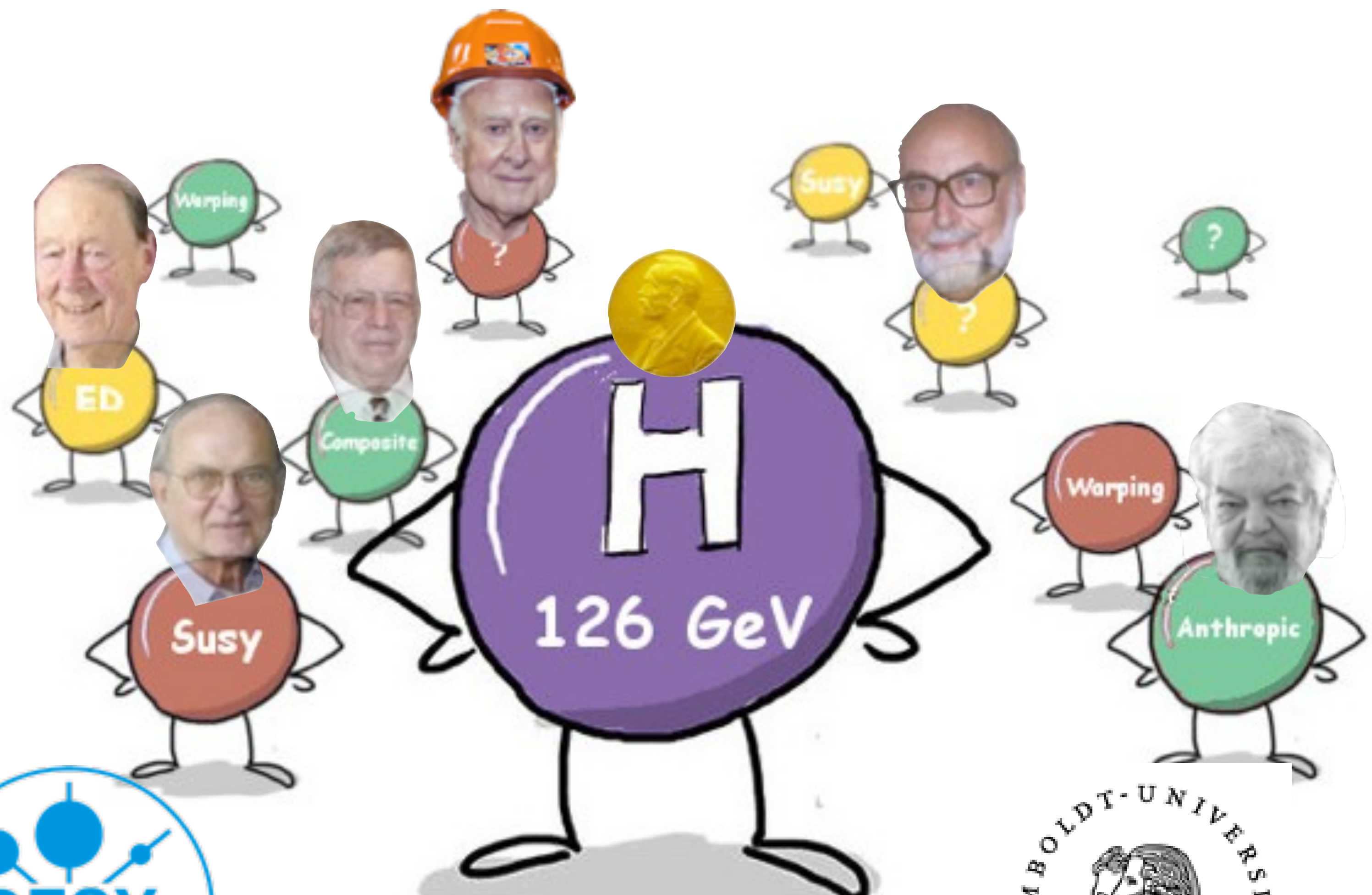
Beyond the Standard Model

CERN summer student lectures 2017



Lecture 3/4

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Outline

- Monday
  - General introduction
  - Higgs physics as a door to BSM
- Tuesday
  - Naturalness
  - Supersymmetry
- Wednesday
  - Grand unification, proton decay
  - Composite Higgs
  - Probing light new force with atomic physics
- Thursday
  - Extra dimensions
  - Cosmological relaxation
  - Quantum gravity

Grand Unified Theory

Evolution of coupling constants

Classical physics: the forces depend on distances

Quantum physics : the charges depend on distances

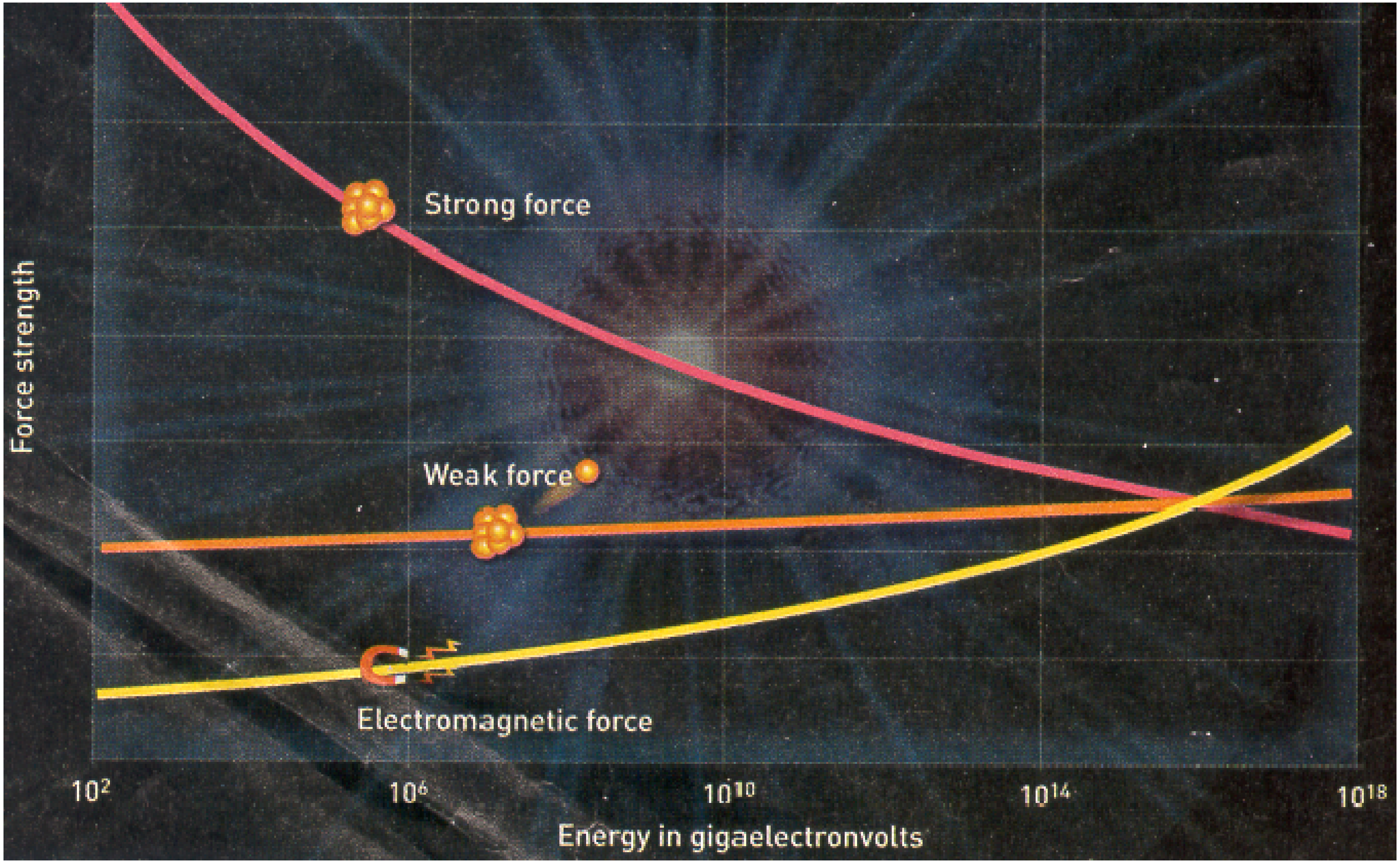
QED: virtual particles screen
the electric charge: $\alpha \searrow$ when d $\nearrow$

QCD: virtual particles (quarks and
gluons) screen the strong charge:
$\alpha_s \nearrow$ when d $\nearrow$

'asymptotic freedom'

$$\frac{\partial \alpha_s}{\partial \log E} = \beta(\alpha_s) = \frac{\alpha_s^2}{\pi}\left(-\frac{11N_c}{6} + \frac{N_f}{3}\right)$$

Grand Unified Theories



A single form of matter

A single fundamental interaction

SU(5) GUT: Gauge Group Structure

SU(3)$_c$xSU(2)$_L$xU(1)$_Y$: SM Matter Content

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}, \quad u_R^c = (\bar{3},1)_{-2/3}, \quad d_R^c = (\bar{3},1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}, \quad e_R^c = (1,1)_1$$

How can you ever remember all these numbers?

SU(3)$_c$xSU(2)$_L$xU(1)$_Y$ ⊂ SU(5)

SU(5)
Adjoint rep.

$$\mathrm{Tr}(T^a T^b) = \frac{1}{2}\delta^{ab}$$

$$\left(\begin{array}{c|c} SU(2) & \\ \hline & SU(3) \end{array}\right)$$

additional U(1) factor that commutes with SU(3)xSU(2)

$$T^{12} = \sqrt{\frac{3}{5}} \left(\begin{array}{cc|ccc} 1/2 & & & & \\ & 1/2 & & & \\ \hline & & -1/3 & & \\ & & & -1/3 & \\ & & & & -1/3 \end{array}\right)$$

$$\boxed{\begin{array}{c} \bar{5} = (1,2)_{-\frac{1}{2}\sqrt{\frac{3}{5}}} + (\bar{3},1)_{\frac{1}{3}\sqrt{\frac{3}{5}}} \\ \bar{5} = L + d_R^c \end{array}}$$

$$\boxed{\begin{array}{c} 10 = (5\times 5)_A = (\bar{3},1)_{-\frac{2}{3}\sqrt{\frac{3}{5}}} + (3,2)_{\frac{1}{6}\sqrt{\frac{3}{5}}} + (1,1)_{\sqrt{\frac{3}{5}}} \\ 10 = u_R^c + Q_L + e_R^c \end{array}}$$

$$T^{12} = \sqrt{\frac{3}{5}} Y \qquad g_5 \sqrt{\frac{3}{5}} = g' \qquad g_5 = g = g_s$$

$$g_5 T^{12} = g' Y$$

$\sin^2\theta_W = \dfrac{3}{8}$ @ M$_{GUT}$

SU(5) GUT: Gauge Group Structure

SU(3)$_c$xSU(2)$_L$xU(1)$_Y$: SM Matter Content

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How can you even ...

the SM matter fits nicely into representations of SU(5), even more nicely into SO(10) unification baryon-lepton

Ac...

Tr(...

$$\begin{pmatrix} & \\ & \begin{matrix} -1/3 & & \\ & -1/3 & \\ & & -1/3 \end{matrix} \end{pmatrix}$$

$$\ldots = (1,2)_{-\frac{1}{2}\sqrt{\frac{3}{5}}} + (\bar{3},1)_{\frac{1}{3}\sqrt{\frac{3}{5}}}$$

$$\bar{5} = L + d_R^c$$

$$T^{12} = \sqrt{\frac{3}{5}} Y \qquad g_5 \sqrt{\frac{3}{5}} = g' \qquad g_5 = g = g_s$$

$$10 = (5 \times 5)_A = (\bar{3},1)_{-\frac{2}{3}\sqrt{\frac{3}{5}}} + (3,2)_{\frac{1}{6}\sqrt{\frac{3}{5}}} + (1,1)_{\sqrt{\frac{3}{5}}}$$

$$10 = u_R^c + Q_L + e_R^c$$

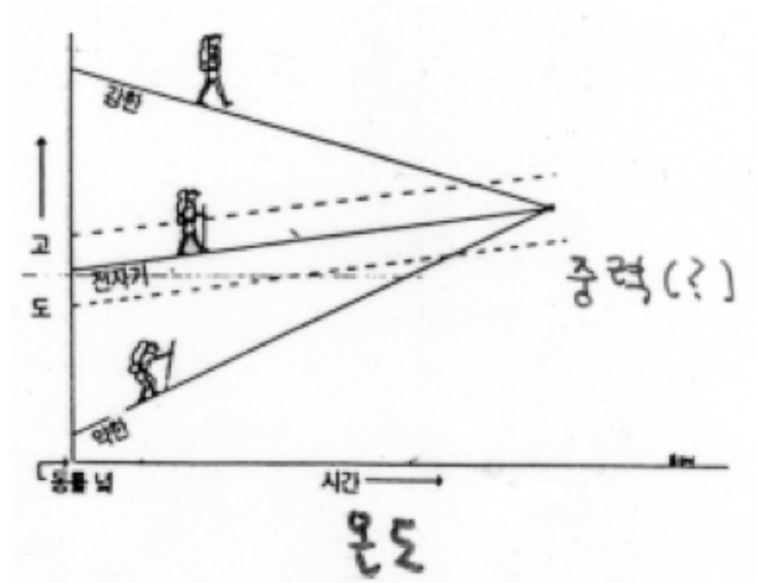
$$g_5 T^{12} = g' Y$$

$\sin^2\theta_W = \frac{3}{8}$ @ M_{GUT}

SU(5) GUT: SM β fcts

g, g′ and g_s are different but it is a low energy artifact!

$$\boxed{\beta = \frac{dg}{d\log\mu} = -\frac{1}{16\pi^2} b g^3 + \ldots}$$



$$\boxed{\frac{1}{g^2(Q)} = \frac{1}{g^2(Q_0)} + \frac{b}{16\pi^2}\ln\frac{Q^2}{Q_0^2}}$$

$$b = \frac{11}{3}T_2(\texttt{spin-1}) - \frac{2}{3}T_2(\texttt{chiral spin-1/2}) - \frac{1}{3}T_2(\texttt{complex spin-0})$$

$$\mathrm{Tr}\left(T^a(R)T^b(R)\right) = T_2(R)\delta^{ab} \qquad T_2(\texttt{fund}) = \frac{1}{2} \qquad T_2(\texttt{adj}) = N$$

$$b_{SU(3)} = \overset{g}{\frac{11}{3}\times 3} - \frac{2}{3}\left(\overset{Q_L}{\frac{1}{2}\times 2\times 3} + \overset{u_R^c}{\frac{1}{2}\times 1\times 3} + \overset{d_R^c}{\frac{1}{2}\times 1\times 3}\right) = 7$$

$$b_{SU(2)} = \overset{W^\pm, Z}{\frac{11}{3}\times 2} - \frac{2}{3}\left(\overset{Q_L}{\frac{1}{2}\times 3\times 3} + \overset{L}{\frac{1}{2}\times 1\times 3}\right) - \overset{H}{\frac{1}{3}\times\frac{1}{2}} = \frac{19}{6}$$

$$b_Y = -\frac{2}{3}\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3\times 2\times 3} + \overset{u_R^c}{\left(-\frac{2}{3}\right)^2 3\times 3} + \overset{d_R^c}{\left(\frac{1}{3}\right)^2 3\times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2\times 3} + \overset{e_R^c}{(1)^2\times 3}\right) - \overset{H}{\frac{1}{3}\left(\frac{1}{2}\right)^2\times 2} = -\frac{41}{6}$$

$$\Rightarrow \quad b_{T^{12}} = -\frac{41}{10}$$

exercise

SU(5) GUT: low energy consistency condition

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \qquad i = SU(3), SU(2), U(1)$$

$\alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z)$ ⟵ experimental inputs

b_3, b_2, b_1 ⟵ predicted by the matter content

3 equations & 2 unknowns (α_{GUT}, M_{GUT})

one consistency relation for unification

$$\epsilon_{ijk} \frac{b_j - b_k}{\alpha_i(M_Z)} = 0 \quad \Rightarrow \quad \boxed{\sin^2\theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1} \frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)}}$$

$$\alpha_{em}(M_Z) \approx \frac{1}{128} \qquad \alpha_s(M_Z) \approx 0.1184 \pm 0.0007$$

$$\Downarrow$$

$$\sin^2\theta_W \approx 0.207$$

not so bad...

SU(5) GUT: low energy consistency condition

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \qquad i = SU(3), SU(2), U(1)$$

$\alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z)$ ⟵ experimental inputs

b_3, b_2, b_1 ⟵ predicted by the matter content

3 equations & 2 unknowns (α_{GUT}, M_{GUT})

one consistency relation for unification

$$M_{GUT} = M_Z \exp\left(2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right) \approx 7 \times 10^{14}\ \text{GeV}$$

$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 41.5$$

self-consistent computation:
- $M_{GUT} < M_{Pl}$ safe to neglect quantum gravity effects
- $\alpha_{GUT} \ll 1$ perturbative computation

SU(5) GUT: SM vs MSSM β fcts

chiral superfield

complex spin-0
Weyl spin-1/2
in same representation R of gauge group

vector superfield

Weyl spin-1/2
real spin-1
in same representation V of gauge group

$$b = \frac{11}{3}T_2(\texttt{vector}) - \frac{2}{3}T_2(\texttt{vector}) - \frac{2}{3}T_2(\texttt{chiral}) - \frac{1}{3}T_2(\texttt{chiral}) = 3\,T_2(\texttt{vector}) - T_2(\texttt{chiral})$$

MSSM Chiral Content

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}, \quad U = (\bar{3},1)_{-2/3}, \quad D = (\bar{3},1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}, \quad E = (1,1)_1, \quad H_u = (1,2)_{1/2}, \quad H_d = (1,2)_{-1/2}$$

$$b_{SU(3)} = \overset{g}{3\times 3} - \left(\overset{Q_L}{\frac{1}{2}\times 2\times 3} + \overset{U}{\frac{1}{2}\times 1\times 3} + \overset{D}{\frac{1}{2}\times 1\times 3}\right) = 3$$

$$b_{SU(2)} = \overset{W^\pm,Z}{3\times 2} - \left(\overset{Q_L}{\frac{1}{2}\times 3\times 3} + \overset{L}{\frac{1}{2}\times 1\times 3}\right) - \overset{H_u}{\frac{1}{2}} - \overset{H_d}{\frac{1}{2}} = -1$$

$$b_Y = -\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3\times 2\times 3} + \overset{U}{\left(-\frac{2}{3}\right)^2 3\times 3} + \overset{D}{\left(\frac{1}{3}\right)^2 3\times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2\times 3} + \overset{E}{(1)^2\times 3}\right) - \overset{H_u}{\left(\frac{1}{2}\right)^2\times 2} - \overset{H_d}{\left(\frac{1}{2}\right)^2\times 2} = -11 \Rightarrow b_{T^{12}} = -\frac{33}{5}$$

SU(5) GUT: MSSM GUT

$$b_3 = 3, \quad b_2 = -1, \quad b_1 = -33/5$$

low-energy consistency relation for unification

$$\sin^2\theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1}\frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)} \approx 0.23$$

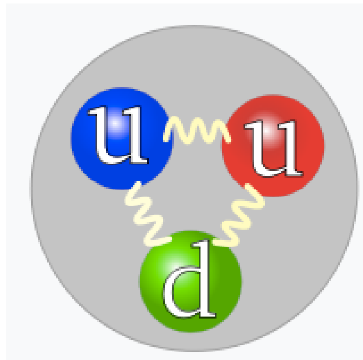
squarks and sleptons form complete SU(5) reps ➙ they don't improve unification!
gauginos and higgsinos are improving the unification of gauge couplings

GUT scale predictions

$$M_{GUT} = M_Z \exp\left(2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right) \approx 2\times 10^{16}\ \mathrm{GeV}$$

$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 24.3$$

Proton Decay

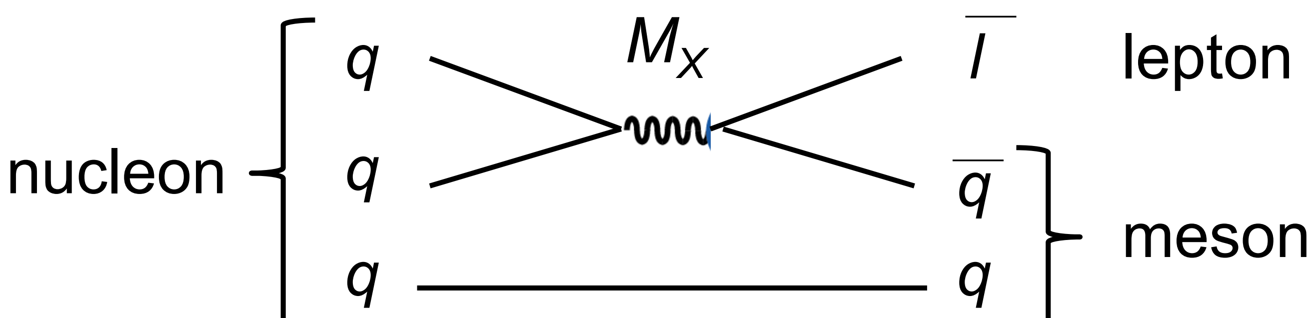


938.2720813(58) MeV

why is the proton stable?

electric charge conservation?

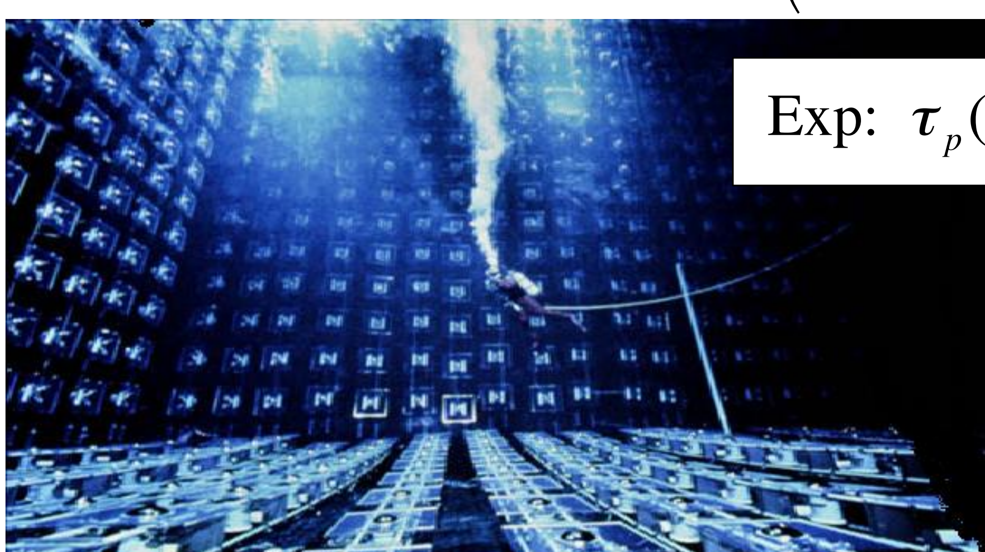
baryon number conservation?



in GUT, "matter" is unstable

decay of proton mediated by new SU(5)/SO(10) gauge bosons

$$\text{GUT:}\quad \tau_p(p \to e^+\pi^0) = \left(\frac{M_X}{10^{15}\ \text{GeV}}\right)^4 10^{31-32}\ \text{yr}$$

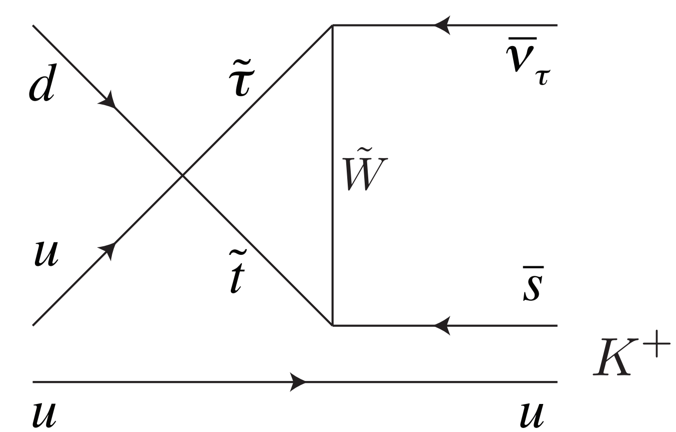


$$\text{Exp:}\quad \tau_p(p \to e^+\pi^0) > 8.2\times 10^{33}\ \text{yr}$$

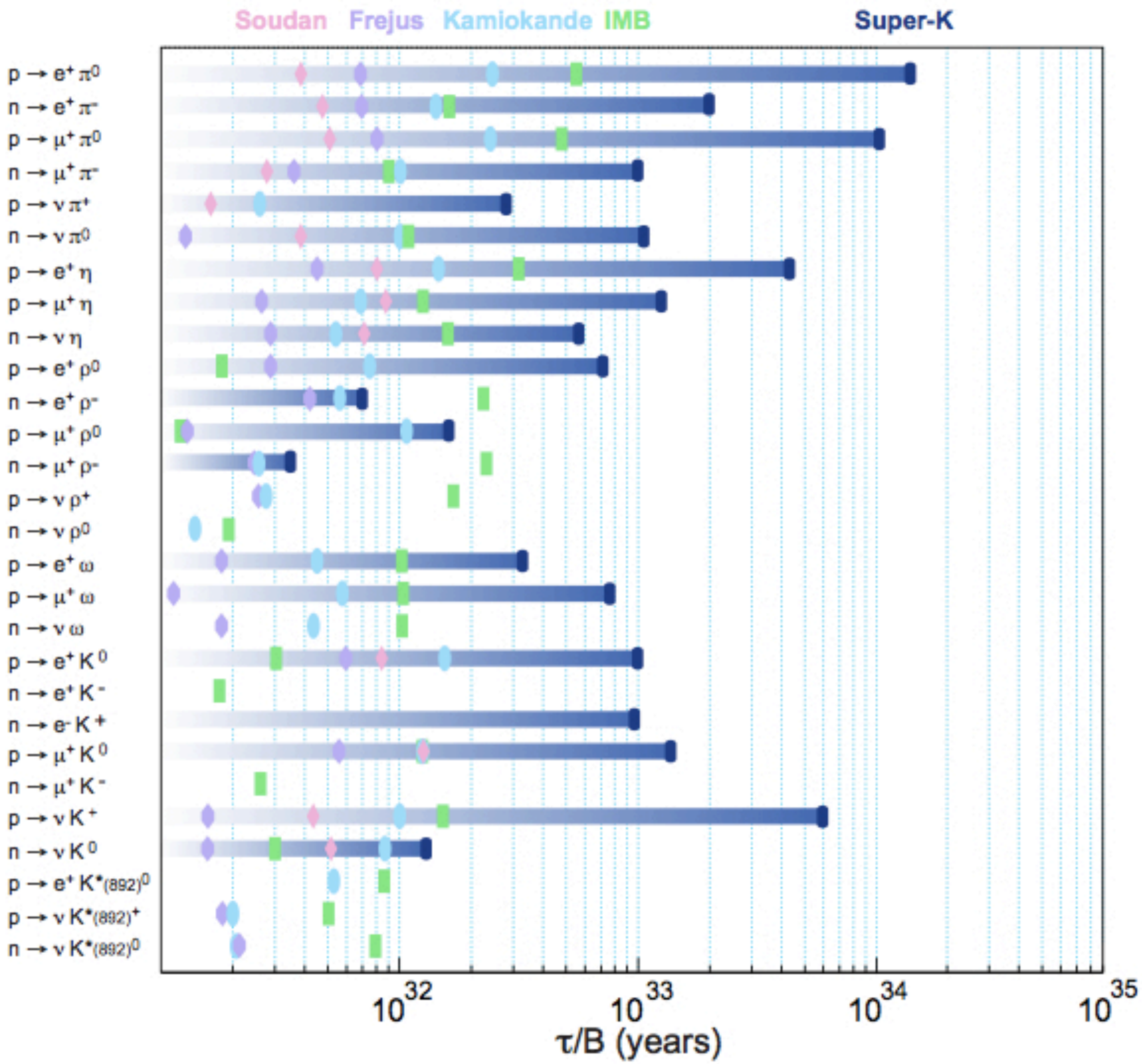
(G. Giudice SSLP'15)

other decay mode:

$$p^+ \to K^+ \overline{\nu}$$



Proton Decay

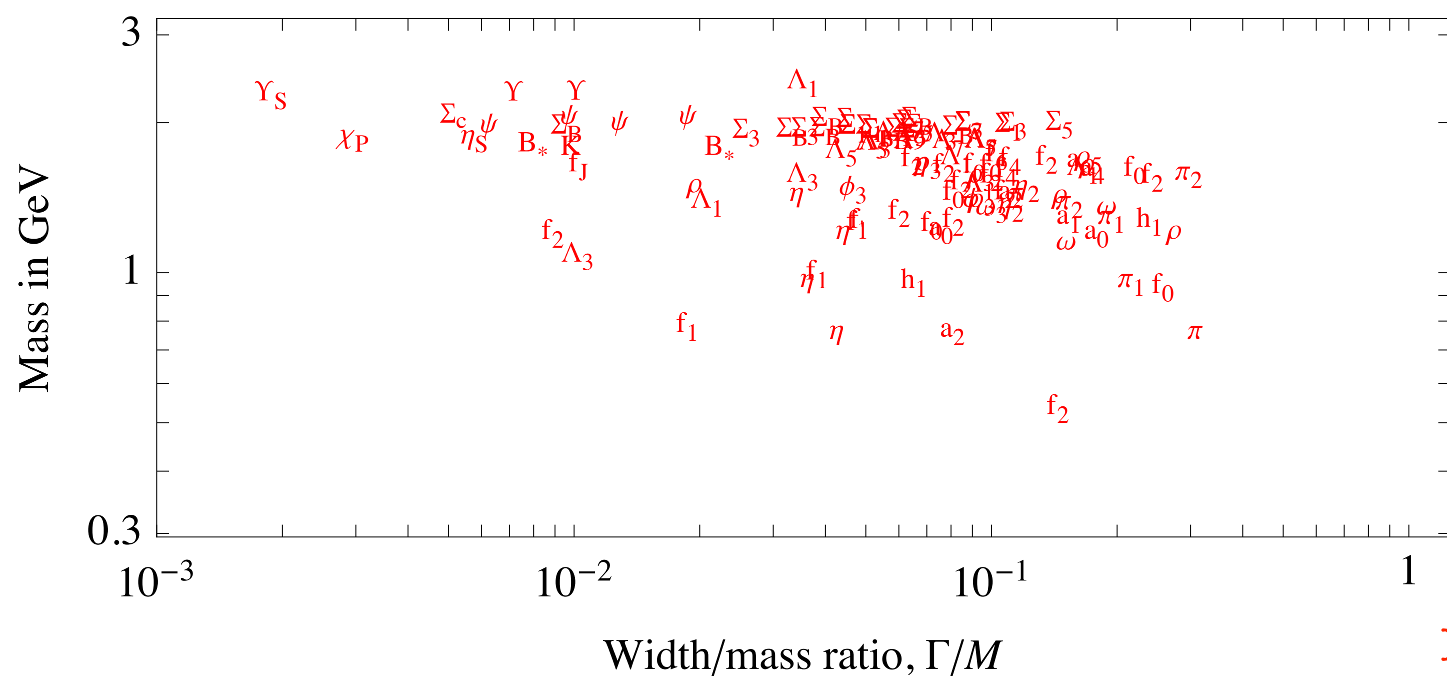


Babu et al '13

Composite Higgs Models

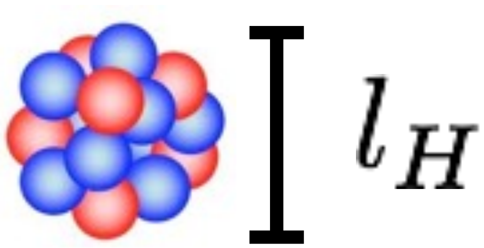
Composite Higgs

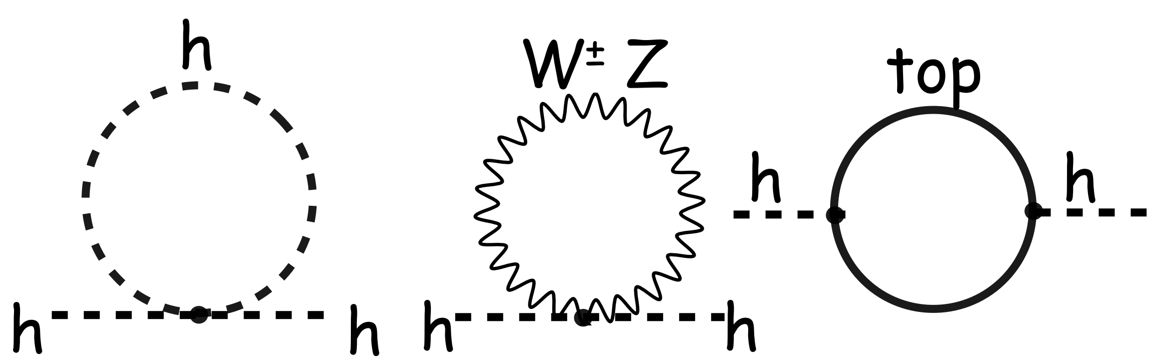
Light scalars exist in Nature but all the ones observed before the Higgs boson discovery were composite bounds states



Franceschini et al. '15

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

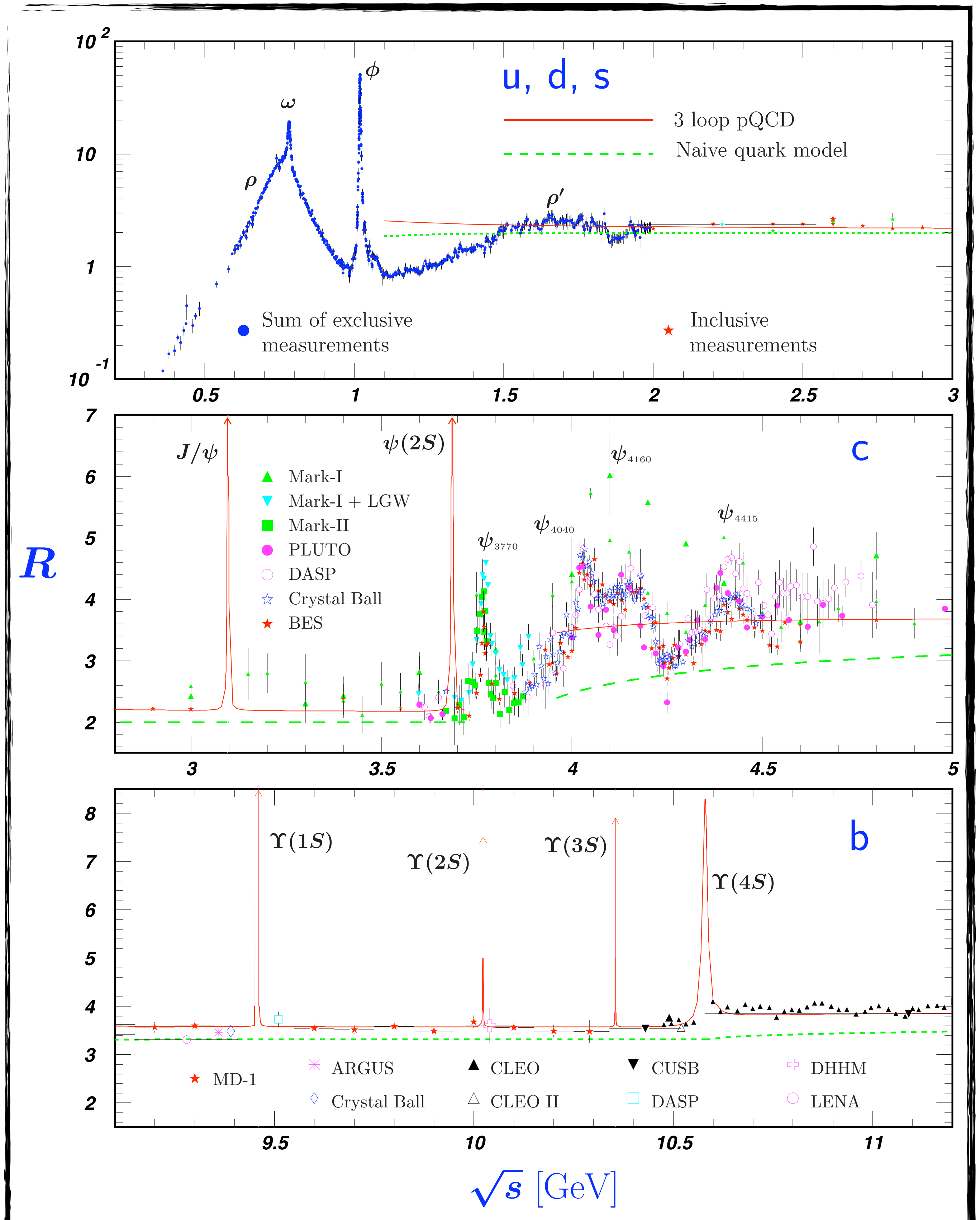




At energy above $1/\ell_H$, the Higgs dissolves, the integrals are smoothed out

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

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

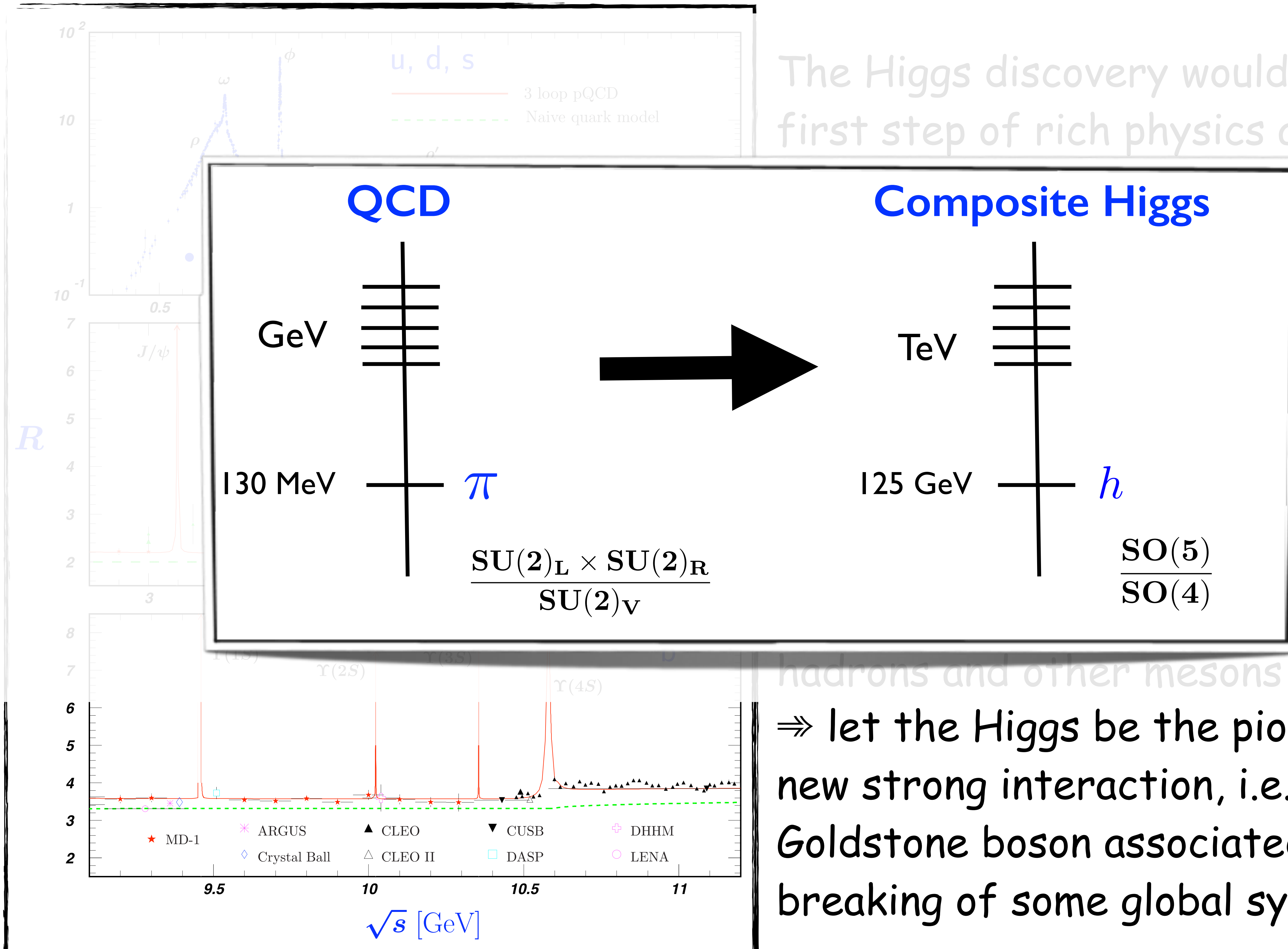
But how come we haven't seen anything of these yet?

⇛ 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:

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...cleons, hadrons and other mesons

$\Rrightarrow$ 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 $SO(4)/SO(3)$ $W^\pm_L$ & Z_L $\Rightarrow$ G/H $W^\pm_L$ & Z_L & h *BSM*

Examples:

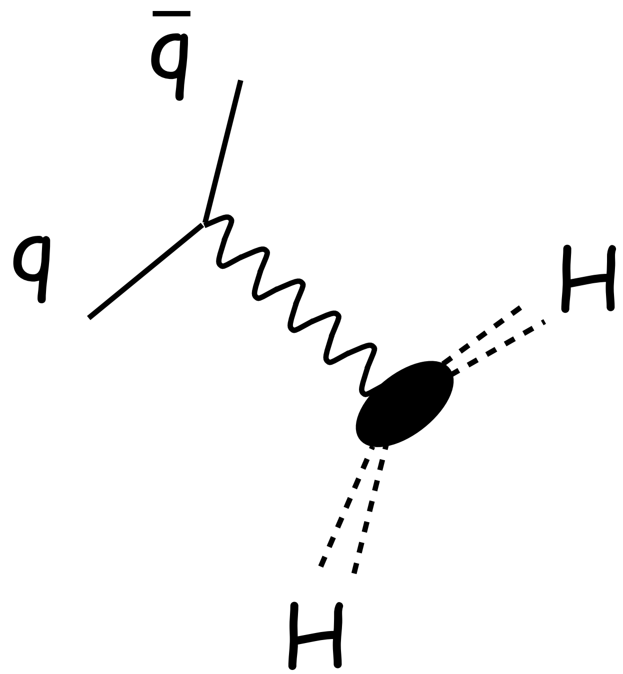
$SO(5)/SO(4)$: 4 PGBs=$W^\pm_L$, Z_L, h ⟷ Minimal Composite Higgs Model
Agashe, Contino, Pomarol '04

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

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

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ⟷ Minimal Composite Two Higgs Doublets
Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

How to probe the compositeness of the Higgs?

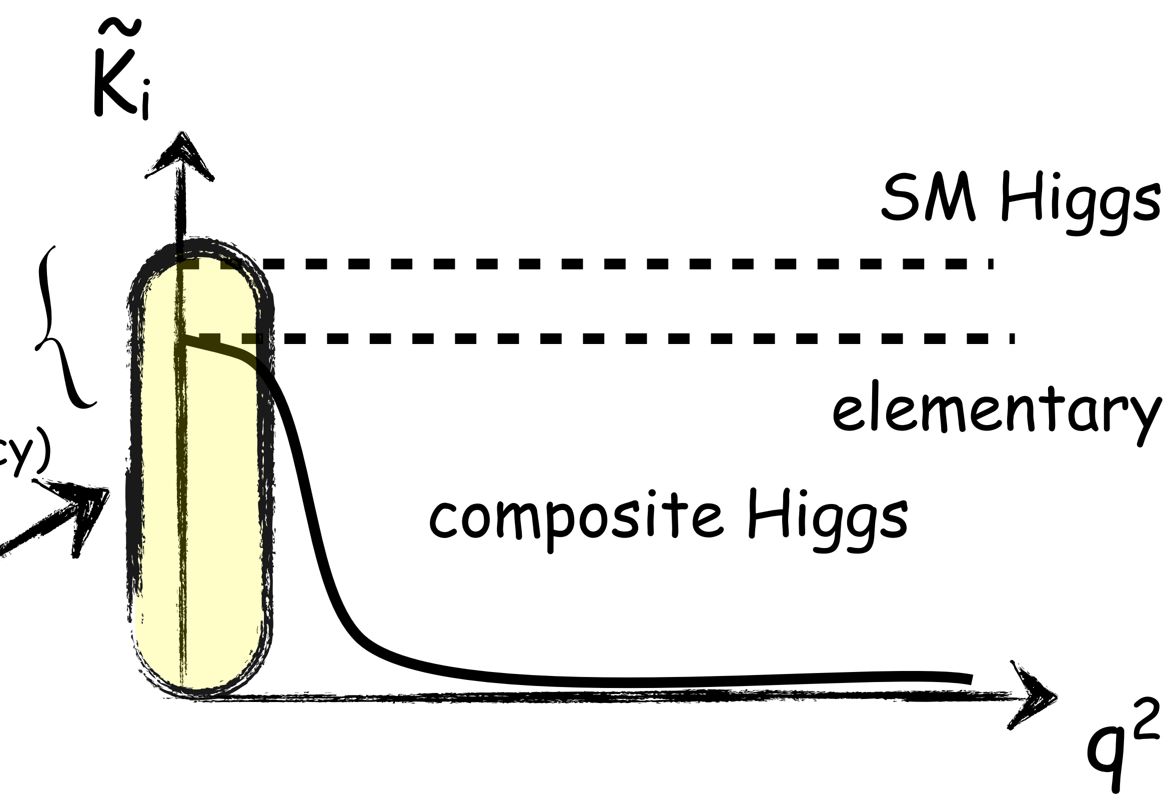


$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4 \theta/2} \frac{E'}{E^3} \left(2\tilde{K}_1 q^2 \sin^2 \theta/2 + \tilde{K}_2 \cos^2 \theta/2\right)$$

Rosenbluth-type cross-section

anomalous couplings
(accessible @ LHC with 20-40% accuracy)

LHC reach ?



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

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

$\Big\}$ 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)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2$$

$$\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2}|H|^6$$

Form factor operators (sensitive to the scale m_ρ)

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

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

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

$$\frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

Higgs anomalous couplings

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

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

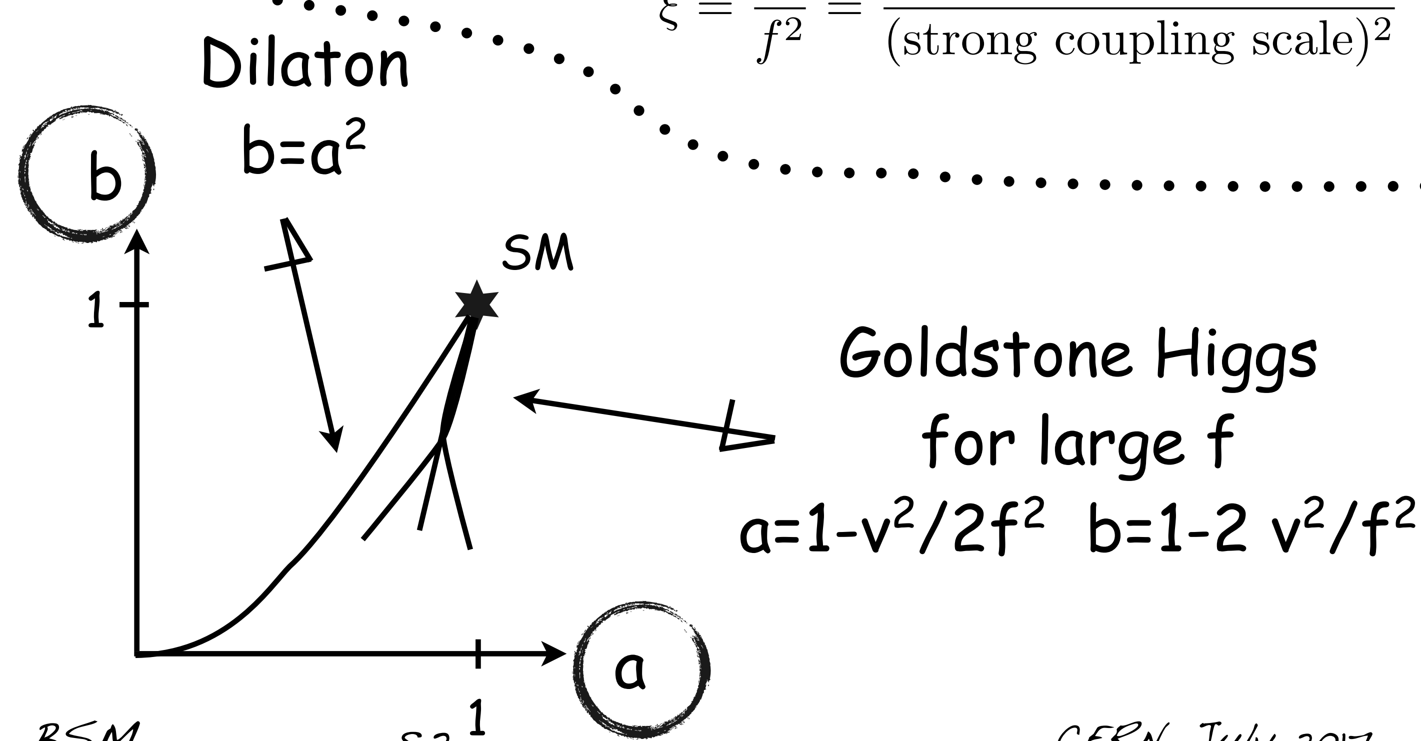
(a single operator at dimension-6 level controls the amplitudes)

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

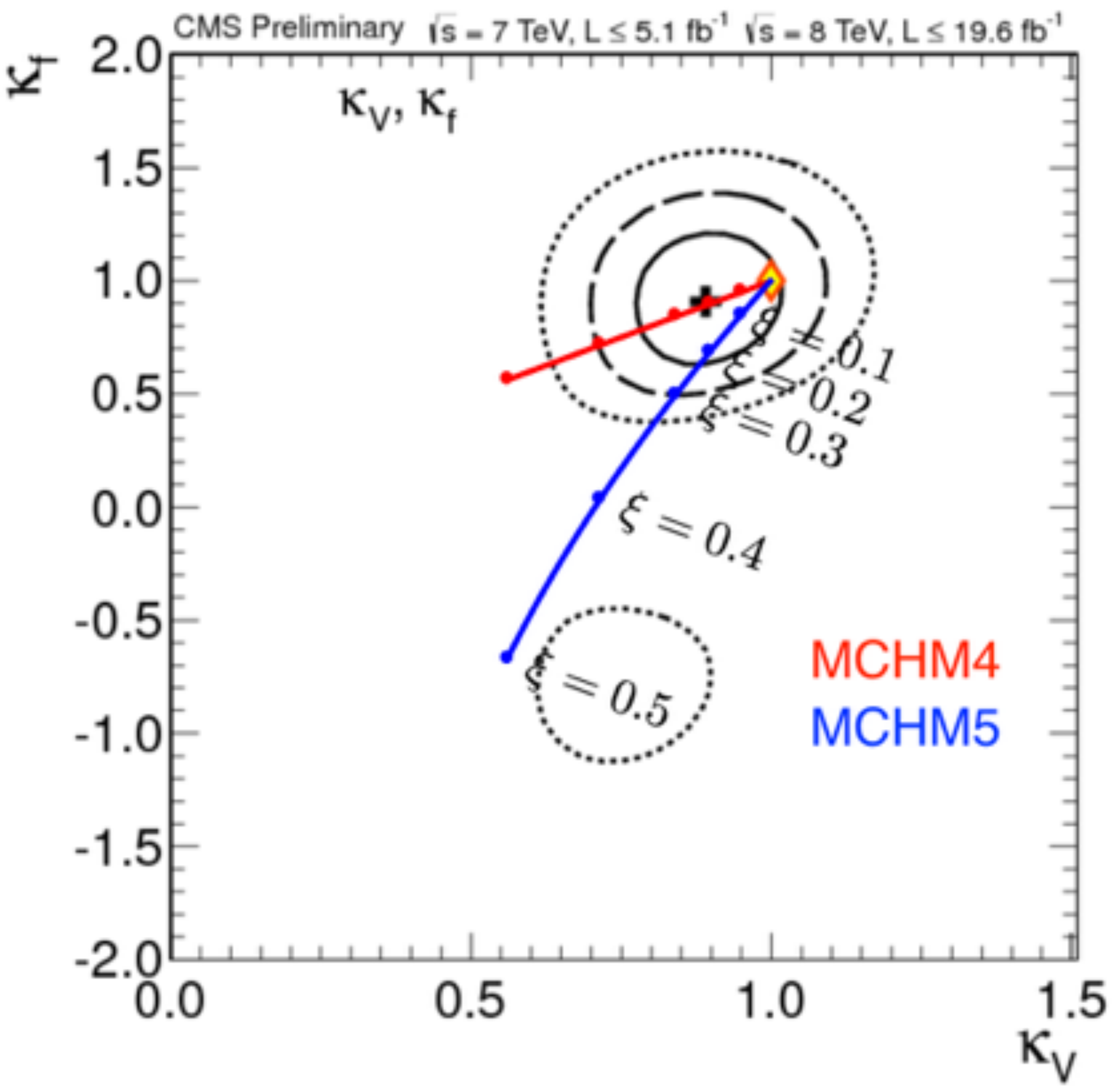
Composite Higgs

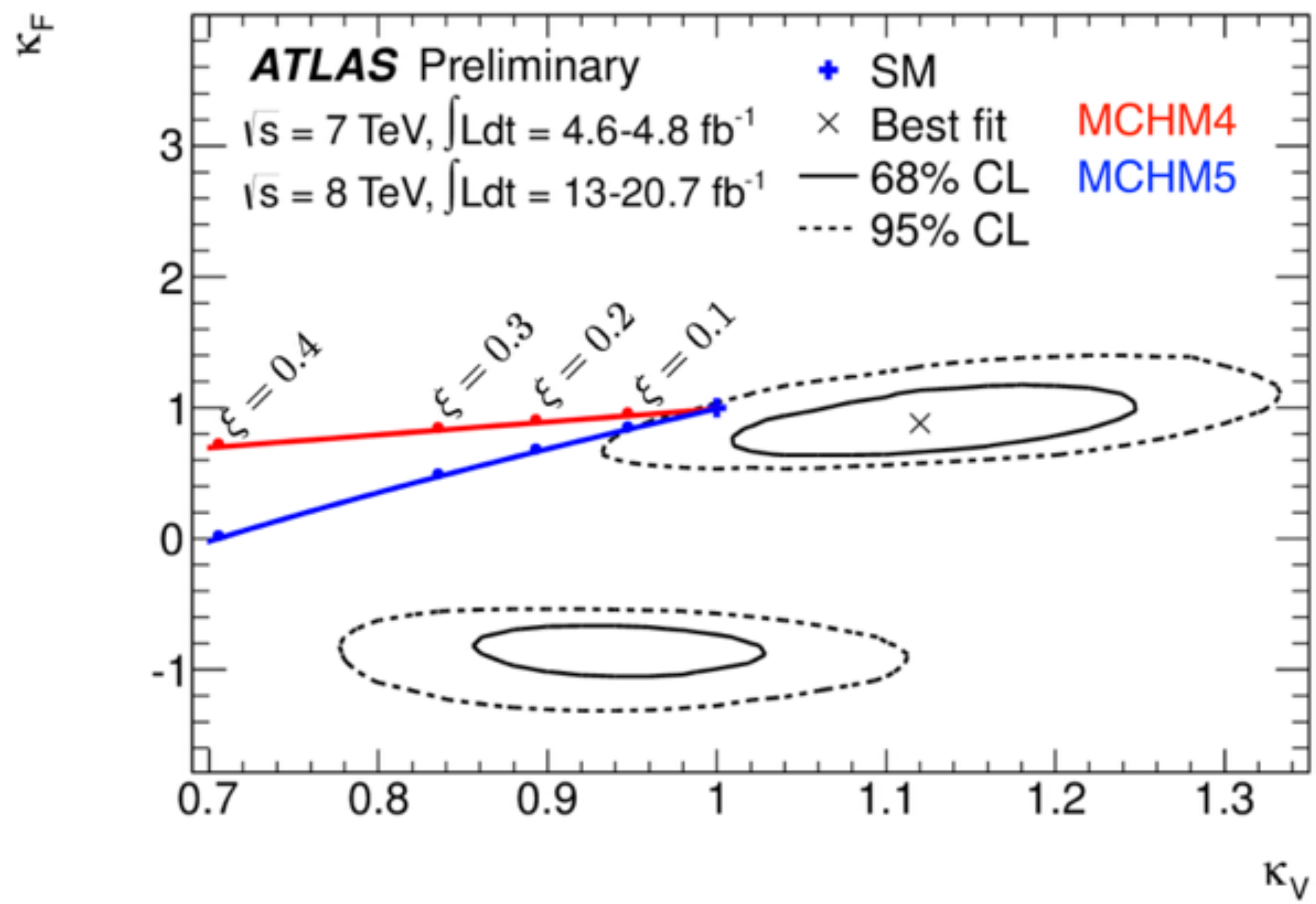
vs.

SM Higgs



Higgs couplings fit





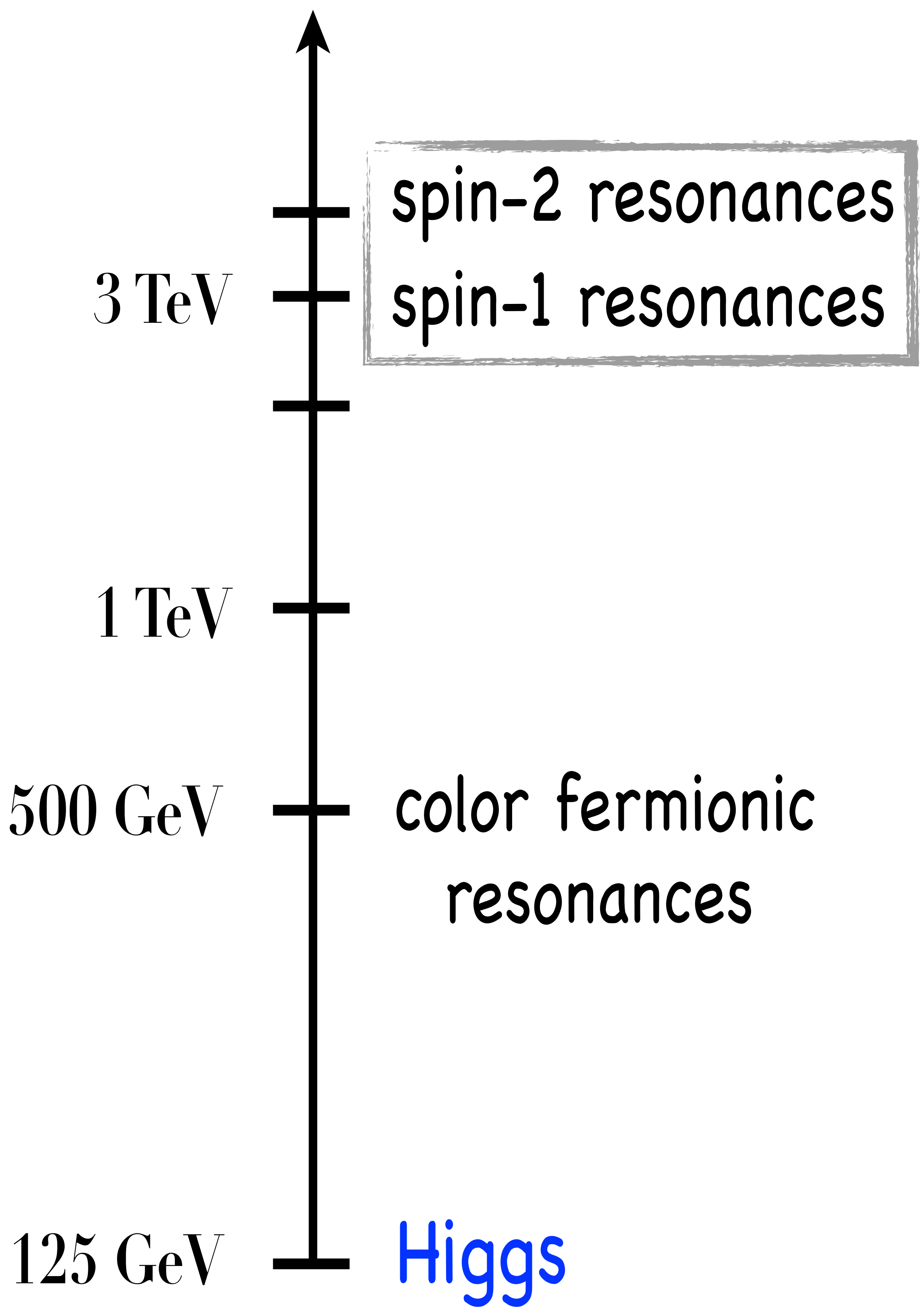
- MCHM4

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

- MCHM5

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

The other resonances



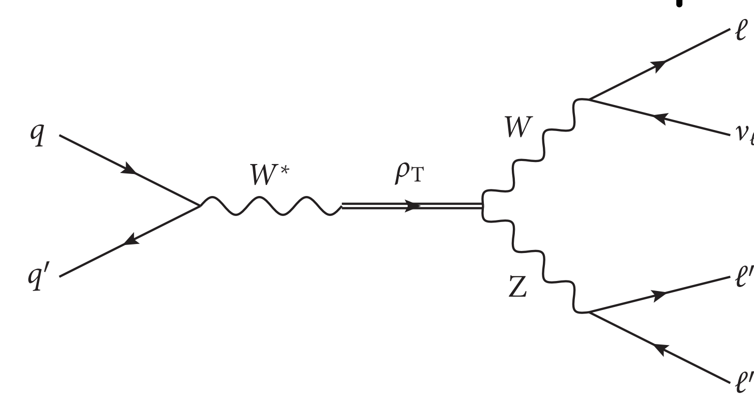
Dominant decays into longitudinal SM gauge bosons

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

Suppressed decays to SM quarks and leptons

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

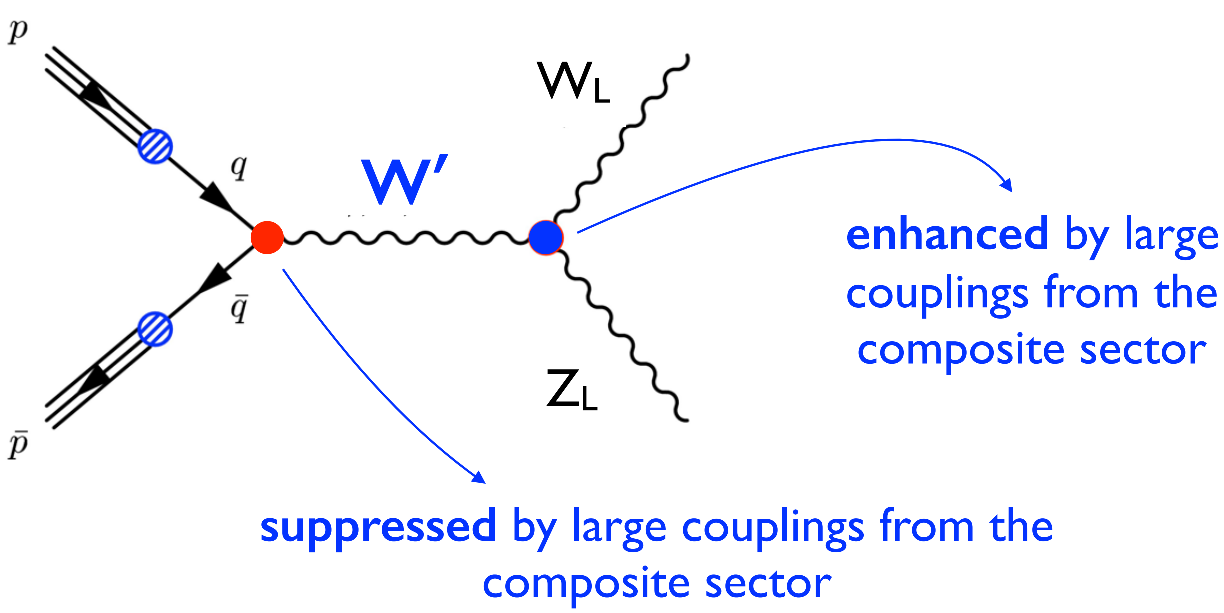
searches in WW, WZ channels in DY processes



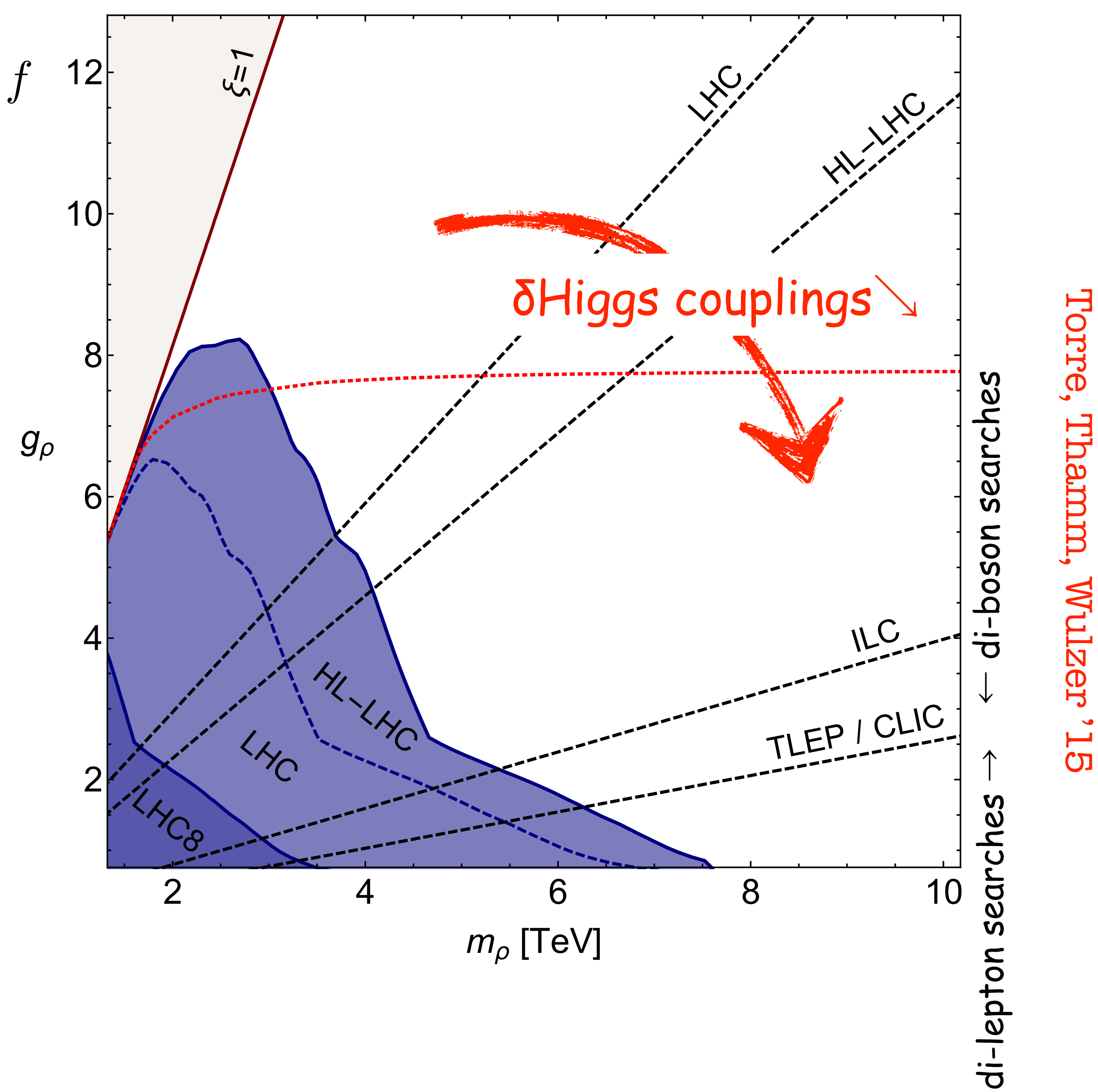
Higgs couplings vs searches for vector resonances

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 $1/g_\rho^2$



Higgs couplings vs searches for vector resonances

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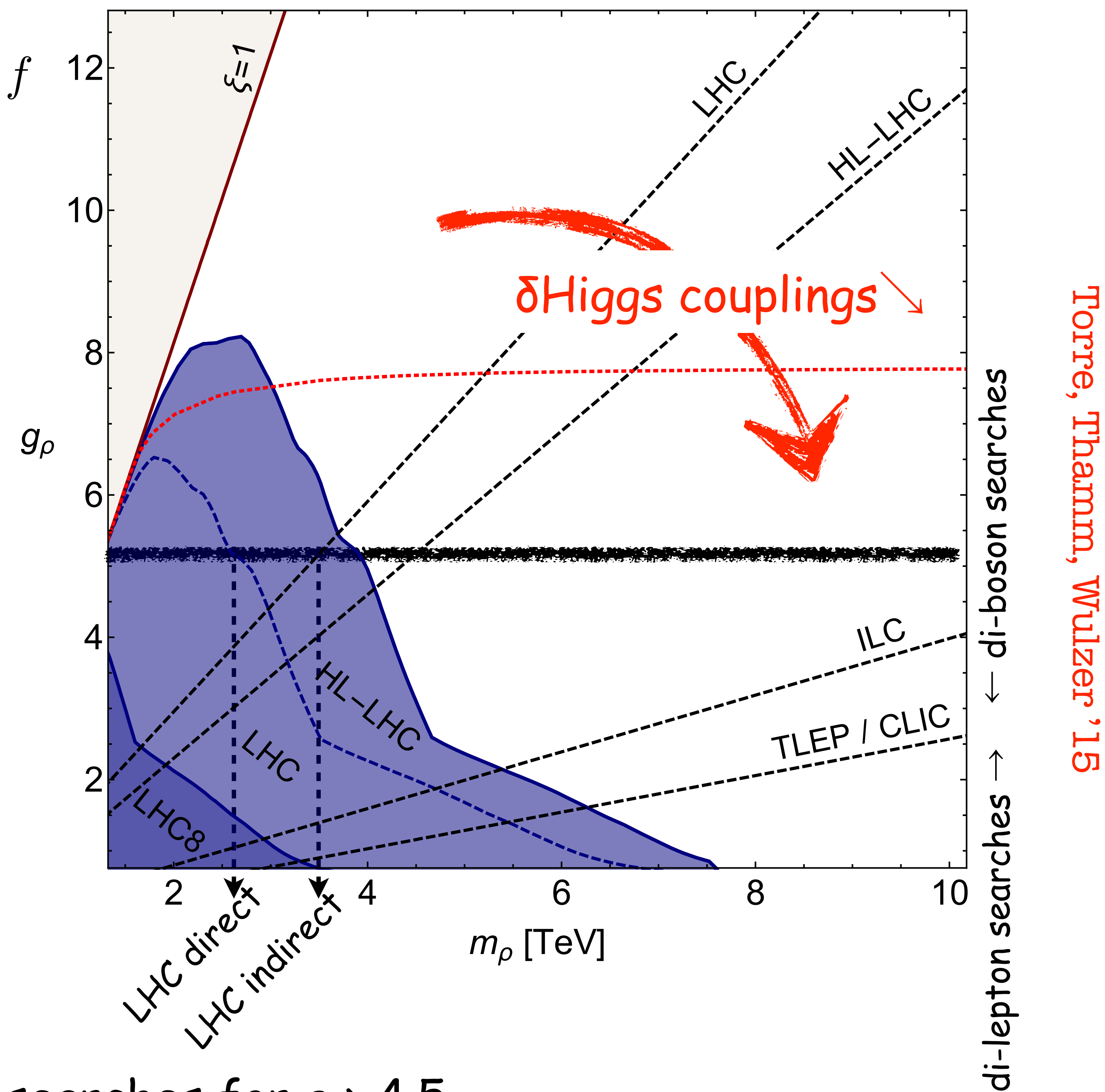
Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV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

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



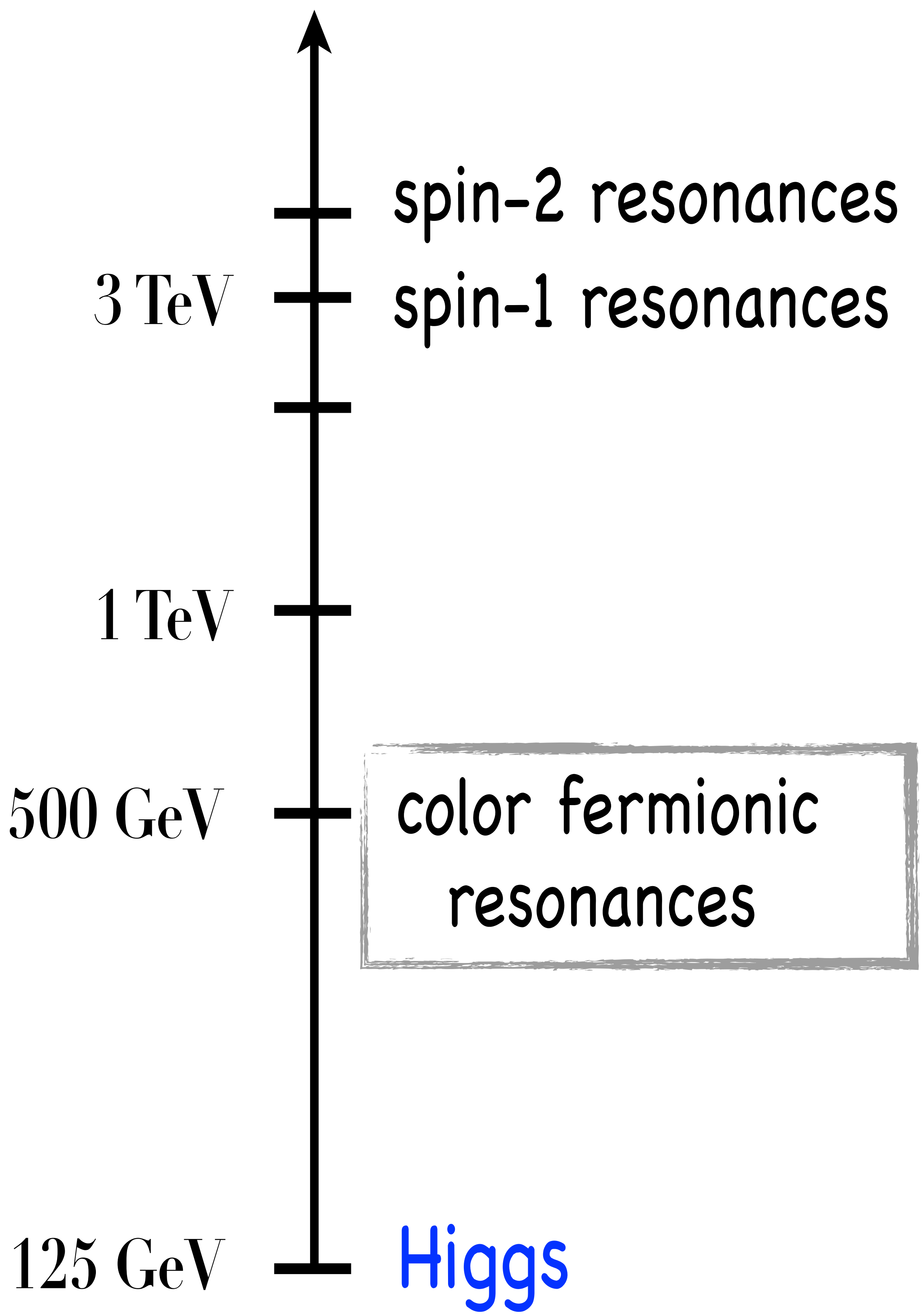
- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

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



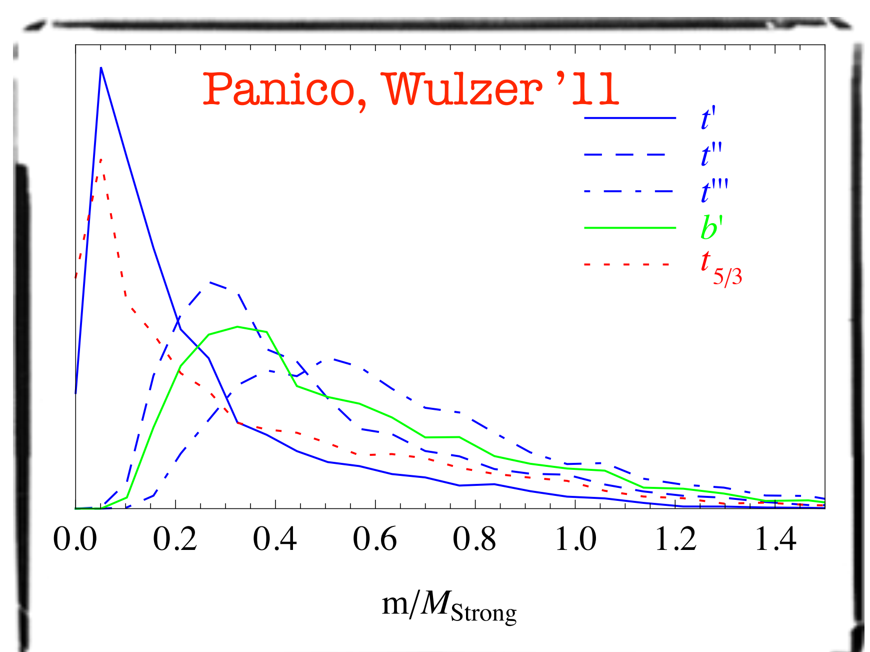
Top partners

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

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

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

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



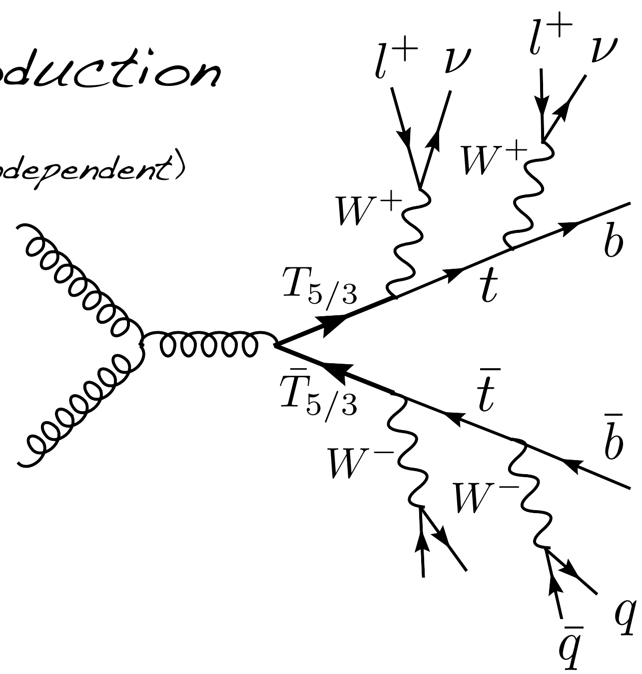
Searching for the top partners

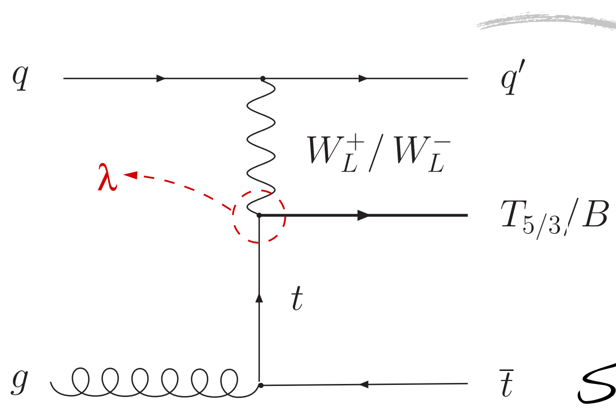
Search in same-sign dilepton events

- $t\bar{t}$+jets is not a background [except for charge mis-ID and fake e$^-$]
- the resonant (tW) invariant mass can be reconstructed

Pair production

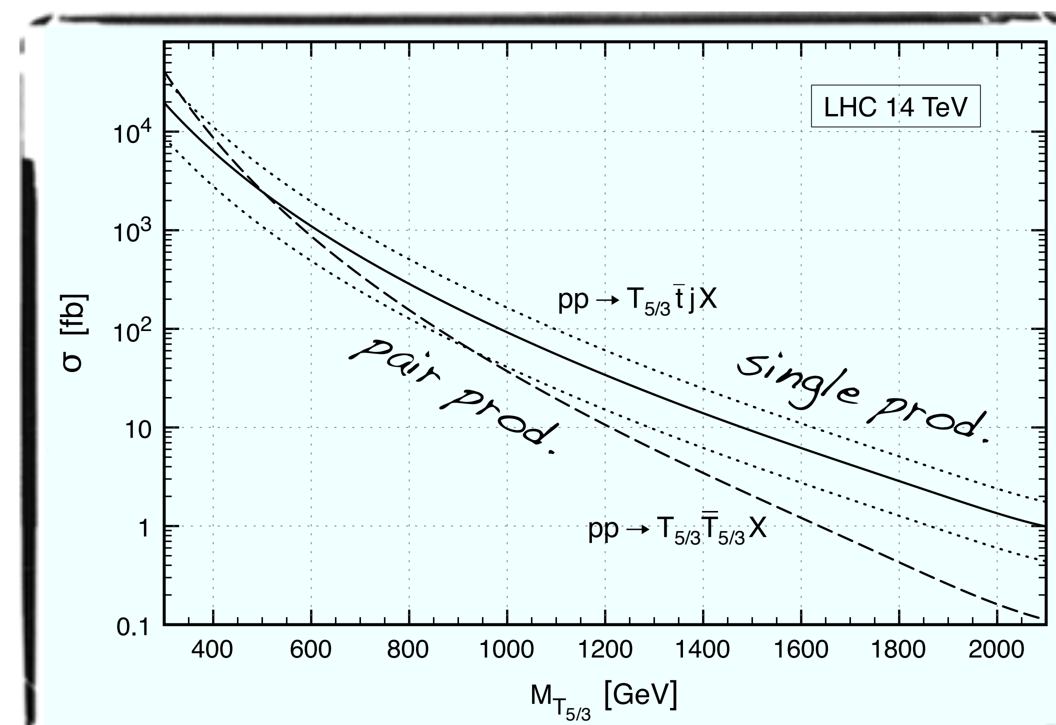
(model independent)





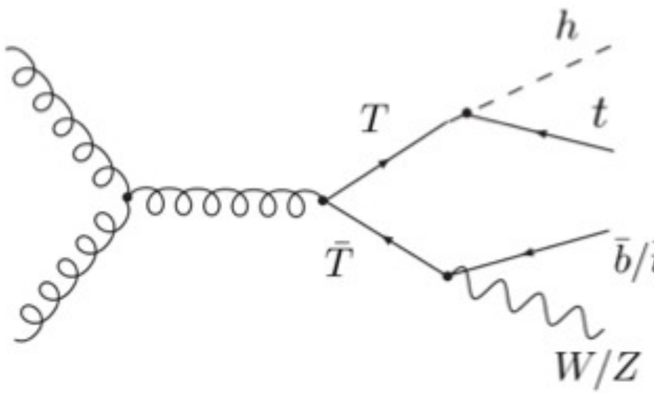
Single production

(model dependent)



[Contino, Servant '08]

Searching for the top partners



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

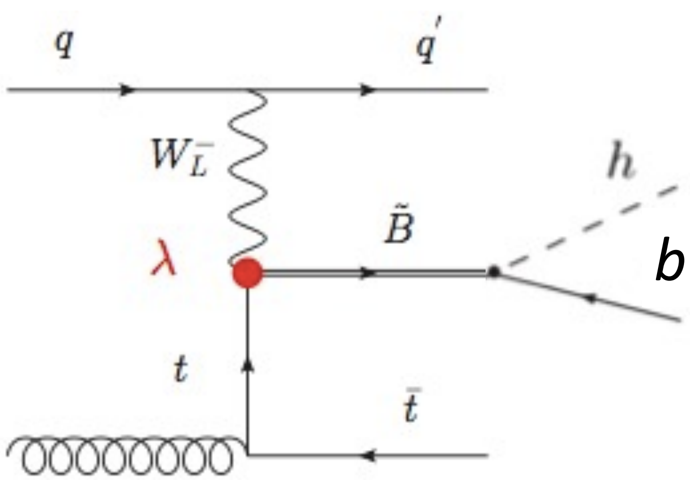
$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

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

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

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

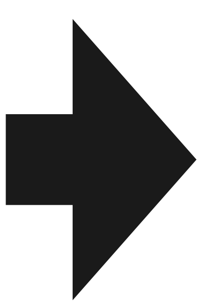
$$thbW/thtZ/thth,\ h \to \gamma\gamma$$



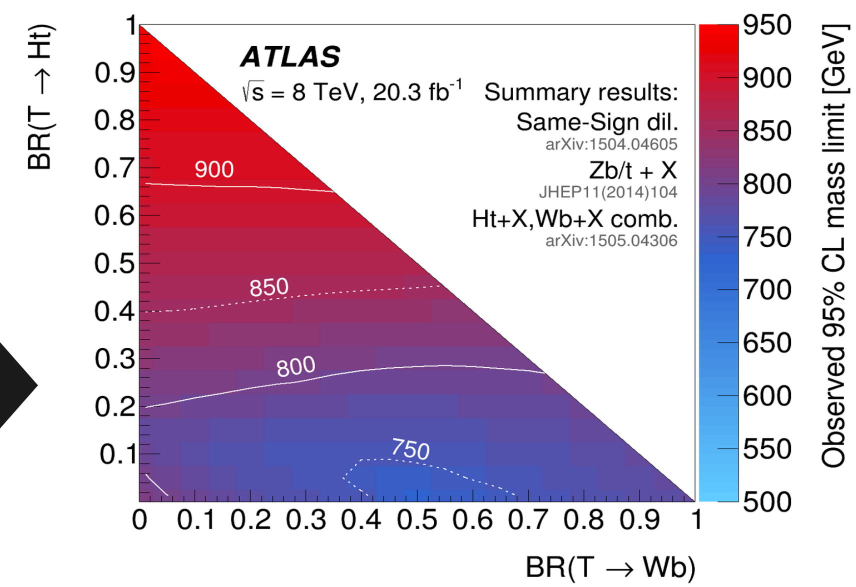
- $\ell^{\pm}$ + 4b final state Vignaroli '12

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

bounds on
charge 2/3 states
from pair production

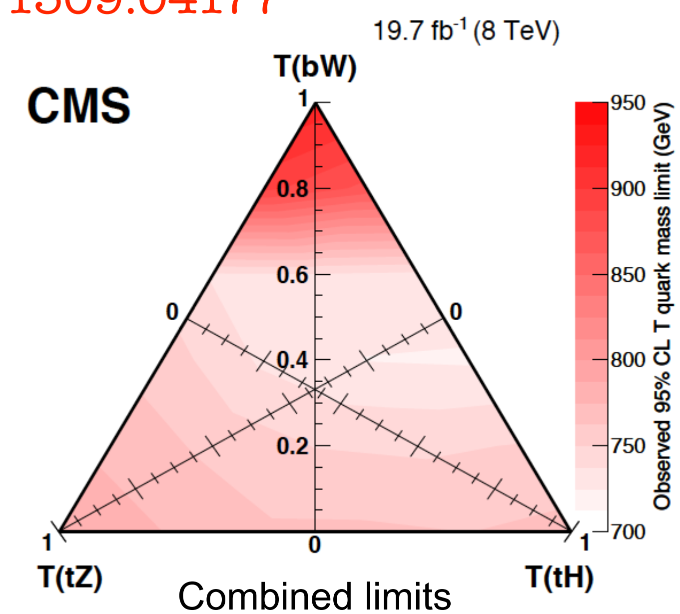


1505.04306



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

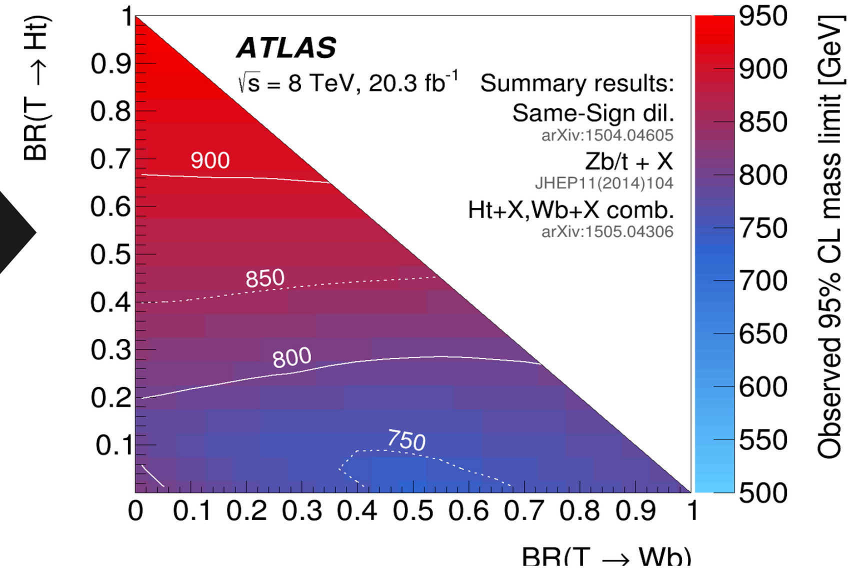
1509.04177



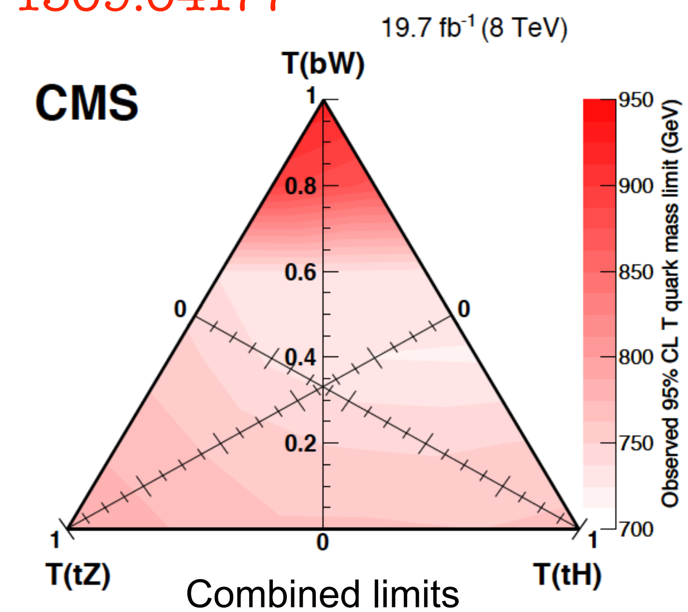
Searching for the top partners

bounds on
charge 2/3 states
from pair production

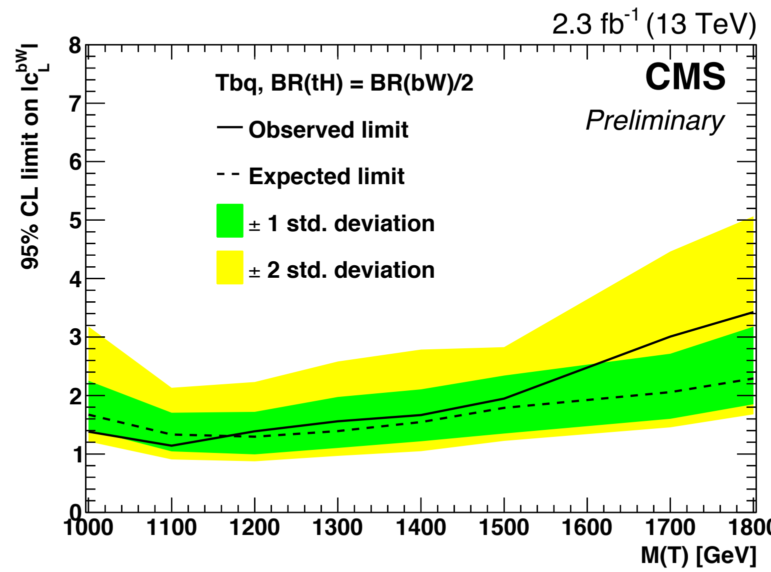
1505.04306

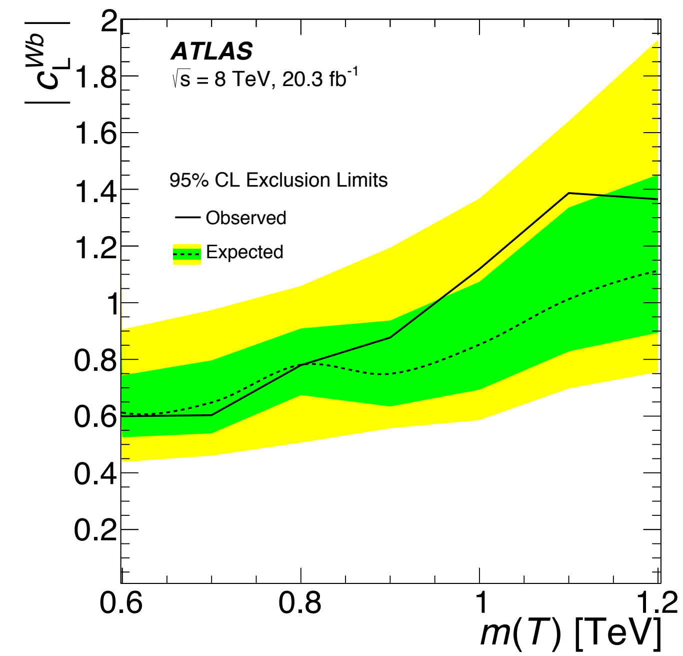


1509.04177

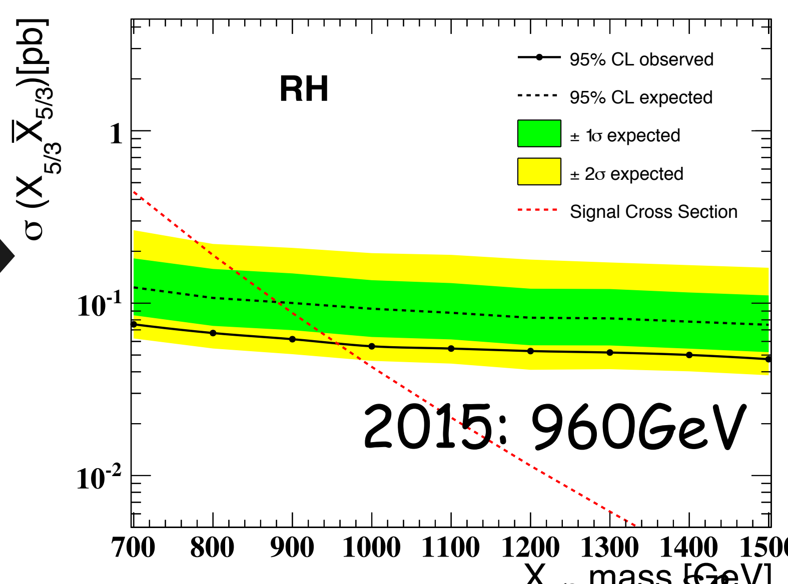


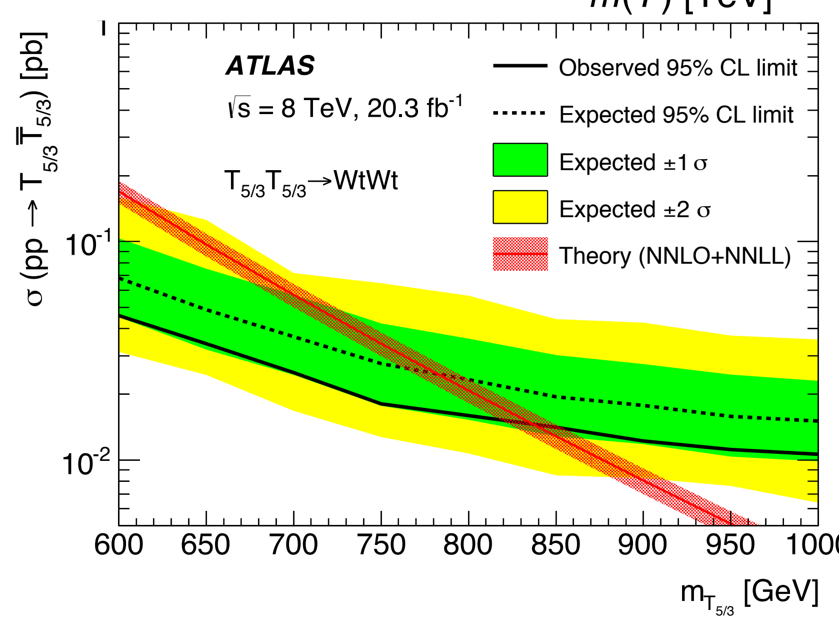
bounds on
charge 2/3 states
from single production





bounds on
charge 5/3 states
from single production

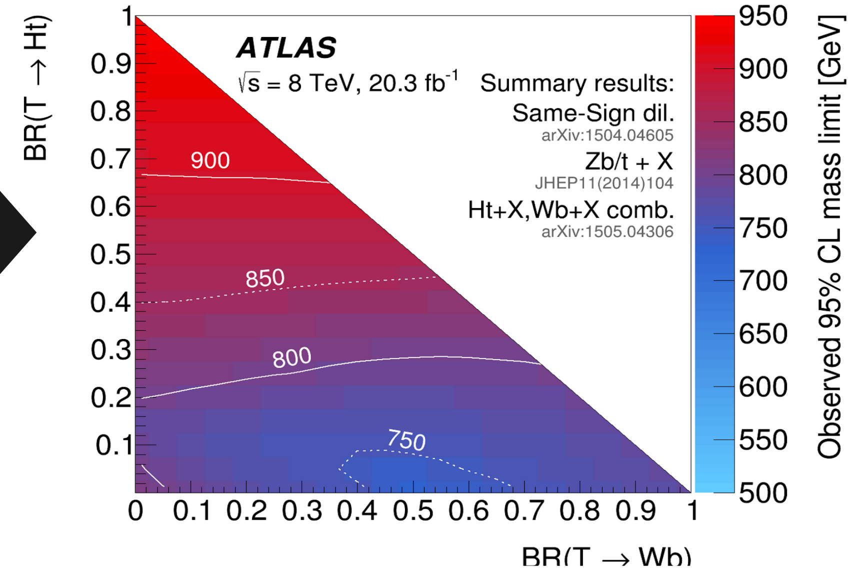




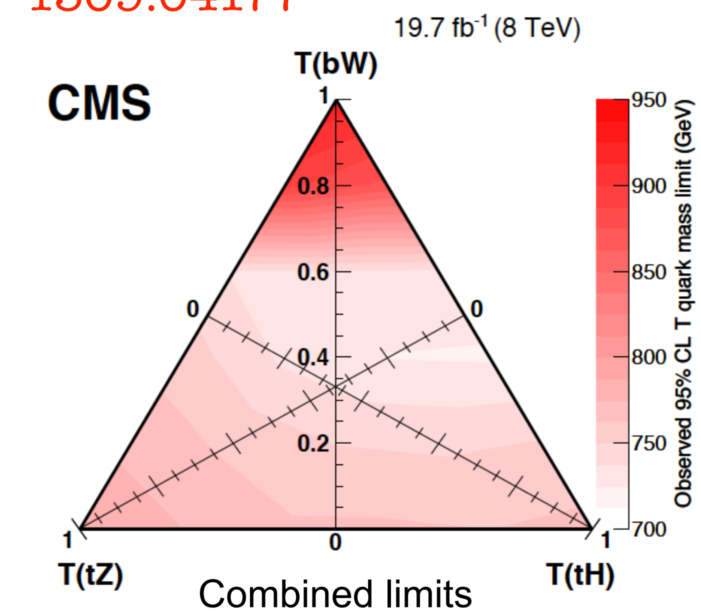
Searching for the top partners

bounds on
charge 2/3 states
from pair production

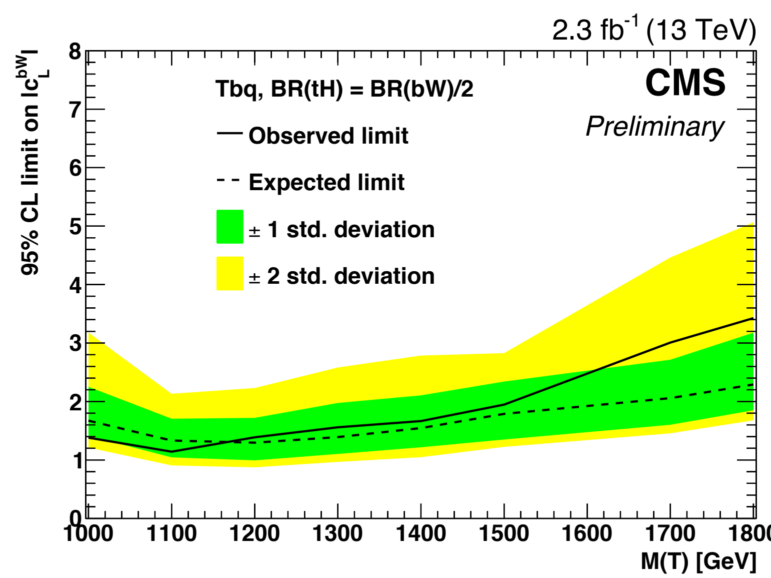
1505.04306

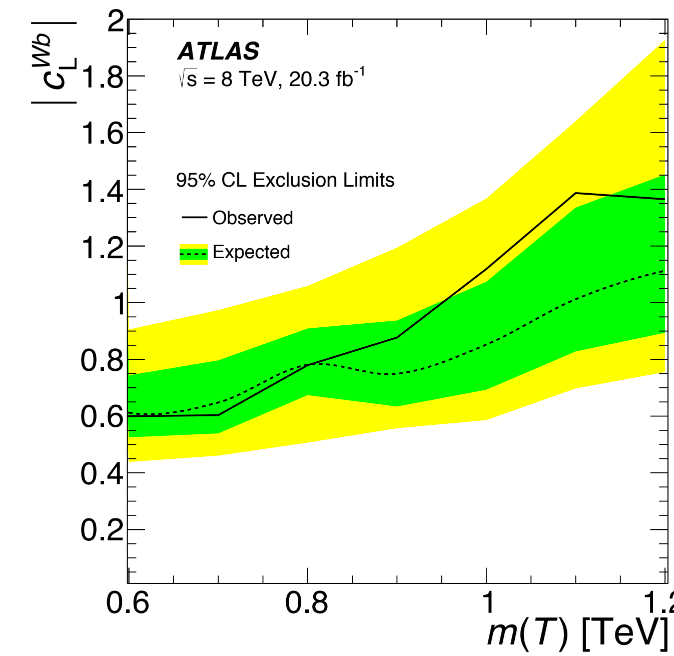


1509.04177

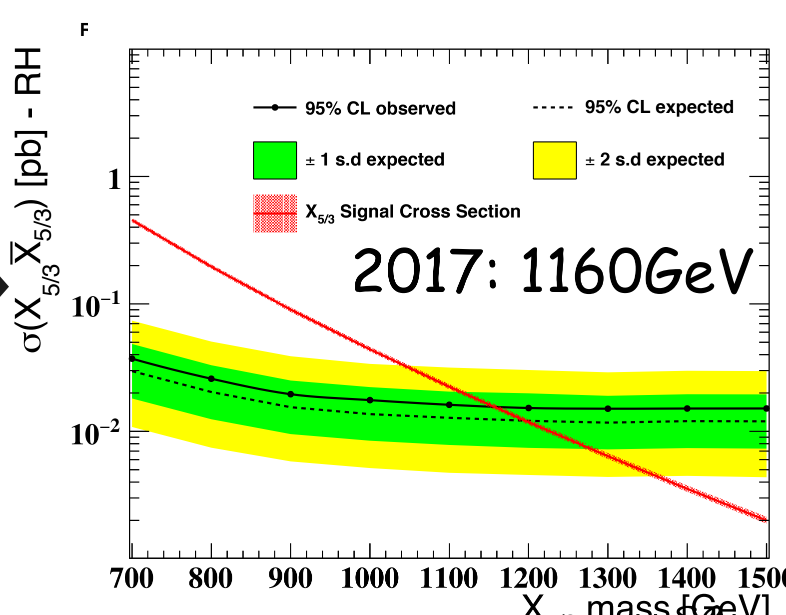


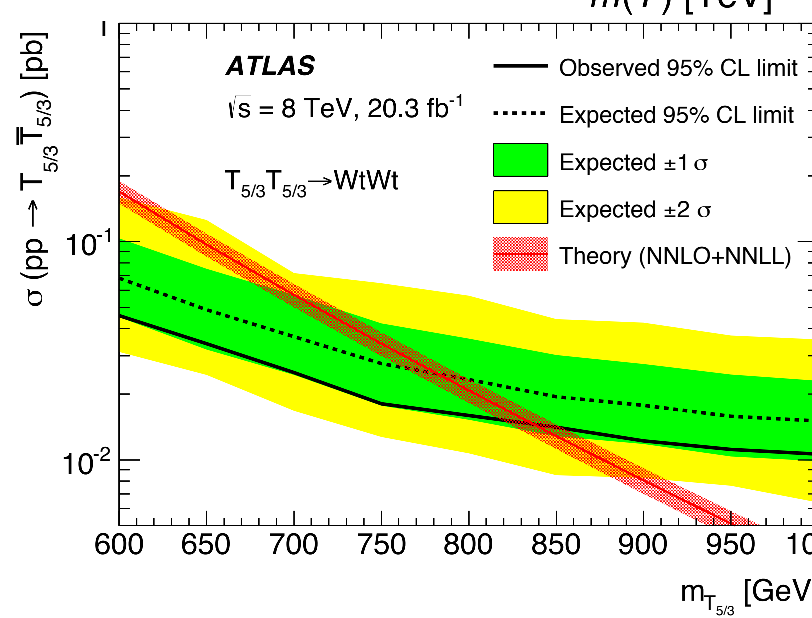
bounds on
charge 2/3 states
from single production





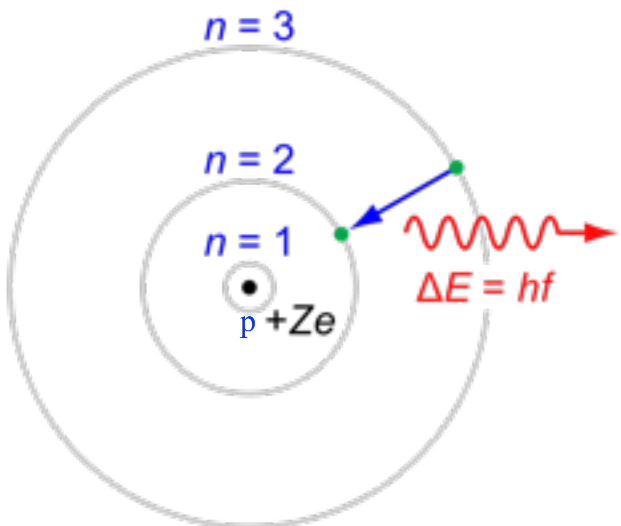
bounds on
charge 5/3 states
from single production





BSM and Atomic Physics

Atomic Clocks as a BSM probe



Physics beyond QED contributes to the frequency of the radiation

$$\frac{1}{\lambda} = R\, Z^2 \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

$|\psi(0)|^2/n^3$ is the wave-function-density at the origin.

$$V_{\rm weak}(r) = -\frac{8 G_{\rm F} m_{Z^0}^2}{\sqrt{2}} \frac{g_e g_A}{4\pi} \frac{e^{-r m_{Z^0}}}{r} \quad \Longrightarrow \quad \delta E_{nlm}^{\rm weak} = -\frac{8 G_F m_Z^2}{\sqrt{2}} \frac{g_e g_A}{4\pi m_Z^2} |\psi(0)|^2 \frac{\delta_{l,0}}{n^3}$$

fifth force ⟹ ?

Exp sensitivity in atomic clock measurements O(10^{-18})

(ms over one billon years)

Not all transitions can be used (yet) for BSM

frequency shifts O(1-100 Hz) over frequencies O(1THz): still a sensitivity O($10^{-6:-9}$)

can be used to detect new (long range) forces

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = \underbrace{K_i\,\mu_{AA'}}_{\text{mass shift}} + \underbrace{F_i\delta\langle r^2\rangle_{AA'}}_{\text{field shift}} + \underbrace{H_i(A-A')}_{\text{BSM or NLO SM/QED}}$$

K_i and F_i are difficult to compute to the accuracy needed but they are the same for different isotopes

The King Plot

W. H. King, *J. Opt. Soc. Am.* 53, 638 (1963)

- First, define modified IS as $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$
- Measure IS in two transitions. Use transition 1 to set $\delta\langle r^2\rangle_{AA'}/\mu_{AA'}$ and substitute back into transition 2:

$F_{21} \equiv F_2/F_1$
$K_{21} \equiv K_2 - F_{21}K_1$
$H_{21} \equiv H_2 - F_{21}H_1$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Isolating the signal: isotope shifts

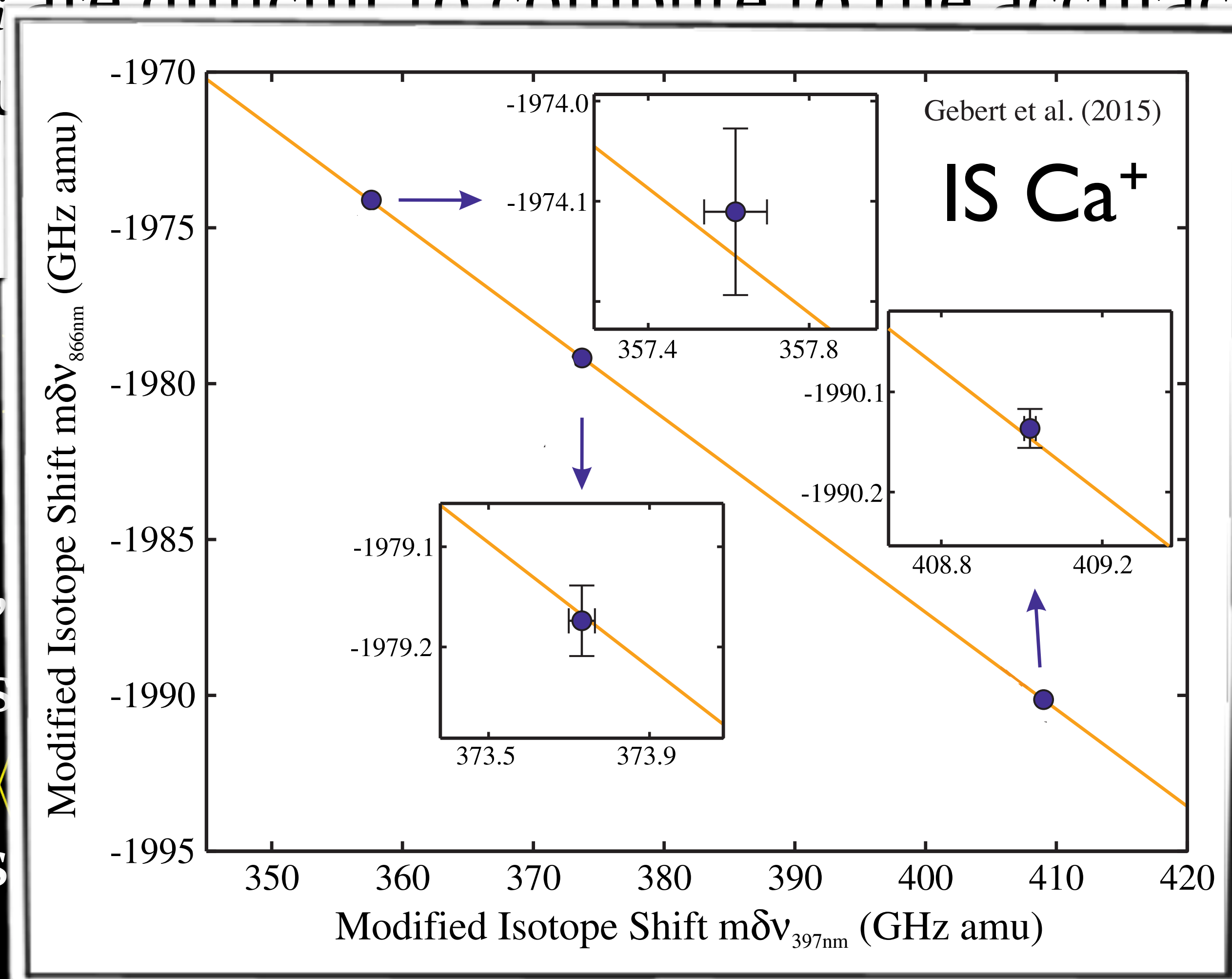
$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = K_i\, \mu_{AA'} + F_i \delta\langle r^2\rangle_{AA'} + H_i(A - A')$$

mass shift field shift BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed

bu es



The . H. King, 638 (1963)

- First, AA'
- Meas 1 to set $\delta\langle$ trans

$\equiv F_2/F_1$

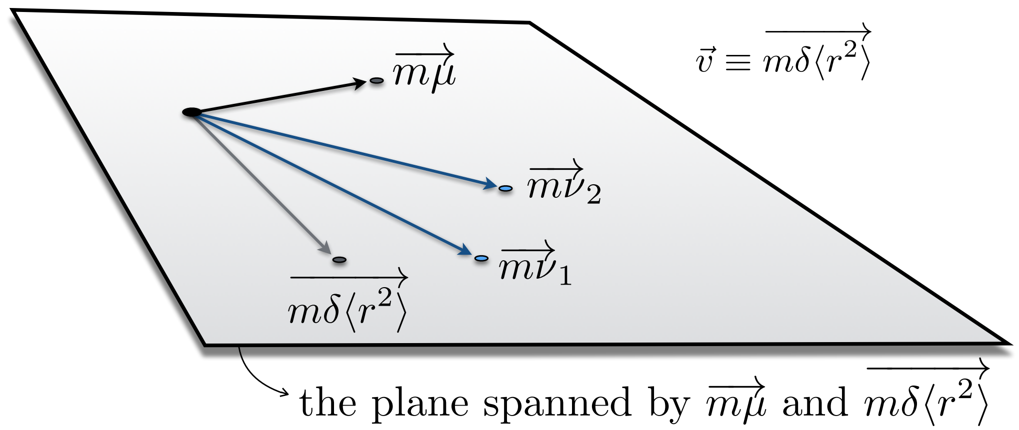
$\equiv K_2 - F_{21}K_1$

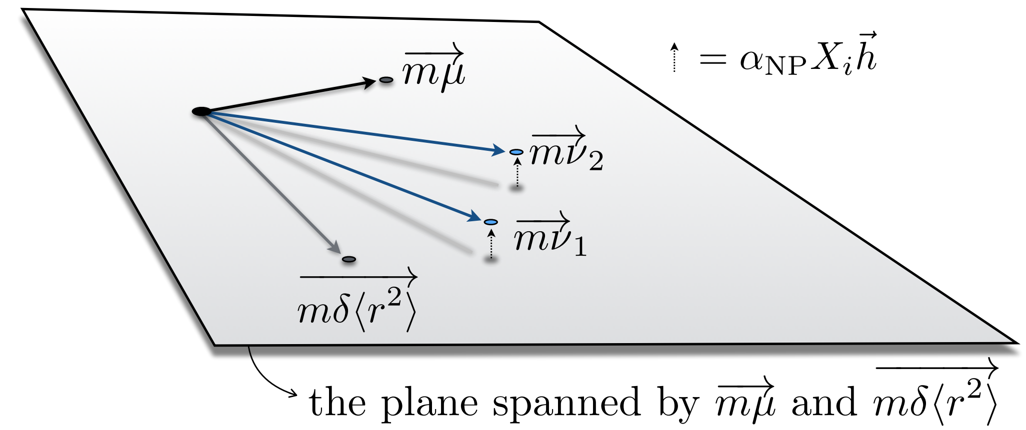
$\equiv H_2 - F_{21}H_1$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21} m\delta\nu^1_{AA'} - AA' H_{21}$$

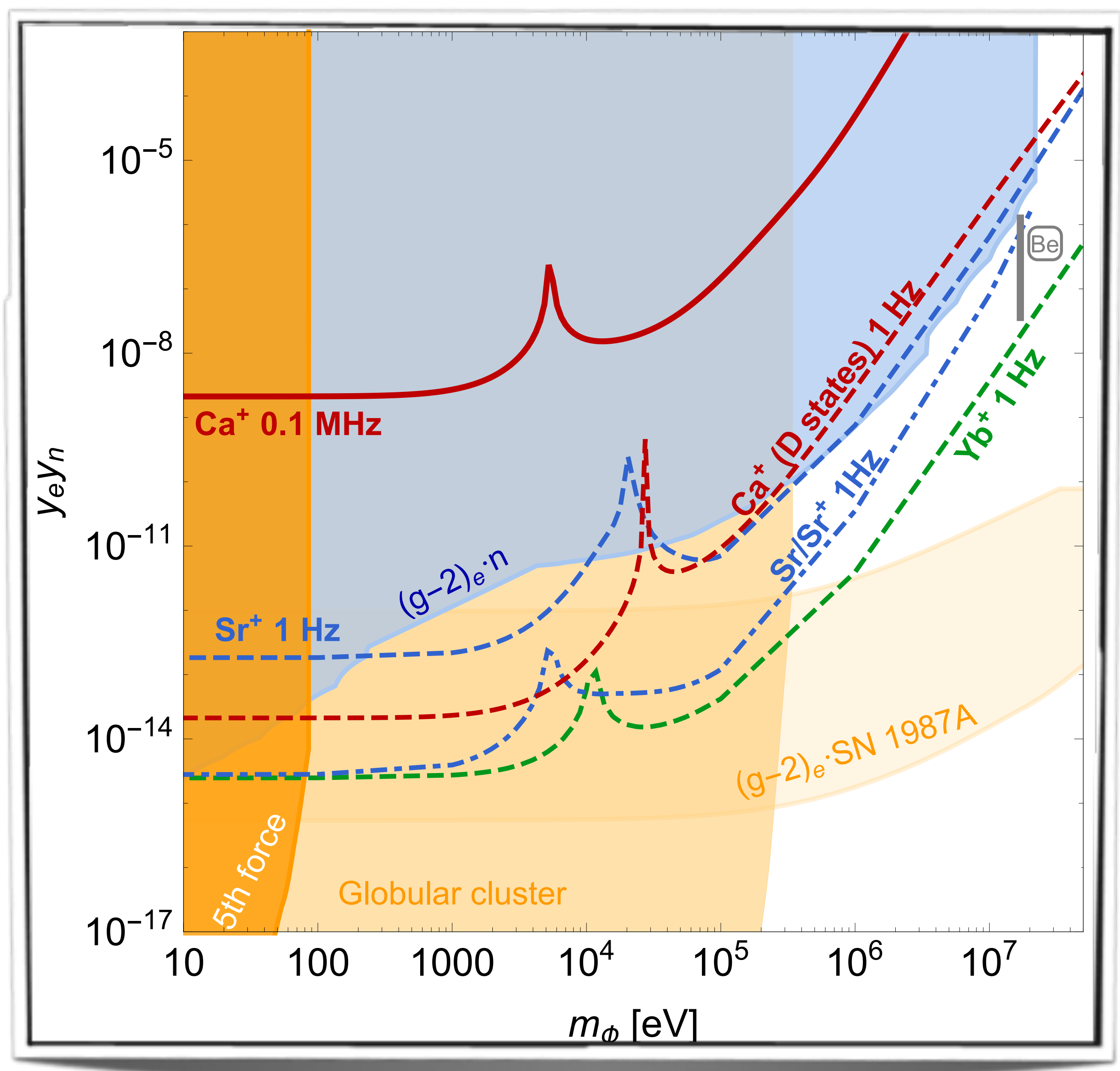
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Constraining light NP





As long as
King linearity deviation
is not observed,
one can bound
new physics sources
More tricky to interpret
if a signal is observed



arXiv:1704.05068v1 [hep-ph]