The Higgs sector where we stand

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Workshop on High Luminosity LHC and Hadron Colliders
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Outline

- Status of the Higgs sector
- Double Higgs production and the extraction of the trilinear Higgs self coupling
- A new Monte Carlo code for Higgs pair production, flexible in the input parameters and in the choice of the top mass renormalization scheme.
- Conclusions

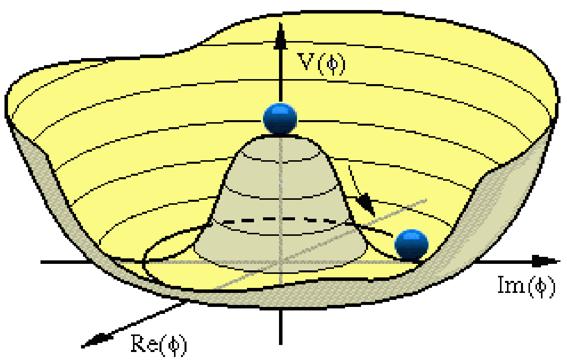
The Higgs sector, what we know

$$\mathcal{L}_{Higgs} = (\lambda_{ij}\bar{\psi}_i\psi_j\phi + h.c) + |D^\mu\phi|^2 - V(\phi)$$

EWSB: m_f, $h\bar{f}f$ $m_{W,Z}$, HVV, HHVV m_H, HHH, HHHH,...

At least one Higgs doublet under SU(2)xU(1)

Before July 4th 2012: the vacuum expectation value

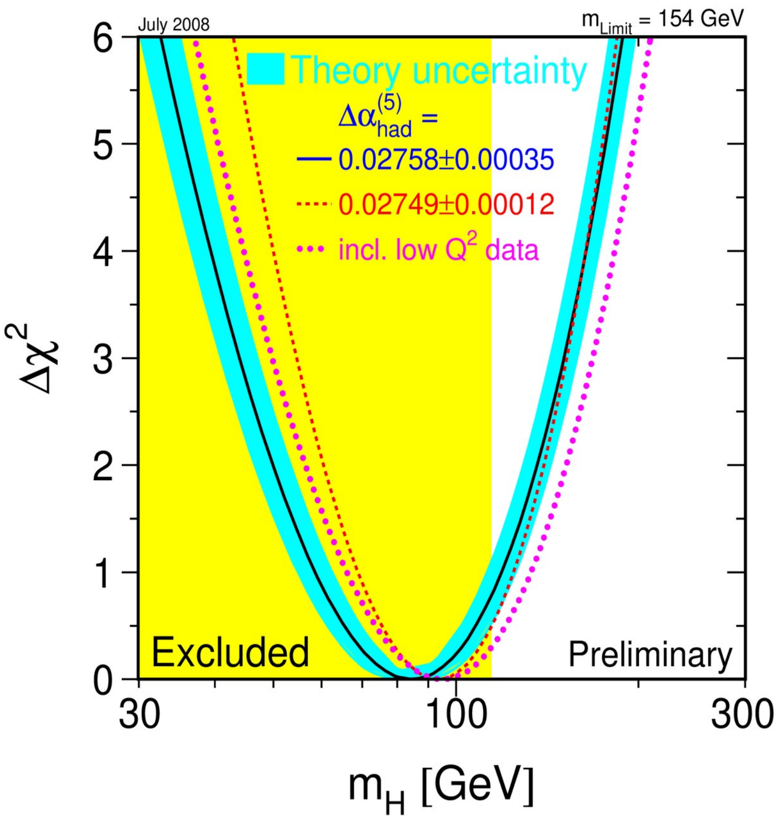


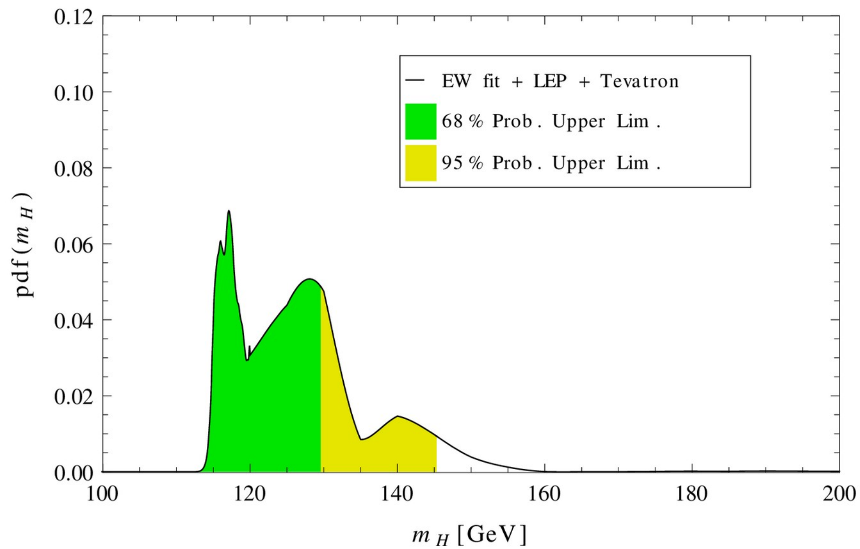
The ground state of the potential known since long time

$$G_\mu = \frac{1}{2v^2}$$

$$v = \langle\phi^\dagger\phi\rangle^{1/2} \sim 246 \text{ GeV}$$

Before July 4th 2012: the LEP legacy





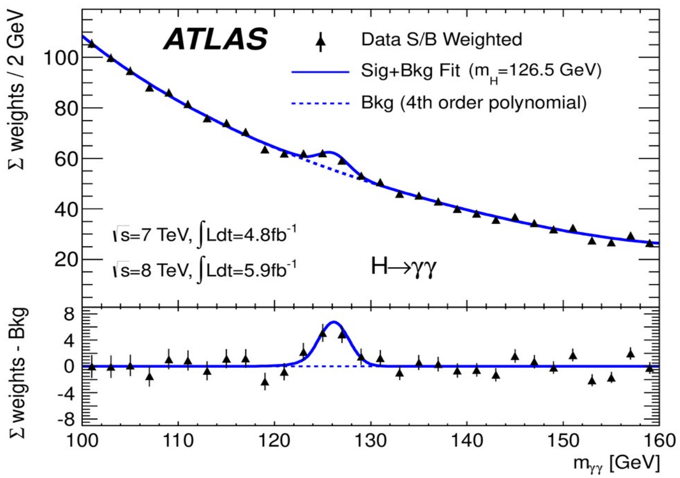
Pdf of m_H including the exclusion limit of Lep

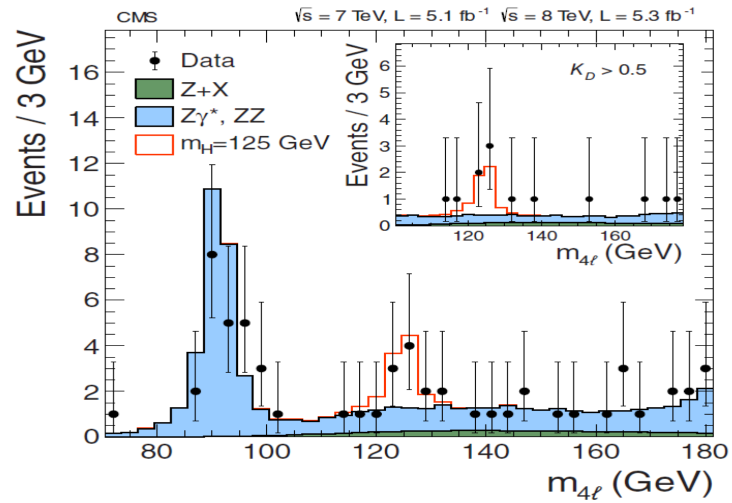
D'Agostini, G.D.1999

- A Higgs boson with mass between 110 and 160 GeV is "basically" SM. No warranty to find something else at the LHC

- A Higgs boson with mass larger than 160 GeV has to be accompanied by something else. (the conspiracy argument)

July 4th 2012





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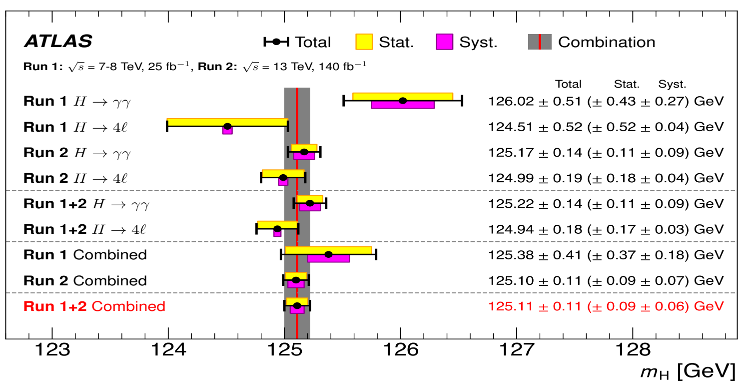


CMS: H→ZZ*→4l

$$m_H = 125.8 \pm 0.1(\mathrm{stat}) \pm 0.08(\mathrm{syst})\ \mathrm{GeV}$$

ATLAS: H→4l + H→γγ

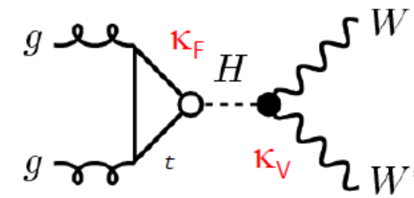
$$m_H = 125.11 \pm 0.11\ \mathrm{GeV}\ (\mathrm{syst}\ 0.09\ \mathrm{GeV})$$

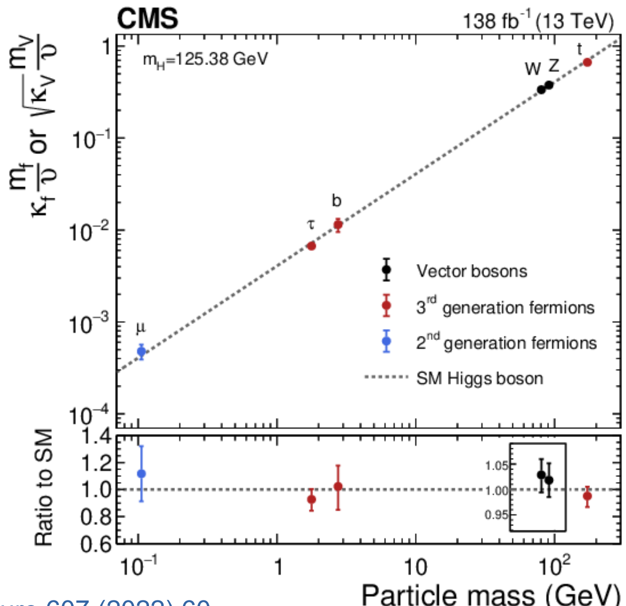
$$\frac{\delta m_H}{m_H} \sim 0.09\%$$

A Higgs boson with mass ~ 125 GeV is “basically” SM.
“basically” means that in the investigation of its property we do not expect, in general, dramatic modifications of the SM picture but likely small deviations from it. To pin down these small deviations we need both very high precise measurements and very high precise theoretical predictions.

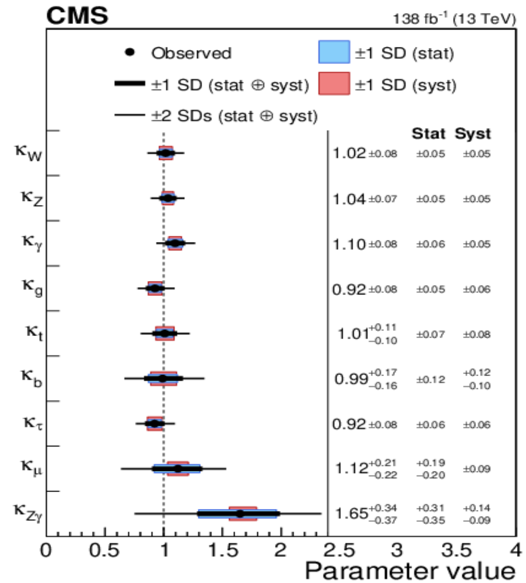
Testing the HVV, Hf̄f couplings

$$\mathcal{L}_{Higgs} = (\lambda_{ij}\bar{\psi}_i\psi_j\phi + h.c) + |D^\mu\phi|^2$$





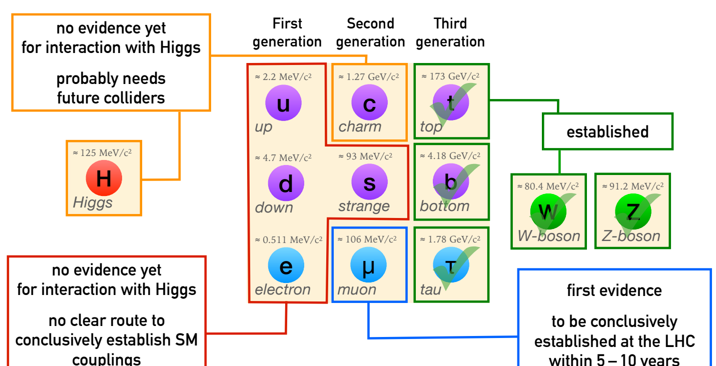
Nature 607 (2022) 60



Boson sector (W,Z,g,γ): 7-8% tested already in:

Fermion sector:
Quarks: 10% (t), 15% (b)
Leptons: 8% (τ), 20% (μ)

G. Salam et al.
Nature 607 (2022) 41



Testing V(H): self-couplings

$$V(H) = \lambda_2 v^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + \ldots$$

n-Higgs production probes (n+1)-Higgs self-coupling

single Higgs production → $\lambda_2 \equiv m_H^2/(2\,v^2)$ $\sigma(pp \to H)_{SM} \sim 50\,pb$

double Higgs production → λ_3 $\sigma(pp \to HH)_{SM} \sim 30\,fb$

triple Higgs production → λ_4 $\sigma(pp \to HHH)_{SM} \sim 0.1\,fb$

SM: at tree-level only λ_3 and λ_4, fixed in terms of λ_2

$$\lambda_3^{SM} = \lambda_4^{SM} = \lambda_2 = m_H^2/(2v^2),\ v = \left(\sqrt{2}G_\mu\right)^{-1/2}$$

Single Higgs production (experimental)

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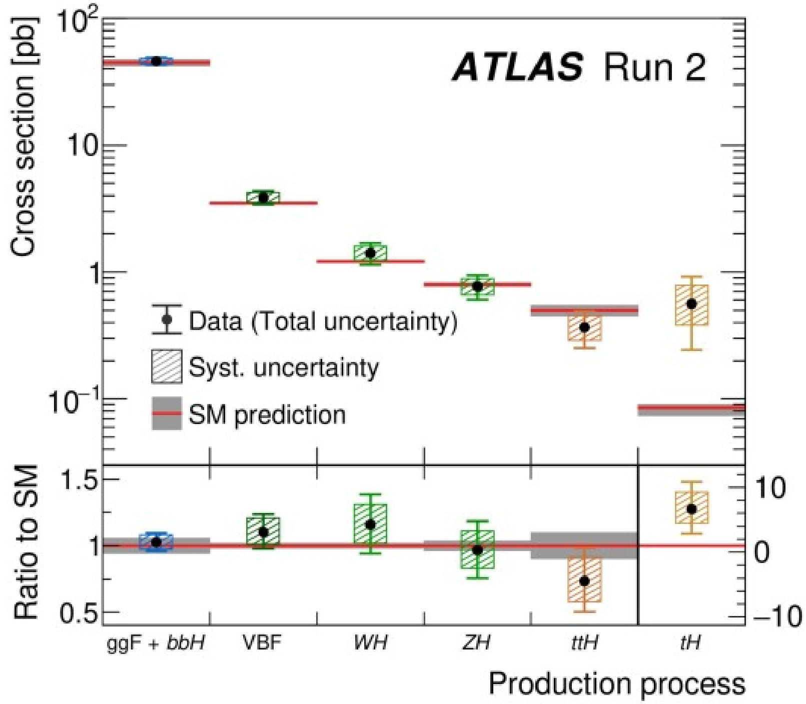
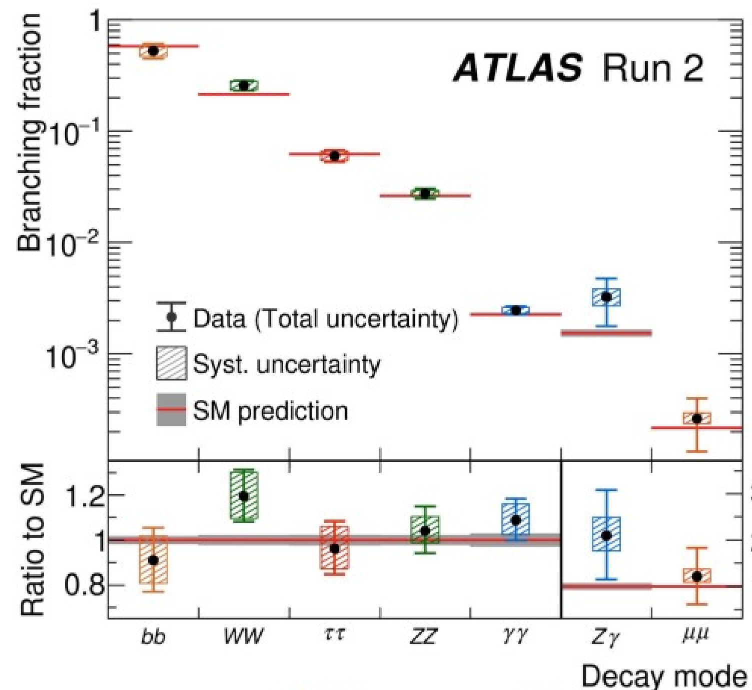
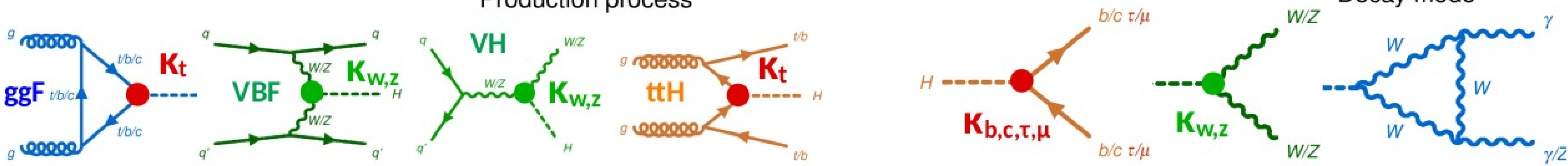






Main production and decay processes observed, measured with <10% – 20% precision

Nicolas Berger
ICHEP 2024 Prague

Single Higgs production, ggH, (theory)

Gluon fusion production mode:

LO exact

(Georgi, Glashow, Machacek, Nanopoulos, 78)

↓

NLO HTL

(-------------------------------)

↓

NLO quark masses

(-------------------------------)

↓

NNLO HTL

(-------------------------------)

↓

N^3LO HTL

(-------------------------------)

↓

NNLO quark masses

(-------------------------------)

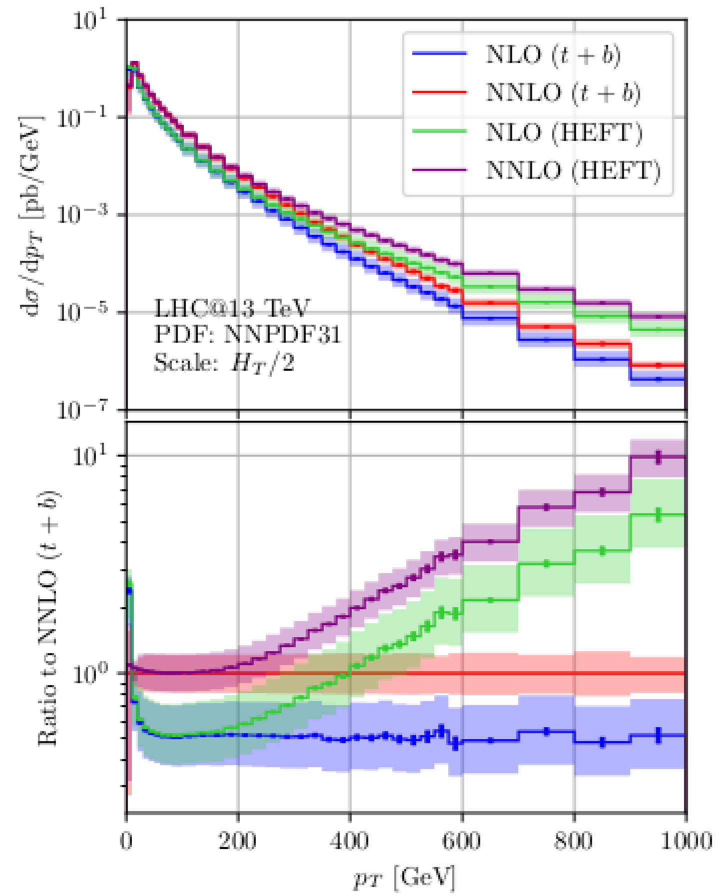
↓

NNLO quark masses

mass-renormalization and flavor schemes

(Czakon et al. 2024)

+ NLO EW



$$\sigma_{ggH} = 48.81(1)^{+0.65}_{-2.02}(\mathrm{N^3LO\,HEFT}) - 0.16^{+013}_{-0.03}(\mathrm{NNLO}\,t) - 174(2)^{+013}_{-0.03}(\mathrm{NNLO}\,t\,\mathrm{x}\,b)\ \mathrm{pb}$$

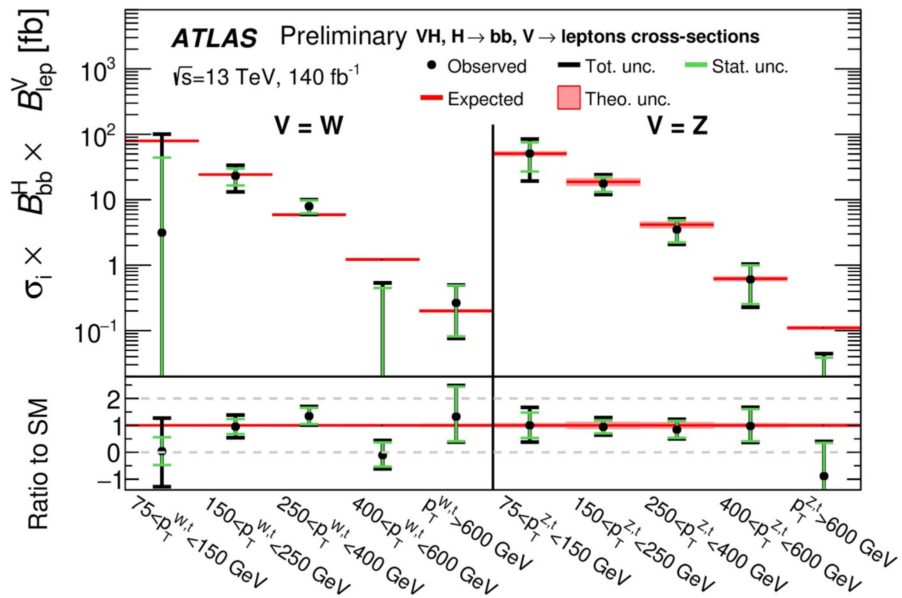
$$\Delta\,\sigma_{ggH} \sim 2\%$$

Single Higgs production, VH (V=W,Z)

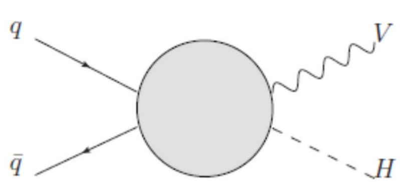
Best sensitivity for the dominant $H \rightarrow b\bar{b}$ decay mode where the leptonic decay of the vector boson enables efficient triggering and a significant reduction of the multi-jet background.

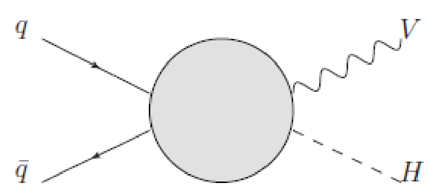
Good agreement with the SM

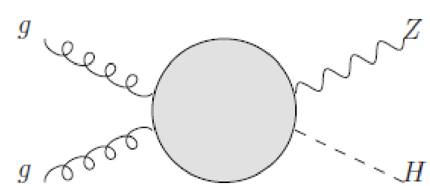
$$\mu_{WH} = 0.95^{+0.21}_{-0.19} \left({}^{+0.15}_{-0.9}\ syst \right)$$
$$\mu_{ZH} = 0.87^{+0.23}_{-0.20} \left({}^{+0.18}_{-0.14}\ syst \right)$$



Notice:
Theory uncertainty larger in the ZH mode with respect to the WH mode because of the gg channel







WH: pure DY, LO → NNLO
+ NLO EW

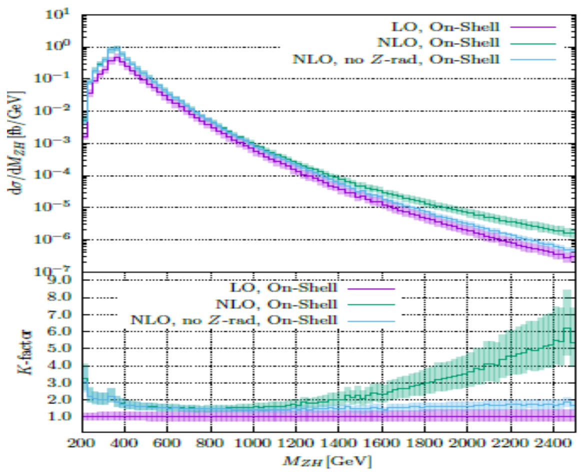
ZH: DY, LO → NNLO; NNLO noDY
gg, LO → NLO with top mass and mass-renormalization
(formally LO → NNLO; NLO → N^3LO)

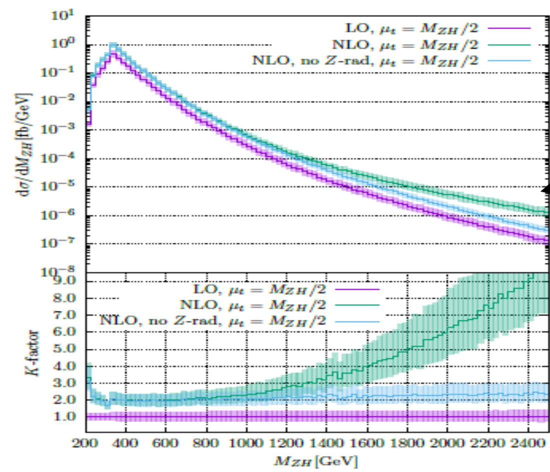
Single Higgs production, ZH

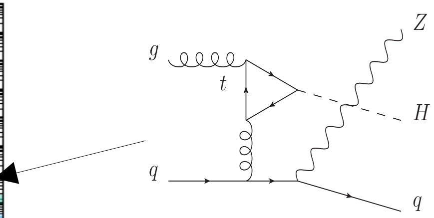
R. Groeber, M.Vitti, X. Zhao, G.D. (22)

Top-mass scheme	LO [fb]	$\sigma_{LO}/\sigma_{LO}^{OS}$	NLO [fb]	$\sigma_{NLO}/\sigma_{NLO}^{OS}$	$K = \sigma_{NLO}/\sigma_{LO}$
On-Shell	$64.01^{+27.2\%}_{-20.3\%}$	-	$118.6^{+16.7\%}_{-14.1\%}$	-	1.85
$\overline{\text{MS}}, \mu_t = M_{ZH}/4$	$59.40^{+27.1\%}_{-20.2\%}$	0.928	$113.3^{+17.4\%}_{-14.5\%}$	0.955	1.91
$\overline{\text{MS}}, \mu_t = m_t^{\overline{\text{MS}}}(m_t^{\overline{\text{MS}}})$	$57.95^{+26.9\%}_{-20.1\%}$	0.905	$111.7^{+17.7\%}_{-14.6\%}$	0.942	1.93
$\overline{\text{MS}}, \mu_t = M_{ZH}/2$	$54.22^{+26.8\%}_{-20.0\%}$	0.847	$107.9^{+18.4\%}_{-15.0\%}$	0.910	1.99
$\overline{\text{MS}}, \mu_t = M_{ZH}$	$49.23^{+26.6\%}_{-19.9\%}$	0.769	$103.3^{+19.6\%}_{-15.6\%}$	0.871	2.10

gg channel

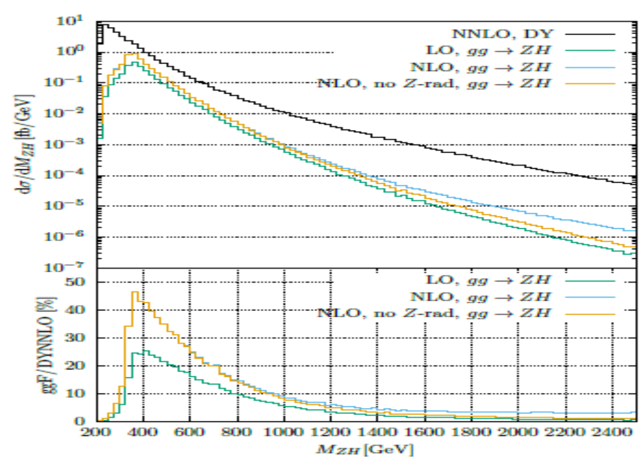




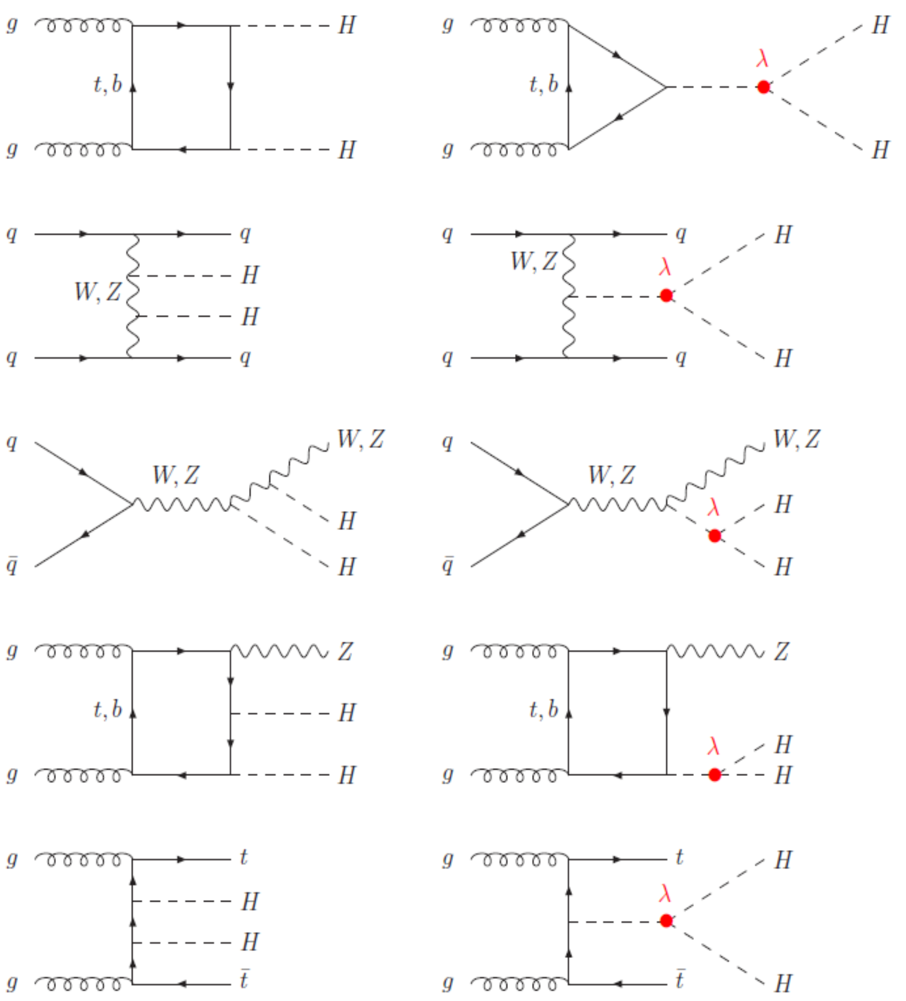


The gg → ZH contribution can reach up to ~ 50% of the Drell-Yan part at $M_{ZH} = 2\, m_t$

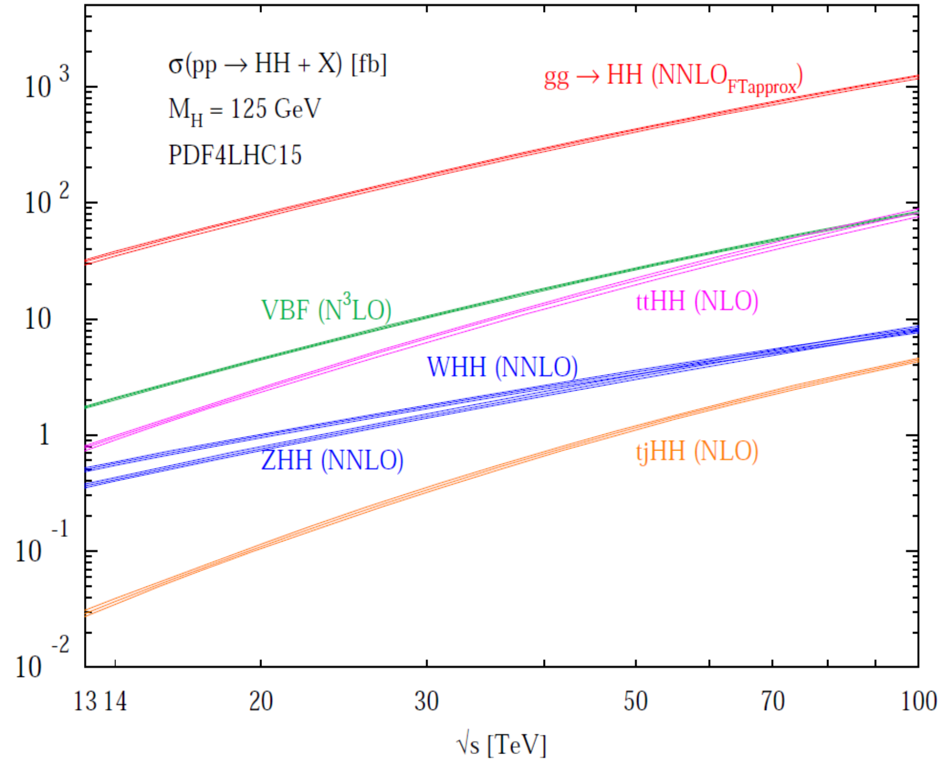
Because of the Z-radiated diagrams the gg contribution falls off as rapidly as Drell-Yan



Testing V(H), the shape : double Higgs production @LHC



destructive interference between signal (λ) and background diagrams



Di Micco et al. (20)

Double Higgs production @LHC (experimental)

The di-Higgs final states

- Given the current **luminosity** and the harsh **experimental conditions**, a good sensitivity is achieved with
  - **Large branching ratio** (H→bb)
  - **Very good selection purity** (H→ττ, H→γγ)

▸ **Run 1**
Only few channels covered

▸ **Early Run 2**
At least one H→bb or multileptons

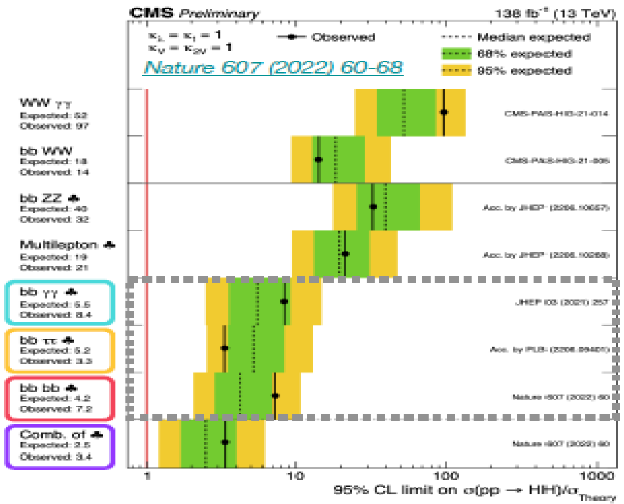
▸ **Full Run 2**
several new final states and production modes investigated by ATLAS and CMS

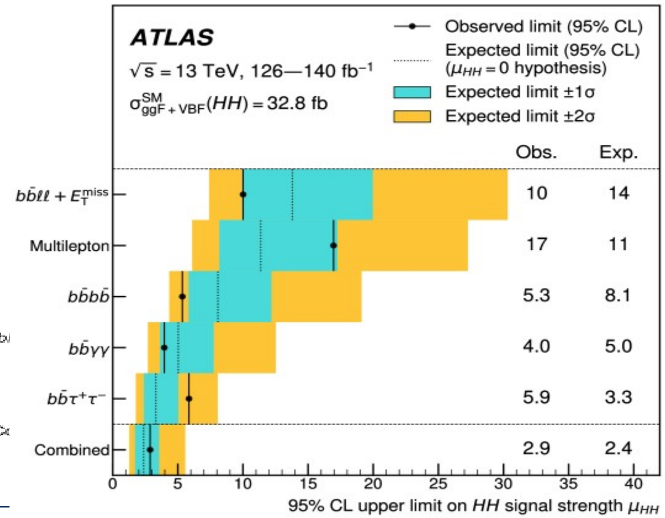
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Not a single golden channel but many (at least three) silver bullets

Limits on di-Higgs production

- The most stringent upper limits on the di-Higgs cross section come from the **combination** of different **final states**





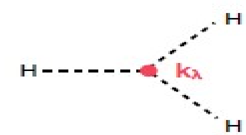
CMS
$\sigma_{HH} < 3.4\ \sigma^{SM}_{HH}$

ATLAS
$\sigma_{HH} < 2.4\ \sigma^{SM}_{HH}$

No channel dominating overall sensitivity

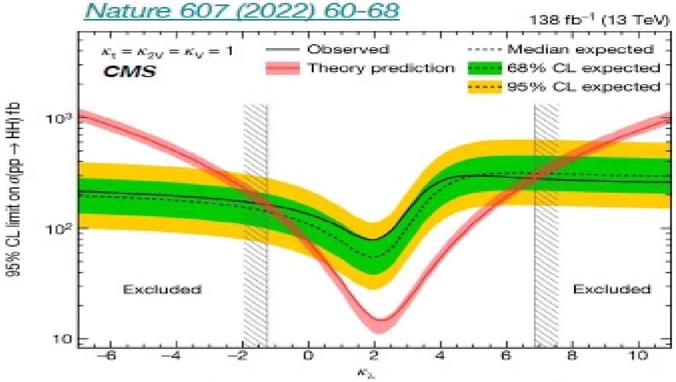
Combination is the key

Limits on anomalous couplings

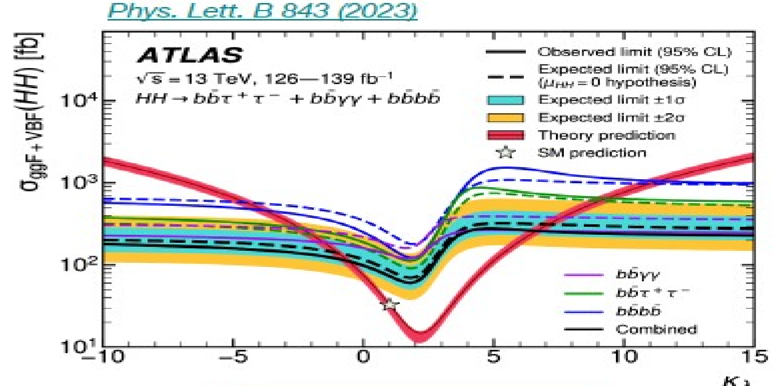


- The limits on di-Higgs production cross section show a **strong dependence** on the k_λ and k_{2V}

Nature 607 (2022) 60-68



Phys. Lett. B 843 (2023)

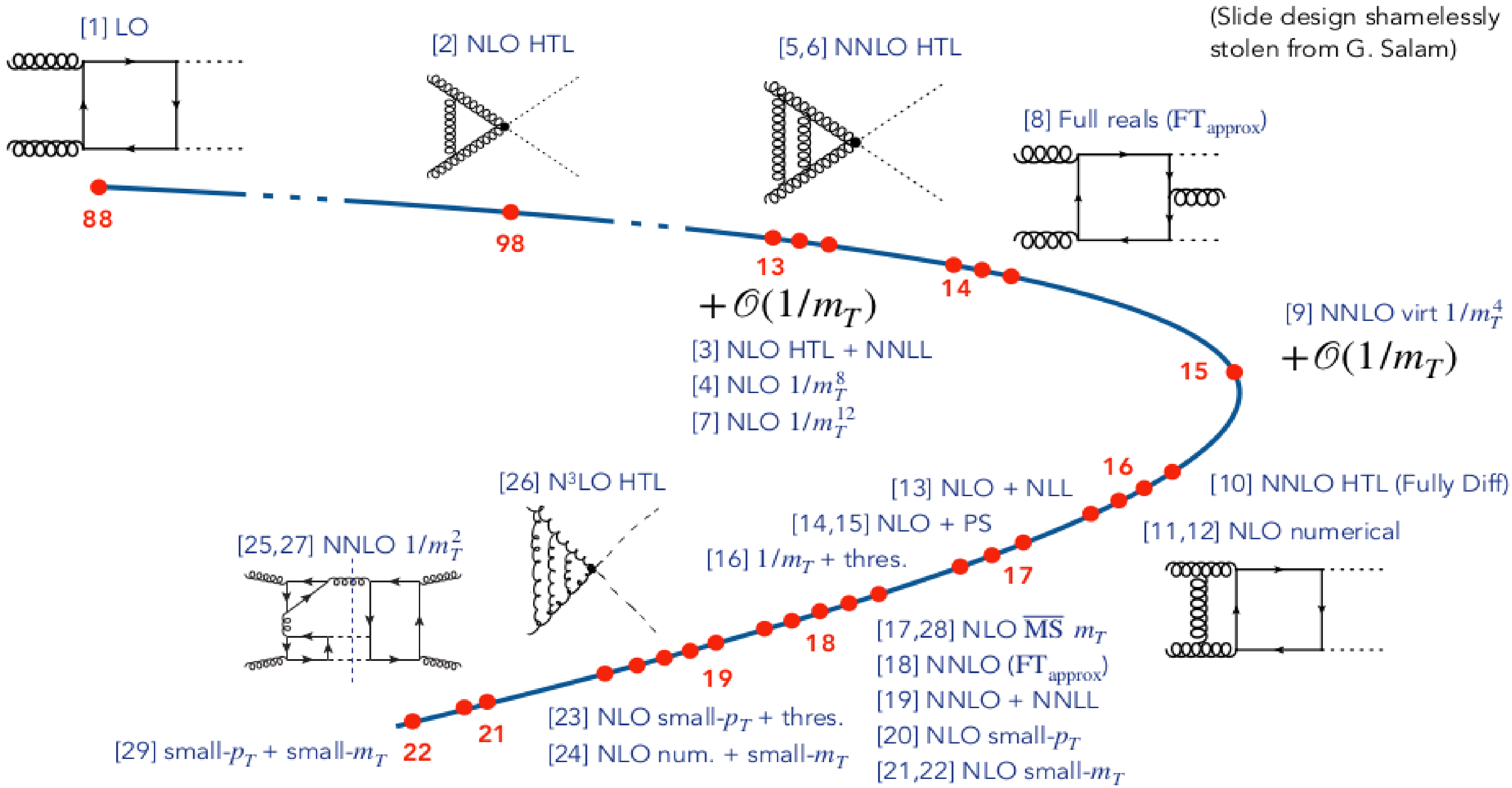


CMS
$-0.6 < k_\lambda < 6.6$ *

ATLAS
$-1.24 < k_\lambda < 6.49$ *

* Assuming other couplings to SM value

Double Higgs production @LHC (theory)

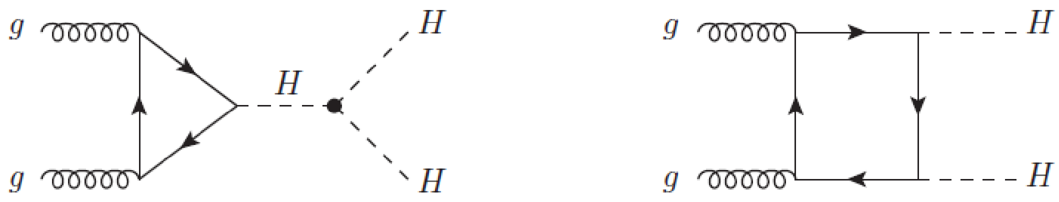


[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

Slide stolen from S. Jones

$gg \to HH$ Feynman diagram topology

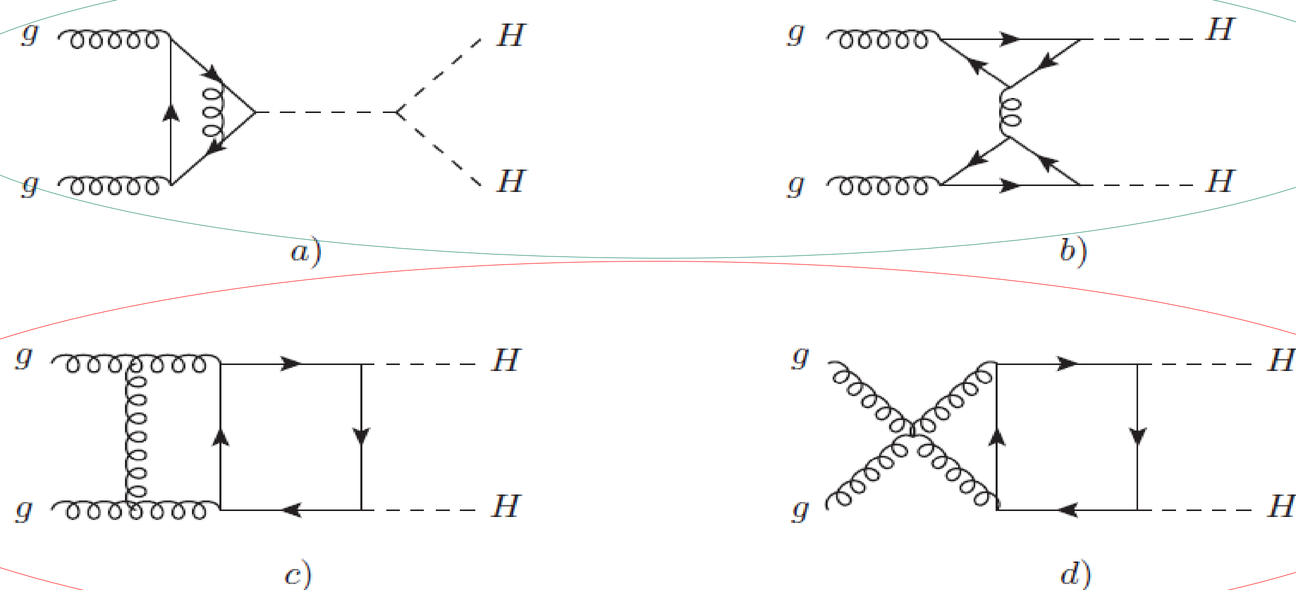
LO:



1 energy scale: s/m_t^2

3 (4) energy scales: $s/m_t^2, t/m_t^2, m_H^2/m_t^2, (m_V^2/m_t^2)$

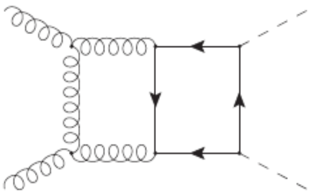
NLO QCD:



Ok 1 energy scale

Bottleneck of the calculation: no analytic results for diagrams with 3 (4) energy scales

What to do with



Numerical evaluation: exact but quite demanding from a computational point of view. The result is pointlike, an interpolating function is needed to cover all points.

Looking for an analytic results, why?

Analytic result: a result expressed in terms of "*functions*" that can be computed with a (public) code in a reasonable (very short) amount of time (ex. Log → HPL, GHPL …)

Virtues: (with respect to a numerical result): flexibility in the input parameters and in modifications of the setup (introduction of kappa parameters), coverage of any phase-space point (no interpolating functions needed). Good features for constructing a MonteCarlo code.

Problem: do not exist *"functions"* of 3 (4) energy scales in terms of which we can express the result of the calculation

Looking for an analytic results, how?

Problem: more energy scales in the diagrams less available "*known*" *functions.*

Solution A: reduce the numbers of scales in the problem. Look for an "*approximate*" result obtained by expanding the diagrams in terms of the ratio of small energy scales v.s. large energy scales. The dependence of the result by the large energy scales is kept exact. The result is valid in specific regions of the phase-space where the energy hierarchy is realized.

N.B. more scales are reduced, more available "*known*" *functions.* But more restricted region of validity of the result (compromise).

Solution B: combine together different "*approximate*" results that cover complementary regions of the phase-space in order to have a full coverage of it.

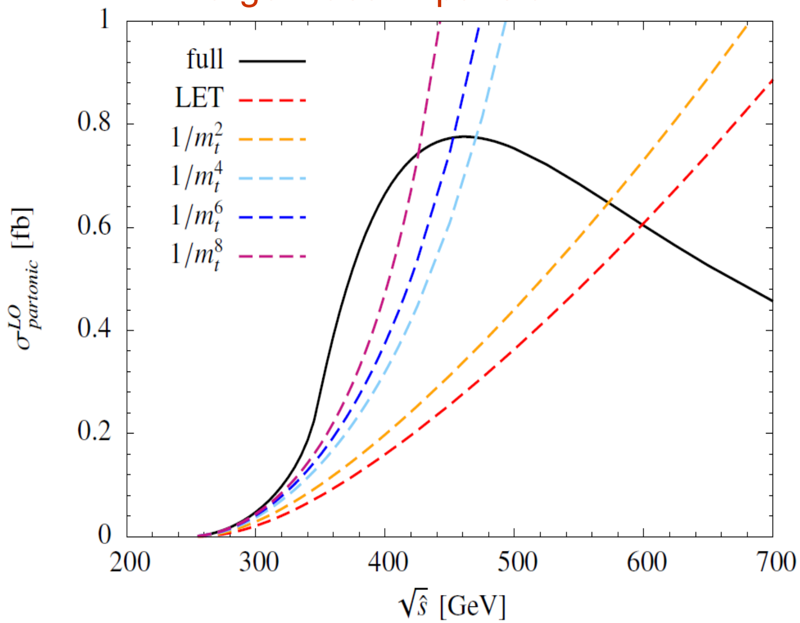
Approximate results:

- Heavy Top Limit (HTL): covers the thershold region (validity $s/(4\,m_t^2) \lesssim 1$, rational functions and logs)
- Forward kinematic expansion (t or p_T -expansion): covers well the region up to $\sqrt{s} \lesssim 750$ GeV (validity $|t|/(4\,m_t^2 \lesssim 1$, GHPL and two elliptic integrals)
- High Energy expansion (HE): covers well the region $\sqrt{s} \gtrsim 700$ GeV (validity $|t|/(4\,m_t^2 \gtrsim 1$, HPL)
- Small external mass expansion: covers the entire phase space, however because the reduction of scales is minimal is almost like a numerical evaluation (elliptic integrals)

p_T and HE expansions cover complementary regions of the phase space

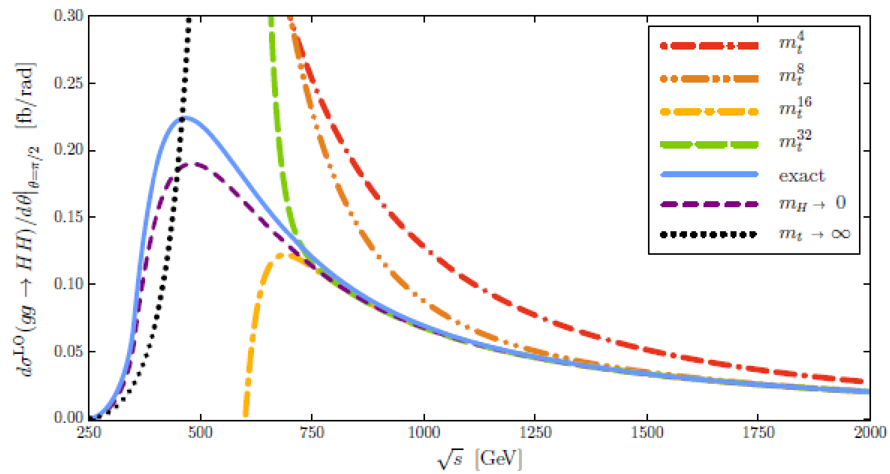
Judging the approximations from the LO in $gg \to HH$

Large Mass Expansion



HTL: Ok threshold

Large Momentum Expansion



Davies, Mishima, Steinhauser, Wellmann (18)

High-Energy expansion: Ok tail

None of these approximations cover the important C.M. energy region $\sqrt{s} \lesssim 700$ GeV

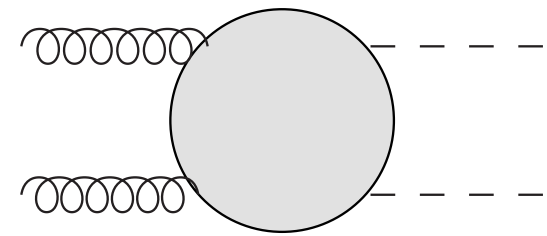
At NLO to try to cure the bad behavior of the approximations in the "wrong" region one can use the reweighting

$$d\sigma_{NLO} = d\sigma_{LO} \frac{d\sigma_{NLO}}{d\sigma_{LO}}$$

exact

$$\frac{\text{approx}}{\text{approx}} \sim \frac{\text{bad}}{\text{bad}} \sim \text{good}$$

Transverse momentum expansion



Consider a forward kinematics: $p_t \to 0$

$$p_1^\mu = p_3^\mu + Q_t^\mu$$
$$Q_t^\mu = \frac{t-m_4^2}{s} p_1^\mu - \frac{t-m_3^2}{s} p_2^\mu + r_\perp^\mu, \; Q_t^2 = t, \; r_\perp^2 = -p_t^2$$

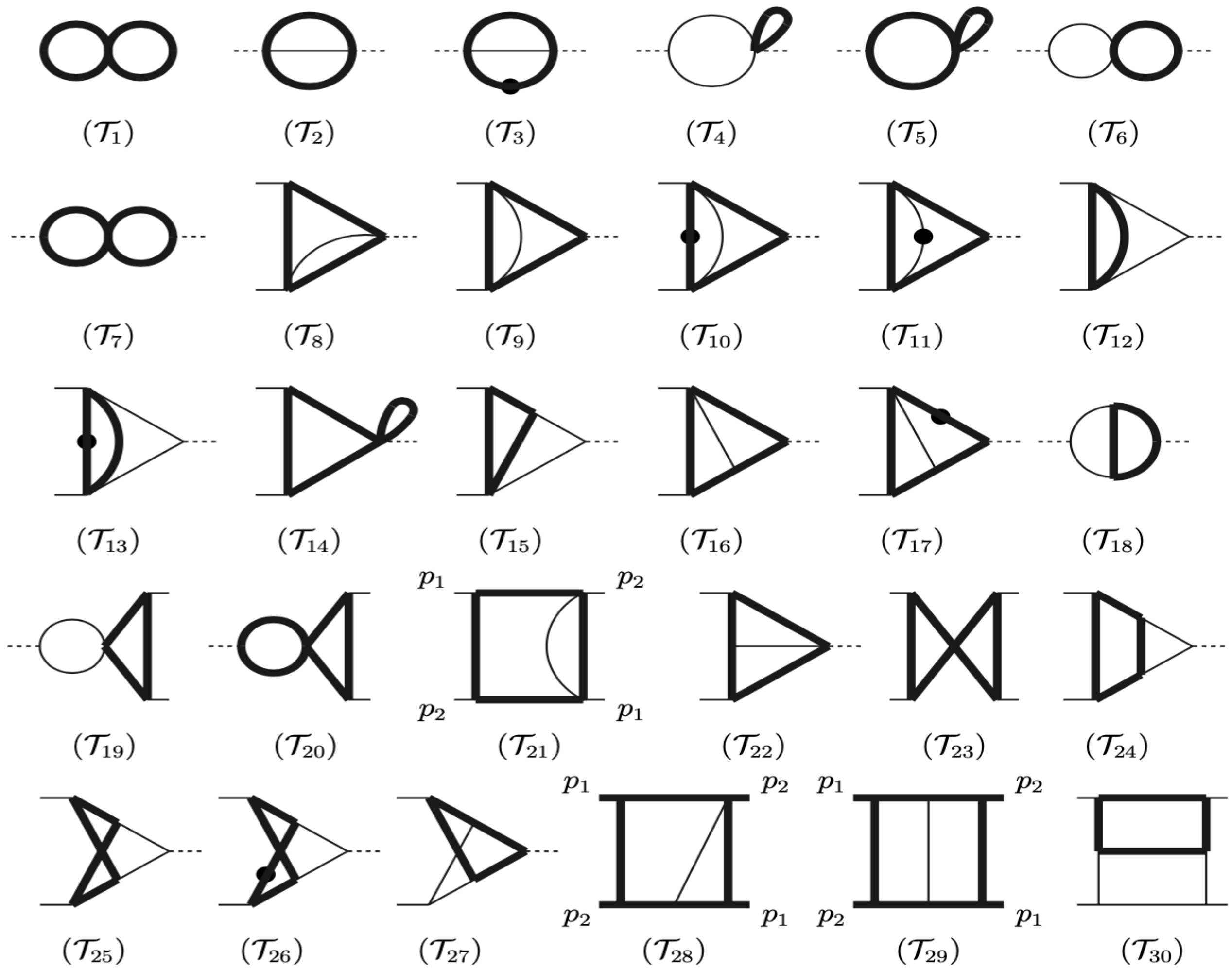
Taylor expand integrals in Q_t assuming: $\frac{m_3^2}{s}, \frac{m_4^2}{s}, \frac{p_t^2}{s} < 1, \; \frac{p_t^2}{4m_t^2} < 1$

always — range of validity

$$\mathcal{A}_i(s,t,m_t^2,m_3^2,m_4^2) = \sum_{n=0} \sum_{k=1}^{52} \left[\frac{(p_T^2)^n}{s^\alpha (m_t^2)^\beta} c_{(n,k)}^{p_T} + \frac{(m_3^2)^n}{s^\alpha (m_t^2)^\beta} c_{(n,k)}^{m_3} + \frac{(m_4^2)^n}{s^\alpha (m_t^2)^\beta} c_{(n,k)}^{m_4} \right] I^k \left(s/m_t^2\right) \; (n = \alpha + \beta)$$

The NLO form factors are expressed in terms of 52 MI that are function of the ratio $x = s/m_t^2$.

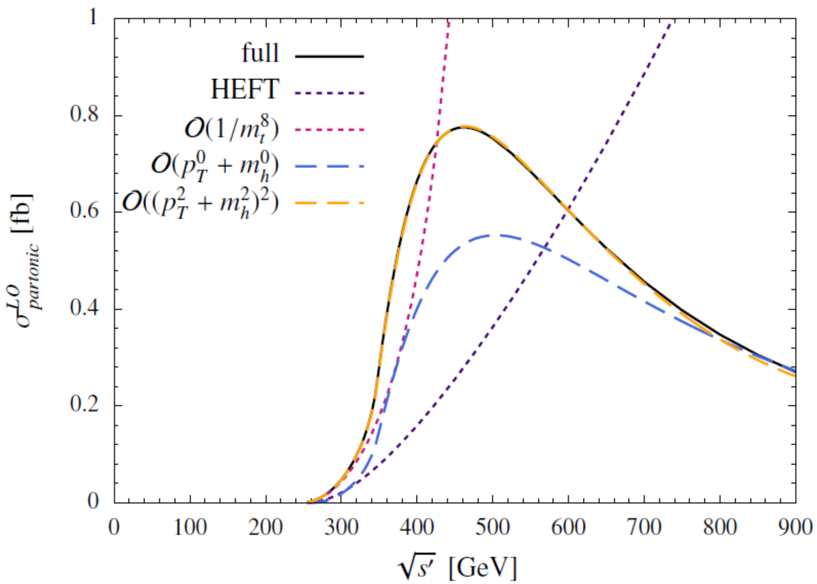
Master Integrals



Courtesy of R. Bonciani

Judging the approximation from the LO in $gg \to HH$

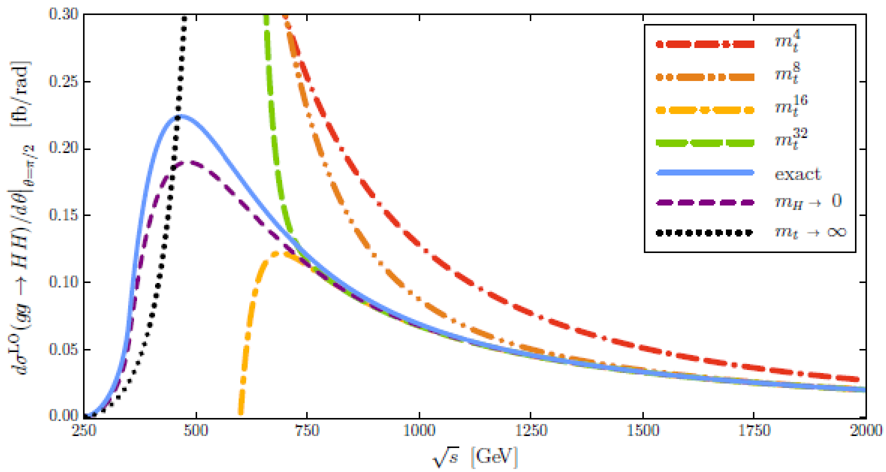
Transverse Momentum Expansion



Bonciani, Giardino, Groeber, G.D. (18)

The important C.M. energy region $\sqrt{s} \lesssim 700$ is perfectly covered

Large Momentum Expansion



Davies, Mishima, Steinhauser, Wellmann (18)

High-Energy expansion: Ok tail

The two expansions cover complementary regions of the phase-space

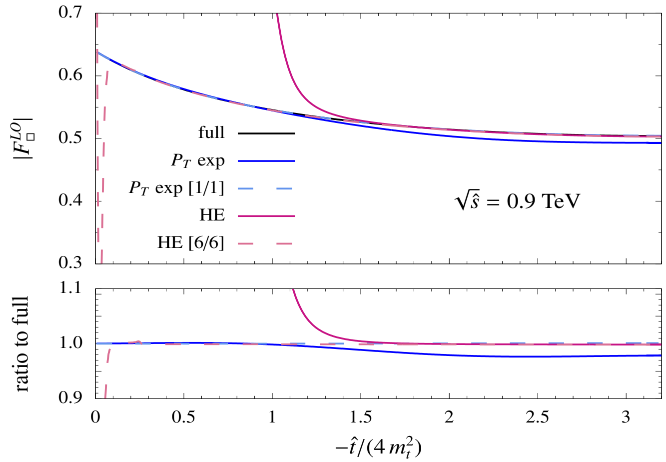
Merging the p_T and HE expansions

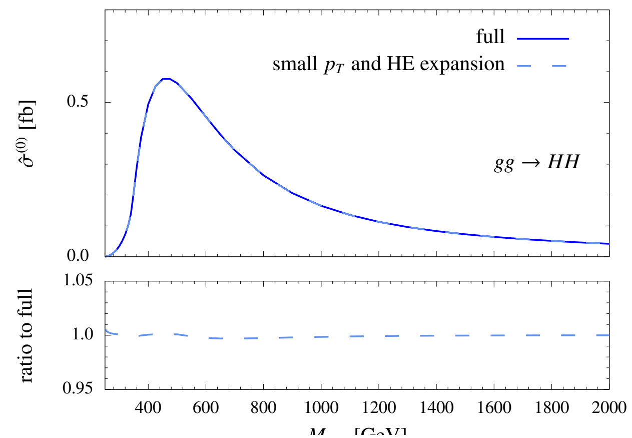
Bellafronte, Giardino, Groeber, Vitti, G.D. (22)

Extend the range of validity of each expansion up to or beyond his border using Pade' approximants.

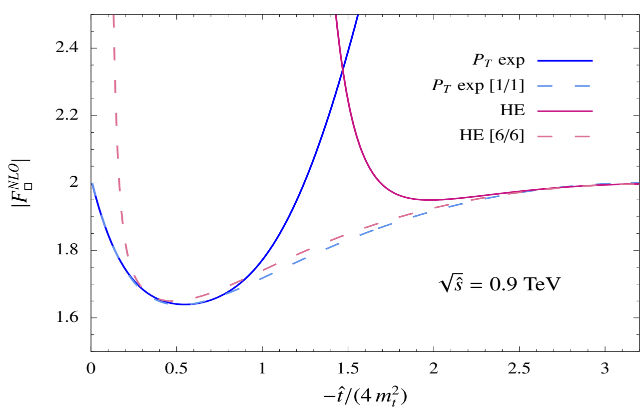
$$f(x) \simeq \sum_{k=0}^{r-1} c_k x^k, \longrightarrow [m/n](x) = \frac{p_0 + p_1 x + \cdots + p_m x^m}{1 + q_1 x + \ldots q_n x^n}, \; m+n+1 = r$$

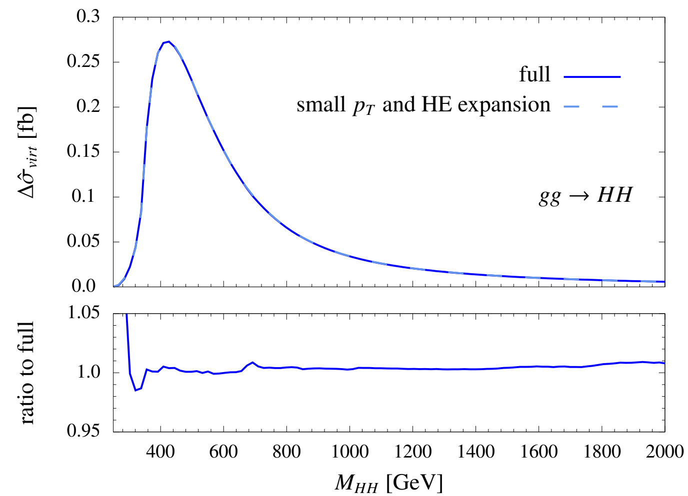
Construct a [1,1] p_T-Pade' and a [6,6] HE-Pade'





LO



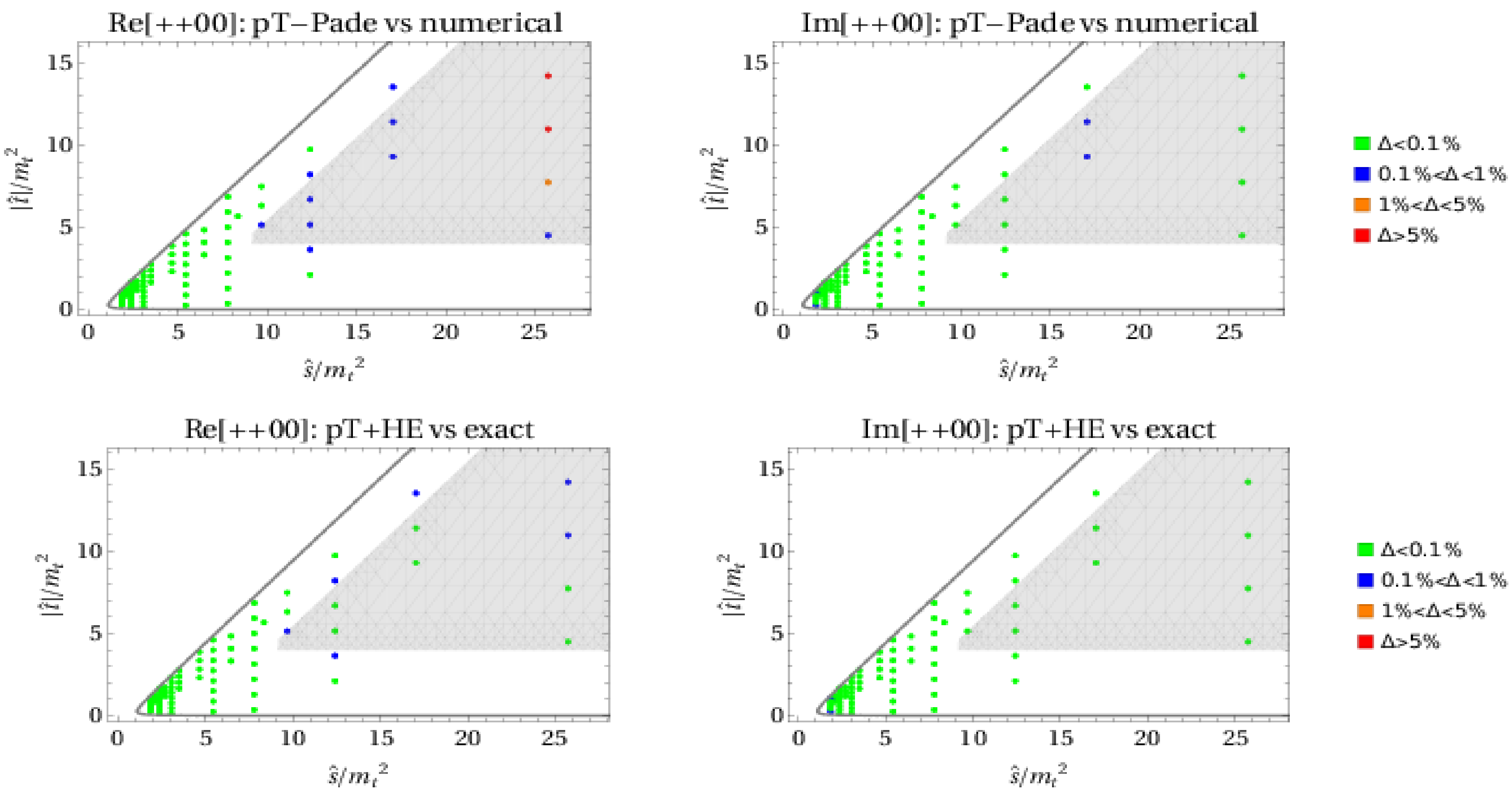


NLO

Comparing our merged result with a numerical one in $gg \to ZZ$

Numerical results for the helicity amplitudes provided by Agarwal, Jones, von Manteuffel (JHEP 05 (21) 256)

$$\mathcal{M}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} = \frac{\alpha_s}{2\pi}\mathcal{M}^{(1)}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + \left(\frac{\alpha_s}{2\pi}\right)^2 \boxed{\mathcal{M}^{(2)}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4}} + \mathcal{O}\left(\alpha_s^3\right)$$

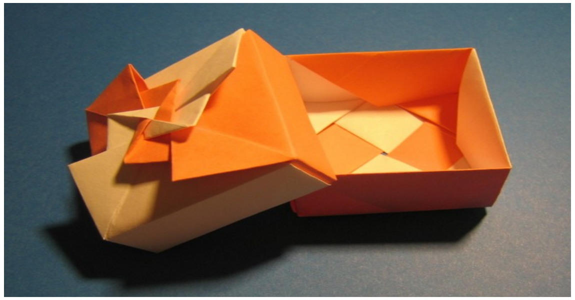


The other side of precision physics

It is obviously important to refine our theoretical predictions by computing as much as possible higher orders in the perturbative series. Also we should not forget the uncertainties related to α_s and the pdf.

However it also important to make our computations available to the experimental community → to insert them in a Monte Carlo. This requires corrections that can be computed in a short time and possibly flexible with respect to input parameters.

G.D.: we all should be thankful to Paolo N. and collaborators that, via the introduction of the POWHEG-BOX, opened basically to everyone a field previously restricted only to specialists.



A new Monte Carlo for $gg \to HH$ on the market

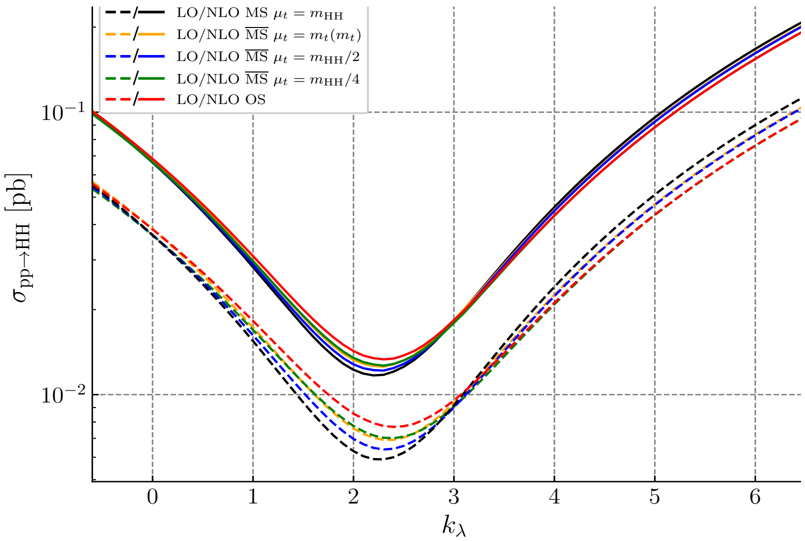
- Currently in the POWHEG-BOX there is a Monte Carlo generator (`GGHH`) for Higgs boson pair production at NLO (Heinrich et a. (17), Jones et al. (18), Heinrich et al. (20)).
  This MC is based around the two-loop numerical results of Borowka et al. (16) which are implemented via a series of interpolating grids (to account for modified trilinear coulings etc..) matched with the HE-expansion results for large values of the center-of-mass energy.
- Inputs are fixed, no possibility to change the renormalization scheme for the top mass.

- We developed a new code Monte Carlo code, always based on the POWHEG-BOX MC framework, based on our analytic evaluation of the two-loop contribution.
- Features:
  a) freedom in the assigment of all input parameters including the trilinear Higgs self-coupling (κ_λ rescaling).
  b) possibility of varying the renormalization scheme employed for the top mass
- Possible future features:
  i) rescaling of the Yukawa coulping (κ_t).
  ii) resonant production.
  iii) …….

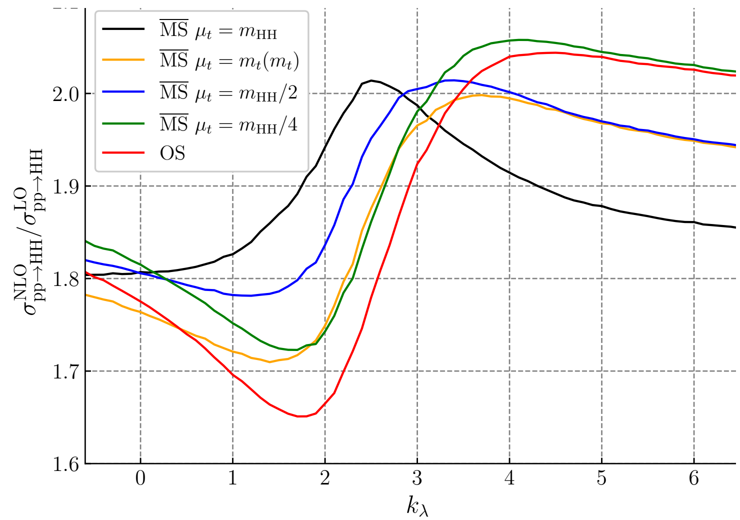
Our Setup: $\sqrt{s}$ =13.6 TeV, PDF =NNPDF31_nlo_as_0118, SHOWER= Pythia 8,
$\mu_R=\mu_F= M_{HH}/2$, α_s taken from PDF ($\alpha_s(M_Z)$ =0.118), M_H = 125 GeV
both OS and $\overline{\text{MS}}$ top mass employed

$$m_t^{\rm OS} = 172.5\,\text{GeV},\; m_t^{\overline{MS}}(\mu_t = m_t^{MS},\, M_{HH}/4,\, M_{HH}/2,\, M_{HH})$$

Incluse cross sections and κ factors



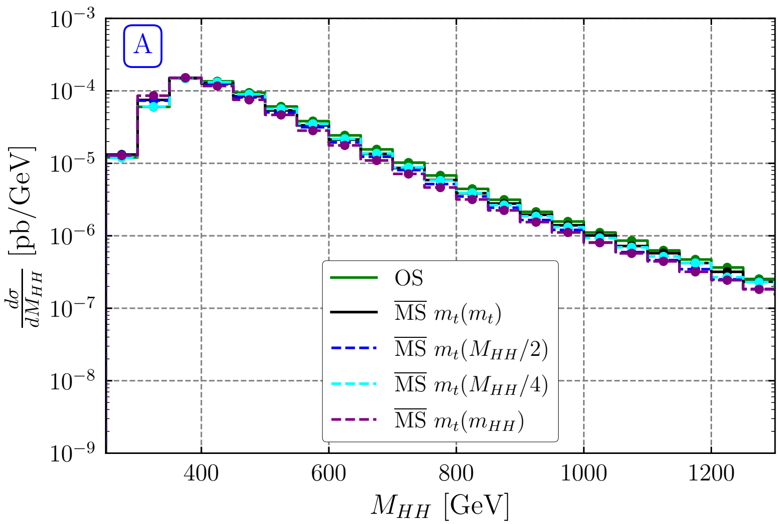
Inclusive cross section at LO and NLO as a function of κ_λ for different top-mass renormalization schemes

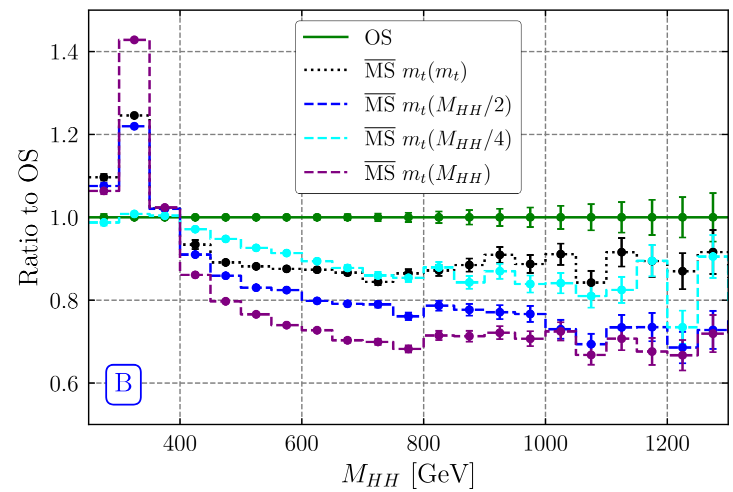


K factors for different top-mass renormalization schemes

- Minimun of the cross section depends on the top scheme.
- LO → NLO curves get closer, K factors vary accordingly.
- Initial discrepancy with the `GGHH` MC for $\kappa_\lambda \neq 1$ resolved after a bug in `GGHH` was fixed by the authors.
- Agreement with the fixed-order calculation of Baglio et al. (19) for $\kappa_\lambda \leq 1$, some discrepancy for higher values of κ_λ . (Probably their numerical integration is not sufficiently accurate in regions of parameter space where thee are strong cancellations) .

SM differential distributions: top mass scheme dependence in M_{HH}

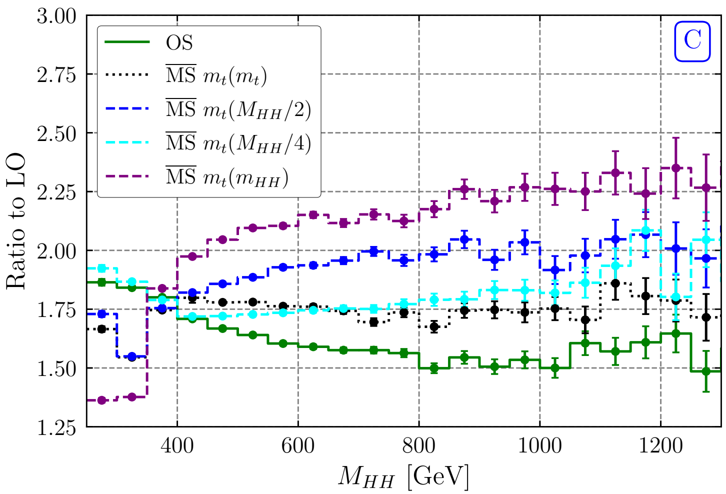


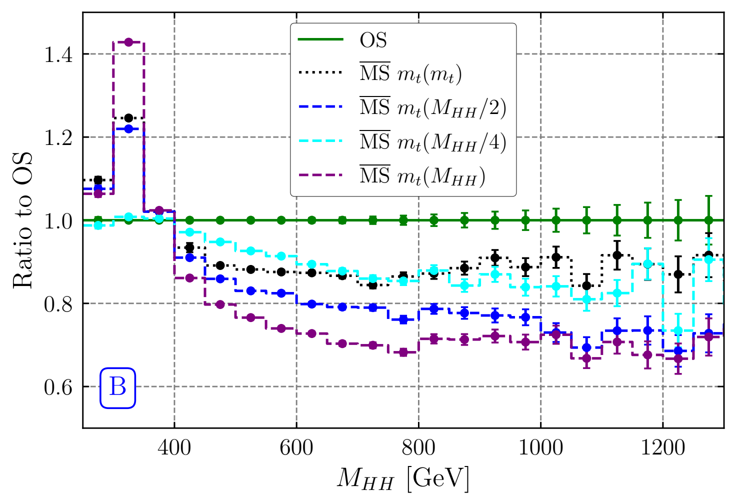


The invariant mass distribution of the two Higgs system for different choices of the top-mass renormalization scheme.
A) absolute distribution at NLO + PS
B) ratio between the $\overline{\text{MS}}$ predictions and the OS one

- Position of the peak depends on the top mass scheme
- Ratio is quite constant for $M_{HH} \geq 600$ GeV. For $M_{HH} \leq 400$ GeV large deviations in the ratio (influence of the position of the peak).

SM differential distributions: top mass scheme dependence in M_{HH}

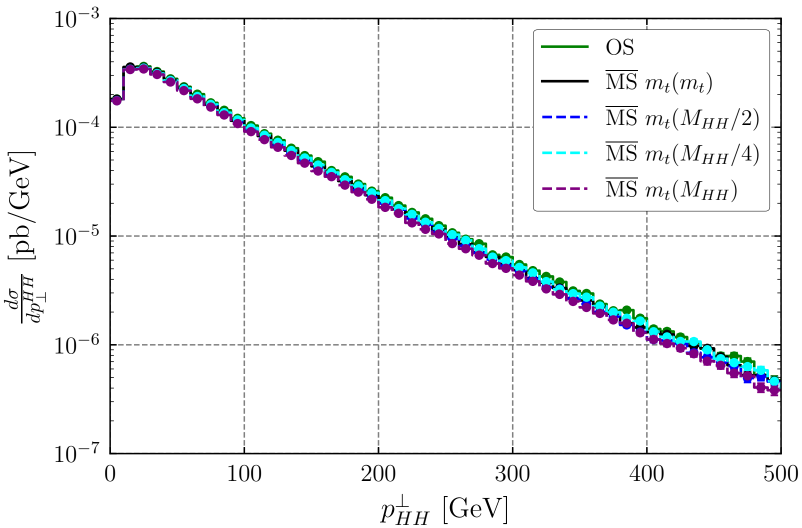


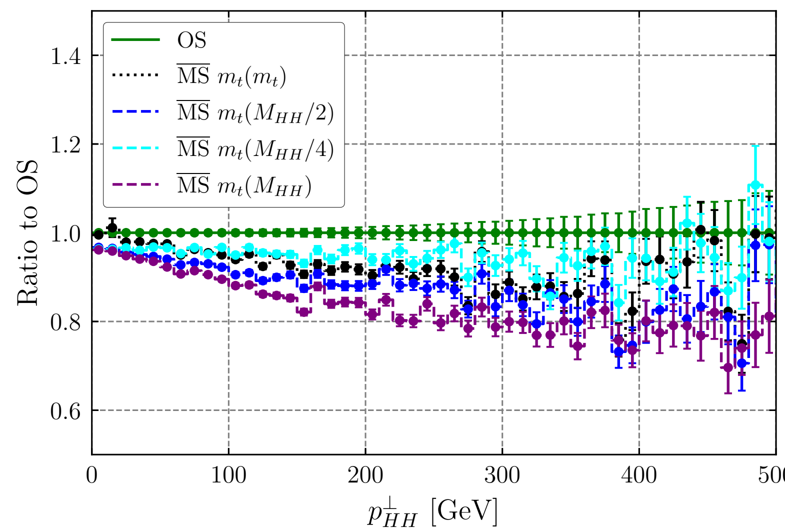


The invariant mass distribution of the two Higgs system for different choices of the top-mass renormalization scheme.
C) K factors
B) ratio between the $\overline{\mathrm{MS}}$ predictions and the OS one

- Position of the peak depends on the top mass scheme
- Ratio is quite constant for $M_{HH} \geq 600$ GeV. For $M_{HH} \leq 400$ GeV large deviations in the ratio (influence of the position of the peak).
- K factors imply the reduction of the scheme dependence LO → NLO

SM differential distributions: transverse momentum of the two higgs system





The transverse momentum distribution of the two Higgs system for different choices of the top-mass renormalization scheme.

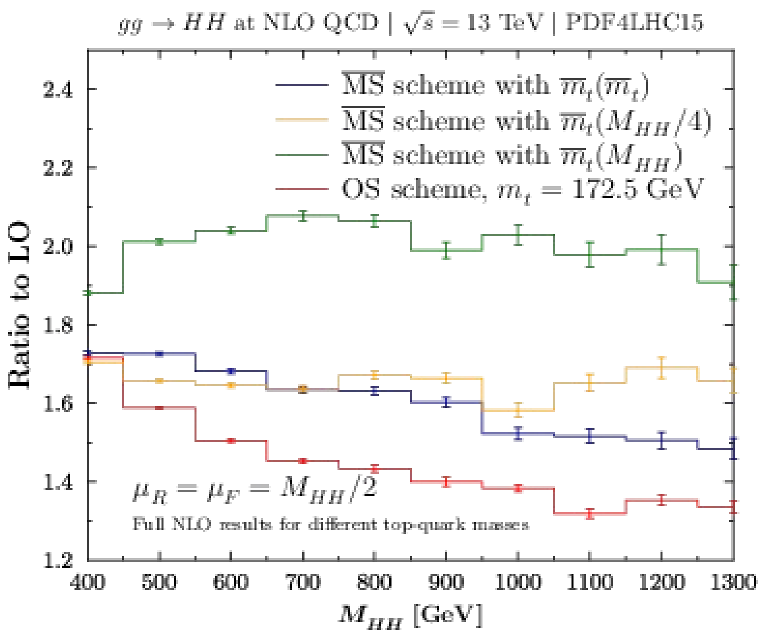
absolute distribution at NLO + PS

ratio between the $\overline{\text{MS}}$ predictions and the OS one

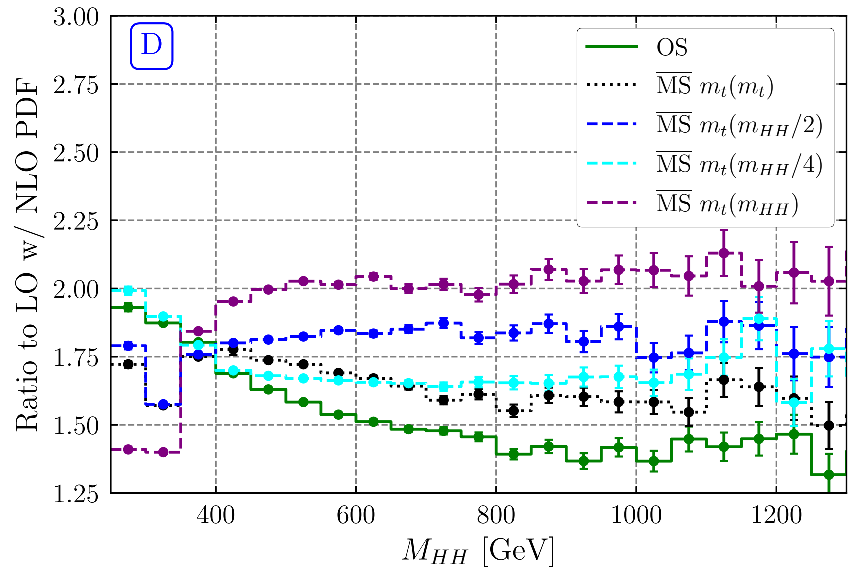
- The slope of p_{HH} depends on the to top mass scheme
- $\overline{\text{MS}}$ results always smaller that the OS one
- In the small p_{HH} region results are all quite close while there is larger spread for high values of p_{HH}

SM differential distributions: top mass scheme dependence in M_{HH}

Comparison with Baglio et al. (21)



NLO



NLO+PS

Good qualitative agreement although the setups were different

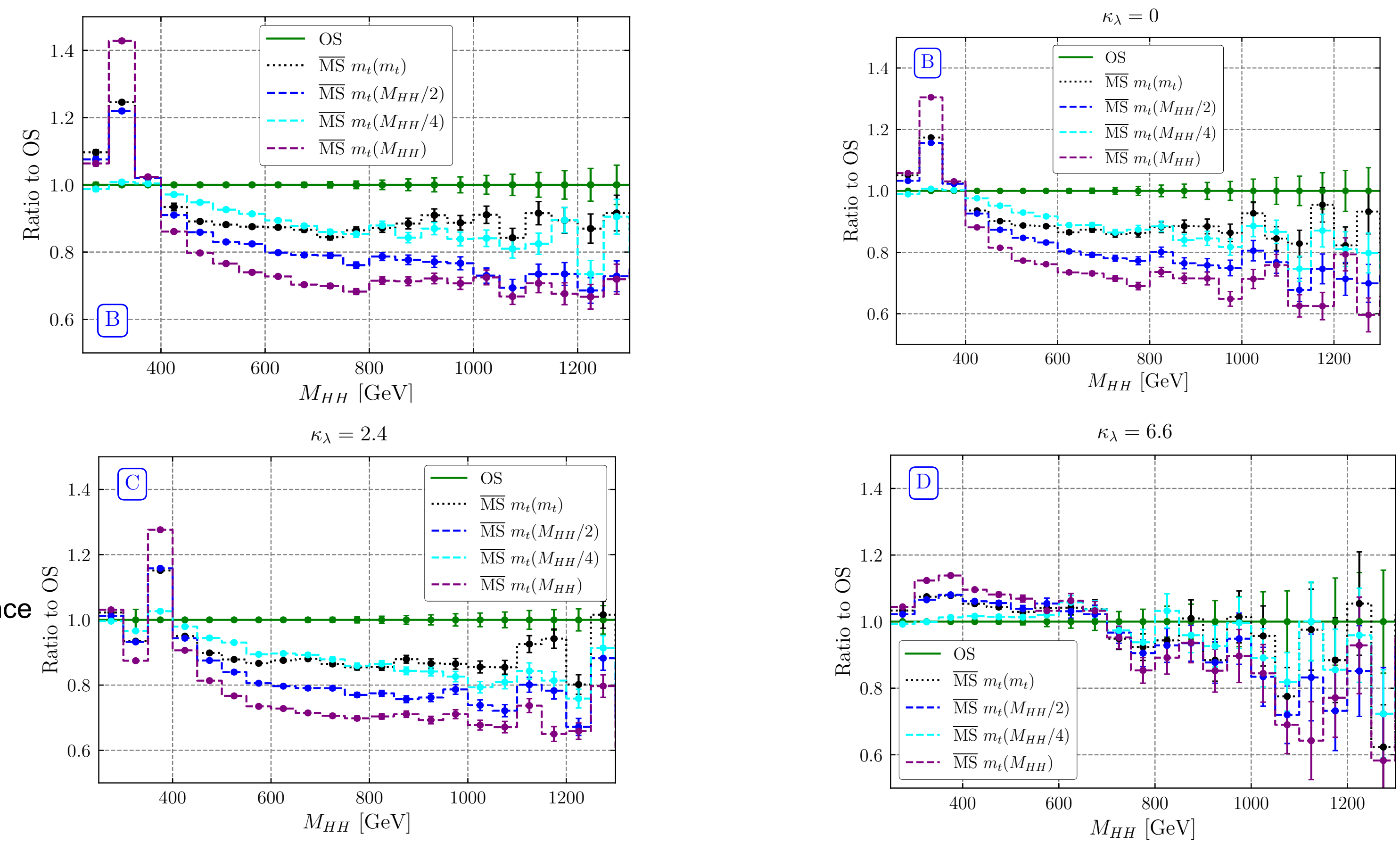
λ_3 differential distributions: top mass scheme dependence in M_{HH}

SM

No signal

Max interference

More signal

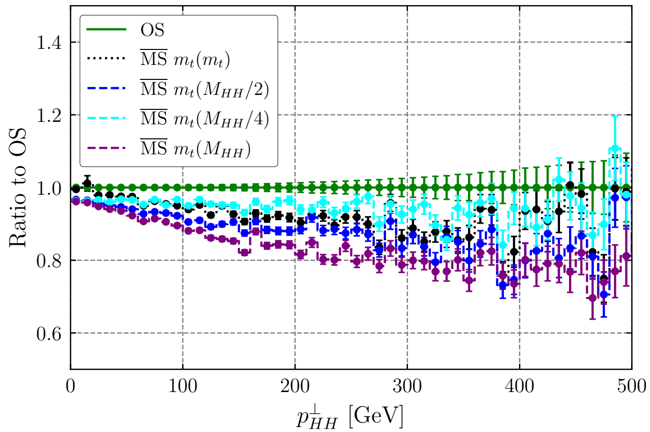


The invariant mass distribution of the two Higgs system for different choices of the top-mass renormalization scheme.

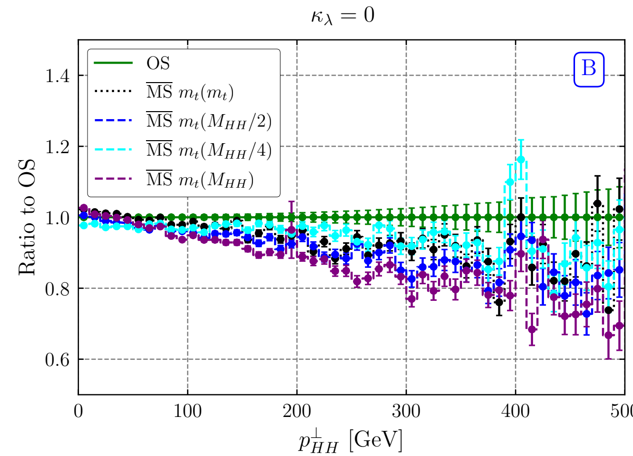
- K_λ = 0: very similar to SM. Scheme dependence of the signal milder than that of the background.
- K_λ = 2.4: the region around the 2 m_t threshold has a large scheme dependence
- K_λ = 6.6: mild scheme dependence

λ_3 differential distributions: transverse momentum of the two higgs system

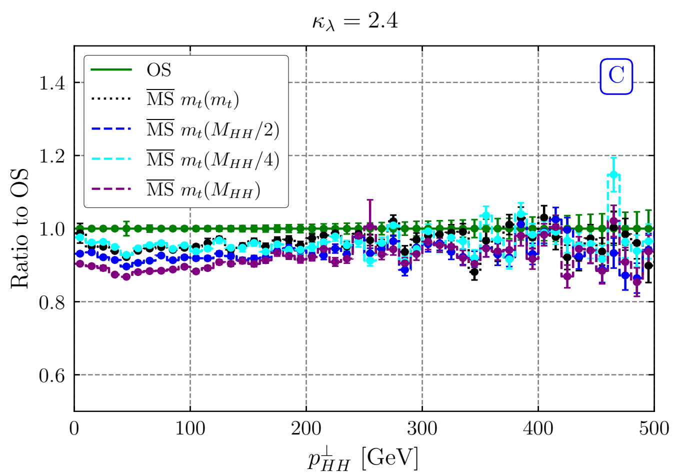
SM



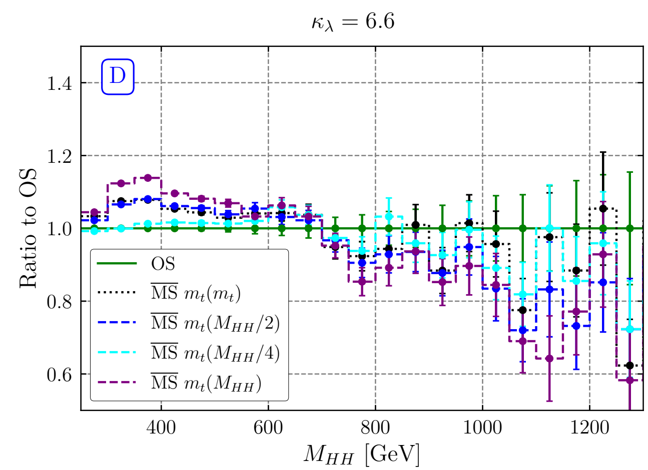
No signal



Max interference



More signal



The transverse momentum distribution of the two Higgs system for different choices of the top-mass renormalization scheme.

- $K_\lambda = 0$: very similar to SM although with less spread
- $K_\lambda = 2.4$: quite small scheme dependence and very similar for any p_{HH}
- $K_\lambda = 6.6$: similar to $K_\lambda = 2.4$ but with more spread

Conclusions

- The scalar particle discovered at CERN on July 4th 2012 looks like very much as the Higgs boson of the SM.

- At the LHC to pin down any departure from the SM picture requires precision both on the experimental and theory side.

- The shape of the Higgs potential is presently very poorly known. Determining the trilinear self couplings from double Higgs production is the new challenge. Accurate predictions are needed.

- $gg \to HH$: I present a new Monte Carlo code based on the analytic evaluation of the virtual corrections whose main feature is flexibility in the input parameters and choice of the renormalization scheme for the top mass. Going from LO to NLO the top mass scheme dependence is reduced but in the SM for large M_{HH} or large p_T can reach up to 20%. Modified trilinear coupling: signal contribution shows a milder scheme dependence than the background one.