Searches for Physics beyond the Standard Model at the LHC

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(On behalf of the ATLAS and CMS Collaborations)

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Motivation

- SM impressively consistent (even after discovery of Higgs) ➔

Still open questions...and no favorite solution!

Focus of this talk ➔ Direct Searches
- New TeV scale interactions/particles?
- Hierarchy problem → Extra dimensions?
- WIMPs as dark matter candidates?

Need highest energies and Luminosities ➔ LHC

No deviations > 3σ! ➔ SM consistent!
Large Hadron Collider

2012: 20/fb per exp. @ 8 TeV \(\rightarrow\) Results in the following

2011: 5/fb per exp. @ 7 TeV

LHC w.r.t. Tevatron: pp, twice the integrated luminosity, four times the center-of-mass energy

\(\rightarrow\) Precision measurements: Tevatron competitive

\(\rightarrow\) Searches for new objects at high mass: LHC dominates
Results from the two general purpose detectors...
HowTo? Example: Dileptons

Two isolated leptons -> Clean signature with low background

➔ Also used for NP searches with small BR to dilepton final states

Highest $m_{\ell\ell}$ event:

- $p_T = 588$ GeV
- $p_T = 584$ GeV
- $m_{\ell\ell} = 1.54$ TeV
Comparison Data-Expectation

- Backgrounds from real electrons from simulation
- Backgrounds form misidentified jets/photons -> data driven method
- Signal: Additional neutral gauge bosons $Z'_{SSM}$ (couplings same as for $Z$, benchmark model)

Dominated by PDF uncertainty ➔ running into kinematic limit

Good agreement of data with expectation ! ➔ Set limits...
Upper limit (95% CL) on $\sigma B$.

Lower mass limit (95% CL) on $Z'_\text{SSM}$ is 2.8 TeV (2.9 TeV when combined with muons)

Large off-shell production

Limit degrades for high masses

Time for higher beam energy!
Discussion limits

Additional neutral gauge bosons:
- $Z'_{SSM}$
- E6 $Z'_{\chi}$ and $Z'_{\psi}$, GUT motivated
- $Z^*$, appear as doublet ($Z^*, W^*$) in various solutions to hierarchy problem, anomalous couplings to fermions

<table>
<thead>
<tr>
<th>Model</th>
<th>Width [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_{SSM}$</td>
<td>3.0</td>
</tr>
<tr>
<td>$Z'_{\chi}$</td>
<td>1.2</td>
</tr>
<tr>
<td>$Z'_{\psi}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$Z^*$</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Low mass:
- Limits get stronger with decreasing width, but effect small...

High mass:
- Off-shell production leads to weaker limits
- Off-shell production increases with increasing width

Limits on benchmark model SSM can be reinterpreted in the context of most narrow models.
Tevatron limits (approx. 1 TeV) reached with 2010 data
- 2011 data $\Rightarrow$ 2.2 TeV limit
- 2012 data $\Rightarrow$ 2.9 TeV limit

Fast increase in limits (1TeV->3TeV) in short period of time!

Also, narrow resonances with 100 times smaller cross section than SSM excluded up to 1.4 TeV
**Z’: Enhanced coupling to 3\textsuperscript{rd} gen?**

What if coupling to 3\textsuperscript{rd} generation enhanced?

**Graph:**
- **Z’ \rightarrow \tau\tau**
- **Data**:
  - ATLAS: **Preliminary**
    - \( \int L \, dt = 19.5 \text{ fb}^{-1} \), \( \sqrt{s} = 8 \text{ TeV} \)
  - Z’ \text{SSM}
    - Observed limit:
      - Expected limit
      - Expected ± 1\(\sigma\)
      - Expected ± 2\(\sigma\)
    - Z’ \text{SSM} th. uncert.

SSM excl. (95% C.L.) below 1.9 TeV, electron/muon limits stronger (2.9 TeV), but...

**Table:**
- Observed limits between 2.1 and 2.7 TeV depending on the model.

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Lepton + missing transverse energy

Search for new (heavy) resonances in lepton plus missing transverse energy (e.g. due to escaping neutrino) spectrum

- $W'$ (SSM, benchmark)
- $W_{KK}$ in Extra Dimension scenario (→ later)
- Dark Matter (DM) pair production (→ later)
- Contact Interaction (CI)

Also here: Search covers many scenarios

$M_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \varphi_{\ell\nu})}$.
Upper limit (95% CL) on $\sigma B$.

Lower mass limit (95% CL) on $W'_\text{SSM}$ is 3.22 TeV (3.28 TeV when combined with muons)

Fast increase in limits in short period of time!

ATLAS and CMS limits are usually comparable

In general no need to show both...
Hierarchy problem: Planck scale @ $10^{16}$ TeV much higher than our usual EW mass scales

Why?

 Leads to fine-tuning problem:

Loop corrections to Higgs: $m_H^2 = m_{H,\text{bare}}^2 - \Delta m_H^2$

$\Delta m_H^2 \propto \Lambda^2$ \(\Lambda: \text{Scale of new physics}\)

If no new physics up to Planck scale, incredible fine-tuning needed

Cancellation of two very large numbers to give observed (125 GeV) Higgs mass

Naturalness problem

One solution: Extra Dimensions?

Higher-dimensional Planck mass could be TeV scale
Randall-Sundrum (RS):
• one warped extra dimension with curvature $k$
• Gravity originates on Planck brane and can propagate through bulk

Gravity appears weak on our 3+1 dim brane

• RS-1: SM confined to 3+1 dimensional brane
• Bulk-RS: SM can propagate into bulk

Higher-dim Planck scale: $M_D = M_{Pl} e^{-k\pi R}$

ADD: Arkani-Hamed, Dimopoulos, Dvali
• $n \geq 1$ additional flat extra dimensions
• Compactified on radius $r$
• If higher-dim Planck scale ($M_D$) about 1 TeV: $n = 1 \rightarrow r = 10^8$ km
  $n = 2 \rightarrow r = 1$ mm
Randall-Sundrum: Dilepton & Diboson

RS-1 model:

- Narrow resonances in dilepton, diphoton (lightest excitation of Graviton, G*)
- Search for Spin-2 resonances (decay to leptons not favored)
  - Further improvement (≈10%) expected when adding diphotons

Bulk-RS model:

- suppressed coupling of graviton to light fermions and quarks, negligible coupling to photons
- decay in heavy bosons and top can be sizeable
- Searches in WW, WZ and ZZ final states (fully hadronic and semi-leptonic decays)
  - No mass limit yet...
**ADD, direct and virtual KK gravitons**

**Exchange of virtual gravitons**
- Modification of SM cross sections (ll, gg)
- Model valid below onset of quantum gravity at scale $M_s$
- Almost continuous spectrum of KK Graviton
- excitations $\Rightarrow$ non-resonant signal

**Direct production of gravitons**

$\Rightarrow$ Jet + missing ET signature (mono-Jet)

- Limits of about 4 TeV set on $M_s$
  (depends on number of extra dimensions)
- Diphoton would add 10 %...

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Black Holes

- (Semi classical) BH production: $M_{th} > M_D$ (higher dim. gravitational scale) (QBH have mass closer to $M_D$)
- Lose mass and angular momentum by Hawking radiation
- Once mass close to $M_D$, decay to small number of SM states (large theor. uncertainties)

Semi-classical versus quantum (non-thermal) black hole:

Experimental signature:
- Ensemble of high-energy particles (very model dependent)
- Rotating BH has less but higher energy particles compared to non-rotating BH
Thermal Black Holes

At least two jets with $E_T > 50$ GeV; binned in multiplicity (all objects $E_T > 50$ GeV)

- $S_T$: scalar sum of all $E_T$
- background (multi-jet) from fit

Black hole mass thresholds are above 5 TeV for six extra dimensions

Stronger limits with higher number of extra dimensions due to larger cross section
ADD and Quantum Black Holes

If collision energy approaches $M_D$

⇒ **Quantum Black Holes** can be produced

(Threshold for QBH production $M_{th}$ assumed to be approx equal to $M_D$)

• QBH decay can violate conservation of lepton and baryon number

⇒ Clean searches as SM background small

• Example: Decay to lepton (e,mu) and jet
• Cross section dominated by uu (charge 4/3) with e,μ+jet BR of 11%

ADD, n= 6 lower limit on $M_{th}$ is 5.3 TeV
(5.2/5.1 TeV for electrons/muons)

Limits on QBH set in various decay channels
( dijet, $\gamma j$, dilepton, ...and with different assumptions)

⇒ Masses up to 5 TeV excluded

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Dark Matter

Evidence for dark matter:

- Orbital velocities of galaxies
- Gravitational lensing (weak)
- Cosmic microwave background

\[ v \propto \frac{1}{\sqrt{r}} \]

Image: E Grocutt, IfA, Edinburgh

Dark Matter

Dark matter properties:
• Gravitational interaction
• Electrically neutral
• Stable or long lived
• (largely) non-baryonic
• (at most) weakly interacting

Popular dark matter candidate:
Weakly Interacting Massive Particle (WIMP)

Search for DM:

Indirect detection: annihilation

Direct detection: WIMP-Nucleon scattering

Production: e.g., LHC
Dark Matter

WIMPs escape detection ➔ Missing ET plus “Tag”

• Strongest limits from monojets,
  (assuming equal coupling of dark matter particles to up and down type quarks)

• Interpretation in context of EFT assuming contact interaction (CI) between quarks and DM particles

• Modeled in EFT with mass scale $M_* \sim \frac{M_{med}}{\sqrt{g_{SM} g_x}}$
Mono-Jet (CMS) and WZ hadr ATLAS


- Examples for similar signals in mono-Jet and mono-W/Z shown.
- If coupling of dark matter particles to up and down type quarks has opposite sign the mono-W channel would be very sensitive.

Mono-W:
- Interference between radiation from u and d quarks (→ d̄d or uu production)
- Destructive (u=d) if equal couplings → small signal
- Constructive if opposite sign (u = -d) couplings

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Lower limits on $M_*$ can be converted into upper limits on WIMP-Nucleon scattering cross section:

- DM search in mono-X ($X = j$, $W$, $Z$, $\gamma$, ...)  
- In general: Most powerful is mono-jet (or mono-$W$ if constructive interference)  
- Complementary sensitivity (in particular at low WIMP mass) to direct detection experiments, but model dependent...
*Only a selection of the available mass limits on new states or phenomena is shown.*

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**Extrapolation via scaling of parton luminosities**

- **q\bar{q} yield of signal @ 3 TeV** 20 times higher at 13 TeV compared to 8 TeV! (unfortunately background yield higher as well)
- **Limits (around 3 TeV)** with 1-3/fb @ 13/14 TeV are comparable to present limits

....eagerly awaiting 2015 data!
LHC Run-1 explored new territory

→ nothing (unexpected) found yet...

• SM impressively consistent (even after discovery of Higgs)
• Direct searches: Much progress (in terms of reach)!
• Starting from 1/fb of 2015 data some analyses surpass current sensitivity!

→ Eagerly awaiting the new data …