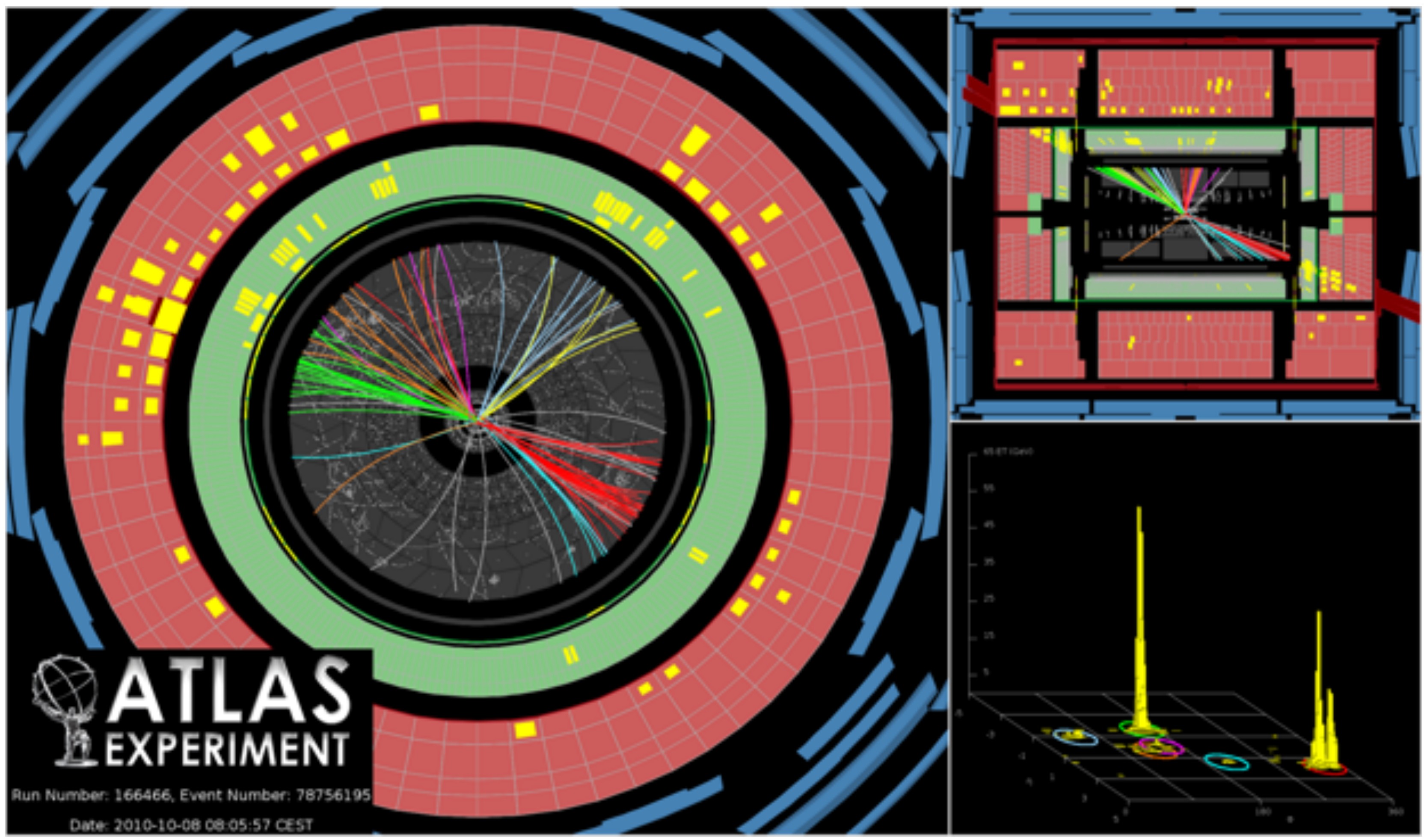
Probing the SM with dijets @ LHC

Javi Serra
(Cornell University)



Planck12
May 30, 2012

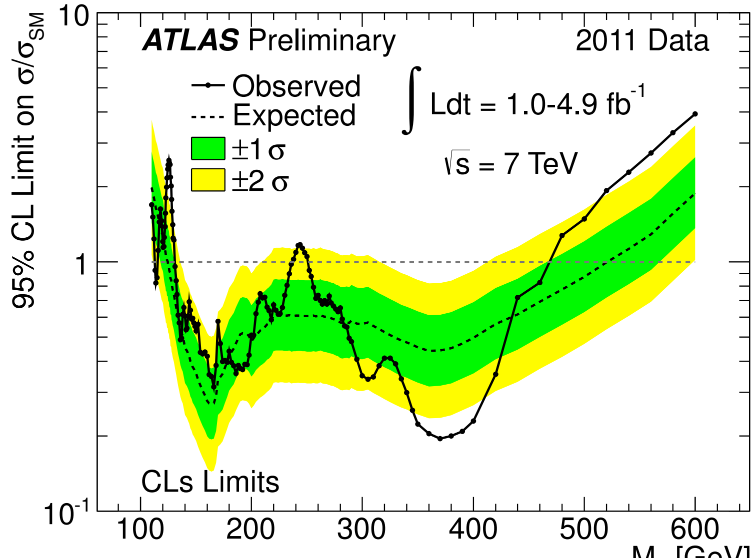
Outline

- **Motivation** (EW & flavor physics)
- **Approach** (EFT)
- **Pre-LHC** (past results)
- **LHC updates** (present results)

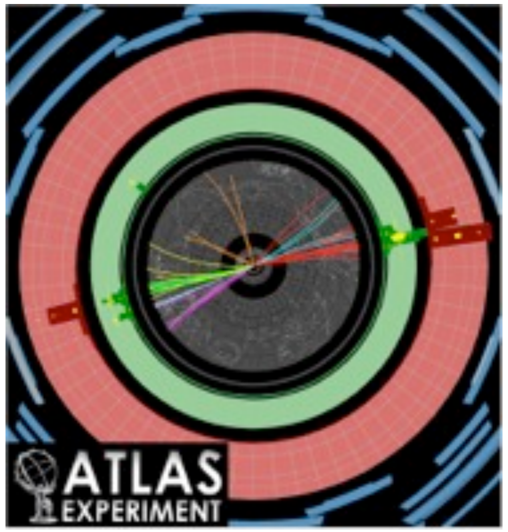
updated results of a collaboration with O.Domenech and A.Pomarol (1201.6510)

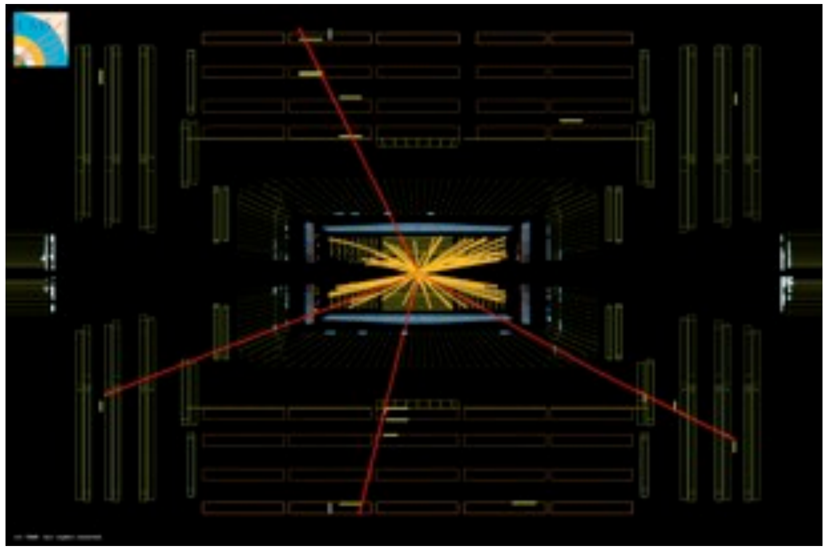
At LHC: elementary or composite?

The LHC is taking data:



(a)





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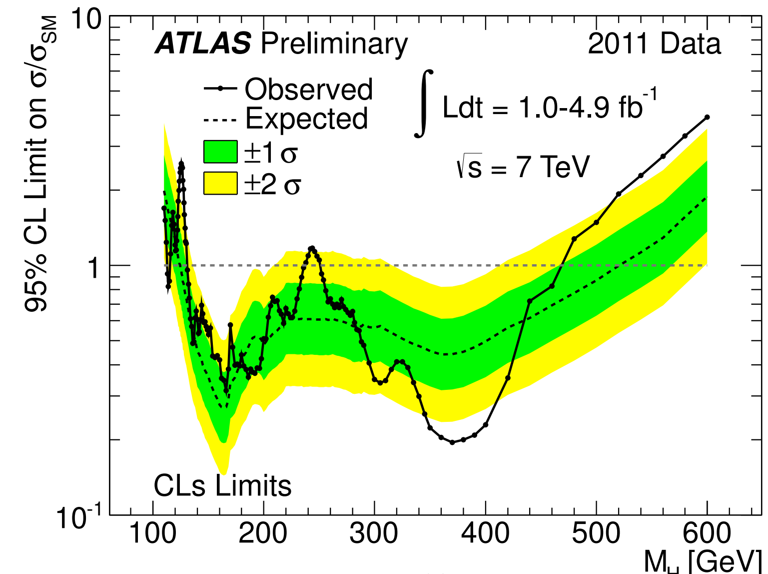

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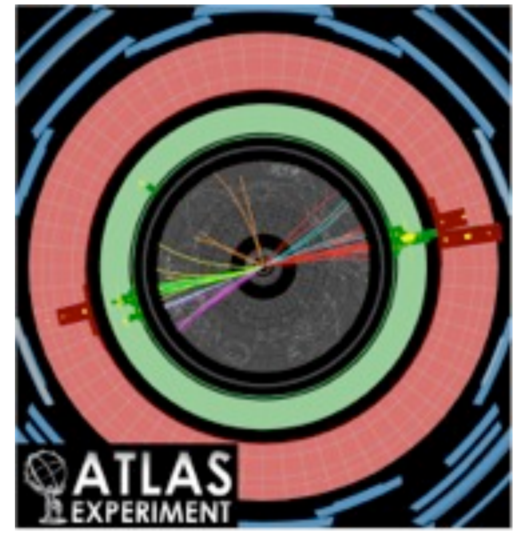
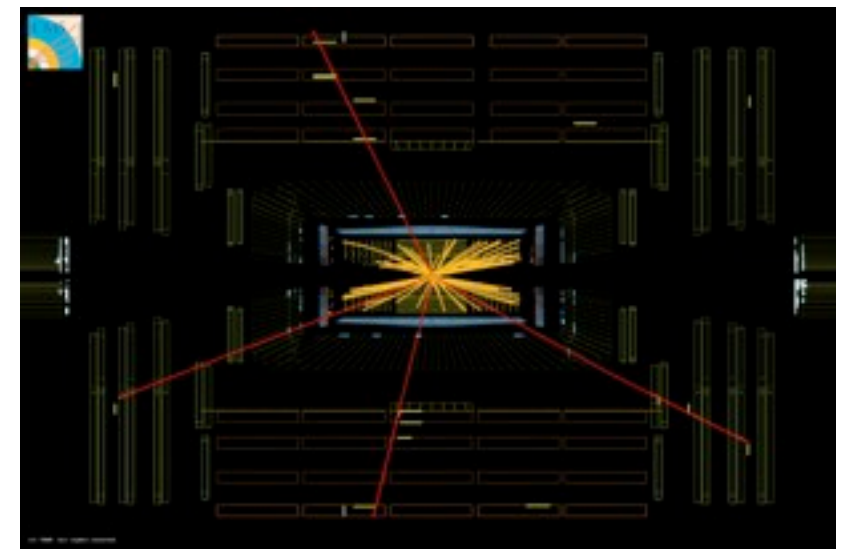
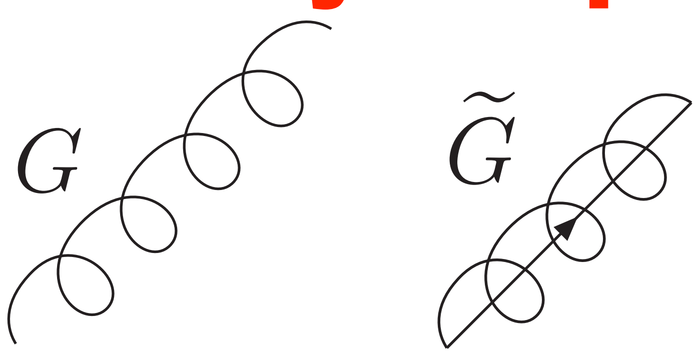




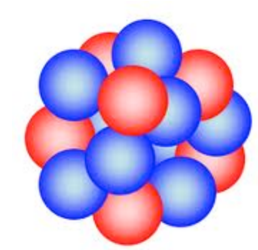
?

Weakly coupled



Supersymmetry

Strongly coupled

$H \sim$ 

Compositeness

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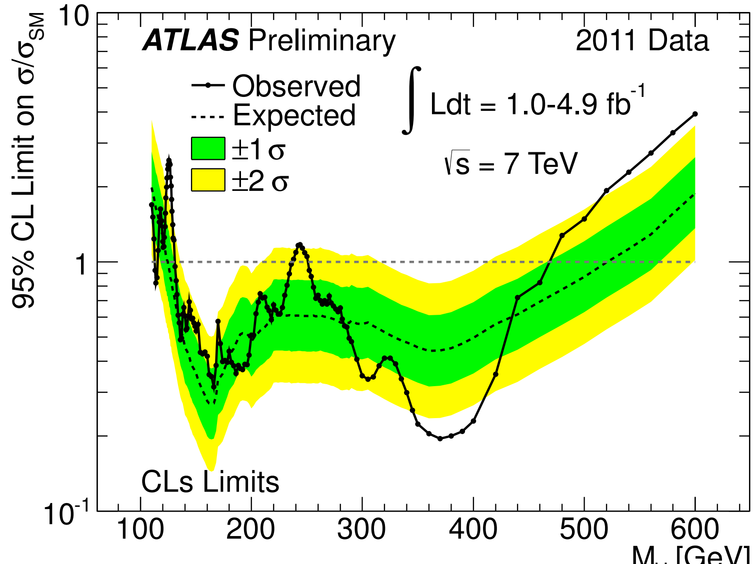

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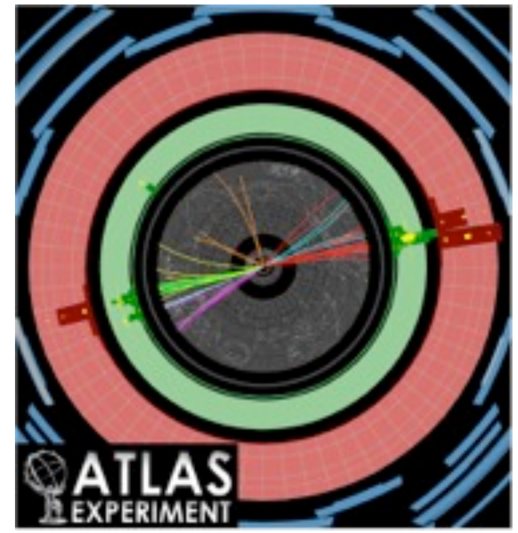

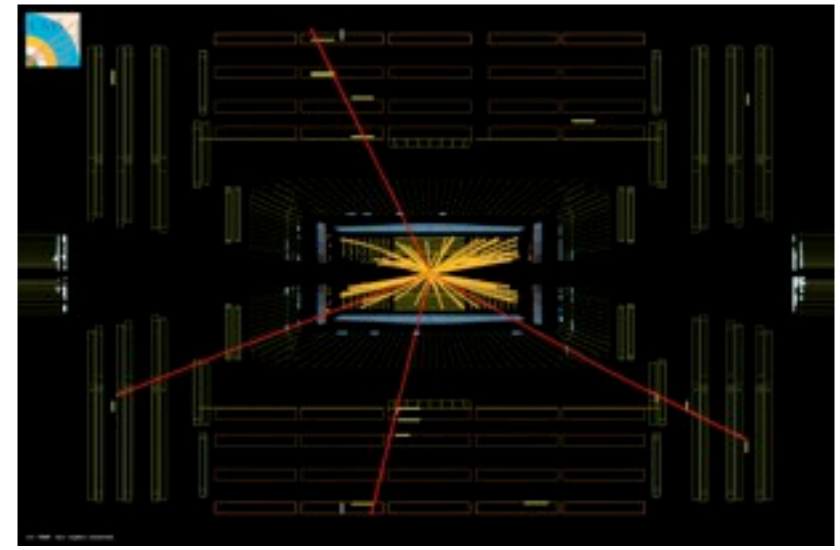

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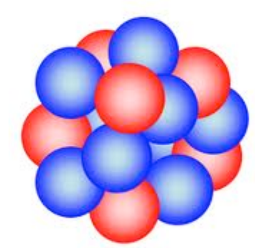
$$H \sim$$ 

Compositeness

Why at the LHC? hierarchies

The hierarchy problem motivation:

$$m_W \overset{?}{\ll} \Lambda$$

from an effective field theory perspective:

$$\mathcal{L}_{eff} \sim \Lambda^2 |H|^2 + Y_d \, \bar{q}_L H d_R + \ldots + \sum_{i,d>4} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_d^i$$

$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

why?

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why?

$$m_u \ll m_c \ll m_t \sim v$$

$$\Lambda > 10^{2-5}\,\mathrm{TeV}$$

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natural expectation

$$\Lambda \sim \mathrm{TeV}$$

scale of New Physics BSM

What is composite? Higgs and top

assume there is a **new strongly-interacting sector** with, due to naturalness arguments, a **compositeness scale**:

$$\Lambda \sim \mathrm{TeV}$$

does any of SM particles belong to this sector?

in "old" examples: **Technicolor:** $W_L\,,\, Z_L$

MSSM: none

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~~**MSSM**: $none$~~

in "modern" scenarios:

Composite Higgs: $H\,, top$

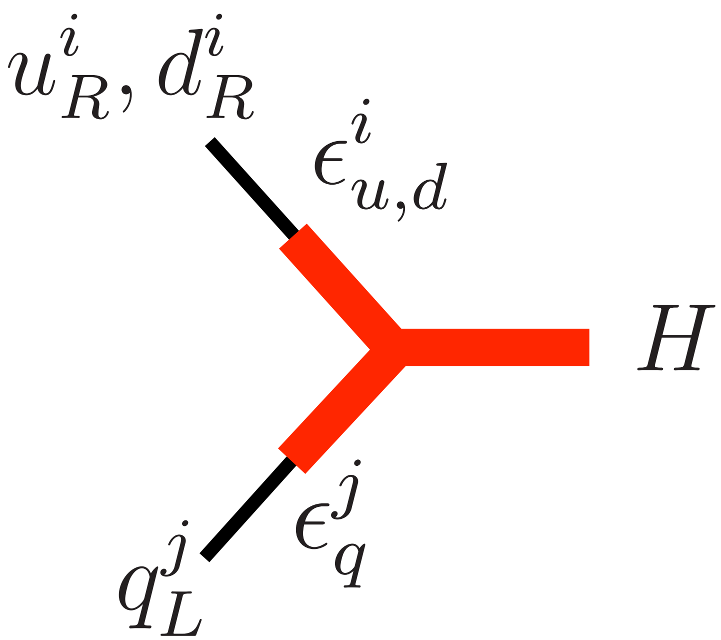
Composite natural SUSY: $H\,, top$

Anything else? from Flavor

one of the two (?) known mechanisms to generate flavor

partial compositeness

$$\mathcal{L}_Y = \epsilon_u^i u_R^i \mathcal{O}_u + \epsilon_d^i d_R^i \mathcal{O}_d + \epsilon_q^i q_L^i \mathcal{O}_q$$



$$Y_{u,d}^{i,j} \sim \epsilon_q^i \epsilon_{u,d}^j g_\rho \qquad 0 < \epsilon < 1$$

ΔF = 1: $\epsilon_q^i \epsilon_d^j g_\rho \dfrac{v}{\Lambda^2} \dfrac{g_\rho^2}{16\pi^2} \bar{d}_L^i \sigma_{\mu\nu} d_R^j G^{\mu\nu}$

ΔF = 2: $\epsilon_q^i \epsilon_q^j \epsilon_q^k \epsilon_q^\ell \dfrac{g_\rho^2}{\Lambda^2} (\bar{q}^i \gamma_\mu q^j)(\bar{q}^k \gamma^\mu q^\ell)$

Anything else? light quarks

Flavor constraints: $\epsilon_K \longrightarrow \Lambda \gtrsim 20\,\mathrm{TeV}$

$\epsilon'/\epsilon,\ b \to s\gamma$, n-EDM $\longrightarrow \Lambda \gtrsim \dfrac{g_\rho}{4\pi} 20\,\mathrm{TeV}$

partial compositeness does not seem enough...

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(beyond) Minimal Flavor Violation

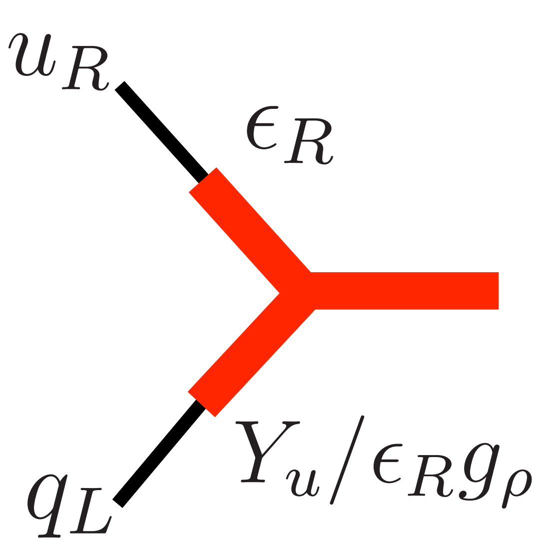
$$U(3)_q \otimes U(3)_d \otimes U(2)_u$$

Barbieri et al.

Redi

we might leave out the RH top

only broken by Yukawa couplings:



perturbativity $\longrightarrow$ $\epsilon_R \gtrsim \frac{Y_u}{g_\rho}$

light quarks could be composite!

Approach to compositeness: EFT

Effective Lagrangian:

$$\mathcal{L}_{eff} \sim \Lambda^2 |H|^2 + Y_d\, \bar{q}_L H d_R + \ldots + \sum_{i,d>4} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_d^i$$

i) Extra powers of ∂^2/Λ^2

$$\bar{q}_L \gamma_\mu q_L D_\nu F^{\mu\nu} \ , \quad \bar{q}_L u_R D_\mu D^\mu H \ , \ \ldots$$

ii) Extra powers of $g_\rho^2 \psi^2/\Lambda^2 \equiv \psi^2/f^2$ $\qquad$ $g_\rho =$ coupling of the composite states

$$\frac{c}{f^2}(\bar{q}_L \gamma_\mu q_L)^2 \ , \quad \frac{c}{f^2}(\bar{q}_L \gamma_\mu q_L)(H^\dagger D^\mu H) \qquad c \sim \mathcal{O}(1)$$

$$\boxed{\Lambda \equiv g_\rho f \gg f \Leftrightarrow g_\rho \gg 1}$$

pre-LHC

what do we already know about the compositeness of the SM particles?

pre-LHC

from LEP, SLAC, Tevatron,...

we know a lot about the SM!

$\sqrt{s}$ (GeV)	Quantity	Average value	SM	Δ
130	$\sigma(q\bar{q})$	82.1±2.2	82.8	-0.3
130	$\sigma(\mu^+\mu^-)$	8.62±0.68	8.44	-0.33
130	$\sigma(\tau^+\tau^-)$	9.02±0.93	8.44	-0.11
130	$A_{FB}(\mu^+\mu^-)$	0.694±0.060	0.705	0.012
130	$A_{FB}(\tau^+\tau^-)$	0.663±0.076	0.704	0.012
136	$\sigma(q\bar{q})$	66.7±2.0	66.6	-0.2
136	$\sigma(\mu^+\mu^-)$	8.27±0.67	7.28	-0.28
136	$\sigma(\tau^+\tau^-)$	7.078±0.820	7.279	-0.091
136	$A_{FB}(\mu^+\mu^-)$	0.708±0.060	0.684	0.013
136	$A_{FB}(\tau^+\tau^-)$	0.753±0.088	0.683	0.014
161	$\sigma(q\bar{q})$	37.0±1.1	35.2	-0.1
161	$\sigma(\mu^+\mu^-)$	4.61±0.36	4.61	-0.18
161	$\sigma(\tau^+\tau^-)$	5.67±0.54	4.61	-0.06
161	$A_{FB}(\mu^+\mu^-)$	0.538±0.067	0.609	0.017
161	$A_{FB}(\tau^+\tau^-)$	0.646±0.077	0.609	0.016
172	$\sigma(q\bar{q})$	29.23±0.99	28.74	-0.12
172	$\sigma(\mu^+\mu^-)$	3.57±0.32	3.95	-0.16
172	$\sigma(\tau^+\tau^-)$	4.01±0.45	3.95	-0.05
172	$A_{FB}(\mu^+\mu^-)$	0.675±0.077	0.591	0.018
172	$A_{FB}(\tau^+\tau^-)$	0.342±0.094	0.591	0.017
183	$\sigma(q\bar{q})$	24.59±0.42	24.20	-0.11
183	$\sigma(\mu^+\mu^-)$	3.49±0.15	3.45	-0.14
183	$\sigma(\tau^+\tau^-)$	3.37±0.17	3.45	-0.05
183	$A_{FB}(\mu^+\mu^-)$	0.559±0.035	0.576	0.018
183	$A_{FB}(\tau^+\tau^-)$	0.608±0.045	0.576	0.018
189	$\sigma(q\bar{q})$	22.47±0.24	22.156	-0.101
189	$\sigma(\mu^+\mu^-)$	3.123±0.076	3.207	-0.131
189	$\sigma(\tau^+\tau^-)$	3.20±0.10	3.20	-0.048
189	$A_{FB}(\mu^+\mu^-)$	0.569±0.021	0.569	0.019
189	$A_{FB}(\tau^+\tau^-)$	0.596±0.026	0.569	0.018

$\sqrt{s}$ (GeV)	Quantity	Average value	SM	Δ
192	$\sigma(q\bar{q})$	22.05±0.53	21.24	-0.10
192	$\sigma(\mu^+\mu^-)$	2.92±0.18	3.10	-0.13
192	$\sigma(\tau^+\tau^-)$	2.81±0.23	3.10	-0.05
192	$A_{FB}(\mu^+\mu^-)$	0.553±0.051	0.566	0.019
192	$A_{FB}(\tau^+\tau^-)$	0.615±0.069	0.566	0.019
196	$\sigma(q\bar{q})$	20.53±0.34	20.13	-0.09
196	$\sigma(\mu^+\mu^-)$	2.94±0.11	2.96	-0.12
196	$\sigma(\tau^+\tau^-)$	2.94±0.14	2.96	-0.05
196	$A_{FB}(\mu^+\mu^-)$	0.581±0.031	0.562	0.019
196	$A_{FB}(\tau^+\tau^-)$	0.505±0.044	0.562	0.019
200	$\sigma(q\bar{q})$	19.25±0.32	19.09	-0.09
200	$\sigma(\mu^+\mu^-)$	3.02±0.11	2.83	-0.12
200	$\sigma(\tau^+\tau^-)$	2.90±0.14	2.83	-0.04
200	$A_{FB}(\mu^+\mu^-)$	0.524±0.031	0.558	0.019
200	$A_{FB}(\tau^+\tau^-)$	0.539±0.042	0.558	0.019
202	$\sigma(q\bar{q})$	19.07±0.44	18.57	-0.09
202	$\sigma(\mu^+\mu^-)$	2.58±0.14	2.77	-0.12
202	$\sigma(\tau^+\tau^-)$	2.79±0.20	2.77	-0.04
202	$A_{FB}(\mu^+\mu^-)$	0.547±0.047	0.556	0.020
202	$A_{FB}(\tau^+\tau^-)$	0.589±0.059	0.556	0.019
205	$\sigma(q\bar{q})$	18.17±0.31	17.81	-0.09
205	$\sigma(\mu^+\mu^-)$	2.45±0.10	2.67	-0.11
205	$\sigma(\tau^+\tau^-)$	2.78±0.14	2.67	-0.042
205	$A_{FB}(\mu^+\mu^-)$	0.565±0.035	0.553	0.020
205	$A_{FB}(\tau^+\tau^-)$	0.571±0.042	0.553	0.019
207	$\sigma(q\bar{q})$	17.49±0.26	17.42	-0.08
207	$\sigma(\mu^+\mu^-)$	2.595±0.088	2.623	-0.111
207	$\sigma(\tau^+\tau^-)$	2.53±0.11	2.62	-0.04
207	$A_{FB}(\mu^+\mu^-)$	0.542±0.027	0.552	0.020
207	$A_{FB}(\tau^+\tau^-)$	0.564±0.037	0.551	0.019

Background	% of $W \to \mu\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$Z/\gamma^* \to \mu\mu$	6.6 ± 0.3	6	11	5
$W \to \tau\nu$	0.89 ± 0.02	1	7	8
Decays in flight	0.3 ± 0.2	5	13	3
Hadronic jets	0.1 ± 0.1	2	3	4
Cosmic rays	0.05 ± 0.05	2	2	1
Total	7.9 ± 0.4	9	19	11

without lepton universality	
χ^2/N_{df}	= 32.6/27
m_Z [GeV]	91.1876± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_h [nb]	41.541 ± 0.037
R^0_e	20.804 ± 0.050
R^0_μ	20.785 ± 0.033
R^0_τ	20.764 ± 0.045
$A^{0,e}_{FB}$	0.0145 ± 0.0025
$A^{0,\mu}_{FB}$	0.0169 ± 0.0013
$A^{0,\tau}_{FB}$	0.0188 ± 0.0017

	Lepton non–universality			Lepton universality
Experiment	$\mathcal{B}(W \to e\bar{\nu}_e)$ [%]	$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$ [%]	$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$ [%]	$\mathcal{B}(W \to \text{hadrons})$ [%]
ALEPH	10.81 ± 0.29*	10.91 ± 0.26*	11.15 ± 0.38*	67.15 ± 0.40*
DELPHI	10.55 ± 0.34*	10.65 ± 0.27*	11.46 ± 0.43*	67.45 ± 0.48*
L3	10.78 ± 0.32*	10.03 ± 0.31*	11.89 ± 0.45*	67.50 ± 0.52*
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48	67.91 ± 0.61
LEP	10.66 ± 0.17	10.60 ± 0.15	11.41 ± 0.22	67.49 ± 0.28
χ^2/d.o.f.	6.8/9			15.0/11

$\sqrt{s}$ (GeV)	WW cross-section (pb) ALEPH	DELPHI	L3	OPAL	LEP	χ^2/d.o.f.
161.3	4.23 ± 0.75*	$3.67^{+0.99}_{-0.87}$ *	$2.89^{+0.82}_{-0.71}$ *	$3.62^{+0.94}_{-0.84}$ *	3.69 ± 0.45 *	} 1.3 / 3
172.1	11.7 ± 1.3 *	11.6 ± 1.4 *	12.3 ± 1.4 *	12.3 ± 1.3 *	12.0 ± 0.7 *	} 0.22/ 3
182.7	15.90 ± 0.63*	16.07 ± 0.70*	16.53 ± 0.72*	15.43 ± 0.66*	15.89 ± 0.35 *	26.4/24
188.6	15.76 ± 0.36*	16.09 ± 0.42*	16.17 ± 0.41*	16.30 ± 0.39*	16.03 ± 0.21 *	
191.6	17.10 ± 0.90 *	16.64 ± 1.00*	16.11 ± 0.92 *	16.60 ± 0.99	16.56 ± 0.48	
195.5	16.61 ± 0.54 *	17.04 ± 0.60*	16.22 ± 0.57 *	18.59 ± 0.75	16.90 ± 0.31	
199.5	16.90 ± 0.52 *	17.39 ± 0.57*	16.49 ± 0.58 *	16.32 ± 0.67	16.75 ± 0.30	
201.6	16.65 ± 0.71 *	17.37 ± 0.82*	16.01 ± 0.84 *	18.48 ± 0.92	17.00 ± 0.41	
204.9	16.79 ± 0.54 *	17.56 ± 0.59*	17.00 ± 0.60 *	15.97 ± 0.64	16.78 ± 0.31	
206.6	17.36 ± 0.43 *	16.35 ± 0.47*	17.33 ± 0.47 *	17.77 ± 0.57	17.13 ± 0.25	

Background	% of $W \to e\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$W \to \tau\nu$	0.93 ± 0.03	2	2	2
Hadronic jets	0.25 ± 0.15	8	9	7
$Z/\gamma^* \to ee$	0.24 ± 0.01	1	1	0
Total	1.42 ± 0.15	8	9	7

without lepton universality	
Γ_{had} [MeV]	1745.8 ±2.7
Γ_{ee} [MeV]	83.92±0.12
$\Gamma_{\mu\mu}$ [MeV]	83.99±0.18
$\Gamma_{\tau\tau}$ [MeV]	84.08±0.22

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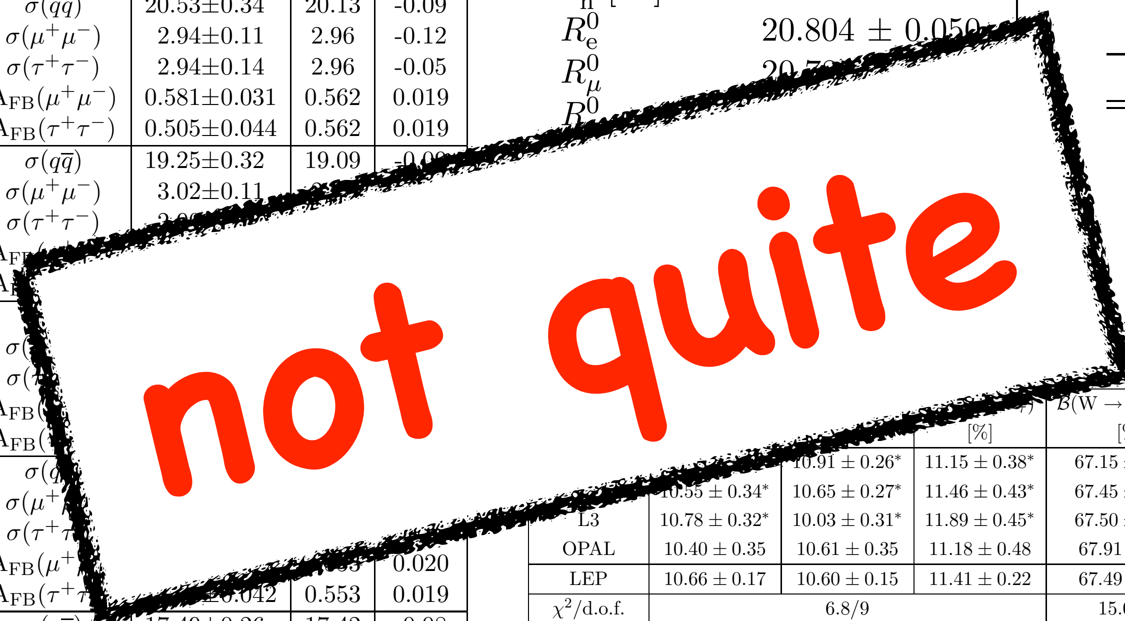
200	[illegible]	[illegible]	[illegible]	[illegible]
202	[illegible]	[illegible]	[illegible]	[illegible]
202	[illegible]	[illegible]	[illegible]	[illegible]
202	[illegible]	[illegible]	[illegible]	[illegible]
202	[illegible]	[illegible]	[illegible]	[illegible]
202	[illegible]	[illegible]	[illegible]	[illegible]
205	[illegible]	[illegible]	[illegible]	[illegible]
205	[illegible]	[illegible]	[illegible]	[illegible]
205	[illegible]	[illegible]	[illegible]	[illegible]
205	[illegible]	[illegible]	[illegible]	0.020
205	[illegible]	[illegible]	0.553	0.019
207	$\sigma(q\overline{q})$	17.49±0.26	17.42	-0.08
207	$\sigma(\mu^+\mu^-)$	2.595±0.088	2.623	-0.111
207	$\sigma(\tau^+\tau^-)$	2.53±0.11	2.62	-0.04
207	$A_{FB}(\mu^+\mu^-)$	0.542±0.027	0.552	0.020
207	$A_{FB}(\tau^+\tau^-)$	0.564±0.037	0.551	0.019

without lepton universality	
$\chi^2/N_{df} = 32.6/27$	
m_Z [GeV]	91.1876± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ_h^0 [nb]	41.541 ± 0.037
R_e^0	20.804 ± 0.050
R_μ^0	[illegible]
R_τ^0	[illegible]

Background	% of $W \to e\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$W \to \tau\nu$	0.93 ± 0.03	2	2	2
Hadronic jets	0.25 ± 0.15	8	9	7
$Z/\gamma^* \to ee$	0.24 ± 0.01	1	1	0
Total	1.42 ± 0.15	8	9	7



[illegible]	[illegible]	[illegible]	[illegible] [%]	$\mathcal{B}$(W → hadrons) [%]
[illegible]	[illegible]	10.91 ± 0.26*	11.15 ± 0.38*	67.15 ± 0.40*
[illegible]	10.55 ± 0.34*	10.65 ± 0.27*	11.46 ± 0.43*	67.45 ± 0.48*
L3	10.78 ± 0.32*	10.03 ± 0.31*	11.89 ± 0.45*	67.50 ± 0.52*
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48	67.91 ± 0.61
LEP	10.66 ± 0.17	10.60 ± 0.15	11.41 ± 0.22	67.49 ± 0.28
χ^2/d.o.f.	6.8/9			15.0/11

without lepton universality	
Γ_{had} [MeV]	1745.8 ±2.7
Γ_{ee} [MeV]	83.92±0.12
$\Gamma_{\mu\mu}$ [MeV]	83.99±0.18
$\Gamma_{\tau\tau}$ [MeV]	84.08±0.22

Background	% of $W \to \mu\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$Z/\gamma^* \to \mu\mu$	6.6 ± 0.3	6	11	5
$W \to \tau\nu$	0.89 ± 0.02	1	7	8
Decays in flight	0.3 ± 0.2	5	13	3
Hadronic jets	0.1 ± 0.1	2	3	4
Cosmic rays	0.05 ± 0.05	2	2	1
Total	7.9 ± 0.4	9	19	11

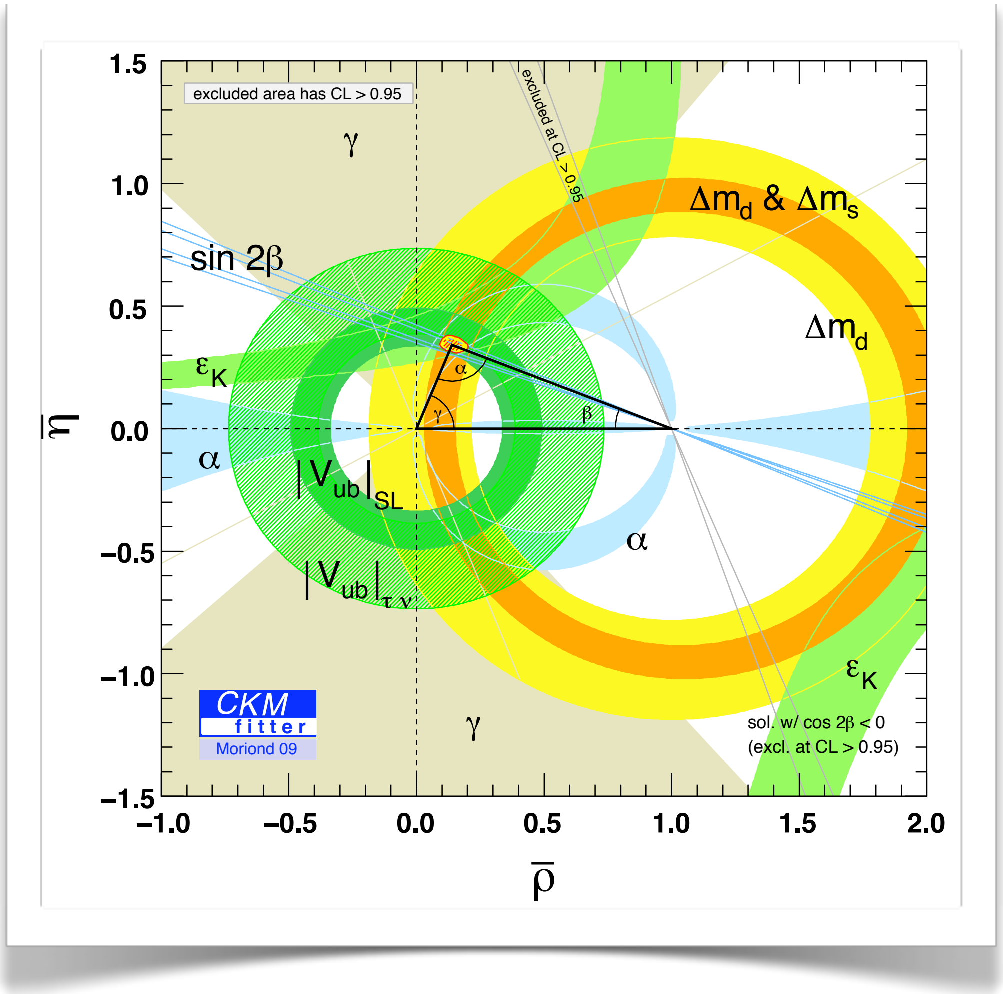
$\sqrt{s}$ (GeV)	WW cross-section (pb) ALEPH	DELPHI	L3	OPAL	LEP	χ^2/d.o.f.
161.3	4.23 ± 0.75*	$3.67\ ^{+0.99}_{-0.87}$ *	$2.89\ ^{+0.82}_{-0.71}$ *	$3.62\ ^{+0.94}_{-0.84}$ *	3.69 ± 0.45 *	} 1.3 / 3
172.1	11.7 ± 1.3 *	11.6 ± 1.4 *	12.3 ± 1.4 *	12.3 ± 1.3 *	12.0 ± 0.7 *	} 0.22/ 3
182.7	15.90 ± 0.63*	16.07 ± 0.70*	16.53 ± 0.72*	15.43 ± 0.66*	15.89 ± 0.35 *	} 26.4/24
188.6	15.76 ± 0.36*	16.09 ± 0.42*	16.17 ± 0.41*	16.30 ± 0.39*	16.03 ± 0.21 *	
191.6	17.10 ± 0.90 *	16.64 ± 1.00*	16.11 ± 0.92 *	16.60 ± 0.99	16.56 ± 0.48	
195.5	16.61 ± 0.54 *	17.04 ± 0.60*	16.22 ± 0.57 *	18.59 ± 0.75	16.90 ± 0.31	
199.5	16.90 ± 0.52 *	17.39 ± 0.57*	16.49 ± 0.58 *	16.32 ± 0.67	16.75 ± 0.30	
201.6	16.65 ± 0.71 *	17.37 ± 0.82*	16.01 ± 0.84 *	18.48 ± 0.92	17.00 ± 0.41	
204.9	16.79 ± 0.54 *	17.56 ± 0.59*	17.00 ± 0.60 *	15.97 ± 0.64	16.78 ± 0.31	
206.6	17.36 ± 0.43 *	16.35 ± 0.47*	17.33 ± 0.47 *	17.77 ± 0.57	17.13 ± 0.25	

pre-LHC: flavor universality

$$c_{LL}\frac{(\bar{q}^i_L\gamma_\mu q^j_L)^2}{f^2}$$

$$c_{LR}\frac{(\bar{q}^i_L q^j_R)(\bar{q}^i_R q^j_L)}{f^2}$$

$$\boxed{f/\sqrt{c} \geqslant 10^{2-5}\,\mathrm{TeV}}$$

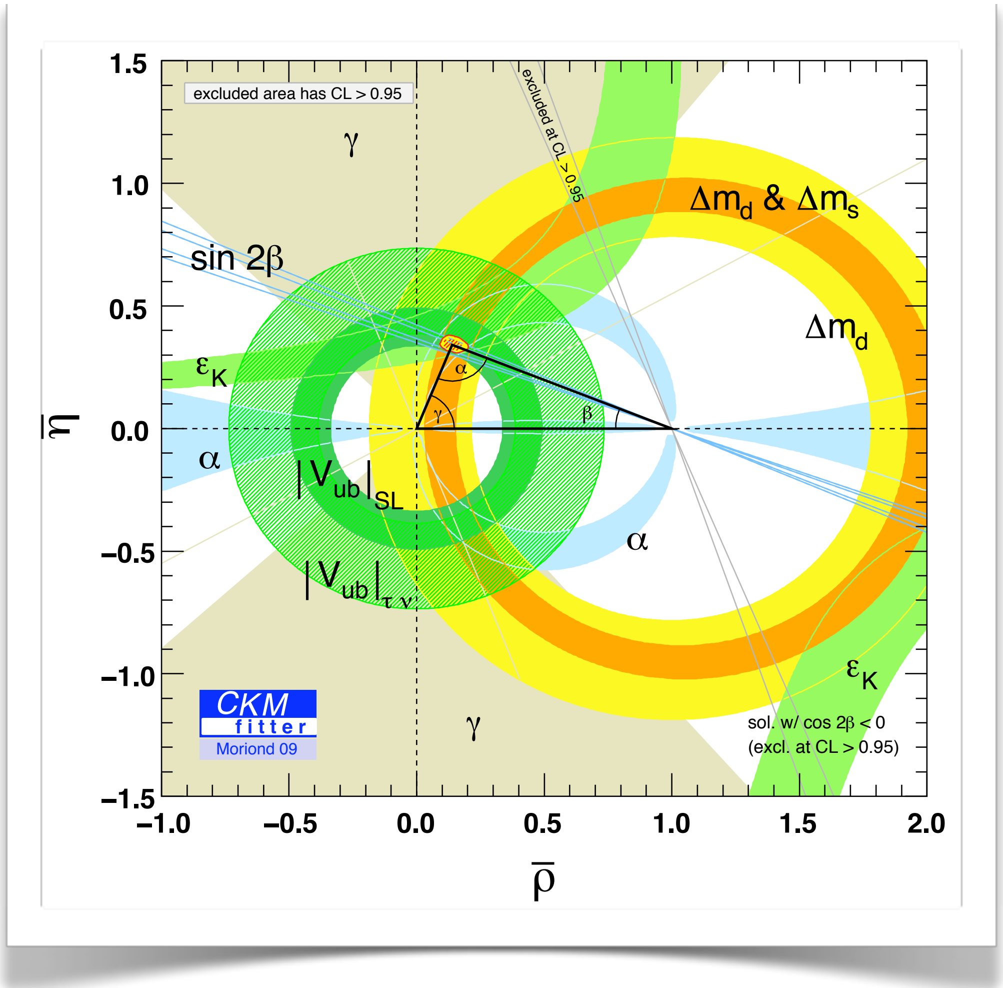


pre-LHC: flavor universality

$$c_{LL}\frac{(\bar{q}_L^i\gamma_\mu q_L^j)^2}{f^2}$$

$$c_{LR}\frac{(\bar{q}_L^i q_R^j)(\bar{q}_R^i q_L^j)}{f^2}$$

$$\boxed{f/\sqrt{c} \geqslant 10^{2-5}\,\mathrm{TeV}}$$



flavor assumption: (beyond) MFV

$$U(3)_q \otimes U(3)_d \otimes U(2)_u$$

we might leave out
the RH top

only broken by Yukawa couplings

pre-LHC: LH-quarks depends on Higgs

elementary in what their couplings to W, Z concerns:

$$c_L \frac{(\bar{q}_L \gamma_\mu q_L)(H^\dagger D^\mu H)}{f^2}$$

$$\boxed{f/\sqrt{c_L} \geqslant 3-4\,\mathrm{TeV}}$$

LEP:

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$

$$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})} = 20.767 \pm .025$$

KLOE:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(6)$$

but if H is composite, c_L is suppressed...

not in their contact interactions:

$$c_L \frac{(\bar{q}_L \gamma_\mu q_L)^2}{f^2}$$

Tevatron:

$$\boxed{f/\sqrt{c_L} \geqslant 1\,\mathrm{TeV}}$$

pre-LHC: RH-quarks not well tested

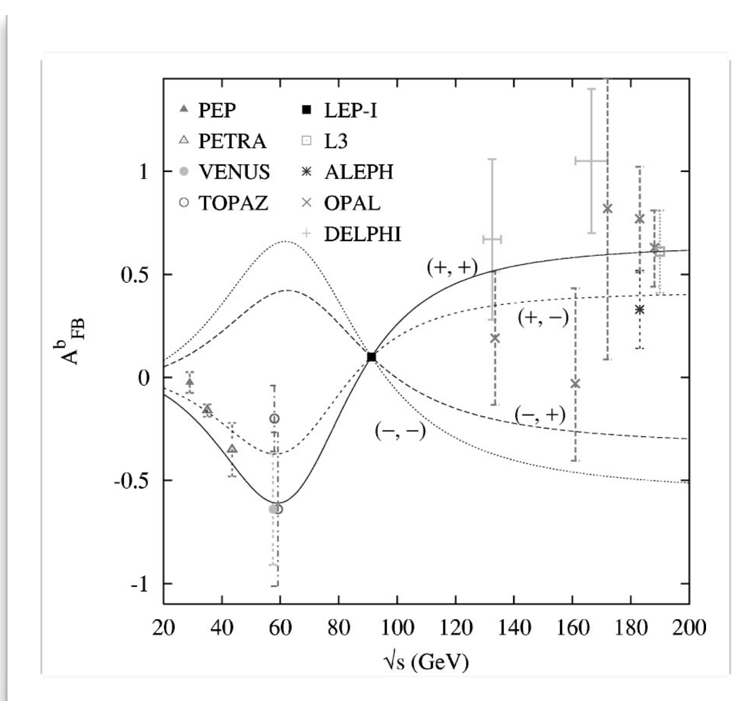
couplings to the Z are very small: $g_{d_R} = Q_d \sin^2\theta_W \sim 0.08$

$$c_R^{(q)} \frac{(\bar{q}_R \gamma_\mu q_R)(H^\dagger D^\mu H)}{f^2}, \quad q = u, d$$

LEP: $$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})} = 20.767 \pm .025$$

$$\boxed{f/\sqrt{c_R^{(u)}} \geqslant 1\,\mathrm{TeV}}$$

$$\boxed{f/\sqrt{c_R^{(d)}} \geqslant 0.5\,\mathrm{TeV}}$$



$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$

$$0 \leqslant \delta g_{b_R} \leqslant 0.2$$

RH quarks and LH quarks (if Higgs not)

LHC updates

what we are already learning from LHC about
the compositeness of the SM fermions

LHC updates

the easiest thing to start with:

if quarks are composite states

$$c_{L,R}\frac{(\bar{q}_{L,R}\gamma_\mu q_{L,R})^2}{\Lambda^2}, \quad q_R = u_R, d_R$$

flavor universal

$$c_{L,R} \leqslant 16\pi^2$$

$$\Downarrow$$

strong dijet production

$$\boxed{pp \to jj}$$

highly energetic: $m_{jj} > 3\,\mathrm{TeV}$

central: $|y_1 - y_2| \leqslant 1.1$

dijets at LHC

Independent 4-quark operators:

full list

$$
\begin{array}{lcl}
\mathcal{O}_{dd}^{(1)} &=& (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{ud}^{(1)} &=& (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{uu}^{(1)} &=& (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma_\mu u_R) \\
\mathcal{O}_{qu}^{(1)} &=& (\bar{q}_L\gamma^\mu q_L)(\bar{u}_R\gamma_\mu u_R) \\
\mathcal{O}_{qd}^{(1)} &=& (\bar{q}_L\gamma^\mu q_L)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{qq}^{(1)} &=& (\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) \\
\mathcal{O}_{qq}^{(3w)} &=& (\bar{q}_L\gamma^\mu \tau^I q_L)(\bar{q}_L\gamma_\mu \tau^I q_L) \\
\mathcal{O}_{qq}^{(8_F)} &=& (\bar{q}_L\gamma^\mu T^P q_L)(\bar{q}_L\gamma_\mu T^P q_L) \\
\mathcal{O}_{uu}^{(8)} &=& (\bar{u}_R\gamma^\mu T^A u_R)(\bar{u}_R\gamma_\mu T^A u_R) \\
\mathcal{O}_{dd}^{(8)} &=& (\bar{d}_R\gamma^\mu T^A d_R)(\bar{d}_R\gamma_\mu T^A d_R) \\
\mathcal{O}_{ud}^{(8)} &=& (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma_\mu T^A d_R) \\
\mathcal{O}_{qq}^{(8_C)} &=& (\bar{q}_L\gamma^\mu T^A q_L)(\bar{q}_L\gamma_\mu T^A q_L) \\
\mathcal{O}_{qu}^{(8)} &=& (\bar{q}_L\gamma^\mu T^A q_L)(\bar{u}_R\gamma_\mu T^A u_R) \\
\mathcal{O}_{qd}^{(8)} &=& (\bar{q}_L\gamma^\mu T^A q_L)(\bar{d}_R\gamma_\mu T^A d_R)
\end{array}
$$

$$
\begin{array}{l}
\mathcal{O}_{td}^{(1)} = (\bar{t}_R\gamma^\mu t_R)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{ut}^{(1)} = (\bar{u}_R\gamma^\mu u_R)(\bar{t}_R\gamma_\mu t_R) \\
\mathcal{O}_{tt}^{(1)} = (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R) \\
\mathcal{O}_{qt}^{(1)} = (\bar{q}_L\gamma^\mu q_L)(\bar{t}_R\gamma_\mu t_R) \\
\mathcal{O}_{ut}^{(8)} = (\bar{u}_R\gamma^\mu T^A u_R)(\bar{t}_R\gamma_\mu T^A t_R) \\
\mathcal{O}_{td}^{(8)} = (\bar{t}_R\gamma^\mu T^A t_R)(\bar{d}_R\gamma_\mu T^A d_R) \\
\mathcal{O}_{qt}^{(8)} = (\bar{q}_L\gamma^\mu T^A q_L)(\bar{t}_R\gamma_\mu T^A t_R)
\end{array}
$$

but many of them are not relevant for LHC dijets

dijets at LHC

Relevant 4-quark operators:

at the LHC at high invariant masses: **pp = uu, ud, dd**

$$\left(\frac{\sigma(u\bar{u}\to u\bar{u})}{\sigma(uu\to uu)}\right)_{SM}^{m_{jj}>2\,\mathrm{TeV}} \simeq 0.04\;, \qquad \left(\frac{\sigma(uc\to uc)}{\sigma(uu\to uu)}\right)_{SM}^{m_{jj}>2\,\mathrm{TeV}} \simeq 0.01$$

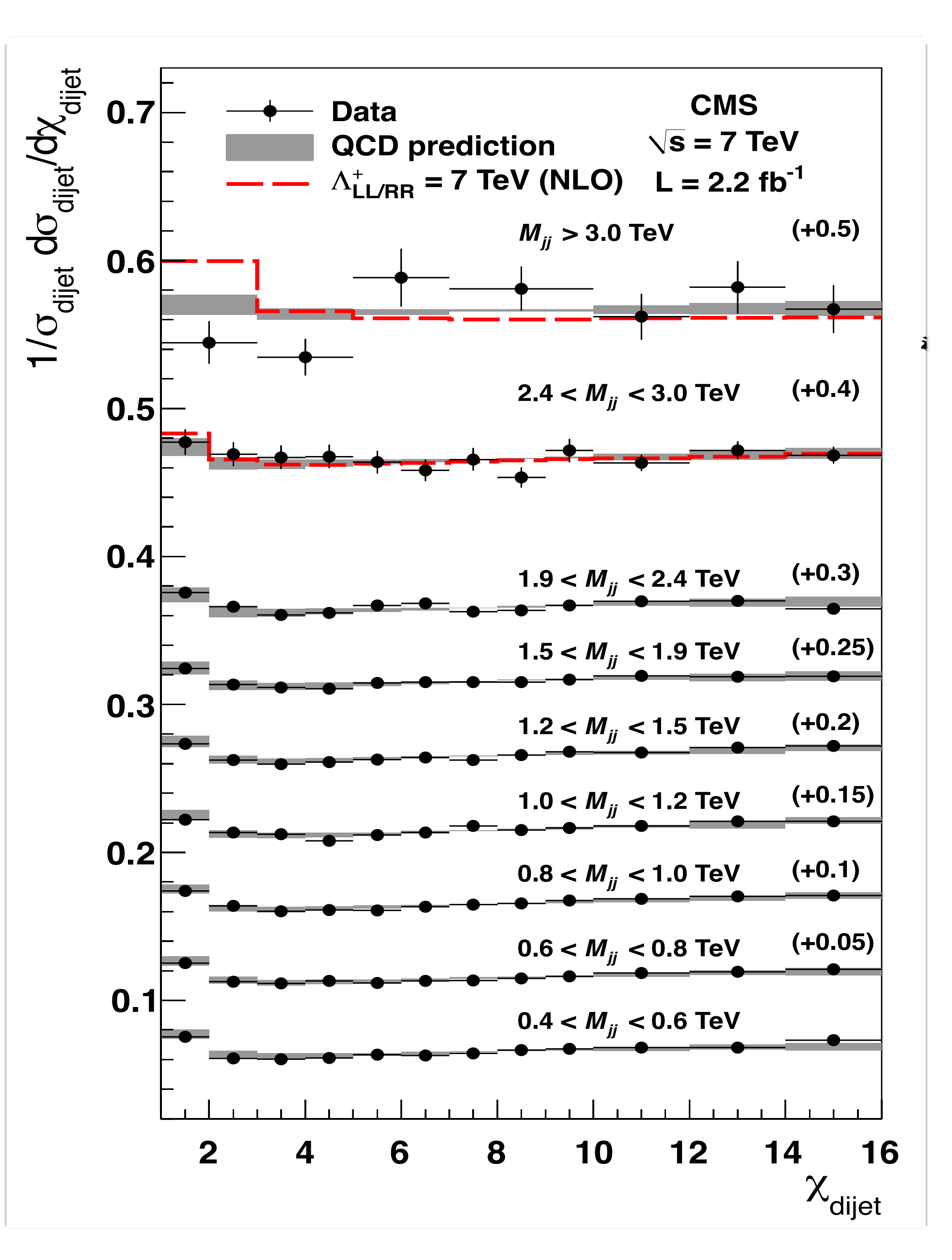
because of our **flavor assumption**, **jj ≠ ss, cc, ...**

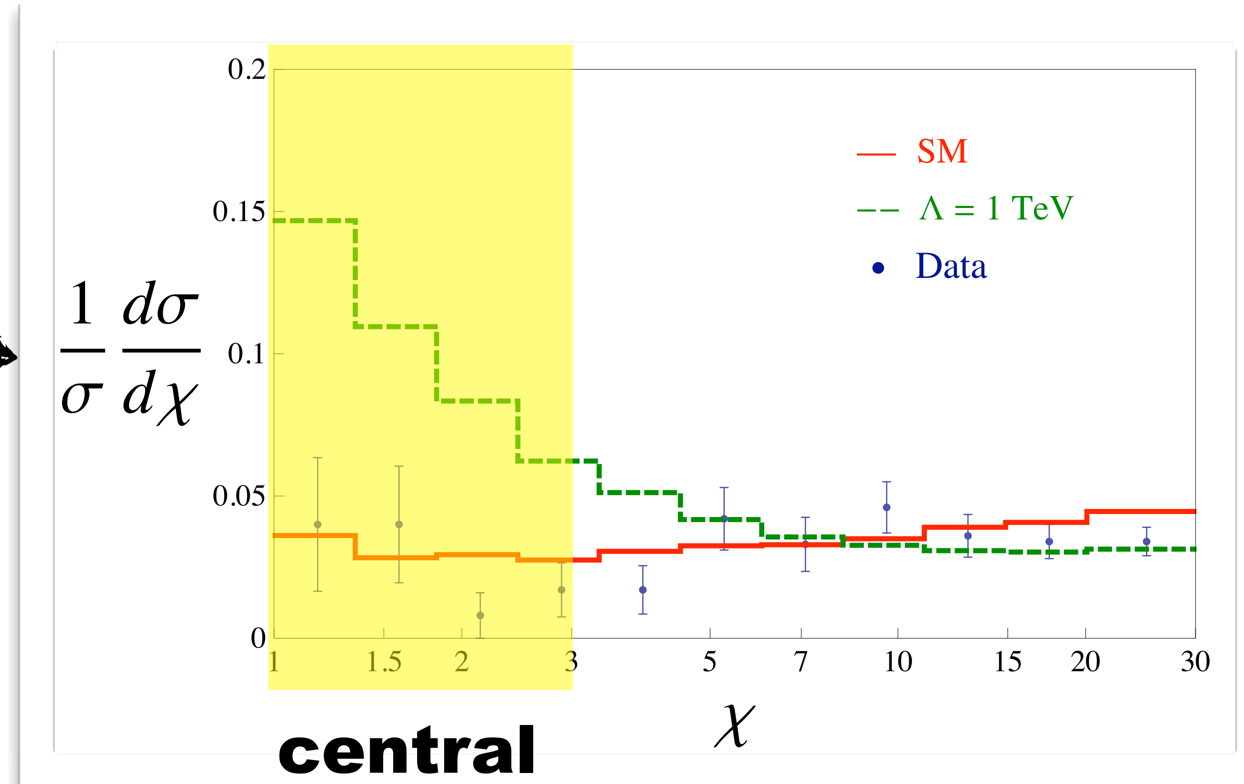
$$\boxed{\begin{array}{c} uu \longrightarrow uu \\ ud \longrightarrow ud \\ dd \longrightarrow dd \end{array}}$$

$$\begin{aligned}
\mathcal{O}_{uu}^{(1)} &= (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma_\mu u_R) \\
\mathcal{O}_{dd}^{(1)} &= (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{ud}^{(1)} &= (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{ud}^{(8)} &= (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma_\mu T^A d_R) \\
\mathcal{O}_{qq}^{(1)} &= (\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) \\
\mathcal{O}_{qq}^{(8)} &= (\bar{q}_L\gamma^\mu T^A q_L)(\bar{q}_L\gamma_\mu T^A q_L) \\
\mathcal{O}_{qu}^{(1)} &= (\bar{q}_L\gamma^\mu q_L)(\bar{u}_R\gamma_\mu u_R) \\
\mathcal{O}_{qu}^{(8)} &= (\bar{q}_L\gamma^\mu T^A q_L)(\bar{u}_R\gamma_\mu T^A u_R) \\
\mathcal{O}_{qd}^{(1)} &= (\bar{q}_L\gamma^\mu q_L)(\bar{d}_R\gamma_\mu d_R) \\
\mathcal{O}_{qd}^{(8)} &= (\bar{q}_L\gamma^\mu T^A q_L)(\bar{d}_R\gamma_\mu T^A d_R)
\end{aligned}$$

dijets at LHC

Angular distributions and exp. results: CMS, 2.2 fb^{-1}





$$\chi = e^{|y_1 - y_2|}$$

$$F_\chi^{3\,\mathrm{TeV}} = \frac{N(\chi < 3, m_{jj} > 3\,\mathrm{TeV})}{N(\chi < 16, m_{jj} > 3\,\mathrm{TeV})}$$

$$\boxed{0.003 \lesssim F_\chi^{3\,\mathrm{TeV}} \lesssim 0.150}$$

at 95% CL

dijets at LHC

One at a time Bounds:

best bounds up to date

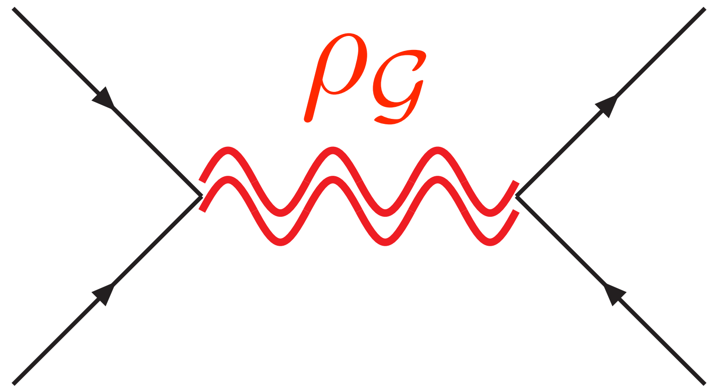
Operator	Λ_-(TeV)	Λ_+(TeV)
$\mathcal{O}_{uu}^{(1)}$	4.5	3.0
$\mathcal{O}_{dd}^{(1)}$	2.4	2.0
$\mathcal{O}_{ud}^{(1)}$	2.2	2.2
$\mathcal{O}_{ud}^{(8)}$	1.8	1.3
$\mathcal{O}_{qq}^{(1)}$	5.0	3.5
$\mathcal{O}_{qq}^{(8)}$	3.4	2.0
$\mathcal{O}_{qu}^{(1)}$	2.5	2.5
$\mathcal{O}_{qu}^{(8)}$	1.9	1.5
$\mathcal{O}_{qd}^{(1)}$	1.9	1.9
$\mathcal{O}_{qd}^{(8)}$	1.4	1.2

$$\times\sqrt{c_i} \leqslant 4\pi \cdot \epsilon$$

interference with QCD: **constructive** **destructive**

dijets at LHC

Compositeness Bounds:



$$\Lambda \equiv m_\rho$$

$$\mathcal{G} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes G_F$$

$$G_F \equiv U(3)_q \otimes U(3)_d \otimes U(2)_u$$

$$u_R \sim (\mathbf{3}, \mathbf{1}, \mathbf{2/3}, \mathbf{1}, \mathbf{1}, \mathbf{2})$$

$$d_R \sim (\mathbf{3}, \mathbf{1}, \mathbf{-1/3}, \mathbf{1}, \mathbf{3}, \mathbf{2})$$

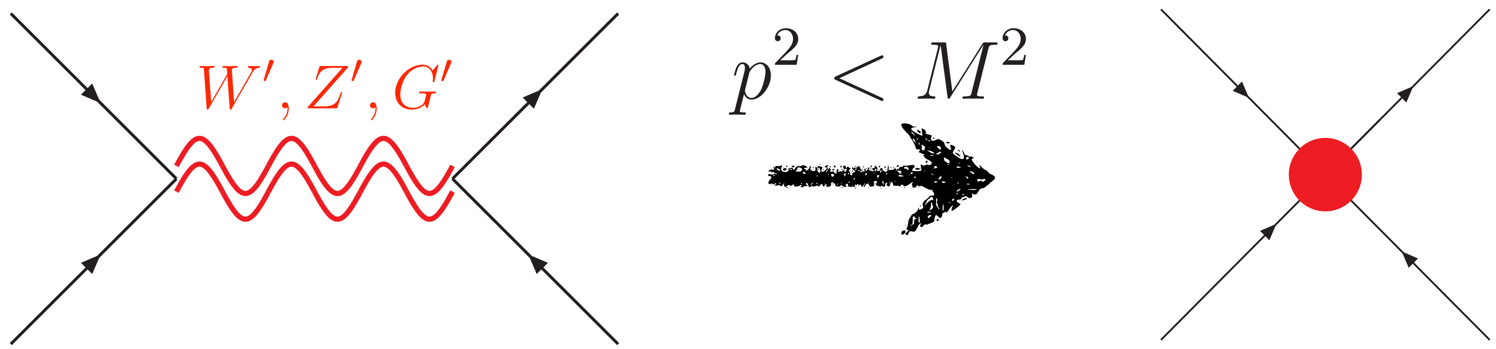
$$q_L \sim (\mathbf{3}, \mathbf{2}, \mathbf{1/6}, \mathbf{3}, \mathbf{1}, \mathbf{2})$$

Composite States	f (TeV)
d_R	1.5
u_R	3.2
u_R, d_R	3.6
q_L	3.8
q_L, d_R	4.0
q_L, u_R	4.9
q_L, u_R, d_R	5.2

$$f = \frac{m_\rho}{g_\rho}$$

dijets at LHC

Heavy gauge bosons Bounds: present in many extensions of the SM

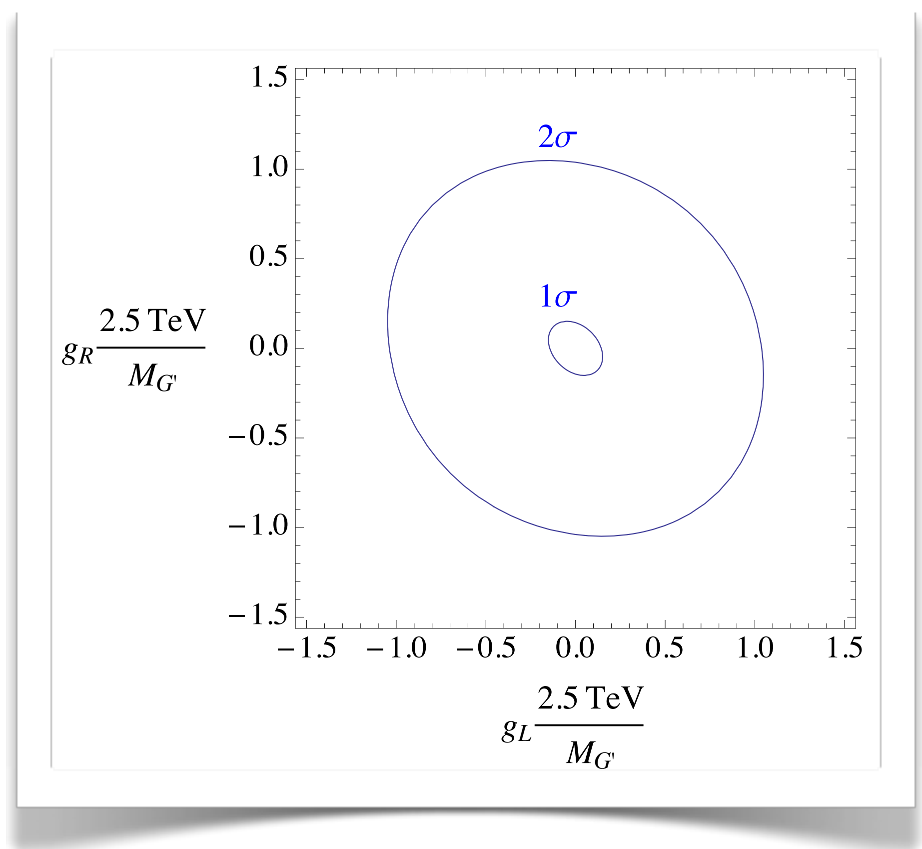


$$\frac{M_{Z'_B}}{g_B} \gtrsim 1.6\,\mathrm{TeV} \qquad \frac{M_{Z'_Y}}{g_Y} \gtrsim 2.3\,\mathrm{TeV} \qquad \frac{M_{W'}}{g_R} \gtrsim 2.3\,\mathrm{TeV}$$

$$G'^{A}_{\mu}\left[g_L \bar{q}_L T^A \gamma^\mu q_L + g_R \bar{q}_R T^A \gamma^\mu q_R\right]$$

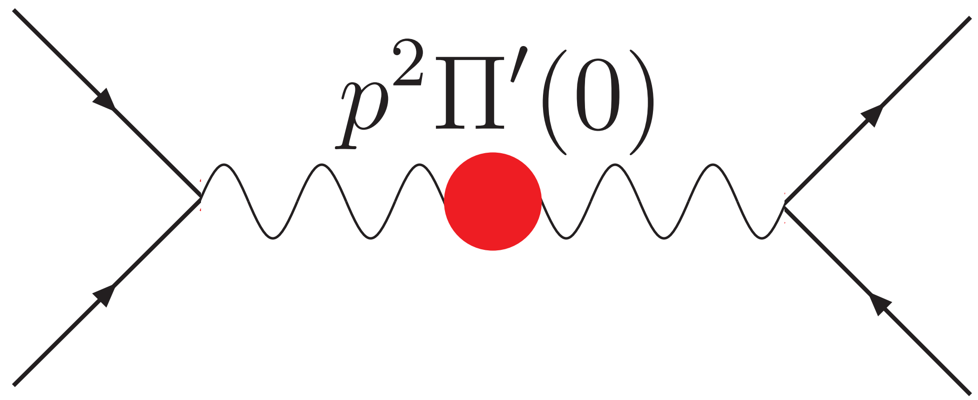
massive gluon solving A_{FB} of tops?

not if heavy

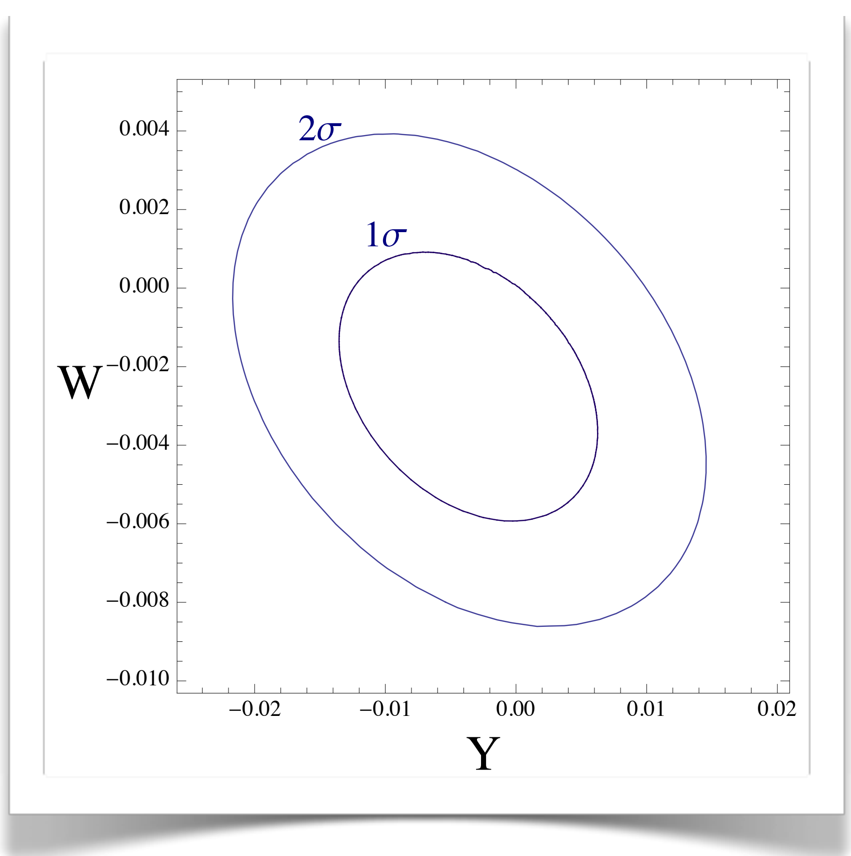


dijets at LHC

SM gauge boson compositeness Bounds



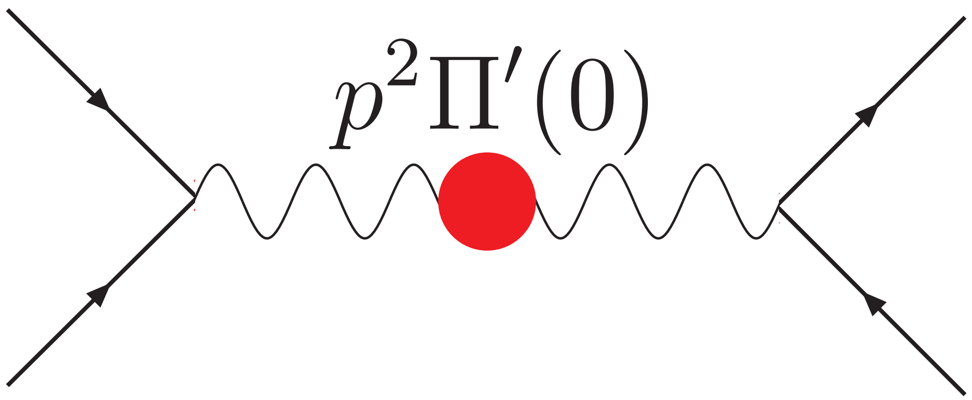
$$\frac{-Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 \quad \frac{-W}{4m_W^2}(D_\rho W^I_{\mu\nu})^2$$



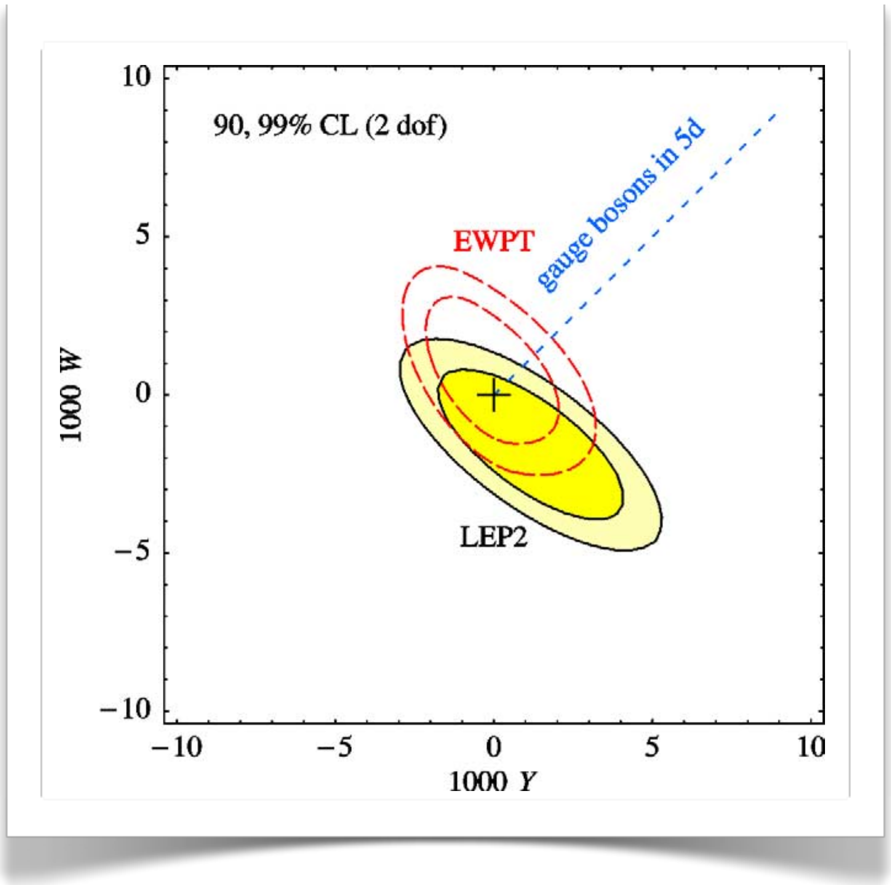
close to best bound from LEP

dijets at LHC

SM gauge boson compositeness Bounds

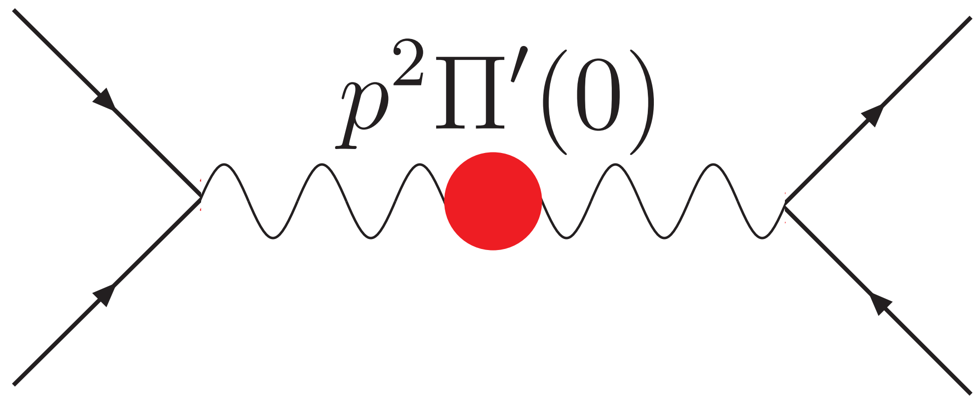


$$\frac{-Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 \quad \frac{-W}{4m_W^2}(D_\rho W^I_{\mu\nu})^2$$



dijets at LHC

SM gauge boson compositeness Bounds



$$\frac{-Z}{4m_W^2}(D_\rho G^A_{\mu\nu})^2$$

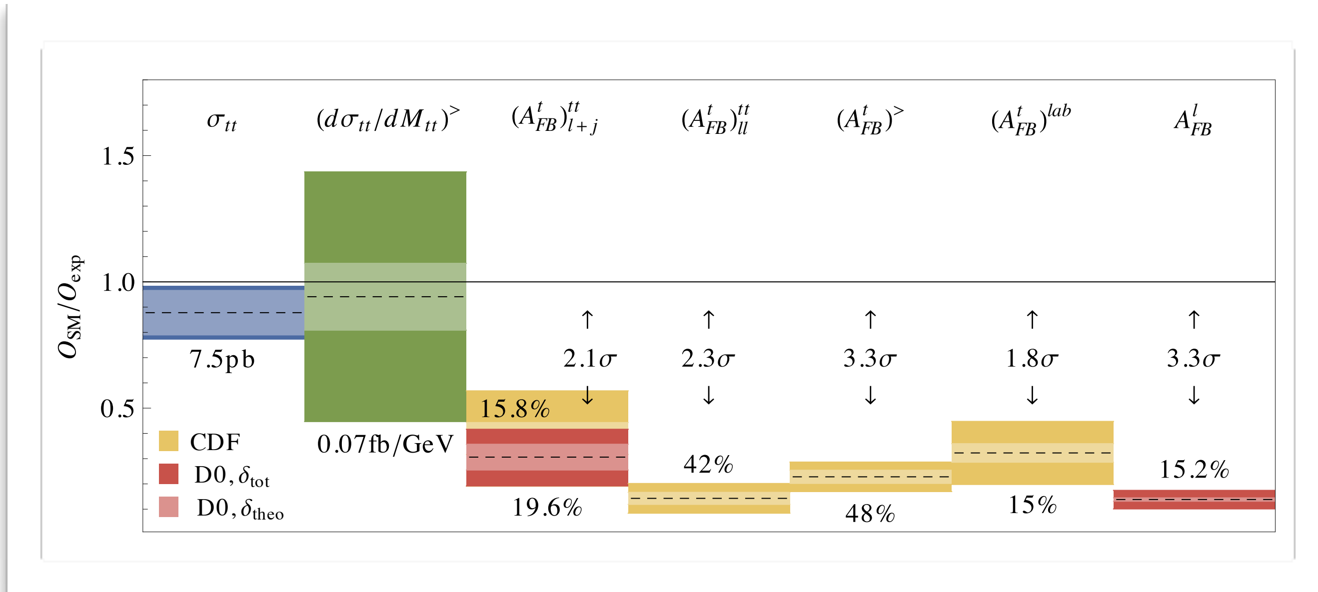
gluon compositeness

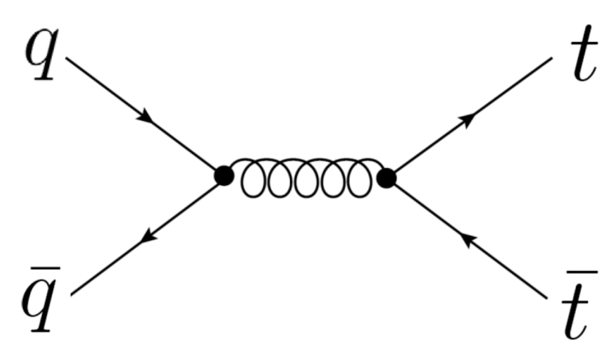
$$-9\times 10^{-4} \lesssim Z \lesssim 3\times 10^{-4}$$

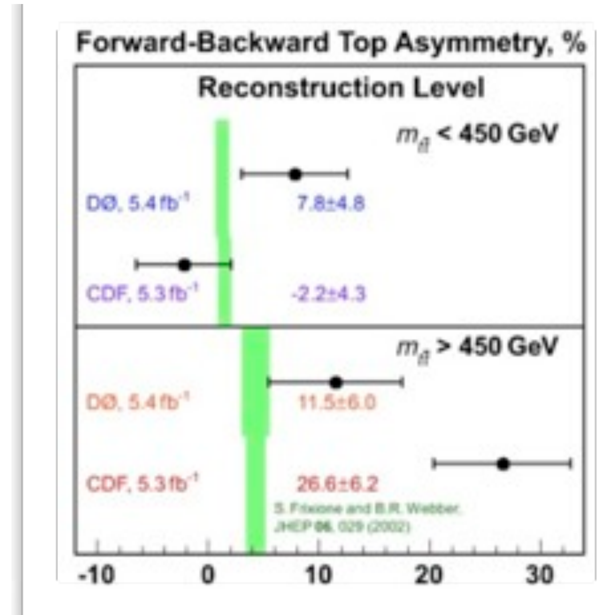
best bound up to date

Some extra motivation

Top Forward-Backward Asymmetry: CDF and D0

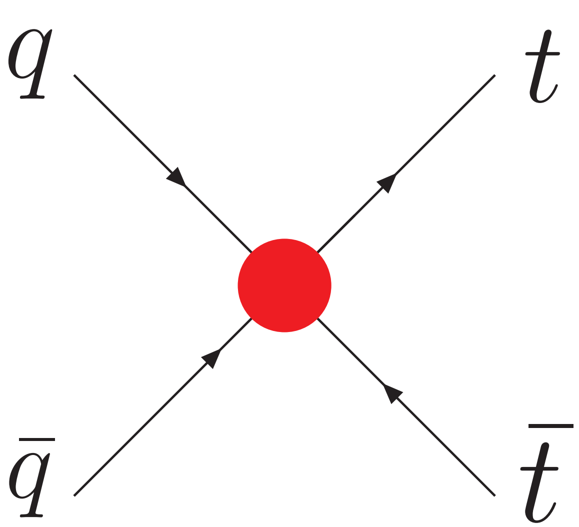




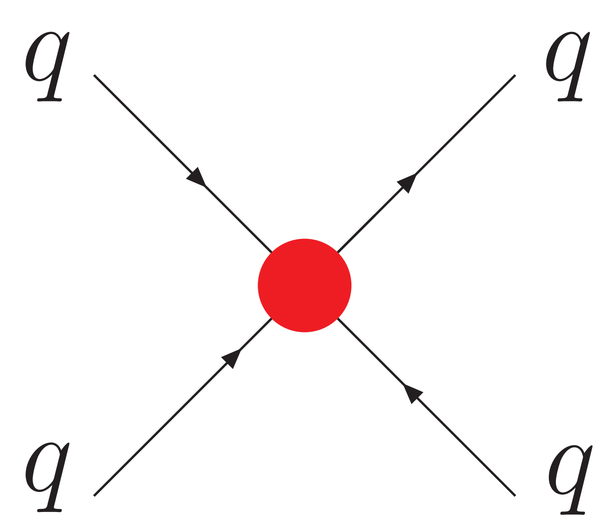


many many models proposed so far

only a handful are not ruled out already...



specific models



dijets at LHC

Top AFB:

$$\frac{c_A^{(8)}}{\Lambda^2}(\bar{u}\,T^A\gamma^\mu\gamma^5 u)(\bar{t}\,T^A\gamma_\mu\gamma^5 t)$$

Tevatron $\longrightarrow$ $\sigma_{t\bar{t}}$ ✓ $A_{FB}^{t\bar{t}}$ ✓

$$\frac{c_A^{(8)}}{\Lambda^2} \sim 2\,\mathrm{TeV}^{-2}$$

Perez et al.

Servant et al.

dijets at LHC

Top AFB:

$$\frac{c_A^{(8)}}{\Lambda^2}(\bar{u}\,T^A\gamma^\mu\gamma^5 u)(\bar{t}\,T^A\gamma_\mu\gamma^5 t)$$

$$\frac{c_A^{(8)}}{\Lambda^2} \sim 2\,\mathrm{TeV}^{-2}$$

Perez et al.

Servant et al.

Tevatron

$\sigma_{t\bar{t}}$ ✓

$A_{FB}^{t\bar{t}}$ ✓

LHC dijets

$$G_F \equiv U(3)_q \otimes U(3)_d \otimes U(2)_u$$

$$\frac{c_A^{(8)}}{\Lambda^2} \lesssim \frac{0.2}{\mathrm{TeV}^2}$$ ✗

dijets at LHC

Top AFB: relaxing flavor assumption

$$\frac{c_A^{(8)}}{\Lambda^2}(\bar{u}\,T^A\gamma^\mu\gamma^5 u)(\bar{t}\,T^A\gamma_\mu\gamma^5 t)$$

$$\frac{c_A^{(8)}}{\Lambda^2} \sim 2\,\mathrm{TeV}^{-2}$$

Perez et al.

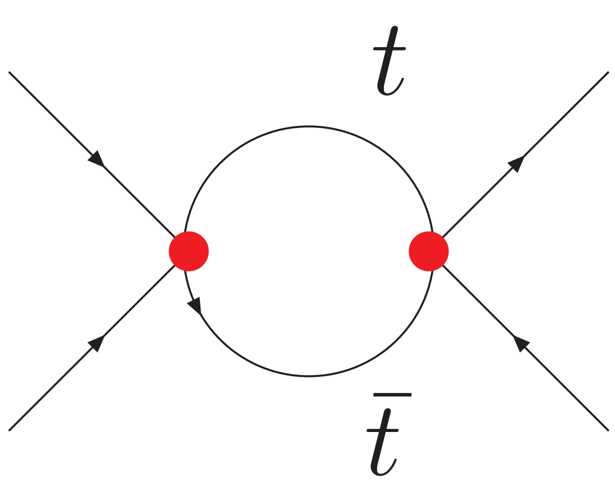
Servant et al.

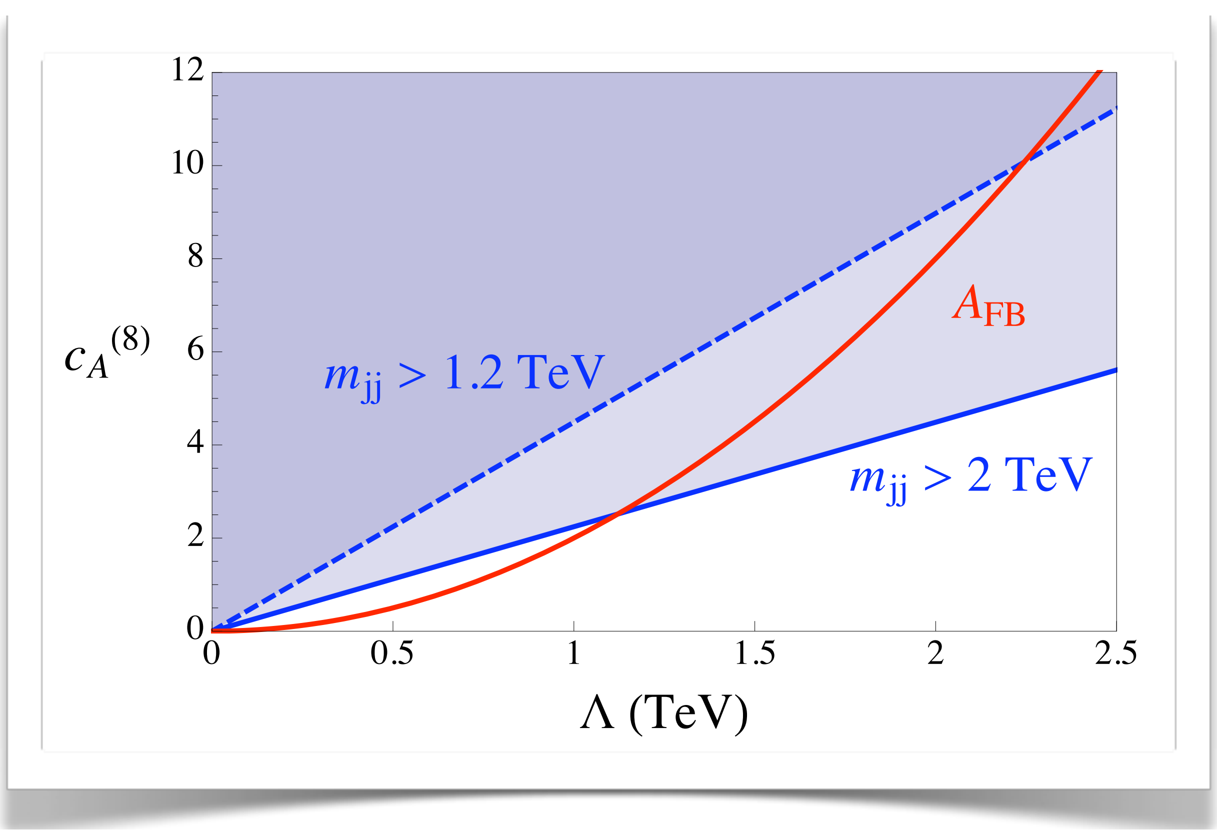
Tevatron

$\sigma_{t\bar{t}}$ ✓

$A_{FB}^{t\bar{t}}$ ✓

LHC dijets





dijets at LHC

Top AFB: relaxing flavor assumption

$$\frac{c_A^{(8)}}{\Lambda^2}(\bar{u}\,T^A\gamma^\mu\gamma^5 u)(\bar{t}\,T^A\gamma_\mu\gamma^5 t)$$

$$\frac{c_A^{(8)}}{\Lambda^2} \sim 2\,\mathrm{TeV}^{-2}$$

Perez et al.

Servant et al.

Tevatron

$\sigma_{t\bar{t}}$ ✓

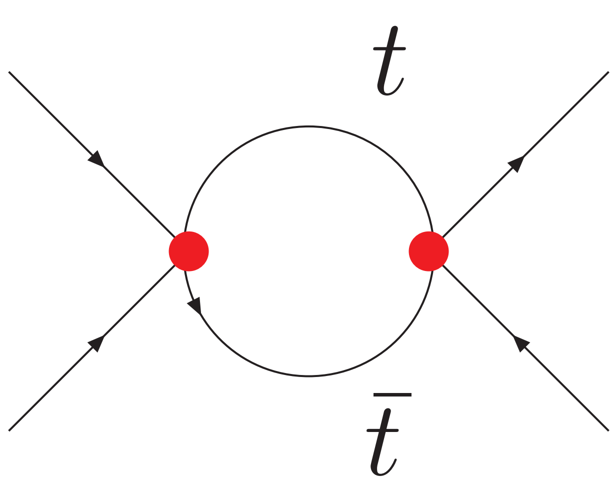
$A_{FB}^{t\bar{t}}$ ✓

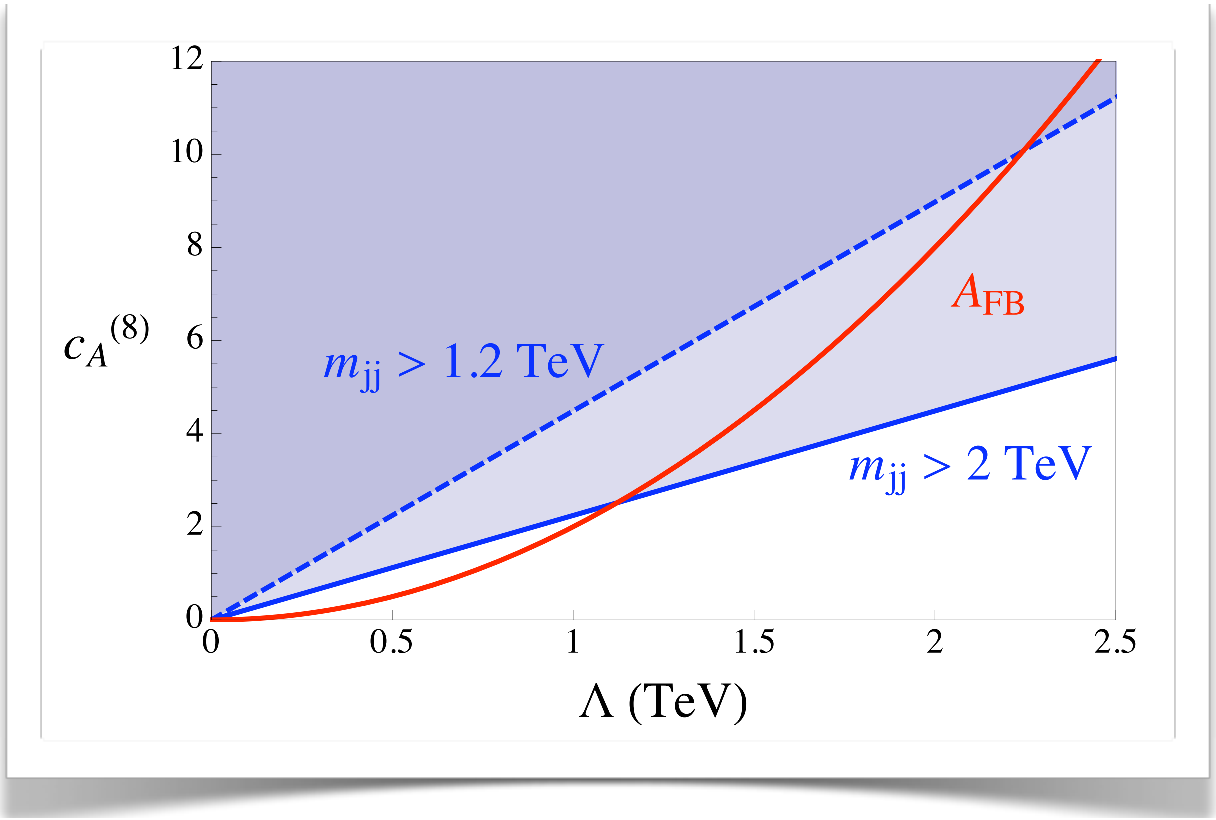
LHC tops

large enhancements expected at high m_{tt}

charge asymmetry

LHC dijets





Conclusions

Direct production of resonances might be out of reach at LHC.

Indirect effects might be the clue for BSM.

LHC is already testing the SM quark sector with high accuracy.

Strong bounds are set, **1 - 5 TeV**, on single operators and compositeness scale.

quarks (& gluon) can not be fully composite at the EW scale

but still viable MFV implementation

and compositeness of the top quark (& Higgs)

stay tuned