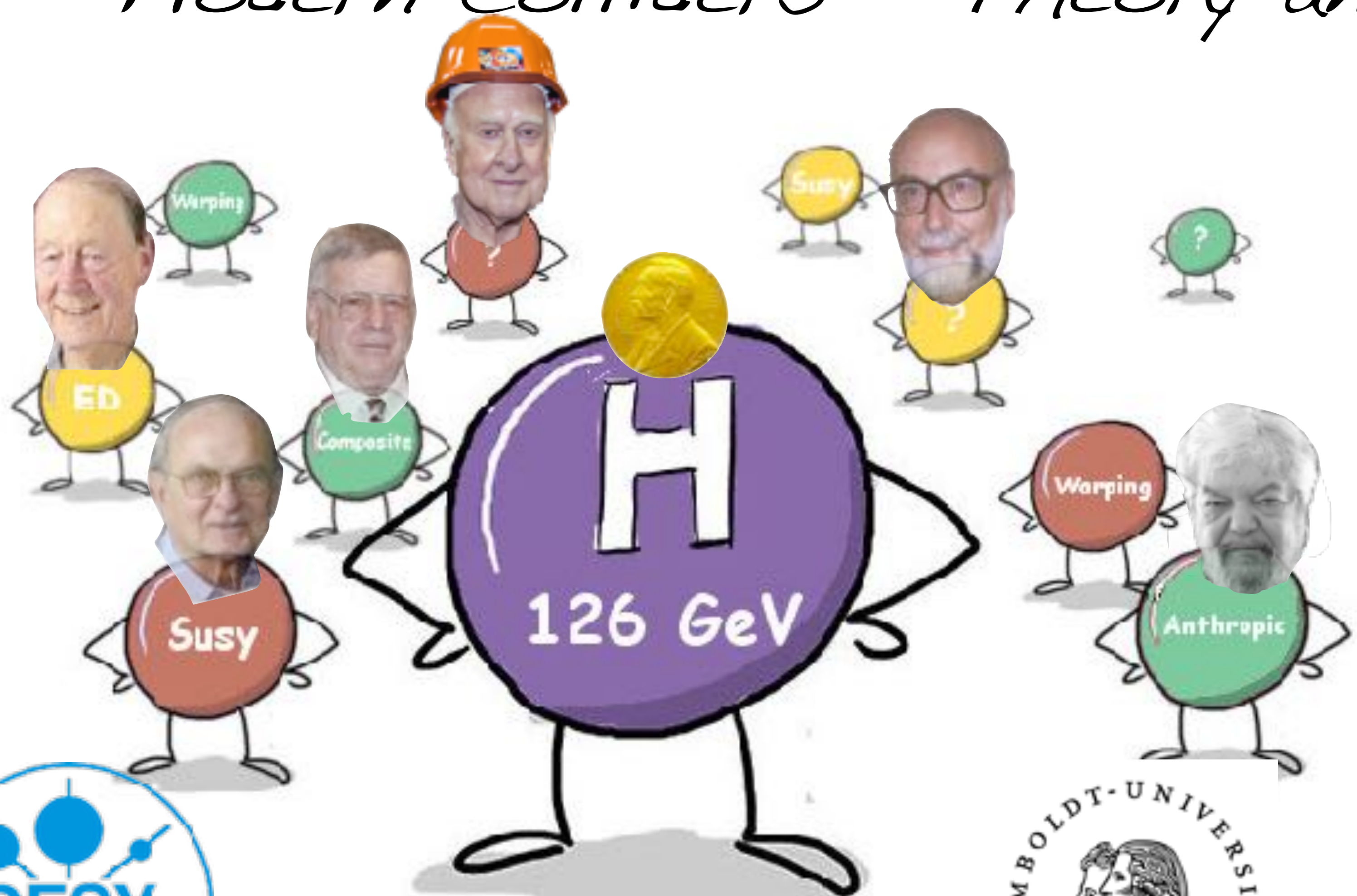
Beyond the Standard Model

Helmholtz International School

" Modern Colliders - Theory and Experiment 2018 "



Lecture 2/3

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Outline

Lecture #1

- General introduction
- Higgs physics as a door to BSM
- Naturalness and the weak scale hierarchy problem
- Supersymmetry

Lecture #2

- Composite Higgs
- Extra dimensions
- Cosmological relaxation: a concrete example of different energy frontier
- NNaturalness

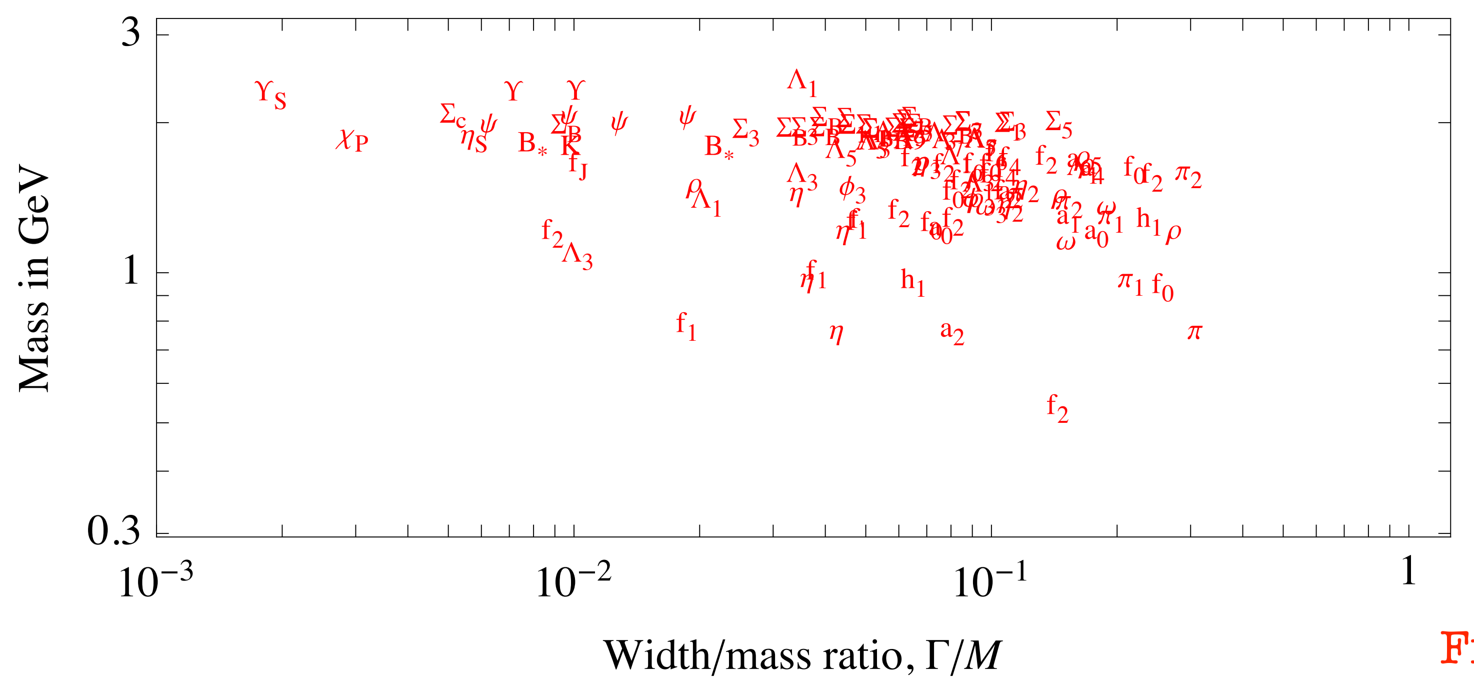
Lecture #3

- Beyond colliders searches for new physics
  - Gravitational waves
  - AMO: isotope spectroscopy
  - Electric dipole moment
  - Neutron-antineutron oscillations
  - Primordial black holes
- Weak gravity conjecture and the swampland

Composite Higgs Models

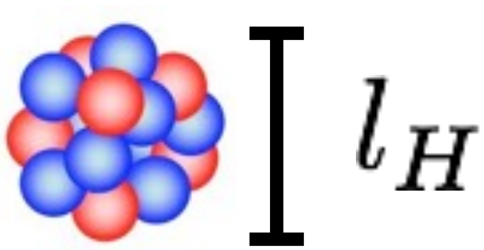
Composite Higgs

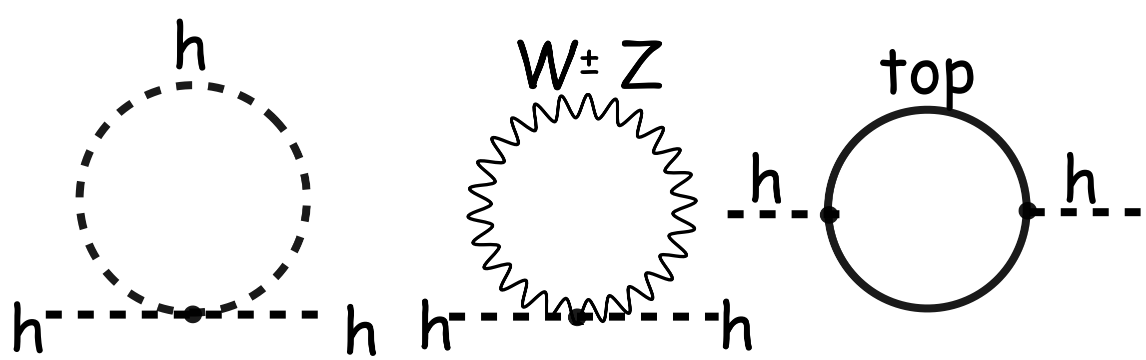
Light scalars exist in Nature but
all the ones observed before Higgs discovery were composite bounds states



Franceschini et al. '15

Could the Higgs be a "hadron" of a new strong force?

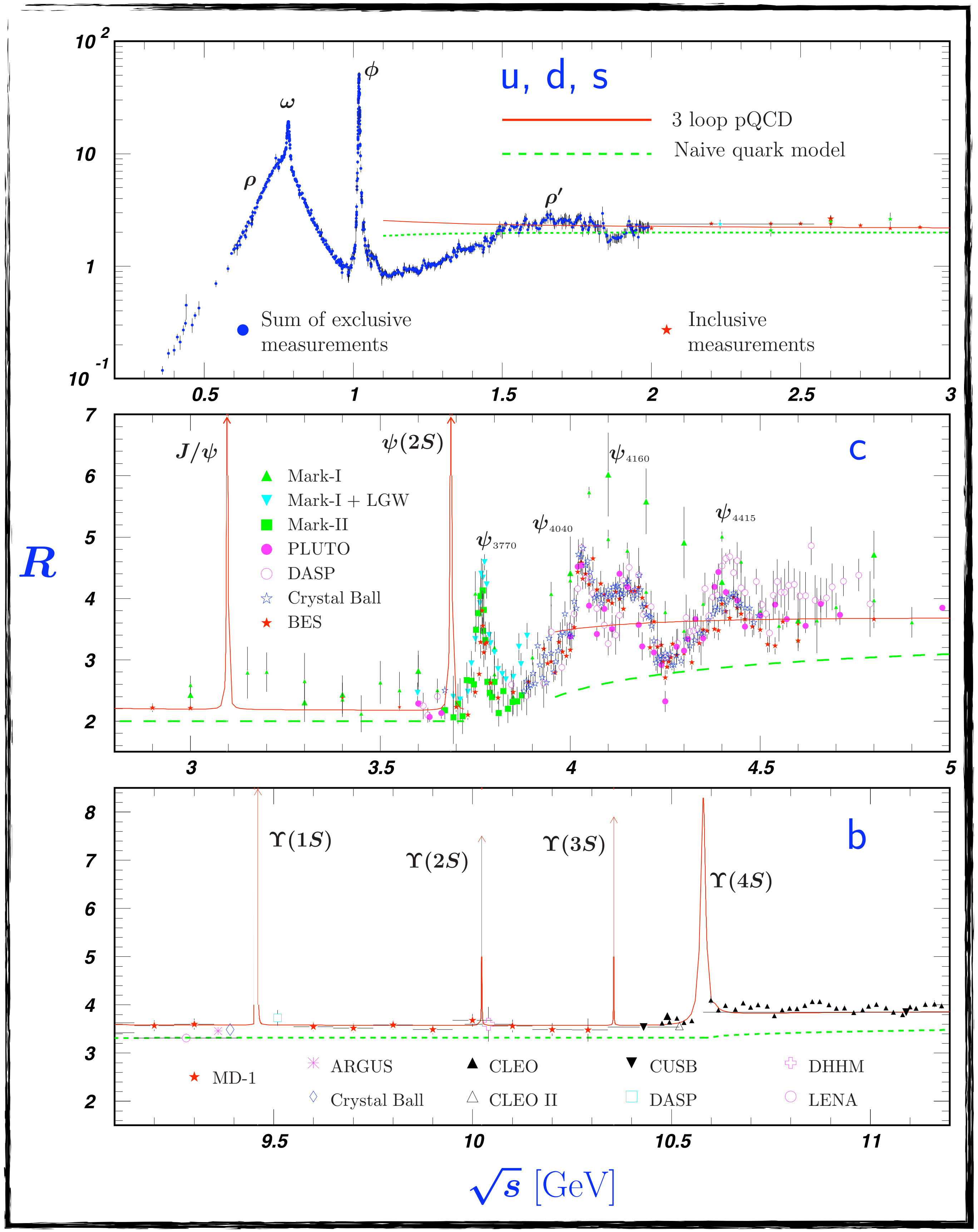




At energy above $1/\ell_H$, the Higgs dissolves, the integrals are smoothed out

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\mathcal{F}_H(k)\frac{1}{k^2-m^2} \propto 1/l_H^2$$

Higgs as a bound state



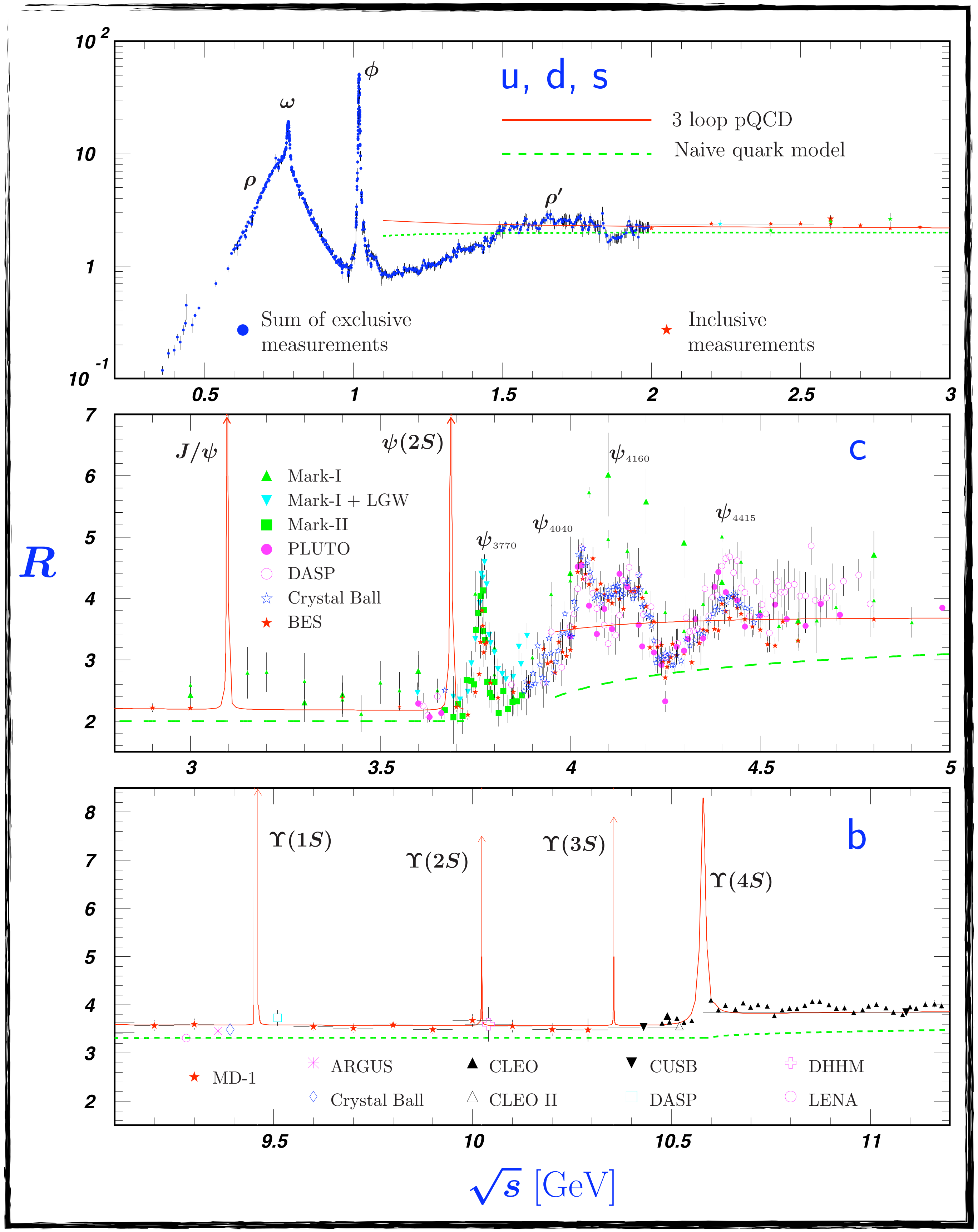
Structure of QCD was understood from inelastic scattering experiments

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Shows some peaks/resonances at each QCD bound states

Eventually the asymptotic value of R also tells the number of color of QCD

Higgs as a bound state



The Higgs discovery would be the first step of rich physics ahead of us:

- discover a new SU(N_c) force
- access to the fundamental constituents
- rich spectrum of bound states

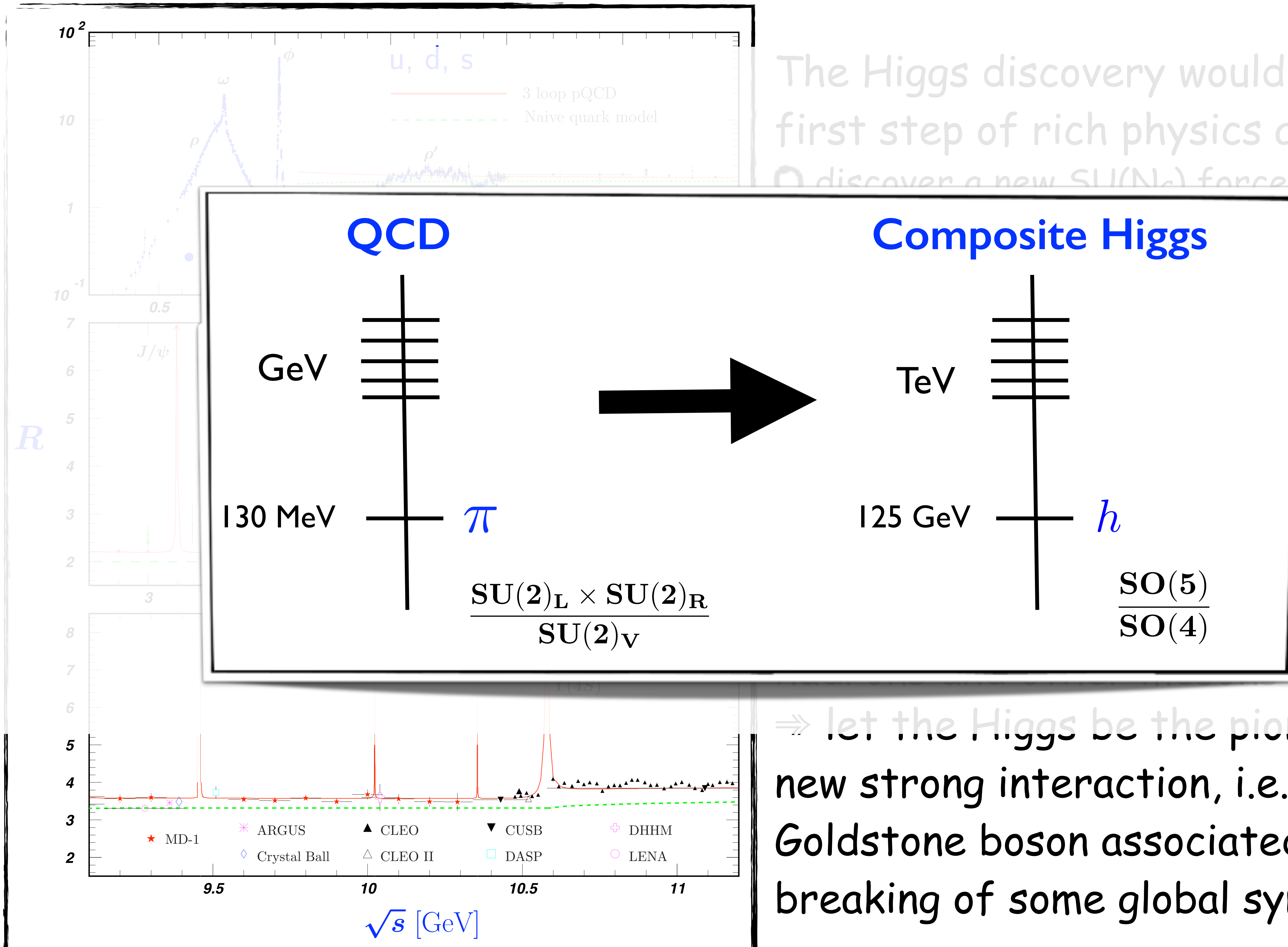
But how come we haven't seen anything of these yet?

⇛ The Higgs has to be lighter than the other bound states

⇛ pions are lighter than nucleons, hadrons and other mesons

⇛ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a bound state



The Higgs discovery would be the first step of rich physics ahead of us:

$\Rightarrow$ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a Goldstone boson

SM $\quad SO(4)/SO(3) \quad W^{\pm}_L$ & Z_L $\quad \Rightarrow \quad G/H \quad W^{\pm}_L$ & Z_L & h $\quad$ BSM

Examples: $SO(5)/SO(4)$: 4 PGBs=$W^{\pm}_L$, Z_L, h ⟷ Minimal Composite Higgs Model

dim=10 dim=6

Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$: 5 PGBs=H, a ⟷ Next MCHM

dim=15 dim=10

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s

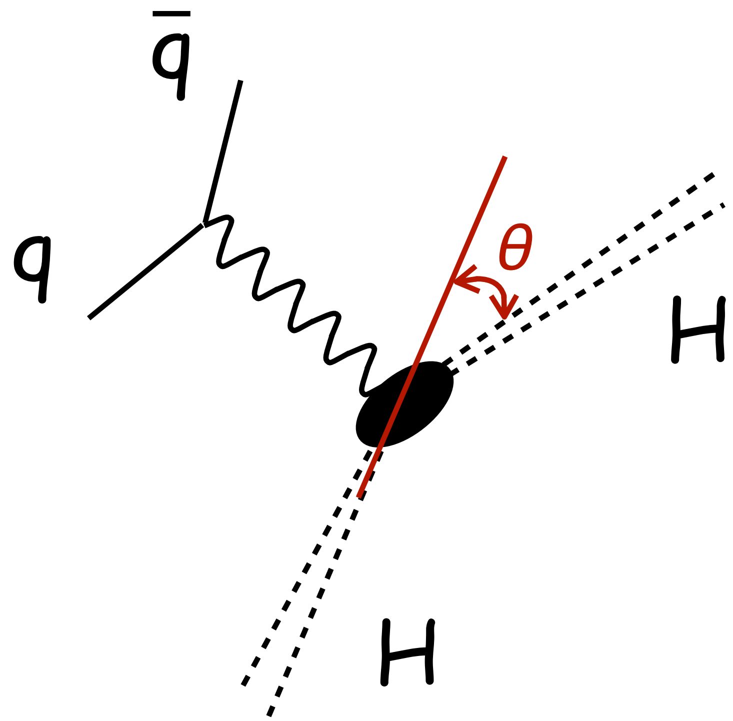
dim=15 dim=10

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ⟷ Minimal Composite Two Higgs Doublets

dim=15 dim=7

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

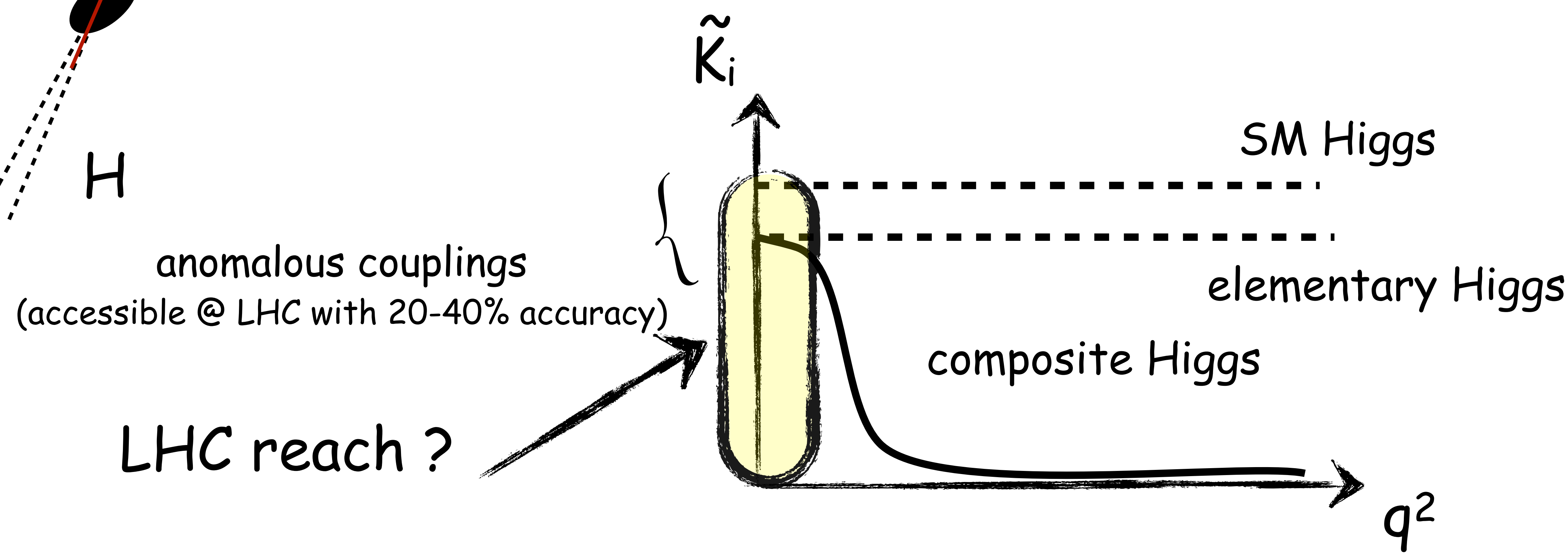
How to probe the compositeness of the Higgs?



Rosenbluth-type cross-section

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2}\,\frac{E'}{E^3}\left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2 \cos^2\theta/2\right)$$

Constants factor for point-like target
Momentum-dependent when target has an internal structure



Need to develop tools to understand the physics of a composite Higgs

- use effective theory approach
- rely on symmetries of the problem

identify interesting processes

Anomalous Couplings for a Composite Higgs

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu \left(|H|^2\right) \partial_\mu \left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

f=compositeness scale of the Higgs boson

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \equiv 1 - \xi/2$

Higgs anomalous coupling: a = √1-ξ ≈ 1-ξ/2

$$\xi = v^2/f^2$$

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2 \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 \qquad \frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.} \qquad \frac{c_6\lambda}{f^2}|H|^6$$

custodial breaking

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \qquad \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \qquad \frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

Higgs anomalous couplings

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

The Higgs couplings deviates from SM ones (a=b=c=1)

and the deviations are controlled by c_H and c_y

Anomalous couplings are related to the coset symmetry and not the spectrum of resonances

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

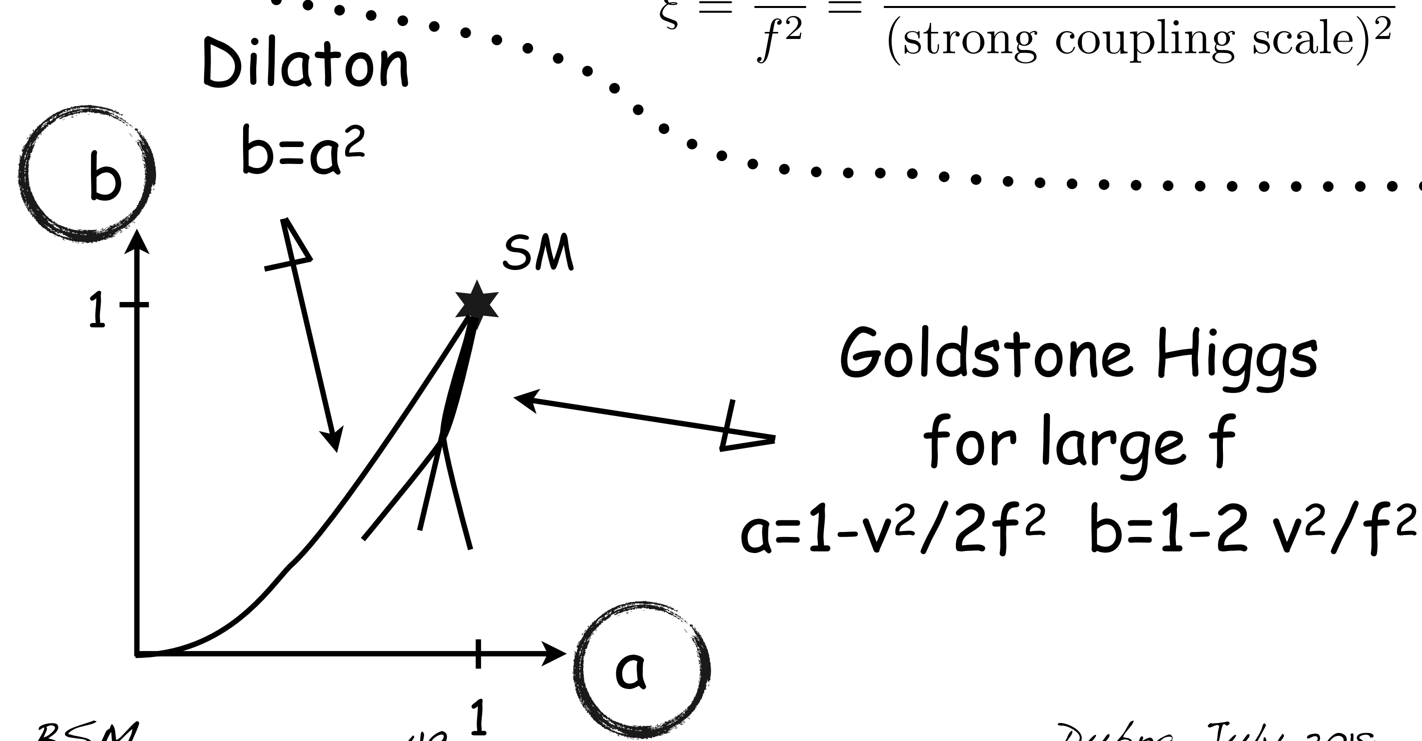
$$a = \sqrt{1-\xi} \qquad b = 1-2\xi \qquad b_3 = -\frac{4}{3}\xi\sqrt{1-\xi} \qquad c = \left(\sqrt{1-\xi}, \frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2 = -(\xi, 4\xi)$$

Uniqueness of Goldstone models in the SM vicinity

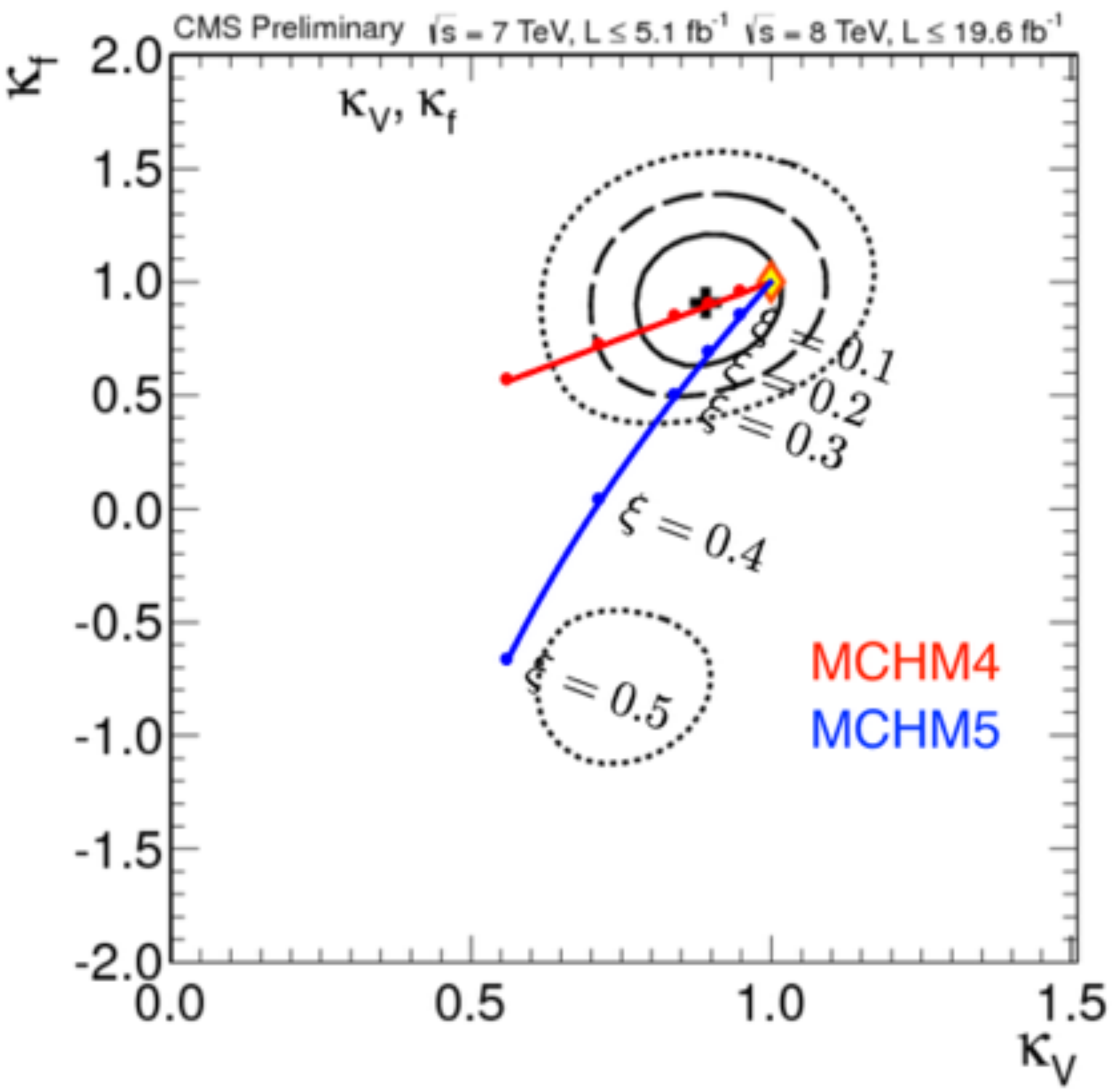
(a single operator at dimension-6 level controls the amplitudes)

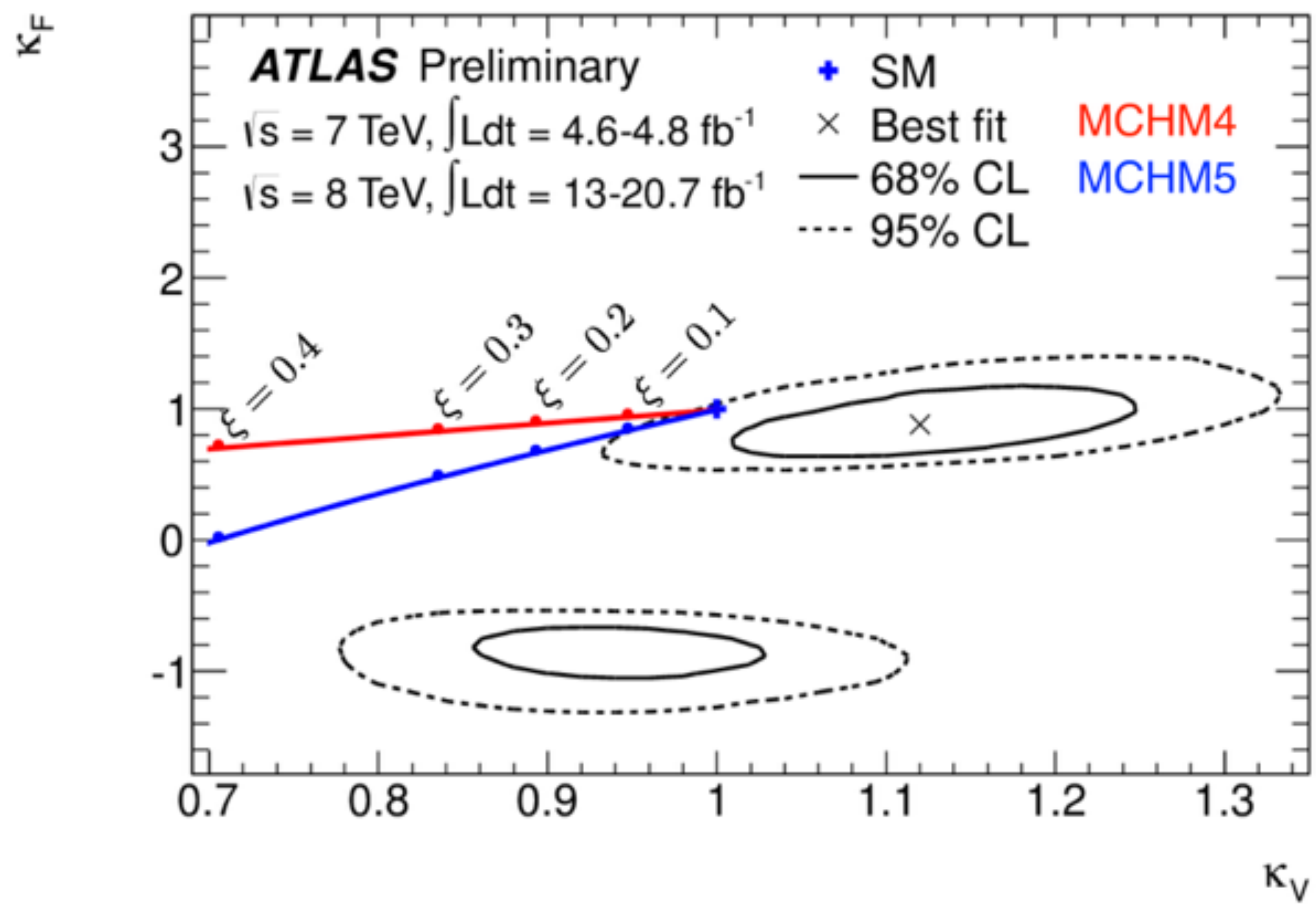
$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

Composite Higgs
vs.
SM Higgs



Higgs couplings fit





- MCHM4

$$\xi < 0.12 \quad \text{at } 95\%\text{CL}$$

- MCHM5

$$\xi < 0.10 \quad \text{at } 95\%\text{CL}$$

Indirect composite signatures

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\text{BSM}} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

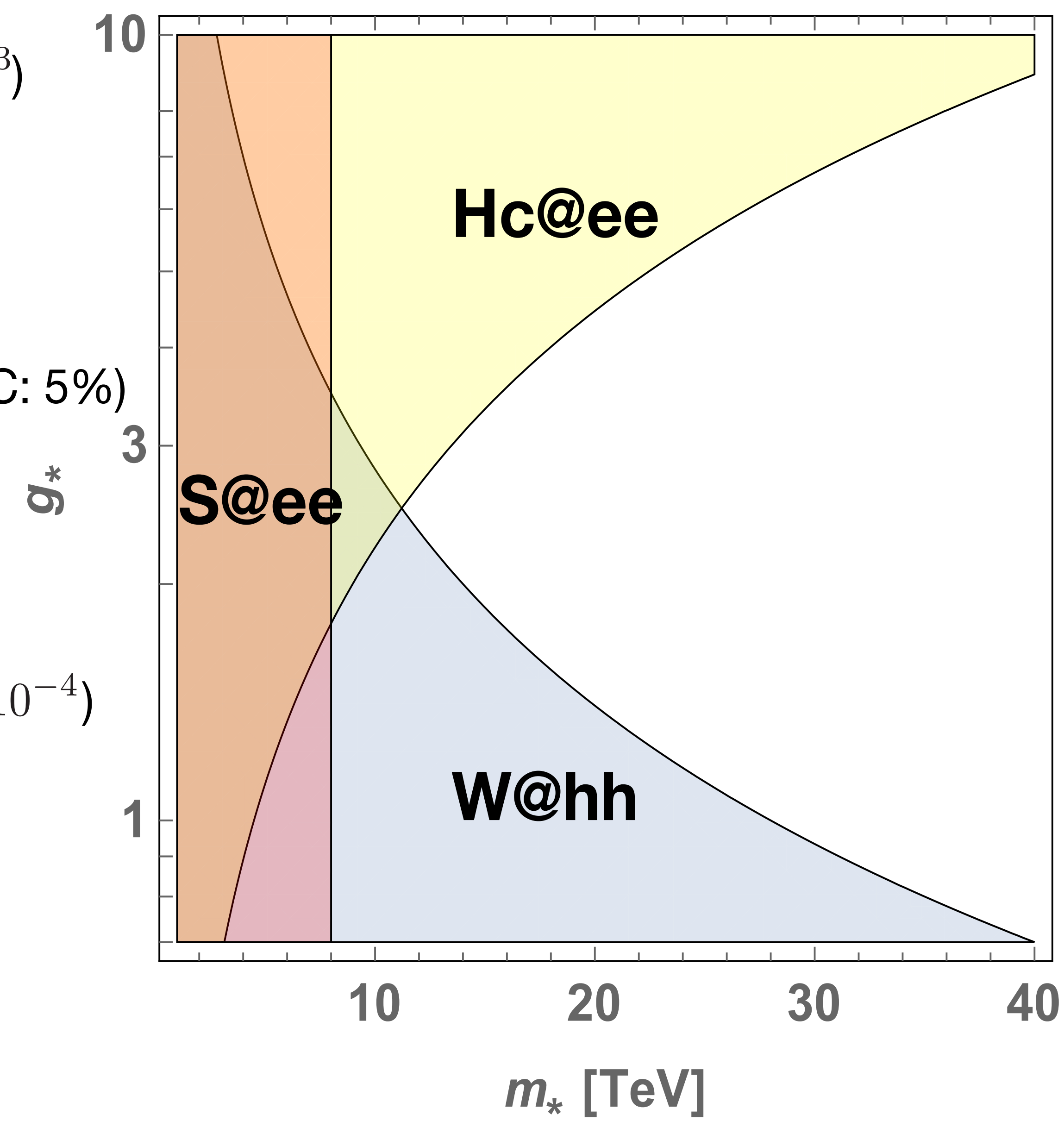
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \;\Rightarrow\; \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \;\Rightarrow\; \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$

W @hh: (energy + accuracy) (HL-LHC< 10^{-4})

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \;\Rightarrow\; W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < \; 10^{-5}$$



Grojean-Wulzer @ FCC physics week '17

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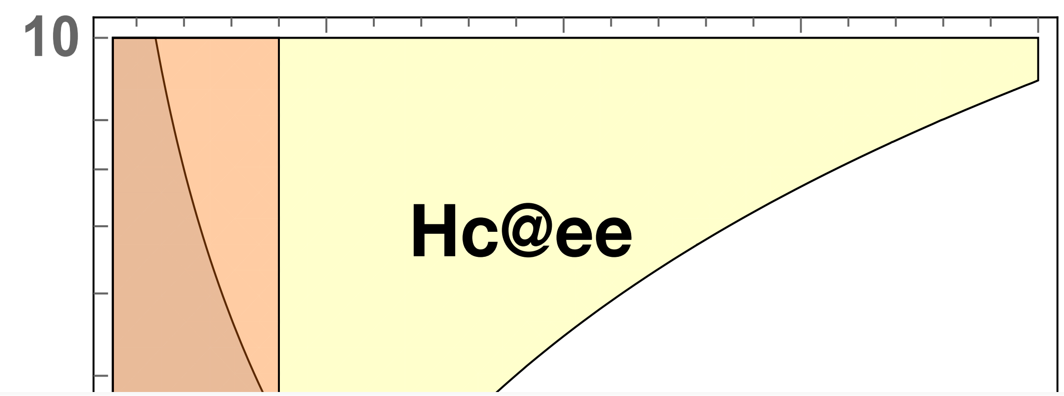

Other signatures in Higgs physics

(discussed by Sven?)

- Higgs+ high pT jet
- off-shell Higgs production
- VV to HH

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Indirect composite signatures

Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}_{\rm BSM}^{d=6} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2 \bar{q}_L H t_R \;\Rightarrow\; \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

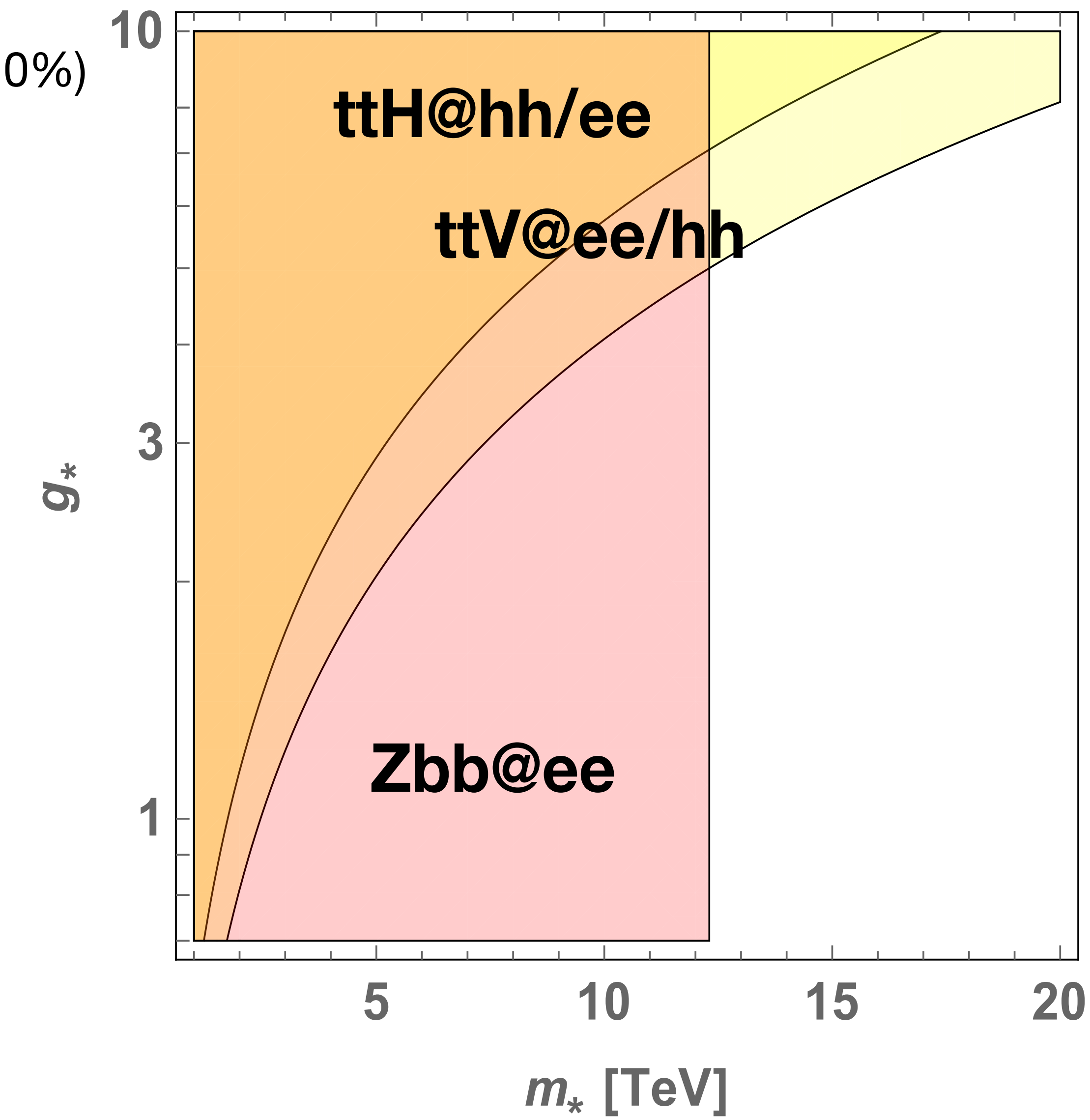
ttV coupling @ee/hh: [Janot / Farina et.al.]

$$\frac{g_*^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \bar{t}_R \gamma^\mu t_R \;\Rightarrow\; \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reach from en. + acc.?

Zbb coupling @ee: [ee Report] (LEP: 10^{-3})

$$\frac{y_t^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \bar{q}_L \gamma^\mu q_L + .. \;\Rightarrow\; \frac{\delta g_b}{g_b} = \frac{m_t^2}{m_*^2} < 2\,10^{-4}$$



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Diff. oper.s comb. in ee and hh!!

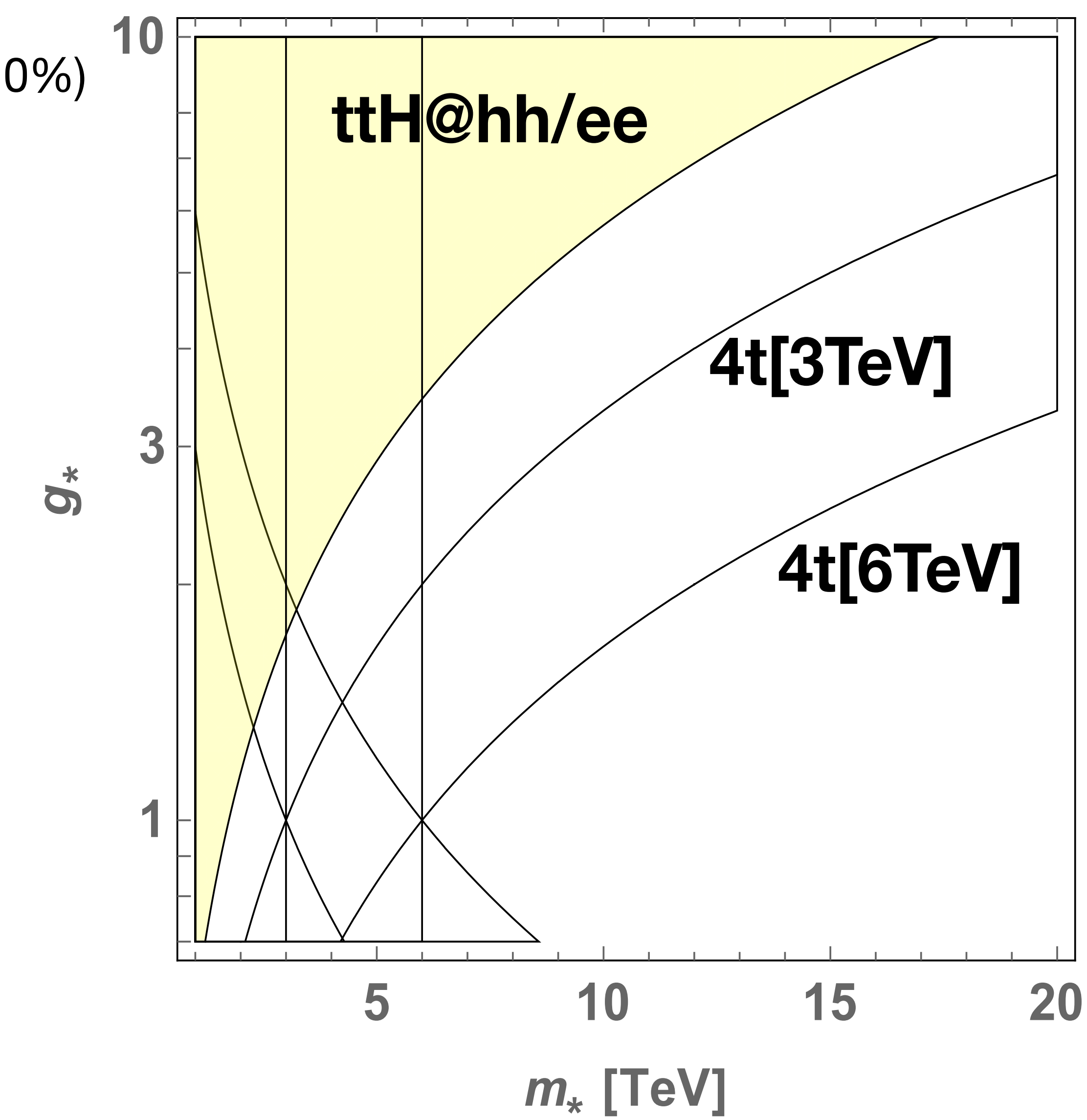
4-top contact interactions @hh:

$$\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)^2 \;\Rightarrow\; \frac{g_*^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^2}{m_*^2}(\bar{q}_L\gamma_\mu q_L)(\bar{t}_R\gamma_\mu t_R) \;\Rightarrow\; \frac{y_t^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^4}{g_*^2 m_*^2}(\bar{q}_L\gamma_\mu q_L)^2 \;\Rightarrow\; \frac{y_t^4}{g_*^2 m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

No study available (?)



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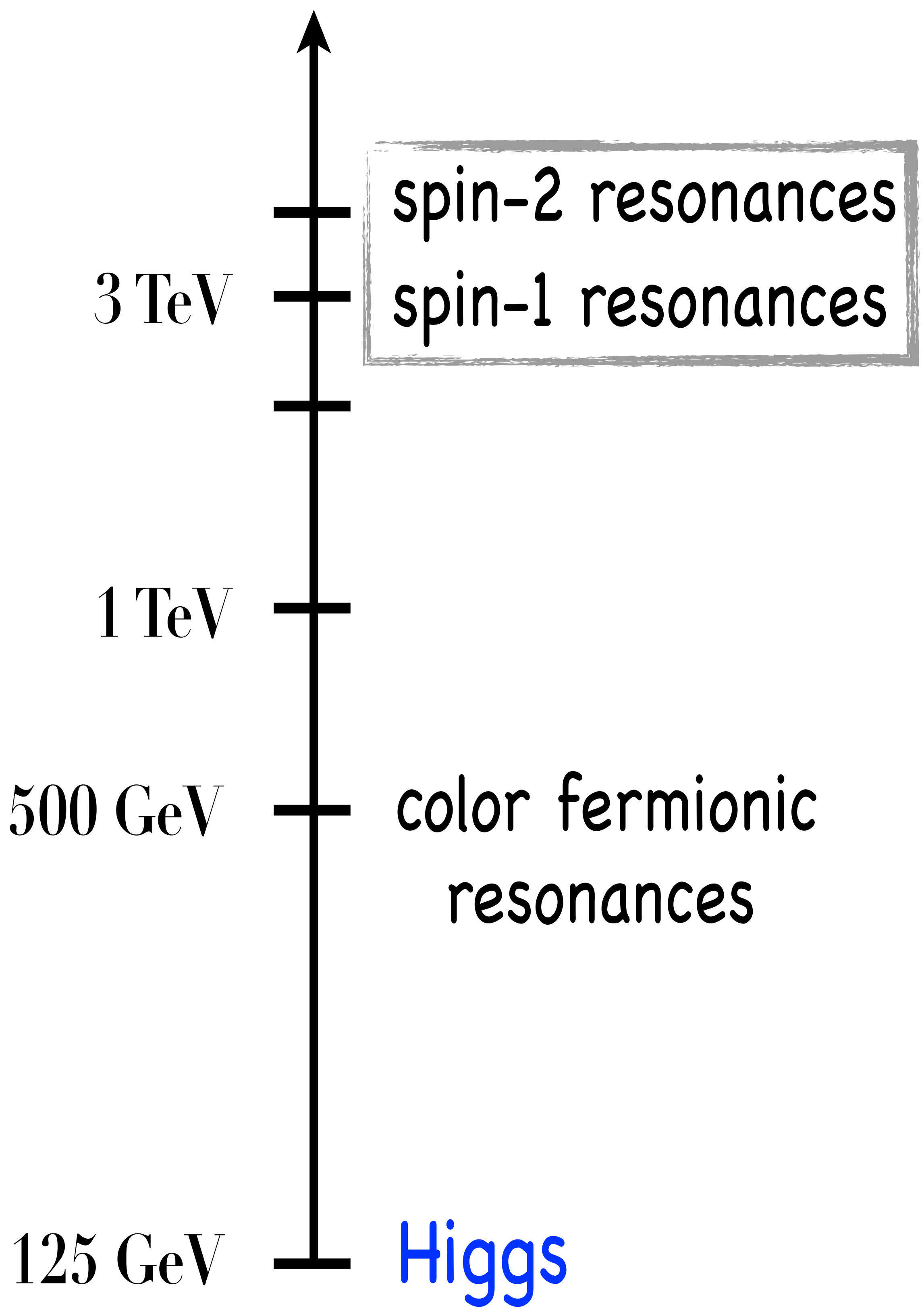
The other resonances



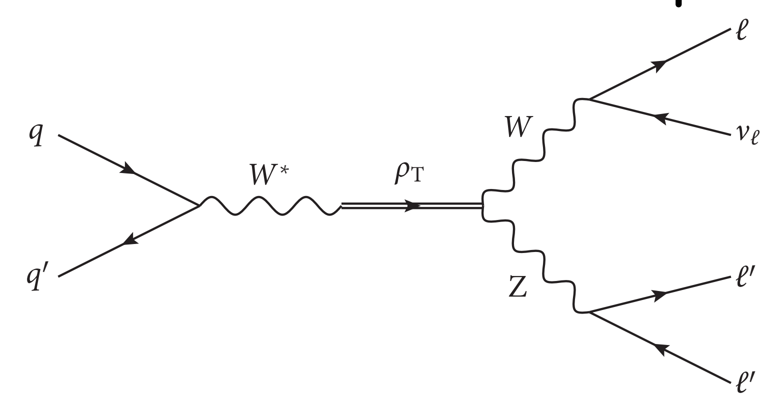
Dominant decays into longitudinal SM gauge bosons

$$\Gamma(\rho^0 \to W^+W^-) \approx \Gamma(\rho^\pm \to ZW^\pm) \approx \frac{m_\rho g_{\rho\pi\pi}^2}{48\pi} = \frac{m_\rho^5}{192\pi g_\rho^2 v^4}$$

Suppressed decays to SM quarks and leptons

$$\mathrm{Br}(\rho^\pm \to e^\pm \nu) \approx 2\mathrm{Br}(\rho^0 \to e^+e^-) \approx \frac{16 m_W^4}{m_\rho^4}$$

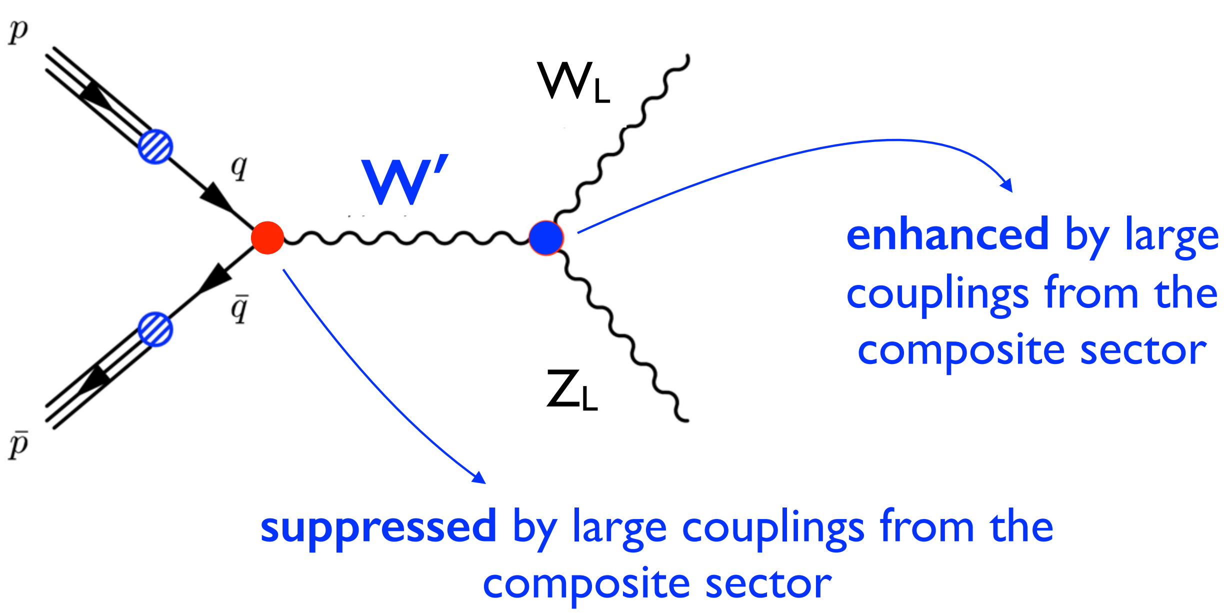
searches in WW, WZ channels in DY processes



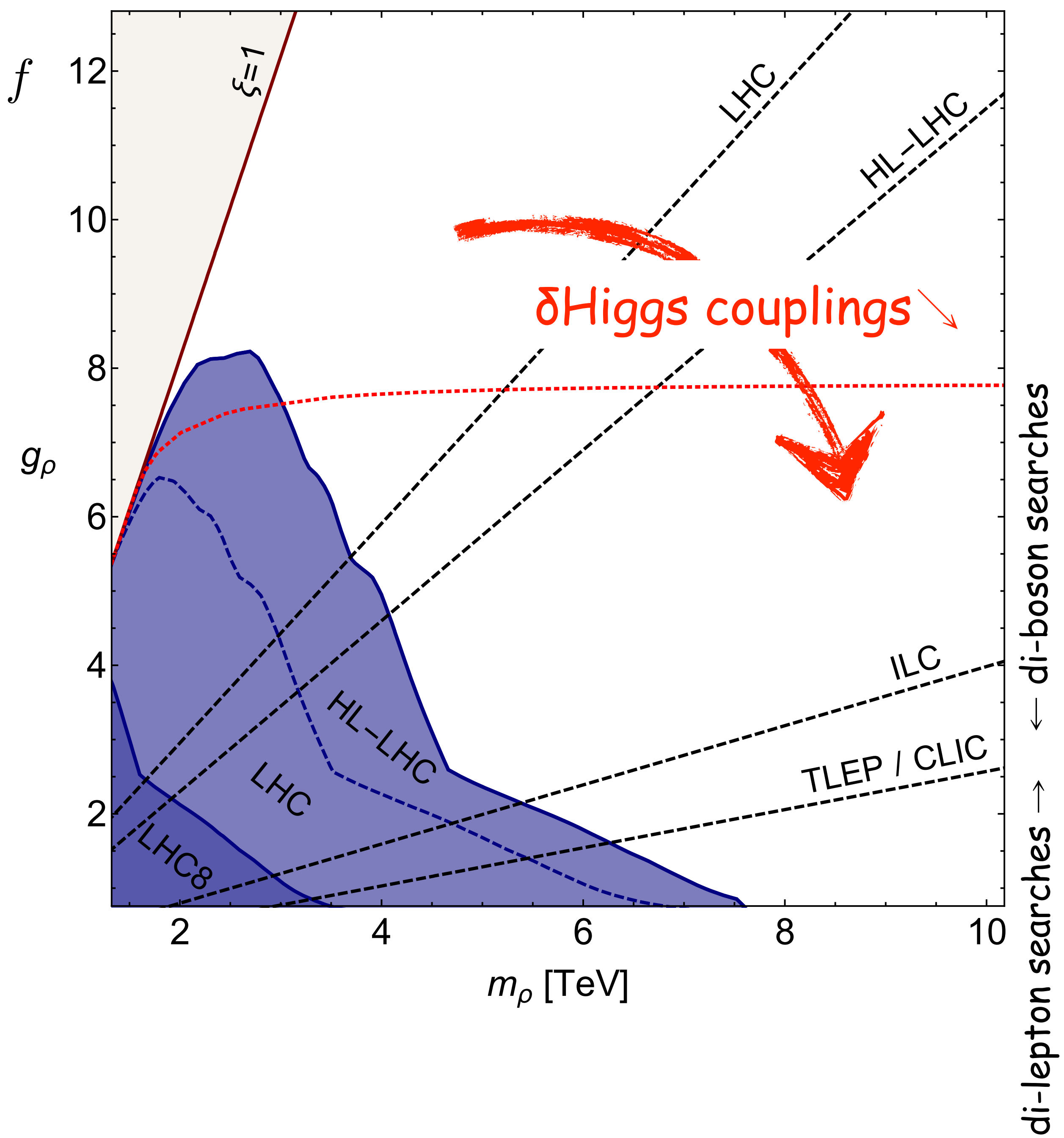
H couplings vs searches for vector resonances

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$



DY production xs of resonances decreases as $1/g_\rho^2$



Torre, Thamm, Wulzer '15

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- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2×10^{-3}

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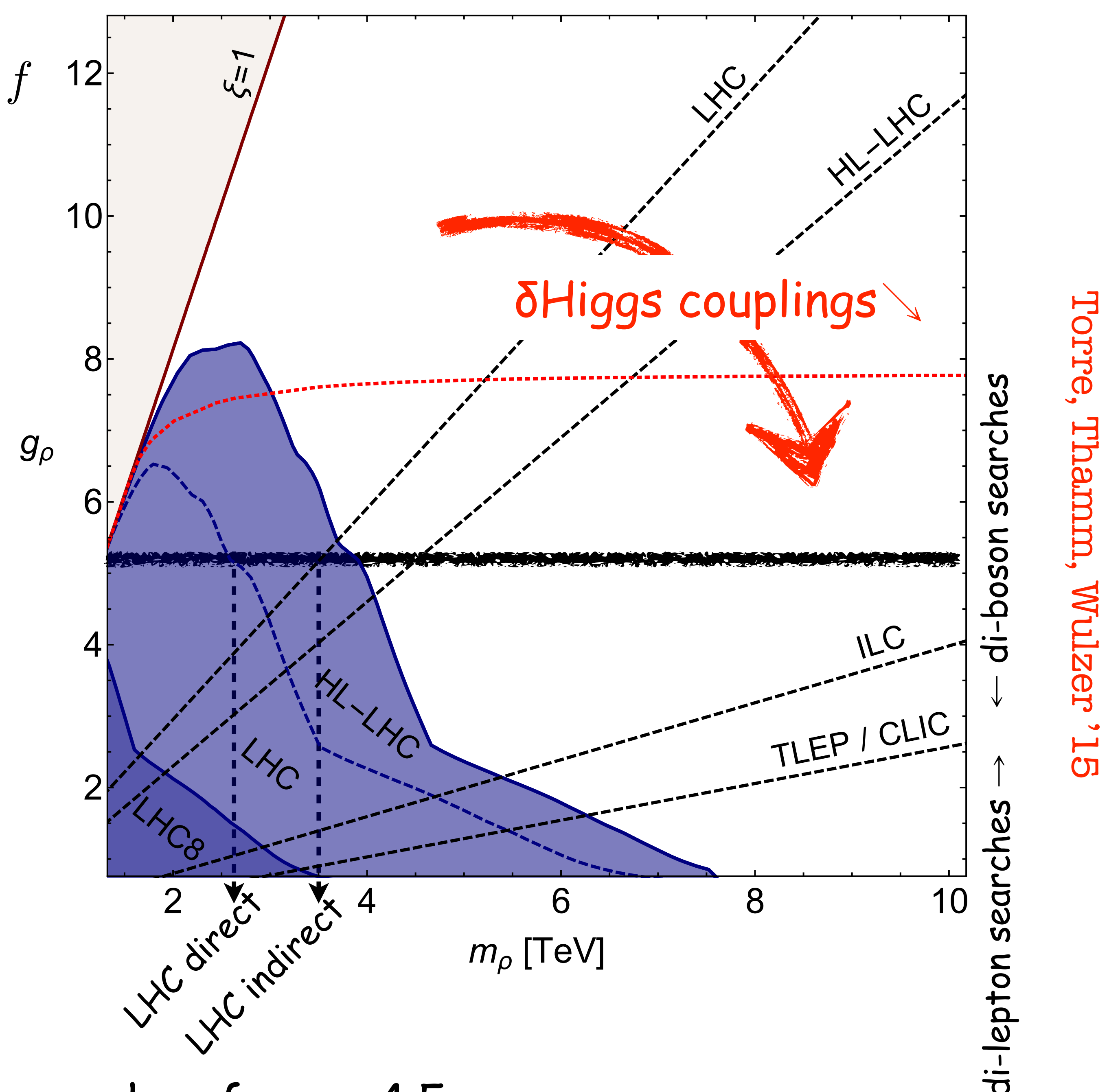


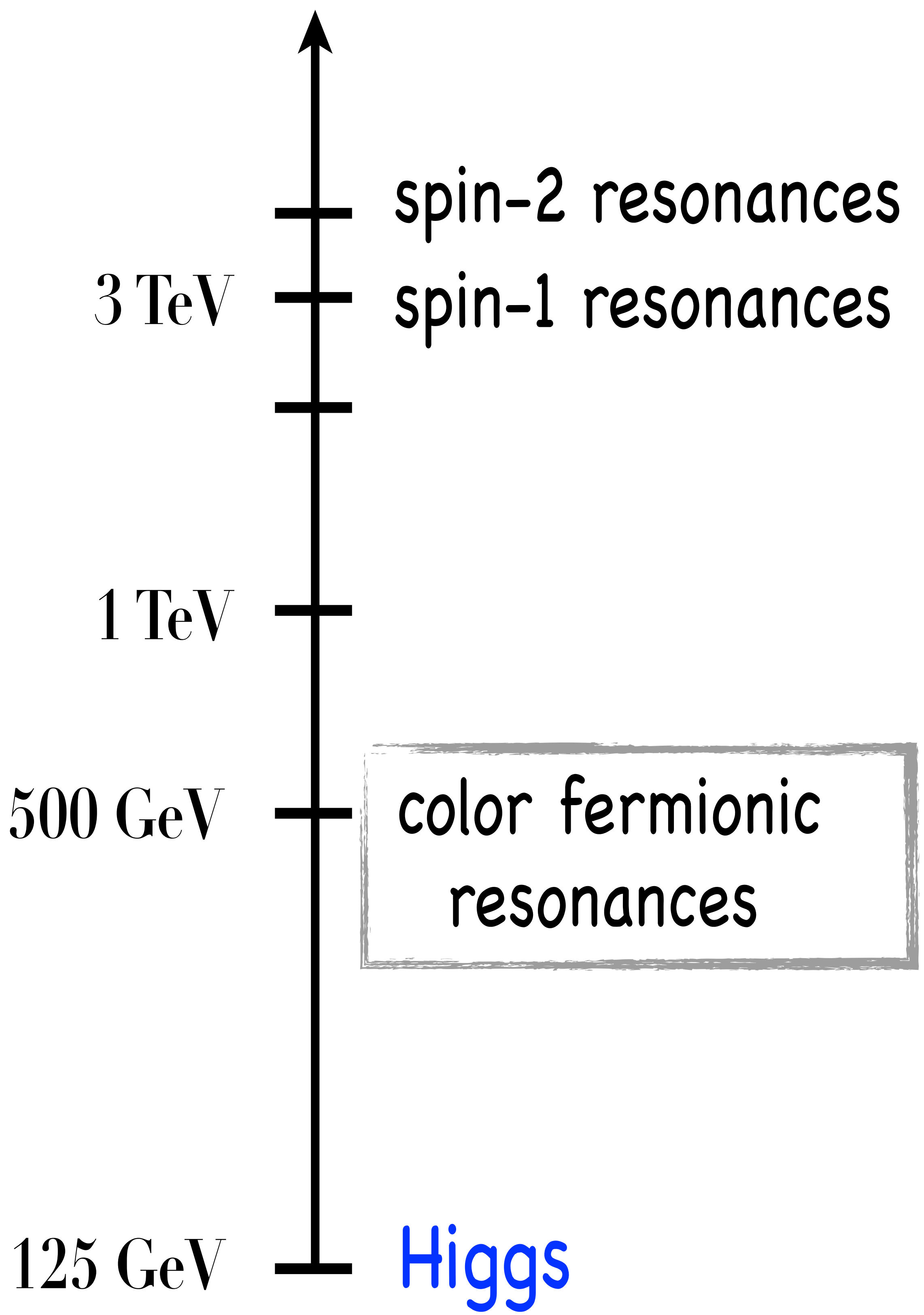
- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

indirect searches at LHC over-perform direct searches for g > 4.5

indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

The other resonances



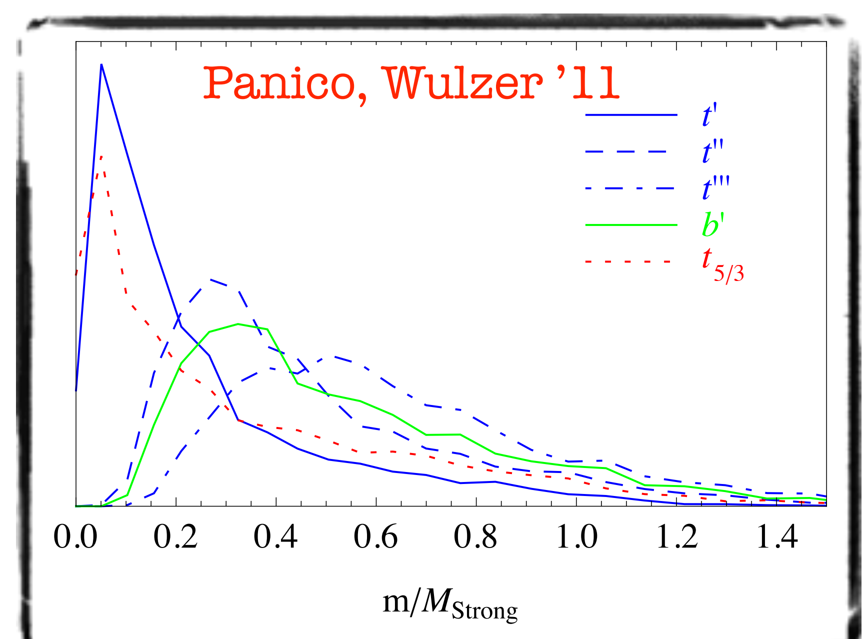
Top partners

SO(4)~SU(2)$_L$xSU(2)$_R$ embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2,\bar{2})_{2/3}$$

$$t_R \equiv (1,1)_{2/3}$$

$$b_R \equiv (1,1)_{-1/3}$$



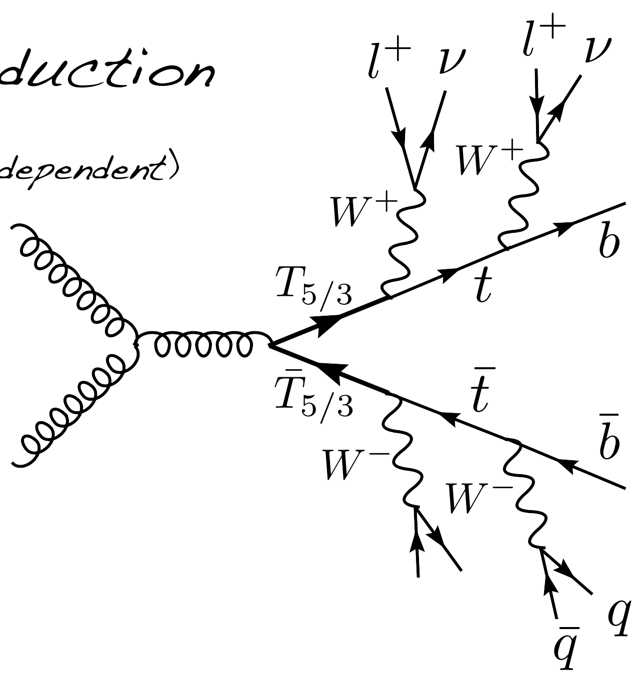
Searching for the top partners

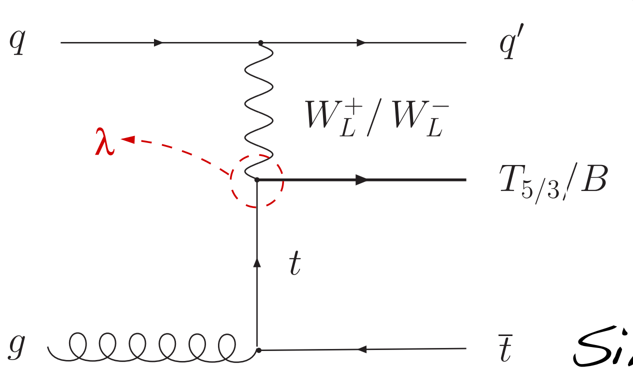
Search in same-sign dilepton events

- *tt+jets* is not a background [except for charge mis-ID and fake e-]
- the resonant (*tW*) invariant mass can be reconstructed

Pair production

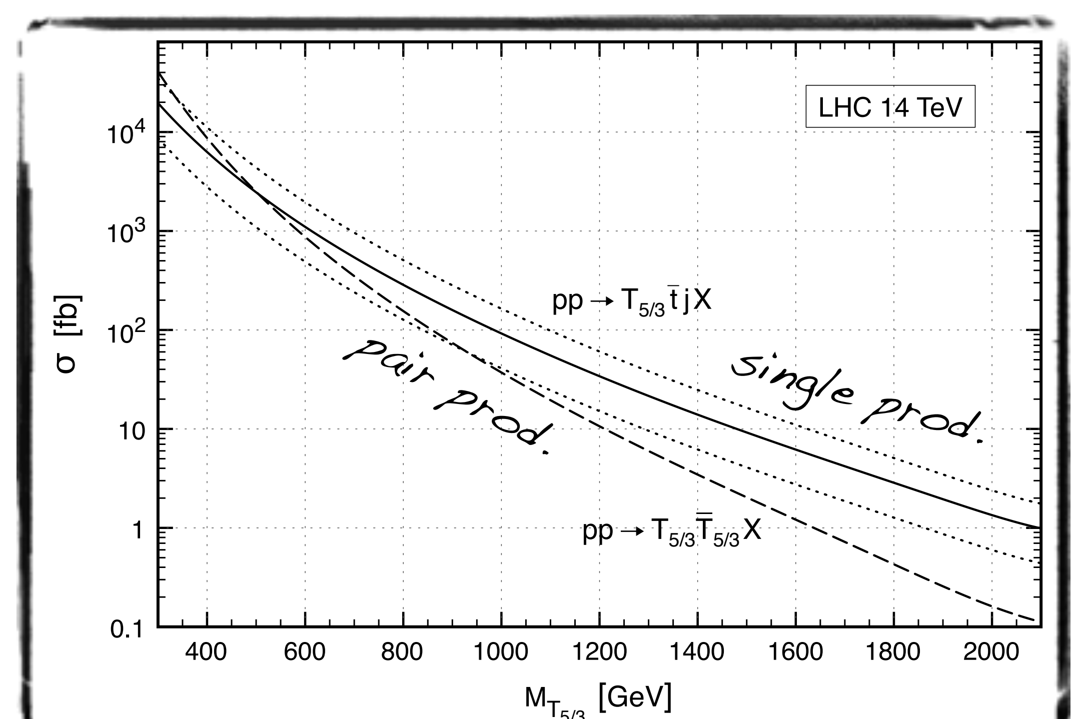
(model independent)





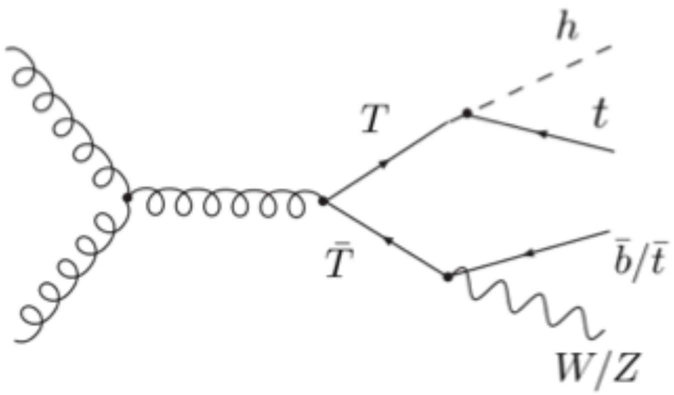
Single production

(model dependent)



[Contino, Servant '08]

Searching for the top partners



- $\ell^{\pm}$ + 4b final state Aguilar-Saavedra '09

$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$

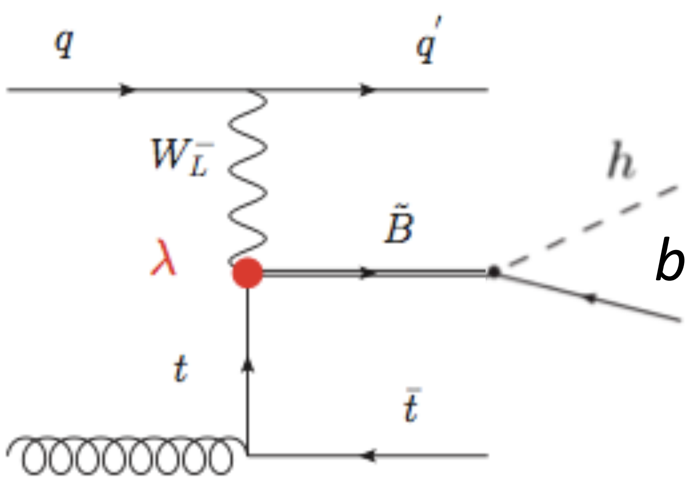
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^{\pm}$ + 6b final state Aguilar-Saavedra '09

$$T\bar{T} \to Ht\,H\bar{t} \to HW^+b\,HW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$$

- $\gamma\gamma$ final state Azatov et al '12

$$thbW/thtZ/thth,\ h \to \gamma\gamma$$

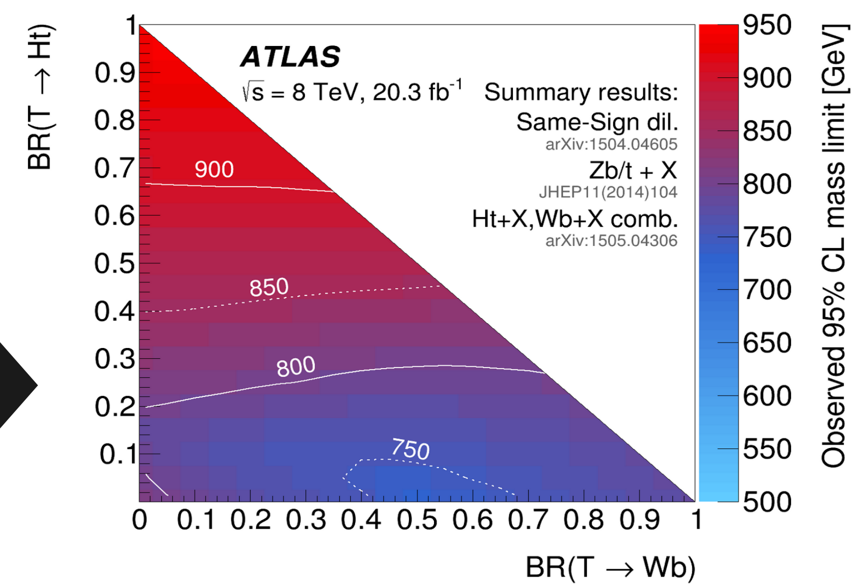


- $\ell^{\pm}$ + 4b final state Vignaroli '12

$$pp \to (\tilde{B} \to (h \to bb)b)t + X$$

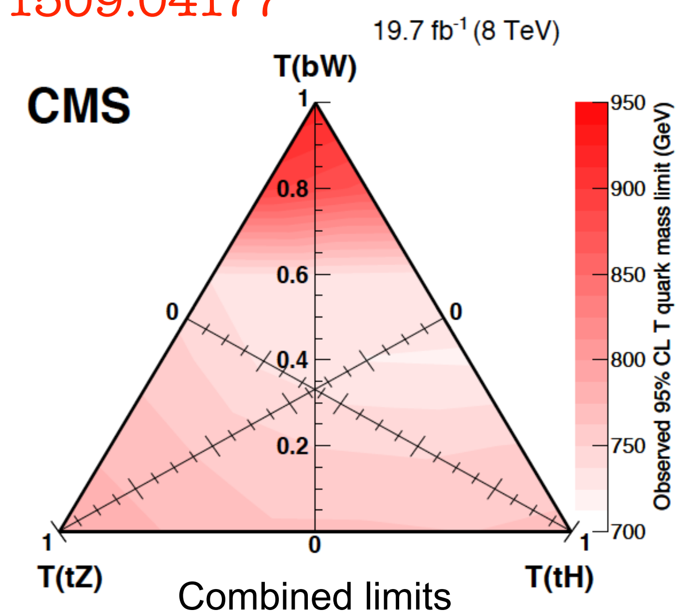
bounds on charge 2/3 states from pair production

1505.04306



(*) Not a combination. Only most restrictive individual bounds shown.

1509.04177



Searching for the top partners

bounds on
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from pair production

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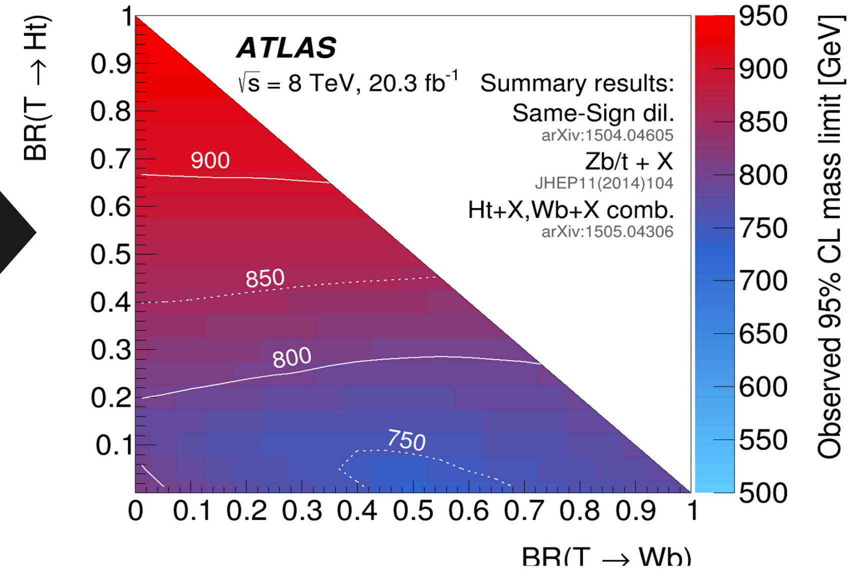

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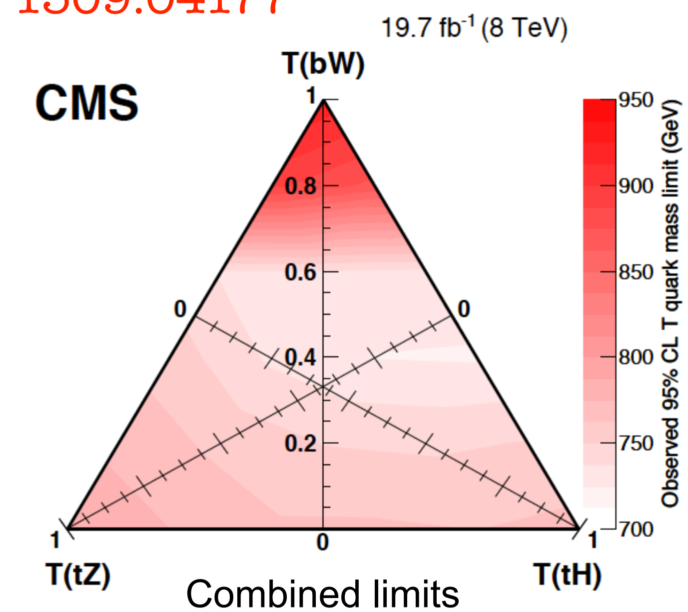
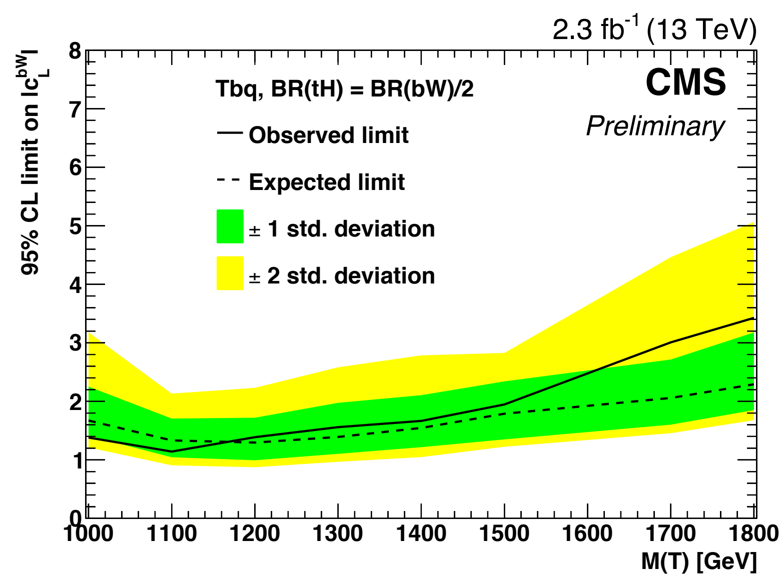
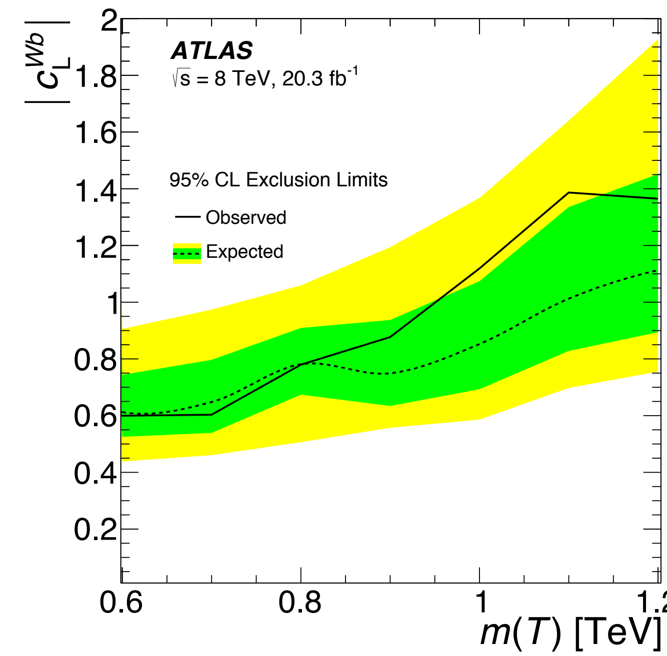
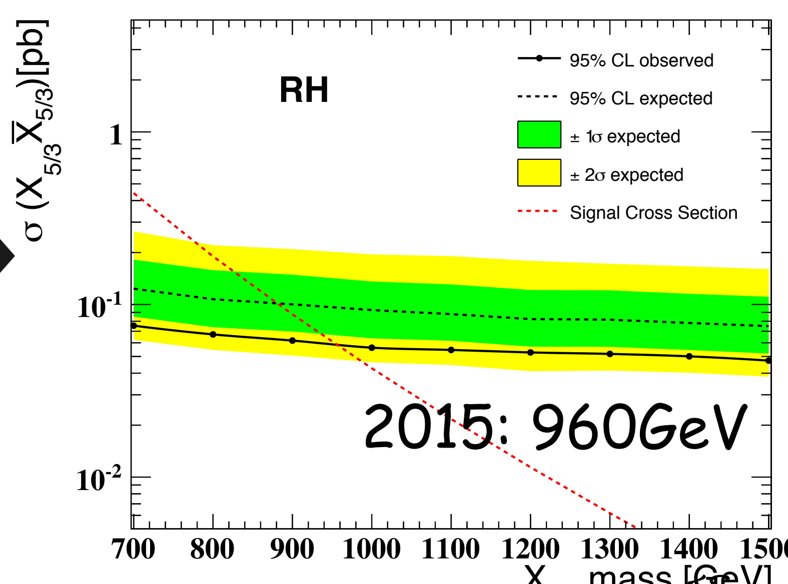


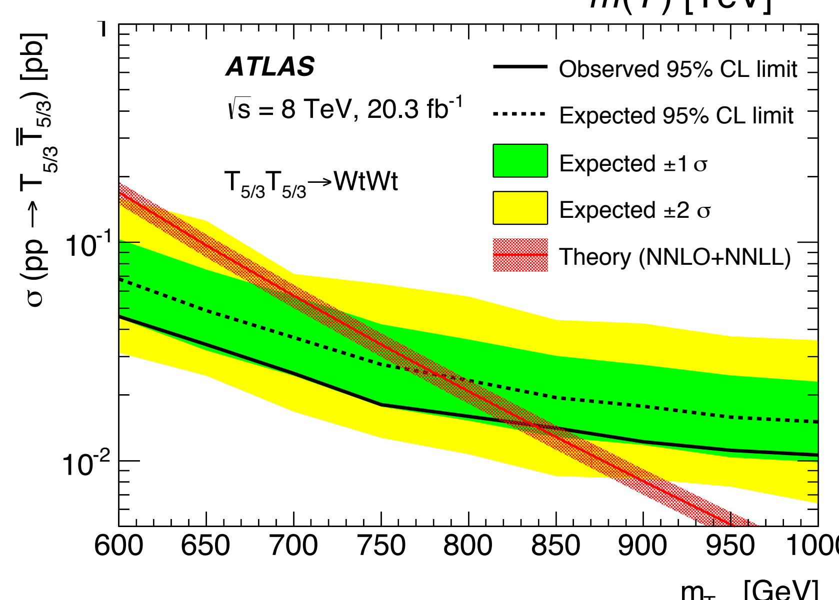
bounds on
charge 2/3 states
from single production





bounds on
charge 5/3 states
from single production





Searching for the top partners

bounds on
charge 2/3 states
from pair production

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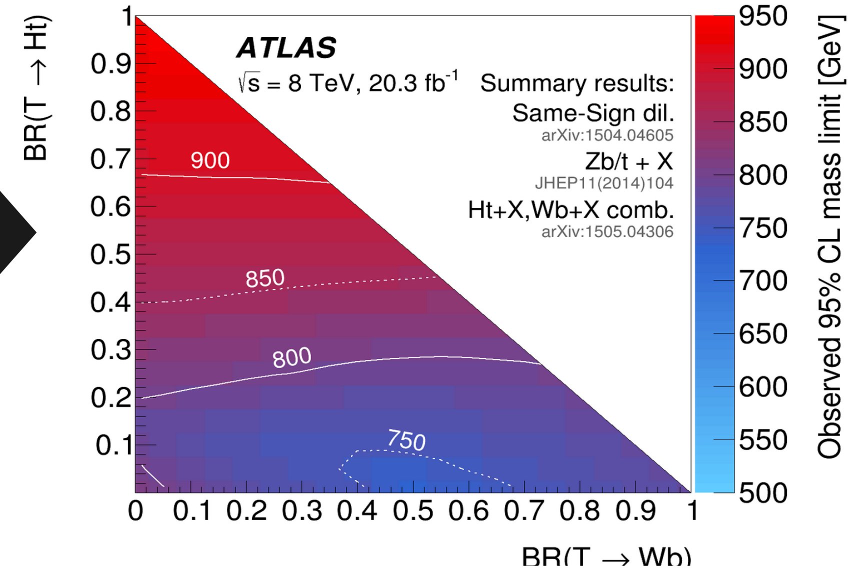

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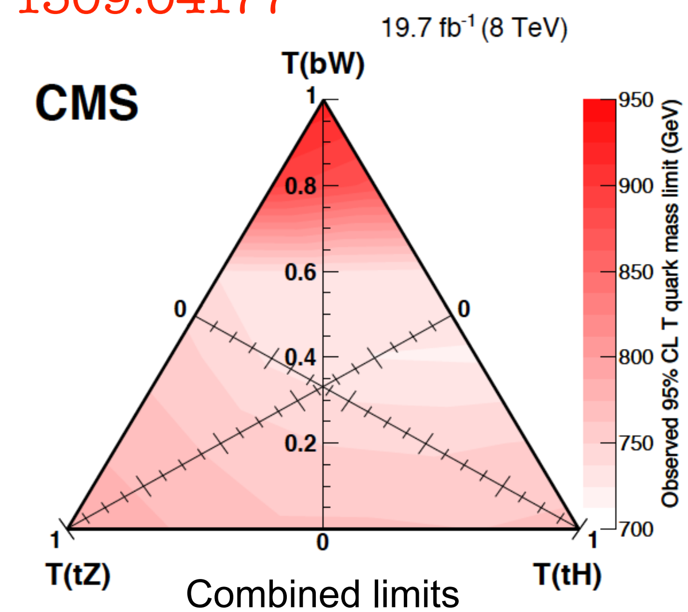

bounds on
charge 2/3 states
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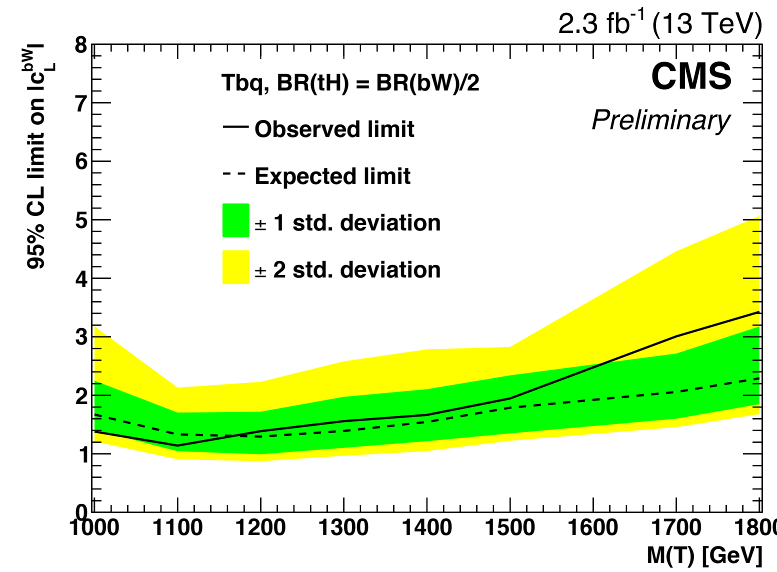
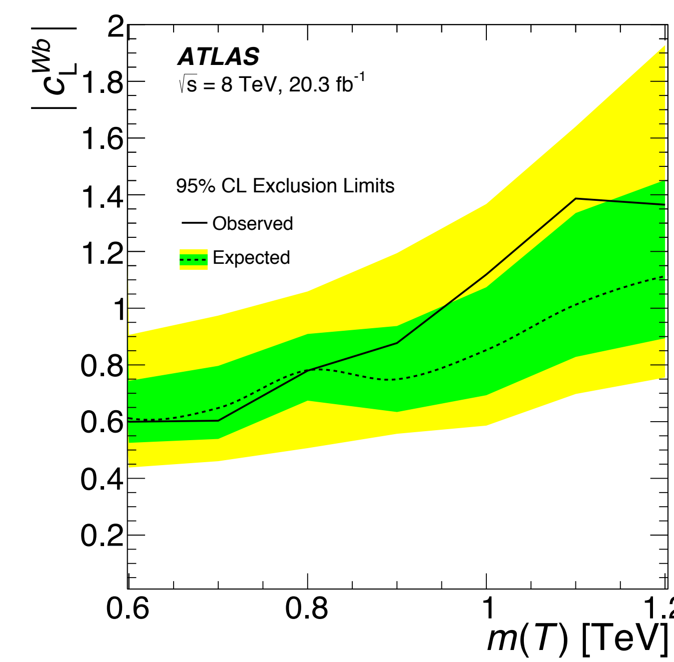
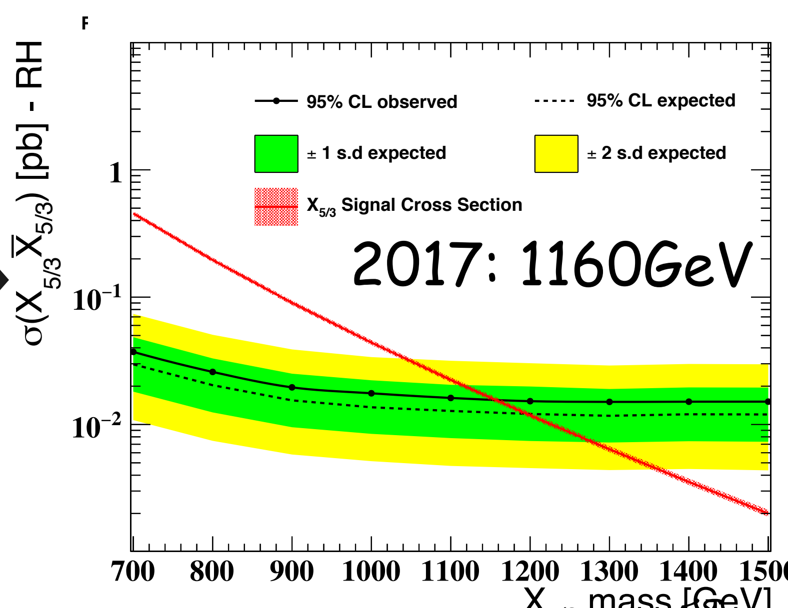
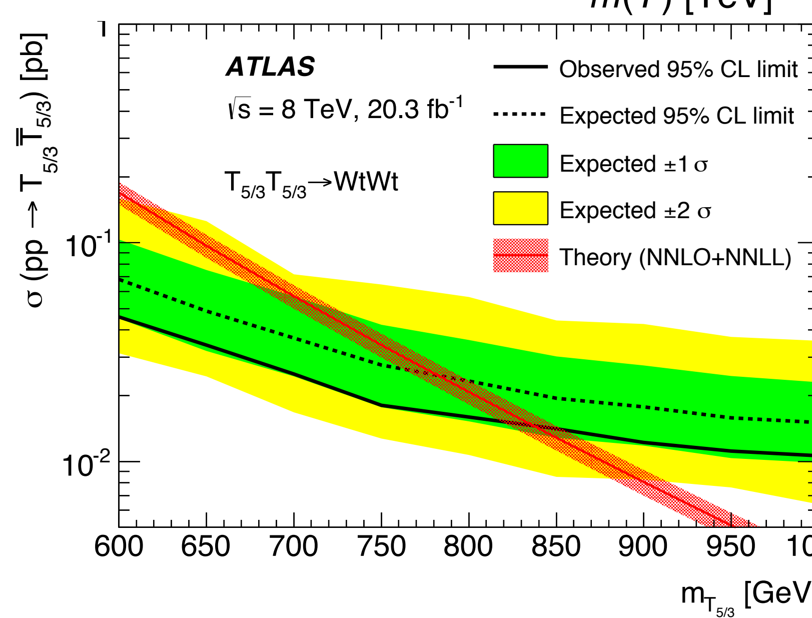




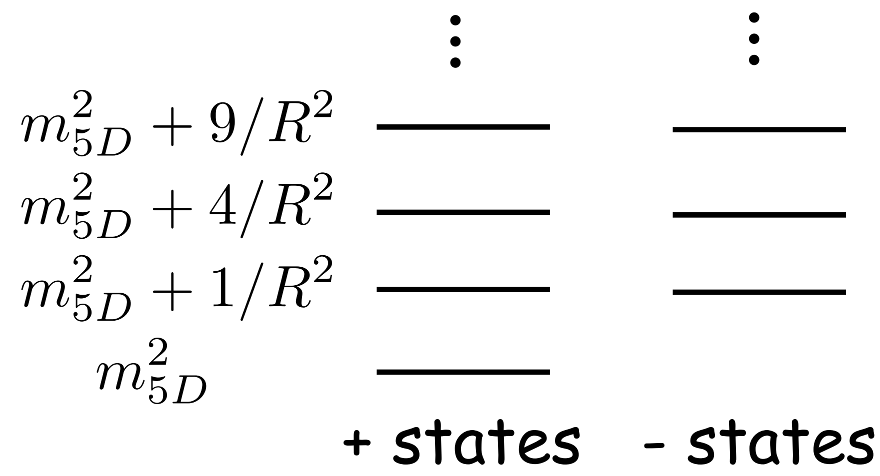
bounds on
charge 5/3 states
from single production





Extra dimensions

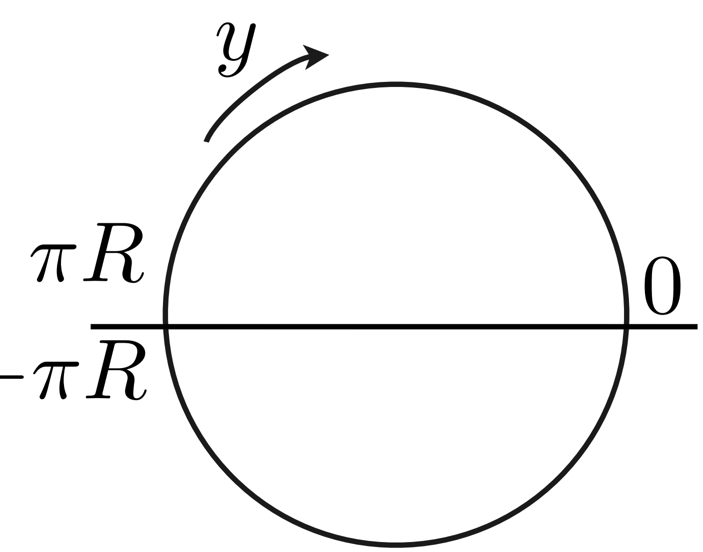
Extra dimensions



5D field=infinite tower of massive 4D fields

depending of the energy available, you can probe more and more of these KK modes

~~ Compactification on a Circle ~~



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}} \pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

Extra dimensions

$\vdots \qquad \vdots$

$m_{5D}^2 + 9/R^2$ ——— ———

$m_{5D}^2 + 4/R^2$ ——— ———

$m_{5D}^2 + 1/R^2$ ——— ———

m_{5D}^2 ———

+ states - states

5D field=infinite tower of massive 4D fields

depending of the energy available, you can probe more and more of these KK modes

~~ Compactification on a Circle ~~

5D General relativity = 4D GR + U(1) gauge symmetry

gauge symmetries are emerging from gravitational interactions in extra dimensions?

beautiful idea of Kaluza & Klein

but

quantization? non-abelian structure? different gauge couplings?

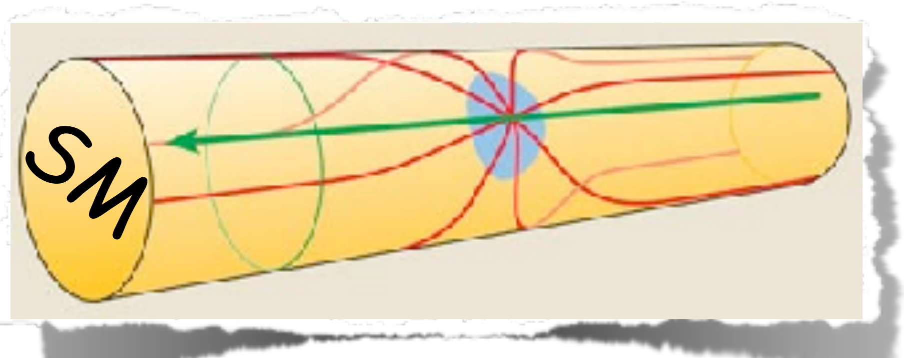
no successful realization till now

localization of KK mode along the xdim

$m_n = p_y^n = \frac{n}{R}$

Extra Dimensions for TeV/LHC Physics

- Hierarchy problem, i.e., why is gravity so weak
  - large (mm size) flat extra dimensions
    - gravity is diluted into space while we are localized on a brane

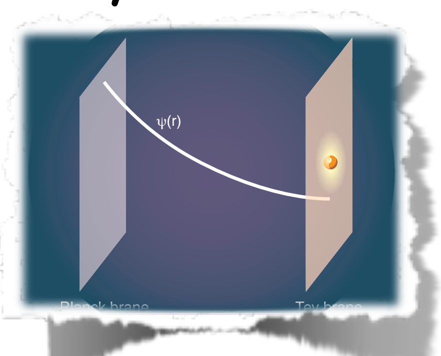


$$\int d^{4+n}x \sqrt{|g_{4+n}|} M_\star^{2+n} \mathcal{R} = \int d^4x \sqrt{|g_4|} M_{Pl}^2 \mathcal{R}$$

$$M_{Pl}^2 = V_n M_\star^{2+n}$$

$M_{Pl} = 10^{19}$ GeV $\quad M_* = 1$ TeV $\quad V_2 = (1\ \mathrm{mm})^2$

  - warped/curved extra dimensions
    - gravity is localized away from SM matter and we feel only the tail of the graviton



graviton wavefunction is exponentially localized away from SM brane

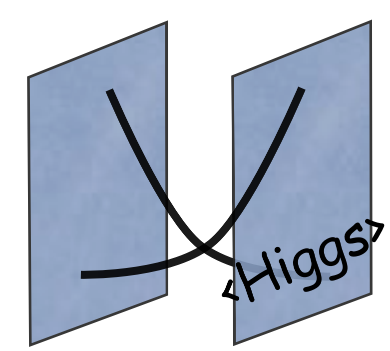
$$v = M_\star e^{-\pi R M_\star}$$

$M_* = 10^{19}$ GeV $\quad v = 250$ GeV $\quad R \sim 11/M_*$

- Fermion mass hierarchy & flavour structure

  fermion profiles:

  the bigger overlap with Higgs vev, the bigger the mass



- EW symmetry breaking by boundary conditions

  Orbifold breaking, Higgsless

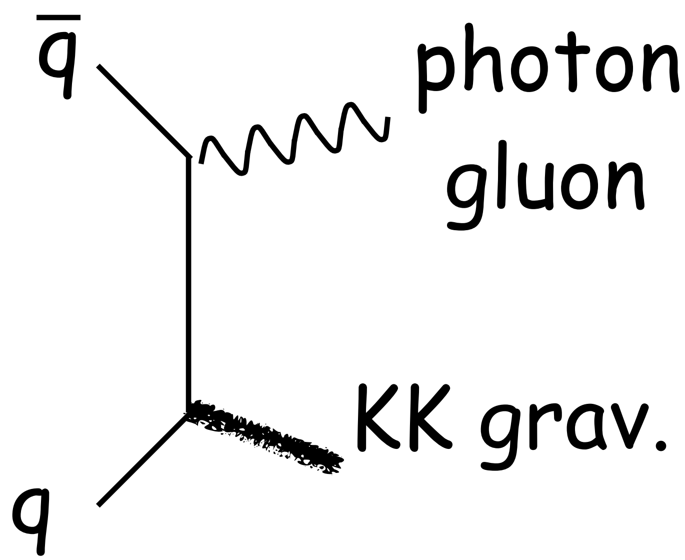
Large volume xdim phenomenology

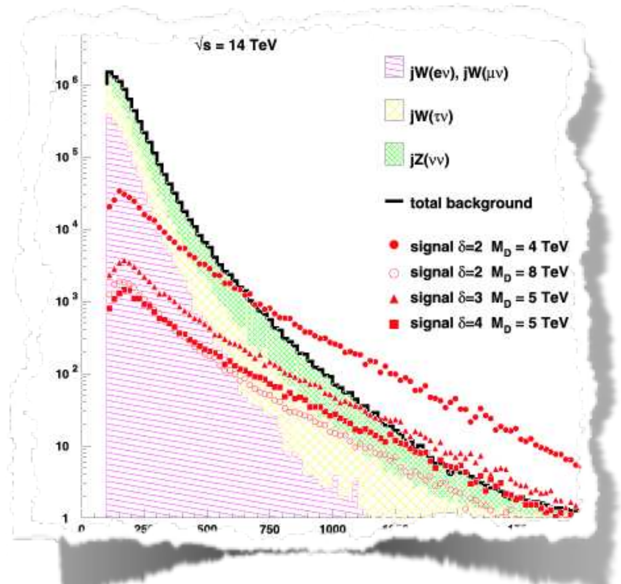
eV splitting between graviton KK modes

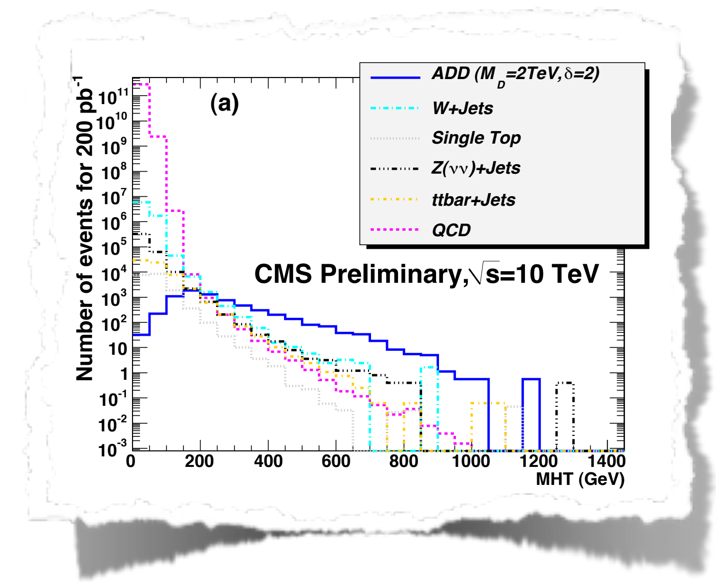
$1/M_{Pl}$ couplings of graviton KK modes to SM

- Graviton production in colliders

monojet+$\not{E}_T$



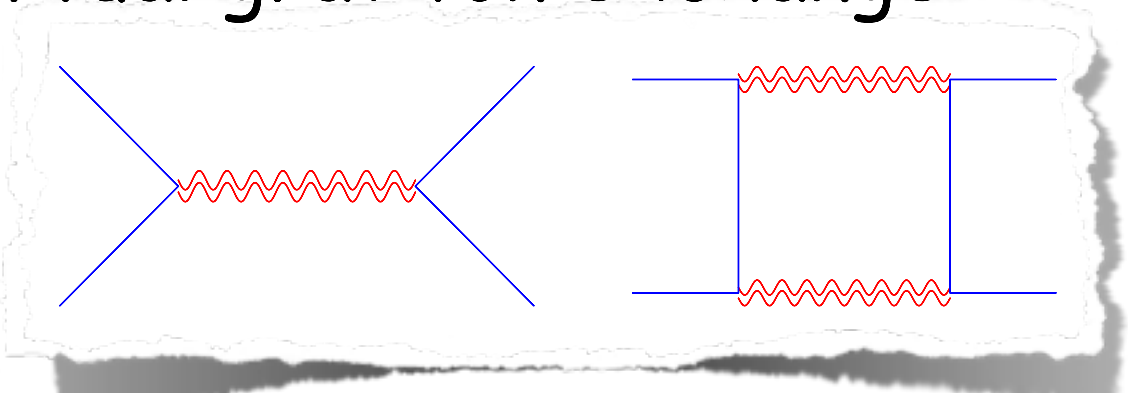




Vacavant, Hinchliffe '01

CMS PAS EXO 09-013

- Virtual graviton exchange

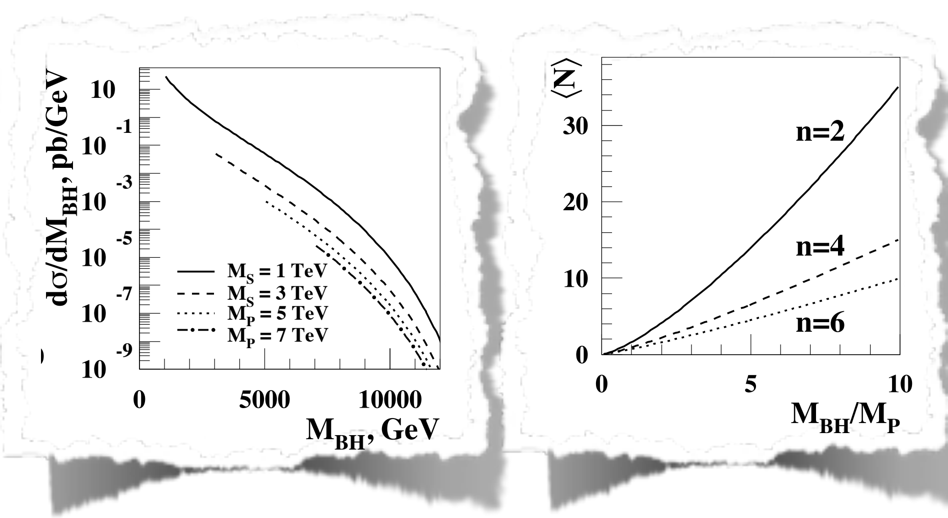


Large volume xdim phenomenology

- Supernova cooling: $M_* > 100$ TeV (for 2 xdim)

- Black Hole production

  classical production (can be very large $10^{3\text{-}4}$ pb),
  Hawking thermal decay, i.e., large decay multiplicity



Dimopoulos, Landsberg, ’01

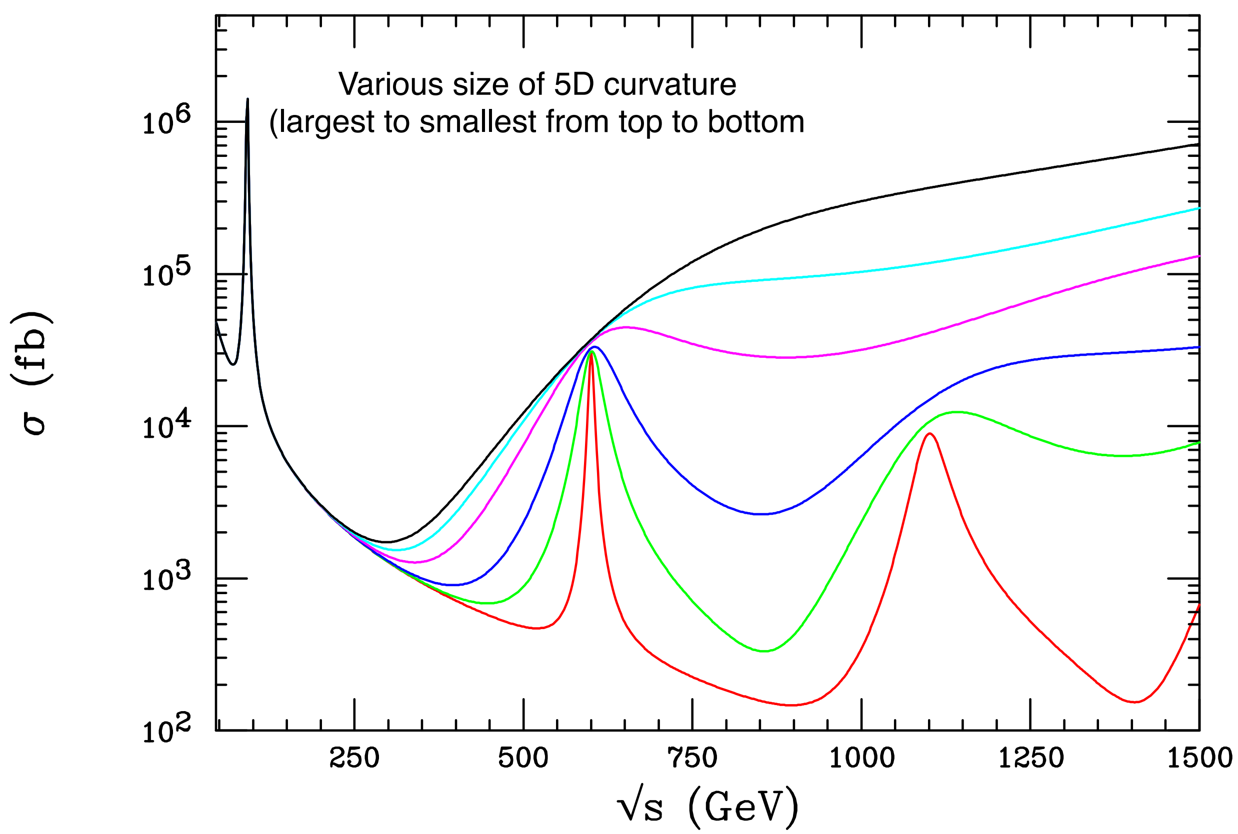
- String resonances production

Curved xdim phenomenology

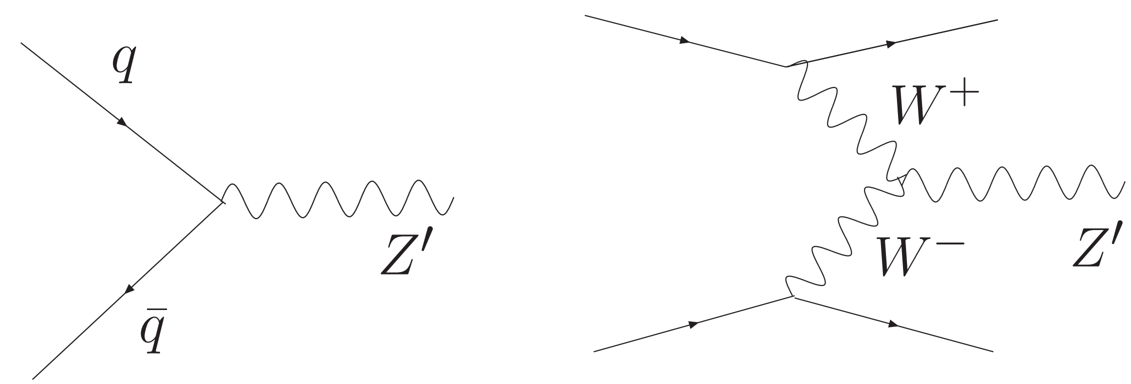
TeV splitting between gauge KK modes

O(g_{SM}) couplings of gauge KK modes to SM

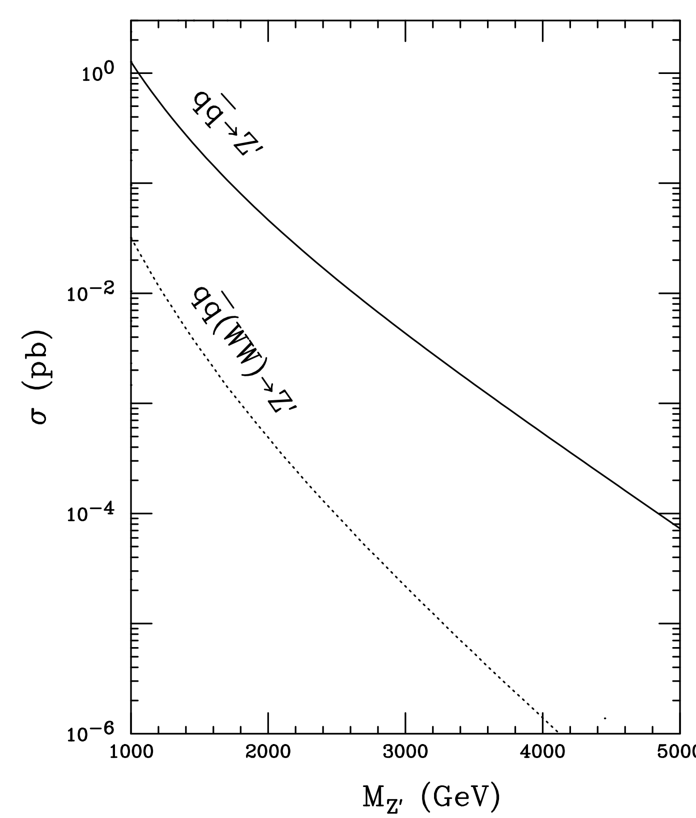
$$e^+e^- \rightarrow \mu^+\mu^-$$



Davoudiasl et al '99



(a) (b)

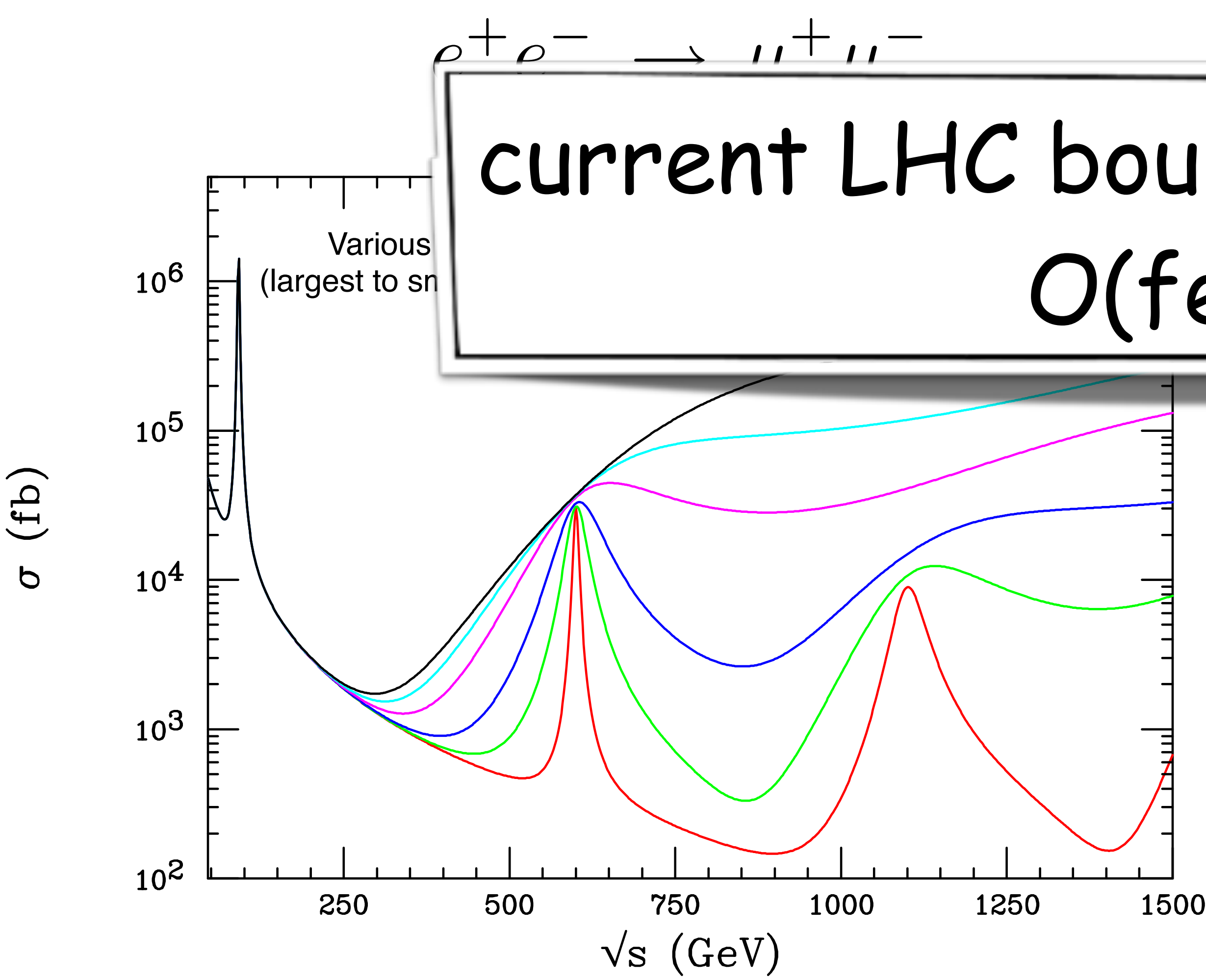


Agashe et al '07

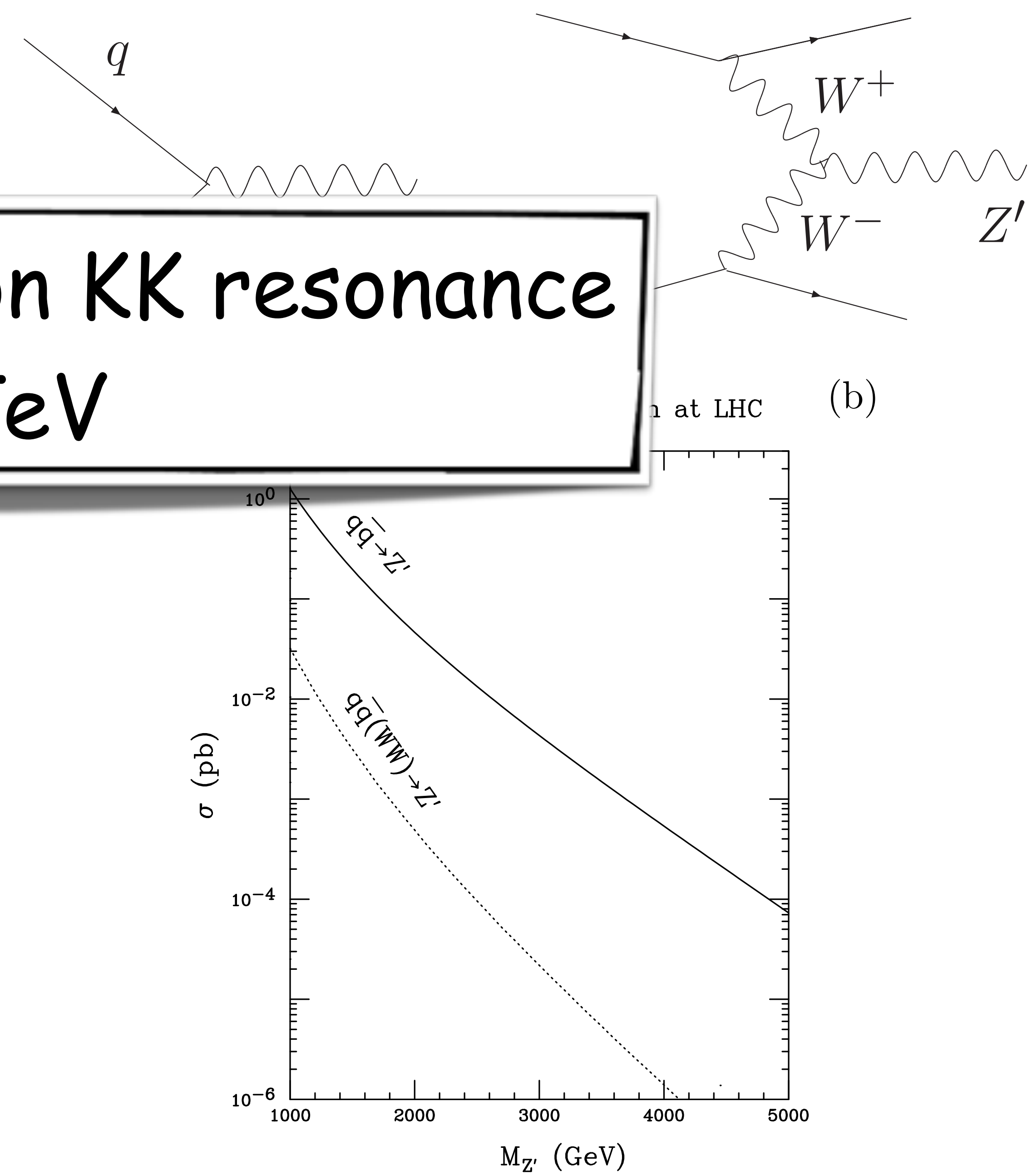
Curved xdim phenomenology

TeV splitting between gauge KK modes

O(g_{SM}) couplings of gauge KK modes to SM



Davoudiasl et al '99



Agashe et al '07

current LHC bounds on KK resonance O(few) TeV

Cosmological relaxation

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

Espinosa et al '15

- $m_H(t)$: $m_H^2(t=-\infty) = \Lambda^2_{\text{cutoff}} \to m_H^2(\text{now}) = -(125\,\text{GeV})^2$
- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe and scans a vast range of Higgs mass. But "Why/How/When does it stop evolving?"
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking back-reacts on the relaxion field and stops the time-evolution of the dynamical system

Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

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Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

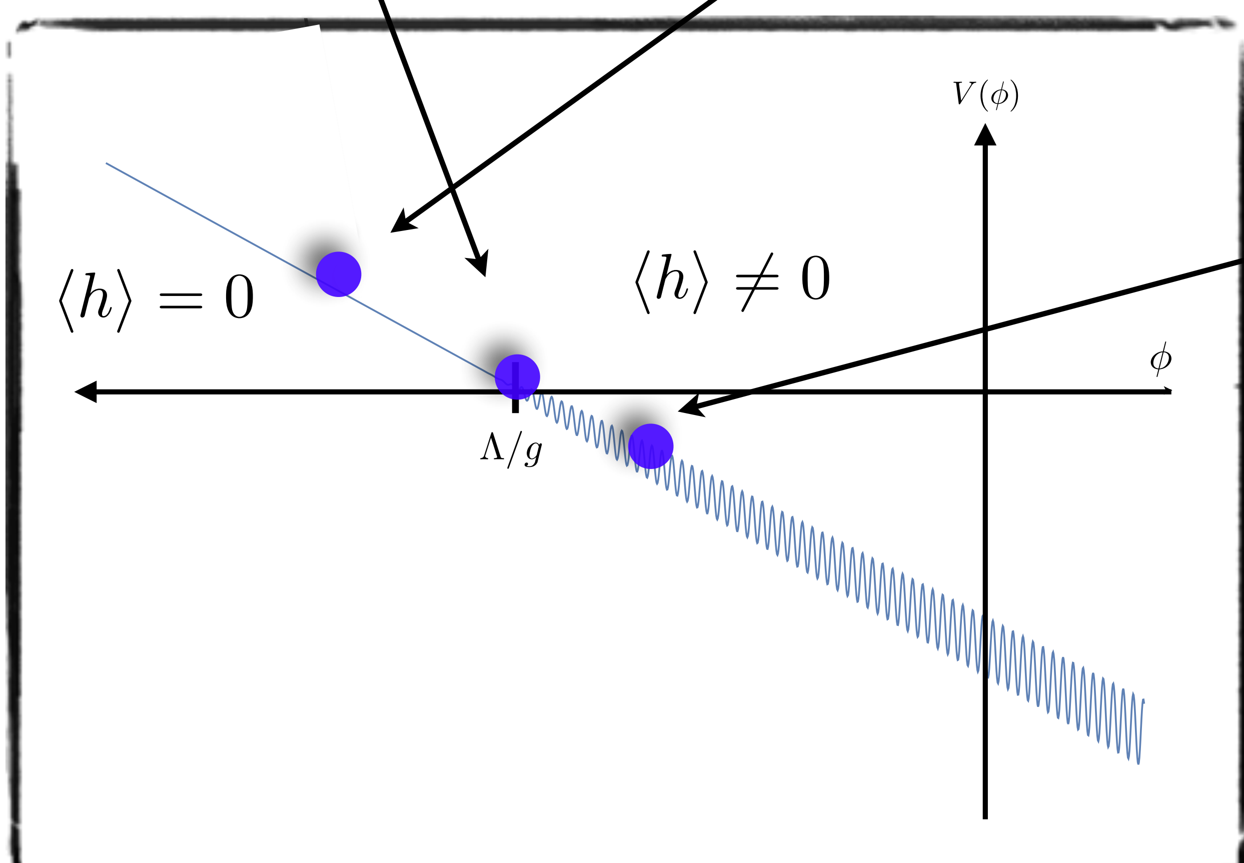
ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev



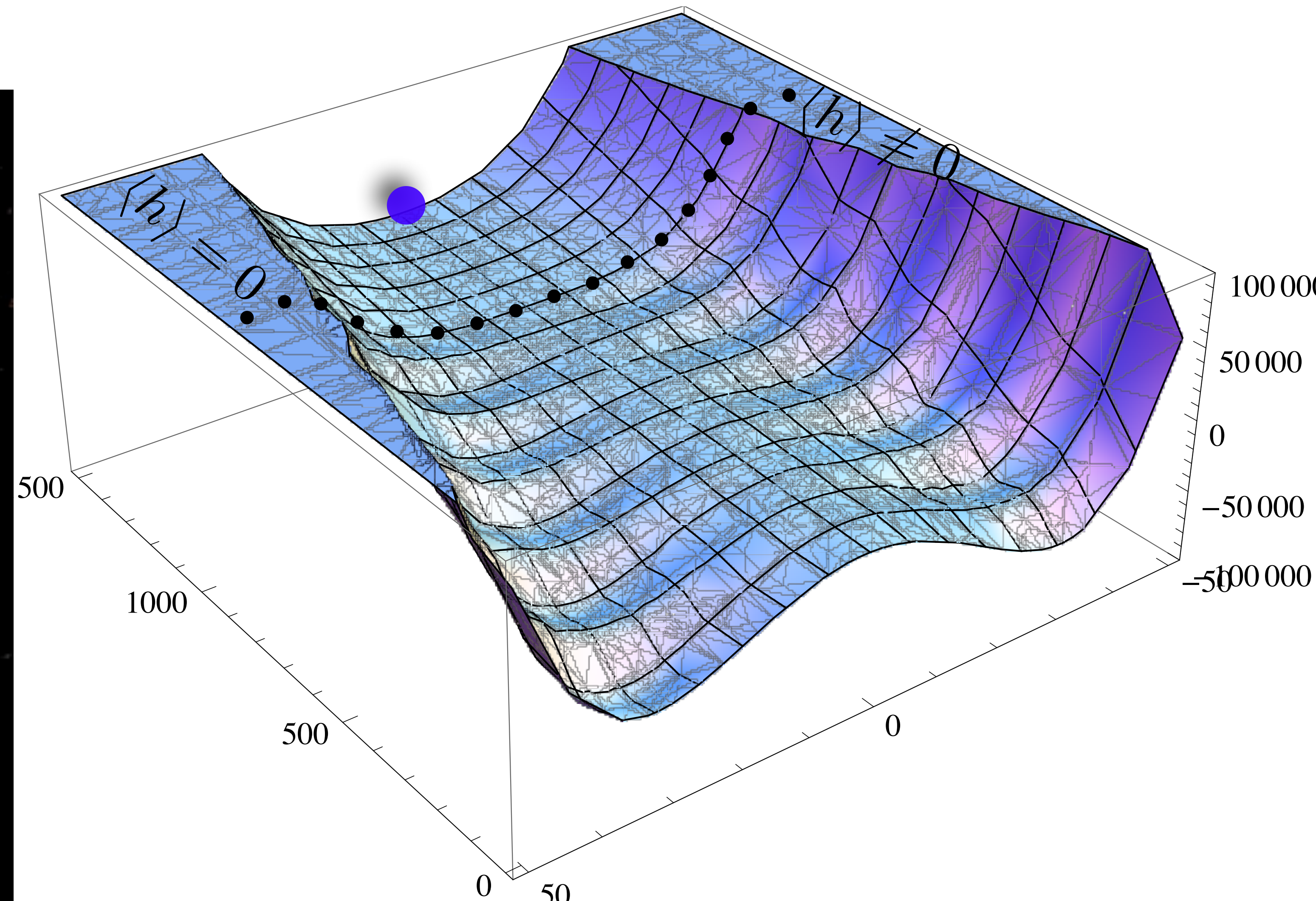
$$\Lambda_{\rm QCD}^3\, h\, \cos\frac{\phi}{f}$$

If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

inflation = friction
to prevent overshooting the EW vacuum

Higgs-axion cosmological relaxation

ham, Kaplan, Rajendran ’15



Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

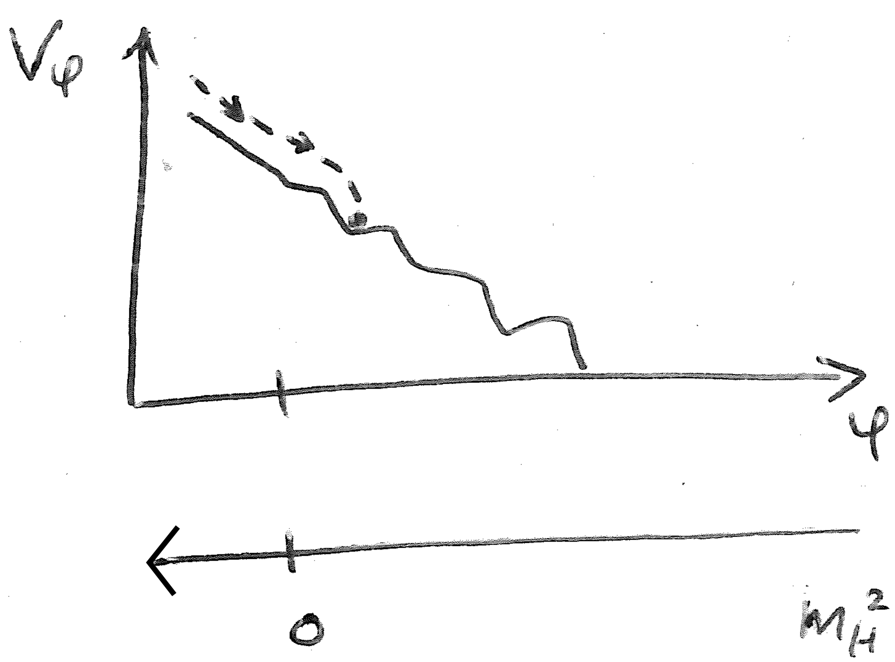
Two classes of relaxion models (so far)

- H-dependent potential barrier

Graham, Kaplan, Rajendran '15

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

potential barriers in the relaxion potential appear soon after EWSB occurs and the relaxion gets trapped in one minimum



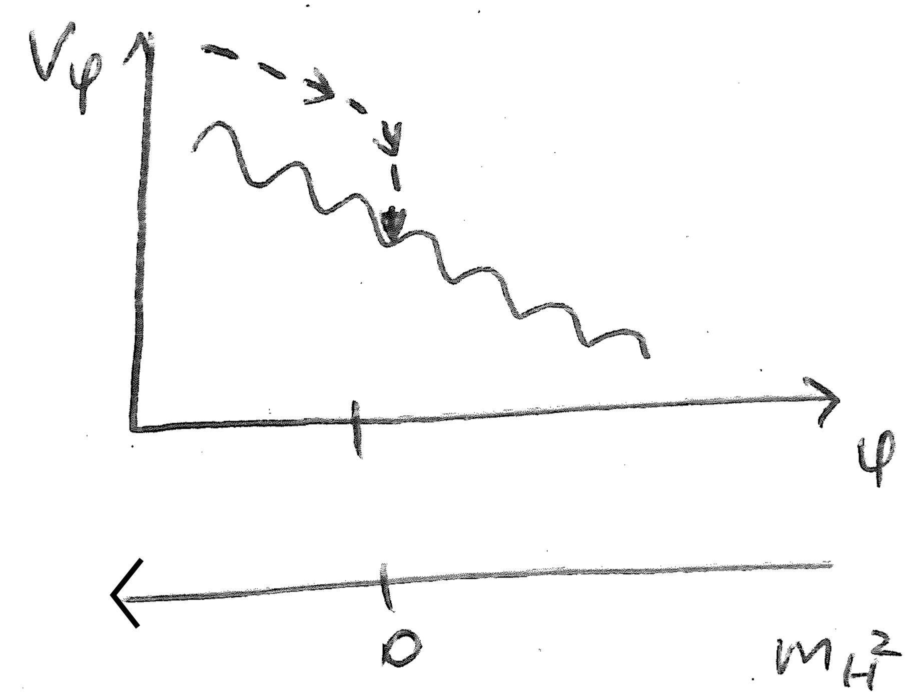
- H-dependent friction

Hook, Marques-Tavares '16

You '17

Fonseca, Morgante, Servant '18

the potential barriers in the relaxion potential always exist but there is no friction to stop the relaxion in one the minimum until the Higgs vev approaches a critical value



drawings borrowed from A. Matsedonskyi, DESY workshop seminar '17

Consistency Conditions

note: v<<Λ provided that g<<1. It doesn't explain why the coupling is small (that question can be postponed to higher energies, requires more model-building engineering, relaxion=PGB?) but it ensures that the solution is stable under quantum correction.

- **Higgs vev stops cosmological rolling**

$$\Lambda^3_{\rm QCD}\frac{v}{f} \sim \frac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$$

- **Slow rolling:** $H_I > \frac{\Lambda^2}{M_P}$

ensures that the energy density stored in ϕ does not affect inflation

- **Classical rolling:** $H_I^3 < g\Lambda^3$

$$\boxed{\frac{\Lambda^6}{M_P^3} < g\Lambda^3 = \Lambda^3_{\rm QCD}\frac{v}{f} \qquad \text{i.e.} \qquad \Lambda < 10^7\,{\rm GeV}\left(\frac{10^9\,{\rm GeV}}{f}\right)^{1/6}}$$

Important issues:

1. $\theta_{QCD} \sim 1 \gg 10^{-10}$. Can be solved but Λ < 30 TeV
2. large field excursion: $\Delta\phi \sim \Lambda/g \sim f\Lambda^3/(v\Lambda^3_{QCD}) \gg 1$, $N_e \sim \frac{f^2\Lambda^8}{v^2\Lambda^6_{QCD}M_P^2} \gg 1$

Quantum stability of relaxing Lagrangians...

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \Lambda_B^4\cos(\phi/f)+\dots$$

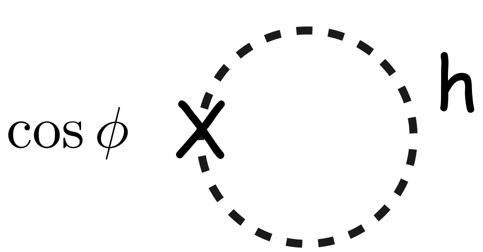
$$\Lambda_B^4 = \Lambda_{B(0)}^4 + \Lambda_{B(1)}^3 h + \Lambda_{B(2)}^2 h^2 + \dots$$

necessary condition for the Higgs vev to stop the relaxion: $\Lambda_B^4 < v^4$

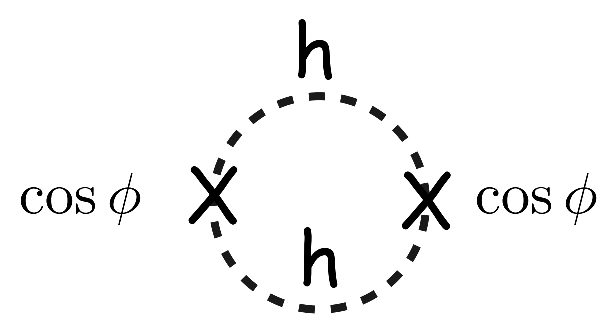
- **n=1:** need another source of EWSB
  - QCD condensate <qq>~ Λ_{QCD}
  - new strongly-coupled sector à la Technicolor

    ⊩ new physics @ TeV, coincidence problem? ⫣

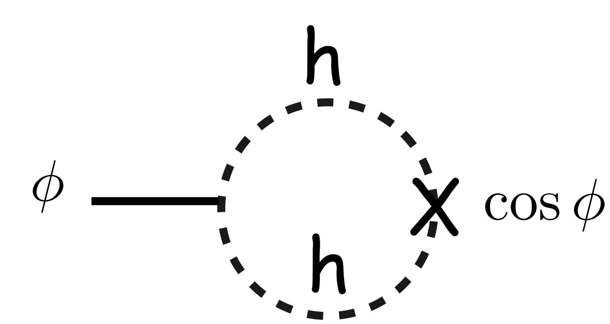
- **n=2:** no extra source of EWSB needed
  - quantum stability? h-loops generate extra interactions that will stop ϕ before the Higgs vev develops unless Λ_B<v (new physics below TeV again)



$\Lambda_{B(2)}^2\Lambda^2\cos(\phi/f)$



$\Lambda_{B(2)}^4\cos^2(\phi/f)$



$g\Lambda\Lambda_{B(2)}^2\phi\cos(\phi/f)$

Cosmological Higgs-Axion Interplay (CHAIN)

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

introduce a second field to scan the potential barrier

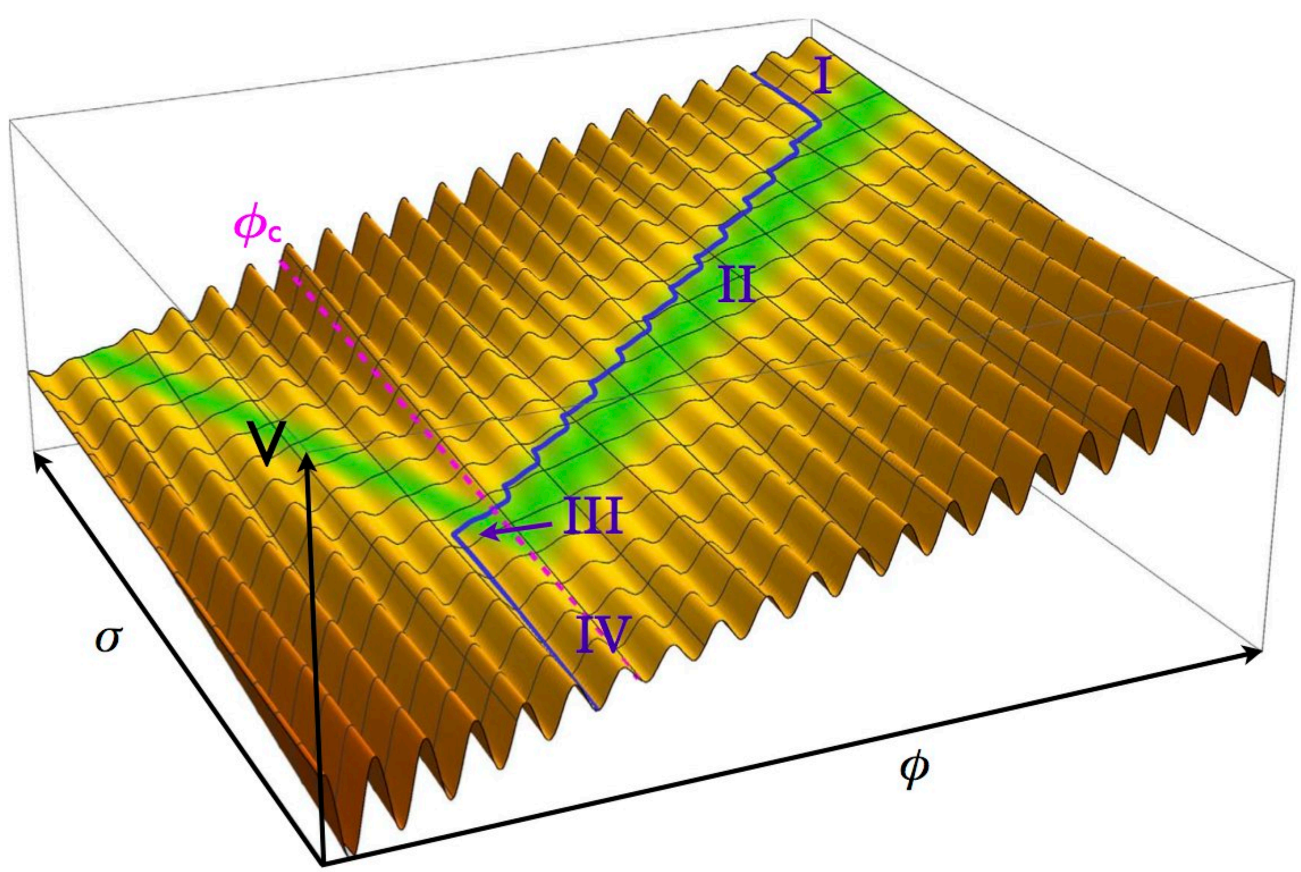
$$V(\phi,\sigma,H)=\Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right)-\Lambda^2\left(\alpha-\frac{g\phi}{\Lambda}\right)|H|^2+\frac{1}{2}\lambda|H|^4+A(\phi,\sigma,H)\cos(\phi/f)$$

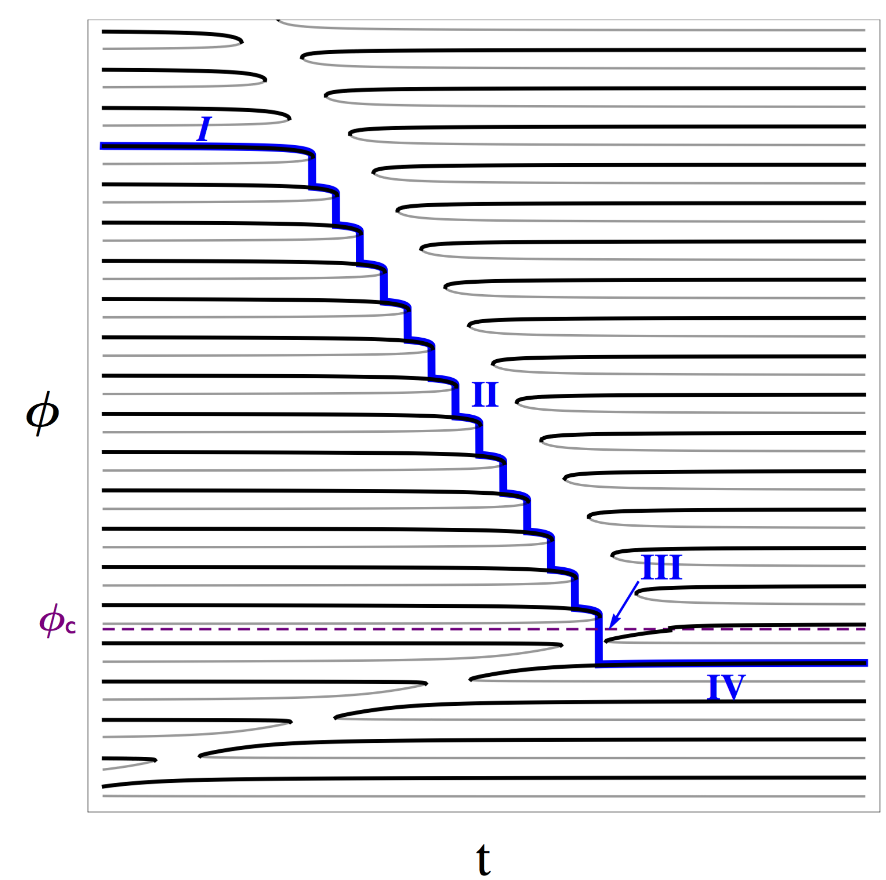
$$\epsilon=\left(\frac{\Lambda_B}{\Lambda}\right)^4 \qquad A(\phi,\sigma,H)\equiv\epsilon\Lambda^4\left(\beta+c_\phi\frac{g\phi}{\Lambda}-c_\sigma\frac{g_\sigma\,\sigma}{\Lambda}+\frac{|H|^2}{\Lambda^2}\right)$$

quantum generated new terms from the $|H|^2\cos(\phi/f)$ term

the new interaction that saves our day

original relaxion-type term



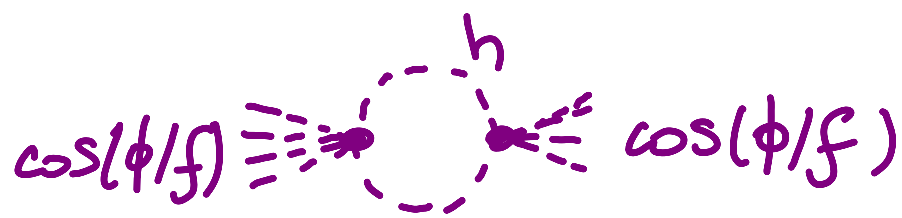


Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

Ex.



$\epsilon^2\Lambda^4\cos^2(\phi/f)$

should be subleading compared to $\epsilon\Lambda^2 h^2\cos(\phi/f)$

Requires $\epsilon \lesssim v^2/\Lambda^2$

courtesy to JR Espinosa

large potential barrier allowed: $\Lambda_B^4 < v^2\Lambda^2$

Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

  ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

- Higgs vev stops cosmological rolling $\frac{\epsilon\Lambda^2 v^2}{f} \sim \frac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$

- Slow rolling: $H_I > \frac{\Lambda^2}{M_P}$ ensures that the energy density stored in σ and ϕ does not affect inflation

- Classical rolling: $H_I^3 < g_\sigma\Lambda^3$

- ϕ tracks σ in the barrier-free valley before EWSB: $c_\phi g^2 > c_\sigma g_\sigma^2$

- ϕ exits the barrier-free valley after EWSB: $(c_\phi - \frac{1}{2\lambda})g^2 < c_\sigma g_\sigma^2$

- large field excursions: $\Delta\phi, \Delta\sigma > \Lambda/g$ to ensure that the Higgs mass scans from Λ to the weak scale

$$\boxed{\frac{\Lambda^3}{M_{\rm Pl}^3} \lesssim g_\sigma \lesssim g \lesssim \frac{v^4}{f\Lambda^3}}$$

Consistency conditions

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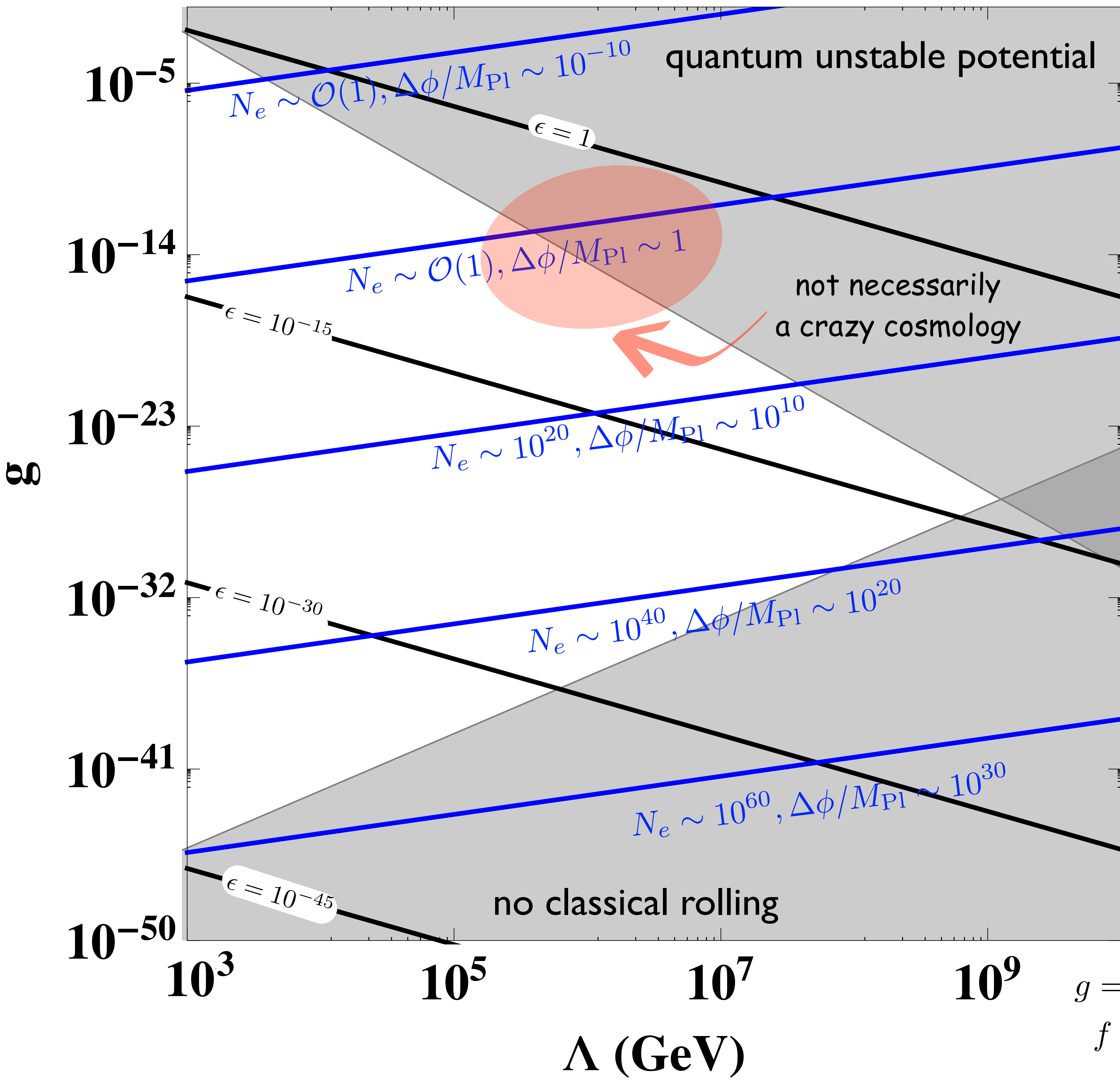
- large field excursions: $\Delta\phi, \Delta\sigma > \Lambda/g$ to ensure that the Higgs mass scans from Λ to the weak scale

$$\boxed{\frac{\Lambda^3}{M_{\rm Pl}^3} \lesssim g_\sigma \lesssim g \lesssim \frac{v^4}{f\Lambda^3}} \Rightarrow \boxed{\Lambda \lesssim \left(v^4 M_{\rm Pl}^3\right)^{1/7} \simeq 2\times 10^9\ \mathrm{GeV}}$$

Consistency conditions



$g = 10 g_\sigma$

$f = \Lambda$

Best solution to little hierarchy pb?

Long epoch of **inflation** to allow the field to explore large range values and reach the critical point without fine-tuning

$$\Delta\sigma \sim N_e \left(\frac{g_\sigma \Lambda^3}{H_I^2}\right) > \Lambda/g_\sigma$$

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

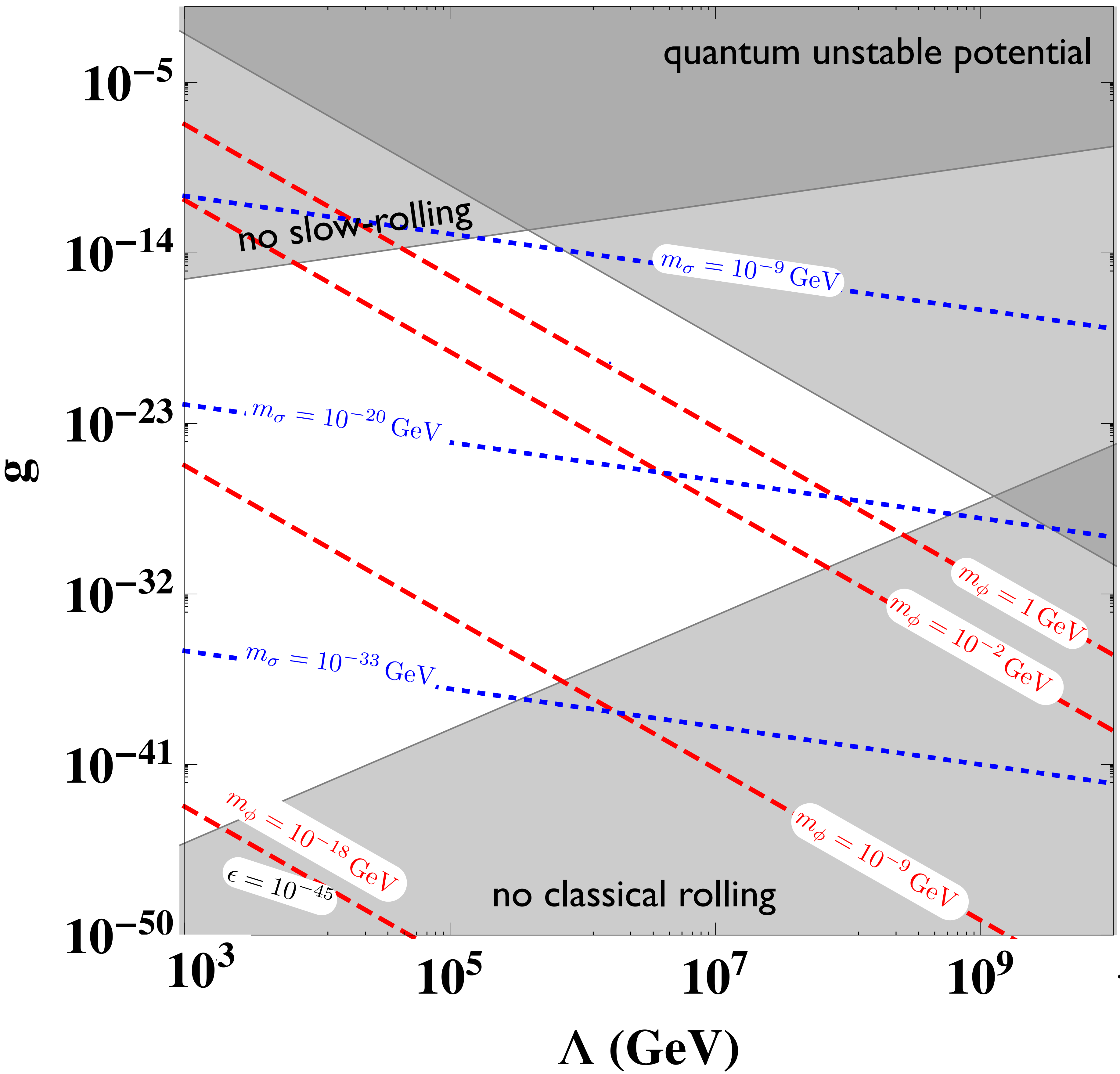
only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim \left(\frac{g\,\Lambda^5}{f\,v^2}\right)^{1/2} \sim (10^{-20} - 10^2)\,\mathrm{GeV}$$

$$m_\sigma \sim g_\sigma \Lambda \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

Phenomenological signatures



$g = 10 g_\sigma$

$f = \Lambda$

Phenomenological signatures

A QFT rationale for light and weakly coupled degrees of freedom

Espinosa et al ’15

Flacke et al ’16

~interesting cosmology signatures~

◎ BBN constraints

◎ decaying DM signs in γ-rays background

◎ ALPs

◎ superradiance

Choi and Im ’16

~interesting signatures @ SHiP~

◎ production of light scalars by B and K decays

~interesting atomic physics~

◎ change of atom sizes

G. Perez et al ‘in progress

Relaxing without multiple vacua: pole attractors

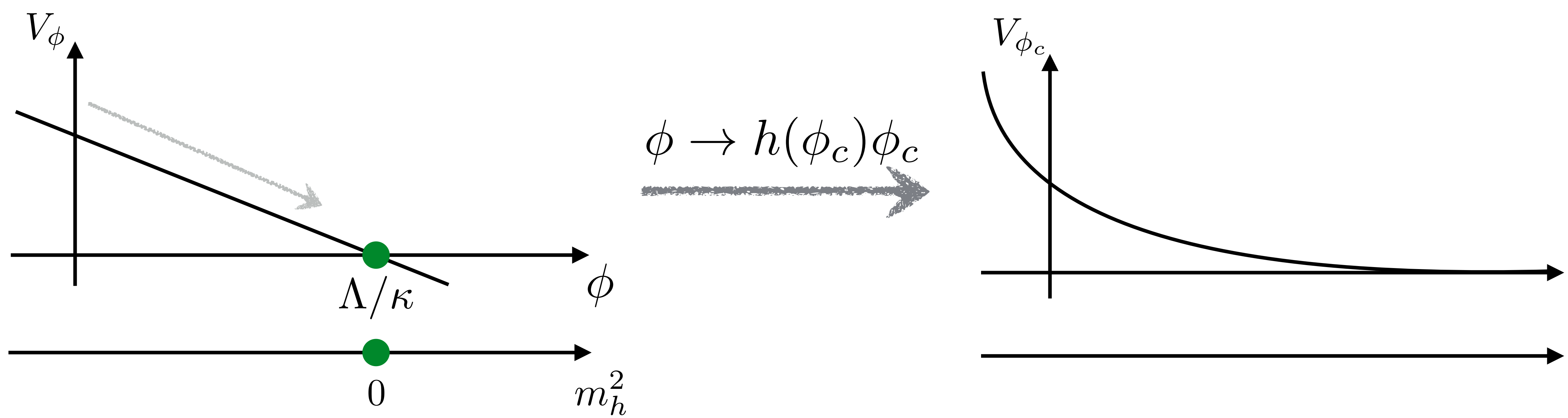
Matsedonskyi, Montull '17

- The Higgs mass is scanned by the relaxion field ϕ

$$V_h \supset (-\Lambda^2 + \kappa\Lambda\phi)\, h^2 \qquad\qquad (V_\phi = -\kappa\Lambda^3\phi)$$

- The relaxion has a non canonical kinetic term $\dfrac{1}{h^{2n}}(\partial_\mu\phi)^2$

- When $\phi \to \Lambda/\kappa$ then $h \to 0$ and the kinetic term grows.



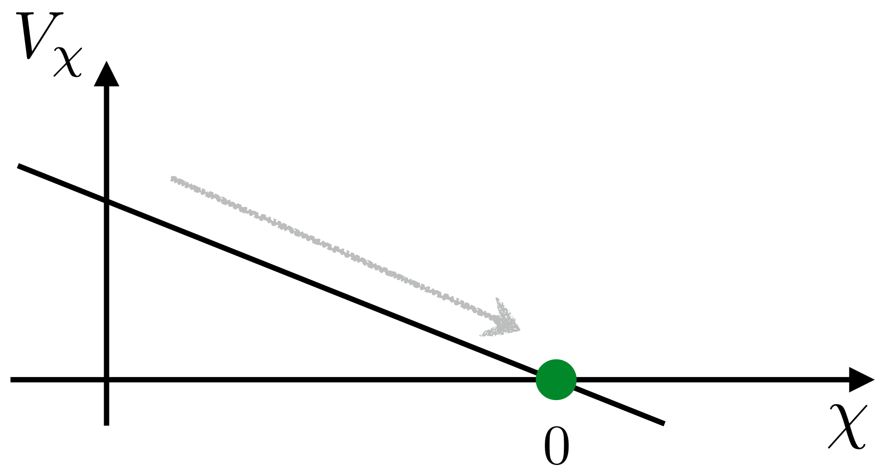
- The slope of the relaxion potential and coupling to the Higgs decrease and the scanning effectively stops.

- derivative Higgs-relaxion couplings becomes non-perturbative

- UV completions unknown

Pole attractors: minimal realistic model

Matsedonskyi, Montull '17

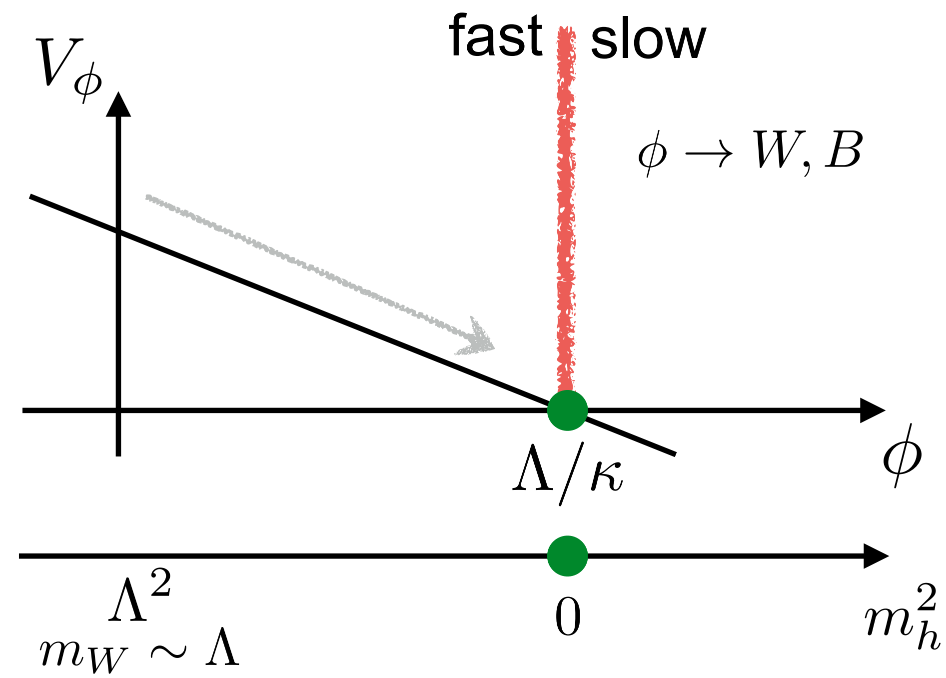


1) kinetic terms controlled by a new field χ

$$\frac{1}{\chi^2}\left\{(\partial\chi)^2+(\partial\phi)^2\right\}$$

motivated by SUSY-based inflation models

2) χ provides a limited time for a scan until it gets to zero and blocks all the evolution



3) ϕ moves quickly before reaching h~0, and after it's slowed down by particle friction provided

$$\dot\phi \gtrsim m_W\, f$$

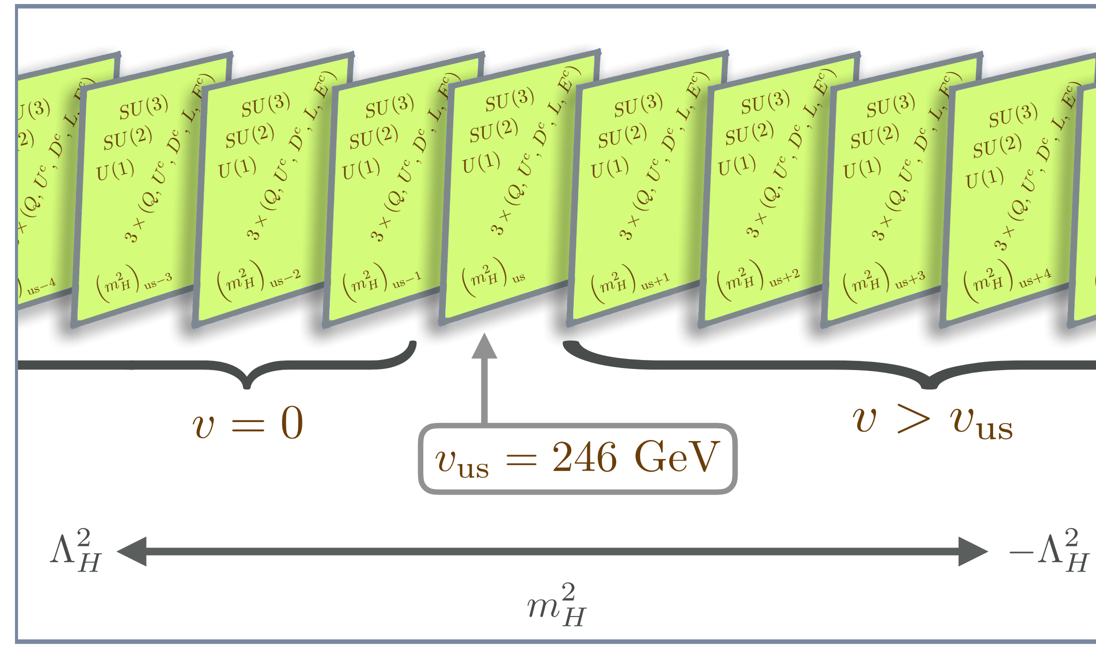
* f controls particle friction

4) remaining part of the limited time relaxion is very slow, almost no scan is possible

NNaturalness

or another way to selection our vacuum

NNaturalness



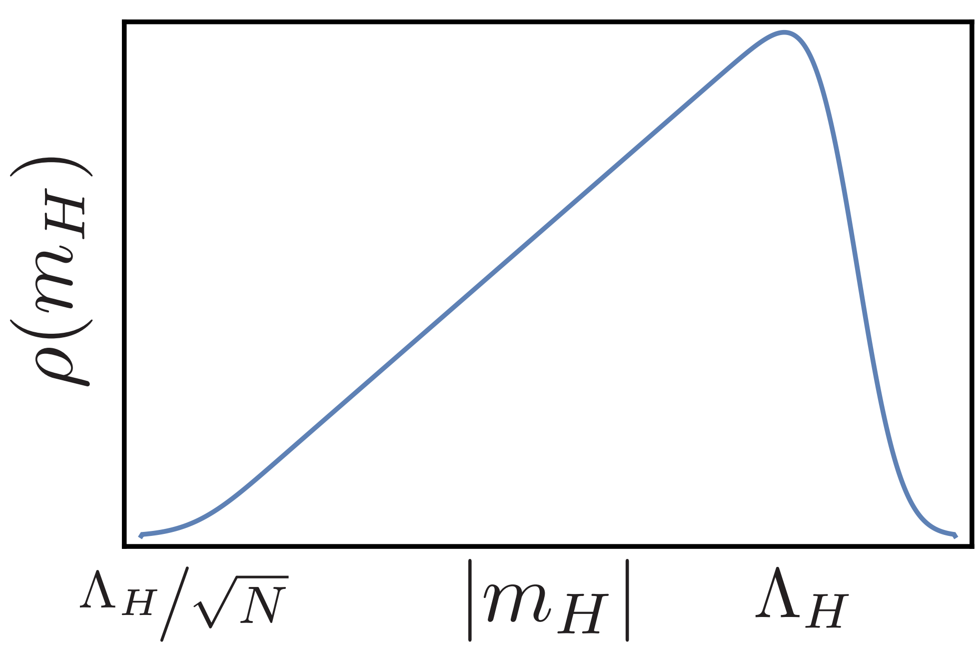
N copies of the SM

High Higgs cutoff Λ_H, high gravity cutoff Λ_G

Two effects:

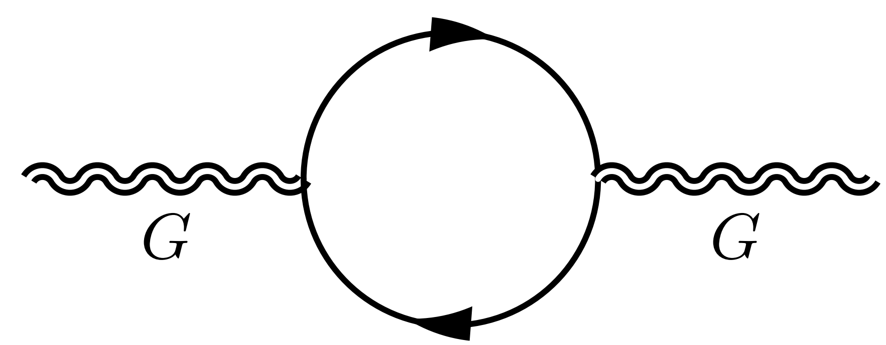
(N. Craig @ Paris'18)

1. Random UV contributions → flat distribution of m_H^2 between $\pm\Lambda_H^2$



At least 1 copy w/ $|m_H| \sim \Lambda_H/\sqrt{N}$

2. Large number of species renormalizes Planck scale (e.g. graviton wavefunction renorm.)



Gravitational strong coupling scale Λ_G below M_{Pl}

$$M_{Pl}^2 \sim N\Lambda_G^2$$

NNaturalness

(N. Craig @ Paris'18)

Scale separation from large N:

M_{Pl}

$\sqrt{N}$

Λ_G

Λ_H

$\sqrt{N}$

$|m_H|_0$

For example:
One copy w/ weak-scale Higgs for

N=10^16:
$\Lambda_H = 10^{10}$ GeV
$\Lambda_G = 10^{10}$ GeV
(That's it.)

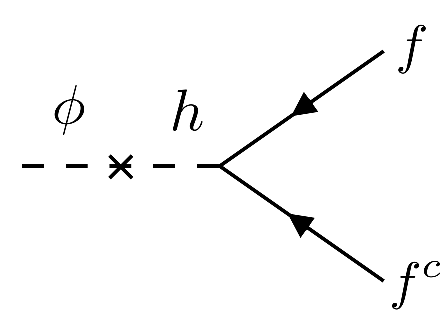
N=10^4:
$\Lambda_H = 10^4$ GeV
$\Lambda_G = 10^{16}$ GeV
(SUSY or compositeness at Λ_H)

Now…why does the copy with the smallest m_H dominate?
Cosmology.

Reheaton ϕ starts universe via $\phi\, |H_i|^2$ couplings

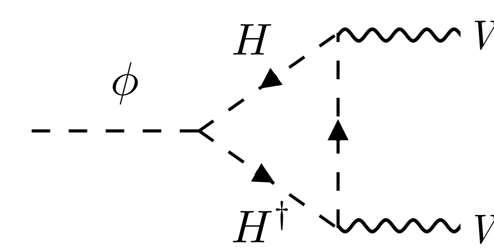
Decays (provided $m_\phi < |m_{H_i}|$)

$$m^2_{H,i} < 0$$



$$\Gamma \propto \frac{1}{m^2_{H,i}}$$

$$m^2_{H,i} \geq 0$$



$$\Gamma \propto \frac{1}{m^4_{H,i}}$$

Preferentially reheats copy w/ smallest $|m_H|$ & $m_H^2 < 0$