NLO for Higgs signals

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Max-Planck-Institut für Physik
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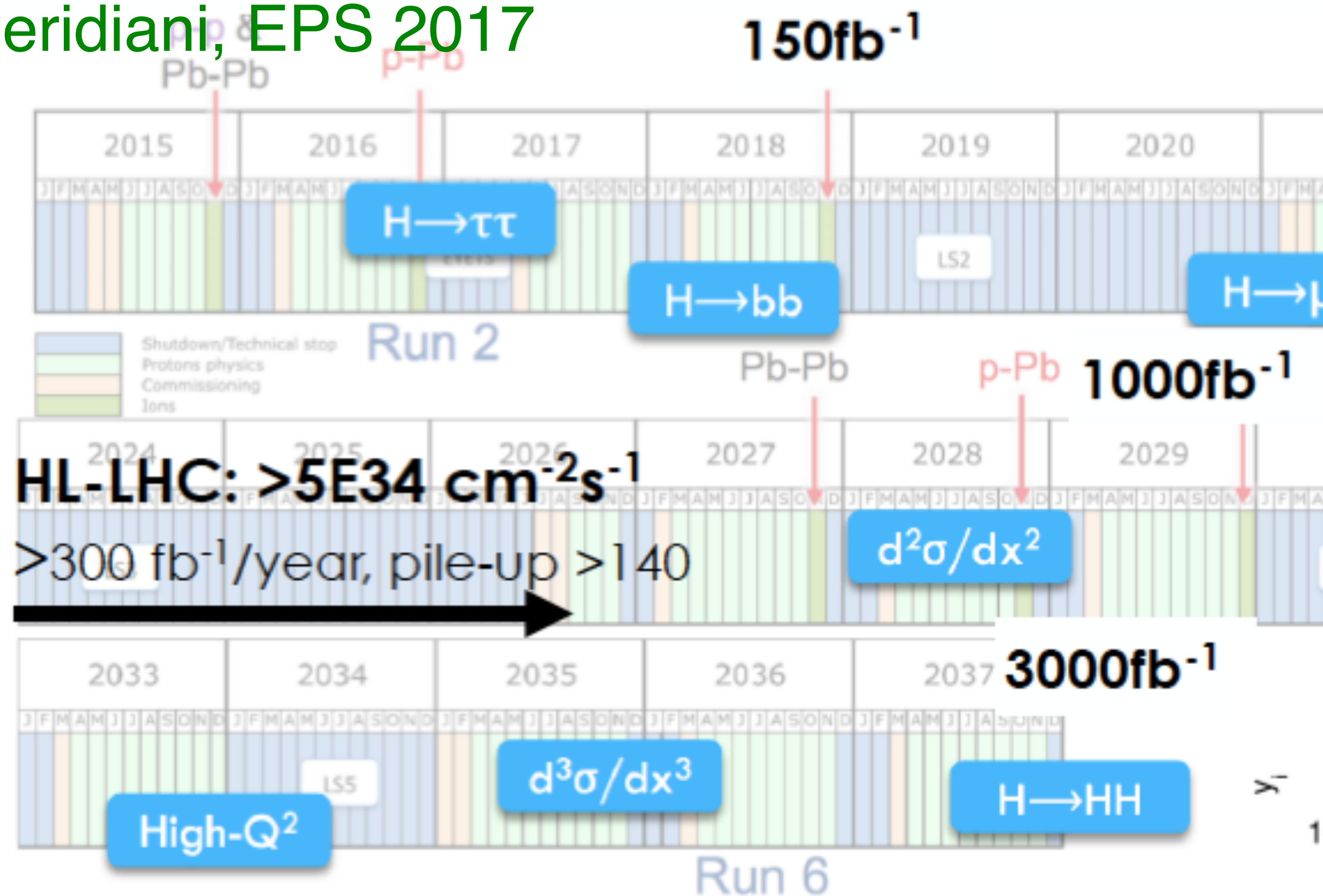
Timeline Beyond Run2

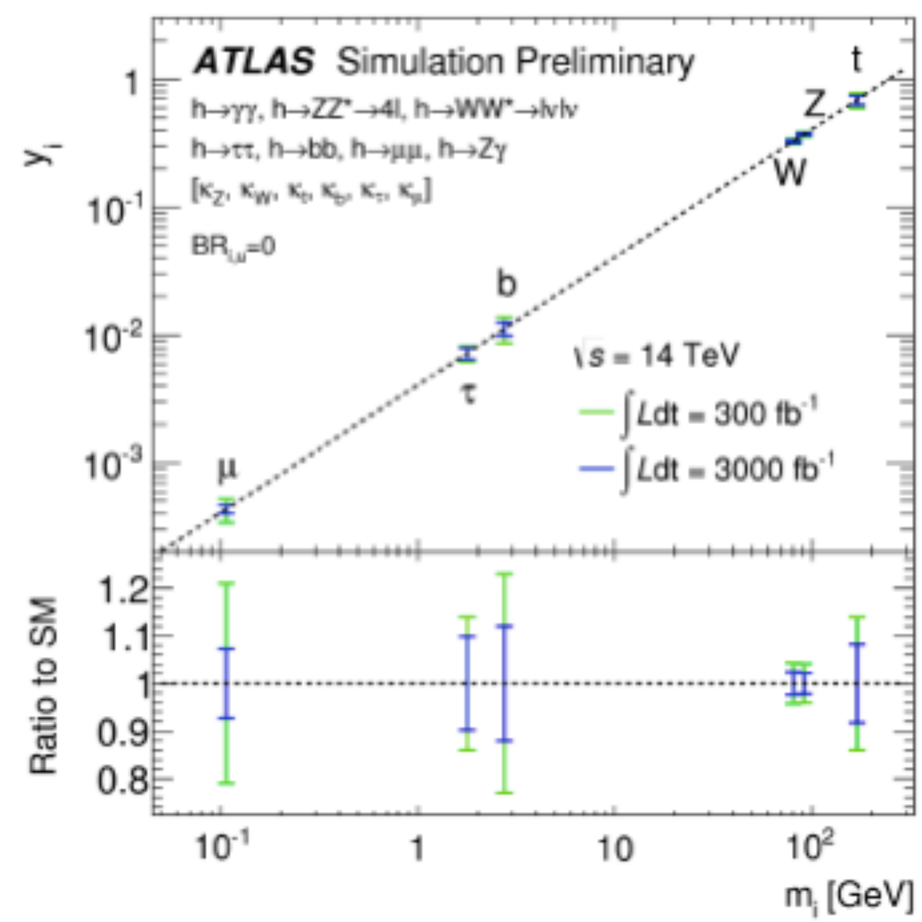
Credits: A. David @ GRC 2017

P.Meridiani, EPS 2017



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

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



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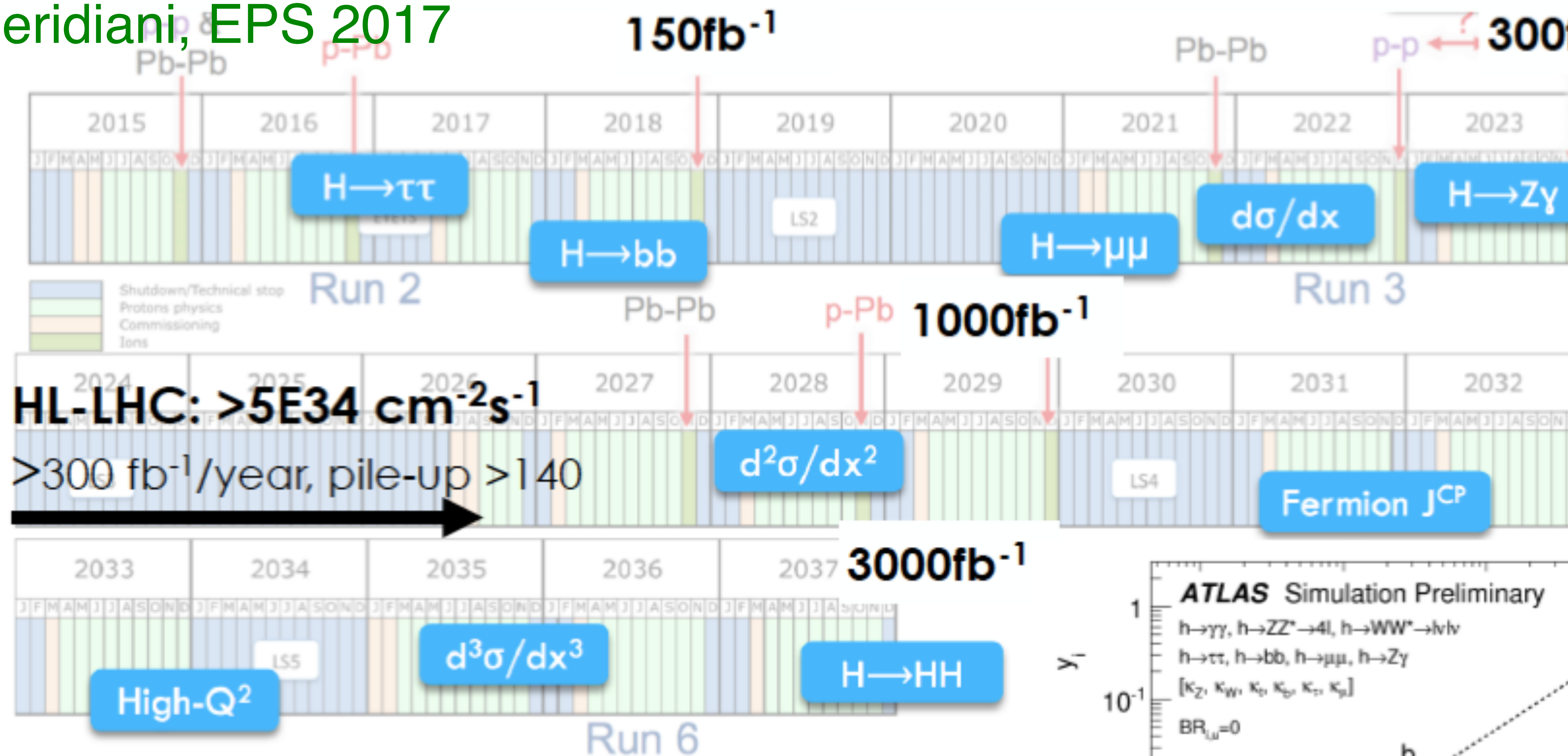

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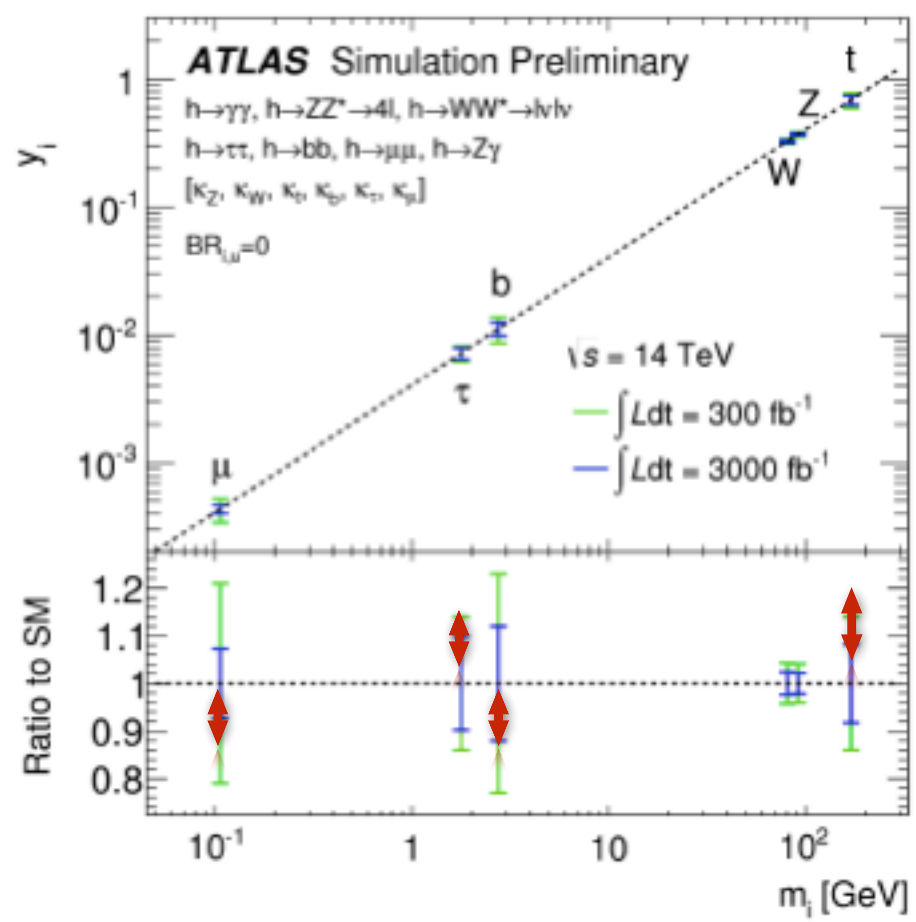


we need to be sure about the systematic uncertainties to see something like this

status of higher (fixed) order predictions involving H

(see also Kirill's talk)

	$\sigma_{\rm tot}$	$d\sigma$	bonus
$gg \to H$	N^3LO	NNLO	N^3LL threshold resum. NLO EW, mixed QCD/EW
VBF	N^3LO	NNLO	NLO EW
$WH\,/\,ZH$	NNLO	NNLO	NLO EW gg to ZH mt dep. approx.
$t\bar{t}H$	NLO	NLO	NNLL threshold resum. NLO EW
$H + \mathrm{single\,top}$	NLO	NLO	
$H + \mathrm{jets}$	1j: NNLO	1j: NNLO	NLO up to 3jets H+1jet NLO: mb dependence
$H\,H$	NNLO	NNLO	NNLL resum. NLO NLL resum.

black: $m_t \to \infty$ (HEFT) blue: m_q dependence

status of higher (fixed) order predictions involving H

	σ_{tot}	$\mathrm{d}\sigma$	bonus
$gg \to H$	N^3LO Anastasiou et al '13-'15	NNLO (+NNLL) De Florian, Grazzini, Tommasini '11,'12 Dulat, Mistlberger '17	N^3LL threshold resum. Bizon, Monni, Re, Rottoli, Torrielli '17 NLO EW, mixed QCD/EW Degrassi, Maltoni '04; Actis, Passarino, Sturm, Uccirati '08; Anastasiou et al '08
VBF	N^3LO Bolzoni, Maltoni, Moch, Zaro '10; Dreyer, Karlberg '16	NNLO Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15	NLO EW Ciccolini, Denner, Dittmaier '07
$WH\,/\,ZH$	NNLO Brein, Djouadi, Harlander '03; Brein, Harlander, Wiesemann, Zirke '11	NNLO Ferrera, Grazzini, Tramontano '11,'14	NLO EW Denner, Dittmaier, Kallweit, Mück '12 gg to ZH 1/mt Altenkamp et al '12 NNLL threshold resum. Harlander et al '14
$t\bar{t}H$	NLO Beenakker et al '01; Dawson, Reina '02; Frederix et al '14	NLO	NLO EW Frixione et al '14; (on-shell) Denner, Lang, Pellen, Uccirati '16 NNLL threshold resum. Kulesza et al '15
$H + \text{single top}$	NLO Demartin, Maltoni, Mawatari, Zaro '15	NLO	
$H + \text{jets}$	1j: NNLO Boughezal, Caola et al '15; Boughezal et al '15; Chen et al '15; Dulat, Mistlberger '17	1j: NNLO	NLO up to 3jets Cullen et al '13 H+1jet NLO: mb dependence Lindert, Melnikov, Tancredi, Wever '17
$H\,H$	NNLO De Florian, Mazzitelli '15; Steinhauser et al '15	NNLO De Florian et al '16	NLO Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke '16 NLL resum. Ferrera, Pires '16

status of parton shower matched results

$gg \to H$	NNLO	Hamilton, Nason, Re, Zanderighi '13; Höche, Li, Prestel '14; Alioli et al '13,'15
VBF	NLO	Nason, Oleari '10; Frixione, Torrielli, Zaro '13; Campanario et al '13; Jäger et al '14
WH / ZH	NLO (+ 0/1-jet merging)	Luisoni, Nason, Oleari, Tramontano '13
	NNLO	Goncalves, Krauss, Kuttimalai, Maierhöfer '15; Astill, Bizon, Re, Zanderighi' 16
	NLO QCD+EW	Granata, Lindert, Oleari, Pozzorini '17
$t\bar{t}H$	NLO	Frederix et al '11; Garzelli et al '11; Hartanto et al '15; QCD **and EW**: Denner, Lang, Pellen, Uccirati '16
H + single top	NLO	Demartin, Maltoni, Mawatari, Zaro '15
H + jets	NLO up to 2jets	Buschmann, Goncalves, Krauss, Kuttimalai, Schönherr, Plehn '14; Frederix, Frixione, Vryonidou, Wiesemann '16
$H\ H$	NLO	GH, Jones, Kerner, Luisoni, Vryonidou '17; Jones, Kuttimalai '17

Higgs@NLO

some pressing problems to solve at NLO:

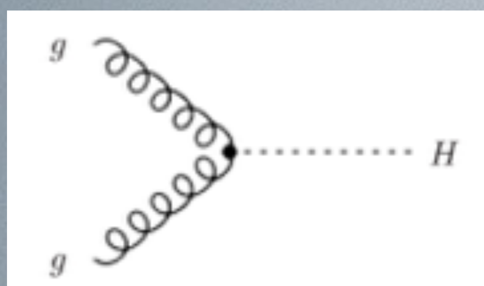
- quark mass effects
  "boosted Higgs can resolve loops from heavy BSM particles"
  → **and** heavy SM particles (top)!
- EW corrections, combination QCD/EW
- consistent combination of EFT and SM NLO corrections
- finding "optimal" scales/assessment of scale uncertainties
  (also shower/resummation scale uncertainties)
- multi-jet merging
- improve logarithmic accuracy of parton showers

Higgs pT

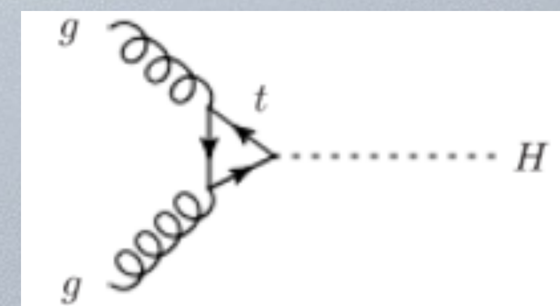
high-energy resummation of Higgs pT in $gg \to H$ with off-shell gluons

Marzani, Ball, del Duca, Forte, Vicini ’08; Forte, Muselli ’15; Caola, Forte, Marzani, Muselli, Vita ’16

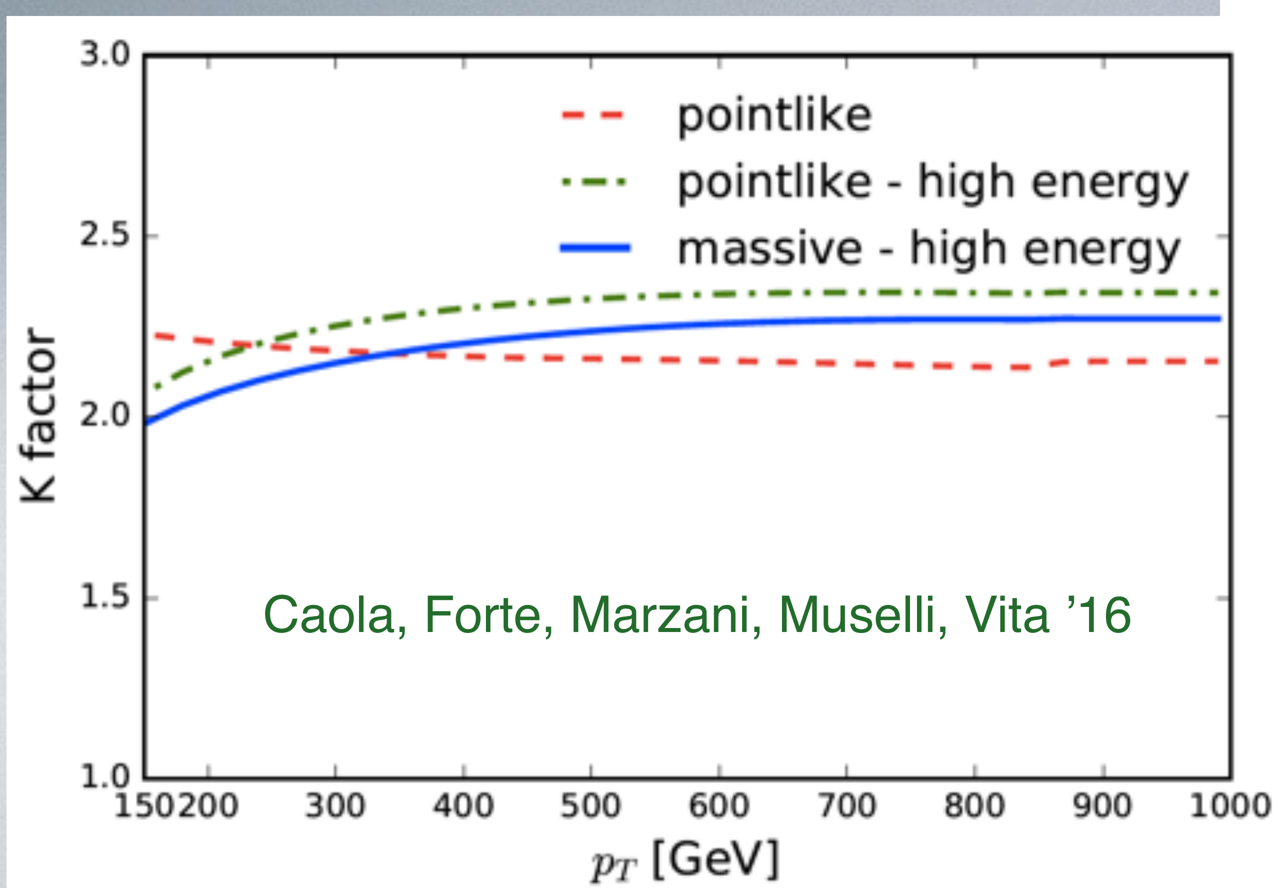
for $p_{T,h} \to \infty$:

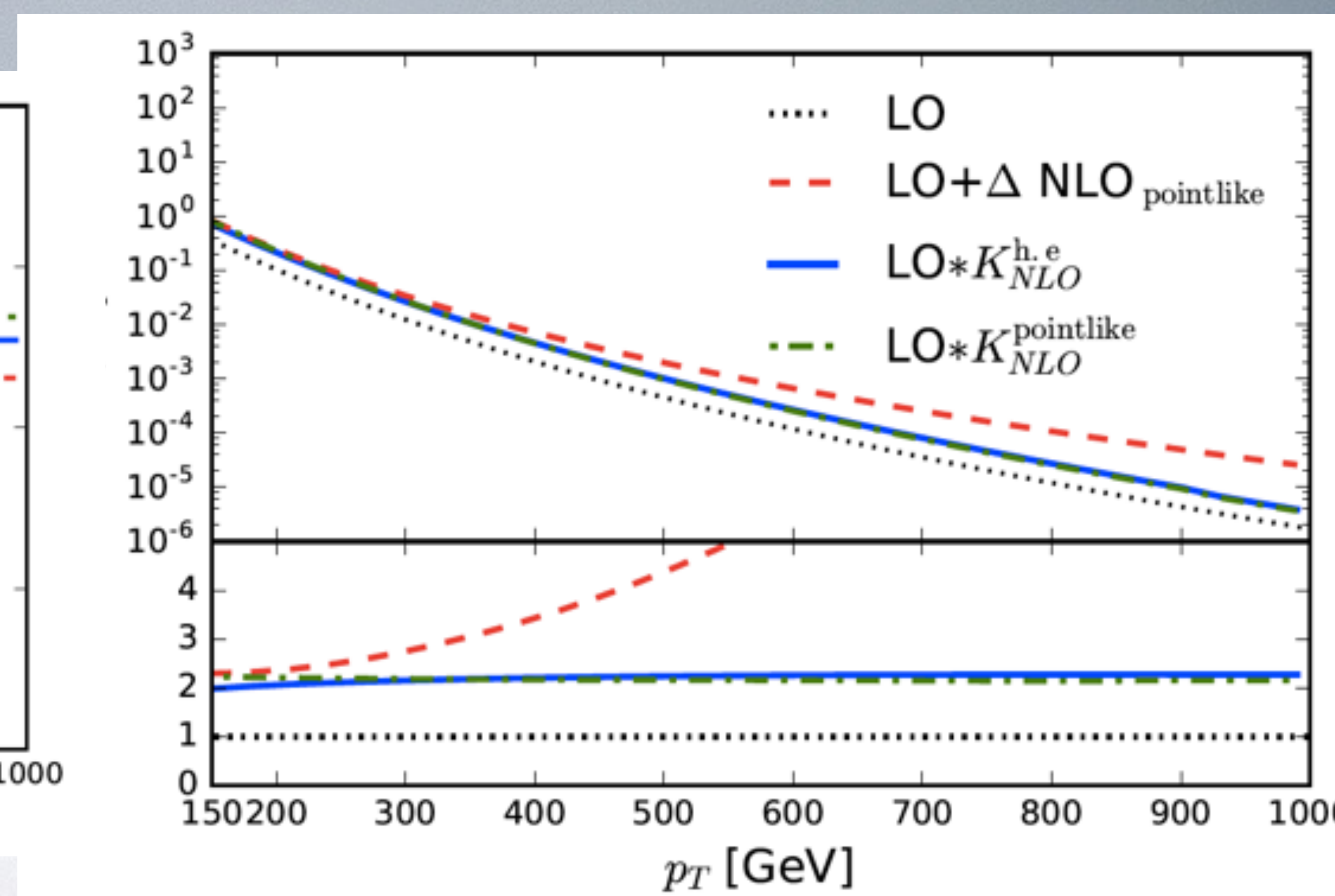


$$d\sigma/dp^2_{T,h} \to (p^2_{T,h})^{-1}$$



$$d\sigma/dp^2_{T,h} \to (p^2_{T,h})^{-2}$$





quark mass effects in Higgs + jets

Greiner, Höche, Luisoni, Schönherr, Winter ’16

cross sections (+Ntuples) for H+1,2,3 jets calculated at

- NLO in HEFT ($m_t \to \infty$ limit)
- LO with full m_t, m_b dependence

default scale choice: $$\mu_F = \mu_R \equiv \frac{\hat{H}'_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right)$$

basic cuts: $$p_{T,\mathrm{jet}} > 30\ \mathrm{GeV}\,, \qquad |y_{\mathrm{jet}}| < 4.4$$

quark mass effects in Higgs + jets

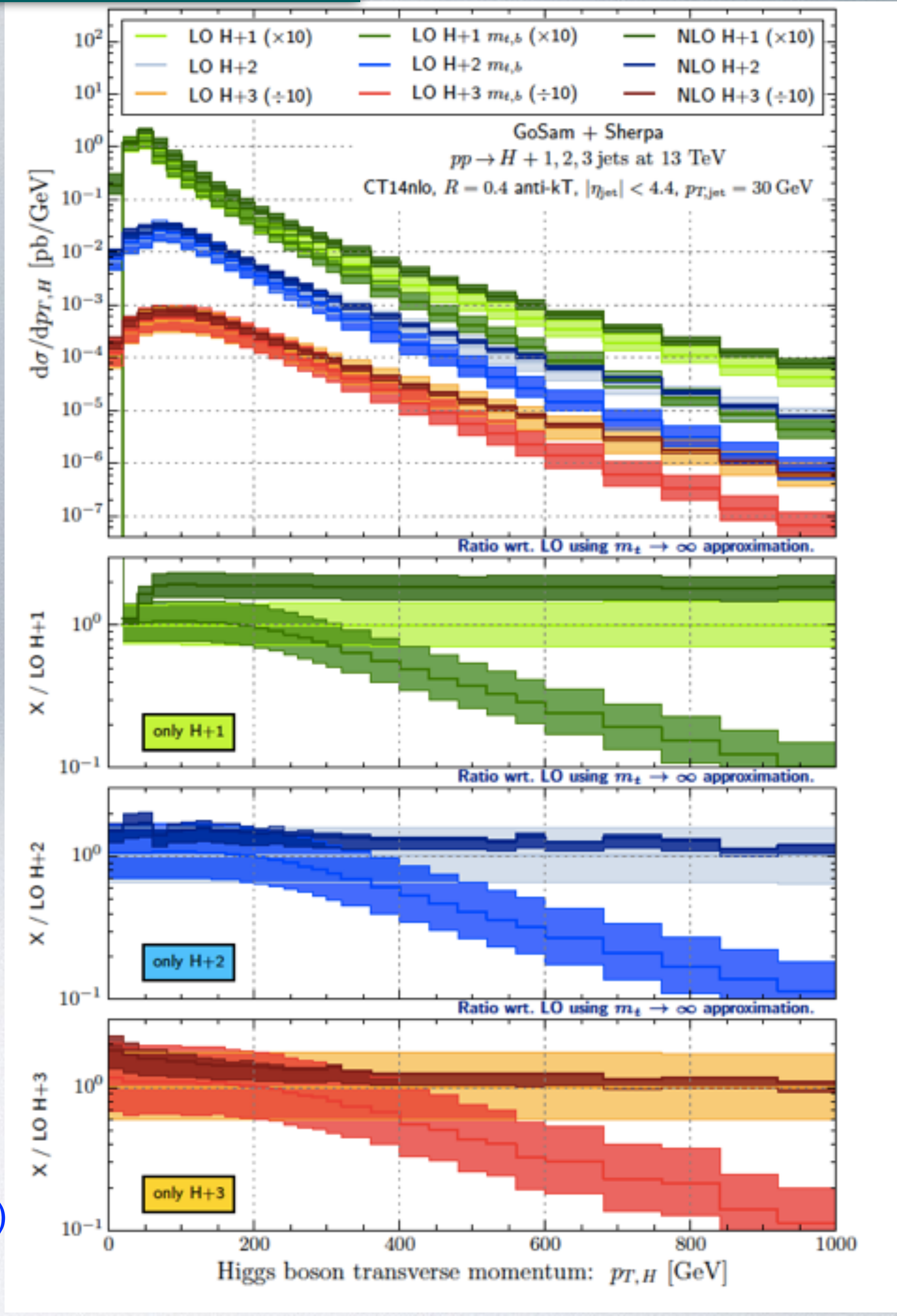
$m_t \to \infty$ limit starts to fail at $p_{T,H} \sim 200\,\mathrm{GeV}$

- different jet multiplicities show very similar behaviour
- leading jet pT distribution also similar

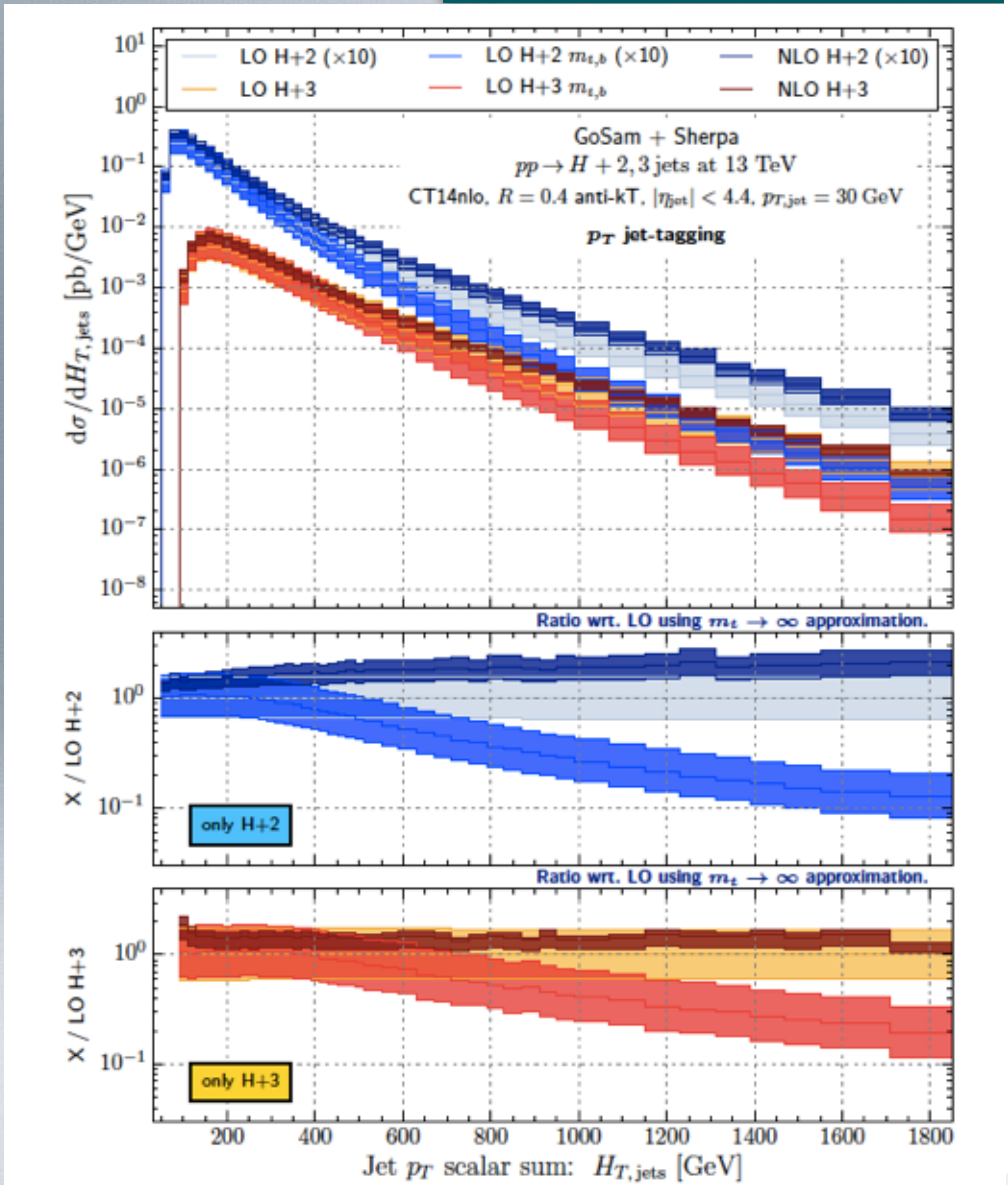
→ suggests that resolution of top quark loops is driven by pT,H or largest pT in the event

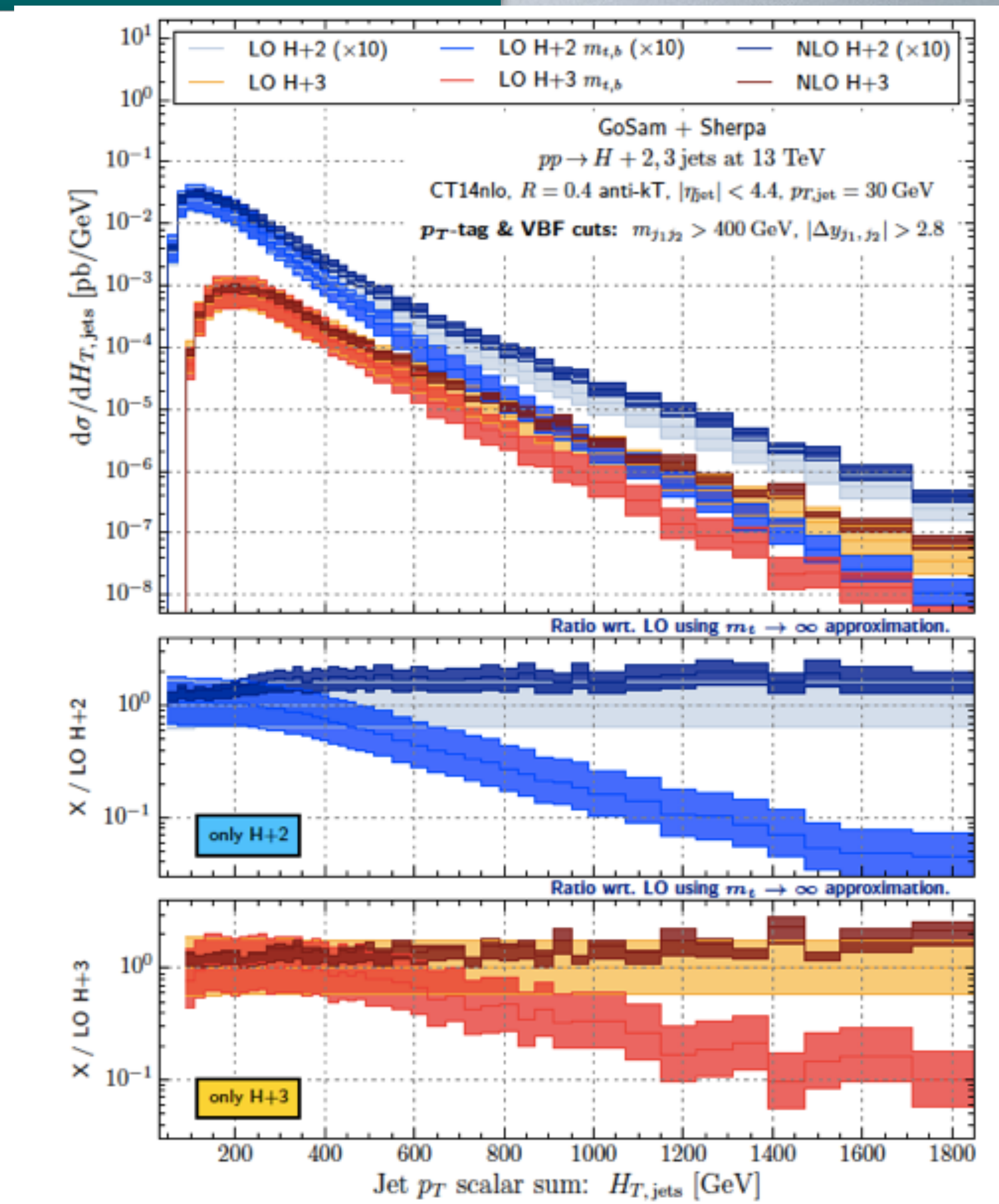
jet multiplicity seems to play minor role

→ needs further investigation (backup slide)



Effect of VBF cuts

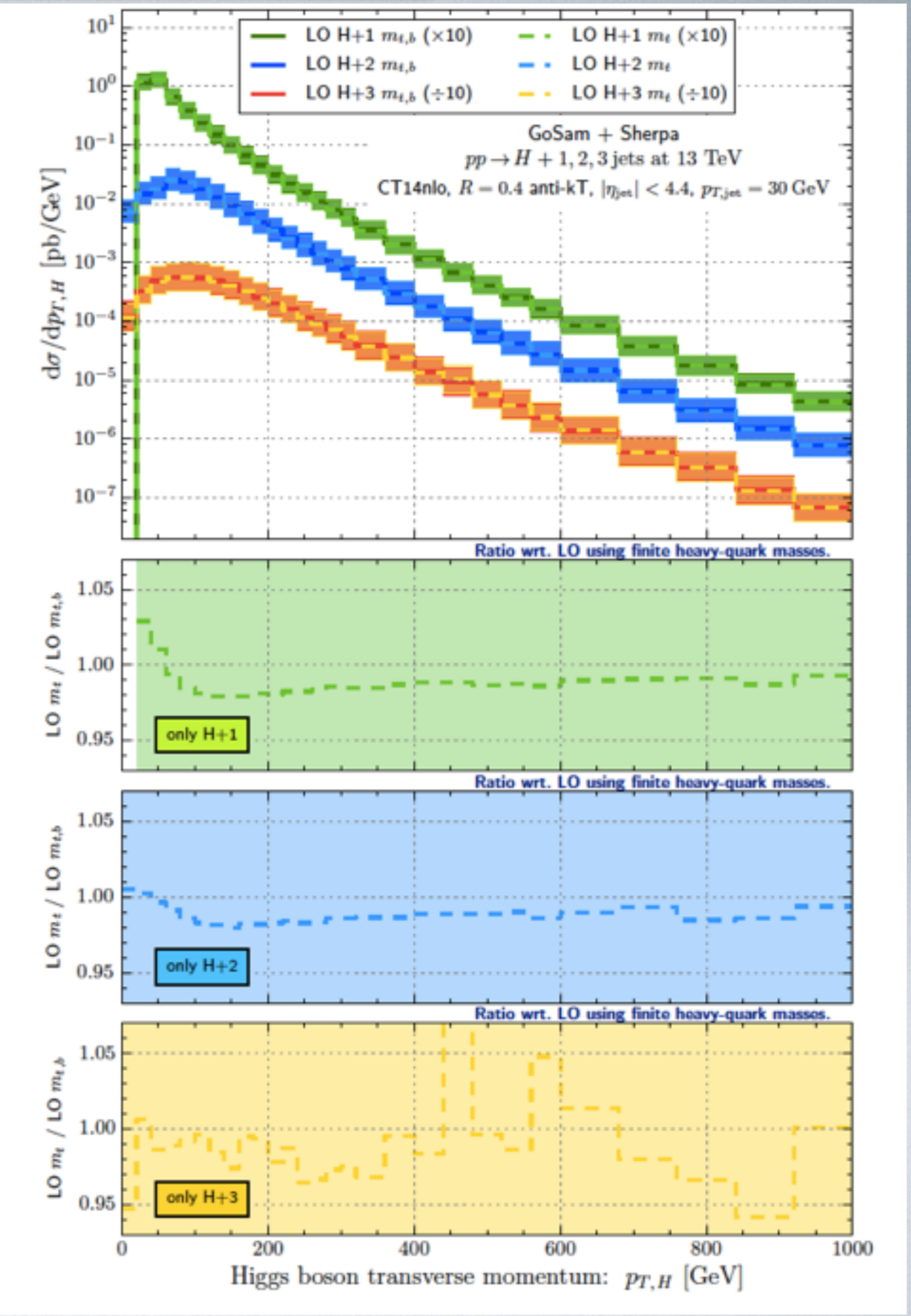




VBF cuts can enhance the deviations of HEFT to full theory

bottom quark effects

- well below the scale uncertainties even at low pT
- depend on jet multiplicity
- destructive interference between top- and bottom-quark loops for H+1jet

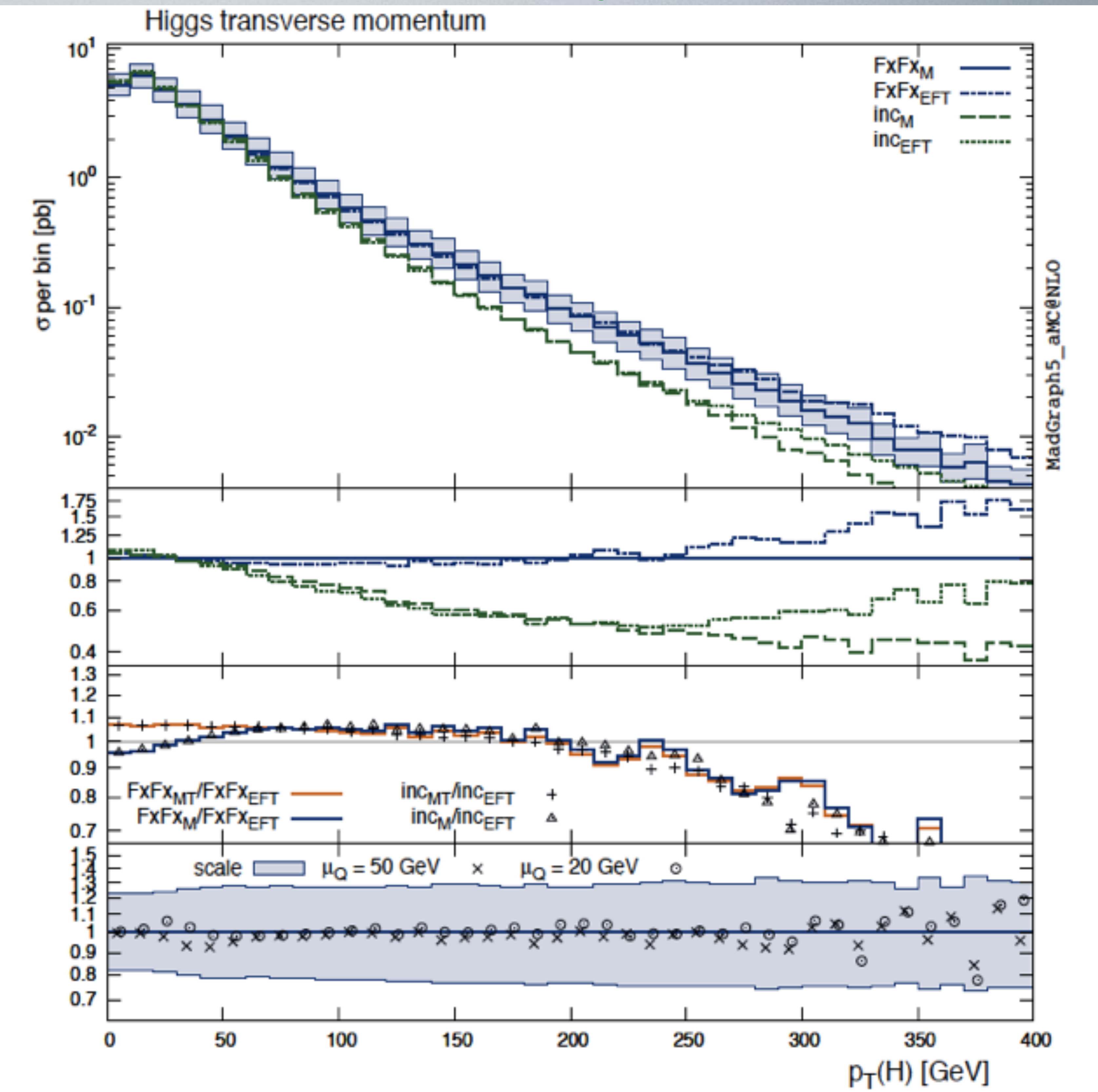


Higgs+0,1,2 jets + parton shower

Frederix, Frixione, Vryonidou, Wiesemann '16

H + n jets:

- exact mass dependence in real radiation
- exact 2-loop virtual for n=0
- rescaled HEFT virtual for n=1,2



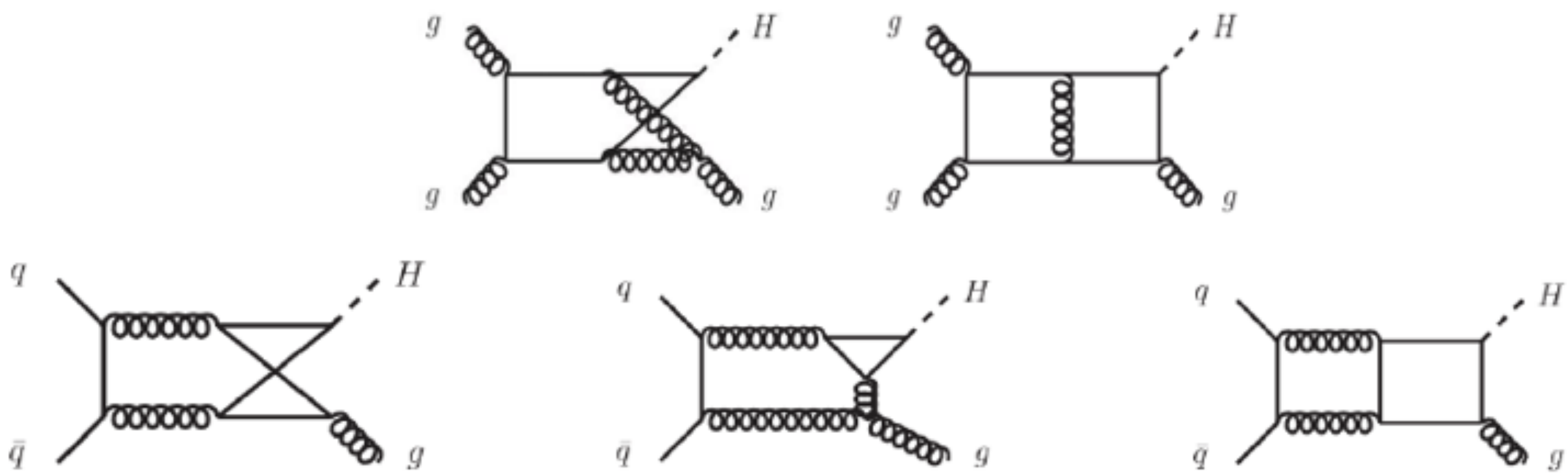
see also
Buschmann, Goncalves, Krauss, Kuttimalai, Schönherr, Plehn '14

Higgs + jet

Lindert, Melnikov, Tancredi, Wever ‘17

$$d\sigma_{tb}^{\rm virt} \sim {\rm Re}\left[\frac{\alpha_s}{2\pi}\left(A_t^{\rm NLO}A_b^{\rm LO*} + A_t^{\rm LO}A_b^{\rm NLO*}\right)\right]$$

- Typical two-loop Feynman diagrams are:



- Exact mass dependence in two-loop Feynman Integrals currently out of reach [planar diagrams: Bonciani et al ’16]

Scale hierarchy: $m_b \ll p_\perp, m_h \ll m_t$ →

Top: *Infinite top mass limit*, well known how to be treated, expanded systematically via effective Lagrangian (HEFT)

Bottom: Small bottom mass expansion is different because loop is resolved → new methods required

Two-loop *bottom amplitudes* expanded in *bottom mass* with differential equation method [Mueller & Ozturk ’15; Melnikov, Tancredi, CW ’16-’17]

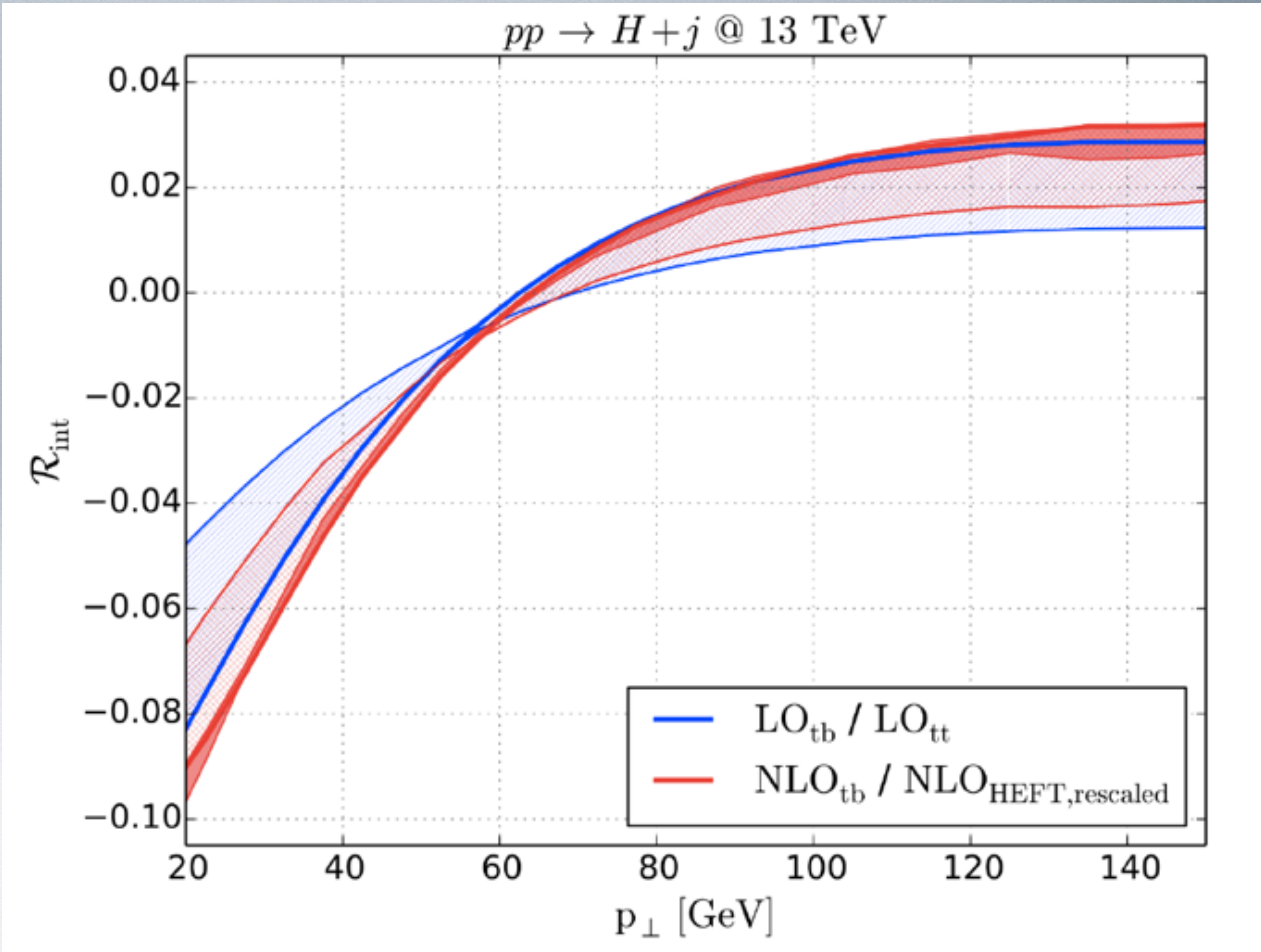
Higgs + jet

Lindert, Melnikov, Tancredi, Wever '17

$$\mathcal{R}_{\text{int}}\left[\mathcal{O}\right] = \frac{\int \mathrm{d}\sigma_{tb}\; \delta(\mathcal{O} - \mathcal{O}(\vec{x}))}{\int \mathrm{d}\sigma_{tt}\; \delta(\mathcal{O} - \mathcal{O}(\vec{x}))}$$

- large relative corrections top-bottom interference to top-top

- large mb renormalisation ambiguities (light bands) reduced at NLO, in particular at low pT



Higgs + jet

- exact mass dependence in real radiation
- virtual part: $1/m_t$ expansion on amplitude level

NLO*:

$$\mathcal{F}^{\text{in}}_{j,\text{SI}} = 2\text{Re}\left(\left[\mathcal{F}^{\text{in}}_j(m_t,m_H,s,t,u)\right]_{\text{asy}} \mathcal{A}^{(1)}_j(m_t,m_H,s,t,u)^*\right)$$

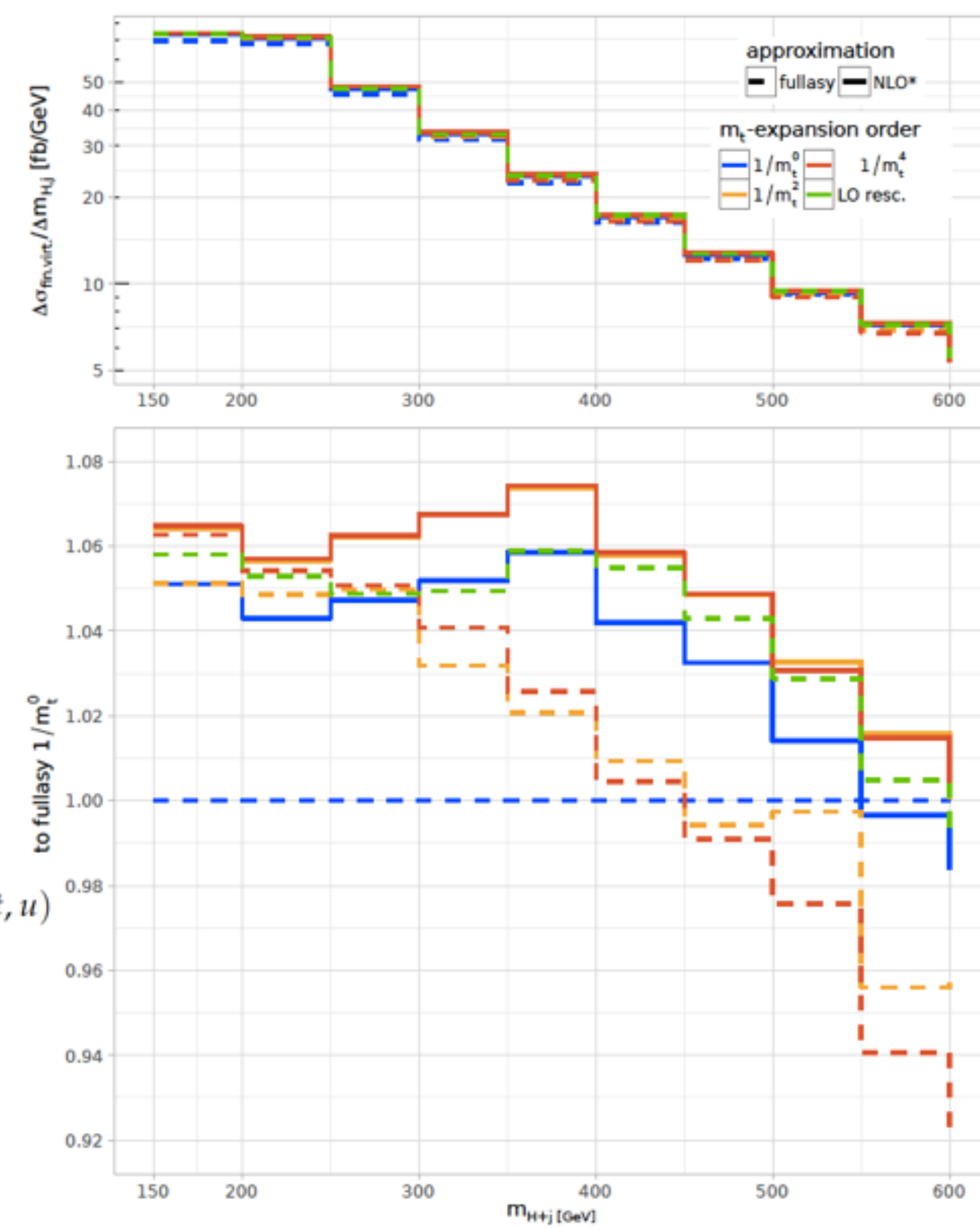
fullasy: expansion on amplitude squared level

$$\mathcal{F}^{\text{in}}_{j,\text{RI}} = 2\left[\text{Re}\left(\mathcal{F}^{\text{in}}_j(m_t,m_H,s,t,u)\mathcal{A}^{(1)}_j(m_t,m_H,s,t,u)^*\right)\right]_{\text{asy}}$$

$$\mathcal{A}^{(2)}_j(m_t,m_H,s,t,u) = \mathcal{I}^j_1(\epsilon,s,t,u)\mathcal{A}^{(1)}_j(m_t,m_H,s,t,u) + \mathcal{F}^{in}_j(m_t,m_H,s,t,u)$$

- method works well for scales up to about 300 GeV

Neumann, Williams '17



towards Higgs + jet at full NLO

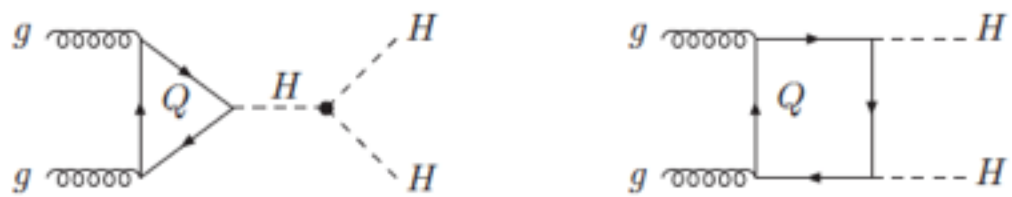
Jones, Kerner, Luisoni

Comparison of HJ and HH

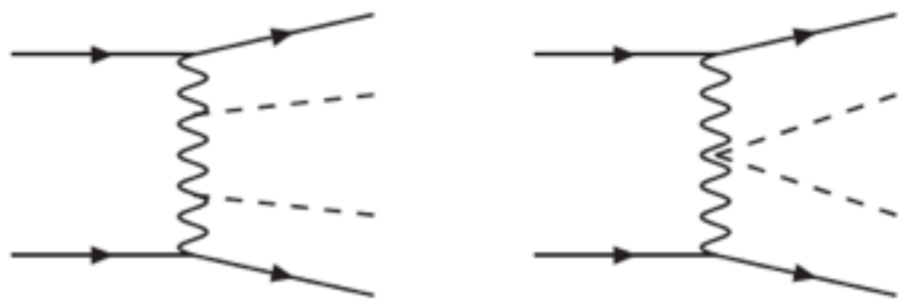
	HJ production	HH production
#Form factors	4+2	2
Full reduction	✓	only planar
(quasi-) finite basis	✓	only planar
#Master integrals including crossings	458	327
#Master integrals neglecting crossings	120	215
#Integrals after sector decomposition and expansion in ϵ	22675	11244
Code size coefficients	~340 MB	~80 MB
Code size integrals	~330 MB	~580 MB
Compile time coefficients	~ 2 weeks	few days
Compile time integrals	~4 hours	~1-2 days
Time for linking the program	~3-4 days	few hours

Higgs boson pair production

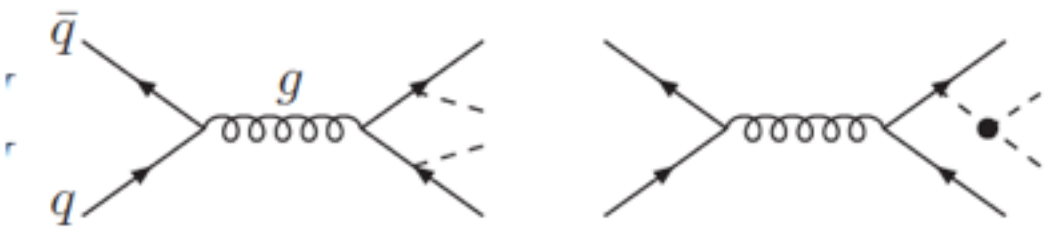
- gluon fusion



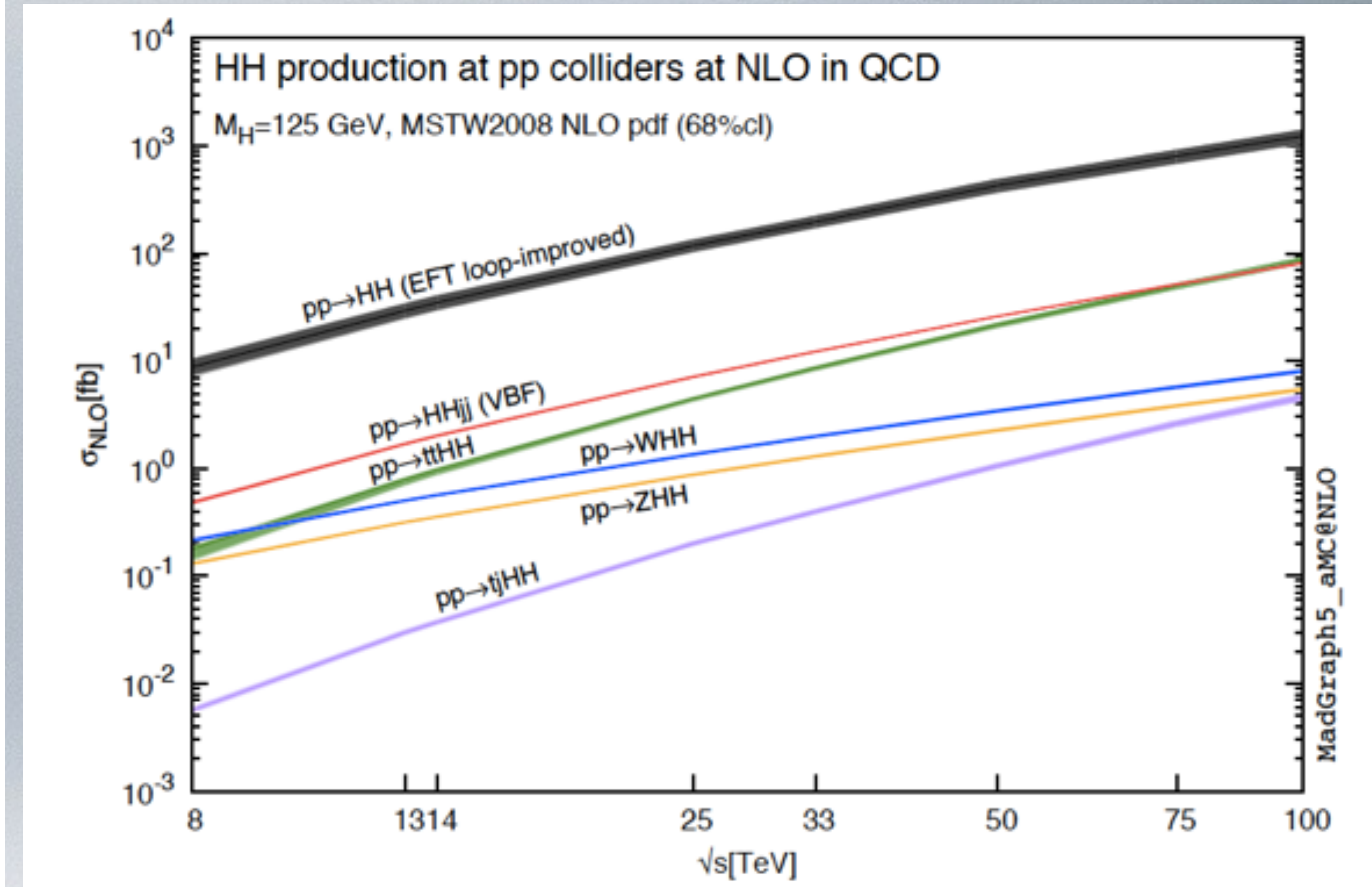
- vector boson fusion



- top-quark associated



- Higgs-strahlung



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

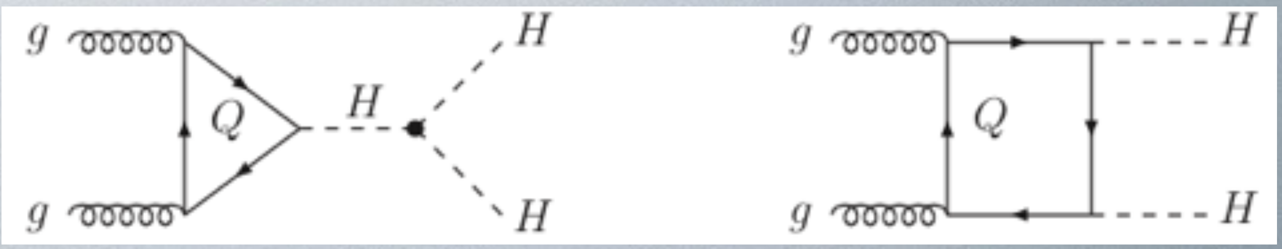
largest cross section from gluon fusion, but still

$$\sigma_{ggHH} \sim 10^{-3}\,\sigma_{ggH}$$

Higgs boson pair production in gluon fusion

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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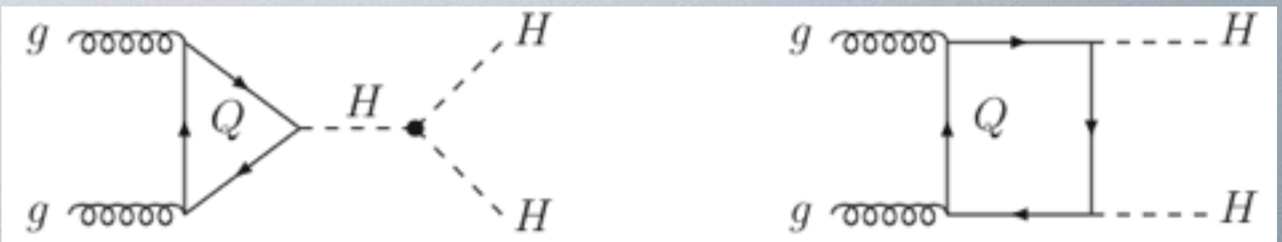
Higgs boson pair production in gluon fusion



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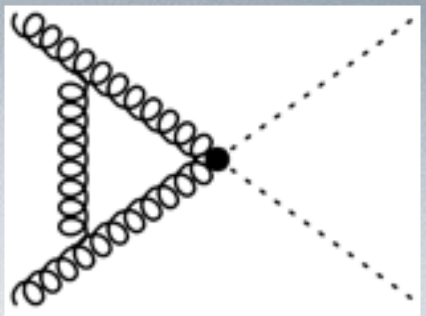
"Born-improved NLO HEFT": rescale by $\mathcal{M}^{LO}(m_t)/\mathcal{M}^{LO}_{\mathrm{HEFT}}$

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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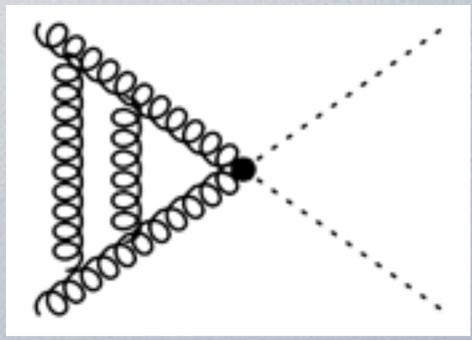
Higgs boson pair production in gluon fusion

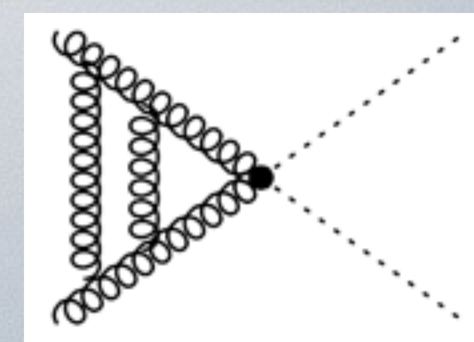


NNLO in $m_t \to \infty$ limit: **+20%**

- **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 **+9%**
- **differential NNLO** De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16

Higgs boson pair production in gluon fusion

NNLO in $m_t \to \infty$ limit: **+20%**



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NLO calculation with full top mass dependence

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

4 independent scales s12, s23, mH, mt

all integrals calculated **numerically** with

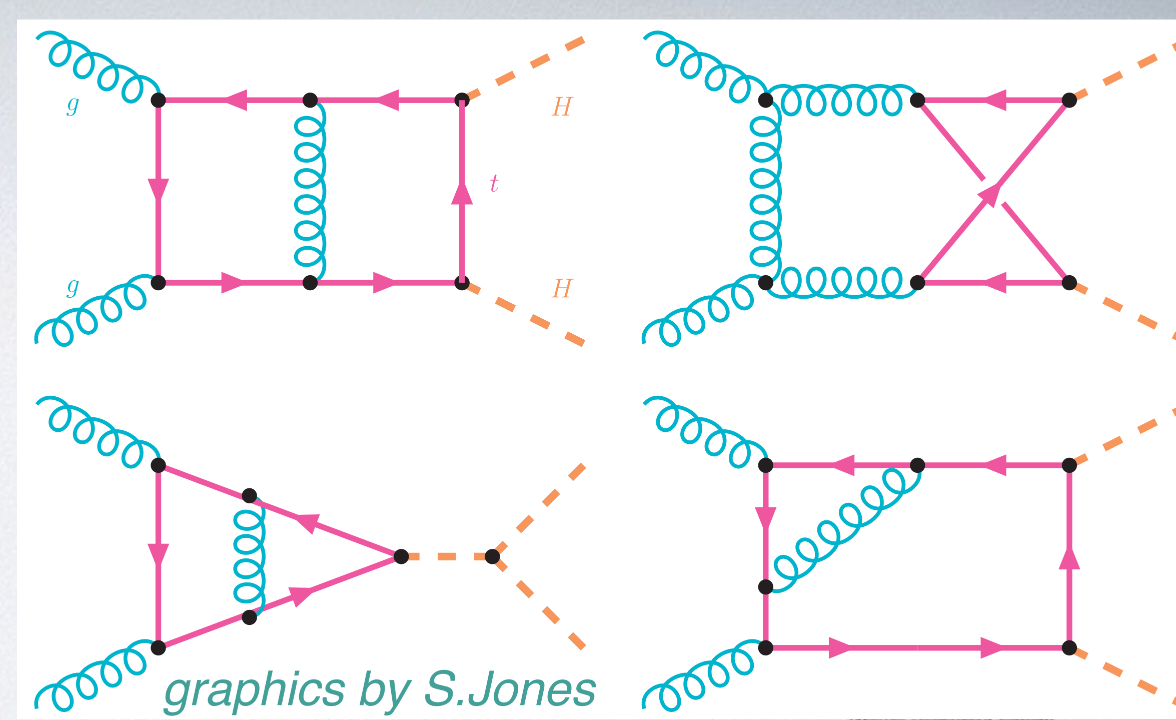
SecDec

Borowka, GH, Jones, Kerner, Schlenk, Zirke '15

Borowka, GH, Jahn, Jones, Kerner, Schlenk, Zirke '17

- q_T **resummation NLL+NLO**

Ferrera, Pires '16



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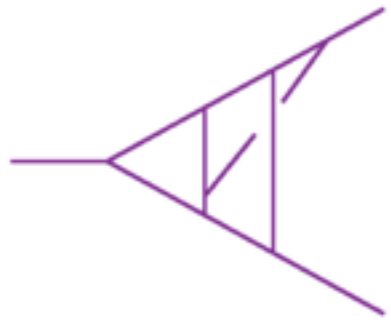
numerical evaluation of multi-loop integrals

http://secdec.hepforge.org https://github.com/mppmu/secdec/releases

SecDec is hosted by Hepforge, IPPP Durham



SecDec

Sophia Borowka, Gudrun Heinrich, Stephan Jahn, Stephen Jones, Matthias Kerner, Johannes Schlenk, Tom Zirke

A program to evaluate dimensionally regulated parameter integrals numerically

home download program user manual faq changelog

NEW! The latest version of pySecDec is available on github. The manual is available on readthedocs.
Download the version 1.1.2 of pySecDec as pySecDec-1.1.2.tar.gz. The manual is available here.
Download version 1.1.1 of pySecDec as pySecDec-1.1.1.tar.gz. The manual is available here.
Download version 1.1 of pySecDec as pySecDec-1.1.tar.gz. The manual is available here.
The first release version of pySecDec can be downloaded as pySecDec-1.0.tar.gz. The manual is available here.
See also the corresponding paper arXiv:1703.09692.

algorithm: T. Binoth, GH ‘00

version 1.0: J. Carter, GH ‘10

version 2.0: S.Borowka, J. Carter, GH ‘12

version 3.0: S.Borowka, GH, S.Jones, M.Kerner, J.Schlenk, T.Zirke ‘15

pySecDec: S.Borowka, GH, S.Jahn, S.Jones, M.Kerner, J.Schlenk, T.Zirke **‘17**

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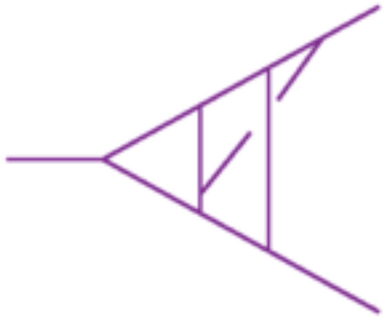

SecDec

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A program to evaluate dimensionally regulated parameter integrals numerically

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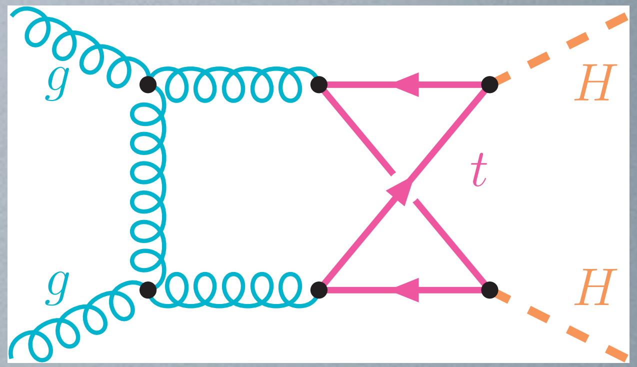
New!
can be used as
an integral library

calculation: building blocks

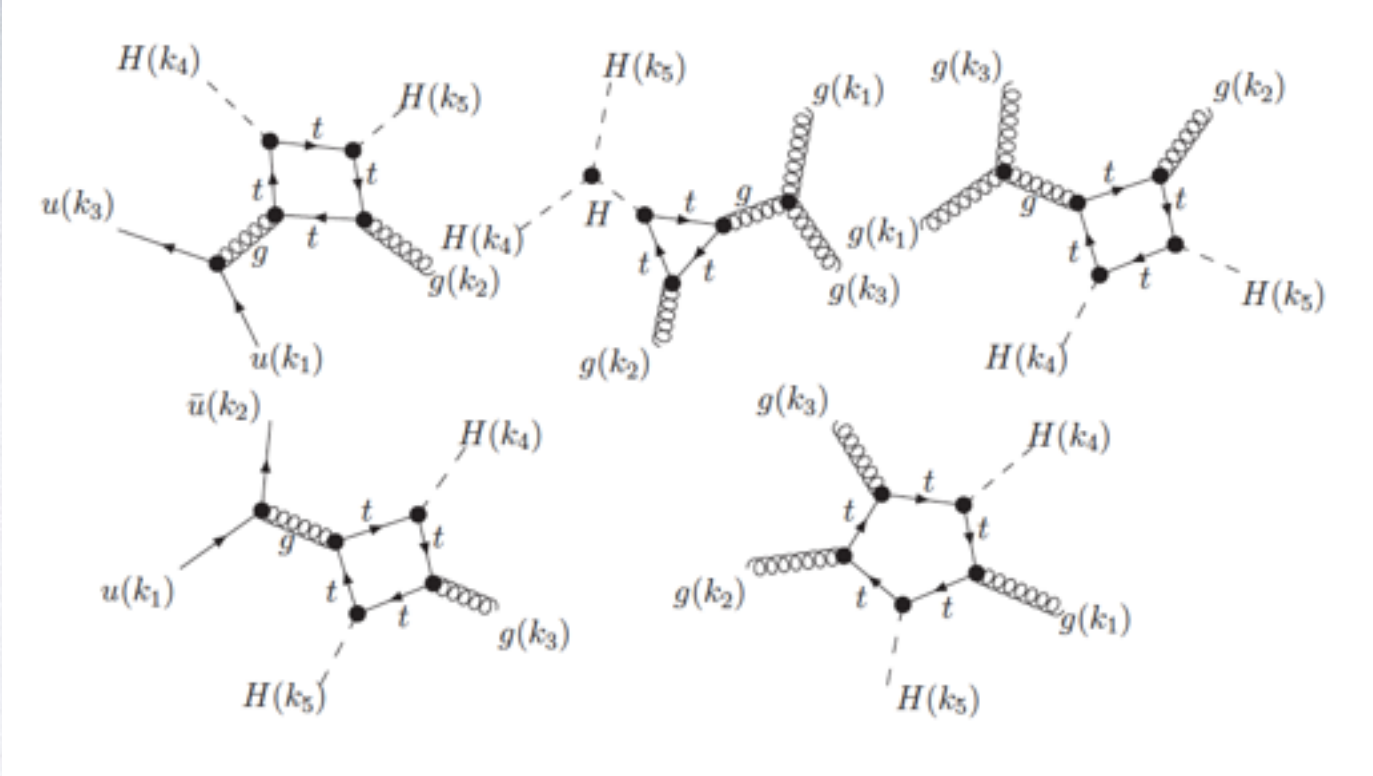
- amplitude generation with 2 setups (custom made and “GoSam-2loop”)
- amplitude reduction with **Reduze** [C. Studerus, A. v.Manteuffel]
- non-planar integrals computed mostly without reduction



- integrals calculated numerically with **SecDec**
- total number of integrals:
  - before reduction: ~10000, after reduction ~330, after sector decomposition 11244 (3086 non-planar)
  - used finite basis for planar integrals
- real radiation:

  (a) GoSam-1L + Catani-Seymour dipole subtraction

  (b) GoSam-1L + POWHEG



MAX-PLANCK-GESELLSCHAFT

top mass effects

total cross sections at 14 TeV $\mu_0 = m_{HH}/2$

	$\sigma_{\rm LO}$[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.	$19.85^{+27.6\%}_{-20.5\%}$	$32.91^{+13.6\%}_{-12.6\%}$	

PDF4LHC15_nlo_30_pdfas

m_H=125 GeV, m_t=173 GeV

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

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

top mass effects: 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	$731.3^{+20.9\%}_{-15.9\%}$	$1511^{+16.0\%}_{-13.0\%}$	$1220^{+11.9\%}_{-10.7\%}$	$1149^{+10.8\%}_{-10.0\%}$

scale uncertainties

preliminary, $\pm$ 0.3 stat. uncertainty

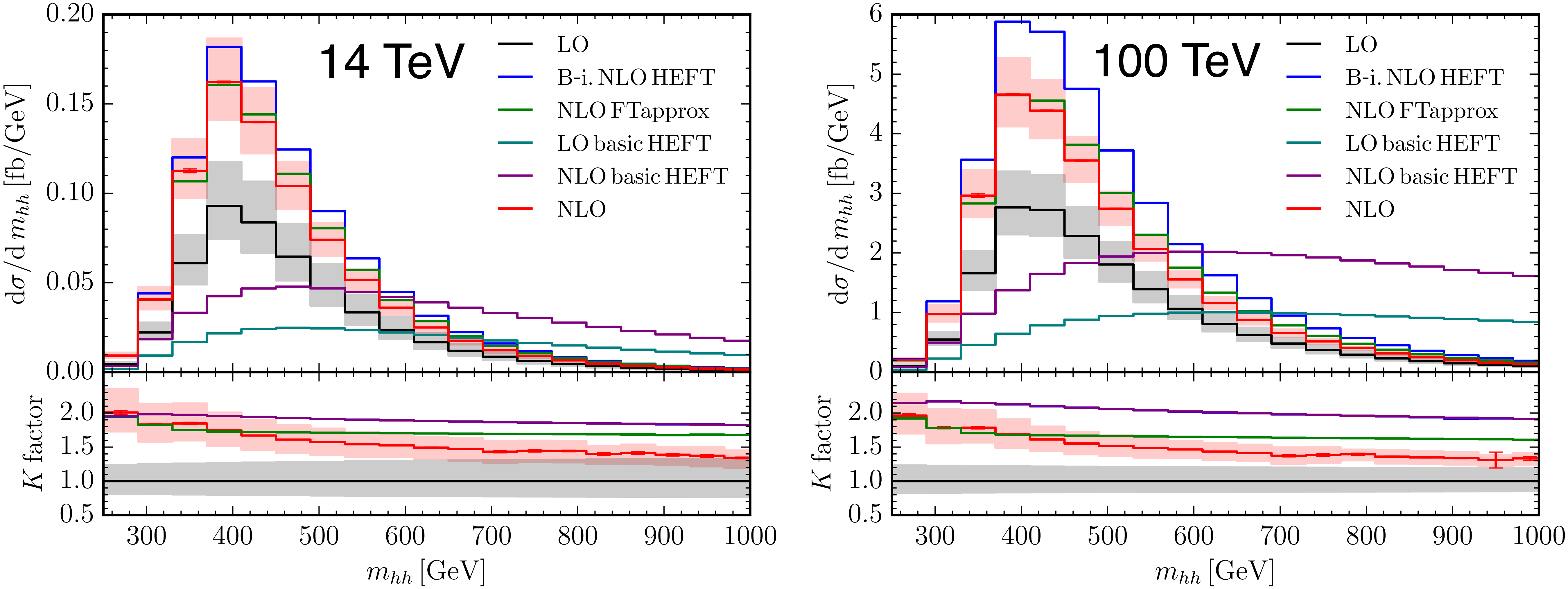
- relative difference Born-improved NLO HEFT to full NLO:

14 TeV: 16.4%

27 TeV: 21.2%

100 TeV: 31.5%

Higgs boson pair invariant mass



for large invariant masses:

Born-improved NLO HEFT overestimates by about 50%, FTapprox by about 40%
(at 14 TeV, worse at 100 TeV)

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

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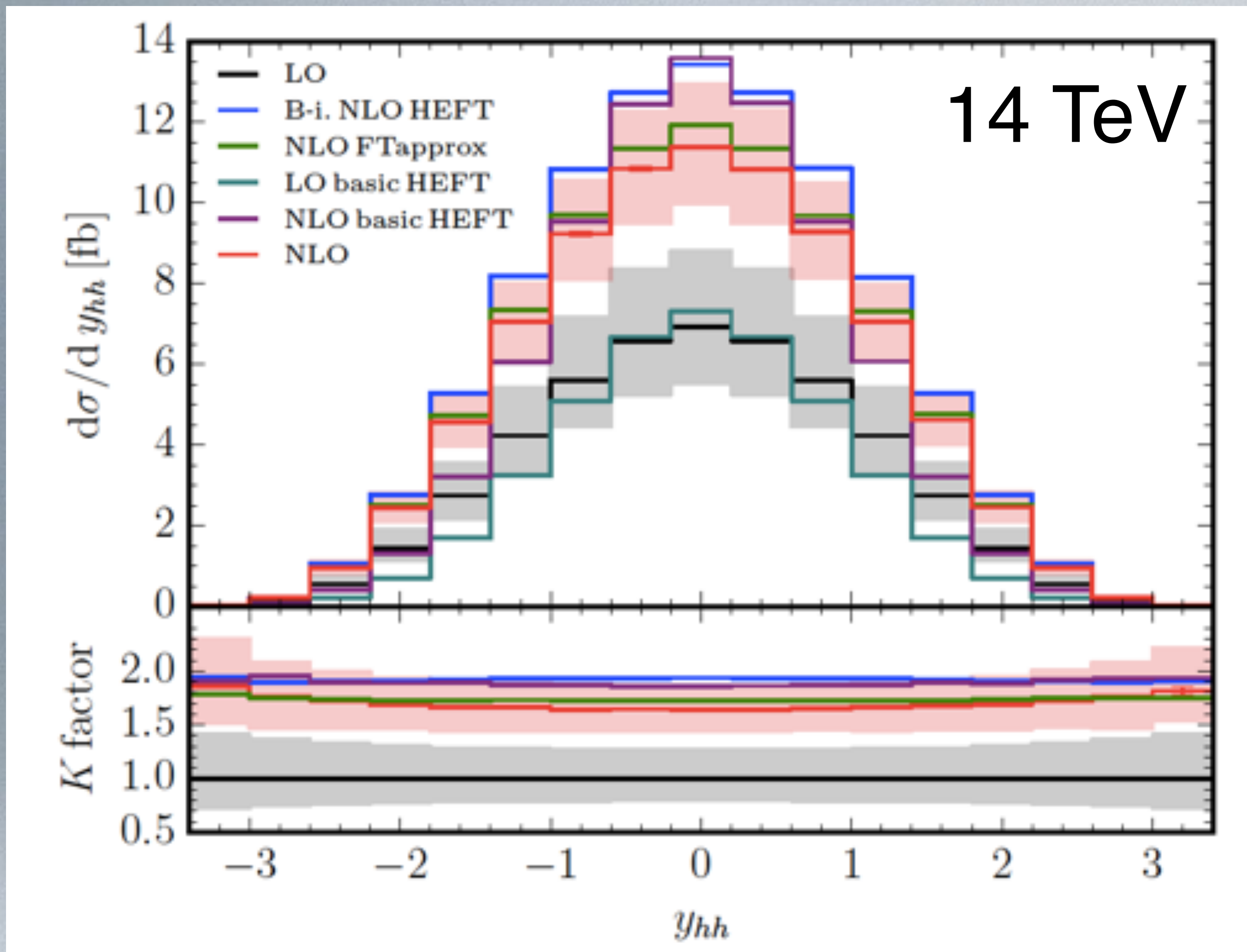
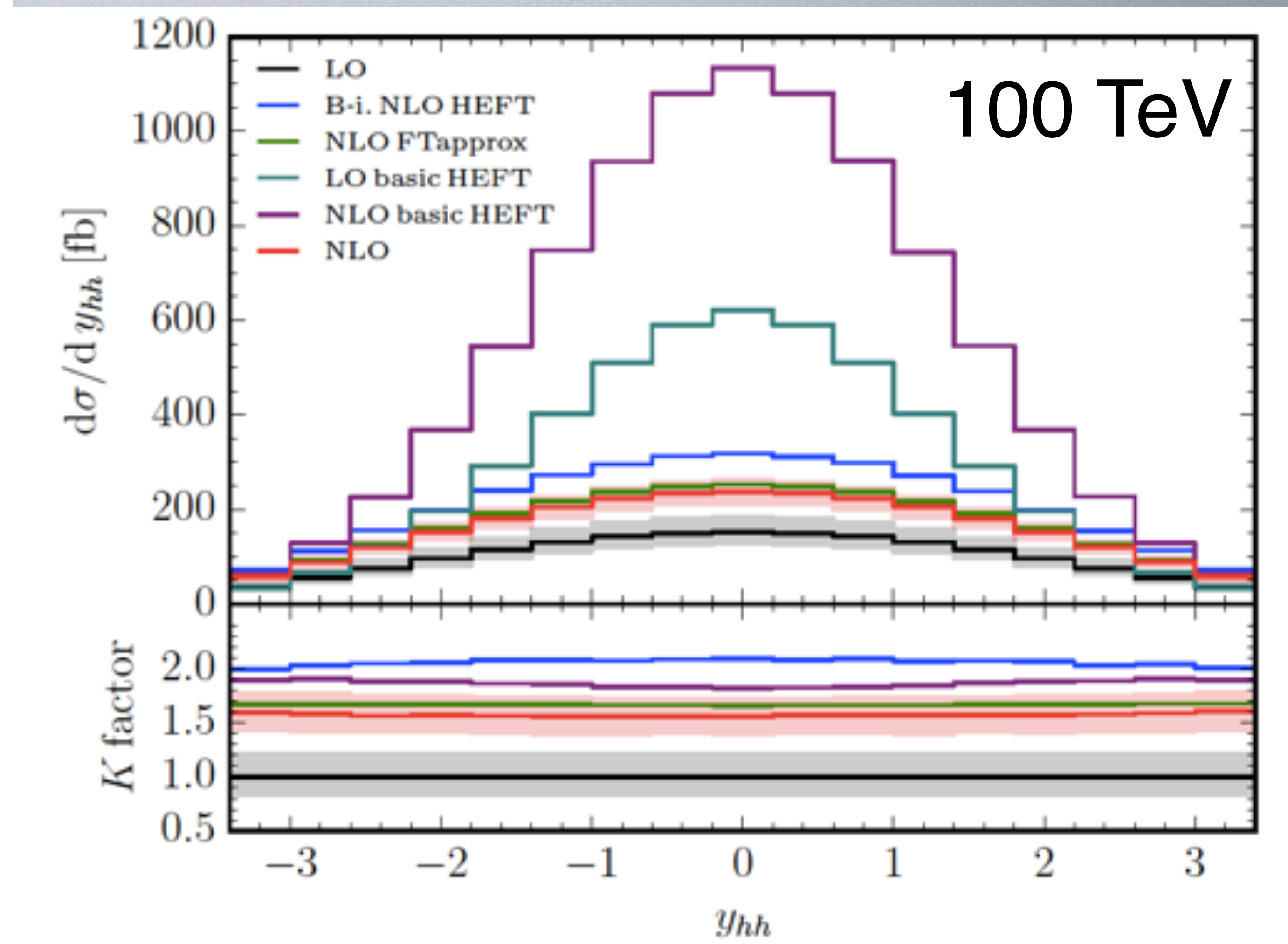
rapidity of the Higgs boson pair





NLO-improved NNLO HEFT

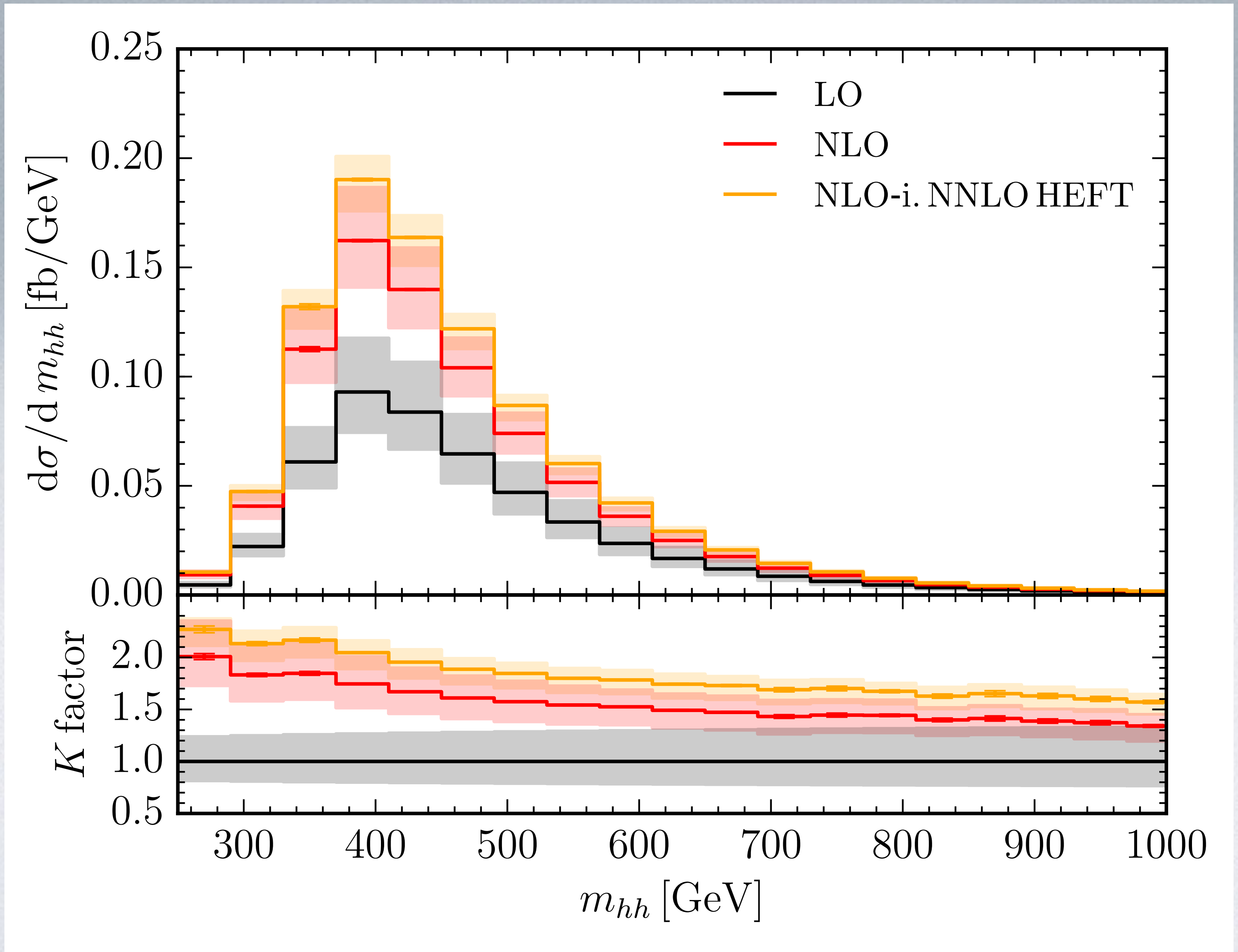
NNLO HEFT:

De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 1606.09519

"NLO-improved NNLO HEFT": [Borowka, Greiner, GH, Jones, Kerner, Schlenk, Zirke 1608.04798]

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

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



would lead to

$$\sigma' = 38.56\, fb$$

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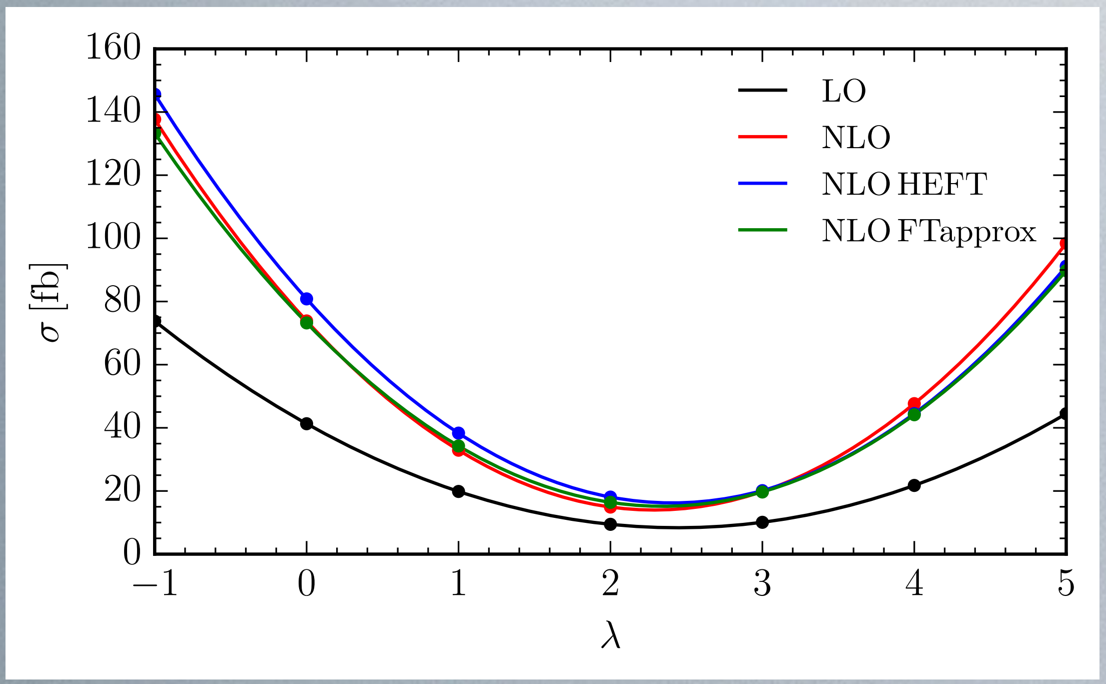
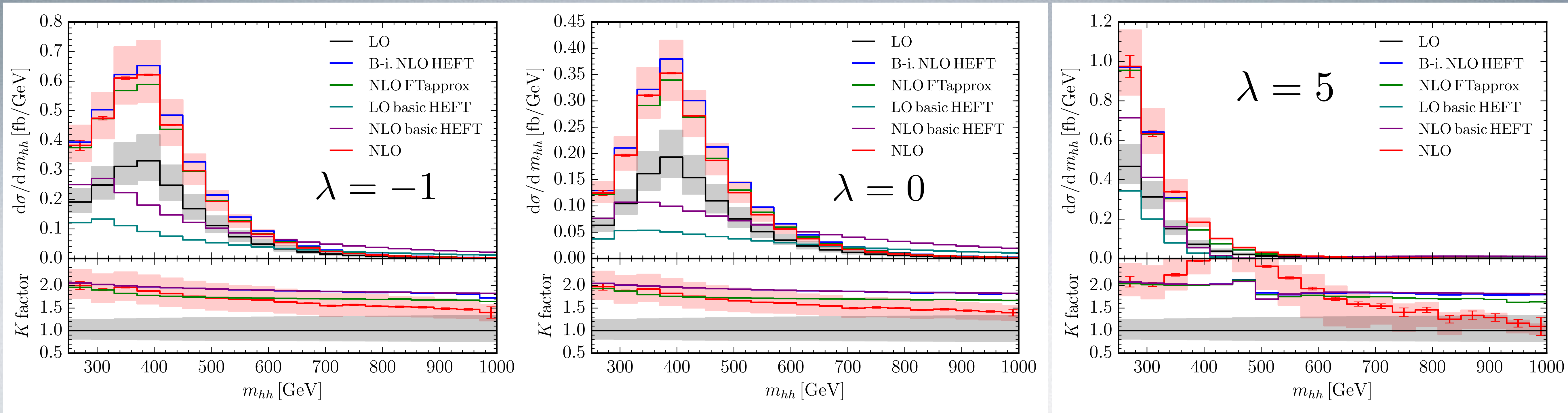
variation of triple Higgs coupling

$$\lambda = \lambda_{BSM}/\lambda_{SM}$$



cross section has a minimum around $\lambda = 2$ due to destructive interference between diagrams containing λ and box-type diagrams

degeneracy due to quadratic λ dependence



distributions can discriminate between degenerate λ values

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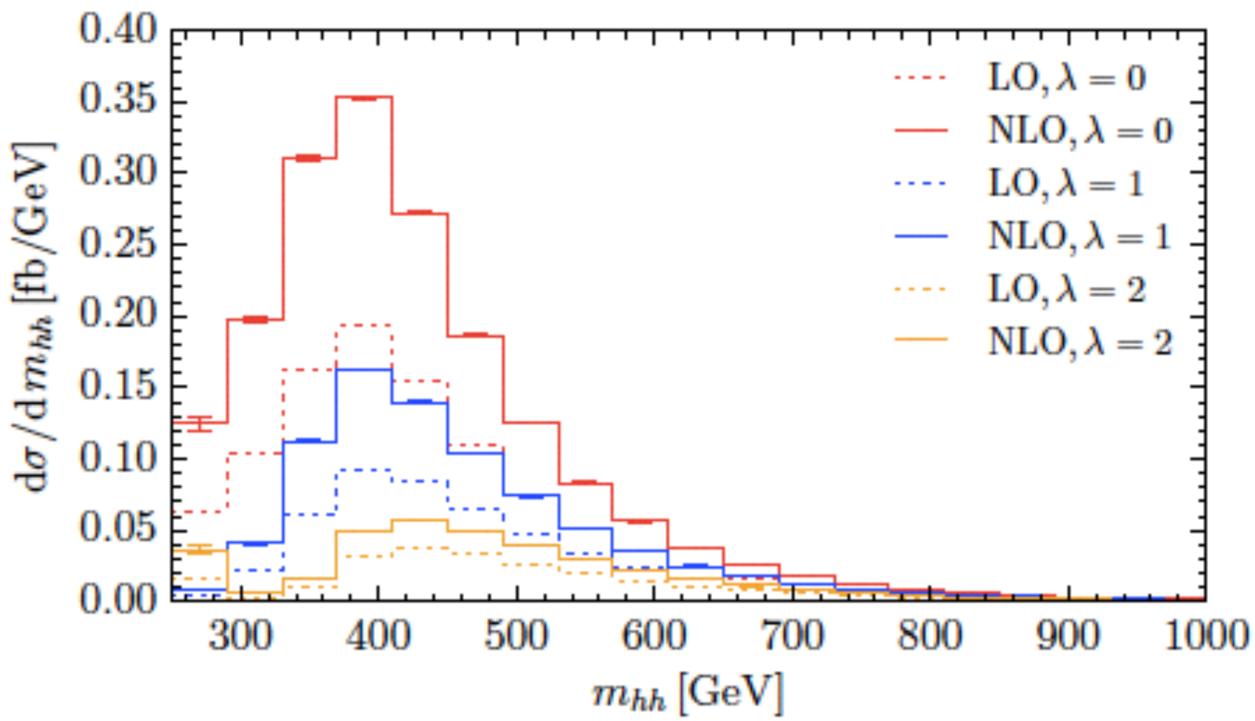
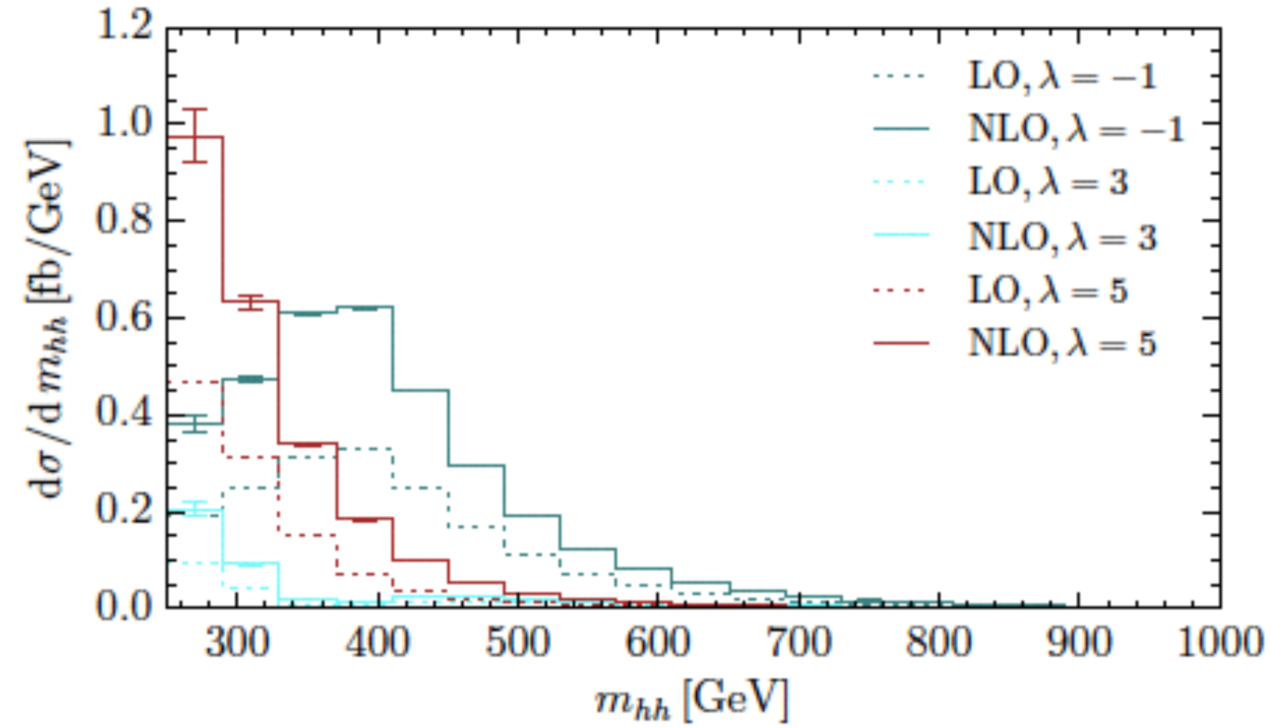
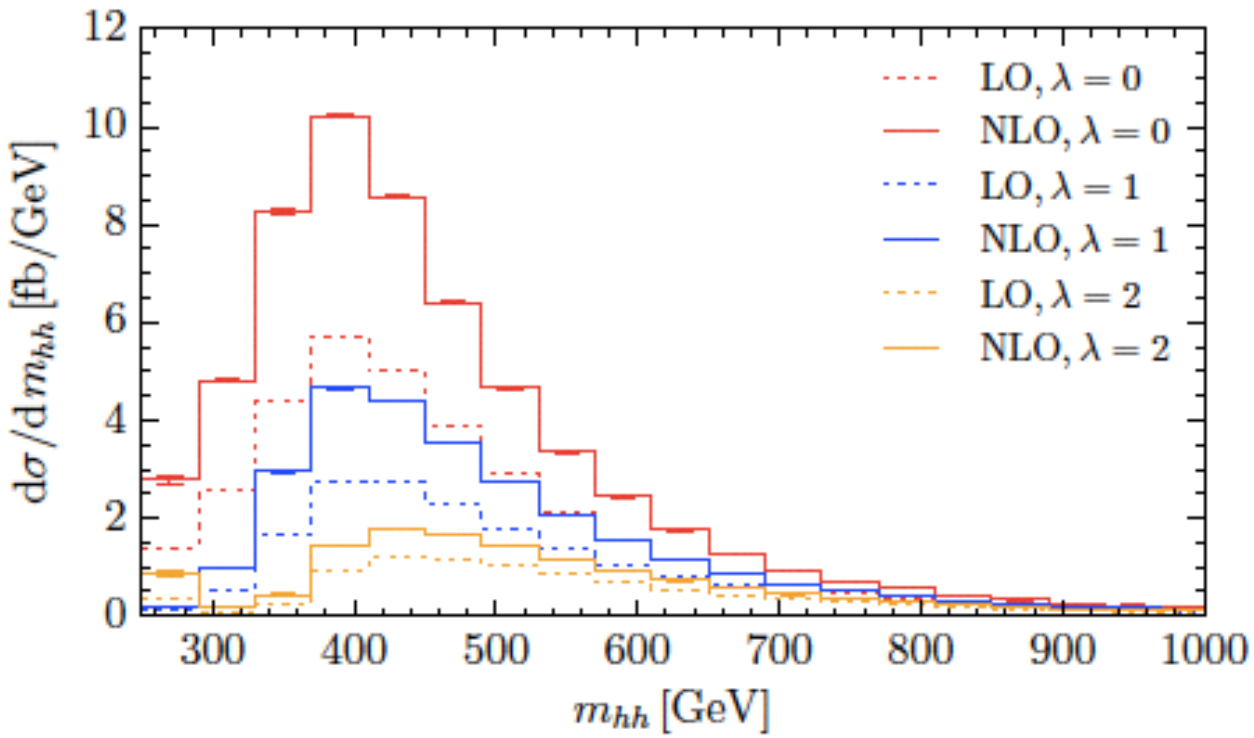
variation of triple Higgs coupling



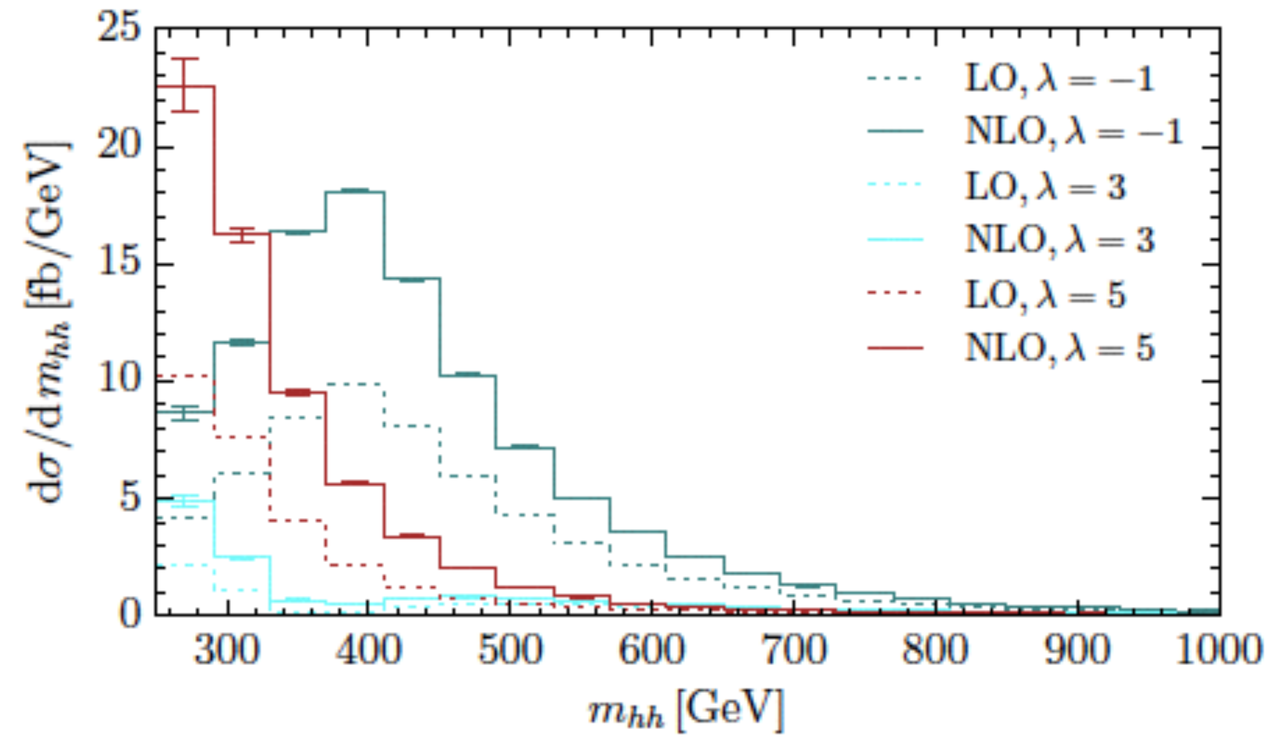
(a) 14 TeV.



(b) 14 TeV.



(c) 100 TeV.



(d) 100 TeV.

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 more uniform distribution

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

combination with POWHEG and MadGraph5_aMC@NLO

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

and Sherpa

combination with parton showers

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

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combination with POWHEG and MadGraph5_aMC@NLO

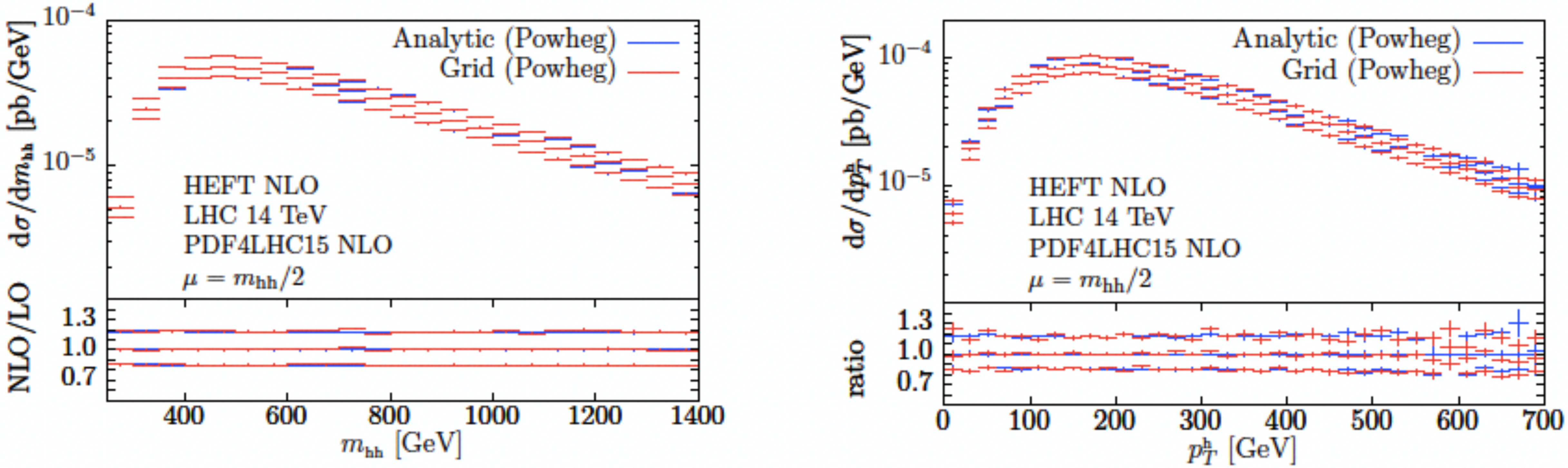
POWHEG-BOX-V2: User-Process-V2/ggHH

and Sherpa — New!

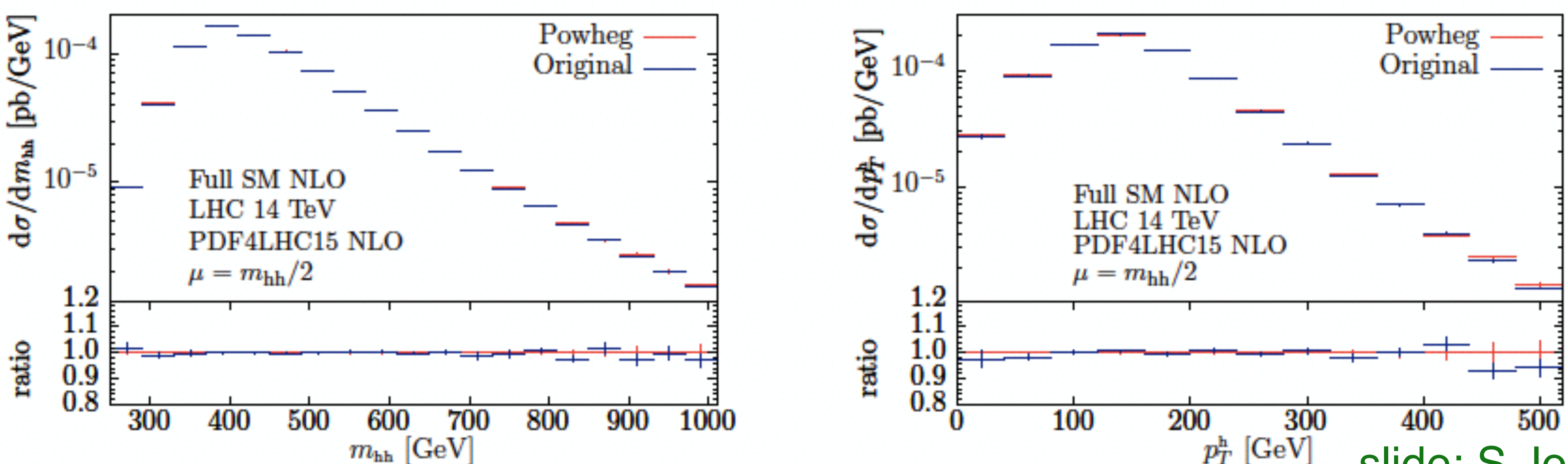
see Silvan Kuttimalai's talk

grid validation

Use HEFT to study validity of grid

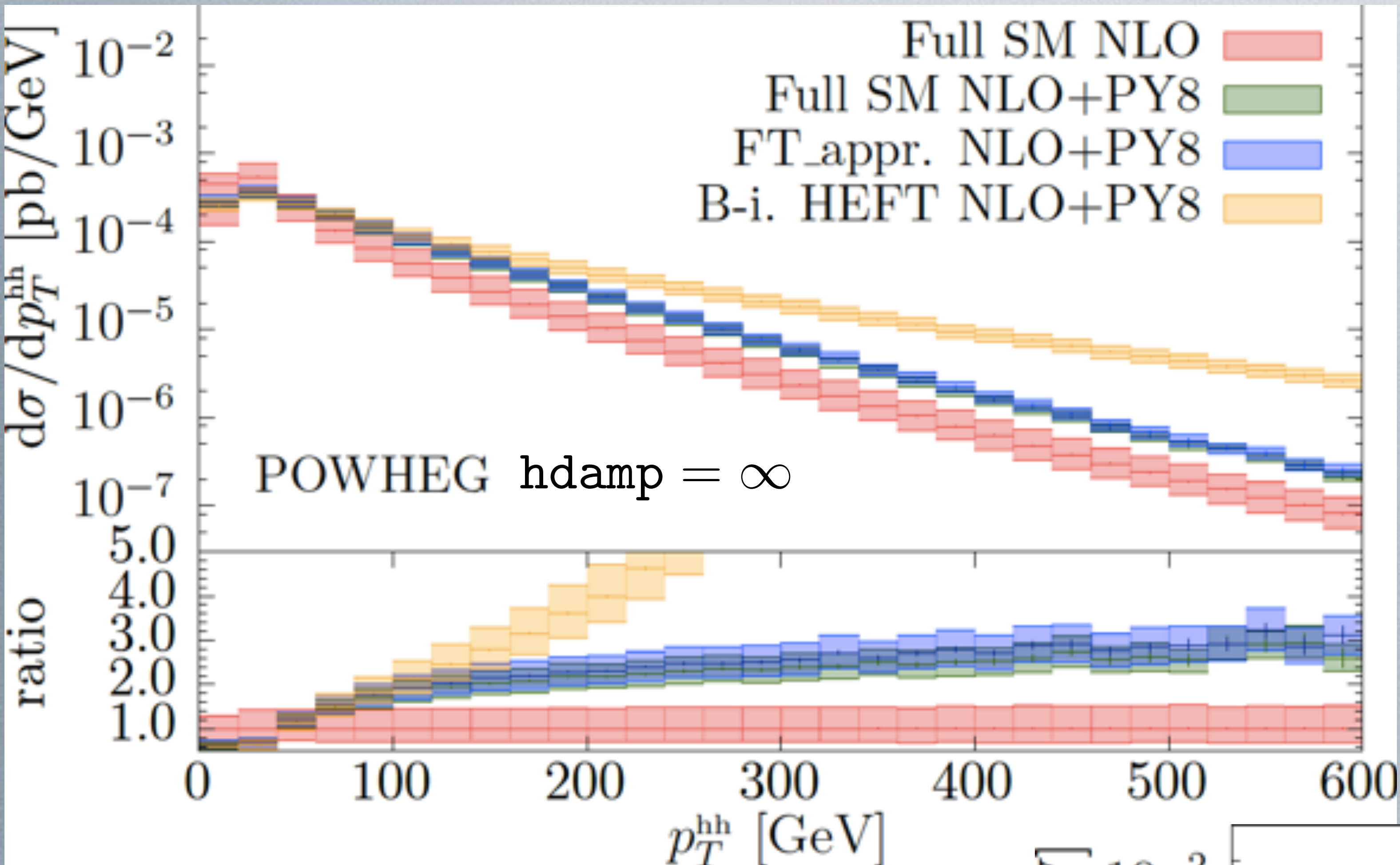


Full SM compare `POWHEG` (grid) with our original results



slide: S.Jones

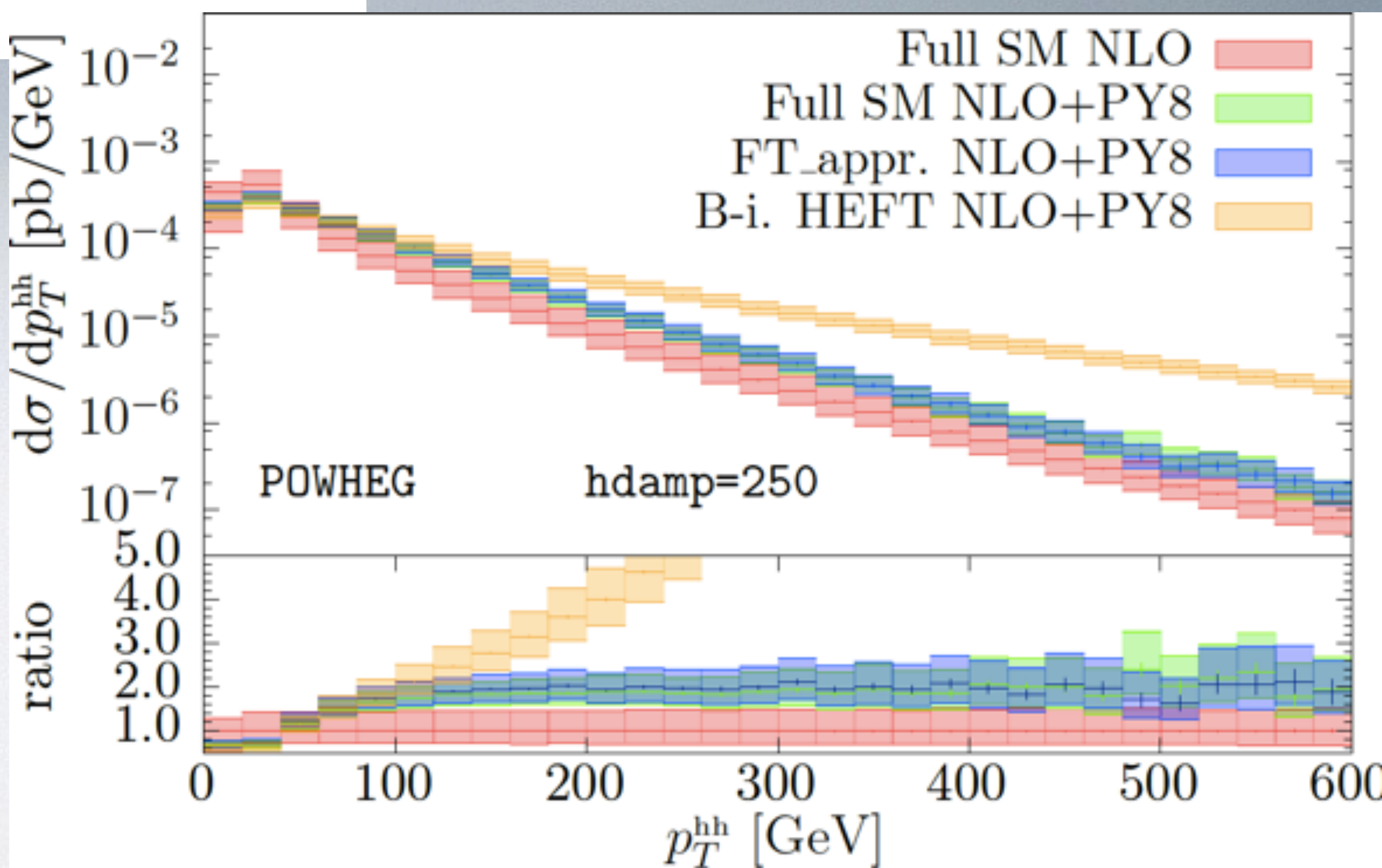
dependence on shower parameters



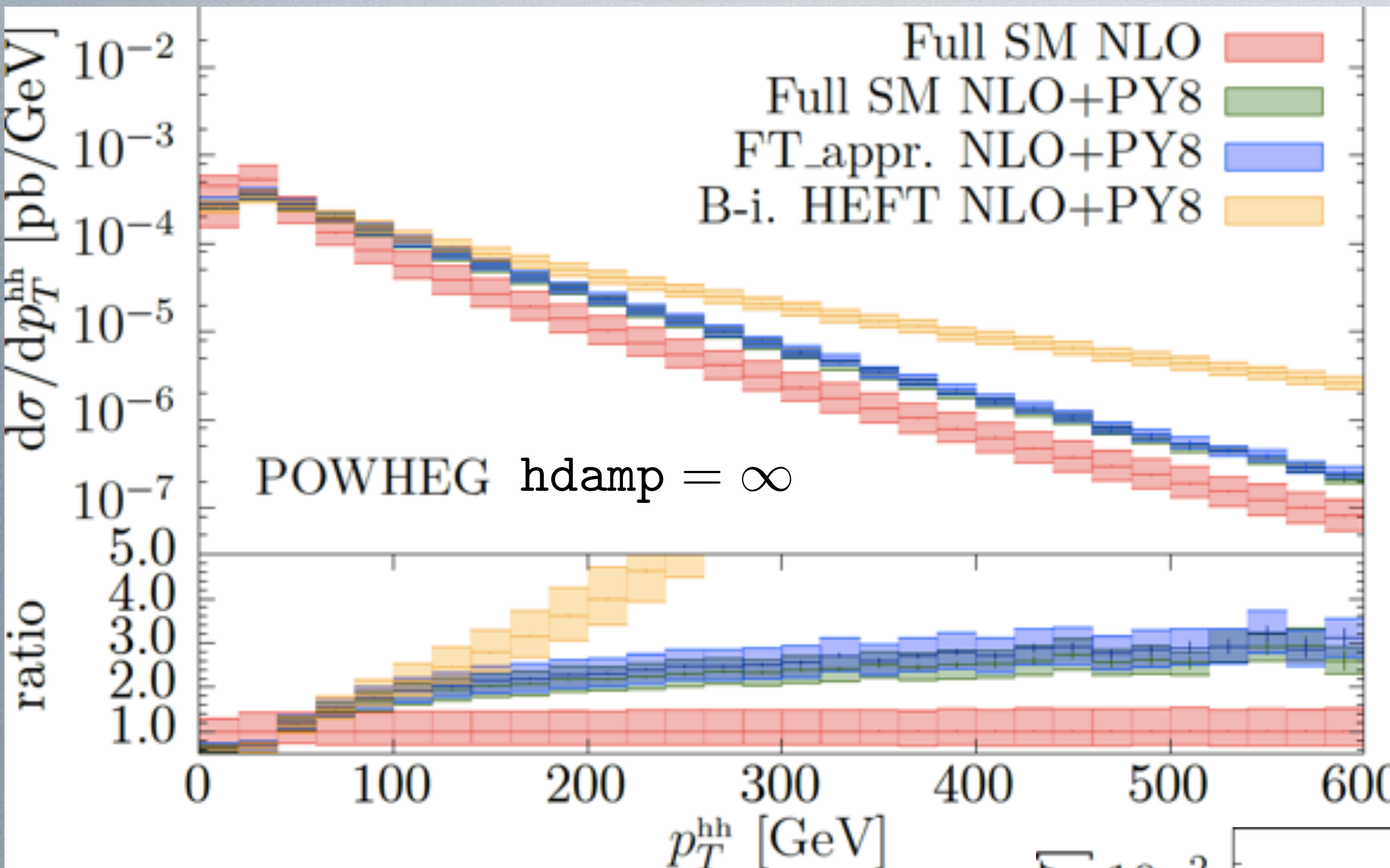
hdamp=h limits amount of exponentiated hard radiation

$$R_{\text{sing}} = R \times F\,,$$
$$R_{\text{reg}} = R \times (1 - F)$$

$$F = \frac{h^2}{(p_T^{\text{hh}})^2 + h^2}$$



dependence on shower parameters

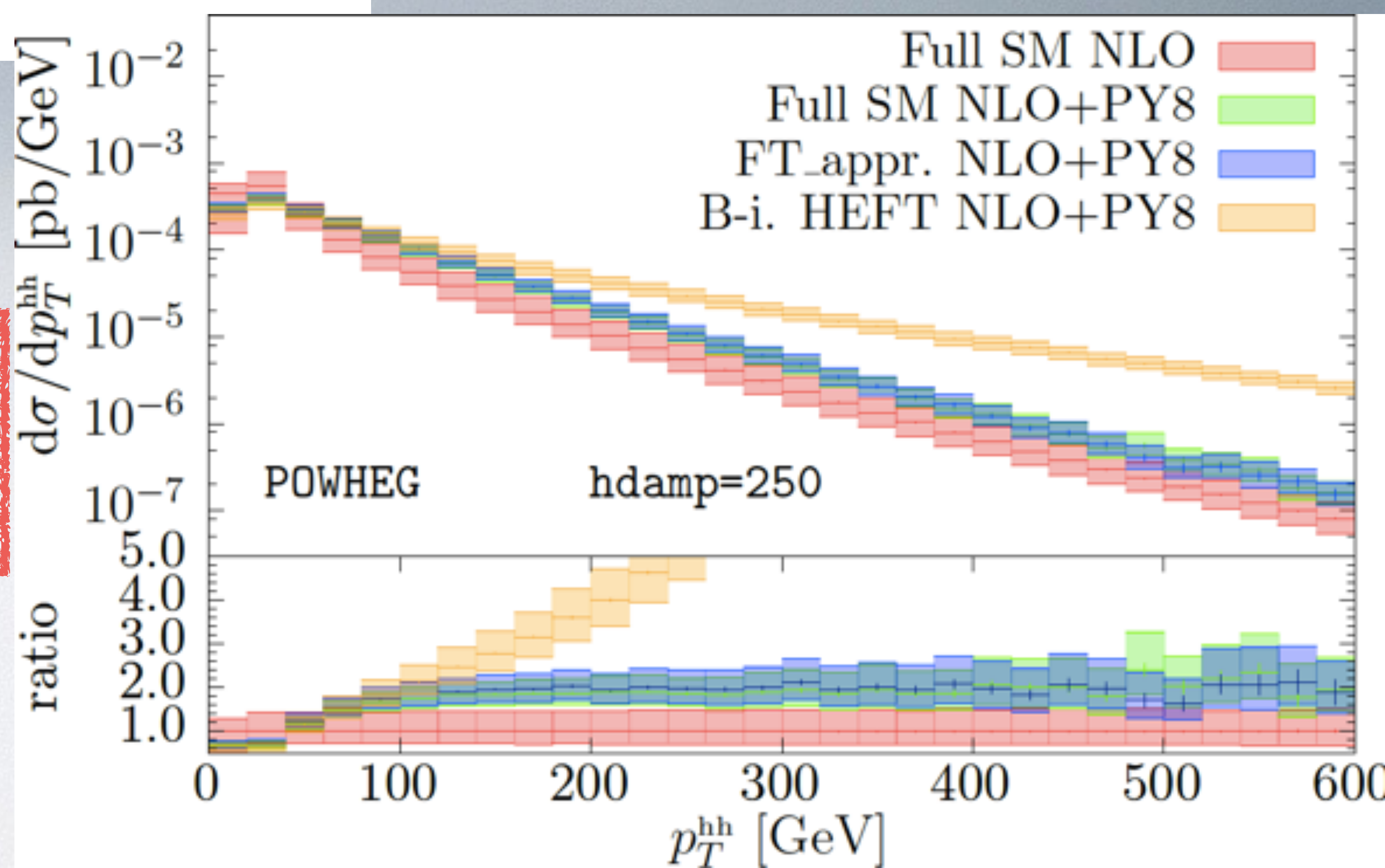


hdamp=h limits amount of exponentiated hard radiation

$$R_{\text{sing}} = R \times F\,,$$
$$R_{\text{reg}} = R \times (1 - F)$$

$$F = \frac{h^2}{(p_T^{\text{hh}})^2 + h^2}$$

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



summary & outlook

- NLO is not “a solved problem”
- finite mass effects are important
  - in particular in tails of distributions, where they need to be distinguished from BSM effects
  - NLO with full top mass dependence for $pp \to HH, pp \to H + jet, gg \to HZ$ means 2-loop integrals with many kinematic scales (too many for an analytic solution currently?)

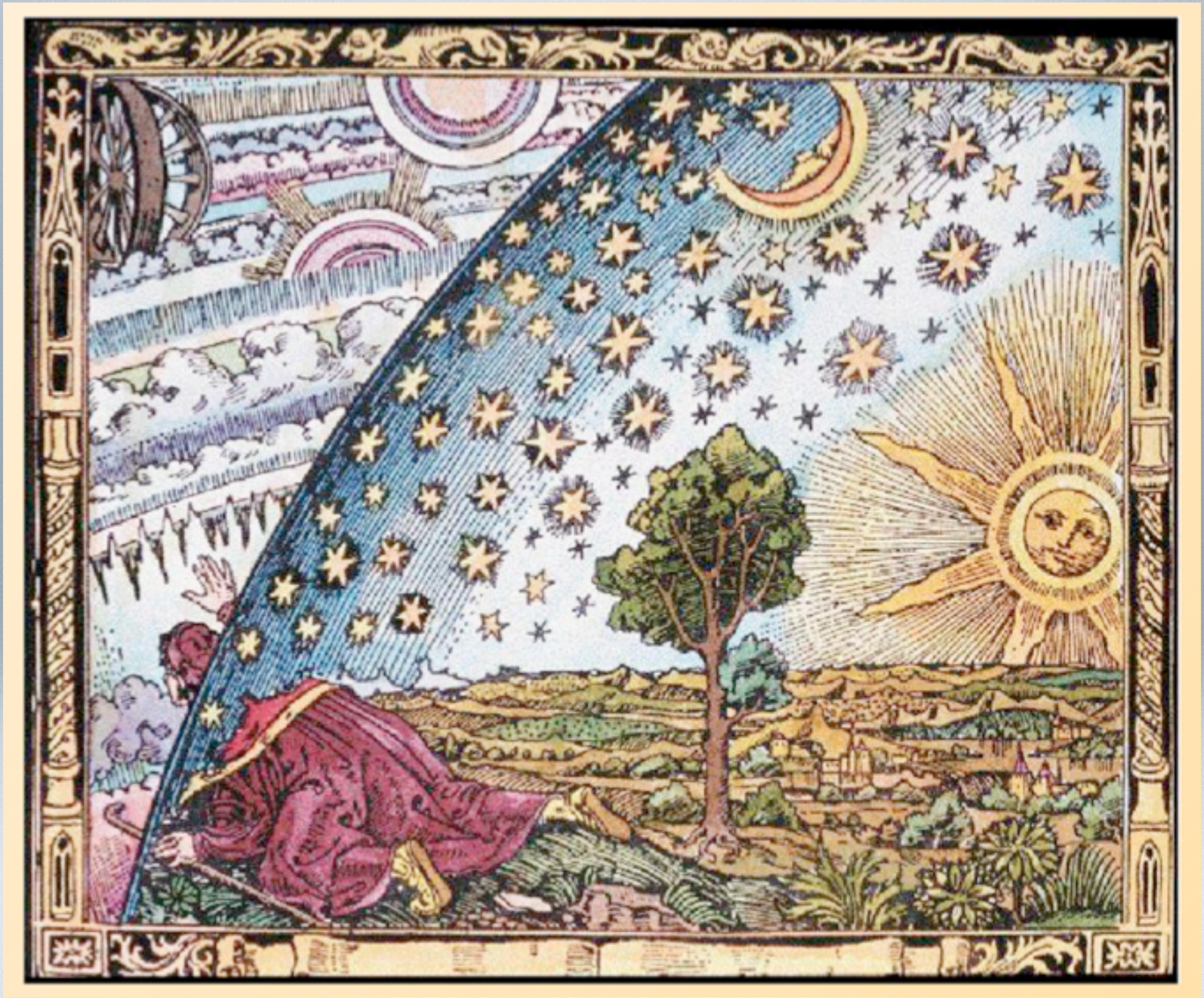
    lots of progress recently

    - HH@NLO done numerically (SecDec)
- combination of QCD corrections with NLO EW and EFT

  talk of Alexander Mück (NLO EW) — many talks (EFT)

- increase precision by improvements on parton shower side (matching uncertainties, merging, log. acc.) and resummation

  talk of Pier-Francesco Monni (resummation)



BACKUP SLIDES

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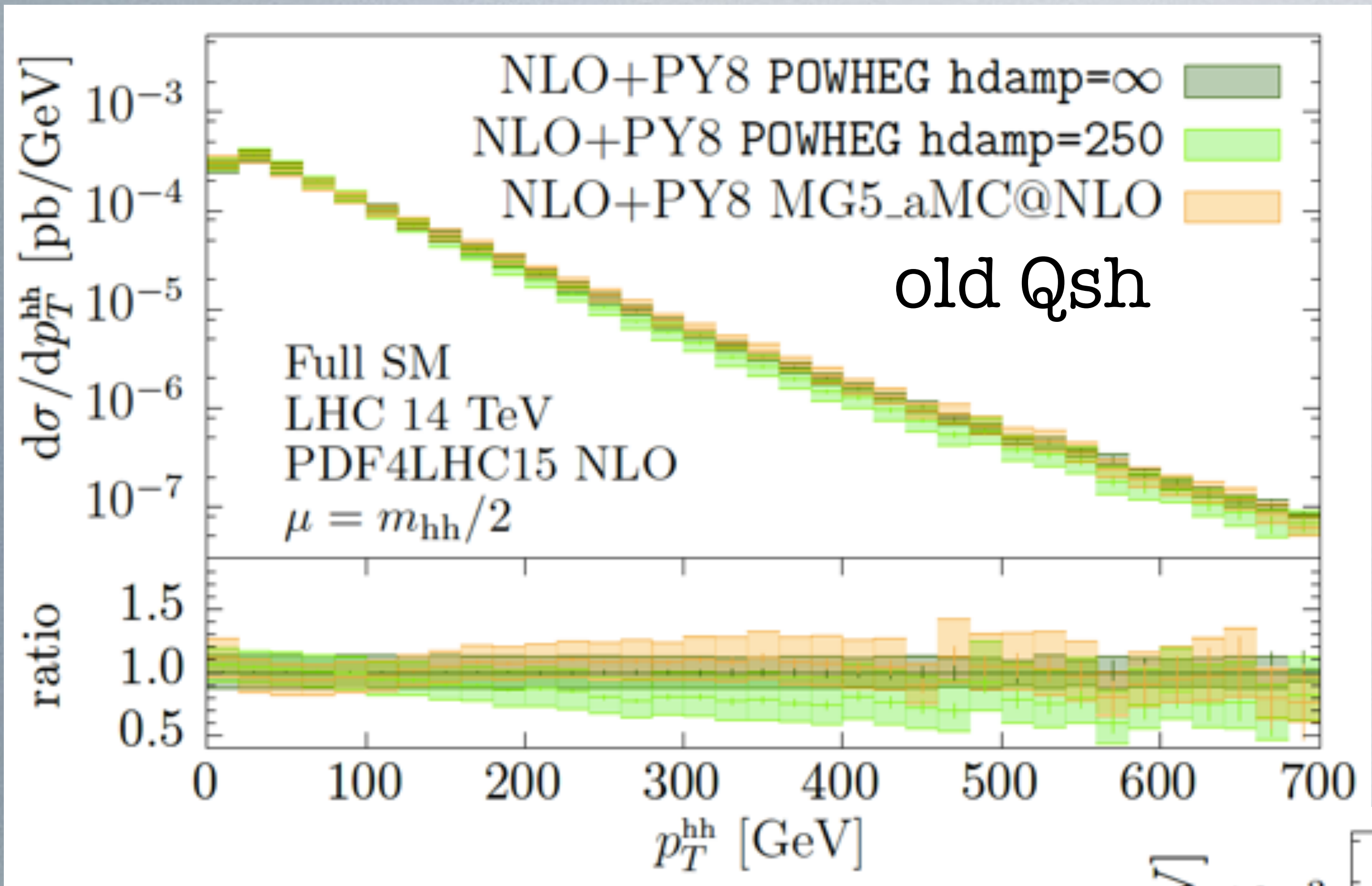
compare POWHEG and MG5_aMC@NLO



MG5_aMC@NLO
old shower starting scale Qsh:

picked with some probability distribution in

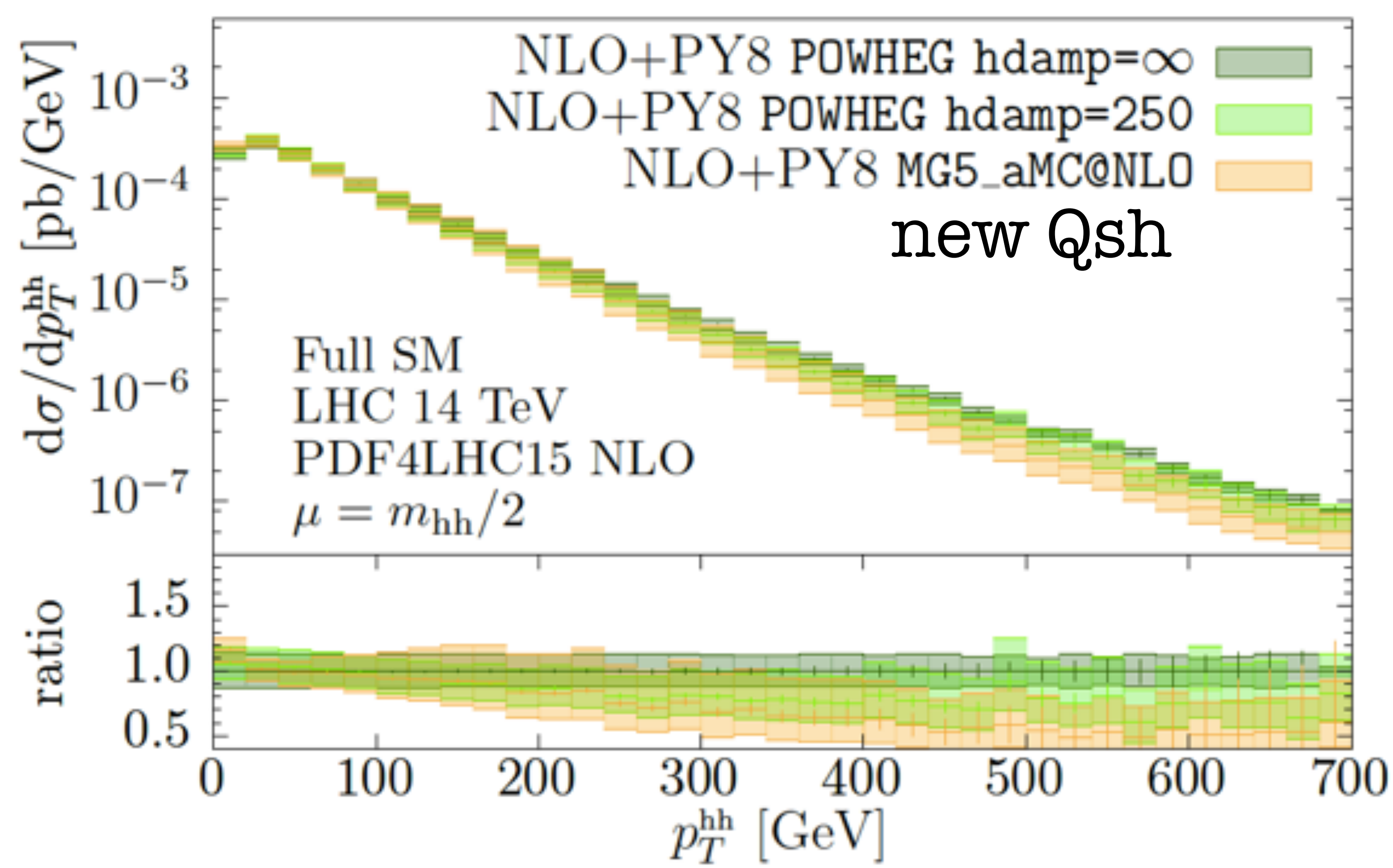
$\texttt{shower\_scale\_factor} \times [0.1\sqrt{\hat{s}}, \sqrt{\hat{s}}]$

MG5_aMC@NLO version 2.5.3:

new Qsh

picked with some probability distribution in

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



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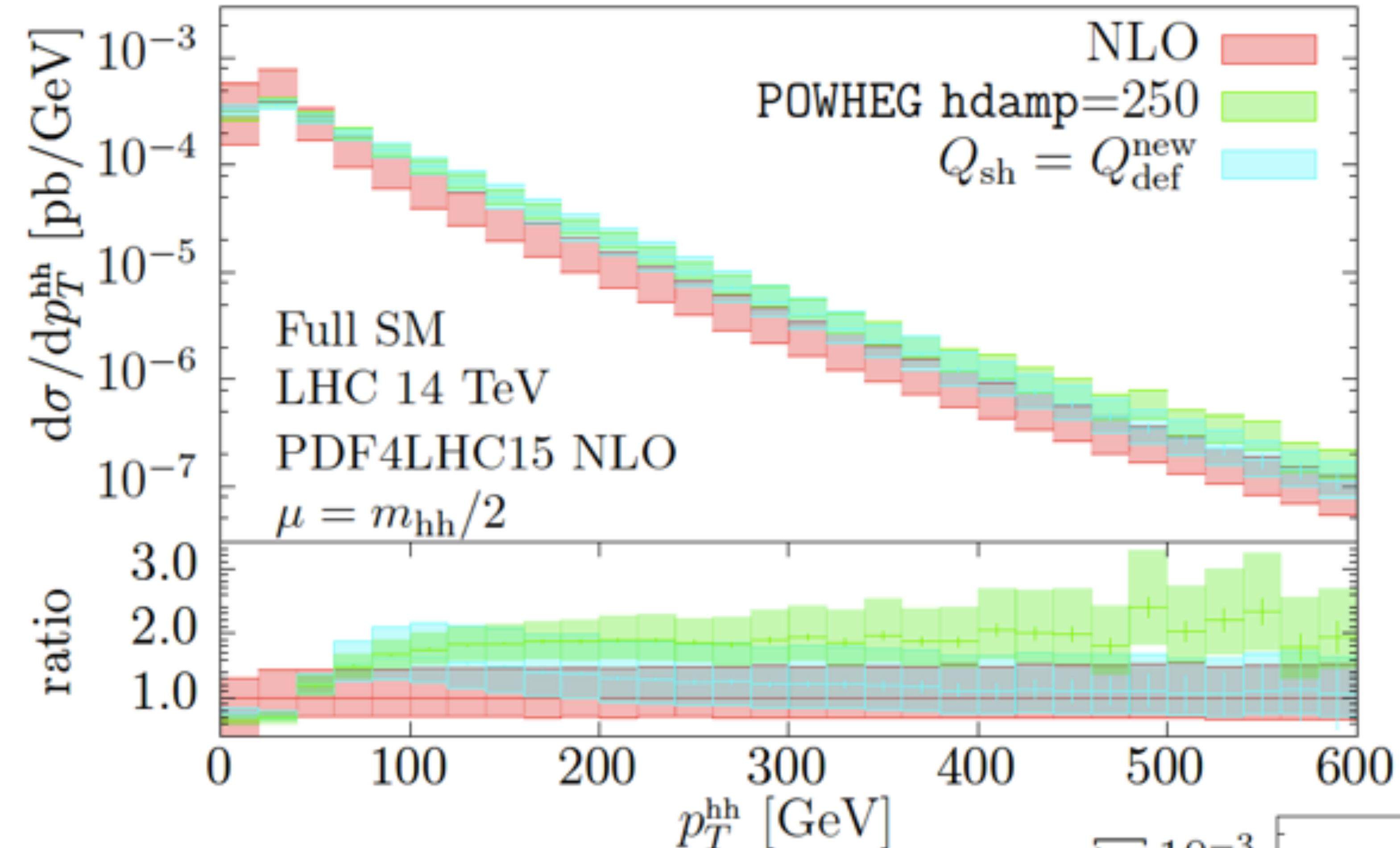
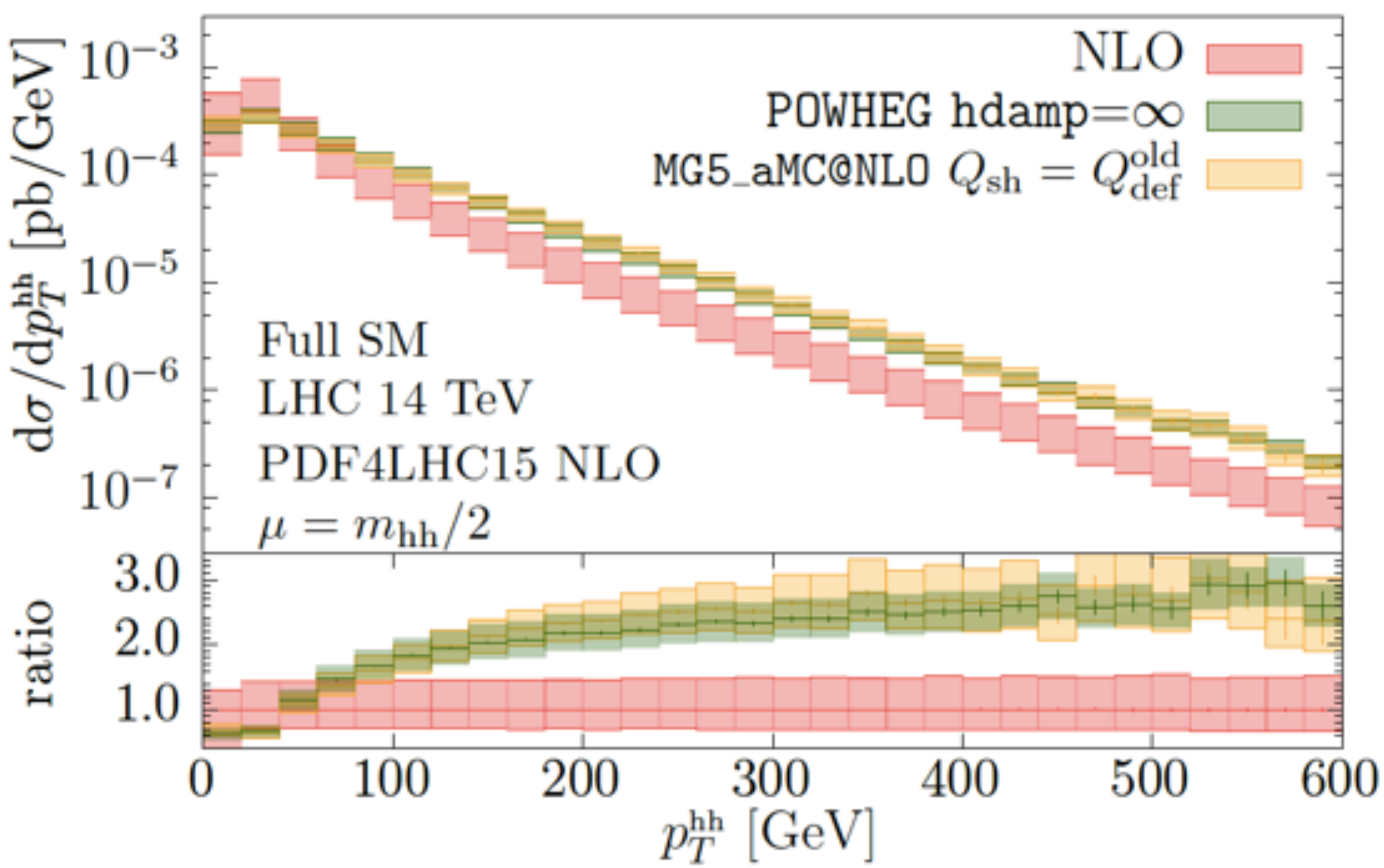
compare POWHEG and MG5_aMC@NLO



new default Qsh matches onto NLO fixed order at large pT



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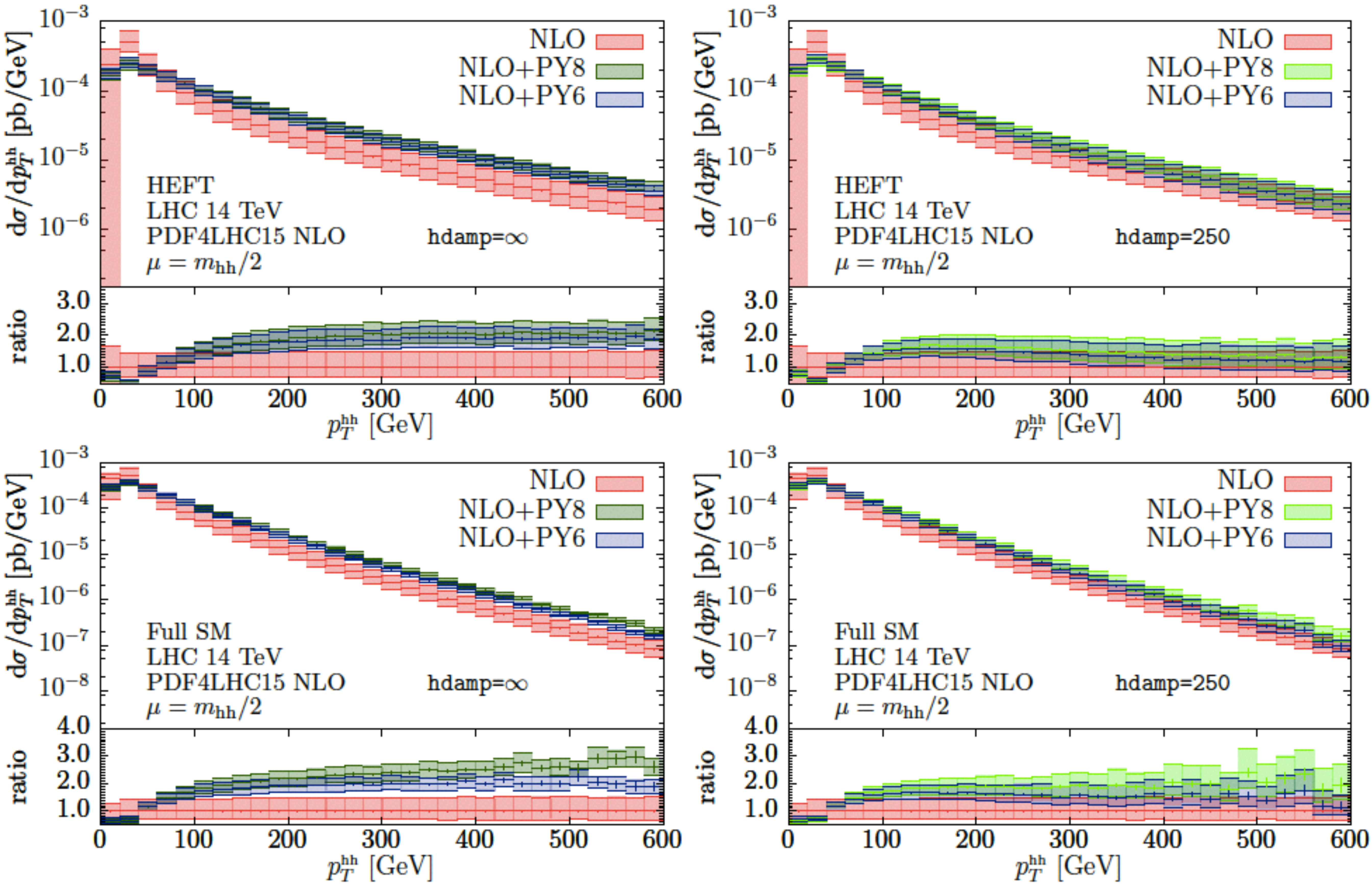
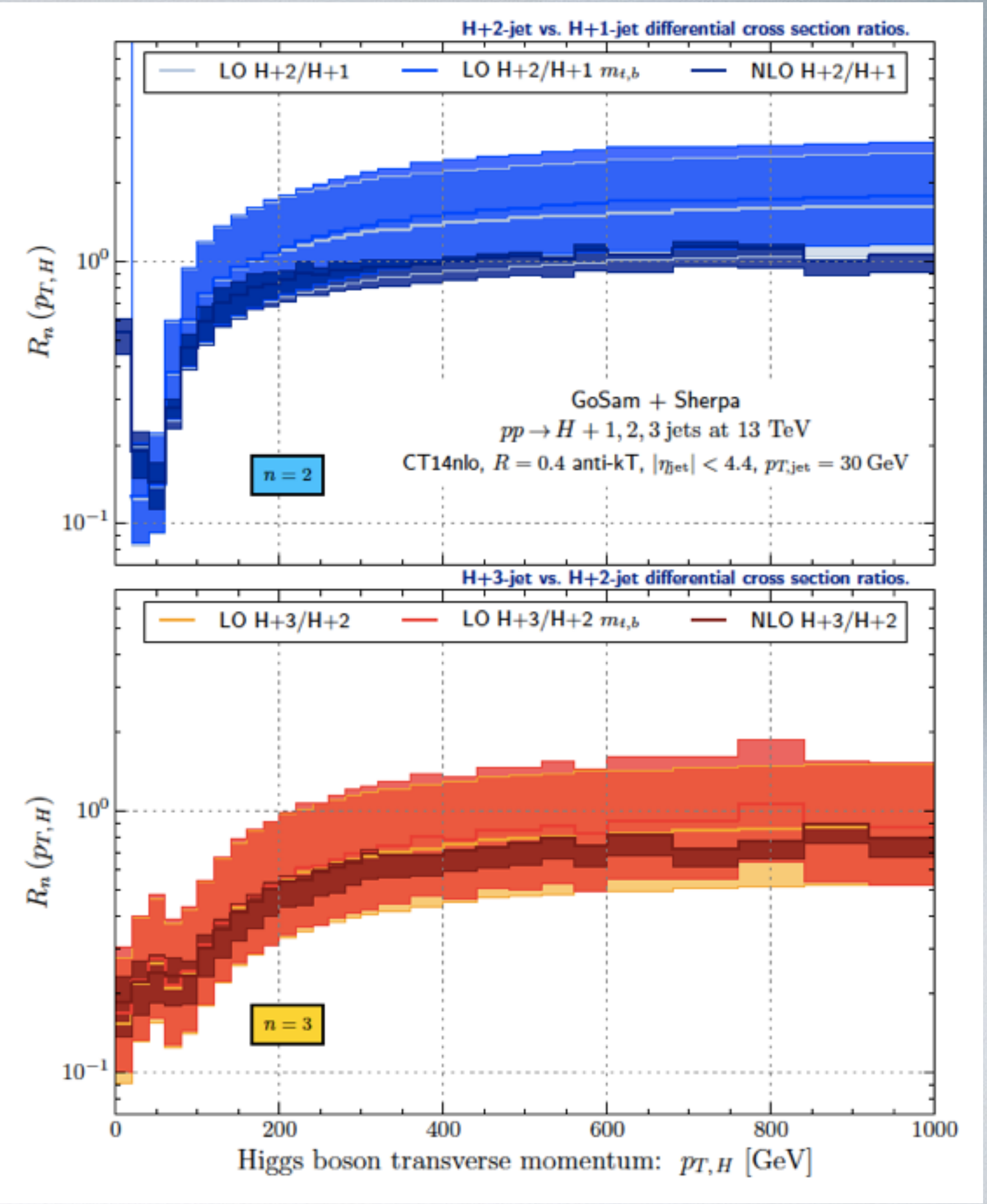
compare Pythia6 and Pythia8



quark mass effects in Higgs + jets

$$R_n(O) = \frac{\frac{d\sigma}{dO}(\mathrm{H}+n\,\mathrm{jets})}{\frac{d\sigma}{dO}(\mathrm{H}+(n-1)\,\mathrm{jets})}$$

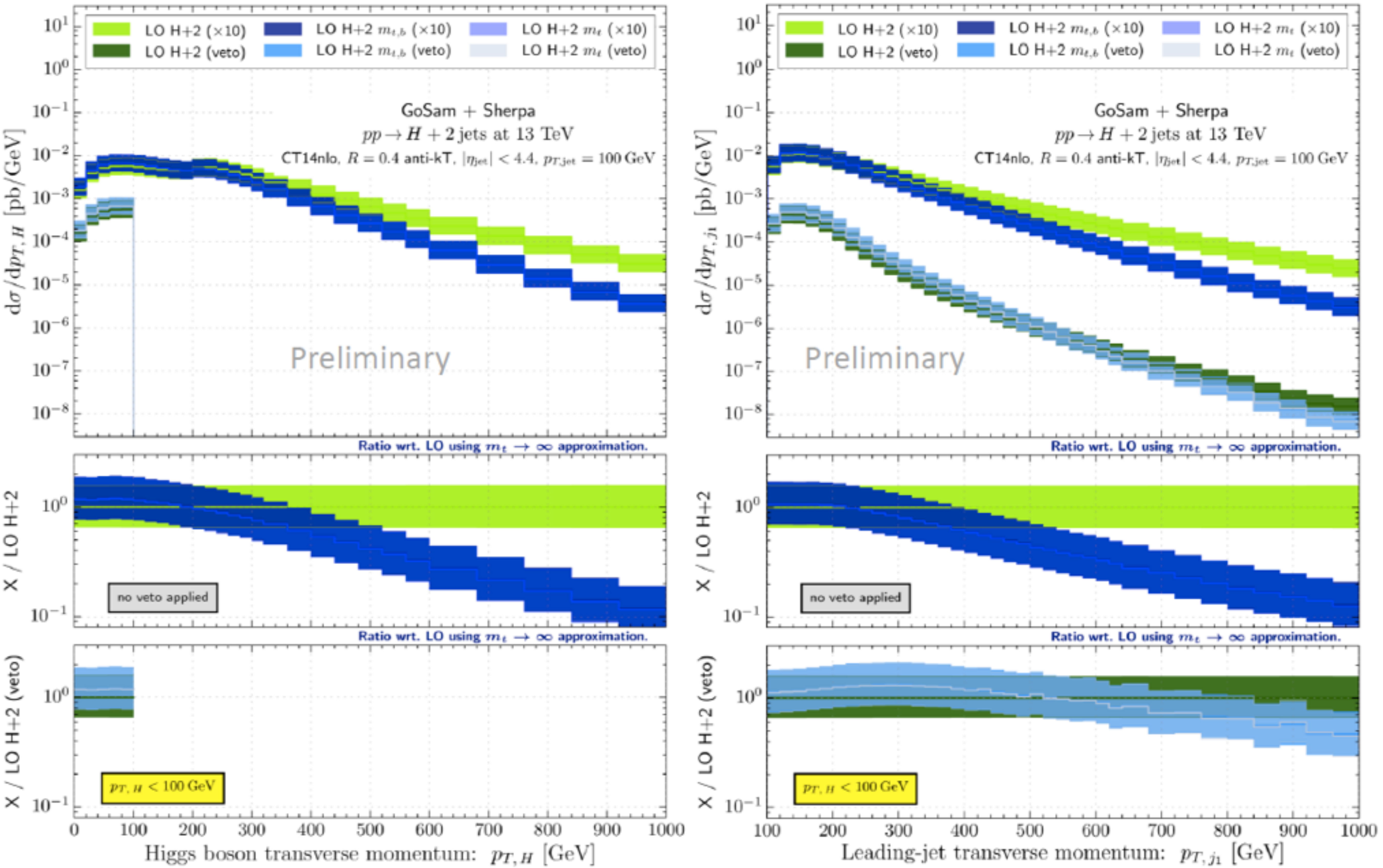
ratio to lower jet multiplicity shows similar behaviour



quark mass effects in Higgs + jets

Applying a veto on the Higgs for H+2j: $p_{T,\,Higgs}$ < 100 GeV:

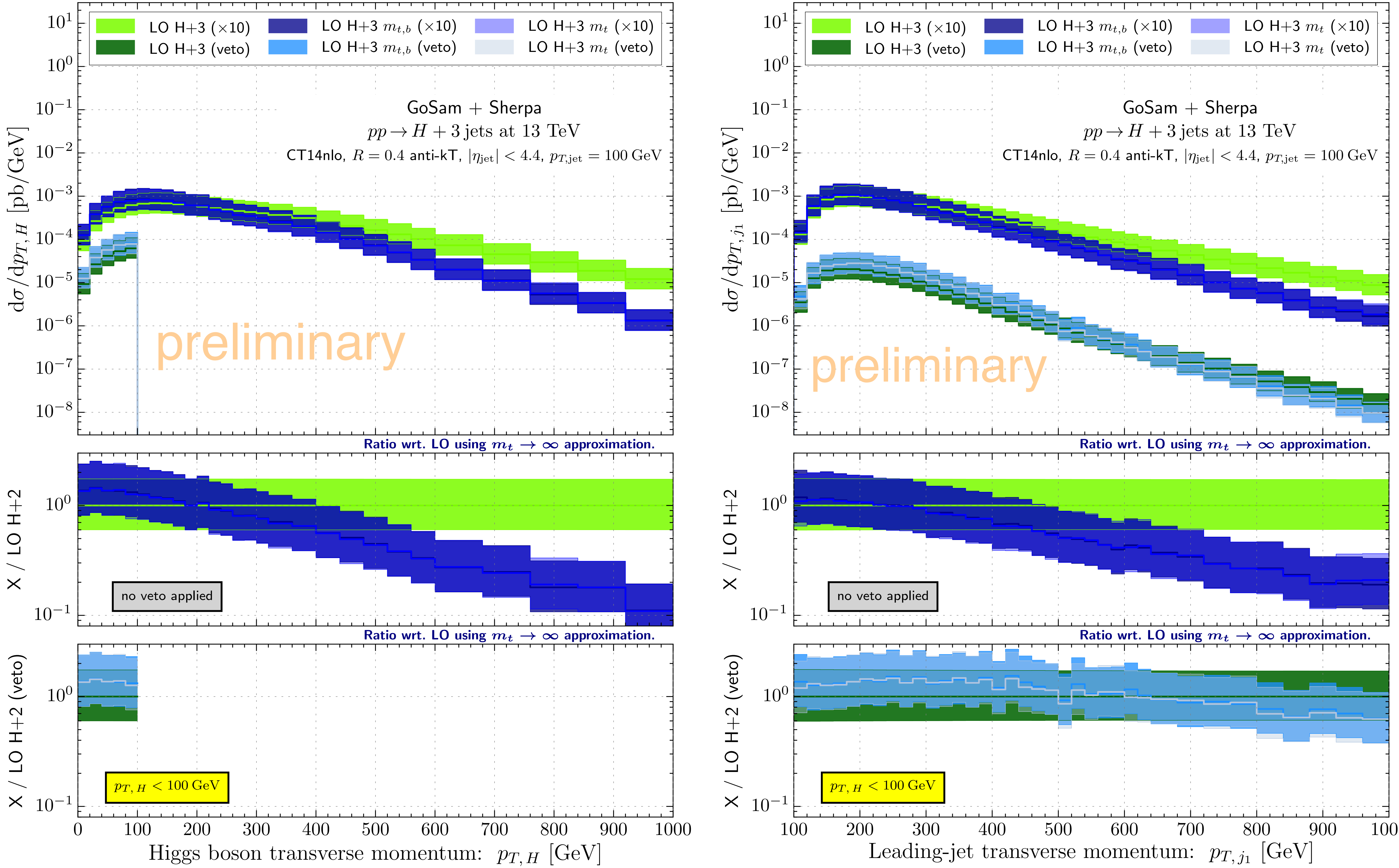
Gionata Luisoni, DIS 2017



quark mass effects in Higgs + jets

Applying a veto on the Higgs for H+3j: $p_{T,\,Higgs}$ < 100 GeV:

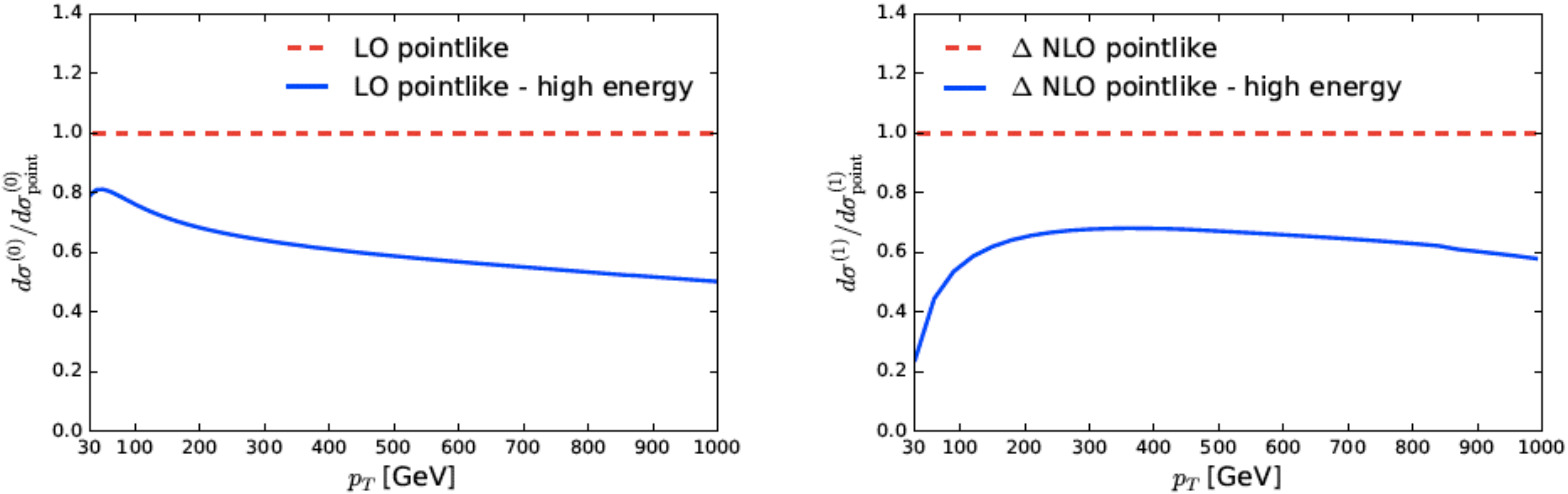
Gionata Luisoni, DIS 2017



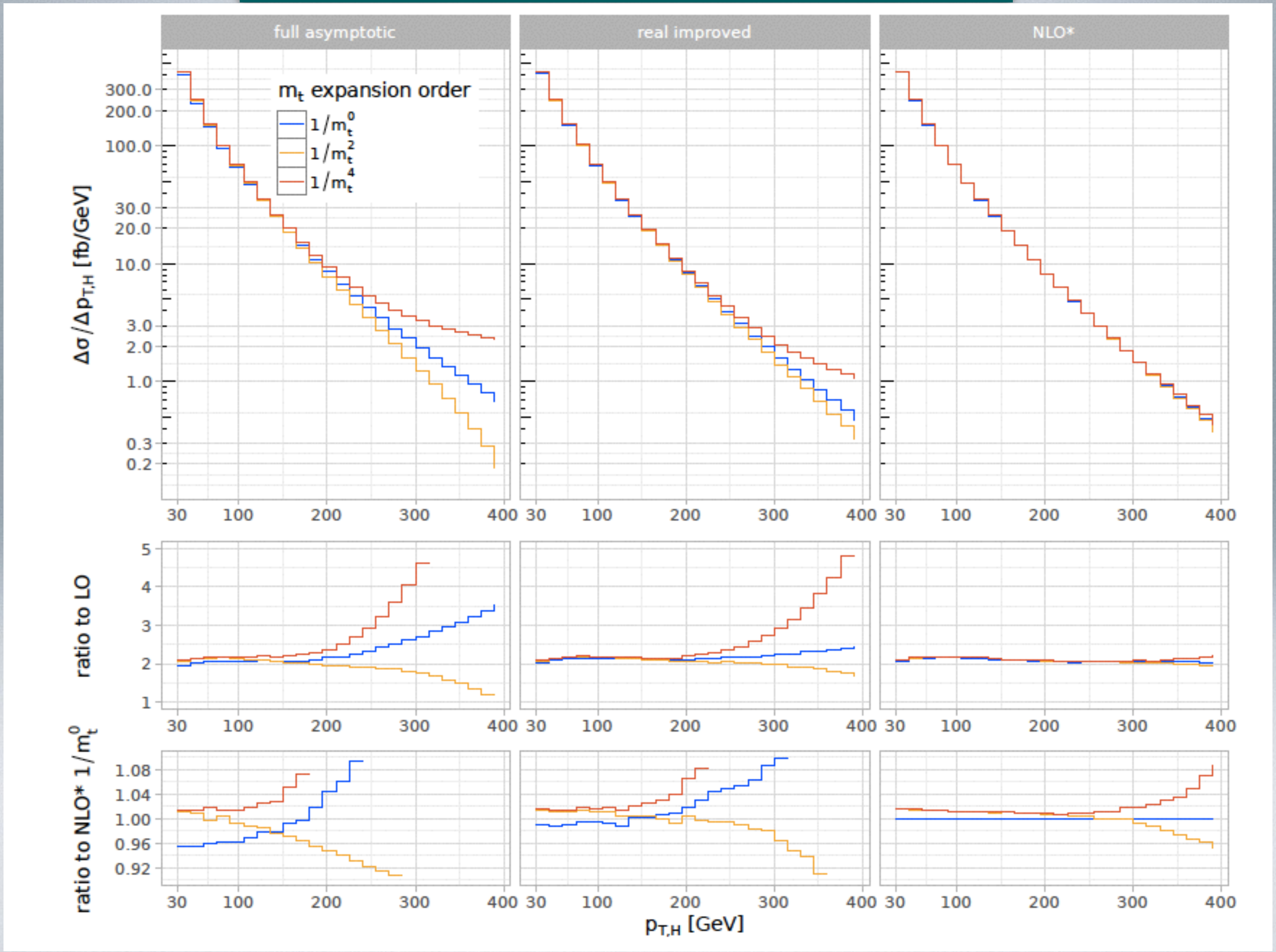
Higgs pT

high-energy resummation of Higgs pT in $gg \to H$ with off-shell gluons

Caola, Forte, Marzani, Muselli, Vita '16



Higgs + jet



Neumann, Williams '17