MPP Project Review 2017, Munich

18 December 2017

Precision Phenomenology: Exploring the Higgs Sector and Beyond

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Stephen Jones

for the MPP Phenomenology Group

MAX-PLANCK-GESELLSCHAFT

Group Goals

What we do:

- Take or develop well motivated mathematical models

(Standard Model, SUSY Theories, Effective Field Theories,…)

- Produce precise, concrete predictions for high energy colliders

(LHC, ILC, FCC, …)

How we do it:

- Establish a mathematical understanding of the theory
- Develop and use state of the art computational tools and techniques

Why we do it:

- With our experimental colleagues, we want to test and refine our understanding of the fundamental forces
- E.g: Probing the nature of Electro-weak symmetry breaking, constraining the solution space for new fundamental particles and interactions

MPP Phenomenology Group

Director:

Wolfgang Hollik

Staff Members:

Thomas Hahn, Gudrun Heinrich

Postdoctoral Researchers:

Stephen Jones, Matthias Kerner, Gionata Luisoni (short-term)

Finishing this year: Joao Pires (Technical Institute of the University of Lisbon)

Welcome: Long Chen

PhD Students:

Henning Bahl, Stephan Hessenberger, Stephan Jahn, Viktor Papara, Cyril Pietsch, Ludovic Scyboz (partial member)

Welcome: Matteo Capozi

Project Highlights

Part 1: Calculations

Triple Higgs coupling effect on $h^0 \to b\bar{b}$ and $h^0 \to \tau^+\tau^-$ in the 2HDM
[A. Arhrib, R. Benbrik, J. El Falaki, W. Hollik]

ZA production in vector-boson scattering at NLO QCD [F. Campanario, M. Kerner, D. Zeppenfeld]

NNLO predictions for Z-boson pair production at the LHC [G. Heinrich, S. Jahn, SJ, M. Kerner, J. Pires]

NNLO QCD predictions for single jet inclusive production at the LHC [J. Currie, E.W.N. Glover, J. Pires]

Part 2: Precision studies

NLO and off-shell effects in top quark mass determinations
[G.Heinrich, A.Maier, R.Nisius, J.Schlenk, M.Schulze, L.Scyboz, J.Winter]

NLO predictions for Higgs boson pair production matched to parton showers
[G. Heinrich, SJ, M. Kerner, G. Luisoni, E. Vryonidou]

Parton Shower and NLO-Matching uncertainties in Higgs Boson Pair Production [SJ, S.Kuttimalai]

Reconciling EFT and hybrid calculations of the light MSSM Higgs-boson mass
[H. Bahl, T. Hahn, S. Heinemeyer, W. Hollik, G. Weiglein]

Part 3: Tools

pySecDec: a toolbox for the numerical evaluation of multi-scale integrals
[S. Borowka, G. Heinrich, S. Jahn, SJ, M. Kerner, J. Schlenk, T. Zirke]

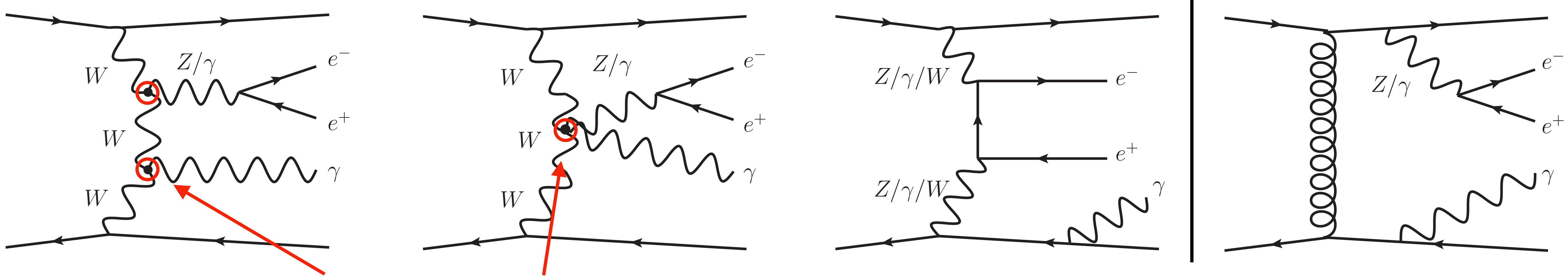
Loopedia: a Database for Loop Integrals
[C. Bogner, S. Borowka, T. Hahn, G. Heinrich, SJ, M. Kerner, A. von Manteuffel, M. Michel, E. Panzer, V. Papara]

Part 1: Calculations

1) NLO QCD Vector Boson Scattering

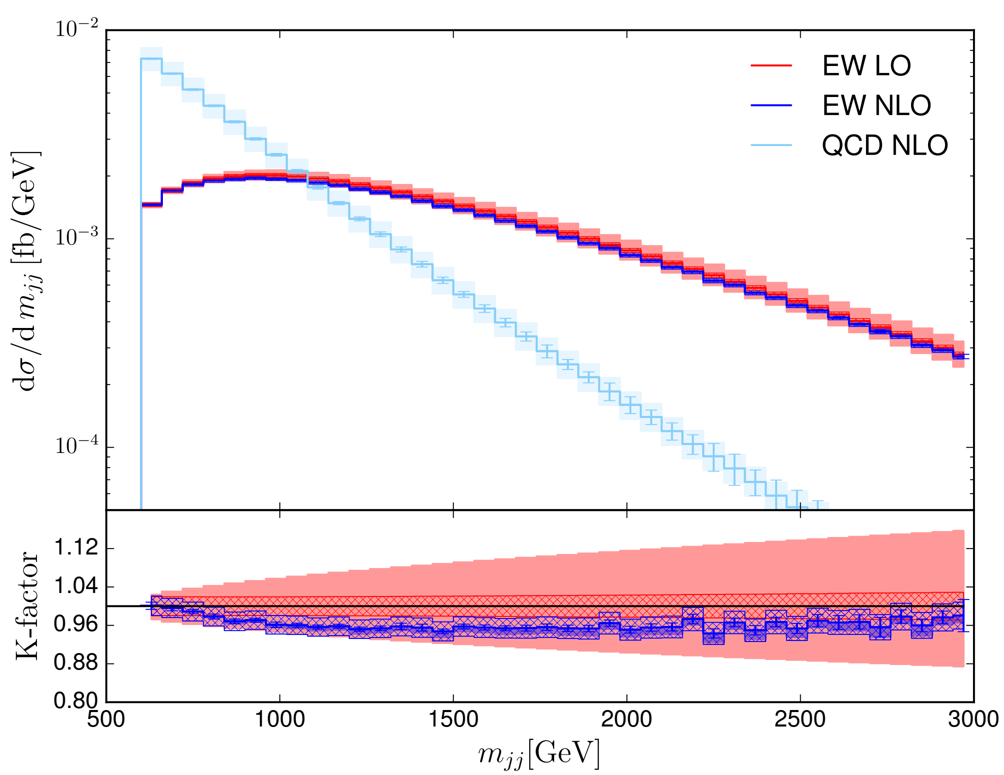
[F. Campanario, M. Kerner, D. Zeppenfeld]

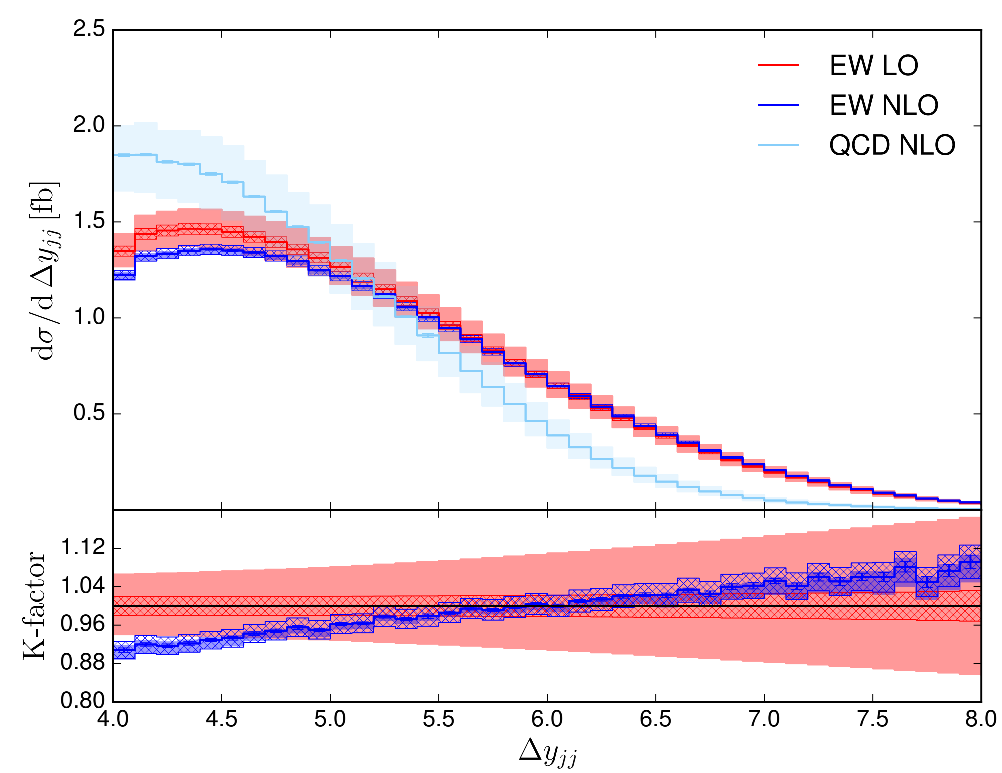
EW production (VBS) | QCD production



sensitivity to triple/quartic gauge couplings

→ important test of EW symmetry breaking mechanism





NLO QCD corrections: significant reduction of scale uncertainty effects of modified gauge couplings investigated using EFT approach

e.g. dimension-8 operator $\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$ (with $U_Y(1)$ gauge field, $\widehat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu}$)

anomalous gauge couplings lead to unitarity violation for large $s = m^2_{Z\gamma}$

Unitarity restored by:

- higher-dimensional operators in UV-complete models
- form factors in model-independent approach

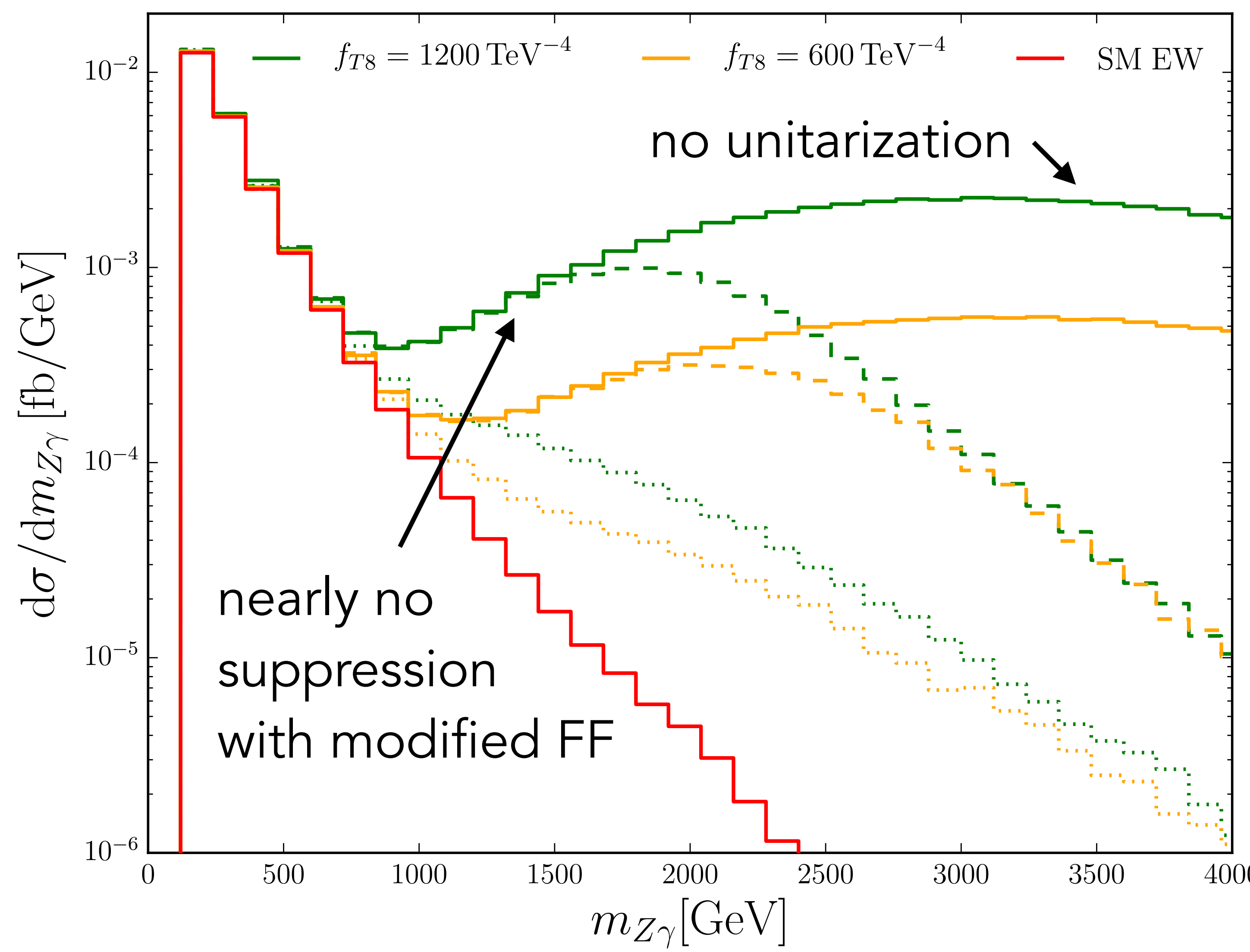
- commonly used form factor: dipole form factor (dotted lines)

$$\mathcal{F}(s) = \left(1 + \frac{s}{\Lambda^2_{FF}}\right)^{-2}$$

- new, modified form factor (dashed lines)

$$\mathcal{F}^c(s) = \left(1 - i\frac{s^2}{{\Lambda^c_{FF}}^4}\right)^{-1}$$

leads to smaller suppression without violating unitarity



2) NNLO Z-boson pair production

[G. Heinrich, S. Jahn, SJ, M. Kerner, J. Pires]

Computed NNLO QCD ZZ production using the "N-Jettiness" method
NNLO calculations consists of several separately divergent pieces

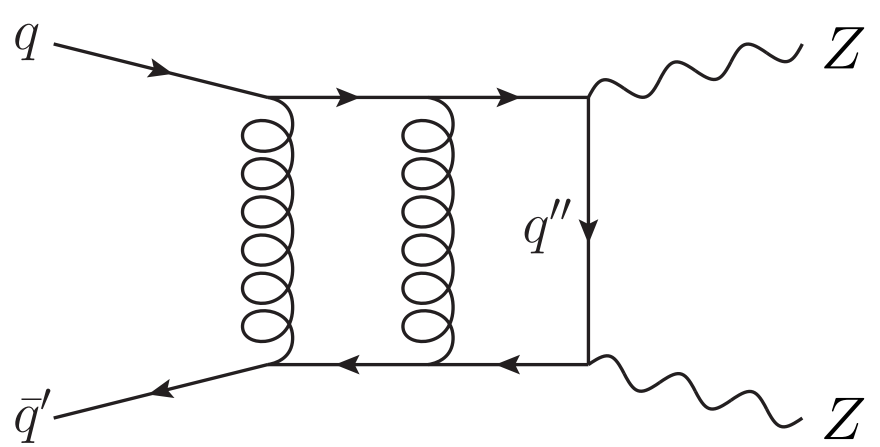


Fig: Gehrmann, von Manteuffel Tancredi 15

NNLO contributions	perturbative order	
$0 \to qZZgg\bar{q}$	tree-level	VBFNLO [1]
$0 \to qZZQ\bar{Q}\bar{q}$	tree-level	
$0 \to qZZg\bar{q}$	one-loop	GOSAM [2]
$0 \to ggZZ$	one-loop	
$0 \to q\bar{q}ZZ$	two-loop	QQVVAMP [3]

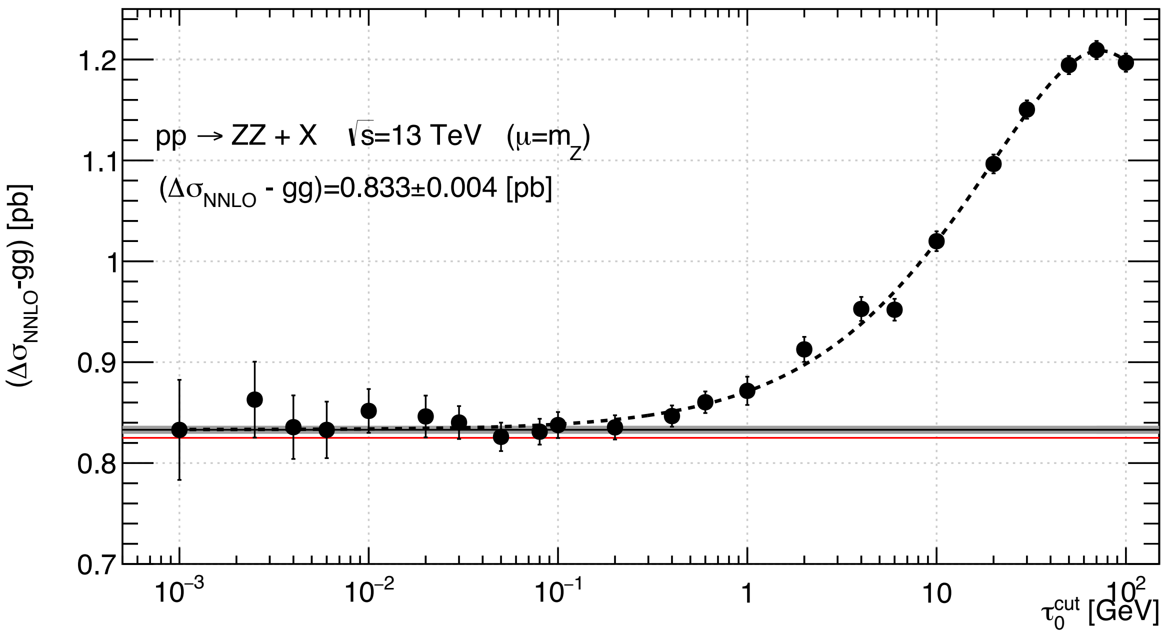
[1] Baglio et al. 11, [2] Cullen 12,14
[3] Gehrmann, von Manteuffel Tancredi 15

N-Jettiness:

$$\mathcal{T}_0 = Q\,\tau_0 = \sum_k \min\left\{e^{Y_{ZZ}} n_a \cdot p_k, e^{-Y_{ZZ}} n_b \cdot p_k\right\}$$

Slice phase space into regions based based on $\mathcal{T}_0$, for small $\mathcal{T}_0$ soft/collinear emissions can be approximated using SCET. Limit $\mathcal{T}_0^{\text{cut}} \to 0$ gives full result.

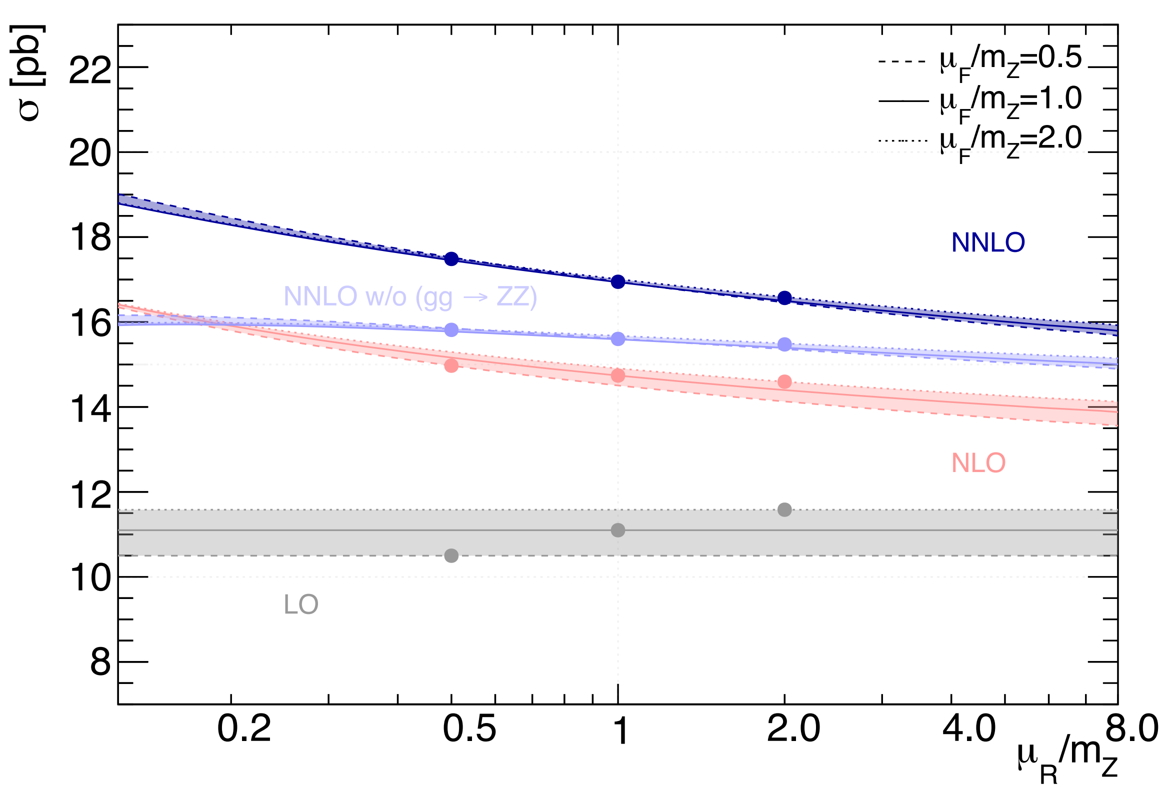
$$\begin{aligned}\sigma_{NNLO} &= \int \mathrm{d}\Phi_N \, |\mathcal{M}_{VV}|^2 + \int \mathrm{d}\Phi_{N+1} \, |\mathcal{M}_{RV}|^2 \, \theta_0^{<} \\ &+ \int \mathrm{d}\Phi_{N+2} \, |\mathcal{M}_{RR}|^2 \, \theta_0^{<} + \int \mathrm{d}\Phi_{N+1} \, |\mathcal{M}_{RV}|^2 \, \theta_0^{>} \\ &+ \int \mathrm{d}\Phi_{N+2} \, |\mathcal{M}_{RR}|^2 \, \theta_0^{>} \\ &\equiv \sigma_{NNLO}(\mathcal{T}_0 < \mathcal{T}_0^{cut}) + \sigma_{NNLO}(\mathcal{T}_0 > \mathcal{T}_0^{cut}) \,.\end{aligned}$$

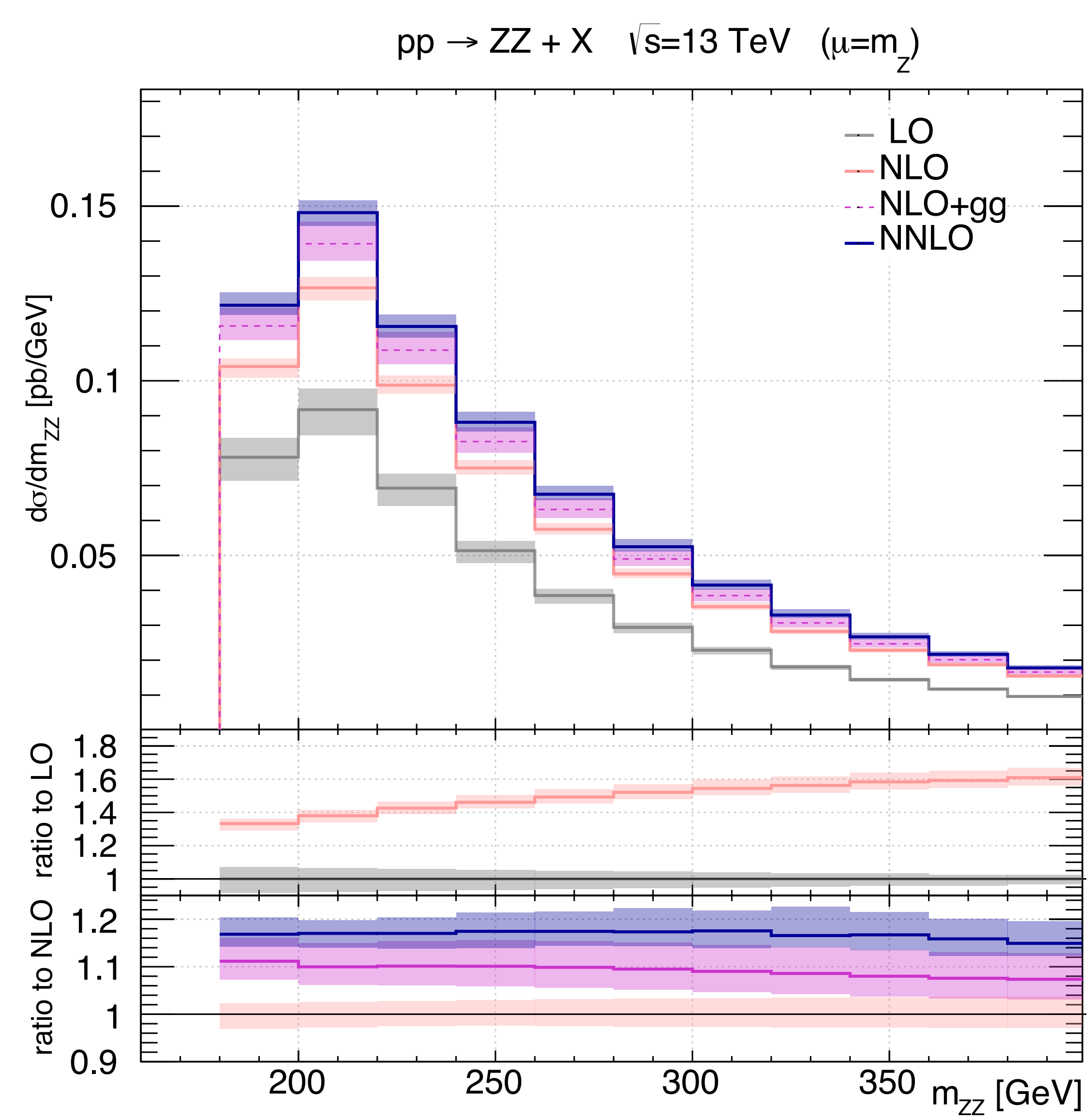


	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]
Our Result	$9.890^{+4.9\%}_{-6.1\%}$	$14.508^{+3.0\%}_{-2.4\%}$	$16.92^{+3.2\%}_{-2.6\%}$
ATLAS	$17.3 \pm 0.6(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.6(\text{lumi.})$		
CMS	$17.2 \pm 0.5(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.4(\text{theo.}) \pm 0.4(\text{lumi.})$		

NNLO corrections move theory prediction towards ATLAS/CMS measurements

Large part of the NNLO result comes from the opening up of the gluon channel



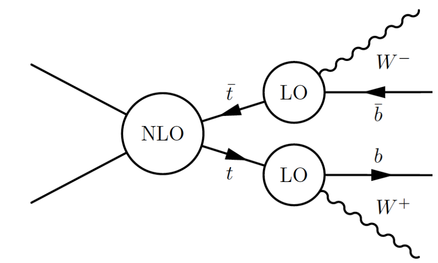


Part 2: Precision studies

1) Top quark mass determinations

[G. Heinrich, A. Maier, R. Nisius, J. Schlenk, M. Schulze, L. Scyboz, J. Winter]

- Compare different theory descriptions of top quark pair production
- Assess impact on top quark mass determinations



$\mathbf{NLO^{LOdec}_{NWA}}$: NLO $t\bar{t}$ production $\otimes$ LO decay

$\mathbf{NLO^{NLOdec}_{NWA}}$: NLO $t\bar{t}$ production $\otimes$ NLO decay

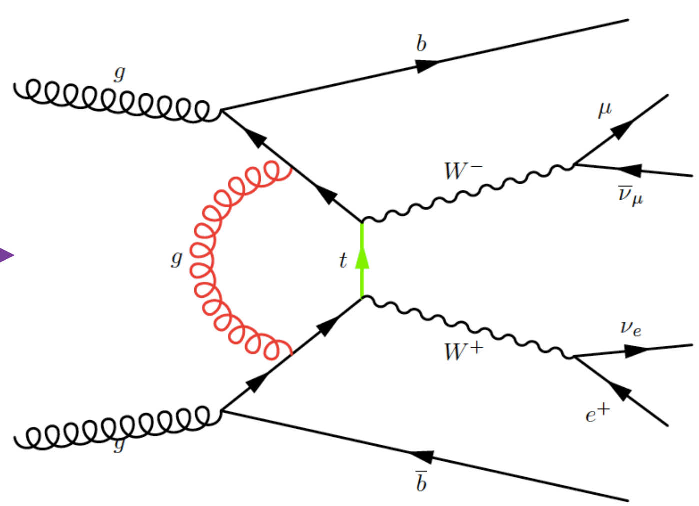
} narrow width approximation

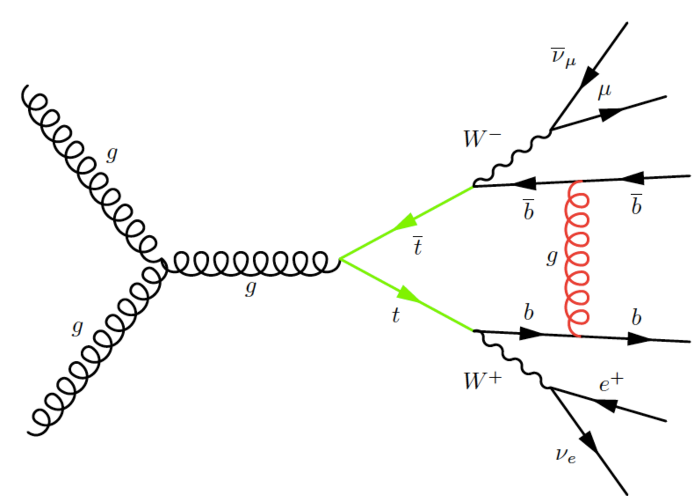
$\mathbf{NLO_{PS}}$: NLO $t\bar{t}$ production $\otimes$ decay via parton showering

$\mathbf{NLO_{full}}$: $pp \to W^+W^-b\bar{b} \to (e^+\nu_e)\,(\mu^-\bar{\nu}_\mu)\,b\bar{b}$ at NLO

↓ contains e.g.

non-resonant →



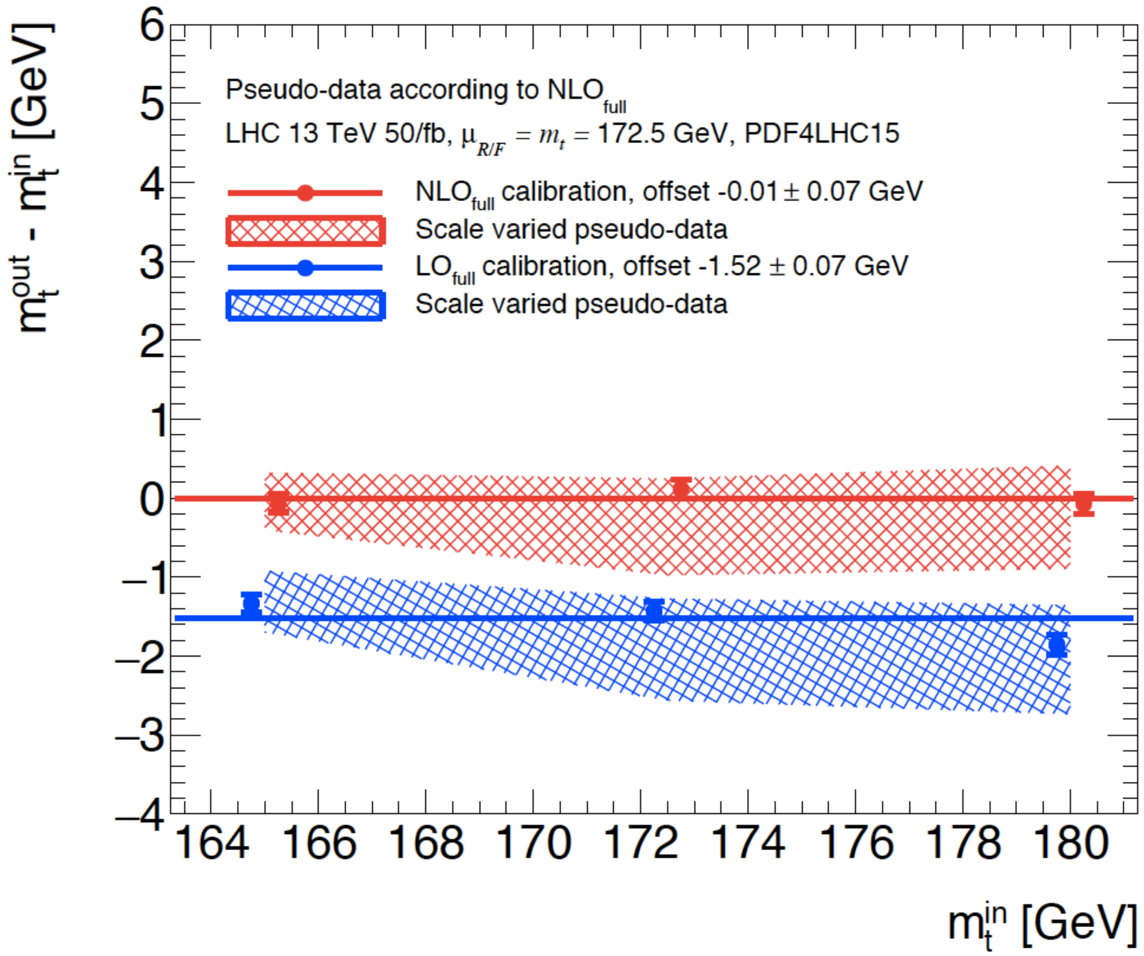


← non-factorising

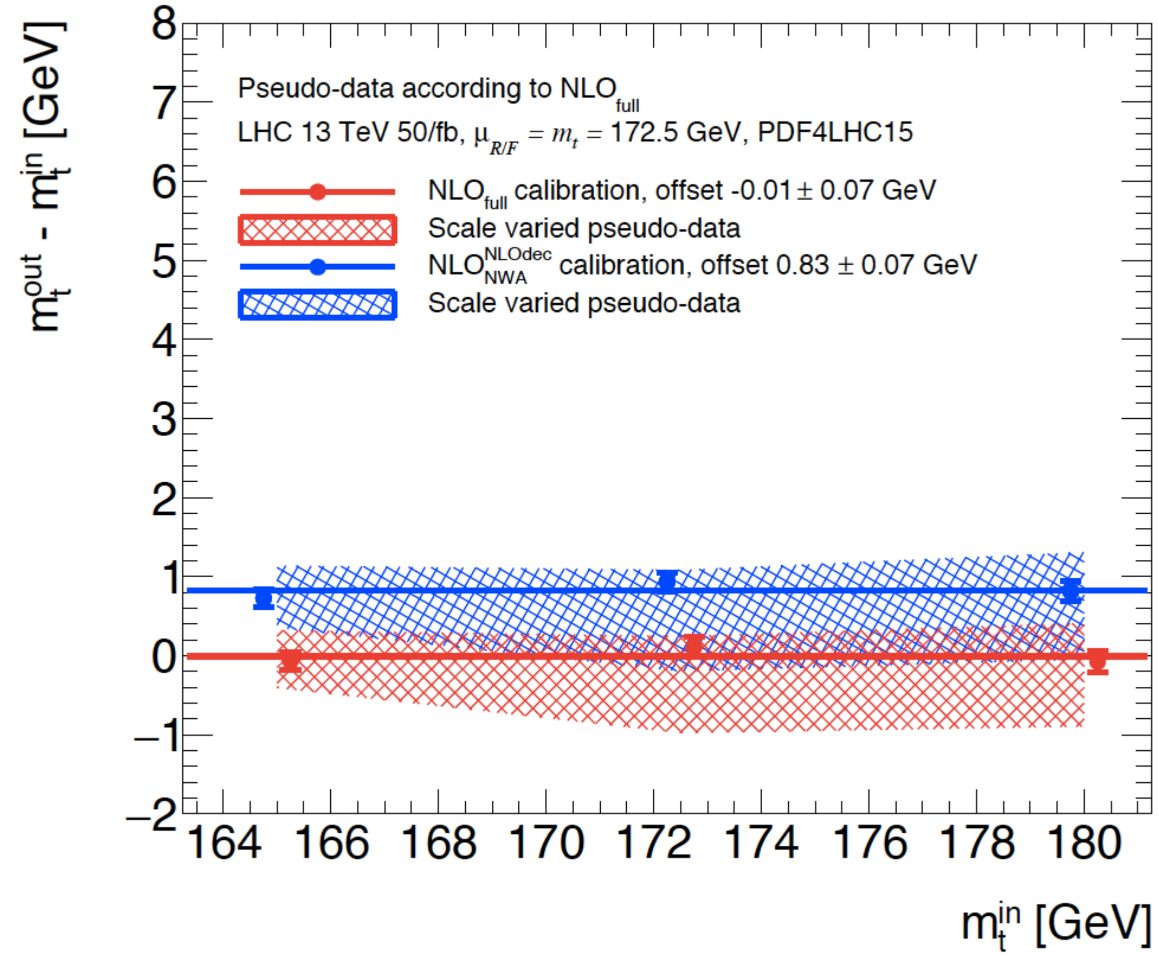
Generate pseudo-data according to $\mathbf{NLO_{full}}$

Use theory descriptions to calibrate template fit functions

Determine off-set in top mass determination



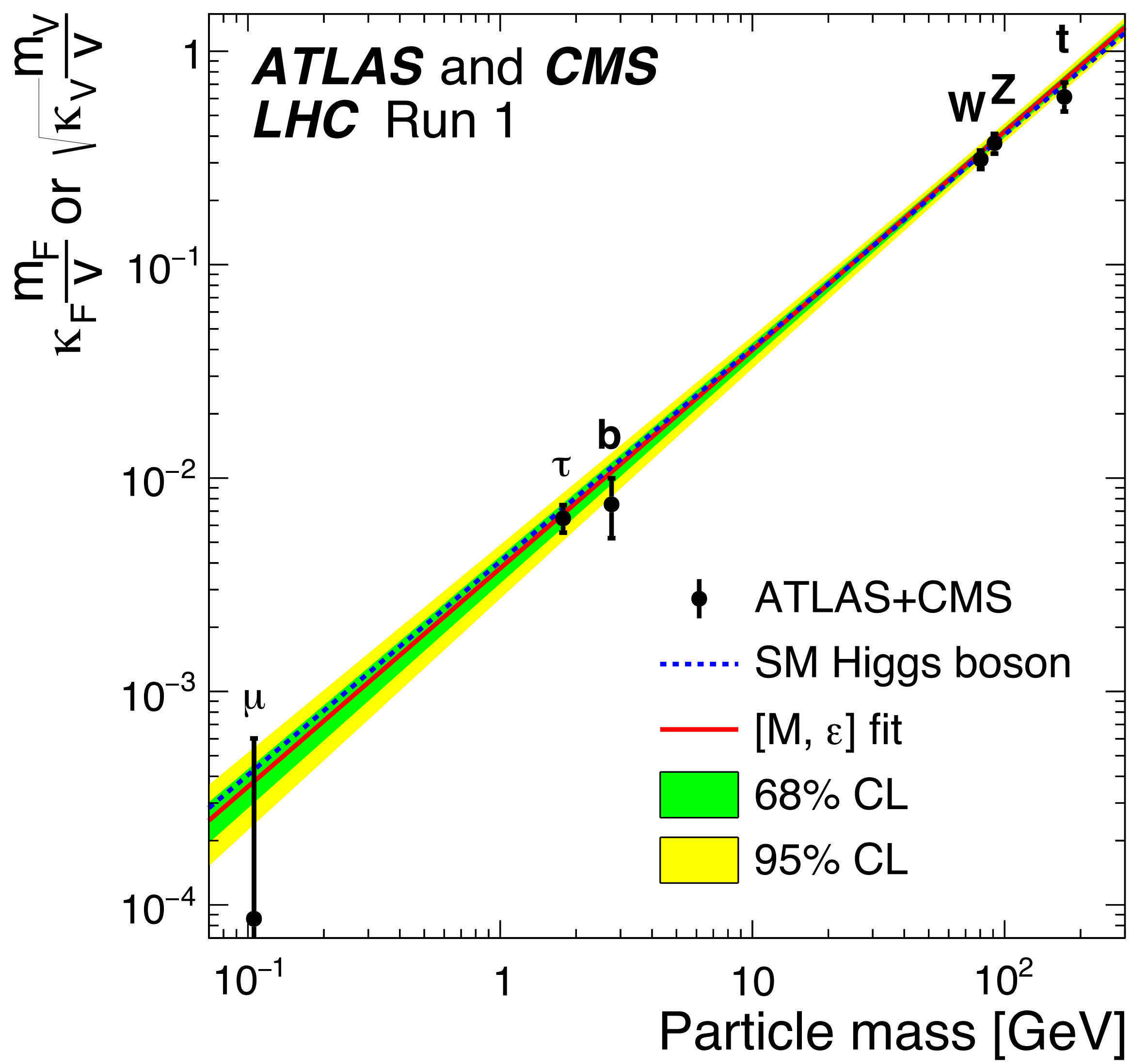
Offset $-1.52 \pm 0.07\,\mathrm{GeV}$ with templates based on LO $W^+W^-b\bar{b}$



Offset $0.83 \pm 0.07\,\mathrm{GeV}$ with templates based on $\mathbf{NLO_{NWA}^{NLOdec}}$

NLO corrections to decay more important than non-factorising/non-resonant contributions

2) NLO Higgs boson pair production + PS



So far, measured Higgs couplings agree with the Standard Model

But: Higgs self coupling not yet well constrained

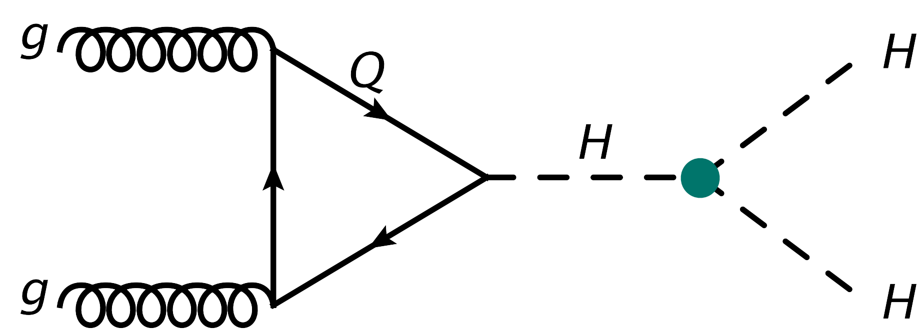
SM Lagrangian:

$$\mathcal{L} \supset -V(\Phi), \quad V(\Phi) = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

EW sym. breaking

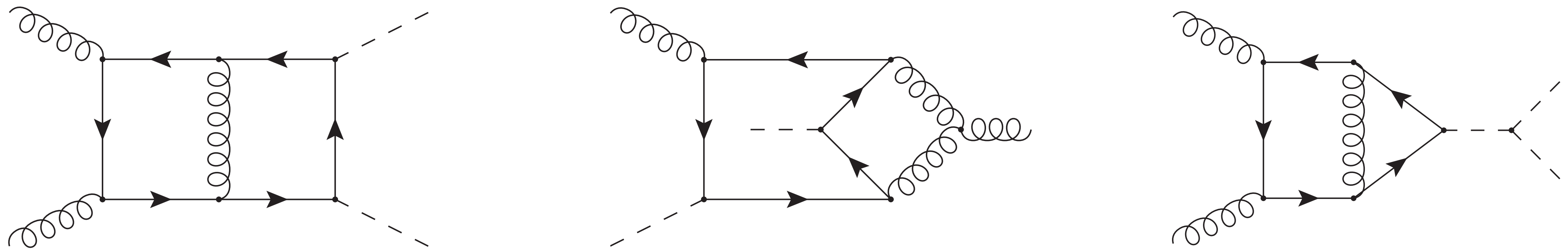
$$\frac{m_H^2}{2}H^2 + \boxed{\frac{m_H^2}{2v}H^3} + \frac{m_H^2}{8v^2}H^4$$

Higgs pair production probes triple-Higgs coupling



Computed NLO QCD (2-loop) corrections to HH production (2016)

[S. Borowka, N. Greiner, G. Heinrich, SJ, M. Kerner, J. Schlenk, U. Schubert, T. Zirke]

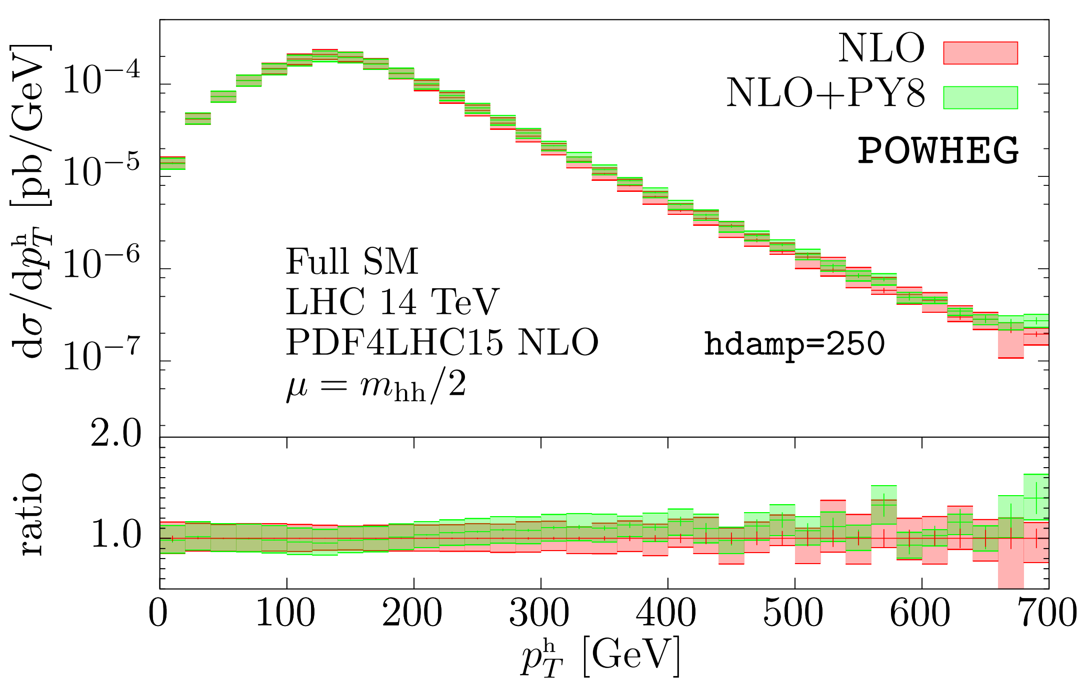


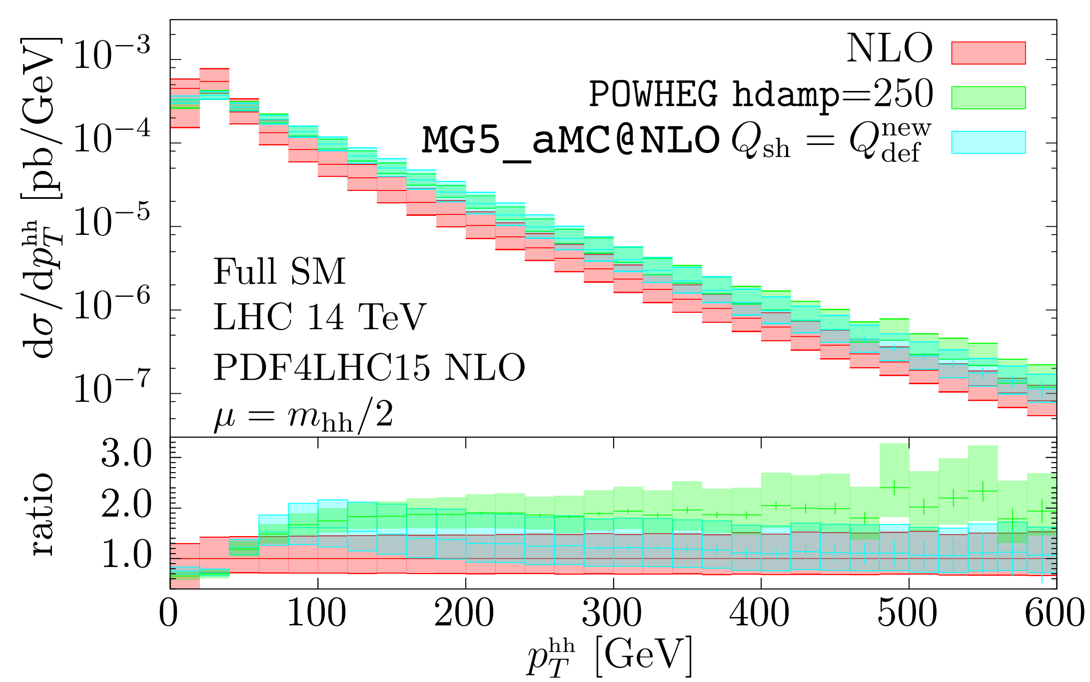
Interfaced to 2 public Monte-Carlo codes (**POWHEG**, **MG5_aMC@NLO**)

- assess impact of NLO matching schemes/parton shower
- full result made available for use by LHC experiments

Large for p_T^{hh}

[G. Heinrich, SJ, M. Kerner, G. Luisoni, E. Vryonidou]



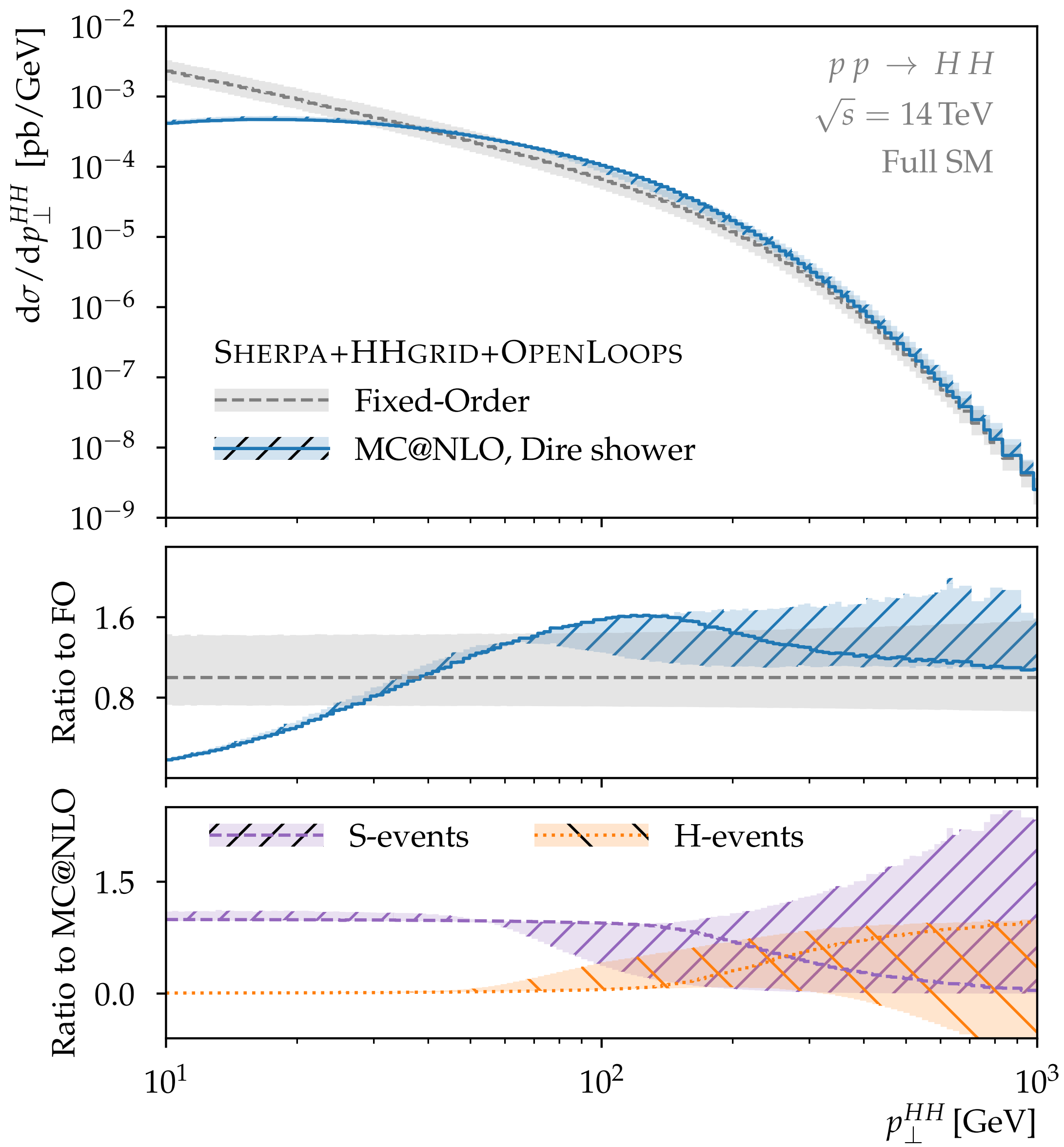


3) NLO matching uncertainties in HH production

[SJ, S. Kuttimalai]

Interfaced NLO HH to a further Monte-Carlo code (SHERPA)

Studied in more detail the matching uncertainties for p_T^{hh} :



$$\langle \mathcal{O} \rangle = \int \left[\bar{B}(\phi_B) - B(\phi_B) \right] \frac{D(\phi_B, \phi_1)}{B(\phi_B)} \Theta(\mu_{\rm PS}^2 - t) \mathcal{O}(\phi_R)\, d\phi_B\, d\phi_1 + \int R(\phi_R) \mathcal{O}(\phi_R)\, d\phi_R.$$

Cancellation spoiled if:

- Large NLO corrections ($\bar{B} - B$)
- Splitting kernels (D) numerically large compared to real radiation
- Phase space accessible to the PS

All features present for HH production

4) Precise prediction of MSSM Higgs Boson Mass

[H. Bahl, T. Hahn, S. Heinemeyer, W. Hollik, G. Weiglein]

- for low scales, fixed-order calculation precise
- for high scales, EFT calculation precise

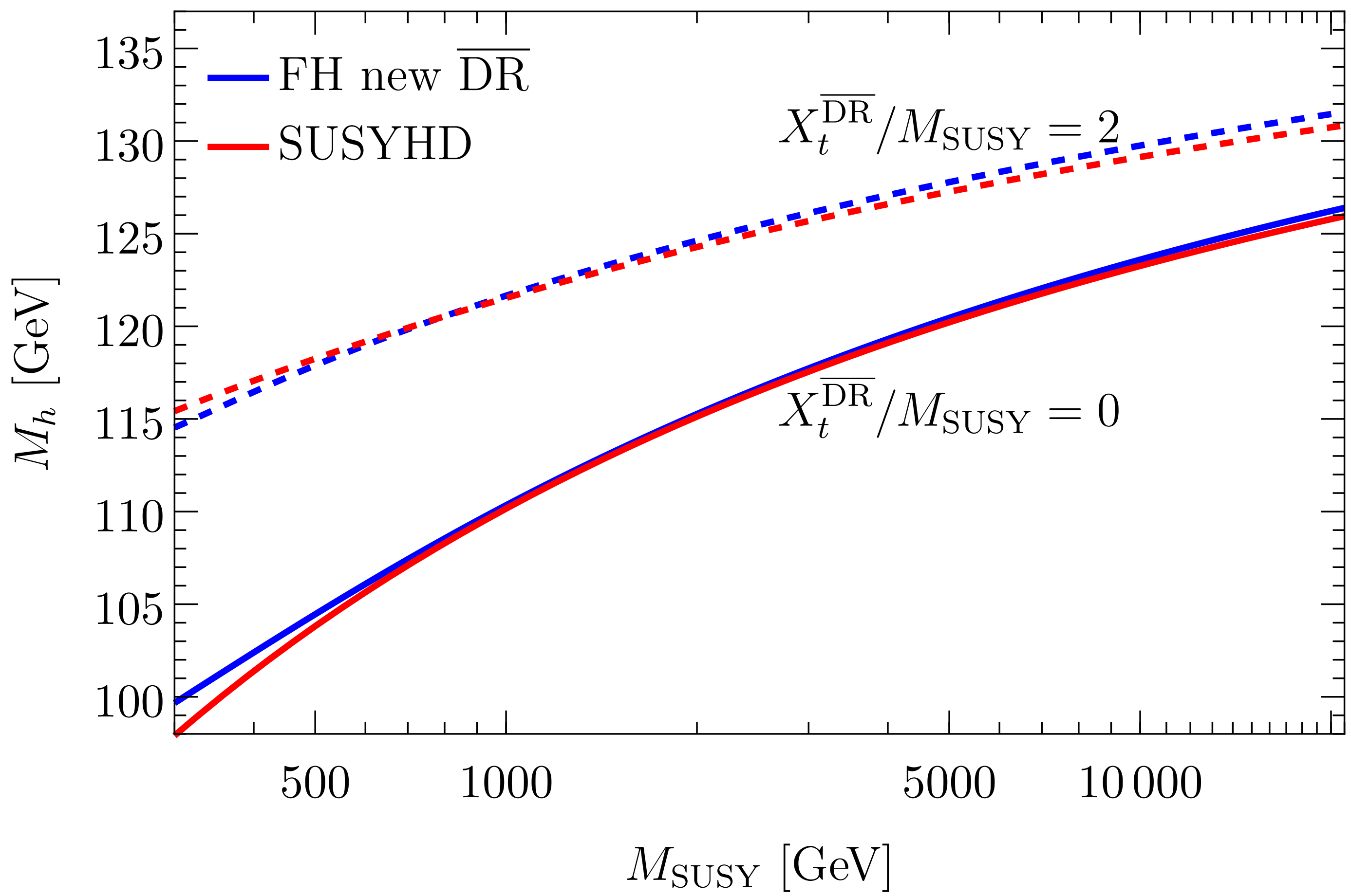
$\Rightarrow$ combine both for precise prediction for all scales (`FeynHiggs`)

but for high scale discrepanies with pure EFT calculation observed

Two main origins found:

- Naive scheme conversion not adequate
- Terms induced by pole determination

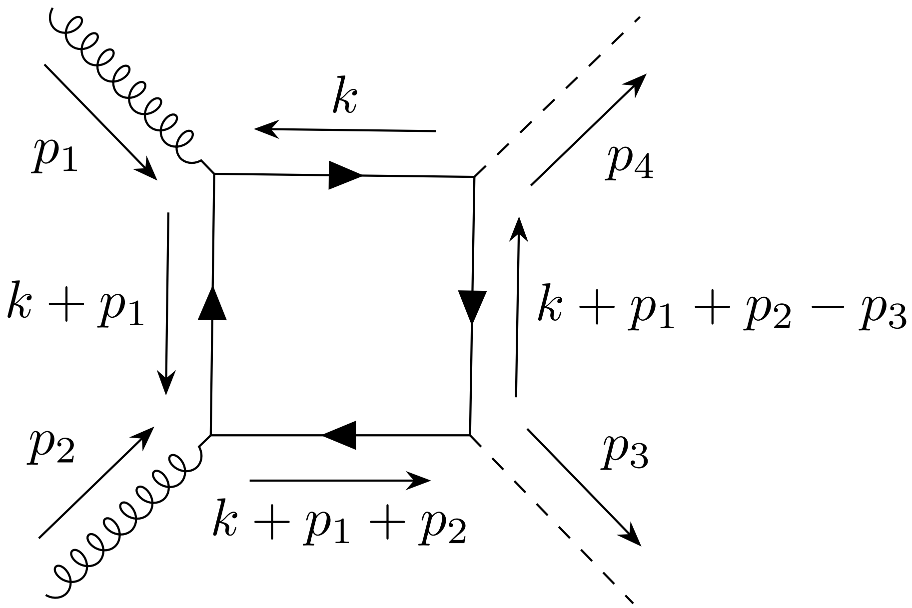
improved in `FeynHiggs 2.14.0`



Part 3: Tools

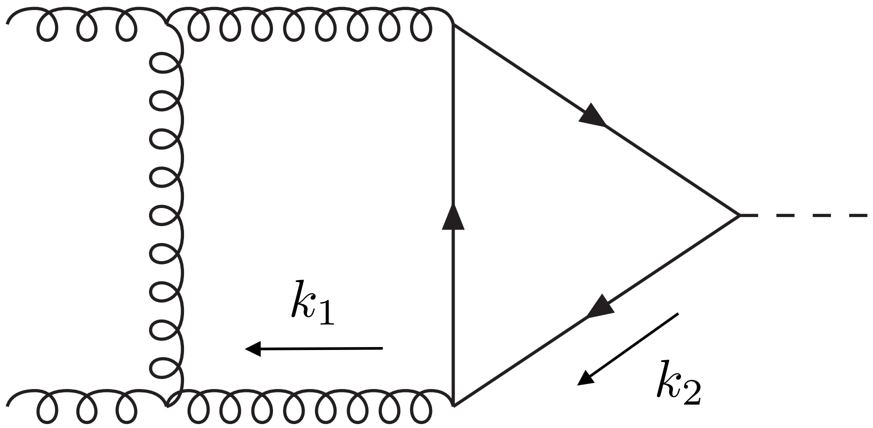
A short aside on loop integrals...

Loops ≡ # Unconstrained Momenta ↔ # of Integrations



$$\sim \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \frac{1}{D_1 D_2 D_3 D_4}$$

$$D_1 = k^2 - m^2$$
$$D_2 = (k + p_1)^2 - m^2$$
$$D_3 = (k + p_1 + p_2)^2 - m^2$$
$$D_4 = (k + p_1 + p_2 - p_3)^2 - m^2$$



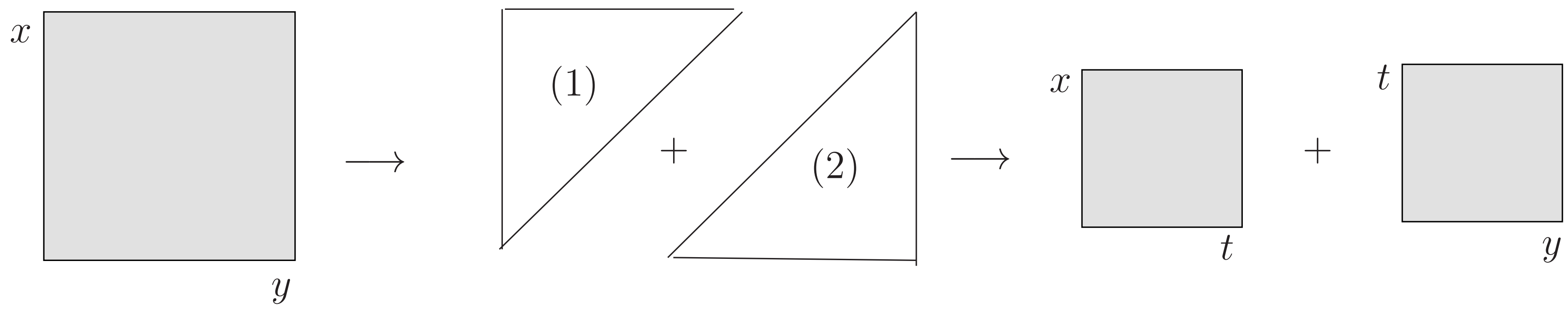
$$\sim \int \frac{\mathrm{d}^4 k_1}{(2\pi)^4} \int \frac{\mathrm{d}^4 k_2}{(2\pi)^4} \frac{1}{P_1 P_2 P_3 P_4 P_5 P_6}$$

Computing multi-loop integrals can be hard (often case-by-case)

1) pySecDec

[S. Borowka, G. Heinrich, S. Jahn, SJ, M. Kerner, J. Schlenk, T. Zirke]

A toolbox for the numerical evaluation of multi-scale integrals (e.g. loop integrals), successor of SecDec 3



Written in **`python`** & **`c++`** using only open source software

Many new features and improvements:

- Arbitrary number of regulators (not just ϵ)
- Improvements to handling of integrals without Euclidean region
- Generates **`c++`** Library (can be linked to your own program)

Download pySecDec: https://github.com/mppmu/secdec
Read the docs: https://secdec.readthedocs.io

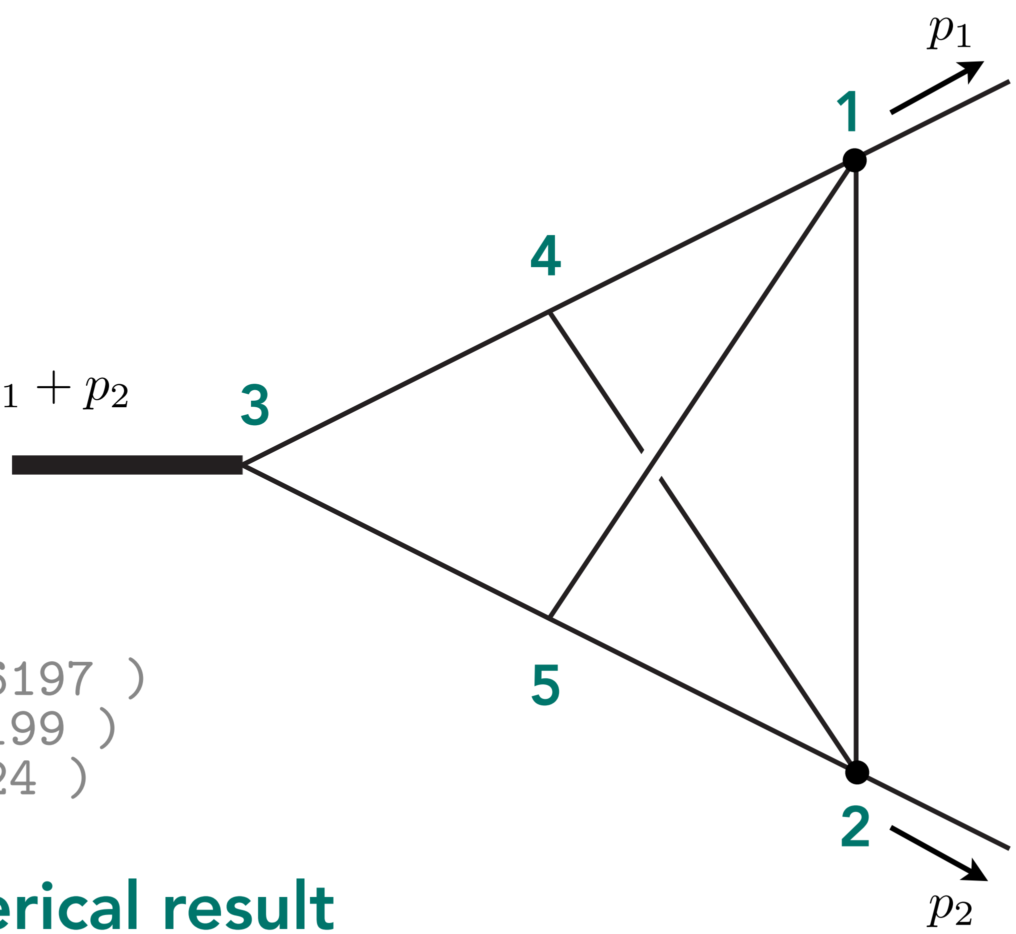
Example: Computing a loop integral with pySecDec

```
from pySecDec.loop_integral import loop_package
import pySecDec as psd
li = psd.loop_integral.LoopIntegralFromGraph(
  internal_lines = [ [0,[1,2]], [0,[1,4]], [0,[1,5]], [0,[2,4]],
                     [0,[2,5]], [0,[3,4]], [0,[3,5]] ],
  external_lines = [['p1',1],['p2',2],['p3',3]],
  replacement_rules = [ ('p1*p1',0), ('p2*p2',0), ('p3*p3','-1'),
                        ('p1*p2','-1/2'), ('p2*p3','1/2'),
                        ('p1*p3','1/2')
                    ]
)
loop_package(
  name = 'triangle3L',
  loop_integral = li,
  real_parameters = [],
  additional_prefactor = '(-eps*gamma(-eps))**3',
  requested_order = 4,
  contour_deformation = False
)
```

Mass of edge

Adjacency list

Kinematics



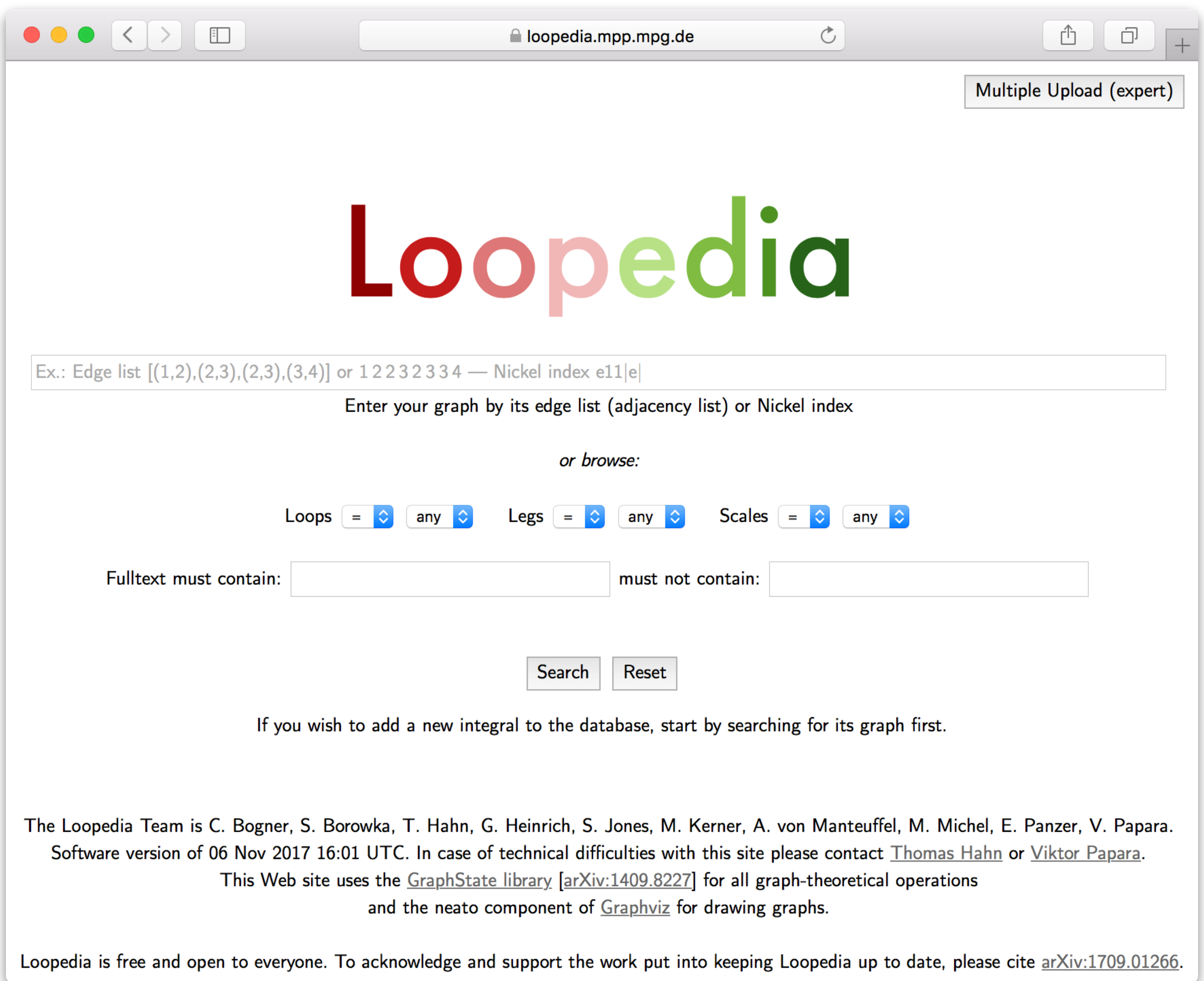

```
$ python generate_triangle3L.py
$ make -C triangle3L
$ time python integrate_triangle3L.py
eps^0: -34.101438860667699 +/- ( 0.029099904446653619 7 )
eps^1: -295.960848811477547 +/- ( 0.265576787789600199 )
eps^2: -2053.19955045435336 +/- ( 1.657607606231547 24 )
<skipped output>
  real        0m1.895s
```

Numerical result

2) Loopedia

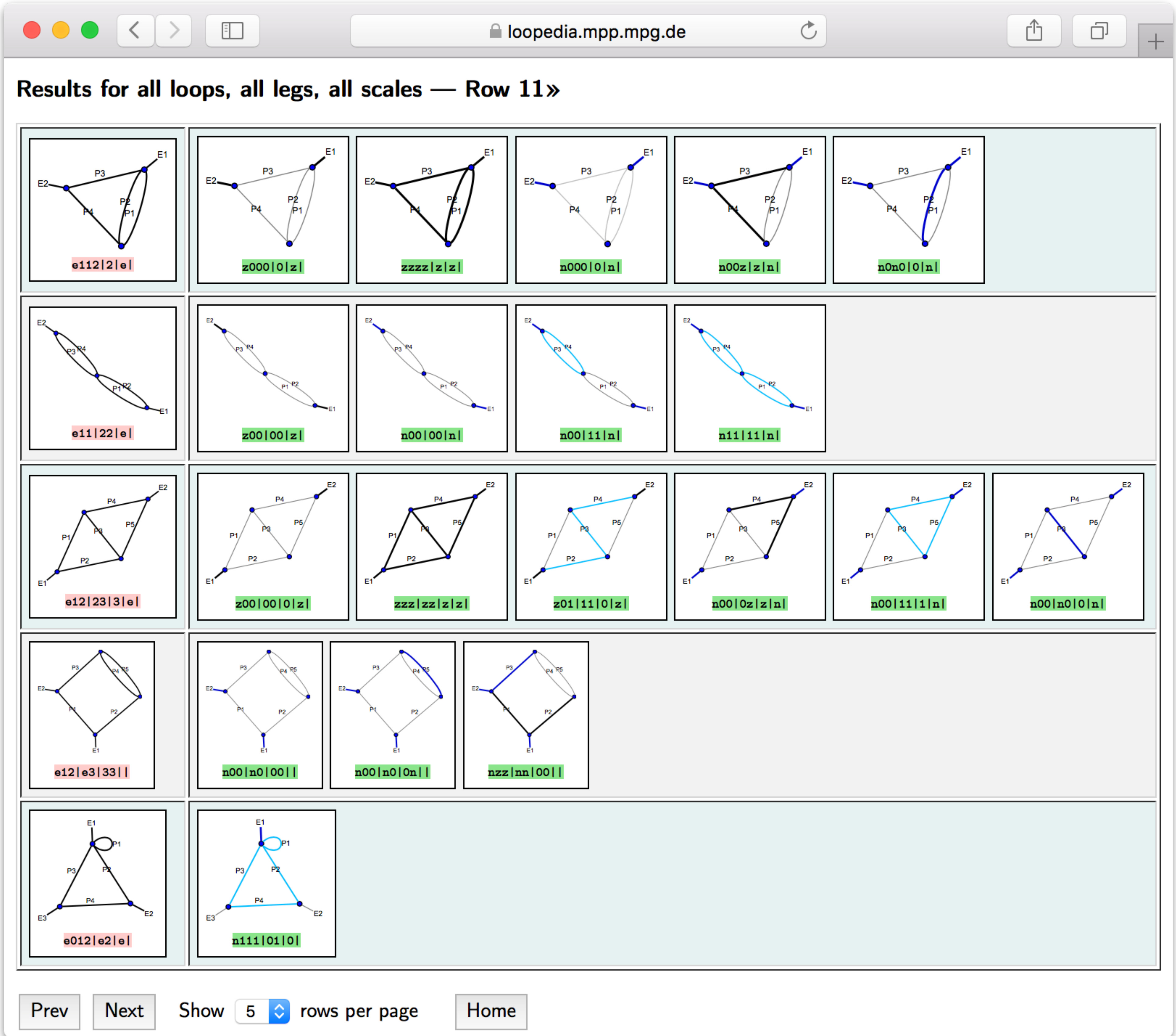
[C. Bogner, S. Borowka, T. Hahn, G. Heinrich, SJ, M. Kerner,
A. von Manteuffel, M. Michel, E. Panzer, V. Papara]

Loopedia is a new database for loop integrals at www.loopedia.org:



- indexed by graph-theoretical properties
- can hold bibliographic but also other information, (e.g. results in some machine-readable format)
- slim CGI design, Unix filesystem doubles as database

Graph Browser:



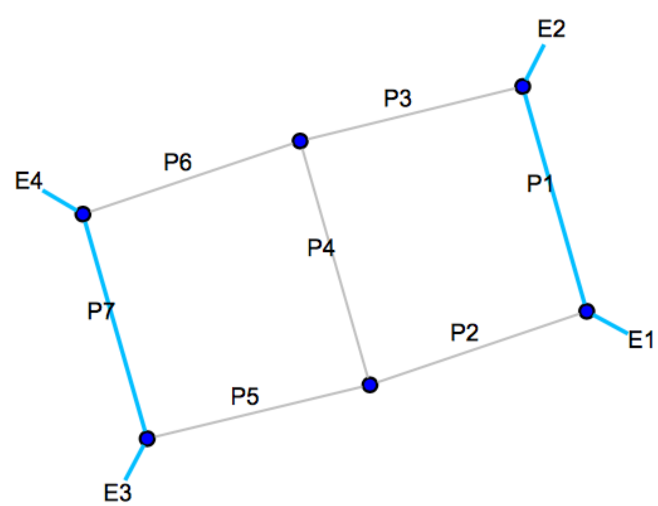
Record Viewer:

loopedia.mpp.mpg.de

Graph e12|e3|34|5|e5|e| — Masses 110|10|00|0|11|1|

Edit • : • | Edit • | Browse • : * | Home

Edge list:	(e,0|1) (0,1|1) (0,2|0) (e,1|1) (1,3|0) (2,3|0) (2,4|0) (3,5|0) (e,4|1) (4,5|1) (e,5|1)
Nickel index:	e12|e3|34|5|e5|e|:110|10|00|0|11|1|
Database path:	2/4/7/e12|e3|34|5|e5|e|/3/110|10|00|0|11|1|



Propagator P1 m = m1
Propagator P2 m = 0
Propagator P3 m = 0
Propagator P4 m = 0
Propagator P5 m = 0
Propagator P6 m = 0
Propagator P7 m = m1

External Leg E1 $q^2 = m1^2$
External Leg E2 $q^2 = m1^2$
External Leg E3 $q^2 = m1^2$
External Leg E4 $q^2 = m1^2$

Choose Configuration

View public records for this configuration ↓BELOW↓ or choose different configuration ↑ABOVE↑

Reference: arXiv:1612.05609
Description: The authors compute the planar 2-loop box master integrals involved in $QQ \to QQ$, where QQ are massive external quarks using the method of differential equations.
Submitter: sophia.borowka@cern.ch

Record 1482239373.Z1Fv
added 20 Dec 2016 13:09 UTC
last modified 23 May 2017 14:07 UTC

Conclusion

Currently at MPI:

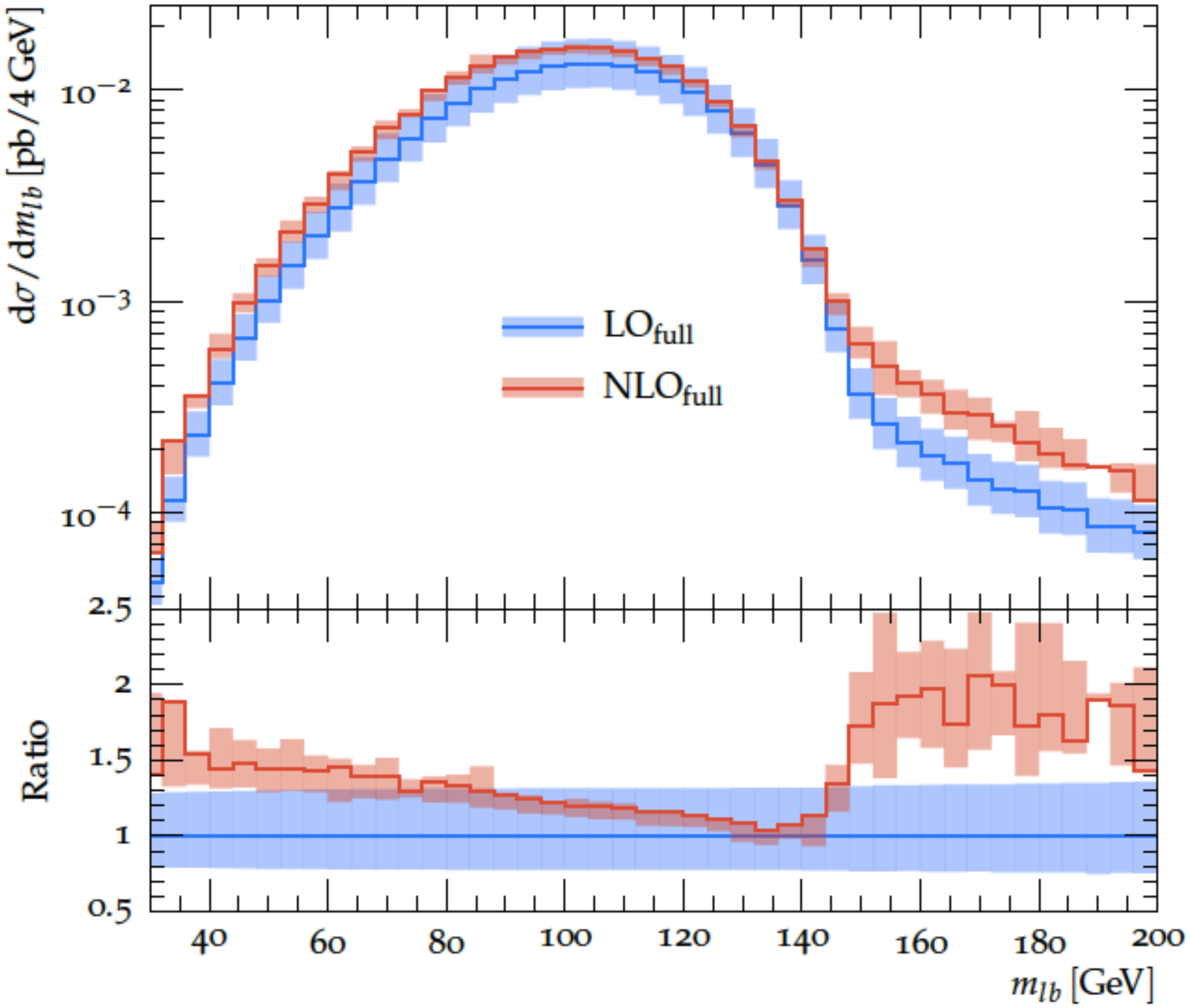
- Studying SM and BSM processes
- Producing cutting edge calculations (e.g. HH, ZZ, NNLO Jet)
- Performing precision studies with direct relevance to current and future colliders
- Collaborating with experimentalists (e.g. top quark mass measurements)
- Developing tools for the HEP community

Future:

- NLO HH EFT study
- NLO QCD Higgs + Jet (including top quark mass)
- Moving towards multi-loop automation (GoSam XLoop)
- …

Thank you for listening!

Backup



m_{lb} lepton - b-jet invariant mass

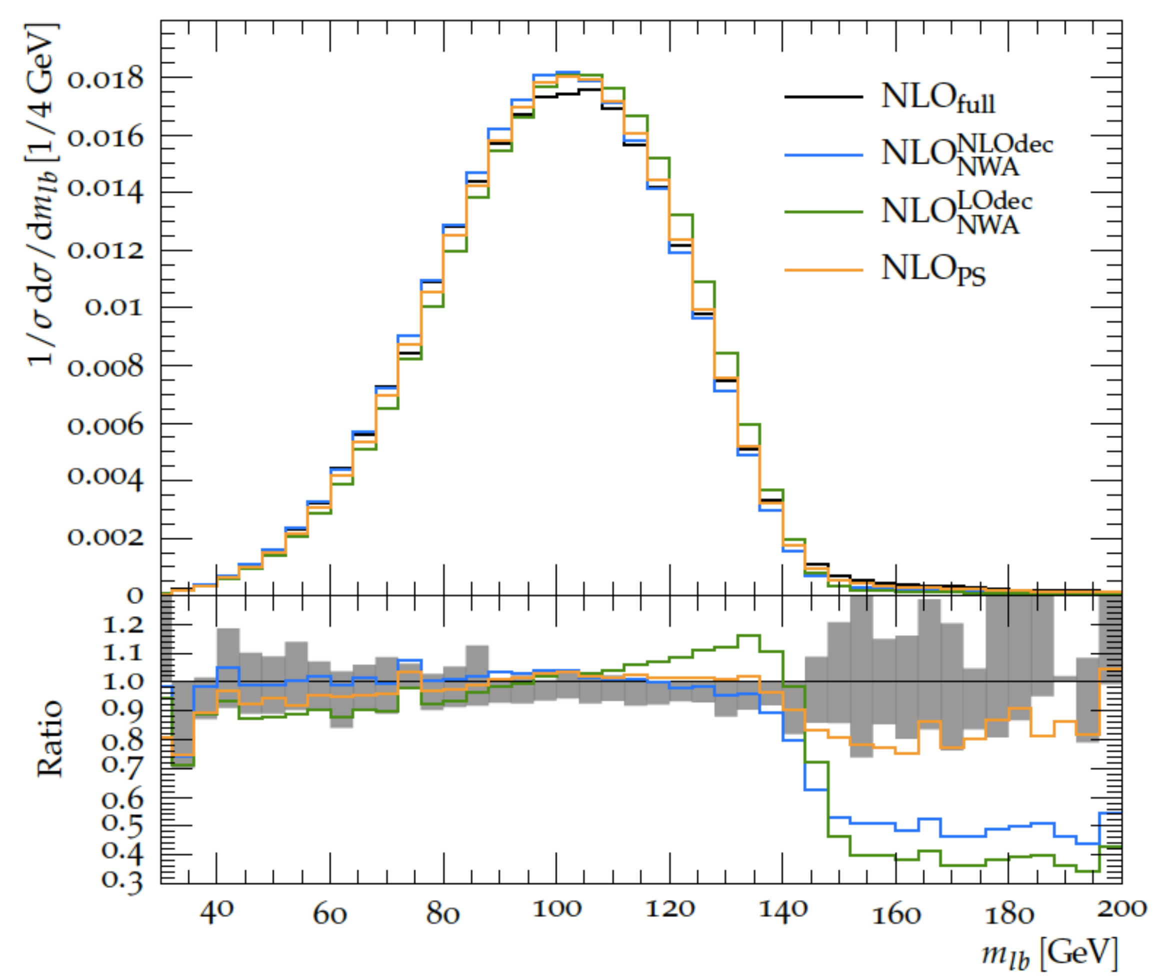
full NLO corrections introduce significant shape changes and asymmetric scale uncertainties

$\mathbf{NLO_{PS}}$ and $\mathbf{NLO_{NWA}^{NLOdec}}$

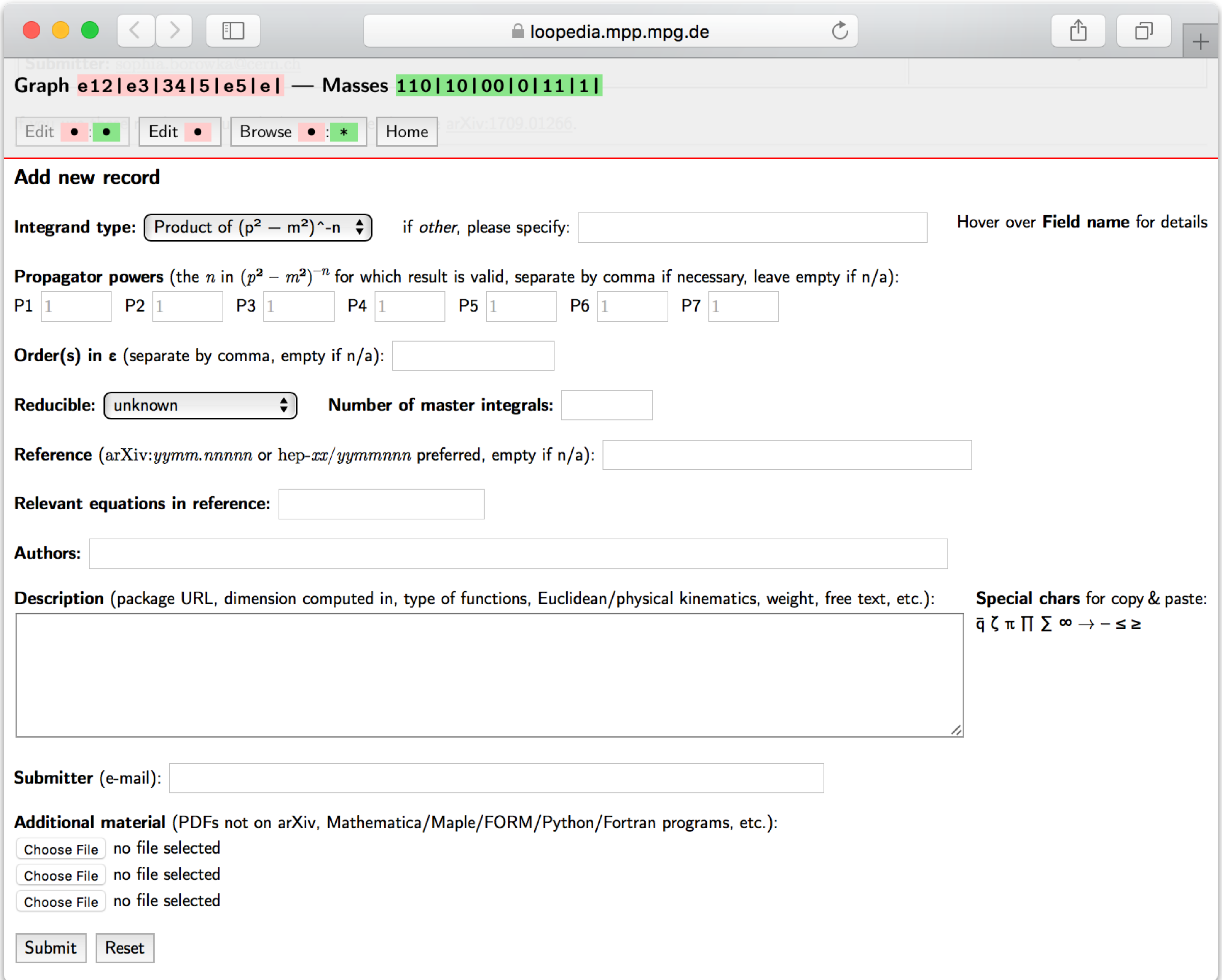
similar in the $\mathbf{NLO_{PS}}$ fit range

$$50 \text{ GeV} \leq m_{lb} \leq 150 \text{ GeV}$$

$\mathbf{NLO_{NWA}^{NLOdec}}$ closer to $\mathbf{NLO_{full}}$ than $\mathbf{NLO_{PS}}$



Loopedia New Record Form:



loopedia.mpp.mpg.de

Graph e12|e3|34|5|e5|e| — Masses 110|10|00|0|11|1|

Edit • : • | Edit • | Browse • : * | Home

Add new record

Integrand type: Product of $(p^2 - m^2)$^-n   if *other*, please specify:

Hover over **Field name** for details

Propagator powers (the n in $(p^2 - m^2)^{-n}$ for which result is valid, separate by comma if necessary, leave empty if n/a):

P1 1   P2 1   P3 1   P4 1   P5 1   P6 1   P7 1

Order(s) in ε (separate by comma, empty if n/a):

Reducible: unknown   **Number of master integrals:**

Reference (arXiv:*yymm.nnnnn* or hep-*xx*/*yymmnnn* preferred, empty if n/a):

Relevant equations in reference:

Authors:

Description (package URL, dimension computed in, type of functions, Euclidean/physical kinematics, weight, free text, etc.):

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Additional material (PDFs not on arXiv, Mathematica/Maple/FORM/Python/Fortran programs, etc.):

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