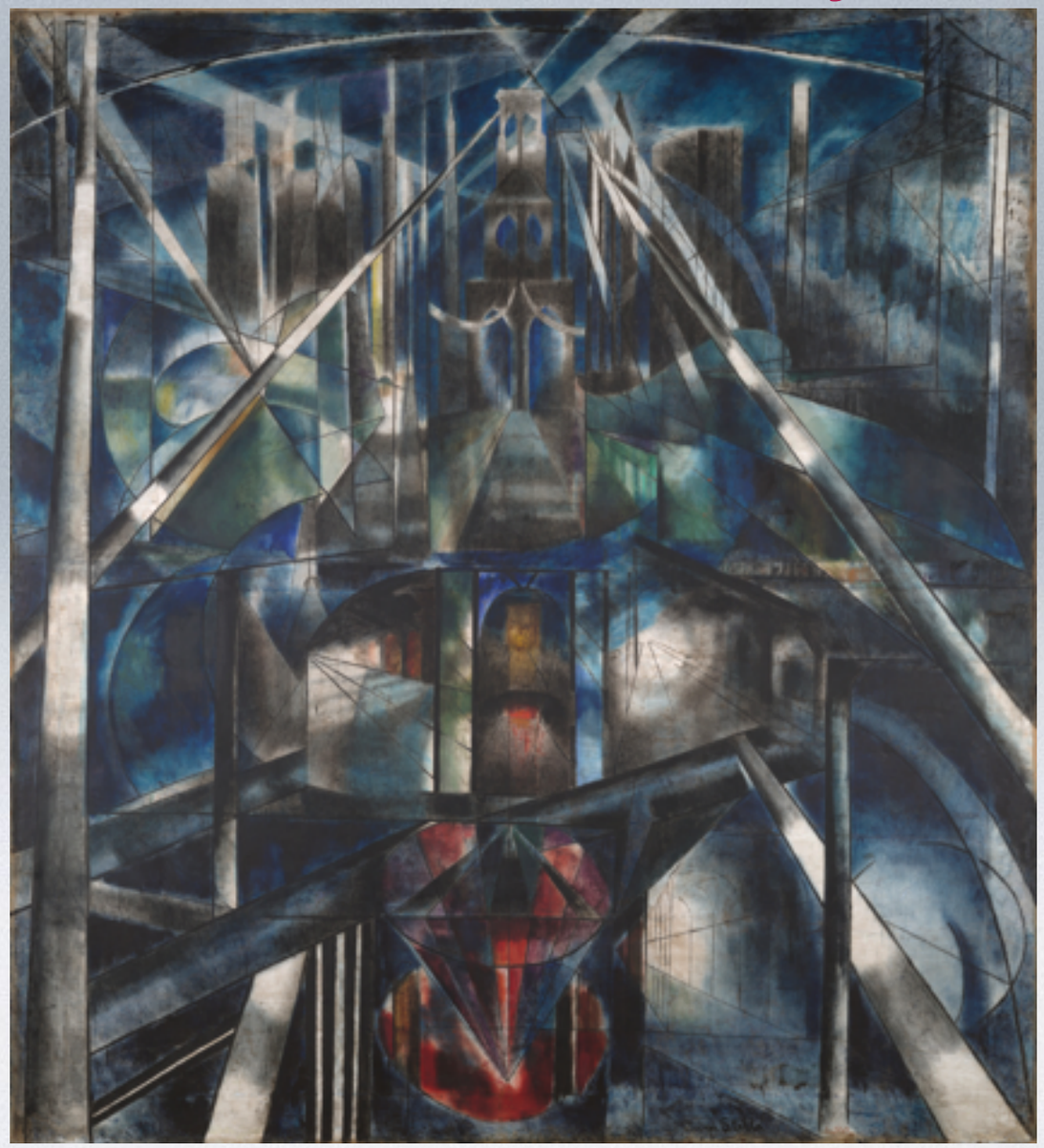
PUSHING THE PRECISION FRONTIER IN COLLIDER PHYSICS

Gudrun Heinrich

Max Planck Institute for Physics, Munich



CERN Colloquium, June 21, 2017

higgstools

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

A note on history

who was the first theorist? (in middle Europe)

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He sought a mathematical understanding of the universe

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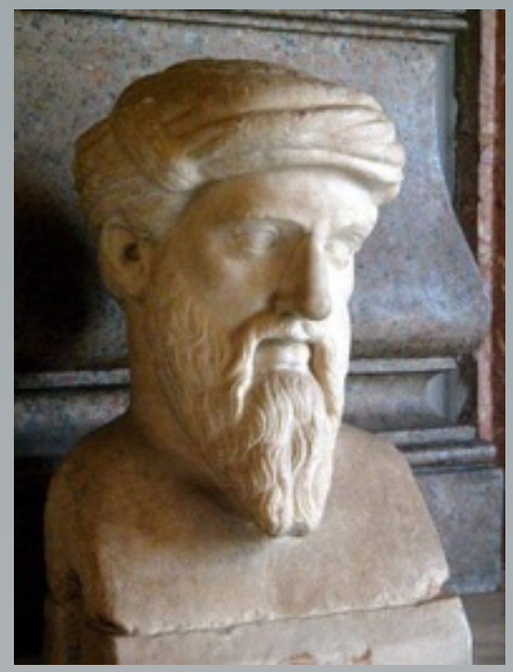

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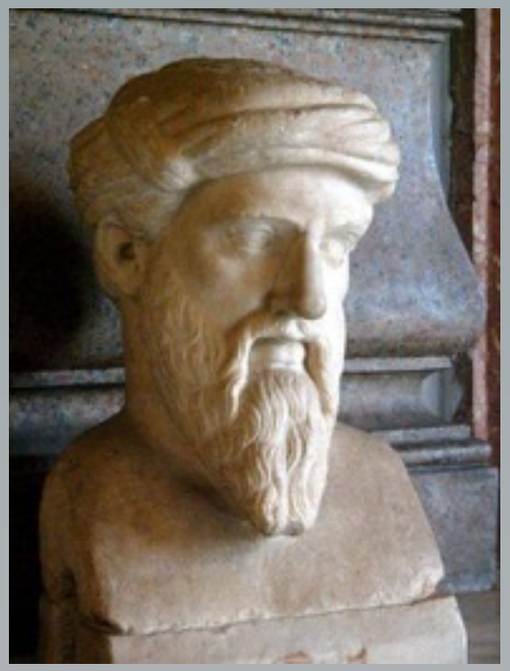

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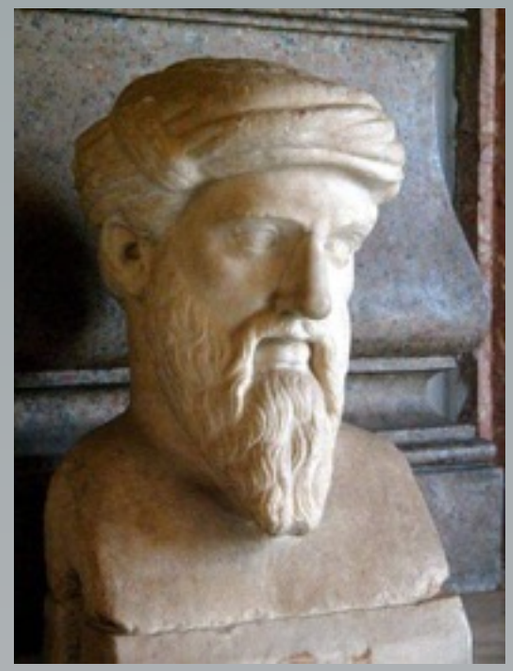
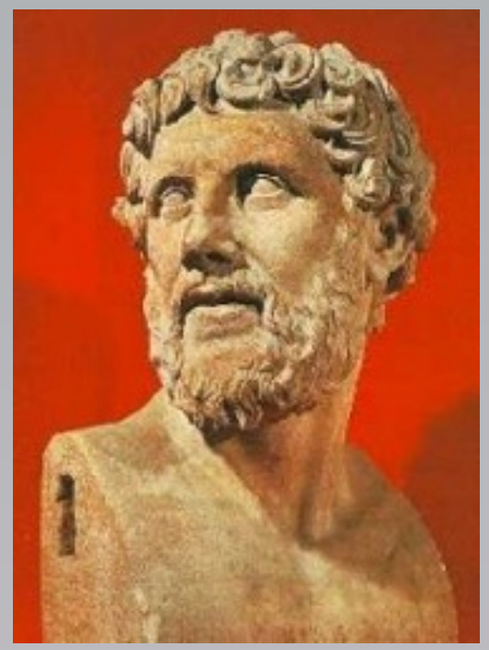


first particle physicist?

Democritos (460 - 370 B.C.)

Thought that the universe consists of empty space and an (almost) infinite number of invisible particles, called **atoms**



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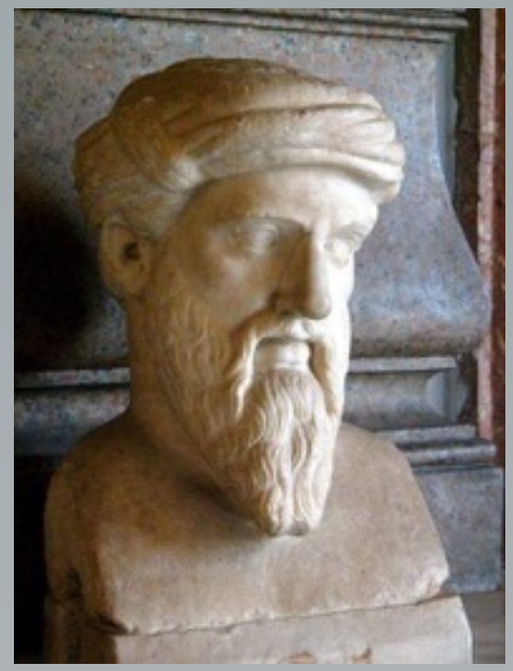

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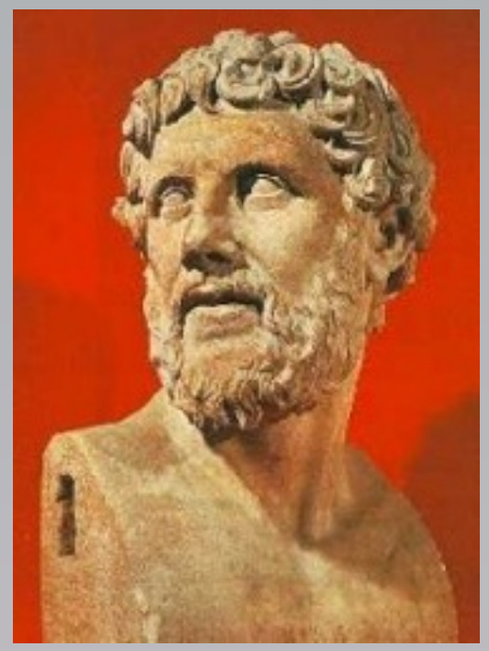

first experimental particle physicist?

… probably lived in Scotland …

pioneer in middle Europe:

Roger Bacon (1214 - 1294 AD)

- taught that in order to learn the secrets of nature we must first **observe**
- provided the method of deductive theories using evidence from the natural world

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⋮

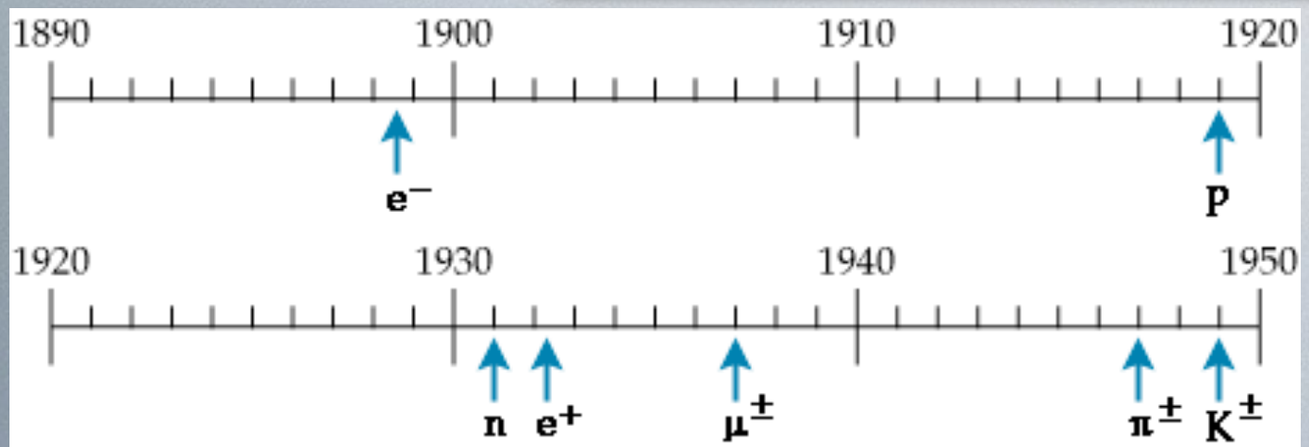
1874: George Stoney develops a theory of the electron and estimates its charge

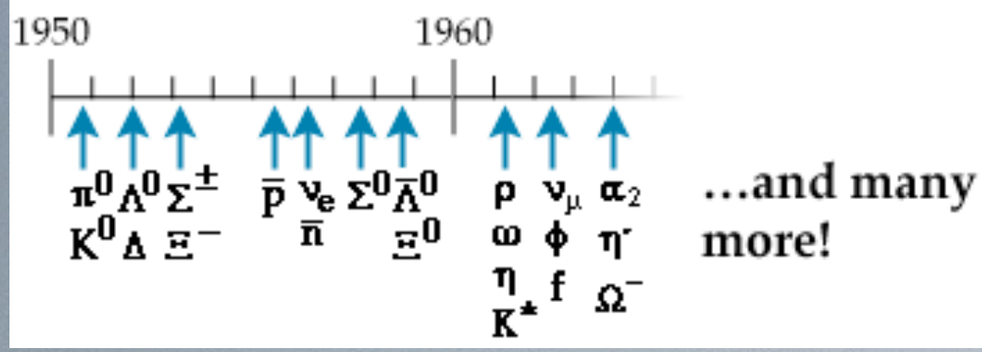
1898: Joseph Thompson measures the electron mass

1909: Robert Millikan measures the electron charge

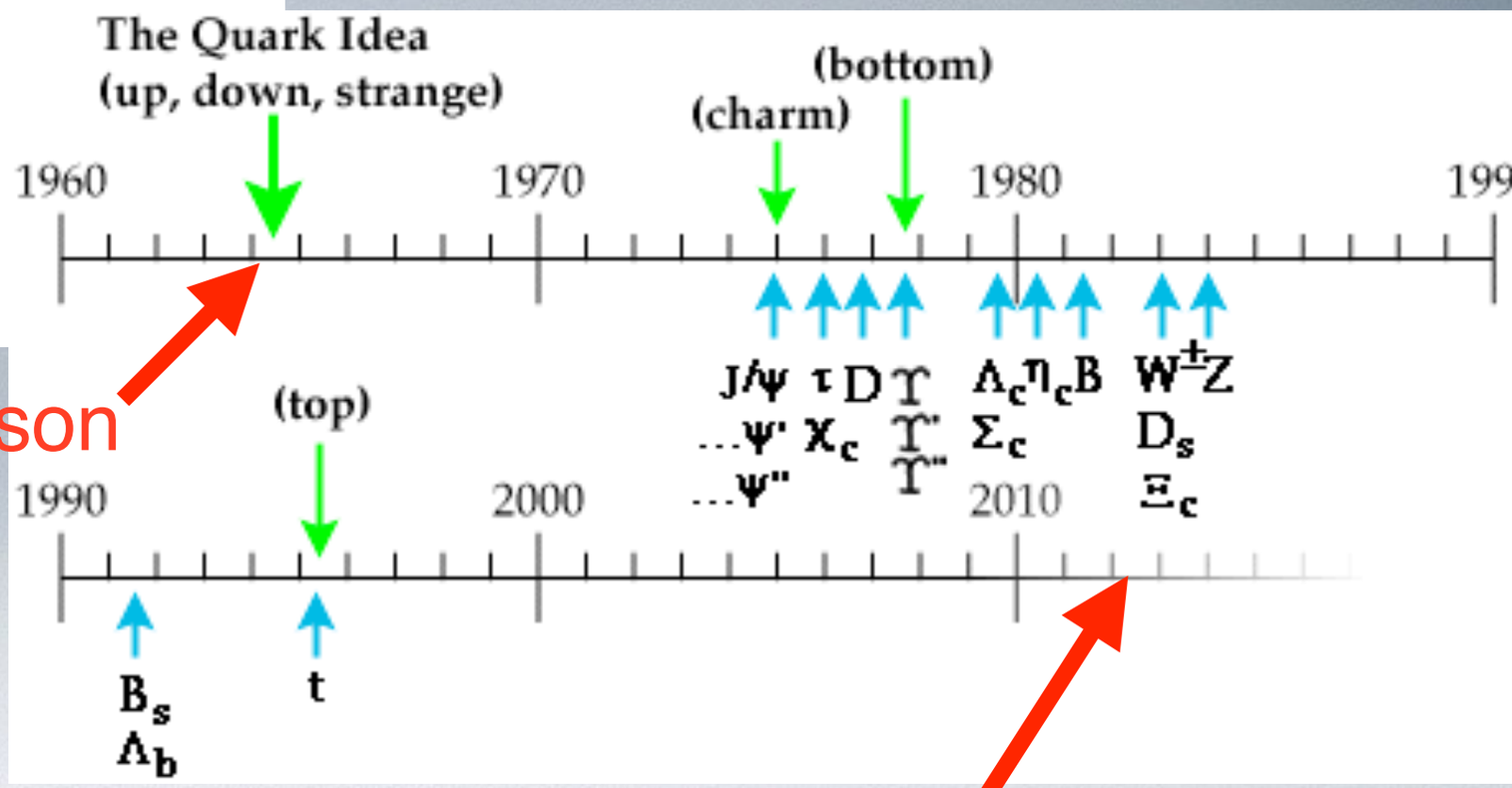
24 (mass) 35 (charge) years after the prediction!

Particle Discoveries





…and many more!

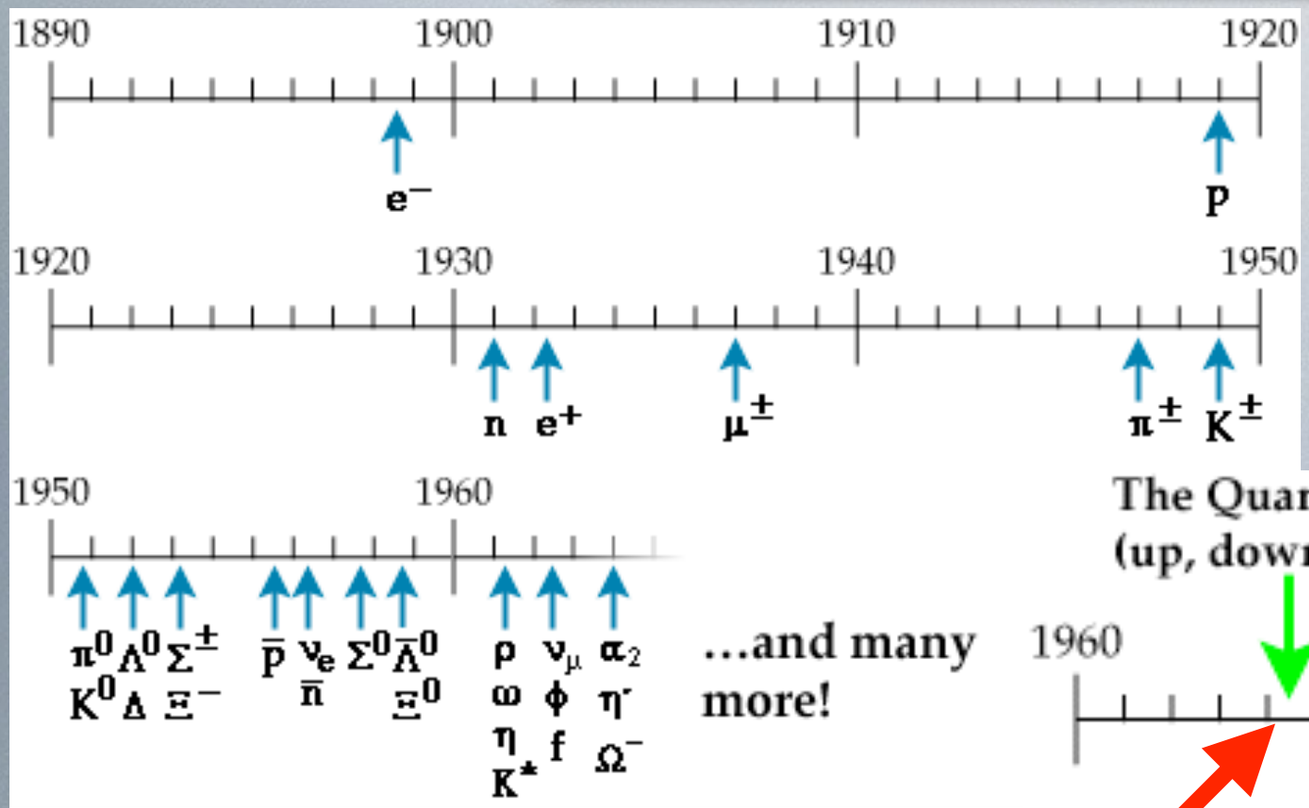


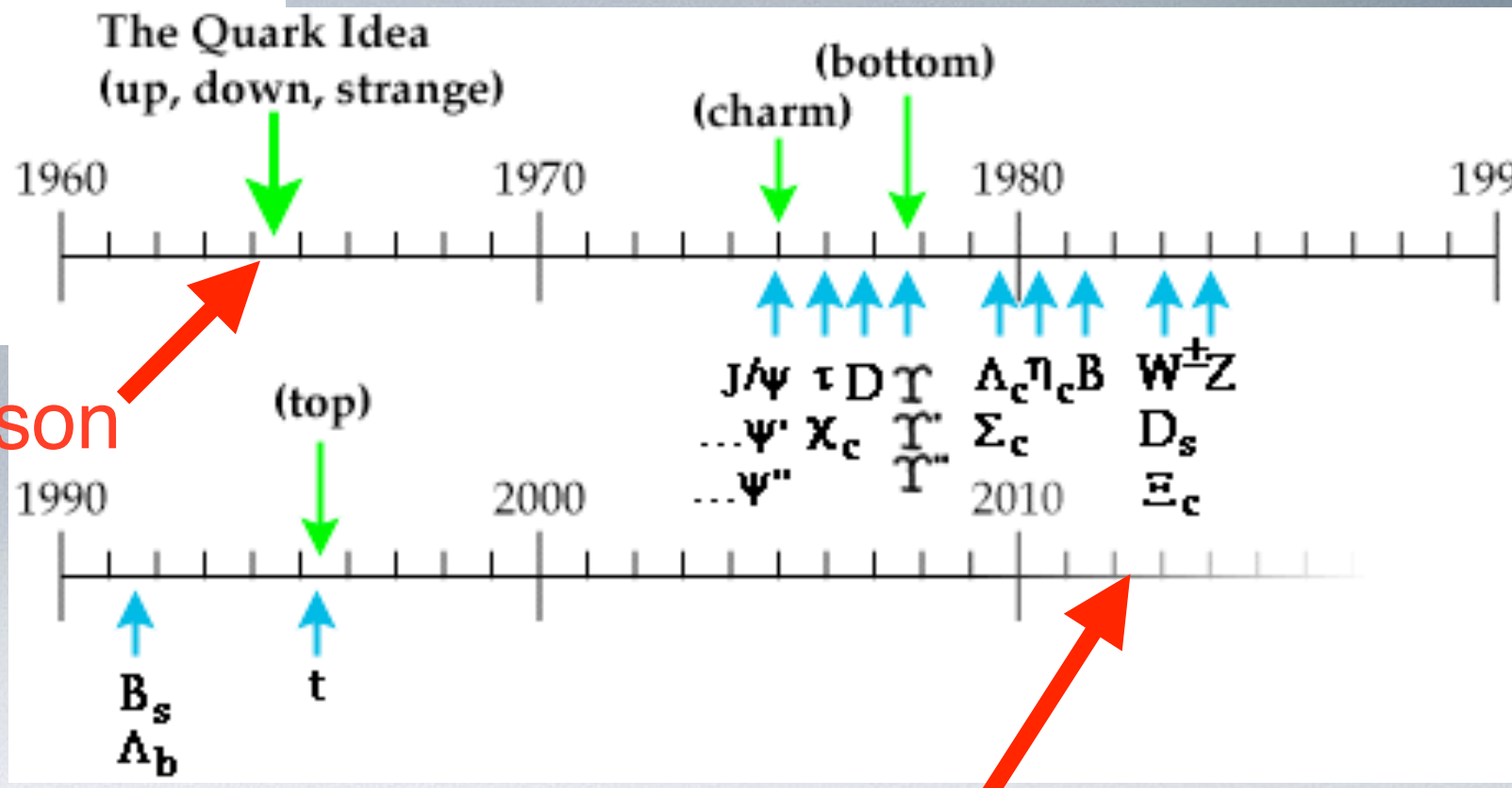
"prediction" of the Higgs boson

mass: 48 years after the prediction

Higgs boson discovery

Particle Discoveries





"prediction" of the Higgs boson

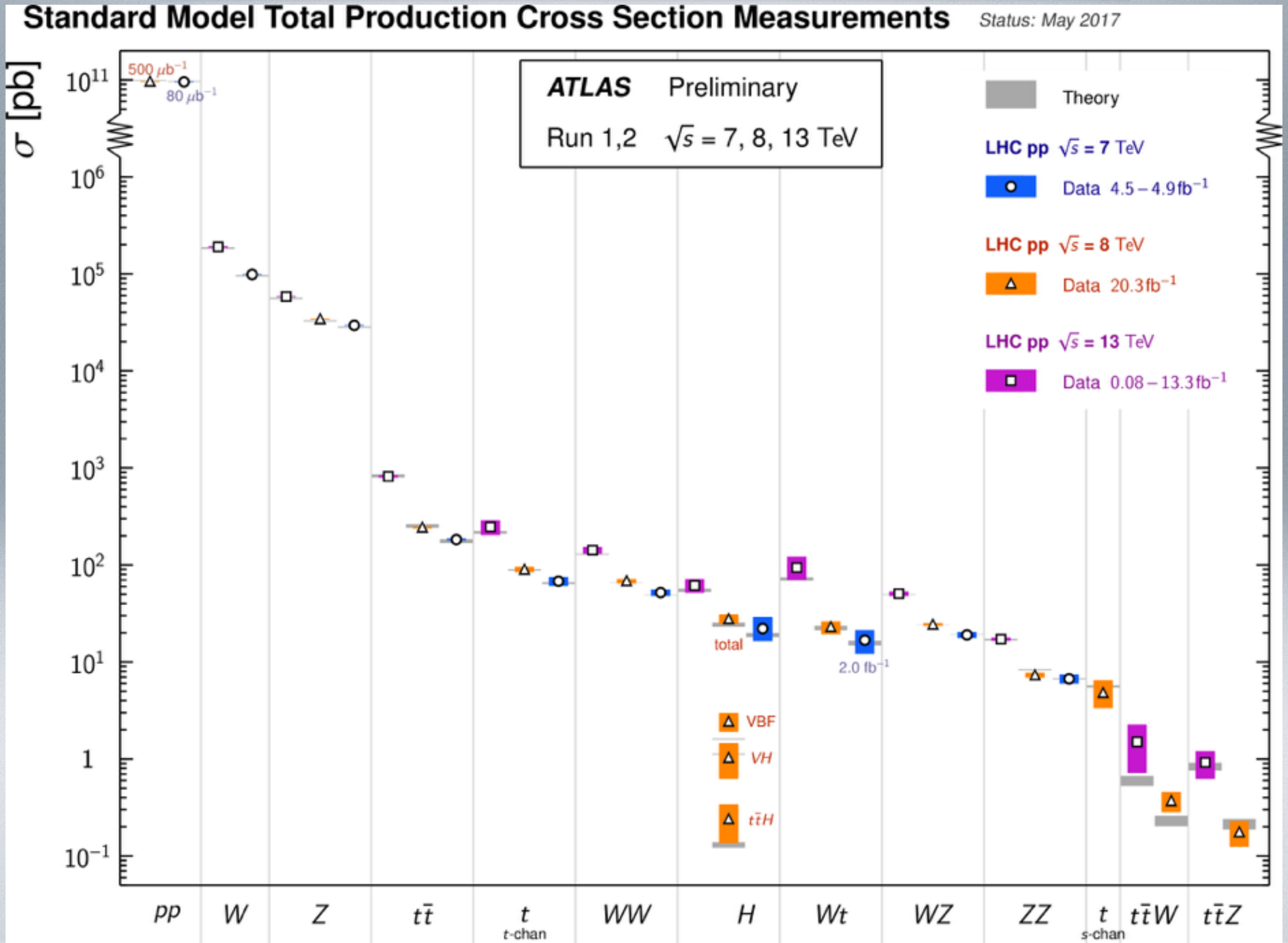
Higgs boson discovery

mass: 48 years after the prediction

self-coupling measurement: 65 years after the prediction

reveals that Higgs boson is not the SM Higgs

status of the Standard Model today



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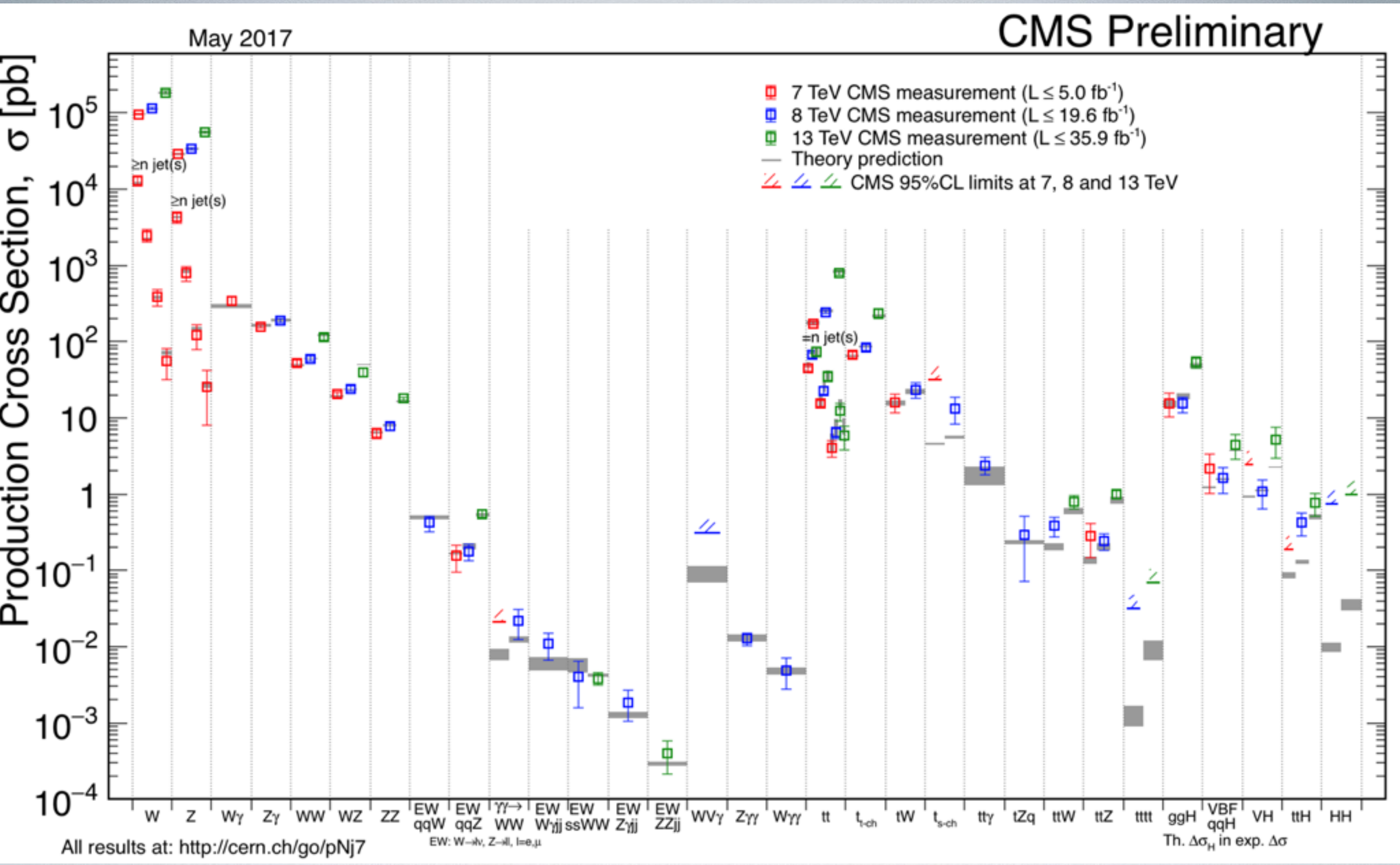

Prospects

"There is nothing new to be discovered in physics now.
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“In this field, almost everything is already discovered,
and all that remains is to fill a few unimportant holes.”

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"In this field, almost everything is already discovered,
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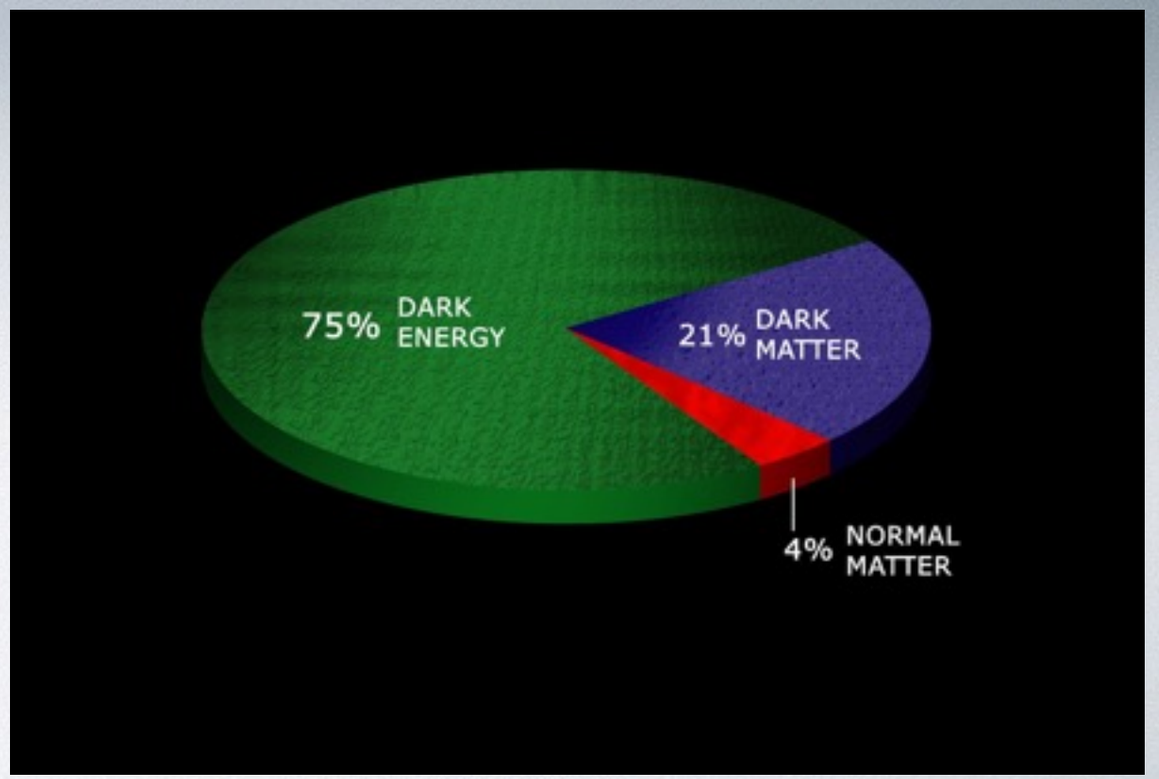
J.P.G. von Jolly, 1809-1884, Professor of Physics,
to Max Planck (considering to study physics)

(Planck replied that he did not wish to discover new things,
but only to understand the known fundamentals of the field)

Progress

- situation nowadays:
- we are well aware of unsolved problems in fundamental physics, e.g.

  - too many “ad hoc” parameters in the SM
  - hierarchy problem
  - quantum theory of gravitation
  - dark matter
  - baryon asymmetry
  - inflation/inflaton
  - cosmological constant
  - ⋮



What can we do from the collider physics side?

- increase the energy (new collliders; limited by technical and financial resources)
- increase the precision (LHC, interplay with theorists)
- have new ideas (theory and experiment)

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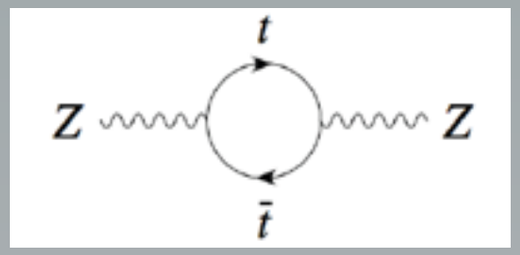
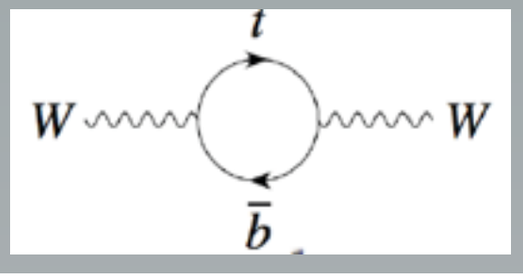
Example for the importance of precision measurements/calculations

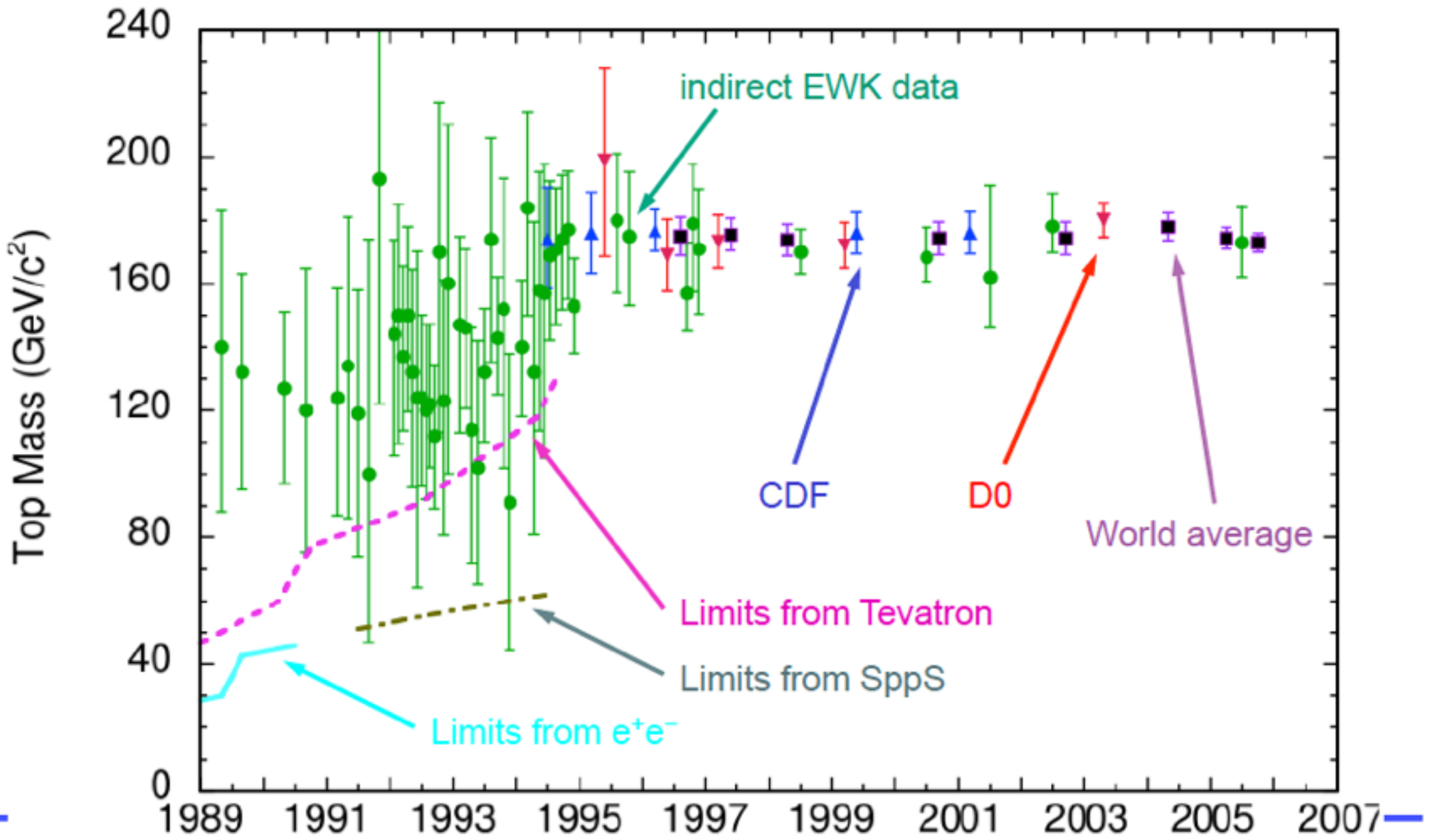
top quark mass enters electroweak precision observables

indirectly via loop effects



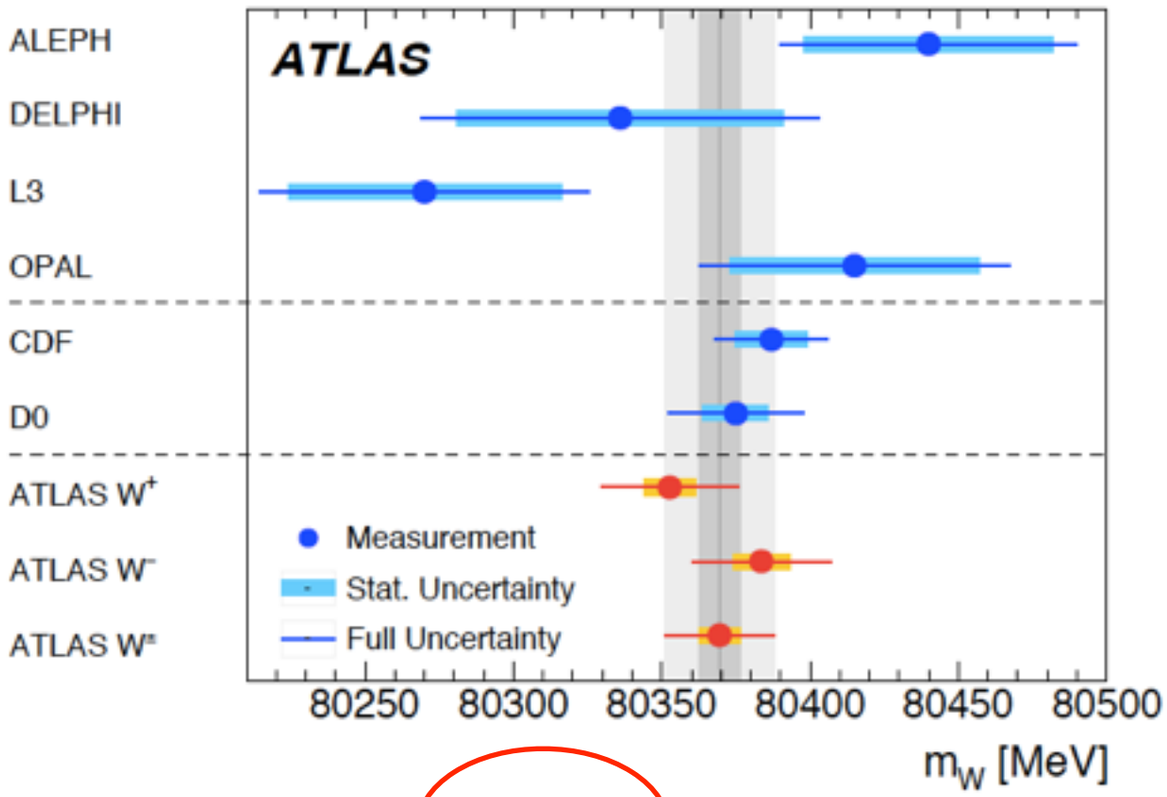


- Limits or estimate vs time



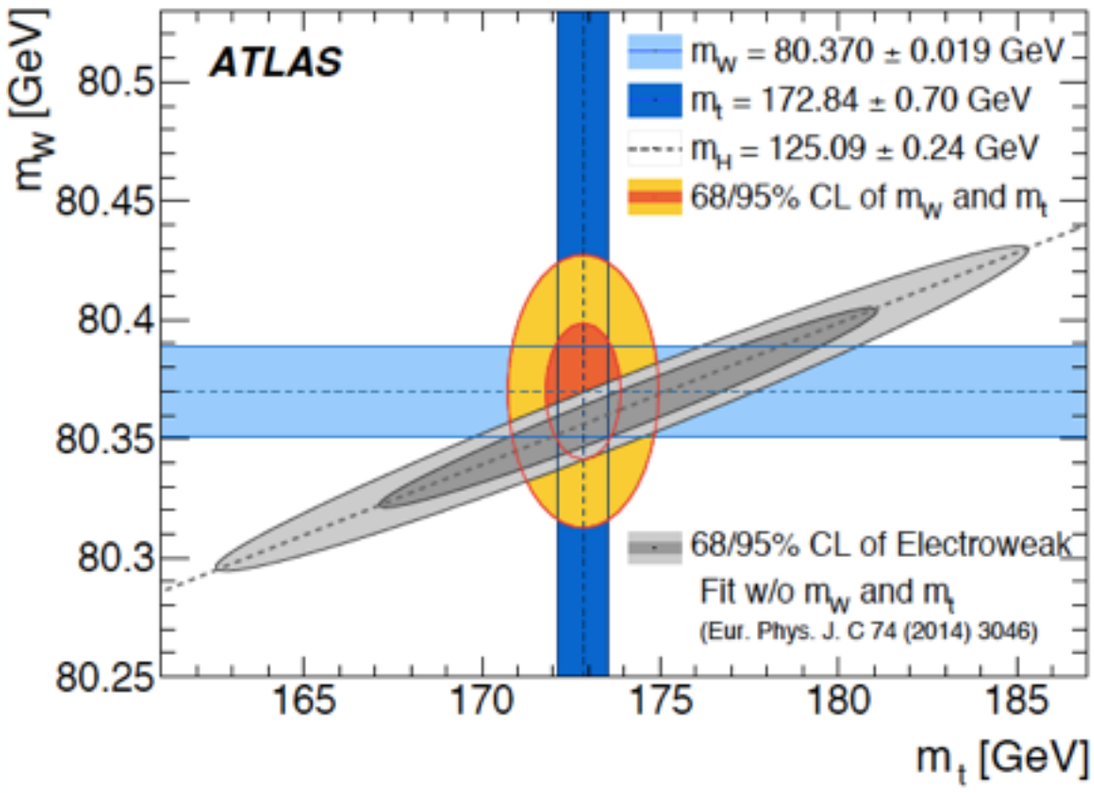
precision measurements: W boson mass

MW experimental values



$m_W = 80370 \pm 19$ MeV ATLAS arXiv:1701.07240

Global EW fit compared to ATLAS results



$m_W = 80356 \pm 8$ MeV

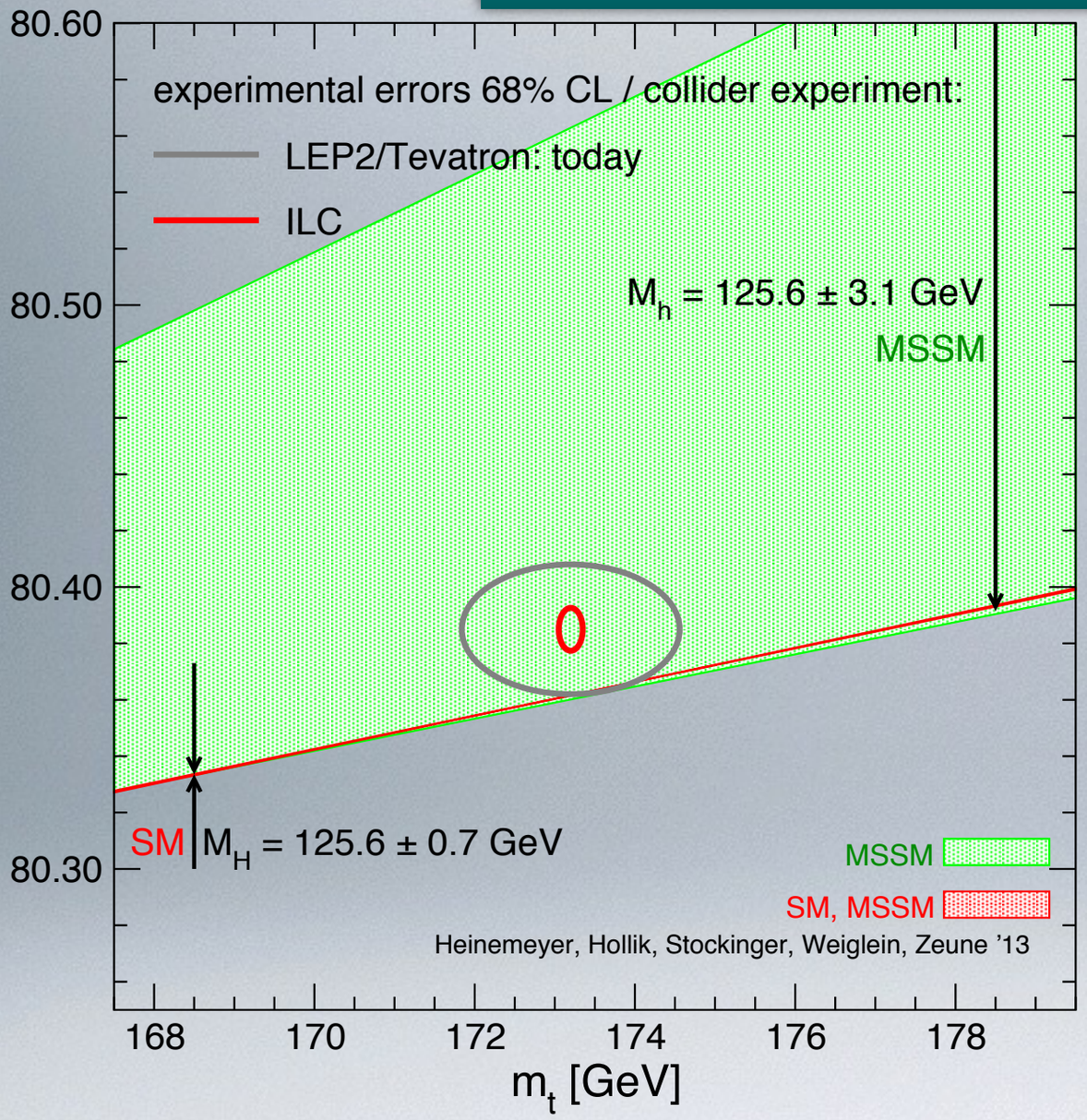
A. Vicini, LHCP 2017

extraction of M_W from **shape** of p_T^l distribution

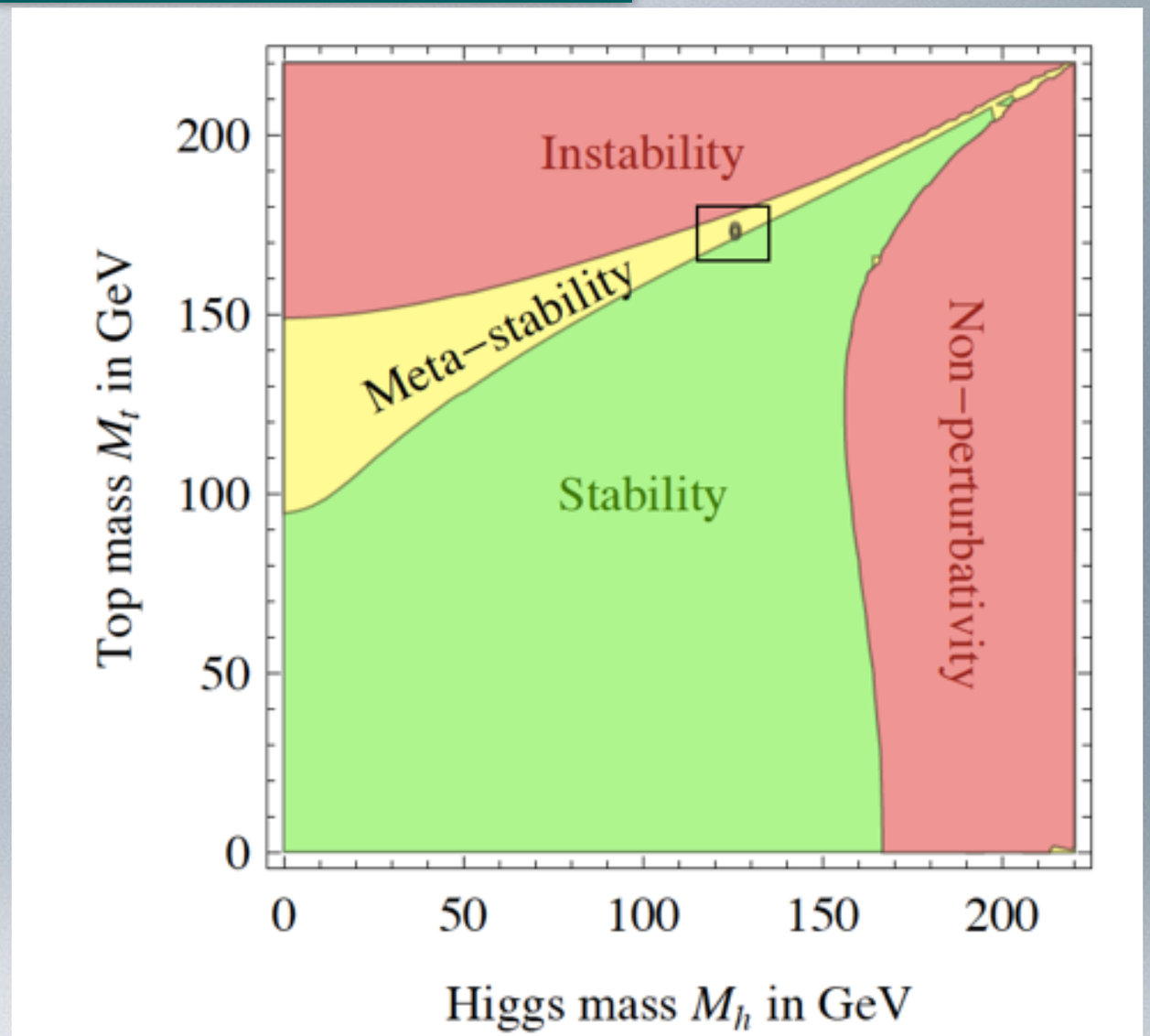
distortion of shape at permil level leads to $\mathcal{O}(10\,\mathrm{MeV})$ shift in mass

$\Rightarrow$ control of radiative corrections distorting the shape extremely important!

importance of precision



Heinemeyer, Hollik, Stöckinger, Weiglein, Zeune '13



Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

there is a lot we can learn without immediate discoveries of new particles

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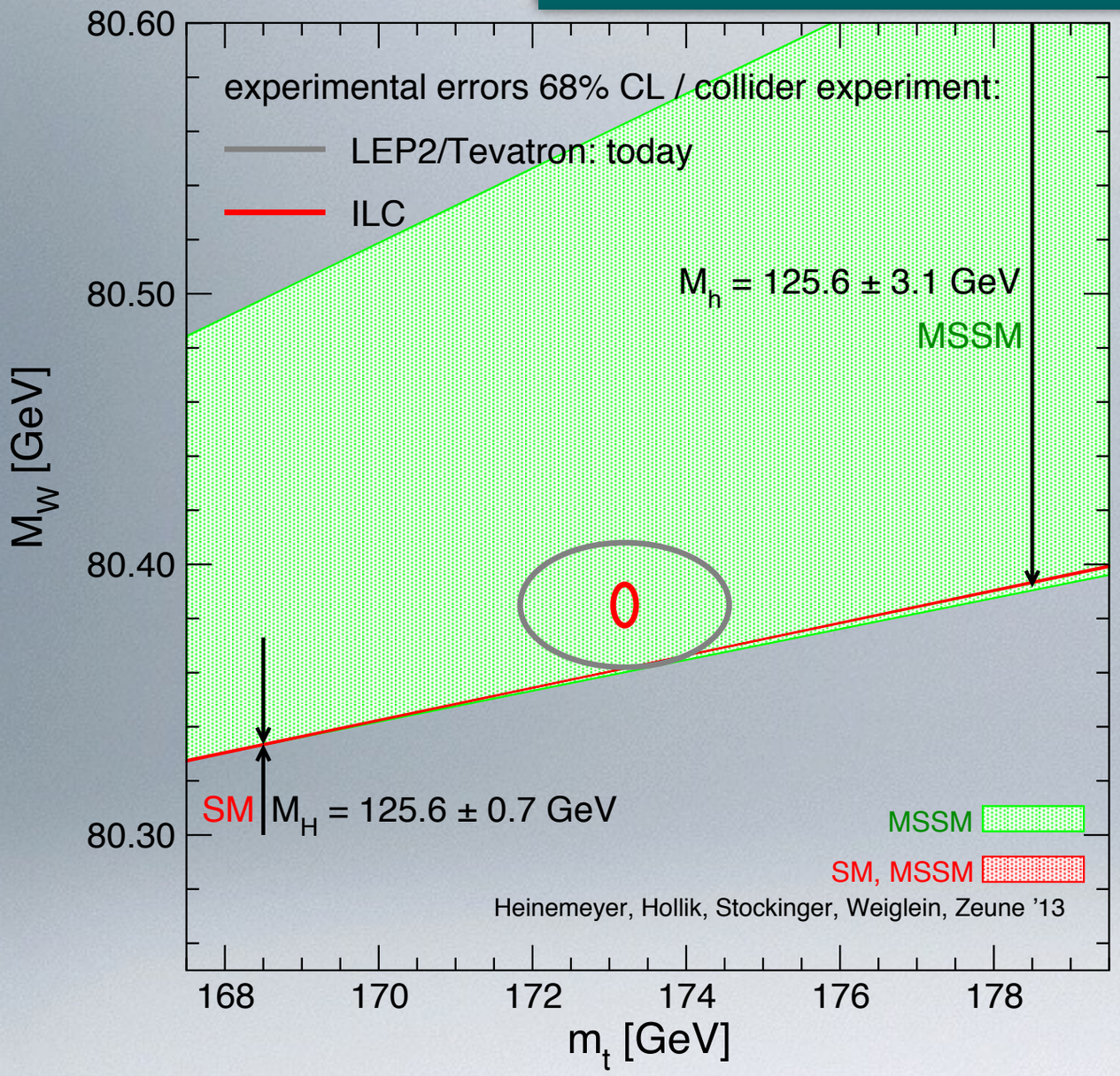

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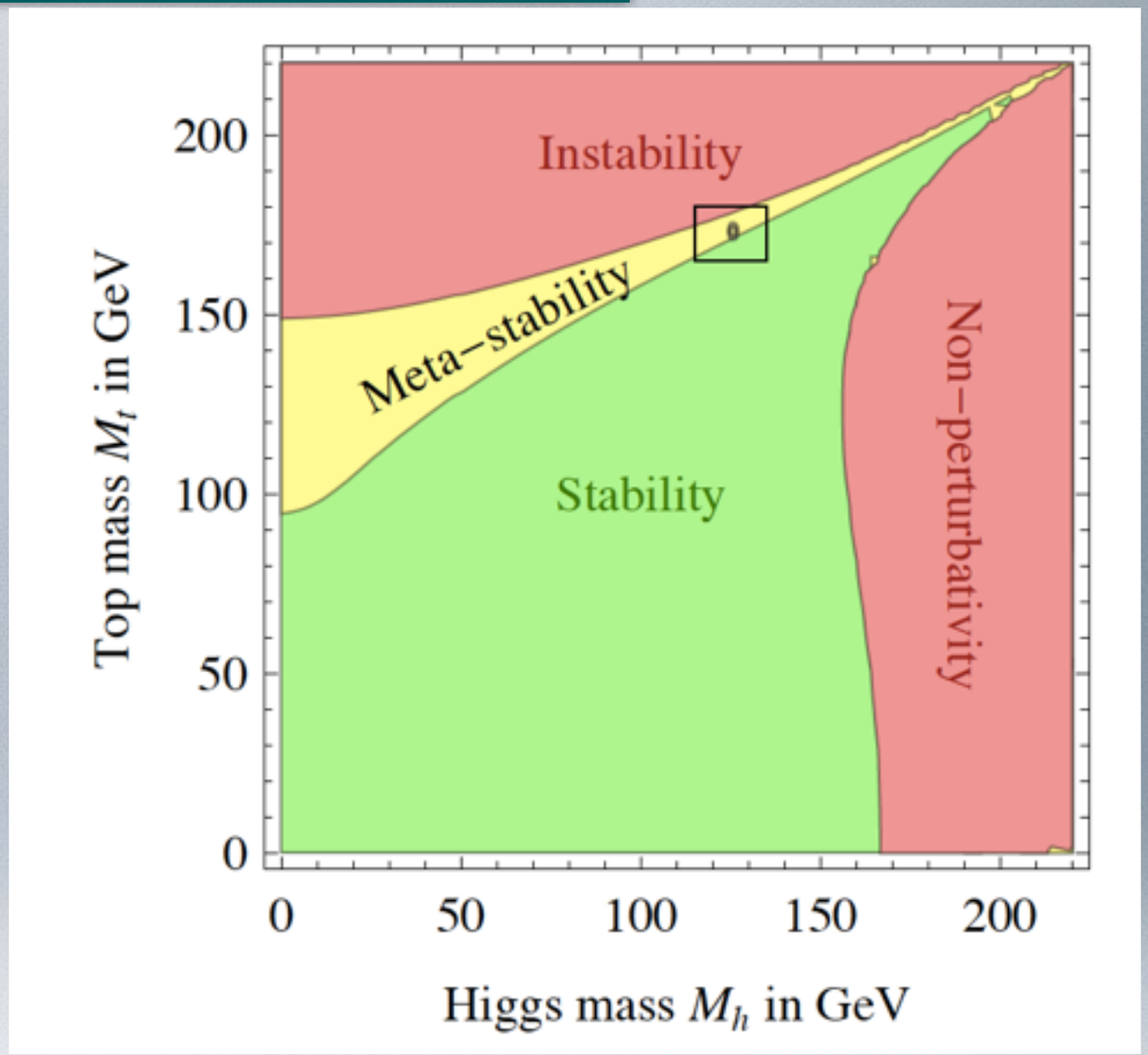

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there is a lot we can learn without immediate discoveries of new particles

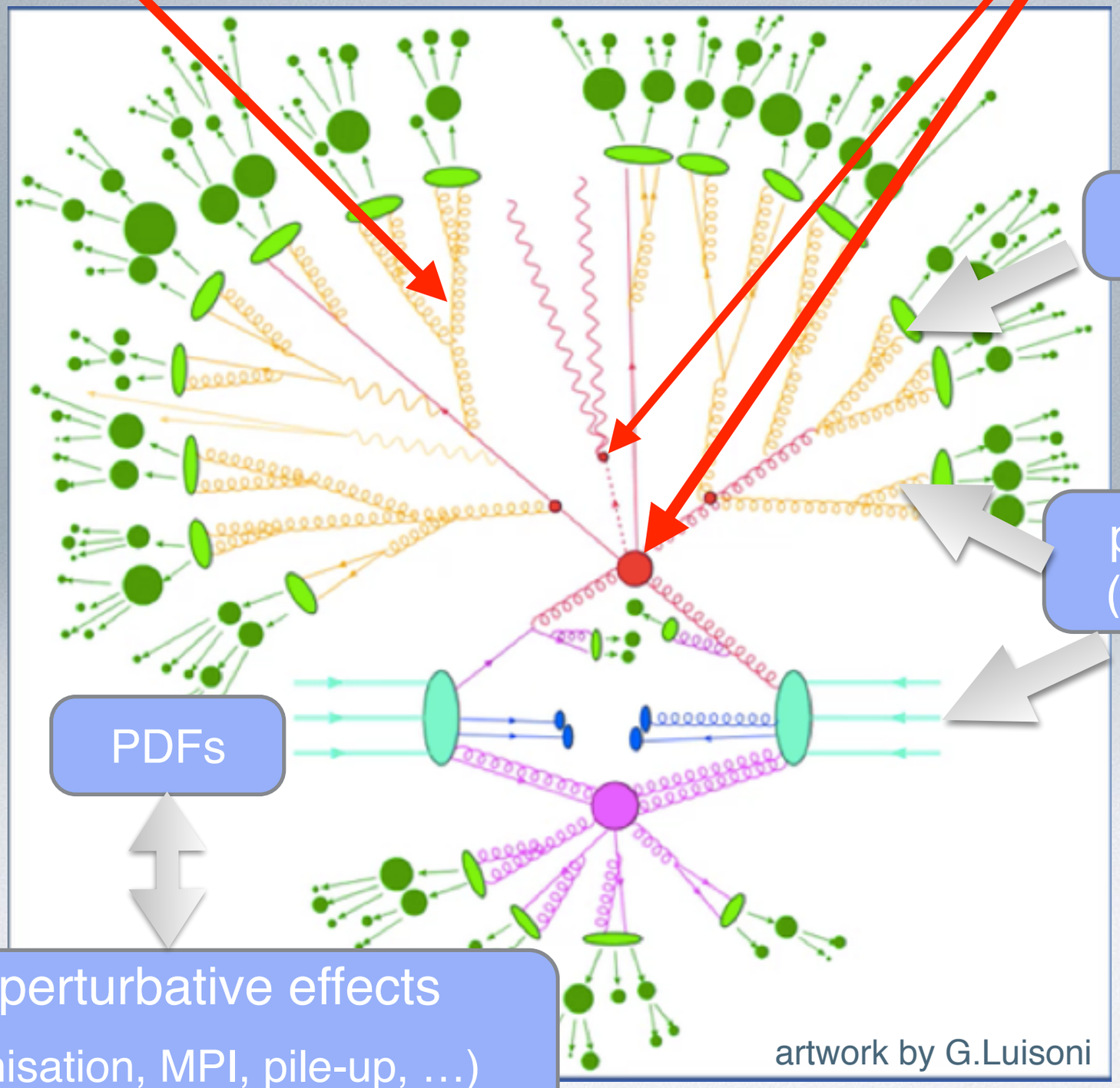
"If you became a particle physicist because you want to discover particles, you better start thinking of what else you could do to be happy in your life." Nima Arkani-Hamed, LHCP2017

The precision frontier

parton shower

resummation

fixed order calculations
NLO (QCD+EW), NNLO, …



quark mass effects

parametric uncertainties
(e.g. couplings, masses)

PDFs

non-perturbative effects
(hadronisation, MPI, pile-up, …)

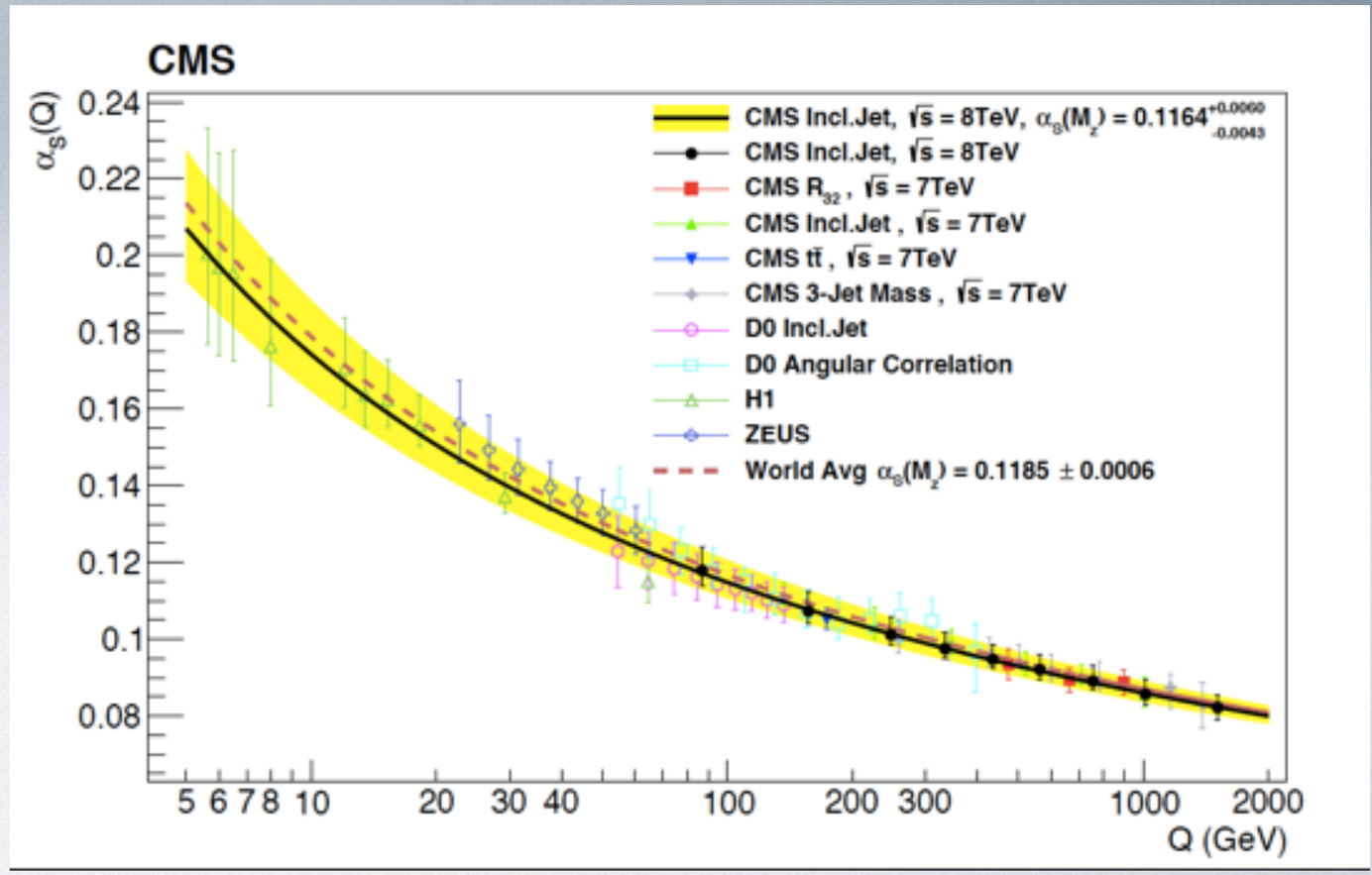
theorist's basic toolbox

- local gauge invariance $SU(2) \times U(1) \times SU(3)_c$
- renormalizability
- perturbative expansions, e.g.

$$\hat{\sigma} = \alpha_s^k(\mu) \left[\hat{\sigma}^{\mathrm{LO}} + \alpha_s(\mu)\, \hat{\sigma}^{\mathrm{NLO}}(\mu) + \alpha_s^2(\mu)\, \hat{\sigma}^{\mathrm{NNLO}}(\mu) + \ldots \right]$$

important principles of QCD:

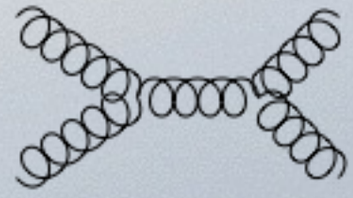
- asymptotic freedom
- factorization



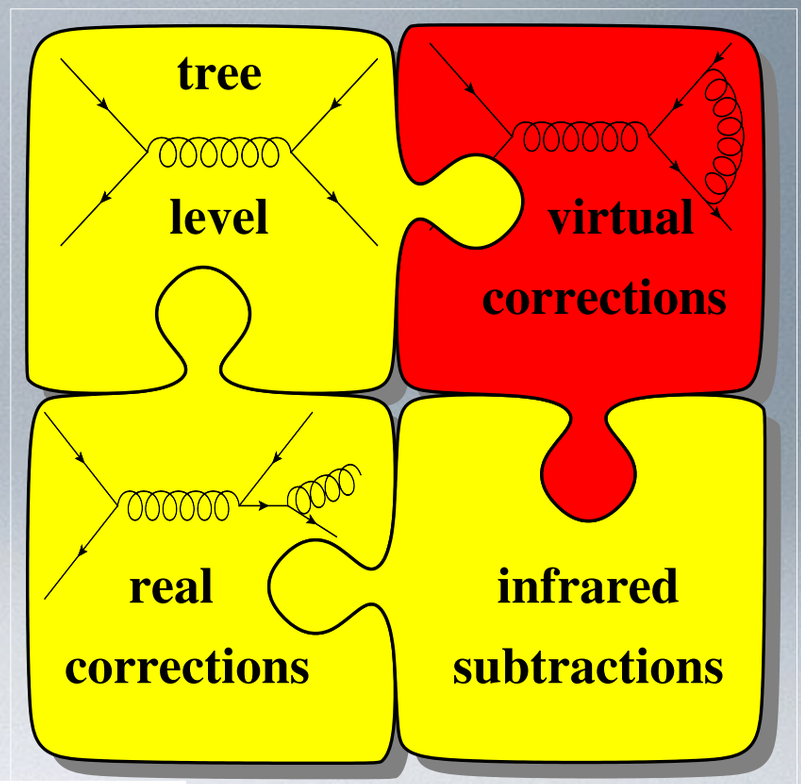
QCD corrections: building blocks

example 2 to 2 scattering

LO: usually tree level diagrams



NLO: one loop (virtual) + extra real radiation + subtraction terms



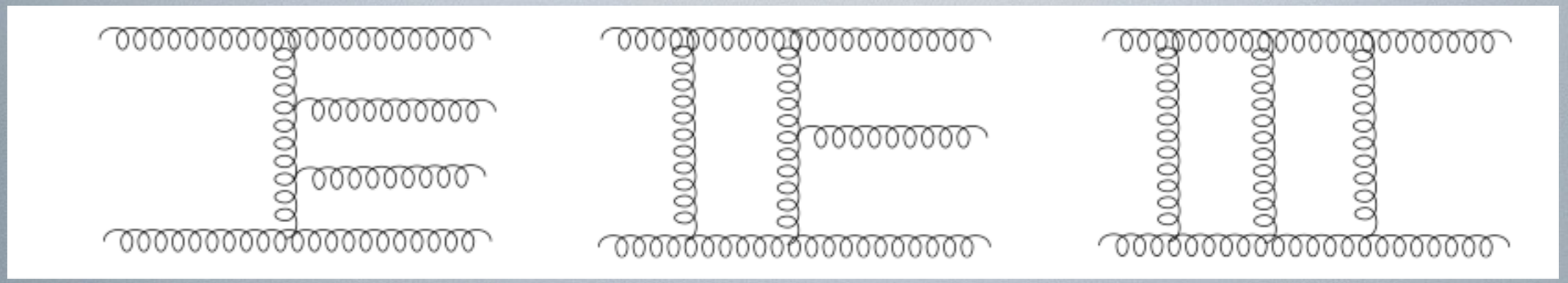
individual contributions are divergent

- requires the isolation of the singularities
  dimensional regularisation: $D = 4 - 2\epsilon$
- need a good subtraction method for singularities of individual contributions

$$\sigma^{NLO} = \underbrace{\int_{m+1} \left[d\sigma^R - d\sigma^S \right]_{\epsilon=0}}_{\text{numerically}} + \underbrace{\int_m \left[\underbrace{d\sigma^V}_{\text{cancel poles}} + \underbrace{\int_s d\sigma^S}_{\text{analytically}} \right]_{\epsilon=0}}_{\text{numerically}}$$

QCD corrections: building blocks

NNLO:



double real

1-loop virtual
⊗ single real

2-loop virtual

implicit IR poles (PS integration)

explicit and implicit poles

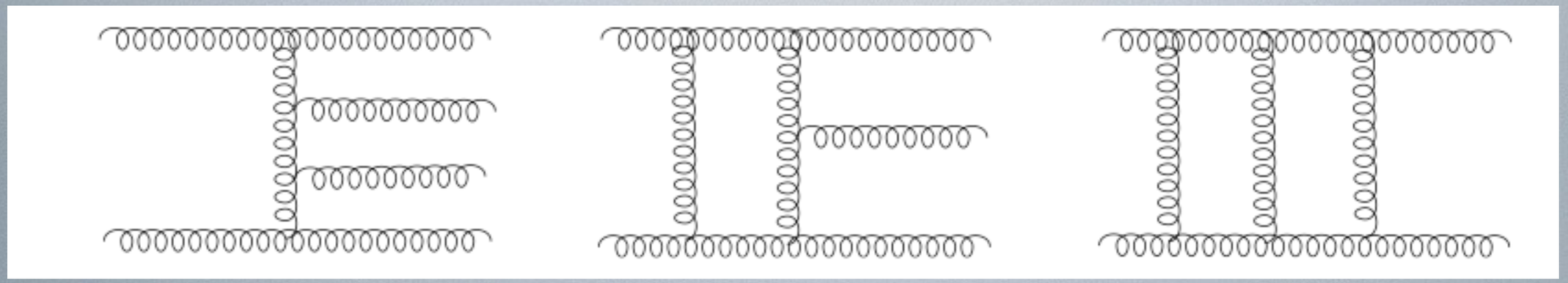
explicit poles $1/\epsilon^{2L}$

bottlenecks: IR subtraction

two-loop integrals

QCD corrections: building blocks

NNLO:



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harder with more massless particles
(intricate IR singularity structure)

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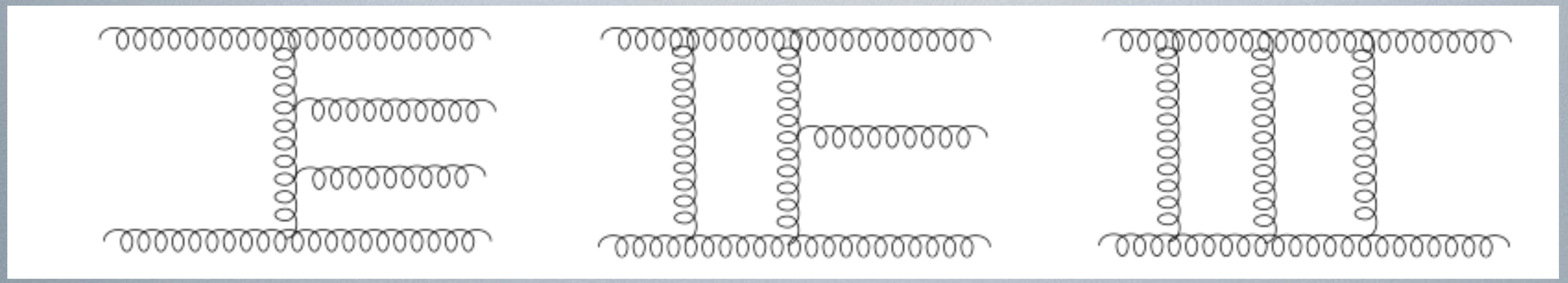

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two-loop integrals

harder with more massive/off-shell particles
(more scales → more complicated
analytic structure)

status

- NLO automation:

phase after

"industrial revolution"

various automated tools

NLO QCD matched to parton shower is new state of the art

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- NLO automation:

phase after

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NLO QCD matched to parton shower is new state of the art

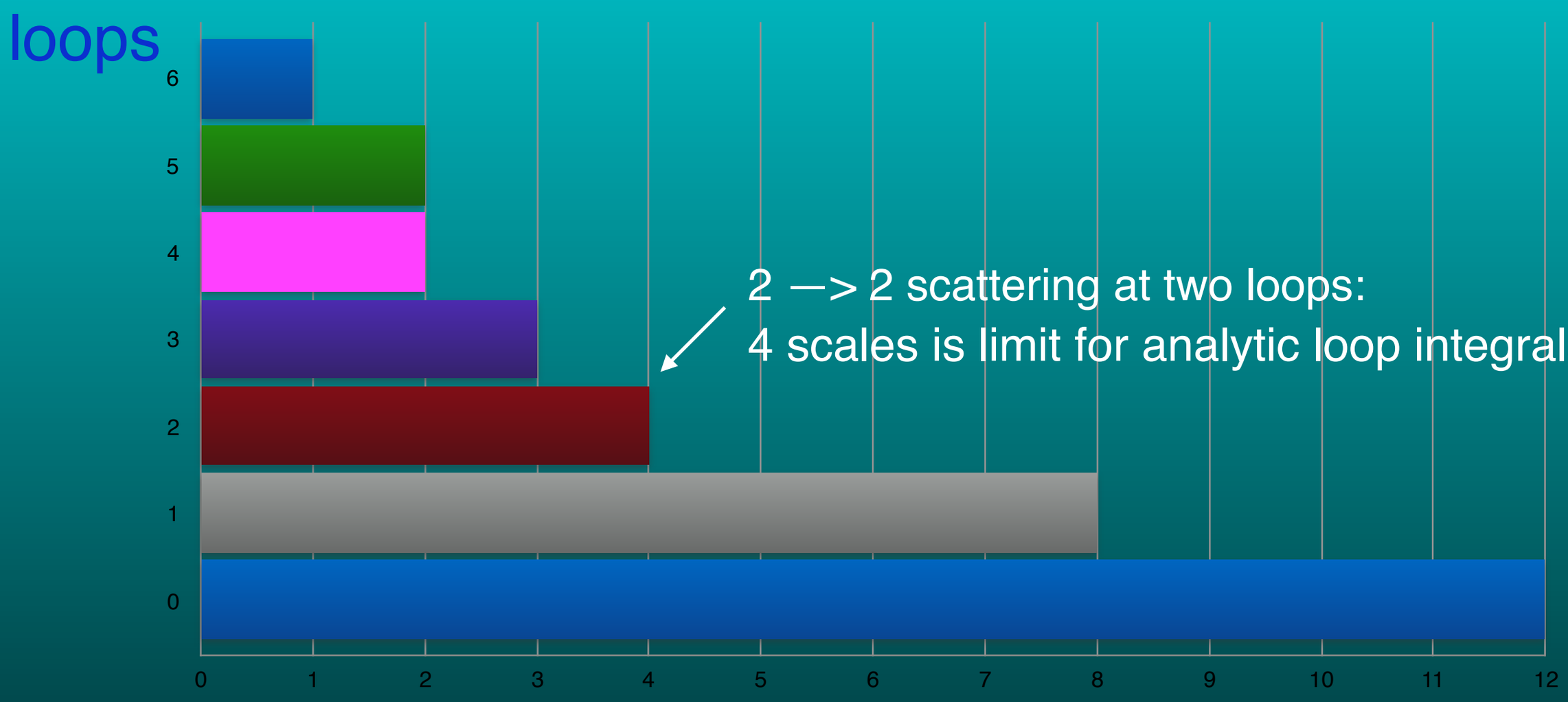
- NNLO: automation starts to become feasible

- NNNLO: some results available!

measure of complexity

#loops + #legs + **#scales (masses, off-shellness)**

complexity does not scale linearly!



(refers to physical results, not individual integrals)

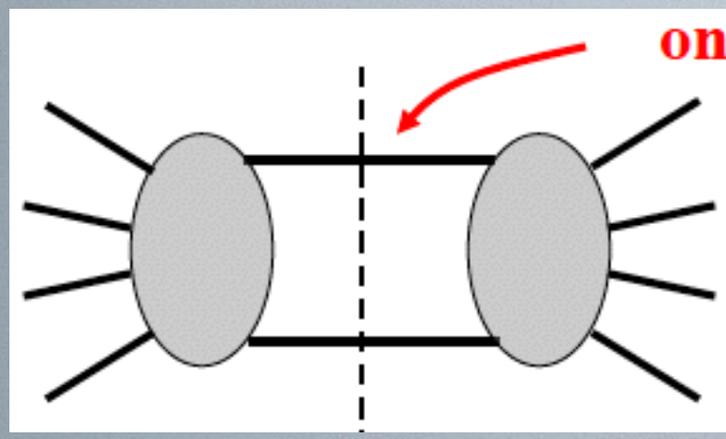
MAX-PLANCK-GESELLSCHAFT

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

what caused the NLO revolution?

gauge dependent off-shell states introduce “spurious” terms

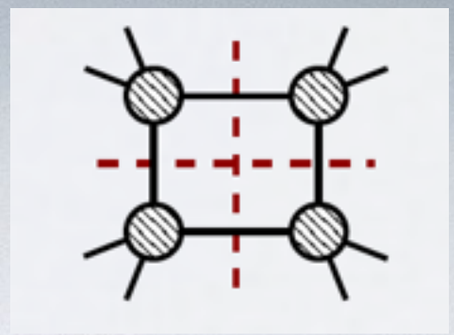
→ try to use **on-shell quantities** as building blocks



Unitarity method

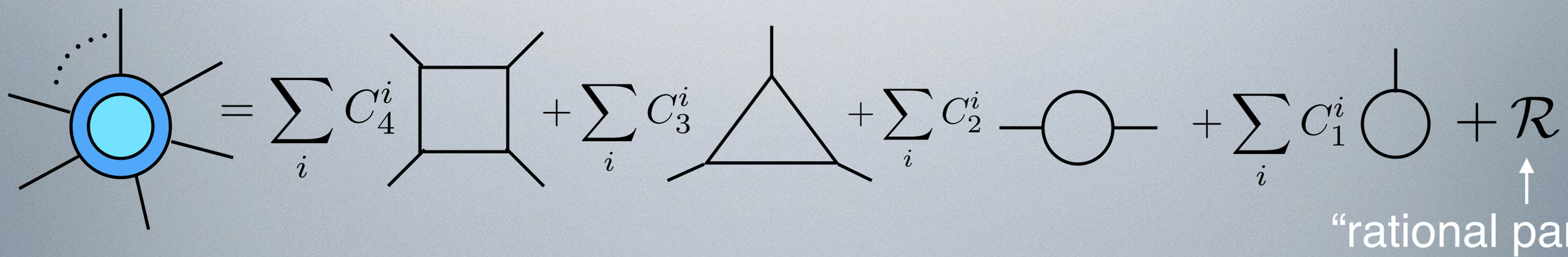
Bern, Dixon, Dunbar and Kosower (BDDK) 1994

- construct N-point one-loop amplitudes from tree amplitudes
  Bern, Dixon, Kosower ‘98
- use of complex momenta in generalised cuts
  Britto, Cachazo, Feng ’04



- numerical reduction at integrand level
  Ossola, Papadopoulos, Pittau ’06
- D-dimensional unitarity
  Anastasiou, Britto, Feng, Kunszt, Mastrolia ’06;
  Forde ’07; Giele, Kunszt, Melnikov ’08, Badger ’09, …

one-loop N-point amplitude:



“master integrals”: boxes, triangles, bubbles, tadpoles

(and pentagons in D-dim.)

most complicated functions are dilogarithms

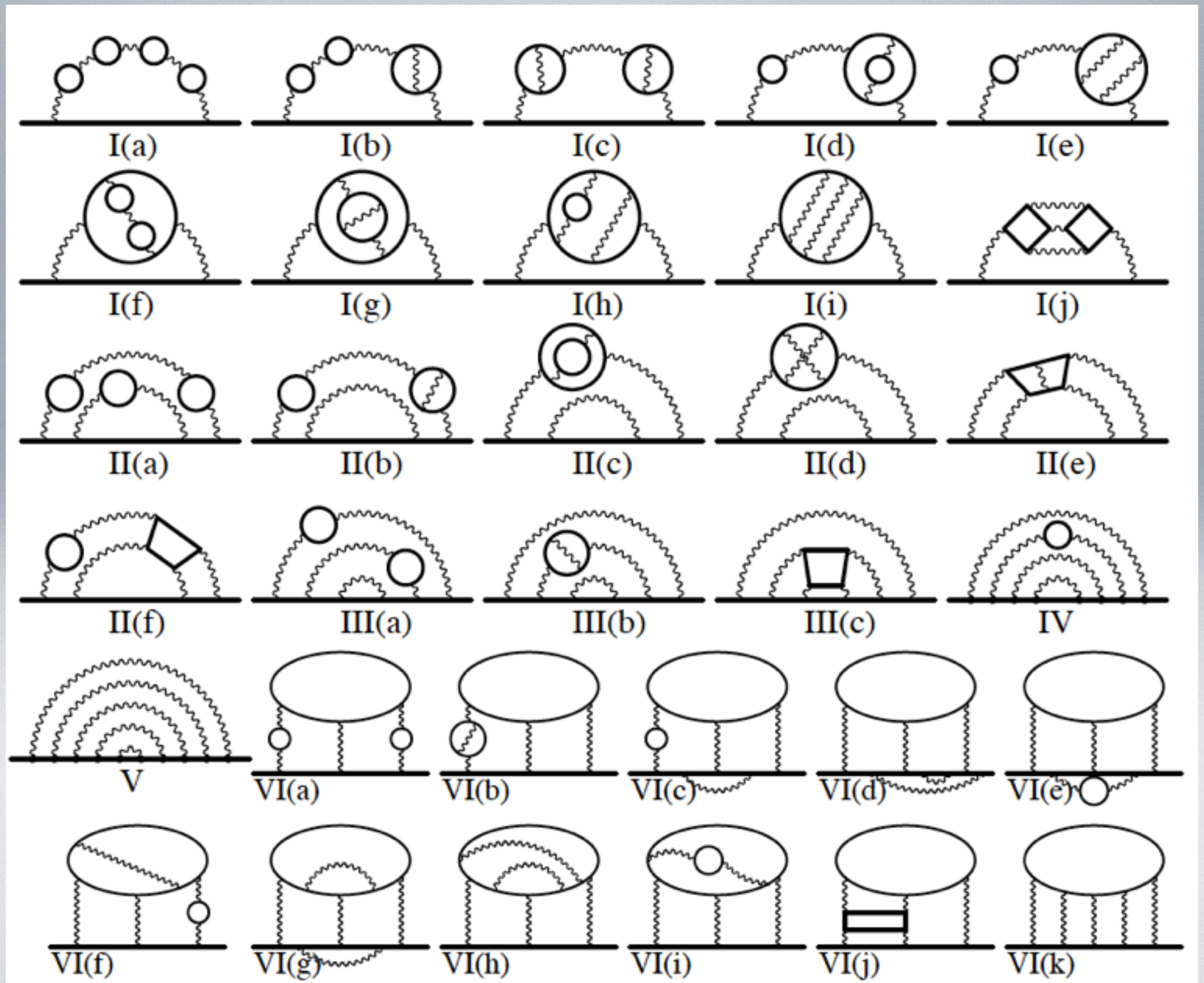
C_n^i can be obtained by numerical reduction at integrand level

very different at two loops (and beyond)

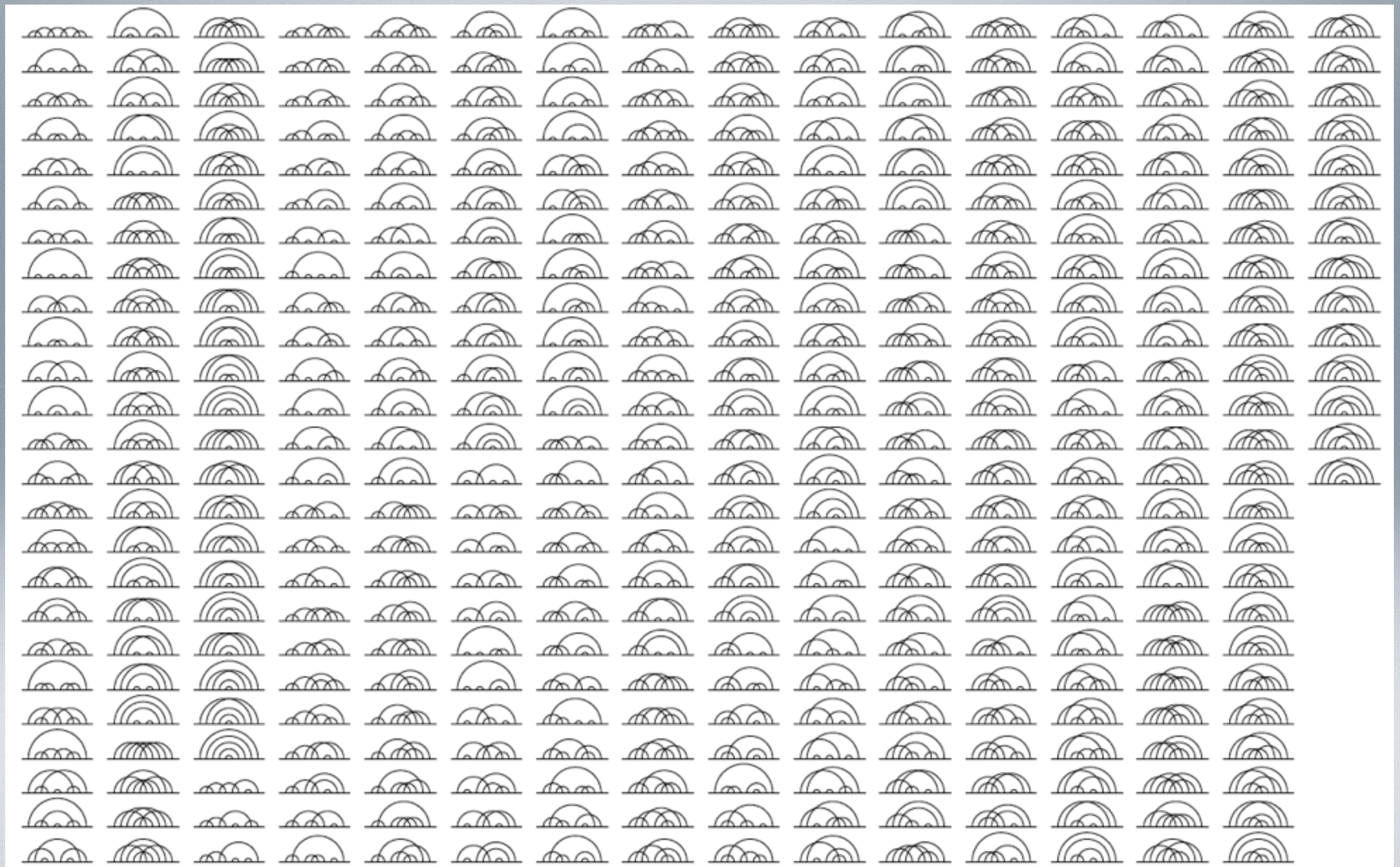
master integrals/function basis not a priori known

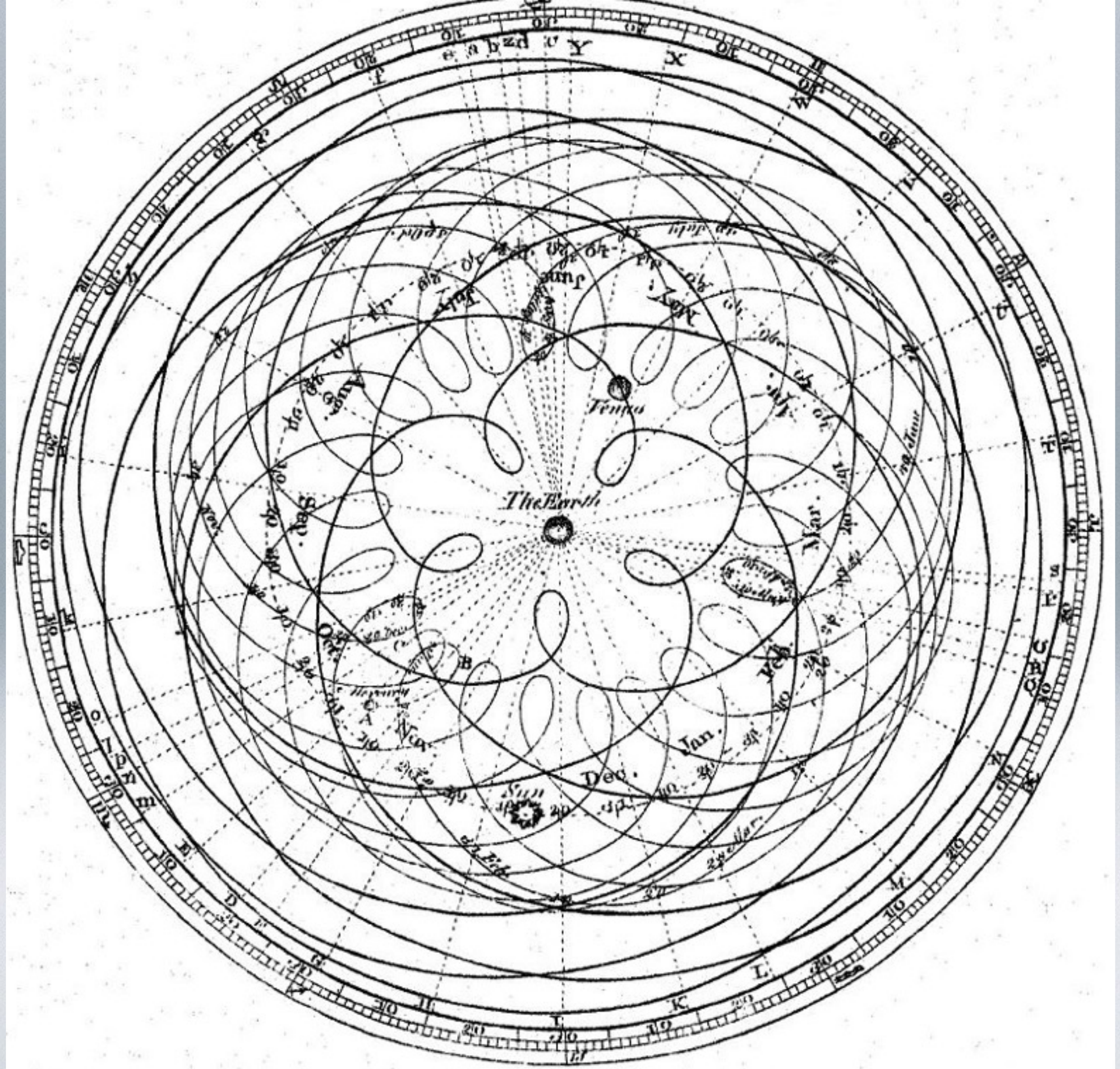
5-loop contributions to electron anomalous magnetic moment

Aoyama, Hayakawa, Kinoshita, Nio ‘14



V-type diagrams




The Earth
Venus
Mercury
Mars
Jupiter
Saturn
Sun
Dec.
Jan.
Feb.
Mar.
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tasks/problems beyond one loop

1. automated amplitude generation

tools e.g. QGRAF [P.Nogueira], FeynArts [T.Hahn et al.]

saturation of Lorentz/spin indices: helicity amplitudes or
projectors to form factors

2. reduction of the loop amplitudes to coefficients ⊗ master integrals

reduction highly non-trivial; no unique master integral basis beyond one loop

multi-purpose **tools** e.g. Reduze [C.Studerus, A.v.Manteuffel], FIRE [A.V.Smirnov],
LiteRed [R.N.Lee], Kira [Maierhoefer, Usovitsch, Uwer '17]

based on integration by parts (IBP) relations

$$\int d^D k \frac{\partial}{\partial k^\mu} v^\mu f(k, p_i) \quad = \quad 0$$

new: reduce complexity by construction of algebraic identities from numerical samples
("finite fields") A.v.Manteuffel, R.Schabinger '14, Peraro '16

two-loop **integrand** reduction:

very interesting new developments, but not ready for automation yet (?)

Mastrolia, Ossola '11; Badger, Frellesvig, Zhang '12; Kosower, Larsen '12,
Mastrolia, Mirabella, Ossola, Peraro '12; Feng, Huang '12;
Papadopoulos et al.'12; Ita '15; Larsen, Zhang '16; Mastrolia, Peraro, Primo '16,
Peraro '16 …

tasks/problems beyond one loop

3. calculation of the master integrals

analytically? may not always be possible

numerically? may not always be accurate/fast enough

4. subtraction of IR divergent real radiation

lots of interesting recent developments (see later)

5. stable and fast Monte Carlo program

(or if not fast: how to make results available in a flexible format)

some methods for (multi-)loop integrals

- **analytic**
  - direct integration [Feynman; 't Hooft, Veltman … ; Brown '08; Panzer '13; Schnetz '13, von Manteuffel, Panzer, Schabinger '15, …] new concept: linear reducibility
  - Mellin-Barnes representation [Tausk '99, Smirnov '99, …]
  - **differential equations** [Kotikov '91; Remiddi '97, Gehrmann, Remiddi '00; **Henn '13, ...**]

canonical form, caused "2-loop revolution"

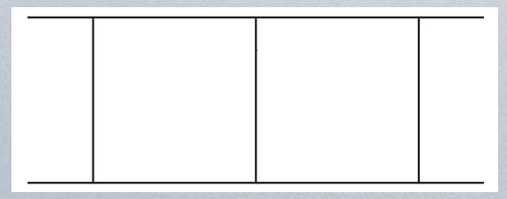
- **(semi-)numerical**
  - numerical solution of differential equations [Caffo, Czyz, Laporta, Remiddi '98; Czakon, Mitov …]
  - dispersion relations [Bauberger et al '94, Bauberger Freitas '17 …]
  - use Bernstein-Sato-Tkachov theorem [Passarino et al '01 …]
  - numerical evaluation of Mellin-Barnes representations [Czakon '05; … Dubovyk, Freitas, Gluza, Riemann, Usovitsch '16]
  - numerical extrapolation [De Doncker, Yuasa, Kato, Fujimoto, Kurihara, Ishikawa, Olagbemi, Shimizu]
  - sector decomposition [Binoth, GH, et al '00 …]
  -
  -
  -

results for two-loop integrals

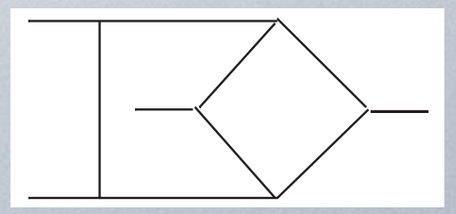
2-loop 4-point:

(black lines are massless)

- all massless:



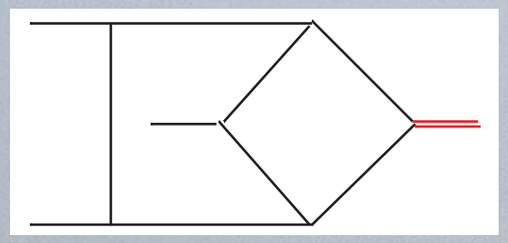
planar: Smirnov ’99



non-planar: Tausk ’99

- one massive leg:

e.g. pp to V+jet

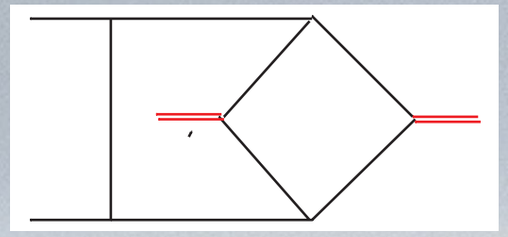


Gehrmann and Remiddi ’00-‘02

Moch, Uwer, Weinzierl ‘02

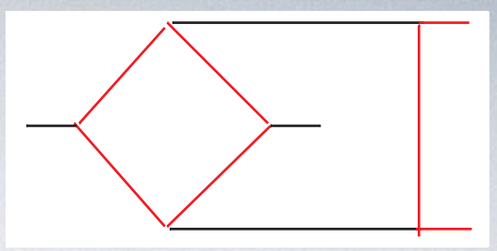
- two massive legs:

e.g. pp to VV



Gehrmann, Tancredi, Weihs ’13
Gehrmann, von Manteuffel, Tancredi, Weihs ‘14
Caola, Henn, Melnikov, Smirnov ‘14
Papadopoulos, Tommasini, Wever ‘14

- massive propagators (also massive on-shell legs) e.g. $t\bar{t}$



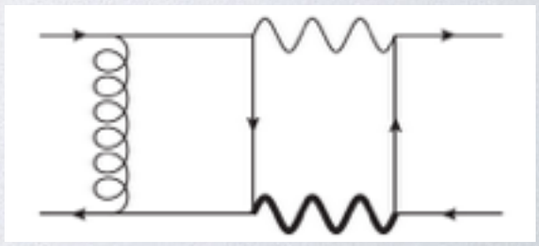
Czakon ’07 (**numerically**)

Bonciani, Ferroglia, Gehrmann, von Manteuffel, Studerus ’10, ‘13 (analytic, partial, tT)

Henn, Smirnov ’13 (analytic, planar, Bhabha)

- massive propagators (one mass)

e.g. mixed QCD-EW corrections to Drell-Yan

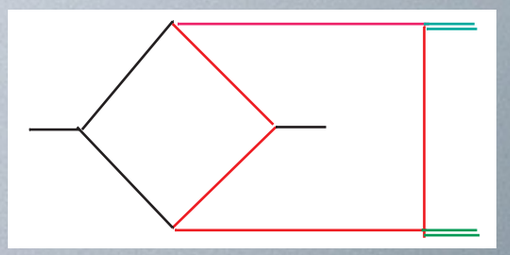


Bonciani, Di Vita, Mastrolia, Schubert ’16;

von Manteuffel, Schabinger ’17

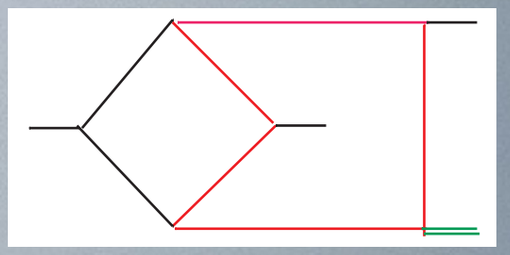
results for two-loop integrals

- massive propagators + massive legs with different mass (two additional mass scales) e.g. $gg \to HH$



Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke ‘16 **numerically**

- same number of scales e.g. H+jet:



lots of work on elliptic functions, some integrals still unknown

Tancredi, Remiddi ’16; Adams, Bogner, Weinzierl ’15,’16

Bonciani, Del Duca, Henn, Frellesvig, Moriello, Smirnov ’16

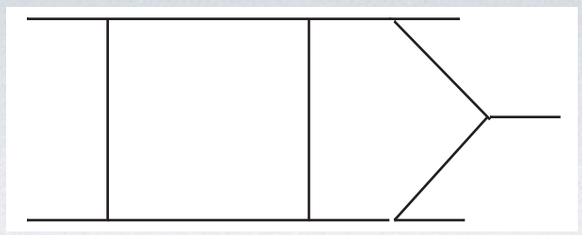
Tancredi, Primo ’16,’17; Abreu, Britto, Duhr, Gardi ’17

b-mass dependence: Melnikov, Tancredi, Wever ’16,’17

2-loop 5-point:

- all massless, planar:

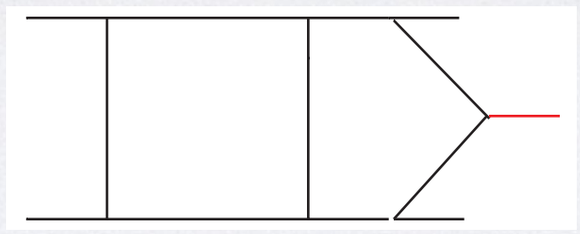
e.g. pp to 3jets



Gehrmann, Henn, Lo Presti ‘15

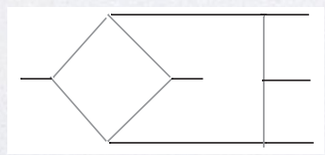
- one off-shell leg, planar:

e.g. pp to H+2jets



Papadopoulos, Tomassini, Wever ’15

- non-planar still unknown



results for two-loop amplitudes

analytic results based on unitarity approach:

- 5-gluon all-plus helicity amplitude

  Badger, Mogull, Ochirov, O'Connell '15; Badger, Mogull, Peraro'16

  Gehrmann, Henn, Lo Presti '15

  Dunbar, Perkins '16

- 6-gluon all-plus helicity amplitude

  Dunbar, Jehu, Perkins '16

remarkable result based on numerical unitarity:

- 4-gluon amplitude (leading colour, all helicities)

  Abreu, Febres Cordero, Ita, Jaquier, Page, Zeng '17

  result known [Glover, Oleari, Tejeda-Yeomans '01; Bern De Freitas, Dixon '02]

  but method seems suitable for automation
  (similar to what caused the "NLO revolution")

NNLO real radiation subtraction methods

- antenna subtraction analytically integrated subtraction terms

  [Gehrmann-DeRidder, Gehrmann, Glover '05]

- qt "subtraction" slicing, (colourless final states)

  [Catani, Grazzini '07]

- N-jettiness slicing

  [Gaunt, Stahlhofen, Tackmann, Walsh '15]

  [Boughezal, Focke, Liu, Petriello '15]

- sector-improved residue subtraction numerically integrated subtraction terms

  [Czakon, Heymes, Mitov '10; Czakon, Heymes '14] [Boughezal et al. '11]

  - nested subtraction [Caola, Melnikov, Röntsch '17]

- projection to Born / structure function approach only special kinematics

  [Goa, Li, Zhu '12] [Brucherseifer, Caola, Melnikov '14] [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

- colorful only final state colour so far

  [Del Duca, Somogyi, Trocsanyi '05]

NNLO

- antenna
- qt
- N-jettiness
- sector improved r.s.
- projection to Born
- colorful

$\gamma + \text{jet}$

$ep \to \text{jet}$

$HH(m_t \to \infty)$

WW HW, HZ

ZH $\gamma\gamma$

ZZ $W + \text{jet}$

$Z\gamma$ $W\gamma$ $Z + \text{jet}$

$ep \to 2\,\text{jets}$

$pp \to 2\,\text{jets}$

$Z + \text{jet}$

$H + \text{jet}\ (m_t \to \infty)$

$H + \text{jet}\ (m_t \to \infty)$

$H + \text{jet}\ (m_t \to \infty)$

$t\,\bar{t}$

$Hjj\,(\text{VBF})$

$e^+e^- \to 3\,\text{jets}$

$\sigma_{\text{tot}}\, t\bar{t}$

$\gamma\gamma$

WH

$\sigma_{\text{tot}}\, Hjj\,(\text{VBF})$

diff W/Z

diff H

diff W/Z

diff H

$\sigma_{\text{tot}}\, WH$

$\sigma_{\text{tot}}\, H$

$e^+e^- \to 3\,\text{jets}$

$e^+e^- \to \text{event shapes}$

$\sigma_{\text{tot}}\, W/Z$

01 2003 2005 2007 2009 2011 2013 2015 2017

what caused the “NNLO revolution”?

- efficient infrared subtraction schemes for double real radiation
- better methods for the analytic calculation of multi-loop integrals
- advances in the numerical calculation of multi-loop integrals

what caused the “NNLO revolution”?

- efficient infrared subtraction schemes for double real radiation
- better methods for the analytic calculation of multi-loop integrals
- advances in the numerical calculation of multi-loop integrals

- a major bottleneck is the reduction to master integrals …

… the revolution due to on-shell methods is still to come!

Exploring the Higgs sector

Exploring the Higgs sector

what do we really know about the Higgs potential?

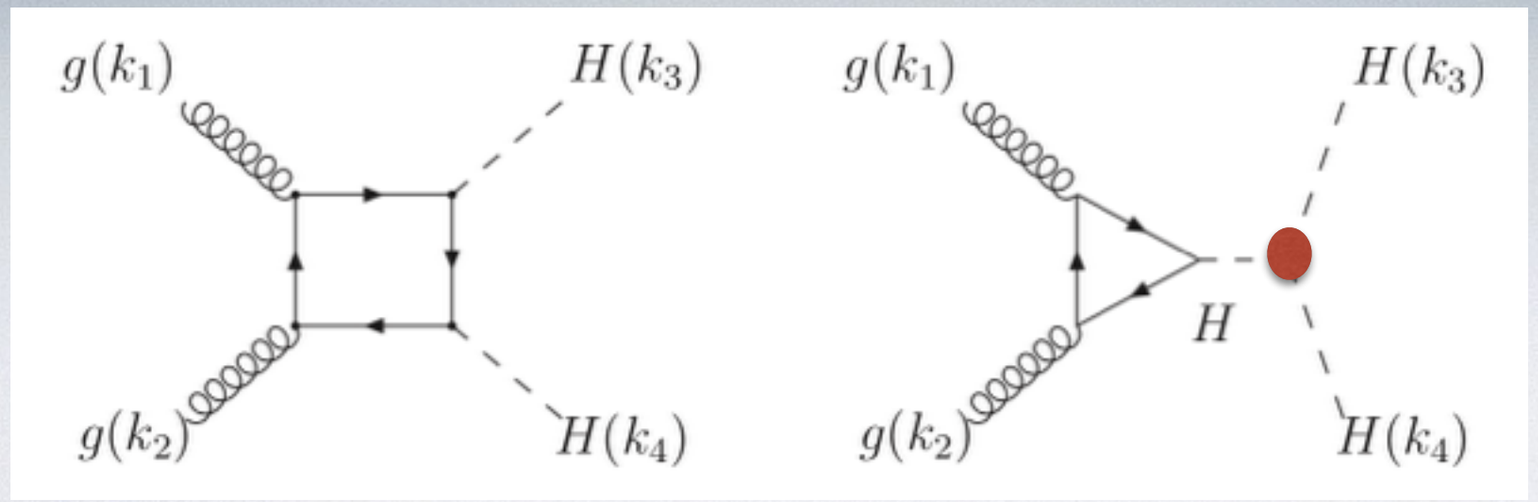
SM: $$V(\Phi) = -\frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

↓ EW symmetry breaking

$$\frac{m_h^2}{2}\,h^2 + \frac{m_h^2}{2v}\,h^3 + \frac{m_h^2}{8v^2}\,h^4$$

λ_{3h} completely determined in the SM

can be measured e.g. in Higgs boson pair production

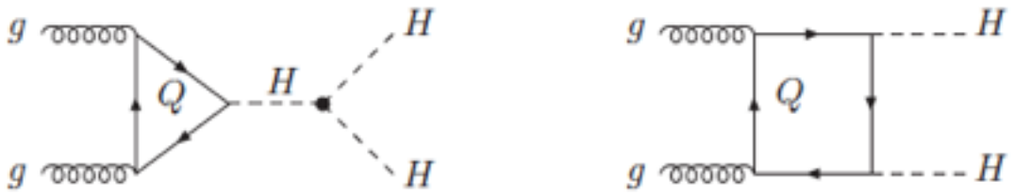


current best limit $\sigma_{HH} \leq 28\,\sigma_{HH}^{SM}$ ($b\bar{b}\tau\tau$ channel)

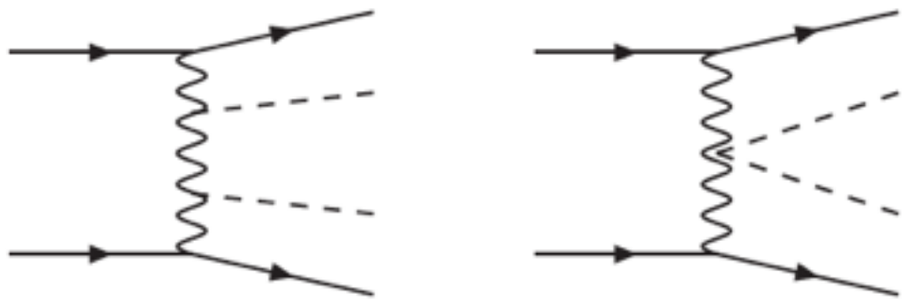
measurement of λ_{3h} only at HL-LHC

Higgs boson pair production mechanisms

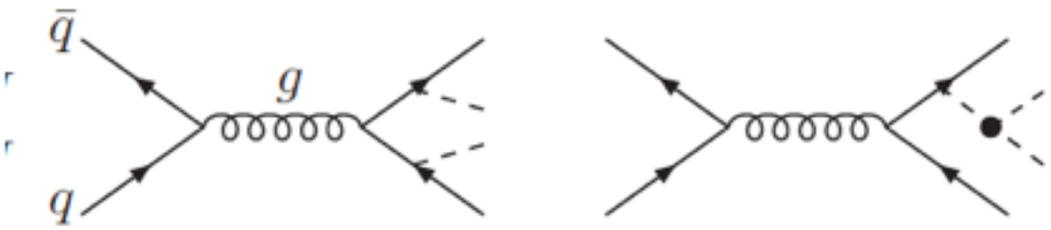
- gluon fusion



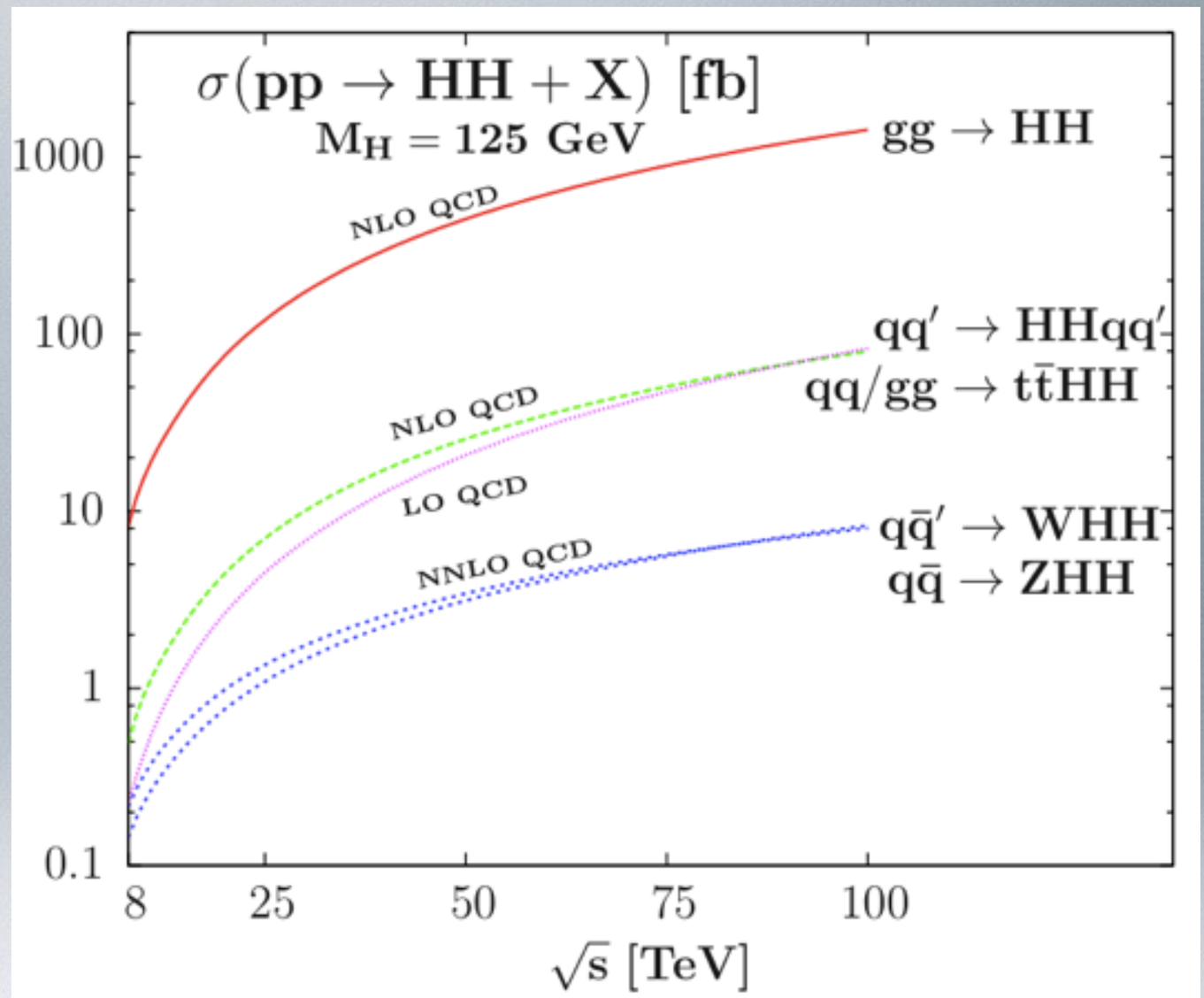
- vector boson fusion



- top-quark associated



- Higgs-strahlung



Baglio, Djouadi, Gröber, Mühlleitner,
Quevillon, Spira '12

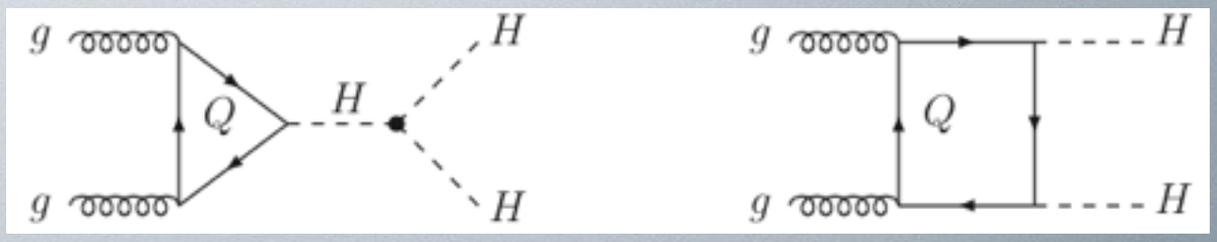
largest cross section from gluon fusion, but still

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

Higgs boson pair production in gluon fusion

LO with full heavy quark mass dependence

Glover, van der Bij '88, Plehn, Spira, Zerwas '96



$m_t \to \infty$ limit: "Higgs Effective Field Theory" (HEFT)

Note:

HEFT strictly valid only for $\sqrt{\hat{s}} \ll 2m_t$

HH production threshold: $2m_H < \sqrt{\hat{s}}$

$\Rightarrow$ validity of HEFT limited to $250\,\mathrm{GeV} < \sqrt{\hat{s}} < 340\,\mathrm{GeV}$

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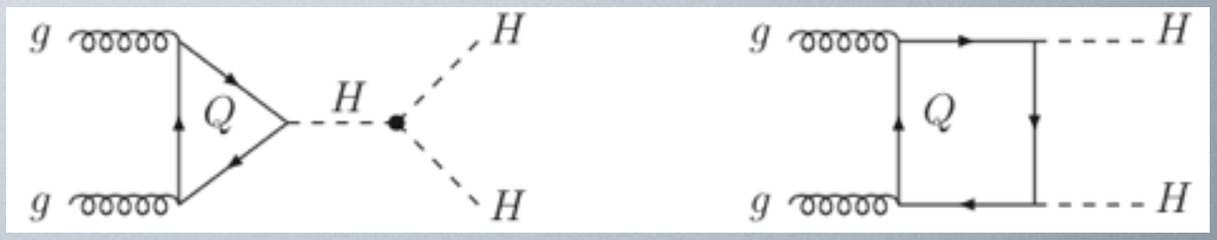

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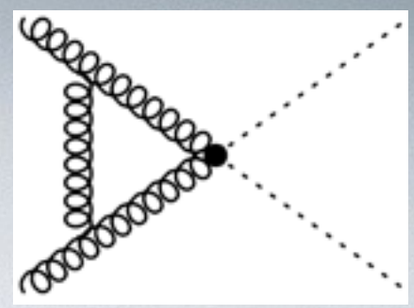
"Born-improved NLO HEFT": rescale by $\mathcal{M}^{LO}(m_t)/\mathcal{M}^{LO}_{\mathrm{HEFT}}$

NLO in Born-improved HEFT Dawson, Dittmaier, Spira '98 (**HPAIR**) $K \simeq 2$



- **supplemented with $1/m_t$ expansion:** $(\pm 10\%)$

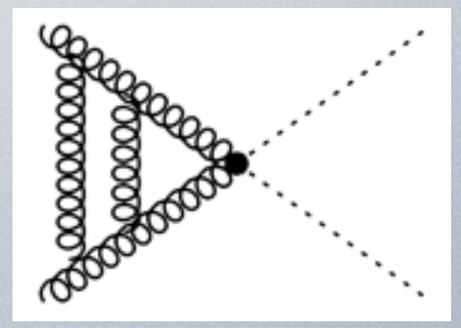
  Grigo, Hoff, Melnikov, Steinhauser '13, '15 ; Degrassi, Giardino, Gröber '16

- **full mass dependence in NLO real radiation ("FTapprox")** **-10%**

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

Higgs boson pair production in gluon fusion

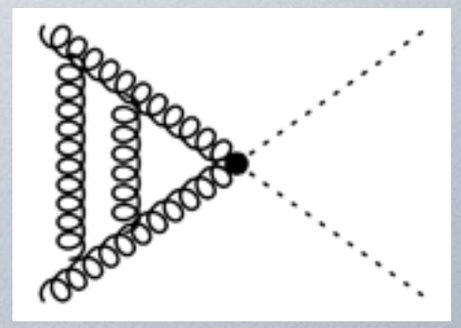
NNLO in $m_t \to \infty$ limit: **+20%**



- **total xs NNLO** De Florian, Mazzitelli '13
- **including all matching coefficients** Grigo, Melnikov, Steinhauser '14
- **supplemented with $1/m_t$ expansion:** Grigo, Hoff, Steinhauser '15
- **soft gluon resummation NNLL matched to NNLO** De Florian, Mazzitelli '15 **+9%**
- **differential NNLO** De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16

Higgs boson pair production in gluon fusion

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



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NLO calculation with full top mass dependence

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

4 independent scales s12, s23, mH, mt

all integrals calculated **numerically** with

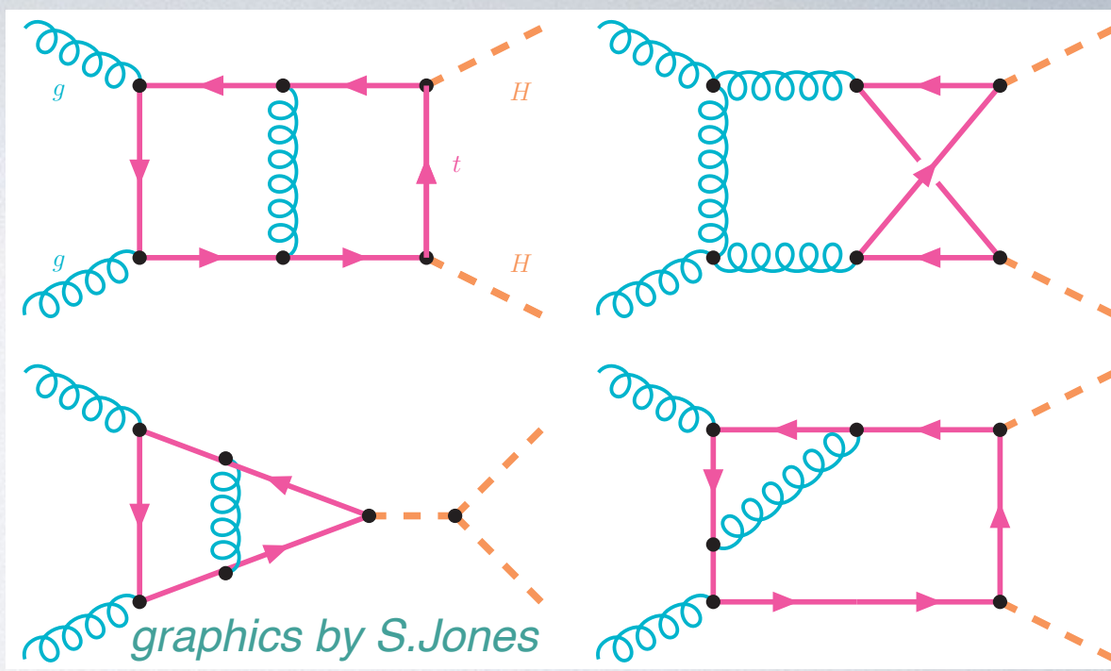
SecDec

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

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

- q_T **resummation NLL+NLO**

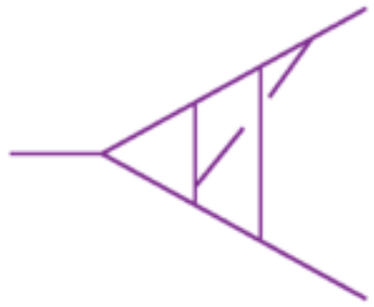
Ferrera, Pires '16



numerical evaluation of multi-loop integrals (advert break)

http://secdec.hepforge.org

SecDec is hosted by Hepforge, IPPP Durham



SecDec

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

A program to evaluate dimensionally regulated parameter integrals numerically

home download program user manual faq changelog

NEW! Download the latest version of pySecDec as pySecDec-1.1.1.tar.gz. The manual is available here.

Download version 1.1 of pySecDec as pySecDec-1.1.tar.gz. The manual is available here.

The first release version of pySecDec can be downloaded as pySecDec-1.0.tar.gz. The manual is available here.
See also the corresponding paper arXiv:1703.09692.

Version 3.0 of the program can be downloaded as SecDec-3.0.9.tar.gz. The manual for this version is available here.

algorithm:	T. Binoth, GH ‘00
version 1.0:	J. Carter, GH ‘10
version 2.0:	S.Borowka, J. Carter, GH ‘12
version 3.0:	S.Borowka, GH, S.Jones, M.Kerner, J.Schlenk, T.Zirke ‘15
pySecDec:	S.Borowka, GH, S.Jahn, S.Jones, M.Kerner, J.Schlenk, T.Zirke ‘**17**

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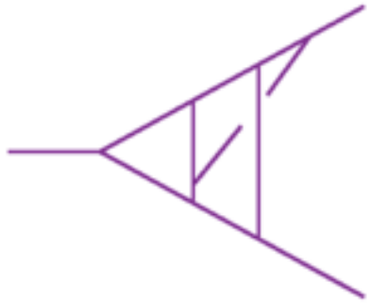

SecDec

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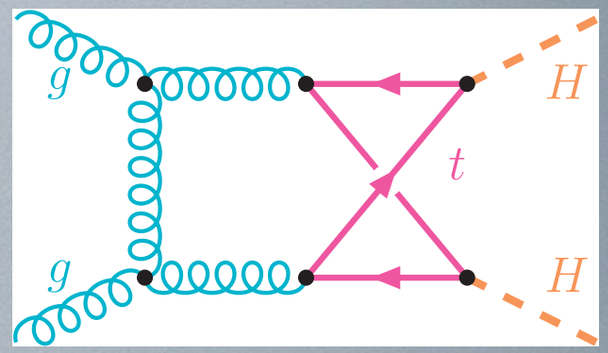
pySecDec: S.Borowka, GH, S.Jahn, S.Jones, M.Kerner, J.Schlenk, T.Zirke ‘**17**

New!
can be used as
an integral library

calculation: building blocks

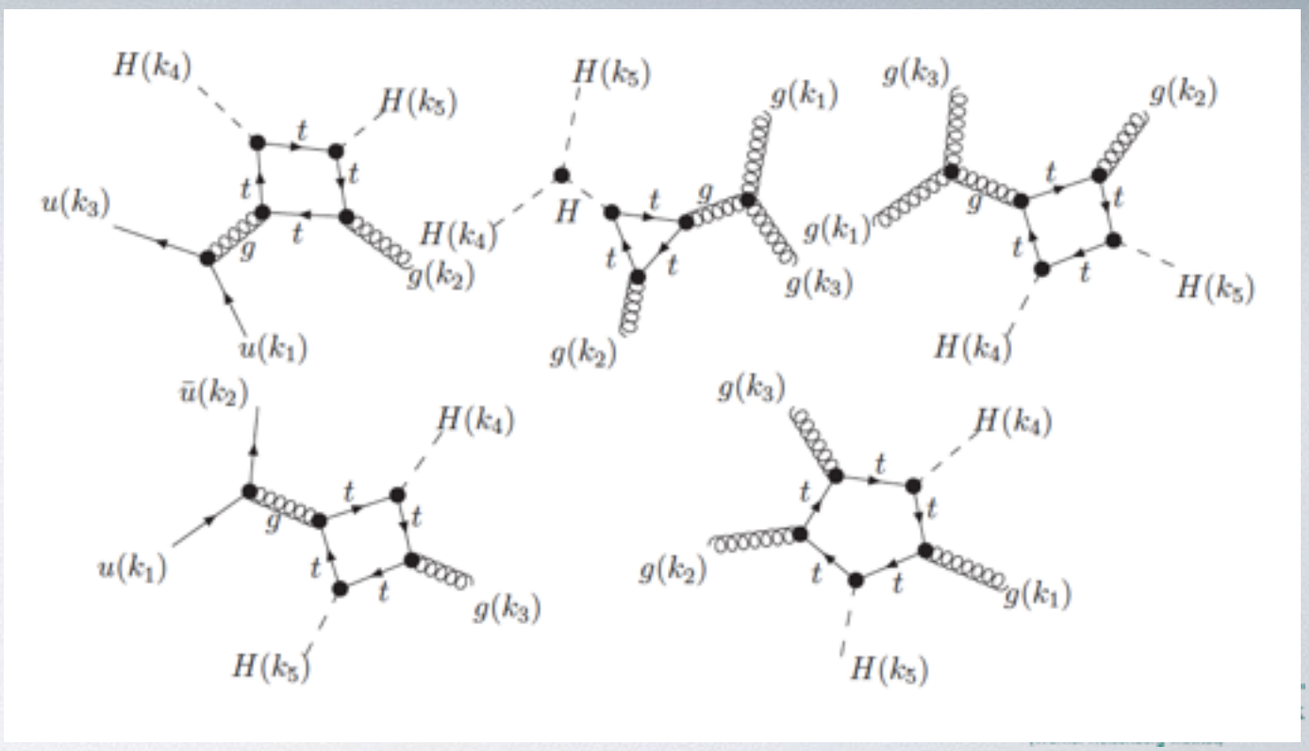
- amplitude generation with 2 setups (custom made and “GoSam-2loop”)
- amplitude reduction with **Reduze** [C. Studerus, A. v.Manteuffel]
- non-planar integrals computed mostly without reduction
- **all** integrals calculated numerically with **SecDec**
- total number of integrals:
  - before reduction: ~10000, after reduction ~330,
    after sector decomposition 11244 (3086 non-planar)
  - used finite basis for planar integrals



- real radiation:

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

(b) GoSam-1L + POWHEG



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automated 2-loop amplitudes: GoSam @ 2 loops

process definition

projectors to form factors

gosam.py process.rc

integral families

create **QGRAF** files

create **python,FORM** files

create reduction files

diagram pictures

run **Qgraf, FORM,python**

run **reduction**

create **amplitude** files

create **SecDec** files

numerical integration

two-loop amplitude

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(Werner-Heisenberg-Institut)

credits

GoSam 2-loop

S. Borowka, N.Greiner, S.Jahn, **S.Jones**,
M.Kerner, G.Luisoni, J.Schlenk et al.

QGRAF

P. Nogueira

FORM

J. Vermaseren, J. Kuipers, B. Ruijl, T. Ueda, J. Vollinga

Reduze

C. Studerus, A. von Manteuffel

GoSam 1-loop

T. Binoth, G.Cullen, H.van Deurzen, N.Greiner, GH,
S.Jahn, **G.Luisoni**, P. Mastrolia, E.Mirabella,
G. Ossola, T. Peraro, T. Reiter, J. Reichel,
J. Schlenk, J.F. von Soden-Fraunhofen, F. Tramontano

SecDec

S.Borowka, GH, S.Jahn, **S.Jones, M.Kerner**, J.Schlenk, T.Zirke

top mass effects

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

	$\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	$\sigma_{\rm NNLO}$[fb]
HEFT	$17.07^{+30.9\%}_{-22.2\%}$	$31.93^{+17.6\%}_{-15.2\%}$	$37.52^{+5.2\%}_{-7.6\%}$
B-i. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	
$\text{FT}_{\text{approx}}$	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$	
full m_t dep.	$19.85^{+27.6\%}_{-20.5\%}$	$32.91^{+13.6\%}_{-12.6\%}$	

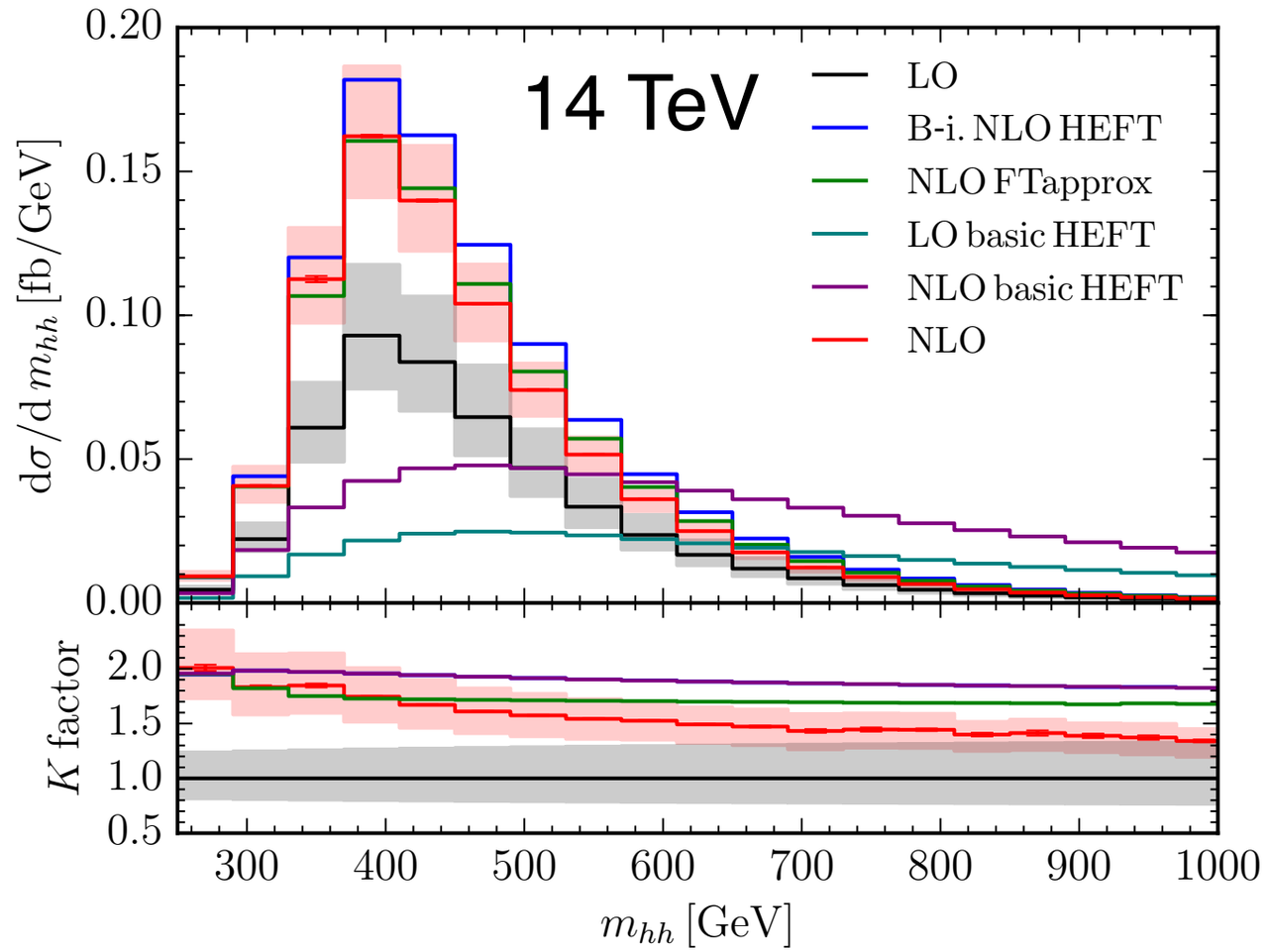
PDF4LHC15_nlo_30_pdfas

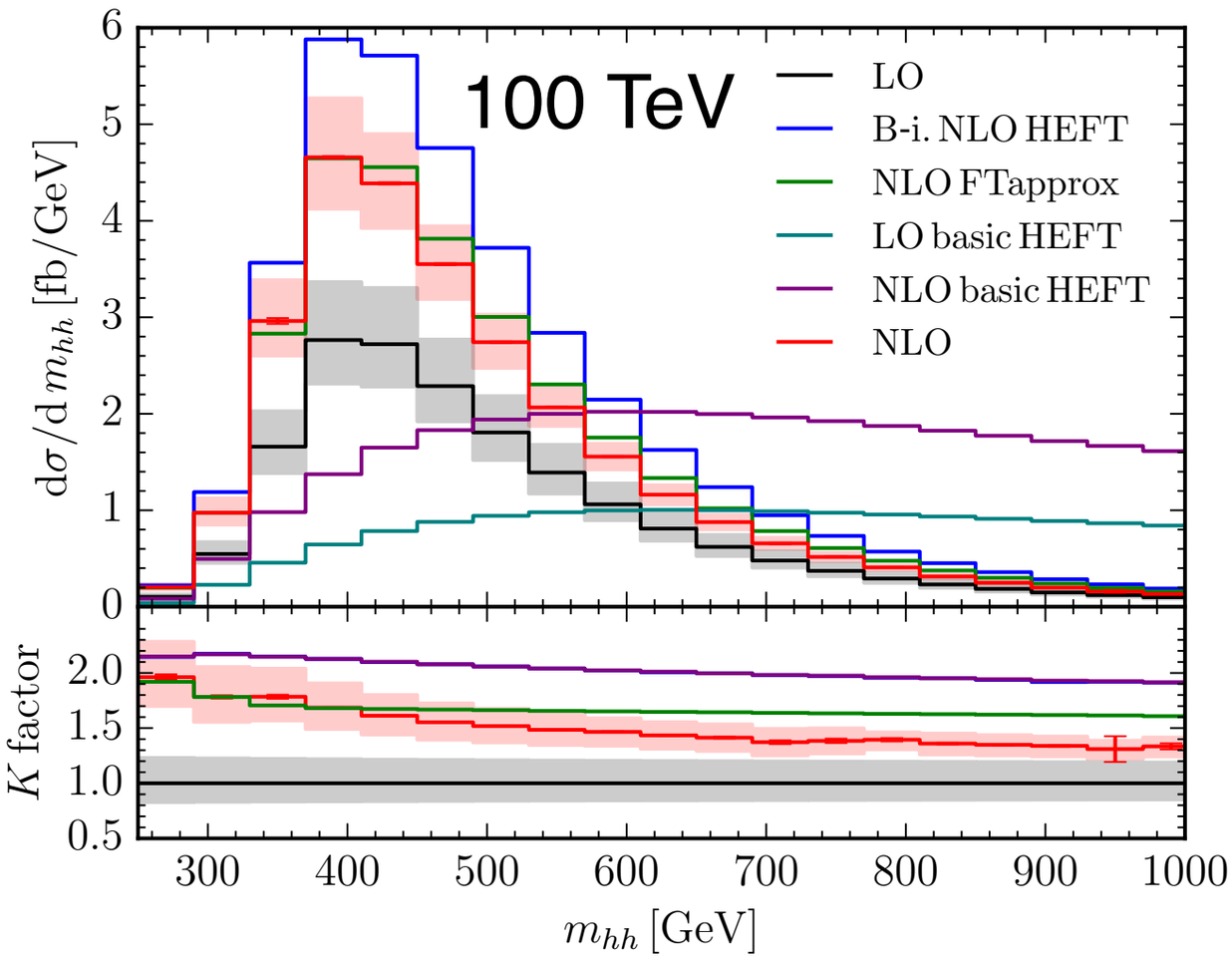
m_H=125 GeV, m_t=173 GeV

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

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

Higgs boson pair invariant mass





for large invariant masses:

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

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

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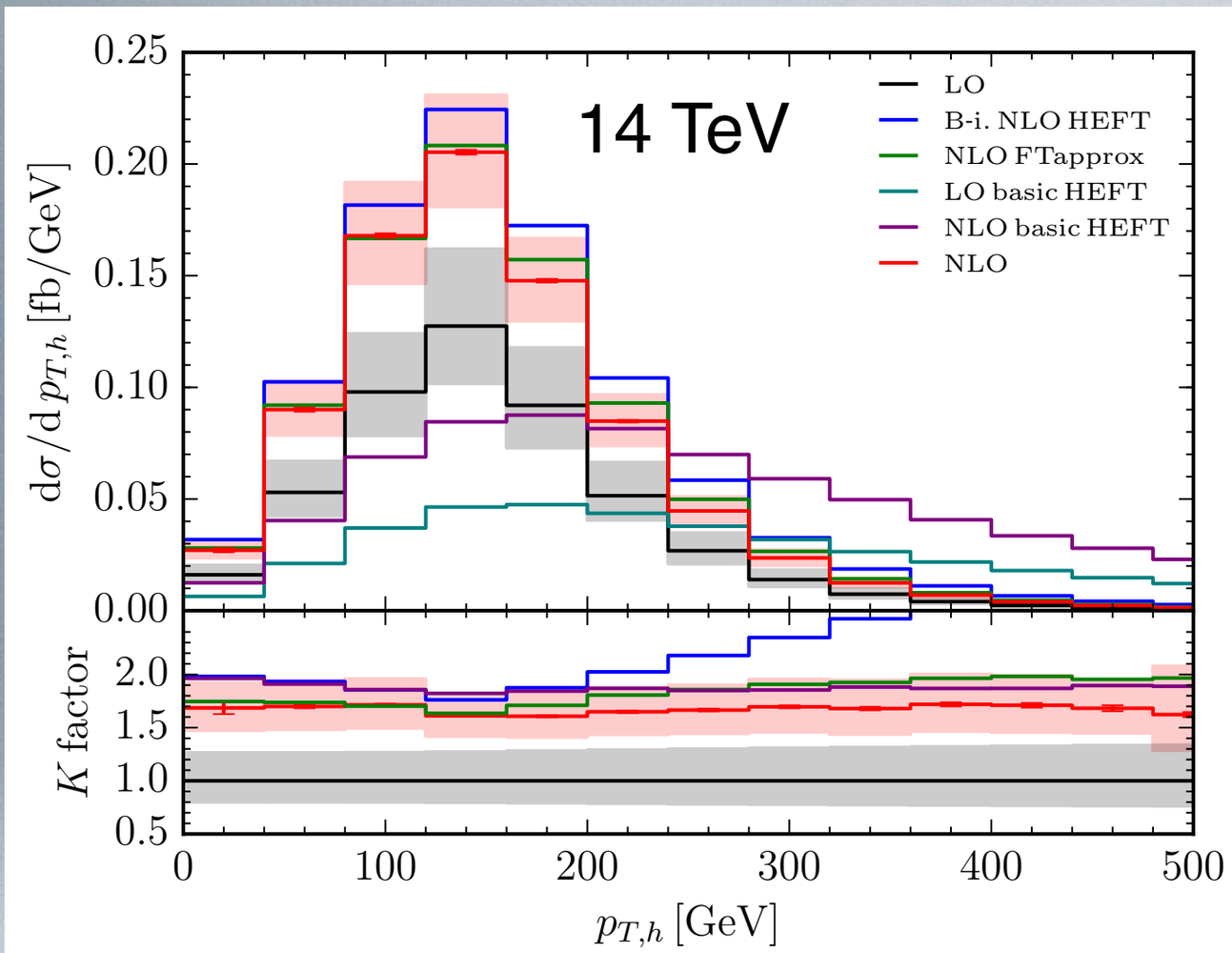
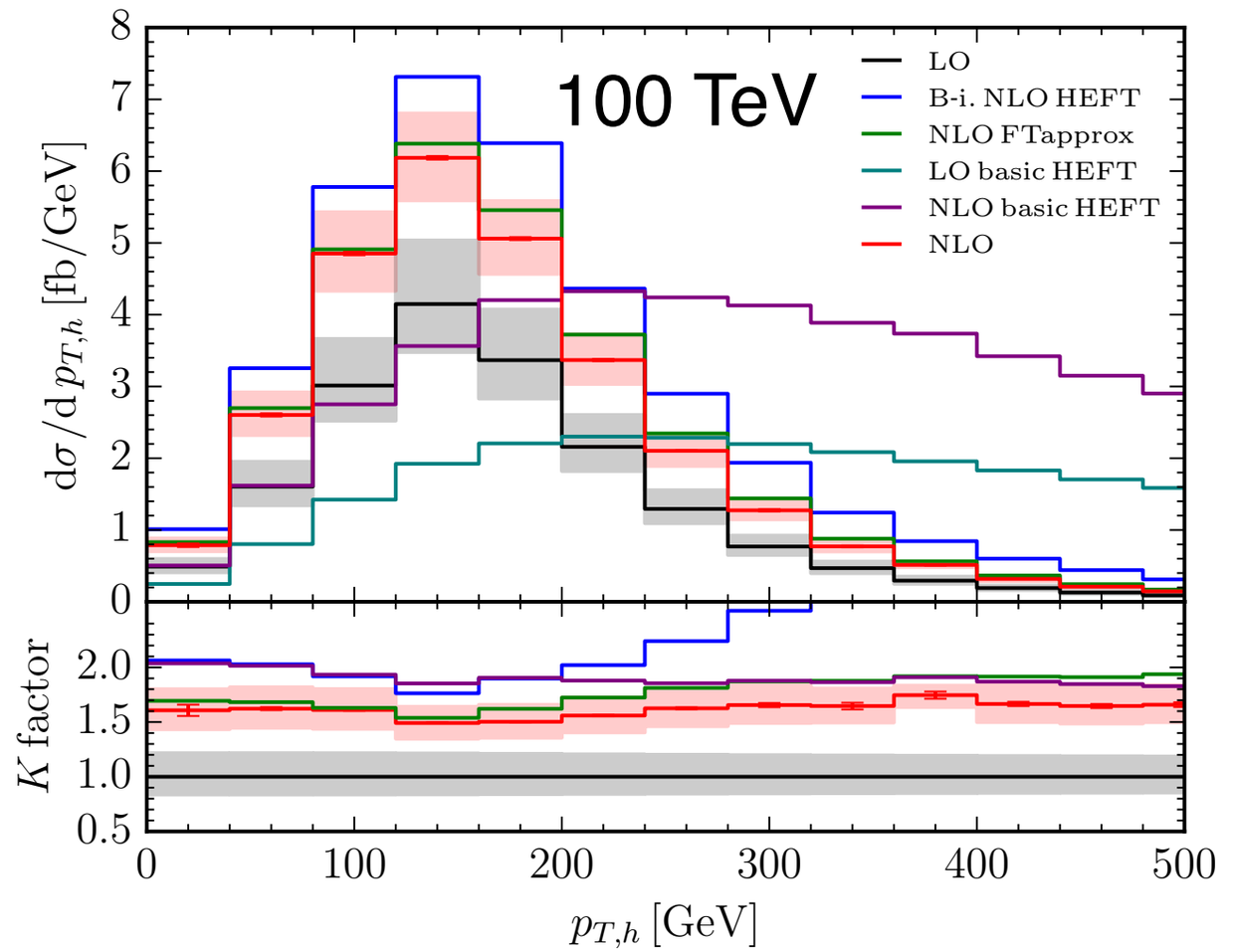
transverse momentum of one of the Higgs bosons





Born-improved NLO HEFT very poor at large pT

full mass dependence at NLO more important for shape than NNLO in an approximate theory (HEFT)

NLO-improved NNLO HEFT

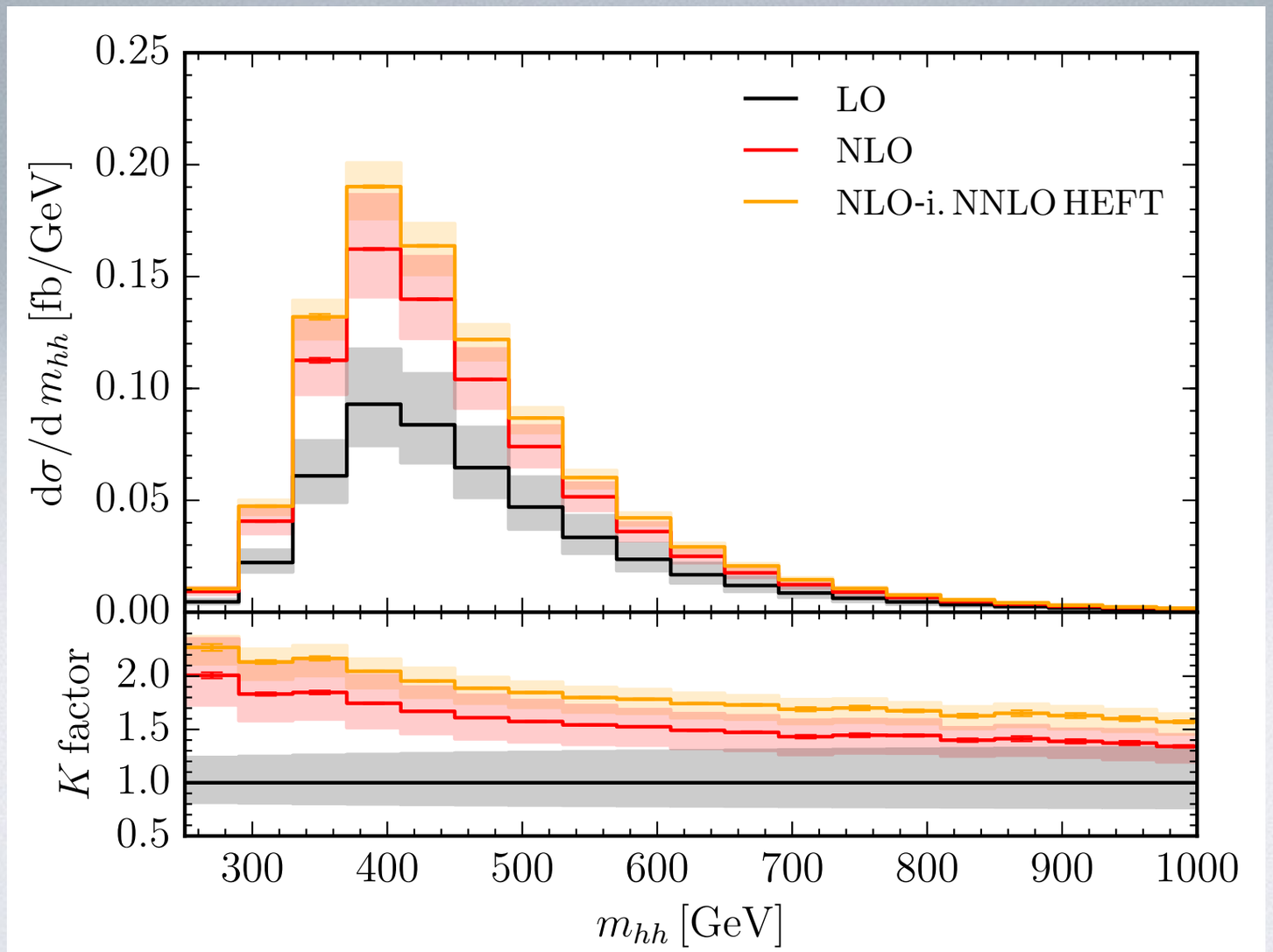
NNLO HEFT:

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

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

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

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



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combination with parton showers

GH, S.Jones, M.Kerner, G.Luisoni, E.Vryonidou 1703.09252

- avoid evaluation of two-loop amplitude for each phase space point
- two-loop amplitude depends only on $\hat{s}, \hat{t}$ $(m_t, m_H \text{ fixed})$

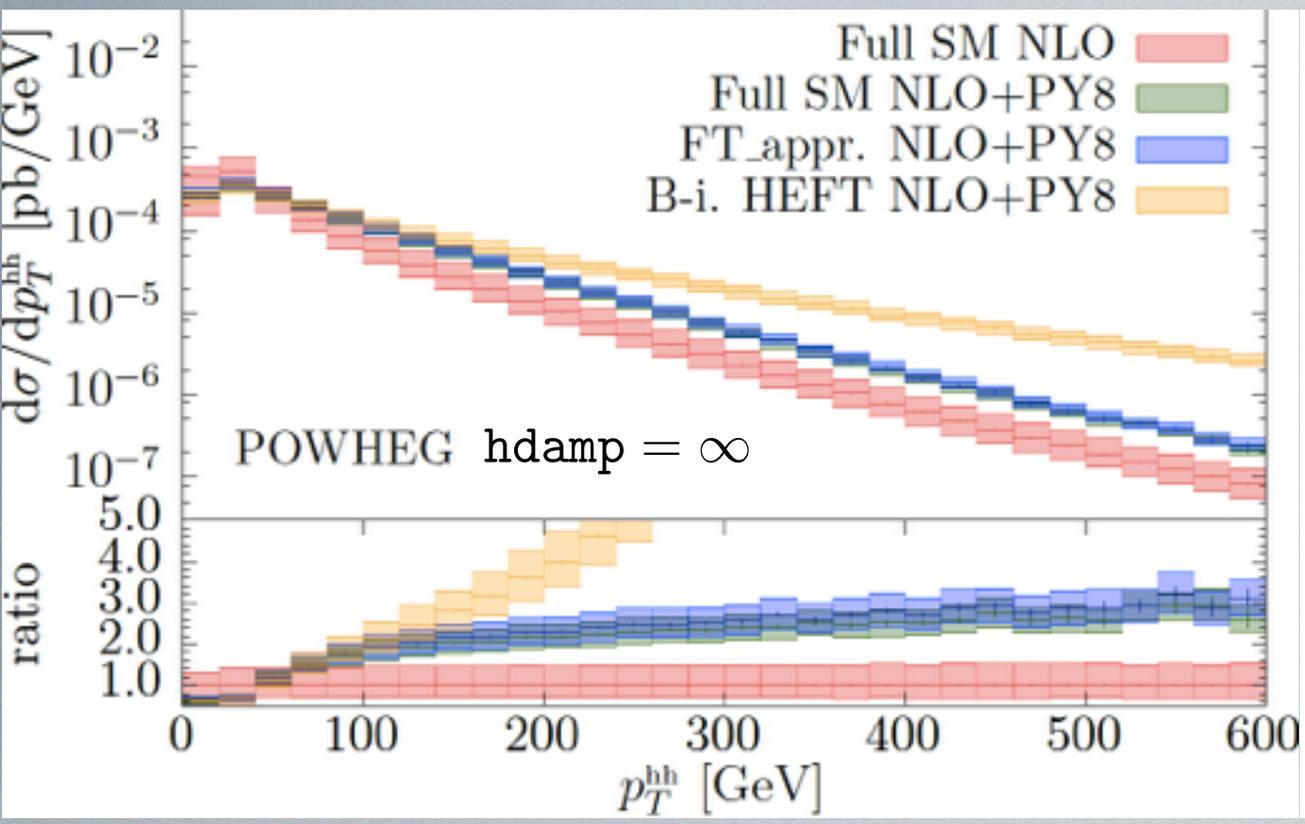
  → construct 2-dim grid
- variable transformation to achieve more uniform distribution

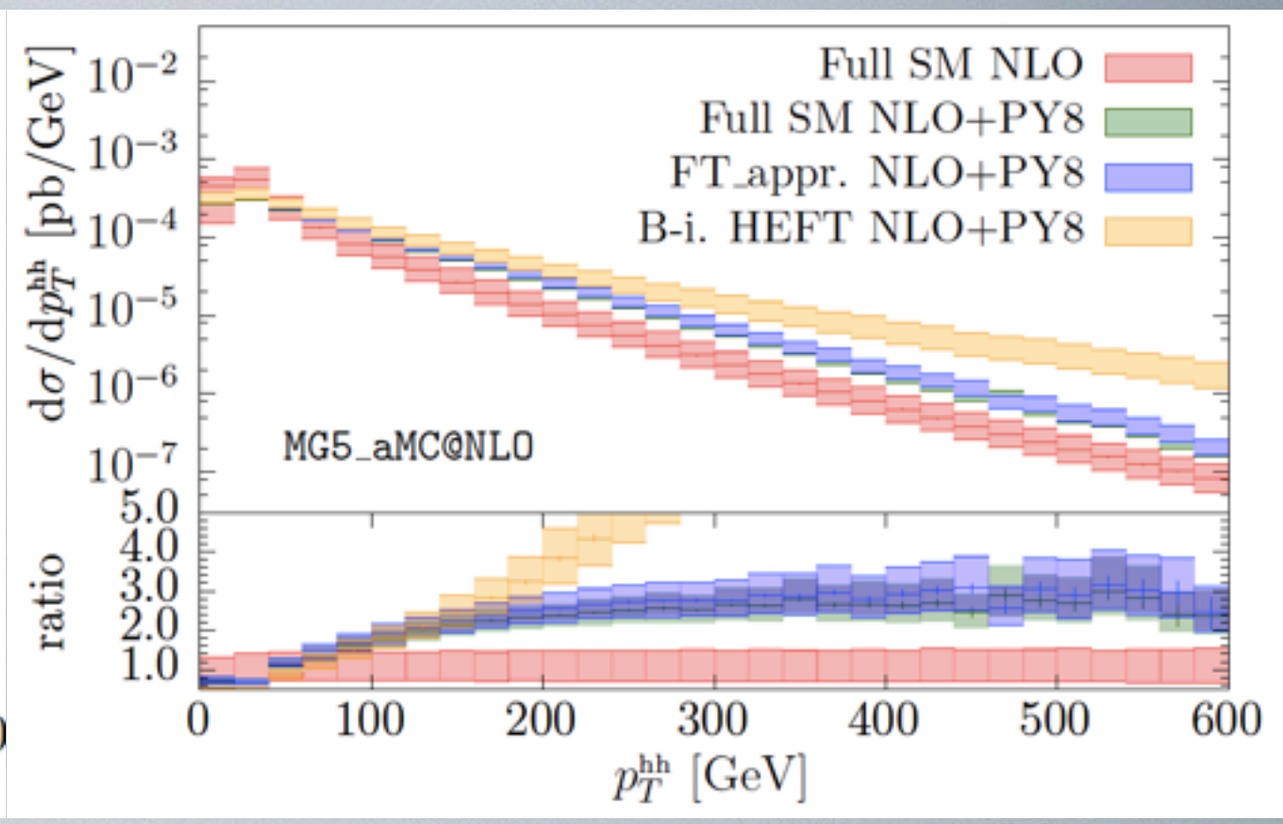
$$x = f(\beta(\hat{s})), \quad c_\theta = |\cos\theta| = \left|\frac{\hat{s} + 2\hat{t} - 2m_H^2}{\hat{s}\beta(\hat{s})}\right| \qquad \beta(\hat{s}) = \sqrt{1 - 4m_H^2/\hat{s}}$$

- choose f according to cumulative distribution of phase space points
- use *SciPy* package for interpolation [Clough, Tocher]

combination with parton showers

combination with both POWHEG and MadGraph5_aMC@NLO



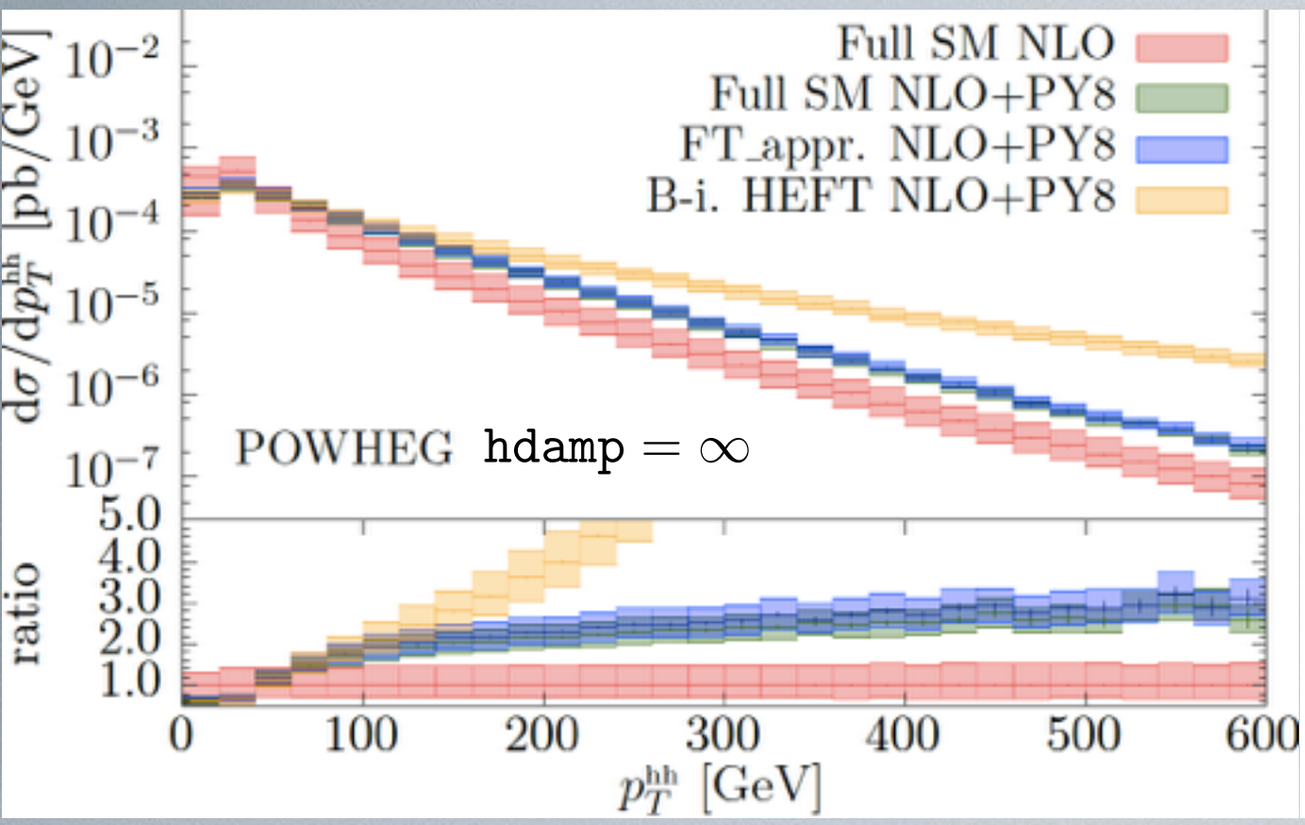


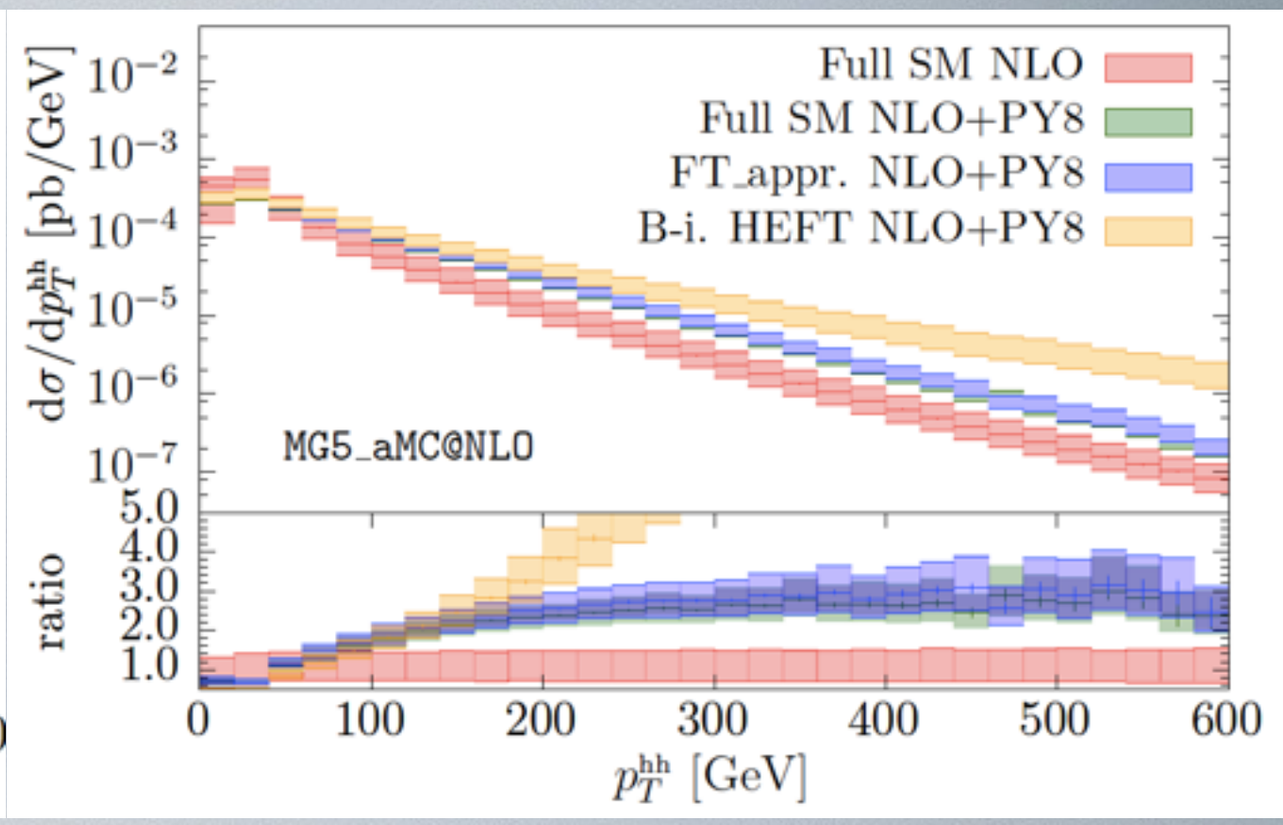
shower effects on p_T^{HH} large

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

combination with parton showers

combination with both POWHEG and MadGraph5_aMC@NLO





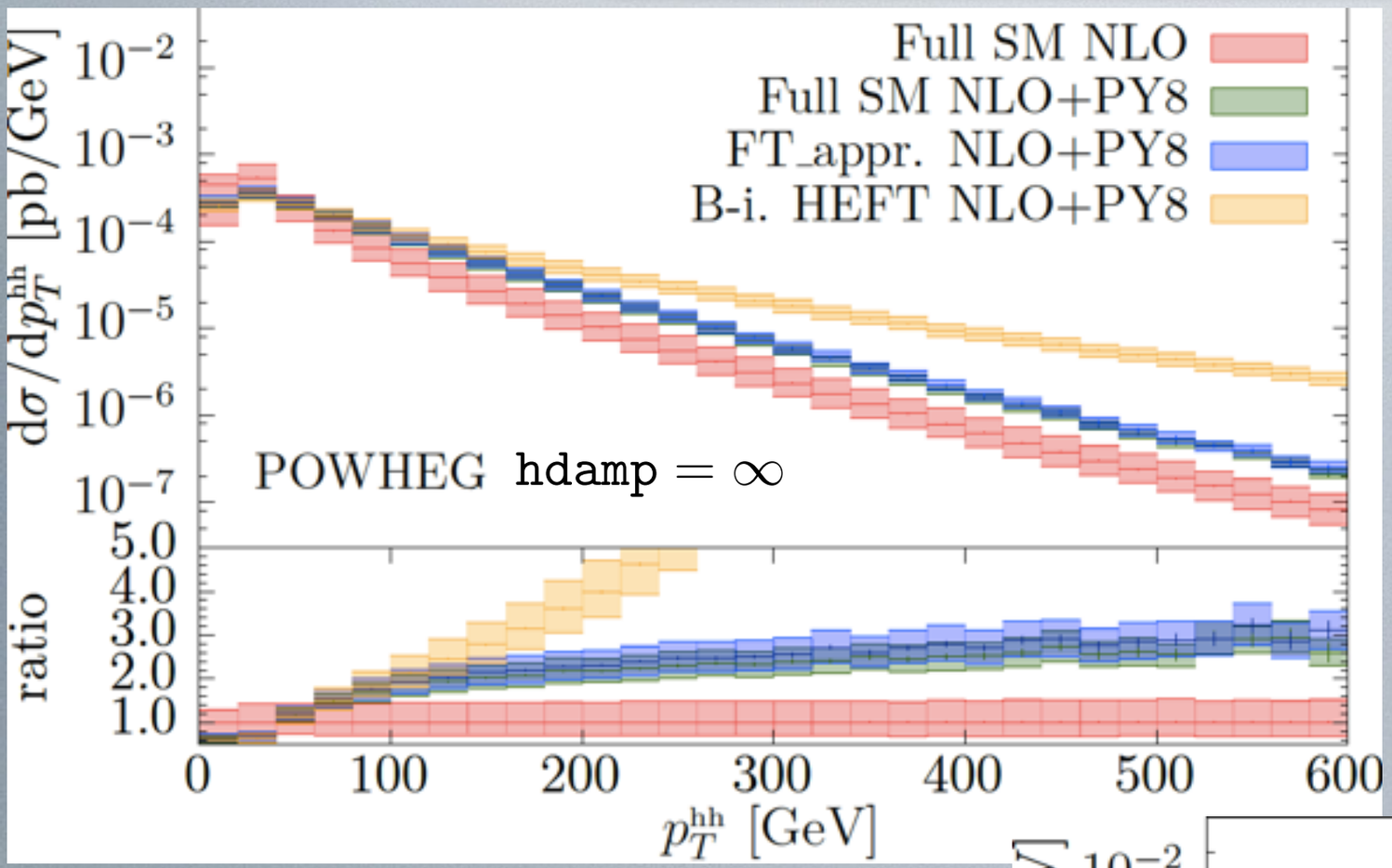
shower effects on p_T^{HH} large

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

POWHEG User-Process-V2/ggHH

2-loop results publicly available, easy to use

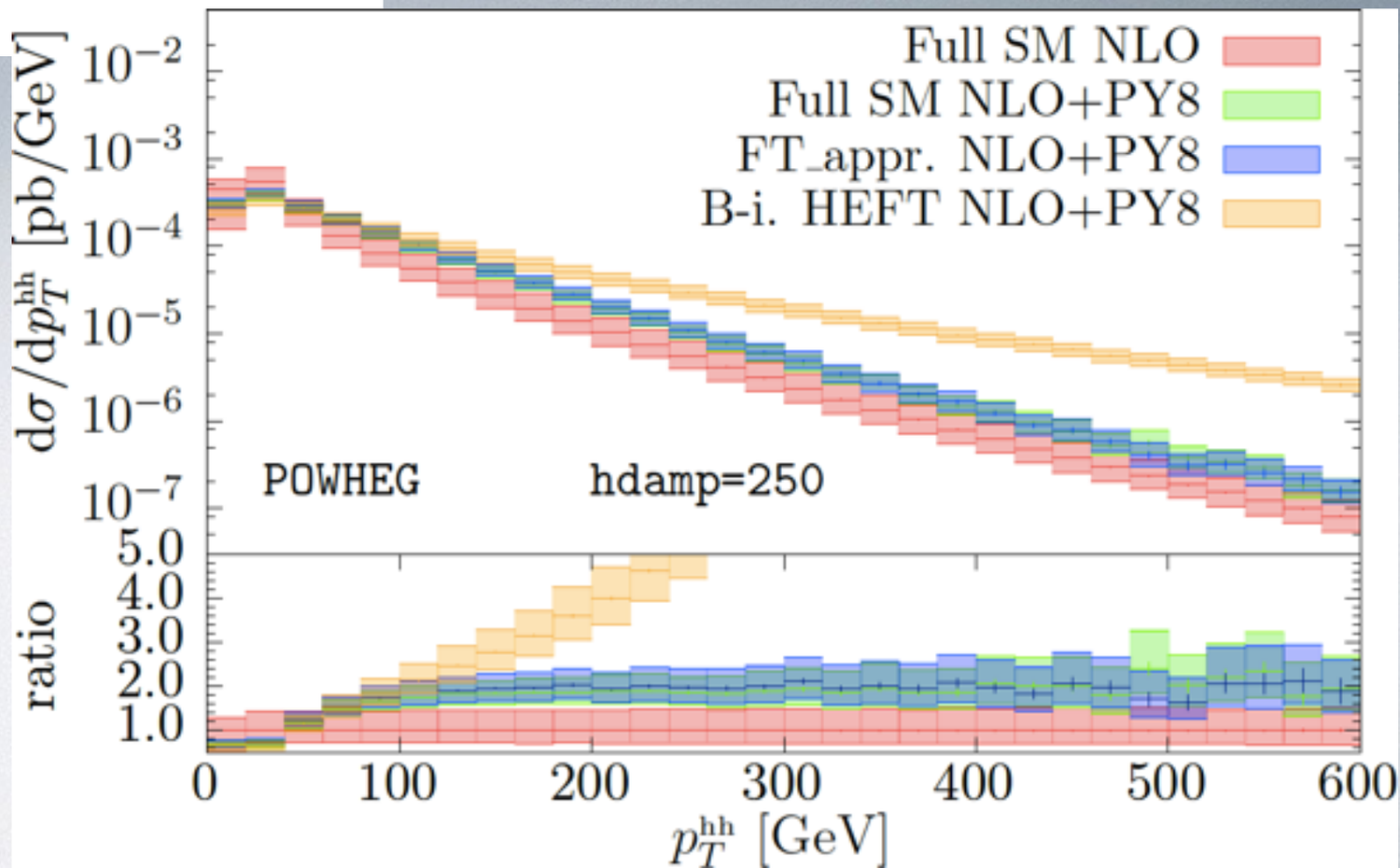
dependence on shower parameters



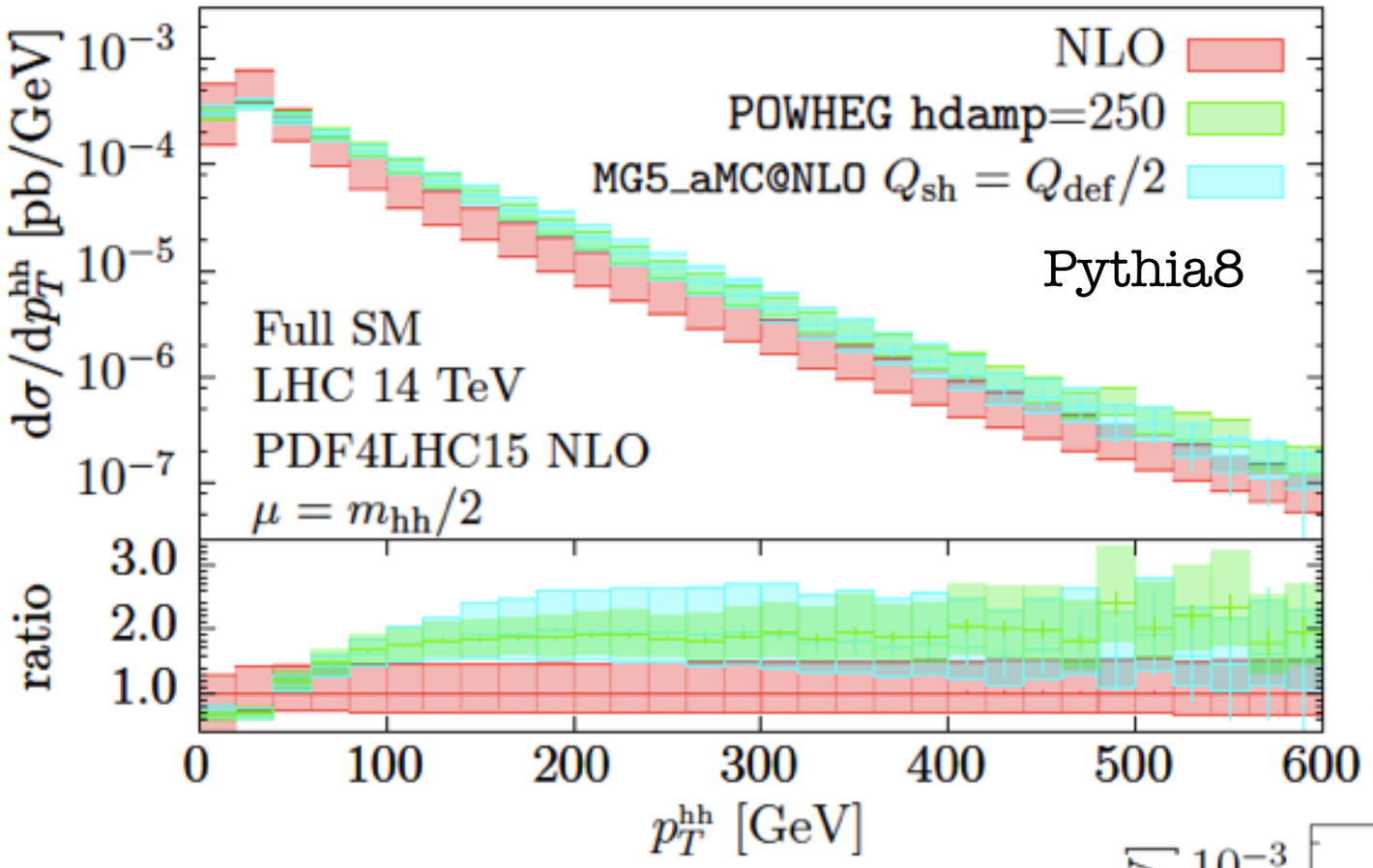
hdamp=h limits amount of exponentiated hard radiation

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

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



dependence on shower parameters



MG5_aMC@NLO:

$Q_{\rm def}$: default shower starting scale

shower starting scale picked with some probability distribution in

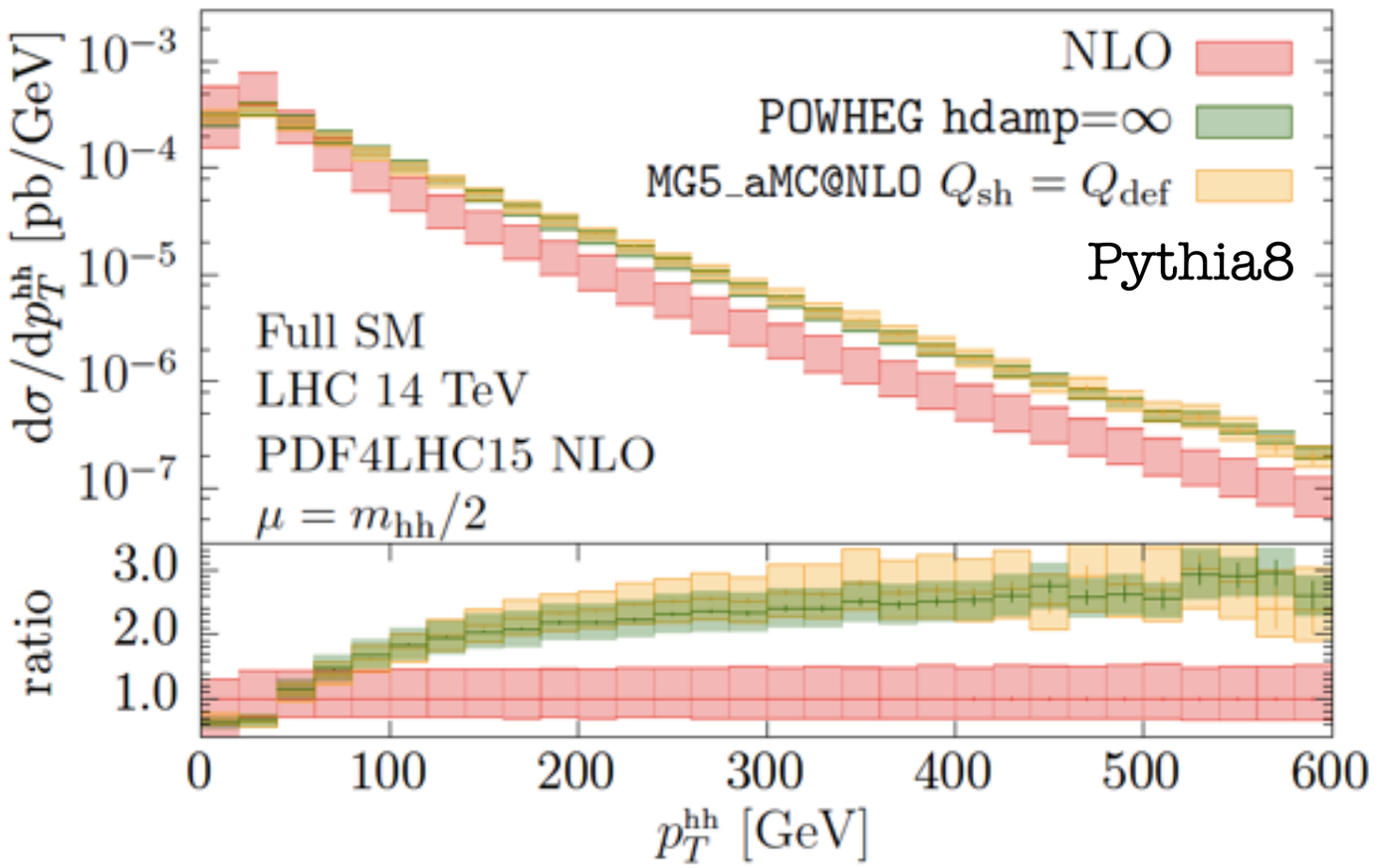
$$\texttt{shower_scale_factor} \times [0.1\sqrt{\hat{s}}, \sqrt{\hat{s}}]$$

Powheg with hdamp $= 250$

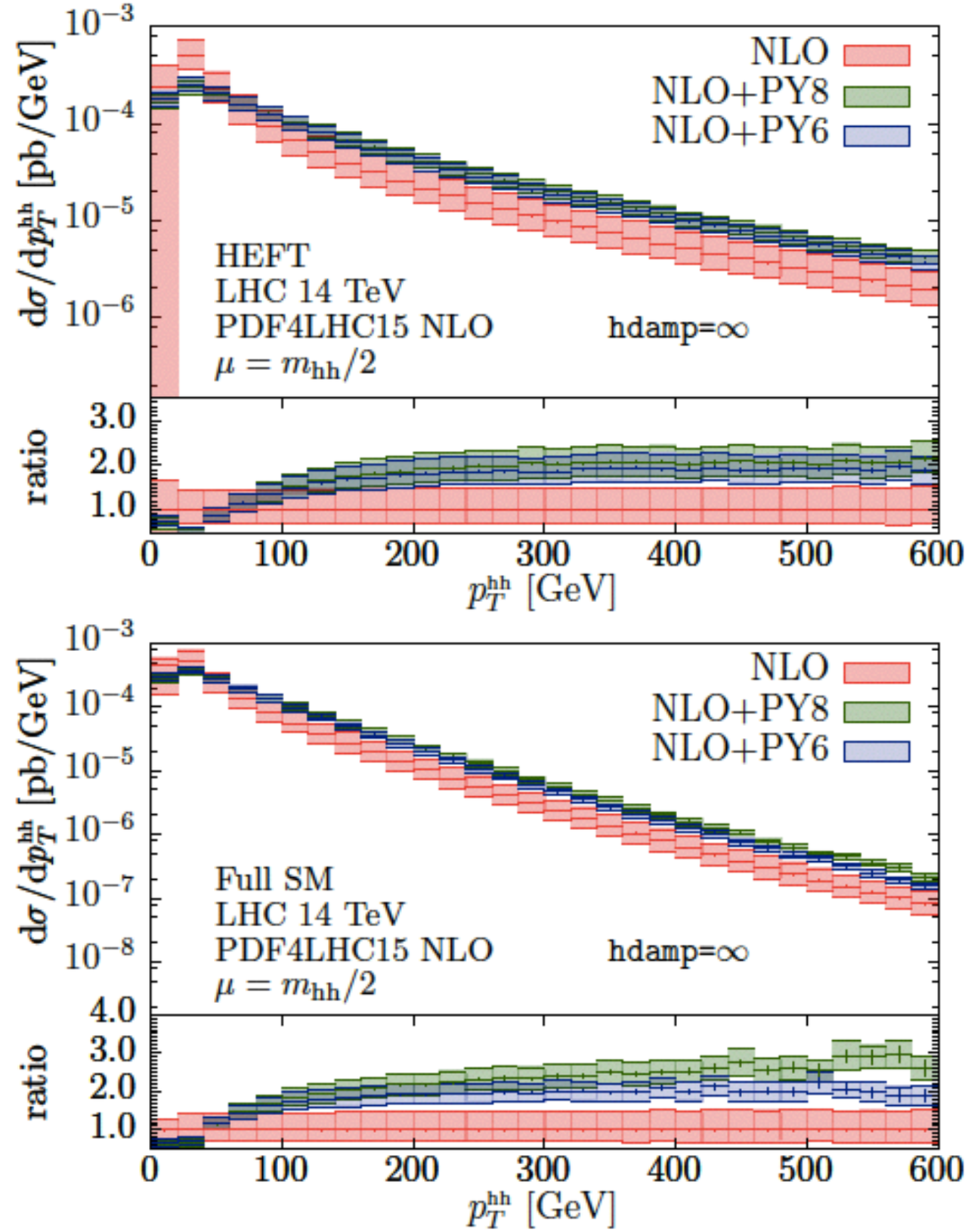
and MG5_aMC@NLO

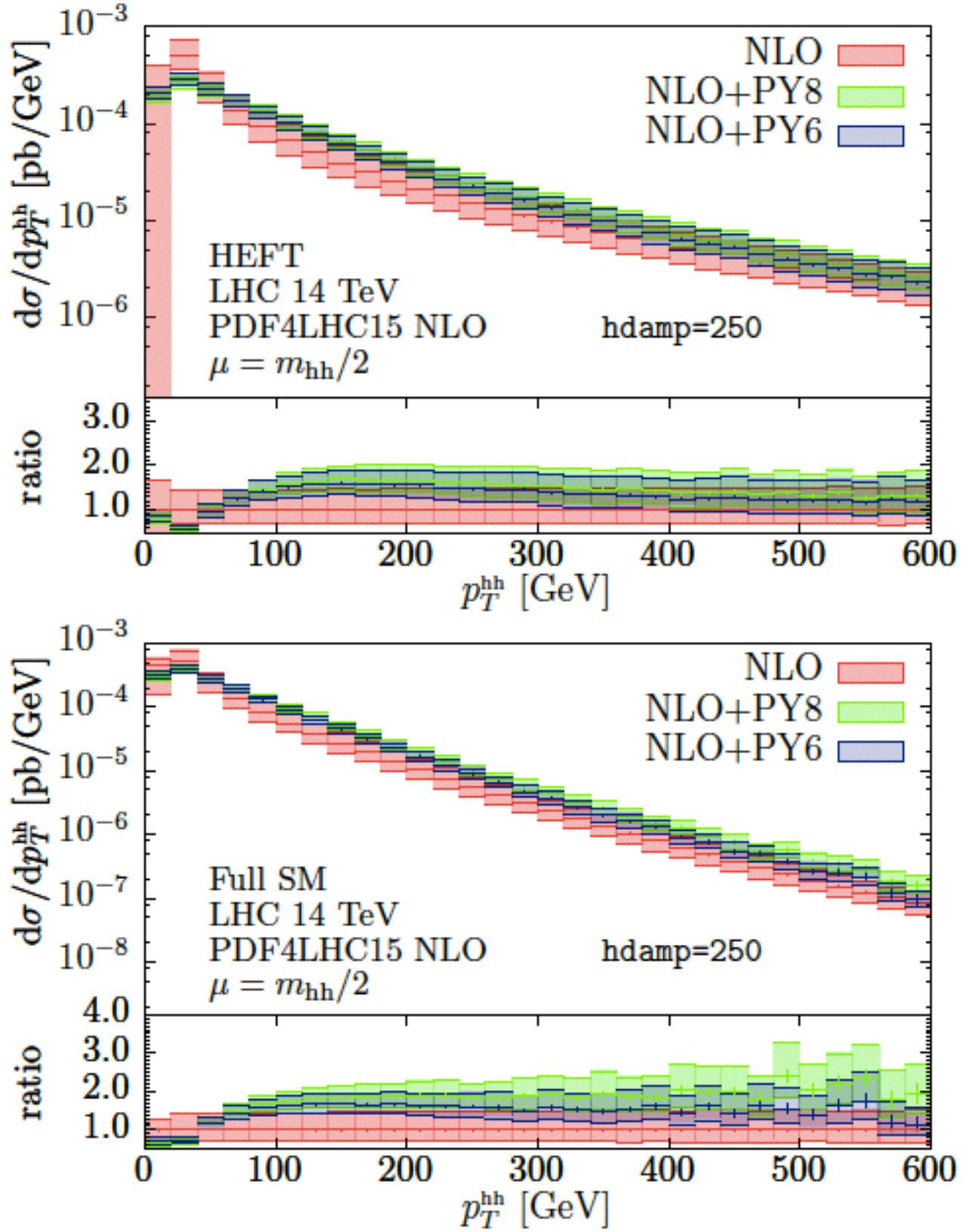
with $Q = Q_{\rm def}/2$

show similar behaviour



comparison Pythia6 vs. Pythia8





thanks: G.Luisoni

Summary and outlook

- the Higgs sector is just starting to get explored
- it is likely that New Physics is hiding in small deviations
- precision calculations and -measurements become vital
- the calculation of higher order predictions saw an amazing boost

due to

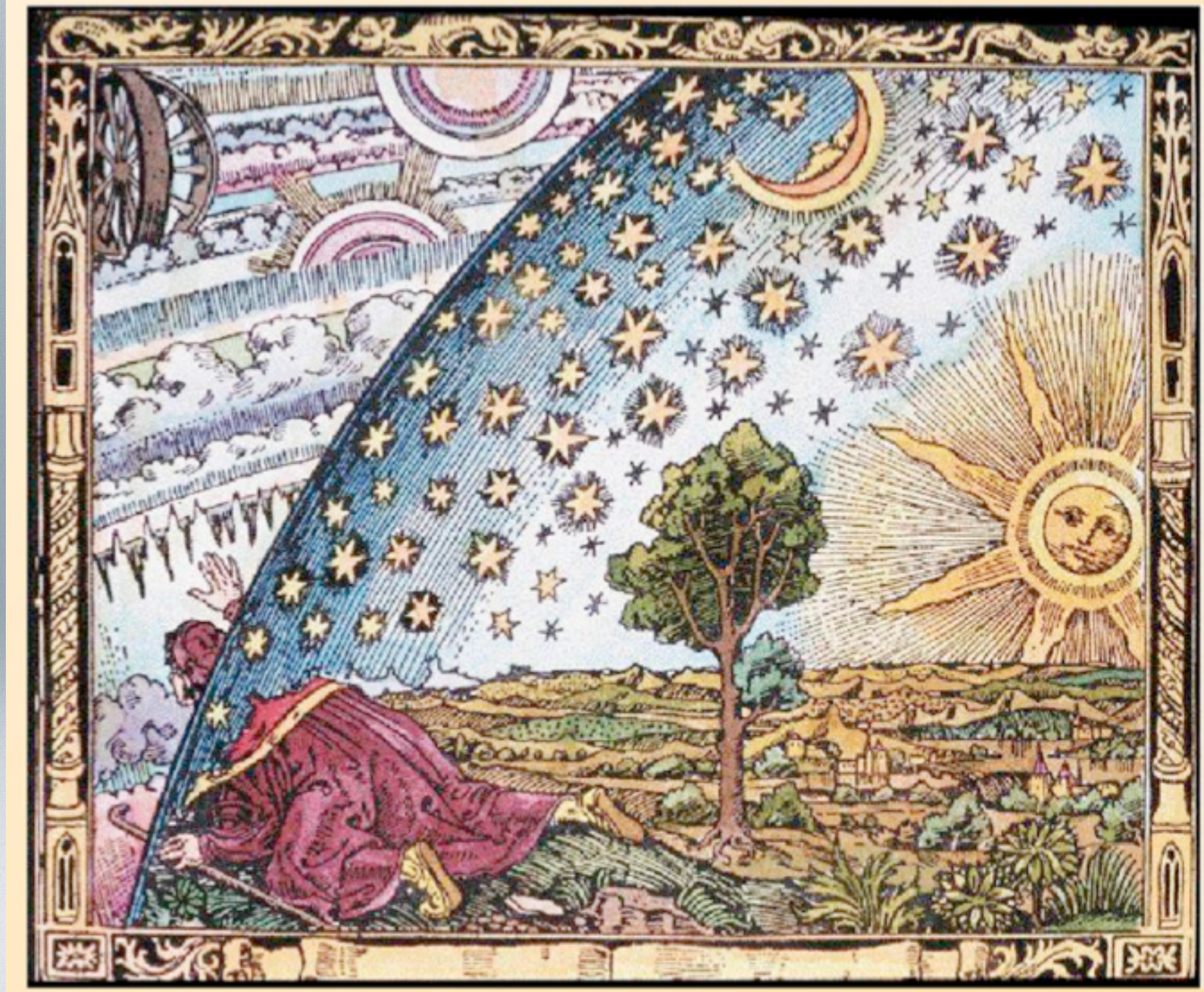
- deeper insights into the structure of scattering amplitudes
- new ideas for the calculation of master integrals, both analytically and numerically
- advances in NNLO infrared subtraction schemes
- advances in numerical methods

example gg to HH:

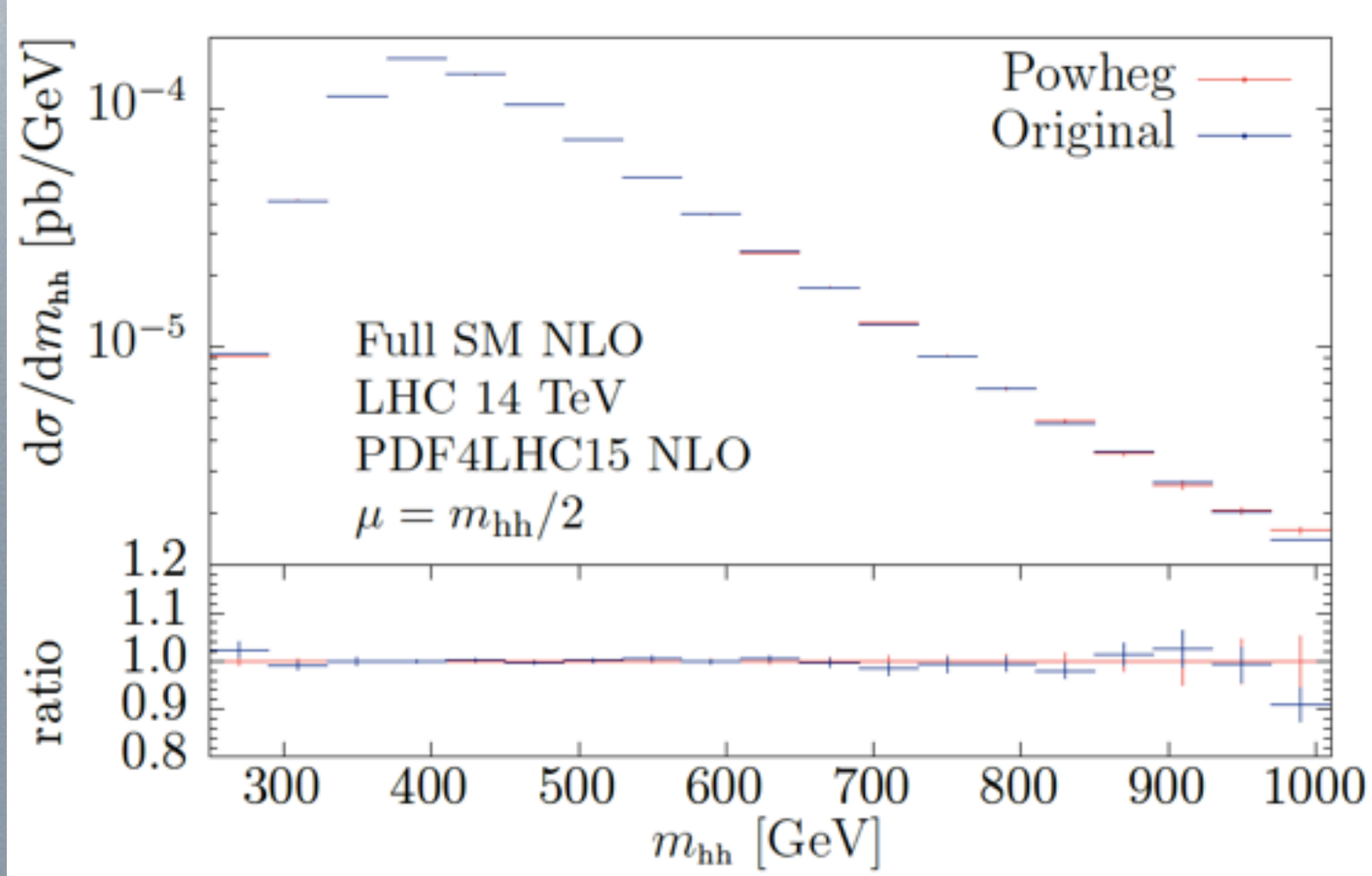
- mass effects more important than shower effects (and HEFT higher order effects)
- **numerical** methods for 2-loop integrals can prove very useful in cases where analytic results are not available

The Standard Model so far has shown us only its “standard face”

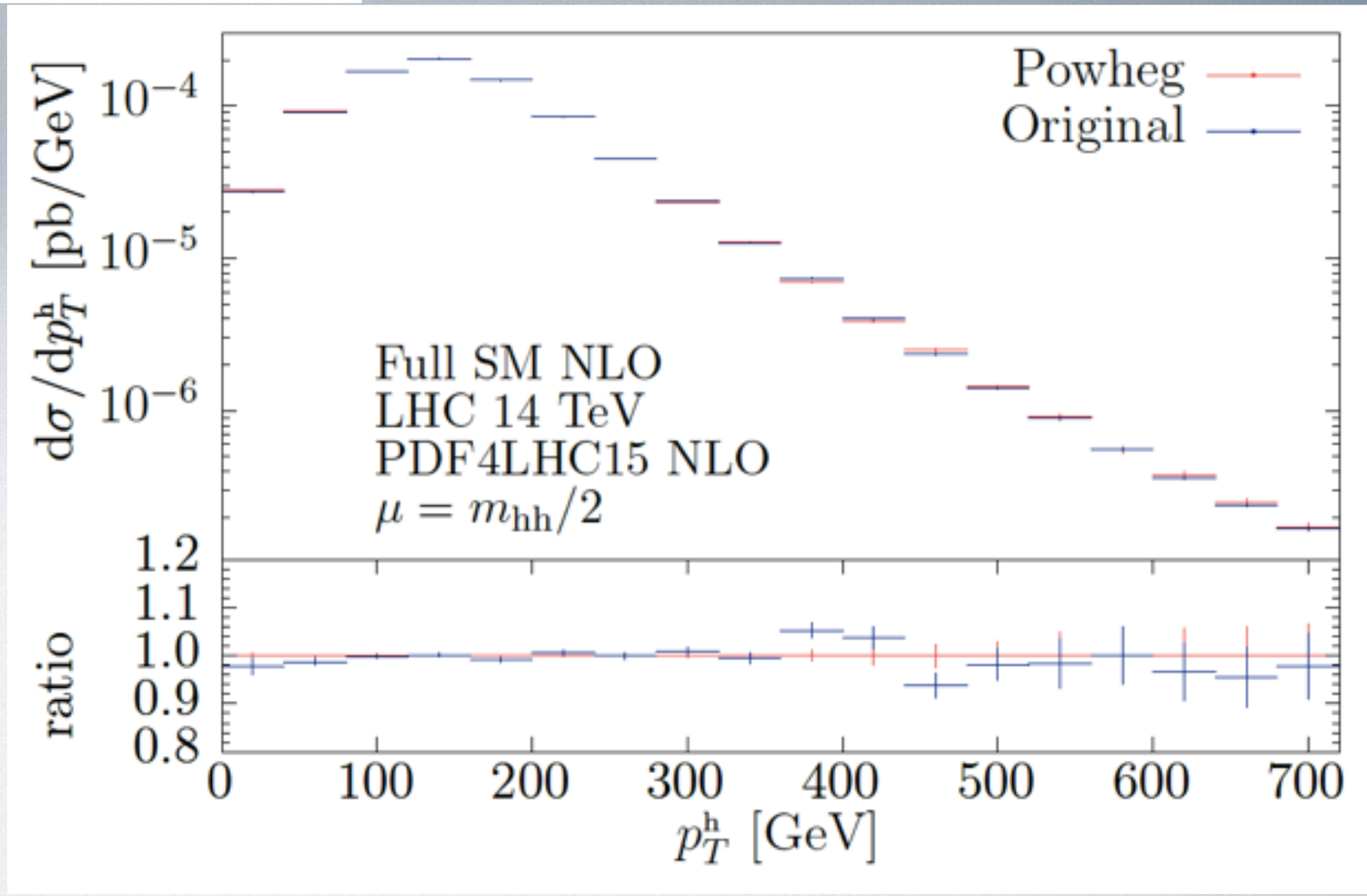
let’s be prepared for the unexpected !



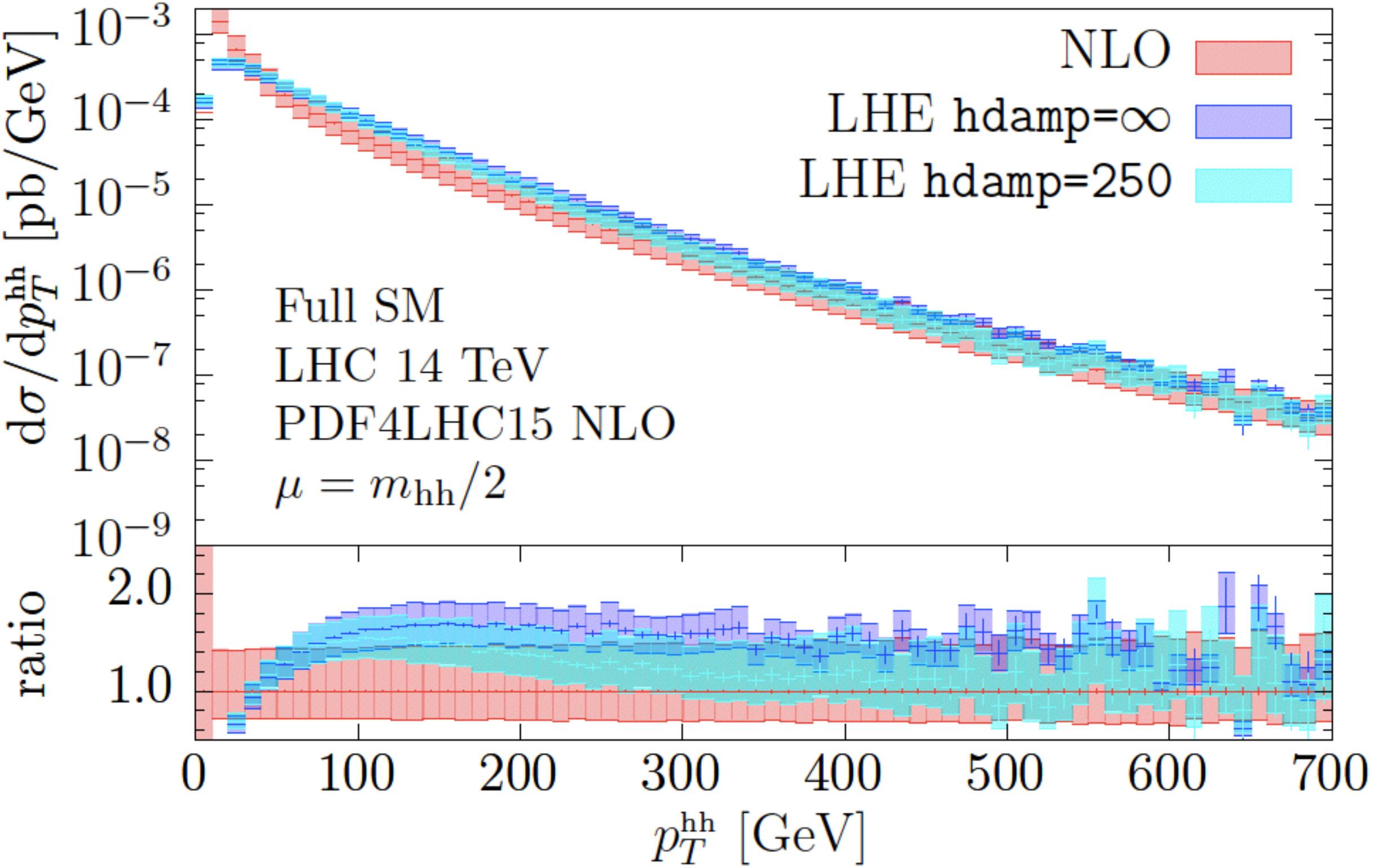
BACKUP SLIDES

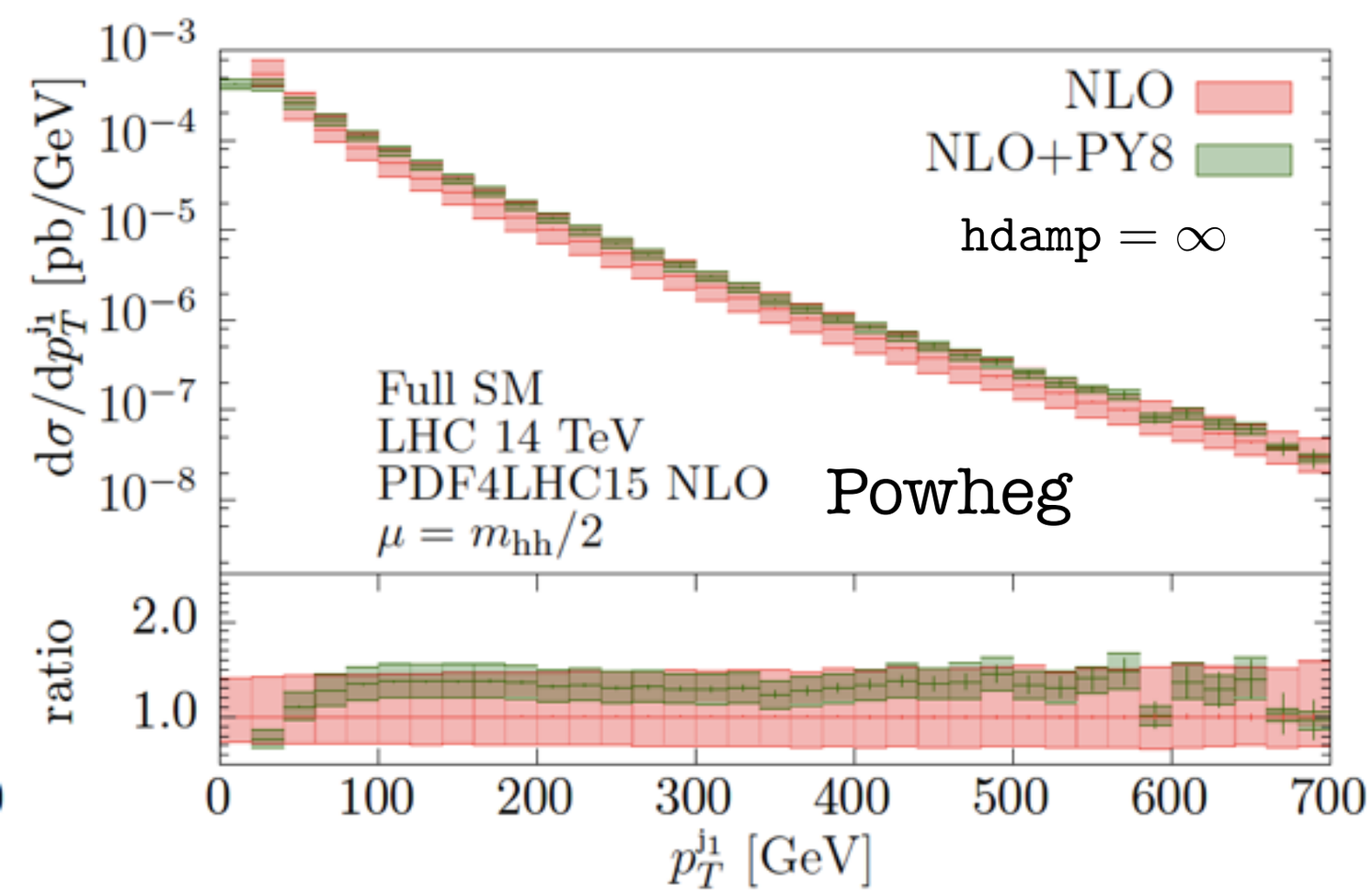


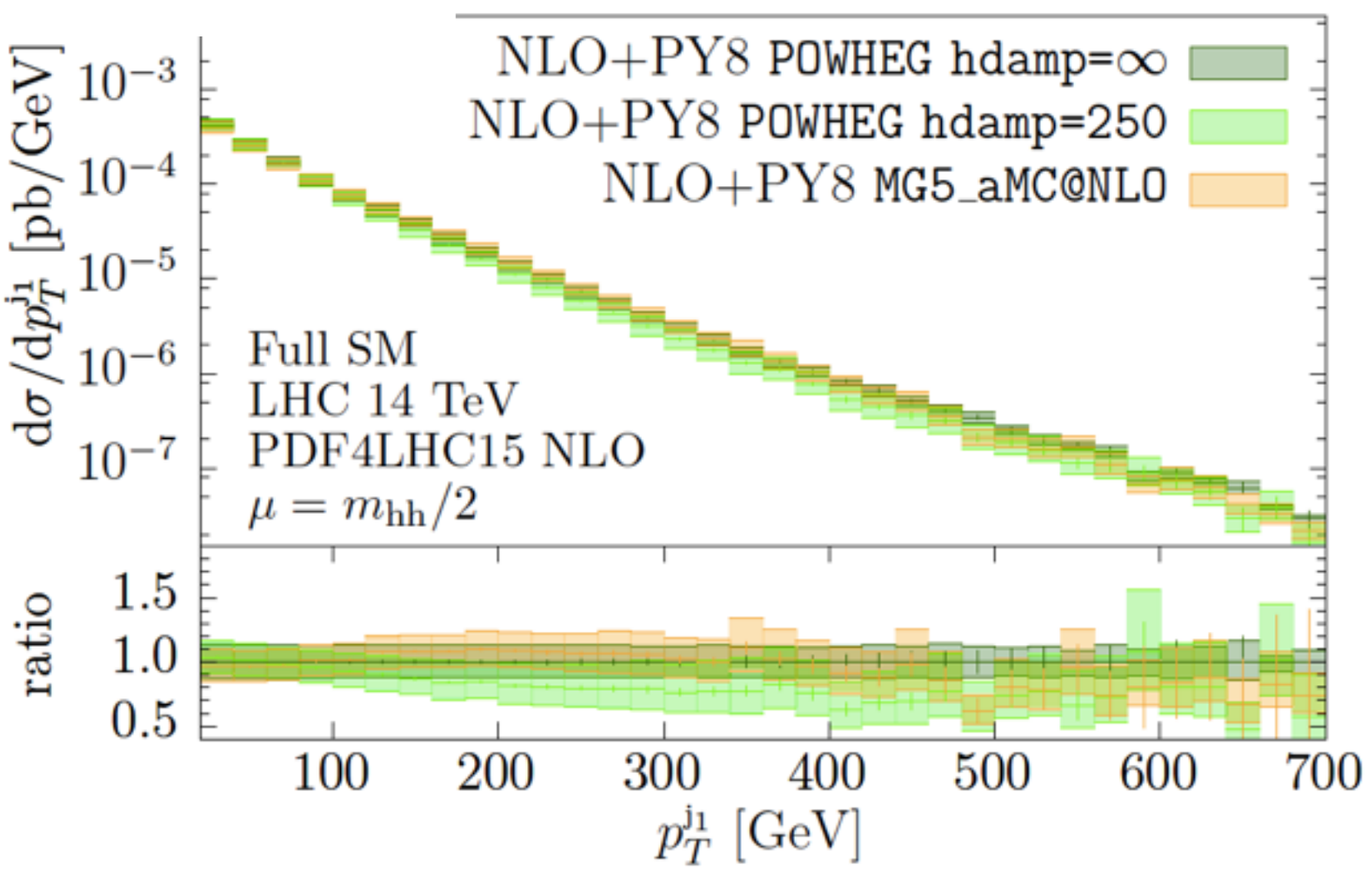
grid validation



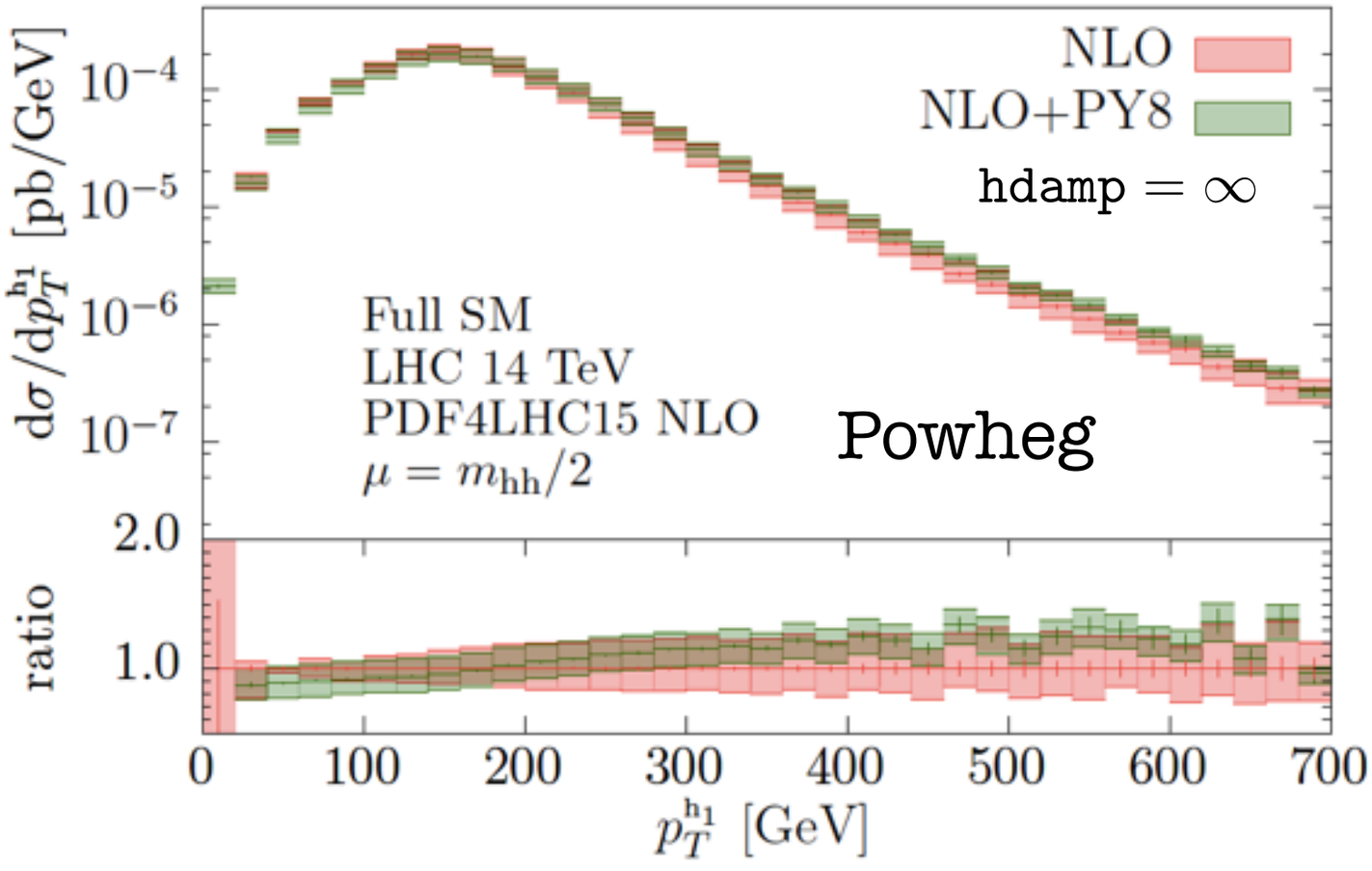
Les Houches event level: shows expected behaviour

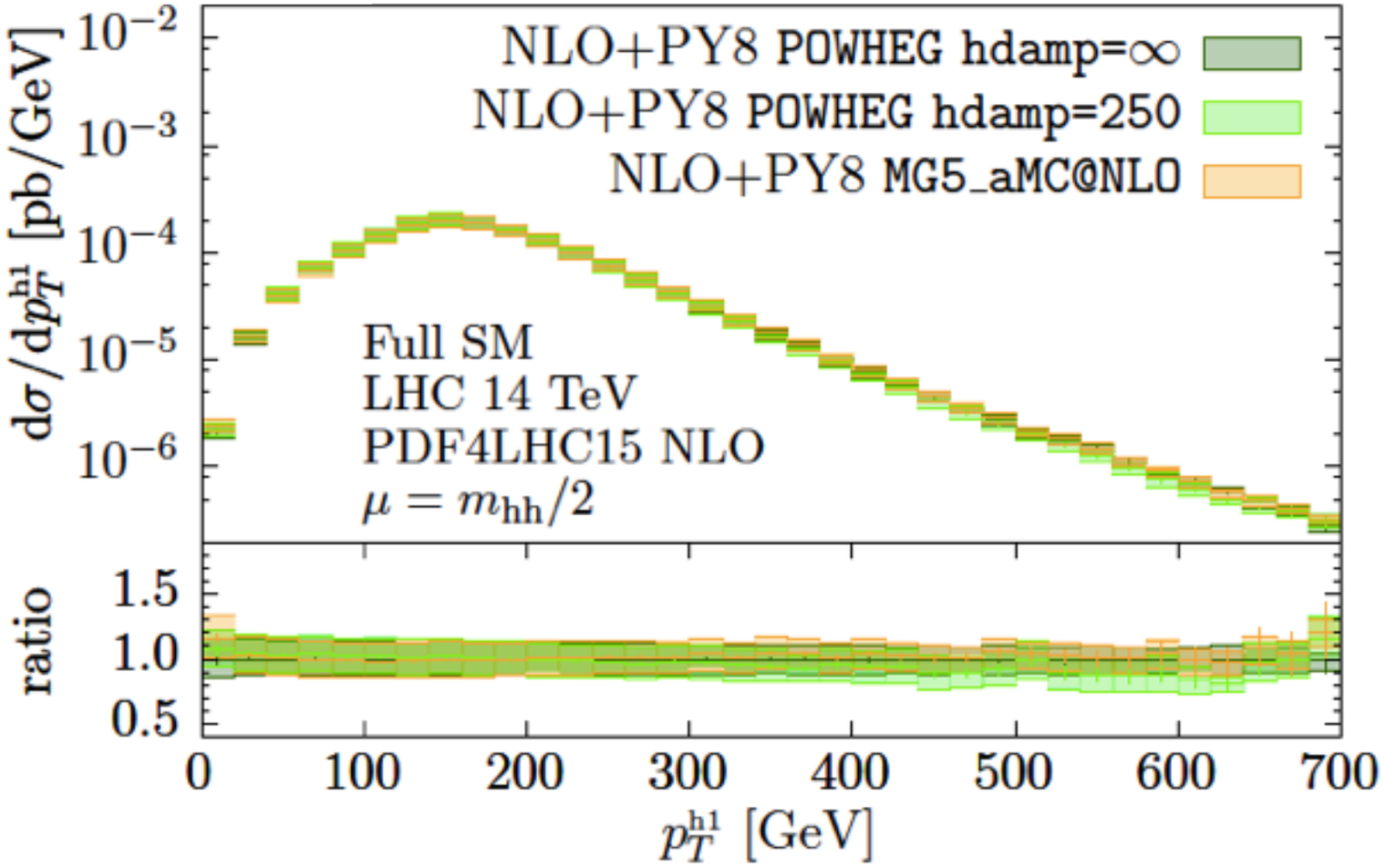






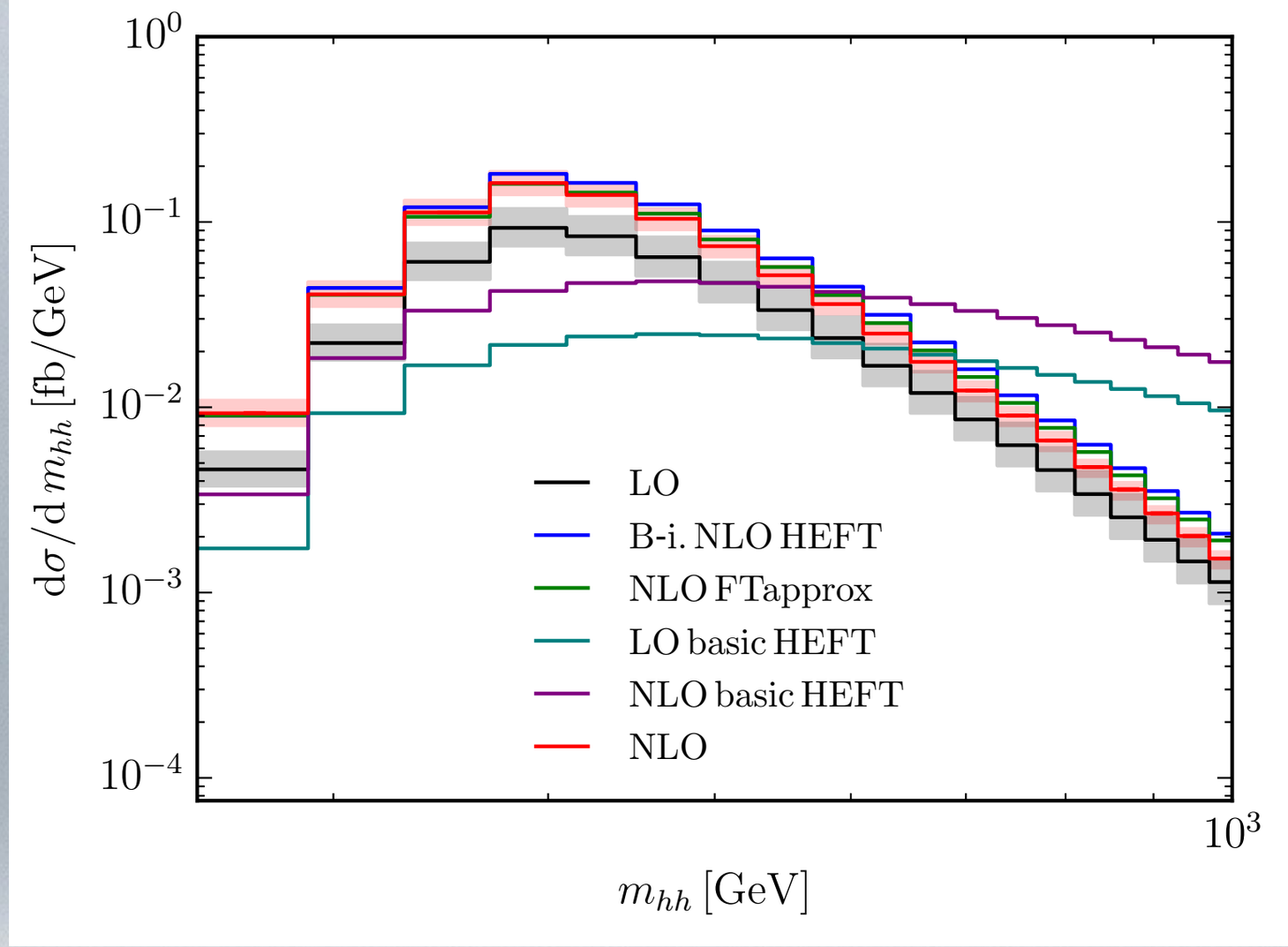
MAX-PLANCK-GESELLSCHAFT





MAX-PLANCK-GESELLSCHAFT

scaling behaviour



$$\frac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}^{-3} \quad \text{i.e. partonic cross section scales as} \quad \hat{s}^{-1}$$

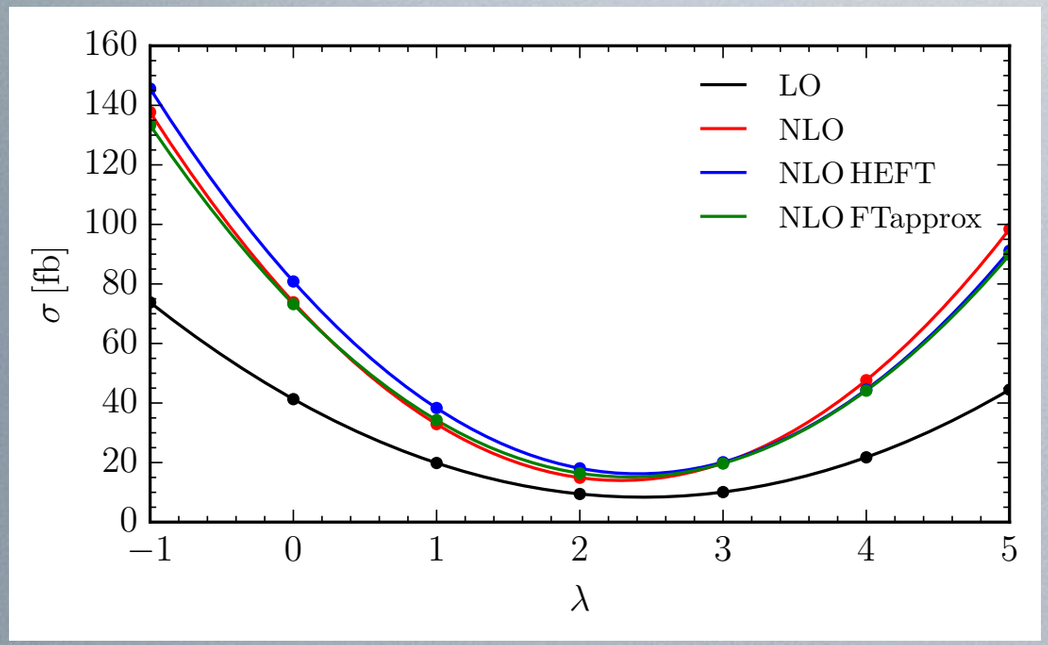
HEFT approximation: $\frac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}$ i.e. $\hat{\sigma} \sim \hat{s}$

similar for H+jet: [Greiner, Höche, Luisoni, Schönherr, Winter '16]

$$\frac{d\hat{\sigma}}{dp_{T,h}} \sim 1/p_{T,h}^{a} \text{ with } a = 2(\text{full}), a = 1(\text{HEFT})$$

variation of triple Higgs coupling

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

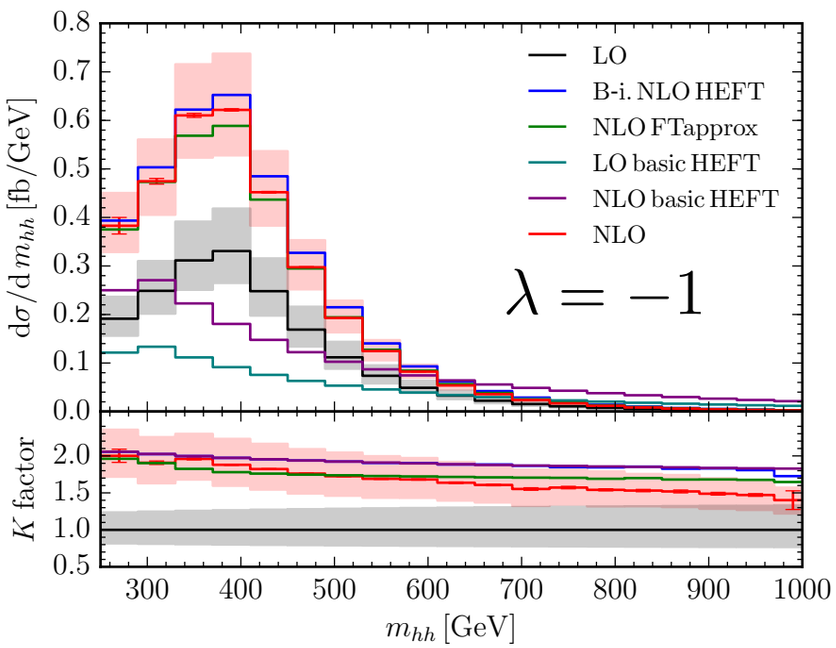


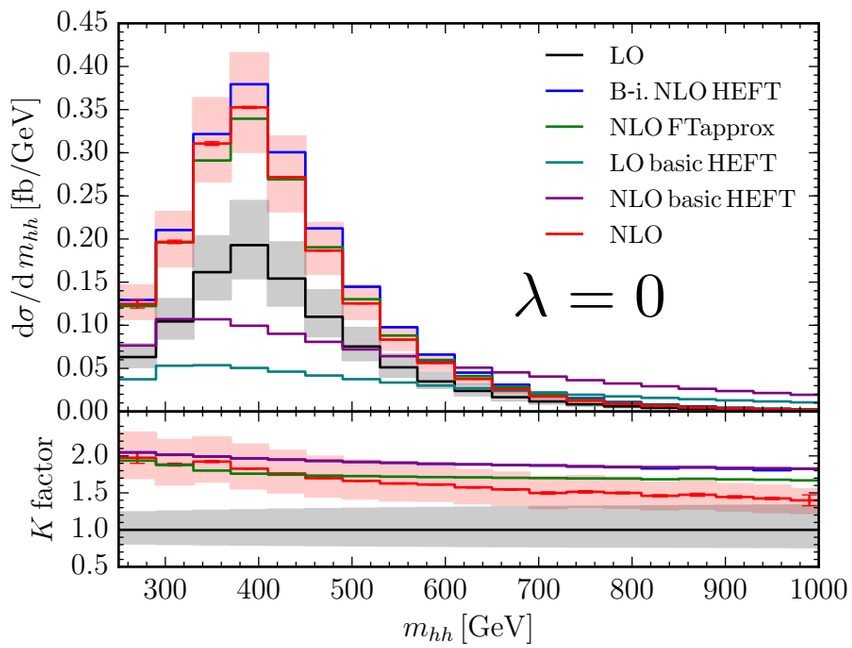
cross section has a minimum around

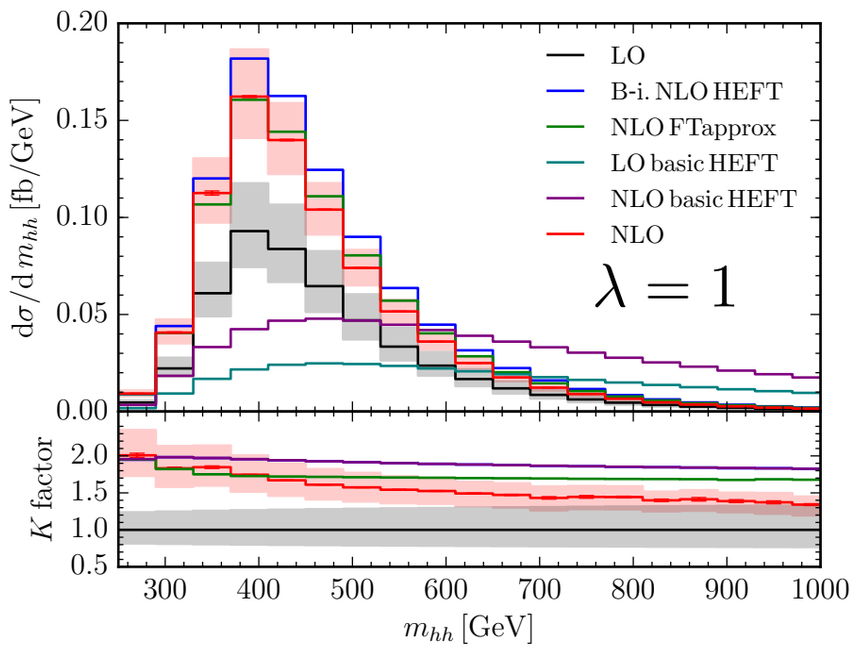
$\lambda = 2$ due to destructive interference

between diagrams containing λ

and box-type diagrams







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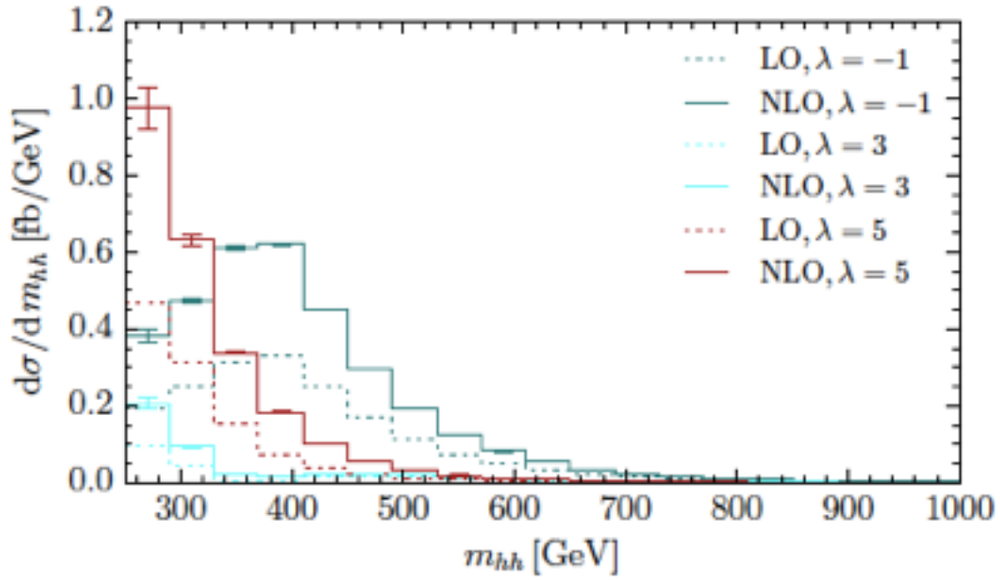
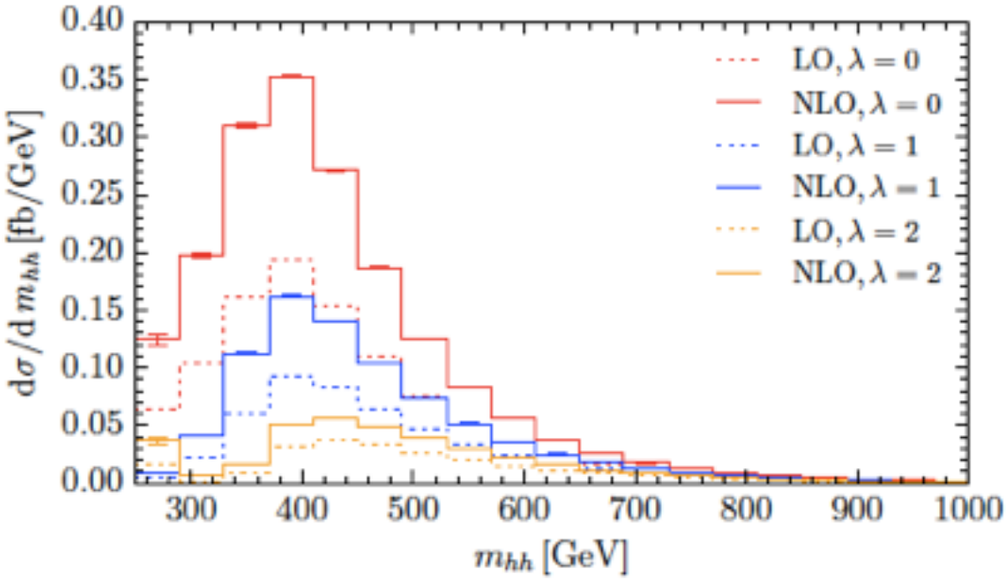
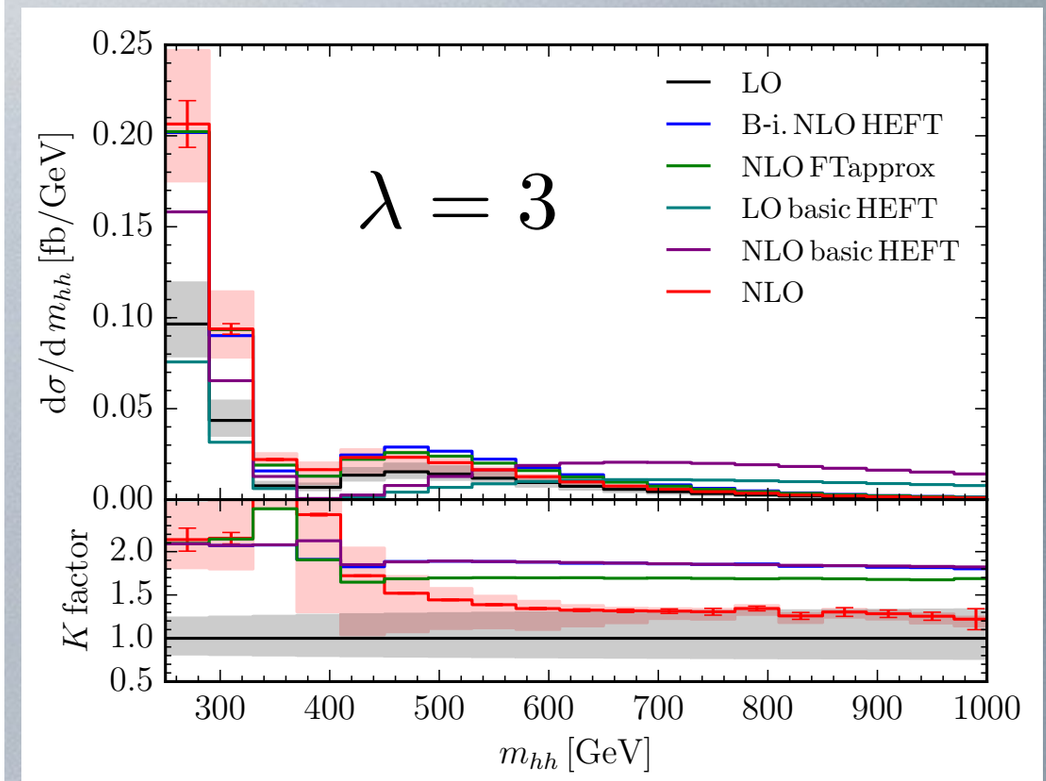
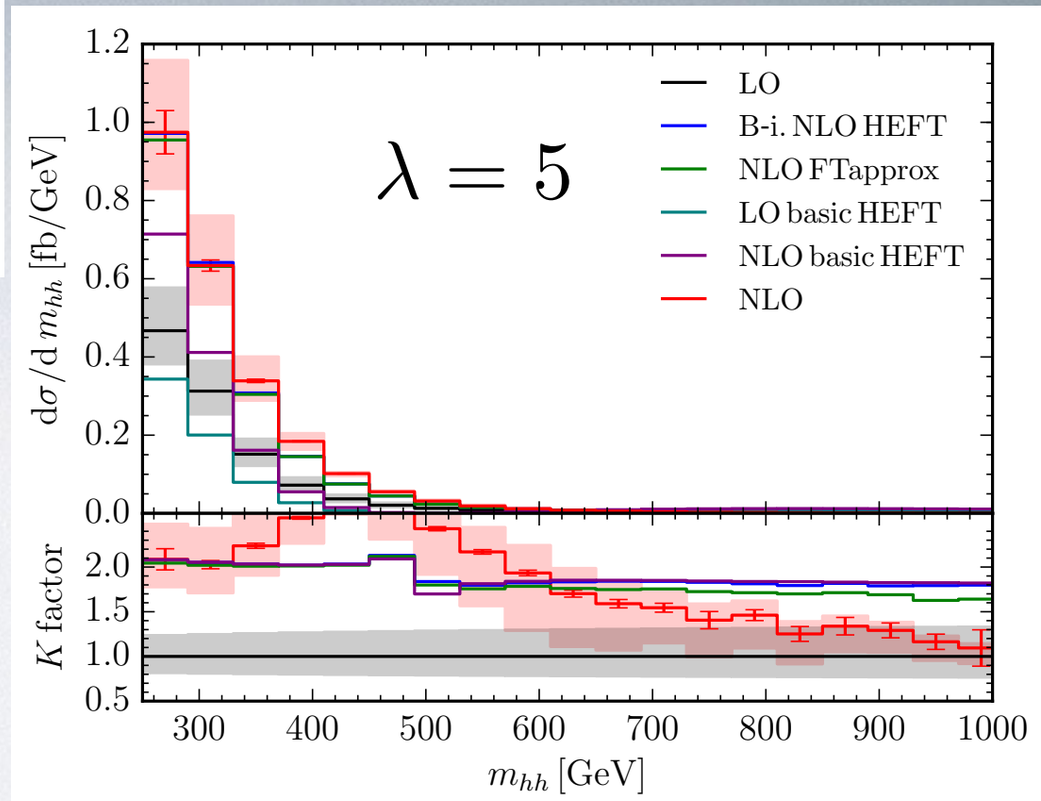
variation of triple Higgs coupling



$\sqrt{s} = 14\,\text{TeV}$







distributions have discriminating power

full analysis requires inclusion of other operators, e.g. $t\bar{t}hh$ coupling

$2 \to 2$ differential, classified by IR subtraction method

- antenna subtraction

$H + \text{jet}$ [Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '14,'16]

$Z + \text{jet}$ [Gehrmann-DeRidder, Gehrmann, Glover, Huss, Morgan '15,'16]

$2\,\text{jets}$ [Currie, Gehrmann-DeRidder, Gehrmann, Glover, Pires '14; Currie, Glover, Pires '16]

$ep \to 2\,\text{jets}$ [Gehrmann, Niehues '16; Currie, Gehrmann, Huss, Niehues, '17]

- qt subtraction (slicing)

WH [Ferrera, Grazzini, Tramontano '07]

$\gamma\gamma$ [Catani, Cieri, De Florian, Ferrera, Grazzini '11]

$Z\gamma$ [Grazzini, Kallweit, Rathlev, Torre '13]

ZH [Ferrera, Grazzini, Tramontano '14]

$W\gamma$ [Grazzini, Kallweit, Rathlev '15]

ZZ [Cascioli, T.Gehrmann, Grazzini, Kallweit, Maierhöfer, Manteuffel, Pozzorini, Tancredi, Weihs '14; Grazzini, Kallweit, Rathlev '15]

WW [T.Gehrmann, Grazzini, Kallweit, Maierhöfer, Manteuffel, Pozzorini, Rathlev, Tancredi '14; Grazzini, Kallweit, Pozzorini, Rathlev, Wiesemann '16]

WZ [Grazzini, Kallweit, Rathlev, Wiesemann '16]

$HH(m_t \to \infty)$ [De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16]

$2 \to 2$ classified by IR subtraction method

- sector-improved residue subtraction
  - $\sigma_{\rm tot} t\bar{t}$ [Czakon, Fiedler, Mitov '13]
  - $H + \rm jet$ [Boughezal, Caola, Melnikov, Petriello, Schulze '15]
  - $t\bar{t}$ [Czakon, Heymes, Mitov '15,'16]
  - Drell-Yan (new variant) [Caola, Melnikov, Röntsch '17]
- N-jettiness (slicing)
  - $H + \rm jet$ [Boughezal, Focke, Giele, Liu, Petriello '15]
  - HW, HZ [Campbell, Ellis, Williams '16]
  - $W + \rm jet$ [Boughezal, Focke, Liu, Petriello '15; Boughezal, Liu, Petriello '16]
  - $Z + \rm jet$ [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15; Boughezal, Liu, Petriello '16]
  - $\gamma\gamma$ [Campbell, Ellis, Li, Williams '16]
  - $\gamma + \rm jet$ [Campbell, Ellis, Williams '17]
- projection to Born ("structure function approach")
  - $Hjj\,(\rm VBF)$ [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]
  - single top [Brucherseifer, Caola, Melnikov '14] [Berger, Gao, Yuan, Zhu '16]
- colourful subtraction
  - $e^+e^- \to 3\,\rm jets$ [Del Duca, Duhr, Kardos, Somogyi, Szor, Trocsanyi, Tulipant '16]