector boson fusion



- top-quark associated



- Higgs-strahlung



Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro '14

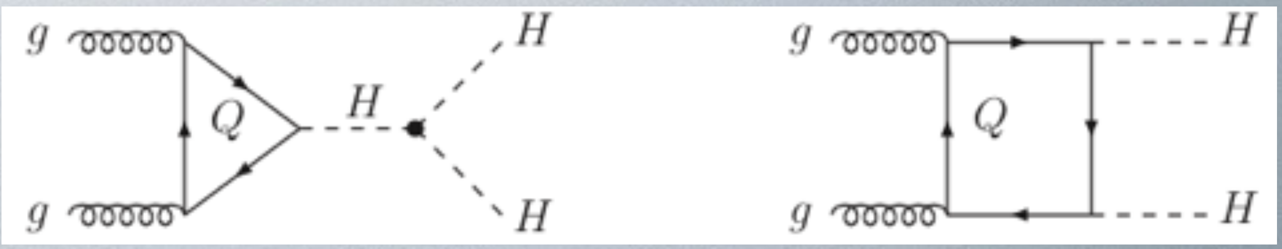
largest cross section from gluon fusion, but still

$$\sigma_{ggHH} \sim 10^{-3}\,\sigma_{ggH}$$ (in the SM)

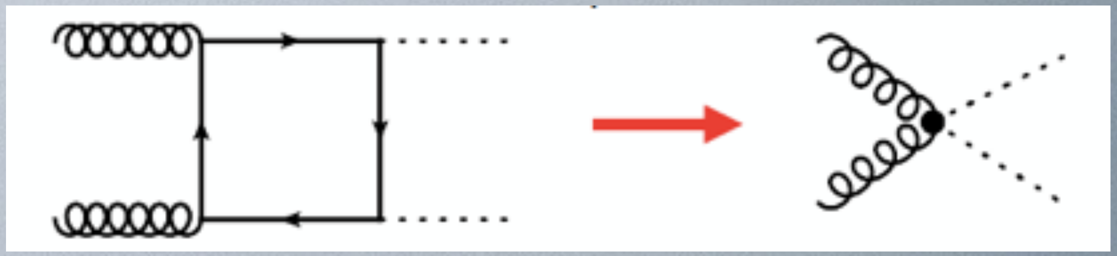
HH in gluon fusion: history and status

LO with full heavy quark mass dependence

Glover, van der Bij '88, Plehn, Spira, Zerwas '96



$m_t \to \infty$ limit: "Higgs Effective Field Theory" (HEFT)



Note:

HEFT strictly valid only for $\sqrt{\hat{s}} \ll 2m_t$
HH production threshold: $2m_H < \sqrt{\hat{s}}$

$\Rightarrow$ validity of HEFT limited to $250\,\mathrm{GeV} < \sqrt{\hat{s}} < 340\,\mathrm{GeV}$

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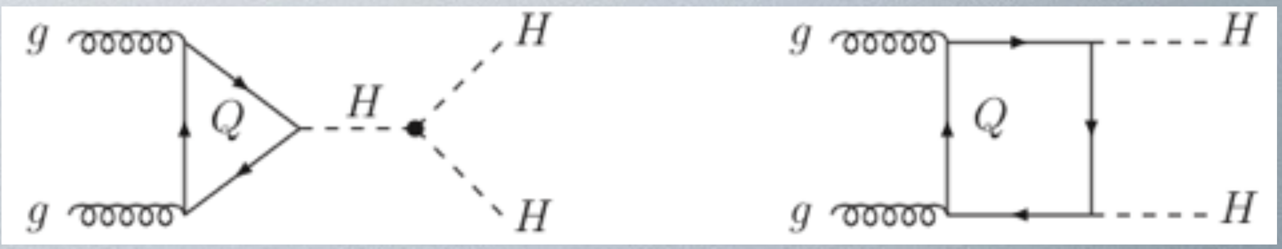

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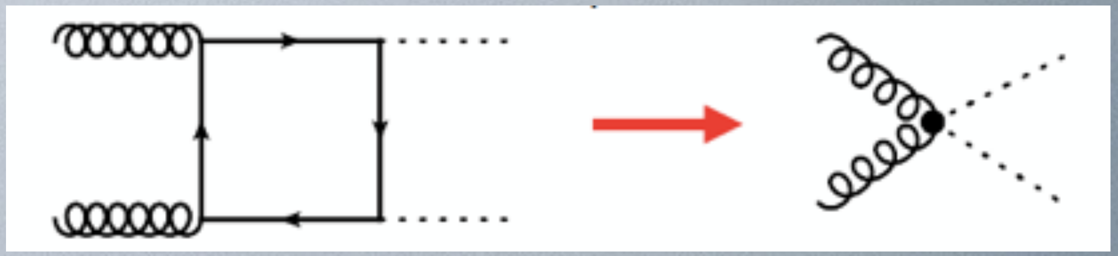

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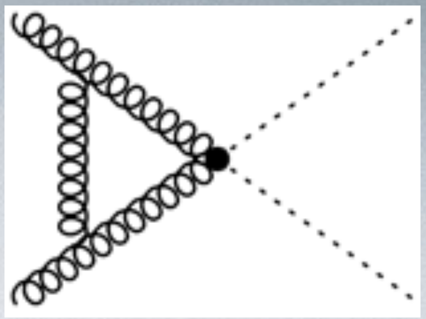
"Born-improved NLO HEFT": rescale by $\mathcal{M}^{LO}(m_t)/\mathcal{M}^{LO}_{\mathrm{HEFT}}$

NLO in Born-improved HEFT Dawson, Dittmaier, Spira '98 (**HPAIR**) $K \simeq 2$



- **supplemented with $1/m_t$ expansion:** $(\pm 10\%)$

  Grigo, Hoff, Melnikov, Steinhauser '13, '15 ; Degrassi, Giardino, Gröber '16

- **full mass dependence in NLO real radiation ("FTapprox")** **-10%**

  Frederix, Hirschi, Mattelaer, Maltoni, Torrielli, Vryonidou, Zaro '14; Maltoni, Vryonidou, Zaro '14

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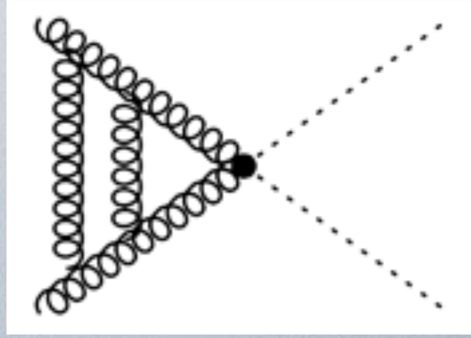
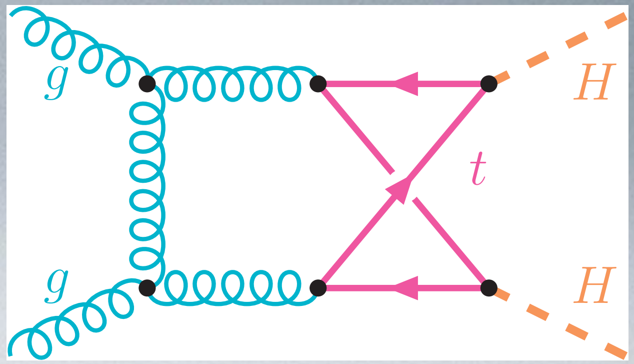


- **total xs NNLO** De Florian, Mazzitelli '13
- **including all matching coefficients** Grigo, Melnikov, Steinhauser '14
- **supplemented with $1/m_t$ expansion:** Grigo, Hoff, Steinhauser '15
- **soft gluon resummation NNLL** Shao, Li, Li, Wang '13; De Florian, Mazzitelli '15
- **differential NNLO** De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16

NLO calculation with full top mass dependence

Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke '16

all integrals calculated numerically with **SecDec**



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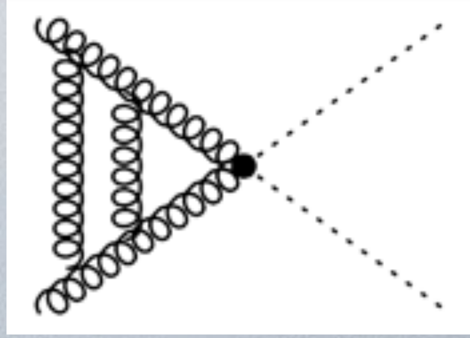

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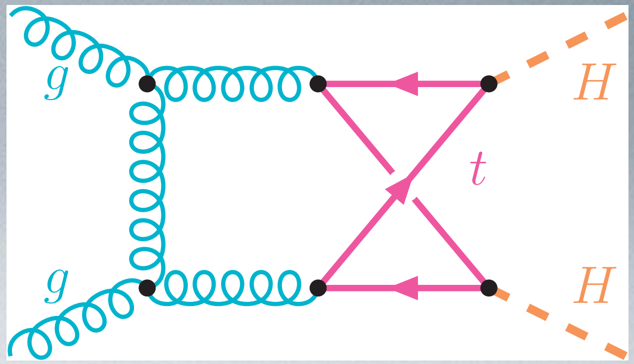
⟶ talks of S.Jahn, M.Kerner



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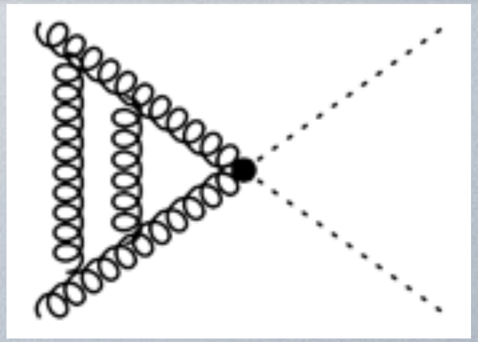

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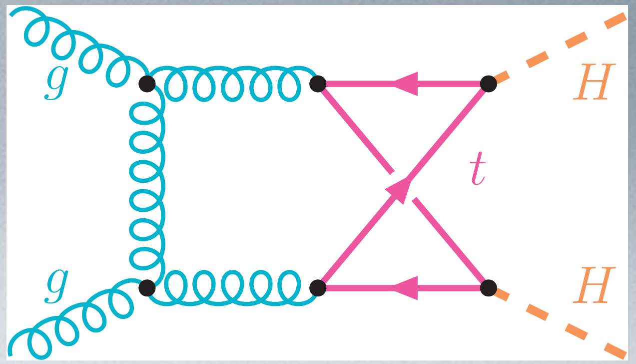

- q_T **resummation NLL+NLO** Ferrera, Pires '16
- **full NLO + parton shower** (Powheg and MG5_aMC@NLO) → this talk

  GH, Jones, Kerner, Luisoni, Vryonidou '17 (Sherpa) Jones, Kuttimalai '17
- **NNLO_approx** Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18 → this talk
- **Expansions+Padé** Gröber, Maier, Rauh '17
- **High energy limit** Davies, Mishima, Steinhauser, Wellmann '18

Status of CERN Yellow Report 4 (March 2017)

total cross sections at 14 TeV

uncertainties: $\mu_{R,F} \in [\mu_0/2, 2\,\mu_0]$ (7-point variation) $\mu_0 = m_{HH}/2$

	$\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	$\sigma_{\rm NNLO}$[fb]
HEFT	$17.07^{+30.9\%}_{-22.2\%}$	$31.93^{+17.6\%}_{-15.2\%}$	$37.52^{+5.2\%}_{-7.6\%}$
B-i. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	
$\rm FT_{approx}$	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$	
full m_t dep.	$19.85^{+27.6\%}_{-20.5\%}$	$32.91^{+13.6\%}_{-12.6\%}$	

used by ATLAS, CMS: $\sigma'_{NNLL} = \sigma_{NNLL} + \delta_t\,\sigma_{NLO}^{\rm HEFT} = 39.64^{+4.4\%}_{-6.0\%}$

$$\delta_t = (\sigma_{NLO}^{\rm full} - \sigma_{NLO}^{\rm B-i.HEFT})/\sigma_{NLO}^{\rm B-i.HEFT}$$

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$$\delta_t = (\sigma^{\mathrm{full}}_{NLO} - \sigma^{\mathrm{B-i.HEFT}}_{NLO})/\sigma^{\mathrm{B-i.HEFT}}_{NLO}$$

top mass effects at NLO: energy dependence

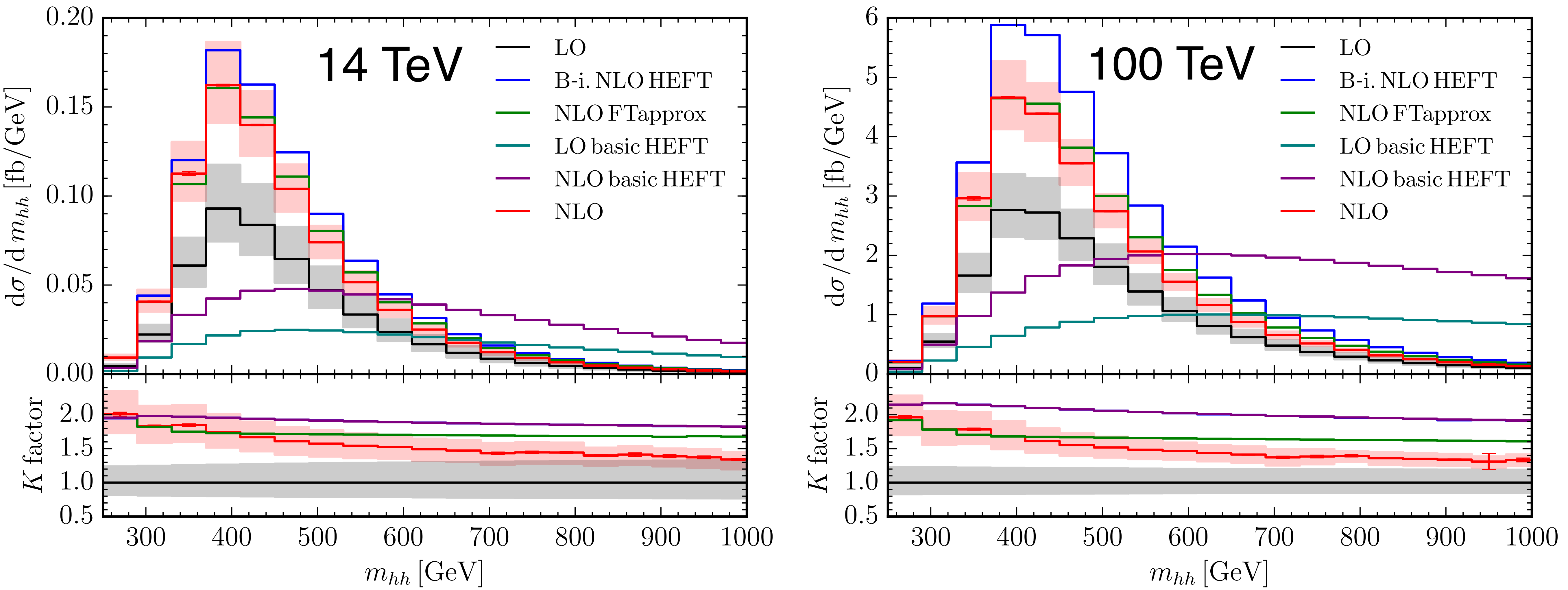
$\sqrt{s}$	LO [fb]	B-i. NLO HEFT [fb]	NLO FT$_{approx}$ [fb]	NLO [fb]
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$
27 TeV	$78.85^{+21.5\%}_{-17.0\%}$	$154.94^{+16.2\%}_{-13.4\%}$	$134.12^{+12.7\%}_{-11.1\%}$	$127.88^{+11.6\%}_{-10.5\%}$
100 TeV	$731.3^{+20.9\%}_{-15.9\%}$	$1511^{+16.0\%}_{-13.0\%}$	$1220^{+11.9\%}_{-10.7\%}$	$1149^{+10.8\%}_{-10.0\%}$

relative differences to full NLO:

	14 TeV	27 TeV	100 TeV
$\Delta_{\rm NLO}^{\rm B-i.\,HEFT}$	16.4%	21.2%	31.5%
$\Delta_{\rm NLO}^{\rm FTapprox}$	4.1%	4.9%	6.2%

$$\Delta^{\rm X}_{\rm NLO} = \frac{\sigma^{\rm X}_{\rm NLO} - \sigma^{\rm full}_{\rm NLO}}{\sigma^{\rm full}_{\rm NLO}}$$

Higgs boson pair invariant mass



at 14 TeV:

Born-improved NLO HEFT outside full NLO scale variation band beyond m_{hh} ~450GeV

FTapprox: outside band for $m_{hh} \geq$ 600 GeV

worse at 100 TeV

top quark loops resolved → HEFT has wrong scaling behaviour at high energies

combination with parton showers

GH, S.Jones, M.Kerner, G.Luisoni, E.Vryonidou '17

- avoid evaluation of two-loop amplitude for each phase space point
- two-loop amplitude depends only on $\hat{s}, \hat{t} \quad (m_t, m_H \text{ fixed})$

→ construct 2-dim grid

- variable transformation to achieve uniform distribution; interpolation

$$x = f(\beta(\hat{s})), \quad c_\theta = |\cos\theta| = \left| \frac{\hat{s} + 2\hat{t} - 2m_H^2}{\hat{s}\beta(\hat{s})} \right| \qquad \beta(\hat{s}) = \sqrt{1 - 4m_H^2/\hat{s}}$$

combination with POWHEG and MadGraph5_aMC@NLO

POWHEG-BOX-V2: User-Process-V2/ggHH

and Sherpa S. Jones, S. Kuttimalai '17

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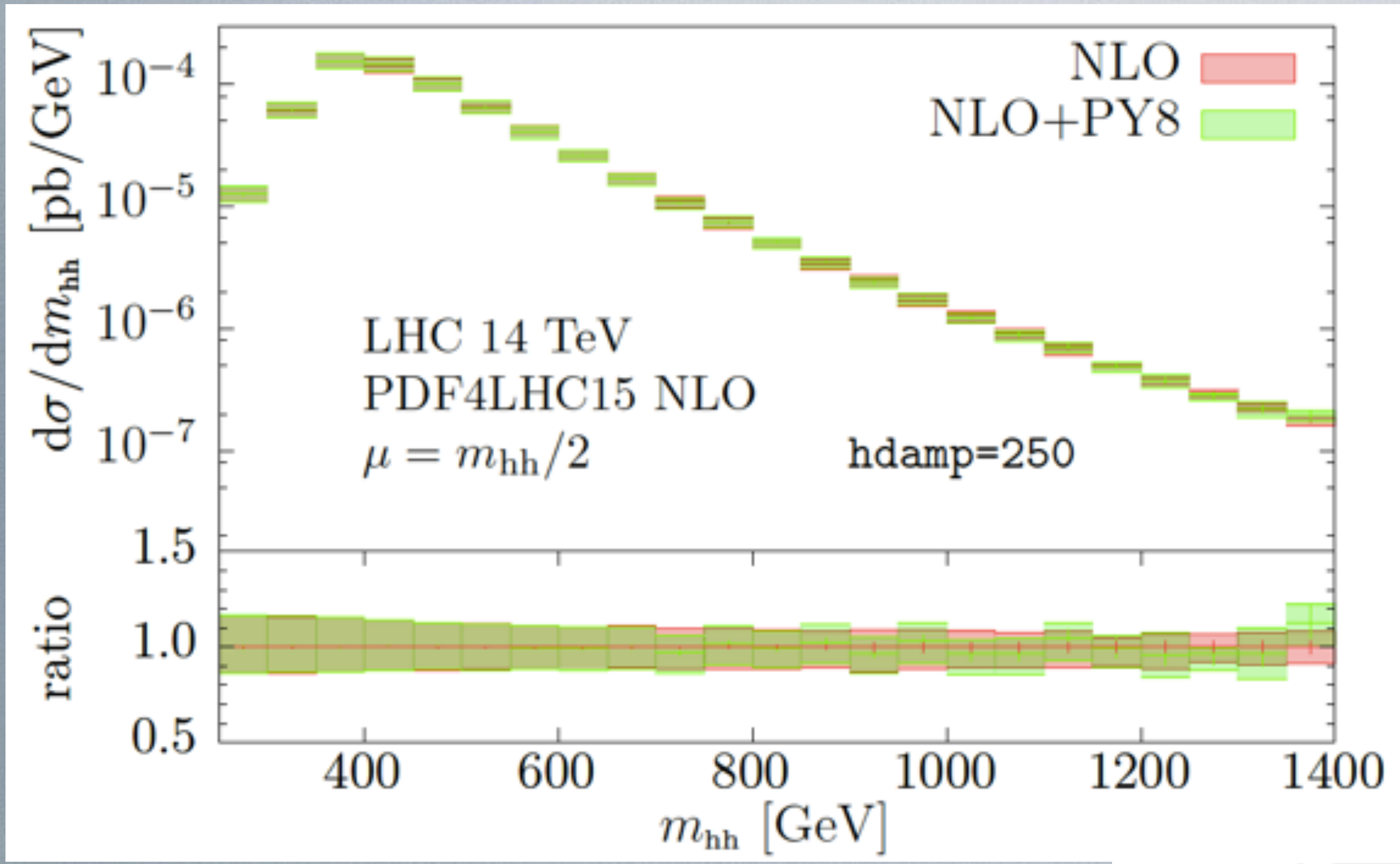
POWHEG-BOX-V2: User-Process-V2/ggHH — public

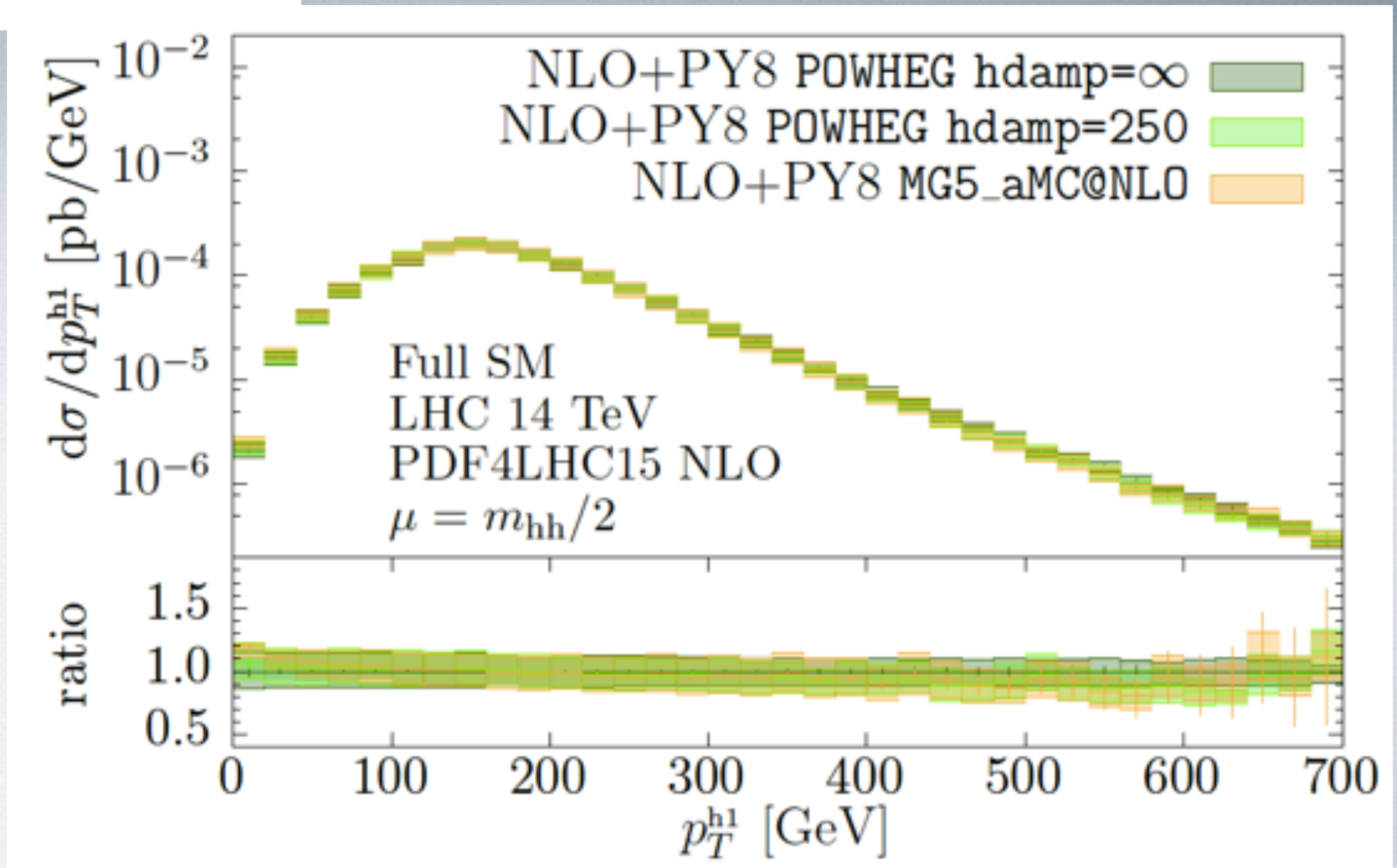
and Sherpa S. Jones, S. Kuttimalai '17

grid also public http://github.com/mppmu/hhgrid

NLO + parton shower



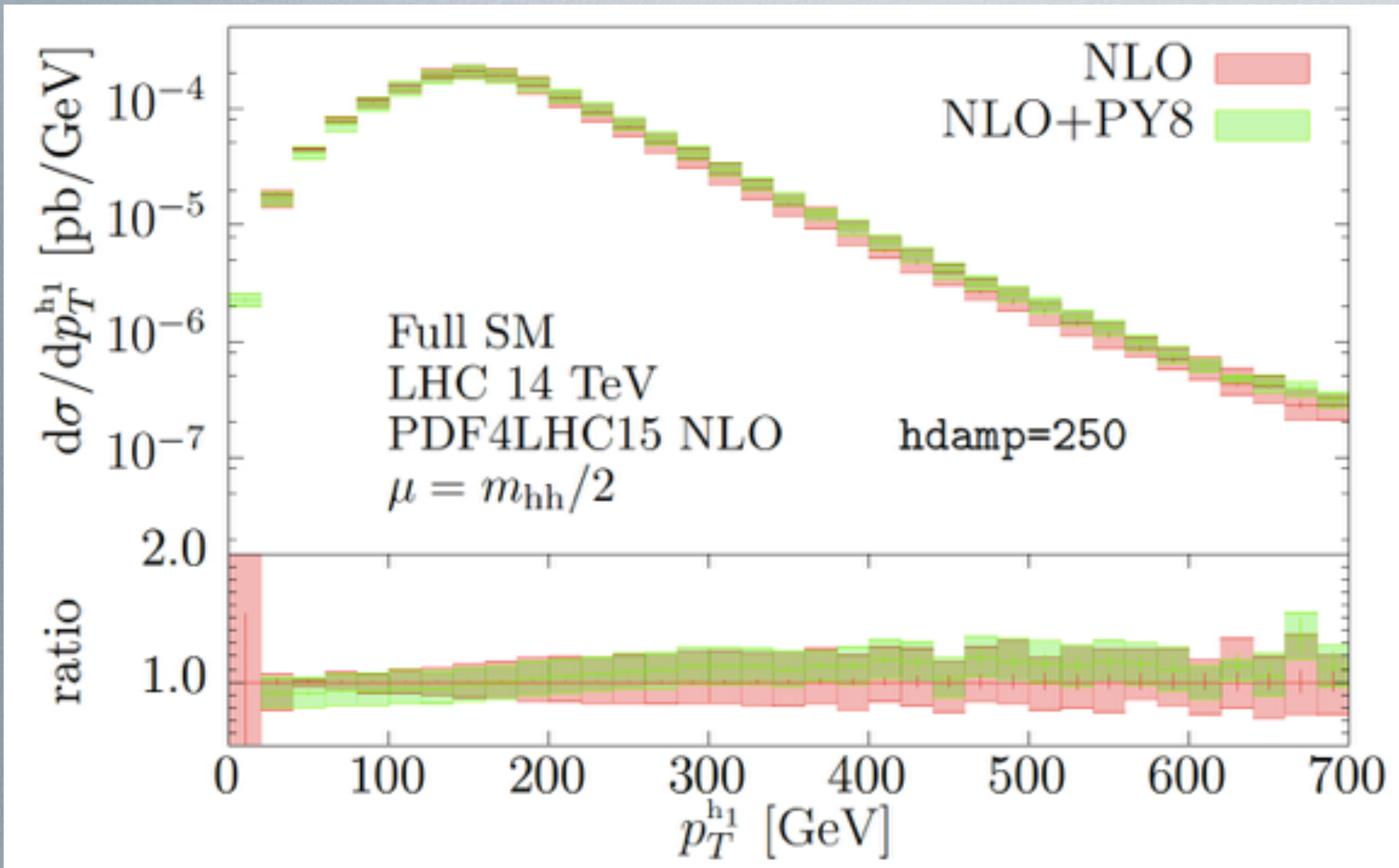
basically no shower effects for observables which are inclusive in extra radiation



moderate impact on NLO accurate observables

note: matching different in Powheg and MG5_aMC@NLO, Pythia8 used in both cases

NLO + parton shower



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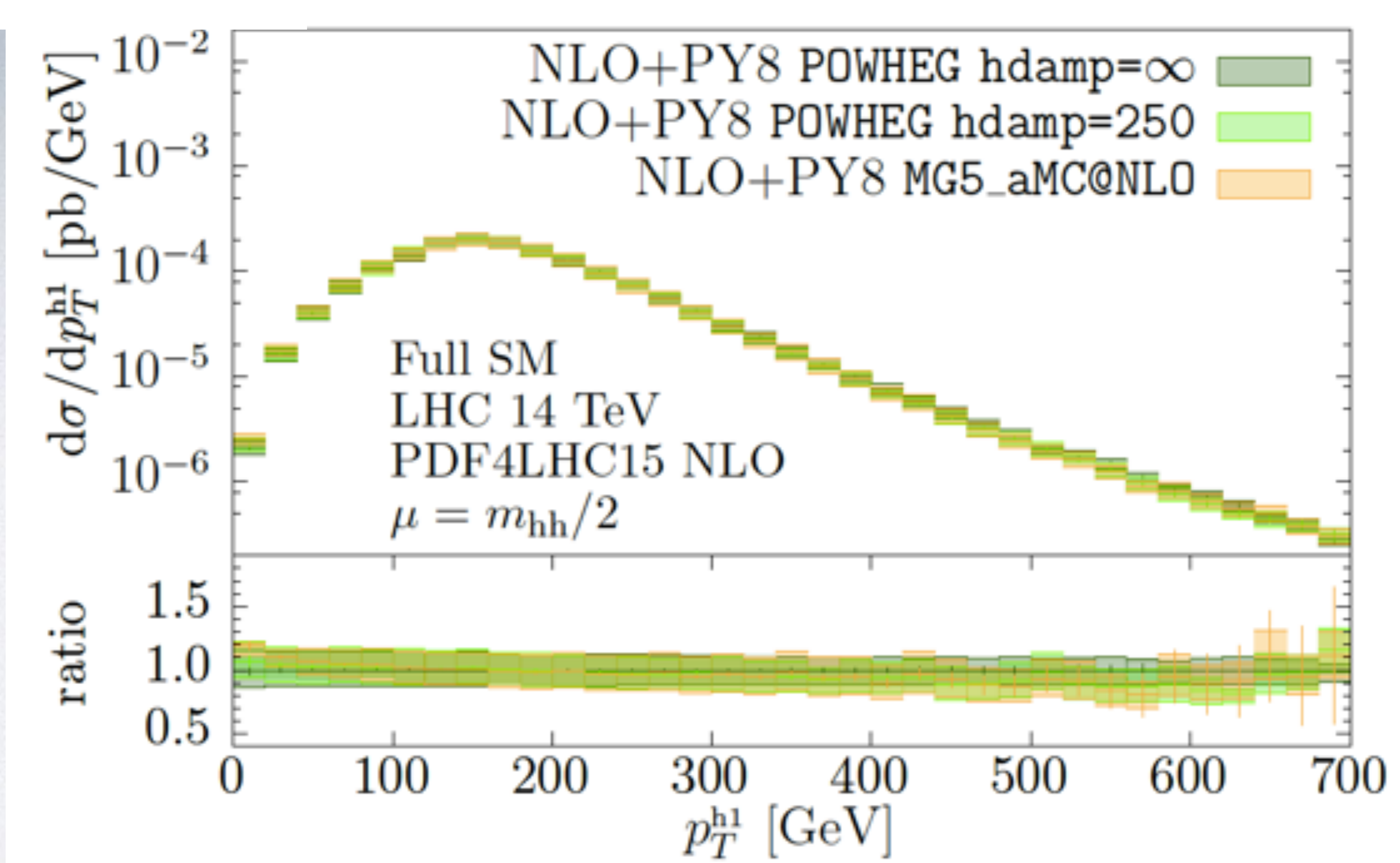

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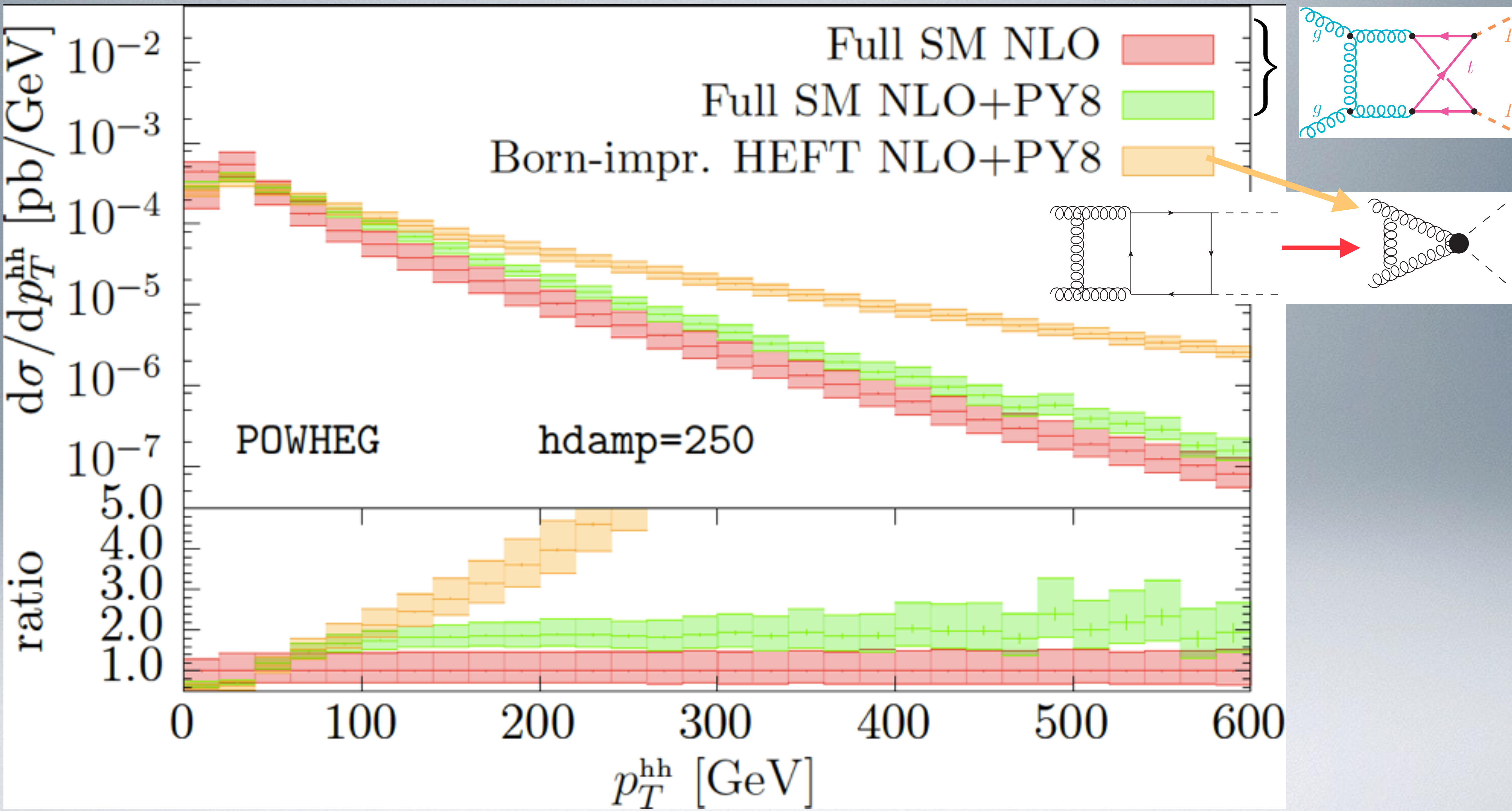
mass effects versus parton shower effects



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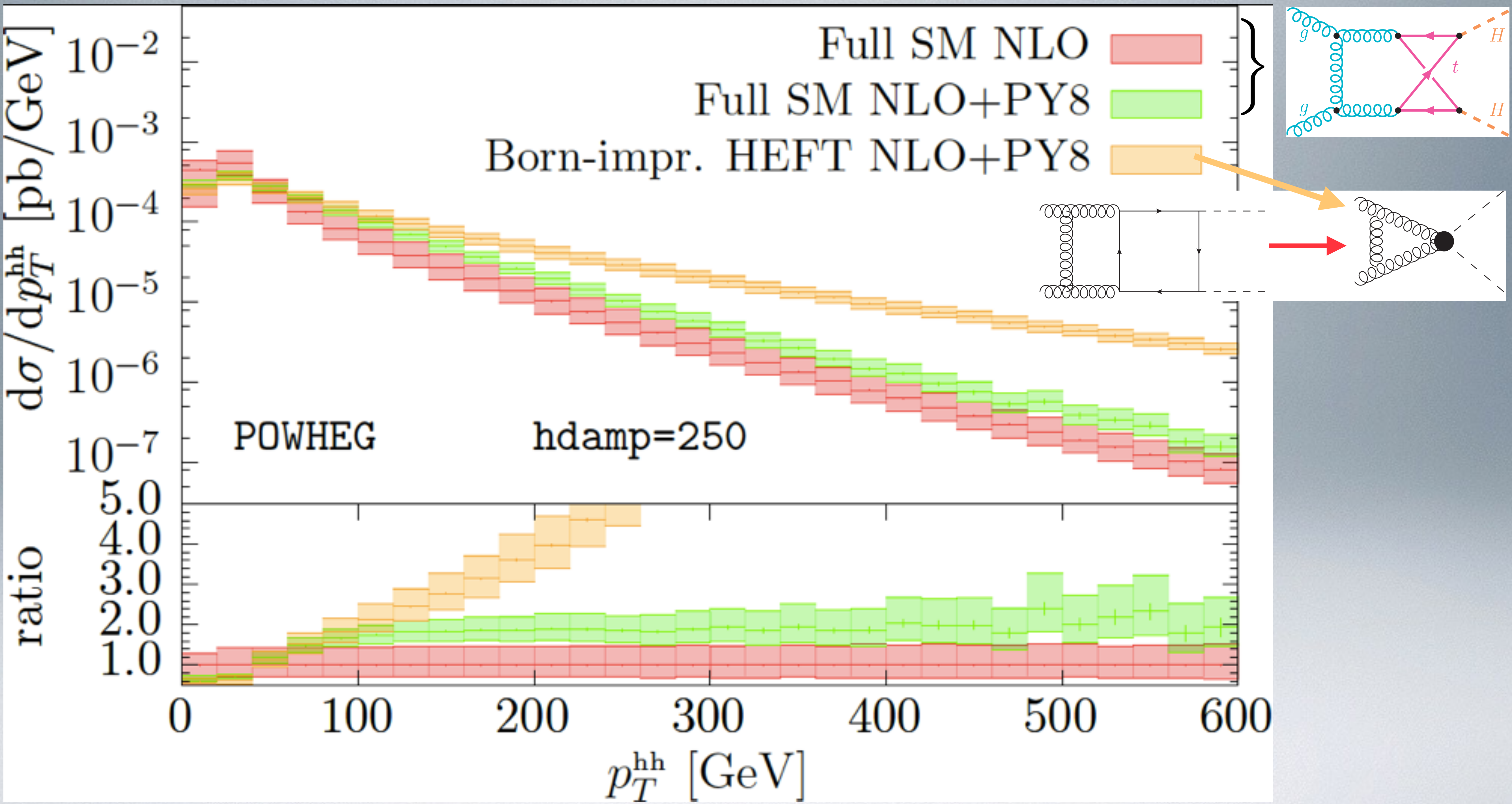


shower effects large but order(s) of magnitude smaller than difference to Born-improved HEFT

combination with Sherpa

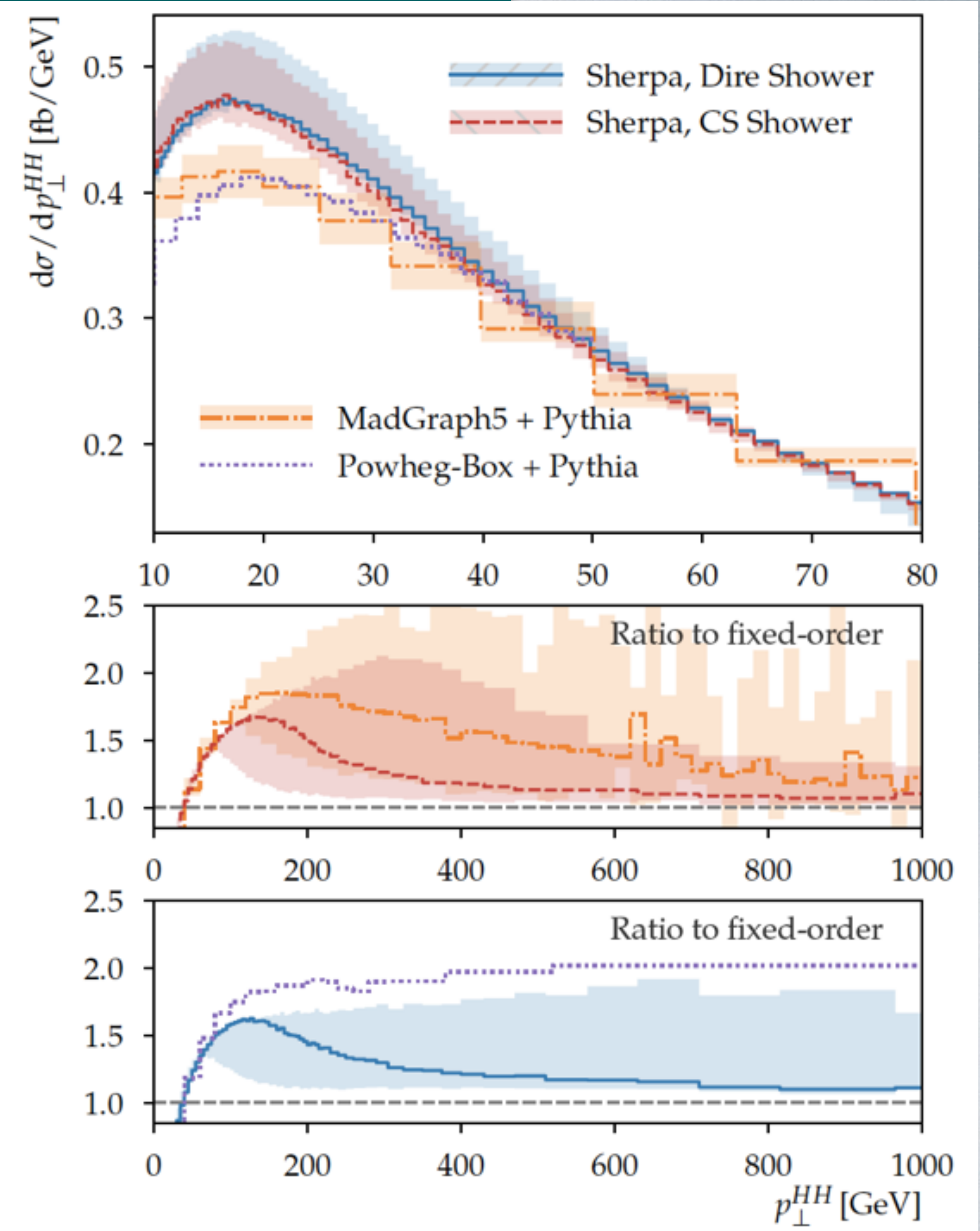
S. Jones,
S. Kuttimalai ‘17

- detailed assessment of parton shower uncertainties

- large $p_\perp^{HH}$ region:

  MG5_aMC@NLO results within (large) uncertainty bands

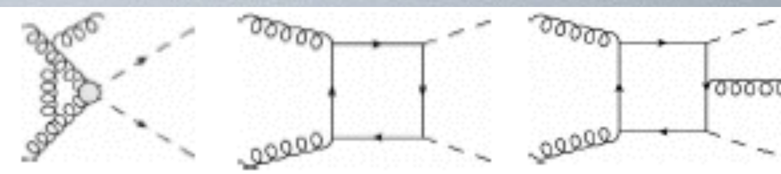
Powheg+PY8 with hdamp=250 not within μ_{PS} variation band; vary hdamp to obtain Powheg uncertainty band



combination with NNLO

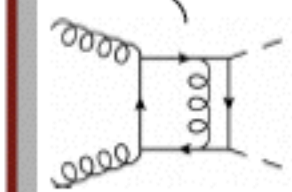
Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli; 1803.02463

Technical ingredients

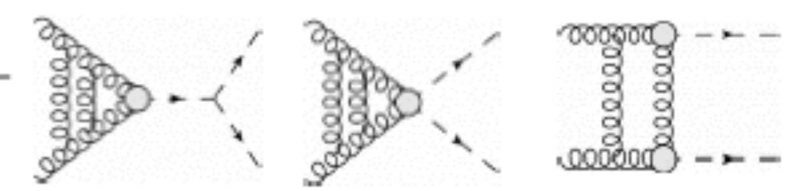


Tree-level and one-loop amplitudes (HEFT and full-M_t) → OpenLoops
[Cascioli, Lindert, Maierhofer, Pozzorini]

Full NLO (two-loop) virtual corrections → two dimensional grid + interpolation
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke, '16]



Analytical results for NNLO two-loop corrections in the HEFT
[de Florian, JM, '13]



NNLO subtraction formalism: q_T-subtraction
[Catani, Grazzini, '07]

Implementation based on public code MATRIX
[Kallweit, Grazzini, Wiesemann, '17]

Javier Mazzitelli

combination with NNLO

three approximations:

- NLO-improved NNLO HEFT **NNLO$_{\text{NLO-i}}$**

$$\frac{d\sigma^{\mathrm{NLO-i.NNLO\,HEFT}}}{dm_{hh}} = \frac{d\sigma_{\mathrm{NLO}}}{dm_{hh}} \times \frac{d\sigma^{\mathrm{HEFT}}_{\mathrm{NNLO}}/dm_{hh}}{d\sigma^{\mathrm{HEFT}}_{\mathrm{NLO}}/dm_{hh}}$$

bin-by-bin rescaling at observable level by NNLO HEFT K-factor

- Born-projected **NNLO$_{\text{B-proj}}$**

only piece where mt dependence enters

reweight each NNLO event by the ratio $\mathrm{Born}^{\mathrm{full}}/\mathrm{Born}^{\mathrm{HEFT}}$

different final state multiplicities in single/double real part → need projection (not unique)

use qT recoil method Catani, De Florian, Ferrera, Grazzini 1507. 06937

- "approximate Full Theory" **NNLO$_{\text{FTapprox}}$**

$\mathcal{O}(\alpha_s^4)$ part: at n-loops in HEFT, X=2-n extra partons: reweight $\mathcal{A}^{(n)}_{\mathrm{HEFT}}(ij \to HH + X)$

with $$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\mathrm{Born}}_{\mathrm{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\mathrm{HEFT}}(ij \to HH + X)}$$

NNLO approximations

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO_{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO_{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\mathrm{NNLO_{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\mathrm{NNLO_{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\mathrm{NNLO_{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$	$\pm 4.6\%$
$\mathrm{NNLO_{FTapprox}/NLO}$	1.118	1.116	1.096	1.067

considerable reduction of scale uncertainties

M_t uncertainties:
half the difference between NNLO_FTapprox and NNLO_NLO-improved

Status now

	$\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]		$\sigma_{\rm NNLO}$[fb]
HEFT	$17.07^{+30.9\%}_{-22.2\%}$	$31.93^{+17.6\%}_{-15.2\%}$		$37.52^{+5.2\%}_{-7.6\%}$
			NLO-i. HEFT	$38.66^{+5.3\%}_{-7.7\%}$
B-i. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$		
			Born-proj. HEFT	$39.58^{+1.4\%}_{-4.7\%}$
$\rm FT_{approx}$	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$		$36.69^{+2.1\%}_{-4.9\%}$
full m_t dep.	$19.85^{+27.6\%}_{-20.5\%}$	$32.91^{+13.6\%}_{-12.6\%}$		

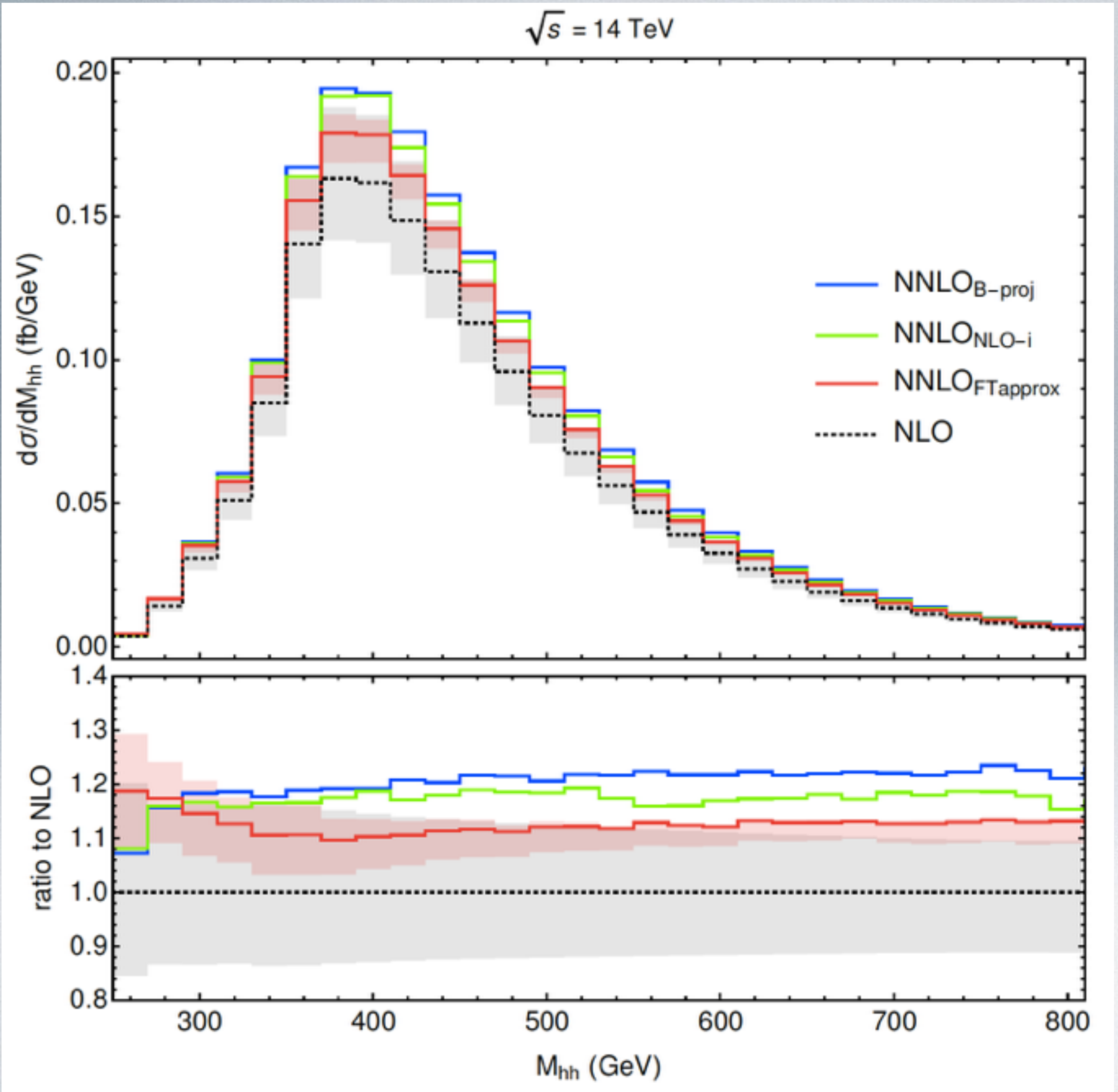
most advanced perturbative prediction

remember YR4: $\sigma'_{NNLL} = \sigma_{NNLL} + \delta_t\, \sigma^{\rm HEFT}_{NLO} = 39.64^{+4.4\%}_{-6.0\%}$

$\frac{\sigma_{\rm NNLL'} - \sigma^{\rm full}_{\rm NLO}}{\sigma^{\rm full}_{\rm NLO}}$: 20.5%

$\frac{\sigma^{\rm FTapprox}_{\rm NNLO} - \sigma^{\rm full}_{\rm NLO}}{\sigma^{\rm full}_{\rm NLO}}$: 11.5%

NNLO: Mhh distribution



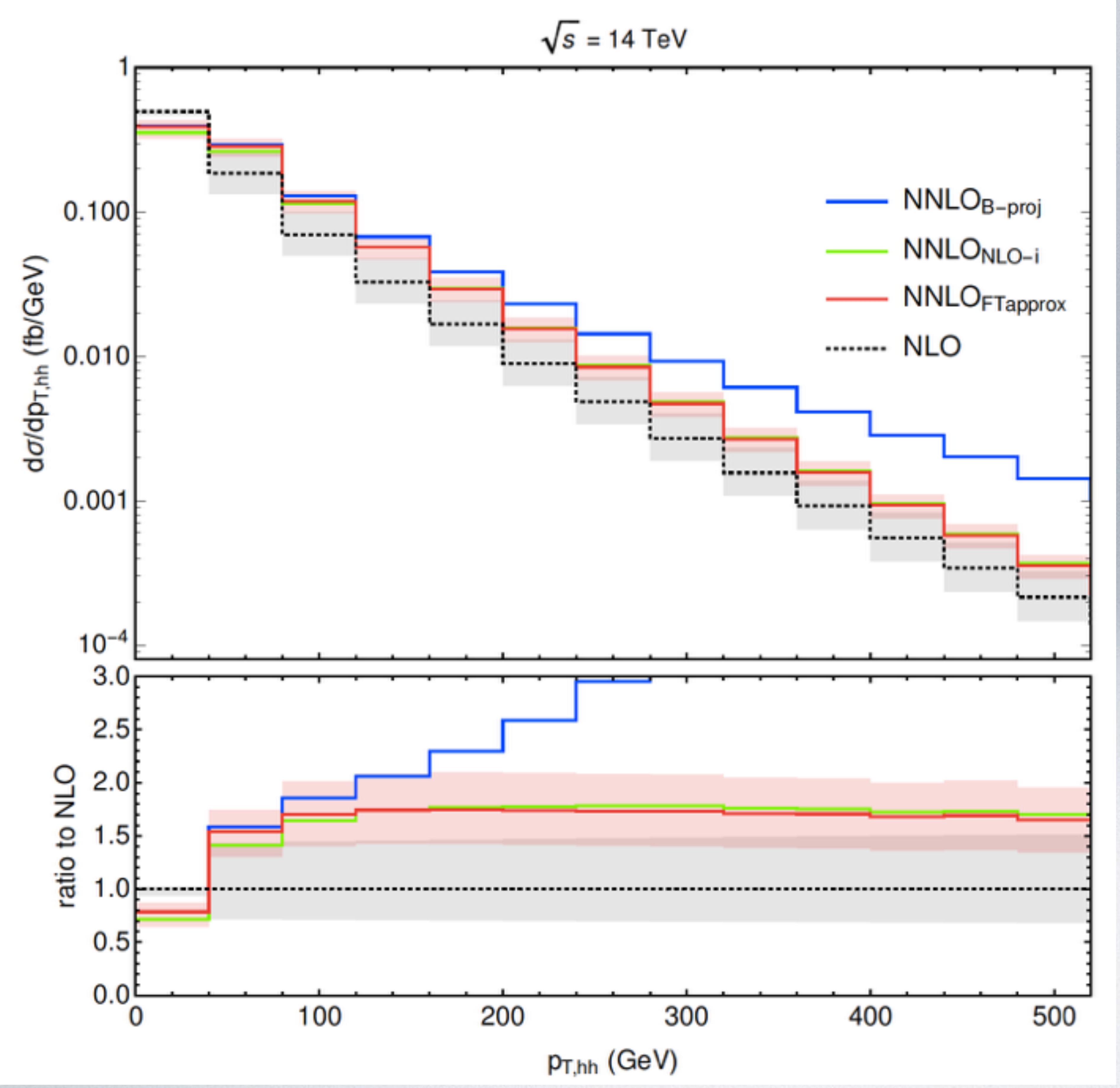
FTapprox:

mostly overlaps with NLO uncertainty band

larger corrections at production threshold

scale uncertainties reduced

pT,hh distribution



NLO is first non-trivial order for pT,hh

⟶ larger corrections and uncertainties than for Mhh

similar pattern as at NLO:

Born-projected has wrong scaling behaviour in the tail

HH in non-linear effective field theory

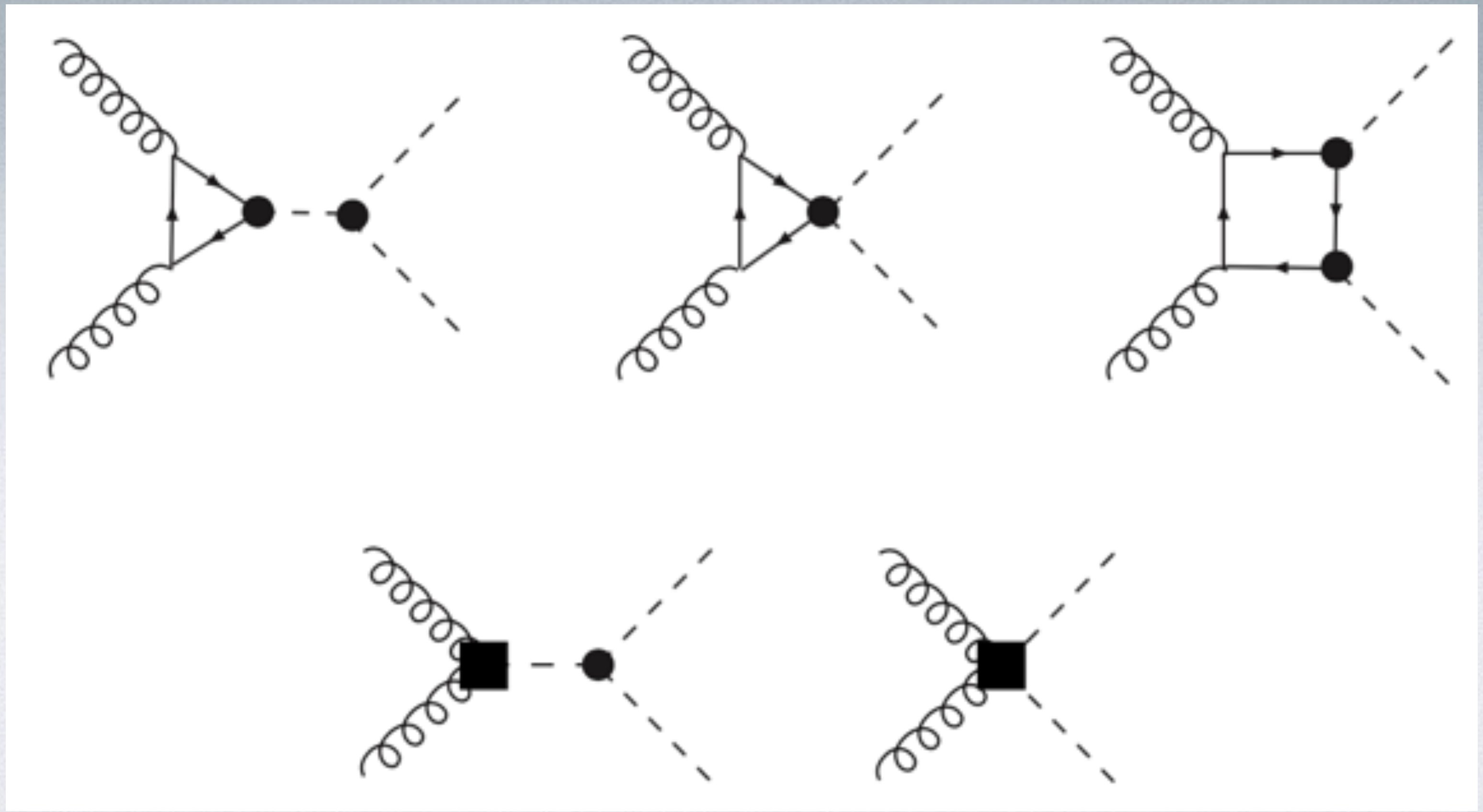
G. Buchalla, M. Capozi, A. Celis, GH, L. Scyboz

effective Lagrangian "electroweak chiral Lagrangian"

$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

5 modified couplings; Higgs field is EW singlet

LO diagrams



HH within EFT

previous higher order calculations based on $m_t \to \infty$ limit

- effects of dimension 6 operators in NLO Born-improved HEFT
  Gröber, Mühlleitner, Spira, Streicher '15
- including CP-violating operators
  Gröber, Mühlleitner, Spira '17
- effects of dimension 6 operators in NNLO rescaled HEFT
  De Florian, Fabre, Mazzitelli '17:

Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	$-\frac{1.6}{3}$	-0.2
3	1.0	1.0	-1.5	0.0	$\frac{0.8}{3}$
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	$\frac{1.6}{3}$	$\frac{1.0}{3}$
6	2.4	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
7	5.0	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
9	1.0	1.0	1.0	-0.4	-0.2
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	$\frac{2.0}{3}$	$\frac{1.0}{3}$
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

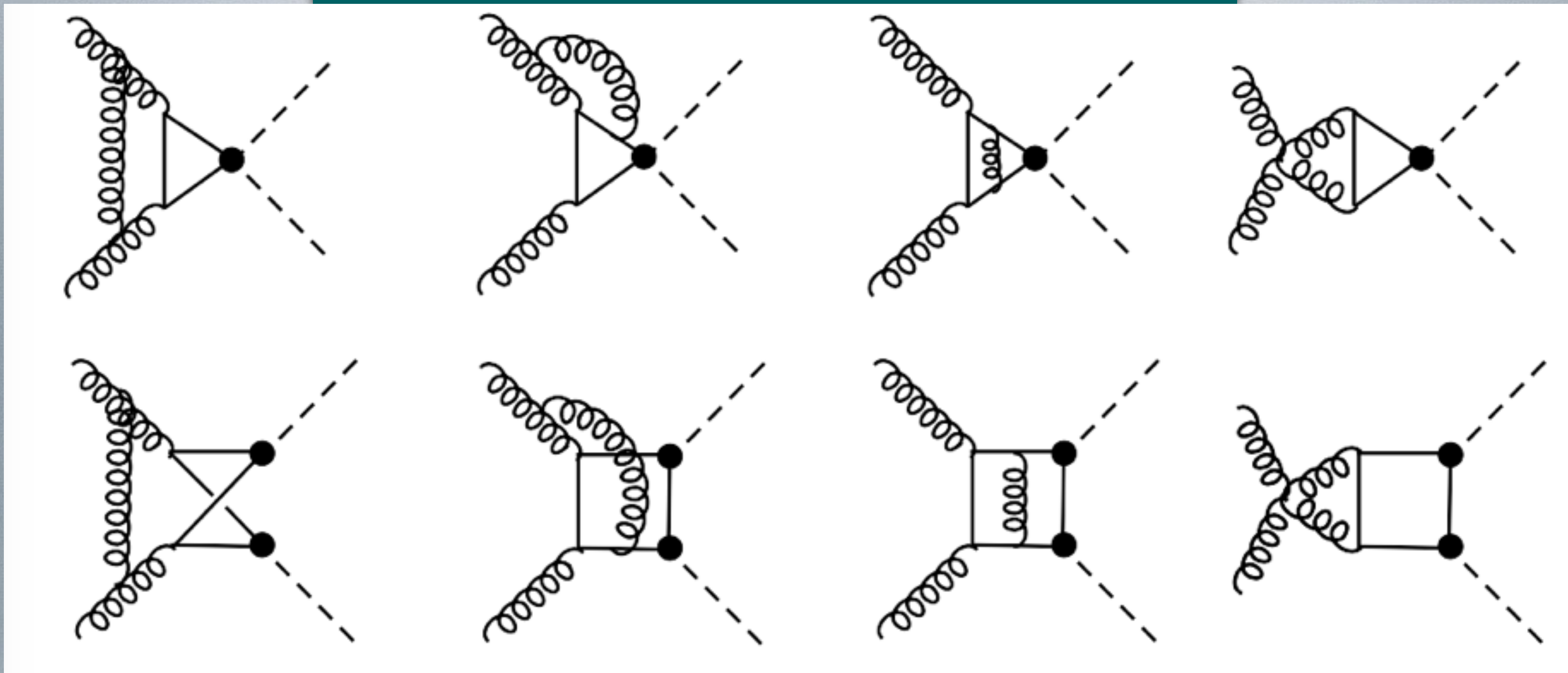
in preparation: [Buchalla, Capozi, Celis, GH, Scyboz]

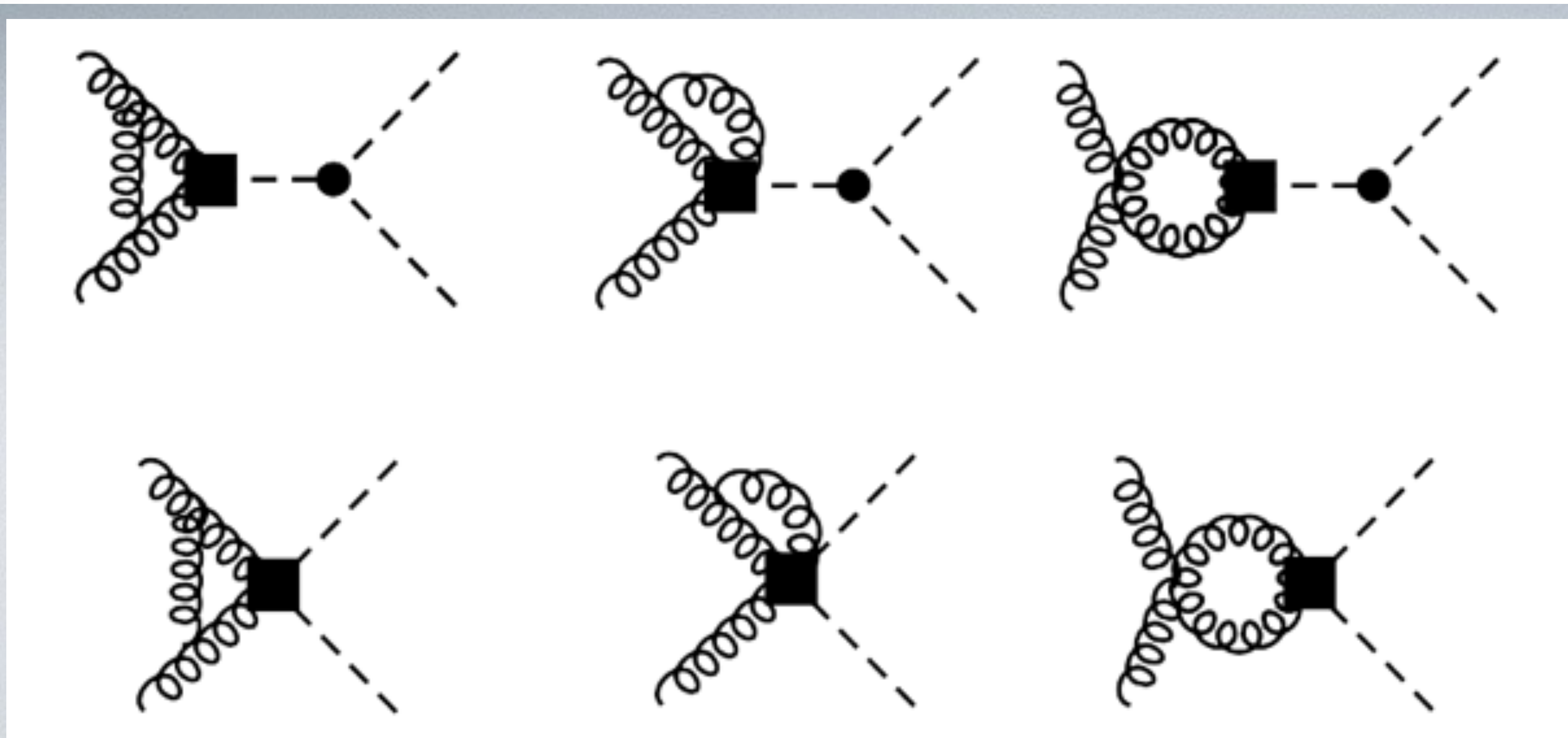
- effects of operators from non-linear effective Lagrangian at NLO QCD with full top mass dependence

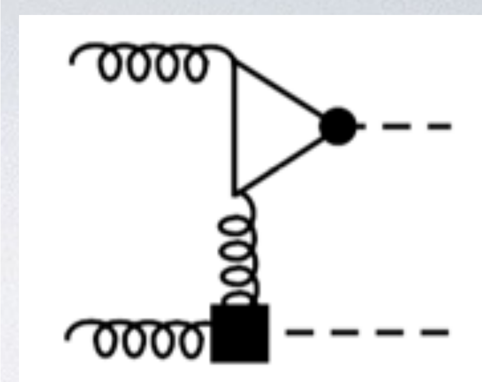
using benchmark points characterising "clusters" of BSM scenarios

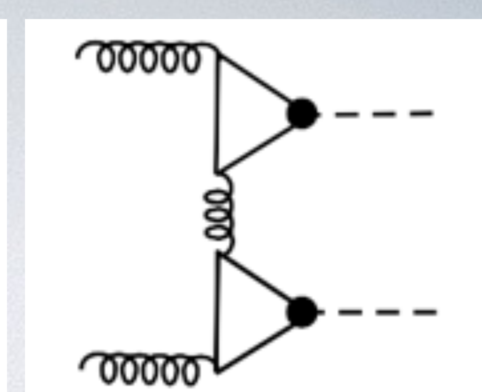
Carvalho, Dall'Osso, Dorigo, Goertz, Gottardo, Tosi '15;
Carvalho, Goertz, Mimasu, Gouzevitch, Aggarwal '17

virtual corrections: example diagrams

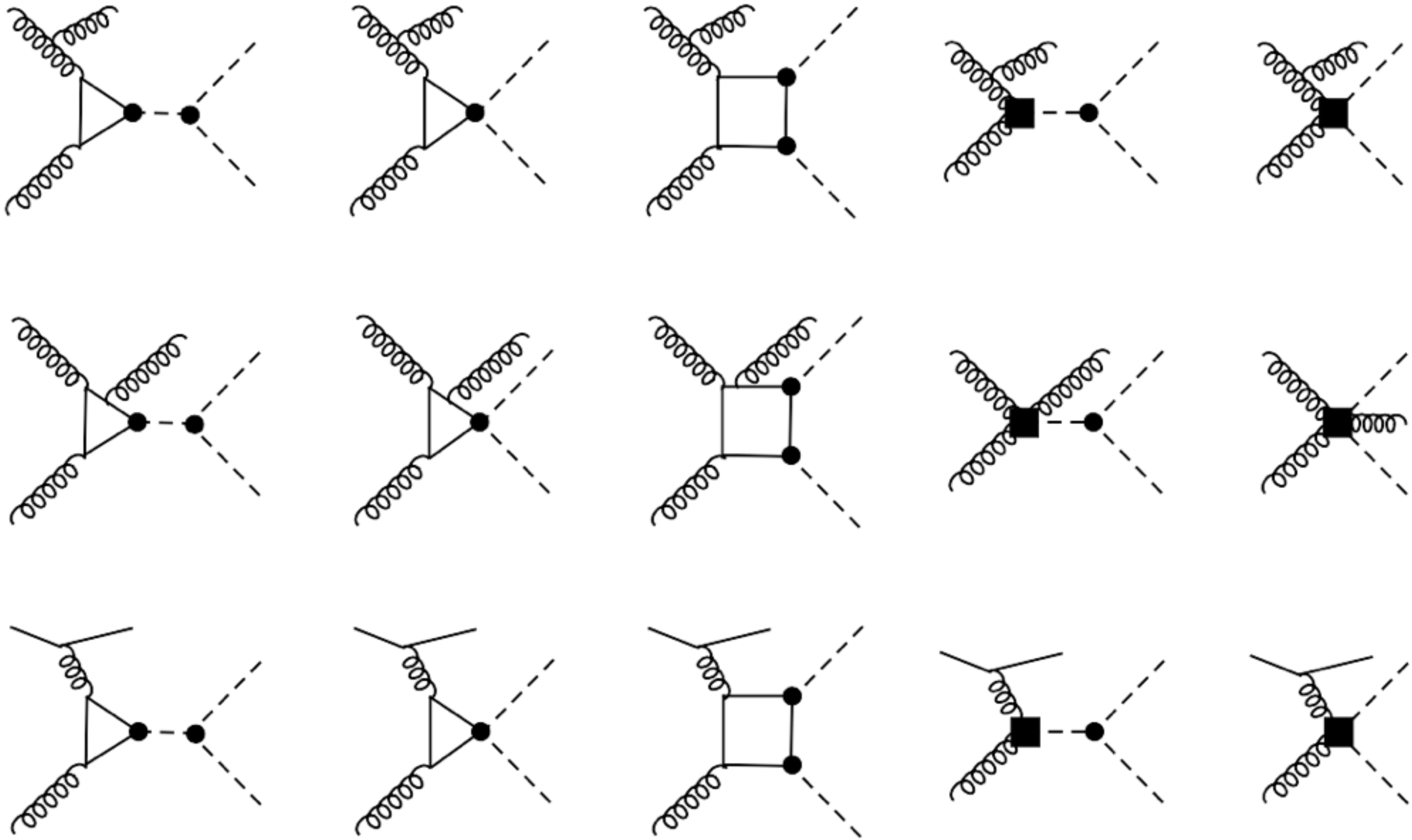




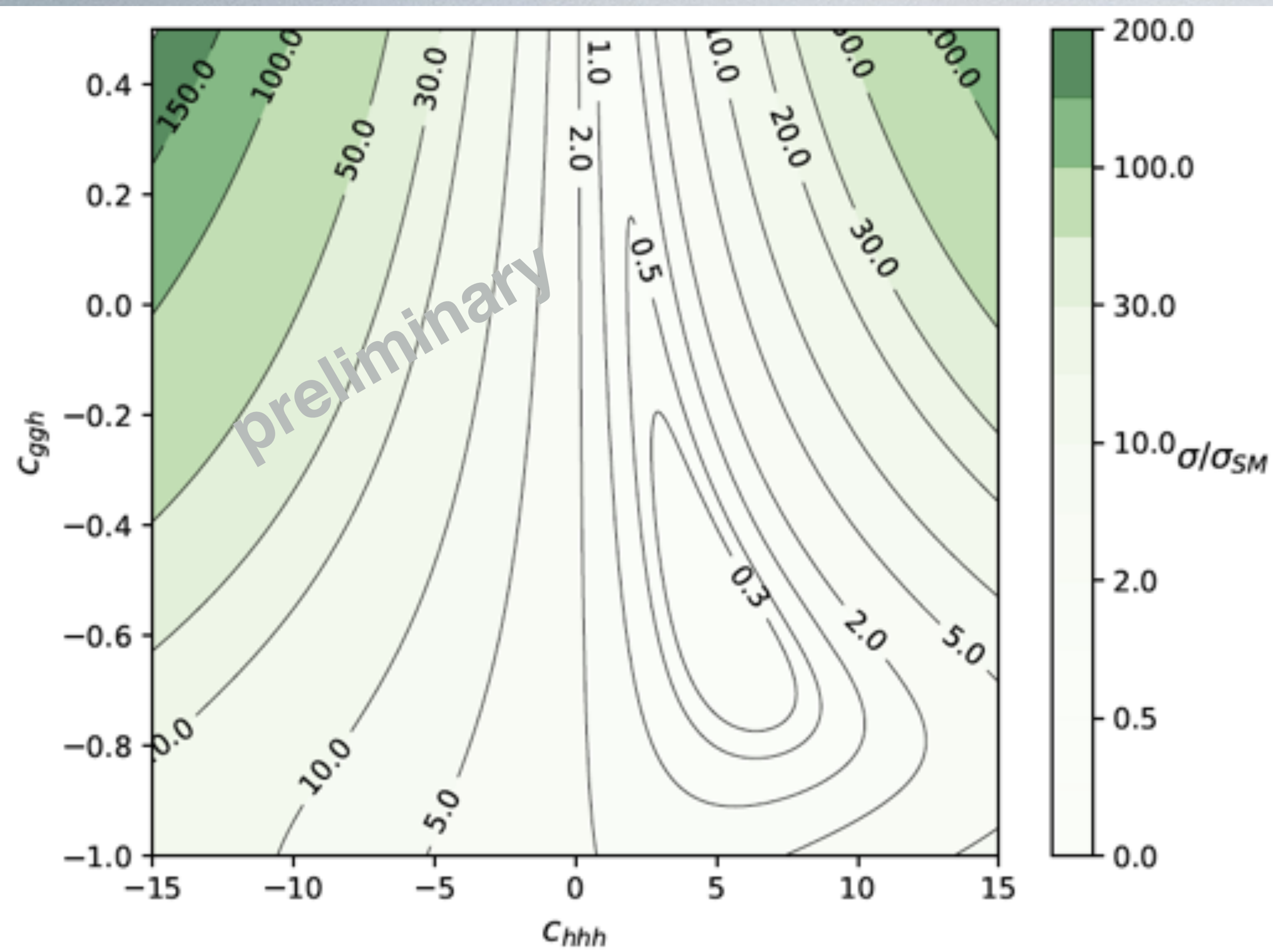




real corrections: example diagrams



results: heat maps



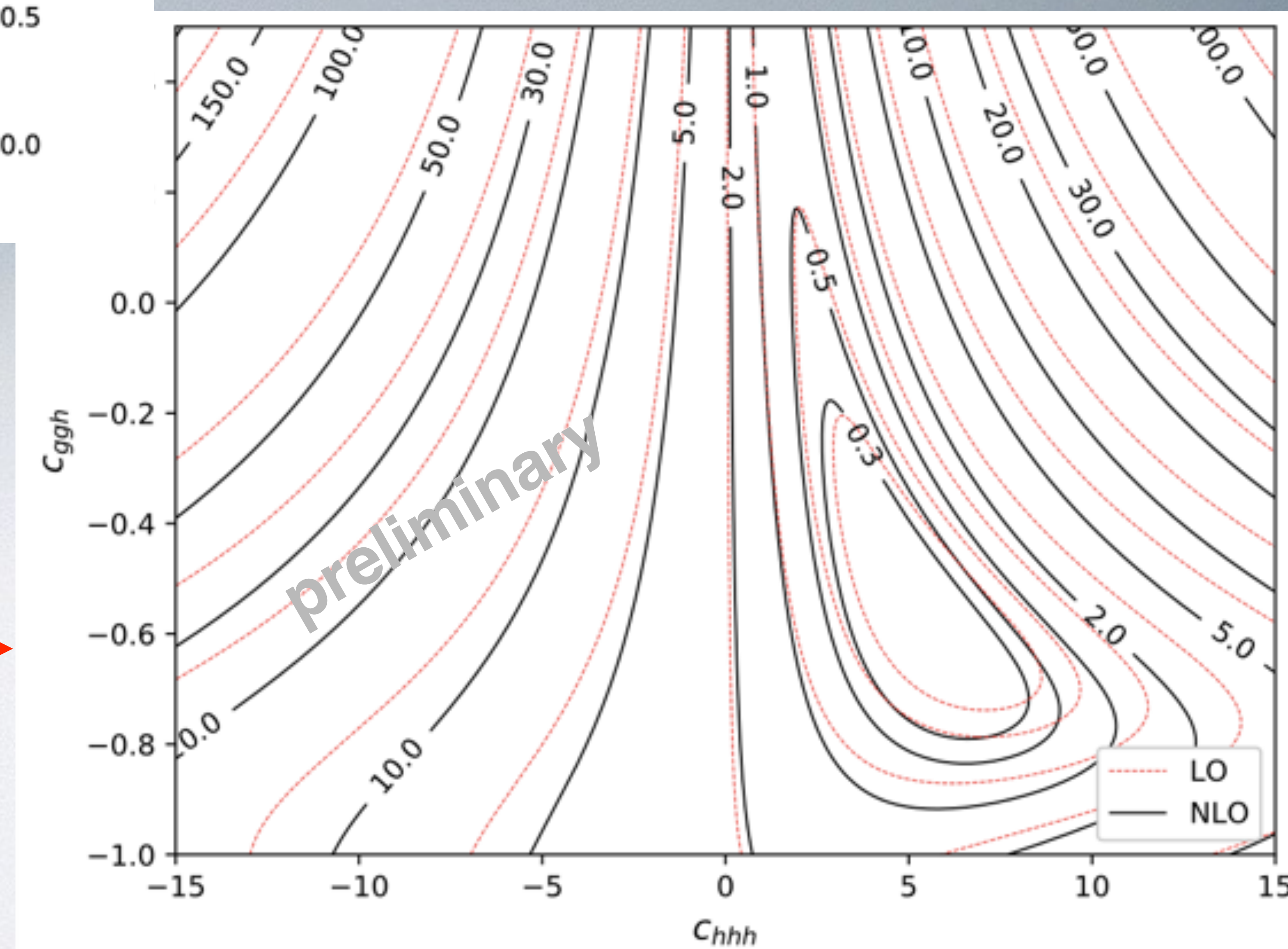
vary c_{hhh}, c_{ggh}

fix $c_t = 1, c_{tt} = c_{gghh} = c_{ggh} = 0$

chosen parameter ranges
consistent with constraints
from EW precision observables

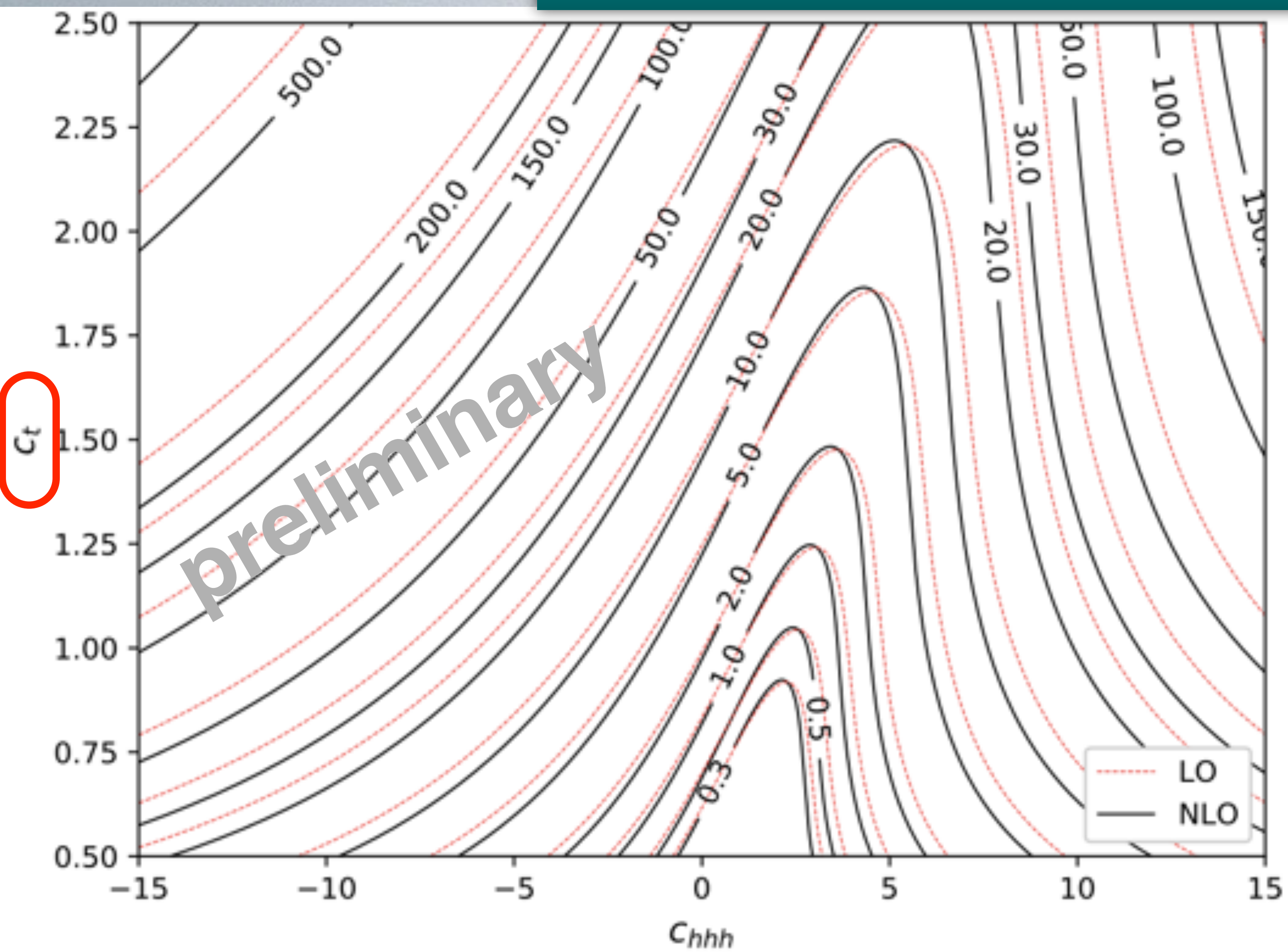
BSM effects can be very large

distortions due to
NLO QCD corrections



Alejandro Celis

results: heat maps

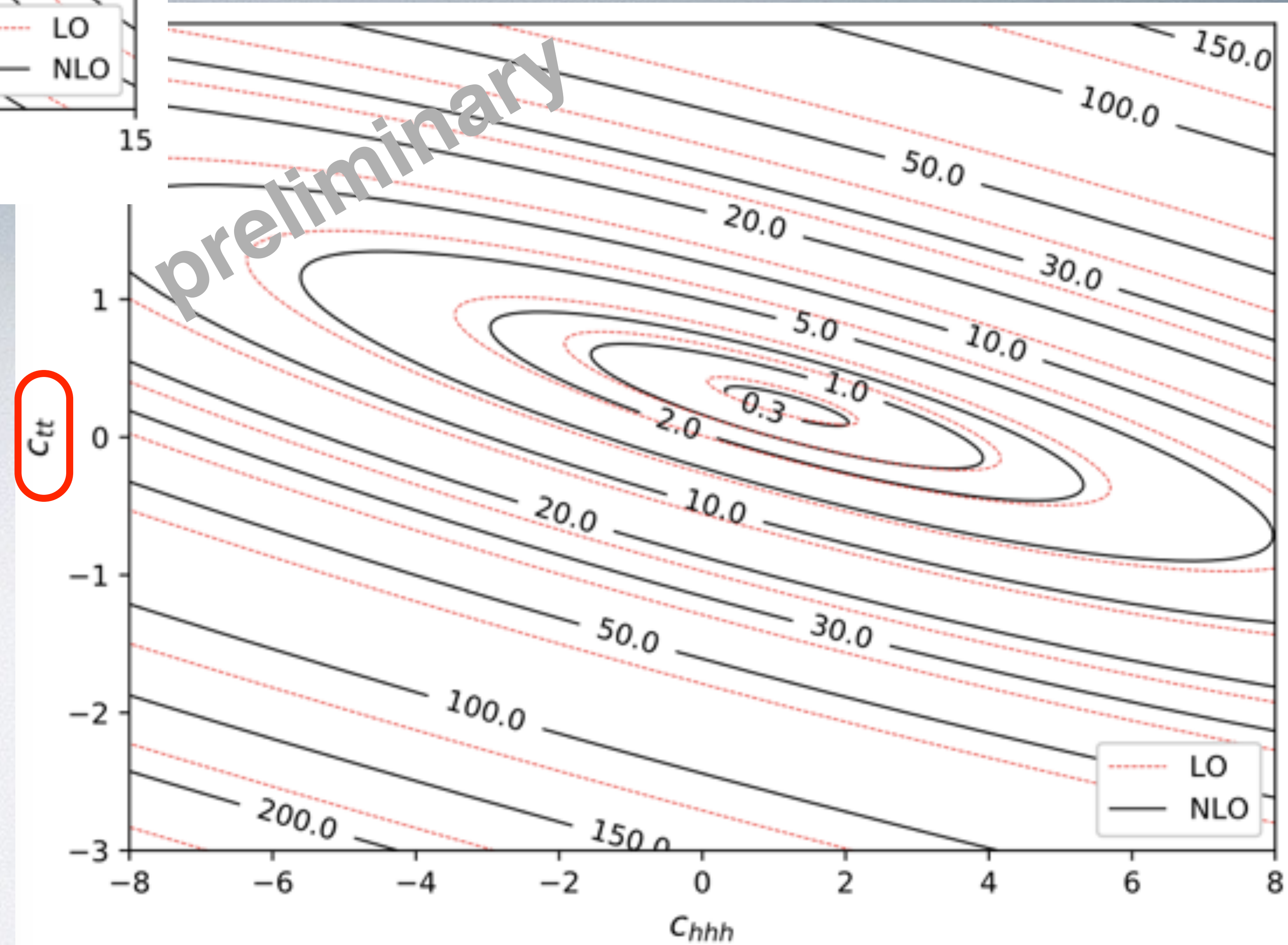


$\sigma/\sigma_{\rm SM}$

other parameters fixed to SM values

large c_t and negative c_{hhh} can lead to huge enhancements

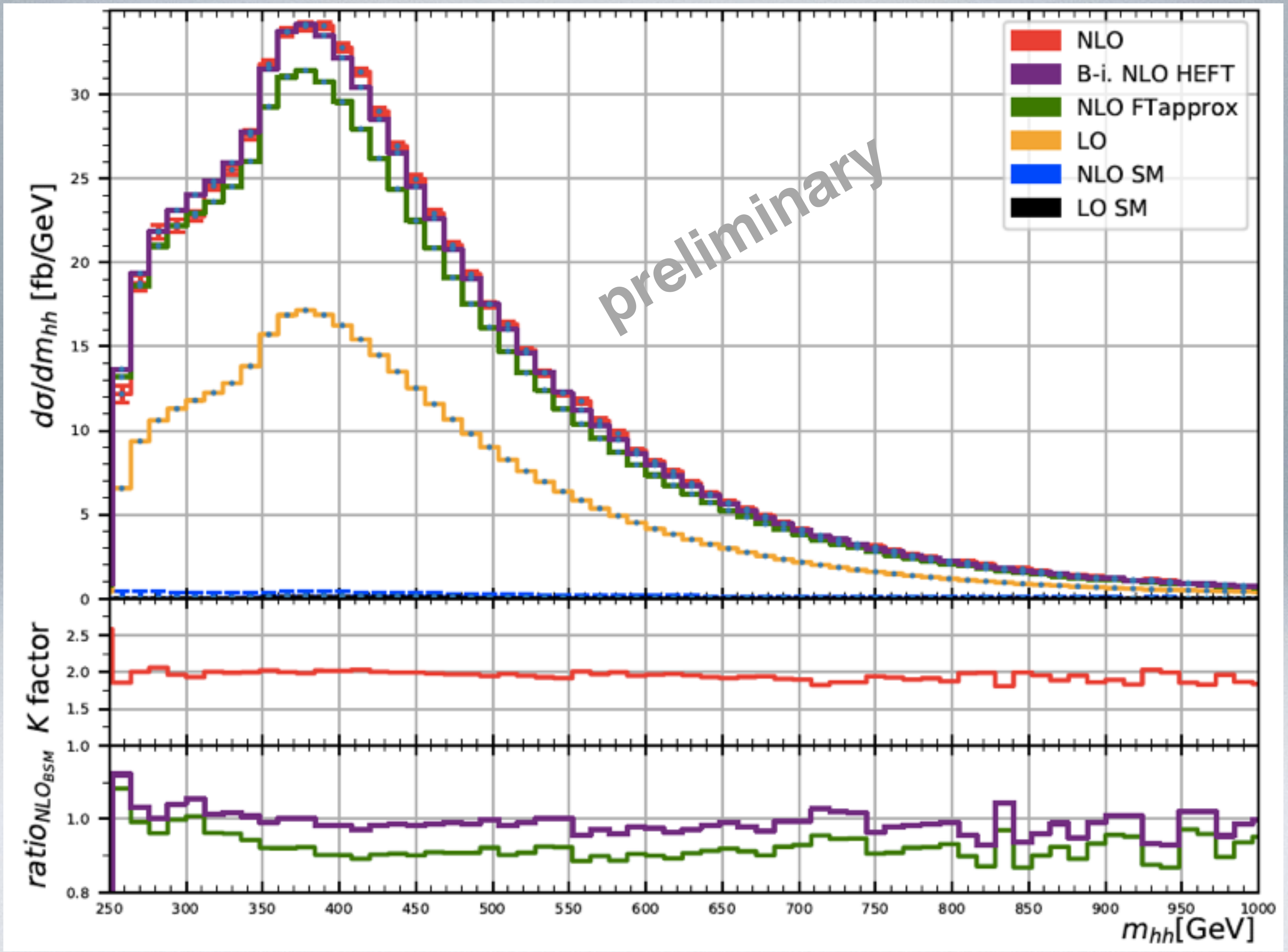
small changes in c_{tt} can lead to substantial differences



Alejandro Celis

results: distributions

benchmark 4 $c_{hhh} = -3.5, c_t = 1.5, c_{tt} = -3, c_{ggh} = 0, c_{gghh} = 0$

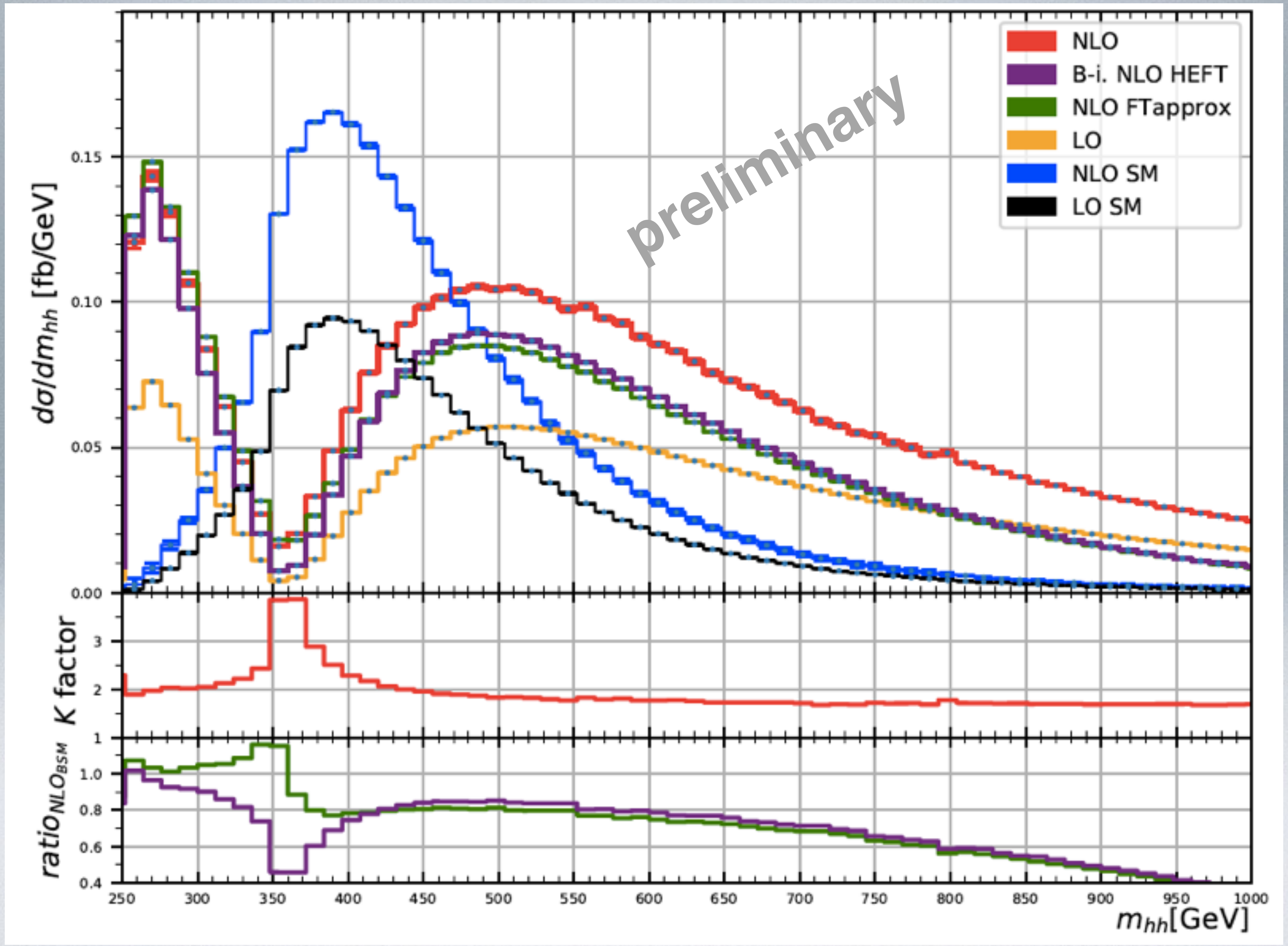


$\sigma^{\mathrm{BSM}}_{NLO}/\sigma^{\mathrm{SM}}_{NLO} \simeq 270$

Matteo Capozi

results: distributions

benchmark 5 $c_{hhh} = 1, c_t = 1, c_{tt} = 0, c_{ggh} = 8/15, c_{gghh} = 1/3$



$\sigma_{NLO}^{\rm BSM}/\sigma_{NLO}^{\rm SM} \simeq 1.24$ shape very different

Matteo Capozi

Summary

- HH NLO generators with full mass dependence available

  GH, S.Jones, M.Kerner, G.Luisoni, E.Vryonidou '17

  POWHEG-BOX, MadGraph5_aMC@NLO

  Sherpa: S. Jones, S. Kuttimalai '17

- combined NNLO HEFT and full NLO to most advanced perturbative prediction

  Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18

- remaining top mass uncertainty estimated to be at the few percent level

- HH@NLO QCD within non-linear EFT framework

  G.Buchalla, M.Capozi, A.Celis, GH, L.Scyboz; to appear

  - BSM effects can be very large
  - BSM effects can be small on total cross section but distort mHH distribution substantially

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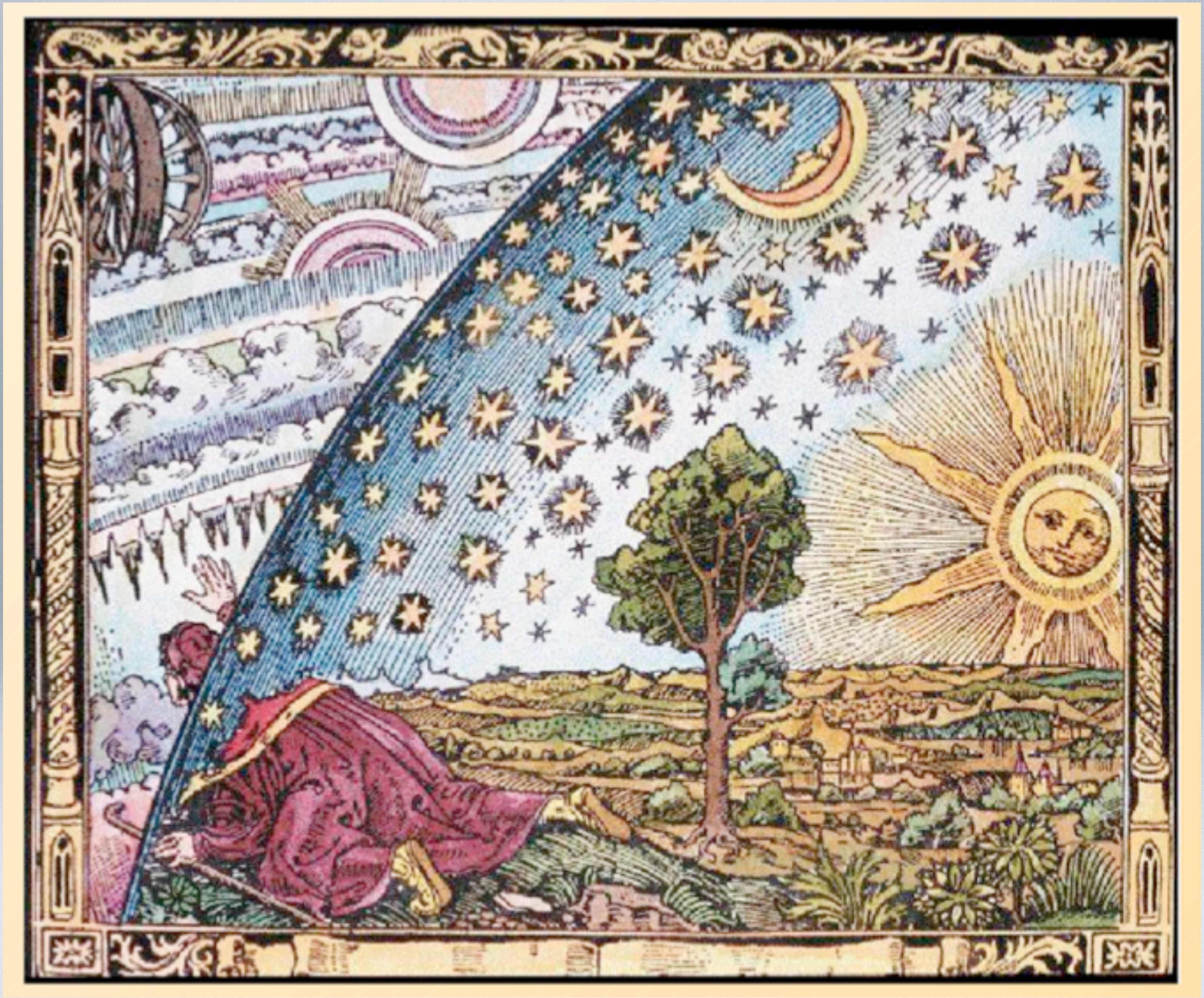
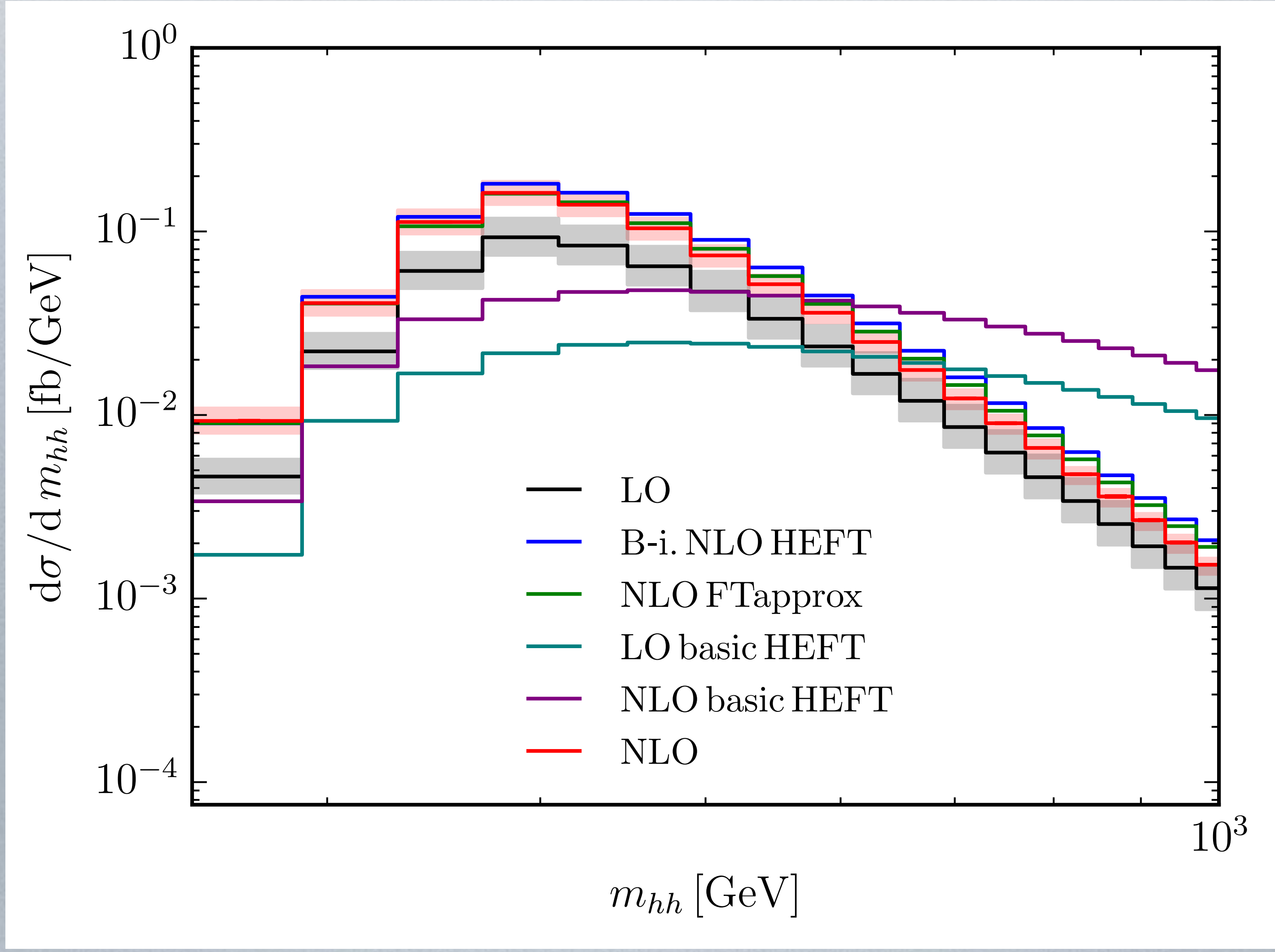
There is room for surprises in the Higgs sector!



BACKUP SLIDES

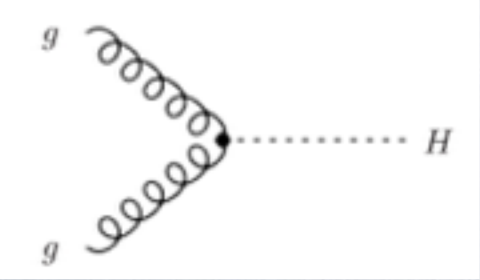
scaling behaviour



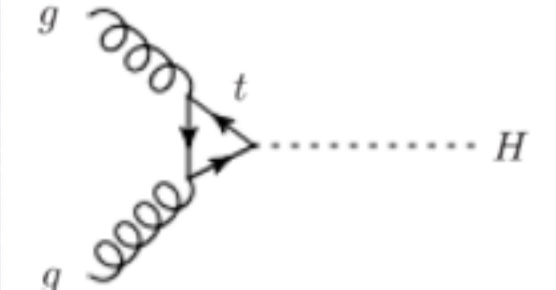
$$\frac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}^{-3}$$ i.e. partonic cross section scales as $\hat{s}^{-1}$

HEFT approximation: $$\frac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}$$ i.e. $\hat{\sigma} \sim \hat{s}$

similar for H+jet(s): Greiner, Höche, Luisoni, Schönherr, Winter ‘16
see also Marzani et al. ’08; Caola, Forte, Marzani, Muselli, Vita ’16

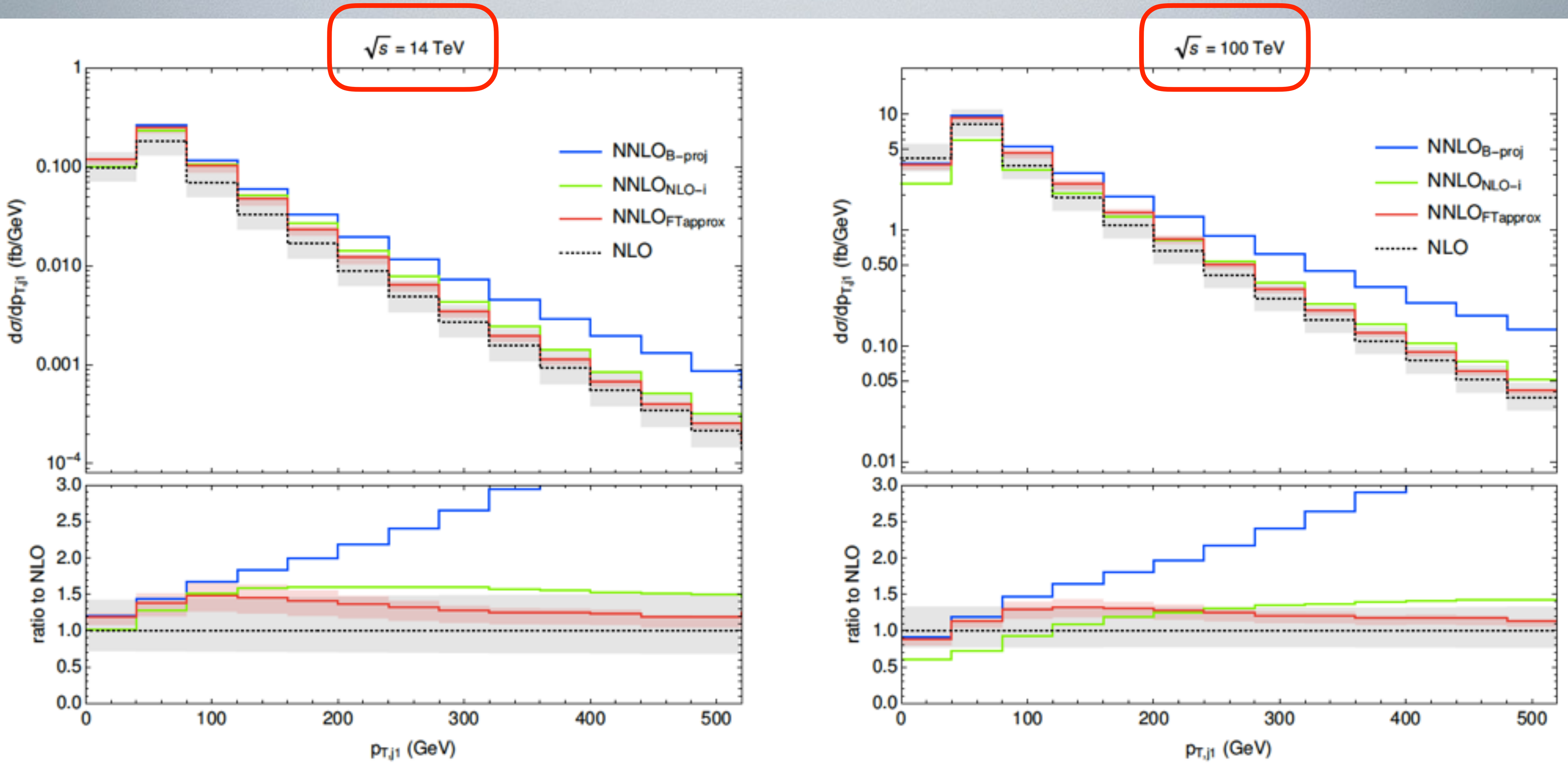


$$d\sigma/dp_{T,h}^2 \to (p_{T,h}^2)^{-1}$$



$$d\sigma/dp_{T,h}^2 \to (p_{T,h}^2)^{-2}$$

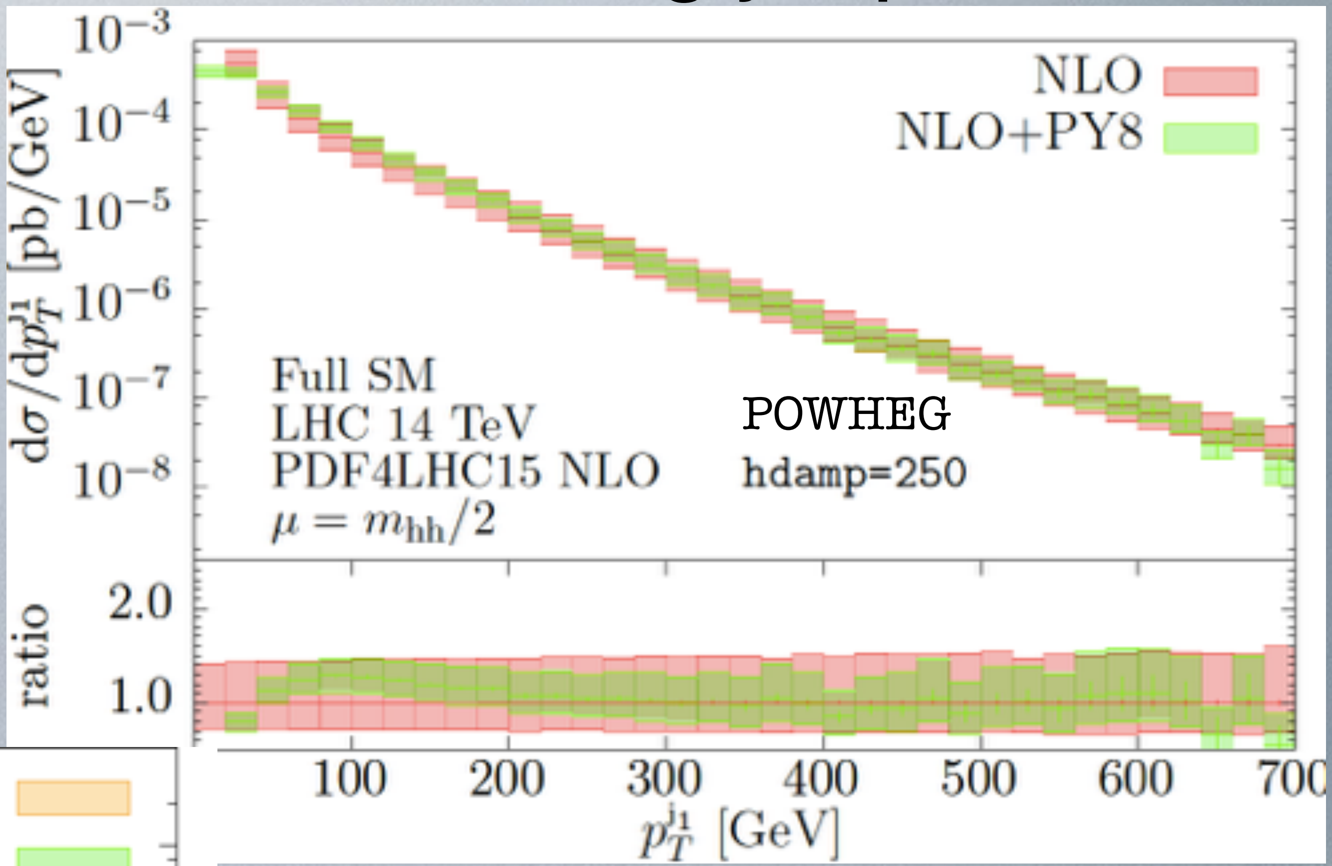
leading jet distribution



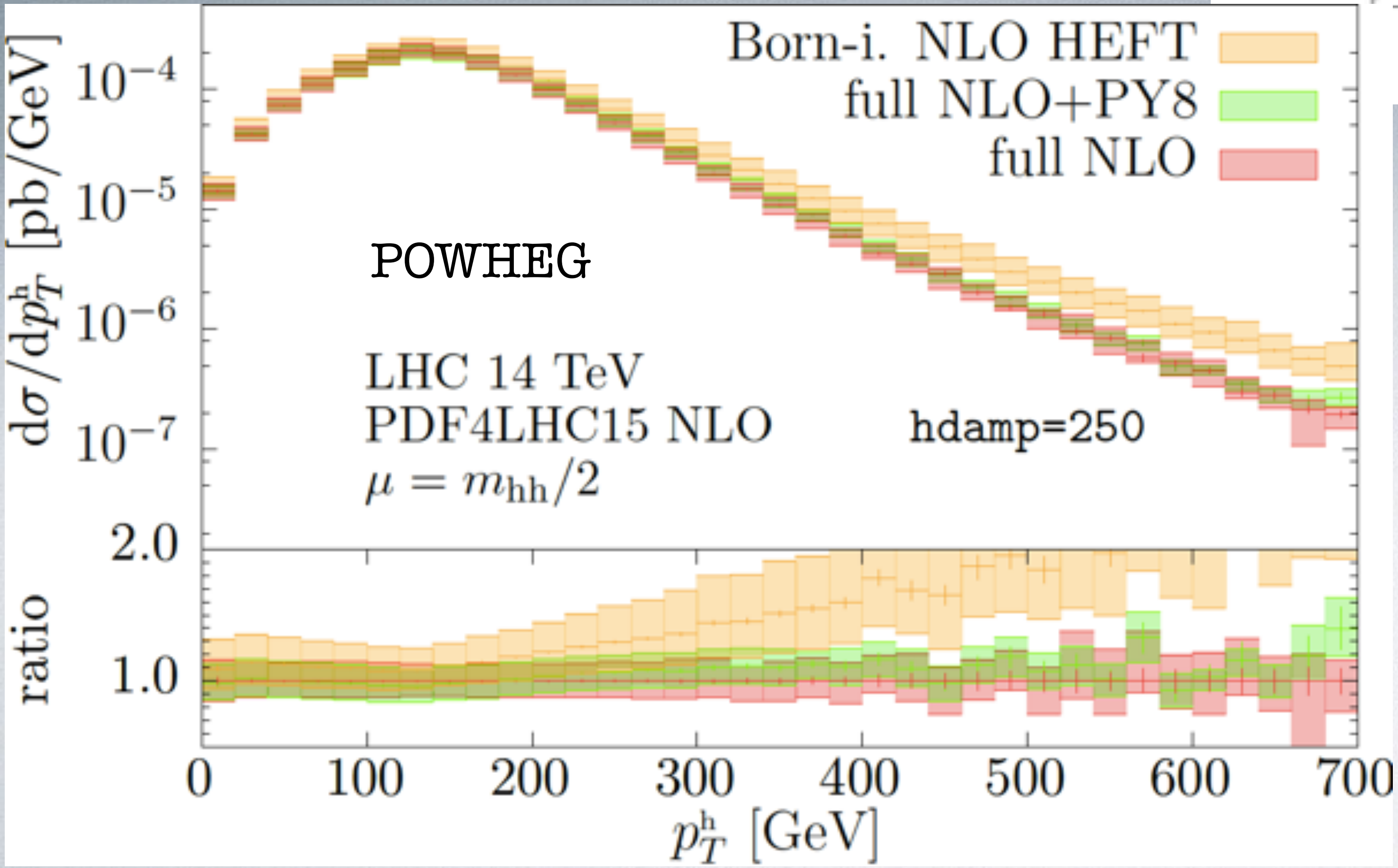
differences between the approximations more pronounced at 100 TeV

other observables

leading jet pT

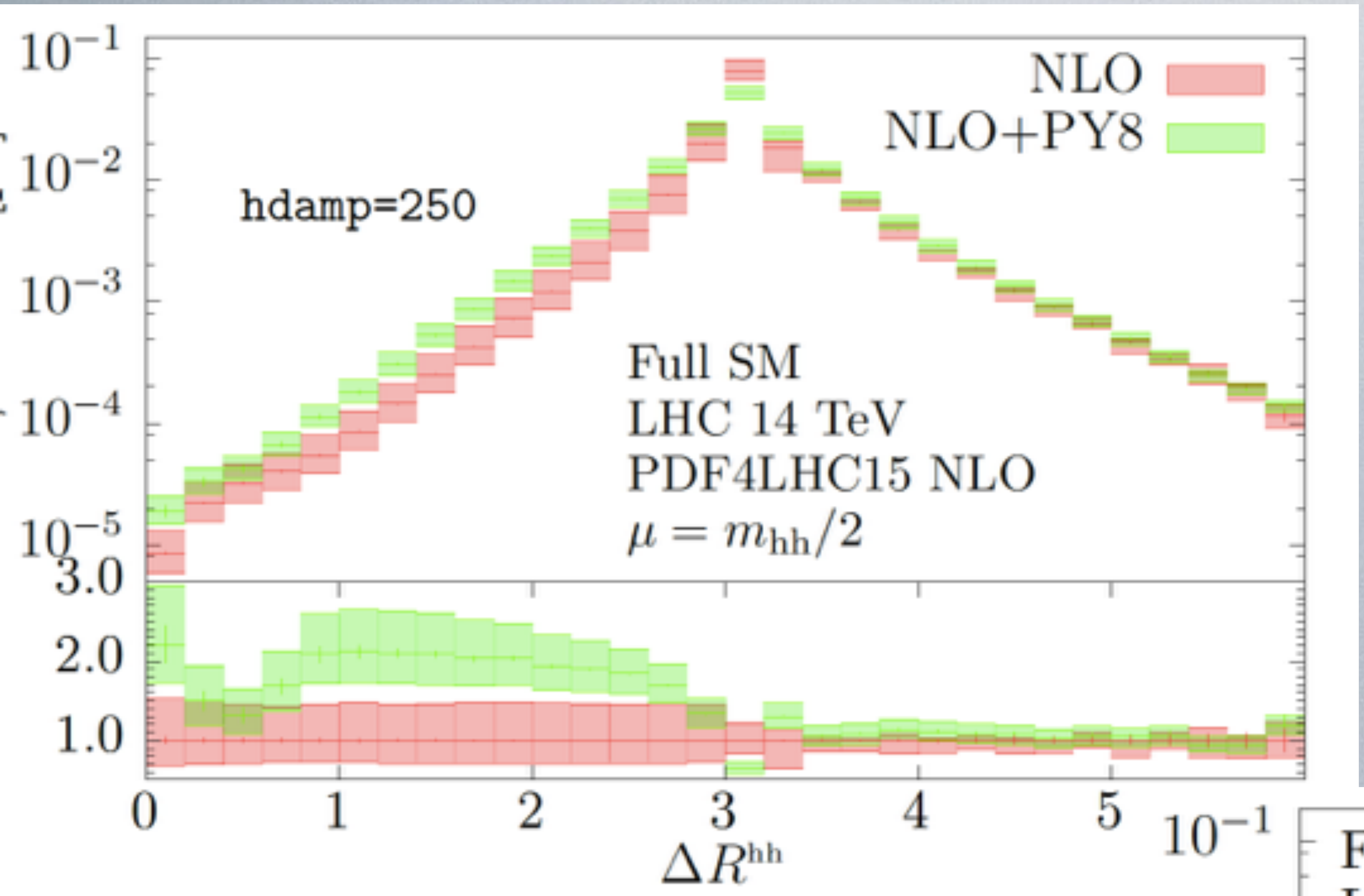


pT of one Higgs boson



Born-improved HEFT:
reweighting at event level

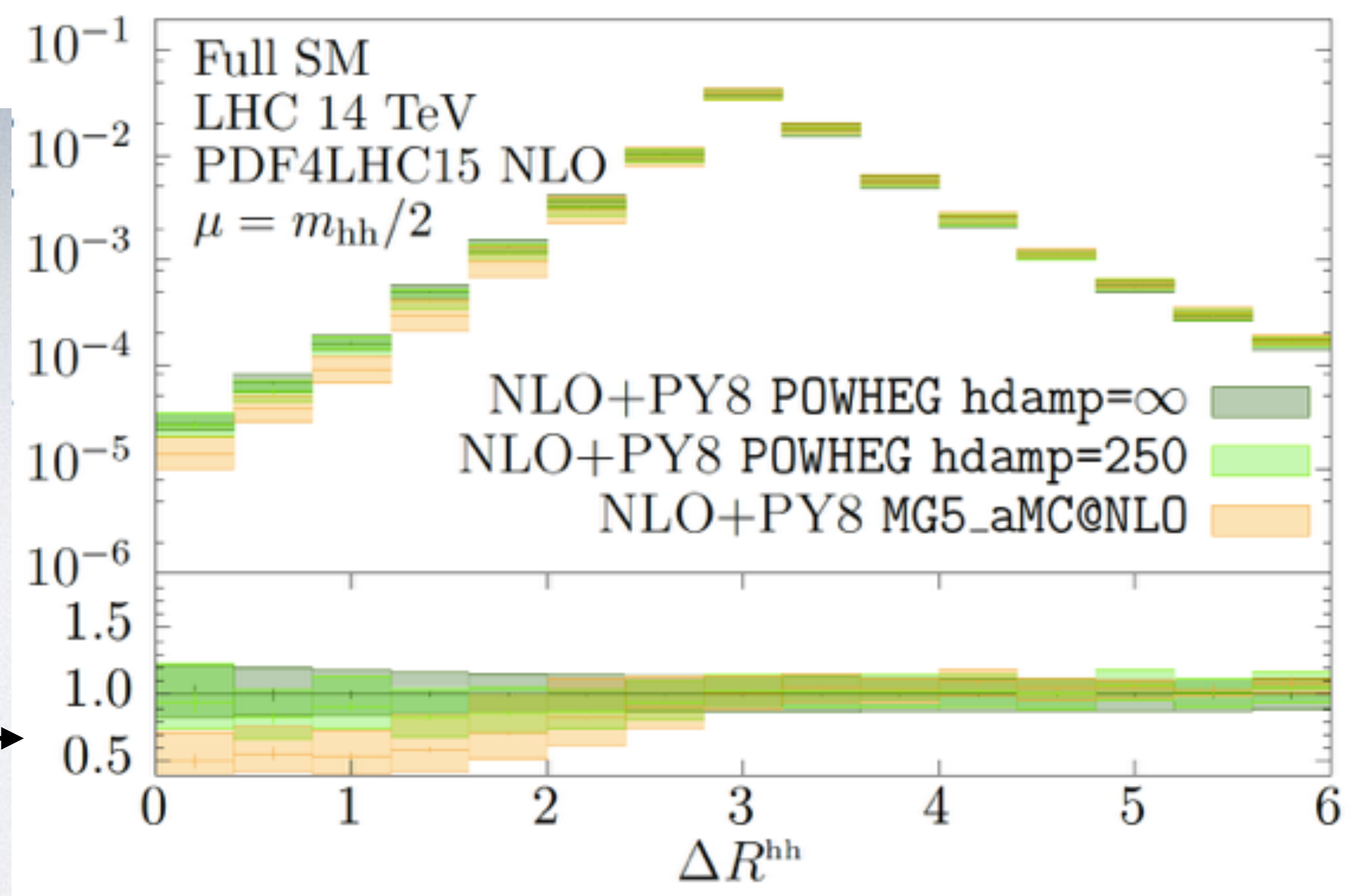
compare fixed order and showered results



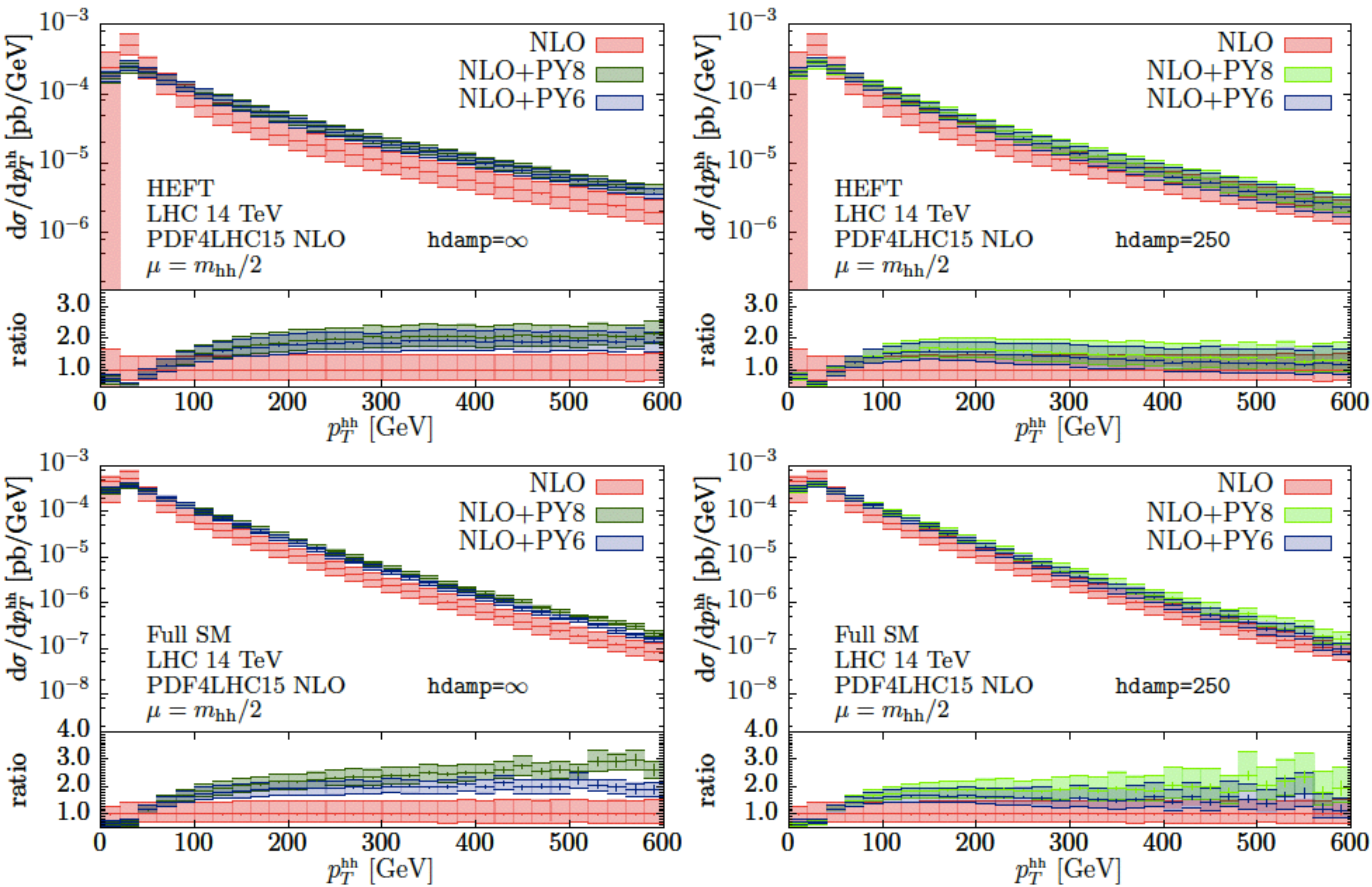
$$\Delta R^{hh} = \sqrt{(\eta_1 - \eta_2)^2 + (\Phi_1 - \Phi_2)^2}$$

for $\Delta R^{hh} < \pi$ fixed order is only "LO accurate"

differences due to different matching procedures visible →



compare Pythia6 and Pythia8



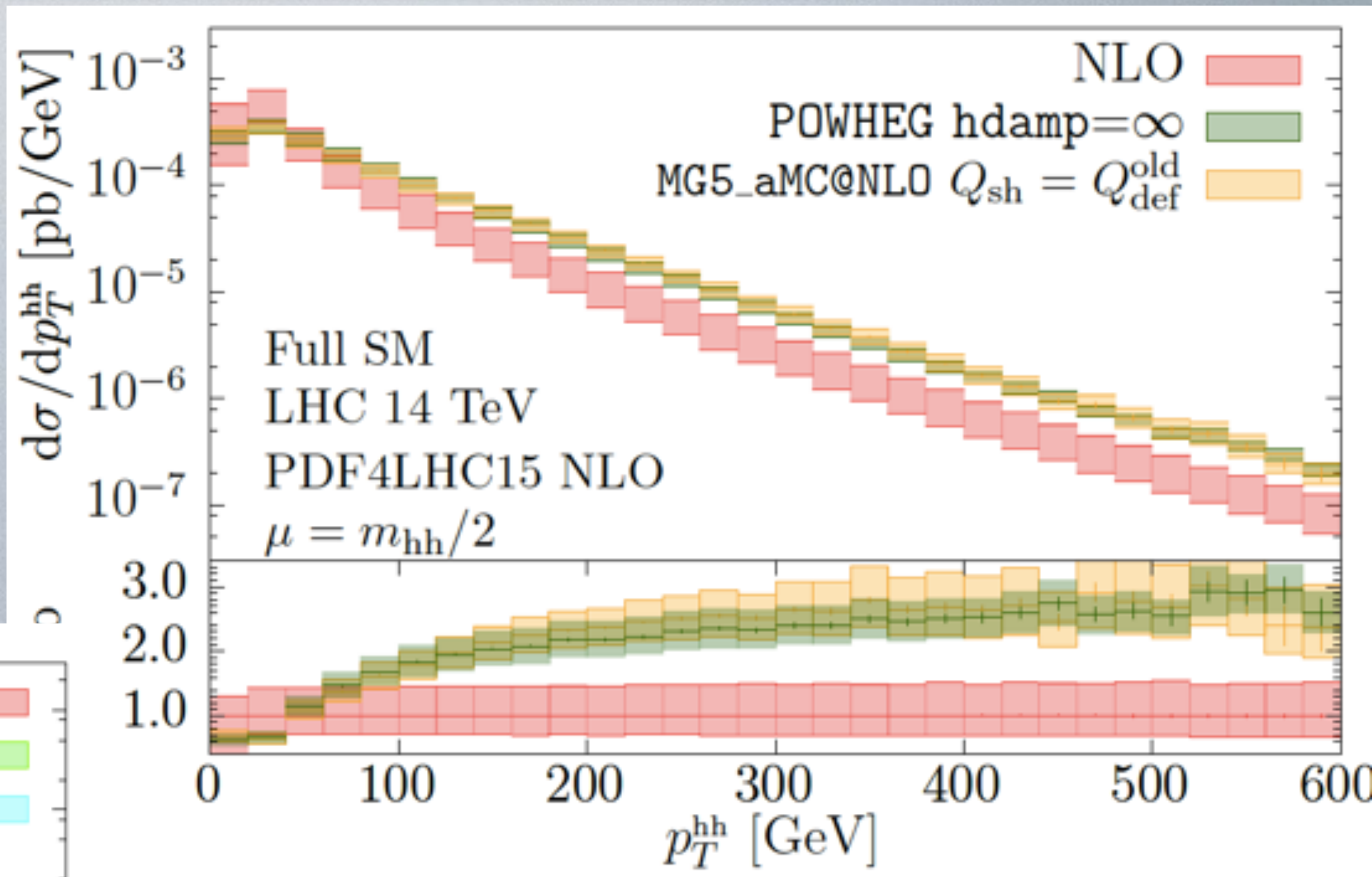
compare POWHEG and MG5_aMC@NLO

MG5_aMC@NLO version 2.5.3:

new Qsh

picked with some probability distribution in

$\texttt{shower\_scale\_factor} \times [0.1\, H_T/2, H_T/2]$

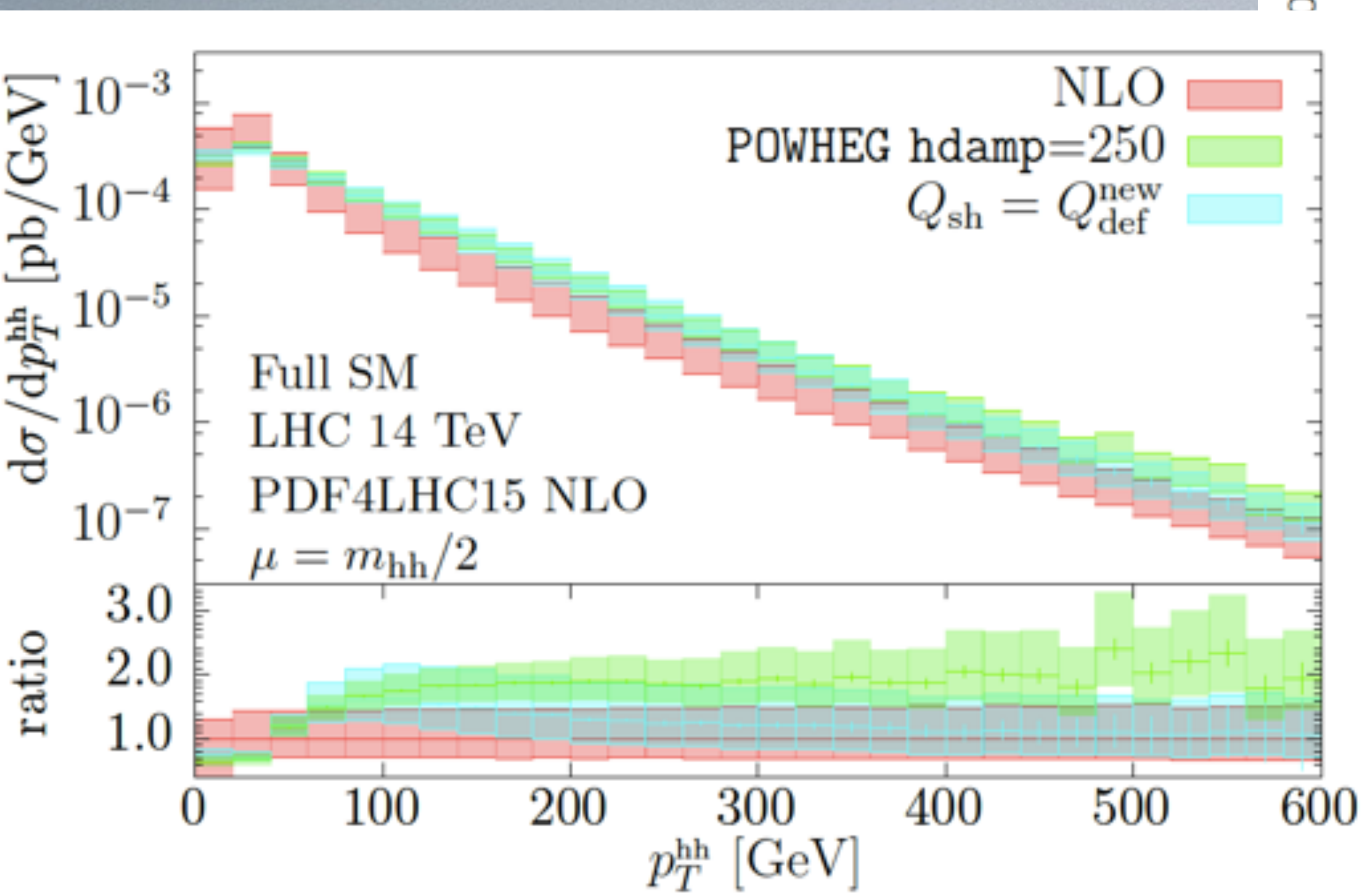


MG5_aMC@NLO

old shower starting scale Qsh:

picked with some probability distribution in

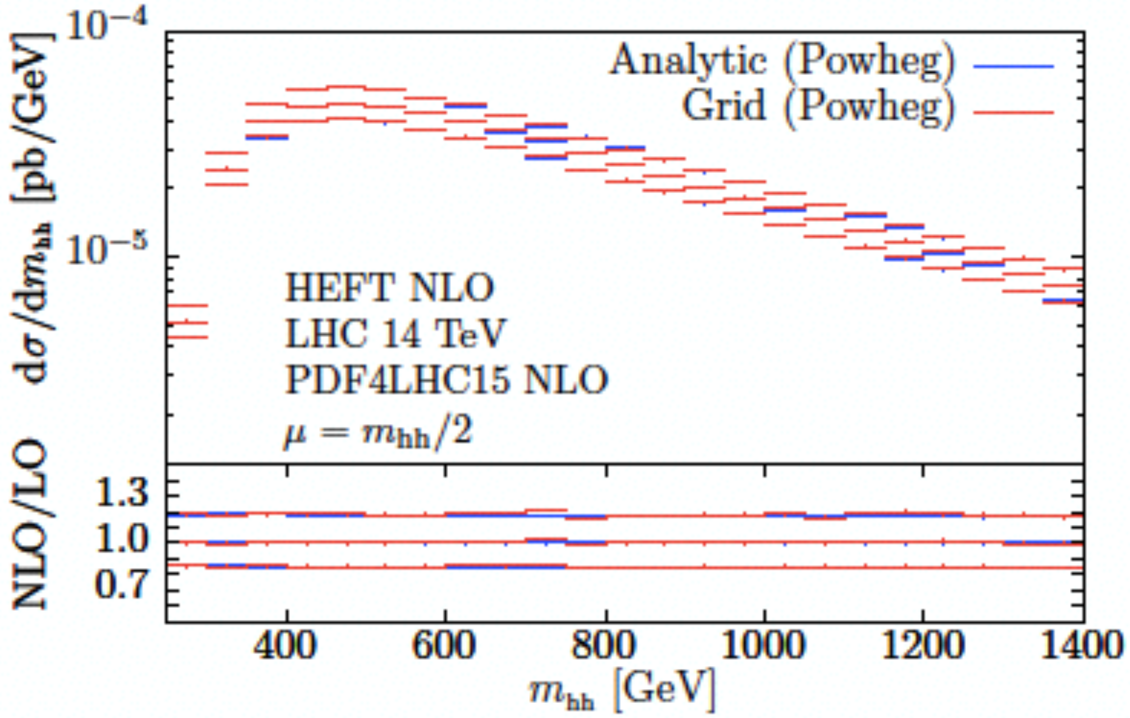
$\texttt{shower\_scale\_factor} \times [0.1\sqrt{\hat{s}}, \sqrt{\hat{s}}]$

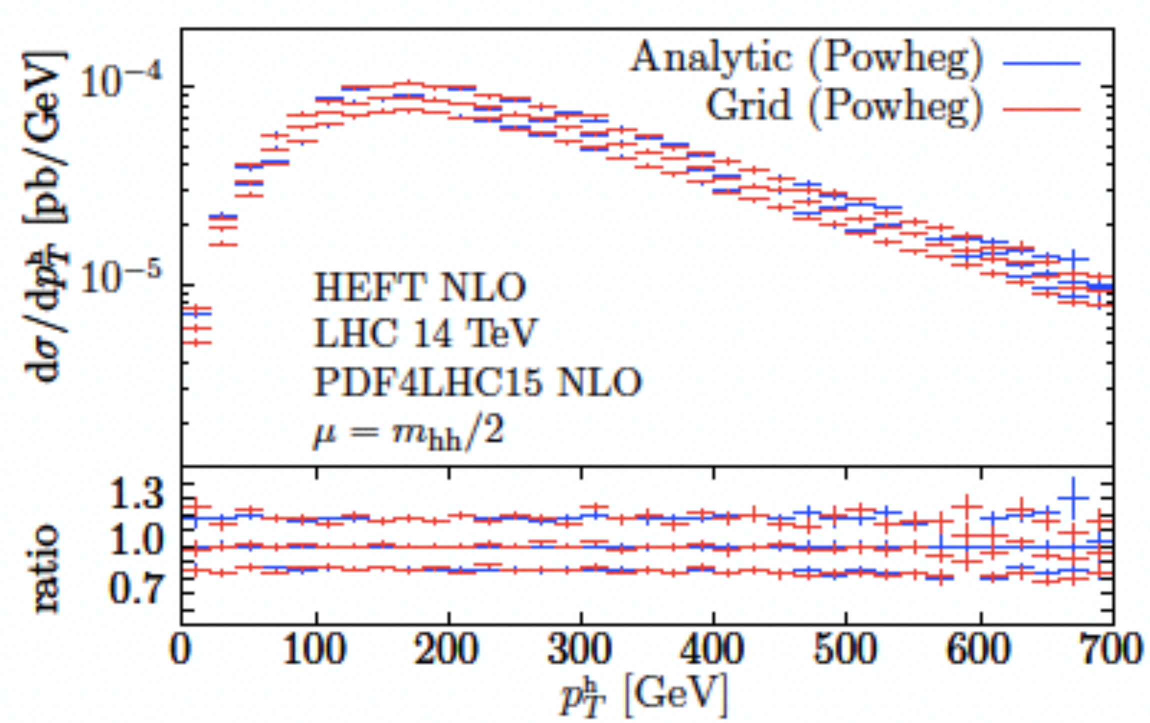


new default shower starting scale matches onto NLO fixed order at large pThh

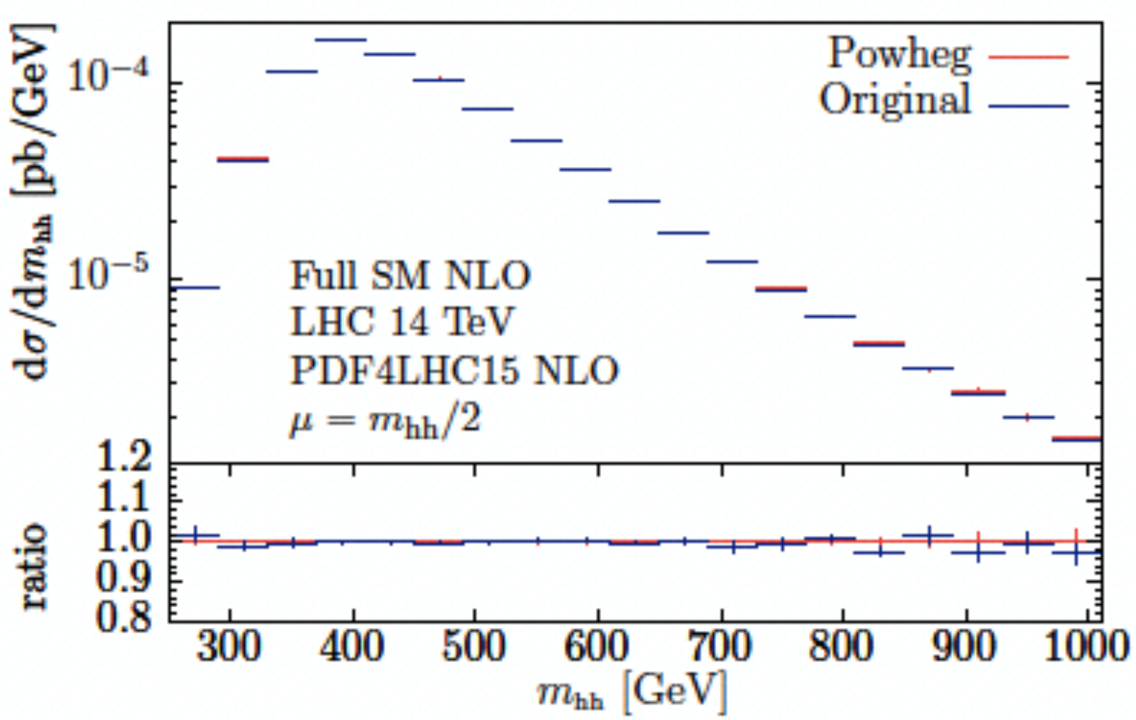
grid validation

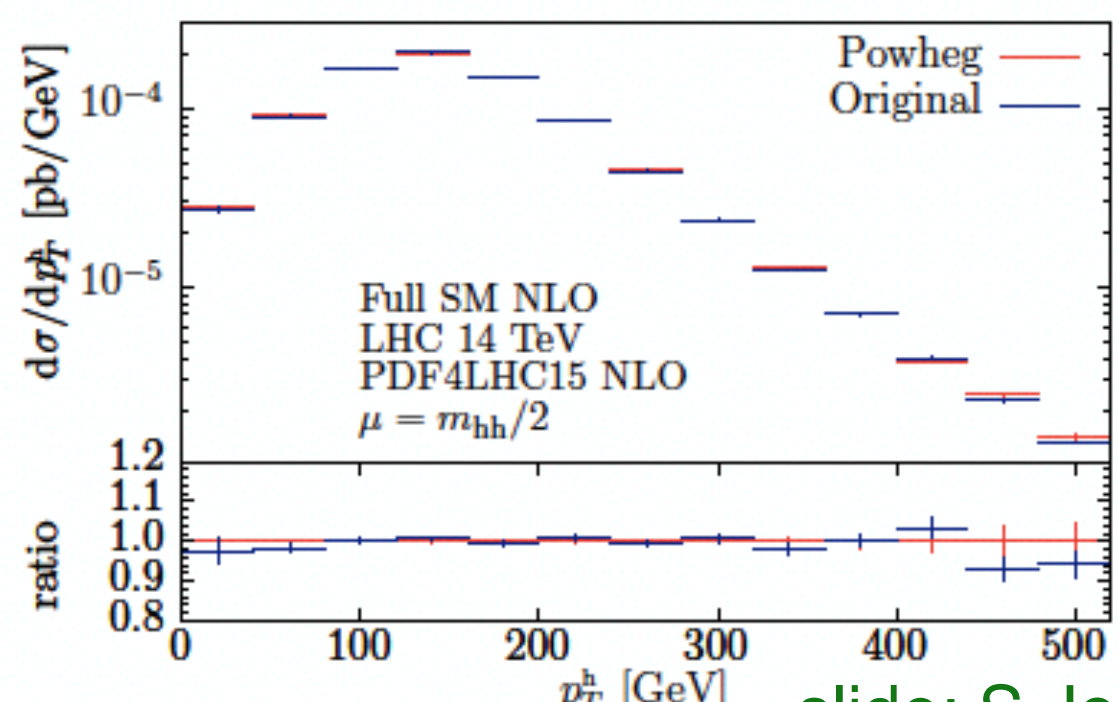
Use HEFT to study validity of grid





Full SM compare `POWHEG` (grid) with our original results





slide: S.Jones