Standard Model at the LHC
(Lecture 3: Measurement of Cross-Sections)

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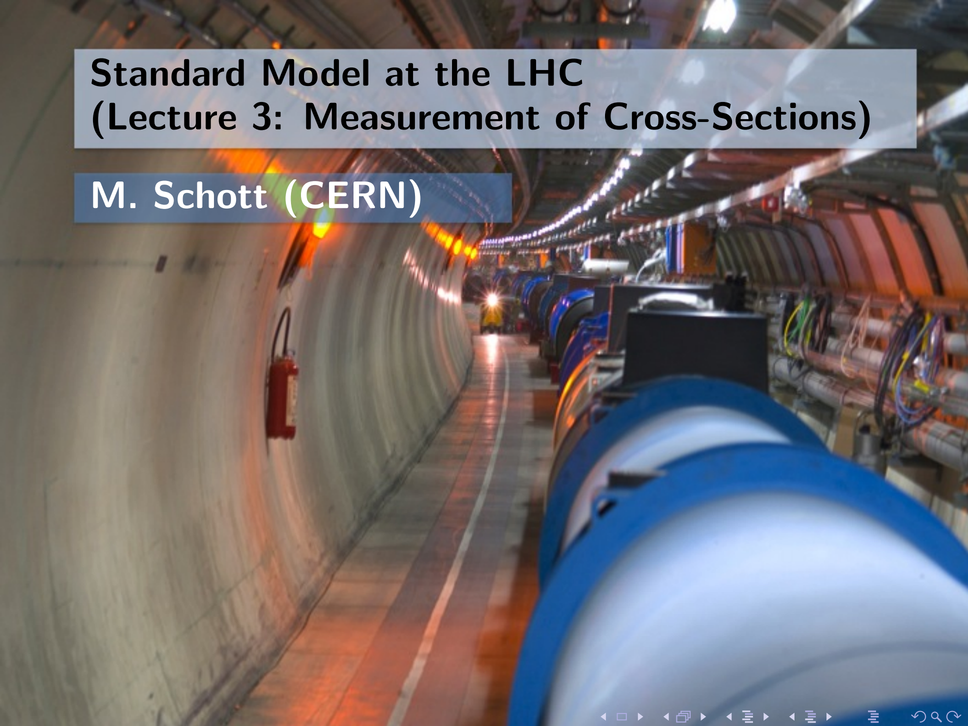


Content

1. Measuring Cross-Sections
2. Hands-On
3. Background Estimations
4. Detector Calibration
5. Recent LHC Results

Cross-Section and Luminosity (1/1)

- Physically, we want to determine the fundamental parameters of a theory
- We are measuring cross-sections, which are functions of these parameters = theoretical event rates
- In experiments we measure numbers of events which reflect
  - The running time of the experiment, and beam and target density, summarized by the luminosity parameter, L
  - Backgrounds, B Detector efficiency, ϵ, and finite acceptance A
- both are related by

$$N = L \cdot \sigma \cdot \epsilon \cdot A + B$$

or

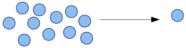
$$\sigma = \frac{N - B}{L\epsilon \cdot A}$$

Cross-Section and Luminosity (2/2)

Cross-sections are defined as surfaces (hence the name!). Hence Luminosity is defined as "N per unit surface" such that the number of collisions is $N_{Coll} = \sigma \times L$

- Consider the problem of classic billiard balls:

Cross-section is here: $\sigma = 4\pi R^2$. Assume now a beam of incoming balls:



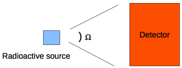
One is easily convinced that the number of collisions is

$$N_{Coll} = \sigma \times \frac{N_{beam}}{\sigma_{beam}} = \sigma \times \frac{dN_{beam}/dt}{\sigma_{beam}} \Delta t == \sigma \times L$$

We keep the same definitions in particle physics...

Acceptance and Efficiencies

These parameters are related to the detector. Imagine the simple example of a detector measuring electrons from β-decay.



Assume the emission is isotropic. The detector will only catch those that come into its direction. The acceptance is the fraction of solid angle covered, as seen from the source:

$$A = \frac{\Omega}{4\pi}$$

The efficiency is the fraction of recorded electrons that pass "quality cuts"

$$\epsilon = \frac{N_{Accepted}}{N_{Recorded}}$$

Uncertainty Information

Simple error propagation gives, in terms of relative uncertainties

$$\frac{\delta\sigma}{\sigma} = \frac{\delta N \oplus \delta B}{N - B} \oplus \frac{\delta L}{L} \oplus \frac{\delta A}{A} \oplus \frac{\delta\epsilon}{\epsilon}$$

Uncertainty on N : the "statistical uncertainty". Event counting follows the Poisson distribution. At large N ($N > 5$), this tends to the Gaussian distribution, of width $\sigma\sqrt{N}$

- Convention
  - Choosing the convention to quote 1σ uncertainties
  - refers to the interval $[\mu - \sigma, \mu + \sigma]$ of the gaussian function
  - We claim that the true value has 68% chance lying in the interval
  - "1σ" ($\approx 68\%$), "2σ" ($\approx 95\%$), "3σ" ($\approx 99.7\%$)

Basic Formula and Summary of Concepts

Theory predicts a certain cross-section σ

- we can calculate it via the Matrix-Element and the Feynman-Rules

Experimentalists measure cross-sections

Basic Formula

$$\sigma = \frac{N-B}{\epsilon \cdot A \cdot L}$$

- How do we know, how a certain process looks in out detector?
- How can we distinguish between signal and background
- How can we estimate the detector efficiency ϵ
- $\rightarrow$ Use Computer Simulations of the detector

Detector Simulation (1/3)

Simulation of proton-proton collisions

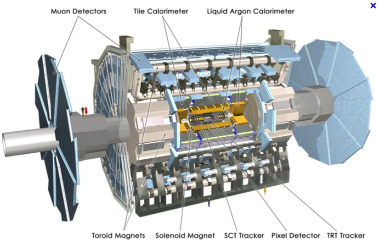
- Step 1: Event-Generator (See previous lectures): Simulate scattering of protons until all final state particles are "stable"
- Step 2: Simulate response of particle detector

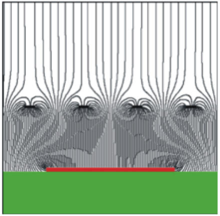
- Precise knowledge of the processes leading to signals in particle detectors is necessary.
- Thanks to the huge available computing power, detectors can be simulated to within 1-10% of reality
- Simulation based on a very precise description of:
  - the fundamental physics processes at the microscopic level (atomic and nuclear cross-sections)
  - the signal processing (electronics and readout),
  - the detector geometry (tens of millions of volumes)

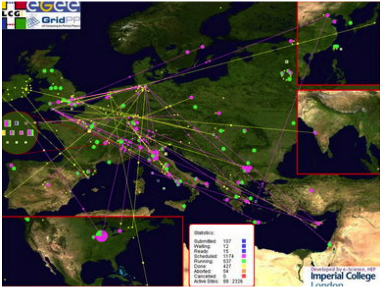
Detector Simulation (2/3)

- Very accurate simulations of particle detectors are possible due to availability of Finite Element simulation programs and computing power.
  - Principle: Follow every single electron by applying first-principle laws of physics.
  - Millions of particle to follow for each simulated Event
  - Very small step-sizes (μm -level)
- Consequences
  - The full MC simulation of one proton-proton collision takes 5-15min in average PC
  - We can simulate only a tiny fraction of proton-proton collisions (requiring specified properties, e.g. at least one Z-Boson should be created)
- Need Large Computer centers not only to reconstruct the recorded events from the detector, but also to simulate millions of specific processes.

Detector Simulation (3/3)







Hands-On Session

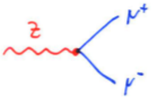
Before we proceed, it is useful to do some basic hands-on sessions

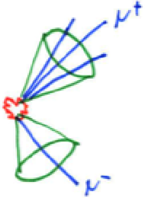
- Calculate the invariant mass of muon pair
- Measure the Z-boson mass with LHC data
- Measure the production cross-section of $\sigma(pp \rightarrow \mu^+\mu^-)$

Calculate the invariant mass

ATLAS/CMS can measure

- the momentum (p_x, p_y, p_z) of the muons
- the charge of the muons
- further properties like isolation





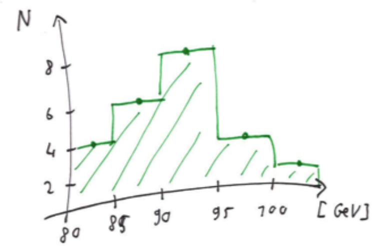
Calculate the invariant mass of two muons with

- $\vec{p}_1 = (4, -47, -171)[GeV]$
- $\vec{p}_2 = (27, -31, -62)[GeV]$
- Assume the muon to be massless and use natural units
- Hint: $P^2 = M^2$

Representing Data

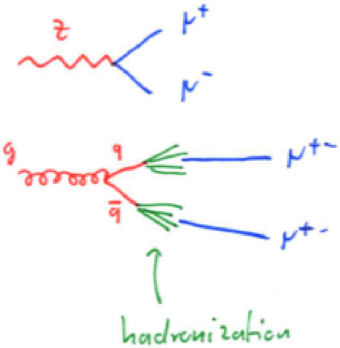
- Step 1: Create your "own" histogram from data
- Step 2: Add the Monte Carlo Prediction
- Step 3: Why do we see differences?

	1st Muon					2nd Muon					Combined Info
N	p_x [GeV]	p_y [GeV]	p_z [GeV]	Charge	Isolation	p_x [GeV]	p_y [GeV]	p_z [GeV]	Charge	Isolation	Invariant Mass [GeV]
1	-3.9	-47.4	-171.7	1	1	27.4	31.4	-62.0	-1	1	92.3
2	-43.9	-14.4	24.5	1	1	41.9	9.0	31.3	1	1	89.2
3	10.8	33.7	-44.4	-1	1	-16.7	-18.2	3.5	1	1	68.8
4	17.6	15.4	-100.0	-1	2	-4.3	-17.7	56.4	1	2	155.4
5	-12.6	15.9	-39.5	-1	3	11.5	-15.1	32.4	-1	2	81.7
6	16.9	-11.6	-31.7	-1	1	-17.1	9.9	41.0	-1	2	82.7
7	-50.7	-19.5	-73.9	1	1	36.4	6.1	-30.0	-1	1	90.7
8	-39.4	14.9	-143.1	1	1	31.0	-17.0	-23.3	-1	1	94.3
9	-33.1	-19.5	0.5	-1	1	31.6	19.6	-57.7	1	1	90.4
10	-5.2	31.1	-12.6	1	1	5.7	-30.8	-55.6	-1	1	70.0
11	-32.6	15.0	36.7	1	1	26.8	-10.4	121.0	-1	1	77.1
12	-15.0	-33.7	-156.0	-1	1	10.4	33.4	-23.2	1	1	93.7
13	-18.2	-53.3	95.2	-1	1	-7.7	38.4	90.8	1	1	91.6
14	10.8	-23.9	164.6	-1	1	2.8	23.6	-3.6	1	1	101.4
15	12.7	-48.4	68.4	-1	1	7.9	42.2	27.4	1	1	93.6
16	22.3	-20.6	8.0	1	1	-18.1	18.4	-89.4	-1	1	94.0
17	-22.8	21.6	-40.9	1	1	20.4	-20.7	24.3	-1	1	87.8
18	-45.8	6.5	211.3	-1	1	41.1	-8.2	174.5	1	1	88.1
19	-26.8	15.7	-26.4	1	2	16.8	-0.7	18.8	-1	2	63.1
20	17.6	-38.9	23.4	-1	1	-6.1	27.8	92.0	1	1	86.4
21	15.7	-39.0	57.2	1	1	-17.7	37.3	16.6	-1	1	88.8
22	-46.7	-17.0	81.9	1	1	37.8	15.3	39.5	-1	1	92.0
23	25.4	-33.0	102.3	1	1	-39.2	-7.4	24.0	-1	1	82.9
24	12.9	-58.7	-62.4	1	1	16.9	5.7	-96.1	-1	1	72.0
25	-2.8	43.7	35.7	-1	1	0.1	-39.7	88.8	1	1	90.1
26	17.4	3.2	-42.0	-1	2	-13.0	0.6	35.8	1	3	83.3
27	47.5	-14.7	-26.0	-1	1	-41.2	12.6	-19.3	1	1	92.7
28	-3.8	-49.1	40.9	-1	1	16.2	33.6	79.4	1	1	90.3
29	-34.7	-1.9	-12.0	-1	1	24.8	5.4	-149.0	1	1	96.3
30	-44.3	0.7	-90.2	1	1	5.1	5.2	9.8	1	1	68.3
31	-52.4	64.7	-73.5	-1	1	-6.7	-25.1	-58.1	1	1	90.1
32	-52.6	9.0	121.3	1	1	34.9	-14.4	118.2	-1	1	90.2



Optimizing Selection

- Two muons can be produced from
  - Z/γ
  - QCD
  - top-pair dacays
- Find ways to descriminate signal from background
  - charge
  - isolation
- Step 4: Select signal-like events and redo the histogram



Calculate Cross-Section and Mass

What do we need?

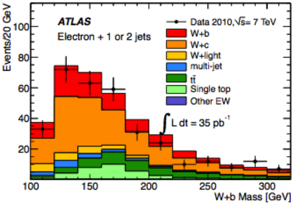
- Number of signal events N_S
- MC Prediction of background events $N_B = 0.0$
- MC Prediction of Detector Efficiency $\epsilon = 0.35$
- Data corresponds to $\mathcal{L} = 0.1 pb^{-1}$

Measure the mass

- Take mean-value of Histogram

Background Estimations

- The Z-Boson decay into leptons is a very clean process.
- Usually the process we are interested have much higher background rates



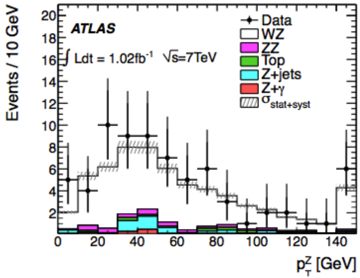
Problem

How to estimate the number of background events in your event selection?

Monte Carlo Prediction

Simplest Approach: Use Monte Carlo prediction of background

- Step 1: Calculate Matrix Elements (Event Generator)
- Step 2: Simulate Detector Response
- Step 3: Apply full event selection
- Step 4: Calculate Systematics
  - Theoretical uncertainty on ME
  - Uncertainties in detector simulation



Limitations of Monte Carlo Prediction

Limitations of MC Prediction

- Large theoretical uncertainties
- Large detector uncertainties
- Limited Monte Carlo Statistics

- Idea: Use data itself to estimate Background
- Large part of LHC data-analysis to find robust and precise ways to estimate background with data
- Guiding Principle
  - Use simulations to test your idea and evaluate systematics
  - Apply method to data

Data-Driven Background Estimation Method

- Side-Band method
- Matrix-Method
- ...

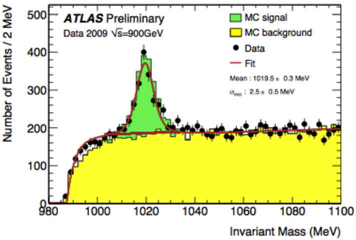
Side-Band Method

Assume that signal is localised in one observable

- Example: Invariant mass of two Kaons from a $\Phi(1020)$ decay

Procedure:

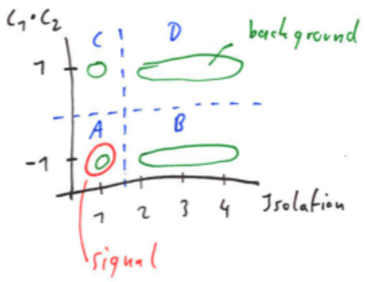
- Define function that describes background
- Fit function to the observed spectra in the regions without signal (=sidebands)
- Estimate background in signal region



Matrix Method

Assume that we have two, uncorrelated(!) observables, which separate signal and background

- Example: Di-muon final state
  - Signal ($Z \to \mu^+\mu^-$) and Background ($QCD \to \mu^+\mu^-$)
  - use charge and isolation



Matrix Method

- Define 4 regions (A,B,C,D)

$$\frac{N_A^{Bkg}}{N_B^{Bkg}} = \frac{N_C^{Bkg}}{N_D^{Bkg}}$$

$$N_A^{Bkg} = \frac{N_C^{Bkg}}{N_D^{Bkg}} \times N_B^{Bkg}$$

How do we know that our MC is good?

Problem: Detector Simulation is a tricky business

- millions of interactions
- lots of nuclear interactions (hard to calculate)
- very complex detectors
- alignment
- ...

Idea:

- Let's use data again to understand our detector
- Calibrate our detector simulation
  - Energy/Momentum Calibration

Energy/Momentum Calibration

Energy/Momentum Resolution

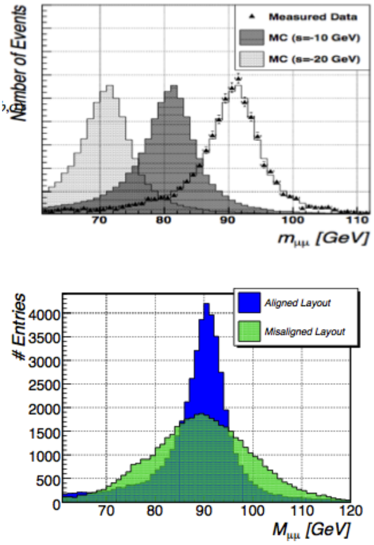
$$p_T^{Reco} = gaus(s \times p_T^{Truth}, \sigma)$$

The truth momentum gets smeared with a gaussian function with center ($s \times p_T^{Truth}$) and width σ

- s = momentum scale
- σ = momentum resolution

How to determine s and σ?

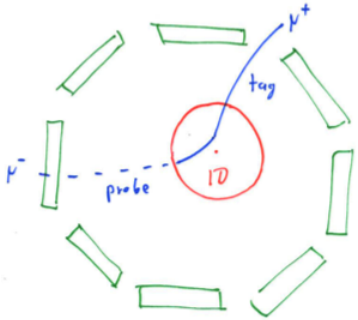
- Use references process
- e.g. Z-Boson mass is extremely well known
  - Compare measurement with prediction → determine s and σ



Efficiency Calibration

Two kind of 'efficiencies':

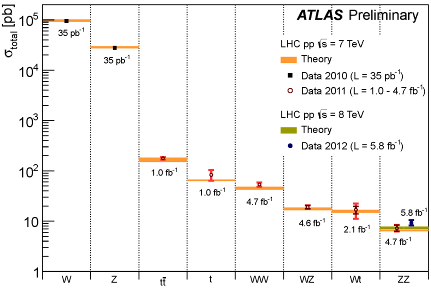
- efficiency that particle is in the geometrical acceptance of the detector
  - called detector acceptance
  - taken from MC simulations
- efficiency that a particle gets reconstructed by the detector
  - how to proof if detector simulation is correct?



Tag&Probe (for e.g. $Z \to \mu\mu$)

- Use redundancy of detector
- muons get reconstucted in ID and MS

Recent LHC Results

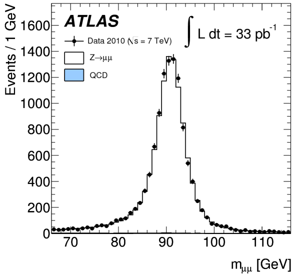


Many of cross-sections have been already measured at the LHC and compared with the SM-prediction. So far we observe a very nice agreement between prediction and measurement

Z-Boson Production Cross-Section

Signal Selection

- Two opposite charged, same flavor leptons
- $p_T 20 GeV$
- isolated
- $60 GeV < m_{ll} < 120 GeV$

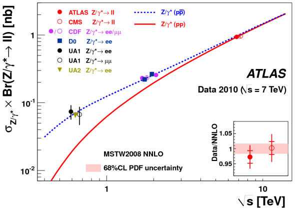


Backgrounds

- some QCD
- some Top

Results (stat+sys+lumi)

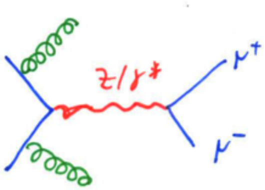
- $\sigma_{meas.} = 937 \pm 6 \pm 18 \pm 32$ pb
- $\sigma_{theo.} = 964 \pm 18$ pb



Differential Z-Boson p_T Cross-Section

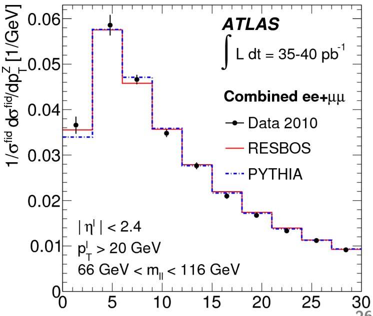
We can also measure differential cross-section vs. observables

- Example: Cross-sections for different bins of p_T^Z



Transverse momentum of the Z-Boson

- not possible at Born-level (lowest order)
- induced by Initial State Radiation (ISR)
  - Important test of perturbative (and even non-perturbative) QCD Calculations



Top-Quark Production Cross-Section

Signal Selection: semi-leptonic decay

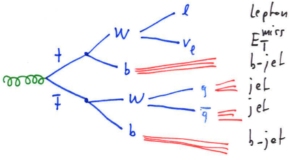
- 1 isolated lepton, p_T20GeV
- 3 reconstructed jets, E_T20GeV
- 1 b-tagged jet
- E_T^{Miss}40 GeV

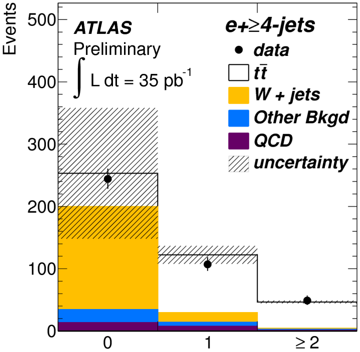
Backgrounds

- some QCD
- some Top

Results (stat+sys+lumi)

- $\sigma_{meas.} = 176 \pm 5 \pm 14 \pm 8$ pb
- $\sigma_{theo.} = 165 \pm 15$ pb

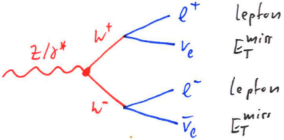




WW-Boson Production Cross-Section

Signal Selection: leptonic decay

- 2 isolated leptons: p_T20GeV
- E_T^{Miss}25, 40 GeV
- Z-Boson veto
- no jets with E_T20GeV

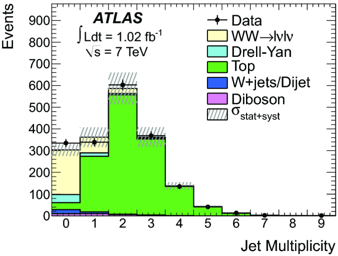


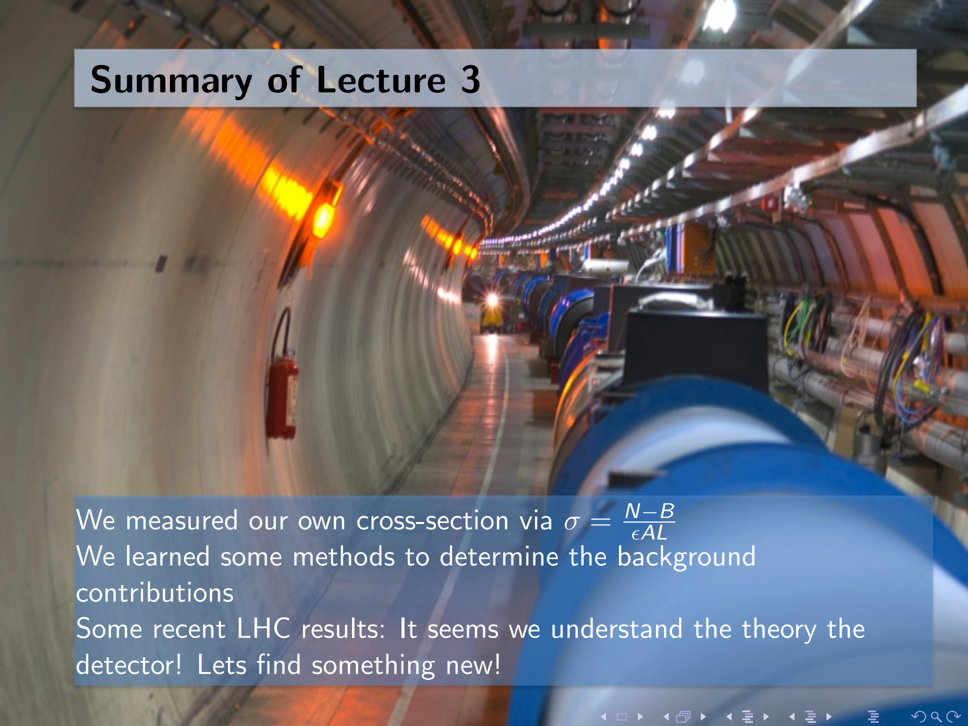
Backgrounds

- Top-Pairs
- Z/γ^*

Results (stat+sys+lumi)

- $\sigma_{meas.} = 48 \pm 4 \pm 6 \pm 2$ pb
- $\sigma_{theo.} = 46 \pm 3$ pb





Summary of Lecture 3

We measured our own cross-section via $\sigma = \frac{N-B}{\epsilon A L}$

We learned some methods to determine the background contributions

Some recent LHC results: It seems we understand the theory the detector! Lets find something new!