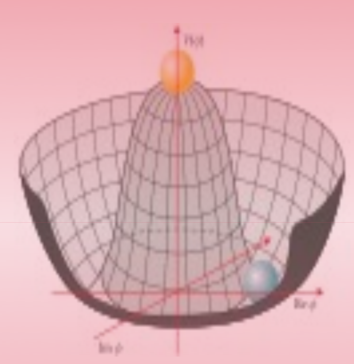
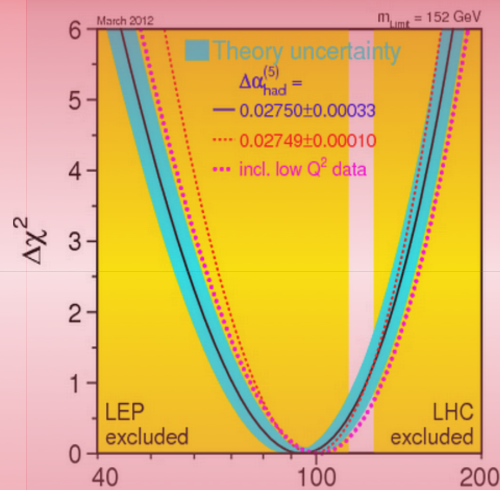
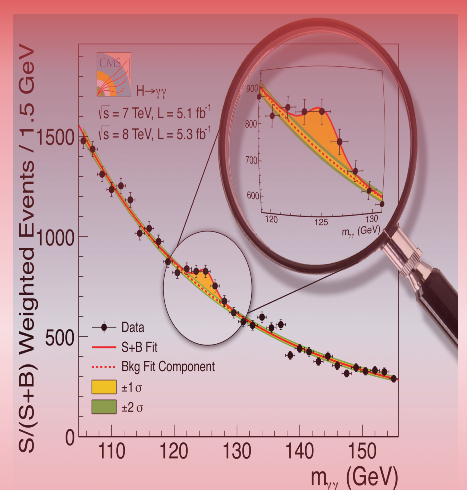


1964

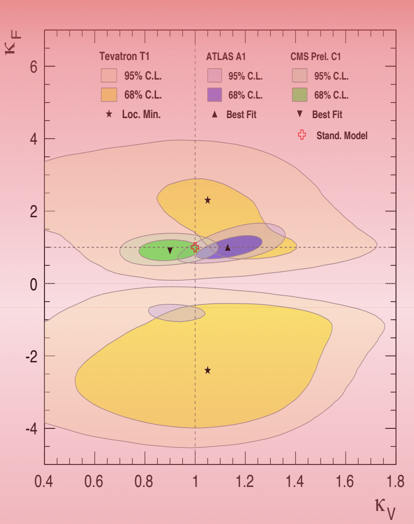


1992-1999

2010



2012



2013

20??

HEP-Theory today & tomorrow

XXVI Rencontres de Blois
Particle Physics and Cosmology
Blois, May 18-23, 2014

Christophe Grojean
ICREA@IFAE/Barcelona
(christophe.grojean@cern.ch)

*iCrea
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

We are living a privileged moment in the history of HEP

A global effort
R. Heuer

(picture: courtesy of A. Hoecker]

The mass conundrum

SM=triumph of Quantum Mechanics + Special Relativity

particles = representations of Poincaré group

these representations are labelled by

(spin, mass)

quantized → spin ← ; mass ← continuous

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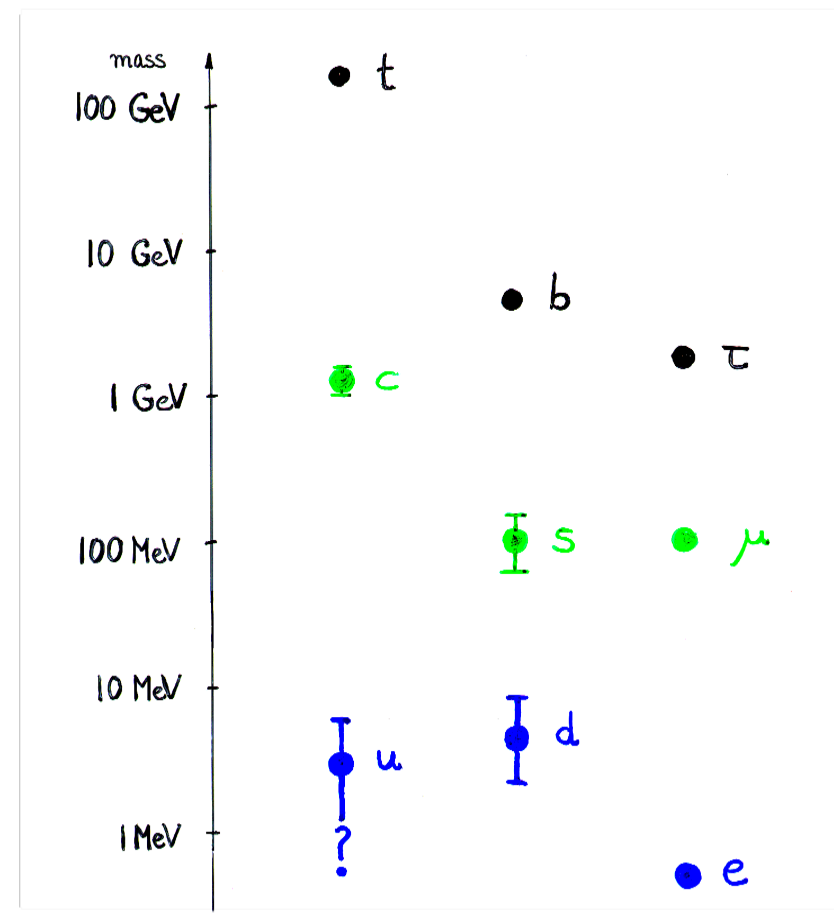

(pictures: courtesy of A. Weiler)

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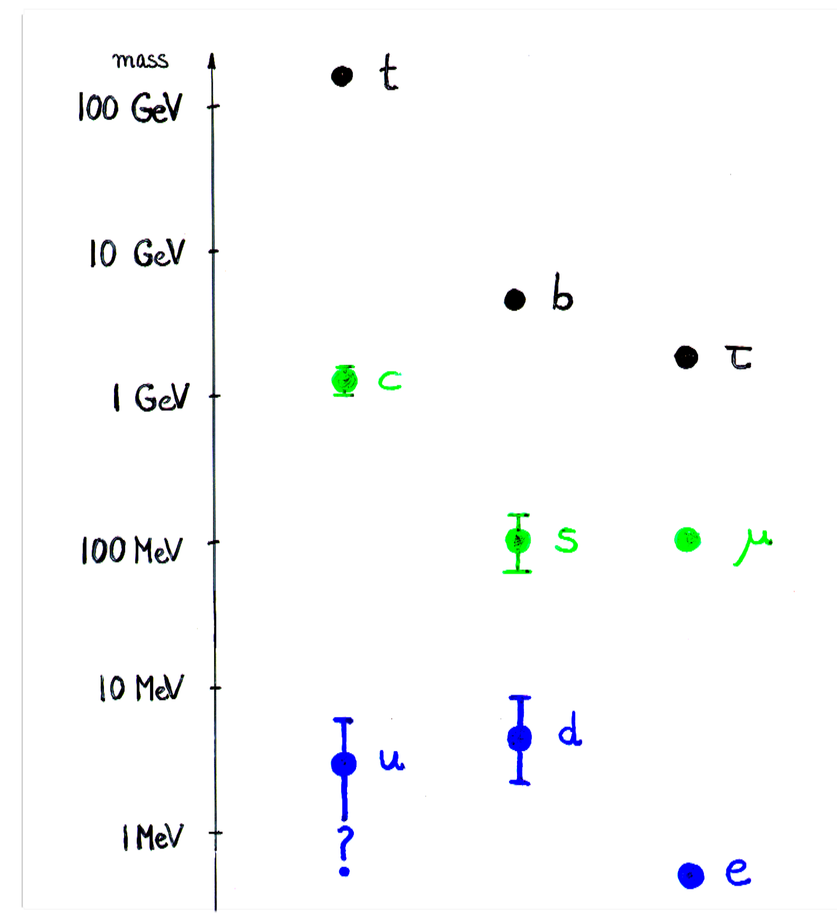


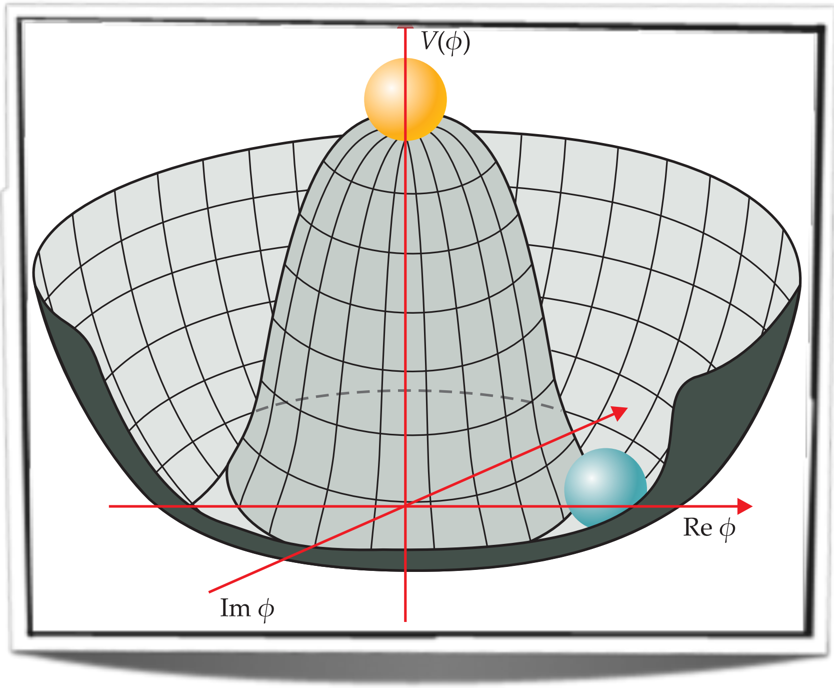
(pictures: courtesy of A. Weiler)

but

incompatible with gauge symmetries
chiral fermion ⇛ m=0 only
gauge boson ⇛ m=0 only

Solution: spontaneous symmetry breaking

The masses are emergent due to a non-trivial structure of the vacuum



vacuum = a space entirely devoid of matter

Oxford English

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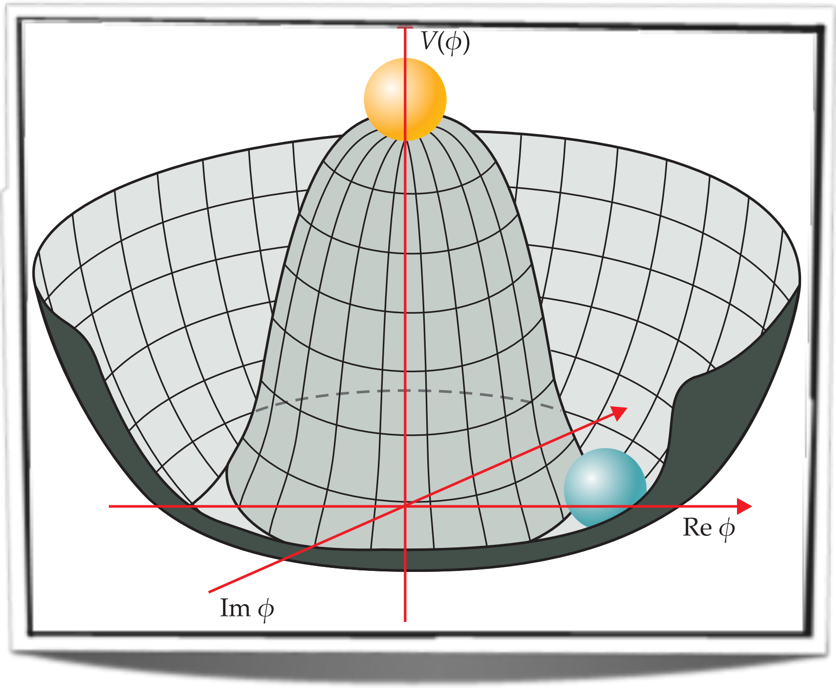

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vacuum = a space filled with Higgs substance

Physics English

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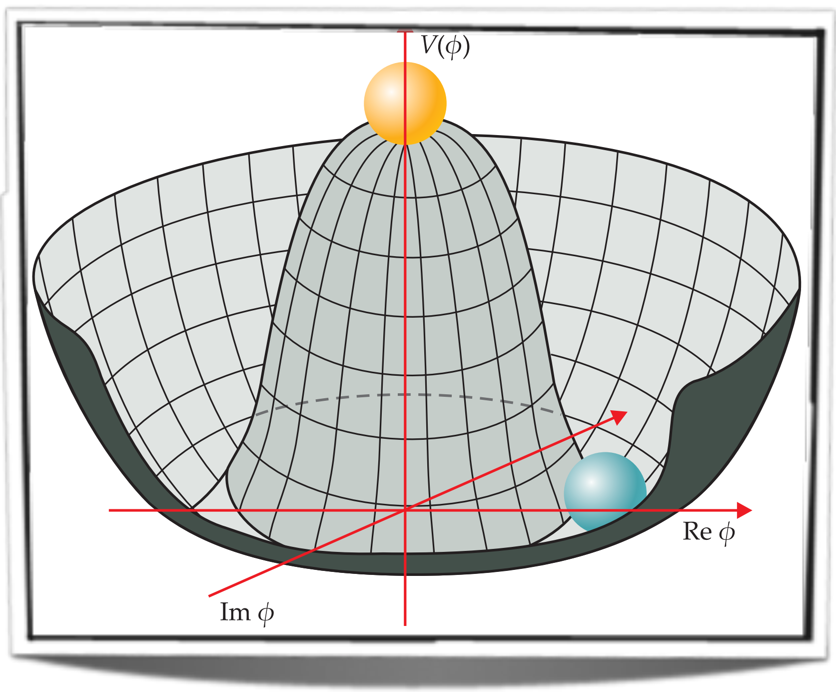

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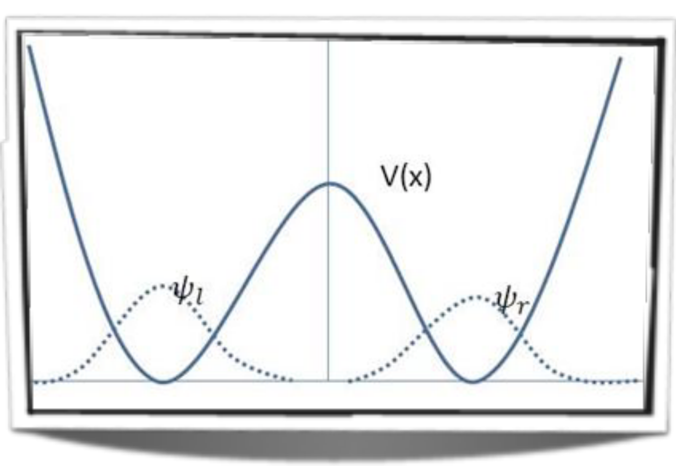
The Brout-Englert-Higgs mechanism is not a trivial thing

(courtesy of J. Lykken@Aspen2014)



ground state of QM double well potential
is a superposition of two states localized on one minimum,
and this superposition preserves the Z_2 symmetry of the potential

Solution: spontaneous symmetry breaking

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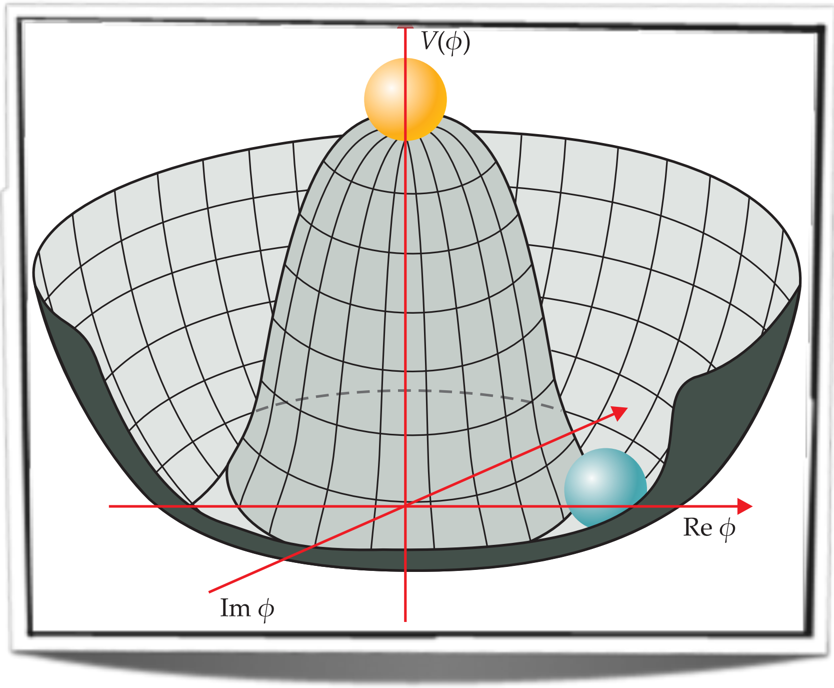

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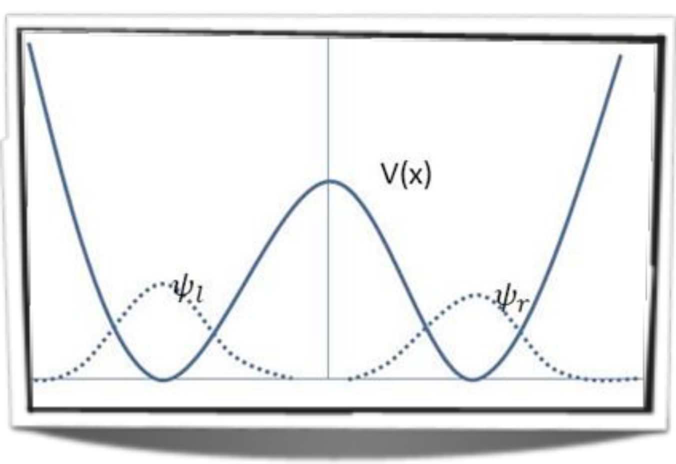

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is a superposition of two states localized on one minimum,
and this superposition preserves the Z_2 symmetry of the potential

the vacuum of the SM breaks SU(2)xU(1) to $U(1)_{em}$

The HEP landscape after LHC_{8TeV}

Nicely summarized by MLM@Aspen'14:

My key message

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

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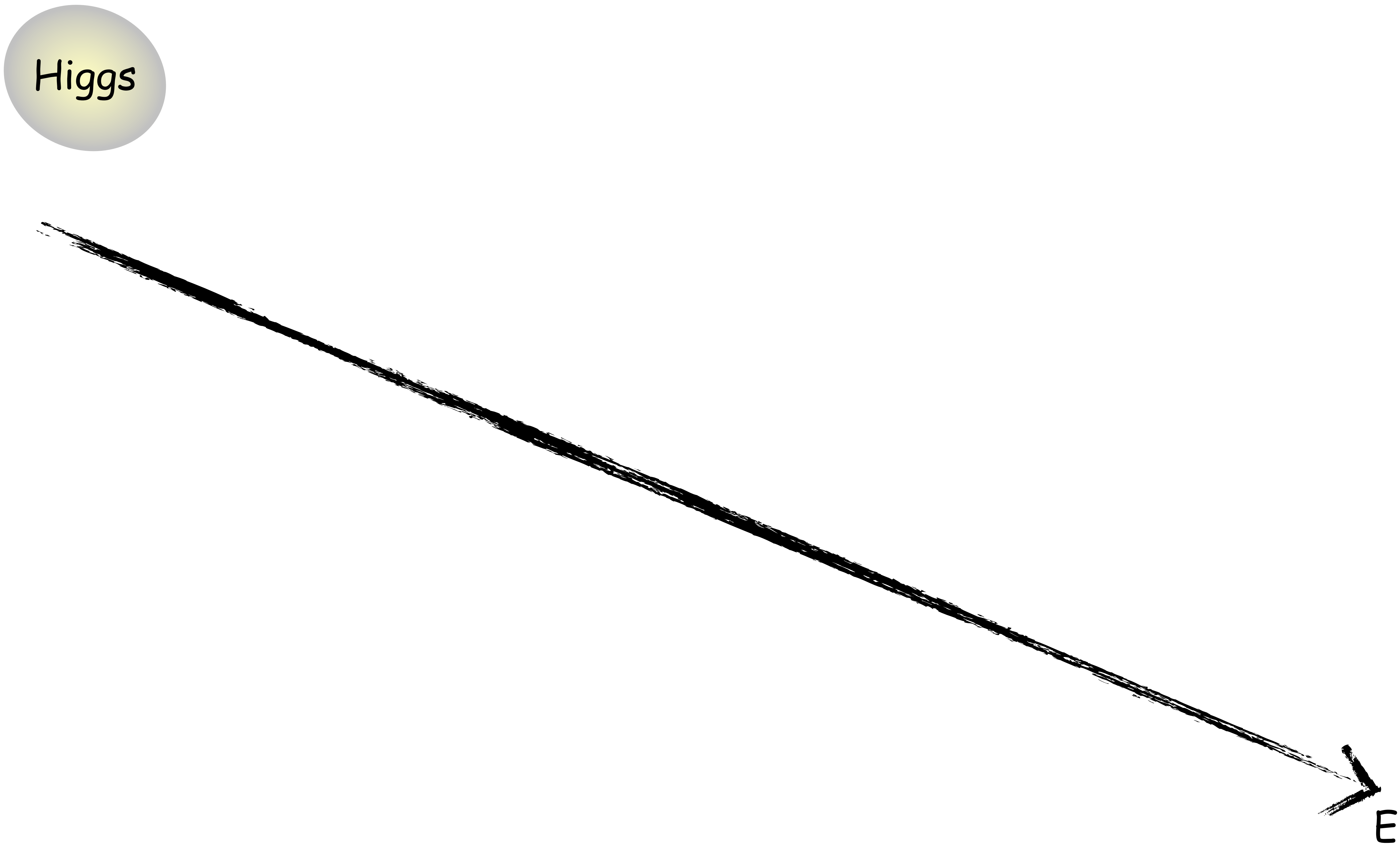
The Higgs discovery sets a large part of the agenda for the theoretical and experimental HEP programs over the next couple of decades.
Unless a new major discovery soon (supersymmetry, DM...)!

We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model



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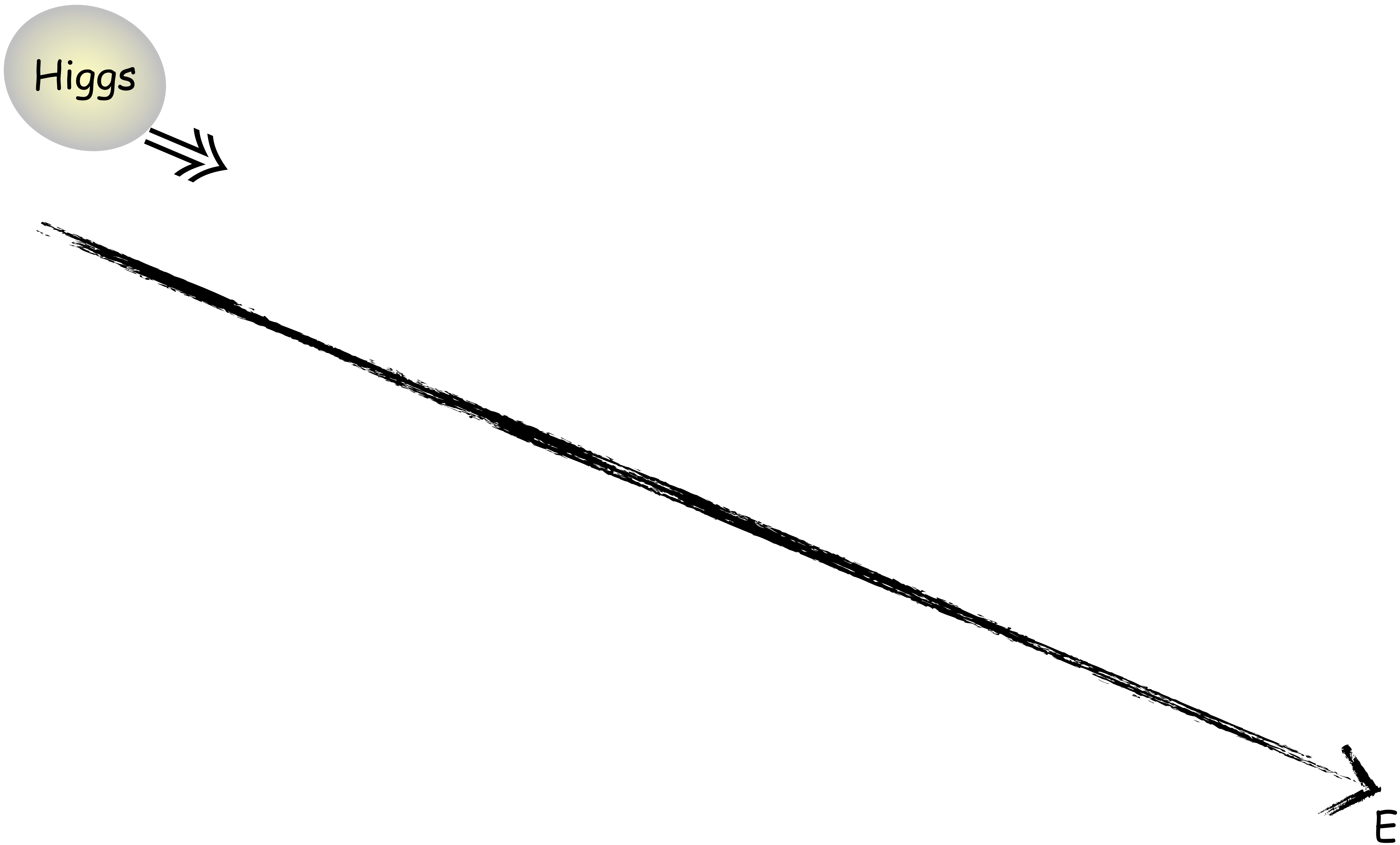

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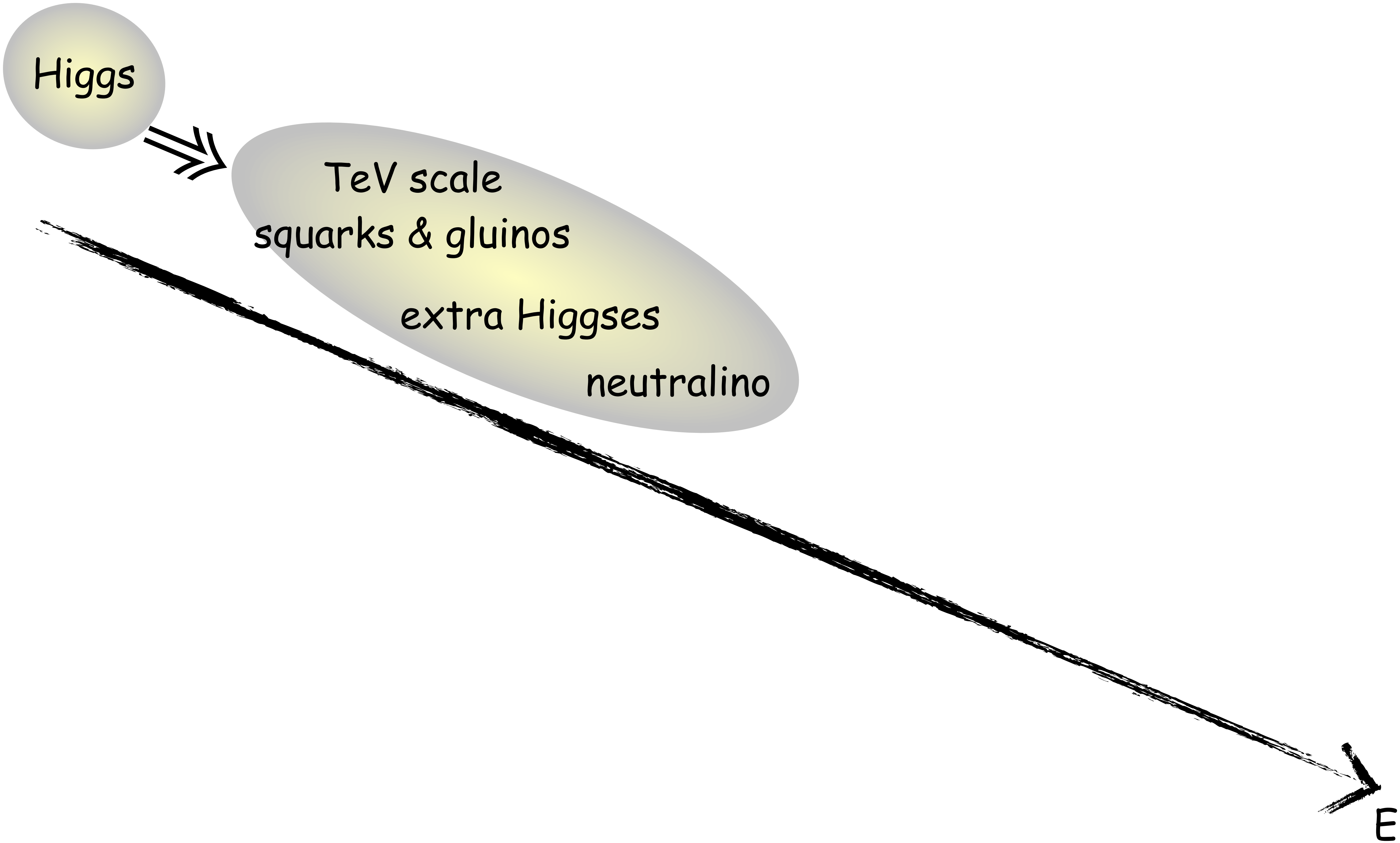

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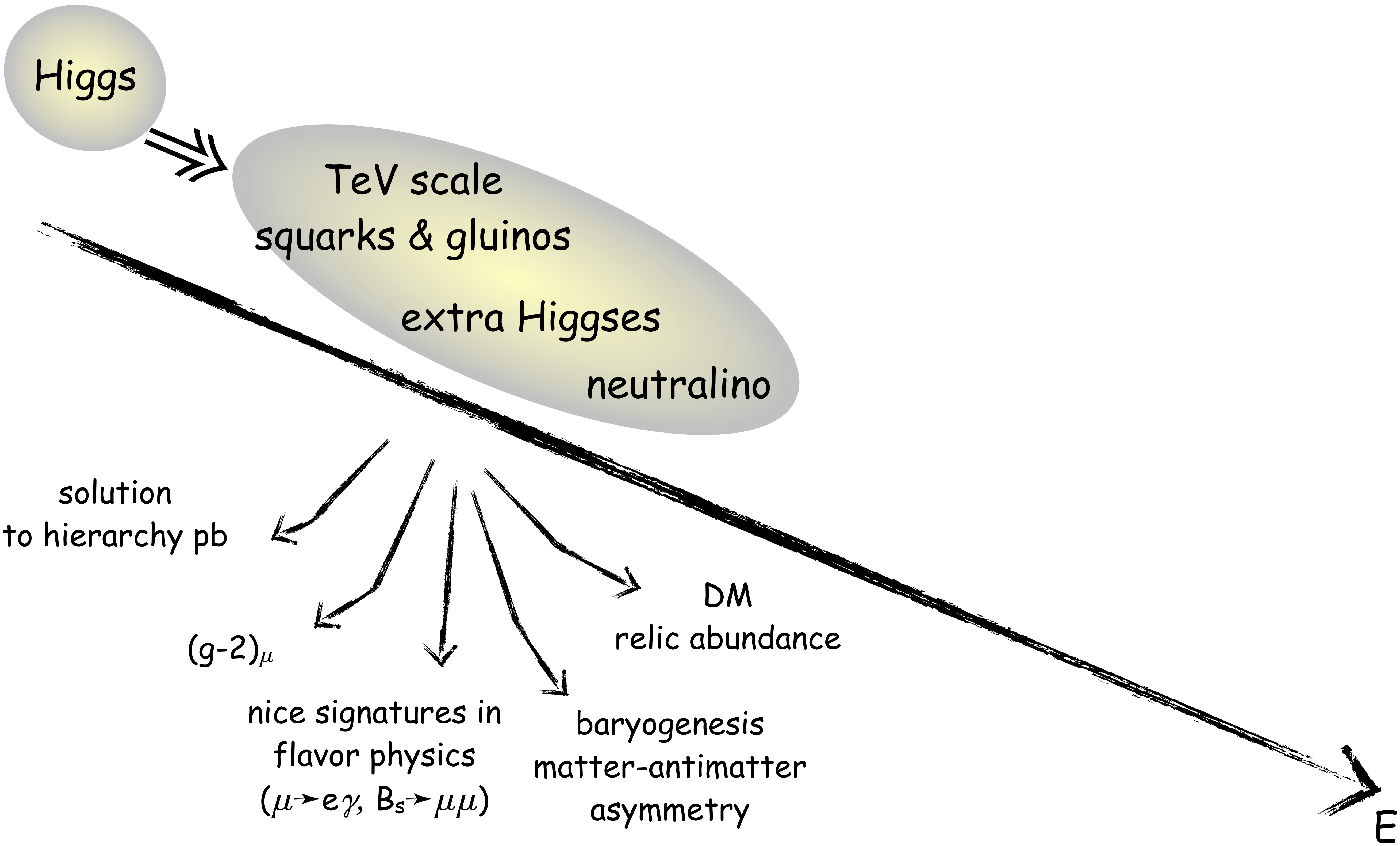

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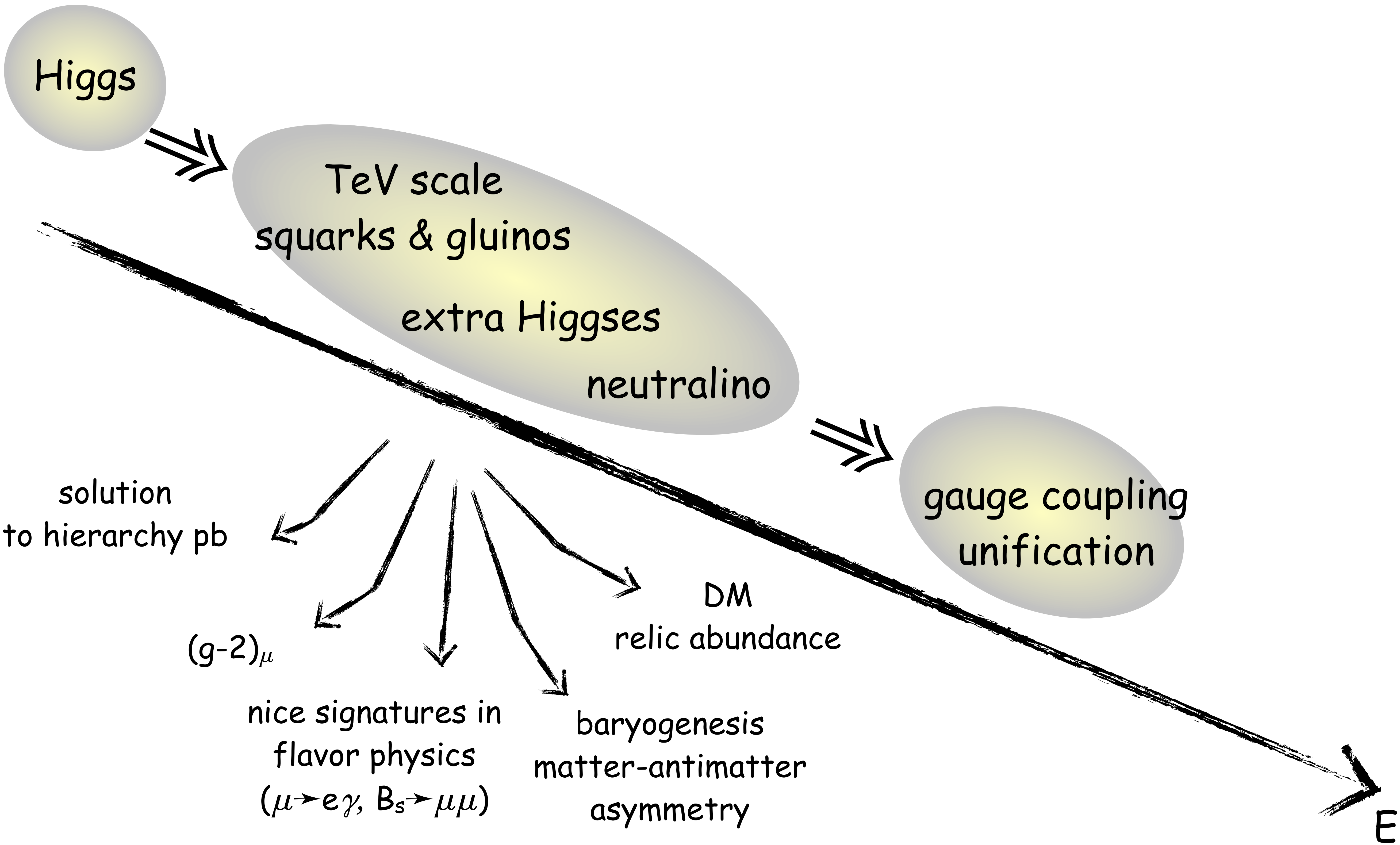

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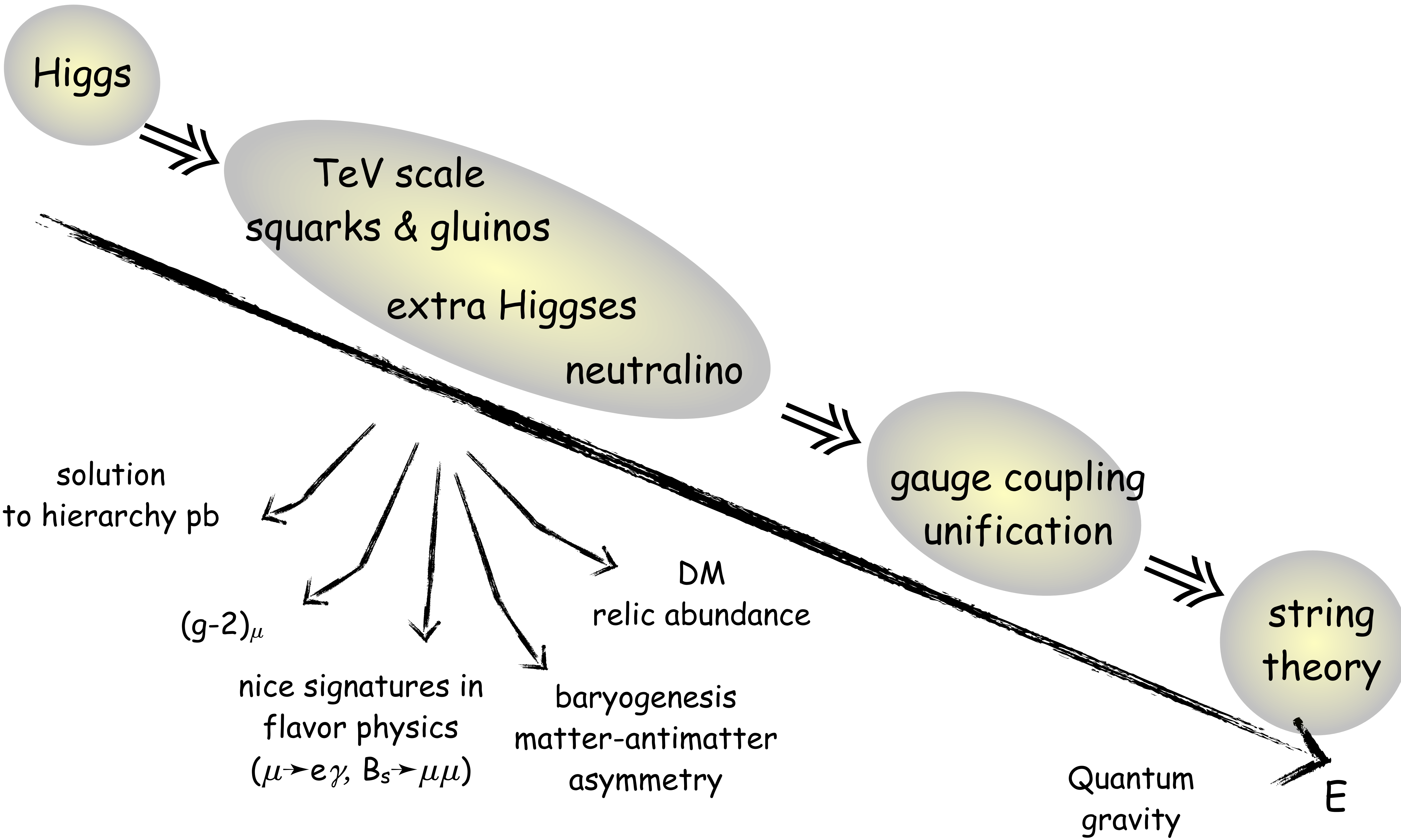

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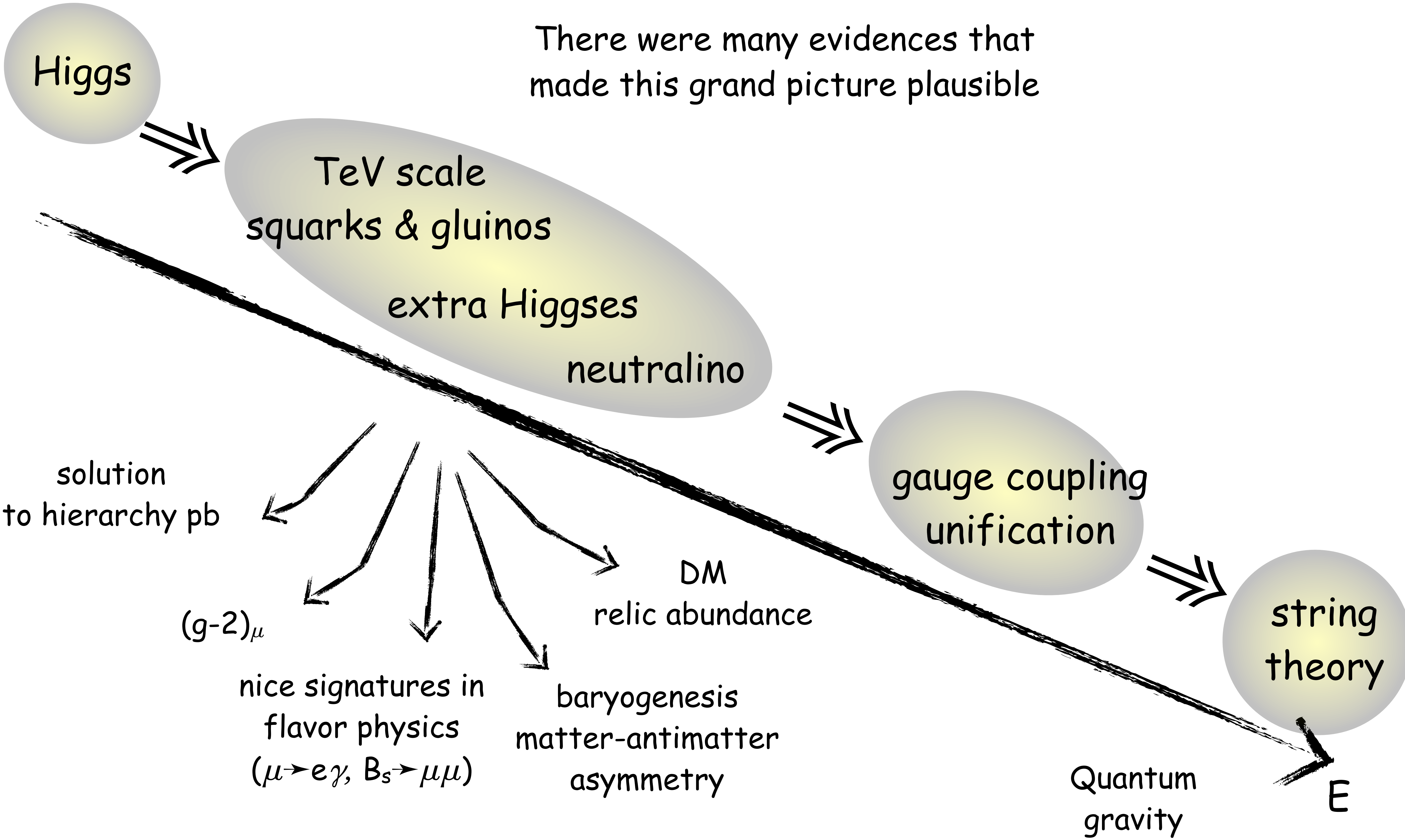

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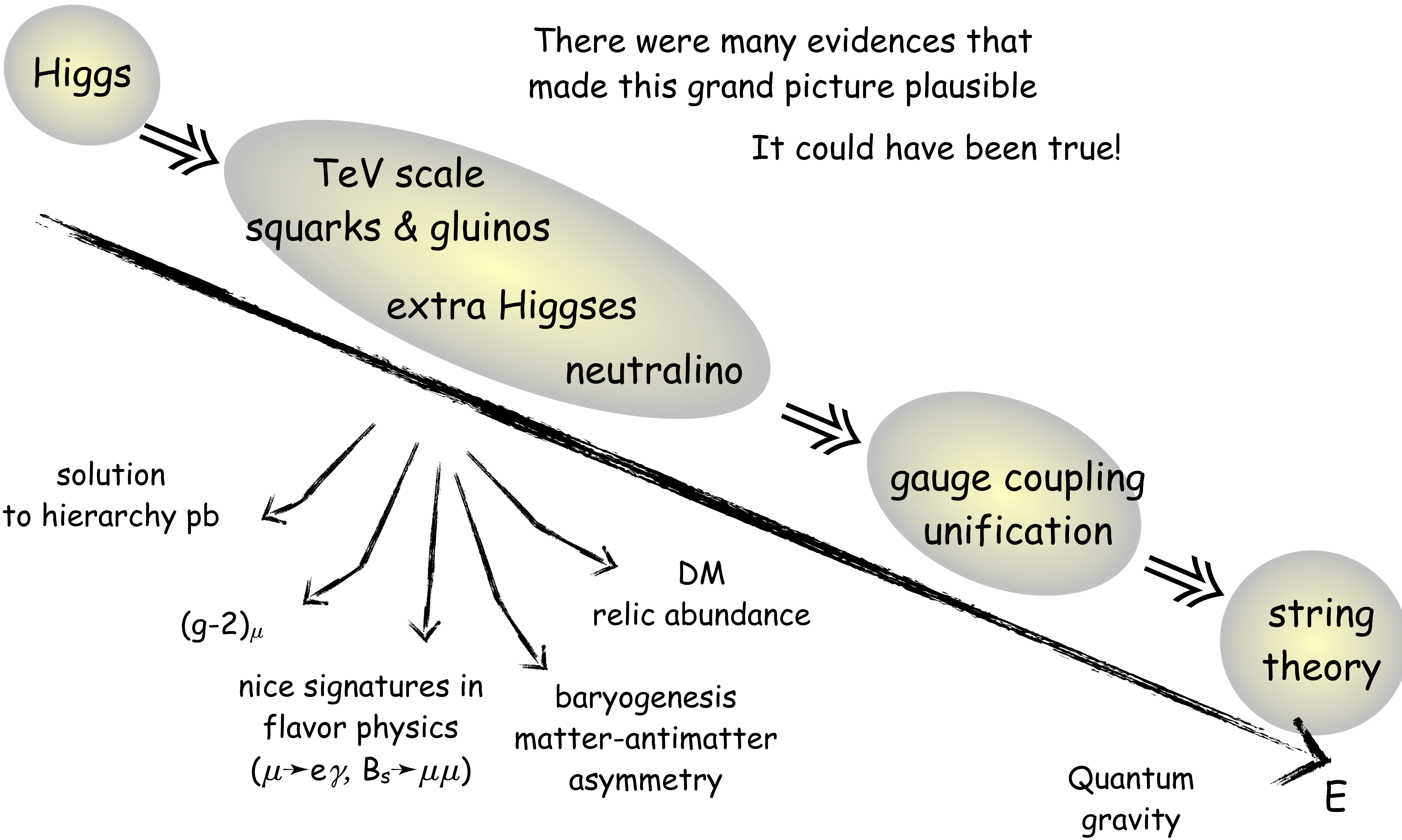
It could have been true!



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Higgs

TeV scale

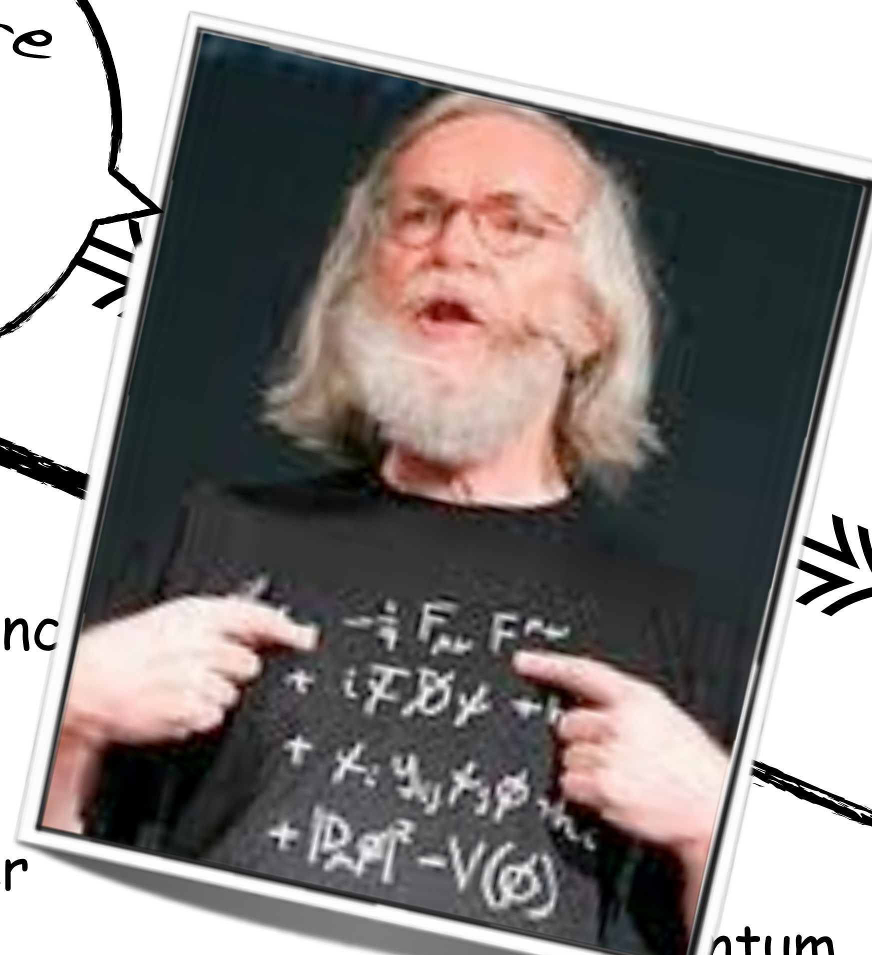
squarks &

SUSY anywhere is better than SUSY nowhere

There were many evidences that made this grand picture plausible

It could have been true!

It can still be true (modulo little tunings)



solution to hierarchy pb

$(g\text{-}2)_\mu$

nice signatures in flavor physics ($\mu \to e\gamma$, $B_s \to \mu\mu$)

baryogenesis matter-antimatter asymmetry

DM relic abundanc

ntum gravity

string theory

E

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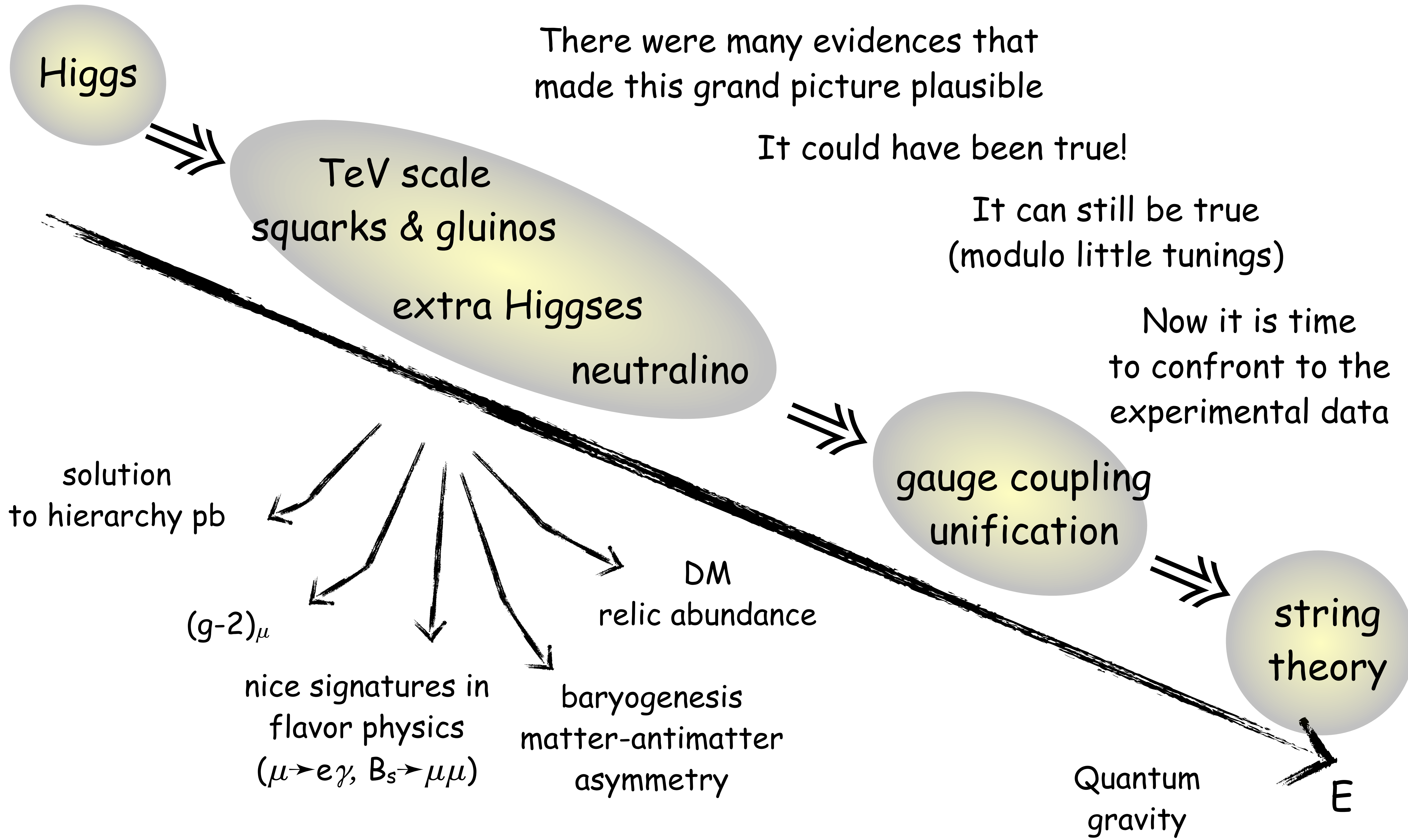

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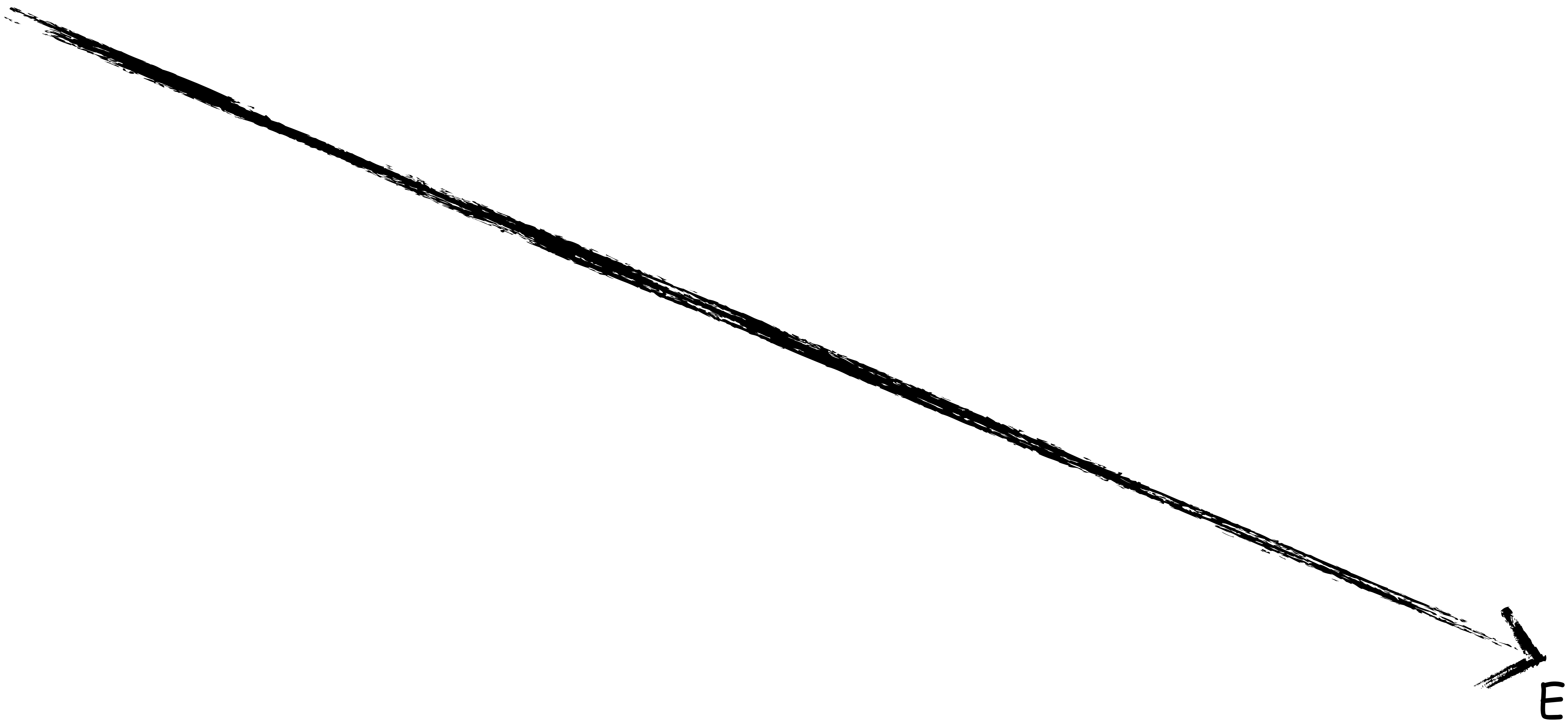

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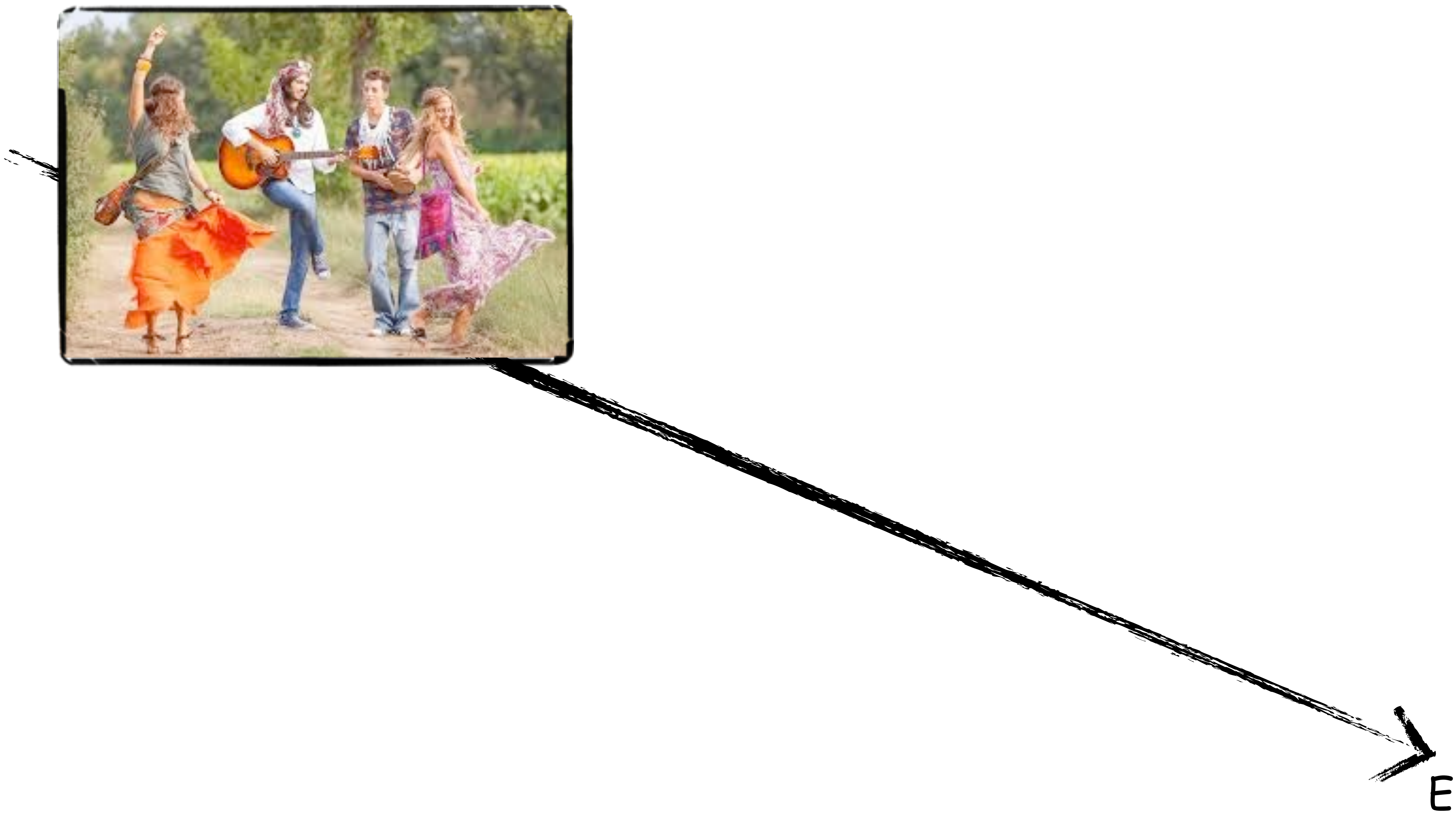
yesterday



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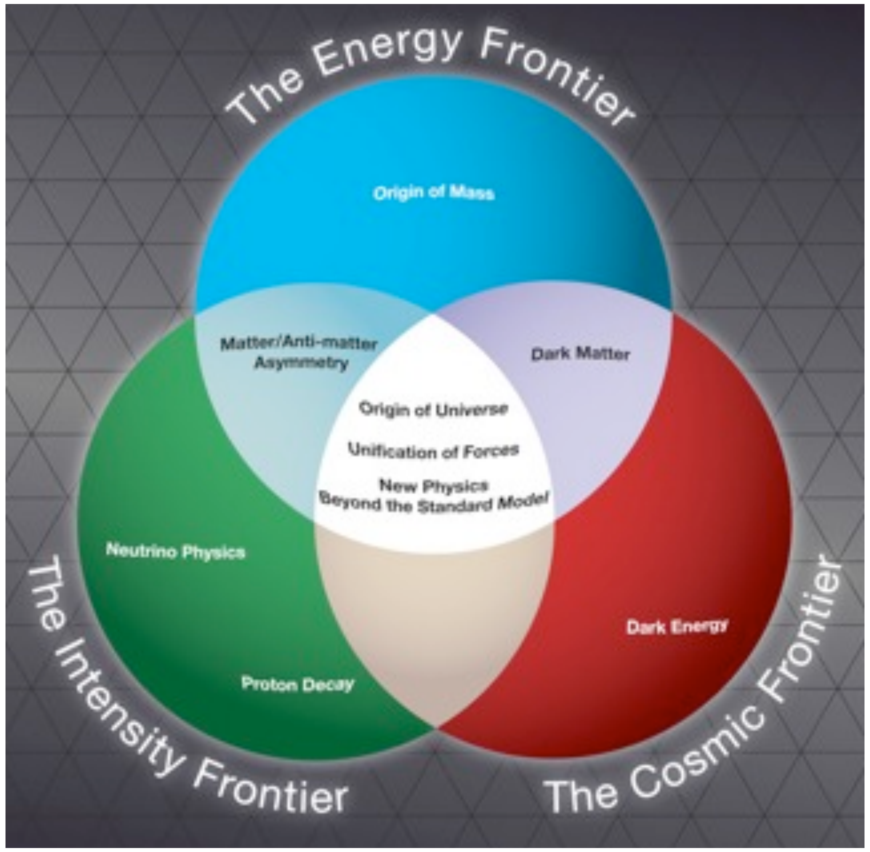
yesterday

today dreaming about tomorrow

E

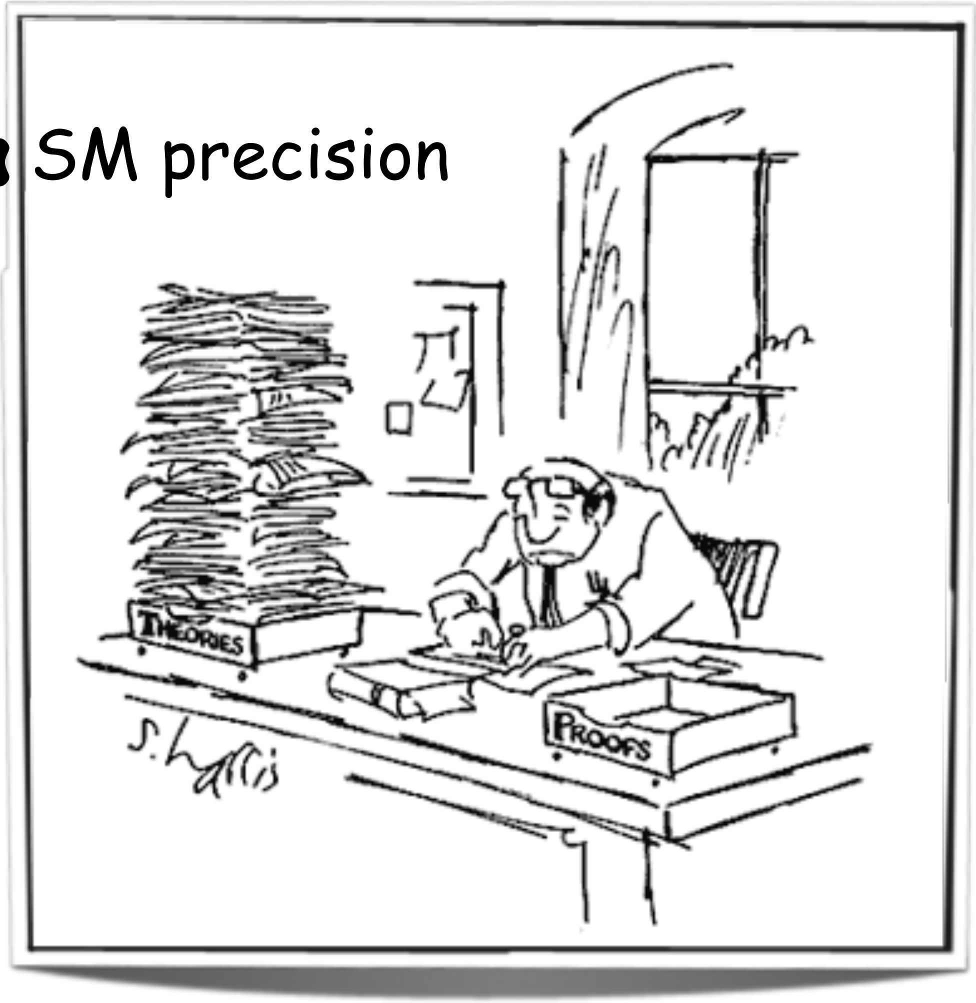
The HEP frontiers

EXP Frontiers



TH Frontiers

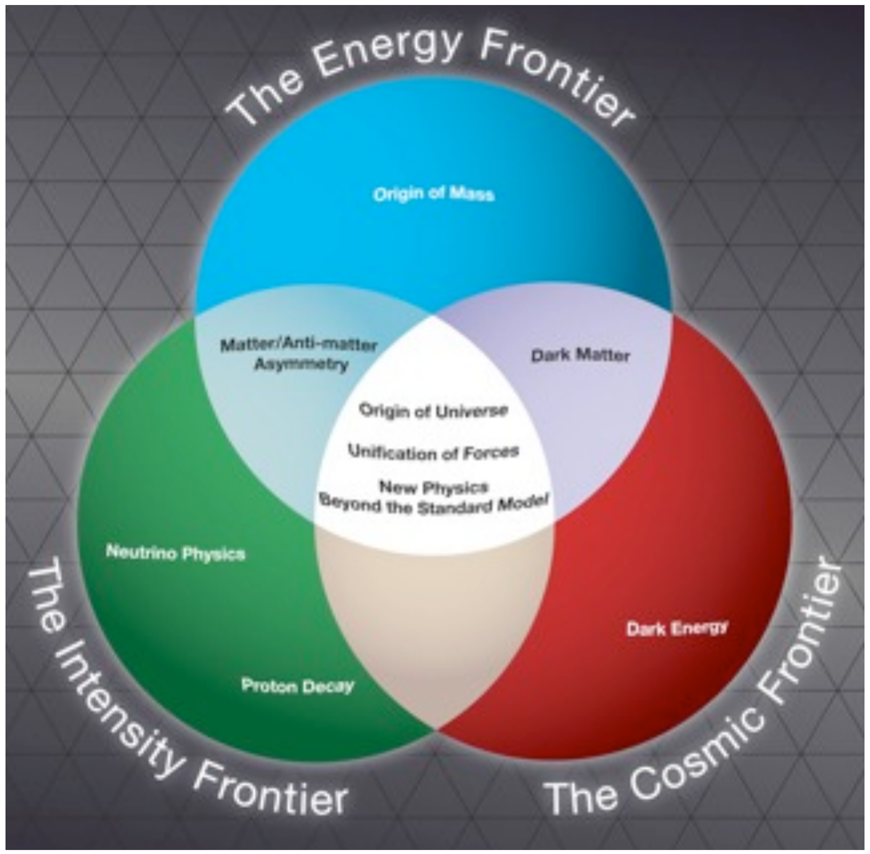
- SM precision



- BSM model building

The HEP frontiers

EXP Frontiers



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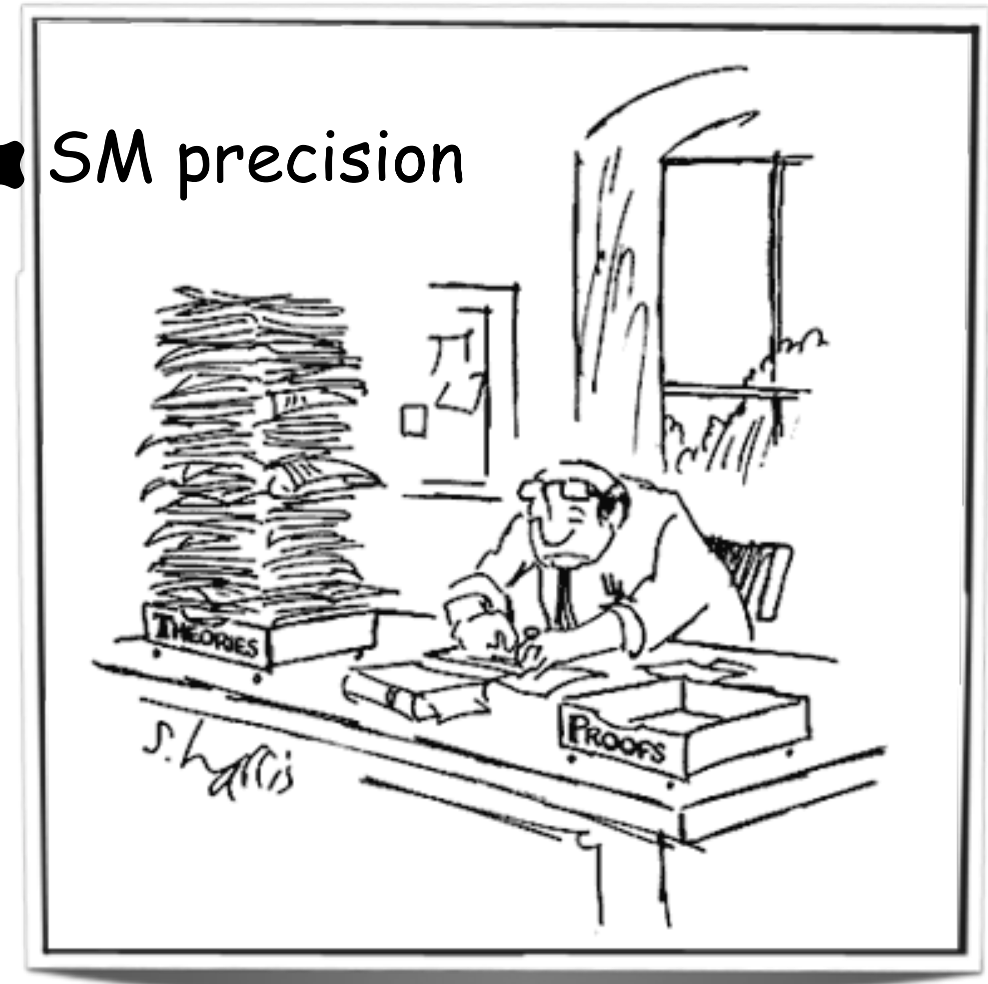
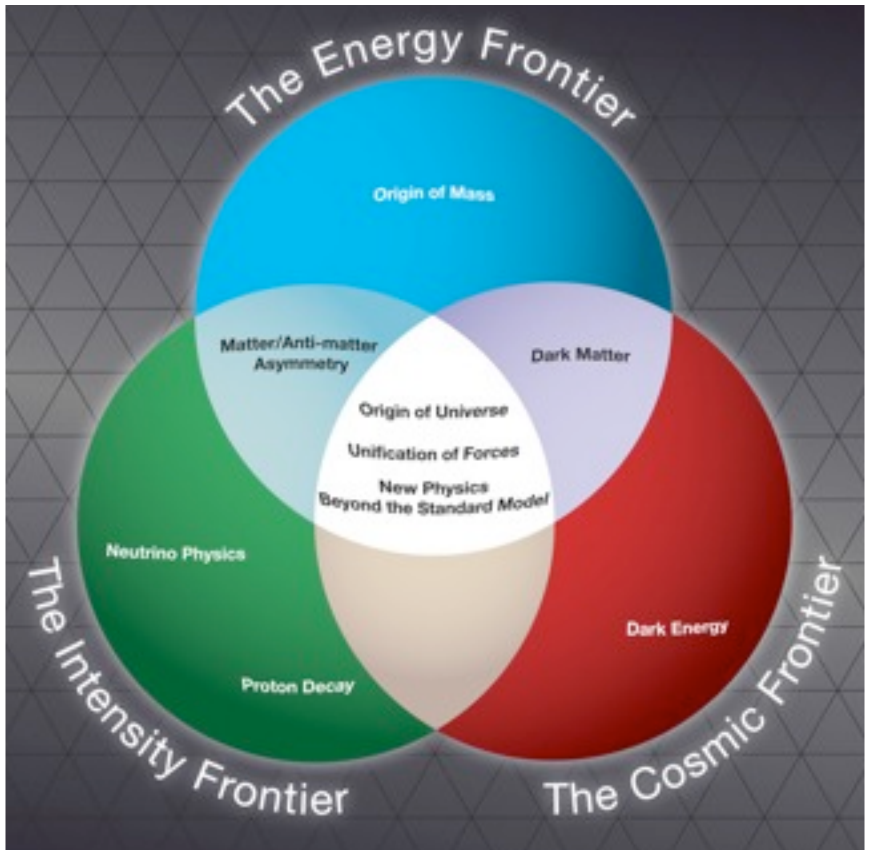


synergy fuels progress

- BSM model building

The HEP frontiers

EXP Frontiers



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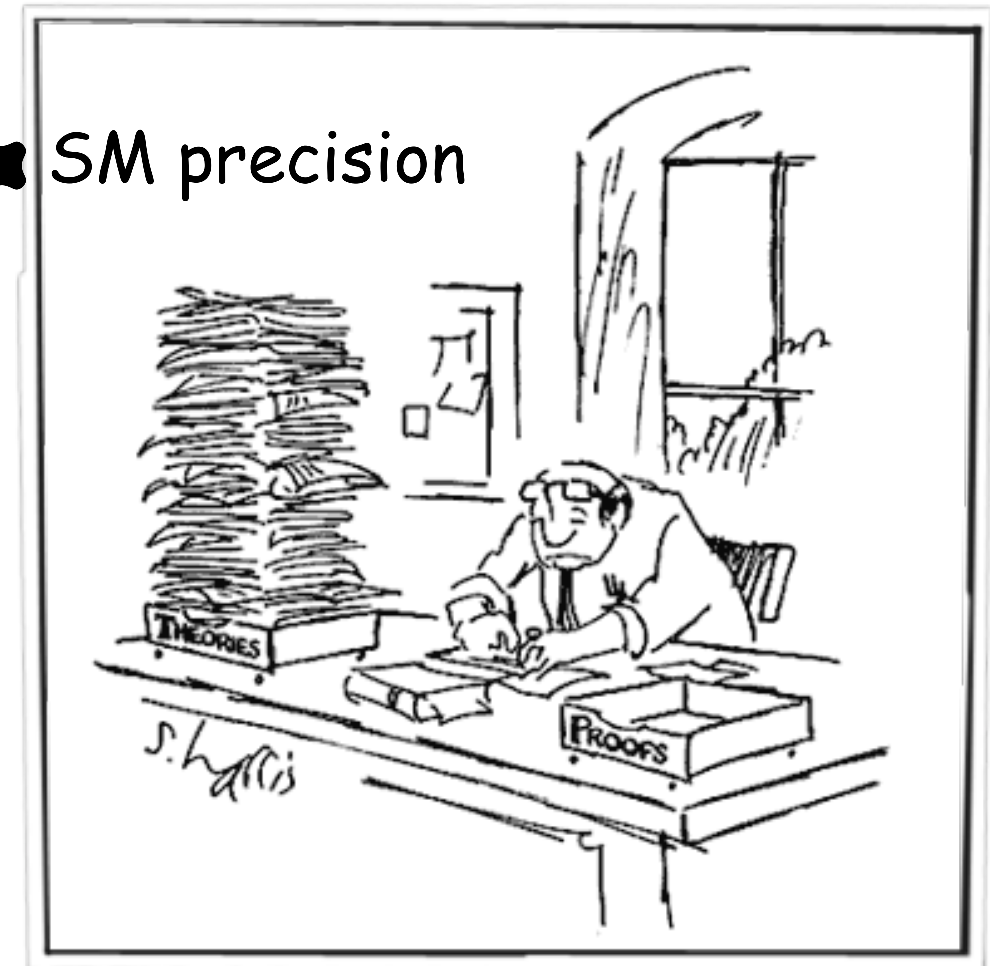


- BSM

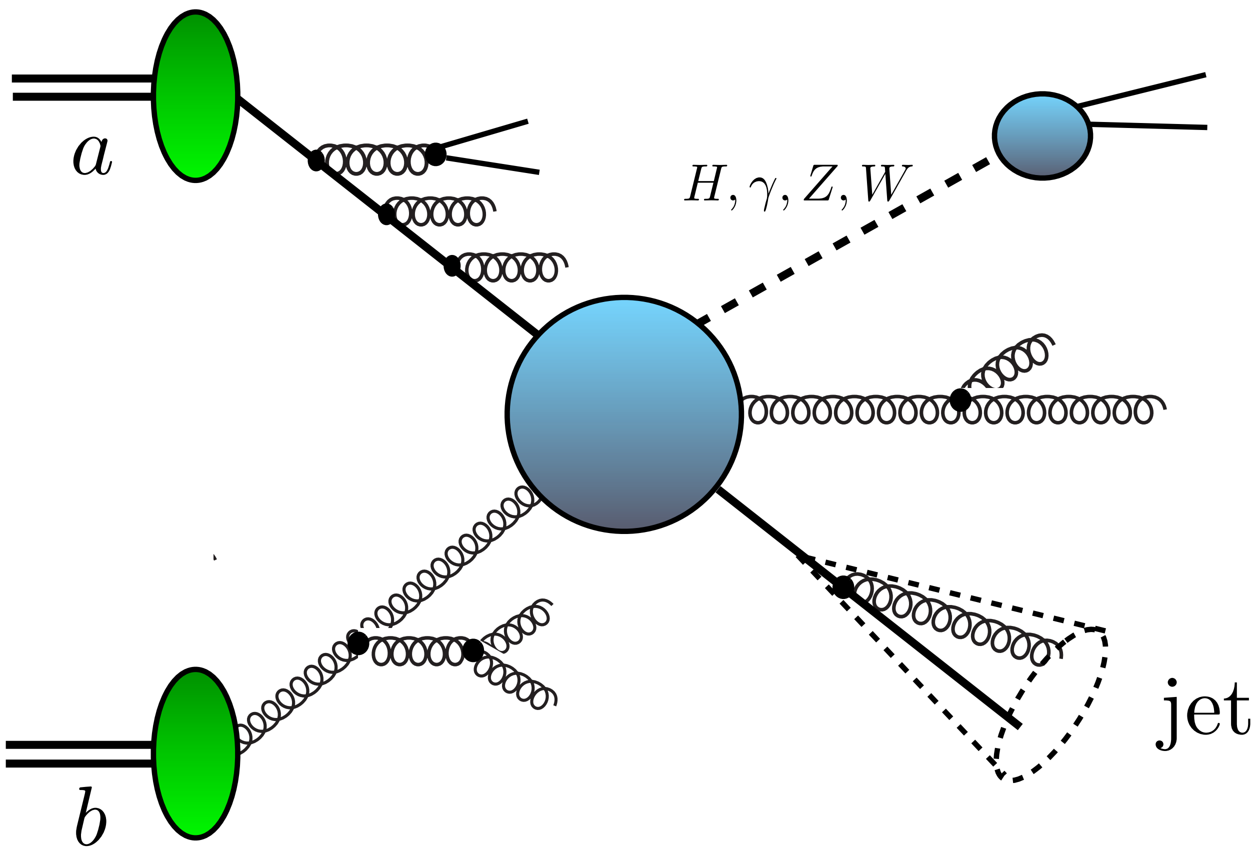
model building

synergy fuels progress

⇓ ⇓ ⇓

no BSM major discovery @ LHC
without a thorough understanding of SM background

The SM precision frontier(s)



(picture courtesy of
D. de Florian@DIS2014)

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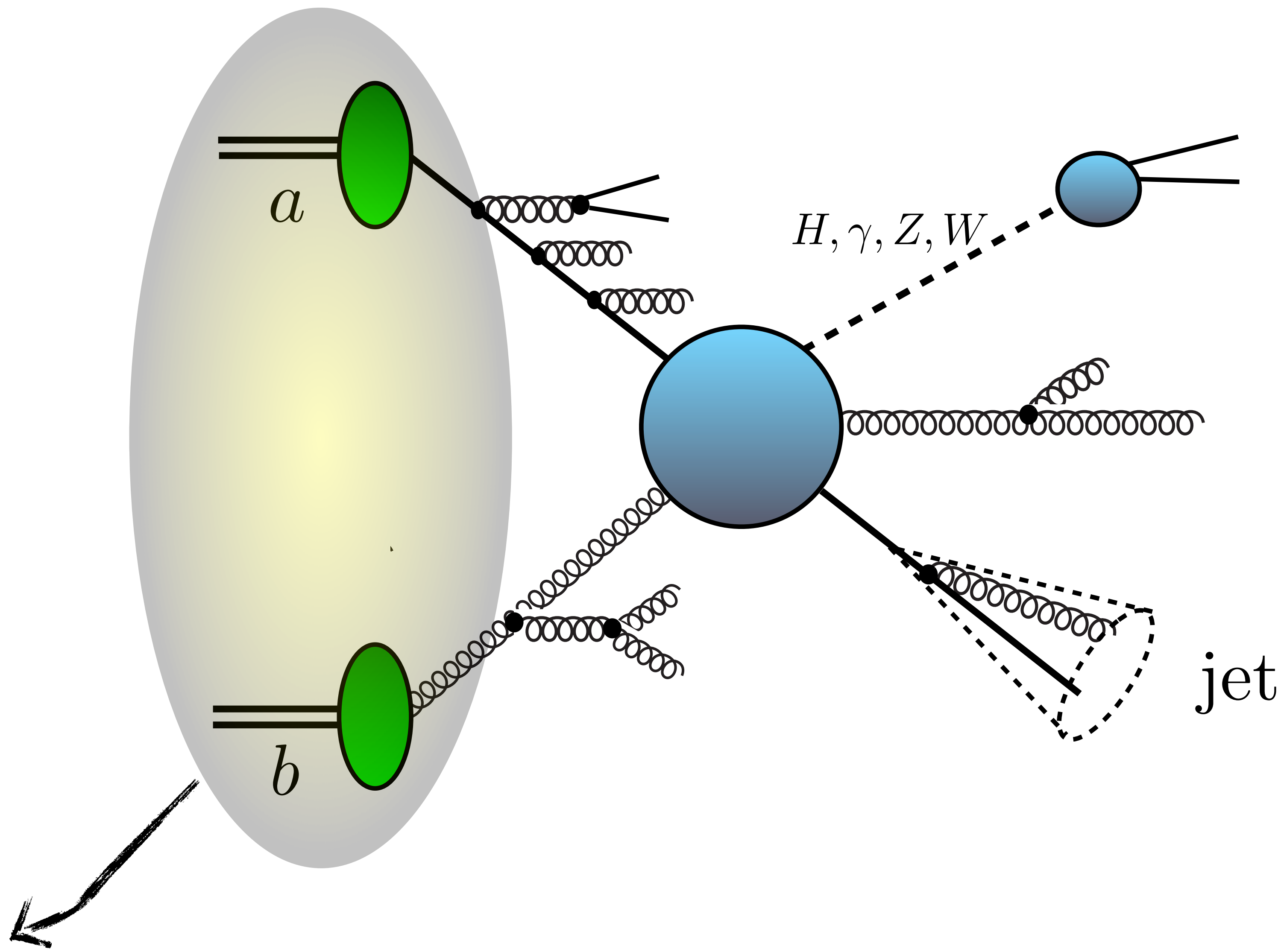

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(non)-perturbative QCD
improve uncertainties
in input parameters
PDFs, α_s, m_{top}...

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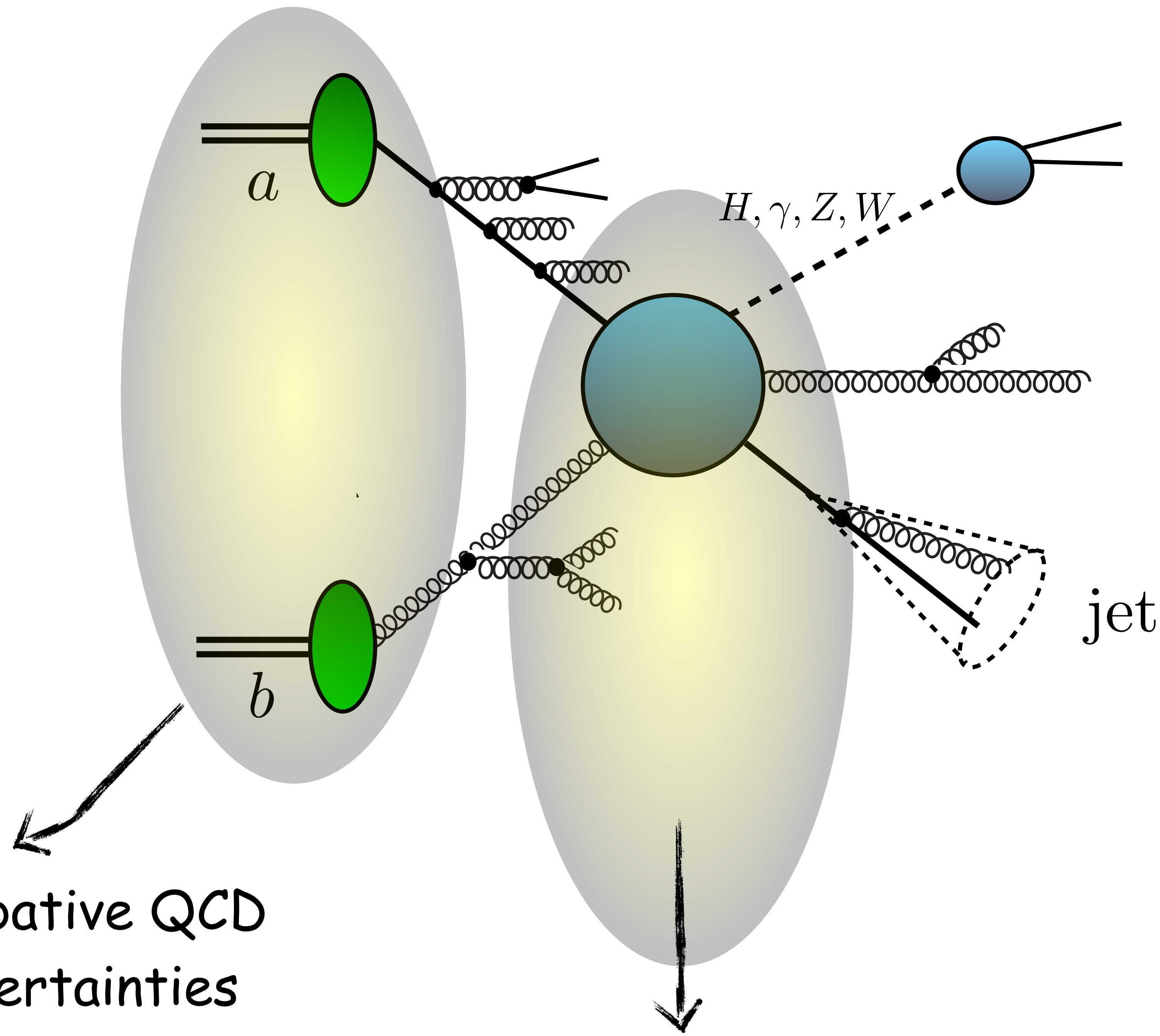

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Perturbative QCD
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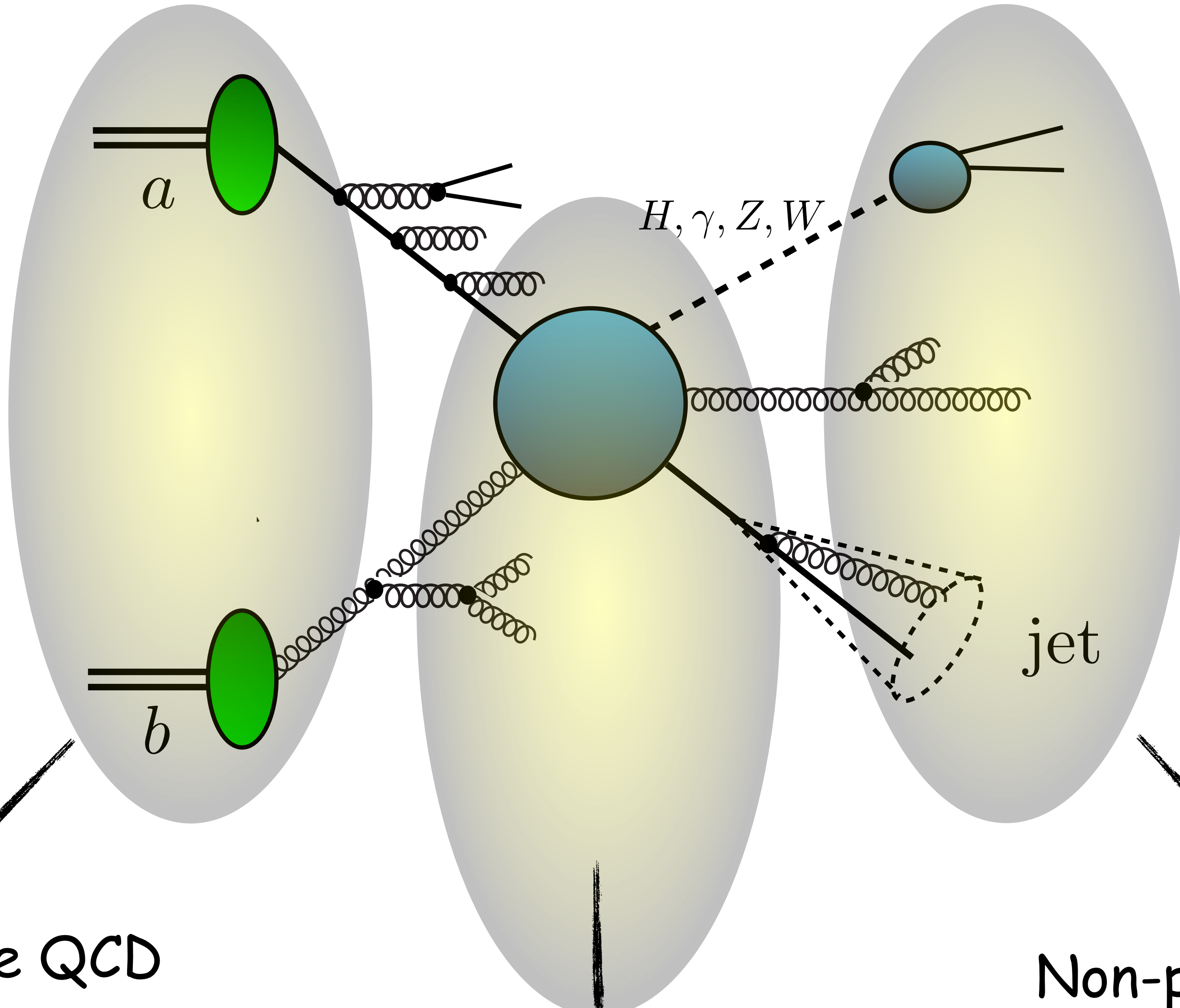

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improve uncertainties
in input parameters
PDFs, α_s, m_{top}...

Perturbative QCD
improve higher
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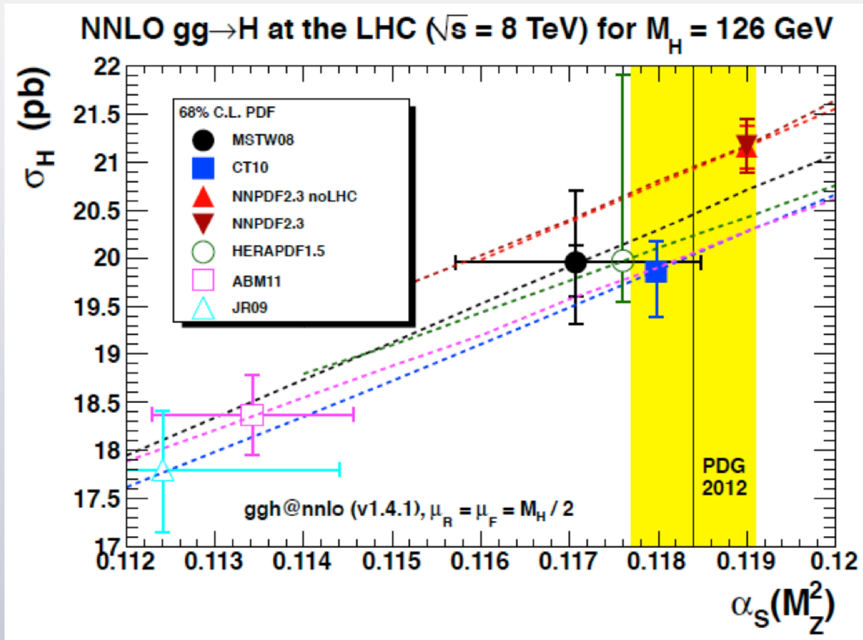
Non-perturbative QCD
improve uncertainties
in parton/hadron transitions

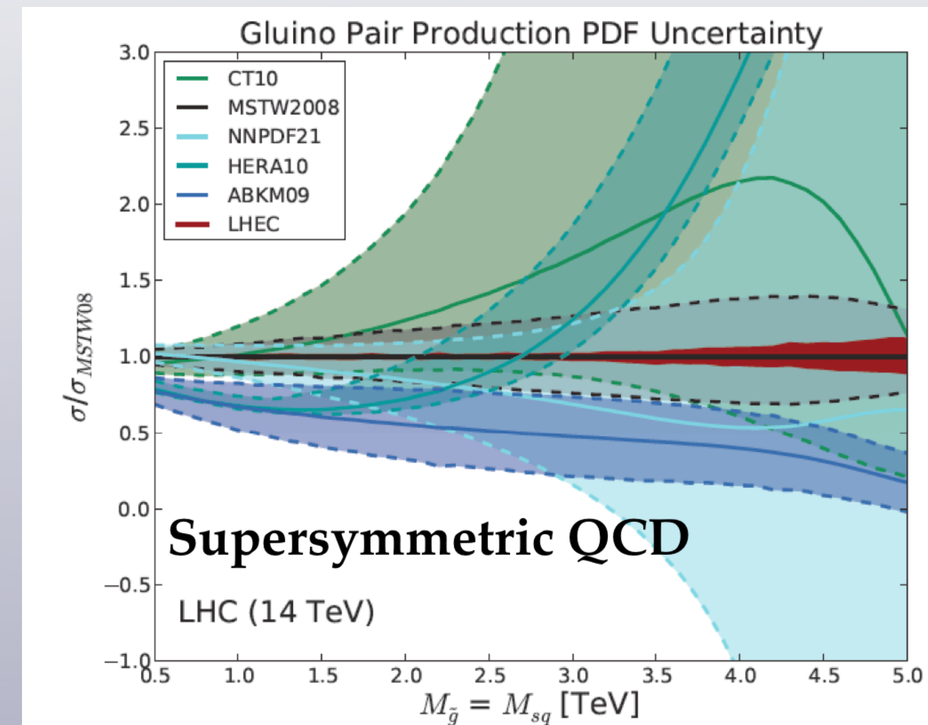
The SM precision frontier: PDF

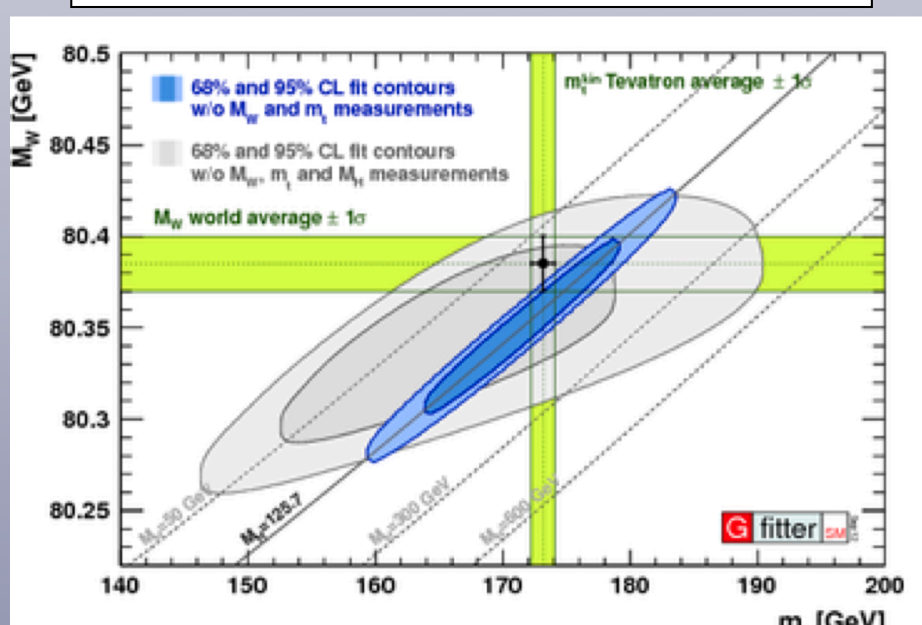
Parton Distributions and LHC phenomenology



1) PDFs fundamental limit for Higgs boson characterization in terms of couplings

2) Very large PDF uncertainties (>100%) for new heavy particle production





3) PDFs dominant systematic for precision measurements, like W boson mass, that test internal consistency of the Standard Model

Juan Rojo La Thuile, 25/02/2014

PDF (and input parameters) are essential to do (SM/BSM) phenomenology @ LHC

The SM precision frontier: PDF

(courtesy of J. Rojo@LaThuile2014)

LHC data are included in global PDF fits

LHC data already **included in PDF fits:**

- ☑ *Inclusive W,Z production*
- ☑ *W production with charm quarks*
- ☑ *Isolated photon production*
- ☑ *Inclusive jet and dijet production*
- ☑ *Low and high-mass off-shell Drell-Yan*
- ☑ *Top quark pair cross-sections*
- ☑ *Ratios of cross-sections between different* E_{cm}

LHC data with potential PDF constraints

- ☑ *Z+jets, high-pT Z production*
- ☑ *Photon+jet production*
- ☑ *Photon+charm, Z+charm*
- ☑ *Single top production*
- ☑ *Top quark pair differential distributions*
- ☑ *Ratios between 13 and 8 TeV*

Theory developments

- QED corrections
- fixed-flavor vs variable-flavor-number heavy quark schemes

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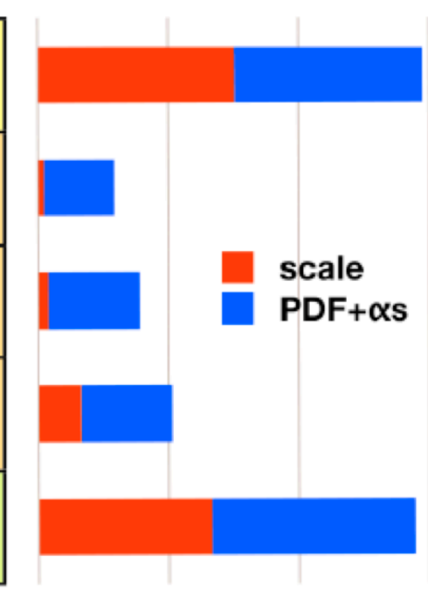
Theory developments

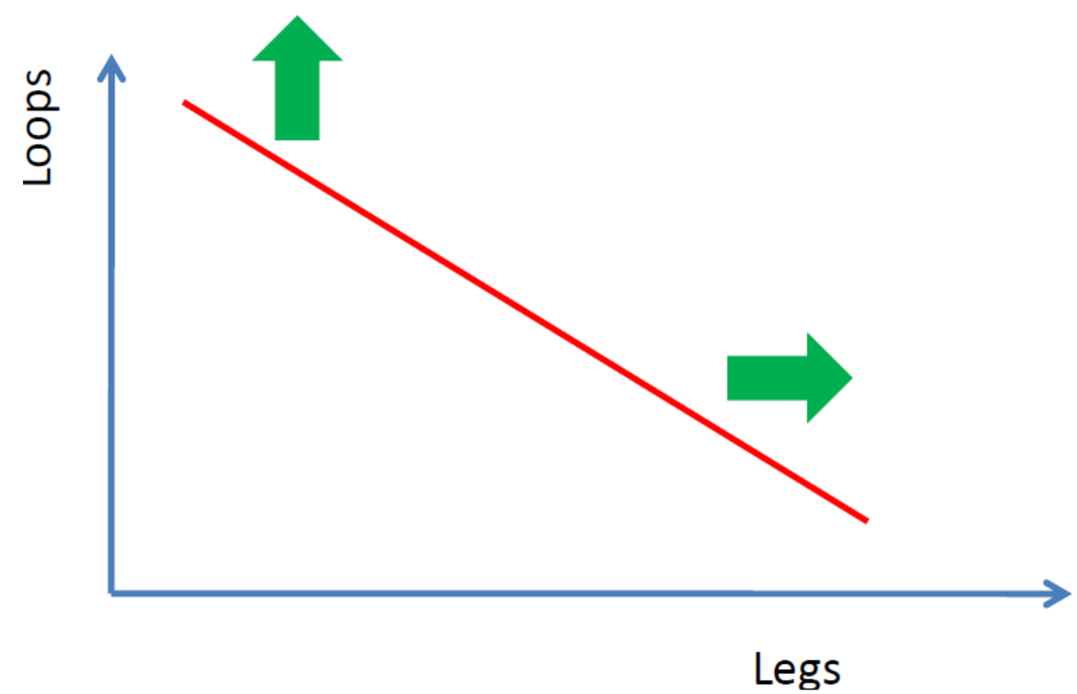
- QED corrections
- fixed-flavor vs variable-flavor-number heavy quark schemes

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



The SM precision frontier: N$^{(k)}$LO

Rough idea of complexity of process ∼ #Loops + #Legs (+ #Scales)



frontiers:

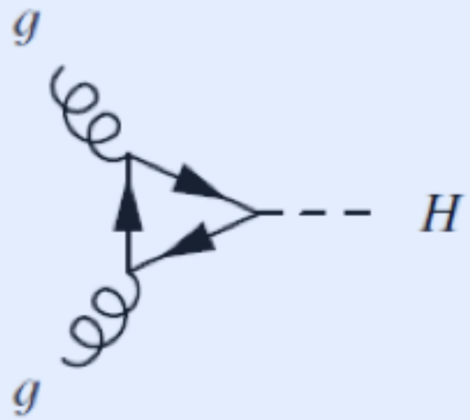
- 2→N @ 1-loop (NLO)
- 2→2 @ 2-loop (N^{2}LO)
- 2→1 @ 3-loop (N^{3}LO)

- loop integrals are ultraviolet/infrared divergent
- complicated by extra mass/energy scales
- loop integrals often unknown
  - ✓ completely solved at NLO
- real (tree) contributions are infrared divergent
- isolating divergences complicated
  - ✓ completely solved at NLO
- currently far from automation
  - ✓ mostly solved at NLO

Current standard: NLO

(courtesy of N. Glover@SM@LHC2014)

The SM precision frontier: $N^{(k)}LO$, ex. gg→H



~TODAY~

N²LO+N²LL QCD

NLO EW

~TOMORROW~

inclusive	Higgs p_T
N³LO QCD	NLO QCD
($m_t=\infty$)	w/ finite m_t,m_b
	(3 scale pb!)

2 → 2 @ 2-loop

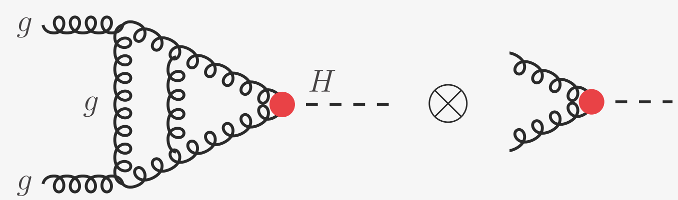
similar to ttbar @ N²LO

recently achieved by Czakon/Mitov

2 → 1 @ 3-loop

Inclusive XS

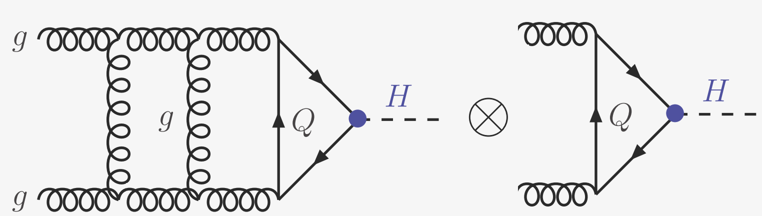
N^2LO_∞ α_s^4 2-loop



g_s^6 g_s^2

Harlander, Kilgore '02 Anastasiou, Melnikov '02

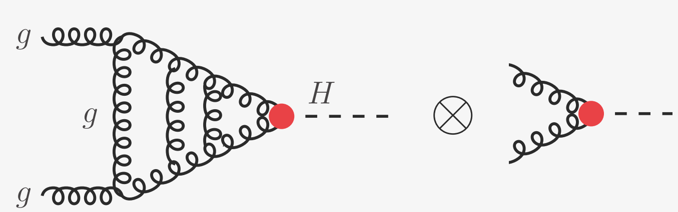
N^2LO_{mt} α_s^4 3-loop



g_s^6 g_s^2

first corrections in 1/mt: Harlander et al '09

N^3LO_∞ α_s^5 3-loop

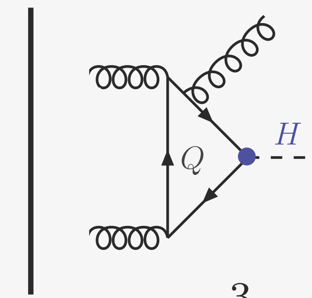


g_s^8 g_s^2

first steps: Ball et al '13 Anastasiou et al '13

Higgs p_T

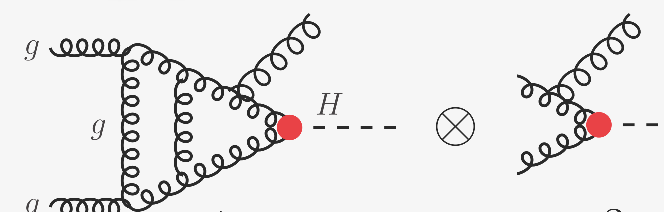
LO_{mt} α_s^3 1-loop



g_s^3

Baur, Glover '90

N^2LO_∞ α_s^5 2-loop



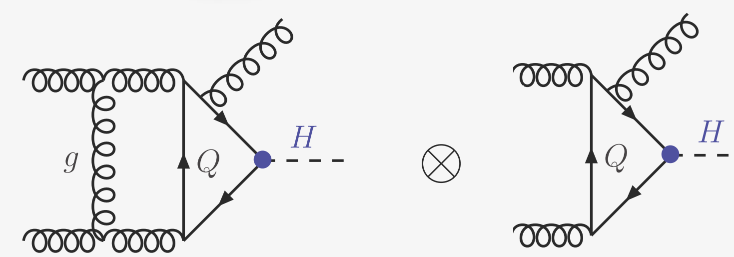
g_s^7 g_s^3

Boughezal et al '13

~TODAY~

~TOMORROW~

NLO_{mt} α_s^4 2-loop



g_s^5 g_s^3

first corrections in 1/mt: Harlander et al '12

The SM precision frontier: $N^{(k)}LO$, ex. gg→H

Inclusive XS

Higgs p_T

N^2LO_∞ α_s^4 2-loop

LO_{mt} α_s^3 1-loop

2

g_s^3 Baur, Glover '90

~TODAY~

N^2LO+N^2LL Q

NLO EW

α_s^5 2-loop

g_s^3

hezal et al '13

~TOMORROW~

inclusive Hig

N^3LO QCD NLO

$(m_t=\infty)$ w/ fini

(3 sc

~TOMORROW~

N^3LO_∞ α_s^5 3-loop

g_s^8 g_s^2

first steps: Ball et al '13 Anastasiou et al '13

NLO_{mt} α_s^4 2-loop

g_s^5 g_s^3

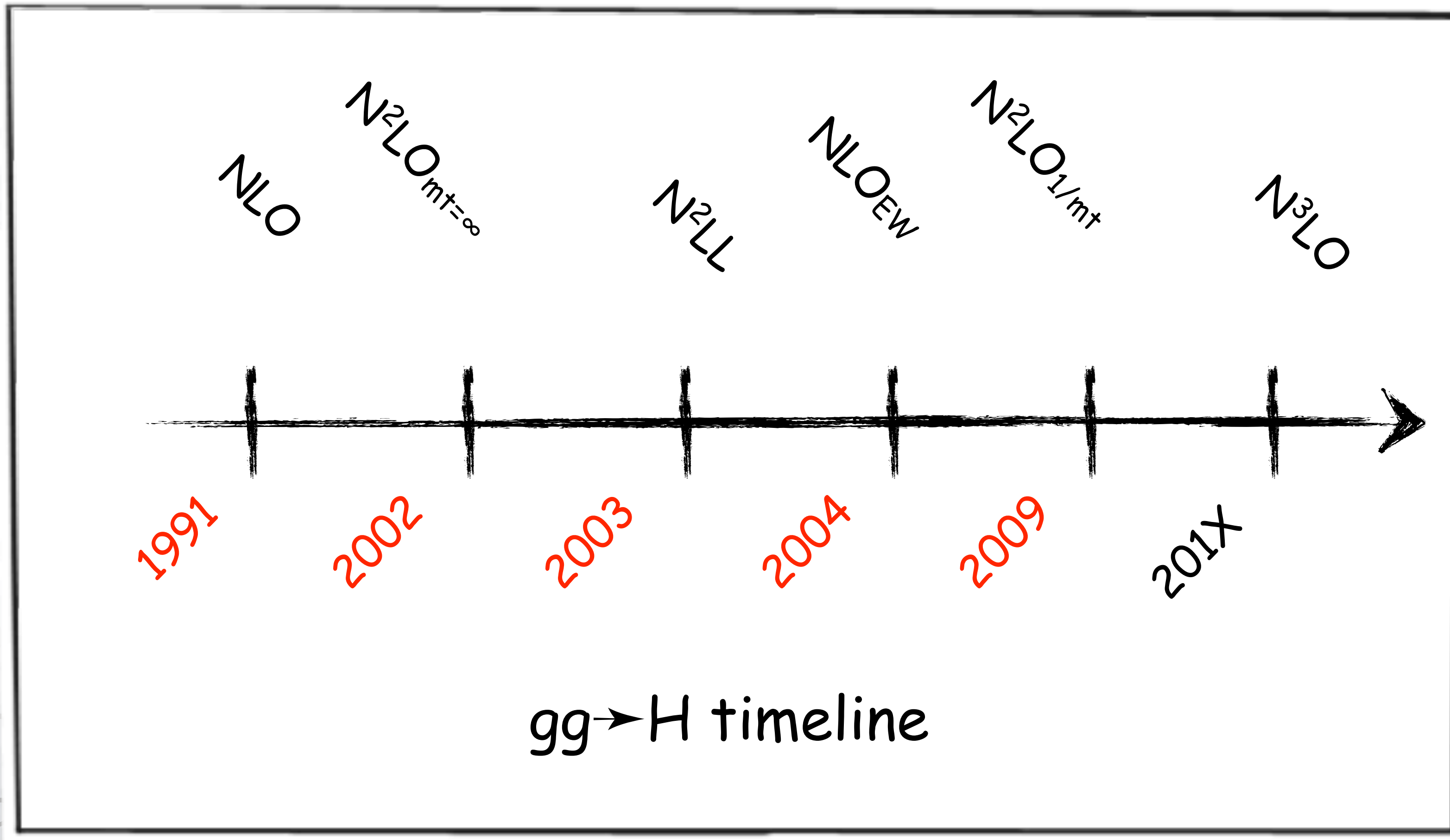
first corrections in 1/mt: Harlander et al '12

2 → 2 @ 2-loop

similar to ttbar @ N^2LO

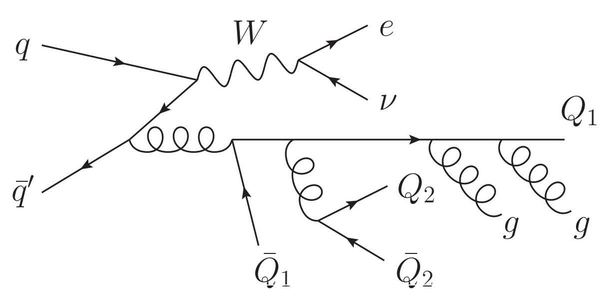
recently achieved by Czakon/Mitov

2 → 1 @ 3-loop

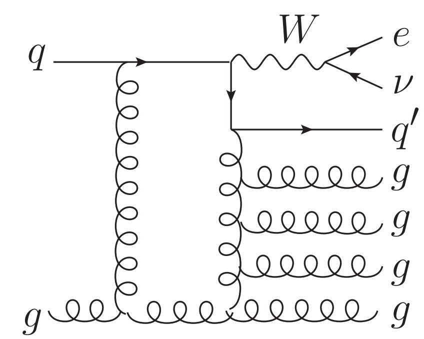


The SM precision frontier: N$^{(k)}$LO, ex. W+5j

BlackHat collaboration '13

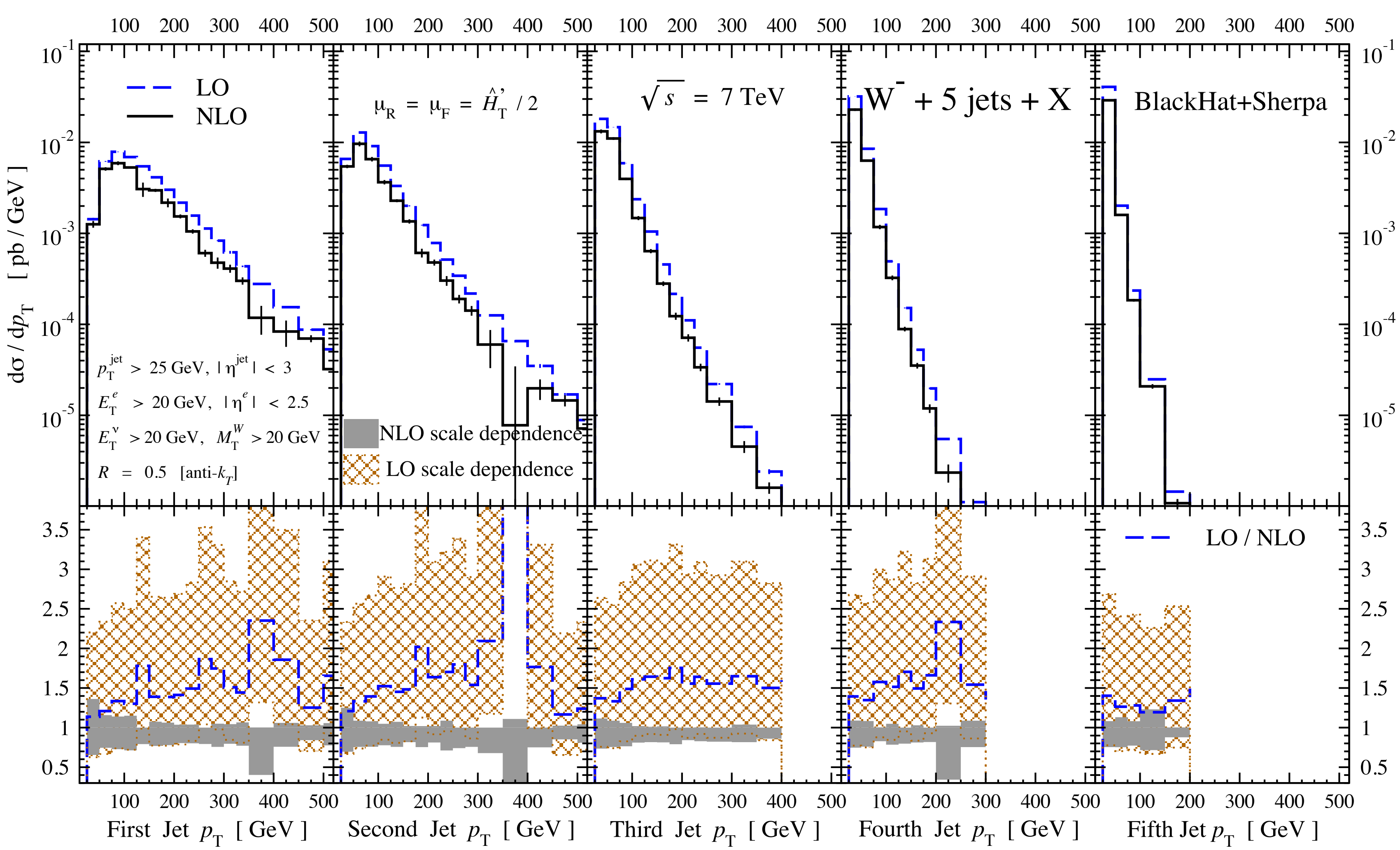


Real $2 \to 8$ SHERPA



Virtual $2 \to 7$ BlackHat

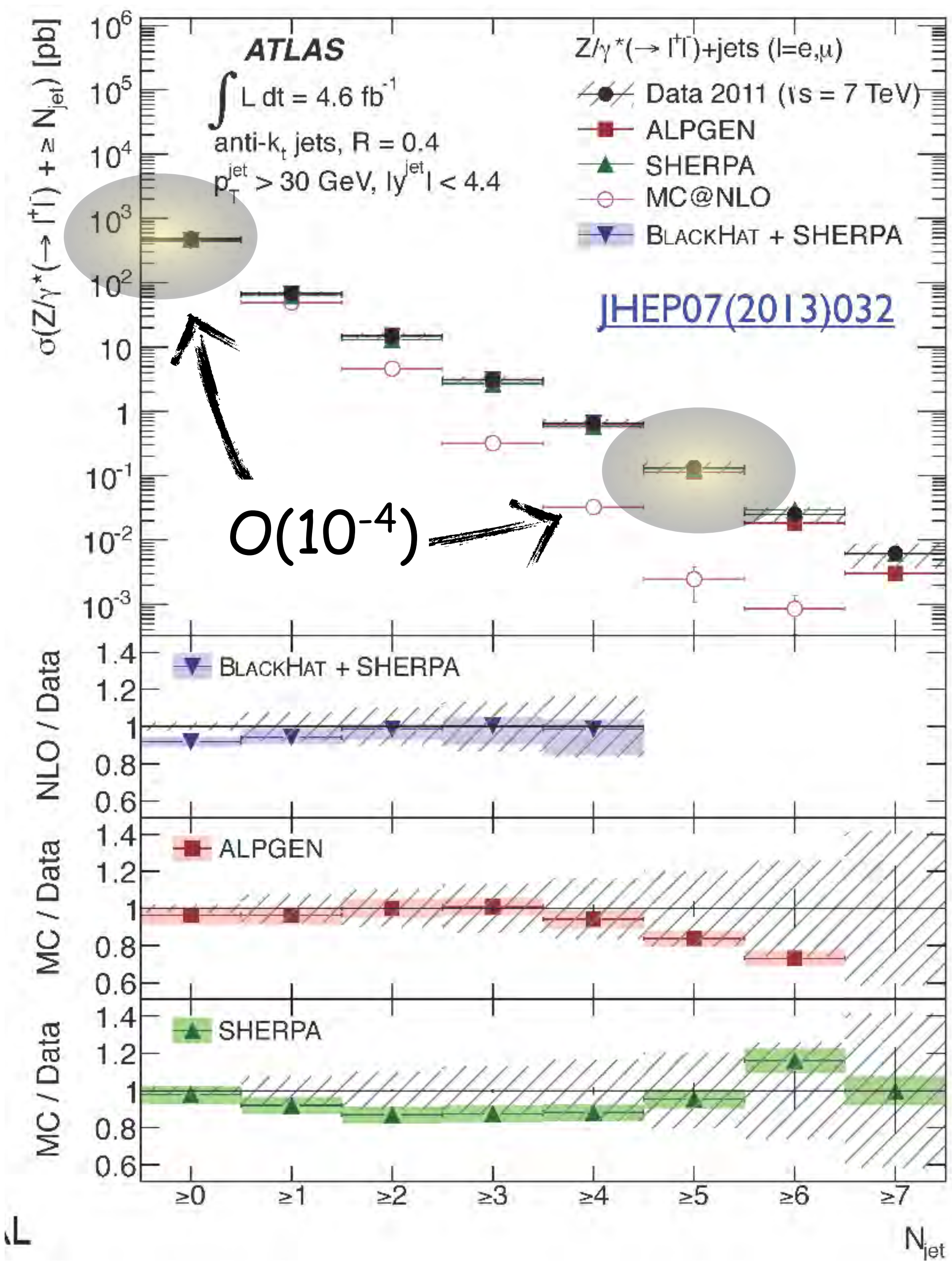
Dynamical Scale choice $\mu_R = \mu_F = \frac{\hat{H}'_T}{2} \equiv \frac{1}{2} \sum_m p_T^m + E_T^W$



- Dramatic reduction in scale dependence (~20%)
- Up to 50% correction (non-trivial in shape)

(courtesy of D. de Florian@DIS2014)

The SM precision frontier: N$^{(k)}$LO, ex. W+5j



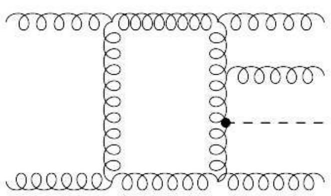
the xs for Z+5j is
~ 4 orders of magnitude smaller
than the inclusive Z xs

the theoretical computations
now allows us to explore the
tiniest corners of the phase space

The SM precision frontier: $N^{(k)}LO$

~~~~ frontiers:

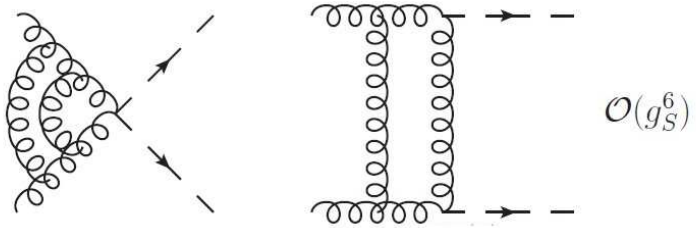
- 2→N @ 1-loop (NLO): ex. pp→H+3 jets @ NLO — Cullen et al '13



- 2→2 @ 2-loop (N^2LO): ex. pp→H+1 jet @ N^2LO — Boughezal et al '13

  ex. pp→ttbar @ N^2LO — Czakon, Mitov et al '13

- 2→1 @ 3-loop (N^3LO): ex. pp→HH @ N^2LO — de Florian, Mazzitelli '13



  ex. pp→$Z\gamma$ @ N^2LO — Grazzini et al '13
~~~~

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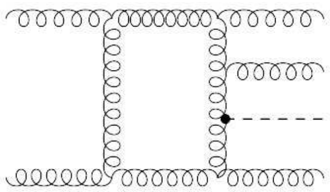

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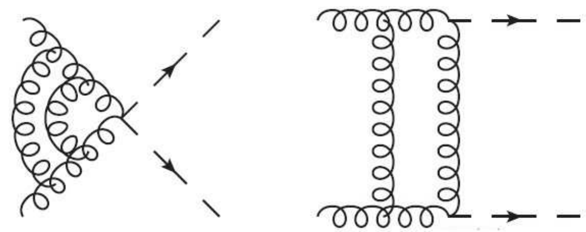

$\mathcal{O}(g_S^6)$

ex. pp→Zγ @ N^{2}LO

Grazzini et al '13

But there are still some LO computations to do for some particular kinematics
ex. recently gg→Z*Z* relevant to bound the Higgs width @ LHC

Campbell et al '13

A Higgs: Now what? What's next?

"The experiment worked better than expected and the analysis uncovered a very difficult to find signal"

the words of a string theorist, Aspen '13

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Have the theorists been lying for so many years?

Have the exp's been too naive to believe the th's?

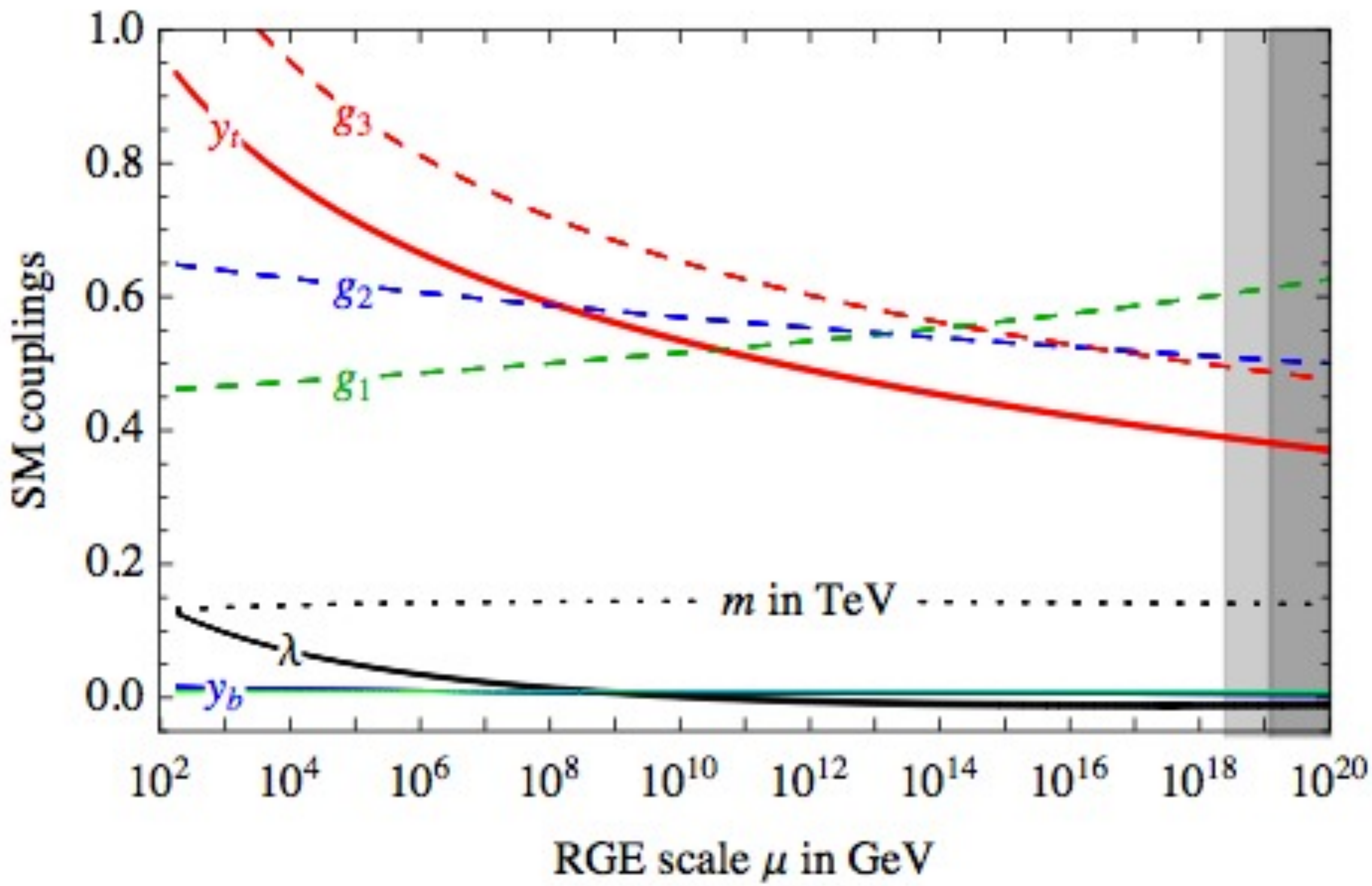
What should we still expect to see beyond the Standard Model?
What should be our guiding principle(s)?

1

The fate of the EW vacuum: a question of precision

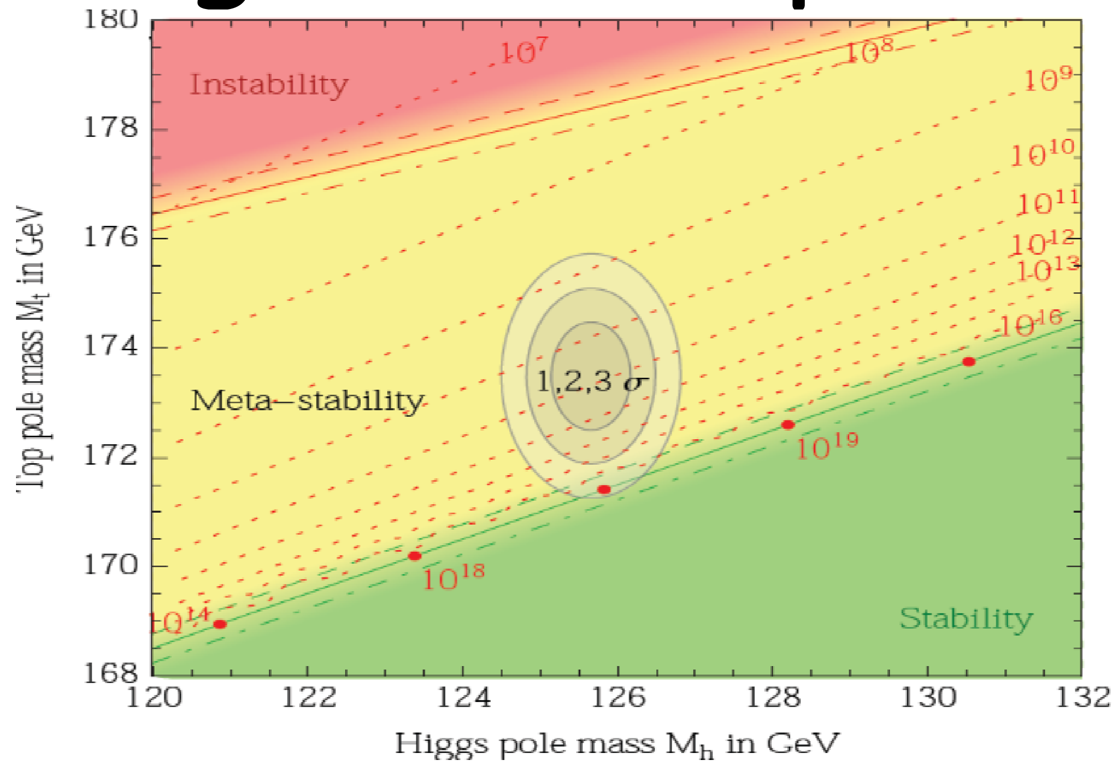
Can we live without new physics?

Buttazzo et al '13



Can the SM (without new physics)
be valid up to M_{Pl} and remain weakly coupled?

Are we living at a edge of the phase diagram?

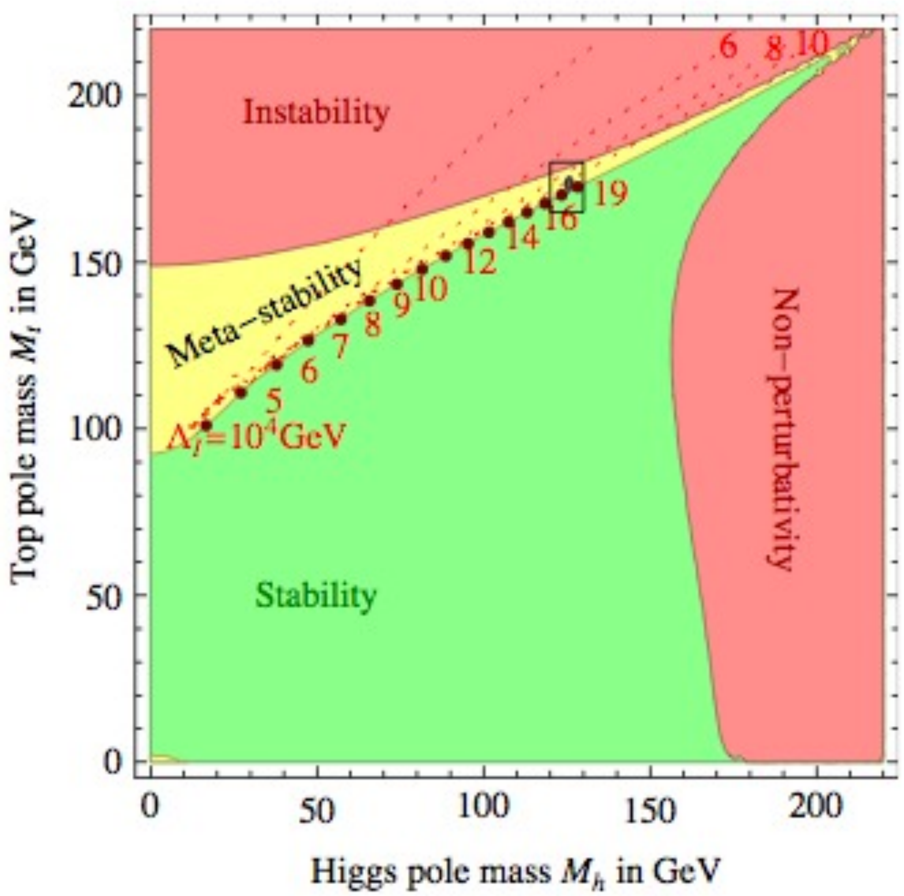


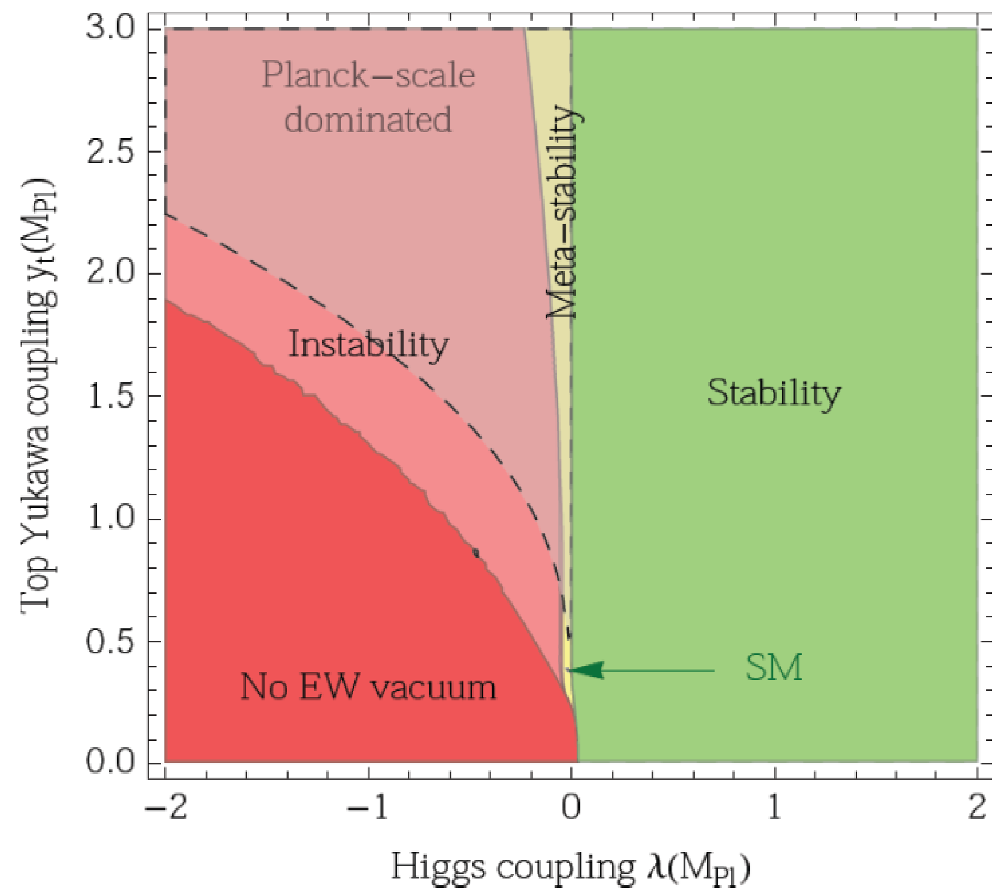
Buttazzo et al '13

see also:

Bezrukov et al '12

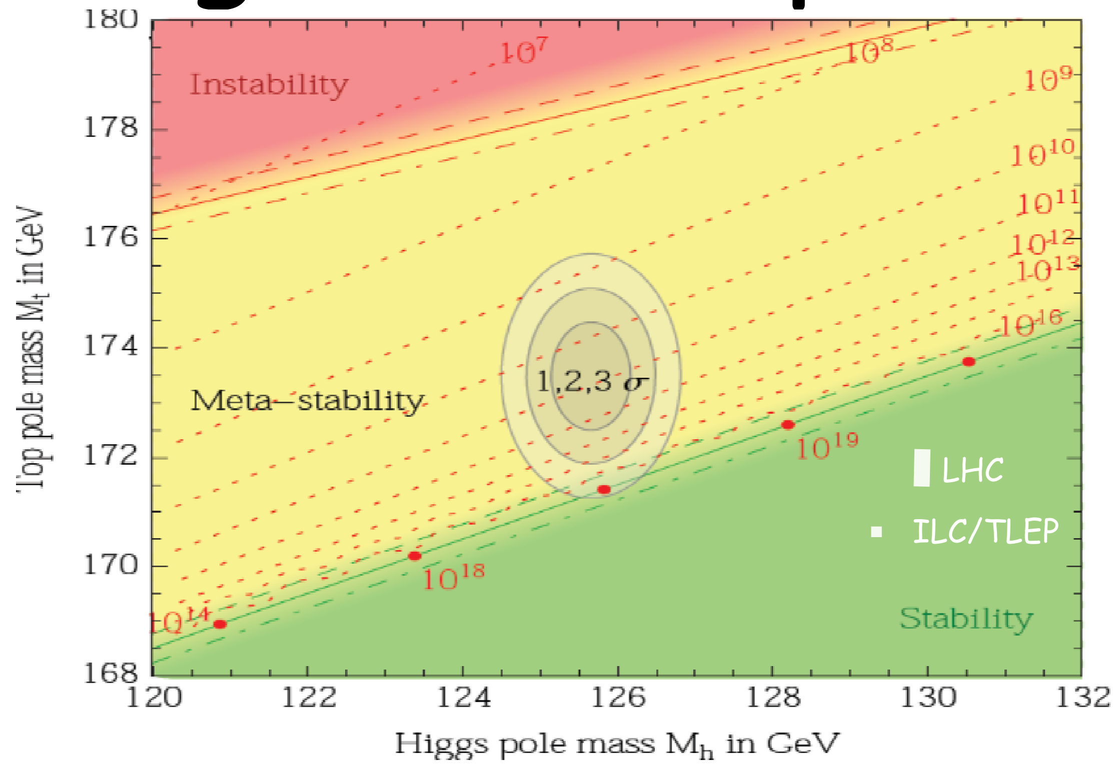
Degrassi et al '12





Are we living at a edge of the phase diagram?

Parameter	Present	LHC	ILC/GigaZ	TLEP
M_H [GeV]	0.4 ⇨	< 0.1	< 0.1	< 0.1
M_W [MeV]	15 ⇨	8 ⇨	5 ⇨	1.3
M_Z [MeV]	2.1	2.1	2.1 ⇨	0.1
m_t [GeV]	0.9 ⇨	0.6	0.1	0.08



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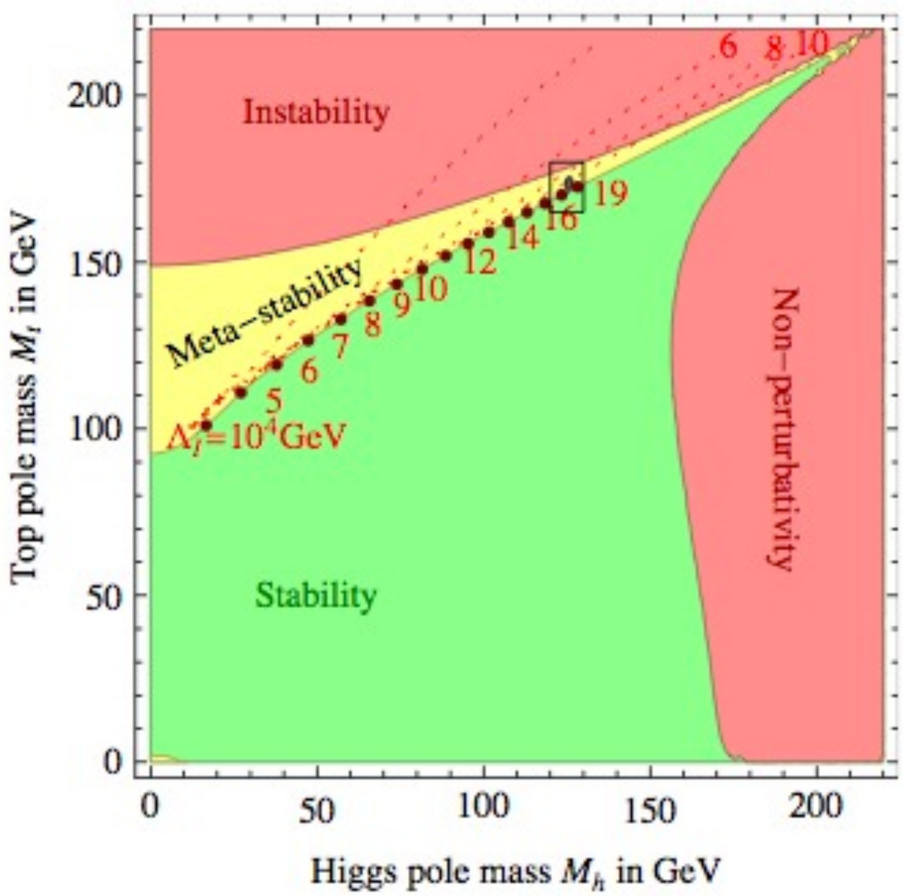
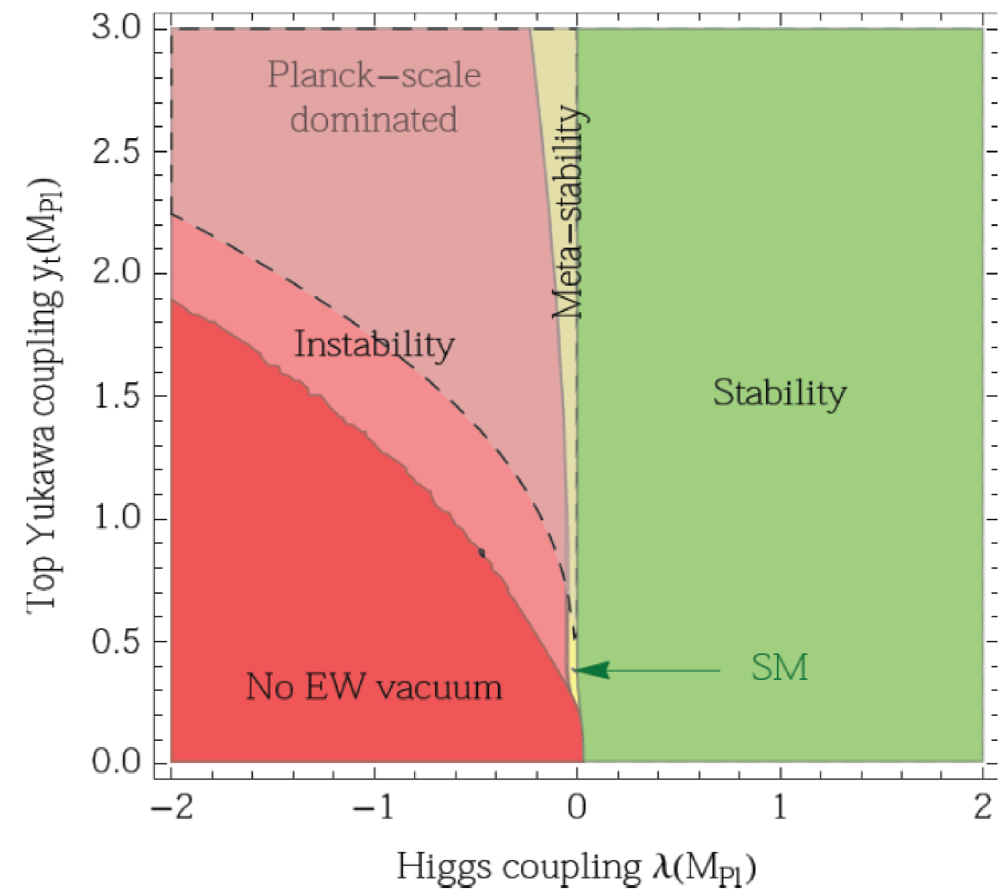




The (near) criticality of our vacuum calls for a precise measurement

2

Higgs and New Physics

With a new SM particle,
a new handle to look for indirect BSM effects

So far, no sign of BSM in the h properties...

Where else should we look for?

- **pp→hW ?**
- **pp→hh double-Higgs production?**
- **h→Vff E,p distributions? CP-violation?**
- **h→Zγ ?**

⋮

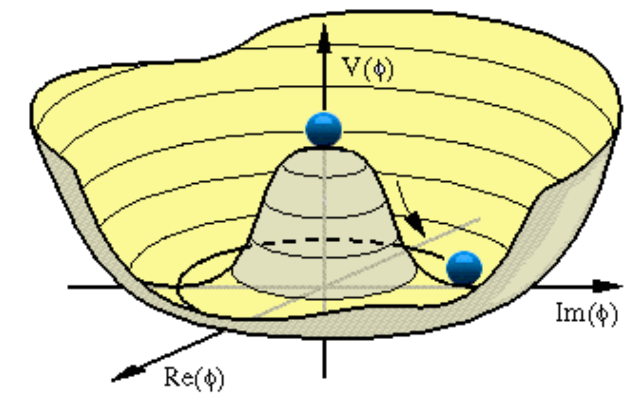
An thorough model-independent analysis is needed

(courtesy of A. Pomarol@Moriond2014)

SM Scalar is the excitation around the EWSB vacuum:

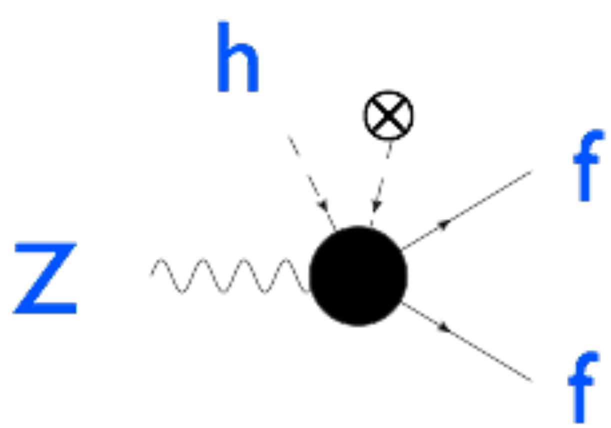
$\phi = v + h$

v → vacuum

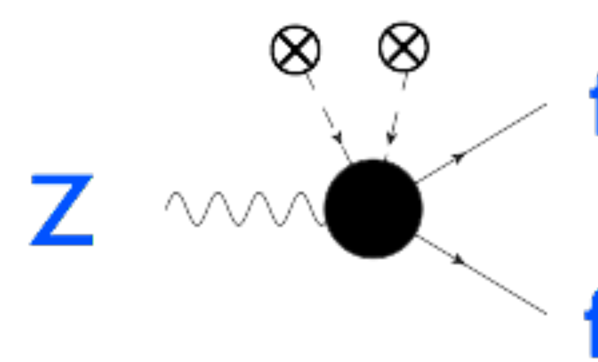


Potentially new BSM-effects in h physics
could have been already tested in the vacuum

e.g.



$$= \frac{1}{2v} \times$$



$$H^\dagger D_\mu H \bar{f} \gamma^\mu f$$

Assuming that the Higgs boson
is part of a doublet

Modifications in $h \to Zff$ related to $Z \to ff$

(courtesy of A. Pomarol@Moriond2014)

Higgs and New Physics

Assuming that New Physics is heavier than the EW scale:
parametrization in terms of Effective Theories,
i.e. higher dimensional operators

For one family of leptons, 59 deformations away from the SM @ leading order

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BSM-effects can hide in

- $h\to\gamma\gamma$, $GG\to h$, $h\to ff$, $h\to VV^*$ (but already tested)
- $GG\to htt$, $h\to Z\gamma$ (to be tested at the LHC next run)

⇒ 8 New Physics directions explored in Higgs physics

No new BSM-effects expected in

- $h\to Zff, Wff$ (small custodial breaking effect & small deviations in momentum distributions)

If discovered here,
we could have been missing light new-physics! or the Higgs is not an EW doublet!

CP violation in Higgs physics?

Is CP a good symmetry of Nature? 2 CP-violating couplings in the SM:

V_{CKM} (large, O(1), but screened by small quark masses) and θ_{QCD} (small, O(10^{-10}))

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$$H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} \qquad (D^\mu H)^\dagger \sigma^i (D^\nu H)\tilde{W}^i_{\mu\nu} \qquad (D^\mu H)^\dagger (D^\nu H)\tilde{B}_{\mu\nu}$$

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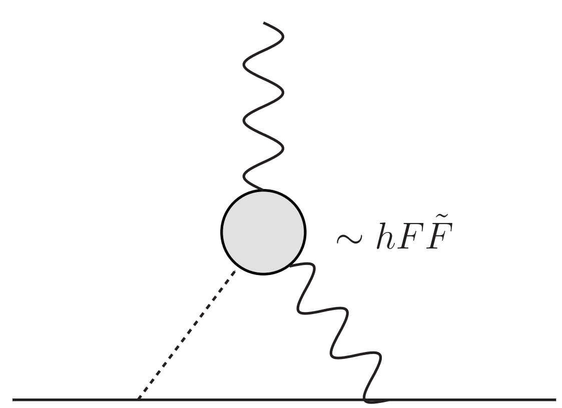
operators with γ:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



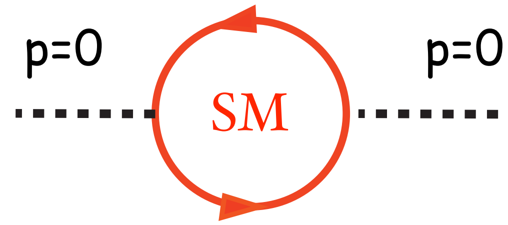
$\Lambda_{\not{CP}}$ > 25 TeV

2

Higgs and Naturalness: a question of precision

Higgs couplings = test of Naturalness?

$$-(125\ \text{GeV})^2 \left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$\delta m_H^2 =$ 

$+$ 

$\sim m_H^2$

charged particles

neutral particles

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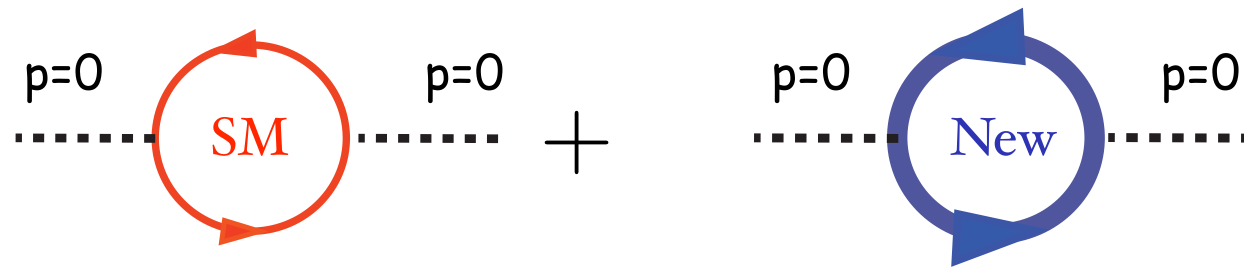
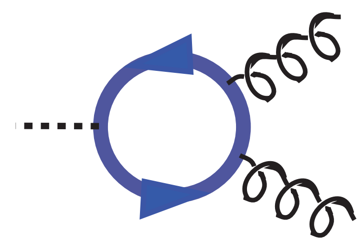
$\delta m_H^2 =$  $\sim m_H^2$

charged particles

generically

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2 \qquad \frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$

$$BR(h\to ii) = BR_{\text{SM}}$$

$$\Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

nice to be able to measure Γ

Generically, natural scenarios come with deviations of the Higgs coupling

$$\frac{\Delta g}{g_{SM}} \approx \frac{g_*^2 v^2}{m_*^2} \approx ?$$

Which Higgs precision to test Naturalness?

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to which level of precision do we need to measure the Higgs couplings
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Models where the Higgs mass is UV insensitive

$$m_H^2 \sim \frac{N_c y_t^2}{16\pi^2} m_*^2 \quad \Rightarrow \quad \frac{\Delta g}{g_{SM}} \sim \frac{N_c g*^2}{16\pi^2}$$

~ 1 for strongly coupled models

~ 1% for weakly coupled models

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e.g. high scale susy breaking

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~ 1

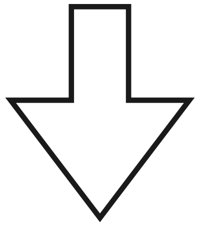
O(1%) precision Higgs physics could be as important as direct searches for new physics
to probe the naturalness of EWSB

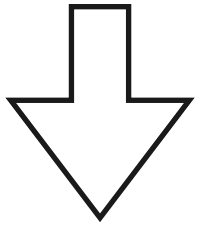
Higgs couplings measurement projections

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Higgs WG@ Snowmass '13





Rich experimental program of (sub)percent precision

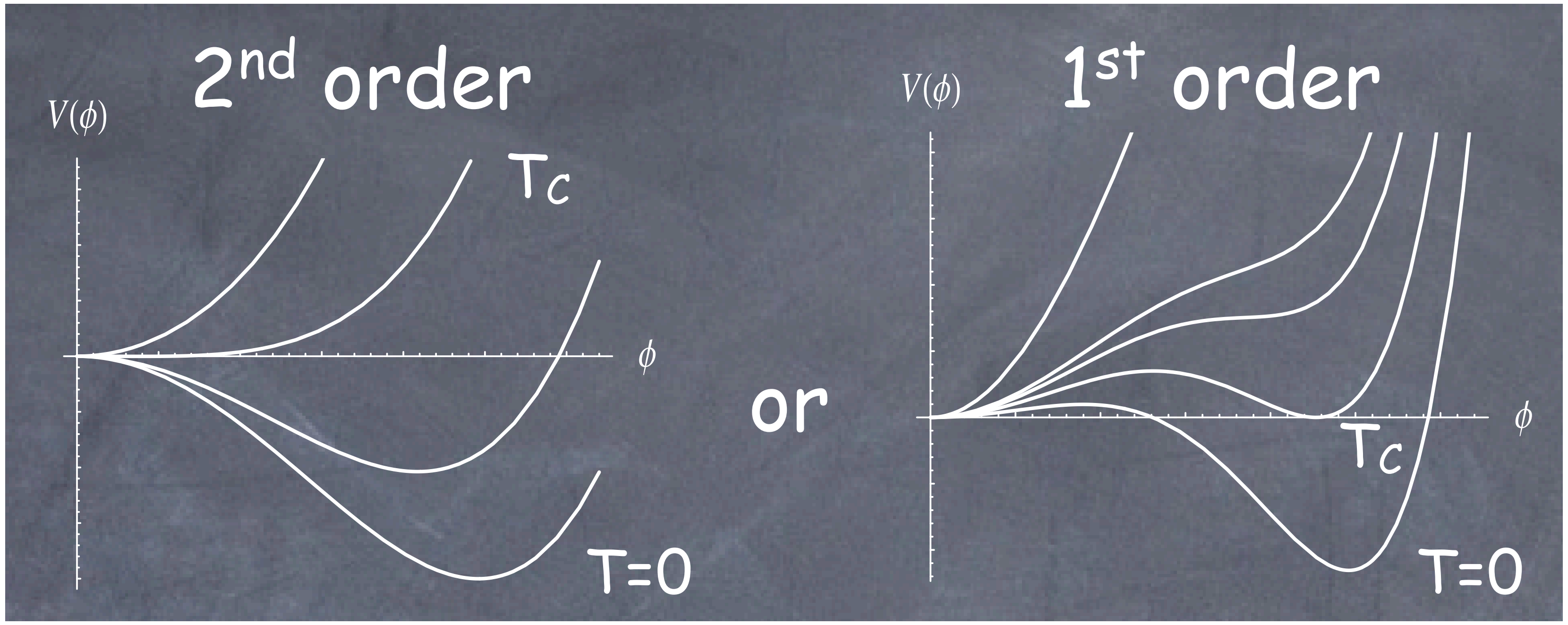
3

EW phase transition: a question of precision

Dynamics of EW phase transition and Cosmology

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition



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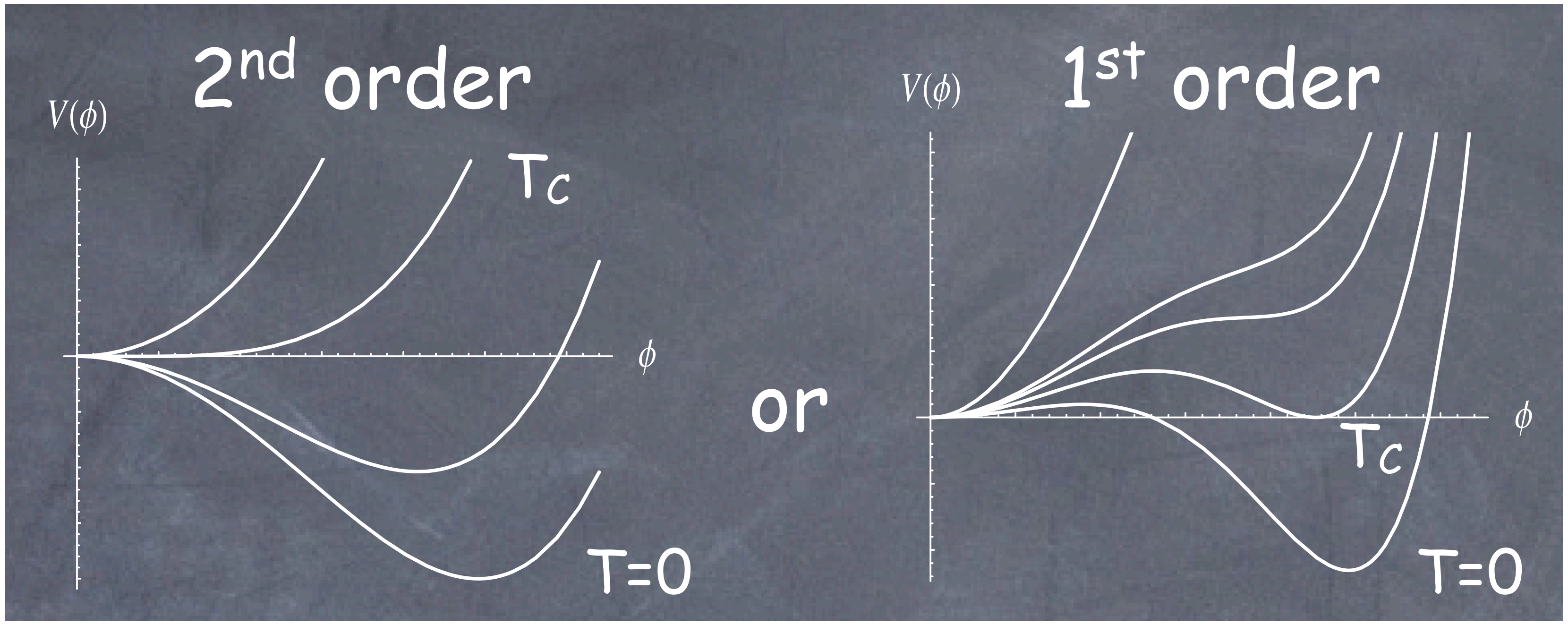

the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine!)

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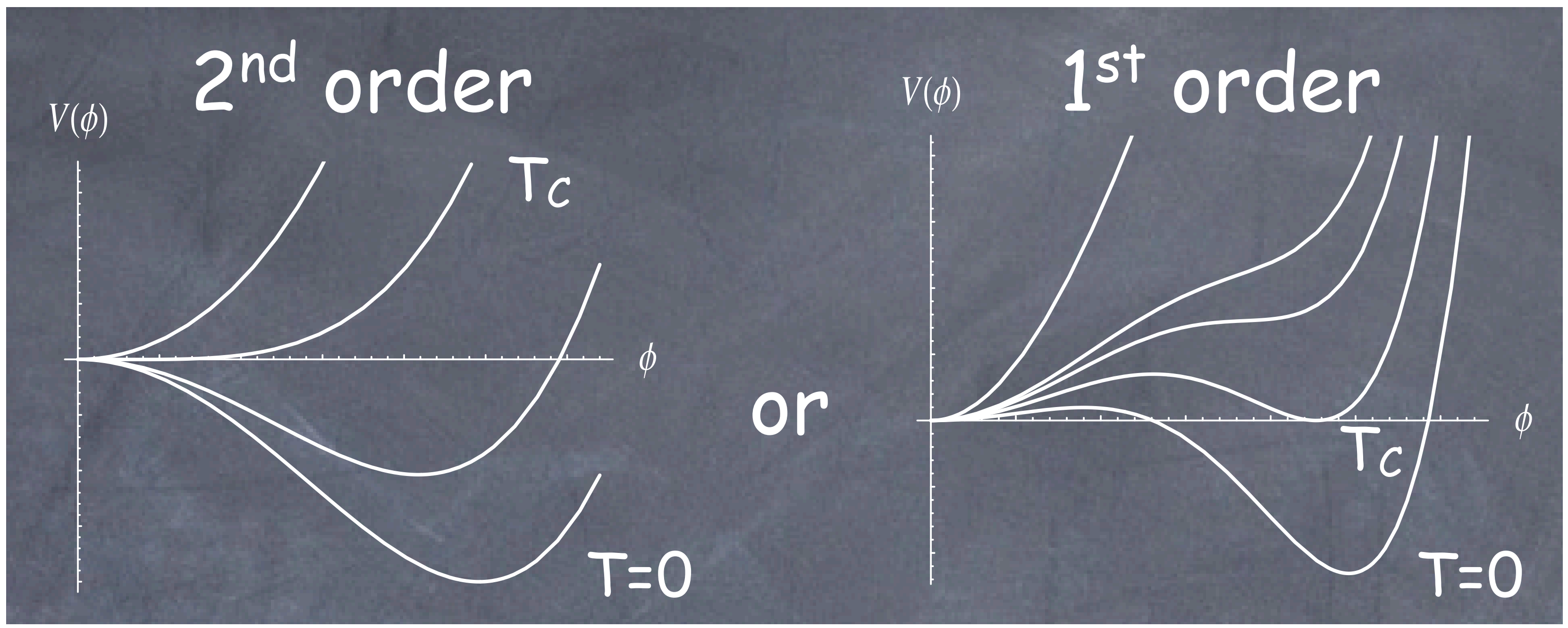

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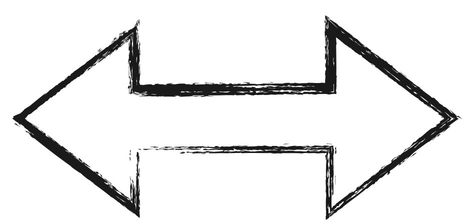
finite T
Higgs potential



Higgs couplings
at T=0

SM: first order phase transition iff mH < 47 GeV

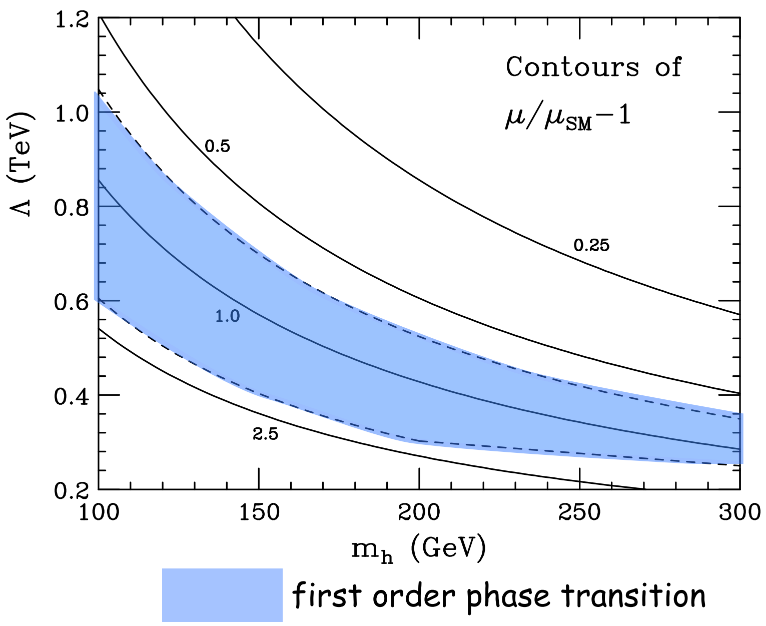
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

Higgs couplings for 1st order EW phase transition

New physics @ tree-level

Grojean, Servant, Wells '04
Noble, Perelstein '07

mixing with other scalars modify the tree-level Higgs potential



$$V(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^3$$

1st order phase transition

comes with 80-200% deviations in Higgs self-interaction

⇓ ⇓

visible @ ILC/TLEP

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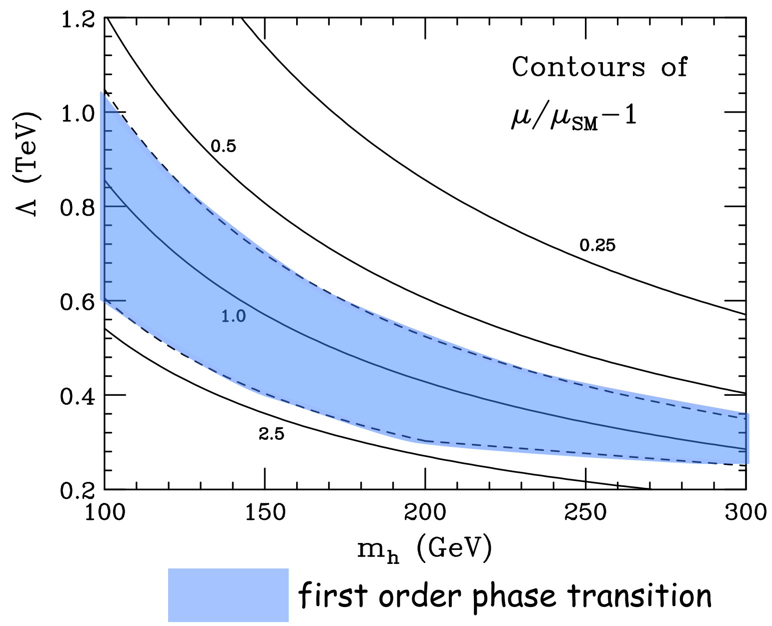

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New physics in loops

Katz, Perelstein '14

new particles, e.g. scalars, coupled to the Higgs without affecting its tree-level potential

$$V \propto \kappa |\Phi|^2 |H|^2$$

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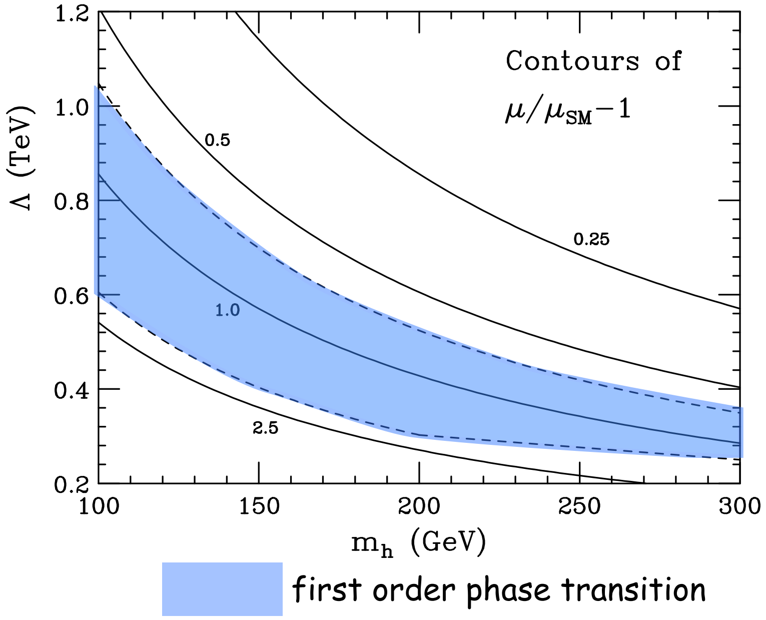

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O(20%) deviation in h→gg

(8%LHC14, 5%HL-LHC,1%ILC,<1%TLEP)

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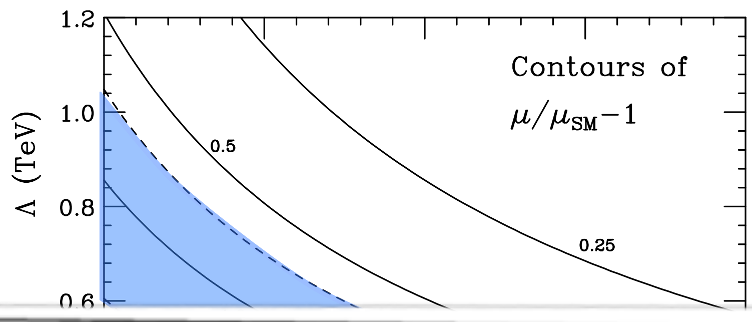

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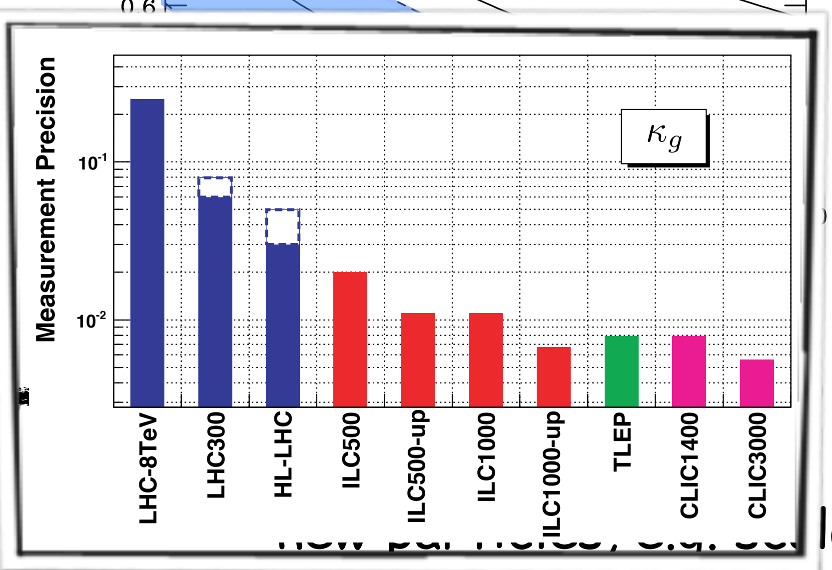

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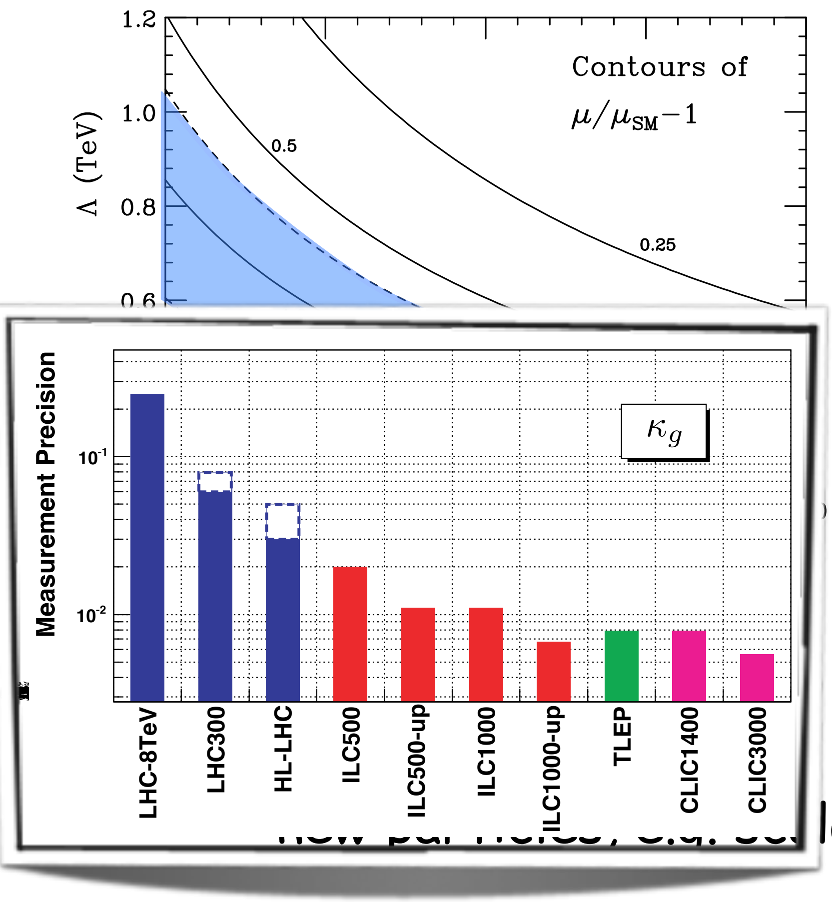

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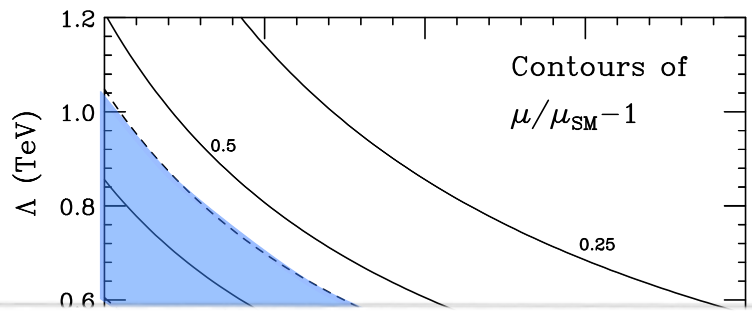

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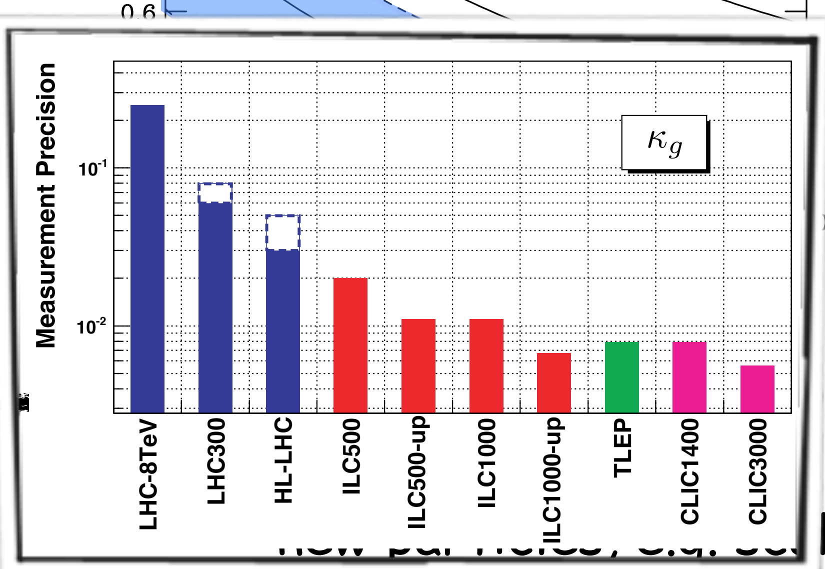
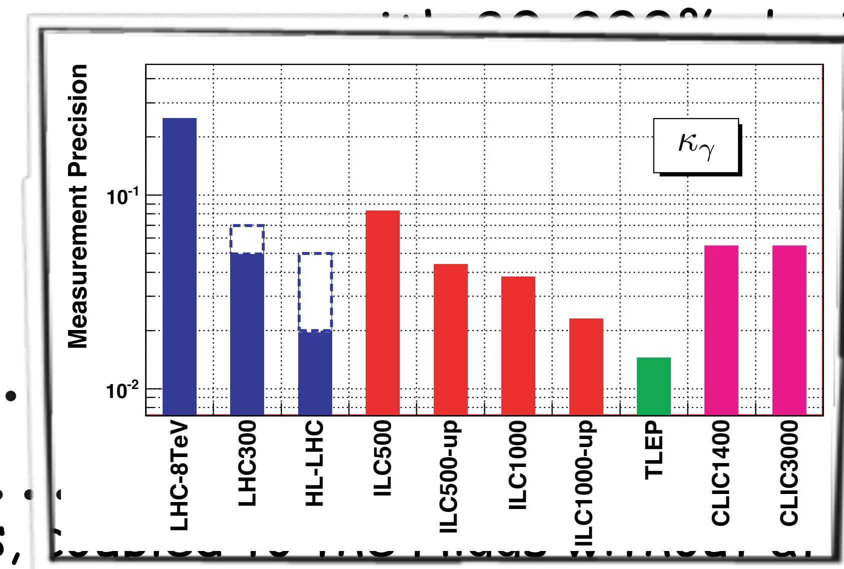
ILC/TLEP





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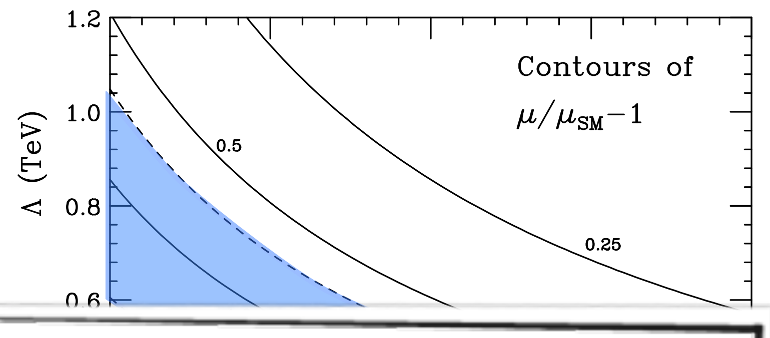

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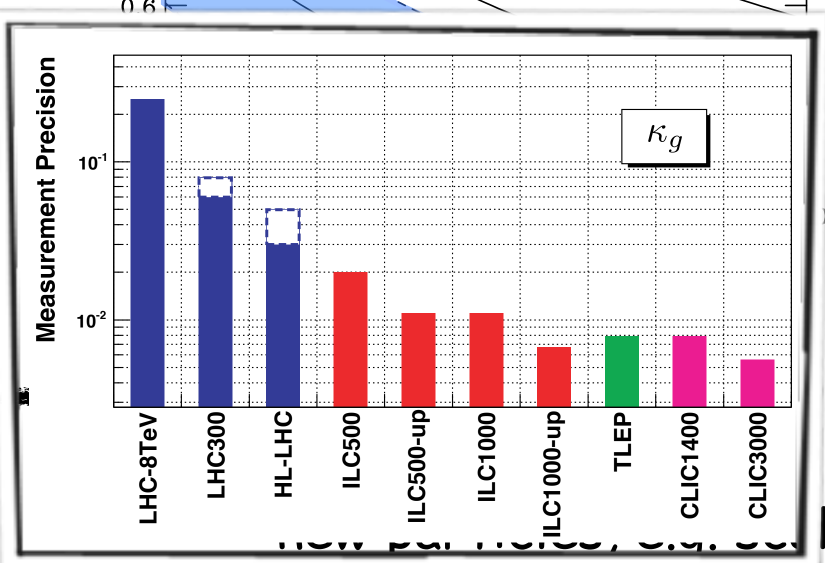

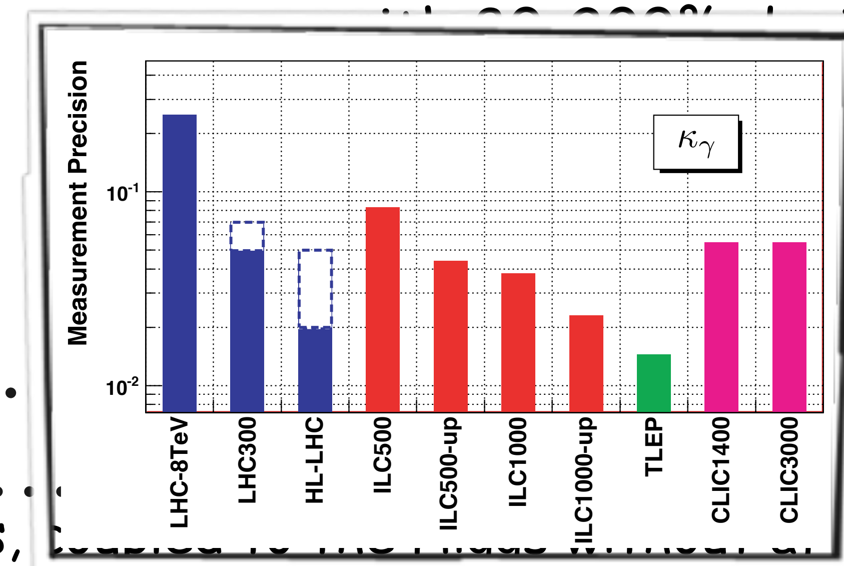

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colored scalars	electrically charged scalars	SM neutral scalars
⇓	⇓	⇓
O(20%) deviation in h→gg	O(5%) deviation in h→γγ	O(1%) deviation in σ(ee→Zh)
(8%LHC14, 5%HL-LHC,1%ILC,<1%TLEP)	(5%LHC14, 2%HL-LHC,2%ILC,1%TLEP)	(10%LHC14, 2%HL-LHC,0.25%ILC,0.05%TLEP)

Higgs couplings for 1st order EW phase transition

New physics @ tree-level

Grojean, Servant, Wells '04
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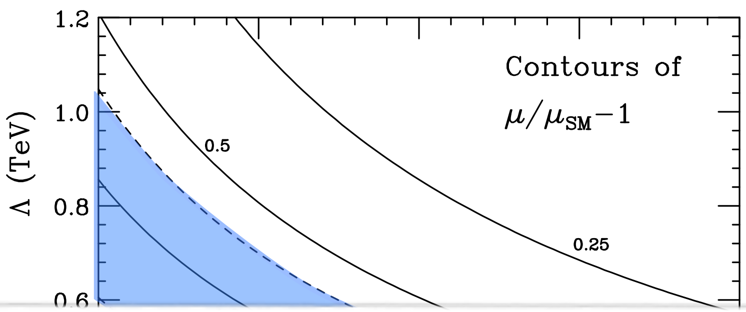

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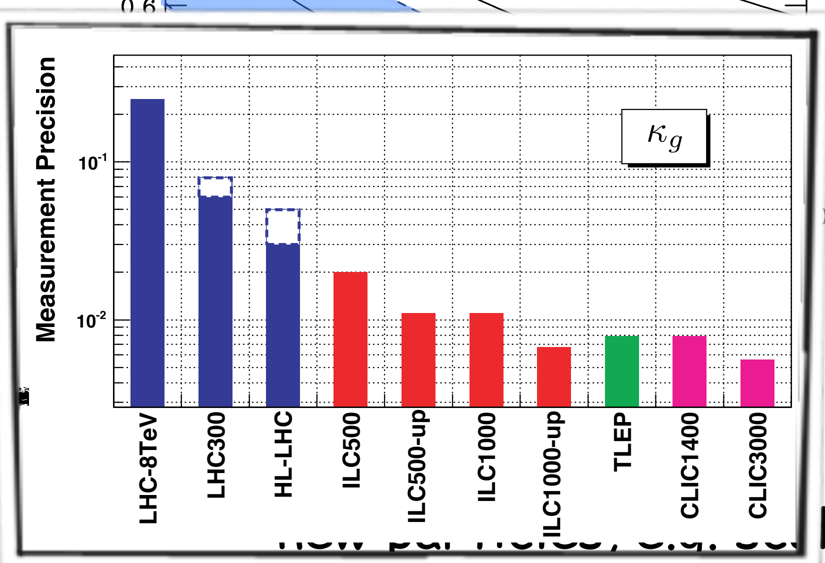
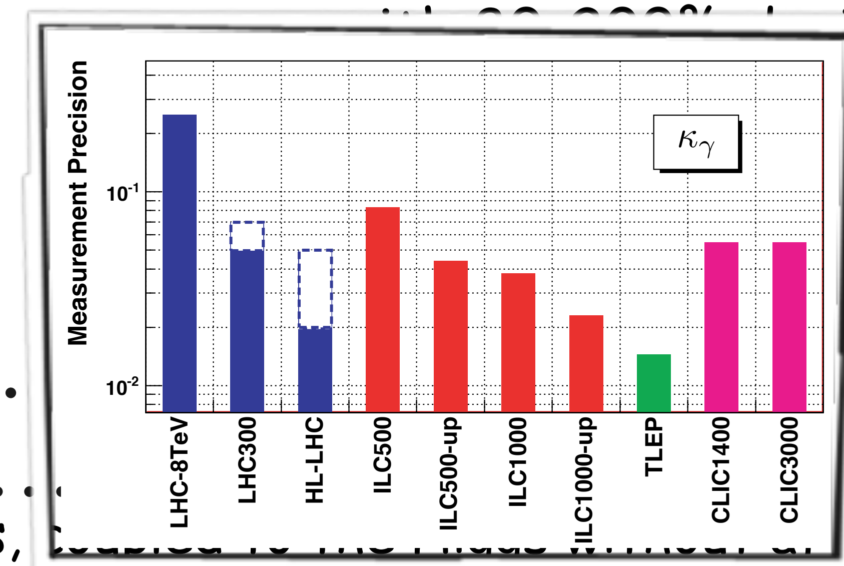
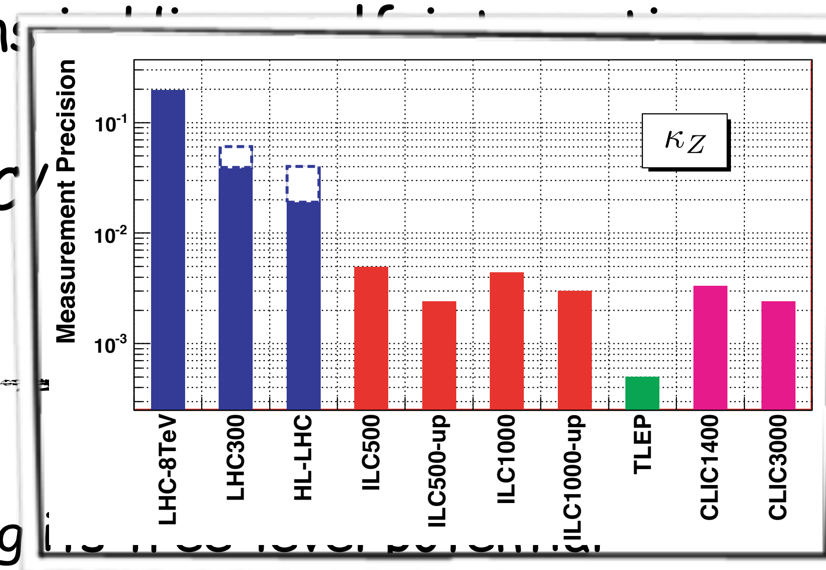
1st order phase transition

...ations...

...ILC...







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4

Multi Higgs, boosted and off-shell Higgs processes

Multi Higgs processes

Producing one Higgs is good. Producing more Higgses is better

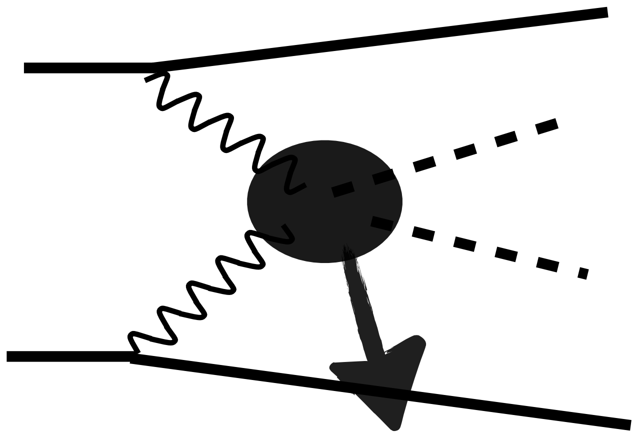
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

The two difficult processes @ LHC (tth and hh) are the real winners of the energy boost
(these 2 processes have to do with the top Yukawa coupling
one of the most promising probe of new physics)

WW→HH: probing Higgs strong interactions

in the SM, the Higgs is essential to prevent strong interactions in EWSB sector

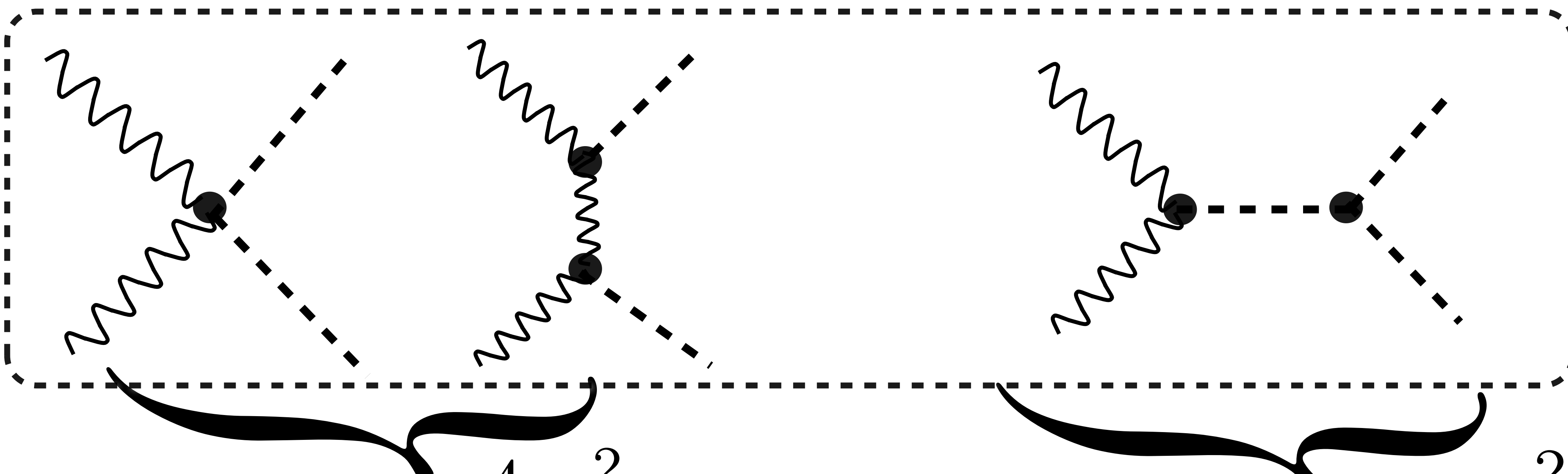
(e.g. WW scattering)



SM: a=b=d_3=d_4=1

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right)$$

$$V(h) = \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4+\dots$$



$$\mathcal{A} \underset{m_{hh}^2\gg m_W^2}{\sim} \left(b-a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2\sim 4m_h^2}{\sim} {\rm cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

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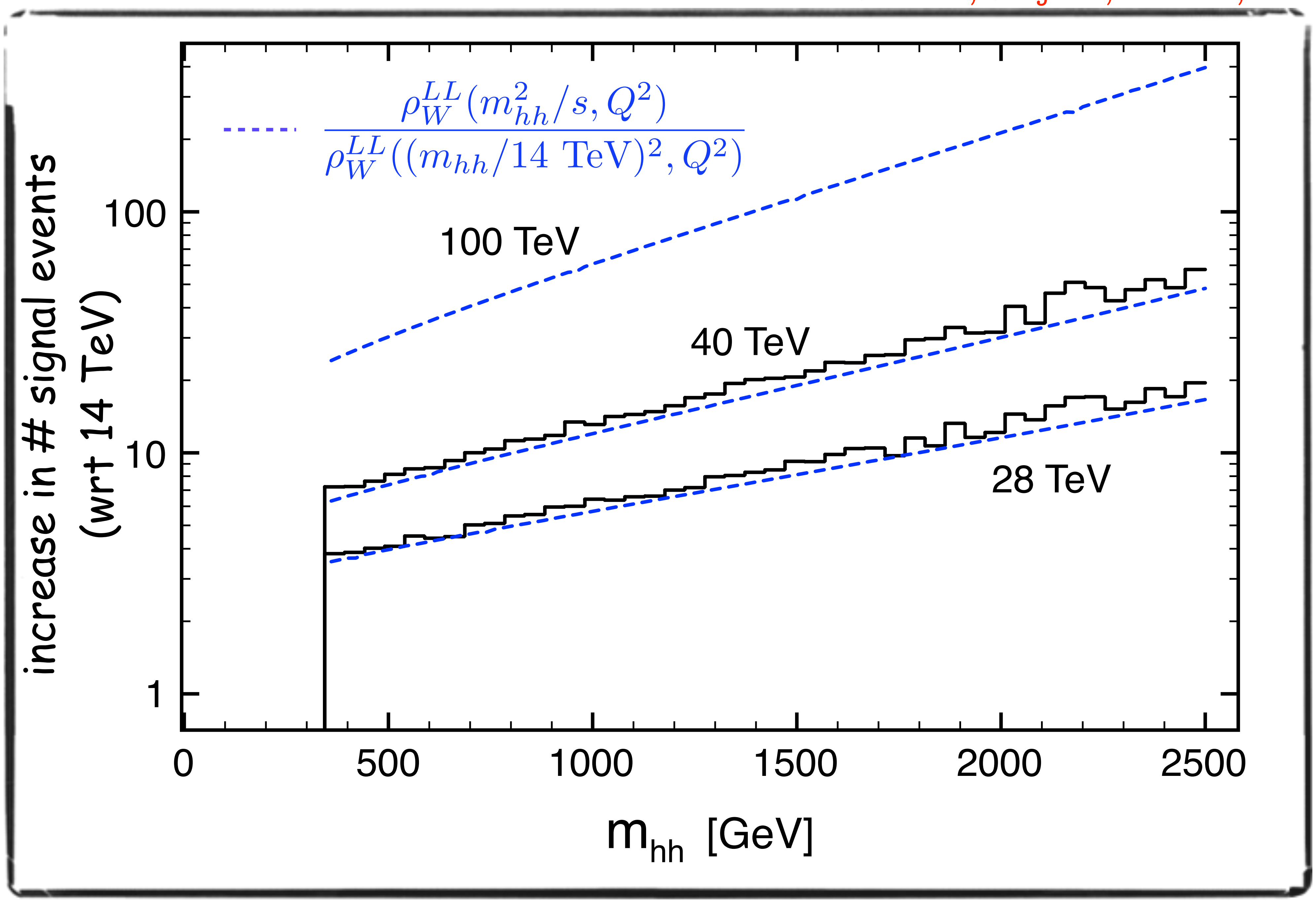
(e.g. WW scattering)

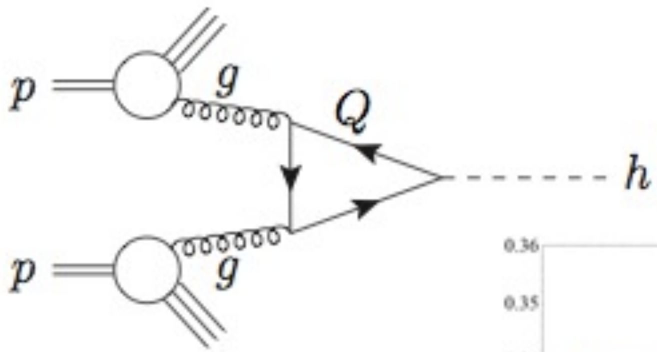
Contino, Grojean, Moretti, Piccinii, Rattazzi '10



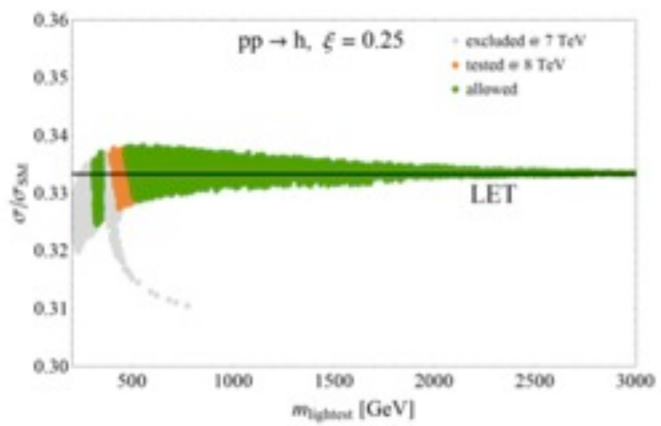
VHE-LHC can probe the high invariant-mass distribution with high statistics

gg→HH: seeing the top partners

~ current single higgs processes are insensitive to top partners ~



$\sigma^{SM}_{14\mathrm{TeV}} \approx 50\ \mathrm{pb}$



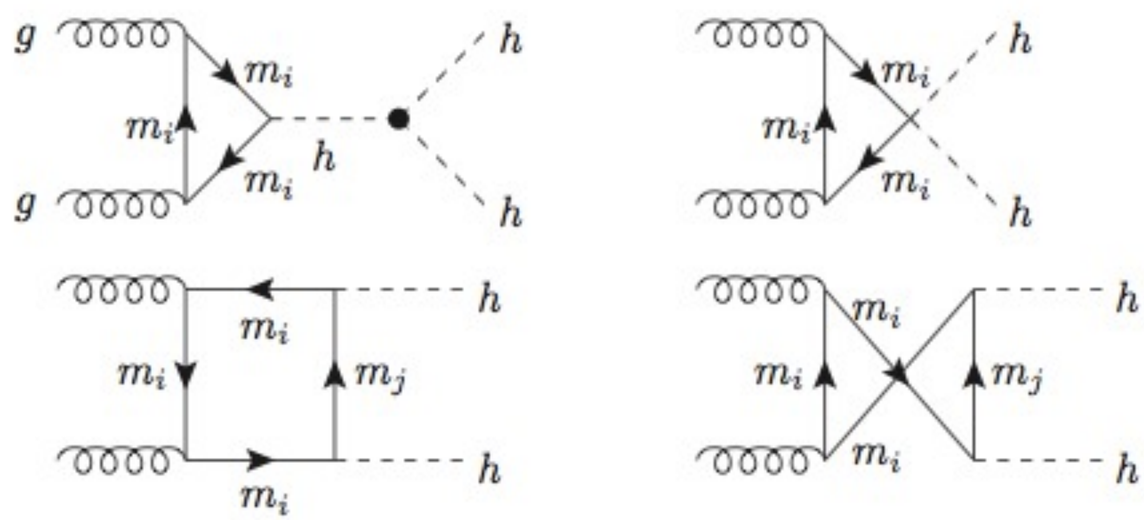
two competing effects that cancel:

- ☑ T's run in the loops
- ☑ T's modify top Yukawa coupling

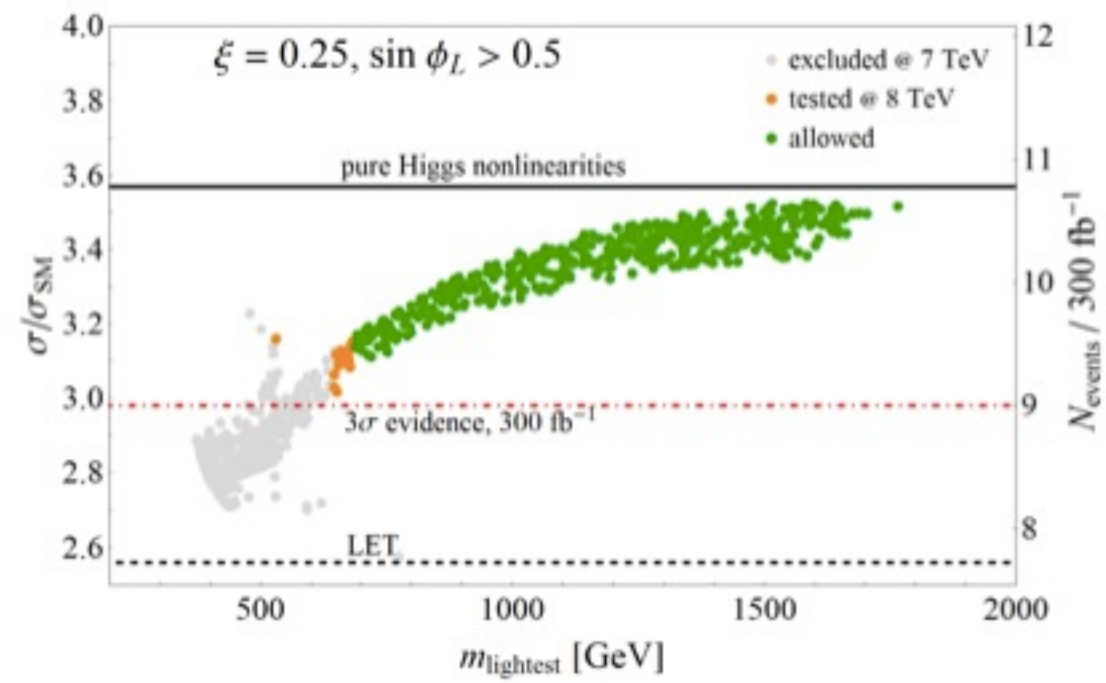
Falkowski '07
Azatov, Galloway '11
Delaunay, Grojean, Perez, '13

~ sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



$\sigma^{SM}_{14\mathrm{TeV}} = 17.9\mathrm{fb}$



competitive to top-partner direct searches

Boosted Higgs

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

the inclusive rate doesn't "see" the finite mass of the top

(*) unless it doesn't decouple (e.g. 4th generation)

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⇛ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop) ⇚

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\text{SM}} = (1+(c_g-c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\text{SM}} = (1+(c_\gamma-4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

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fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

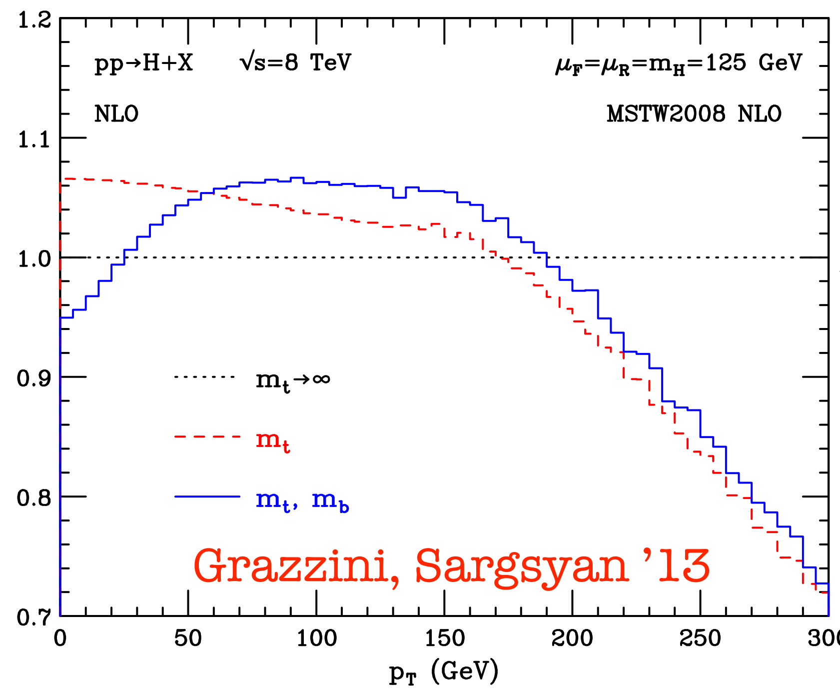
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

Beyond inclusive channels: Boosted Higgs

cut open the top loops

high $p_T \approx$ Higgs off-shell
we "see" the details of the particles running inside the loops

Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



Note: LO only
NLO_{m_t} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

the high p_T tail is tens' % sensitive to the mass of top

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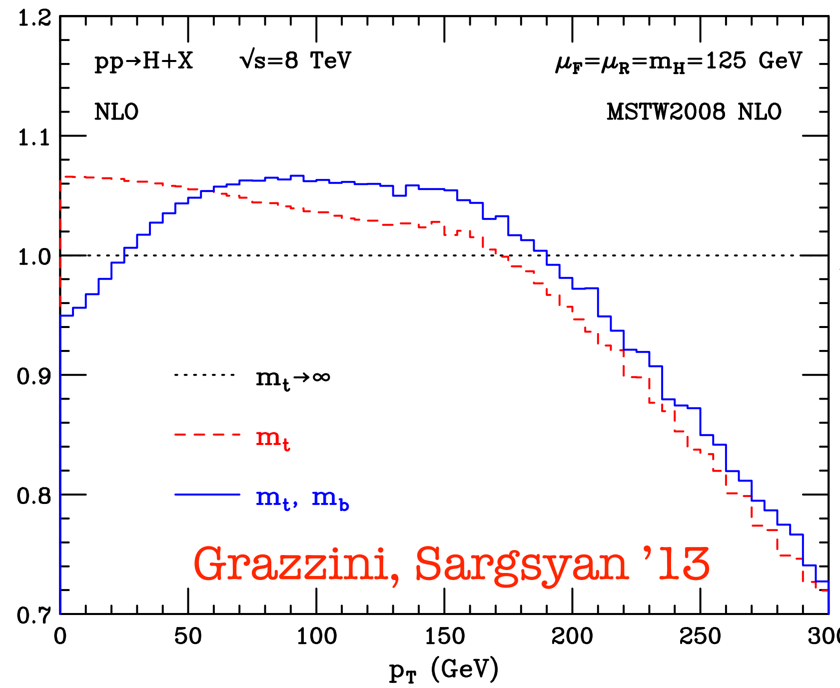

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Harlander et al '12

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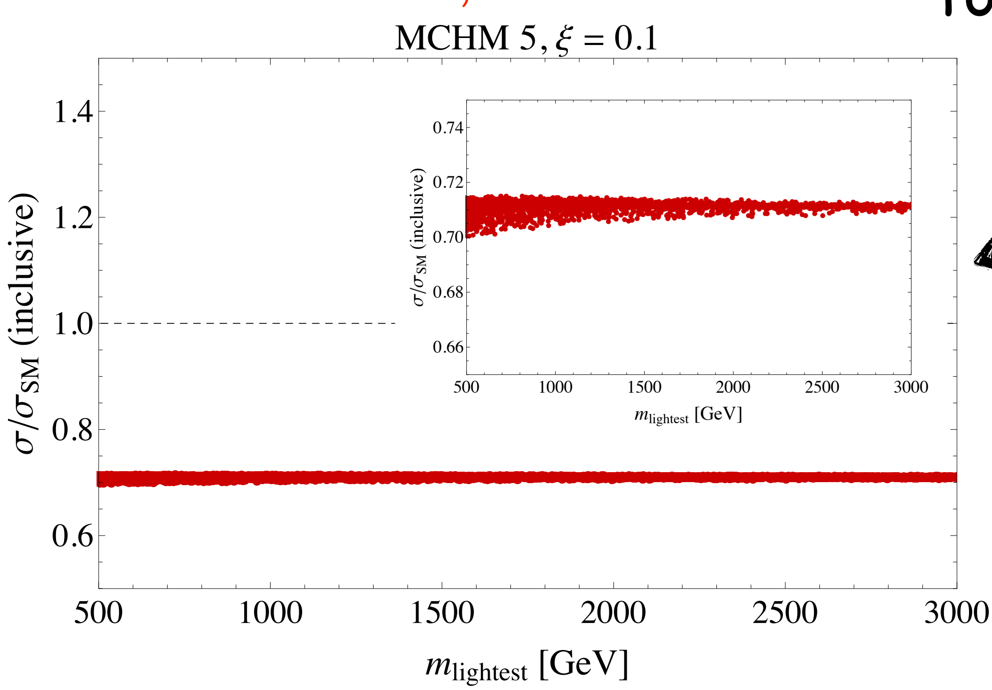
Composite Higgs Model

top partners contributions

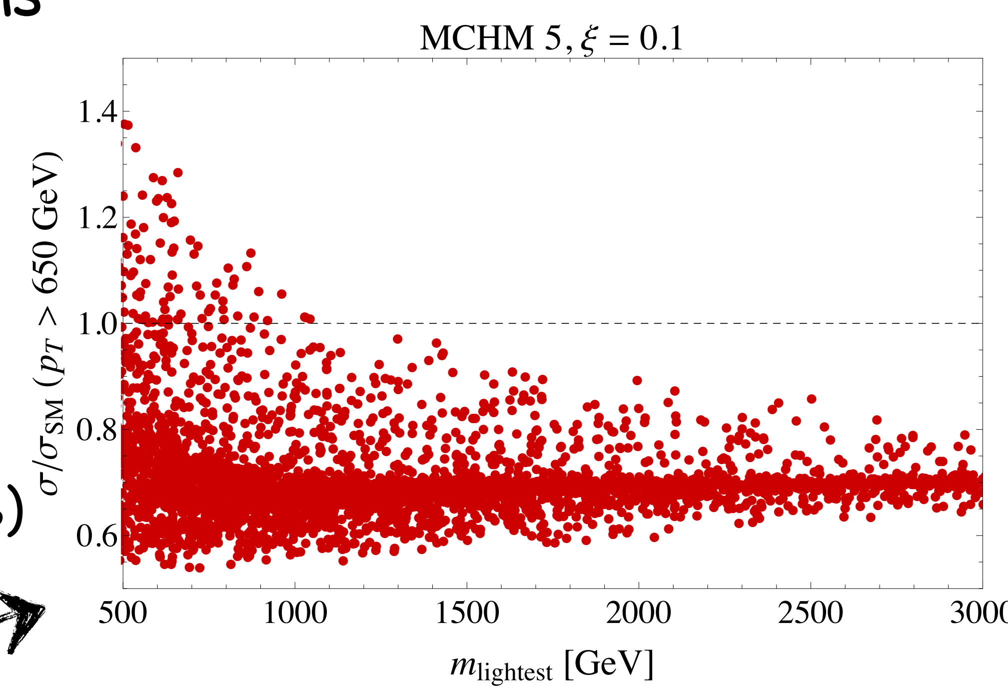
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: O(%)

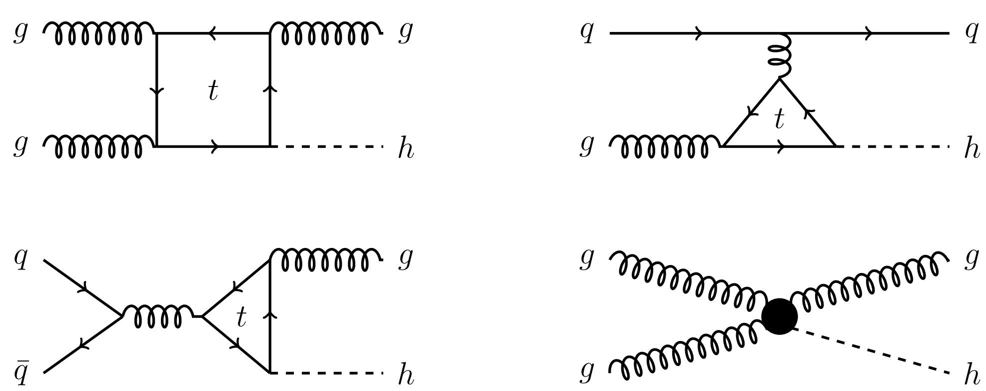
with high-p_T cut: O(x10'%)



high-p_T tail "sees" the top partners that are missed by the inclusive rate

Boosted Higgs

Grojean, Salvioni, Schlaffer, Weiler ‘13



$$\frac{\sigma_{p_T^{\min}}(\kappa_t, \kappa_g)}{\sigma^{SM}_{p_T^{\min}}} = (\kappa_t + \kappa_g)^2 + \delta\, \kappa_t\, \kappa_g + \epsilon\, \kappa_g^2$$

large pT, small rates

need to focus on dominant decay modes

$$h \to b\bar{b}, WW, \tau\tau$$

non-isolated “ditau-jets”

(separation between the 2 tau’s: $\Delta R \sim 2m_h/p_T \lesssim 0.5$)

$$\epsilon_{\rm tot} = {\rm BR}(h \to \tau\tau) \left(\sum_{i=\tau_\ell\tau_\ell,\, \tau_\ell\tau_h,\, \tau_h\tau_h} {\rm BR}(\tau\tau \to i)\, \epsilon_i \right) \simeq 2 \times 10^{-2}$$

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{SM}_{p_T^{\min}}$ [fb]	δ	ϵ	$gg,\ qg$ [%]
14	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57
100	500	970	1.8	3.1	72, 28
	2000	1.0	14	78	56, 43

x 150 enhancement

VHE-LHC is the machine to decipher the gg→h process

Off-shell Higgs

Off-shell Higgs effects:

naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs

but enhancement due to the particular couplings of H to V_L

Recent analysis of $gg \to H \to ZZ \to 4l$

(about 15% of the Higgs events are far off-shell m_{4l}>300GeV)

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH} g_{HZZ} \frac{F(m_{ZZ})}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

Kauer, Passarino '12
Caola, Melnikov '13
Campbell et al '13

Englert, Spannowski '14

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Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via the measure the mass shift or via the rate

Narrow Width Approx.: on-shell

ratios of κ only

$\sigma^{on-peak}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$ no direct access to the width itself

(upper bound if κ_V < 1 is assumed
e.g. Dobrescu, Lykken '12)

off-shell

different width dependence

Γ_H can be fitted w/o assumption

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What do we learn?

Not competitive with global fits on BR_{inv}

Model independent analysis might not be robust because of unitarity issues

Englert, Spannowski '14

Conclusions

- HEP program should aim at providing answers to fundamental questions like
  - stability of the EW vacuum
  - naturalness of EW symmetry breaking
  - matter-antimatter asymmetry
  - dynamics behind EW symmetry breaking (weak vs strong forces)
  - is the Higgs boson responsible for the masses of all elementary particles?
  - flavor structure via the access to rare processes (not covered in this talk)
  - nature of dark matter (not covered in this talk)
  - exotic new physics (not covered in this talk)
  - ...

Our understanding of the SM has reached an
unprecedented level of sophistication/precision
that paves the way to a discovery of New Physics

We have a rich EXP program to achieve that