Higgs theory overview

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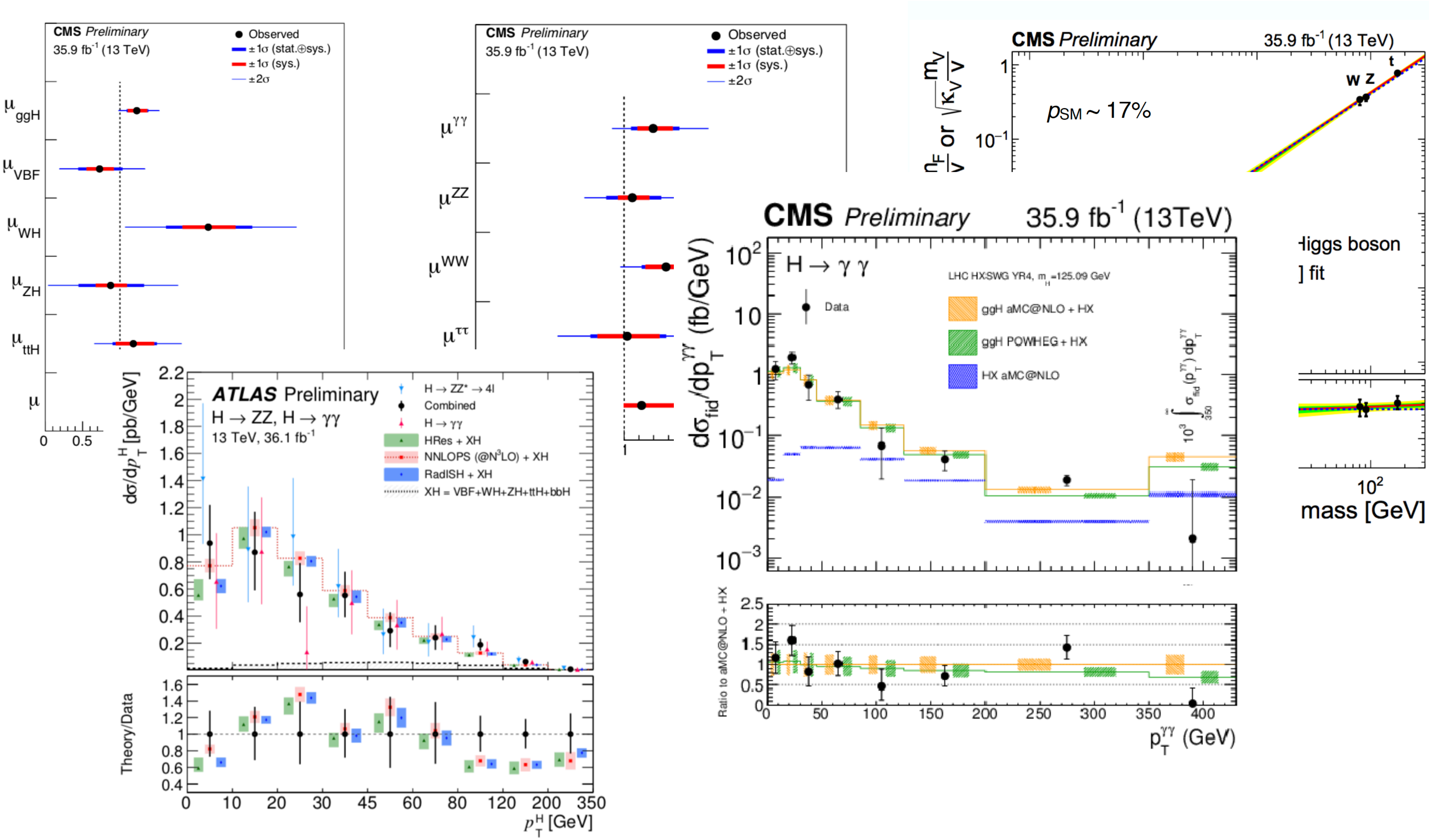
Universität Zürich[UZH]

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

Outline

- Introduction
- Accurate signals
- Taming backgrounds
- Higgs p_T
- The LHC Higgs Cross Section WG
- Prospects for HL/HE LHC and 100 TeV
- Summary & Outlook

Status Moriond 2018



The Higgs boson is perfectly consistent with what predicted by the SM

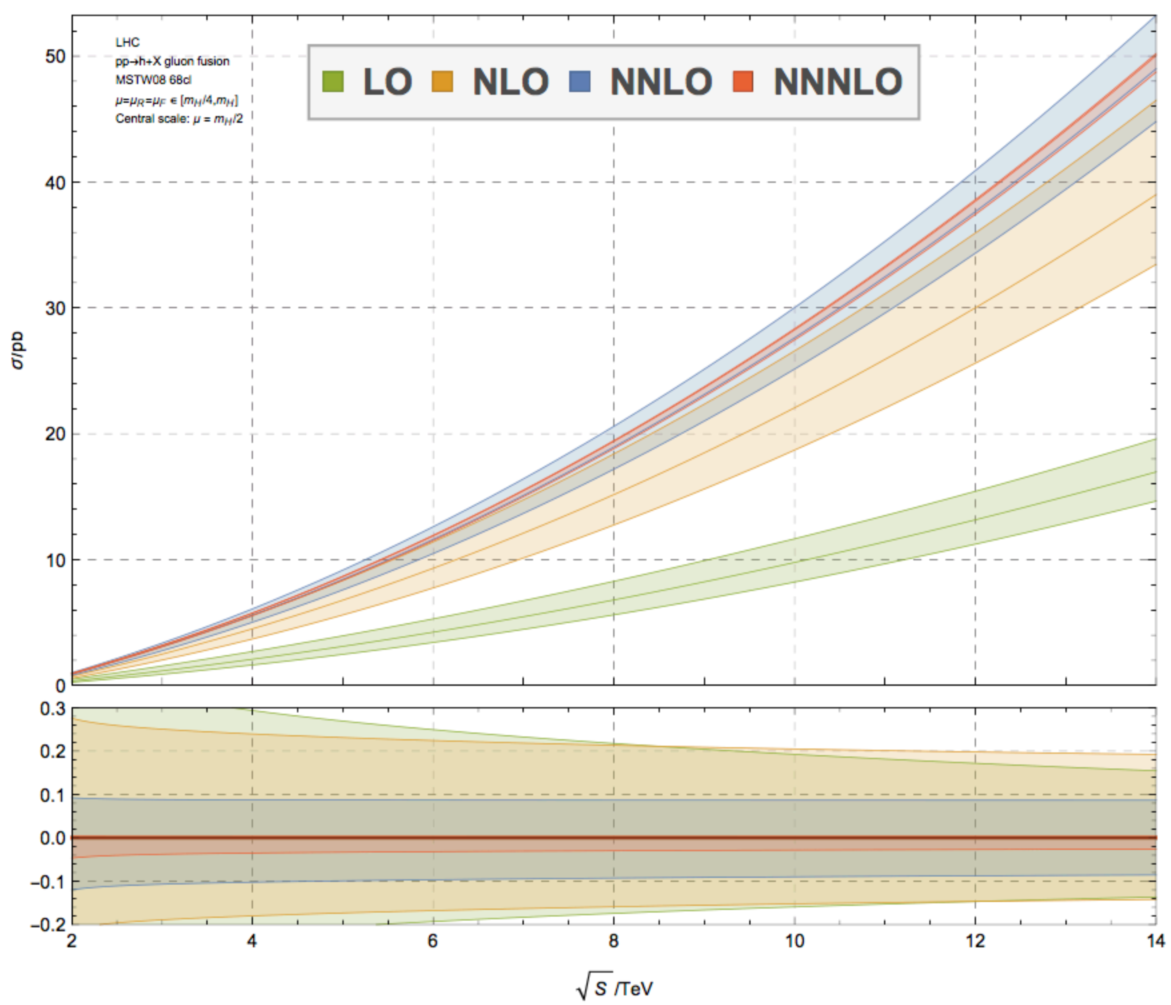
This conclusion requires good control over SM predictions

Theory precision: gg→H at N3LO

C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger (2015)

Really impressive achievement:

- first complete calculation at N3LO in hadronic collisions !
- O(10^5) diagrams; O(10^3) master integrals



Obtained through a series expansion around the soft limit (37 terms !)

$$1 - z = 1 - m_H^2/\hat{s}$$

"distance" from partonic threshold

Important reduction of perturbative uncertainties

Impact of N3LL resummation on top of N3LO very small

M.Bonvini et al. (2016)
(see also M.Spira, T.Schmidt (2015))

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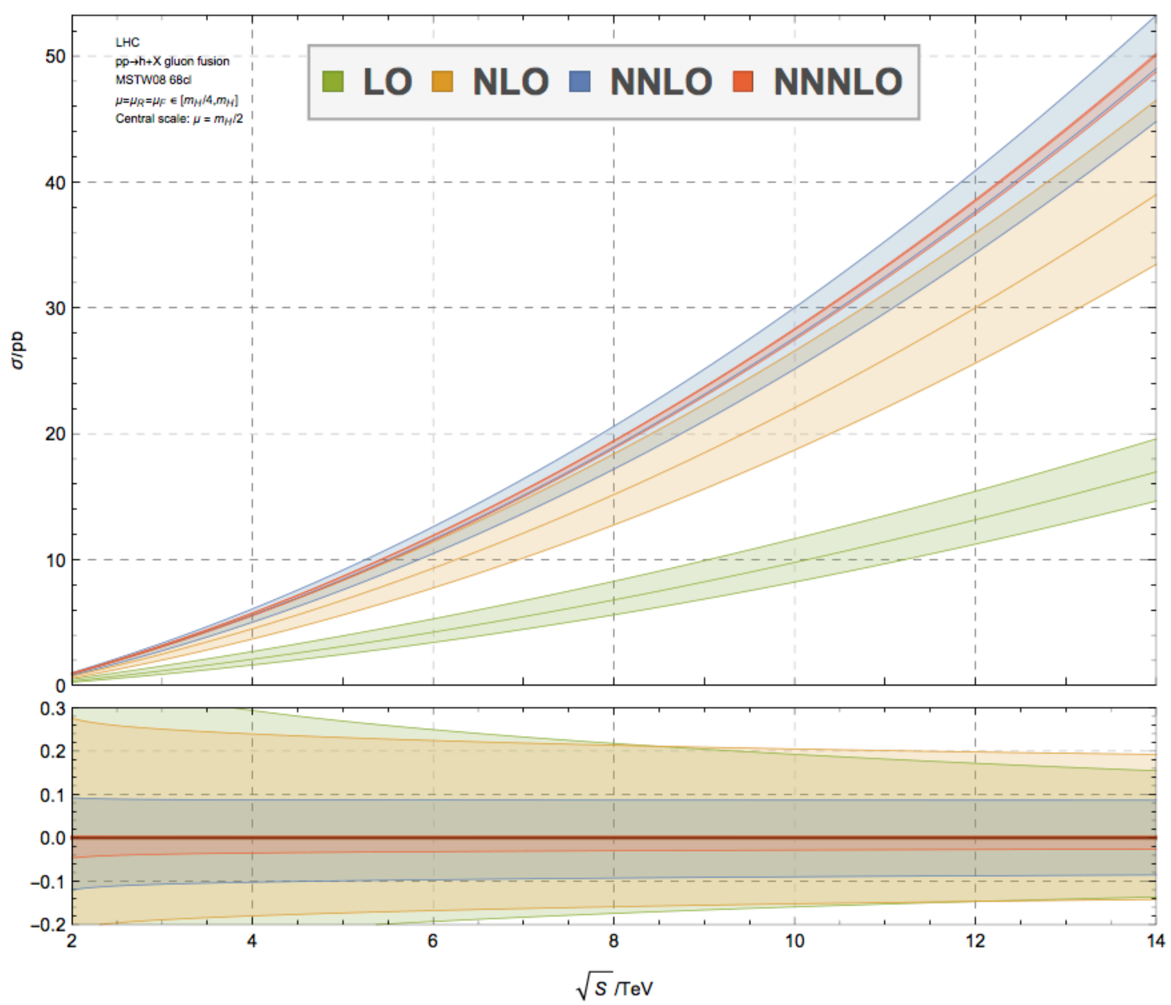

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“distance” from partonic threshold

Recently completed exact calculation confirms these results (just a 2 per mille difference)

B.Mistlberger (2018)

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C.Anastasiou, C.Duhr, F.Dulat, E.Furlan, T.Gehrmann, F.Herzog, A.Lazopoulos, B.Mistlberger (2016)

N3LO calculation accompanied by a thorough study of the theoretical uncertainties

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

missing higher-orders

uncertainty from the soft expansion

missing N3LO PDFs

missing mixed QCD-EW corrections

uncertainty from heavy-quark mass dependence

uncertainty in the 1/mt included corrections

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

N3LO YR4

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

NNLL+NNLO YR3

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N3LO YR4

CMS scenario 2 (50% reduction of theory uncertainties) !

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N3LO YR4

Not yet there if you consider it linearly
(gaussian interpretation would lead to 3.9%)

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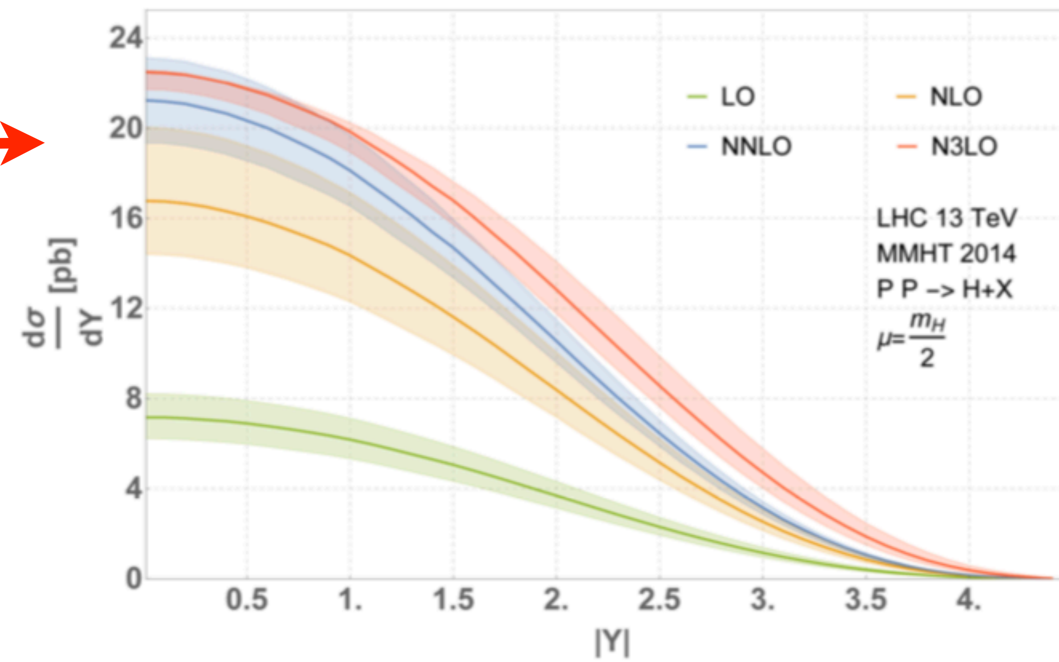
NNLL+NNLO
YR3

Theory precision: gg→H at N^{3}LO

Inclusive cross section important for normalisation but ongoing work also for differential distributions

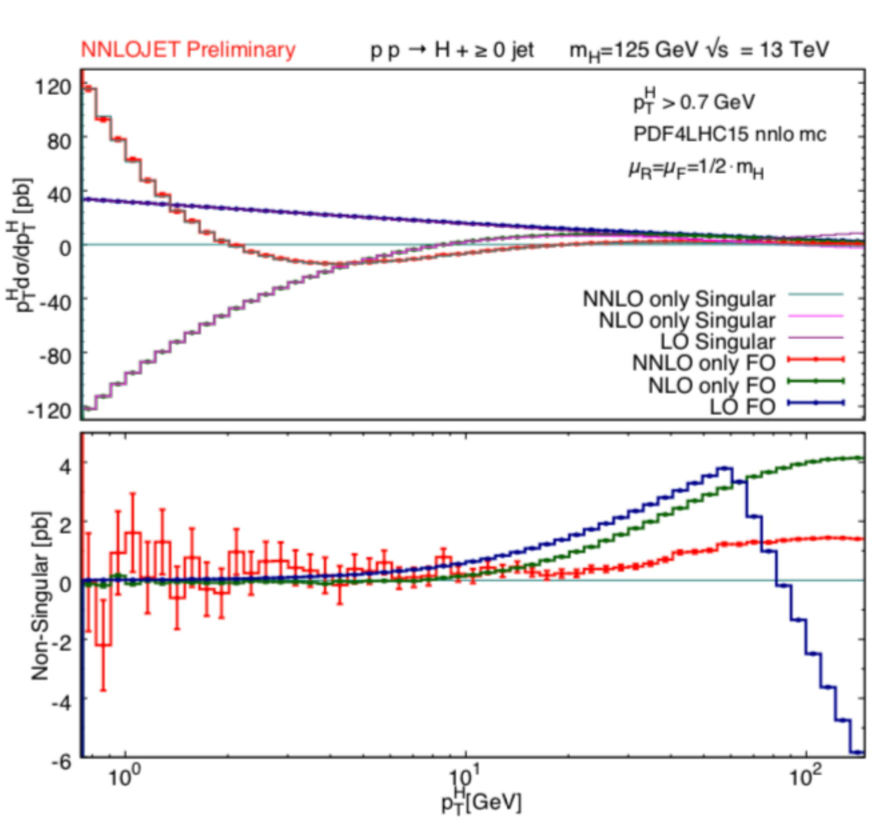
Analytically through an expansion around threshold: inclusive over QCD radiation

First two terms in threshold expansion



F.Dulat, B.Mistlberger, A.Pelloni (2017)

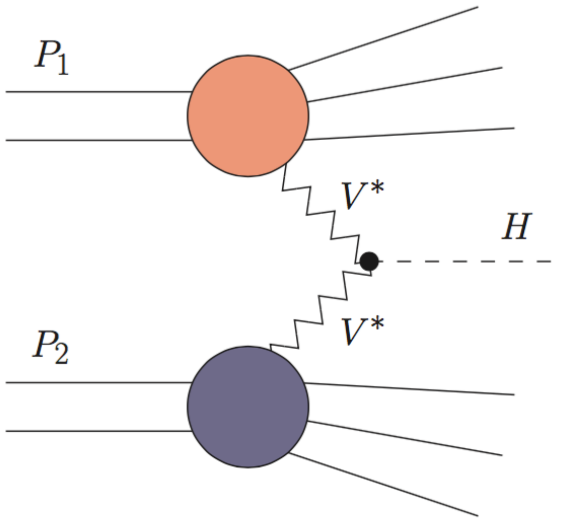
Can be made fully exclusive when combined with available H+jet calculations at the same order



Xuan Chen, SCET 2018

Numerically, starting from H+jet NNLO calculation and using analytic form of large logarithmic terms as subtraction counter term

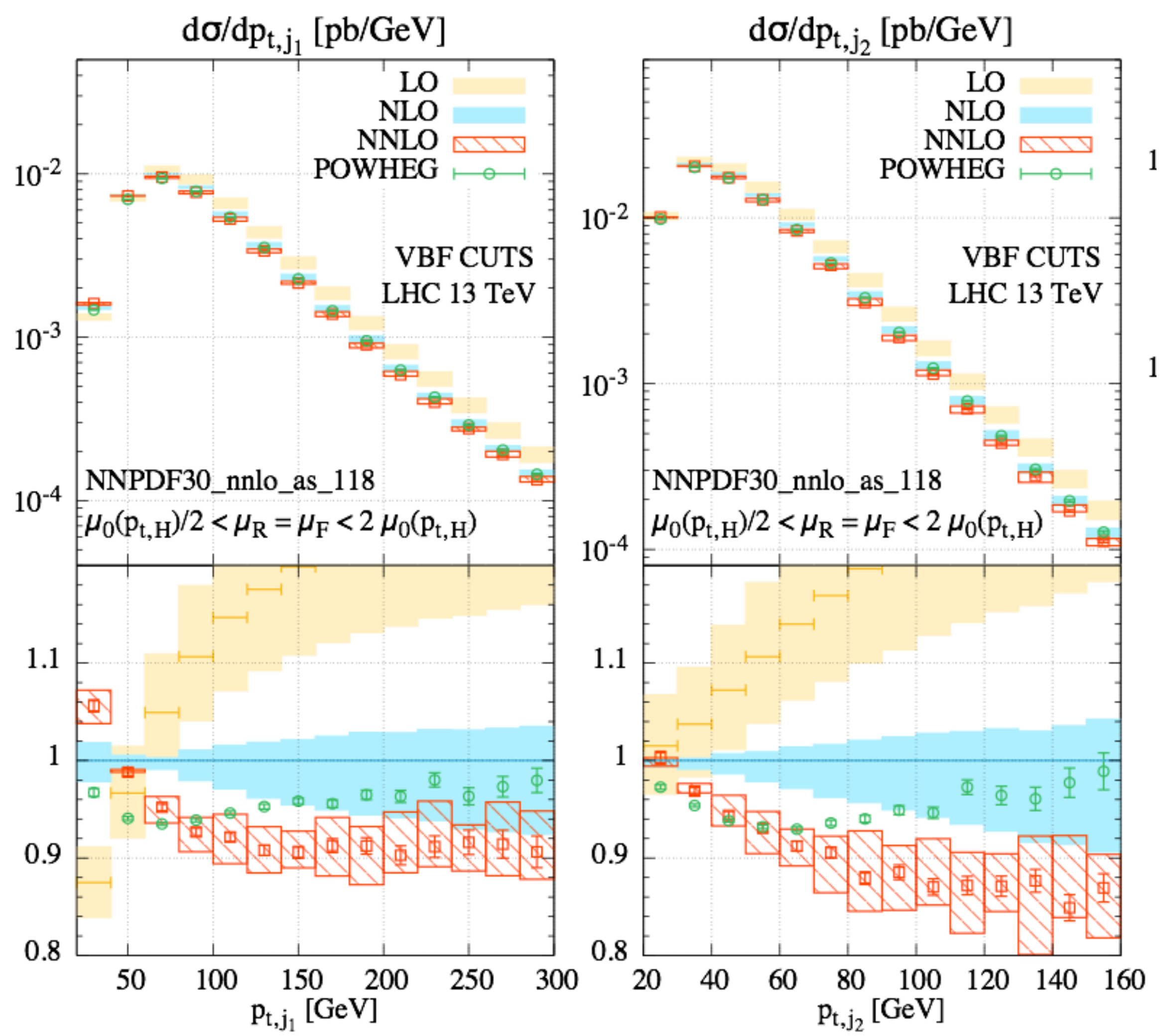
Theory precision: VBF



NNLO QCD corrections computed in the structure function approach (neglecting color connections between the upper and lower part of the diagrams)

First fully differential NNLO computation completed three years ago

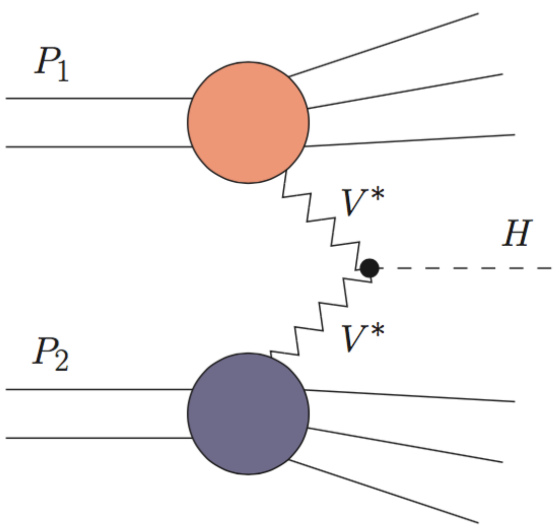
P.Bolzoni, F.Maltoni, S.Moch,M.Zaro (2010)



M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)

Relatively large corrections at the level of differential distributions

Theory precision: VBF



NNLO QCD corrections computed in the structure function approach (neglecting color connections between the upper and lower part of the diagrams)

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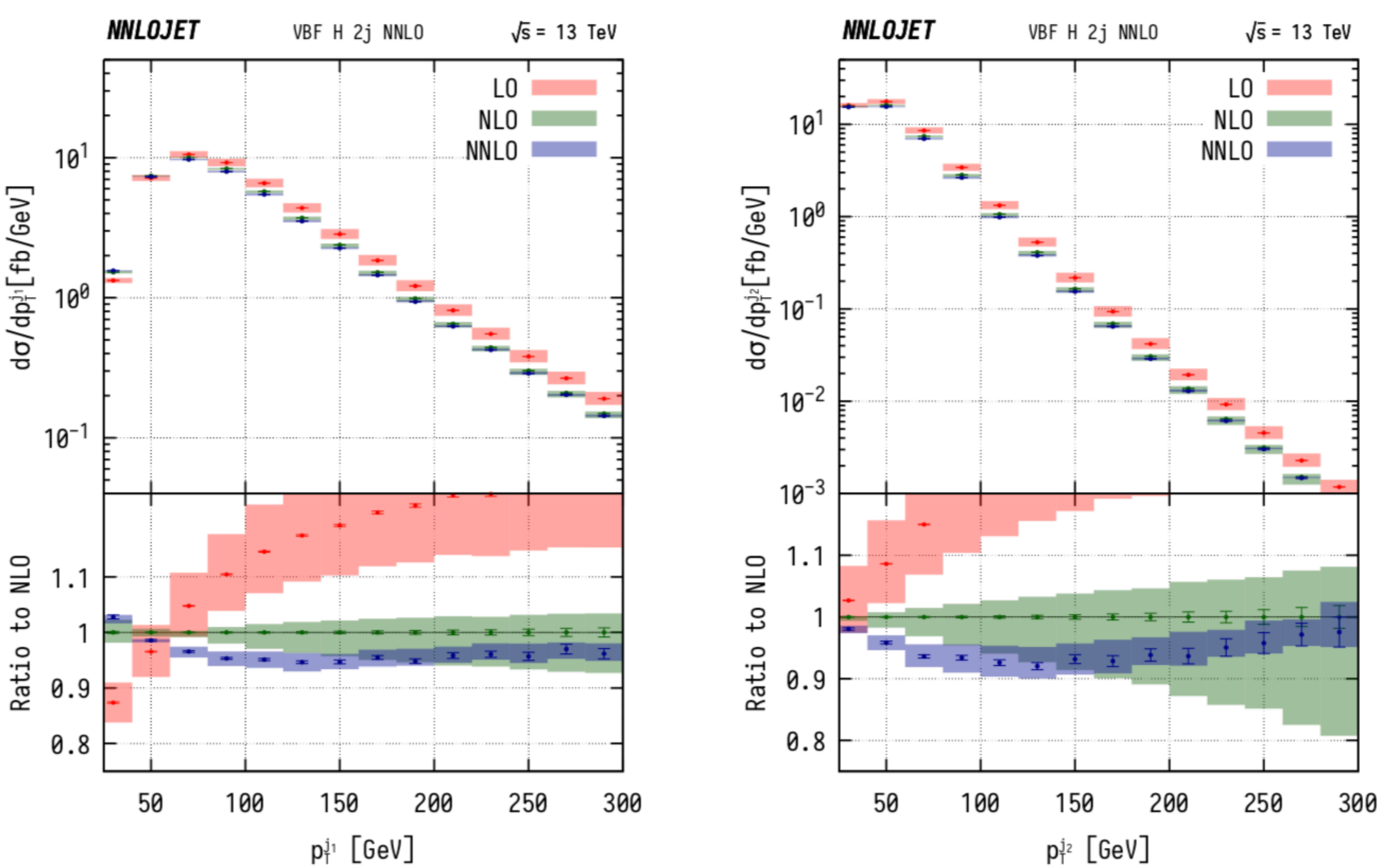
Recently an independent computation allowed to correct an error in previous results



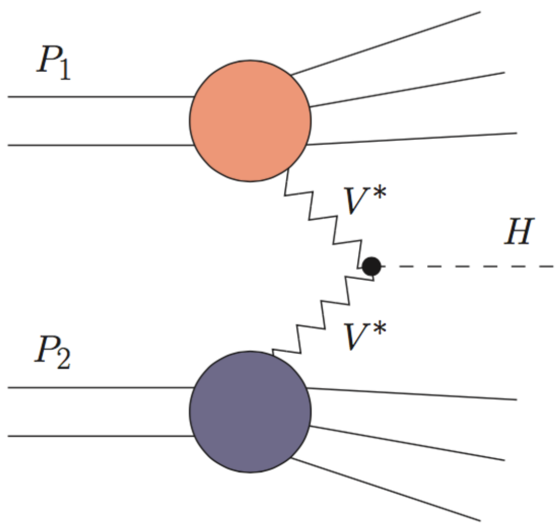
J. Cruz-Martinez, T. Gehrmann, E.W.N. Glover, A. Huss (2018)

Still relevant NNLO effects though more moderate in size

Theory precision: VBF

Inclusive N3LO calculation recently completed (structure function approach: neglecting color connections between the upper and lower part of the diagrams)

F.Dreyer, A.Karlberg (2016)



Residual scale uncertainty at the per mille level

Could potentially lead to a differential N3LO calculation with the same method adopted at NNLO

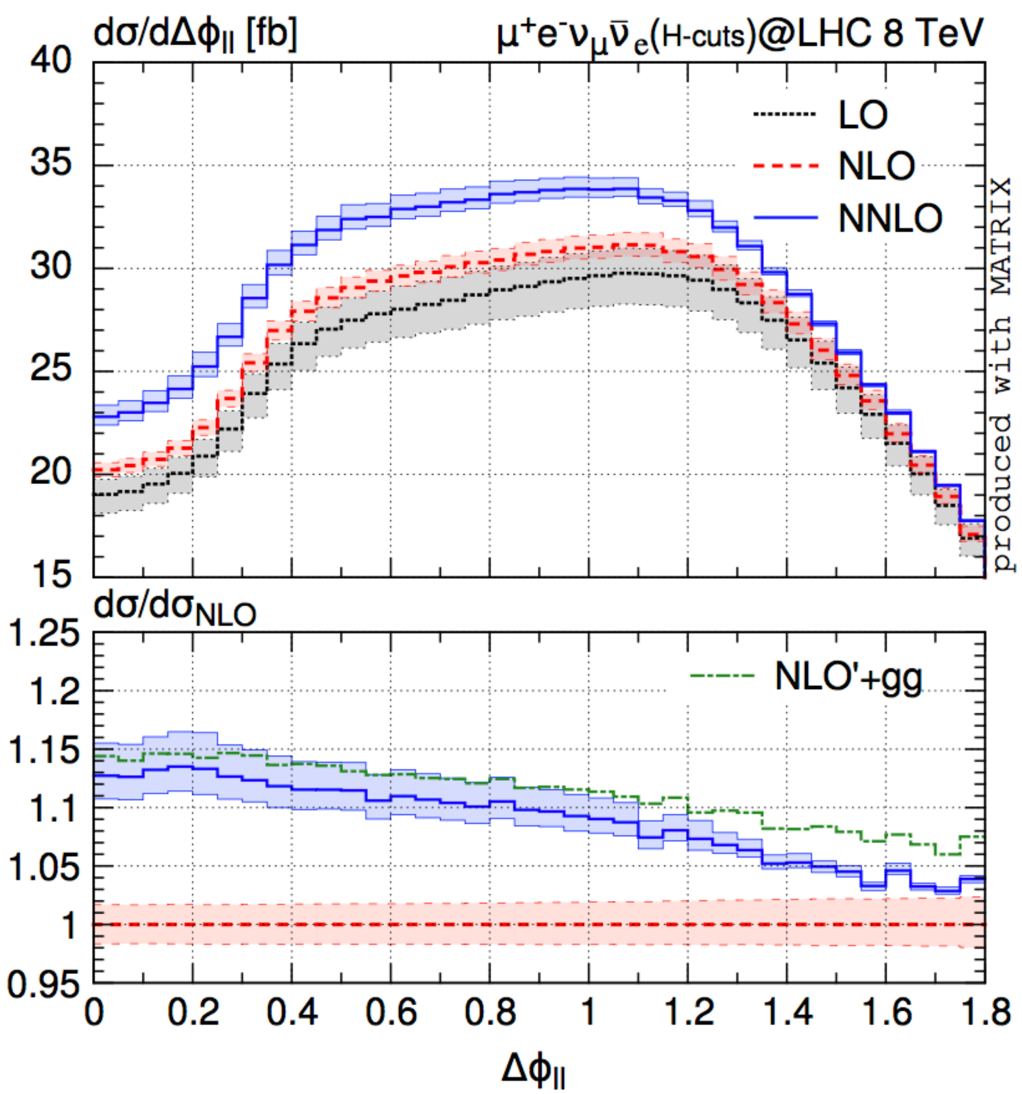
Remaining issues:

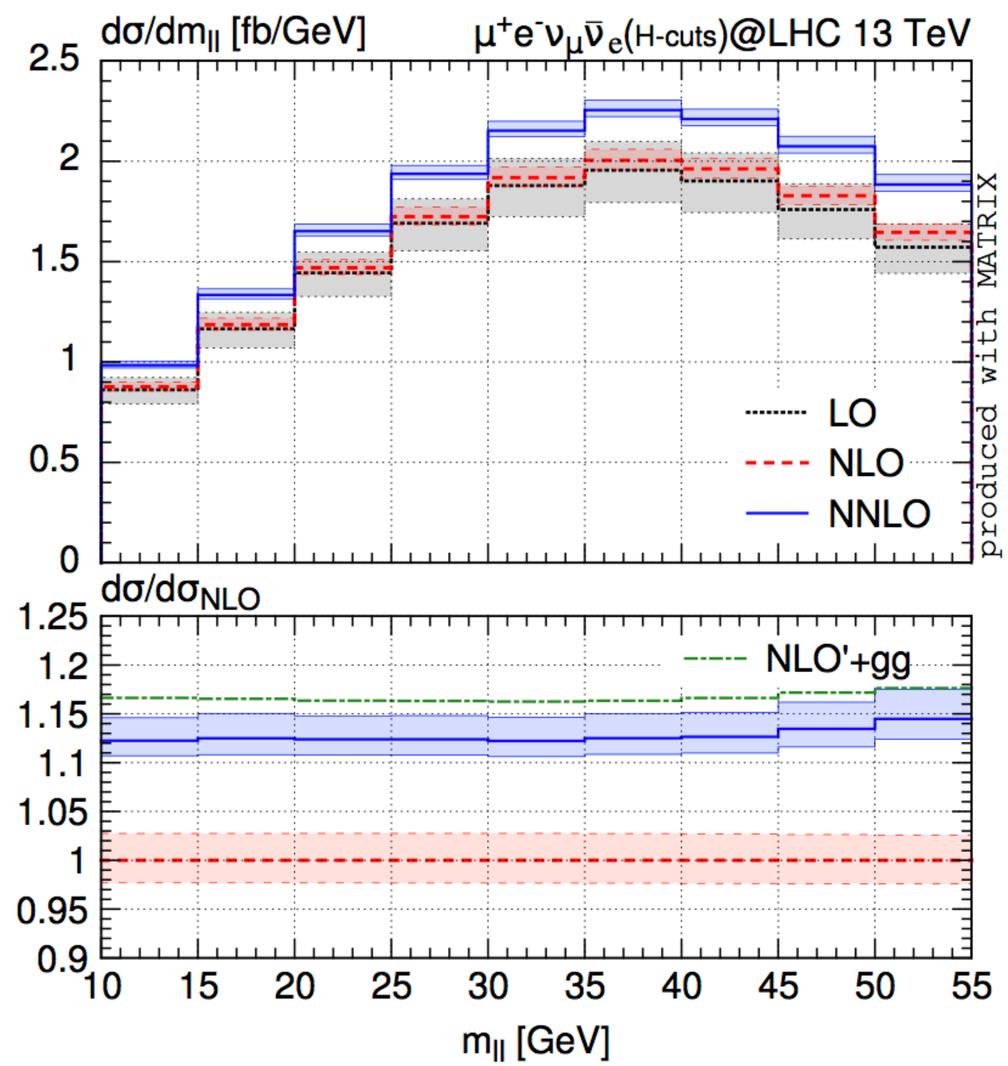
- ggF contamination: large uncertainties
- central jet veto: when matching to PS different showers give significantly different results

Ongoing studies within the VBF subgroup of the HXSWG

Taming backgrounds

All diboson backgrounds computed to NNLO QCD





Now available in a general purpose parton level Montecarlo program: MATRIX

S.Kallweit, M.Wiesemann, MG (2017)

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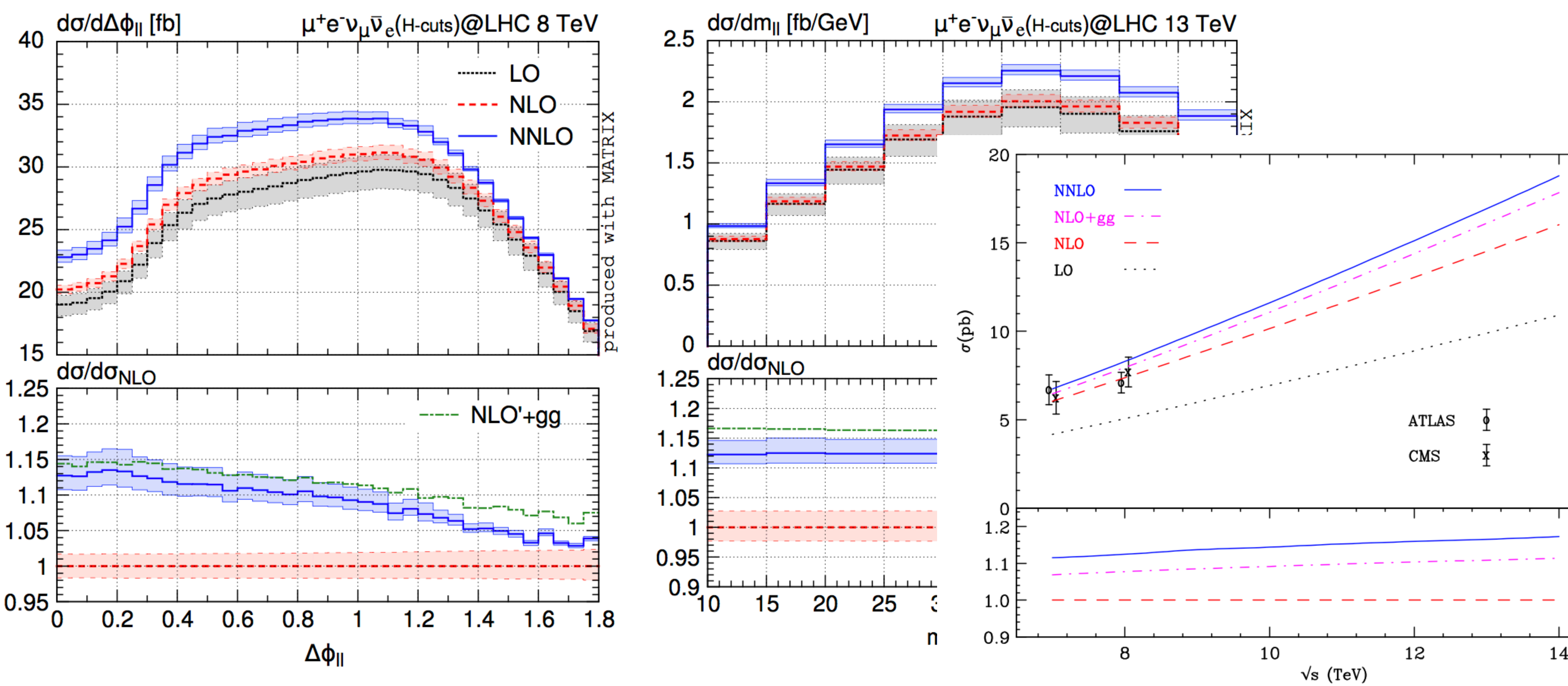

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S.Kallweit, M.Wiesemann, MG (2017)

Taming backgrounds

Consider $pp \to ZZ \to 4$ leptons at 8 TeV and compare on shell ZZ selection with the Higgs background case

S. Kallweit, D. Rathlev, MG (2016)

- **On-shell ZZ**

  $p_{Tl} > 7$ GeV $|\eta_l| < 2.7$ $\Delta R(l,l) > 0.2$

  66 GeV $< m_{Z1}, m_{Z2} <$ 116 GeV

  → $\sigma_{NNLO}/\sigma_{NLO} \sim 1.15$

- **Higgs background ZZ**

  40 GeV $< m_1 <$ 120 GeV

  12 GeV $< m_2 <$ 120 GeV 120 GeV $< m_{4l} <$ 130 GeV

$p_{T1} > 20$ GeV $p_{T2} > 10$ GeV

$p_{Te} > 7$ GeV $|\eta_e| < 2.5$ $p_{T\mu} > 5$ GeV $|\eta_\mu| < 2.5$

lepton isolation: Σ (p_{Ti} of all particles i with $\Delta R(l,i) < 0.4$) $< 0.4\, p_{Tl}$

$\Delta R(l,l) > 0.1$

Leading pair: same flavour pair with smallest $|m-m_Z|$ → m_1

Subleading pair: remaining same flavour pair with smallest $|m-m_Z|$ → m_2

Jets: anti-kt with R=0.4

Use PDF4LHC15 at NLO and NNLO with $\mu_F = \mu_R = m4l$ as central scale

Taming backgrounds

Consider pp→ZZ→4 leptons at 8 TeV and compare on shell ZZ selection with the Higgs background case

S. Kallweit, D. Rathlev, MG (2016)

Since the Higgs cuts are not very aggressive we would expect the impact of radiative corrections not to change

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NLO+gg} (fb)	σ_{NNLO} (fb)
$e^+e^-e^+e^-$	$0.1347(1)^{+10\%}_{-11\%}$	$0.1485(2)^{+2.4\%}_{-3.6\%}$	$0.1584(2)^{+2.4\%}_{-3.6\%}$	$0.159(1)^{+0.7\%}_{-0.9\%}$
$\mu^+\mu^-\mu^+\mu^-$	$0.1946(2)^{+10\%}_{-11\%}$	$0.2150(2)^{+2.4\%}_{-3.6\%}$	$0.2291(2)^{+2.4\%}_{-3.6\%}$	$0.230(1)^{+0.9\%}_{-0.8\%}$
$e^+e^-\mu^+\mu^-$	$0.3165(3)^{+10\%}_{-11\%}$	$0.3457(3)^{+2.4\%}_{-3.6\%}$	$0.3677(2)^{+2.3\%}_{-3.5\%}$	$0.3690(6)^{+0.5\%}_{-0.8\%}$

+9-10%   +6-7%   0-1%

With this choice of parameters NLO corrections for on shell inclusive ZZ production amount to +23%

The combination of the cuts acts to reduce the impact of radiative corrections !

gg contribution provides almost the entire NNLO corrections
NLO corrections to gg known (no fermonic channels)

F.Caola, K.Melnikov, R.Röntsch, L.Tancredi (2015)

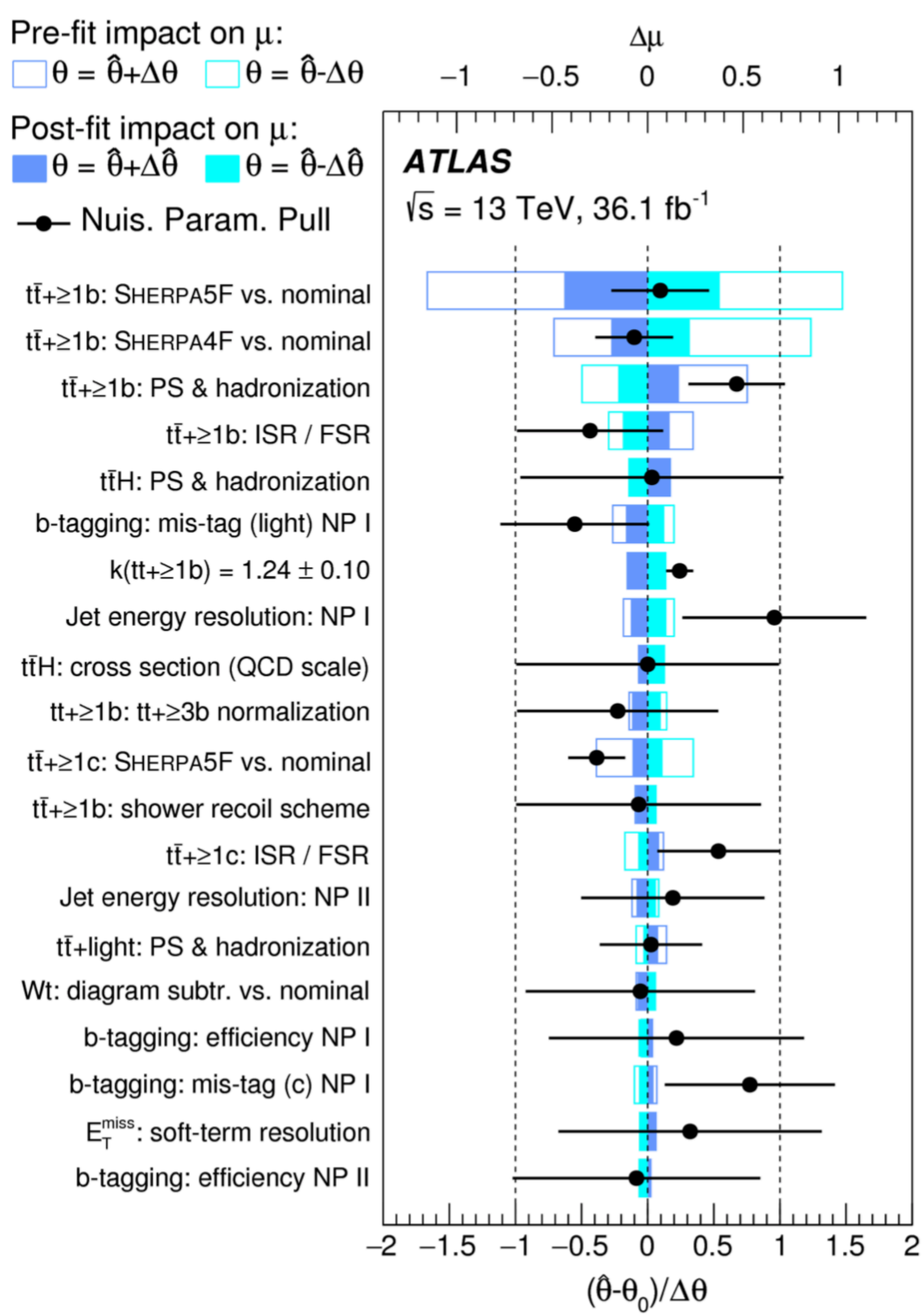
Inclusion in the MATRIX framework in progress

Taming backgrounds

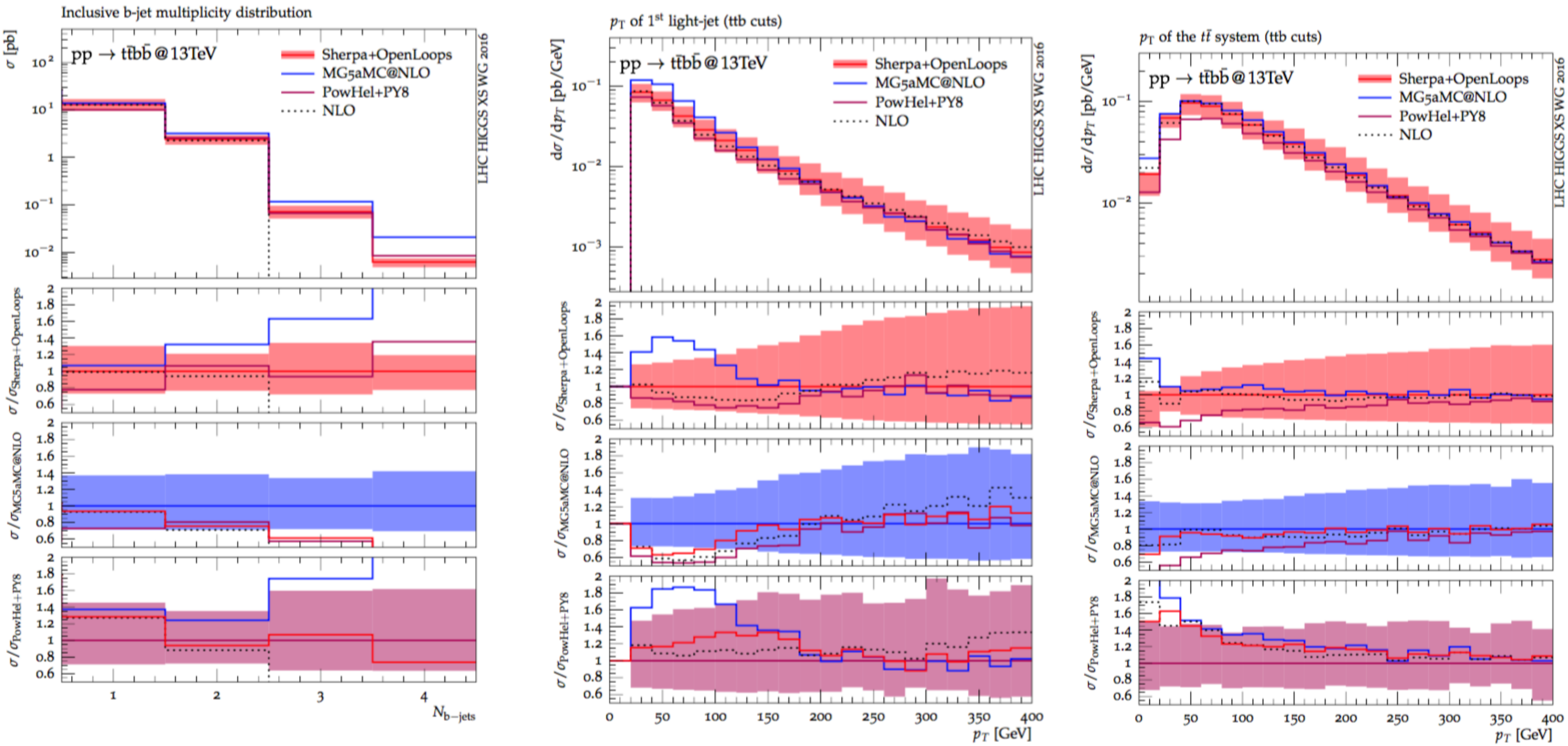
ttH analyses

Backgrounds can be extracted from data but the procedure requires the extrapolation from a control region through a MC generator

Requires good control on the shapes



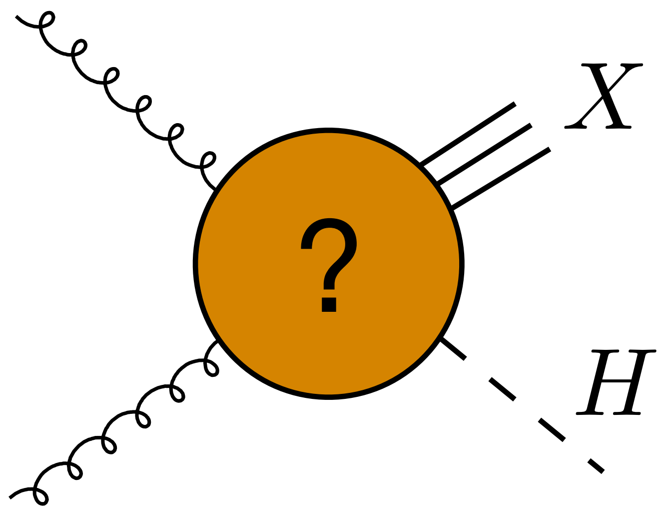
Taming backgrounds: ttH



S.Pozzorini et al., YR4 HXSWG (2016)

Large differences currently under study within the HXSWG

Higgs p_T



When we are inclusive over the radiation recoiling against the Higgs boson we measure its p_T spectrum

Higgs production at high-p_T can be useful to test new physics scenarios

For example: current constraints on the charm Yukawa y_c are rather weak but if y_c is very different from its SM value → effect on Higgs p_T distribution

see e.g. F.Bishara, U.Haisch,P.Monni, E.Re (2016)

When considering the transverse momentum spectrum it is important to distinguish two regions of transverse momenta

The region $p_T \sim m_H$ can be described by fixed order H+jet(s) calculations while for $p_T << m_H$ resummation is needed

State of the art in Run1: HRes (NNLL+NLO)

D. De Florian, G.Ferrera, D.Tommasini, MG (2012)

Higgs p_T

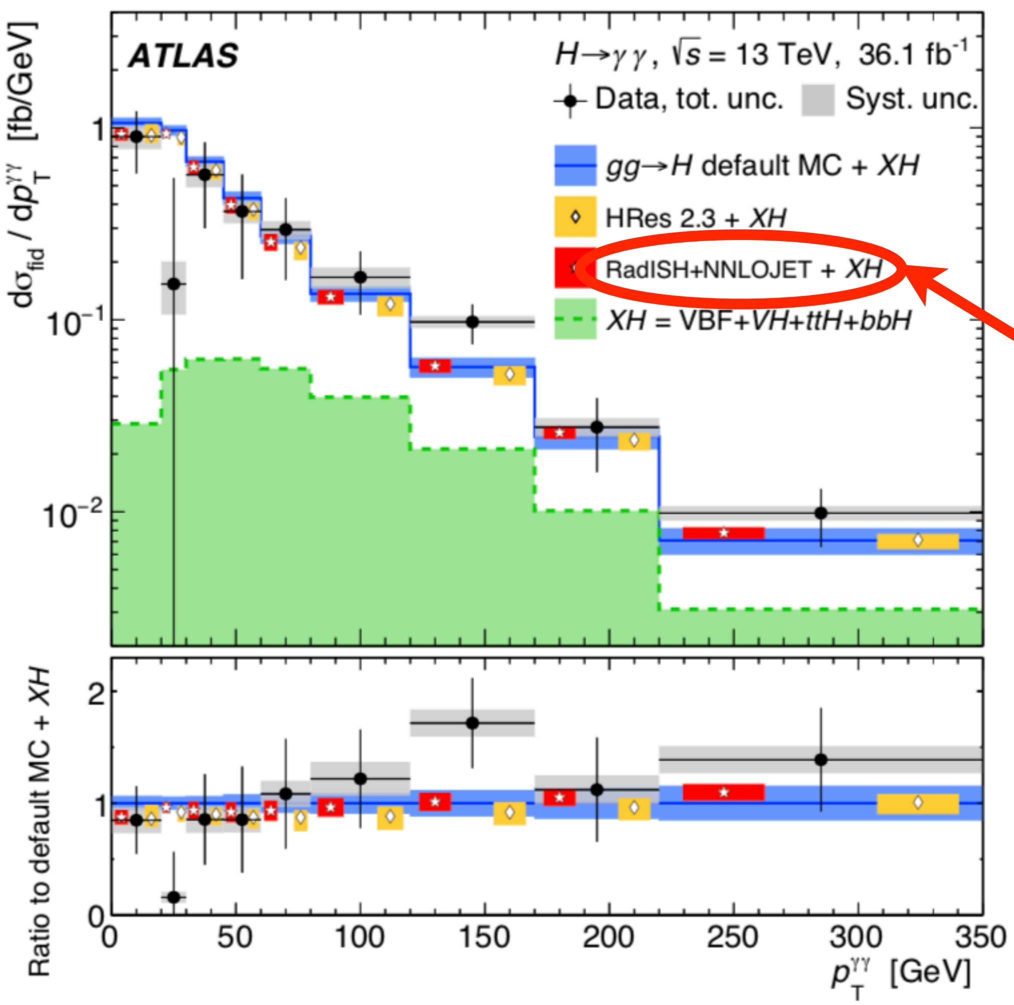
Low-p_T: Improvements may come from:

- Extend logarithmic accuracy of the resummed computation
  The required resummation coefficient has been recently computed

Y. Li and H. X. Zhu (2016)
A.Vladimirov (2016)

- Improved accuracy of the fixed-order contribution

X. Chen, T. Gehrmann, N. Glover, M. Jaquier (2014,2016)
R.Boughezal, F.Caola, K.Melnikov, ,F.Petriello, M.Schulze (2015)
R.Boughezal, C.Focke, W.Giele ,X.Liu, F.Petriello (2015)



First resummed predictions at (almost) N^3LL+NNLO

P.Monni et al. (2017)

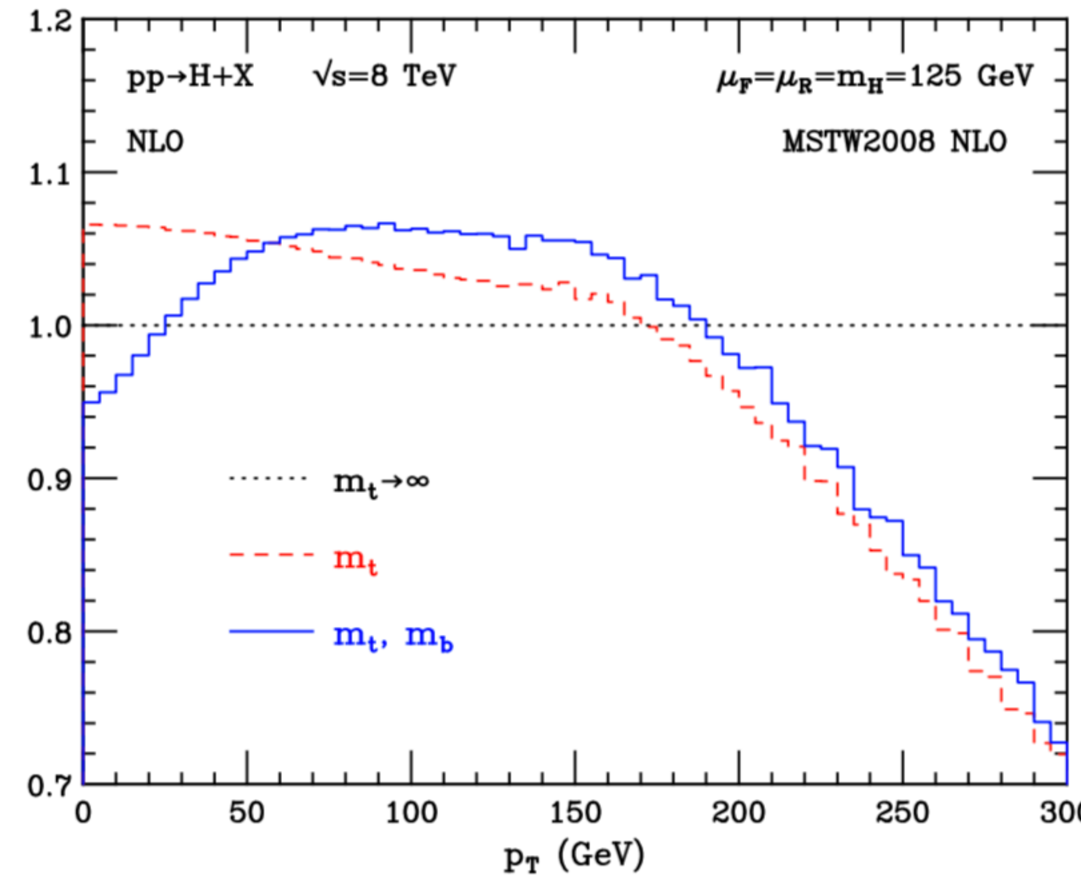
X. Chen, T. Gehrmann, N. Glover, M. Jaquier (2014,2016)

Higgs p_T

High-p_T:

Up to very recently the theoretical predictions beyond LO only available in the large-m_t limit

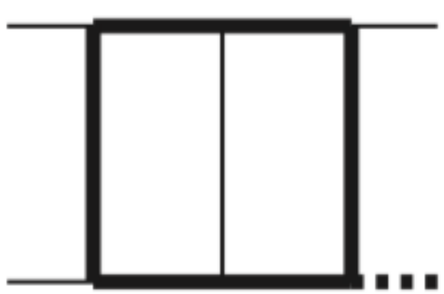
At high p_T this is bound to fail: recoiling QCD parton(s) become sensitive to the heavy quark loop



H.Sargsyan, MG (2013)

Exact NLO calculation requires 2-loop amplitudes with different mass scales: this is at the forefront of current technologies !

Two-loop planar master integrals recently computed in terms of elliptic functions: this is an important first step

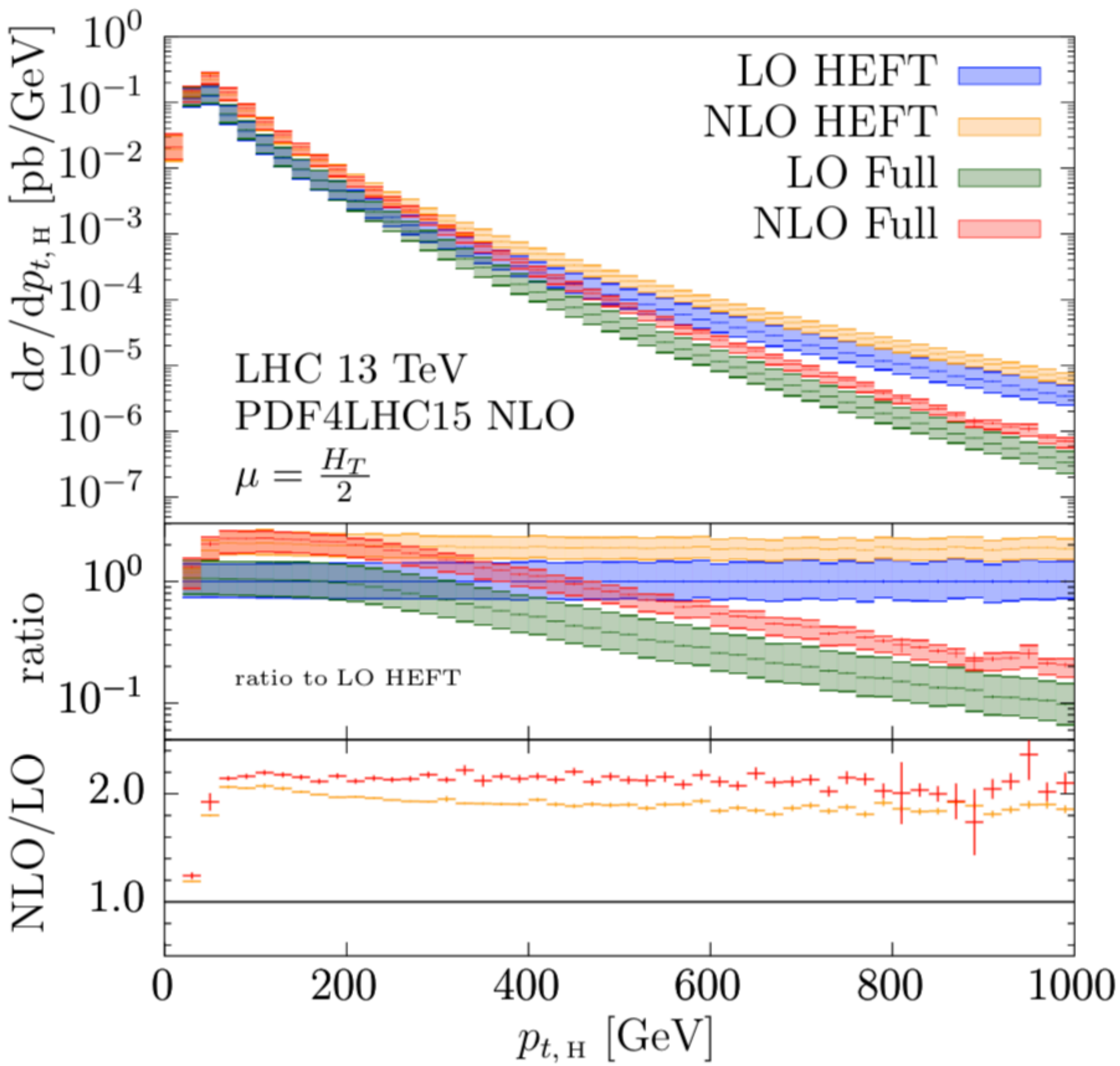


Exciting but....not even enough to get the leading color contribution !

V. Del Duca et al. (2016)

D.Kara, T.Gehrmann (in progress)

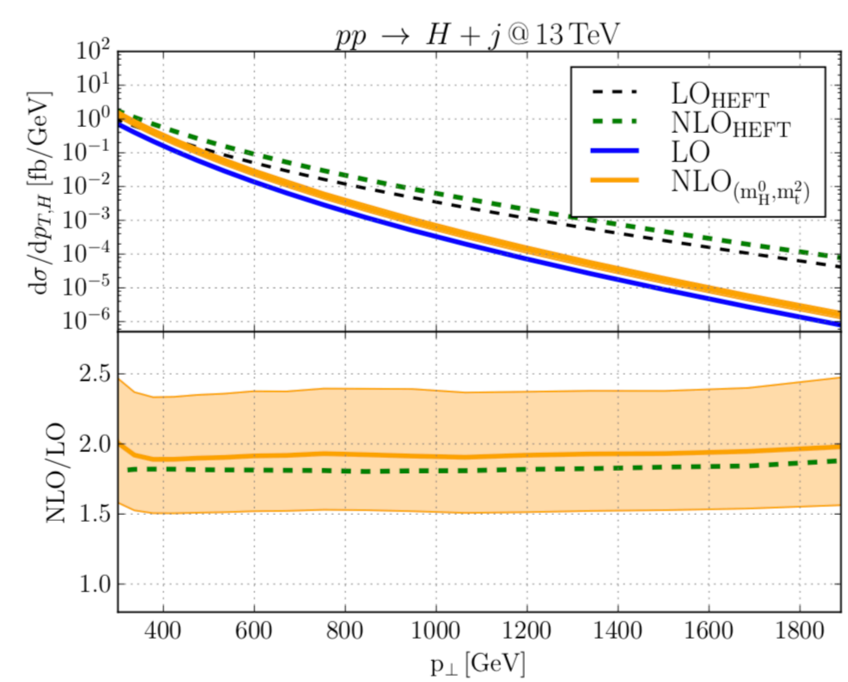
Higgs p_T



First exact NLO calculation recently completed numerically

S.Jones, M.Kerner, G.Luisoni (2018)

K-factor similar to the one obtained in the large-m_{top} limit



Trick used: $m_H^2/m_{top}^2 = 12/23$

Consistent with approximate result valid at large p_T

J.Lindert et al (2018)

Higgs p_T

Need of counting on the best predictions triggered by recent CMS high-p_T H→bbar analysis

CMS PAS HIG-17-010

HIGGS BOSON PRODUCTION AT LARGE PT

Conclusions

- Best prediction: NNLO-EFT + NLO-full QCD multiplicative combination
- VBF is half of ggF
- NLO H+J accurate MCs with finite top mass effects compatible with FO.

p_T^{cut}	$\mathrm{NNLO}^{\mathrm{approximate}}_{\mathrm{quad.unc.}}$ [fb]
400 GeV	$35.3^{+4.2\%}_{-9\%}$
430 GeV	$24.3^{+4\%}_{-8.9\%}$
450 GeV	$19.1^{+4\%}_{-8.9\%}$

B.Mistlberger, HXSWG meeting, march 2018

Intermezzo: the HXSWG

The Higgs Cross Section Working Group was created in January 2010

Aim: *"produce agreement on cross sections, branching ratios and pseudo-observables relevant to SM and MSSM Higgs boson(s).*

In spring 2012, the group was restructured and new subgroups were added with the goal of discussing Higgs property/measurement and BSM extensions.

Four Yellow Reports: 2011, 2012, 2013, 2016

These achievements paved the way to the interpretation of Higgs results since the beginning of the LHC physics programme.

The HXSWG is the open forum where theoretical results and tools relevant to Higgs physics can be scrutinised and discussed in order to produce consensus and eventually the recommendations to be adopted by ATLAS and CMS

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

(Small) BSM effects

If direct evidence for new physics signal is not found one can

- **Use an Effective Field Theory approach**

Local Operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

New Physics scale

W. Buchmuller and D. Wyler (1986)
B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek (2010)
A. Pomarol and F. Riva (2013)
....

- **Use pseudo-observables**

A set of experimentally accessible well defined quantities capturing all relevant NP effects

M.Gonzalez-Alonso, A.Greljo, G.Isidori, D.Marzocca (2014)

E.g. H→4f decays

$$\mathcal{A}_{n.c.}\left[h \to f(p_1)\bar{f}(p_2)f'(p_3)\bar{f}'(p_4)\right] = i\frac{2m_Z^2}{v_F} \sum_{f=f_L,f_R} \sum_{f'=f'_L,f'_R} (\bar{f}\gamma_\mu f)(\bar{f}'\gamma_\nu f')\mathcal{T}^{\mu\nu}(q_1,q_2)$$

$$\mathcal{T}^{\mu\nu}(q_1,q_2) = \left[F_1^{ff'}(q_1^2,q_2^2)g^{\mu\nu} + F_3^{ff'}(q_1^2,q_2^2)\frac{q_1{\cdot}q_2\ g^{\mu\nu} - {q_2}^\mu {q_1}^\nu}{m_Z^2} + F_4^{ff'}(q_1^2,q_2^2)\frac{\varepsilon^{\mu\nu\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

BSM effects on Higgs p_T

A.Ilnicka,M.Spira, M.Wiesemann, MG (2016)

Small deviations from the SM predictions in Higgs p_T → Parametrize them with an EFT approach $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$

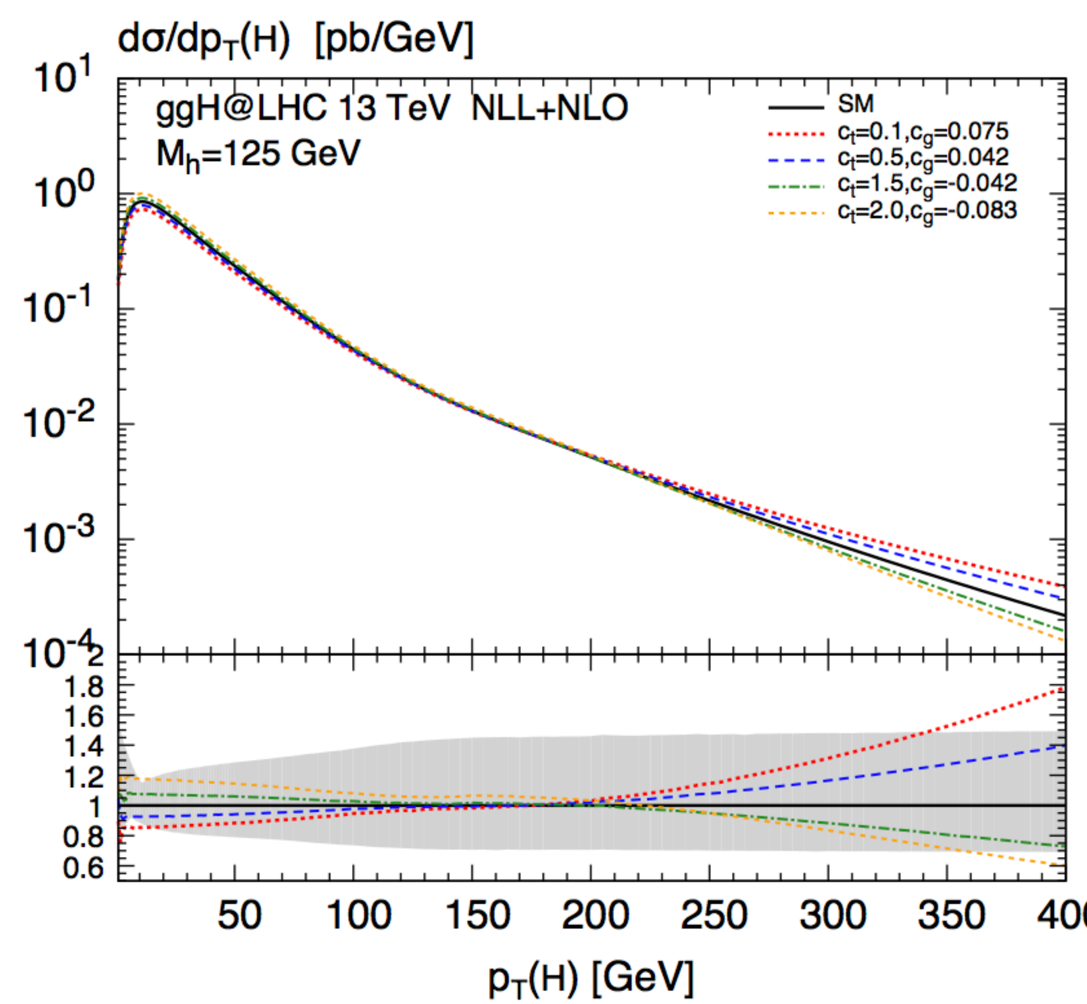
$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu} \longrightarrow \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c. \longrightarrow \frac{m_t}{v} c_t h \bar{t} t$$

$$\mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c. \longrightarrow \frac{m_b}{v} c_b h \bar{b} b$$

$$\mathcal{O}_4 = \bar{Q}_L H \sigma^{\mu\nu} T^a u_R G^a_{\mu\nu} + h.c. \longrightarrow c_{tg} \frac{g_S m_t}{2v^3}(v+h)G$$

NLL+NLO computation which consistently includes the effect of O_1 O_2 and O_3 operators

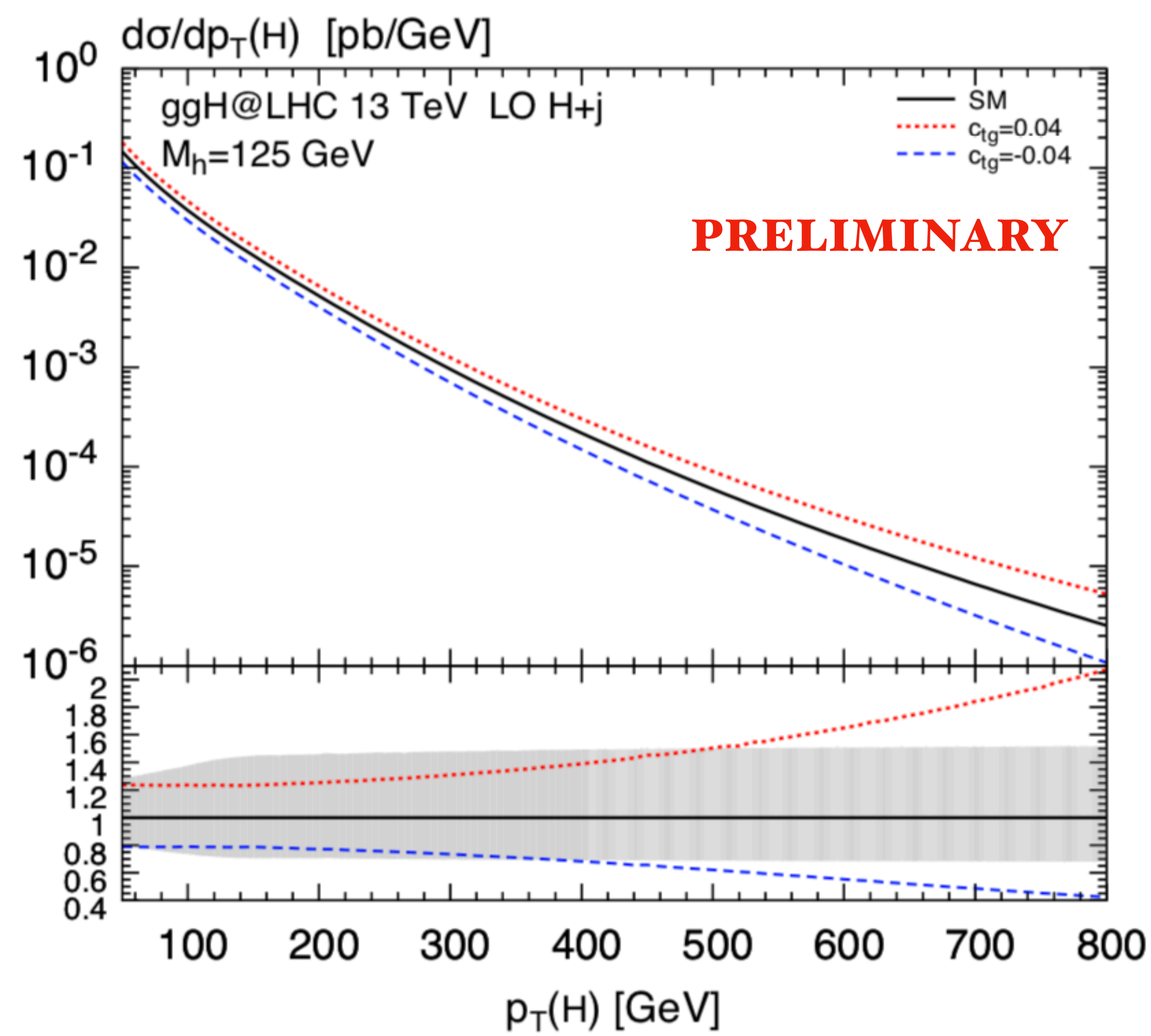


the simultaneous effect of two or more operators can significantly distort the spectrum, still keeping the total rate consistent with the SM prediction

BSM effects on Higgs p_T

The chromomagnetic operator is mainly constrained in top-pair production

D.B.Franzosi, C.Zhang (2015)



A.Ilnicka,M.Spira, MG (to appear)

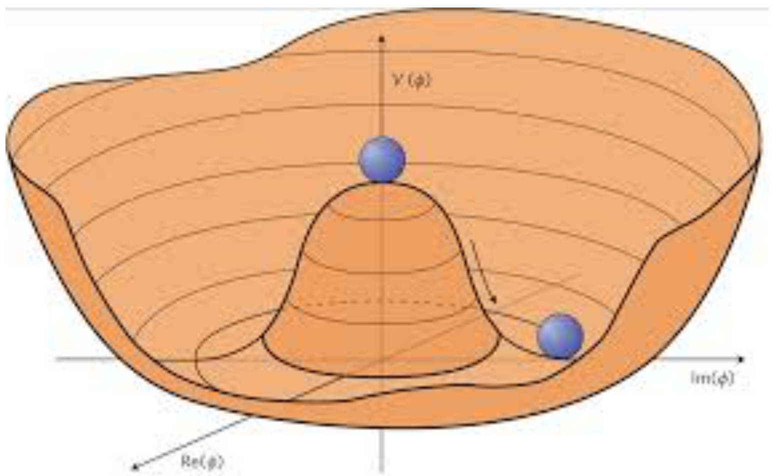
Despite these constraints its impact can be quite relevant and similar to the ggH contact interaction

Public tool in preparation

Similar results in the MG5_aMC framework

F.Maltoni, E.Vryonidou, C.Zhang (2016)

The Higgs potential



SM Higgs Lagrangian

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

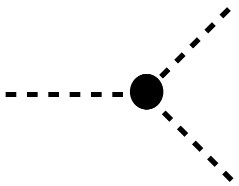
$$\Phi = 1/\sqrt{2}(\eta_1 + i\eta_2, v + H + i\eta_3)^T$$

EW symmetry breaking

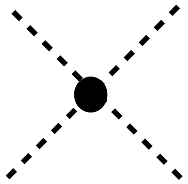
$$V_{\text{int}} = \frac{\lambda_3}{3!} H^3 + \frac{\lambda_4}{4!} H^4$$

with

$$\lambda_3 = 3m_H^2/v$$



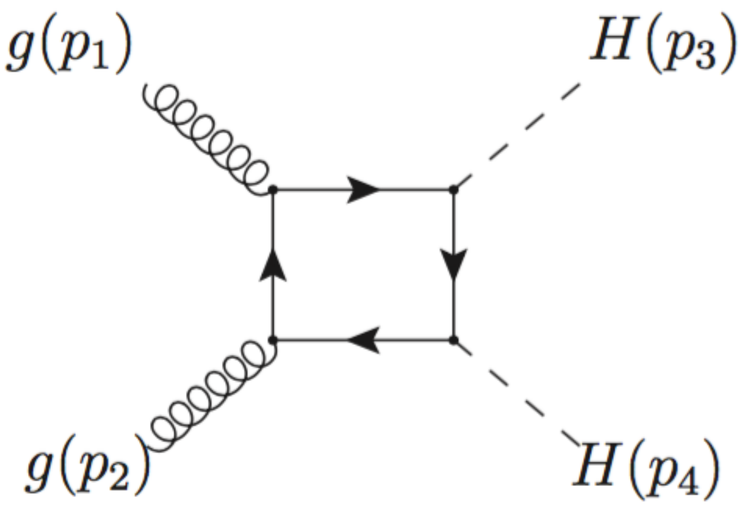
$$\lambda_4 = 3m_H^2/v^2$$

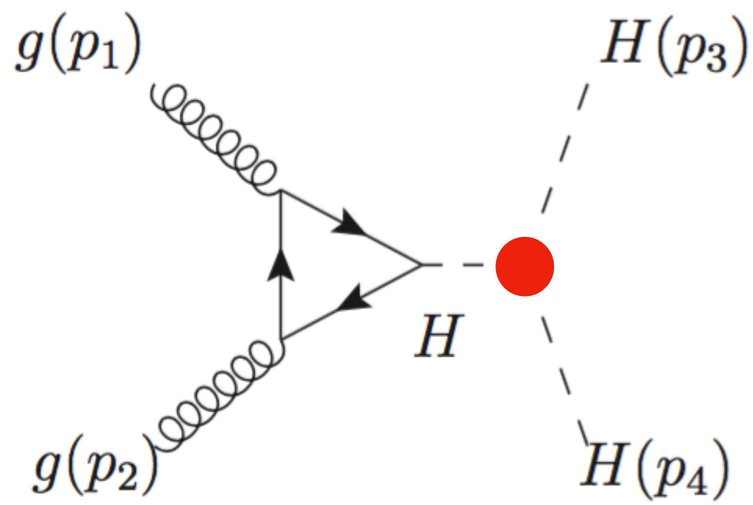


In the SM the trilinear and quadrilinear Higgs couplings are fixed once m_H (and v) are fixed

But the Higgs potential is largely untested and NP models may alter this picture

HH





Large cancellations and small available phase space makes rate very small

It is the process that gives direct access to the Higgs self coupling λ

Up to very recently QCD corrections at NLO and NNLO known only in the large-m_{top} approximation

S.Dawson,S.Dittmaier,M.Spira (1998)
D. de Florian, J.Mazzitelli (2013)

NNLL resummation available

D. de Florian, J.Mazzitelli (2015)

Main issue: large-m_{top} approximation known not to work so well

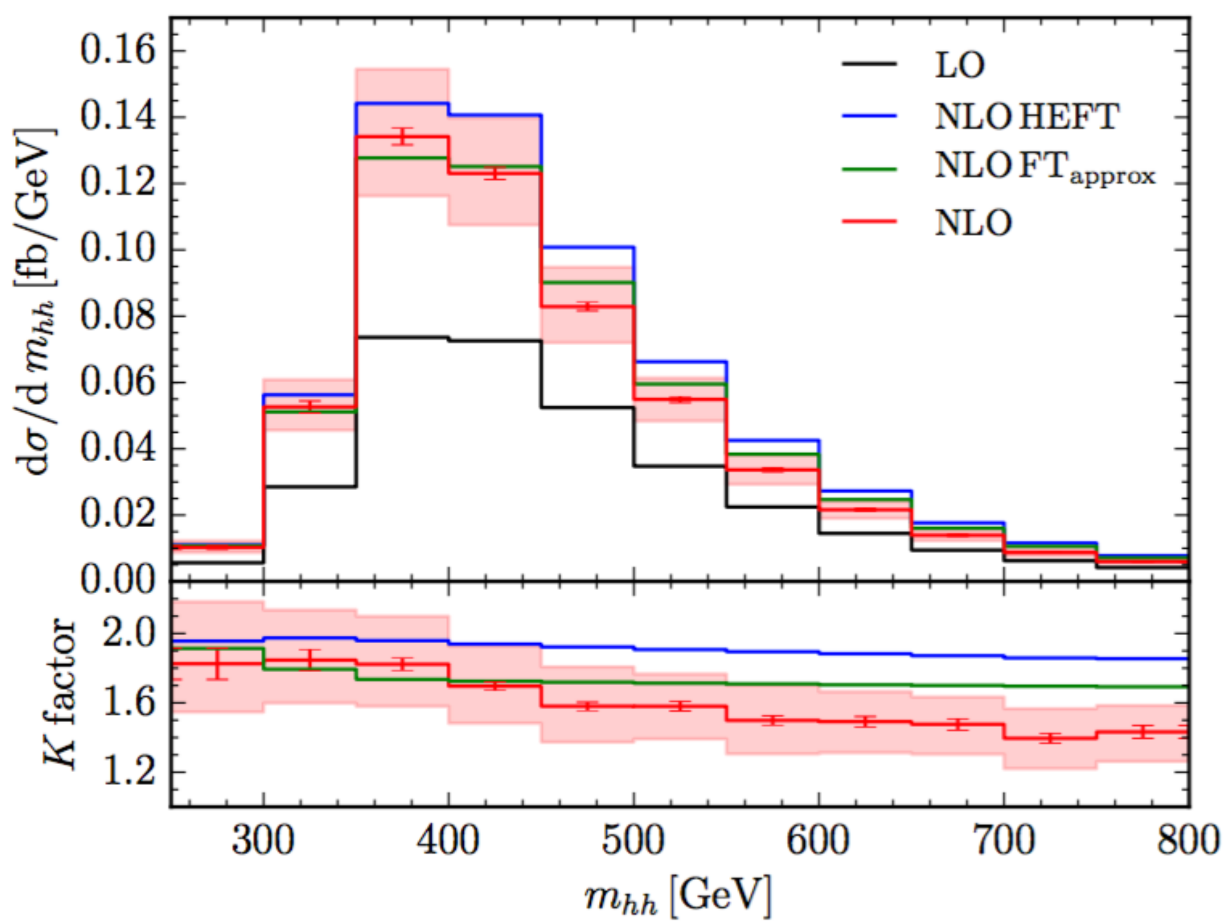
J.Grigo et al. (2013)

HH

Recent breakthrough: exact NLO calculation completed

S.Borowka et al (2016)

Multi scale two-loop integrals evaluated numerically

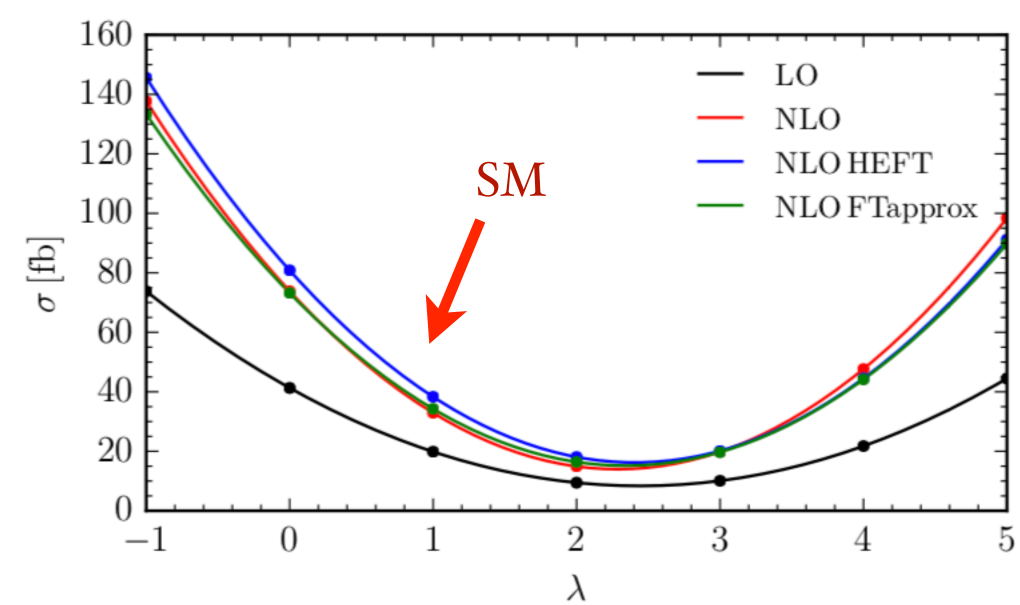


Accurate predictions must account for exact NLO

Promising for other important multi scale NLO calculations

Independent computation ongoing at PSI

S.Glaus, M.Spira et al. (in progress)



HH

G.Heinrich, S.Jones, S.Kallweit, M.Kerner, J.Lindert,MG (2018)

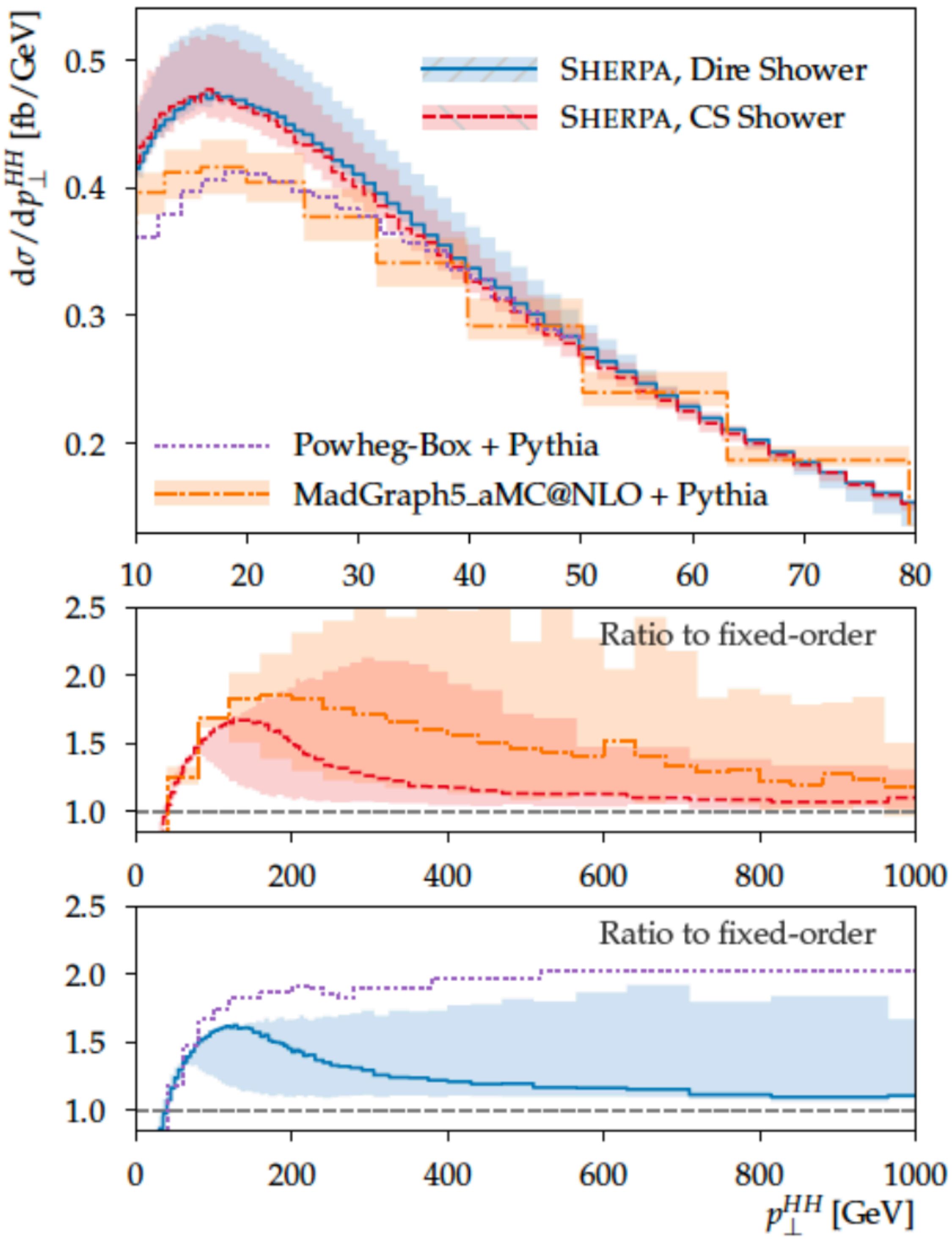
Approximate NNLO calculation recently presented combining the most advanced perturbative information available at present

NNLO effect obtained combining exact double real emission amplitudes with suitably reweighted single real and double virtual contributions

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

Uncertainty from finite m_{top} effects down to the few percent level

HH

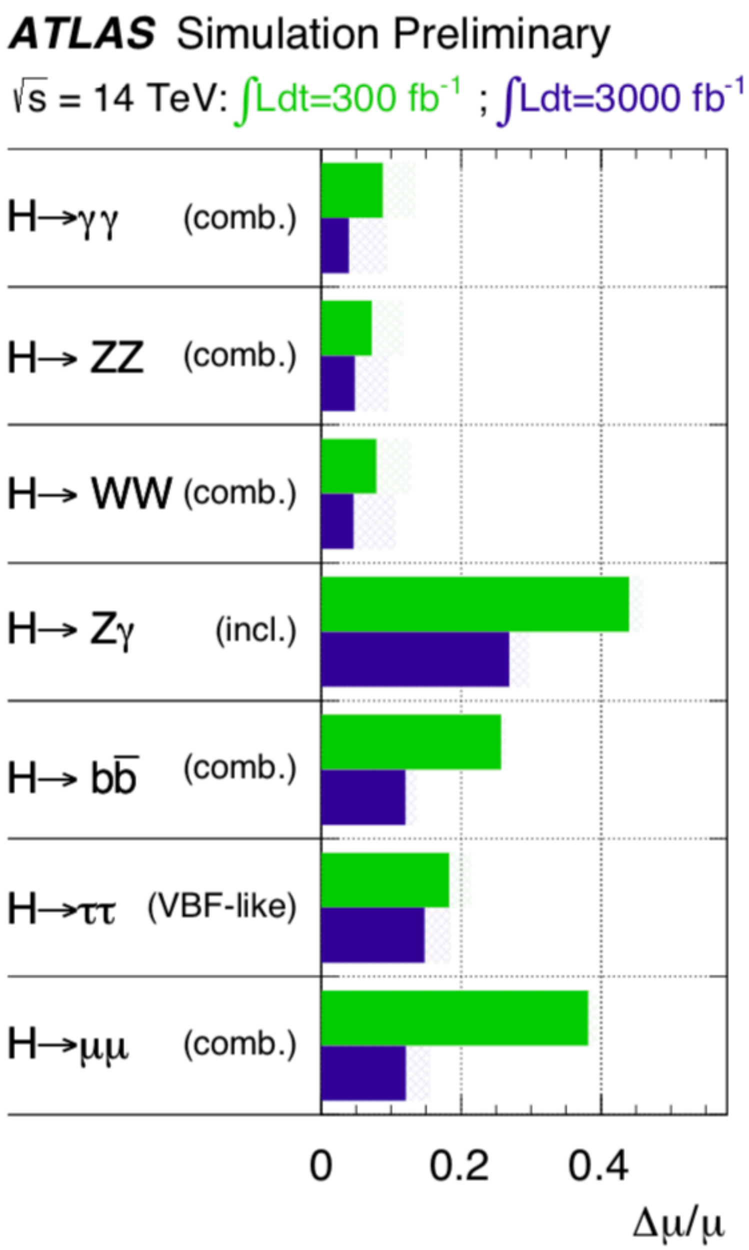


S.Jones, S.Kuttimalai (2017)

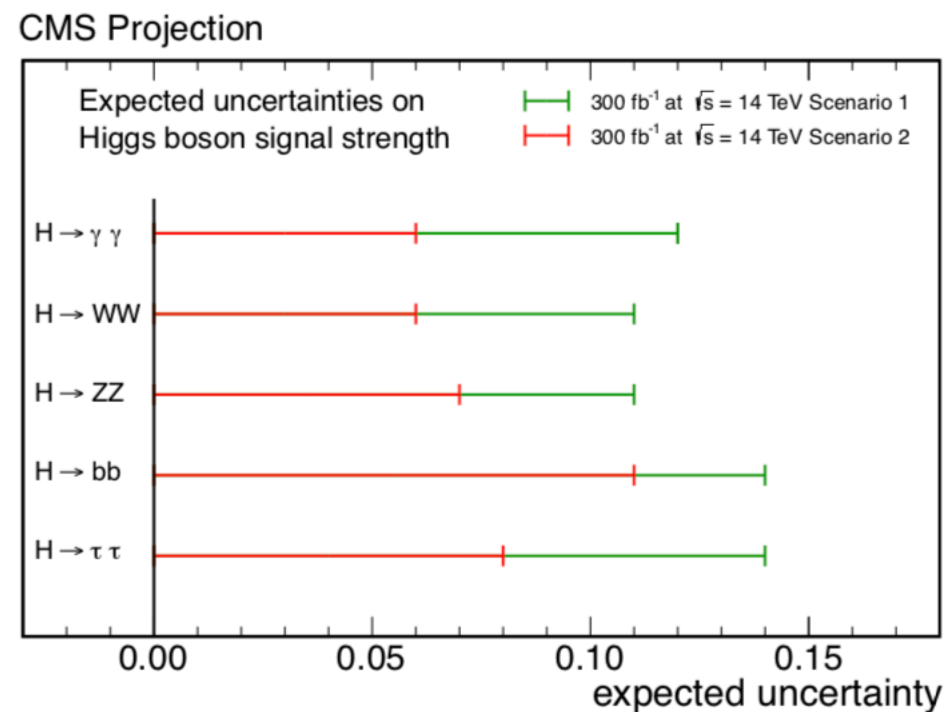
Despite the theoretical progress ATLAS and CMS have to rely on MC simulations based on NLOPS tools

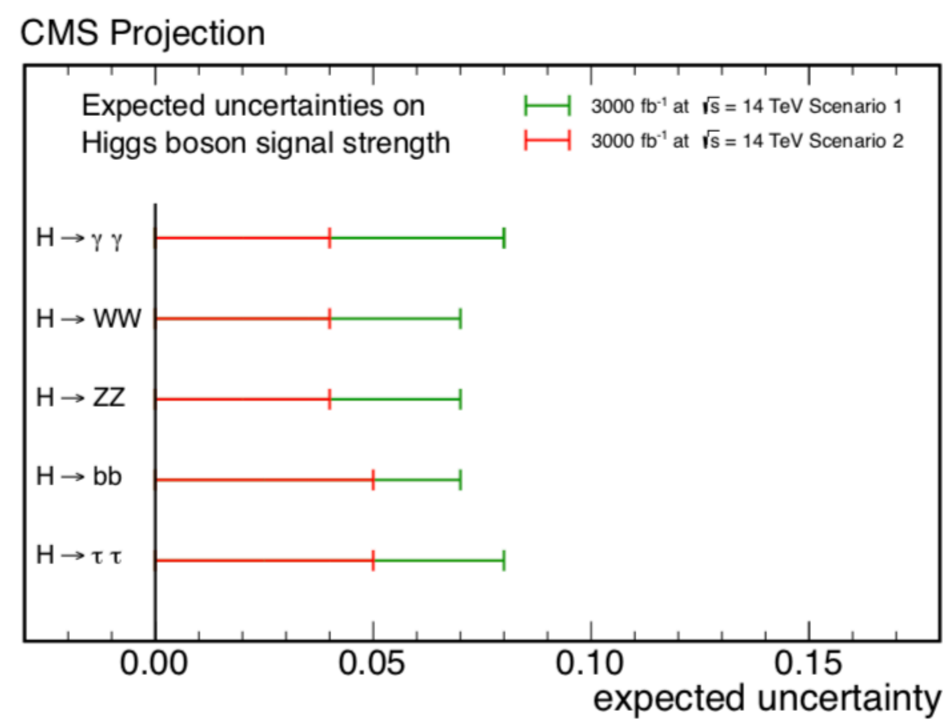
Large differences observed between different NLOPS matching schemes and also between different showers

Prospects: high luminosity



ATL-PHYS-PUB-2014-016

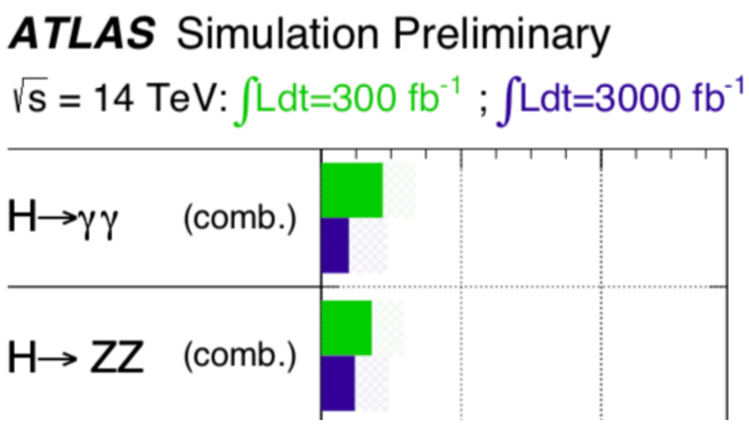


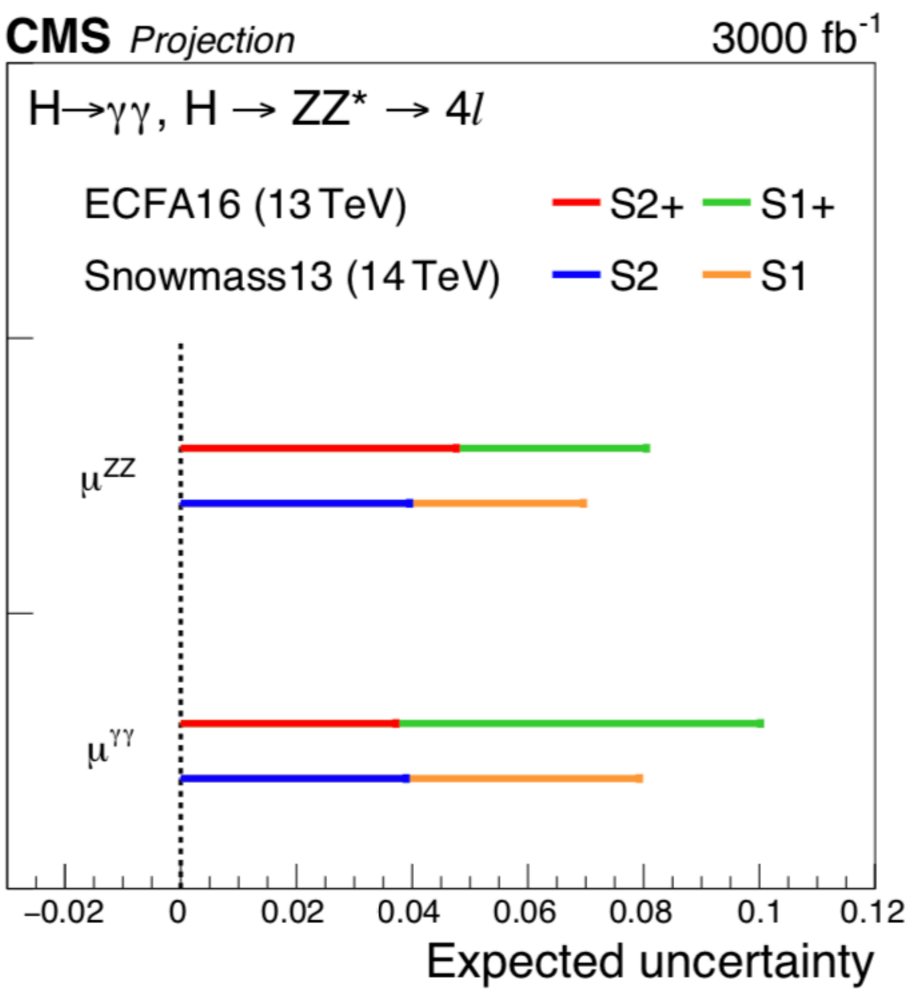


CMS NOTE-13-002

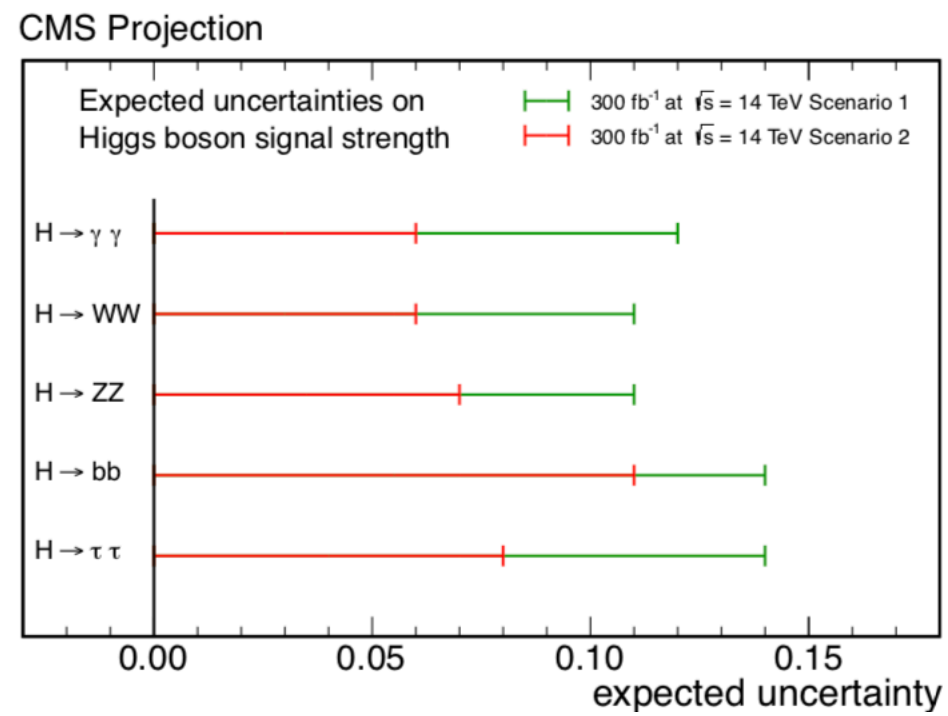
CMS PAS FTR-16-002

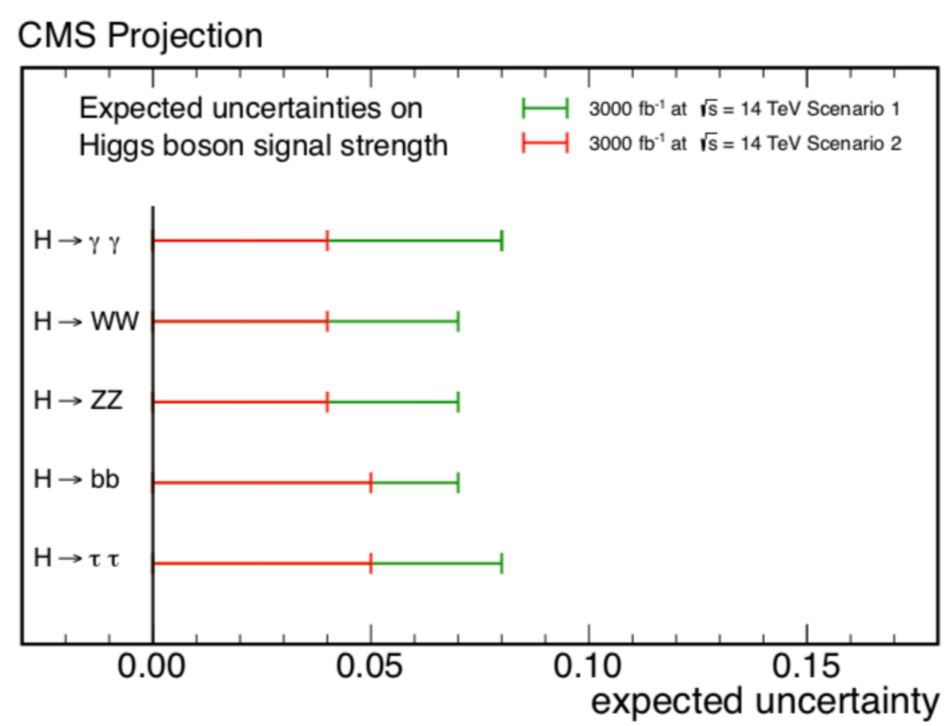
Prospects: high luminosity





CMS PAS FTR-16-002





CMS NOTE-13-002

Prospects: high luminosity

What can we learn from HL-LHC ?

- Higgs couplings at the O(5-10%) level
- First exploration of Higgs potential
- Couplings to second generation (e.g. $H \to \mu\mu$)
- Exploit rare Higgs decays
- Study Higgs couplings in kinematic regions to reveal possible signs of new physics

Prospects: high luminosity

DiHiggs Prospects @ 3000 fb^{-1}

	CMS	ATLAS
HH->2b2g	1.43 σ	1.5 σ $0.2 < \lambda_{HHH} / \lambda_{SM} < 6.9$ (95%CL)
HH->2b2tau	1.6 σ 52.2xSM for VBF mode alone	0.6 σ $-4.0 < \lambda_{HHH} / \lambda_{SM} < 12.0$ (95%CL)
HH->4b	0.39 σ	$-4.1< \lambda_{HHH} / \lambda_{SM} < 8.7$ (ggF, 95%CL) (0.35 σ for ttHH, HH->4b)
HH->2b2W	0.45 σ	

M.Cepeda, HXSWG meeting, march 2018

HE LHC: 30% on λ with 30 ab^{-1}

D.Goncalves, T.Han, F.Kling, T.Plehn, M. Takeuchi (2018)

Higgs physics at future colliders

More energy + more luminosity = more Higgs bosons !

Higgs bosons in 3ab^{-1}:

14 TeV	> 150 millions
33 TeV	> 500 millions
100 TeV	> 2 billions

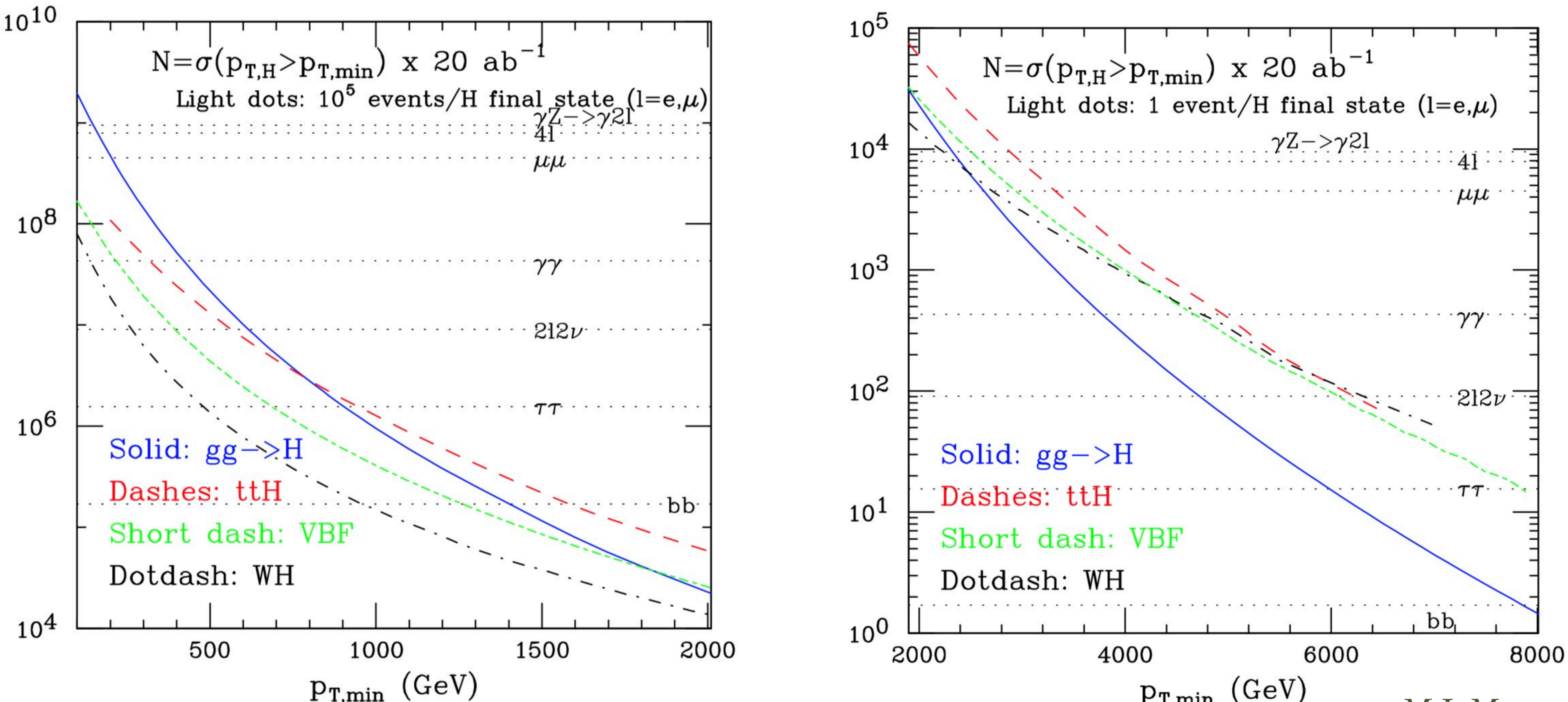
$\sqrt{s} = 100$ TeV	σ	N / 10ab^{-1}
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

M.L.Mangano, HXSWG meeting, July 2015

- Better measurement of Higgs mass and width
- Precision measurements of Higgs couplings
- Study of rare decays
- Access to different production modes/phase space regions

Opportunities at 100 TeV: high p_T

Two ways to make stress tests: 1) extreme kinematic regions



M.L.Mangano

Hierarchy of production channels changes at high p_T
(e.g. σ(ttH)>σ(ggF) above 800 GeV)

Opportunities at 100 TeV: high p_T

Two ways to make stress tests: 2) rare associated production processes

Process	σ_{NLO}(8 TeV) [fb]	σ_{NLO}(100 TeV) [fb]	ρ
$pp \to H\ (m_t, m_b)$	$1.44 \cdot 10^4\ ^{+20\%}_{-16\%}\ ^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ ^{+28\%}_{-27\%}\ ^{+2\%}_{-2\%}$	38
$pp \to Hjj$ (VBF)	$1.61 \cdot 10^3\ ^{+1\%}_{-0\%}\ ^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-1\%}$	46
$pp \to Ht\bar{t}$	$1.21 \cdot 10^2\ ^{+5\%}_{-9\%}\ ^{+3\%}_{-3\%}$	$3.25 \cdot 10^4\ ^{+7\%}_{-8\%}\ ^{+1\%}_{-1\%}$	269
$pp \to Hb\bar{b}$ (4FS)	$2.37 \cdot 10^2\ ^{+9\%}_{-9\%}\ ^{+2\%}_{-2\%}$	$1.21 \cdot 10^4\ ^{+2\%}_{-10\%}\ ^{+2\%}_{-2\%}$	51
$pp \to Htj$	$2.07 \cdot 10^1\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$5.21 \cdot 10^3\ ^{+3\%}_{-5\%}\ ^{+1\%}_{-1\%}$	252
$pp \to HW^{\pm}$	$7.31 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$1.54 \cdot 10^4\ ^{+5\%}_{-8\%}\ ^{+2\%}_{-2\%}$	21
$pp \to HZ$	$3.87 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$8.82 \cdot 10^3\ ^{+4\%}_{-8\%}\ ^{+2\%}_{-2\%}$	23
$pp \to HW^+W^-$ (4FS)	$4.62 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^2\ ^{+5\%}_{-6\%}\ ^{+2\%}_{-1\%}$	36
$pp \to HZW^{\pm}$	$2.17 \cdot 10^0\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$9.94 \cdot 10^1\ ^{+6\%}_{-7\%}\ ^{+2\%}_{-1\%}$	46
$pp \to HW^{\pm}\gamma$	$2.36 \cdot 10^0\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$7.75 \cdot 10^1\ ^{+7\%}_{-8\%}\ ^{+2\%}_{-1\%}$	33
$pp \to HZ\gamma$	$1.54 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.29 \cdot 10^1\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-2\%}$	28
$pp \to HZZ$	$1.10 \cdot 10^0\ ^{+2\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^1\ ^{+4\%}_{-6\%}\ ^{+2\%}_{-1\%}$	38
$pp \to HW^{\pm}j$	$3.18 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-1\%}$	$1.07 \cdot 10^4\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	34
$pp \to HW^{\pm}jj$	$6.06 \cdot 10^1\ ^{+6\%}_{-8\%}\ ^{+1\%}_{-1\%}$	$4.90 \cdot 10^3\ ^{+2\%}_{-6\%}\ ^{+1\%}_{-1\%}$	81
$pp \to HZj$	$1.71 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+1\%}_{-1\%}$	$6.31 \cdot 10^3\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	37
$pp \to HZjj$	$3.50 \cdot 10^1\ ^{+7\%}_{-10\%}\ ^{+1\%}_{-1\%}$	$2.81 \cdot 10^3\ ^{+2\%}_{-5\%}\ ^{+1\%}_{-1\%}$	80

Large enhancement for various processes: will this help ?

P.Torrielli, (2014)

Table 1: Production of a single Higgs boson at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown. For $pp \to HVjj$, on top of the transverse-momentum cut of section 2, I require $m(j_1, j_2) > 100$ GeV, j_1 and j_2 being the hardest and next-to-hardest jets, respectively. Processes $pp \to Htj$ and $pp \to Hjj$ (VBF) do not feature jet cuts.

Opportunities at 100 TeV: trilinear coupling

Most of the studies focus on HH→bbγγ

- 30-40% with 3 ab^{-1}
  10% with 30 ab^{-1}

A.J. Barr, M.J. Dolan, C.Englert, D.E. Ferreira de Lima, M.Spannowsky (2015);
Contino, Azatov, Panico, Son (2015)

- 15% with 3 ab^{-1}
  5% with 30 ab^{-1}

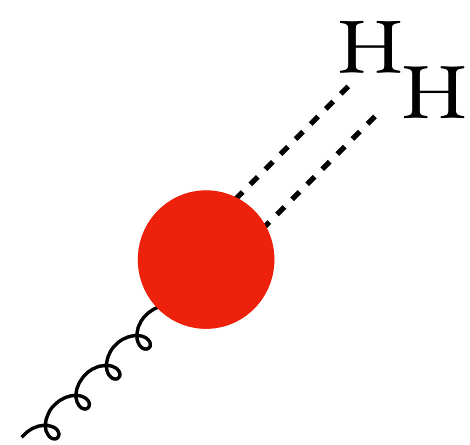
H.J. He, J.Ren, W.Yao (2015)

- 10% with 30 ab^{-1}

D.Goncalves, T.Han, F.Kling, T.Plehn, M. Takeuchi (2018)

Recently also HH+jet was considered with HH→bbττ and HH→bbbb

- 8% with 30 ab^{-1}



HH pair with small invariant mass sensitive to λ modifications

From 14 to 100 TeV
σ_{HH} increases by a factor 39
σ_{HH+jet} increases by a factor 80

S.Banerjee, C.Englert, M.Mangano, M.Selvaggi, M.Spannowsky, (2018)

Summary

- The current LHC data indicate that the Higgs boson is perfectly consistent with what predicted by the SM
- This conclusion is based on a good control on SM predictions to which the data are compared, including radiative corrections
- I have offered a personal selection of the most recent results with an eye on the contribution from Switzerland
- The Swiss community has given a crucial contribution in the most recent developments and will play a key role in the future
- The HL-luminosity phase of the LHC will allow more precise measurements of the Higgs couplings and will permit a first exploration of the Higgs potential
- More detailed studies require new facilities

Backup

Indirect probes of trilinear coupling

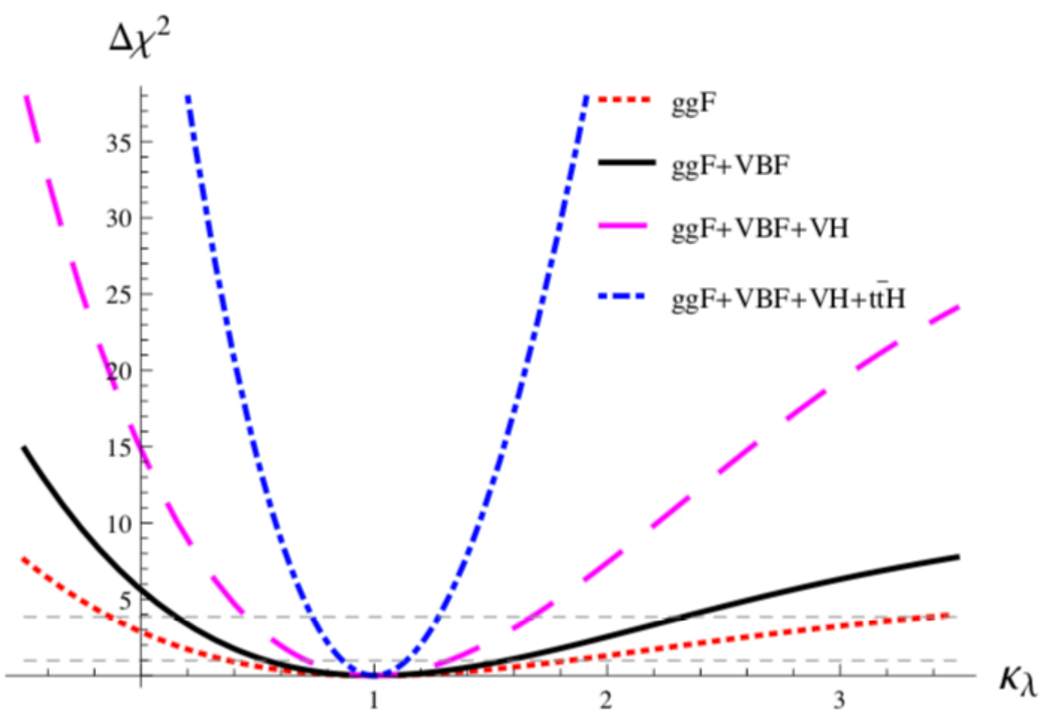
Study the impact of an anomalous trilinear coupling on electroweak loops for single Higgs production

In e^+e^- collisions

M.McCullough (2014)

At the LHC

G. Degrassi, P.Giardino, F.Maltoni, D.Pagani, M.Zaro (2016)



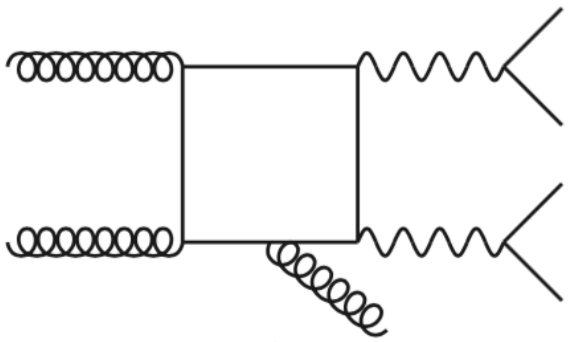
$$\kappa_\lambda^{1\sigma} = [-0.7, 4.2] \qquad 3\text{ab}^{-1}$$

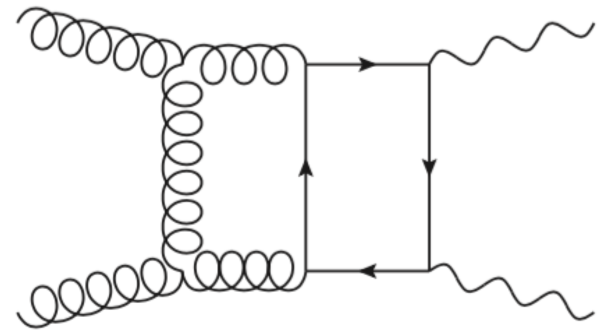
Comparable with what obtained from double Higgs production

How different can the trilinear coupling be from its SM value ?

gg→ZZ+X at NLO

F.Caola, K.Melnikov, R.Röntsch, L.Tancredi (2015)





NLO corrections to the gluon channel are known to be large

NLO corrections to gg→ZZ recently completed (no fermionic channels) and found to be large, as happens for Higgs production

By using our NNLO setup they get an additional +6% shift of the ZZ cross section at 8 TeV (+7% at 13 TeV) which exceeds the O(3%) scale uncertainty at NNLO

Inclusion in the MATRIX framework in progress

Combination with EW corrections in the near future

Comparison of precision on Higgs couplings

The start of a journey.....

Parameter	HL-LHC	FCC-ee	FCC-ee	ILC	CLIC	CEPC	μ-Coll
$\sqrt{s}$[TeV]	14	350	240	250	1400	240	125
Lum/IP[E34]	5	1.9	8.5	1.35	1.5	2	0.01?
total[ab^{-1}]	3+(3)	1.3+1.3	5+5	2	1.5	2+2	0.002?
years[Sn'm'ss]	6	6.8	5.9	15	10	10	2?
Δm_h[MeV]	$\sim$ 100			14	47	5.9	0.06
Γ_h[%]	-	1.2	2.4	3.9	3.7	2.7	3.6
Δg_{hZZ}[%]	4	0.15	0.16	0.38	0.8	0.26	
Δg_{hWW}[%]	4.5	0.19	0.85	1.8	0.9	1.2	2.2
Δg_{hbb}[%]	11	0.42	0.88	1.8	1.0	1.3	2.3
$\Delta g_{h\tau\tau}$[%]	9	0.54	0.94	1.9	1.7	1.4	2.3
$\Delta g_{h\gamma\gamma}$[%]	4.1	1.5	1.7	1.1	5.7	4.7	5
Δg_{hcc}[%]	-	0.71	0.71	2.4	2.3	1.7	10
Δg_{hgg}[%]	6.5	0.8	0.80	2.2	1.8	1.5	-
Δg_{htt}[%]	8.5	-	-	-	4.2	-	-
$\Delta g_{h\mu\mu}$[%]	7.2	6.2	6.4	5.6	14.1	8.6	2.1
$\Delta\Gamma_{\text{invis}}$[%]	~10			0.32			
Δg_{hhh}[%]	-400,1200	-	-	-	40	-	
References	ATL-PHYS-PUB	1308.6176	1308.6176	1710.07621	1608.07538	IHEP-CEPC-DR	1304.5270
	-2014-016			1711.00568		-2015-01	1308.2143

Many questionable and/or dated numbers!

Table inspired by talk of M Klute, Higgs couplings,2015

HH @ CLIC

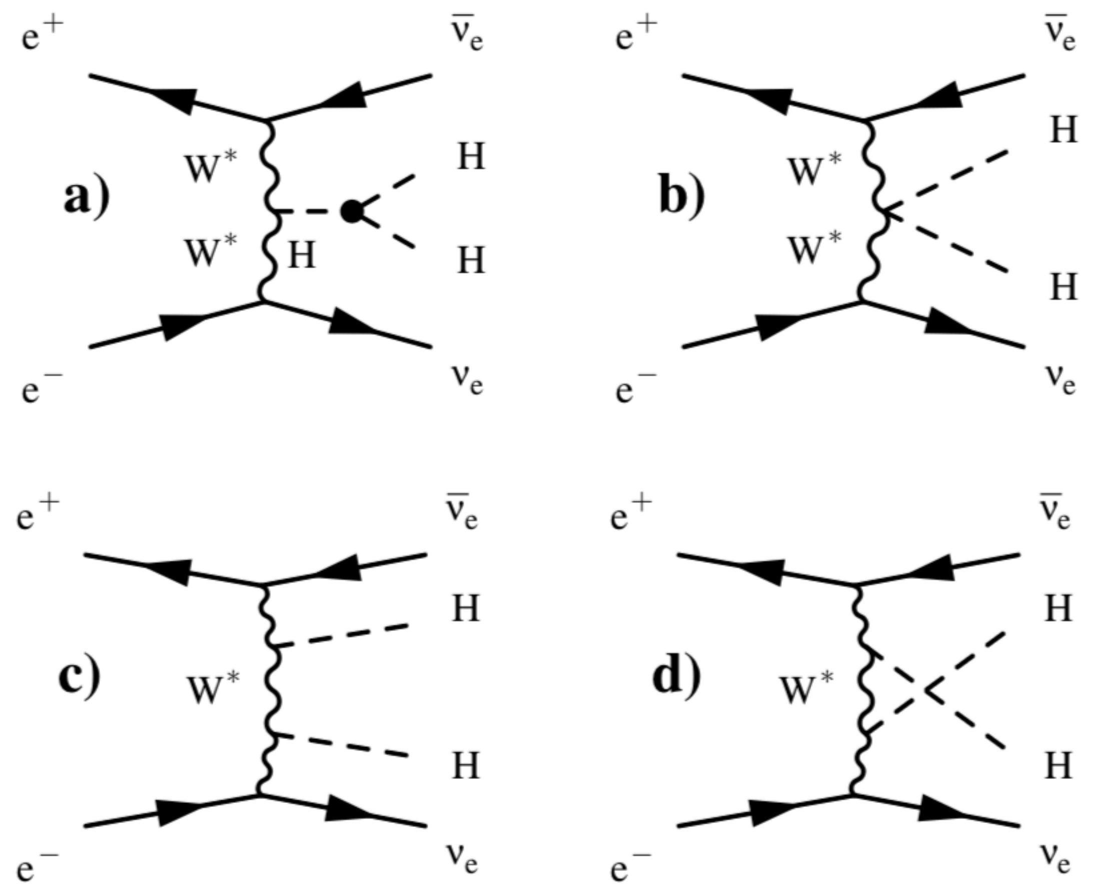


Fig. 24: Feynman diagrams of leading-order processes that produce two Higgs bosons and missing energy at CLIC at $\sqrt{s} = 1.4\,\text{TeV}$ and $3\,\text{TeV}$. The diagram (a) is sensitive to the trilinear Higgs self-coupling λ. The diagram (b) is sensitive to the quartic coupling g_{HHWW}. All four diagrams are included in the generated $e^+e^- \to \text{HH}\nu_e\bar{\nu}_e$ signal samples.

$$\Delta\lambda/\lambda = 54\,\% \;\text{ at } \sqrt{s} = 1.4\,\text{TeV}\,,$$
$$\Delta\lambda/\lambda = 29\,\% \;\text{ at } \sqrt{s} = 3\,\text{TeV}\,.$$