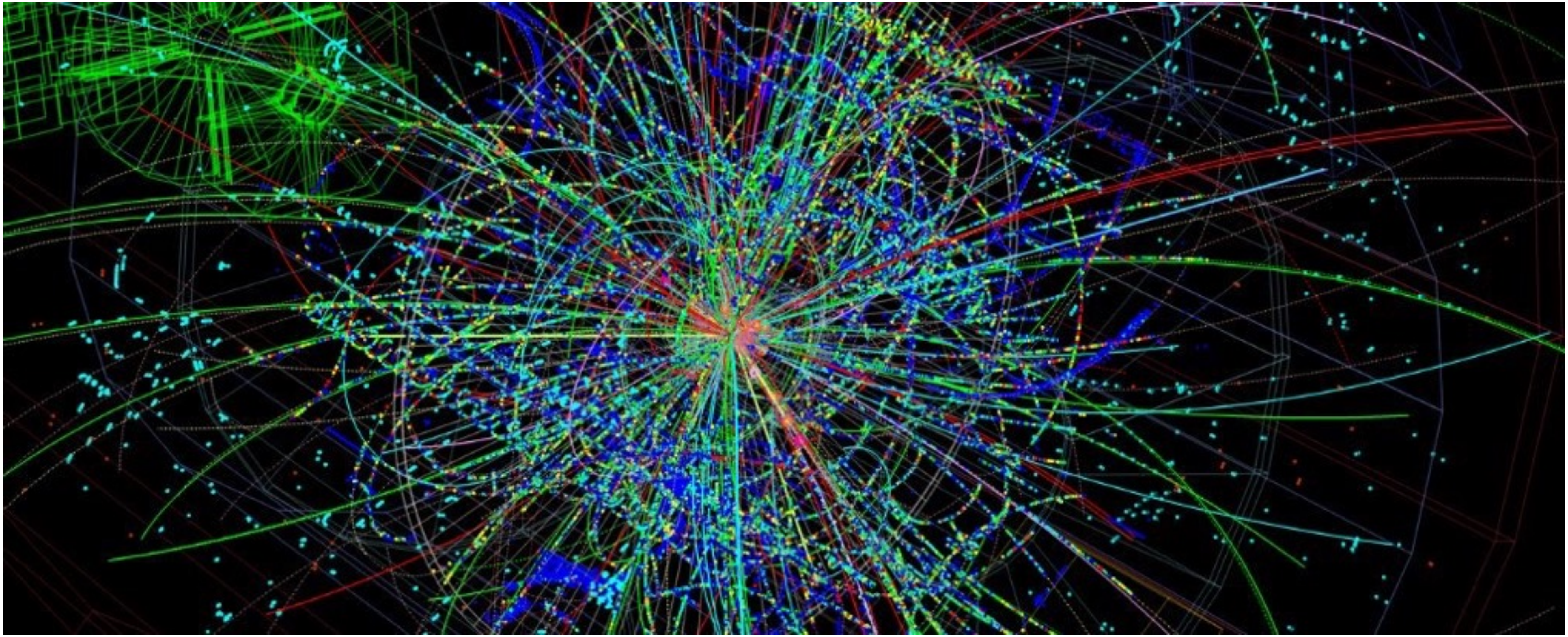
Pushing the precision frontier in Collider Physics

Gudrun Heinrich
Max Planck Institute for Physics, Munich

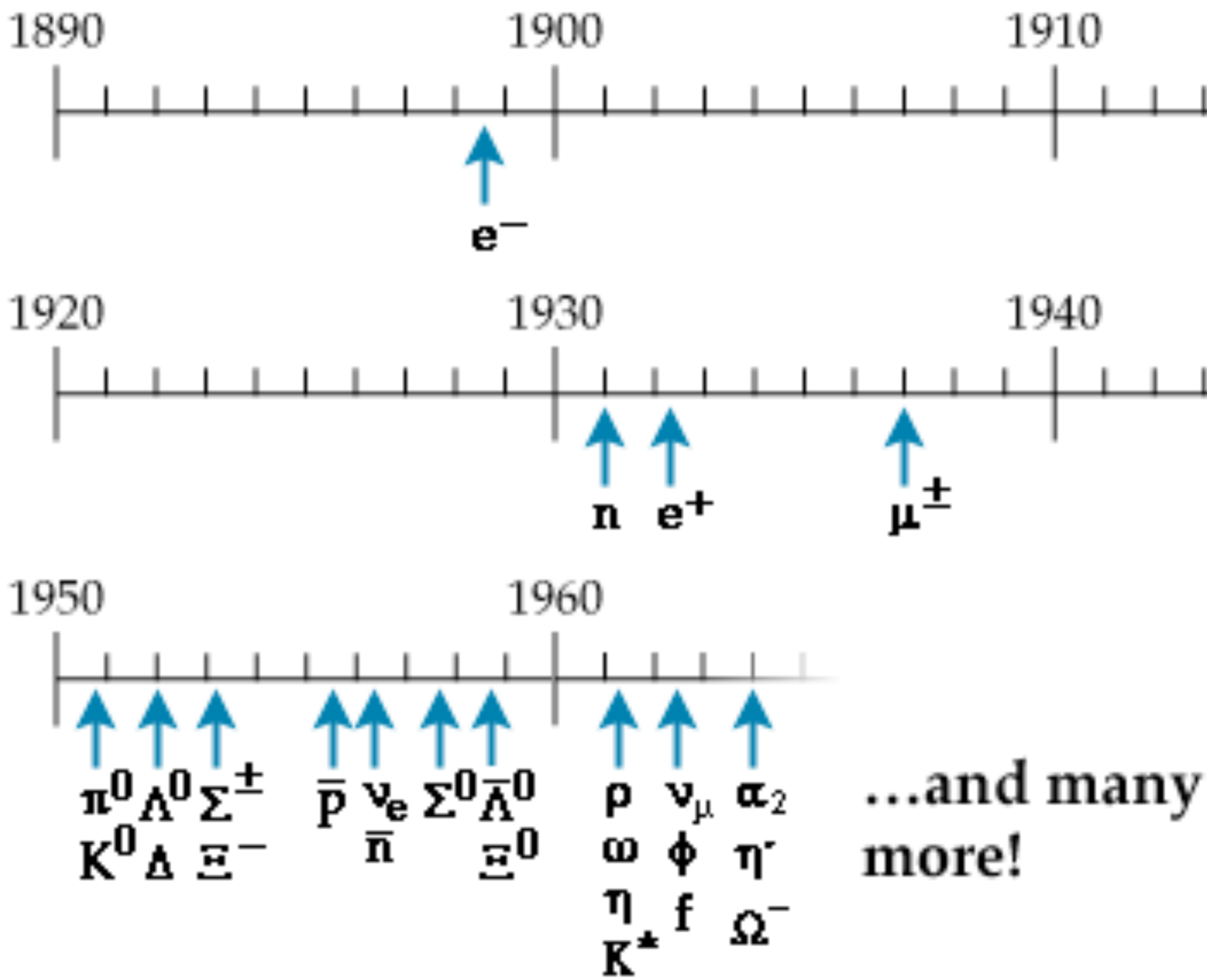


Laboratori Nazionali di Frascati,
March 28, 2019

MAX-PLANCK-GESELLSCHAFT

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

Particle Discoveries



- around 1950: "particle zoo"

  new developments were **driven by experiment**

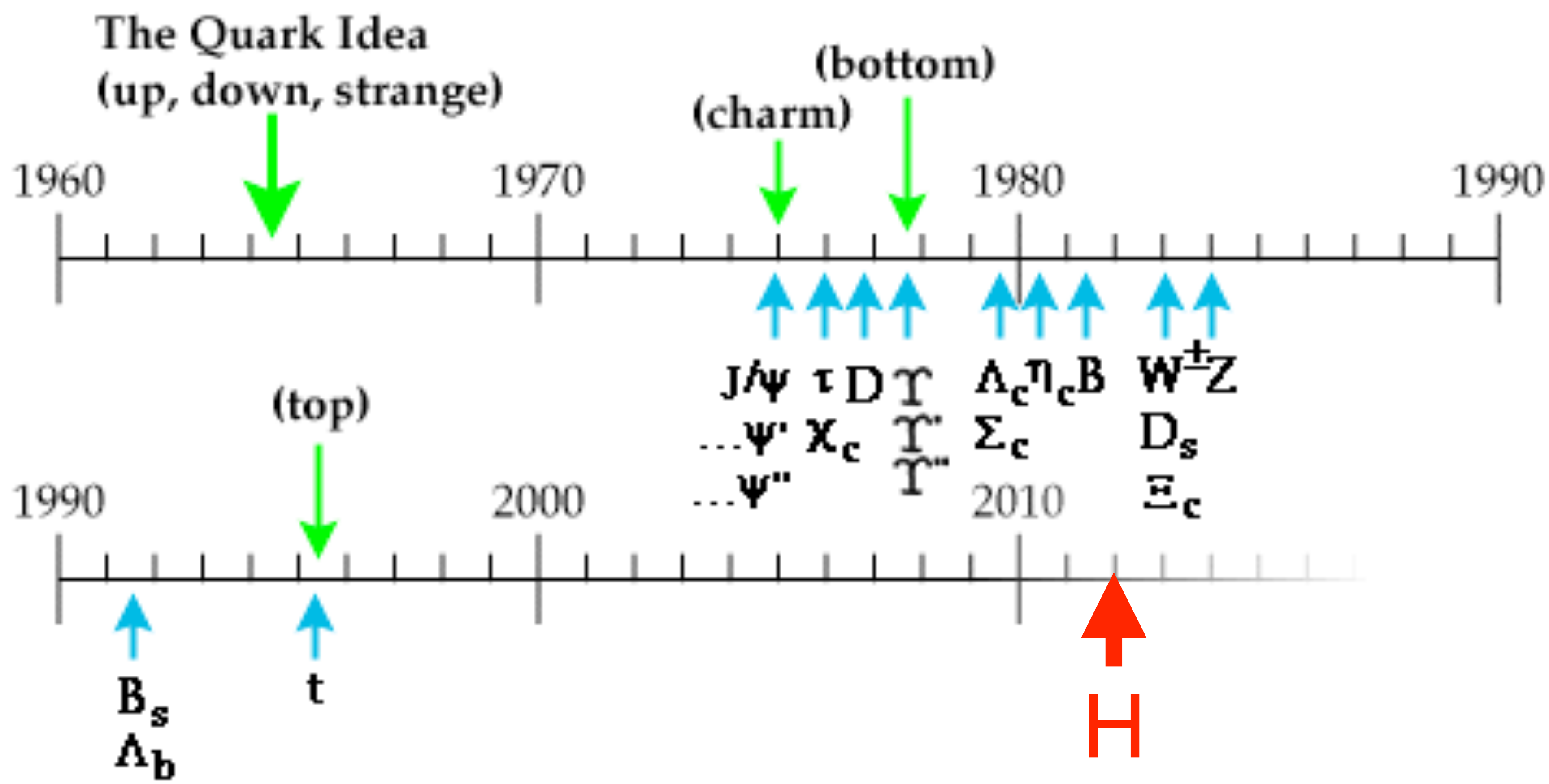
  led to the development of the quark model [Gell-Mann, Zweig 1964]

- 1960's: beginning of a **theory-driven** era

  development of the Standard Model, concept of gauge theories

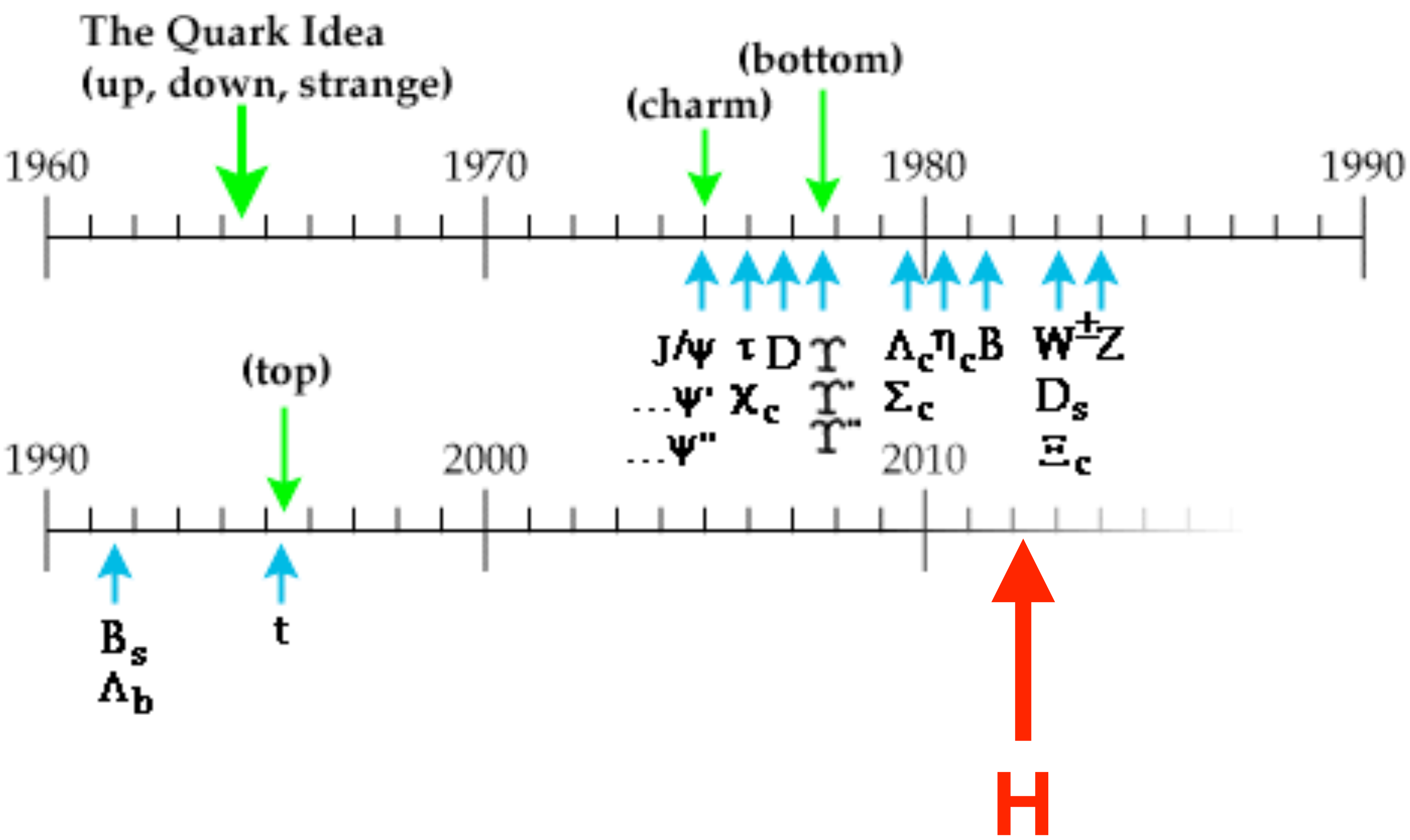
  [Glashow, Salam, Weinberg 1967; Higgs 1964; t'Hooft, Veltman 1972, …]

The theory-driven era



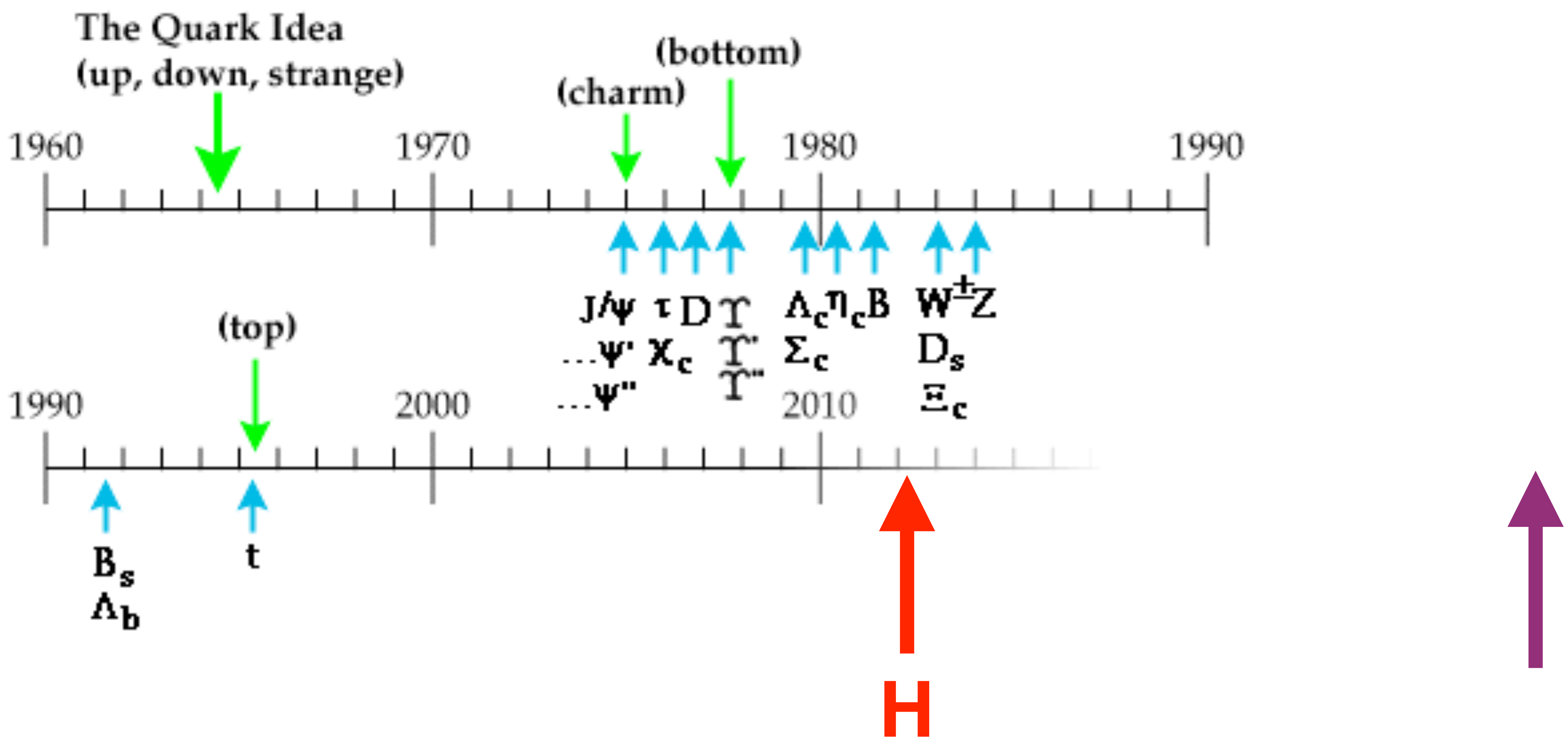
	predicted	discovered
charm quark	1964	1974
bottom quark	1973	1977
W/Z bosons	1968	1983
top quark	1973	1995
Higgs boson	1964	2012

Particle Discoveries



mass: 48 years after the prediction

Particle Discoveries



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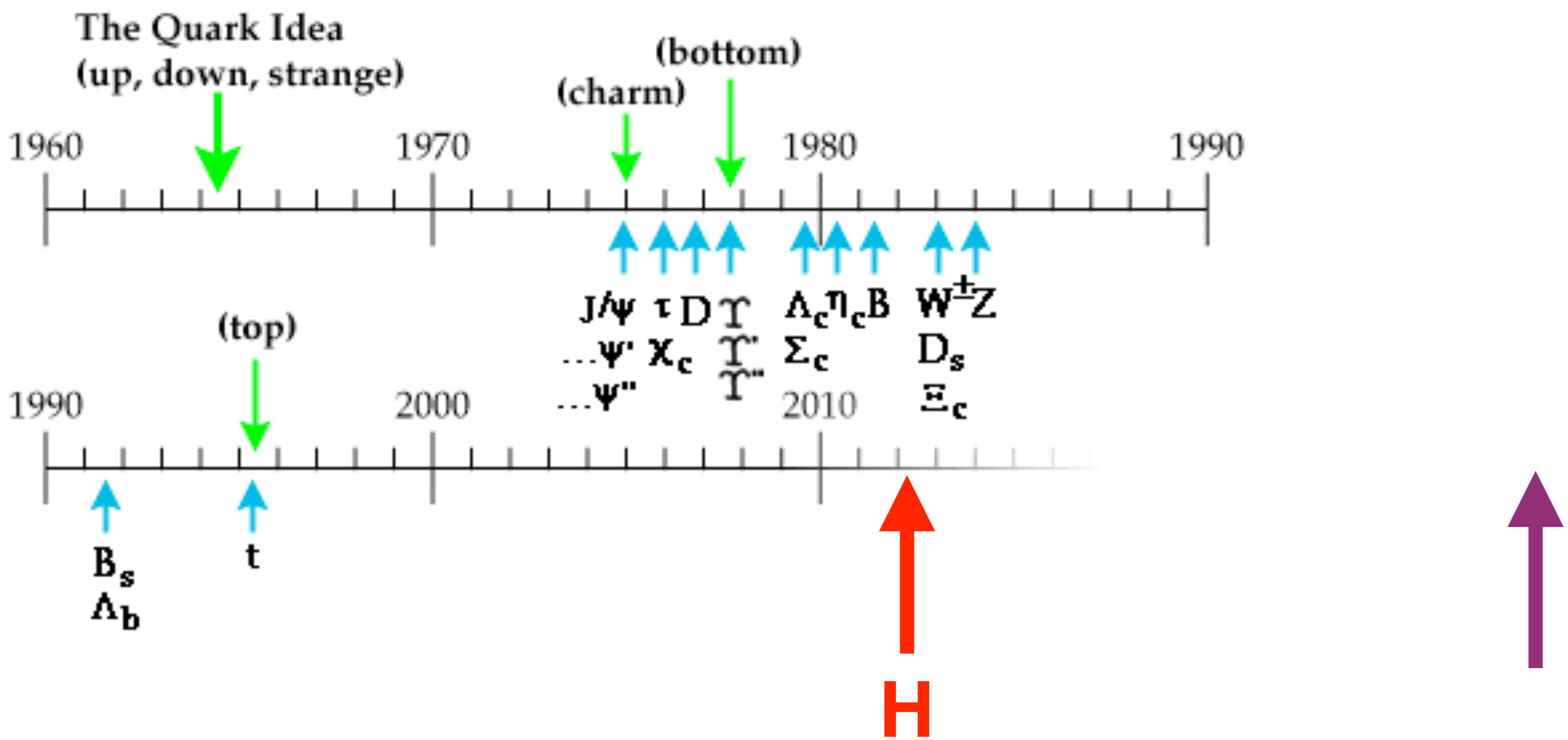
H self-coupling:
70 years after the prediction?

Particle Discoveries



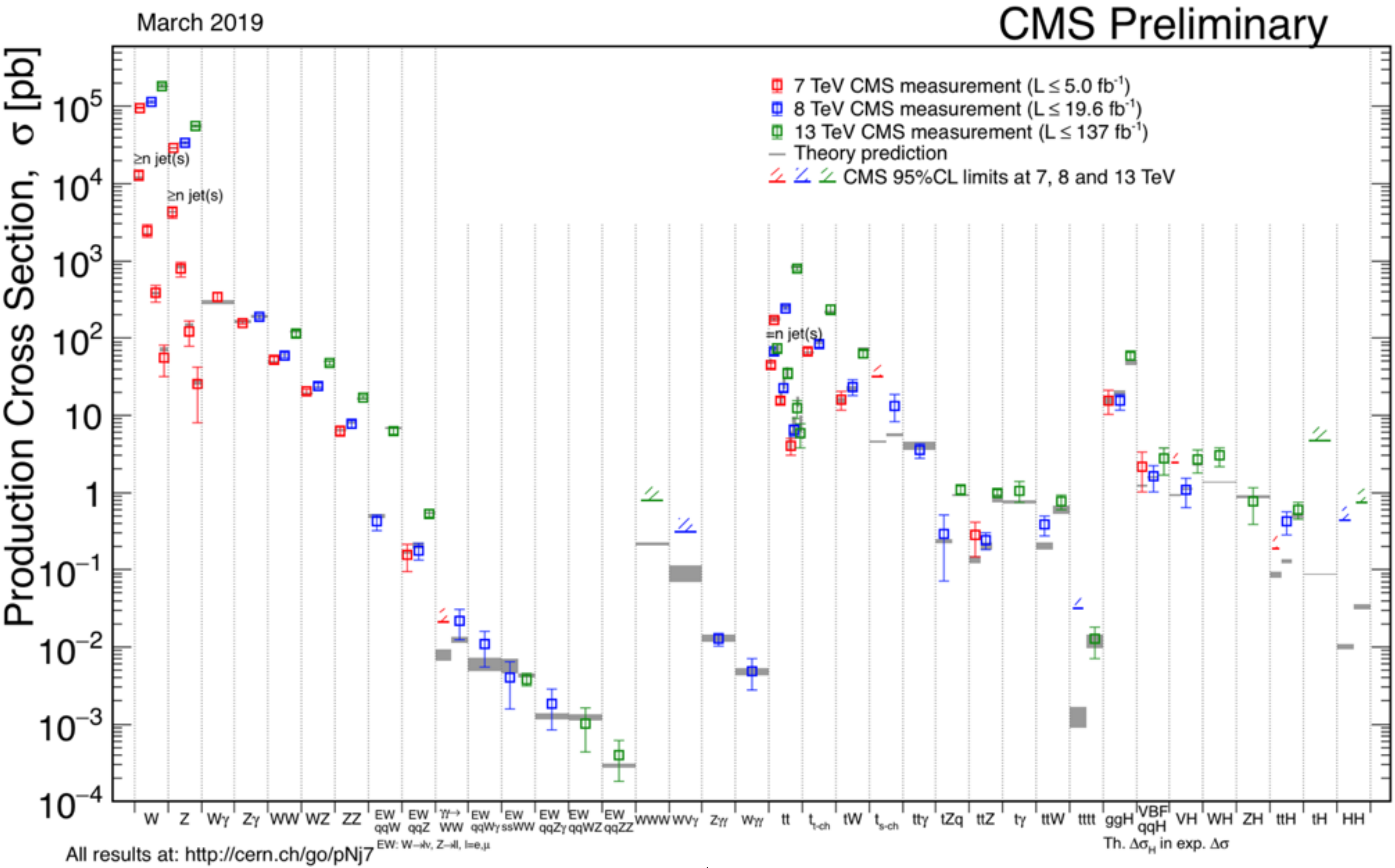
mass: 48 years after the prediction

H self-coupling:
70 years after the prediction?

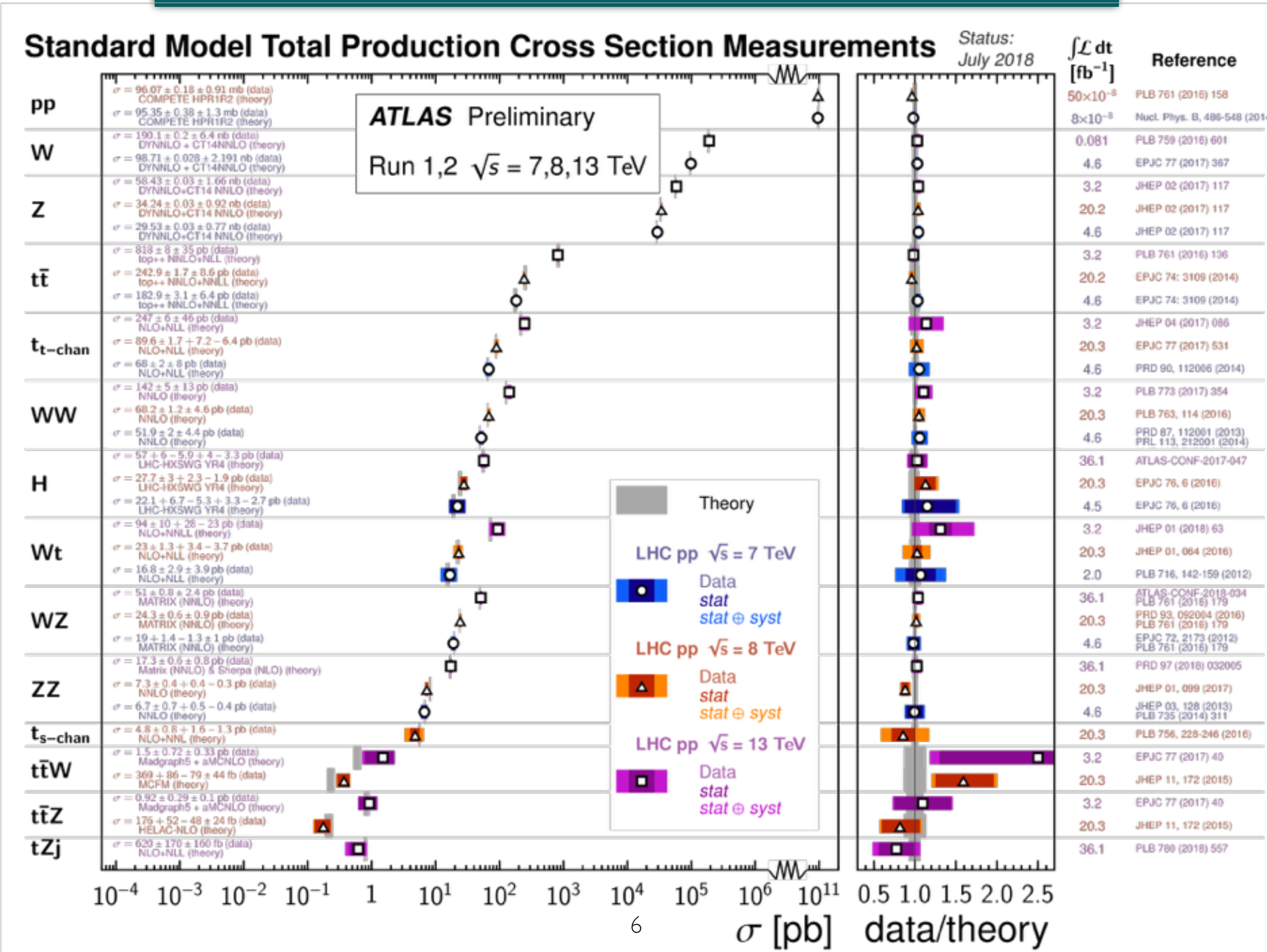
we still do not know if the Higgs potential is SM-like

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

Status of the Standard Model today



Status of the Standard Model today



Perspectives

"There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement."

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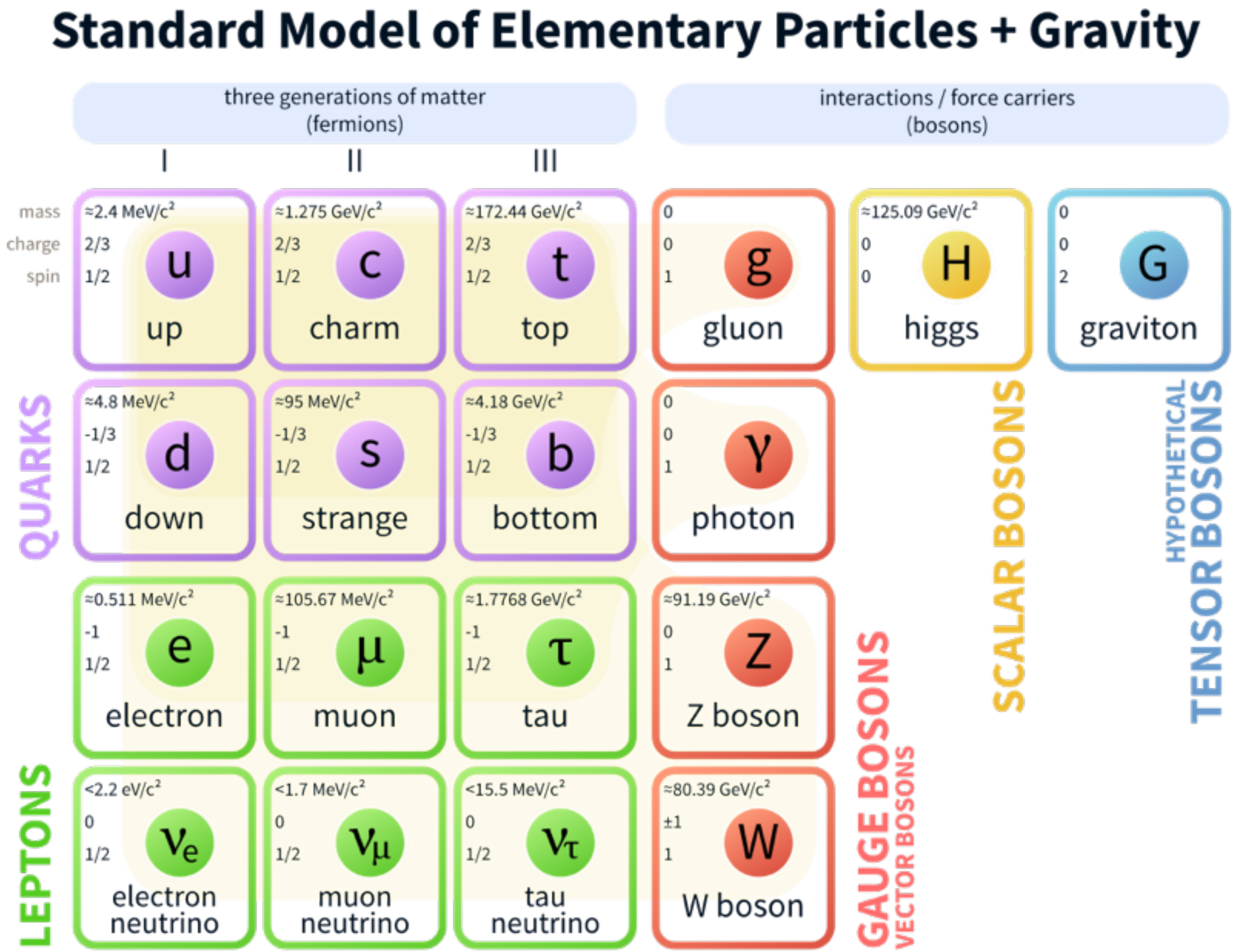
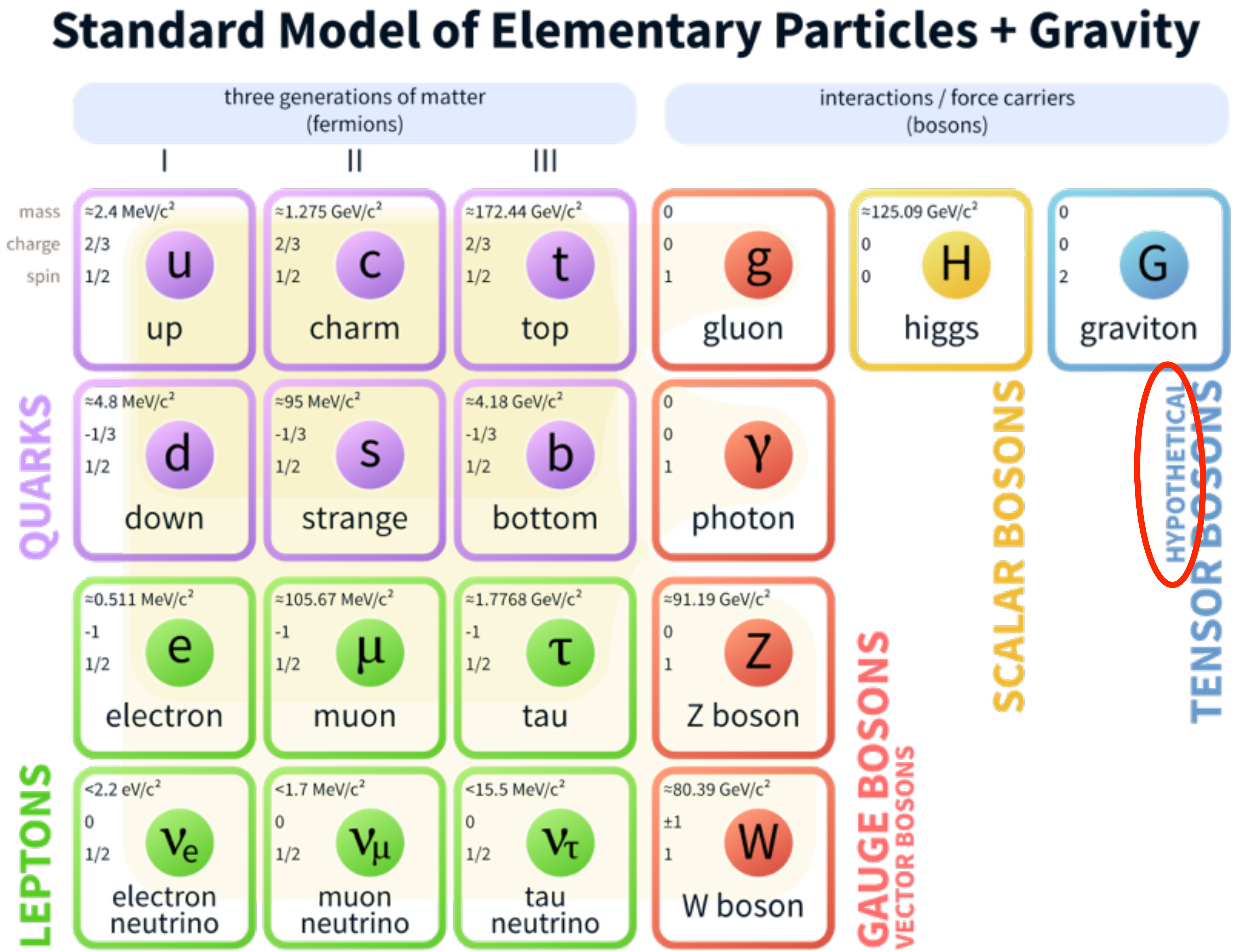
J.P.G. von Jolly, 1809-1884, Professor of Physics, to Max Planck (considering to study physics)

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

Standard Model limitations



Standard Model limitations

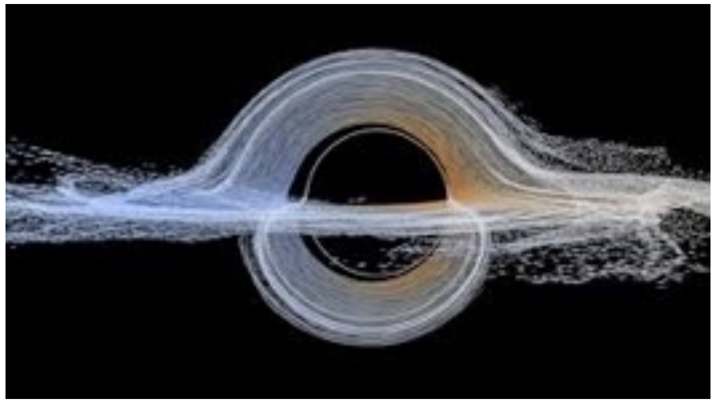


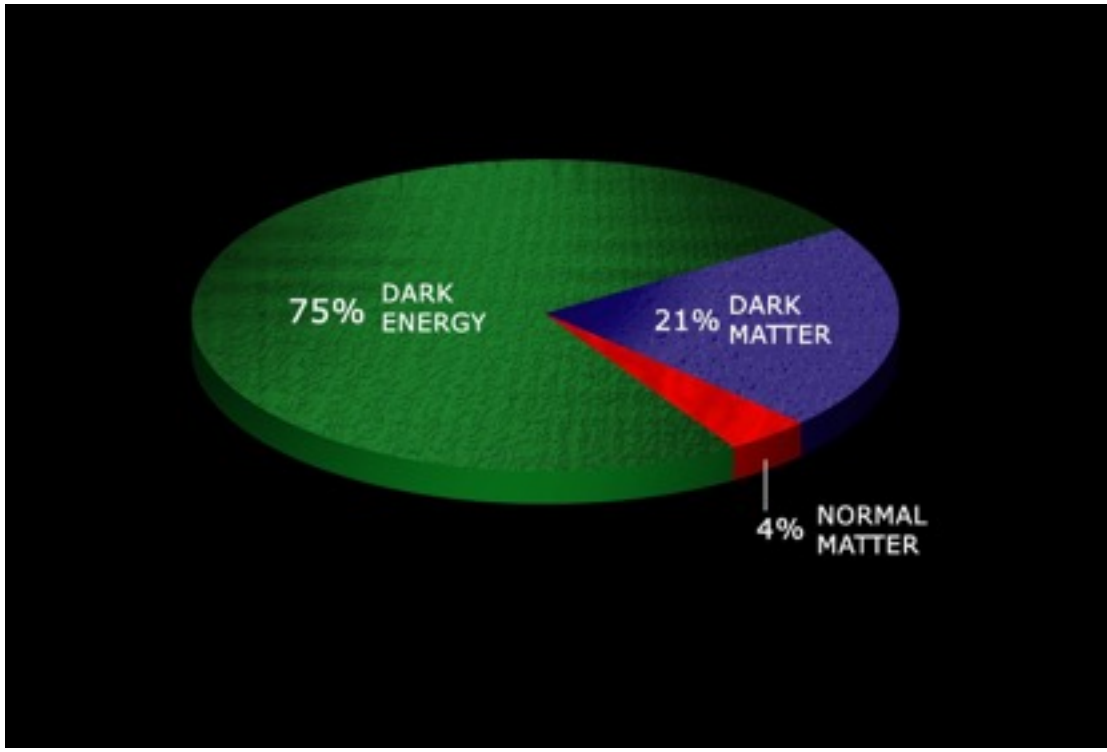
Standard Model limitations

The Standard Model is “complete”,
but leaves many puzzling questions!

- too many “ad hoc” parameters in the SM
- neutrino masses
- hierarchy problem
- dark matter
- baryon asymmetry in the Universe
- what drove inflation
- quantum theory of gravitation

⋮





We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the scale of new physics, unlike the case with the Higgs, and for not being sure of its couplings to other particles, except that they are probably all very small.

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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

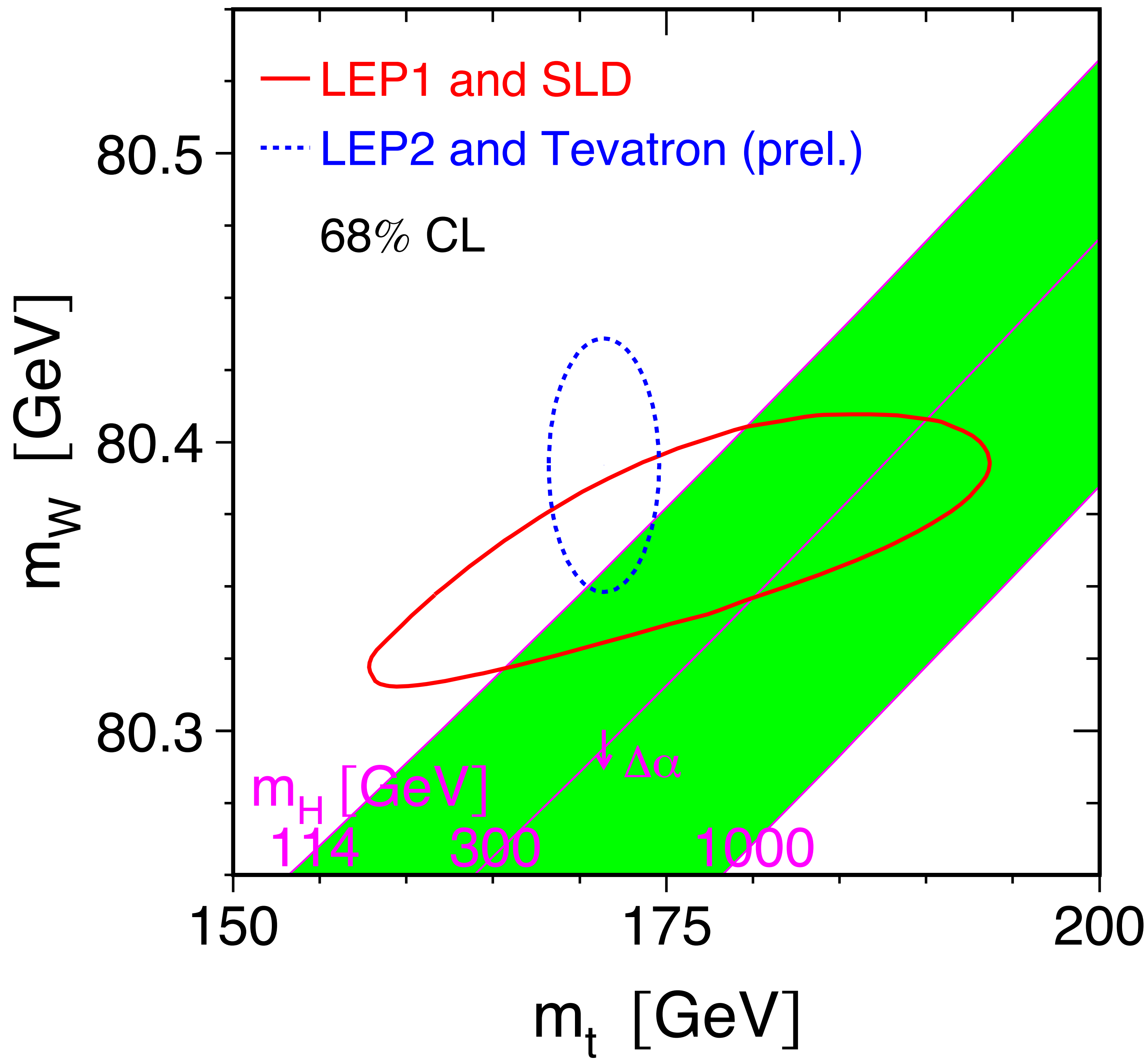
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

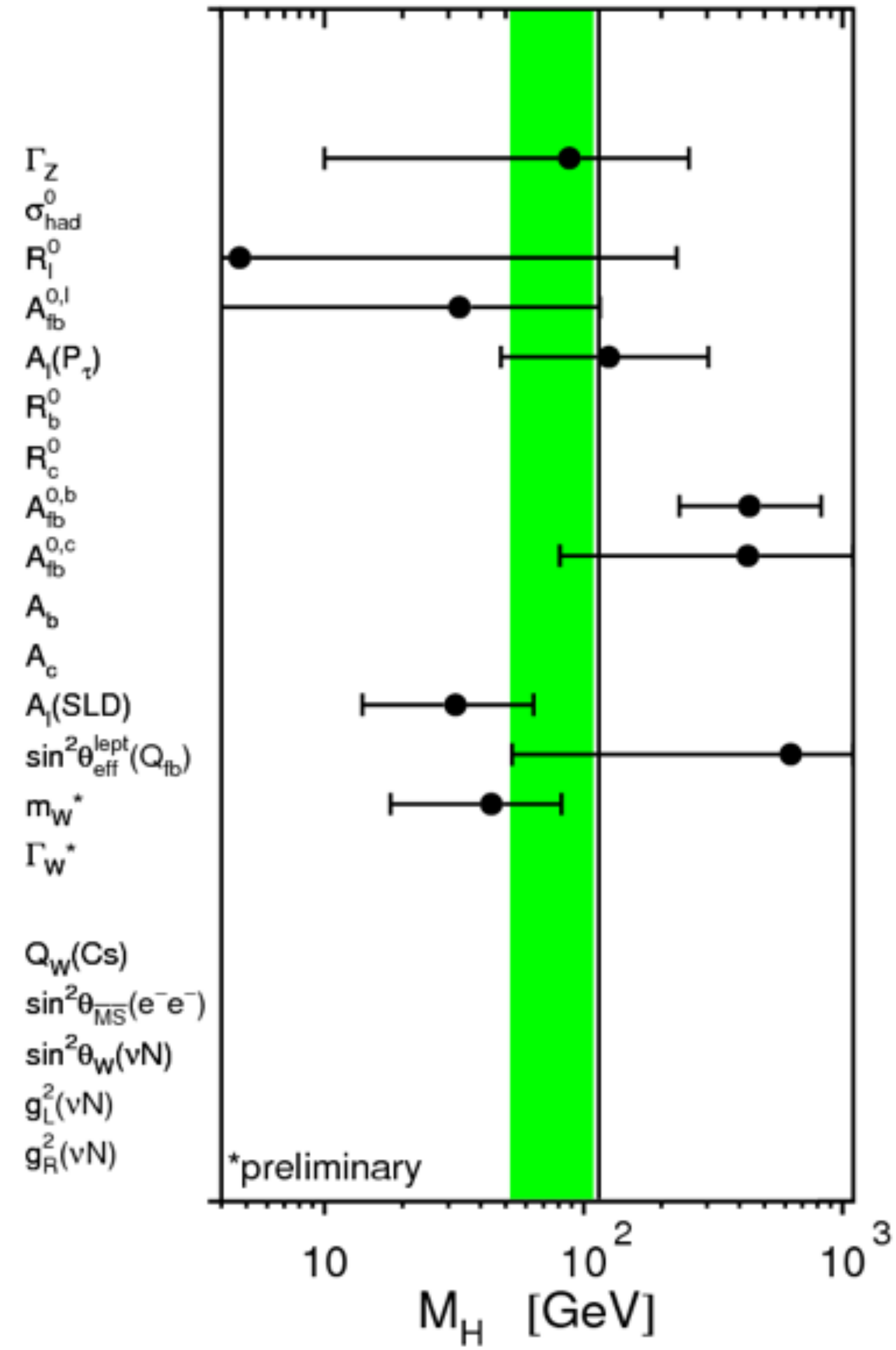
334 *J. Ellis et al. / Higgs boson*

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Precision measurements cornered the Higgs boson mass



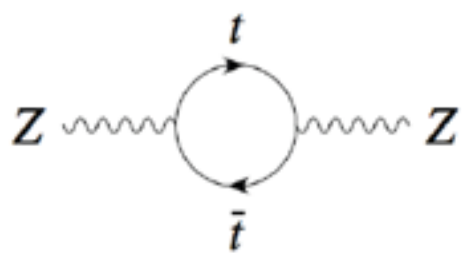
LEP EW working group 2006

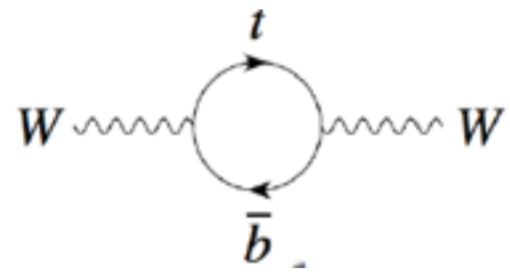


LEP EW working group 2009

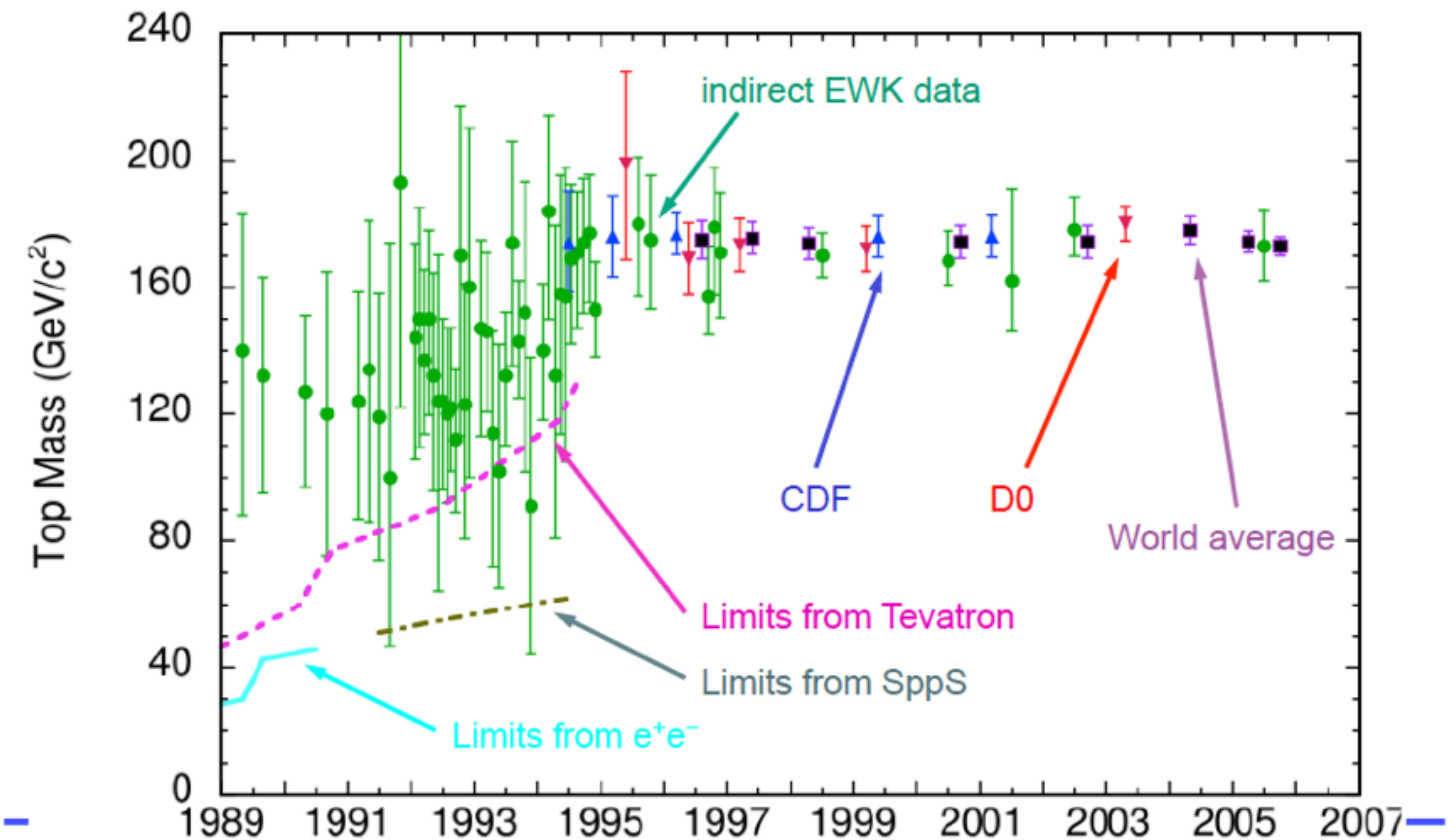
top quark: importance of precision measurements/calculations

top quark mass enters electroweak precision observables **indirectly** via loop effects

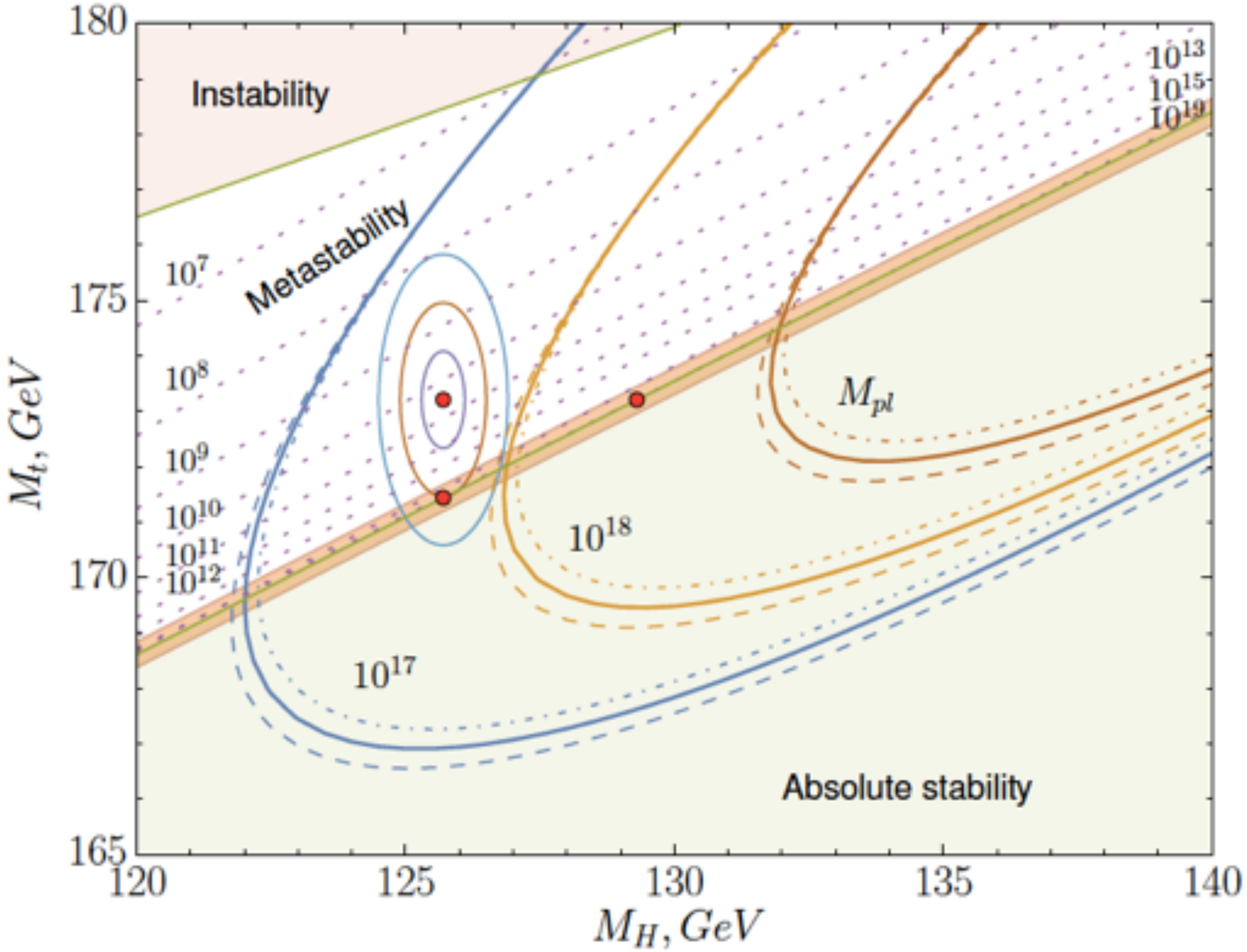




- Limits or estimate vs time

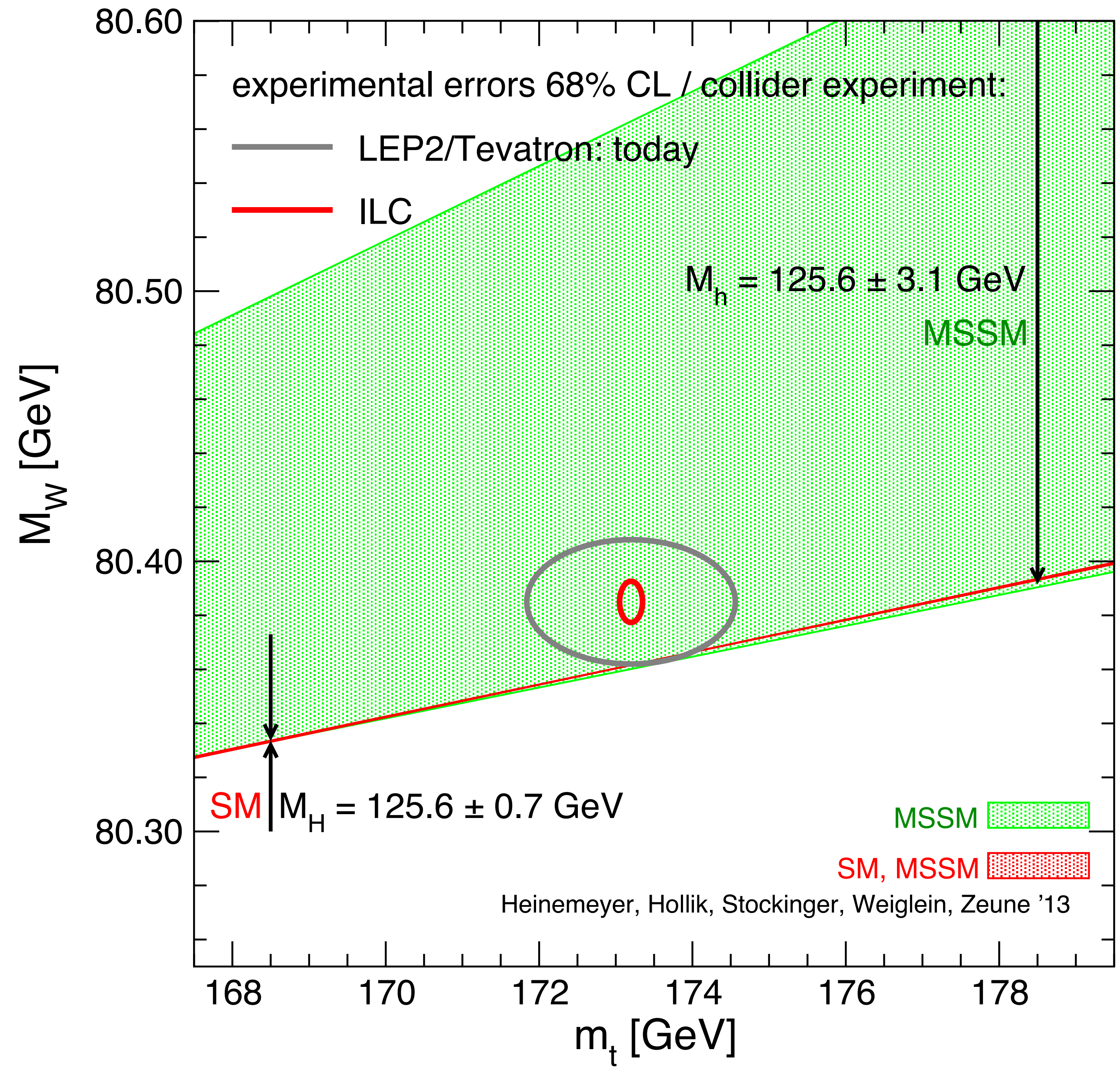


Importance of precision



Bednyakov, Kniehl, Pikelner, Veretin '15

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia '13



Heinemeyer, Hollik, Stöckinger, Weiglein, Zeune '13

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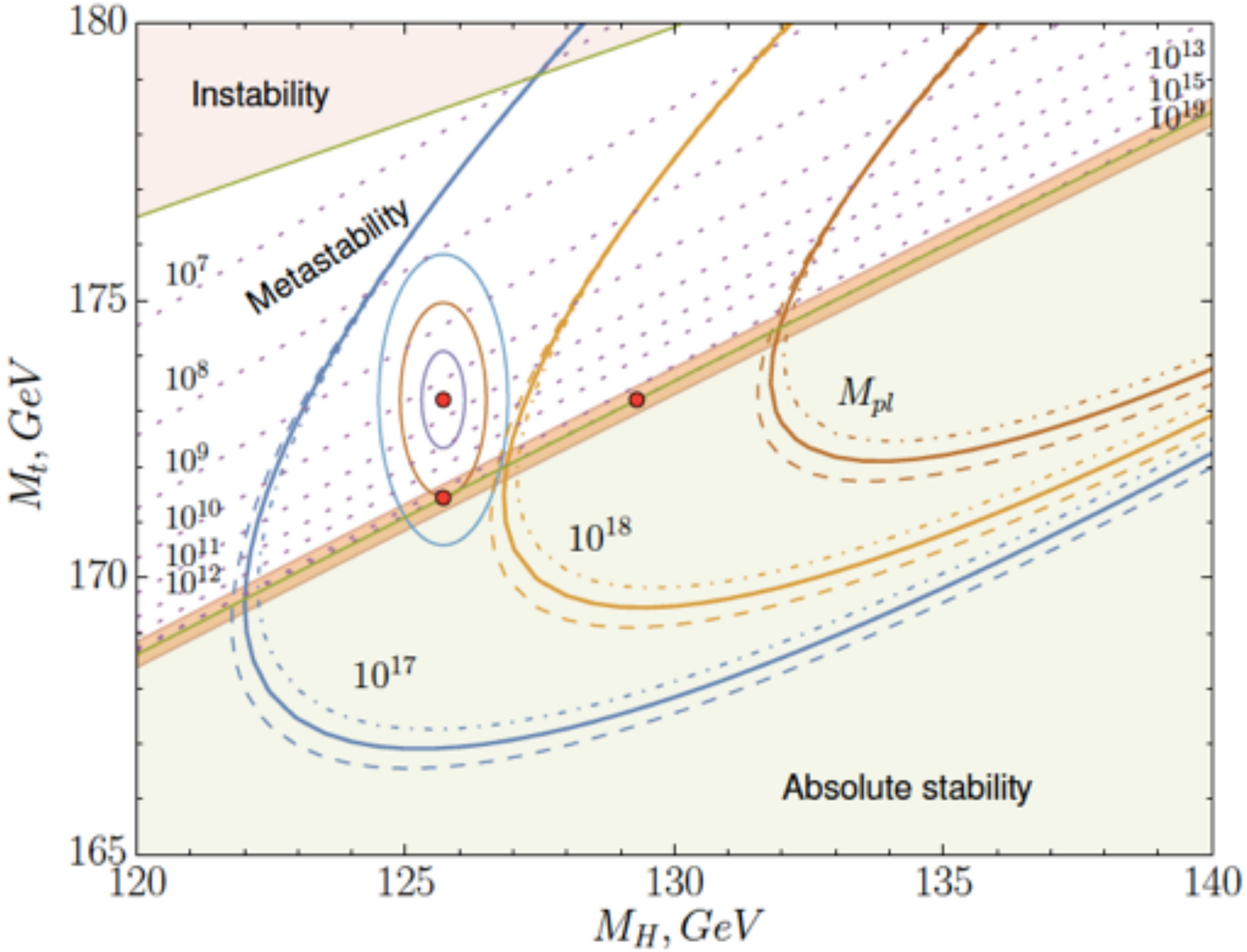

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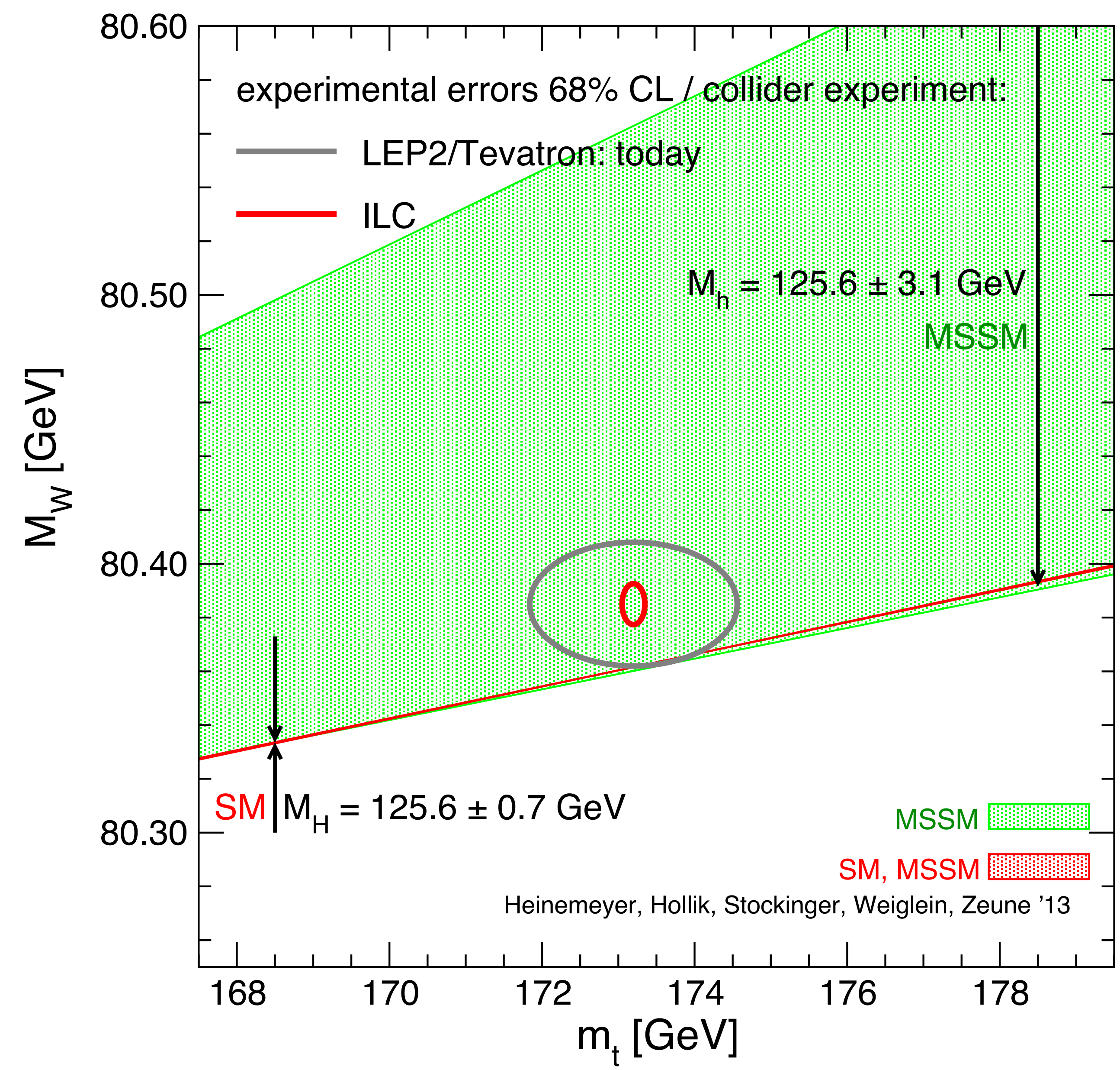


Heinemeyer, Hollik, Stöckinger, Weiglein, Zeune '13

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

The precision frontier

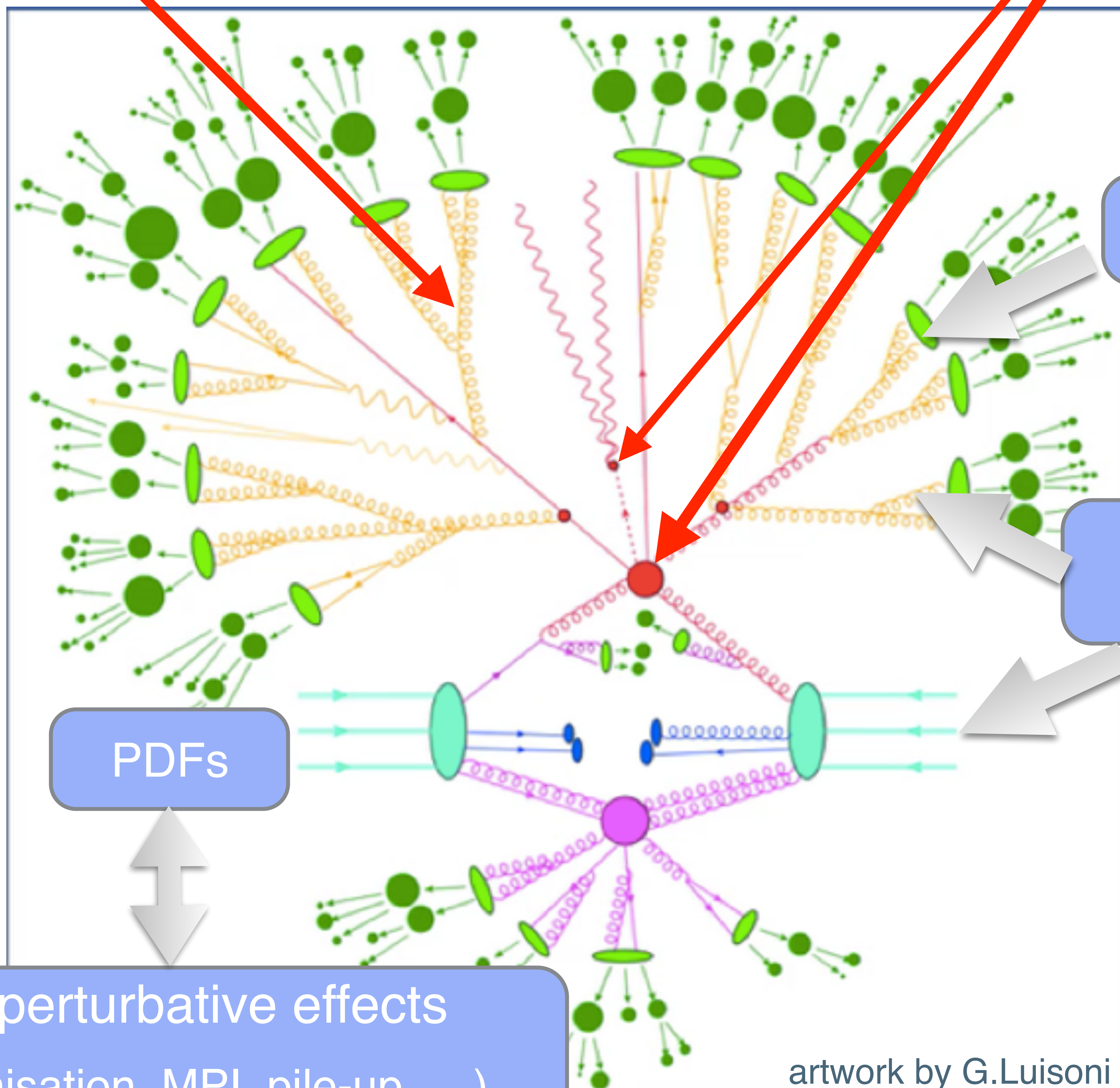
parton shower

resummation

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

quark mass effects

parametric uncertainties
(e.g. couplings, masses)



artwork by G.Luisoni

PDFs

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

Theorist's basic toolbox

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

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

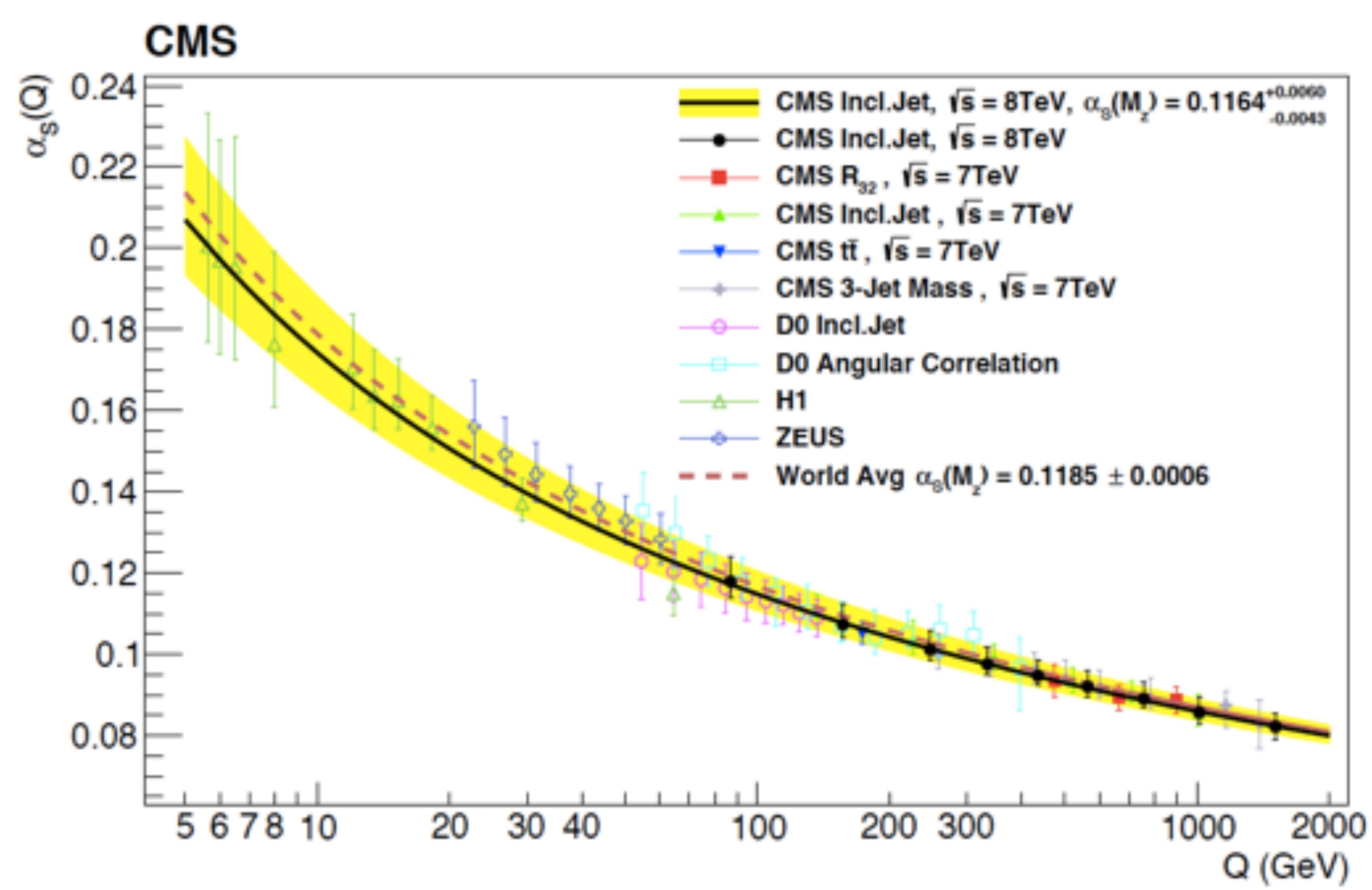
important principles of QCD:

- asymptotic freedom

  quarks and gluons almost free particles at large energy scales

- factorisation

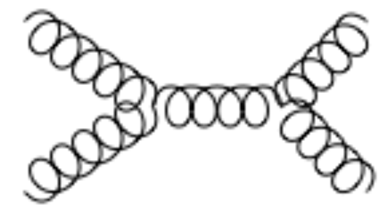
  short- and long distance effects can be separated



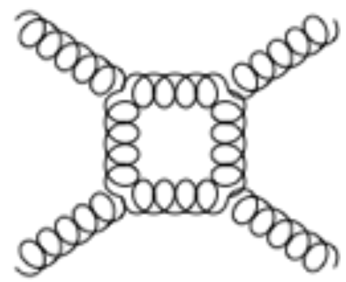
QCD corrections: building blocks

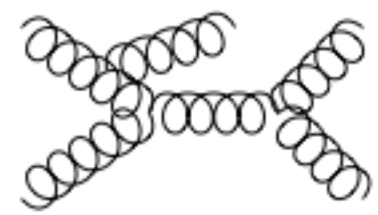
example 2 to 2 scattering

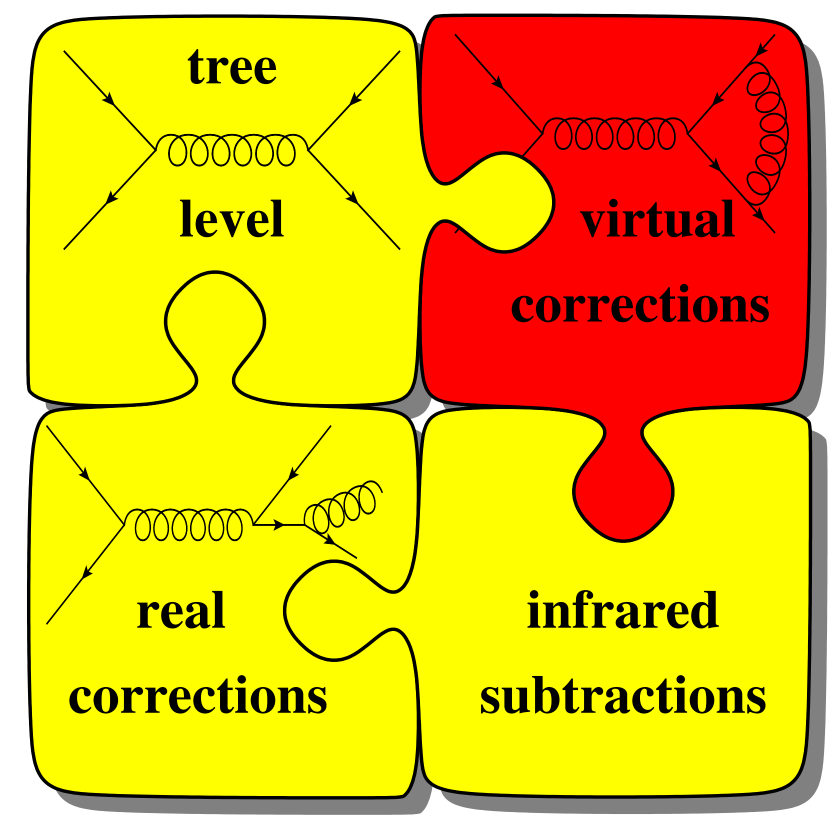
LO: usually tree level diagrams



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







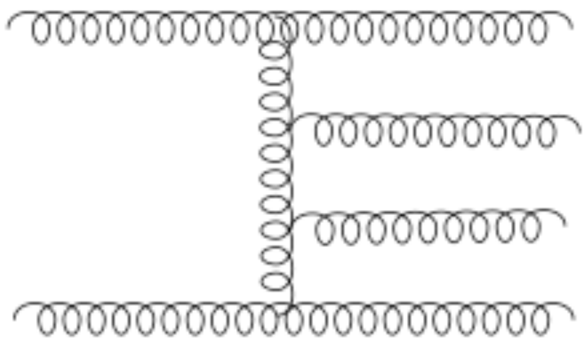
individual contributions are divergent

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

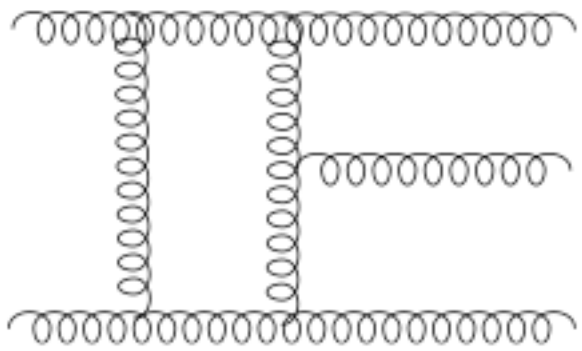
$$\sigma^{NLO} = \underbrace{\int_{m+1}\left[d\sigma^R - d\sigma^S\right]_{\epsilon=0}}_{\text{numerically}} + \underbrace{\int_m \left[\underbrace{d\sigma^V}_{\text{cancel poles}} + \underbrace{\int_s d\sigma^S}_{\text{analytically}}\right]_{\epsilon=0}}_{\text{numerically}}$$

QCD corrections: building blocks

NNLO:

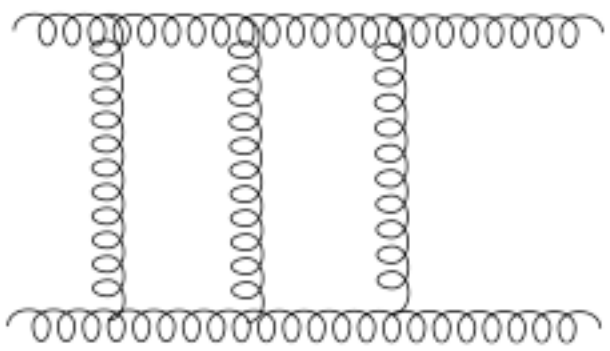


double real



1-loop virtual

$\otimes$ single real

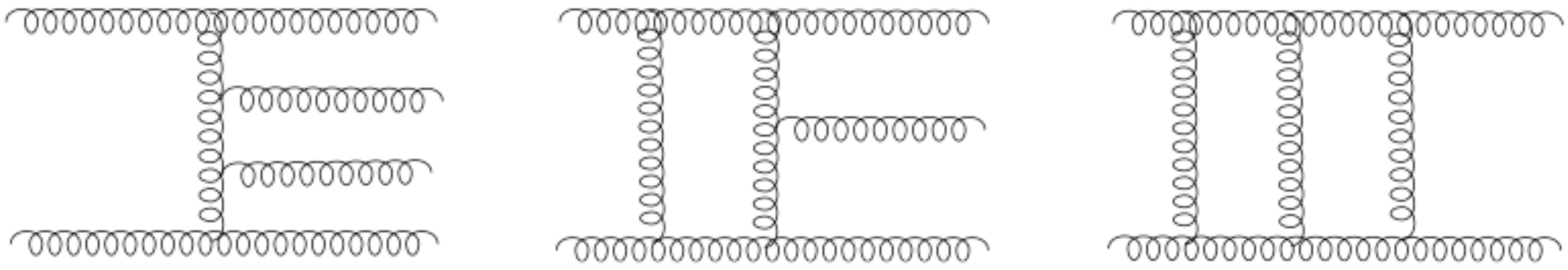


2-loop virtual

implicit IR poles (PS integration) ↓ explicit and implicit poles ↓ explicit poles $1/\epsilon^{2L}$

QCD corrections: building blocks

NNLO:



double real

1-loop virtual
$\otimes$ 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

harder with more massless particles
(intricate IR singularity structure)

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

"industrial revolution"

various automated tools

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

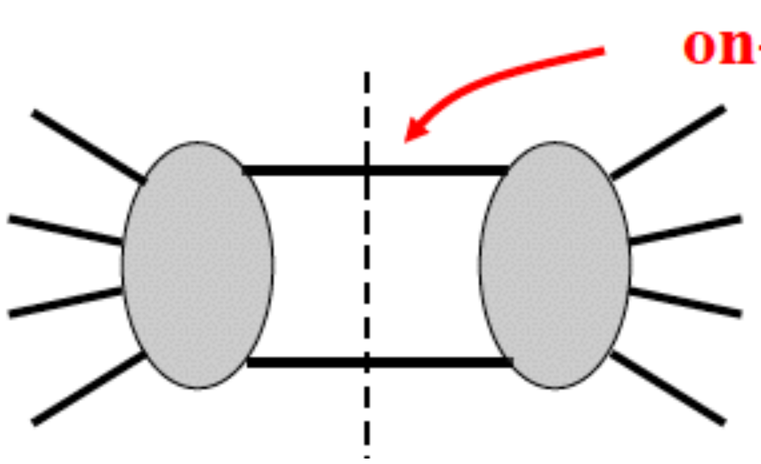
- NNLO: automation starts to become feasible

- NNNLO: some results availabe!

What caused the NLO revolution?

gauge dependent off-shell states introduce “spurious” terms

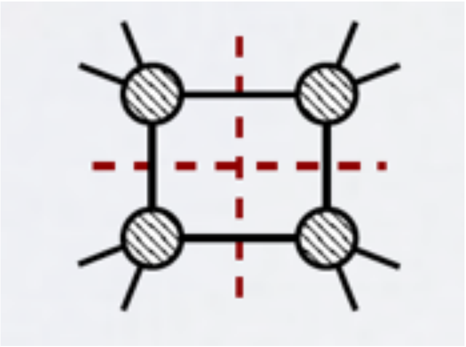
try to use on-shell quantities as building blocks



Unitarity method

Bern, Dixon, Dunbar and Kosower (BDDK) 1994

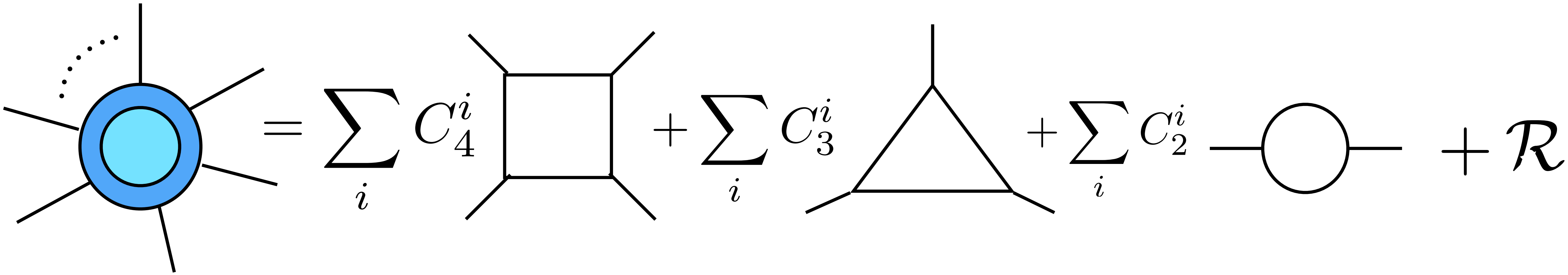
- construct N-point one-loop amplitudes from tree amplitudes
  Bern, Dixon, Kosower ‘98
- use of complex momenta in generalised cuts
  Britto, Cachazo, Feng ’04



- 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, …

NLO amplitudes

one-loop N-point amplitude:



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

most complicated functions are dilogarithms

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

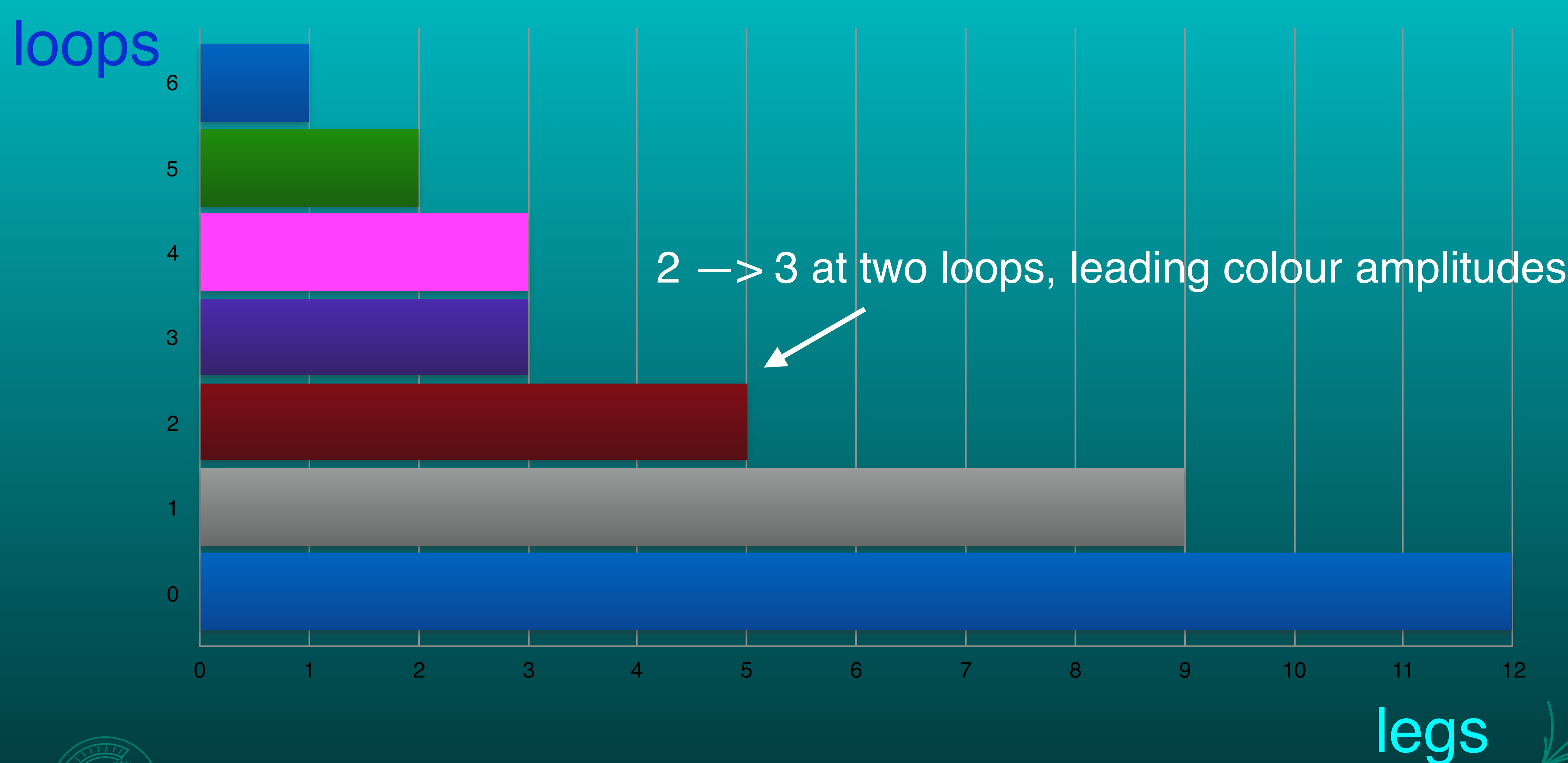
very different at two loops (and beyond)!

master integrals not a priori known

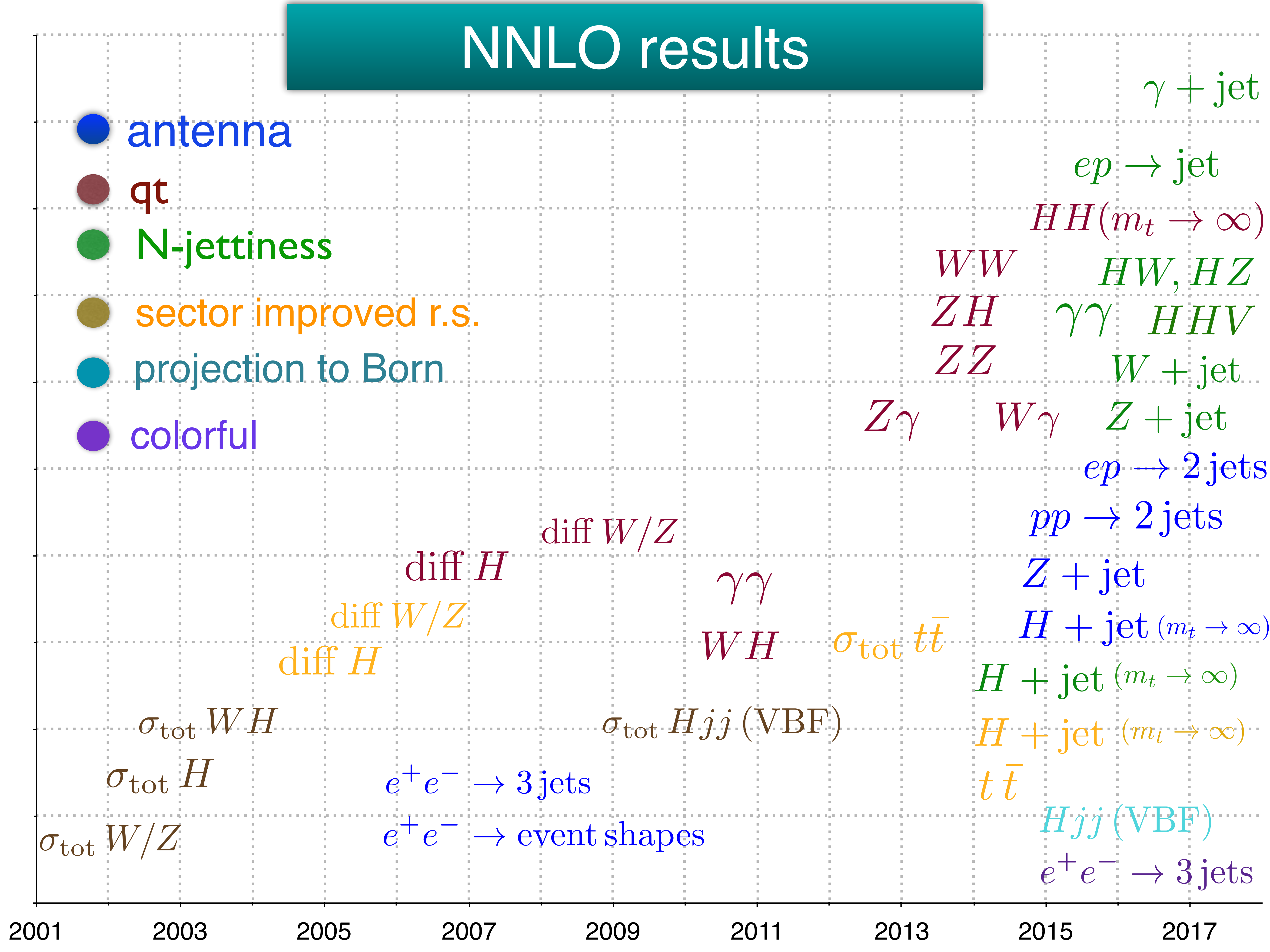
measure of complexity

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

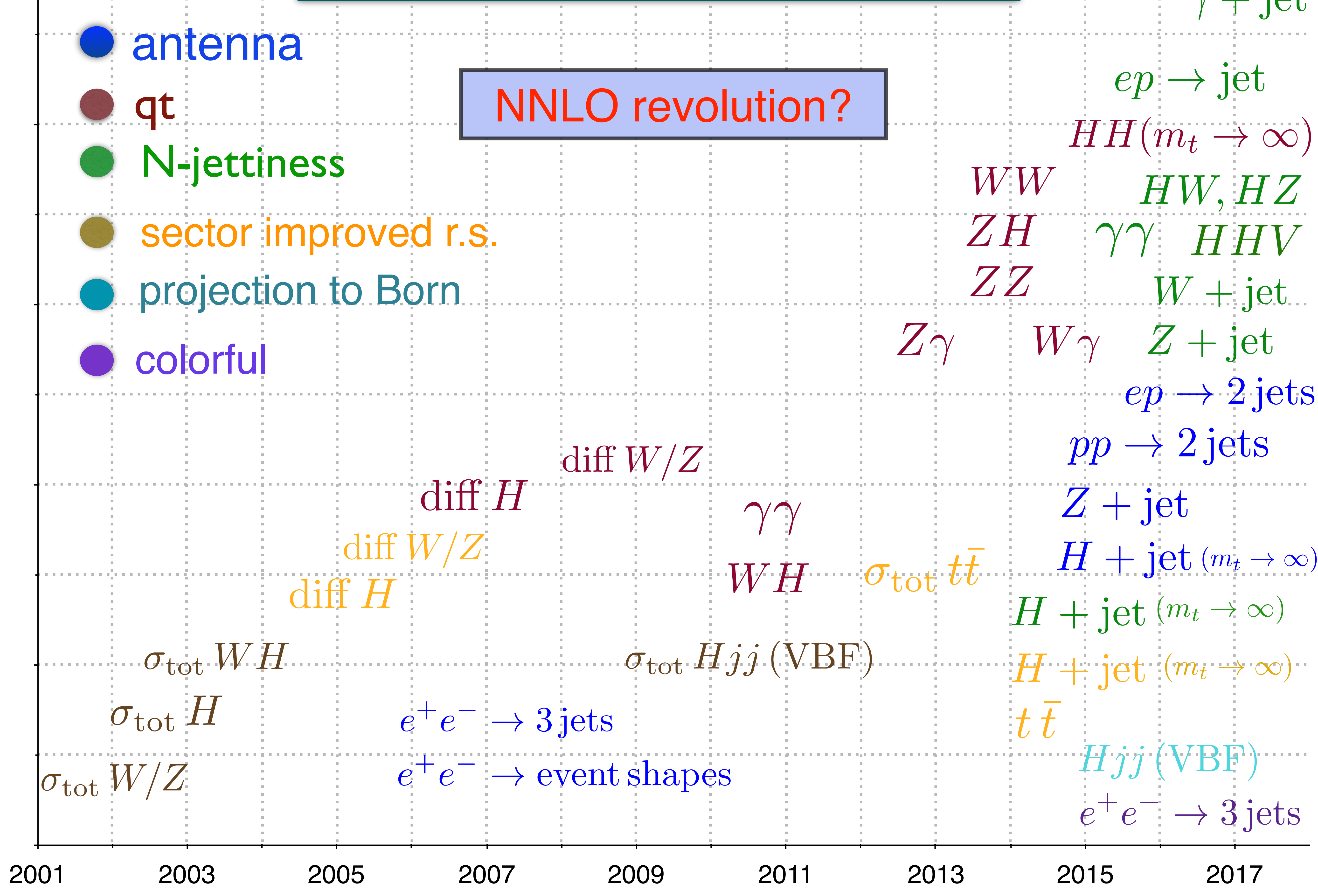
complexity does not scale linearly!



(refers to physical results, not individual integrals)


NNLO results
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
$\gamma\gamma$
HHV
ZZ
$W + \text{jet}$
$Z\gamma$
$W\gamma$
$Z + \text{jet}$
$ep \to 2\,\text{jets}$
$pp \to 2\,\text{jets}$
diff W/Z
diff H
$\gamma\gamma$
$Z + \text{jet}$
diff W/Z
$H + \text{jet}\ (m_t \to \infty)$
WH
$\sigma_{\text{tot}}\ t\bar{t}$
diff H
$H + \text{jet}\ (m_t \to \infty)$
$\sigma_{\text{tot}}\ WH$
$\sigma_{\text{tot}}\ Hjj\ (\text{VBF})$
$H + \text{jet}\ (m_t \to \infty)$
$\sigma_{\text{tot}}\ H$
$e^+e^- \to 3\,\text{jets}$
$t\,\bar{t}$
$Hjj\ (\text{VBF})$
$\sigma_{\text{tot}}\ W/Z$
$e^+e^- \to \text{event shapes}$
$e^+e^- \to 3\,\text{jets}$
2001
2003
2005
2007
2009
2011
2013
2015
2017

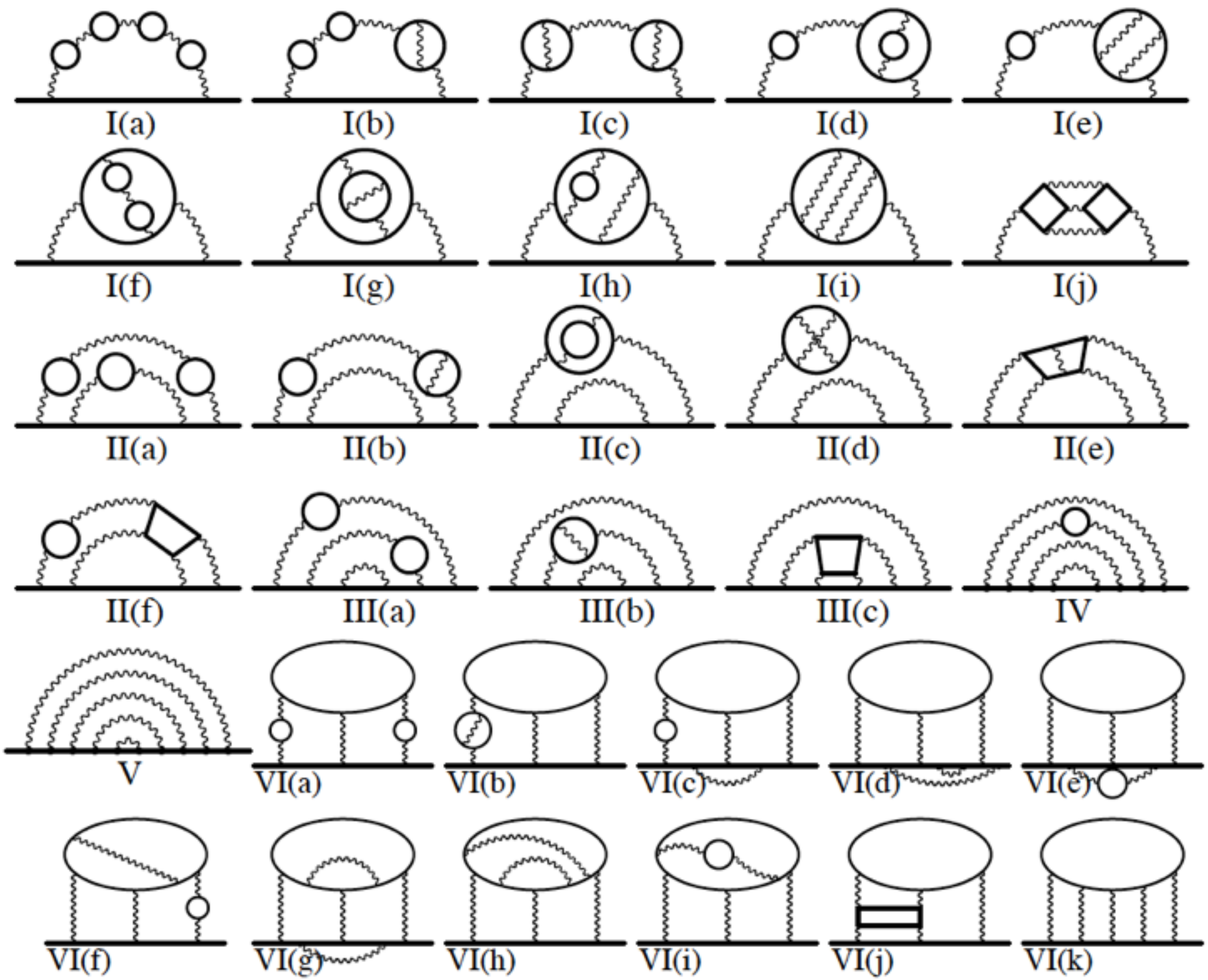
NNLO results



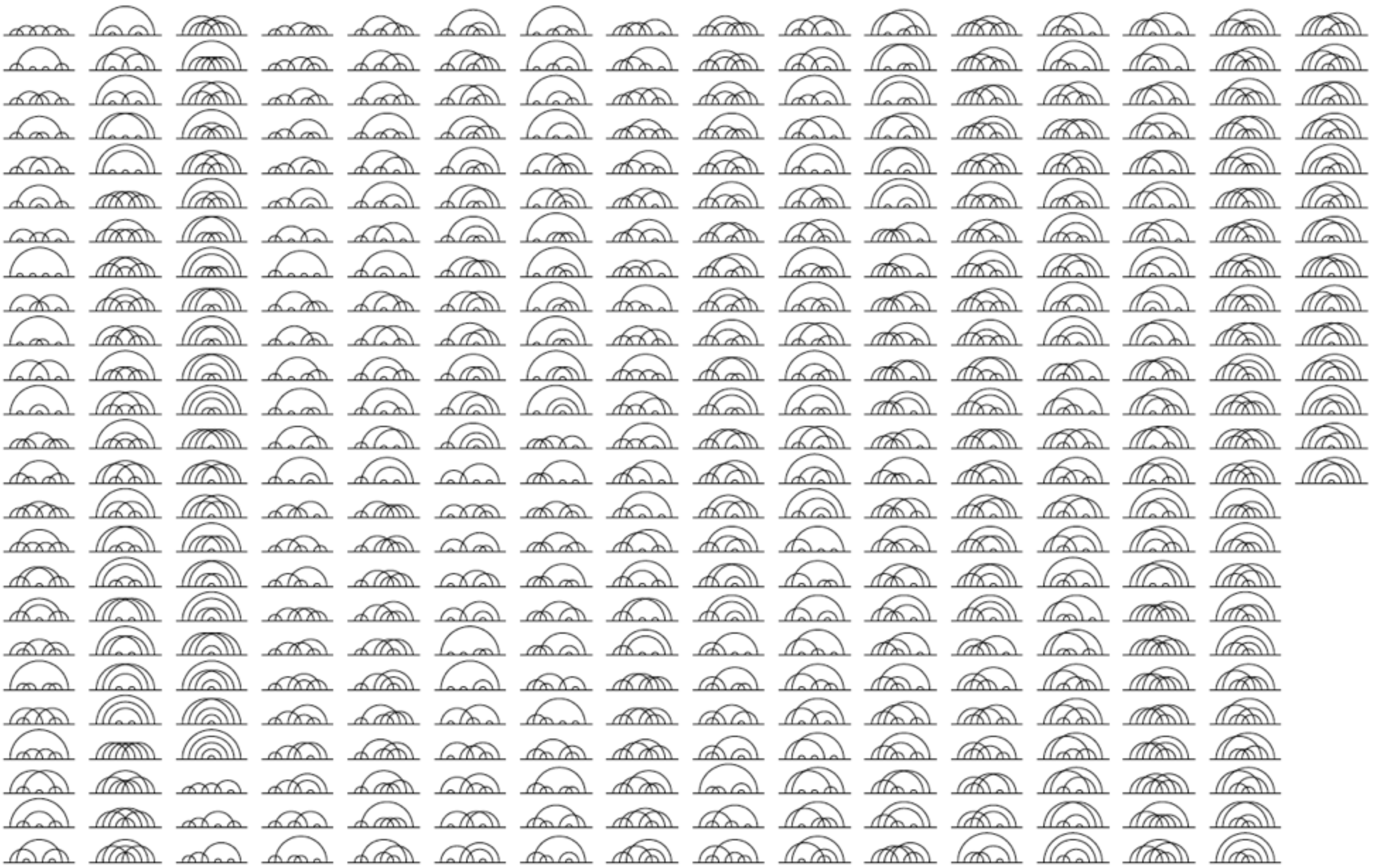
The art of perturbation theory

example: 5-loop contributions to electron anomalous magnetic moment

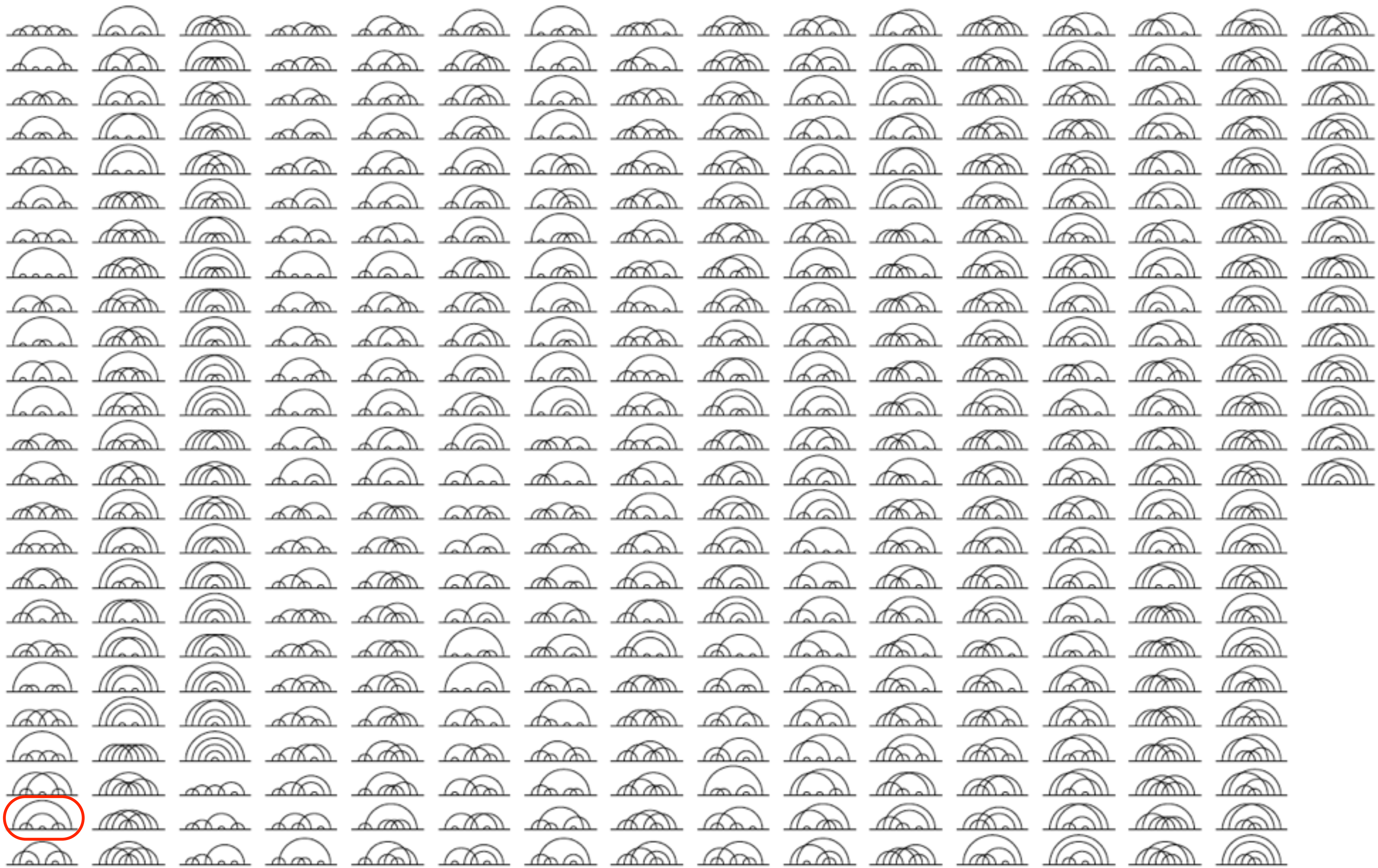
Aoyama, Hayakawa, Kinoshita, Nio ’15-’18; S. Volkov ‘18

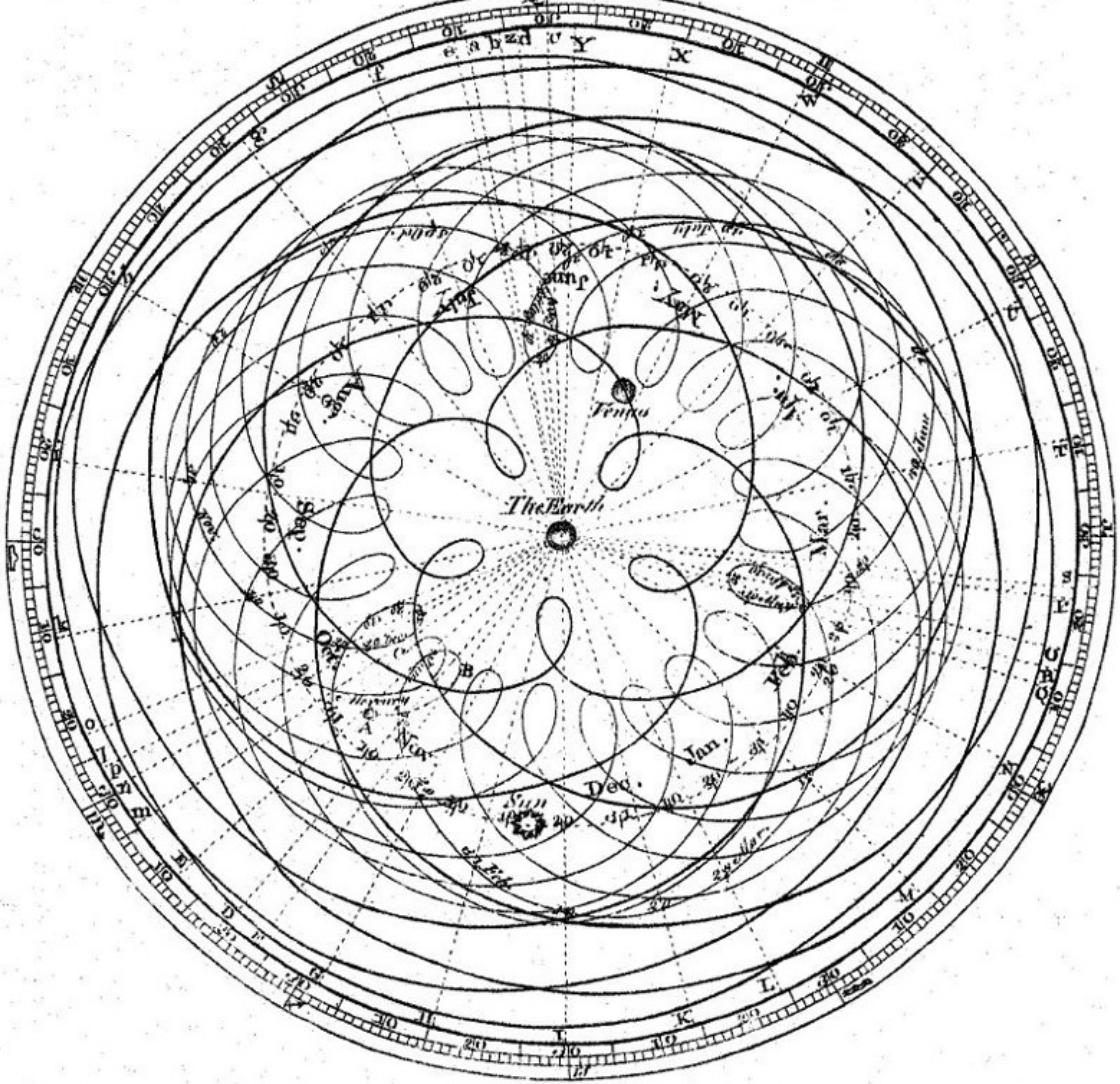


V-type diagrams

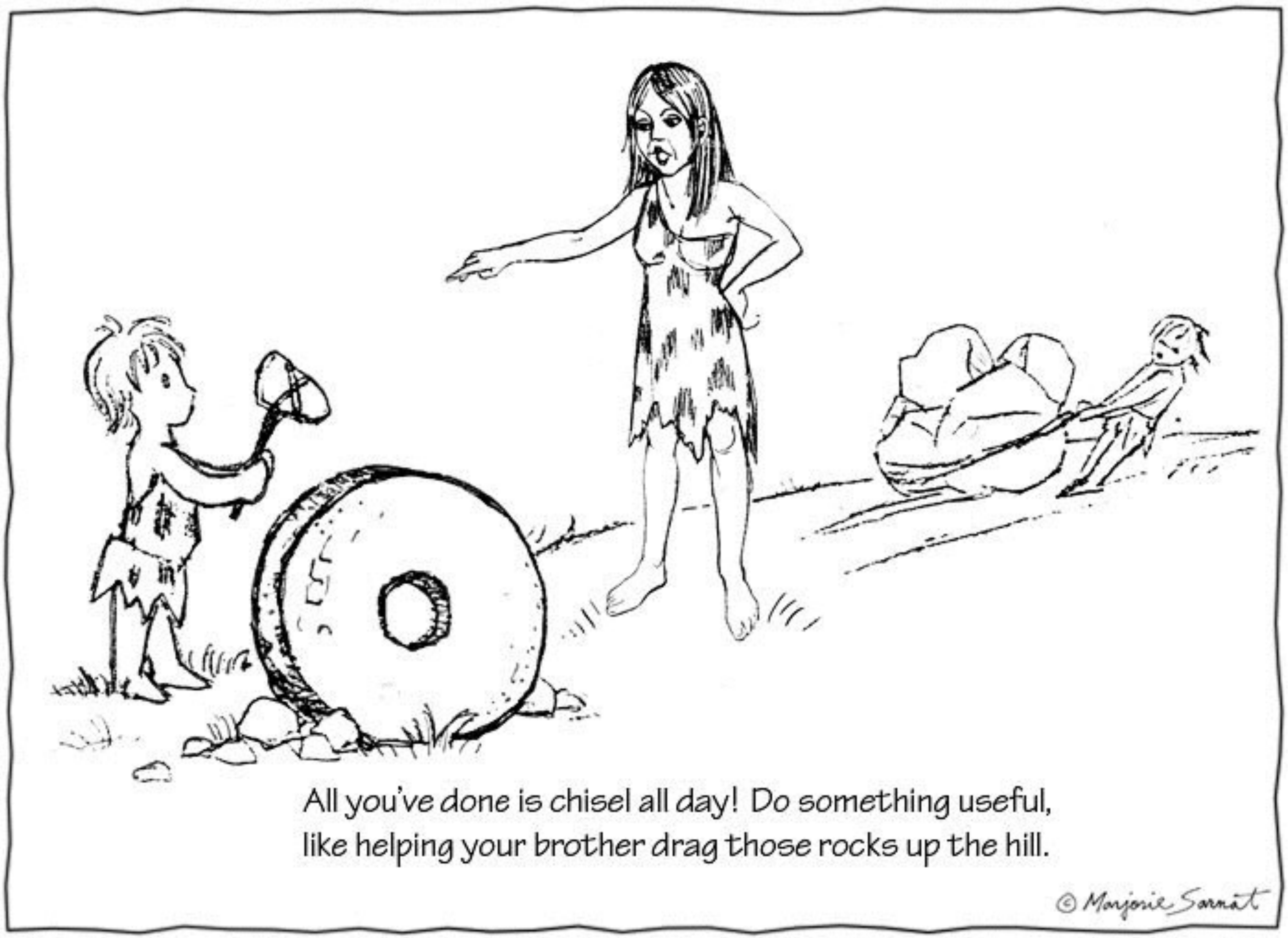


V-type diagrams




The Earth
Venus
Sun
Dec.
Jan.
Mar.

Do we need a completely different approach?



Exploring the Higgs sector

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

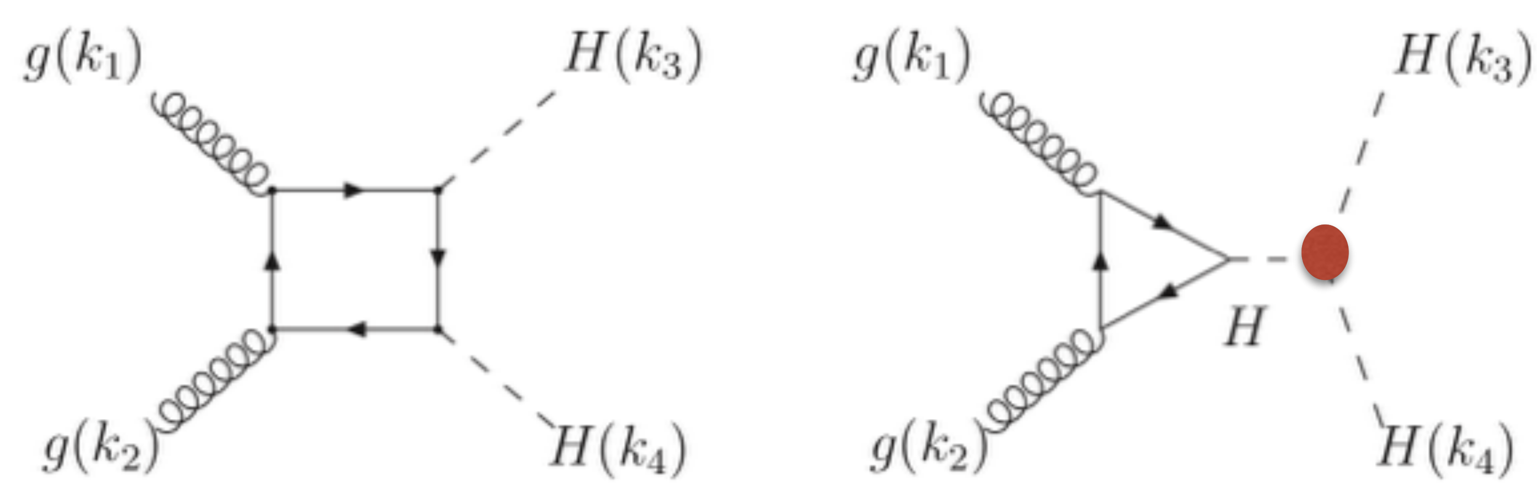
$$\phi^0 = \frac{1}{\sqrt{2}}(v+h)$$

$$V(h) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

λ_{3h} completely determined in the SM

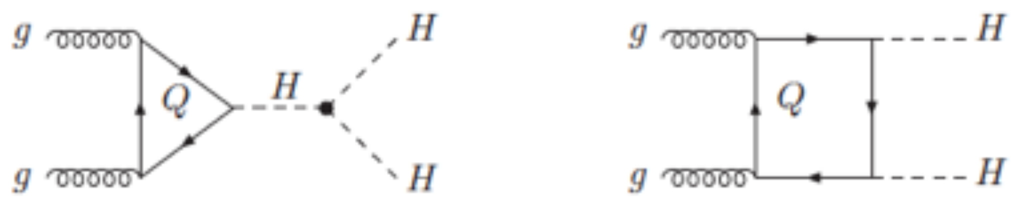
Any deviation in the trilinear or quartic coupling would be a clear sign of New Physics

λ_{3h} can be measured e.g. in Higgs boson pair production

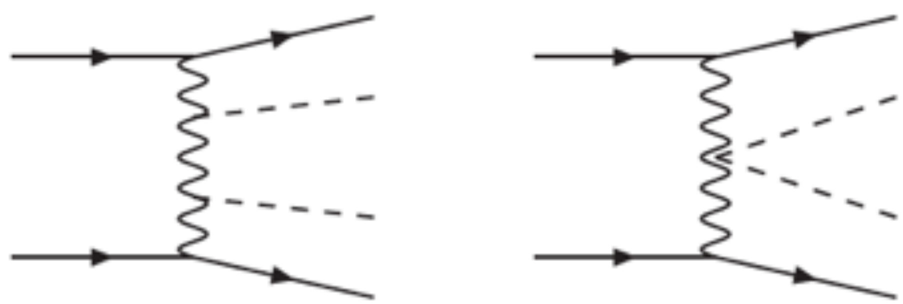


Higgs boson pair production channels

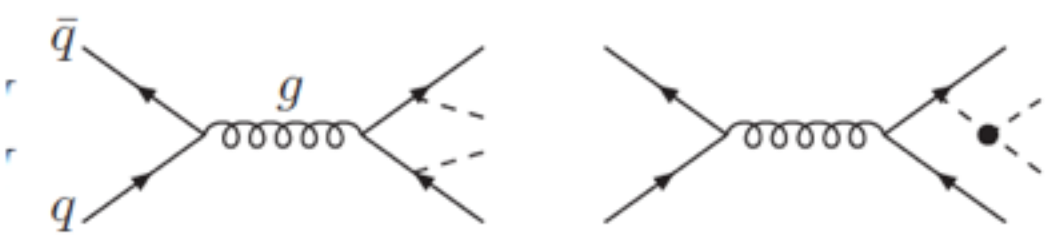
- gluon fusion



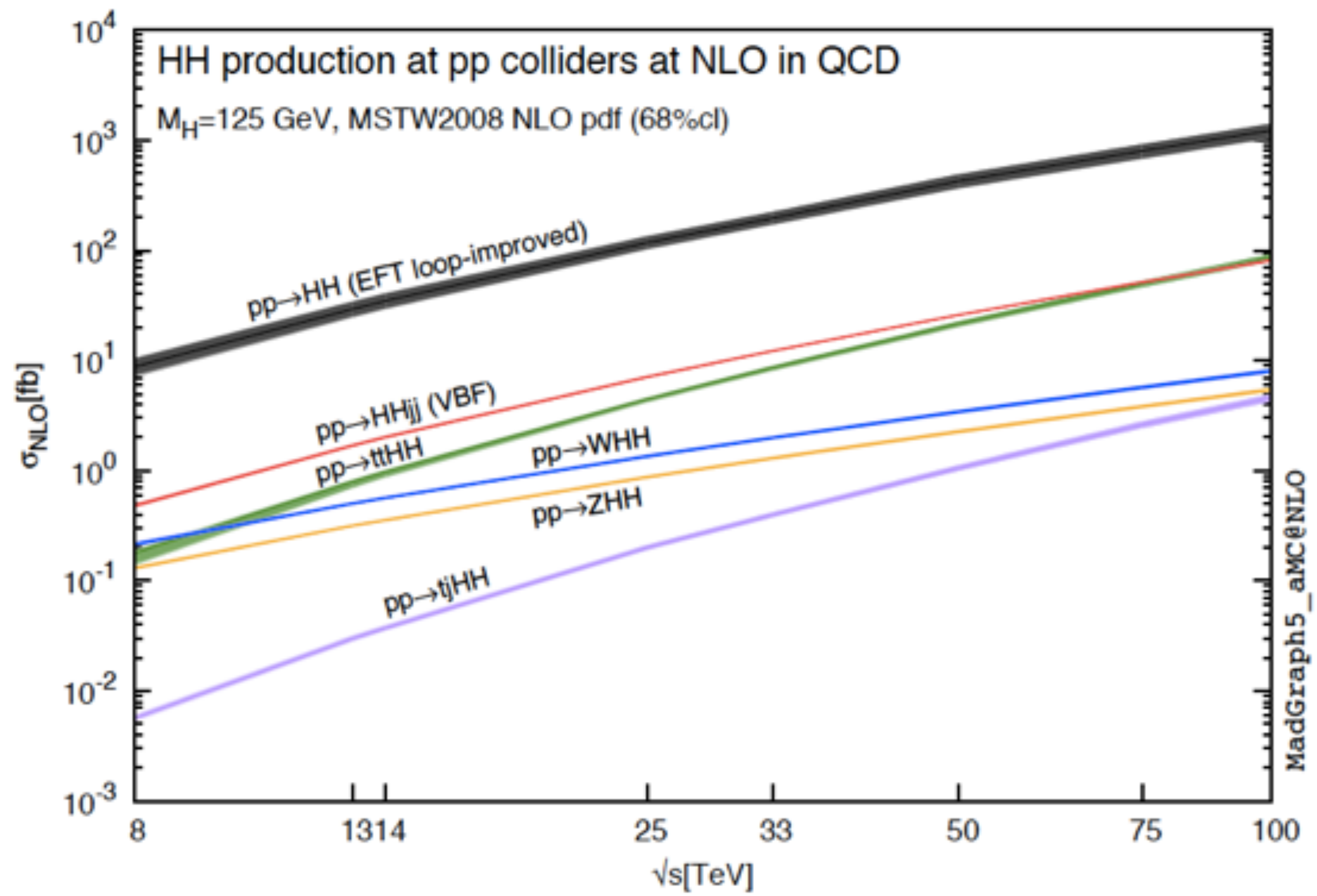
- vector boson fusion



- top-quark associated



- Higgs-strahlung



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

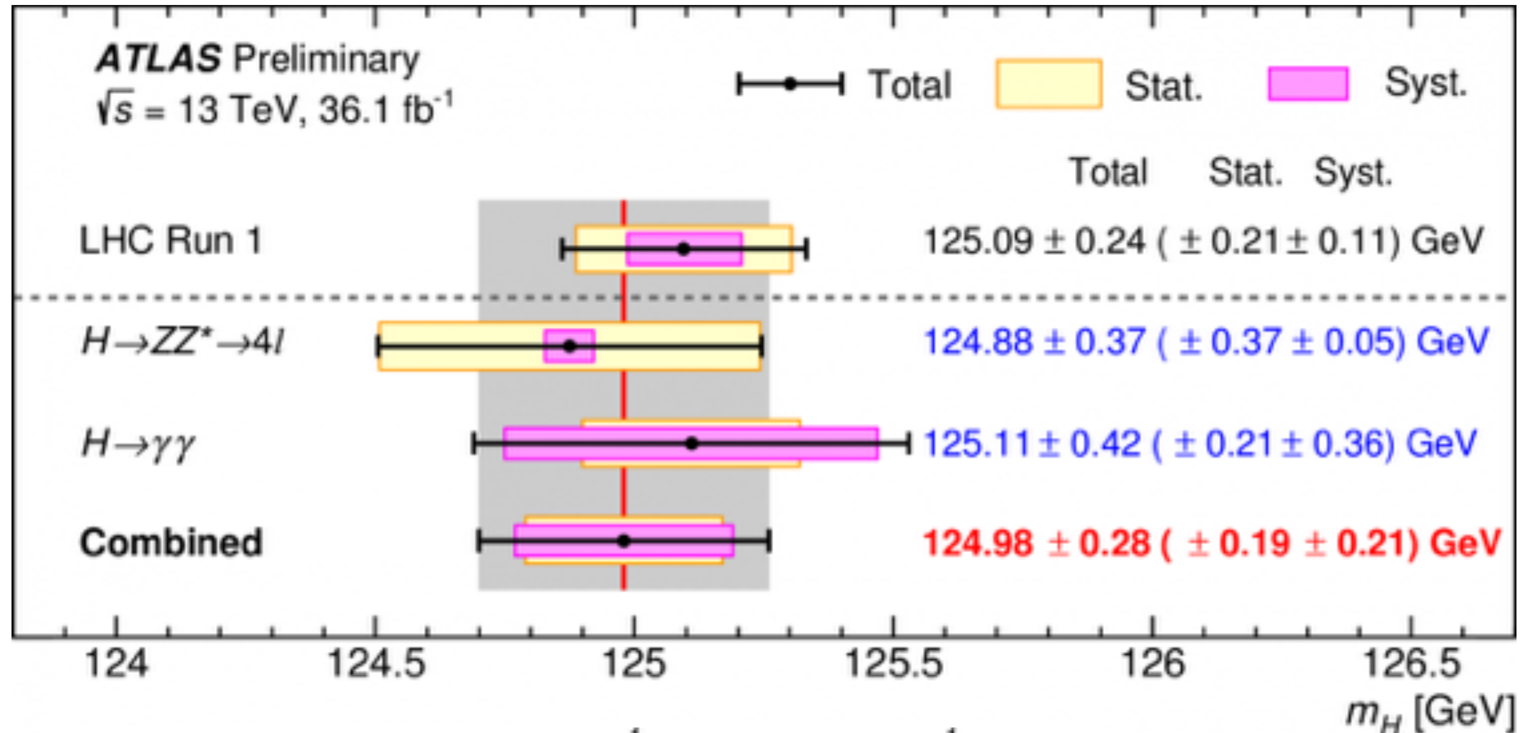
largest cross section from gluon fusion, but still

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

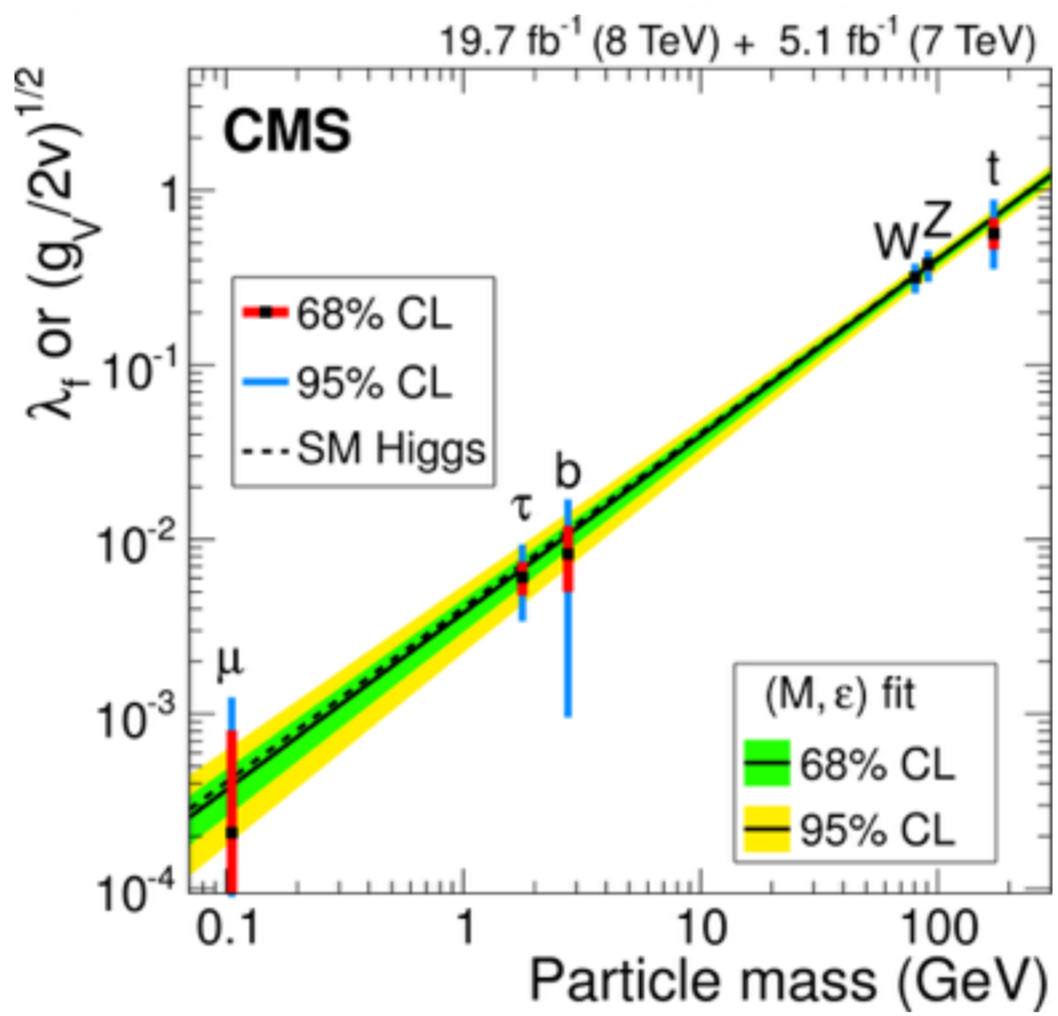
$\Rightarrow$ difficult measurement

Exploring the Higgs sector

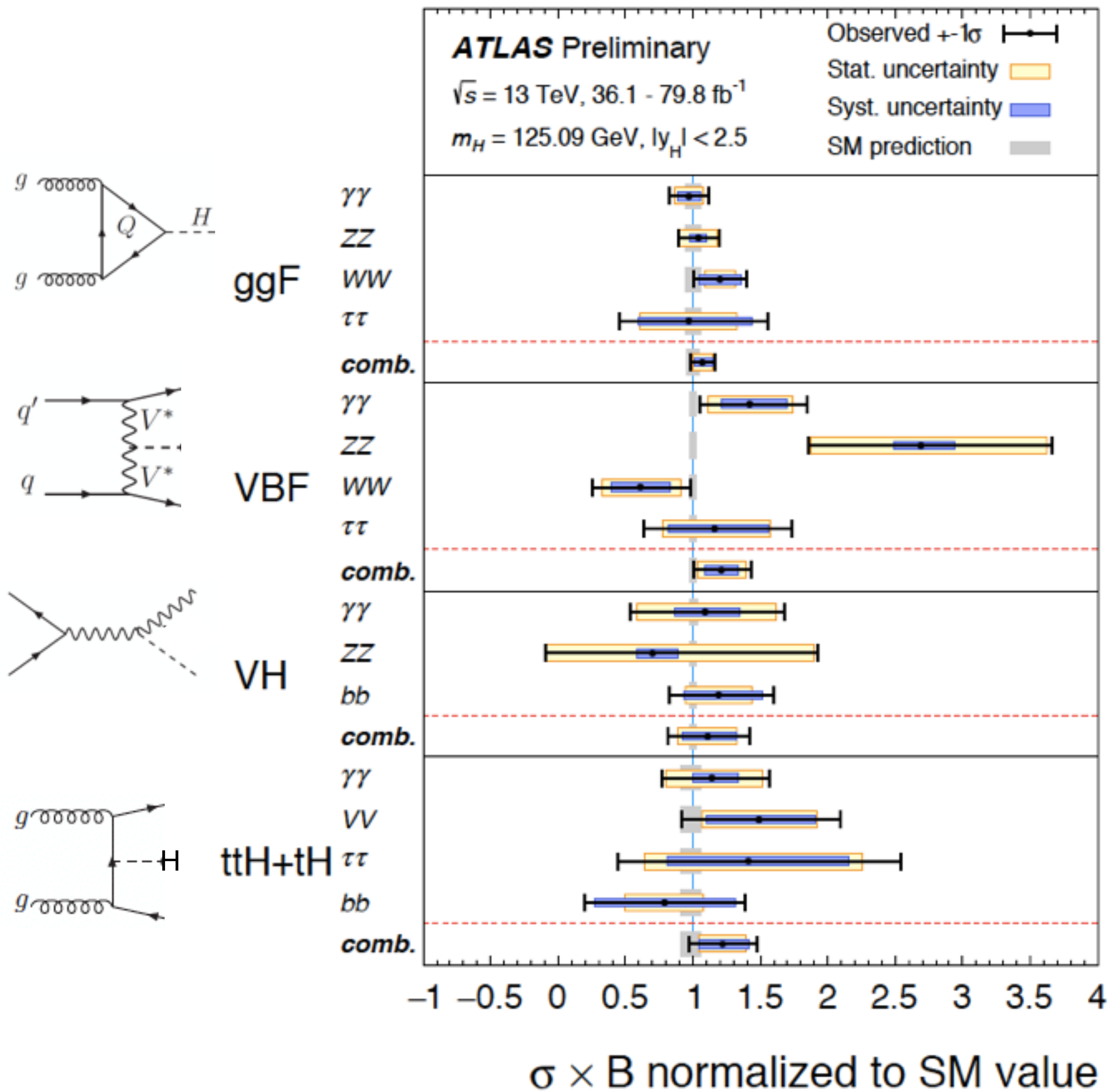
the parameter in the Higgs potential measured quite well meanwhile: m_h



couplings to vector bosons and fermions also measured increasingly well



Main Higgs production and decay channels



Higgs boson self-coupling(s)

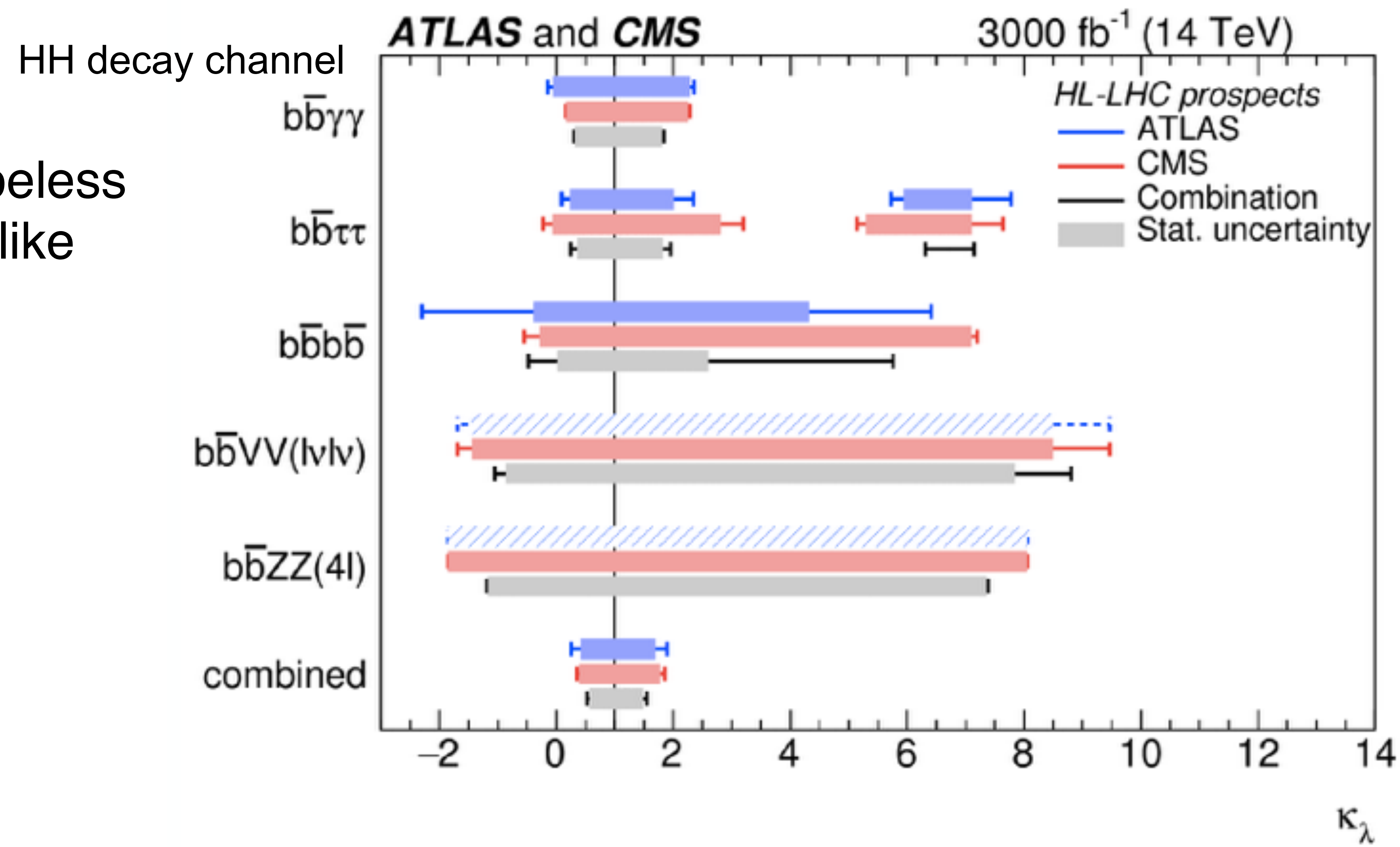
ATLAS-Conf-2018-043: $-5.0 \leq \kappa_\lambda \leq 12.1$ at 95% CL

CMS 1811.09689: $-11.8 \leq \kappa_\lambda \leq 18.8$ at 95% CL

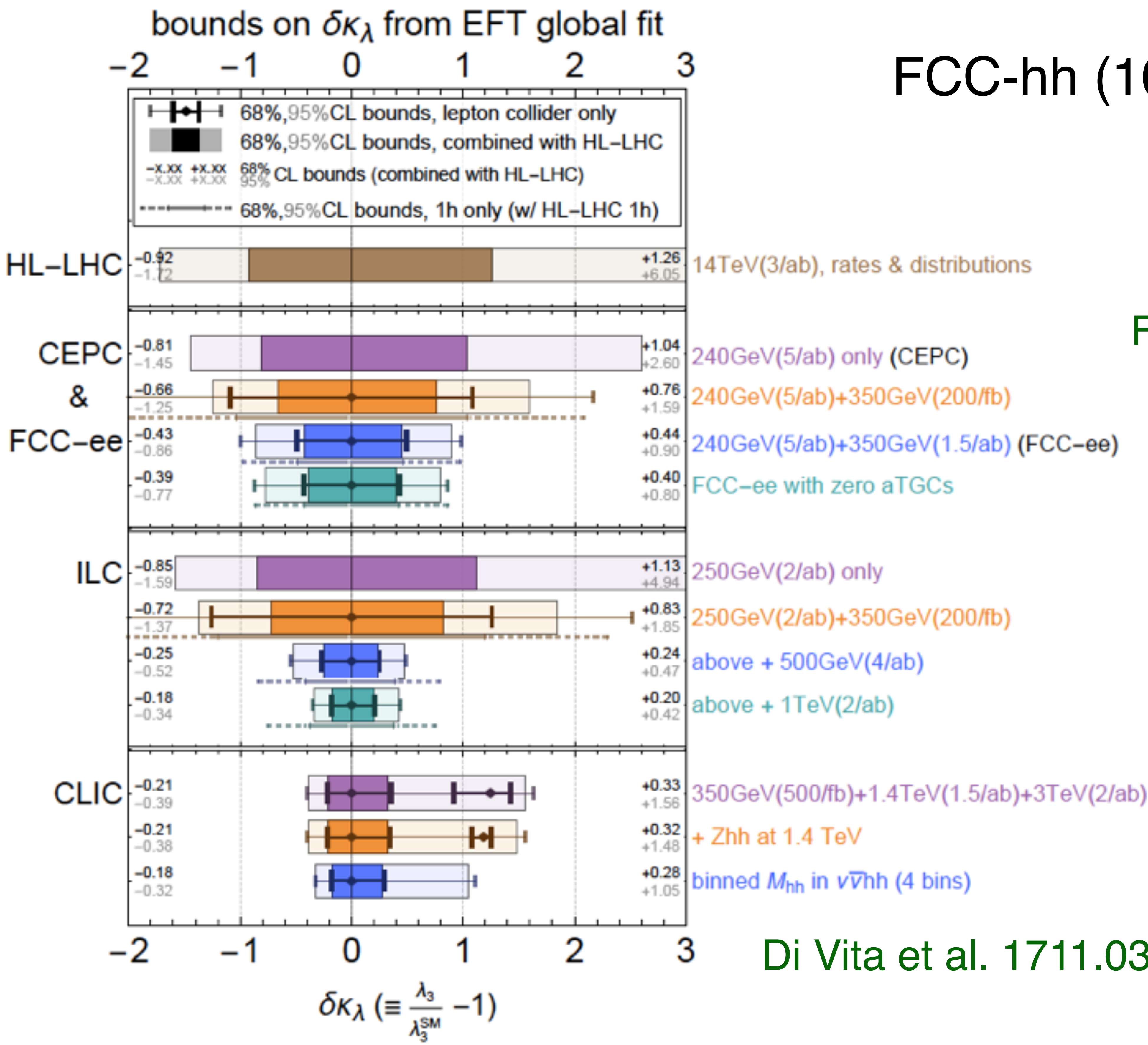
$$\kappa_\lambda = \lambda_{3h}/\lambda_{3h}^{\rm SM}$$

HL-LHC: κ_λ can be measured at to ~ 30-50% with $3\,\mathrm{ab}^{-1}$

λ_{4h} is rather hopeless if it is SM-like



Prospects at future colliders



FCC-hh (100TeV, 30/ab):

$$\delta\kappa_\lambda \sim 5\%$$

$$\lambda_{4h} \in \sim [-4, 16]$$

FCC YR, 1710.06353

Di Vita et al. 1711.03978

Theoretical considerations: form of the Higgs potential

The Higgs potential

- could have higher terms in λ consistent with SM symmetries

$$V(h) = v^4 \sum_{n=2}^{\infty} f_{V,n} \left(\frac{h}{v}\right)^n$$

EFT operators, see e.g. YR4 1610.07922

- could have logarithmic dependence on the Higgs field

  (e.g. Coleman-Weinberg type) $\sim \Phi^4 \ln\left(\Phi^2/\Lambda^2\right)$

see e.g. Englert et al 1301.4224

- could have exponential dependence $\sim \exp\left(-1/\Phi\right)$

e.g. Reichert et al 1711.00019

Theoretical considerations: how large can the trilinear coupling be?

there is no truly model-independent answer

- perturbativity should break down at a scale $\lesssim 13\,\mathrm{TeV}/|\delta_3|$
  Chang, Luty 1902.05556
  $\delta_3 = (\lambda - \lambda_{\mathrm{SM}})/\lambda_{\mathrm{SM}}$
- from vacuum stability and validity of EFT approach: $|\lambda_{3h}| \lesssim 4$
  Falkowski, Ratazzi 1902.05936
- from unitarity (based on partial wave analysis for hh -> hh) and perturbativity: $|\lambda_{3h}| \lesssim 6.5$
  Di Luzio, Gröber, Spannowsky 1704.03211
- from Higgs portal models, assuming other couplings are close to SM: $|\lambda_{3h}| \lesssim 6$
  Di Vita, Grojean, Panico, Riembau, Vantalon 1704.01953
- models with more specific assumptions can lead to stronger bounds
  e.g. singlet scalar extension, Lewis, Sullivan 1701.08774

Indirect ways to measure the trilinear coupling

trilinear coupling enters also in

- EW corrections to single Higgs production processes

McCullough ‘13

Bizon, Gorbahn, Haisch, Zanderighi ‘16

Degrassi, Giardino, Maltoni, Pagani ‘16

Maltoni, Pagani, Shivaji, Zhao ’17, ‘18

Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao ‘18

Nakamura, Shivaji ’18

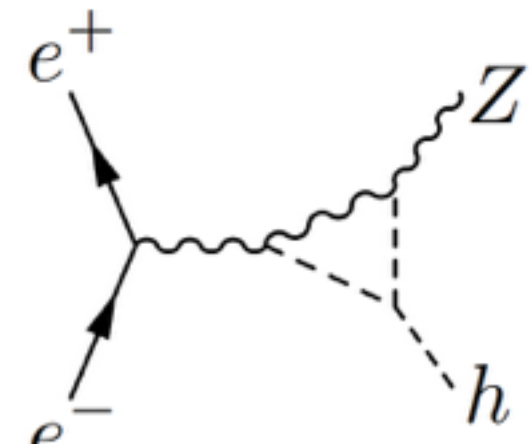
Gorbahn, Haisch ‘19

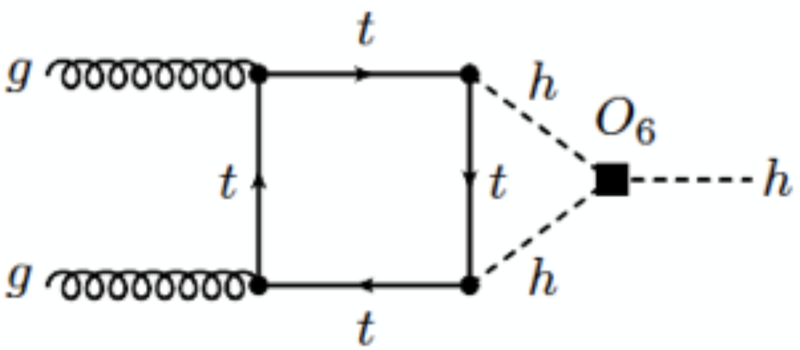
- EW precision observables

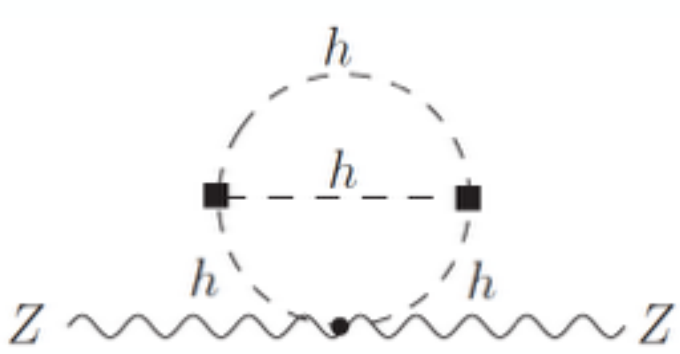
Degrassi, Fedele, Giardino ‘17

Kribs, Maier, Rzehak, Spannowsky, Waite ‘17

(example diagrams)







Indirect ways to measure the trilinear coupling

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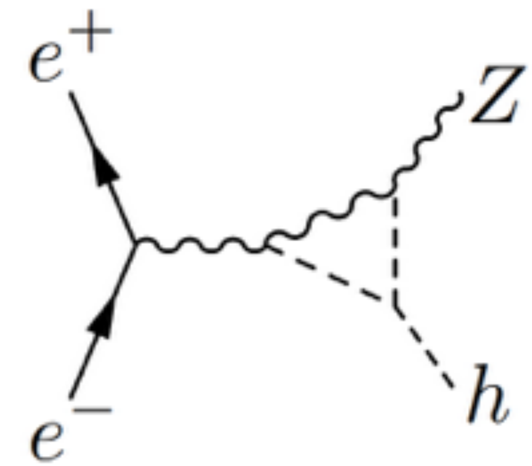

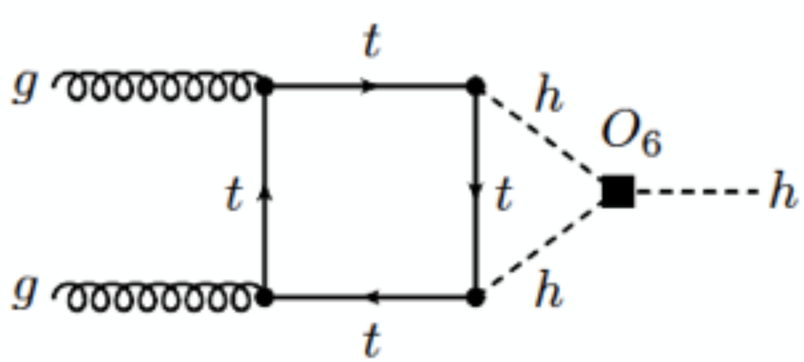

- EW precision observables

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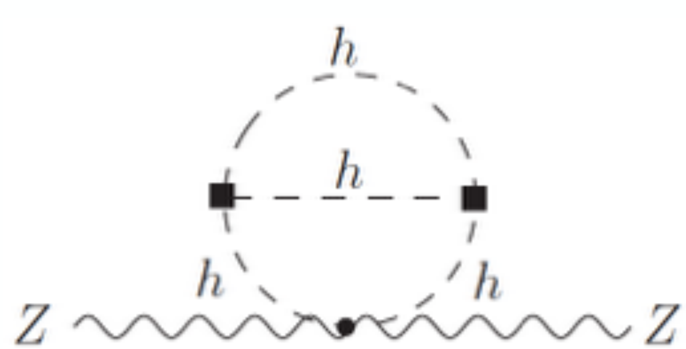
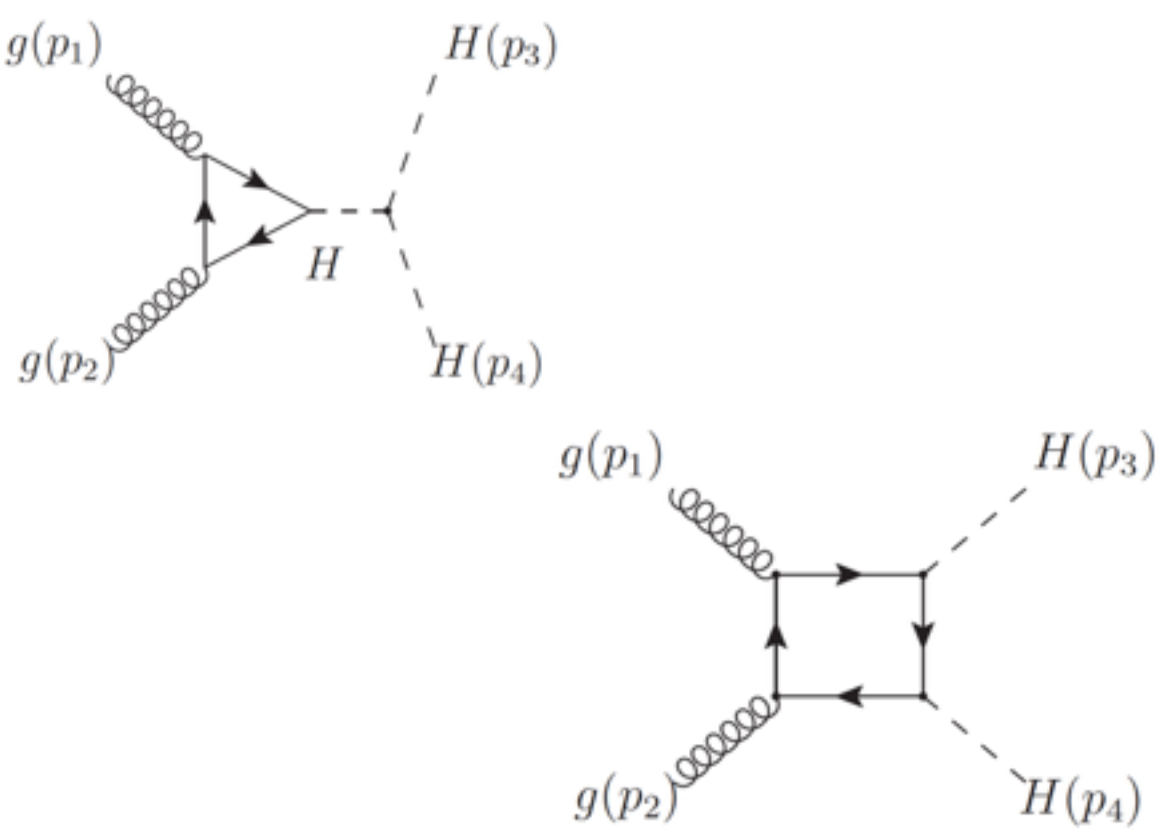
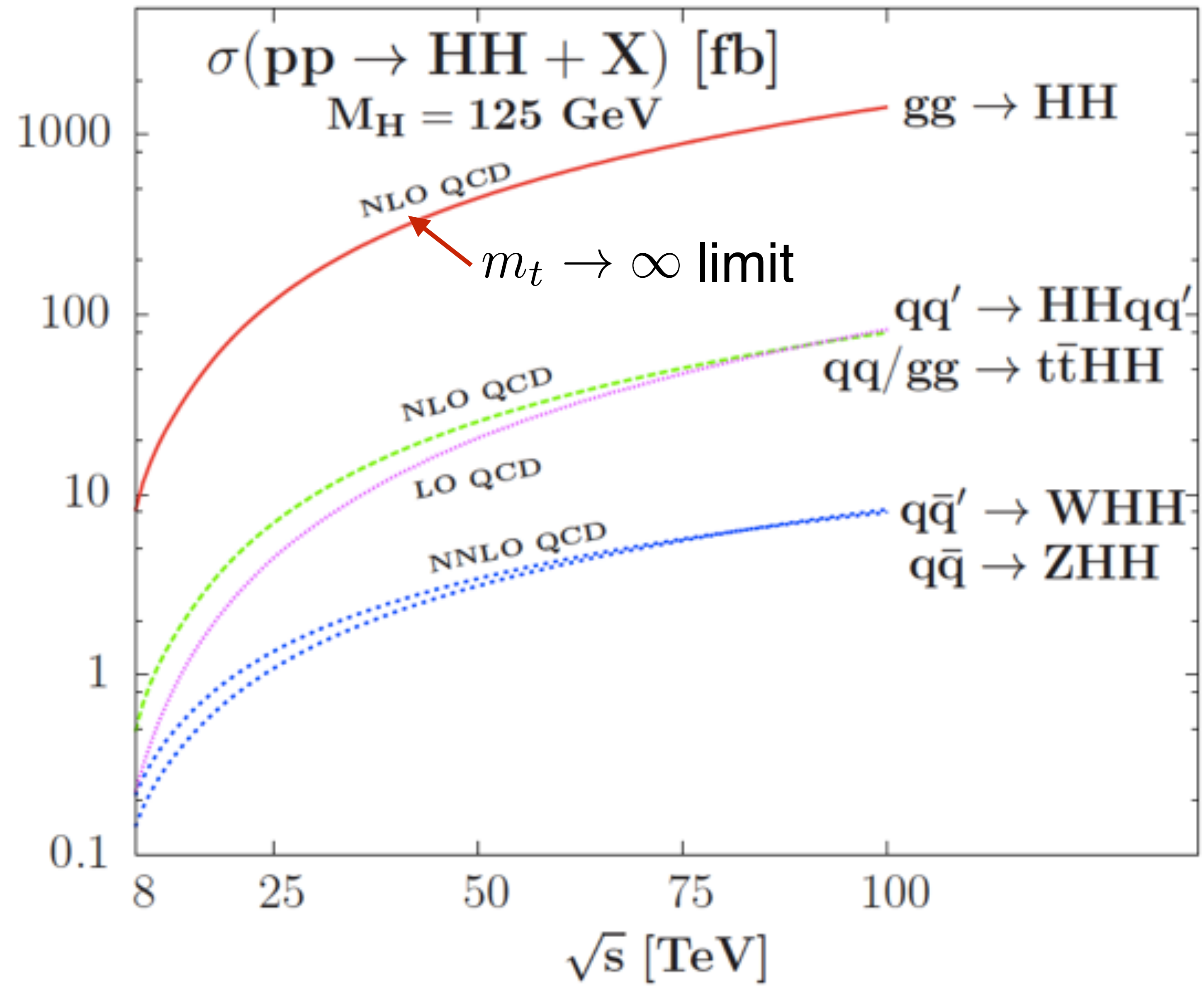


The problem is that other operators are also likely to enter at the same level $\Rightarrow$ requires global analysis

Direct Higgs boson pair production

- gluon fusion: production channel with largest cross section
- process is loop-induced





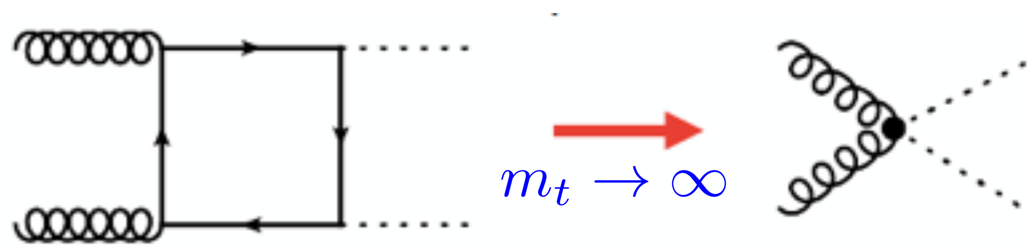
LO calculation:

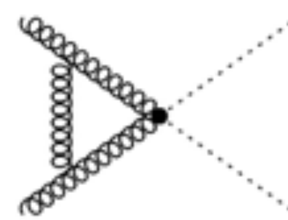
Glover, van der Bij ’88,
Plehn, Spira, Zerwas ’96

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira ‘13

Higgs boson pair production in gluon fusion

- NLO calculation: technically difficult 2-loop integrals (2 mass scales)
- approximations:
  - "Heavy Top Limit" (HTL, also called HEFT, "Higgs Effective Field Theory")





  - "Born-improved NLO HTL":

    rescale NLO result in $m_t \to \infty$ limit by $\mathcal{M}^{LO}(m_t)/\mathcal{M}^{LO}_{\mathrm{HEFT}}$

    Dawson, Dittmaier, Spira '98 (**HPAIR**) $K = \sigma_{NLO}/\sigma_{LO} \simeq 2$

    supplemented with $1/m_t$ expansion: $(\pm \mathbf{10\%})$

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

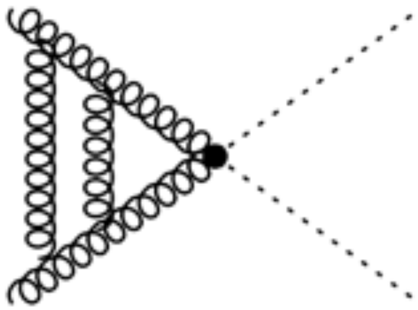
Note:

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 $250\,\mathrm{GeV} < \sqrt{\hat{s}} < 340\,\mathrm{GeV}$

Higgs boson pair production in gluon fusion

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

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



- **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** Shao, Li, Li, Wang '13; De Florian, Mazzitelli '15 **+9%**
  - **differential NNLO** De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16

uncertainties due to missing full top mass dependence were unclear at that point

Higgs boson pair production in gluon fusion

NLO calculation with full top mass dependence

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

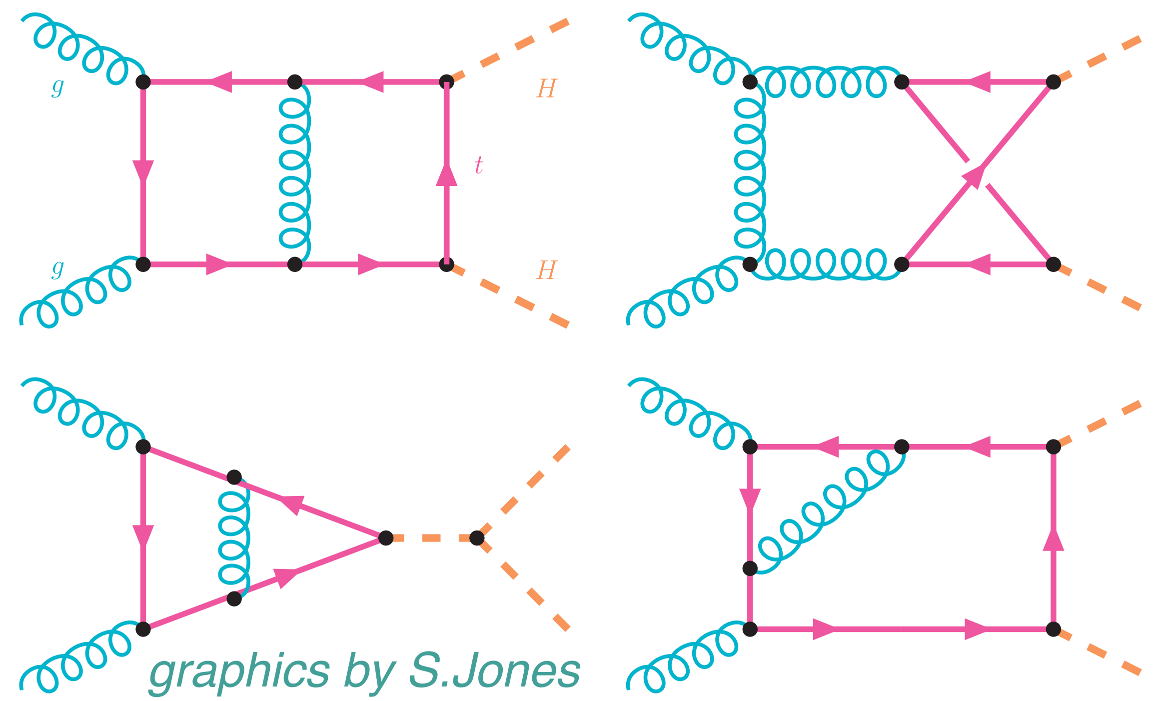
4 independent scales s12, s23, mH, mt

all integrals calculated **numerically** with

SecDec

Borowka, GH, Jones, Kerner, Schlenk, Zirke ‘15

Borowka, GH, Jahn, Jones, Kerner, Schlenk, Zirke ’17,’19



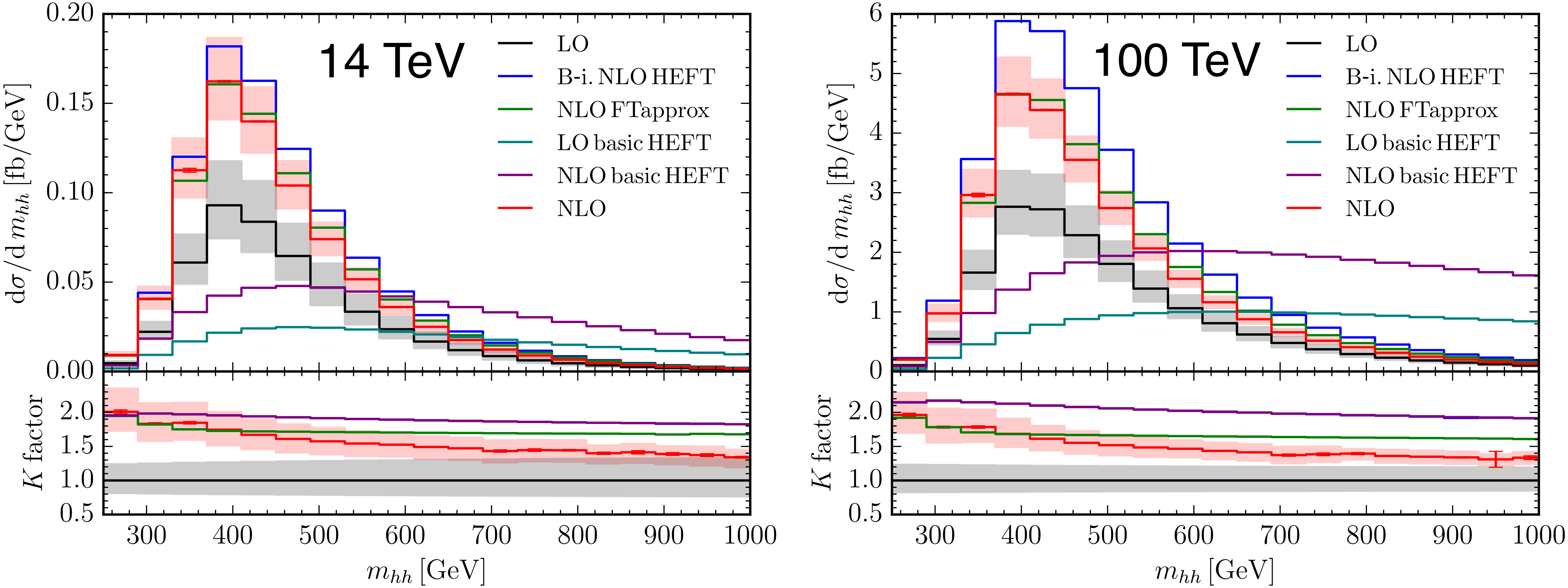
graphics by S.Jones

meanwhile confirmed with independent calculation by Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher ‘18

based on full NLO calculation:

- q_T resummation NLL+NLO Ferrera, Pires ‘16
- full mass dependence in NNLO real radiation,“NNLO_approx” Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli ‘18
- NNLL soft gluon resummation on top of NNLO_approx De Florian, Mazzitelli ‘18

Higgs boson pair invariant mass



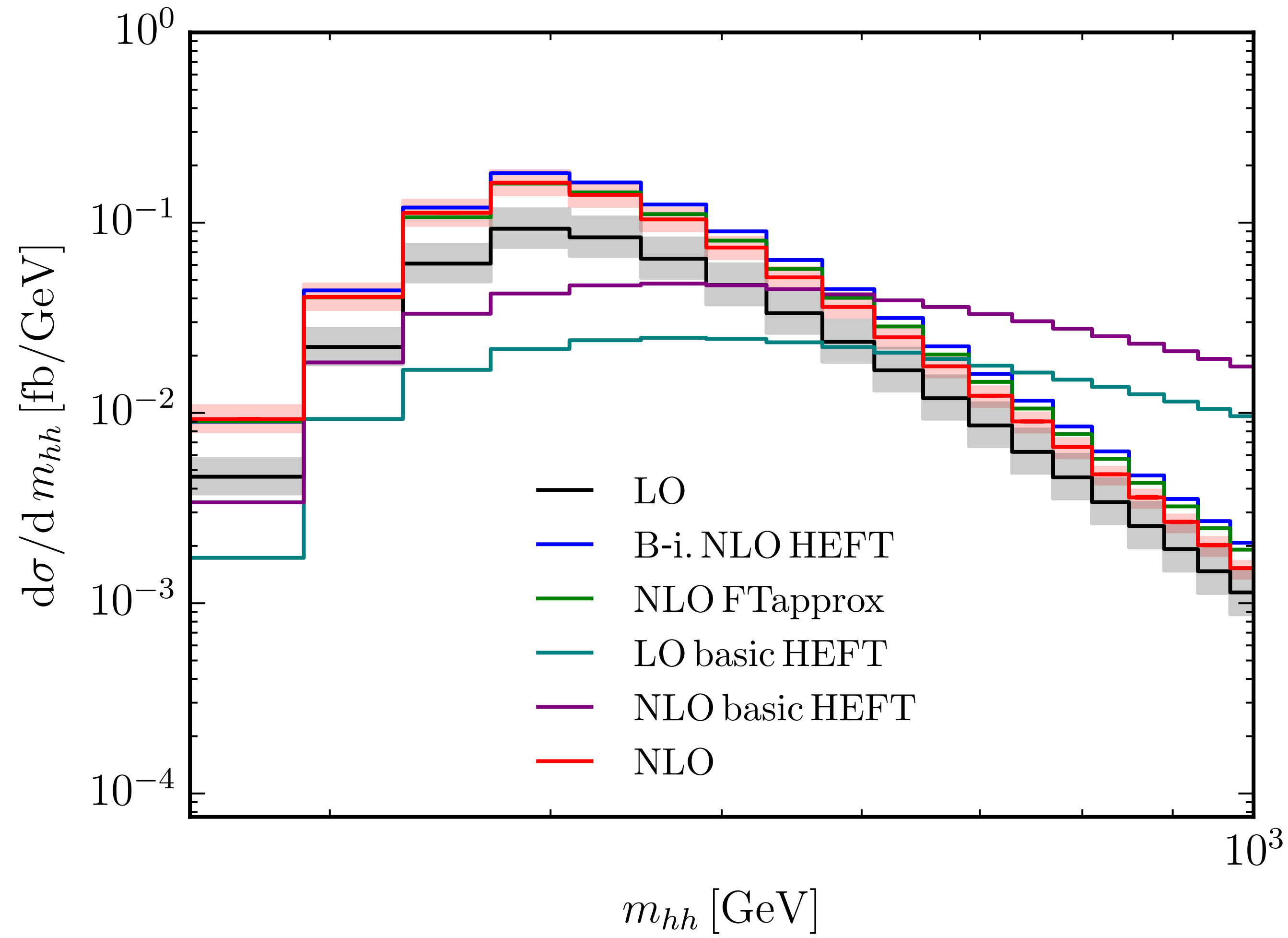
for large invariant masses:

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

$\sigma_{\rm tot}$: FTapprox overestimates by about 14%

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

high energy behaviour

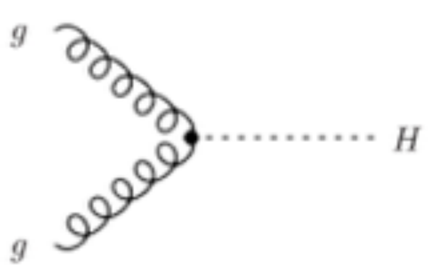


full: $\dfrac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}^{-3}$ i.e. partonic cross section scales as $\hat{s}^{-1}$

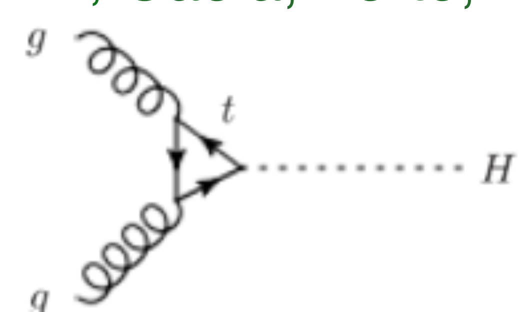
HEFT approximation: $\dfrac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}$ i.e. $\hat{\sigma} \sim \hat{s}$

similar for H+jets: Jones, Kerner, Luisoni '18

see also Marzani et al. '08; Caola, Forte, Marzani, Muselli, Vita '16



$d\sigma/dp_{T,h}^2 \to (p_{T,h}^2)^{-1}$



$d\sigma/dp_{T,h}^2 \to (p_{T,h}^2)^{-2}$

HH@NLO + parton shower

- **full NLO + parton shower**

Powheg and MG5_aMC@NLO + Pythia GH, Jones, Kerner, Luisoni, Vryonidou ‘17

Sherpa Jones, Kuttimalai ‘17

Powheg + Pythia 8.2, Powheg + Herwig 7.1 GH, Jones, Kerner, Luisoni, Scyboz 1903.08137

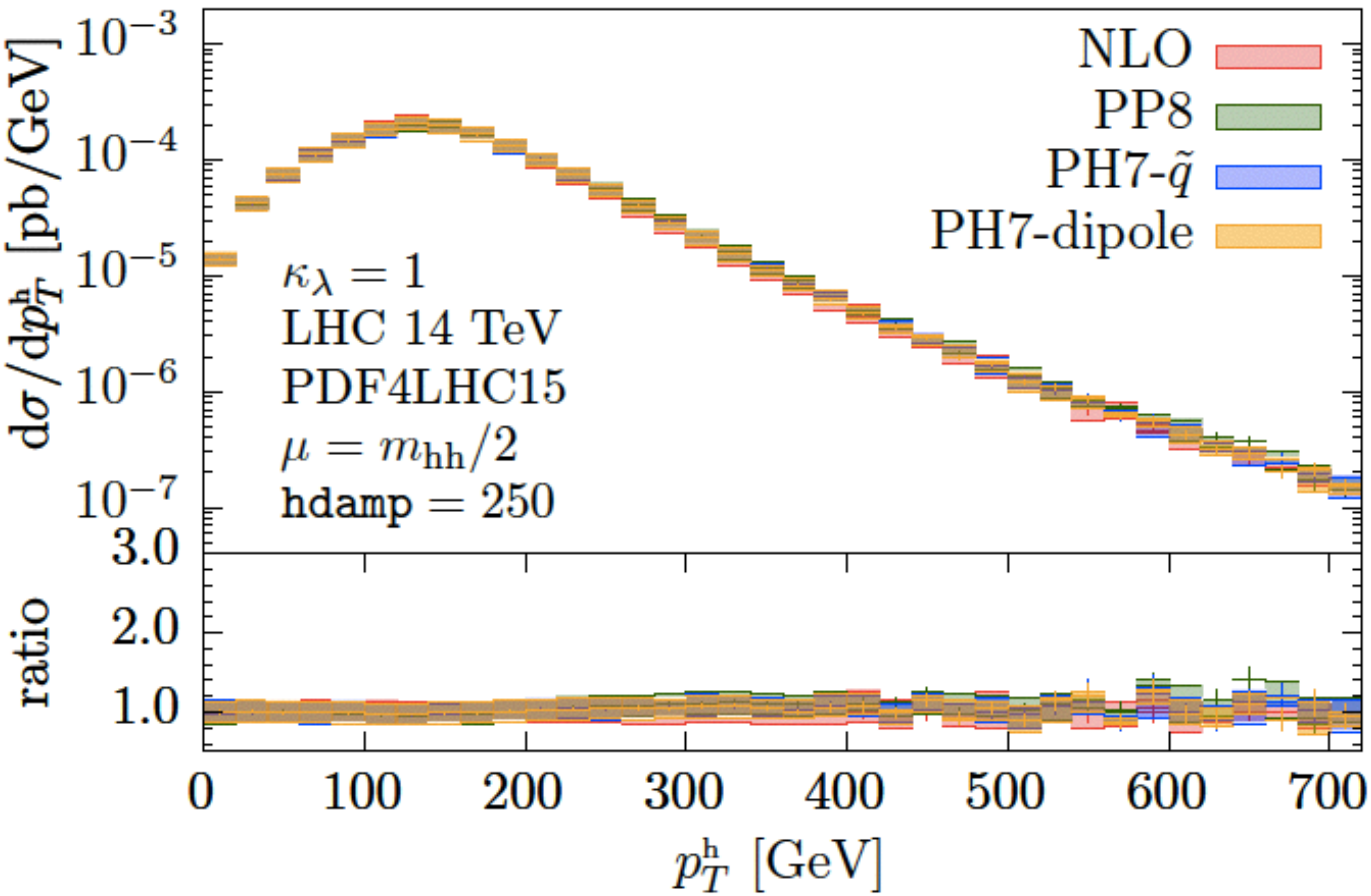
including possibility to vary trilinear Higgs coupling

also allows variations of top-Higgs Yukawa coupling

publicly available

POWHEG-BOX-V2: User-Process-V2/ggHH

HH@NLO + parton shower

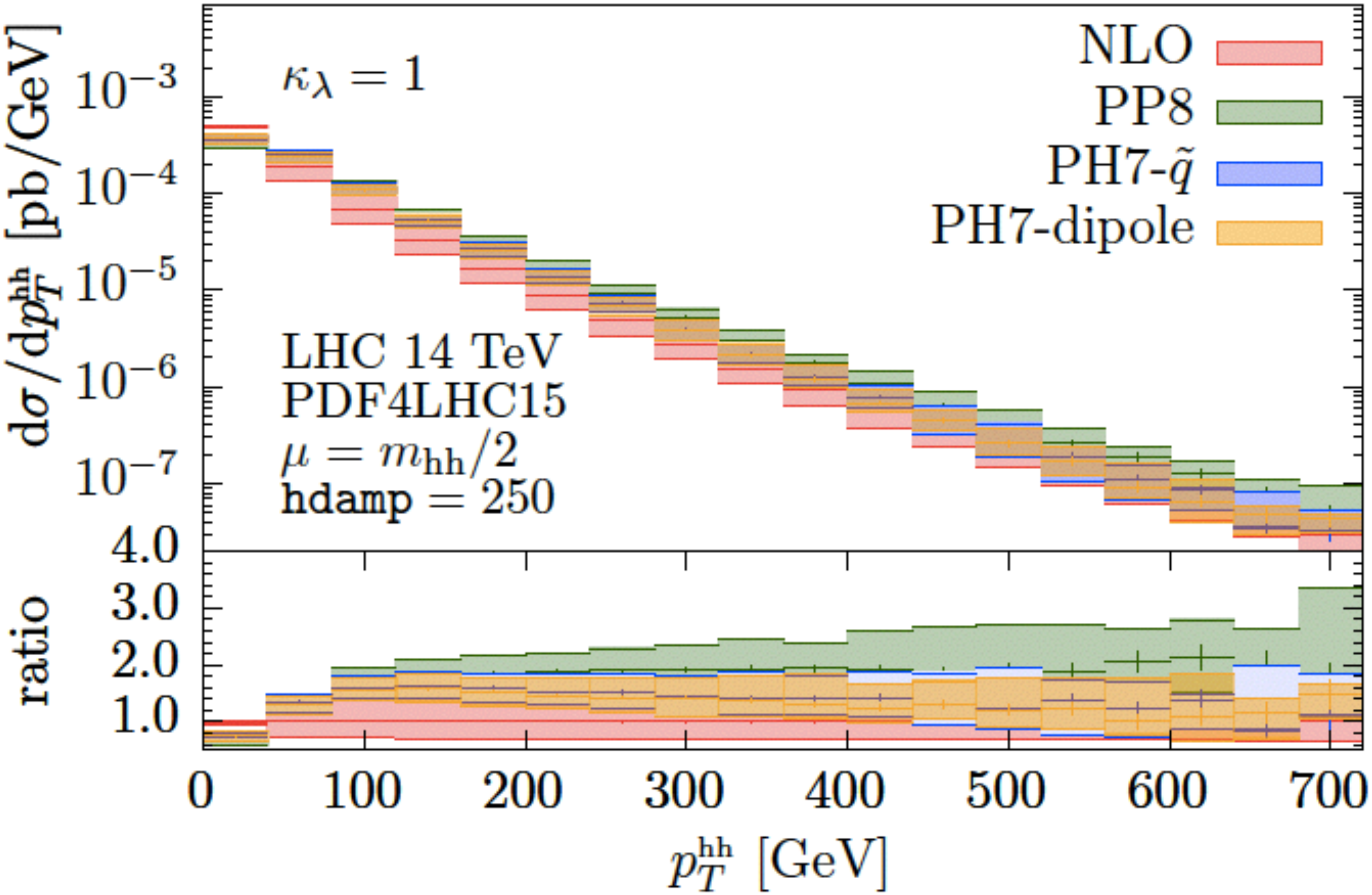


Pythia8
Herwig7 angular-ordered
Herwig7 dipole

- transverse momentum of one of the Higgs bosons:

  inclusive in additional radiation, not very sensitive to shower differences

HH@NLO + parton shower



Pythia8

Herwig7 angular-ordered

Herwig7 dipole

- transverse momentum of Higgs boson pair: NLO is first non-trivial order
- very sensitive to extra radiation
- Pythia8 produces additional hard sub-leading jets

HH@NLO + Sherpa

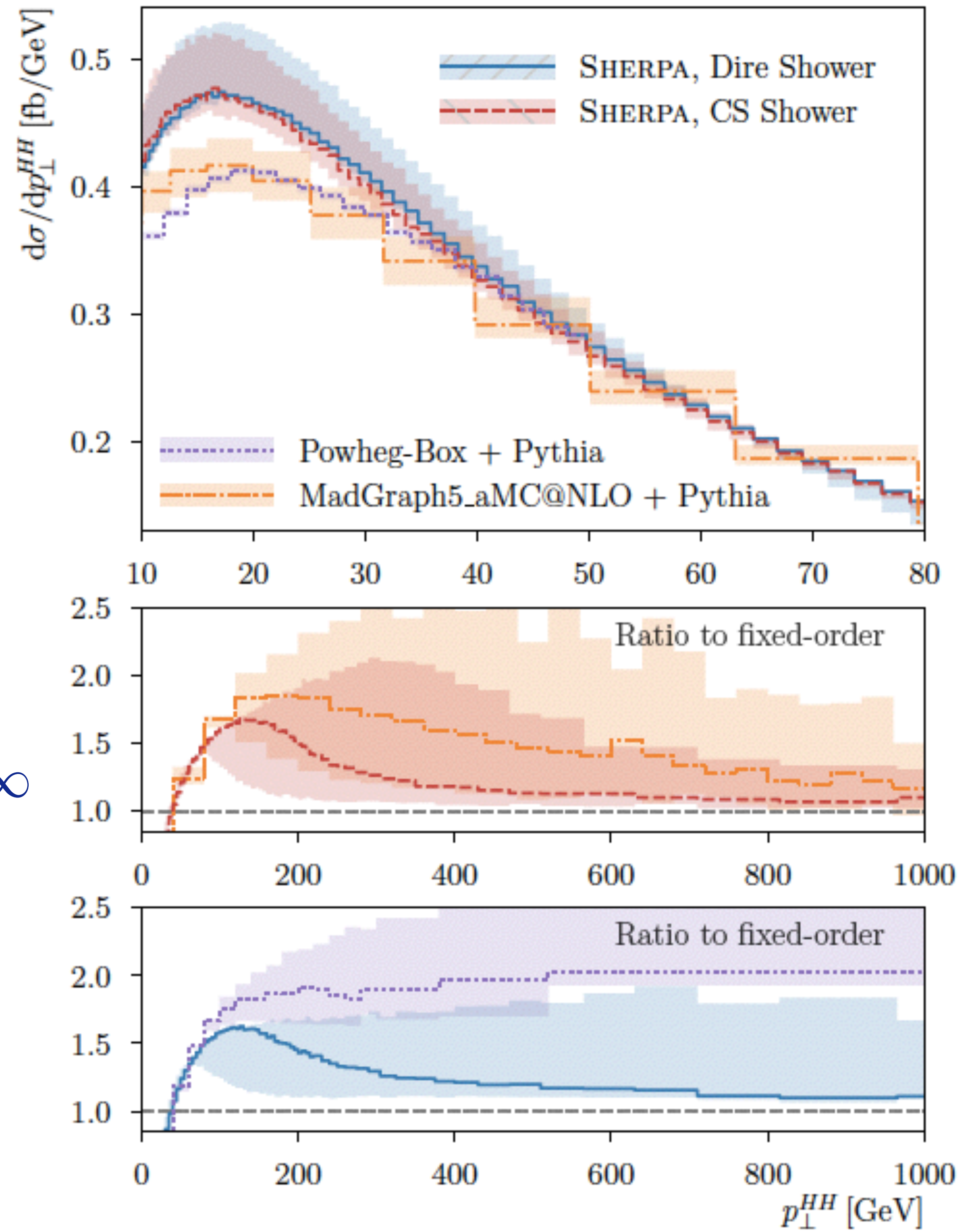
S. Jones,
S. Kuttimalai '17

- differences in peak region due to different matching algorithms

- large pTHH region:

MG5_aMC@NLO results within (large) uncertainty bands

Powheg with $h_{\mathrm{damp}} = 150, 250, \infty$ not within μ_{PS} variation band



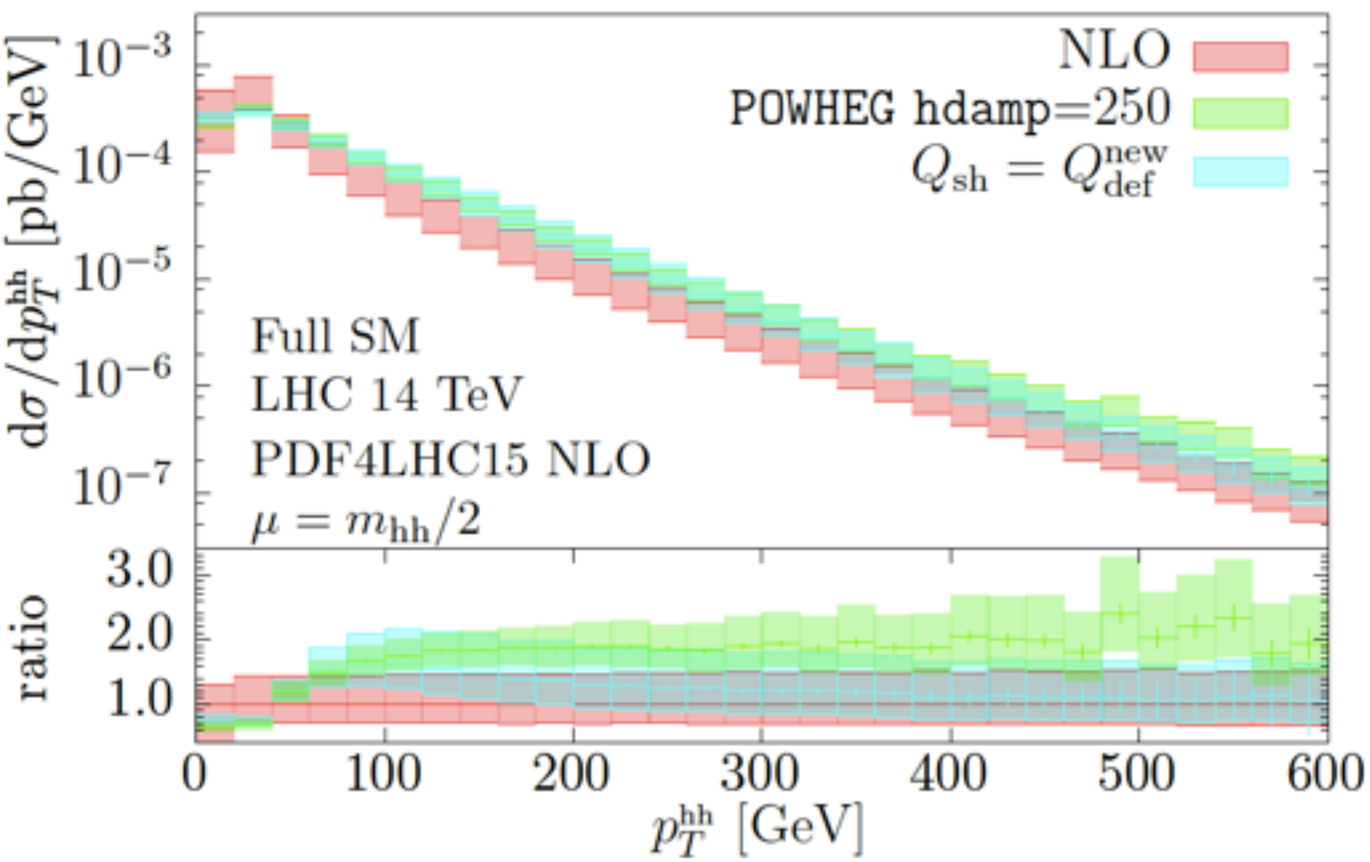
compare POWHEG and MG5_aMC@NLO

MG5_aMC@NLO version 2.5.3:

new shower starting scale `Qsh`

picked with some probability distribution in

$\texttt{shower\_scale\_factor} \times [0.1\, H_T/2, H_T/2]$



new default shower starting scale matches onto NLO fixed order at large `pThh`

compare POWHEG and MG5_aMC@NLO

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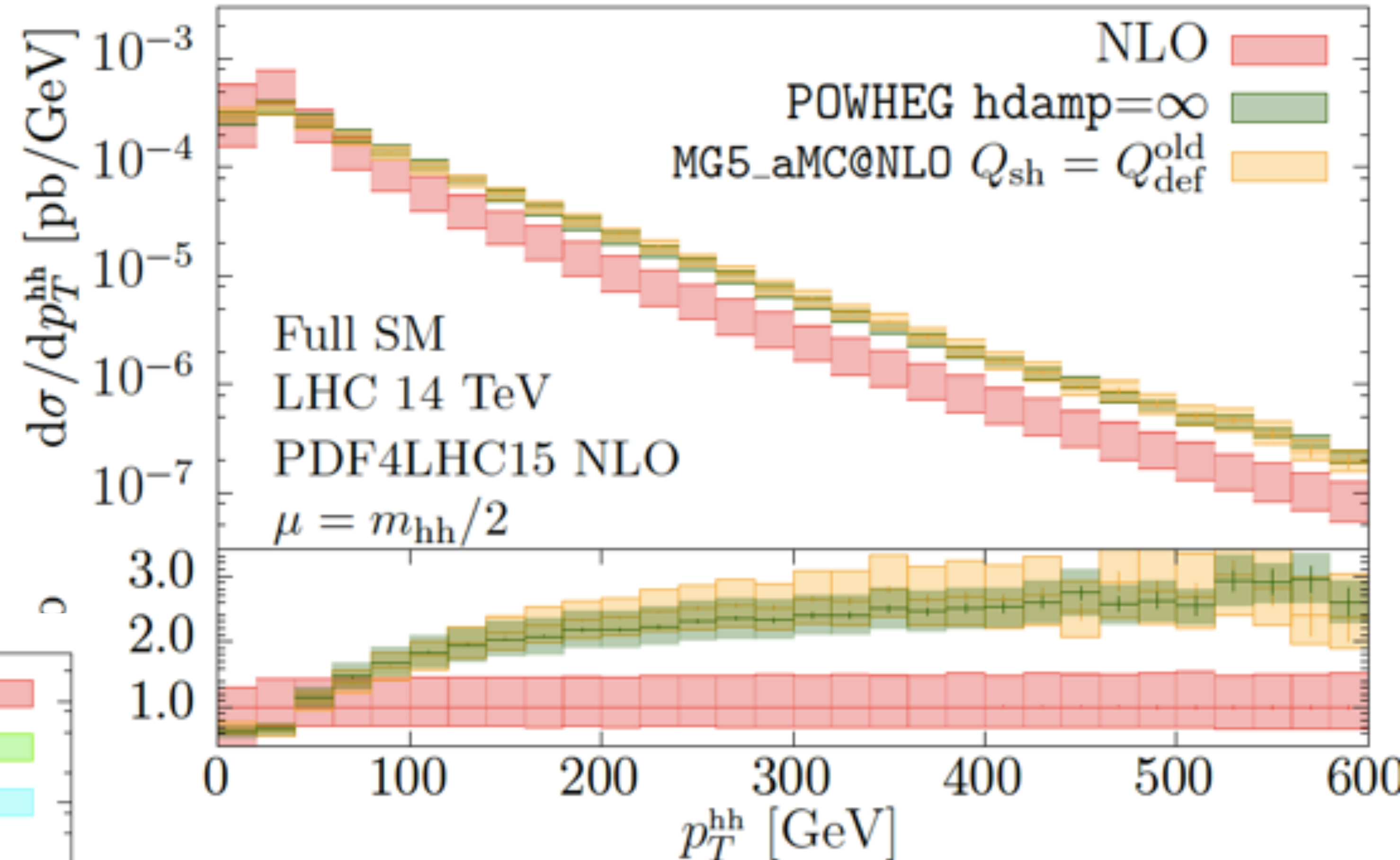
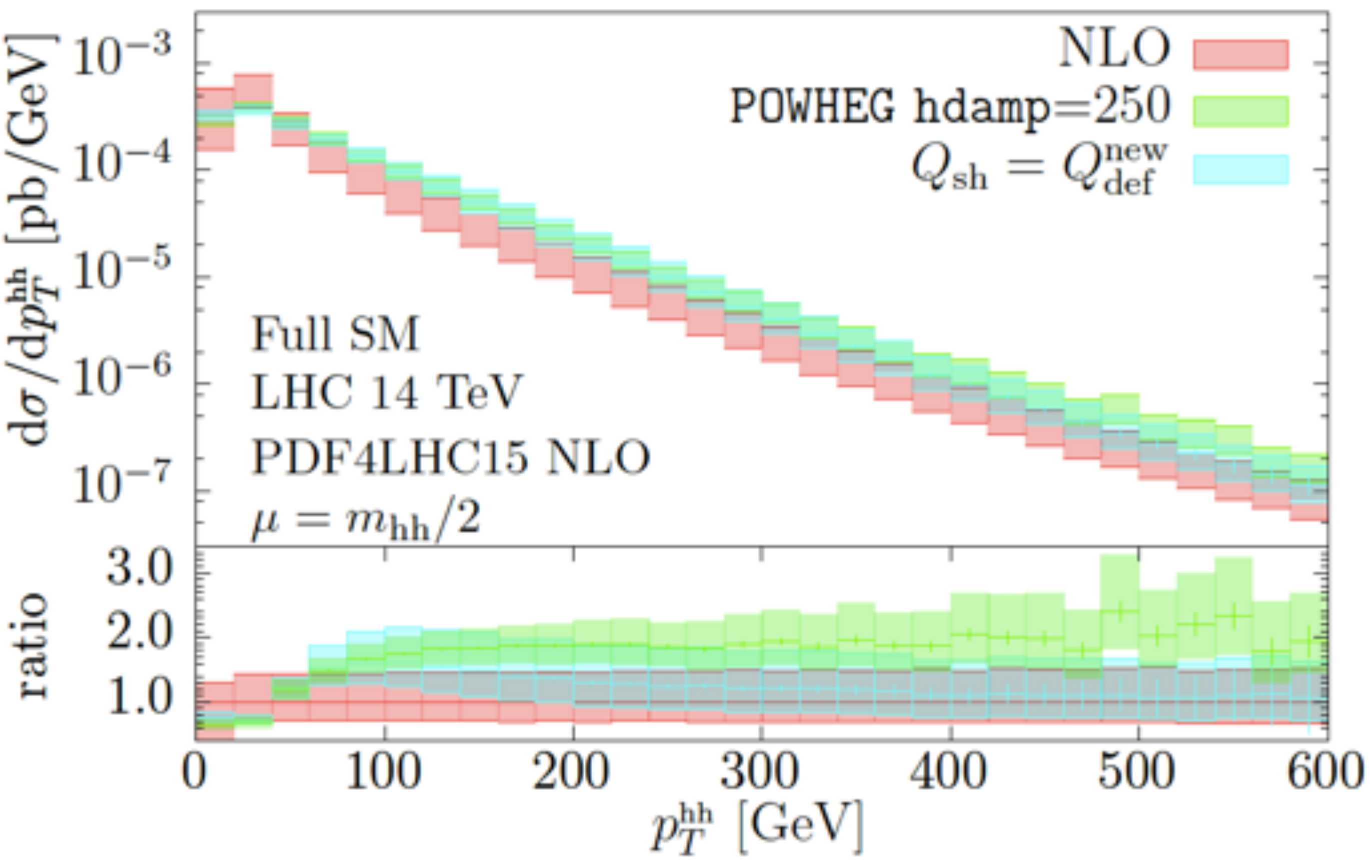




MG5_aMC@NLO

old shower starting scale `Qsh`:

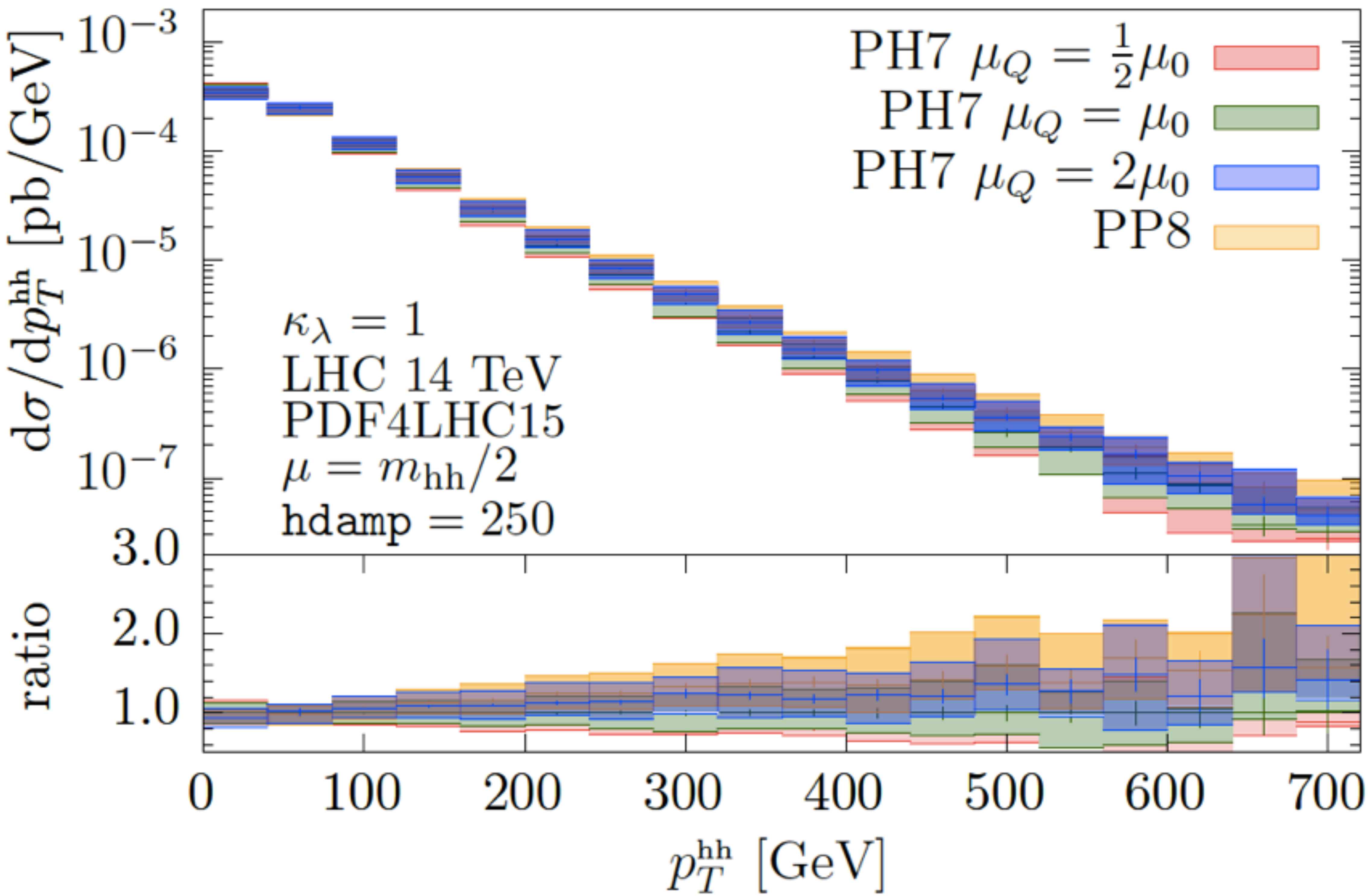
picked with some probability distribution in

$\texttt{shower\_scale\_factor} \times [0.1\sqrt{\hat{s}}, \sqrt{\hat{s}}]$

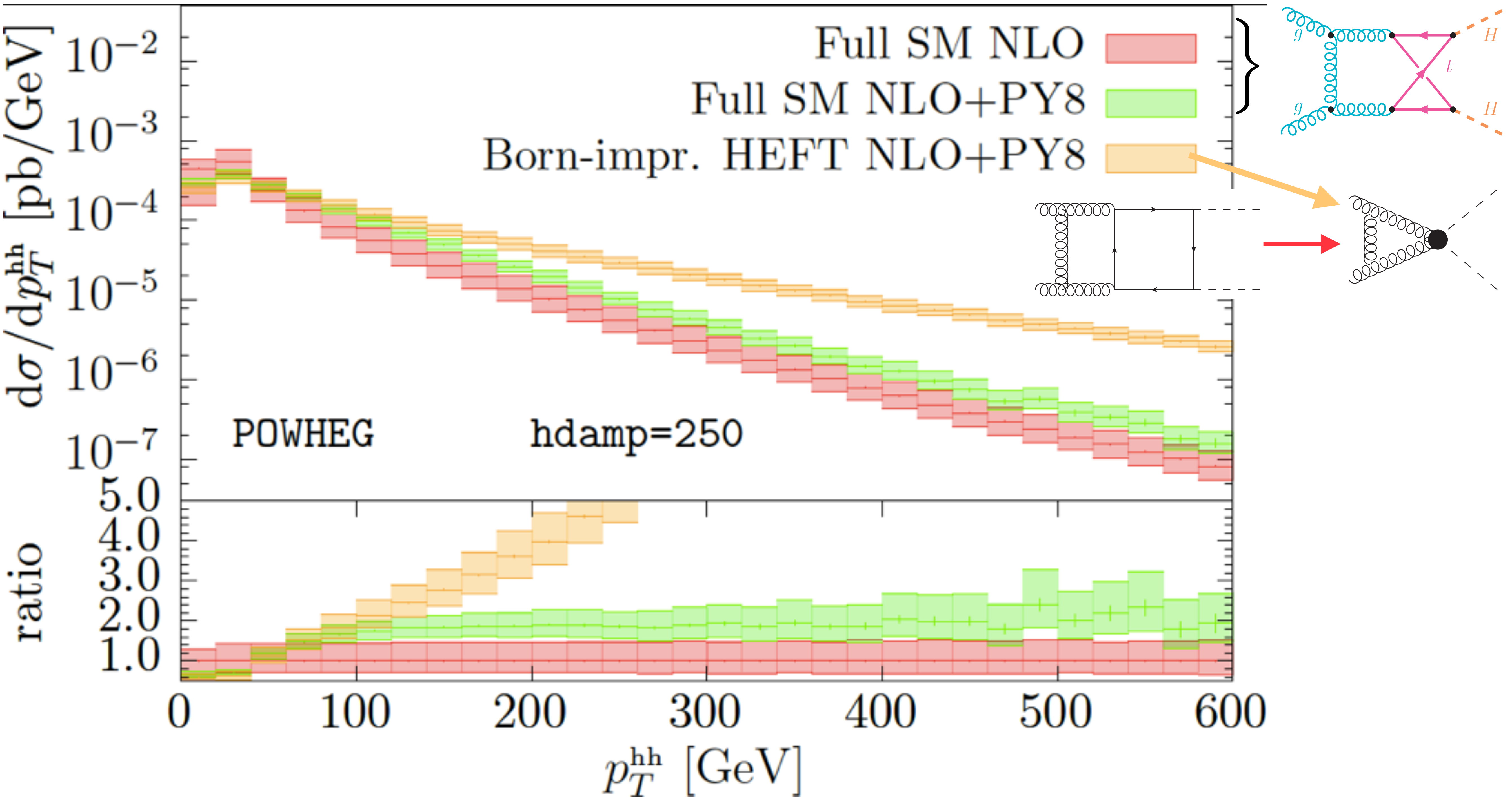
new default shower starting scale matches onto NLO fixed order at large `pThh`

HH@NLO + parton shower

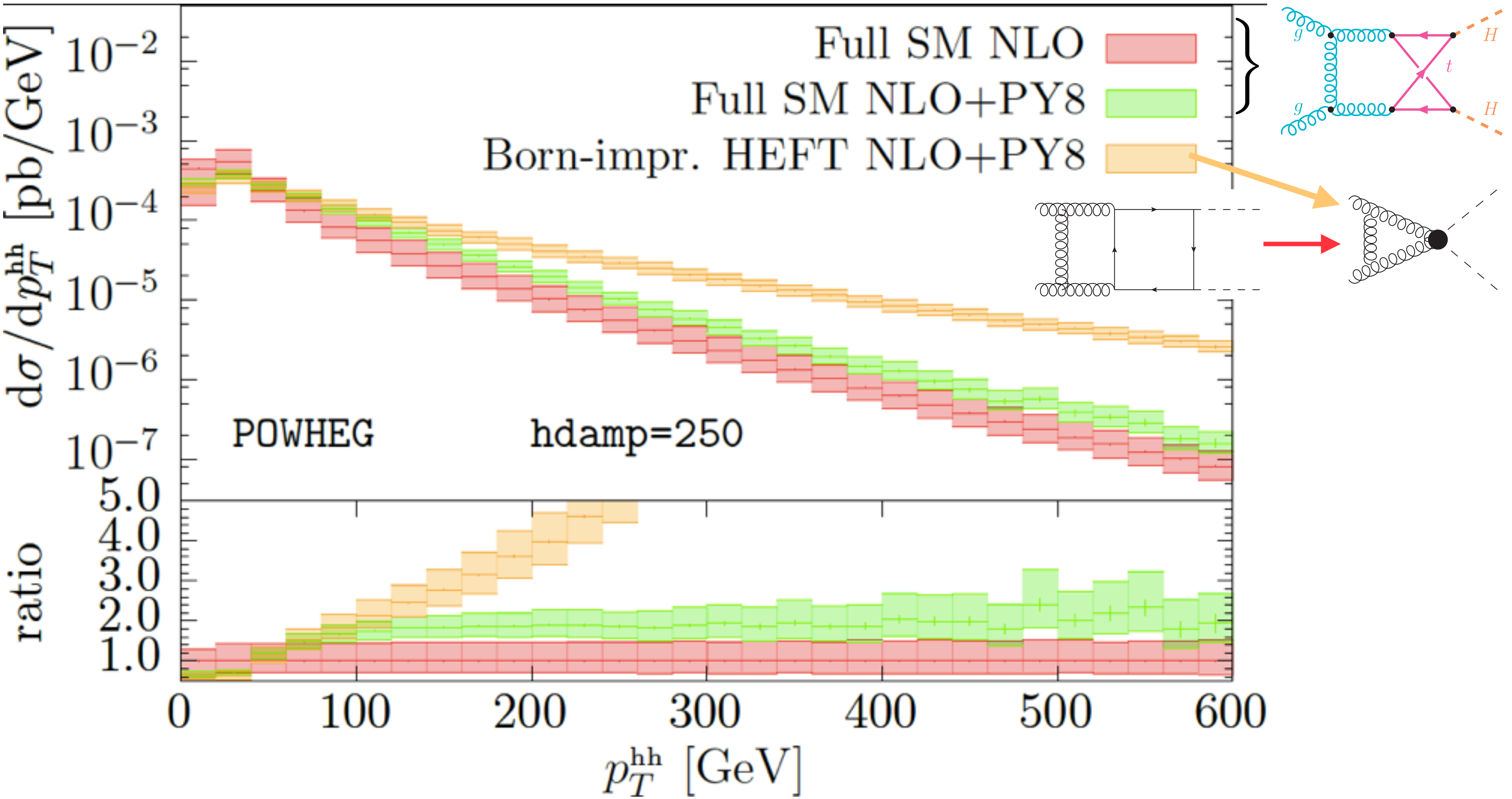
variation of hard shower scale in Herwig7, compared to Pythia8



mass effects versus parton shower effects

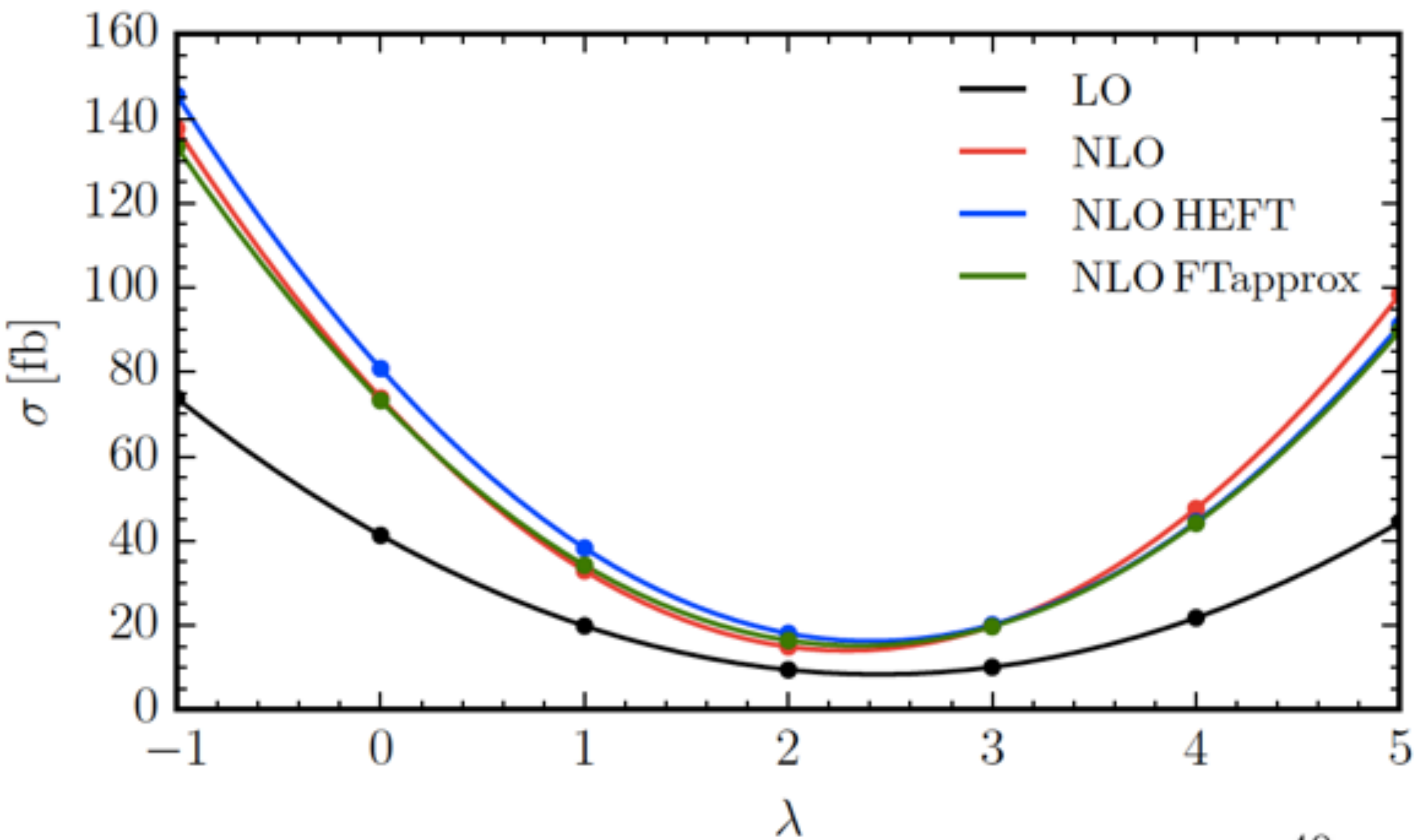


mass effects versus parton shower effects



shower effects can be large but order(s) of magnitude smaller than difference to Born-improved HEFT

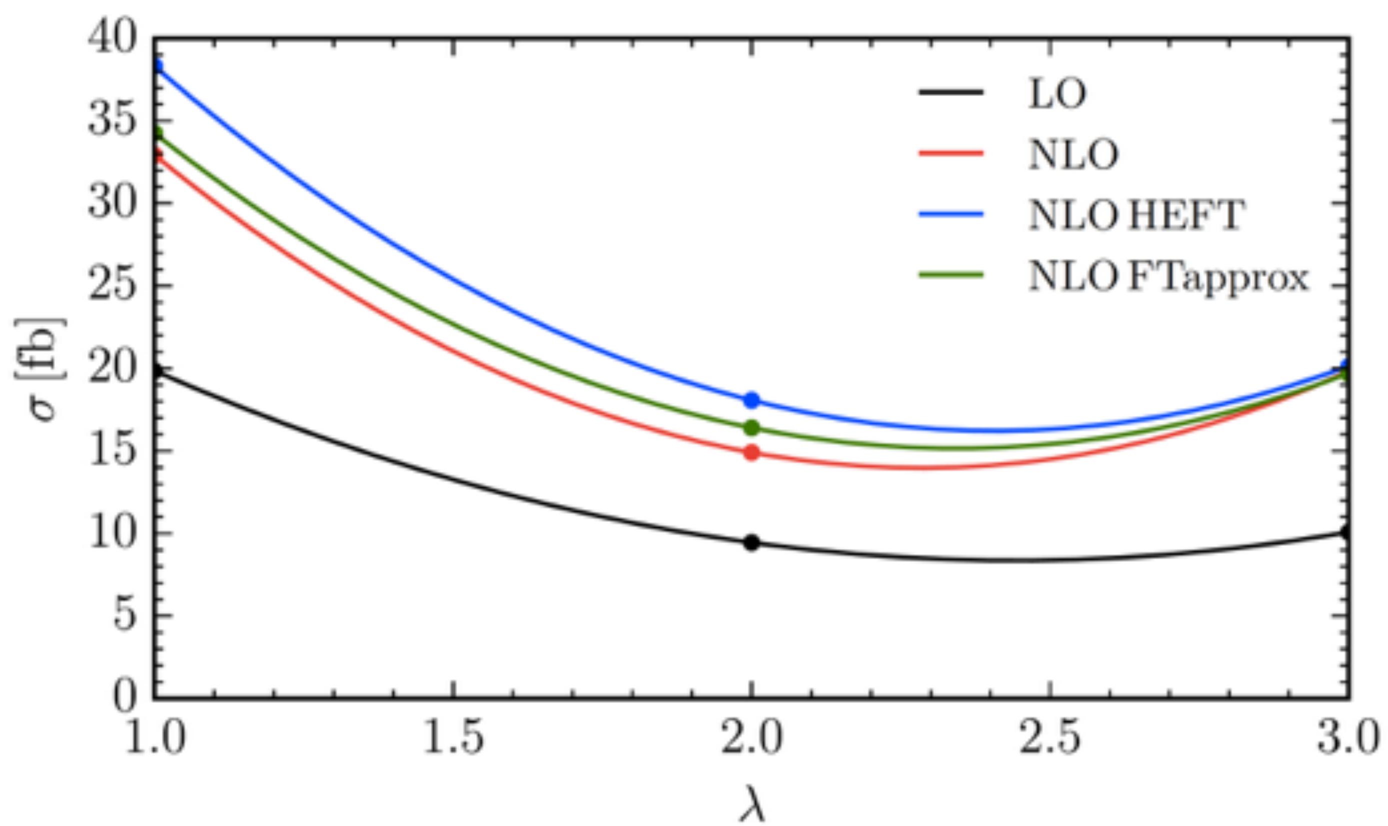
variation of the triple Higgs coupling



cross section is quadratic polynomial in λ

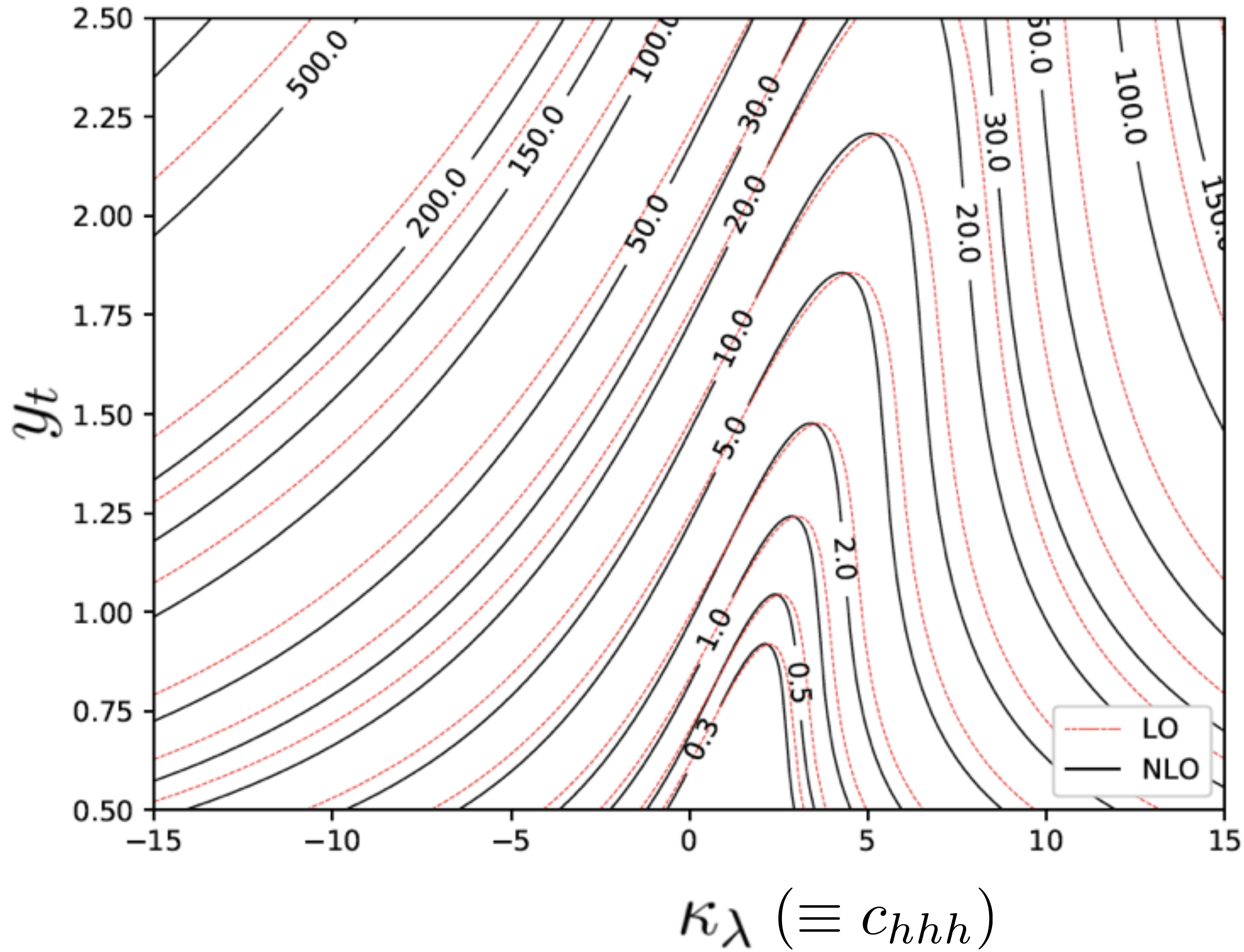
maximal destructive interference between box-type and triangle-type contributions around

$$c_{hhh} = \lambda_{\rm BSM}/\lambda_{\rm SM} \approx 2.4$$

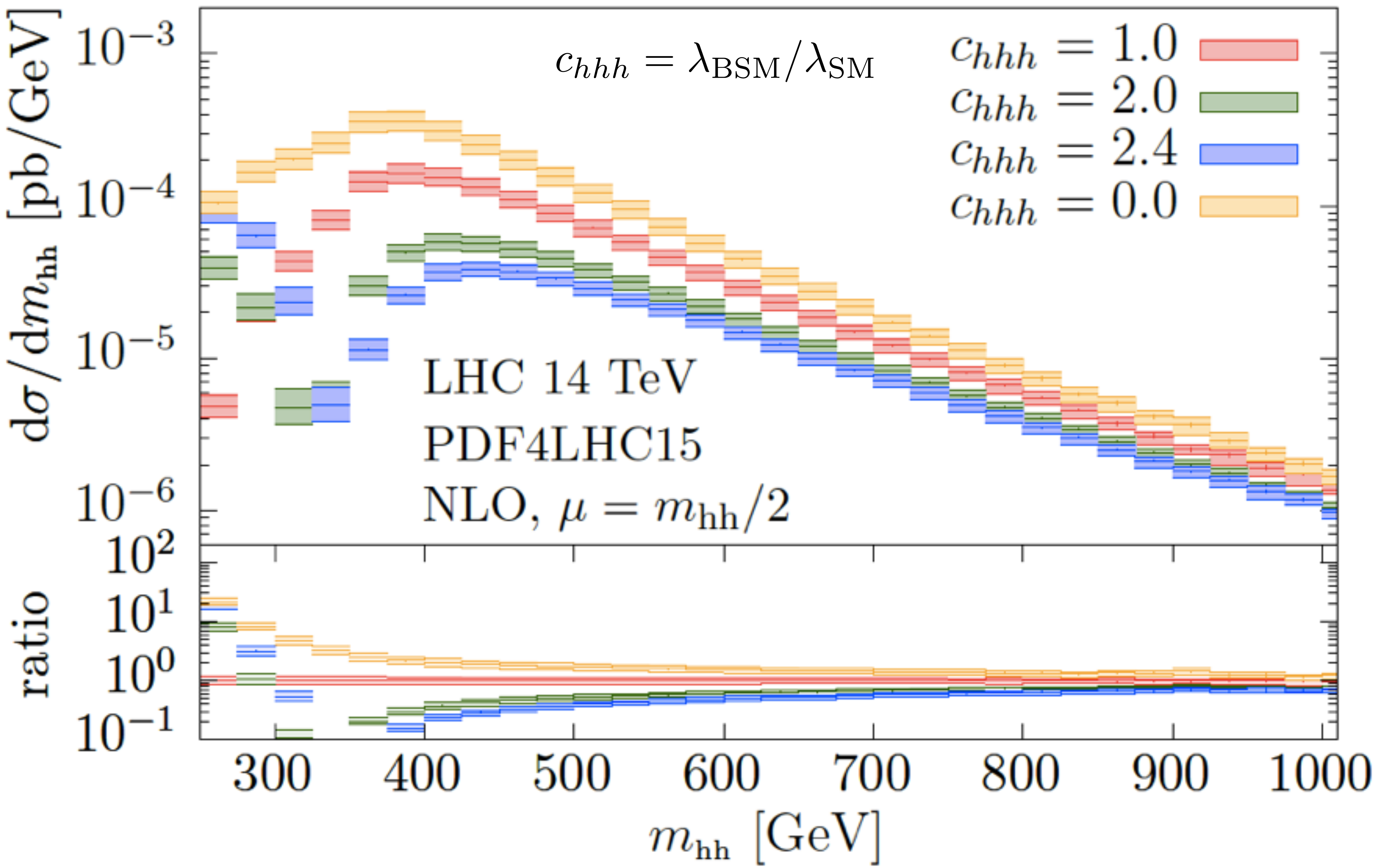


iso-contours for the total cross section

$\sigma/\sigma_{\rm SM}$ varying both, Yukawa coupling and κ_λ



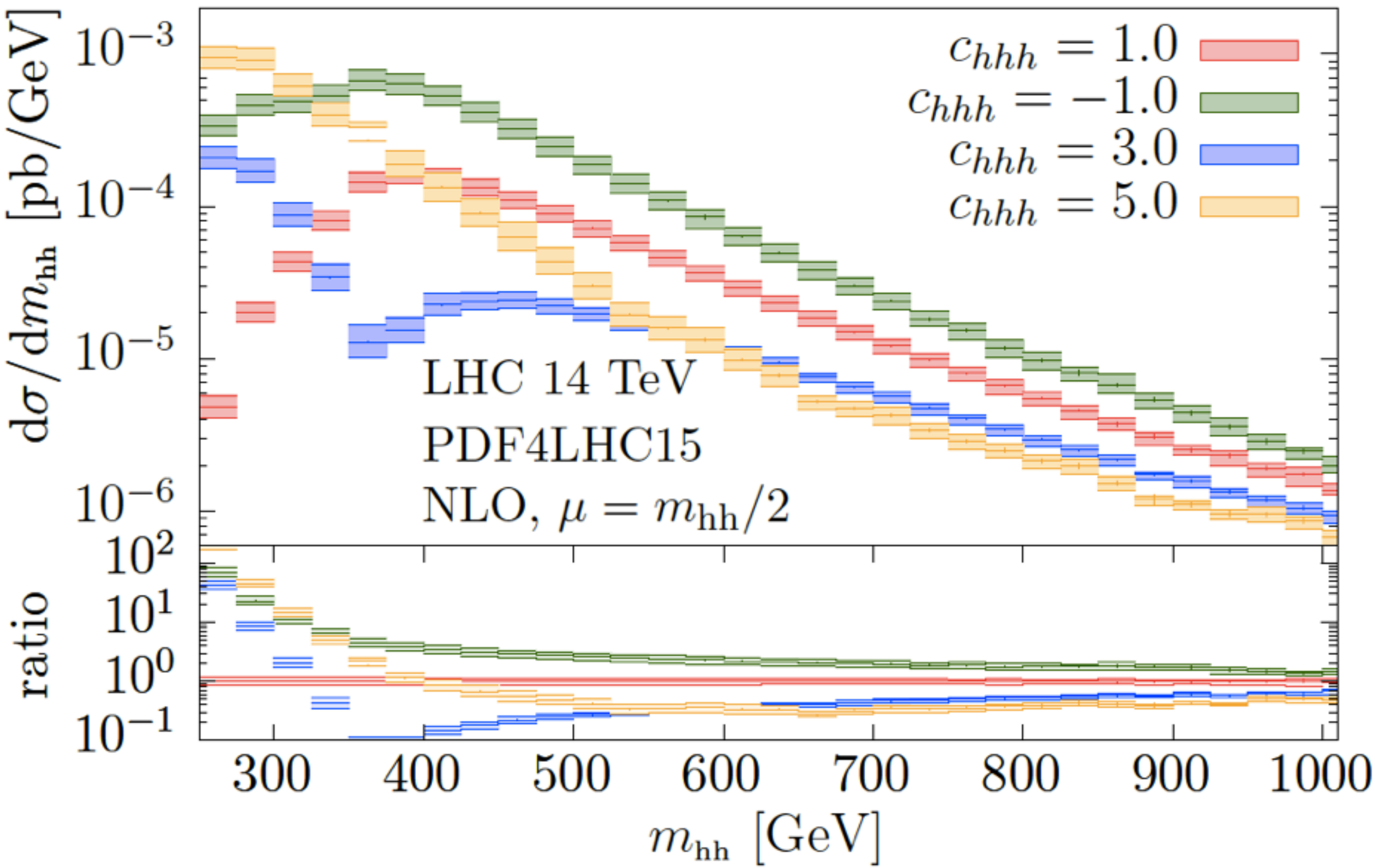
variation of the triple Higgs coupling



dip in m_{hh} distribution near 350 GeV for c_{hhh} values around 2.4

$c_{hhh} = 0$ largest in this group

variation of the triple Higgs coupling



degenerate total cross sections have clearly distinct shapes

BSM couplings in the Higgs sector

non-linear EFT framework:
Electro-weak chiral Lagrangian (EWChL) [Buchalla et al. '13]

Lagrangian relevant for $gg \to HH$ (at chiral dimension 4)

$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

- 5 (possibly) anomalous couplings
- Goldstone fields: $U = \exp\left(2i\varphi^a T^a / v\right)$ (non-linear realisation)
- 3 scales: EW scale v, scale f of Higgs sector dynamics, cut-off scale $\Lambda = 4\pi f \;\Rightarrow$
- expansion parameters $\xi = v^2/f^2$ and $f^2/\Lambda^2 = 1/(16\pi^2)$ (loop factor)
- SMEFT assumes $\xi \ll 1$, expansion in powers of ξ

Relation to SMEFT
(restricted to Higgs sector + QCD)

SMEFT:

$$\Delta\mathcal{L}_{\rm dim6} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \text{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3 + \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}t_R + \text{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\,G^a_{\mu\nu}G^{a\mu\nu}$$

EWChL:

$$\Delta\mathcal{L}_{d\chi\leq 4} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

relations: $c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u\,,\quad c_{tt} = -\frac{\bar{c}_H + 3\bar{c}_u}{2}\,,\quad c_{hhh} = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6\,,$

$$c_{ggh} = 2c_{gghh} = 128\pi^2\bar{c}_g\,.$$

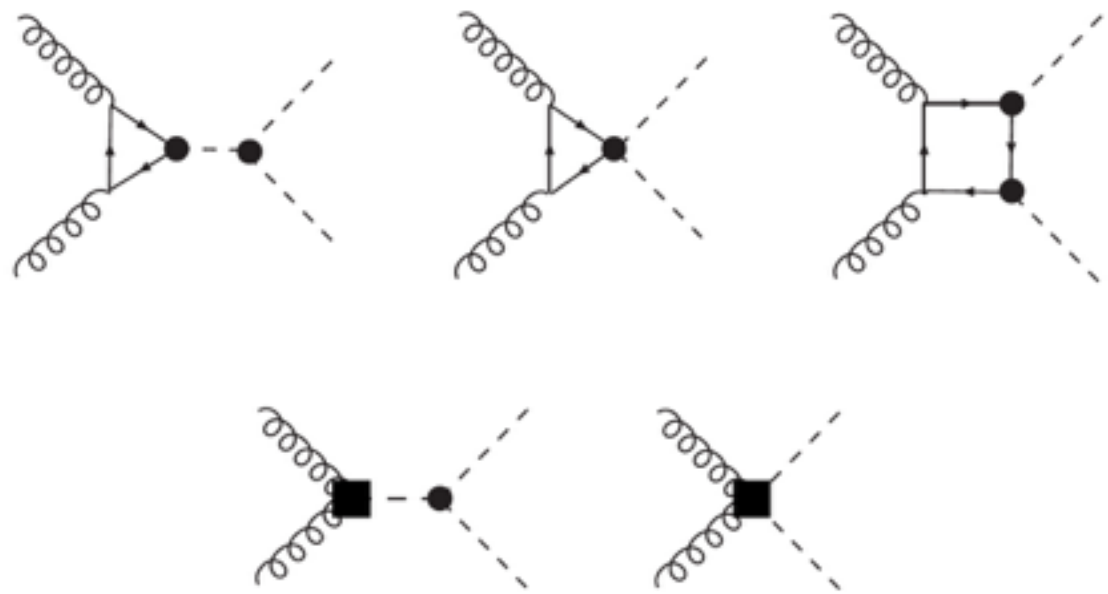
non-linear EFT calculation + NLO QCD

Buchalla, Capozi, Celis, GH, Scyboz '18

LO diagrams:

$d\chi \leq 4$

and $\mathcal{O}(g_s^2)$

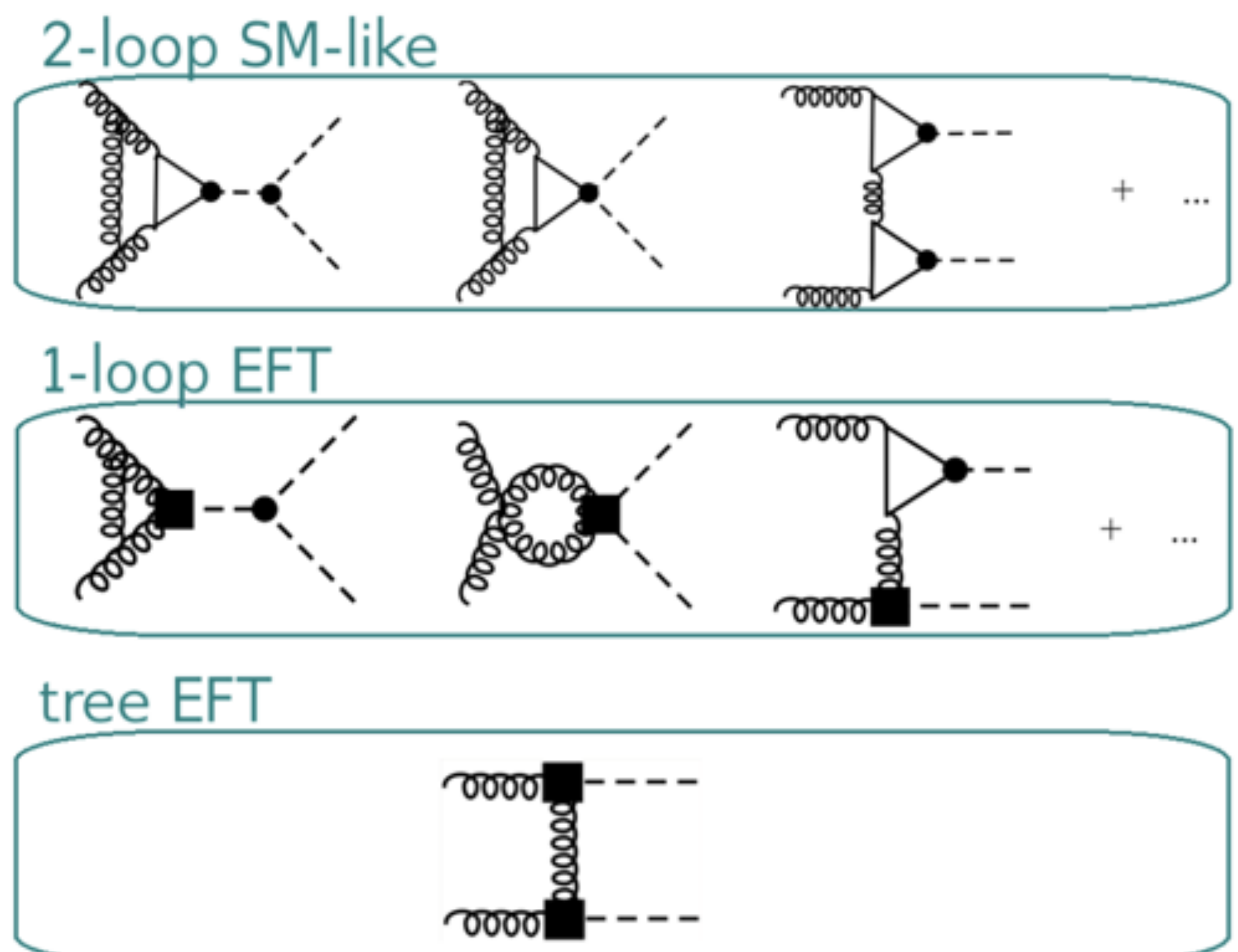


NLO diagrams:

(virtual corrections)

$d\chi \leq 6$ and

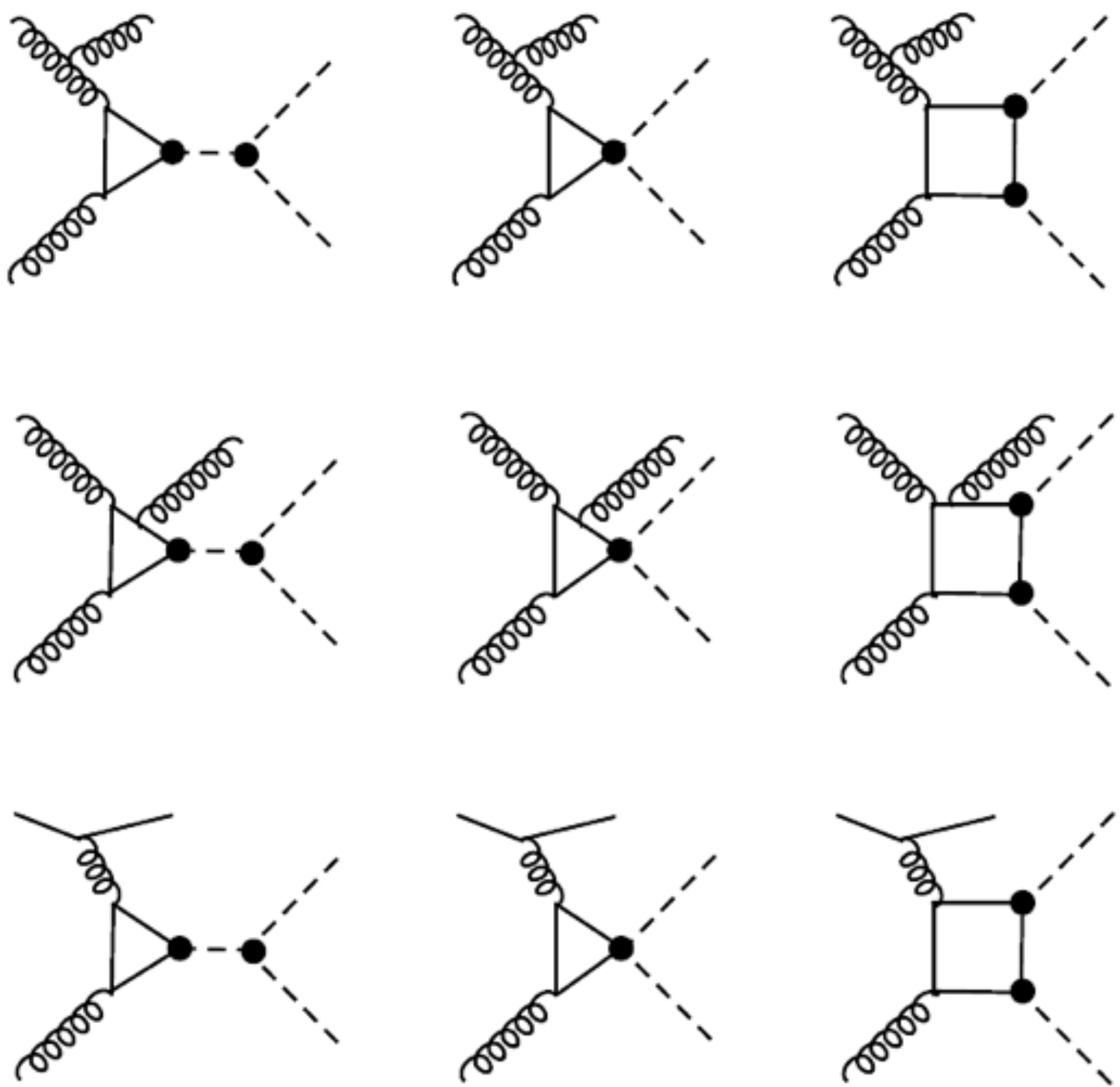
$\mathcal{O}(g_s^4)$ at diagram level



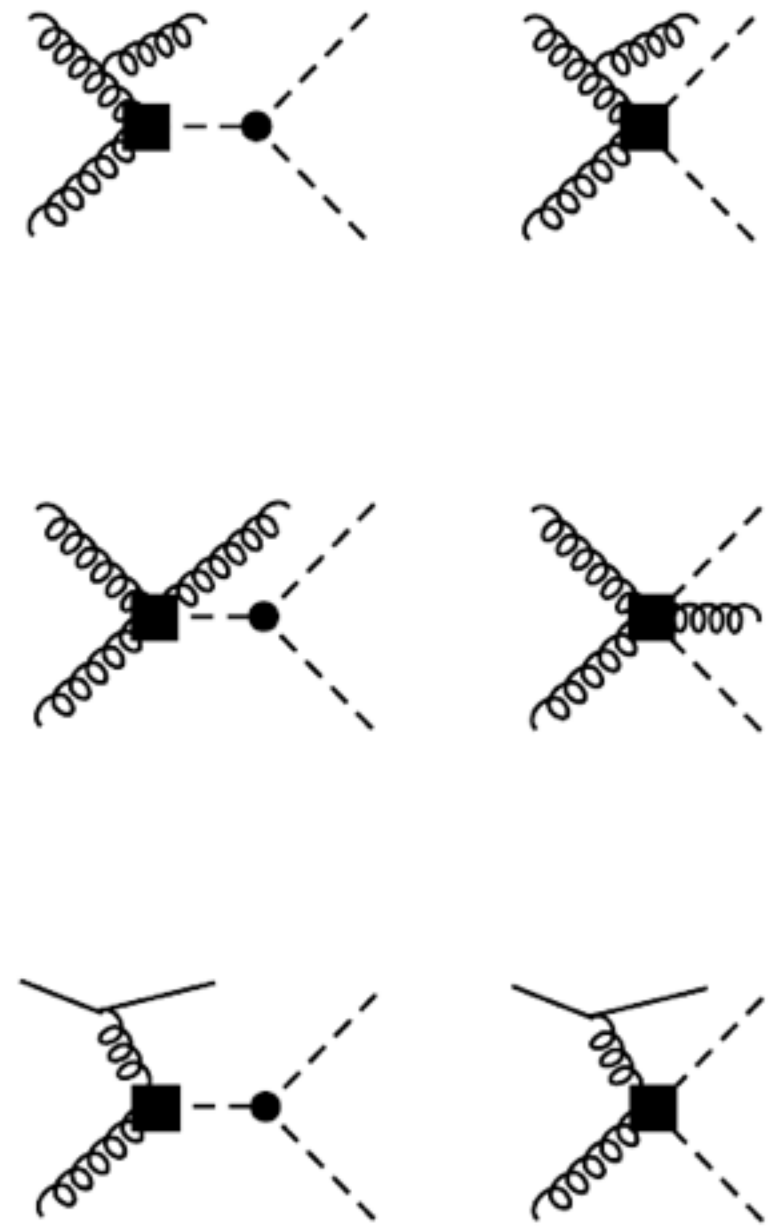
non-linear EFT calculation + NLO QCD

examples of NLO diagrams: real radiation corrections

5-point 1-loop diagrams



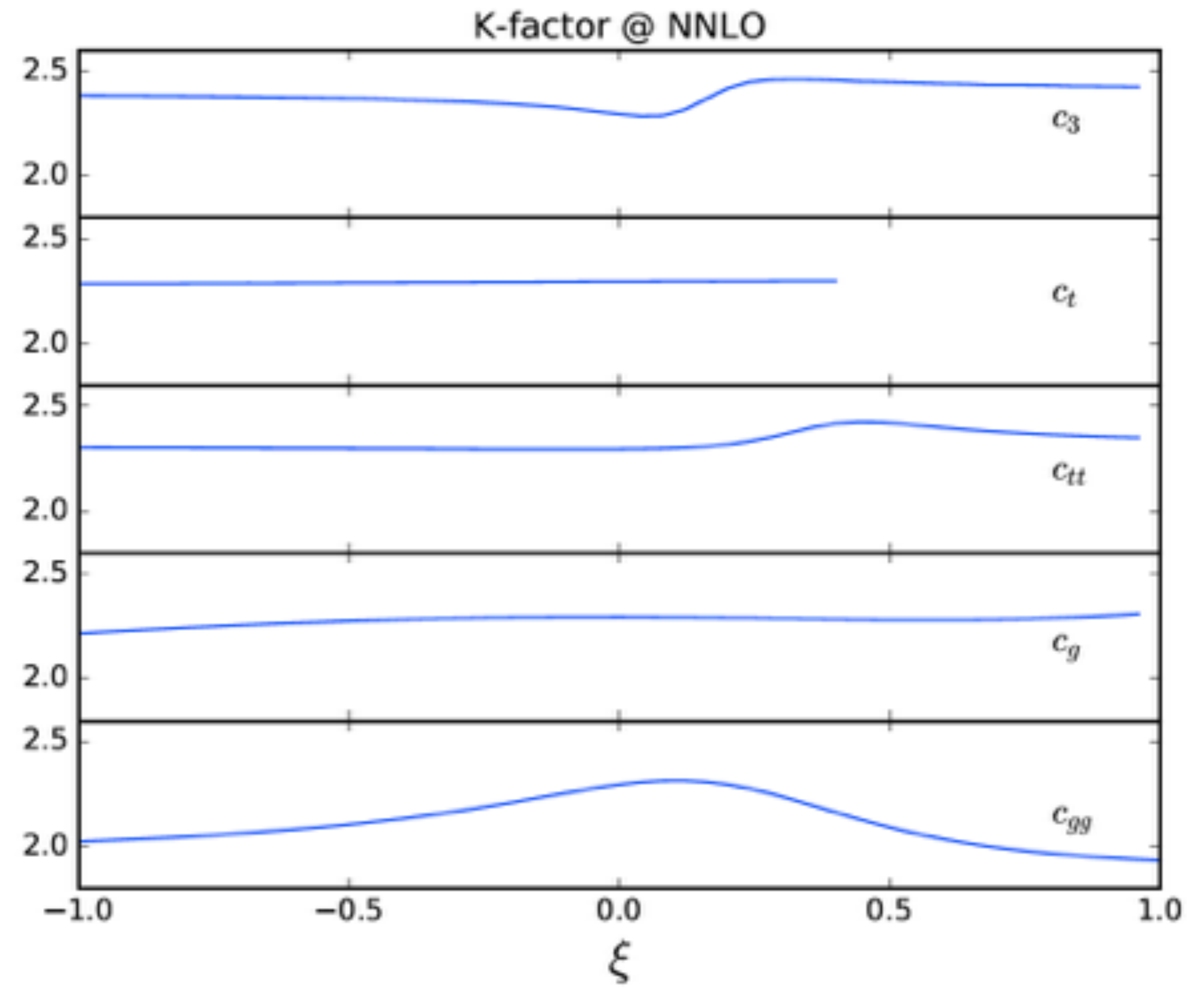
tree diagrams $\propto c_{ggh}$, c_{gghh}

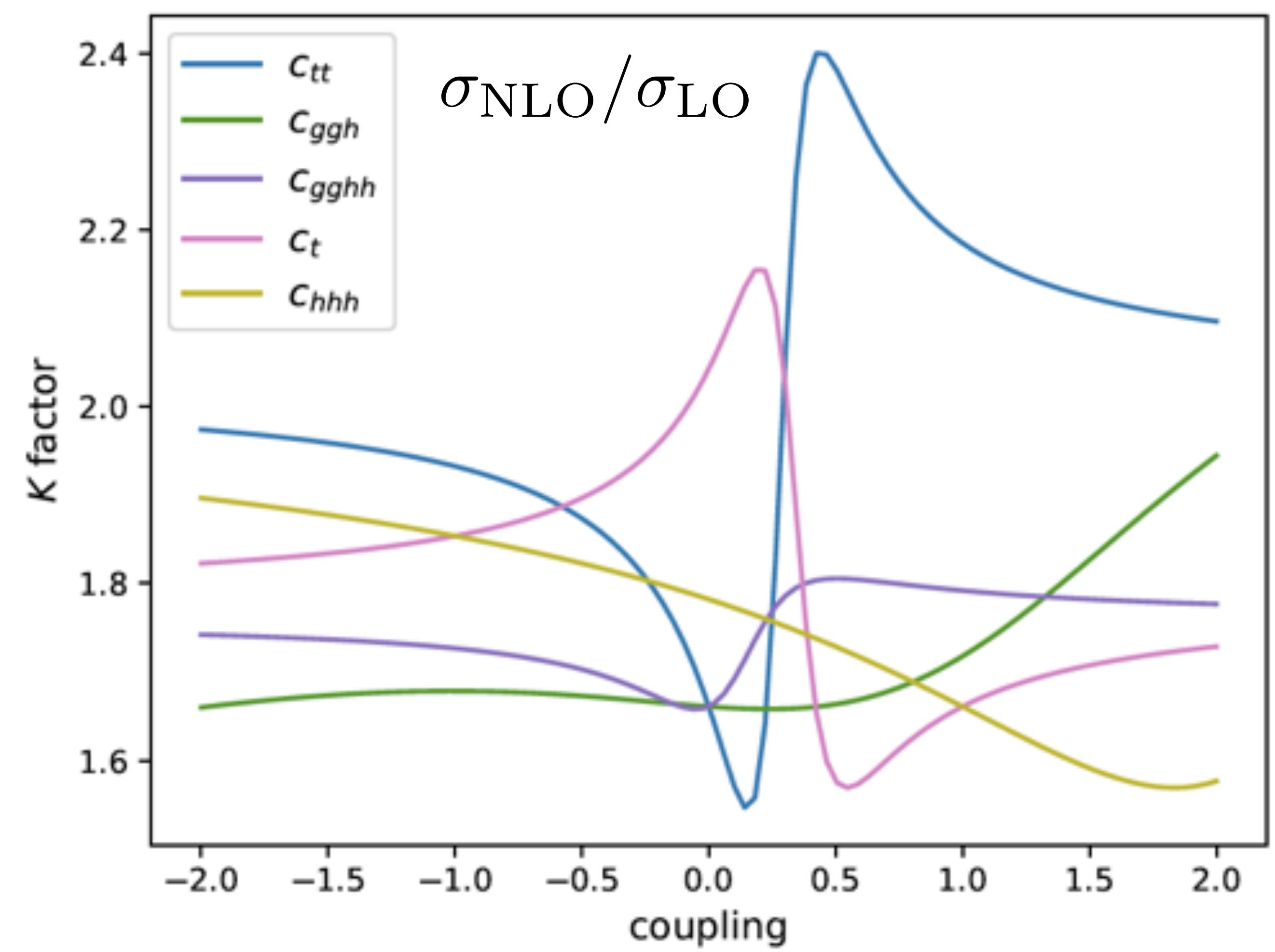


thanks: Ludovic Scyboz

non-linear EFT calculation + NLO QCD

K-factors $\sigma_{N(N)LO}/\sigma_{LO}$ as functions of the BSM couplings





NNLO rescaled HEFT $(m_t \to \infty)$

De Florian, Fabre, Mazzitelli '17

NLO with full m_t dependence

Buchalla, Capozi, Celis, GH, Scyboz '18

SM values: $\xi = 0$

$$\begin{aligned} c_3 &= 1 + 10\,\xi\,, \\ c_t &= 1 + 0.35\,\xi\,, \\ c_{tt} &= 1.5\,\xi\,, \\ c_g &= 0.15\,\xi\,, \\ c_{gg} &= 0.15\,\xi\,. \end{aligned}$$

top mass effects very important!

Summary & Outlook

- it is likely that New Physics is (currently) hiding in small deviations

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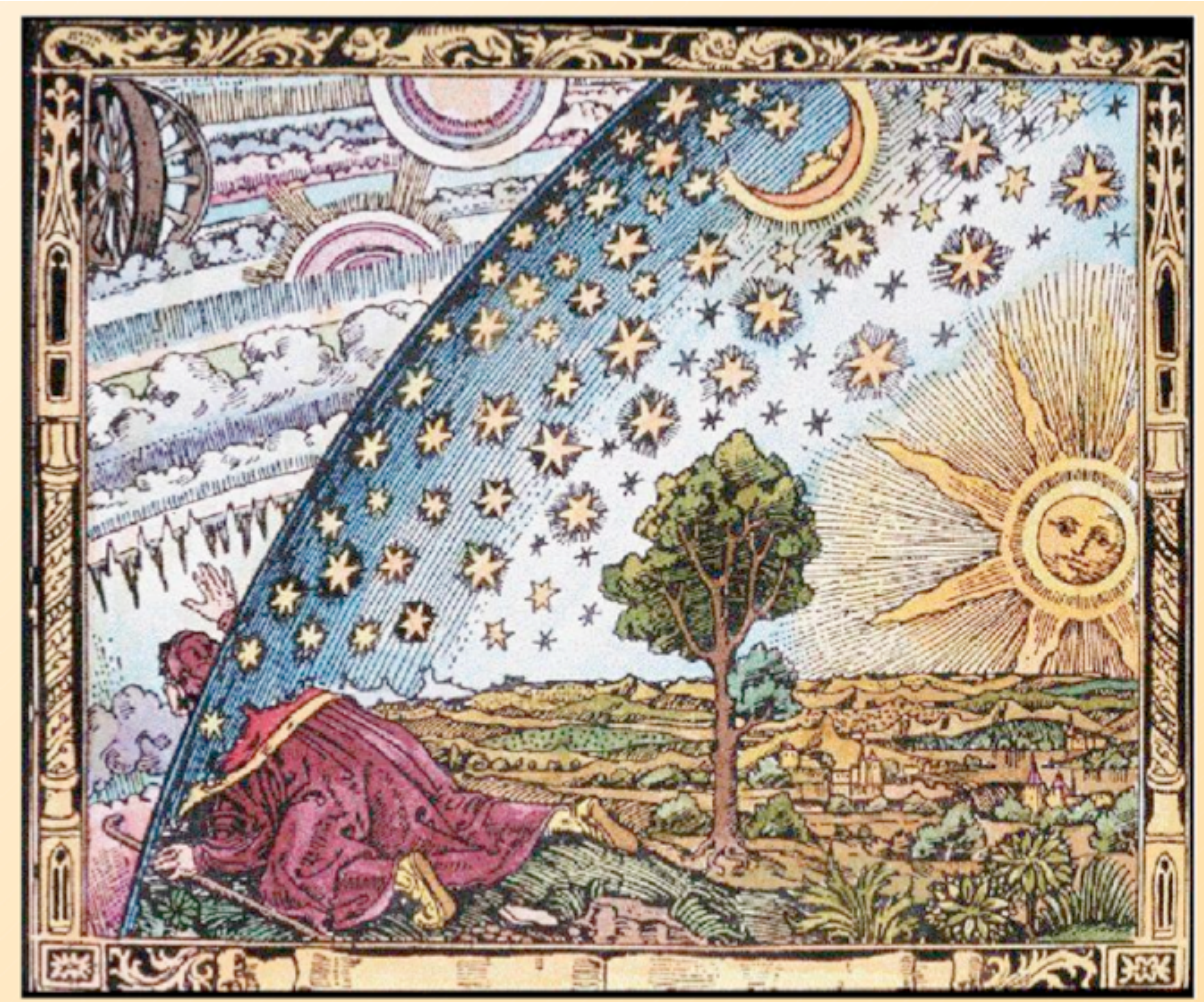
- other modified couplings also need to be taken into account $\longrightarrow$ requires global EFT analysis

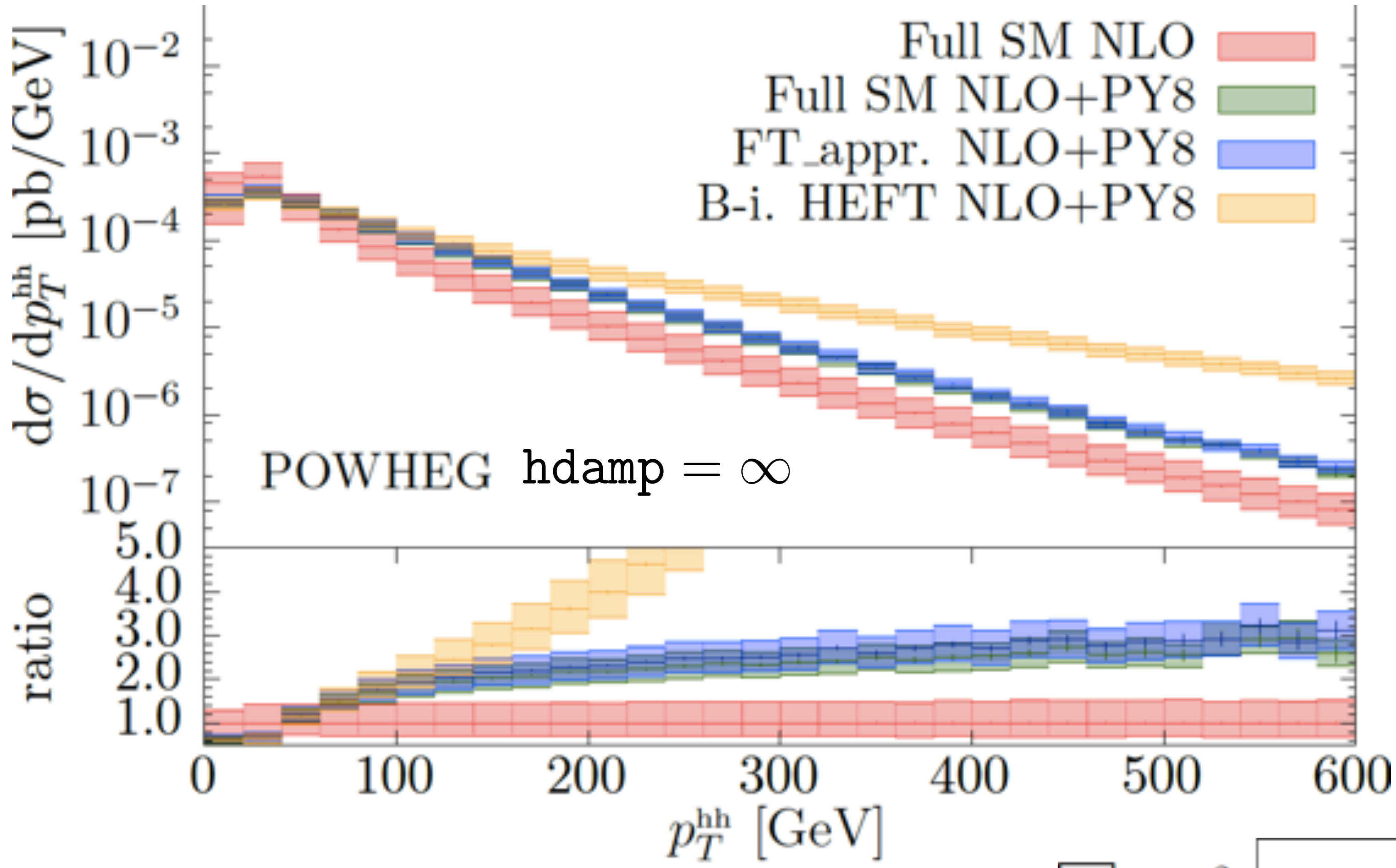
The Standard Model is unlikely to be the full picture

precision calculations/measurements
may uncover the unexpected !



BACKUP SLIDES

dependence on shower parameters

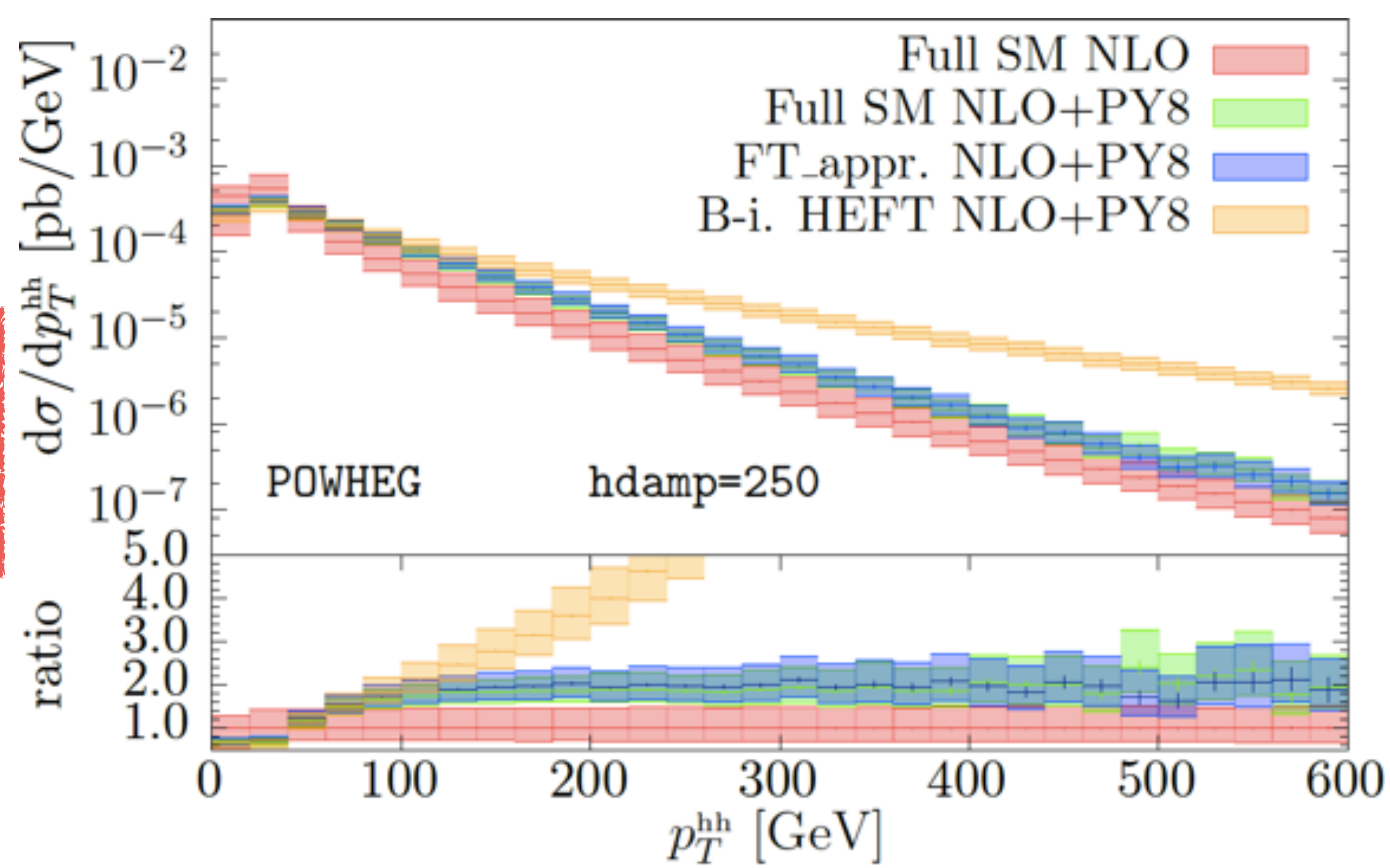


hdamp=h limits amount of exponentiated hard radiation

$$R_{\text{sing}} = R \times F\,,$$

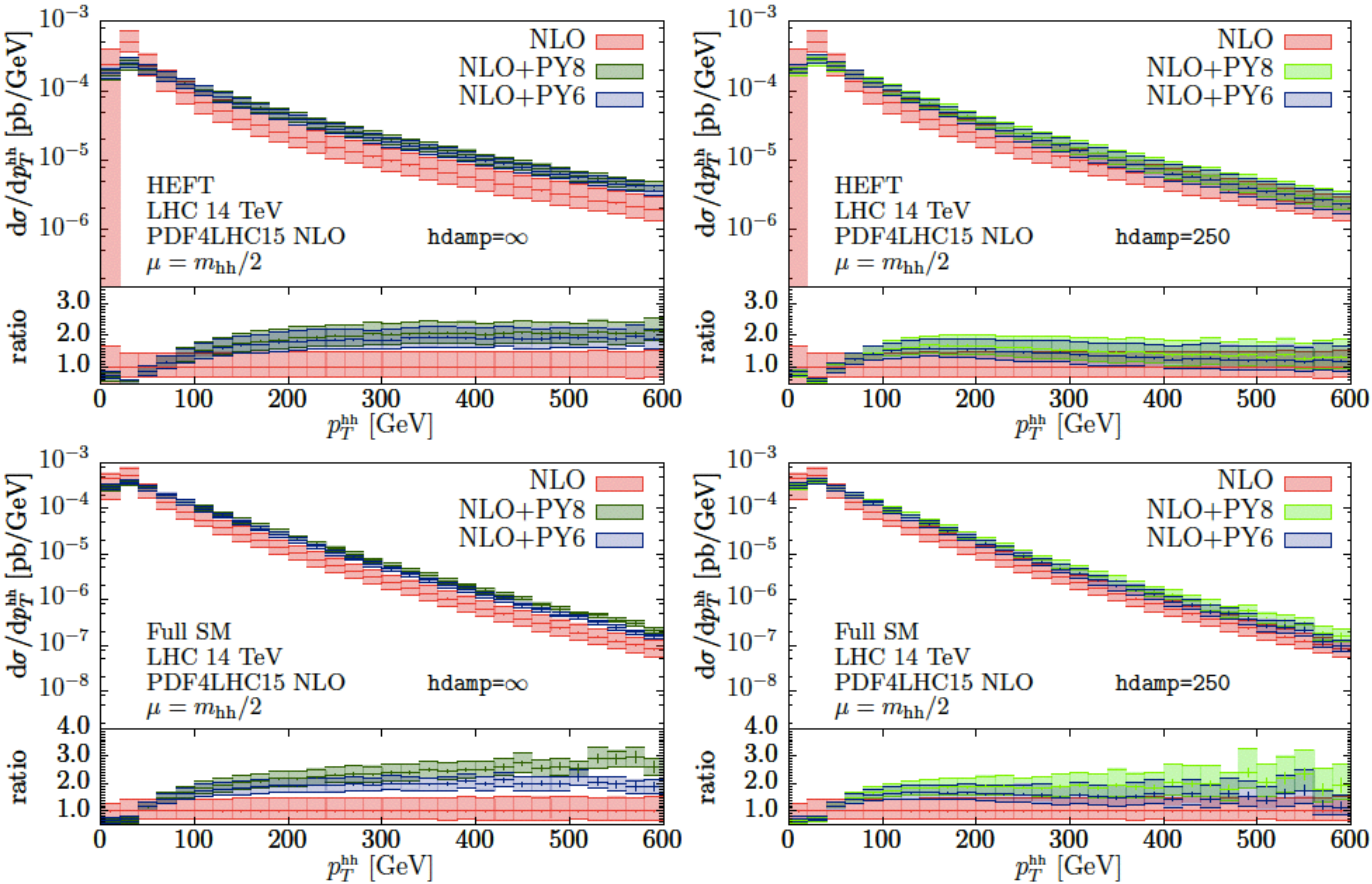
$$R_{\text{reg}} = R \times (1 - F)$$

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



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

compare Pythia6 and Pythia8



top quark mass effects

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

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

PDF4LHC15_nlo_30_pdfas HXSWG: $\sigma'_{NNLL} = \sigma_{NNLL} + \delta_t\, \sigma_{NLO}^{\mathrm{HEFT}} = 39.64^{+4.4\%}_{-6.0\%}$

m_H=125 GeV, m_t=173 GeV

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

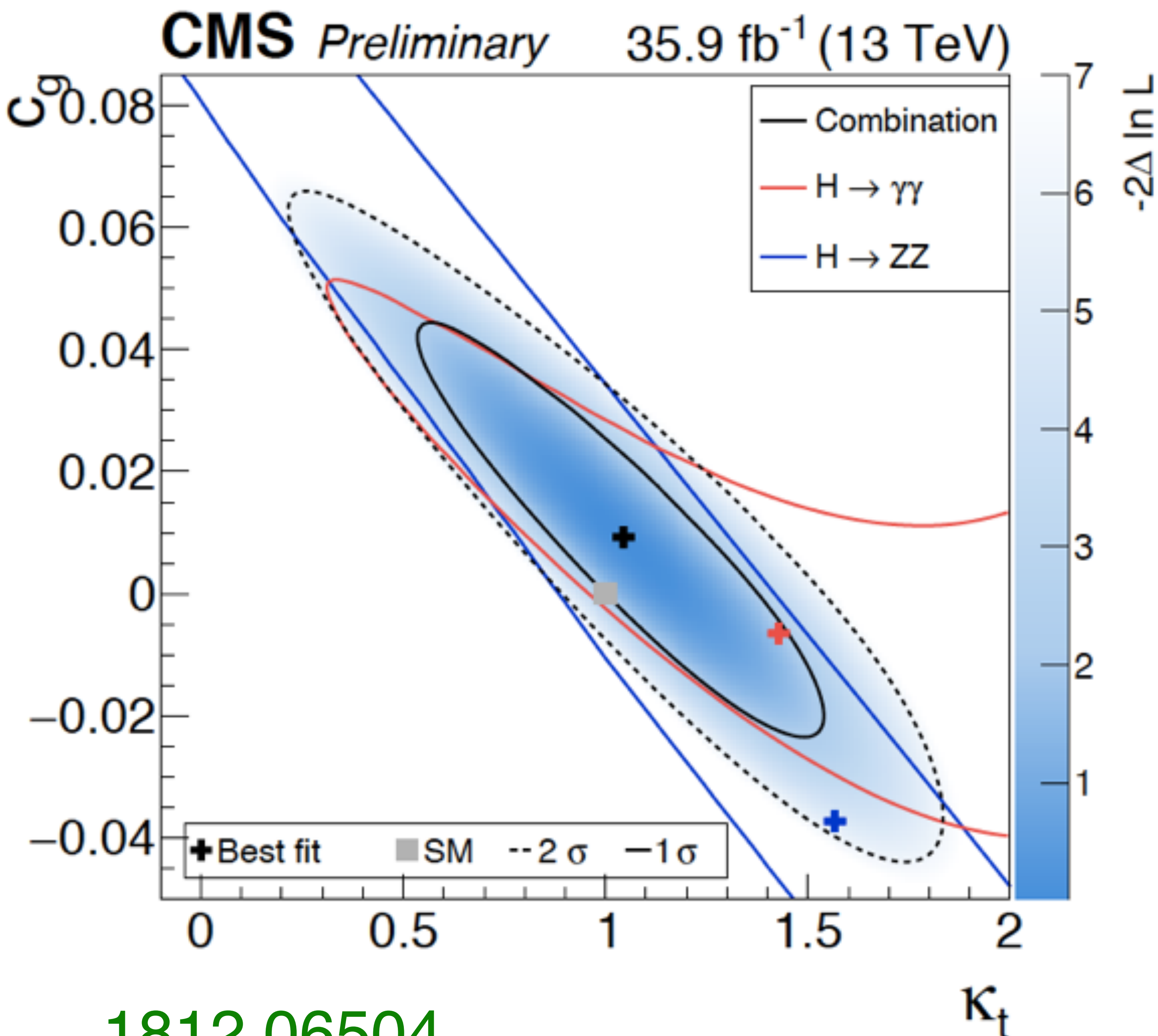
NNLO approximations

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO_{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO_{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\mathrm{NNLO_{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\mathrm{NNLO_{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\mathrm{NNLO_{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$	$\pm 4.6\%$
$\mathrm{NNLO_{FTapprox}/NLO}$	1.118	1.116	1.096	1.067

considerable reduction of scale uncertainties

M_t uncertainties:
half the difference between NNLO_FTapprox and NNLO_NLO-improved

constraints on cg and top Yukawa couplings



1812.06504

c_{ggh} and κ_t
are already quite well
constrained from other processes
(single Higgs, ttH)

Approximations

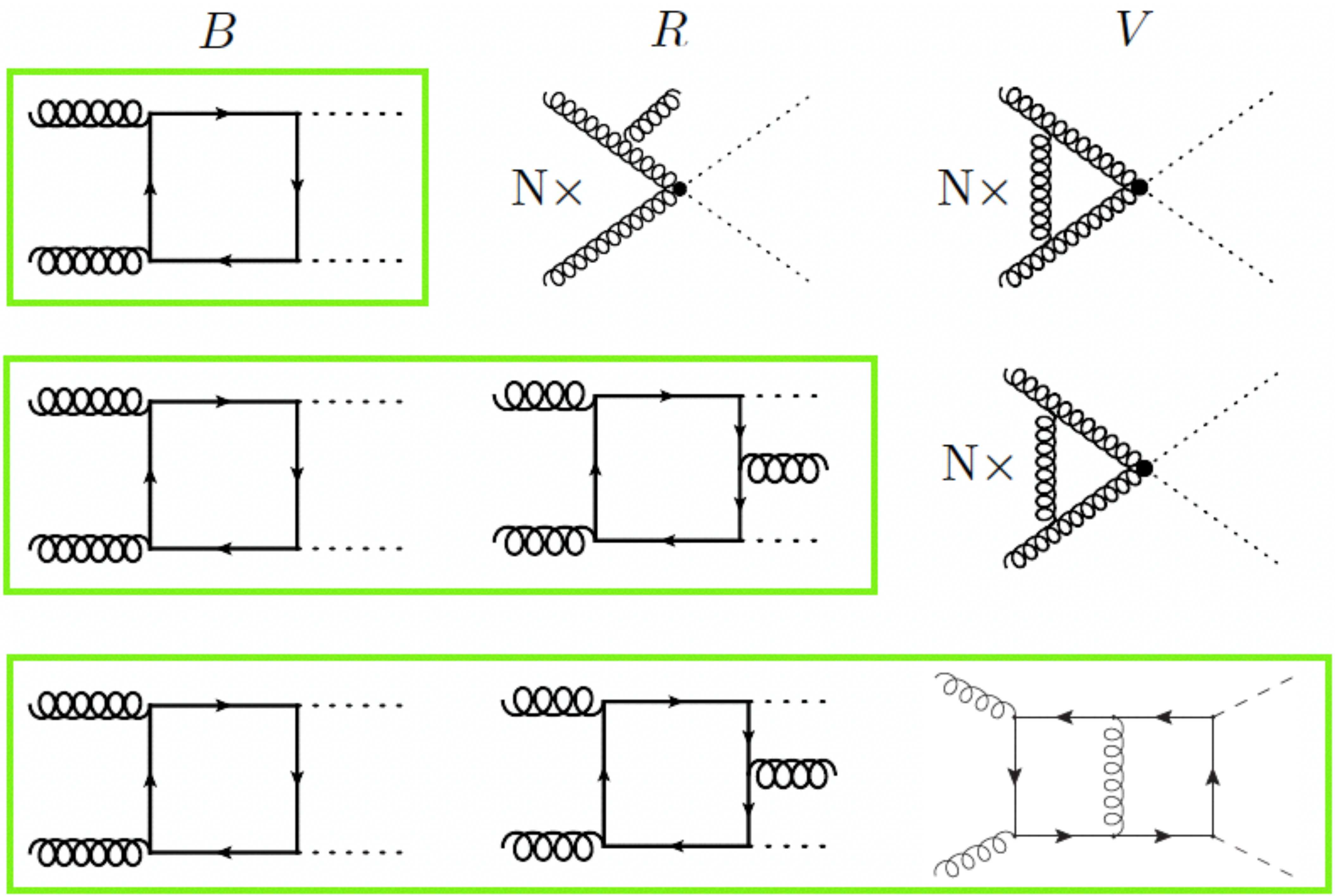
B-i HTL:

Dawson, Dittmaier, Spira 98

FTapprox:

Maltoni, Vryonidou, Zaro 14

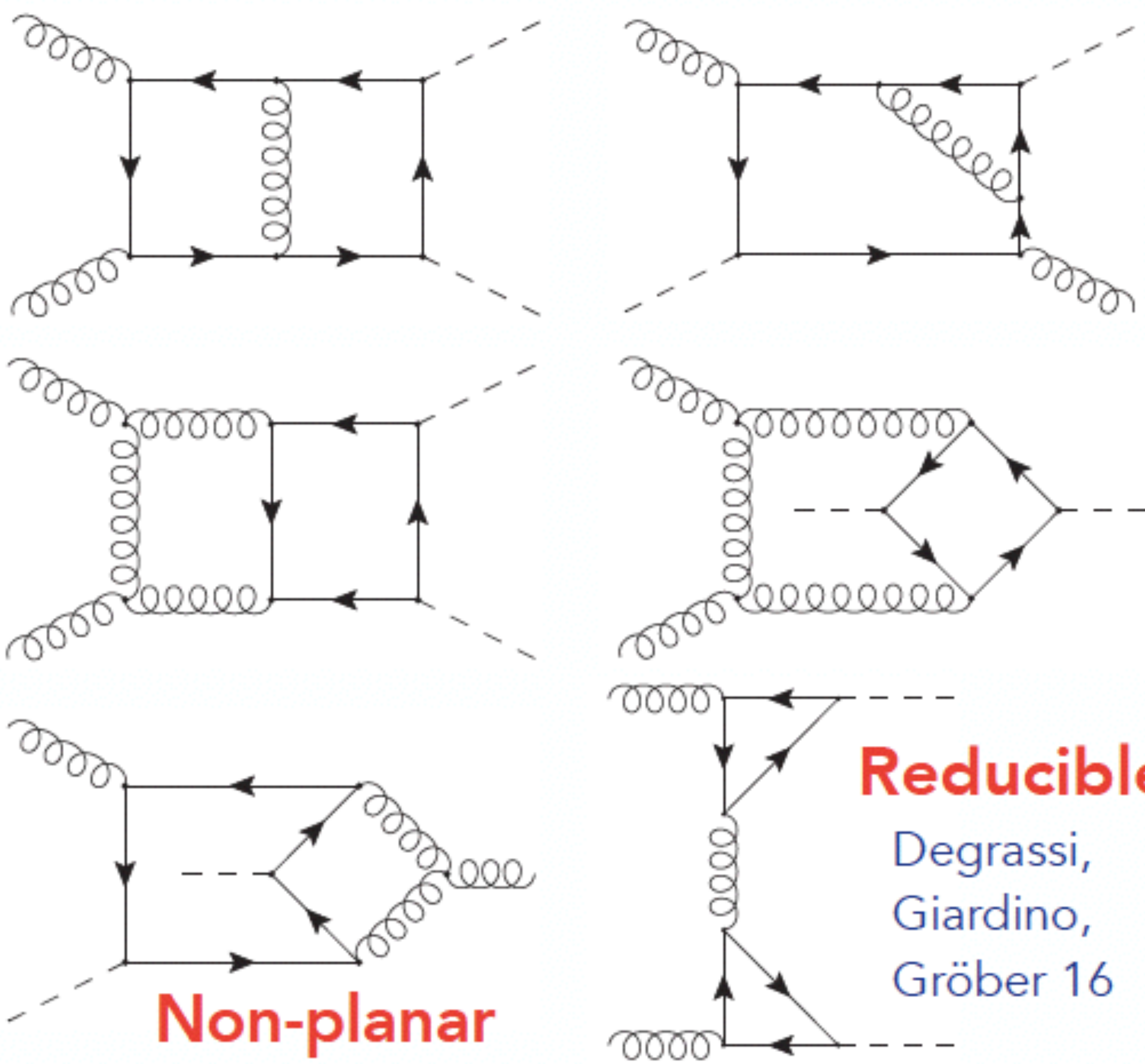
Full Theory:



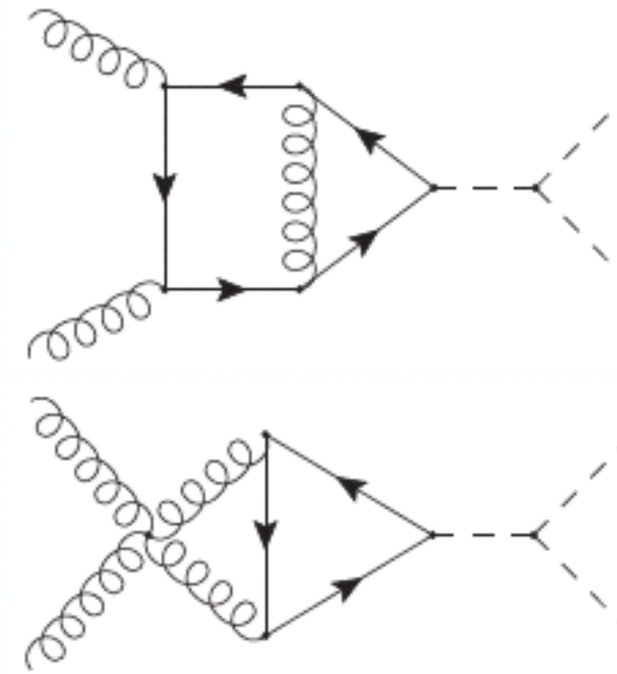
slide by Stephen Jones

Some two-loop integrals for gg to HH

Yukawa only (≤ 4-point)



Self-coupling (≤3-point)



Integrals Known
$gg \to H$

Spira, Djouadi et al. 93, 95;
Bonciani, P. Mastrolia 03,04;
Anastasiou, Beerli et al. 06;

slide by Stephen Jones

Many integrals not known analytically, except:

$H \to Z\gamma$ Bonciani, Del Duca, Frellesvig et al. 15; Gehrmann, Guns, Kara 15;

NLO automation

Monte Carlo program
- tree amplitudes
- infrared subtractions
- phase space integration/ event generation
- parton shower (optional)

BLHA or custom made

One-loop provider
- virtual amplitude

- Powheg
- Sherpa
- Herwig7/Matchbox
- Geneva
- Vincia

- Blackhat
- FeynArts
- GoSam
- Madloop
- NJet
- OpenLoops
- Recola

all in one:
- MG5_aMC@NLO
- Helac-NLO
- Grace

collection of pre-computed processes:
- MCFM
- VBFNLO