Introduction to particle physics: experimental part

- **RAW data to Physics**
  - **The road from collisions to physics publications**

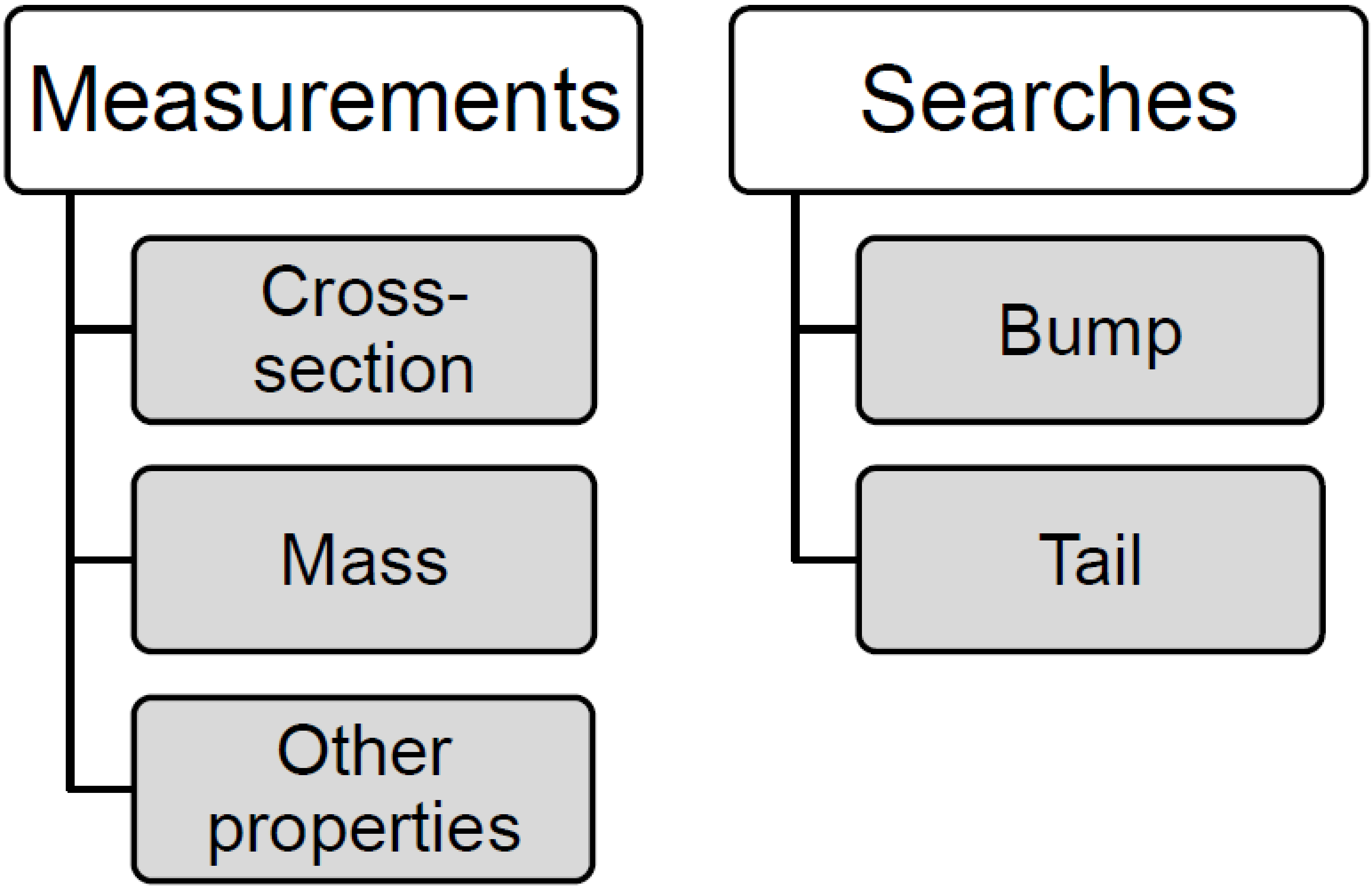
- **From RAW data to Standard Model particles**
  - **About measuring properties of the final particles created from proton-proton collisions**

- **From Standard Model particles to measurements and searches**
  - **About how we analys data using ingredients we have constructed**

Large fraction of slides from A. Sfyrla lectures at CERN Summer School 2018

Prof. dr hab. Elżbieta Richter-Wąs

Physics analyses



Physcis analyses

Measurements

- Allow important tests of the consistency of the theory.
- Typically limited by systematic uncertainties.

Searches

- … For new particles.
- If no signal, set limits on some model.
- If signal, a potential discovery!
- More data typically improve a search.

Physics analyses

Measurements

- Allow important tests of the consistency of the theory.
- Typically limited by systematic uncertainties.

Searches

- … discovery!
- More data typically improve a search.

> "Systematic" uncertainties are introduced by inaccuracies in the methods used to perform the measurement.

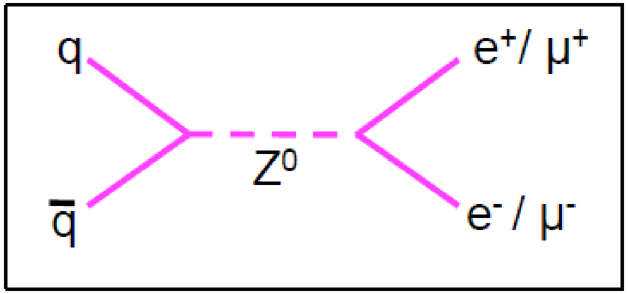
Physics analyses

SIMPLE EXAMPLE:

MEASURING Z^0 CROSS-SECTION AT LHC

Measuring Z^0 cross-section at LHC

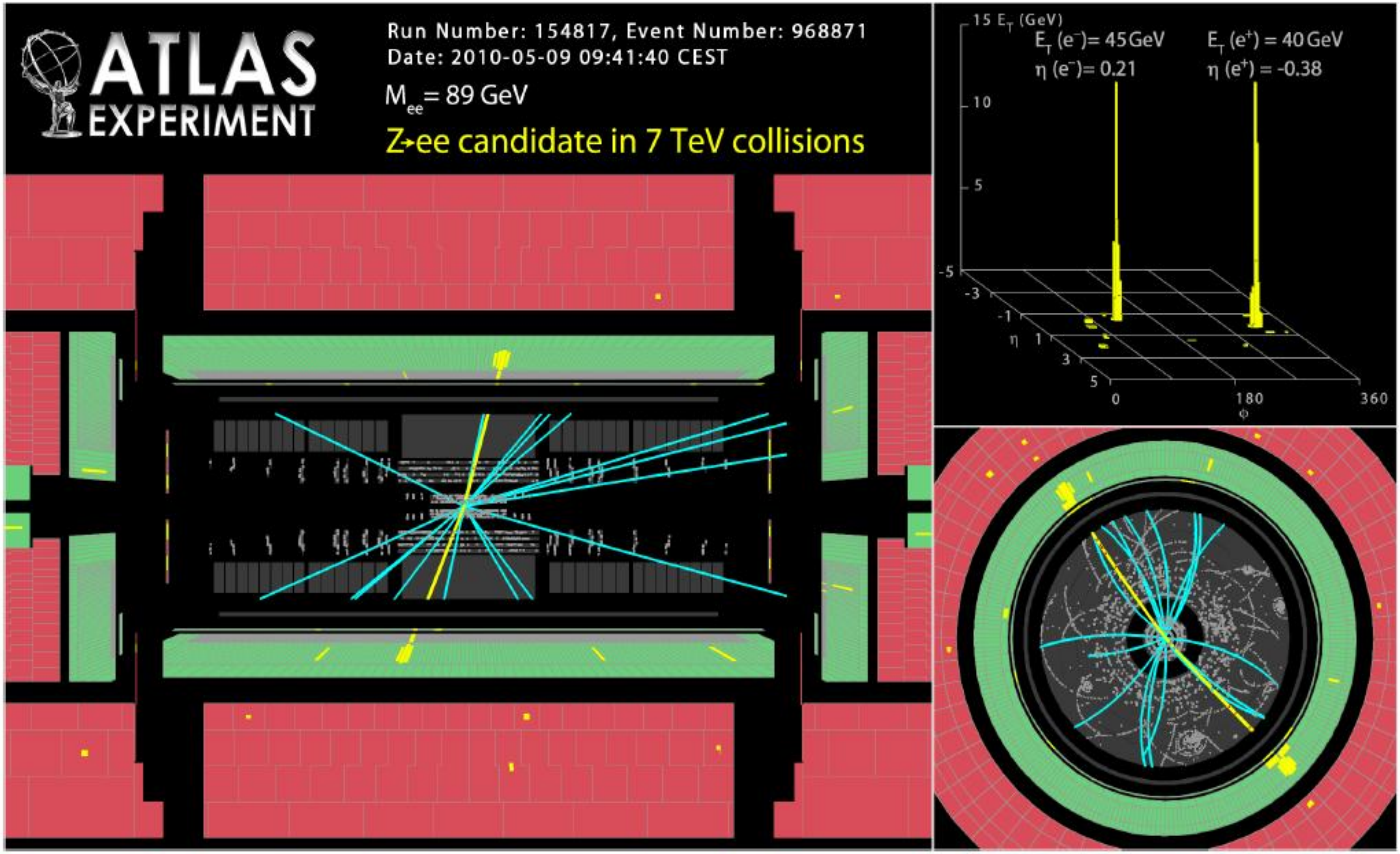
- **Z^0 boson decays to lepton or quark pairs**
  - We can reconstruct it in the e^+e^- or $\mu^+\mu^-$ decay modes



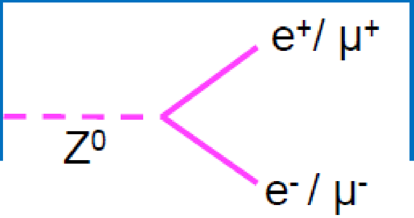
- Discovery and study of the Z^0 boson was a critical part understanding the electroweak force.

- And now, at the LHC?
  - **Important test of theory**: does the measurement agree with the theoretical prediction at LHC collision energy?
  - **A standard candle** for studying reconstruction and deriving calibrations.
  - Can be used for luminosity determination!

Physics analyses



Reconstructing Z^0's



How do we know it's a Z^0?

Identify Z decays using the invariant mass of the 2 leptons
$M^2 = (L_1+L_2)^2$ where $L_i = (E_i,\mathbf{p}_i)$ = 4-vector for lepton i

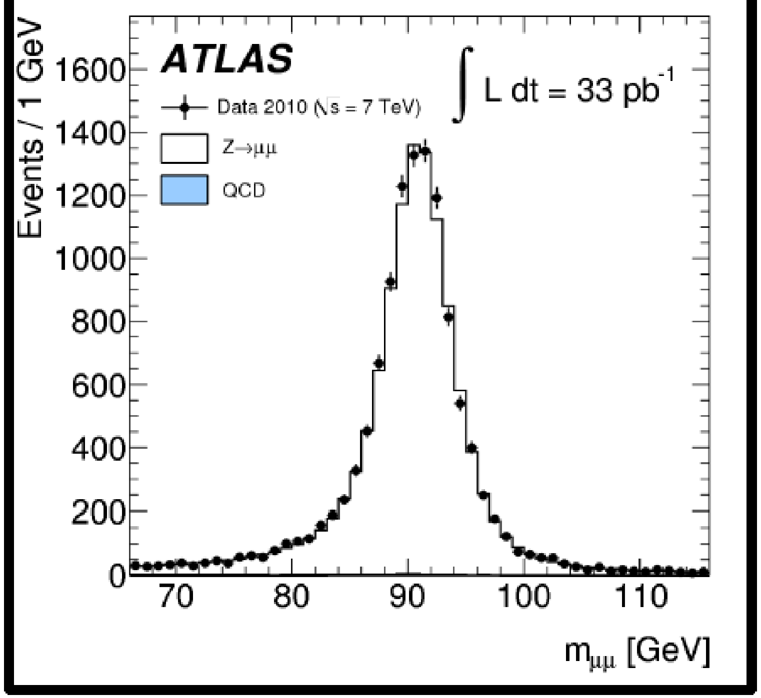
Under assumption that lepton is massless compared to mass of Z^0
=> $M^2 = 2\,E_1\,E_2\,(1-\cos\vartheta_{12})$ where ϑ_{12}= angle between the leptons

- So need to reconstruct the electron and muon energy and direction. Then can calculate the mass.

Select Z^0 events with 'analysis cuts':

- Events with 2 high momentum electrons or muons
- Require the electrons or muons are of opposite charge
- With di-lepton mass close to the Z^0 mass (e.g. $70<m_{l+l-}<110$ GeV)

Very little background in Z^0 mass region!



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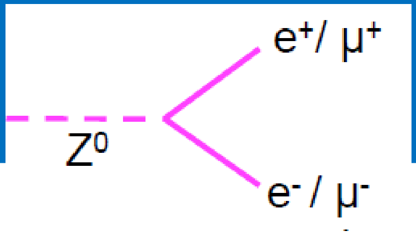

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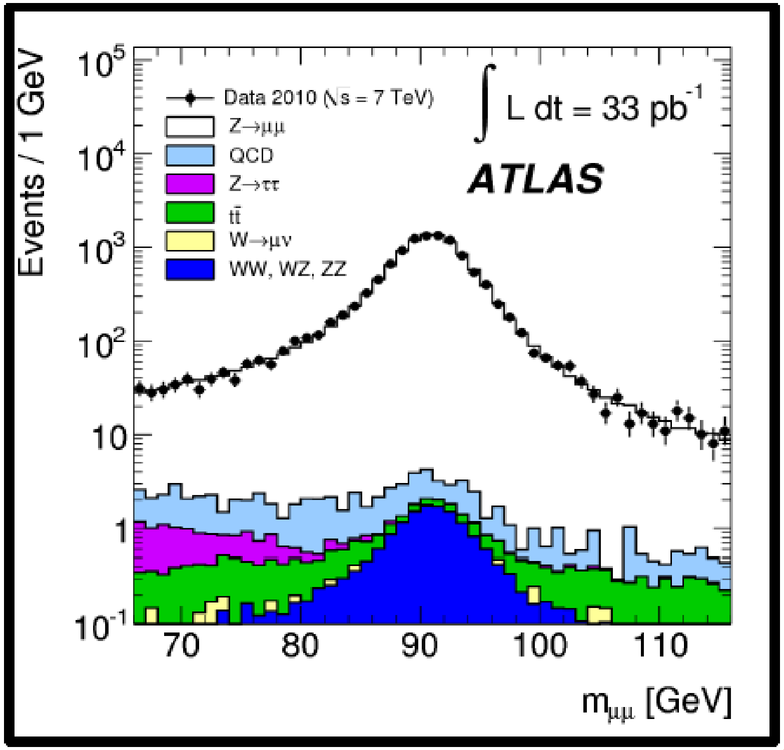
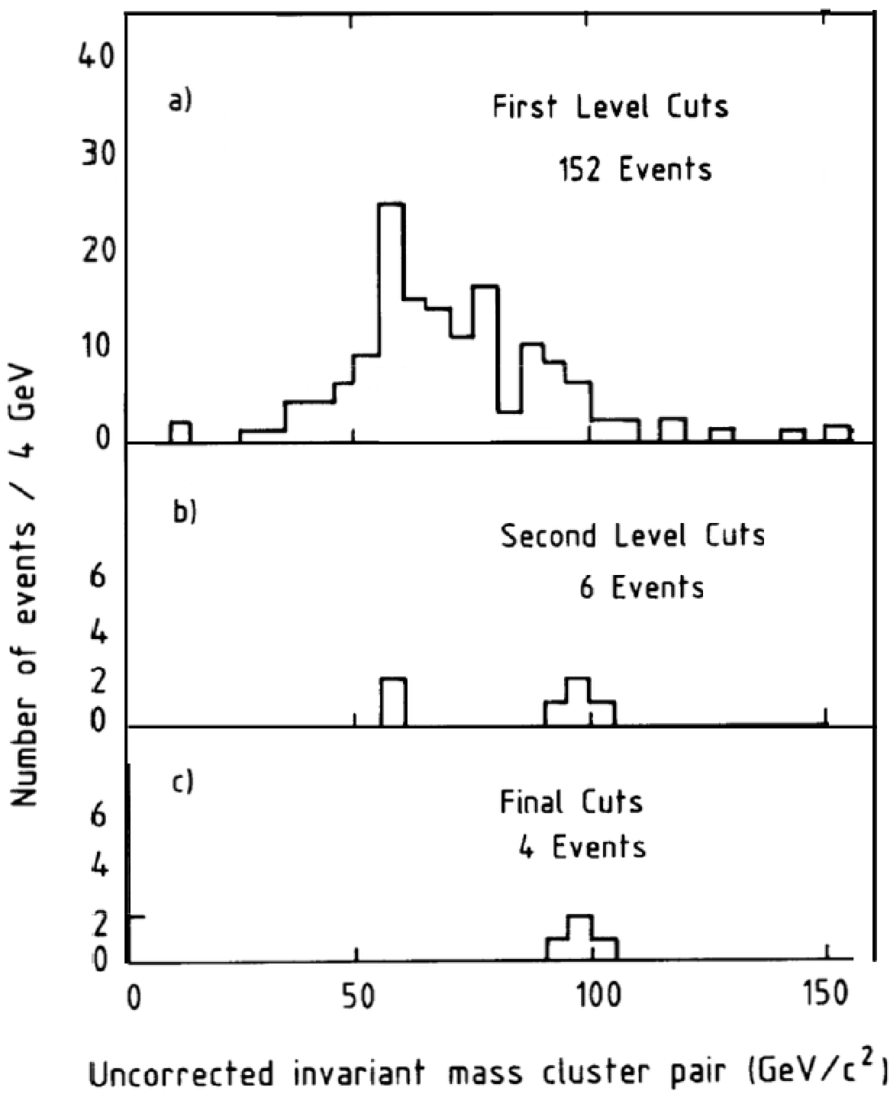


A step back in time …



Z->ee in UA1

Two EM clusters with E_T>25GeV.

As above plus a track with p_T>7GeV pointing to the cluster. Hadronic and track isolation requirements applied.

A second custer has also an isolated track.

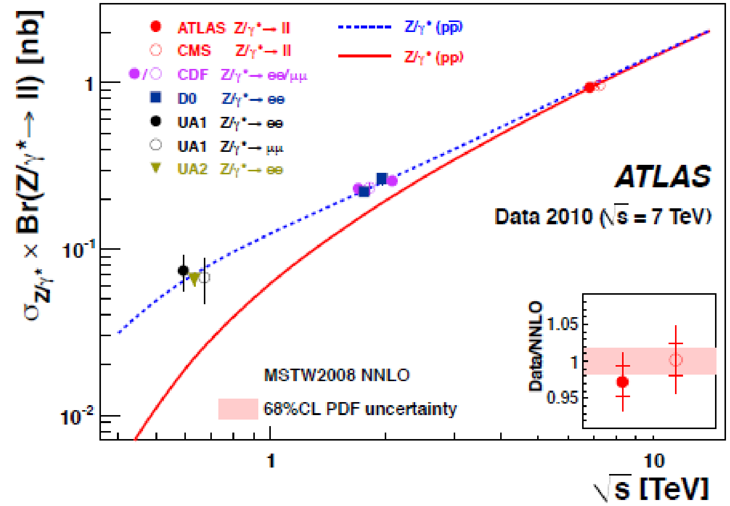
http://www.nobelprize.org/nobel_prizes/physics/laureates/1984/rubbia-lecture.pdf 20

Measuring the Z^0 cross-section

Theoretically

Cross-section calculated for:

- Specific production mechanism (pp, $p\bar{p}$, e^+e^-)
- Centre-of-Mass of the collisions (7, 8, 13 TeV at LHC)



Experimentally

$$\sigma \cdot \mathrm{BR} = \frac{\mathrm{Number\ of\ events}}{\alpha \cdot \epsilon \cdot \mathrm{L}}$$

N of events:

N of events on data – N of expected background events

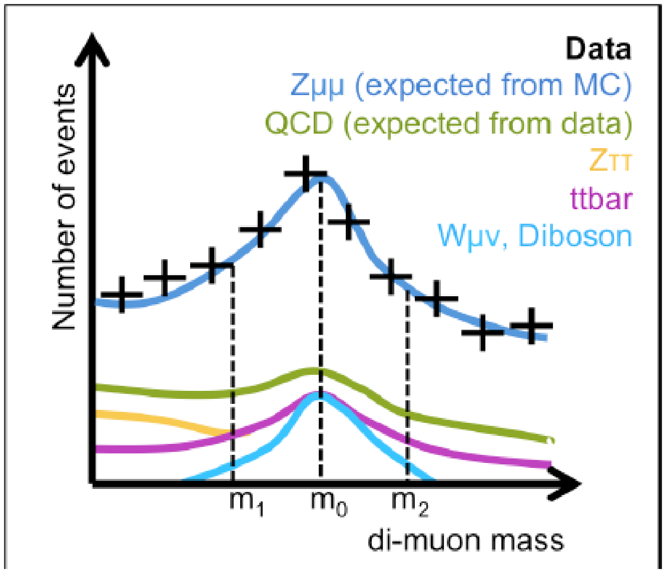
α – acceptance:

fraction of events passing selection requirements

ε – efficiency:

reconstruction efficiency of relevant objects

L – luminosity



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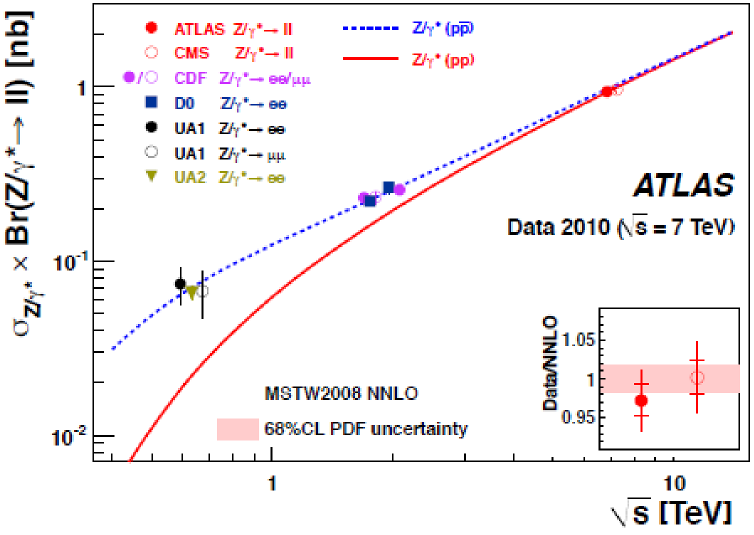


Experimentally

$$\sigma \cdot \mathrm{BR} = \frac{\text{Number of events}}{\alpha \cdot \epsilon \cdot \mathrm{L}}$$

N of events:

N of events on data – N

α – acceptance:

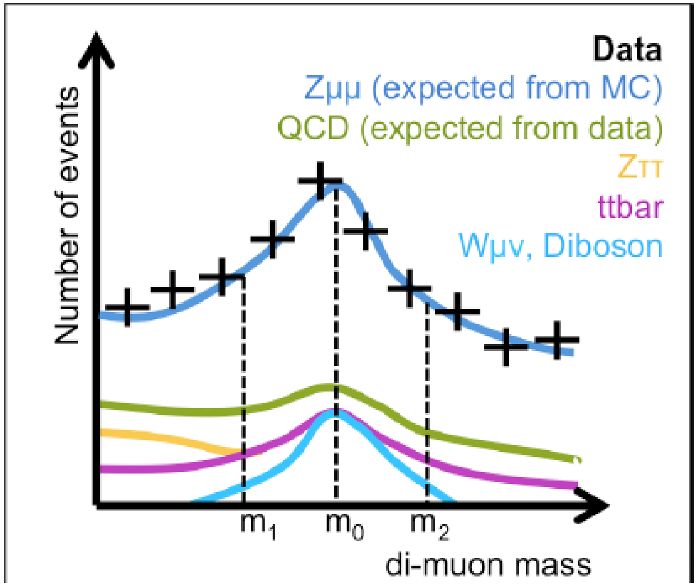
fraction of events passi

ϵ – efficiency:

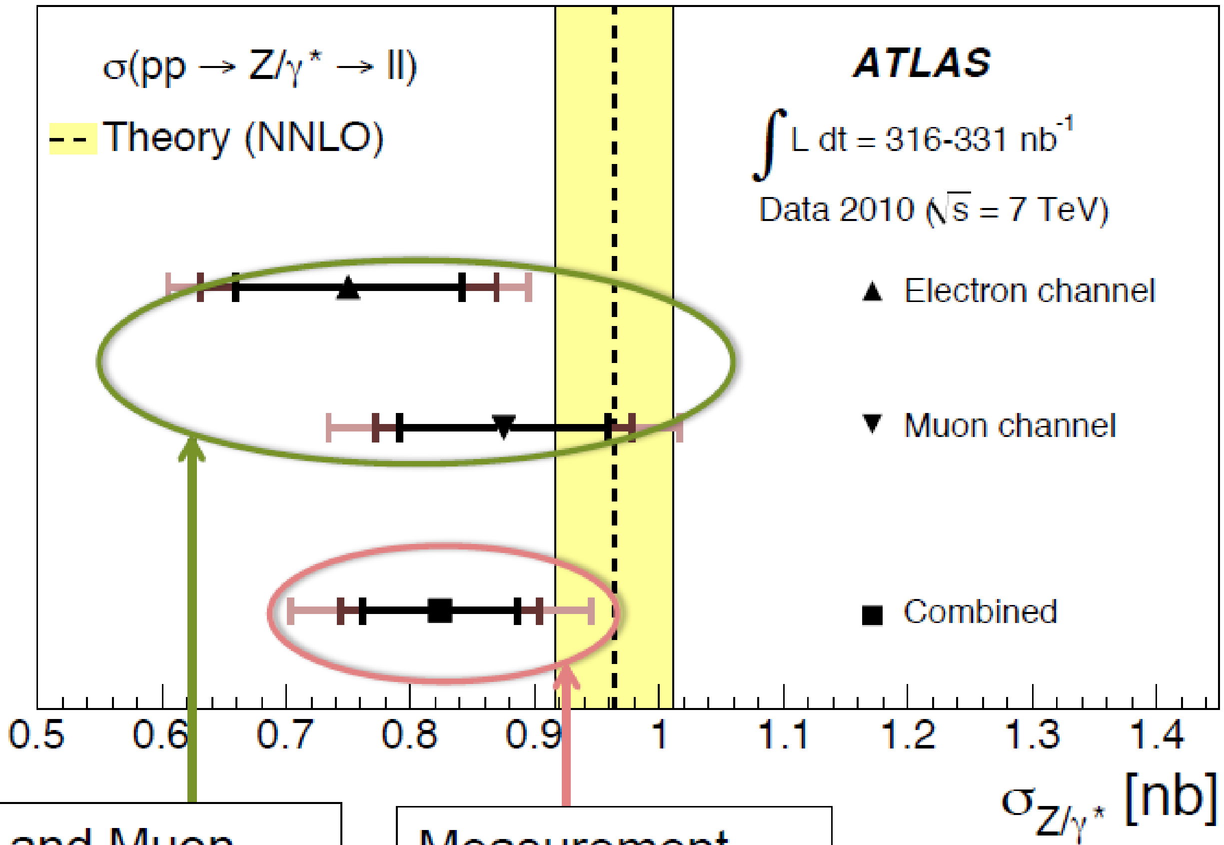
reconstruction efficienc

L – luminosity

All numbers carry uncertainties – both "statistical" and "systematic"!



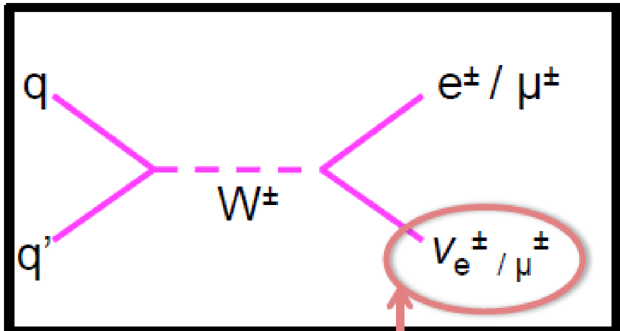
Measuring the Z^0 cross-section



Electron and Muon channel agree within uncertainties

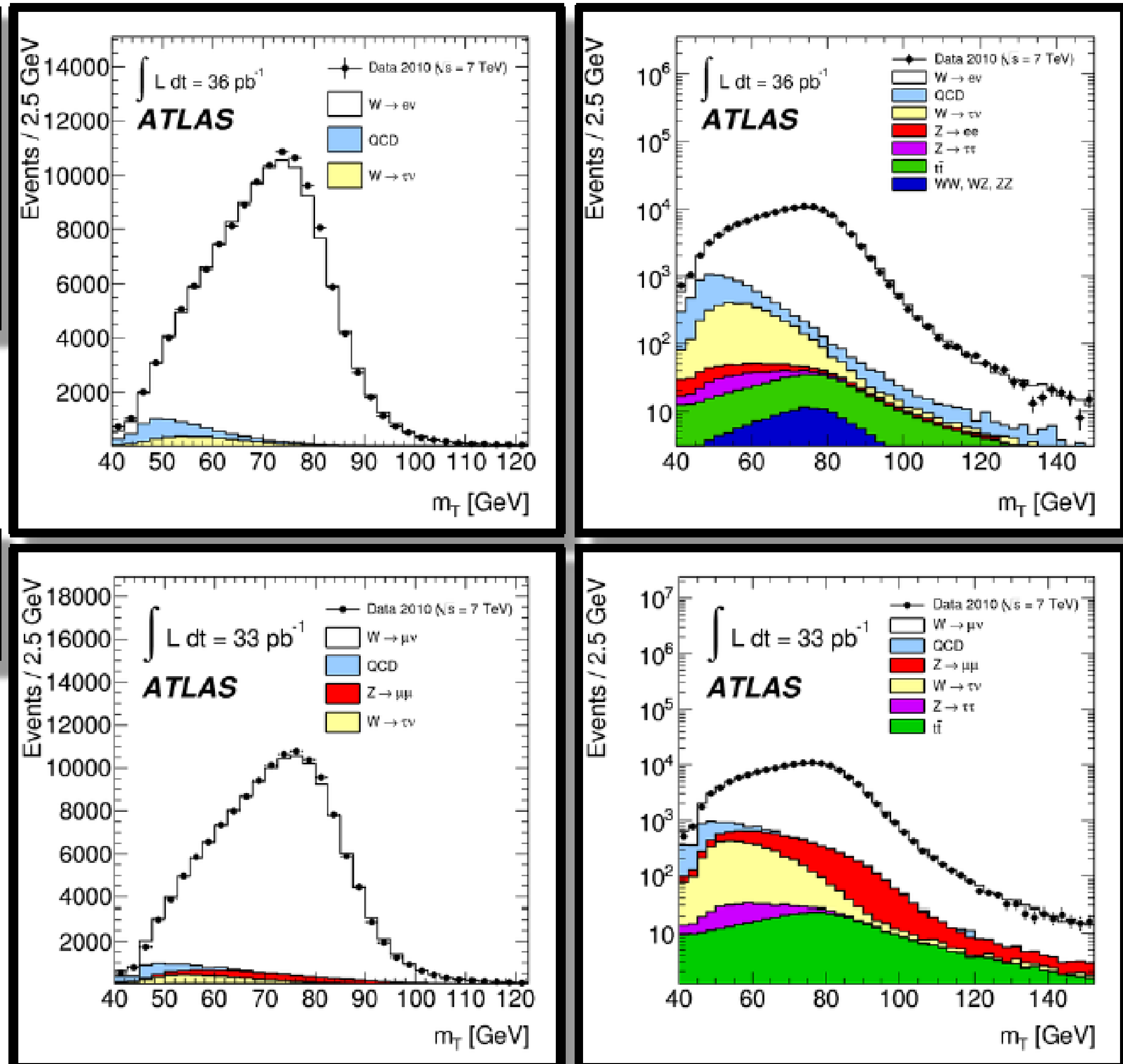
Measurement consistent with prediction within uncertainties

Measuring the W cross-section

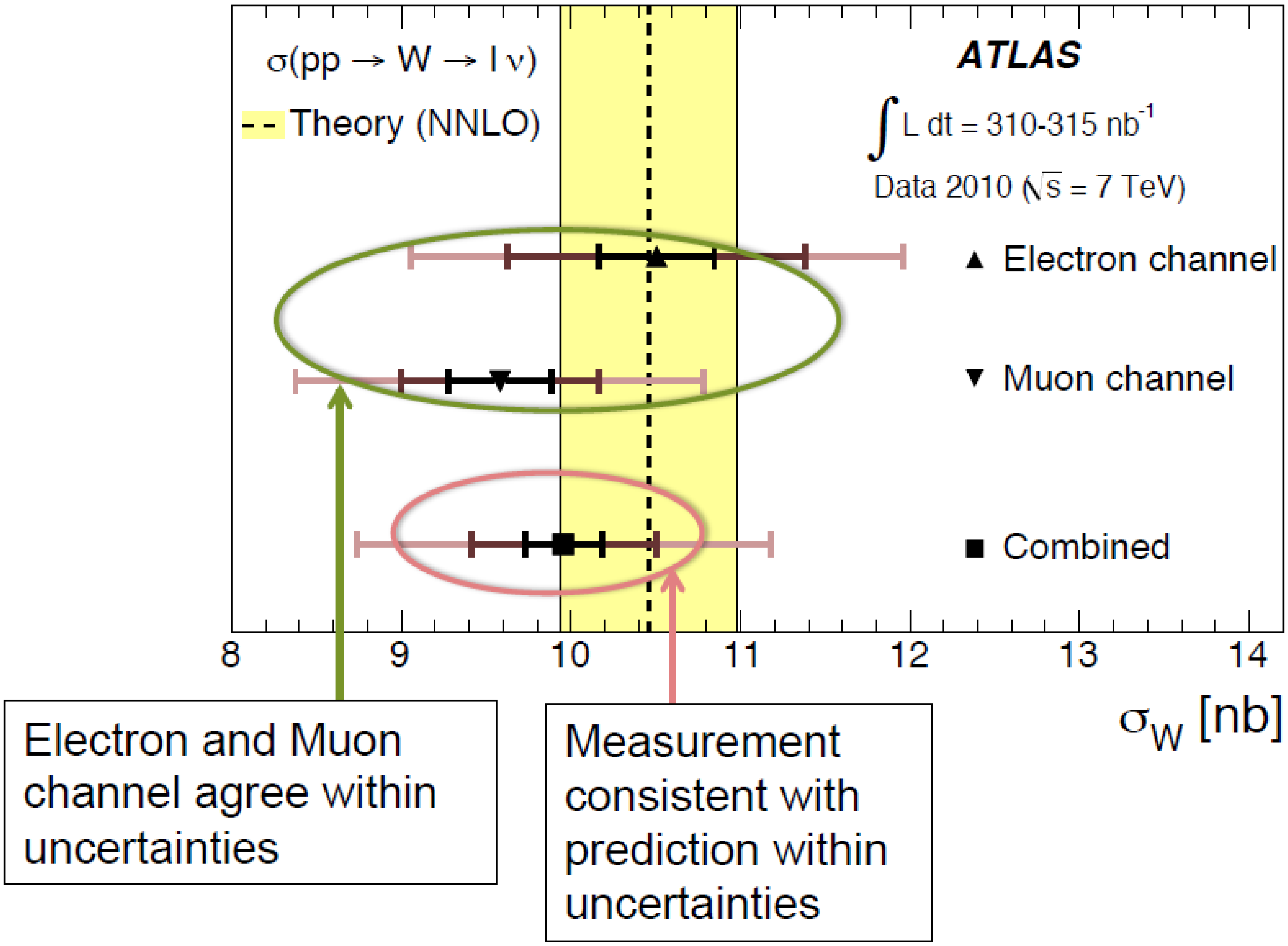


Available in the transverse plane only!

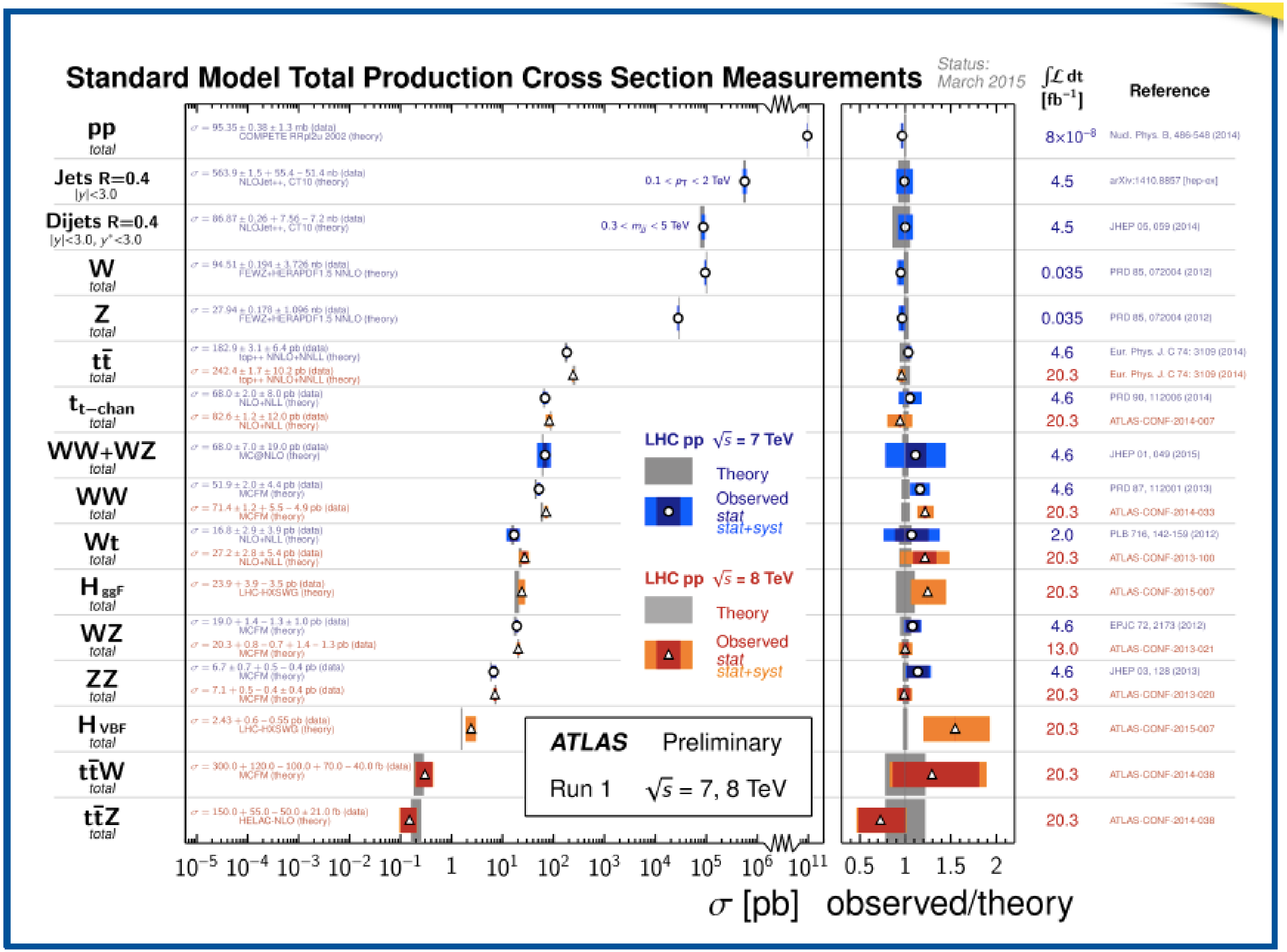
$$M_T^2 = 2\, E_{T1}\, E_{T2}\, (1-\cos\vartheta_{12})$$



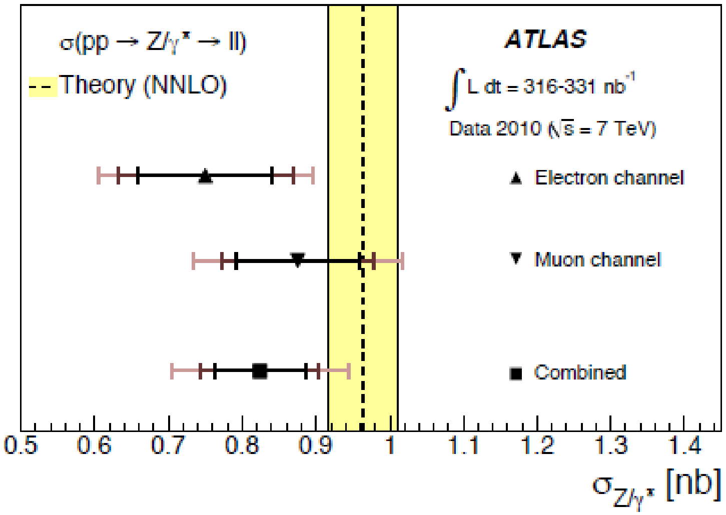
Measuring the W cross-section

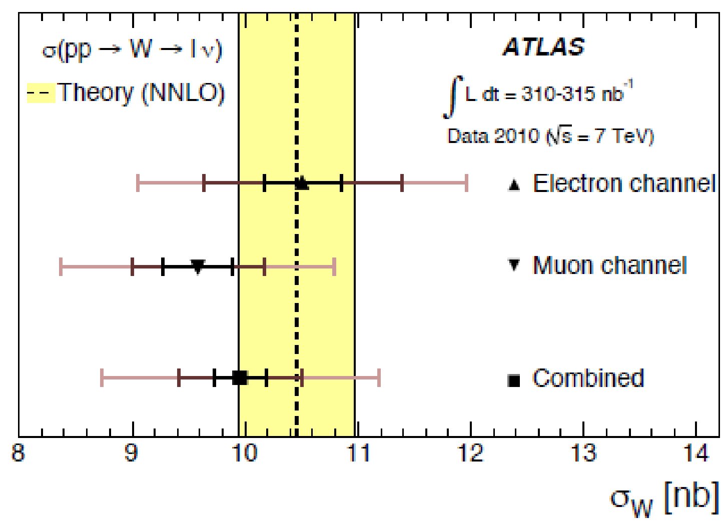


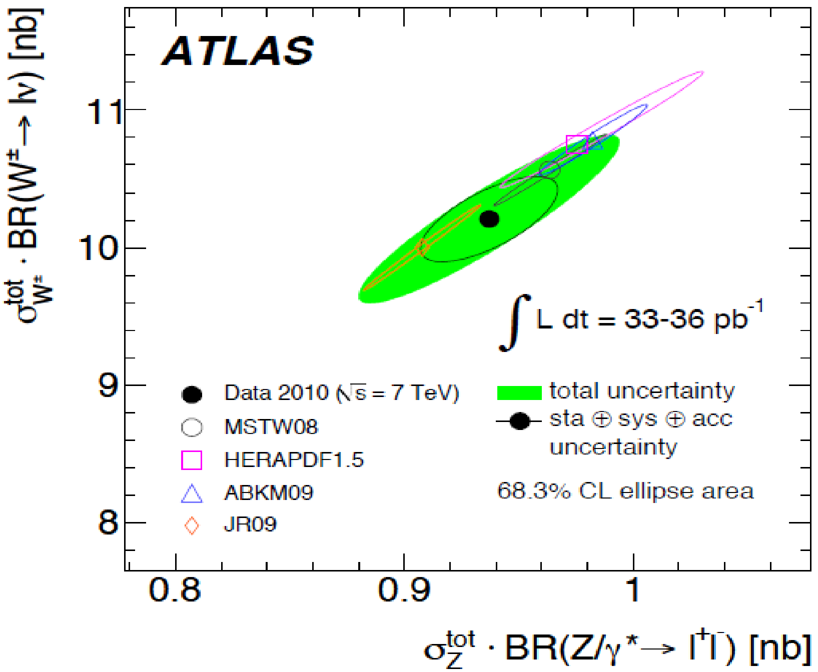
„Final” calibration

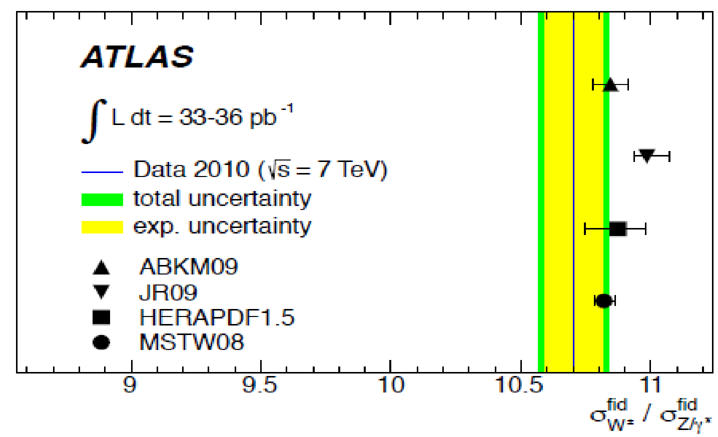


Measuring cross-sections ratio

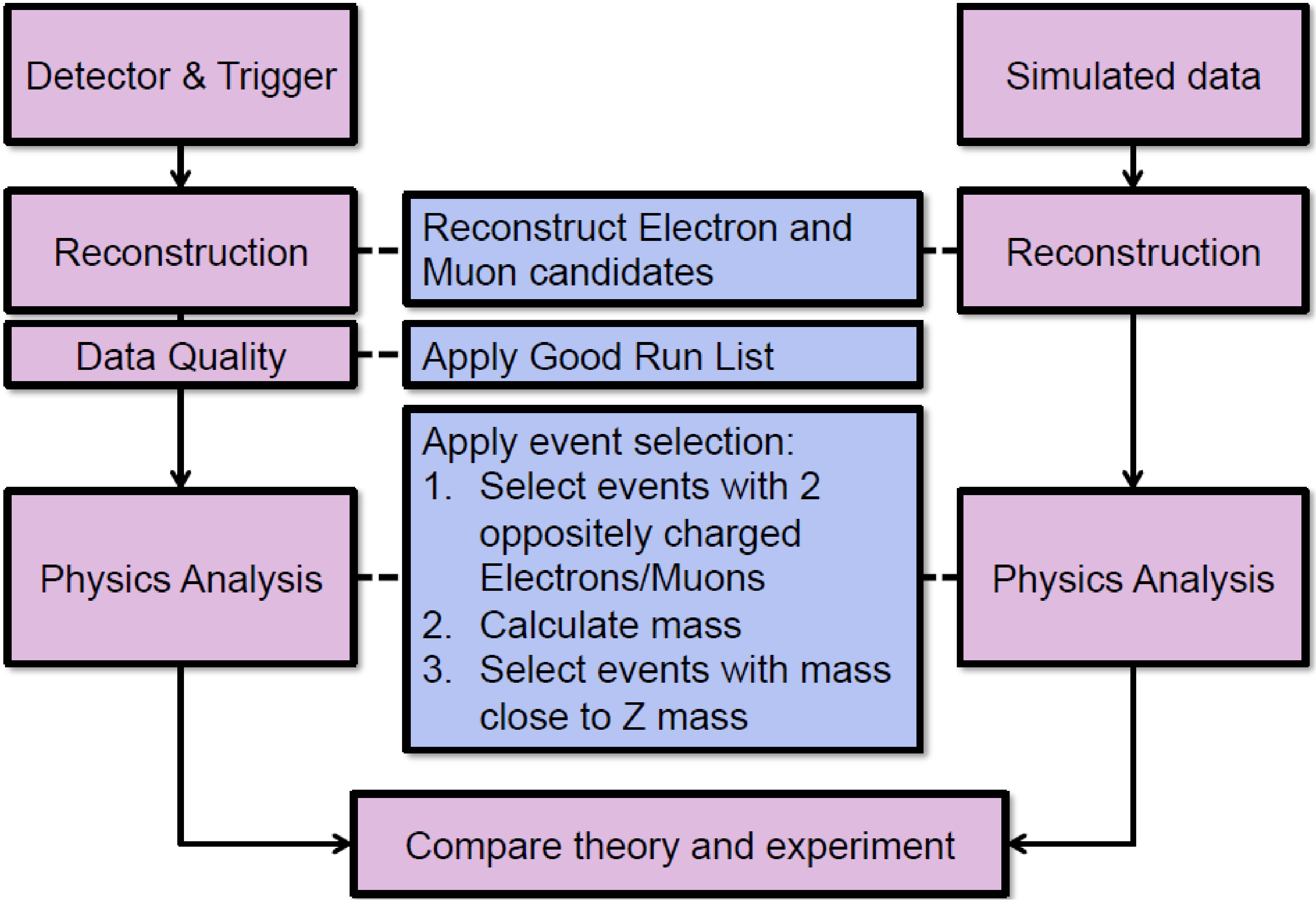




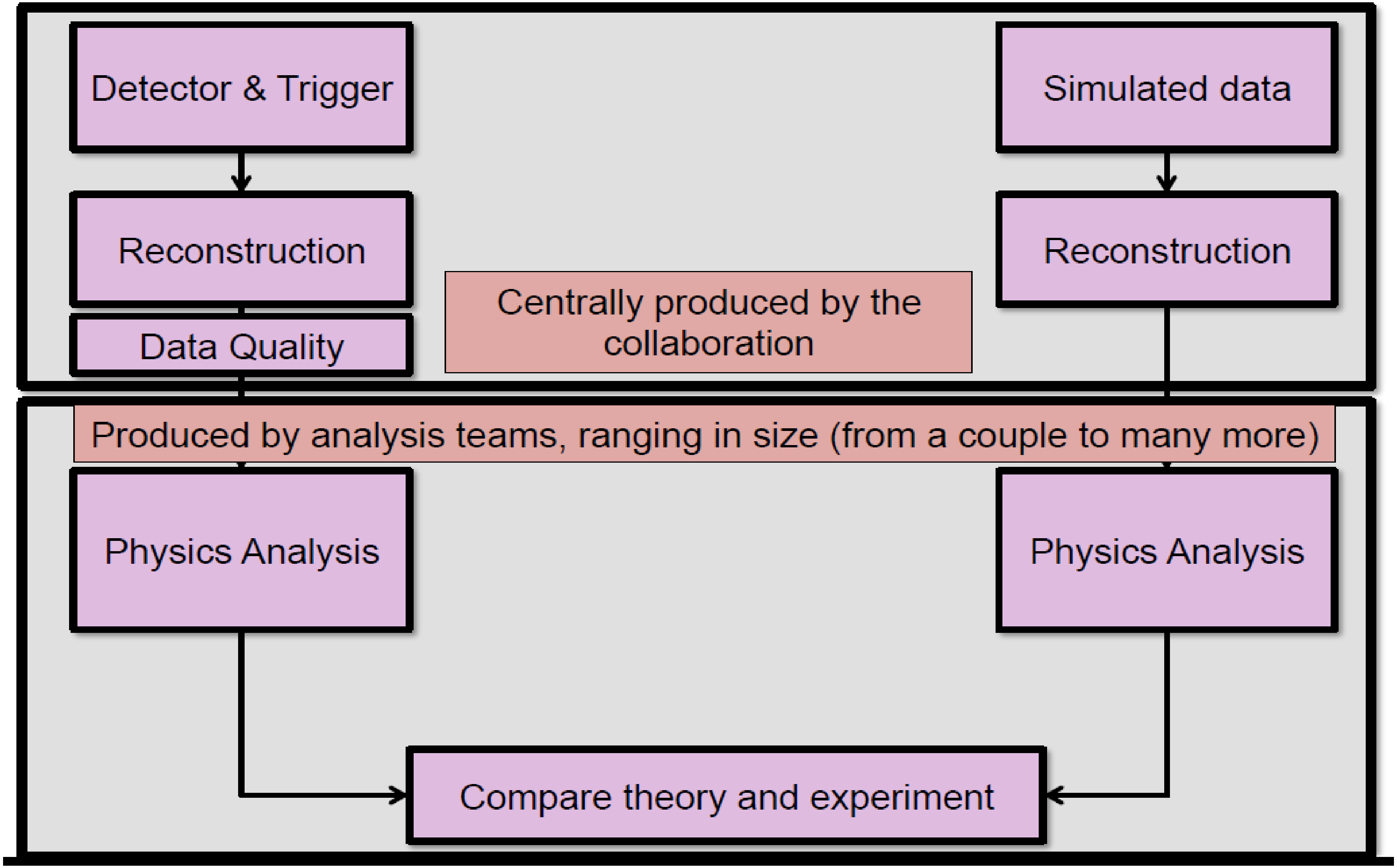


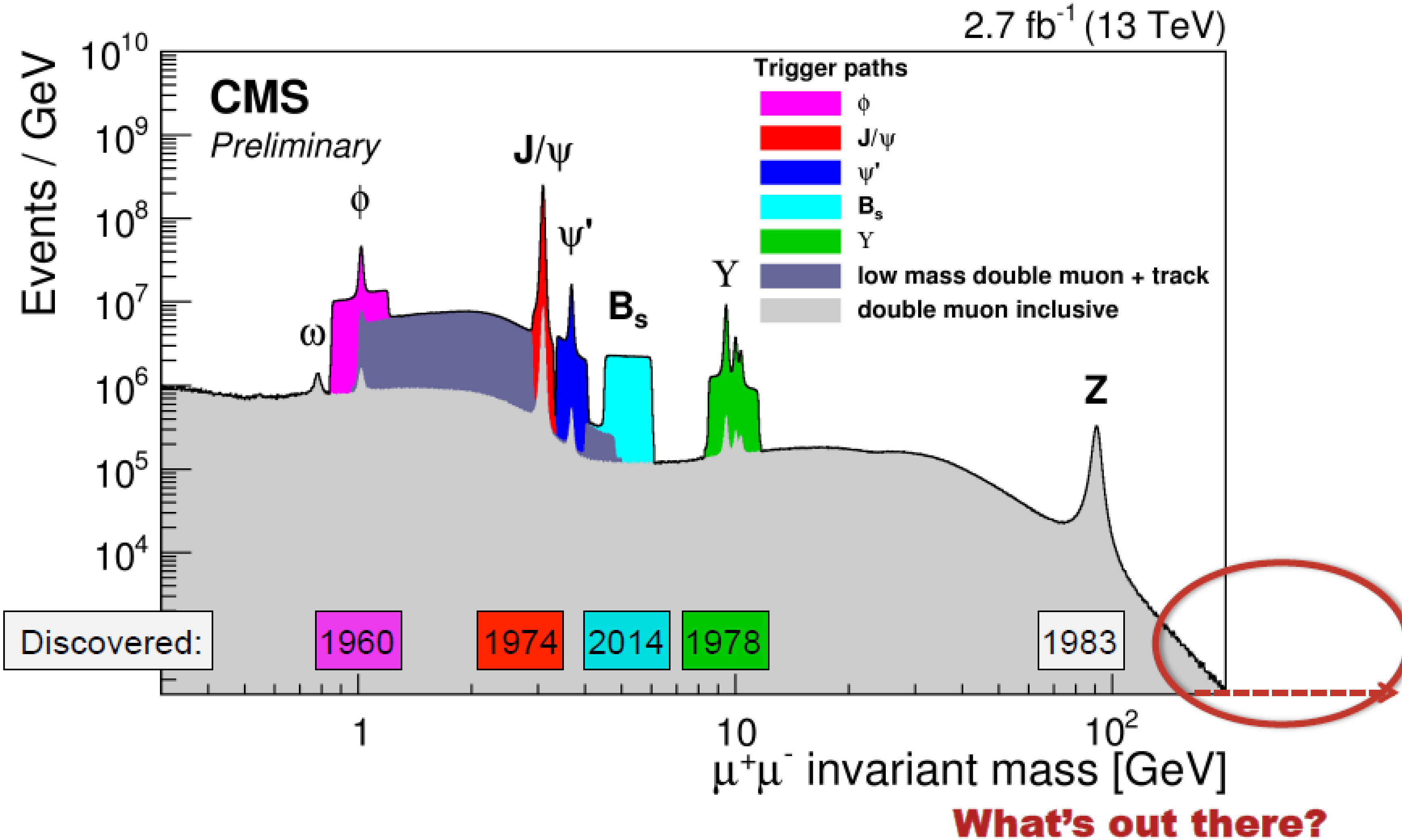


Analysis flow in Z^0 cross-section measurement



Analysis flow in Z^0 cross-section measurement




2.7 fb-1 (13 TeV)
CMS
Preliminary
Events / GeV
Trigger paths
ϕ
J/ψ
ψ'
Bs
Υ
low mass double muon + track
double muon inclusive
ω
Z
Discovered:
1960
1974
2014
1978
1983
μ+μ- invariant mass [GeV]
What's out there?

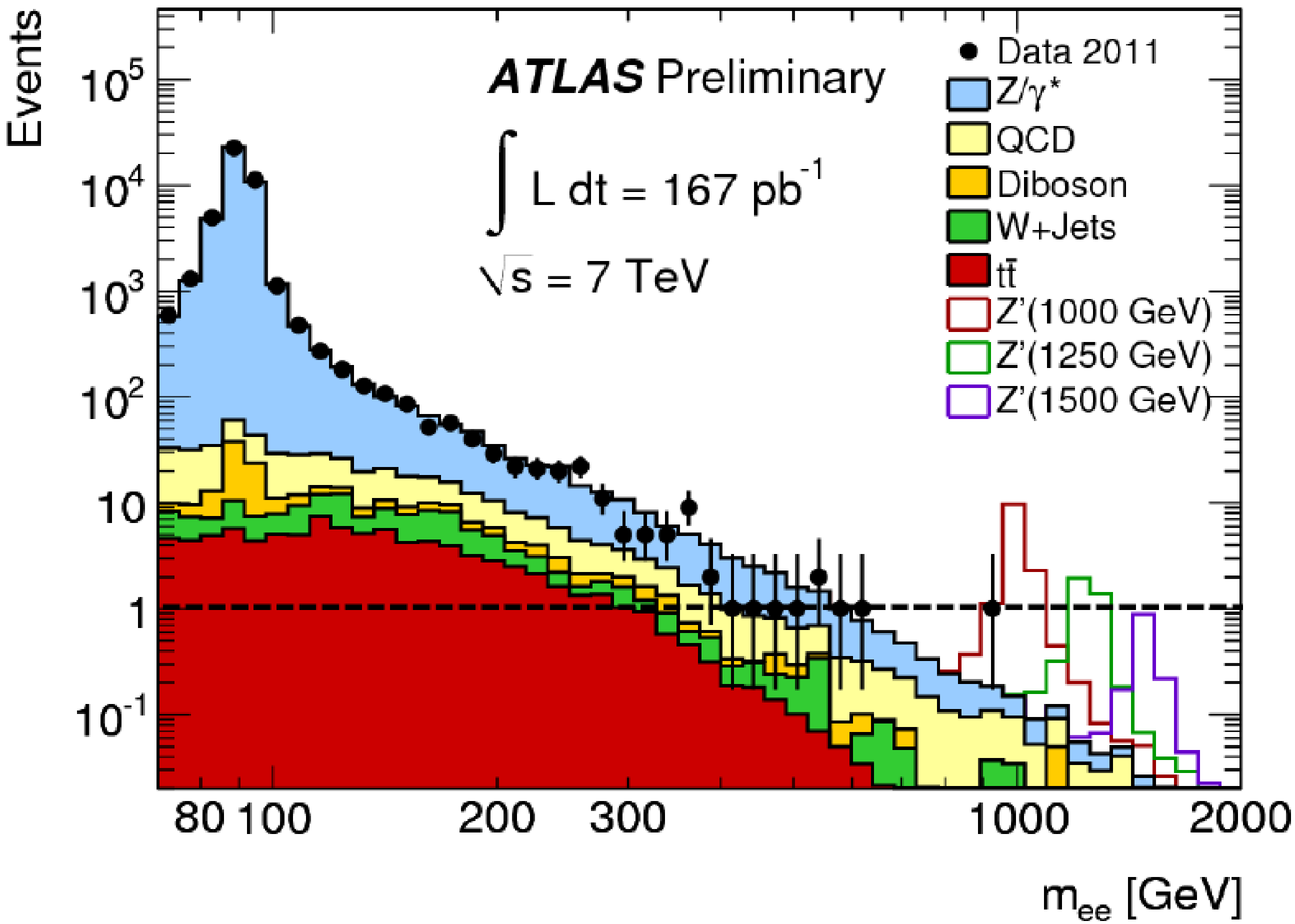
Simple search example

SIMPLE SEARCH EXAMPLE:

SEARCH FOR A HEAVY Z'

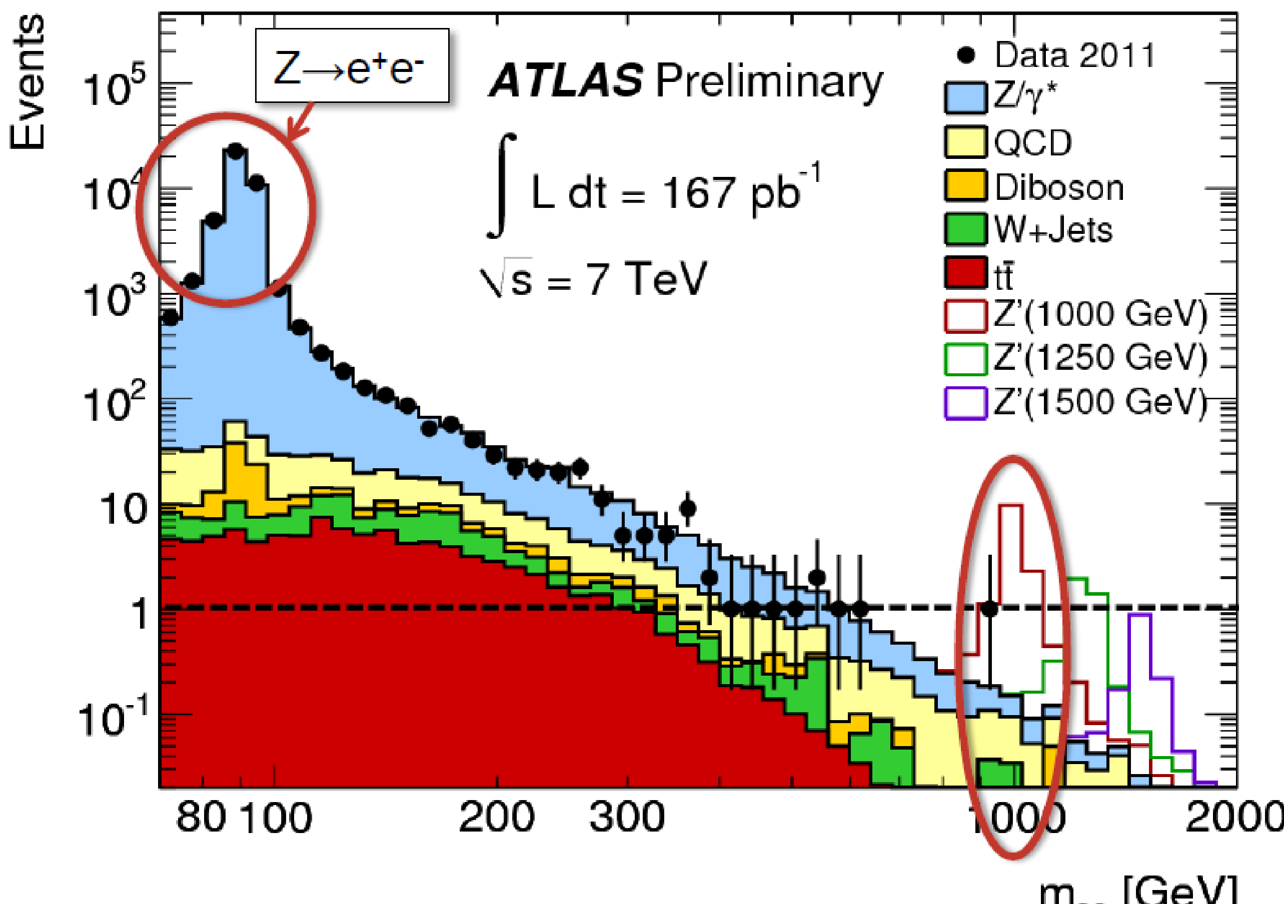
Search for a new heavy Z'

- Like Z->ee but at higher mass.



Search for a new heavy Z'

◎ **Like Z->ee but at higher mass.**



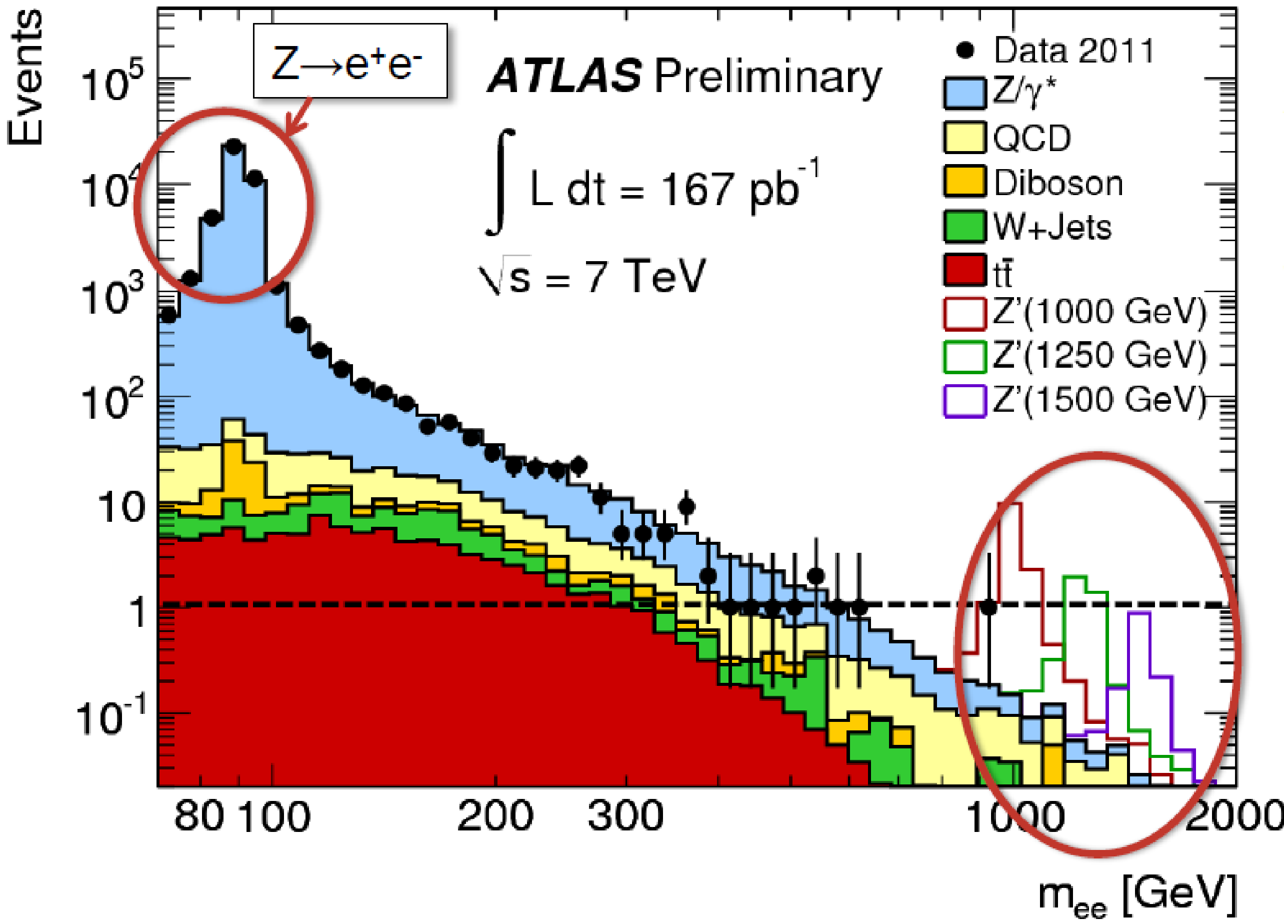
Select 2 electron candidates and plot their invariant mass for:

1. **Data**
2. **Simulated background events**
3. **Simulated signal with different masses**

Data inconsistent with a 1TeV Z'

Search for a new heavy Z'

◎ **Like Z->ee but at higher mass.**



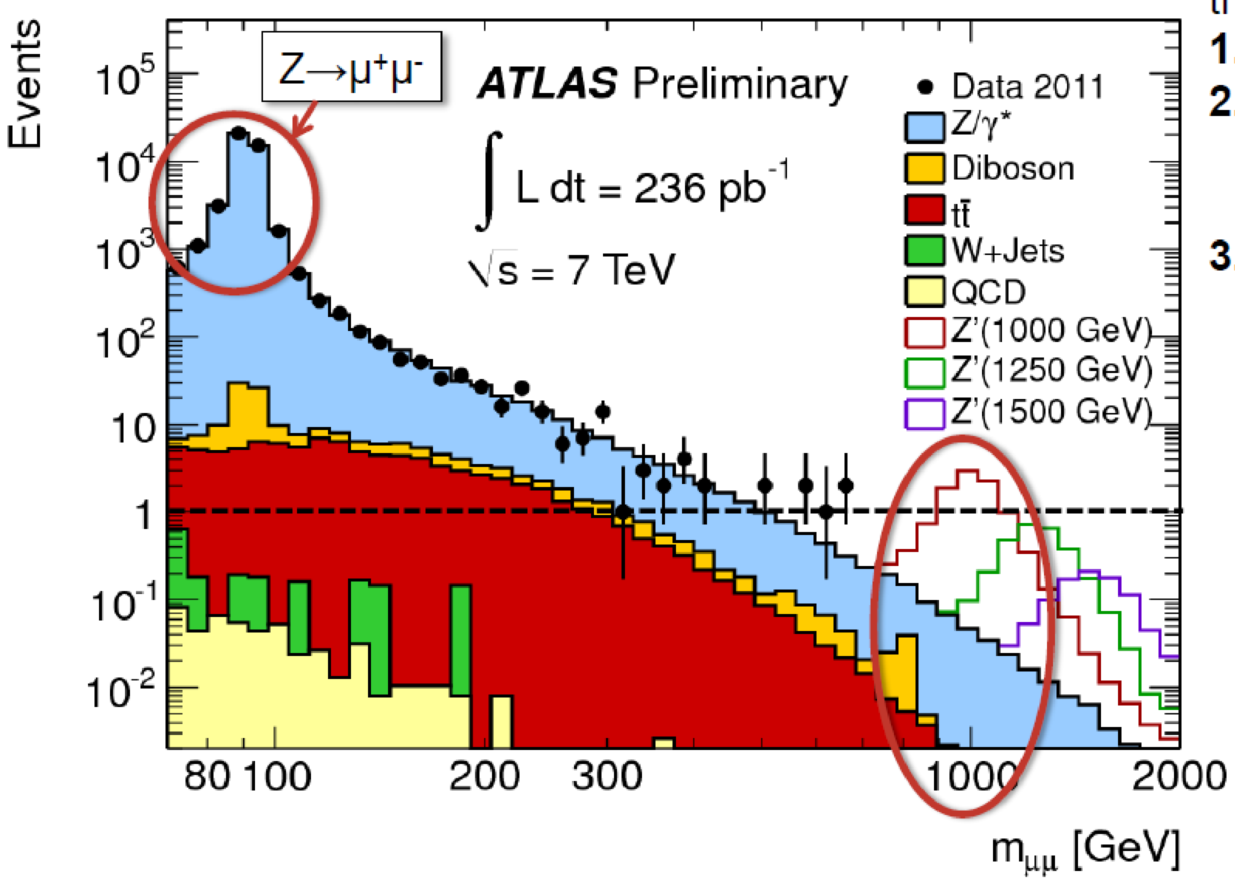
Select 2 electron candidates and plot their invariant mass for:

1. **Data**
2. **Simulated background events**
3. **Simulated signal with different masses**

Cross-section decreases with mass (higher the mass of the Z', the more data needed to discover it)

Search for a new heavy Z'

⊚ **And similar for muons**

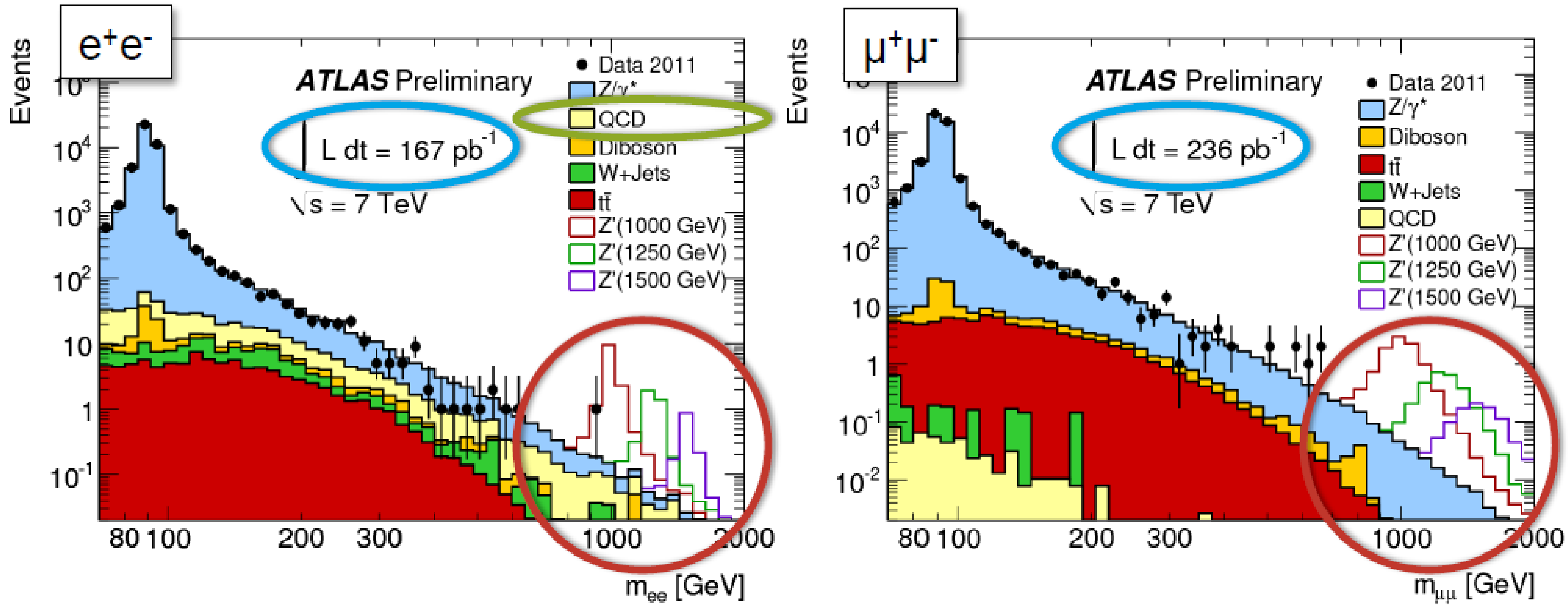


Select 2 muon candidates and plot their invariant mass for:

1. **Data**
2. **Simulated background events**
3. **Simulated signal with different masses**

Data inconsistent with a 1TeV Z'

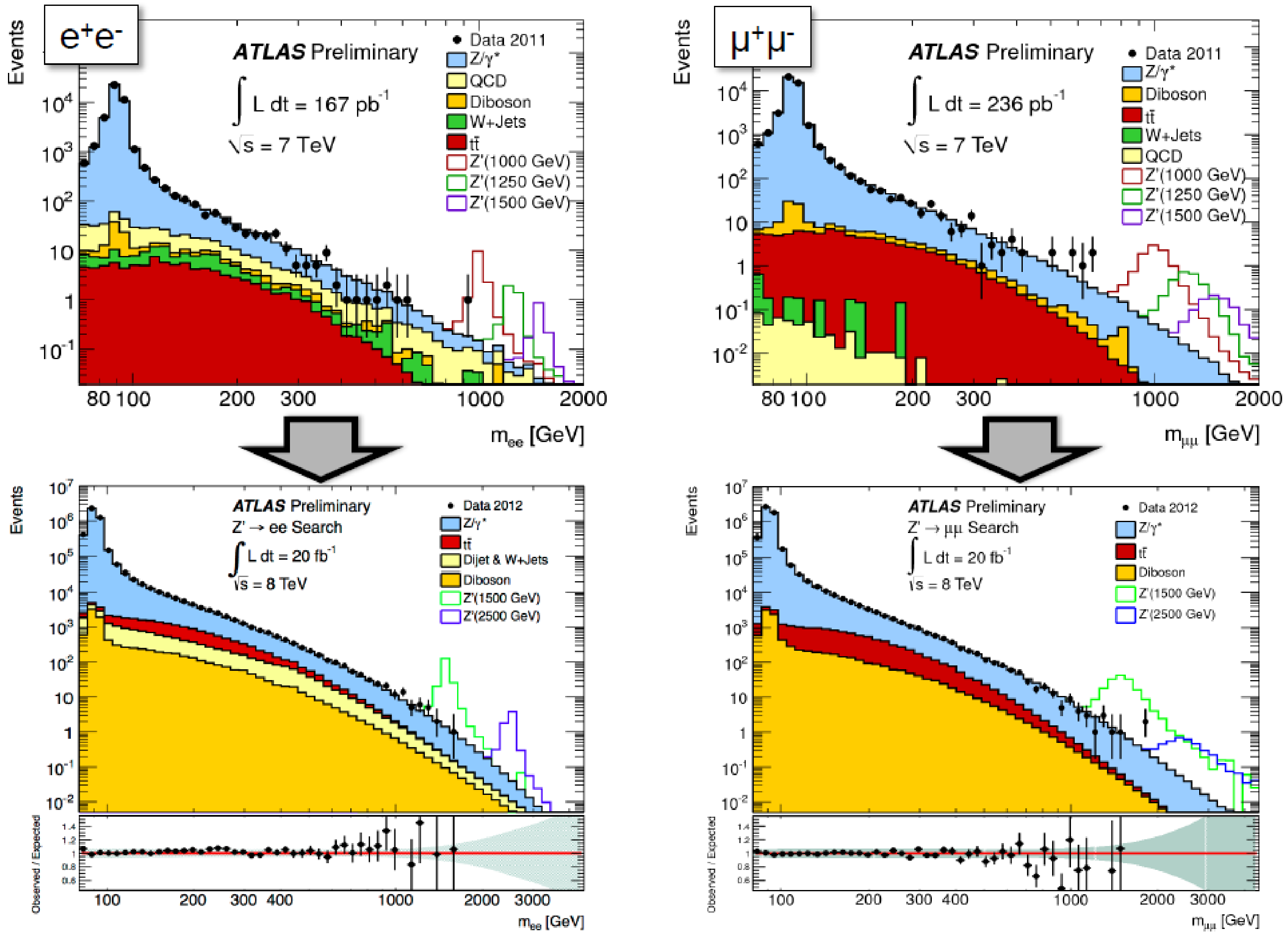
A small comparison



Differences in:

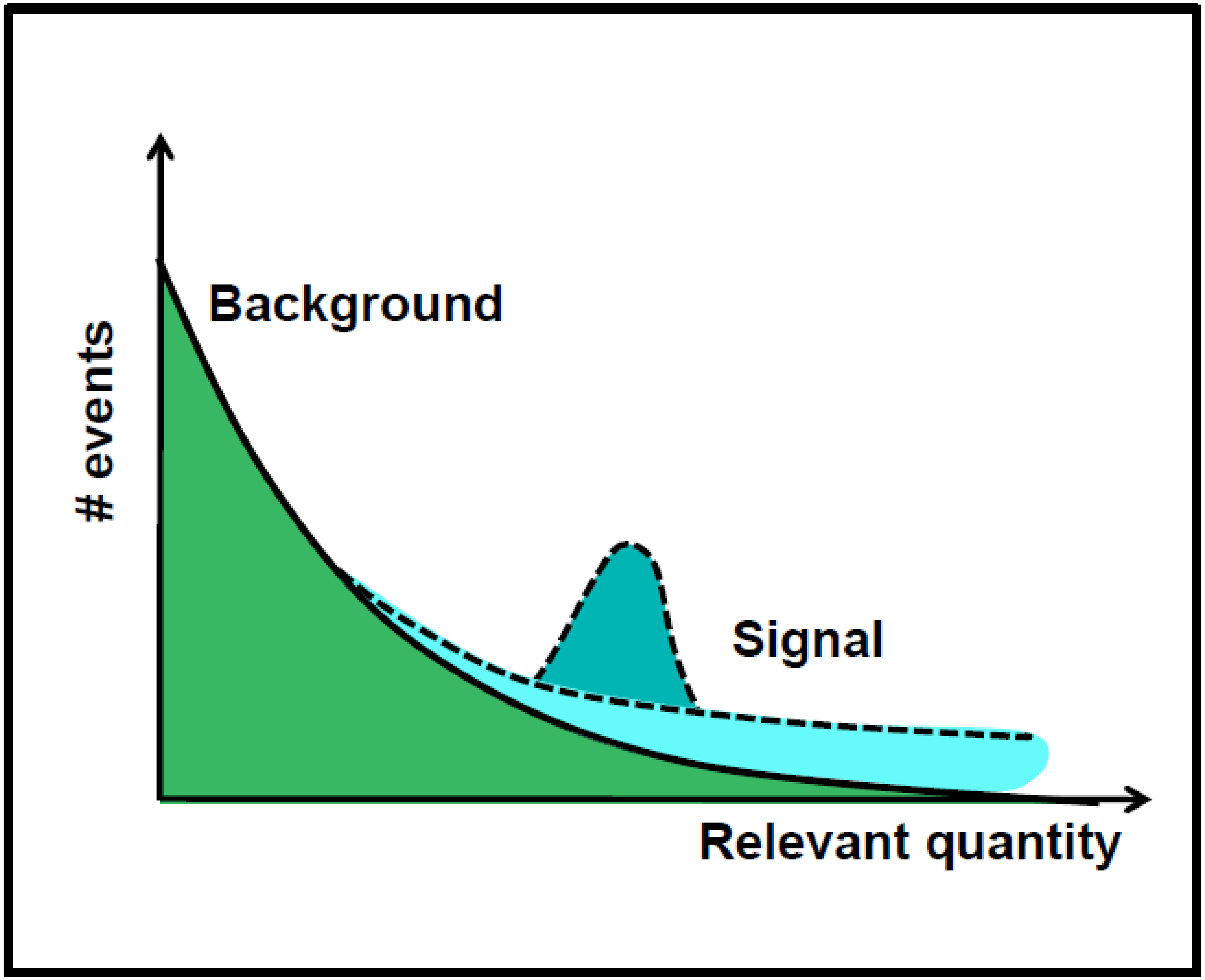
- **Resolution**
- **Background composition**
- **Dataset**

Evolution…

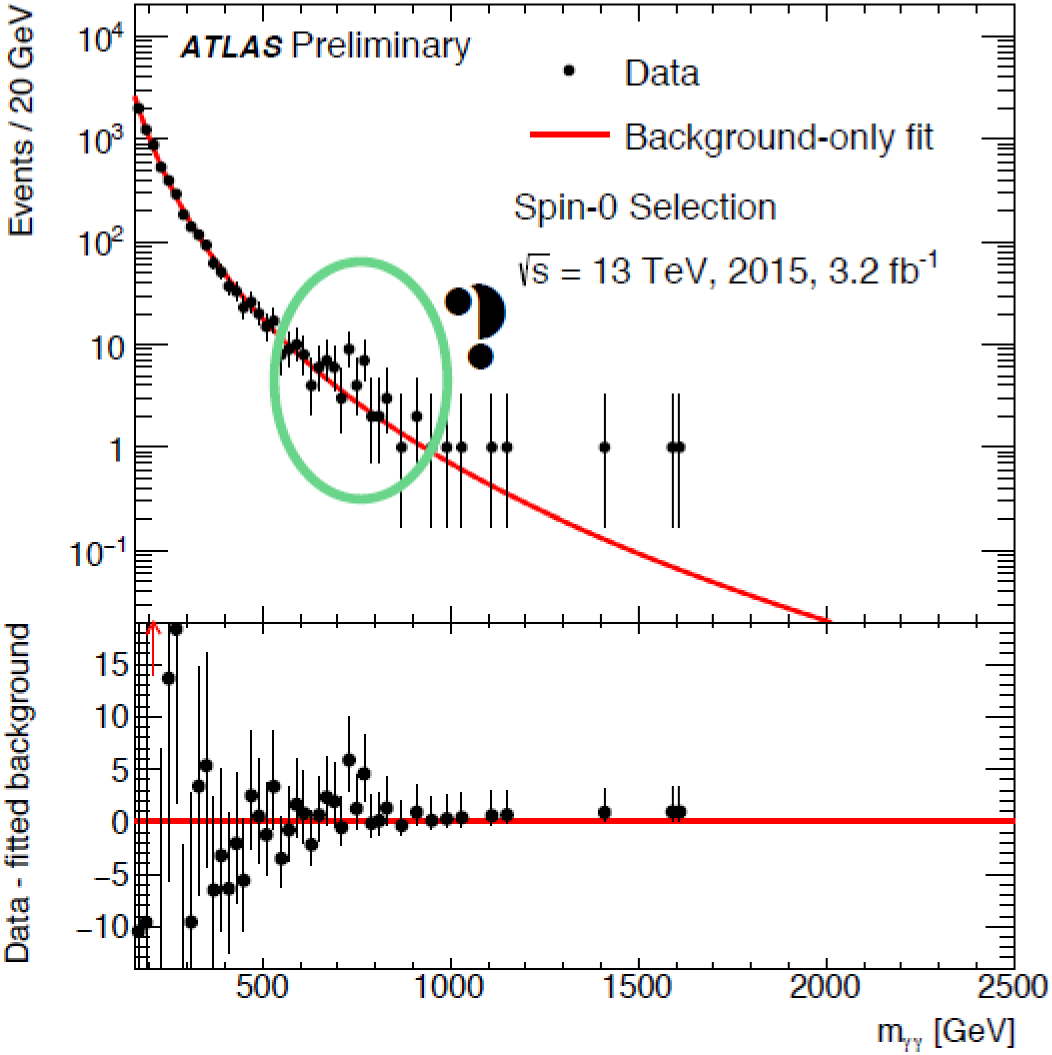


e+e-
ATLAS Preliminary
∫ L dt = 167 pb-1
√s = 7 TeV
Data 2011
Z/γ*
QCD
Diboson
W+Jets
tt̄
Z'(1000 GeV)
Z'(1250 GeV)
Z'(1500 GeV)
Events
m_ee [GeV]
μ+μ-
∫ L dt = 236 pb-1
m_μμ [GeV]
ATLAS Preliminary
Z' → ee Search
∫ L dt = 20 fb-1
√s = 8 TeV
Data 2012
Dijet & W+Jets
Z'(2500 GeV)
Observed / Expected
Z' → μμ Search

Searches



A well known bump search



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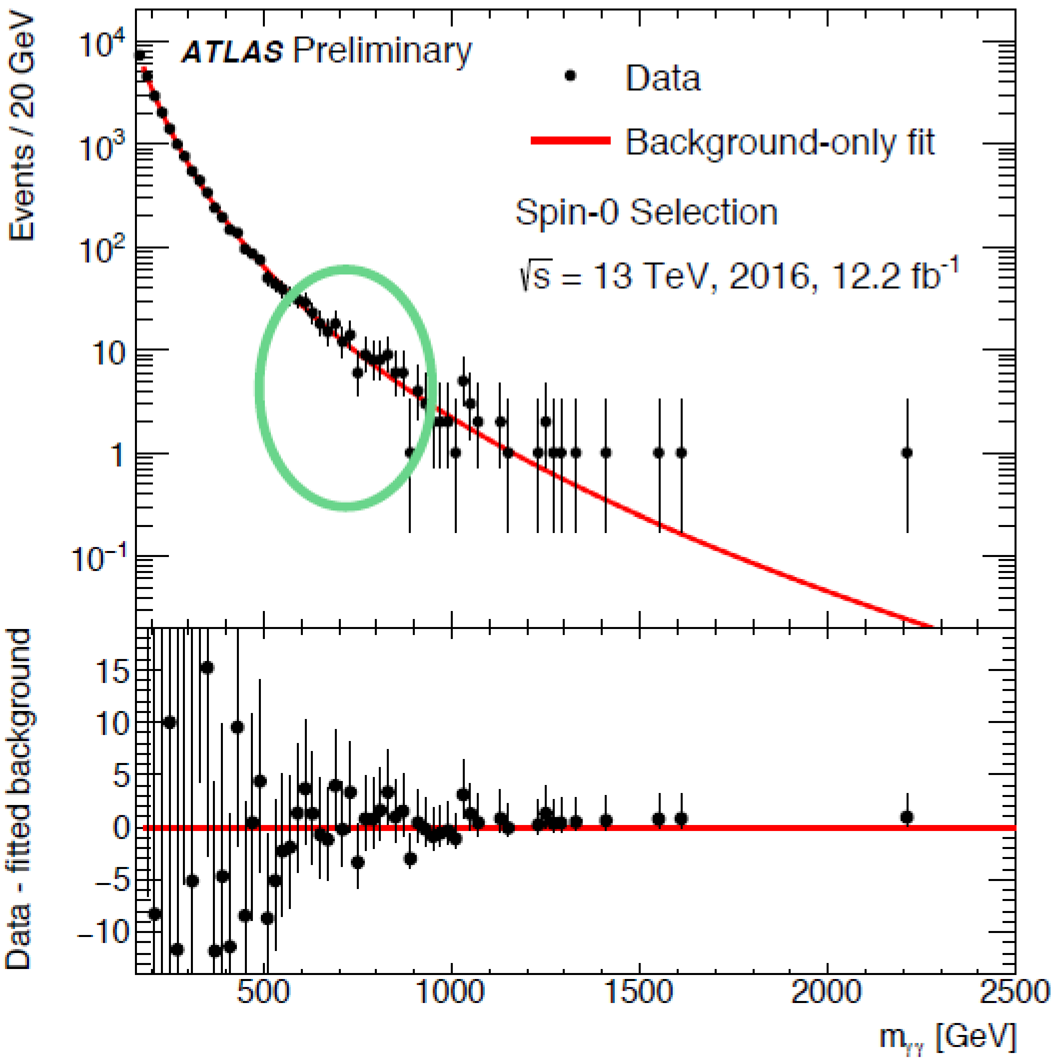
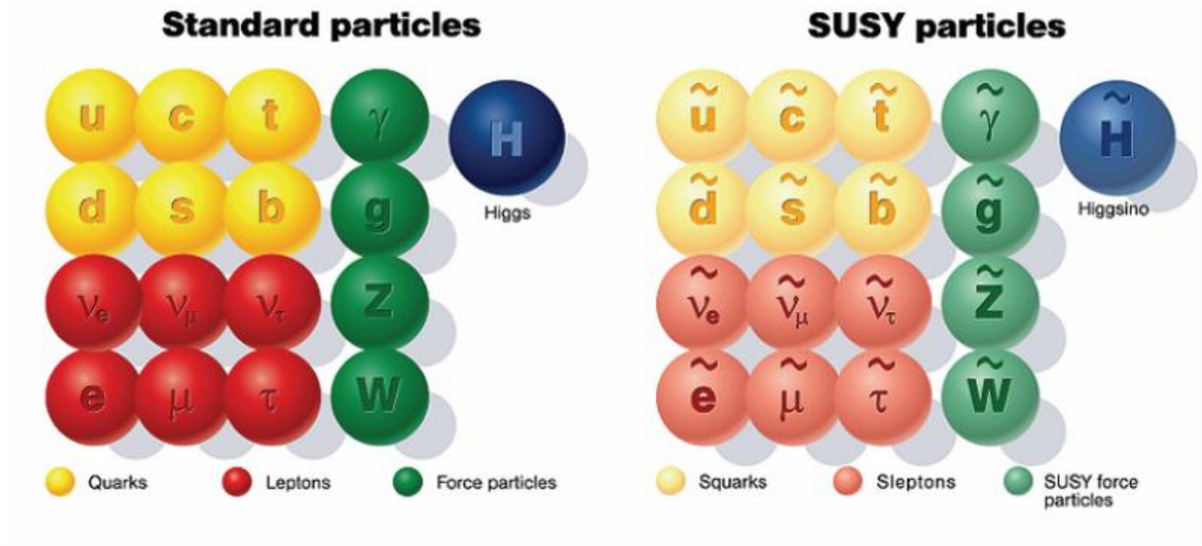


Typical SUSY searches

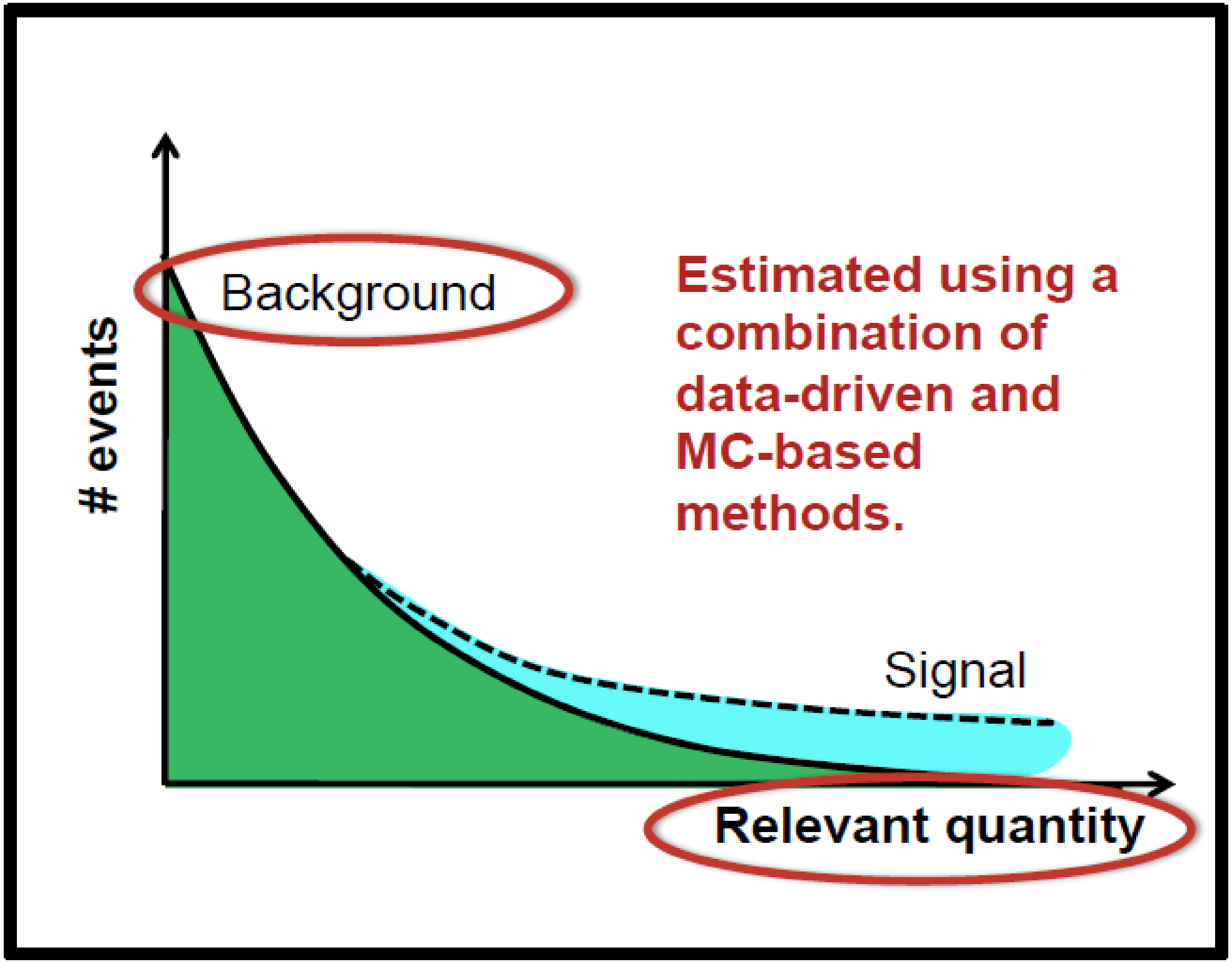
- Super-symmetry?



- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

Typical SUSY searches

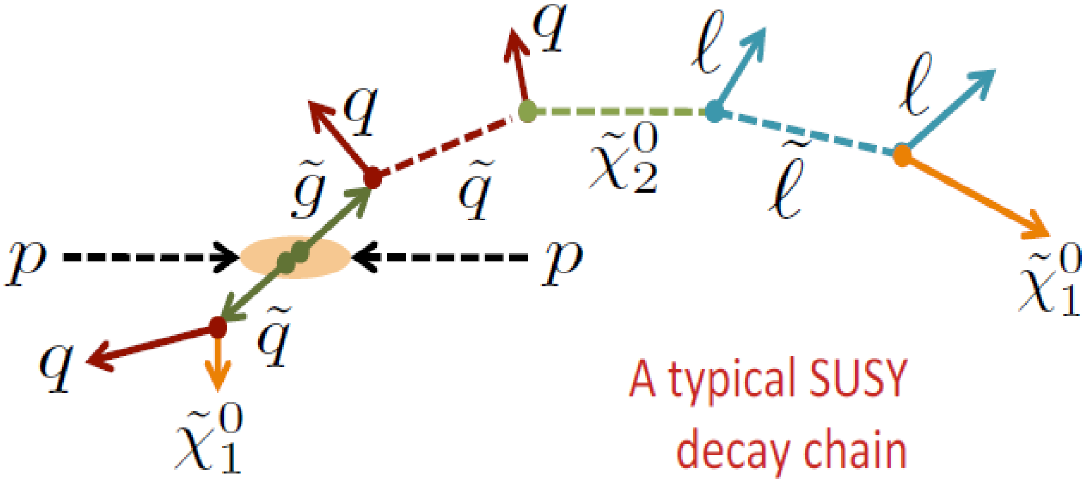


Estimated using a combination of data-driven and MC-based methods.

E.g. MET

Another search example

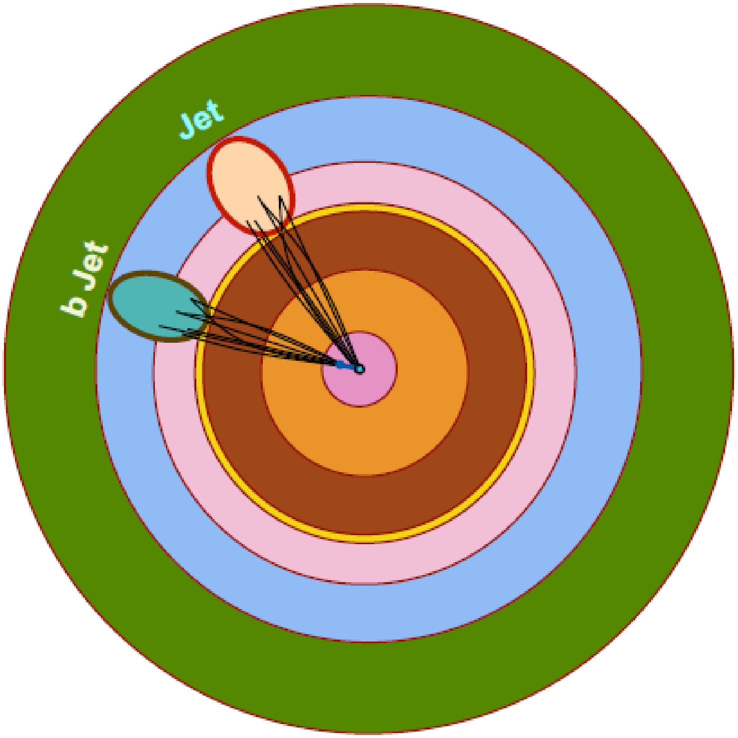
SEARCH FOR SUSY IN EVENTS WITH LARGE JET MULTIPLICITIES

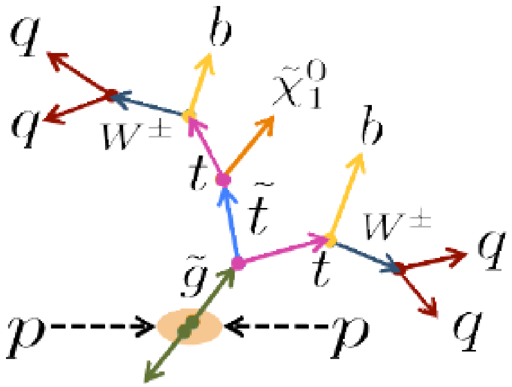


A typical SUSY decay chain

Event selection

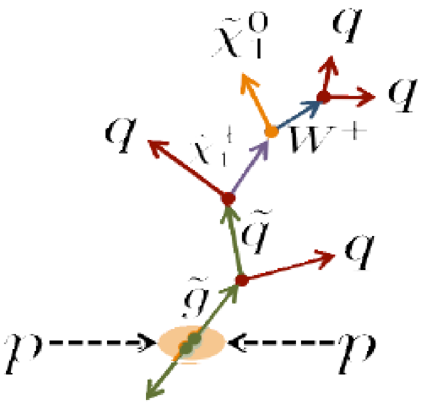
b-jets

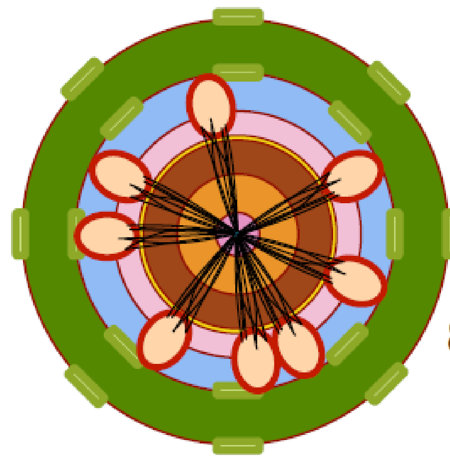




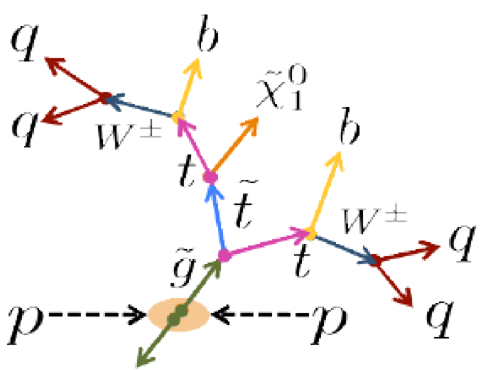
Event selection

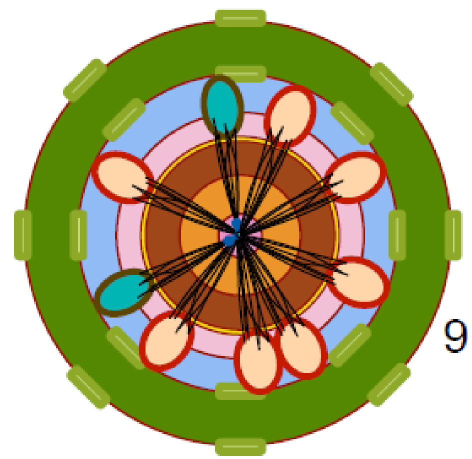
b-jets





8 jets, 0 b-jets



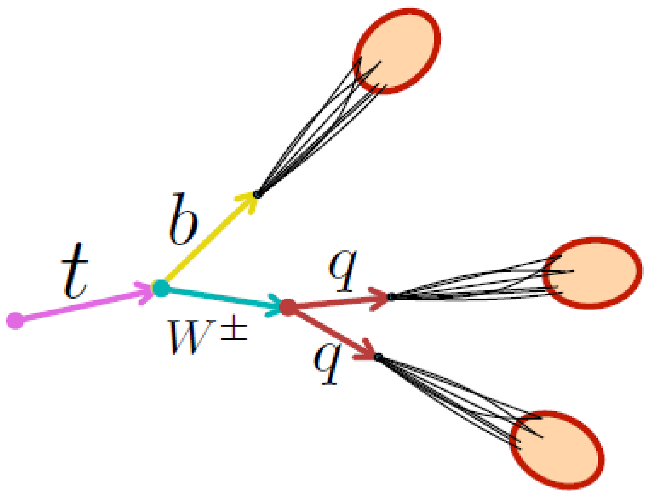


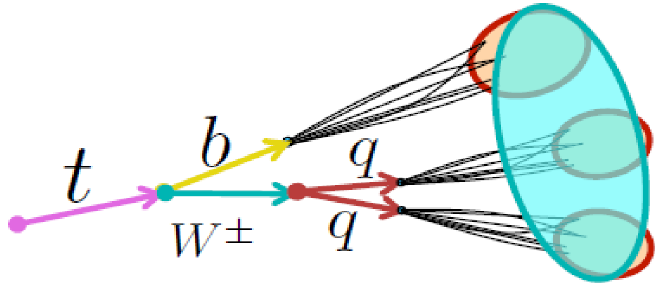
9 jets, ≥2 b-jets

Signal regions can range in jet p_T and jet & b-jet multiplicity.

Event selection

"fat-jets"

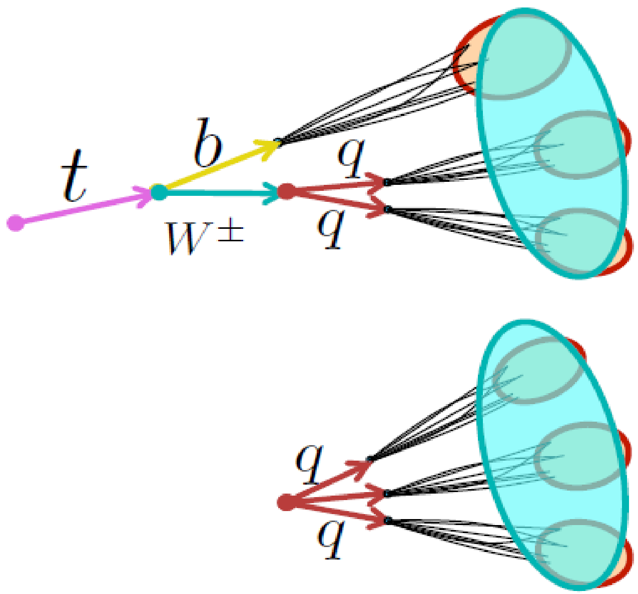


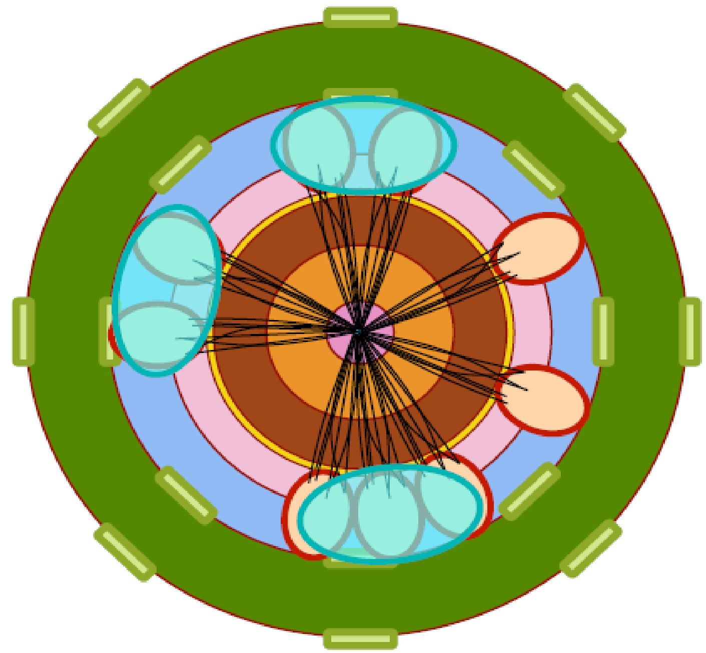


Fat-jets are a key signature in searches for boosted objects, e.g. boosted tops.

Event selection

"fat-jets"





$$m_j\ (\mathrm{QCD}) < m_j\ (\mathrm{SUSY})$$

Proposed in arXiv:1202.0558

$$M_J^{\Sigma} = \sum_{i=1}^{nJ} m_{j_i}$$

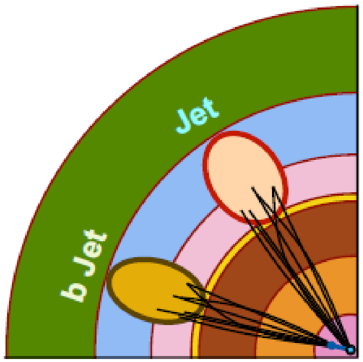
Signal regions can range in jet multiplicity and M_J^{Σ} cuts.

60

Example of search

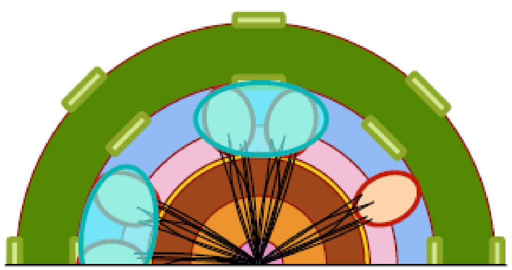
"b-jet stream"

ID	8j50			9j50			≥10j50	7j80			≥8j80		
Jet $\lvert\eta\rvert$	< 2.0												
Jet p_T	50 GeV							80 GeV					
Jet count	=8			=9			≥10	=7			≥8		
b-jets	0	1	≥2	0	1	≥2	-	0	1	≥2	0	1	≥2
$ME_T/\sqrt{H_T}$	> 4 GeV $^{1/2}$												



"fat-jet stream"

ID	≥8j50		≥9j50		≥10j50	
Jet $\lvert\eta\rvert$	< 2.8					
Jet p_T	50 GeV					
Jet count	≥8		≥9		≥10	
M_J^{Σ} (GeV)	>340	>420	>340	>420	>340	>420
$ME_T/\sqrt{H_T}$	> 4 GeV $^{1/2}$					



Proposed in arXiv:1202.0558

$$M_J^{\Sigma} = \sum_{i=1}^{nJ} m_{j_i}$$

Results

b-jet stream

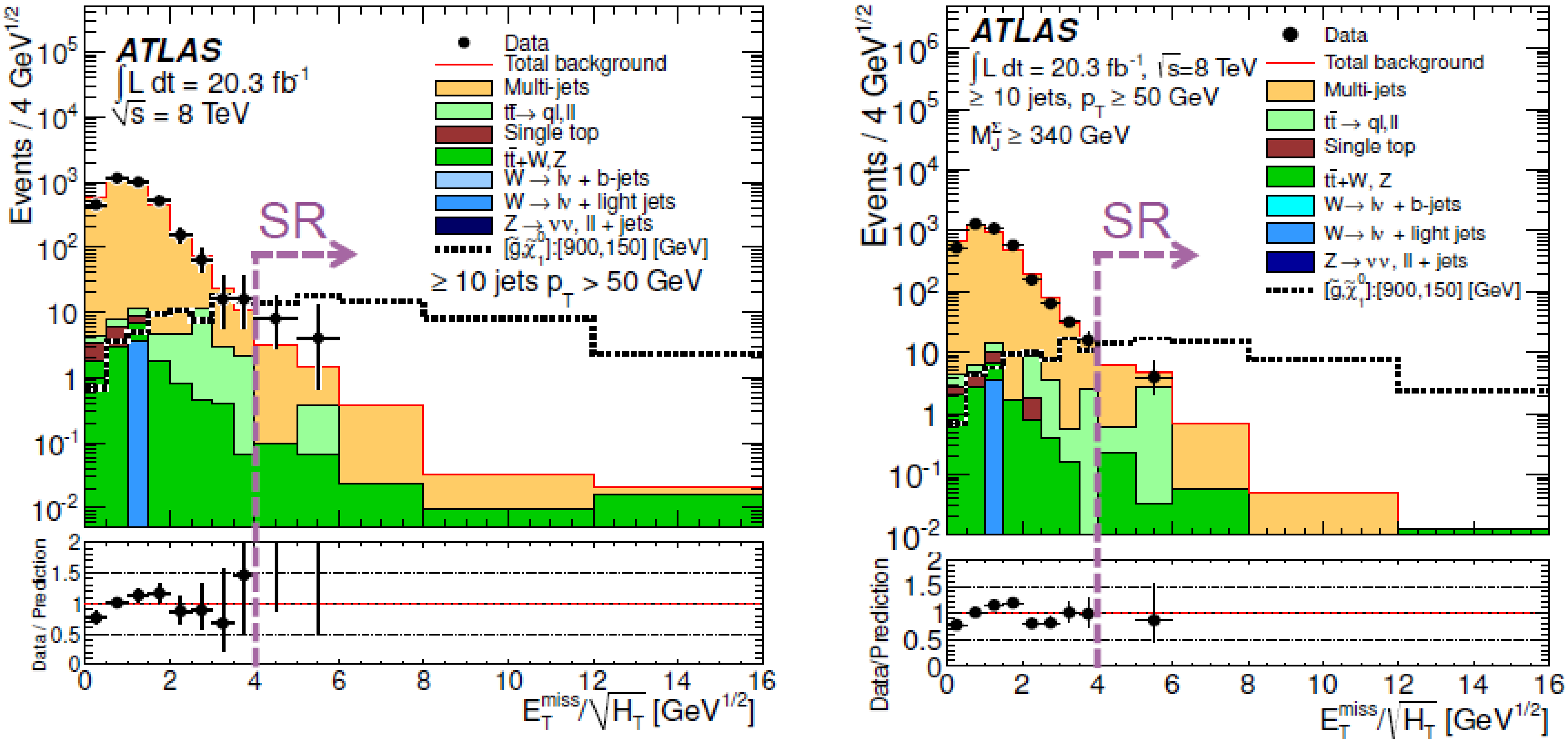
ID	8j50			9j50			≥10j50
b-jets	0	1	≥2	0	1	≥2	0
Expected evts	35±4	40±10	50±10	3.3±0.7	6.1±1.7	8.0±2.7	1.37±0.35
Observed evts	40	44	44	5	8	7	3
Significance (σ)	0.7	-0.02	-0.6	0.8	0.6	-0.28	1.11

ID	7j80			≥8j80		
b-jets	0	1	≥2	0	1	≥2
Expected evts	11.0±2.2	17±6	25±10	0.9±0.6	1.5±0.9	3.3±2.2
Observed evts	12	17	13	2	1	3
Significance (σ)	0.05	-0.14	-1.0	0.9	-0.28	-0.06

fat-jet stream

ID	≥8j50		≥9j50		≥10j50	
M_J^{Σ} (GeV)	340	420	340	420	340	420
Expected evts	75±19	45±14	17±7	11±5	3.2±3.7	2.2±2.0
Observed evts	69	37	13	9	1	1
Significance (σ)	-0.27	-0.6	-0.6	-0.34	-0.8	-0.6

Results


ATLAS
$\int L\,dt = 20.3\ fb^{-1}$
$\sqrt{s} = 8$ TeV
Data
Total background
Multi-jets
$t\bar{t} \to ql, ll$
Single top
$t\bar{t}$+W,Z
$W \to l\nu$ + b-jets
$W \to l\nu$ + light jets
$Z \to \nu\nu$, ll + jets
$[\tilde{g},\tilde{\chi}_1^0]$:[900,150] [GeV]
$\geq$ 10 jets p_T > 50 GeV
SR
Events / 4 GeV$^{1/2}$
Data / Prediction
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]
ATLAS
$\int L\,dt = 20.3\ fb^{-1}$, $\sqrt{s}$=8 TeV
$\geq$ 10 jets, $p_T \geq$ 50 GeV
$M_J^{\Sigma} \geq$ 340 GeV
Data
Total background
Multi-jets
$t\bar{t} \to ql, ll$
Single top
$t\bar{t}$+W, Z
$W \to l\nu$ + b-jets
$W \to l\nu$ + light jets
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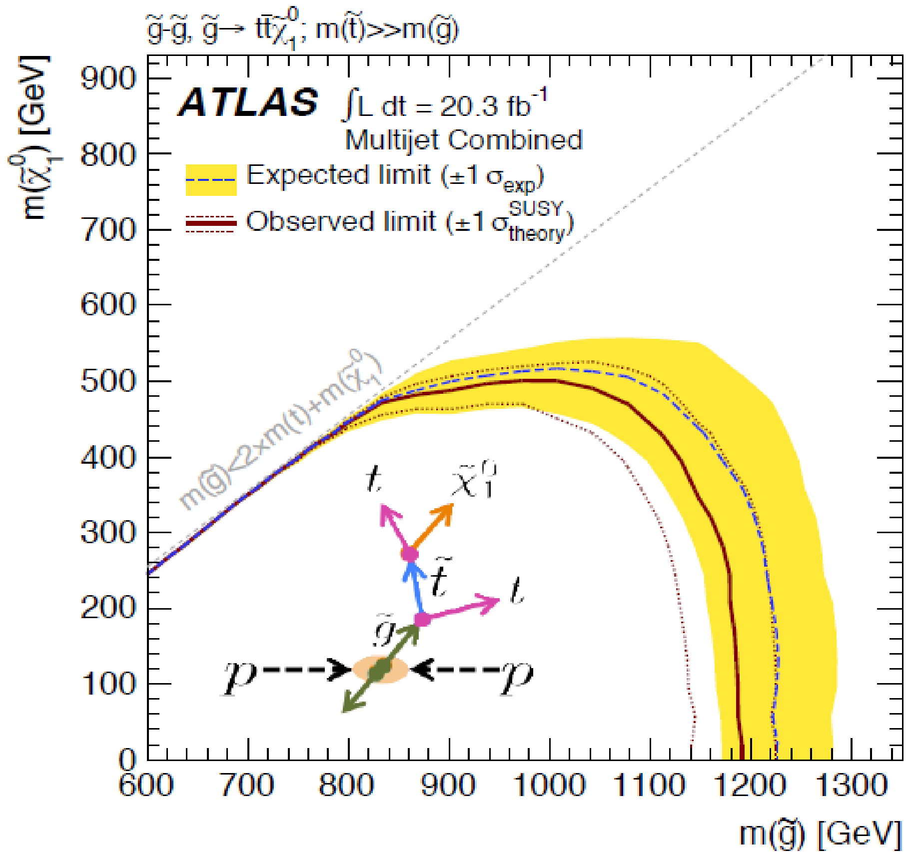
$[\tilde{g},\tilde{\chi}_1^0]$:[900,150] [GeV]
SR
Events / 4 GeV$^{1/2}$
Data/Prediction
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]

Interpretations

Real or Simplified models

- Simplified topologies include typically one production and one decay process. Provide useful information for theorists.



CONTENTS OF A RANDOM SEARCH INTERNAL DOCUMENTATION

Contents

Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Compotents of a physics analysis

- ◎ Data-set and Monte Carlo samples
- ◎ Trigger
- ◎ Object definitions
- ◎ Background dete
- ◎ Systematic unce
- ◎ Statistical metho
- ◎ Results
- ◎ [Interpretations]

The data and simulation samples used in the analysis. Data for the measurement / search, simulation to compare data to predictions.

Data-set specifics:

- ◎ Data quality ⇒ Good run list.
- ◎ Luminosity.

Monte carlo sample specifics:

- ◎ Generator, tunes.
- ◎ Statistics.

Compotents of a physics analysis

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The trigger used to collect the data with.

Trigger specifics:

- Prescales; typically unprescaled triggers are used, prescaled triggers for QCD / high stat measuments.
- Trigger (in)efficiencies.

Compotents of a physics analysis

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- Sy
- Stati
- Resu
- [Inter

The exact definition of objects (electrons, muon, jets, …) and how these are combined in selecting events to be analyzed.

Object definition specifics:

- “Flavor” of the identification (loose, medium, tight).
- Calibrations.

Event selection specifics:

- Event cleaning (e.g. from noise and cosmics).
- Momentum, geom. acceptance and multiplicity of objects.
- Higher level cuts, such as invariant mass.
- “**Signal regions**”.

Compotents of a physics analysis

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Events that are imitating the signal we are searching for or measuring.

Background determination specifics:

- Can/must be **data-driven** or **simulation-based**.
- "**Validation regions**" and "**control regions**" required. These can use different triggers wrt signal regions.

Compotents of a physics analysis

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- Any 'intermediate' measurement we have performed carries uncertainties (statistical and systematic).
- **"Systematic" uncertainties are introduced by inaccuracies in the methods used to perform the measurement.**
- Efficiencies, acceptance, number of events, luminosity, cross sections used in Monte Carlo scaling…
- Some of them are "centrally" assessed by the performance groups of an experiment. Some of them are analysis-specific.

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Dealing with large data-sets, we use statistical methods to make sense of the numbers we measure.

Typical method:

- Do a fit to extract signal from background.

Methodologies can vary a lot, but nowdays they are pretty unified within and across experiments.

Neural nets and other machine learning methods are broadly used, primarily to improve signal over background discrimination!

Compotents of a physics analysis

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Produce the results in tables and plots. These include details of what is found in the signal region.

Compotents of a physics analysis

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Put the results into context: interpret them in theoretical models.

(Instead of) conclusions