Physics at Hadron Colliders
Part I

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The Standard Model Lagrangian

\[ \mathcal{L} = -\frac{1}{4} F^{\alpha \mu \nu} F_{\alpha \mu \nu} + i \bar{\psi} D\psi + \psi_i \chi_{ij} \psi_j h + \text{h.c.} + |D_\mu h|^2 - V(h) + \frac{1}{M} L_i \chi^\nu_{ij} L_j h^2 \text{ or } L_i \chi^\nu_{ij} N_j \]

... and beyond?

supersymmetry (many variants)
extra spacetime dimensions
compositeness
strong electroweak symmetry breaking
... something new?!

[W. J. Stirling]
**Status of the art**

- The SM (in terms of its QCD and EWK parts) WORKS PERFECTLY well, up to the % level at the highest energies probed so far (7 and 8 TeV)

- We have very advanced theory tools at hand

- There is a new boson of mass \(\sim 125\) GeV, with properties consistent with the SM Higgs, within the current uncertainties. More data needed to ascertain the nature of this object.

- So far, no indications of BSM physics from direct searches at the HEF: colored SUSY particles (first generations) ruled out up to \(O(1\) TeV), for a light LSP;
  - “natural” SUSY probed at level of a few hundred GeV of 3rd generation spartners;
  - **exotica**: heavy objects probed up to masses of 2-3 TeV;
    - a lot of room still to be explored, 14 TeV will be essential!

- very few anomalies in the world-wide HEF data, no strongly smoking gun most important: at the LHC, we are JUST AT THE BEGINNING of the HEF exploration!
Problem I: Where is the Higgs boson?

• Precision measurements of
  – \( M_W = 80.399 \pm 0.023 \text{ GeV}/c^2 \)
  – \( M_{\text{top}} = 173.3 \pm 1.2 \text{ GeV}/c^2 \)
  – Precision measurements on Z pole

• Prediction of higgs boson mass within SM due to loop corrections

Solved ??!!!
Problem II: Where did all the Antimatter go?

- Not explained by Standard Model
Problem III: Hierarchy Problem

- Free parameter $m^2_{H_{\text{tree}}}$ needs to be “finetuned” to cancel huge corrections
  - Can be solved by presence of new particles at $M \sim 1$ TeV
  - Already really bad for $M \sim 10$ TeV

- Why is gravity so weak?
  - $M_W/M_{\text{Planck}} \sim 10^{16}$ or $G_F/G_N \sim 10^{32}!$

$m^2_H \approx (200 \text{ GeV})^2 = m^2_{H_{\text{tree}}} + \delta m^2_{H_{\text{top}}} + \delta m^2_{H_{\text{gauge}}} + \delta m^2_{H_{\text{higgs}}}$

\[\text{Fine tuning the Higgs} \quad \Delta \approx 10 \text{ TeV}\]
(Some) More Problems …

• **Matter:**
  – SM cannot explain number of fermion generations
  – or their large mass hierarchy
    • \( \frac{m_{\text{top}}}{m_{\text{up}}} \sim 100,000 \)

• **Gauge forces:**
  – electroweak and strong interactions do not unify in SM
  – SM has no concept of gravity

• **What is Dark Energy?**

  “Supersymmetry” (SUSY) can solve some of these problems
Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

\[
L = \frac{f_{\text{rev}} \cdot n_{\text{bunch}} \cdot N_p^2}{4 \pi \sigma_x \sigma_y}
\]

LHC:
- revolving frequency: \( f_{\text{rev}} = 11245.5 / s \)
- #bunches: \( n_{\text{bunch}} = 2808 \)
- #protons / bunch: \( N_p = 1.15 \times 10^{11} \)
- Area of beams: \( 4\pi \sigma_x \sigma_y \sim 40 \mu m \)

- Rate of physics processes per unit time directly related:

\[
N_{\text{obs}} = \int L \text{d}t \cdot \epsilon \cdot \sigma
\]

Efficiency:
- optimized by experimentalist

Cross section \( \sigma \):
- Given by Nature
  (calc. by theorists)

Ability to observe something depends on \( N_{\text{obs}} \)
### LHC and Tevatron Machine Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC (today)</th>
<th>LHC (design)</th>
<th>Tevatron (achieved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>8 TeV</td>
<td>14 TeV</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>Number of coll. bunches</td>
<td>1368</td>
<td>2808</td>
<td>36</td>
</tr>
<tr>
<td>Peak Luminosity ($10^{30}$ cm$^{-2}$s$^{-1}$)</td>
<td>7700</td>
<td>10000</td>
<td>400</td>
</tr>
<tr>
<td>Integrated Luminosity: $\int L dt$</td>
<td>21.6 fb$^{-1}$</td>
<td>&gt;100 fb$^{-1}$</td>
<td>~12 fb$^{-1}$</td>
</tr>
</tbody>
</table>
Instantaneous Luminosity

- Tevatron: $4.0 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- LHC: $7.7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
  - it takes about 24h to get 80 pb$^{-1}$
Integrated Luminosity

- Tevatron: 12 fb\(^{-1}\) delivered
- LHC: almost 22 fb\(^{-1}\) delivered
  - Very steeply rising due to progress in accelerator
## Example: ATLAS Detector Performance

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>97.3%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.2%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.1%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>97.9%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>96.8%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.9%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>99.9%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>98.5%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.0%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>98.4%</td>
</tr>
</tbody>
</table>
Cross section

• Cross section measurements in particle physics:
  – Connecting Theory and Experiment
• Cross section: definition
  – Luminosity
  – Counting the number of events
  – Efficiency & acceptance corrections
  – Use of Monte Carlo simulations
  – Systematic uncertainties
  – Unfolding of measured data to quantities predicted by theory
• Examples of cross section measurements
Motivation

• Cross section is a fundamental physics observable
  – Cross section measurements were crucial to achieve the model of particle physics as we have it today
• Most measurements at LHC, HERA, Tevatron are cross section measurements
• Concepts of a cross section measurement are common to most analyses addressed today
Cross section at fixed target

Number of beam particles: $N_1$

Target density: $n_2 = N_2 / (A \cdot dx)$

Target thickness: $dx$

Number of interactions / time:

$$\dot{N} = \left( N_1 \cdot n_2 \, dx \right) \cdot \sigma .$$

- Number of interactions per time $\dot{N}$ is proportional to material-specific cross section $\sigma$
- Geometrically, $\sigma$ is the effective fraction of the target area
- Unit: [\sigma] = 1 b = 1 barn = 10^{-24} cm^2
- The factor $L = N_1 \cdot n_2 \cdot dx$ is called luminosity (flux of particles)
- Example: Geometrical cross section of the proton: 31 mb (proton radius: \sim 1 fm)
Differential cross section: $d\sigma/d\Omega$:

Probability of a scattered particle in a given quantum state per solid angle $d\Omega$
Probing the Structure of Matter

- Perform scattering experiments
- Measure scattering angles and energy
- Structure has been explored down to $10^{-18}$ m (upper limit for quark radius)

1908: Atoms have nuclei
1956: Nuclei are extended
1962: Nuclei have substructure
Since 70's: Quarks and gluons (PDF)
Since 90's: Do quarks have substructure?
Theory and Experiment

• Cross Section: A measure of the number of collisions
  – Experiment: Measurement of rate of events in particular final state
  – Theory: Calculation of transition probability using matrix elements and phase space

\[ \lambda_{if} = \frac{2\pi}{\hbar} \left| M_{if} \right|^2 \rho_f \]

Fermi’s Golden Rule

– Repeat experiment (collision) many times: relate experiment to theory

Test / distinguish theoretical models by comparison of prediction with measurement
Theory and Experiment

Example: Calculation of \( H \rightarrow ZZ \rightarrow 4 \) leptons

Theory predicts cross section (number of events per luminosity)

![Production Cross Section](image1)

Branching Ratios

Parton Distribution Functions (PDF)

Standard Model Cross Section calculations known up to NNLO (accuracy 5-10%)
Theory and Experiment: Higgs

Gluon fusion process (87%)  
Vector Boson fusion (7%)  
Associated production with W/Z (5%)  
Associated production with top (1%)

LHC Higgs Cross Section Working Group

Cross section [pb] at $m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>ggF</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(pp \to H+X)$</td>
<td>19.1</td>
<td>1.6</td>
<td>0.7</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

BR [%] at $m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>WW</th>
<th>ZZ</th>
<th>gg</th>
<th>Zg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR} %$</td>
<td>22</td>
<td>2.8</td>
<td>0.23</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Several processes contributing to the total Higgs cross section (gg, VBF, VH, ttH, ...)
Hadron collision physics

Protons are complex objects:
Partonic substructures:
Quarks and Gluons

\[ Q^2 \approx (M^2 + p_T^2) \]

Björken-x:
Fraction of proton momentum carried by the parton

- Hard scattering processes: high momentum transfer \((Q^2)\)
- Quark-quark
- quark-gluon
- gluon-gluon scattering or annihilation

Hard scattering processes are a small fraction of the total inelastic cross section
\(~ 70\) mb dominated by low momentum transfer processes
Theory and Experiment

Parton Distribution Functions (PDF)

- PDF can not be calculated, but are universal (assumed and proven)
  - within given approximation and scheme (e.g. NNLO DGLAP)

- Determined from different experiments
  - mostly from HERA, now from LHC data

- High energy proton collisions are really parton collisions, mostly gluons
  - parton luminosity

- Generic pp cross section is sum of partonic cross sections

\[
\sigma = \sum_{i,j} \int_0^1 dx_1 \, dx_2 \, f_i(x_1, \mu) \, f_j(x_2, \mu) \, \hat{\sigma}_{ij}
\]
Calculation of a cross section

- Cross section is convolution of pdf's and Matrix Element
  
  \[ \sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 \ f_i(x_1, \mu_F) f_j(x_2, \mu_F) \ \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu_R), Q^2, \mu_R, \mu_F). \]

- Calculations are done in perturbative QCD
  
  - Possible due to factorization of hard ME and pdf's
    - Can be treated independently
  
  - Strong coupling (\(\alpha_s\)) is large
    - Higher orders needed
    - Calculations complicated
The Proton Composition

- It’s complicated:
  - Valence quarks, Gluons, Sea quarks
- Exact mixture depends on:
  - $Q^2: \sim (M^2 + p_T^2)$
  - Björken-x:
    - fraction or proton momentum carried by parton
- Energy of parton collision:

\[
\hat{S} = \mathcal{X}_p \cdot \mathcal{X}_{\bar{p}} \cdot S
\]

\[
M_X = \sqrt{s}
\]
Initially two beam particles are coming in towards each other. Normally each particle is characterized by a set of parton distributions, which defines the partonic substructure in terms of flavour composition and energy sharing. This determines the energy of the interacting partons \((x_1, x_2)\)

\[
\sigma(p(p_1) + p(p_2) \rightarrow Y) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1)f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1P) + \bar{q}_f(x_2P) \rightarrow Y)
\]

Incoming beams: Parton densities

Partonic x-section: phase space* matrix element
Parton Kinematics

- Parton densities rise dramatically towards low $x$
  - Results in larger cross sections for LHC

Examples:
- Higgs: $M \approx 100 \text{ GeV/c}^2$
  - LHC: $<x_p> = 100/14000 \approx 0.007$
  - TeV: $<x_p> = 100/2000 \approx 0.05$
- Gluino: $M \approx 1000 \text{ GeV/c}^2$
  - LHC: $<x_p> = 1000/14000 \approx 0.07$
  - TeV: $<x_p> = 1000/2000 \approx 0.5$

pdf's measured in deep-inelastic scattering
• Describe energy distribution of partons inside proton.

• There are several PDF’s parametrizations, determined by the data from ep experiments at Hera or from Tevatron or fixed target.

• u- and d-quarks dominate at large x, while gluons dominate at low x.
Physics Cross Sections

\[ M_X = \sqrt{x_1 \cdot x_2 \cdot s} \]

<table>
<thead>
<tr>
<th>Process</th>
<th>( M_X ) (GeV)</th>
<th>( \sigma(\text{LHC @ 7 TeV}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>qq( \rightarrow )W</td>
<td>80</td>
<td>3</td>
</tr>
<tr>
<td>qq( \rightarrow )Z'(_{\text{SM}})</td>
<td>1 TeV</td>
<td>50</td>
</tr>
<tr>
<td>gg( \rightarrow )H</td>
<td>120</td>
<td>20</td>
</tr>
<tr>
<td>qq/gg ( \rightarrow )tt</td>
<td>2x173 GeV</td>
<td>15</td>
</tr>
<tr>
<td>gg( \rightarrow )gg</td>
<td>2x400 GeV</td>
<td>1000</td>
</tr>
</tbody>
</table>

- \( \int L dt = 1 \text{ fb}^{-1} \) at LHC competitive with 10 \( \text{fb}^{-1} \) at Tevatron for high mass processes
- \( \int L dt = 100 \text{ pb}^{-1} \) already interesting in some cases
From where do we know $x$?

The proton structure was investigated in the Deep Inelastic Scattering experiments:

Important role played in the past by: HERA ep collider at DESY
Scattering of 30 GeV electron on 900 GeV protons:
→ Test of the proton structure up to $10^{-18}$ m
What are the results on the value of $x$?

Density function of the parton (pdf):
Quark $u- e\ d$ dominate at high $x$
Gluons dominate at small $x$!
QCD Approach: Quarks & Gluons

**Parton Distribution Functions**
- $Q^2$ dependence predicted from QCD

**Quark & Gluon Fragmentation Functions**
- $Q^2$ dependence predicted from QCD

**Quark & Gluon Cross-Sections**
- Calculated from QCD

**TABLE I. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses.**

| Subprocess | $|A|^2$ |
|------------|--------|
| 1. $q_iq_j \to q_iq_j$ ($j \neq f$) | $\frac{4}{9} \frac{3^2 + \bar{u}^2}{\bar{u}^2}$ |
| 2. $q_i\bar{q}_f \to q_i\bar{q}_f$ | $\frac{4}{9} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} + \frac{3^2 + \bar{u}^2}{\bar{u}^2} \right) - \frac{8}{27} \frac{3^2}{\bar{u}^2}$ |
| 3. $q_i\bar{q}_f \to q_i\bar{q}_f$ | $\frac{4}{9} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} + \frac{\bar{u}^2 + \bar{u}^2}{\bar{u}^2} \right) - \frac{8}{27} \frac{\bar{u}^2}{\bar{u}^2}$ |
| 4. $q_i\bar{q}_f \to gg$ | $\frac{32}{27} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} \right) - \frac{8}{3} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} \right)$ |
| 5. $gg \to q_i\bar{q}_f$ | $\frac{1}{6} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} \right) - \frac{8}{3} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} \right)$ |
| 6. $q_i\bar{q}_f \to gg$ | $\frac{4}{9} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} + \frac{\bar{u}^2 + \bar{u}^2}{\bar{u}^2} \right)$ |
| 7. $gg \to gg$ | $\frac{9}{2} \left( \frac{3^2 + \bar{u}^2}{\bar{u}^2} - \frac{\bar{u}^2 + \bar{u}^2}{\bar{u}^2} \right)$ |
σ_{tot} = σ_{EL} + σ_{SD} + σ_{DD} + σ_{ND}

1.8 TeV: 78mb = 18mb + 9mb + (4-7)mb + (47-44)mb

The “Non diffractive” component contains both “hard” and “soft” collisions.
Proton-Proton Collisions at the LHC

Elastic Scattering

\[ \sigma_{\text{tot}} = \sigma_{\text{EL}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{ND}} \]

Elastic interactions: no colour flow between colliding protons

Inelastic interactions: result in multi-particle final states. Characterized as non-diffractive or diffractive

Non-diffractive events involve colour exchange between partons
• Diffractive events typically produce particles in the very forward region

• A large fraction of these events goes undetected

• Characterised experimentally by large rapidity gaps
Cross Section Measurement

- Number of collision events is the product of cross section and luminosity

\[
dN/dt = \sigma \cdot \mathcal{L}
\]

- Luminosity: Number of incident particles per area per time (unit: cm\(^{-2}\)s\(^{-1}\))
  - Example: LHC design luminosity LHC: \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)

- Cross section equals number of events per time-integrated luminosity
  - depends on particle and process type (unit: barn, 1 b = \(10^{-28}\)m\(^2\))

Experimentally, we need to:
- subtract background events
- correct for detector response
- correct for detector acceptance
- divide by branching ratio
- determine luminosity
Number of Events

\[ \sigma = \frac{N_{\text{meas}} - N_{\text{backgd}}}{\epsilon \cdot A \cdot BR \cdot \int L dt} \]
**Number of Events: Cut and Count**

Works if good separation of signal and background. Advantage: simple & robust

Example: top pair production cross section measured in the di-lepton channel at LHC

\[
\sigma = \frac{N_{\text{meas}} - N_{\text{backgd}}}{\epsilon \cdot A \cdot BR \cdot \int L dt}
\]

Data sample: 5.3 fb\(^{-1}\)

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(e^+e^-)</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>386(\pm)116</td>
</tr>
<tr>
<td>Non-W/Z leptons</td>
<td>25(\pm)10</td>
</tr>
<tr>
<td>Single top quark</td>
<td>127(\pm)28</td>
</tr>
<tr>
<td>VV</td>
<td>30(\pm)8</td>
</tr>
</tbody>
</table>

- Total background: 569\(\pm\)120 \(e^+\mu^-\), 802\(\pm\)159 \(\mu^+\mu^-\), 886\(\pm\)130 events
- \(t\bar{t}\) dilepton signal: 2728\(\pm\)182 \(e^+e^-\), 3630\(\pm\)250 \(\mu^+\mu^-\), 9624\(\pm\)504 events
- Data: 3204 \(e^+e^-\), 4180 \(\mu^+\mu^-\), 9982 events

~9% background

### Summary

- **\(e^+e^-\)**
  - \(\epsilon_{\text{total}}\) (\%): 0.203 \(\pm\) 0.012
  - \(\sigma_{\text{\(t\bar{t}\)}}\) (pb): 244.3 \(\pm\) 5.2 \(\pm\) 18.6 \(\pm\) 6.4

- **\(\mu^+\mu^-\)**
  - \(\epsilon_{\text{total}}\) (\%): 0.270 \(\pm\) 0.017
  - \(\sigma_{\text{\(t\bar{t}\)}}\) (pb): 235.3 \(\pm\) 4.5 \(\pm\) 18.6 \(\pm\) 6.1

- **\(e^+\mu^-\)**
  - \(\epsilon_{\text{total}}\) (\%): 0.717 \(\pm\) 0.033
  - \(\sigma_{\text{\(t\bar{t}\)}}\) (pb): 239.0 \(\pm\) 2.6 \(\pm\) 11.4 \(\pm\) 6.2

Error: 5.4%
Separation of signal and background

2 methods commonly used:
  – Side band fit
  – Template fit
Number of Events: Template Fits

Example: Top Quark Pair Production in all hadronic channel

- **Signature**
  - 6 or more jets
  - 2 b-tagged

- **Analysis**
  - kinematic fit to reconstruct top masses
  - background shape from b-unteaggedJets

- **Selected Sample**
  - background is large (~75 %)

- **Measurement**
  - Determine fraction of signal in sample from fit of signal plus background shapes to the data
  - Correct for signal efficiency and luminosity

\[
\sigma_{t\bar{t}} = \frac{f_{\text{sig}} \cdot N}{\epsilon \cdot L_{\text{int}}},
\]

\[
\epsilon = 0.22\%
\]

\[
\sigma_{t\bar{t}} = 139 \pm 10_{\text{stat}} \pm 26_{\text{syst}} \pm 3_{\text{lumi}} \ \text{pb}
\]

20%
Background estimate in DY: side band fit

The $Z \rightarrow ee$ MC is scaled to match the total estimated signal yield in the $Z$-mass window.
Efficiency and Acceptance

$$\sigma = \frac{N_{\text{meas}} - N_{\text{backgd}}}{\epsilon \cdot A \cdot BR \cdot \int \mathcal{L} dt}$$
Experimental Corrections

• Factorization Ansatz: \( \epsilon \cdot A \cdot BR \)

• Efficiency: selection of reconstructed signatures (detector response)

\[
\epsilon = \frac{\text{Number of reconstructed and selected events}}{\text{Number of signal events in kin. range}}
\]

• Acceptance: kinematic selection (phase space)

\[
A = \frac{\text{Number of signal events in kin. range}}{\text{Number of all signal events}}
\]

• Branching ratio (if applicable)

\[
BR = \frac{\text{Number of all signal events (in measured decay channel)}}{\text{Number of all signal events (in all decay channels)}}
\]
Experimental corrections from data: Tag & Probe

**Method:**
select final state, e.g.:
Drell-Yan $\ Z\rightarrow ee, \ Z\rightarrow \mu\mu \ events$
$J/Psi\rightarrow ee, \ J/Psi\rightarrow \mu\mu \ events$
$W\rightarrow e\nu$

Require one particle ($\mu, \ e, \nu$) to be identified (“tag”)
Test if the other is also identified (“probe”)

Used for, e.g.:
Efficiency determination
Energy calibration

---

Example: ATLAS measured

$1.2 \times 10^6 \ Z\rightarrow ee \ events \ in \ 2011$
$\sim 5 \times 10^6 \ Z\rightarrow ee \ events \ in \ 2012$

$1.7 \times 10^6 \ Z\rightarrow \mu\mu \ events \ in \ 2011$
$\sim 7\ \times 10^6 \ Z\rightarrow \mu\mu \ events \ in \ 2012$
Detector Efficiency
example: reconstruction of electrons in ATLAS

Efficiency between 80-97% depending on detector region, electron identification requirements, electron energy and transverse momentum.
Detector Acceptance

- Experimentally accessible kinematic region is limited (can not measure very small $p_T$ and large $\eta$)

- Measure in 'visible' range (‘fiducial’ volume)

- Use theory to extrapolate into inaccessible phase space

\[ \sigma_{\text{tot}}^{\text{meas}} = \sigma_{\text{vis}}^{\text{meas}} \frac{\sigma_{\text{tot}}^{\text{theo}}}{\sigma_{\text{vis}}^{\text{theo}}} \]
“Visible” or “fiducial” Cross Section

Example: ttbar+jets from ATLAS:
Measure additional jets in top pair production

\[ \alpha_s(Q_i) \]

- Limits theory dependent corrections
- Particularly important for measurements with large uncertainties on the theoretical predictions

\[ \sigma_{\text{visible}} = \frac{N_{\text{meas}} - N_{\text{backgd}}}{\epsilon \cdot BR \cdot \int L \, dt} \]

- Compare with theory in form of MC models in same kinematic range
- Calculations in limited phase space are generally more difficult
- Provide information such that extrapolations to the full phase space can be made with theoretical models at any time
Branching Ratio

Example: top quark pairs

$W$ decay universal $e: \mu: \tau: \text{jets} \sim 1:1:1:6$

t-$\rightarrow$Wb to almost 100%

Branching ratios well determined, use known numbers for cross section measurements