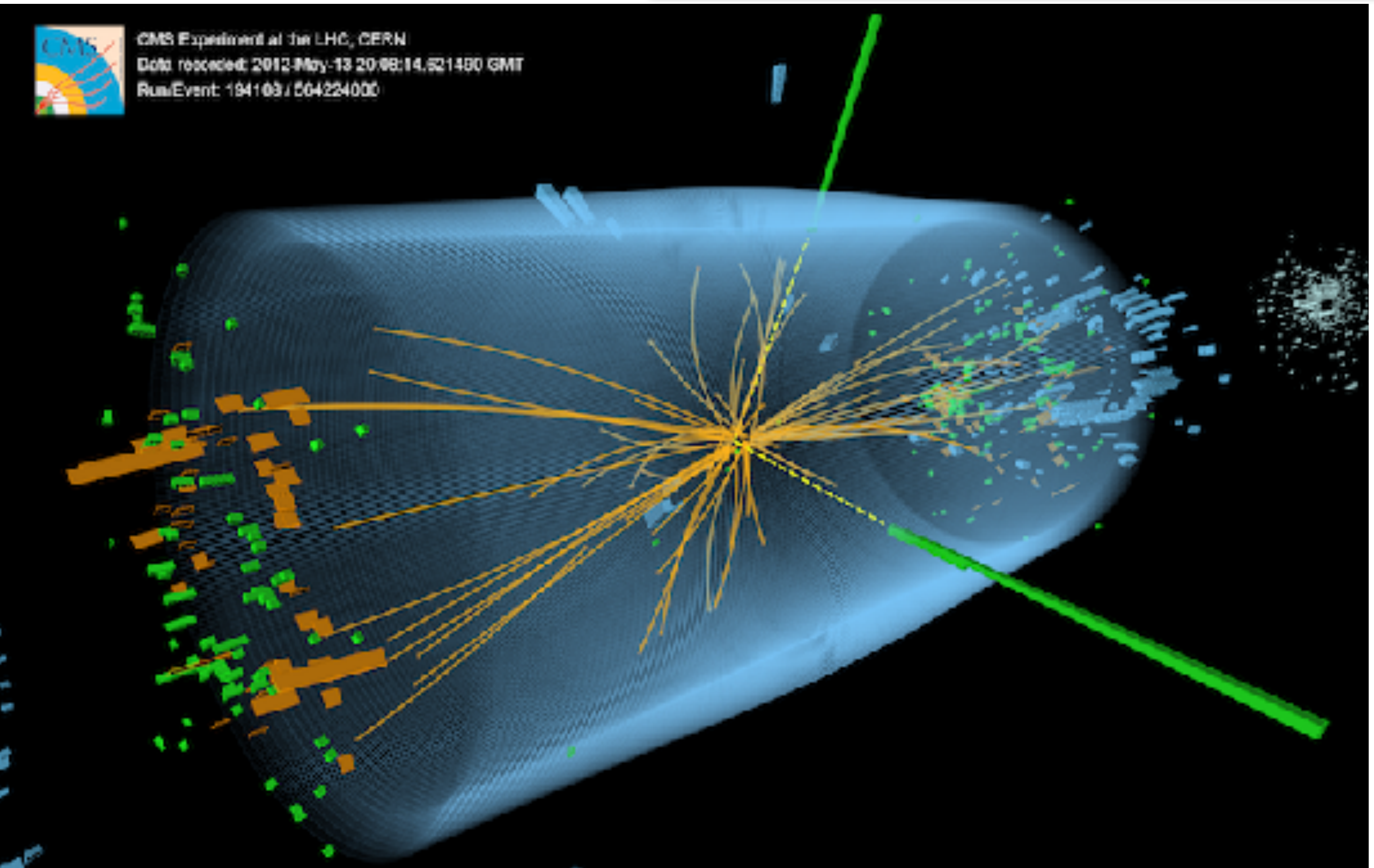
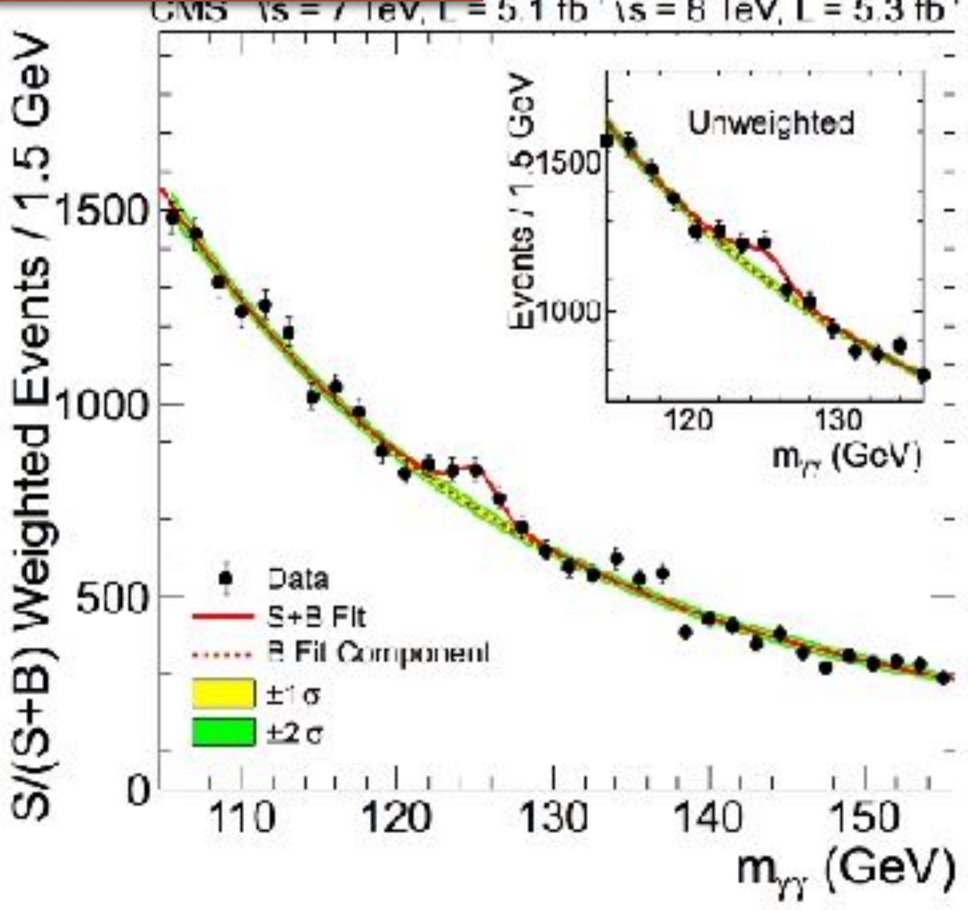
Precision physics in the LHC era

Pier Paolo Giardino

Brookhaven National Laboratory - 01/08/2020

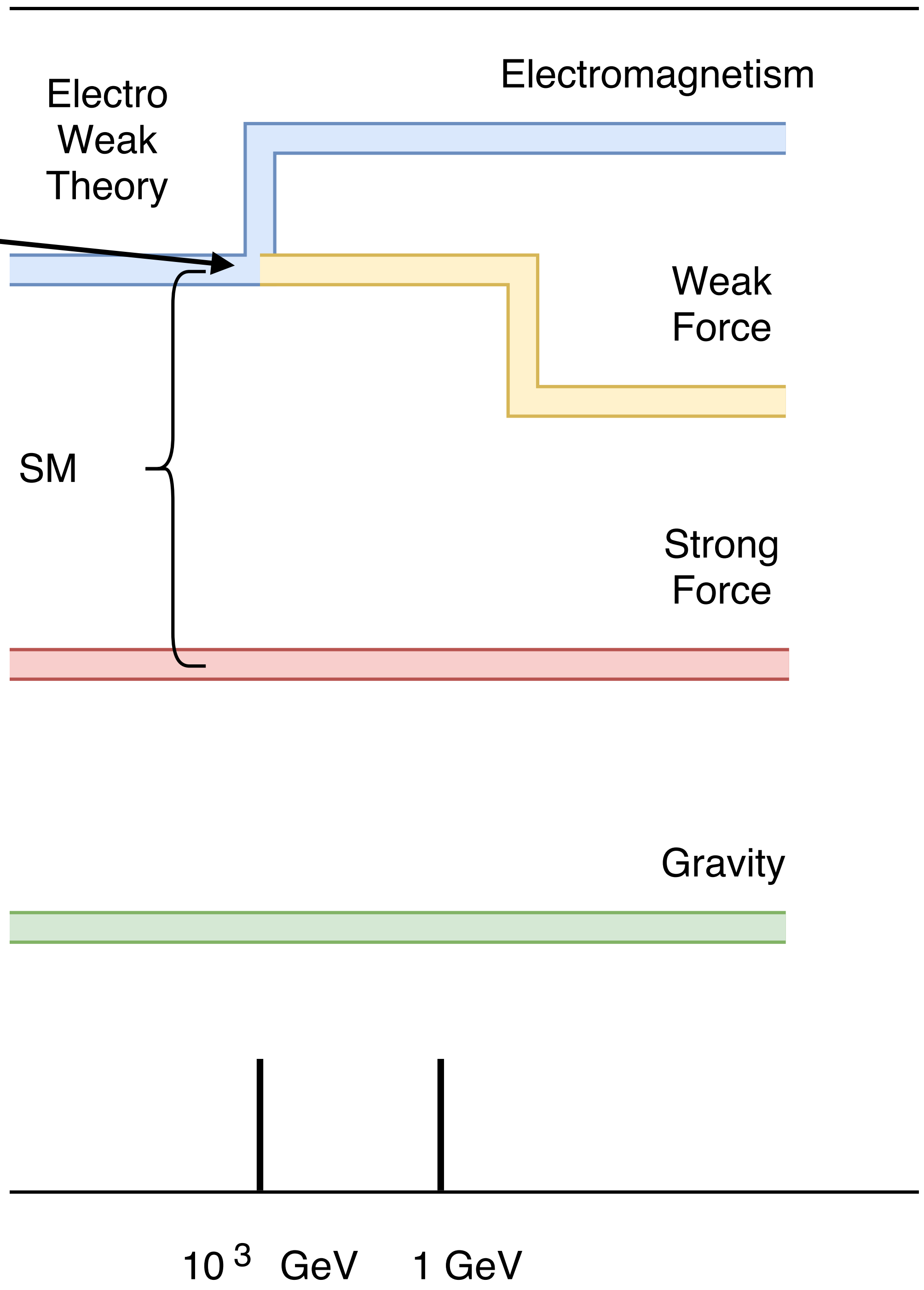
The Higgs boson was the last piece of the SM puzzle.

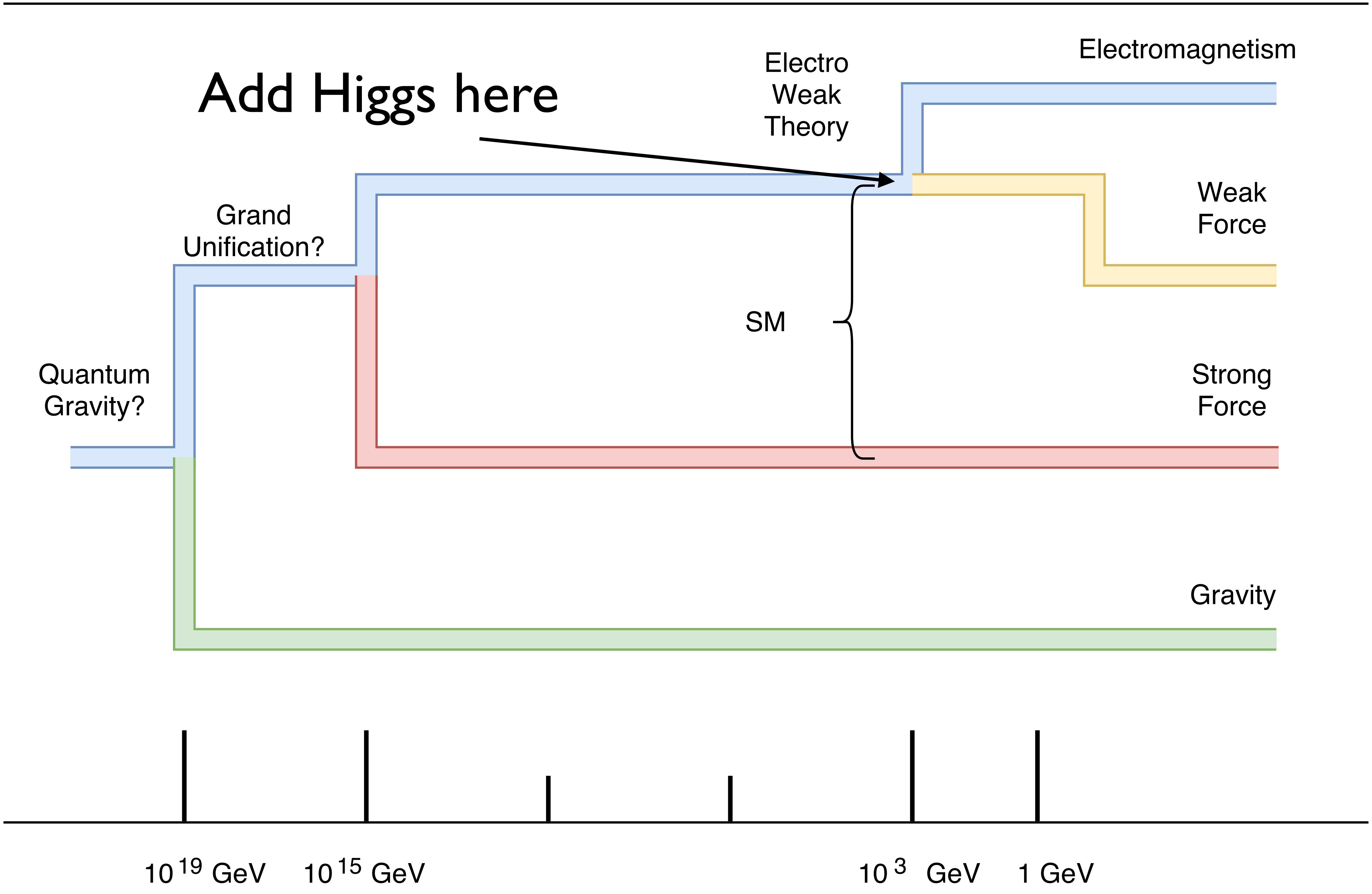




Add Higgs here

We have a good description of Nature up to ~1TeV




Add Higgs here
Electro
Weak
Theory
Electromagnetism
Weak
Force
Grand
Unification?
SM
Quantum
Gravity?
Strong
Force
Gravity
10^{19} GeV
10^{15} GeV
10^{3} GeV
1 GeV

Experimental evidence that SM needs NP

Neutrinos

Dark Matter

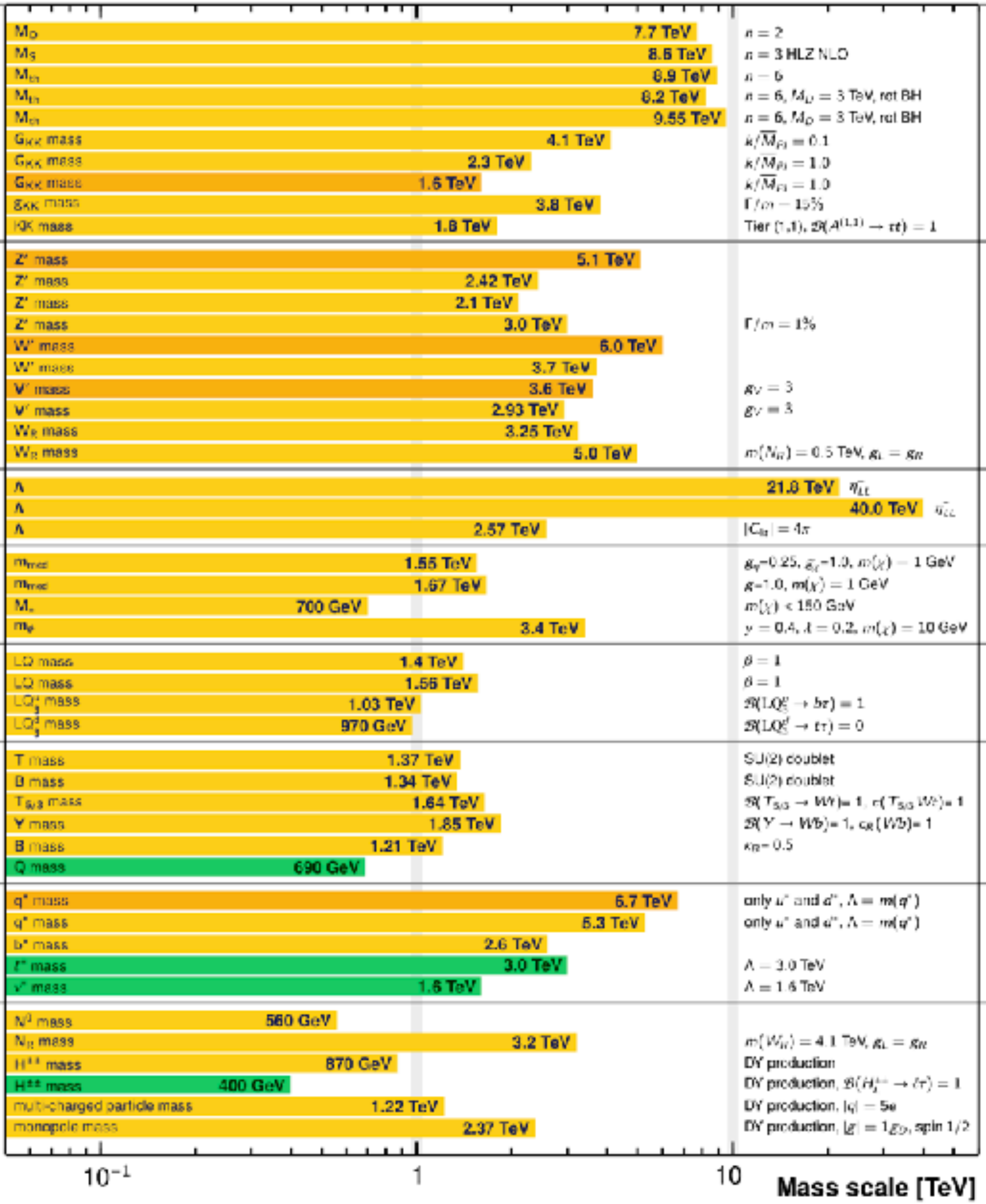
Baryon-Antibaryon asymmetry

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

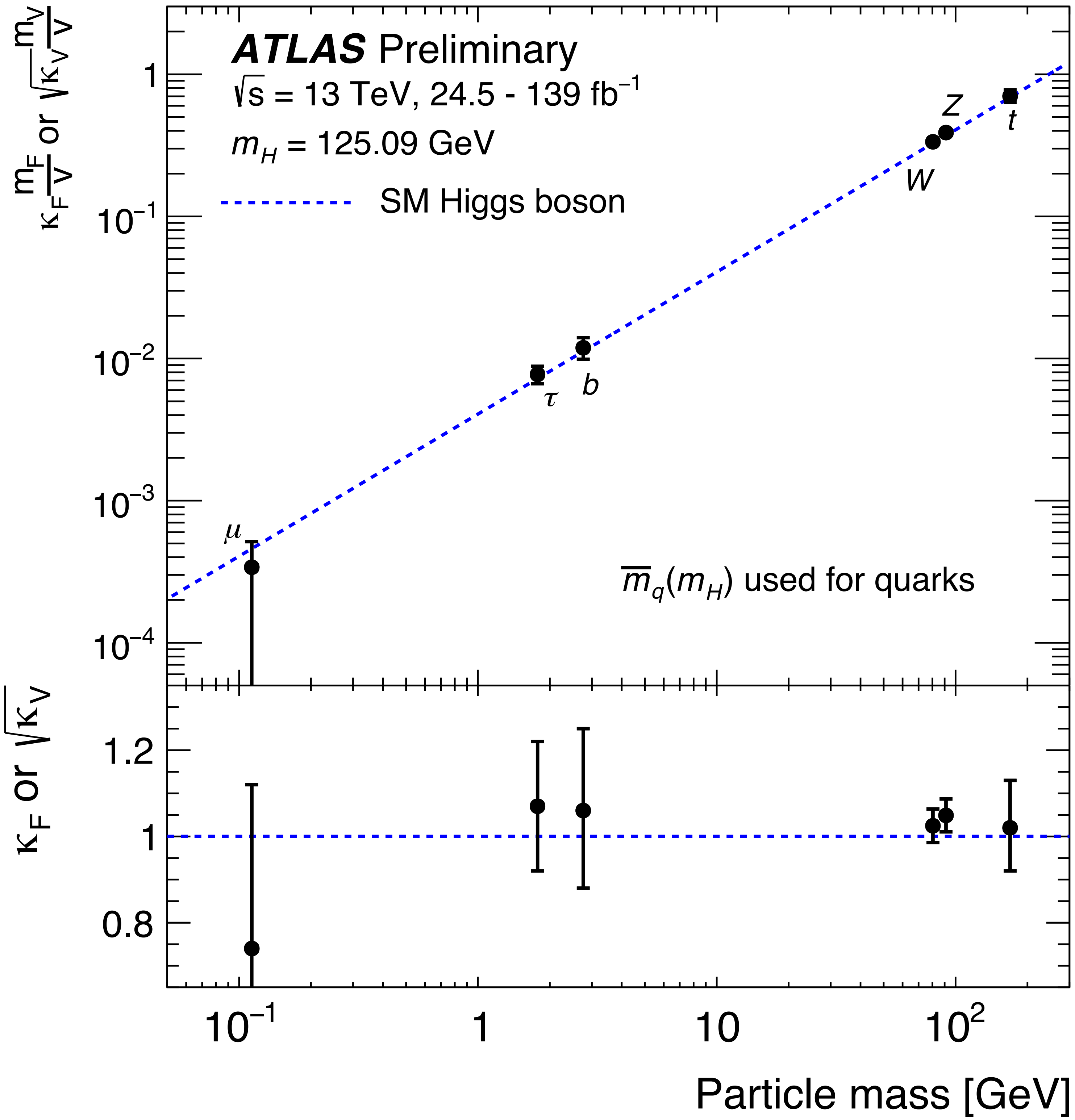
$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 − 4 j	Yes	36.1	M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$	0 e, μ	2 J	–	139	G_{KK} mass	1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	139	W' mass	6.0 TeV		CERN-EP-2019-100
	SSM $W' \rightarrow \tau\nu$	1 τ	–	Yes	36.1	W' mass	3.7 TeV		1801.06992
	HVT $V' \rightarrow WZ \rightarrow qqqq$ model B	0 e, μ	2 J	–	139	V' mass	3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \rightarrow tb$	multi-channel			36.1	W_R mass	3.25 TeV		1807.10473
	LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ	40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\|C_{4t}\| = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV_{\chi\chi}$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass	1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass	1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass	1.03 TeV	$\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass	970 GeV	$\mathcal{B}(LQ_3^d \rightarrow t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel			36.1	T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\|T_{5/3} \rightarrow Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \rightarrow Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \rightarrow Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \rightarrow WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	–	2 j	–	139	q* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	36.7	q* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	36.1	b* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass	1.22 TeV	DY production, $\|q\| = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\|g\| = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).



The Higgs appears to be quite standard (?)

There is still space to for NP to appear

$$\mathscr{L}_{\phi} = (y\bar{\psi}\psi\phi + h.c.) + |D_{\mu}\phi|^{2} + V(\phi)$$

Fermion masses and couplings $\sim 15\ \%$

Vector bosons masses and couplings $\sim 8\ \%$

Higgs potential Not directly measured

In this talk I would like to address the following points:

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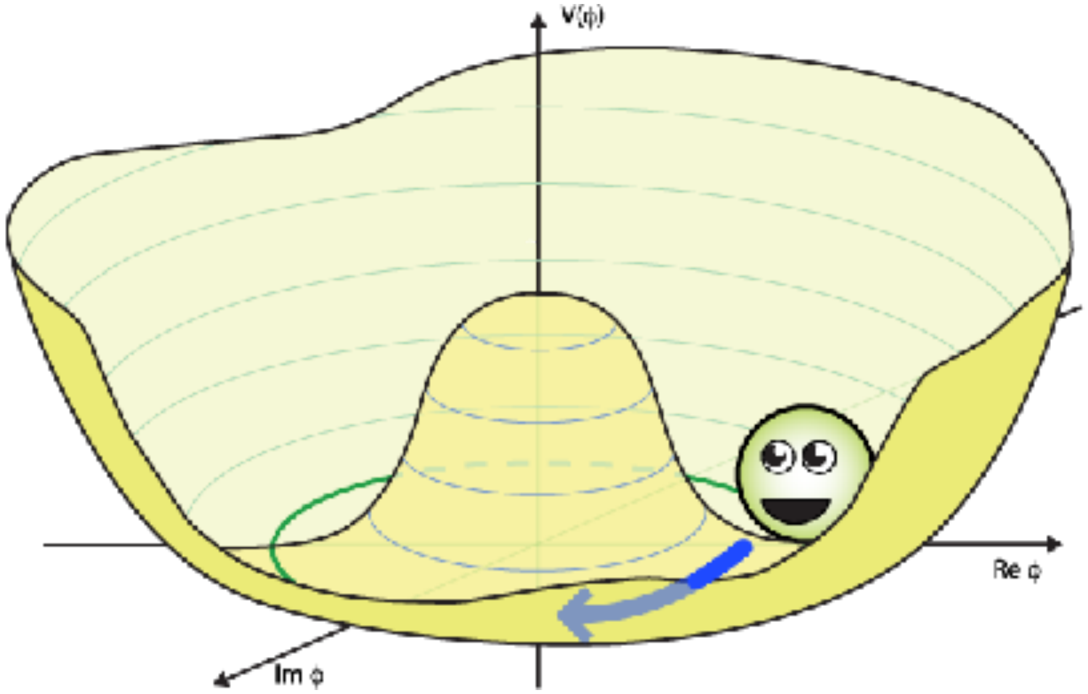
- Precise measurements can tell us something about NP even if LHC doesn't find a bump.
- Precise theoretical predictions are equally important.
- The Higgs sector is a particularly interesting place for these studies.



$$V(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

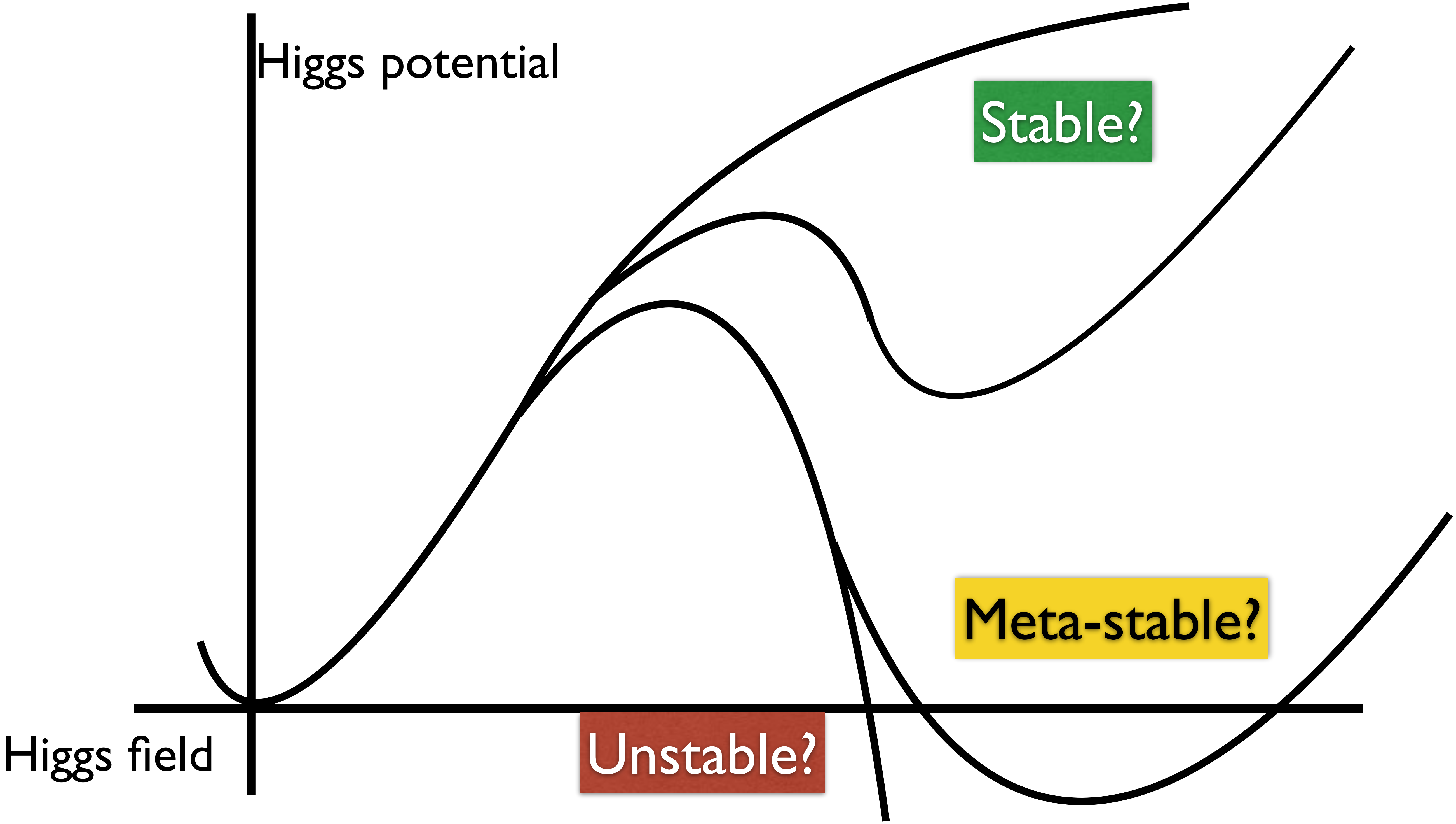
$$V(H) = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

The Higgs potential at low energy has the nice "bottom of a champagne bottle" shape.

But what is its shape at high energies?

And why do we care?

Stability of the EW vacuum



An unstable potential would mean the end of the physics (and chemistry and biology) that we know

What is the Higgs potential at high energies?

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What is the Higgs potential at high energies?

At high energy we can ignore v

$$V(H) = \frac{1}{2}(2\cancel{\lambda v^2})H^2 + \cancel{\lambda v}H^3 + \frac{1}{4}\lambda H^4 \longrightarrow$$

What is the Higgs potential at high energies?

At high energy we can ignore v

$$V(H) = \frac{1}{2}(2\cancel{\lambda v}^2)H^2 + \lambda\cancel{v}H^3 + \frac{1}{4}\lambda H^4 \quad \Longrightarrow \quad \boxed{V(H) \sim \frac{1}{4}\lambda H^4}$$

We just need to know how λ behaves

We want to know how the SM parameters behave at high energy: solve a bunch of first order DE (RGE)

$$(4\pi)^2 \frac{dg}{d\ln\mu} = \beta_g$$

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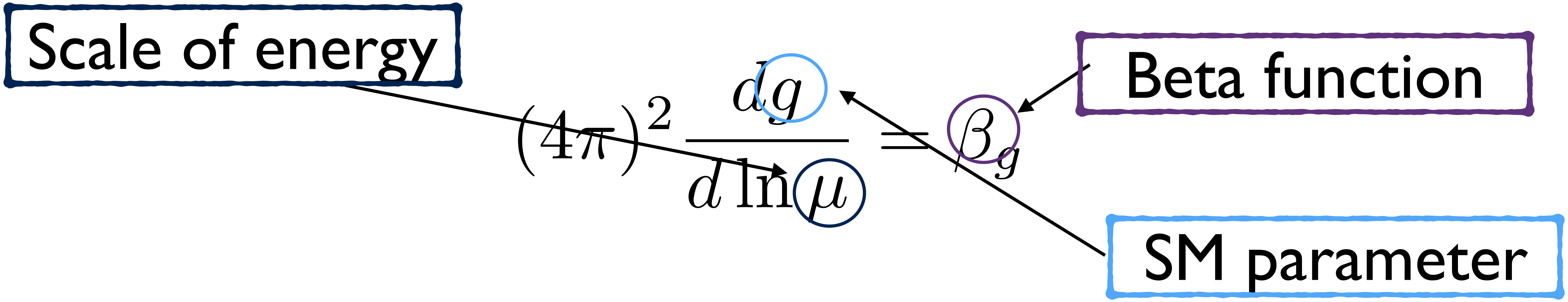

Scale of energy

$$(4\pi)^2 \frac{dg}{d\ln\mu} = \beta_g$$

Beta function

SM parameter

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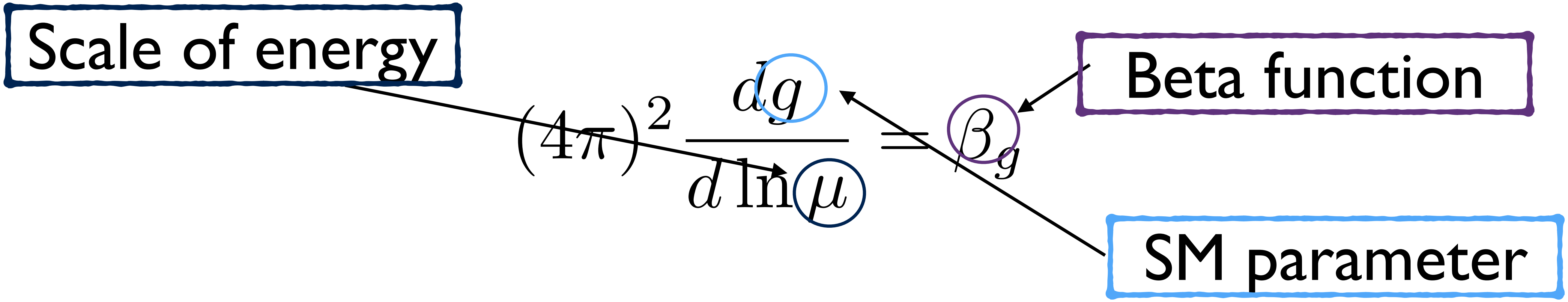

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$$\beta_g \propto g^n \rightarrow g \neq 0$$

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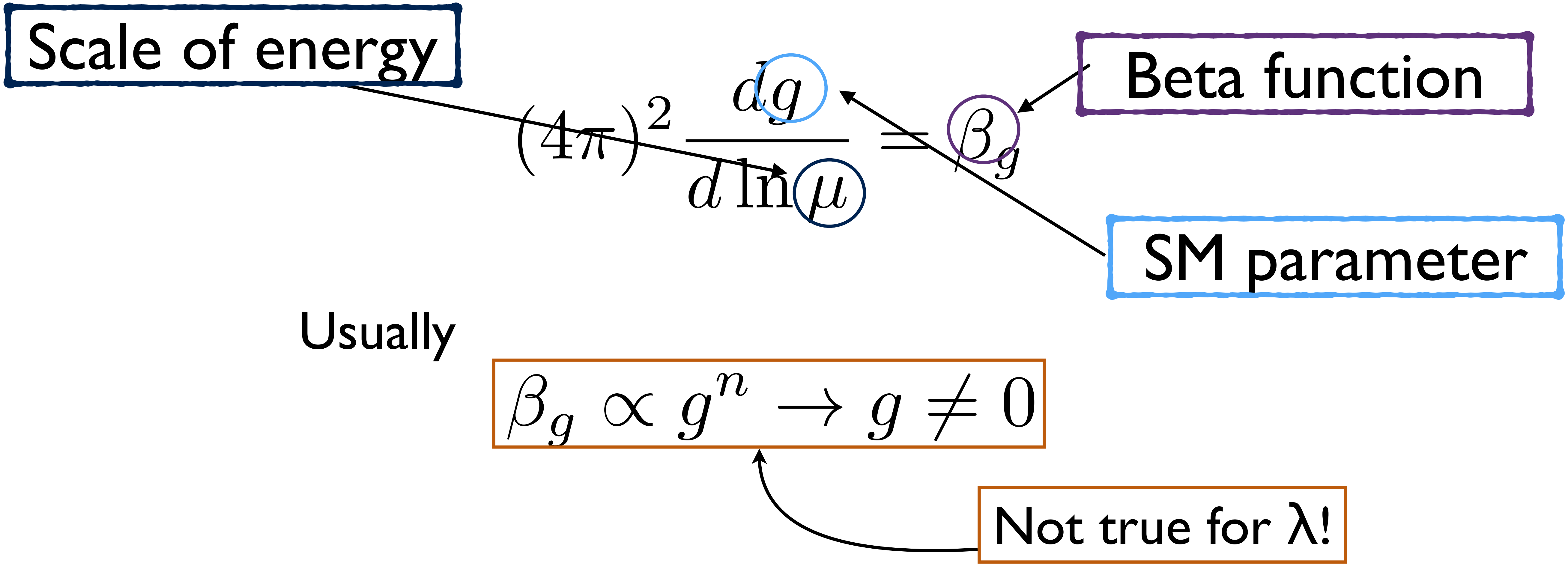

Scale of energy

$$(4\pi)^2 \frac{dg}{d\ln\mu} = \beta_g$$

Beta function

SM parameter

Usually

$$\boxed{\beta_g \propto g^n \rightarrow g \neq 0}$$

Not true for λ!

$$(4\pi)^2 \frac{d\lambda}{d\ln\mu} = \beta_\lambda$$

$$(4\pi)^2 \frac{d\lambda}{d\ln\mu} = \enclose{circle}{\beta_\lambda}$$

$$\enclose{circle}{\beta_\lambda} = 24\lambda^2 - 6y_t^4 + \cdots$$

$$(4\pi)^2 \frac{d\lambda}{d\ln\mu} = \beta_\lambda$$

$$\beta_\lambda = 24\lambda^2 - 6y_t^4 + \cdots$$

If the Higgs is too heavy λ becomes non perturbative at high energies

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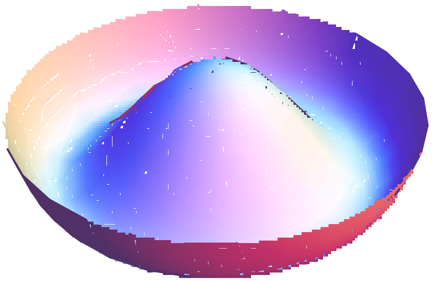
If the Top is too heavy λ becomes negative at high energies

If the Higgs is too heavy λ becomes non perturbative at high energies

$$(4\pi)^2 \frac{d\lambda}{d\ln\mu} = \boxed{\beta_\lambda}$$

$$\boxed{\beta_\lambda} = \boxed{24\lambda^2} - \boxed{6y_t^4} + \cdots$$

If the Top is too heavy λ becomes negative at high energies



your Champagne bottle

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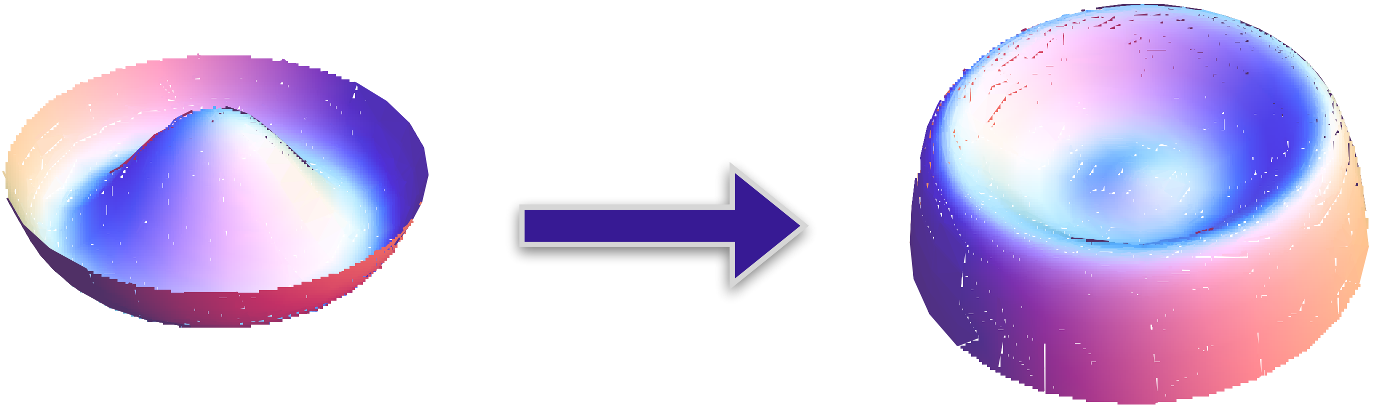

your Champagne bottle becomes a dog bowl

Where are we?

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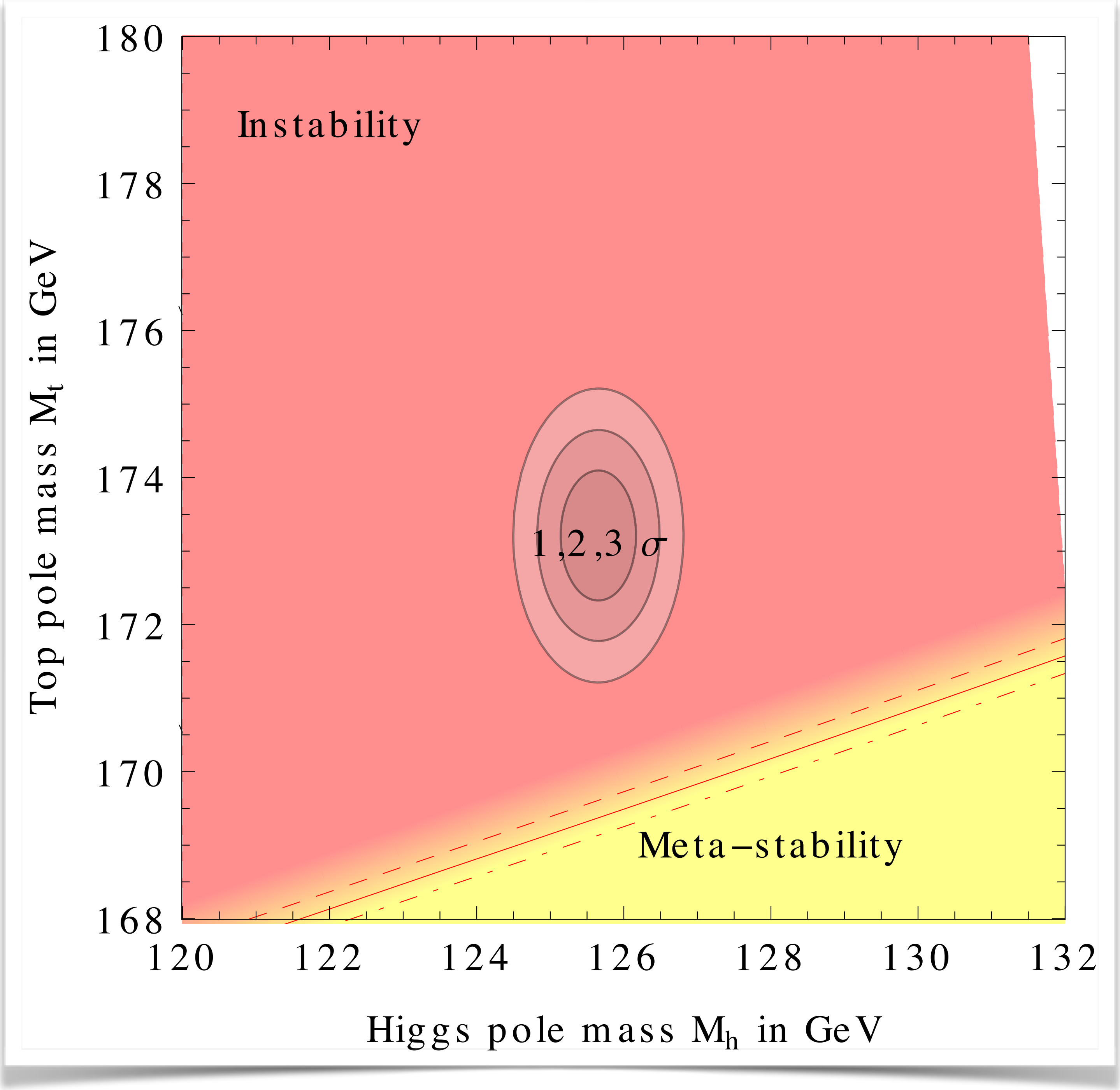
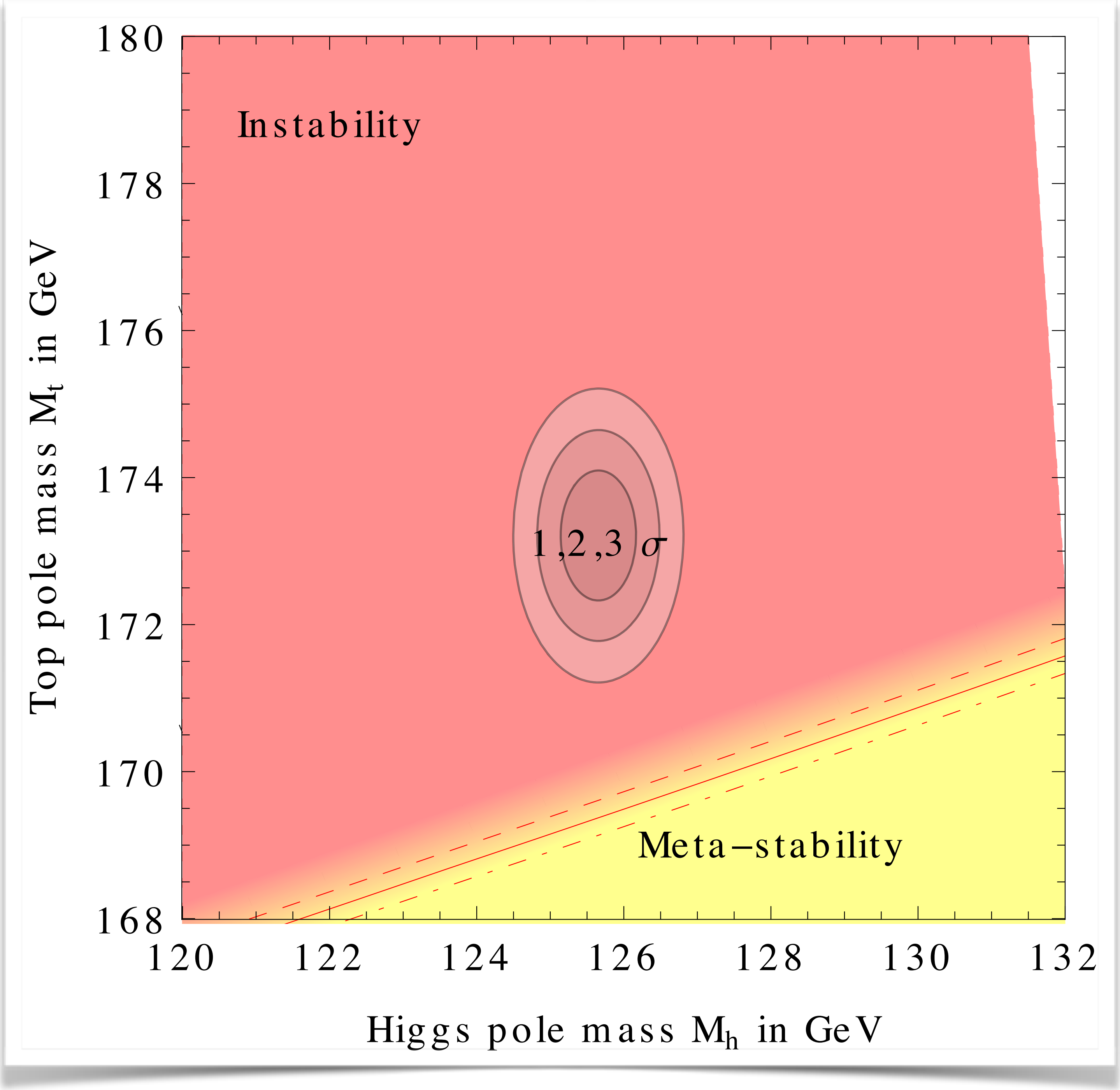

Instability
Meta−stability
1,2,3 σ
180
178
176
174
172
170
168
120
122
124
126
128
130
132
Top pole mass M_t in GeV
Higgs pole mass M_h in GeV

Where are we?



Unfortunately
this is only the first order of a perturbative expansion…

We need the perturbative corrections to the beta functions.

- LO QCD: Gross, Wilczek 73; Politzer 73;
- NLO SM: Fischler, Hill 81; Jones 82; Fischler, Oliensis 82; Machacek, Vaughn 83, 84, 85; Jack, Osborn 84, 85; Ford, Jack, Jones 92; Luo, Xiao 03;
- NNLO: Mihaila, Salomon, Steinhauser 12; Bednyakov, Pikelner, Velizhanin 12, 13; Chetyrkin, Zoller 12, 13;
- NNNLO: van Ritbergen, Vermaseren, Larin 97; Chakon 05; Zoller 15; Martin 15; Chetyrkin, Zoller 15;

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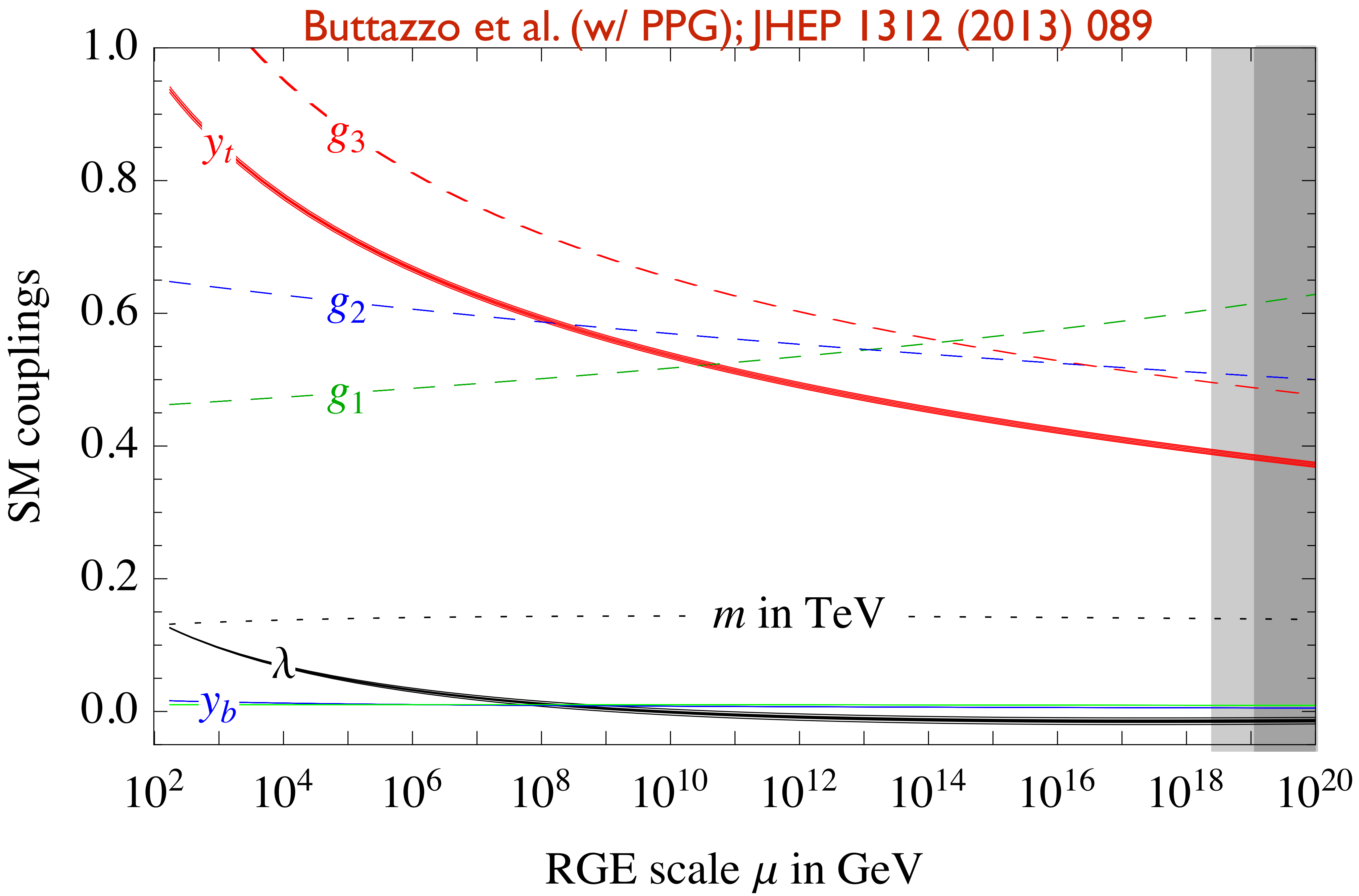

We are still not done

A system of differential equations needs initial conditions.

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$$M_H^2 = 2\lambda v^2$$

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Very difficult to measure

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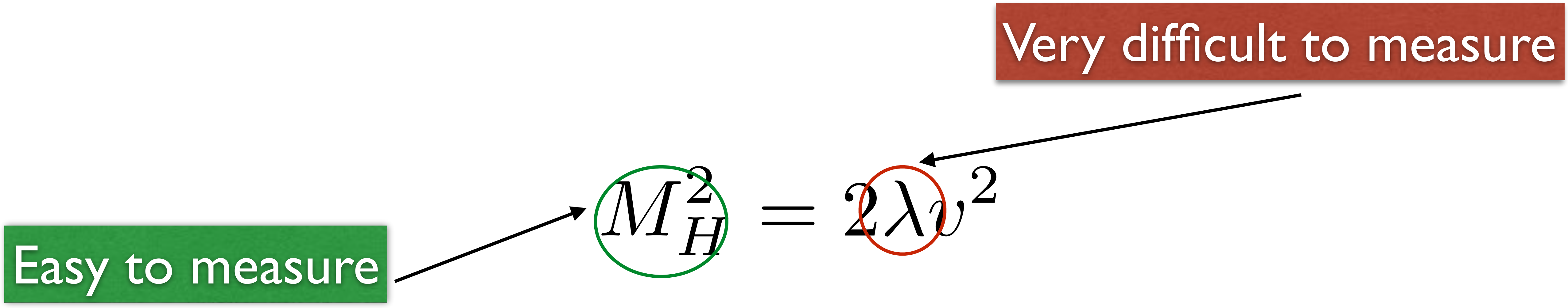

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Easy to measure

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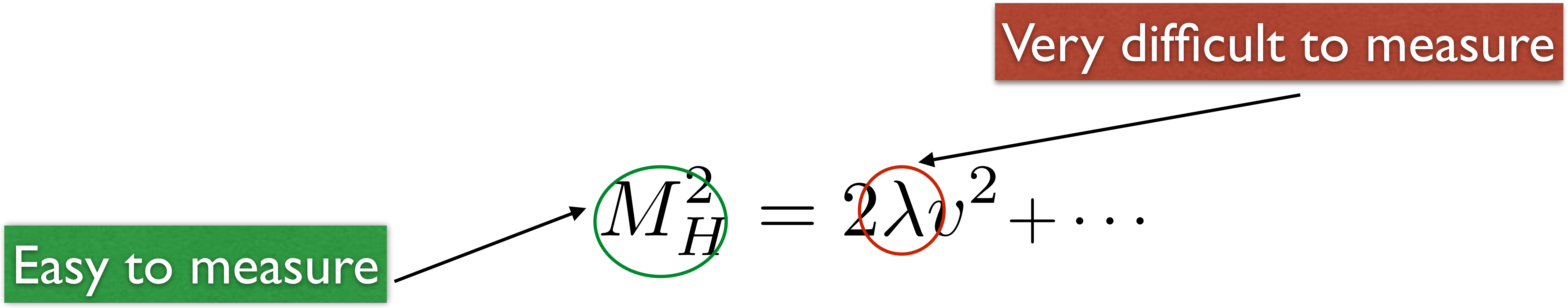


Very difficult to measure

Easy to measure

$$M_H^2 = 2\lambda v^2 + \cdots$$

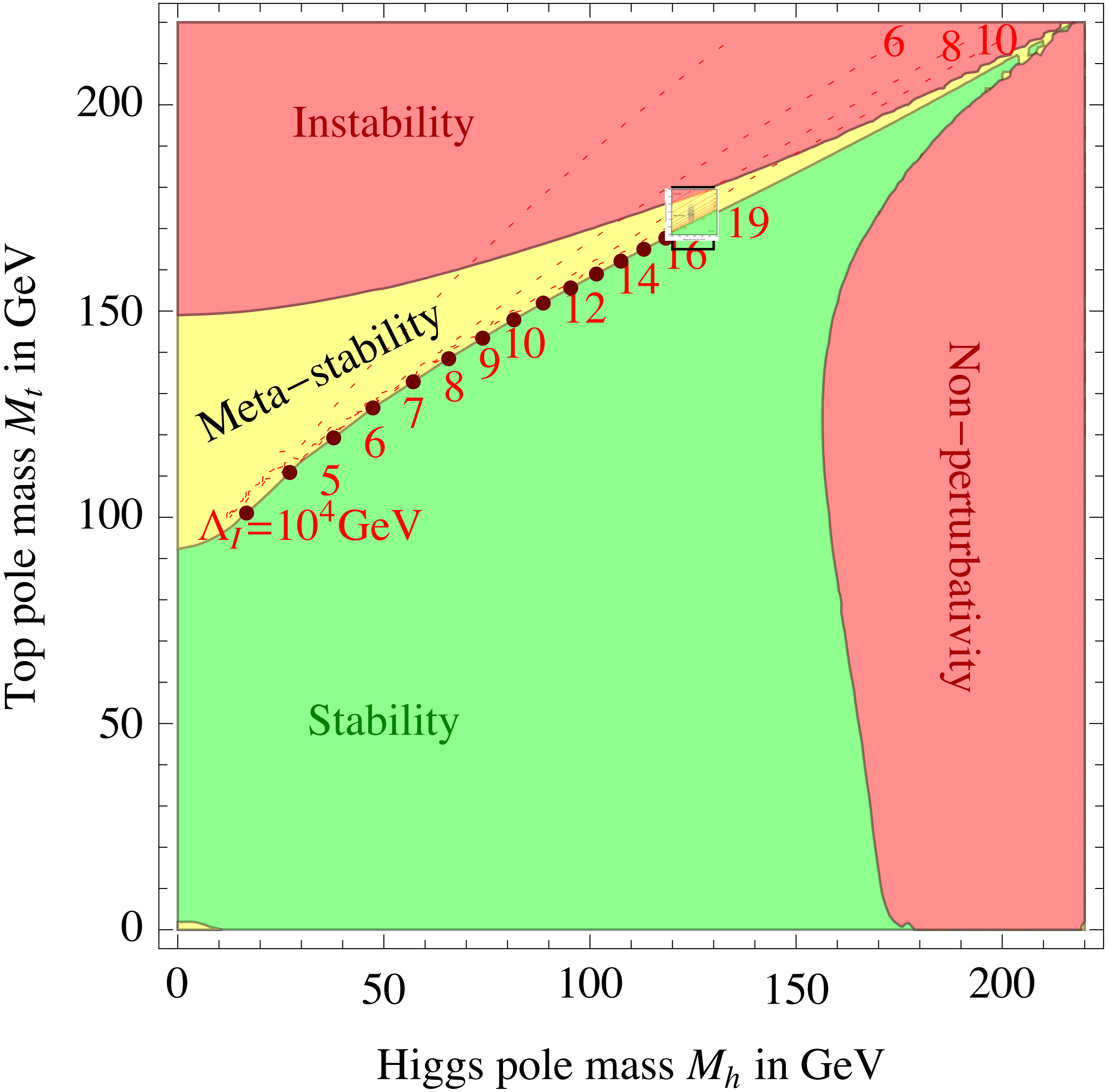
The easy relation is spoiled by perturbative corrections!

Citations

- Full NLO: Sirlin 80; Marciano Sirlin 80; Tarrach 81; Hempfling, Kniehl 95; Sirlin Zucchini 86;
- Partial NNLO: Bezrukov, Kalmykov, Kniehl, Shaposhnikov 12; Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia 12;
- Full NNLO: Buttazzo et al. (w/ PPG); JHEP 1312 (2013) 089; Kniehl, Pikelner, Veretin 15;

Stability of the EW vacuum:

Buttazzo et al. (w/ PPG); JHEP 1312 (2013) 089



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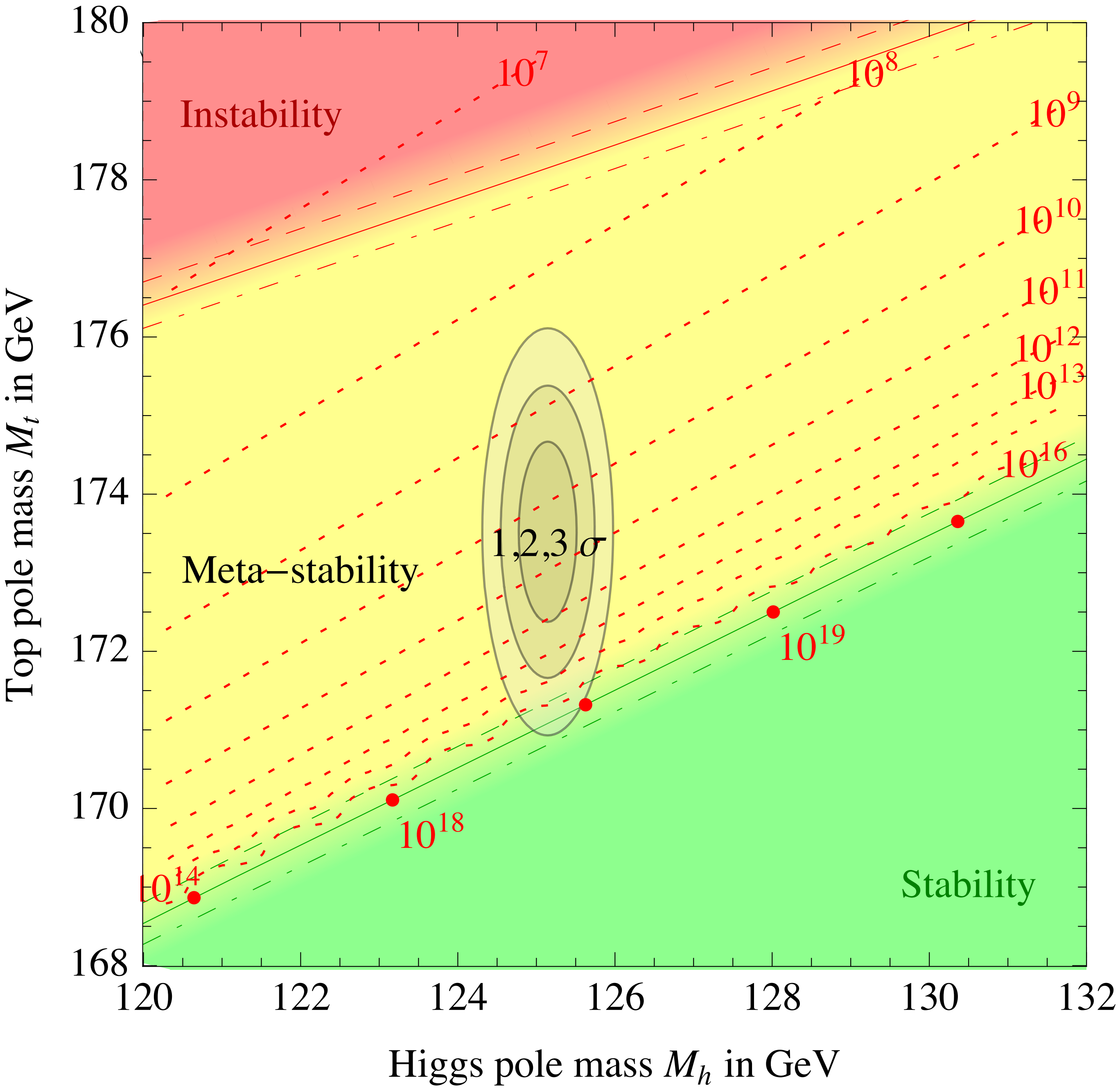

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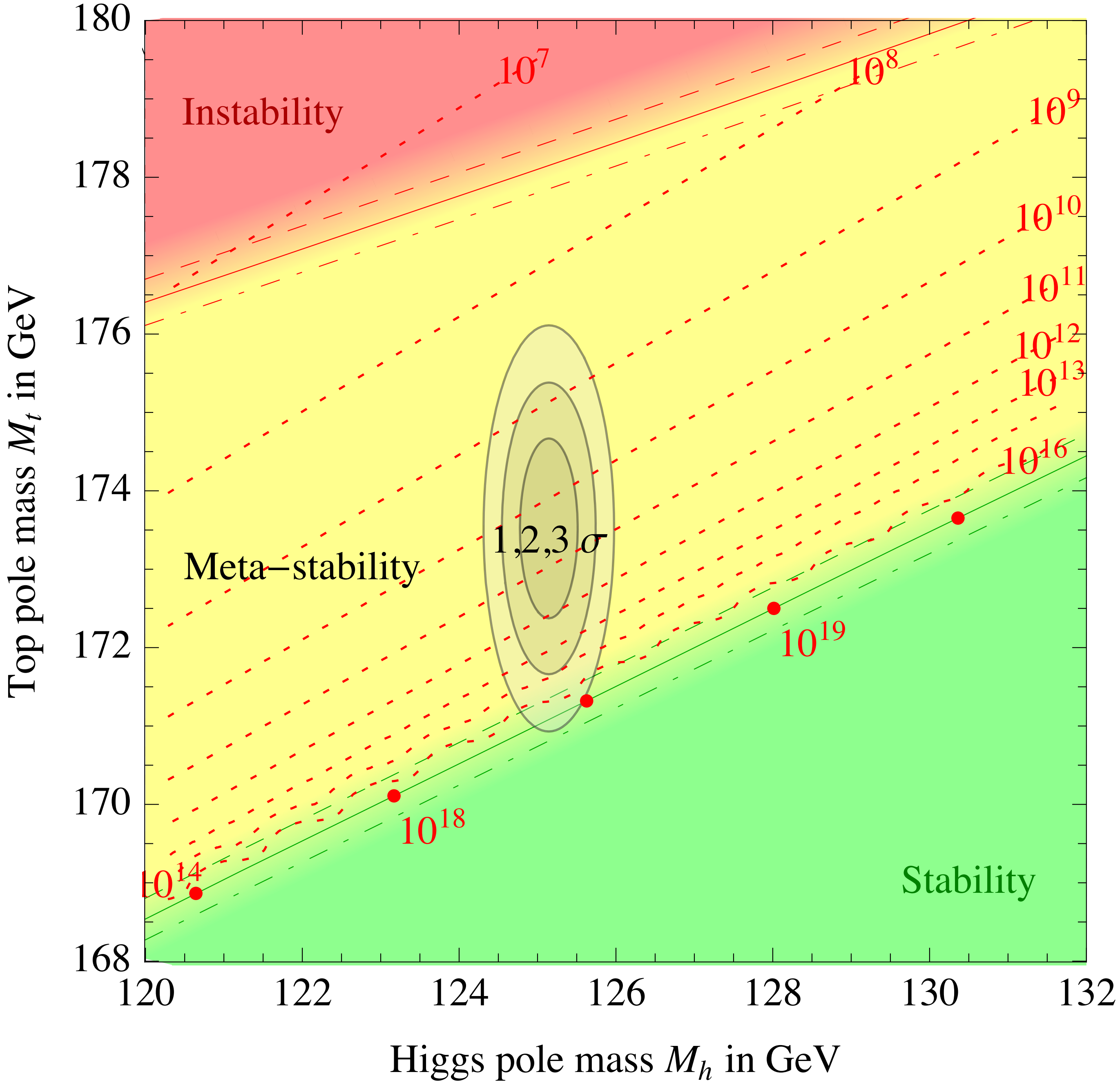

Currents bounds on stability:

Andreassen, Frost, Schwartz, arXiv: 1707.08124

$$\boxed{\tau_{SM} = 10^{139^{+102}_{-51}}\,\text{yrs}}$$

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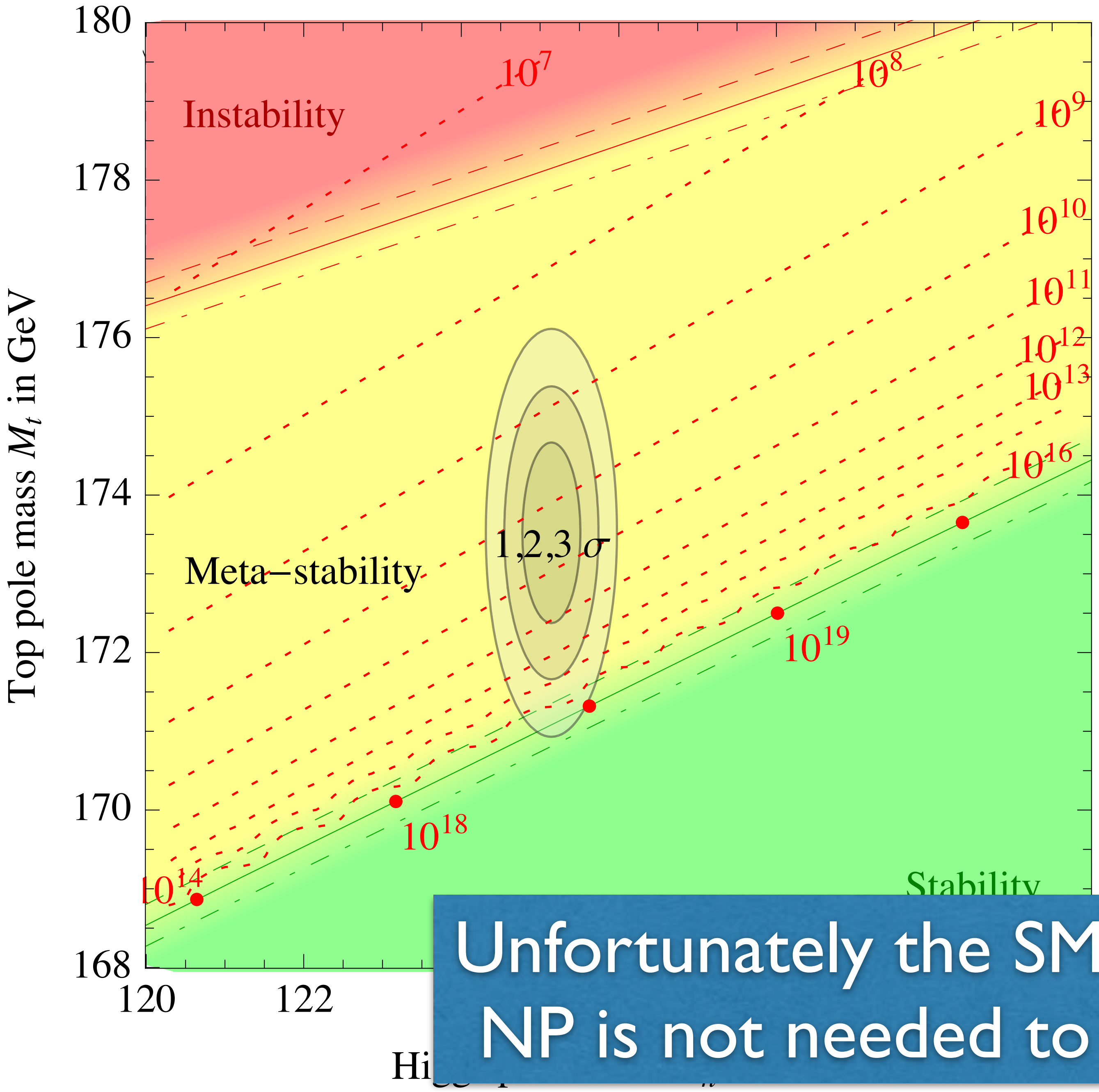

Currents bounds on stability:

Andreassen, Frost, Schwartz, arXiv: 1707.08124

$$\boxed{\tau_{SM} = 10^{139^{+102}_{-51}}\ \text{yrs}}$$

Unfortunately the SM is not unstable:
NP is not needed to solve the crisis

Some EW precision observables

W and Z masses

$M_W \quad M_Z$

$SU(2) \times U(1) \to U(1)$

Mixing angle θ_W

Fermi constant

$$G_\mu^2 \propto \frac{1}{\tau_\mu}; \quad G_\mu = \frac{1}{\sqrt{2}v^2}$$

Fine-structure constant

α

Some EW precision observables

W and Z masses

$M_W \quad M_Z$

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Mixing angle θ_W

$$M_W = M_Z \cos(\theta_W)$$

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Some EW precision observables

W and Z masses

$M_W \quad M_Z$

$SU(2) \times U(1) \rightarrow U(1)$

Mixing angle θ_W

$$M_W = M_Z \cos(\theta_W)$$

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2} G_\mu \sin^2(\theta_W)}$$

Fermi constant

$$G_\mu^2 \propto \frac{1}{\tau_\mu}; \quad G_\mu = \frac{1}{\sqrt{2} v^2}$$

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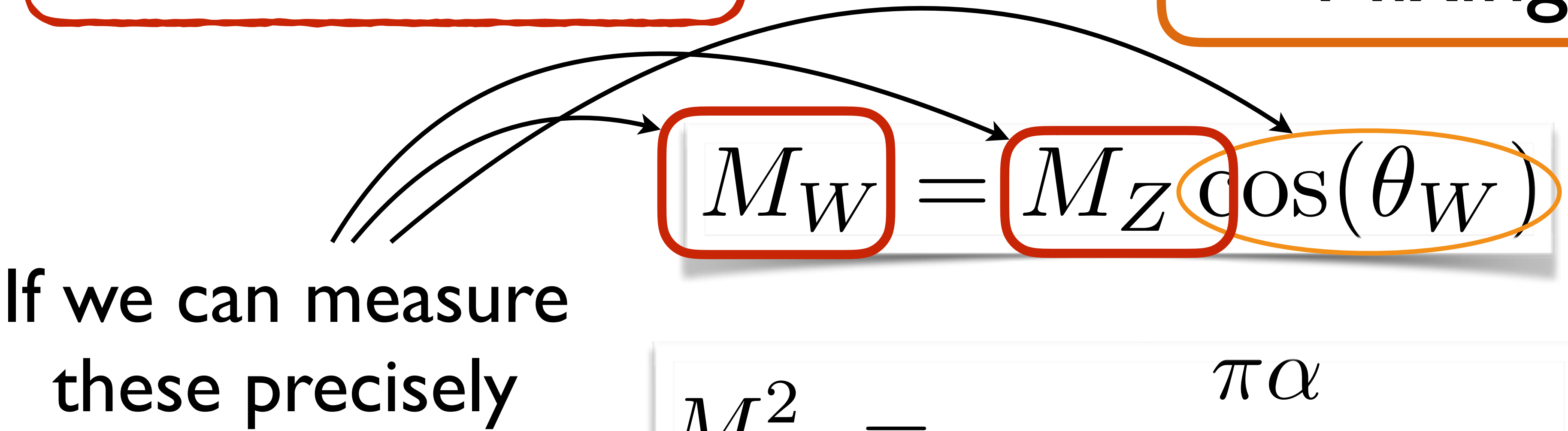

If we can measure these precisely

$$\boxed{M_W} = \boxed{M_Z} \cos(\theta_W)$$

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2} G_\mu \sin^2(\theta_W)}$$

Fermi constant

$$G_\mu^2 \propto \frac{1}{\tau_\mu}; \quad G_\mu = \frac{1}{\sqrt{2} v^2}$$

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α

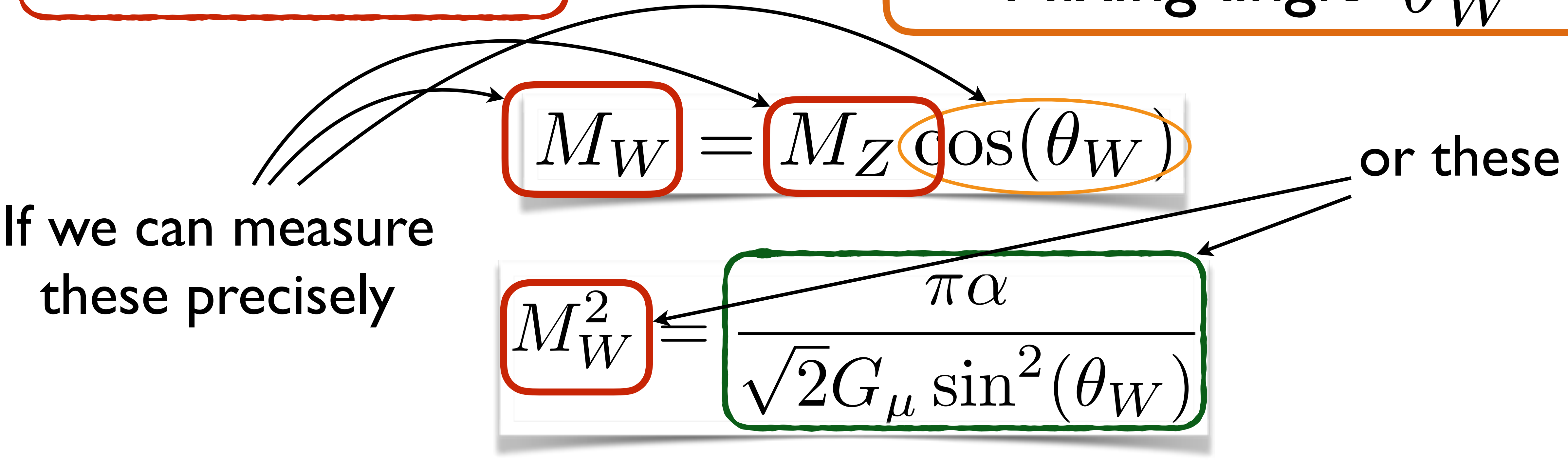
Some EW precision observables

W and Z masses

$M_W \quad M_Z$

$SU(2) \times U(1) \rightarrow U(1)$

Mixing angle θ_W



$$\boxed{M_W} = \boxed{M_Z} \cos(\theta_W)$$

or these

If we can measure these precisely

$$\boxed{M_W^2} = \boxed{\frac{\pi\alpha}{\sqrt{2}G_\mu \sin^2(\theta_W)}}$$

Fermi constant

$$G_\mu^2 \propto \frac{1}{\tau_\mu}; \quad G_\mu = \frac{1}{\sqrt{2}v^2}$$

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we can find inconsistencies!

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Degrassi, Gambino, PPG; JHEP 1505 (2015) 154

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How can we use it to systematically look for new physics?

Assume the SM is low energy limit of an EFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{k=5} \sum_{i} \frac{\mathscr{C}_i^k}{\boxed{\Lambda^{k-4}}} \boxed{\mathscr{O}_i^k}$$

Scale of new physics

Operators respect SM gauge symmetries

The theory is renormalizable order by order in powers of Λ

We consider only Dimension-6 operators

We use SMEFT to study the EWPO at NLO

Dawson, PPG; arXiv:1909.02000

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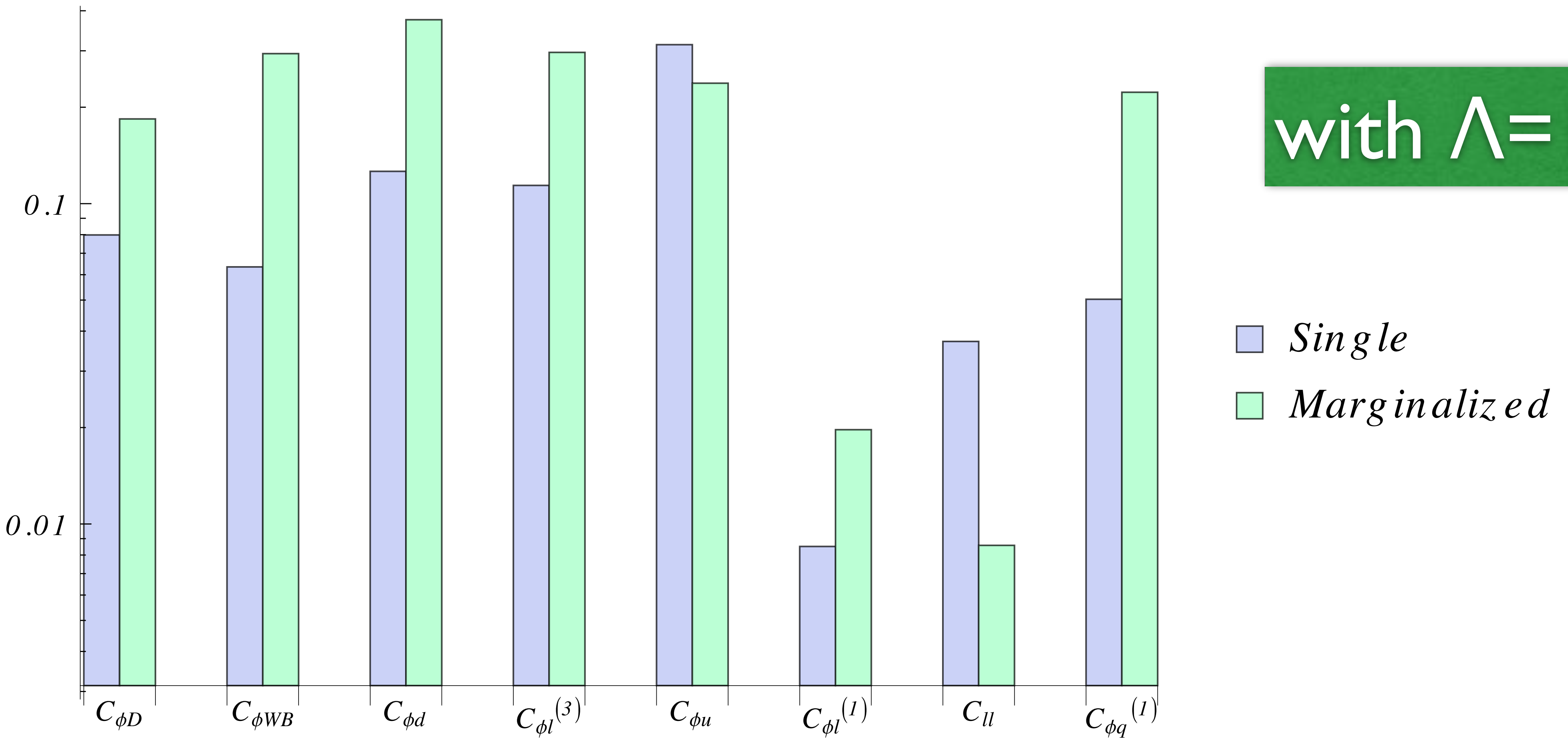
Single fit vs. Marginalized fit at LEP

Dawson, PPG; arXiv:1909.02000

Observables : $M_W, \Gamma_W, \Gamma_Z, \sigma_h, R_l, R_b, R_c, A_{l,FB}, A_{b,FB}, A_{c,FB}, A_l, A_b, A_c$

NLO contribution



with Λ=1 TeV

Large uncertainties not taken in account at LO

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- NLO corrections to the SMEFT are relevant.

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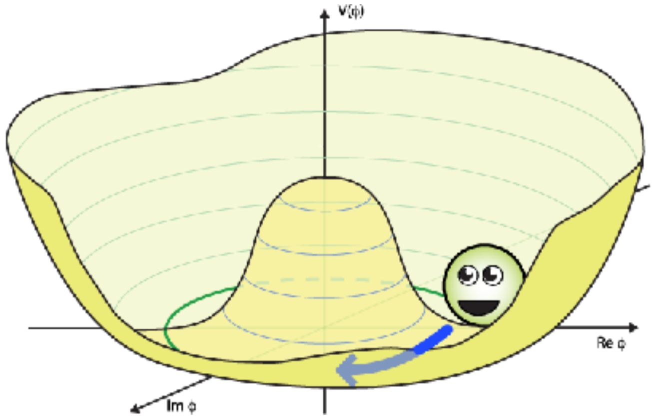
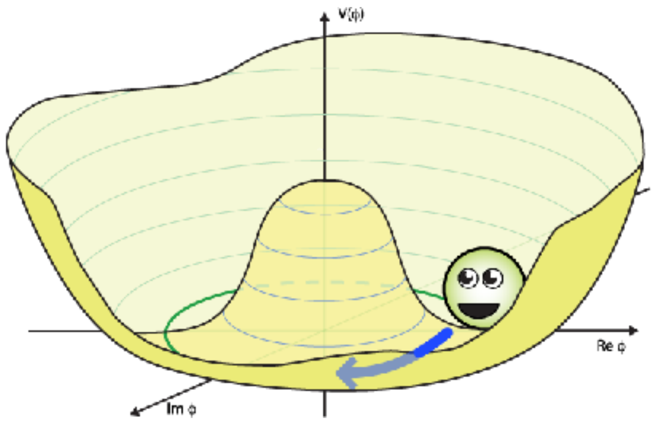
No direct measurement of the Higgs potential!



$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$V(H) = \frac{1}{2}M_H^2H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$



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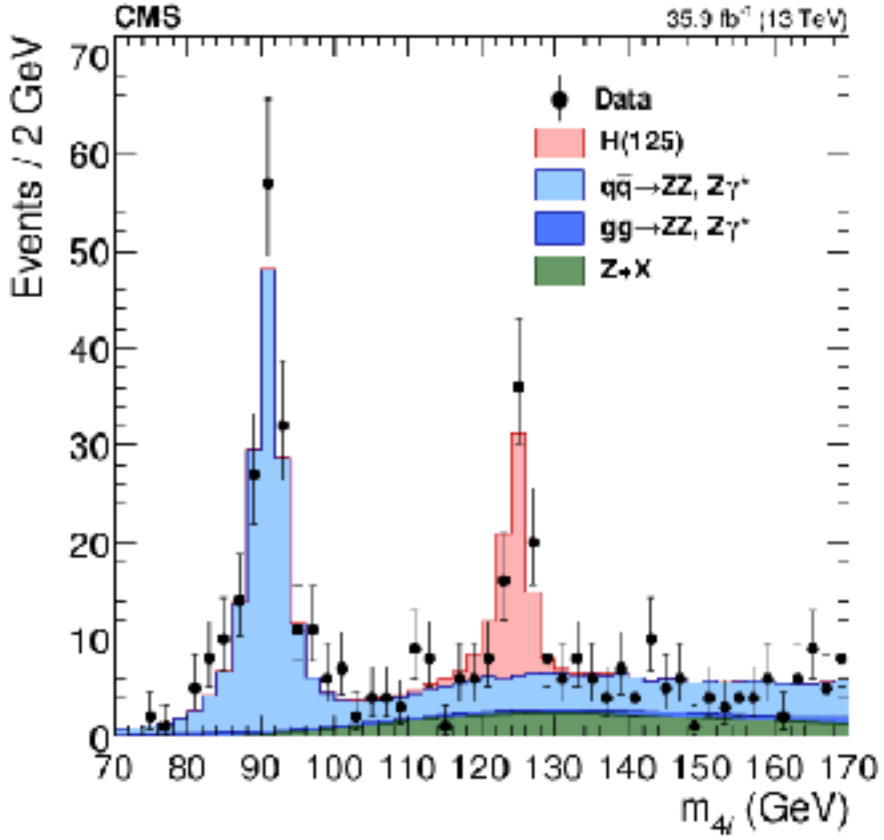

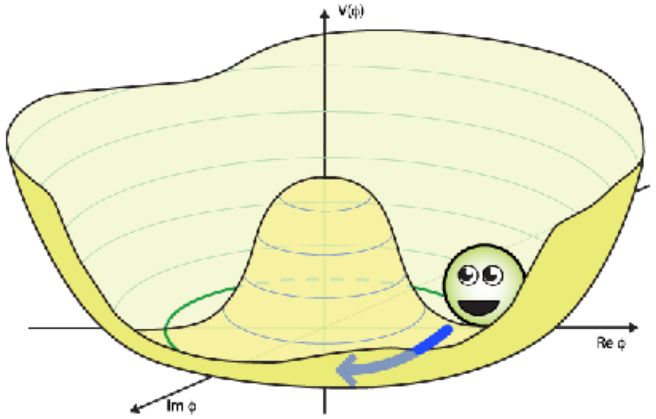

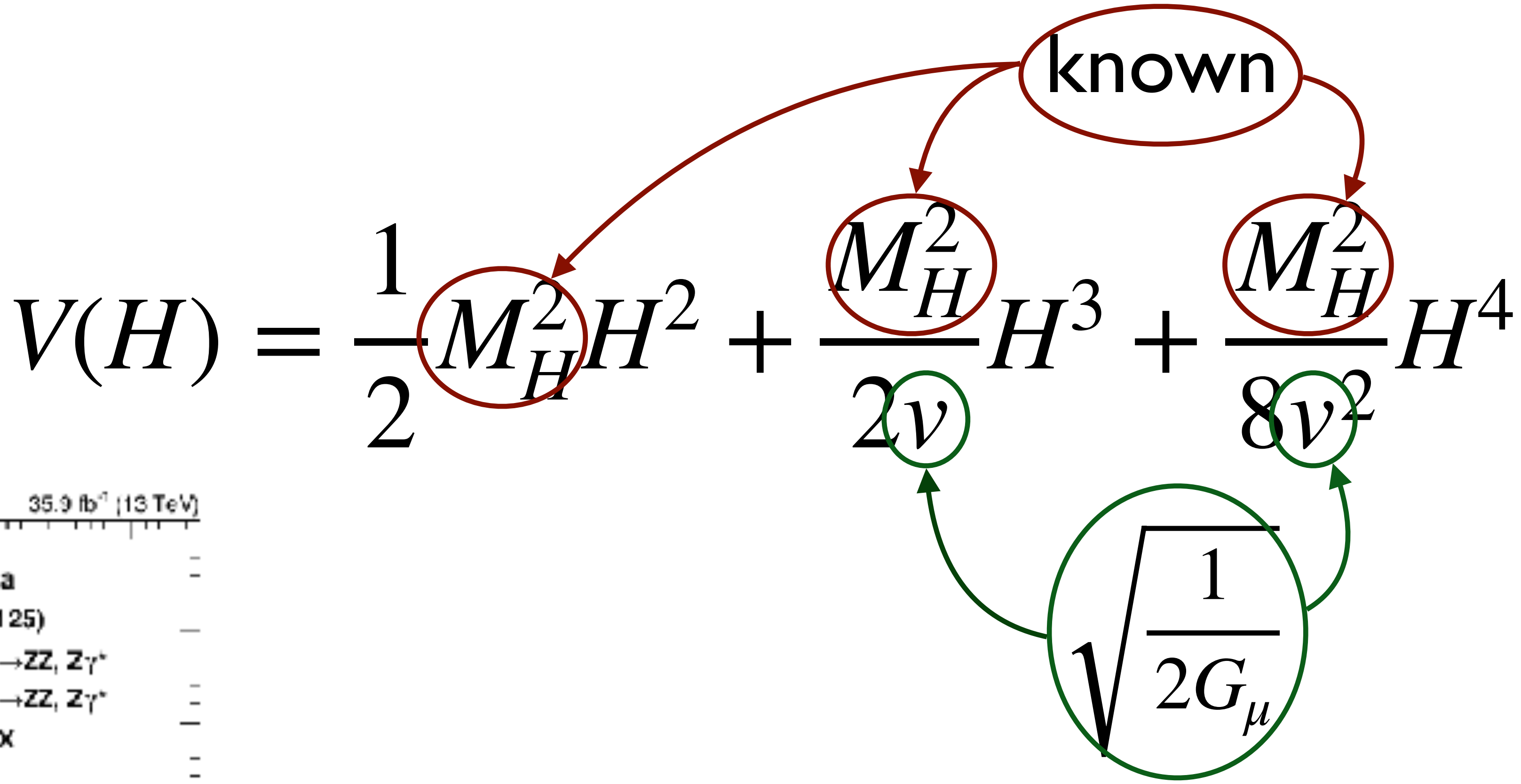

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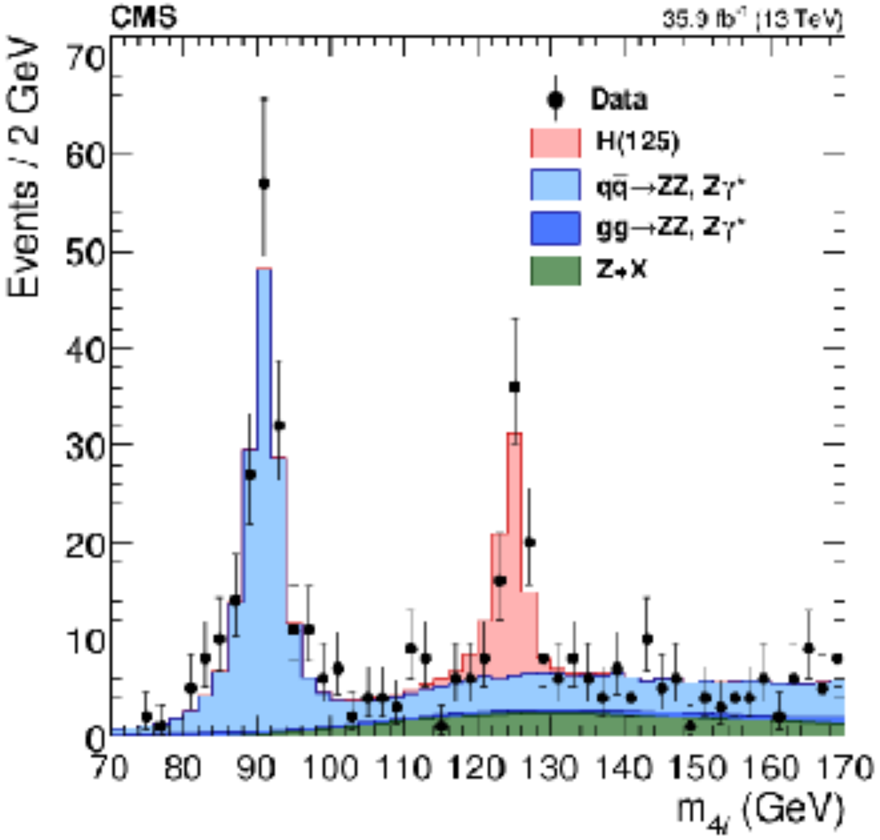

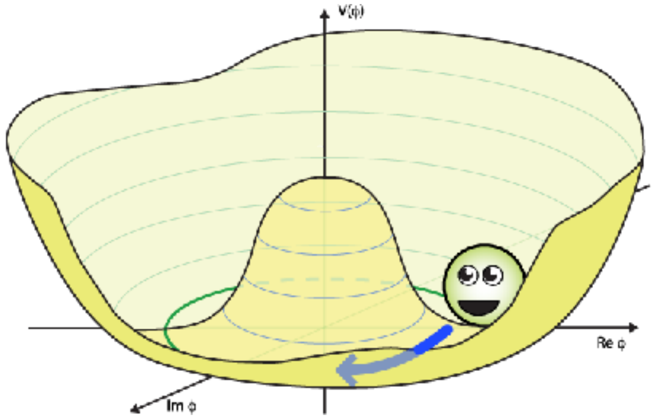

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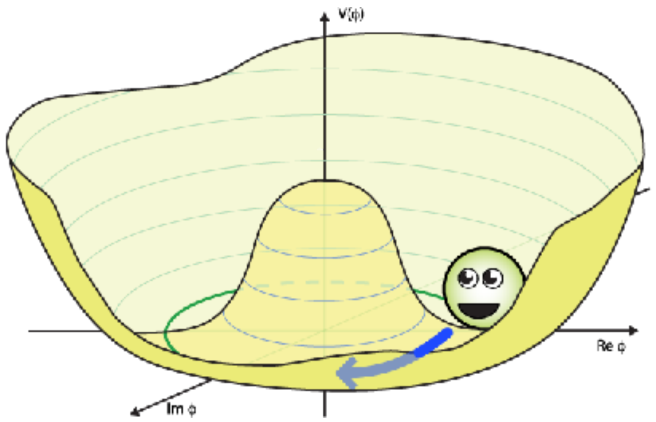
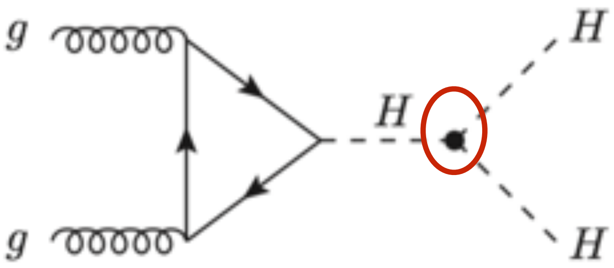
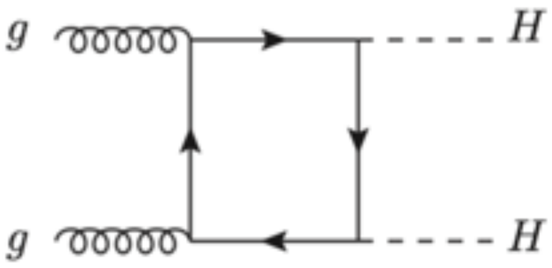
From double Higgs production







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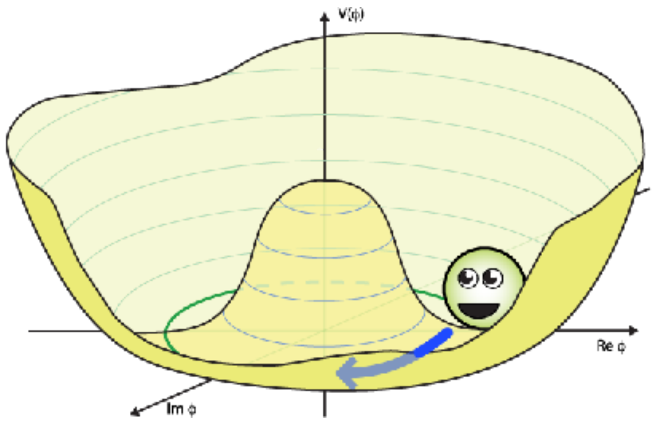

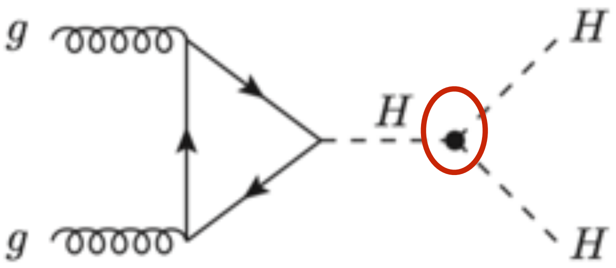

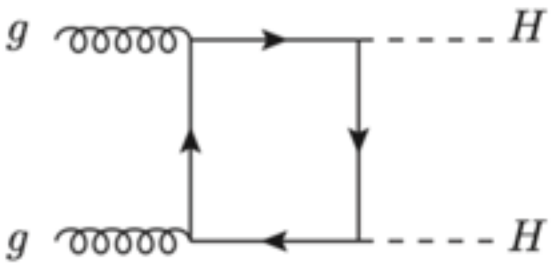

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From triple Higgs production $\sigma(gg \to HHH) \sim 0.1$ fb

The trilinear appears at NLO in Single Higgs processes.

G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080

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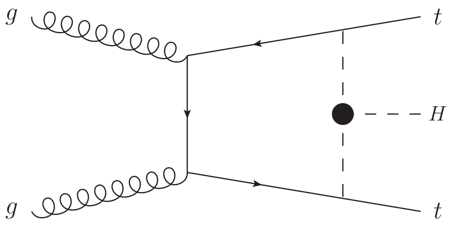

Due to the presence of different Loop structures these contributions cannot be captured by a local rescaling.

For similar ideas:

M. McCullough Phys. Rev. D90 (2014), no. 1 015001

M. Gorbahn and U. Haisch, arXiv:1607.03773 [hep-ph];

$$\Sigma_{NLO} = Z_H \Sigma_{LO}(1 + \kappa_\lambda C_1)$$

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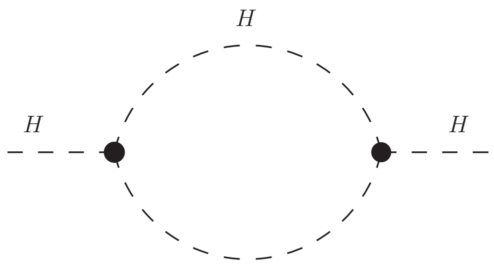

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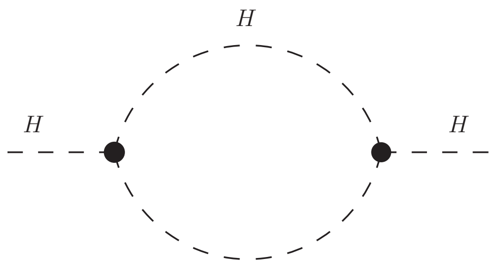

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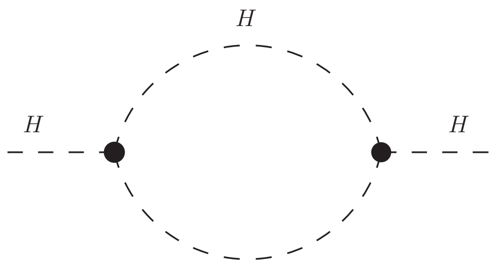

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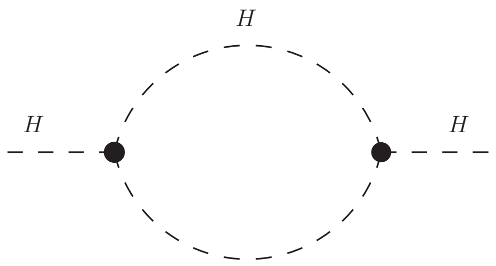

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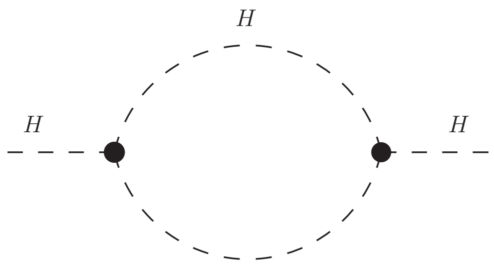

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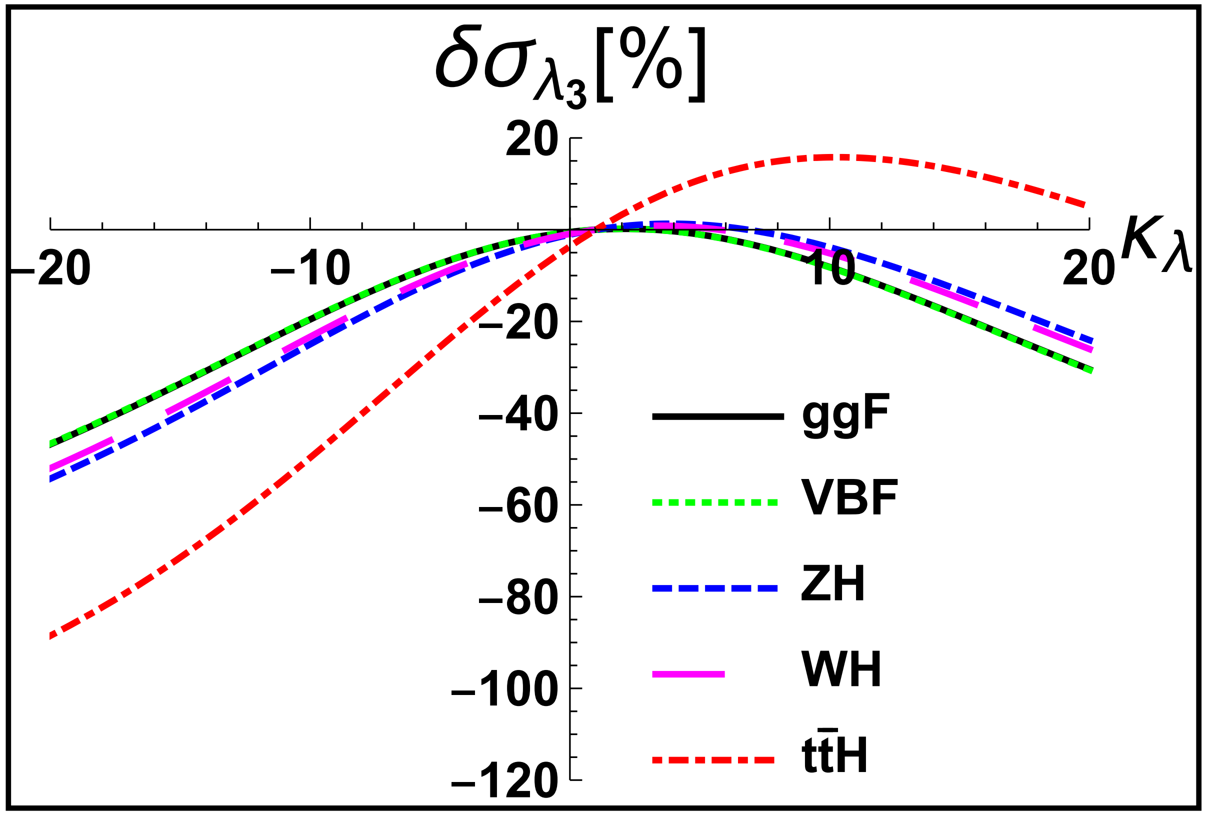
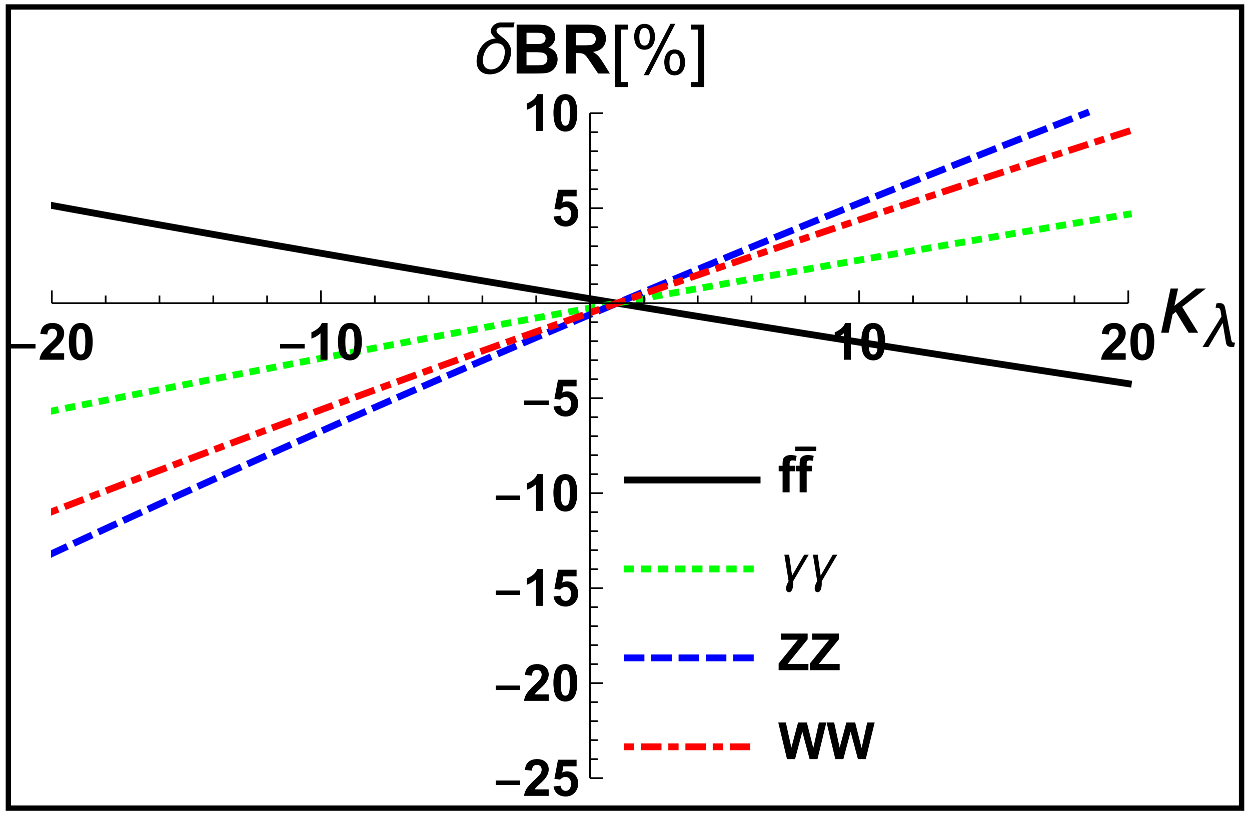
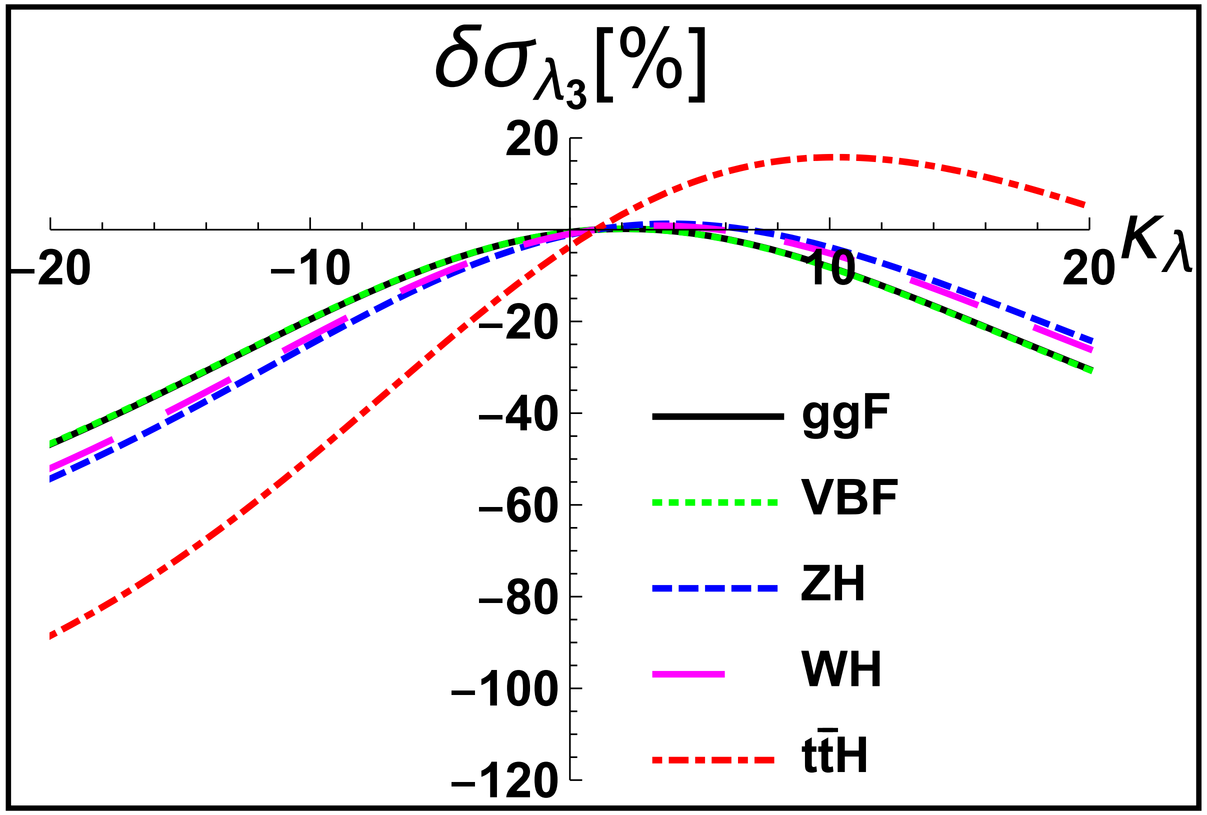
Amplitudes at LO and NLO

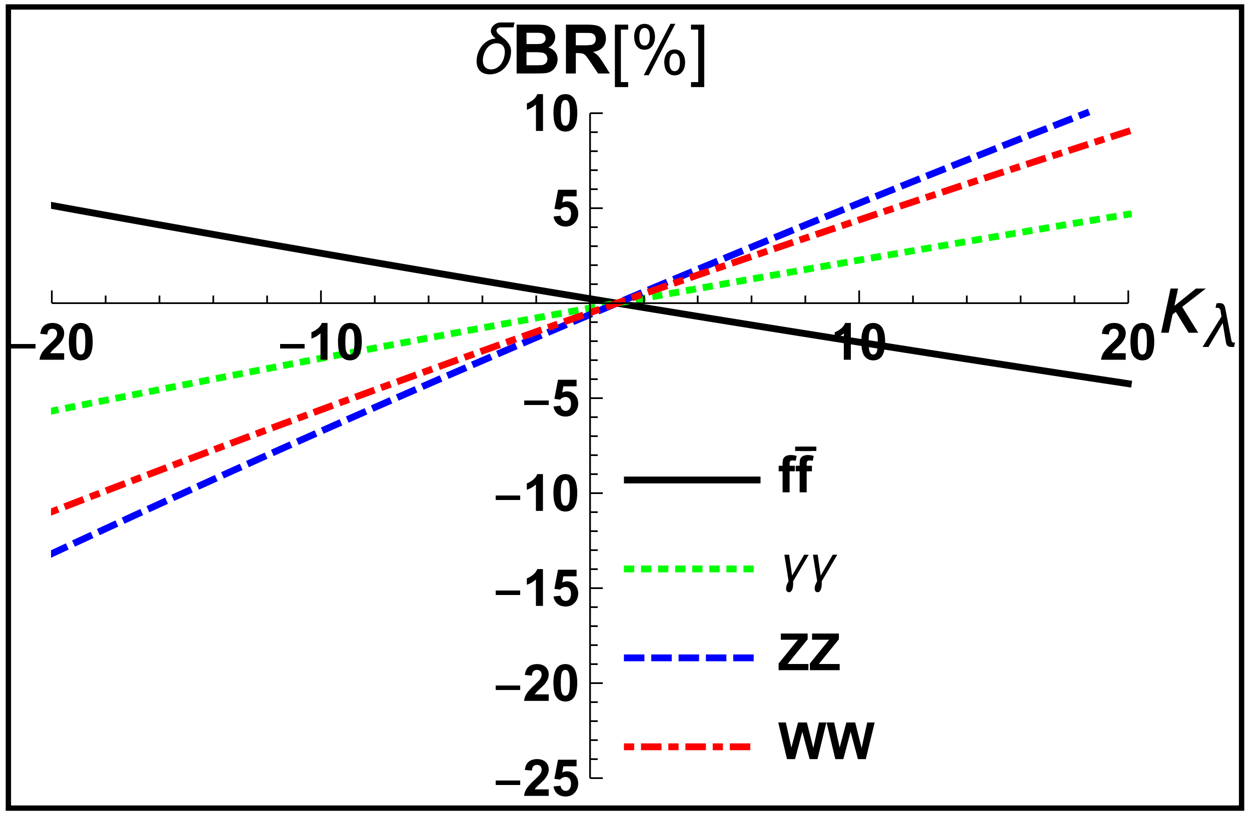
G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080





G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080





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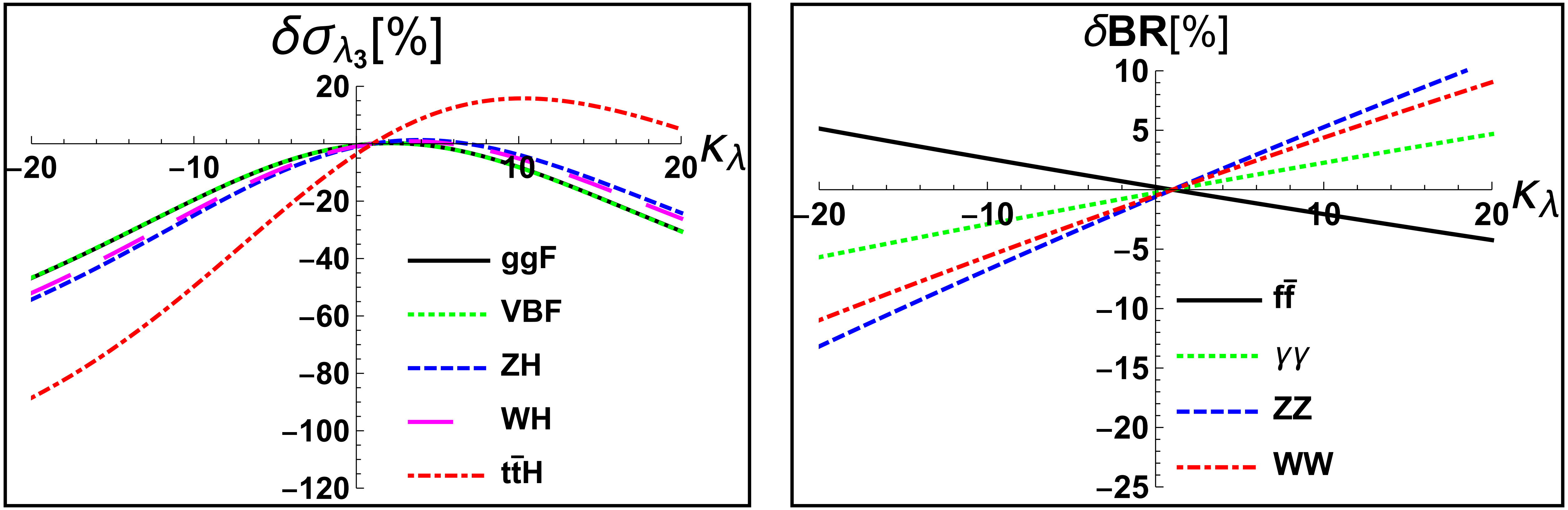
All the other receive very small positive corrections

G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080



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In the range close to the SM, the decays are more sensitive to κ_λ than the production processes

G. Degrassi, M. Fedele, PPG, JHEP 1704 (2017) 155

Another source of information: P.O.

$$m_W^2 = \frac{\hat{\rho}\, m_Z^2}{2} \left\{ 1 + \left[1 - \frac{4\hat{A}^2}{m_Z^2 \hat{\rho}} (1 + \Delta\hat{r}_W) \right]^{1/2} \right\}$$

G. Degrassi, M. Fedele, PPG, JHEP 1704 (2017) 155

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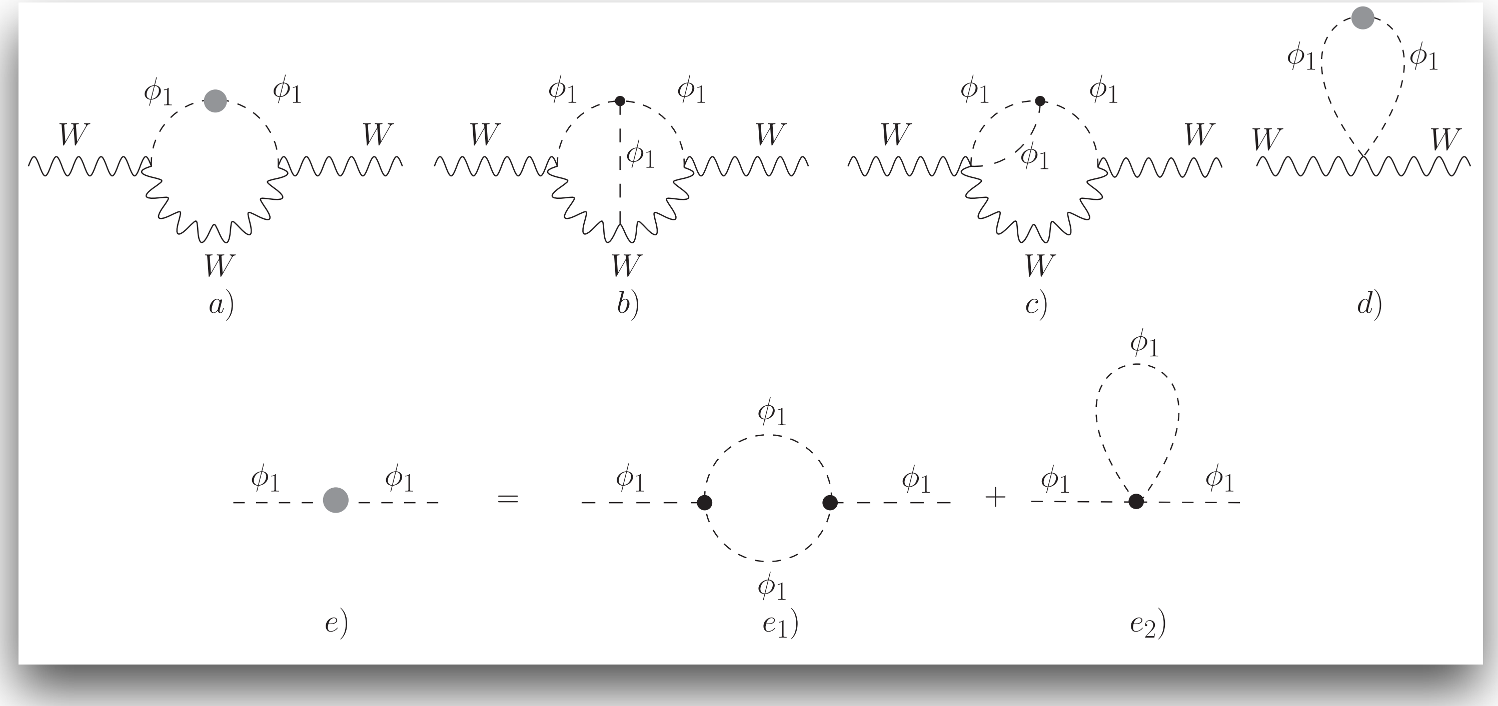

Two loops dependence on κ

G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080 G. Degrassi, M. Fedele, PPG, JHEP 1704 (2017) 155

Constraints on trilinear coupling

- Run I:
    - ATLAS and CMS: $\mathcal{O}(\pm(15-20))$
    - Our constraint using ggF+VBF: $\kappa_\lambda > -14.3$
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    - Pair production: $-5.0 < \kappa_\lambda < 12.1$ at $36\,\text{fb}^{-1}$
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G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080 G. Degrassi, M. Fedele, PPG, JHEP 1704 (2017) 155

Constraints on trilinear coupling

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G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080 G. Degrassi, M. Fedele, PPG, JHEP 1704 (2017) 155

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Data from JHEP 1608 (2016) 045

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PDG2016

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  - Pair production: $-5.0 < \kappa_\lambda < 12.1$ at 36 fb^{-1}
  - Single Higgs: $-3.2 < \kappa_\lambda < 11.9$ at 80 fb^{-1}

Moriond '19

G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080 G. Degrassi, M. Fedele, PPG, JHEP 1704 (2017) 155

Constraints on trilinear coupling

- Run I:
  - ATLAS and CMS: $\boxed{\mathcal{O}(\pm(15-20))}$
  - Our constraint using ggF+VBF: $\kappa_\lambda > -14.3$
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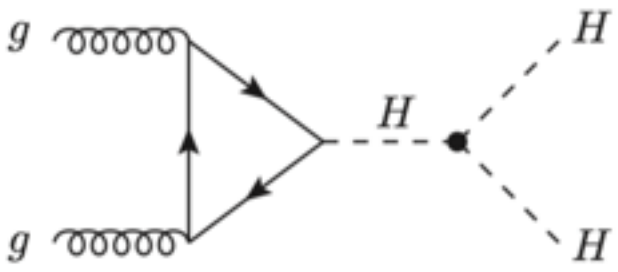
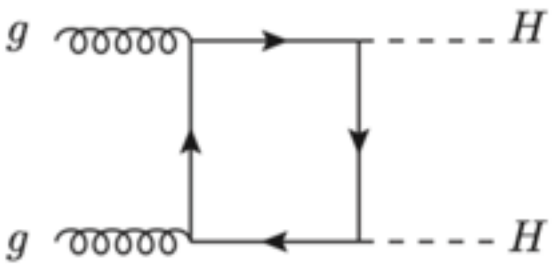
Measuring the Higgs potential

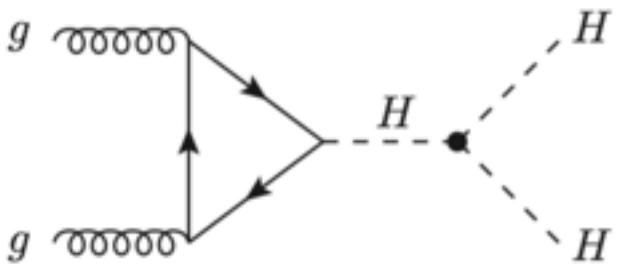


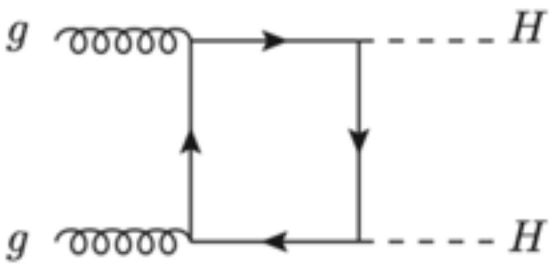


LO is known

Exact analytical result

Glover, van der Bij (88)





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(QCD) NLO fully known only numerically

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert and Zirke, (16)
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher (18)

- Total cross section including the full top-quark dependence.
- One phase-space point ~ 2 hours per node
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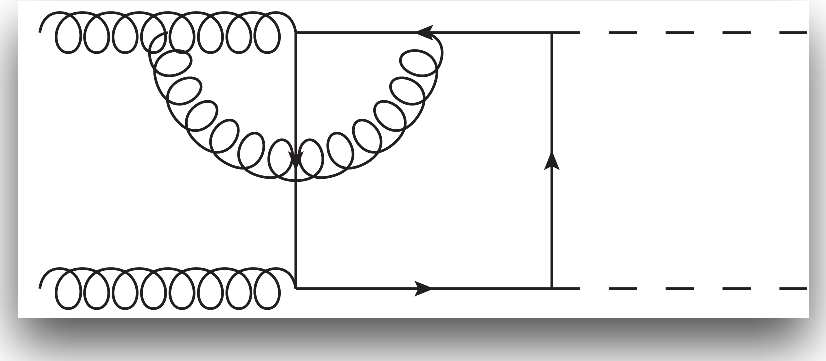
Too many scales (3)



Approaches to an analytical approximation of NLO

HEFT $(m_t \to \infty)$

Dawson, Dittmaier, Spira (98)

$\sqrt{\hat{s}} \lesssim 350\,\text{GeV}$

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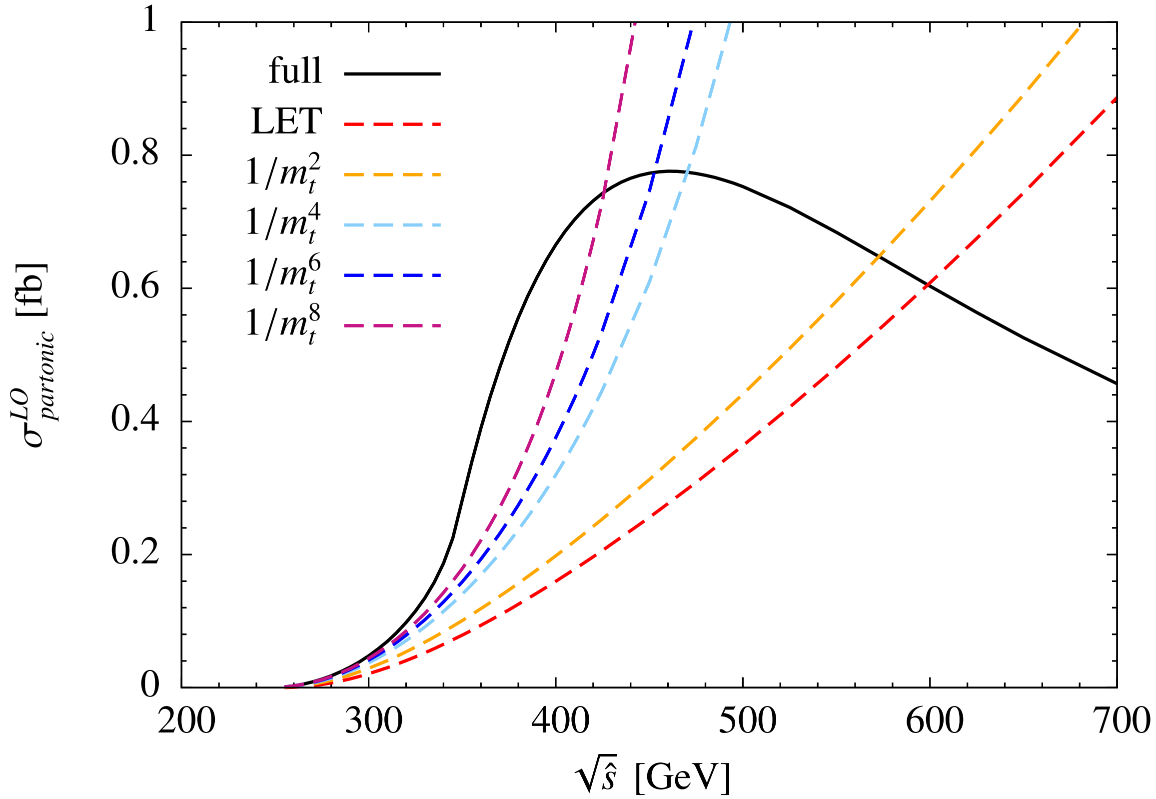

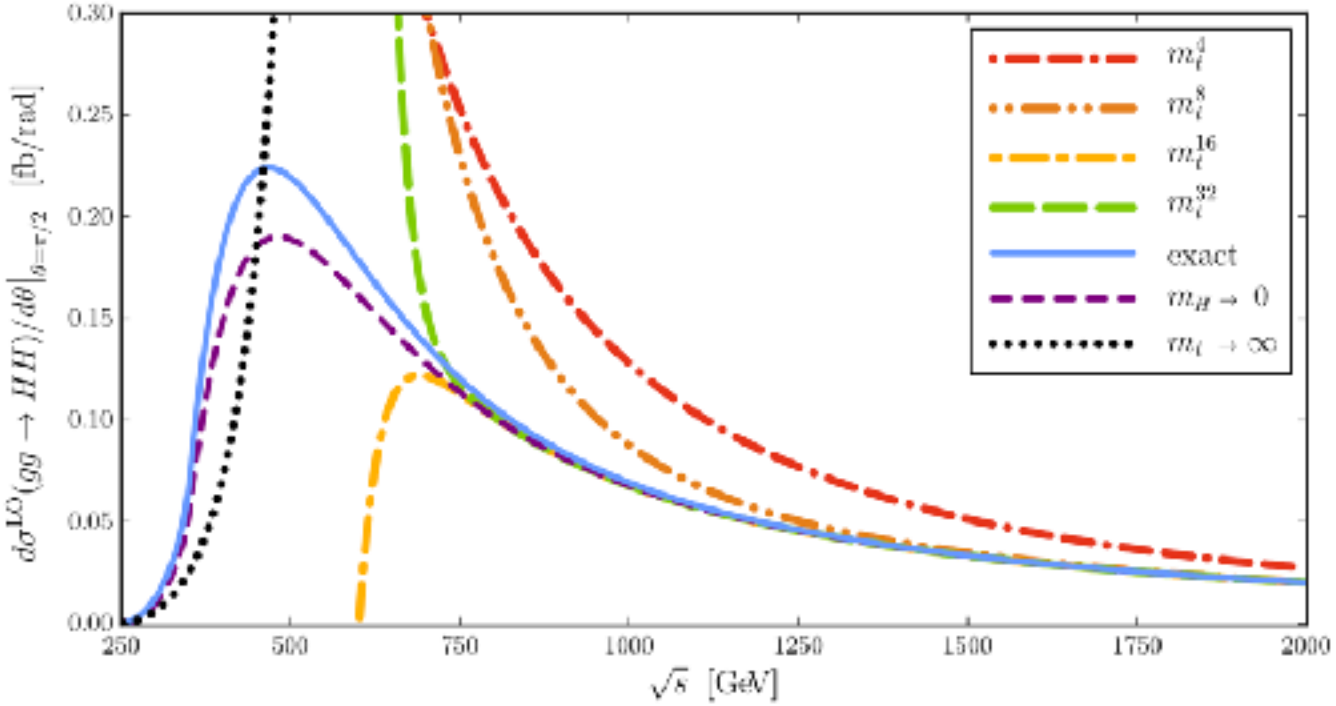

Region $350\,\text{GeV} \lesssim \sqrt{\hat{s}} \lesssim 750\,\text{GeV}$ not covered!!

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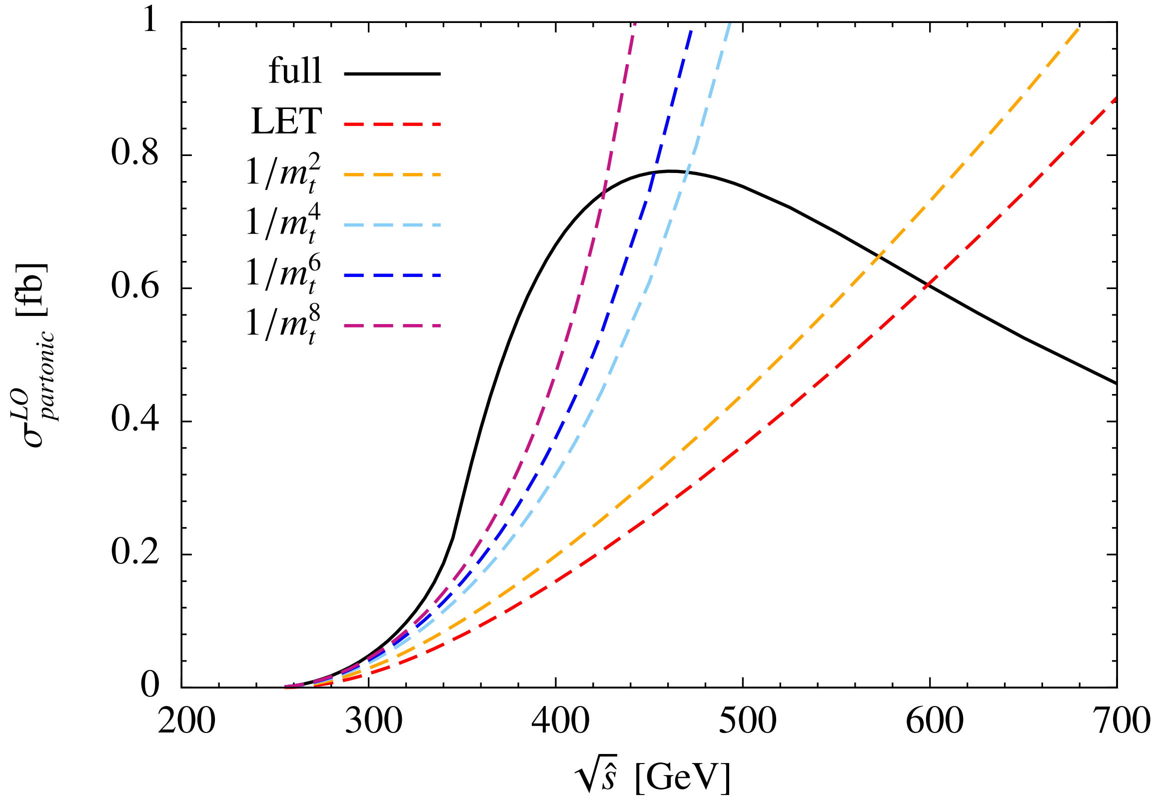

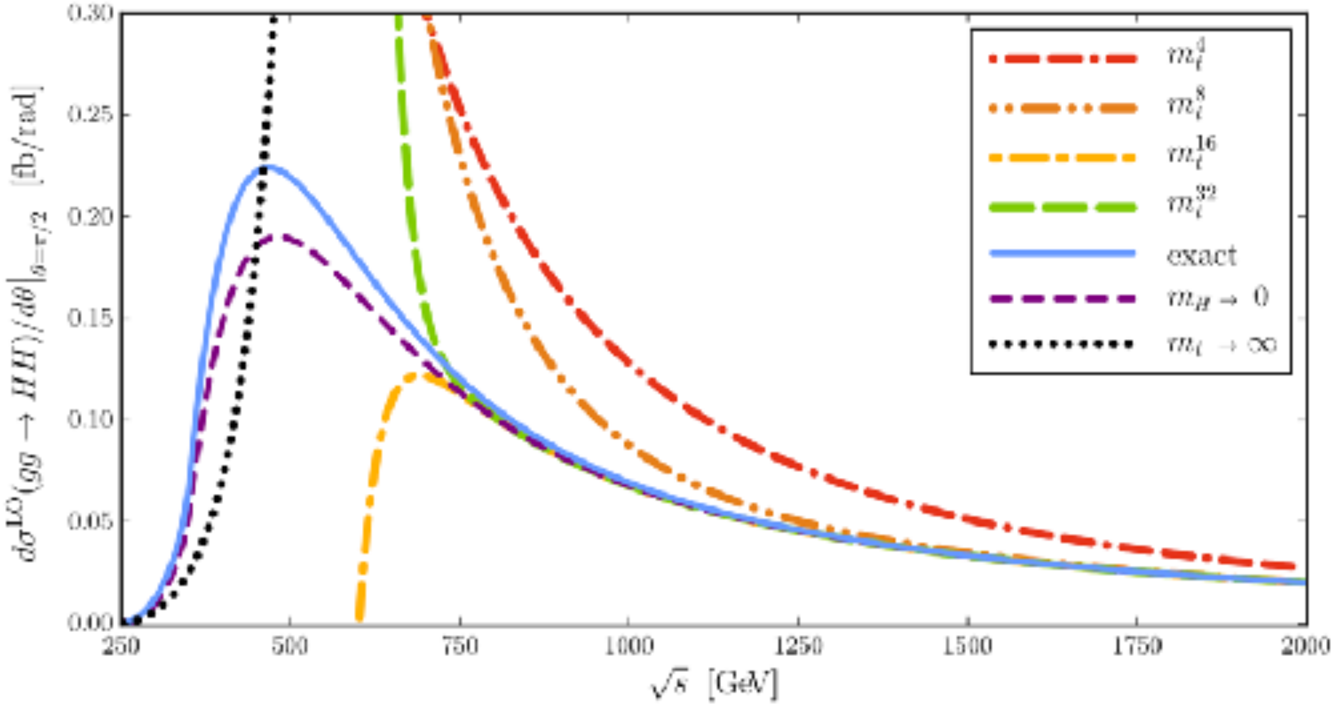

Region $350\,\text{GeV} \lesssim \sqrt{\hat{s}} \lesssim 750\,\text{GeV}$ not covered!!

~95% of hadronic cross section (13 TeV LHC)

Three scales: $$\boxed{\frac{m_t^2}{\hat{s}}, \frac{p_T^2}{\hat{s}}, \frac{m_H^2}{\hat{s}}}$$

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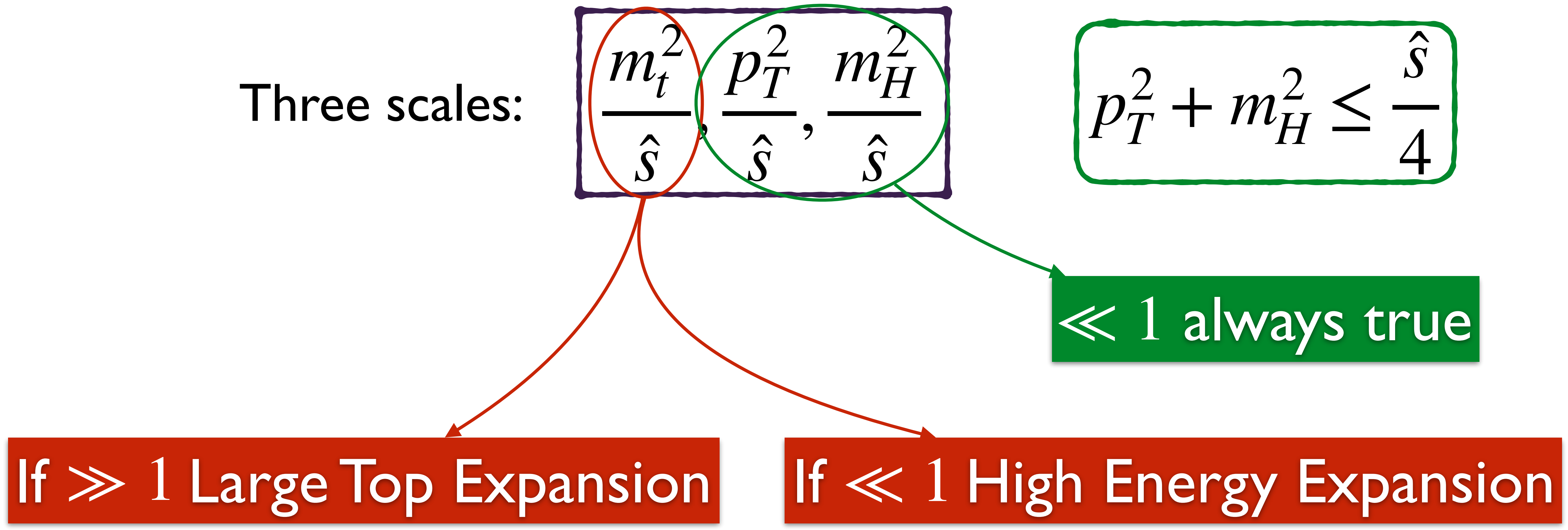

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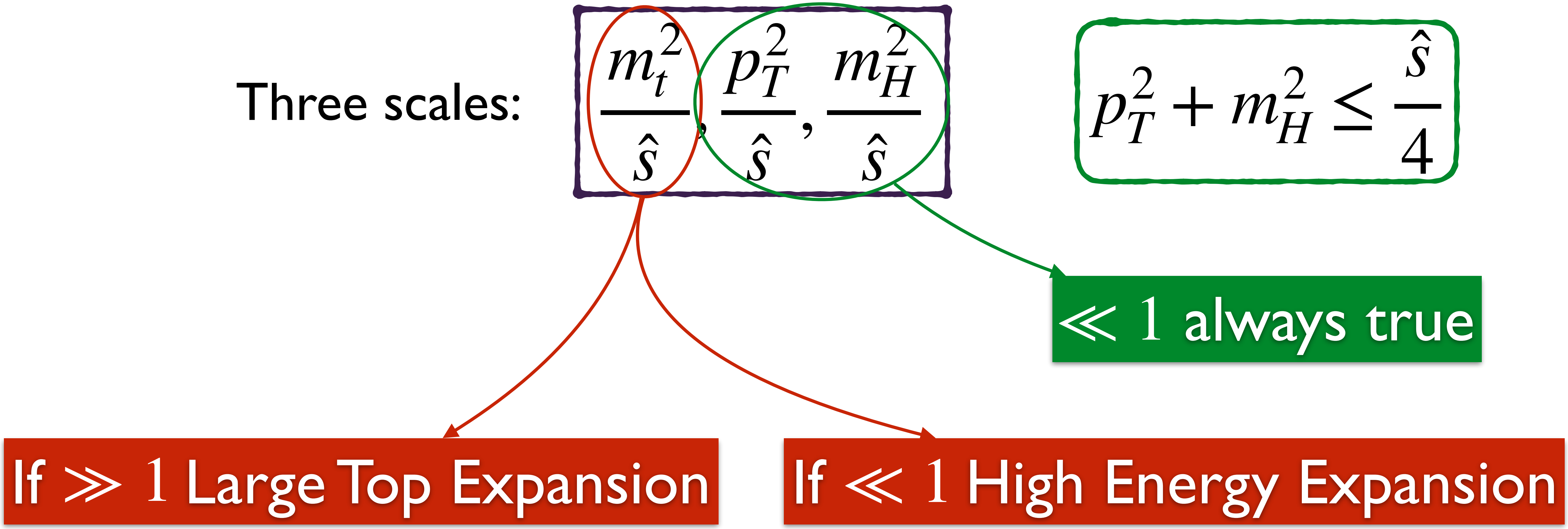

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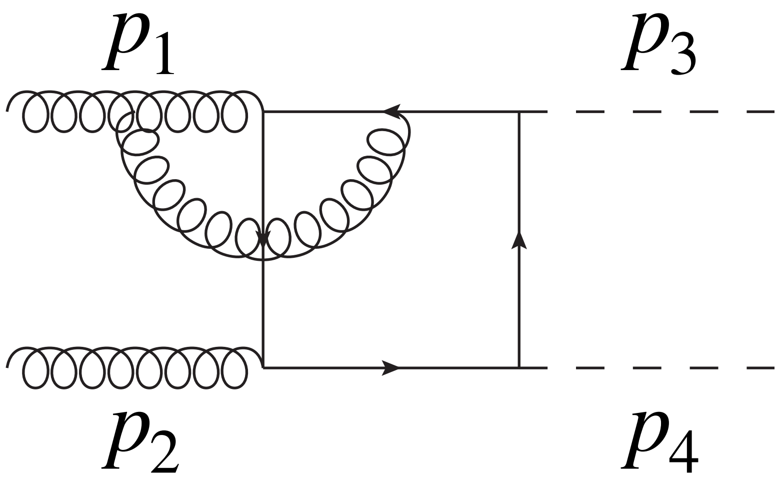
If $\gg 1$ Large Top Expansion

If $\ll 1$ High Energy Expansion

We can try to keep $m_t^2/\hat{s}$ arbitrary and expand on p_T^2 and m_H^2



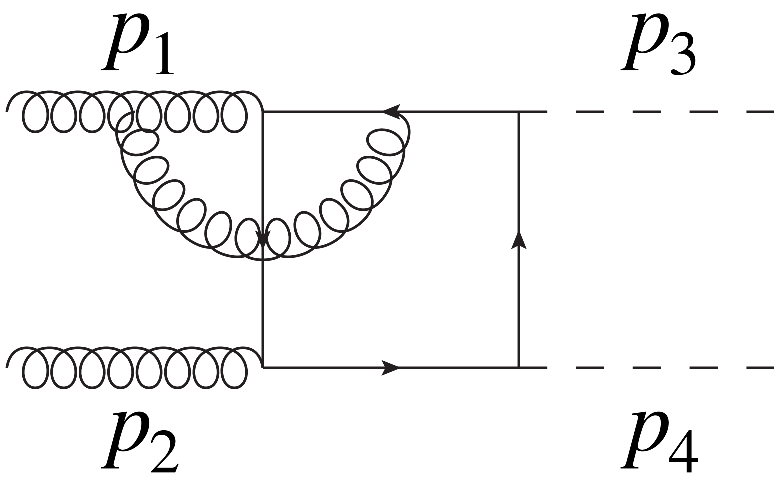
$$\hat{s} = (p_1 + p_2)^2 \qquad \hat{t} = (p_1 + p_3)^2$$

$$\hat{u} = (p_2 + p_3)^2$$

We can use

$$\boxed{\hat{t} \sim 0 \Rightarrow p_T^2 \sim 0}$$

$$p_T^2 = \frac{\hat{t}\hat{u} - m_H^4}{\hat{s}}$$



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 & \hat{t} \sim 0\,, \hat{u} \sim -\hat{s} \\
p_T^2 \sim 0 \arrow[ur] \arrow[dr] & \\
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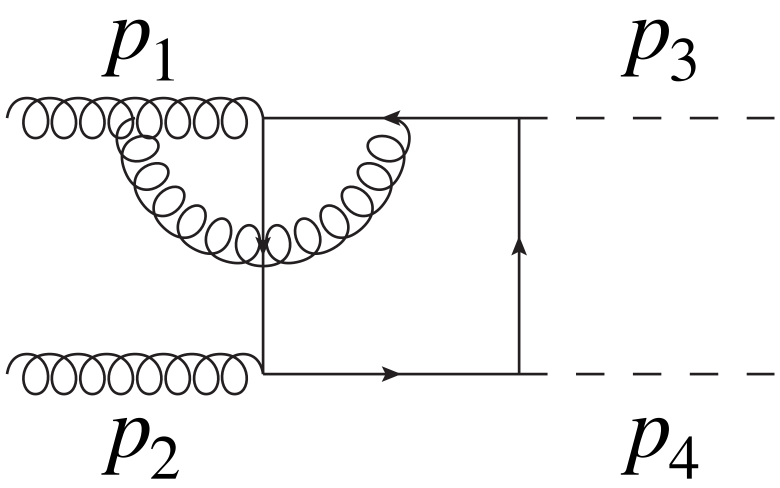

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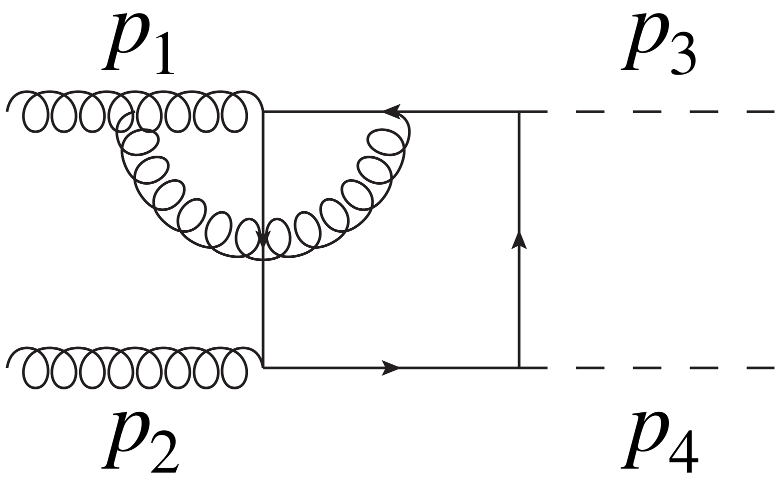
Symmetry!



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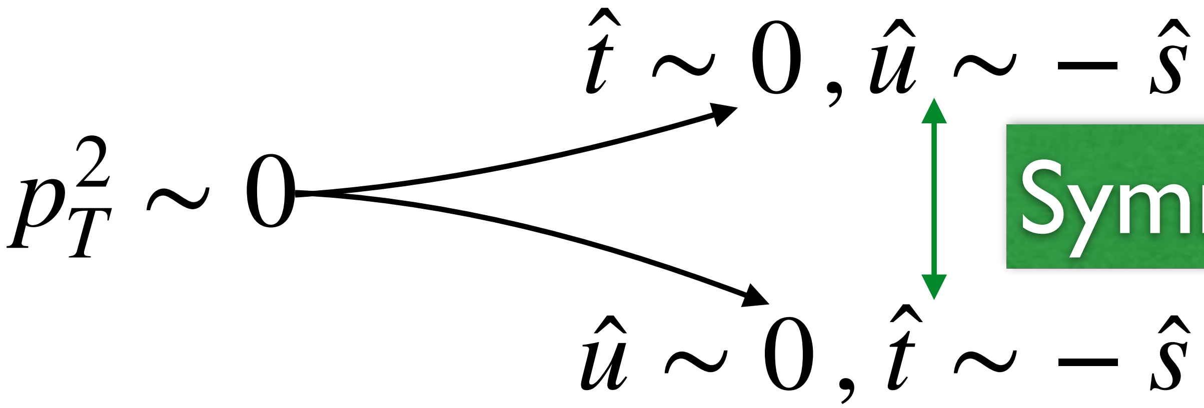

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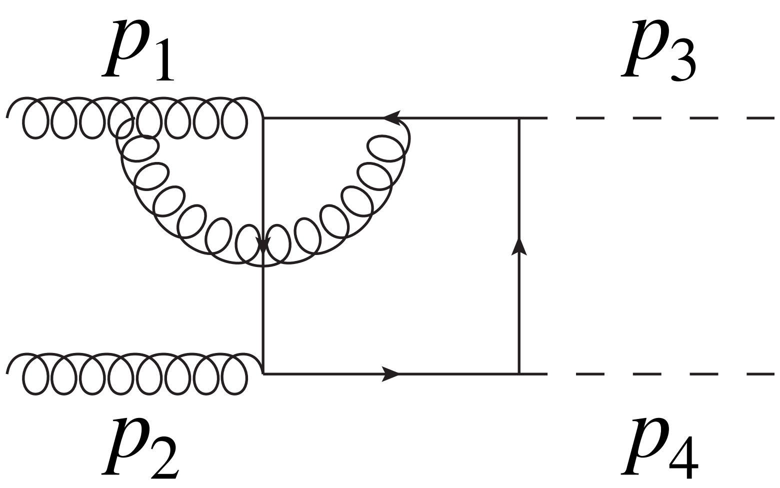
$$\boxed{\sigma \propto \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t}\,\mathcal{G}(\hat{t}) \sim \int_{\hat{t}_-}^{\hat{t}_m} d\hat{t}\,\mathcal{G}(\hat{t} \sim 0) + \int_{\hat{t}_m}^{\hat{t}_+} d\hat{t}\,\mathcal{G}(\hat{t} \sim -\hat{s}) = \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t}\,\mathcal{G}(\hat{t} \sim 0)}$$



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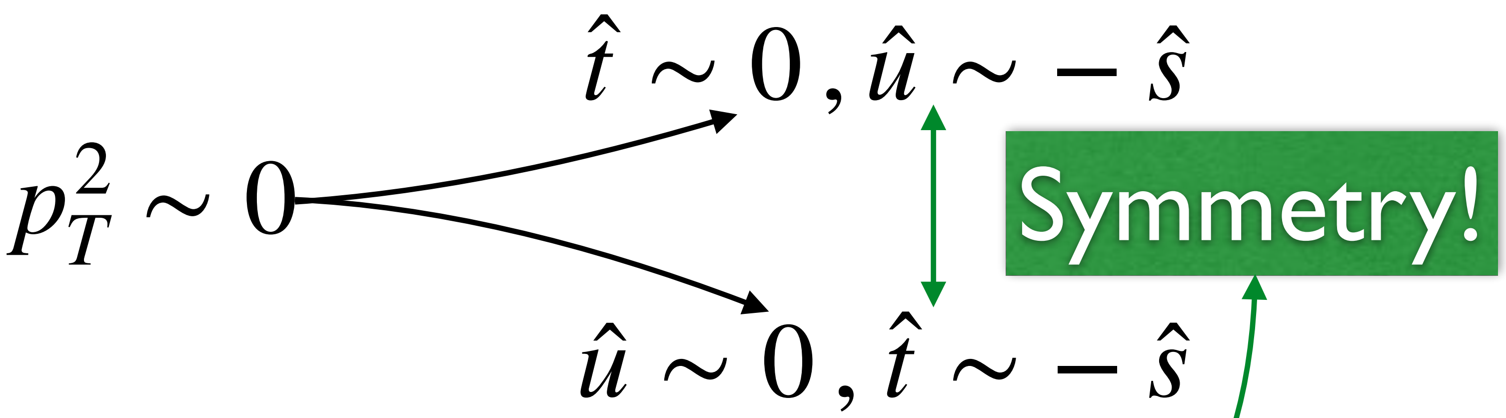

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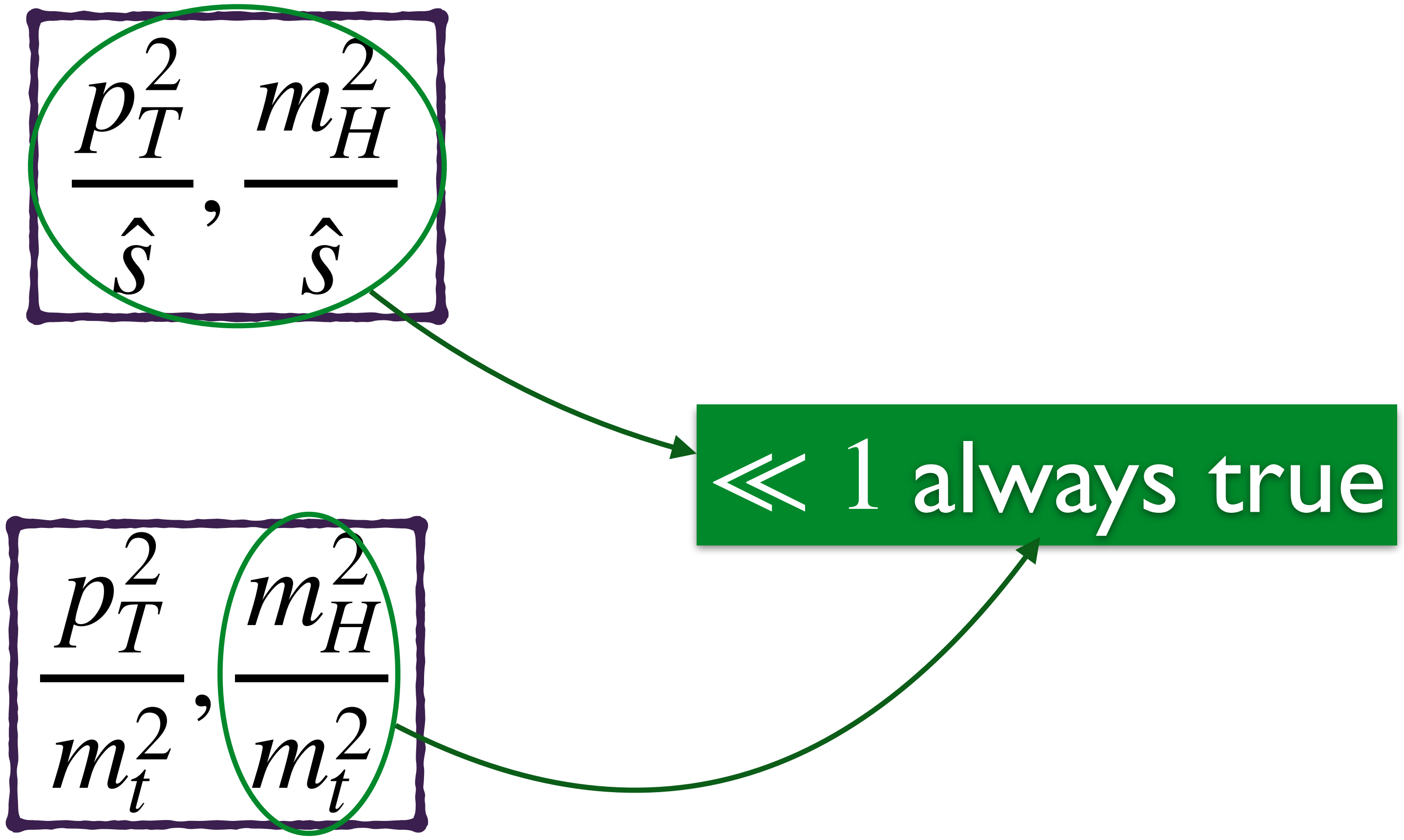

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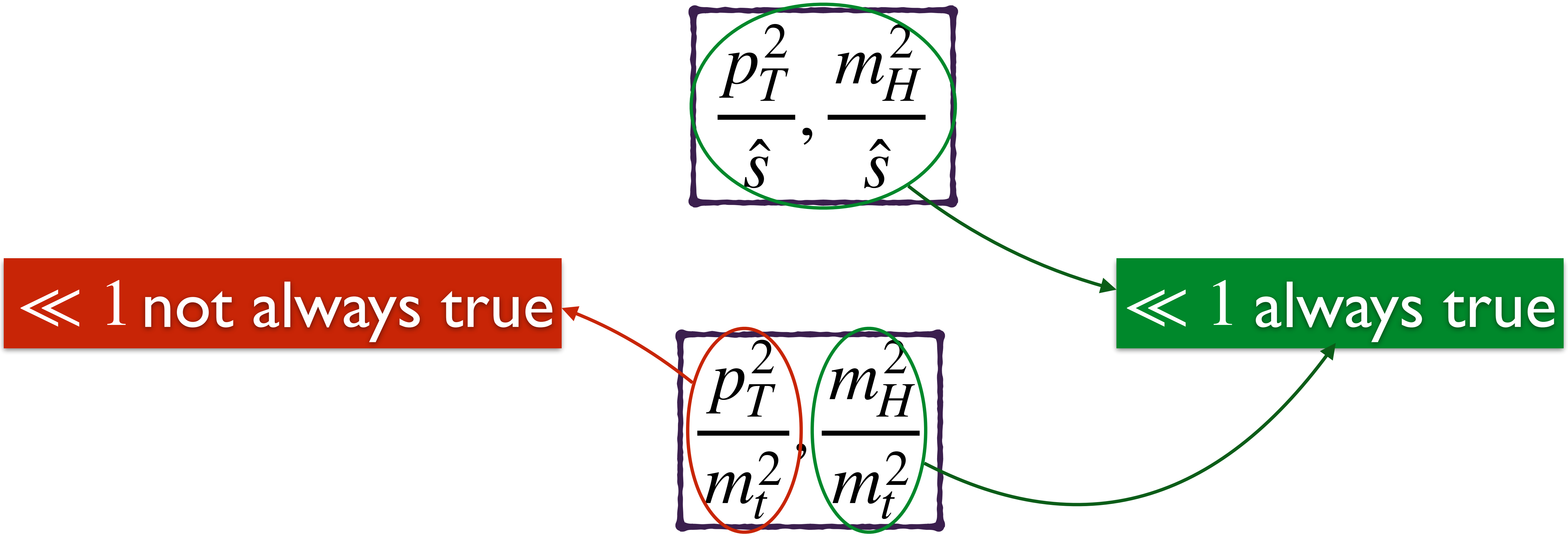

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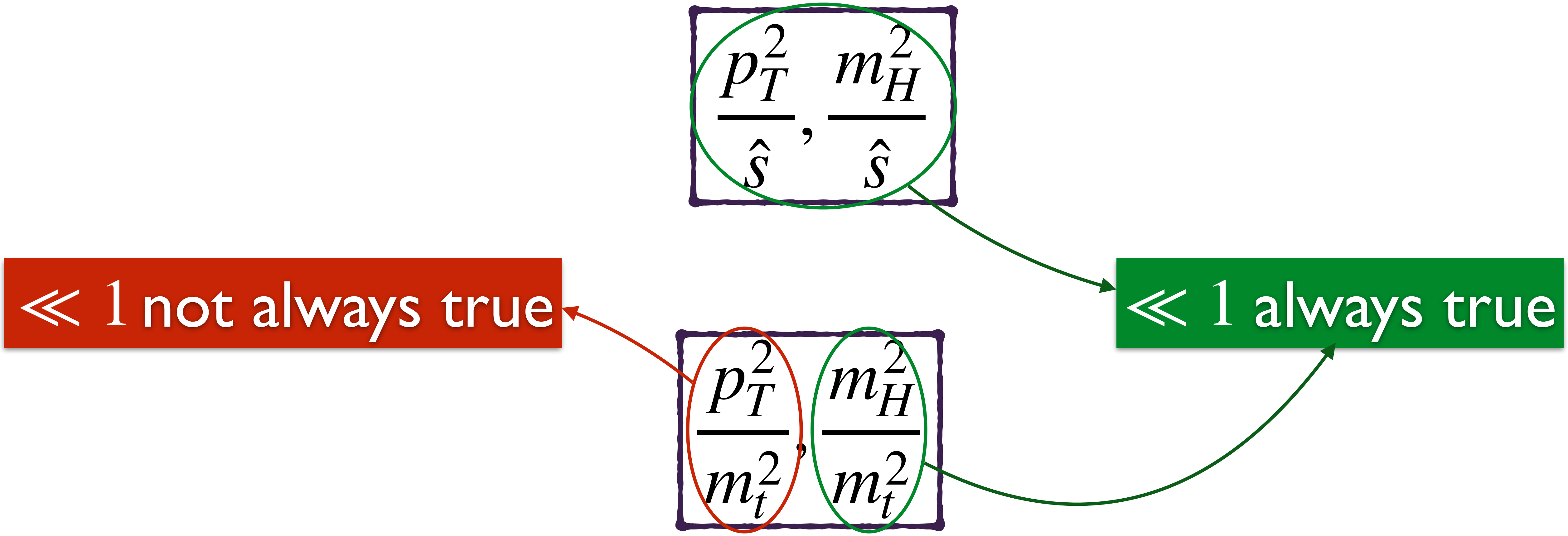

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$\Delta\sigma$ — $\hat{s}$	$4m_t^2$	$6m_t^2$	$8m_t^2$	$12m_t^2$	$16m_t^2$	$32m_t^2$
$p_T^0 \times 10^{-1}$	6.2	4.4	3.2	1.8	1.0	0.3
$p_T^2 \times 10^{-2}$	8.5	4.4	1.1	2.4	5.1	33.2
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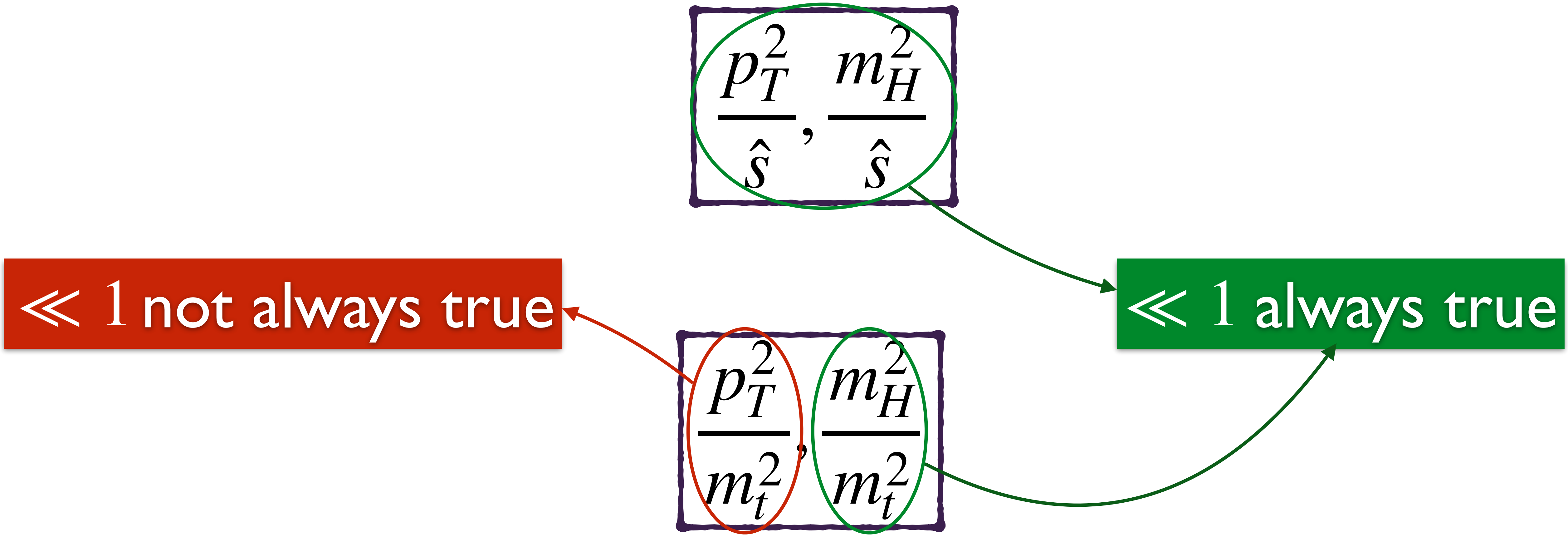

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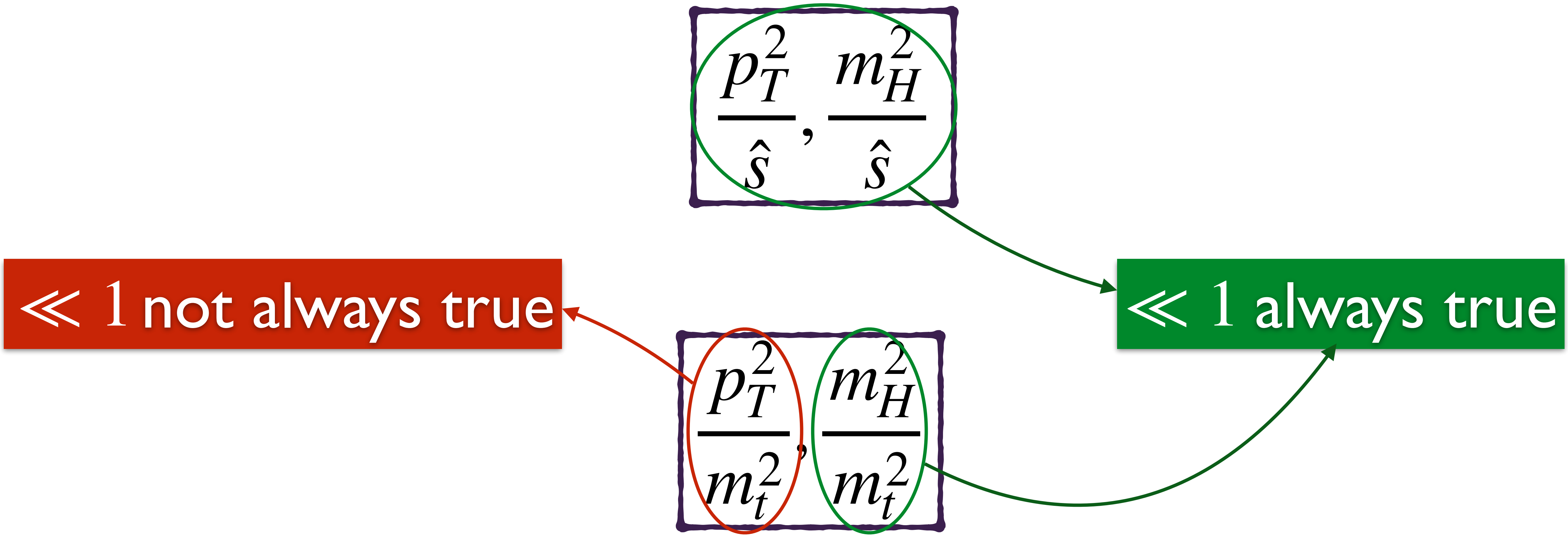
It starts diverging around

$$\sqrt{\hat{s}} \lesssim 500 - 600\, GeV$$



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It starts diverging around

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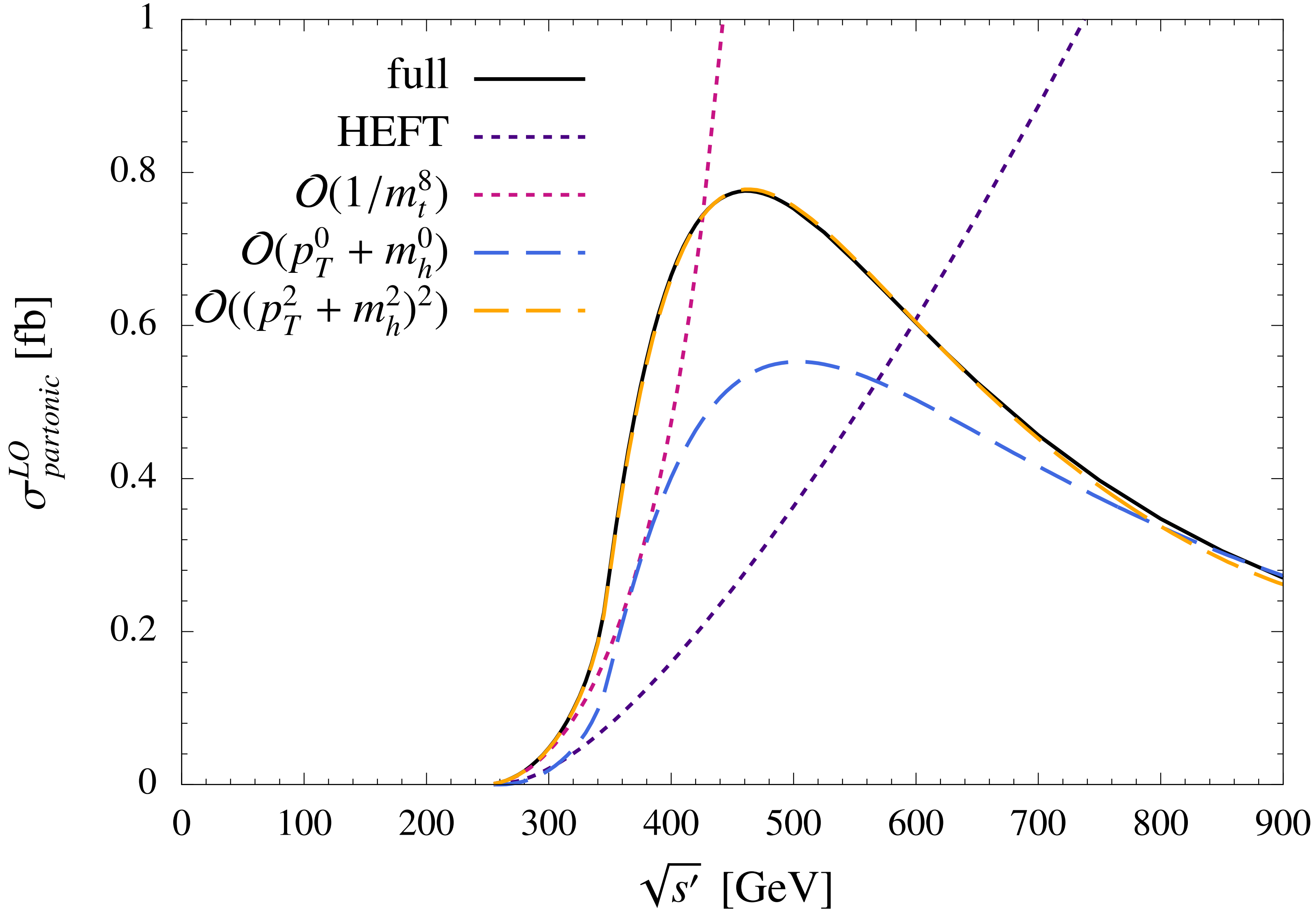
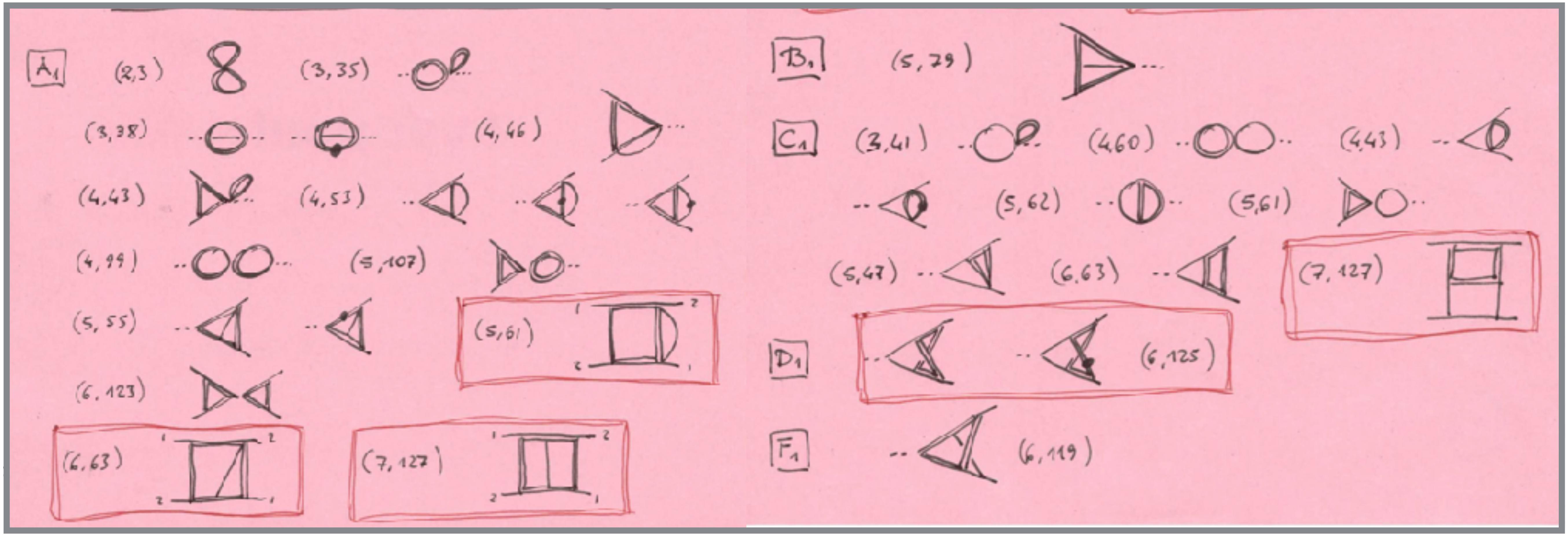
Good approximation up to $\sqrt{\hat{s}} \lesssim 800 - 900\, GeV$!

R. Bonciani, G. Degrassi, PPG, R. Gröber; Phys.Rev.Lett. 121 (2018) no.16, 162003



The middle region is perfectly covered!

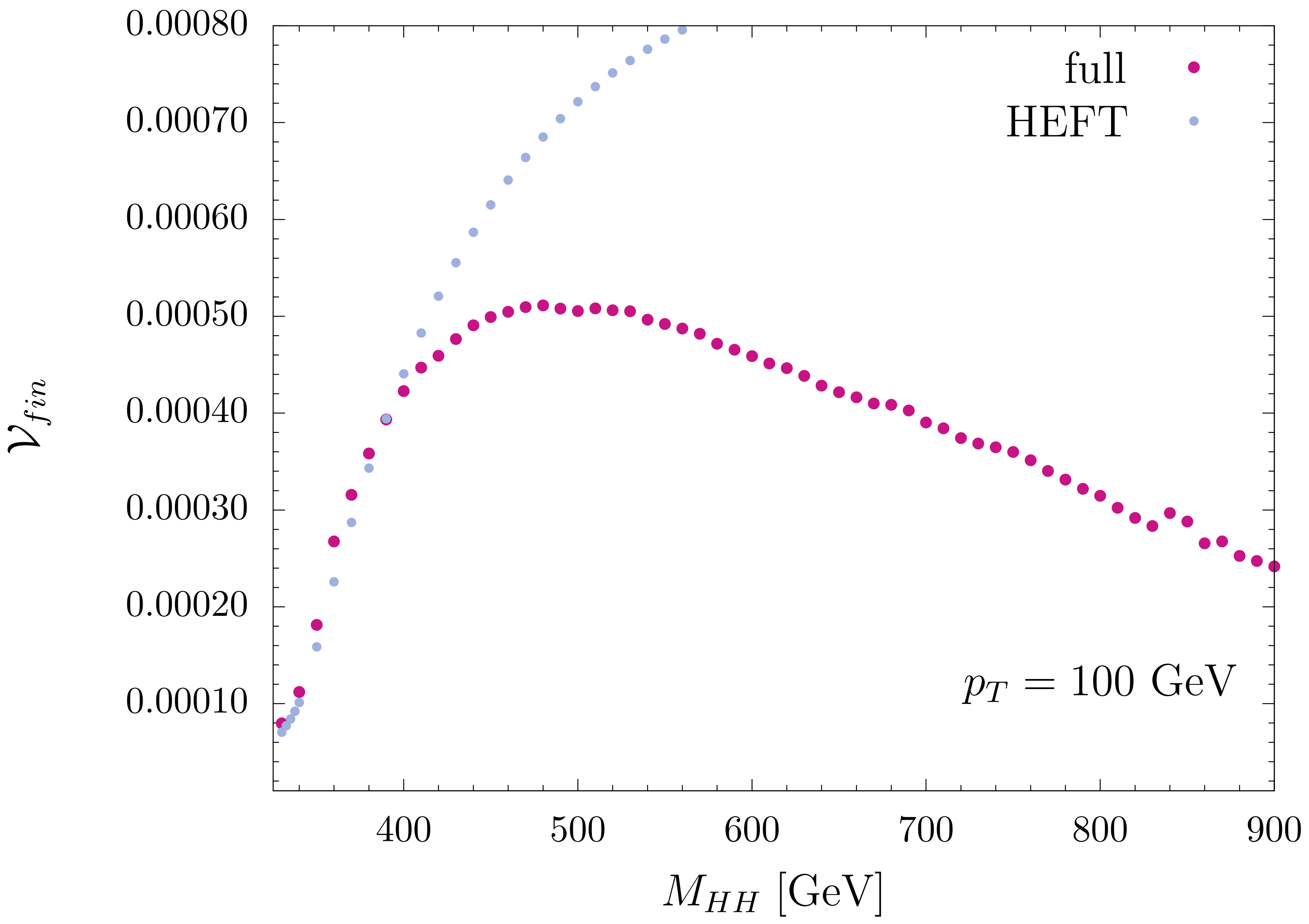
We did the expansion at the amplitude level and then reduced



~50 MI known (recomputed in forward kinematics)

Nearly all expressed in terms of HPL

R. Bonciani, G. Degrassi, PPG, R. Gröber; Phys.Rev.Lett. 121 (2018) no.16, 162003



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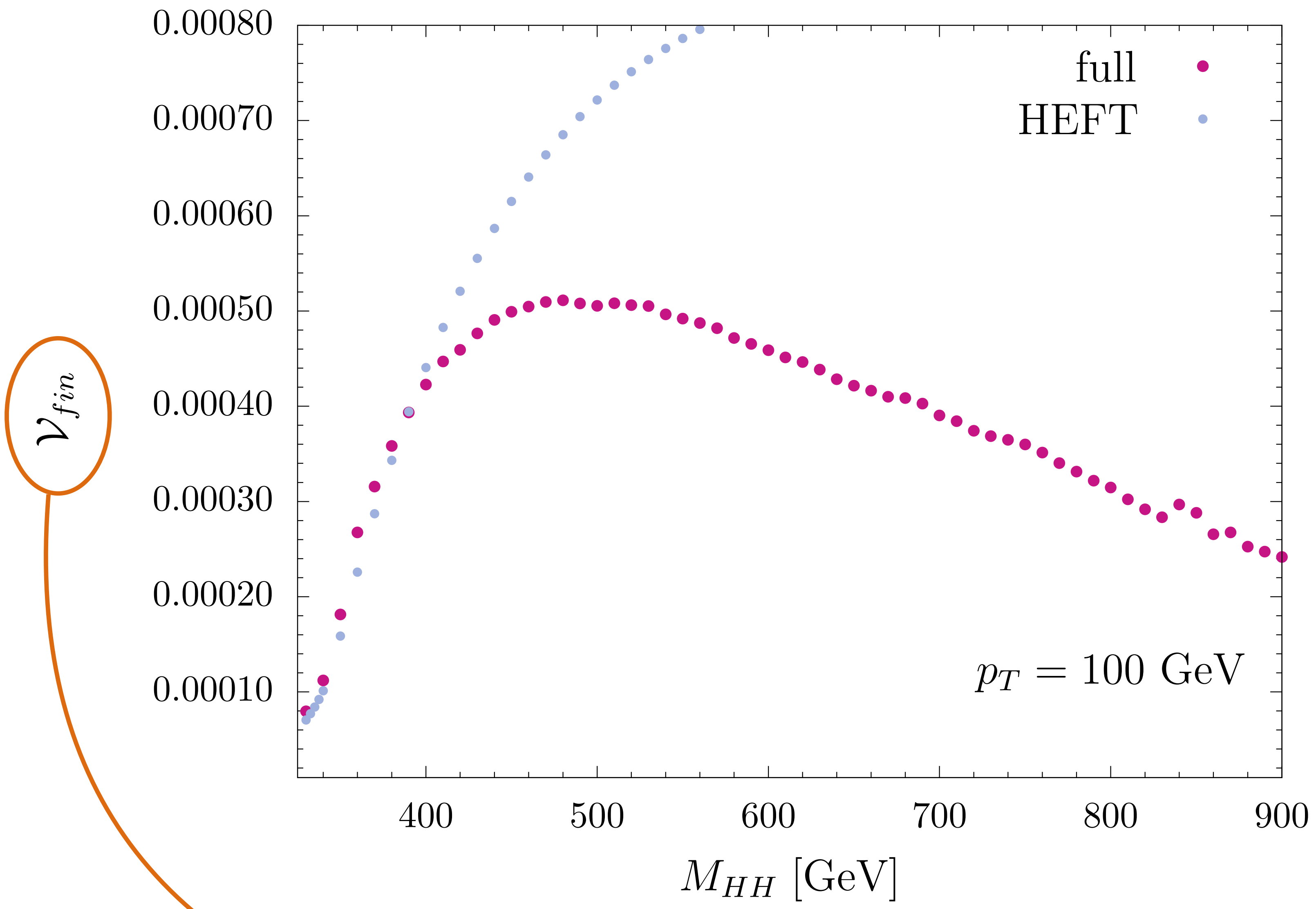
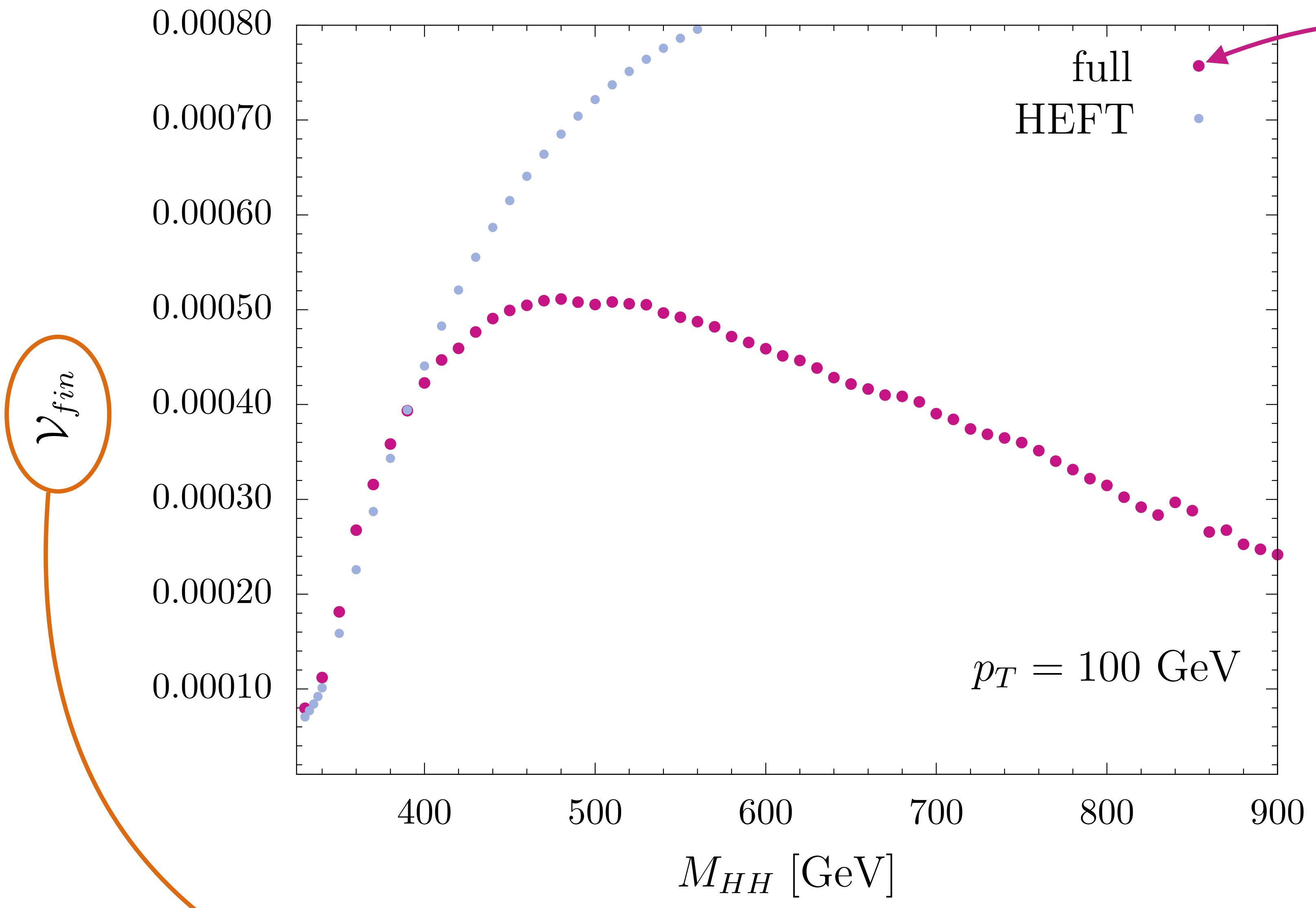


Finite part of the virtual correction

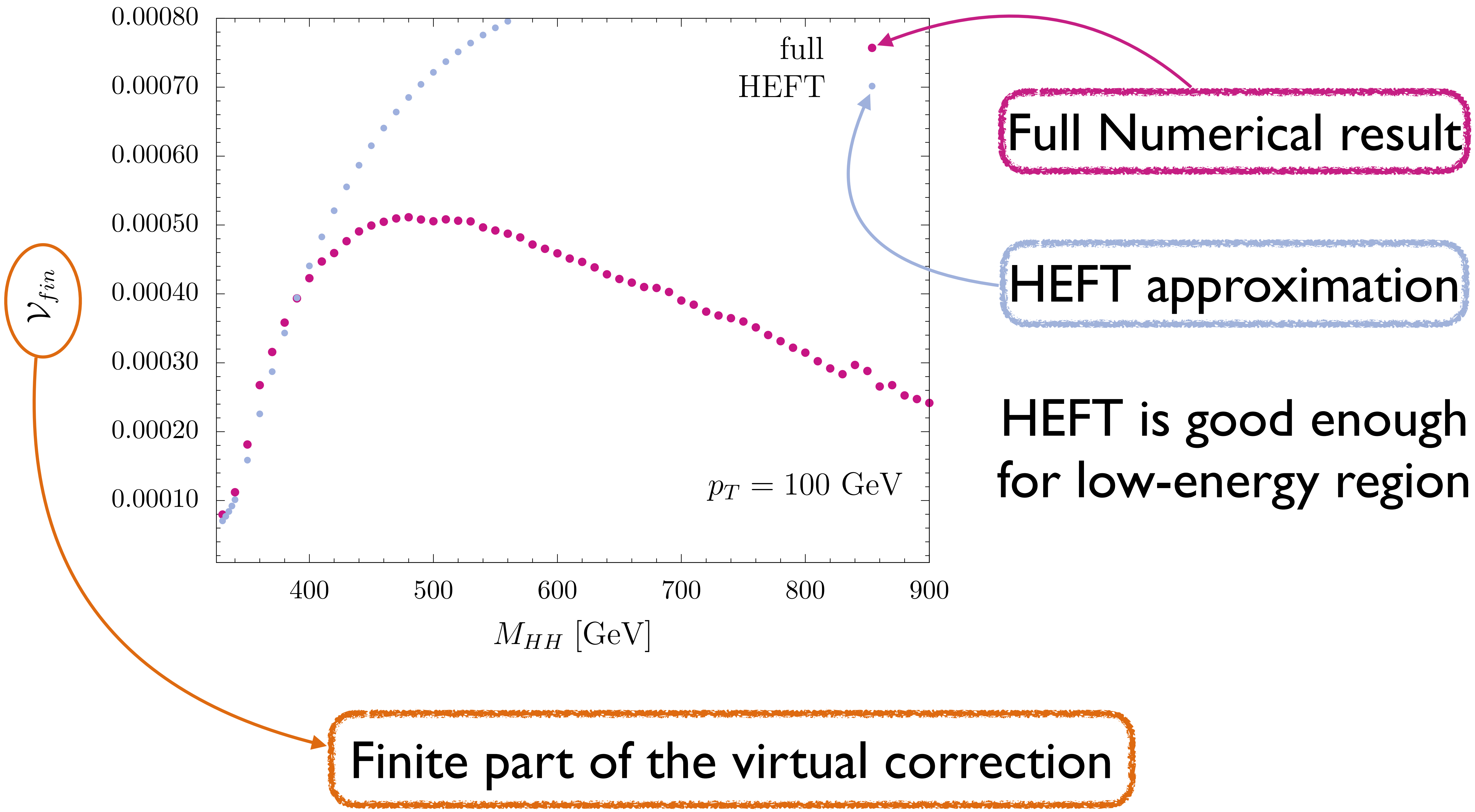
R. Bonciani, G. Degrassi, PPG, R. Gröber; Phys.Rev.Lett. 121 (2018) no.16, 162003



Full Numerical result

Finite part of the virtual correction

R. Bonciani, G. Degrassi, PPG, R. Gröber; Phys.Rev.Lett. 121 (2018) no.16, 162003



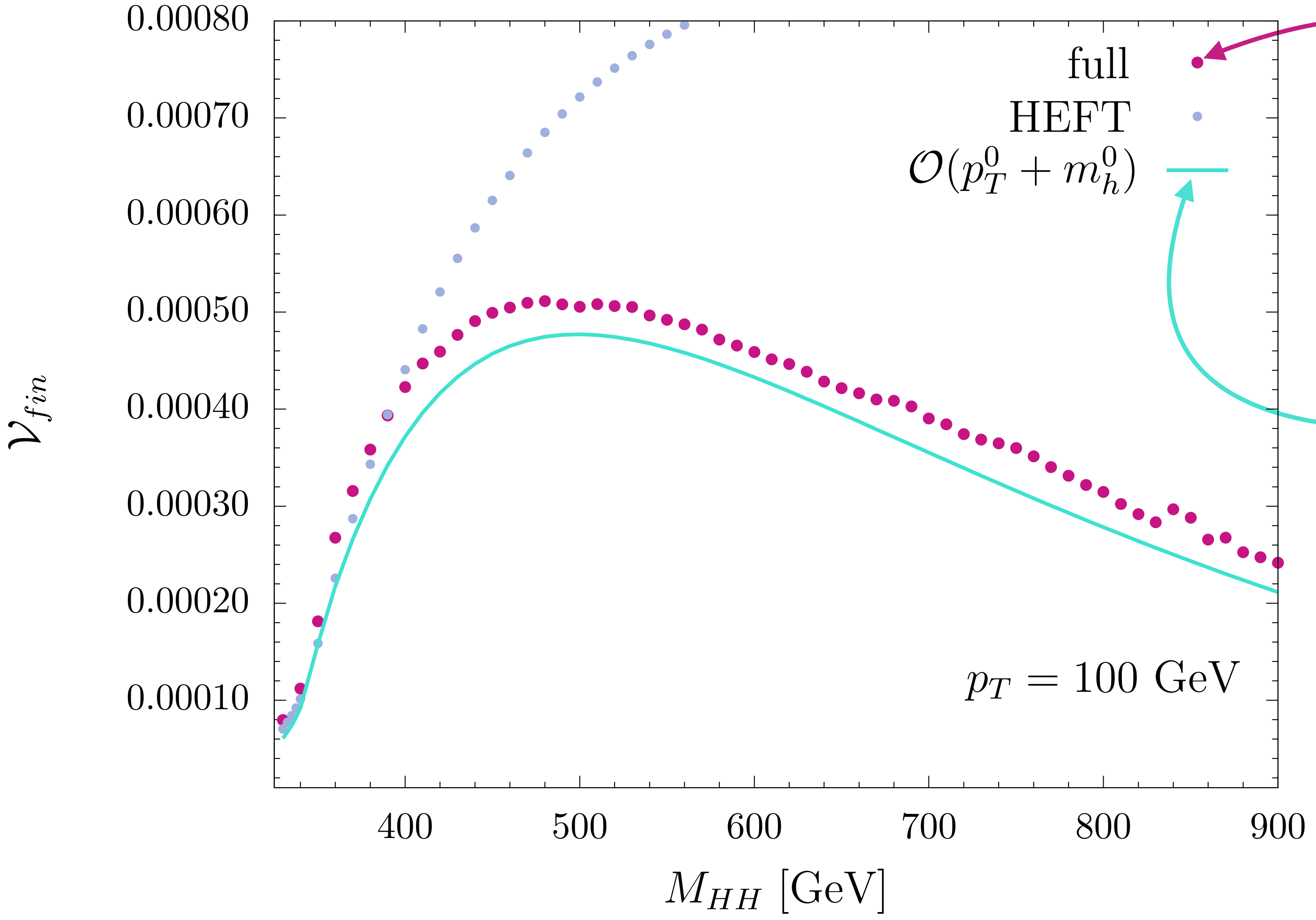
Full Numerical result

HEFT approximation

HEFT is good enough for low-energy region

Finite part of the virtual correction

R. Bonciani, G. Degrassi, PPG, R. Gröber; Phys.Rev.Lett. 121 (2018) no.16, 162003

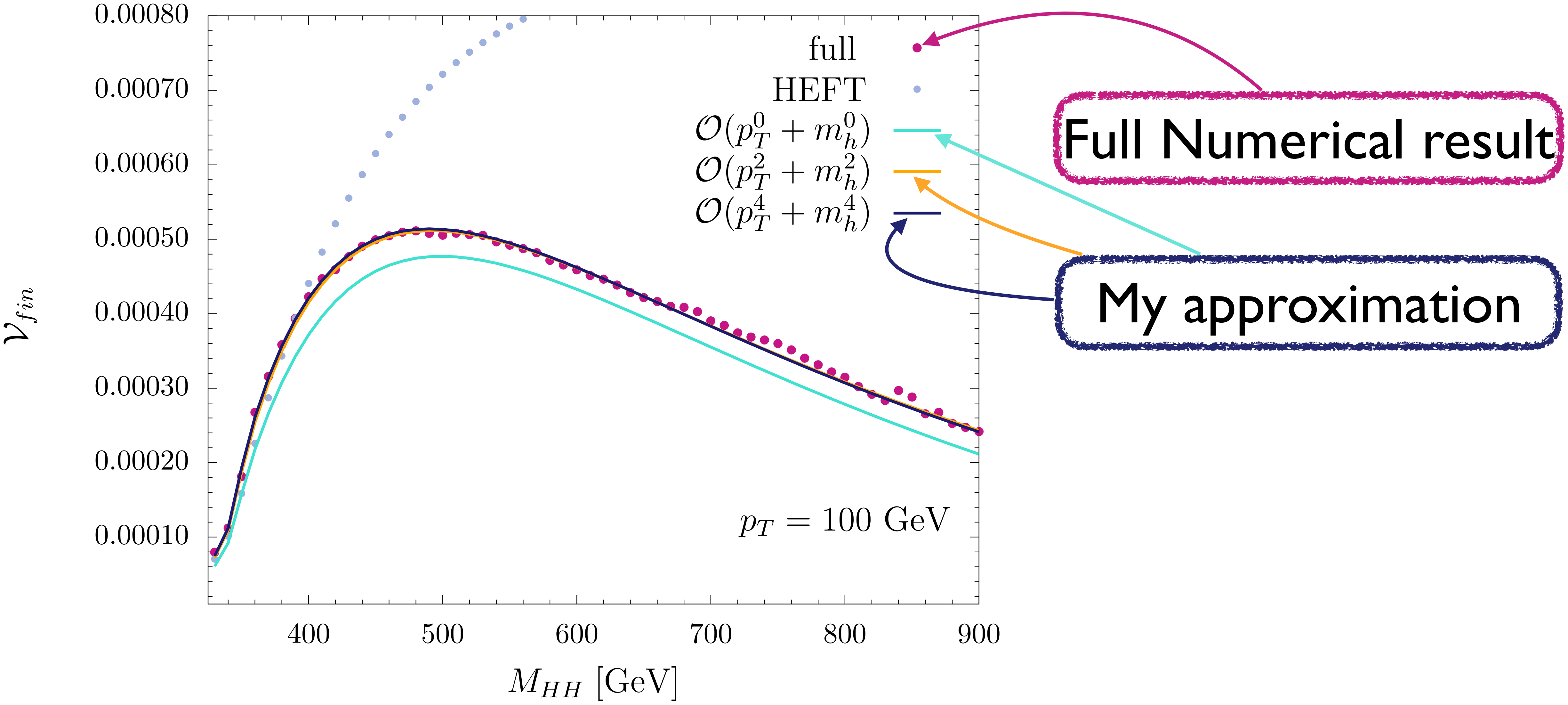


Full Numerical result

My approximation

Approximation good already at order $\mathcal{O}(p_T^0)$

R. Bonciani, G. Degrassi, PPG, R. Gröber; Phys.Rev.Lett. 121 (2018) no.16, 162003



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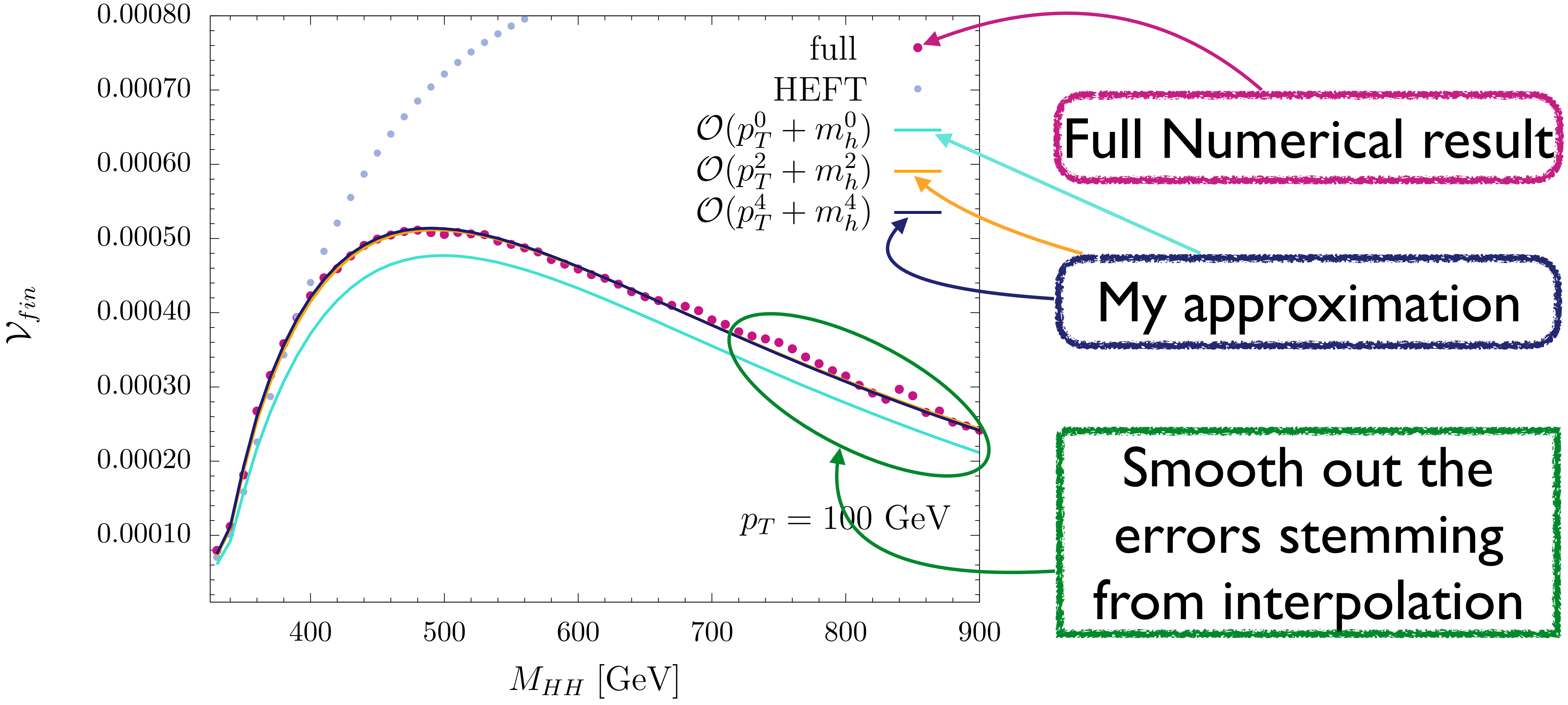
My approximation

R. Bonciani, G. Degrassi, PPG, R. Gröber; Phys.Rev.Lett. 121 (2018) no.16, 162003



Full Numerical result

My approximation

Smooth out the errors stemming from interpolation

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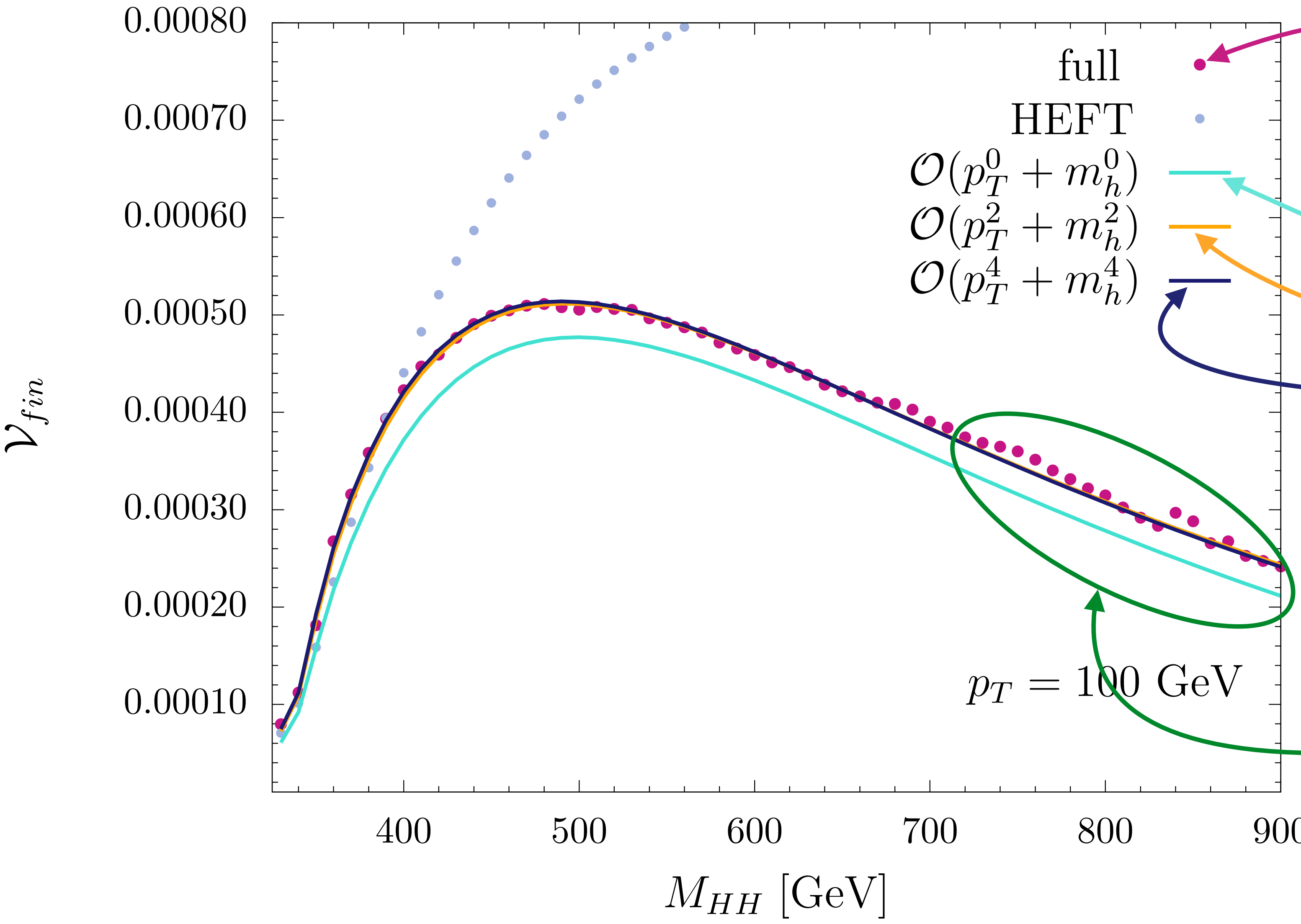

Full Numerical result

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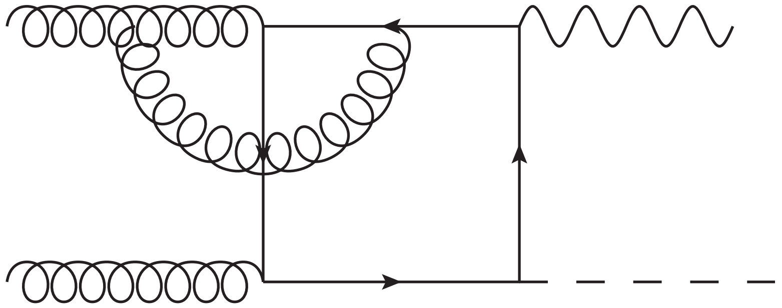
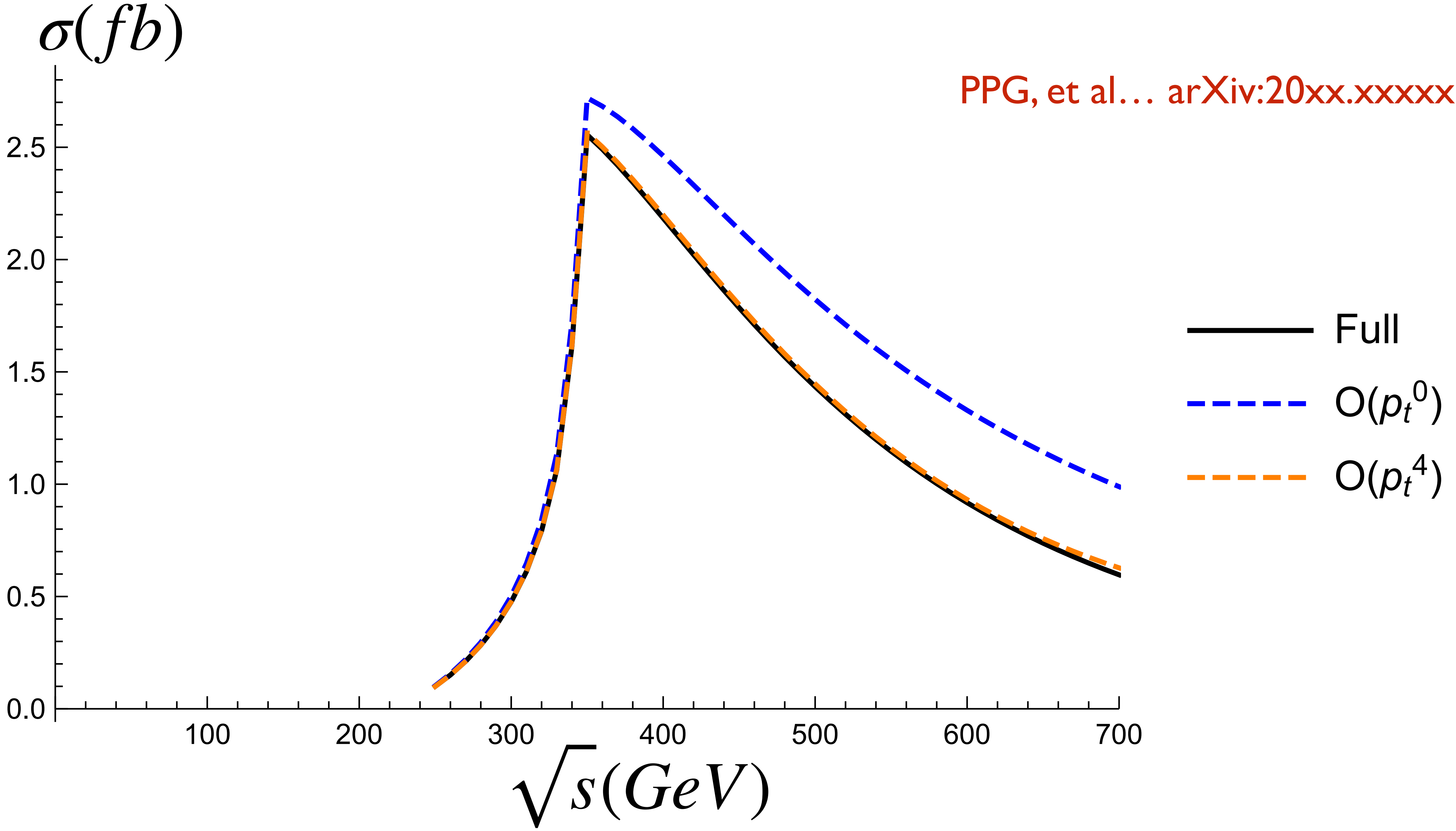
1 phase-space point: ~4 seconds on a MacBook Air



$gg \to HZ$



PPG, et al… arXiv:20xx.xxxxx

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- It describes well the region of energy < 800-900 GeV.
- The Higgs trilinear coupling can be investigated from single Higgs processes.
- Compared to Higgs pair production, the bounds obtained are competitive and complementary!

Outlook

- Many SM processes are already known at NLO.
- But many still miss a complete description.
- The technique used for gg → HH could be adapted to other processes.
- There are already plans to use it for gg → HZ and gg → ZZ.
- And possibly to processes where the adaptation is less straightforward like gg → Hg , gg → WW, 2 → 3 processes, etc.

Outlook

- NLO corrections to the SMEFT have large effects for the EWPO fit.
- It is important to study what would be the impact on other sectors (Higgs and Top).
- Most Higgs decays have been calculated. [Dawson, PPG Phys.Rev. D97 (2018) no.9, 093003 - Phys.Rev. D98 (2018) no.9, 095005]
- The calculation of the main Higgs production processes at NLO in the SMEFT is timely and feasible.

Outlook

- The Higgs sector is not the only that can benefit from precision measurements and calculations.
- E.g. top width direct measurements suffer from very large uncertainties, while indirect ones have strong assumptions on NP
- We [PPG, C. Zhang, Phys.Rev. D96 (2017) no.1, 011901] proposed a method based on tagging the b-quark charge.
- This method is largely independent from assumptions on NP and has small systematic uncertainties.

Conclusions

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Conclusions

- LHC is a fantastic machine that delivered what it promised: the discovery of the Higgs.
- We now need to know where to go from there.
- The precise measurement of SM parameters is one way to light the road ahead of us.
- The experimental effort must be supported by an equal theoretical effort.
- There is still a lot to do for both experimentalists and theoreticians in particular in the Higgs sector.

Thank you!

Olena Shmahalo/Quanta Magazine