Recent progress in the SMEFT

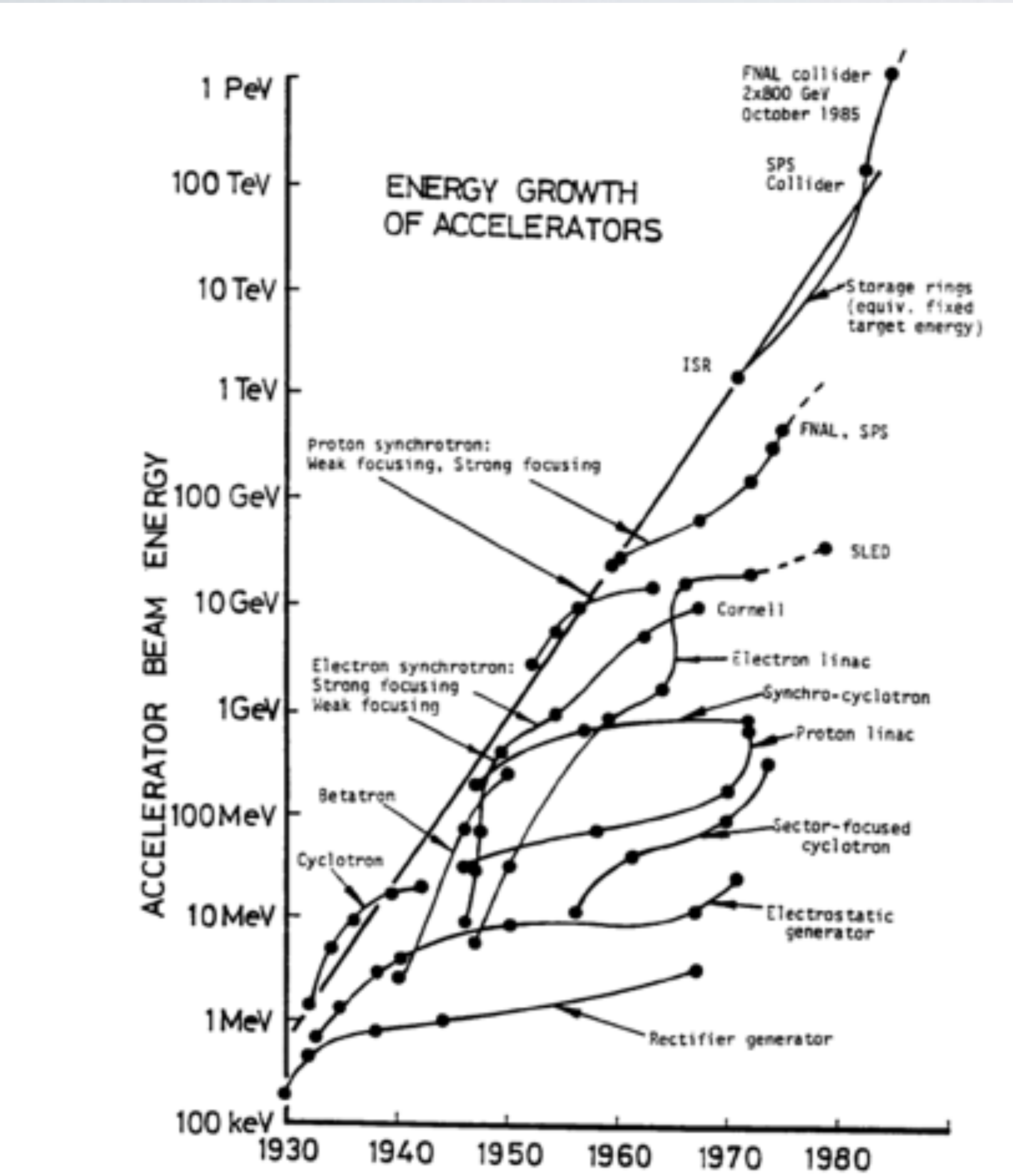
- M. Trott

(Or, reducing anxiety about LEP constraints to a rational minimum.)

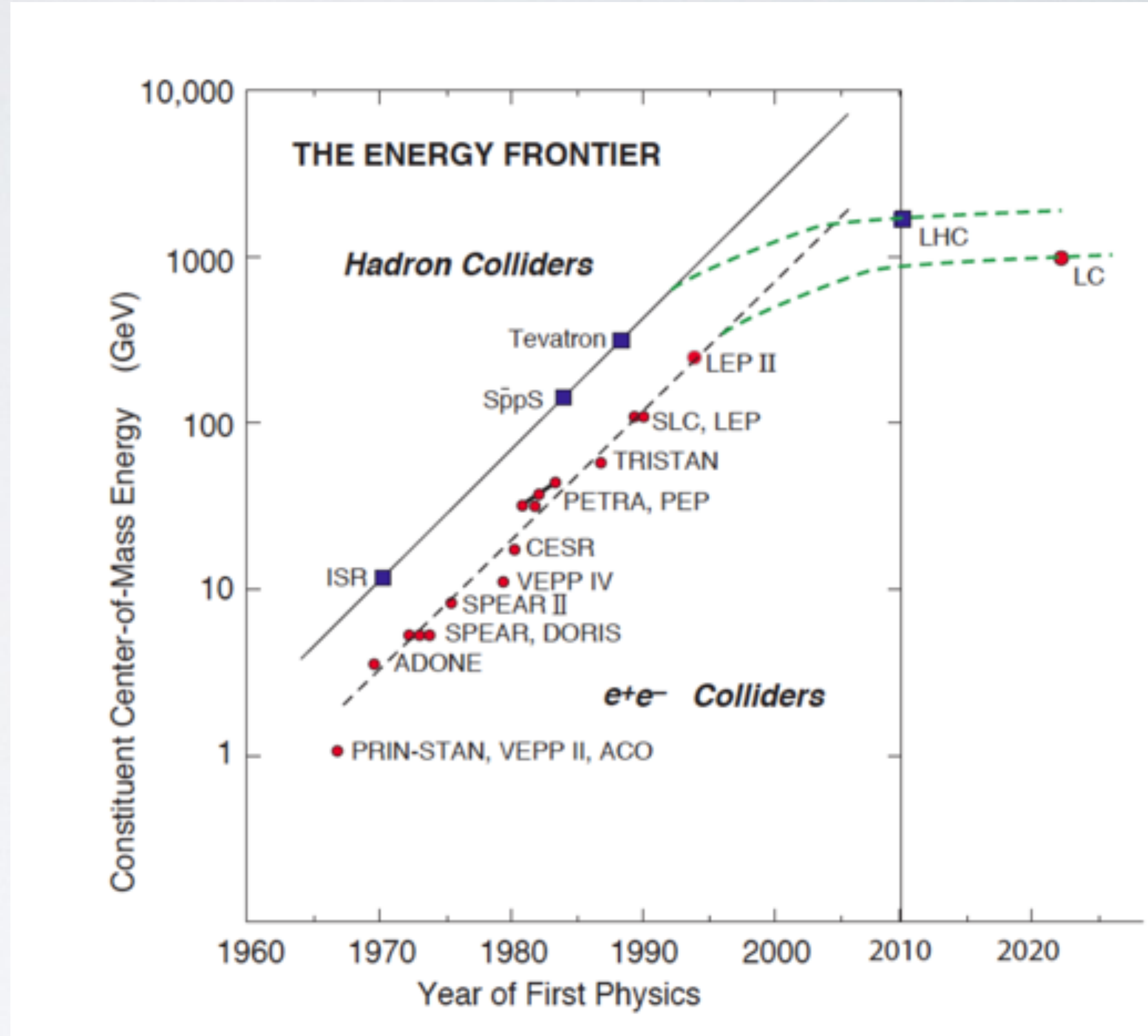
NBI, 15th Sept. 2016

Niels Bohr Institute, Copenhagen, Denmark.

What is the big picture?



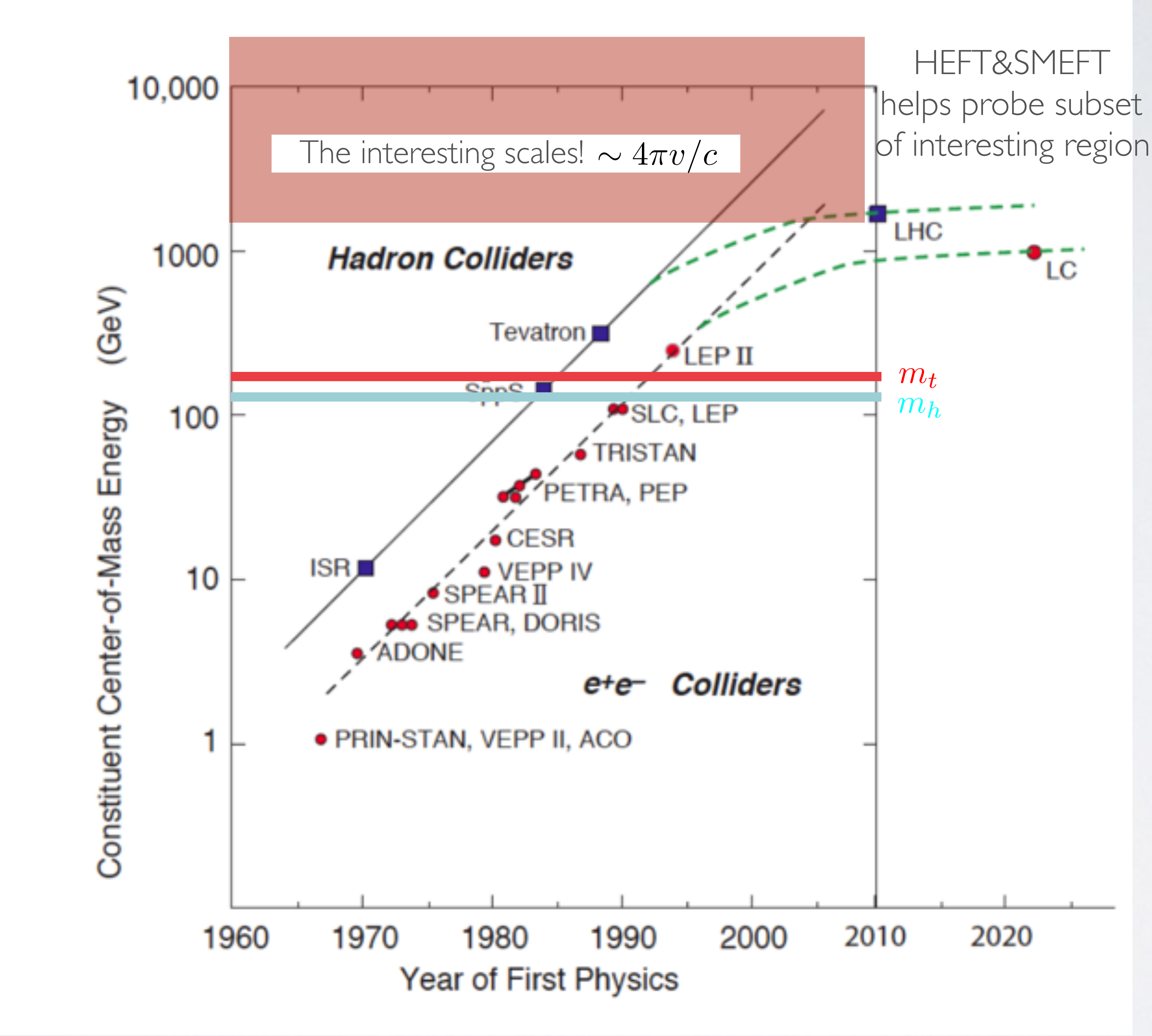
Livingston chart: 1985



Livingston chart: 2014

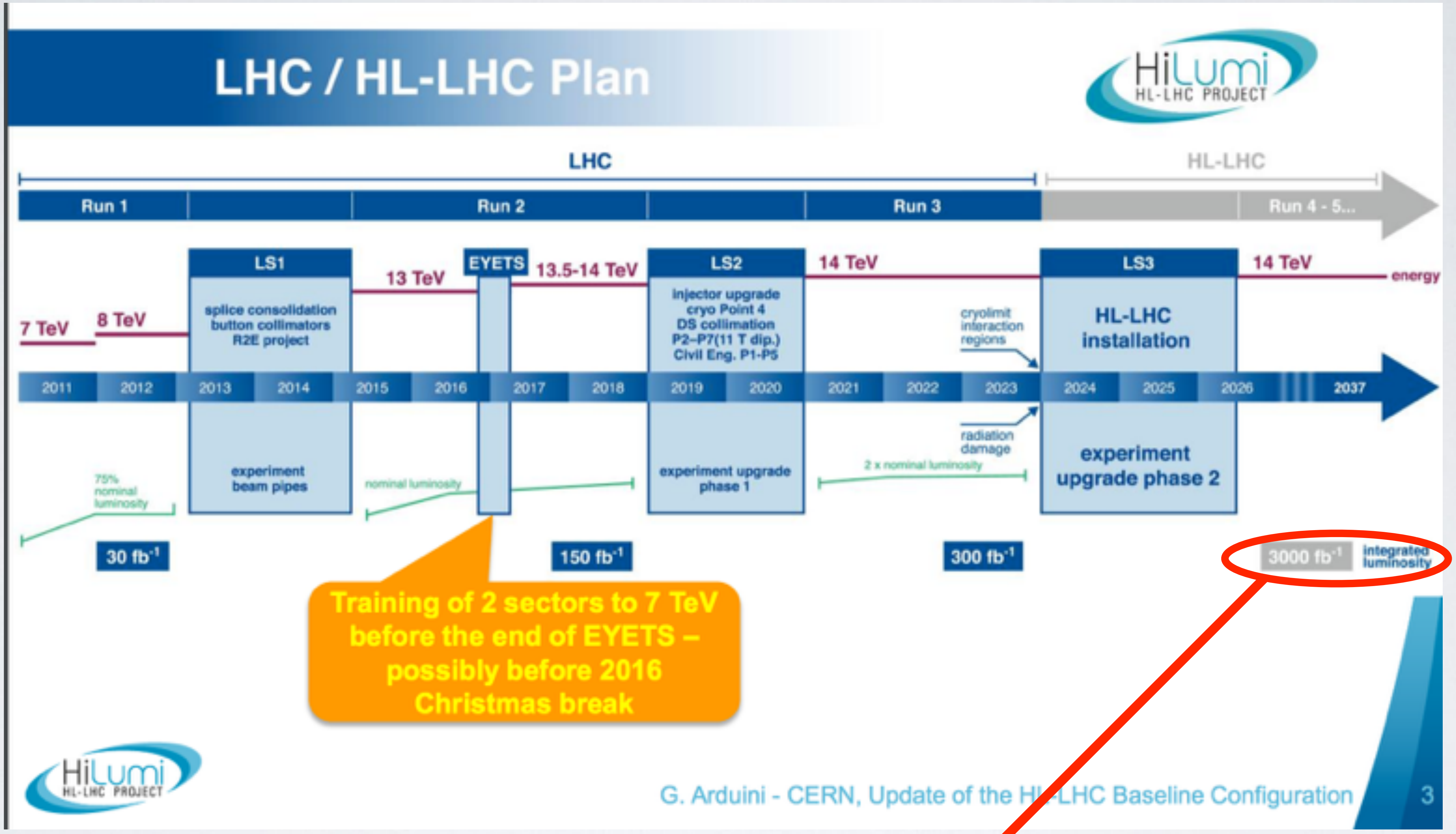
Images: http://www.hep.ucl.ac.uk/iop2010/talks/14.pdf

What is the big picture?



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

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



http://indico.cern.ch/event/432527/contributions/1071739/attachments/1320540/1980263/HL-LHC_ICHEP_04082016.pdf#page=3

And a lot more data..

(Thanks to helpful
experimental sources.)

Insufficient amazement at the data set:

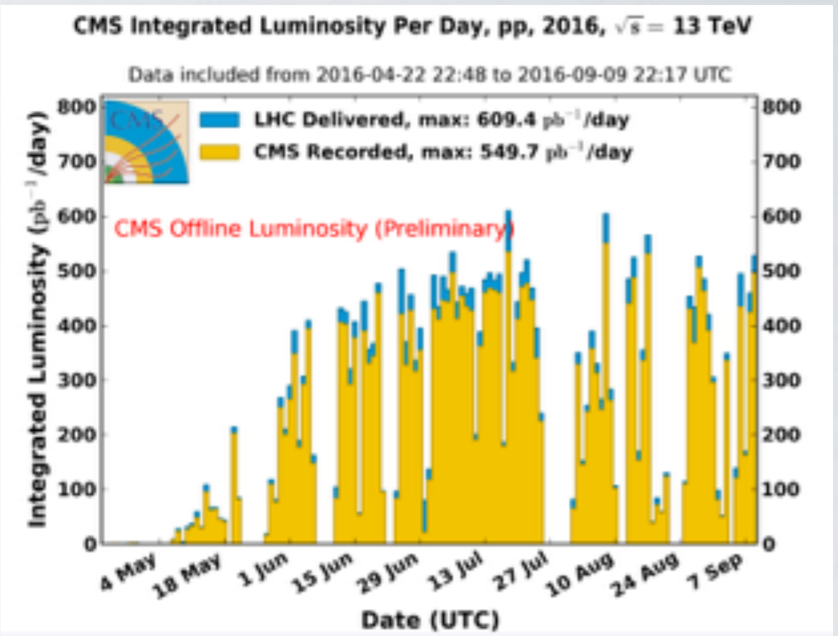
The data set in context:

Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

LEP1

Year	Mean energy $\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
1995, 1997	130.3	6
	136.3	6
	140.2	1
1996	161.3	12
	172.1	12
1997	182.7	60
1998	188.6	180
1999	191.6	30
	195.5	90
	199.5	90
	201.8	40
2000	204.8	80
	206.5	130
	208.0	8
Total	130 – 209	745

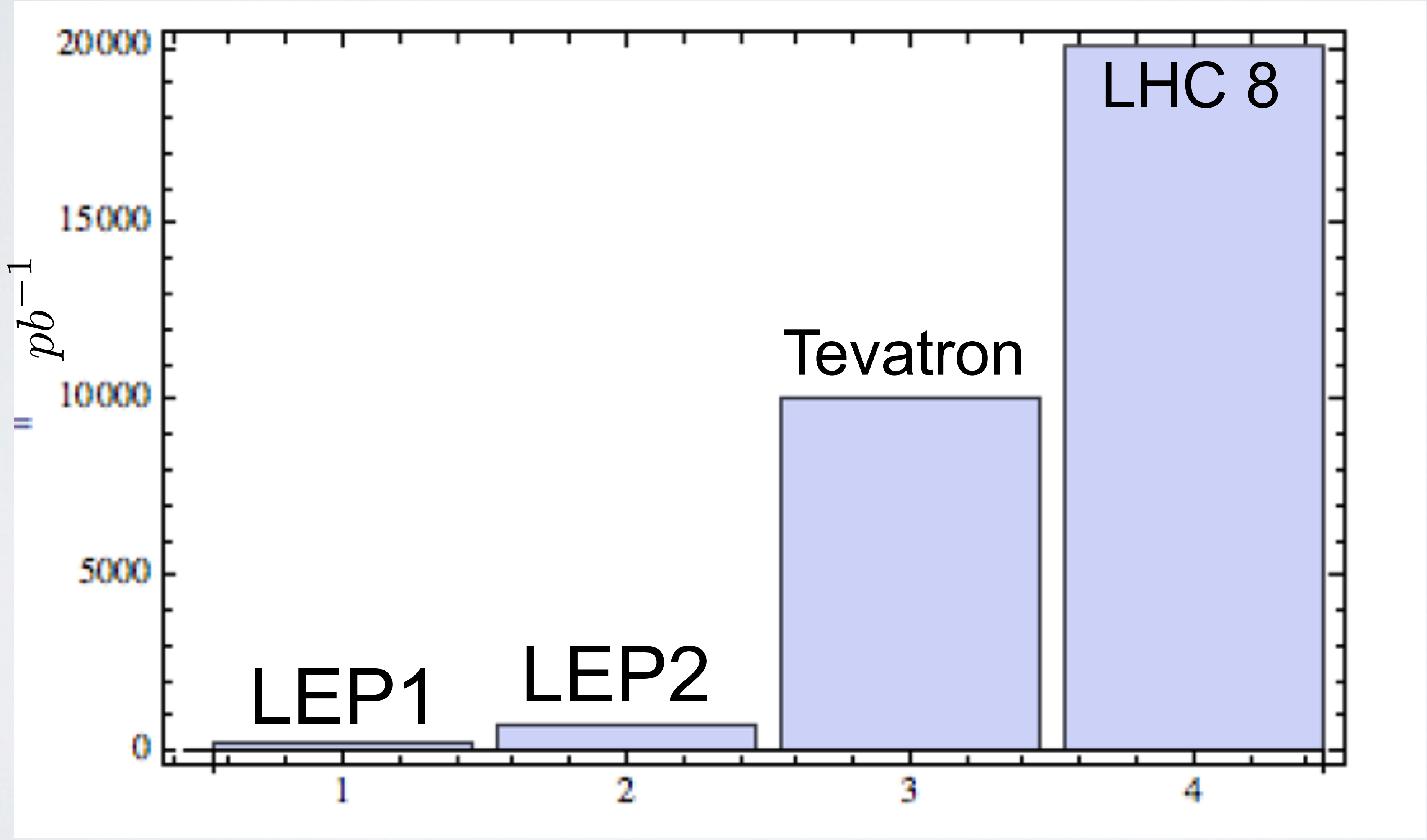
LEP2



CMS/day!

Insufficient amazement at the data set:

The data set in context:



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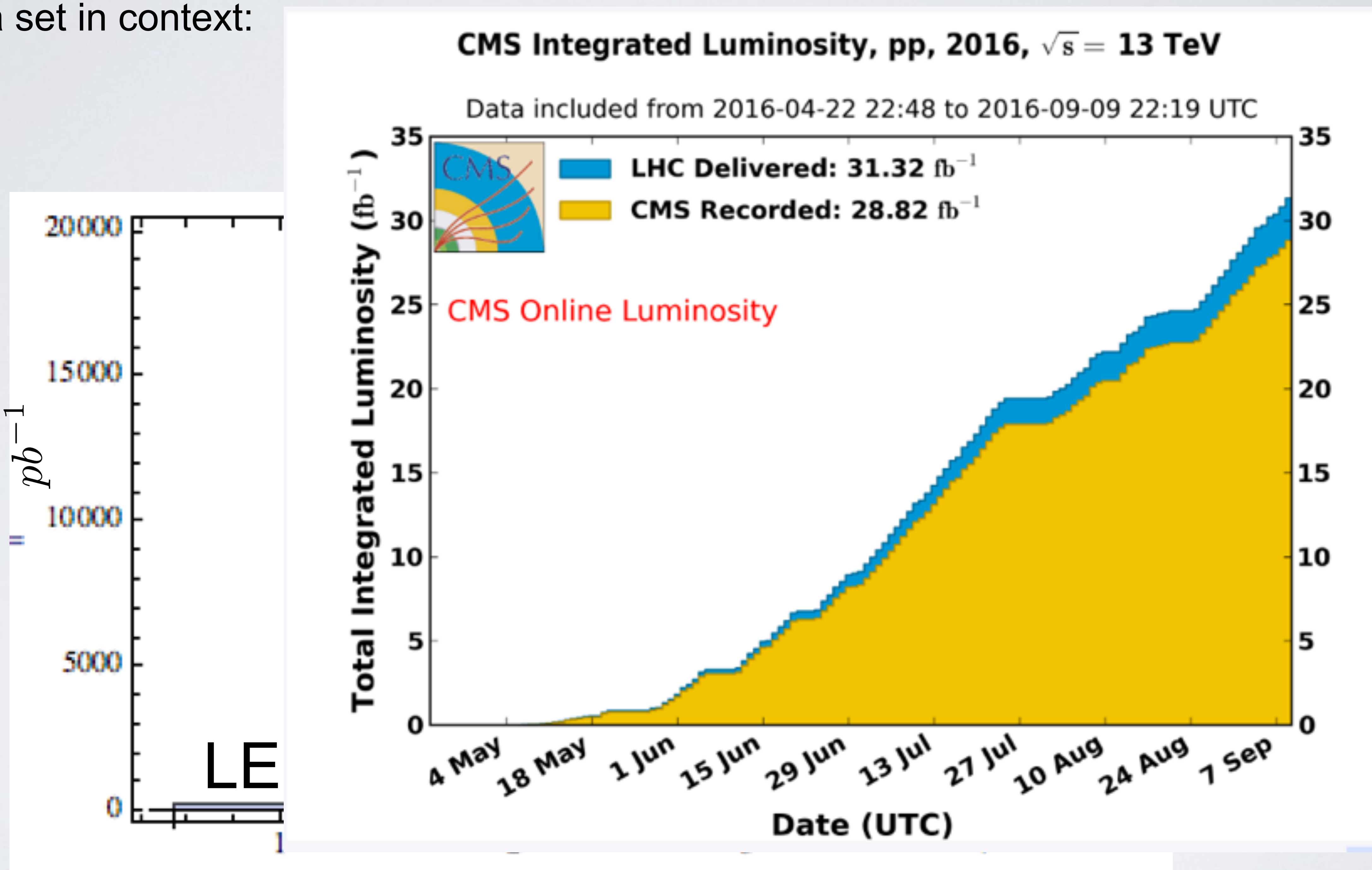
The data set in context:

THIS YEAR!!



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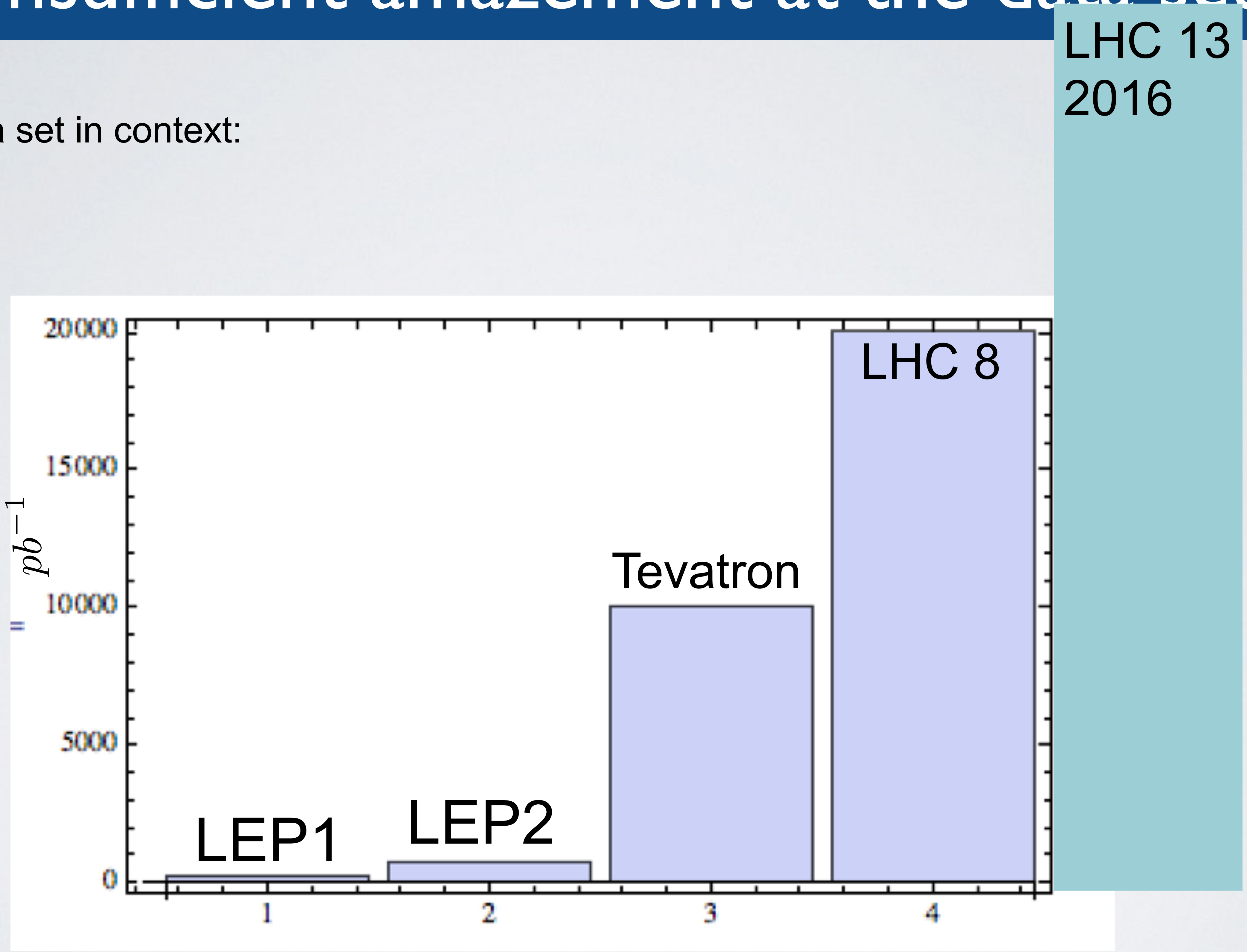

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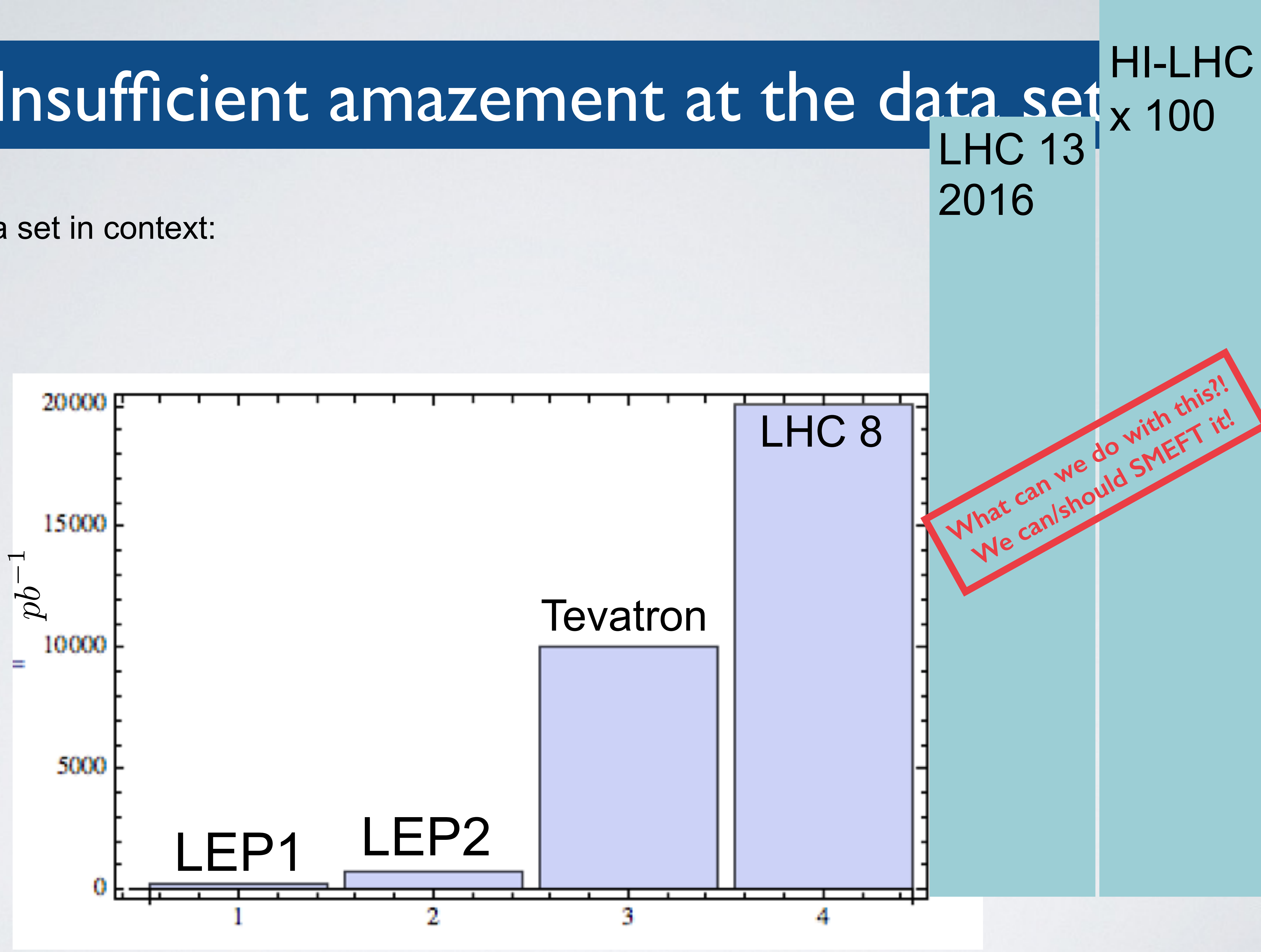
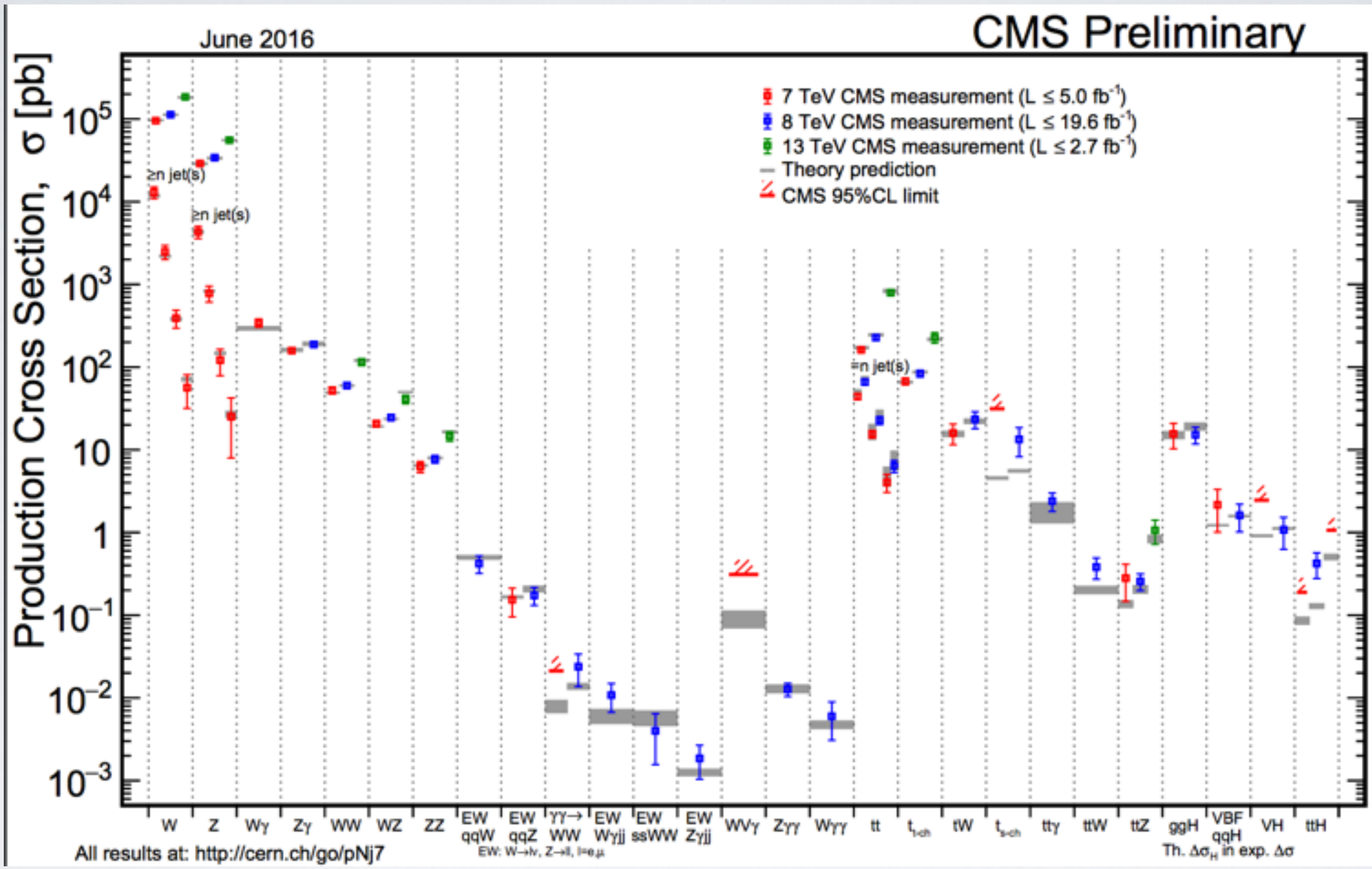
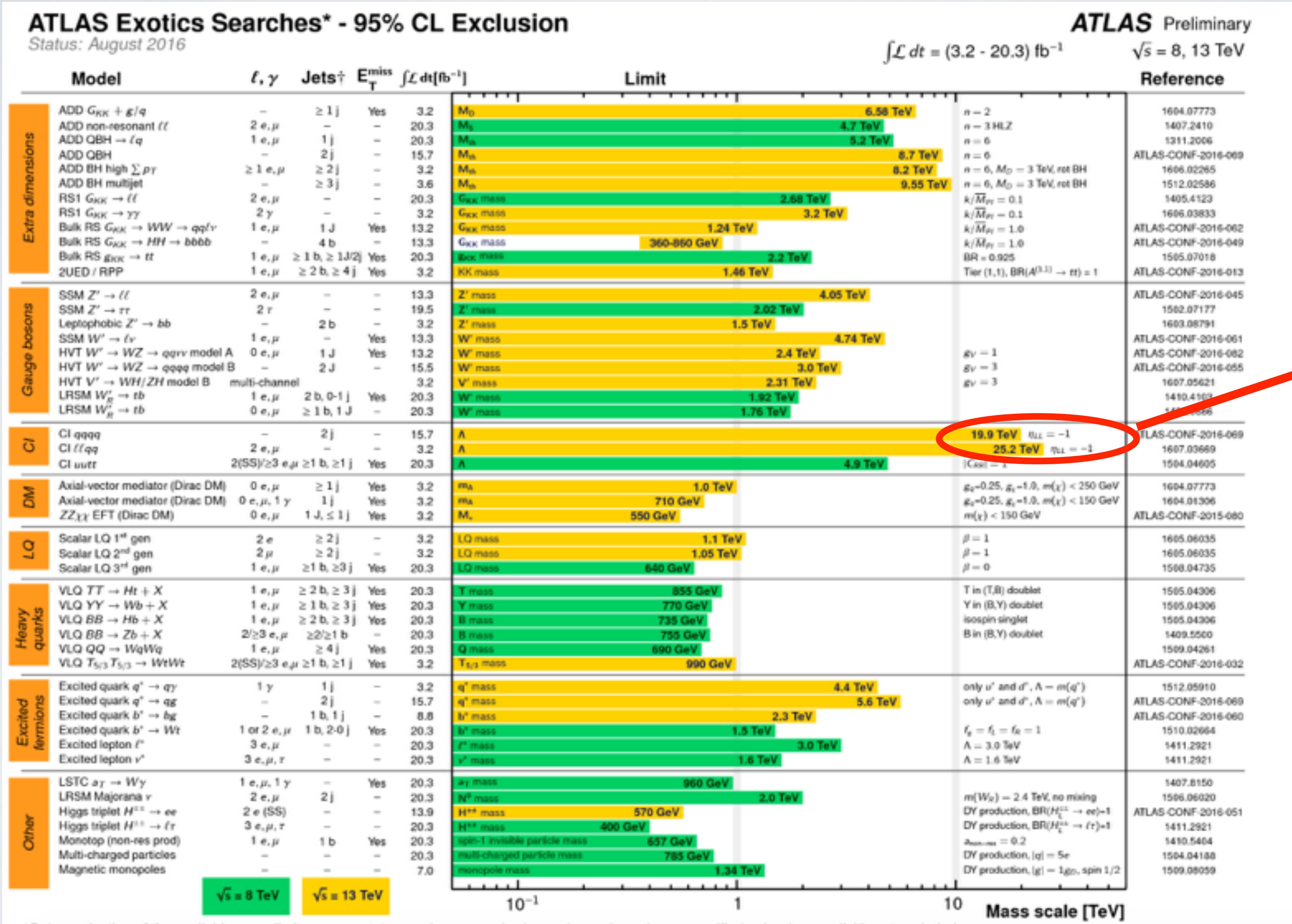


Big picture: SM a very good approx.



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

Resonance searches ATLAS.



Bounds on

g^2/M^2

when limits exceed reach check fine print

In this case

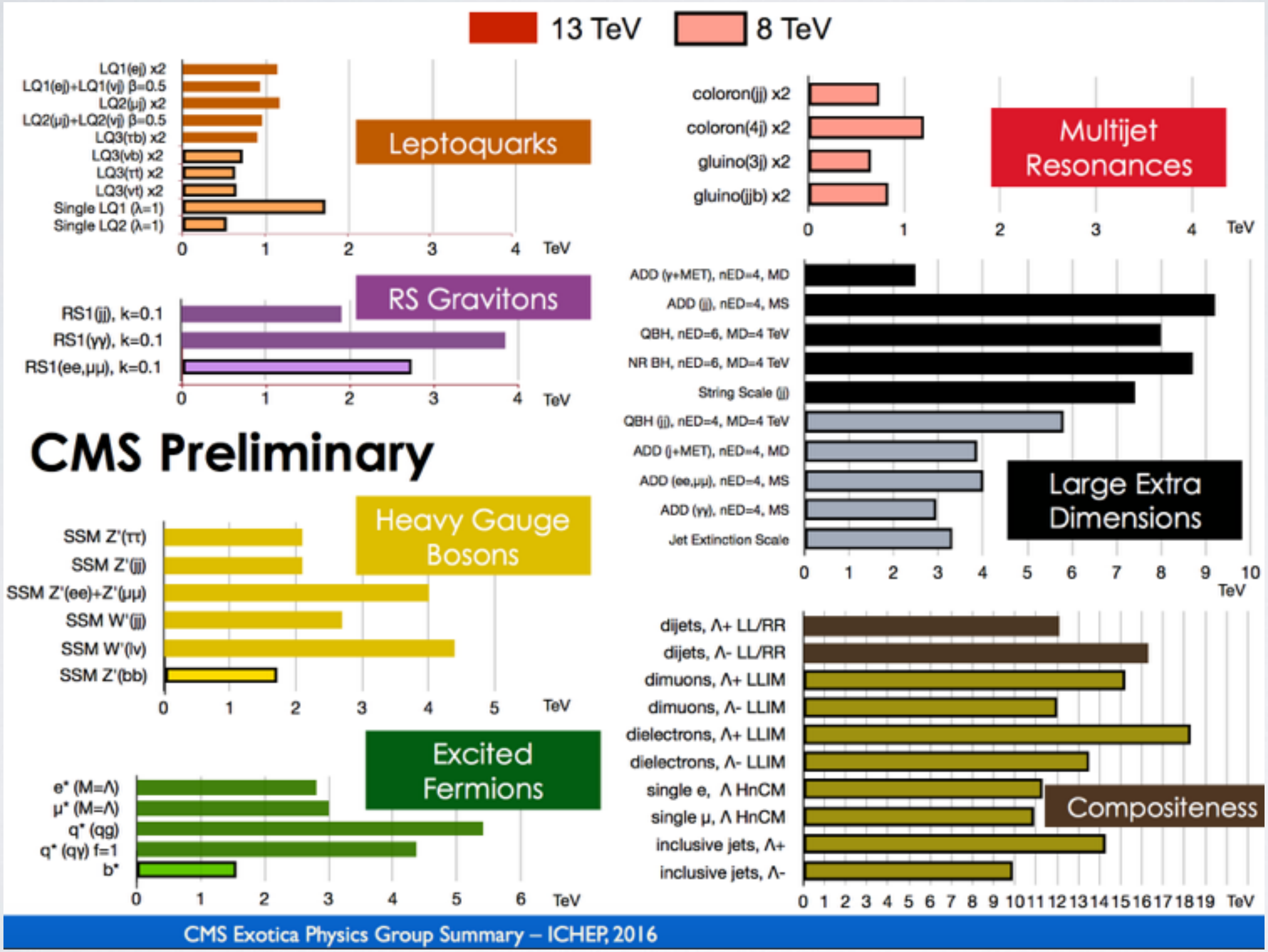
$g^2 = 4\,\pi$

For $g^2 = 1$ limit falls to

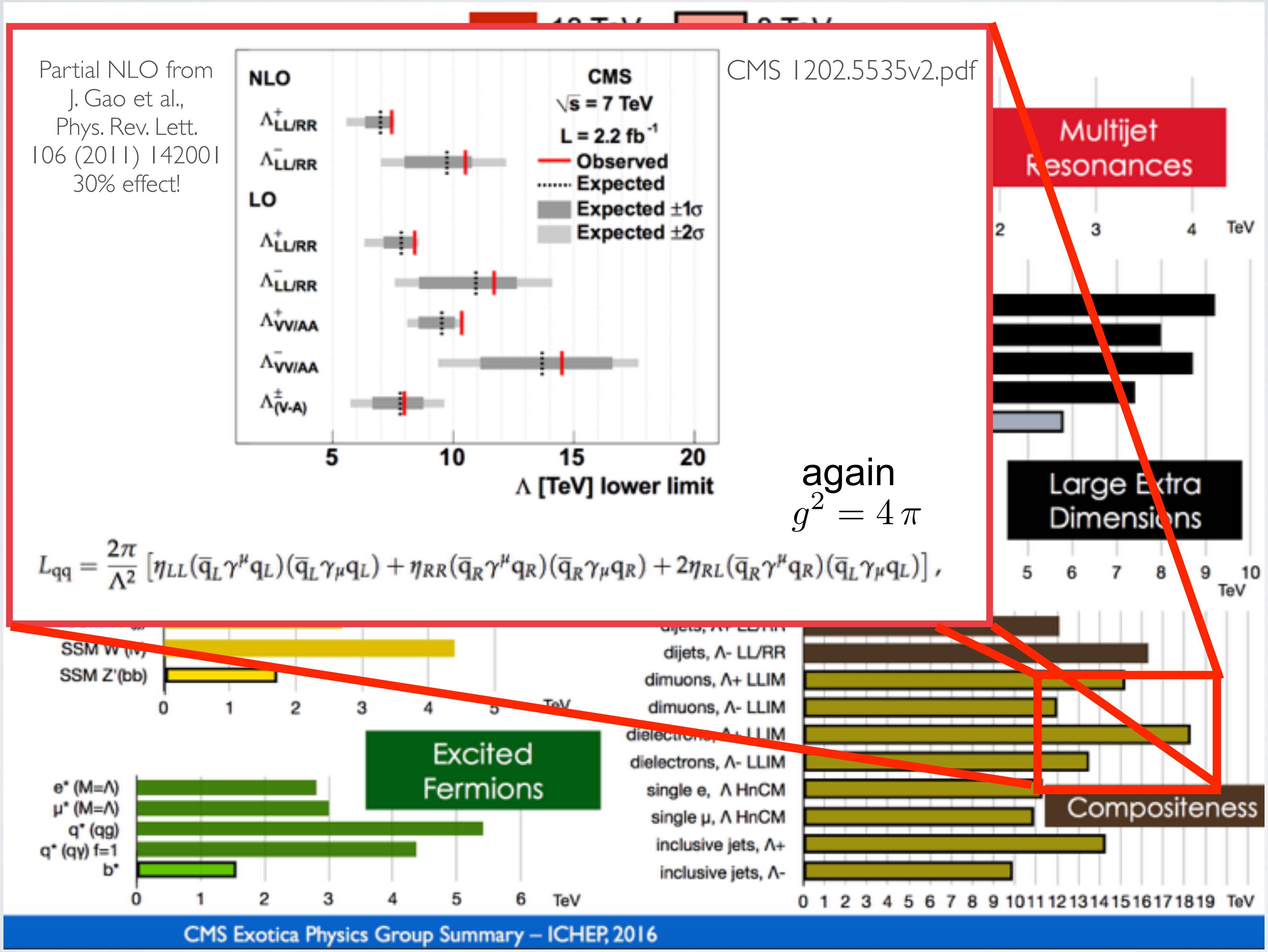
$1.6\,\mathrm{TeV}$

$2.0\,\mathrm{TeV}$

Resonance searches CMS.



Resonance searches CMS.



Typical size of effects to search for

- When you don’t rely on a resonance discovery the SM interactions are perturbed by local interactions

Unknown UV: M_i , g_j → $\sum_{i,j} \frac{g_i^2 M_j^2}{16\,\pi^2} h^2$

- Singlet scalars - should be proximate to the cut off scale.

  More than a loop factor above the scalar mass, unless sym protected, tuning can be required.

- We now have a scalar with mass $m_h \sim 125\,\mathrm{GeV}$ reasonable to expect $g_i\, M_j \sim few\,\mathrm{TeV}$

So integrate out and do SMEFT.

- LHC reach $\lesssim 14/6 \sim 2\,\mathrm{TeV}$ (rule of thumb due to PDF suppression)

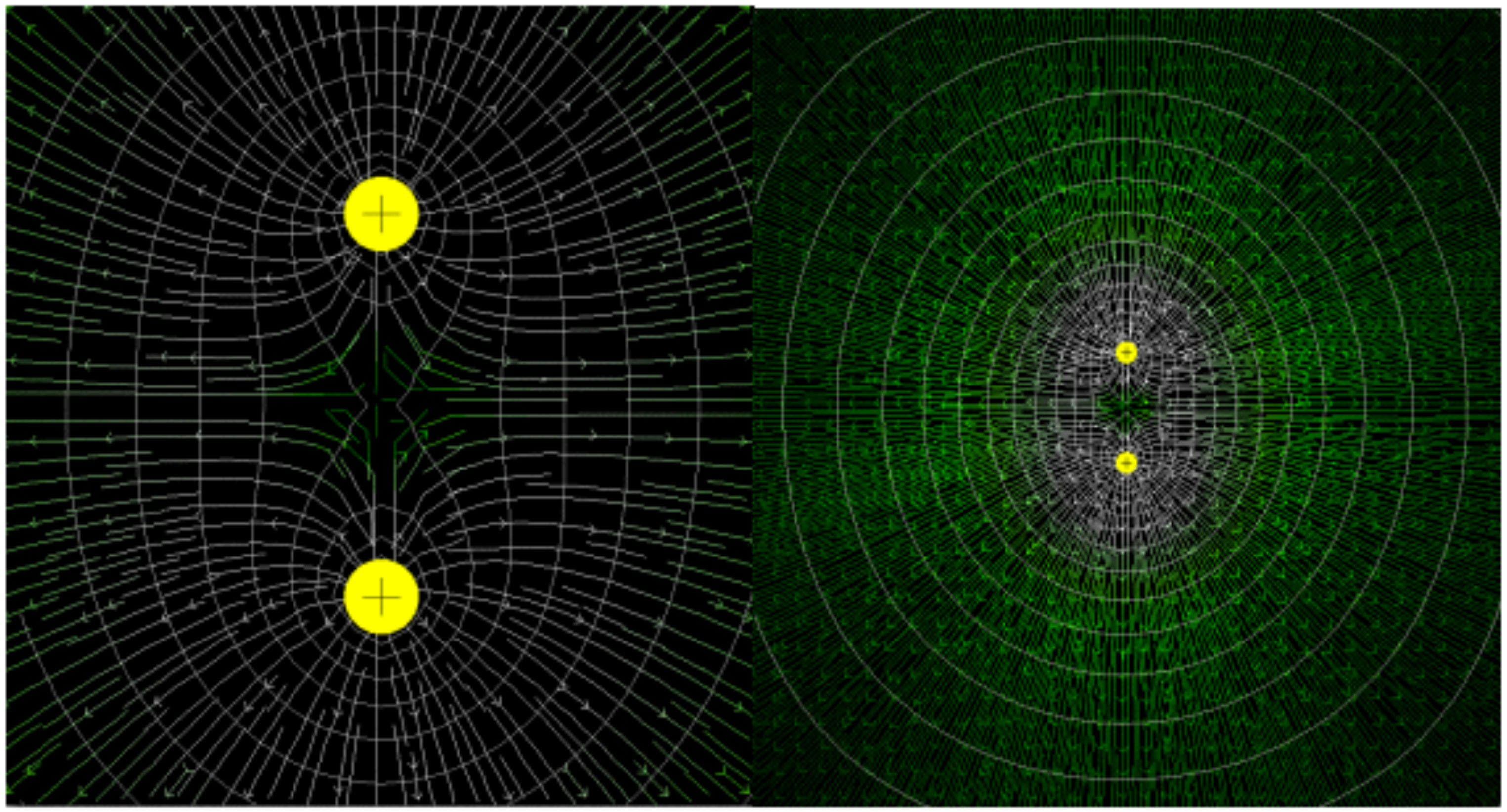
- Corrections expected on the order of $\frac{v^2}{\Lambda^2} \sim few\,\%$ $\frac{E^2}{\Lambda^2} \sim few - tens\%$

  (LEP data few % to 0.1 % precise)

$\Lambda \sim M/\sqrt{g}$ in this talk

Some extra hope in the ~ relation

- An EFT captures the IR physics of some underlying sector by definition. This does NOT just correspond to heavy particle exchange. Important for matching derivative operators.



The field far away looks just like a point charge.

- Consider the electrostatics multipole expansion

$$V(r) = \frac{1}{r}\sum c_{lm} Y_{lm}(\Omega)\left(\frac{a}{r}\right)^l$$

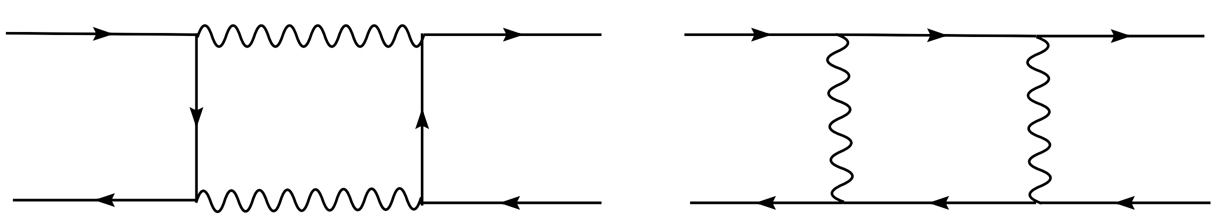
- By adding a series of terms (operators) like the dipole quadraple etc one approx the field

- Correspond to "cut off scale effects" that are not generally small in a strongly interacting theory. Reason is resonance exchange pro. in mass to cut off in a predictive EFT of a strong sector. "Non-minimal" coupling effects should be there.

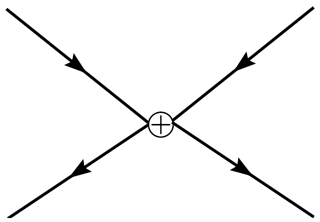
1305.0017 Jenkins,Manohar,Trott, Seminars at: - NBI Winter School lec 2015, MTCP Higgs 2015

also 1603.03064 Liu, Pomarol, Rattazzi, Riva

Flavour and CP assumptions



VS



Recall SM contribution to meson mixing:

$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^\star\,V_{3j})^2\langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\,d_L^j)^2|M\rangle$$

SM PATTERN has GIM suppression, CKM suppression , and loop suppression

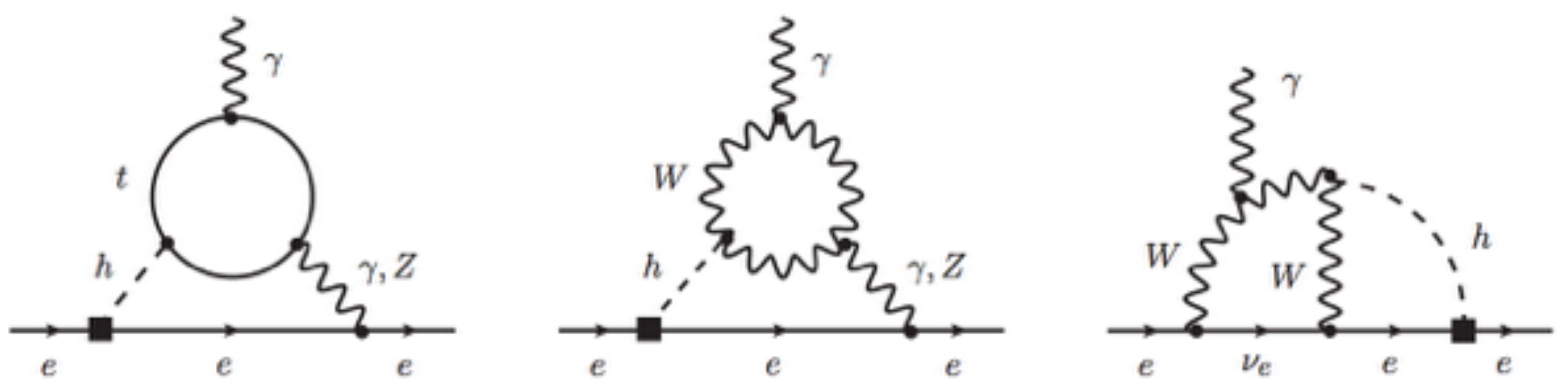
$\lambda \sim 0.2$ so $\lambda^8 \sim 10^{-6}$ $\lambda^4 \sim 10^{-3}$

Integrate out your desired NP states/sector

$$O_{ij} = \frac{c_{ij}}{\Lambda^2}\,(\bar{Q}_L^i\,\gamma^\mu\,Q_L^j)^2$$

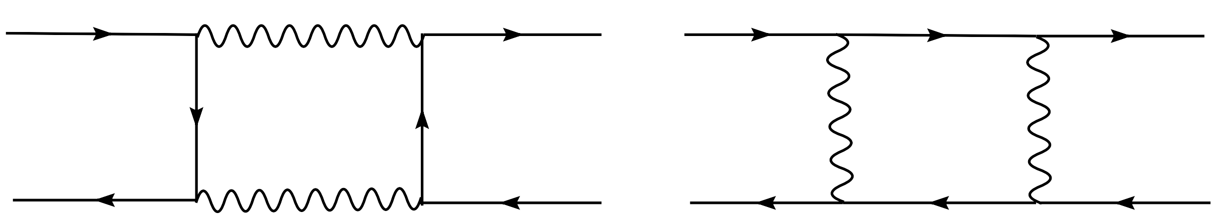
We assume MFV for TeV new physics to be robust (for now).

- Similarly CP violation constrained by EDMs:

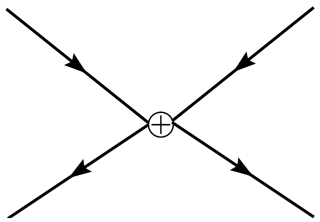


See: Altmannshofer, Brod, Schmaltz, 1503.04830, Brod, Haisch, JZ, 1310.1385, Cirigliano, de Vries, Dekens, Mereghetti, 1603.03049

Flavour and CP assumptions



vs



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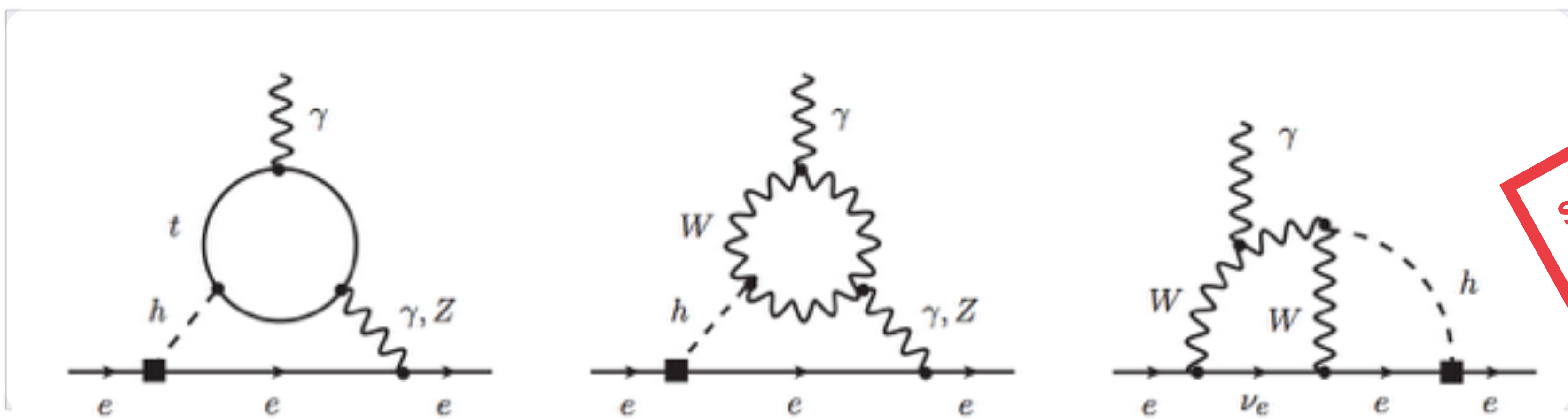
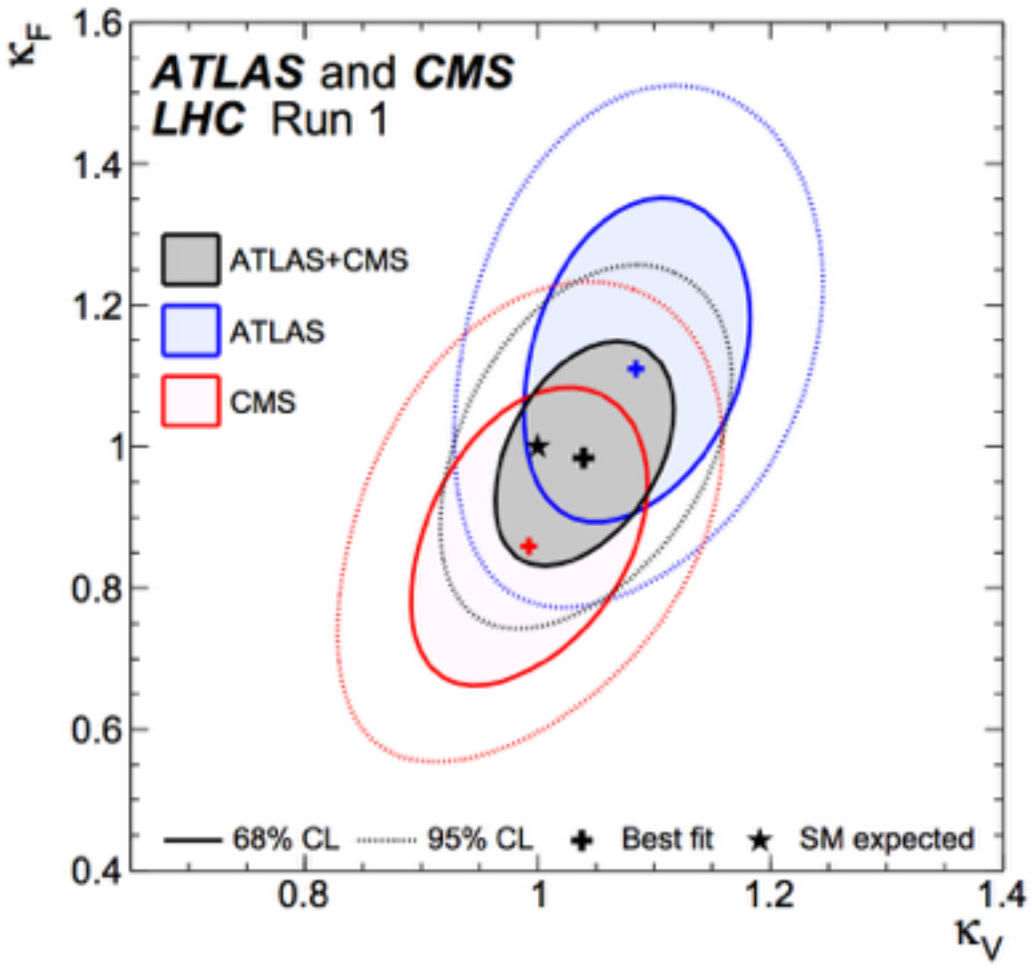


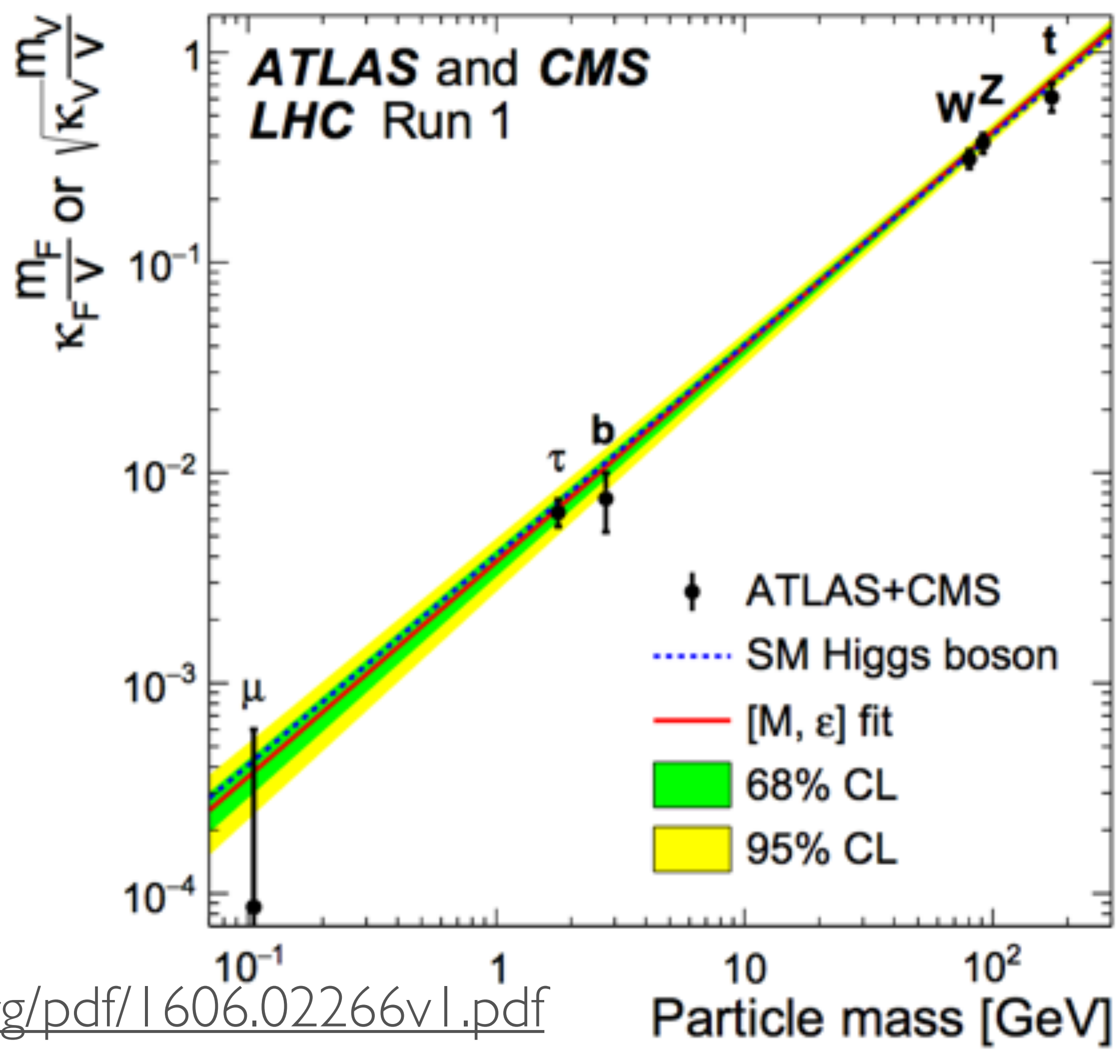
start with MFV and CP sym and relax these assumptions if we can in time

See: Altmannshofer, Brod, Schmaltz, 1503.04830, Brod, Haisch, JZ, 1310.1385, Cirigliano, de Vries, Dekens, Mereghetti, 1603.03049

Higgs Run I Legacy

- What do we know? Without a doubt a very Higgs like boson. This screams DECOUPLING at least to TeV scales.





Atlas/CMS: https://arxiv.org/pdf/1606.02266v1.pdf

Rather similar to analysis first shown in:
Azatov, Contino, Galloway arXiv:1202.3415
Espinosa,Grojean, Muhlleitner ,Trott arXiv:1202.3697
Carmi, Falkowski, Kuflik, Volansky arXiv:1202.3144 (v2)

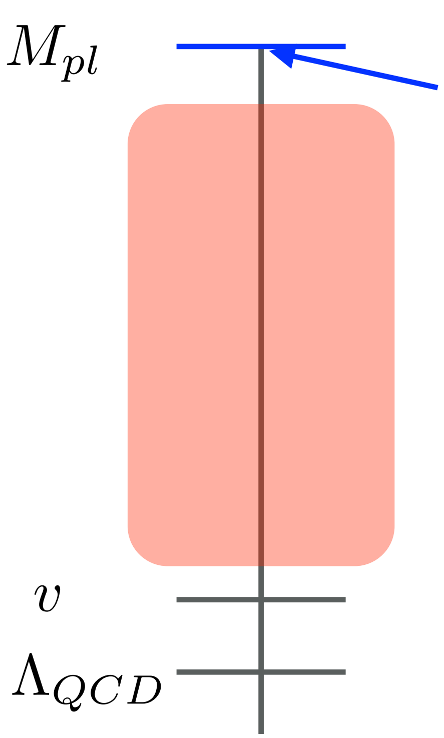
Rather similar to analysis first shown in:
Ellis and You arXiv:1204.0464

The Cut Off scale(s)

- What do we know? Without a doubt a very Higgs like boson.

1. SM is of course consistent with the data.

The observed Higgs LIKE boson pushed the unitarity implied cut off scale away from the EW scale.



Exactly the SM Higgs.
Nothing else coupled to the SM.

“Higgs like scalar” cut off set
by new mass scales

Relevant questions are - how far is the cut off scale?
What is the right EFT to capture the IR limit of the unknown UV.
This question is not trivially about assuming the Higgs mechanism or not.

HEFT as the bottom up construction

Two options. Not obvious to choose between them for cut off scale reasons stated.

1) Nonlinear EFT - built of

Idea stumbled upon over and over..
F. Feruglio arXiv:hepph/9301281
Burgess et al. 9912459
Grinstein Trott , arXiv:0704.1505

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

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

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

"Higgs like boson" couplings are given by adding all possibly "h" interactions

$$\mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - V(h) + \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) \left[1 + 2\, a_{W,Z} \frac{h}{v} + b_{Z,W} \frac{h^2}{v^2} + b_{3,Z,W} \frac{h^3}{v^3} + \cdots \right],$$

$$- \frac{v}{\sqrt{2}} (\bar{u}_L^i \bar{d}_L^i) \Sigma \left[1 + c_i^{u,d} \frac{h}{v} + c_{2,j}^{u,d} \frac{h^2}{v^2} + \cdots \right] \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c.,$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{d_3}{6} \left(\frac{3\, m_h^2}{v} \right) h^3 + \frac{d_4}{24} \left(\frac{3 m_h^2}{v^2} \right) h^4 + \cdots .$$

SM mass scales then unrelated to scalar couplings - ***this approach justifies "kappa" fits.***

HEFT: Rapid developments

- Used in Higgs data analysis and developed into kappa formalism

  1202.3415 Azatov, Contino galloway , 1202.3697 Espinosa, Grojean, Muhlleitner,, MT

  1209.0040 Higgs XS working group 1504.01707 Buchalla et al.

- Subleading operator basis developed 1212.3305 Alonso et al.

  1203.6510 Buchalla Cata (no h), 1307.5017 Buchalla Cata Krause (+ h)

- Matchings/correlations explored

  1311.1823 Brivio et al. 1405.5412 Brivio et al. 1406.6367 Gavela et al. 1409.1589 Alonso et al. 1603.05668 Feruglio et al. 1412.6356,1608.03564 Buchalla et al.

- Power counting discussion

  1312.5624 Buchalla et al, 1601.07551 Gavela et al. 1603.03062 Buchalla et al.

- Curvature interpretation (linear/nonlinear distinction = field redef. invariant curvature measure)

  1511.00724 1602.00706, 1605.03602 Alonso et al.

What is the SMEFT?

Built of H doublet + higher D ops

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$$

If you do an analysis in the SMEFT, to a certain order in the power counting, you retain all operators allowed by symmetry assumptions and allow the data to constrain.

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- (red) Glashow 1961, Weinberg 1967 (Salam 1967)
- (blue) Weinberg 1979, Zee, Wilczek 1979
- (dark green) Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak,Rosiek 2010
- (cyan) Weinberg 1979, Abbott Wise 1980
- (black) Lehman 1410.4193, Henning et al. 1512.03433
- (light green) Lehman,Martin 1510.00372, Henning et al. 1512.03433

The Lagrangian expansion theory technology is essentially a solved problem

Complexity is scaling up…

Built of H doublet + higher D ops

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$$

14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)

1 operator, and 7 extra parameters

Complexity is scaling up…

Dim 6 counting is a bit non trivial.

Class		$N_{\rm op}$	CP-even n_g	1	3	CP-odd n_g	1	3
	1	g^3X^3	4	2	2	2	2	2	2
	2	H^6	1	1	1	1	0	0	0
	3	H^4D^2	2	2	2	2	0	0	0
	4	$g^2X^2H^2$	8	4	4	4	4	4	4
	5	$y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
	6	$gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
	7	ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
ψ^4	8 :	$(\bar{L}L)(\bar{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
ψ^4	8 :	$(\bar{R}R)(\bar{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
ψ^4	8 :	$(\bar{L}L)(\bar{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
ψ^4	8 :	$(\bar{L}R)(\bar{R}L)$	1	n_g^4	1	81	n_g^4	1	81
ψ^4	8 :	$(\bar{L}R)(\bar{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
ψ^4	8 :	All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total			59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Complexity is scaling up…

Linear EFT - built of H doublet + higher D ops

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$

- 

Can reduce the number of relevant parameters to about 29 or so using flavour symmetry and neglecting CP violation, using scaling when near resonances..

- WE CAN DO THE RELEVANT GENERAL CASE!
- Consistent power counting can also be done.
- There is no need for extra model dependence to be introduced or vague assumptions..

Can always restrict to less general case AFTER general analysis.

LO SMEFT = dim 6 shifts

- Warsaw basis: 1008.4884 Grzadkowski, Iskrzynski, Misiak, Rosiek

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

6 gauge dual ops

28 non dual operators

25 four fermi ops

59 + h.c. operators

NOTATION:

$\widetilde X_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} X^{\rho\sigma} \quad (\varepsilon_{0123} = +1)$

$\widetilde\varphi^j = \varepsilon_{jk}(\varphi^k)^\star \qquad \varepsilon_{12} = +1$

$\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \equiv i\varphi^\dagger \left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$

$\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \equiv i\varphi^\dagger \left(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I\right)\varphi$

LO SMEFT = dim 6 shifts

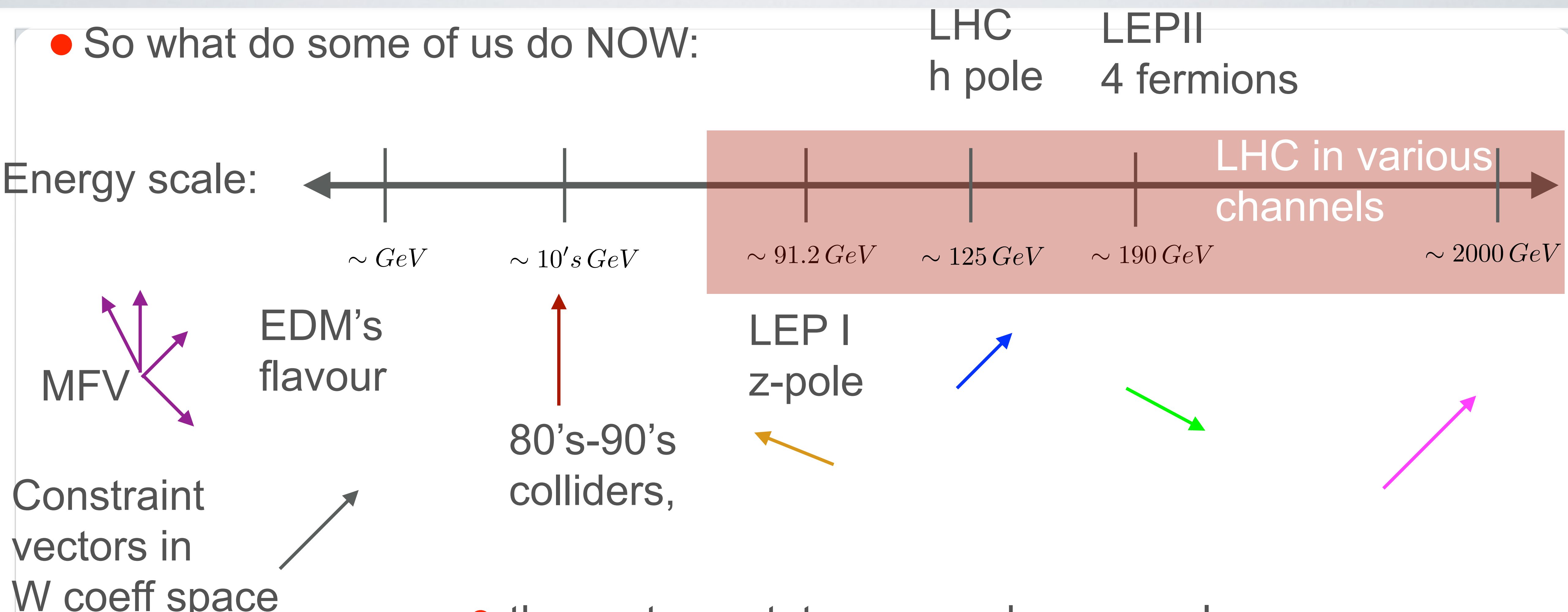
- Four fermion operators: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)(\bar{R}R)$		$8:(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

Post Modern Discovery Physics

- So what do some of us do NOW:



- the vectors rotate as you change scale..

- To combine the various constraints consistently take into account they rotate as you change scale.. or introduce theory error.
- Any future discovery has to be projected back on these constraints to check consistency.

Data incorporated in the analysis

- Similar to past work in: Grinstein and Wise Phys.Lett. B265 (1991) 326-334

  Han and Skiba http://arxiv.org/abs/hep-ph/0412166

  Pomarol and Riva https://arxiv.org/abs/1308.2803

  Falkowski and Riva https://arxiv.org/abs/1411.0669

- Key improvements: Non redundant basis.
  (Han skiba before Warsaw developed)

  Attempt at theory error FOR THE SMEFT included.

  More data, and LEPII done in a more consistent fashion.

Data incorporated in the analysis

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  Han and Skiba http://arxiv.org/abs/hep-ph/0412166

  Pomarol and Riva https://arxiv.org/abs/1308.2803

  Falkowski and Riva https://arxiv.org/abs/1411.0669

- Key improvements:

First step - 103 obs: PEP, PETRA, TRISTAN, SpS, Tevatron, SLAC, LEPI and LEP II, as well as low energy precision data

Berthier,Trott https://arxiv.org/abs/1508.05060

Global constraints on dim 6.

Consider LEP I,II observables:

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[38]	-	-
$\hat{m}_W$[GeV]	80.385 ± 0.015	[39]	80.365 ± 0.004	[40]
σ_h^0 [nb]	41.540 ± 0.037	[38]	41.488 ± 0.006	[41]
Γ_Z[GeV]	2.4952 ± 0.0023	[38]	2.4942 ± 0.0005	[41]
R_ℓ^0	20.767 ± 0.025	[38]	20.751 ± 0.005	[illegible]
R_b^0	0.21629 ± 0.00066	[38]	0.21580 ± 0.00015	[illegible]
R_c^0	0.1721 ± 0.0030	[38]	0.17223 ± 0.00005	[41]
A_{FB}^ℓ	0.0171 ± 0.0010	[38]	0.01616 ± 0.00008	[42]
A_{FB}^c	0.0707 ± 0.0035	[38]	0.0735 ± 0.0002	[42]
A_{FB}^b	0.0992 ± 0.0016	[38]	0.1029 ± 0.0003	[42]

SM theory uncertainty

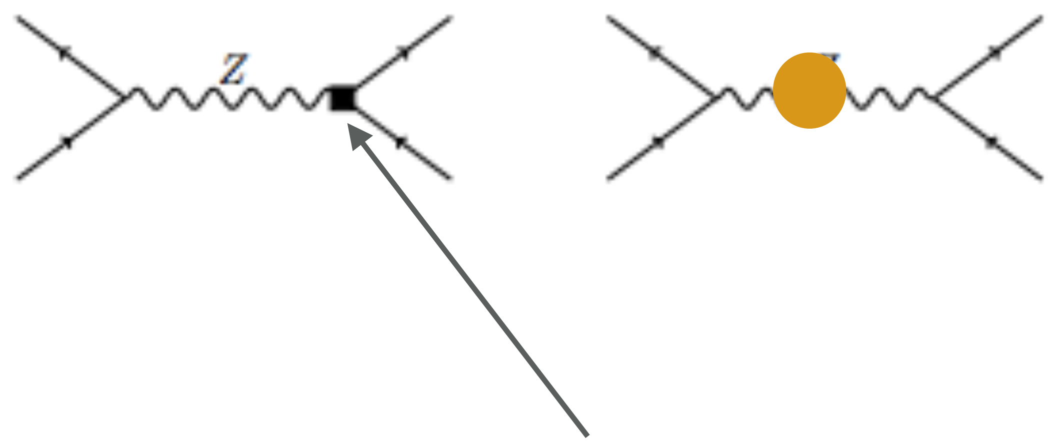
Many 2 loop SM calculations, 2 loop SM can be comparable to one loop SMEFT for error

arXiv:1502.02570
Berthier, Trott

- **If you go beyond % constraints, LO SMEFT alone can be insufficient to incorporate (depends on UV).**

Global constraints on dim 6-update

- The old paradigm of STU was based on the idea that the effects of physics undiscovered should give mass to the W,Z, like the higgs



- The idea is that you have small vertex corrections (like in the case of the SM higgs) and large 2 point effects.

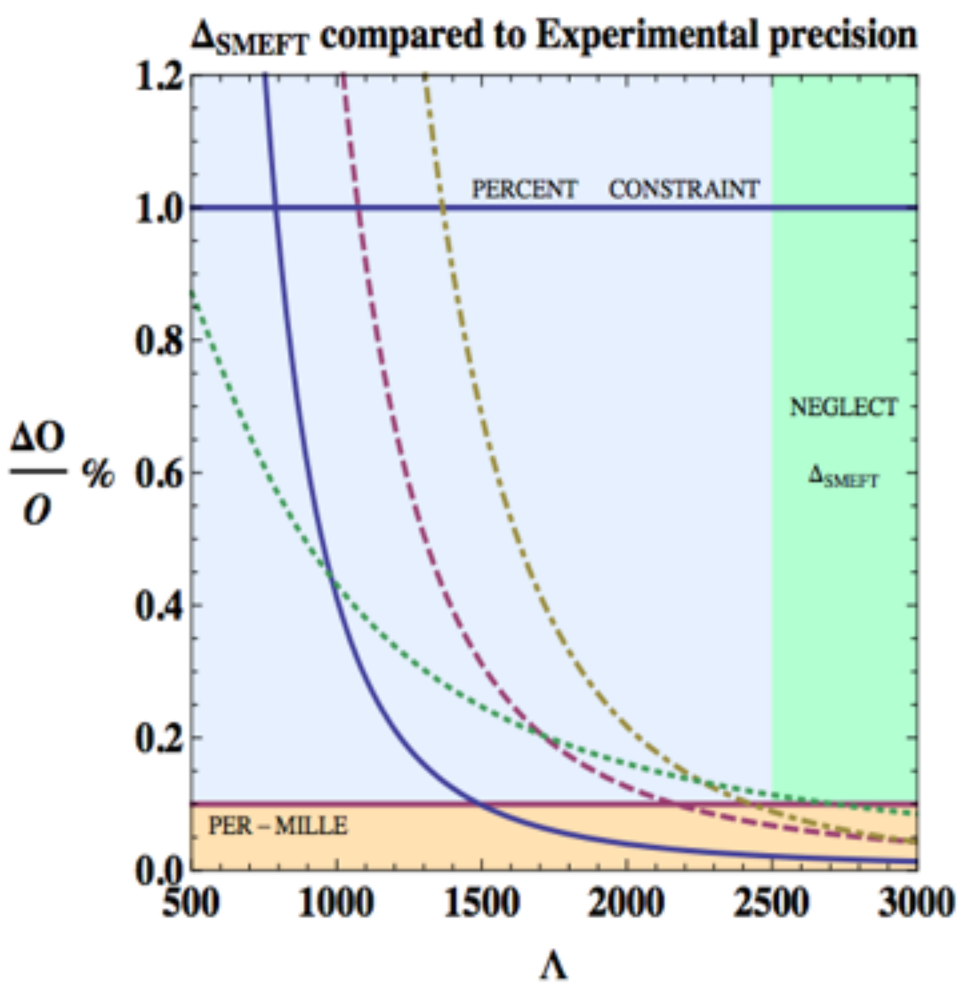
- Unfortunately this is not a field redefinition invariant distinction, so if really is assuming restricted UV (like a Higgs)

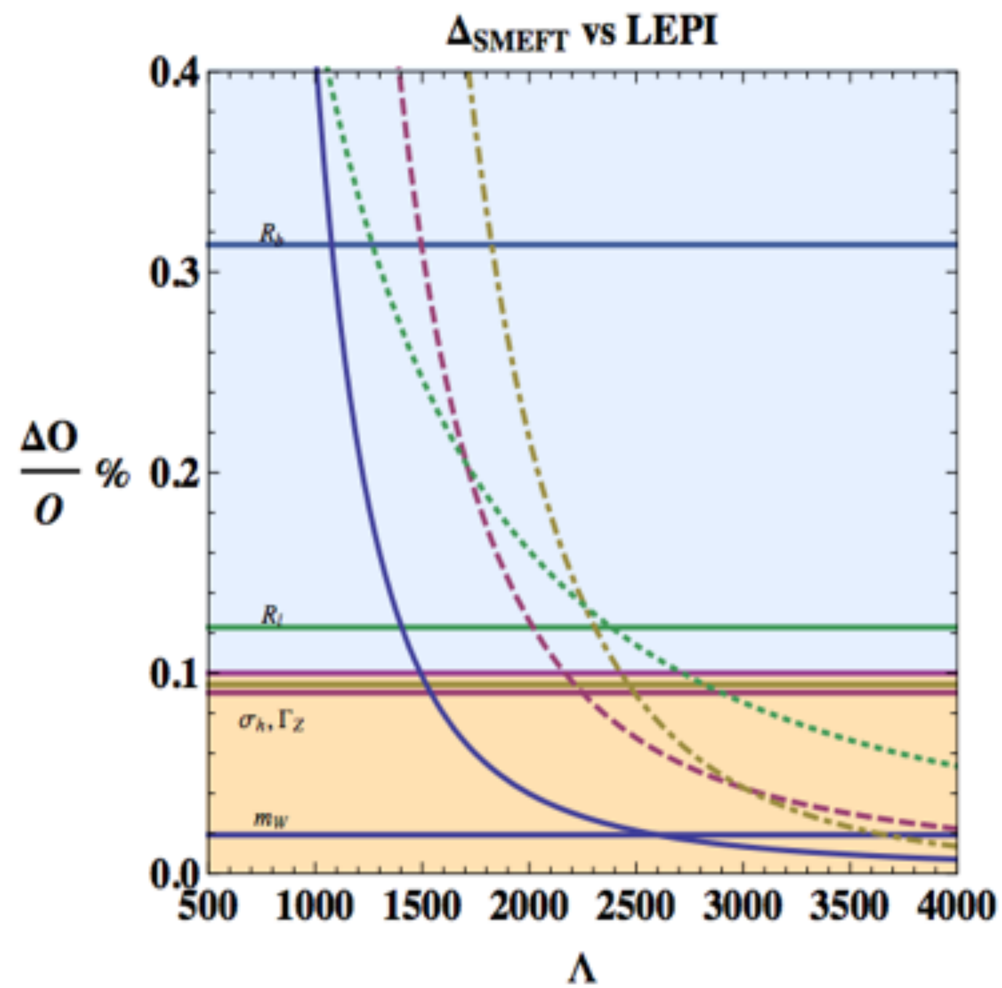
- Now that we found a Higgs like scalar, this is no longer appropriate to assume in general - need SMEFT analysis

Global constraints on dim 6.

For precise observables, we can't ignore error in SMEFT itself:

arXiv:1508.05060 Berthier, Trott





Remember:

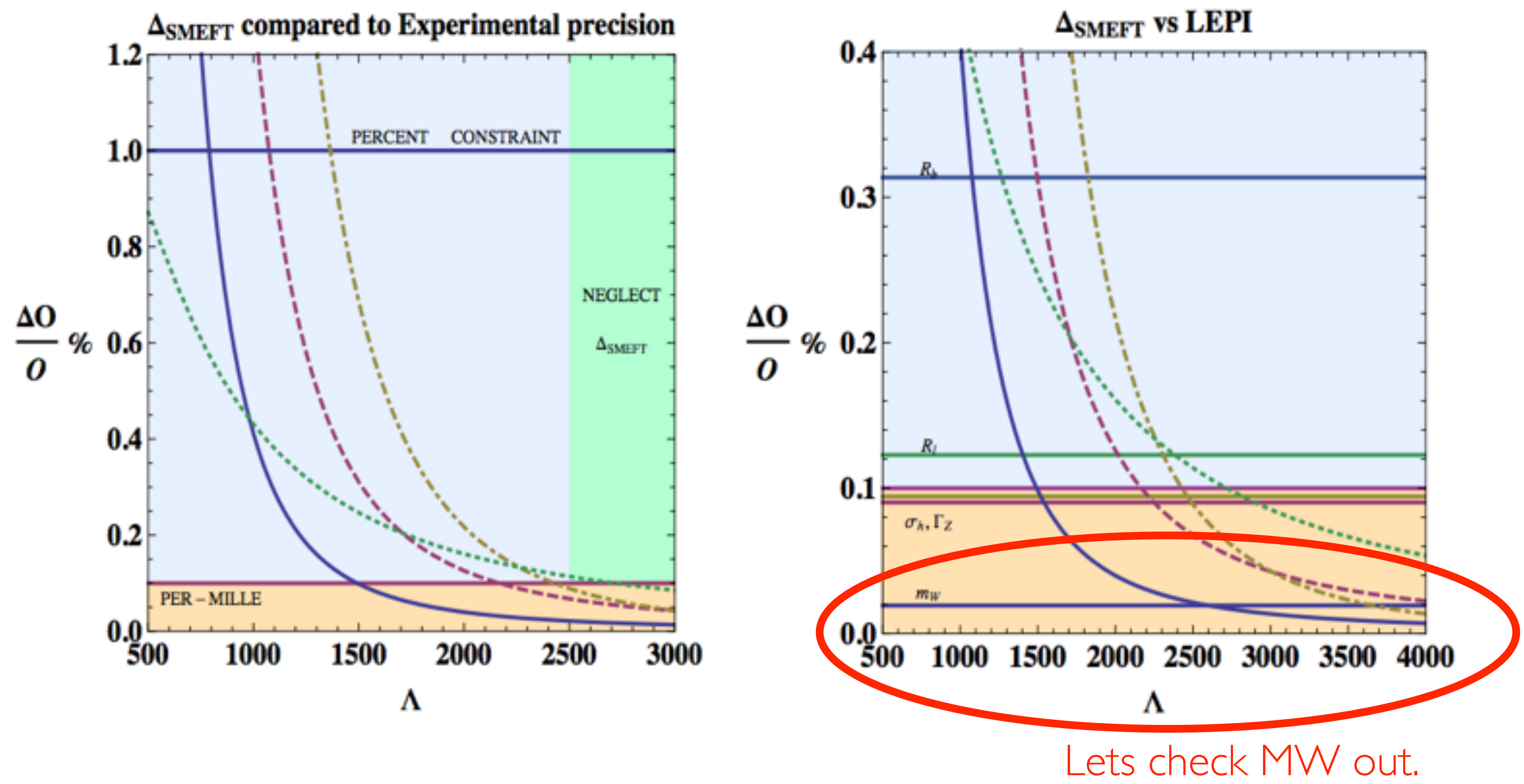
$$\frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$ 535+h.c. operators!

$$\Delta^i_{SMEFT}(\Lambda) \simeq \sqrt{N_8}\, x_i \frac{\bar{v}_T^4}{\Lambda^4} + \frac{\sqrt{N_6}\, g_2^2}{16\,\pi^2}\, y_i \log\left[\frac{\Lambda^2}{\bar{v}_T^2}\right] \frac{\bar{v}_T^2}{\Lambda^2}.$$

Global constraints on dim 6.

For precise observables, we can't ignore error in SMEFT itself:

arXiv:1508.05060 Berthier, Trott

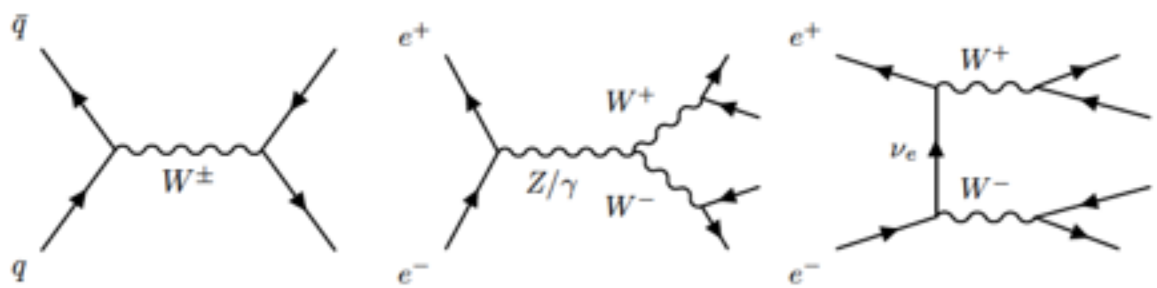


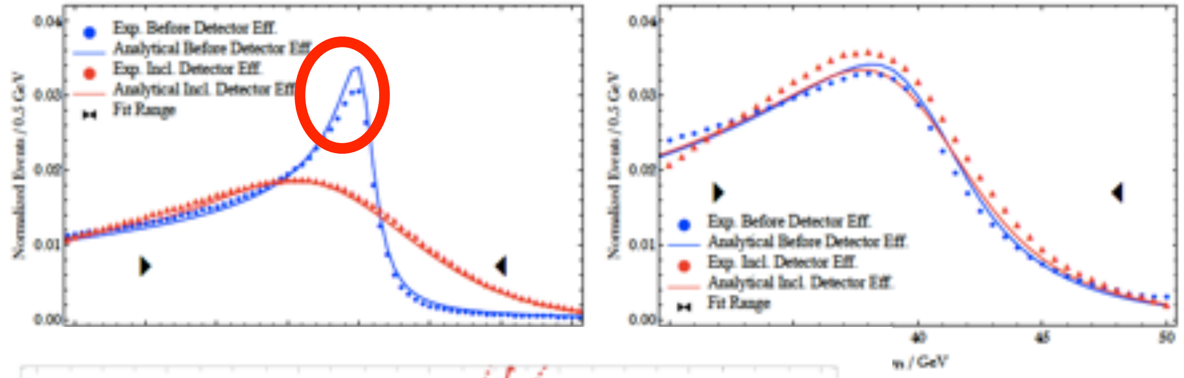
Mw measurements in SMEFT

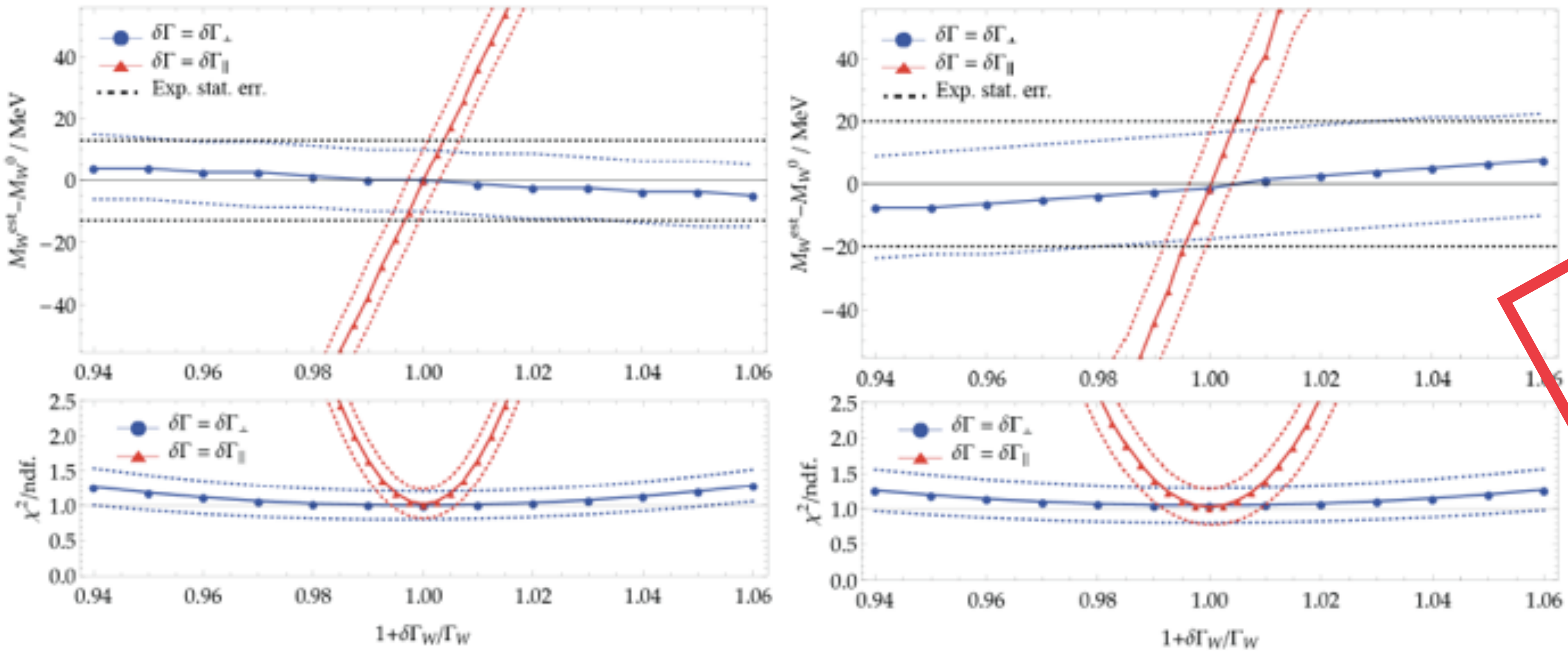
Mw is a template fit at LEP and at the Tevatron.

1606.06502 Bjorn, Trott

Transverse mass Jacobian peak







Below percent measurements in SMEFT at Hadron colliders possible

Bias on the extraction for the Tevatron is OK in the SMEFT!

Straightforward LO

- Expand around the vev the dim 6 operators, go to mass eigenstates
- Canonically normalize the field theory.
- Choose some input parameters to relate to:

Now the path is open to use MW in the SMEFT as an input

(α, G_F, M_Z) a choice than can be made is an alpha scheme

(m_W, G_F, M_Z) equally you can choose to use a Gf scheme (associated with an onshell renormalization scheme usually)

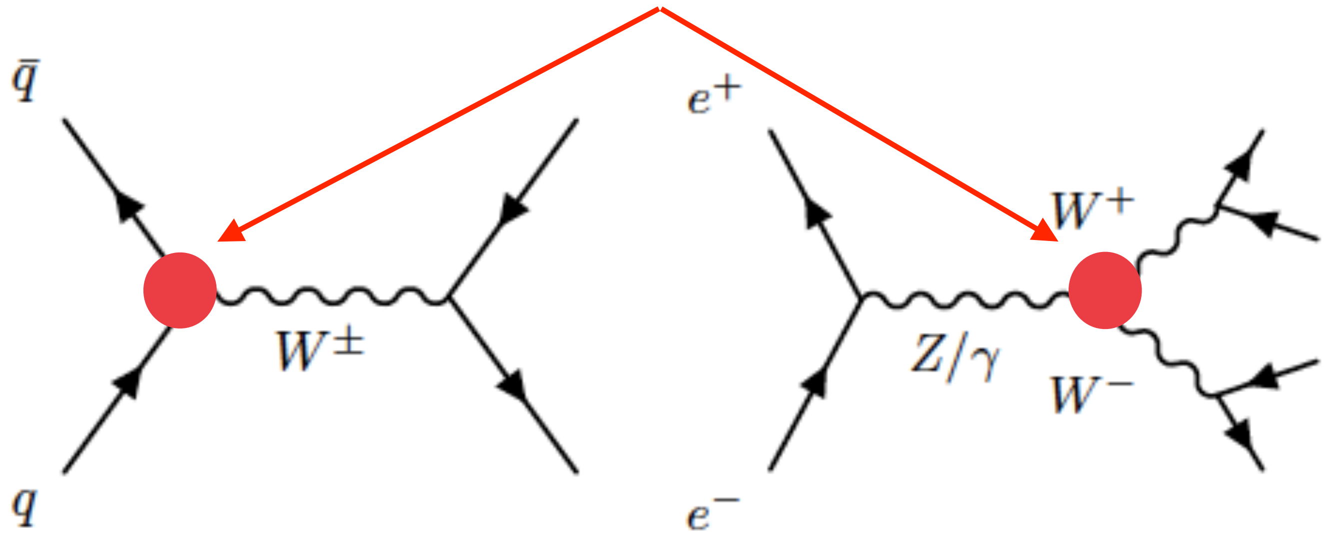
The choice is yours. This is not part of the Basis definition. Relation to input parameters differs as the SMEFT is a different theory than the SM. For example

$$\delta M_Z^2 \equiv \frac{1}{2\sqrt{2}} \frac{\hat{m}_Z^2}{\hat{G}_F} C_{HD} + \frac{2^{1/4}\sqrt{\pi}\sqrt{\hat{\alpha}}\,\hat{m}_Z}{\hat{G}_F^{3/2}} C_{HWB},$$

These differences taken into account with straightforward expansion.
Trivial to do LO SMEFT directly, in a manner that can be improved to NLO.

Global constraints on dim 6-update

- Global SMEFT data analysis of critical data from essentially sorted out now.
  PEP, PETRA, TRISTAN, SpS, Tevatron, SLAC, LEPI and LEP II
- Important ingredient is off shell $e^+e^- \to 4f$ data
- Field redefinitions can also move SMEFT deformations between the TGC vertex and the 2 point functions



- So we need to do the general calculation to close the door honestly in the SMEFT.

Global constraints on dim 6-update

- We have performed an analysis of this form. Fit with 177 obs now (1606.06693 Berthier, Bjorn, MT). Key is to add the "TGC data" in the SMEFT correctly.
- Interesting subtlety is how these processes are defined, in a double pole approximation around the resonances:

$$\mathcal{A}(s_{12}, s_{34}) = \frac{1}{s_{12} - \bar{m}_W^2} \frac{1}{s_{34} - \bar{m}_W^2} \mathrm{DR}[s_{12}, s_{34}, \Omega] + \frac{1}{s_{12} - \bar{m}_W^2} \mathrm{SR}_1[s_{12}, s_{34}, d\Omega], \\ + \frac{1}{s_{34} - \bar{m}_W^2} \mathrm{SR}_2[s_{12}, s_{34}, d\Omega] + \mathrm{NR}[s_{12}, s_{34}, d\Omega].$$

Need to include $\frac{\delta m_W^2}{\hat{m}_W^2} = \frac{c_{\hat{\theta}} s_{\hat{\theta}}}{(c_{\hat{\theta}}^2 - s_{\hat{\theta}}^2)\, 2\sqrt{2} \hat{G}_F} \left[4 C_{HWB} + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} C_{HD} + 4 \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C_{Hl}^{(3)} - 2 \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C_{ll} \right].$

when fixing $s_{12} = s_{34} = \bar{m}_W^2$ the shift of the pole in the SMEFT itself.

- As not using Mw as input still not ideal as an expansion in the prop.

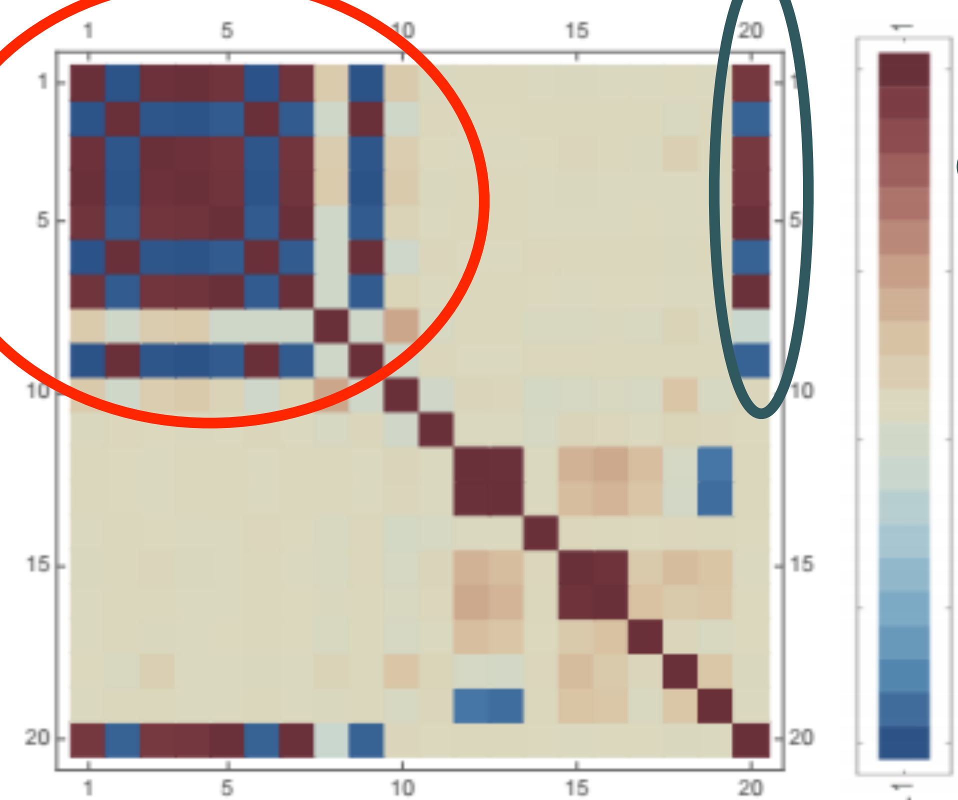
Global constraints on dim 6-update

- The Wilson coefficient constraints are highly correlated

arXiv:1606.06693 Berthier, Bjorn, Trott

Z vertex corrections LEP I

TGC vertex corrections LEPII



Order of magnitude improvement on these TGC parameter extractions at LHC (maybe)

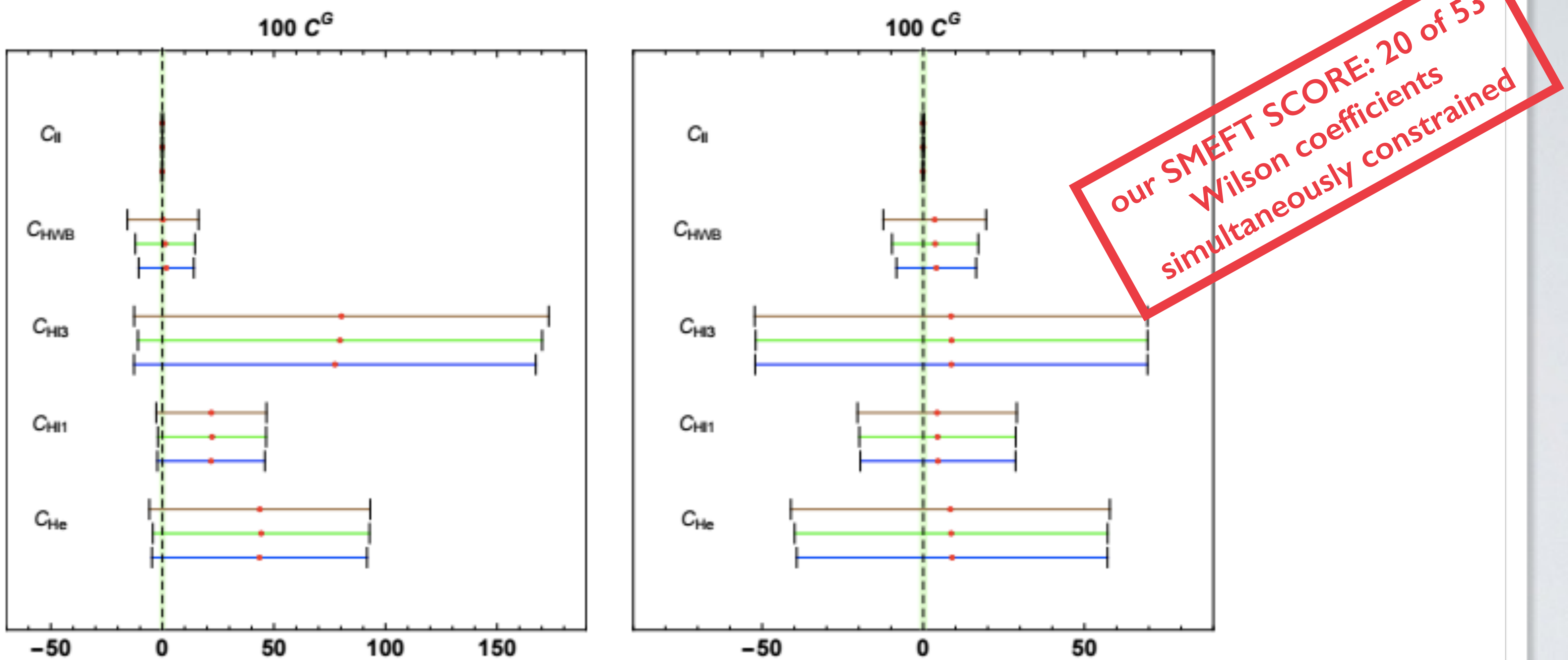
arXiv:1511.08188 Corbett et al.
arXiv:1604.03105 Butter et al.

Figure 5: Color map of the correlation matrix between the Wilson coefficients when there is no SMEFT error.The Wilson coefficients are ordered as in Eqn.3.6.

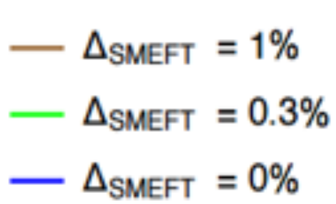
- UV assumptions or sloppy TGC bound treatment can have HUGE effect on the fit space once profiled down.

Global constraints on dim 6-update

- Summary Warsaw basis profiling down to 1 coeff at a time 2 sigma:



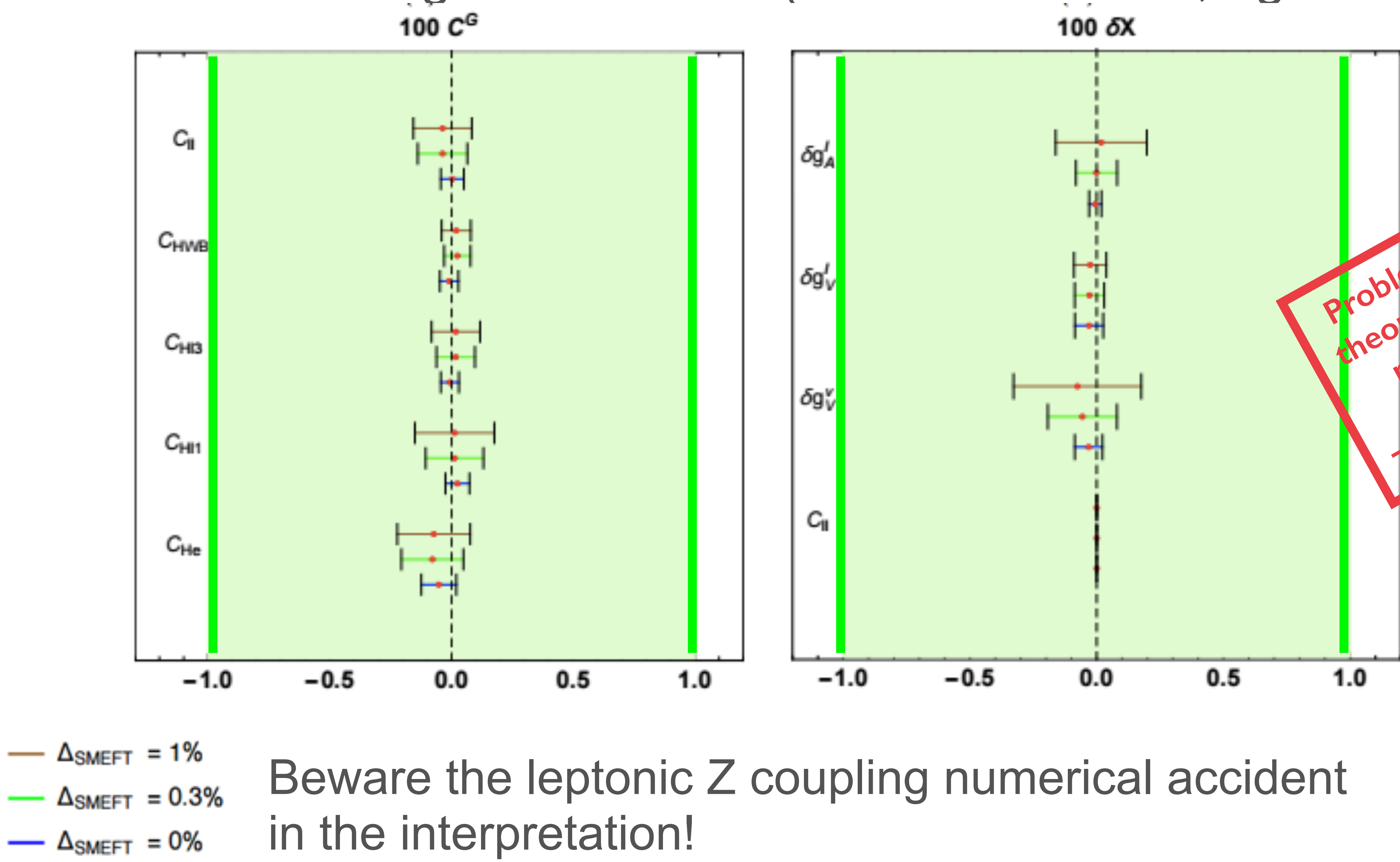
arXiv:1606.06693 Berthier, Bjorn, Trott



- theory error does not impact significantly when cancelations/tunings allowed, so weak constraints

Global constraints on dim 6-update

- When not allowing cancelations (left one at a time, right mass eigen.)



Problems here are theory correlations, naive th error, and the leptonic Z coupling accident.

Beware the leptonic Z coupling numerical accident in the interpretation!

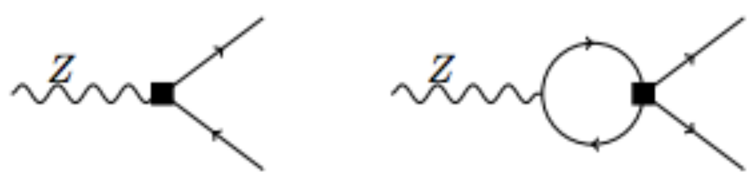
arXiv:1606.06693 Berthier, Bjorn, Trott

Why are calculations at NLO being done?

- It is required to study constraints at many different scales to constrain all the parameters in the LO SMEFT model independently.

  Hierarchies of constraints exist. At higher scales different combinations of parameters present due to NLO effects.

arXiv:1310.4838 Jenkins, Manohar, Trott



$$\mu \frac{d}{d\mu} C^{(1)}_{\substack{Hl \\ rs}} = \frac{1}{48\pi^2} g_1^2 \mathsf{y}_H \Big(\mathsf{y}_H C^{(1)}_{\substack{Hl \\ rs}} + N_c \mathsf{y}_d C_{\substack{ld \\ rsww}} + \mathsf{y}_e C_{\substack{le \\ rsww}} + 2\mathsf{y}_l C_{\substack{ll \\ rsww}} + \mathsf{y}_l C_{\substack{ll \\ rwws}} + \mathsf{y}_l C_{\substack{ll \\ wsrw}} + 2\mathsf{y}_l C_{\substack{ll \\ wwrs}} + 2N_c \mathsf{y}_q C^{(1)}_{\substack{lq \\ rsww}} + N_c \mathsf{y}_u C_{\substack{lu \\ rsww}} \Big).$$

Constraints of effective Z coupling at one scale a combination of effective Z coupling and 4 lepton operators at different scales.

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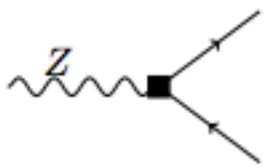

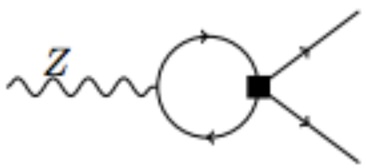

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  Constraints of effective Z coupling at one scale a combination of effective Z coupling and 4 lepton operators at different scales.

  Naive LO analysis just imposes the strongest constraint!

  But <u>completely unconstrained directions in 4 lepton operators</u> (Falkowski,Mimouni 1511.07434)
  A consistent NLO treatment gets that right, and informs the theory error for the LO result.

Percent/per-mille precision need loops

We need loops for the SMEFT for future precision program to reduce theory error. So renormalize SMEFT as first step.

- We know the Warsaw basis is self consistent at one loop as it has been completely renormalized - DONE!

  arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott
  arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott
  arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

- Some partial results were also obtained in a “SILH basis”

  arXiv:1302.5661, 1308.1879 Elias-Miro, Espinosa, Masso, Pomarol
  1312.2928 Elias-Miro, Grojean, Gupta, Marzocca

- Recent results obtained in alternate scheme approach:

  arXiv:1505.03706 Ghezzi, Gomez-Ambrosio, Passarino, Uccirati

Assume deviation h to gam gam: then what?

- Maybe a part of the 3 loop result in the SM is needed. It will be checked out.

- Maybe an operator that contributes at tree level or one loop has modified the decay.

Signal strength modified as: $\mu_{\gamma\gamma} = |1 + \frac{A_{h\gamma\gamma}}{A^{SM}_{h\gamma\gamma}}|^2$

$$\frac{A_{h\gamma\gamma}}{A^{SM}_{h\gamma\gamma}} \simeq 16\,\pi^2 \left(\Sigma_i\, f_i\, C^{tree}_{NP,i} + \frac{\Sigma_j\, f_j\, C^{loop}_{NP,j}}{16\,\pi^2} \right) \frac{v^2}{\Lambda^2}$$

Three operators in chosen basis.

Thirteen more operators in chosen basis in the U(3)^5 limit

$$C^{tree,NP}_{\gamma\gamma} = C_{HW} + C_{HB} - C_{HWB}$$

$$\begin{aligned}
\mathcal{O}^{(0)}_{HB} &= g_1^2\, H^\dagger\, H\, B_{\mu\nu}\, B^{\mu\nu}, \\
\mathcal{O}^{(0)}_{HW} &= g_2^2\, H^\dagger\, H\, W^a_{\mu\nu}\, W^{\mu\nu}_a, \\
\mathcal{O}^{(0)}_{HWB} &= g_1\, g_2\, H^\dagger\, \sigma^a H\, B_{\mu\nu}\, W^{\mu\nu}_a,
\end{aligned}$$

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Thirteen more operators in chosen basis in the U(3)^5 limit

$$\mathcal{O}^{(0)}_{\substack{eW\\rs}} = g_2\,\bar{l}_{r,a}\sigma^{\mu\nu}\,e_s\,\tau^I_{ab}\,H_b\,W^I_{\mu\nu}, \quad \mathcal{O}^{(0)}_{\substack{eB\\rs}} = g_1\,\bar{l}_{r,a}\sigma^{\mu\nu}\,e_s\,H_a\,B_{\mu\nu}, \quad \mathcal{O}^{(0)}_{\substack{uW\\rs}} = g_2\,\bar{q}_{r,a}\sigma^{\mu\nu}\,u_s\,\tau^I_{ab}\,\tilde{H}_b\,W^I_{\mu\nu},$$

$$\mathcal{O}^{(0)}_{\substack{uB\\rs}} = g_1\,\bar{q}_{r,a}\sigma^{\mu\nu}\,u_s\,\tilde{H}_a\,B_{\mu\nu}, \quad \mathcal{O}^{(0)}_{\substack{dW\\rs}} = g_2\,\bar{q}_{r,a}\sigma^{\mu\nu}\,d_s\,\tau^I_{ab}\,H_b\,W^I_{\mu\nu}, \quad \mathcal{O}^{(0)}_{\substack{dB\\rs}} = g_1\,\bar{q}_{r,a}\sigma^{\mu\nu}\,d_s\,H_a\,B_{\mu\nu},$$

$$\mathcal{O}^{(0)}_{\substack{eH\\pr}} = H^\dagger H(\bar{l}_p e_r H), \quad \mathcal{O}^{(0)}_{\substack{uH\\pr}} = H^\dagger H(\bar{q}_p u_r \tilde{H}), \quad \mathcal{O}^{(0)}_{\substack{dH\\pr}} = H^\dagger H(\bar{q}_p d_r H),$$

$$\mathcal{O}^{(0)}_{H} = (H^\dagger H)^3, \quad \mathcal{O}^{(0)}_{H\Box} = H^\dagger H \Box (H^\dagger H), \quad \mathcal{O}^{(0)}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H),$$

$$\mathcal{O}^{(0)}_{W} = g_2^3\,\epsilon_{abc} W^{a\nu}_{\mu} W^{b\rho}_{\nu} W^{c\mu}_{\rho}.$$

Assume deviation: then what?

- Maybe a part of the 3 loop result in the SM is needed. It will be checked out.
- Maybe an operator that contributes at tree level or one loop has modified the decay.

Signal strength modified as: $\mu_{\gamma\gamma} = |1 + \frac{A_{h\gamma\gamma}}{A^{SM}_{h\gamma\gamma}}|^2$

$$\frac{A_{h\gamma\gamma}}{A^{SM}_{h\gamma\gamma}} \simeq 16\,\pi^2 \left(\Sigma_i\, f_i\, C^{tree}_{NP,i} + \frac{\Sigma_j\, f_j\, C^{loop}_{NP,j}}{16\,\pi^2} \right) \frac{v^2}{\Lambda^2}$$

Three operators in chosen basis.

$$C^{tree,NP}_{\gamma\gamma} = C_{HW} + C_{HB} - C_{HWB}$$

Thirteen more operators in chosen basis in the U(3)^5 limit

To be able to robustly follow a hint in the SMEFT we want to be able to accommodate

$$C^{tree}_{NP} \sim C^{loop}_{NP}, \qquad C^{tree}_{NP} \lesssim C^{loop}_{NP}, \qquad C^{loop}_{NP} \lesssim C^{tree}_{NP}$$

So we need to do the one loop correction to capture some of these cases.
Idea of SMEFT: avoid theory bigotry, treat all possible SM deviations equally as a consistent EFT to avoid missing anything.

SMEFT counter-terms feeding in.

- Here is how this works in $\Gamma(h \to \gamma\,\gamma)$, need mixing with the "tree" level operators
  Defining the basis of operators as

$$\mathcal{O}_i = (\mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_W, \mathcal{O}_{eB}, \mathcal{O}^*_{eB}, \mathcal{O}_{uB}, \mathcal{O}^*_{uB}, \mathcal{O}_{dB}, \mathcal{O}^*_{dB}, \mathcal{O}_{eW}, \mathcal{O}^*_{eW}, \mathcal{O}_{uW}, \mathcal{O}^*_{uW}, \mathcal{O}_{dW}, \mathcal{O}^*_{dW})$$

$$\begin{aligned}\mathcal{L}_6^{(0)} &= Z_{SM}\, Z_{i,j}\, C_i\, \mathcal{O}_j^{(r)}, \\ &= Z_{SM}\, N_{HB}\, \mathcal{O}_{HB}^{(r)} + Z_{SM}\, N_{HW}\, \mathcal{O}_{HW}^{(r)} + Z_{SM}\, N_{HWB}\, \mathcal{O}_{HWB}^{(r)}.\end{aligned}$$

- 3x3 sub-matrix of ops that contribute at tree level and first at one loop

$$Z_{i,j} = \frac{1}{16\,\pi^2} \begin{pmatrix} \frac{g_1^2}{4} - \frac{9g_2^2}{4} + 6\lambda + Y & 0 & g_1^2 \\ 0 & -\frac{3g_1^2}{4} - \frac{5g_2^2}{4} + 6\lambda + Y & g_2^2 \\ \frac{3g_2^2}{2} & \frac{g_1^2}{2} & -\frac{g_1^2}{4} + \frac{9g_2^2}{4} + 2\lambda + Y \end{pmatrix}$$

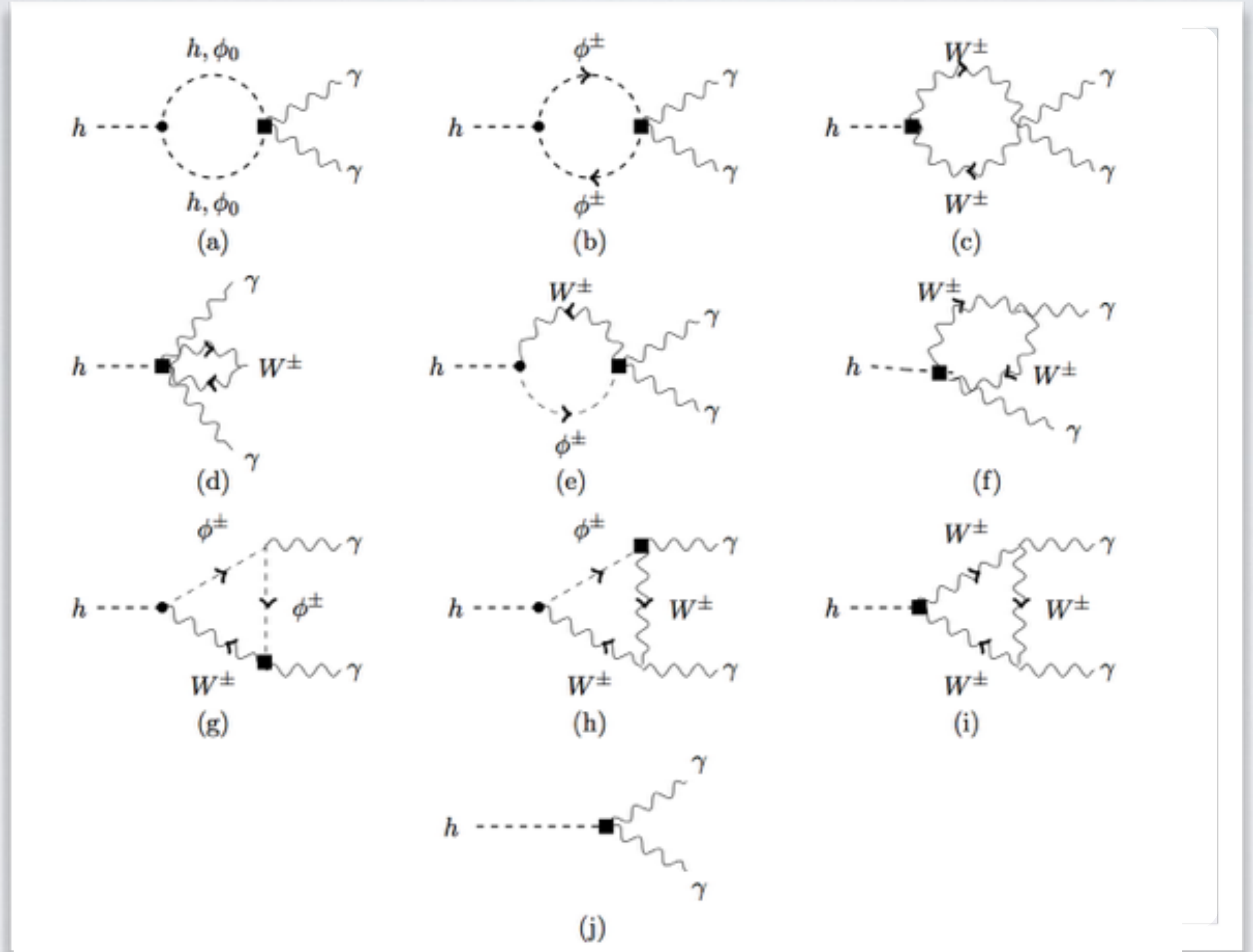
$$\begin{pmatrix} 0 & -\frac{15}{2}\, g_2^4 & \frac{3}{2}\, g_2^4 \\ -(y_l + y_e)\, Y_e & 0 & -\frac{1}{2}\, Y_e \\ -(y_l + y_e)\, Y_e^\dagger & 0 & -\frac{1}{2}\, Y_e^\dagger \\ -N_c\,(y_q + y_u)\, Y_u & 0 & \frac{1}{2}\, N_c\, Y_u \\ -N_c\,(y_q + y_u)\, Y_u^\dagger & 0 & \frac{1}{2}\, N_c\, Y_u^\dagger \\ -N_c\,(y_q + y_d)\, Y_d & 0 & -\frac{1}{2}\, N_c\, Y_d \\ -N_c\,(y_q + y_d)\, Y_d^\dagger & 0 & -\frac{1}{2}\, N_c\, Y_d^\dagger \\ 0 & -\frac{1}{2}\, Y_e & -(y_l + y_e)\, Y_e \\ 0 & -\frac{1}{2}\, Y_e^\dagger & -(y_l + y_e)\, Y_e^\dagger \\ 0 & -\frac{1}{2}\, N_c\, Y_u & N_c\,(y_q + y_u)\, Y_u \\ 0 & -\frac{1}{2}\, N_c\, Y_u^\dagger & N_c\,(y_q + y_u)\, Y_u^\dagger \\ 0 & -\frac{1}{2}\, N_c\, Y_d & -N_c\,(y_q + y_d)\, Y_d \\ 0 & -\frac{1}{2}\, N_c\, Y_d^\dagger & -N_c\,(y_q + y_d)\, Y_d^\dagger \end{pmatrix}$$

arXiv:1301.2588, 1308.2627, 1310.4838, 1312.2014

- note that this counter-term subtraction is proportional to v

The required loops.

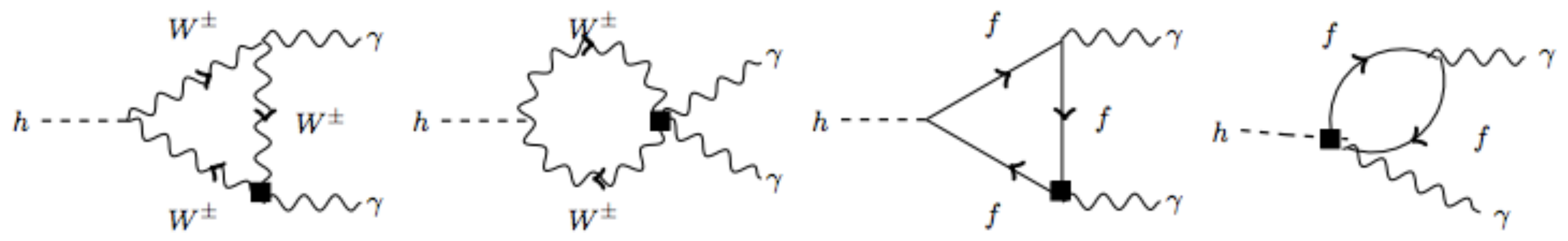
- Calculate in BF method, in R_ξ gauge, for operators that contribute at tree level



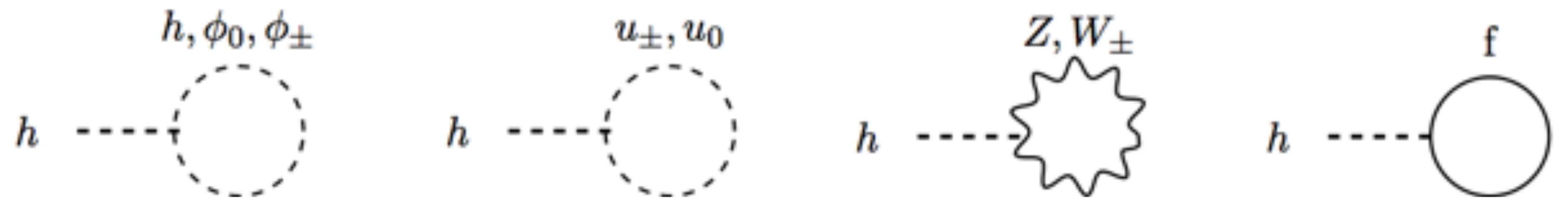
- Gauge dependence cancels ☑ remaining divergences cancel exactly ☑

The required loops.

- Calculate in BF method, in R_ξ gauge, for operators that contribute at loop level only



- Define vev of the theory as the one point function vanishing - fixes δv



$$
\begin{aligned}
T = \; m_h^2 \, h \, v \, \frac{1}{16\pi^2} \Bigg[& -16\pi^2 \frac{\delta v}{v} + 3\,\lambda \left(1 + \log\left[\frac{\mu^2}{m_h^2}\right]\right) + \frac{m_W^2}{v^2} \xi \left(1 + \log\left[\frac{\mu^2}{\xi\, m_W^2}\right]\right), \\
& + \frac{1}{2} \frac{m_Z^2}{v^2} \xi \left(1 + \log\left[\frac{\mu^2}{\xi\, m_Z^2}\right]\right) - \frac{1}{2} \sum_i y_i^4 \, N_c \frac{1}{\lambda} \left(1 + \log\left[\frac{\mu^2}{m_i^2}\right]\right), \\
& + \frac{g_2^2}{2} \frac{m_W^2}{m_h^2} \left(1 + 3 \log\left[\frac{\mu^2}{m_W^2}\right]\right) + \frac{1}{4} (g_1^2 + g_2^2) \frac{m_Z^2}{m_h^2} \left(1 + 3 \log\left[\frac{\mu^2}{m_Z^2}\right]\right)\Bigg].
\end{aligned}
$$

Finite terms from renorm conditions

- The finite terms that are fixed by renormalization conditions (at one loop) in the theory enter as

$$\langle h(p_h)|S|\gamma(p_a,\alpha),\gamma(p_b,\beta)\rangle_{BSM} = (1+\frac{\delta R_h}{2})\,(1+\delta R_A)\,(1+\delta R_e)^2\, i \sum_{x=a..o} \mathcal{A}_x.$$

Cancels!

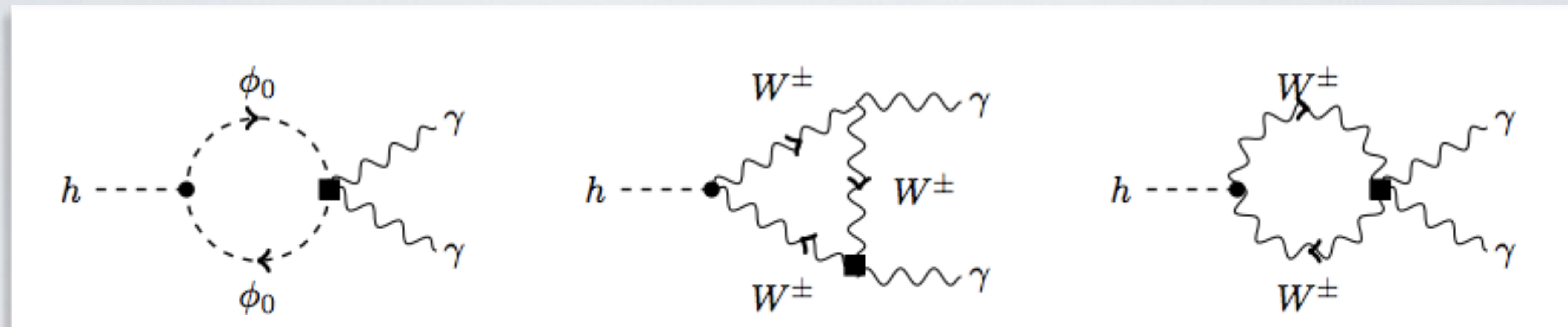
- Remaining finite terms fixed by defining in renormalization conditions on the couplings and two point function residues and poles

$$\delta R_h = -\frac{\partial \Pi_{hh}(p^2)}{\partial p^2}|_{p^2=m_h^2} \qquad \delta R_e = -\frac{1}{2}\delta R_A,$$

This relation follows from a Ward identity using BFM.

SMEFT gauge fixing issues.

- Some interesting subtleties in the SMEFT. Consider



- These terms give divergences proportional to v^2 but counter-terms all come in proportional to v. So what is going on?

- Resolution of this issue is to rethink gauge fixing

$$\mathcal{L}_{GF} = -\frac{1}{2\,\xi_W}\sum_a \left[\partial_\mu W^{a,\mu} - g_2\,\epsilon^{abc}\hat{W}_{b,\mu}W_c^\mu + i\,g_2\,\frac{\xi}{2}\left(\hat{H}_i^\dagger \sigma^a_{ij} H_j - H_i^\dagger \sigma^a_{ij}\hat{H}_j\right)\right]^2,$$

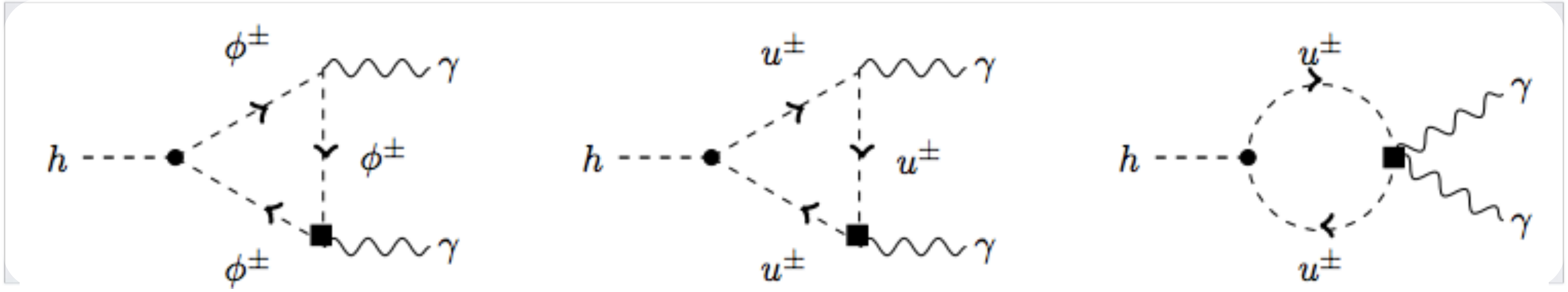
$$-\frac{1}{2\,\xi_B}\left[\partial_\mu B^\mu + i\,g_1\,\frac{\xi}{2}\left(\hat{H}_i^\dagger H_i - H_i^\dagger \hat{H}_i\right)\right]^2.$$

SMEFT gauge fixing issues.

- The fields are redefined at each order in the power counting, this leads to the appearance of L6 Wilson coefficients in the gauge fixing term.

$$\mathcal{L}_{FP} = -\bar{u}^\alpha \frac{\delta G^\alpha}{\delta \theta^\beta} u^\beta.$$

Some operators in $\mathcal{L}_6$ then source ghosts!



- This cancels the unusual divergences exactly.
- The mismatch of the mass eigenstates in the SMEFT with the SM means gauge fixing in the former also results in some interesting local contact operators

$$-\frac{c_w\, s_w}{\xi_B\, \xi_W}(\xi_B - \xi_W)\,(\partial^\mu A_\mu\, \partial^\nu Z_\nu) - \frac{C_{HWB} v^2 (s_w^2 - c_w^2)(s_w^2 \xi_B + c_w^2 \xi_W)}{\xi_B\, \xi_W}\,(\partial^\mu A_\mu\, \partial^\nu Z_\nu)\,.$$

NLO EFT - Final tree result

1505.02646, 1507.03568 Hartmann, Trott
1505.03706 Ghezzi et al.

- The final result is of the form

$$
\begin{aligned}
\frac{i\,\mathcal{A}^{NP}_{total}}{i\,v\,e^2\,A^{h\gamma\gamma}_{\alpha\beta}} &= C_{\gamma\gamma}\left(1+\frac{\delta R_h}{2}+\frac{\delta v}{v}\right), \\
&+\left(\frac{C_{\gamma\gamma}}{16\,\pi^2}\left(\frac{g_1^2}{4}+\frac{3\,g_2^2}{4}+6\,\lambda\right)+\frac{C_{HWB}}{16\,\pi^2}\left(-3\,g_2^2+4\,\lambda\right)\right)\log\left(\frac{m_h^2}{\Lambda^2}\right), \\
&+\frac{C_{\gamma\gamma}}{16\,\pi^2}\left(\left(\frac{g_1^2}{4}+\frac{g_2^2}{4}+\lambda\right)\mathcal{I}[m_Z^2]+\left(\frac{g_2^2}{2}+2\lambda\right)\mathcal{I}[m_W^2]+(\sqrt{3}\,\pi-6)\,\lambda\right), \\
&+\frac{C_{HWB}}{16\,\pi^2}\left(2e^2\left(1+6\frac{m_W^2}{m_h^2}\right)-2\,g_2^2\left(1+\log\left(\frac{m_W^2}{m_h^2}\right)\right)+\left(4\,\lambda-g_2^2\right)\mathcal{I}[m_W^2],\right. \\
&\qquad\left.+4\left(3e^2-g_2^2-6e^2\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right), \\
&-\frac{g_2^2\,C_{HW}}{4\,\pi^2}\left(3\,\frac{m_W^2}{m_h^2}+\left(4-\frac{m_h^2}{m_W^2}-6\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right). \quad +\cdots \qquad (3.6)
\end{aligned}
$$

$$C^{NP}_{\gamma\gamma} = C_{HB} + C_{HW} - C_{HWB}$$

- <u>The RGE is not a good proxy for the full one loop structure of the SMEFT. Logs simply not that big before decoupling region.</u>

Do we need this SMEFT NLO?

- Developing the SMEFT lets you reduce theory errors in the future.
- For the current precision it is not a disaster to not have it:

Hartmann, Trott 1507.03568

Correcting tree level conclusion for 1 loop neglected effects
errors introduced added in quadrature, $C_i \sim 1$:

Current data for: $-0.02 \leq \left(\hat{C}^{1,NP}_{\gamma\gamma} + \frac{\hat{C}^{NP}_i f_i}{16\,\pi^2}\right) \frac{\bar{v}_T^2}{\Lambda^2} \leq 0.02.$

$\Lambda = 800\,\mathrm{GeV}$ $\Lambda = 3000\,\mathrm{GeV}$

$\kappa_\gamma = 0.93^{+0.36}_{-0.17}$ ATLAS data - naive map to C corrected $[29, 4]\,\%$

$\kappa_\gamma = 0.98^{+0.17}_{-0.16}$ CMS data - naive map to C corrected $[52, 7]\,\%$

- The future precision Higgs phenomenology program clearly needs it:

$\kappa_\gamma^{proj:RunII} = 1 \pm 0.045$ - naive map to C (tree level) corrected $[167, 21]\,\%$

$\kappa_\gamma^{proj:HILHC} = 1 \pm 0.03$ $[250, 31]\,\%$

$\kappa_\gamma^{proj:TLEP} = 1 \pm 0.0145$ $[513, 64]\,\%$

Big effect as new parameters at one loop not present at tree level

Conclusions

- Exploiting the poles of the SM with the upcoming data set using SMEFT analyses can AND SHOULD be done, with the consistent EFT.

- Enormous work to just do this at tree level for LHC. Not necessarily enough. Also need NLO results for the most precise observables in some UV. (and to cancel scheme dependence on other less precise observables

- Era of NLO SMEFT results has now been kicked off:
  - Pioneering full calculation $\mu \rightarrow e\,\gamma$ Pruna, Signer arXiv:1408.3565
  - Other processes tacked in 1505.03706 Ghezzi et al. (partial EW precision)
  - Partial $\Gamma(h \rightarrow f\,\bar{f})$ R. Gauld, B. D. Pecjak and D. J. Scott, arXiv:1512.02508,1607.06354
  - QCD corrections partial SMEFT P. Artoisenet et. al., arXiv:1306.6464
  - QCD NLO Higgs associated production K. Mimasu, et al. arXiv:1512.02572
  - QCD NLO Higgs+ 2 t pair production F. Maltoni et al. 1607.05330
  - QCD NLO Higgs pair production R. Grober et al. arXiv:1504.0657
  - QCD NLO single top production C.Zhang, arXiv:1512.02508

If interested in this EFT for LHC

HEFT - 2016 will be at Copenhagen Oct 26th-28th

https://indico.nbi.ku.dk/conferenceDisplay.py?confId=855

you are invited to come (back)…

P.S. Higgs data

Atlas/CMS: https://arxiv.org/pdf/1606.02266v1.pdf

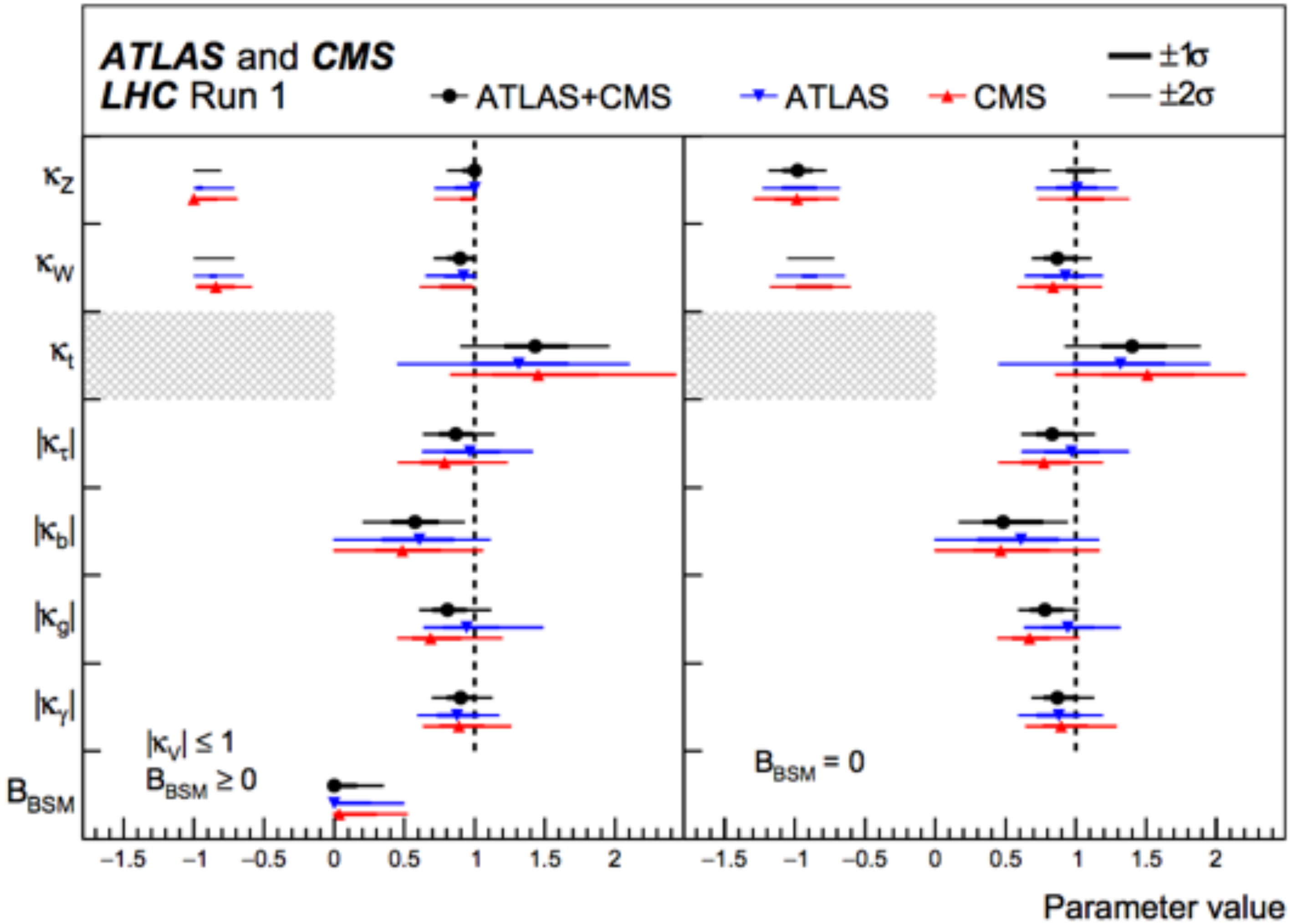


Figure 15: Fit results for two parameterisations allowing BSM loop couplings discussed in the text: the first one assumes that $B_{BSM} \geq 0$ and that $|\kappa_V| \leq 1$, where κ_V denotes κ_Z or κ_W, and the second one assumes that there are no additional BSM contributions to the Higgs boson width, i.e. $B_{BSM} = 0$. The measured results for the combination of ATLAS and CMS are reported together with their uncertainties, as well as the individual results from each experiment. The hatched areas show the non-allowed regions for the κ_t parameter, which is assumed to be positive without loss of generality. The error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals. When a parameter is constrained and reaches a boundary, namely $|\kappa_V| = 1$ or $B_{BSM} = 0$, the uncertainty is not defined beyond this boundary. For those parameters with no sensitivity to the sign, only the absolute values are shown.