The Higgs Boson
Key to Our Understanding of the Universe

Margarete Mühlleitner, KIT

Symposium Quantum Physics
at the High-Energy Frontier:
The Higgs Boson in the
Standard Model and Beyond

Göttingen, 10 September 2025

Outline

- The Higgs Quantum Legacy
- The Higgs Laboratory for New Physics
- The Higgs Potential
- The Higgs Connection to Cosmology and Astrophysics
- Phenomenological Results

The Higgs Quantum Legacy

100 Years of Quantum Mechanics

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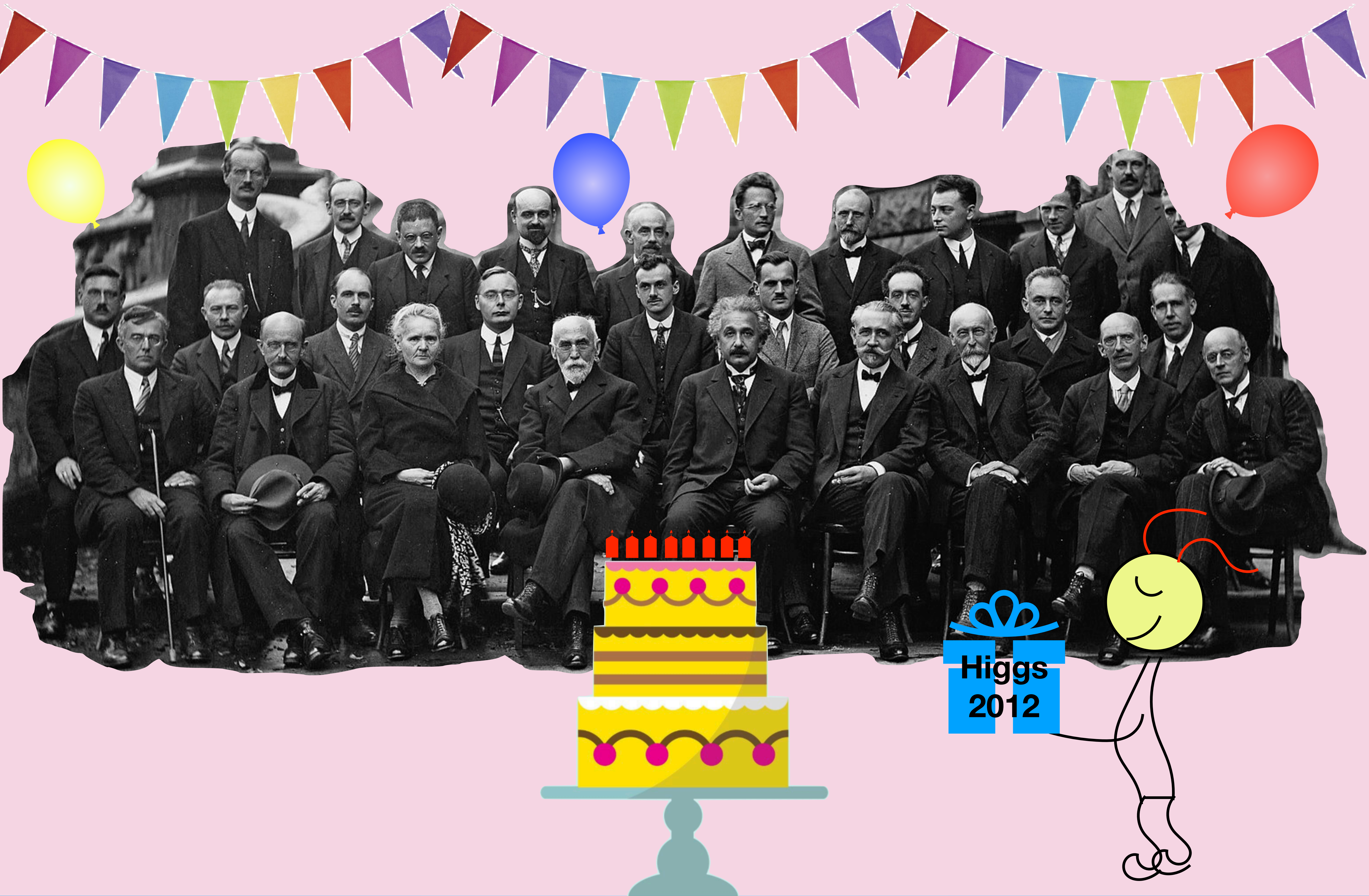
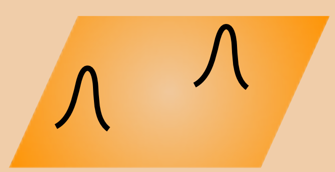


Deep Connection of Quantum Mechanics and Particle Physics

Quantum Mechanics
delivers the framework
for the exploration of the
elementary particles and the
fundamental forces between them

Basics of modern particle physics:
Quantum Field Theory (QFT)

- **quantisation** of the **fields**
- particles: **quantum excitations** of the fields
- integrating special relativity

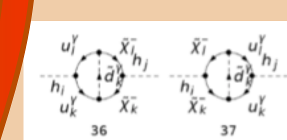


Manifestations of quantum physics

Quantum fluctuations omnipresent in the particle world and testable in high-precision experiments

Symmetries: guiding principle for the formulation of the QFT explaining nature

Symmetries must also hold at the **quantum level**: powerful tool for consistency tests



Higgs - A Remarkable Legacy of Quantum Physics

Result of the deep interplay of quantum field theory and symmetry principles

More than just a particle:
Bridge between the abstract mathematics of quantum physics and the fundaments of our Universe

Reminds us about the basic principles behind the apparent complexity our cosmos

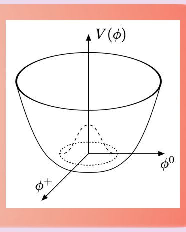
Last but not least it may be the key to our remaining open questions

What is so Special about the Higgs Boson?

fund. forces ↔ fund. symmetries

massive gauge bosons & fermions

Spontaneous Symmetry Breaking (SSB)



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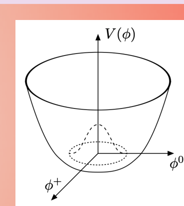
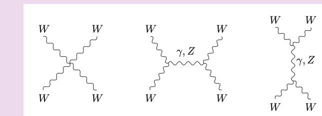
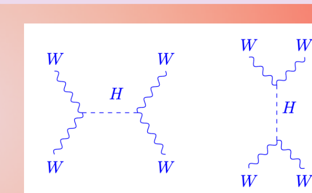


Ensure unitarity



Scalar particle w/ $g^{H}_{SMSM} \sim m^{(2)}_{SM}$



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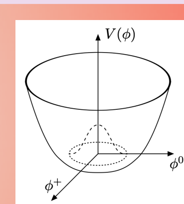

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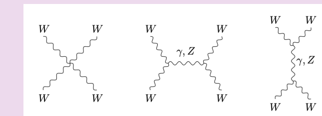

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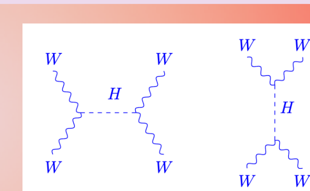

Higgs Boson

$$\mathscr{L}_{\mathrm{Higgs}} = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi) + \mathscr{L}_{\mathrm{yuk}}$$

Weakly interacting theory with massive gauge bosons and fermions up to high energies

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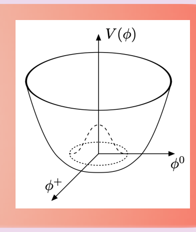

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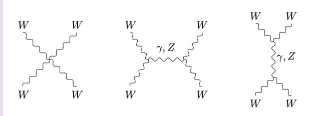

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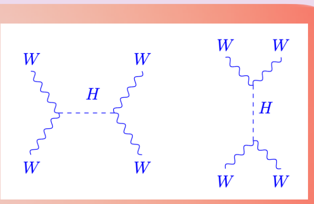

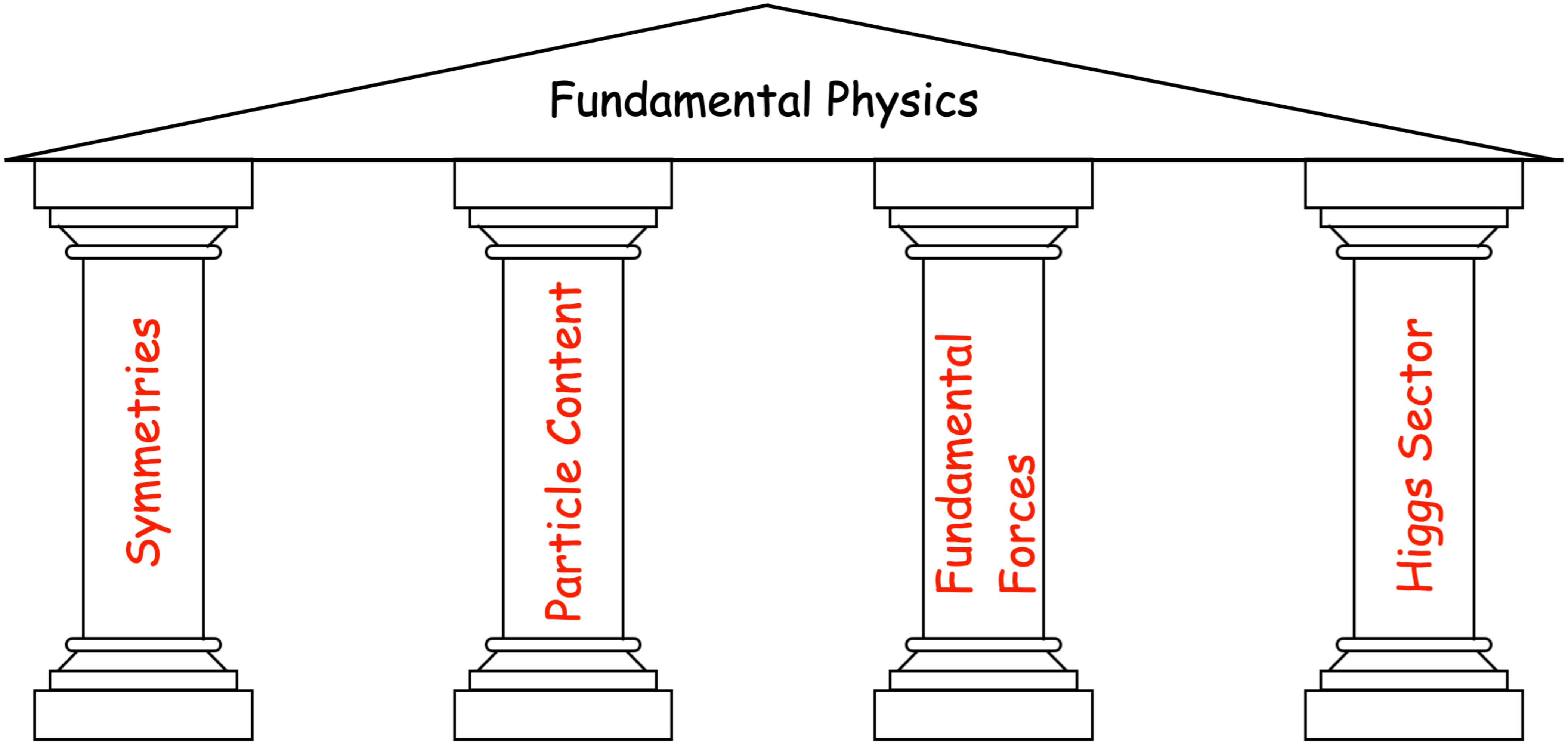

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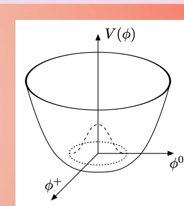

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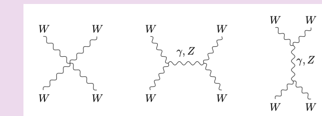

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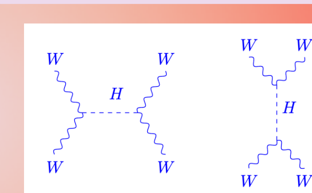
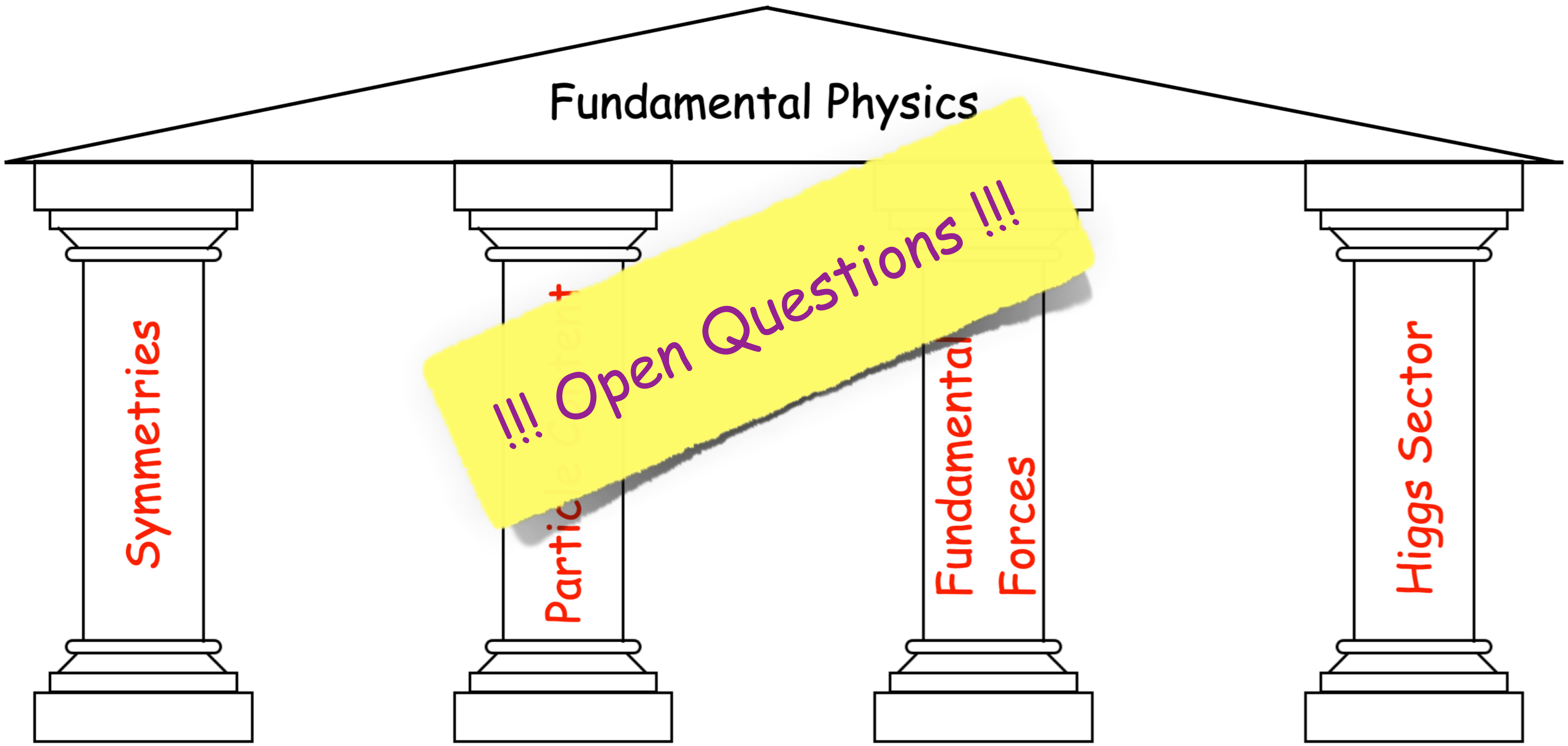
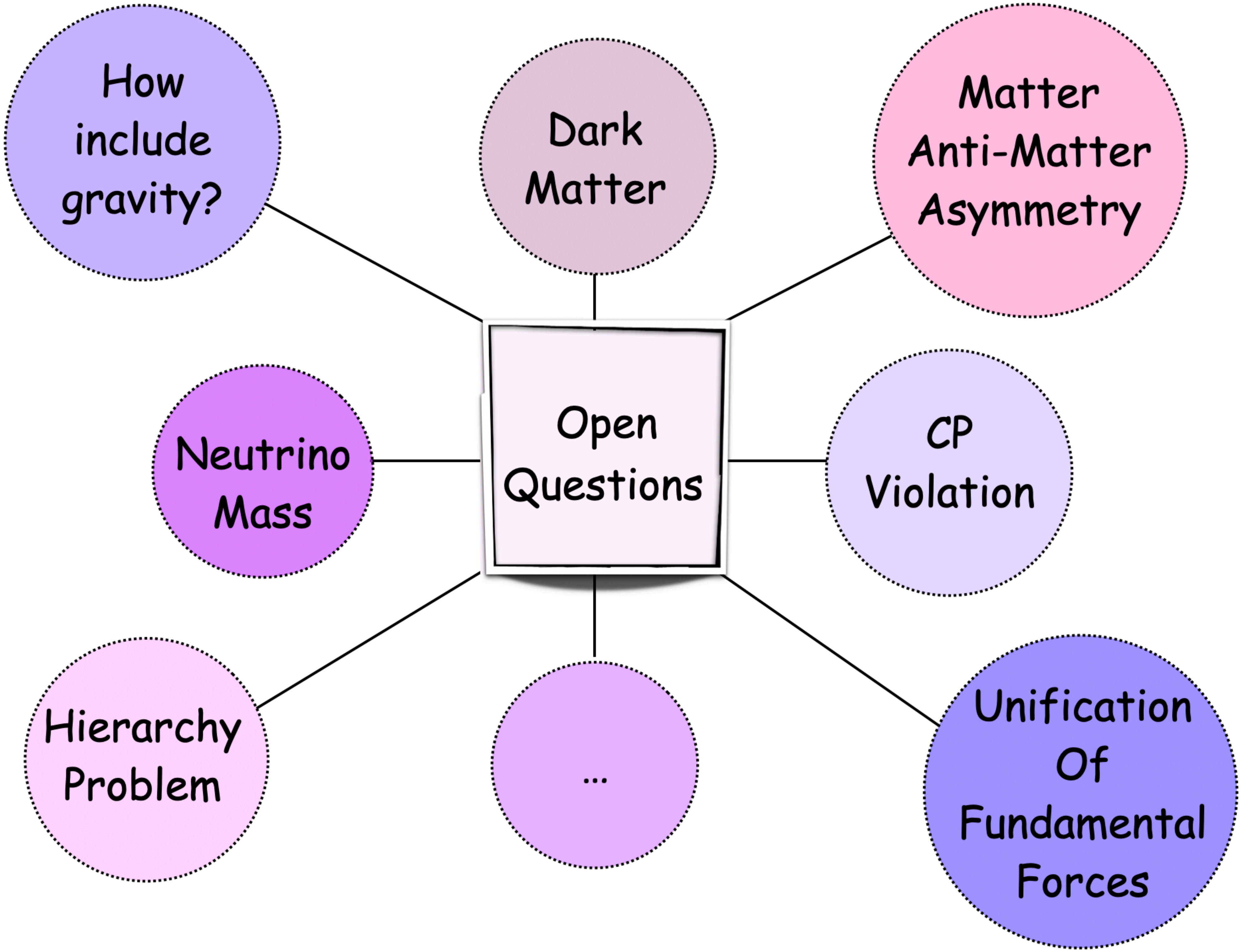


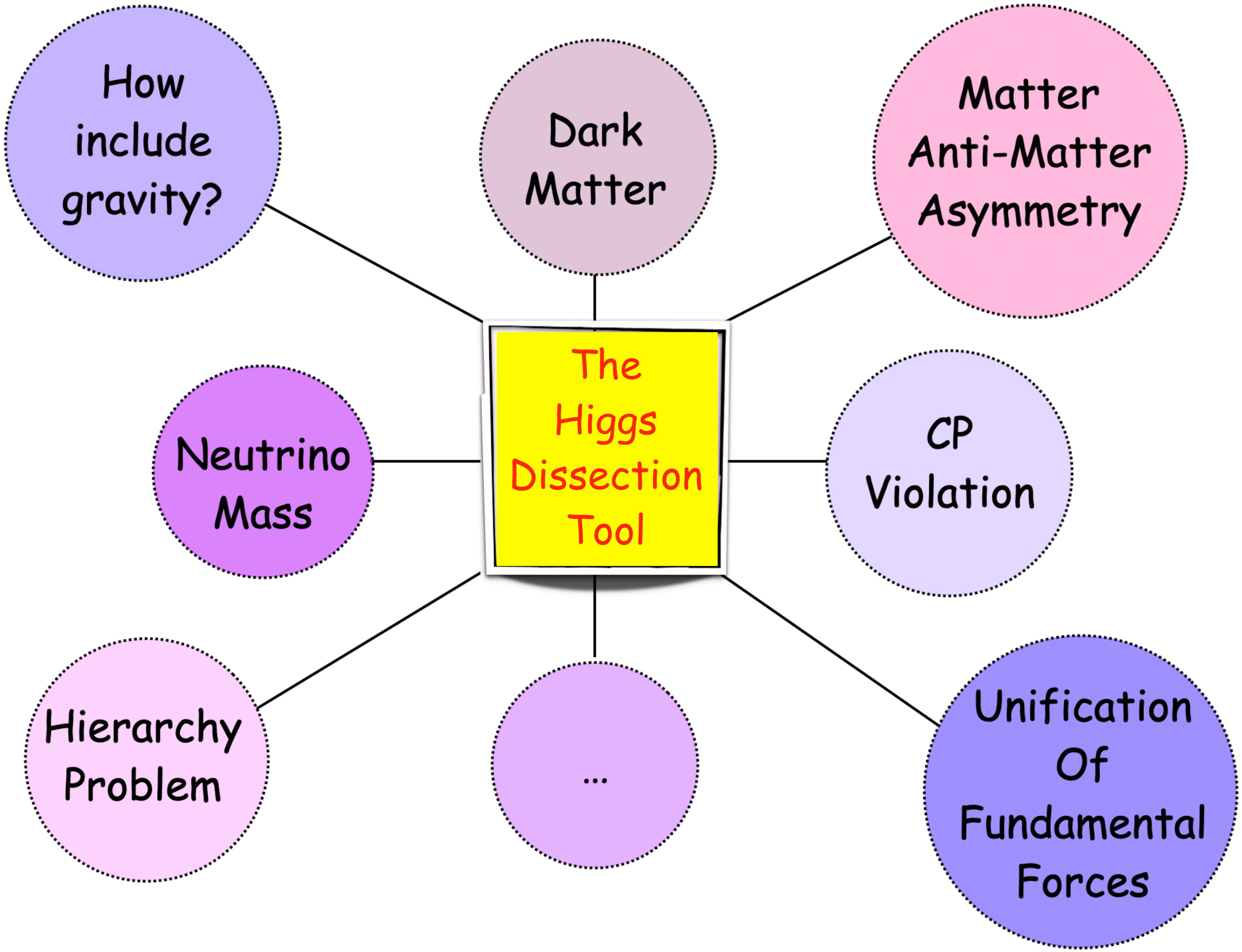


Open Questions



The Higgs Laboratory for New Physics

Open Questions



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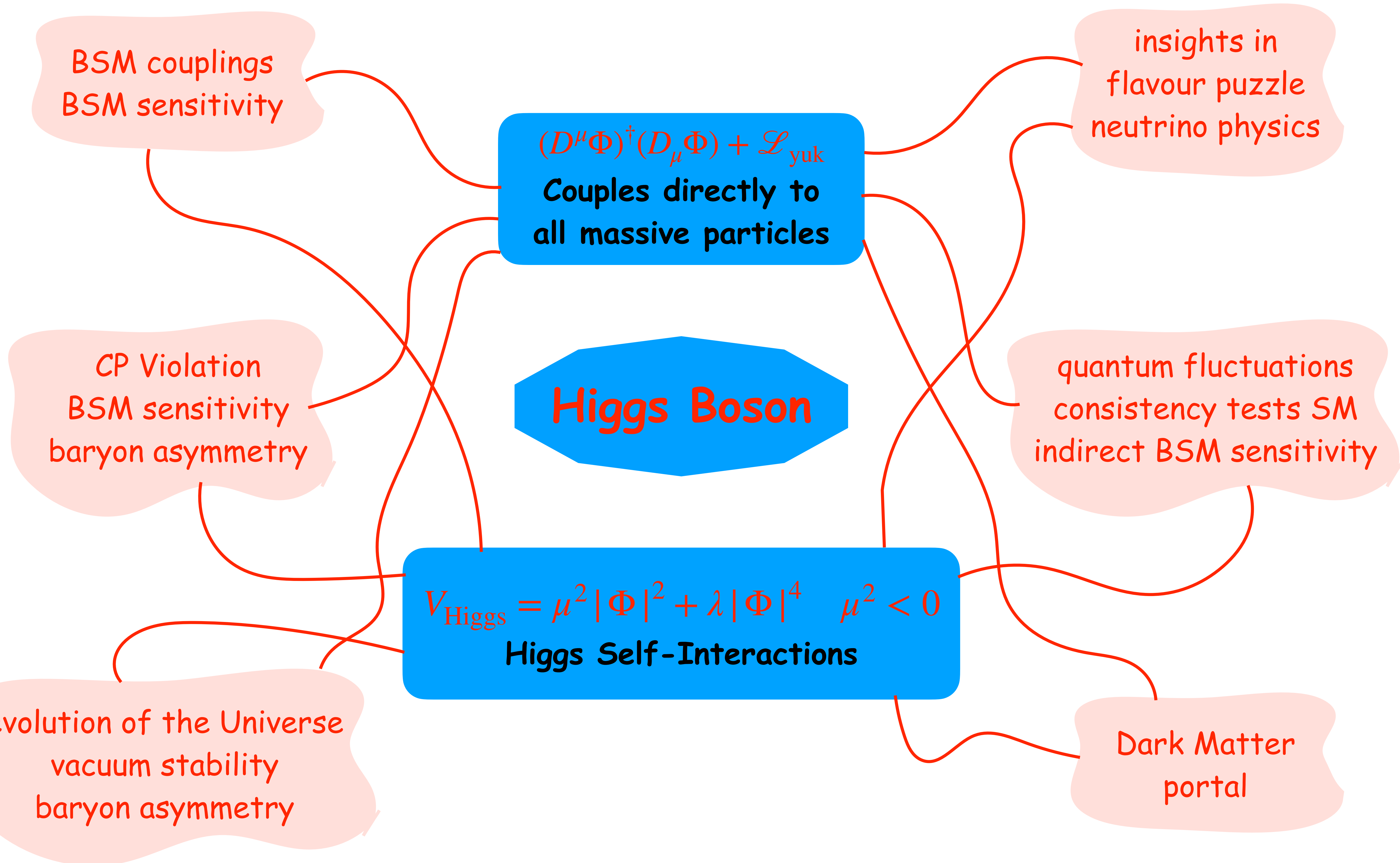
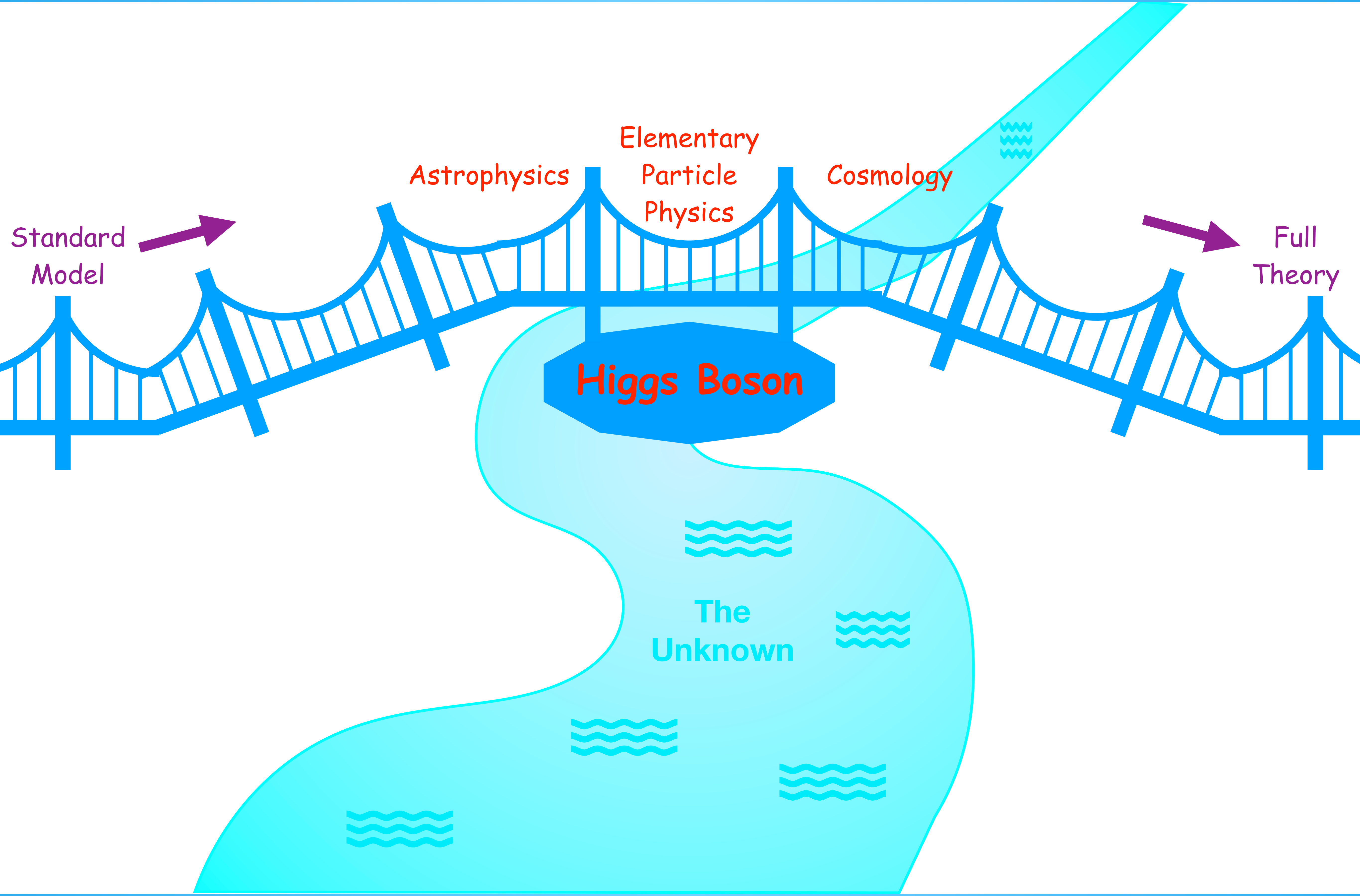


The Higgs Bridge to New Physics

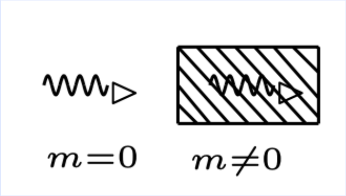


What we Know about the Higgs

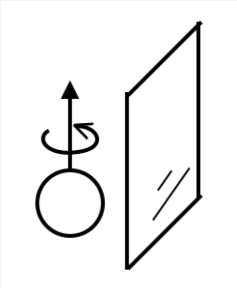
Test of the Higgs Mechanism

❖ Discovery M_H

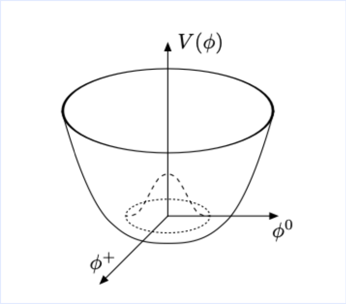
❖ Interactions $g^{\mathrm{H}}_{\mathrm{SMSM}} \sim m^{(2)}_{\mathrm{SM}}$



❖ Spin, parity quantum numbers J^{PC}

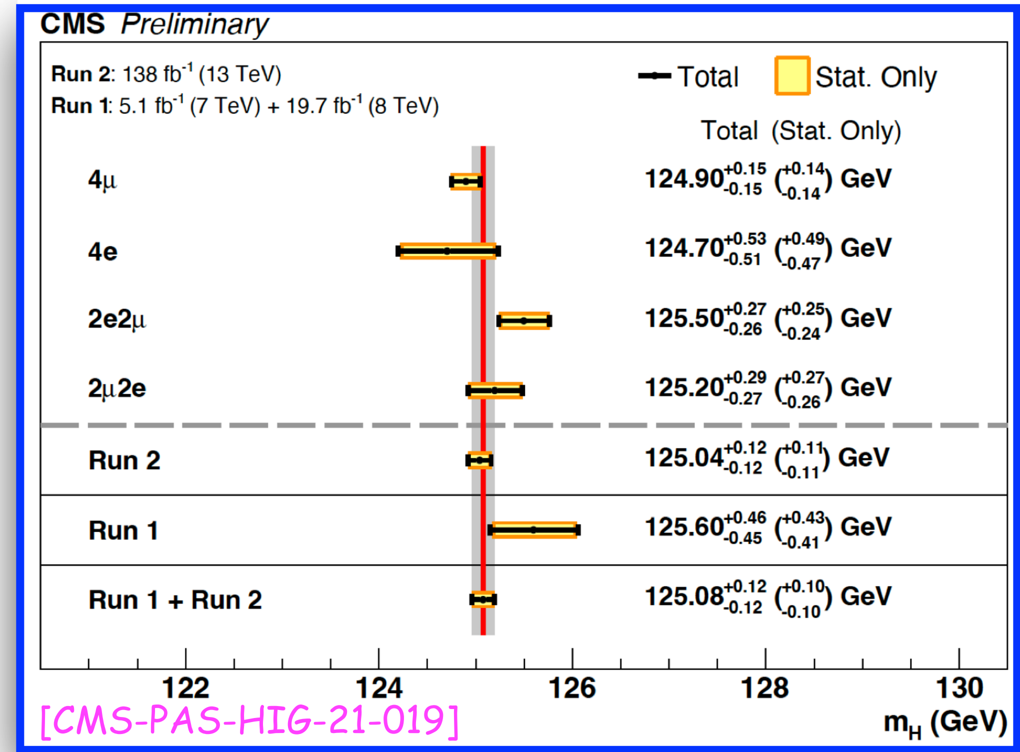


❖ EWSB Higgs potential $\lambda_{\mathrm{HHH}}, \lambda_{\mathrm{HHHH}}$



What we Know about the Higgs

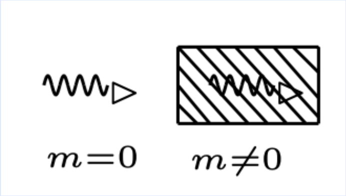
m_H = 125.04 ± 0.11 (stat.) ±0.05 (syst.) GeV



... of The Higgs Mechanism

M_H

$g^{H}_{SMSM} \sim m^{(2)}_{SM}$



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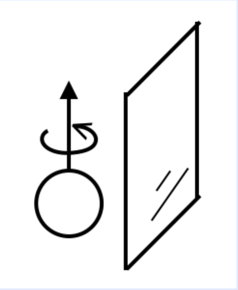

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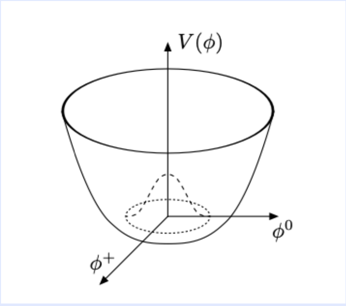

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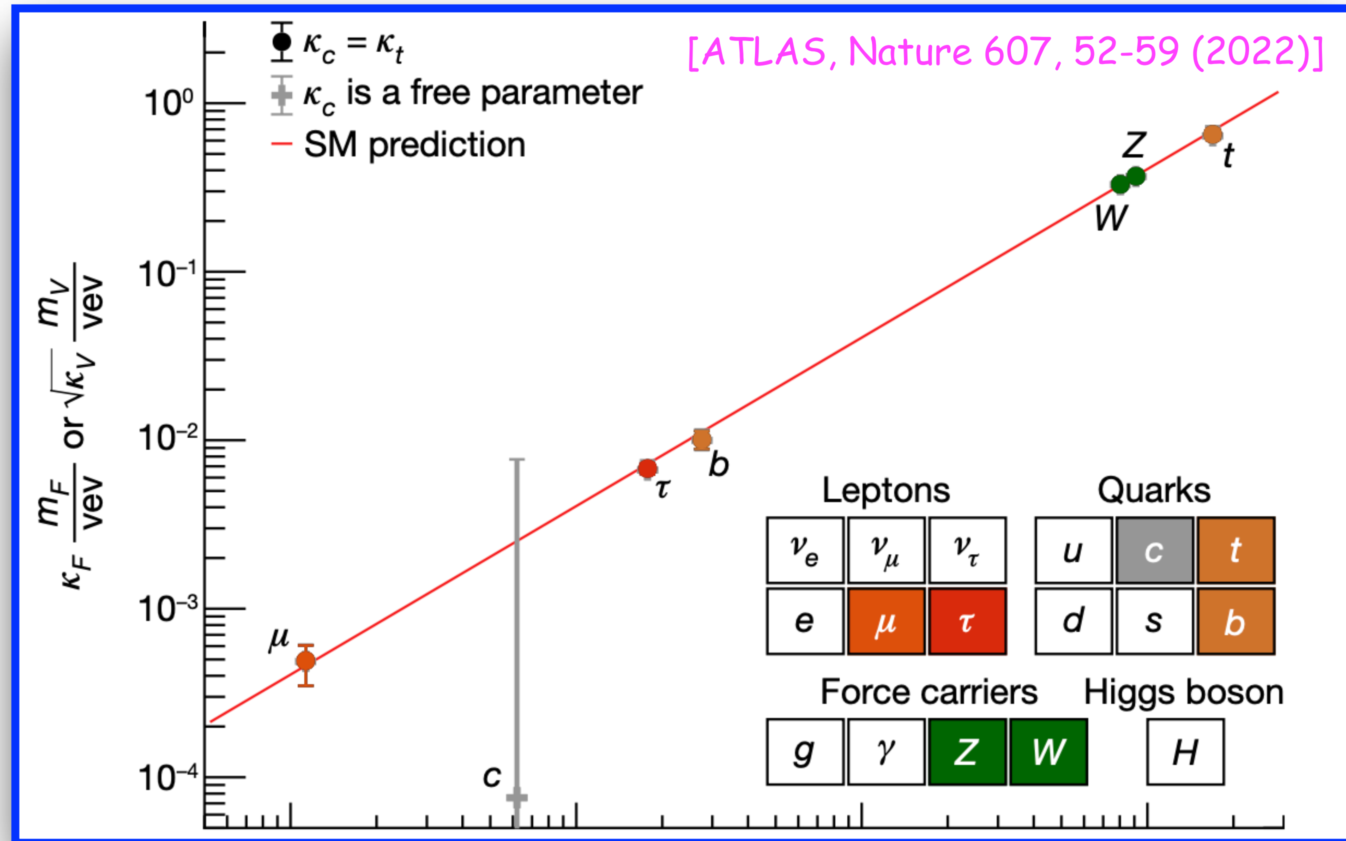

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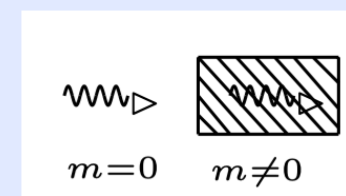

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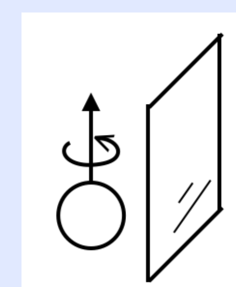

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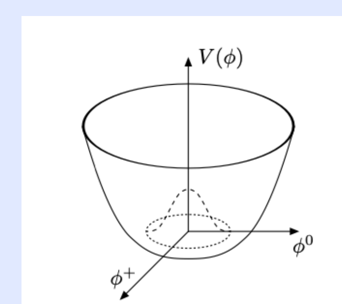

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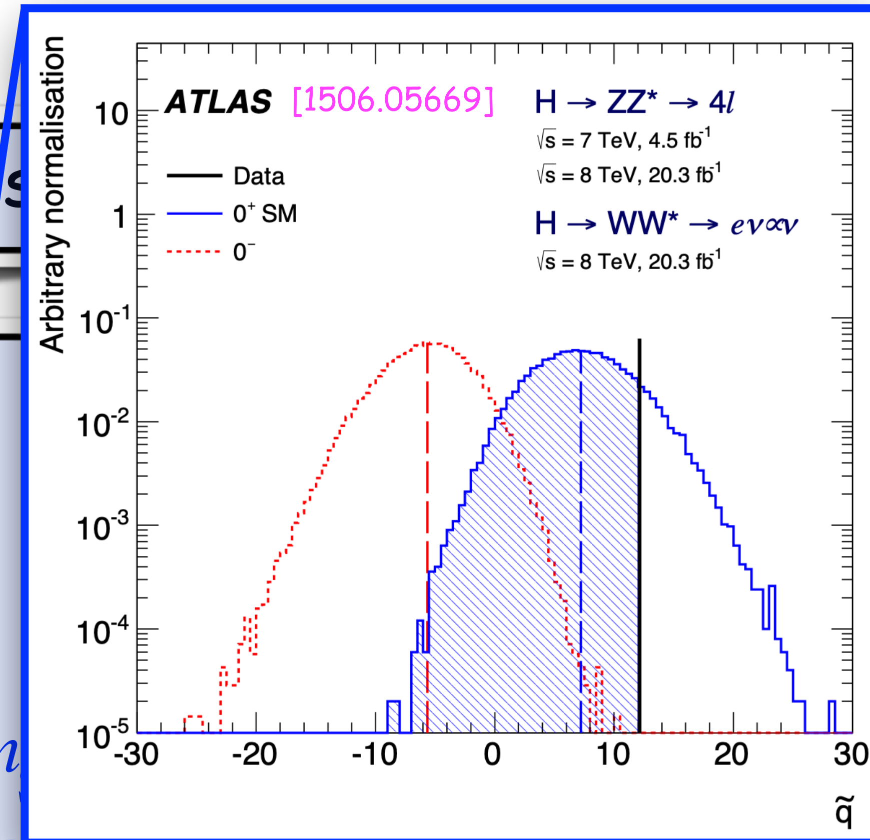
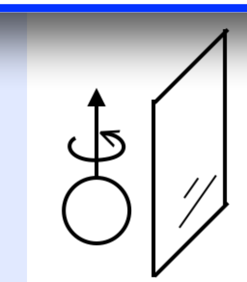
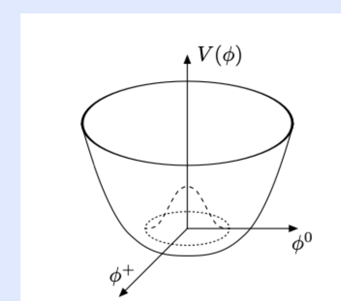


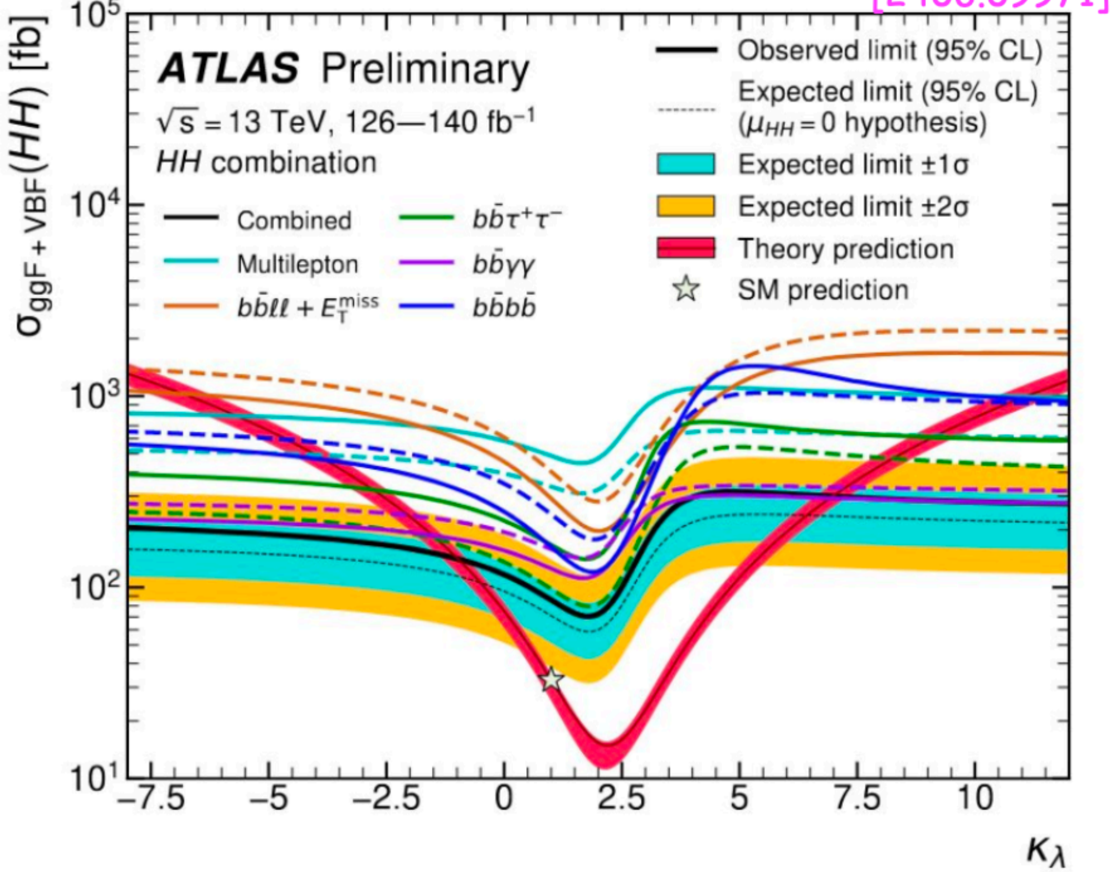




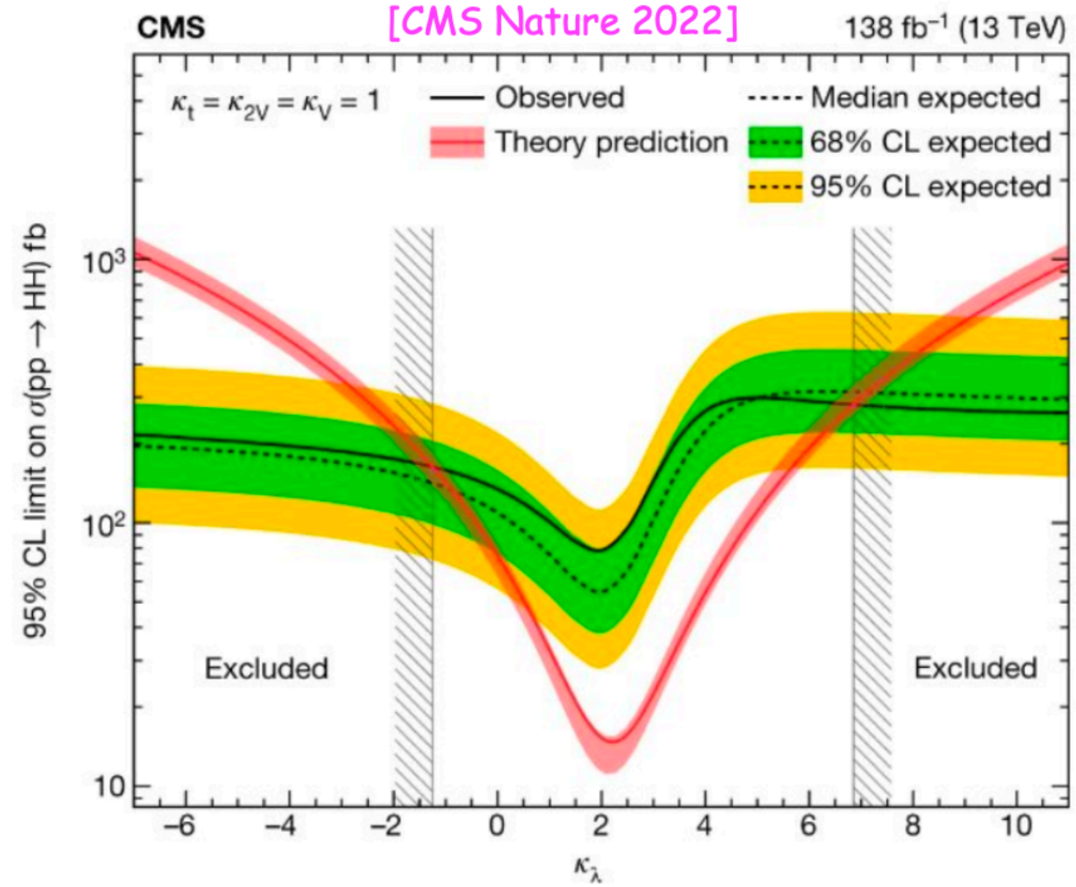
What we Know about the Higgs

ATLAS: $-1.2 < \kappa_\lambda < 7.2$ at 95 % CL   CMS: $-1.24 < \kappa_\lambda < 6.49$ at 95 % CL

[2406.09971]



[CMS Nature 2022]



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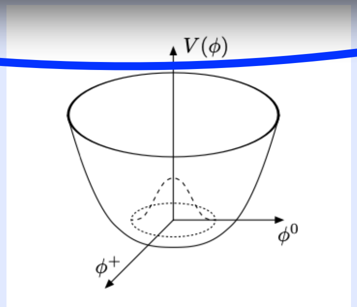


What we Know about the Higgs

T… …anism

More in

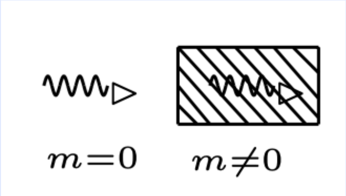
Karsten Köneke

Present:

The Higgs boson revealed - what we know

❖ Discovery

❖ Interactions $g^{H}_{SMSM} \sim m^{(2)}_{SM}$



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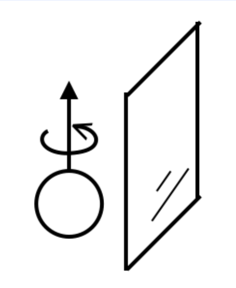

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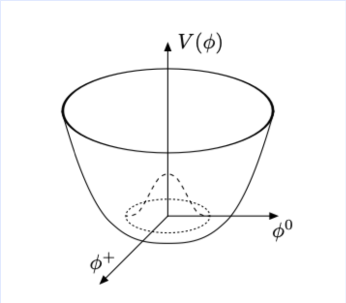
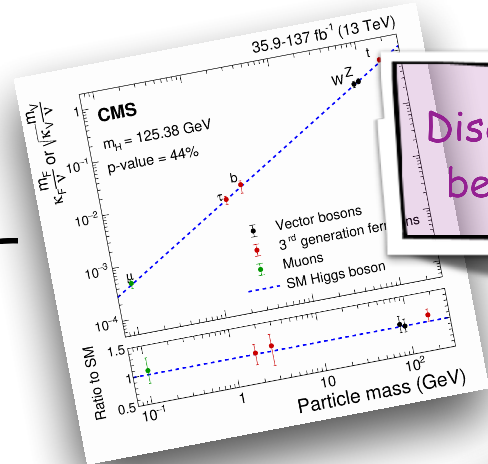
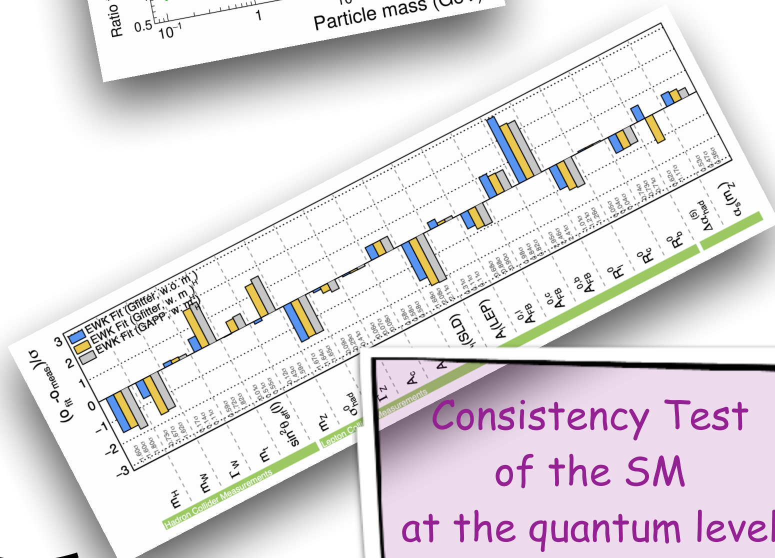
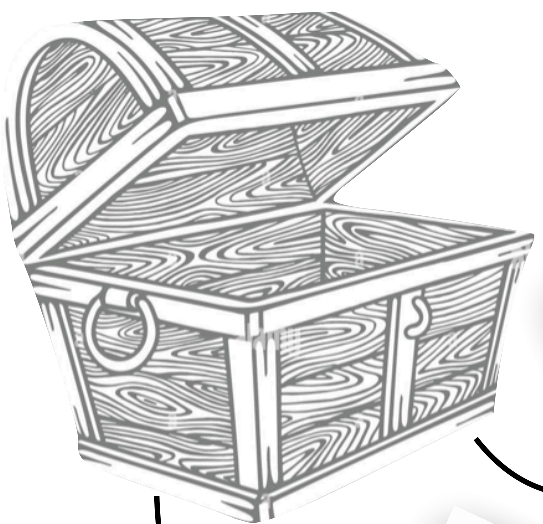


The Higgs Laboratory for Beyond-SM Physics

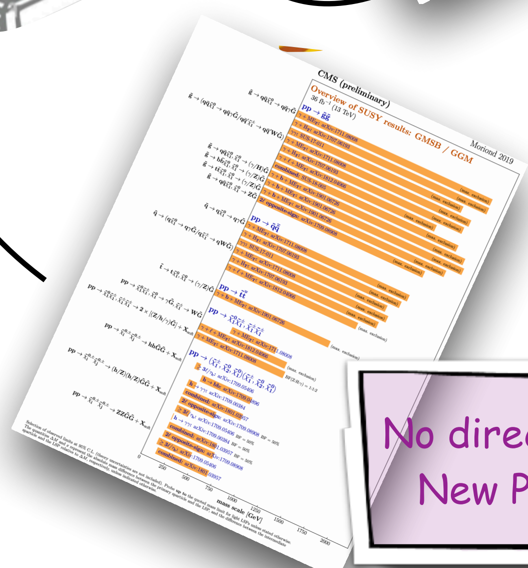


Discovered Higgs Boson behaves very SM-like





Consistency Test of the SM at the quantum level



No direct discovery of New Physics so far

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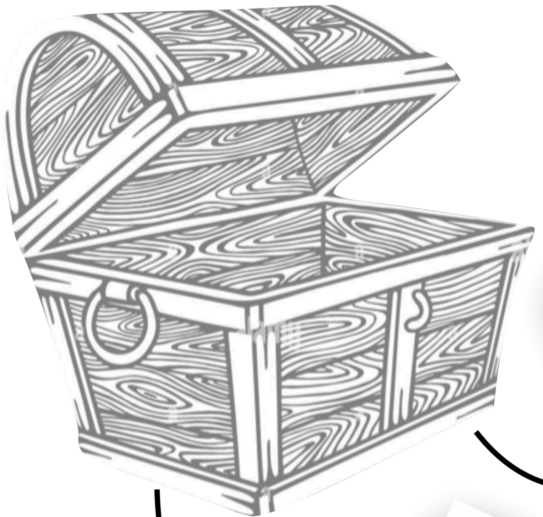

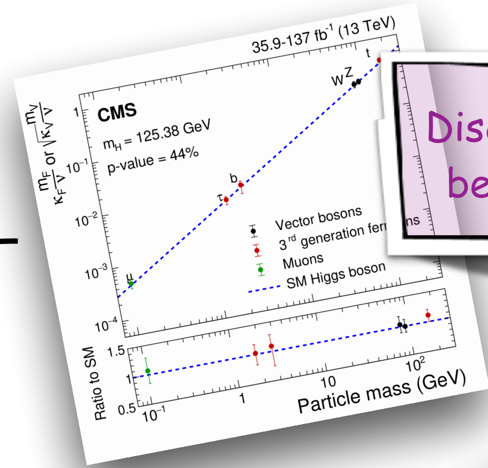

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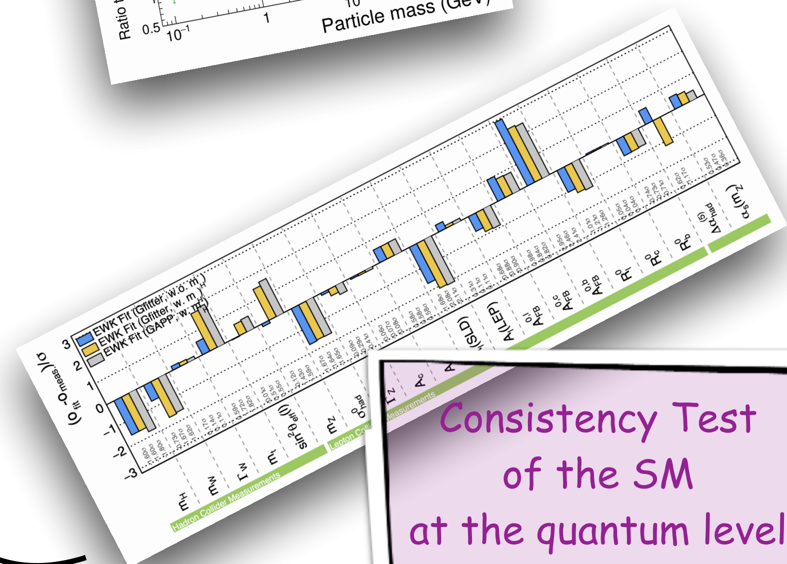


Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

We have the Higgs Boson

Higgs Laboratory for New Physics

Direct search through Higgs couplings to new physics

Indirect search through new physics **quantum fluctuations** in Higgs observables

Direct & indirect sensitivity to new physics in **Higgs parameters** -> significant **BSM imprints** in **Higgs self-coupling** still possible

The Higgs Potential

$$V_{\text{Higgs}}^{\text{SM}} = \frac{1}{2} M_{\text{H}}^2 H^2 + \lambda_{\text{HHH}} H^3 + \lambda_{\text{HHHH}} H^4$$

The Role of the Higgs Potential Parameters

The Role of the Higgs boson mass

✦ Present Accuracy:

M_H = 125.35 ± 0.15 [CMS] 125.11 ± 0.11 [ATLAS]

✦ Why precision?

* Self-consistency test of SM at quantum level
  (e.g.: Higgs loop corrections to W boson mass)

* $M_H \leftrightarrow$ stability of the electroweak vacuum [Degrassi eal;Bednyakov eal]

* Higgs mass uncertainty feeds back in uncertainty on Higgs observables

* Test parameter relations in beyond-SM theories

indirect constraints on viable BSM parameter space

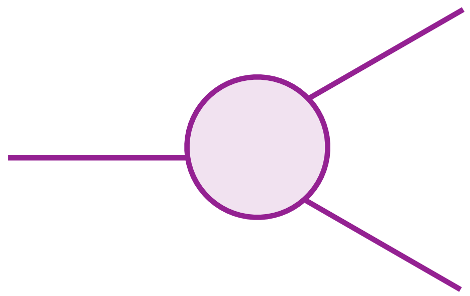
Higgs Mass and Quantum Fluctuations

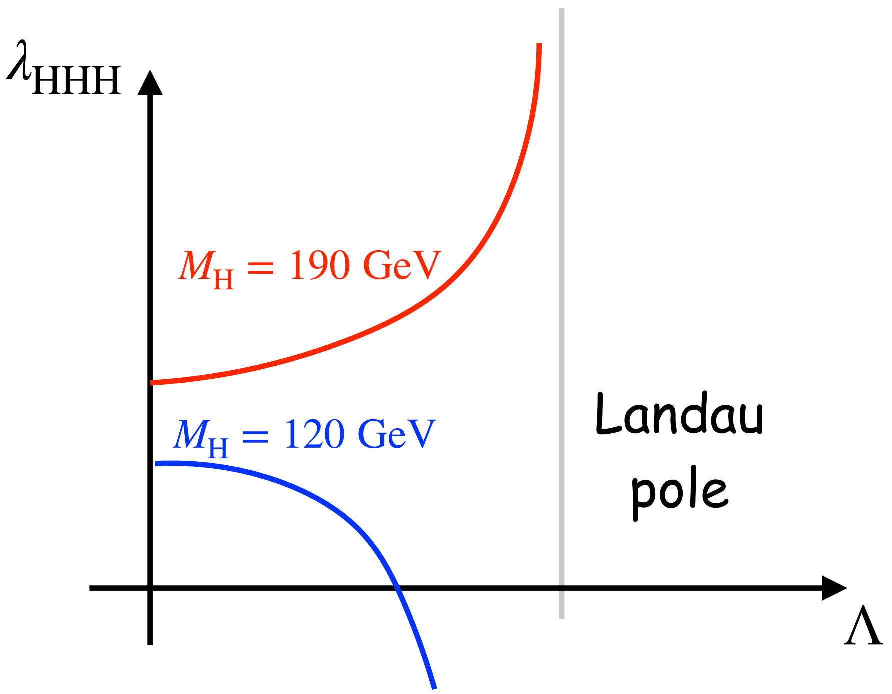
- Standard Model Higgs Potential: **connects Higgs boson mass and Higgs self-couplings**

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} H^3 + \frac{1}{4!} \lambda_{HHHH} H^4 \quad \text{with} \quad \lambda_{HHH} = 3\frac{M_H^2}{v}, \; \lambda_{HHHH} = 3\frac{M_H^2}{v^2}$$

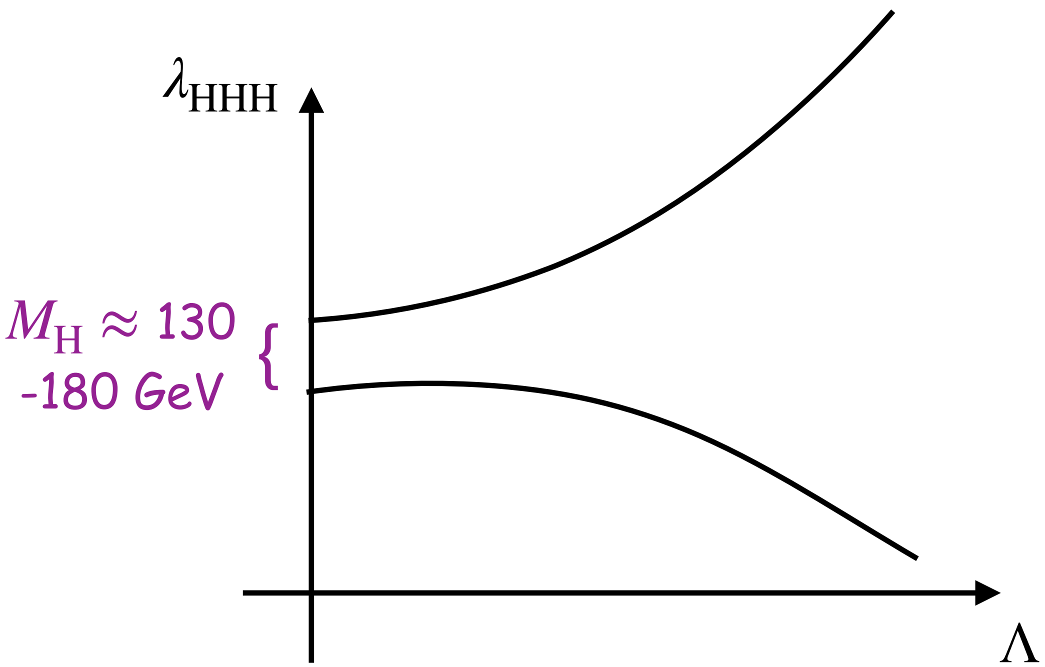
Quantum corrections to self-coupling from all SM particles

top: negative contribution, all other particles: positive contr.





We knew before the discovery



if SM valid until Planck scale

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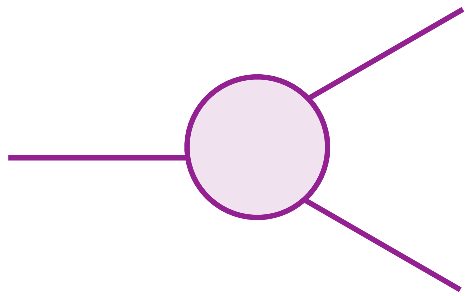
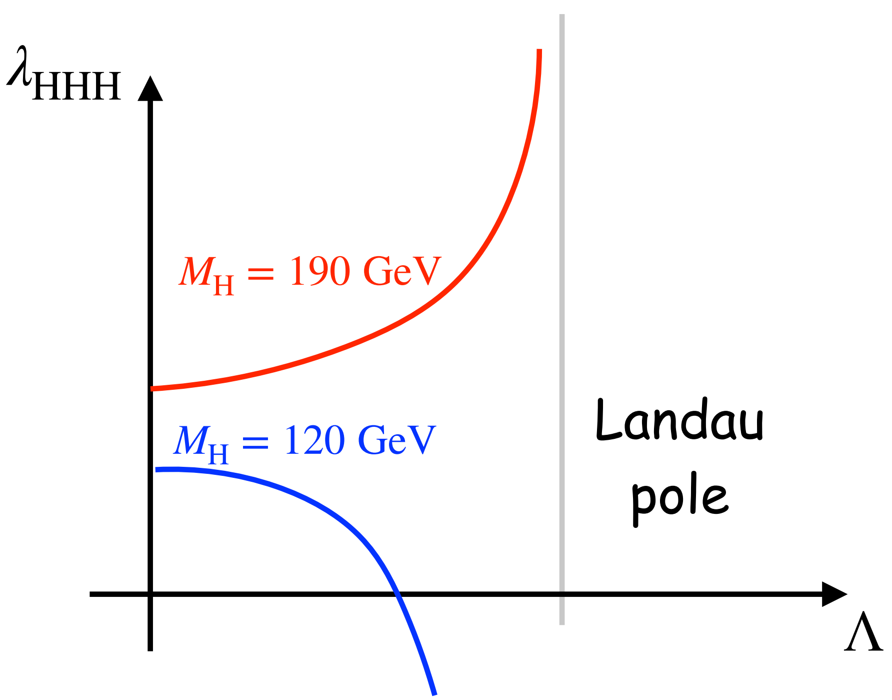
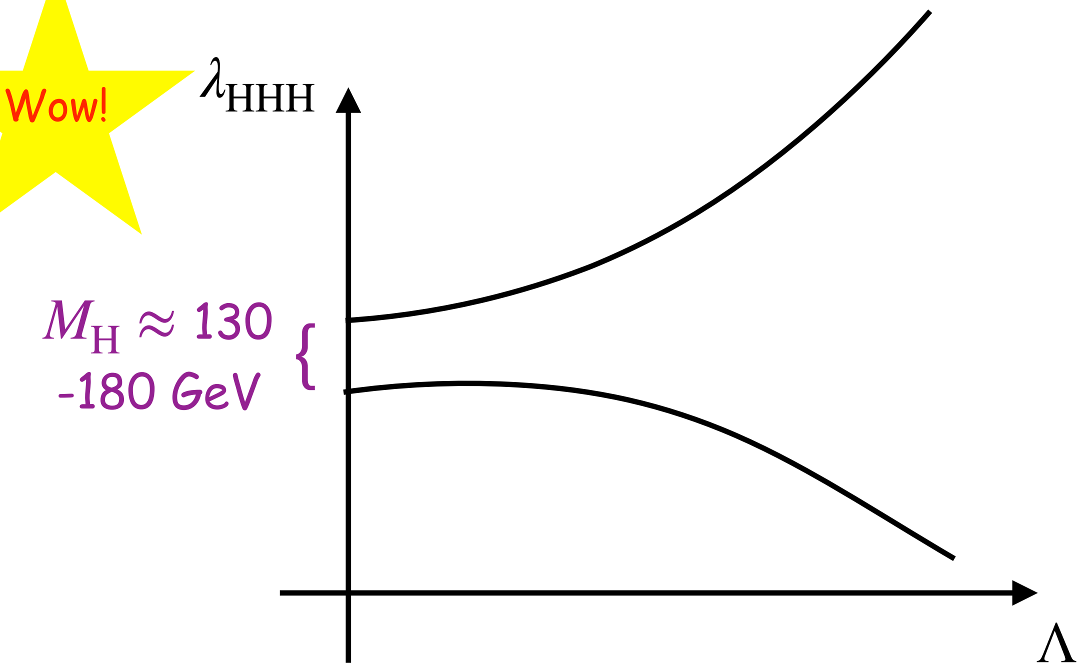




We knew before the discovery Wow!



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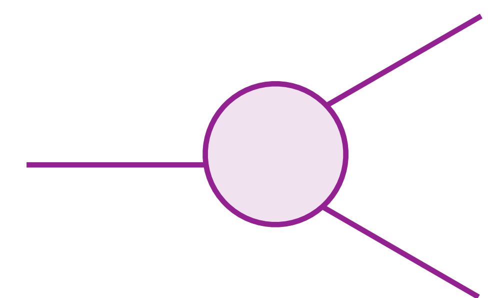
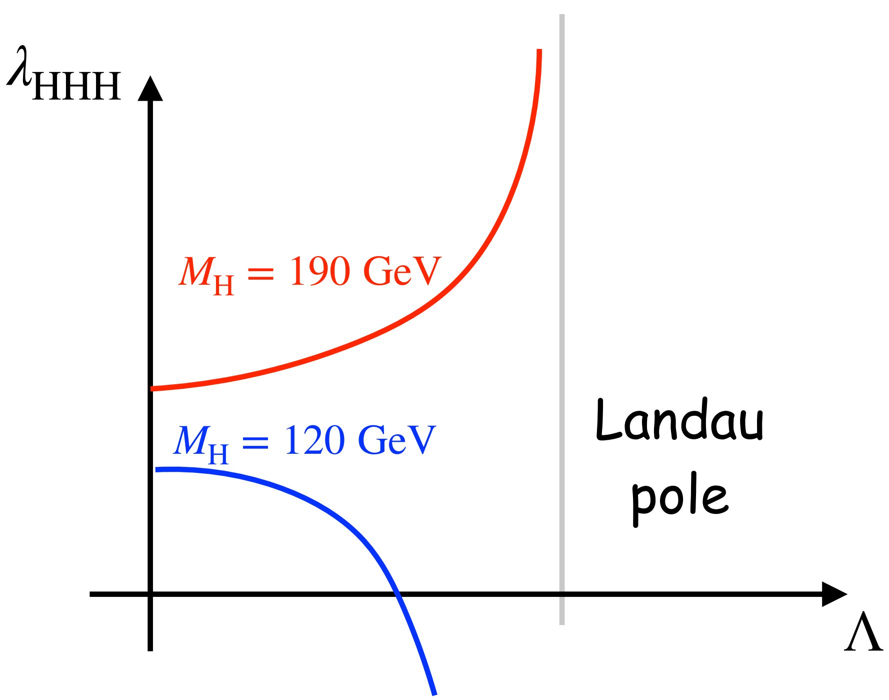
More in

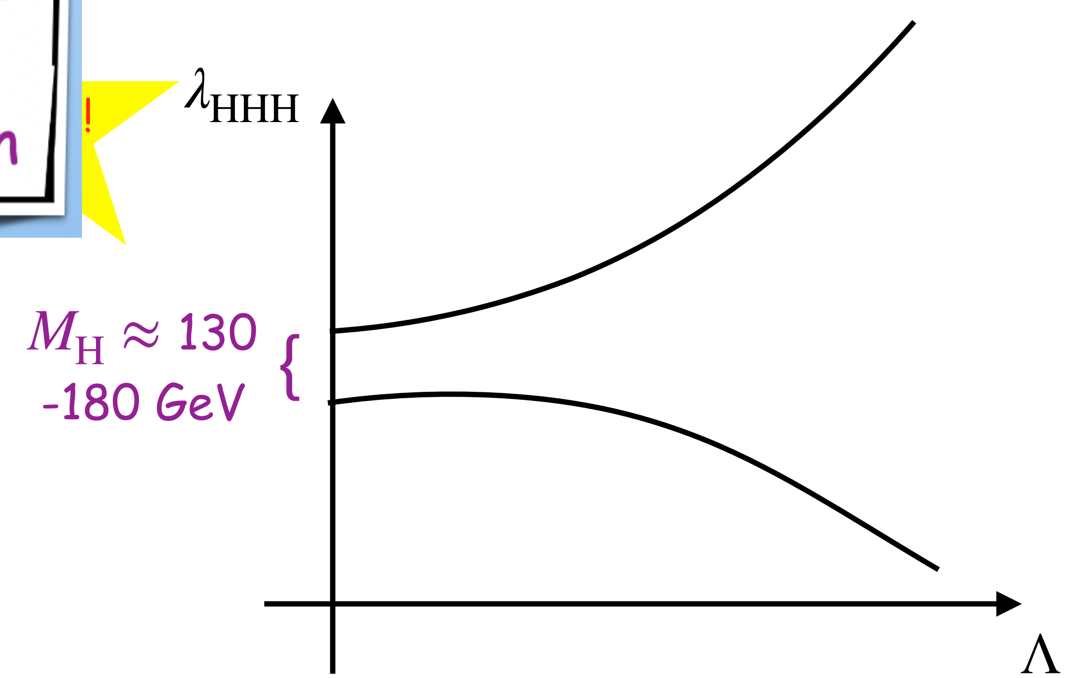
Karl Jacobs

Past:
The path to the discovery of the Higgs boson





the discovery

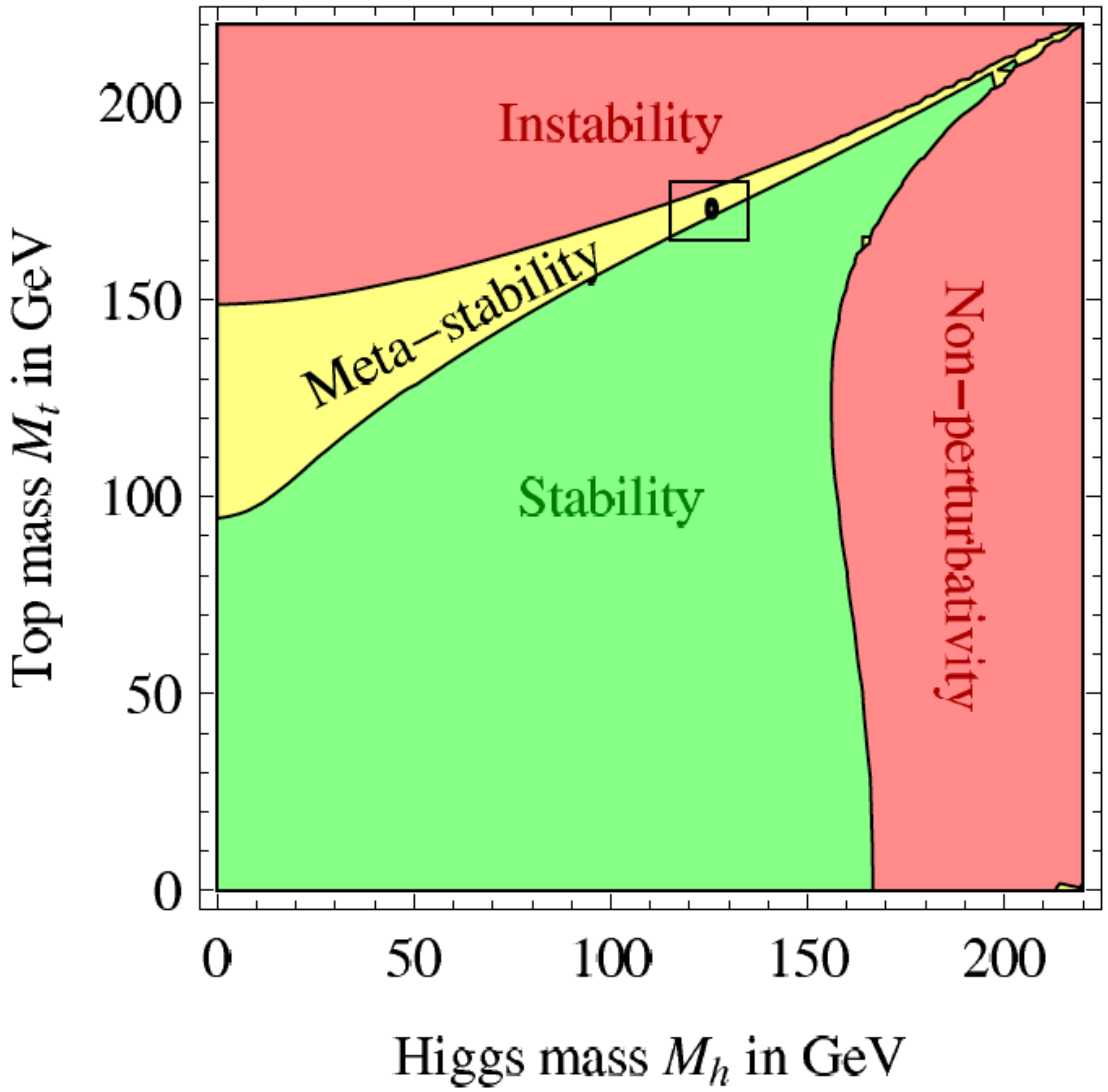


if SM valid until Planck scale

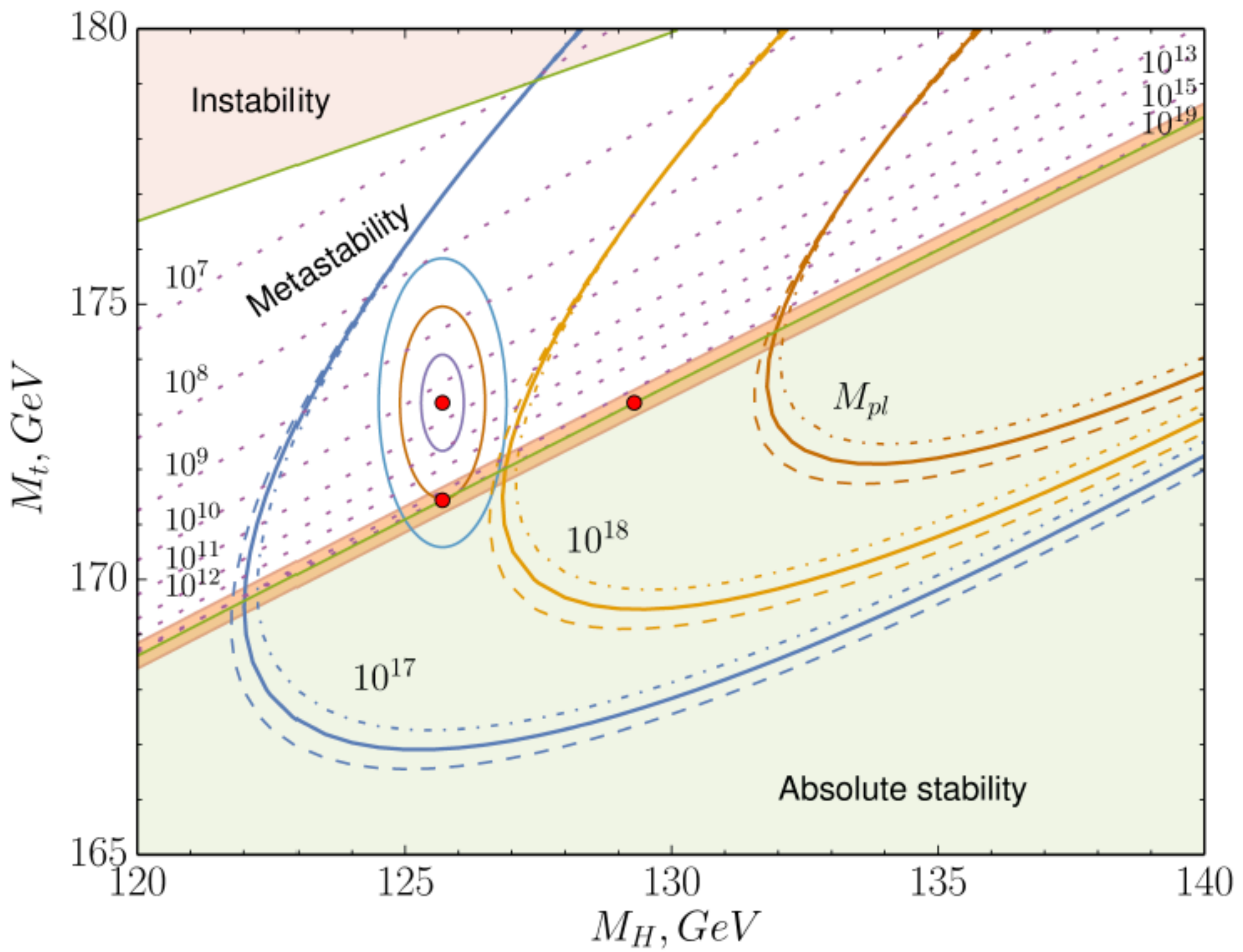
Higgs Mass and Quantum Fluctuations

- Stability of the Electroweak Vacuum?!

[Degrassi,Di Vita,Elias-Miro,Espinosa,'12]



[Bednyakov,Kniehl,Pikelner,Veretin,'15]

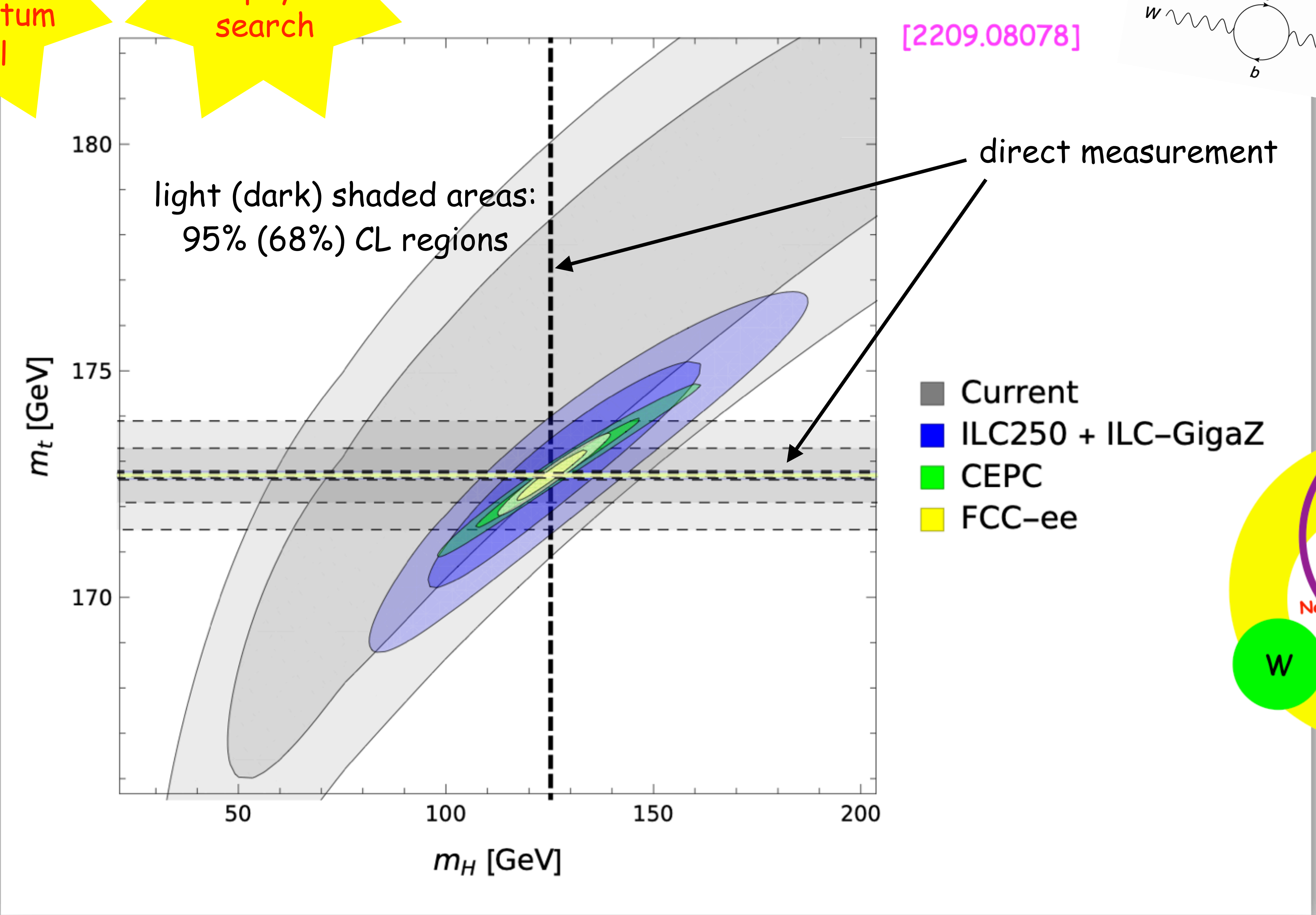


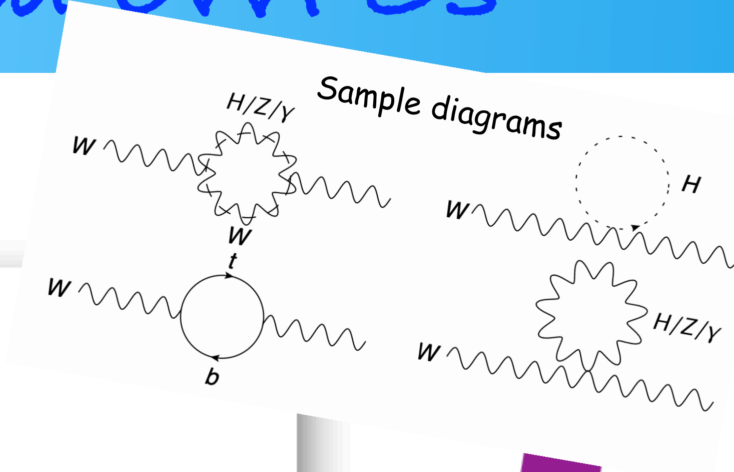
Quantum Fluctuations: Higgs and EWPOs

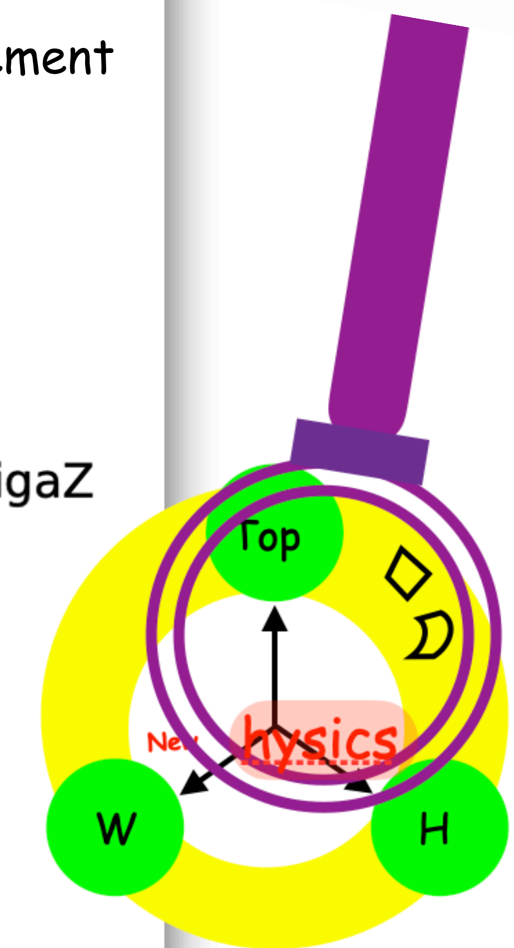
Consistency test of SM at quantum level

Indirect new physics search

SM Fit to all EWPOs







Indirect sensitivity to m_H and m_t for a fit of SM theory predictions to current and projected future data for electroweak precision tests (W mass and Z-pole quantities)

Importance of the Higgs Self-Coupling

❖ Ultimate test of the Higgs mechanism: Measurement of the Higgs potential

$$V^{SM}_{Higgs} = \frac{1}{2} M_H^2 H^2 + \frac{3M_H^2}{3!v} H^3 + \frac{3M_H^2}{4!v^2} H^4$$

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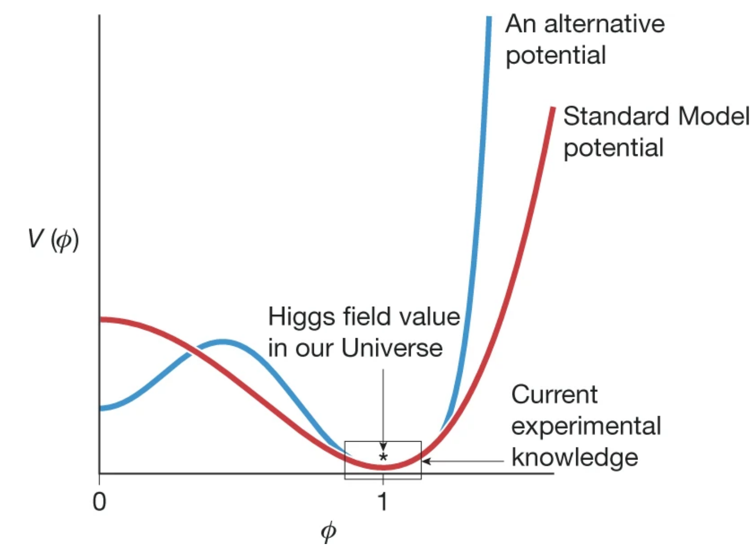

[Nature 607,41 (2022)]

Measurement of the scalar boson self-couplings and Reconstruction of the EWSB potential	} Experimental verification Of the scalar sector of the EWSB mechanism

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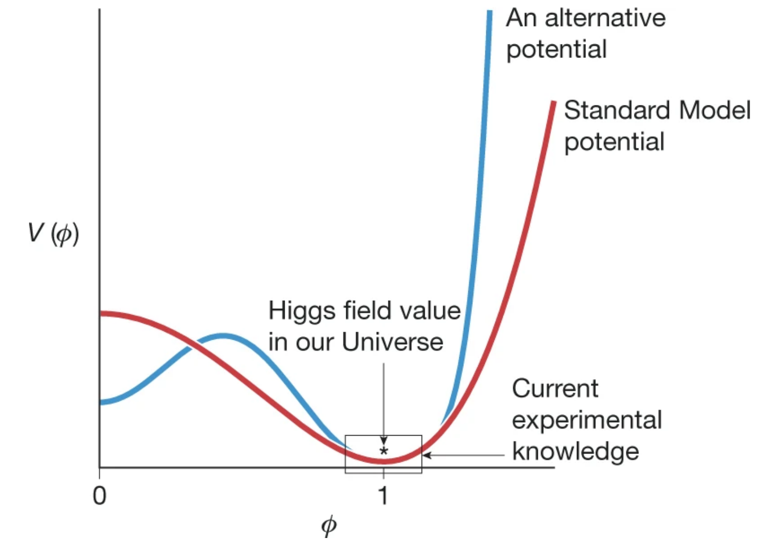

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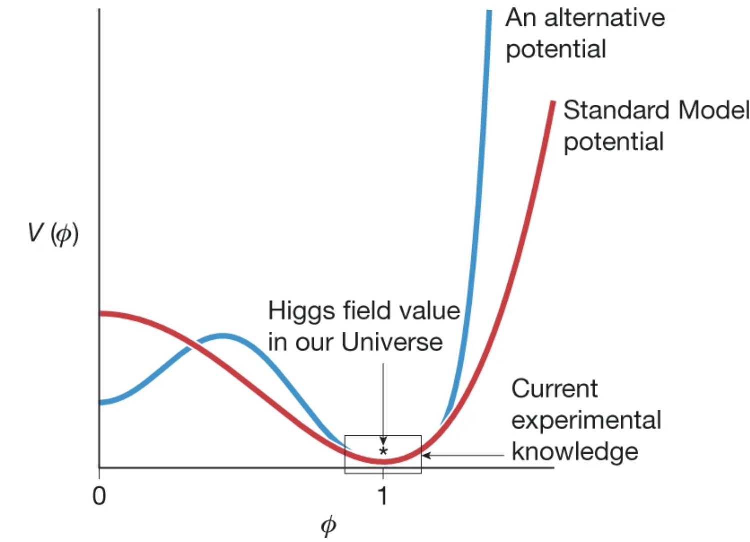

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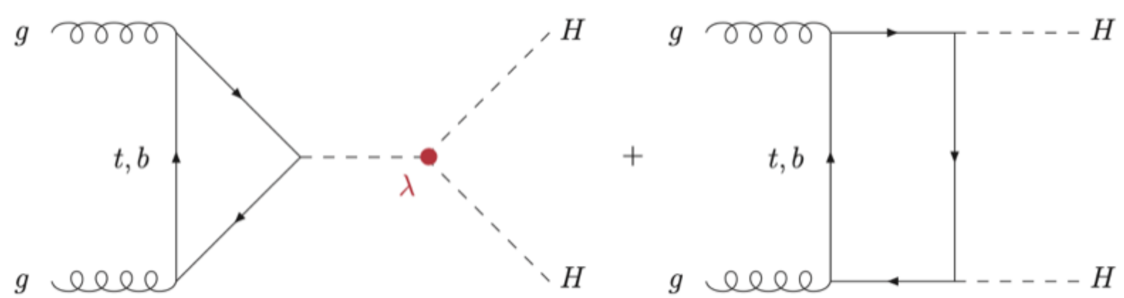
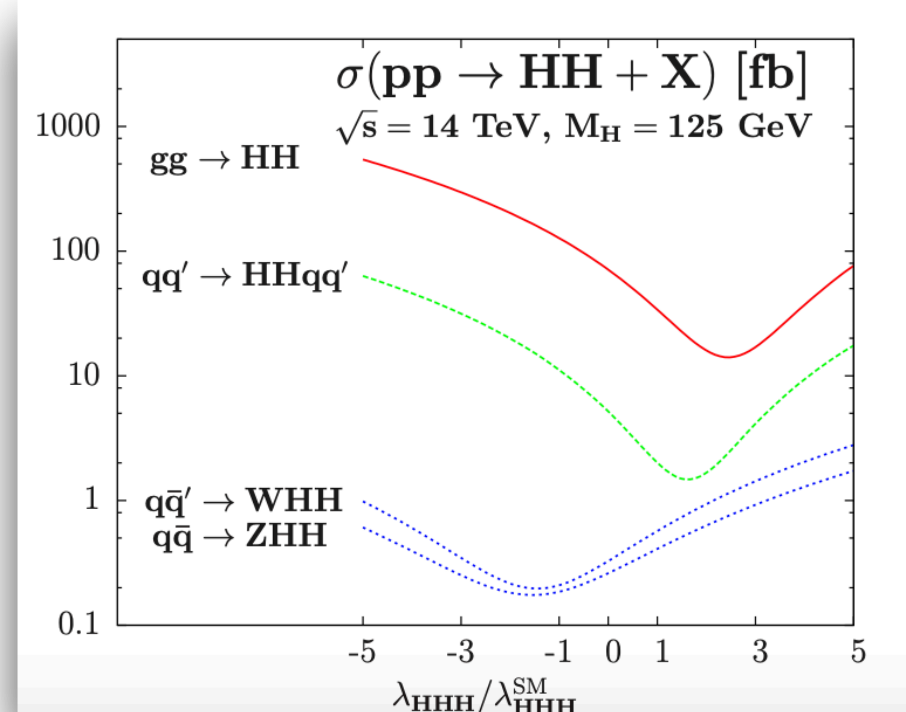
- At LHC: λ_{HHH} directly accessible in Higgs pair production: [Baglio,Djouadi,Gröber,MM,Quévillon,Spira]



$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$



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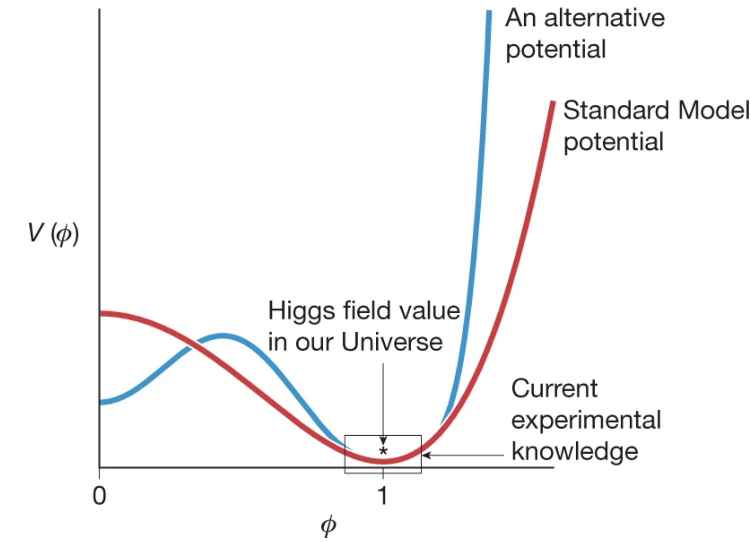

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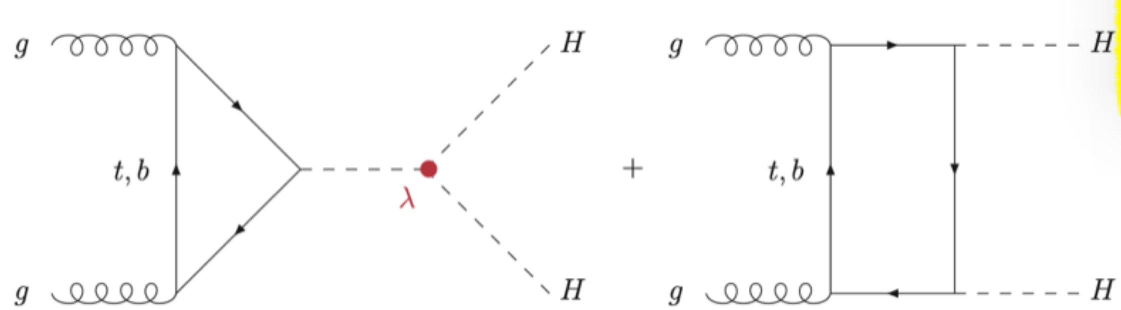
$\sigma_{gg}(HH)$ of 38 fb in the SM
~> experimental measurement is challenging

❖ At LHC: λ_{HHH} directly accessible in Higgs

ber,MM,Quévillon,Spira]



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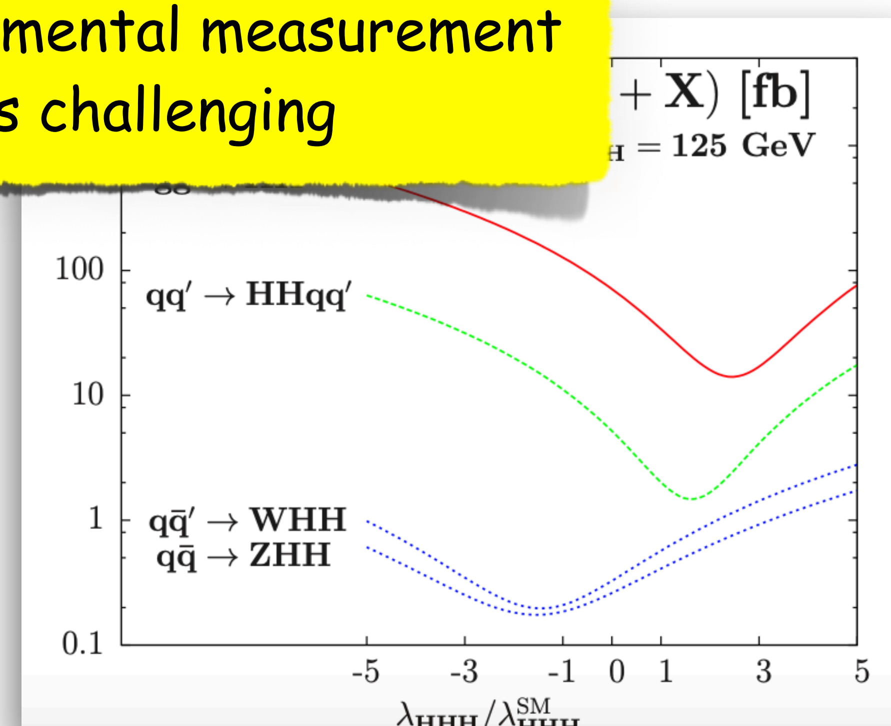

Trilinear Higgs Self-Coupling in BSM Theories

Deviations from SM value in the CP-conserving & CP-violating 2-Higgs-Doublet Model (R2HDM, C2HDM), the Next-to-2HDM (N2HDM), the Next-to-Minimal Supersymmetric SM (NMSSM)

[Azevedo et al,'21]

Here: tree-level values **at NLO even larger deviations** in λ_{HHH} from SM value possible **=> significant room for new physics**

	R2HDM		C2HDM	
	$y^{\text{R2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{R2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{C2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{C2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

	N2HDM		NMSSM	
	$y^{\text{N2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{N2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{NMSSM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{NMSSM}}_{3H_{\text{SM}}}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

The Higgs Connection to Cosmology and Astrophysics

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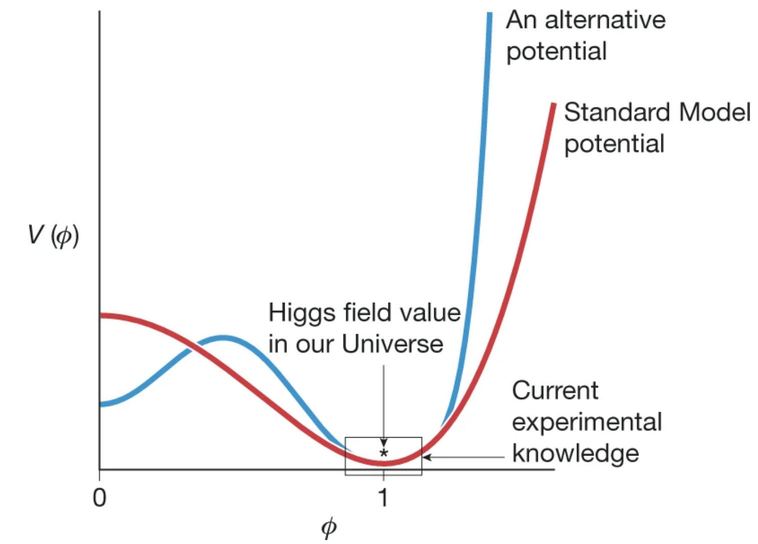

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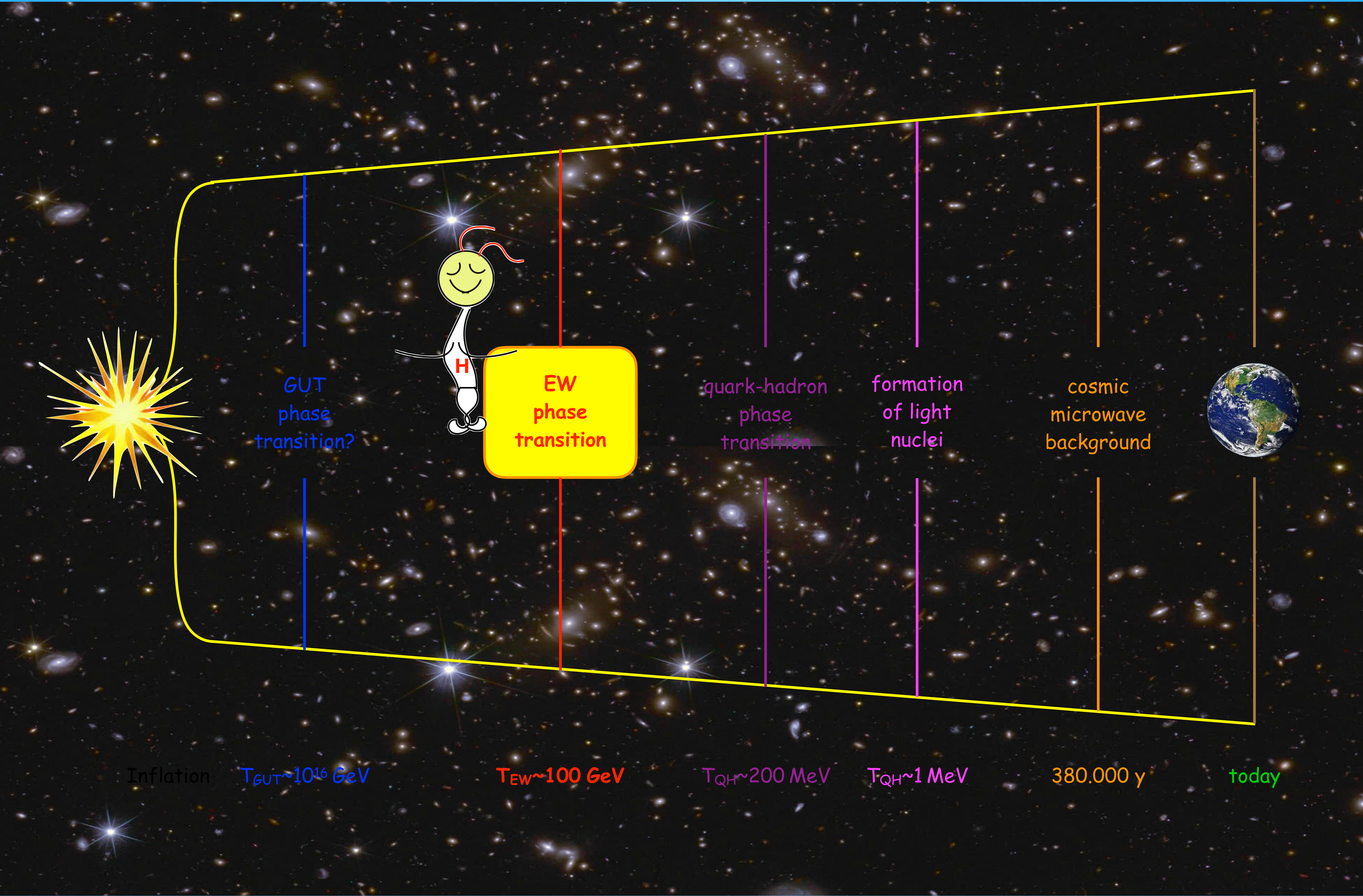
Higgs & the Evolution of the Universe

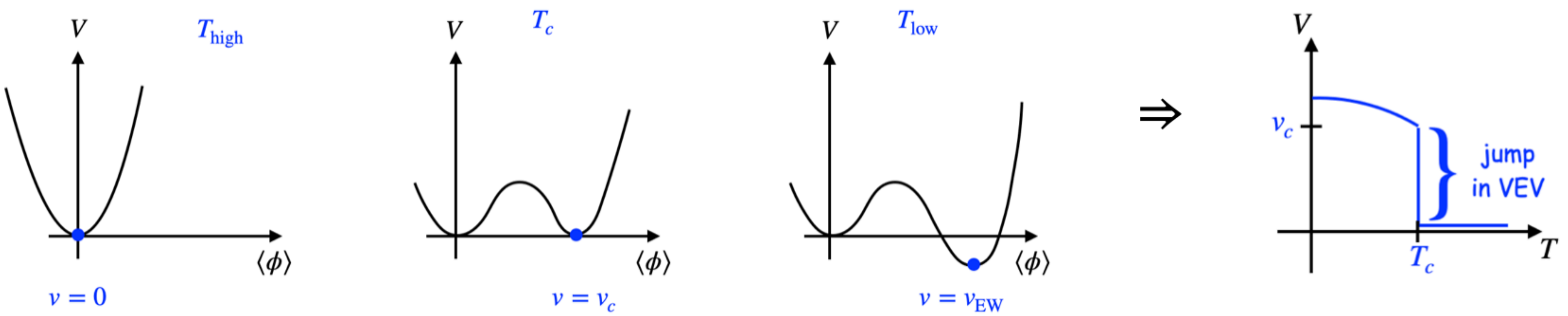


Electroweak Phase Transitions

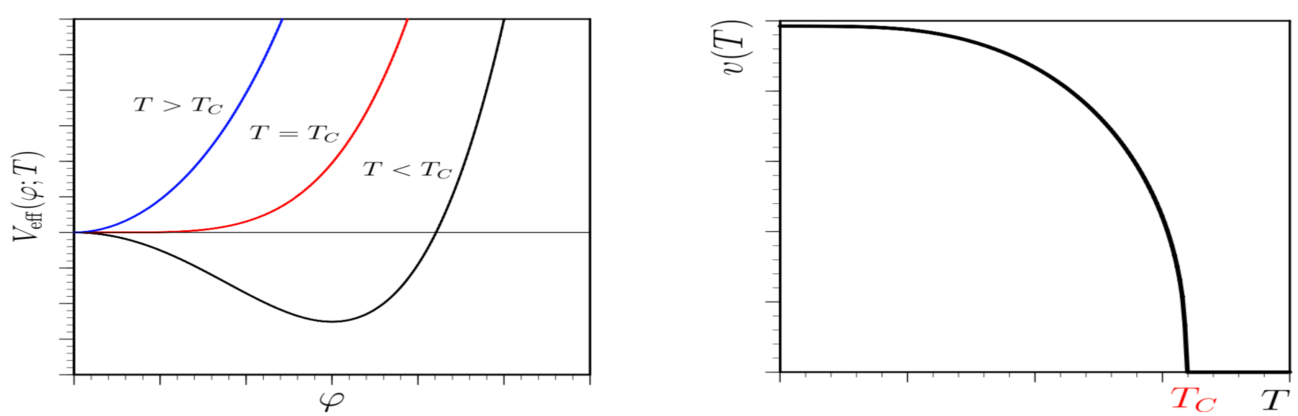
- Electroweak phase transition: order parameter is the vacuum expectation value (VEV)

$$v = 0 \;\Rightarrow\; v \neq 0$$

- First-order phase transition (FOPT): jump in the VEV at the PT



- Second-order phase transition: smooth transition



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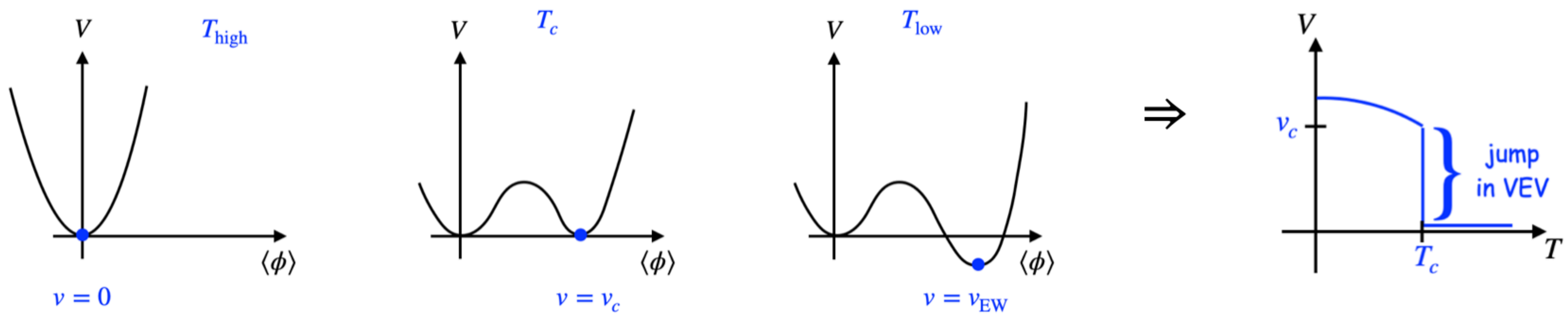

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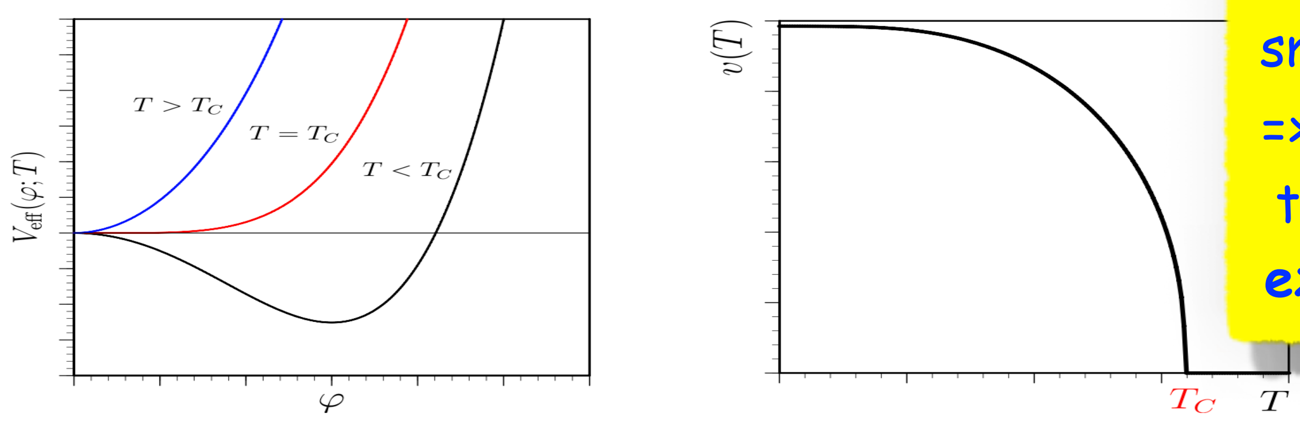

For M_H=125 GeV: smooth cross-over in SM => FOPT requires beyond the SM **(BSM) physics: extended Higgs sectors**

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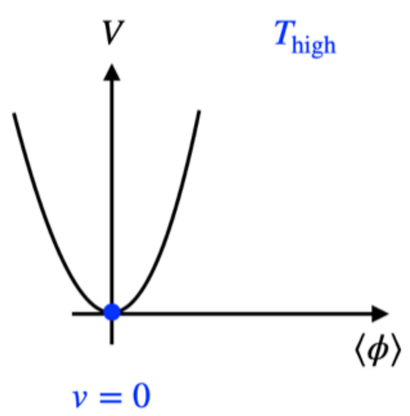

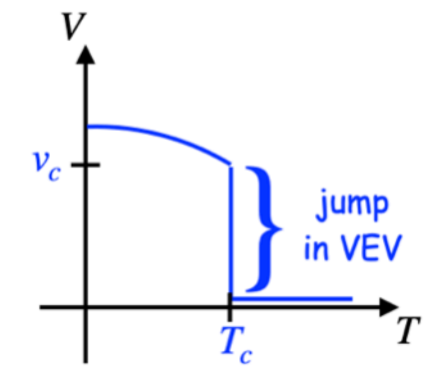

- Second-order phase tran

Electroweak baryogenesis:
dynamical generation of
observed baryon asymmetry

Successful baryogenesis requires
Sakharov conditions:

* baryon-number violations
* C and CP violation
* departure from thermal equilibrium

+ **strong first-order phase trans. (SFOPT)** to avoid wash-out of generated baryon asymmetry

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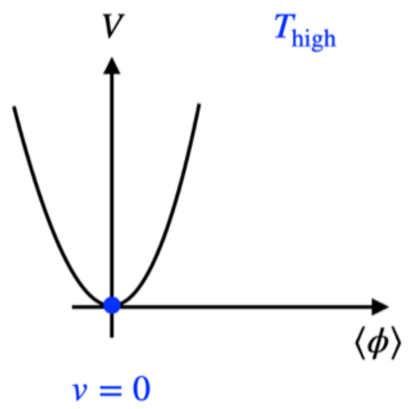

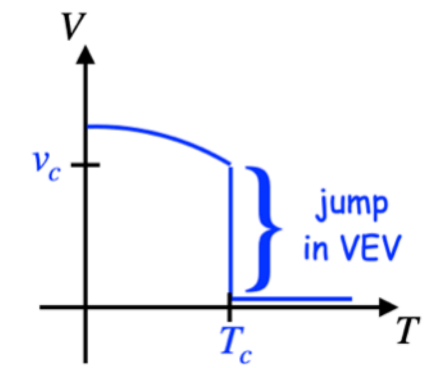

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Computation of quantum corrections to effective Higgs potential at $T \neq 0$

For M_H=125 GeV:
smooth cross-over in SM
=> FOPT requires beyond the SM **(BSM) physics: extended Higgs sectors**

SFOEWPTS and Gravitational Waves

SFOEWPT
(for EWBG)

↓ can source

Gravitational Waves
(GW)

↑ sensitive to

Pulsar timing arrays, LISA
(space bound interferometer)

SFOEWPTS and Gravitational Waves

Directly probe echo of Cosmological SFOPT

Discovery of Physics Beyond the SM

SFOEWPT (for EWBG)

↓ can source

Gravitational Waves (GW)

↑ sensitive to

Pulsar timing arrays, LISA (space bound interferometer)

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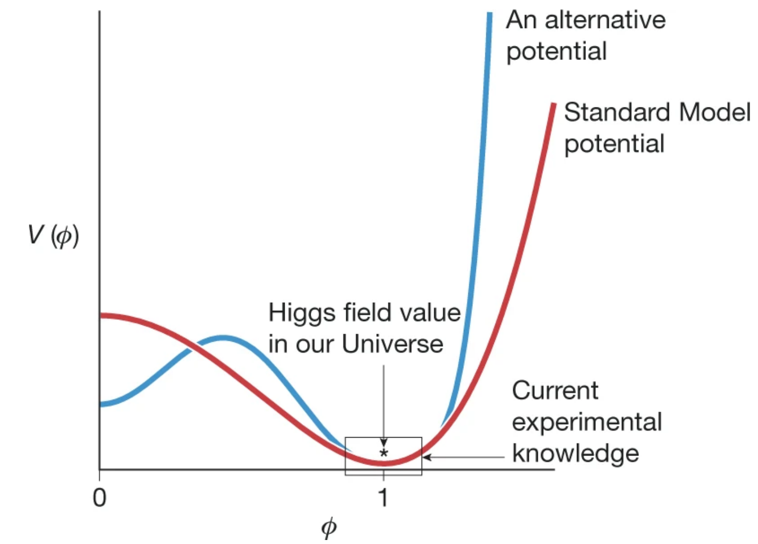

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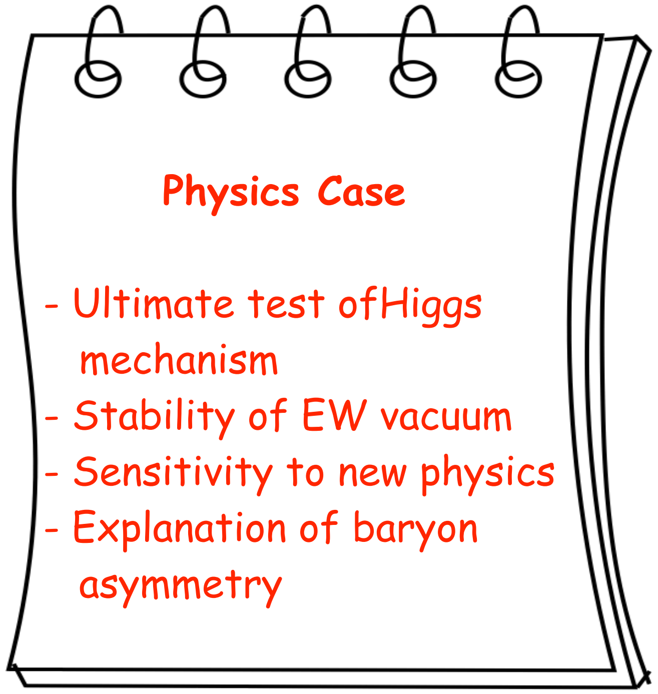
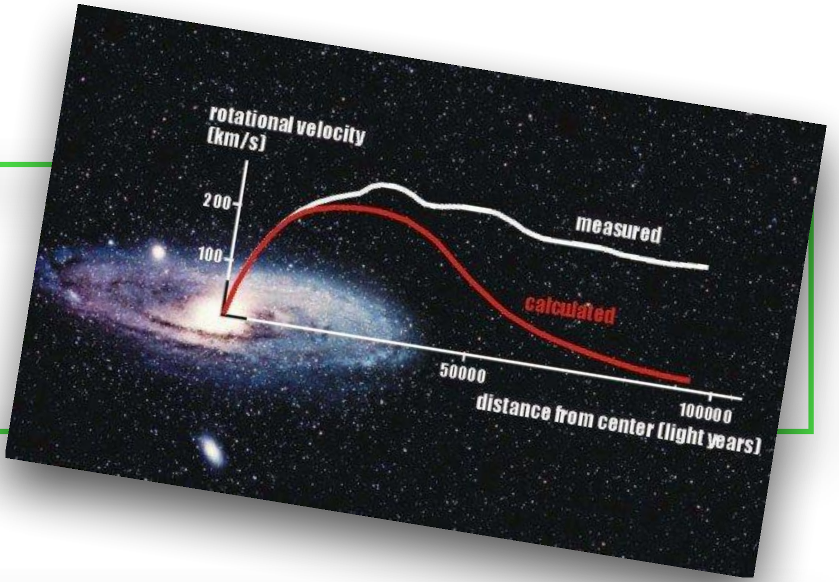


Higgs Portal to Dark Matter (DM)



- Astrophysical and cosmological observations: Dark Matter
- Nature of Dark Matter: unknown

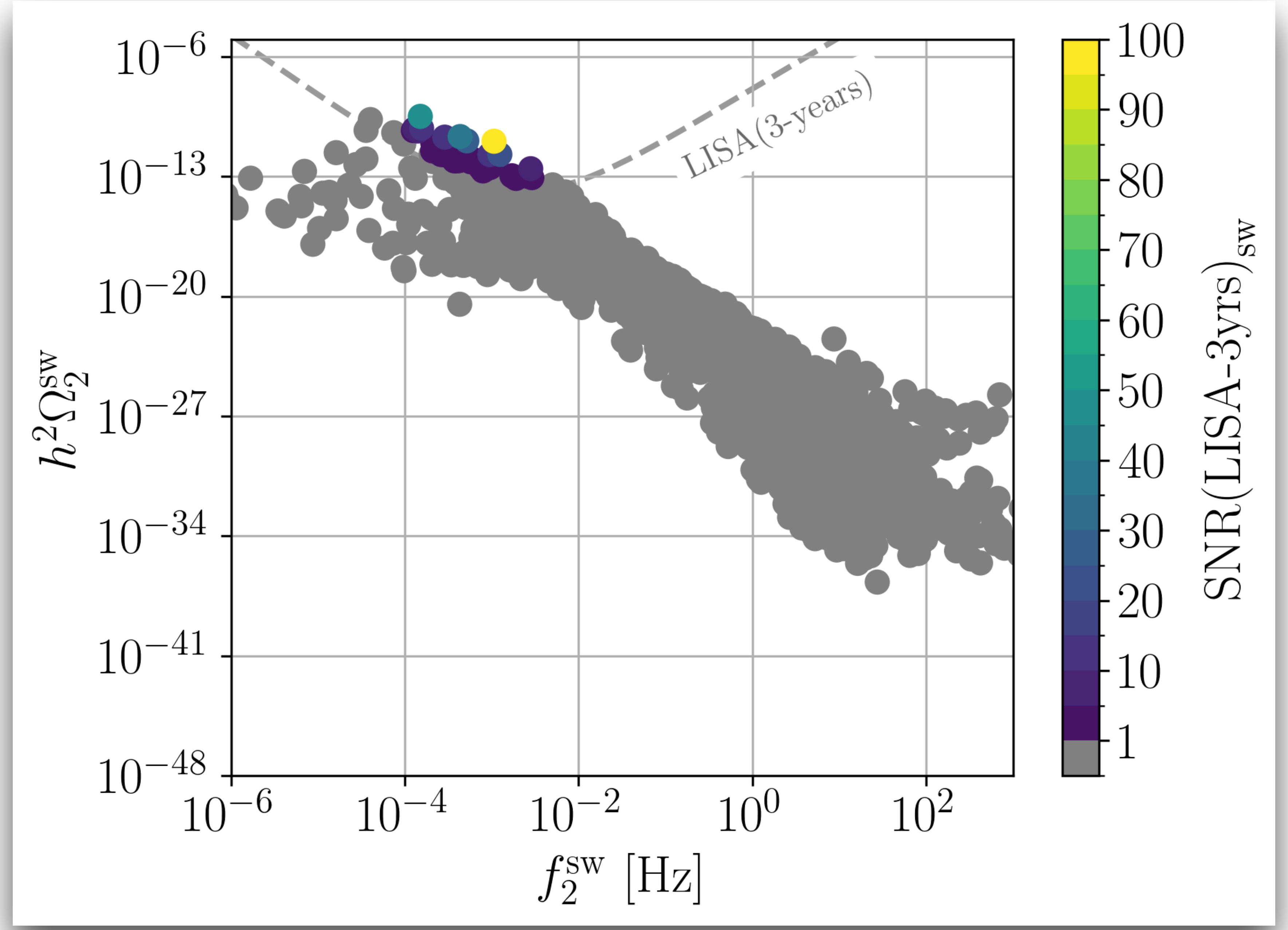
- Higgs portal to Dark Matter: Higgs as mediator between dark sector and visible world
- Phenomenological requirement: DM must reproduce measured relic density
  DM must comply with limits from direct detection

- Model „CP in the Dark“: extended Higgs sector with two doublet and one singlet fields and discrete $\mathbb{Z}_2$ symmetry $\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2, \Phi_s \to -\Phi_s$
  one SM-like Higgs plus dark sector: $h_1,h_2,h_3,H^\pm$
- CP-Violation of „CP in the Dark“: solely in the dark sector <- not constrained by EDMs

Phenomenological Results

GWs from SFOEWPT in „CP in the Dark“

Coloured points: signal-to-noise ratio (SNR) testable at LISA

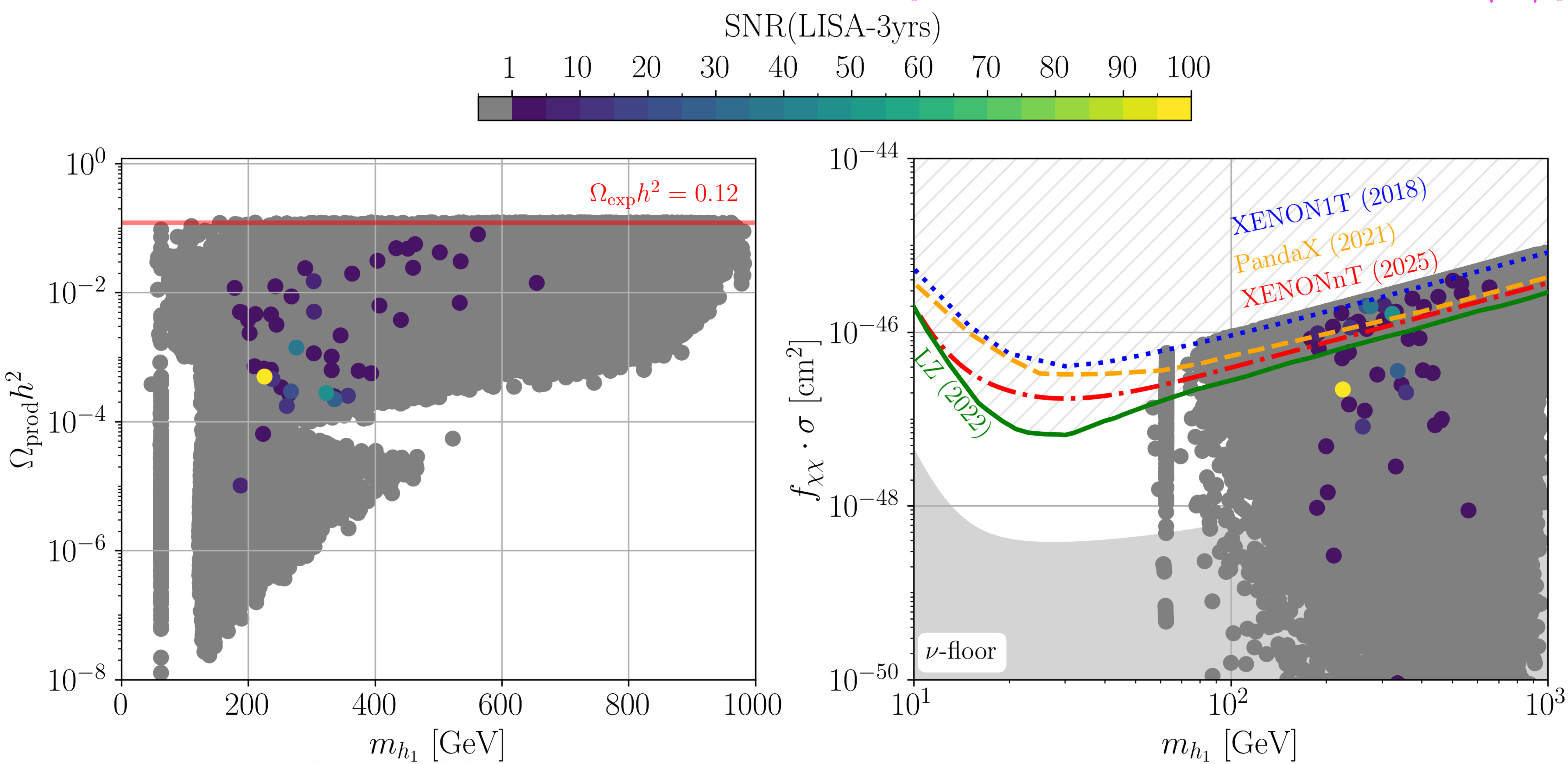


[Basler,Biermann, MM,Müller, Santos,Viana, in preparation]

all points compatible w/ relevant theoretical and experimental constraints

DM Observables and GWs in „CP in the Dark“

[Basler,Biermann,MM,Müller,Santos,Viana,in prep.]

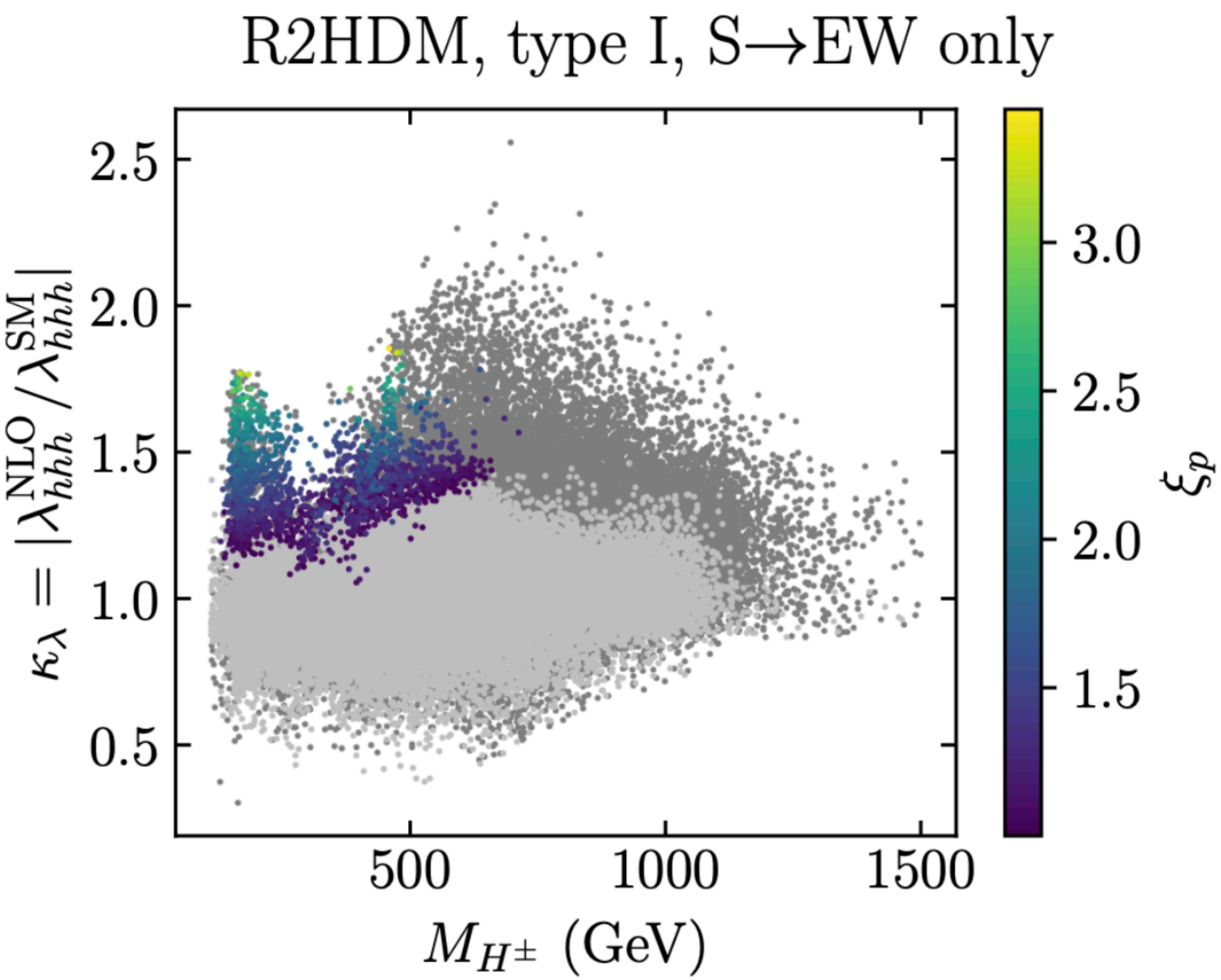


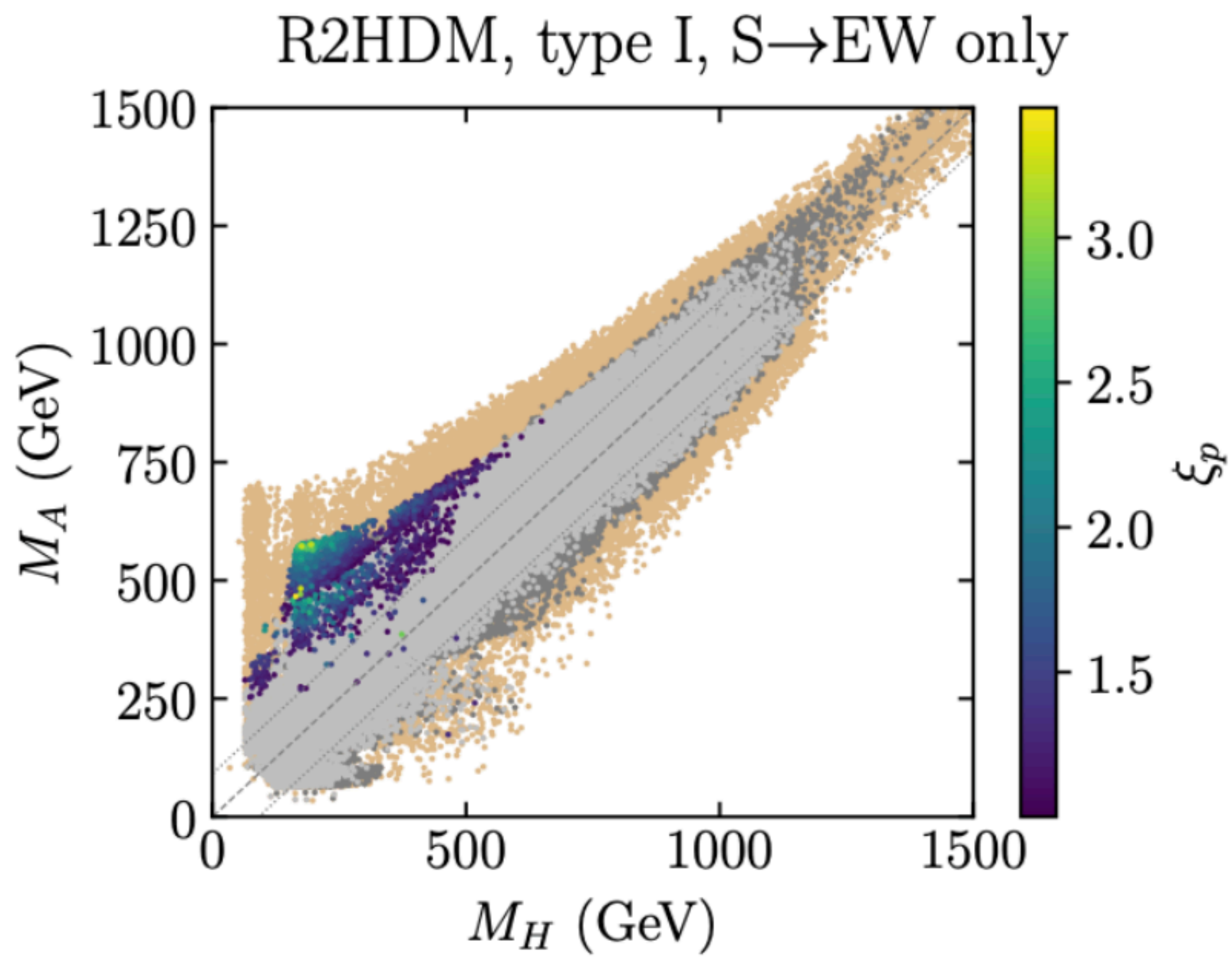
- Viable GW points (SNR(LISA-3yrs)>1 - colored points):
  compatible w/ relic density ($< \Omega_{\rm exp}h^2$), (some) above neutrino floor
  testable at future direct detection experiments

Collider Implications of an SFOEWPT

✦ Example: CP-conserving 2-Higgs-Doublet Model (R2HDM) [Biermann,Borschensky,MM, Santos,Viana,in prep.]

dark gray: no EW symmetry restoration (EWSR) at high T, **light gray:** $\xi_p < 1$, **colored:** $\xi_p \geq 1$, i.e. SFOEWPT





2HDM SFOEWPT requires **enhanced trilinear Higgs self-coupling** of the SM-like Higgs

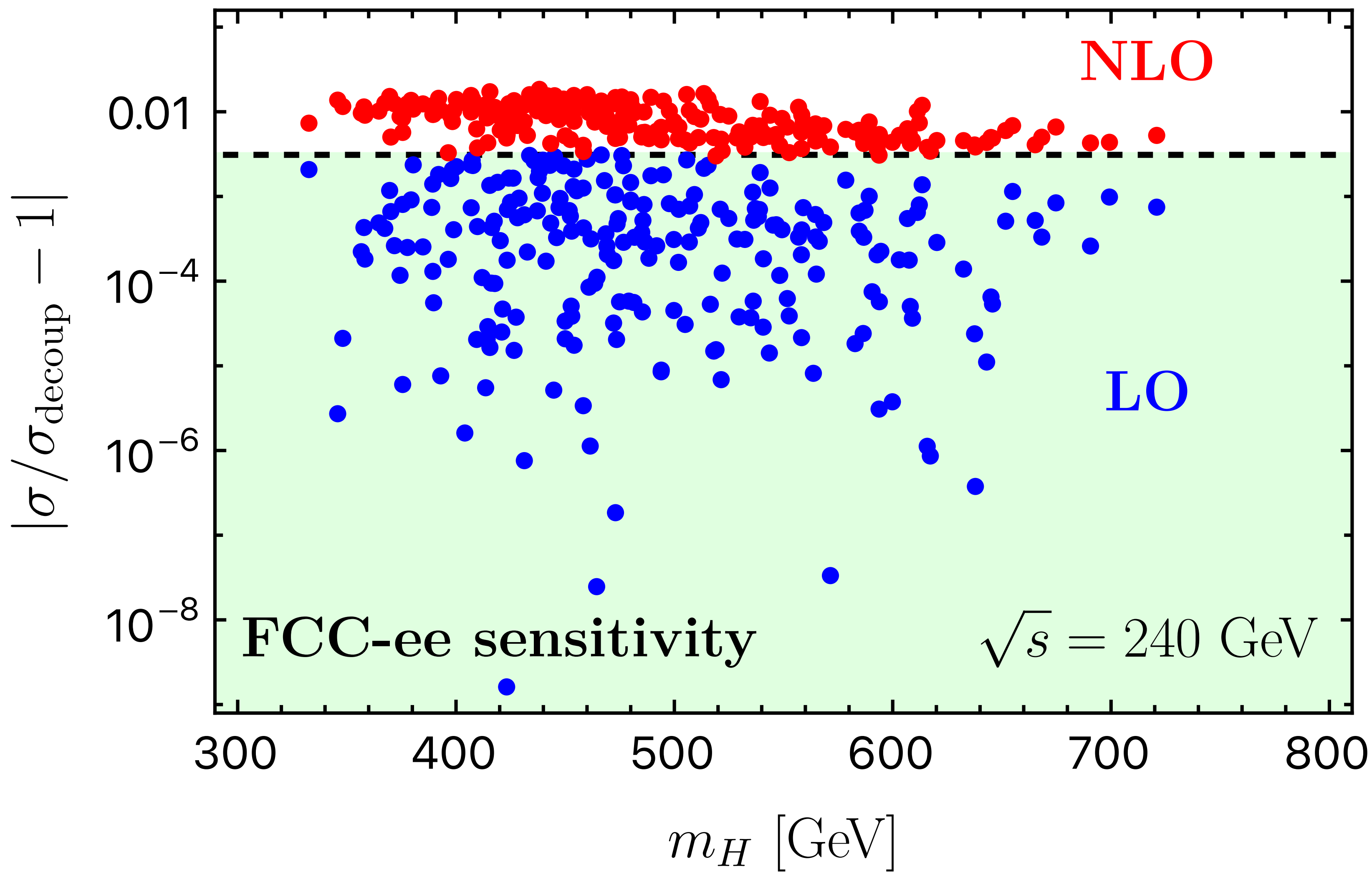
2HDM SFOEWPT typically: **A-H mass gap** ⇝ $A \to ZH$ signatures (need not, however)

Similar findings e.g. [Dorsch eal,'13,'14; Biekötter eal,'23]

Single-Di-Higgs-PT Relations at Future Colliders

All 2HDM points compatible w/ outcome of FCC-ee Z-pole programme

⇝ $\sigma_{ZH}^{\rm LO}$ forced into alignment limit



[Anisha,Arco,diNoi, Englert,MM,'25]

Points w/ strong first-order (SFO) PT incompatible w/ SM alignment

⇝ quantum corrections single out an strong first-order electroweak PT

modifications large enough for $e^+e^- \to ZH$ programme to test new physics!

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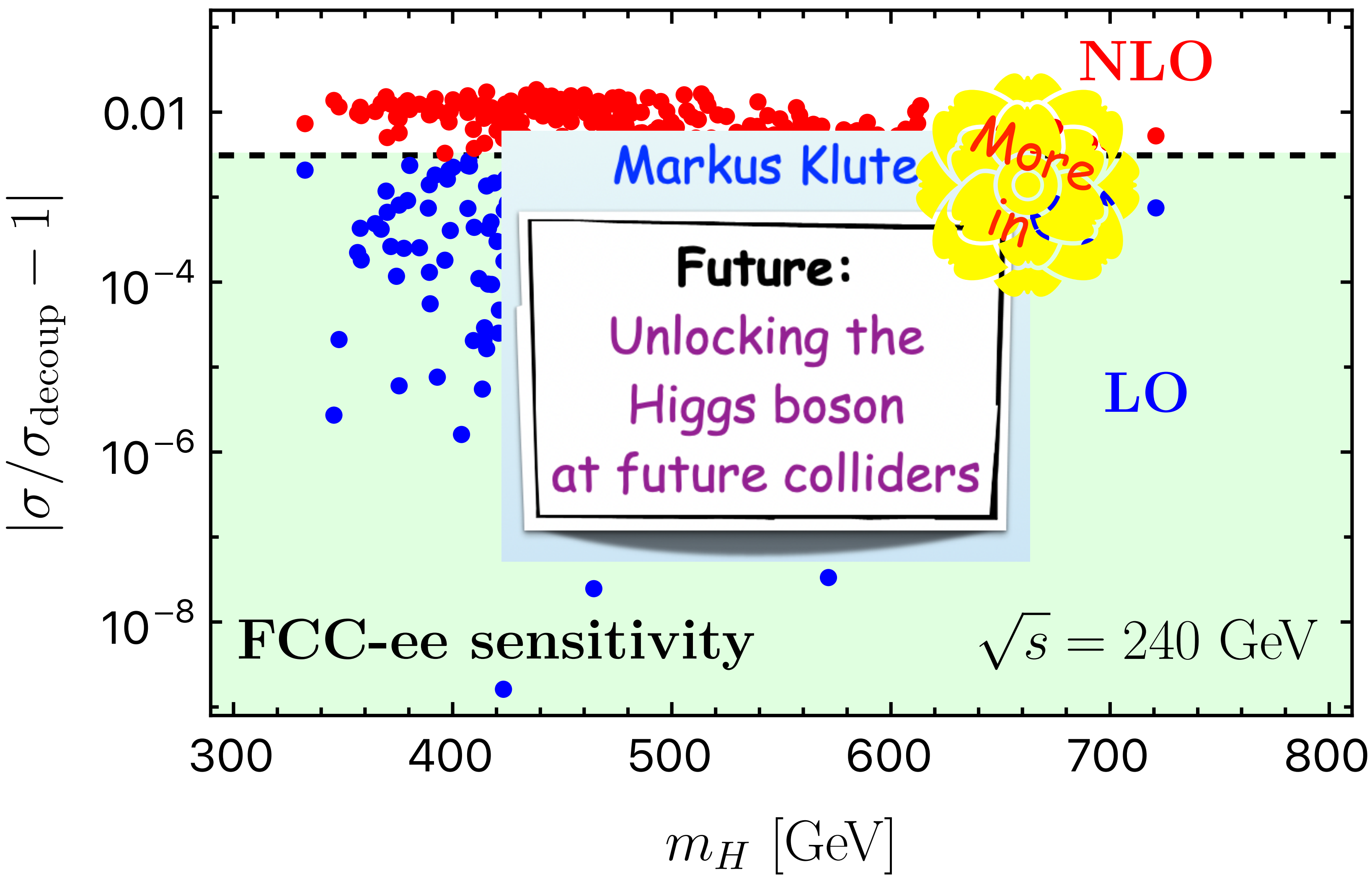

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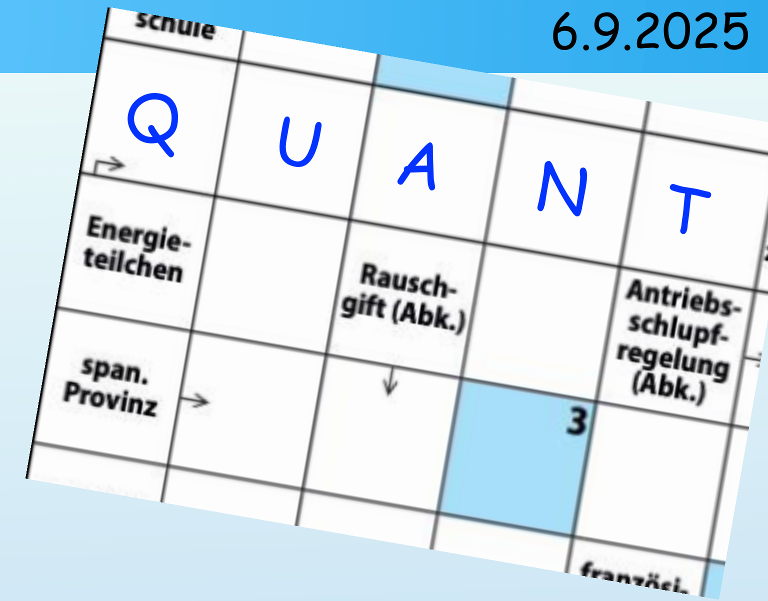
Conclusions

Badische Neueste Nachrichten, 6.9.2025



Masses & gauge symmetries — Pillar of the SM — Unitarity of the SM

Insights in Evolution of Universe

Special Quantum Higgs Boson

Access to Dark Matter

Indirect: quantum fluctuations — Laboratory for BSM Physics — Direct: coupling to NP

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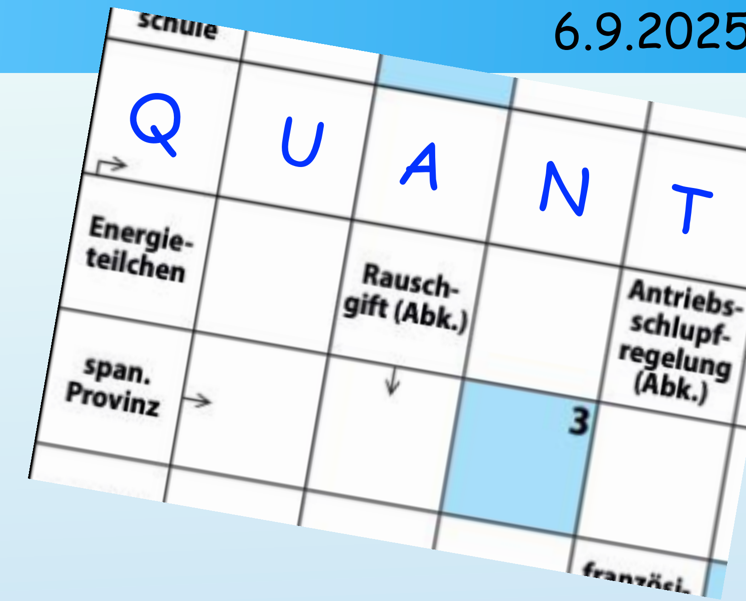

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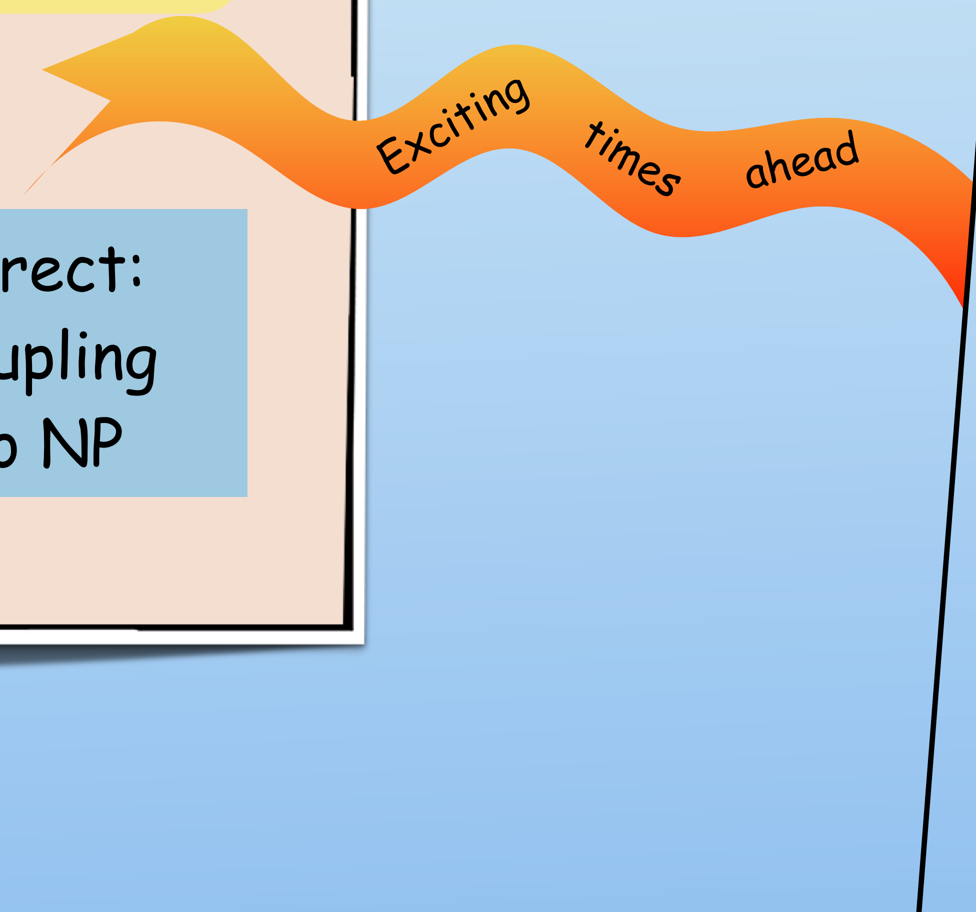

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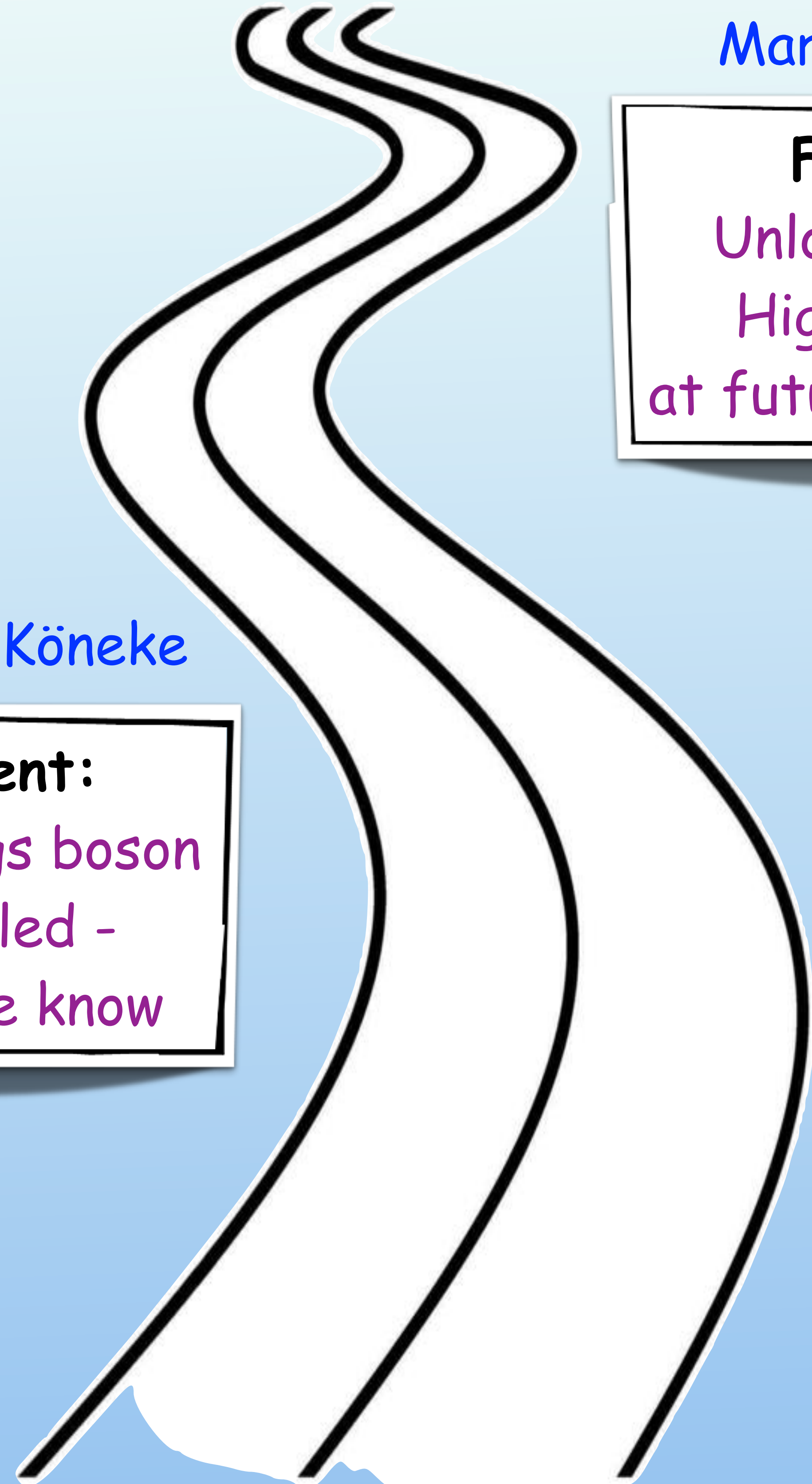


Markus Klute

Future:
Unlocking the Higgs boson at future colliders

Karsten Köneke

Present:
The Higgs boson revealed - what we know

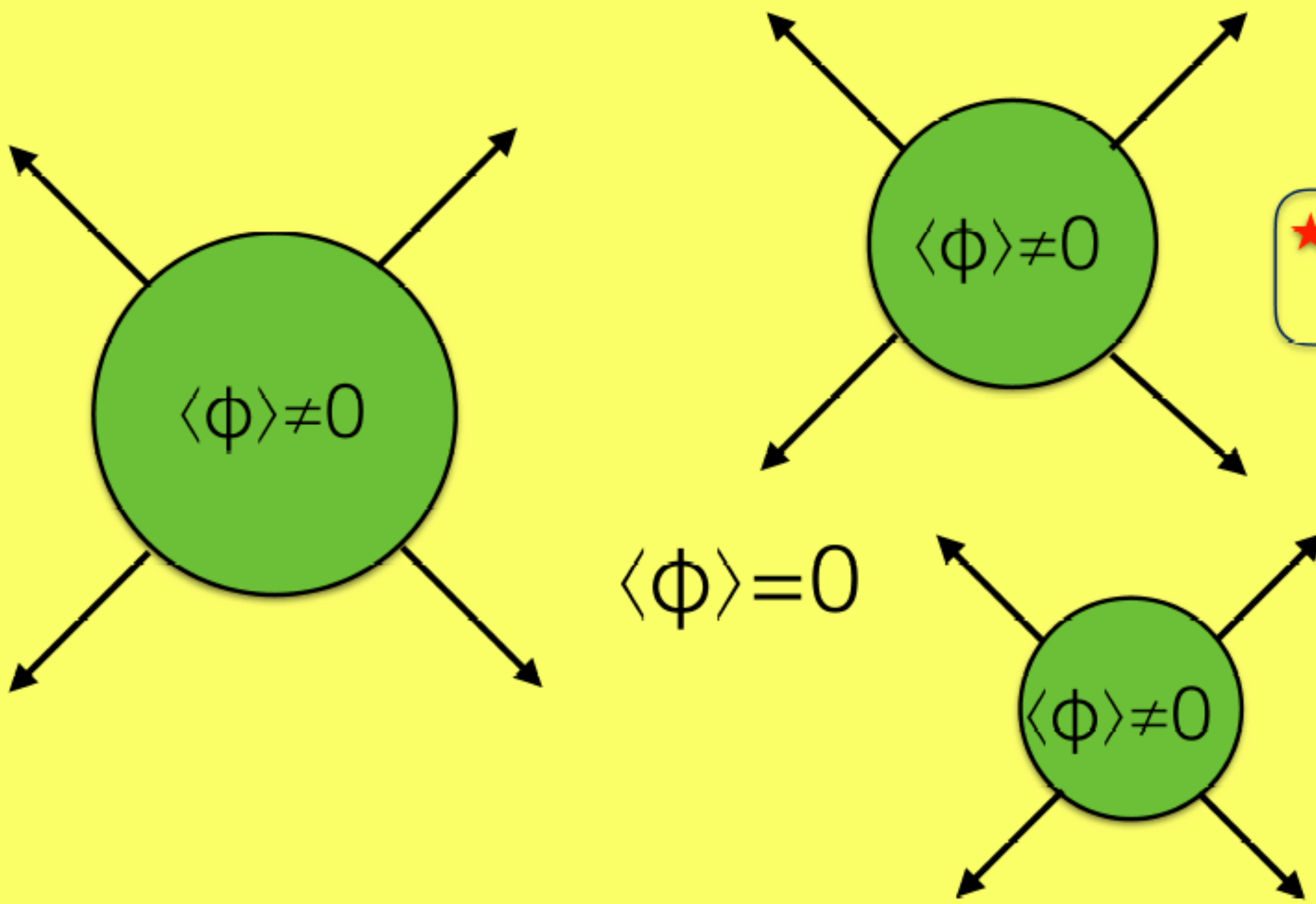
Karl Jacobs

Past:
The path to the discovery of the Higgs boson


Thank you for your attention!

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle \phi_c(T_c)\rangle / T_c \geq 1$

ϕ_c, T_c
VEV and *T* at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall ★