From RAW data to the Higgs and beyond

Physics Object ID, Analyses techniques, Higgs results and future prospects

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Outline of the lectures

- Part I
  - Experimental signatures of Higgs events
  - Search feasibility and detector requirements
  - Physics Object Identification techniques

- Part II
  - Higgs analyses in ATLAS and CMS and the respective analyses techniques
  - Recent Higgs results

- Part III
  - Future prospects of Higgs measurements at HL-LHC, ILC and FCC ee/pp
Higgs Production @ the LHC(I)

- Gluon fusion [19.3 pb @ 8TeV]

- Dominant production mechanism
- Loop dominated by top
- Often accompanied by radiation
  - presence of jets in the final state
Higgs Production @ the LHC (II)

- Vector boson fusion [1.6 pb @ 8TeV]

- 10x lower cross section than gluon fusion

- Distinct experimental signature
  - Two jets in the final state
  - Large opening angle between the jets
Higgs Production @ the LHC (III)

- Associated production with a vector boson (W/Z)
- WH: 0.70 pb, ZH: 0.40 pb @ 8 TeV

- Cross section very small
- However presence of vector boson in the final state makes the final state clean - reducing backgrounds
Higgs Production @ the LHC (IV)

- Associated production with a top pair
  
  \[0.12\text{pb @8TeV}\]

- Cross section extremely small
  
  - 120 events per fb\(^{-1}\)

- Unique final state with 2 b jets, 2 W bosons and a Higgs boson
  
  - Major background is tt pairs +X
Higgs decays for $M_H$ around 125 GeV

- A plethora of decay modes @125 GeV
  - Let's take them one by one...
H → bb [BR = 57% @ 125 GeV]

- Fully reconstructed final state
  - Dominated by jet resolution
- ggH → bb not feasible
  - Direct bb production 10^7 times larger
  - Impossible to even trigger the events
- VBF H → bb probably feasible
  - But very hard since background is direct 2b 2jet production
  - Angular separation and bb mass peak can decrease the background but not enough to be competitive to other modes
H → bb [BR = 57% @ 125 GeV]

- WH feasible
  - But W needs to decay to lepton + neutrino
    - ~ 40 events per fb\(^{-1}\) per lepton flavor [e, mu, tau]
  - Backgrounds: W + bb, WZ

- ZH feasible
  - Z needs to decay to two charged leptons or two neutrinos
    - 8 events per fb\(^{-1}\) per lepton flavor, 46 events for the Z → νν
  - Backgrounds Z + bb, Z + fake MET
H → bb [BR = 57% @ 125 GeV]

- ttH is also possible with enough statistics
  - Main background is tt + bb
  - Normally at least one W needs to decay to leptons
    - to reduce QCD background
    - to trigger the event
  - ~68 events per fb⁻¹ before requirements on W decays
  - ~7 events for a semileptonic decay [per lepton flavor]
\( H \rightarrow WW^* \) [BR =22% @ 125 GeV]

- Not fully reconstructed state
  - 2 neutrinos
- Most final states require a di-leptonic WW decay
  - Or else overwhelmed by \( W + \text{jets} \)
- Requiring both \( W \) decays electrons or muons
  - Makes effective BR\( \sim 0.9\% \)
- Higgs \( \rightarrow \) spin 0
  - Spin correlations give collinear lepton signature
    - Can be exploited experimentally
Feasible H → WW* signatures

• gg → H → WW*
  • 170 events / fb⁻¹
  • Backgrounds: SM WW, tt, W+jets [with fake leptons]

• VBF H → WW*+2 jets
  • 14 events / fb⁻¹
  • Backgrounds: WW+2 jets, tt, W+3jets

• WH → WWW*
  • For all W leptonic, 1.7 events per fb⁻¹
  • Backgrounds: WZ, WW+jets
Feasible $H \rightarrow WW^*$ signatures

- Associated production with top also possible
  - $2b + 4W$ final states
  - Any of the 4 $W$ can decay leptonically leading to final states of 1 – 4 leptons
  - 26 events/fb-1 before any $W$ decay
- A lot of combinatorics/multilepton based search
- Main backgrounds $ttZ/ttW/tt+$fake leptons
H → gg and H → cc

- H → gg impossible at LHC due to very large jet backgrounds
- H → cc practically impossible @ LHC
  - With much lower branching ratio to bb, higher background cross sections and less performant c jet vs b jet identification
    - b-jet identification relies to the long lifetime of B hadrons
    - Lifetime of c hadrons smaller → need much better vertex capabilities
- Both of those modes can however be studied in an e^+e^- collider
$H \rightarrow \tau\tau$ \[BR = 6.3\% \, @125 \, \text{GeV}\]

- Due to heavy tau mass \([1.78 \, \text{GeV}]\) easiest accessible leptonic final state

- Tau lepton decays to an electron or a muon and two neutrinos about 20\% of the time

- Taus decay to hadrons \(~60\%\) of the time

- In addition since tau is boosted it appears as a very collimated jet in the detector

  - **Crucial to identify the tau decays and discriminate against jets to be able to exploit the significant di-tau branching ratio**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Resonance</th>
<th>Mass (MeV/$c^2$)</th>
<th>Branching ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow e^- \bar{v}<em>e \nu</em>\tau$</td>
<td></td>
<td></td>
<td>17.8 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- \bar{v}<em>\mu \nu</em>\tau$</td>
<td></td>
<td></td>
<td>17.4 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \nu_\tau$</td>
<td></td>
<td></td>
<td>11.6 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \pi^0 \nu_\tau$</td>
<td>$\rho$</td>
<td>770</td>
<td>26.0 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$</td>
<td>$a_1$</td>
<td>1200</td>
<td>10.8 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$</td>
<td>$a_1$</td>
<td>1200</td>
<td>9.8 %</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^+ \pi^0 \nu_\tau$</td>
<td></td>
<td></td>
<td>4.8 %</td>
</tr>
<tr>
<td>Other hadronic modes</td>
<td></td>
<td></td>
<td>1.7%</td>
</tr>
</tbody>
</table>
H → ττ final states

- Depending on the tau decays, several final states with 2-4 neutrinos occur
  - Final state mass not fully reconstructed
  - Lepton spectrum softer so selection efficiency much lower [i.e. than WW]
- In gluon fusion 1200 evts/fb-1
  - Before tau decays
  - Overwhelmed by Z → taутau
    - Need hard cuts and good mass reconstruction to reject it
VBF $H \rightarrow \tau\tau$

- Promising final state!
  - $\sim 100$ events /fb-1 before tau decays

- Main background: $Z \rightarrow \tau\tau\tau +2$ jets
  - can be suppressed by exploiting VBF signature

- VH also possible but lower performance due to V+jets background
H → ZZ* \[BR = 2.6\% @ 125 \text{ GeV}\]

- Fully reconstructed final state with excellent resolution in the case of 4 leptons
- At low mass both Z need to decay to leptons \([e/\mu]\) to avoid Z+jets background
  - Effective BR = \(1.25 \times 10^{-4}\)
  - Background dominated by SM ZZ production
    - Very small for mass \(< 2M_z\)
- At gluon fusion 2.5 events/fb\(^{-1}\)
  - But very clean final state with fully reconstructed mass
- VBF harder \([0.2\text{ events/fb}^{-1}]\)
- Challenge: excellent lepton efficiency and large detector coverage
$H \rightarrow \gamma \gamma \ [\text{BR} = 2.2 \times 10^{-3} \ @ \ 125 \ GeV]$

- Fully reconstructed final state with excellent resolution
- Background dominated by direct di-photon production + QCD with fake photon
- Experimentally challenging
  - Photon identification
  - Identification of the primary vertex
  - Rejection of jet background
H → γγ final states

• At gluon fusion, 40 events /fb\(^{-1}\) expected
  • Large falling di-photon background

• With VBF \(\sim 3.5\) events/fb\(^{-1}\) expected
  • Large di photon background suppressed by VBF requirements

• VH/ttH also possible
  • With lower sensitivity but very small background
H → Zγ and H → μμ

• H → Zγ has a similar branching ratio to γγ [1.5x10^{-3} @ 125 GeV]
  • However for exploiting the experimental signature Z needs to decay to leptons
    – 6% of the branching ratio available. Need very high luminosity to observe it

• H → mumu has very low BR [2.2x10^{-4} @ 125 GeV]
  • Overwhelmed by huge Z → mumu background
  • Maybe possible at very high luminosity with tight VBF selection
Summary of the feasible LHC searches

The big five

- $H \rightarrow ZZ^* \rightarrow 4l \ [ggH/VBF]$
- $H \rightarrow WW^* \rightarrow 2l2nu \ [ggH/VBF/VH/ttH]$
- $H \rightarrow yy \ [ggH/VBF/VH/ttH]$
- $H \rightarrow tautau \ [ggH/VBF/VH/ttH]$
- $H \rightarrow bb \ [VH/ttH ]$

Prospects for High Luminosity

- $H \rightarrow Z\gamma \ [ggH/VBF]$
- $H \rightarrow \mu\mu \ [ggH/VBF]$
Experimental requirements

- Excellent lepton identification performance even at low $p_T$
  - To identify leptons in ZZ, WW and tautau
- Excellent lepton momentum resolution
  - To reconstruct a narrow $ZZ \rightarrow 4l$ peak
- Excellent photon identification performance and resolution
  - To reconstruct the $H \rightarrow \gamma\gamma$ gamma gamma events and reject fake photon background
- Good jet energy resolution
  - To reconstruct $bb$ pairs and form VBF observables
- Good b-tagging performance
  - To remove the light jet background in $bb /ttH$
- Good MET resolution
  - To reconstruct the WW and tautau final states
The basic principle of HEP detector

- **Tracking Detector**: Detects charged particles (mostly muons at the outside layer).
- **Hadron Calorimeter**: Detects and measures energy of hadrons.
- **EM calorimeter**: Detects electrons and photons.
- **Muon detector**: Detects charged particles.
Coordinate systems

- Coordinate system
  - X axis pointing to the center of the ring
  - Y axis upwards
  - Z axis along the beam
- Instead of the polar angle $\theta$, the pseudorapidity $\eta$ is used:

  $$\eta = -\ln \tan \frac{\theta}{2}$$
**Principles of Particle Identification**

**Charged hadrons**
- Leave track in inner tracker
- Deposit most of the energy in HCAL

**Neutral hadrons**
- Deposit most of the energy in HCAL

**Electrons**
- Leave a track in the inner tracker
- Deposit almost all their energy in the ECAL

**Muons**
- Interact very little in the calorimeters
- Leave a track in the inner tracker and the muon system

**Photons**
- Interact mostly in the ECAL
- Deposit almost all their energy
Measurement of track momentum

Track trajectory $y=f(x)$ reconstructed from $N$ measurement points

In the case of a straight line

$$y = \tan \theta x + d \approx \theta x + d$$

Track parameters and errors estimated by minimizing a Chi2

$$\chi^2 = \sum_i \frac{(y_i - f(x_i))^2}{\sigma_i^2}$$

Error of each point

In uniform magnetic field

$$p_T = 0.3BR$$

The helix can be parameterized by a parabola

$$y = \frac{1}{2R} x^2 + \theta x + d$$

After minimization

$$\delta d \approx \frac{\sigma}{\sqrt{N}}$$

$$\delta \theta \approx \frac{\sigma}{L\sqrt{N}}$$

$$\delta \frac{1}{2R} \approx \frac{\sigma}{L^2\sqrt{N}}$$

~ microns

<< mrad
Transverse momentum resolution

\[ \rho_T = 0.3BR \rightarrow \frac{\delta \rho_T}{\rho_T} = \frac{\delta R}{R} = 2R\delta \frac{1}{2R} = \frac{2R\sigma}{L^2\sqrt{N}} \]

\[ \frac{\delta \rho_T}{\rho_T} = \frac{2\sigma \rho_T}{0.3BL^2\sqrt{N}} \]

Measurement degrades as tracks become straight

- Large magnetic field
- Many measurement points
- Large tracker size
Multiple scattering (M.S.)

- Charged particles deflected in the material by an angle

- The track propagation can be done iteratively by using the M.S. information in the $\chi^2$!

- The momentum resolution can be limited by M.S

  - if the uncertainties on the material are large compared to module position uncertainties

\[
\frac{\delta p}{p} = \frac{1}{0.3BL} \frac{0.015 \text{ MeV}}{\beta} \sqrt{\frac{L}{X_{\text{rad}}}}
\]

\[
\sqrt{\langle \theta_{\text{MS}}^2 \rangle} = \frac{15 \text{ MeV}/c}{\beta p} \sqrt{\frac{\text{thickness}}{X_{\text{rad}}}}
\]

\~ 0.9 mrad/(\beta p) for a 300 \text{ \mu m} silicon detector
EM interactions

- EM interactions characterized by the radiation length ($X_0$):
  - Mean distance over a high energy electron loses all by 1/e of its energy
  - Or 7/9 of the mean free path for pair production of a high energy photon
- EM Calorimeters need to be $\sim$15-30 $X_0$ to contain the shower

Transverse position resolution of the shower depending on the Moliere radius ($R_M$)

- Contains 90% of the shower energy

\[ \sim R_M \]
\[ \sim X_0 \]
Calorimeter resolution

• The EM energy resolution is parameterized as

\[
\left( \frac{\sigma}{E} \right)^2 = \left( \frac{S}{\sqrt{E}} \right)^2 + \left( \frac{N}{E} \right)^2 + C^2
\]

- **Statistical term**
  - Related to the photon counting in the photodetectors!
  - Intrinsic shower fluctuations, material in front of the calorimeter, sampling fluctuations

- **Noise term**
  - Electronics or physics noise

- **Constant term**
  - Radiation damage, non uniformity, calibration uncertainty and energy leakage
Hadron Interactions

- Hadron interactions characterized by the interaction length ($\lambda_I$)

  - Mean free path of a hadron before ongoing a hadronic interaction

  - Typical hadron calorimeters span from 8-12 interaction lengths

  Hadron interactions $\rightarrow$ low # particles

  - In case of neutral pions, photons
    $\rightarrow$ EM showers

  - Charged deposit energy by ionization, excitation, interaction with nuclei

  - Significant fraction of energy lost!
# The ATLAS and CMS Detectors

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnetic field</strong></td>
<td>2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)</td>
<td>4 T solenoid + return yoke</td>
</tr>
<tr>
<td><strong>Tracker</strong></td>
<td>Silicon pixels and strips + transition radiation tracker [\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01]</td>
<td>Silicon pixels and strips (full silicon tracker) [\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005]</td>
</tr>
<tr>
<td><strong>EM calorimeter</strong></td>
<td>Liquid argon + Pb absorbers [\sigma/E \approx 10%/\sqrt{E} + 0.007]</td>
<td>PbWO$_4$ crystals [\sigma/E \approx 3%/\sqrt{E} + 0.003]</td>
</tr>
<tr>
<td><strong>Hadronic calorimeter</strong></td>
<td>Fe + scintillator / Cu+LaR (10%) [\sigma/E \approx 50%/\sqrt{E} + 0.03 \text{ GeV}]</td>
<td>Brass + scintillator (7 &amp; + catcher) [\sigma/E \approx 100%/\sqrt{E} + 0.05 \text{ GeV}]</td>
</tr>
<tr>
<td><strong>Muon</strong></td>
<td>[\sigma/p_T \approx 2% @ 50\text{GeV} to 10% @ 1\text{TeV} (Inner Tracker + muon system)]</td>
<td>[\sigma/p_T \approx 1% @ 50\text{GeV} to 10% @ 1\text{TeV} (Inner Tracker + muon system)]</td>
</tr>
<tr>
<td><strong>Trigger</strong></td>
<td>L1 + HLT (L2+EF)</td>
<td>L1 + HLT (L2 + L3)</td>
</tr>
</tbody>
</table>
Muon Identification

- Muons identified as penetrating tracks through the whole detector
  - Starting from an inner track and reconstructed local segments in the muon system
- Different reconstruction philosophies used based on the transverse momentum and required purity
Inside-Out muons

- Segments are reconstructed in the muon system
- Inner tracks are extrapolated [taking into account the material] and are matched to segments
- The muon momentum is derived by the tracker track
- Suitable for low pt muons that do not penetrate the whole muon system
Combined muons

- Full standalone tracks are reconstructed in the muon system
- Inner and standalone tracks are extrapolated and matched
- Combined tracks are made
- Muon momentum comes from the combined track at high Pt or from inner track in the region that the tracker dominates
Standalone Muons

- Tracks only in the muon system (extrapolated to vertex)
  - Not very much used due to the low purity
- In the case of CMS, standalone resolution limited by muon detector resolution and M.S. in iron yoke
- In the case of ATLAS standalone track has very good resolution
  - Used in the forward region outside tracker coverage
Muon backgrounds

- Semileptonic decays of heavy quarks
  - Real muons inside jets
- Decays in flight of pions and Kaons
  - Pion becoming a muon far from the vertex and penetrates the muon system
- Punch through hadrons
  - Particles that escape the calorimeter into the muon system

Kink can be detected to reject decays in flight
Muons are the workhorse of major physics searches!

Extremely pure and very precisely measured!
Muon fake rate from pions

- Fake rate from pions @ $10^{-3}$ level
- Main background in the muon final states from real muons in other processes
Electron Identification

- Electrons are identified by a track connected to an EM deposit.
  - EM deposit often broad due to shower in the tracker material
- Tracker material budget → crucial for electron ID
  - Both ATLAS/ CMS → a lot of material
Calorimeter clustering

- Identify individual energy deposits in the calorimeters
  - Specific algorithm depends on calorimeter technology + granularity
- Example: CMS ECAL
  1. Identify local maxima as seeds
  2. Grow topoclusters around seeds
  3. Make clusters from seeds and share hits in the same topo cluster
Clustering in reality

- Calorimeter clustering in CMS ECAL and HCAL
Outside -In Electrons

- Used in ATLAS and CMS
- An EM cluster is built in the ECAL
  - In case of high granularity, a cluster of clusters is made
    - by growing in phi to account radiation
- Cluster seeds tracking with the GSF algorithm
  - Takes into account energy loss
- Track -Calorimeter observables are created for ID
Inside-Out Electrons

- Used at CMS at low pt
- Starting from a track extrapolate tangents to collect brem photons
- Then a GSF track is built from the standard track
- Track and clusters are linked and combined observables are formed
Electron ID observables

- Good discrimination for the electron observables
- Can be combined through a MVA technique [BDT/LHR] to boost performance
Electron Identification efficiency

- Several working points are used based on the required background rejection in the analysis!
- In the case of electrons backgrounds come from EM fluctuations in jets
Electron momentum measurement

- ECAL is dominating the measurement at higher Pt
  - Tracker dominates at low pt!
- Combine both using a simple combination or MVA technique to get best performance!
Photon reconstruction

- Exactly the same technique as the electron in the calorimeter
  - Broad cluster is used to account for conversions in the tracker material
- Conversions can also be tagged by reconstructing electron tracks
  - And their invariant mass
Conversion reconstruction

Electron tracks are shown in purple, and their superclusters in pink in the ECAL. General tracks are in blue and tracker clusters (silicon strips) are shown by small squares.

electrons produced at the same vertex. Candidate properties confirm the electron hypothesis.
The Particle Flow approach

- The idea of Particle Flow is to combine information from all sub-detectors to reconstruct a mutually exclusive list of particles (PF candidates)
  - Charged hadrons
  - Neutral Hadrons
  - Photons
  - Electrons
  - Muons
- The list of PF candidates can be used to create higher level physics objects such as Jets, hadronic tau decays, MET
The gains of PF

- HCAL resolution much worse that tracker
  - In case of charged hadrons the momentum is calculated from the track
  - More precise

- Low HCAL resolution affects only neutral hadrons
  - 10% of a jet energy
  - Photons are measured with very precise and high granularity ECAL
Example: a jet of 4 particles

- A 65 GeV jet of a K0, pi+, pi-, pi0
ECAL deposits

- The neutral pion forms two clusters for the two photons
- The K0 interacts mainly in ECAL forming a cluster
- The pi- deposits also some ECAL energy forming another cluster
HCAL deposits

- HCAL much lower granularity
- Two clusters formed by two charged pions
- K0 does not deposit significant energy
Track - ECAL linking

- If track lands on one of the rechits link track+ECAL
- Happens only for the pi- in this example
Links summary

A tree of links forms a block

- K0 ECAL only → becomes PF photon
Particle creation $\rightarrow$ step 1

- Photons from pi0 not linked to track $\rightarrow$ PF photons

- In the tracker boundary ECAL+HCAL = photon+ neutral hadron
Particle creation → step 2

- If tracks linked to multiple HCAL keep only the closest
Particle creation → step 3

- For the track + HCAL elements compare the HCAL energy to the expected calorimeter resolution for this track
  - If no excess make charged hadron
- For the track+ECAL +HCAL elements compare track momentum with expected charged hadron resolution in ECAL and HCAL
  - If compatible make charged hadron
  - If ECAL excess create photon+charged hadron
  - If HCAL excess create charged +neutral hadron
  - If track excess and loose muon ID make muon+photon+neuytral hadron
Summary of the PF reconstruction

- The real event had
  - $K_0, \pi^+, \pi^-, \pi^0$

- PF will create
  - Two PF photons from $\pi^0$ decay
  - Two charged hadrons for the two pions
  - One PF photon corresponding to the $K_0$
    - Since no HCAL deposit PF cannot predict a neutral hadron
Reconstruction of a full event

Showing jets >50 GeV made out of PF particles
Hadronic tau identification

- A collimated jet with one or three charged particles

- Two philosophies
  - Cone based approach
    - Define a signal cone and an isolation cone
    - Check the number of charged particles in the cone
  - Decay mode approach
    - Reconstruct individual tau decay mode
    - Define everything else as isolation

Decay mode reconstruction favored in Particle Flow!
Decay mode: Tau ID in CMS

- Create 3 decay modes combinatorially around jets
  - A single charged hadron
  - A charged hadron + an EM strip of PF photons
    - To account for material effects
  - Three charged particles
- In case of multiple decay modes pick the one with highest Pt
- Use the mass of the intermediate meson to reject background
- All other particles in the vicinity are used for isolation
Validation with data: Tau mass
Tau identification efficiency and fakes

- ~50% efficiency for fake rate of 1%
- Background is from jets!
- Additional information from lifetime improves performance
Jet reconstruction

Jet reconstruction identifies the signatures of quarks and gluons in the detector

Jet algorithms cluster detector elements to form jets

- Detector elements can be Calorimeter cells [e.g. ATLAS] and the resulting jets are Calorimeter jets
- Particles from Particle Flow are also used [e.g. CMS]
  - Good correspondence with the MC quantities
  - Large improvement since tracker is used to measure most particles [charged hadrons] especially at low pt
- At high jet energies, calorimeter resolution comparable with tracker
  - PF and Calorimeter jets converge to the same performance
Jet algorithms

- Several algorithms to cluster particles into jets

- Requirements
  - **IR safe**: robust against the presence of low energy particles radiated by the partons
  - **Collinear safe**: Parton splits into pair of collinear partons recombined into the original one

- ATLAS and CMS use the anti-kt algorithm

\[
d_{ij} = \min \left( \frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2} \right) \frac{\Delta_{ij}^2}{R^2},
\]

\[
d_{iB} = \frac{1}{k_{T,i}^2},
\]

\[
\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
\]
Missing transverse energy

- Neutrinos cannot be identified in the detector
- Their contribution is approximated by looking at the missing transverse energy

\[ E_{T}^{\text{miss}} = \sum_{i} \vec{E}_{T} \]

- Specific corrections to the missing transverse energy and multivariate techniques are also employed
Tagging of jets from b-quarks

- Exploiting the lifetime of B hadrons
- Producing displaced vertices

**Observables**

Signed decay length of secondary vertexes

**Observables**

Signs of Impact parameter and of vertex decay length are defined according to jet direction

Signed impact parameter of tracks in the jet

Observables often combined in MVA discriminants
b-tagging performance

- Typical efficiency of 50% with a mistag probability of 1-2%
Lepton and Photon Isolation

- Leptons and photons from interesting processes are isolated in the detector

  - Isolation is a handle to reject backgrounds from non-prompt objects
    - Which can be real
      - i.e. muons from b decays
    - or fake
      - jet misidentified as electron

- Definition of combined Isolation
  \[ I = \frac{I_{ch} + I_{ECAL} + I_{HCAL}}{p_T} \]

- Sum of tracks and hits in a cone
Isolation with Particle Flow

- Isolation with PF candidates also possible
- Improves performance
  - Does not double count the calorimeter deposits of the charged hadrons
The challenge of pileup

- At high luminosity several pairs of protons can interact
  - Producing multiple interactions in the detector
  - Event of interest overlayed with other events
- We need to separate them in analysis level
Effects of PU in the analysis

- Particles from additional collisions degrade analysis performance
  - Isolation is spoiled for prompt leptons
  - Particles degrade Jet and MET resolution
  - Electron ID variables spoiled by PU hadronic deposits
- Special techniques needed for PU mitigation
Example: PU mitigation in isolation

- Charged particles are selected by vertex requirements
  - Problem is the neutrals
- Neutrals from PU can be predicted by measuring the charged deposit from PU in the same cone
  - And assuming charged:neutral = 2:1
Out of time PU

- In case a detector is slower than a bunch crossing particles in previous bunch create PU in the detector
  - Mostly affecting Calorimeters
- With LHC running @25ns OOT PU becomes major issue
  - Can be mitigated at low level by looking at the pulses in the detector
OOT PU: Time samples

Looking at a specific calorimeter hit vs time

- Reconstructing time sample 0 has 20% OOT contribution
- Granularity of the calorimeter helps! → less chance of overlap
- Need smart technique to estimate the bx0 contribution
Example OOT PU mitigation

- Assumption that we know the pulse shape
  - e.g. 20% of the energy in the next bx
  - This ratio could vary in the detector → hit calibration

\[
0.8BX(0) + 0.2BX(-1) = c \\
0.8BX(-1) = b \\
0.2BX(0) = a
\]

BX0 energy estimated from pulse shape

- Realistic case harder!
  - Deposits in continuous bunch crossings
  - Complicated pulse fits and looking at neighboring hits!
Summary of the first lecture

- Reviewed the Higgs phenomenology
  - What we expect at LHC and which modes are relevant
- Looked at the detector requirements for the Higgs search
  - How we identify objects
  - What is the typical performance
  - How we solve experimental problems to improve sensitivity of the analyses
- Next: Look at the main Higgs analyses in depth and review the higher level techniques