Outline

◆ Why is the **top** quark interesting, phenomenologically?

  Ex.: *(i)* Mass & Xsection *(vs. theory)* *(ii)* Asymmetries *(AFB, A_c, A_l)*.

◆ Why is the **top** quark interesting, theoretically?

  The linkage to electroweak (EW) symmetry breaking;

  Battle for naturalness: *(i)* direct searches, \( t \)-partners \& \( t \)-resonances; *(ii)* indirect searches, Higgs.

◆ The up flavor connection *(implications for searches \w non-degenerate squarks)*.

◆ **Top** \(& light Higgs\) living dangerously.

◆ Conclusions.

*Impossible to cover everything: subjective talk, focus on last few years stuff.*
Why is the top quark interesting phenomenologically?
Top (exp’) uniqueness, mass

• The heaviest point like particle known to exist.

\[ m_t \approx 10^5 \times m_u \approx 180 \times m_{pr} \approx 10^{-22} \text{ gr} \]
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- The heaviest point-like particle known to exist.

\[ m_t \approx 10^5 \times m_u \approx 180 \times m_{pr} \approx 10^{-22} \text{ gr} \]
Top (exp’) uniqueness, spin

- $t \rightarrow$ only quark to decay before it hadronizes.

- Direct access to its spin & charge (its production & decay info’).
Some interesting pheno’-exp’ facts

◆ Tevatron: **top** mass now known to 0.5%, \( m_t = 173.2 \pm 0.9 \text{ GeV} \)

Tevatron combination (11).

Standard Model (SM): **top** coupling to Higgs is perturbative but LARGE: 
\[ y_t \simeq 1 \]

Quantum effects (virtual **tops**) \( \Rightarrow \) dramatic impact on EW & flavor phys.:
\[ \frac{2N_c y_t^2}{16\pi^2} \simeq 5\% \]

Theory: **t-Xsection** (Tevatron) now known to NNLO (+NNLL resum’)

\[
\sigma_{\text{tot}}^{\text{res}} = 7.067 \pm 0.143_{-0.232}^{+0.166} \text{ (2.9\%)} \text{ [scales]} \pm 0.186_{-0.122}^{+0.088} \text{ (2.6\%)} \text{ [pdf]} 
\]

Bärnreuther, Czakon & Mitov (12).
Some interesting pheno’-exp’ facts

♦ Tevatron: top mass now known to 0.5%, $m_t = 173.2 \pm 0.9$ GeV

- Approach 3 of 3: Extract $M_{top}$ from the top cross-section.
- Theoretically very good control.
- Extraction not as sensitive to $M_{top}$: $(\delta M_{top}/M_{top}) = \pm 3\%$.
- A good independent cross-check. So far well consistent with direct measurements.

Tevatron combination (11).

- Flavor phys.: $\frac{2N_c y_t^2}{16\pi^2} \approx 5\%$

- Independent F/R scales
- MSTW2008NNLO
- $m_t = 173.3\text{ GeV}$

Best prediction at NNLO+NNLL

Theory: $t$-Xsection (Tevatron) now known to NNLO (+NNLL resum’)

$\sigma_{tot}^{\text{res}} = 7.067^{+0.143 (2.0\%)}_{-0.232 (3.3\%)} \text{ [scales]}^{+0.186 (2.6\%)}_{-0.122 (1.7\%)} \text{ [pdf]}$

Bärnreuther, Czak & Mitov (12).
Some interesting pheno’-exp’ facts

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Tevatron combination (11).

LARGE: \( y_t \approx 1 \)

\[
\frac{2N_c y_t^2}{16\pi^2} \approx 5\%
\]

But possibly one step from shedding light on a Tevatron anomaly!

Theory: \( t \)-Xsection (Tevatron) now known to NNLO (+NNLL resum’)

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\sigma_{tot}^{res} = 7.067^{+0.143}_{-0.232} (2.9\%) \quad [\text{scales}] \quad +0.186^{+0.122}_{-0.232} (2.6\%) \quad [\text{pdf}]
\]

Bärnreuther, Czakon & Mitov (12).
Tevatron’s \( t\bar{t} \) forward backward asymmetry.

2 kind of anomalous asymmetries (6 measurements):

(i) Top forward backward asymmetry \((A_{FB})\).

- Combined CDF+DO results: \( A_{FB}^{\text{inclusive}} \approx (18\pm4)\% \) \( \text{post-Moriond 2012} \)
- \( A_{FB}^{>450\text{GeV}} \approx (28\pm6)\% \) \( \text{in ttbar rest frame} \)

QCD+EW state of the art: \( A_{FB}^{[\text{inclusive}]>[450\text{GeV}]} \approx [6.6|10]\% \pm?? \) (NLOx30%?)

Delaunay, Top physics workshop, CERN 12.

(ii) Lepton asymmetry \((A_\ell)\).

- CDF with \( 8.7 \text{ fb}^{-1} \)
  - \( A_\ell = 6.6 \pm 2.5\% \)
- D0 with \( 5.4 \text{ fb}^{-1} \)
  - \( A_\ell = (11.8 \pm 3.2)\% \) \( \text{(NLOx30%?)} \)
- SM
  - \( A_\ell \approx 4\% \)
**AFB & $A_{\ell}$ within the SM**

◆ Contribution to $AFB$ start at NLO QCD, i.e. $\sim(\alpha_s)^3$. Kuhn & Rodrigo (98)

Higher order soft effects probed. No essential new effects (beyond Kuhn & Rodrigo). Awaiting for real EW calculation & most importantly the NNLO answer!

Kuhn, Moch, Penin & Smirnov (01); Almeida, Sterman, Wogelsang (08); Melnikov, Schultze (09); Ahrens, Ferroglia, Neubert, Pecjak, Yang; Kuhn & Rodrigo; Hollik, Pagani (11); Manohar, Trott; Skands, Webber, Winter (12).

QCD+EW state of the art: $A_{FB}[\text{inclusive}|>450\text{GeV}] \approx [6.6|10]\% \pm ?? (\text{NLOx}30\%)$

◆ Contribution to $A_{\ell}$, now known to full NLO. Bernreuther & Si(10,12); Campbell & Ellis (12).

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- $A_{\ell} = 6.6 \pm 2.5\%$

D0 with 5.4 fb$^{-1}$

- $A_{\ell} = (11.8 \pm 3.2)\%$

New update, D0, this conf.

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**◆ Contribution to AFB start at NLO QCD, i.e. \( \sim (\alpha_S)^3 \).** Kuhn & Rodrigo (98)

**\( A_\ell \) vs. AFB “uncorrelation” plots** (DØ, CERN Top Phys. workshop, 5/12)

**◆ Co**
- 100,000 pseudo experiments made from signal and background simulation
- Results from actual experiment shown in red
- Left: Detector level results; Right: Unfolded results

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**AFB & $A_l$ within the SM**

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- **$A_l$ vs. $AFB$ “uncorrelation” plots** (D0, CERN Top Phys. workshop, 5/12)

  ![Graphs showing correlation plots](image)

- **Bottom line:** among few serious anomalies, perturbative nature, should able to get sharp predictions within SM!

- **Co**
  - 100,000 pseudo experiments made from signal and background simulation
  - Results from actual experiment shown in red
  - Left: Detector level results; Right: Unfolded results

  - $A_l = 6.6 \pm 2.5\%$
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  - $A_l \approx 4\%$

  New update, D0, this conf.
Some features of new physics (NP) interpretations*

◆ Top asymmetry is special, not only top sector is probed:
Large asymmetry (PDFs) => new dynamics couple to both $u\bar{u}$ & $t\bar{t}$ .
(furthermore the lepton asymmetry need not be related to top physics) Falkowski, GF & Schmaltz (11)

◆ Challenged by agreement \ w SM Xsec' => SM-NP interference.

◆ Two broad classes of models: (i) hard physics; (ii) on shell physics.

* Hundreds of papers, just give brief subjective impression.
Relevant observables (constraints) @ the LHC

◆ Charged asymm’ $A_c$, large errors, consistent \w SM,

$$A_c(l+jets) = -0.018 \pm 0.028 \pm 0.023$$
$$A_c(\text{dilept.}) = 0.057 \pm 0.024 \pm 0.015$$
$$A_c(\text{comb.}) = 0.029 \pm 0.018 \pm 0.014$$

MC@NLO: $0.006 \pm 0.002$

◆ $tt\bar{t}$ spectrum finally approaching the 2TeV barrier, both differential & cumulative distributions consistent \w SM (more below):

$$S = \frac{\int_{m_{tt}>1 \text{TeV/c}^2} d\sigma_{SM+NP} d m_{tt}}{\int_{m_{tt}>1 \text{TeV/c}^2} d\sigma_{SM} d m_{tt}} < 2.6 \text{ at 95\% CL}$$

CMS:1204.2488.
Hard physics explanation (e.g.: heavy axigluon-KKgluon variety)

A rough idea is obtained from effective field theory (EFT) analysis:

\[ \mathcal{L}_{\text{eff}} = \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i \equiv \sum_i c_i \mathcal{O}_i, \quad \mathcal{O}_A^8 = (\bar{u}\gamma_\mu \gamma^5 T^a u)(\bar{t}\gamma^\mu \gamma^5 T^a t), \quad \mathcal{O}_V^8 = (\bar{u}\gamma_\mu T^a u)(\bar{t}\gamma^\mu T^a t). \]

Issues: spectrum; dijet; flavor \( g_{u\bar{u}} = -g_{t\bar{t}} \).


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\]

Issues: spectrum; dijet; flavor \( g_{u\bar{u}} = -g_{t\bar{t}} \).

On shell (e.g.: “s-channel”, ”t-channel” models)

Impossible to cover all models, common exchange light particles.

Issues: spectrum; dijet; flavor; \( A_c \); \( t\bar{t} + j \);

& APV (atomic parity violation).

Update by J. Zupan, CERN, Th. colloquium, 6/12.
Near future improvement:

- **LHC**: Progress on $A_c$ & spectrum (more channels, better sys’ & stat’).

- **Tevatron**: looking at $AFB$ vs. $A_l$ as a function of the lepton $p_T$ (since are correlated within the SM)

  Progress \w: Falkowski, Mangano, Martin, GP & Winter.
  See also: Godbole et al. (10); Krohn, et al.; Jung, et al.; Cao et al.; Berger, et al. x2 (11); Fajfer, et al.; Berger, et al. (12);

  "Trade" $AFB$ curve for $A_l$ or look at slope $\Rightarrow$ cleaner extraction:

  \[ A_{TT} = A_{SM} + A_{NP} \]

  RH chiral gluon

  axigluon

  SM

  LH chiral gluon
Why is the \textbf{top} quark interesting theoretically?

(i) Electroweak symmetry breaking.

(ii) The fine tuning problem.

(iii) The (NP) flavor puzzle.
The top & electroweak (EW) breaking

- Coupling to the Higgs => top mass; biggest coupling @ the TeV.
- In most natural models top is linked to EW symmetry breaking.
The top & electroweak (EW) breaking

- Coupling to the Higgs => top mass; biggest coupling @ the TeV.

- In most natural models top is linked to EW symmetry breaking.

Top physics might give insight on the nature of EW breaking.
125 GeV Higgs \rightarrow \text{top} \text{ is } \sim \text{saturating metastability}

\[ m_h > 111 \text{ GeV} + 2.8 \text{ GeV} \left( \frac{m_t - 173.2 \text{ GeV}}{0.9 \text{ GeV}} \right) - 0.9 \text{ GeV} \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 3 \text{ GeV}. \]

See e.g.: Cabibbo, et al.; Hung (79); Elias-Miro, et al. (11); Degrassi et al.; Alekhin et al.; Bezrukov et al. (12)

A raise of < 3% in top Yukawa \Rightarrow \text{weakless universe!}
The top & the fine tuning problem

- Higgs mass & EW scale are sensitive to quantum corrections.

- The most severe problem is due to top coupling:

Assume cutoff $\Lambda = 6$ TeV; $\delta_t m_h^2 = \frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim (1.2\text{TeV})^2$

$m_{h,\text{phys}}^2 = m_{\text{tree}}^2 + \delta_t m_h^2 = m_{\text{tree}}^2 + (1.2\text{TeV})^2 \approx (0.125\text{TeV})^2$

fine tuning of $\sim 1:100$!
Dominant paradigm to solve fine tuning problem

- Extending top sector adding top partners states that due to sym’ contribute to Higgs mass in opposite way => reduce sensitivity.
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\[
\left(\frac{m_W^2}{m_{Pl}^2}\right)_{\text{obs}} \sim \left(\frac{m_H^2 + \delta m_H^2}{m_{Pl}^2}\right) \sim m_W^2 + m_H^2 + H - H - H - H
\]
Dominant paradigm to solve fine tuning problem

- Extending top sector adding top partners states that due to sym’ contribute to Higgs mass in opposite way => reduce sensitivity.

\[ \left( \frac{m_W^2}{m_{P1}^2} \right)_{\text{obs}} \sim \left( \frac{m_H^2 + \delta m_H^2}{m_{P1}^2} \right) \sim m_W^2 + \delta m_H^2 \]

Top physics expected to yield insight on how the fine tuning problem is solved.
So where are those top partners?

(i) SUSY: stop searches & fine tuning;
(ii) Composite Higgs: t’ searches & fine tuning, + top resonance searches;
(iii) Indirect: impact on Higgs couplings.
Squarks & Gluino searches at the LHC

Naively: $\tilde{m}_q \gtrsim 1.5 \text{ TeV}$ $\tilde{m}_g \gtrsim 1 \text{ TeV}$
Squarks & Gluino searches at the LHC

More in R. Sundrum’s talk this afternoon.

Naively: \( \tilde{m}_q \gtrsim 1.5 \text{ TeV} \)

However, nothing to do with naturalness, only 3rd generation partners’ mass matters.

(see e.g.: Barbieri-Giudice (88) & many more since ...)

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(see e.g.: Barbieri-Giudice (88) & many more since ...)
Natural SUSY endures, only now gaining sensitivity to robustly test models

LHC: excluding \( \tilde{m}_t \lesssim 500 \) GeV

MSSM higgs: LEP2 tuning vs. direct stop searches.

\[
\delta m^2_H \big|_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left( m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2 \right) \log \left( \frac{\Lambda}{\text{TeV}} \right)
\]

Composite Higgs

More in A. Pomarol’s talk this afternoon.

LHC: excluding $m_{t'} \lesssim 500$ GeV

Plots from update by: Gillioz, Grober, Grojean, Muhlleitner & Salvioni (12).

See also: Contino, Da Rold & Pomarol (06); Berger, Hubisz & Perelstein; Redi & Tesi; Matsedonskyi, Panico & Wulzer; Marzocca, Serone & Shu, Pomarol & Riva (12).
Partner’s mass & fine tuning?

\[ f = 500 \text{ GeV} \]

Taken from: Redi & Tesi (12) [analyzing the MCH5 of Contino, da Rold, Pomarol, (06)]
Resonances searches & emergence of top jets

(i) Strong dynamics inspired models (composite Higgs, Randall-Sundrum ...) => heavy Kaluza-Klein (KK) resonances, $m_{KK} \gtrsim 1 \text{ TeV}$.
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(ii) Fine tuning solution => New states decay quickly to top pairs.
Resonances searches & emergence of top jets

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(ii) Fine tuning solution \(\Rightarrow\) New states decay quickly to top pairs.

(iii) Since \(m_t \ll m_{\text{KK}}\) the outgoing tops are ultra-relativistic, their products collimate \(\Rightarrow\) top jets.

Agashe, Belyaev, Krupovnickas, GP & Virzi (06); Lillie, Randall & Wang (07).
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Agashe, Belyaev, Krupovnickas, GP & Virzi (06); Lillie, Randall & Wang (07).
Need to distinguish between top & ordinary QCD jet
Need to understand the energy flow inside jet jet shapes or jet substructure

Still learning ...
Important in other direction, e.g. EW phys..
[Butterworth, Davison, Rubin & Salam(08)]
Annual meeting: Boost 2012.
Boosted jets’ angular distribution, angularity $\tau_{-2}$

\[
\frac{d\sigma}{d\theta} \rightarrow \frac{d\sigma}{d\tau_{-2}} \approx 1/\tau_{-2}, \quad \tau_{-2}^{\text{min}} = \left( \frac{m_J}{2E_J} \right)^3 (\tau_{-2} \sim \sum_{i \in J} E_i \theta_i^4)
\]

Almeida, et al. (10)

jets with mass $\in (90, 120)$ GeV/c, $p_T > 400$ GeV/c
Boosted jets’ angular distribution, angularity $\tau_{-2}$

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Almeida, et al. (10)

qualitative success of 2-body LL approx’

jets with mass $\in (90, 120)$ GeV/c$^2$, $p_T > 400$ GeV/c

Alon, Duchovni, GP $\Rightarrow$ CDF (11).
Left: The W tagging algorithm uses a jet “pruning” technique. Right: the size of the mass shift in anti-kt $R = 0.6$ jets \w& \wo pileup. For rev. see: Boost 2011 writeup,1201.0008.
**tt resonance searches**

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**All-Hadronic Results**

- Shape analysis performed using several signal models
- Z' narrow and wide resonances
- KK Gluon production
- Mass ranges up to ~2 TeV are excluded

Recently submitted for publication in JHEP


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**Bottom line:** \( m_X \gtrsim 2 \text{ TeV} \) (still long way to go ...)

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![Graph showing upper limit on cross-section times branching ratio as a function of tt invariant mass at CMS, L = 5 fb\(^{-1}\) at \(\sqrt{s} = 7\) TeV. The graph includes KK Gluon Assumption and observed (95% CL) expected (95% CL) ± 1 s.d. Expected ± 2 s.d. Expected. The shaded band indicates the uncertainty in the normalization of the Standard Model prediction, but does not include the shape uncertainty or the impact of uncertainties on reconstructed objects. The variable bin size is chosen to match the mass resolution for a resonant signal.](image-url)
Indirect searches via Higgs precision tests (HPTs)

Beginning of HPTs era, sensitive to partners mass & couplings:

\[
\frac{\text{Measured Higgs rate}}{\text{SM prediction}} = 1.02 \pm 0.15 \quad \text{Giardino, et al. (5/7)}
\]

However, it’s pretty hard to raise di-photon rate via t-partners in “real” natural theories ...

Falkowski (07); Low & Vichi (10); Azatov & Galloway (11); Gillioz, et al.; Blum, et al.; Carena, et al.; Corbett, et al.; Benbrik, et al.; Arbey, et al. (12);
The up flavor connection
uFCNC data, a crucial test of NP structure

- General: dominant NP constraints coming from extended strong sector, need not “talk” to down & charged lepton sector:

\[ \begin{align*}
D^0 & \quad \tilde{g} \quad \tilde{g} \quad \tilde{g} \\
\text{c} & \quad \text{u} \\
\text{c} & \quad \text{u}
\end{align*} \]

\[ \begin{align*}
D^0 & \quad G^{(1)} \quad \tilde{D}^0 \\
\text{c} & \quad \text{u} \\
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- Down & lepton flavor violation maybe removed via alignment, anarchic NP is diagonal in down/charged-lepton mass basis.

[ Nir & Seiberg (93); Fitzpatrick, GP & Randall (08); Csaki, GP, Surujon, & Weiler (09)].

careful domino alignment
uFCNC data, a crucial test of NP structure

General: dominant NP constraints coming from extended strong sector, need not “talk” to down & charged lepton sector:

\begin{align*}
D^0 & \quad \tilde{g} \quad \tilde{g} \\
\bar{D}^0 & \quad \tilde{g} \quad \tilde{g}
\end{align*}

\text{SUSY}

\begin{align*}
D^0 & \quad t \quad t \\
\bar{D}^0 & \quad t \quad t
\end{align*}

\text{RS}

Down & lepton flavor violation maybe removed via alignment, anarchic NP is diagonal in down/charged-lepton mass basis.

[Nir & Seiberg (93);
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The importance of up-type FCNC

What if down/lepton alignment is at work?
The importance of up-type FCNC

What if down/lepton alignment is at work?

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on $\Lambda$ in TeV ($c_{ij} = 1$)</th>
<th>Bounds on $c_{ij}$ ($\Lambda = 1$ TeV)</th>
<th>Observables</th>
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<td>Re</td>
<td>Im</td>
<td>Re</td>
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<td>$3.2 \times 10^5$</td>
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</tbody>
</table>

| $\bar{L}_i \sigma^{\mu\nu} e_{Rj} H F_{\mu\nu}$ | $1.7 \times 10^4$ | $3.3 \times 10^2$ | $2.6 \times 10^2$ | $Br(\mu \rightarrow e\gamma)$ |
| $\bar{\mu} \gamma^\mu P_L e$ | $1.9 \times 10^2$ | | | $\frac{\sigma(\mu^- Ti\rightarrow e^- Ti)}{\sigma(\mu^- Ti\rightarrow capture)}$ |

Flavor anecdotes

- System see Ref. [1]. The $\frac{\sigma(\mu^- Ti\rightarrow e^- Ti)}{\sigma(\mu^- Ti\rightarrow capture)}$
## The importance of up-type FCNC

**What if down/lepton alignment is at work?**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on $\Lambda$ in TeV ($c_{ij} = 1$)</th>
<th>Bounds on $c_{ij}$ ($\Lambda = 1$ TeV)</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Re</td>
<td>Im</td>
<td>Re</td>
</tr>
<tr>
<td>$(s_L\gamma^\mu u_L)$</td>
<td>$3.0 \times 10^2$</td>
<td>$1.6 \times 10^4$</td>
<td>$9.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>$(c_R u_L)(s_L u_R)$</td>
<td>$1.8 \times 10^4$</td>
<td>$3.2 \times 10^5$</td>
<td>$6.9 \times 10^{-9}$</td>
</tr>
<tr>
<td>$(\bar{c}_L \gamma^\mu u_L)^2$</td>
<td>$1.2 \times 10^3$</td>
<td>$2.9 \times 10^3$</td>
<td>$5.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>$(\bar{c}_R u_L)(\bar{c}_L u_R)$</td>
<td>$6.2 \times 10^3$</td>
<td>$1.5 \times 10^4$</td>
<td>$5.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$(\bar{b}_L \gamma^\mu b_L)^2$</td>
<td>$5.1 \times 10^2$</td>
<td>$9.3 \times 10^2$</td>
<td>$3.3 \times 10^{-6}$</td>
</tr>
<tr>
<td>$(\bar{t}_L \gamma^\mu t_L)^2$</td>
<td>$1.9 \times 10^4$</td>
<td>$3.6 \times 10^3$</td>
<td>$5.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>$(\bar{t}_L \gamma^\mu u_L)^2$</td>
<td>$1.1 \times 10^2$</td>
<td>$7.6 \times 10^{-5}$</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$(L_L \gamma^\mu \phi_\mu)$</td>
<td>$1.7 \times 10^4$</td>
<td>$3.3 \times 10^2$</td>
<td></td>
</tr>
<tr>
<td>$(\bar{L}<em>L \gamma^\mu \phi</em>\mu)$</td>
<td>$3.3 \times 10^4$</td>
<td>$3.3 \times 10^2$</td>
<td></td>
</tr>
<tr>
<td>$(\bar{L}_L \gamma^\mu L_L)$</td>
<td>$9.0 \times 10^3$</td>
<td>$9.0 \times 10^3$</td>
<td></td>
</tr>
<tr>
<td>$(\bar{L}<em>L \gamma^\mu \phi</em>\mu)$</td>
<td>$1.9 \times 10^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Same sign $t$'s
What if down/lepton alignment is at work?

### Operators and Bounds

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<tr>
<th>Operator</th>
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<th>Bounds on $c_{ij}$ ($\Lambda = 1$ TeV)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>s_L\gamma^\mu u_L</td>
<td>^2$</td>
<td>$8.6 \times 10^4$</td>
</tr>
<tr>
<td>$(\bar{c}_R u_L)(\bar{c}_L u_R)$</td>
<td>$1.8 \times 10^4$</td>
<td>$6.9 \times 10^{-9}$</td>
<td>$\Delta m_K;</td>
</tr>
<tr>
<td>$(\bar{c}_L \gamma^\mu u_L)^2$</td>
<td>$1.2 \times 10^3$</td>
<td>$5.6 \times 10^{-7}$</td>
<td>$\Delta m_D;</td>
</tr>
<tr>
<td>$(\bar{c}_R u_L)(\bar{c}_L u_R)$</td>
<td>$6.2 \times 10^3$</td>
<td>$1.0 \times 10^{-7}$</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$(\bar{t}_L \gamma^\mu u_L)^2$</td>
<td>$1.7 \times 10^4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\bar{u}_L \gamma^\mu P_L e)$</td>
<td>$3.3 \times 10^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\bar{u}<em>\mu P_L e)\bar{u}</em>\tau P_L e$</td>
<td>$1.9 \times 10^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**uFCNNC remove immunities**

**Observables**

- $\Delta m_K, \epsilon_K$
- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_D; |q/p|, \phi_D$
- $\Delta m_D; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
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- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
- $\Delta m_K; |q/p|, \phi_D$
Last 3 yrs: dramatic progress in studying charm CPV

More in S. Stone’s talk this afternoon.

SUSY implications: no hope for non-degeneracy ...

\[
\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \leq \begin{cases} 
0.034 & \text{maximal phases} \\
0.27 & \text{vanishing phases}
\end{cases}
\]

(squark doublets, gluino, 1 TeV)

Blum, Grossman, Nir & GP (09)

With phases, first 2 gen’ squark need to have almost equal masses. Looks like squark anarchy/alignment is dead!

However ...

Successful alignment models guarantee small physical CP phase!

Gedalia, Kamenik, Ligeti & GP (12)
Degeneracy of Squarks

- No strong degeneracy required!
- Ex.: $m_{\tilde{g}} = 1.3$ TeV, $m_{\tilde{Q}_2} = 550$ GeV, $m_{\tilde{Q}_1} = 950$ GeV
Can this be consistent with LHC data??

$m_{Q_2}=550$ GeV, $m_{Q_1}=950$ GeV
How do limits change?

Estimate:

\[ \sigma \sim \frac{1}{m_q^5} \]

Decouple 6 dof:

\[ \Rightarrow \frac{\Delta m_{\text{max}}}{m_{\text{max}}} = 1 - 4^{-\frac{1}{5}} \sim 25\% \]

TOO NAIVE!

Limits affected by:

- squark multiplicity
- signal efficiencies
- PDFs
Efficiencies

Signal efficiency falls very rapidly with decreasing squark mass Below $\sim 600$ GeV $\epsilon\sigma = 1$
In fact, all 4 flavor “sea” squarks can be light!
So far crazily reasonable, is there alternative paradigm?

Potential implications for a 125GeV Higgs on flavor physics

$y_t \lesssim 1.03 + 1.8 \cdot 10^{-3} \ (m_H - 125.5 \text{ GeV})$

A raise of $< 3\%$ in top Yukawa $\implies$ weakless universe!

A new coincidence, top $(H)$ flavor puzzle?
Getting a two-peaks distributions, ultra speculative solution to flavor puzzle (question more important than answer ...)

- Interpretation for quark spectrum, in view of new Higgs mass:

- RGE + “strong dynamics” inspired models can generate binary dist’.

\[
y = 0 \quad \Lambda_{\text{QCD}}/M_W \quad m, p_{\gamma}, p_{\gamma}(\gamma) \propto e^{m},
\]

\[
y \propto e^Q, \quad p_Q(Q) \propto Q^n, \quad p_e(e) \propto e^m, \quad y \propto e^\gamma, \quad p_{\gamma}(\gamma) \propto e^{a\gamma^2},
\]

\[
\text{Figure 3: PDF of a single Yukawa coupling. The solid blue (dashed black) line corresponds to Equation (4) with } n = m = 2 	ext{ and } Q_{\text{max}} = 100 (a = 3.1, y_0 = 6.8 \times 10^3) \text{ and } \varepsilon = 0.012). \text{ Left Panel: the original distributions as applied at the Planck scale. Right panel: the distributions after one-loop RGE running down to the weak scale.}
\]
Summary

- Entered precision top phys. phase,
  LHC data => fantastic & consistent with SM.
- Combine effort resolving forward backward anomaly &
  go beyond the 2TeV $m_{tt\bar{t}}$ scale.
- Top partner searches => testing naturalness paradigm.
- Light (non-”sups”) squarks maybe buried (regardless of alignment).
- Is criticality of top Yukawa-Higgs mass coincidence?
Top physics, theory

Thank you

Gilad Perez

CERN & Weizmann Inst.
Backups
EFT constraints from charge asym' & enhancement of differential mass distribution

Thanks to: Delaunay, Gedalia, Hochberg & Soreq (to appear).
Top physics, theory

Thank you

Gilad Perez

CERN & Weizmann Inst.
What is the fine tuning problem (personal view)?
What is the fine tuning problem (personal view)?

Coincidence of $1:10^2$ - moon subtends an angle of $\sim 0.52^\circ$ while sun of $\sim 0.53^\circ$. 
What is the fine tuning problem (personal view)?

Coincidence of $1:10^2$ - moon subtends an angle of $\sim 0.52^\circ$ while sun of $\sim 0.53^\circ$.

Imagine that they were equal to $1:10^{32}$!
What is the fine tuning problem (personal view)?

Coincidence of $1:10^2$ - moon subtends an angle of $\sim 0.52^\circ$ while sun of $\sim 0.53^\circ$.

Imagine that they were equal to $1:10^{32}$!

It would raise two questions:

(i) What set their precise distance? $\iff$ Tuning problem.

why is $\delta \theta / \theta_{\text{max}} \sim 10^{-32} \ll 1$? $\iff$ why is $(m^2_{H,W}/m^2_{\text{Pl}})_{\text{obs}} \sim 10^{-32} \ll 1$?

\[(\text{displacing the sun by } \sim 10^{-19} \text{ m } \Rightarrow \delta \theta \sim 10^{-32})\]

“Additive” sensitivity / fine tuning due to top-Higgs coupling:

\[
\left( \frac{m_W^2}{m_{\text{Pl}}^2} \right)_{\text{obs}} \sim \left( m_H^2 + \delta m_H^2 \right) / m_{\text{Pl}}^2 \sim m_H^2 + m_{\tilde{t}}^2
\]

\[
\sim 0.0100000000000000000000000000000000000000000000000000000000000000 - 0.01 \sim 10^{-32}
\]

\[
\text{(displacing the sun by } \sim 10^{-19} \text{ m } \Rightarrow \delta \theta \sim 10^{-32} \text{ )}
\]

“Additive” sensitivity / fine tuning due to top-Higgs coupling:

\[
\left( \frac{m_W^2}{m_{Pl}^2} \right)_{\text{obs}} \sim \left( \frac{m_H^2 + \delta m_H^2}{m_{Pl}^2} \right) \sim m_H^2 + \delta m_H^2 \sim 0.01 \sim 10^{-32}
\]
The fine tuning problem


\[(\text{displacing the sun by } \sim 10^{-19} \text{ m } \Rightarrow \delta \theta \sim 10^{-32})\]

\[ \left( \frac{m_W^2}{m_{Pl}^2} \right)_{\text{obs}} \sim \left( m_H^2 + \delta m_H^2 \right) / m_{Pl}^2 \sim m_H^2 + \] 

\[ \sim 0.0100000000000000000000000000000000001 - 0.01 \sim 10^{-32} \]
The fine tuning problem


\( (\text{displacing the sun by } \sim 10^{-19} \text{ m } \Rightarrow \delta \theta \sim 10^{-32} ) \)

“Additive” sensitivity / fine tuning due to top-Higgs coupling:

\[
\left( \frac{m_W^2}{m_{Pl}^2} \right)_{\text{obs}} \sim \left( m_H^2 + \delta m_H^2 \right) / m_{Pl}^2 \sim m_H^2 + H \]

\[
\sim 0.0100000000000000000000000000000001 - 0.01 \sim 10^{-32}
\]
The fine tuning problem


\[(\text{displacing the sun by } \sim 10^{-19} \text{ m } \Rightarrow \delta \theta \sim 10^{-32})\]

“Additive” sensitivity / fine tuning due to top-Higgs coupling:

\[\left(\frac{m_W^2}{m_{Pl}^2}\right)_{\text{obs}} \sim \left(\frac{m_H^2 + \delta m_H^2}{m_{Pl}^2}\right) \sim m_H^2 + \delta m_H^2 + \delta \theta \sim \left(\frac{m_H^2}{m_{Pl}^2}\right) \sim 0.01 \sim 10^{-32}\]
The fine tuning problem


\[(\text{displacing the sun by } \sim 10^{-19} \text{ m } \Rightarrow \delta\theta \sim 10^{-32})\]

"Additive" sensitivity / fine tuning due to top-Higgs coupling:

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\[\sim 0.0100000000000000000000000000000001 - 0.01 \sim 10^{-32}\]