Many contributions

- 15 Parallel Sessions
- 536 Parallel Talks
- 55 Plenary Talks
- 18 Additional Talks

Theory $\sim$ 30%

Lots of Physics
Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism

\[ \theta = \frac{v}{\sin \theta} \]

\[ v = 246 \text{ GeV} \]

\[ M_Z \cos \theta_W = M_W = \frac{1}{2} v g \]

Kibble, Guralnik, Hagen, Englert, Brout
Higgs 1964

Glashow
Weinberg
Salam

SU(2)_L ⊗ U(1)_Y
**Precision QCD**
(towards N^kLO + PS)

- **Hard QCD**: Badger, Biedermann, Boito, Cieri, Duhr, Greiner, Guzzi, Rodrigo, Sborlini...
- **Jets**: Cacciari, Mateu, Monni, Re, Sapeta...
- **PDFs**: Alekhin, Chekelian, D’Enterria, Ellinghaus, Lipka, Motylinski, Rojo, Wichmann...
- **EW**: Campanario, Hofer, Melia, Rontsch, Yokoya...

**Tools for Higgs Physics**

- **Cross Section**
  - \(gg\) → H + jet
  - \(V/W\) + H
  - \(tt\) + H
  - \(bb\) + H
  - \(WW/ZZ\) + H

**PDFs**
- NNPDF3.0
- NNPDF2.3

Compiled by R. Tanaka, Jan. 2014
Good agreement between theory and experiment

Standard Model Production Cross Section Measurements

Status: July 2014

ATLAS Preliminary
Run 1 $\sqrt{s} = 7, 8$ TeV

LHC pp $\sqrt{s} = 7$ TeV
- Theory
- Data $4.5 - 4.7$ fb$^{-1}$

LHC pp $\sqrt{s} = 8$ TeV
- Theory
- Data $20.3$ fb$^{-1}$
\( \alpha_s \) Determination

- \( \tau \) decays (N^3LO)
- Lattice QCD (NNLO)
- DIS jets (NLO)
- Heavy Quarkonia (NLO)
- e^+e^- jets & shapes (res. NNLO)
- Z pole fit (N^3LO)
- p\bar{p} \rightarrow jets (NLO)

PDG 2013

- \( \tau \)-decays
- Lattice
- DIS
- e^+e^- annihilation
- Z pole fits

Roda

\( Q \) = 0.1185 ± 0.0006

QCD \( \alpha_s(M_Z) \) = 0.1185 ± 0.0006
Quark Masses & $\alpha_s$ from Lattice QCD

review by F. Sanfilippo @ Lattice 2014

- $m_c/m_s$
- $m_b/m_c$

PDG 2014

- HPQCD (Wilson loops)
- HPQCD (c-c correlators)
- Maltman (wilson loops)
- JLQCD (Adler functions)
- PACS-CS (vac. pol. fctns.)
- ETM
- BBGPSV (static en.)
Exotic Spectroscopy

Zc States

Ali, Skwarnicki
**Heavy-Ion Collisions**

- Near-perfect relativistic fluid
- Jet quenching
- Screening ($J/\psi, \Upsilon$)
- Regeneration ($J/\psi$)
- Evidence for collective phenomena in p-Pb

The emergence of a “standard picture” of high-energy heavy-ion collisions

```
Initial state  Pre-equilibrium  QGP  Hadronization  Thermal freeze-out
```

Relativistic hydrodynamics
In the last decade, it was found that the S-matrix of spin 1 and spin 2 massless theories is largely determined WITHOUT explicit input from LOCALITY.

Intricate mathematics being uncovered:
- twistor diagrams
- on-shell recursion relations
- generalized unitarity
- grassmanians
- permutations and Yangian symmetry
- amplituhedron
- ...

SLOGAN
Must “unlearn” Feynman diagrams

Parke-Taylor

+ + + + = one-line answer

AdS/QCD
- glueball-meson spectra
- xSB
- topological susceptibility
- dynamics of color plasma

AdS/CMT
- superfluids/superconductors
- strange metals
- topological insulators
- transport without quasiparticles
The Heaviest Mass Scale

\[ y_t = \frac{\sqrt{2}}{v} m_t = 2^{3/4} G_F^{1/2} m_t = 1 \]  

(0.995)

The top quark:

- Sensitive probe of Electroweak Symmetry Breaking
- Non-perturbative (strong) dynamics?
- Very different from other quarks: \( y_b = 0.025, \ y_c = 0.007 \ldots \)
- Is it really a SM quark?

So far, we only know the decay \( t \rightarrow b W^+ \)

| Single-top   | \( |V_{tb}| \)       |
|--------------|---------------------|
| ATLAS ‘14    | > 0.88 (95% CL)     |
| CMS’14       | > 0.92 (95% CL)     |
| CDF’14       | > 0.84 (95% CL)     |
| D0 ‘13       | > 0.92 (95% CL)     |
Production Asymmetries

Tevatron:

\[ A_{FB} = A_{\overline{t}t} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \]

LHC:

\[ A_{C} = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)} \]

\[ \Delta y = y_t - y_{\overline{t}}, \quad \Delta |y| = |y_t| - |y_{\overline{t}}| \]

Data is now consistent with the SM

(still 1.7 excess at CDF)

Models predicting larger asymmetries don’t pass other phenomenological tests or are rather ad-hoc
TOP MASS

- Monte Carlo mass:
  \[ M_t^{MC} = (173.34 \pm 0.76) \text{ GeV} \]
  Lacks a proper QCD definition: \[ M_t^{\text{pole}} = M_t^{MC} + \Delta M_t^{\text{th}} \]
  \[ |\Delta M_t^{\text{th}}| \approx O(1 \text{ GeV}) \]
  Hoang-Stewart, 0808.0222

- Cross section: \( \sigma_{t\bar{t}} \) NNLO+NNLL
  Well-defined mass

Aldaya, Bernardi, Carli

Czakon et al, Bärnreuther et al, Cacciari et al
Possible Improvements:

- **Differential distribution in** \[ \rho_s = m_0 \sqrt{S_{t\bar{t}+j}} \]
  
  Alioli et al, 1303.6415

  \[ R(m_{t_{\text{pole}}}^\text{pole}, \rho_s) \equiv \frac{1}{\sigma_{t\bar{t}+1\text{jet}}} \frac{d\sigma_{t\bar{t}+1\text{jet}}}{d\rho_s} \]

- **Weight function method:** Lepton energy distribution
  
  Kawabata et al, 1405.2395

  \[ \sigma\left(\ell^+\ell^- \rightarrow t\bar{t}\right)_{\text{threshold}} \]

  Hoang et al, Beneke et al, Ruiz-Femenia, Martinez-Miquel

  \[ \delta m_t < 100 \text{ MeV} \]

- Precision measurement needed to test the EW theory
A New Higgs-like Boson

\[ H \rightarrow \gamma \gamma \]

\[ H \rightarrow ZZ^* \rightarrow 4l \]

\[ H \rightarrow \gamma \gamma \]

\[ H \rightarrow ZZ^* \rightarrow 4l \]

\[ M_{H}^{\text{ATLAS}} = (125.36 \pm 0.37 \pm 0.18) \, \text{GeV} \]

\[ M_{H}^{\text{CMS}} = \left(125.03 + 0.26 + 0.13 - 0.27 - 0.15\right) \, \text{GeV} \]
Beautiful Discovery

Boson (J = 0)

Fermions = Matter ; Bosons = Forces

- Fundamental Boson: New interaction which is not gauge
- Composite Boson: New underlying dynamics

If New Physics exists at $\Lambda_{NP}$

$$\delta M^2_H \sim \frac{g^2}{(4\pi)^2} \Lambda_{NP}^2 \log \left( \frac{\Lambda_{NP}^2}{M^2_H} \right)$$

Which symmetry keeps $M_H$ away from $\Lambda_{NP}$?

- Fermions: Chiral Symmetry
- Gauge Bosons: Gauge Symmetry
- Scalar Bosons: Supersymmetry, Scale/Conformal Symmetry ... ?
Possible Scenarios of EWSB

1. **SM scalar:** Favoured by EW precision tests

2. **Alternative perturbative EWSB:**
   - Scalar Doublets and Singlets

3. **Dynamical (non-perturbative) EWSB:**
   - Pseudo-Goldstone Boson
   - Scalar Resonance
The open questions about the Higgs

- Is it the SM Higgs?
- Is it an elementary/composite particle?
- Is it unique/solitary?
- Is it temporary?
- Is it natural?
- Is it the first supersymmetric particle ever observed?
- Is it really “responsible” for the masses of all the elementary particles?
- Is it mainly produced by top quarks or by new heavy vector-like quarks?
- Is it a portal to a hidden world?
- Is it at the origin of the matter-antimatter asymmetry?
- Has it driven the inflationary expansion of the Universe?
SM Higgs

Favoured by EW precision tests
SM Scalar Potential

\[ V(\Phi) - V_0 = \lambda \left( |\Phi|^2 - \frac{v^2}{2} \right)^2 = \frac{1}{2} M_H^2 H^2 \left( \frac{1 + H/v + H^2/4v^2}{v^2} \right) \]

\[ M_H = 125.47 \pm 0.27 \rightarrow \lambda = \frac{M_H^2}{2v^2} = 0.13 \]

Loop corrections:

\[ M_H^2 = 2\lambda(\mu)v^2 + \frac{2y_t^2v^2}{(4\pi)^2} \left[ 2\lambda + 3(\lambda - y_t^2) \log\left( \frac{m_t^2/\mu^2}{v^2} \right) \right] + \cdots \]

Vacuum stability: \[ \lambda(\Lambda) \geq 0 \]

Meta-stable vacuum

\[ \Lambda = M_{\text{Planck}} \]

\[ M_H > 129.1 \pm 1.5 \text{ GeV} \]

\[ M_t < 171.53 \pm 0.42 \text{ GeV} \]

Buttazzo et al, 1307.3536

Buttazzo et al, 1307.3536
\( \kappa_i \equiv \frac{g_i}{g_i^{SM}} \)

**H(125) Couplings are SM-like**

Strong evidence for \( H \) coupling to \( \tau \) and \( b \)

ATLAS Preliminary

- \( H \to bb \)
- \( H \to \tau\tau \)
- \( H \to 4l \)
- \( H \to \gamma\gamma \)
- \( H \to \nu\nu \)

Combined

Best Fit

CMS Preliminary

- \( m_H = 125 \text{ GeV} \)

- \( VH \rightarrow b\bar{b} \)

- \( H \rightarrow \tau\tau \)

- Combined

- SM prediction

68\% Contour

95\% Contour

(\( M, \mu \)) fit

- 68\% CL

- 95\% CL

19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)

\( \lambda \) or \((g/2e)^2\)

mass (GeV)

- 68\% CL

- 95\% CL

- SM Higgs

\( \int L \, dt = 20.3 \text{ fb}^{-1} \)

\( \int L \, dt = 4.6 - 4.8 \text{ fb}^{-1} \)

\( \int L = 20.3 \text{ fb}^{-1} \)

\( \int L = 8 \text{ TeV} \)

\( \mu_{ggF} \times B/B_{SM} \)

- Best fit

- 95\% Contour

- 68\% Contour

- Background only

- SM prediction

- \( VH \to b\bar{b} \)

- \( H \to \tau\tau \)

- Combined

\( -2 \Delta \ln L \)

- 3.8\( \sigma \)

- 3.2\( \sigma \)

- 2.1\( \sigma \)

Standard model

- 3.8\( \sigma \)

- 3.2\( \sigma \)

- 2.1\( \sigma \)
Strong (indirect) evidence for $H$ coupling to $t$

Dominant Production Mechanism

$$\Gamma \sim |1 - 0.21|^2$$

Direct (tree-level) sensitivity through $t\bar{t}H$
Quark Mixing

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

\[ V_{ub}^*/V_{cd} V_{cb}^* \]

\[ V_{tb}^*/V_{cd} V_{cb}^* \]

\[ \bar{\rho}, \bar{\eta} \]

**Successful CKM Mechanism** (Tree / Loop / CP-c / CP-v)

Hadronic inputs from Lattice, \( \chi \)PT, HQET...

Derkach

\[ \bar{\eta} \equiv \eta \left(1 - \frac{1}{2} \eta^2 \right) = 0.351 \pm 0.014 \]

\[ \bar{\rho} \equiv \rho \left(1 - \frac{1}{2} \rho^2 \right) = 0.132 \pm 0.023 \]

\[ A = 0.821 \pm 0.012 \quad ; \quad \lambda = 0.2254 \pm 0.0006 \]
Flavour Physics

Isidori

Twofold role of Flavor Physics
- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- Probe physics at energy scales not directly accessible at accelerators

SM + non-SM flavor

Higgs sector

“intermediate” BSM sector

flavor-violating interactions

High-scale [flavor-symmetric?] theory

Two key open questions:
- Are there other sources of flavor symmetry breaking?
- What determines the observed pattern of quark & lepton mass matrices?

$\text{BR}(\mu \rightarrow e\gamma)^{\exp} < 5.7 \times 10^{-13}$

MEG '13

“large” flavor symmetry + “small” breaking is the best way to explain the absence of NP signals so far in FCNCs

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...
Bounds on New Flavour Physics

\[ L_{\text{eff}} = L_{\text{SM}} + \sum_{D>4} \sum_k \frac{c_k^{(D)}}{\Lambda_{\text{NP}}^{D-4}} O_k^{(D)} \]

Isidori, 1302.0661

### Operator
<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on ( \Lambda ) in TeV (( c_{\text{NP}} = 1 ))</th>
<th>Bounds on ( c_{\text{NP}} ) (( \Lambda = 1 ) TeV)</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\bar{s}_L \gamma^\mu d_L)^2)</td>
<td>(9.8 \times 10^2)</td>
<td>(1.6 \times 10^4)</td>
<td>(9.0 \times 10^{-7})</td>
</tr>
<tr>
<td>((\bar{s}_R d_L)(\bar{s}_L d_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 d_L)^2)</td>
<td>(6.6 \times 10^2)</td>
<td>(9.3 \times 10^2)</td>
<td>(2.3 \times 10^{-6})</td>
</tr>
<tr>
<td>((\bar{b}_R d_L)(\bar{b}_L d_R))</td>
<td>(2.5 \times 10^3)</td>
<td>(3.6 \times 10^3)</td>
<td>(3.9 \times 10^{-7})</td>
</tr>
<tr>
<td>((\bar{b}_L \gamma^\mu s_L)^2)</td>
<td>(1.4 \times 10^2)</td>
<td>(2.5 \times 10^2)</td>
<td>(5.0 \times 10^{-5})</td>
</tr>
<tr>
<td>((\bar{b}_R s_L)(\bar{b}_L s_R))</td>
<td>(4.8 \times 10^2)</td>
<td>(8.3 \times 10^2)</td>
<td>(8.8 \times 10^{-6})</td>
</tr>
</tbody>
</table>

- **Generic flavour structure** \([c_{\text{NP}} \sim O(1)]\) ruled out at the TeV scale
- **\( \Lambda_{\text{NP}} \sim 1 \) TeV** requires \( c_{\text{NP}} \) to inherit the strong SM suppressions (GIM)

**Minimal Flavour Violation:** The up and down Yukawa matrices are the only source of quark-flavour symmetry breaking

D’Ambrosio et al, Buras et al
B_{s} Mixing & CP

\[ \phi_{s}^{c\bar{c}s} = 2\left(\phi_{s}^{M} + \phi_{s}^{D}\right) \quad ; \quad \phi_{s}^{c\bar{c}s}_{\text{SM}} \approx -2\beta_{s} \equiv -2 \text{arg}\left(-\frac{V_{ts}V_{tb}^{*}}{V_{cs}V_{cb}^{*}}\right) \]

\[ A_{s}^{b} \equiv \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} \]

\[ a_{q}^{d} \equiv \frac{\Gamma(\bar{B}_{q}^{0} \rightarrow \mu^{+}X) - \Gamma(B_{q}^{0} \rightarrow \mu^{-}X)}{\Gamma(\bar{B}_{q}^{0} \rightarrow \mu^{+}X) + \Gamma(B_{q}^{0} \rightarrow \mu^{-}X)} = \frac{\Delta M_{q}}{\Delta \Gamma_{q}} \tan \phi_{q} \]

\[ \phi_{q} \equiv \text{arg}\left(-M_{12}^{q}/\Gamma_{12}^{q}\right) \sim \frac{m_{c}^{2}}{m_{b}^{2}} \]
Rare Decays

- No tree-level contribution
- Strong CKM suppression

$B \rightarrow \mu^+ \mu^-$ sensitive to (pseudo) scalar contr.

$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) \right]$

$B_{s}^0 \rightarrow \mu^+ \mu^-$

$B \rightarrow s \gamma$

$C_{S}^{(t)}$, $C_{P}^{(t)}$, $C_{10}^{(t)}$

$C_{7}^{(t)}$, $C_{9}^{(t)}$, $C_{10}^{(t)}$

$C_{i}^{(t)}$ for $i = 1, 2, 3, 6, 8, 9, 10$ and $P$

SM

Gluon penguin
Photon penguin
Electroweak penguin
Higgs (scalar) penguin
Pseudoscalar penguin
**B_d \rightarrow K^{*0} \mu^+\mu^-**

Phen. analysis with “clean observables”
(FF independent)

Descotes-Genon et al

### P'5 Anomaly

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
<th>SM prediction</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>{P_5}[0.1,2]</td>
<td>(0.03^{+0.14}_{-0.15})</td>
<td>(0.172^{+0.020}_{-0.021})</td>
<td>-1.0</td>
</tr>
<tr>
<td>{P_5}[2,4,3]</td>
<td>(0.50^{+0.09}_{-0.07})</td>
<td>(0.234^{+0.060}_{-0.057})</td>
<td>+2.9</td>
</tr>
<tr>
<td>{P_5}[1,4,8]</td>
<td>(-0.25^{+0.07}_{-0.08})</td>
<td>(-0.407^{+0.049}_{-0.037})</td>
<td>+1.7</td>
</tr>
<tr>
<td>{P_5}[1,6]</td>
<td>(0.33^{+0.11}_{-0.12})</td>
<td>(0.084^{+0.060}_{-0.078})</td>
<td>+1.8</td>
</tr>
</tbody>
</table>

**Fit with “New Physics” effective operators**

**New Physics?**

Altmannshofer-Straub, Beaujean et al, Descotes-Genon et al, Horgan et al.

**Hadronic uncertainties?**

Jäger & Martín-Camalich, Zwicky et al.
Flavour-Violating Higgs Couplings

\[
L = -h \left\{ Y_{e\mu} \bar{e}_L \mu_R + Y_{e\tau} \bar{e}_L \tau_R + Y_{\mu\tau} \bar{\mu}_L \tau_R + \cdots \right\}
\]

Blankenburg et al, Celis et al, Harnik et al, Davidson-Verdier, Kopp-Nardecchia

\[
\text{Br}(H \rightarrow \mu\tau) < 1.57\% \quad (95\% \text{ CL})
\]
Two-Higgs Doublet Models

5 scalar fields: \( H^\pm, \phi_i^0 = (h, H, A) \)  

\[ 3 \times 3 \text{ mixing } R_{ij} \]

\[
g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 = \left( g_{hVV}^{\text{SM}} \right)^2
\]

\[
\Gamma = \begin{bmatrix}
\cos \tilde{\alpha} & \sin \tilde{\alpha} & 0 \\
-\sin \tilde{\alpha} & \cos \tilde{\alpha} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
g_{\phi_iVV} / g_{\phi_iVV}^{\text{SM}} = R_{i1} = \cos \tilde{\alpha} \equiv \cos(\beta - \alpha)
\]

Yukawas:

\[
L_Y = -Q'_L (\Gamma_1 \phi_1 + \Gamma_2 \phi_2) d'_R + \cdots
\]

EWSB

\[
L_Y = -\frac{\sqrt{2}}{v} Q'_L (M'_d \Phi_1 + Y'_d \Phi_2) d'_R + \cdots
\]

\( M'_f \) & \( Y'_f \) unrelated (not simultaneously diagonal)

FCNCs

Solutions:

(same for \( u_R \) and \( \ell_R \) Yukawas)

- Natural Flavour Conservation: \( \Gamma_1 = 0 \) or \( \Gamma_2 = 0 \) (\( Z_2 \) models)

  Glashow-Weinberg...

- Alignment: \( \Gamma_1 \propto \Gamma_2 \)

  \( Y_{d,l} = \zeta_{d,l} M_{d,l} \), \( Y_u = \zeta^*_u M_u \)

  AP-Tuzón

- BGL Models: “controlled” FCNC (symmetries)

  Branco et al, Nebot
5 scalar fields: \( H^\pm, \varphi^0_i = (h, H, A) \) [3x3 mixing \( R_{ij} \)]

\[
v = \sqrt{v_1^2 + v_2^2}, \quad \tan \beta = \frac{v_2}{v_1}
\]

CP-conserving potential:

\[
R = \begin{bmatrix}
\cos \tilde{\alpha} & \sin \tilde{\alpha} & 0 \\
-\sin \tilde{\alpha} & \cos \tilde{\alpha} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
g_{\nu \nu \varphi^0_i} / g_{\nu \nu \varphi^0_j} = R_{ij} = \cos \tilde{\alpha} \equiv \cos(\beta - \alpha)
\]

Yukawas: (SM units)

\[
y^{\varphi^0_i}_{d,l} = R_{i1} + \left(R_{i2} + i R_{i3}\right) \zeta_{d,l}
\]

\[
y^{\varphi^0_i}_{u} = R_{i1} + \left(R_{i2} - i R_{i3}\right) \zeta_u^*
\]
Flavour Alignment (Aligned 2HDM)

General setting without FCNCs & new sources of CP violation

\[ Y_{d,l} = \xi_{d,l} M_{d,l}, \quad Y_u = \xi_u^* M_u \]

- **Rich phenomenology @ LHC**
  - Altmannshofer et al, Barger et al, Celis et al, Cervero-Gerard, López-Val et al...
- Many allowed possibilities
- Search for light $H^\pm, H, A$
- **CP violation**
- **Flavour constraints fulfilled**
  - Celis et al, Jung et al, Li et al
- **EDMs**
- **Usual $Z_2$ models recovered in particular (CP-conserving) limits**

| $\cos \bar{\alpha}$ | > 0.80 (90% CL) |
\( \nu \) Oscillations

Forero et al, 1405.7540

\[ \Delta m_{31}^2 [10^{-3} \text{ eV}^2] \]

\( \sin^2 \theta_{23} \)

\( \sin^2 \theta_{13} \)

González-García et al

\[ |U|_{3\sigma} = \begin{pmatrix}
0.801 \rightarrow 0.845 & 0.514 \rightarrow 0.580 & 0.137 \rightarrow 0.158 \\
0.225 \rightarrow 0.517 & 0.441 \rightarrow 0.699 & 0.614 \rightarrow 0.793 \\
0.246 \rightarrow 0.529 & 0.464 \rightarrow 0.713 & 0.590 \rightarrow 0.776
\end{pmatrix} \]

Flavour mixing is very different for quarks & leptons

Goswami, Tortola

Flavour mixing is very different for quarks & lepton
Neutrino Properties from Cosmology

success of $\Lambda$CDM
+ 3 active neutrinos
+ $\Sigma m_\nu \geq 0.06$ eV
(from oscillations)

$\Rightarrow$ limits on $\Sigma m_\nu$
and $N_{\text{eff}}$

$N_{\text{eff}} = 3.32 \pm 0.27$ (68\% CL)

$\Sigma m_\nu < 0.28$ eV (95\% CL)
Open Questions in $\nu$ Physics

Mass Hierarchy

- Normal
- Inverted

Dirac / Majorana

Mass Scale
Sterile $\nu_R$?
CP Violation
Flavour Symmetries
Leptogenesis

Low-E Effective Theory:

1. $\text{SU}(2)_L \otimes U(1)_Y$ invariant operator with $d=5$

$$L = L_{SM} + \sum_d \frac{C_d}{\Lambda^{d-4}} O_d$$

Small Majorana Mass:

$$m_\nu > 0.05 \text{ eV}$$

$$\Lambda / c_{ij} < 10^{15} \text{ GeV}$$
Desperately Seeking SUSY (Dulcinea)

In all the world there is no maiden fairer than the Empress of La Mancha, the peerless SUSY del Toboso.

Your worship should bear in mind that SUSY is badly broken; got heavy through anomaly mediation.
### ATLAS SUSY Searches - 95% CL Lower Limits

**Status:** ICHEP 2014

<table>
<thead>
<tr>
<th>Model</th>
<th>$e,\mu,\tau,\gamma$ Jets</th>
<th>$E_t^{\text{miss}}$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSMSS</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
</tr>
<tr>
<td>MSUGRA/CMSMSS</td>
<td>1</td>
<td>$e,\mu,\tau$ jets</td>
<td>Yes</td>
</tr>
<tr>
<td>GMSB (NLSP)</td>
<td>2</td>
<td>$e,\mu,\tau$ jets</td>
<td>Yes</td>
</tr>
<tr>
<td>GGM (higgsino-Dark Matter)</td>
<td>2</td>
<td>$e,\mu,\tau$ jets</td>
<td>Yes</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>0</td>
<td>mono-jet</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*The table lists various models with their respective selection criteria, $E_t^{\text{miss}}$ values, and corresponding mass limits at 95% CL. The mass limits are given in TeV.*

---

### EW Direct

- **$\tilde{g}$, $\tilde{q}$, $\tilde{b}$ Production**
  - $2 e, 2 \mu, 2 \tau$ jets
  - $E_t^{\text{miss}}$ Yes 20.3
  - Mass limit: 100-620 GeV

- **$\tilde{b}_1, \tilde{b}_1 \to \tilde{\chi}_1^0 + b$**
  - $2 e, 2 \mu, 2 \tau$ jets
  - $E_t^{\text{miss}}$ Yes 20.3
  - Mass limit: 100-620 GeV

- **Implications for Long-lived Particles**
  - $\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \gamma \gamma$ (RPV)
  - $1 \mu, \text{displ. vtx}$
  - Mass limit: 100-287 GeV

*The EW Direct section lists various production processes with corresponding mass limits at 95% CL.*

---

### RPV

- **Scalar gluon pair, $sgluon \to \tilde{g}$**
  - 0 4 jets
  - 10.5
  - Mass limit: 100-287 GeV

*The RPV section lists different processes with their respective mass limits at 95% CL.*

---

### Other

- **Scalar gluon pair, $sgluon \to \tilde{q}$**
  - 2 0 14.3
  - Mass limit: 350-890 GeV

*The Other section lists other processes with their respective mass limits at 95% CL.*

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### References

- ATLAS-CONF-2013-062
- ATLAS-CONF-2013-051
- ATLAS-CONF-2013-058
- ATLAS-CONF-2013-069
- ATLAS-CONF-2013-099
- ATLAS-CONF-2013-0934
- ATLAS-CONF-2013-096
- ATLAS-CONF-2013-095
- ATLAS-CONF-2013-094
- ATLAS-CONF-2013-099
- ATLAS-CONF-2013-096
- ATLAS-CONF-2013-095
- ATLAS-CONF-2013-094
- ATLAS-CONF-2013-0934
- ATLAS-CONF-2013-096
- ATLAS-CONF-2013-095
- ATLAS-CONF-2013-094
Strong limits on SUSY partners

Tension with Higgs mass:

\[ M_h^2 \leq M_Z^2 \cos^2(2\beta) + \varepsilon \]

\[ \varepsilon \approx \frac{3 m_t^4}{2 \pi^2 v^2 \sin^2(\beta)} \left[ \log \left( \frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right) \right] \]

Decoupling \( (M_A \gg M_Z) \)

\[ \cos^2(2\beta) \rightarrow 1 \]

Maximal stop mixing \( X_t \)

Improved higher-order calculations allow slightly larger values of \( M_h \)

Heinemeyer et al

A. Pich

Theory Highlights & Outlook
Which SUSY?

- **Looks bad in CMSSM** (120 MSSM parameters reduced to 4 + 1 sign)
- **More freedom in the Phenomenological MSSM**
  - Many SUSY variants: NMSSM, Split, High-Scale, Stealth, 5D ...
- **Naturalness?** \[ \Delta M_h^2 \propto M_{\text{SUSY}}^2 \]

Data-driven search

Bharucha, Bosch, De Vries, Di Chiara, López, Rolbiecki, Sarrazin
Massive & dark SUSY states show up through a hidden portal from a warped dimension.

Look, your worship, it's just the spectrum of the Standard Model.
Effective Field Theory

\[ L_{\text{eff}} = L^{(4)} + \sum_{D>4} \sum_{k} \frac{c_k^{(D)}}{\Lambda_{\text{NP}}^{D-4}} O_k^{(D)} \]

- Most general Lagrangian with the SM gauge symmetries
- Light \((m \ll \Lambda_{\text{NP}})\) fields only
- The SM Lagrangian corresponds to \(D=4\)
- \(c_k^{(D)}\) contain information on the underlying dynamics:

\[ L_{\text{NP}} \doteq g_X (\bar{q}_L \gamma^\mu q_L) X_\mu \quad \Rightarrow \quad \frac{g_X^2}{M_X^2} (\bar{q}_L \gamma^\mu q_L) (\bar{q}_L \gamma_\mu q_L) \]

- Options for \(H(126)\):
  - SU(2)_L doublet (SM)
  - Scalar singlet
  - Additional light scalars
Custodial Symmetry

\[
\Sigma \equiv (\phi_c, \phi) = \begin{pmatrix} \phi^{(0)*} & \phi^{(+)} \\ -\phi^{(-)} & \phi^{(0)} \end{pmatrix} = \frac{1}{\sqrt{2}}[v + H(x)] \ U(\phi), \quad U(\phi) = \exp\left\{ \frac{i}{v} \bar{\sigma} \phi \right\}
\]

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

\[
= \frac{1}{2} \operatorname{Tr} \left[ (D^\mu \Sigma)^\dagger D^\mu \Sigma \right] - \frac{\lambda}{4} \left( \operatorname{Tr} \left[ \Sigma^\dagger \Sigma \right] - v^2 \right)^2
\]

\[
= \frac{v^2}{4} \operatorname{Tr} \left[ (D^\mu U)^\dagger D^\mu U \right] + O \left( H / v \right)
\]

- **Invariant under global** \( \text{SU}(2)_L \otimes \text{SU}(2)_R \supset \text{SU}(2)_L \otimes \text{U}(1)_Y \)

\[
\Sigma \rightarrow g_L \cdot \Sigma \cdot g_R^\dagger, \quad g_x \in \text{SU}(2)_x
\]

- **Same Lagrangian than QCD pions:** \( f_\pi \rightarrow v, \quad \pi^\pm, \pi^0 \rightarrow \phi^\pm, \phi^0 \rightarrow W^\pm_L, W^0_L \)

**Chiral Goldstone Bosons:** \( \text{SU}(2)_L \otimes \text{SU}(2)_R \rightarrow \text{SU}(2)_C \)
Deviations of the SM gauge couplings imply bad UV behaviours

New states needed to restore unitarity

\[ \mathcal{L} = \frac{v^2}{4} \left\langle D_\mu U^\dagger D_\mu U \right\rangle \left[ 1 + 2a \frac{H}{v} + b \frac{H^2}{v^2} \right] \]

\[ A(s, t, u) = \frac{s}{v^2} (1 - a^2) + \frac{4}{v^2} \left\{ a'_4(\mu) (t^2 + u^2) + 2 a'_5(\mu) s^2 \right\} \]

\[ + \frac{1}{16\pi^2 v^2} \left\{ \frac{1}{9} (14 a^4 - 10 a^2 - 18 a^2 b + 9 b^2 + 5) s^2 + \frac{13}{18} (1 - a^2)^2 \left( t^2 + u^2 \right) \right. \]

\[ - \frac{1}{2} (2 a^4 - 2 a^2 - 2 a^2 b + b^2 + 1) s^2 \log \left( \frac{-s}{\mu^2} \right) \]

\[ + \frac{1}{12} (1 - a^2)^2 \left[ (s^2 - 3 t^2 - u^2) \log \left( \frac{-t}{\mu^2} \right) + (s^2 - t^2 - 3 u^2) \log \left( \frac{-u}{\mu^2} \right) \right] \}

SM: \quad a = b = 1 , \quad a_4 = a_5 = 0 \quad \Rightarrow \quad A(s, t, u) \sim \mathcal{O}(M_H^2/v^2)

\[ A(\gamma\gamma \rightarrow W_L^+ W_L^-)_{\text{NLO}} \sim \frac{(a^2 - 1)}{8\pi^2 v^2} \]

Sanz-Cillero
First evidence of $W^\pm W^\pm$ scattering $(3.6 \, \sigma)$

ATLAS, arxiv:1405.6241

CMS (preliminary) $19.4 \, fb^{-1}$ (0 TeV)

CMS-PAS-SMP-13-015
Strongly-Coupled Scenarios

- **Symmetry Breaking:** \( SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_C \)

- **Goldstone Dynamics** → Electroweak Effective Theory

- **Strong Electroweak Dynamics** → Heavy Resonances

- **Many possibilities:** (Walking, Conformal) Technicolour, CFT, 5D...

- **Light Scalar Resonance** \( H(125) \)
  - Pseudo-Goldstone (composite) Higgs, Dilaton...

González-Fraile, Kozlov, Lu, Maas, Mescia, Rosell, Sanz-Cillero, Valencia...
The power of the dark side
Holds the Universe together and makes 85% of all the matter in it!

Interacts very weakly (not charged)
→ Gravity ✓
→ Higgs-like Interactions ?

SUSY and the WIMP Miracle ?

- If the LSP is the lightest neutralino it will behave as WIMP dark matter
- In the MSSM the lightest neutralino is generically a mixture of the Bino, Wino, and the two Higgsinos
- If you are more ambitious, can try to require that the LSP is a thermal relic with the correct abundance to explain all ALL dark matter

Carena

SUSY and the WIMP “Miracle”

Bino-Higgsino mixture, closest case to the WIMP Miracle

Pure Bino needs co-annihilation with other quasi-degenerate superpartners

Bino-like that can annihilate through the h or Z “funnels”

Higgsino, ~ 1.5 TeV

Wino, ~ 3 TeV

Snowmass'13 (Hewett, Rizzo, et al)
Hidden Portals

Coupling to a hidden Dark Sector through new SM-singlet particles

- Higgs Portal: $\chi H^+H$, $\chi^2 H^+H$
- Vector Portal: $V_{\mu\nu}F_{\mu\nu}$
- Neutrino Portal: $\bar{L}_L H N_R$
- Axion Portal: $a \tilde{G}_{\mu\nu}G^{\mu\nu}$, $\partial^\mu a \bar{\psi} \gamma_\mu \gamma_5 \psi$

DM candidates in many BSMs

Kim, Ko, Sokolowska, Swiezewska...

Complementary experimental information
Dark Photon

Kinetic Mixing:

\[ L = -\frac{\epsilon}{2} V_{\mu\nu} F^{\mu\nu} \]

Pospelov et al, Arkani-Hamed et al, Essig et al...

BaBar 1406.2980

Palladino
Mining for WIMPs

Snowmass Community Summer Study 2013
Cosmic Frontier CF1: WIMP Dark Matter Detection

Araujo

A. Pich
Theory Highlights & Outlook
51
Inflation Paradigm

- **Negative Pressure** $\implies$ **Repulsive Gravity.**
- **State dominated by scalar field potential energy** $\implies$ **Negative Pressure.**

**Planck**

$\Omega = 1.0010 \pm 0.0065$

**BICEP2**

$\rho_{\text{inf}}^{1/4} = 2.2 \times 10^{16}$ GeV $\left(\frac{r}{0.2}\right)^{1/4}$
\[ r = 0.020 \pm 0.07 - 0.05 \quad (\text{tensor} / \text{scalar}) \]

- Evidence of inflationary gravitational waves?
- Foreground polarized dust emission?

Planck 2014
Milky Way’s (dust) magnetic fingerprint

Flauger et al 1405.7351, Mortonson-Seljak 1405.5857
**Inflaton**

- **Another scalar field?**

- **Could “Higgs Inflation” work?**

\[ S_G = -\frac{1}{2} \int d^4x \sqrt{-g} \left\{ M_{Pl}^2 R + \xi H^2 R \right\} \]

\[ \xi \approx 47000 \sqrt{\lambda} \quad \text{(COBE)} \quad \Rightarrow \quad n_s \approx 0.97, \quad r \approx 0.003 \]

**Quantum effects:** \( M_H > M_{\text{crit}} \approx 129.6 \text{ GeV} \)

Close to \( M_{\text{crit}} \), \( n \) and \( r \) strongly depend on \( M_H \) and \( m_t \)

Bezrukov-Shaposhnikov, 1403.6078
The SM appears to be the right theory at the EW scale

The $H(125)$ behaves as the SM scalar boson

The CKM mechanism works very well

Neutrinos do have (tiny) masses. Lepton flavour is violated

Different flavour structure for quarks & leptons

New physics needed to explain many pending questions: Flavour, CP, baryogenesis, dark matter, cosmology...

How far is the Scale of New-Physics $\Lambda_{NP}$?

Which symmetry keeps $M_H$ away from $\Lambda_{NP}$? Supersymmetry, scale/conformal symmetry...

Which kind of New Physics?
Awaiting great discoveries @ LHC

This, no doubt, Sancho, will be a most mighty and perilous adventure, in which it will be needful for me to put forth all my valour and resolution.

Let your worship be calm, senor. Maybe it's all enchantment, like the phantoms last night.