Higgs physics: recent developments

Gudrun Heinrich
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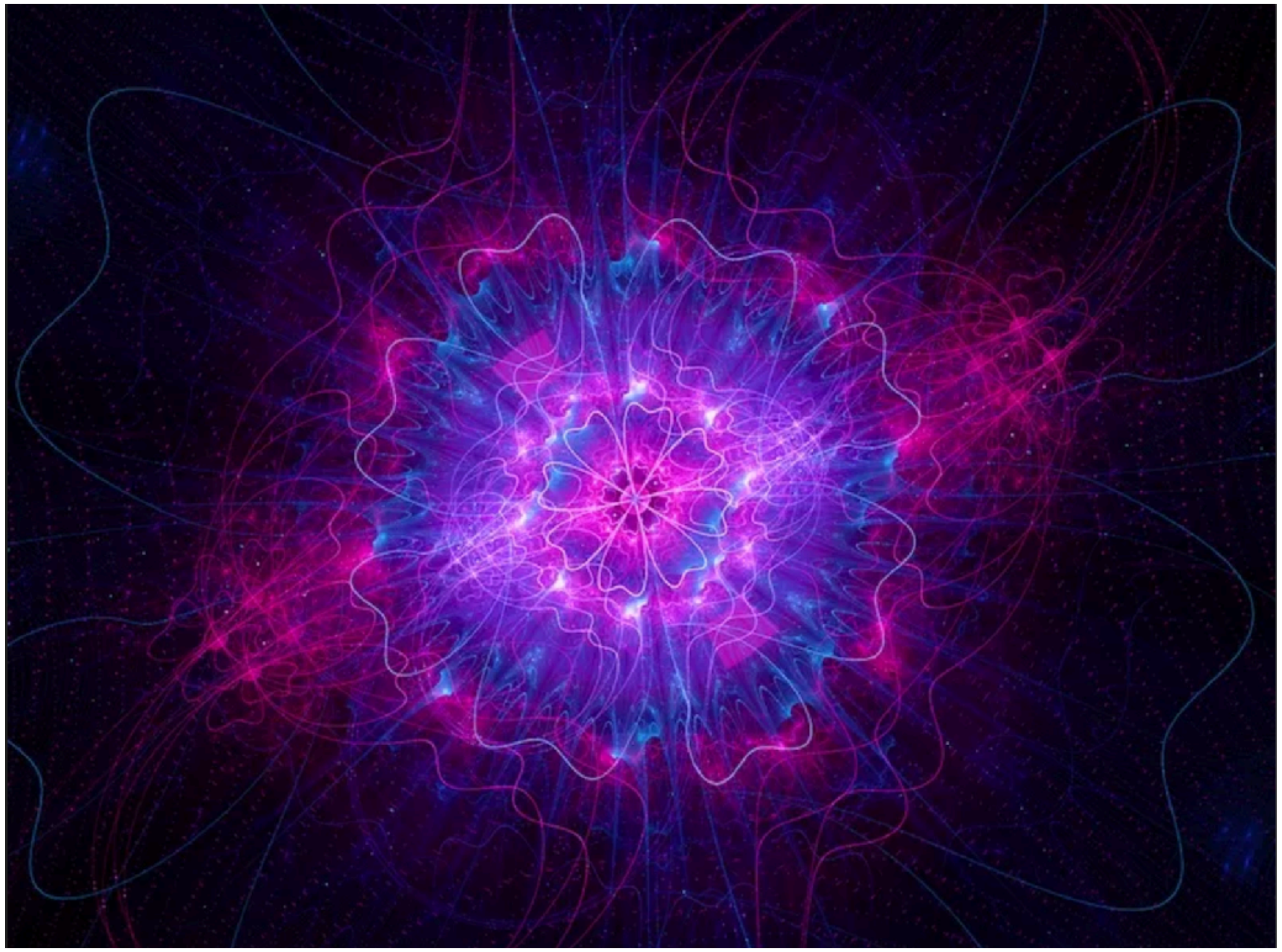

an artists's view of
the Higgs boson
Sakkmesterke
Shutterstock.com

CRC Annual Meeting, 6.10.2020

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Higgs-related questions

- Higgs properties (mass, CP, width)
- couplings to vector bosons and fermions → flavour physics
  neutrino masses
- Higgs potential (self-couplings)
- Higgs and the Universe
  (meta-stability, baryogengesis, portal to dark matter, …)
- the only elementary scalar? compositeness?

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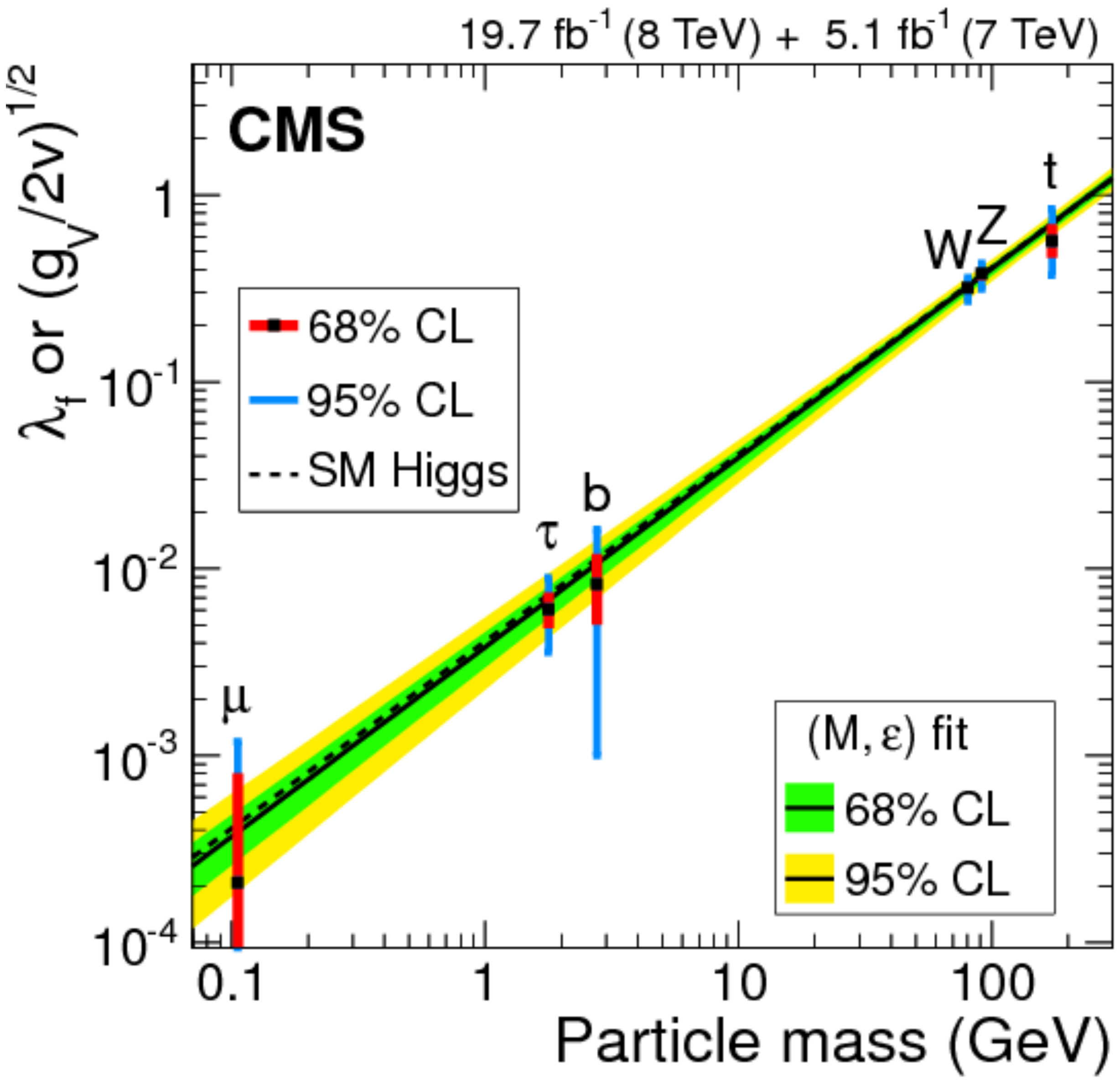
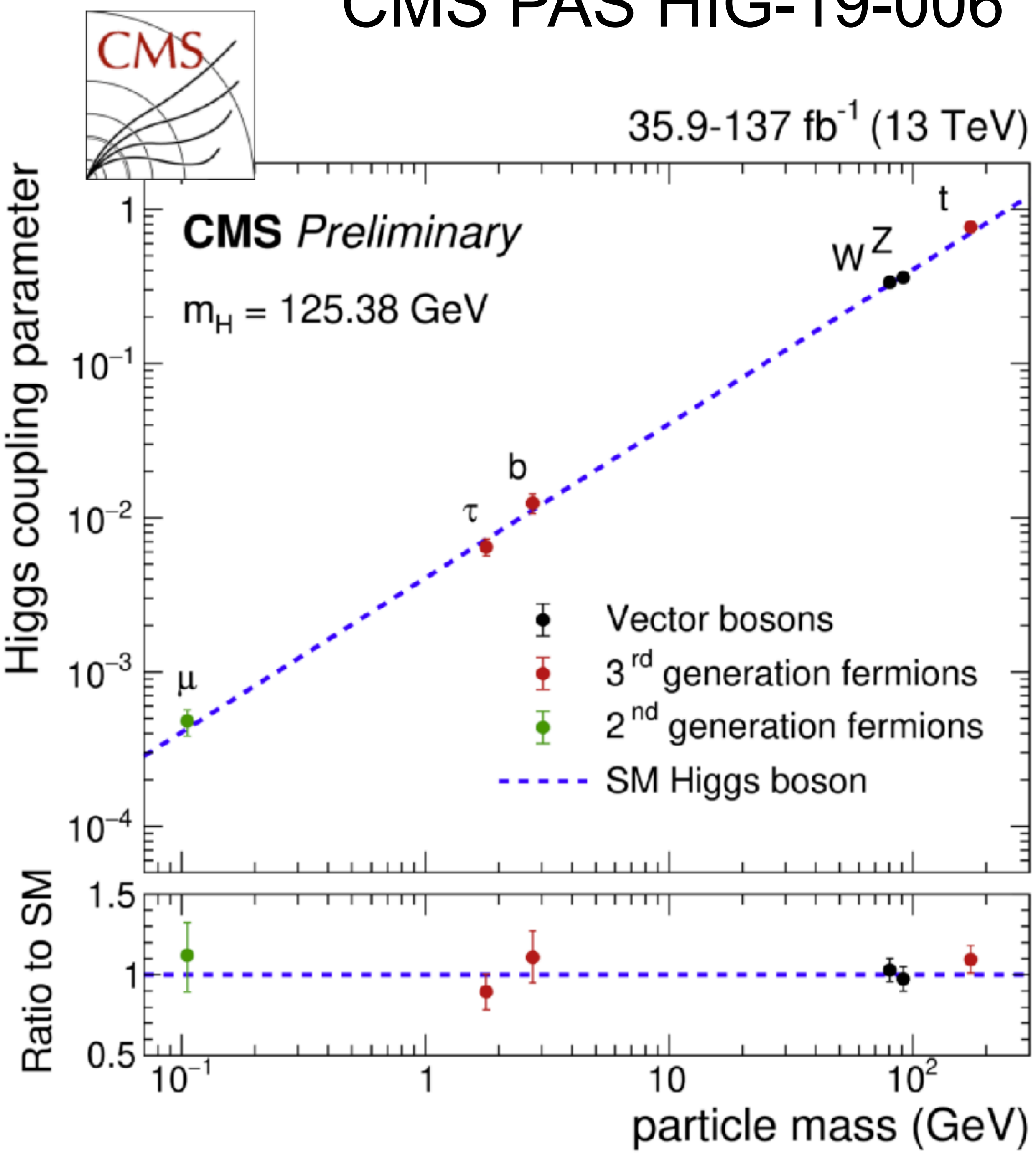
The Higgs sector might be a window to physics at higher scales

Higgs couplings

Run I



CMS PAS HIG-19-006



H?

How do we address these questions?

- precision measurements
- test specific BSM models
- EFT parametrisations of new physics effects

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d=6}^{\infty} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

$$\Rightarrow \quad (\sigma \times BR) = (\sigma \times BR)_{\text{SM}} \, (1 + \Delta)$$

for typical energy scale E of measurement: $\Delta \sim \left(\frac{E}{\Lambda} \right)^2$

The SM as an effective field theory

$$\Delta \sim \left(\frac{E}{\Lambda}\right)^2$$

example Higgs production: typical energy scale $E \sim v = 0.25\,\mathrm{TeV}$

$$\Rightarrow \Delta \sim (0.25)^2 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \sim 0.06 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

$\Rightarrow$ to generate $\gtrsim$ 1% deviations need $\Lambda \lesssim 2.5\,\mathrm{TeV}$

boosted Higgs, tails of distributions: $E \sim 1\,\mathrm{TeV}$

$\Rightarrow$ with $\Lambda = 2.5\,\mathrm{TeV}$ we achieve $\Delta = 1/(2.5)^2 \simeq 16\%$

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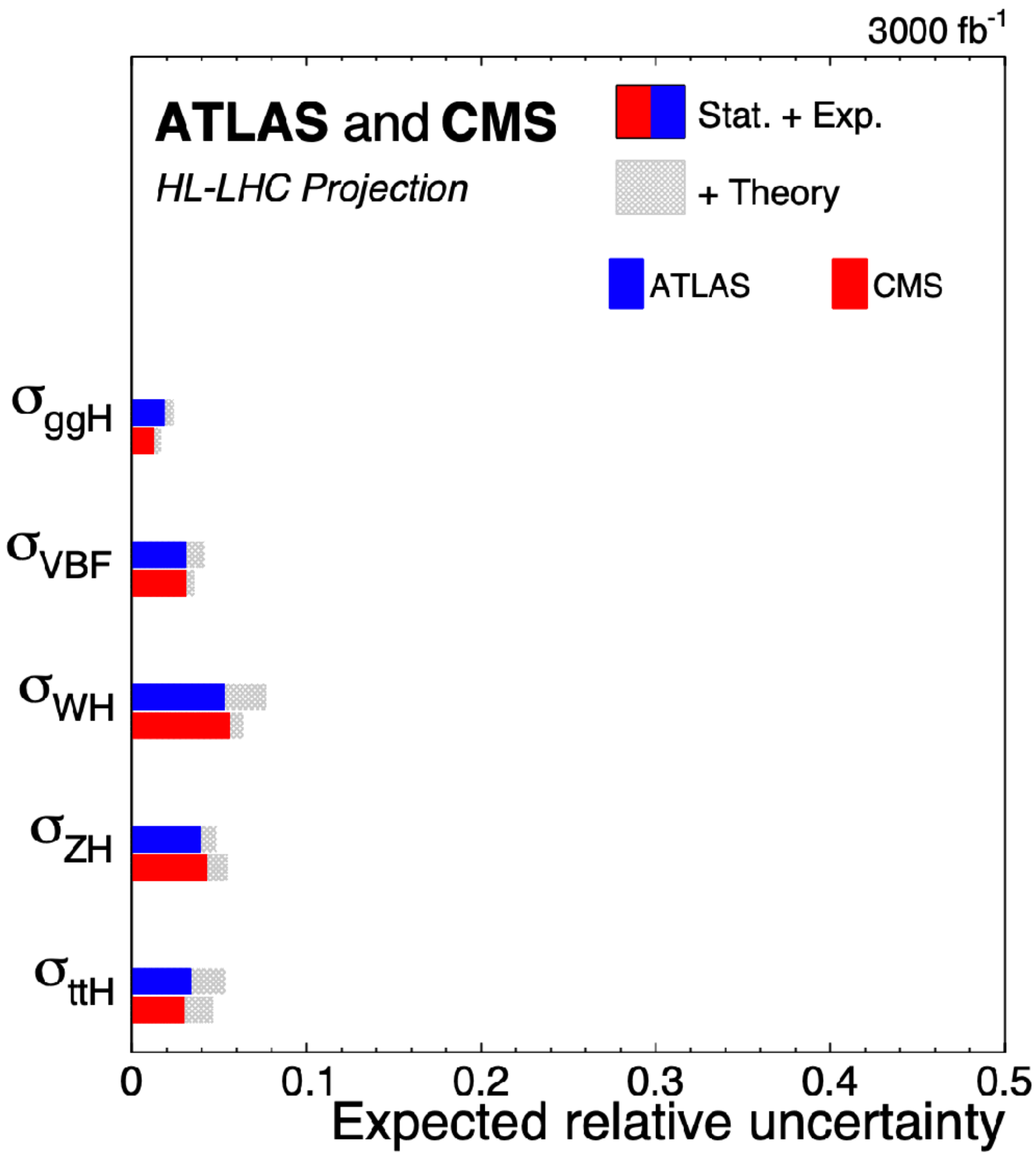
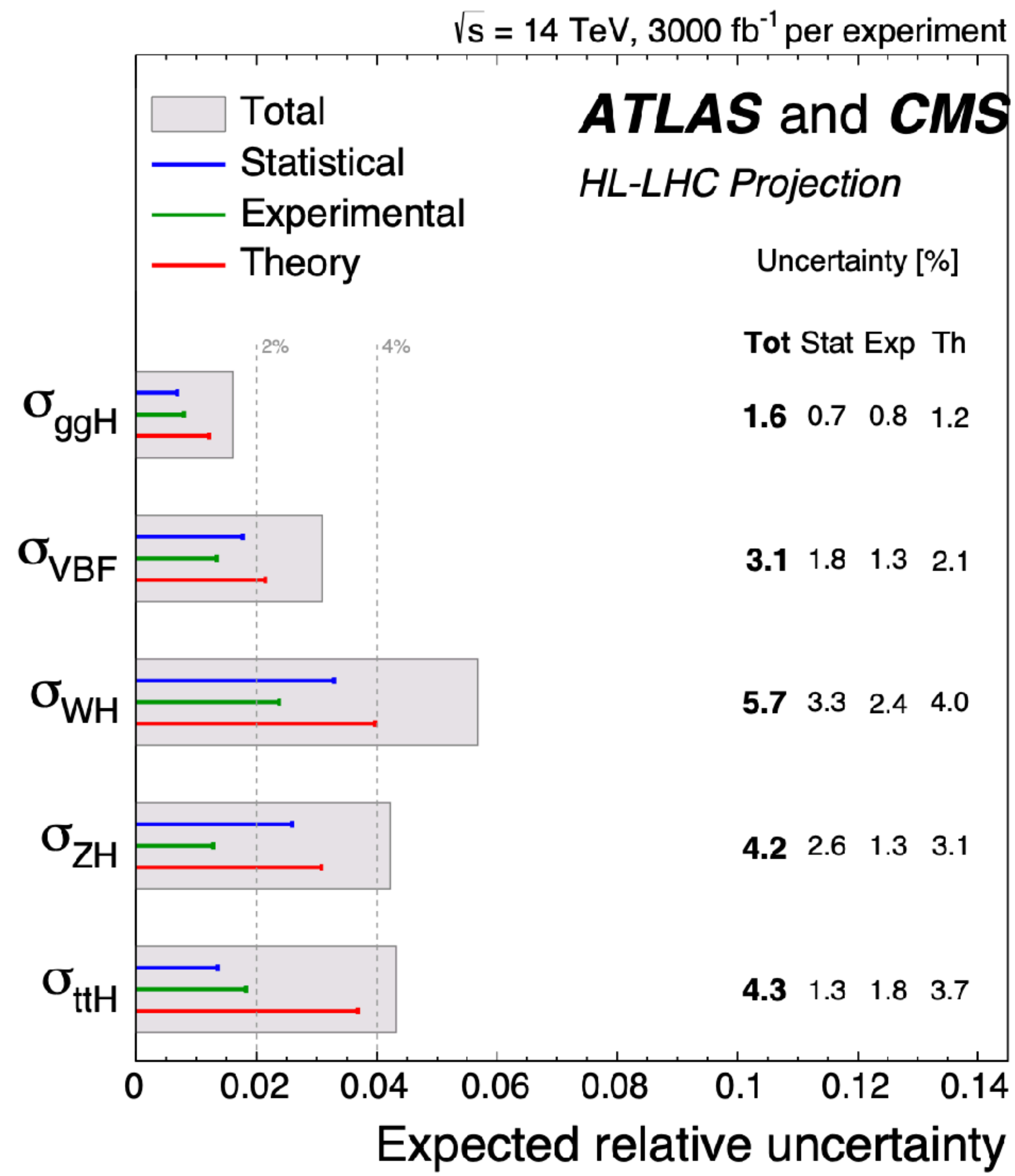
$\Rightarrow$ off-shell measurements, tails of distributions very important!

precision

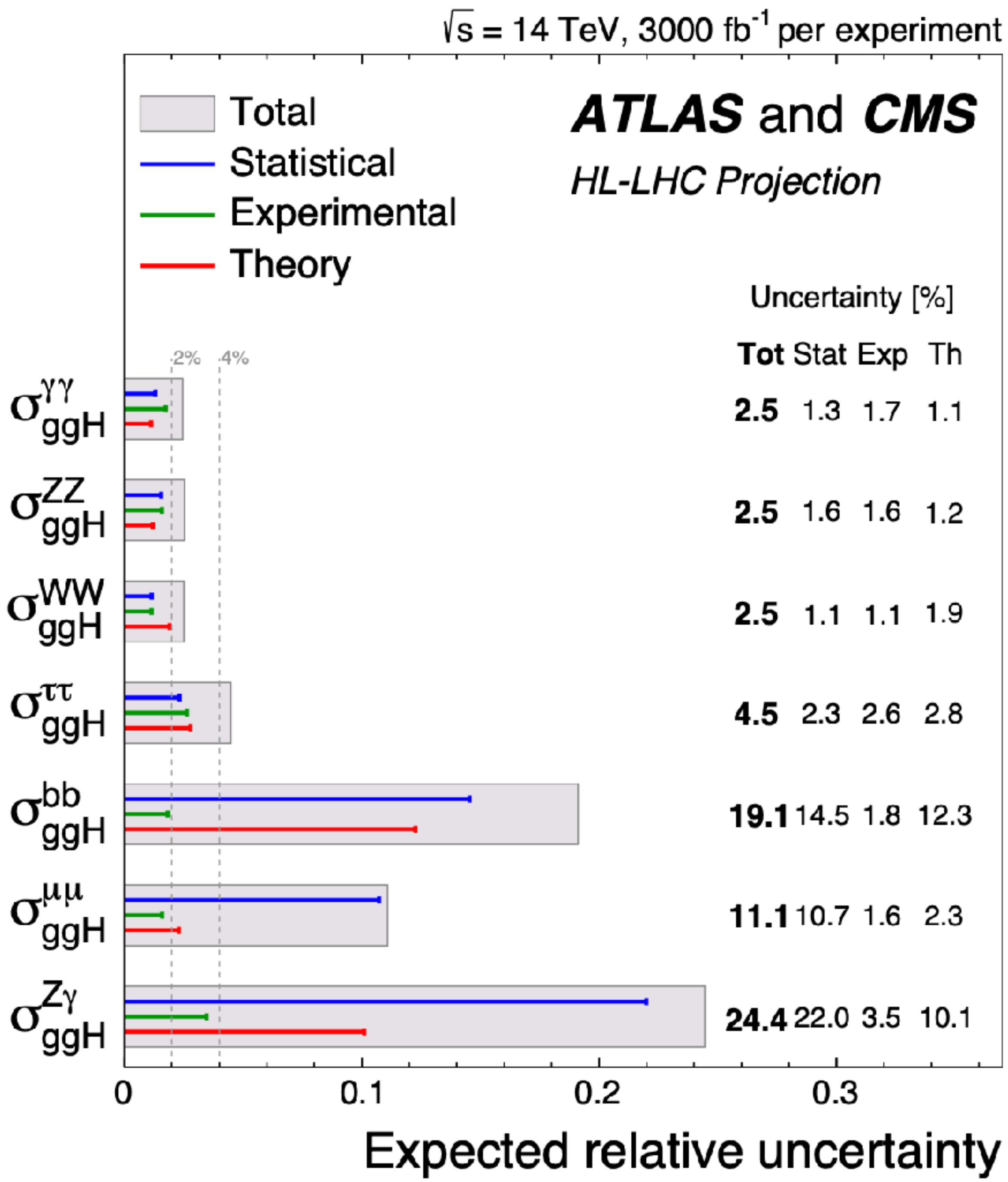




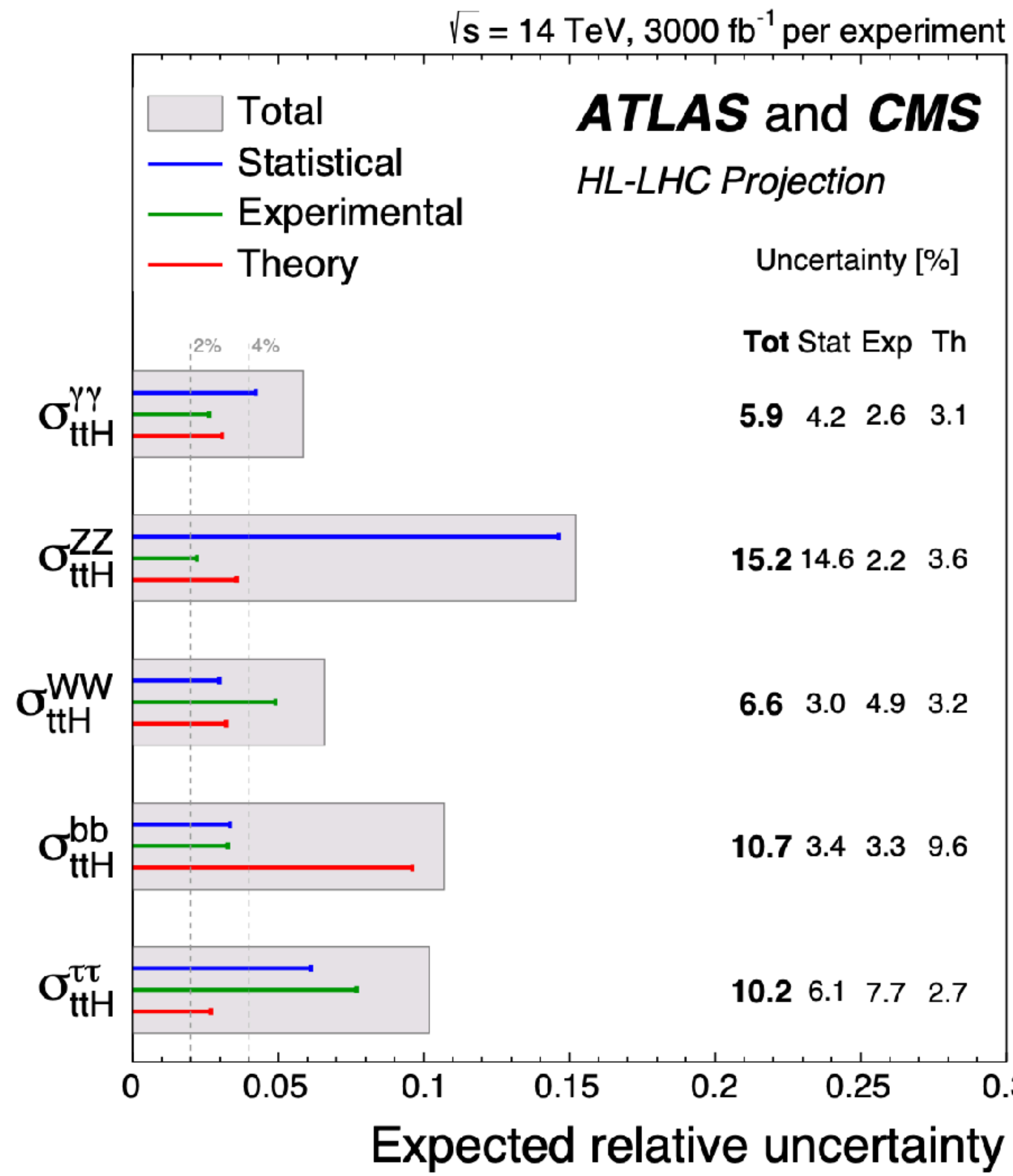
HL-HE YR, 1902.00134

projected uncertainties

gluon fusion



ttH



fixed order precision frontier

N3LO available for:

gluon fusion Higgs, bbH, Drell-Yan, VBF H, VBF HH, gluon fusion HH

	Drell-Yan	gluon fusion Higgs
LO	1970	1978
NLO	1978-80	1991 (HTL) 1995 (full mt)
NNLO	1991	2002 (HTL) 2009-2020 (mass effects)
N3LO	2020 Duhr, Dulat, Mistlberger	2015 (HTL, threshold exp.) Anastasiou, Duhr, Dulat, Herzog, Mistlberger 2018 (HTL) Mistlberger 2020 Das, Moch, Vogt partial N4LO

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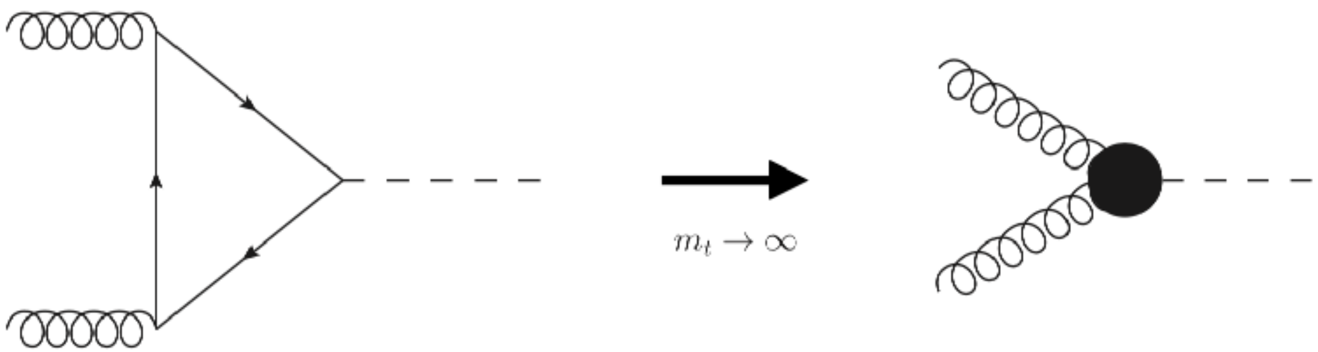
aside: heavy top limit

- Higgs production in gluon fusion:

  leading order already contains one loop

  (same for HH, HJ, HZ, … in gluon fusion)

- many calculations of high perturbative order use "heavy top limit" (HTL)



- good approximation for inclusive Higgs production if rescaled with full Born

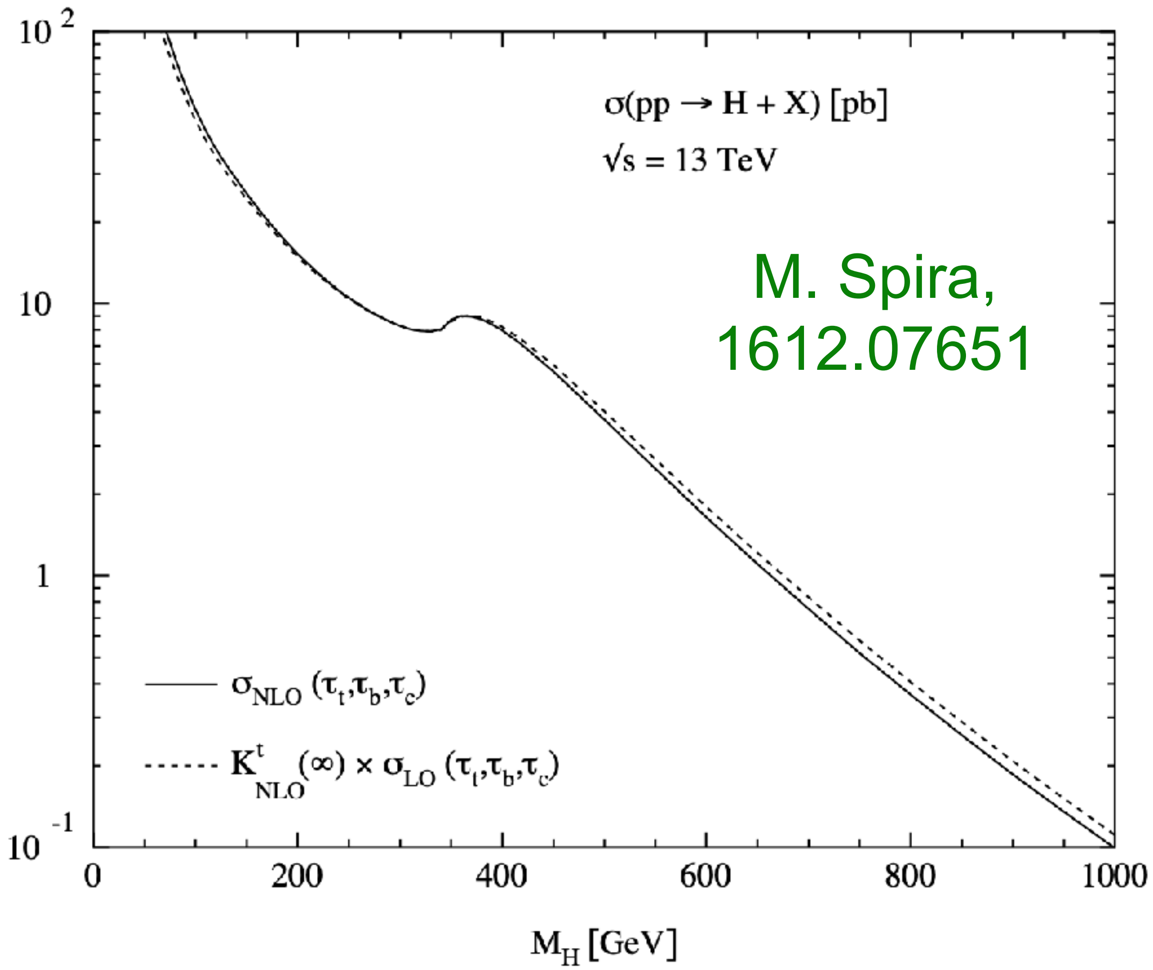
- not justified if top loops can be resolved (e.g. high energy tails of distributions)

  (in fact only justified below threshold, $E \lesssim 2m_t$)

  example HH production: only valid for $250\,\mathrm{GeV} \leq m_{HH} \lesssim 350\,\mathrm{GeV}$

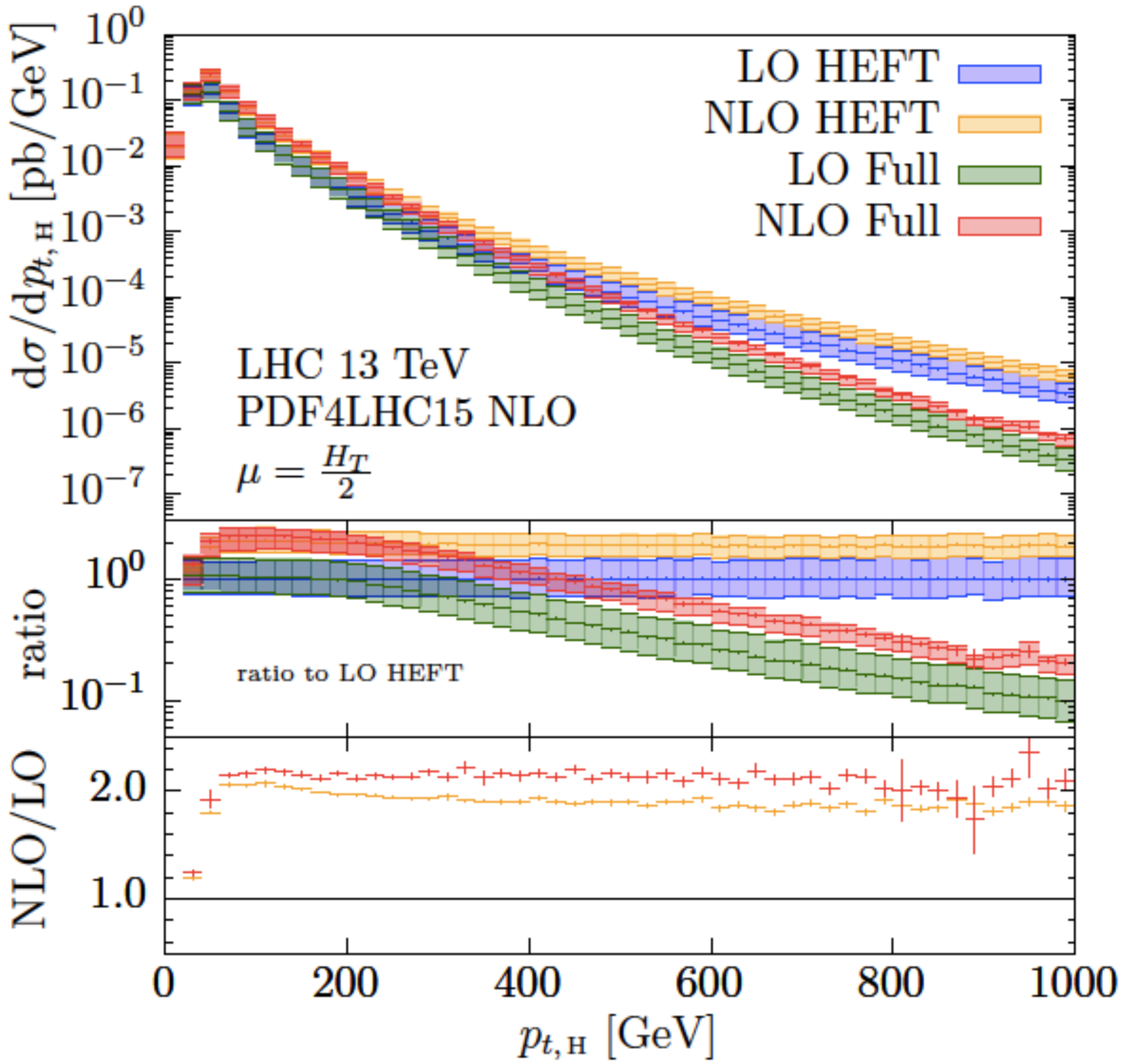
heavy top limit

inclusive Higgs production



"Born-improved" NLO HTL

Higgs+jet production



Jones, Kerner, Luisoni '18

("HEFT"=HTL)

fixed order precision frontier

	VBF Higgs	Higgs pairs gluon fusion
LO	1979	1988
NLO	1992 (structure func.approx.) 2003 (full)	1998 (HTL) 2016 (full mt)
NNLO	2015	2013 (HTL) 2013-2020 (mass effects)
N3LO	2016 Dreyer, Karlberg (VBF HH 2018)	2019 (HTL+mass effects) Chen, Li, Shao, Wang

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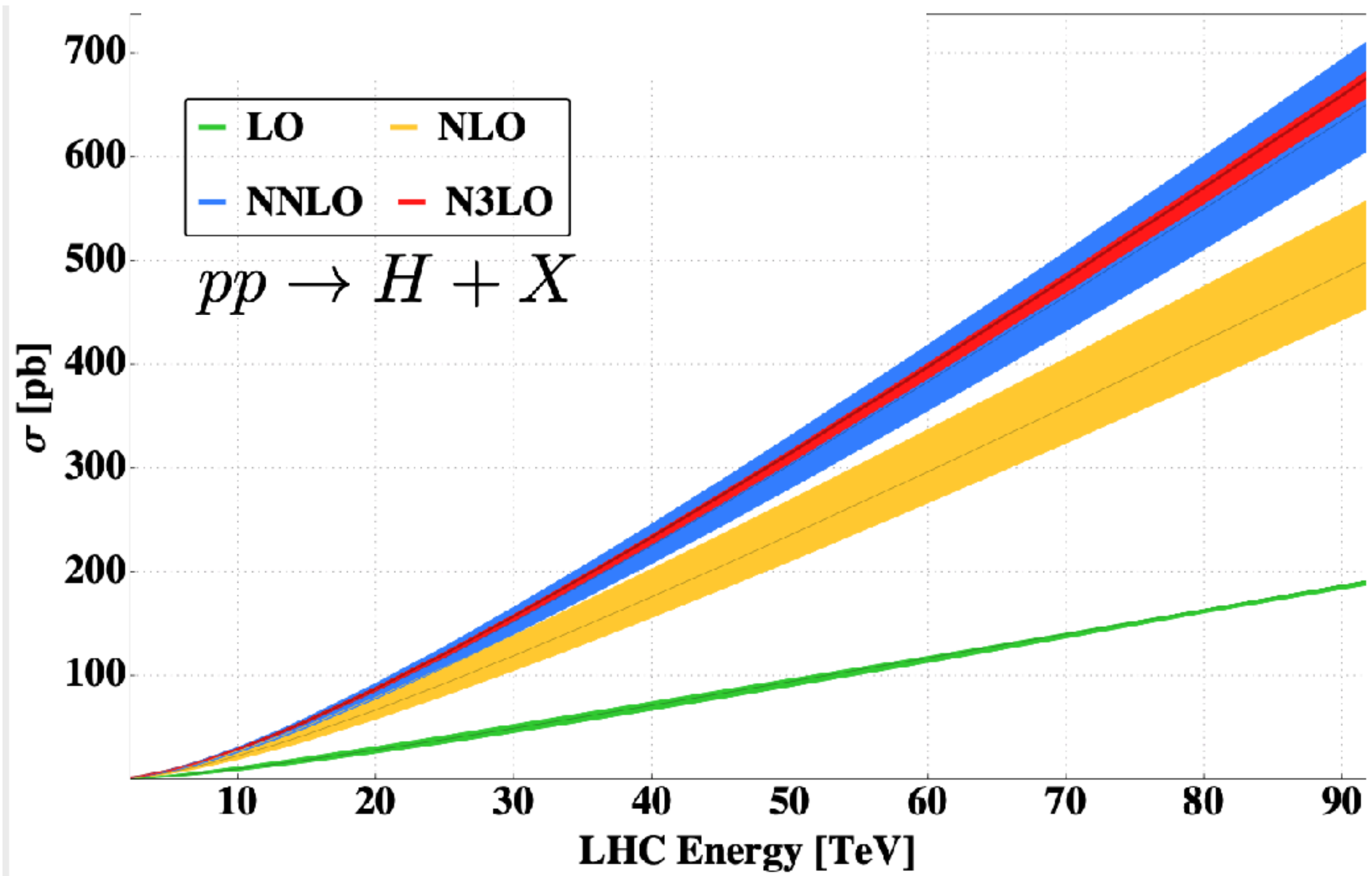
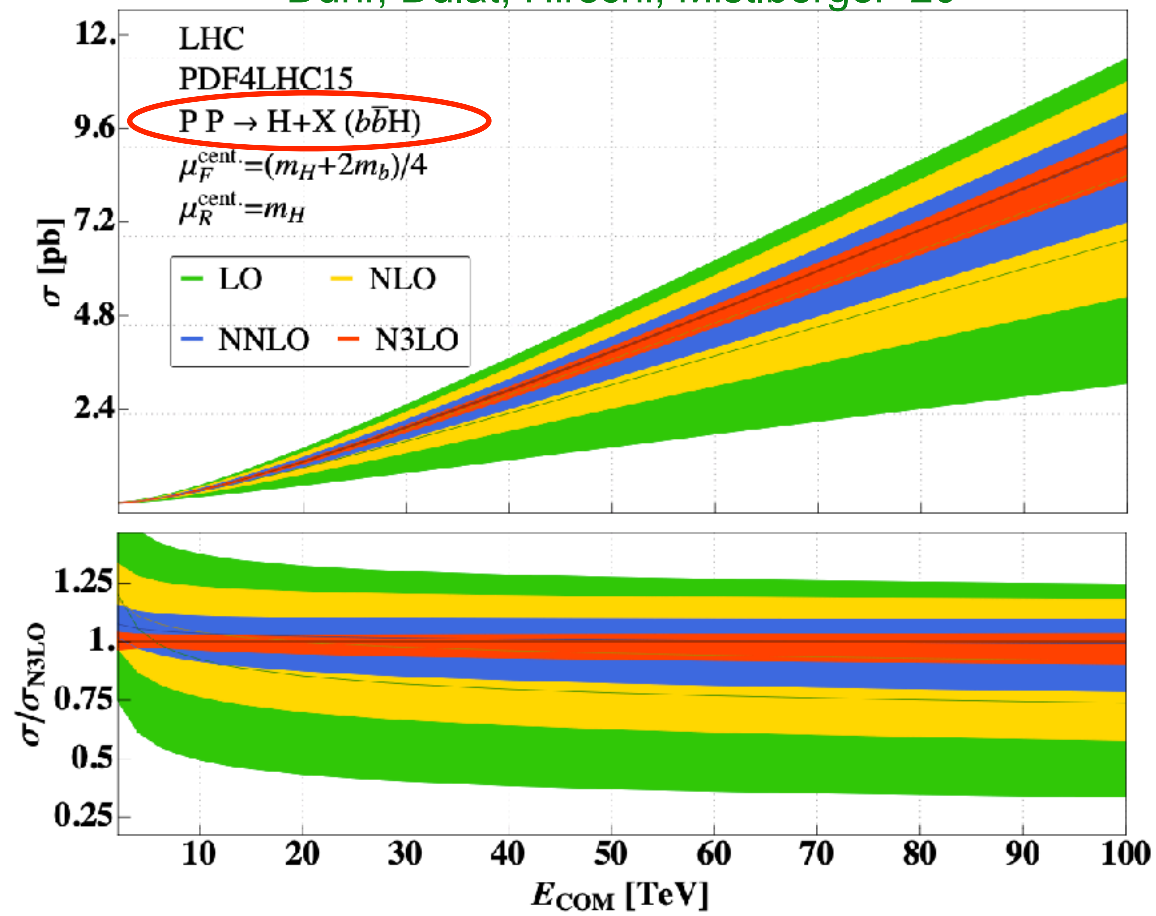
precision frontier

Anastasiou, Duhr, Dulat, Herzog, Mistlberger ‘15



Duhr, Dulat, Hirschi, Mistlberger ‘20



shift of focus:

at N3LO scale uncertainties under control, but need to address

- QCDxEW corrections
- massive quarks at higher orders
- PDF, α_s uncertainties, non-perturbative effects
- parton shower uncertainties

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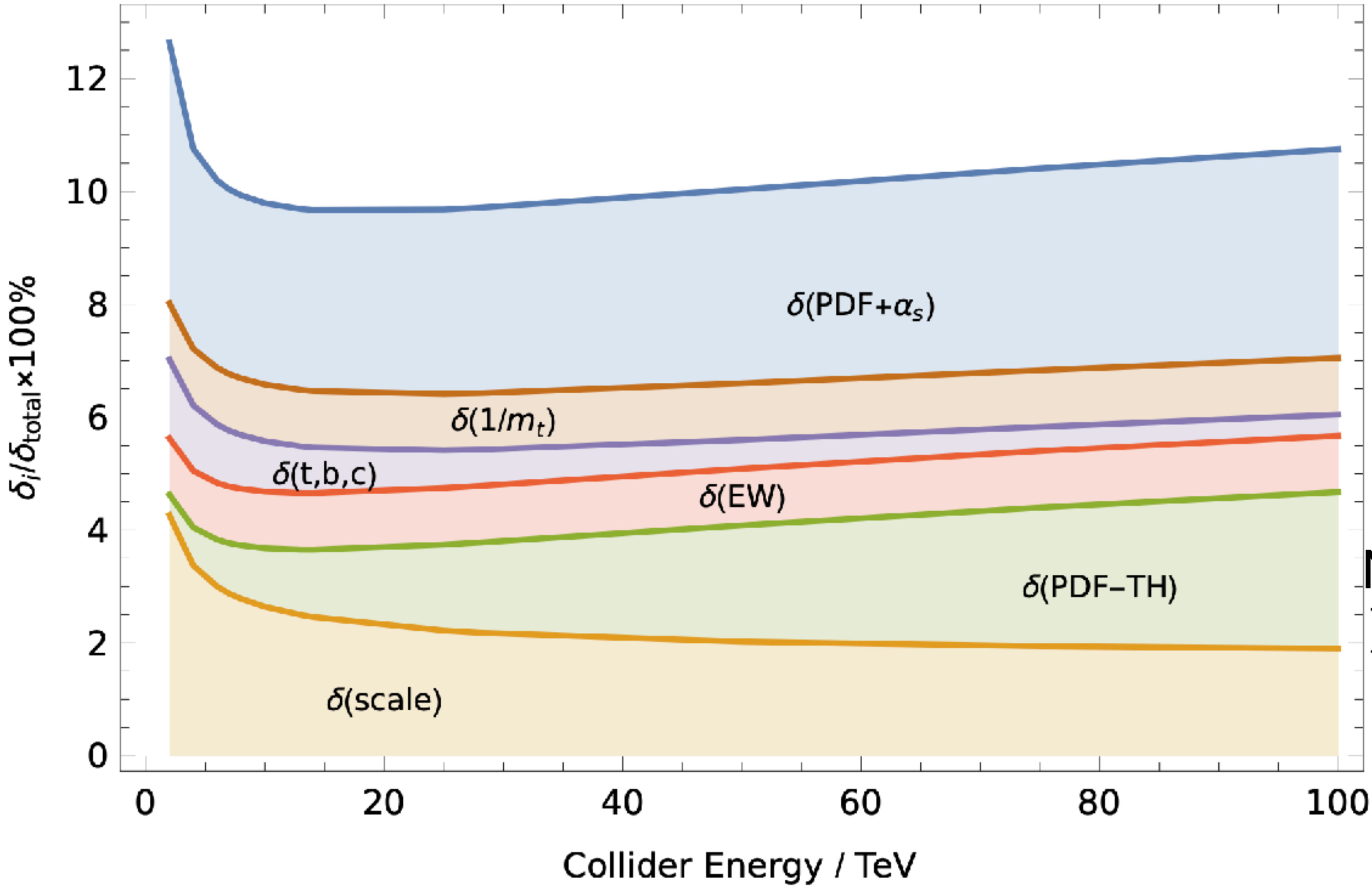
H in gluon fusion: uncertainties

$\delta(\text{scale})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
$^{+0.10}_{-1.15}$ pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb	$\pm$ 0.89 pb	$^{+1.25}_{-1.26}$ pb
$^{+0.21\%}_{-2.37\%}$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$	$\pm 1.85\%$	$^{+2.59\%}_{-2.62\%}$

2009.00516

scale uncertainties no longer the dominant uncertainties



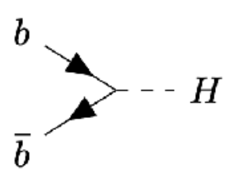
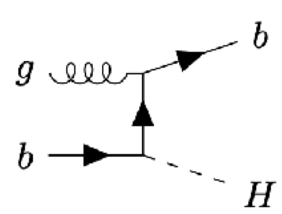
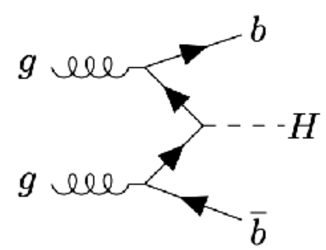
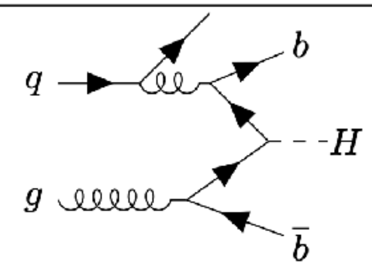
NNLO PDFs with $\mathrm{N^3LO}\ \sigma$

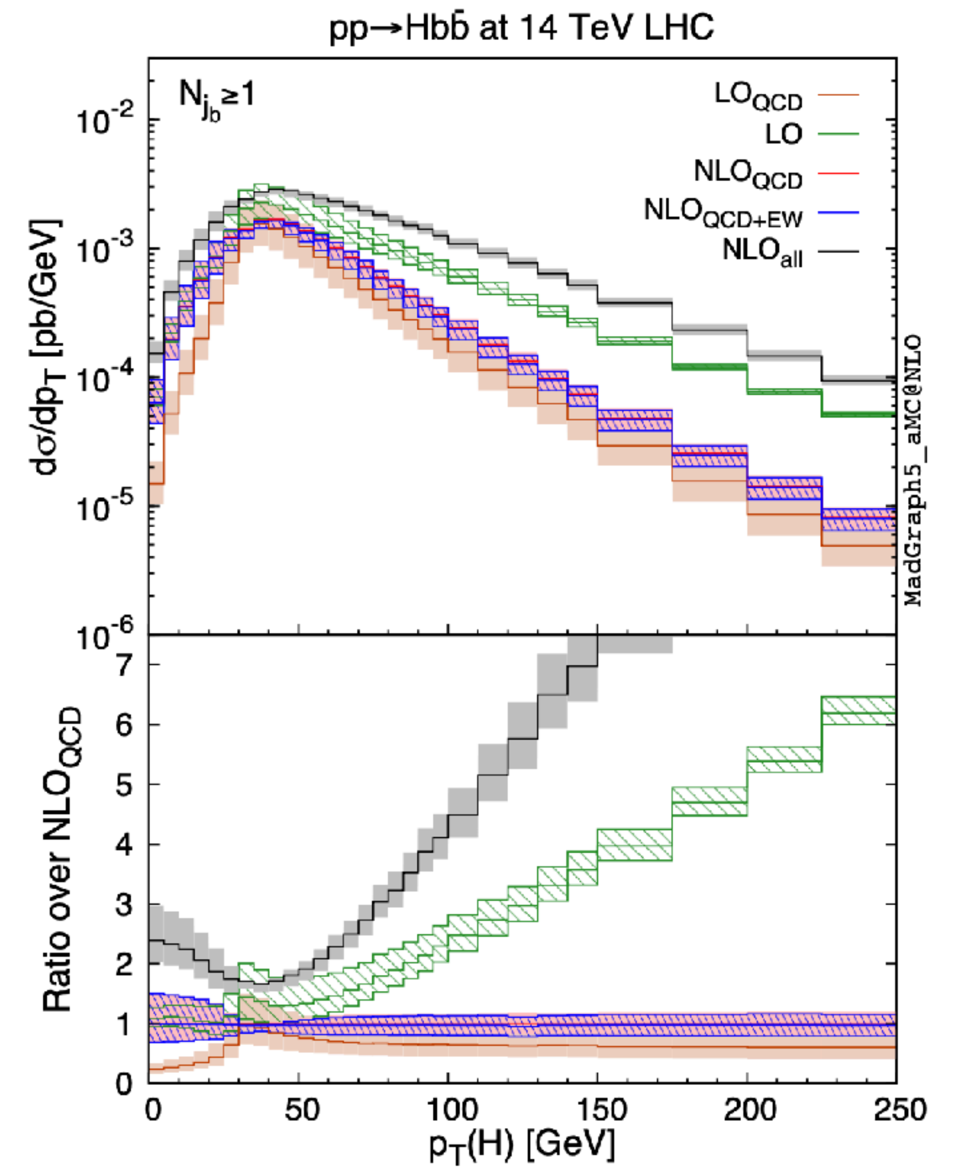
1902.00134

Hbb

N3LO in 5-flavour scheme Duhr, Dulat, Hirschi, Mistlberger 2004.04752

matched to NLO in 4-flavour scheme $(m_b \neq 0)$

				
4FS	–	–	LO	NLO
5FS	LO	NLO	NNLO	N^{3}LO

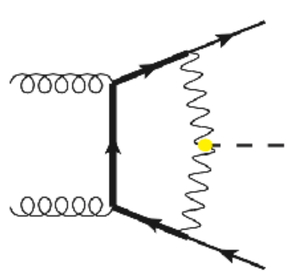


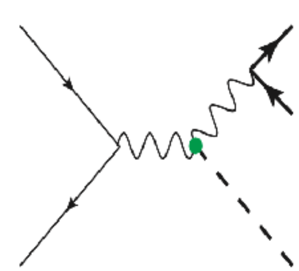
$pp \to Hb\bar{b}$ as a way to directly measure y_b :

Pagani, Shao, Zaro 2005.10277

calculation of full QCD-EW NLO corrections, including ZH and VBF production channels

conclusion: overwhelming backgrounds, in particular due to VBF and $ZH(Z \to b\bar{b})$





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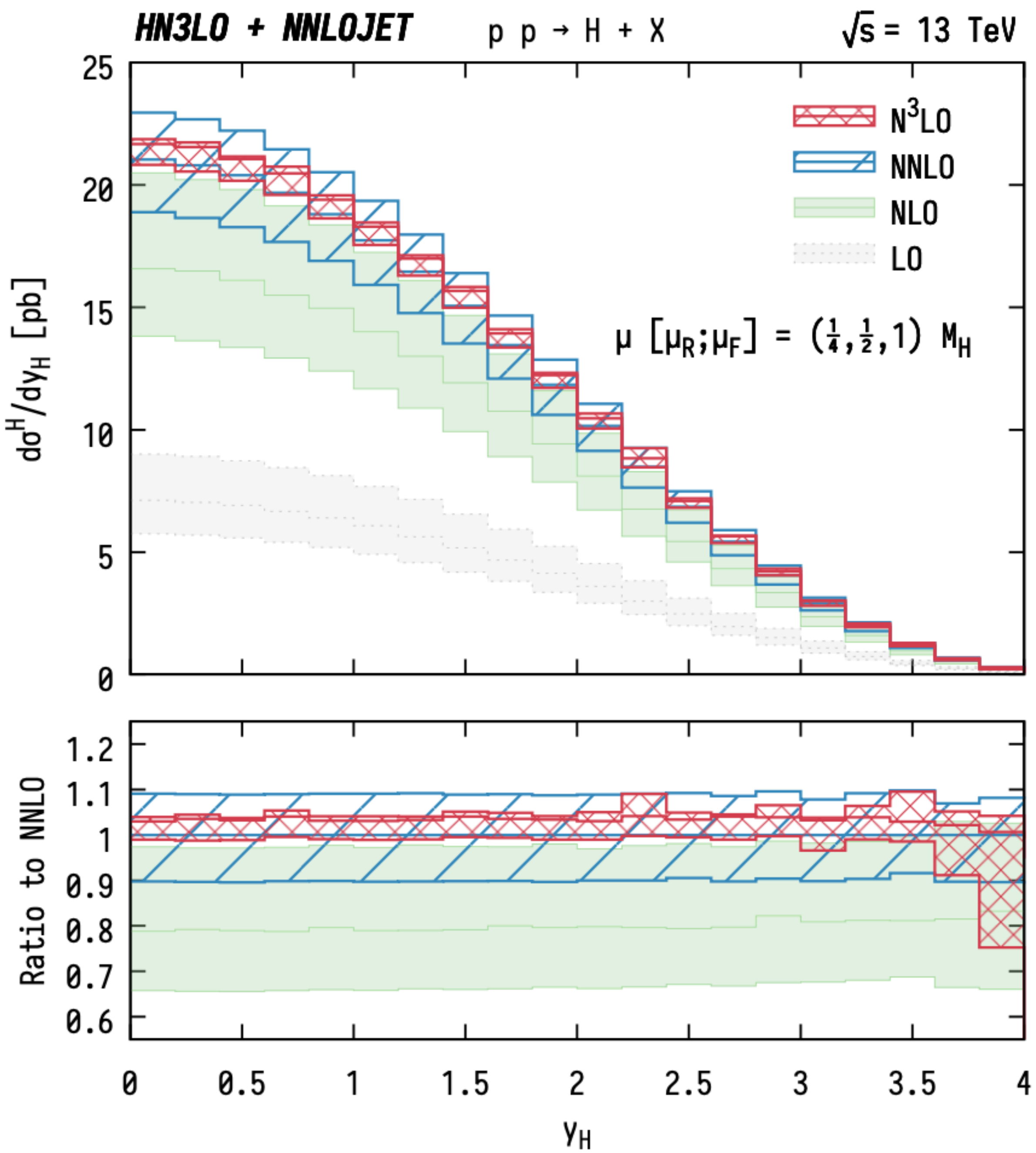
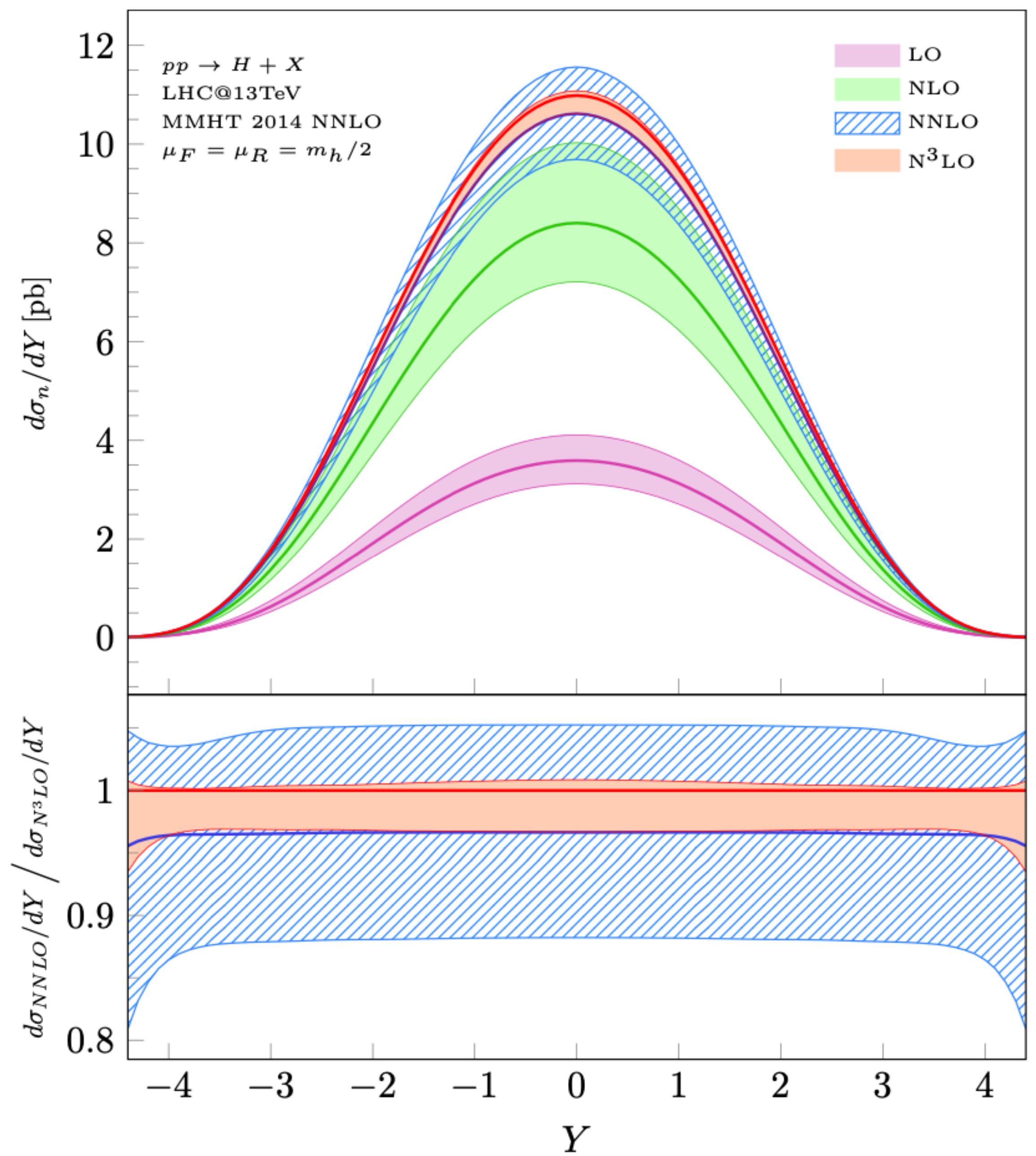
differential N3LO results



Cieri, Chen, Gehrmann, Glover, Huss
1807.11501



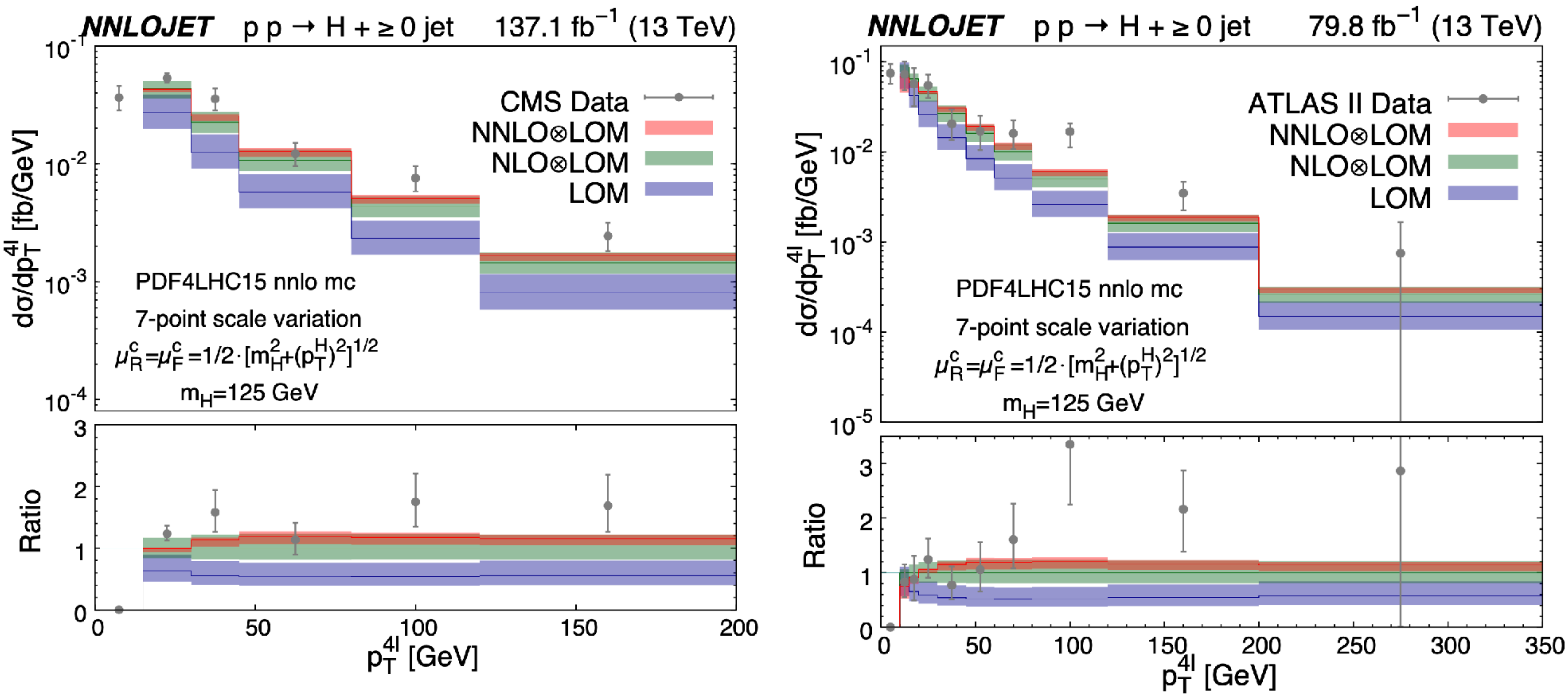
Dulat, Mistlberger, Pelloni
1810.09462

scale uncertainties reduced by more than 50% w.r.t. NNLO

gluon fusion H NNLO differential results

$$pp \to H + \leq 1\,j \to 4l + \leq 1\,j$$

Chen, Gehrmann, Glover, Huss
1905.13738

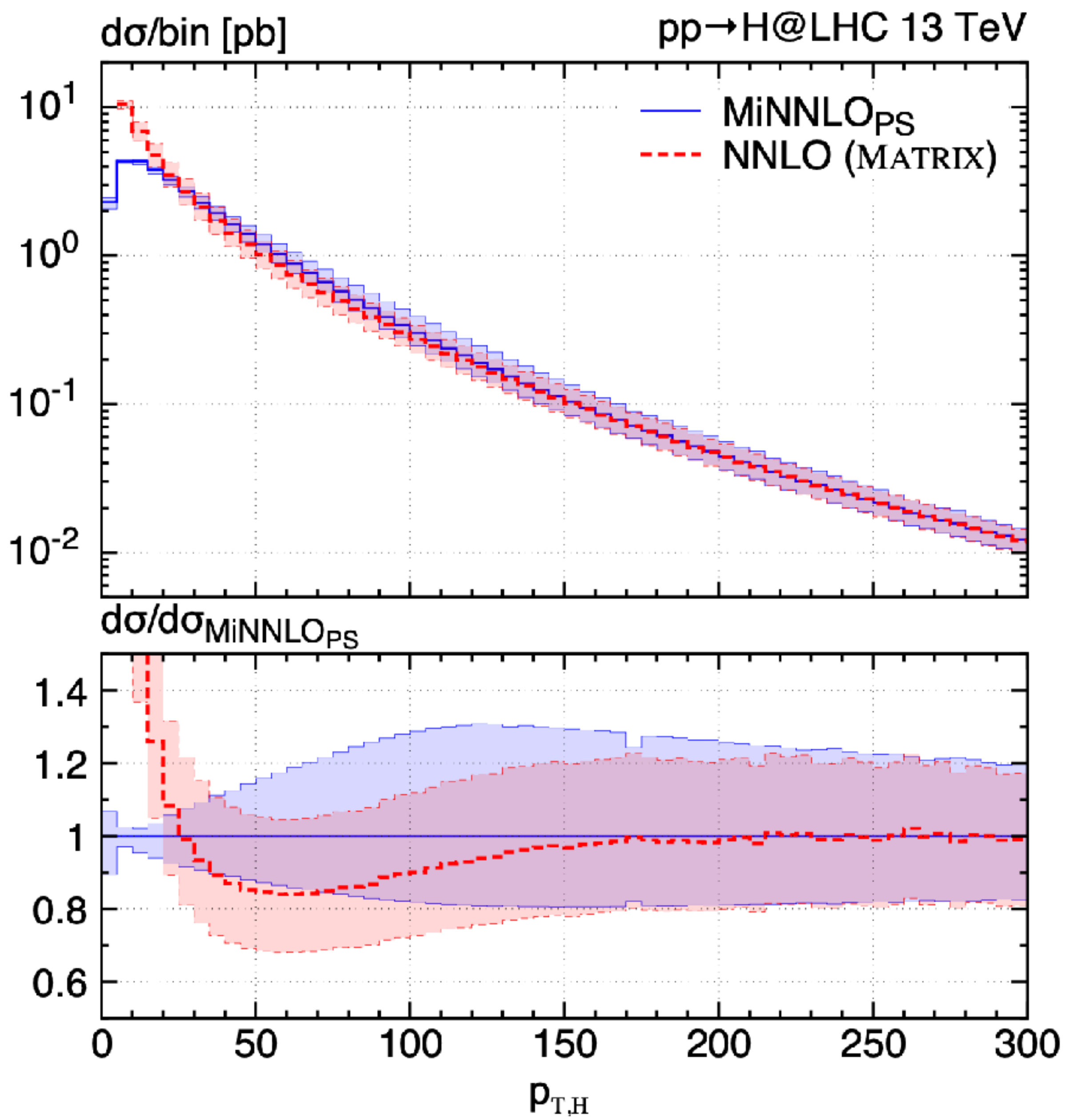


study of perturbative stability of lepton acceptance cuts

beyond fixed order

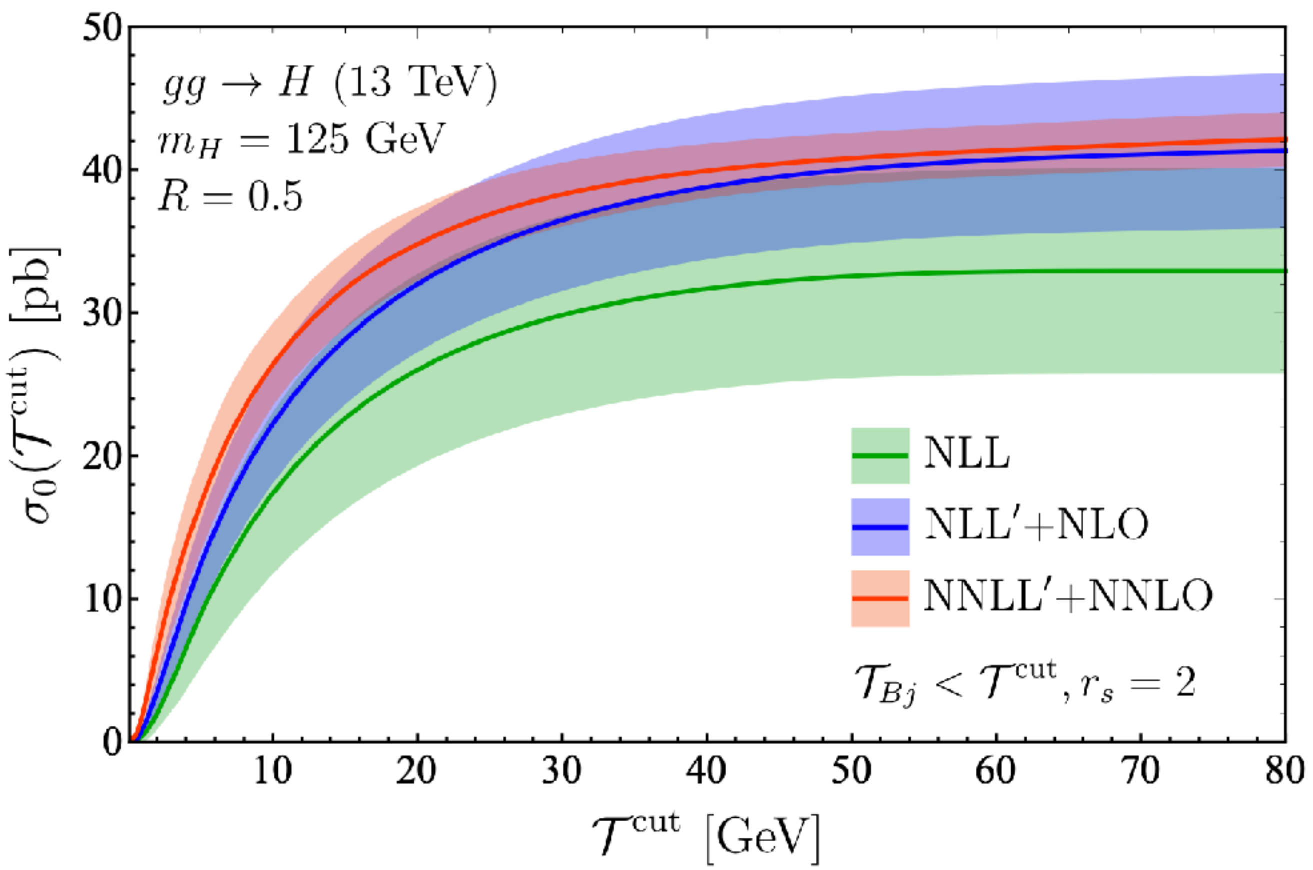
NNLO+PS

Monni, Re, Wiesemann
2006.04133



Higgs production with a jet veto

Gangal, Gaunt, Tackmann, Vryonidou
2003.04323



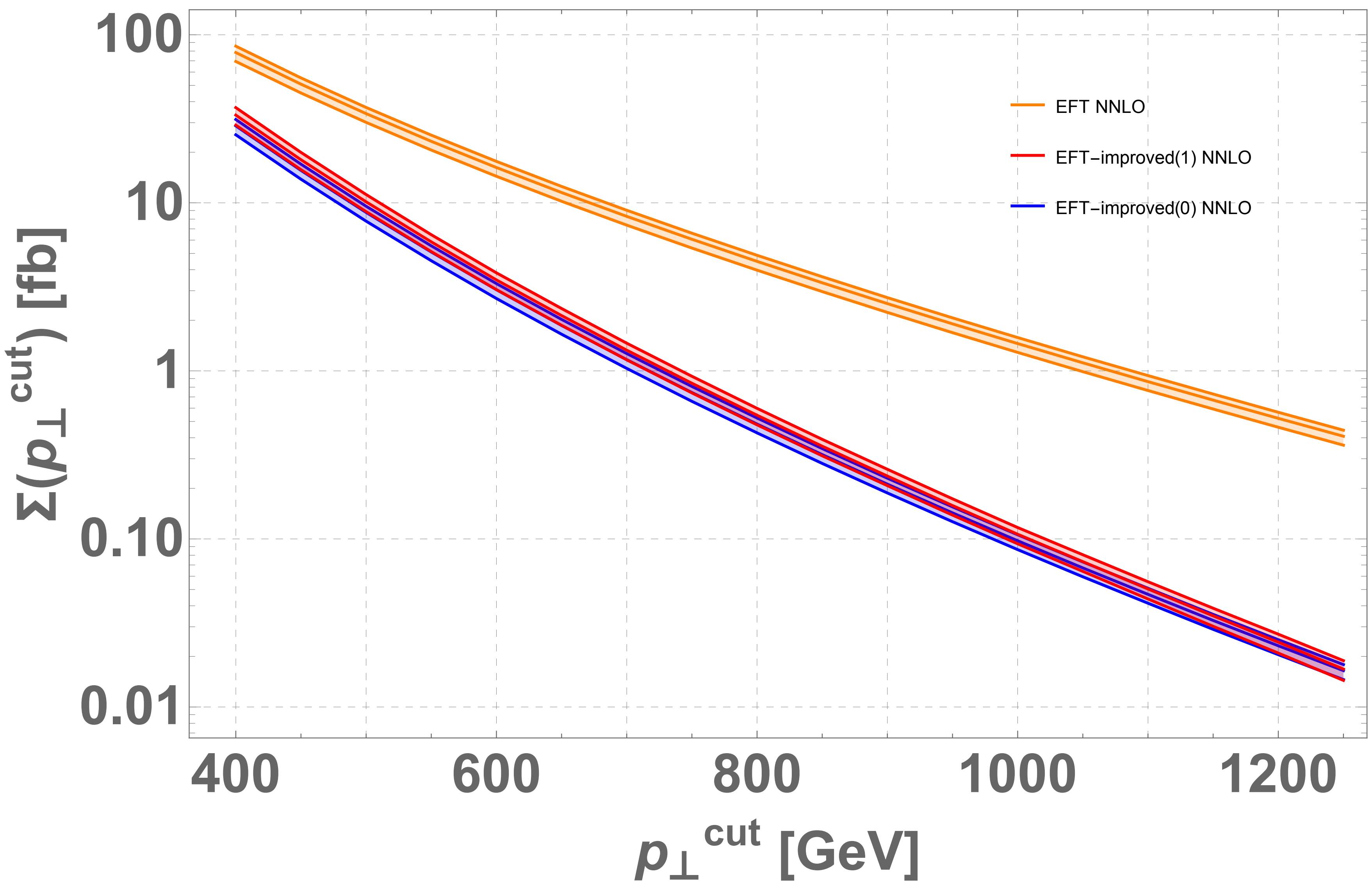
resummation up to NNLL’+NNLO with rapidity dependent jet veto

reduced sensitivity to hadronisation effects

large-pT Higgs + jet production

combine NNLO (HTL) with NLO (full m_t)   (not unique)

$$\Sigma^{\text{EFT-improved (1), NNLO}}(p_\perp^{\text{cut}}) \equiv \frac{\Sigma^{\text{SM, NLO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, NLO}}(p_\perp^{\text{cut}})}\,\Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$



7-point scale variations

red curve also contains estimated δ_{m_t} (on-shell top mass scheme)

Becker et al. 2005.07762

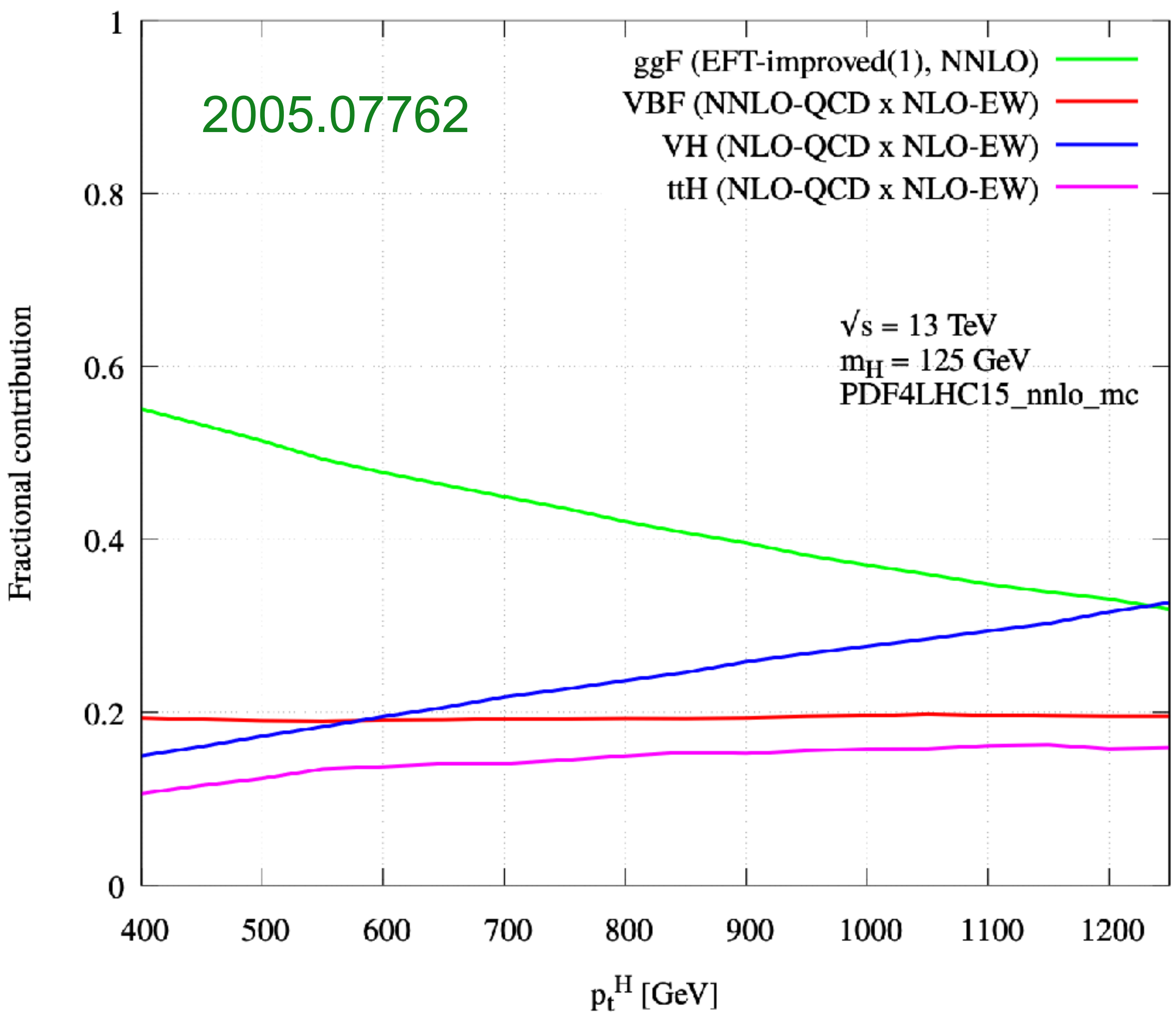
large-pT Higgs + jet production

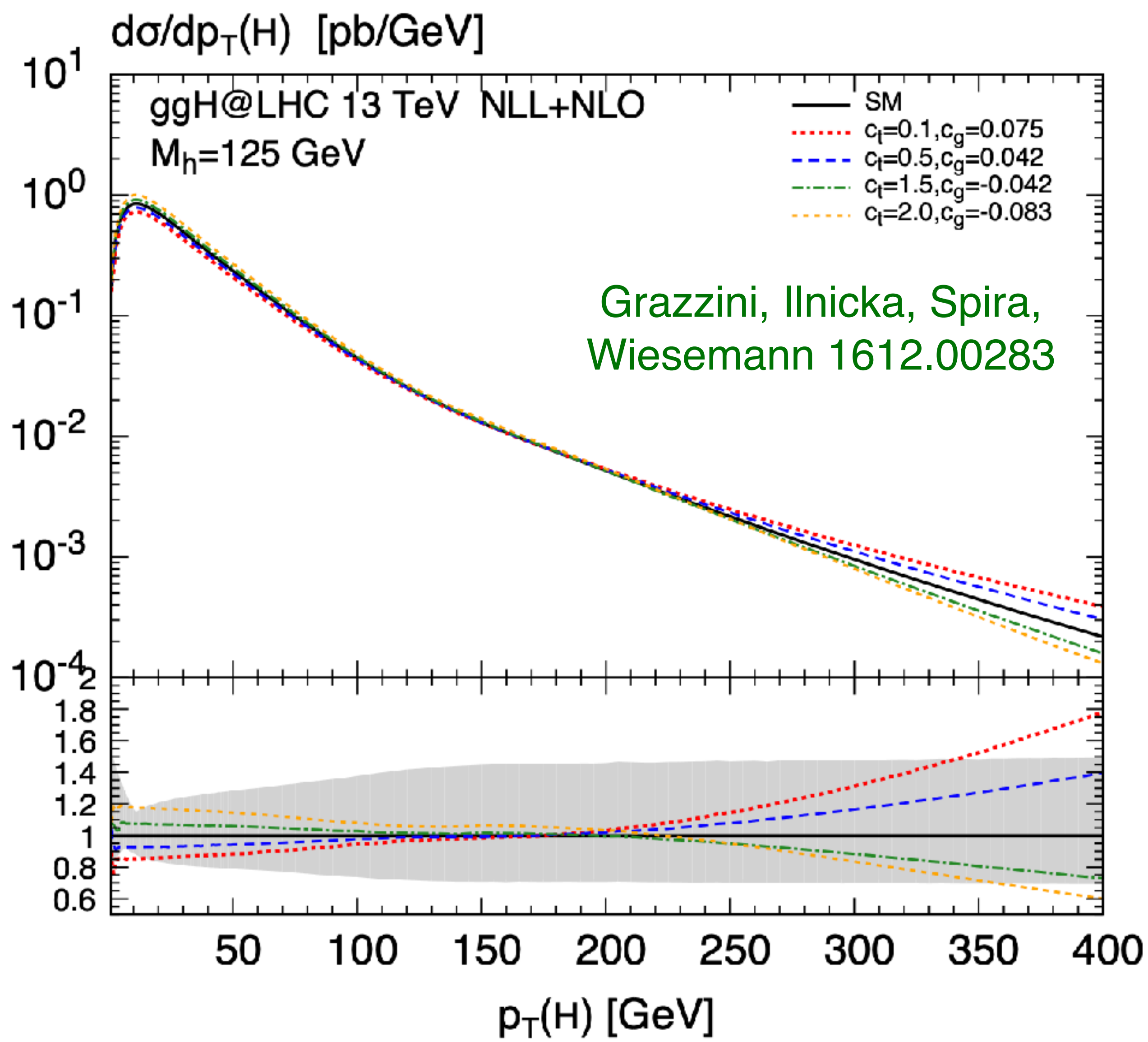
Becker et al. 2005.07762

$p_\perp^{\text{cut}}$	$\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb]	HJ-MINLO [fb]	MG5_MC@NLO [fb]
400 GeV	$33.3^{+10.9\%}_{-12.9\%}$	$29^{+24\%}_{-21\%}$	$31.5^{+31\%}_{-25\%}$
430 GeV	$23.0^{+10.8\%}_{-12.8\%}$	-	$21.8^{+31\%}_{-25\%}$
450 GeV	$18.1^{+10.8\%}_{-12.8\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

reasonable agreement with state-of-the art generators
within (large) uncertainties

large-pT Higgs + jet production





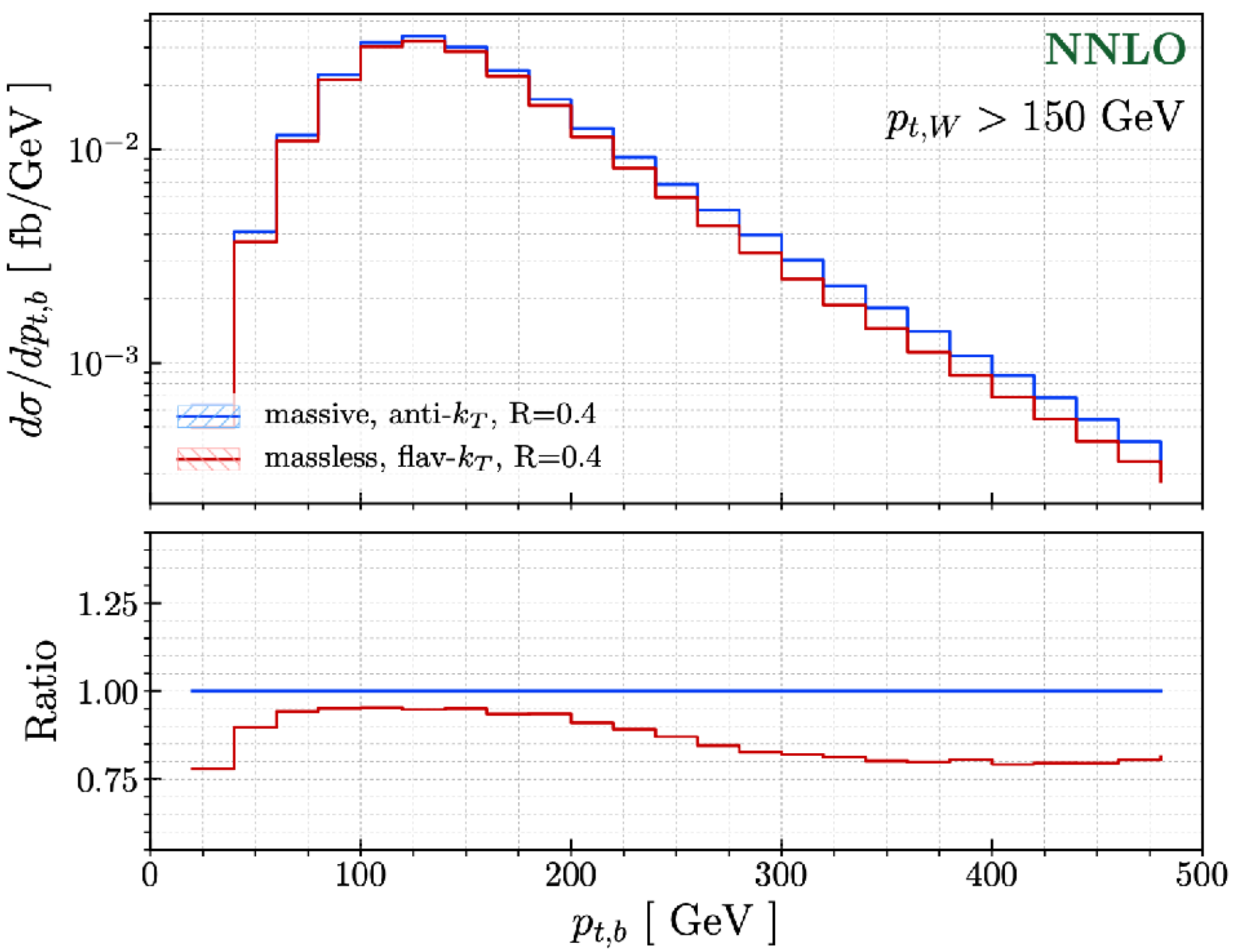
other channels gain importance at large pT, in particular VH

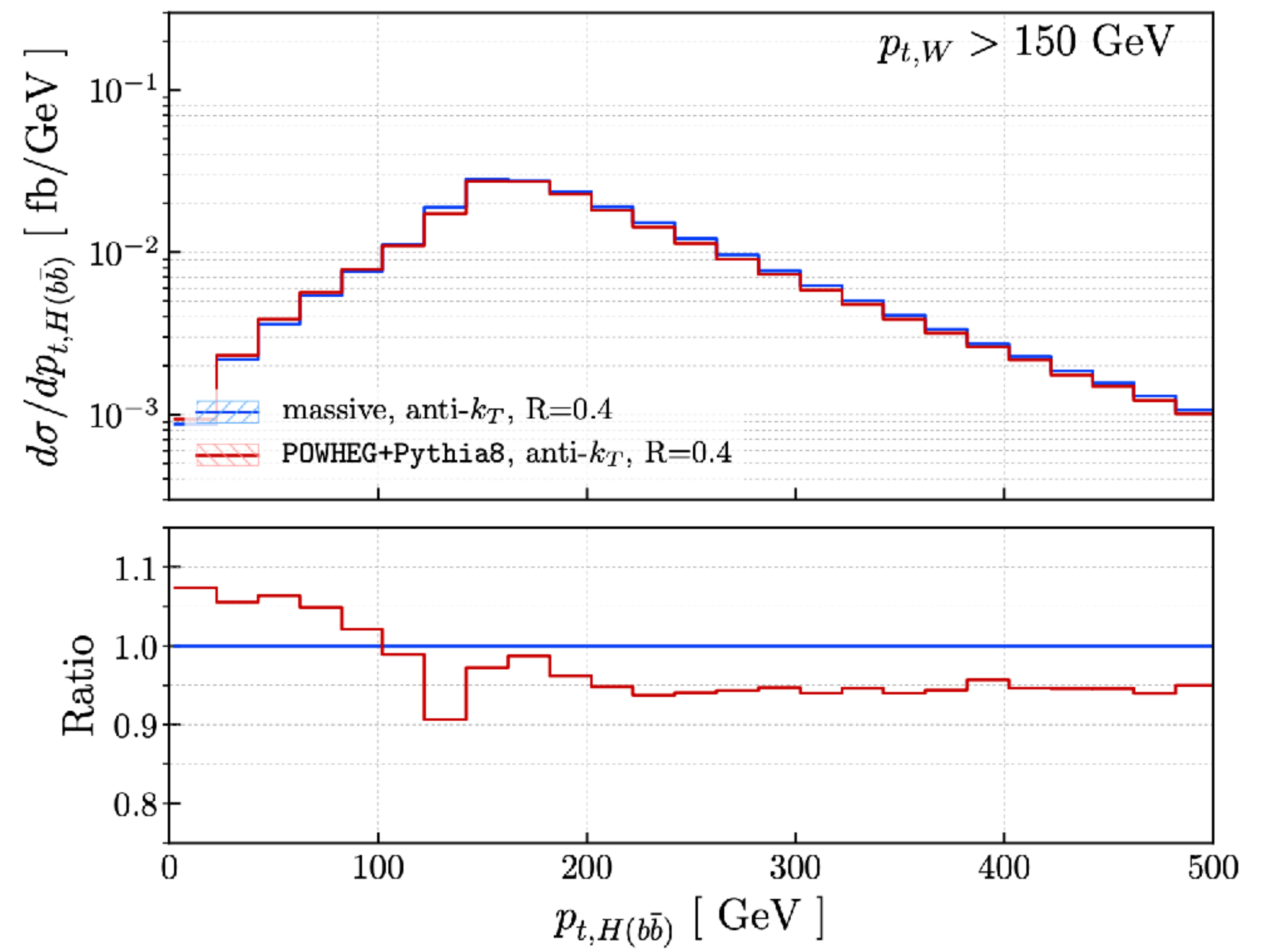
effects of anomalous couplings mostly at high pT

vector bosons associated production

WH production at NNLO with $H \to b\bar{b}$ with massive b-quarks

Behring, Bizon, Caola, Melnikov, Röntsch 2003.08321





significant differences between

massive and massless case

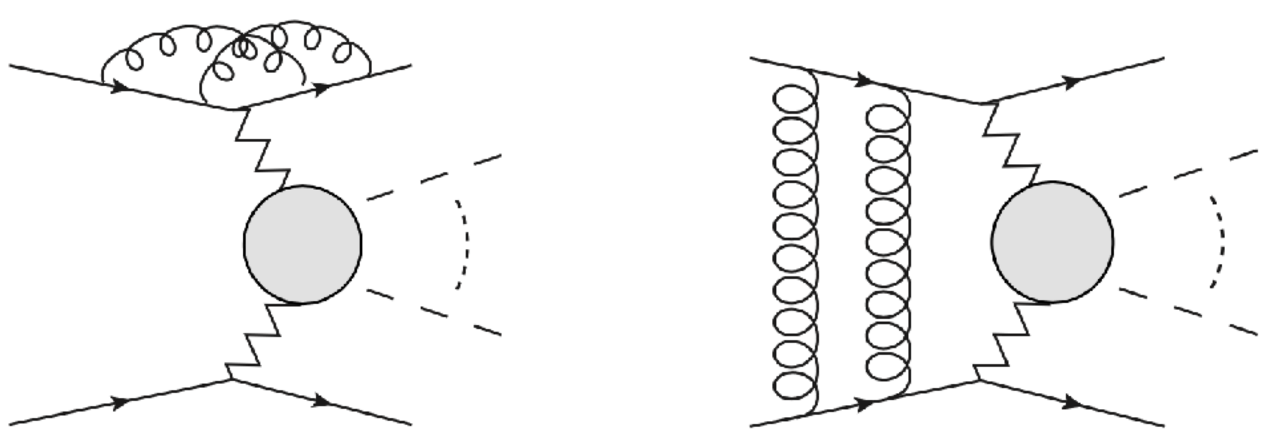
and NNLO vs NLO+PS

H and HH in vector boson fusion

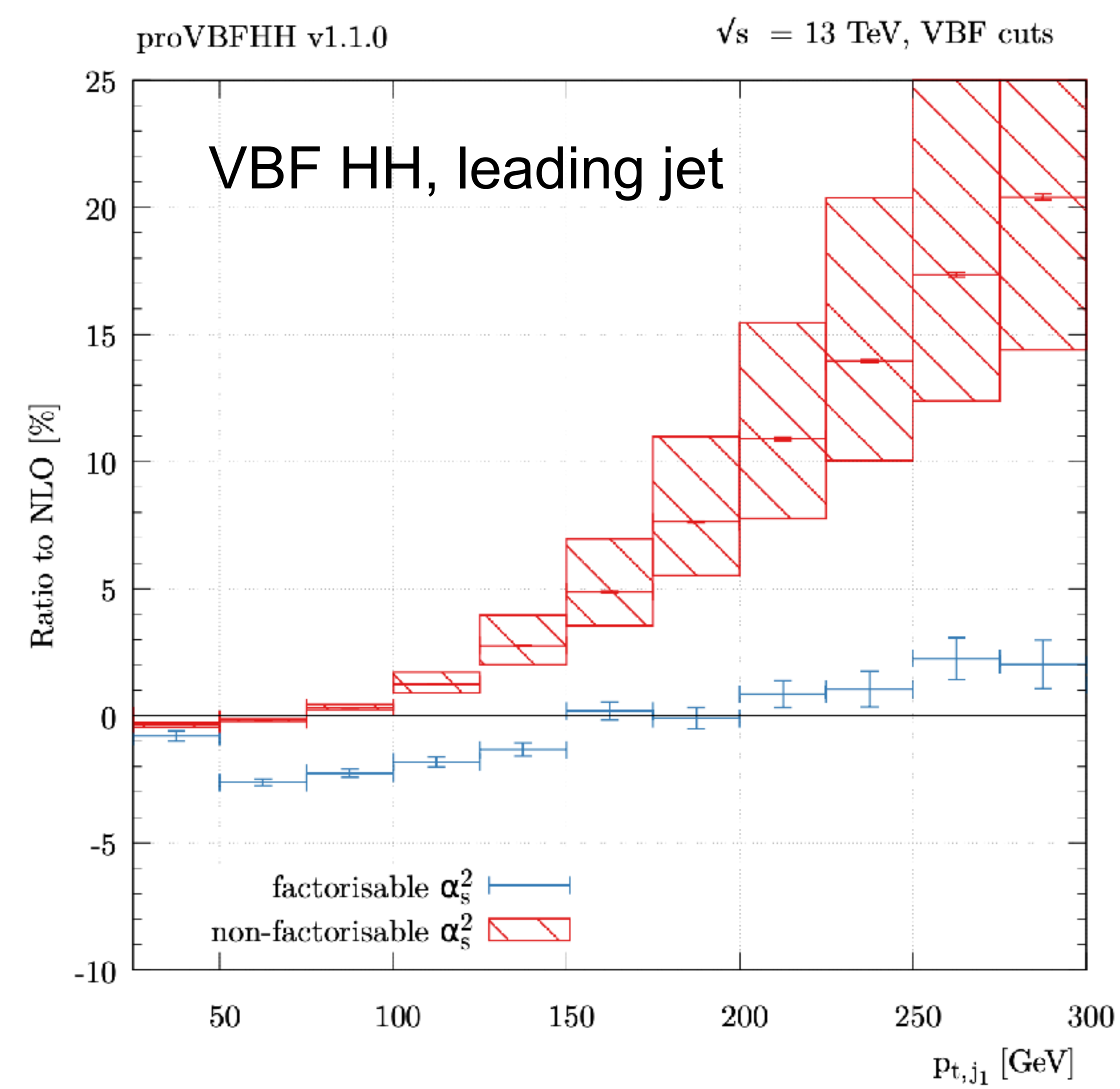
calculated up to N3LO in structure function approach Dreyer, Karlberg '16 (H), '18 (HH)

non-factorisable contributions to VBF H Lui, Melnikov, Penin 1906.10899

non-factorisable contributions to VBF H and HH Dreyer, Karlberg, Tancredi 2005.11334



factorisable non-factorisable

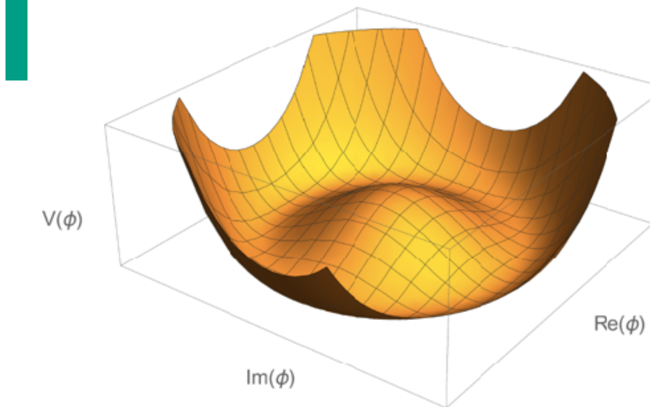


VBF H: non-factorisable corrections (mostly) within scale uncertainty band

VBF HH: cancellation among diagrams spoiled by non-factorisable corrections

⇒ relative size large

The Higgs Potential



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

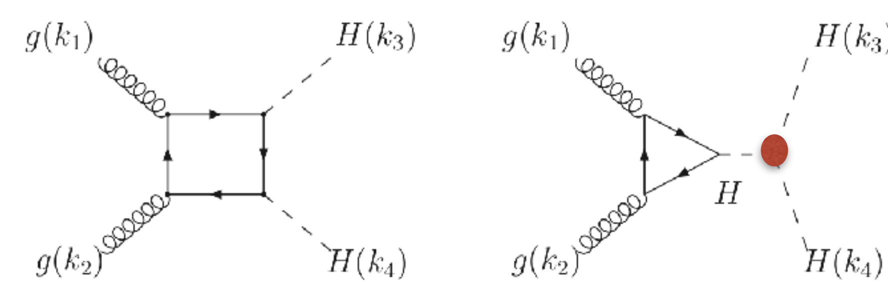
EW symmetry breaking

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

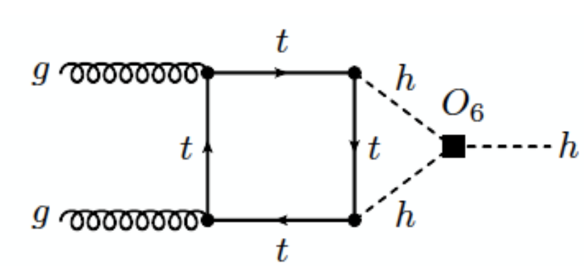
λ_{3h} completely determined in the SM

- is it really of this form?
- how large (or small) can the triple Higgs coupling be?

try to get information from



- non-resonant HH production (direct measurement)
- indirect constraints (e.g. from single H)



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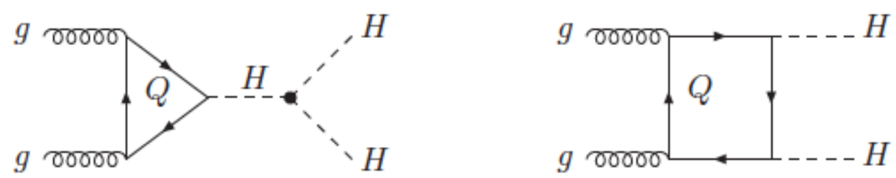
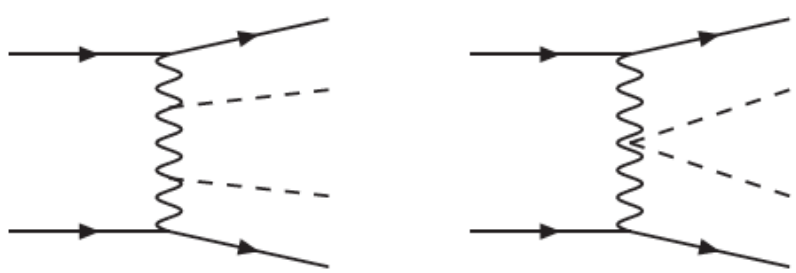
HH production channels

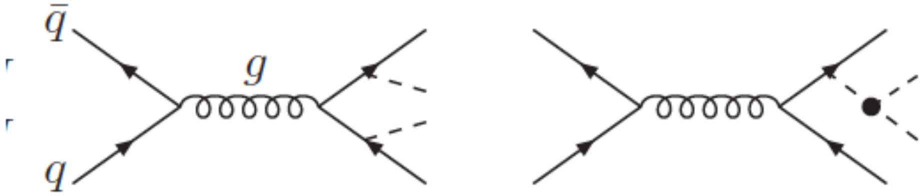
- gluon fusion



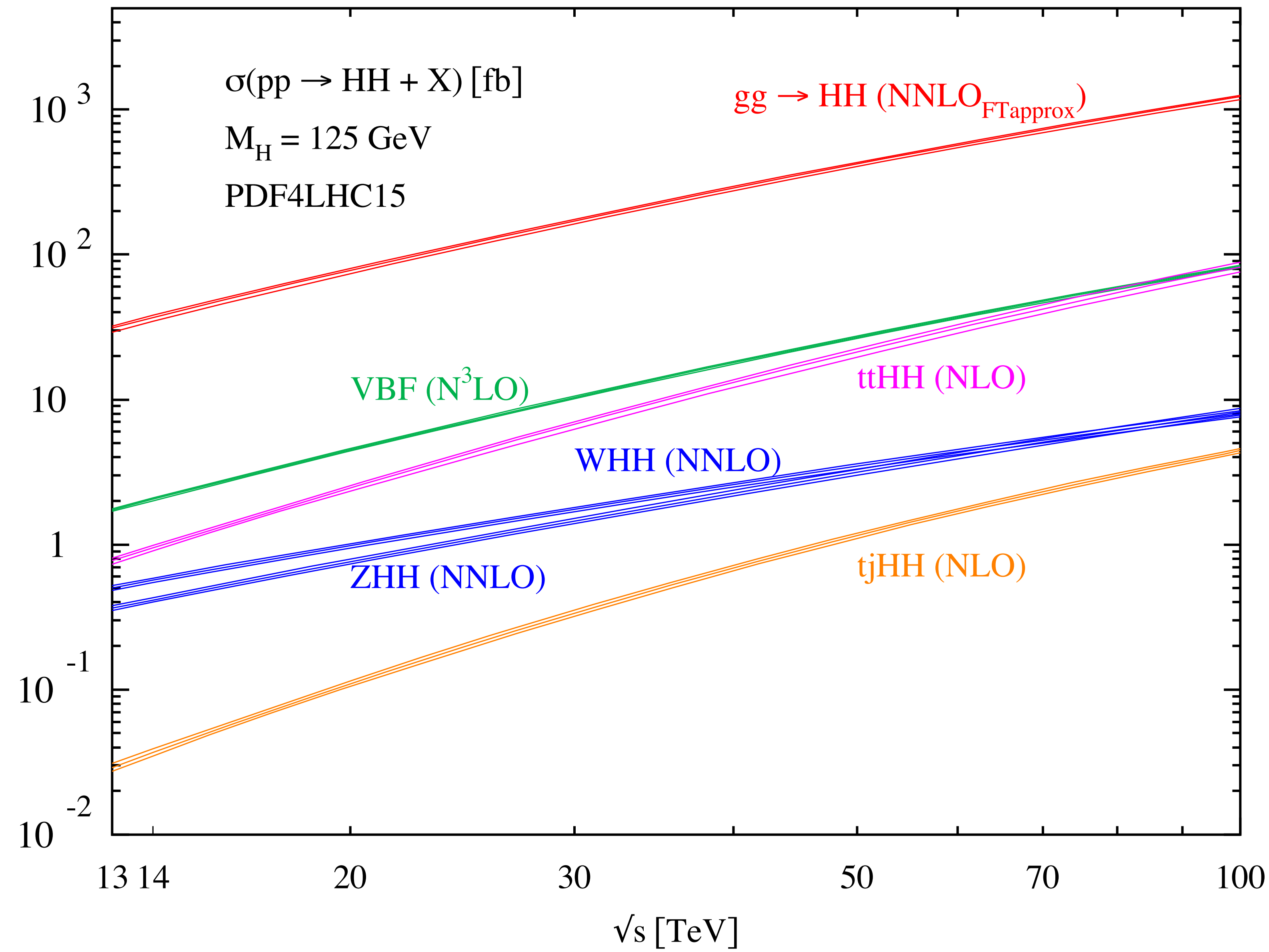
- vector boson fusion



- top-quark associated



- Higgs-strahlung



LHC Higgs WG YR4
1610.07922

Higgs boson pair production in gluon fusion

current status:

N3LO: Chen, Li, Shao, Wang '19
(HTL with mt effects)

NNLO: De Florian, Mazzitelli '13
Grigo, Melnikov, Steinhauser '14

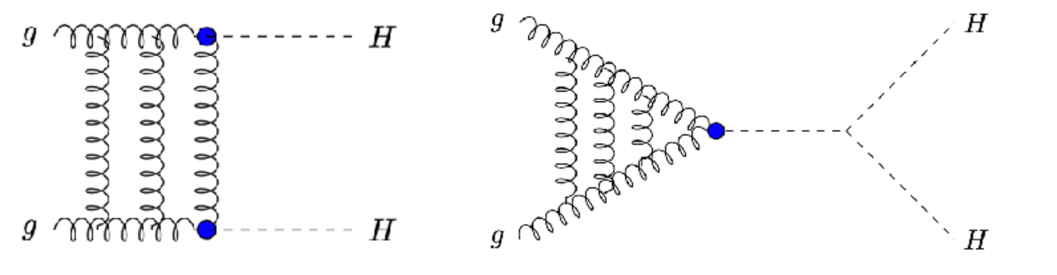


image: S. Borowka

$\mathrm{NNLO}_{\mathrm{FTapprox}}$

current recommendation of LHC Higgs Working Group

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

NLO full m_t

Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16

Baglio, Campanario, Glaus Mühlleitner, Spira, Streicher '18

Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19

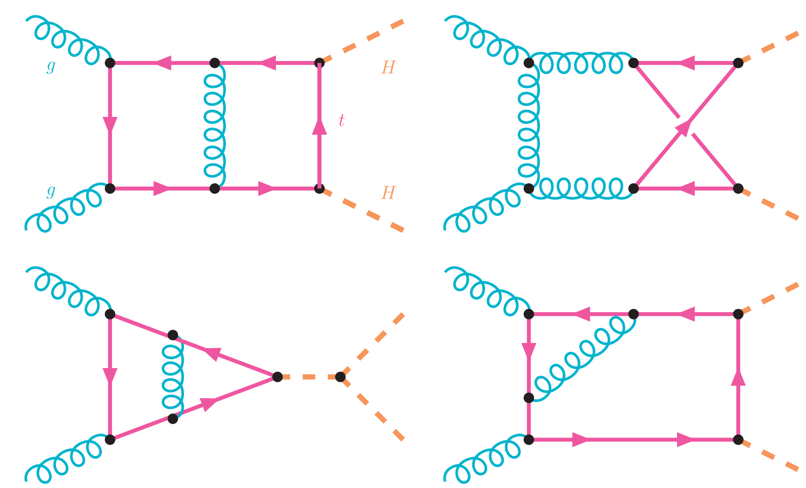


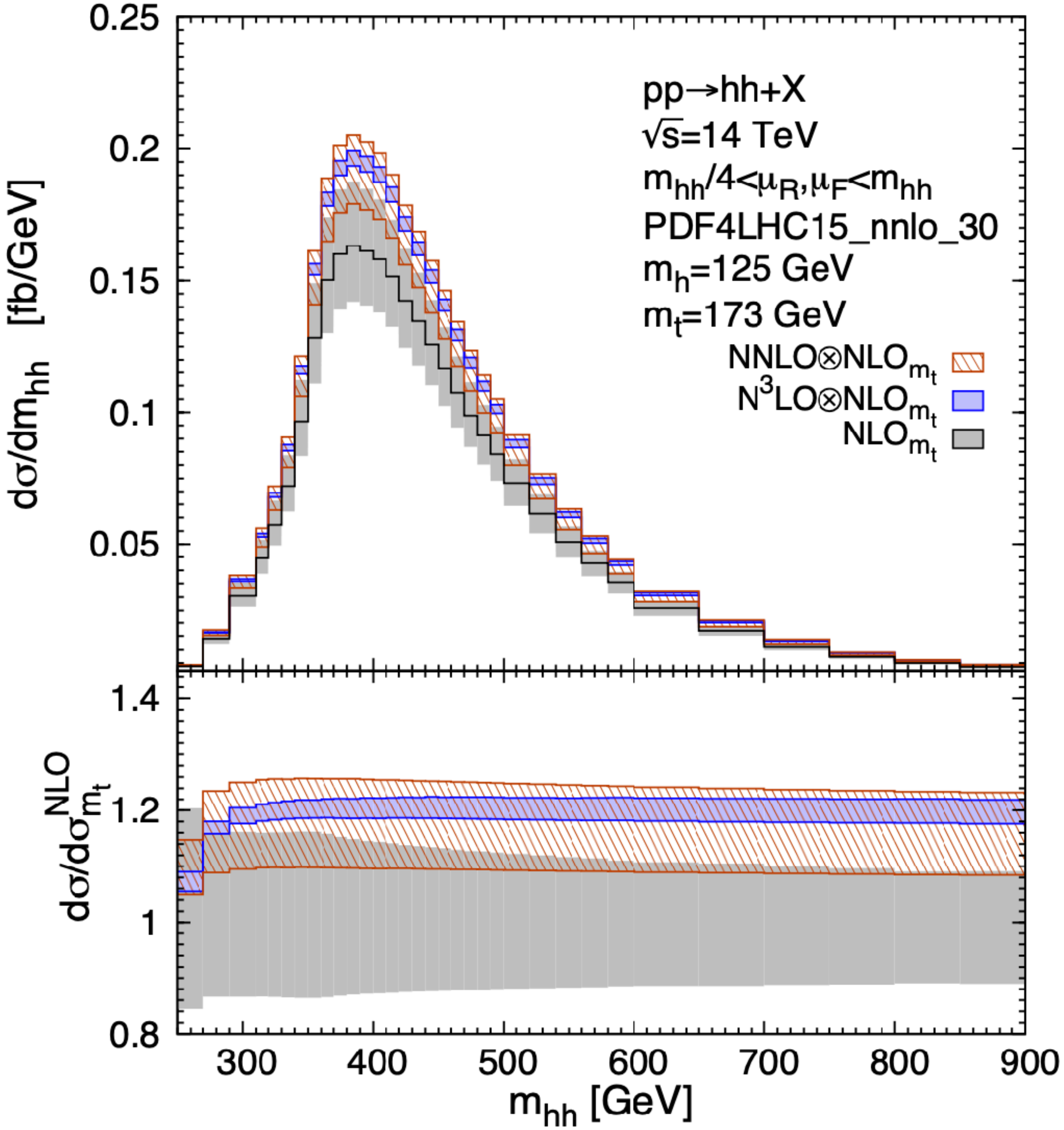
image: S. Jones

top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

Baglio, Campanario, Glaus Mühlleitner, Ronca, Spira 2008.11626

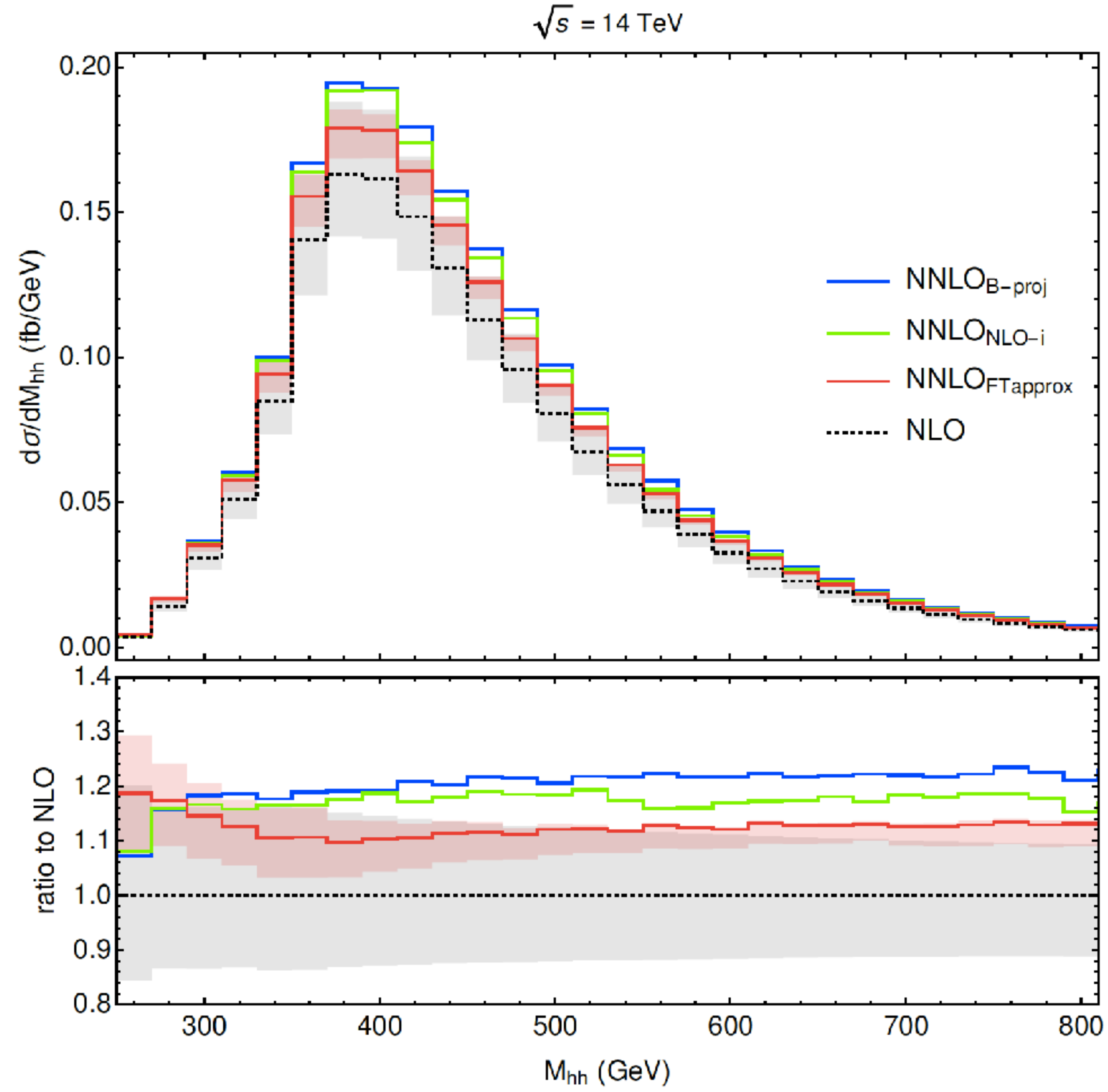
Higgs boson pair production in gluon fusion

Chen, Li, Shao, Wang 1912.13001



$\sqrt{s} = 14$ TeV

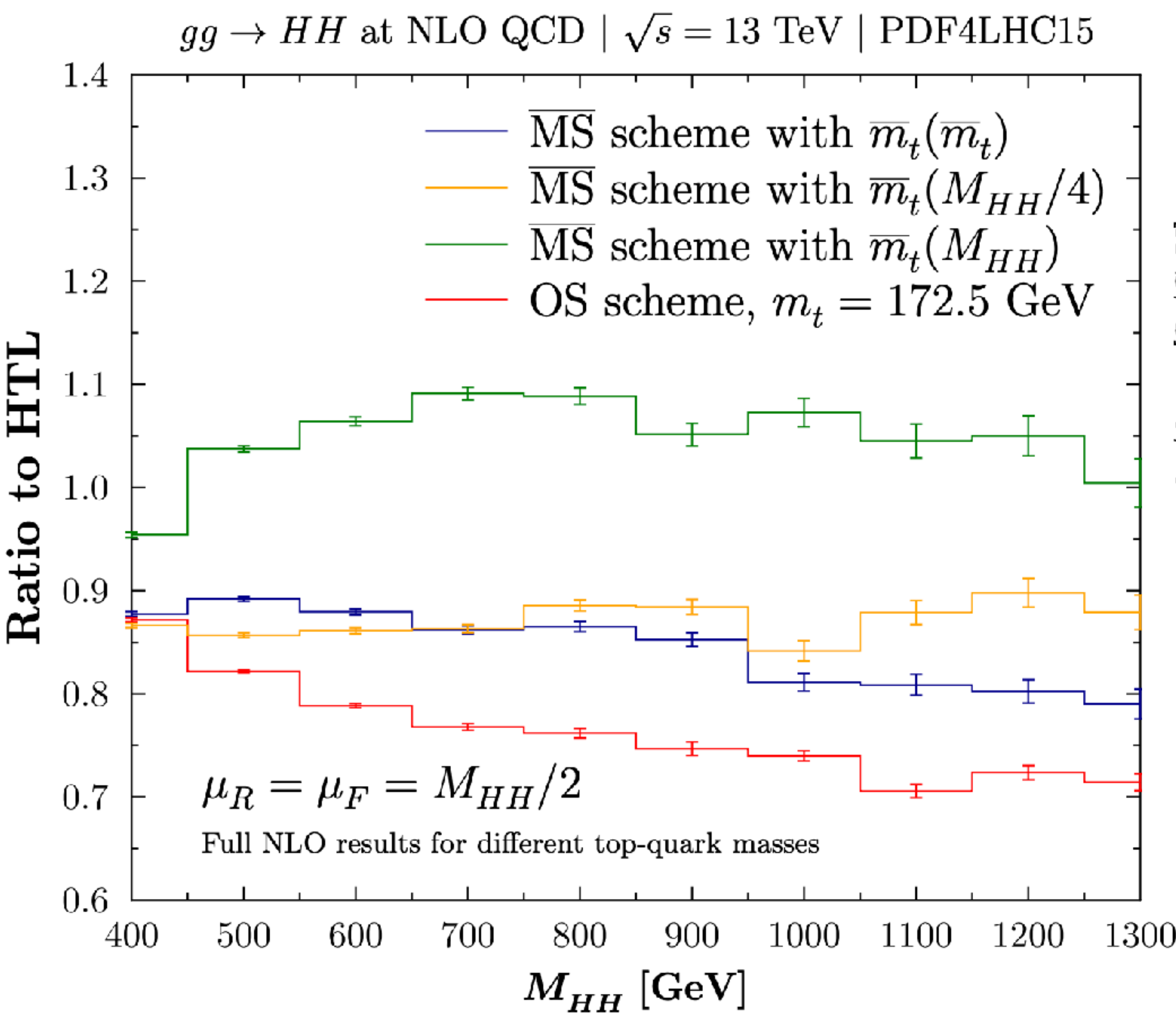
Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli 1803.02463

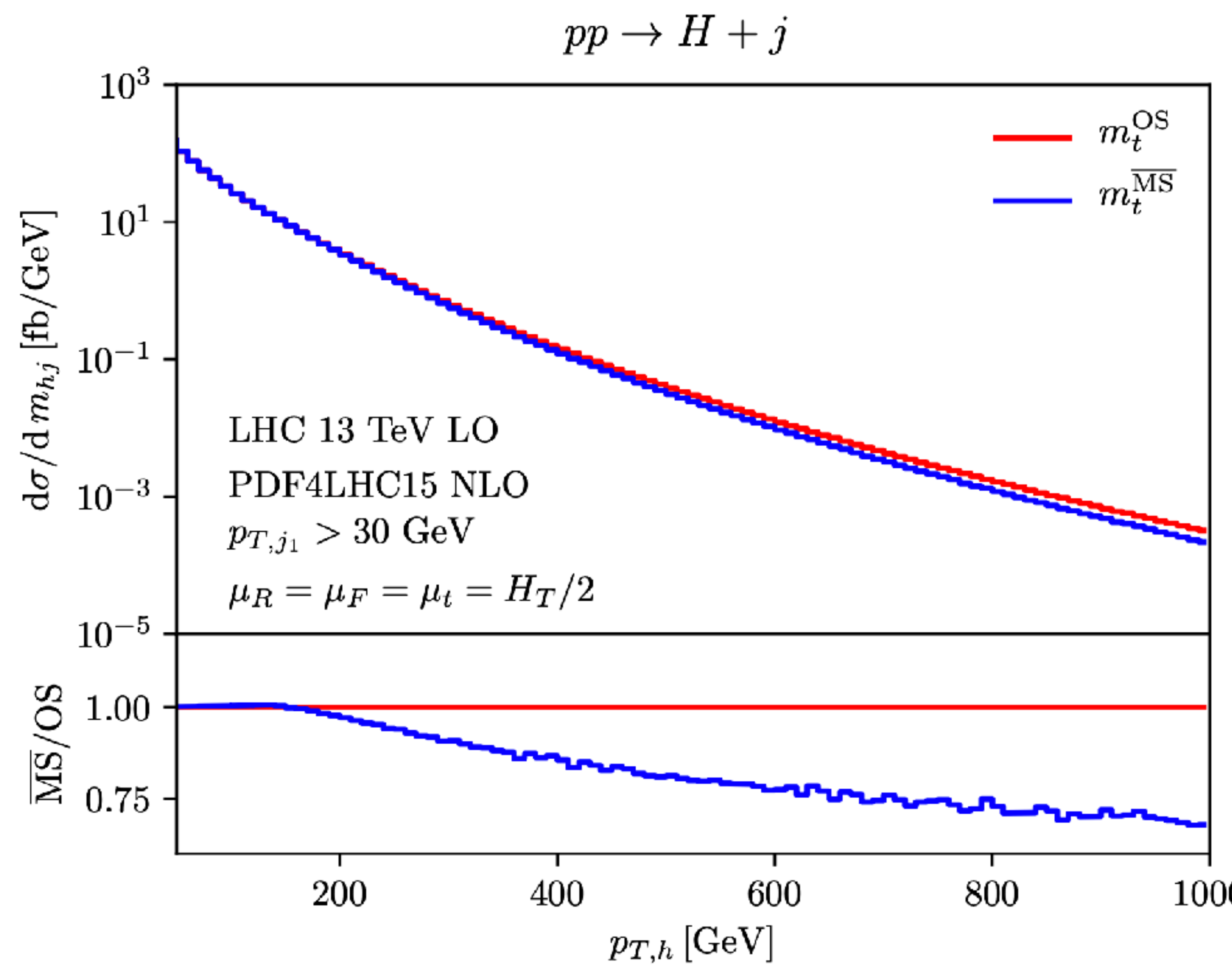


scheme dependence

$$\overline{m}_t(m_t) = \frac{m_t}{1 + \frac{4}{3}\frac{\alpha_s(m_t)}{\pi} + K_2\left(\frac{\alpha_s(m_t)}{\pi}\right)^2 + K_3\left(\frac{\alpha_s(m_t)}{\pi}\right)^3}$$

relation between pole mass and $\overline{\text{MS}}$ mass





Baglio, Campanario, Glaus Mühlleitner, Ronca, Spira 2008.11626

also present in other loop induced processes

Jones, Spira Les Houches 2019

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HH at NLO within EFT

SMEFT:

$$\Delta\mathcal{L}_{\rm dim6} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \text{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3$$
$$+ \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}t_R + \text{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\,G^a_{\mu\nu}G^{a\mu\nu}$$

HEFT (non-linear EFT):

$$\Delta\mathcal{L}_{d\chi\leq 4} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3$$
$$+ \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

SMEFT relations: $c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u\,,\quad c_{tt} = -\frac{\bar{c}_H + 3\bar{c}_u}{2}\,,\quad c_{hhh} = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6\,,$

$$c_{ggh} = 2c_{gghh} = 128\pi^2\bar{c}_g\ .$$

HH K-factors

K-factors as functions of the BSM couplings

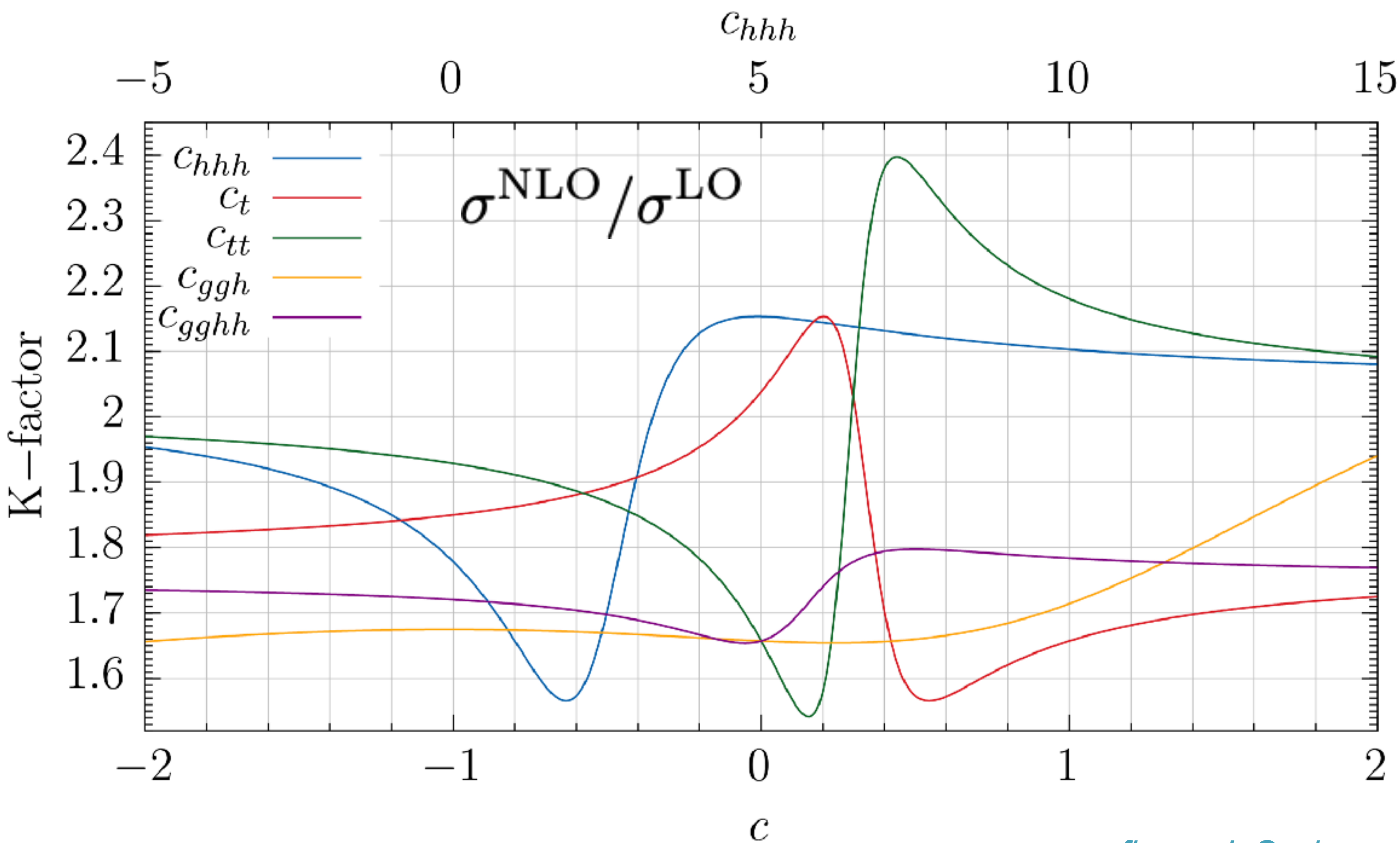


figure: L.Scyboz

vary substantially (much less variation in heavy top limit)

HH full NLO MC tool

- Monte Carlo program (within Powheg-Box) to produce full NLO results for Higgs pair production in gluon fusion

  GH, Jones, Kerner, Luisoni, Scyboz 2006.16887,1903.08137

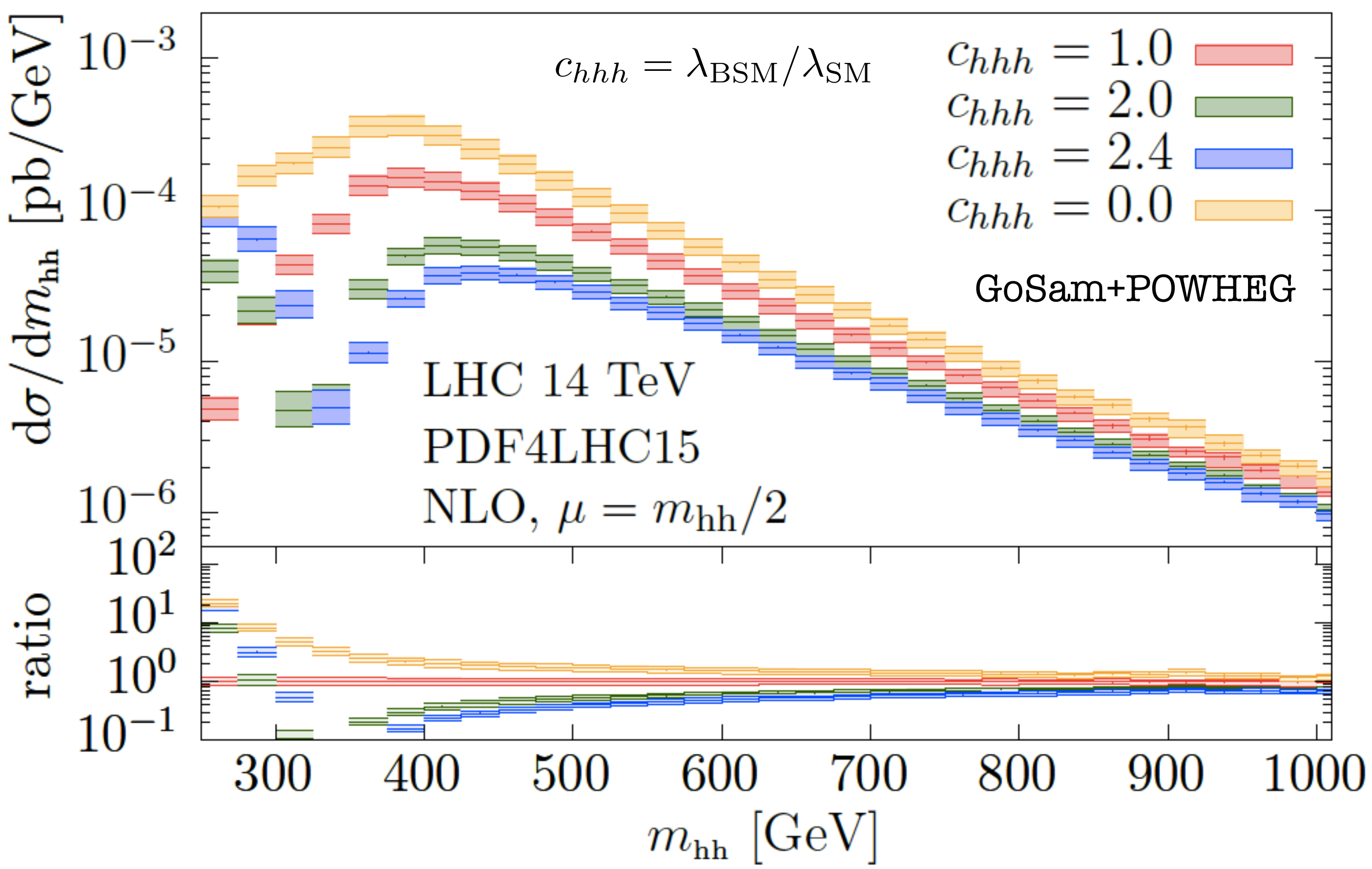
- interface to Pythia and two different Herwig parton showers

- 5 anomalous couplings $c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}$ can be varied by the user

- publicly available at

http://powhegbox.mib.infn.it/User-Process-V2/ggHH

HH invariant mass with variation of the self-coupling

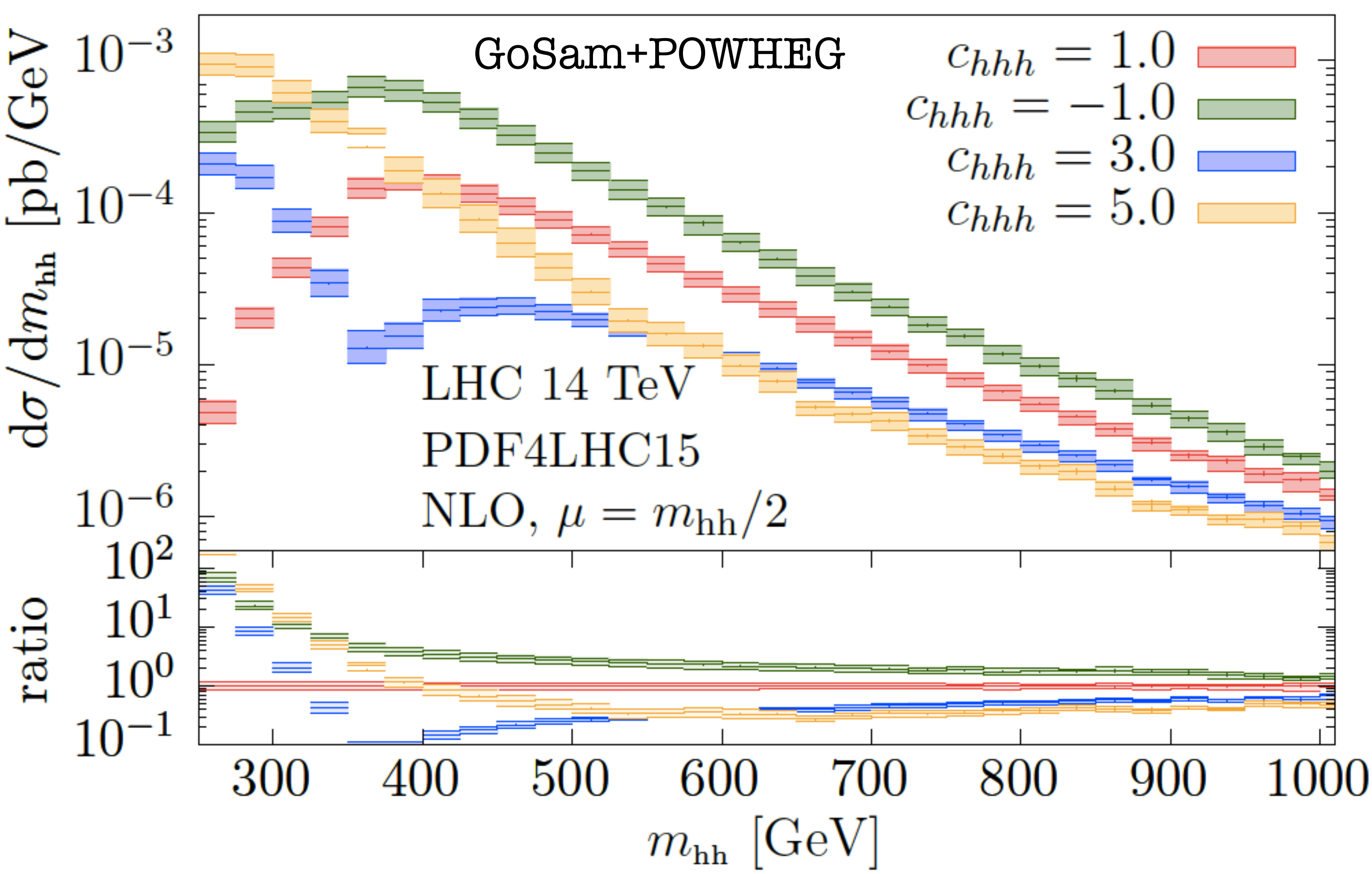


dip in m_{hh} distribution

at 350 GeV for c_{hhh} ~ 2.4

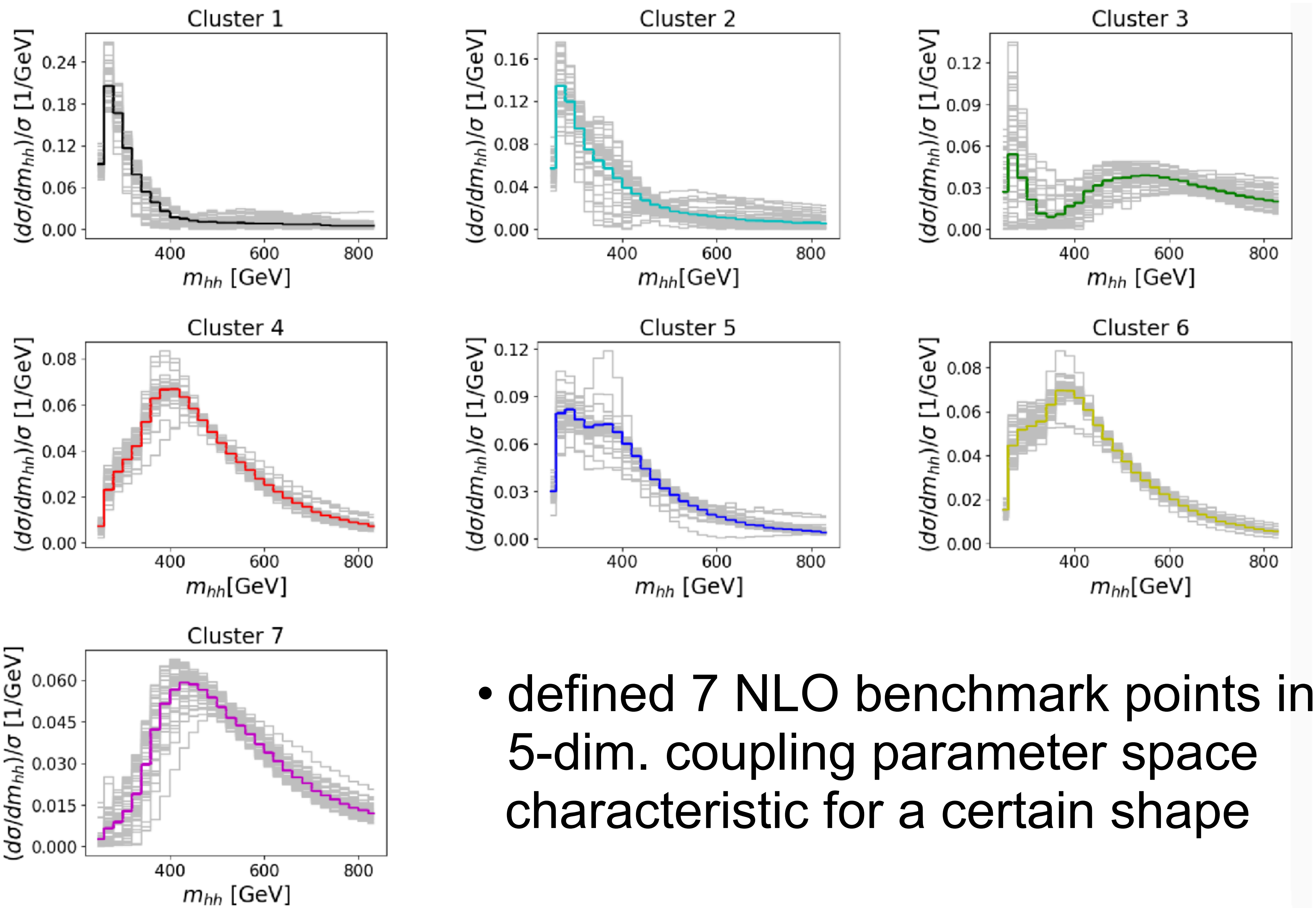
due to maximal destructive interference

bands: 3-point scale variations



Karlsruhe Institute of Technology

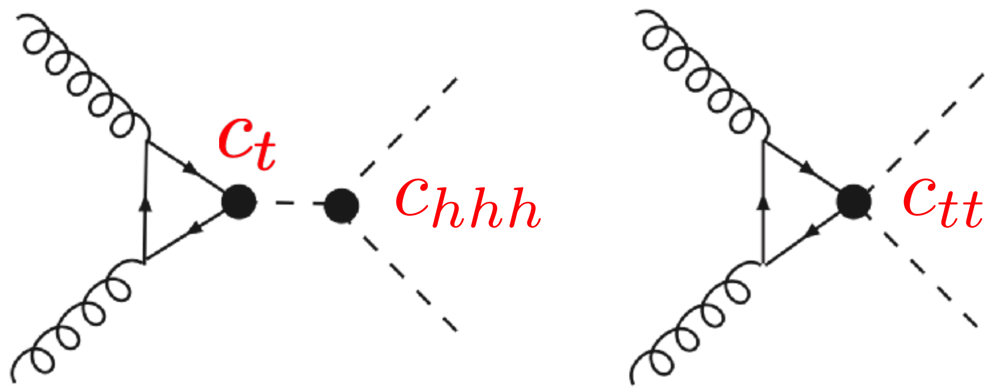
m_{hh} shape analysis

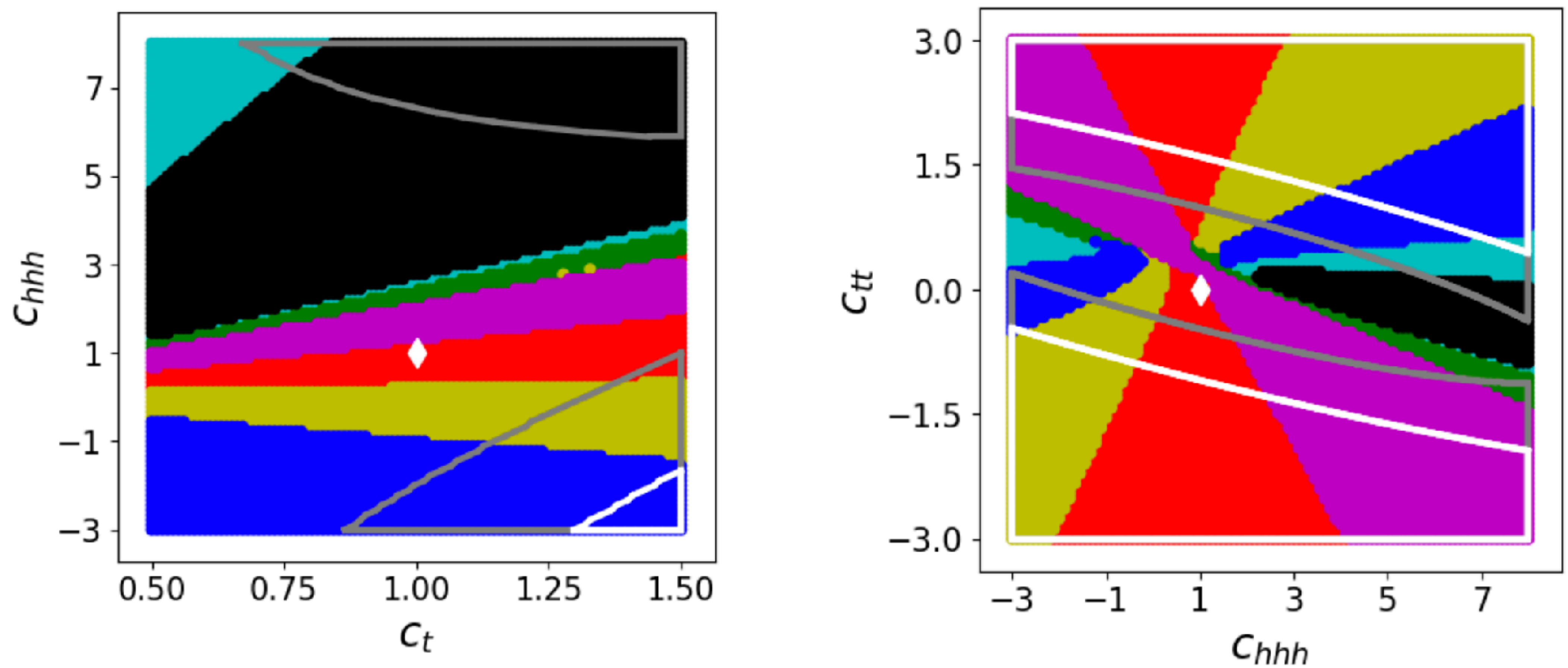


- defined 7 NLO benchmark points in 5-dim. coupling parameter space characteristic for a certain shape

- based on autoencoder and K-means clustering Capozi, GH 1908.08932

m_{hh} shape analysis





c_{hhh} and c_{tt} have strong influence on shape

shape combined with bounds on total σ gives better constraints

Summary

- the Higgs sector might offer windows to new physics
- precision is the key at current energies
- great progress in precision calculations

  for some processes scale uncertainties no longer the dominant uncertainties

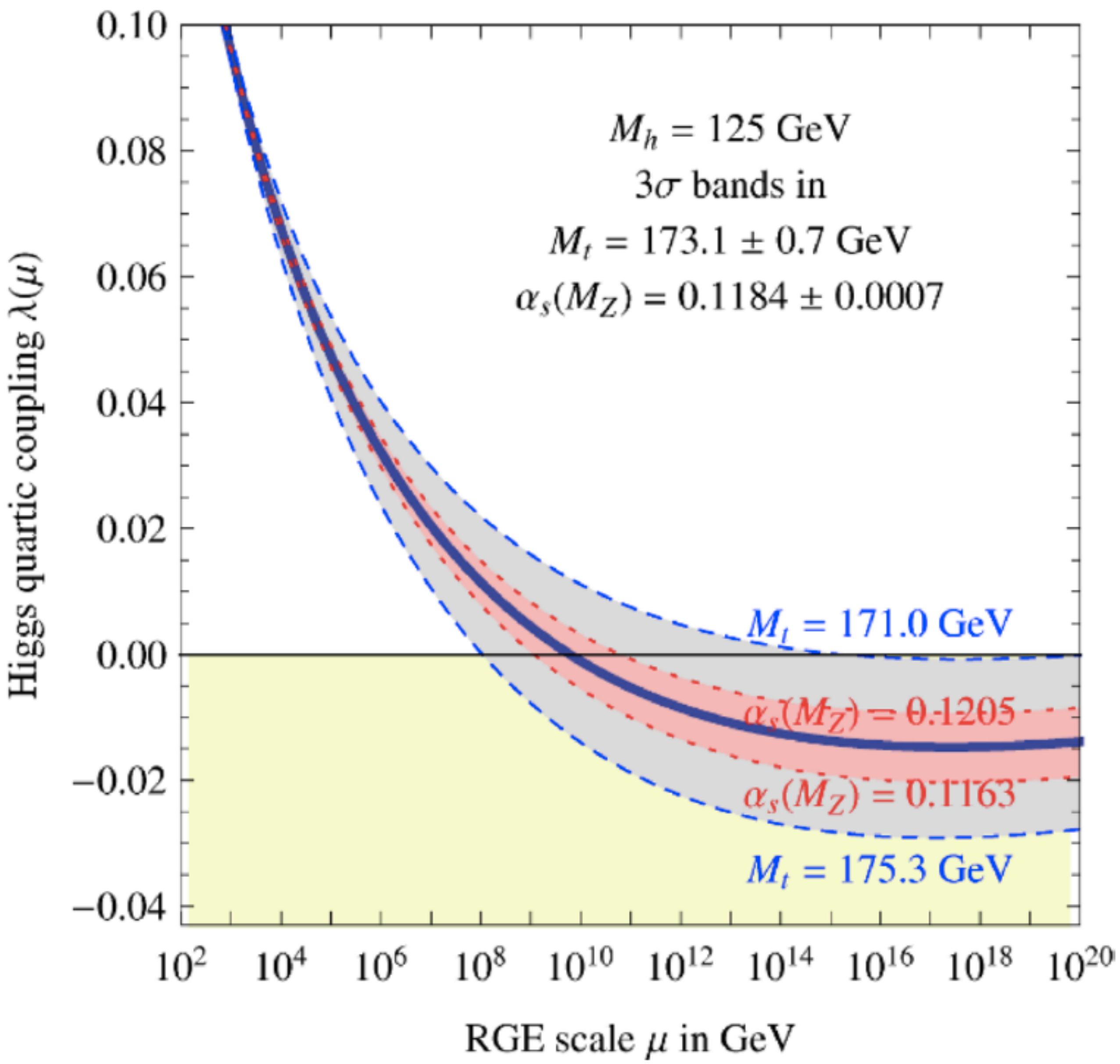
- current main challenges:
  - mass effects
  - mixed EW-QCD corrections
  - $2 \to 3$ processes at NNLO
  - reduce PDF, α_s-uncertainties
  - NNLO+PS/analytic resummation
  - BSM, EFT + higher orders

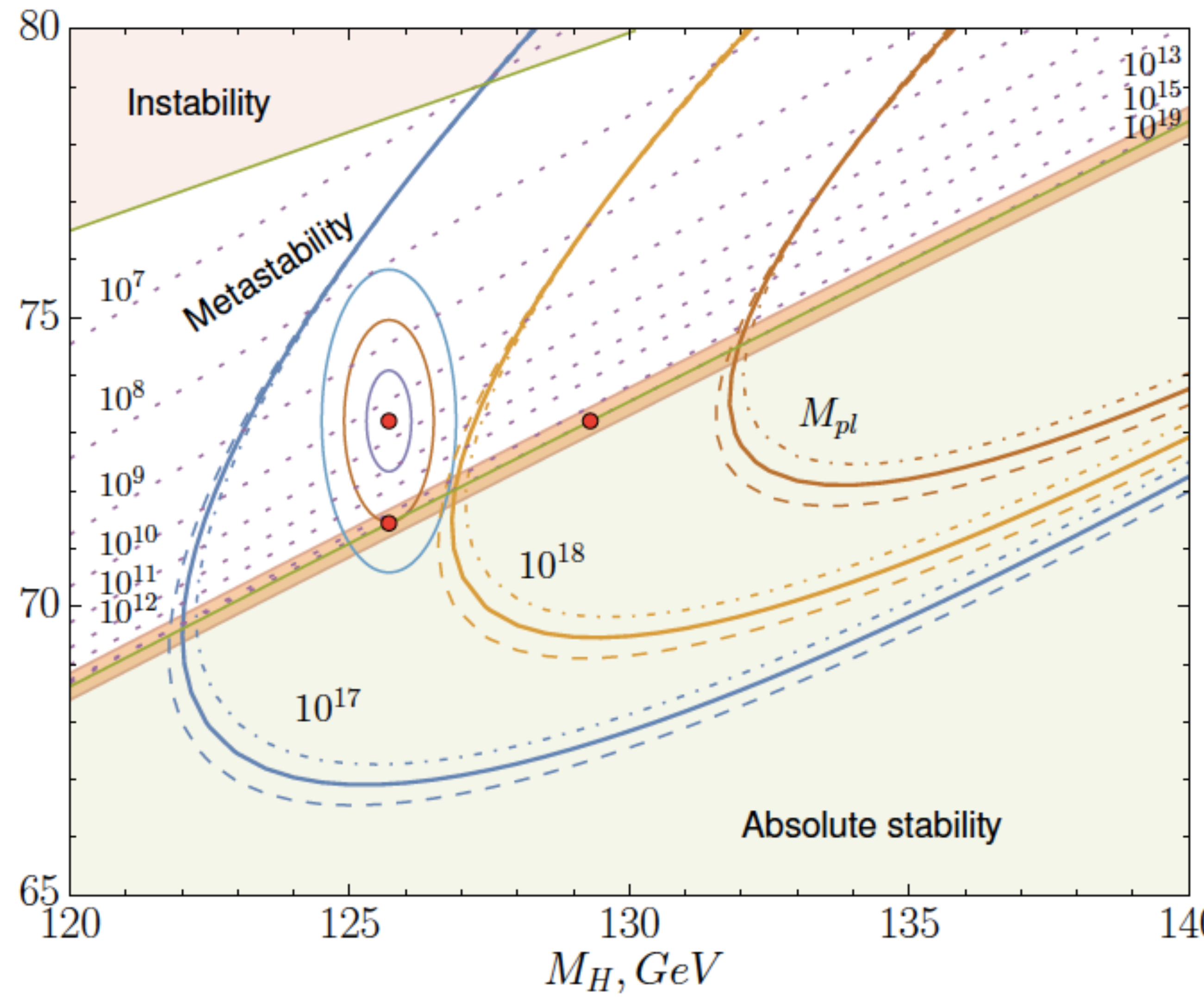
The Standard Model is unlikely to be the full picture

with precision we may see imprints of physics at higher scales!

(e.g. watch the shadows)

Higgs and the universe





Bednyakov, Kniehl, Pikelner, Veretin '15

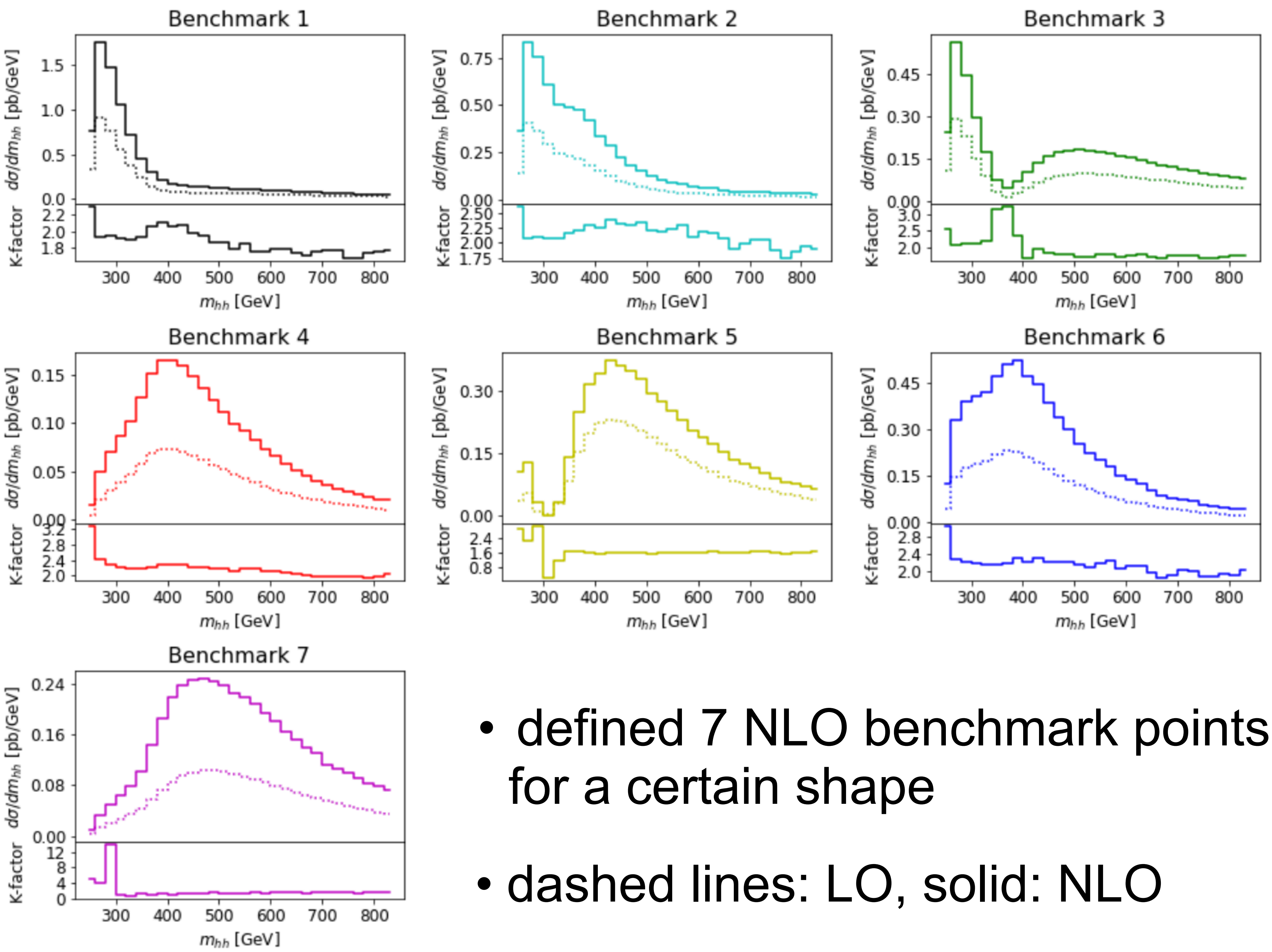
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia '13

$\lambda = \lambda(\mu)$ is a running coupling (through quantum corrections, in the SM dominated by top and Higgs loops)

HH shape analysis

Capozi, GH 1908.08932

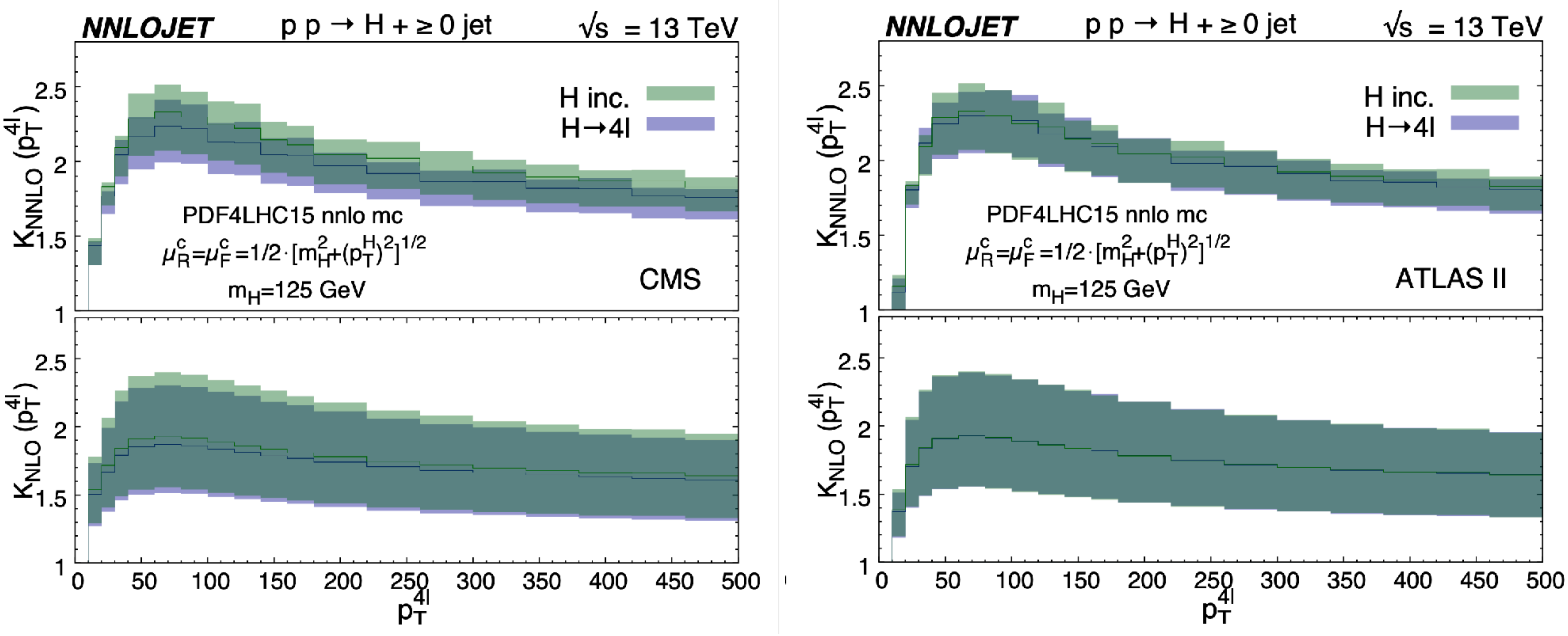


- defined 7 NLO benchmark points characteristic for a certain shape
- dashed lines: LO, solid: NLO

ggF H NNLO differential results

$$pp \to H + \leq 1\,j \to 4l + \leq 1\,j$$

Chen, Gehrmann, Glover, Huss
1905.13738



study of perturbative stability of lepton acceptance cuts

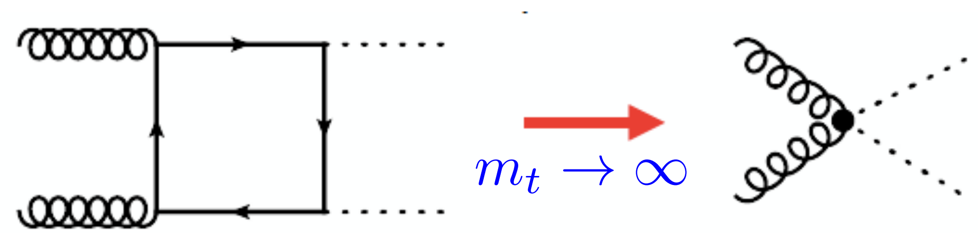
Invariant mass of the Higgs boson pair

Observable: $m_{hh}^2 = (p_{h_1} + p_{h_2})^2$

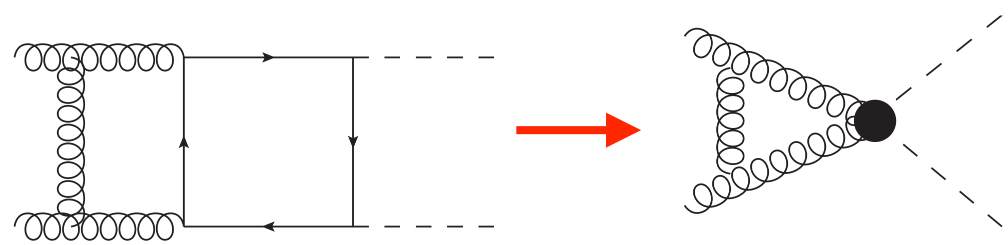
approximations:

- $m_t \to \infty$ limit (HEFT):

  ("Higgs Effective Field Theory")



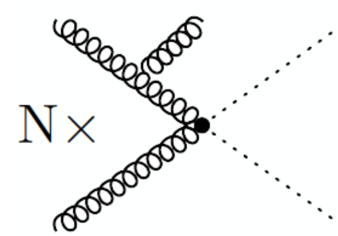
Leading Order (LO)



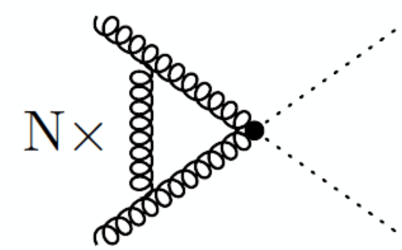
Next-to-Leading Order (NLO)

- Born-improved HEFT:

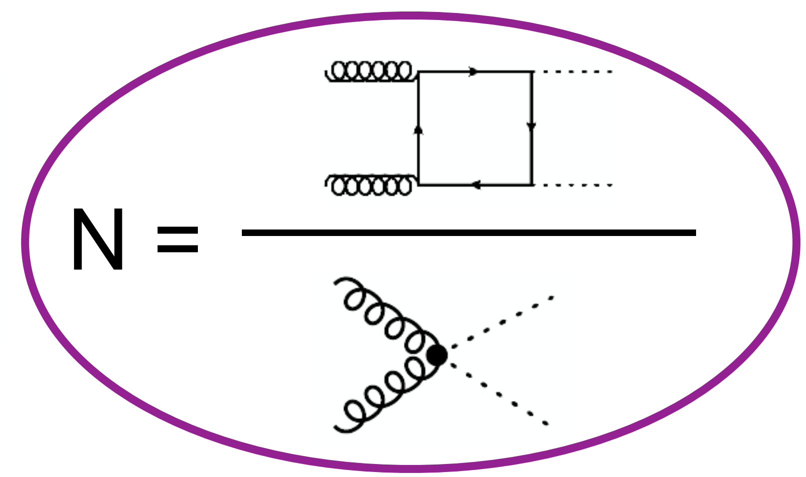
$$d\sigma^{\mathrm{NLO}}_{m_t \to \infty} \times \frac{d\sigma^{\mathrm{LO}}(m_t)}{d\sigma^{\mathrm{LO}}_{m_t \to \infty}}$$



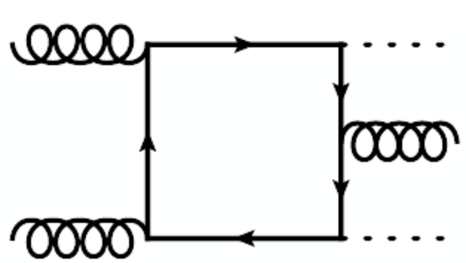
NLO real

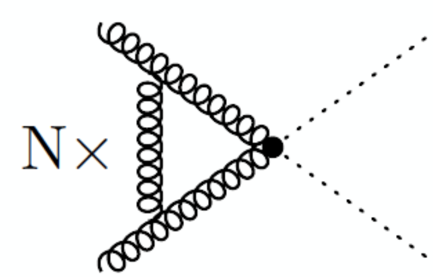


NLO virtual



- FTapprox:





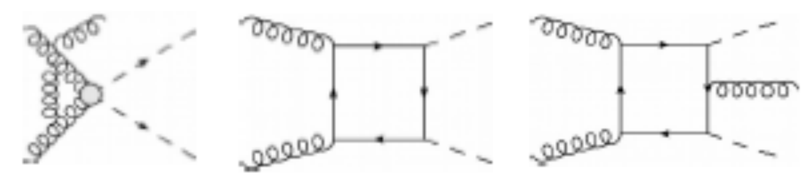
NLO real:
full m_t-dependence

NLO virtual:
Born-improved HEFT

full NLO combined wit NNLO

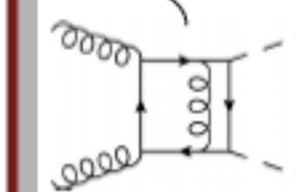
Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli; 1803.02463

Technical ingredients

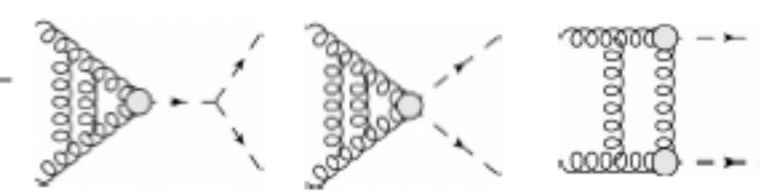


Tree-level and one-loop amplitudes (HEFT and full-M_t) → OpenLoops
[Cascioli, Lindert, Maierhofer, Pozzorini]

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



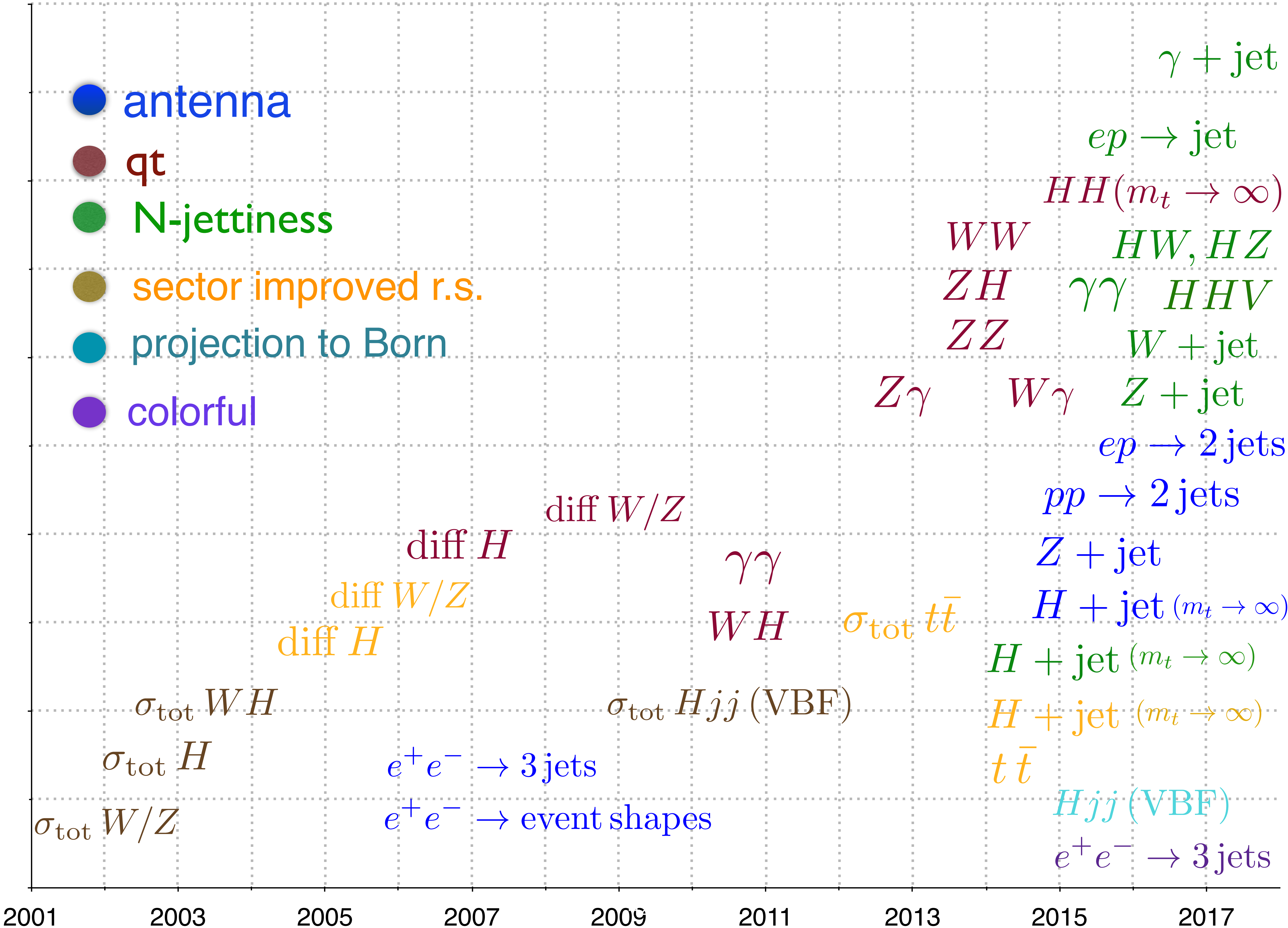
Analytical results for NNLO two-loop corrections in the HEFT
[de Florian, JM, '13]



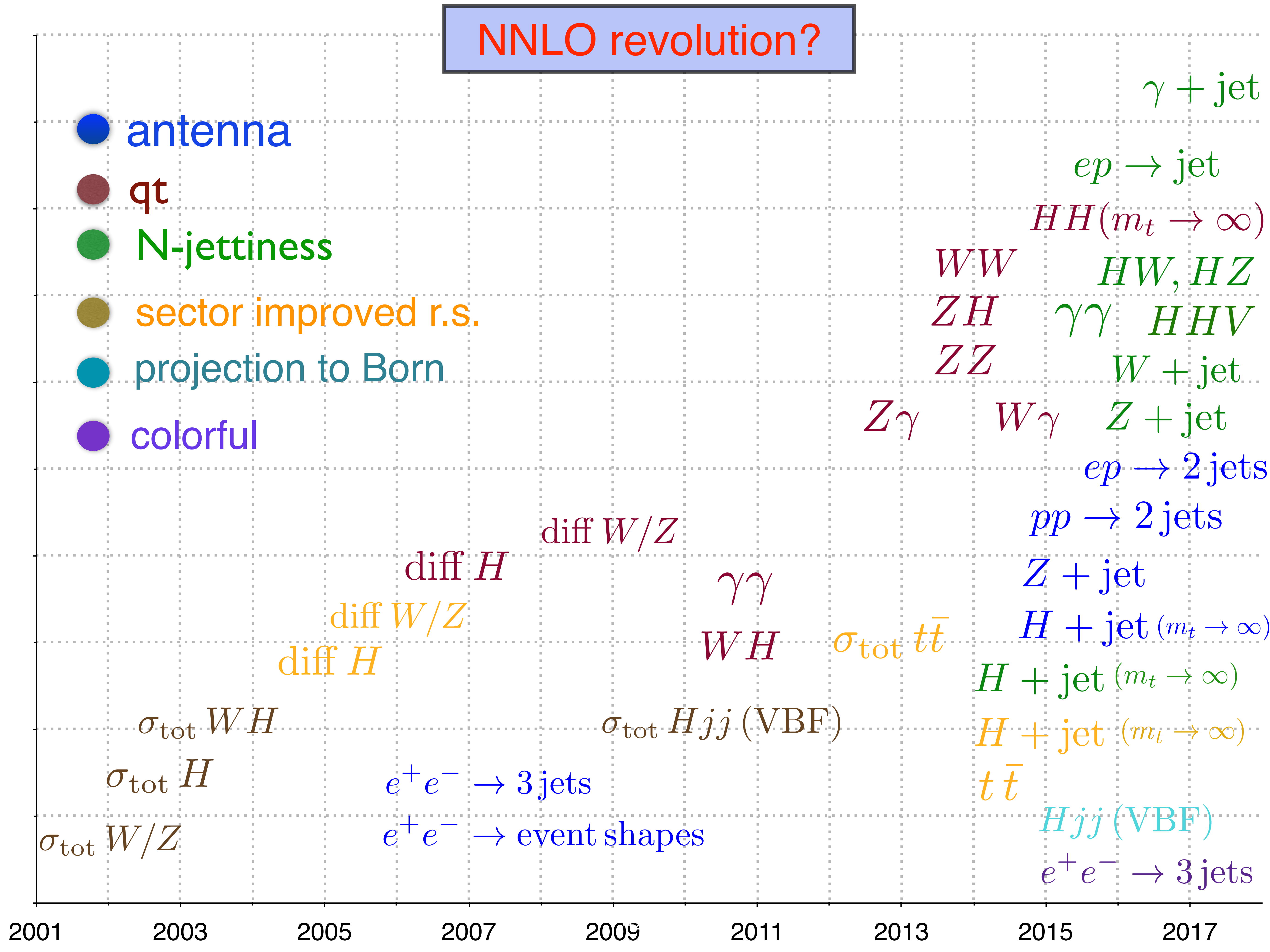
NNLO subtraction formalism: q_T-subtraction
[Catani, Grazzini, '07]

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

slide by Javier Mazzitelli



antenna
qt
N-jettiness
sector improved r.s.
projection to Born
colorful
$\gamma + \text{jet}$
$ep \to \text{jet}$
$HH (m_t \to \infty)$
WW
HW, HZ
ZH
$\gamma\gamma$
HHV
ZZ
$W + \text{jet}$
$Z\gamma$
$W\gamma$
$Z + \text{jet}$
$ep \to 2\,\text{jets}$
$pp \to 2\,\text{jets}$
diff W/Z
diff H
$\gamma\gamma$
$Z + \text{jet}$
diff W/Z
$H + \text{jet}\ (m_t \to \infty)$
diff H
WH
$\sigma_{\text{tot}}\ t\bar{t}$
$H + \text{jet}\ (m_t \to \infty)$
$\sigma_{\text{tot}}\ WH$
$\sigma_{\text{tot}}\ Hjj$ (VBF)
$H + \text{jet}\ (m_t \to \infty)$
$\sigma_{\text{tot}}\ H$
$e^+e^- \to 3\,\text{jets}$
$t\,\bar{t}$
Hjj (VBF)
$\sigma_{\text{tot}}\ W/Z$
$e^+e^- \to$ event shapes
$e^+e^- \to 3\,\text{jets}$
2001
2003
2005
2007
2009
2011
2013
2015
2017


NNLO revolution?
antenna
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N-jettiness
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projection to Born
colorful
γ + jet
$ep \to$ jet
$HH (m_t \to \infty)$
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HW, HZ
ZH
$\gamma\gamma$
HHV
ZZ
W + jet
$Z\gamma$
$W\gamma$
Z + jet
$ep \to$ 2 jets
$pp \to$ 2 jets
diff W/Z
diff H
$\gamma\gamma$
Z + jet
diff W/Z
H + jet $(m_t \to \infty)$
diff H
WH
$\sigma_{tot}\ t\bar{t}$
H + jet $(m_t \to \infty)$
$\sigma_{tot}\ WH$
$\sigma_{tot}\ Hjj$ (VBF)
H + jet $(m_t \to \infty)$
$\sigma_{tot}\ H$
$e^+e^- \to$ 3 jets
$t\bar{t}$
Hjj (VBF)
$\sigma_{tot}\ W/Z$
$e^+e^- \to$ event shapes
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2001
2003
2005
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