The SMEFT/geoSMEFT- the modern EFT analysis of collider data

Prepared for: QUC summer school

Michael Trott, NBI

Outline for today/this week

First lecture:

- SMEFT via Higgs. SMEFT method to collider data, with symmetry orientation. Old EWPD (S andT)

Second lecture:

- Parameter counting in SMEFT, with symmetry guidance. Modern EWPD via SMEFT. Basics of dimension six corrections to SM predictions input parameters.

Third lecture:

- W mass interpretation and anomaly. Hierarchy prob in EFT.
  Higgs and SMEFT example: Higgs Width in detail at leading order.

Forth lecture:

- Going beyond the leading order - loops and dimension eight challenges
  Modern developments and problems that led to the geoSMEFT.

geoSMEFT seminar: The current state of the art and open challenges.

SMEFT review 1706.08945, Manohar EFT review 1804.05863, Burgess Review hep-th/0701053

Lecture one.

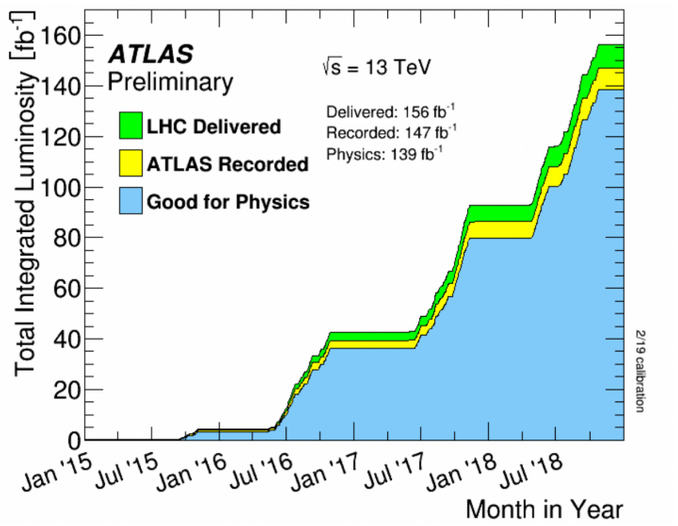
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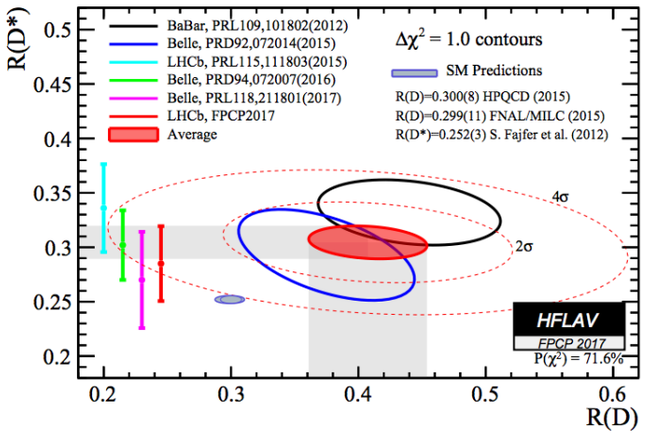
First lecture

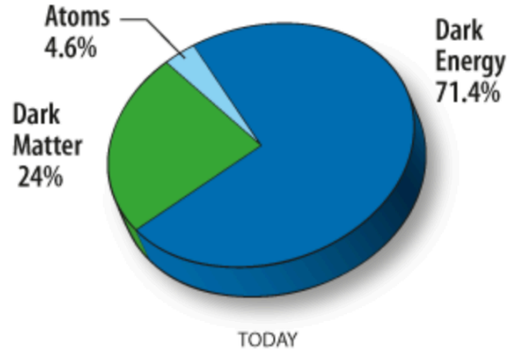
- Motivation for EFT approaches considering the global data set now/in the future
- Massive vectors/a scalar in the spectrum- Higgs and SMEFT vs HEFT
- SM Higgs and custodial symmetry - ST EWPD analysis - support for SM
- Cut off scales and SMEFT and HEFT

Motivation for global EFT

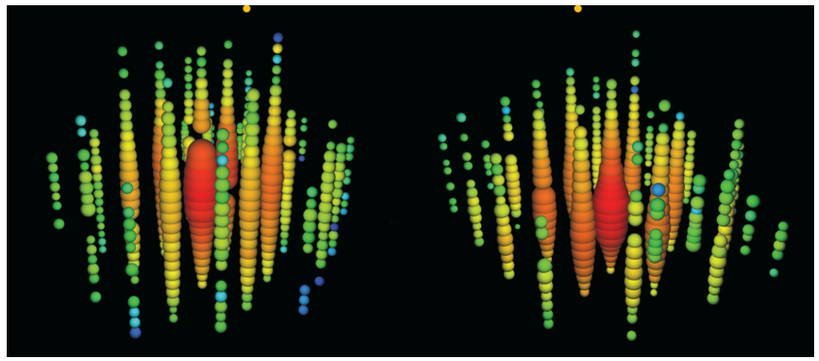
The golden age of data rich particle physics is now

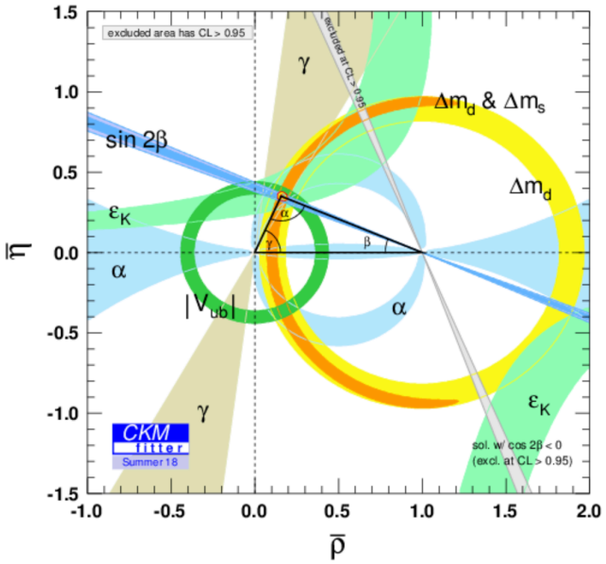


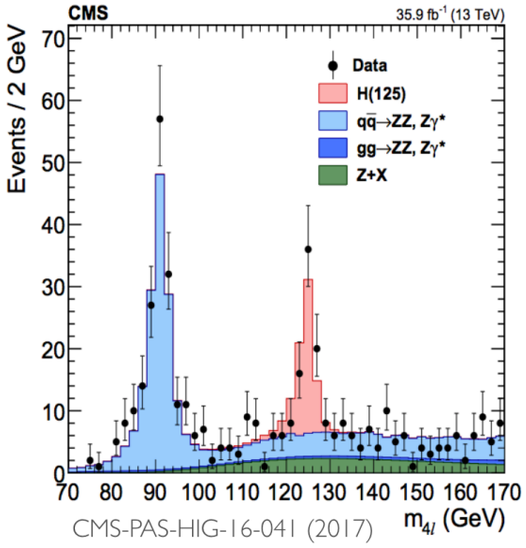


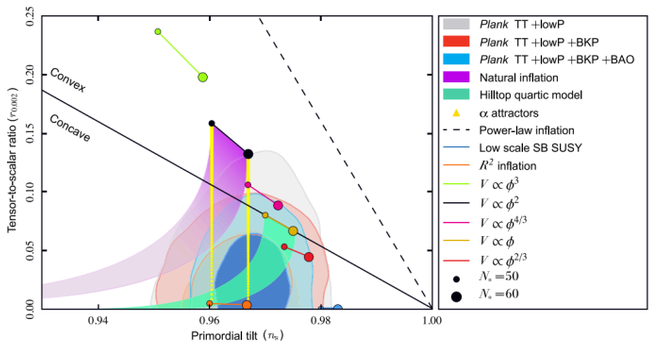


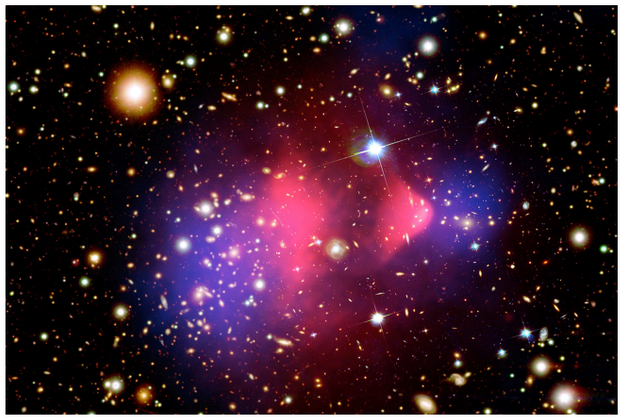
Credit: NASA/WMAP Science Team

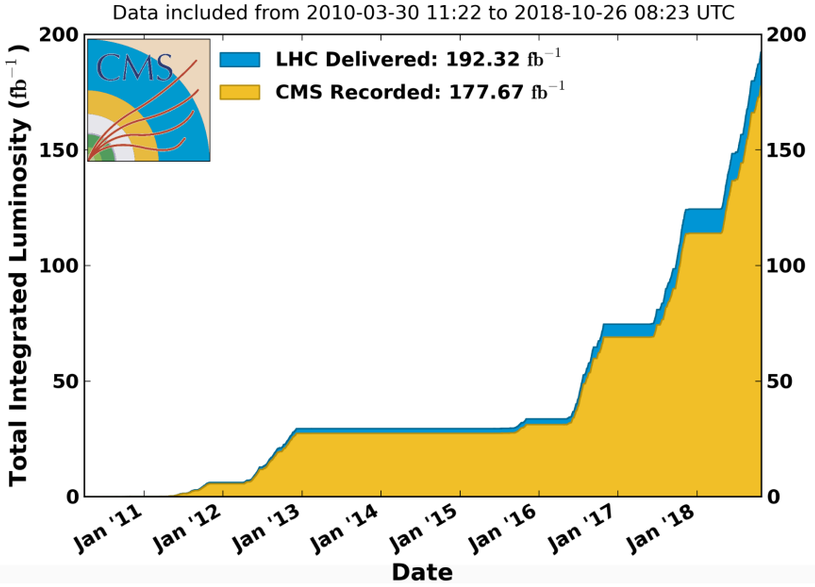




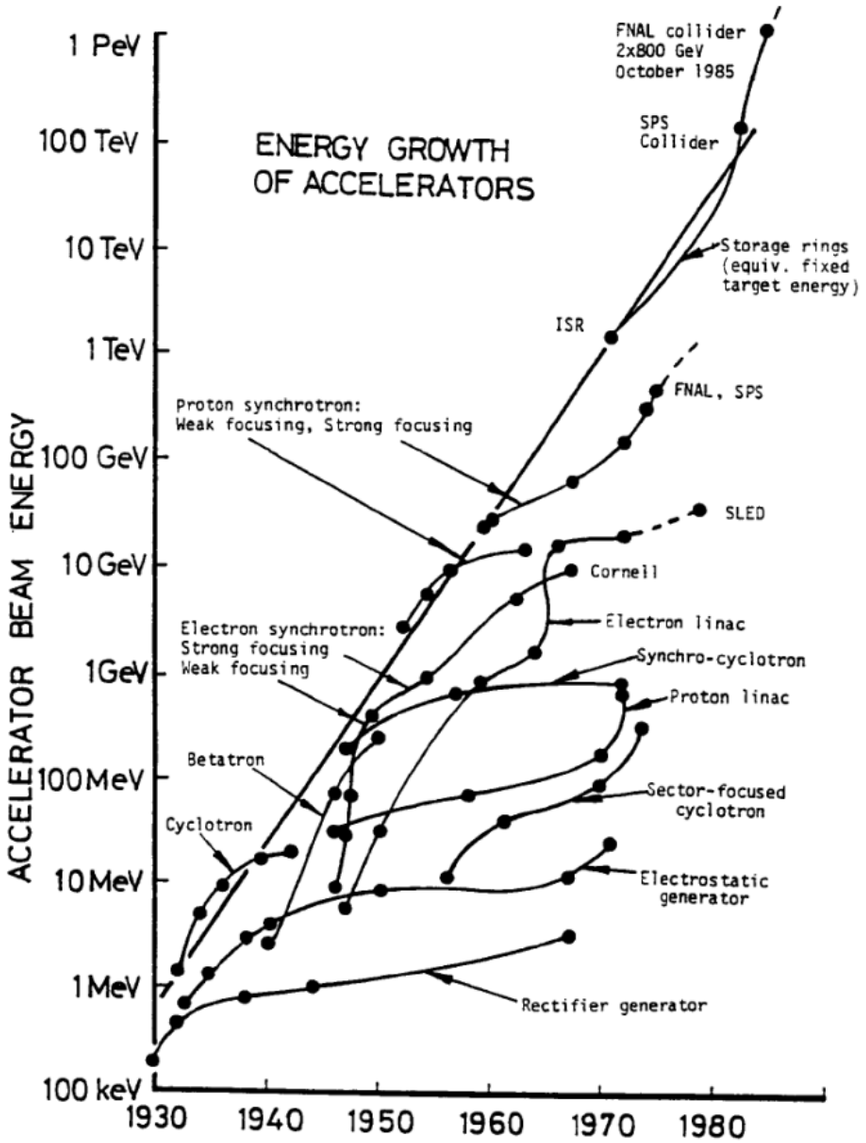




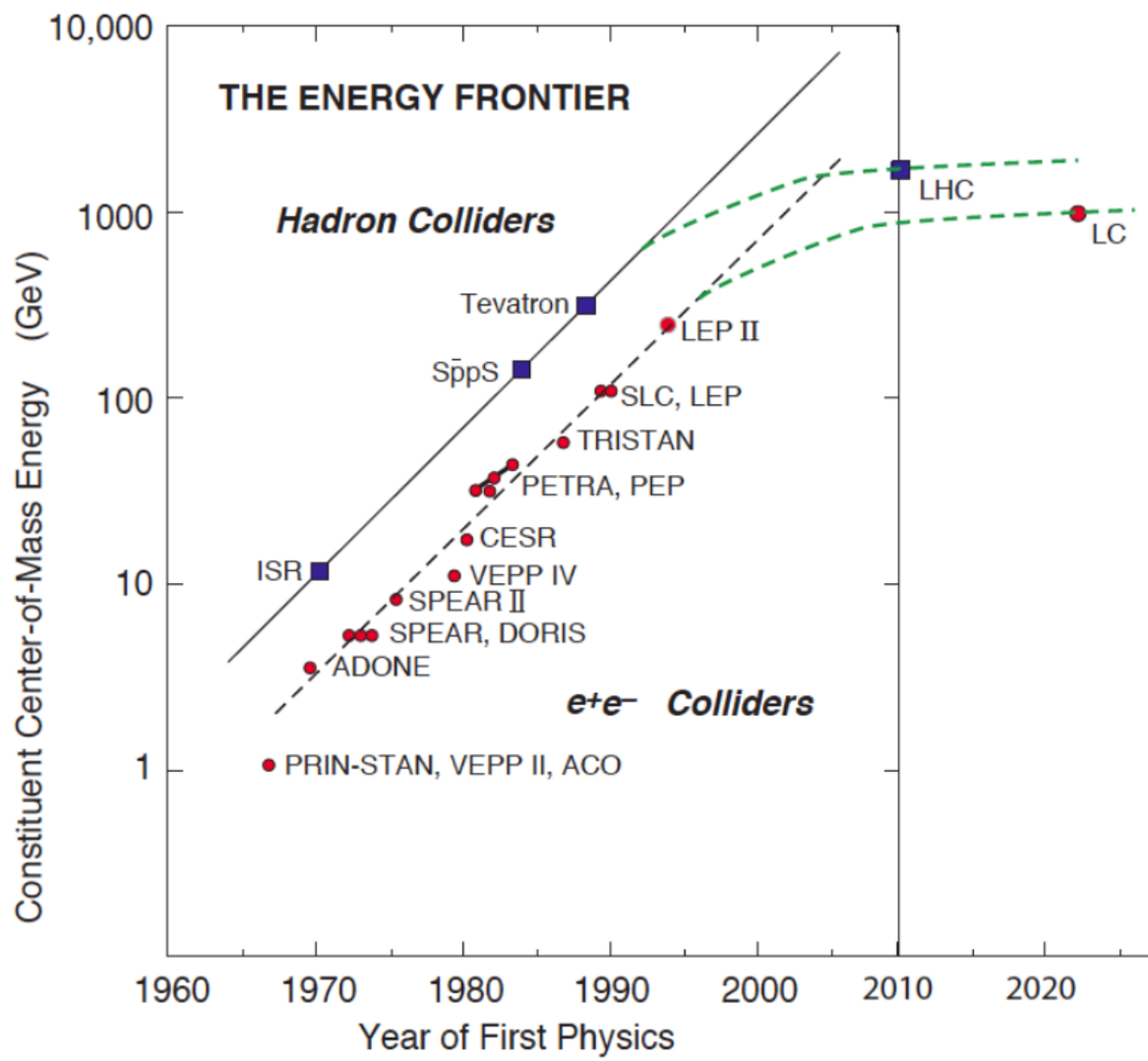




What is the big EXP picture?



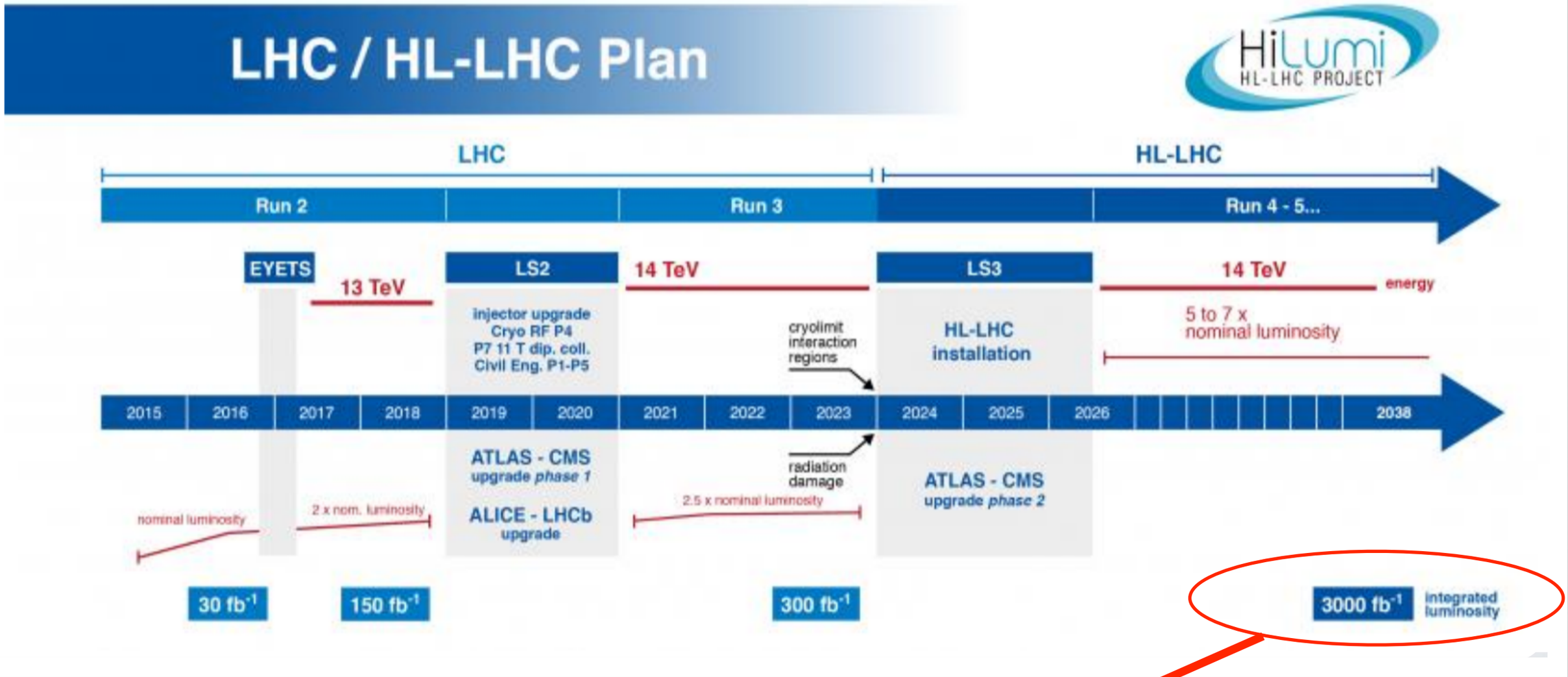
Livingston chart: 1985



Livingston chart: 2014

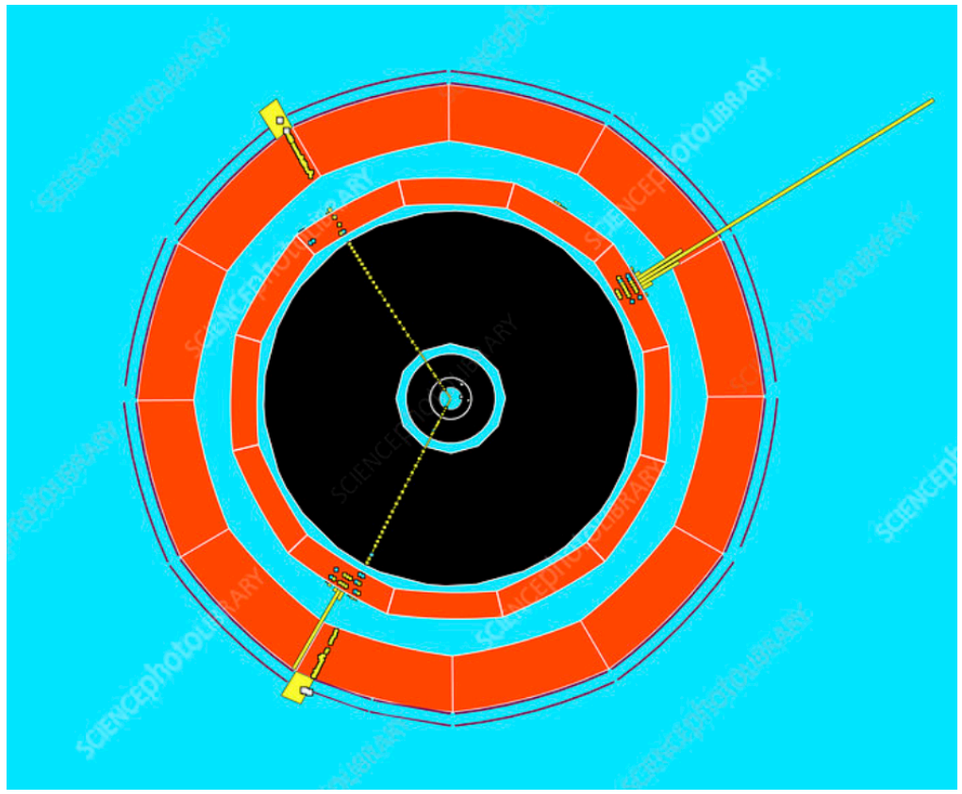
Images: http://www.hep.ucl.ac.uk/iop2010/talks/14.pdf

We will get a bit more $\sqrt{s}$ reach

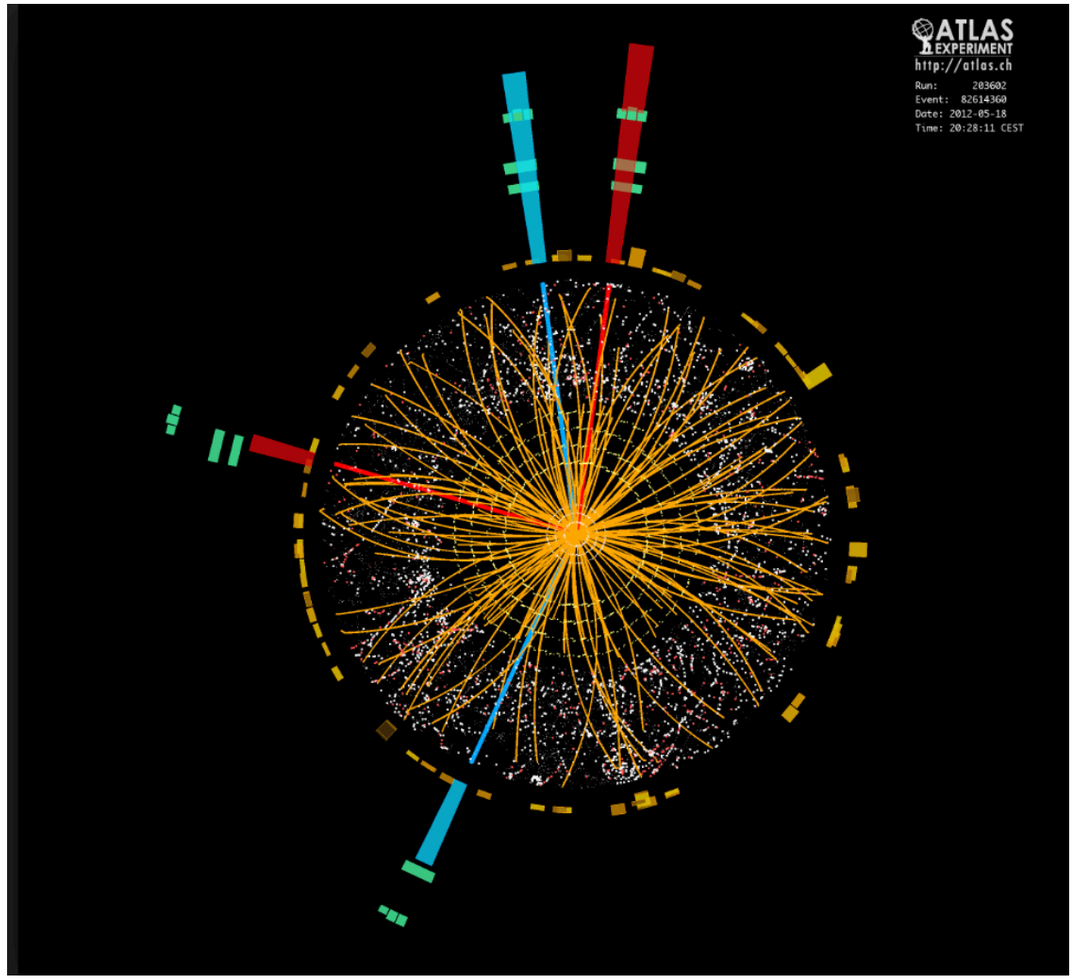


And a lot more data..

Collision characteristics different

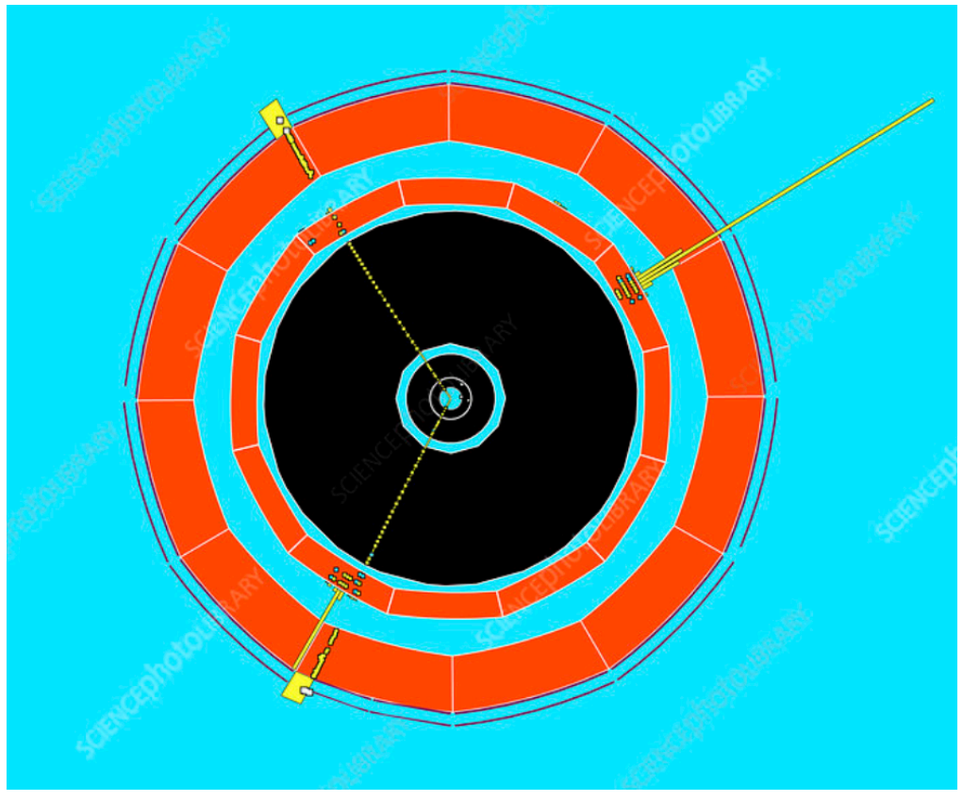


Typical LEP Z event (Aleph).

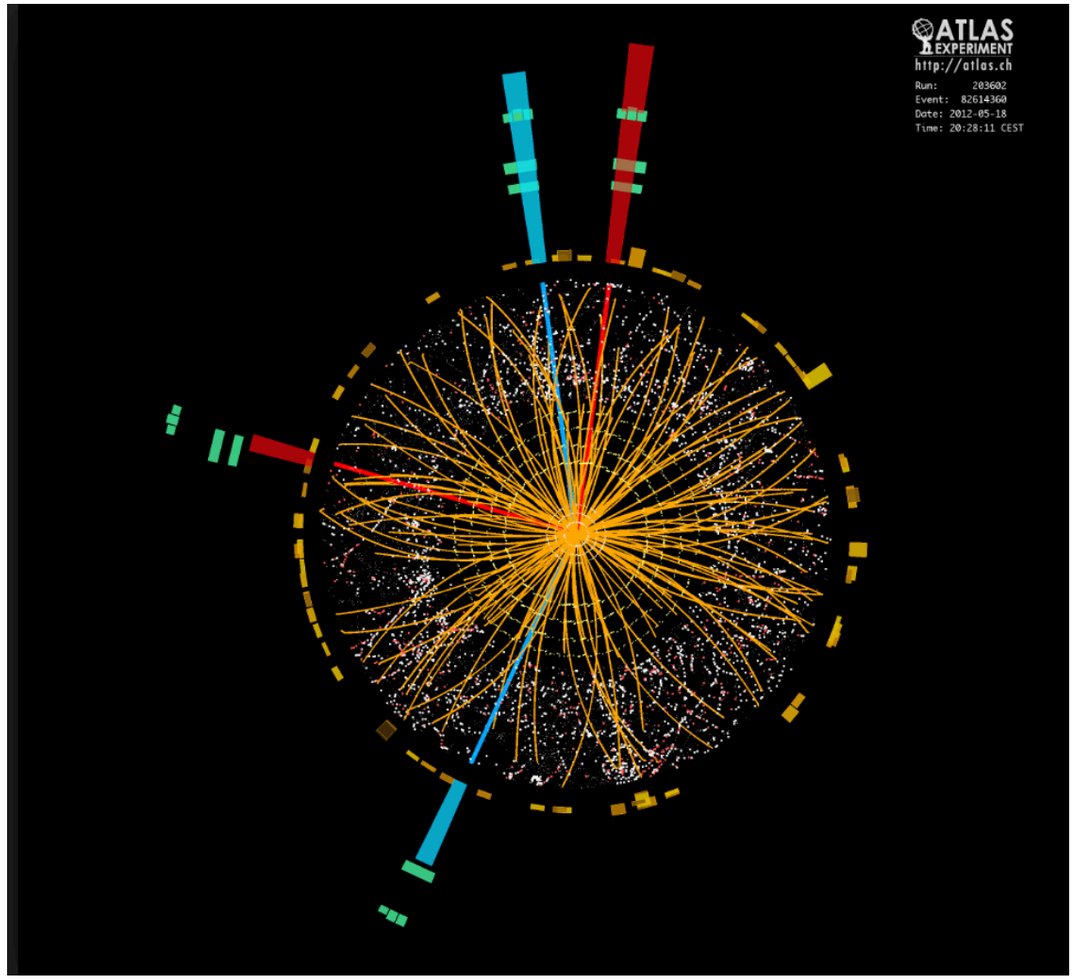


Typical H event (Atlas).

… but unified data analysis emerging



Typical LEP Z event (Aleph).

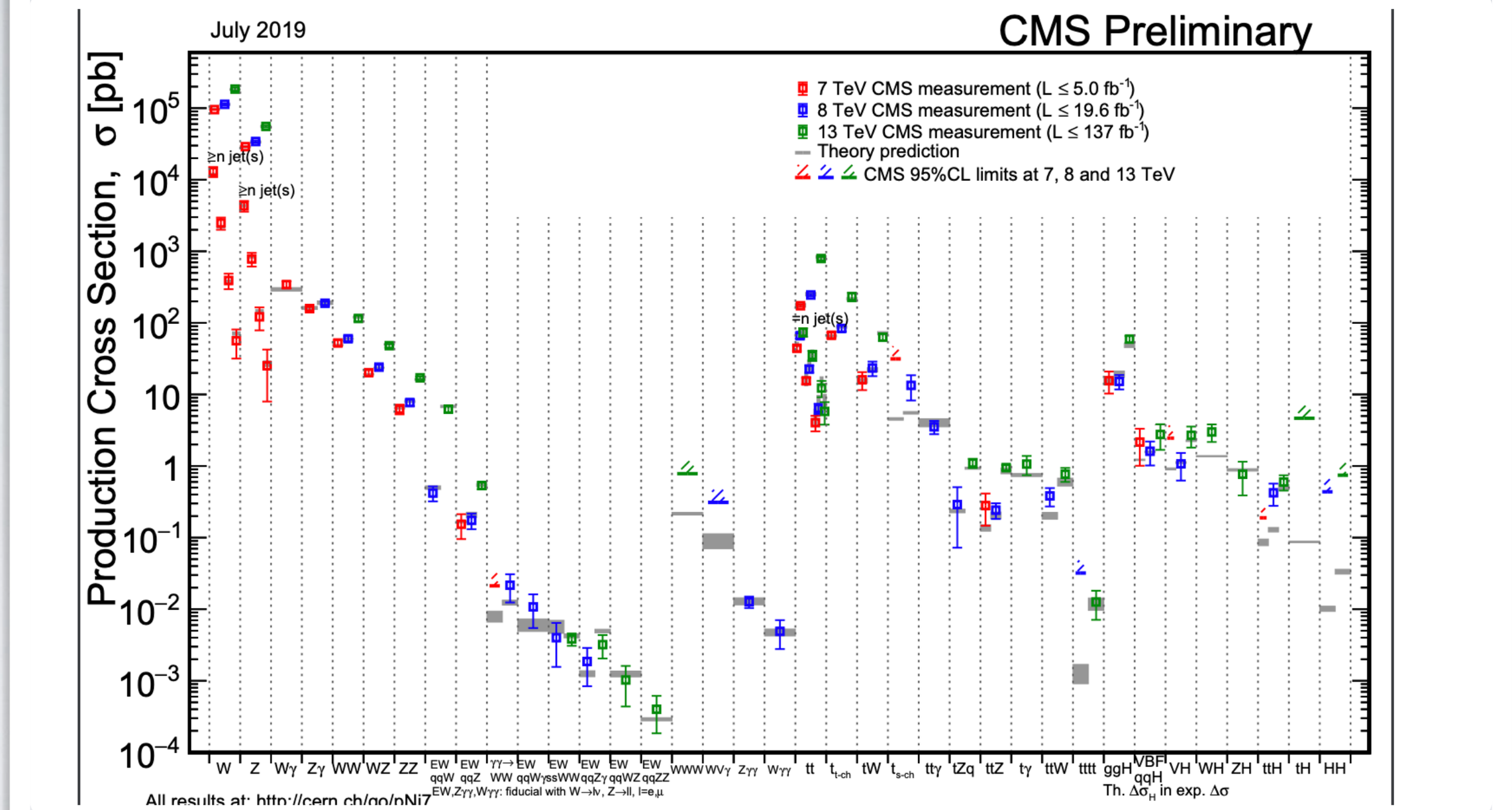


Typical H event (Atlas).

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots,$$

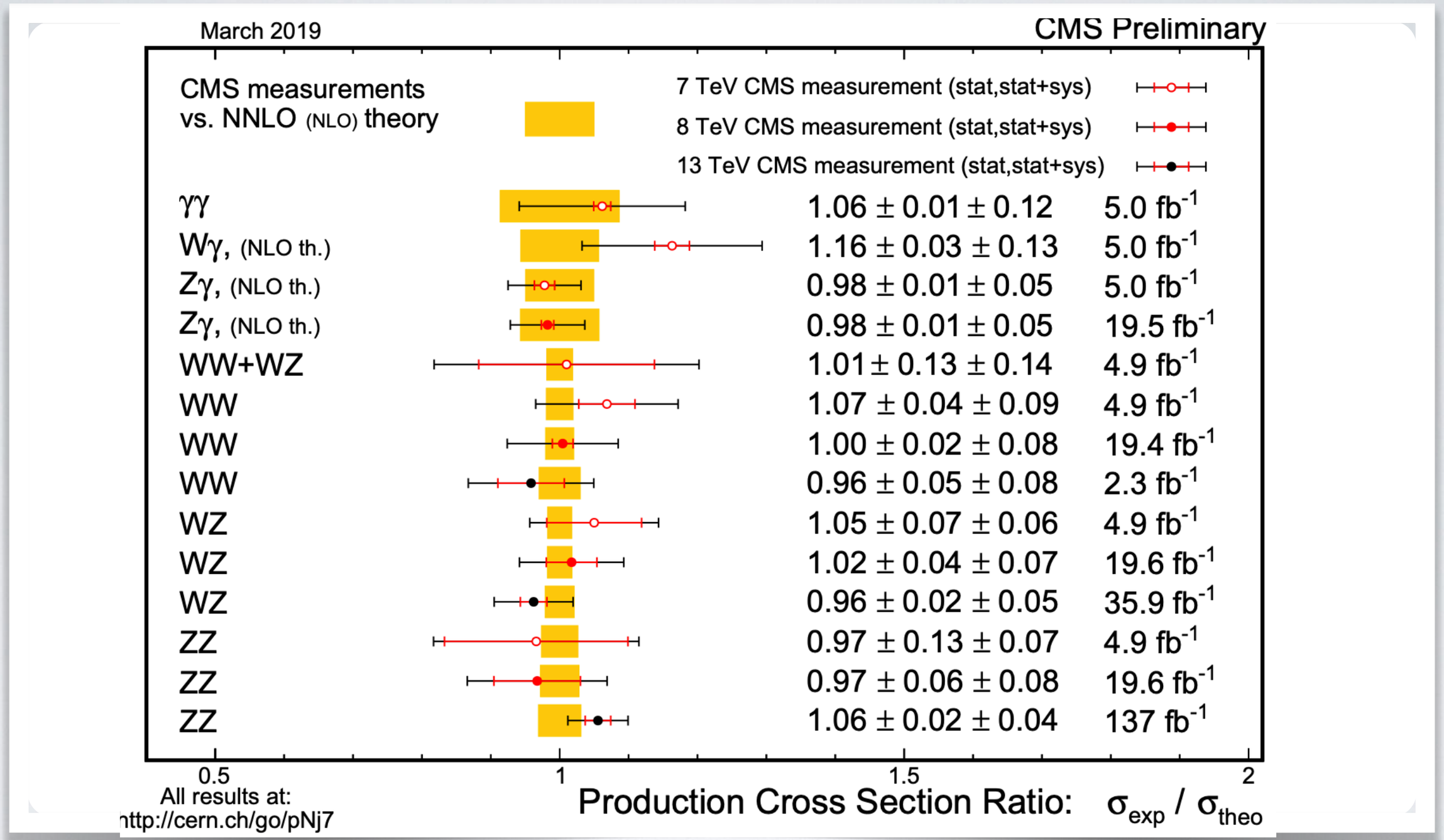
$$\mathcal{L}^{(d)} = \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_i^{(d)} \text{ for } d > 4.$$

Big TH picture: SM a good approx at colliders



- The measurement precision and accuracy is generically not at the % level

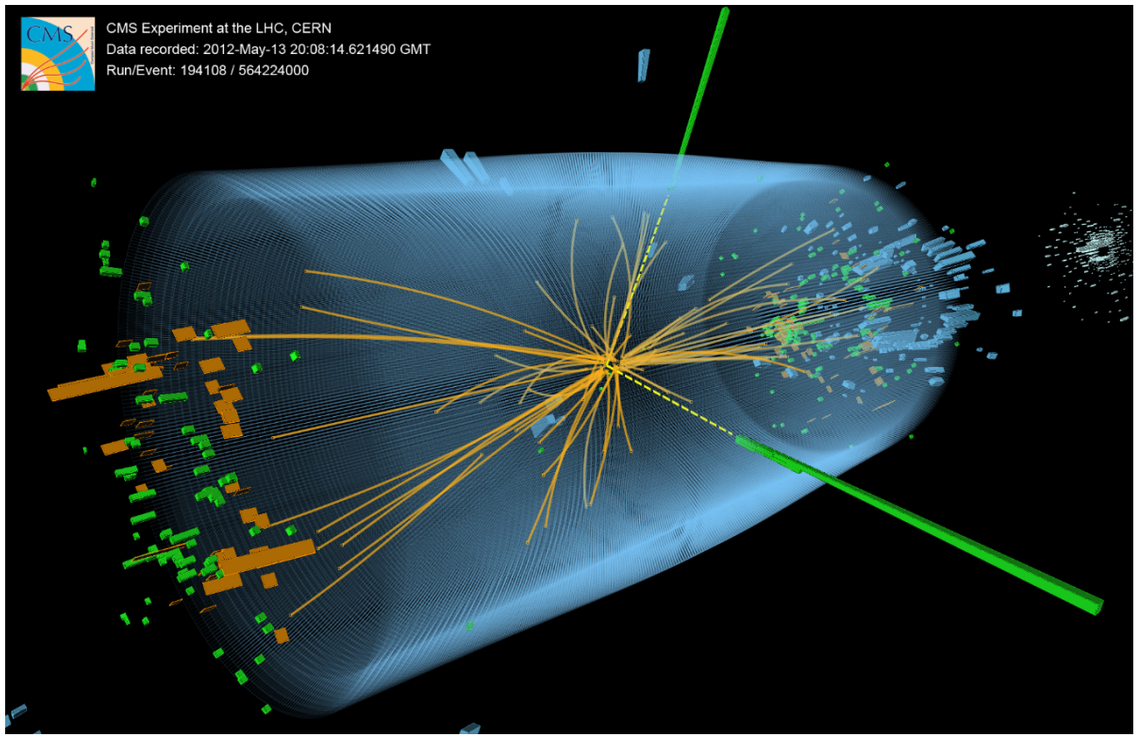
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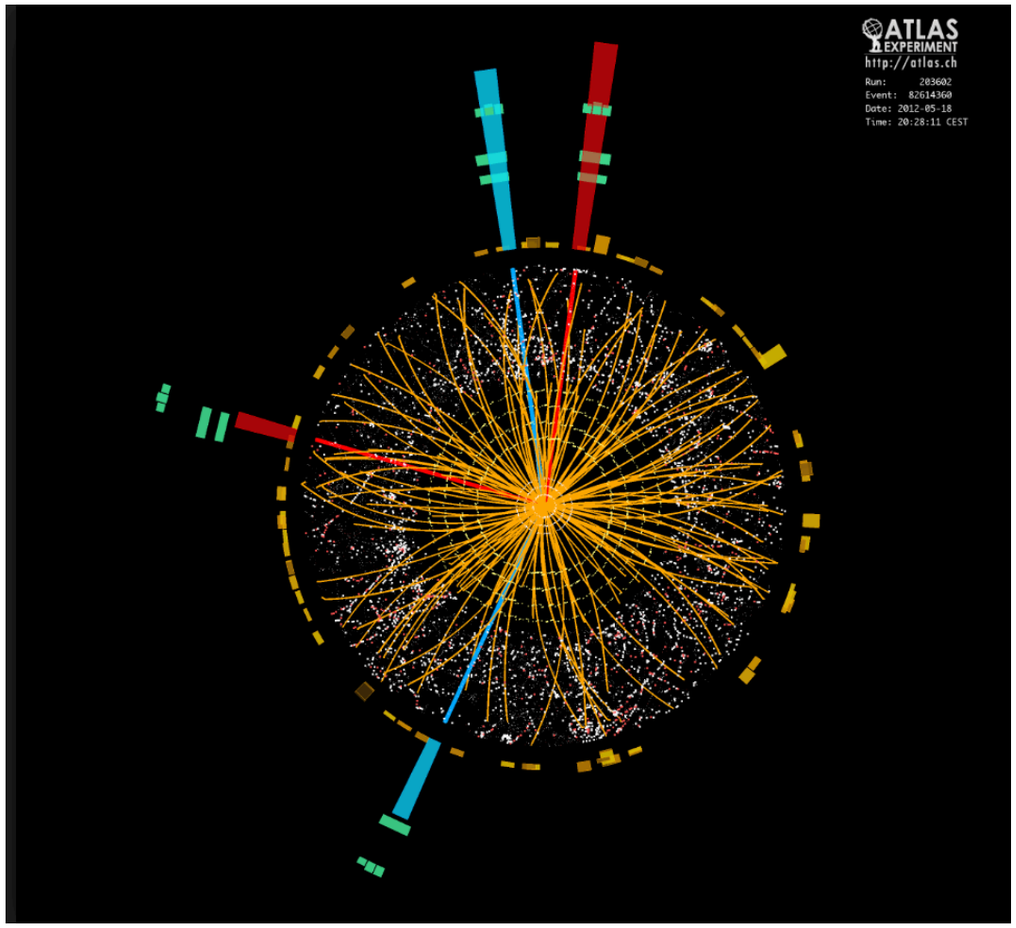
- The measurement precision and accuracy ***is generically not at the % level***

New (expected) particle in spec

- Discovery of a (Higgs like) $J^P \sim 0^+$ particle in 2012



CMS-PAS-HIG-16-041 (2017)

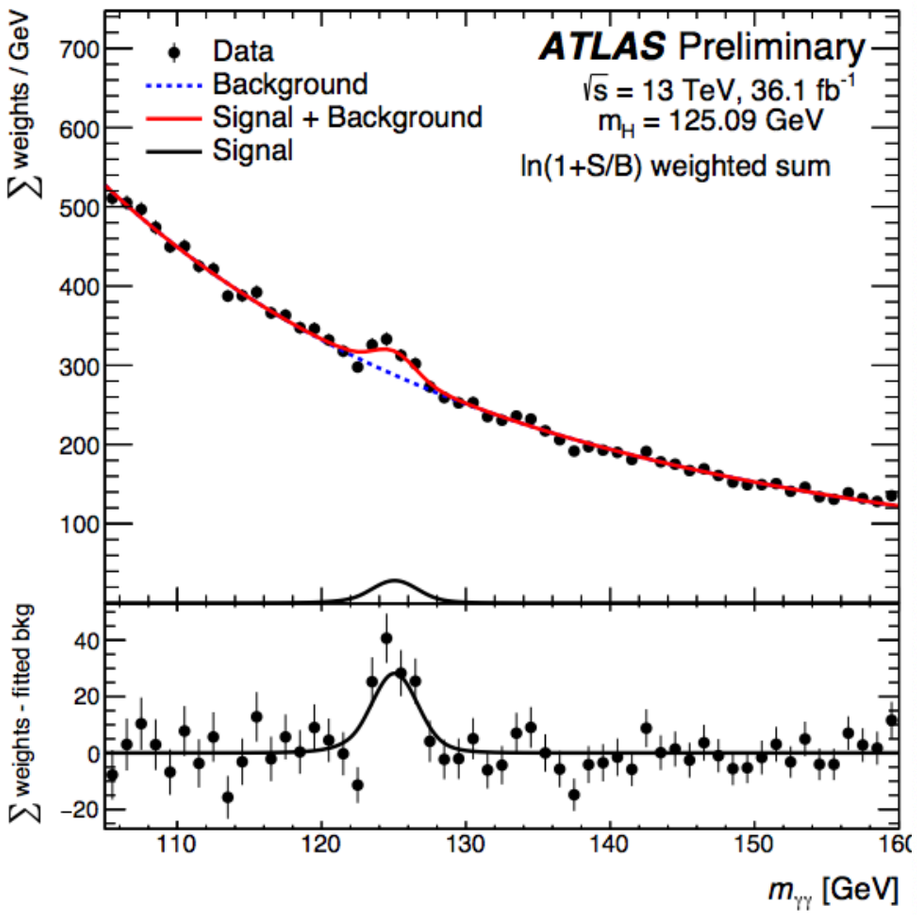


ATLAS-CONF-2017-045 (2017)

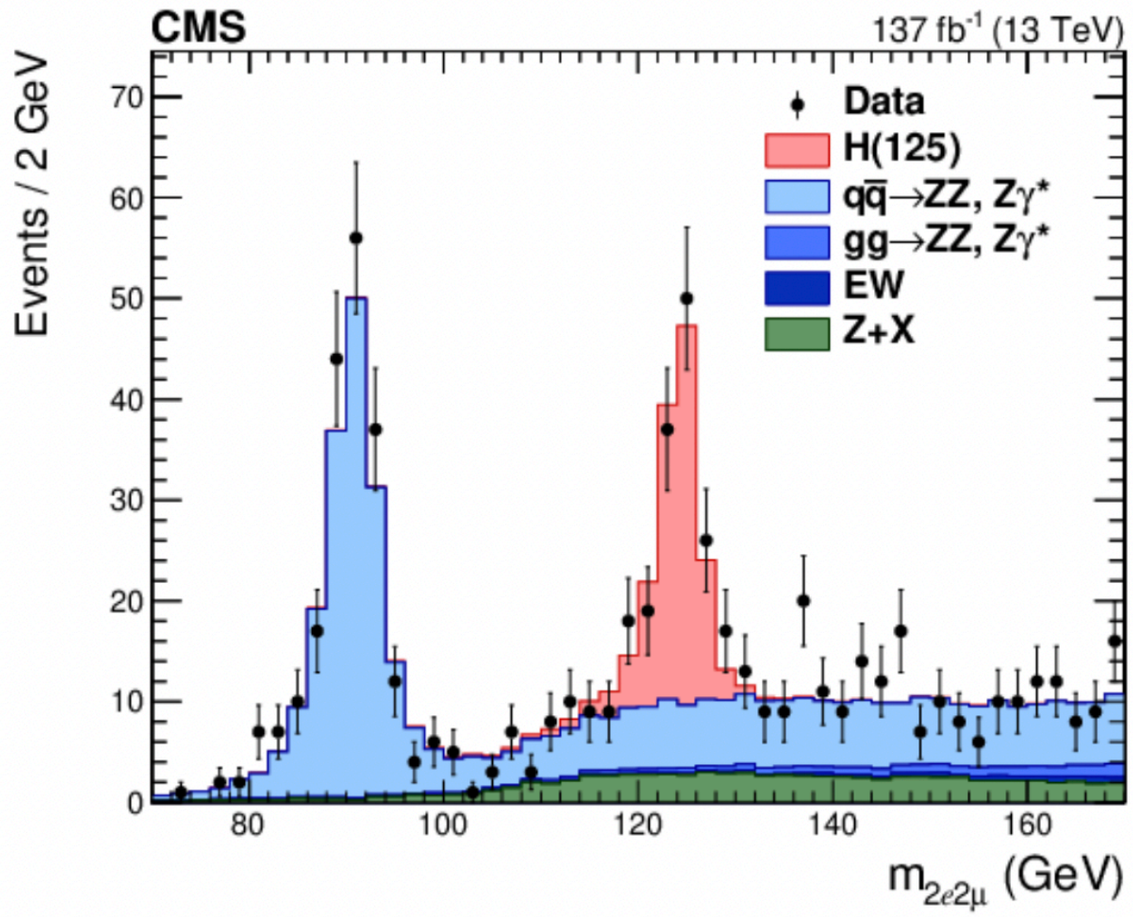
- What is this new particle phenomena in properties if SM incomplete?

New (expected) particle in spec

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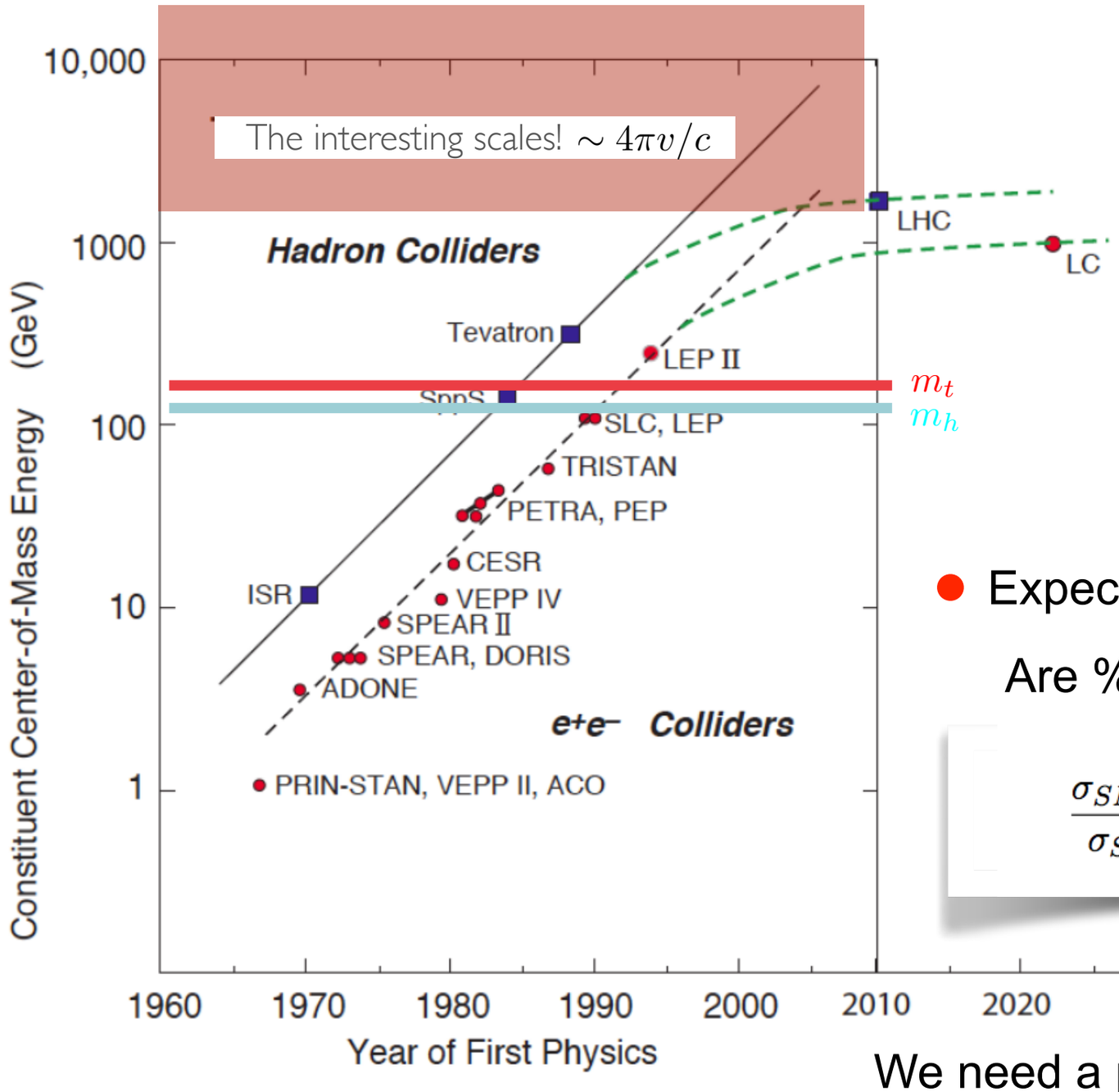
CERN-EP-2017-288 (2017)

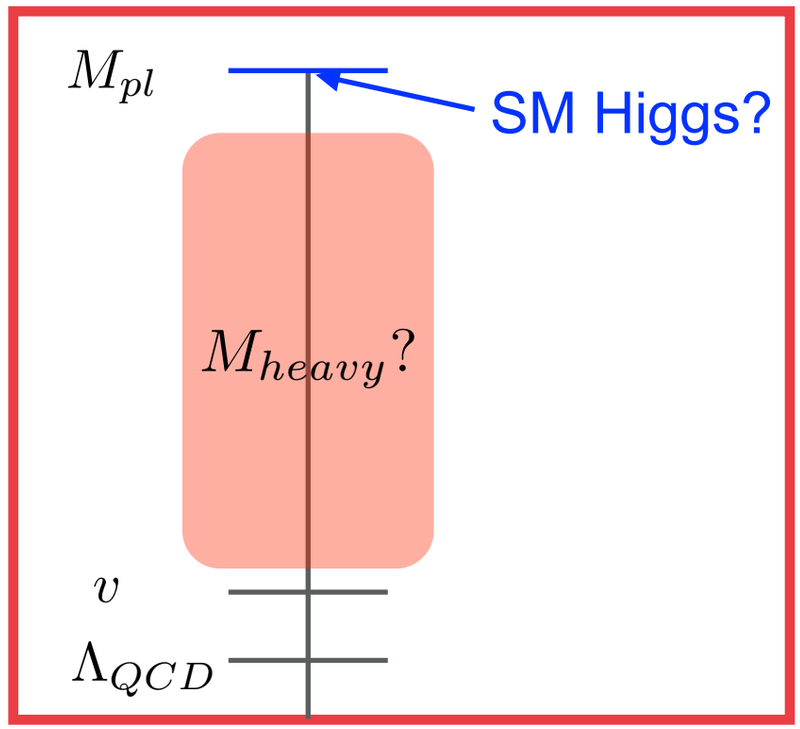


CERN-EP-2021-016

- What is this new particle phenomena in properties if SM incomplete?

Very Interesting scales a bit out of direct reach





- Expect % effects on Higgs properties

Are % level deviations ruled out? NO.

$$\frac{\sigma_{SM+i}}{\sigma_{SM}} \simeq \frac{1}{16\,\pi^2}\left(\frac{N_i^2\,|\kappa_i|^2\kappa'}{g_{SM}\,\lambda}\right)+\cdots$$

We need a precision Higgs pheno program!

Massive vectors/a scalar in the spectrum- Higgs

Recall the issue of masses of gauge fields

- This Lagrangian is invariant under a *global* phase transformation $f = e^{i\alpha} f$

$$\mathcal{L}_{free\,fermion} = \bar{f} i\gamma_\mu \partial^\mu f - m\bar{f} f$$

- One can also consider a theory of this form where the fermion couples to the gauge field, and preserves a local symmetry, like QED

$$\mathcal{L}_{Afield+freefermion} = -\frac{1}{4} A^{\mu\nu} A_{\mu\nu} + \bar{f} i\gamma_\mu \partial^\mu f - m\bar{f} f$$

Couple the fields as

$$\mathcal{L} = -\frac{1}{4} A^{\mu\nu} A_{\mu\nu} + \bar{f} i\gamma^\mu D_\mu f - m\bar{f} f$$

$$D_\mu = \partial - ieA_\mu$$

$$f \to e^{i\alpha(x)} f,$$

$$A_\mu \to A_\mu + \partial_\mu \alpha(x)$$

- For a massless photon, there is (in a sense) a local symmetry here called a gauge symmetry. There is also an interesting accident at work here due to low operator dimension, ask me later if interested.

Recall the issue of masses of gauge fields

- If one adds a mass to a U(1) gauge field by hand

$$\mathcal{L} = -\frac{1}{4}A^{\mu\nu}A_{\mu\nu} + m_A^2 A^\mu A_\mu + \bar{f}i\gamma^\mu D_\mu f - m\bar{f}f$$



The linear symmetry is no longer present. But a nonlinear realisation of the symmetry Is still possible due to a Stuckelberg mass (1938!!):

Die Wechselwirkungskräfte in der Elektrodynamik und in der Feldtheorie der Kräfte", *Helv. Phys. Acta.* **11:** 225)

$$\mathcal{L} = -\frac{1}{4}A^{\mu\nu}A_{\mu\nu} + \bar{f}i\gamma_\mu D^\mu f - m\bar{f}f + (D^\mu\phi)^\dagger(D_\mu\phi) - \lambda(\phi^\dagger\phi - \frac{v^2}{2})^2$$

Have the scalar take on a vev and then take the SCALAR mass to infinity ($\lambda \to \infty$):

$$\mathcal{L} = -\frac{1}{4}A^{\mu\nu}A_{\mu\nu} + m_A^2 A^\mu A_\mu + \bar{f}i\gamma^\mu D_\mu f - m\bar{f}f \quad + \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

As an EFT this can be done. NOTE: Nonlinear realisation of a symmetry.
The vev of scalar around, the scalar itself generating that vev is not in the spectrum.

When you see massive vectors …
you can be seeing another phase…



Plasmons, Gauge Invariance, and Mass

P. W. Anderson
Phys. Rev. **130**, 439 – Published 1 April 1963

ABSTRACT

Schwinger has pointed out that the Yang-Mills vector boson implied by associating a generalized gauge transformation with a conservation law (of baryonic charge, for instance) does not necessarily have zero mass, if a certain criterion on the vacuum fluctuations of the generalized current is satisfied. We show that the theory of plasma oscillations is a simple nonrelativistic example exhibiting all of the features of Schwinger's idea. It is also shown that Schwinger's criterion that the vector field $m\neq 0$ implies that the matter spectrum before including the Yang-Mills interaction contains $m = 0$, but that the example of superconductivity illustrates that the physical spectrum need not. Some comments on the relationship between these ideas and the zero-mass difficulty in theories with broken symmetries are given.

Received 8 November 1962

W,Z have mass

- So just write down mass as an EFT with a non linear realisation! BUT, the EFT consistent with what we knew (80‘s -00‘s) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4}W^{\mu\,\nu}W_{\mu\,\nu} - \frac{1}{4}B^{\mu\,\nu}B_{\mu\,\nu} - \frac{1}{4}G^{\mu\,\nu}G_{\mu\,\nu} + \bar{\psi}iD\psi$$

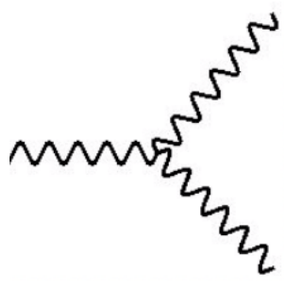
$$+ \quad \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger\, D^\mu\Sigma) \quad -\frac{v}{\sqrt{2}}\,(\bar{u}^i_L \bar{d}^i_L)\,\Sigma \begin{pmatrix} y^u_{ij}\, u^j_R \\ y^d_{ij}\, d^j_R \end{pmatrix} + h.c.,$$

$$\Sigma = e^{i\sigma_a\,\pi^a/v}$$

T. Appelquist and C. Bernard, Phys. Rev. D22 (1980) 200.
A. Longhitano, Phys. Rev. D22 (1980) 1166; Nucl. Phys. B188 (1981) 118.

$$W_a^{\mu\nu} = \partial^\mu W_a^\nu - \partial^\nu W_a^\mu - g_2\epsilon_{abc}W_\mu^b W_\nu^c$$

Extra problem here is non-abelian vector fields



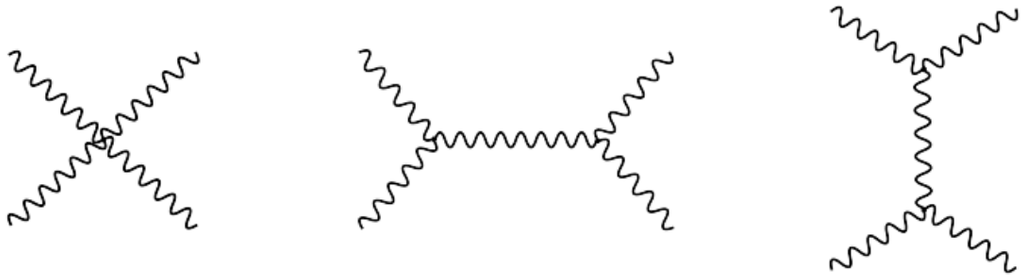
Why is this a problem? You can construct scatterings not present in the U(1) case that grow quite rapidly with energy.

How is the cut off scale working?

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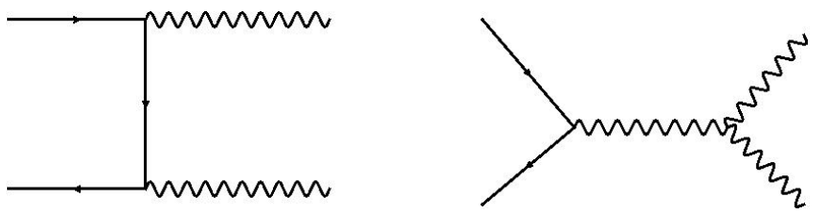
$$\mathcal{L} = -\frac{1}{4} W^{\mu\,\nu} W_{\mu\,\nu} - \frac{1}{4} B^{\mu\,\nu} B_{\mu\,\nu} - \frac{1}{4} G^{\mu\,\nu} G_{\mu\,\nu} + \bar{\psi} i D \psi$$

$$+ M_w^2 W_\mu^+ W \mu_- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu - \psi_L M \psi_R + h.c. \; + \cdots$$



$$W_L^+ W_L^- \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{g^2}{4\, m_W^2} (s+t)$$

$$\epsilon_L^\mu \simeq p^\mu / m_W$$



$$\psi\, \bar{\psi} \to W_L^+ W_L^- : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}$$

Lee, Quigg, Thacker Phys.Rev.D 16 (1977) 1519 **Cornwall, Levin,Tiktopoulos** Phys.Rev.D 10 (1974) 1145
Chanowitz,Gaillard Nucl.Phys. B261 (1985) 379 **Vayonakis** Lett.Nouvo Cim 17 (1976) 383
Appelquist,Chanowitz, Phys. Rev. Lett. 59, 2405 (1987) [Erratum-ibid. 60, 1589 (1988)].
Chanowitz, Furman, Hinchliffe Phys. Lett. B78, 285 (1978), Nucl Phys B153, 402 (1979)

Why worry about unitarity?

- If the amplitudes grow with energy too fast, partial wave unitarity is violated.

- Hamiltonian constructed from (approximate low energy) real Lagrangian density is Hermitian. So unitary by definition .

$$i\hbar\frac{d}{dt}\psi = H\psi \qquad \text{(Schrodinger Equation)}$$

If unitarity fails - an approximation fails.



- Usually the approximation is that the low energy effective theory is taken beyond its regime of validity.This regime of validity is approximated by the cut off scale Λ present in the EFT power counting.

$$\langle p_1 \cdots p_a | S_{1..n} | k_1 \cdots k_b \rangle^{\rm UV}_{p^2 \ll M^2} \equiv \langle p_1 \cdots p_a | S_{1..n} | k_1 \cdots k_b \rangle^{\rm EFT}$$

- Beyond this scale, the EFT is not expected to reproduce the S matrix of the full theory.

- New states are usually required with mass scale proximate (and below) Λ

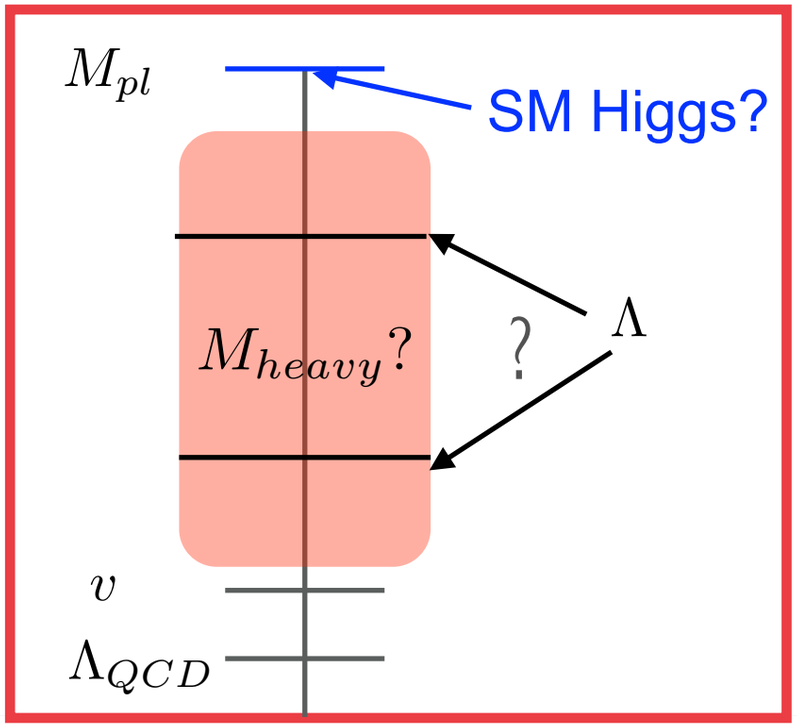
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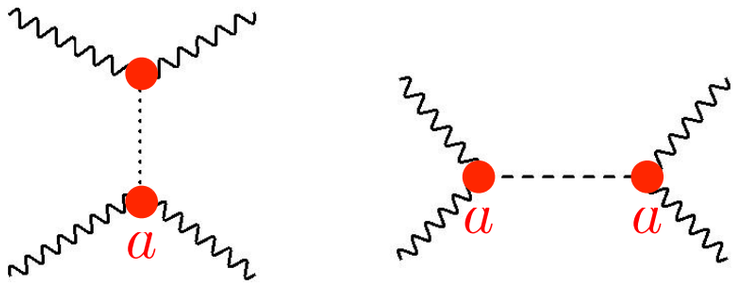


How is the cut off scale working?

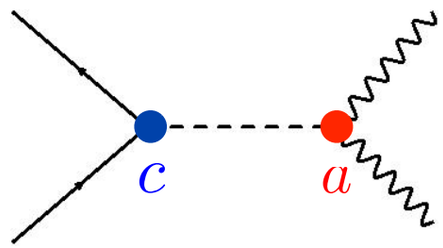
- Why should a 0^+ state be part of the nature of EW symmetry breaking?
  The EFT consistent with what we knew (80‘s -00‘s) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{\psi} i D \psi$$

$$+ \quad \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) - \frac{v}{\sqrt{2}} (\bar{u}^i_L \bar{d}^i_L) \Sigma \; y \begin{pmatrix} y^u_{ij} \, u^j_R \\ y^d_{ij} \, d^j_R \end{pmatrix} + h.c.,$$



$$W^+_L W^-_L \to W^+_L W^-_L : \quad \mathcal{A} \simeq \frac{g^2}{4 m^2_W} (s+t)(1 - a^2)$$



$$\psi \bar{\psi} \to W^+_L W^-_L : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2} \; (1 - a\,c)$$

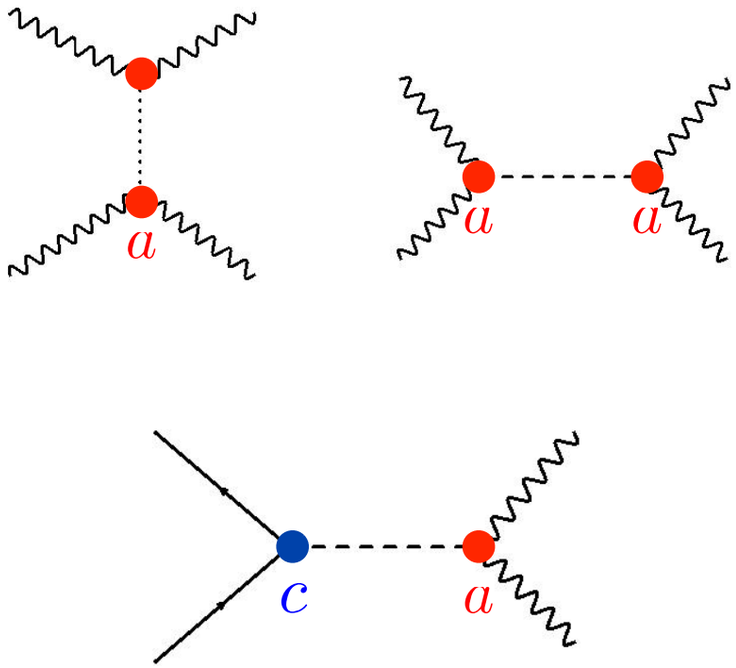
Introduce a 0^+ scalar with general couplings, sets the correction to be such that the cut off scale will be pushed up.

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$$+ \quad \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma)\left(1 + \frac{v}{\sqrt{2}}\right)^2 (\bar{u}^i_L \bar{d}^i_L)\,\Sigma \begin{pmatrix} y^u_{ij}\, u^j_R \\ y^d_{ij}\, d^j_R \end{pmatrix} + h.c.,$$



- For WW scattering the cut off scale for the EFT with the addition of a scalar is raised:

$\Lambda \simeq 4\,\pi\,v$ ..raised to... $\Lambda \simeq 4\,\pi\,v/\sqrt{|1-a^2|}$

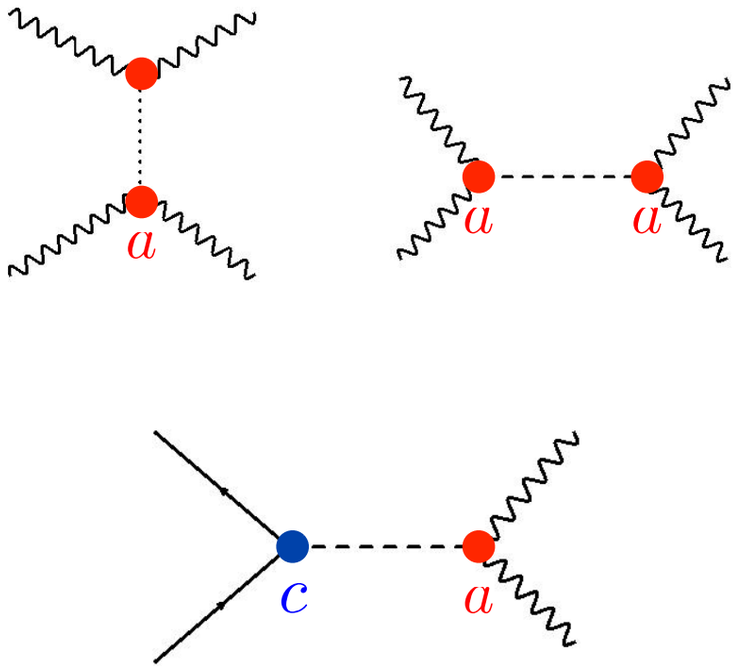
Couplings within 10% of the SM,
in this case, cut off scale 7 TeV...

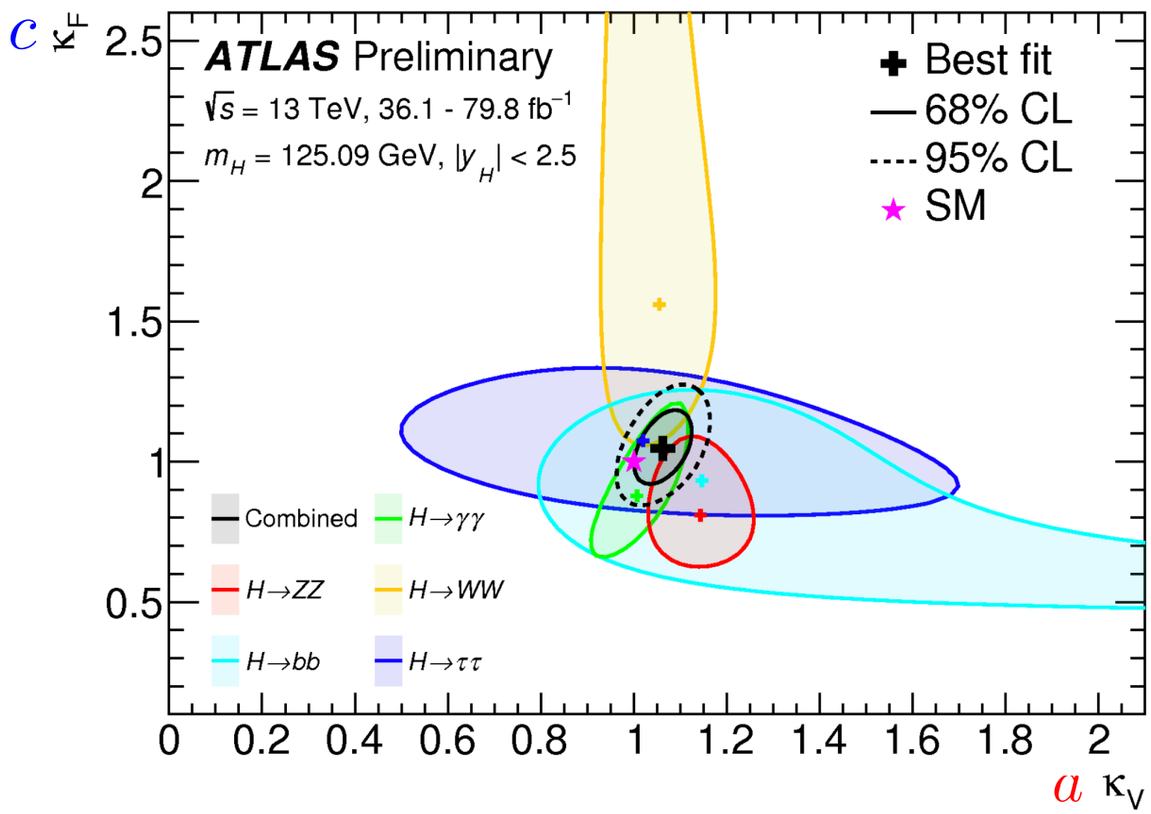
How is the cut off scale working?

- Why should a 0^+ state be part of the nature of EW symmetry breaking?
  The EFT consistent with what we knew (80‘s -00‘s) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4}W^{\mu\nu}W_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}G^{\mu\nu}G_{\mu\nu} + \bar{\psi}iD\psi$$

$$+ \quad \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma)\left(1 + \frac{v}{\sqrt{2}}\right)^2 (\bar{u}_L^i \bar{d}_L^i)\,\Sigma \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c.,$$





The case of the SM Higgs.

When you see massive vectors …
Scalars coupled to them can also supply their mass

Broken Symmetry and the Mass of Gauge Vector Mesons

F. Englert and R. Brout
Phys. Rev. Lett. **13**, 321 – Published 31 August 1964

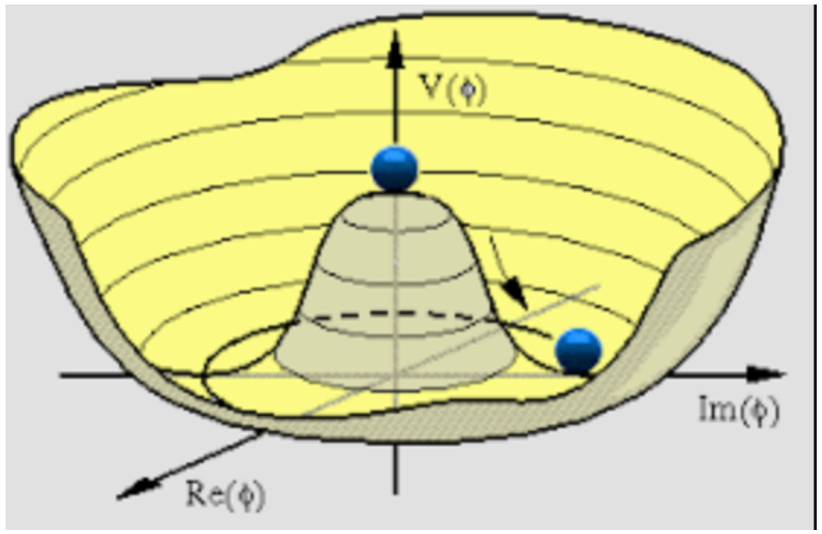
Broken Symmetries and the Masses of Gauge Bosons

Peter W. Higgs
Phys. Rev. Lett. **13**, 508 – Published 19 October 1964

Global Conservation Laws and Massless Particles

G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble
Phys. Rev. Lett. **13**, 585 – Published 16 November 1964

Higgs (etc) Mechanism



$$\mathcal{L} = (D^\mu H)^\dagger (D_\mu H) - \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2$$

- Higgs doublet complex SU(2) rep

$$H = \begin{bmatrix} H^+ \\ H^0 \end{bmatrix}$$

Complex, 2 degrees of freedom

Complex, 2 degrees of freedom

- SU(2) generators are $T^a = \sigma^a/2$

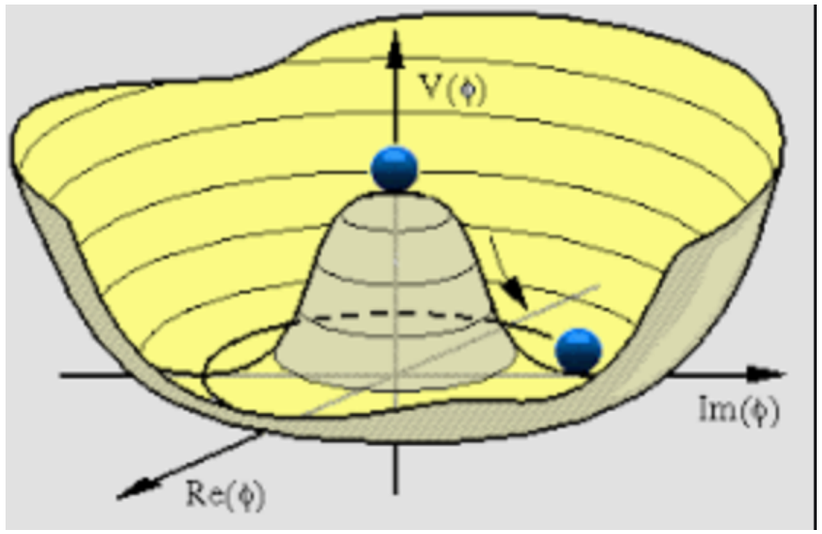
$$\sigma^1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \qquad \sigma^2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, \qquad \sigma^3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix},$$

Hypercharge generator diagonal.Can use global rotations to get

$$\langle H \rangle = \begin{bmatrix} 0 \\ v/\sqrt{2} \end{bmatrix}$$

- Three broken generators, three massless goldstones

Higgs Mechanism



- One unbroken generator

$$Q = T^3 + Y = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \qquad Q\langle H \rangle = 0$$

- Expand around this vacuum expectation

$$H = \begin{bmatrix} h^+ \\ v\sqrt{2} + h^0 \end{bmatrix}$$

- One finds directly

$$V(H^\dagger H) = \frac{\lambda}{4}\left(|h^+|^2 + |h^0|^2 + \sqrt{2}vRe(h^0)\right)^2$$

Three broken generators, three massless goldstones

($Im(h_0)$ massless)

Gauge bosons

- Expanding out covariant derivative

$$(D^\mu H)^\dagger (D_\mu H) \to \frac{g_2^2\, v^2}{8}\left(W_1^2 + W_2^2\right) + \frac{v^2\sqrt{g_1^2+g_2^2}}{8}^2 \left(\frac{g_2}{\sqrt{g_1^2+g_2^2}} W^3 - \frac{g_1}{\sqrt{g_1^2+g_2^2}} B\right)^2$$

$cos\,\theta$ $sin\,\theta$

$$2W^+W^- \qquad m_W^2 = \frac{v^2}{4} g_2^2$$

$$Z^2 \qquad m_Z^2 = \frac{v^2}{4}\left(g_1^2+g_2^2\right)$$

- Photon is massless orthogonal combination $A = sin\,\theta\, W^3 + cos\,\theta\, B$

$$m_A = 0$$

- In limit Hyper charge coupling turned off

$$(D^\mu H)^\dagger (D_\mu H) \to \frac{g_2^2\, v^2}{8}\left(W_1^2 + W_2^2\right) + \frac{v^2\sqrt{g_1^2+g_2^2}}{8}^2 \left(\frac{g_2}{\sqrt{g_1^2+g_2^2}} W^3 \right)^2$$

There is a triplet with the same mass (W_1, W_2, W_3)

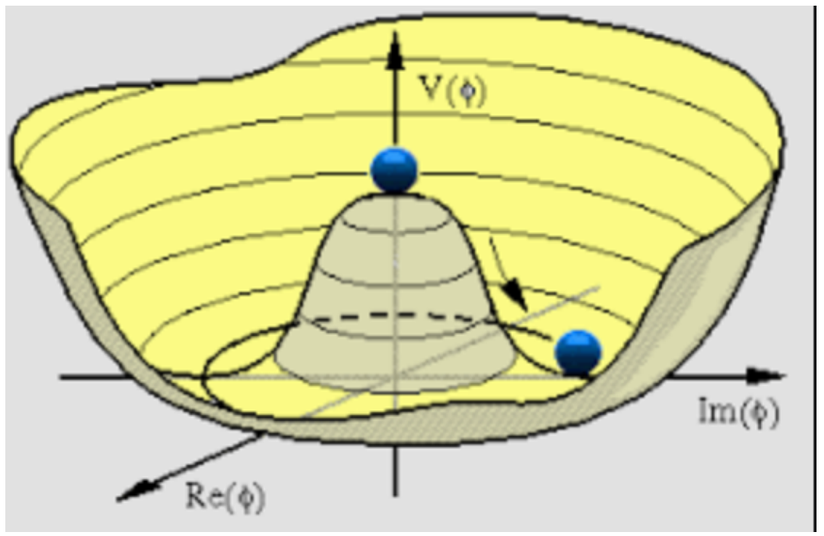
SM Higgs and custodial sym/ST EWPD analysis

Custodial Symmetry

- There is a triplet with the same mass (W_1, W_2, W_3). This mass Is also given by $m_Z^2 cos^2\theta$

$$\rho = \frac{m_W^2}{c_\theta^2 m_Z^2} \sim 1$$

Under what symmetry group is this a triplet?



$$V(H^\dagger H) = \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$$

As a function of $H^\dagger H = \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2$

This potential has an $SO(4)$ symmetry

Isomorphic to $SO(4) \sim SU(2)_L \times SU(2)_R$

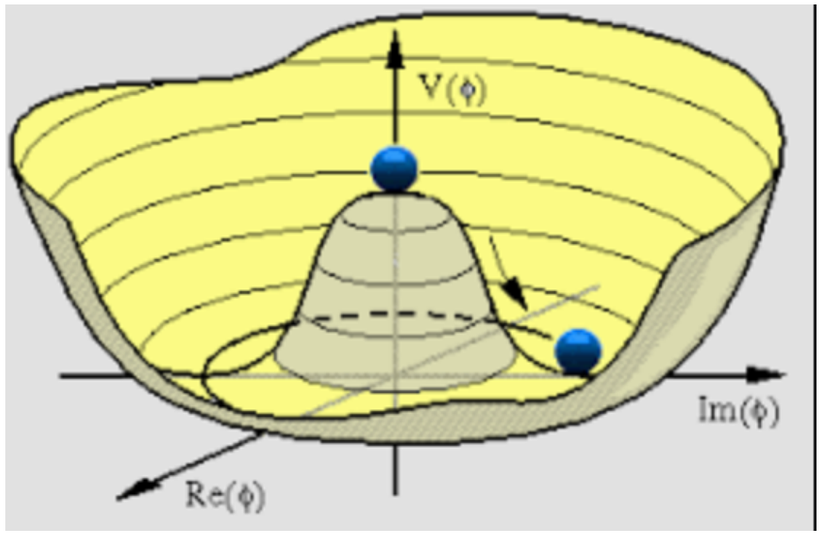
To make symmetry breaking manifest introduce $\Phi = \left(i\sigma^2 H^\star, H\right)$

This bi-doublet transforms linearly under $SU(2)_L \times SU(2)_R$ $\tilde{H} = i\sigma^2 H^\star$

Custodial Symmetry

- When the Higgs gets a vev

$$\langle H \rangle = \begin{bmatrix} 0 \\ v/\sqrt{2} \end{bmatrix} \qquad \langle \Phi \rangle = \begin{bmatrix} \frac{v}{\sqrt{2}} & 0 \\ 0 & \frac{v}{\sqrt{2}} \end{bmatrix},$$



- Manifest that the breaking is to the diagonal subgroup

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

- (W_1, W_2, W_3) Is a triplet under $SU(2)_V$

- Custodial symmetry is broken by the Hypercharge interactions and also mass doublet splitting in $SU(2)_L$ fermion doublet.
- Can calculate such contributions to the W and Z mass

Custodial Symmetry in the SM

- Breaking due to $SU(2)_L$ doublets:

$$q_1 = \begin{bmatrix} u_L \\ d'_L \end{bmatrix}, \quad q_2 = \begin{bmatrix} c_L \\ s'_L \end{bmatrix}, \quad q_3 = \begin{bmatrix} t_L \\ b'_L \end{bmatrix}, \quad \ell_1 = \begin{bmatrix} \nu_L^{e\prime} \\ e_L \end{bmatrix}, \quad \ell_2 = \begin{bmatrix} \nu_L^{\mu\prime} \\ \mu_L \end{bmatrix}, \quad \ell_3 = \begin{bmatrix} \nu_L^{\tau\prime} \\ \tau_L \end{bmatrix},$$

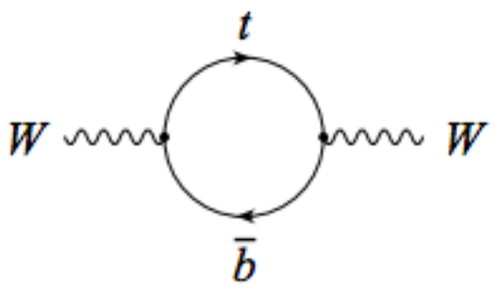
Right handed singlet fermions

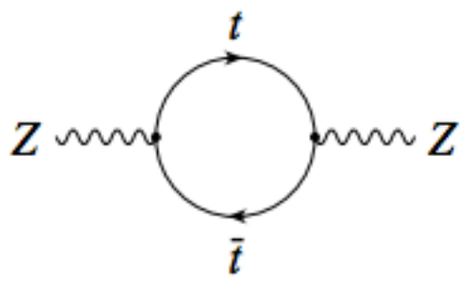
Via interactions:

$$\left[H^{\dagger j} \overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j} \overline{u}\, Y_u\, q_j + H^{\dagger j} \overline{e}\, Y_e\, l_j + \text{h.c.} \right]$$

Left handed doublet fermions

Biggest contributions



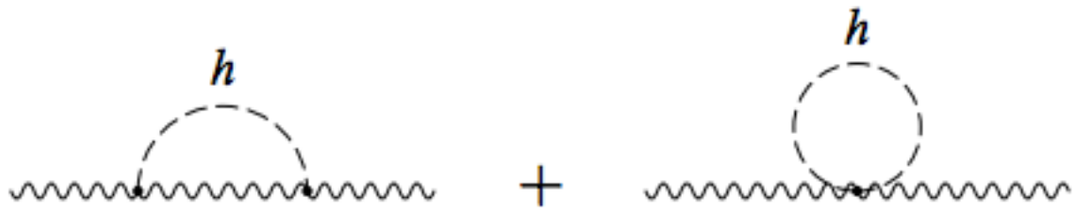


Gives:

$$\hat{\rho} \approx 1 + \frac{3G_F}{8\pi^2\sqrt{2}} \left(m_t^2 + m_b^2 - 2\frac{m_t^2 m_b^2}{m_t^2 - m_b^2} \ln \frac{m_t^2}{m_b^2} \right)$$

Custodial Symmetry in the SM

- Breaking due to Hypercharge at one loop: $(D_\mu H)^\dagger \ (D^\mu H)$



gives $-\frac{11 G_F M_Z^2 \sin^2\theta_W}{24\sqrt{2}\pi^2} \ln\frac{m_h^2}{M_Z^2}$.

We see this custodial breaking in precision EW measurements:

$$\hat{\rho} \approx 1 + \frac{3G_F}{8\pi^2\sqrt{2}}\left(m_t^2 + m_b^2 - 2\frac{m_t^2 m_b^2}{m_t^2 - m_b^2}\ln\frac{m_t^2}{m_b^2}\right) - \frac{11 G_F M_Z^2 \sin^2\theta_W}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2} .$$

Divide this out and examine the residual, which should be one.

$$\rho_0 \equiv \frac{M_W^2}{M_Z^2 \hat{c}_Z^2 \hat{\rho}} ,$$

$$\rho_0 = 1.00039 \pm 0.00019 ,$$
$$\alpha_s(M_Z) = 0.1189 \pm 0.0016 ,$$

EW PDG 2019

Custodial Symmetry in BSM

- When considering BSM physics, non SM effects on the mass relationship is parameterised as

$$\hat{\alpha}(M_Z)\,T \equiv \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

Large BSM contributions to the T parameter need to be avoided.

For quite a few years the standard approach to EWPD was S,T fits

$$\frac{\hat{\alpha}(M_Z)}{4\,\hat{s}_Z^2\,\hat{c}_Z^2}\,S \equiv \frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} - \frac{\hat{c}_Z^2 - \hat{s}_Z^2}{\hat{c}_Z\,\hat{s}_Z}\frac{\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

(S violates custodial symmetry too ….
but does not contribute to ρ at tree level)

Custodial Symmetry in BSM

- Heavy new physics can contribute to these deviations

$$S = \frac{16\,\pi\,v^2}{g_1\,g_2}\,C_{HWB}, \qquad T = -2\pi v^2\left(\frac{1}{g_1^2}+\frac{1}{g_2^2}\right)C_{HD}\,.$$

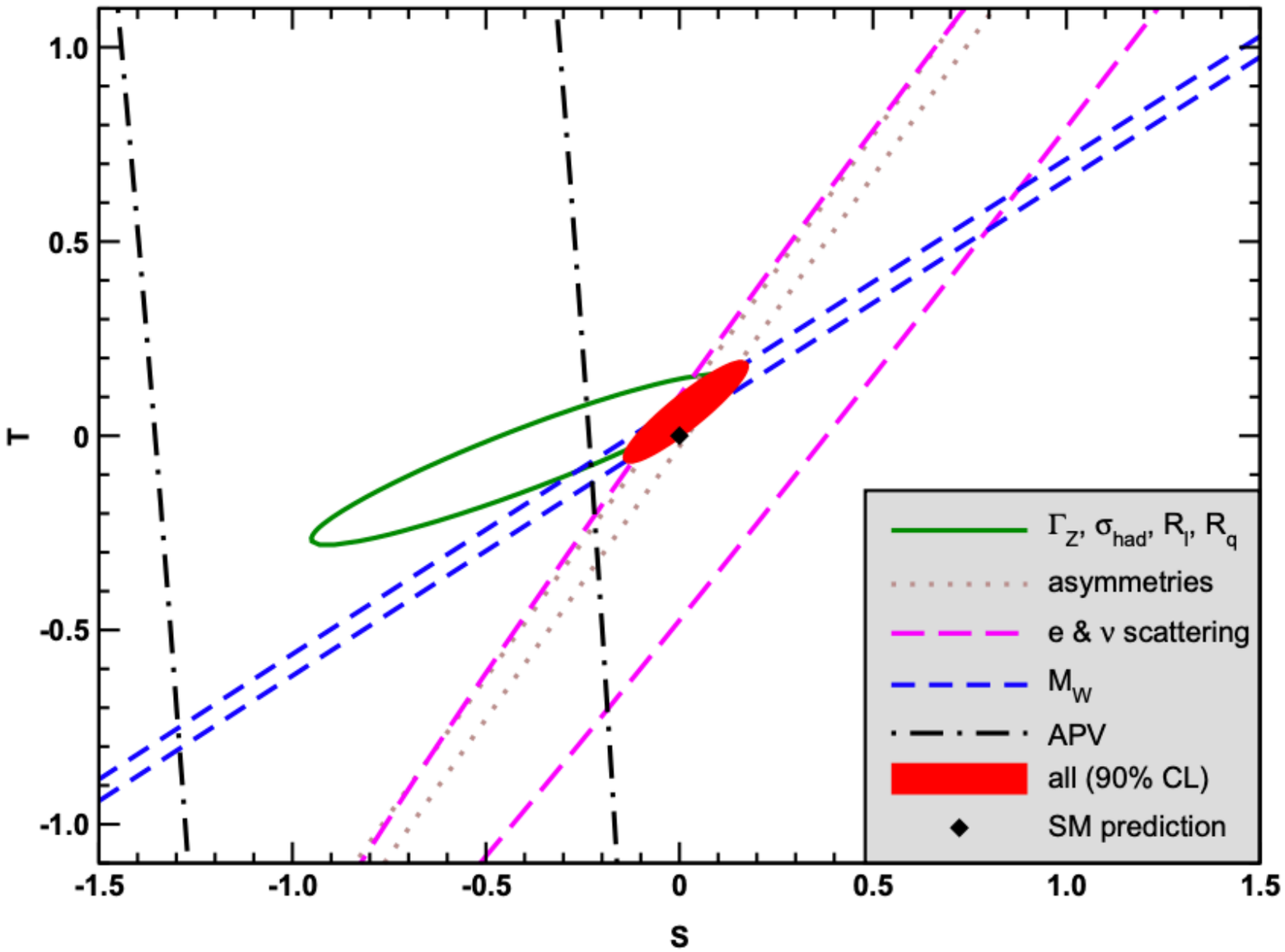
Where the C are some unknown numbers that multiply the operators

Q_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	Q_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$

In the Warsaw basis of operators extending the SM

B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek,
Dimension-Six Terms in the Standard Model Lagrangian, JHEP 1010 (2010) 085, [arXiv:1008.4884].

Old school EWPD analysis



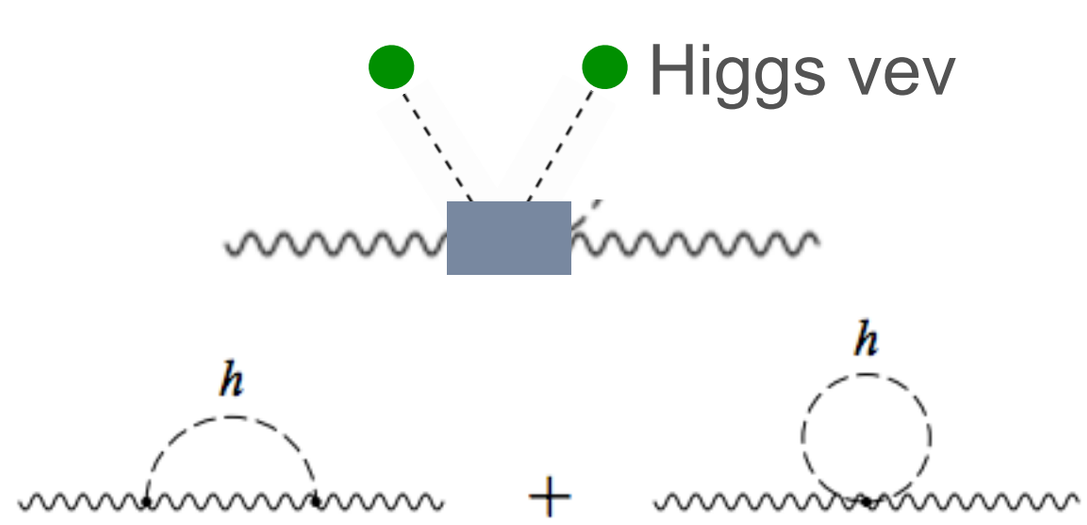
- Careful with interpretation, if hypothesis testing SM - OK!
- NOT a proper general constraint for arbitrary new physics sectors.

Parameters that change SM predictions based on symmetry expectations *can be strongly constrained*

Why were ST analyses a good idea?

- S,T analyses were responsive to the actual global data available.
  No Higgs discovered, no LHC, no WW LEP2 run..etc AT THE TIME

- They were oriented to test what Generates mass
  - effects the 2 point functions of observed bosons



Post 2012: Oblique/Universal Theories. Just stop.

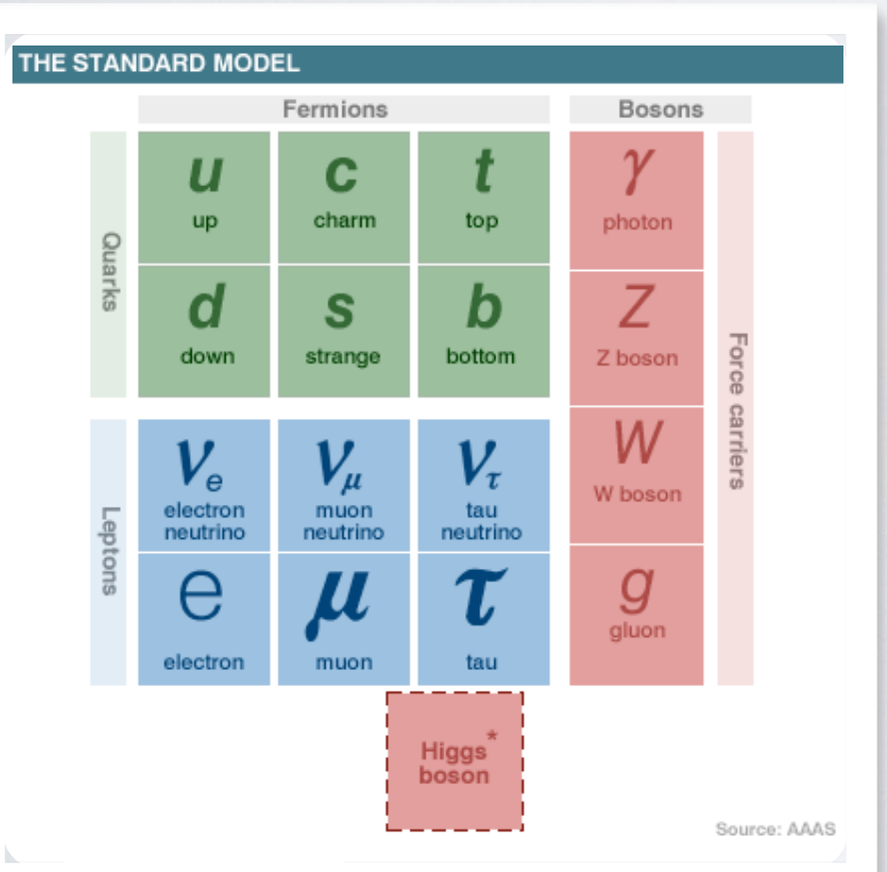
- SM Higgs (supported by all current data) then this built in.
  New physics more complex expression in op forms
  - need a SMEFT analysis. Not just 2 point ST effects.

Cut off scales in EFT: SMEFT and HEFT

The Standard model ...

- The SM, an SU(3) xSU(2)xU(1) ***linearly realized gauge theory*** :

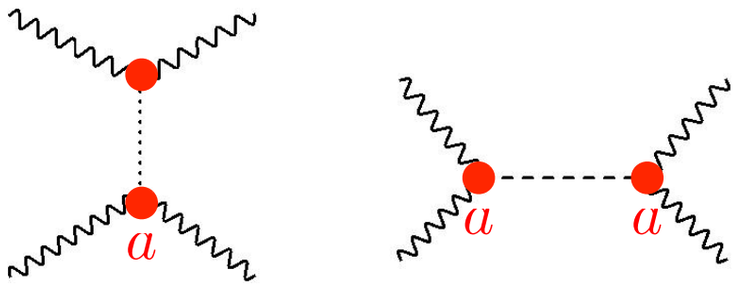
$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$
$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$



Then how is the cut off scale working?

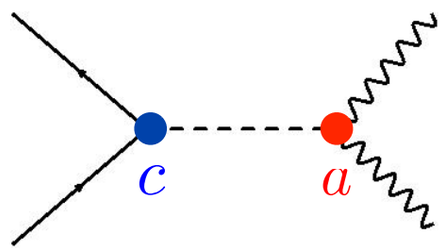
- When you introduce a scalar doublet in this manner, the cut off scalar raises dramatically.

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$
$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$



$$W_L^+ W_L^- \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{g^2}{4\, m_W^2}\,(s+t)\,(1 - a^2) \to 0$$

Case of SM Higgs.

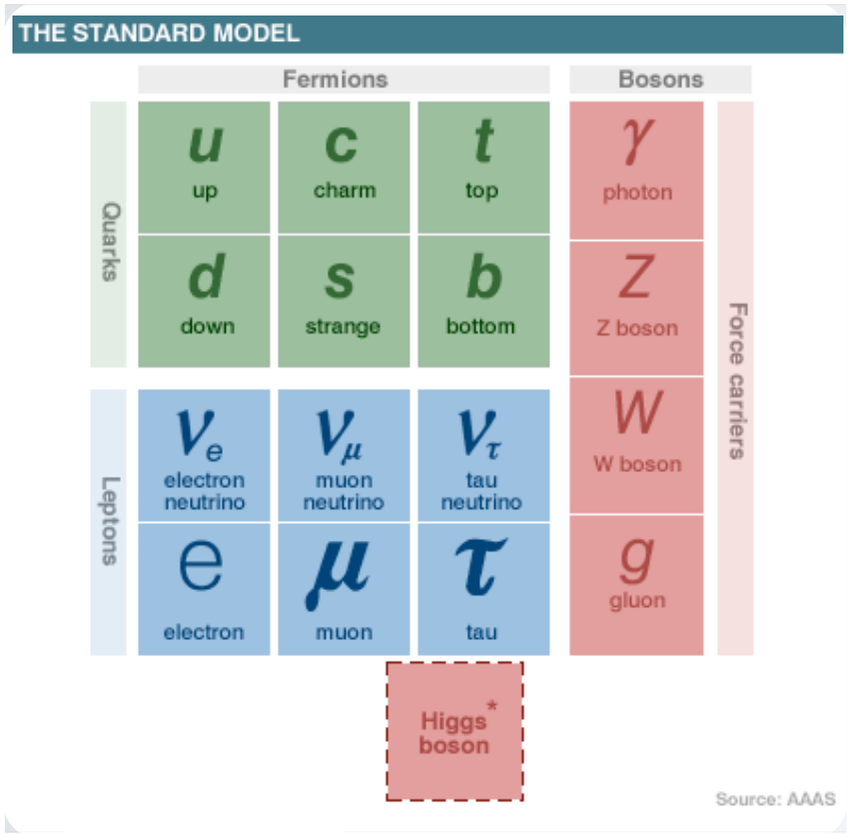


$$\psi\,\bar{\psi} \to W_L^+ W_L^- : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}\,(1 - a\,c) \to 0$$

The Standard model EFT

- An SU(3) xSU(2)xU(1) ***linearly realised EFT***:

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$
$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$



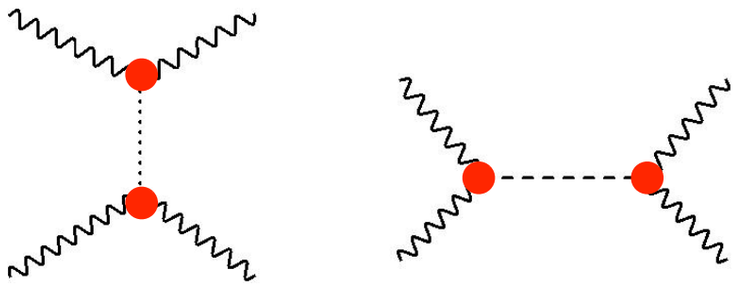
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- $\mathcal{L}_{SM}$: Glashow 1961, Weinberg 1967 (Salam 1967)
- $\mathcal{L}_5$: Weinberg 1979, Wilczek and Zee 1979
- $\mathcal{L}_6$: Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak,Rosiek 2010

Then how is the cut off scale working?

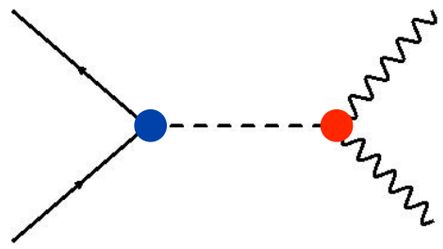
- When you introduce a scalar doublet in this manner, the cut off scale raises dramatically.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$



$$W_L^+ W_L^- \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{g^2}{4\, m_W^2}\,(s+t)\, F_1(C_i)\,\frac{v^2}{\Lambda^2},\ s$$

Case of SMEFT



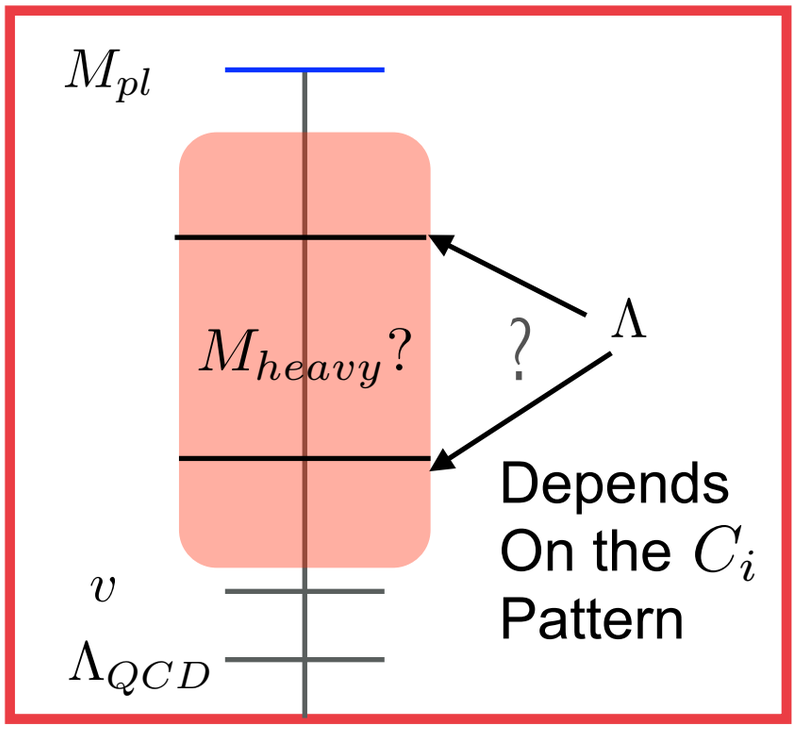
$$\psi\,\bar{\psi} \to W_L^+ W_L^- : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}\ F_2(C_i)\,\frac{v^2}{\Lambda^2},\ s$$

- Now a linear order higher d op insertion

Then how is the cut off scale working?

- When you introduce a scalar doublet in this manner, the cut off scalar raises dramatically.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$



$$W_L^+ W_L^- \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{g^2}{4\, m_W^2}\,(s+t)\, F_1(C_i)\frac{v^2}{\Lambda^2},\ s$$

Case of SMEFT

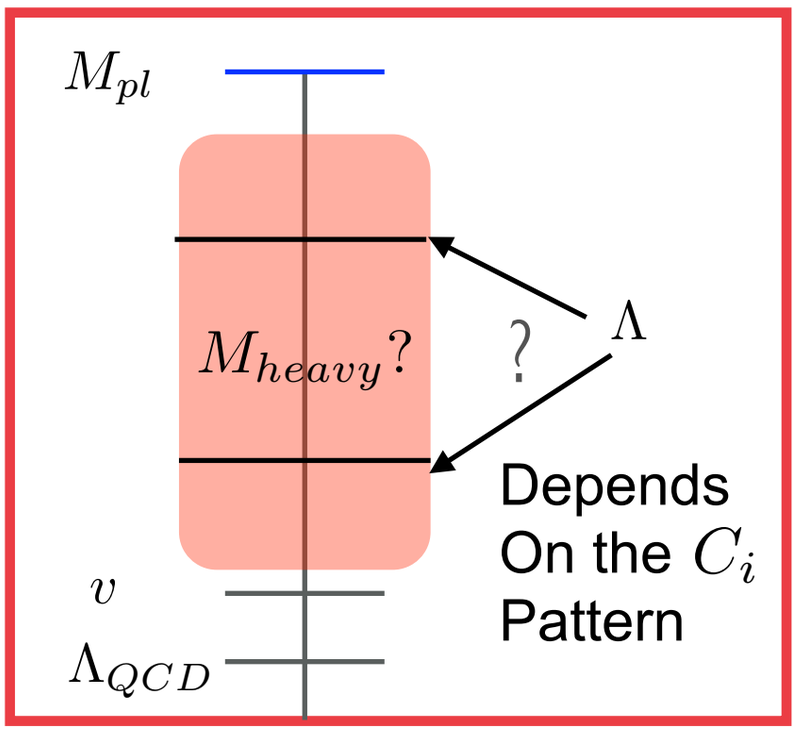
$$\psi\,\bar{\psi} \to W_L^+ W_L^- : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}\ F_2(C_i)\frac{v^2}{\Lambda^2},\ s$$

- Deviations from the SM the theory WILL break down at lower scales

Then how is the cut off scale working?

- When you introduce a scalar doublet in this manner, the cut off scalar raises dramatically.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$



- Note expansion parameters in the SMEFT:

$\frac{\langle H^\dagger H \rangle}{\Lambda^2}$ Expansion in SM vev -relevant For SM dominated phase space measurements - i.e. “pole parameters”

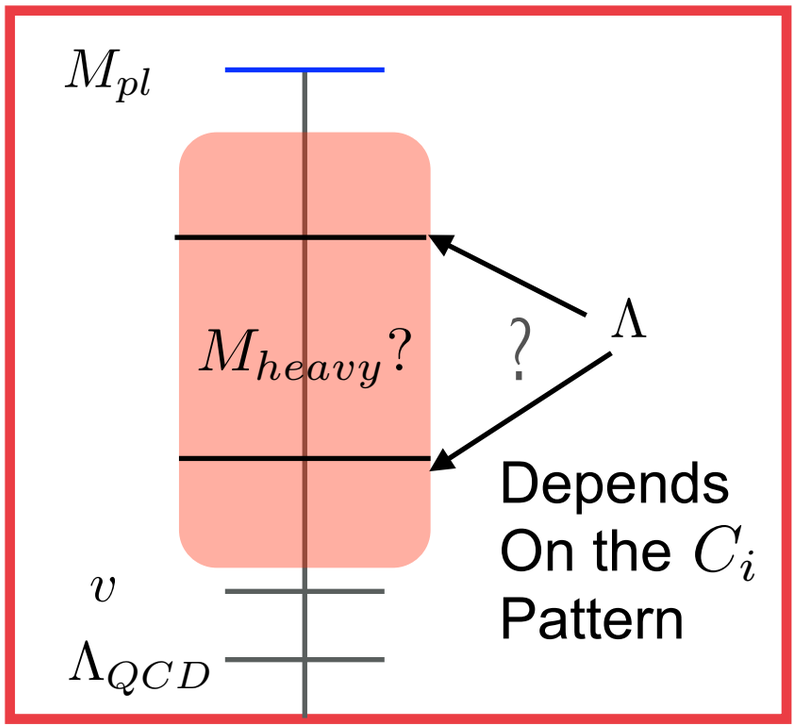
$\frac{p_i \cdot p_j}{\Lambda^2}$ Expansion parameter(s) in novel kinematic regions (tails of distributions)

- Deviations from the SM the theory WILL break down at lower scales

Then how is the cut off scale working?

- When you introduce a scalar doublet in this manner, the cut off scalar raises dramatically.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$



- Note expansion parameters in the SMEFT:

$\frac{\langle H^\dagger H \rangle}{\Lambda^2}$ Better theoretical control, less operators
Can be exactly solved using geometry.
More precise measurements needed.

$\frac{p_i \cdot p_j}{\Lambda^2}$ Less theoretical control, stronger sensitivity to theory breakdown.
Less precise measurements can deviate

- Deviations from the SM the theory WILL break down at lower scales

HEFT: Nonlinear chiral+ singlet

- General EFT : Nonlinear SU(2)xU(1) + Singlet scalar* $\Sigma = e^{i\sigma_a \pi^a/v}$

$$\begin{aligned}
\mathcal{L} &= \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\,a_{W,Z}\,\frac{h}{v} + b_{Z,W}\,\frac{h^2}{v^2} + b_{3,Z,W}\,\frac{h^3}{v^3} + \cdots\right], \\
&\quad -\frac{v}{\sqrt{2}}\,(\bar{u}^i_L \bar{d}^i_L)\,\Sigma\left[1 + c_i^{u,d}\,\frac{h}{v} + c_{2,j}^{u,d}\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y^u_{ij}\,u^j_R \\ y^d_{ij}\,d^j_R \end{pmatrix} + h.c., \\
V(h) &= \frac{1}{2}\,m_h^2\,h^2 + \frac{d_3}{6}\left(\frac{3\,m_h^2}{v}\right)h^3 + \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \cdots\,.
\end{aligned}$$

- Also higher dimensional operators: (hats -dual fields) SEE RODRIGO's lectures

$$\begin{aligned}
\mathcal{L}^5_{HD} &= c_g\,g_3^2\frac{h}{v}\,G_{\mu\nu}\,G^{\mu\nu} + c_W\,g_2^2\frac{h}{v}\,W_{\mu\nu}\,W^{\mu\nu} + c_B\,g_1^2\frac{h}{v}\,B_{\mu\nu}\,B^{\mu\nu}, \\
&\quad + \hat{c}_W\,g_2^2\frac{h}{v}\,\hat{W}_{\mu\nu}\,W^{\mu\nu} + \hat{c}_B\,g_1^2\frac{h}{v}\,\hat{B}_{\mu\nu}\,B^{\mu\nu} + \hat{c}_G\,g_3^2\frac{h}{v}\,\hat{G}_{\mu\nu}\,G^{\mu\nu}
\end{aligned}$$

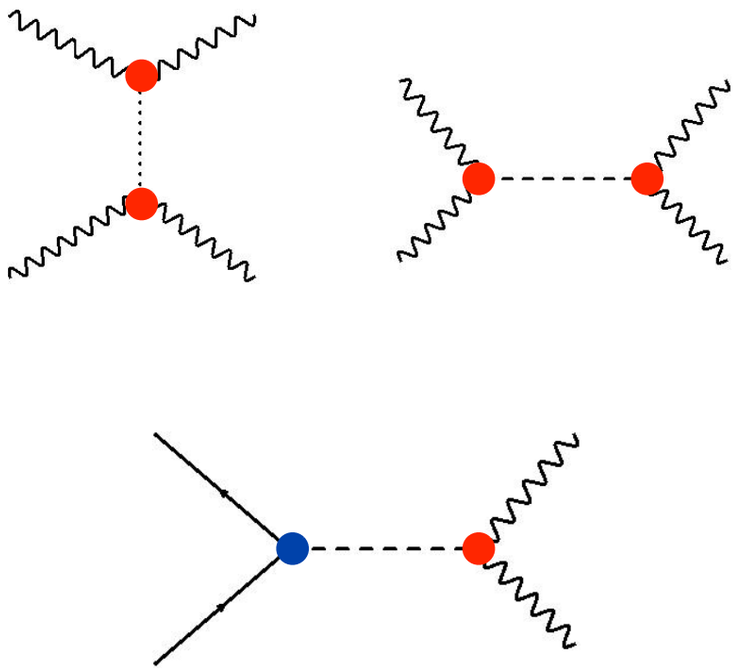
* Grinstein/Trott 0704.1505, see also Bagger et al 9306256, Feruglio 9301281 for Technicolour sigma version, informed discussion in Burgess et al hep-ph/9912459
Modern foundation: 1203.6510, 1212.3305, 1307.5017

(Rediscovered - at least 4 times independently!!! - convergent physics evolution!)

Then how is the cut off scale working?

- When you introduce a scalar doublet in this manner, the cut off scalar raises dramatically.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\,a_{W,Z}\frac{h}{v} + b_{Z,W}\frac{h^2}{v^2} + b_{3,Z,W}\frac{h^3}{v^3} + \cdots\right],$$
$$-\frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_i^{u,d}\frac{h}{v} + c_{2,j}^{u,d}\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c.,$$



$$\mathcal{A} \simeq \frac{g^2}{4\,m_W^2}(s+t) \qquad f^2\Lambda^2\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{\phi}{f}\right]^{N_\phi}\left[\frac{A}{f}\right]^{N_A}\left[\frac{\psi}{f\sqrt{\Lambda}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

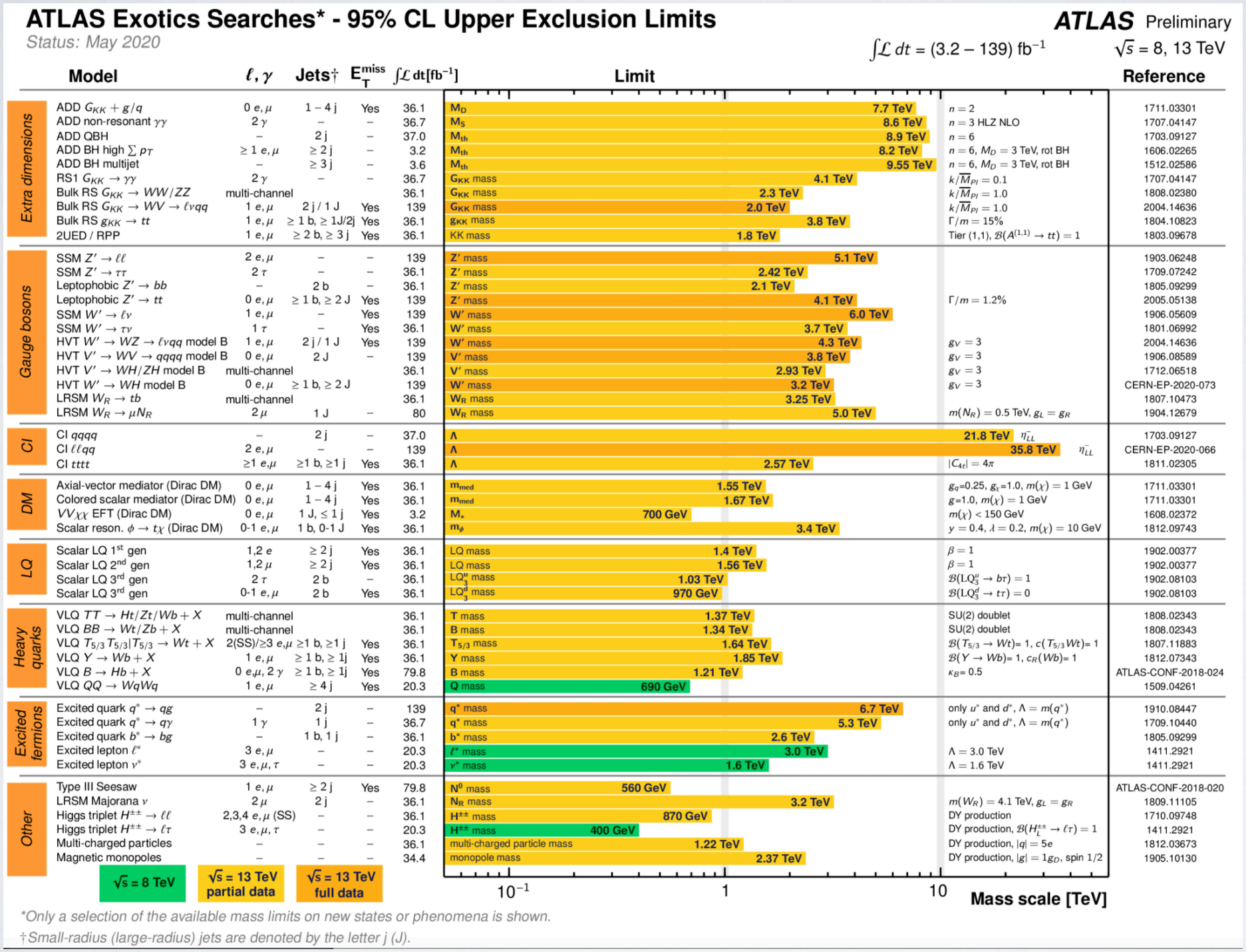
Case of HEFT deviations in Higgs properties expected to be bigger, and cut off scale lower

$$\mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2} \qquad f^2\Lambda^2\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{\phi}{f}\right]^{N_\phi}\left[\frac{A}{f}\right]^{N_A}\left[\frac{\psi}{f\sqrt{\Lambda}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

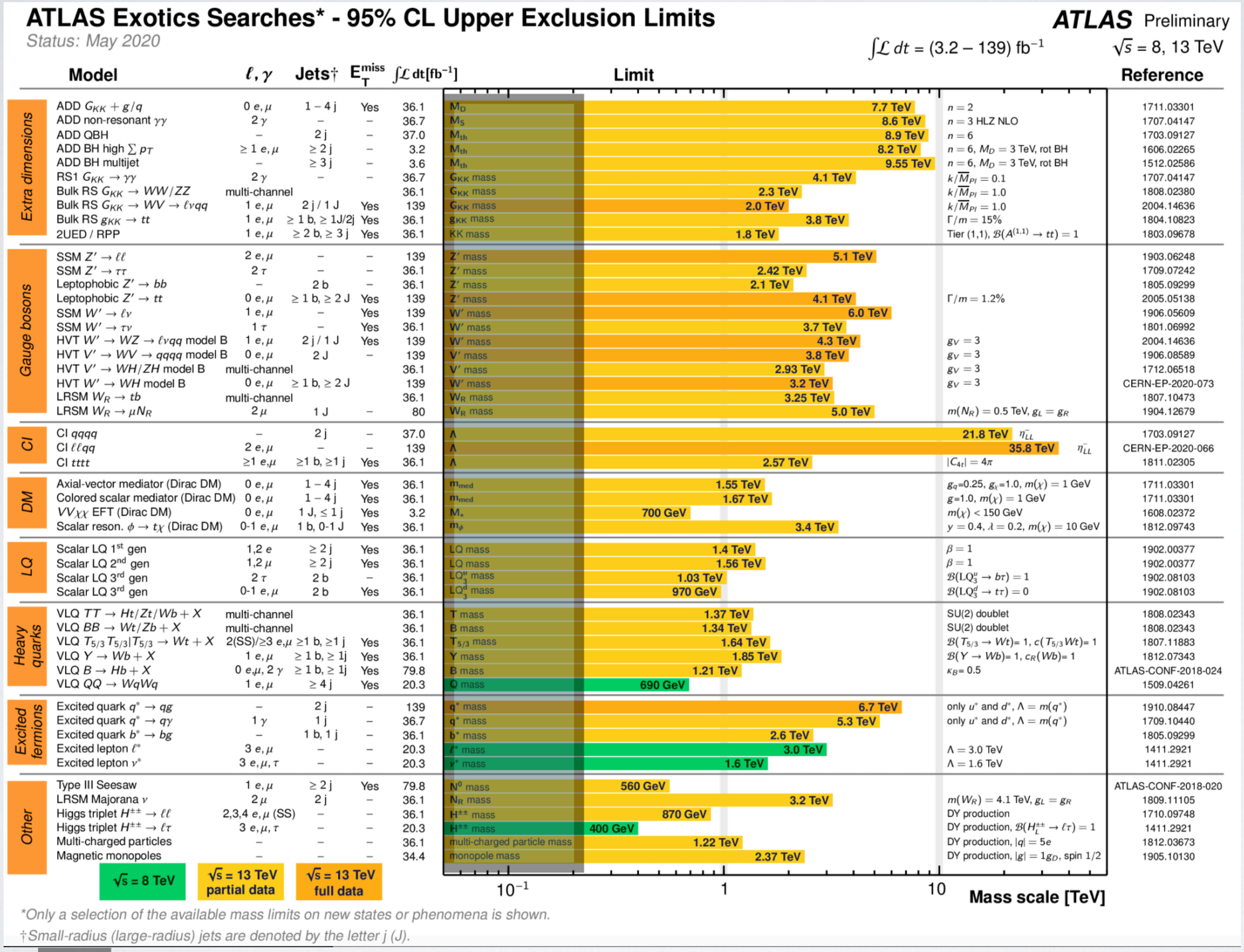
G. Buchalla, O. Cat`a and C. Krause, Phys. Lett. B 731, 80 (2014) [arXiv:1312.5624
B. M. Gavela, E. E. Jenkins, A. V. Manohar and L. Merlo, arXiv:1601.07551

- Now a linear order higher d op insertion

LHC consistent with either setup, no other states around

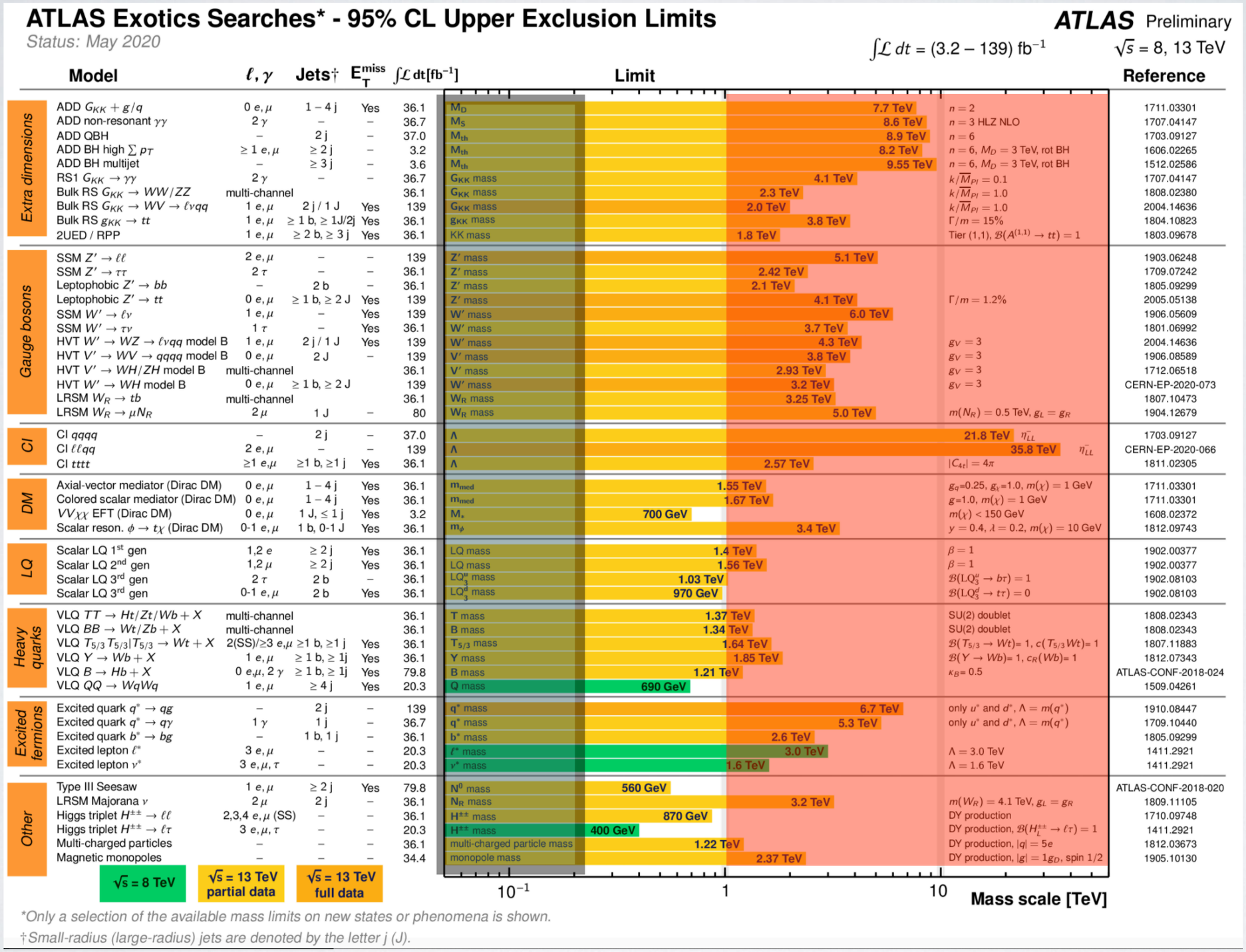


LHC consistent with either setup, no other states around



Masses of EW scale ($\sim g\, v$) states m_W, m_Z, m_t, m_h

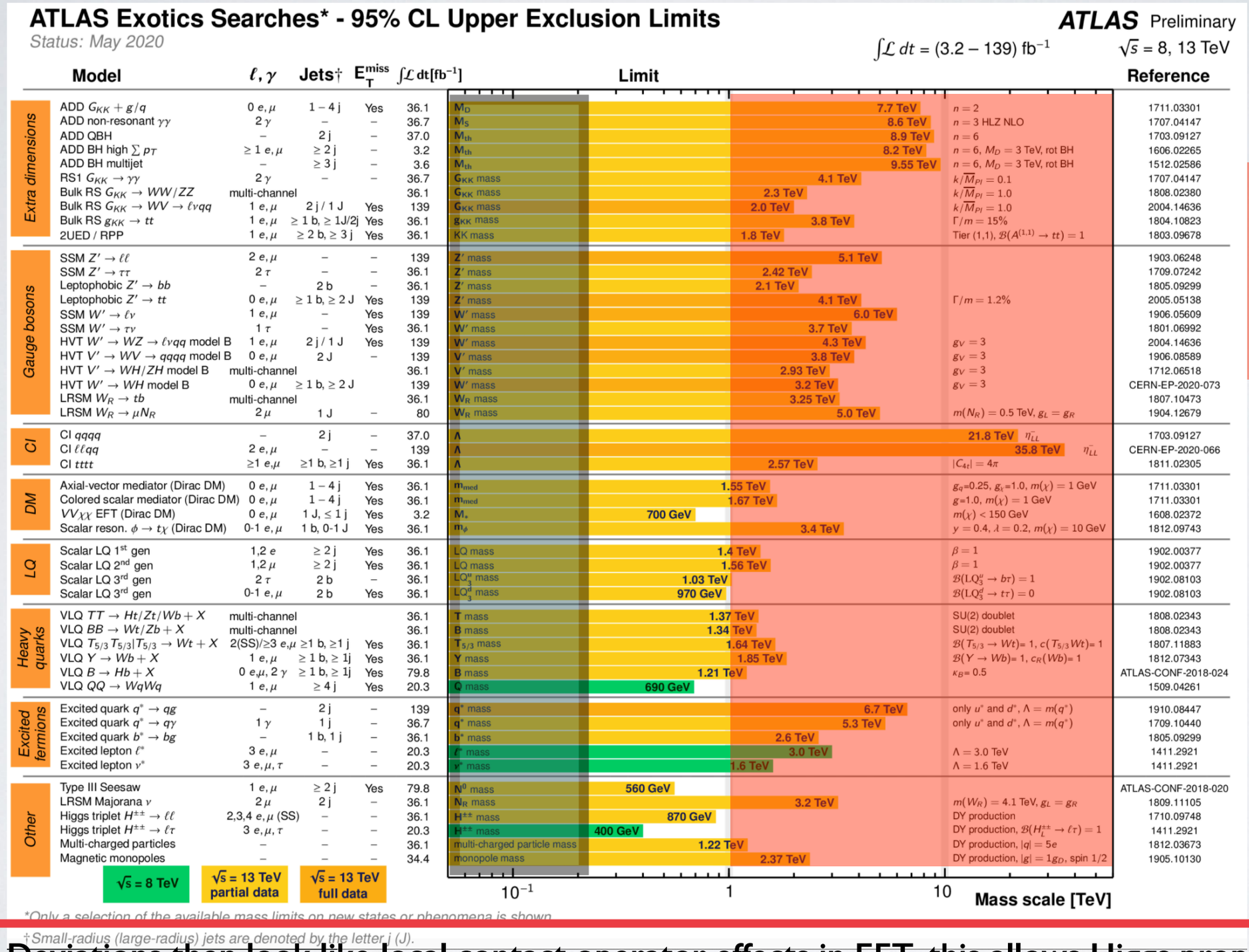
LHC consistent with either setup, no other states around



These bounds have been pushed away from

$$v \sim m_h$$

RunII and beyond: Resonance limits to local operators



These bounds have been pushed away from

$$v \sim m_h$$

USE that

$$v/M < 1$$

Deviations then look like local contact operator effects in EFT, this allows Higgs properties to be consistently studied allowing the SM to break at higher energies

A "BSM is heavy" approach is SMEFT/HEFT

No BSM resonance seen

Decoupling

$v/M < 1$

VERY! Efficient to constrain BSM/interpret the data in EFT

no other (hidden) light states.

SMEFT
observed scalar in doublet

HEFT
observed scalar not in doublet

Rodrigo's lectures.

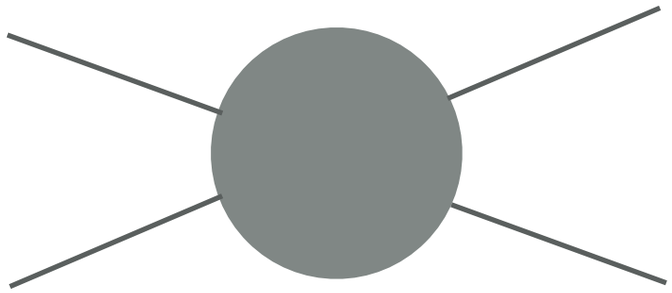
Basics of the SMEFT formulation: IR operator form

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

UV dependent Wilson coefficient and suppression scale

EFT basics.

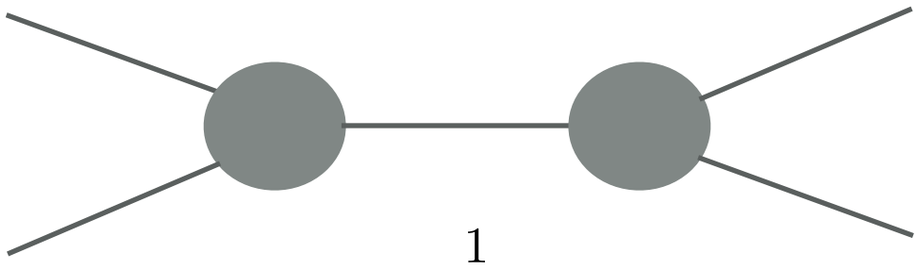
When you do measurements below a particle threshold



- Observable is a function of the Lorentz invariants:

$$f(s,t,u)$$

- Generally an analytic function of these invariants, except in special regions of phase space, ex. where an internal state goes on-shell.



$$\sim \frac{1}{s - m^2 + i\Gamma(s)\, m}$$

IF the collision probe does not reach $\sim m^2_{heavy}$
THEN observable's dependence on that scale simplified

EFT approach not a guess.

General approach based on S matrix theory and motivated by experimental situation.

- You can Taylor expand in LOCAL functions (operators)

$$\langle\rangle \sim O^0_{SM} + \frac{f_1(s,t,u)}{M^2_{heavy}} + \frac{f_2(s,t,u)}{M^4_{heavy}} + \dots$$

This is the core idea of EFT interpretations of the data.

How formally do we know the M_{heavy} dependence is so simple?

- Why don't you generate arbitrarily complicated math functions with no simple expansion? Without a controlled dependence on M_{heavy}? (Assumed in later works - probably naively)

On the Multiplication of the causal function in the quantum theory of fields

N.N. Bogoliubov, O.S. Parasiuk (1957)

Published in: *Acta Math.* 97 (1957) 227-266

- Formal decoupling theorem (not applied to useful examples IMO)

Infrared singularities and small distance behavior analysis

K. Symanzik (DESY) (Apr, 1973)

Published in: *Commun.Math.Phys.* 34 (1973) 7-36

Europe/US communication gap!

Infrared singularities and massive fields

Thomas Appelquist and J. Carazzone
Phys. Rev. D **11**, 2856 – Published 15 May 1975

EFT Applied to physics of the SM.

- Applied decoupling theorem extremely instructive and inductive reasoning, applied to real data!

Heavy Quark Contributions to Deep Inelastic Scattering

Edward Witten (Princeton U.)
Dec, 1975

32 pages
Published in: *Nucl.Phys.B* 104 (1976) 445-476

SHORT DISTANCE ANALYSIS OF WEAK INTERACTIONS *

Edward WITTEN **
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

Received 12 July 1976

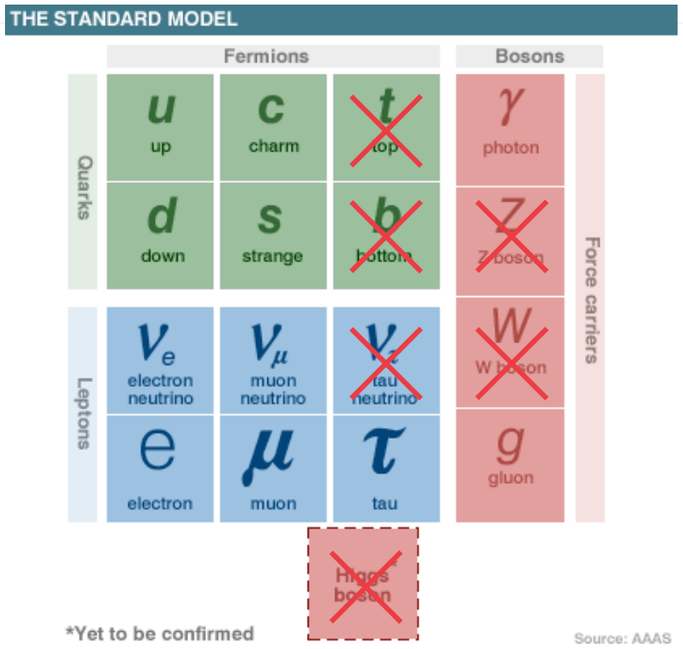
Effective Hamiltonian for Delta s = 1 Weak Nonleptonic Decays in the Six Quark Model

Frederick J. Gilman (SLAC), Mark B. Wise (SLAC)
May, 1979

It works as expected
Applied to actual data!

- For many leading theorists at this point, the EFT paradigm is rather clear.

EFT Applied to physics beyond the SM.



Not discovered yet in early/mid 70's

- These examples were with physics of that was becoming established as the SM
- A good idea to also apply to EXTENDING the SM with heavy unknown physics low energy effects, such as leading to neutrino mass.

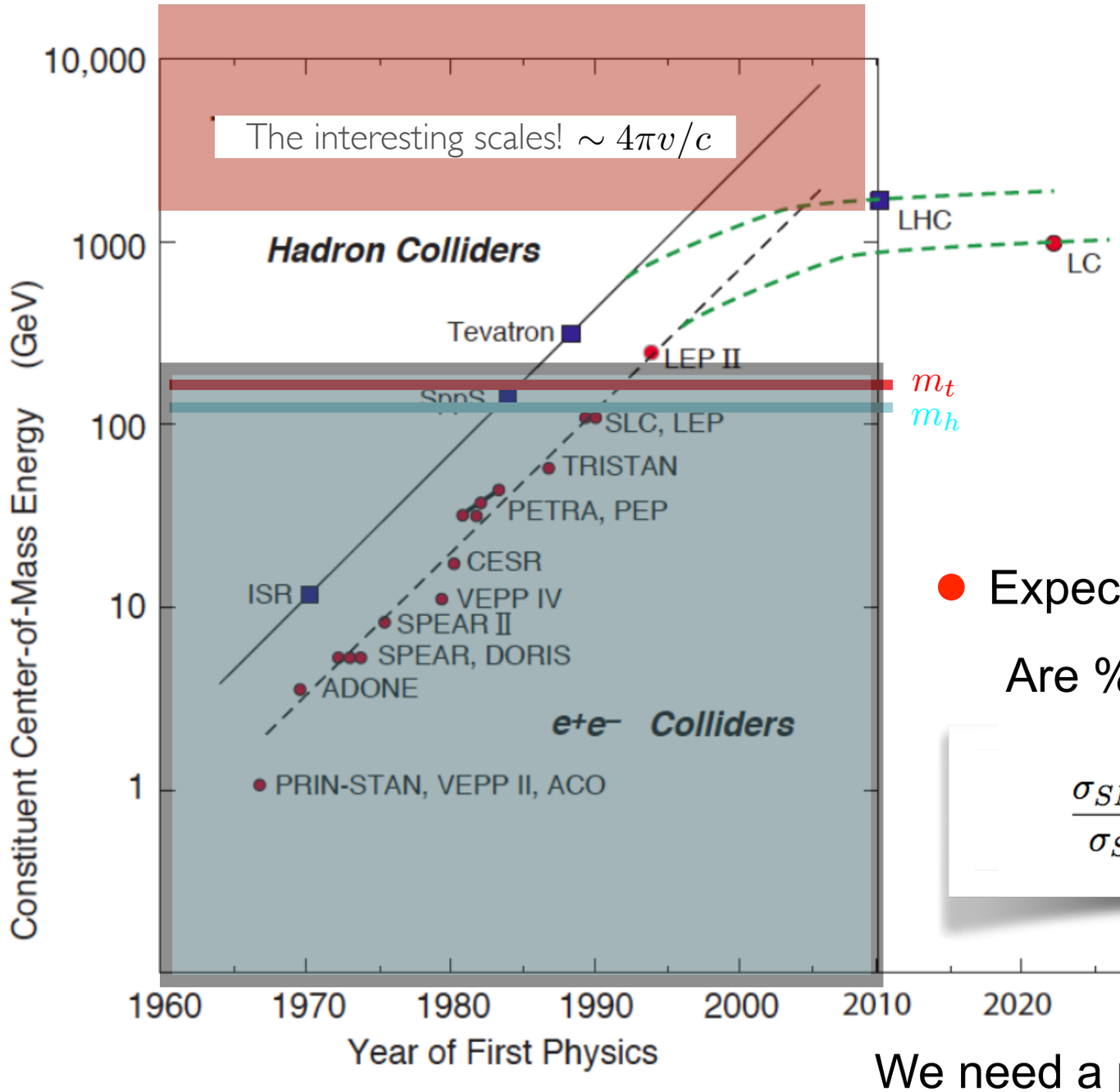
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

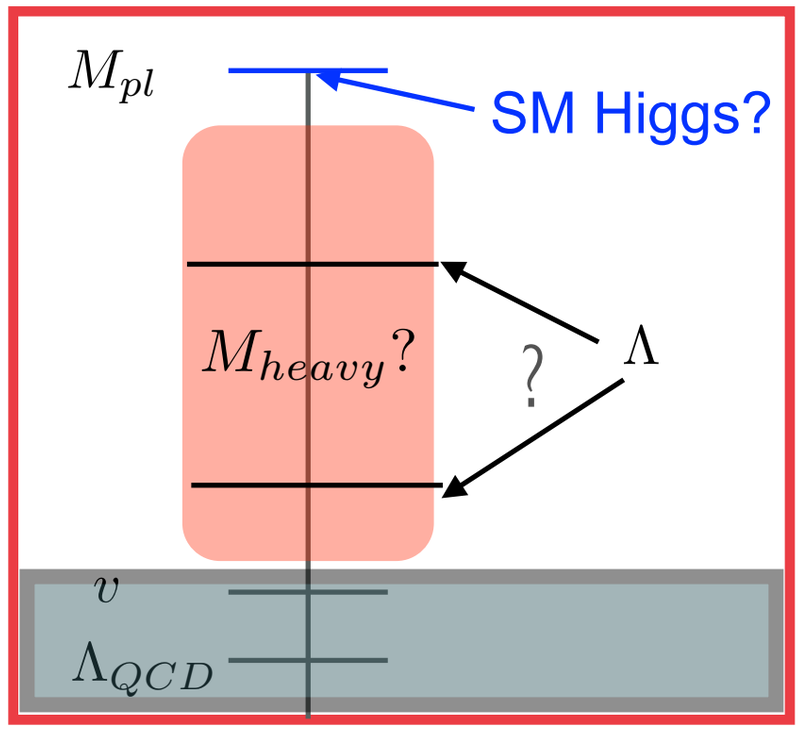
Glashow 1961, Weinberg 1967 (Salam 1967)

Weinberg 1979, Wilczek and Zee 1979

Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak,Rosiek 2010

Very Interesting scales a bit out of direct reach





- Expect % effects on Higgs properties

  Are % level deviations ruled out? NO.

$$\frac{\sigma_{SM+i}}{\sigma_{SM}} \simeq \frac{1}{16\,\pi^2}\left(\frac{N_i^2\,|\kappa_i|^2\kappa'}{g_{SM}\,\lambda}\right)+\cdots$$

We need a precision Higgs pheno program!