Probing the SM with dijets (Description: University) Probing the SM with dijets (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:







At LHC: elementary or composite?

The LHC is taking data:



At LHC: elementary or composite?

The LHC is taking data:







Strongly coupled



Compositeness

Why at the LHC? hierarchies

The hierarchy problem motivation:



from an effective field theory perspective:



Why at the LHC? hierarchies

The hierarchy problem motivation:



from an effective field theory perspective:



Why at the LHC? hierarchies

The hierarchy problem motivation:



from an effective field theory perspective:

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

SU(3)_C × SU(2)_L × U(1)_Y

natural expectation

 $\Lambda \sim \text{TeV}$

What is composite? Higgs and top

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

 $\Lambda \sim \text{TeV}$

does any of SM particles belong to this sector?

in "old" examples:

Technicolor: W_L, Z_L MSSM: none

What is composite? Higgs and top

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

 $\Lambda \sim \text{TeV}$

does any of SM particles belong to this sector?

in "old" examples:

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

$$\mathcal{L}_{Y} = \epsilon_{u}^{i} u_{R}^{i} \mathcal{O}_{u} + \epsilon_{d}^{i} d_{R}^{i} \mathcal{O}_{d} + \epsilon_{q}^{i} q_{L}^{i} \mathcal{O}_{q}$$

$$u_{R}^{i}, d_{R}^{i} \qquad H \qquad Y_{u,d}^{i,j} \sim \epsilon_{q}^{i} \epsilon_{u,d}^{j} g_{\rho} \qquad 0 < \epsilon < 1$$

$$\Delta \mathbf{F} = \mathbf{1} : \quad \epsilon_{q}^{i} \epsilon_{d}^{j} g_{\rho} \frac{v}{\Lambda^{2}} \frac{g_{\rho}^{2}}{16\pi^{2}} \ \bar{d}_{L}^{i} \sigma_{\mu\nu} d_{R}^{j} G^{\mu\nu}$$

$$\Delta \mathbf{F} = \mathbf{2} : \quad \epsilon_{q}^{i} \epsilon_{q}^{j} \epsilon_{q}^{k} \epsilon_{q}^{\ell} \frac{g_{\rho}^{2}}{\Lambda^{2}} \ (\bar{q}^{i} \gamma_{\mu} q^{j}) (\bar{q}^{k} \gamma^{\mu} q^{\ell})$$

Anything else? light quarks

Flavor constraints: $\epsilon_K \longrightarrow \Lambda \gtrsim 20 \text{ TeV}$ $\epsilon'/\epsilon, \ b \longrightarrow s\gamma$, n-EDM $\longrightarrow \Lambda \gtrsim \frac{g_{\rho}}{4\pi} 20 \text{ TeV}$

partial compositeness does not seem enough...

Anything else? light quarks

Flavor constraints: $\epsilon_K \longrightarrow \Lambda \gtrsim 20 \text{ TeV}$ $\epsilon'/\epsilon, \ b \longrightarrow s\gamma$, n-EDM $\longrightarrow \Lambda \gtrsim \frac{g_{\rho}}{4\pi} 20 \text{ TeV}$

partial compositeness does not seem enough...

(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:



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

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

ii) Extra powers of $g_{
ho}^2 \psi^2 / \Lambda^2 \equiv \psi^2 / f^2$ $g_{
ho} = \frac{coupling}{composite}$ states

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





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}		Average			\sqrt{s}		Average		
(GeV)	Quantity	value	SM	Δ	(GeV)	Quantity	value	SM	Δ
130	$\sigma(q\overline{q})$	82.1 ± 2.2	82.8	-0.3	192	$\sigma(q\overline{q})$	22.05 ± 0.53	21.24	-0.10
130	$\sigma(\mu^+\mu^-)$	$8.62 {\pm} 0.68$	8.44	-0.33	192	$\sigma(\mu^+\mu^-)$	$2.92{\pm}0.18$	3.10	-0.13
130	$\sigma(\tau^+\tau^-)$	$9.02 {\pm} 0.93$	8.44	-0.11	192	$\sigma(\tau^+\tau^-)$	$2.81 {\pm} 0.23$	3.10	-0.05
130	$A_{FB}(\mu^+\mu^-)$	$0.694{\pm}0.060$	0.705	0.012	192	$A_{FB}(\mu^+\mu^-)$	$0.553 {\pm} 0.051$	0.566	0.019
130	$A_{FB}(\tau^+\tau^-)$	$0.663 {\pm} 0.076$	0.704	0.012	192	$A_{FB}(\tau^+\tau^-)$	$0.615 {\pm} 0.069$	0.566	0.019
136	$\sigma(q\overline{q})$	66.7 ± 2.0	66.6	-0.2	196	$\sigma(q\overline{q})$	20.53 ± 0.34	20.13	-0.09
136	$\sigma(\mu^+\mu^-)$	$8.27 {\pm} 0.67$	7.28	-0.28	196	$\sigma(\mu^+\mu^-)$	$2.94{\pm}0.11$	2.96	-0.12
136	$\sigma(\tau^+\tau^-)$	$7.078 {\pm} 0.820$	7.279	-0.091	196	$\sigma(\tau^+\tau^-)$	$2.94{\pm}0.14$	2.96	-0.05
136	$A_{FB}(\mu^+\mu^-)$	$0.708 {\pm} 0.060$	0.684	0.013	196	$A_{FB}(\mu^+\mu^-)$	$0.581 {\pm} 0.031$	0.562	0.019
136	$A_{FB}(\tau^+\tau^-)$	$0.753 {\pm} 0.088$	0.683	0.014	196	$A_{FB}(\tau^+\tau^-)$	$0.505 {\pm} 0.044$	0.562	0.019
161	$\sigma(q\overline{q})$	$37.0{\pm}1.1$	35.2	-0.1	200	$\sigma(q\overline{q})$	19.25 ± 0.32	19.09	-0.09
161	$\sigma(\mu^+\mu^-)$	$4.61 {\pm} 0.36$	4.61	-0.18	200	$\sigma(\mu^+\mu^-)$	3.02 ± 0.11	2.83	-0.12
161	$\sigma(\tau^+\tau^-)$	$5.67 {\pm} 0.54$	4.61	-0.06	200	$\sigma(\tau^+\tau^-)$	$2.90{\pm}0.14$	2.83	-0.04
161	$A_{FB}(\mu^+\mu^-)$	$0.538 {\pm} 0.067$	0.609	0.017	200	$A_{FB}(\mu^+\mu^-)$	$0.524 {\pm} 0.031$	0.558	0.019
161	$A_{FB}(\tau^+\tau^-)$	$0.646 {\pm} 0.077$	0.609	0.016	200	$A_{FB}(\tau^+\tau^-)$	$0.539 {\pm} 0.042$	0.558	0.019
172	$\sigma(q\overline{q})$	29.23 ± 0.99	28.74	-0.12	202	$\sigma(q\overline{q})$	19.07 ± 0.44	18.57	-0.09
172	$\sigma(\mu^+\mu^-)$	3.57 ± 0.32	3.95	-0.16	202	$\sigma(\mu^+\mu^-)$	2.58 ± 0.14	2.77	-0.12
172	$\sigma(\tau^+\tau^-)$	4.01 ± 0.45	3.95	-0.05	202	$\sigma(\tau^+\tau^-)$	2.79 ± 0.20	2.77	-0.04
172	$A_{FB}(\mu^+\mu^-)$	0.675 ± 0.077	0.591	0.018	202	$A_{FB}(\mu^+\mu^-)$	0.547 ± 0.047	0.556	0.020
172	$A_{FB}(\tau^+\tau^-)$	$0.342 {\pm} 0.094$	0.591	0.017	202	$A_{FB}(\tau^+\tau^-)$	$0.589 {\pm} 0.059$	0.556	0.019
183	$\sigma(q\overline{q})$	24.59 ± 0.42	24.20	-0.11	205	$\sigma(q\overline{q})$	18.17 ± 0.31	17.81	-0.09
183	$\sigma(\mu^+\mu^-)$	$3.49 {\pm} 0.15$	3.45	-0.14	205	$\sigma(\mu^+\mu^-)$	2.45 ± 0.10	2.67	-0.11
183	$\sigma(\tau^+\tau^-)$	$3.37 {\pm} 0.17$	3.45	-0.05	205	$\sigma(\tau^+\tau^-)$	2.78 ± 0.14	2.67	-0.042
183	$A_{FB}(\mu^+\mu^-)$	$0.559 {\pm} 0.035$	0.576	0.018	205	$A_{FB}(\mu^+\mu^-)$	0.565 ± 0.035	0.553	0.020
183	$A_{FB}(\tau^+\tau^-)$	0.608 ± 0.045	0.576	0.018	205	$A_{FB}(\tau^+\tau^-)$	0.571 ± 0.042	0.553	0.019
189	$\sigma(q\overline{q})$	22.47 ± 0.24	22.156	-0.101	207	$\sigma(q\overline{q})$	17.49 ± 0.26	17.42	-0.08
189	$\sigma(\mu^+\mu^-)$	3.123 ± 0.076	3.207	-0.131	207	$\sigma(\mu^+\mu^-)$	2.595 ± 0.088	2.623	-0.111
189	$\sigma(\tau^+\tau^-)$	$3.20{\pm}0.10$	3.20	-0.048	207	$\sigma(\tau^+\tau^-)$	2.53 ± 0.11	2.62	-0.04
189	$A_{FB}(\mu^+\mu^-)$	$0.569 {\pm} 0.021$	0.569	0.019	207	$A_{FB}(\mu^+\mu^-)$	0.542 ± 0.027	0.552	0.020
189	$A_{FB}(\tau^+\tau^-)$	$0.596 {\pm} 0.026$	0.569	0.018	207	$A_{FB}(\tau^+\tau^-)$	$0.564 {\pm} 0.037$	0.551	0.019

	% of	δm	n_W (MeV	V)
Background	$W \to \mu \nu$ data	m_T fit	p_T fit	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	$N_{\rm df} = 32.6/27$					
$m_{\rm Z} \; [{\rm GeV}]$	91.1876 ± 0.0021					
$\Gamma_{\rm Z} \ [{\rm GeV}]$	2.4952 ± 0.0023					
$\sigma_{\rm h}^0 \; [{\rm nb}]$	41.541 ± 0.037					
$R_{ m e}^0$	20.804 ± 0.050					
R^0_μ	20.785 ± 0.033					
$R_{ au}^{0}$	20.764 ± 0.045					
$A_{ m FB}^{ m 0,e}$	0.0145 ± 0.0025					
$A_{\mathrm{FB}}^{\overline{0},\overline{\mu}}$	0.0169 ± 0.0013					
$A_{ m FB}^{0, au}$	0.0188 ± 0.0017					

Lepton

non-universality

[%]

 $10.91\pm0.26^*$

 $10.65 \pm 0.27^{*}$

 10.61 ± 0.35

 10.66 ± 0.17 10.60 ± 0.15 11.41 ± 0.22

6.8/9

[%]

 $11.15 \pm 0.38^{*}$

 $11.46 \pm 0.43^{*}$

 11.18 ± 0.48

 $10.03 \pm 0.31^*$ $11.89 \pm 0.45^*$

Experiment $\mathcal{B}(W \to e\overline{\nu}_e)$ $\mathcal{B}(W \to \mu\overline{\nu}_{\mu})$ $\mathcal{B}(W \to \tau\overline{\nu}_{\tau})$

[%]

 $10.81\pm0.29^*$

 $10.55\pm0.34^*$

 $10.78\pm0.32^*$

 10.40 ± 0.35

ALEPH

DELPHI

L3

OPAL

LEP

 $\chi^2/d.o.f.$

	% of	δm_W (MeV)						
Background	$W \to e \nu$ data	m_T fit	p_T fit	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 lep	ton universality
$\Gamma_{\rm had} [{\rm MeV}]$	1745.8 ± 2.7
$\Gamma_{\rm ee} [{\rm MeV}]$	$83.92{\pm}0.12$
$\Gamma_{\mu\mu}$ [MeV]	$83.99 {\pm} 0.18$
$\Gamma_{\tau\tau}$ [MeV]	$84.08 {\pm} 0.22$

$\chi^2/d.o.f.$		WW cross-section (pb)									
	LEP	OPAL	L3	DELPHI	ALEPH	(GeV)					
} 1.3 / 3	3.69 ± 0.45 *	$3.62 \ {}^{+}_{-} \ {}^{0.94}_{0.84} \ {}^{*}_{-}$	$2.89 \ ^{+}_{-} \ ^{0.82}_{0.71} \ ^{*}_{-}$	$3.67 \ {}^{+}_{-} \ {}^{0.99}_{0.87} \ {}^{*}_{-}$	$4.23\pm0.75^*$	161.3					
$\} 0.22/3$	$12.0 \pm 0.7 *$	$12.3\ \pm 1.3\ ^{*}$	$12.3\ \pm 1.4\ *$	11.6 \pm 1.4 *	11.7 ± 1.3 *	172.1					
)	$15.89 \pm 0.35 \ ^*$	$15.43\pm0.66^*$	$16.53\pm0.72^*$	$16.07\pm0.70^*$	$15.90 \pm 0.63^{*}$	182.7					
	$16.03 \pm 0.21 \ ^{*}$	$16.30\pm0.39^*$	$16.17 \pm 0.41^{*}$	$16.09 \pm 0.42^{*}$	$15.76 \pm 0.36^{*}$	188.6					
	16.56 ± 0.48	16.60 ± 0.99	$16.11 \pm 0.92 \ ^{*}$	$16.64\pm1.00^*$	$17.10 \pm 0.90 \ ^{*}$	191.6					
26 4/24	16.90 ± 0.31	18.59 ± 0.75	$16.22 \pm 0.57 \ ^{*}$	$17.04\pm0.60^*$	$16.61 \pm 0.54 \ ^{*}$	195.5					
20.4/24	16.75 ± 0.30	16.32 ± 0.67	$16.49 \pm 0.58 \ ^{*}$	$17.39 \pm 0.57^{*}$	$16.90 \pm 0.52 \ ^{*}$	199.5					
	17.00 ± 0.41	18.48 ± 0.92	$16.01 \pm 0.84 \ ^{*}$	$17.37\pm0.82^*$	$16.65 \pm 0.71 \ ^{*}$	201.6					
	16.78 ± 0.31	15.97 ± 0.64	$17.00 \pm 0.60 \ ^{*}$	$17.56 \pm 0.59^{*}$	$16.79 \pm 0.54 \ *$	204.9					
J	17.13 ± 0.25	17.77 ± 0.57	$17.33 \pm 0.47 \ ^{*}$	$16.35\pm0.47^*$	$17.36 \pm 0.43 \ ^{*}$	206.6					

Lepton

universality

 $\begin{array}{c} \mathcal{B}(W \rightarrow hadrons) \\ [\%] \end{array}$

 $67.15 \pm 0.40^{*}$

 $67.45 \pm 0.48^{*}$

 $67.50 \pm 0.52^{*}$

 67.91 ± 0.61

 67.49 ± 0.28

15.0/11

pre-LHC

from LEP, SLAC, Tevatron,...

we know a lot about the SM!

	\sqrt{s}		Average		1	\sqrt{s}		Average						<u>.</u>						
	(GeV)	Quantity	value	SM	Δ	(GeV)	Quantity	value	SM	Δ	W	ithout lep	ton univer	rsality						
	130	$\sigma(q\overline{q})$	82.1±2.2	82.8	-0.3	192	$\sigma(q\overline{q})$	22.05 ± 0.53	21.24	-0.10		$v^2/N_{\rm H}$	x = 32.6/	27			% of	δm	$_W$ (MeV	7)
	130	$\sigma(\mu^+\mu^-)$	$8.62 {\pm} 0.68$	8.44	-0.33	192	$\sigma(\mu^+\mu^-)$	$2.92{\pm}0.18$	3.10	-0.13		$\frac{\lambda}{[O, V]}$	$\frac{11}{10} = \frac{102.0}{100}$	0.0001	Backg	round I	$V \rightarrow e \nu data$	m_{T} fit	n_T fit	ิช fit
	130	$\sigma(\tau^+\tau^-)$	9.02 ± 0.93	8.44	-0.11	192	$\sigma(\tau^+\tau^-)$	2.81 ± 0.23	3.10	-0.05	$m_{\rm Z}$	[GeV]	91.1870±	0.0021	Duckg	iouna ,		1101 110	<i>P1</i> 110	<u><u><u></u></u><u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u><u></u></u></u>
	130	$A_{FB}(\mu^+\mu^-)$	0.694 ± 0.060	0.705	0.012	192	$A_{FB}(\mu^+\mu^-)$	0.553 ± 0.051	0.566	0.019	$\Gamma_{\rm Z}$	[GeV]	$2.4952~\pm$	0.0023	W -	$\rightarrow \tau \nu$	0.93 ± 0.03	2	2	2
	130	$A_{FB}(\tau^+\tau^-)$	0.663 ± 0.076	0.704	0.012	192	$A_{FB}(\tau^+\tau^-)$	0.615 ± 0.069	0.566	0.019	σ_1^0	[nb]	$41.541 \pm$	0.037	Hadror	nic jets	0.25 ± 0.15	8	9	7
	136	$\sigma(q\overline{q})$	66.7 ± 2.0	66.6	-0.2	196	$\sigma(q\overline{q})$	20.53 ± 0.34	20.13	-0.09	D^0	[~]	$20.804 \perp$	0.050	7/*	J	0.94 ± 0.01	- 1	1	0
	136	$\sigma(\mu^+\mu^-)$	8.27±0.67	7.28	-0.28	196	$\sigma(\mu^+\mu^-)$	2.94 ± 0.11	2.96	-0.12	$n_{\rm e}$		20.804 ±	0.0	Z/γ	$\rightarrow ee$	0.24 ± 0.01	1	1	0
	136	$\sigma(\tau \tau)$	7.078 ± 0.820	7.279	-0.091	196	$\sigma(\tau \ \tau)$	2.94 ± 0.14	2.96	-0.05	R^0_μ		20,000,000,000,000		To	tal	1.42 ± 0.15	8	9	7
	130	$A_{FB}(\mu^+\mu^-)$	0.708 ± 0.000	0.084	0.013	190	$A_{FB}(\mu^+\mu^-)$	0.581 ± 0.031	0.502	0.019	R^0	and the second	BYALS N.							
-	161	$A_{FB}(7,7)$	0.755 ± 0.000	0.000	0.014	200	$A_{FB}(7,7)$	0.505 ± 0.044	0.502	0.019	a series									
	161	$\sigma(qq)$	37.0 ± 1.1 4.61 ±0.36	- 35.2 - 4.61	-0.1	200	$\sigma(qq)$	19.25 ± 0.52 3.02 ± 0.11	19.09	A Same and a	a share a			•						
	161	$\sigma(\mu^{-}\mu^{-})$	5.67 ± 0.54	4.01	-0.18	200	$\begin{bmatrix} \sigma(\mu^+ \mu^-) \\ \sigma(\tau^+ \tau^-) \end{bmatrix}$	3.02 ± 0.11	a								without	lopton un	ivorgali	1.7
	161	$A_{\rm FR}(\mu^+\mu^-)$	0.538 ± 0.067	0.609	0.017	200	Applet										without	lepton un	Iversan	бy
	161	$A_{FB}(\tau^+\tau^-)$	0.646 ± 0.077	0.609	0.016	200	Arts													
	172	$\sigma(q\overline{q})$	29.23 ± 0.99	28.74	-0.12	202											$\Gamma_{\rm had}$ [MeV] 1745	8 ± 2.7	
	172	$\sigma(\mu^+\mu^-)$	$3.57 {\pm} 0.32$	3.95	-0.16	202	σ								oton]	$\Gamma_{\rm ev}$ [MeV]	83	$92 \pm 0.1^{\circ}$	2
	172	$\sigma(\tau^+\tau^-)$	$4.01 {\pm} 0.45$	3.95	-0.05	202	$\sigma(r)$								sality		$\Gamma = [M, V]$	00	00 ± 0.1	0
	172	$A_{FB}(\mu^+\mu^-)$	$0.675 {\pm} 0.077$	0.591	0.018	202	A_{FB}								$3(W \rightarrow hadrons)$		$\Gamma_{\mu\mu}$ [MeV]	83	99 ± 0.1	8
	172	$A_{FB}(\tau^+\tau^-)$	$0.342{\pm}0.094$	0.591	0.017	202	$A_{FB}(\mathbf{i})$							[%]	[%]		$\Gamma_{\tau\tau}$ [MeV]	84	08 ± 0.2	2
	183	$\sigma(q\overline{q})$	24.59 ± 0.42	24.20	-0.11	205	$\sigma(q, \sigma)$					المنظرة المبتني المنظرين المن المنظر المنظر المنظرين المنظري	10.91 ± 0.26	* $11.15 \pm 0.38^{*}$	$67.15 \pm 0.40^{*}$					
	183	$\sigma(\mu^+\mu^-)$	$3.49 {\pm} 0.15$	3.45	-0.14	205	$\sigma(\mu^+)$	-			ر مربعه این محمد است 1.3 محمد المربع المربع	10.55 ± 0.3 10.78 ± 0.3	10.65 ± 0.27 10.03 ± 0.31	* $11.46 \pm 0.43^{\circ}$ * $11.89 \pm 0.45^{\circ}$	$67.45 \pm 0.48^{\circ}$ $67.50 \pm 0.52^{\circ}$					
	183	$\sigma(\tau^+\tau^-)$	3.37 ± 0.17	3.45	-0.05	205	$\sigma(\tau^+\tau)$		34.7.2	1000	OPA	L 10.40 ± 0.3	10.05 ± 0.01 35 10.61 + 0.35	$5 11.18 \pm 0.48$	67.91 ± 0.61					
	183	$A_{FB}(\mu^+\mu^-)$	0.559 ± 0.035	0.576	0.018	205	$A_{FB}(\mu^+)$	and the second second	10,00	0.020	LEF	10.66 ± 0.1	$17 10.60 \pm 0.15$	$5 11.41 \pm 0.22$	67.49 ± 0.28					
	183	$A_{FB}(\tau^+\tau^-)$	0.608 ± 0.045	0.576	0.018	205	$A_{FB}(\tau^{+}\tau)$	0.042	0.553	0.019	$\chi^2/d.c$	o.f.	6.8/9		15.0/11					
	189	$\sigma(q\overline{q})$	22.47 ± 0.24	22.156	-0.101	207	$\sigma(q\overline{q})$	17.49 ± 0.26	17.42	-0.08				•						
	189	$\sigma(\mu \cdot \mu)$	3.123 ± 0.076	3.207	-0.131	207	$\sigma(\mu \cdot \mu) = \sigma(\pi^+ \pi^-)$	2.595 ± 0.088	2.623				\sqrt{s}		WV	V cross-secti	ion (pb)		$\chi^2/d.c$	o.f.
	180	$\frac{O(1 + \tau)}{\Lambda_{\text{PP}}(u^+ u^-)}$	3.20 ± 0.10 0.560±0.021	0.560	-0.048	207	$\begin{bmatrix} o(\tau + \tau) \\ \Lambda_{\rm PP}(u^+ u^-) \end{bmatrix}$	2.00 ± 0.11 0.549 \pm 0.097	2.02	-0.04			(GeV)	ALEPH	DELPHI	L3	OPAL	LEP		
	189	$A_{\rm FB}(\mu^+\mu^-)$	0.509 ± 0.021 0.596 ± 0.026	0.509	0.019	207	$\begin{bmatrix} \mathbf{A}_{\mathrm{FB}}(\mu^+\mu^-) \\ \mathbf{A}_{\mathrm{FB}}(\tau^+\tau^-) \end{bmatrix}$	0.542 ± 0.027 0.564 ±0.037	0.552	0.020			161.3	$4.23\pm0.75^*$	$3.67 \ {}^{+}_{-} \ {}^{0.99}_{0.87} \ {}^{*}_{-}$	2.89 + 0.8 - 0.7	32 * 3.62 + 0.94 * - 0.84	3.69 ± 0.45	* } 1.3	/ 3
L	103		0.000±0.020	0.003	0.010	201	F.B(/ /)	0.004±0.001	0.001	0.013	J		172.1	11.7 ± 1.3 *	11.6 \pm 1.4 *	12.3 ± 1.4	4 * 12.3 ± 1.3 *	$12.0 \hspace{0.2cm} \pm \hspace{0.2cm} 0.7$	* } 0.22	2/ 3
					~~ ^	-							182.7	$15.90 \pm 0.63^{*}$	$16.07\pm0.70^*$	16.53 ± 0.7	72^* $15.43 \pm 0.66^*$	15.89 ± 0.35	*	
					% of	δm_W	(MeV)						188.6	$15.76 \pm 0.36^{*}$	$16.09\pm0.42^*$	16.17 ± 0.4	41* $16.30 \pm 0.39^*$	16.03 ± 0.21	*	
			Backgro	ound W	$\rightarrow \mu \nu$ data	m_T fit	p_T nt p_T nt						191.6	17.10 ± 0.90 *	$16.64\pm1.00^*$	16.11 ± 0.9	$2 * 16.60 \pm 0.99$	16.56 ± 0.48		
			$Z/\gamma^{+} - W$	$\rightarrow \mu\mu$	0.0 ± 0.3	0	11 5 7 9						195.5	16.61 ± 0.54 *	$17.04\pm0.60^*$	16.22 ± 0.5	$57 * 18.59 \pm 0.75$	16.90 ± 0.31		
			$W \rightarrow Decays in$	$\tau \nu = 0$	0.09 ± 0.02 0.3 ± 0.9	1	13 3						199.5	16.90 ± 0.52 *	$17.39\pm0.57^*$	16.49 ± 0.5	$68 * 16.32 \pm 0.67$	16.75 ± 0.30	26.4/2	24
			Hadroni	c iets	0.0 ± 0.2 0.1 ± 0.1	2	3 4						201.6	16.65 ± 0.71 *	$17.37\pm0.82^*$	16.01 ± 0.8	$4 * 18.48 \pm 0.92$	17.00 ± 0.41		
			1100010111		~· ··-	-	~ +						1 1				1	1		1

204.9

206.6

 16.79 ± 0.54 *

 17.36 ± 0.43 *

 $17.56 \pm 0.59^{*}$

 $17.00 \pm 0.60 \ ^{*}$

 $16.35 \pm 0.47^*$ $17.33 \pm 0.47^*$

 15.97 ± 0.64

 17.77 ± 0.57

 16.78 ± 0.31

 17.13 ± 0.25

Cosmic rays 0.05 ± 0.05

Total

 7.9 ± 0.4

2

9

2

1

19 11

pre-LHC: flavor universality

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

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



pre-LHC: flavor universality





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 $W_{r}Z$ concerns:

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 suppresent the suppresent $G_{F}|_{quarks} - 1 < 10^{-3}$

not in their contact interactions:

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

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

$$c_L rac{(ar q_L \gamma_\mu q_L)^2}{f^2}$$
 Tevatron:



pre-LHC: RH-quarks not well tested

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

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



$$f/\sqrt{c_R^{(u)}} \ge 1 \text{ TeV}$$

 $f/\sqrt{c_R^{(d)}} \ge 0.5 \text{ TeV}$



$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$
$$0 \leqslant \delta g_{b_R} \leqslant 0.2$$

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



Independent 4-quark operators:

full list

$\mathcal{O}_{dd}^{(1)}$	=	$(\bar{d}_R \gamma^\mu d_R) (\bar{d}_R \gamma_\mu d_R)$	
$\mathcal{O}_{ud}^{(1)}$	=	$(\bar{u}_R \gamma^\mu u_R) (\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}_{td}^{(1)} = (\bar{t}_R \gamma^\mu t_R) (\bar{d}_R \gamma_\mu d_R)$
$\mathcal{O}_{uu}^{(1)}$	=	$(\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma_\mu u_R)$	$\mathcal{O}_{ut}^{(1)} = (\bar{u}_R \gamma^\mu u_R) (\bar{t}_R \gamma_\mu t_R)$
			$\mathcal{O}_{tt}^{(1)} = (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma_\mu t_R)$
$\mathcal{O}_{qu}^{(1)}$	=	$(\bar{q}_L\gamma^\mu q_L)(\bar{u}_R\gamma_\mu u_R)$	$\mathcal{O}_{qt}^{(1)} = (\bar{q}_L \gamma^\mu q_L) (\bar{t}_R \gamma_\mu t_R)$
$\mathcal{O}_{qd}^{(1)}$	=	$(\bar{q}_L\gamma^\mu q_L)(\bar{d}_R\gamma_\mu d_R)$	
$\mathcal{O}_{qq}^{(1)}$	=	$(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$	
$\mathcal{O}_{qq}^{(3_W)}$	=	$(\bar{q}_L \gamma^\mu \tau^I q_L) (\bar{q}_L \gamma_\mu \tau^I q_L)$	
$\mathcal{O}_{qq}^{(8_F)}$	=	$(\bar{q}_L \gamma^\mu T^P q_L) (\bar{q}_L \gamma_\mu T^P q_L)$	
$\mathcal{O}_{uu}^{(8)}$	=	$(\bar{u}_R\gamma^{\mu}T^A u_R)(\bar{u}_R\gamma_{\mu}T^A u_R)$	$\mathcal{O}_{ut}^{(8)} = (\bar{u}_R \gamma^\mu T^A u_R) (\bar{t}_R \gamma_\mu T^A t_R)$
$\mathcal{O}_{dd}^{(8)}$	=	$(\bar{d}_R\gamma^\mu T^A d_R)(\bar{d}_R\gamma_\mu T^A d_R)$	
$\mathcal{O}_{ud}^{(8)}$	=	$(\bar{u}_R \gamma^\mu T^A u_R) (\bar{d}_R \gamma_\mu T^A d_R)$	$\mathcal{O}_{td}^{(8)} = (\bar{t}_R \gamma^\mu T^A t_R) (\bar{d}_R \gamma_\mu T^A d_R)$
$\mathcal{O}_{qq}^{(8_C)}$	=	$(ar{q}_L\gamma^\mu T^A q_L)(ar{q}_L\gamma_\mu T^A q_L)$	
$\mathcal{O}_{qu}^{(8)}$	=	$(\bar{q}_L\gamma^{\mu}T^Aq_L)(\bar{u}_R\gamma_{\mu}T^Au_R)$	$\mathcal{O}_{qt}^{(8)} = (\bar{q}_L \gamma^\mu T^A q_L) (\bar{t}_R \gamma_\mu T^A t_R)$
$\mathcal{O}_{qd}^{(8)}$	=	$(\bar{q}_L\gamma^{\mu}T^Aq_L)(\bar{d}_R\gamma_{\mu}T^Ad_R)$	

but many of them are not relevant for LHC dijets

Relevant 4-quark operators:

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

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

because of our flavor assumption, jj # ss, cc, ...

$$uu \to uu$$
$$ud \to ud$$
$$dd \to dd$$

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

Angular distributions and exp. results:

CMS, 2.2 fb⁻¹





One at a time Bounds:

best bounds up to date



Compositeness Bounds:

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

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

$$u_R \sim (3, 1, 2/3, 1, 1, 2)$$

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

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

$$\left| \begin{array}{c} \hline \Omega_F \\ \hline$$

 $d_R \sim$



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



$$G^{\prime A}_{\mu} \left[g_L \bar{q}_L T^A \gamma^{\mu} q_L + g_R \bar{q}_R T^A \gamma^{\mu} q_R \right]$$

massive gluon solving *A*_{*FB*} **of tops?** not if heavy



Is bounds about the transition the state of

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Is boundsaonbe transited twister within a mali property (I, B, 1,13,32)1, 3,

 $\frac{g_{44}^{(8)}}{g_{44}^{(8)}} = \frac{g_{45}^{(8)}}{g_{45}^{(8)}} = \frac{g_{45}^{(8)}}{g_{45}^{(8)}$

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e willwoeus figure 1. Figure 1. High the sense of the sense will we have been a sense of the sen $\frac{q_L, u_R, d_{Rq_L}, \pi_R^3.7d_R^2}{134.7} = \frac{37}{14} = \frac{27}{14} = \frac{27}{1$ Table 2: Conficient Coldmonstration of Fratos induced symptotic area and the second symptotic area and the second second

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 $ho_{\mathcal{G}}$

 $g_{44}^{(8)} / g_{36}^2 - g_{37}^{(8)} / g_{47}^2 - g_{47}^{(8)} / g_{47}^2 - g_{47}^{(8)} / g_{47}^2 - g_{4$

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 $\frac{q_L, u_R, d_{Rq_L}, \pi_R^3, 7d_R^2}{1 \text{ symmetry is U} = c} = \frac{37}{10} \frac{7}{10} \frac{7}{10}$ Table 2: Conficient Coefficients of the oneratorie of the officient of the oneratories of

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best bound up to date

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Some extra motivation

Top Forward-Backward Asymmetry: CDF and D0







many many models proposed so far

only a handful are not ruled out already...



Top AFB:



Servant et al.

Top AFB:



Servant et al.

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

$$\frac{c_A^{(8)}}{\Lambda^2} \lesssim \frac{0.2}{\text{TeV}^2} \,\mathbf{X}$$

Top AFB: relaxing flavor assumption



Top AFB: relaxing flavor assumption



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