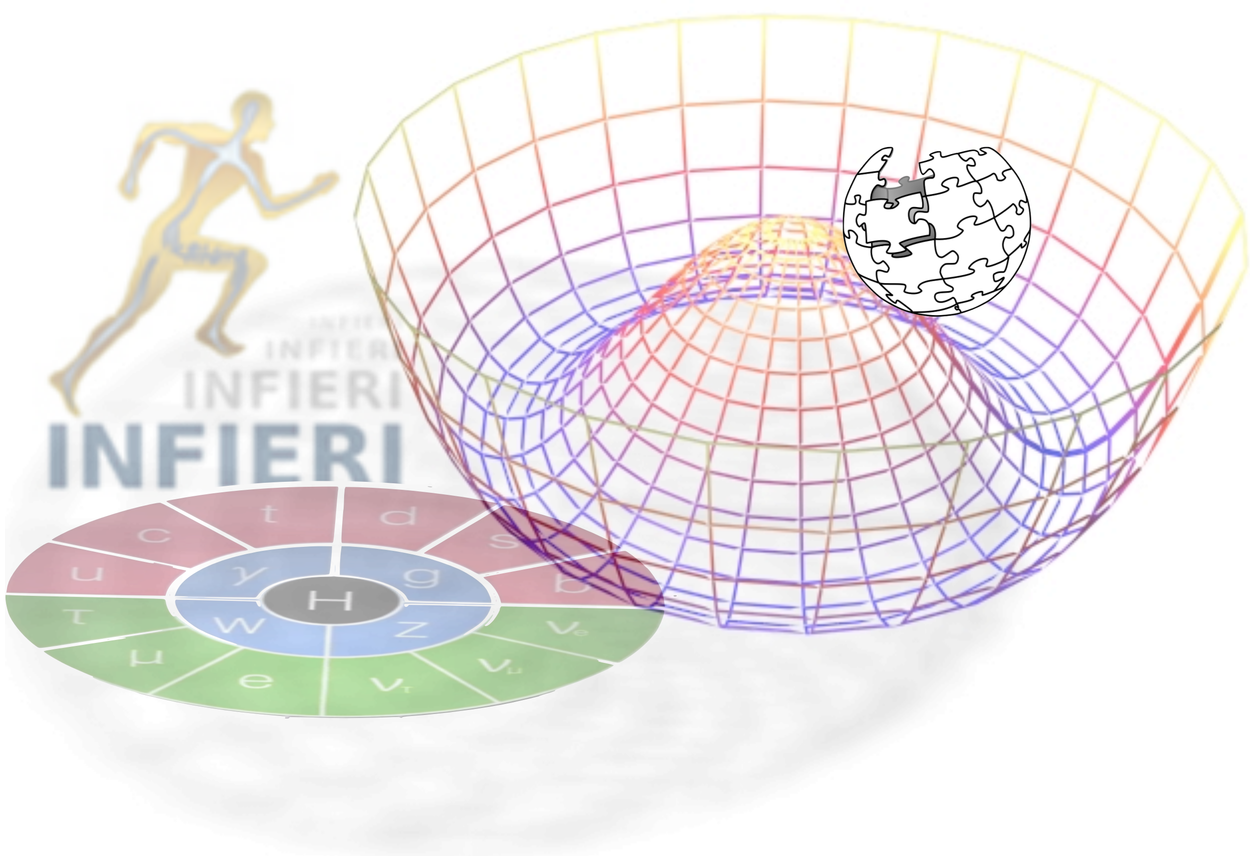
# Higgs and Beyond

## what will we learn at the future accelerators

*International Summer School series on*

*" Intelligent Signal Processing for Frontier Research and Industry"*

*UAM, April 22, 2021*





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# Technical Details

# Dimensional Analysis

# Natural & Planck Units

- $[G_N]$=mass$^{-1}$ L$^3$ T$^{-2}$
- $[\hbar]$=mass L$^2$ T$^{-1}$
- $[c]$=L T$^{-1}$

- Planck mass: $M_{\rm Pl} = \sqrt{\frac{\hbar c}{G_{\rm N}}} \sim 10^{19}\,{\rm GeV/c^2} \sim 2\times 10^{-5}\,{\rm g}$
- Planck length: $l_{\rm Pl} = \sqrt{\frac{\hbar G_{\rm N}}{c^3}} \sim 10^{-33}\,{\rm cm}$
- Planck time: $\tau_{\rm Pl} = \sqrt{\frac{\hbar G_{\rm N}}{c^5}} \sim 10^{-44}\,{\rm s}$

In High Energy Physics, it is current to use a system of units for which ħ=1 and c=1

Mass ~ distance$^{-1}$ ~ time$^{-1}$

## Unit conversion: SI ↔ HEP

| E | T | L |
|---|---|---|
| 1eV | $10^{-16}$s | $10^{-7}$m |
| $10^{-16}$eV | 1s | $10^{9}$m |
| $10^{-7}$eV | $10^{-9}$s | 1m |

- The string theorists will remember:

$$M_{\rm Pl} \sim 10^{19}\,{\rm GeV} \quad \leftrightarrow \quad \tau_{\rm Pl} \sim 10^{-44}\,{\rm s} \quad \leftrightarrow \quad l_{\rm Pl} \sim 10^{-33}\,{\rm cm}$$

- The nuclear physicists will remember:

$$\hbar c \sim 200\,{\rm MeV}\cdot{\rm fm}$$
$$10^8\,{\rm eV} \quad \leftrightarrow \quad 10^{-15}\,{\rm m} \quad \leftrightarrow \quad 10^{-24}\,{\rm s}$$

- The others will remember:

average mosquito

m~$10^{-3}$g=100$M_{Pl}$ which corresponds to a distance 0.01$L_{Pl}$=$10^{-35}$cm

(much smaller than its physical size, so a mosquito is not a Black Hole)

# Dimensional Analysis

$$[S]_m = 0 \quad \Rightarrow \quad [\mathcal{L}]_m = 4$$

$$S = \int d^4x\, \mathcal{L}$$

**Scalar field** $\mathcal{L} = \partial_\mu \phi \partial^\mu \phi + \ldots$ ⇒ $[\phi]_m = 1$

**Spin-1/2 field** $\mathcal{L} = \psi^\dagger \gamma^0 \gamma^\mu \partial_\mu \psi$ ⇒ $[\psi]_m = 3/2$

**Spin-1 field** $\mathcal{L} = F_{\mu\nu} F^{\mu\nu} + \ldots$ with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + \ldots$ ⇒ $[A_\mu]_m = 1$

Particle lifetime of a (decaying) particle: $[\tau]_m = -1$ Width: $[\Gamma = 1/\tau]_m = 1$

Cross-section ("area" of the target): $[\sigma]_m = -2$

# Lifetime “Computations”

muon and neutron are unstable particles

$$\mu \to e \nu_\mu \bar{\nu}_e$$

$$n \to p\, e\, \bar{\nu}_e$$

The interactions responsible for the decay of muon and neutron can be described by the Fermi Lagrangian

$$\mathcal{L} = G_F\, \psi^4 \quad \Rightarrow \quad \Gamma \propto G_F^2 m^5$$

$\mathcal{L}$: $[\text{mass}]^4$; $G_F$: $[\text{mass}]^{-2}$; $\psi^4$: $[\text{mass}]^{3/2\times 4}$; $\Gamma$: $[\text{mass}]$

$G_F$ = Fermi constant: $G_F \sim \dfrac{10^{-5}}{m^2_{\text{proton}}} \sim 10^{-5}\,\text{GeV}^{-2}$

For the **muon**, the relevant mass scale is the muon mass $m_\mu$=105MeV:

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} \sim 10^{-19}\,\text{GeV} \quad \text{i.e.} \quad \tau_\mu \sim 10^{-6}\,\text{s}$$

exercice:

For the **neutron**, the relevant mass scale is $(m_n\text{-}m_p)\approx 1.29$MeV:

$$\Gamma_n = \mathcal{O}(1)\frac{G_F^2 \Delta m^5}{\pi^3} \sim 10^{-28}\,\text{GeV} \quad \text{i.e.} \quad \tau_{\text{n}} \sim 10^3\,\text{s}$$

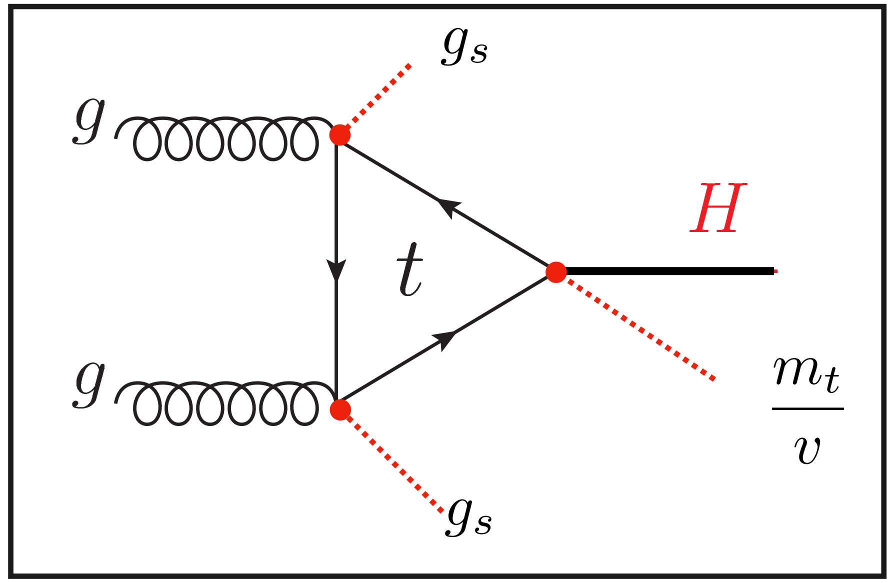
# Higgs production “Computation”

At the LHC, the dominant Higgs production mode is gluon fusion

strong coupling constant $g_s \sim 1$

$$g_s\, G_\mu \bar{t} \gamma^\mu t$$

[mass]$^0$ [mass]$^1$ [mass]$^{3/2\text{x}2}$




Higgs coupling proportional to the mass

$$g_{ttH}\, \bar{t} t H$$

[mass]$^0$ [mass]$^{3/2\text{x}2}$ [mass]$^1$

v=246 GeV

exercice:

$$\sigma = \frac{1}{8\pi} \frac{1}{16\pi^2} g_s^4 \frac{m_t^2}{v^2} \frac{1}{m_t^2}$$

flux loop couplings dimensionally $[\sigma]_m$=-2

i.e. $\sigma \sim 10^{-25}\,\mathrm{eV}^{-2} \sim 10^{-39}\,\mathrm{m}^2 = 10\,\mathrm{pb}$

$$1\,\mathrm{barn} = 10^{-28}\,\mathrm{m}^2$$

One could think that all the quarks should give a similar contribution to the Higgs production since mt factors cancel. But it can be shown that this cancelation holds only for quarks heavier than the Higgs. Still, a heavy fourth generation is indeed ruled out.

How many Higgs bosons produced at LHC? $\sigma \times \int dt\, \mathcal{L} = 10\,\mathrm{pb} \times 100\,\mathrm{fb}^{-1} \sim 10^6$

# Higgs Lifetime “Computation”

Higgs couplings proportional are proportional to the mass of the particles it couples to.
It will therefore decay predominantly decay into the heaviest particle that is lighter than $m_H/2$

$$\Gamma \sim \frac{1}{8\pi}\left(\frac{m_b}{v}\right)^2 m_h \sim \frac{1}{10}\left(\frac{4\,\mathrm{GeV}}{246\,\mathrm{GeV}}\right)^2 125\,\mathrm{GeV} \sim 1\,\mathrm{MeV}$$

phase space

couplings to b-quark

dimensionally $[\Gamma]_m=1$

$$\Rightarrow \quad \tau \sim 10^{-21}\,\mathrm{s}$$

Putting all factors and considering the other decay modes, Higgs width = 4MeV in the SM

exercice:

$$\Gamma_Z = \frac{7}{48\pi} g^2 m_Z \sim 2\,\mathrm{GeV} \quad \text{i.e.} \quad \tau_Z \sim 10^{-25}\,\mathrm{s}$$

# Technical Details

# GUT

# SU(5) GUT: Gauge Group Structure

## $SU(3)_c$x$SU(2)_L$x$U(1)_Y$: 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(5) GUT: Gauge Group Structure

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How can you ever remember all these numbers?

## SU(3)cxSU(2)LxU(1)Y ⊂ SU(5)

SU(5)
Adjoint rep.

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

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

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

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

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

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

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

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

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

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

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

# 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 $(\alpha_{GUT}, M_{GUT})$

one consistency relation on low energy parameters

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

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

⇓

$\sin^2\theta_W \approx 0.207$ not bad… (observed value: 0.23)
Even better in MSSM

# SU(5) GUT: low energy consistency condition

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3 equations & 2 unknowns $(\alpha_{GUT}, M_{GUT})$

one consistency relation on low energy parameters

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

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

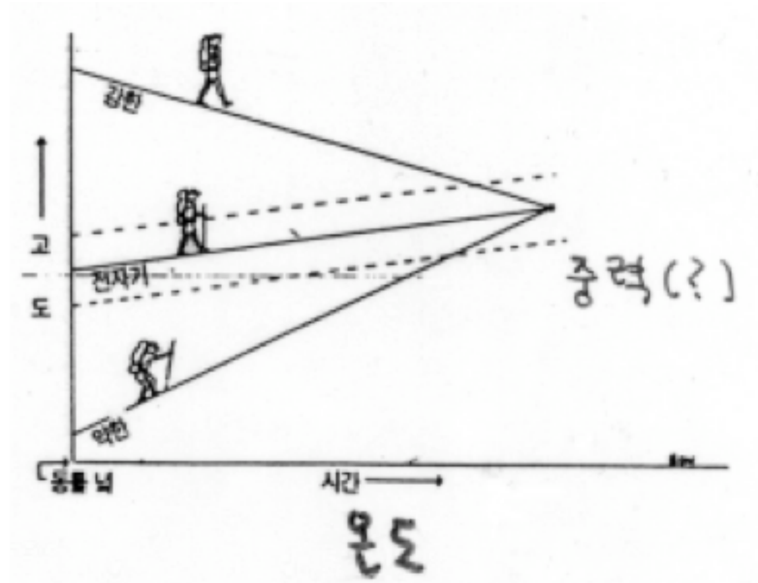
self-consistent computation:

- $M_{GUT} << M_{Pl}$ safe to neglect quantum gravity effects
- $\alpha_{GUT} << 1$ perturbative computation valid

# SU(5) GUT: SM $\beta$ fcts

g, g' and $g_s$ are different but this is a low energy artefact!

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




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

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

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

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

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

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

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

# SU(5) GUT: SM vs MSSM $\beta$ fcts

**chiral superfield**

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

**vector superfield**

Weyl spin-1/2
real spin-1
in same representation 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

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

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

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

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

$\Rightarrow$ $b_{T^{12}} = -\dfrac{33}{5}$

# 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

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

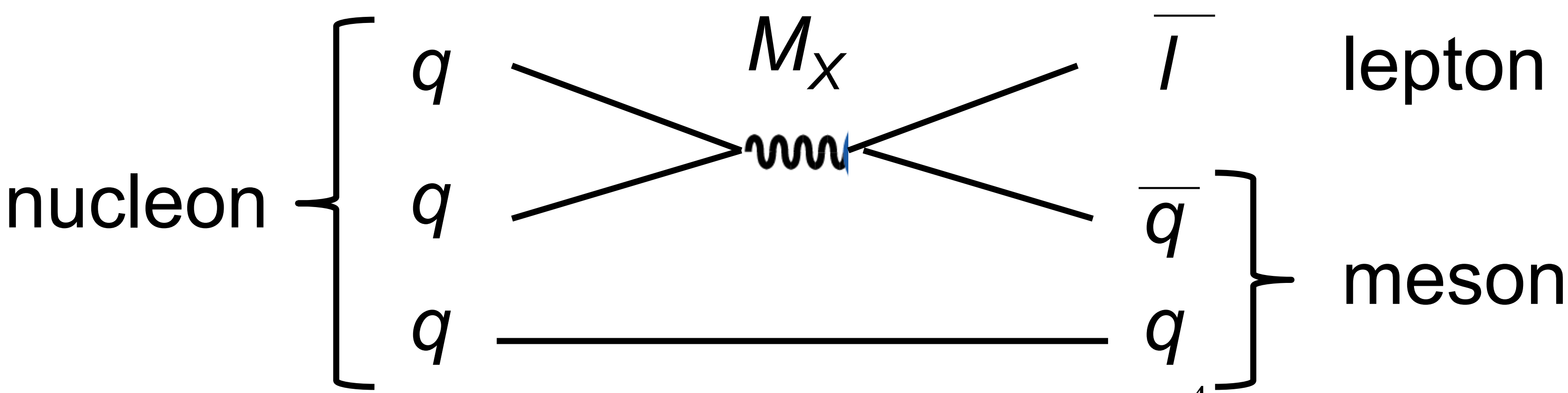
$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 24.3$$

# Proton Decay

(G. Giudice SSLP'15)

in GUT, matter is unstable

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




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

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

(Age of the Universe: $10^{10}$ years)

# Proton Decay

| | Mode | Partial mean life ($10^{30}$ years) | Confidence level |
|---|---|---|---|
| | | **Antilepton + meson** | |
| $\tau_1$ | $N \to e^+ \pi$ | $> 2000$ ($n$), $> 8200$ ($p$) | 90% |
| $\tau_2$ | $N \to \mu^+ \pi$ | $> 1000$ ($n$), $> 6600$ ($p$) | 90% |
| $\tau_3$ | $N \to \nu \pi$ | $> 1100$ ($n$), $> 390$ ($p$) | 90% |
| $\tau_4$ | $p \to e^+ \eta$ | $> 4200$ | 90% |
| $\tau_5$ | $p \to \mu^+ \eta$ | $> 1300$ | 90% |
| $\tau_6$ | $n \to \nu \eta$ | $> 158$ | 90% |
| $\tau_7$ | $N \to e^+ \rho$ | $> 217$ ($n$), $> 710$ ($p$) | 90% |
| $\tau_8$ | $N \to \mu^+ \rho$ | $> 228$ ($n$), $> 160$ ($p$) | 90% |
| $\tau_9$ | $N \to \nu \rho$ | $> 19$ ($n$), $> 162$ ($p$) | 90% |
| $\tau_{10}$ | $p \to e^+ \omega$ | $> 320$ | 90% |
| $\tau_{11}$ | $p \to \mu^+ \omega$ | $> 780$ | 90% |
| $\tau_{12}$ | $n \to \nu \omega$ | $> 108$ | 90% |
| $\tau_{13}$ | $N \to e^+ K$ | $> 17$ ($n$), $> 1000$ ($p$) | 90% |
| $\tau_{14}$ | $p \to e^+ K^0_S$ | | |
| $\tau_{15}$ | $p \to e^+ K^0_L$ | | |
| $\tau_{16}$ | $N \to \mu^+ K$ | $> 26$ ($n$), $> 1600$ ($p$) | 90% |
| $\tau_{17}$ | $p \to \mu^+ K^0_S$ | | |
| $\tau_{18}$ | $p \to \mu^+ K^0_L$ | | |
| $\tau_{19}$ | $N \to \nu K$ | $> 86$ ($n$), $> 5900$ ($p$) | 90% |
| $\tau_{20}$ | $n \to \nu K^0_S$ | $> 260$ | 90% |
| $\tau_{21}$ | $p \to e^+ K^*(892)^0$ | $> 84$ | 90% |
| $\tau_{22}$ | $N \to \nu K^*(892)$ | $> 78$ ($n$), $> 51$ ($p$) | 90% |
| | | **Antilepton + mesons** | |
| $\tau_{23}$ | $p \to e^+ \pi^+ \pi^-$ | $> 82$ | 90% |
| $\tau_{24}$ | $p \to e^+ \pi^0 \pi^0$ | $> 147$ | 90% |
| $\tau_{25}$ | $n \to e^+ \pi^- \pi^0$ | $> 52$ | 90% |
| $\tau_{26}$ | $p \to \mu^+ \pi^+ \pi^-$ | $> 133$ | 90% |
| $\tau_{27}$ | $p \to \mu^+ \pi^0 \pi^0$ | $> 101$ | 90% |
| $\tau_{28}$ | $n \to \mu^+ \pi^- \pi^0$ | $> 74$ | 90% |
| $\tau_{29}$ | $n \to e^+ K^0 \pi^-$ | $> 18$ | 90% |

**ΔB=ΔL=1 decay bounds**

| | Mode | Partial mean life ($10^{30}$ years) | Confidence level |
|---|---|---|---|
| | | **Lepton + meson** | |
| $\tau_{30}$ | $n \to e^- \pi^+$ | $> 65$ | 90% |
| $\tau_{31}$ | $n \to \mu^- \pi^+$ | $> 49$ | 90% |
| $\tau_{32}$ | $n \to e^- \rho^+$ | $> 62$ | 90% |
| $\tau_{33}$ | $n \to \mu^- \rho^+$ | $> 7$ | 90% |
| $\tau_{34}$ | $n \to e^- K^+$ | $> 32$ | 90% |
| $\tau_{35}$ | $n \to \mu^- K^+$ | $> 57$ | 90% |
| | | **Lepton + mesons** | |
| $\tau_{36}$ | $p \to e^- \pi^+ \pi^+$ | $> 30$ | 90% |
| $\tau_{37}$ | $n \to e^- \pi^+ \pi^0$ | $> 29$ | 90% |
| $\tau_{38}$ | $p \to \mu^- \pi^+ \pi^+$ | $> 17$ | 90% |
| $\tau_{39}$ | $n \to \mu^- \pi^+ \pi^0$ | $> 34$ | 90% |
| $\tau_{40}$ | $p \to e^- \pi^+ K^+$ | $> 75$ | 90% |
| $\tau_{41}$ | $p \to \mu^- \pi^+ K^+$ | $> 245$ | 90% |

**ΔB=-ΔL=1 decay bounds**

# Technical Details

# SUPERSYMMETRY

# SUSY 1.0.1

Wess, Zumino '74

fermion ⇔ boson

$$\mathcal{L} = \partial^\mu \phi^\dagger \partial_\mu \phi + i\bar{\psi}\gamma^\mu\partial_\mu\psi$$

- susy transformations:

$$\delta\phi = \bar{\epsilon}\psi$$
$$\delta\psi = -i\left(\gamma^\mu\partial_\mu\phi\right)\epsilon$$

$$\delta\mathcal{L} = \text{total derivative}$$


- susy algebra:

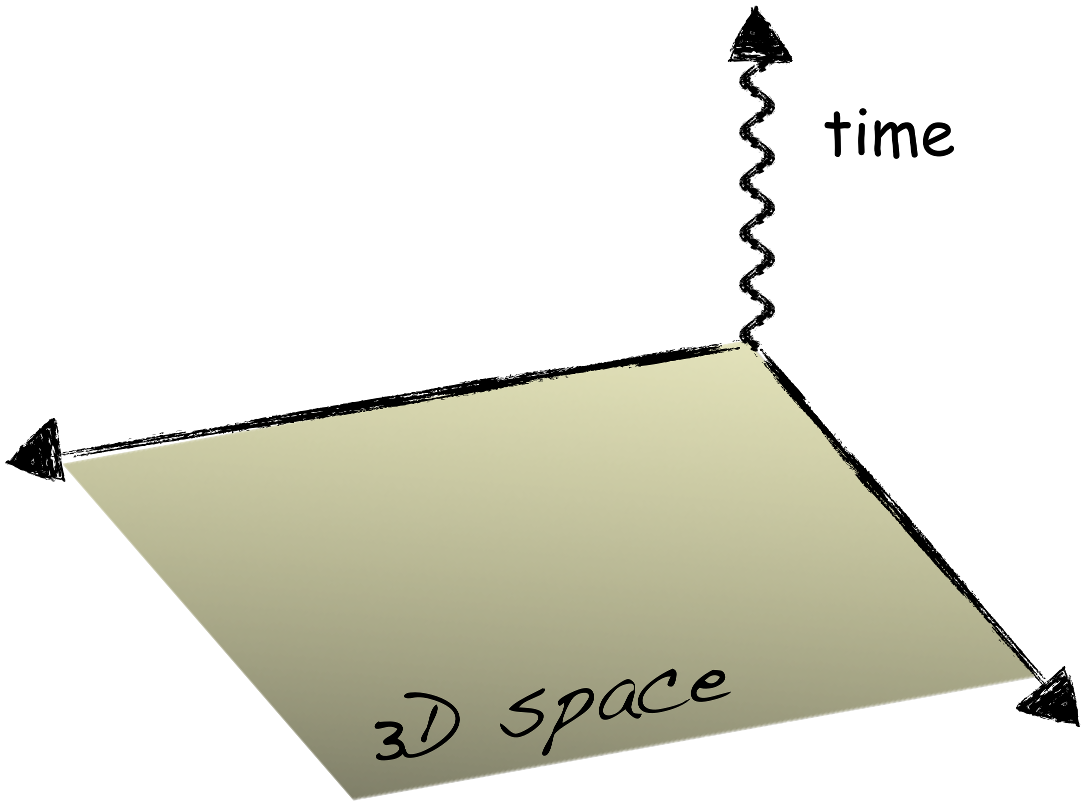
$$[\delta_{\epsilon_1}, \delta_{\epsilon_2}] \begin{pmatrix} \phi \\ \psi \end{pmatrix} = -i\left(\bar{\epsilon_2}\gamma^\mu\epsilon_1\right)\partial_\mu \begin{pmatrix} \phi \\ \psi \end{pmatrix}$$

susy$^2$ = 4D translation


How to introduce interactions?

# SUSY: a Quantum Space-Time

(G. Giudice HCPSS'09)



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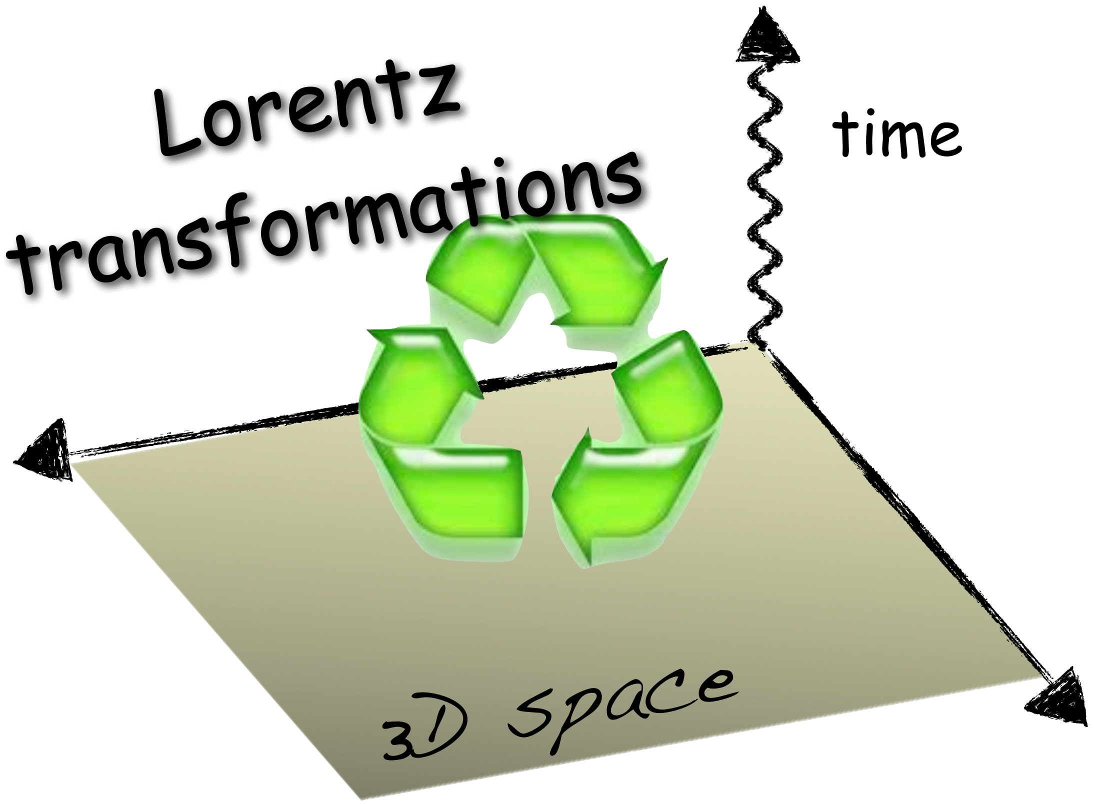

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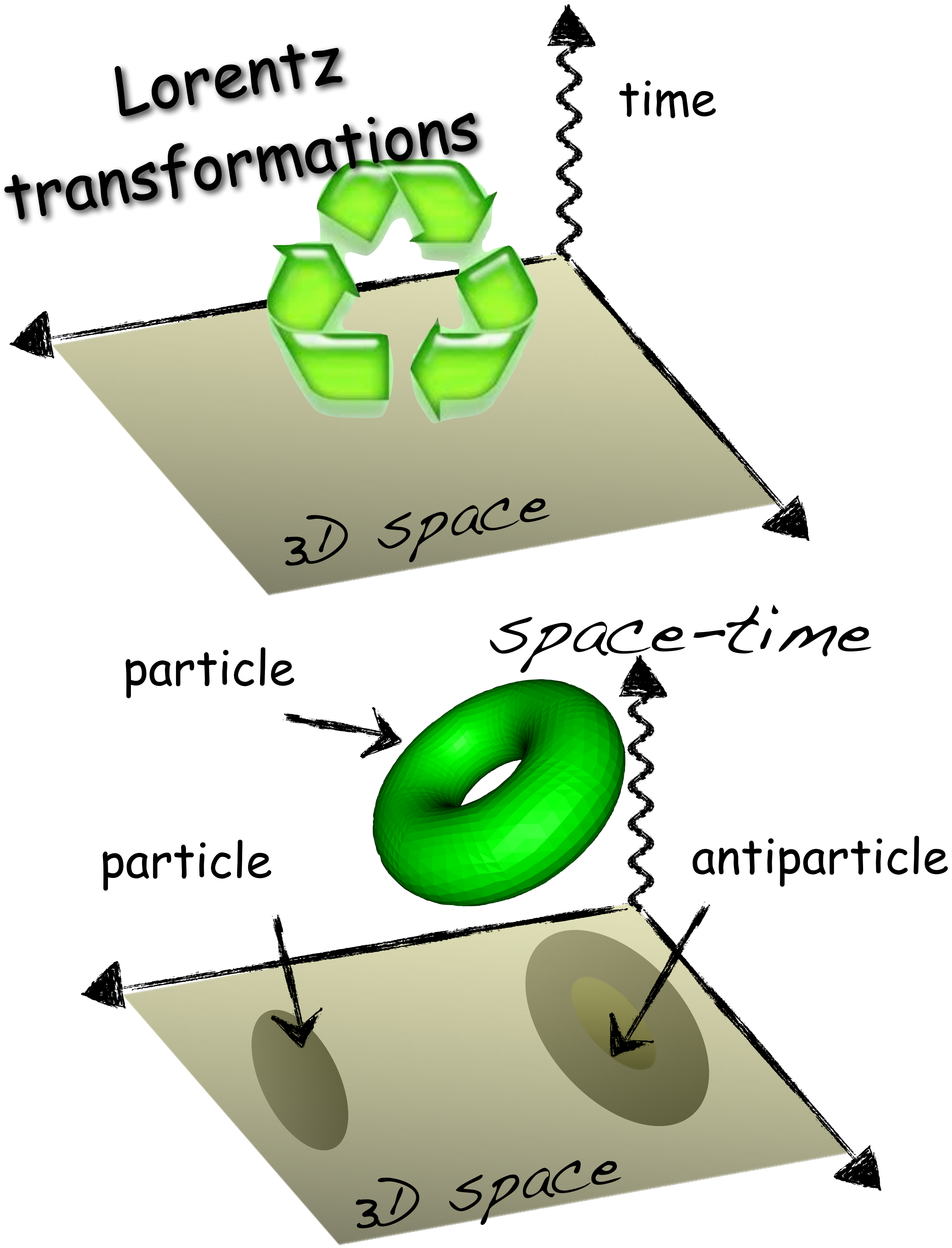

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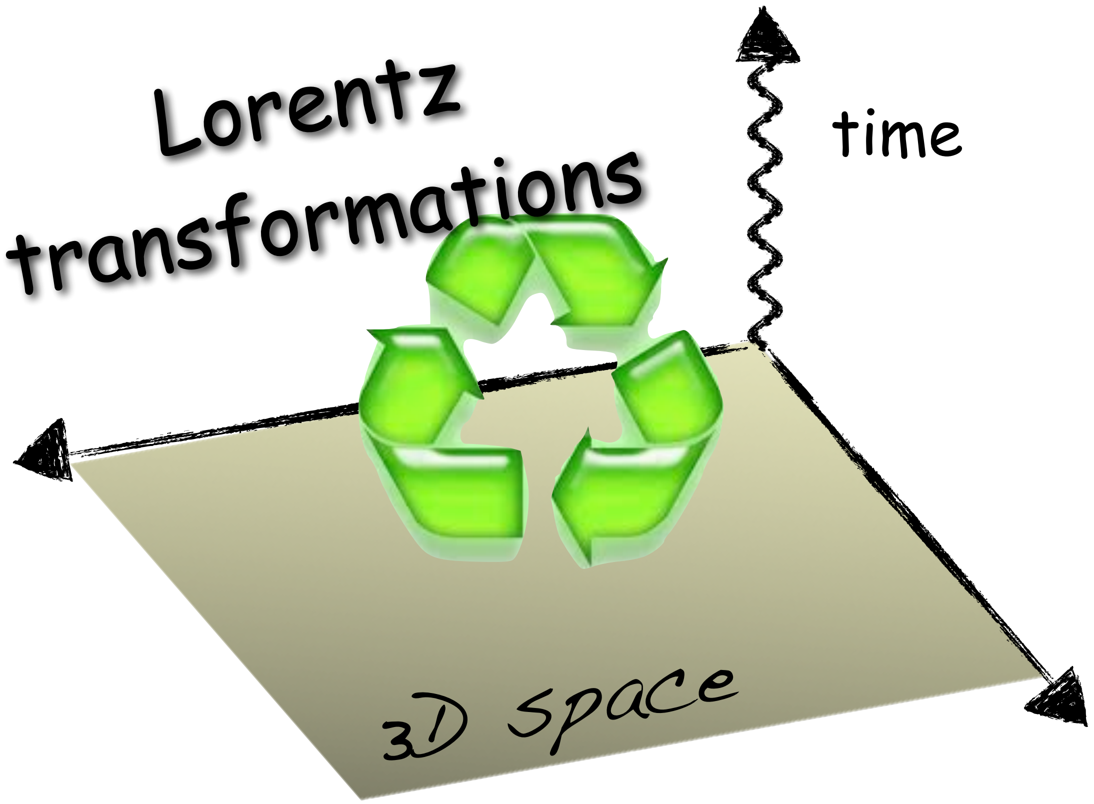
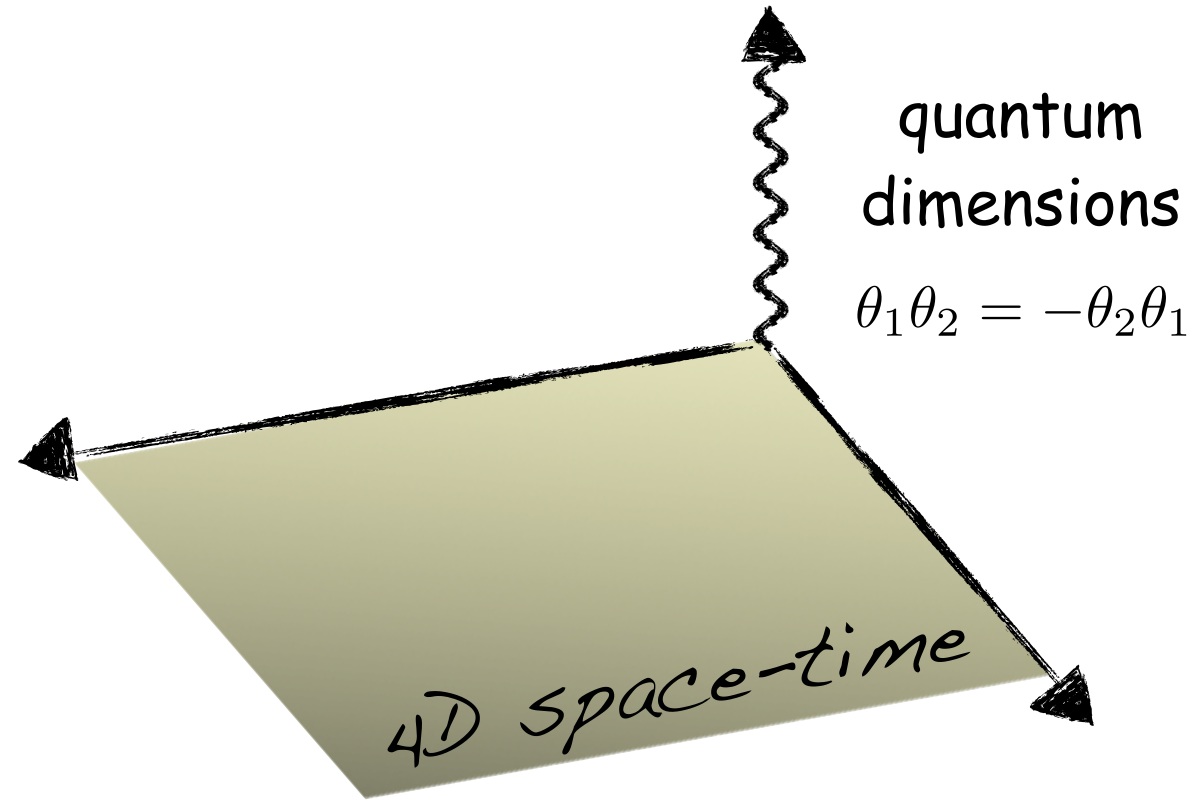
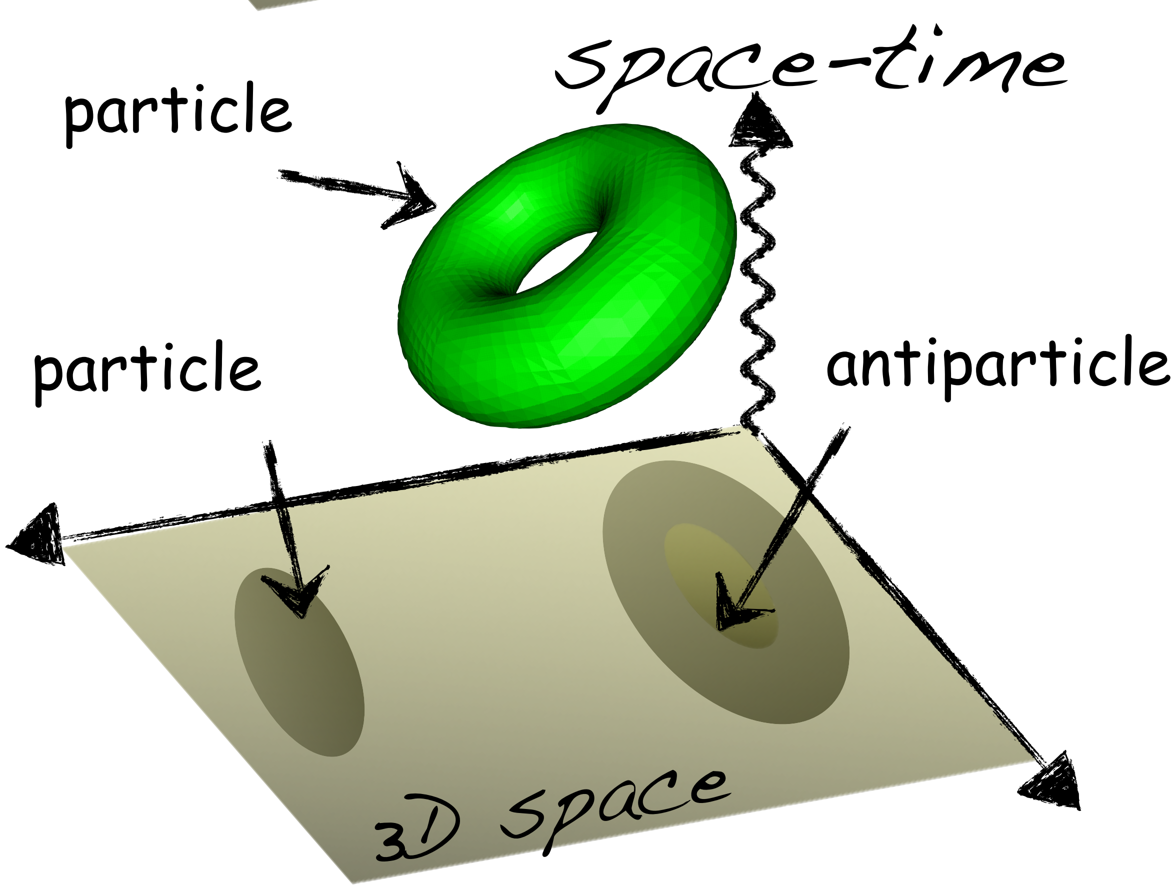
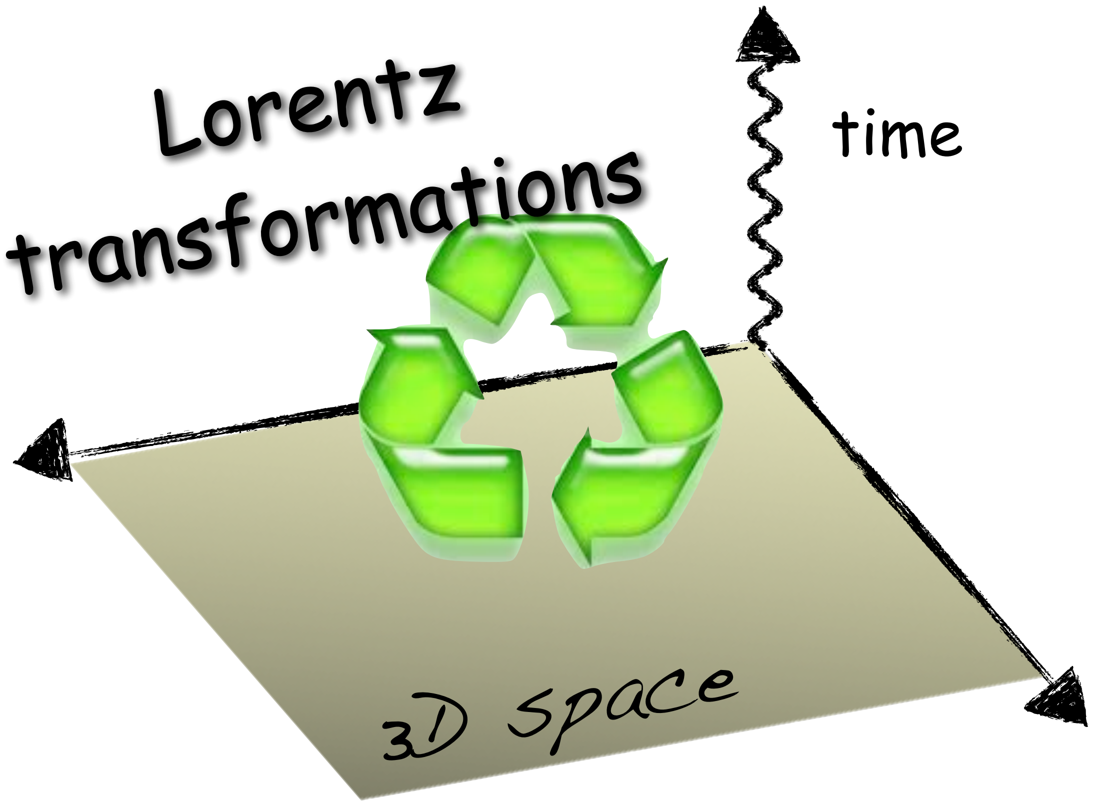


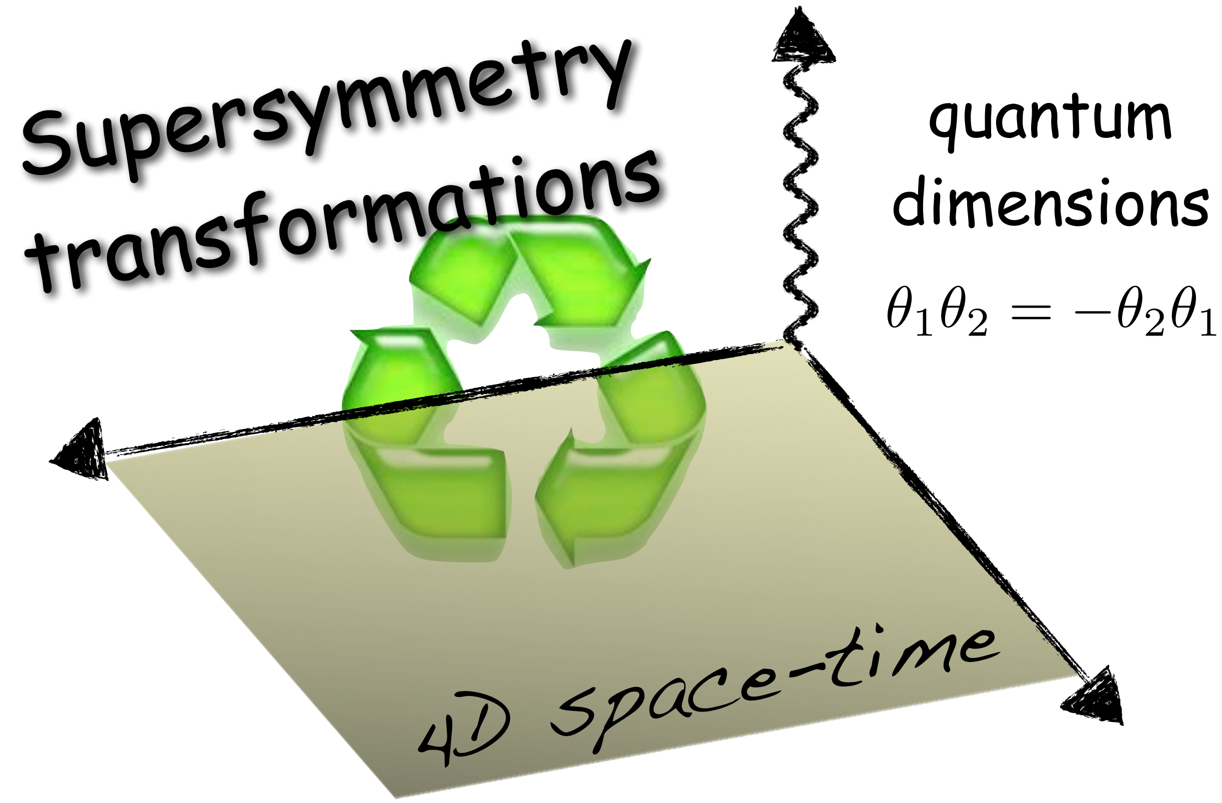



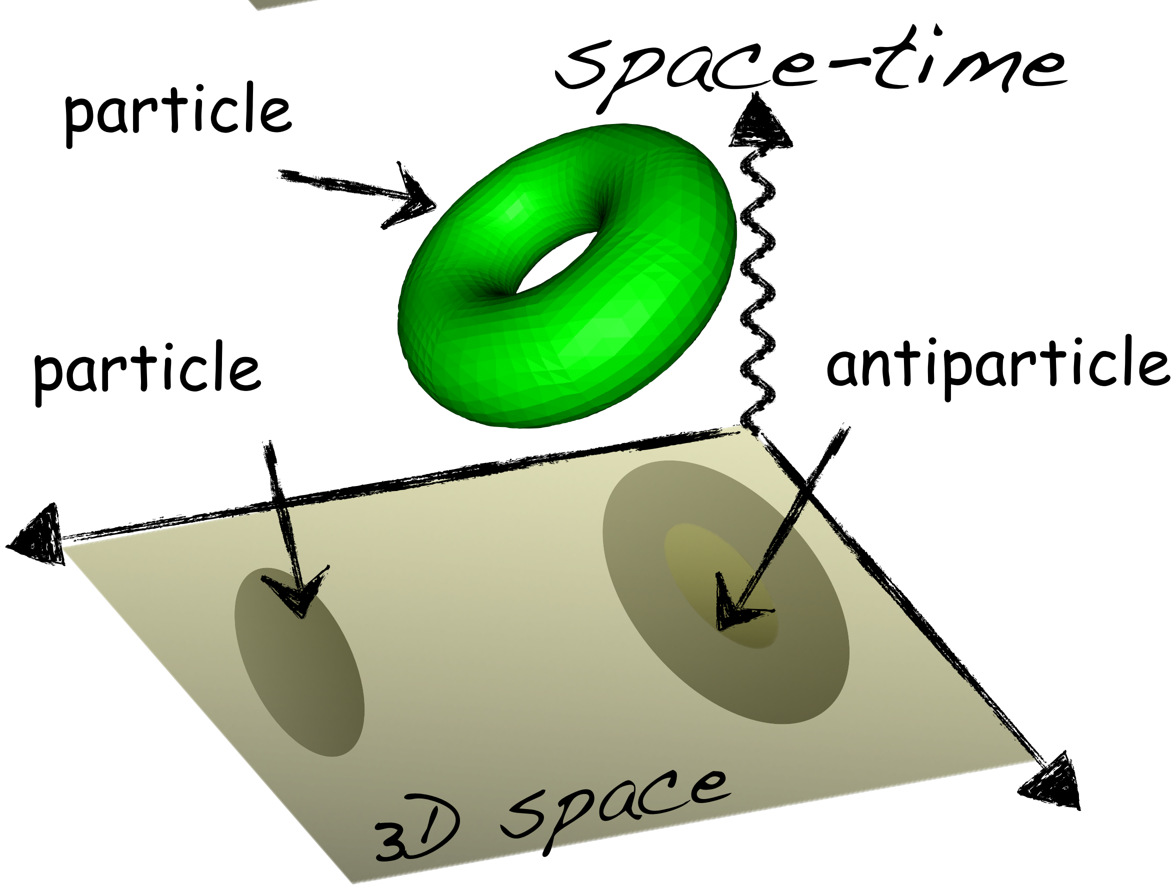



# SUSY: a Quantum Space-Time

(G. Giudice HCPSS'09)



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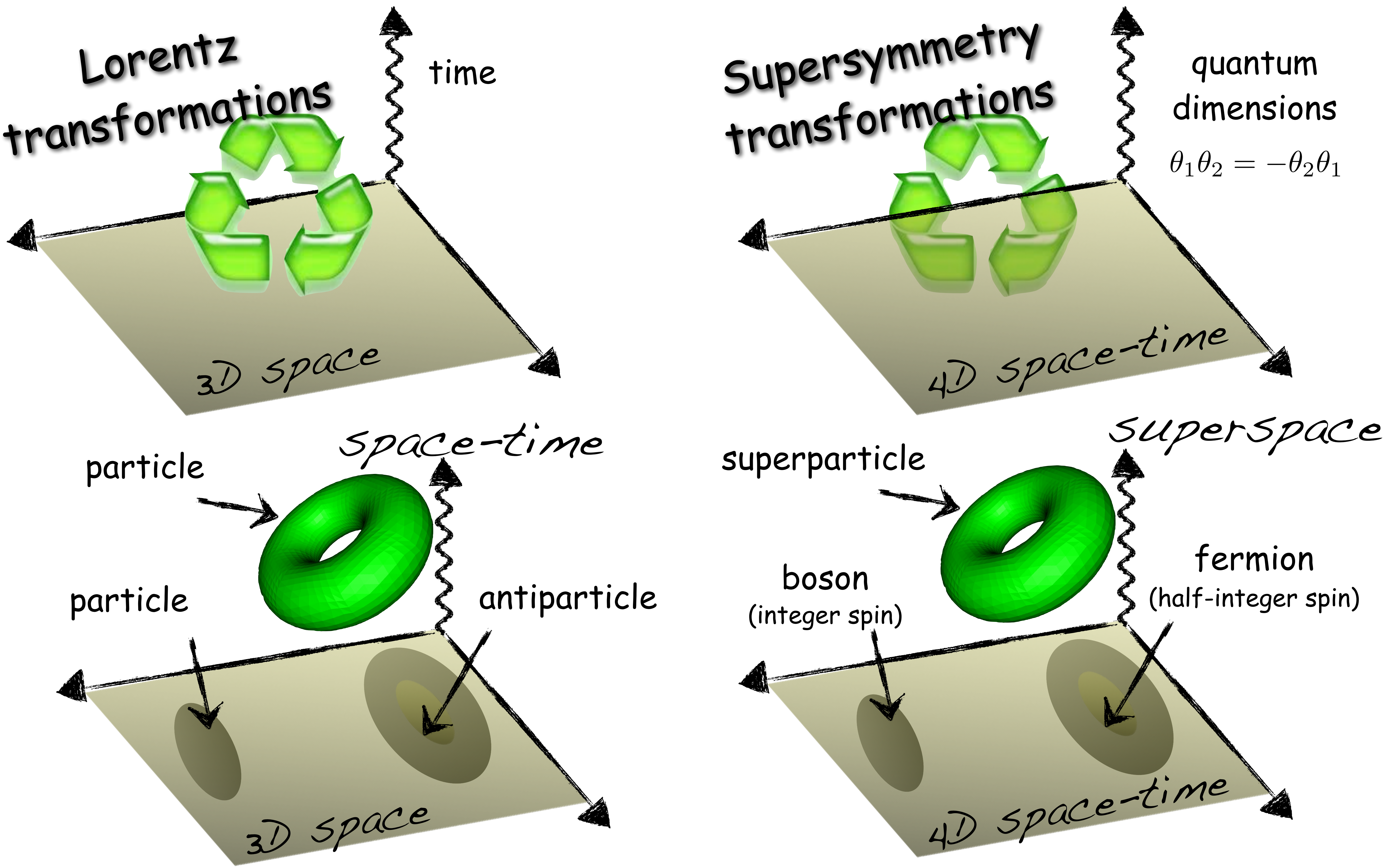

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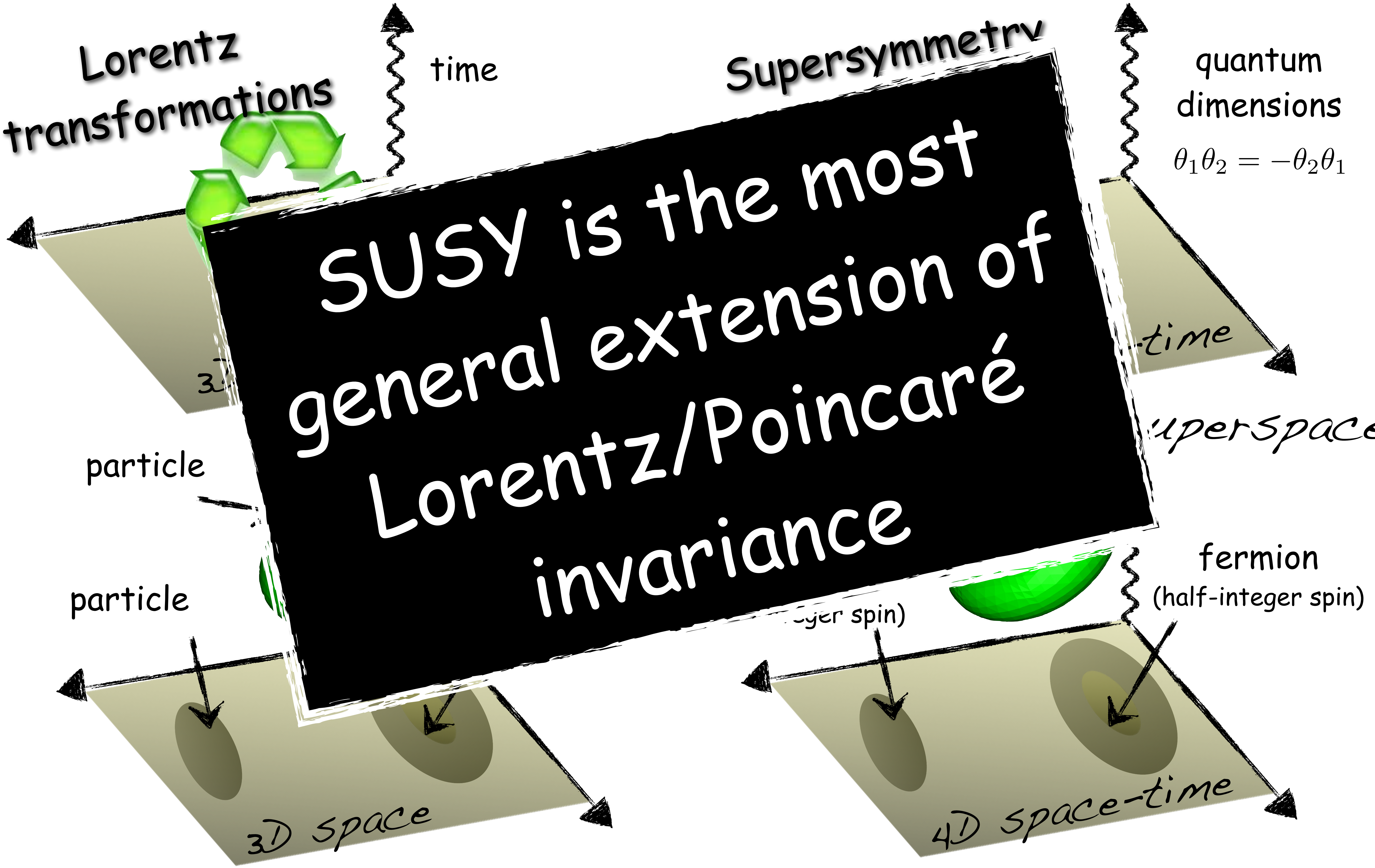


SUSY is the most general extension of Lorentz/Poincaré invariance

# Superspace

$$\left(x^{\mu}, \theta, \bar{\theta}\right)$$

usual 4D space-time coordinates

new fermionic/Grassmanian coordinates

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A general superfield can be Taylor-expanded in the superspace

$$F(x,\theta,\bar{\theta}) = f(x) + \theta\chi(x) + \bar{\theta}\bar{\chi}(x) + \theta\theta m(x) + \bar{\theta}\bar{\theta}\bar{m}(x) + \theta\sigma^\mu\bar{\theta}v_\mu(x) + i\theta\theta\bar{\theta}\bar{\lambda}(x) - i\bar{\theta}\bar{\theta}\theta\lambda(x) + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}d(x)$$

complex spin-0 fields: $f(x), m(x), \bar{m}(x), d(x)$ 4x2=8 real off-shell degrees of freedom

complex spin-1 fields: $v_\mu(x)$ 1x8=8 real off-shell degrees of freedom

Weyl spin-1/2 fields: $\chi(x), \bar{\chi}, \lambda(x), \bar{\lambda}(x)$ 4x4=16 real off-shell degrees of freedom

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- Chiral superfield $\bar{D}_{\dot{\alpha}}F = 0$

covariant derivative

ie commute with supersymmetry

⇒ $F = \phi(x) + \theta\psi(x) + \theta\theta f(x)$

| | $\phi(x)$ | $\psi(x)$ | $f(x)$ |
|---|---|---|---|
| off-shell dof | 2 | 4 | 2 |
| on-shell dof | 2 | 2 | 0 |

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### Vector superfield

$F = F^\dagger$

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| | $v_\mu(x)$ | $\lambda(x)$ | $d(x)$ |
|---|---|---|---|
| off-shell dof | 3 | 4 | 1 |
| on-shell dof | 2 | 2 | 0 |

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  massless gauge field

# SUSY Interactions - Superpotential

superpotential W = holomorphic fct of chiral superfields

$$\mathcal{L} = \mathcal{L}_{\text{kin}} - \left| \frac{\partial W}{\partial \phi} \right|^2_{|\theta=0} - \frac{1}{2} \frac{\partial^2 W}{\partial \phi^2}_{|\theta=0} \psi\psi + h.c.$$

is invariant under susy

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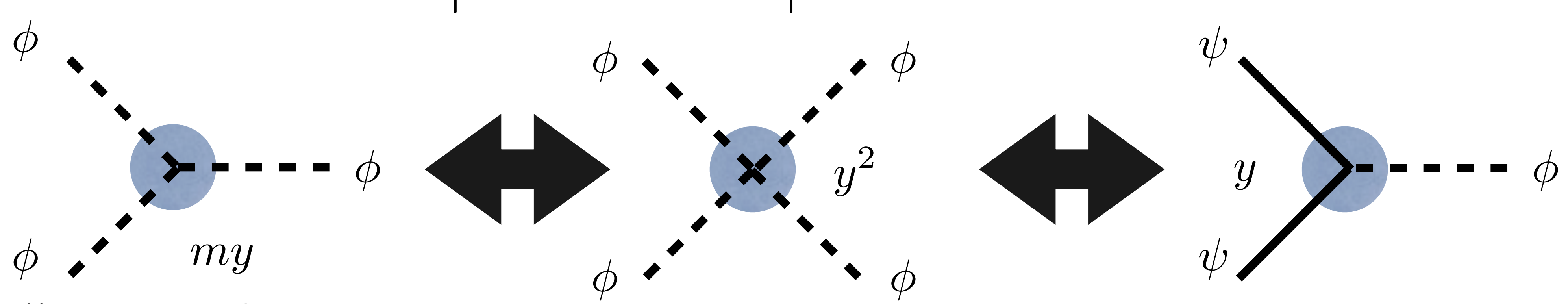
## example: susy Yukawa interaction

$$W = \frac{1}{2}m\phi^2 + \frac{1}{3!}y\phi^3 \qquad \partial_\phi W = m\phi + \frac{1}{2}y\phi^2 \qquad \partial^2_\phi W = m + y\phi$$

$$\mathcal{L} = \mathcal{L}_{\rm kin} - \left|m\phi + \frac{1}{2}y\phi^2\right|^2 - \frac{1}{2}\left(m + y\phi\right)\psi\psi + h.c.$$

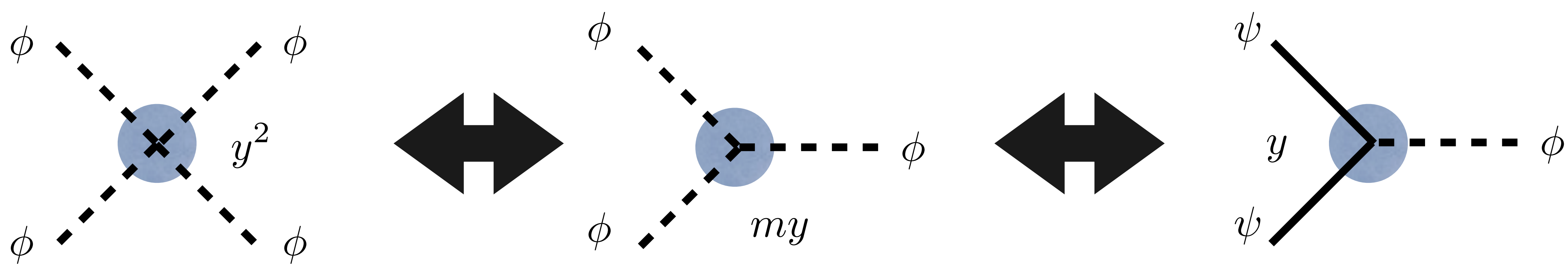



will be modified by soft susy breaking

will survive soft susy breaking

# SUSY Interactions

heuristic rule:
replace bosons with fermions in the interaction



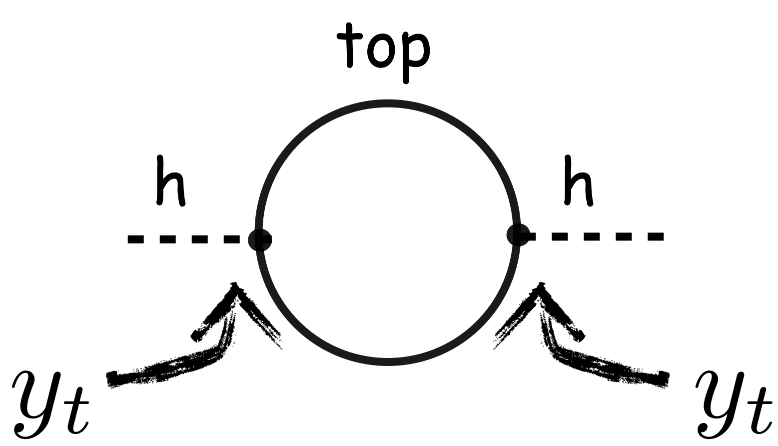

Scalar potential is not arbitrary any longer:
dictated by gauge and Yukawa interactions.
One important consequence: upper bound on Higgs mass in simplest models

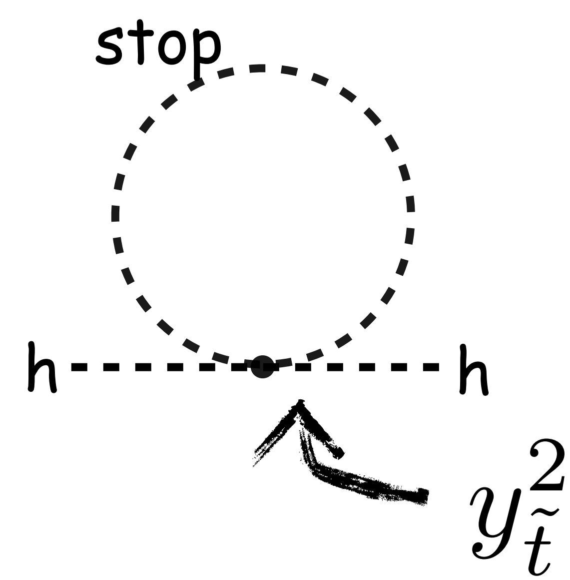
**SUSY predictions**

many new particles
many new interactions

# SUSY and the (big) Hierarchy Problem

(DE Kaplan HCPSS'07)




$$\delta m_H^2 \propto \left(y_t^2 - y_{\tilde{t}}^2\right) \Lambda^2 + \left(m_t^2 - m_{\tilde{t}}^2\right) \log \Lambda$$

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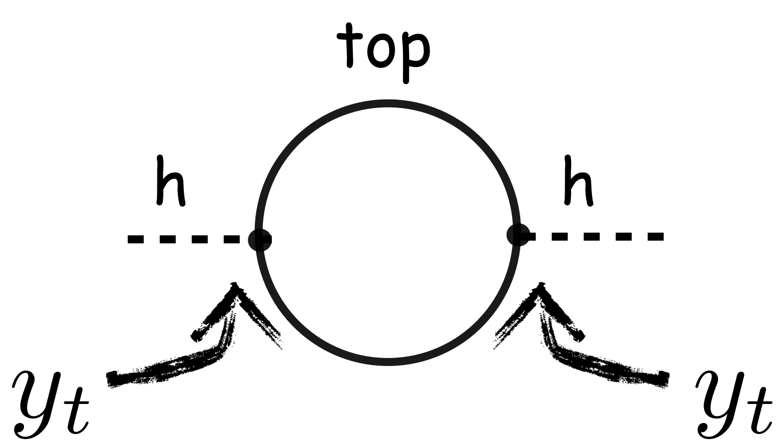


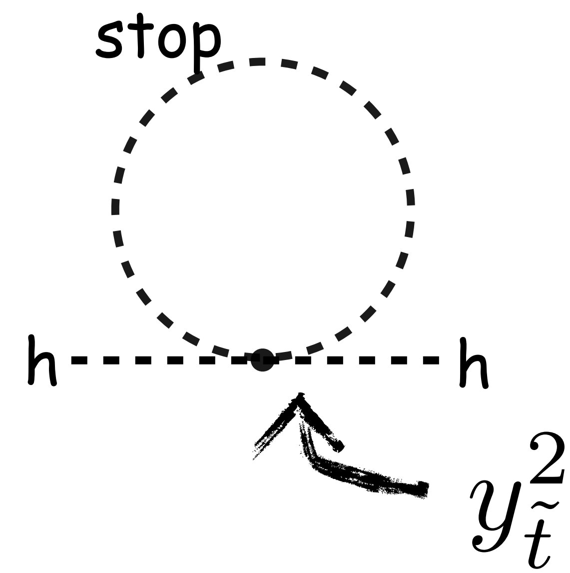


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$y_t \neq y_{\tilde{t}}$ ⇩ $\Lambda^2$ dv — hard susy breaking

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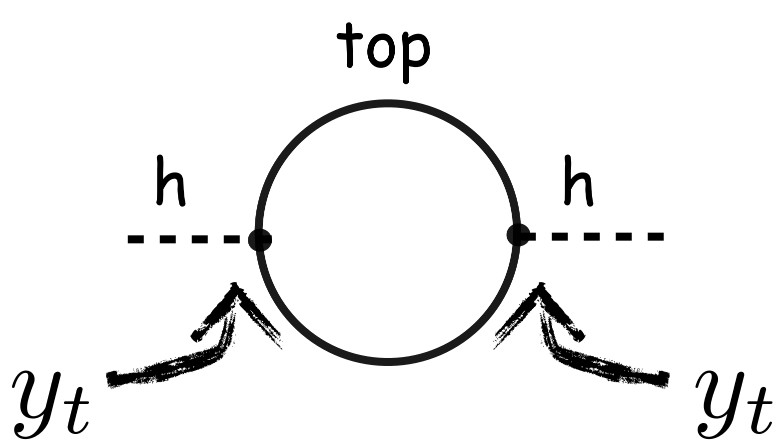


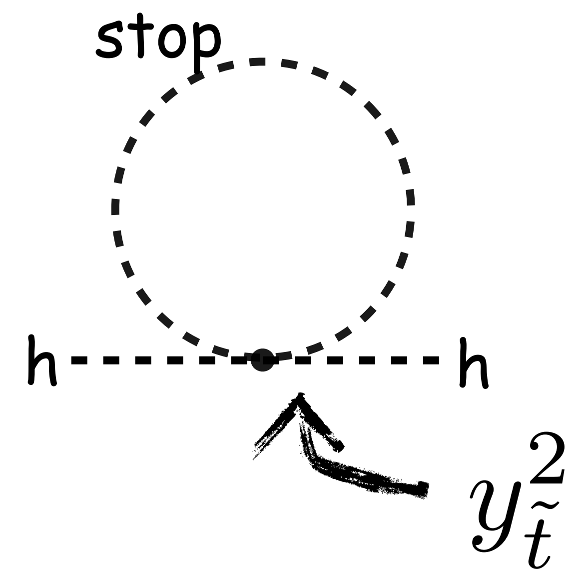


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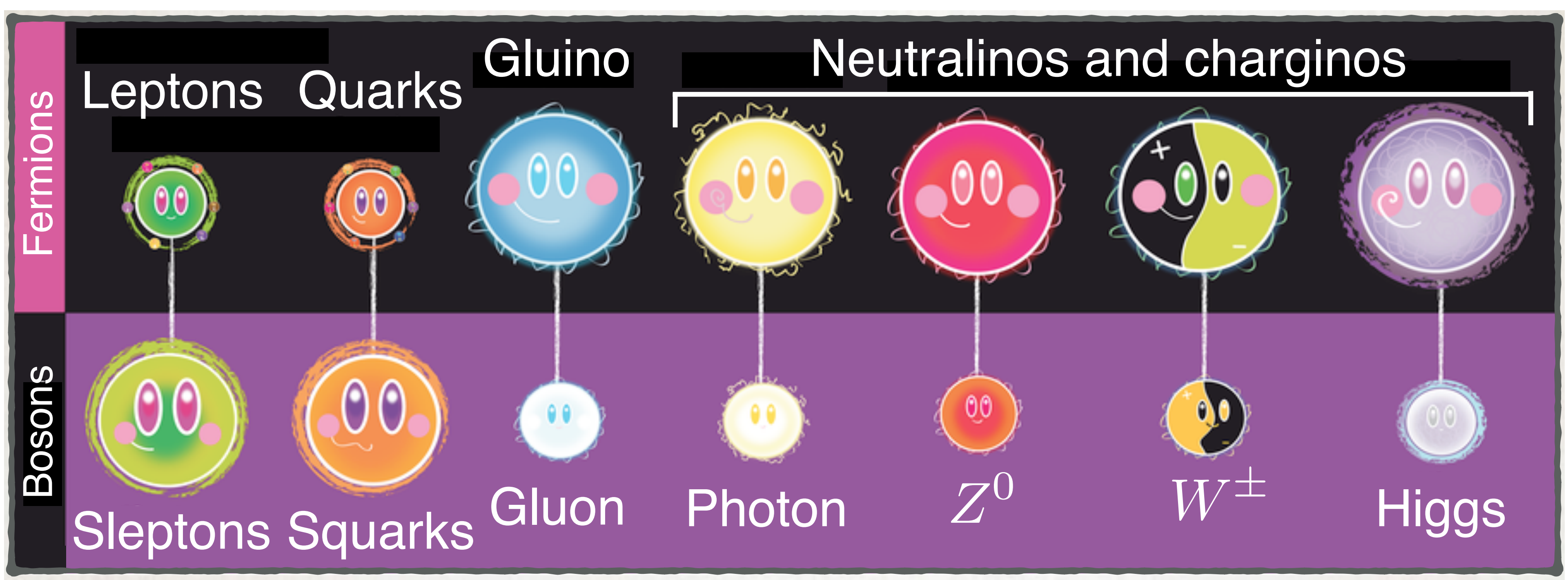
SUSY biggest pb: how to dynamically generate soft breaking terms compatible with exp constraints?

# Minimal Supersymmetric SM

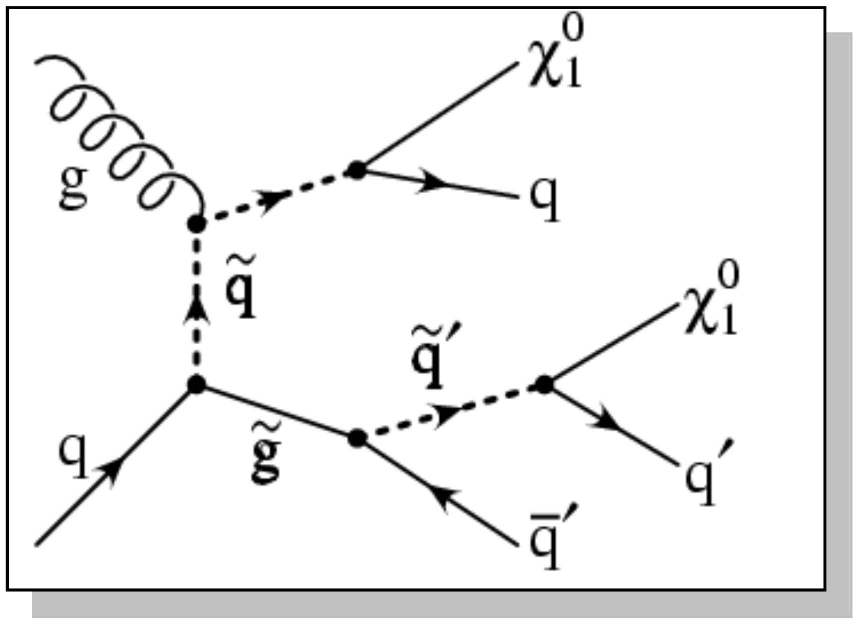
| particles | | | | Sparticles | | | |
|---|---|---|---|---|---|---|---|
| *quarks* | $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $u_R$ | $d_R$ | *squarks* | $\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$ | $\tilde{u}_R$ | $\tilde{d}_R$ |
| *leptons* | $\begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$ | $e_R$ | | *sleptons* | $\begin{pmatrix} \tilde{e}_L \\ \tilde{\nu}_L \end{pmatrix}$ | $\tilde{e}_R$ | |
| *Higgs doublets* | $H_1$ (hypercharge $= -1$)<br>$H_2$ (hypercharge $= +1$) | | | *Higgsinos* | $\tilde{H}_1$<br>$\tilde{H}_2$ | | |
| | $W_\mu^\pm, W_\mu^3$ | | | *winos* | $\tilde{\omega}^\pm, \tilde{\omega}^3$ | | |
| | $B_\mu$ | | | *bino* | $\tilde{b}$ | | |
| | $G_\mu^A$ | $A = 1,\ldots,8$ | | *gluinos* | $\tilde{g}^A$ | | |

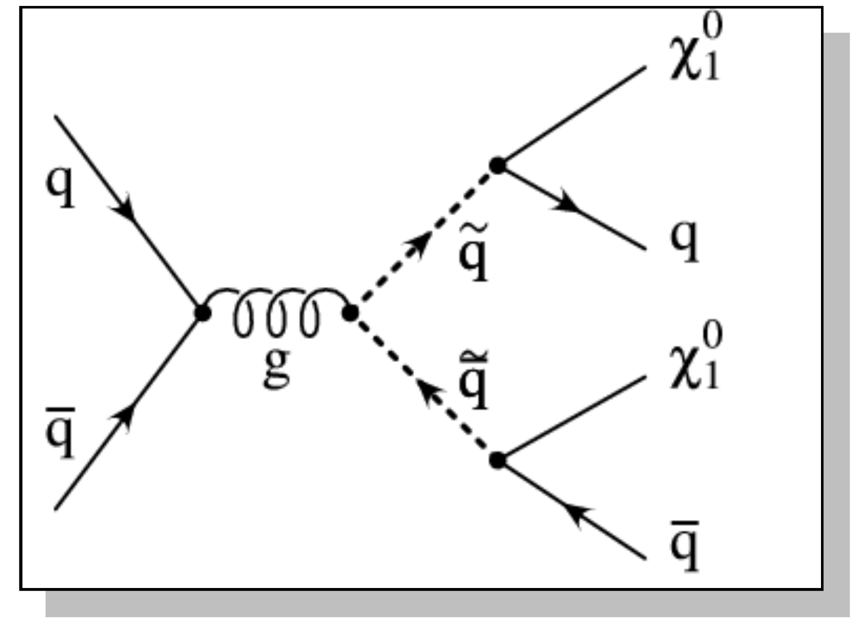
(G. Giudice HCPSS'09)



# SUSY Searches

gluinos and squarks are produced by QCD interactions



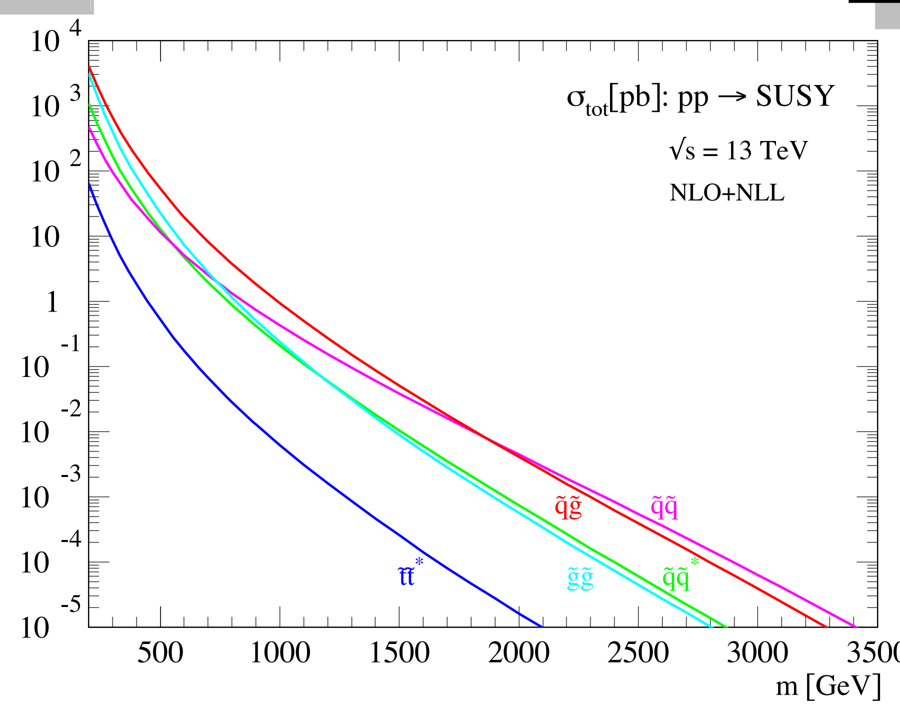




Figure 1: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 13$ TeV.

LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

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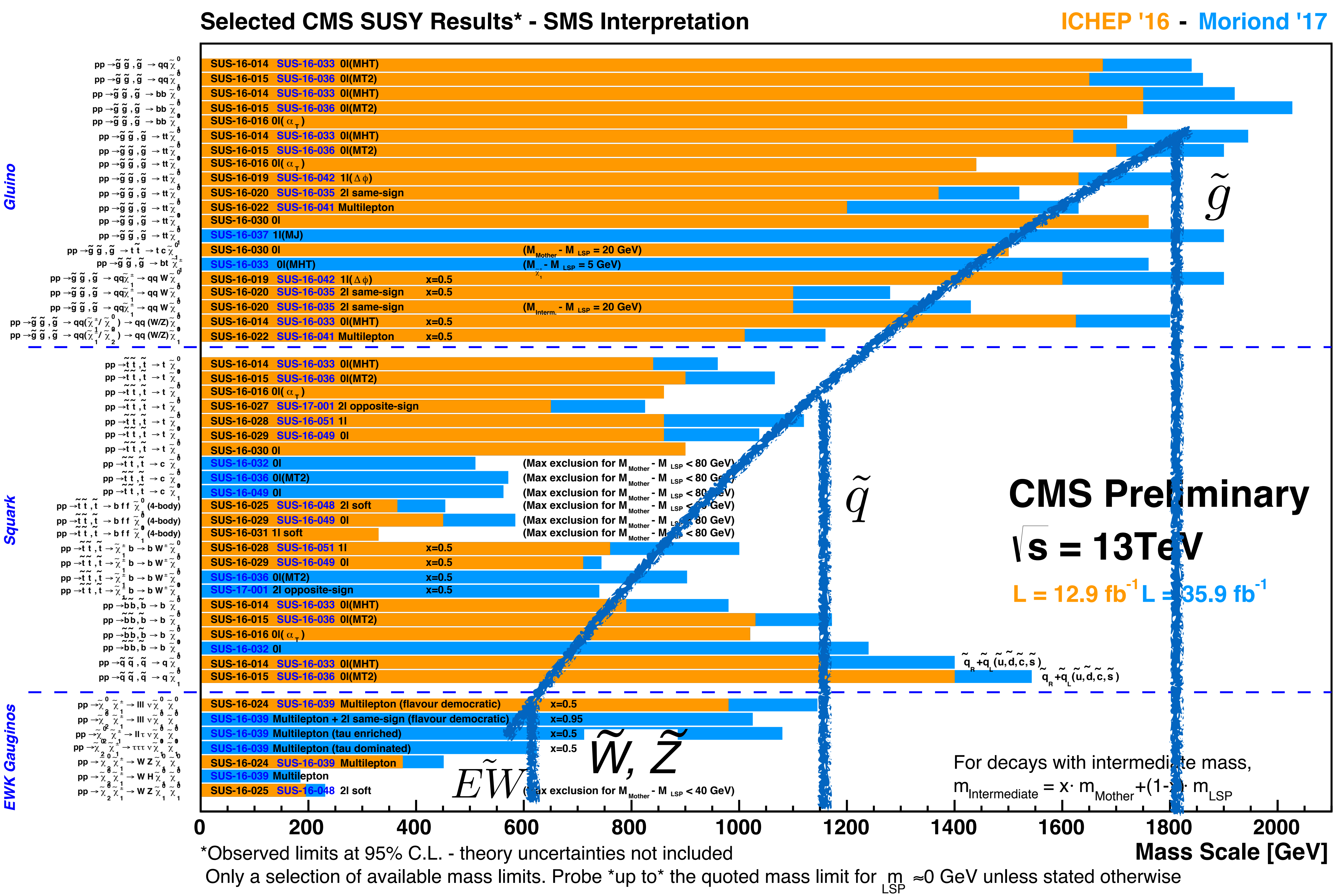


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# MSSM Higgs mass and Stop Searches

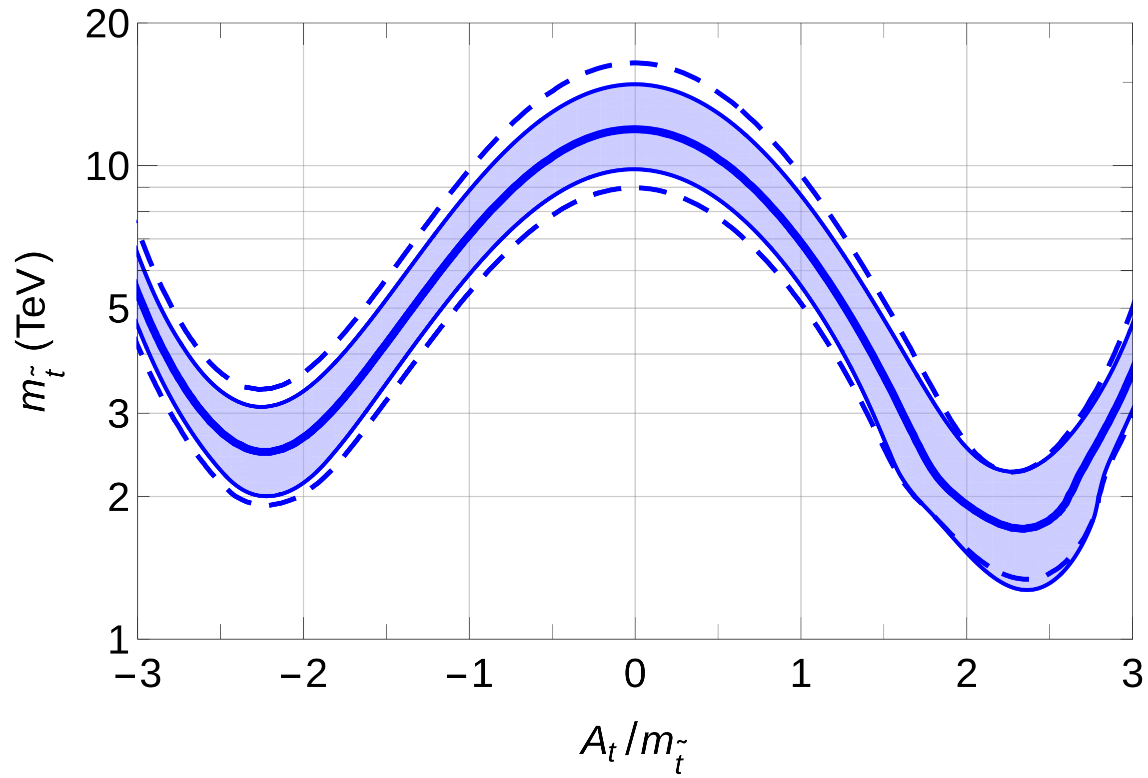


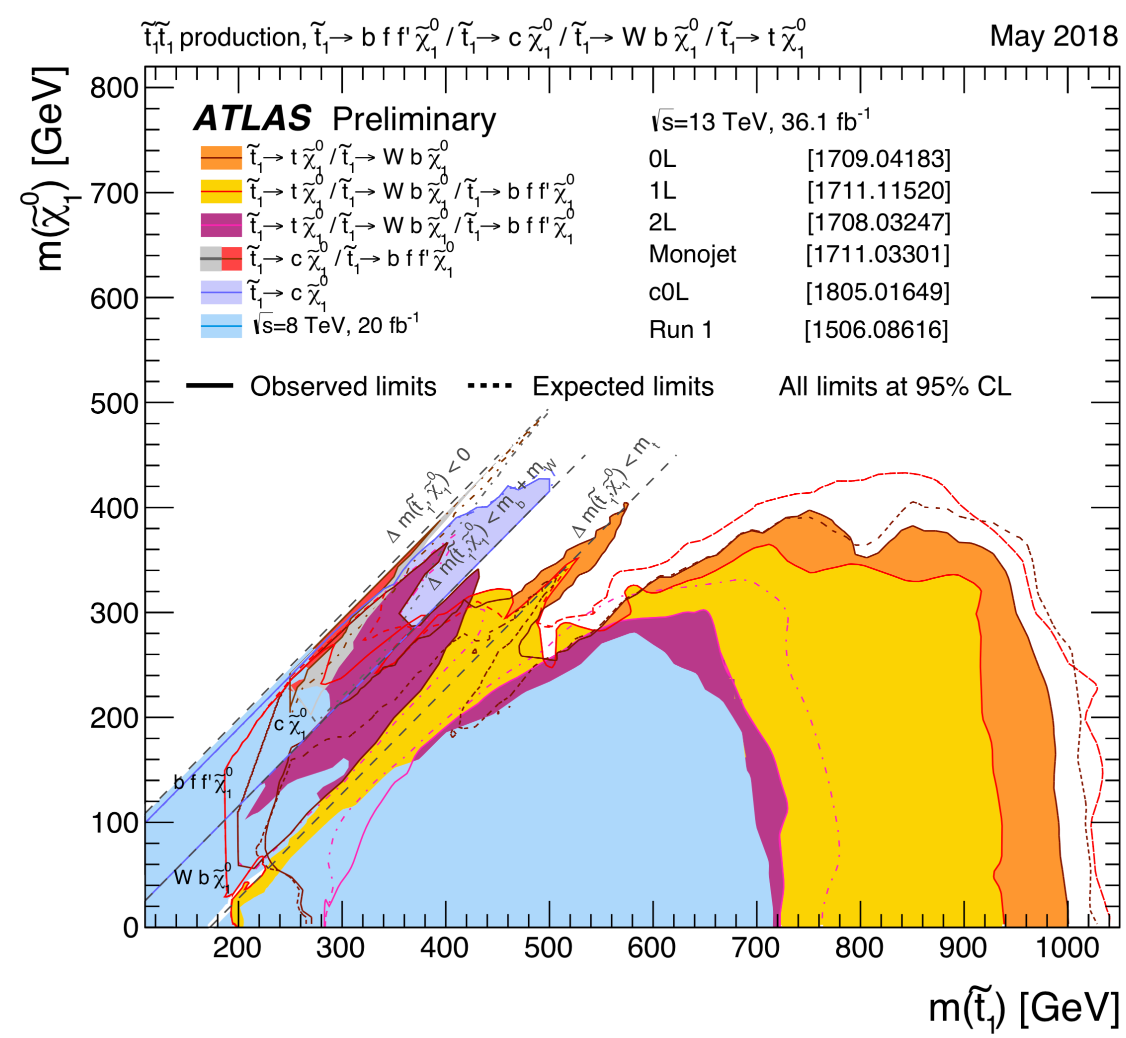

Figure 5: *Allowed values of the OS stop mass reproducing $m_h = 125$ GeV as a function of the stop mixing, with $\tan\beta = 20$, $\mu = 300$ GeV and all the other sparticles at 2 TeV. The band reproduce the theoretical uncertainties while the dashed line the $2\sigma$ experimental uncertainty from the top mass. The wiggle around the positive maximal mixing point is due to the physical threshold when $m_{\tilde{t}}$ crosses $M_3 + m_t$.*

Pardo Vega, Villadoro '15 + many others

One needs heavy stop(s) to obtain a 125GeV Higgs (within the MSSM)

Current and future bounds on stop mass

LHC (2018)



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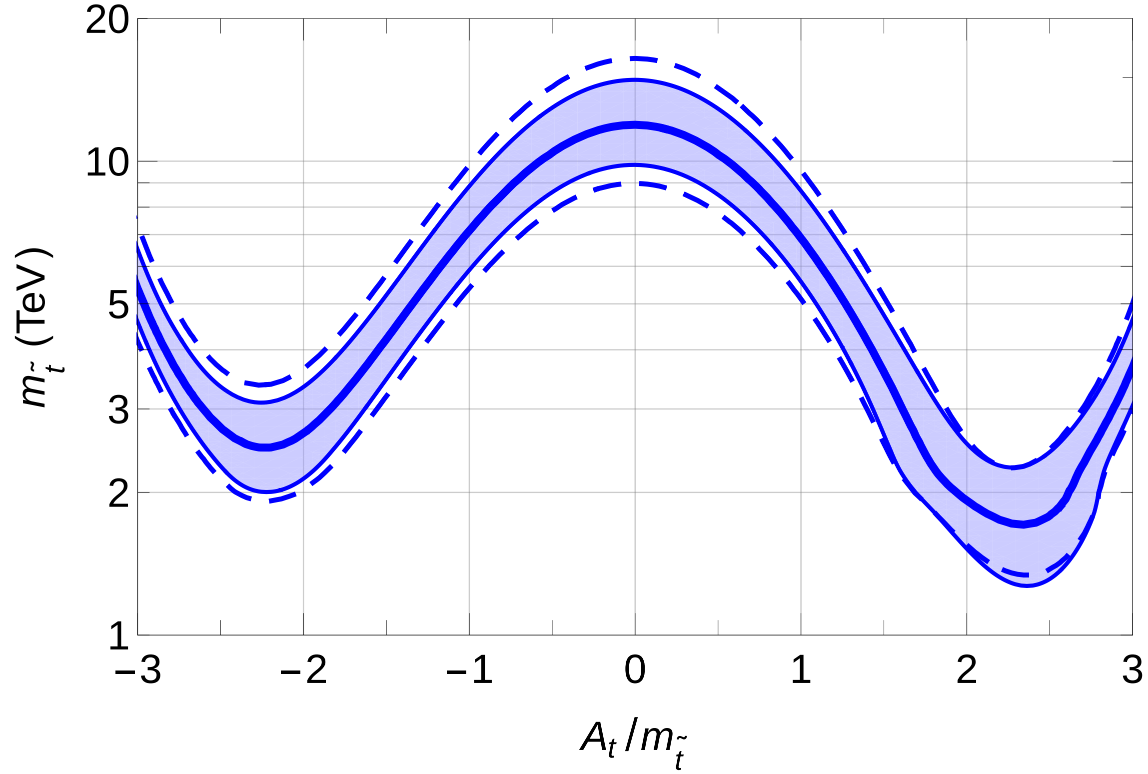


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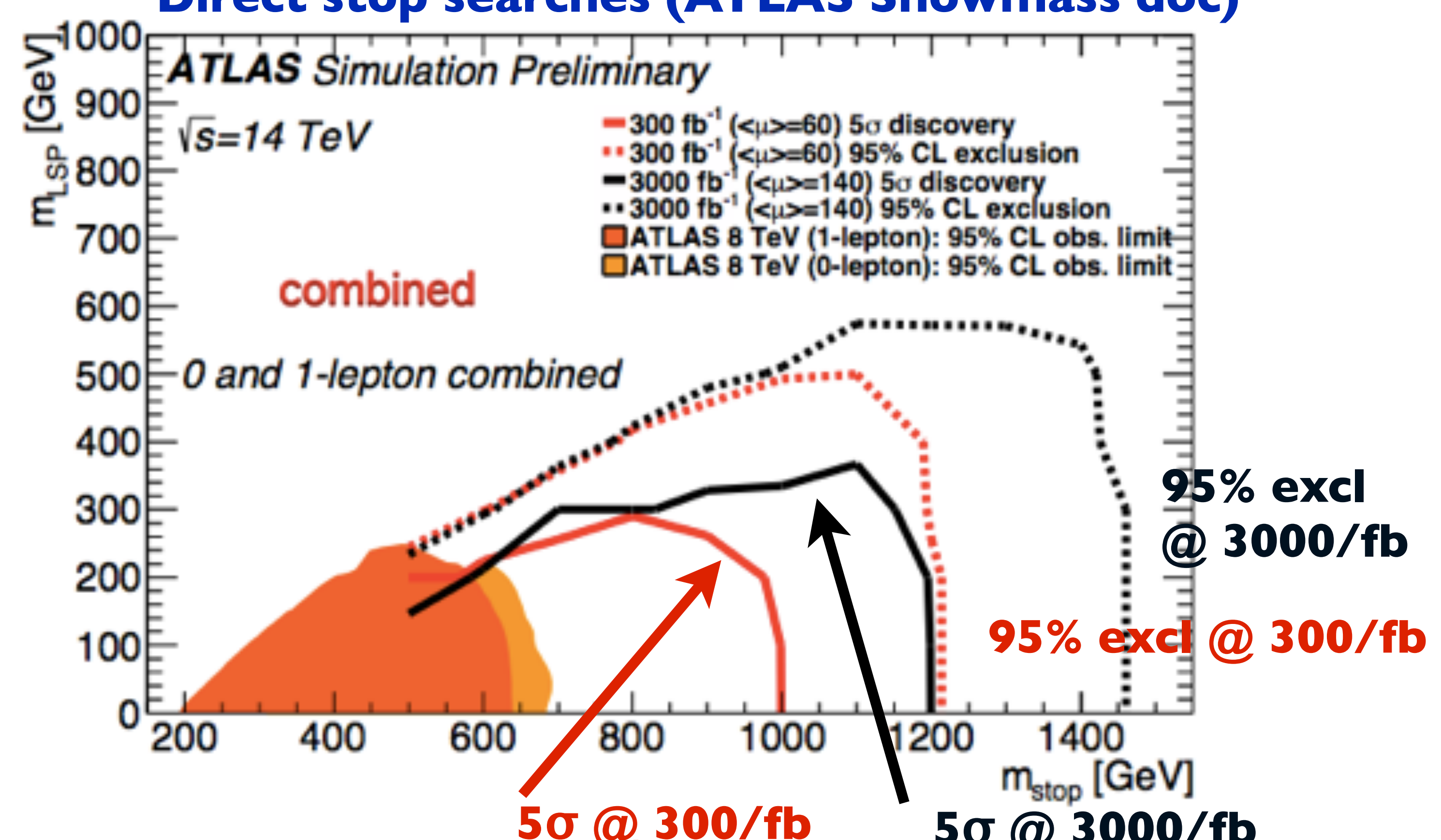
**Direct stop searches (ATLAS Snowmass doc)**




Current and future bounds on stop mass

HL-LHC (2030)

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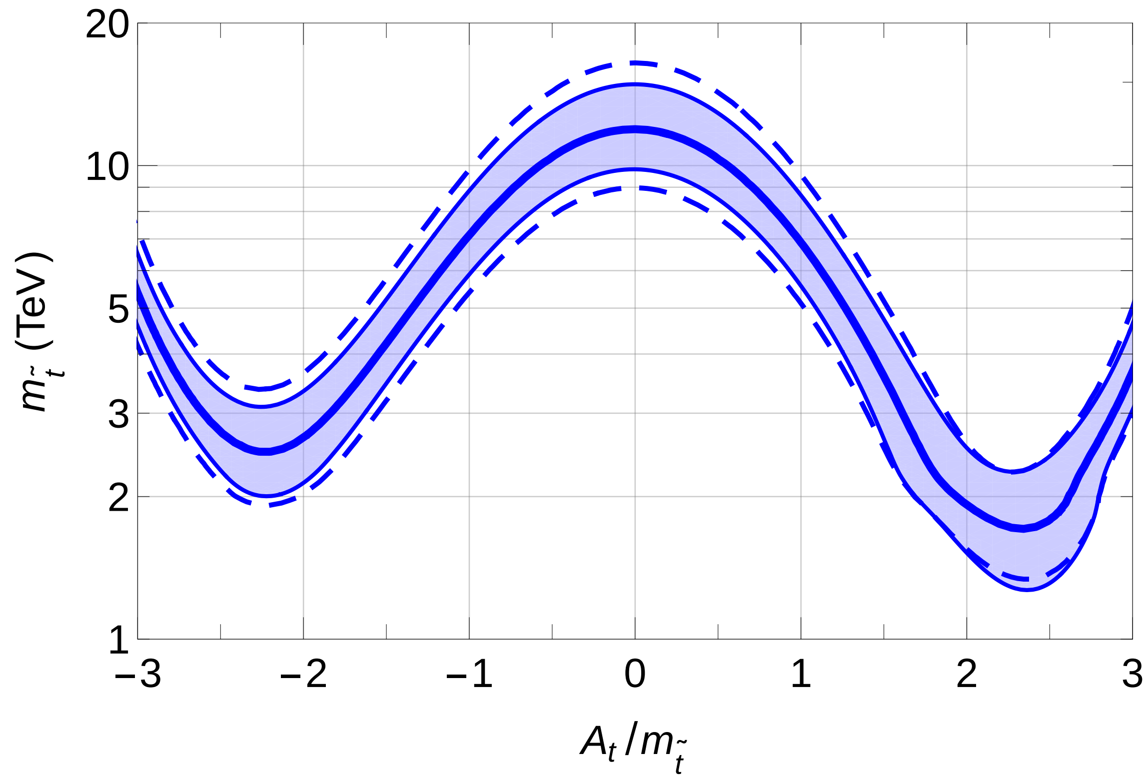
Pardo Vega, Villadoro '15 + many others

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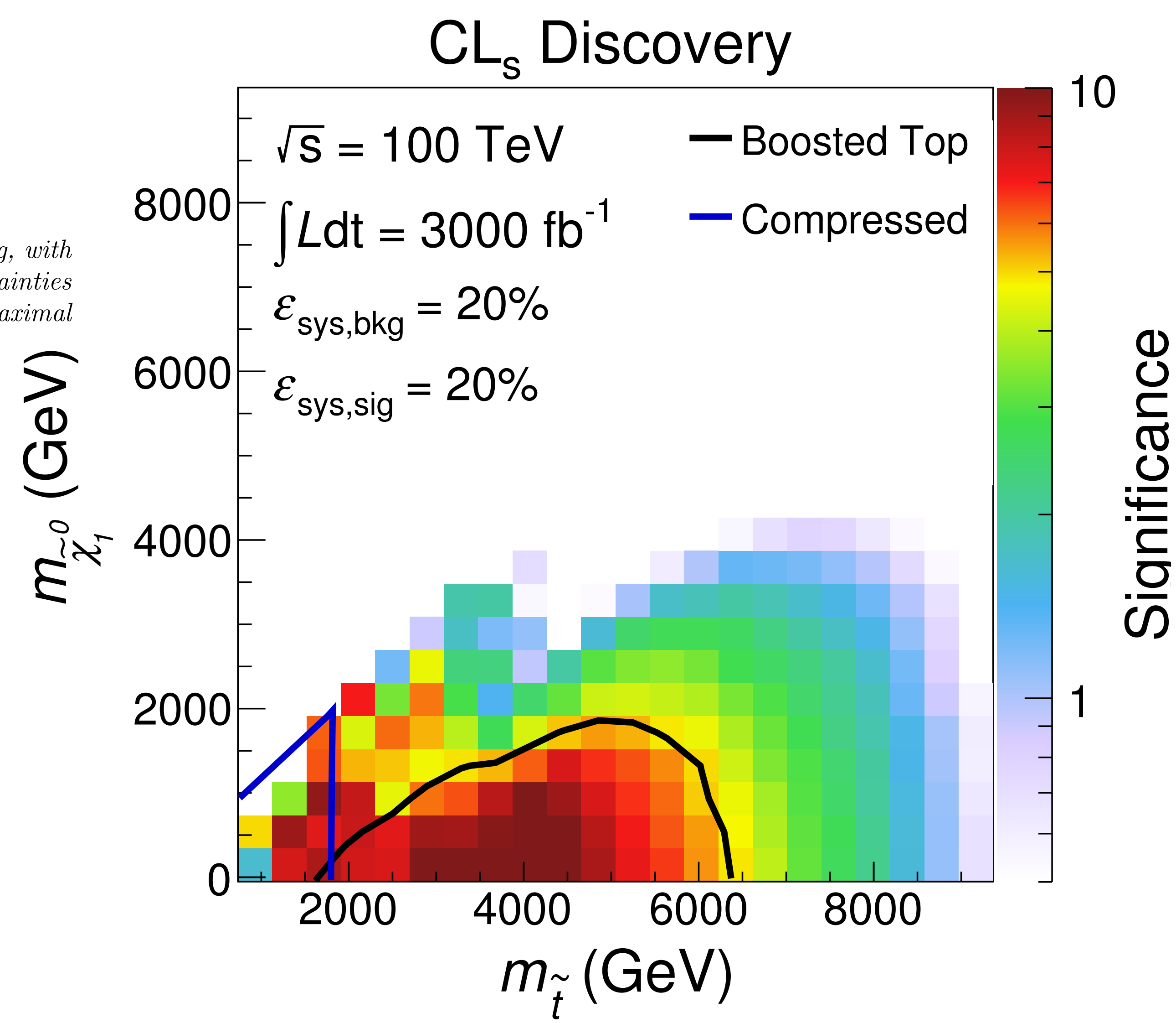
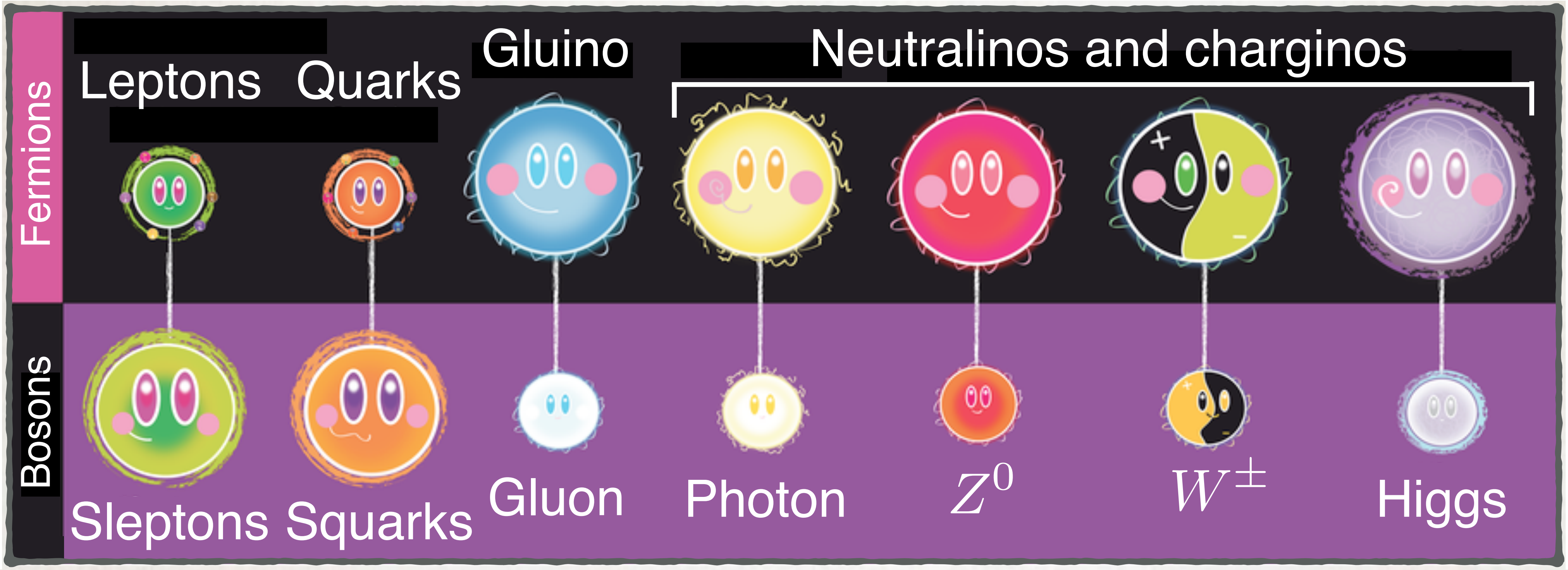
FCC-hh @ 100TeV (2060)



# Natural SUSY: where is everybody?




Two-loops: gluinos $\mathcal{O}\left(\frac{16\,\pi^2}{\text{Log}} m_h\right)$

One-loop: stops $\mathcal{O}\left(\sqrt{\frac{16\,\pi^2}{\text{Log}}} m_h\right)$

Tree-level: Higgsinos $\mathcal{O}(m_h)$

HIGGSINO

$$\mu \lesssim 200\,\text{GeV}\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

STOP

$$m_{\text{stop}} \lesssim 500\,\text{GeV}\,\frac{\sin\beta}{\sqrt{1+(A_t/m_{\text{stop}})^2}}\sqrt{\frac{3}{\log(\Lambda/\text{TeV})}}\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

GLUINO

$$m_{\text{gluino}} \lesssim 1000\,\text{GeV}\,\sin\beta\,\frac{3}{\log(\Lambda/\text{TeV})}\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

TIM COHEN [UNIVERSITY OF OREGON]

Tuning: $\Delta \equiv \frac{2\,\delta m_H^2}{m_h^2}$

# Saving SUSY

SUSY is Natural
but not plain vanilla

- ~~CMSSM~~
- pMSSM
- NMSSM
- colorless stops ("folded susy")
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families) Mahbubani et al
  - reduce MET (e.g. R-parity, Csaki et al compressed spectrum)
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy) Fan et al

## $LHC_{300(0) fb^{-1}}$ will tell!

Good coverage of

hidden natural susy

- mono-top searches (DM, flavored naturalness - mixing among different squark flavors-, stop-higgsino mixings)
- mono-jet searches with ISR recoil (compressed spectra)
- precise tt inclusive measurement+ spin correlations (stop → top + soft neutralino)
- multi-hard-jets (RPV, hidden valleys, long decay chains)

# MSSM Superpotential

the most general ("renormalizable") superpotential of the MSSM

$$W = H_u Q D + H_u Q U + H_d L E + \mu H_u H_d + L Q D + U D D + L L E + \mu_L L H_u$$

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$\not{B}, \not{L}$

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$\not{B}, \not{L}$

lead to fast p decay

R parity forbids all the dangerous terms

| superfields | R-parity | fields |
|---|---|---|
| $Q, D, U, L : -1$ <br> $H_u, H_d : +1$ | doesn't commute with susy <br> $\theta : -1$ | $\phi_{\rm SM} : +1$ <br> $\phi_{\rm superpartner} : -1$ |

nice consequences:

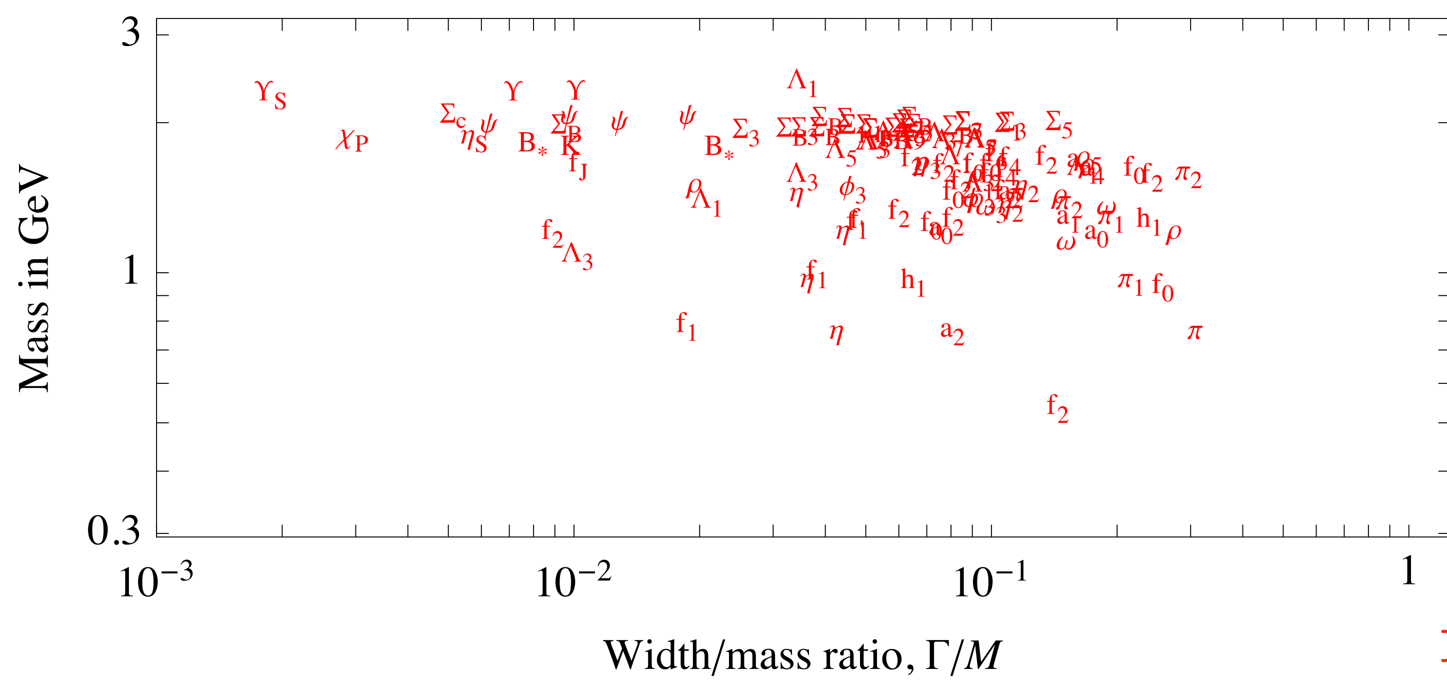
- superpartners are pair-produced
- Lightest Supersymmetric Particle is stable → DM?

# Technical Details

# 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

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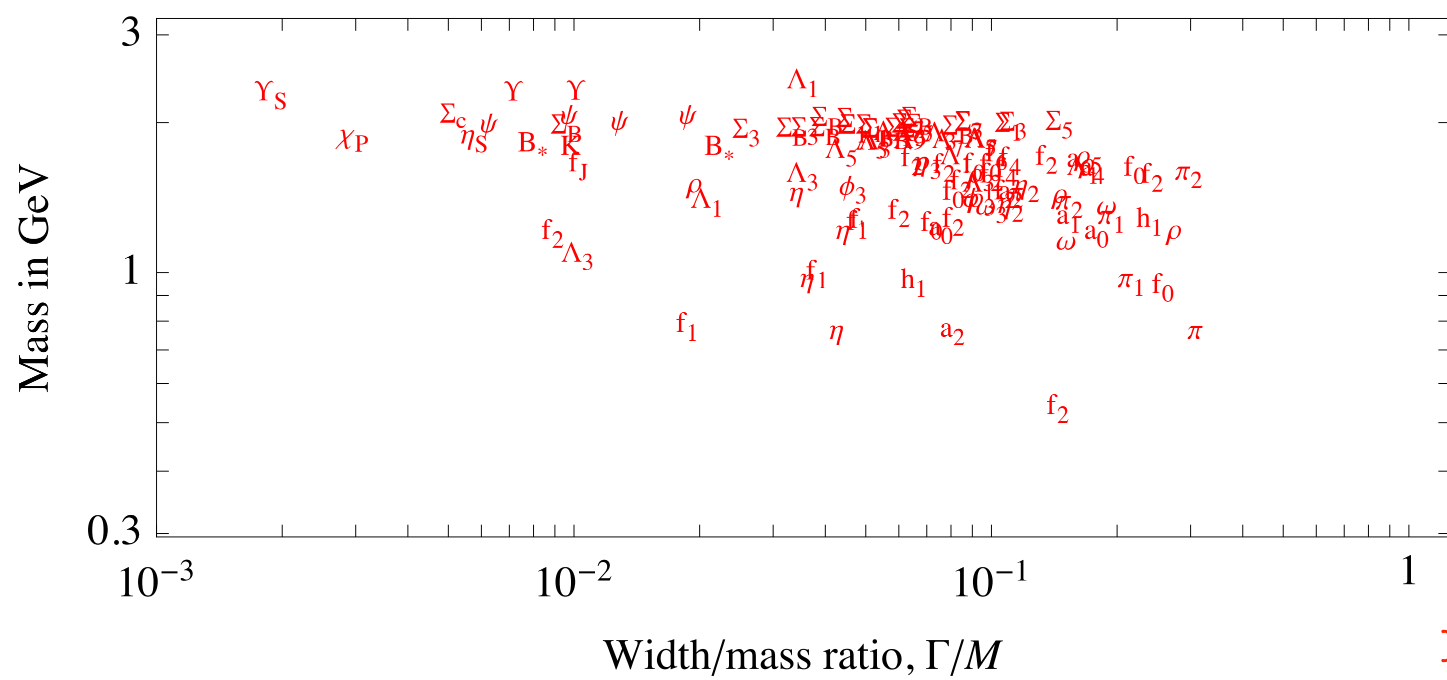


Franceschini et al. '15

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

# Composite Higgs

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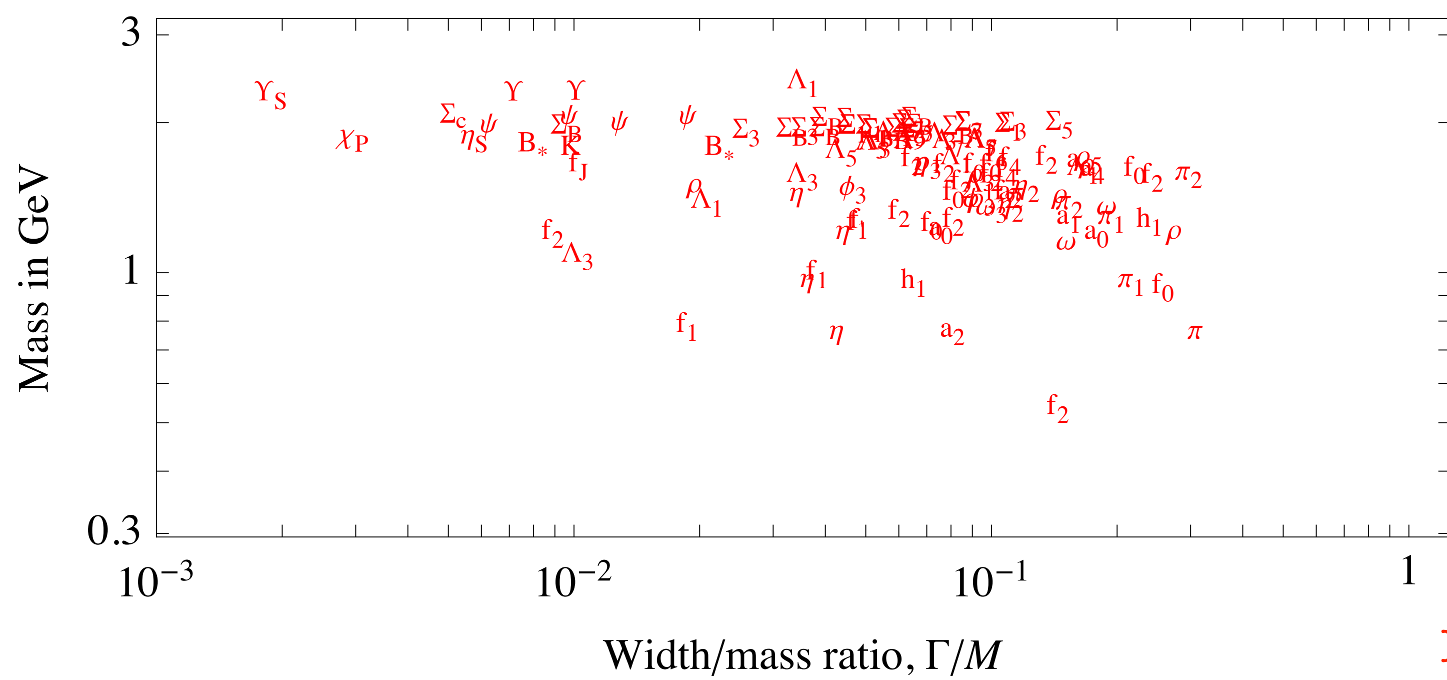


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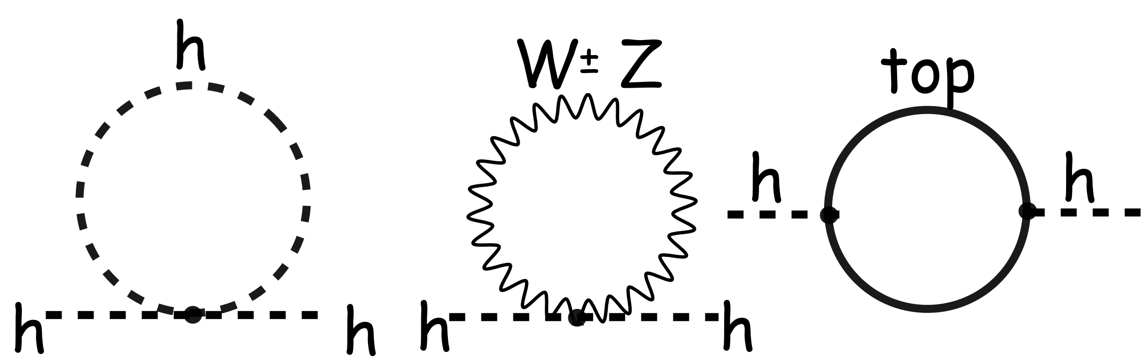


$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2$$

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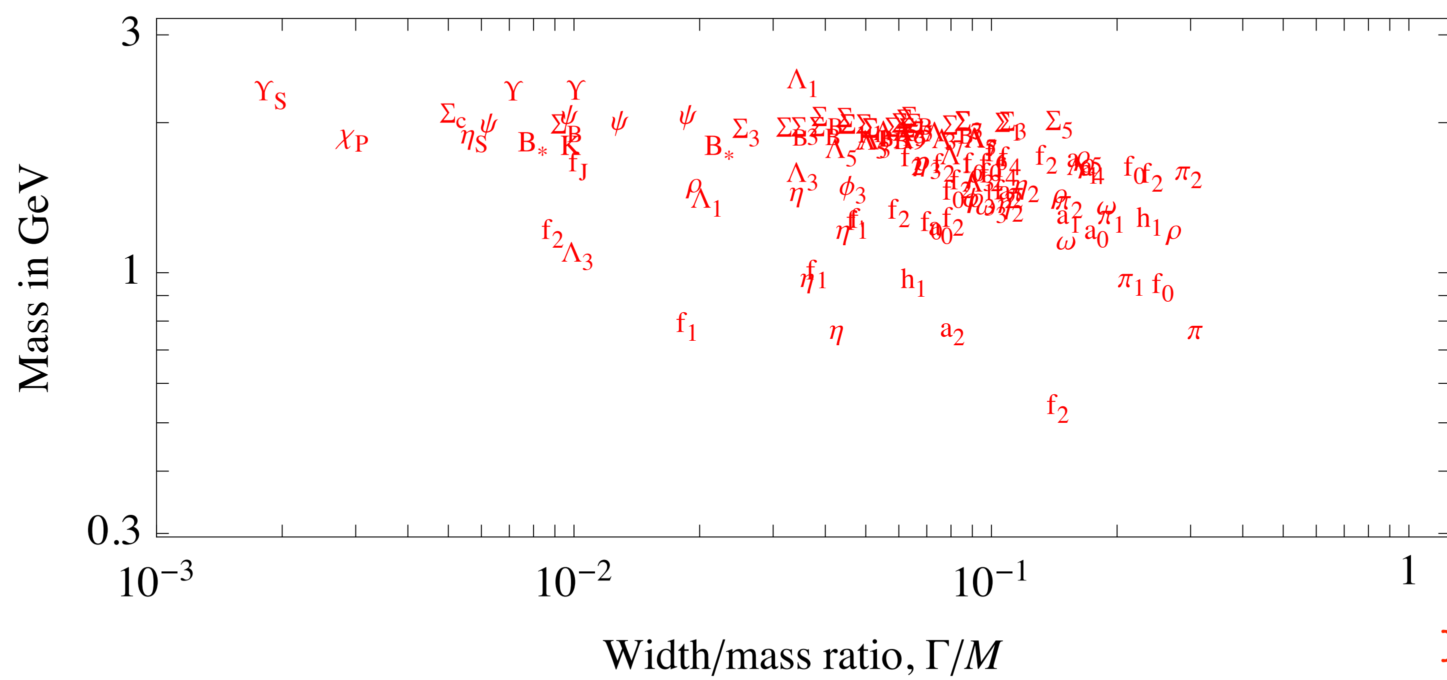


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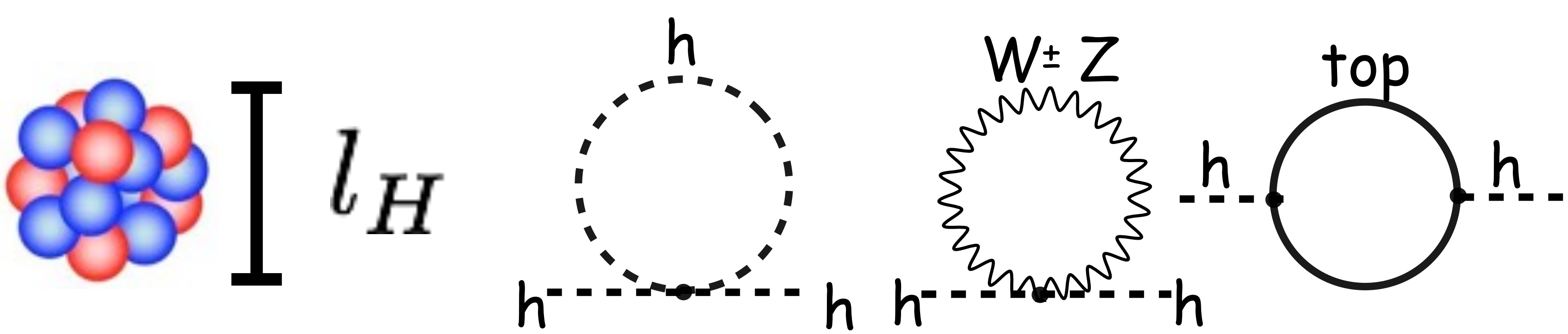
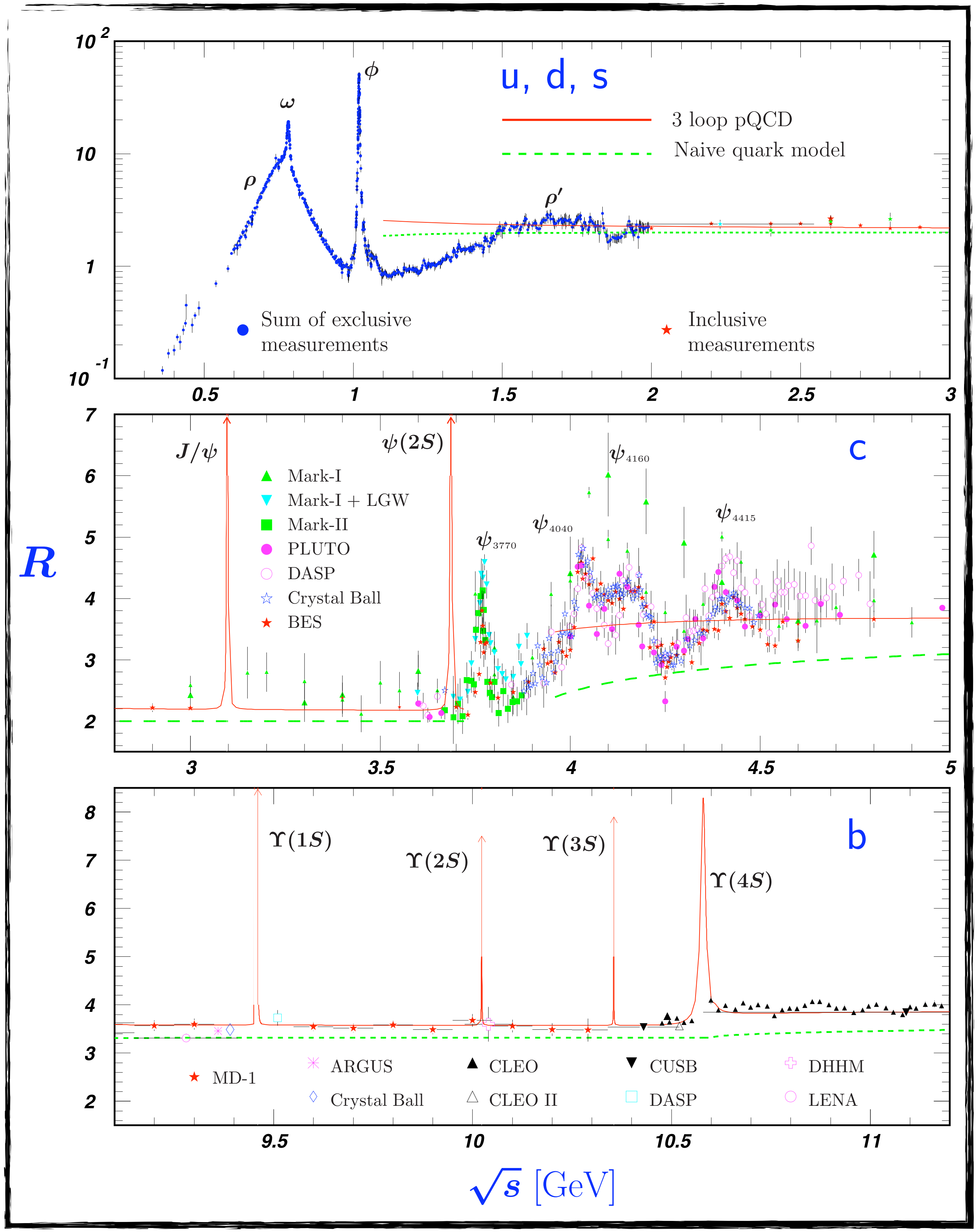



At energy above $1/\ell_H$, the Higgs dissolves, the integrals are smoothed out

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

# Higgs as a Bound State



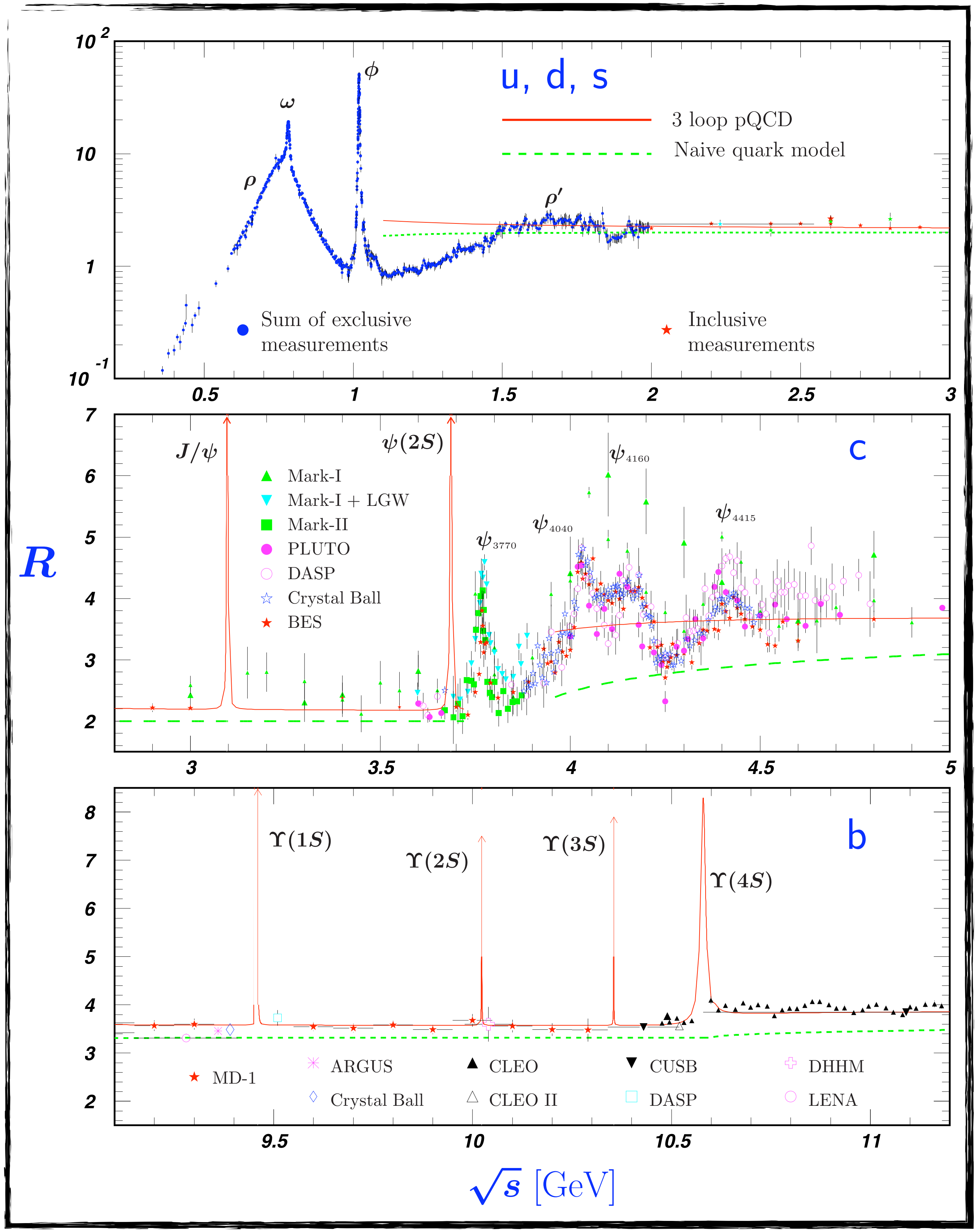

Structure of QCD was understood from inelastic scattering experiments

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

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
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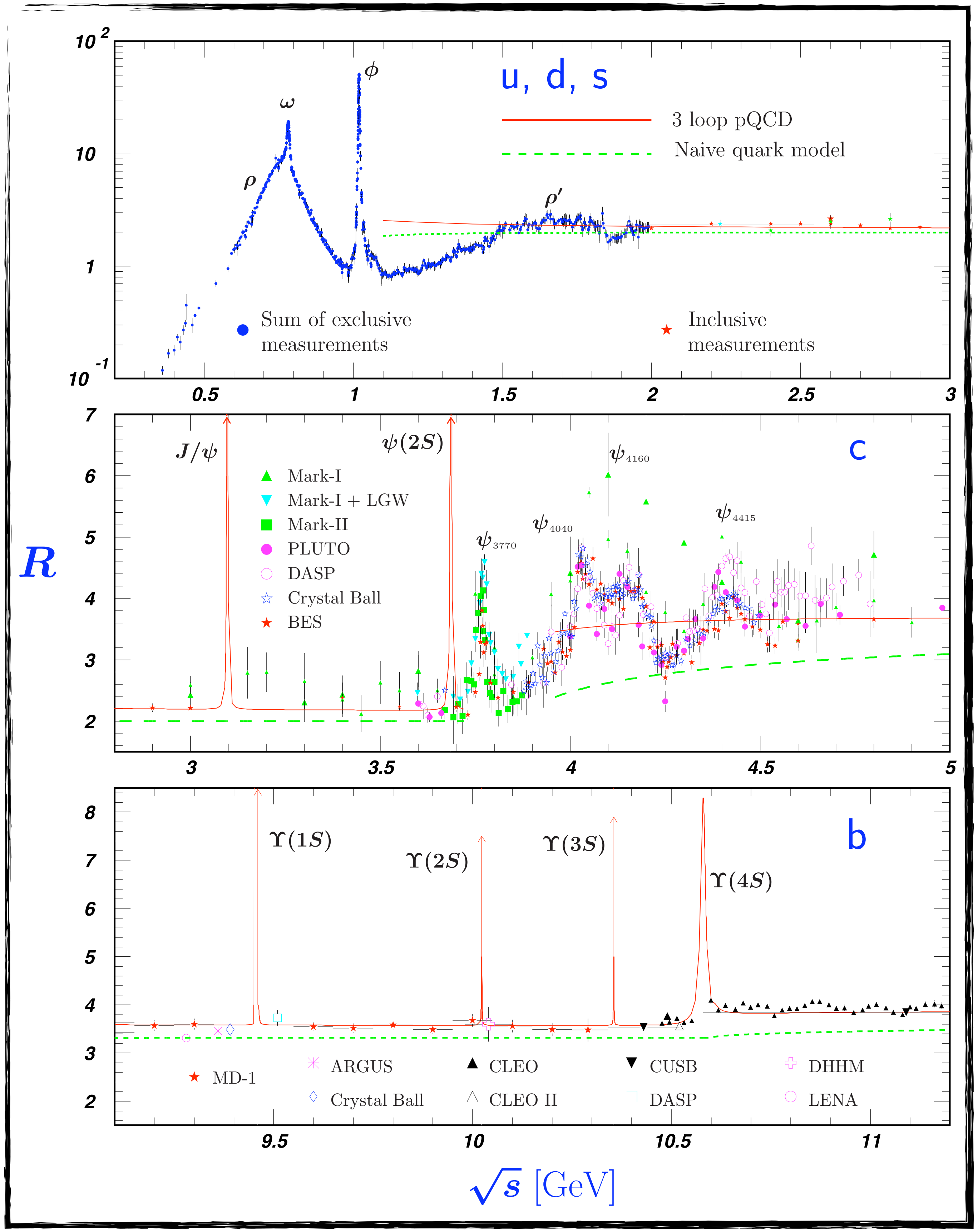


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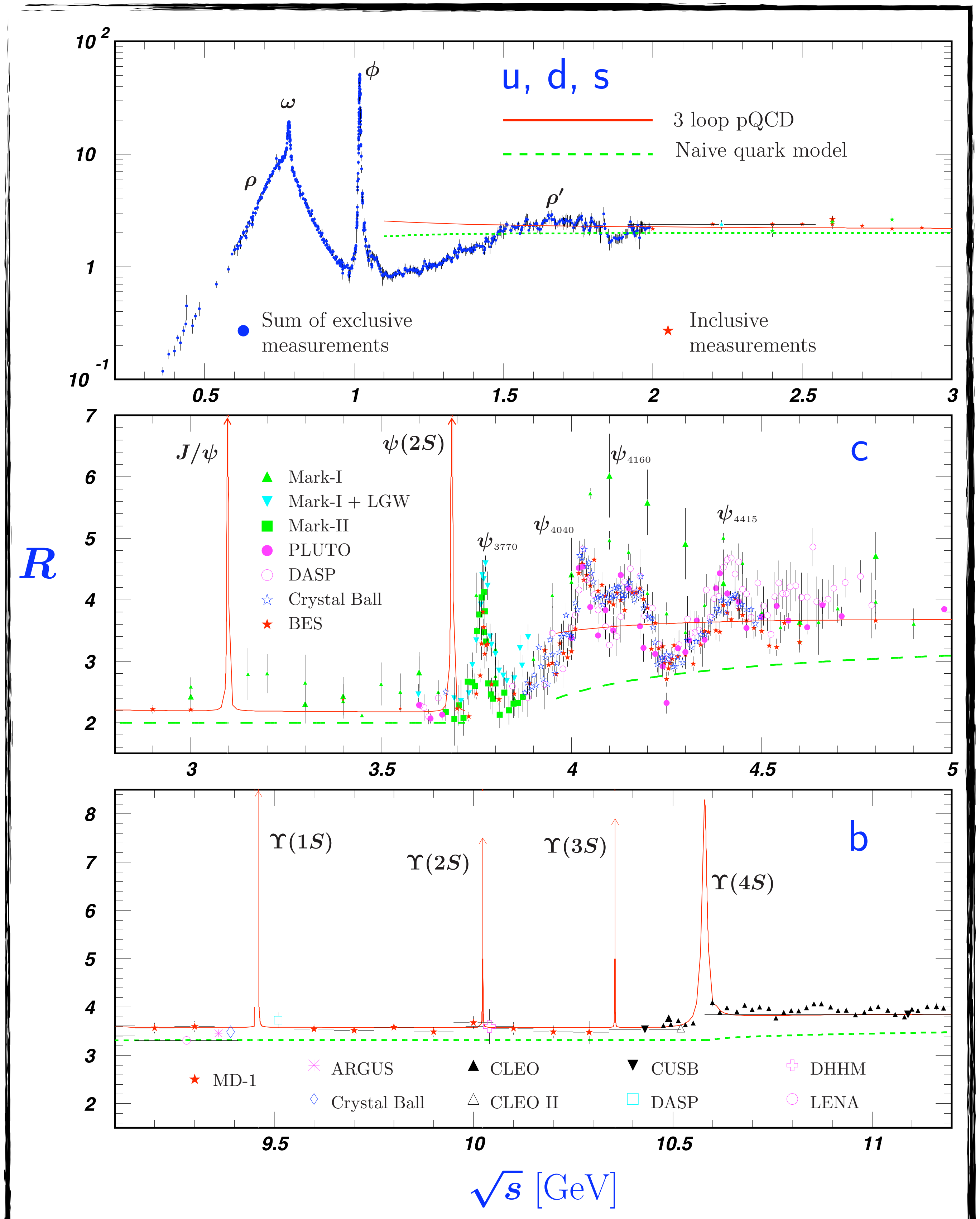


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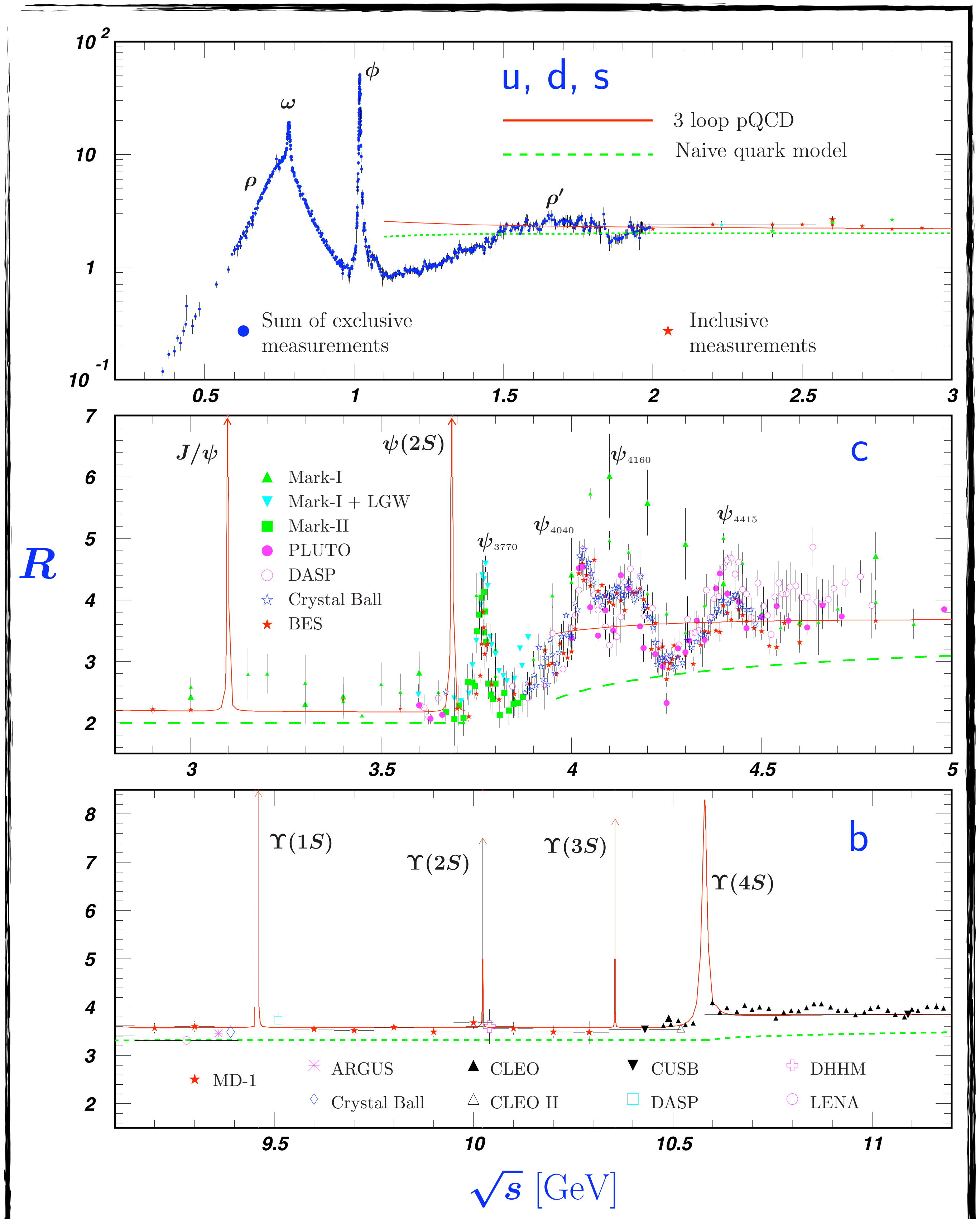


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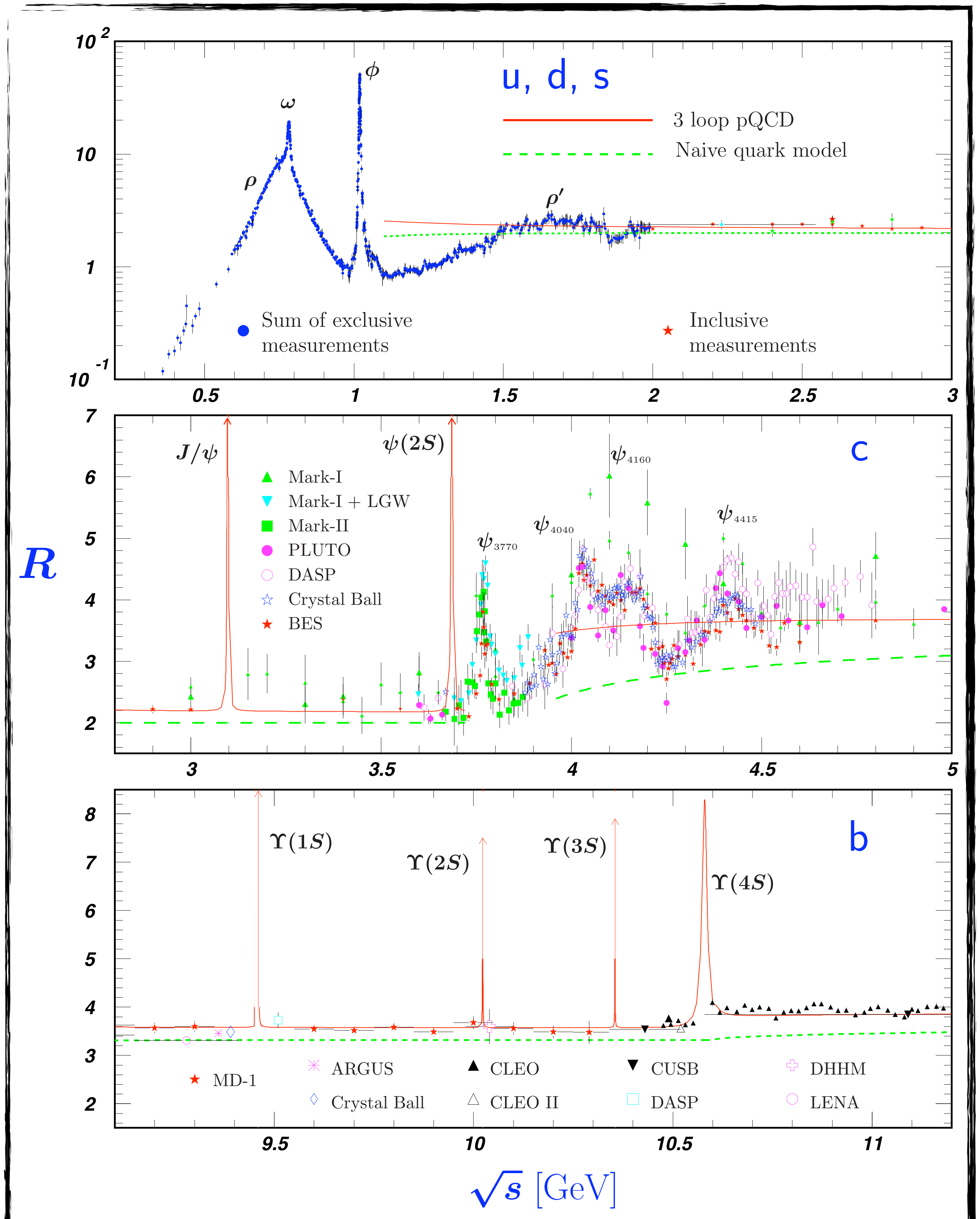


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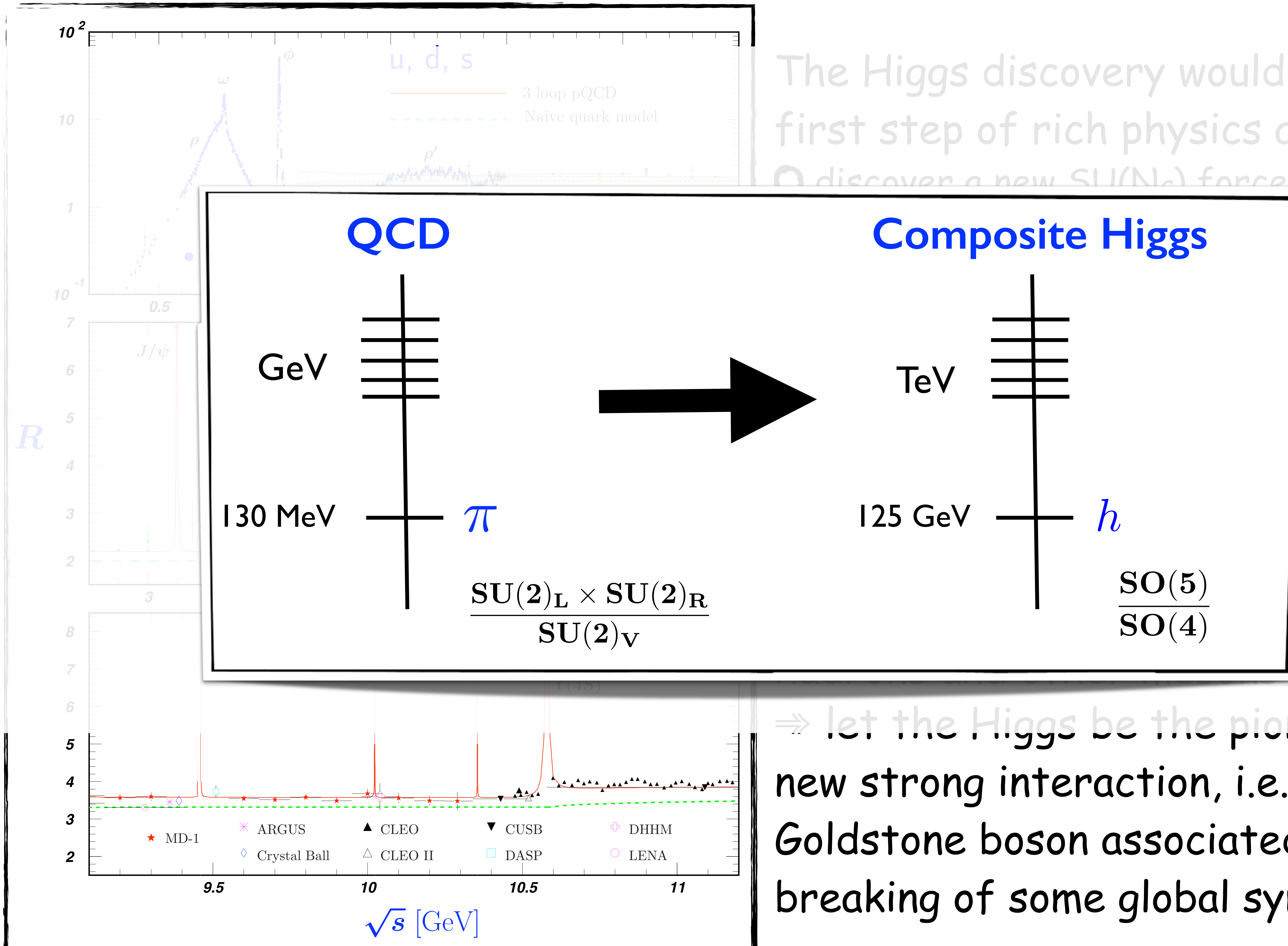


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# Higgs as a Goldstone Boson

SM

$SO(4)/SO(3)$

$W^{\pm}_L$ & $Z_L$

# Higgs as a Goldstone Boson

SM $SO(4)/SO(3)$ $\Rightarrow$ $G/H$ BSM

$W^{\pm}_L$ & $Z_L$

$W^{\pm}_L$ & $Z_L$ & $h$

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

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 = $H$, $s$

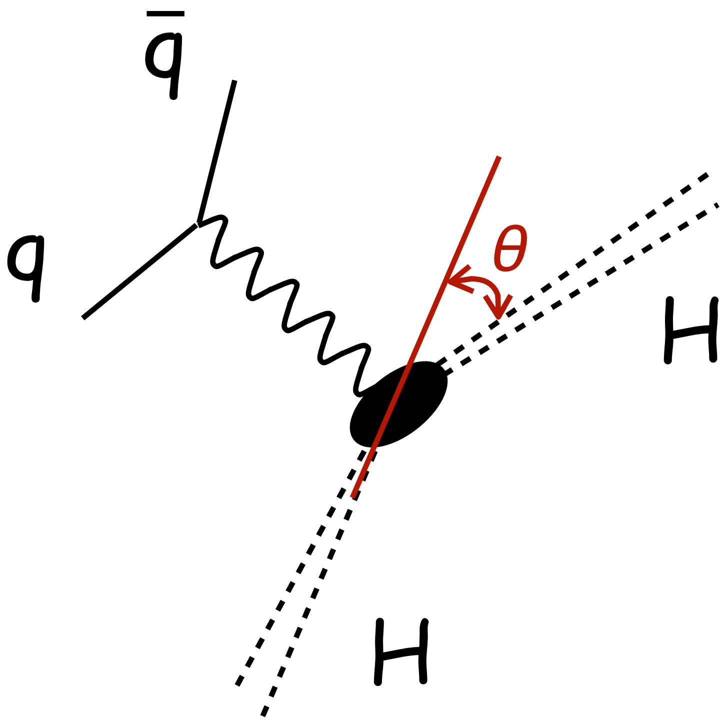
dim=15 dim=10

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

dim=15 dim=7

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

# Probe the Compositeness of the Higgs?




Rosenbluth-type cross-section

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

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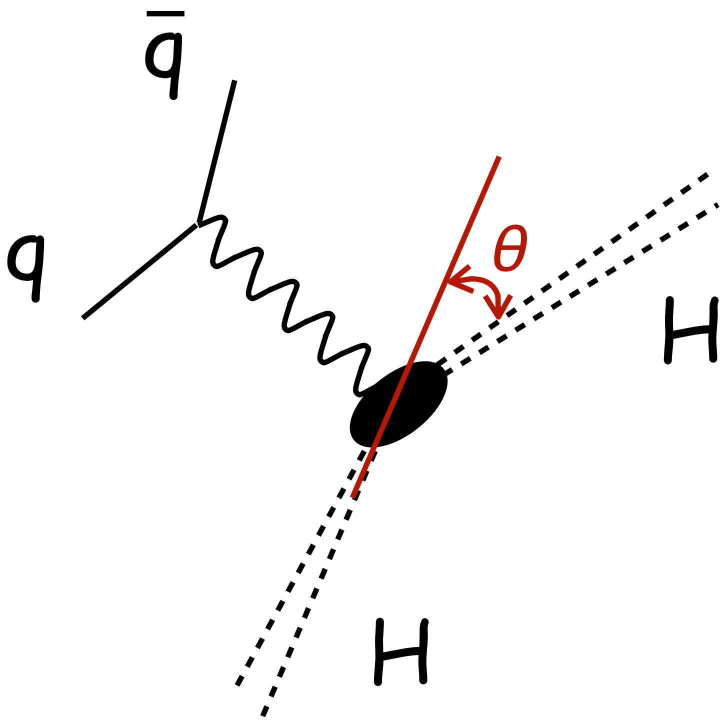


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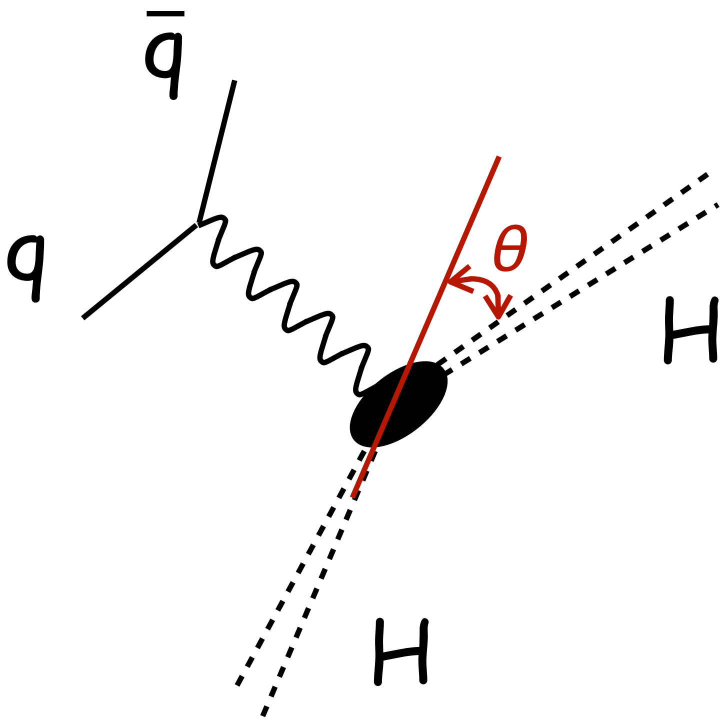


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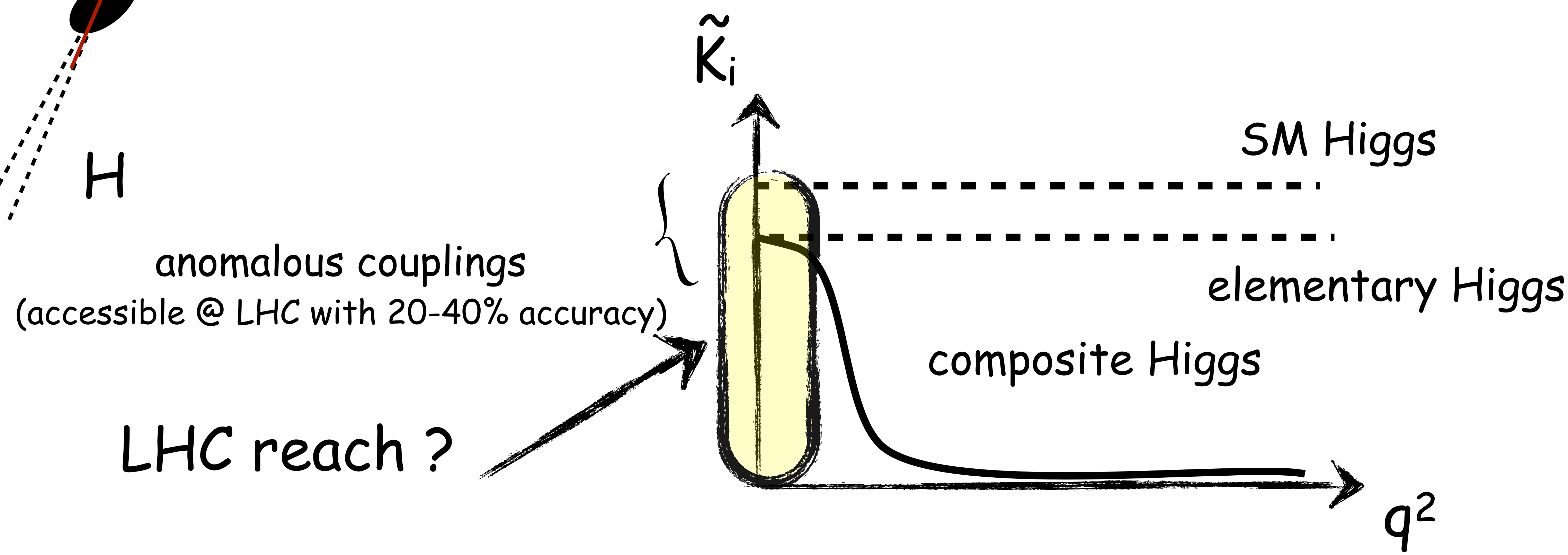

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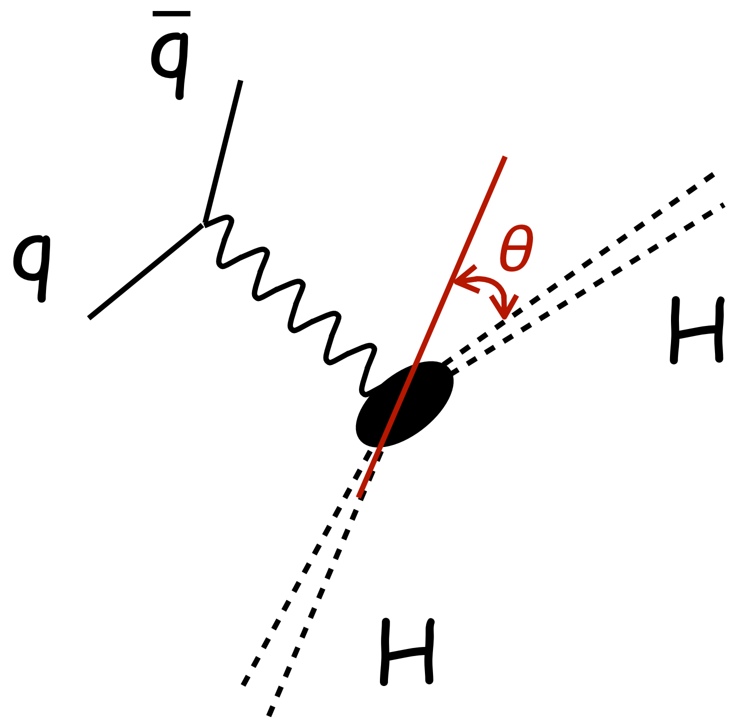


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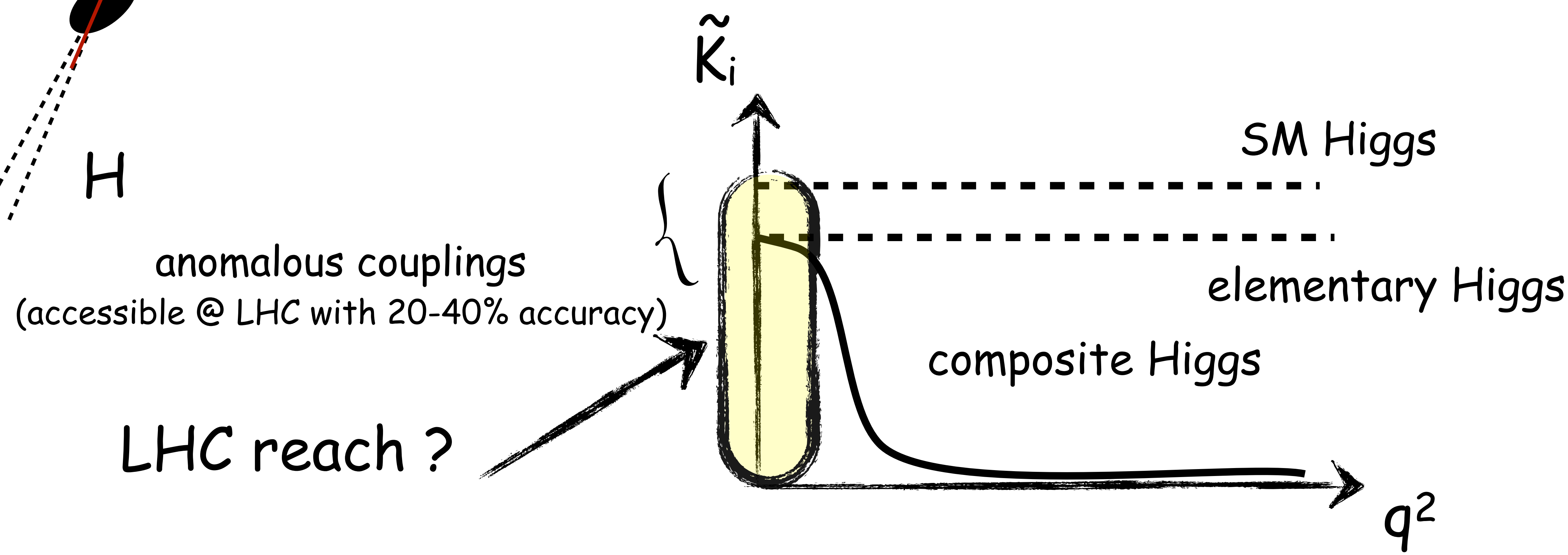


Need to develop tools to understand the physics of a composite Higgs

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

} identify interesting processes

# Higgs Anomalous Couplings

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

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

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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

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

# 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

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

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

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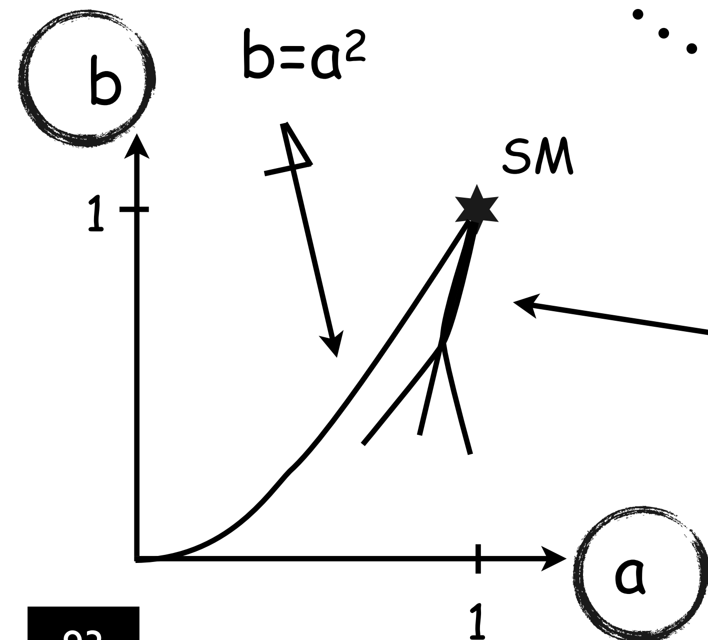
Uniqueness of Goldstone models
in the SM vicinity
(a single operator at dimension-6 level
controls the amplitudes)

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

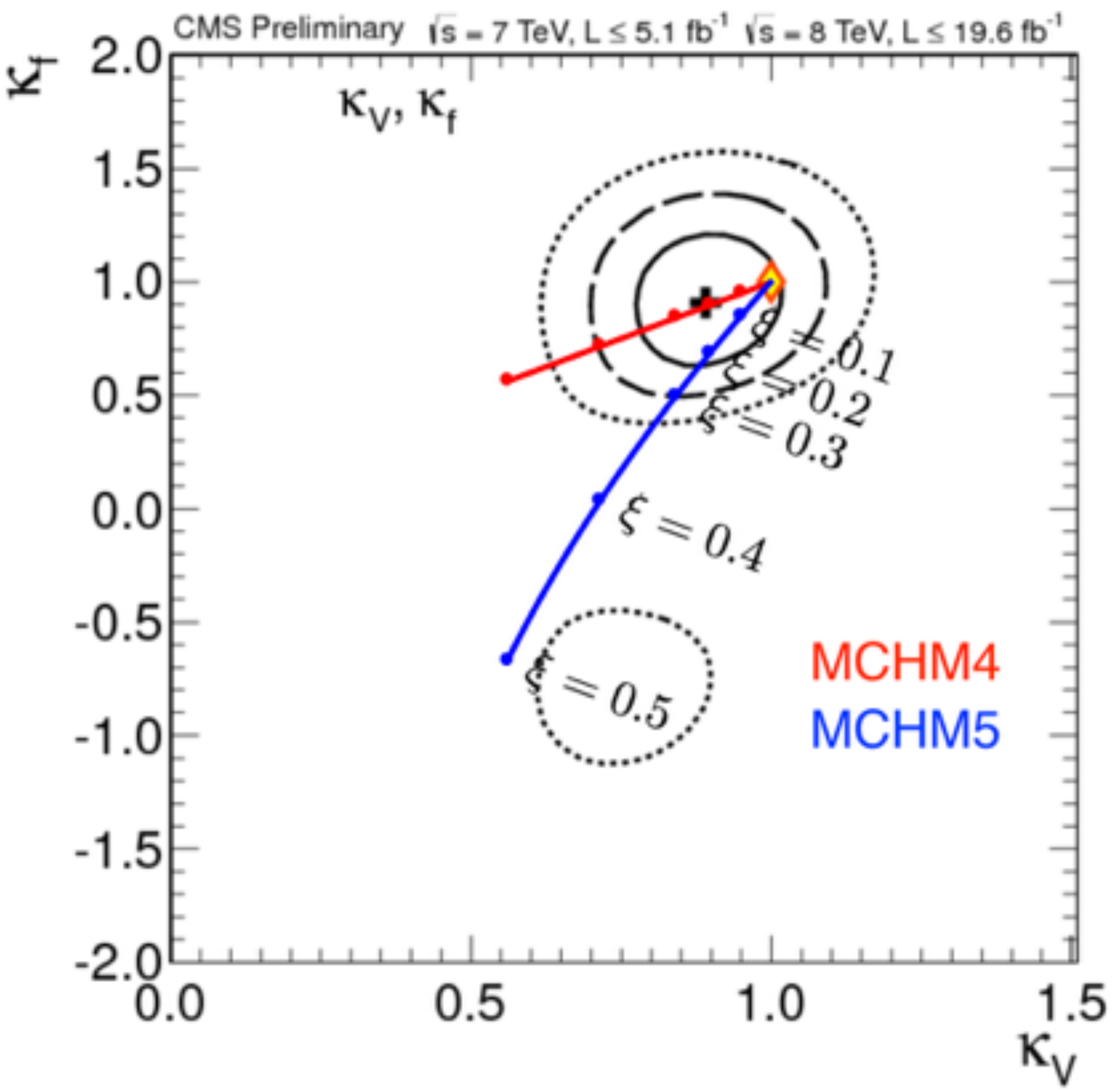
Composite Higgs
vs.
SM Higgs

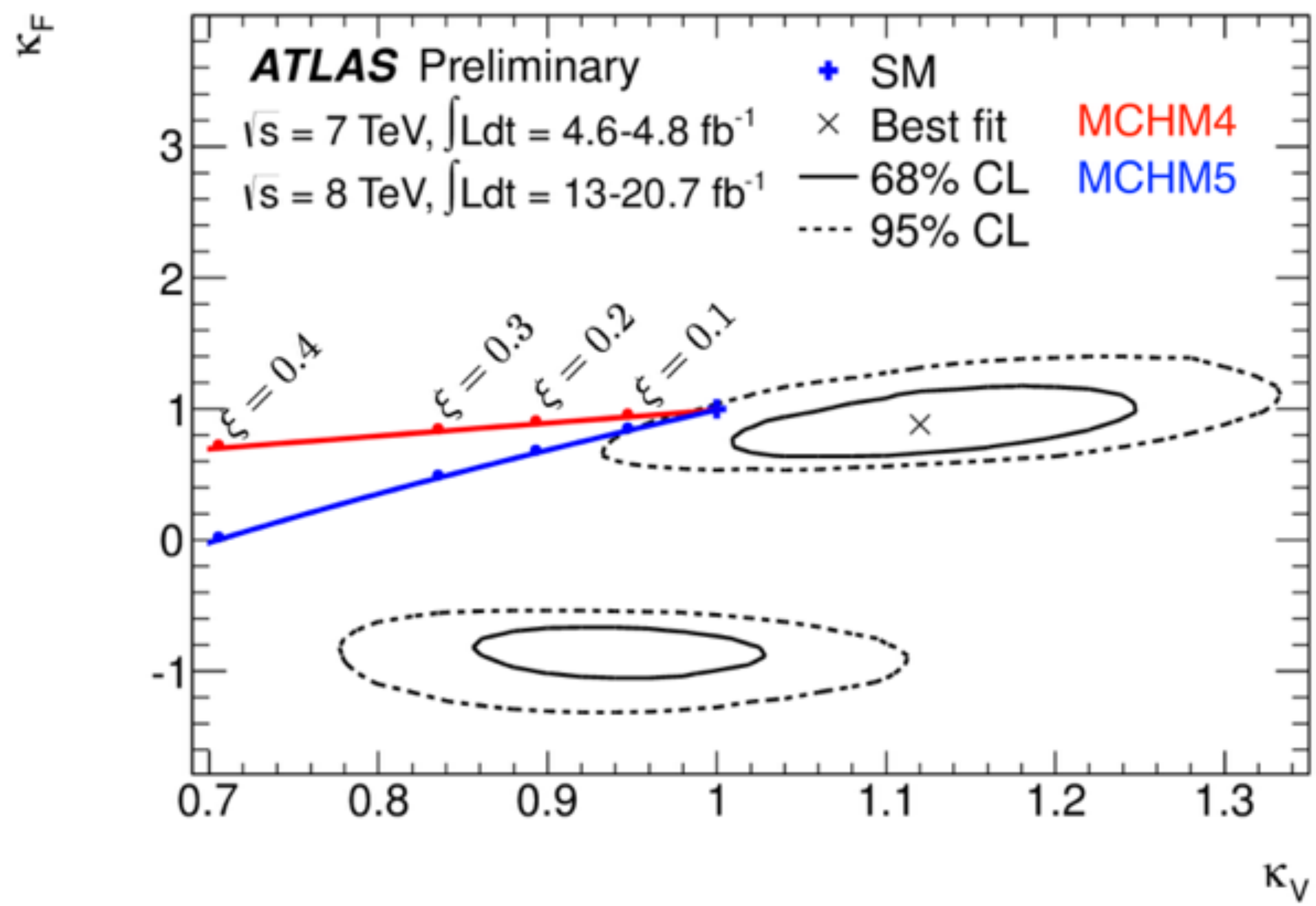
Dilaton
$b=a^2$




Goldstone Higgs
for large f
$a=1-v^2/2f^2$ $b=1-2\,v^2/f^2$

# Higgs Couplings Fit



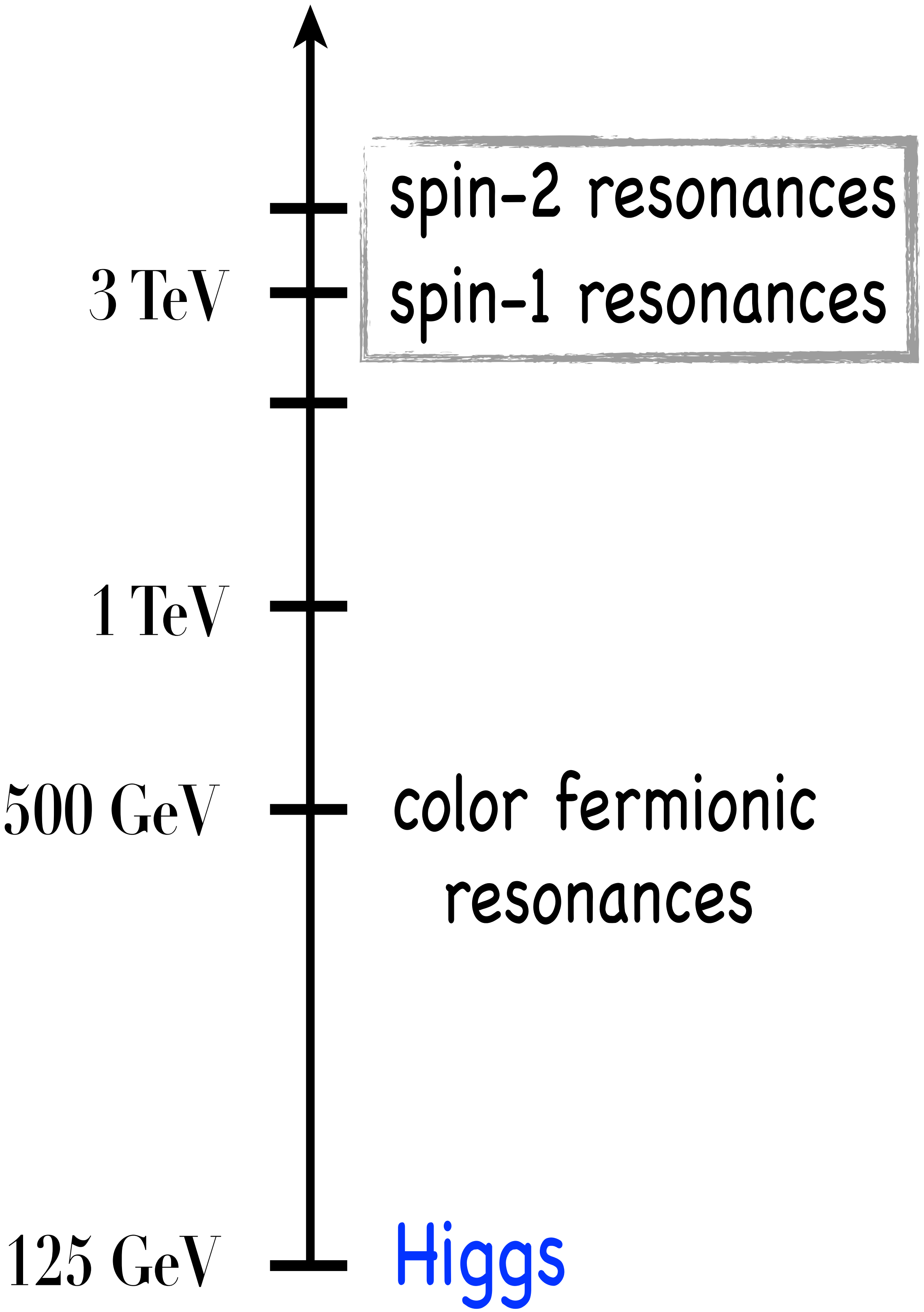

- MCHM4

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

- MCHM5

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

# The Other Composite Resonances



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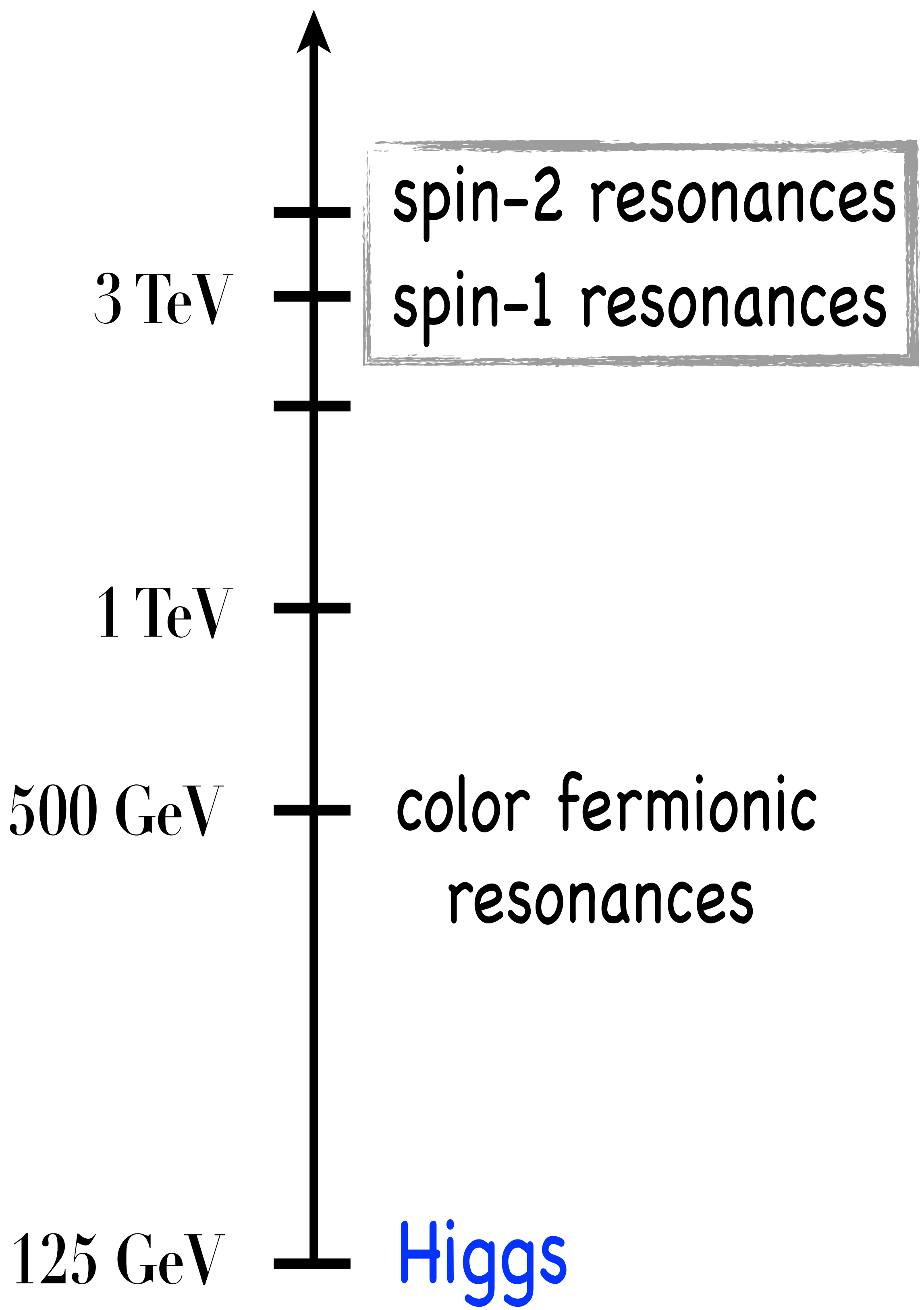


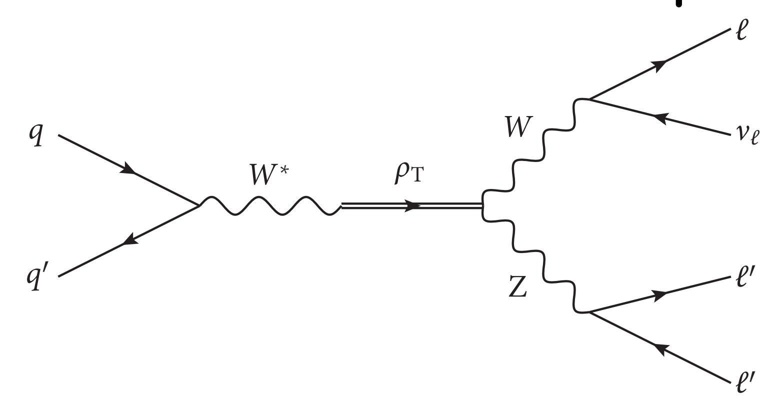

Dominant decays into longitudinal SM gauge bosons

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

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)

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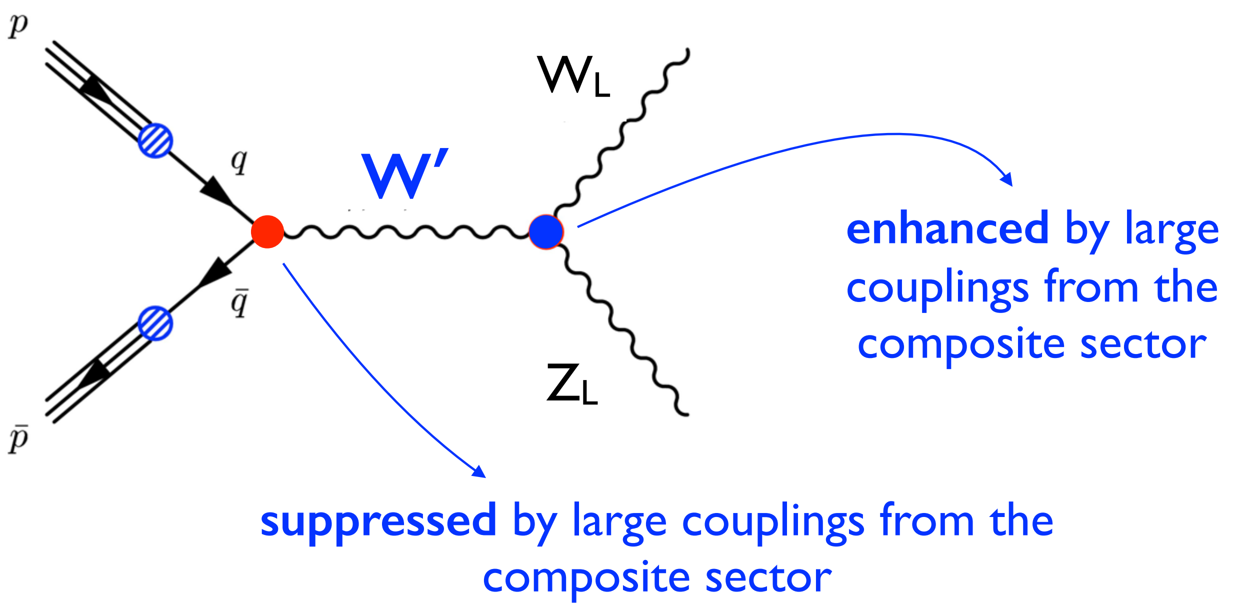

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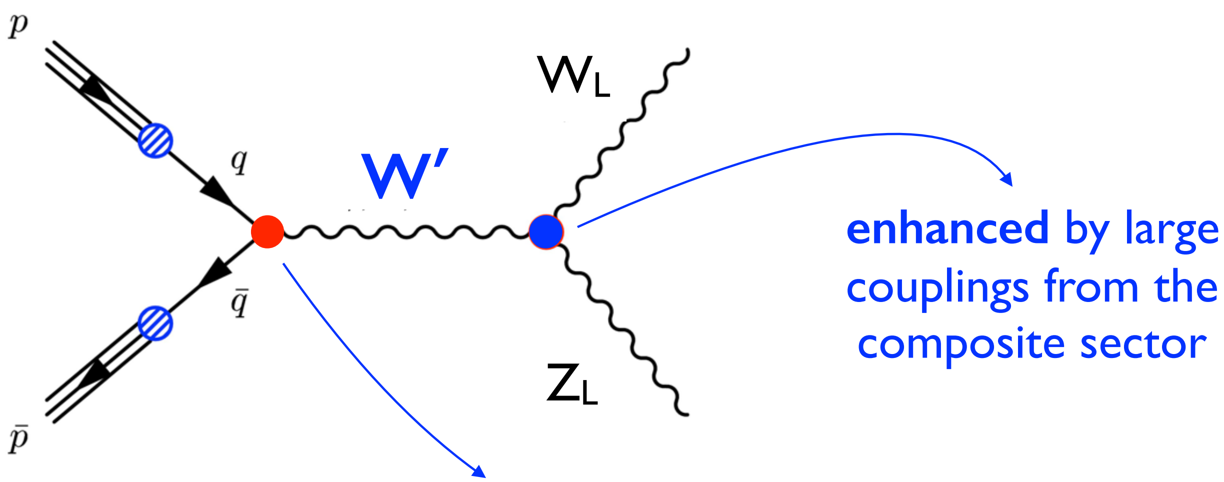
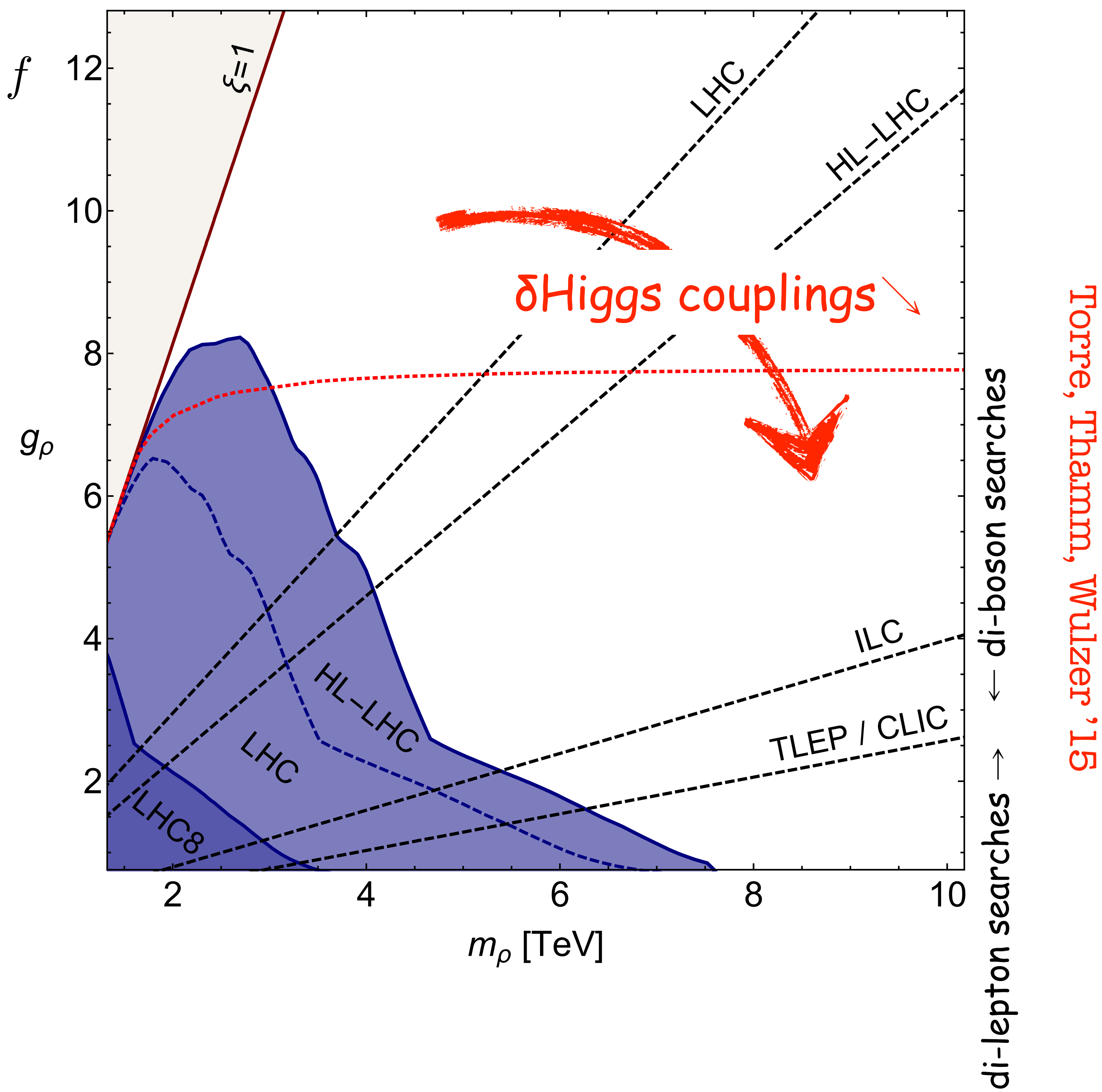



DY production xs of resonances decreases as $1/g_\rho^2$



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| Collider | Energy | Luminosity | $\xi$ [1$\sigma$] |
|---|---|---|---|
| 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<br>+ 500 GeV | 250 $fb^{-1}$<br>500 $fb^{-1}$ | 4.8-7.8 $\times 10^{-3}$ |
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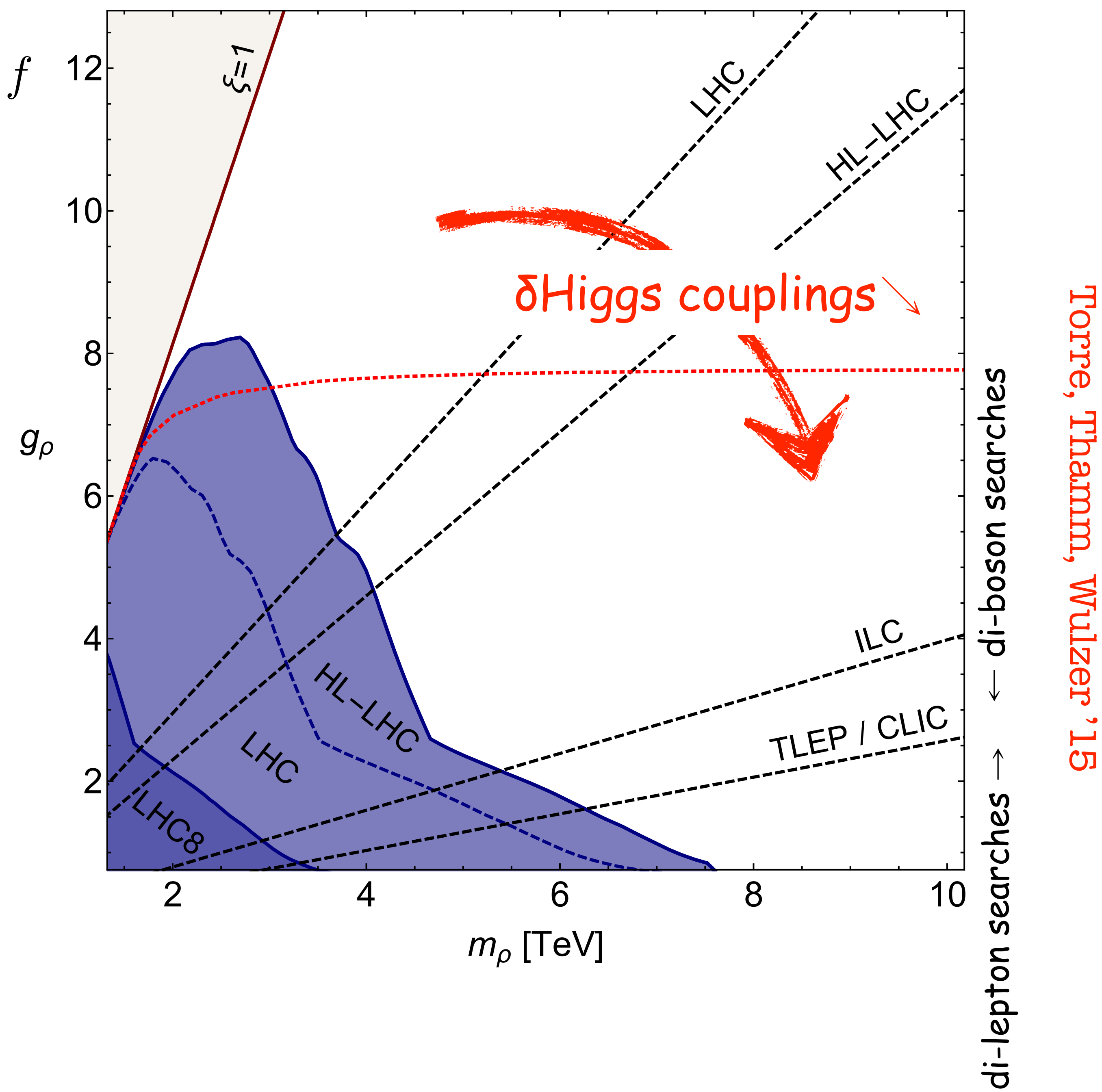

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- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

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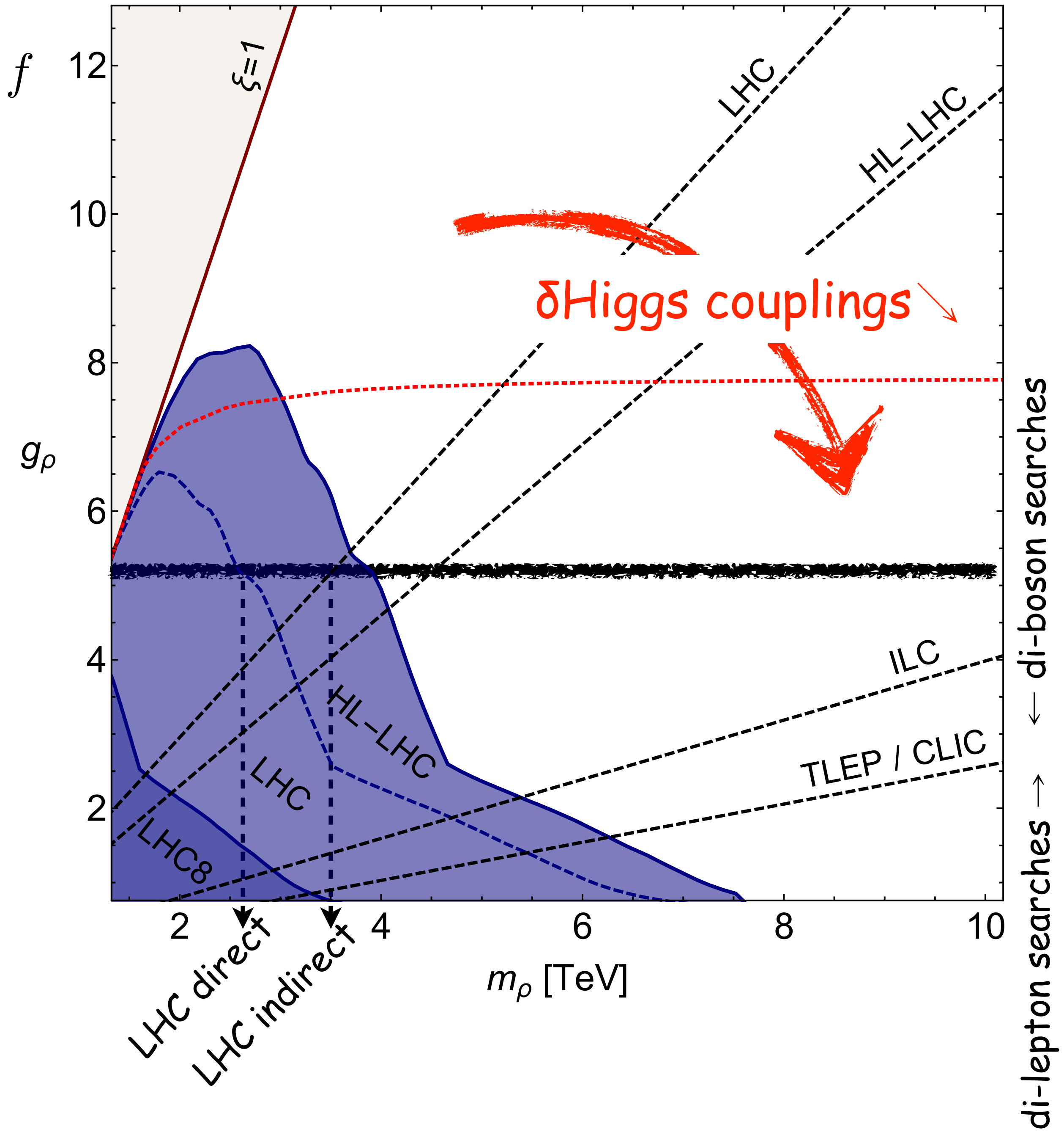


Torre, Thamm, Wulzer '15

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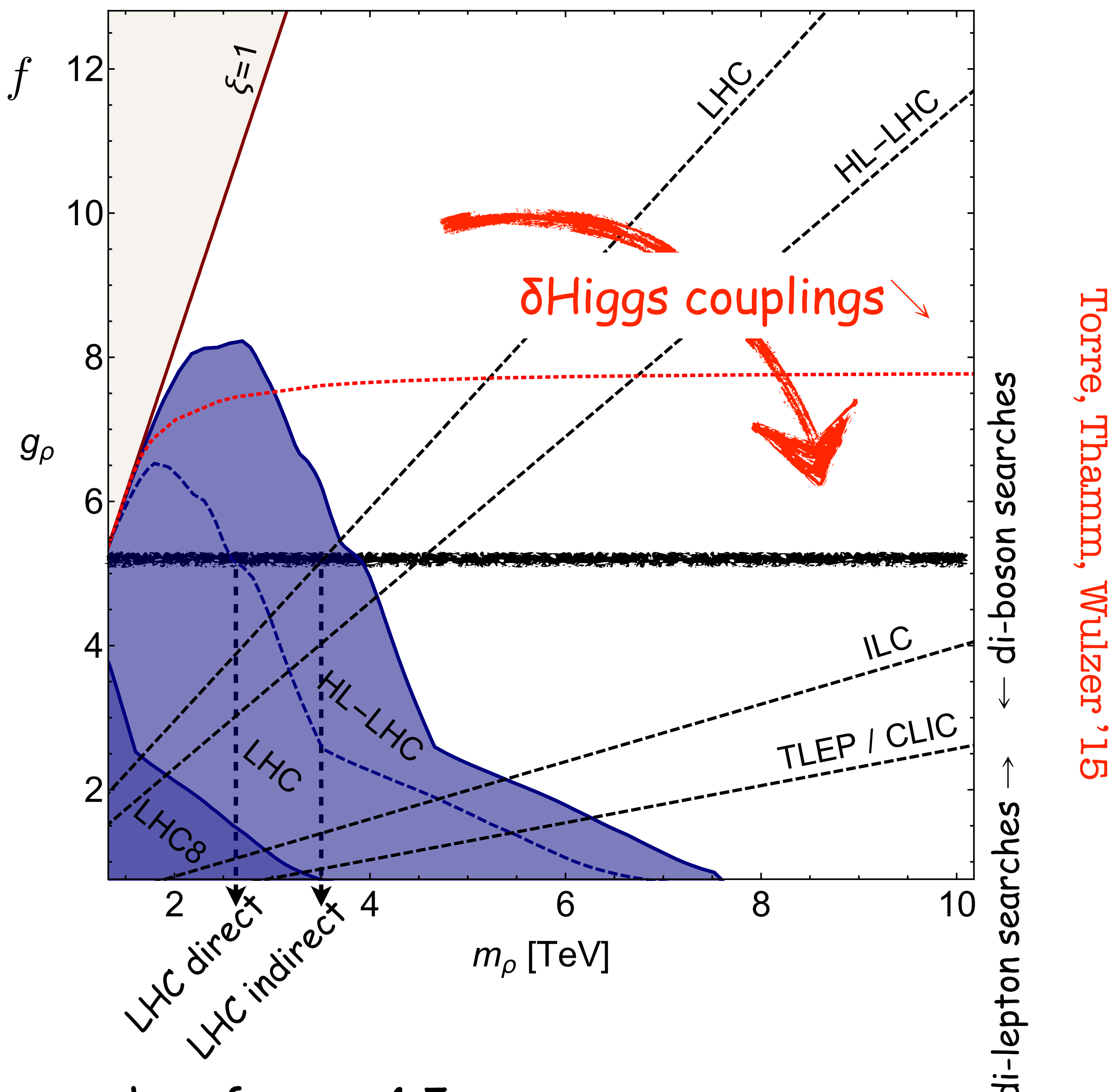


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e.g.
indirect searches at LHC over-perform direct searches for g > 4.5
indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

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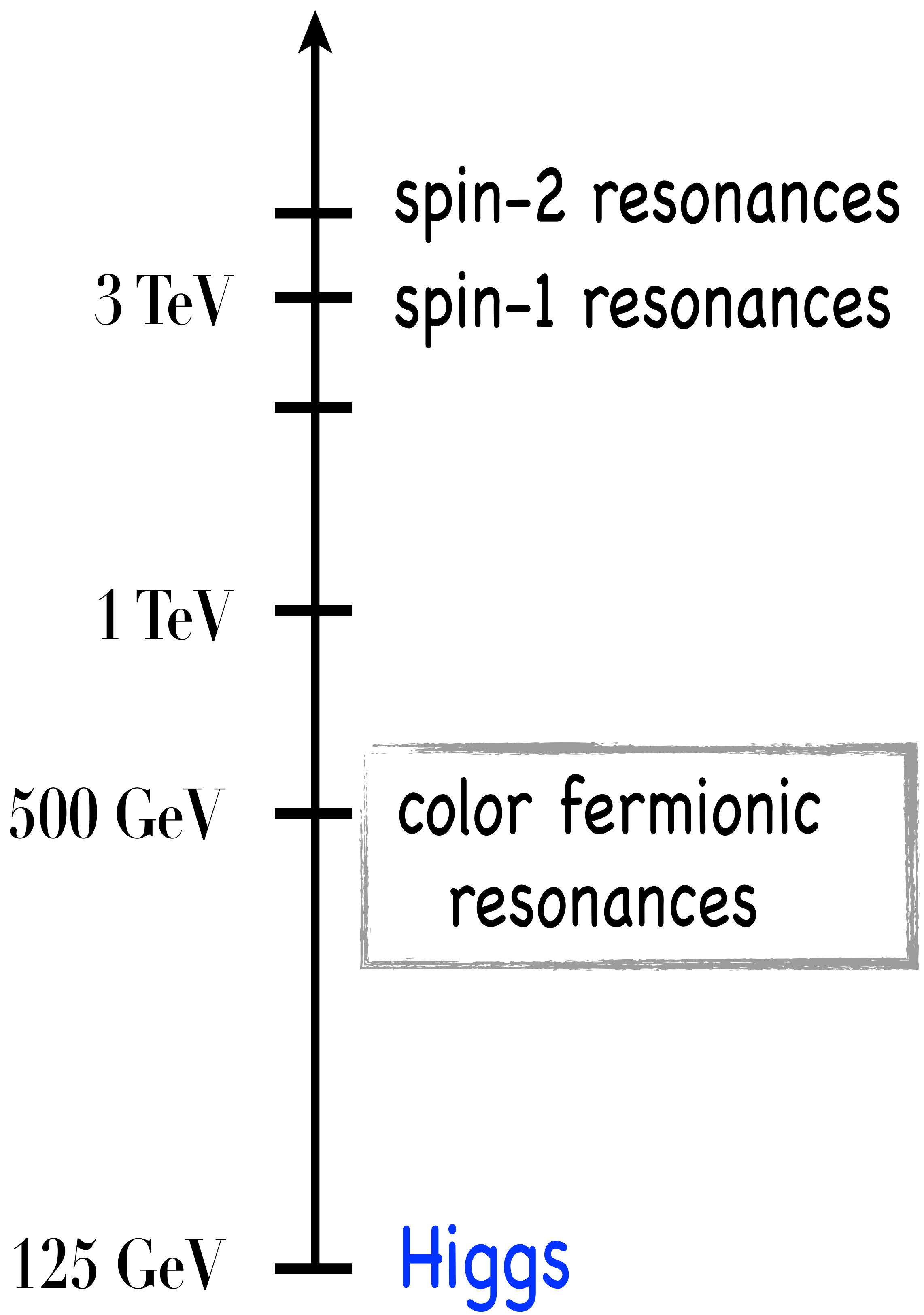
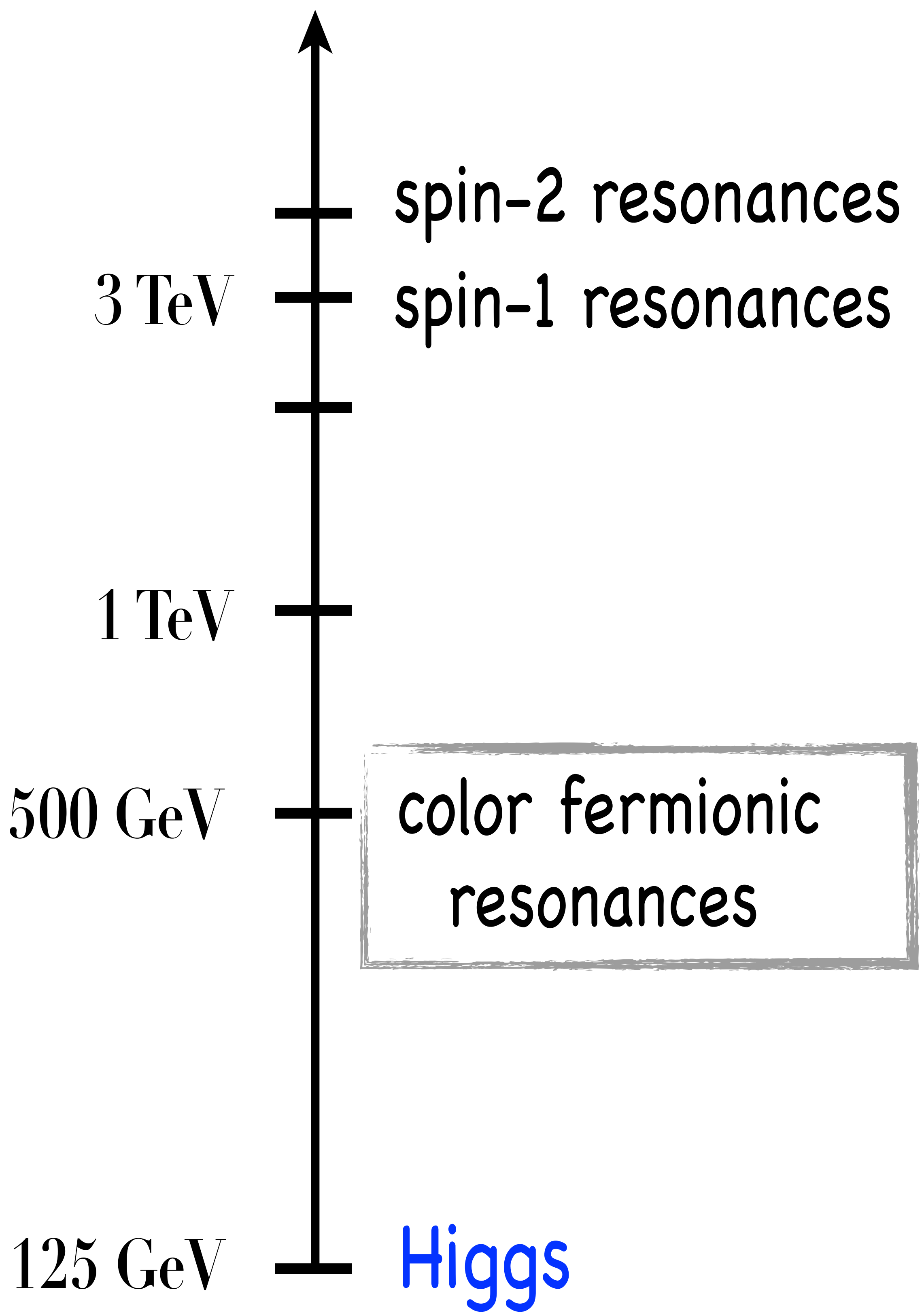


# The Other Composite Resonances



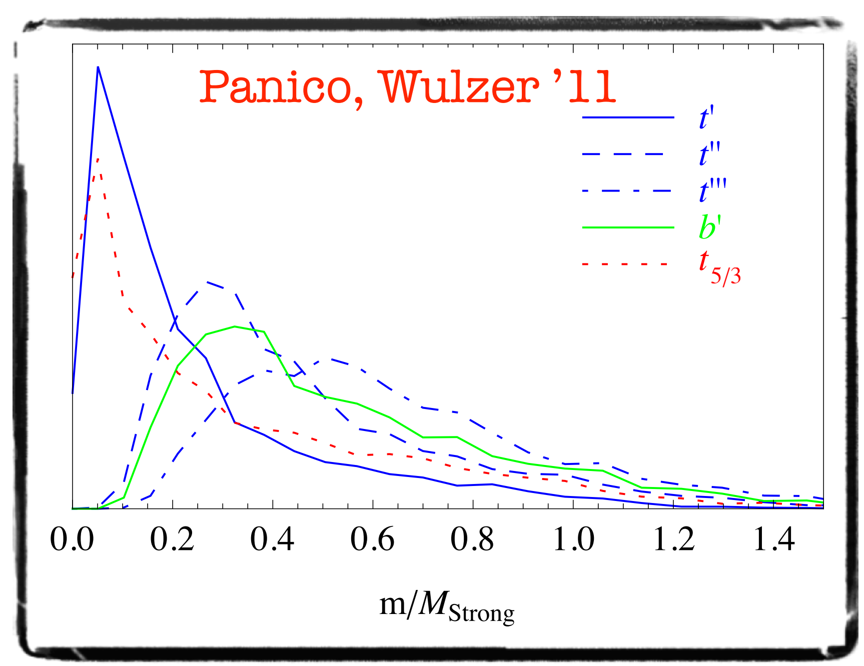

**Top partners**

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

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

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

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



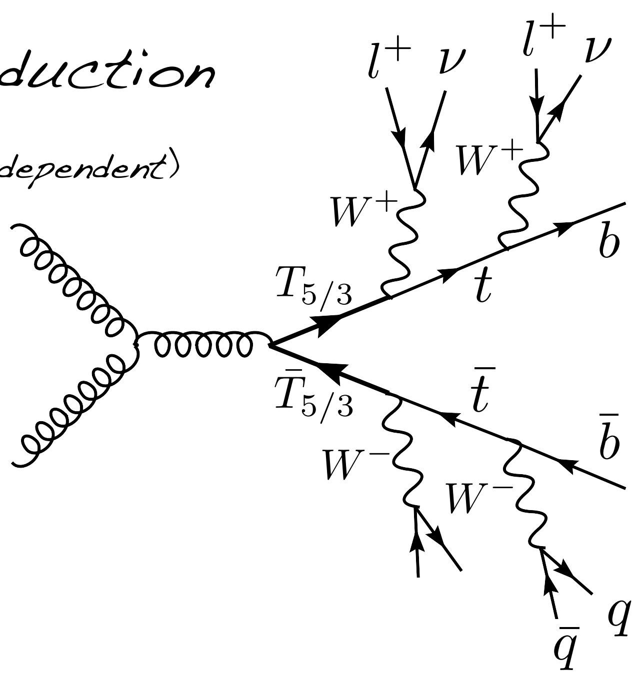
# Searching for the Top Partners

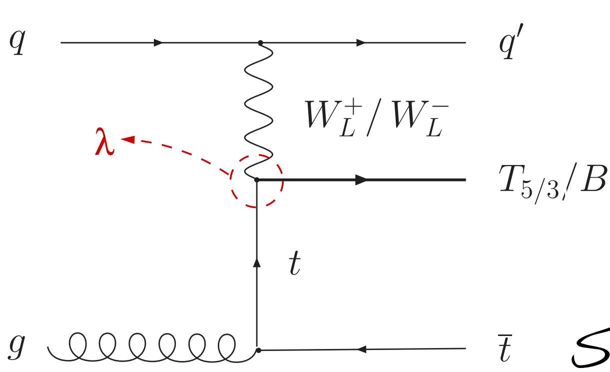
## Search in same-sign dilepton events

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

*Pair production*

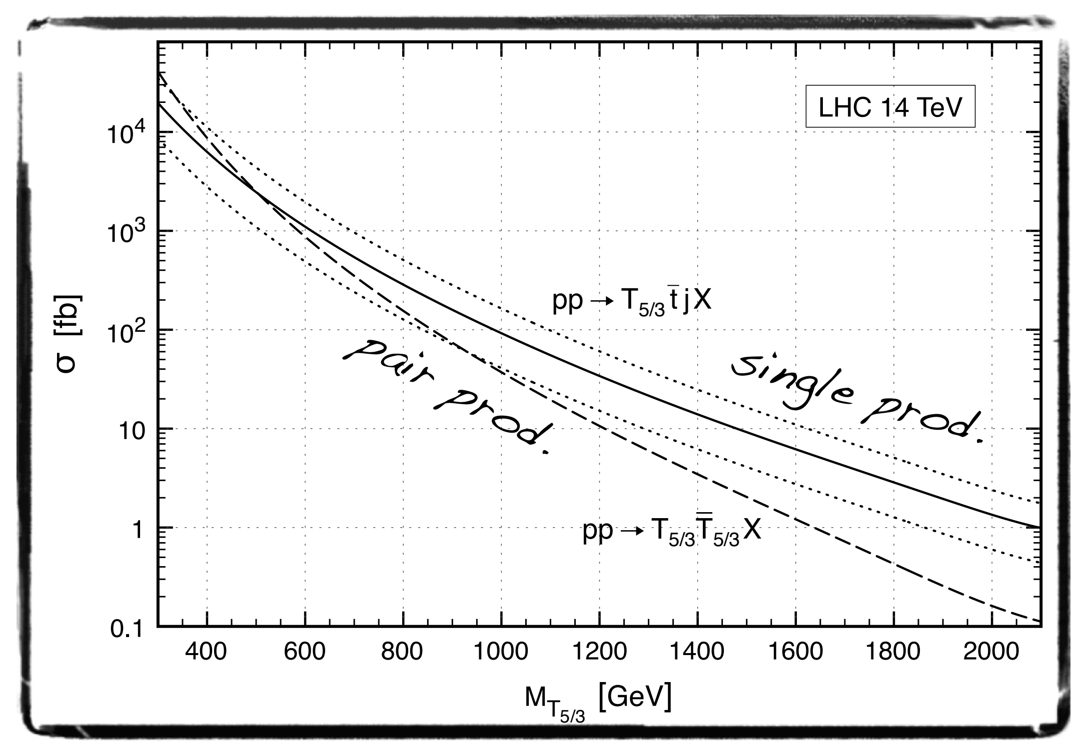
*(model independent)*



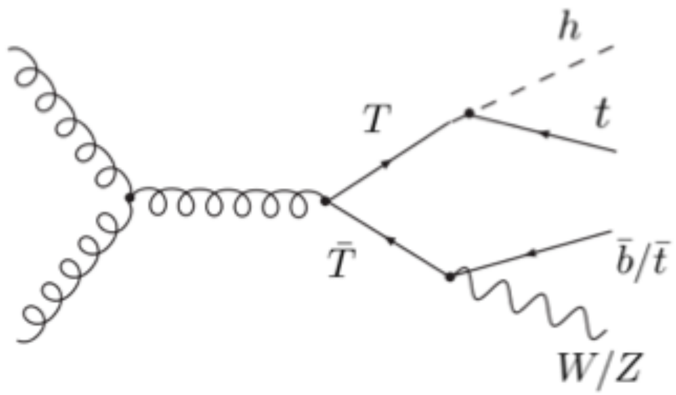

*Single production*

*(model dependent)*




[Contino, Servant '08]

# Searching for the Top Partners




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

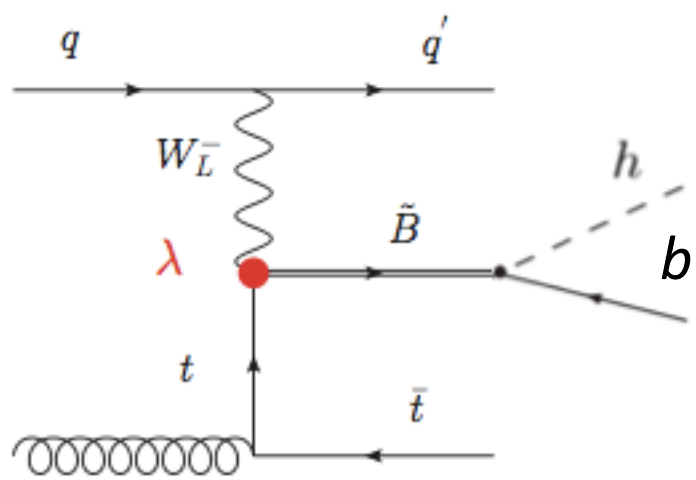
$$T\bar{T} \to HtW^{-}\bar{b} \to HW^{+}bW^{-}\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$
$$T\bar{T} \to HtV\bar{t} \to HW^{+}bVW^{-}\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^{\pm}$ + 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

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

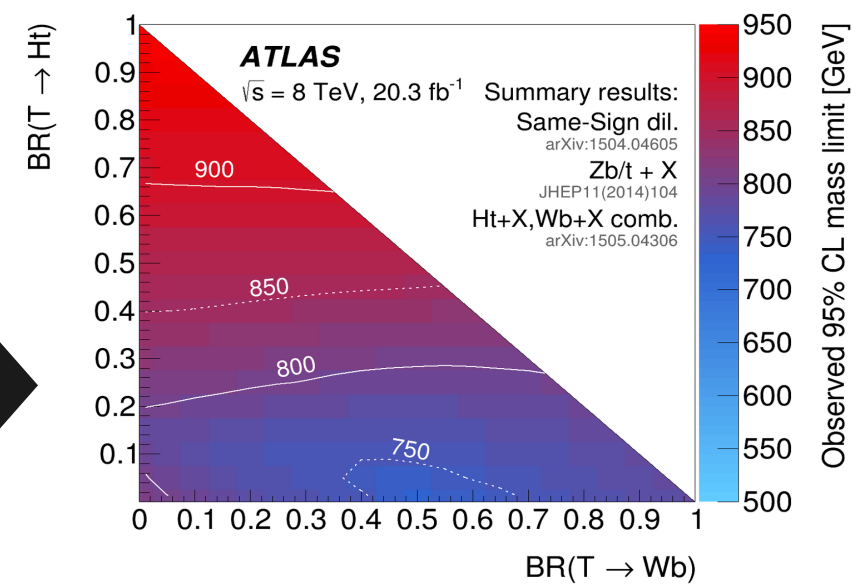



- $\ell^{\pm}$ + 4b final state Vignaroli '12

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

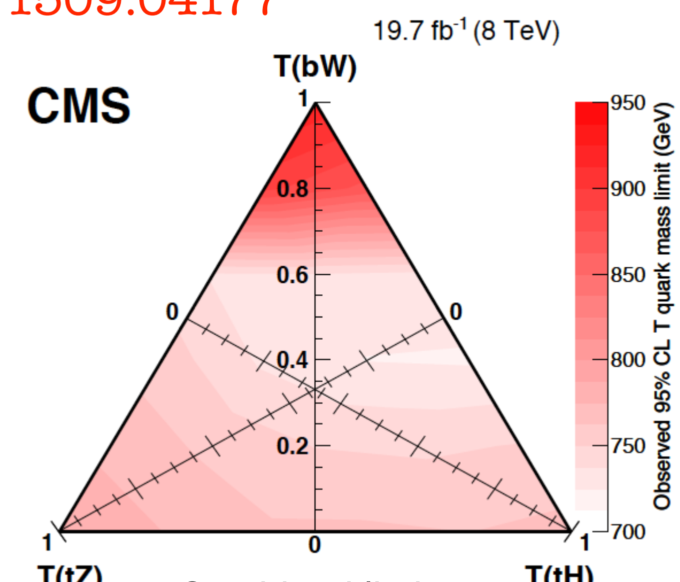
bounds on
charge 2/3 states
from pair production

1505.04306




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

1509.04177

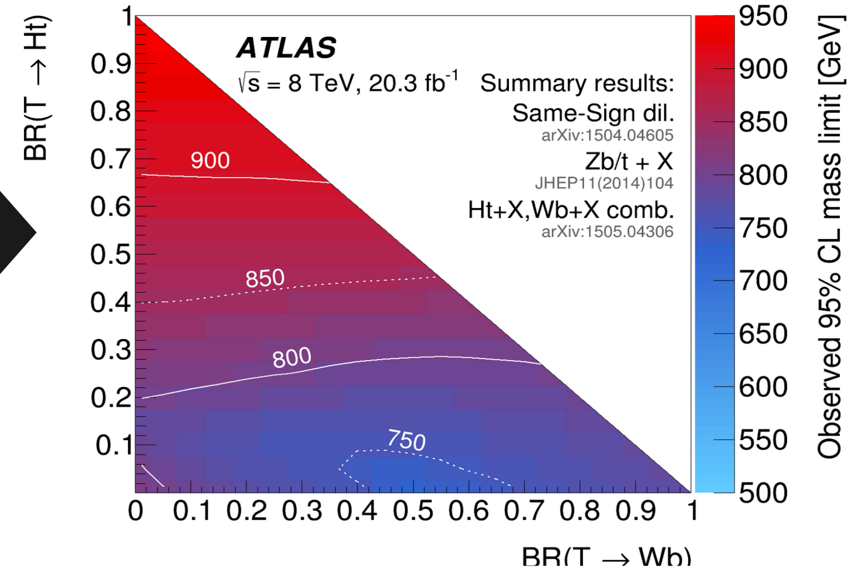



Combined limits

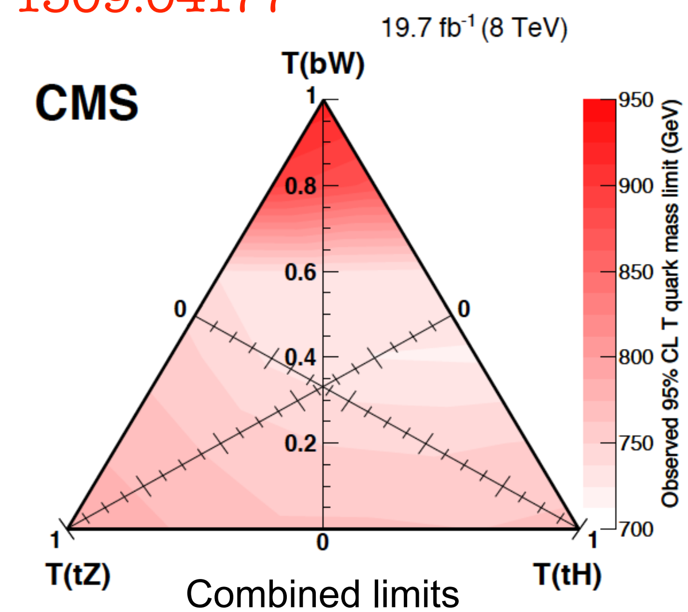
# Searching for the Top Partners

bounds on
charge 2/3 states
from pair production

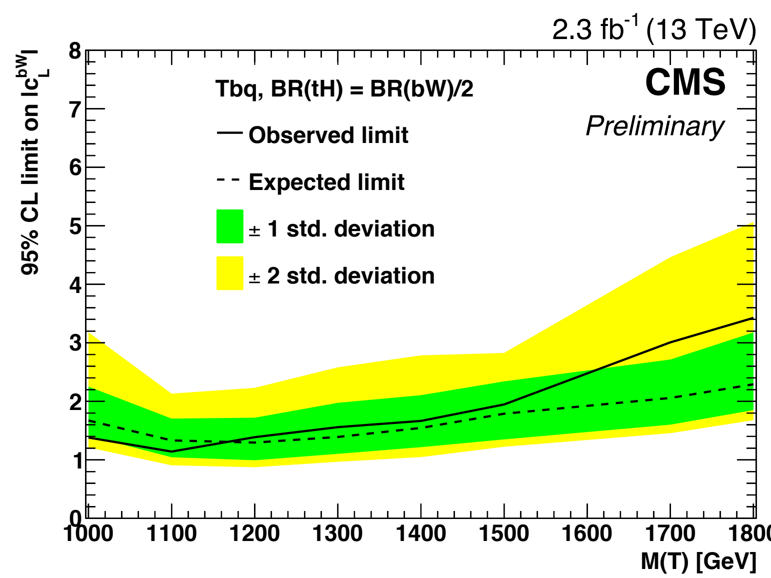
1505.04306

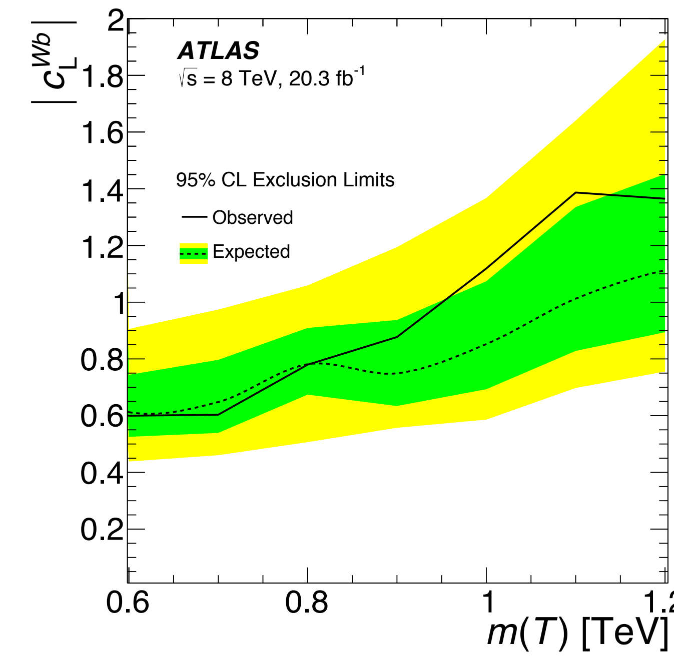



1509.04177

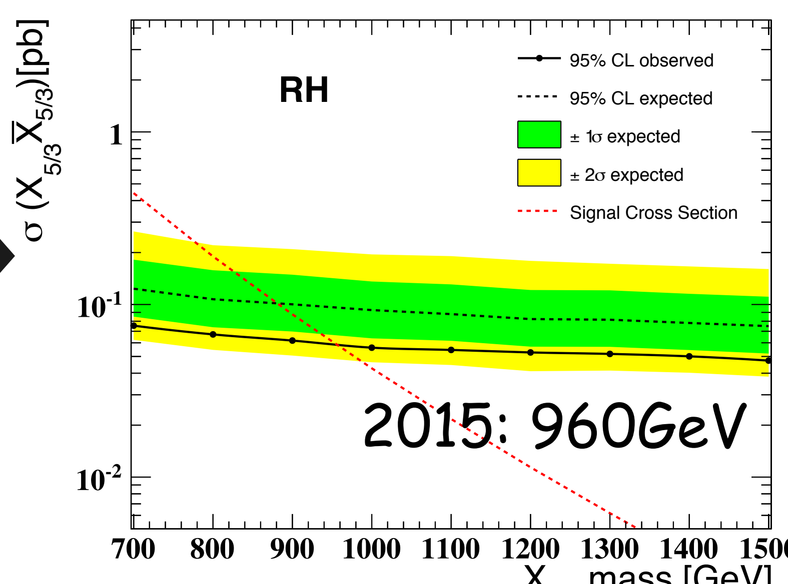


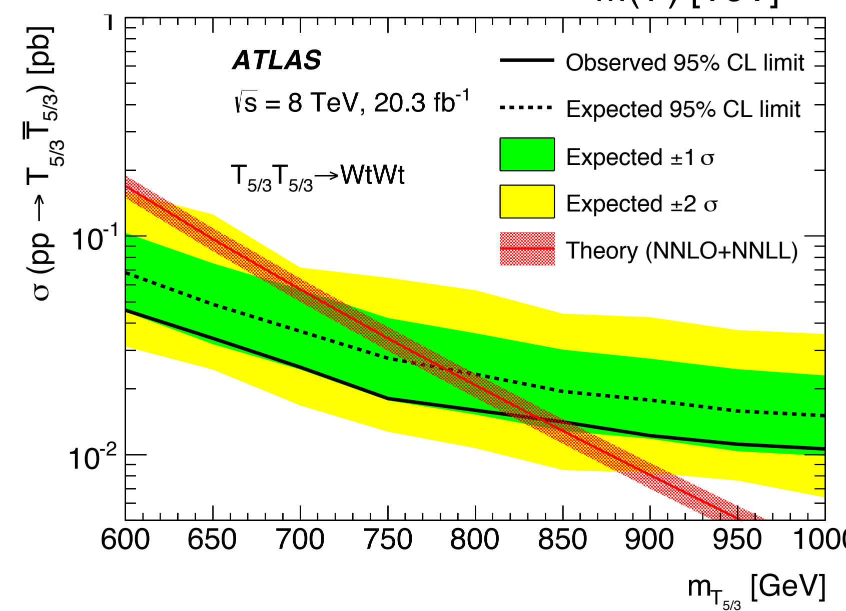

bounds on
charge 2/3 states
from single production




bounds on
charge 5/3 states
from single production



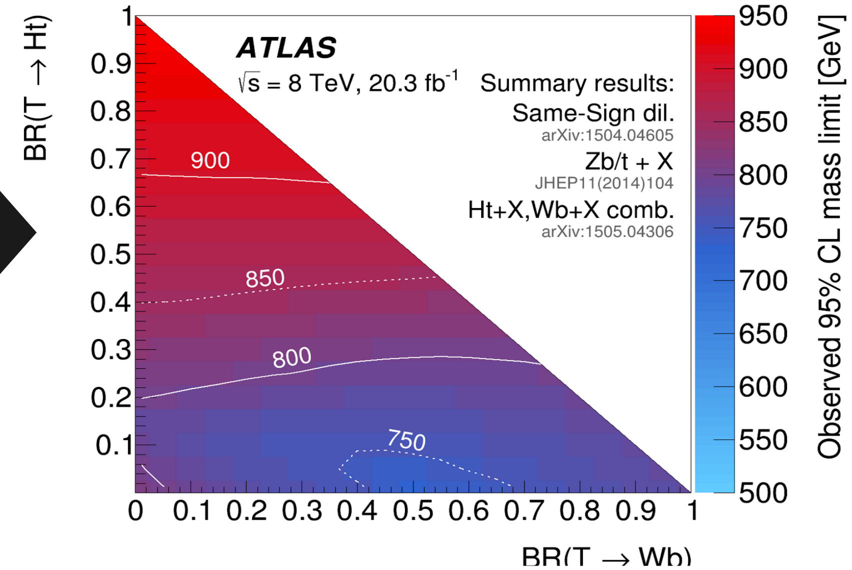




Christophe Grojean

# Searching for the Top Partners

bounds on
charge 2/3 states
from pair production

1505.04306

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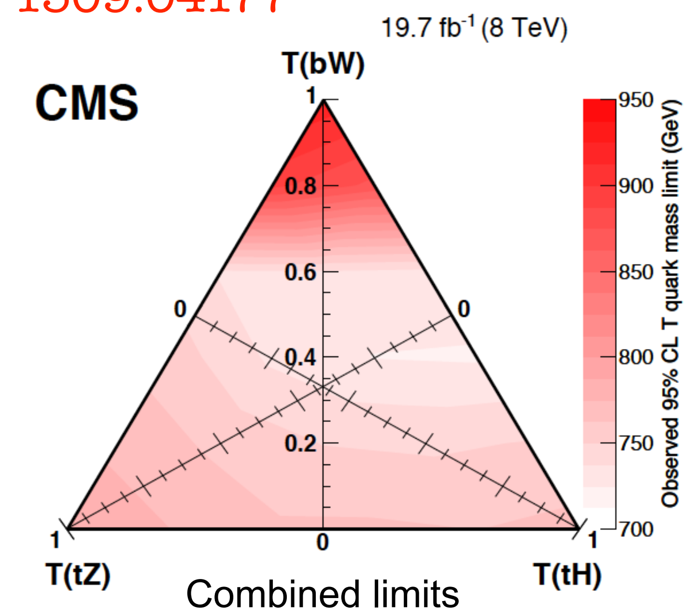
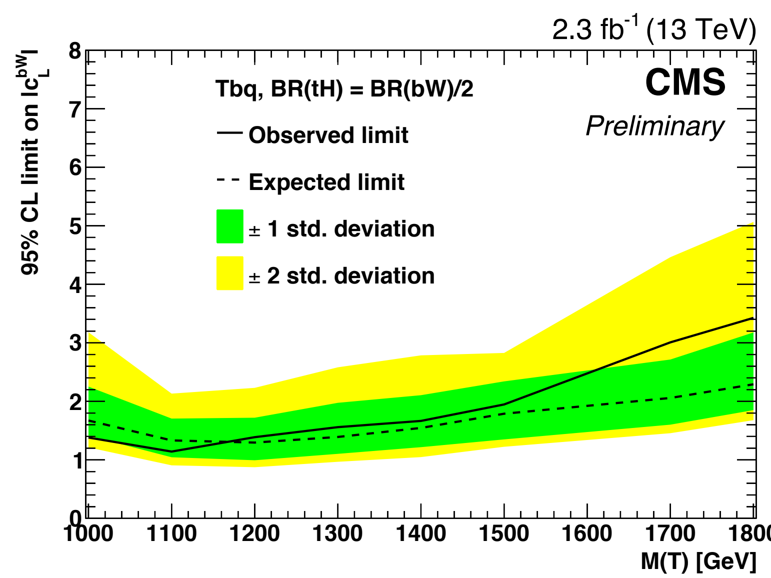
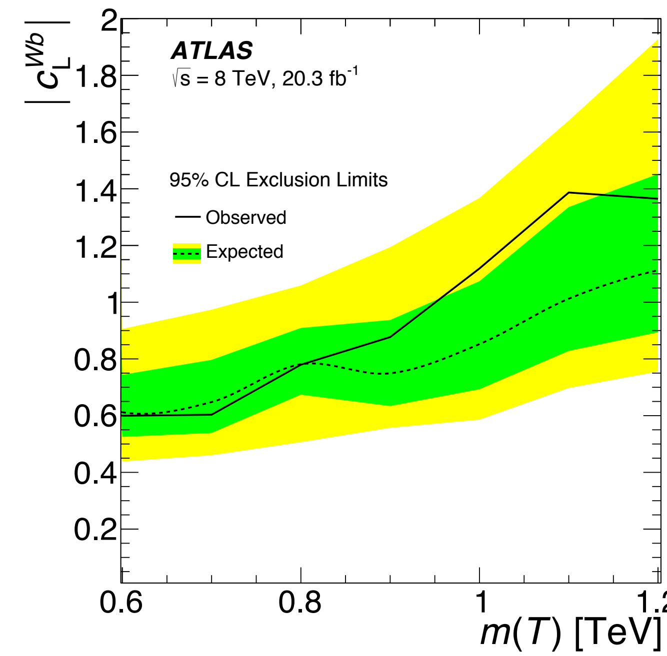



bounds on
charge 2/3 states
from single production




bounds on
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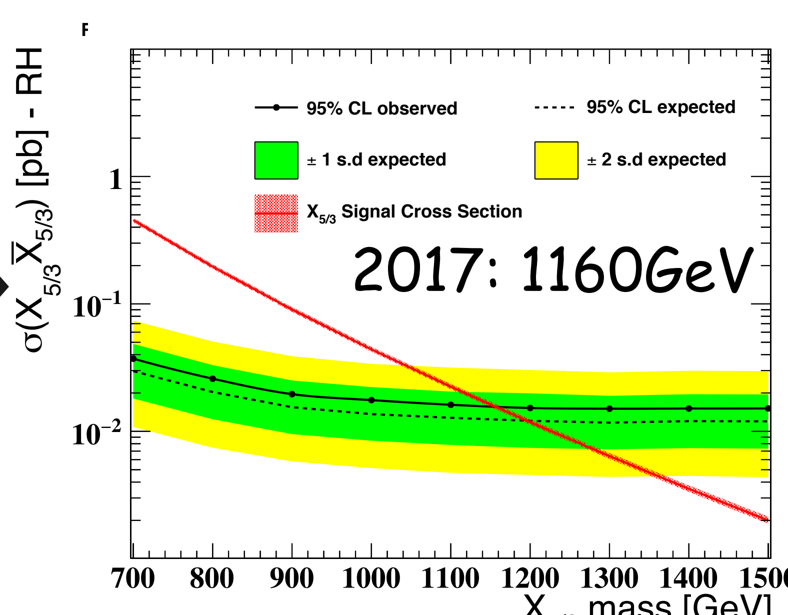


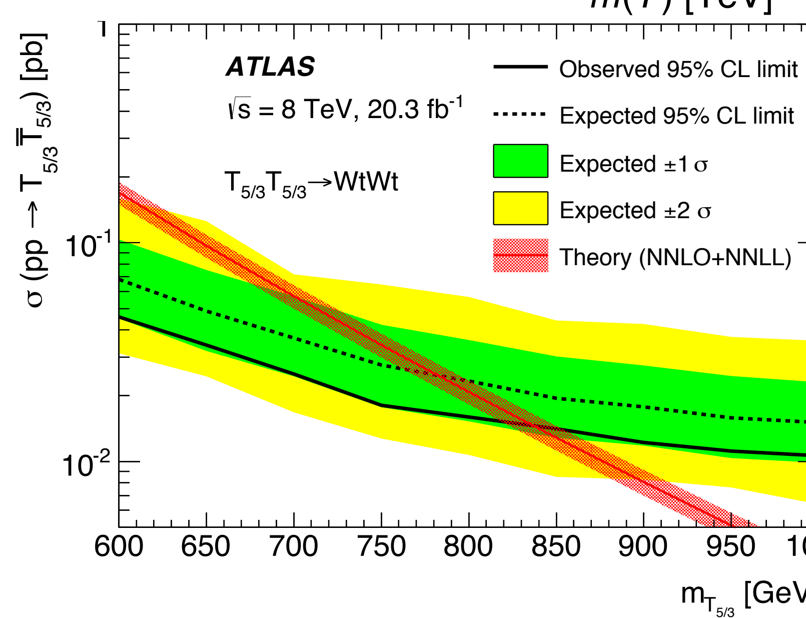


Christophe Grojean

# Technical Details

# EXTRA DIMENSIONS

# Extra dimensions

mass from motion in extra dimensions

$$m_D^2 = E^2 - \vec{p}_3{}^2 - \vec{p}_\perp{}^2$$

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mass from motion in extra dimensions

$$m_D^2 = E^2 - \vec{p}_3{}^2 - \vec{p}_\perp{}^2 \quad \Rightarrow \quad m_D^2 + \vec{p}_\perp{}^2 = E^2 - \vec{p}_3{}^2 = m_4^2$$

momentum along extra dimensions ~ 4D mass

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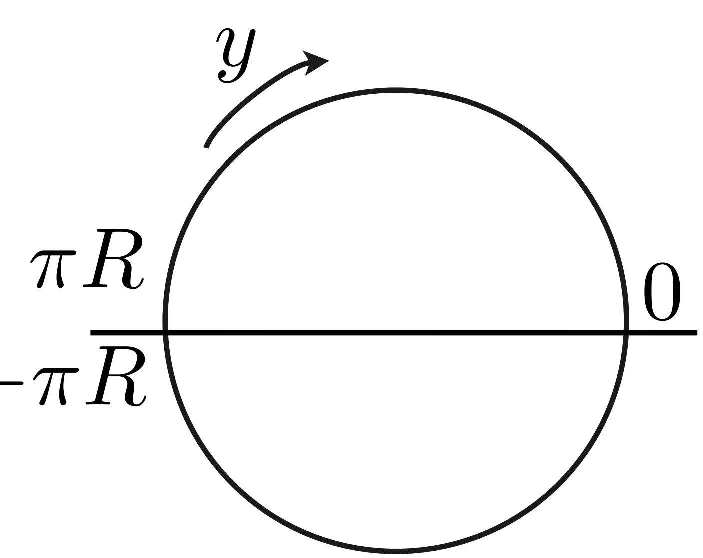
momentum along extra dimensions ~ 4D mass

~~ Compactification on a Circle ~~




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

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

# Extra dimensions

mass from motion in extra dimensions

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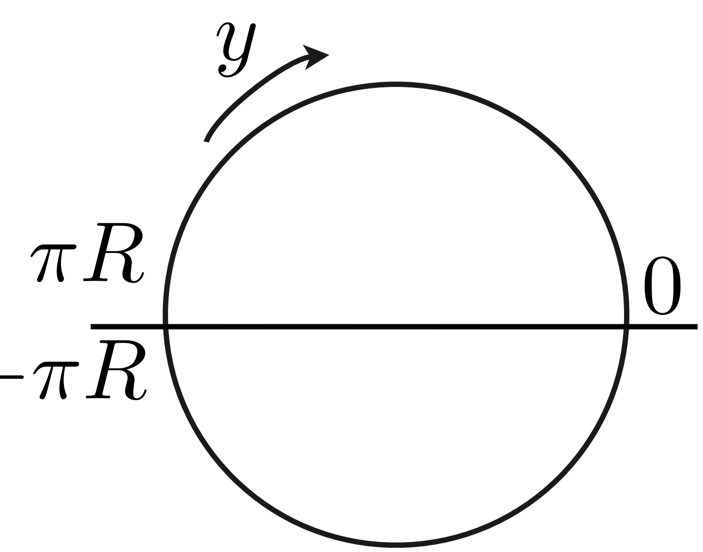


circle:
$$y \sim y + 2\pi R$$
$$\phi(y + 2\pi R) = \phi(y)$$

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

5D
field

# Extra dimensions

mass from motion in extra dimensions

$$m_D^2 = E^2 - \vec{p_3}^{\,2} - \vec{p}_\perp^{\,2} \quad \Rightarrow \quad m_D^2 + \vec{p}_\perp^{\,2} = E^2 - \vec{p_3}^{\,2} = m_4^2$$

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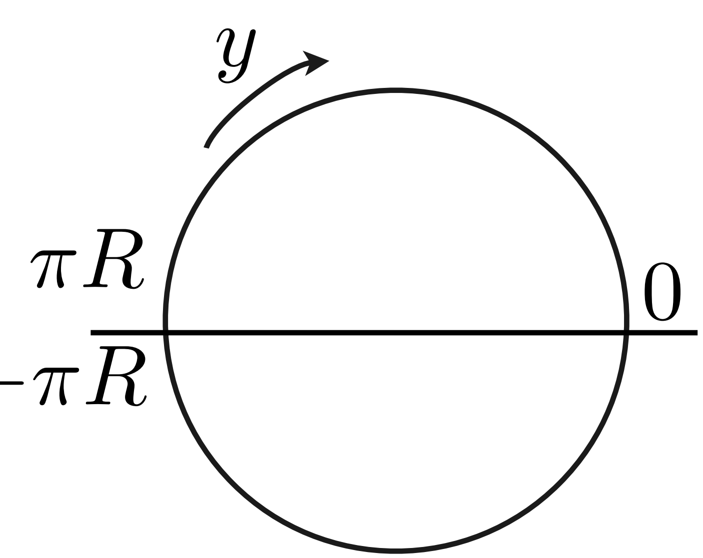


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5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

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

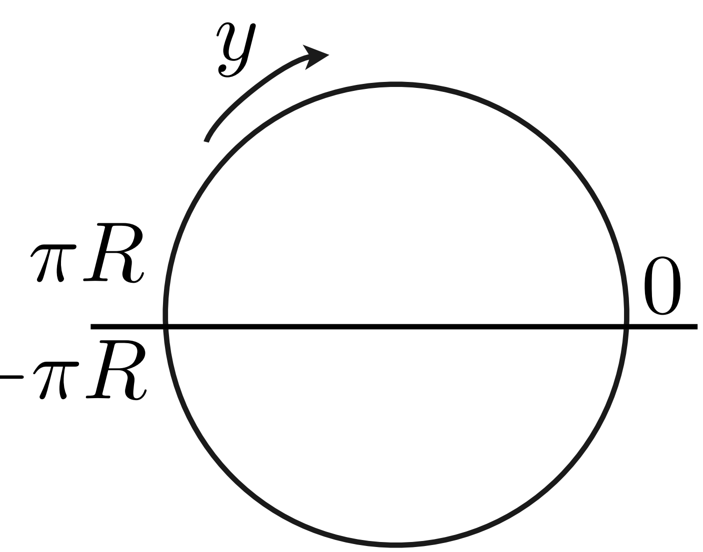
# Extra dimensions

| | + states | - states |
|---|---|---|
| ⋮ | ⋮ | ⋮ |
| $m_{5D}^2 + 9/R^2$ | ——— | ——— |
| $m_{5D}^2 + 4/R^2$ | ——— | ——— |
| $m_{5D}^2 + 1/R^2$ | ——— | ——— |
| $m_{5D}^2$ | ——— | |

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

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| $m_{5D}^2$ | —— | |

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**

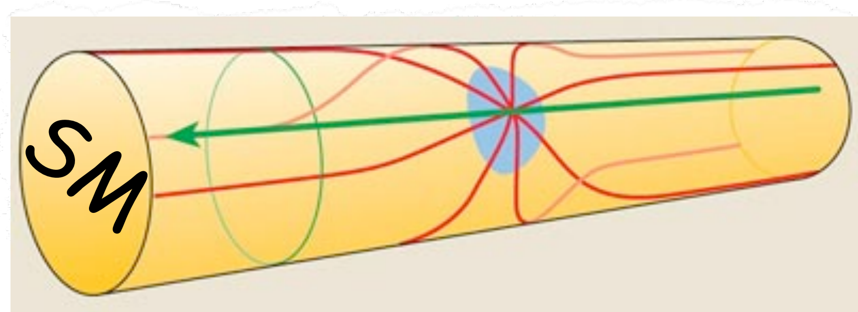
gauge symmetries are emerging from
gravitational interactions in extra dimensions?
beautiful idea of Kaluza & Klein
but
quantization? non-abelian structure? different gauge couplings?
no successful realization till now

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

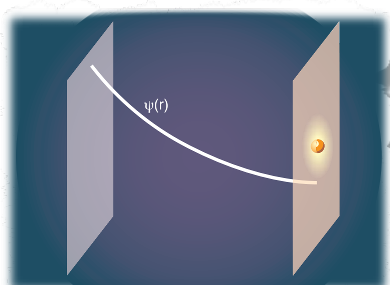



$$\int d^{4+n}x\,\sqrt{|g_{4+n}|}M_\star^{2+n}\mathcal{R} = \int d^4x\,\sqrt{|g_4|}M_{Pl}^2\mathcal{R}$$

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

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

  - 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

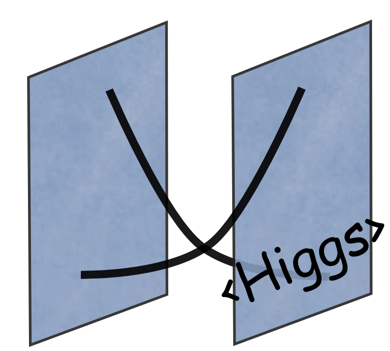
$$v = M_\star e^{-\pi R M_\star}$$

$M_* = 10^{19}$ 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

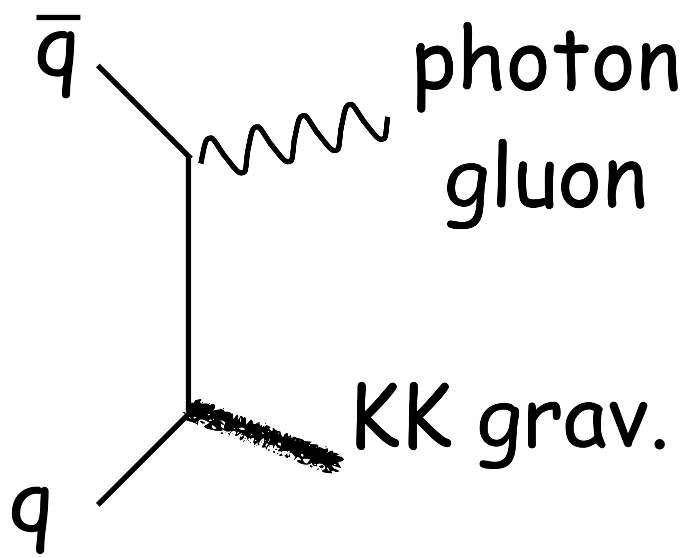
  Orbifold breaking, Higgsless

# Large Volume Xdim Phenomenology

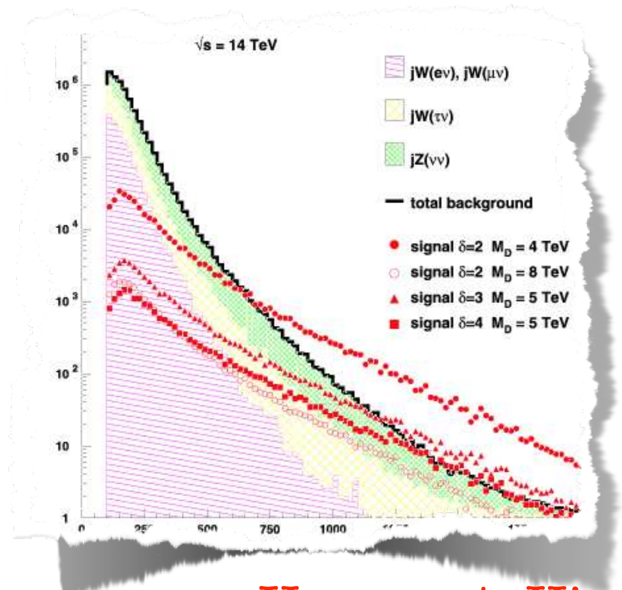
eV splitting between graviton KK modes

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

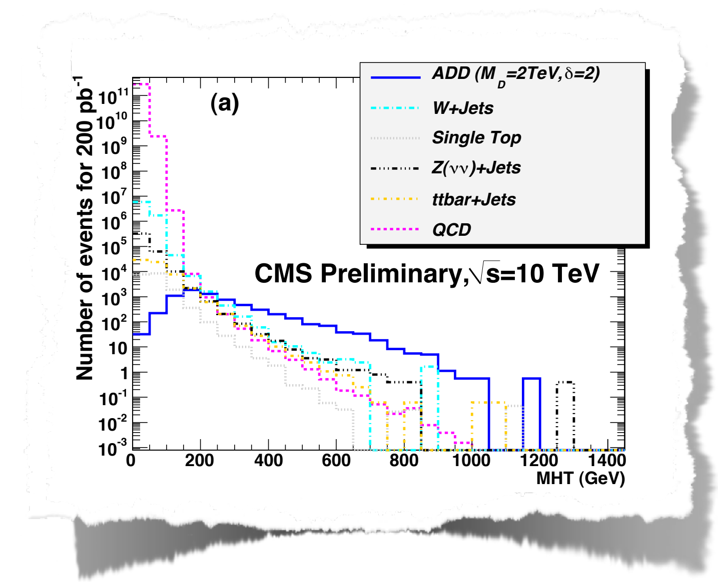
- Graviton production in colliders




monojet+$\not{E}_T$

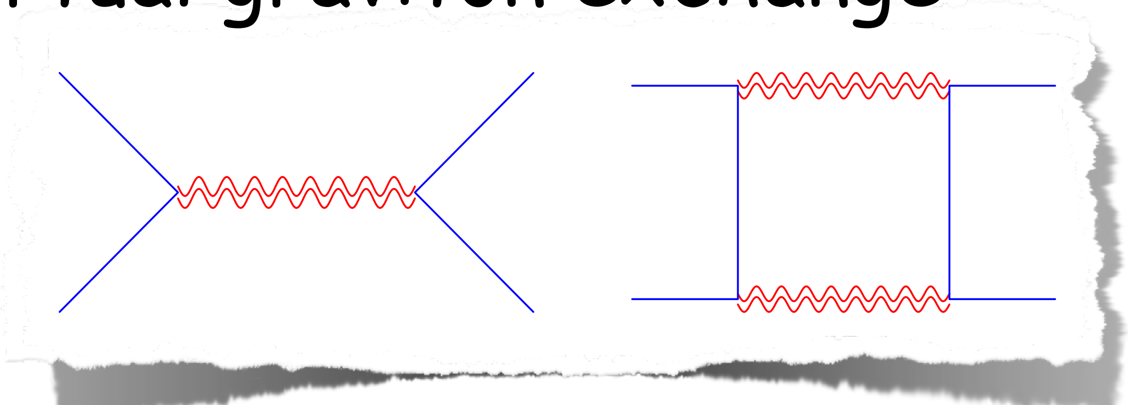



Vacavant, Hinchliffe '01




CMS PAS EXO 09-013

- Virtual graviton exchange

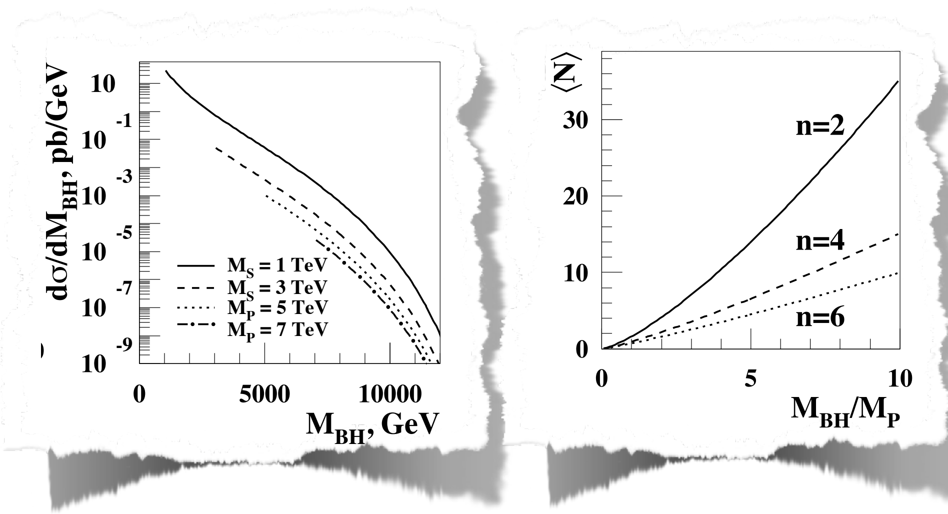


# Large Volume Xdim Phenomenology

- 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

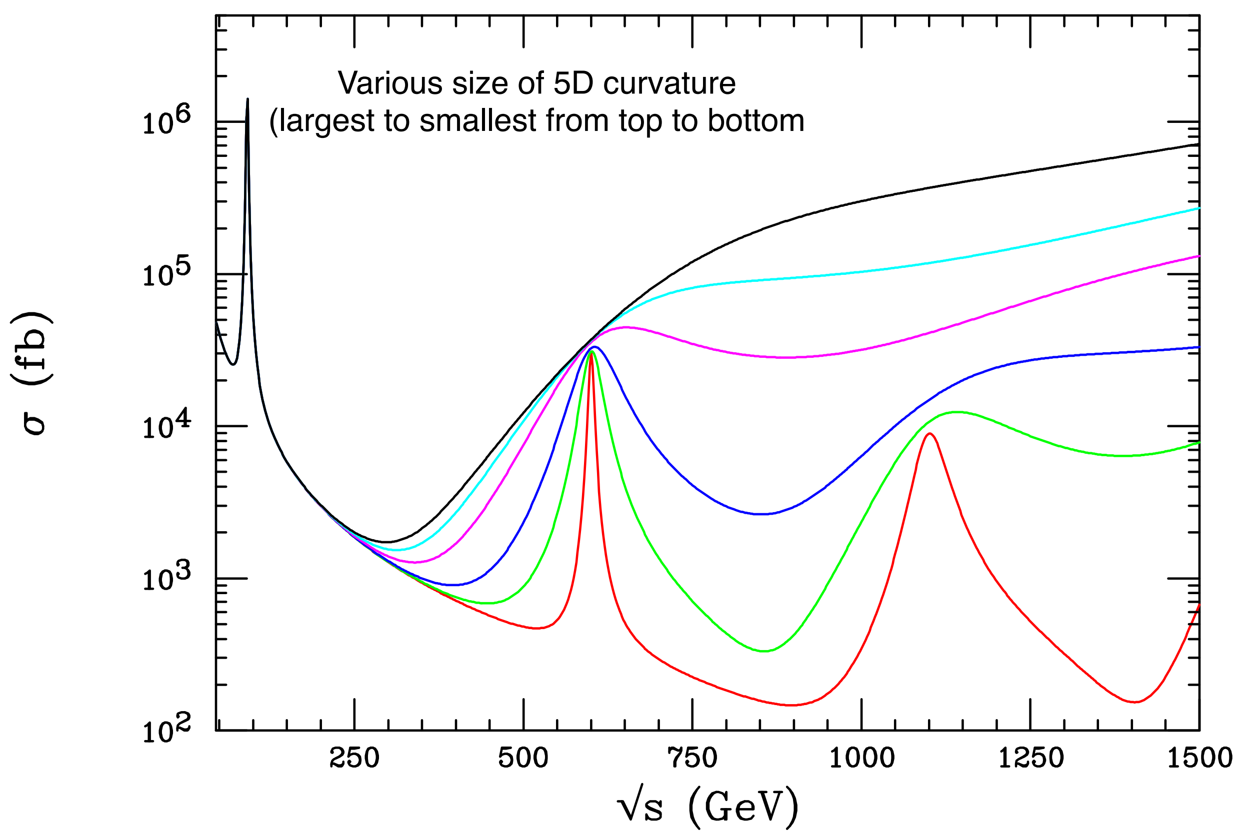
- String resonances production

# Curved Xdim Phenomenology

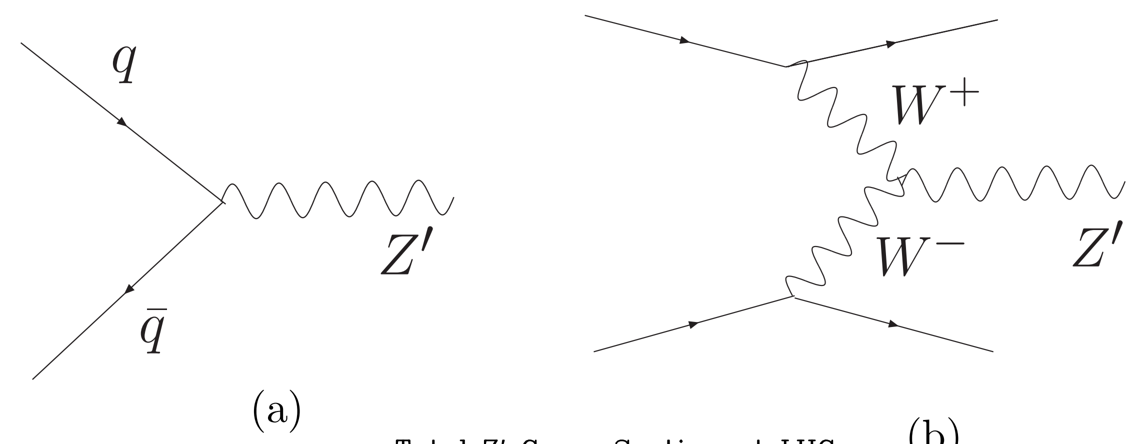
TeV splitting between gauge KK modes

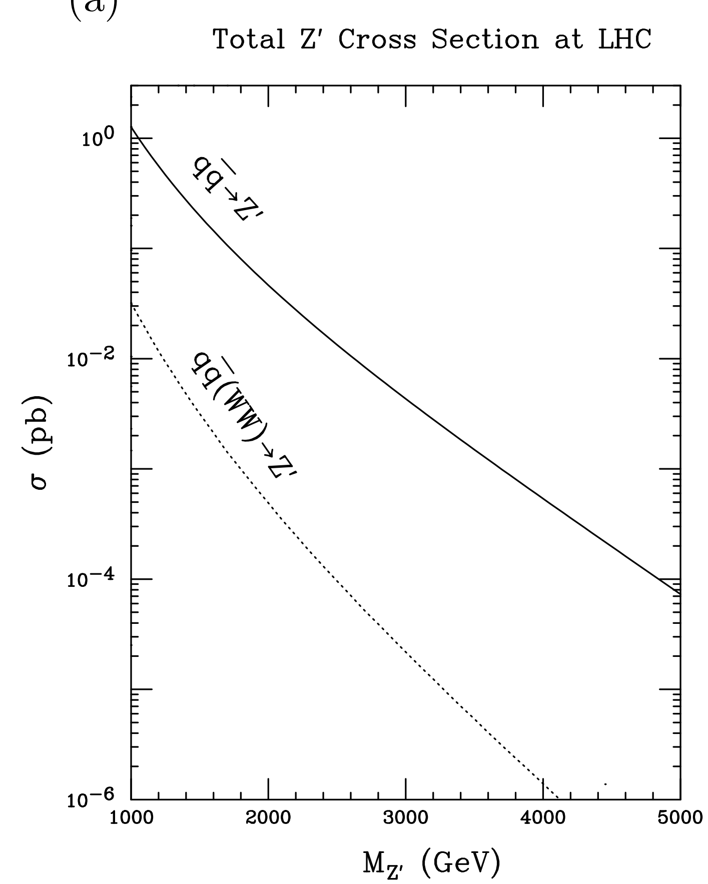
$O(g_{SM})$ couplings of gauge KK modes to SM

$$e^+e^- \to \mu^+\mu^-$$




Davoudiasl et al '99




Agashe et al '07

# Curved Xdim Phenomenology

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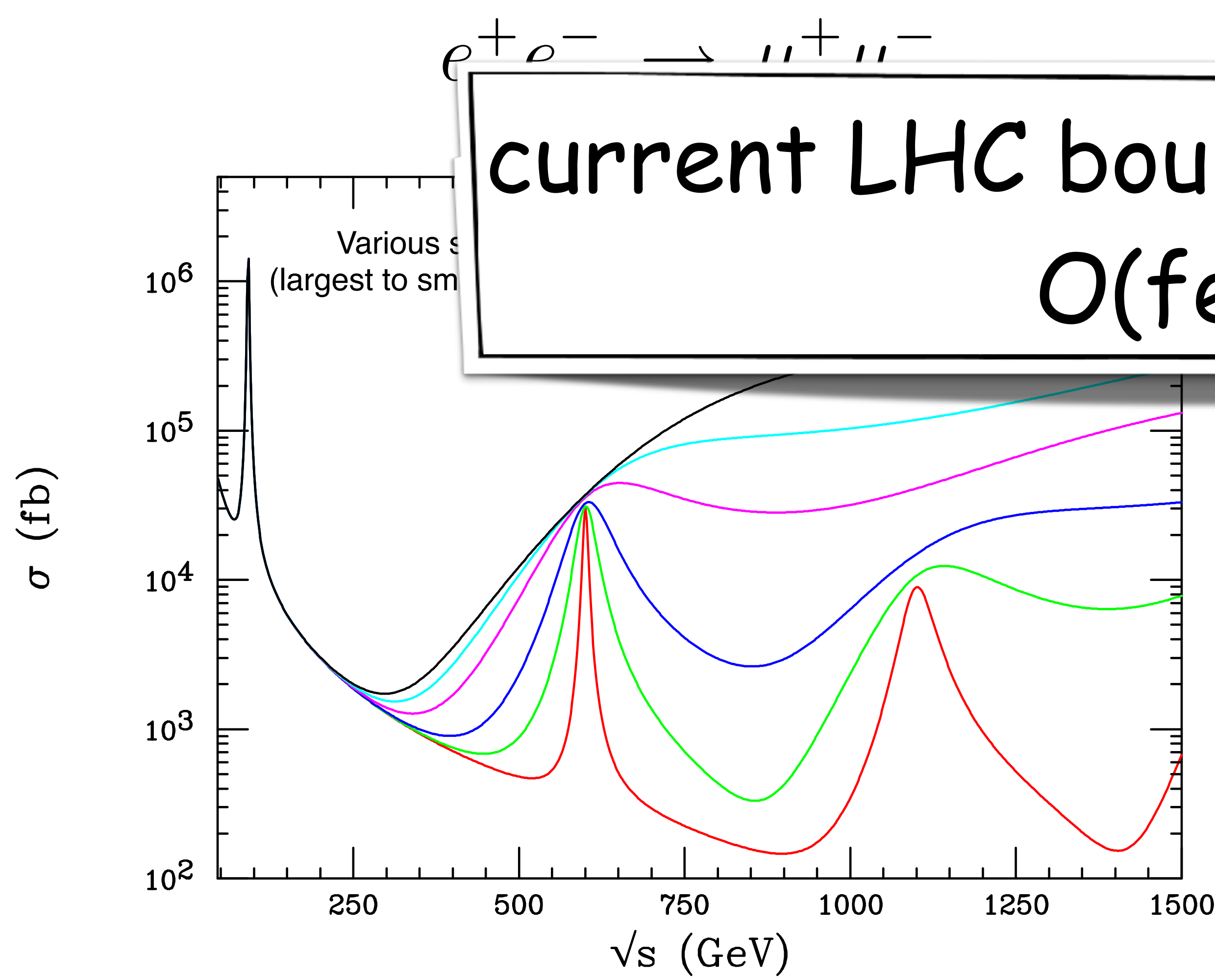
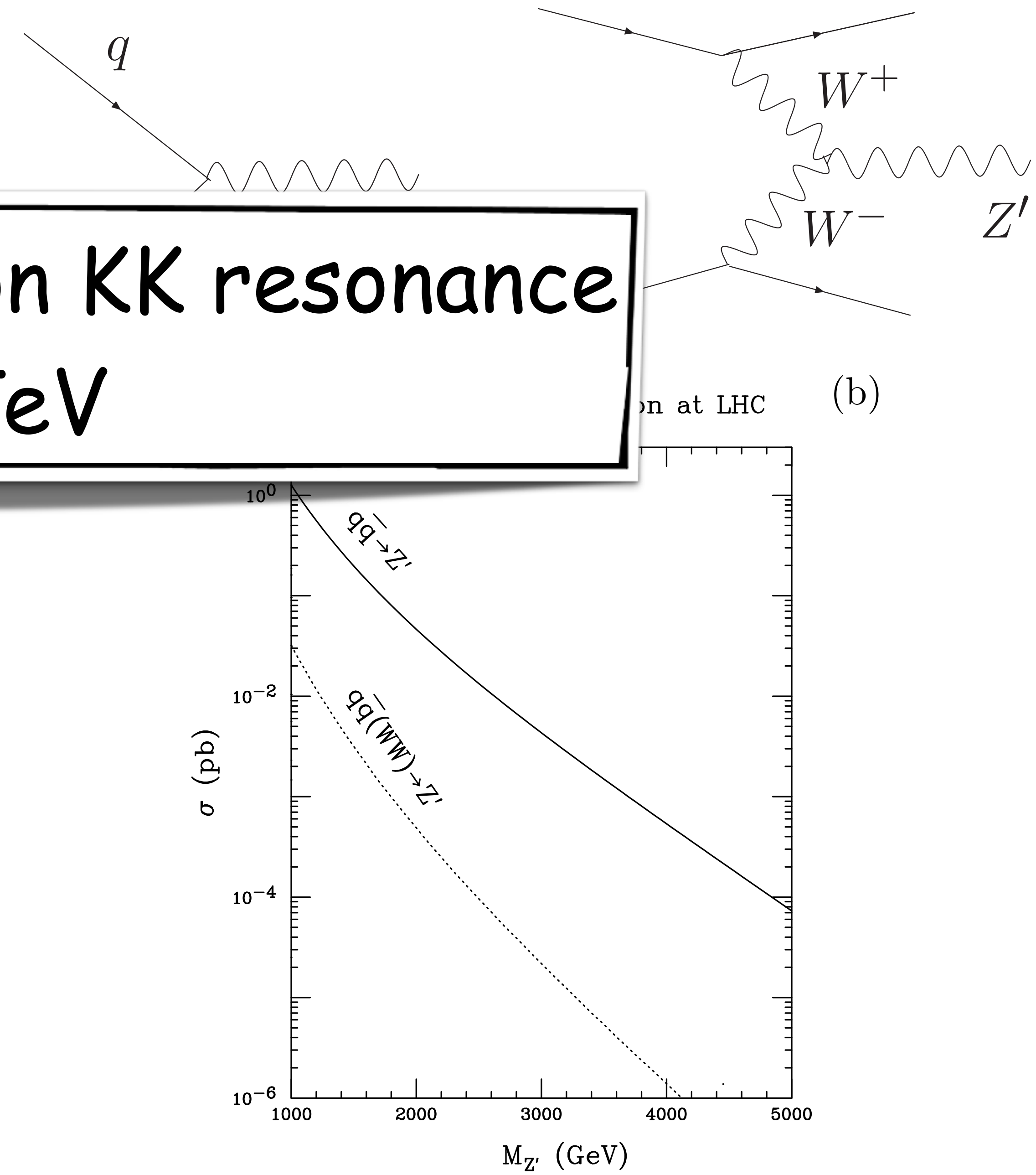



Davoudiasl et al '99

**current LHC bounds on KK resonance O(few) TeV**




Agashe et al '07