LHC phenomenology – made in Munich

“Munich MPI Project Review 2014”.

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Max Planck Institute for Physics

Munich

LHC phenomenology – made in Munich

[Munich MPI Project Review 2014]

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– MPP Munich, Germany –

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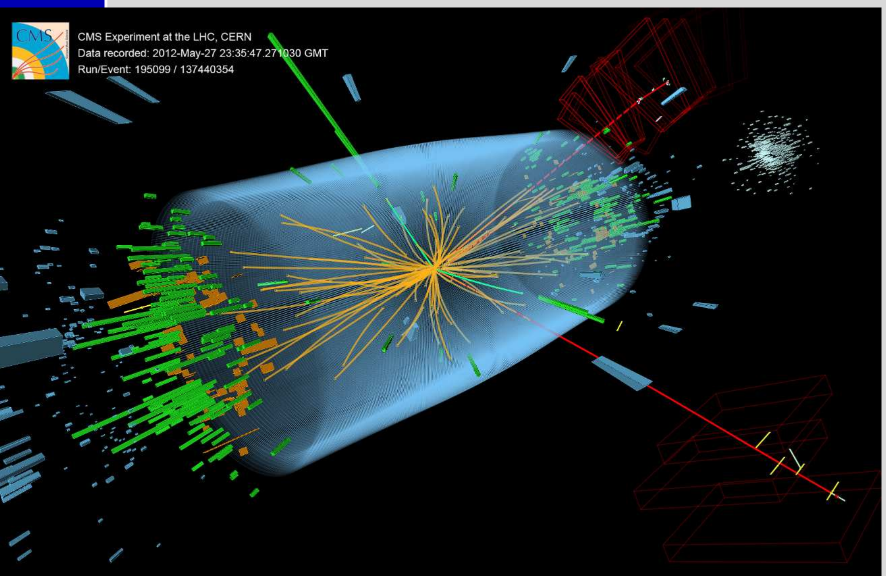
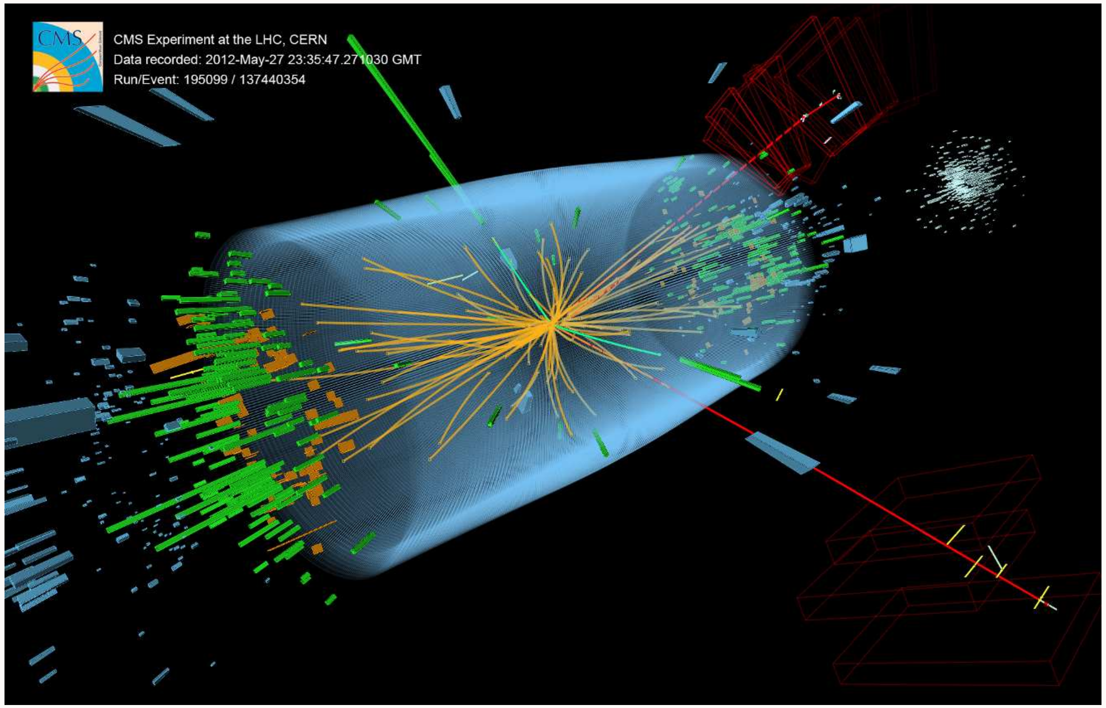
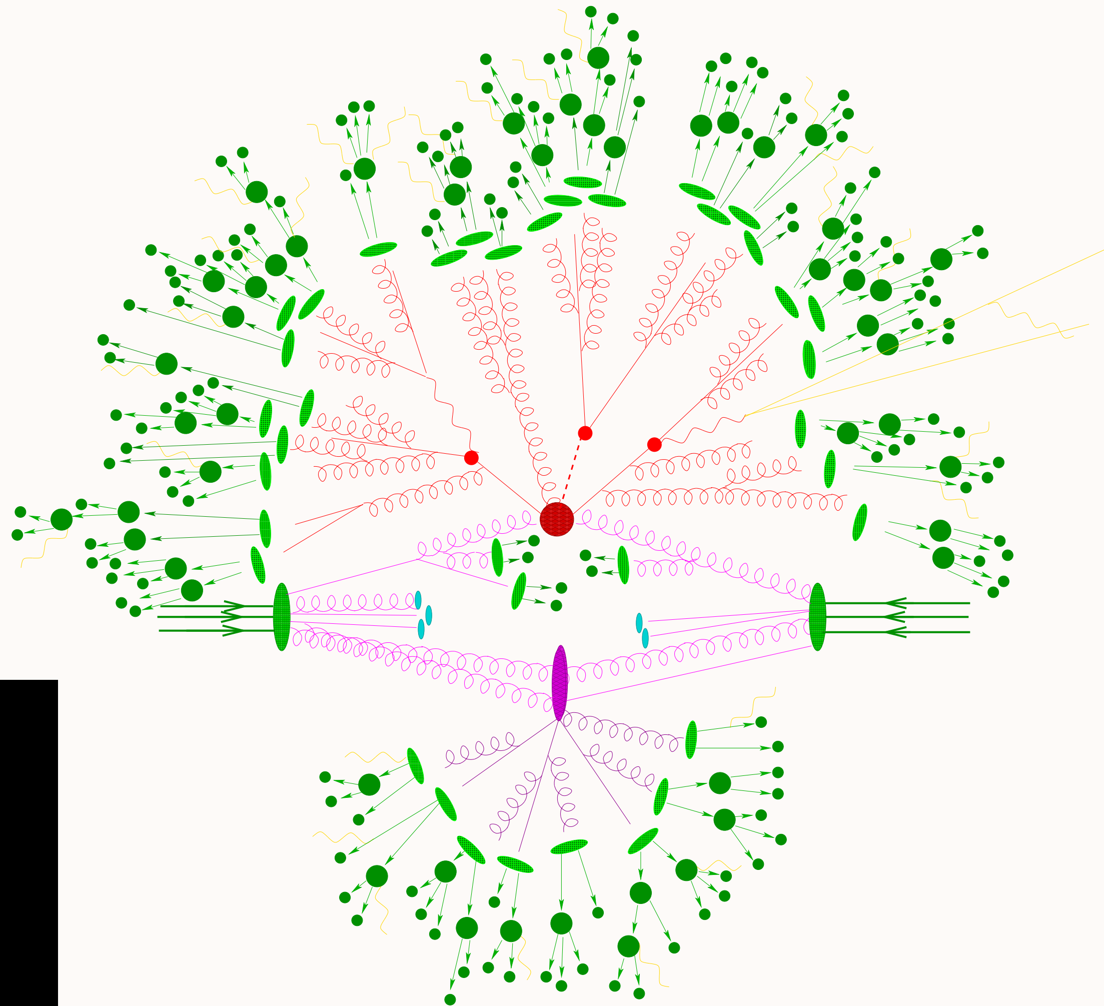


- ➡ ***Introduction: Monte Carlo event generation.***
- ***The TH Pheno Group at the MPI.***
- ***Examples of SM and BSM applications.***
- ***Summary.***

➜ *Visualizing the events.*

- As we have seen already, this is how a four-lepton event looks like in the CMS detector.





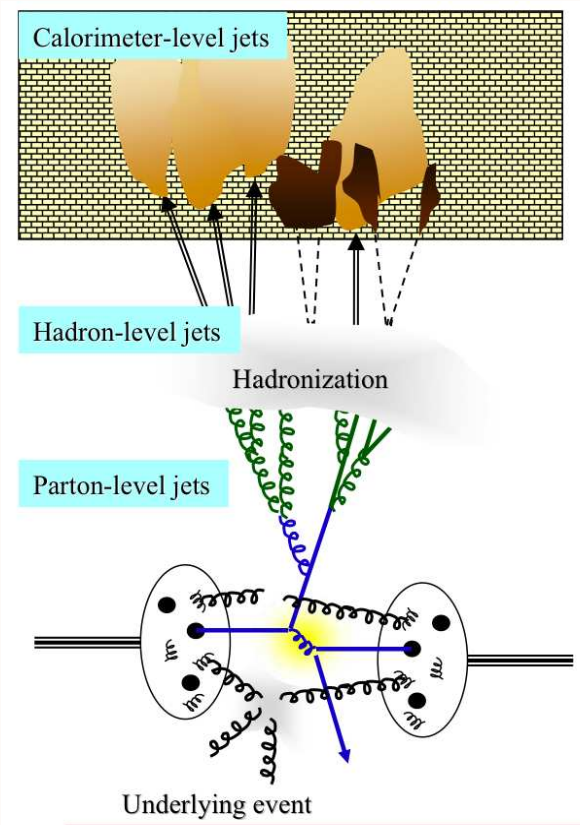
- Illustration of the various phases in the evolution of an event. To simulate an event, we use Monte Carlo techniques.

Event evolution

➡ ***Incoming protons ready for head-on collision.***

Protons are made of (valence/sea) quarks, (sea) antiquarks and gluons (= partons). It is the individual partons that collide, with only a fraction of the proton's energy being available to a single parton collision.

Quark, gluons, partons? We only ever see JETS.

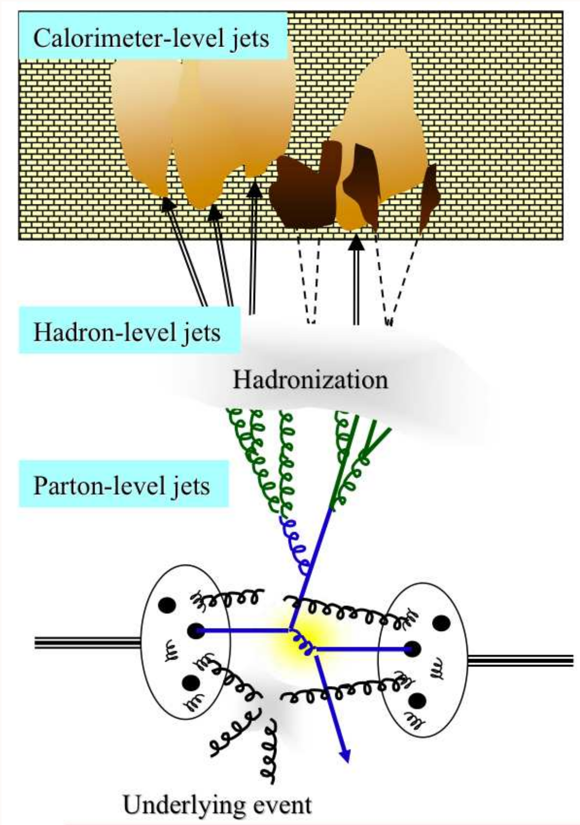


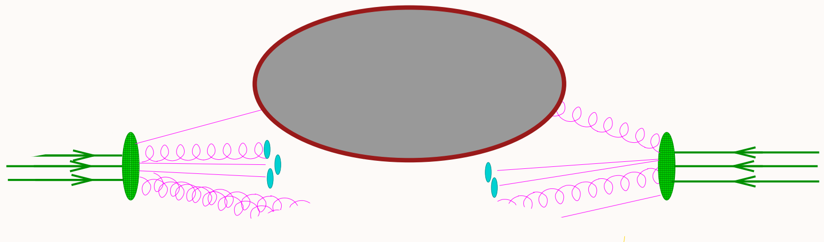
Event evolution

➡ ***The hard interaction.***

Partonic interaction calculated from "phase space times matrix element squared". Convolution with PartonDensityFunctions. Numerical integration method using multidimensional Monte Carlo.

Quark, gluons, partons? We only ever see JETS.





Event evolution

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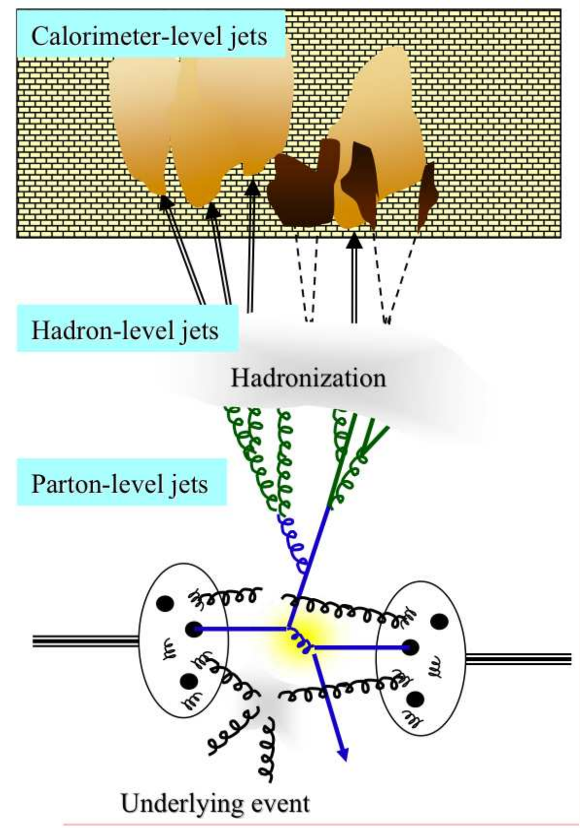
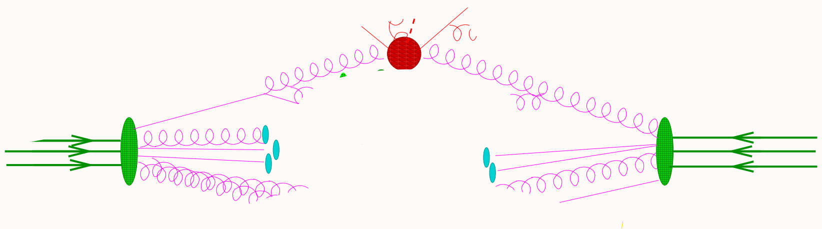


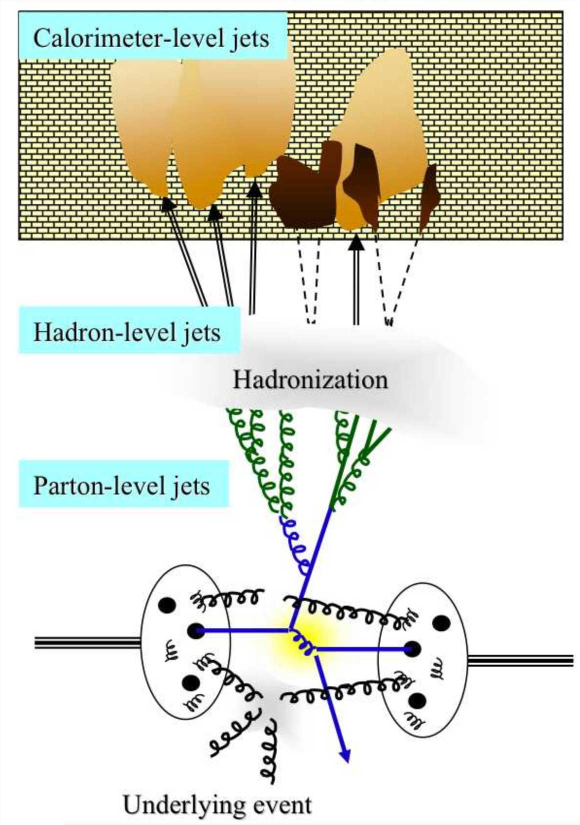


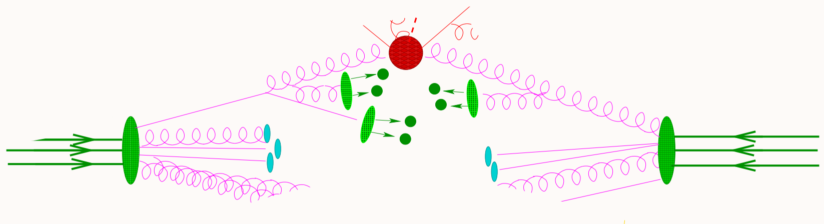
Event evolution

➡ ***Initial state radiation.***

Multiple soft/collinear emission from incoming partons. Backward evolution since both ends of evolution are fixed.

Quark, gluons, partons? We only ever see JETS.



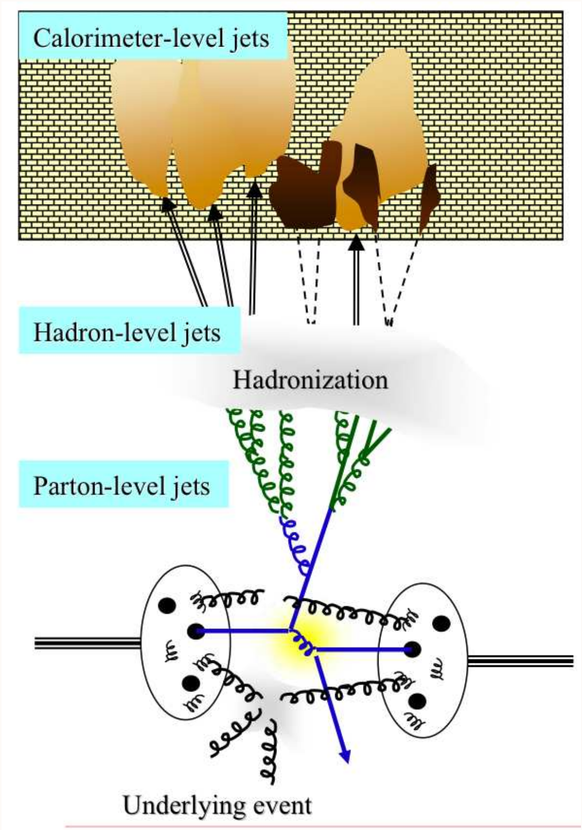


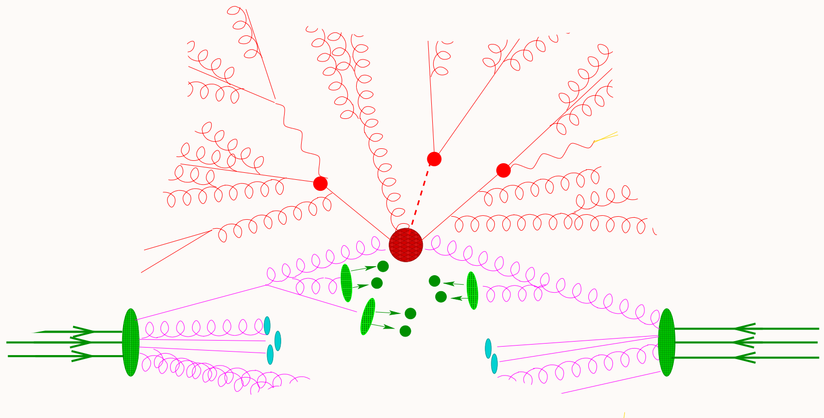
Event evolution

➡ ***Final state radiation.***

In pQCD, probability that parton emits a gluon is $\sim \alpha_s \frac{dE}{E} \frac{d\theta}{\theta}$, which diverges for small gluon energies E and/or small angles θ. A quark never survives unchanged, it always emits a (low-energy) gluon (at small angles). Each gluon radiates a further gluon, and so forth.
Numerically treated through Metropolis-type algorithms.

Quark, gluons, partons? We only ever see JETS.

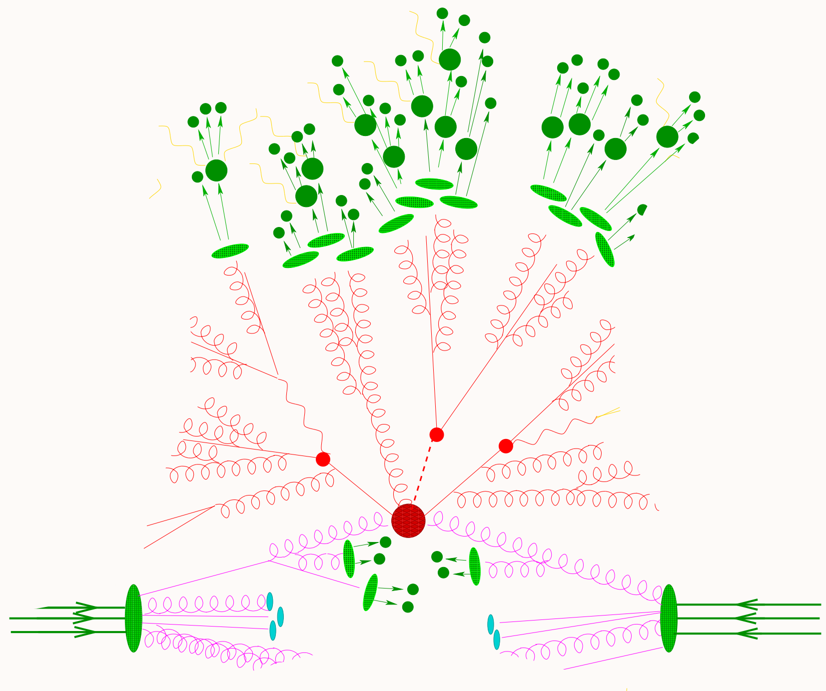




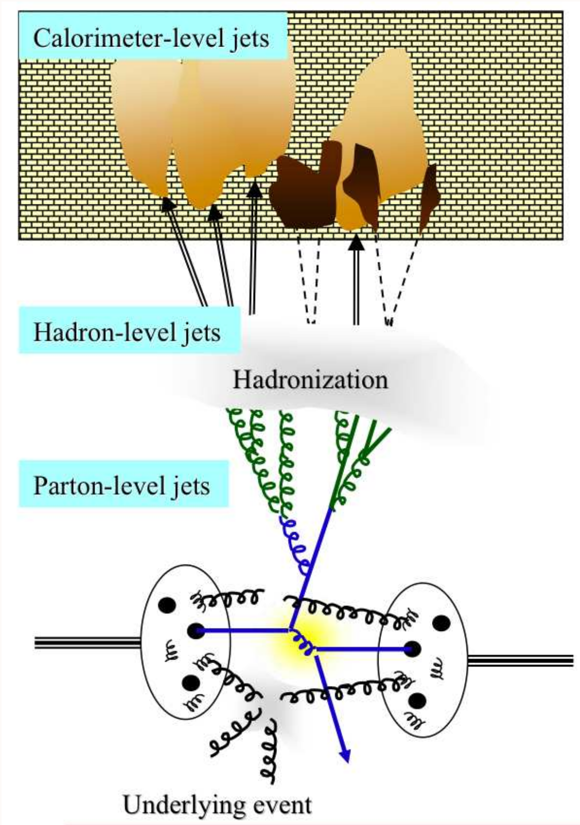
Event evolution

➡ ***Parton-to-hadron transition of jets.***

Phenomenological models tuned to data based on universality of the parton-to-hadron transition setting in at scales of the order of $1\,\mathrm{GeV}$.



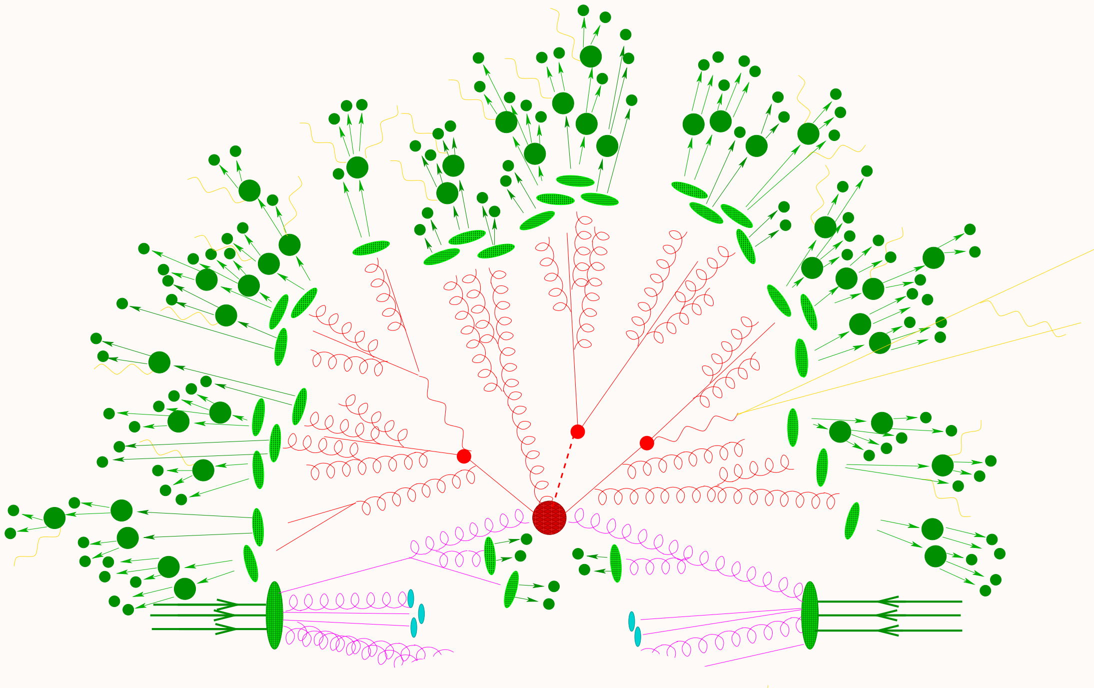
Quark, gluons, partons? We only ever see JETS.



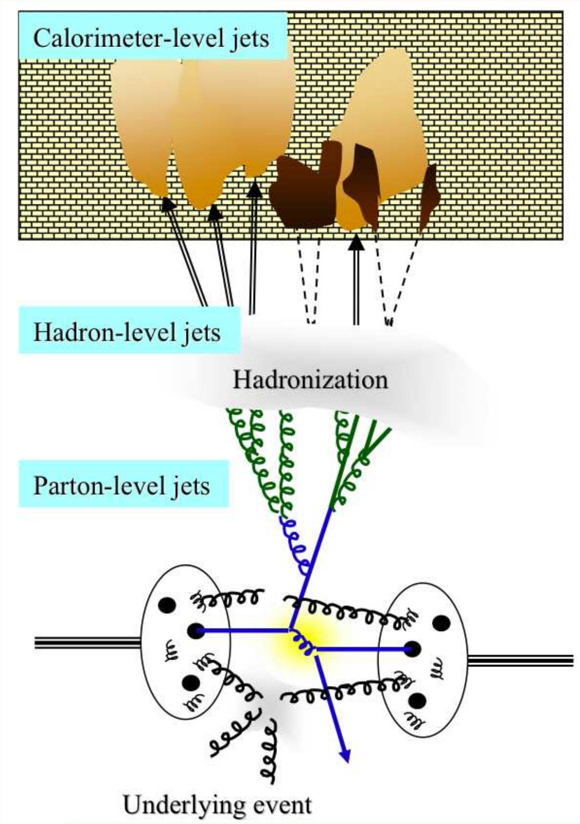
Event evolution

➡ ***Hadronization and decay of primary hadrons.***

Photon emissions.



Quark, gluons, partons? We only ever see JETS.

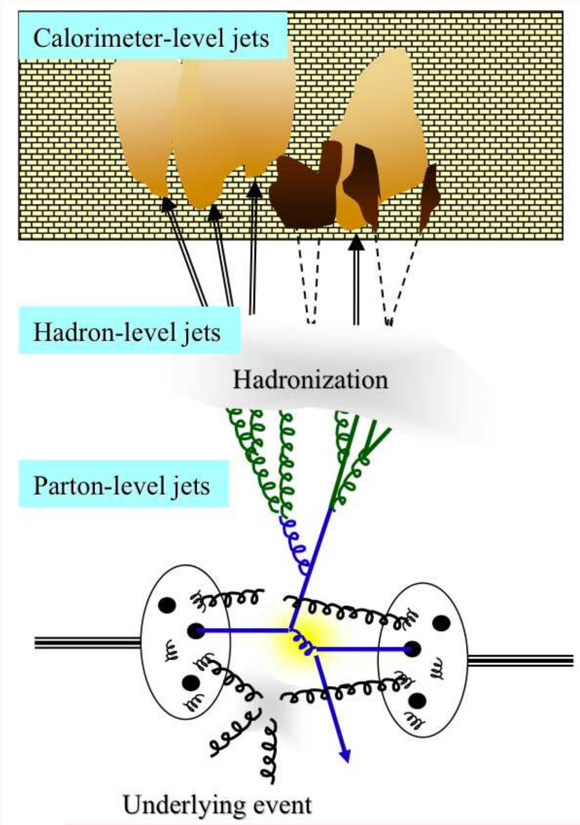


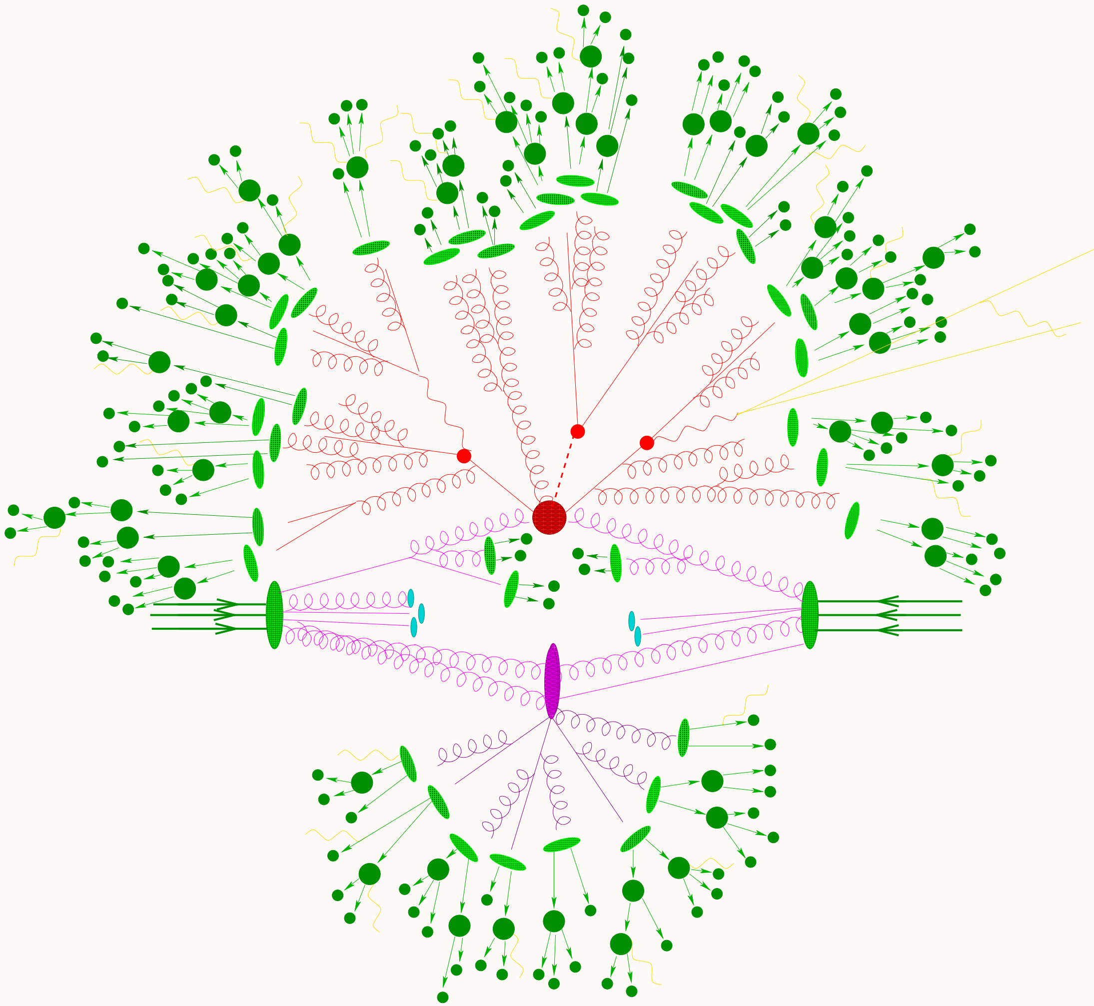
Event evolution

➡ ***Multiple parton interactions/underlying event.***

Secondary interactions at lower energies
compared to hard event.

Quark, gluons, partons? We only ever see JETS.





THX TO FRANK KRAUSS

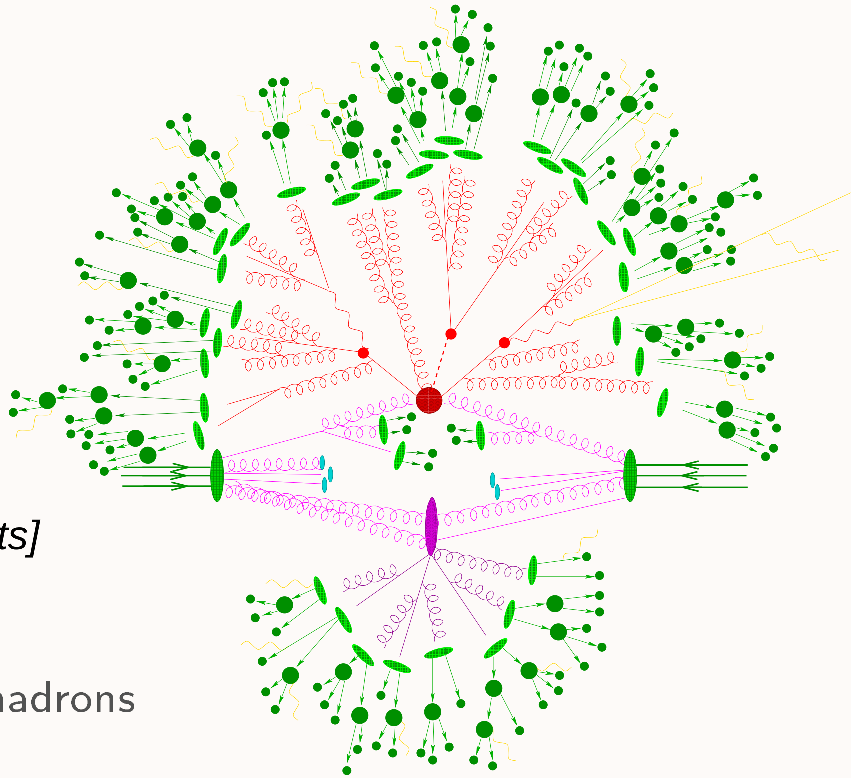
Monte Carlo event generation

Event generators are used to model multi-hadron final states of high-energy particle collisions.

Factorization approach: divide jet simulation into different phases – use Monte Carlo methods.

➡ *Perturbative Phases:* *[parton jets]*

- ***Hard process/interaction (hard jet production)***
  exact matrix elements $|\mathcal{M}|^2$
- ***QCD bremsstrahlung (soft/coll multiple emissions)***
  initial- and final-state parton showering
- ***Multiple/Secondary interactions***
  modelling the underlying event



➡ *Non-perturbative Phases:* *[jet confinement – particle jets]*

- ***Hadronization***
  phenomenological models to convert partons into primary hadrons
- ***Hadron decays***
  phase-space or effective models to decay unstable into
  stable hadrons as observed in detectors

➔ predictions at hadron level – comparable to experimental data if corrected for detector effects

Munich pheno group developments aim at improving the description of hard interactions.

Often these have the largest phenomenological impact, and we can study signatures at the parton level to already get most of the idea.

Luckily the other perturbative and the non-perturbative phases can be handled in a more universal manner. They are essential ingredients of Monte Carlo event generators, and we have learned (are learning) how to match parton showers with the higher-order calculations in a consistent way.

MPI Pheno Group Members.

- ***Director:*** *Wolfgang Hollik*
- ***Staff members:*** ***Thomas Hahn, Gudrun Heinrich, Pierpaolo Mastrolia***

- **Postdoctoral Researchers:**
  Stefano Di Vita, Stephen Jones, Matthias Kerner, Gionata Luisoni, Edoardo Mirabella, Jan Winter, Valery Yundin, Tom Zirke
- **PhD Students:**
  Tao-Li Cheng, Hans van Deurzen, Stephan Hessenberger, Viktor Papara, Cyril Pietsch, Johannes Schlenk, Ulrich Schubert, Johann Felix von Soden-Fraunhofen

- **Congratulations! Successfully graduated this year (now off to their 1st PostDoc):**
  Sophia Borowka (U Zurich), Sebastian Passehr (DESY Hamburg), Tiziano Peraro (Edingburgh)
- **Best of luck! Left the PostDoc team:** Nicolas Greiner
- **Welcome! New PostDocs to the team:** Stephen Jones, Matthias Kerner, Tom Zirke

- ***Sofja Kovaleskaja Award Team, PI:*** ***Pierpaolo Mastrolia***

  Gionata Luisoni, Valery Yundin, Hans van Deurzen, Tiziano Peraro, Ulrich Schubert

MPI Pheno Group Tools.

➡ ***LHC phenomenology needs tools for precision calculations.***

- **GoSam [= Golem + Samurai]**
  automated generation of one-loop amplitudes within & beyond the Standard Model ⇒ GoSam 2.0
  [v.Deurzen, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, Peraro, Schlenk, v.Soden-Fraunhofen, ...]
- **Ninja [C++ library]** [Mastrolia, Mirabella, Peraro]
  interfaced with GoSam to provide faster & more stable integrand reduction for multi-scale processes
- **NJet [C++ library]** [Yundin, ...]
  multi-parton one-loop MEs in massless QCD (many legs!), NLO predictions through interface to Sherpa
- **Sherpa [Monte Carlo event generator (written in C++)]** [Winter, ...]
  using OLPs, it provides NLO results, as well as matched/merged, fully showered/hadronized events
- **SecDec** [Borowka, Heinrich, Schlenk, ...]
  numerical integration of multi-loop integrals (and other integrals)
- **FeynHiggs** [Hahn, Hollik, ...]
  calculation of Higgs masses and cross sections in the MSSM
- **FeynArts & FormCalc** [Hahn, ...]
  Feynman diagram and amplitude generation & simplification of Feynman diagrams up to one loop
- **Cuba & LoopTools** [Hahn, ...]
  multi-dimensional numerical integration & library of one-loop integrals

MPI Pheno Group New Methods.

➡ *LHC phenomenology improves with our ability to handle more complex computations. This is a call for simplifying HEP calculations and trying out new methods. The new frontier is NNLO calculations (for everything), i.e. two-loop integral calculations attract much attention.*

- **Multi-loop recursive integrand reduction**
  Reduction of n-denominator to (n-1)-denominator integrand plus remainder (=residue).
  Motivated by quest for unique mathematical framework for loop amplitudes and search for hidden properties in QFT. [Mastrolia, Mirabella, Peraro, ...]

- **Method of Differential Equations for the evaluation of Feynman integrals**
  Recipies to find the canonical form of systems of equations for master integrals.
  (canonical form → separation of dependence on dimensional parameter from kinematics)

  "Magnus and Dyson Series for Master Integrals"
  [JHEP 1403 (2014) 082; Di Vita, Mastrolia, Mirabella, Schlenk, Schubert, ...]
  "Three-loop master integrals for ladder-box diagrams with one massive leg"
  [JHEP 1409 (2014) 148; Di Vita, Mastrolia, Schubert, Yundin]

Examples of

phenomenological applications and tool developments.

Thanks to all group members for providing me with plenty of material !!

GoSam

Slides from N. Greiner, G. Heinrich and G. Luisoni.

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

GoSam-2.0: a tool for automated one-loop calculations within the Standard Model and Beyond

Gavin Cullen[1], **Hans van Deurzen**[a,2],
Nicolas Greiner[b,2], **Gudrun Heinrich**[c,2],
Gionata Luisoni[d,2], **Pierpaolo Mastrolia**[e,2,3],
Edoardo Mirabella[f,2], **Giovanni Ossola**[g,4,5],
Tiziano Peraro[h,2], **Johannes Schlenk**[i,2],
Johann Felix von Soden-Fraunhofen[j,2],
Francesco Tramontano[k,6]

[1]Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany
[2]Max-Planck-Institut für Physik, München, Germany
[3]Dipartimento di Fisica, Università di Padova, Italy
[4]New York City College of Technology, City University of New York, USA
[5]The Graduate School and University Center, City University of New York, USA
[6]Dipartimento di Scienze Fisiche, Università di Napoli and INFN, Sezione di Napoli, Italy

Abstract We present the version 2.0 of the program package GoSam for the automated calculation of one-loop amplitudes. GoSam is devised to compute one-loop QCD and/or electroweak corrections to multi-particle processes within and beyond the Standard Model. The new code contains improvements in the generation and in the reduction of the amplitudes, performs better in computing time and numerical accuracy, and has an extended range of applicability. The extended version of the "Binoth-Les-Houches-Accord" interface to Monte Carlo programs is also implemented. We give a detailed description of installation and usage of the code, and illustrate the new features in dedicated examples.

Keywords NLO calculations · automation · hadron colliders

PACS 12.38.-t · 12.38.Bx · 12.60.-i

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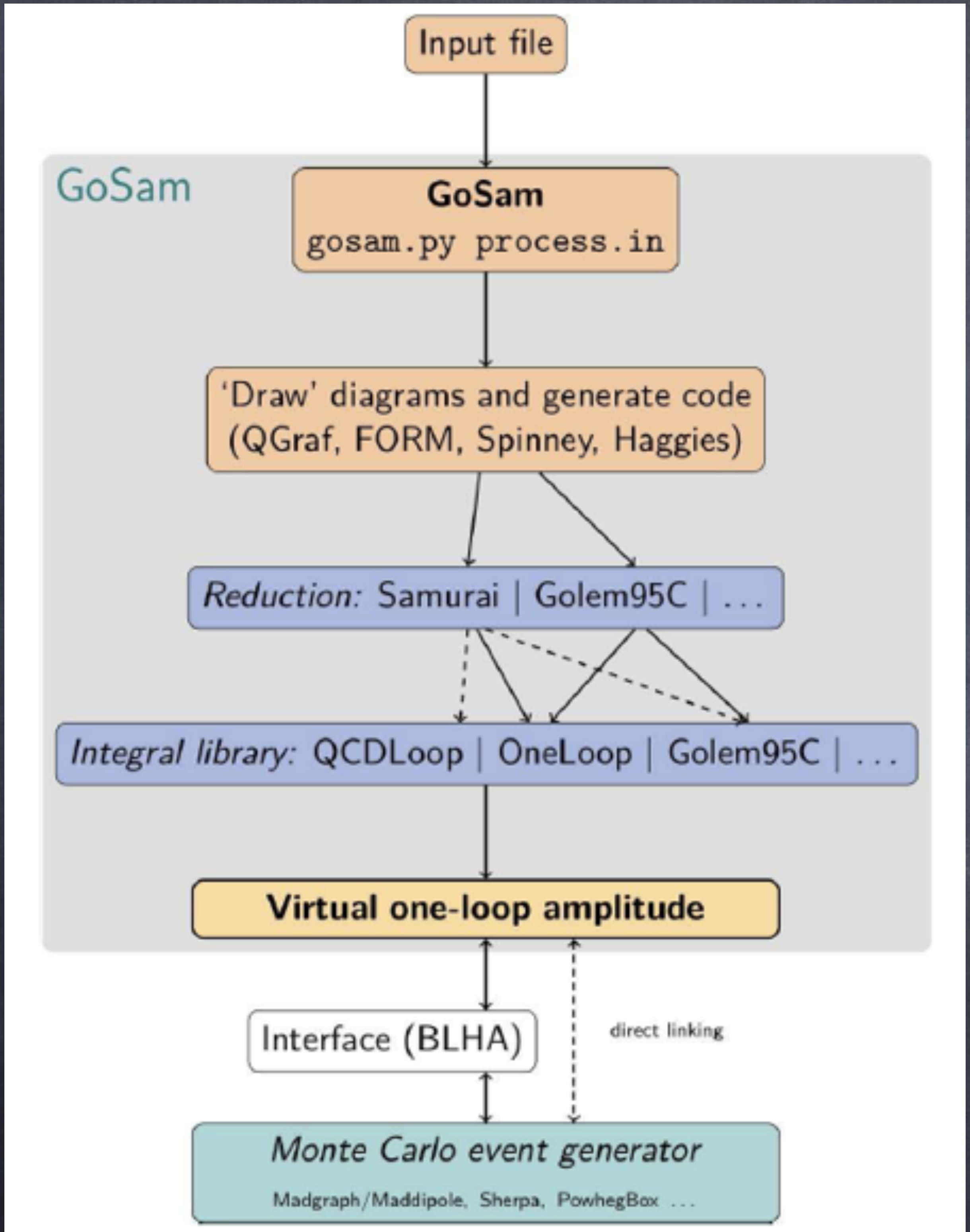
GoSam for pedestrians



1. Input file process.in
   Specify process (ud~ -> W+gggg) and options/parameters.
2. Generation of Feynman diagrams
   QGraf, Form, Spinney
   Translation into Fortran code
   Haggies

---

3. At runtime: Reduction of Tensor Integrals
   Samurai, Golem95
4. Evaluation of scalar integrals
   QCDLoop, OneLoop, Golem95

---

5. Interface with numerical Phase space integration for xsec and distributions

GoSam-2.0

program available at

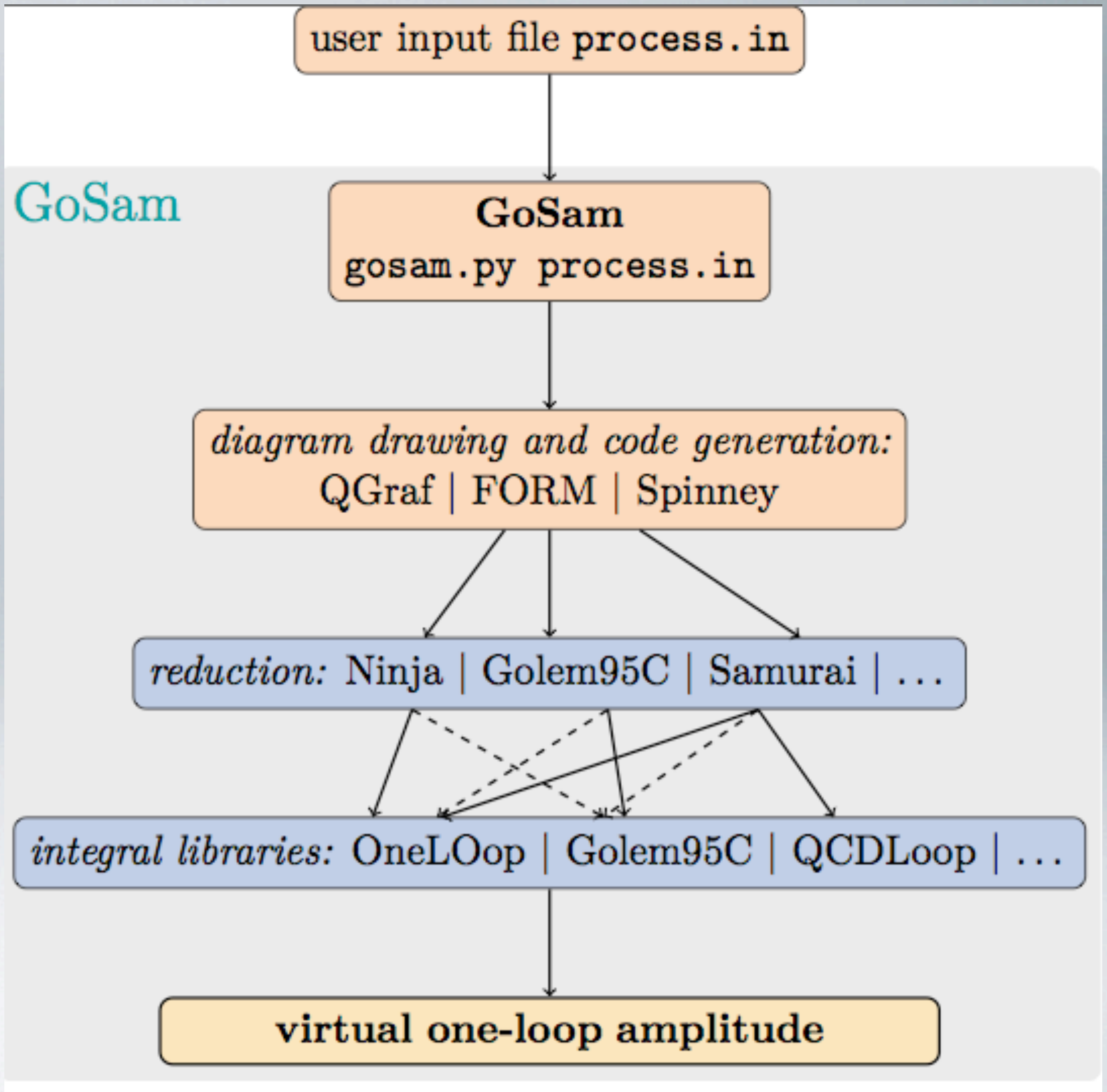
http://gosam.hepforge.org

very simple usage

example input file for

$$e^+e^- \to t\bar{t}$$

```
process_path=eett
in=     e+, e-
out=    t, t~
order= gs, 0, 2
```



arXiv:1404.7096

Cullen, Greiner, GH, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Schlenk, van Deurzen, von Soden-Fraunhofen, Tramontano

NLO Results

- Ingredients for a full NLO calculation:

$$\sigma_{\rm NLO} = \int_{d\Phi_m} d\sigma_{\rm Born} + \int_{d\Phi_{m+1}} \left(d\sigma^{\rm R}_{\rm NLO} - d\sigma^{\rm S}_{\rm NLO} \right) + \int_{d\Phi_m} \left[\int_{d\Phi_1} d\sigma^{\rm S}_{\rm NLO} + d\sigma^{V}_{\rm NLO} \right]$$

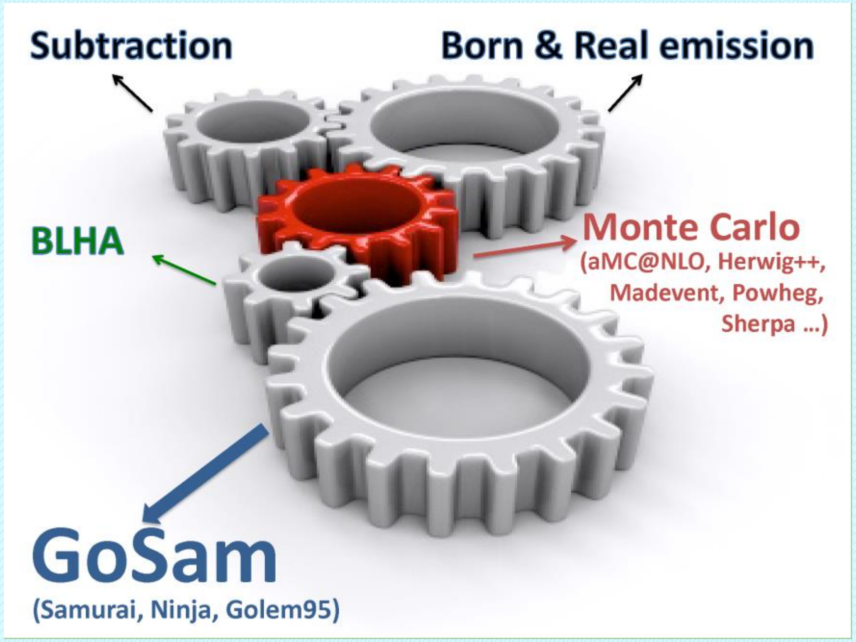
- Virtual corrections

One Loop Program

BLHA-1

Monte Carlo

- Tree amplitude
- Subtraction scheme
- Phase space integral



Recent NLO results using GoSam

- **GoSam + MadGraph/MadDipole/MadEvent**
  - pp - > $b\bar{b}b\bar{b}$ [Greiner, Guffanti, Reiter, Reuter]
  - pp - > $W^+ W^- j\, j$ [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]
  - pp - > $\tilde{\chi}^0\tilde{\chi}^0\, j$ [Cullen, Greiner, Heinrich]
  - pp - > $\gamma\, \gamma\, j$ / $\gamma\, \gamma\, j\, j$ [Gehrmann, Greiner, Heinrich]
  - pp - > G (-> $\gamma\, \gamma$) j [Greiner, Heinrich, Reichel, v. Soden-Fraunhofer]

http://gosam.hepforge.org/diphoton

- **GoSam + Powheg**
  - pp - > HW j / HZ j [G.L., Nason, Oleari, Tramontano]
- **GoSam + Sherpa**
  - pp - > H j j [in ggf] [v. Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro, v. Soden-Fraunhofer, Tramontano]
  - pp - > $t\,\bar{t}$ (j) [Höche, Huang, G.L., Schönherr, Winter]
  - pp - > $H\, t\,\bar{t}$ (j) [v.Deurzen, G.L., Mastrolia, Mirabella, Ossola, Peraro]
  - pp - > $W^+ W^- b\bar{b}$ [Heinrich, Schlenk, Winter]

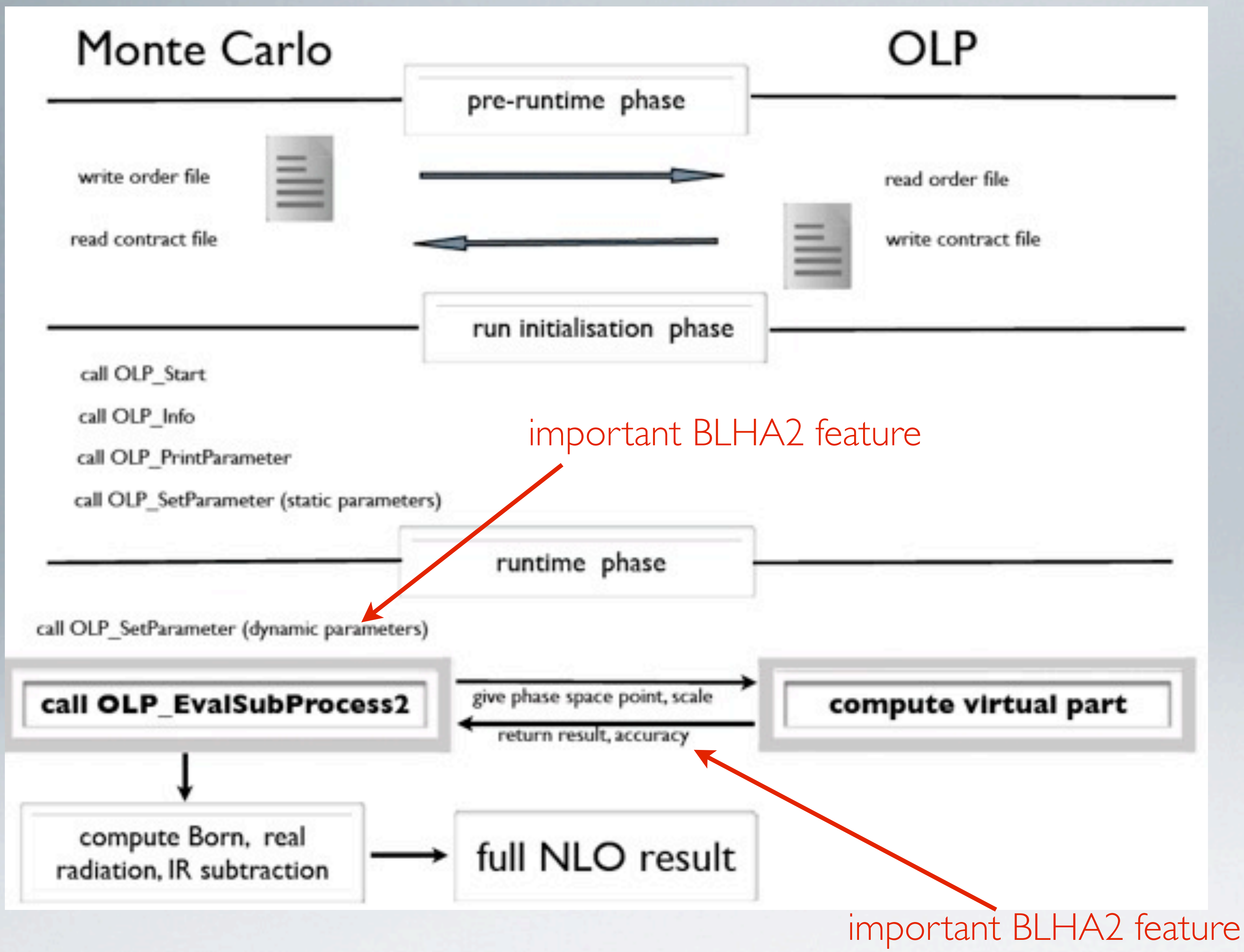
Other process packages available at:
http://gosam.hepforge.org/proc/

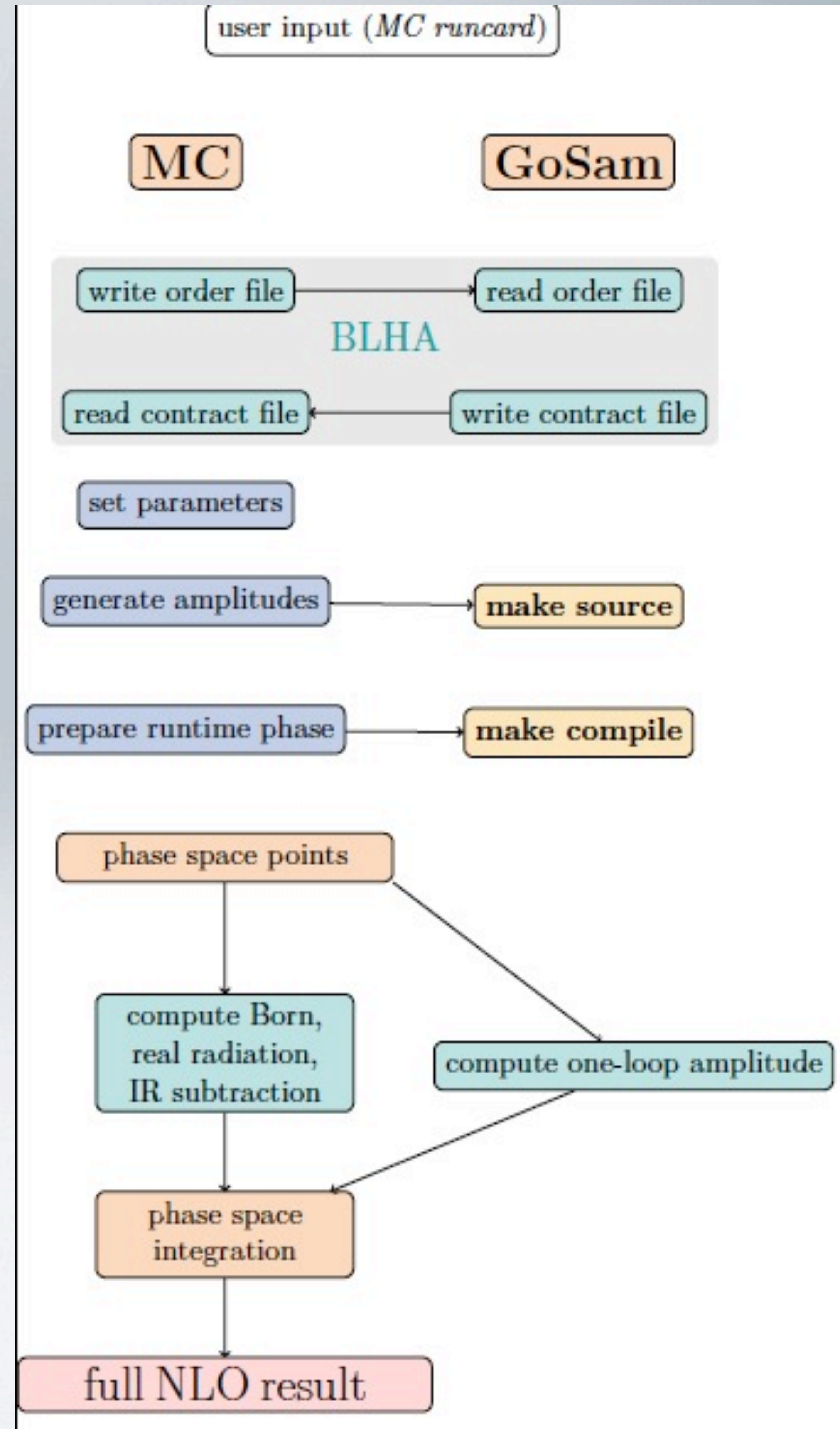
- **GoSam + MadGraph/MadDipole/MadEvent + Sherpa**
  - pp - > H j j j [in ggf]

[Cullen, v. Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro, Tramontano]

Interface to Monte Carlo programs

both original Binoth-Les-Houches-Accord and extended standards [CPC 185 (2014)] are supported





allows combination with different MC programs

MAX-PLANCK-GESELLSCHAFT

Interface with Monte Carlo Programs

Universal interface that enables us to combine one-loop programs (OLP) with Monte Carlo programs (MC).

➡ ***Full NLO automation.***

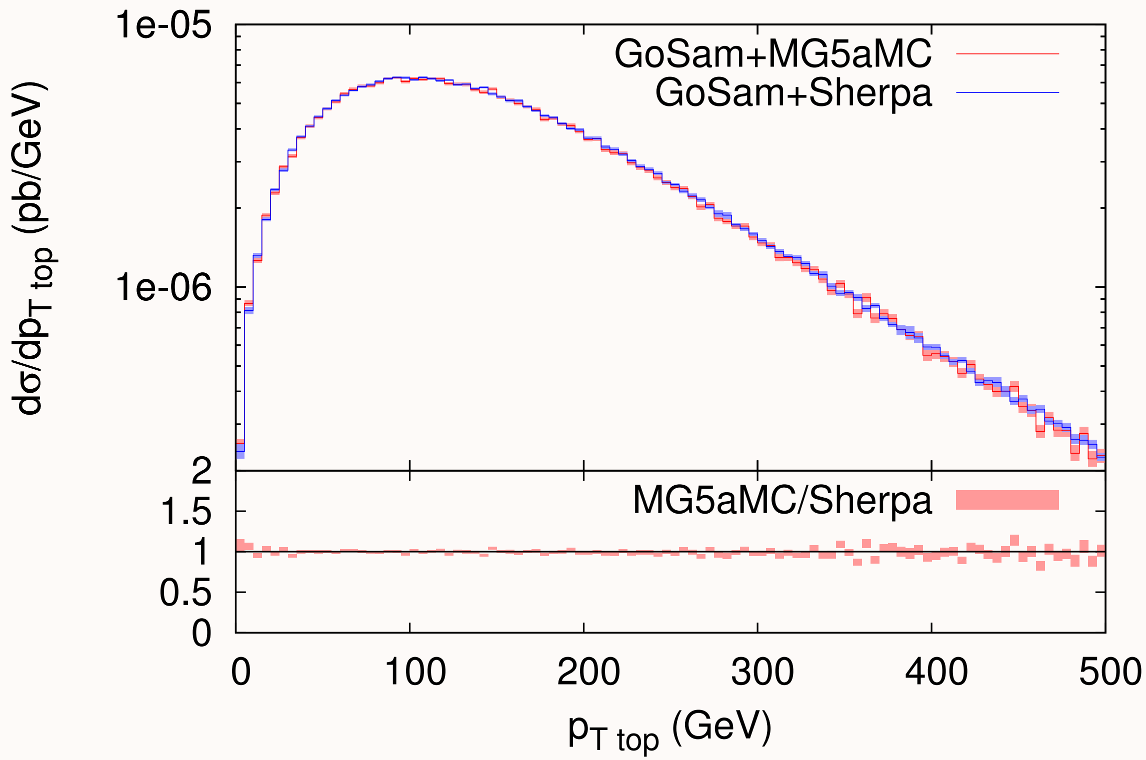
➡ **GoSam interfaces exist with:**

- MadGraph/MadDipole/Madevent.
- Sherpa.
- Powheg.

Successfully tested for several benchmark processes also for:

- Herwig.
- aMC@NLO.

e.g. in top quark pair production associated with two jets,
[V.DEURZEN, FREDERIX, HIRSCHI, LUISONI, MASTROLIA, OSSOLA]

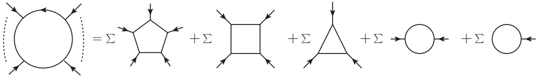


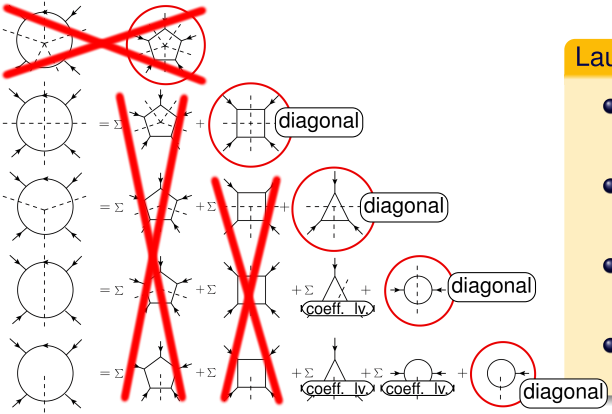
Ninja

Slide from T. Peraro.

Integrand reduction via Laurent expansion (NINJA)

Integrand decomposition:





Laurent-expansion method

- pentagons not needed
- boxes never subtracted
- diagonal systems of equations
- subtractions at coefficient level

Higgs boson plus jets in gluon-gluon fusion

Slides from G. Luisoni.

(in prep; Greiner, Höche, Luisoni, Schönherr, Winter, Yundin)

H+jets in gluon-gluon fusion

H+3 jets

- Calculation setup so far:
  - B amplitudes: Sherpa (Amegic)
  - V amplitudes: GoSam

  } PS integration: Sherpa (BLHA)

  - IRS amplitudes: MG4/MadDipole

  } PS integration: MadEvent

  → Full NLO

- New ongoing calculation:
  - B amplitudes: Sherpa (Comix)
  - V amplitudes: GoSam
  - IRS amplitudes: Sherpa (Comix)

  } PS integration: Sherpa (BLHA)

  → Full NLO + merging + shower

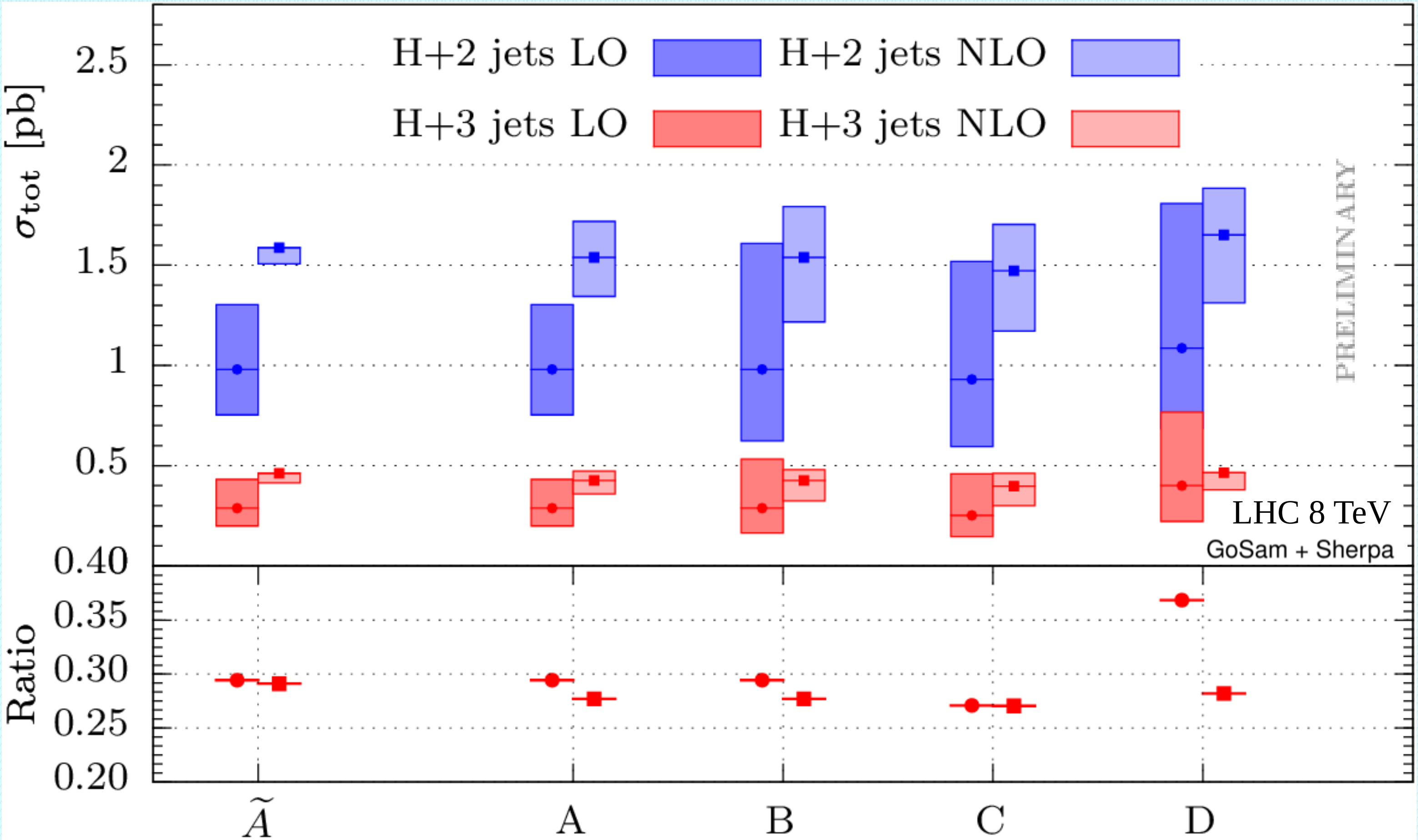
  → NLO Events as NTuples

H+jets: virtual corrections

	Processes	# Diagrams	# Helicities	# Groups	Timing (col.+hel. summed)
H+0 jets	$g+g \longrightarrow H$	1	1	1	< 1 ms
H+1 jets	$q+\bar{q} \longrightarrow H+g$	14	4	3	~ 3 ms
	$g+g \longrightarrow H+g$	48	8	3	~ 7 ms
		62			
H+2 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'$	32	4	6	~ 9 ms
	$q+\bar{q} \longrightarrow H+q+\bar{q}$	64	6	8	~ 15 ms
	$q+\bar{q} \longrightarrow H+g+g$	179	8	12	~ 56 ms
	$g+g \longrightarrow H+g+g$	651	16	12	~ 309 ms
		926			
H+3 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'+g$	467	8	32	~ 68 ms
	$q+\bar{q} \longrightarrow H+q+\bar{q}+g$	868	12	44	~ 157 ms
	$q+\bar{q} \longrightarrow H+g+g+g$	2519	16	60	~ 999 ms
	$g+g \longrightarrow H+g+g+g$	9325	32	60	~ 8‘960 ms
		13179			

Dependence on scale choice

PRELIMINARY



A: $\alpha_s(x\,\frac{H_T}{2})^3\alpha_s(m_H)^2$

B: $\alpha_s(x\,\frac{H_T}{2})^3\alpha_s(x\,m_H)^2$

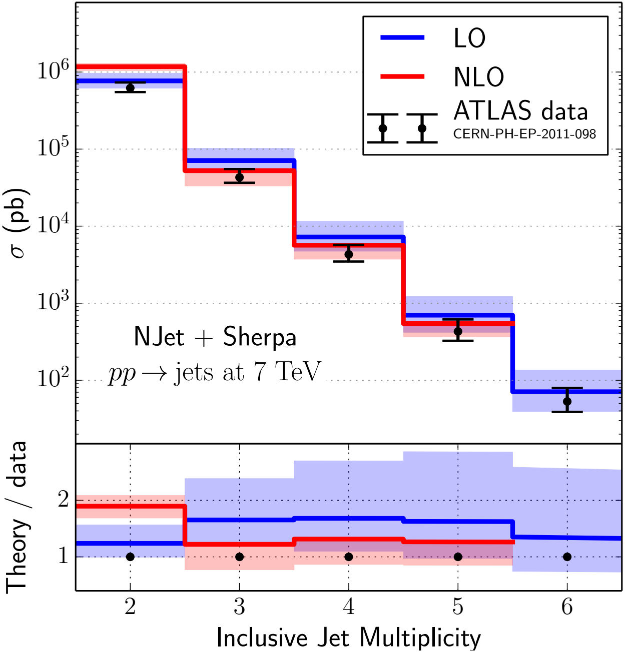
C: $\alpha_s(x\,\frac{H_T}{2})^5$

D: $\alpha_s(x\,m_H)^5$

NJet

Slide from V. Yundin.

NJet+Sherpa: total XS for 2, 3, 4, 5 jets at 7 TeV vs ATLAS measurements



Cuts

anti-kt $R = 0.4$

$p_T^{\text{1st}} > 80$ GeV

$p_T^{\text{other}} > 60$ GeV

$|\eta| < 2.8$

NLO

$\mu_R = \mu_F = \hat{H}_T/2$

vars. $\hat{H}_T/4$ and $\hat{H}_T$

$\alpha_s(M_Z) = 0.118$

NNPDF23 PDF set

FormCalc & Friends / SecDec / BSM applications

Slides from T. Hahn, G. Heinrich and W. Hollik.

Summary

FeynArts 3.9:

- MSSMCT model file incl. complete 1-loop renormalization.

FormCalc 8.4:

- Support for run-time renormalization-scheme selection.
- Automated vectorization of helicity loop.
- Suppression of negligible helicity combinations.
- Ninja interface.

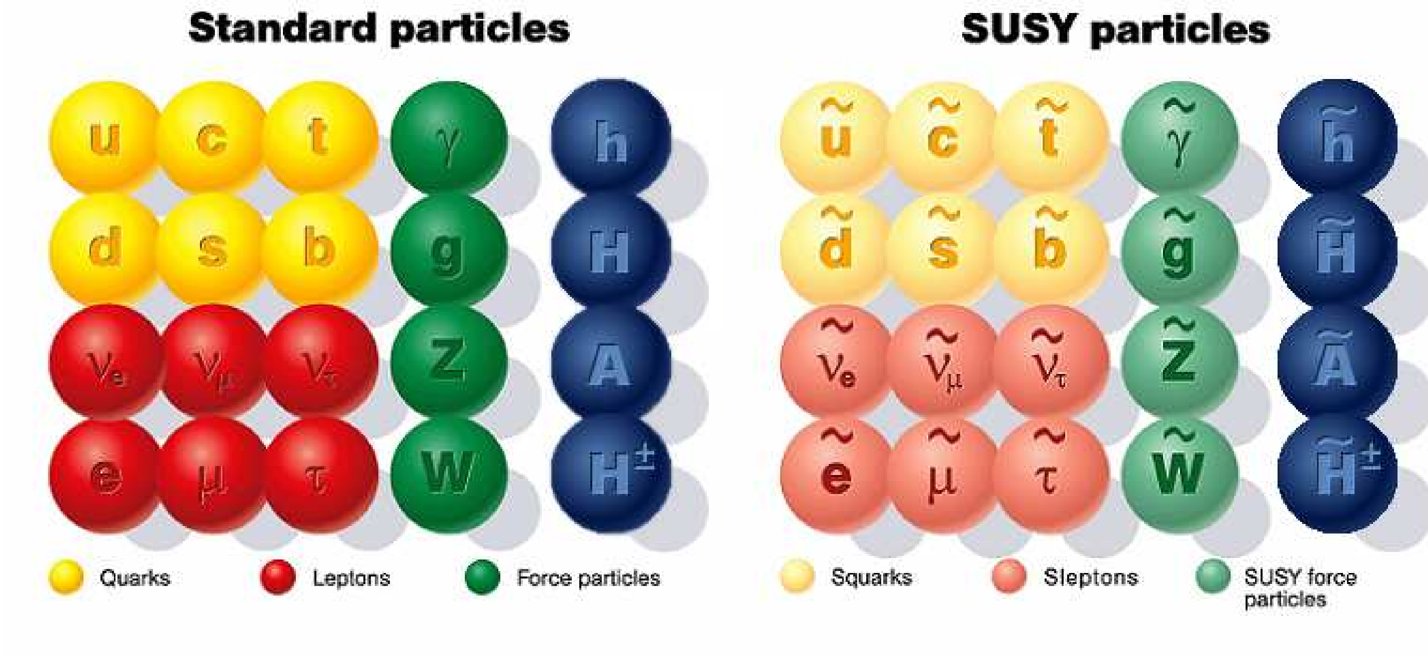
LoopTools 2.10:

- Cache concurrency issues solved.

Cuba 3.3:

- Ways to fine-tune distribution of points to cores suited for vectorization/GPU ‘on top’ of Cuba’s `fork`/`wait`.

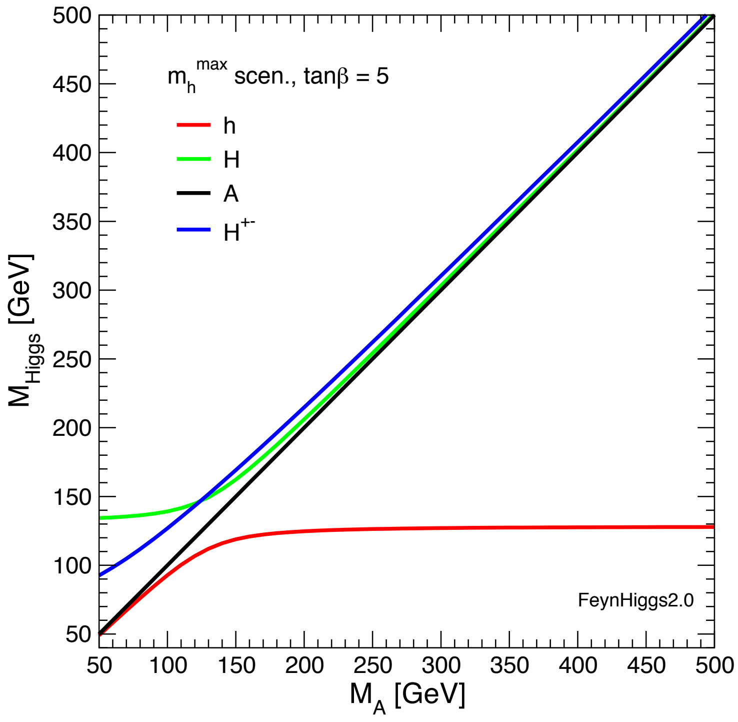
Supersymmetry



- gauge coupling unification
- dark matter candidate (lightest SUSY particle, LSP)
- physical Higgs bosons: $h^0,\ H^0,\ A^0,\ H^{\pm}$

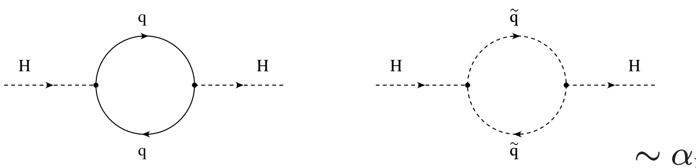
  lightest Higgs boson h^0 < 130 GeV

Higgs bosons in the MSSM: $h^0, H^0, A^0, H^\pm$



- *light Higgs boson h^0 predicted*
- *for heavy $A^0, H^0, H^\pm$:*
  h^0 like Standard Model Higgs boson

m_h^0 strongly influenced by quantum effects, e.g. $t, \tilde{t}$



$\sim \alpha_t$

public tool: FEYNHIGGS

Hahn, Hollik [MPP] +Heinemeyer, Rzehak, Weiglein

recent progress in precision calculations

- full momentum dependence of self-energies
  at 2-loop order $O(\alpha_t \alpha_s)$

$$\Sigma(0) \ \ [\text{effective potential}] \ \rightarrow \ \Sigma(q^2)$$

  Borowka, Hahn, Heinrich, Heinemeyer, Hollik   EPJC 74(2014)2994

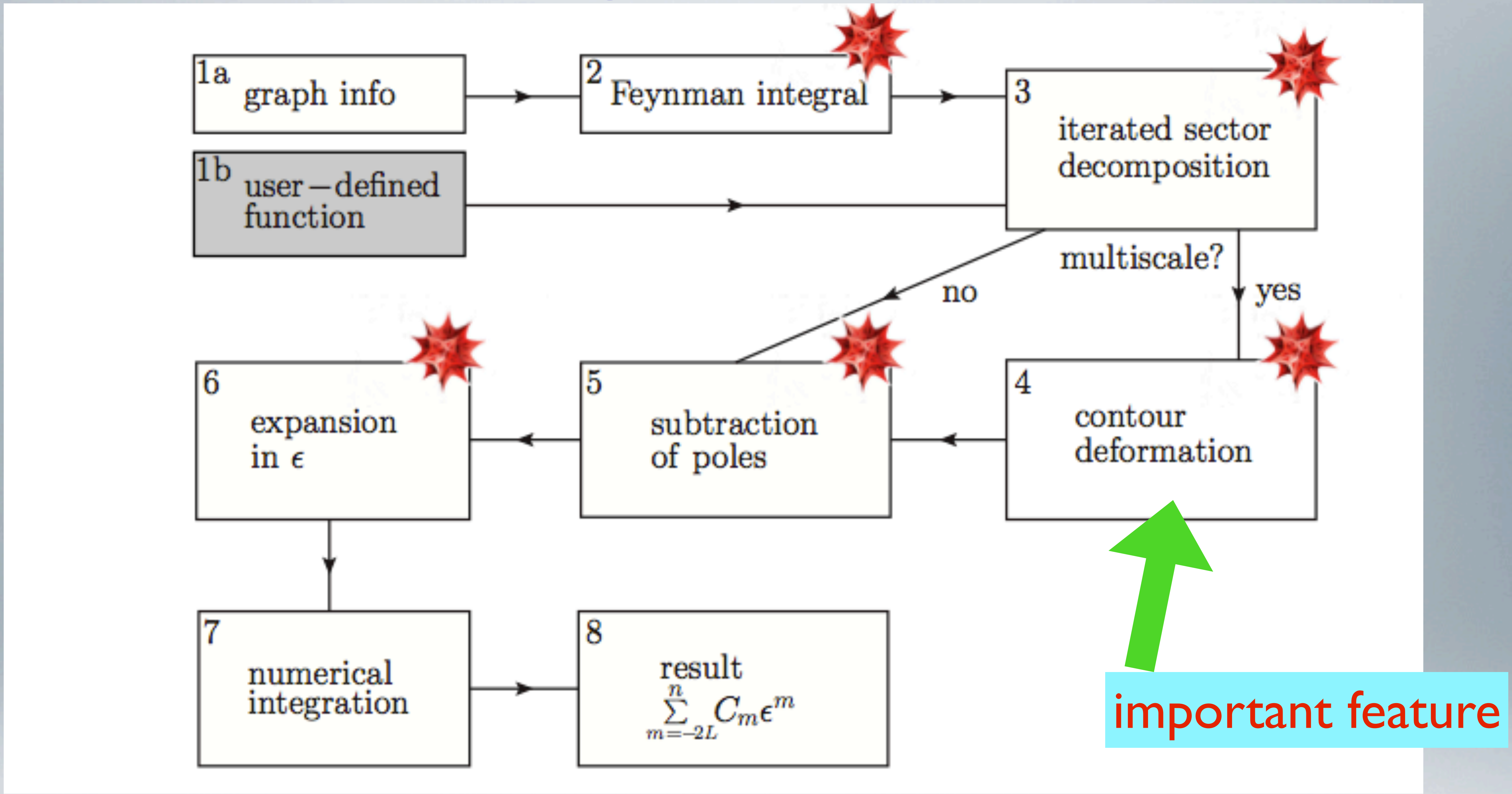
- MSSM with complex parameters ($\rightarrow CP$-violation):
  contributions of 2-loop order $O(\alpha_t^2)$ with complex phases

  Hollik, Paßehr   PLB 733(2014)144; JHEP 10(2014)171

- resummation of large logarithms $\log(M_S/m_t)$ at LL and NLL
  for large SUSY mass scales M_S
  $\Rightarrow$ allows predictions also for high M_S $\rightarrow$ TeV scale

  Hahn, Heinemeyer, Hollik, Rzehak, Weiglein   PRL 112(2014)14180

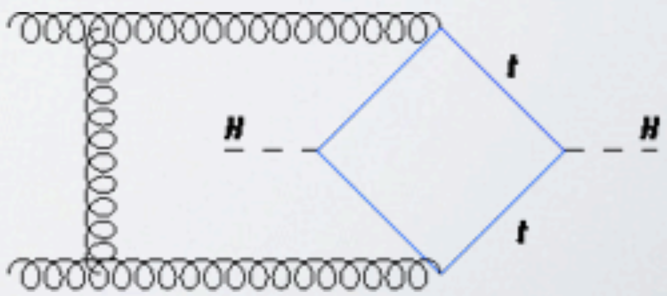
The program SecDec



[S. Borowka, J. Carter, G.Heinrich '12,'13]

- allows calculation of multi-loop integrals with several mass scales

- **current project:**
  two-loop integrals entering **double Higgs production** with full top mass dependence
  (analytical calculation not in reach)



Recent application of SecDec

momentum dependent $\mathcal{O}(\alpha_s \alpha_t)$ corrections to neutral Higgs boson masses in the MSSM

[S. Borowka, T. Hahn, S. Heinemeyer, GH, W. Hollik 2014]

- requires calculation of Higgs boson self-energies up to two-loop level

$$\Gamma \equiv \Delta^{-1}_{\mathrm{Higgs}} = \begin{pmatrix} p^2 - m^2_{H,\mathrm{tree}} + \hat{\Sigma}_H(p^2) & \hat{\Sigma}_{hH}(p^2) \\ \hat{\Sigma}_{hH}(p^2) & p^2 - m^2_{h,\mathrm{tree}} + \hat{\Sigma}_h(p^2) \end{pmatrix}$$

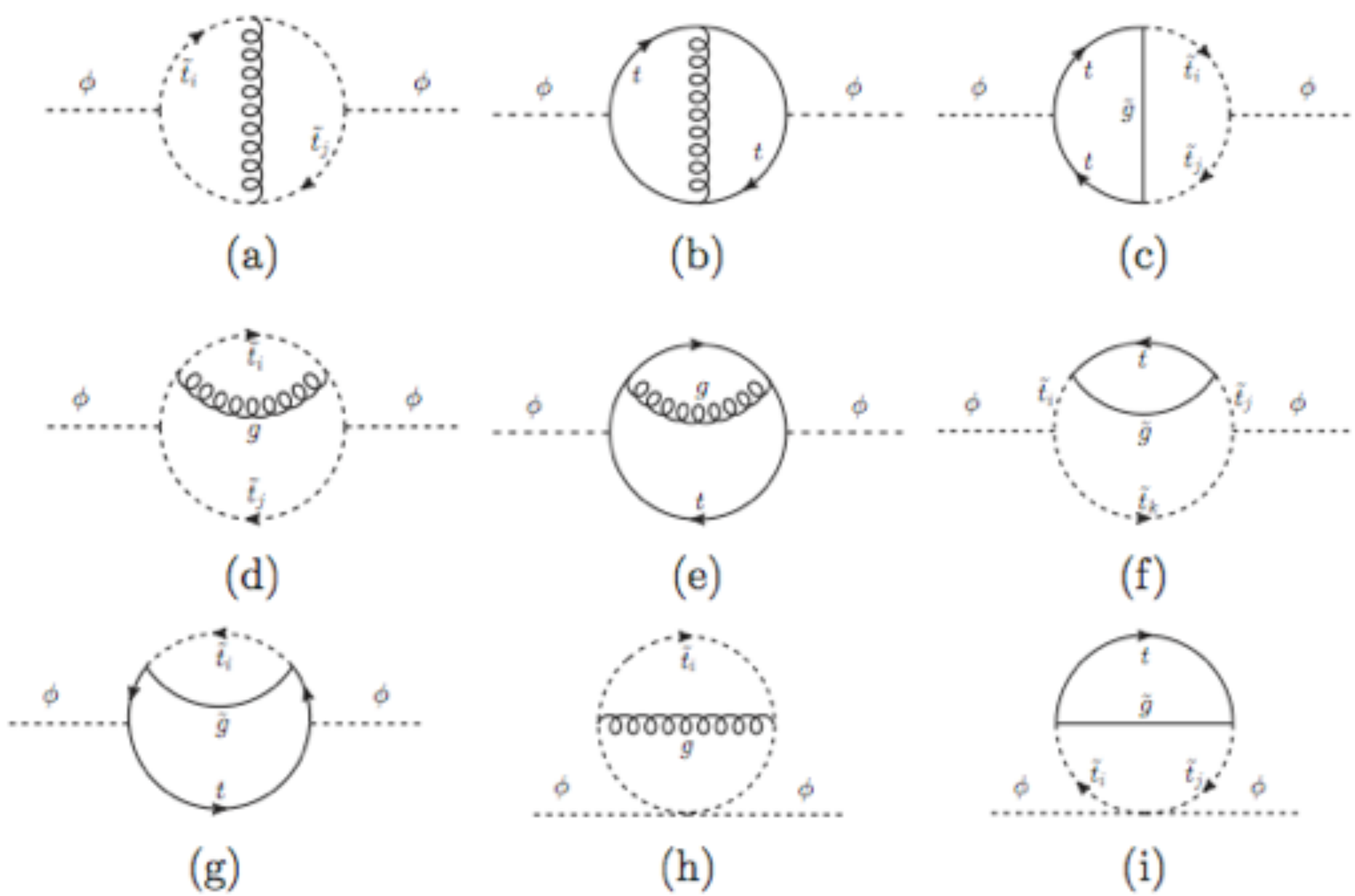
- find the complex solutions of $\det \Gamma = 0$
- the masses are identified with the real parts of the solutions

note: experimental precision on Higgs boson mass:

ATLAS:	$M_H^{\mathrm{exp}} = 125.5 \pm 0.4 \pm 0.2$ GeV
CMS:	$M_H^{\mathrm{exp}} = 125.7 \pm 0.3 \pm 0.3$ GeV

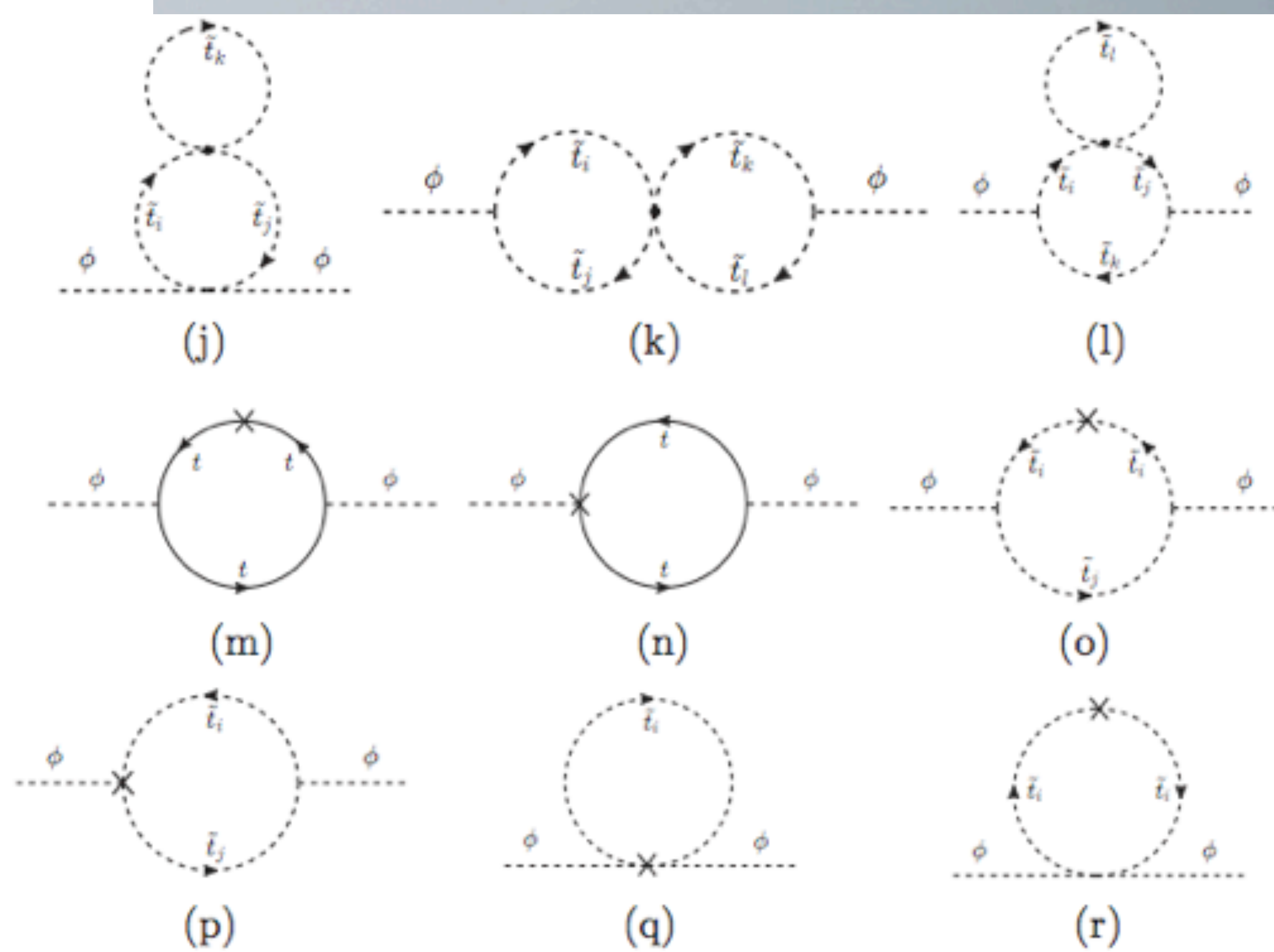
theoretical precision (MSSM): $\Delta M_h \simeq 3\,\mathrm{GeV}$

two-loop Higgs boson selfenergy diagrams



- only few of these integrals are known analytically
- up to 4 different masses
- was technically not feasible so far:

  momentum dependence



→ numerical calculation possible with

SecDec-2.1

[S. Borowka, GH]

Status of corrections in real MSSM

public programs:

FeynHiggs Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '00 '03 '07 '14

SoftSusy Allanach '02 SPheno Porod '03 Staub '11

CPsuperH Carena, Choi, Drees, Ellis, Lee, Pilaftsis, Wagner '04 '09 '12

Suspect Djouadi, Kneur, Moultaka '07

H3m Kant, Harlander, Mihaila, Steinhauser '10

implemented corrections:

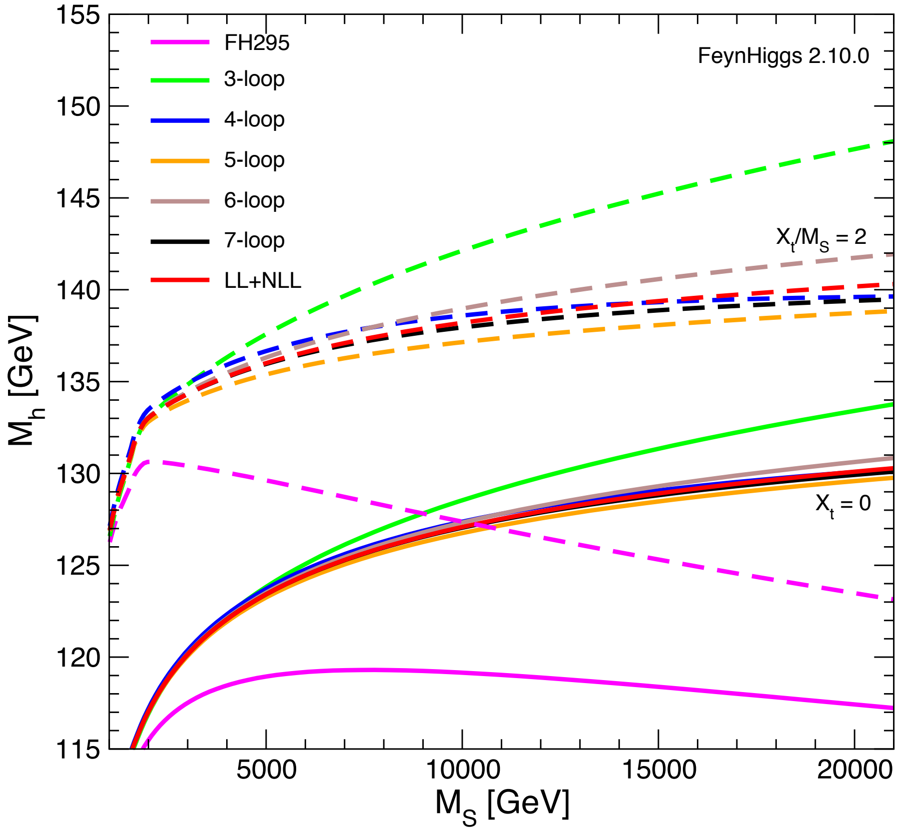
- 1-loop : complete
- 2-loop : $\mathcal{O}(\alpha_s\alpha_t), \mathcal{O}(\alpha_t^2), \mathcal{O}(\alpha_s\alpha_b), \mathcal{O}(\alpha_b^2), \mathcal{O}(\alpha_t\alpha_b)$ at $p^2 = 0$
- 3-loop : $\mathcal{O}(\alpha_s^2\alpha_t)$ at $p^2 = 0$

now: 2-loop $\mathcal{O}(\alpha_s\alpha_t)$ at $p^2 \neq 0$

[Borowka, Hahn, Heinemeyer, GH, Hollik 04/2014]

[Degrassi, Di Vita, Slavich 10/2014]

impact of large log resummation *[Hahn et al.]*



— fixed order

— full resummation of LL and NLL

$\tilde{t}$*-squark mass matrix* $\mathcal{M}^2_{\tilde{t}} =$

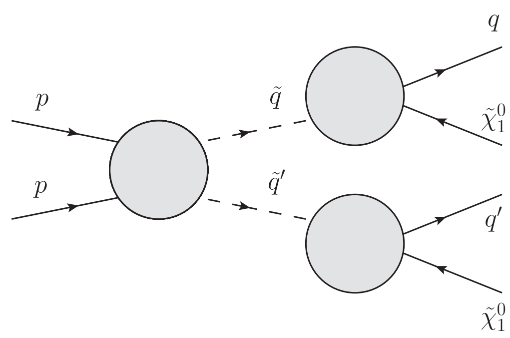
$$\begin{pmatrix} M_S^2 + m_t^2 & m_t X_t \\ m_t X_t & M_S^2 + m_t^2 \end{pmatrix}$$

- sizeable upward shift for heavy top-squarks
- large impact for confronting constrained models with the Higgs signal at 125 GeV

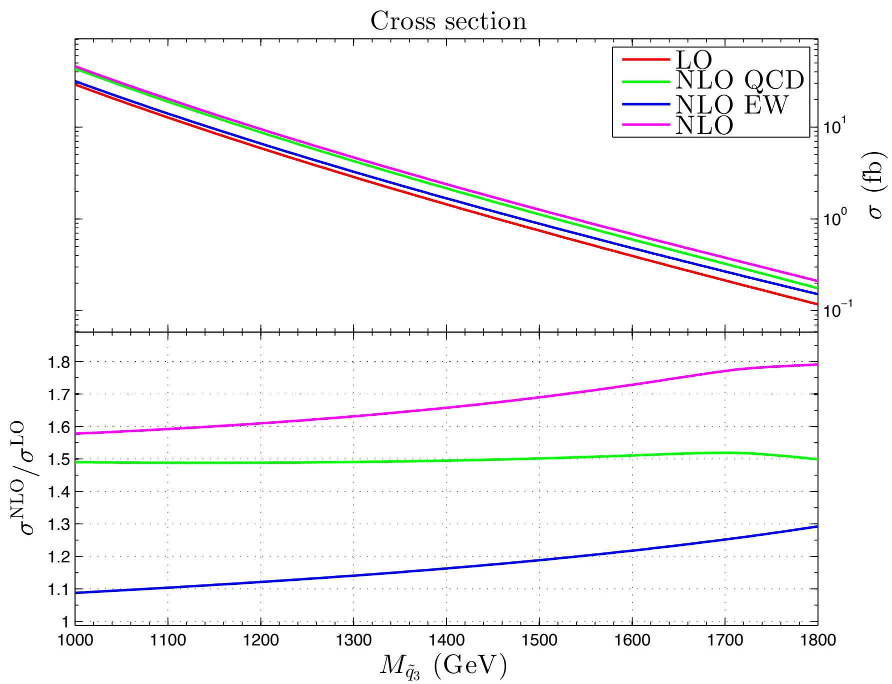
Buchmueller, ... Hahn, Hollik, ... EPJC 74(2014)14180

SUSY searches at the LHC

- **searches need predictions for production and decays of SUSY particles**



- **NLO calculations required for stable predictions**



top-squark pair production at the LHC

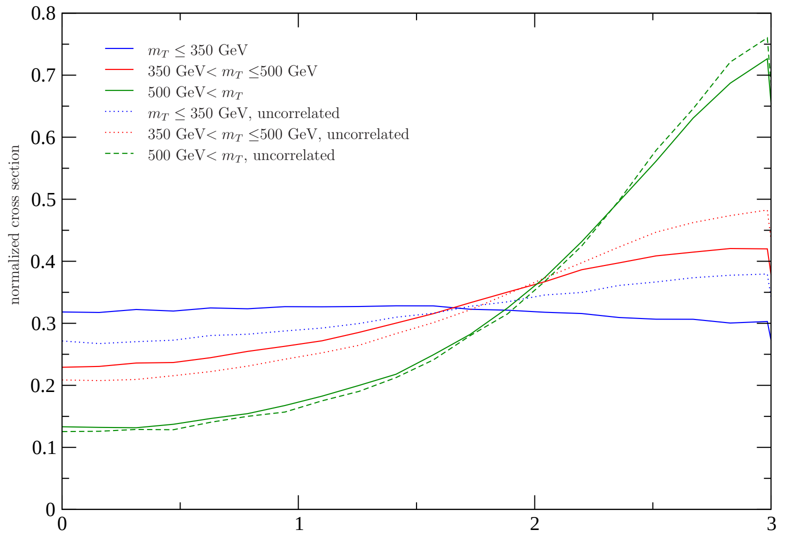
$$pp \to \tilde{t}_1 \tilde{t}_1^*$$

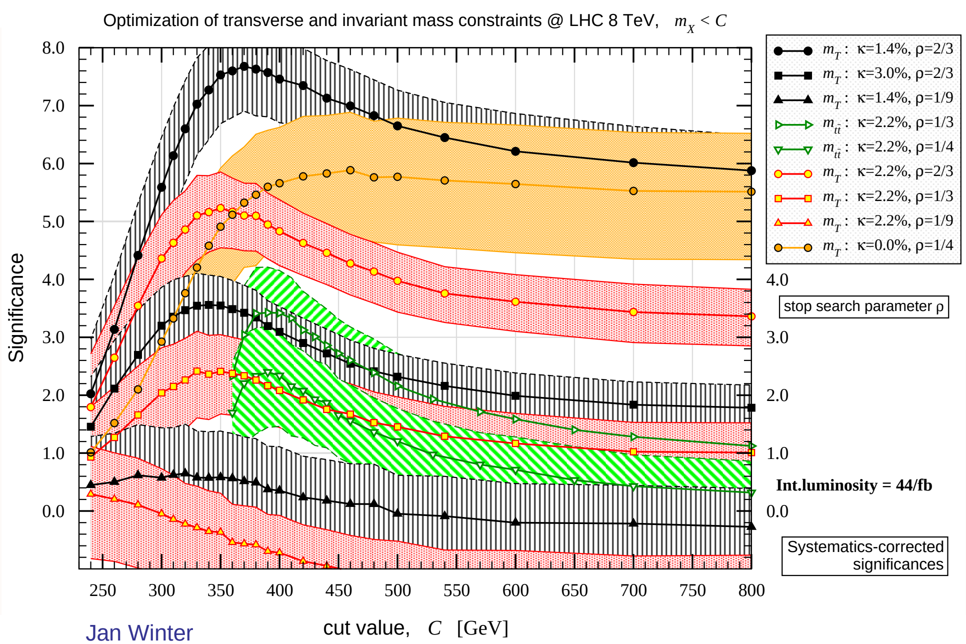
QCD and electroweak NLO

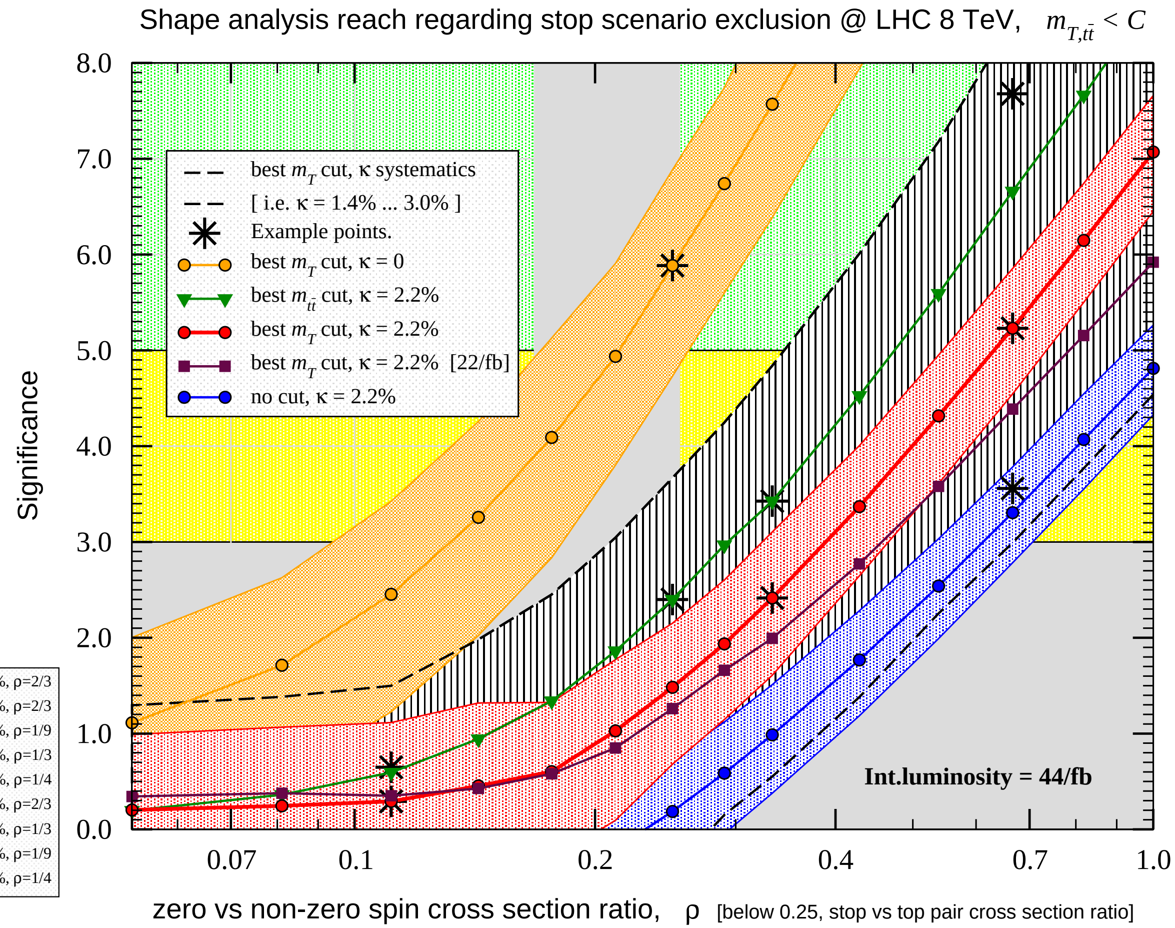
[Hollik, Lindert, Mirabella
JHEP 09(2014)022]

Spin correlations in top quark pair production

Use the shape of the lepton azimuthal angle separation in the dilepton channel to search for contamination from light stop quarks.







[IN PREP; MAHBUBANI, PARKE, RZEHAK, WINTER]

Summary.

The activities of the group cover a large spectrum of LHC phenomenology
in and beyond the Standard Model.

Precision calculations: automated NLO corrections, also for multi-scale and multi-leg processes,
Higgs masses and cross sections in the MSSM, top-squark pair production.

Development of computational tools that are useful for and being used by the entire community.

Development of new analytical/numerical methods
at the calculational frontier (NNLO/multi-loops).

Great collaboration with Monte Carlo generator experts.
There is nice cross-talk between MPI experimentalists and pheno-group members already.
An increase in this exchange between EXP & TH would be something we are definitely looking forward to.

The end. (:o) Thank You.

Magnus/Dyson series for Master Integrals

[Argeri, Di Vita, Mastrolia, Mirabella, Schlenk, Schubert, Tancredi JHEP 1403 (2014) 082]

A modern multi-loop and -leg calculation is done in three steps

1. Find integral basis for the process IBP, Multiloop integrand reduction (MIR)
2. Determine “coordinates” in such basis Feynman diags., Generalized unitarity, OPP, MIR
3. Calculate basis elements Feynman/Schwinger, Mellin-Barnes, Differential Equations

Differential Equations for d-dimensional Feynman Integrals of a given topology

IBP relations $\Rightarrow$ **most integrals linearly dep.** Choose indep “Master Integrals”, functions of:

1. the kinematic invariants x_i built with the external momenta
2. the internal masses
3. the number of spacetime dimensions d

IBP relations $\Rightarrow$ MIs obey **system of first order linear differential equations in** ∂_{x_i}
Conjecture: basis choice can simplify the solution of such systems! [Henn 13]

bad choice

$$\partial_{x_i}\vec{g}(\vec{x},\epsilon) = A_{x_i}(\vec{x},\epsilon)\vec{g}(\vec{x},\epsilon)$$

good choice (if $\exists$)

$$\partial_{x_i}\vec{g}(\vec{x},\epsilon) = \epsilon\, A_{x_i}(\vec{x})\vec{g}(\vec{x},\epsilon)$$

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with a good (**canonical**) choice:

- integration (order by order in ϵ) is just algebra, iterated $\int$ over kernels
- system dictates form of the integration kernels and analytic properties
- most of the boundary conditions can be obtained *algebraically* by exploiting analytical properties of the solution (regularity at pseudothresholds etc)

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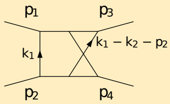
How to find good basis? Is it possible to proceed in *algorithmic* way? Still open question.

A first proposal: use **Magnus Exponential** to turn ϵ-linear systems into canonical systems
[Argeri, Di Vita, Mastrolia, Mirabella, Schlenk, Schubert, Tancredi JHEP 1403 (2014) 082]

Two-loop non-planar box [Tausk 99; Anastasiou, Gehrmann, Oleari, Remiddi, Tausk 00]

[Argeri, Di Vita, Mastrolia, Mirabella, Schlenk, Schubert, Tancredi JHEP 1403 (2014) 082]

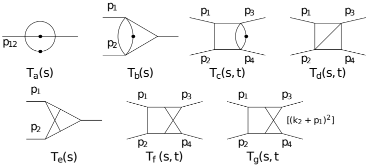
12 MI's for the crossed topology



$x = -\frac{t}{s}, \quad s > 0\,, t < 0\,, |s| > |t|$

This choice of the MIs f's obeys an ϵ-**linear DE**

$$f_1 = \epsilon^2\, s\, T_a(s)\,, \quad f_2 = \epsilon^2\, t\, T_a(t)\,, \quad f_3 = \epsilon^2\, u\, T_a(u)\,,$$
$$f_4 = \epsilon^3\, s\, T_b(s)\,, \quad f_5 = \epsilon^3\, s\, t\, T_c(s,t)\,, \quad f_6 = \epsilon^3\, s\, u\, T_c(s,u)\,,$$
$$f_7 = \epsilon^4\, u\, T_d(s,t)\,, \quad f_8 = \epsilon^4\, s\, T_d(t,u)\,, \quad f_9 = \epsilon^4\, t\, T_d(u,s)\,,$$
$$f_{10} = \epsilon^4\, s^2\, T_e(s)\,,$$
$$f_{11} = \epsilon^4\, s\, t\, u\, T_f(s,t) - \frac{3}{4\, s\,(4\epsilon+1)} \left[\epsilon^2 \left(s^2\, T_a(s) + t^2\, T_a(t) + u^2\, T_a(u)\right) - 4\epsilon^4 \left(u^2\, T_d(s,t) + s^2\, T_d(t,u) + t^2\, T_d(u,s)\right)\right],$$
$$f_{12} = \epsilon^4\, s\, t\, T_g(s,t) - \frac{3}{8\, u\,(4\epsilon+1)} \left[\epsilon^2 \left(s^2\, T_a(s) + t^2\, T_a(t) + u^2\, T_a(u)\right) - 4\epsilon^4 \left(u^2\, T_d(s,t) + s^2\, T_d(t,u) + t^2\, T_d(u,s)\right)\right],$$



$$\partial_x f(\epsilon, x) = \left(A_0(x) + \epsilon\, A_1(x)\right) f(\epsilon, x) \qquad A_i(x) = \frac{M_{i,1}}{x} + \frac{M_{i,2}}{1-x}$$

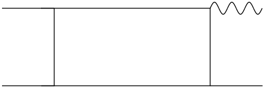
Magnus Exponential $\Rightarrow$ get rid of A_0, g's obey a canonical DE

$$\partial_x g(\epsilon, x) = \epsilon\, \hat{A}_1(x)\, g(\epsilon, x) \qquad \hat{A}_1(x) = \frac{M_1}{x} + \frac{M_2}{1-x}$$

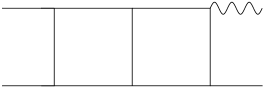
$$M_1 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{3}{2} & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{3}{2} & -3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-6 & -6 & -\frac{9}{2} & 0 & -4 & -2 & -18 & -12 & -12 & 1 & 1 & -2 \\
\frac{3}{4} & \frac{9}{4} & -\frac{21}{4} & 3 & 2 & -3 & 12 & -6 & -18 & 0 & 0 & -2
\end{pmatrix}$$

$$M_2 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{3}{2} & 0 & 3 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{3}{2} & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 \\
\frac{1}{2} & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-6 & -6 & -\frac{9}{2} & 0 & -4 & -2 & -18 & -12 & -12 & 1 & 1 & -2 \\
-\frac{21}{4} & \frac{9}{4} & -\frac{27}{4} & -6 & 2 & -4 & 12 & -6 & -24 & 1 & -1 & 0
\end{pmatrix}$$

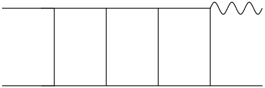
Three-loop Higgs + 1Jet ladder-box [Di Vita, Mastrolia, Schubert, Yundin JHEP 1409 (2014) 148]



4 MI's [Kindergarten]

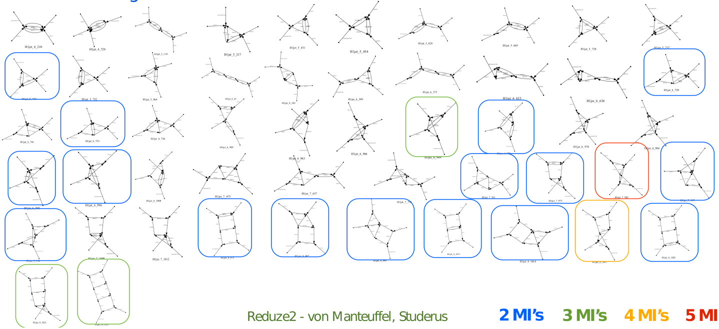


18 MI's [Gehrmann, Remiddi 00]



85 MI's!!

- 85 Master Integrals



Reduze2 - von Manteuffel, Studerus

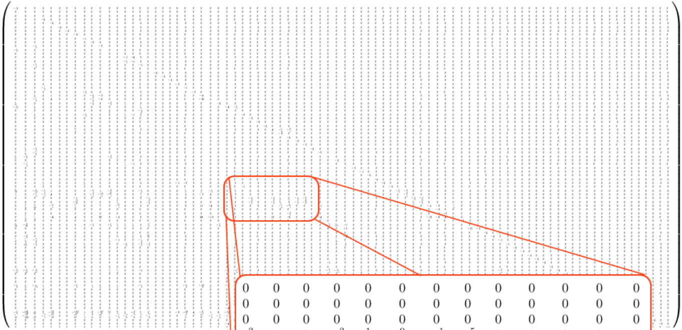
2 MI's **3 MI's** **4 MI's** **5 MI's**

now 2 integration variables, not just two "letters" $\{x, 1-x\}$ but a bigger *alphabet* $\{x, 1-x, y, 1-y, 1-x-y, x+y\}$

own GHPL code + REDUZE [Studerus, Studerus and von Manteuffel] + GiNaC [Bauer, Frink and Kreckel; Vollinga and Weinzierl]

Three-loop Higgs + 1Jet ladder-box [Di Vita, Mastrolia, Schubert, Yundin JHEP 1409 (2014) 148]

$1/x$



$$
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{3}{2} & 0 & 0 & -\frac{3}{2} & \frac{1}{2} & \frac{9}{4} & -\frac{1}{2} & -\frac{5}{2} & 0 & 0 & 0 & 0 & 0 \\
-\frac{3}{2} & 0 & 0 & -\frac{7}{2} & \frac{1}{3} & 2 & -\frac{1}{2} & -\frac{5}{2} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 5 & -\frac{1}{6} & -\frac{11}{4} & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 12 & 0 & -6 & 0 & 0 & 0 & -4 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & \frac{1}{12} & -1
\end{pmatrix}
$$

Three-loop Higgs + 1Jet ladder-box [Di Vita, Mastrolia, Schubert, Yundin JHEP 1409 (2014) 148]