Standard Model @ Hadron Colliders

I. Introduction

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Standard model pillar I: Matter

Unique topic for hadron colliders
Experiments just started

'light' quarks intensive studies via hadrons

Neutrinos tiny masses
Transition matrix to be measured

charged leptons deeply scrutinized
Standard Model pillar II: Forces

Strength of all interactions very precisely known

\[ \alpha_s(M = M_Z) = 0.1184(7) \]

\[ \alpha_{em} = 1/137.03499976(50) \]

\[ G_F(M = m_\mu) = 1.16639(1) \cdot 10^{-5} \text{ GeV}^{-2} \]

\[ M_Z = 91.1882(22) \text{ GeV} \]

Dynamics of interactions well tested at energies \( \sim 100 \text{ GeV} \)

LHC: still true at several TeV?
Evidently this could only have been (re)found by someone working at a Scottish university ..... and likes to walk in the Highlands!
Standard Model Pillar III: Higgs

Boson masses and fermion masses break gauge symmetries

\( \rightarrow \) Non – renormalisable theory

Standard Model way out:
Four Higgs fields
- Three give mass to W/Z bosons
- One is physical with well defined properties (except mass)

FOUND ???
(Almost) All parameters of the Standard Model known
LHC (currently) the only place to study mechanism
\( \rightarrow \) see Bill Murray‘s lecture
Why Standard Model @ Hadron Colliders?

- Explore phase space not determined from first principles
- Probe at highest energies
- Scutinize Top Quark
- Explore the 'Higgs (?)' boson (or alternative EWSB mechanisms)

Standard model: the way towards establishing 'New Physics'?

- Standard Model processes background to 'New Physics'
- will provide tools for searches for new phenomena
- Testing Standard Model to the extreme ➔ may reveal a glimpse of 'New Physics'
Experimental Standard Model

1. Experimental environment for SM Tests @ proton colliders
2. Some basics of pp collisions
3. Soft QCD processes
5. Hard parton scattering – Structure of jets
6. QCD aspects of W/Z production
8. The top quark: production
9. The top quark: properties
Standard Model @ Hadron Colliders
I. Experimental Environment
Yesterday’s flagship Tevatron

Proton – Antiproton Collisions @ 2 TeV c.m. energy

2 Experiments (CDF & D0)

Each collected 10 fb⁻¹
Today’s flagship LHC

Proton – Proton Kollisionen @ 14 TeV c.m. energy (currently 8 TeV)
4 Experiments

Will focus on ATLAS and CMS

ALICE: quark – gluon plasma
LHCb: bottom physics

Note: difference to Gaelic LHC too lazy to dig???
but they love symmetry!
The outstanding LHC performance

ATLAS Online Luminosity \( \sqrt{s} = 8 \text{ TeV} \)

Total Delivered: 11.25 fb\(^{-1}\)
Total Recorded: 10.54 fb\(^{-1}\)

ATLAS Online Luminosity

\[
\text{Peak Luminosity per Fill [10}^{33} \text{ cm}^2 \text{s}^{-1}]
\]

\begin{itemize}
\item LHC Stable Beams
\item Peak Lumi: \(7.21 \times 10^{33} \text{ cm}^2 \text{s}^{-1}\)
\end{itemize}

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CMS = Compact Muon Solenoid

21.6 m long
14.6 m diameter
12 500 tons
3275 authors

Hermetic up to $|\theta| = 0.014$ rad
Hermetic up to $|\theta| = 0.015$

Largest particle detector ever .... but would float in water

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Biggggg & sophisticated
Inner Tracker

**Inner part:** Silicon, outer TRT
**Magnetic field:** 2 Tesla
**Radii:** 50 - 107 mm
**# of measurements:** 11 Silicon + 35 straws

**All silicon**
**Magnetic field:** 4 Tesla
**Radii:** 44 - 110
**# of measurements:** 17 Silicon

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Momentum resolution

Curvature $k = 1/R$

Resolution is
- linear with $1/magnetic\ field$
- quadratic in projected length of track
- linear in $p_T$

In addition multiple scattering (low $p_T$)
⇒ reduce material!

$$\frac{\delta k_{res}}{k} = \frac{p_{xy}}{0.3 \cdot B} \frac{\delta_{point}}{L^2} \sqrt{\frac{720}{N_{point} + 4}}$$

Equal at $\sim 45\ GeV/90\ GeV$ for ATLAS/CMS

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Impact parameter resolution

Simplified: 2 measurements at $r_1, r_2$
same precision $\sigma$

$$\sigma(d_0) = \sigma^2 \frac{r_1^2 + r_2^2}{(r_2 - r_1)^2}$$

Plus multiple scattering term

$$\sigma(d_0) = c / p_T \oplus d$$

- Close as possible to IP
- Long lever arm
- High precision

Little material before measurement

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Calorimeter system

Tile barrel

Tile extended barrel

LAr hadronic end-cap (HEC)

LAr electromagnetic end-cap (EMEC)

LAr electromagnetic barrel

LAr forward (FCal)

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Calorimeter: electromagnetic

**ATLAS**

Outside magnetic field
Liquid – argon sampling
Granularity: 0.025x0.025
Longitudinal segmentation

**CMS**

Inside magnetic field
Crystals PbWO$_4$
Granularity: 0.017 x 0.017

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Energy resolution

\[ \frac{\sigma(E)}{E} = \frac{0.1}{\sqrt{E}} \oplus 0.002 \quad \frac{\sigma(E)}{E} = \frac{0.028}{\sqrt{E}} \oplus \frac{0.12}{E} \oplus 0.003 \]

Note: assumes no material in front
Reality: 2-4 \( X_0 \) (ATLAS) magnet!

0.6 \( X_0 \) (CMS)

Very high resolution for electromagnetic interaction
Importance of directional information
Calorimeter: hadronic

ATLAS

Outside magnetic field
Sampling Iron-Scintillator
fwd: Cu or W + LAr
Granularity: 0.1 x 0.1

\[
\frac{\sigma(E)}{E} = \frac{0.45}{\sqrt{E}} \oplus 0.013
\]

CMS

Inside magnetic field
Sampling Brass-Scintillator
Granularity: 0.087 x 0.087

\[
\frac{\sigma(E)}{E} = \frac{1}{\sqrt{E}}
\]

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Muon chambers

ATLAS

In strong toroidal magnets
Both fast trigger chambers & precision chambers
Gaseous detectors and high sophisticated alignment system

CMS

In iron return yoke

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Muon momentum resolution

Stand – alone track finding/fitting in µ chambers

ATLAS: 3-4% (central)  CMS: 10% resolution

Identification & best resolution: combine ID & µ - chambers

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Trigger + DAQ

ATLAS: 'region of interest'

CMS: Early merging of all regions no L2

L1 Trigger based on $\mu$ chamber & calorimeter
~ 200 – 400 Hz stored on disk

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## Comparing the ATLAS-CMS lay-out

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAGNET (S)</strong></td>
<td>Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region</td>
<td>Solenoid Only 1 magnet Calorimeters inside field</td>
</tr>
<tr>
<td><strong>TRACKER</strong></td>
<td>Si pixels + strips TRT → particle identification $B = 2T \quad \sigma/p_T \sim 3.8 \times 10^{-4} p_T \oplus 0.015$</td>
<td>Si pixels + strips No particle identification $B = 4T \quad \sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$</td>
</tr>
<tr>
<td><strong>EM CALO</strong></td>
<td>Pb-liquid argon $\sigma/E \sim 10%/\sqrt{E}$ uniform longitudinal segmentation</td>
<td>PbWO$_4$ crystals $\sigma/E \sim 2-5%/\sqrt{E}$ no longitudinal segm.</td>
</tr>
<tr>
<td><strong>HAD CALO</strong></td>
<td>Fe-scint. + Cu-liquid argon (10 $\lambda$) $\sigma/E \sim 50%/\sqrt{E} \oplus 0.03$</td>
<td>Cu-scint. (&gt; 5.8 $\lambda$ +catcher) $\sigma/E \sim 100%/\sqrt{E} \oplus 0.05$</td>
</tr>
<tr>
<td><strong>MUON</strong></td>
<td>Air $\rightarrow \sigma/p_T \sim 10%$ at 1 TeV standalone ($\sim 7%$ combined with tracker)</td>
<td>Fe $\rightarrow \sigma/p_T \sim 15-30%$ at 1 TeV standalone (5% with tracker)</td>
</tr>
</tbody>
</table>

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II. Some basics of pp - physics
Reminder: how ‘protons’ interact

Proton scattering = scattering of quarks and gluons

\[ \sigma(pp \rightarrow YX) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \rightarrow Y) \]
Reminder: \( x, M \)

\[
M_{\text{scatter}} = \sqrt{x_1 \cdot x_2 \cdot E_{\text{pp}}}
\]

\( \text{resolution power} \)

For LHC: 8 TeV

I.e. high masses requires large \( x \) - values

LHC and Tevatron:
LHC has 4 (7)\( x \) higher energy,

Note for \( M \sim 400 - 1000 \) TeV: Tevatron qq - LHC gg

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Some basics: rapidity

Rapidity a 'natural' observable for consequitive branchings

\[ \frac{d\sigma}{dy} = \text{const} \]

\[ y = \frac{1}{2} \ln \left( \frac{E + p_{||}}{E - p_{||}} \right) = \frac{1}{2} \ln \left( \frac{E + p_{||}}{\sqrt{m^2 + p_T^2}} \right) \]

\[ y \implies y' = y + \frac{1}{2} \ln \left( \frac{1 + \beta}{1 - \beta} \right) \]

Frequently used \( y \to \eta \) assuming massless particles \('pseudo – rapidity'\)

\[ \eta = \frac{1}{2} \ln \left( \tan \theta / 2 \right) \]
LHC a strong interaction collider

Remember: strong coupling rises with decreasing $Q^2$

Difficulty:
- At around $Q \sim 1$ GeV too strong to be calculable in perturbation theory
- ’too many gluons emitted’

Basic limitation of theoretical description
hard scatter: two in $\rightarrow$ two out

This can be calculated:

Incoming partons $p_1, p_2$ with momenta $P_1, P_2$

Outgoing partons $X, Y$

\[
\sigma(p_1(P_1) + p_2(P_2) \rightarrow Y + X + \text{Rest}) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1) F_{\overline{f}}(x_2) \sigma(q_1(x_1P) + q_2(x_2P) \rightarrow Y + X + \text{Rest})
\]
A more comprehensive picture

Proton remnants interact: 'underlying event'

Only QCD 'motivated' models – not from first principles!

\[
\sigma(p_1(P_1) + p_2(P_2) \rightarrow Y + X + \text{Rest}) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1) F_{\bar{f}}(x_2) \sigma(q_1(x_1 P) + q_2(x_2 P) \rightarrow Y + X + \text{Rest})
\]
QCD in the detector

A lot of 'isotropic' hadron production

One bunch Xing:
Some 20 pp – interactions 'pile – up'

Started with
qq → qq
Result: 1000 hadrons
Standard Model tests: Type I
Underlying event

\[ \sigma(p_1(P_1) + p_2(P_2) \rightarrow Y + X + \text{Rest}) \]

\[ = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1) F_{\bar{f}}(x_2) \sigma(q_1(x_1 P) + q_2(x_2 P) \rightarrow Y + X + \text{Rest}) \]

Take from previous measurements
Well known process

Measure underlying event

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Standard Model tests: Type II
Parton distribution function

\[ \sigma(p_1(P_1) + p_2(P_2) \rightarrow Y + X + \text{Rest}) \]

Measure parton distribution function
Standard Model tests: Type III

The hard scatter process

\[
\sigma(p_1(P_1) + p_2(P_2) \rightarrow Y + X + \text{Rest})
\]

\[
= \int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1)F_{\bar{f}}(x_2) \sigma(q_1(x_1P) + q_2(x_2P) \rightarrow Y + X + \text{Rest})
\]

Take from previous measurements

Measure hard process

Take from models

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III. Soft QCD interactions
Measure underlying events

Basic idea: find region not affected by hard scatter

Select 2 back-to-back jets in plane transverse to beam

→ define four quadrants

→ assume transverse quadrants little affected by jets
Note: only possible if no pile-up events (low luminosity)

Ideally: flat with jet $p_T$ ➔ cross talk from hard jets?

Can be reasonably described by models
UE in Drell – Yan events

Particle flow in pp \(\rightarrow \mu^+\mu^-\) events

Colour – neutral \(\rightarrow\) no X-talk

But: colour flow different from most LHC processes

\(\rightarrow\) measurements to test and constrain models

Will a precise and consistent modelling ever be possible?

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Double parton interactions

Use photon as a probe
Select events with (2) 3 jets

Combine
a. $\gamma$ + hardest jet
b. 2 other jets
$\Rightarrow$ $\Delta \phi$ between momenta

QCD bremsstrahlung: correlation
Dble parton interaction: flat

Data show correlations but also a flat contribution
Comparison with models: $\sim$ 10% double parton interactions
$\Rightarrow$ Additional constraints on models
Pile up: the prize of high luminosity

Number of interactions/bunch Xing:
- linear with luminosity
- slowly increasing with energy
- proportional 1/bunch Xing distance

currently: 50 nsec, future: 25 nsec
Pile up: the price of luminosity

Z⁰ with 25 reconstructed vertices

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Pile up events: multiplicity

Pile – up events can be measured:

pp – interactions without trigger bias, 'minimum bias events'

At 7 TeV: 6 charged particles per $|\Delta \eta| = 1$, mostly low $p_T$

Rather isotropically distributed

30 pile – up events $\rightarrow$ 1000 charged particles in tracker volume

Models have deficiencies
Minimum Bias events: $p_T$

Most particles have low transverse momentum.

- Isotropic contribution to hard processes.

'Noise' of ~ 20 - 30 GeV/bunch Xing.

Significant effect on object reconstruction.

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Modelling 'soft interactions'

Minimum bias + underlying events:
Measured in special environment
Extrapolate to all conditions:
try to model applying several ad–hoc concepts

Overlap of protons

Colour screening

Colour reconnection

Challenging! Only an approximate description possible!

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Parton distribution functions

Energy fractions of different kinds of partons $f$ in proton

\[
\sigma(p_1(P_1) + p_2(P_2) \rightarrow Y + X + \text{Rest}) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1) F_{\bar{f}}(x_2) \sigma(q_1(x_1P) + q_2(x_2P) \rightarrow Y + X + \text{Rest})
\]

Various measurements at $M_1^2$

theoretical evolution to $(M^2)_2$

Just one of several pdf parametrisations

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Significant uncertainties

G.Watt

low x: many gluons ➞ Theoretical & experimental uncertainties

High x: few gluons ➞ Large uncertainty

LHC will allow some self-calibration

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IV. Hard QCD interactions - Jets
Hard interaction: Jets
Jets are universal

**e^+ e^- collisions**

**e p collisions**

Jets: representative of quarks and gluons

⇒ stringent test of theory

⇒ experimental challenge: extract partons from 1000 hadrons

⇒ experimentally attainable direction and energy + (sometimes) parton flavour

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How to find a jet?

Unambiguous connection to underlying partons → Comparison to theory

Not so straight – forward: example cone – jet finder

Low momentum 'infrared' particle changes jets

Two 'collinear' particles change jets

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Sequential jet finder

'Reverse evolution of event‘

1 Select one particle (e.g. most energetic)
2 Find 'most similar‘ particle, (e.g. smallest angle, $p_t$)
3 Is combination smaller than predefined 'cut off‘ value
   (e.g. maximum angle, maximum mass ....)

IF YES:
4 Combine to a new 'pseudo – particle‘ (e.g. sum 4 – momenta)
5 Go to 2

IF NO:
4 Jet found: sum of all associated particles
Favoured jet finding at LHC: 'Anti – kt'

\[ d_{ij} = \min(p_{t_i}^{-2}, p_{t_j}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \]

\[ \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \]

Infrared + collinear safe

Select hard particles as 'seeds' for jets: favoured by \( \min(p_{t}^2) \)

Hard particles separated in space are distinct seeds: large \( \Delta R_{ij} \)

Low \( p_{t} \), close by particles assigned to seeds
The final jets

All particles assigned to jets

Close to circular in space good for experimental corrections

Note: special treatment of particles close to beam
In a nutshell:

Hard process
= (data
  - pile up events from simultaneous pp – collisions
  - underlying event from proton remnants)
x (transfer from jets \(\rightarrow\) partons)
x (unfolding of parton energies = parton distribution fct.)

Involved,

....... but with experimental knowledge feasible