NEWS FROM THE LHC

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Open Questions in SM

Main open questions in Particle Physics:

- Hierarchy problem: small Higgs mass vs large Planck Mass
- Does Higgs boson exist?
- Origin of Dark Matter
- Flavor puzzle: flavor parameter small and hierarchical
- Neutrino masses
- ...

LHC will give an answer to many of those
Multiple Ways to Crosscheck SM @ LHC

- search for the Higgs
  - in the whole mass range $O(100\text{GeV} \div 600\text{GeV})$
- measure SM parameters
  - e.g. forward-backward asymm., $m_t$
- look for deviations in EWK processes
  - e.g. anomalous triple gauge couplings
- check for processes beyond SM
  - e.g. SUSY with missing $E_T$
- search for new resonances
  - e.g. $Z'$ at large masses
Outline of the Talk

- focus on the **EWK physics results**
  - W/Z
  - Top
  - Higgs
- some flavor of **searches** of physics **beyond SM**
- **DISCLAIMER:**
  - ATLAS/CMS oriented talk
  - small fraction of physics results detailed
- **complete list** of physics output here:
  - **ATLAS:** [https://twiki.cern.ch/twiki/bin/view/AtlasPublic](https://twiki.cern.ch/twiki/bin/view/AtlasPublic)
  - **CMS:** [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults)
LHC and Integrated Luminosity

- **pp collisions at 7TeV**
- **great performance, beyond expectations**
  - luminosity peak \( \sim 2.2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
  - \( \sim 80 \text{ pb}^{-1}/\text{day} \)
  - 50 ns bunch spacing
- \( \sim 2.7 \text{ fb}^{-1} \) delivered so far
- \(<6-7 \text{ collisions}> \) per crossing

**Future:**
- **fast increase** in luminosity
- \( O(5-10 \text{ fb}^{-1}) \) expected for Moriond12
- \( O(30 \text{ fb}^{-1}) \) expected for end of 2012
## Detectors

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field</td>
<td>solenoid (2 T) + toroid (0.5÷1T)</td>
<td>3.8 T solenoid + return yoke</td>
</tr>
<tr>
<td>Tracker</td>
<td>Si pixel, strips + TRT</td>
<td>Si pixel, strips</td>
</tr>
<tr>
<td>EM Calorimeter</td>
<td>Pb + LAr</td>
<td>PbWO4 crystals</td>
</tr>
<tr>
<td>Had Calorimeter</td>
<td>Fe+scint./Cu+LAr/W+Lar (≥11λ)</td>
<td>Brass+scintillator(≥7λ)/Fe+quartz</td>
</tr>
<tr>
<td>Muon</td>
<td>air-toroid muon spectrom.</td>
<td>iron return-yoke muon spectrom.</td>
</tr>
<tr>
<td>Trigger</td>
<td>L1+Rol-based HLT</td>
<td>L1+HLT</td>
</tr>
</tbody>
</table>
### Reconstructed Objects: Summary

<table>
<thead>
<tr>
<th><strong>Electrons</strong></th>
<th><strong>Muons</strong></th>
<th><strong>Photons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• track/calo-cluster match</td>
<td>• match between tracker and muon detector</td>
<td>• calo-only+conversions (with tracker)</td>
</tr>
<tr>
<td>• isolation to reject jets</td>
<td>• isolation to reject jets</td>
<td>• isolation to reject jets</td>
</tr>
<tr>
<td>• <strong>scale known to</strong> 0.3%-1.5%</td>
<td>• <strong>scale known to better than</strong> 1.0%</td>
<td>• <strong>scale known to better than</strong> 1.0% (CMS)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Jets</strong></th>
<th><strong>MET</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• reconstructed with calorimetric deposits, with tracks or with the whole detector information</td>
<td>• negative vector sum of -calorimetric objects</td>
</tr>
<tr>
<td>• anti-Kt algorithm</td>
<td>-(or) tracks</td>
</tr>
<tr>
<td>• ΔR cone 0.4-0.5</td>
<td>-(or) all objects from whole detectors</td>
</tr>
<tr>
<td>• <strong>scale known to</strong> 2%-8% ( (p_T \text{ and } \eta \text{ dep.}) )</td>
<td>• projected on the transverse plane</td>
</tr>
<tr>
<td></td>
<td>• cleaning to remove detector noise</td>
</tr>
</tbody>
</table>

**Fantastic detector performance, already close to design**
Reconstructed Objects: Calibration

ATLAS

Electrons

CMS

Muons

Photons

Jets

MET

CMS

CMS-PAS-EWK-10-005

$\pi^0 \rightarrow \gamma \gamma$ Calibration Trigger

$\sigma_{data} = 8.2\%$

$\sigma_{MC} = 8.1\%$

$\sqrt{s} = 7$ TeV

ATLAS

Data 2010 $\sqrt{s} = 7$ TeV

MC $W \rightarrow e\nu$

MC $W \rightarrow \tau\nu$

MC $ttbar$

MC $WW$

MC $Z \rightarrow ee$

MC $WZ$
HIGH ENERGY FRONTIER: NICE DISPLAY

\[ m(\text{jet-jet}) = 4.0 \, \text{TeV} \quad \text{Missing } E_T = 100 \, \text{GeV} \]
TUNING OF TRIGGERS

Dimuon mass distribution obtained from overlapping several trigger paths.
PILE-UP CHALLENGE

Past: <nPU> ~ 6.  Future: <nPU> > 15!
Precise W/Z measurements important for many reasons:

- **deviations** from SM as a sign of new physics, e.g. anomalous TGCs in di-boson production
- **test of perturbative QCD**, constrain proton PDFs
- **understand backgrounds** for new physics searches and Higgs
- **detector and physics objects** fine tuning
  - W, Z: source of isolated high $p_T$ leptons
  - benchmark for lepton reconstruction and identification (understand efficiency, resolution)
- **crosschecks for LHC luminosity**
**W and Z Production and Signature**

**LO:**

\( \text{DY} \quad \text{W/Z} + \text{jet} \)

**Rate:** 10M W per fb\(^{-1}\) (\(\#Z \sim 1/10 \) of the \(\#W\))

**Signature:**

1) \(\sim\)high \(p_T\) and isolated leptons
2) missing \(E_T\) (W) due to neutrino
**W and Z Extraction and Backgrounds**

**W → ev**

CMS preliminary

36 pb⁻¹ at √s = 7 TeV

- Use of missing E_T or transverse mass $m_T = \sqrt{2p_T^e p_T^\tau (1 - \cos(\phi_e - \phi_\tau))}$

**Z → ee**

ATLAS

- Di-lepton invariant mass

**Backgrounds:**

QCD (real or fake leptons), EWK WW, WZ, ZZ, W with tau decay, Z with one missing lepton (background to W)
**W/Z Cross Section**

- **inclusive cross section** (and vs pseudorapidity) **sensitive to PDFs** (due to acceptance cuts)

- **cross section vs $p_T$** **sensitive to extra jet radiation**, i.e. to NLO corrections

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**Ratio limited by theory systematics**

(PDF + fixed order calculation)
**Charge Asymmetry**

- at LHC W charge asymmetry due to $N(u_v) > N(d_v) \Rightarrow N(W^+) > N(W^-)$

- W pseudo-rapidity cannot be reconstructed $\Rightarrow$ **lepton asymmetry**

\[
A_{exp}(\eta) = \frac{\frac{dN}{d\eta} (\ell^+) - \frac{dN}{d\eta} (\ell^-)}{\frac{dN}{d\eta} (\ell^+) + \frac{dN}{d\eta} (\ell^-)}
\]

- inclusive measured to be $1.43 \pm 0.05$ (CMS)

- asymmetry vs pseudorapidity to check $u/d$ ratio and sea antiquark densities in different ranges of $x$
W Polarization

• at LHC dominant high $p_T$ W+jet production mechanism is $qg \rightarrow Wq$

• combining with V-A nature of weak interactions

$\Rightarrow$ W is polarized: left handed

• $\cos\theta^*$ (angle of the lepton in the W rest frame with respect to the W direction in the lab) cannot be measured (neutrino $p_z$ unknown)

$\Rightarrow$ use of

$$L_p = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

News from the LHC
Drell-Yan FB Asymmetry

\[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \]

where
\[ \sigma_F \text{ for } \cos\theta^*_{CS} > 0 \]
\[ \sigma_B \text{ for } \cos\theta^*_{CS} < 0 \]

\[ \theta^*_{CS} = \text{so called Collins-Soper angle} \]
calculated with respect to direction closer to dilepton direction

- sensitive to \( \sin^2\theta_W \)
- in bins of \( M_\parallel \) and looking at the full kinematics

\[ \sin^2\theta_{\text{eff}} = 0.2287 \pm 0.0020\,(\text{stat.}) \pm 0.0025\,(\text{syst.}) \]

to be compared with (world ave.) \( 0.23153 \pm 0.00016 \)
\[ \text{(D0 exp)} \quad 0.2309 \pm 0.0010 \]
**ZZ/WW/ZW Cross Section**

- **fundamental test** of the Standard Model
  - self interaction between ewk bosons, triple gauge couplings (TGC)
- **probe for new physics** (resonances, anomalous TGC)
- **backgrounds for Higgs** searches (high mass)

\[
\sigma(WW) = 48.2 \pm 4.0 \text{(stat)} \\
\pm 6.4 \text{(syst)} \pm 1.8 \text{(lumi)} \text{ pb}
\]

\[
\sigma(WZ) = 17.0 \pm 2.4 \text{(stat)} \\
\pm 1.1 \text{(syst)} \pm 1.0 \text{(lumi)} \text{ pb}
\]

\[
\sigma(ZZ) = 3.8^{+1.5}_{-1.2} \text{(stat)} \pm 0.2 \text{(syst)} \\
\pm 0.2 \text{(lumi)} \text{ pb}
\]

\[
\text{(NLO expected 46\pm3 pb )} \\
\text{(NLO expected 19.790\pm0.088 pb )} \\
\text{(NLO expected 6.4\pm0.6 pb )}
\]
LHC: FROM EWK PHYSICS TO HIGGS

25 years

6 months

Dec 2010 data

Jun 2011 data

CMS

Higgs
TOP PHYSICS
**Top Physics: Motivations**

- **most massive** constituent of matter
- **$M(\text{top}) \sim$ EW breaking scale**
- decay and strong production rate as tests of SM
- coupling to the Higgs $\sim 1$
  - Special role in EWK symmetry breaking?
- various **scenarios with direct/indirect coupling to new physics**
  - from extra dimensions to new strong forces
Top Production

probe low x in pdfs $\rightarrow$ gluon fusion dominated

top pairs:
strong

$\sigma = 165^{+11}_{-11} \text{ pb}$

t chan

$\sigma = 64^{+3}_{-3} \text{ pb}$

Wt chan

$\sigma = 15.7^{+1.3}_{-1.4} \text{ pb}$

s chan

$\sigma = 4.6\pm0.3 \text{ pb}$

Aliev et al 2011
Beneke et al 2010
Langefeld Moch
Uwer 2009
Moch, Uwer 2008

Kidonakis 2010
**Top Pair Signatures and Selection**

- **Top decays before it can hadronize**
  - almost exclusively $t \rightarrow Wb$

- **Top pair event classification**

  - **Dileptons**
    - BR $\sim 5\%$
    - Background small mainly $Z+\text{jets, EW}$

  - **Lepton + jets**
    - BR $\sim 30\%$
    - Background moderate mainly $W+\text{jets}$

  - **All hadronic**
    - BR $\sim 46\%$
    - Background high mainly QCD

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**Diagram**

- **ATLAS Preliminary**
  - All channels
  - Data
  - Events $\int L dt = 0.70 \text{ fb}^{-1}$
  - Dilepton

- **CMS Preliminary**
  - 1.09 fb$^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
  - CMS fully hadronic

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Daniele del Re

News from the LHC
TOP PAIR CROSS SECTION

- measurements using **different signatures** with similar performance from both experiments performed
- most precise measurement now at ~7% uncertainty
- combination not yet there but can be as low as 5%
- NNLO calculation to be challenged
- also **sensitive to PDFs**
### Single Top

- challenging because of **small cross section and large bkg**
- **measurement of** $V_{tb}$, **b-parton in proton, anomalous couplings**
- s-channel even more challenging at LHC
- require leptons+(b)jets+MET

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**For $M_t = 172.5$ GeV**

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{tb}$</th>
<th>$\sigma_{tqb}$</th>
<th>$\sigma_{tW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pp @ 7 TeV</strong></td>
<td>$4.6 \pm 0.3$ pb</td>
<td>$64.6 \pm 3.3 -2.6$ pb</td>
<td>$15.7 \pm 1.4$ pb</td>
</tr>
</tbody>
</table>

large at Tevatron  
small at Tevatron
**Single Top Results**

**t-channel “seen” by both experiments**

**ATLAS:** \( \sigma_t = 90^{+9}_{-9}^{\text{(stat)}} +^{31}_{-20}^{\text{(syst)}} \) pb

**CMS:** \( \sigma = 83.6 \pm 29.8 \text{ (stat + syst)} \pm 3.3 \text{ (lumi)} \) pb

**not enough sensitivity for s-channel and Wt production**

**ATLAS**

s-channel: \( \sigma_s < 26.5 \) pb

Wt: \( \sigma(pp \rightarrow Wt + X) < 39.1 \) pb (obs.)
**Top Charge Asymmetry**

- at leading order in SM, quark pair production symmetric under charge conjugation
- at higher orders asymmetry appears (sensitive to NP)
- wider pseudorapidity distribution for top compared to anti-top

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

\[ \Delta|Y| = |Y_t| - |Y_{\bar{t}}| \]

<table>
<thead>
<tr>
<th>CMS</th>
<th>( A_{C}^{n} = -1.6 \pm 3.0 \text{(stat)}^{\pm1.0 \text{(syst)}} % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>( A_{C}^{y} = -2.4 \pm 1.6 \text{(stat)} \pm 2.3 \text{(syst)} % )</td>
</tr>
</tbody>
</table>

ATLAS Preliminary

\( \int L = 0.70 \text{ fb}^{-1} \)

\[ \mu + \geq 4 \text{ jets (b tag)} \]

Events

![Graph showing the distribution of top and anti-top quarks](image)
Top Mass

- done in **dilepton and lepton + jets modes**
- full sample not yet used (36-700pb⁻¹)
- **statistical** error already similar to Tevatron
- need to **work on systematics**. Main contributions:
  - jet energy scale
  - ISR/FSR

Mass of the Top Quark

*August 2011* *(preliminary)*

CDF-I dilepton

*CDF-I dilepton*

CDF-II dilepton

*CDF-II dilepton*

DØ-I dilepton

*167.4 ± 11.4 (±10.3 ± 4.9)*

CDF-I lepton+jets

*168.4 ± 12.8 (±12.3 ± 3.6)*

CDF-II lepton+jets

*170.6 ± 3.8 (±2.2 ± 3.1)*

DØ-II lepton+jets

*174.0 ± 3.1 (±1.8 ± 2.5)*

CDF-I alljets

*176.1 ± 7.4 (±5.1 ± 5.3)*

CDF-II alljets

*180.1 ± 5.3 (±3.9 ± 3.0)*

DØ-II alljets

*173.0 ± 1.2 (±0.6 ± 1.1)*

CDF-I MET+jets

*174.9 ± 1.5 (±0.8 ± 1.2)*

CDF-II MET+jets

*186.0 ± 11.5 (±10.0 ± 5.7)*

Tevatron combination

*173.2 ± 0.9 (±0.6 ± 0.8)*

*χ²/dof = 8.3/11 (68.5%)*

Atlas lepton+jets

*175.0 ± 2.8 (±0.9 ± 2.7)*

CMS lepton+jets/dilepton

*173.4 ± 3.3 (±1.9 ± 2.7)*

*arXiv:1007.3178*
BSM Searches
## SUSY as a Possible SM Extension

- **new symmetry** between fermions and bosons (every SM particle has a partner differing by 1/2 in spin)
- **solves hierarchy and other SM problems**
- **SUSY particles** produced in pairs
- **stable and neutral lightest SUSY particle** (LSP)
  - good candidate for Dark Matter

<table>
<thead>
<tr>
<th>SM Particles</th>
<th>SUSY Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>quarks: ( q )</td>
<td>squarks: ( q )</td>
</tr>
<tr>
<td>leptons: ( l )</td>
<td>sleptons: ( \tilde{l} )</td>
</tr>
<tr>
<td>gluons: ( g )</td>
<td>gluino: ( \tilde{g} )</td>
</tr>
<tr>
<td>charged weak boson: ( W^\pm )</td>
<td>( W^\pm ) ( \tilde{W}^\pm )</td>
</tr>
<tr>
<td>Higgs: ( H^0 )</td>
<td>Wino: ( \tilde{H}^\pm ) ( \tilde{H}^0 )</td>
</tr>
<tr>
<td>neutral weak boson: ( Z^0 )</td>
<td>( Z^0 ) ( \tilde{Z}^0 )</td>
</tr>
<tr>
<td>photon: ( \gamma )</td>
<td>photino: ( \gamma )</td>
</tr>
</tbody>
</table>
SUSY: SIGNATURE

Event topology:

• high $p_T$ jets from squark-gluino decays
• large missing $E_T$ from LSP
• high $p_T$ leptons from sgaugino/slepton
• high $p_T$ b-jets, $\tau$-jets depending on models
**Searches in Jets + MET**

- **Strong production of massive particles**
  - require high $p_T$ jets
  - leptons are vetoed

- **Different techniques**:
  - large missing $E_T$
  - large jet hadronic transverse energy ($H_T$)
  - large jet multiplicities (large cascades)
  - QCD topology rejection

- **Striking signature** from SUSY
Searches in Leptons + MET

- require leptons + MET

- different lepton selections
  - 1 lepton
  - 2 opposite-sign leptons (same cascade)
  - 2 same-sign leptons with same or opposite flavor (opposite cascades)

- use kinematic constraint of the SUSY cascade to identify signal

- less stringent limits than fully hadronic but complementary
SUMMARY OF SUSY RESULTS

- no hints of SUSY so far
- much more stringent limits than for previous experiments
  - limits at 1TeV for \(m(\text{squark}) = m(\text{gluino})\)
- \(x10\) statistics helps but limited by 7TeV energy
SEARCHES FOR HEAVY RESONANCES

• predicted by numerous extensions of SM
  – sequential SM, GUT-inspired theories, technicolor, Kaluza-Klein ED

• relatively clean with good S/B and identified by a peak!

• care for energy/momentum reconstruction above 1 TeV

• no peak so far

![Graphs showing di-μ and di-jet results from ATLAS and CMS](image-url)
**All Exotica Searches**

- Full list, to have a feeling of the scanned phase-space

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- CMS
  - similar for ATLAS
Higgs Physics
in SM electroweak symmetry broken via the Higgs mechanism

\[ V(|\phi|) = \mu |\phi|^2 + \lambda |\phi|^4 \]

- W and Z bosons acquire mass, photon remains massless
- Higgs not yet seen
- limits for the Higgs bosons from direct searches and global EW fits

http://arxiv.org/abs/1107.0975  \( M_H \, \text{GeV} \)
Higgs Cross Sections @ LHC and BR
Higgs Cross Sections @ LHC and BR
**Higgs Cross Sections @ LHC and BR**

- $M_H < 130$ GeV
  - $H \rightarrow \gamma\gamma$ dominates

- $130$ GeV $< M_H < 200$ GeV
  - $H \rightarrow WW$ dominates

- $M_H > 200$ GeV
  - $H \rightarrow ZZ$ dominates
# BACKGROUND, SIGNATURE, AND S/B

<table>
<thead>
<tr>
<th>mode</th>
<th>backgrounds</th>
<th>signature</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>H→γγ</td>
<td>born/box diphoton QCD photon+ jet</td>
<td>two photons peak in inv. mass</td>
<td>low O(0.1)</td>
</tr>
<tr>
<td>H→WW</td>
<td>ttbar drell-yan pp→WW</td>
<td>two leptons with opposite charge MET</td>
<td>medium O(1)</td>
</tr>
<tr>
<td>H→ZZ</td>
<td>pp→ZZ</td>
<td>four leptons with right charge peaks in inv. mass (Z and Higgs)</td>
<td>high &gt;1</td>
</tr>
</tbody>
</table>
• **crucial** channel in the mass **region preferred by EWK fit**

• **sensitivity** to either excluded or see Higgs **not reached yet**
  – exclusion at about **3xSM**

• with **O(10fb⁻¹)** possible to give a **final answer**
• best channel for exclusion in the **intermediate mass region**
  – but **tough for discovery** since no peak
• MET and topology requirements (e.g. $\Delta \phi$ between leptons)
• exclusion in $140\text{GeV} < M_H < 200\text{GeV}$
\[ H \rightarrow ZZ \]

- **very clean** signature (peak over ZZ SM) **but low statistics**
  - best channel for discovery at high masses
- **sensitivity** (>200GeV) already reached
- exclusion in combination with other ZZ modes (e.g. 2l2ν)
Higgs Combination: Upper Limit

- final limits **combining more than 10 channels**
- ATLAS-CMS combination in progress
- expect that at 95% confidence level Higgs is excluded in region $140 \text{GeV} < M_H < 450 \text{GeV}$
Higgs Combination: P-Value

- **p-value** = probability that data are consistent with a background-only hypothesis
- **no significant excess yet...**
**Higgs: Conclusions and Perspectives**

- **Tevatron results are almost superseded** (except for very low mass)
- Higgs with **large mass (>140GeV)** is unlikely
  - excluded with a decent CL by LHC
- **tough job at low masses**
  - major player will be $H \rightarrow \gamma\gamma$
- **Personal view:**
  - $O(10 fb^{-1})$ enough to exclude on the whole range
  - $\Rightarrow \sim$ Moriond 2012
  - end of 2012 for a final answer
**CONCLUSIONS**

- **LHC is doing great.** >2fb⁻¹ so far. Fast increase expected
- **Fantastic performance of ATLAS and CMS**
  - physics objects and trigger already deeply understood
- **Wide physics output (>100 ATLAS+CMS papers)**
  - EWK and Top physics already at precision level
  - extensive searches of physics beyond SM
  - Higgs hunting providing world-best exclusions
- **Short summary of searches**
  - no hint of new physics or Higgs. Exclusion at 95% CL:

| SUSY \( m_{\text{squark}} = m_{\text{gluino}} \) | <1TeV |
| New Gauge Bosons (Sequential SM) | <2TeV |
| **Higgs** | \( 140 \text{GeV} < M_H < 450 \text{GeV} \) |
dilepton rest frame