Particle and Astroparticle Physics at the Large Hadron Collider

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Outline

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• Part 1: Results on Standard Model measurements and searches for new physics
• Part 2: LHC results for Astroparticle physics
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  • Forward measurements
  • Cosmic ray measurements
  • LHC and light ions?
• Summary
The LHC Machine and Experiments

LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015  Run-2 starts

Most analyses presented today based on the 13 TeV data sample
LHC Now in the 2017 Run!

2017 run: started 23 May

- Peak luminosity so far $1.53 \times 10^{34}$ Hz/cm$^2$ with
  - 2544 bx colliding (maximum in BCMS)
  - $1.11 \times 10^{11}$ p/bx (average)
  - $\varepsilon_N = 2.2 \, \mu$m normalized emittance (NB $\sigma = (\varepsilon \beta^*)^{1/2}$)

Plan to increase the luminosity adiabatically to about $2 \times 10^{34}$ Hz/cm$^2$

- Expect to collect $\sim 90$ fb$^{-1}$ in 2017-2018 → gives around 130 fb$^{-1}$ total in Run-2

NO change of beam energy in 2017 and 2018

Goal is to prepare the LHC to run at 14 TeV during Run 3.
The Main Physics Case for the LHC

**Understand the mechanism Electroweak Symmetry Breaking**

**Discover physics beyond the Standard Model**

Reminder: The Standard Model
- tells us how but not why
  - 3 flavour families? Mass spectra? Hierarchy? 19 parameters!
- needs fine tuning of parameters to level of $10^{-30}$!
- has no connection with gravity
- no unification of the forces at high energy

Most popular extensions around 2000

- Supersymmetry
- Extra space dimensions

Many other ideas: More symmetry and gauge bosons, composite Higgs models, L-R symmetry, quark & lepton substructure, Little Higgs models, Technicolor, Hidden Valleys, Vector-like quarks...

Higgsless models rather disfavoured these days
New Physics Hunters @ the LHC

The ATLAS experiment

The CMS experiment

...And also LHCb and MoEDAL
PART I

Results on Standard Model Measurements and Searches for New Physics
Standard Model Measurements

Example: Papers published by CMS on physics results

Important fraction of the results on Standard Model measurements

Similar for ATLAS
Standard Model Measurements

Grand Summary: The Standard Model works very well at 13 TeV!!
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model.
The Higgs Boson

4th of July 2012

The party 5 years ago

What happened since?
We continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, heavier Higgses, charged Higgses...

We know already a lot on this Brand New Higgs Particle!!

Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width
< 24 MeV
(95%CL)

Couplings are
within ~20% of
the SM values

Spin =
0+(+) preferred
over 0-,1,2

Brief Higgs Summary from Run-1
The newly found boson has properties as expected for a Standard Model Higgs.

**Signal strength/SM:**

\[ \mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07} \text{ (stat)} \times 10^{0.04}_{-0.04} \text{ (expt)} \times 10^{0.03}_{-0.03} \text{ (thbgd)} \times 10^{0.07}_{-0.06} \text{ (thsig)}, \]
New 13 TeV Higgs Results

News on the Higgs from EPS from the 13 TeV Run-2

- The particle is still there!! 😊
- Precision on eg cross sections improves with factor 2 wrt Run-1
- Observation of $H \rightarrow \tau\tau$
- Evidence for $H \rightarrow bb$
- No deviations from Standard Model Higgs expectations yet

The Higgs Boson is still very much Standard Model-like!
New Physics?

New Gauge Bosons?

Supersymmetry

ZZ/WW resonances?

Technicolor?

Extra Dimensions?

Black Holes???

Little Higgs?

Hidden Valleys?

What stabilizes the Higgs Mass? Many ideas, not all viable anymore
A large variety of possible signals. We have to search a wide phase space
Supersymmetry: a new symmetry in Nature?

Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

SUSY particle production at the LHC

Picture from Marusa Bradac
No sign of SUSY in the LHC data to date... 😞
Use effective theory or better simplified models to relate measurements to Dark Matter studies.

- Mono-jets: Generally very powerful
- Mono-photons: First used for dark matter searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to top quarks
- Mono-Higgs: Higgs-portals

Eg: arXiv:1407.8257
    arXiv:1411.0535
Monojet Searches

The Dark Matter Particles WIMP hypothesis
Neutral weakly-interacting massive and stable on detector distance scales
→ Dark Matter appears as Missing Transverse Momentum MET in detectors
Comparison with Direct Detection

Axial-vector mediator and spin-dependent direct limits

Vector mediator and spin-independent direct limits

More reliable comparisons with direct detection results now possible using the Simplified Model analyses techniques

90% CL limits

Similar results from ATLAS
A New Particle at 750 GeV: $X \rightarrow \gamma \gamma$?

December 2015: Some excitement on an mild observed excess in both experiments for a diphoton mass of around 750 GeV.

ATLAS-CONF-2015-081

3.9 σ local sign.

Conclusion:

ATLAS-CONF-2016-059

RIP
Andre David: http://jsfiddle.net/adavid/bk2tmc2m/show/ 11/7/2017

Constant rate of 2 papers on the arXiv/ working day till August 2016!

... and still new entries continue to appear since August 2016...

Everybody (?) is eagerly awaiting a discovery...
Lepton Universality Violation?

Will the Standard Model crack in a different place?

Ratio of $B^0 \to K^{*0} \mu^+ \mu^-$ to $B^0 \to K^{*0} e^+ e^-$

This is a 2-2.5σ effect at present.

Watch that space!
PART II
LHC Results for Astroparticle Physics
The LHC provides a significant lever-arm in providing data to constrain high energy cosmic ray Monte Carlo programs.
Inelastic Cross Section at 13 TeV

- Based on counting minimum bias events
- No acceptance for $\xi < 10^{-6}$
- Corrected based on 7/8 TeV experience with the ALFA proton tagger in ATLAS (~15%)

$$\xi = \frac{M_x^2}{S}$$

$\sigma_{inel} = 79.3 \pm 0.6(\text{exp}) \pm 1.3(\text{lum}) \pm 2.5(\text{extr}) \text{ mb}$

arXiv:1606.02625
Total and Inelastic Cross Sections

New result from the TOTEM experiment at 2.76 TeV

The analysis of the 13 TeV data is in progress

M. Deile, Blois 2017, Prague

New TOTEM result @ $\sqrt{s} = 2.76$ TeV

$$\sigma_{\text{tot}} = 84.7 \pm 3.3 \text{ mb}$$
$$\sigma_{\text{inel}} = 62.8 \pm 2.9 \text{ mb}$$
$$\sigma_{\text{el}} = 21.8 \pm 1.4 \text{ mb}$$
Inclusive Particle Spectra

LHC experiments have made measurements of charged particle spectra and energy flows in the central region for minimum bias pp collisions. Some examples for data at 13 TeV:

- Useful for tuning of models, see T. Pierog later this meeting
- Any particular measurements still needed/required??

The underlying event is everything except the hard scattering and its radiation.

Measure the particle flow in transverse region as function of the leading track or jet in the event.

The activity keeps increasing with increasing CM energy!!
Correlations Between Produced Particles

- Select high multiplicity events
- Study the correlation between two charged particles in the angles $\phi$ (transverse): $\Delta\phi$ and $\theta$ (longitudinal): $\Delta\theta$

$\eta = -\ln \tan \theta/2$

A new phenomenon in the ‘stronge force’?

- Understanding the “ridge” in pp collisions?
- Was first seen in AA, then pp (unexpected) and now also pA (~unexpected)
Correlations Between Produced Particles

For pp collisions the effect is the same at 7 and 13 TeV

ALICE: Production of baryons with multiple strangeness number equally enhanced in pp, pPb (and PbPb) when compared as function of charged track multiplicity

Nature Physics Vol13 June 2017

Multiple interactions? Glass condensates? Hydrodynamic models? Still a bit of a mystery!!
Forward Coverage of the Experiments

Particle and energy flow as function of pseudorapidity (polar angle) $\eta = -\ln \tan \theta/2$

- Most of the energy flow is in regions at large $|\eta|$, i.e., beam directions.
- Particle density is highest in the central region.
- Forward energy/particle flow of particular interest for cosmic ray air showers!
- Detectors @LHC extending up to $|\eta|<5$ + special detectors for larger $|\eta|$.
Forward Detectors in CMS

Detector configuration during 2010 - 2011

ZDC
(|η| > 8.1)

CASTOR
(5.2 < |η| < 6.6)

140m

CMS

Hadronic Forward (HF)
(3.0 < |η| < 5.0)

140m

BSC

W-absorbers/quartz plates
12 longitudinal modules/16 azimuthal sectors

Hadron Forward:
@11.2m from interaction point
Rapidity coverage: 3 < |η| < 5
Steel absorbers/quartz fibers
(Long+short fibers)
0.175x0.175 η/φ segmentation
Acceptance limited to |η| < 4.9 at analysis level

New: Precision Proton Spectrometer together with TOTEM (CT-PPS)
Forward Detectors in ATLAS

2.07 < |η| < 3.86
MBTS
(Scintill. Det.)

5.6 < |η| < 5.9
LUCID
(PMT-Cerenkov)

|η| > 8.3
ZDC
(W-Quartz Cal.)

10.6 < |η| < 13.5
AFP (2 Sts)
(RPs-Si-ToF)

ALFA
(SciFi tracker)
Event Characteristics in the Forward Region

Energy Flow in the extended forward region of CMS

arXiv:1701.08695

Cosmic ray models

Pythia/Herwig++ variations

Pseudorapidity ranges: -6.6 < \eta < -5.5

Stable particle results
The LHCf Experiment

LHCf is a two arm detectors with calorimeters at zero degrees with respect to the beam axis, at 140 m from the IP (ATLAS)

Photon at $\sqrt{s}=13$TeV, p-p

See talk of H. Menjo yesterday

LHCf is a dedicated experiment at the LHC to make measurements relevant for cosmic ray studies

- QGSJET-II-04 is in good agreement for $\eta>10.94$, softer at $8.81<\eta<8.99$
- EPOS-LHC is in good agreement for $E<3\text{-}5$ TeV, harder at higher energy
- SIBYLL2.3 gives a harder prediction for $8.81<\eta<8.99$

CERN-EP-2017-051
The LHCf Experiment

Neutron measurements in pp at 13 TeV (ARM2)

No Model works well for $\eta > 10.76$, except QGSJET-II-04 (qualitatively)
EPOS-LHC has better agreement for $8.99 < \eta < 9.22$ and $8.81 < \eta < 8.99$

Common analyses with ATLAS ongoing, eg for diffraction studies...
Precision measurements of diffractive components at the LHC within reach

\[ \sigma^{SD} (\xi < 0.05) = 8.84 \pm 0.08 \text{ (stat.)} +1.49_{-1.38} \text{ (syst.)} +1.17_{-0.37} \text{ (extrap.) \, mb} \]

\[ \sigma^{DD} (\Delta \eta > 3) = 5.17 \pm 0.08 \text{ (stat.)} +0.55_{-0.57} \text{ (syst.)} +1.62_{-0.51} \text{ (extrap.) \, mb} \]
Central and Forward Particle Density

A common CMS+TOTEM measurement

arXiv:1405.0722

A challenge for the phenomenological models?
Does it Help? Yes!!

T. Pierog: UHECR meeting in Kyoto Japan October’16
New results expected here at ICRC 2017
Detection of Cosmic Rays at the LHC

- ALICE is located at LHC Point 2, 52m underground (28m rock above)
- Muon energy threshold ~16 GeV
To measure the cosmic charge ratio wrt momentum for single muons for two cases: near vertical and horizontal (central barrel).

To measure the cosmic charge ratio wrt muon multiplicity.

Study in detail the properties of muon bundles.

LEP detectors at CERN have been used to study cosmic muons and in particular muon bundles passing the detectors. These results were not understood at the time (even assuming pure Fe).
Detectors used for cosmic-ray data taking in the central barrel:

- **Trigger**
  - ACORDE
  - TOF
  - SPD
- **Tracking**
  - TPC

**2010-2013** Recorded 30.8 days of cosmic triggers: ~7.5K events with > 4 μ’s

**2015-2016** 43 days collected. Now being analyzed

More data will be collected this & next year. **Upgrades foreseen for Run-3**
The observed rate is consistent with the predictions of CORSIKA 7350 with QGSJET II-04 model using pure Fe primary composition and energy $>10^{16}$ eV.
Other Experiments at the LHC?

Interest expressed by some groups in ATLAS (J. Pinfold)

- ATLAS would measure CR muons directly using unprecedented areas of precision $\mu$-tracking + calorimetry $\sim 70m$ underground
- ATLAS will use two triggers
  - The existing ATLAS cosmic ray trigger (that runs during data taking)
  - A trigger provided by the Surface Array ($\sim 1/60$ Hz)
- ATLAS - used to measure the muon content of the shower - will be combined with a surface array via the ATLAS trigger
- The surface array used to measure the energy & shower direction

Note decided yet. Some plans for a small surface detector test
pp, pPb and PbPb at the LHC

lead-lead collision at 5 TeV/nucleon

proton-lead collision at 8.2 TeV/nucleon

Many particle production results available for pPb and PbPb by ALICE, CMS, ATLAS and LHCb
Light Ions in the LHC?

Of interest for cosmic ray studies would be collisions of light nuclei → Initial study at the LHC by D. Mangluki in 2012. Still preliminary results and an in depth study is required. See: https://indico.cern.ch/event/223562

Main conclusions:
• CERN can provide light nucleon beams for the LHC
• Collisions can be pA, AA, and AB

ECR source

• The source can “deliver anything”, however...
  – It takes time to commission the whole chain with new species (16 weeks minimum for LEIR/PS/SPS)
  – Switching between two species within one year is difficult (~ 4 weeks to switch ECR for completely different species)
    -> competition with Pb-Pb and p-Pb in LHC, and primary ions in North Area (Ar, Xe, Pb)
• Oxygen is support gas for Pb
  – One can imagine running O for a short period within Pb year
    • Opens possibility for O-O and p-O
• Other ion mixtures
  – N + O, S + O “Easy”
  – MIVOC (Metal Ions from Volatile Compounds) for Fe...
Light ions in the LHC

- Estimates of rough conservative luminosities (D. Mangluki 2012)
- Set-up time substantial but parallel with running of the pp facility
- So far not foreseen in the CERN plan! Needs strong motivated request based on the physics case. Interest also from the medical sector

Estimations of Luminosity [cm$^{-2}$ s$^{-1}$]

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<th>$\beta^*$=50 cm</th>
<th>O-O</th>
<th>N-N</th>
<th>S-S</th>
<th>Fe-Fe</th>
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<td>3.2E+29</td>
<td>6.2E+28</td>
<td>2.4E+28</td>
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<table>
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<th>$\beta^*$=10 m</th>
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<th>p-N</th>
<th>p-S</th>
<th>p-Fe</th>
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<thead>
<tr>
<th>$\beta^*$=50 cm</th>
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<td>1.4E+28</td>
<td>6.2E+27</td>
<td>3.8E+27</td>
<td>1.9E+27</td>
<td></td>
</tr>
</tbody>
</table>

- Injection optics $\beta=10$m in case of short runs
- Assume 300 bunches
- Running at 7•ZTeV

If this option is considered to be interesting for the cosmic ray community it is a good time to speak up now!
Summary

• LHC is now running at 13 TeV. No significant anomalies observed so far in the searches and SM measurements.

• The Higgs particle is at the rendez-vous at 13 TeV. Expect good precision measurements in Run-2. Already now factor two improvement with Run-1 in cross section measurements.

• Many measurements are made which are useful for astroparticle physics and model tuning. LHC data has already impact on these tunes. The data at the new energy of 13 TeV will be an asset for further tuning

• There are no doubt other measurements which can or should be done. Input welcome! Lots of data on tape!

• ALICE has a cosmic ray study program. Groups in ATLAS also interested.

• Outlook: Also pPb, PbPb collisions on tape. pA & AA values at lower A values in future?
Backup
MoEDAL: Search for Monopoles

First monopole search at the LHC at 13 TeV