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Luminosity
LEP/TeVatron results
H → ZZ → llll
Caveats

For LHC I will often only show ATLAS
- CMS is broadly similar
- But I know ATLAS better

Don't trust the numbers!
- What is important is that you understand the principle rather than getting the right answer
- If you want to check Higgs discovery, look at the papers
Who am I?

- I work at Rutherford Appleton Laboratory
  - Permanent since 1993
  - A post I got saying I wanted to look for the Higgs
- I worked on the LEP Higgs search
  - I am still DELPHI Higgs convener!
- I have spent some time looking at a muon collider as a Higgs factory
- I was Higgs convenor of ATLAS up to end 2011
Co-ordinates

- pp (\(\overline{p}p\)) collisions are between partons
  - Proton remnants carry \(p_z\) down beampipe
  - Therefore \(z\) component of momentum is of reduced interest
- Tracker quotes \(p_T\), calorimeter \(E_T\)
  
  \[
  y = \frac{1}{2} \log \frac{E + p_z}{E - p_z} 
  \]

- Rapidity \(y\)
- Pseudo-\(y\) \(\eta = \log \tan (\theta/2)\)
- Hadron colliders use not \(\theta, \phi\) but \(\eta, \varphi\)
\[ \Delta R \]

- \( y \) differences invariant under boost
  - In massless aprox. \( y = \eta \)

Jet finding/isolation is done using \( dR \) distances:
\[ \Delta R^2 = \Delta \eta^2 + \Delta \phi^2 \]

- This has drawbacks for massive objects
  - \( \Delta y = \Delta \eta \) breaks down
  - Physical size of jets shrinks as \( \eta \) grows

- There is no perfect solution
  - So continuous development
## Some Colliders

<table>
<thead>
<tr>
<th>Collisions</th>
<th>LEP</th>
<th>LC</th>
<th>TeVatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>e^+e^-</td>
<td>e^+e^-</td>
<td>pp</td>
<td>pp</td>
</tr>
<tr>
<td>208</td>
<td>?1000?</td>
<td>2000</td>
<td>7000/8000</td>
<td>13000/14000</td>
</tr>
<tr>
<td>0.5fb^{-1}</td>
<td>Large</td>
<td>10fb^{-1}</td>
<td>30fb^{-1}</td>
<td>300fb^{-1}</td>
</tr>
<tr>
<td>1</td>
<td>100K+</td>
<td>10000</td>
<td>300000</td>
<td>10M</td>
</tr>
<tr>
<td>0-115</td>
<td>0-800+</td>
<td>Hard</td>
<td>100-1000</td>
<td>100-1000</td>
</tr>
</tbody>
</table>

- **Max E, GeV**
  - **LEP**: 208
  - **LC**: ?1000?
  - **TeVatron**: 2000
  - **LHC**: 7000/8000

- **Integrated lumi.**
  - **LEP**: 0.5fb^{-1}
  - **LC**: Large
  - **TeVatron**: 10fb^{-1}
  - **LHC**: 30fb^{-1}

- **Higgs (125GeV)**
  - **LEP**: 1
  - **LC**: 100K+
  - **TeVatron**: 10000
  - **LHC**: 300000

- **Higgs reach**
  - **LEP**: 0-115
  - **LC**: 0-800+
  - **TeVatron**: Hard
  - **LHC**: 100-1000
Luminosity

- Define: \( R = l \sigma \)
  - Interaction rate is luminosity times cross-section

For a circular machine

- \( f = n_b c/2\pi r \) is interaction rate,
- \( n \) the number of particles / bunch
- \( \sigma \) the beam size

\[
l = f \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}
\]
Emittance

Envelope of beam particles
- units m x Rad
- \( \varepsilon_x = \pi \sigma_x \sigma'_x \):
  - Assumes uncorrelated

Higher dimensional emittance
- The 6-dimensional particle correlation x, y, z, x', y', z'
- \( \varepsilon \) a conserved quantity (Liouville's theorem):
  - Reduce one \( \sigma \), other grows
- \( \varepsilon_T \) is almost a conserved quantity – is what LHC quotes

LHC has round beams: \( \varepsilon = \varepsilon_x \)

Normalised emittance: \( \epsilon_N \equiv \beta_y \epsilon_y \)
- This is invariant under acceleration
- It is so useful, it is often called emittance.
Emittance examples

- All these have zero emittance
More Emittance examples

- Finite emittance
- Initially $x'$ small
- Lens correlates $x, x'$
- Drift to focus makes $x$ small.
- Area is conserved
Luminosity and Emittance

Define $\beta^*$ as $\sigma_x / \sigma'_x$,

This is the strength of the focusing magnets

- 'Low Beta quads'

\[ l = f \frac{n_1 n_2}{4 \pi \sigma_x \sigma_y} \]

\[ l = f \frac{n_1 n_2}{4 \sqrt{\epsilon_x \beta^*_x \epsilon_y \beta^*_y}} \]
Beam Emittance

- $e^+e^-$ rings set by synchrotron radiation
  - Electron machines `have no memory`
- pp machines limited by beam preparation
  - Stochastic cooling
  - Emittance growth is cumulative
    - Beam-beam effects increase LHC emittance during fill
    - Actually LHC has some KeV synchrotron radiation
- For linear accelerators preparation and beam blowup contribute.
Luminosity Optimisation

$$l = f \frac{n_1 n_2}{4 \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

- **Increase** $f$
  - Bunch separation, power constraints

- **Increase** $n_i$
  - Space charge, power, particle availability, pileup
  - But quadratic gain in rate...

- **Decrease** $\beta^*$
  - Strong Quads inside detectors apparatus, blowup, beam aperture limitations, **bunch length**

- **Decrease** $\epsilon$
  - ‘colder beams’ improve performance
  - But too small and beam-beam interaction destructive
Other Luminosity limits

Beam beam interaction:
- Each beam feels field of the other: Disruptive if beams very small (linear v circular collider)

Accelerating power
- Available watts of RF power limit currents – not LHC

Cooling power
- Limit may be keeping accelerator cold

Electron cloud
- Positive beam can pull electrons off wall
  - They can amplify when they collide with wall
  - LHC needs scrubbing to reduce this

Pile-up
- LHC designed for 25 collisions per bunch crossing
  - much more will swamp detectors
Luminosity - practical example

Sample LHC 2011 parameters:
- $1.35 \times 10^{11}$ particles/bunch
- $2 \times 10^{-6}$ normalised transverse emittance
- 1320 colliding bunches, 27km circumference
- $\beta^* = 1.5\text{m}$

Peak Instantaneous luminosity $2.4 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$
- Use $10^7$ seconds in a year (4 months working)
- $2.4 \times 10^{40}\text{cm}^2$/year
- $1\text{fb} = 10^{-28}\text{m}^2$
- 24$\text{fb}^{-1}$ per year
- Drop ~ factor 5-10 for filling, breakage, average-to-peak

http://lpc.web.cern.ch/lpc/lumi.html
The Standard Model Higgs
LEP results
Production via Higgstrahlung
- W boson fusion kinematically suppressed (<10%)
- But included in cross-section calculations
Established first extensive Higgs limits
Either initial or final Z boson is off mass-shell
Z boson decays characterise state
Search at LEP I - $E_{\text{CMS}} = 91 \text{GeV}$

- Great effort - which I have no time to describe
- Many modes:
  - Stable, $\gamma\gamma, ee, \mu\mu, \pi\pi, \tau\tau, bb$
- Clean Z decays ($ll$, $\nu\nu$) used
- Prior to LEP only some patchy constraints

The mass range from 0 to ~65 excluded, no holes.
LEP 2: 200+ GeV

- Energy raised in steps from $m_Z$ to 208 GeV
- Around 0.5fb$^{-1}$ of data
- Sensitive to $Z^* \rightarrow ZH$
- Therefore approximate reach:
  \[ E_{\text{CoM}} - m_Z - 2 \]
  Or 115GeV/c$^2$ at 208.
- In final year energy was raised to 206 then 208.
The best candidate, ALEPH

(14-Jun-2000, 206.7 GeV)

B jets well tagged plus muon

High $p_T$, muon

Missing Momentum
Sum of four experiments:

Distribution of the reconstructed Higgs boson mass with a Higgs boson of mass 115 GeV/c²

Yellow is background
Red is Higgs, if it weighs 115 GeV
Higgs then: LEP SM Higgs

Final LEP result:

\[ M_H > 114.4 \text{GeV} \] (95% CL)

Excess at 115 GeV would happen in 9% cases without signal.
TeVatron results
TeVatron Higgs production

- Cross-sections of order pb
- $10^{fb^{-1}}$ data gives thousands
- But the background are large
The Higgs problem

- Rates are low
  - So luminosities must be large
- One event in $10^{10}$ is signal
  - 10,000 events is tiny
Tevatron analyses Channels

- **H → WW**
  - WW → lνlν: Most sensitive
- **H → bb**
  - WH, ZH, ttH useful but hard
- **H → γγ**
  - Rare, helps for low mass
- **H → ττ**
  - Hard, low mass, rare
- **H → ZZ**
  - ZZ → llll: Cleanest mode but low rate
Tevatron dataset, $12\text{fb}^{-1}$

September 2011

10fb$^{-1}$: Higgs territory
Tevatron Major channels

Approximate ranges for channels

- ZH → lllbb
- ZH → ννbb
- WH → lνbb
- WH → WWW
- H → WW → lνlν

$M_H$, GeV/c$^2$
SM Higgs: WH→lνbb

- Signature: high $p_T$ lepton, MET and b jets
- Backgrounds: W+bb, W+qq, top/tt, Non-W(QCD)
- Key issue: estimating W+bb background
- Shape from MC, normalization from data

CDF 9.4 fb$^{-1}$

DØ, 9.7 fb$^{-1}$

Final Discriminant

$M_H = 125$ GeV ($\times 20$)
SM Higgs: ZH/WH→MET+bb

- Signature: MET and b jets
- Backgrounds: Z+bb, Z+qq, top, QCD
- Key issues: estimating W+bb background
  - Shape from MC, normalization from data

CDF 9.4fb⁻¹

ZH→ννbb analysis sample (tight b-tag)
SM Higgs: $H \rightarrow WW$

- $H \rightarrow WW \rightarrow \ell \nu \ell \nu$ - signature: Two high $p_T$ leptons and MET
  - Primary backgrounds: WW and top in di-lepton decay
  - CDF and D0 both using NN on many kinematic quantities
  - Many independent channels ($n_{jets}$, lepton quality)

![CDF Run II Preliminary](image1)

 OS 0 Jets, High S/B
 $M_H = 165 \text{ GeV}/c^2$

Opposite-Sign Leptons, 0 jets

Signal Discriminant

![DØ Preliminary](image2)

$L = 9.7 \text{ fb}^{-1}$

$e\mu$ + MET

- data
- $Z$+jets
- Diboson
- Multijet
- $W$+jets
- $t\bar{t}$bar

$M_H = 165 \text{ GeV}$
Tevatron Higgs Combination

Tevatron Run II Preliminary, $L \leq 10.0 \text{ fb}^{-1}$

- Observed
- Expected w/o Higgs
- $\pm 1$ s.d. Expected
- $\pm 2$ s.d. Expected

Tevatron + ATLAS+CMS Exclusion

ATLAS+CMS Exclusion

$95\% \text{ CL Limit/SM}$

$m_{H} (\text{GeV/c}^2)$

June 2012
Tevatron 'Evidence for'

Observe $>3.3\sigma$ for $m_{H^\sim} 135\text{GeV}$ with $10\text{fb}^{-1}$

$3.1\sigma$ global significance
LHC results
The LHC situation

- The 7/8TeV pp energy raises the Higgs cross section
  - Factor 10 c/f 2TeV Tevatron

- Designed for $10^{34}$ luminosity
  - 7 $10^{33}$ achieved
  - c/f 4 $10^{32}$ at Tevatron

- Decades of preparation continue
  - 0.05fb$^{-1}$ delivered 2010
  - 5fb$^{-1}$ in 2011
  - 12fb$^{-1}$ in 2012 so far
Data taking in 2012

- Peak Luminosity almost stable
- Improvements slow now

- Recording efficiency 93%
  - Less than 10% bad data by subdetector
Pileup

- Serious at LHC
  - Fairly stable so far
  - But double 2011
- 20 interactions per event
- 50ns bunch trains
  - So pileup also from previous and subsequent interactions
  - Affects calorimeters more than trackers
- Simulation difficult as rates must be measured
  - Need to reweight spectra
This 2011 event is pretty typical for 2012.
Higgs production

- Higgs cross-sections for gluon fusion
  - LHC
  - Tevatron
- At least a factor 10 advantage

Backgrounds to $WW, \gamma\gamma$ are $qq$ annihilation
- $pp$ collider suppresses these c/f $pp$
- Effect is small at 7 TeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
Reminder: Gain from $E_{CMS}$

- 8TeV: 10% to factor 4 increases in $\sigma$
  - Higgs increased by 30%
  - Emittance shrinks by 8/7 as well
  - Luminosity was slightly easier

Graph showing ratios of gluon-gluon luminosities: 8 TeV / 7 TeV and 9 TeV / 7 TeV (i.e. increase in production rate).
LHC analyses Channels

- **H → ZZ**
  - ZZ → llvv: Good High mass
  - ZZ → llbb: Also high-mass

- **H → WW**
  - WW → lνlν: Most sensitive

- **H → γγ**
  - Rare, best for low mass

- **H → ττ**
  - Good s/b, low mass, rare

- **H → bb**
  - ττH, WH, ZH useful but hard

![Branching ratios](image_url)
SM Higgs modes used

- Higgs decays to Bosons
  - Coupling structure favours it
  - Kinematics forces quark decays below 140GeV

<table>
<thead>
<tr>
<th>mH, GeV</th>
<th>WW → ℓνℓν</th>
<th>ZZ → 4ℓ</th>
<th>γγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>127</td>
<td>1.5</td>
<td>43</td>
</tr>
<tr>
<td>150</td>
<td>390</td>
<td>4.6</td>
<td>16</td>
</tr>
<tr>
<td>300</td>
<td>89</td>
<td>3.8</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Rates?

- LHC backgrounds! $10^{10}$

Every event at a lepton collider is physics; every event at a hadron collider is background

Sam Ting
How we search for the thing

- If Higgs boson had been heavy (>140GeV/c^2)
  - Serious decays to WW, ZZ
  - These have clear leptonic decay modes
  - ZZ \rightarrow 4l is frankly nicer, but WW \rightarrow l\nu l\nu more common
  - The discovery is fairly straightforward.

- If Higgs boson is light (<140GeV/c^2)
  - (and it is)
  - WW/ZZ still important, but rarer
  - Use H \rightarrow \gamma \gamma
  - Or VBF H \rightarrow \tau \tau – can trigger leptons
  - H \rightarrow bb is dominant mode – can we find it?
    - Not without something to make it stand out
    - Z/W+H, ttH
Golden channel $m_H > 190\text{GeV}/c^2$
- Above $\sim 200$ two real Z's
- Down by 125 ZZ*, 1 or even both off shell

Good mass resolution, trigger

Require 4 leptons
- Isolated, prompt
- One pair 50-106 GeV
- The other variable

Backgrounds:
- Irreducible QCD ZZ to $\ell\ell\ell\ell$ dominates
- Reducible Zbb, tt especially for low masses
Trigger efficiencies (ATLAS)

- Crucial to a hadron collider – the trigger
  - Most channels use single lepton \( \sim 20\text{GeV} \, p_T \)
- 3 level trigger system
  - L1: 2\( \mu \)s, local objects
  - L2: 'ROI' complete information
  - EF: full reconstruction
- Efficiency plateau
  - 80% \( \mu \) efficiency
    - Multi-leptons give good total
  - \( \sim 98\% \) electron efficiency
- Ultimately 99% efficient
Muon reconstruction (ATLAS)

- Combined muons (top)
- Combined + segment tagged (bottom)
- Final efficiency good
- Difficulties:
  - $\eta=0$ (no muon chambers)
  - $\eta=1.2$ (barrel/forward transition)
- In 2012 use 'stand alone' to improve to 2.7
Isolation effects

- Reducible background involves $e/\mu$ from b/c quarks
- Is there a jet here?
  - Define cone around lepton, size $\Delta R$
  - Sum energy in cone
  - Require $E_{\text{cone}}/E_{\text{lept}} < X$
- Need to optimise selection
  - Measure efficiency
  - And Background
Impact parameters

- Suppression of b quarks with impact parameters
  - Lepton closest approach to proton collision
  - $H \rightarrow ZZ \rightarrow llll$ have no decay length
  - Lepton from b quarks have $\sim 100\mu m$ impact
- Plotted is larger SIP for l3, l4

![CMS Preliminary 2011 Graph](chart.png)

- $\sqrt{s} = 7$ TeV
- $L = 1.66$ fb$^{-1}$
- DATA
- $t\bar{t}$
- Z+jets
- $Zb\bar{b}/c\bar{c}$
- $Z+\gamma$ma
- Single top
- WW
- WZ
- ZZ
- $m_H=200$ GeV/c$^2$
Estimation of background

For ZZ:
- Shape from MC (gg,qq)
- Rate fitted to data with theory constraint

For non Z+jets, tt:
- Relax isolation cuts
  - More background
- tt fitted to $m_{12}$
- Z+jets fitted to $m_{34}$
- Extrapolate to signal region
Lepton thresholds

- We wish to explore towards $m_H = 115\text{GeV}$
- $M_Z = 91$, so little energy for $Z^*$
- Therefore important to use leptons of low $p_T$
  - $7\text{GeV}$ threshold used
    - (5GeV for muons in CMS)
- Need to understand eff, background
  - Tag and probe used normally
    - $W$, $Z$ must be extended with $J/\psi \rightarrow \ell\ell$
- Backgrounds get more acute at low $p_T$. 
Lepton $p_T$ distribution

- $m_H << 2m_Z$
- The decay involves one $Z$ being far from mass-shell
- The softest lepton is typically below 10 GeV $p_T$
- Need to push lepton momentum range

CMS Simulation, $\sqrt{s} = 8$ TeV

$H \rightarrow ZZ^* \rightarrow 2e2\mu$

$\mathbf{m}_H = 126$ GeV

- Before analysis selection
- After analysis selection
Lepton isolation/impact pars

- Nothing in MC is trusted
- The efficiency of the isolation and impact parameter cuts is checked with data
- The $Z \rightarrow \mu\mu$ peak allows efficiency measurement
  - But few $Z$ produce leptons of only 7 GeV
## Selection methods

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum lepton $p_T$</td>
<td>7 GeV (e) / 6 GeV (μ)</td>
<td>7 GeV (e) / 5 GeV (μ)</td>
</tr>
<tr>
<td>Mass $Z_1$</td>
<td>50 - 106</td>
<td>40 - 120</td>
</tr>
<tr>
<td>Mass, $Z_2$</td>
<td>17.5 - 115</td>
<td>12 - 120</td>
</tr>
</tbody>
</table>

- CMS cuts always a little looser, more efficient
  - ATLAS efficiency: 36%, 21%, 18% in $μμμμ, eeμμ, eeee$
  - CMS efficiency 40%, 27%, 18% in $μμμμ, eeμμ, eeee$
  - 10% higher efficiency in CMS

- Backgrounds similar despite different cuts:
  - ATLAS background expected (120-130): 4.9
  - CMS background (121.5 - 130.5): 3.8
  - 10% less background in CMS per GeV

- CMS also uses 'matrix element'
  - Uses leptons angles & $Z$ masses to separate sig. from back.
Mass resolution

- A function of $m_H$
- Detector performance, lepton type etc
- Of order 2GeV for mass below 200
- Dominated by natural width above

![ATLAS Simulation](attachment:ATLAS.png)

$H \rightarrow ZZ^* \rightarrow 2e2\mu$ ($\sqrt{s} = 8$ TeV)

$m = (129.16 \pm 0.04)$ GeV

$\sigma = (2.02 \pm 0.04)$ GeV

Fraction outside $\pm 2\sigma$: 22%
Event rates 120-130GeV

<table>
<thead>
<tr>
<th>Signal</th>
<th>$ZZ^{(*)}$</th>
<th>$Z + \text{jets, } tt$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4$\mu$</td>
<td>2.09±0.30</td>
<td>1.12±0.05</td>
<td>0.13±0.04</td>
</tr>
<tr>
<td>2$e2\mu/2\mu2e$</td>
<td>2.29±0.33</td>
<td>0.80±0.05</td>
<td>1.27±0.19</td>
</tr>
<tr>
<td>4$e$</td>
<td>0.90±0.14</td>
<td>0.44±0.04</td>
<td>1.09±0.20</td>
</tr>
</tbody>
</table>

- Five signal expected in ZZ channel now
  - Twice the non-resonant ZZ background
- Non-ZZ Background small c/f signal
  - 120% in $\text{eeee}$
  - 6% in $\mu\mu\mu\mu$
  - The Z+ee is much dirtier than Z+\mu\mu
- There is an excess, all channels
Candidate masses: $m_1 \neq m_2$

- CMS plot showed few events with $m_{Z1} > 90$ GeV
- Had sparked theoretical papers!
- ATLAS version is reassuring
CMS 'MELA' values, $K_D$

- Matrix element likelihood analysis
- Uses 5 angles and 2 $Z$ masses of the $H \rightarrow ZZ \rightarrow llll$ system
- Background modelled as $ZZ^*/Z\gamma^*$
- Several events are 125 GeV are seen to have very high 'MELA' values, $K_D$
Interpreting the distribution

Need a model of background
  - CMS use analytic functions for background
  - ATLAS use MC distributions

Use s,b densities to define $\ln LR$ for each candidate
  - Sum these
  - Compare with expectation
Statistical interpretation

- Non-trivial business, with Frequentist and Bayesian methodologies
- For now ATLAS+CMS quote 'CLs' results
  - Derived as a compromise, acceptable to both schools
  - Glen must have discussed this
- A useful approximation for low rate counting experiments with negligible systematic errors:
  \[
  \langle Z_w \rangle = \sqrt{2\left( (s + b) \ln \left( 1 + \frac{s}{b} \right) - s \right)}
  \]
- This is much better than \( s/\sqrt{b} \) in the case of low numbers
  - Can be used to optimise analyses
Expected limits

- Expected upper limit
- Observed generally follows
  - Except at 125GeV

- Shape reflects the H to llll expected event rate
Both ATLAS and CMS exclude most of 130-500GeV
- Small expected hole at 170GeV
- Excess neat 125GeV
Observed limits

- CMS sensitivity improved by 'MELA'
- Each has one p-value below 1 in 1000
- Both peaks at the same place
Conclusion

- Tevatron still interesting
  - $V_{bb}$ excess of $\sim 3\sigma$ for $m_H \sim 125$

- $ZZ$ to $llll$ discussed in some detail

- Other channels I discuss tomorrow

- Combination and interpretation next week