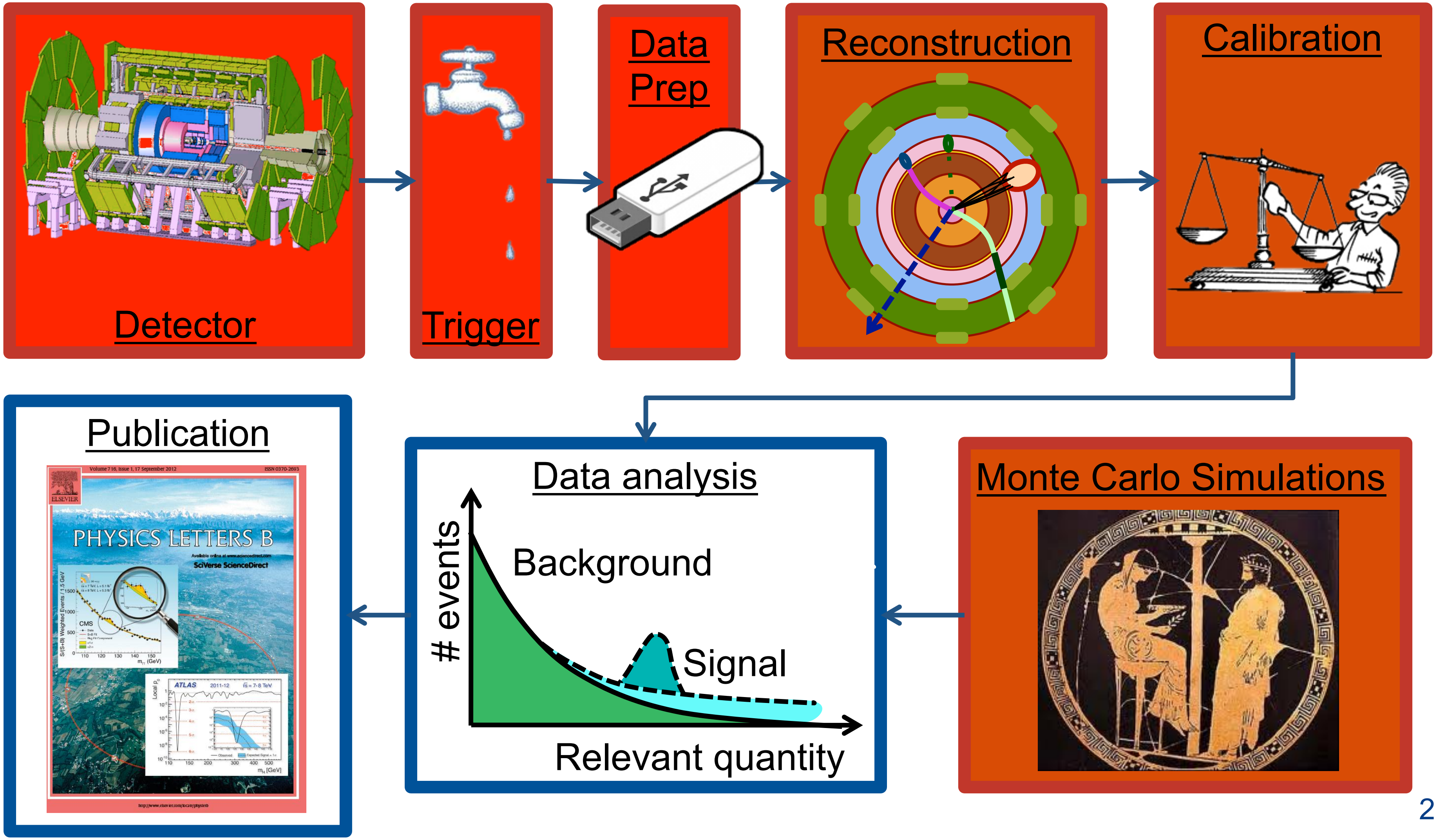
FROM RAW DATA TO PHYSICS

LECTURE 3

LECTURE 3



Detector

Trigger

Data Prep

Reconstruction

Calibration

Data analysis

Monte Carlo Simulations

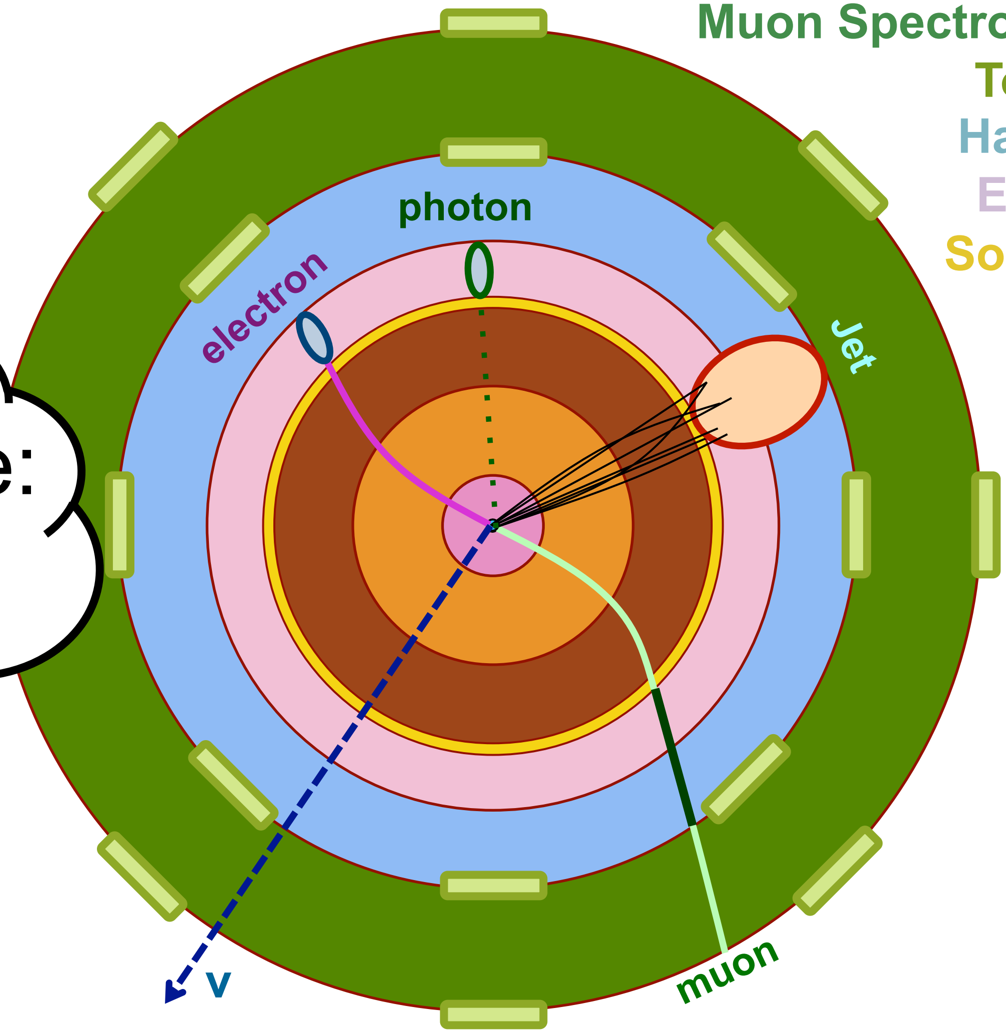
Publication

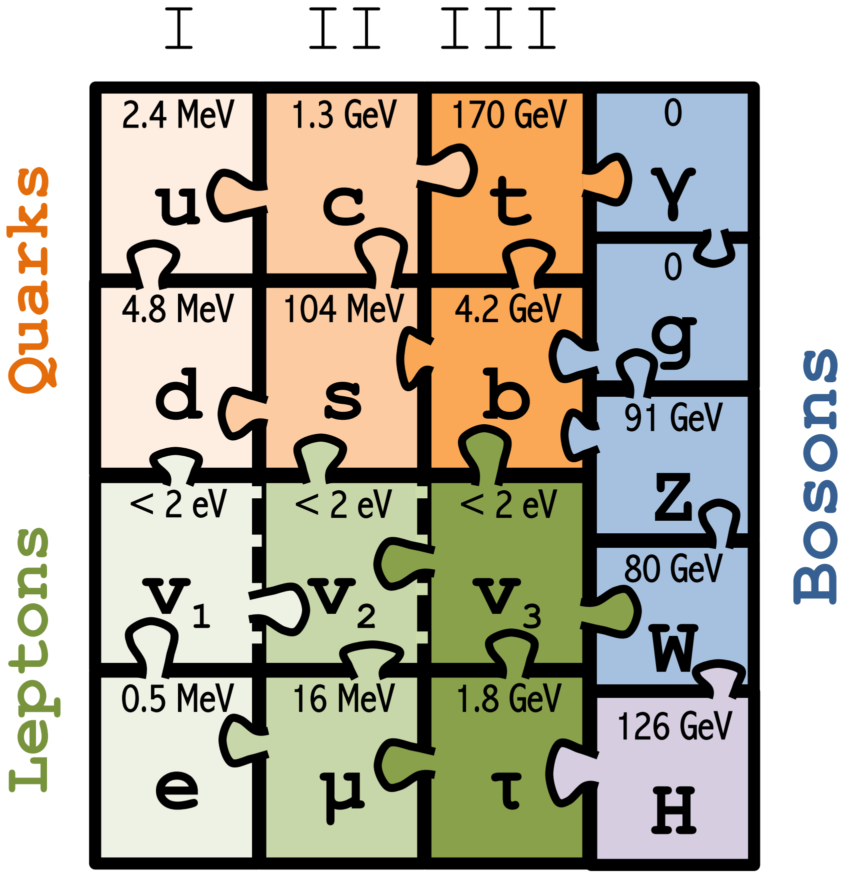
WHAT DO WE RECONSTRUCT

Tracks and **Clusters**

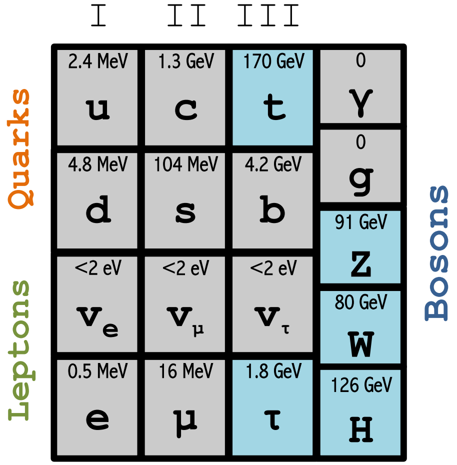
Combining those: "**objects**" ("particles")

Simplified Detector Transverse View



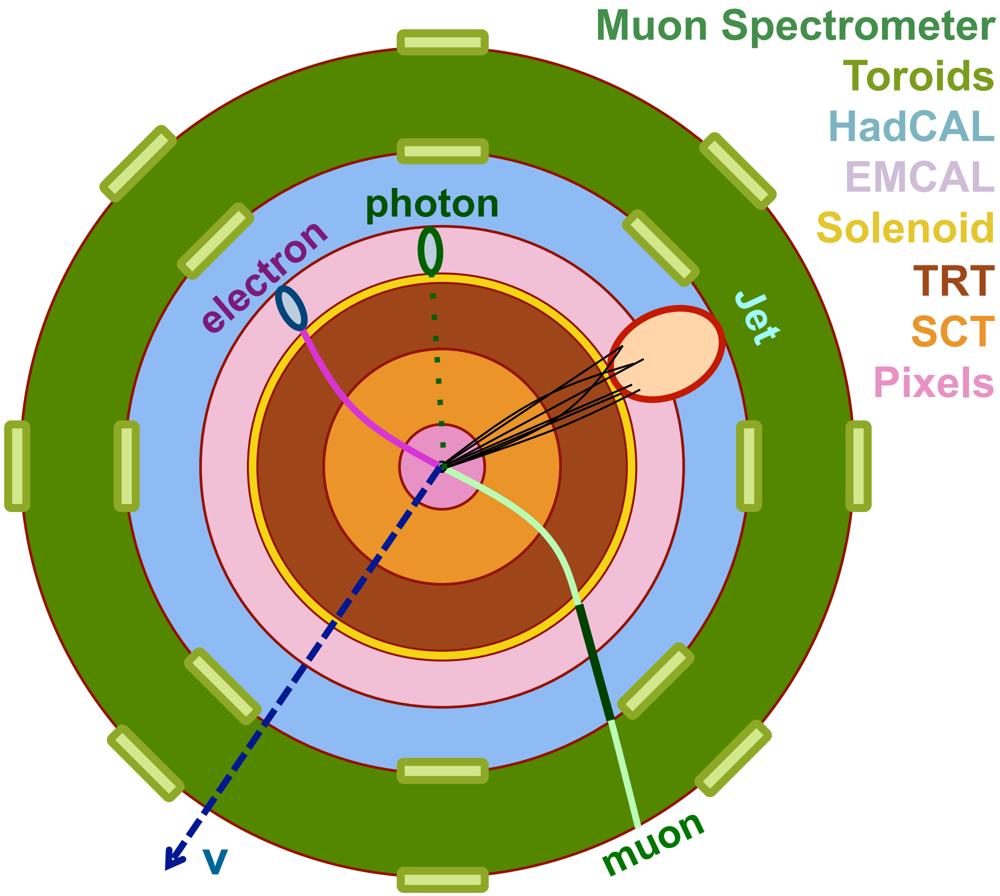

I
II
III
Quarks
Leptons
Bosons
2.4 MeV
u
1.3 GeV
c
170 GeV
t
0
γ
4.8 MeV
d
104 MeV
s
4.2 GeV
b
0
g
91 GeV
Z
< 2 eV
ν_1
< 2 eV
ν_2
< 2 eV
ν_3
80 GeV
W
0.5 MeV
e
16 MeV
μ
1.8 GeV
τ
126 GeV
H

RECONSTRUCTING PARTICLES



	I	II	III	Bosons
Quarks	2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
	4.8 MeV d	104 MeV s	4.2 GeV b	0 g 91 GeV Z
Leptons	<2 eV ν_e	<2 eV ν_μ	<2 eV ν_τ	80 GeV W
	0.5 MeV e	16 MeV μ	1.8 GeV τ	126 GeV H

Simplified Detector Transverse View

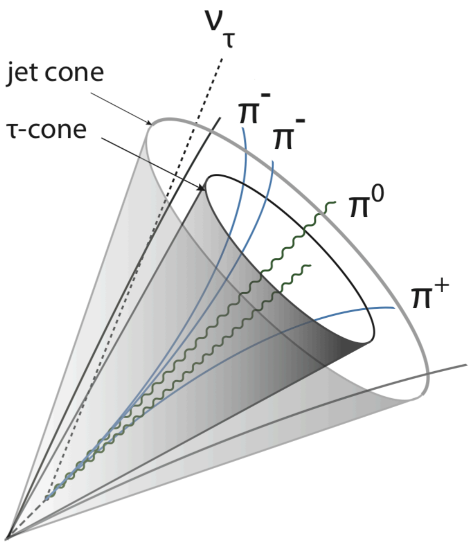


TAUS

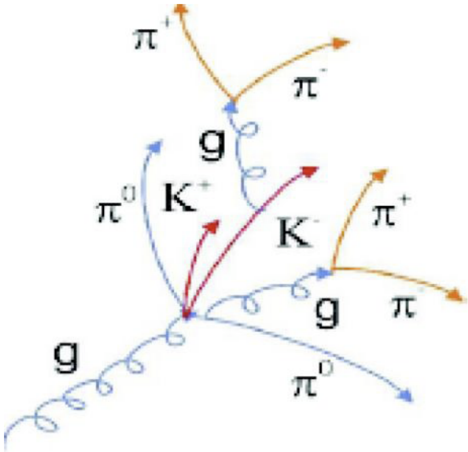
Tau Decay Mode			B.R.
Leptonic		$\tau^\pm \rightarrow e^\pm + \nu + \nu$	17.8%
		$\tau^\pm \rightarrow \mu^\pm + \nu + \nu$	17.4%
Hadronic	1-prong	$\tau^\pm \rightarrow \pi^\pm + \nu$	11%
		$\tau^\pm \rightarrow \pi^\pm + \nu + n\pi^0$	35%
	3-prong	$\tau^\pm \rightarrow 3\pi^\pm + \nu$	9%
		$\tau^\pm \rightarrow 3\pi^\pm + \nu + n\pi^0$	5%
Other			~5%

- Hadronic tau reconstruction extremely challenging.
- Using **multi-variate** techniques based on track multiplicity and shower shapes.

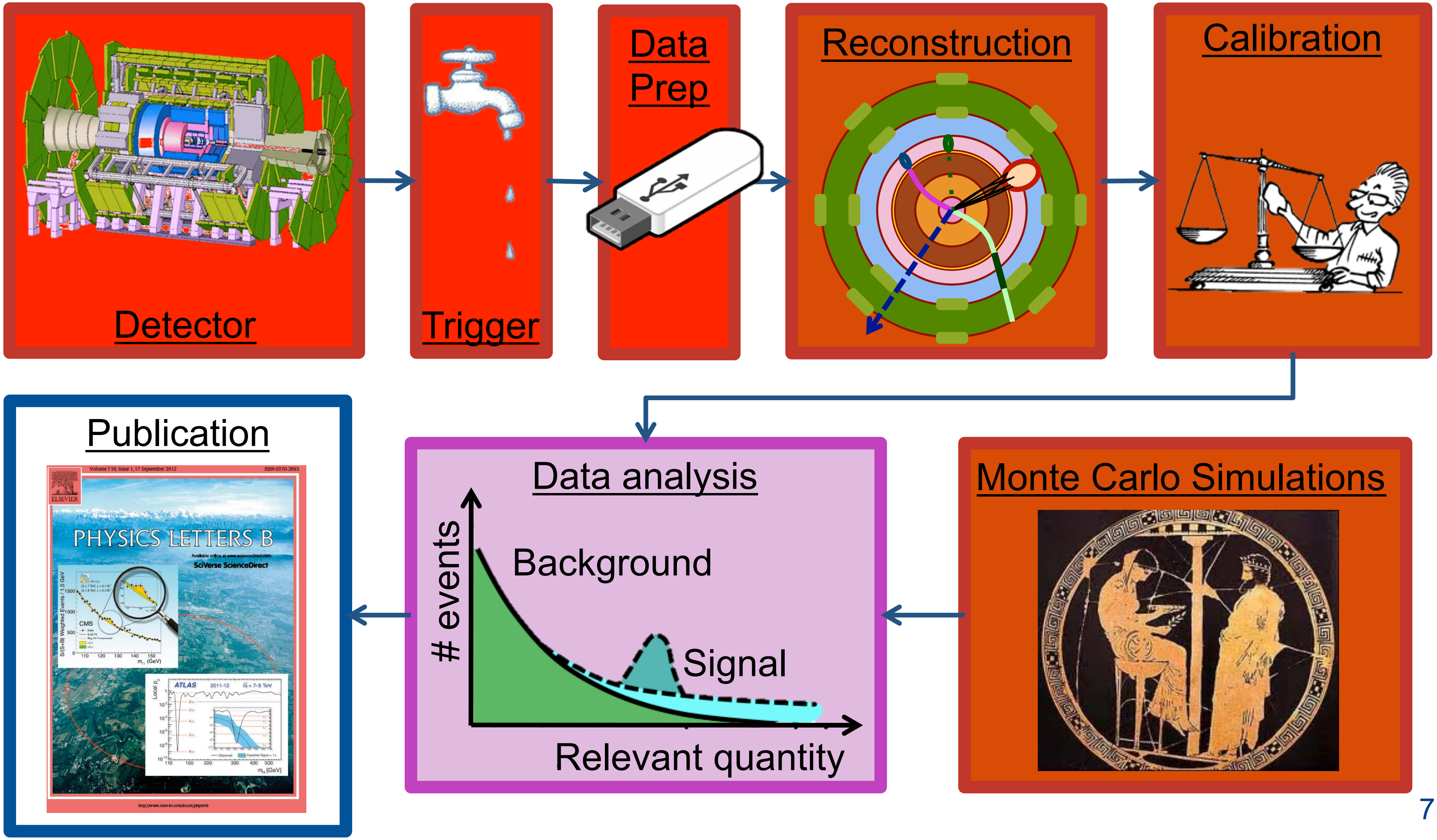
A tau jet (signal)…



…vs. a QCD jet (background)



LECTURE 3



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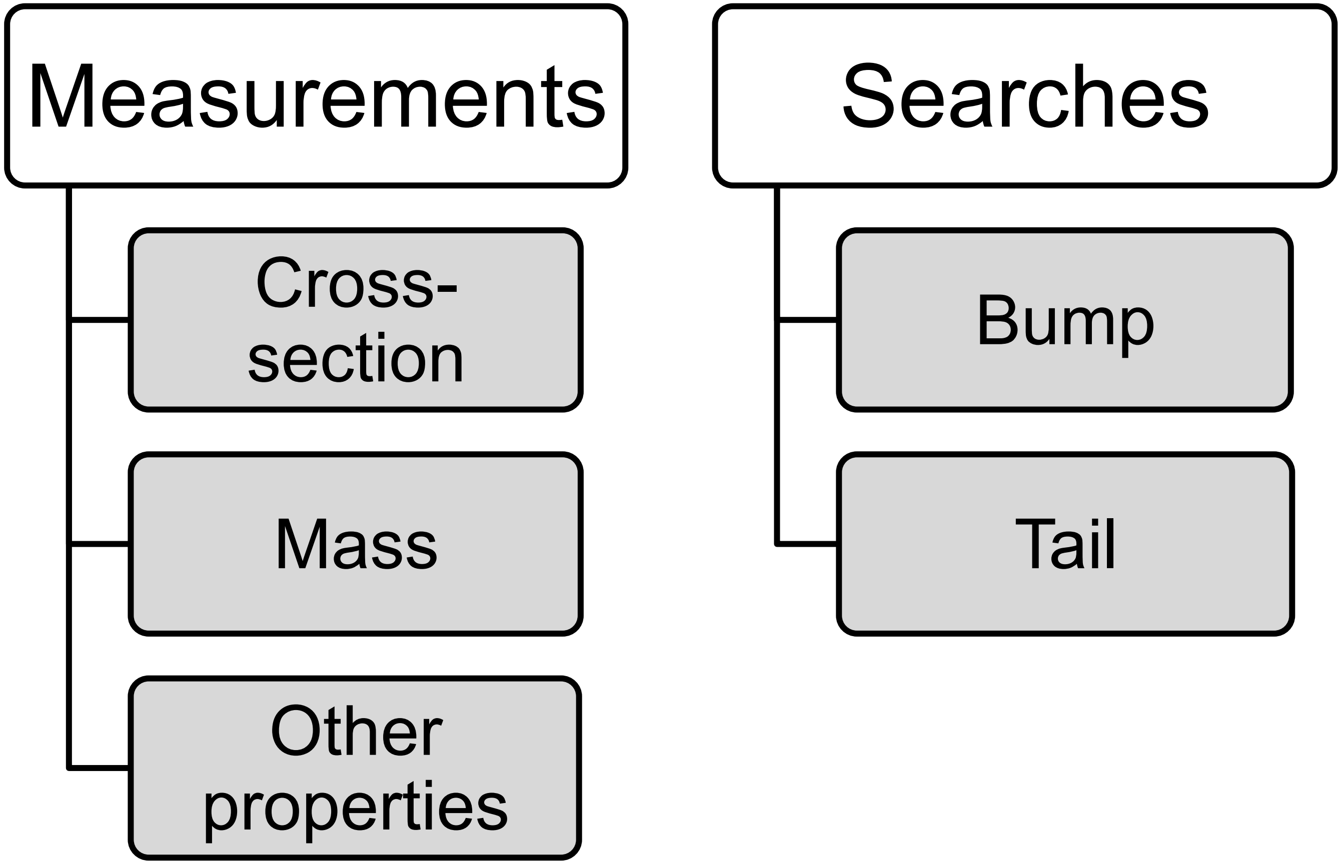
PHYSICS ANALYSES



Measurements
- Cross-section
- Mass
- Other properties

Searches
- Bump
- Tail

PHYSICS ANALYSES

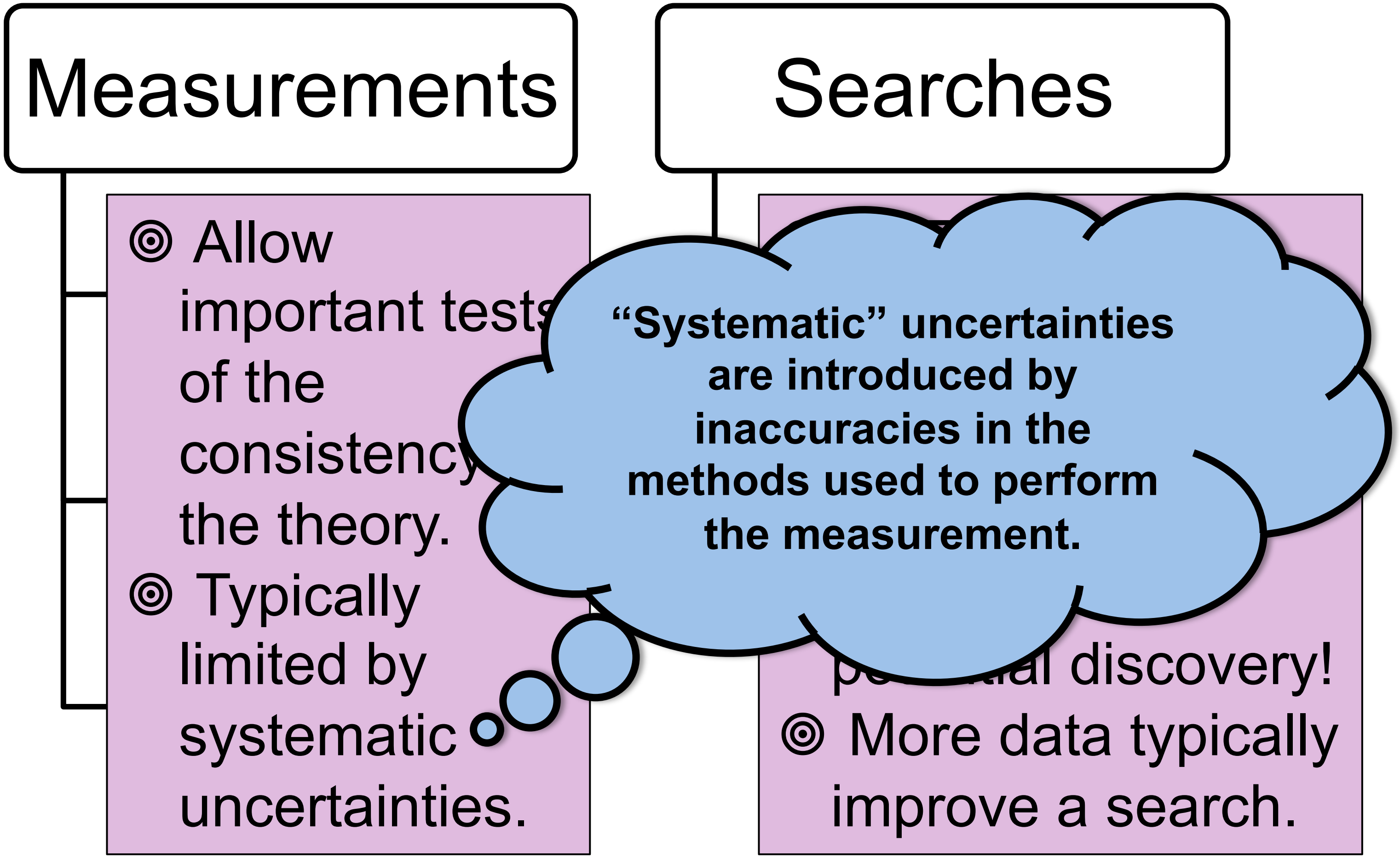
Measurements

- 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

al discovery!

- ◎ More data typically improve a search.

“Systematic” uncertainties are introduced by inaccuracies in the methods used to perform the measurement.

PHYSICS ANALYSES

Measurements

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

Searches

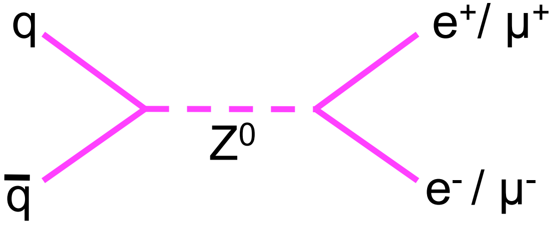
- … For new particles.
- If no signal, set limits on some model.
- If signal, a potential discovery!
- More data typically improve a search.

A 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 of understanding the electroweak force**
- **Measuring the Z^0 cross-section at the LHC important test of theory**
  - Does the measurement agree with the theoretical prediction at LHC collision energy?

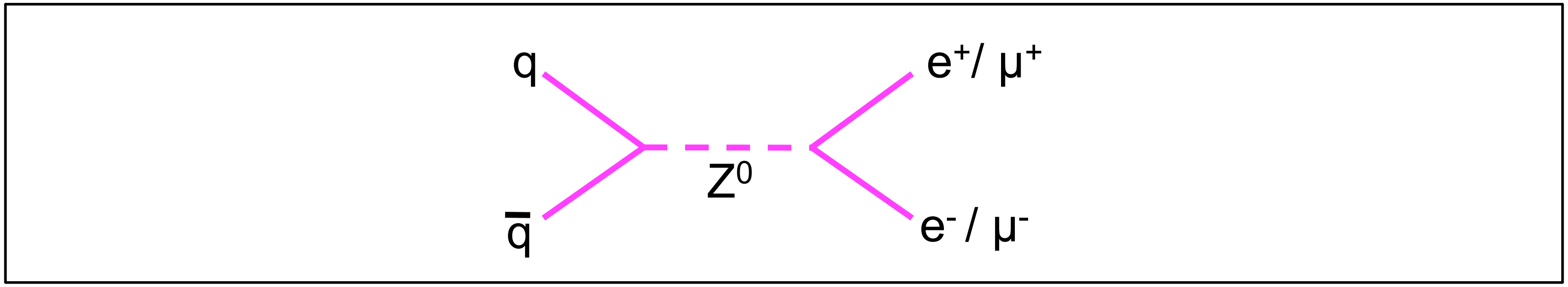


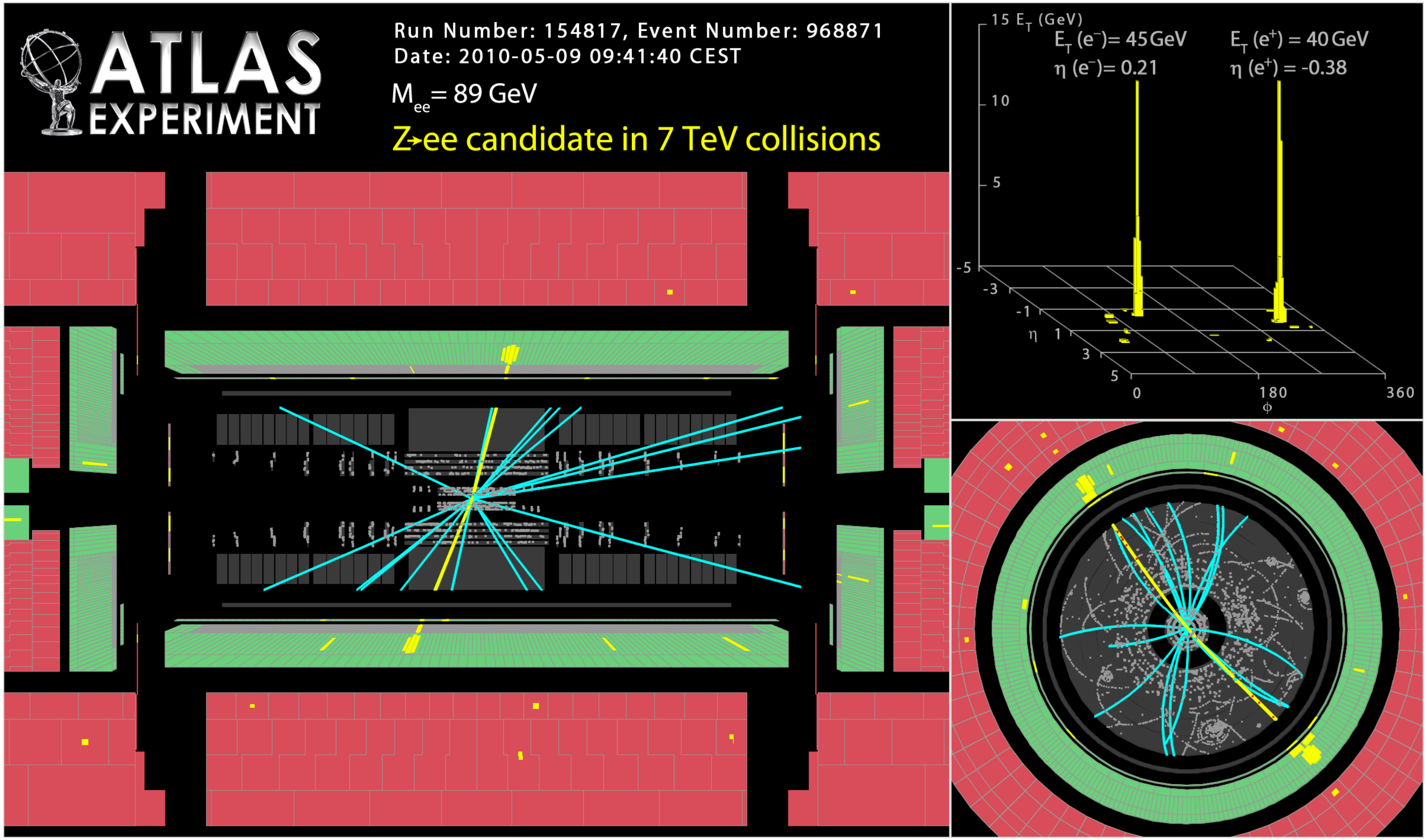
$$\sigma \cdot \mathrm{BR} = \frac{\text{Number of events}}{\alpha \cdot \epsilon \cdot \mathrm{L}}$$

α : acceptance
ϵ : efficiency
L : luminosity

- Z^0 cross-section is related to the probability that we will produce a Z^0 at the LHC.
- Now we use the Z^0 as a tool for studying electron and muon reconstruction and deriving calibrations.

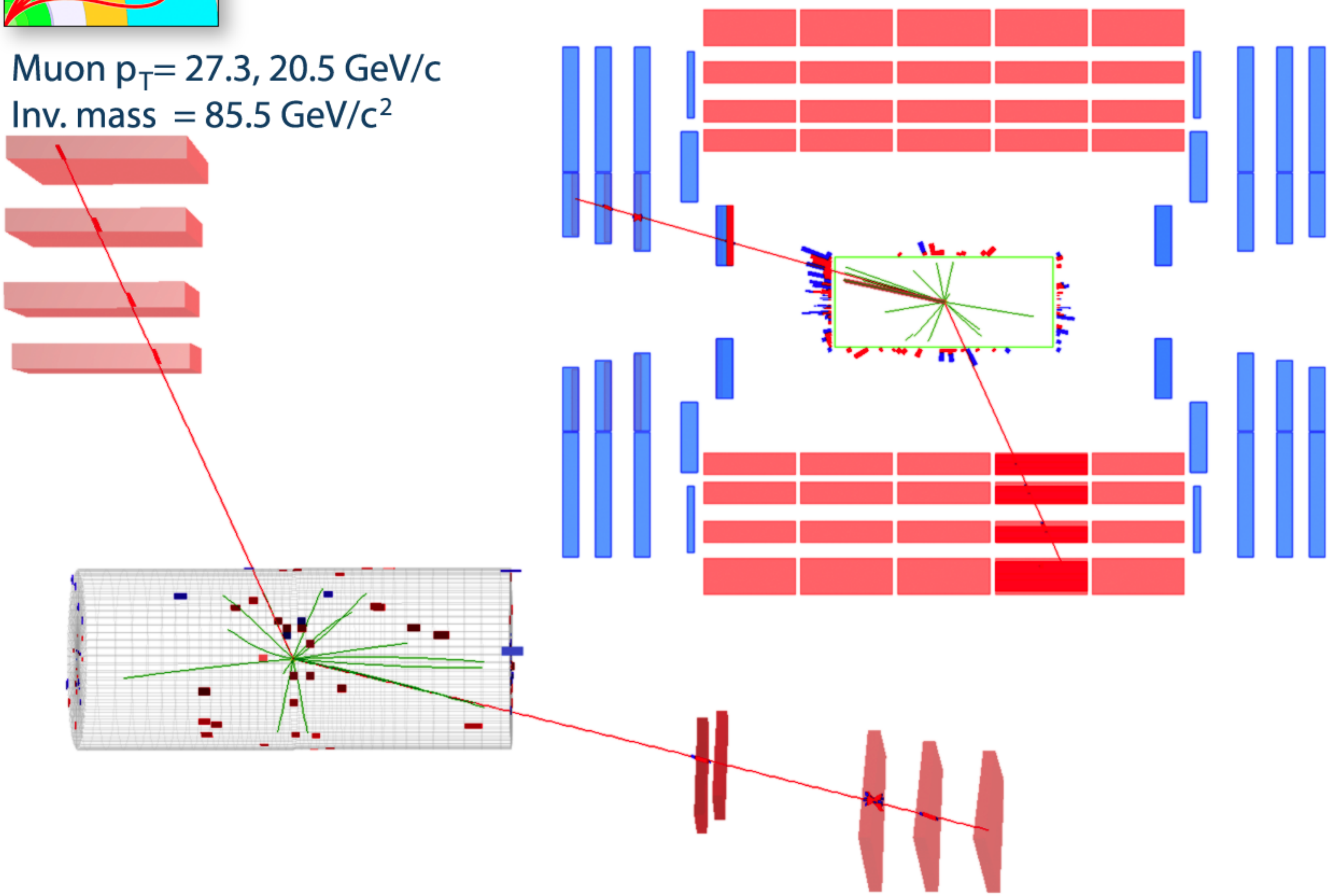
MEASURING Z^0 CROSS-SECTION AT LHC





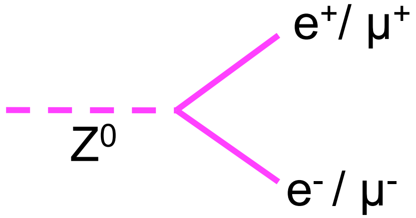
Z->μμ event in CMS

CMS Experiment at LHC, CERN
Run 136087 Event 39967482
Lumi section: 314
Mon May 24 2010, 15:31:58 CEST



Muon p_T= 27.3, 20.5 GeV/c
Inv. mass = 85.5 GeV/c^2

RECONSTRUCTING Z^0'S



How do we know if 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

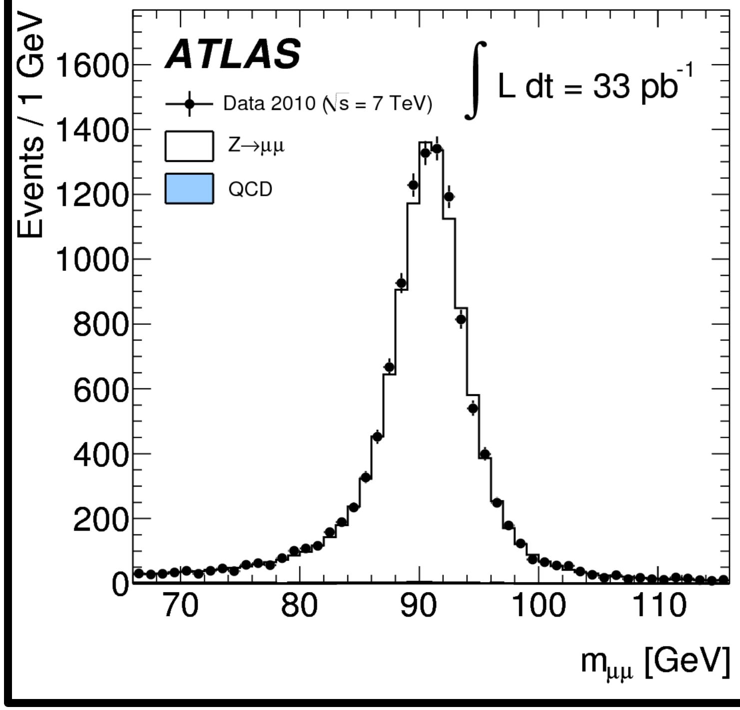
Under assumption that lepton is massless compared to mass of Z^0
=> $M^2 = 2 E_1 E_2 (1-\cos\vartheta_{12})$ where ϑ_{12}= angle between the leptons

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

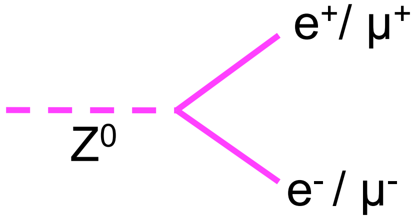
Select Z^0 events with 'analysis cuts':

- 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 the Z^0 mass region



RECONSTRUCTING Z⁰'S



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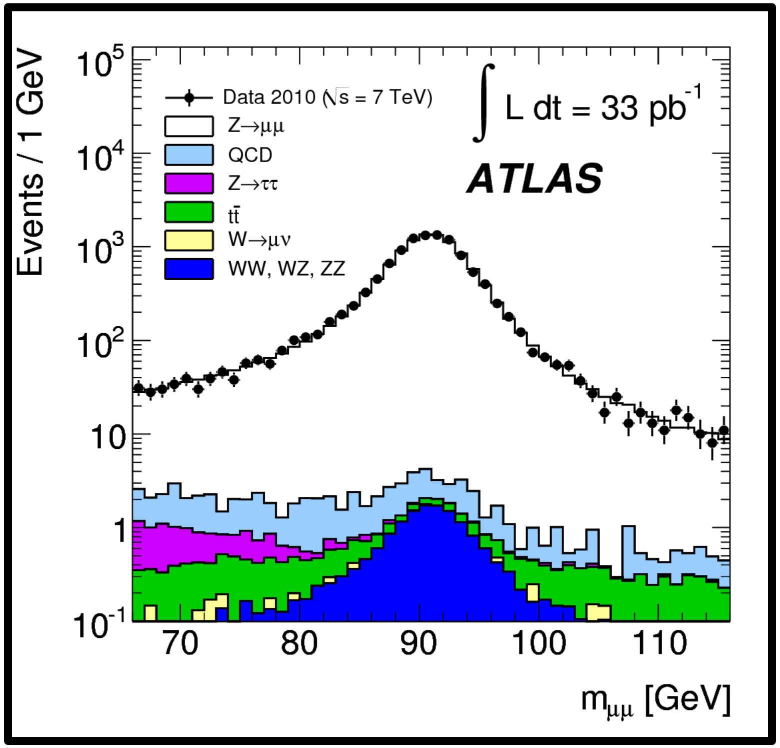
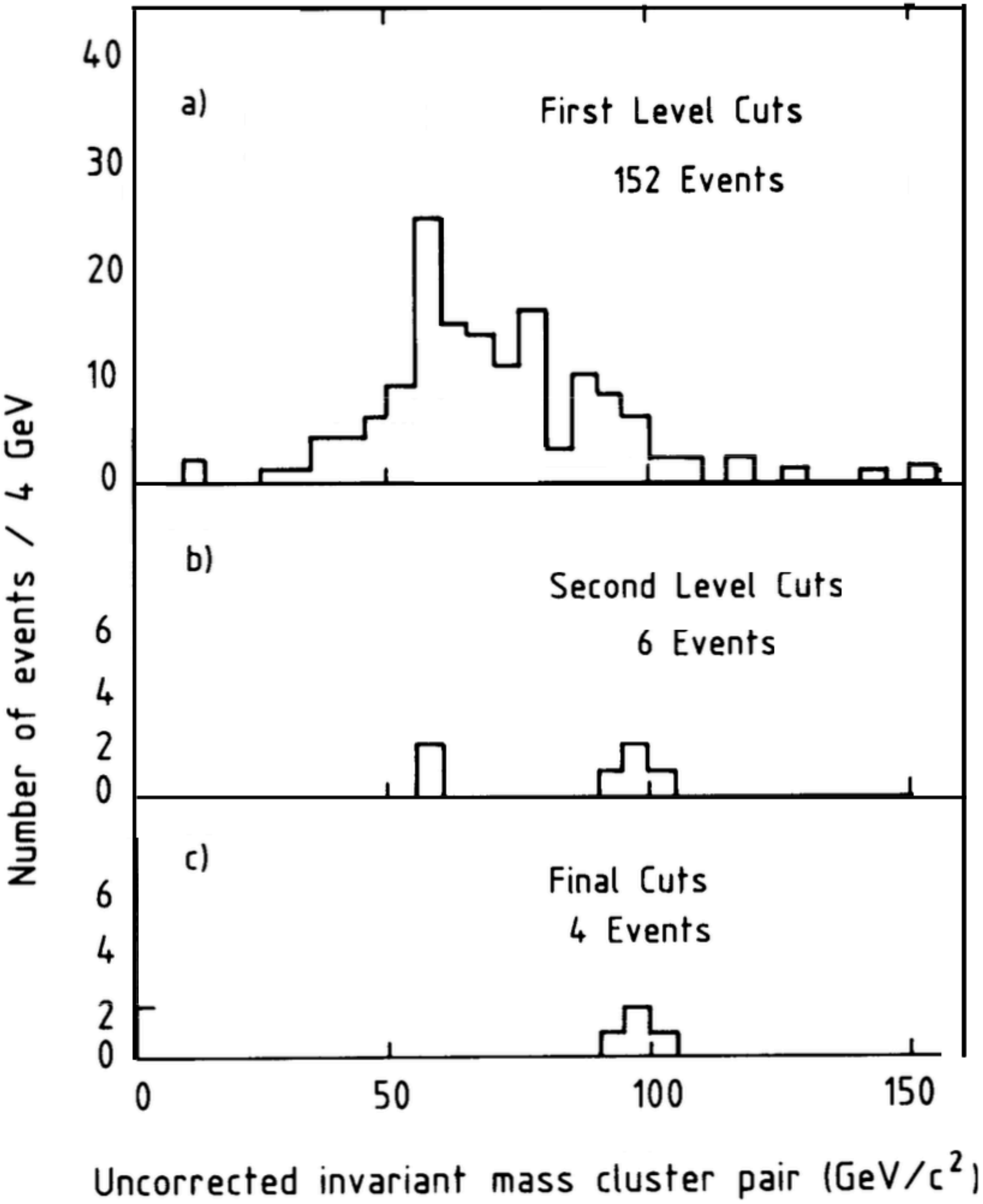


A STEP BACK IN TIME…



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.

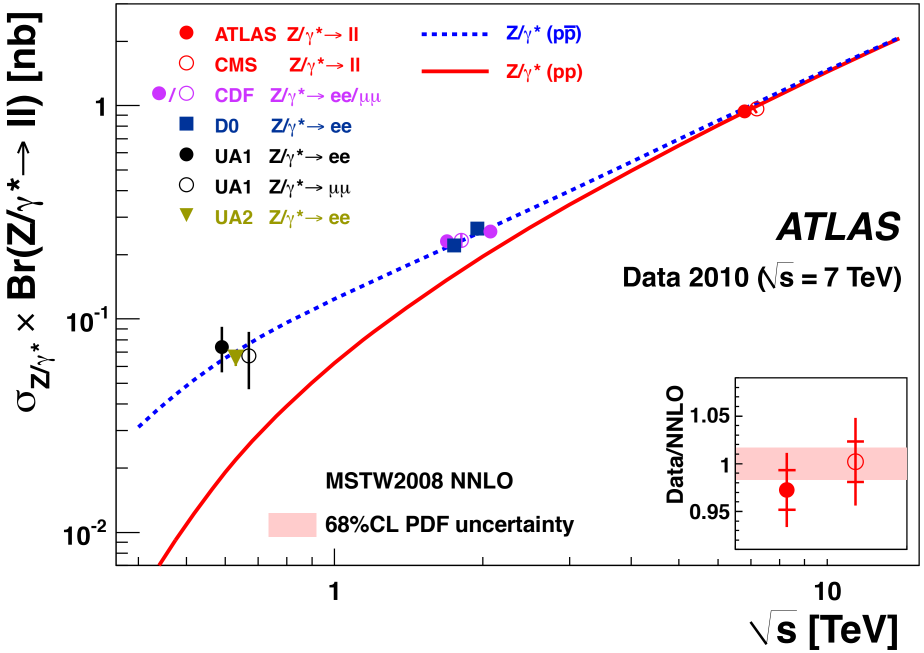
http://www.nobelprize.org/nobel_prizes/physics/laureates/1984/rubbia-lecture.pdf

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

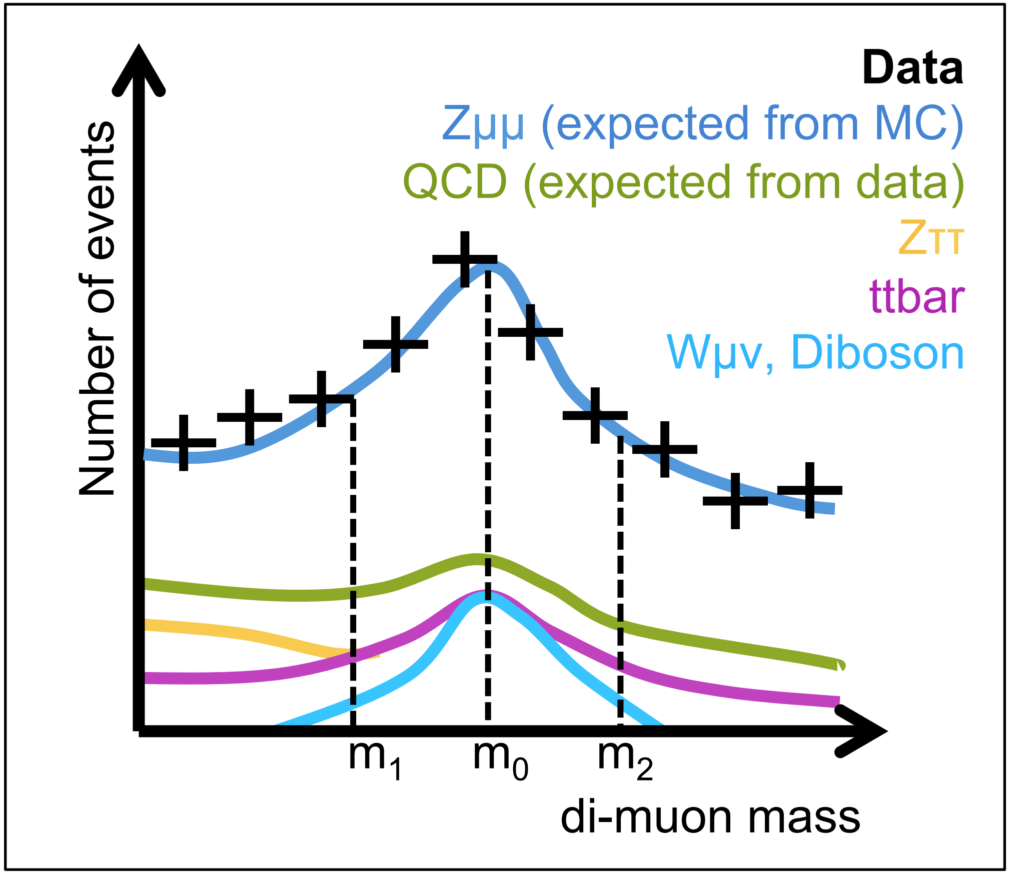
$$\sigma \cdot \mathrm{BR} = \frac{\mathrm{N}}{\alpha \cdot \epsilon \cdot \mathrm{L}}$$

N : number of observed – background events

α : acceptance of selection

ϵ : efficiency of selection

L : luminosity (amount of data)



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

α : acceptance
ϵ : efficiency
L : luminosity

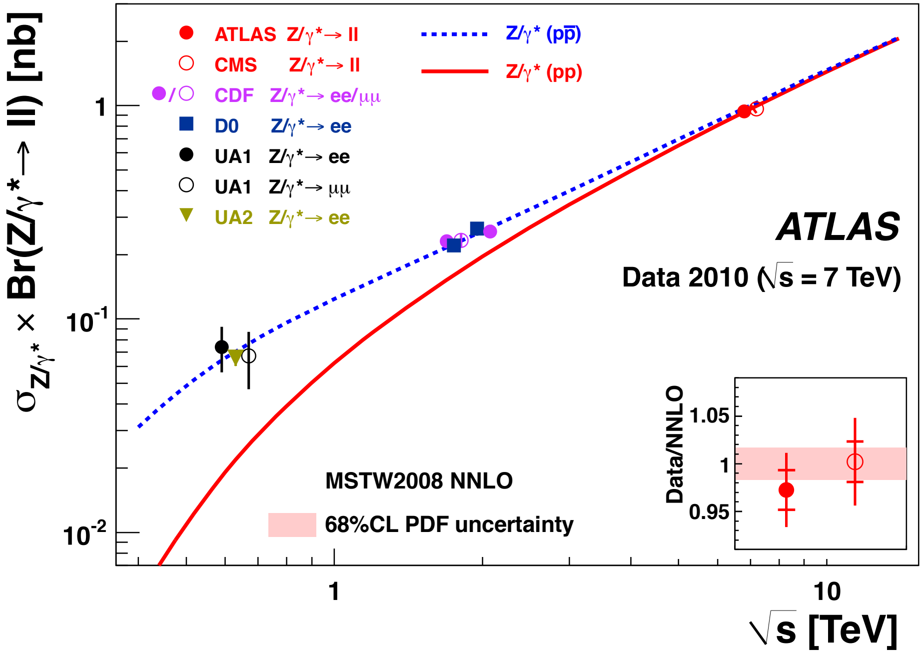
N of events = N of events on data – N of expected background events
α – acceptance = fraction of events passing selection requirements
ε – efficiency = reconstruction efficiency of relevant objects

MEASURING THE Z^0 CROSS-SECTION

Theoretically

Cross-section calculated for:

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



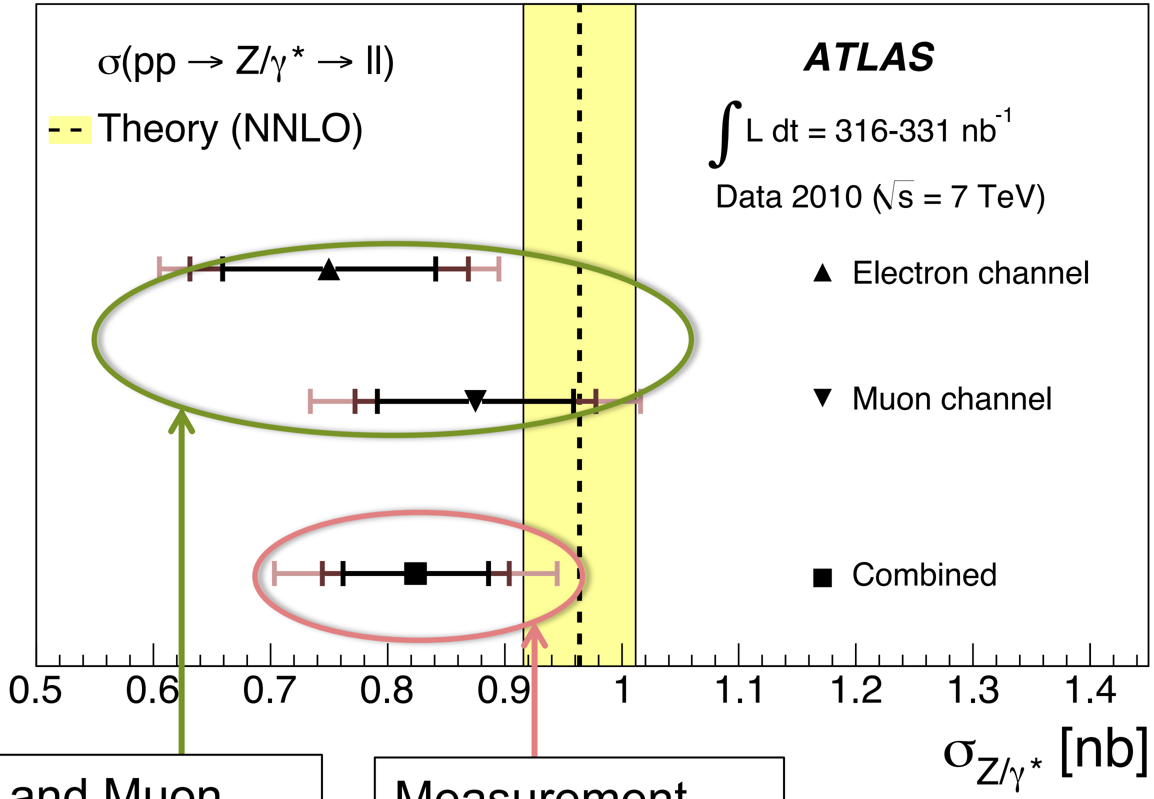
Experimentally

$$\sigma \cdot \mathrm{BR} = \frac{\mathrm{N}}{\alpha\cdot\epsilon\cdot\mathrm{L}}$$

$$\left.\begin{array}{l}\mathrm{N}:\ \text{number of observed -- background events}\\ \alpha:\ \text{acceptance of selection}\\ \epsilon:\ \text{efficiency of selection}\\ \mathrm{L}:\ \text{luminosity (amount of data)}\end{array}\right\}$$

All numbers carry **uncertainties** – both **“statistical”** and **“systematic”**.

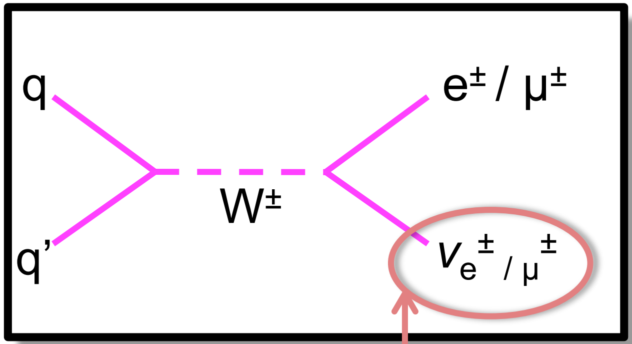
MEASURING THE Z^0 CROSS-SECTION



Electron and Muon channel agree within uncertainties

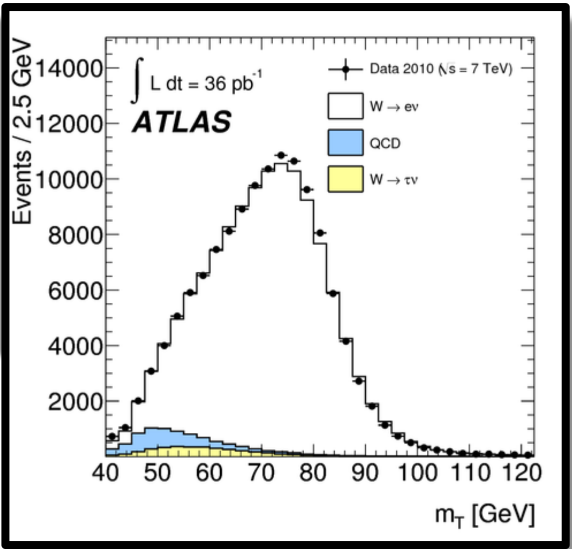
Measurement consistent with prediction within uncertainties

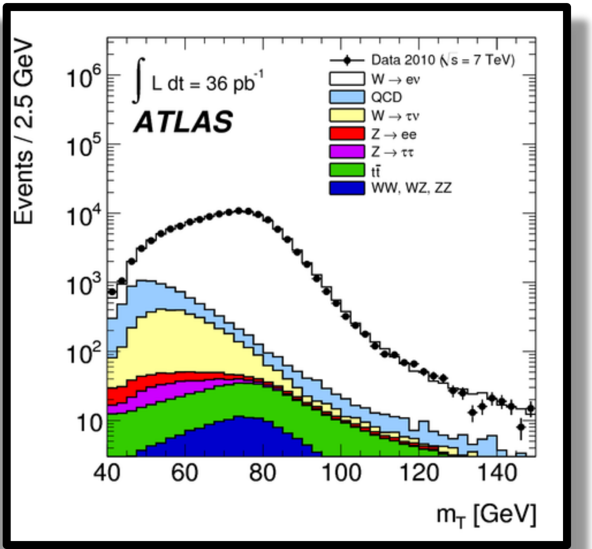
MEASURING THE W CROSS-SECTION

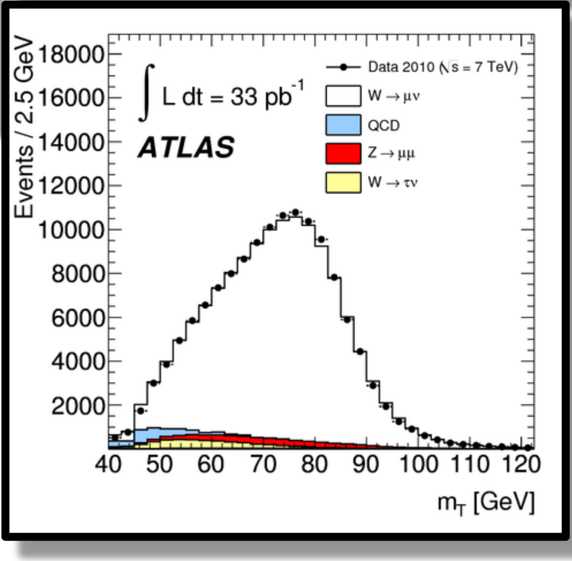


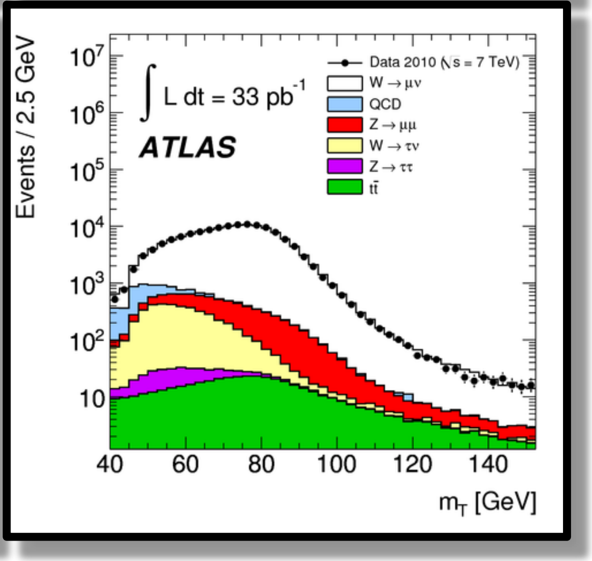
Available in the transverse plane only!

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

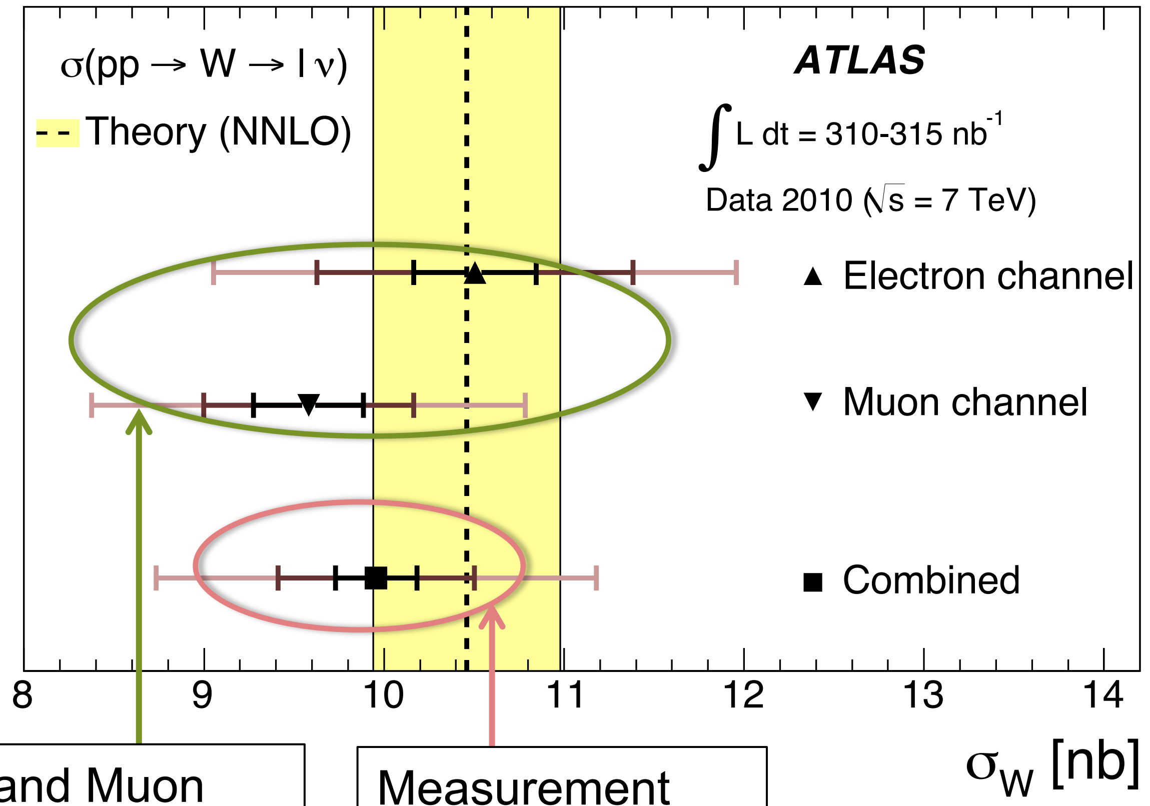








MEASURING THE W CROSS-SECTION

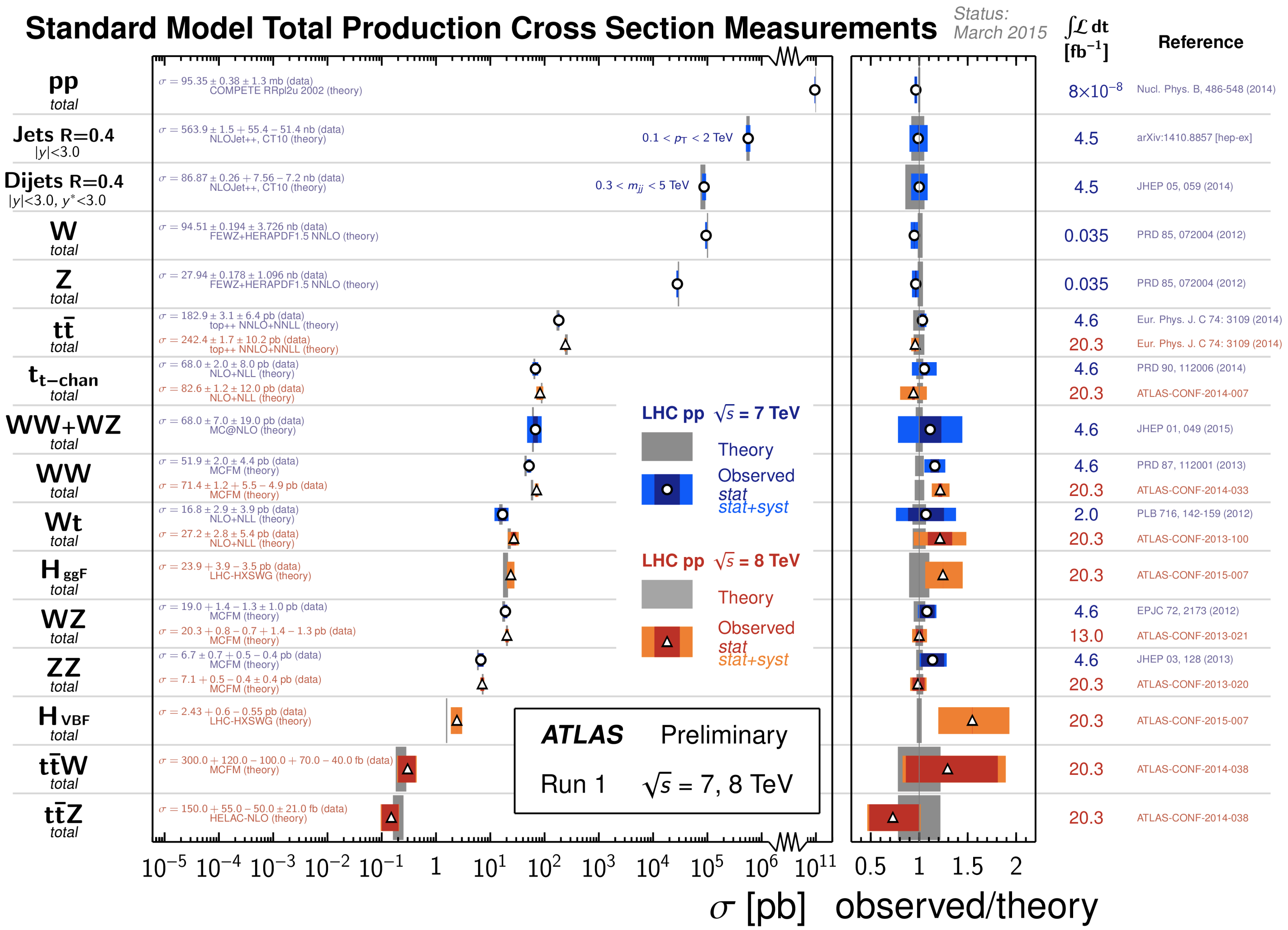


Electron and Muon channel agree within uncertainties

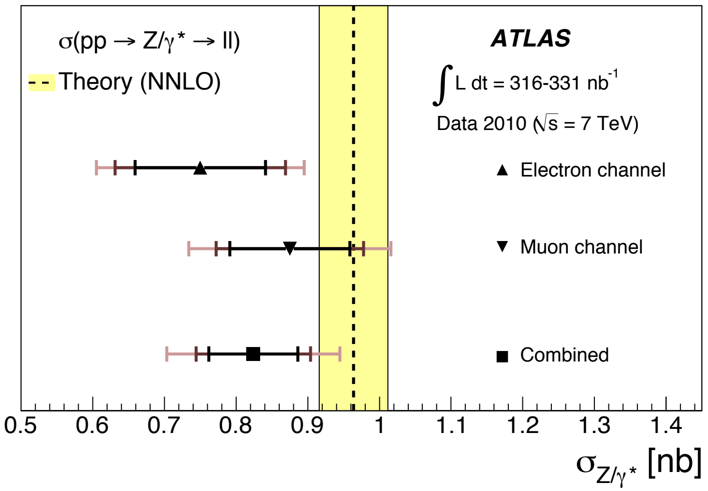
Measurement consistent with prediction within uncertainties

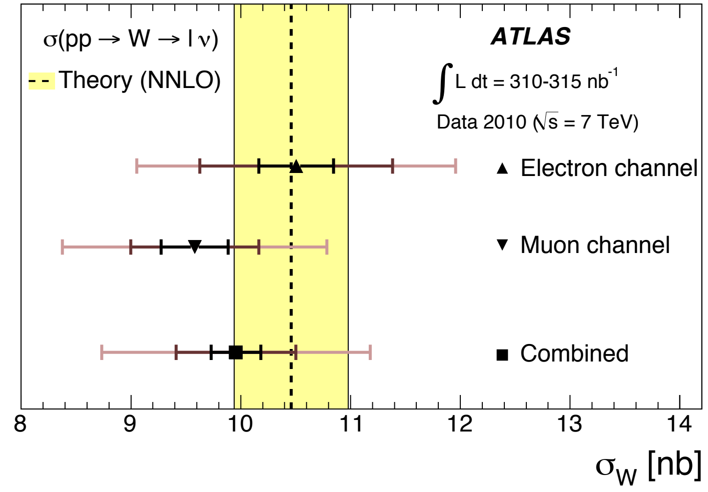
“FINAL” CALIBRATION

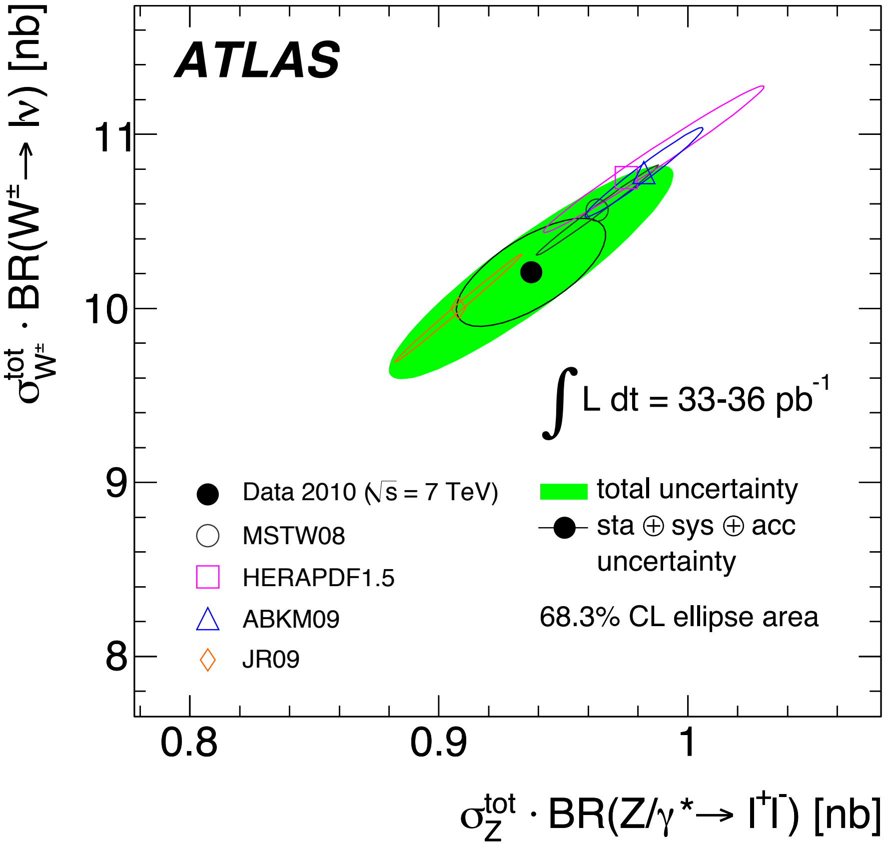
Reminder!

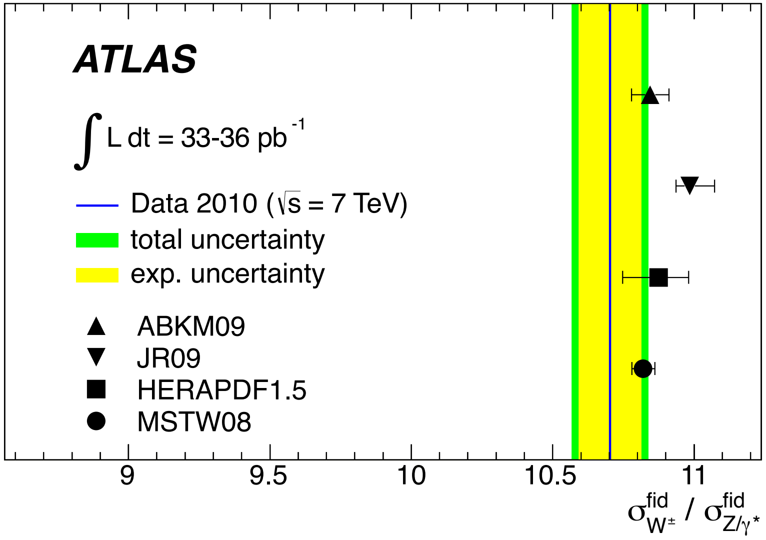


MEASURING CROSS-SECTION RATIOS









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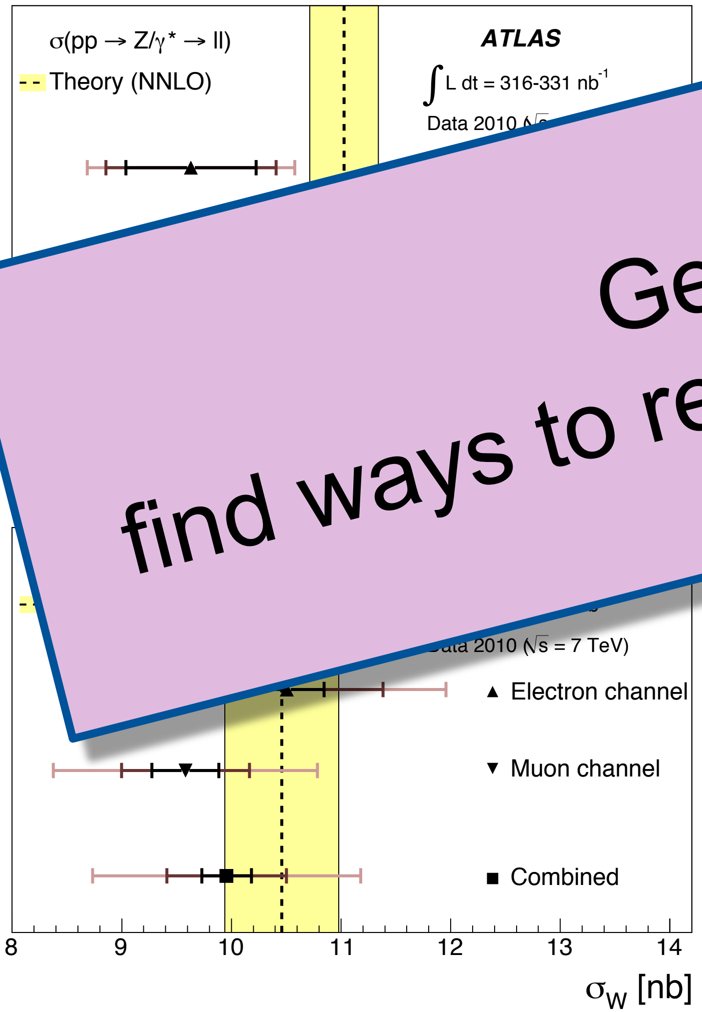
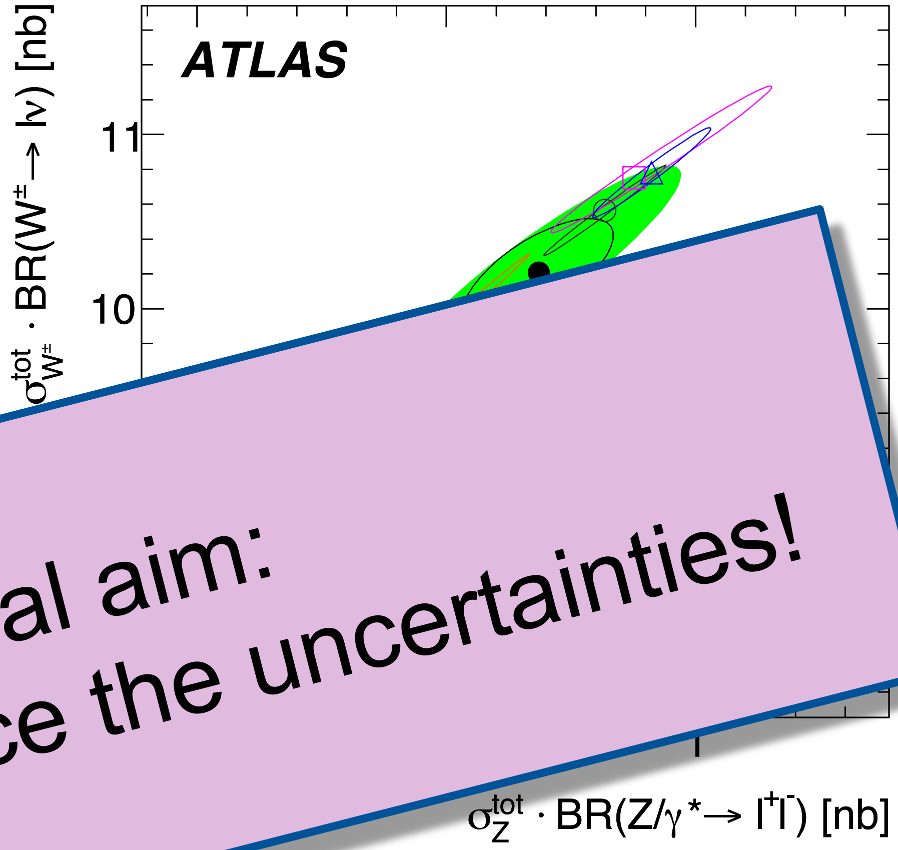
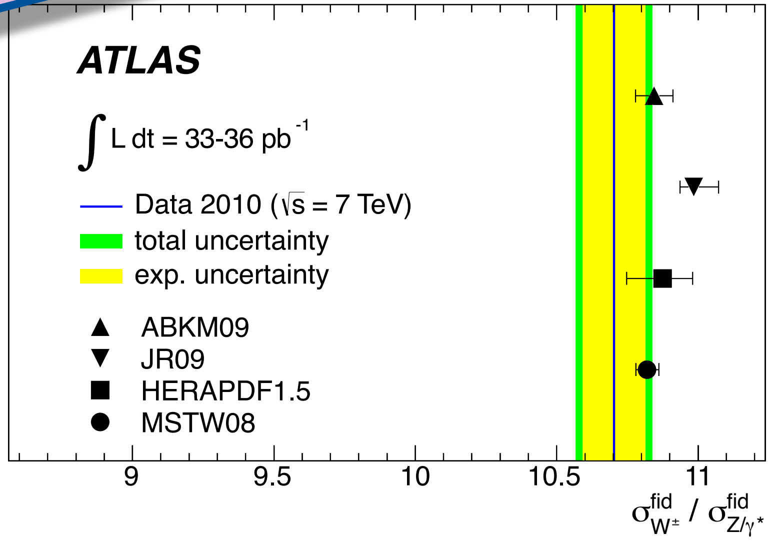
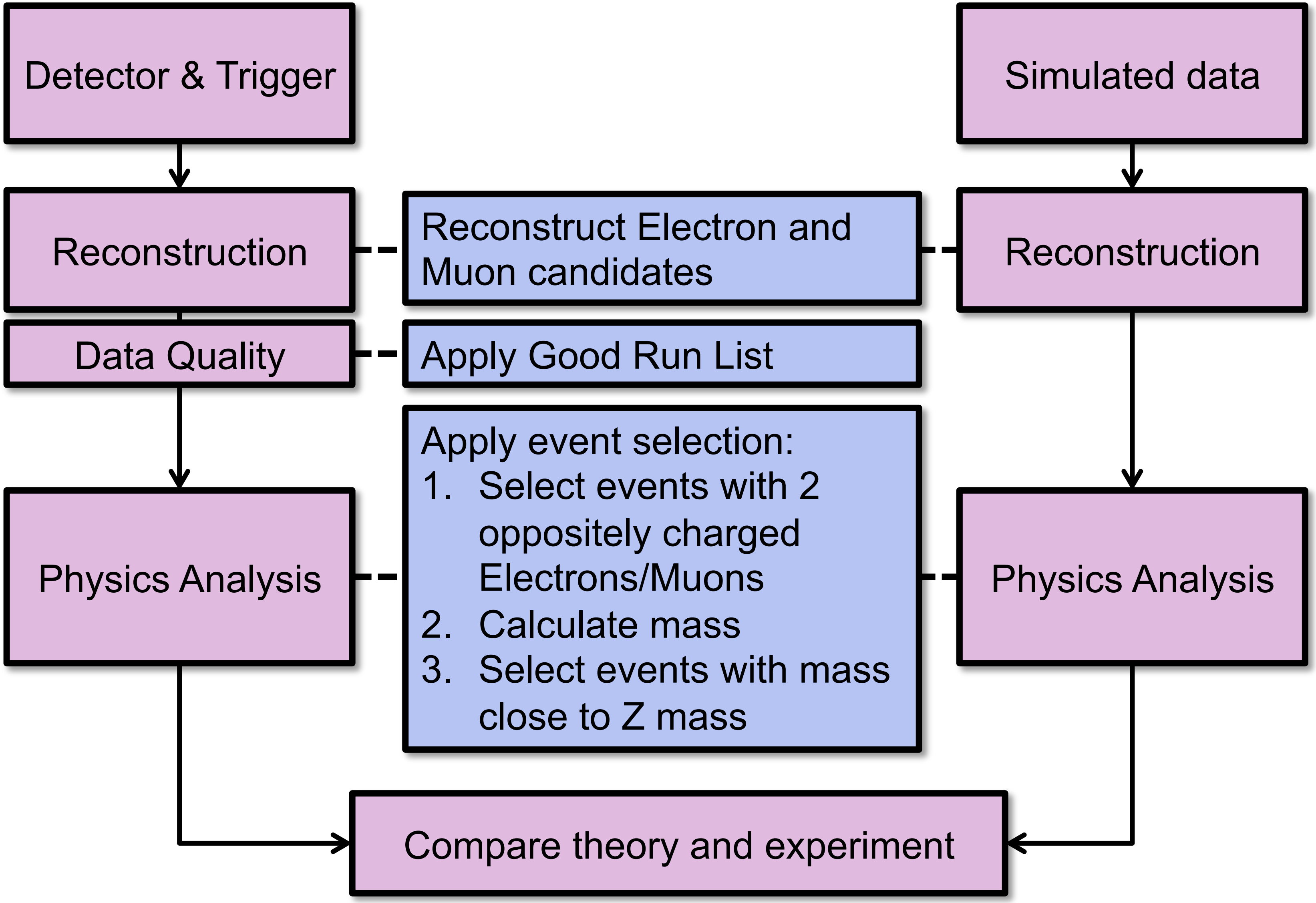






General aim:
find ways to reduce the uncertainties!

ANALYSIS FLOW IN Z^0 CROSS-SECTION MEASUREMENT



Detector & Trigger

Simulated data

Reconstruction

Reconstruct Electron and Muon candidates

Reconstruction

Data Quality

Apply Good Run List

Physics Analysis

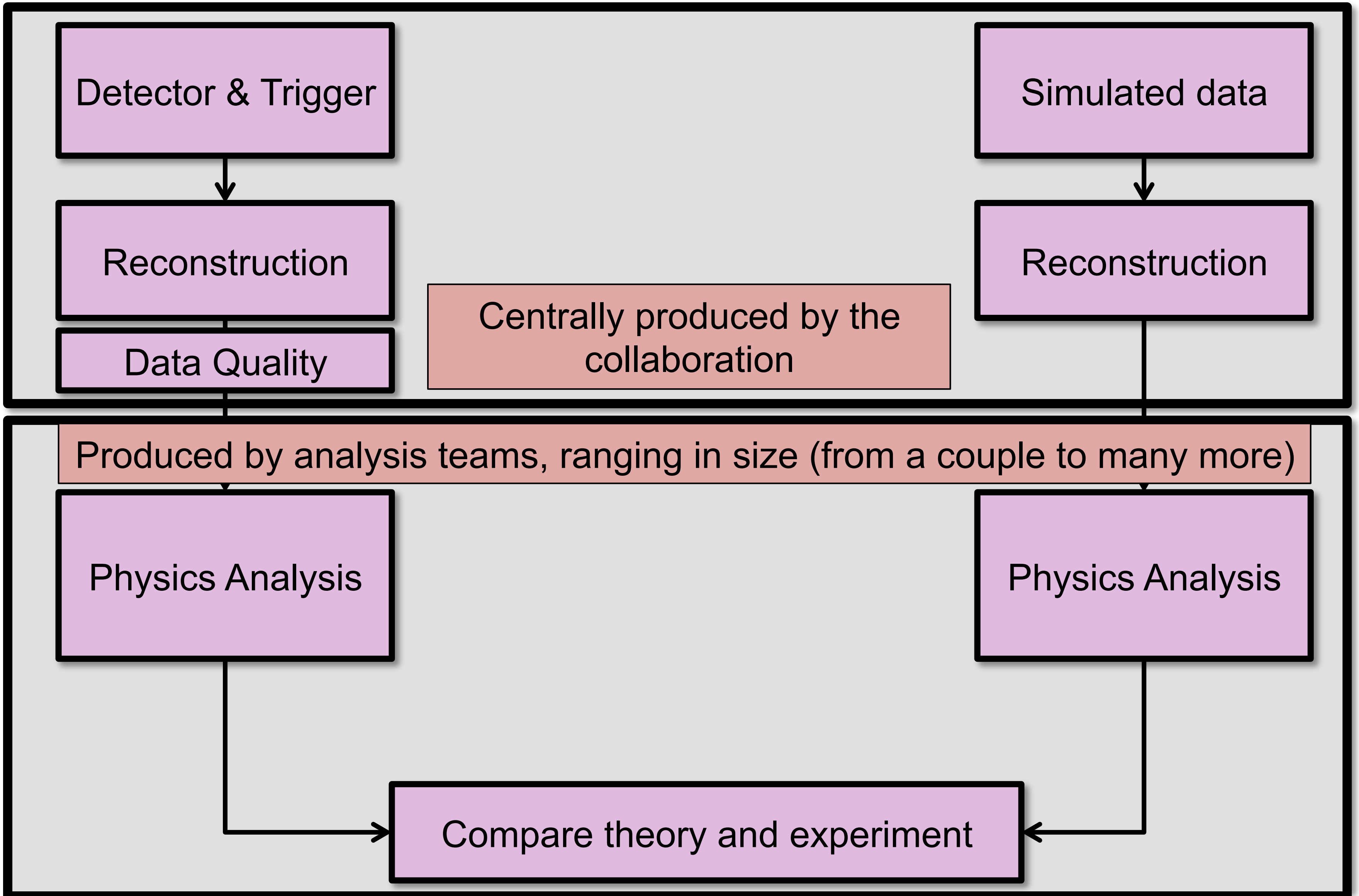
Apply event selection:

1. Select events with 2 oppositely charged Electrons/Muons
2. Calculate mass
3. Select events with mass close to Z mass

Physics Analysis

Compare theory and experiment

ANALYSIS FLOW IN Z^0 CROSS-SECTION MEASUREMENT



Detector & Trigger

Reconstruction

Data Quality

Simulated data

Reconstruction

Centrally produced by the collaboration

Produced by analysis teams, ranging in size (from a couple to many more)

Physics Analysis

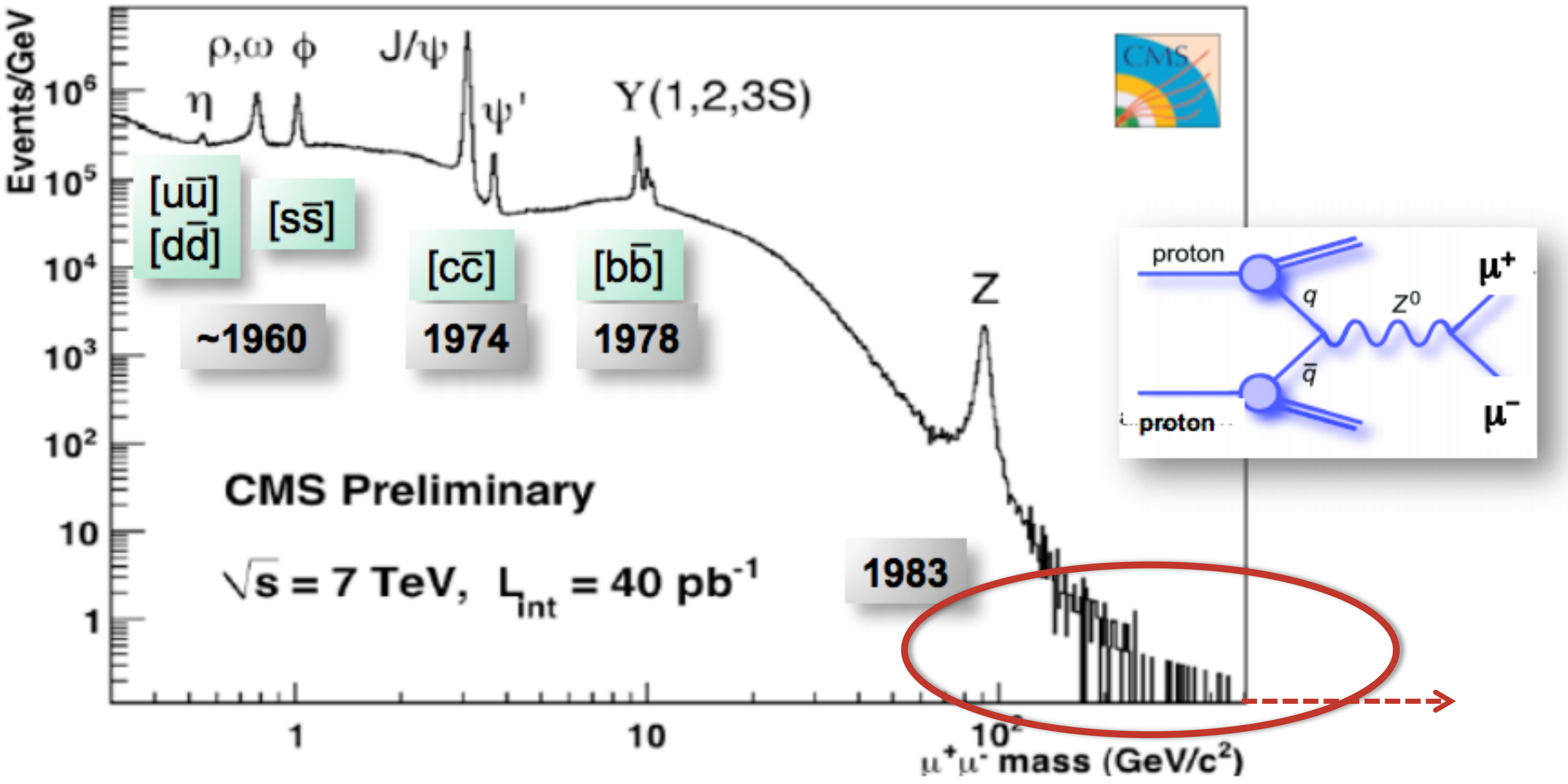
Physics Analysis

Compare theory and experiment

ANOTHER SIMPLE EXAMPLE:

SEARCH FOR A HEAVY Z’

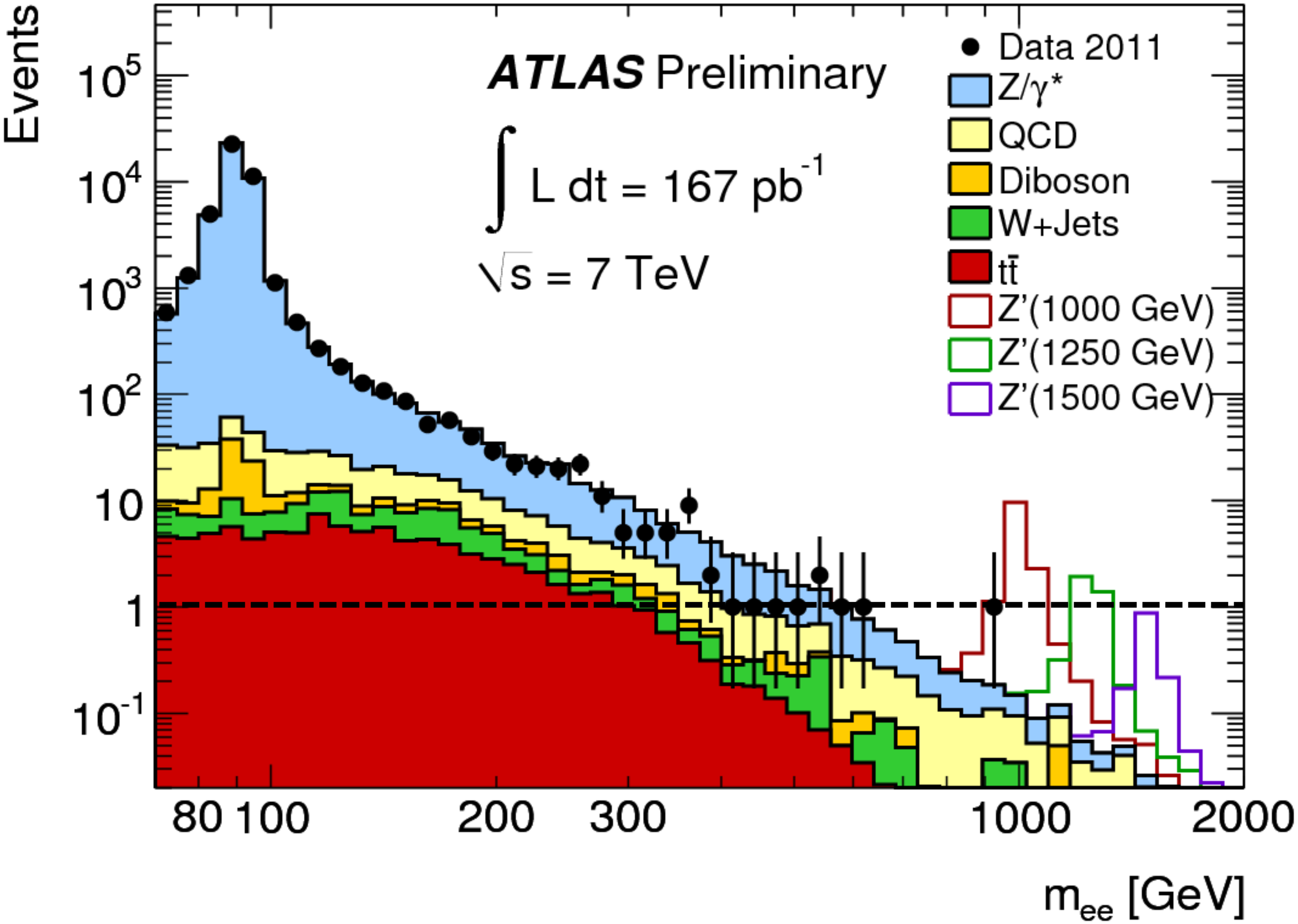
WHAT IS THIS SEARCH ABOUT



What's out there?

SEARCH FOR A NEW HEAVY Z'

- **Like Z->ee but at higher mass.**



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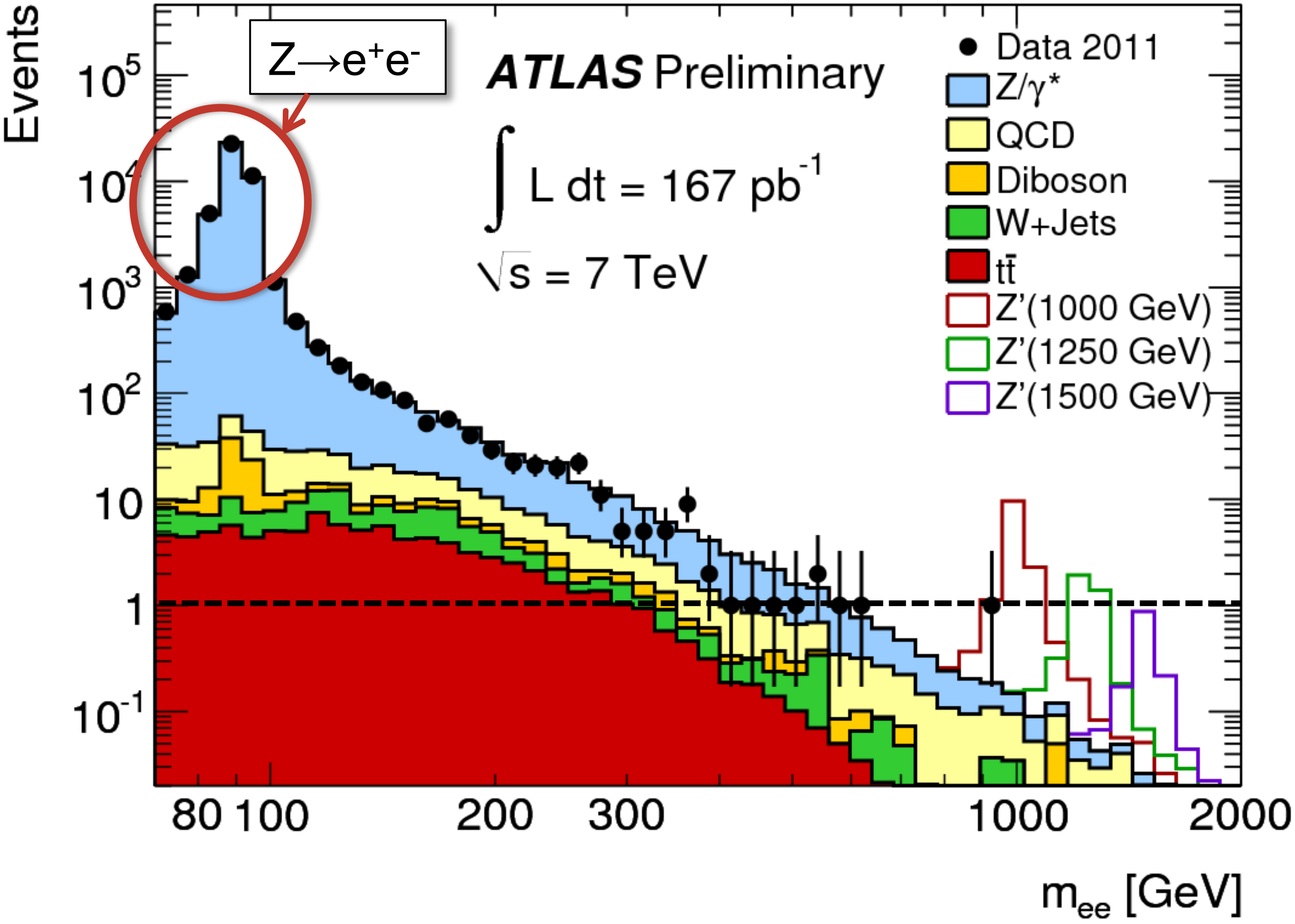

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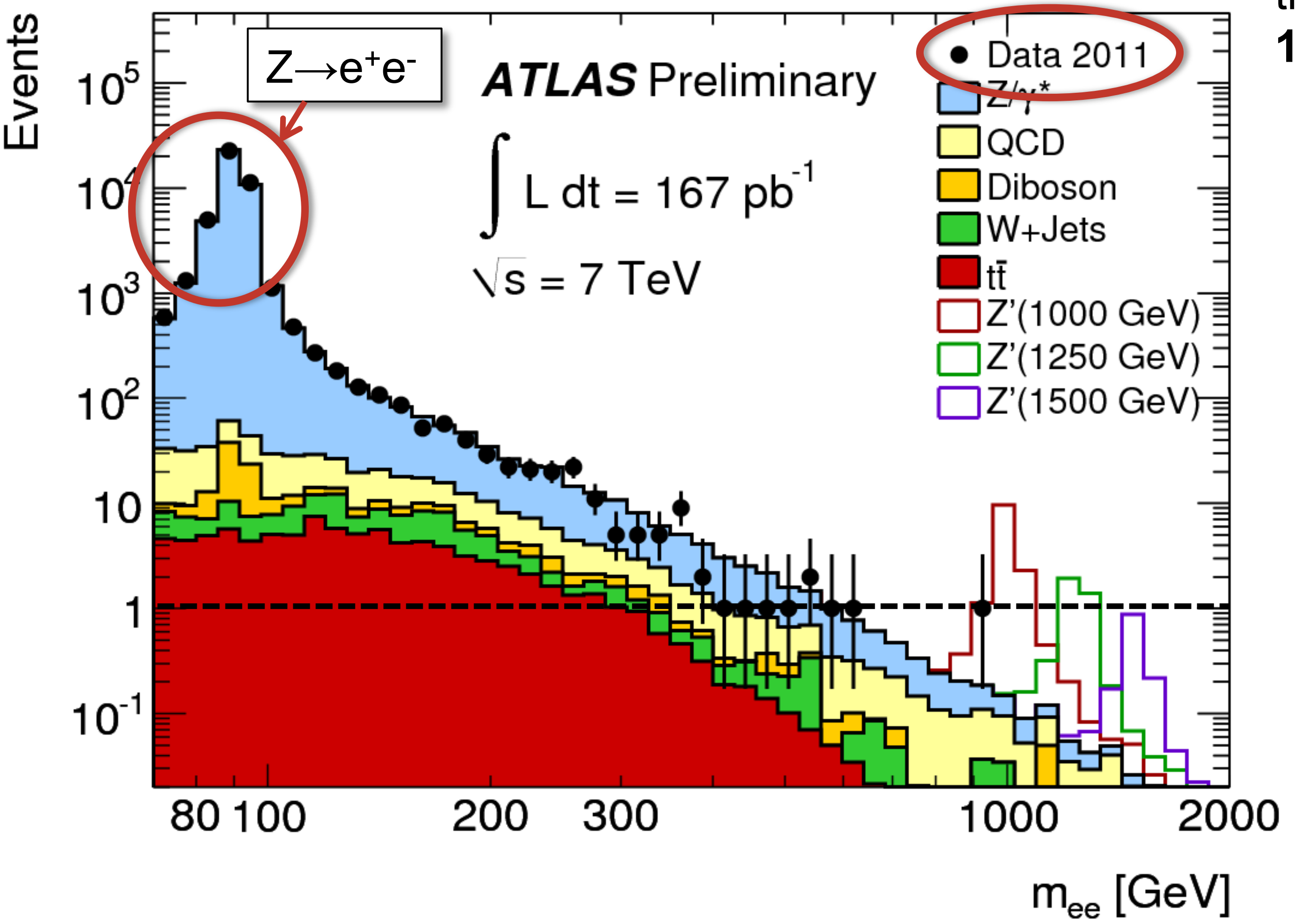
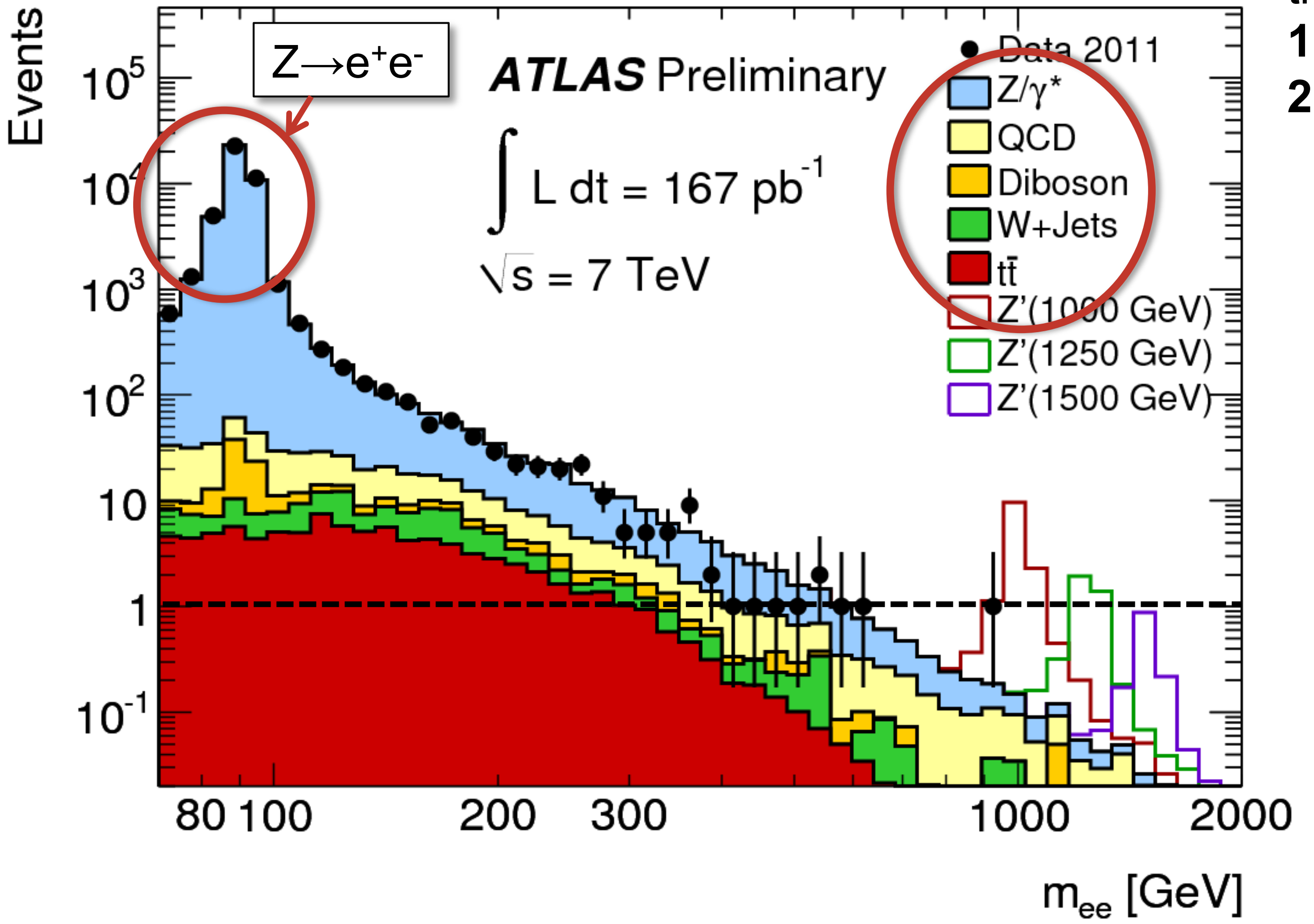


Select 2 electron candidates and plot their invariant mass for:

1. **Data**

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**

SEARCH FOR A NEW HEAVY Z’

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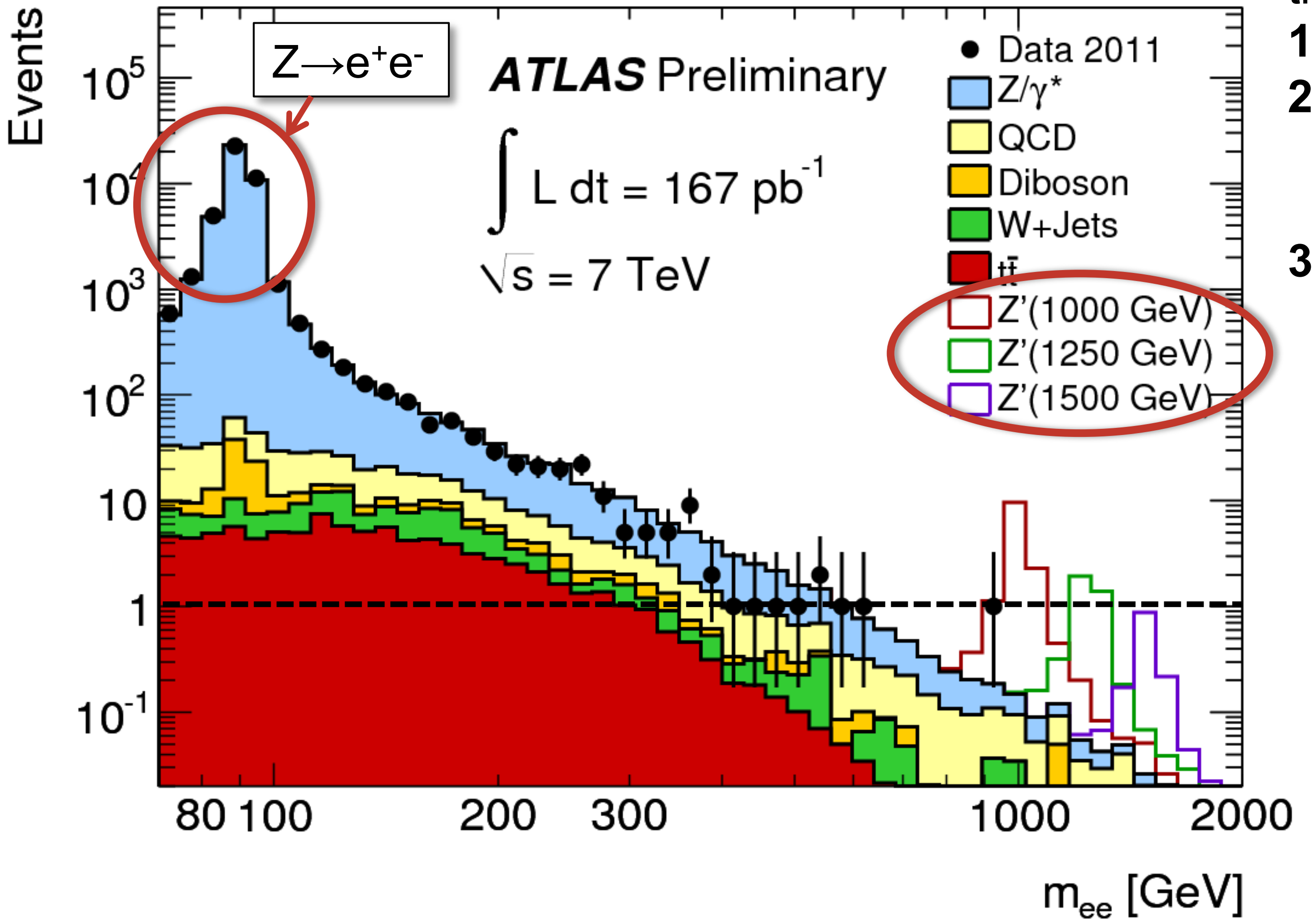
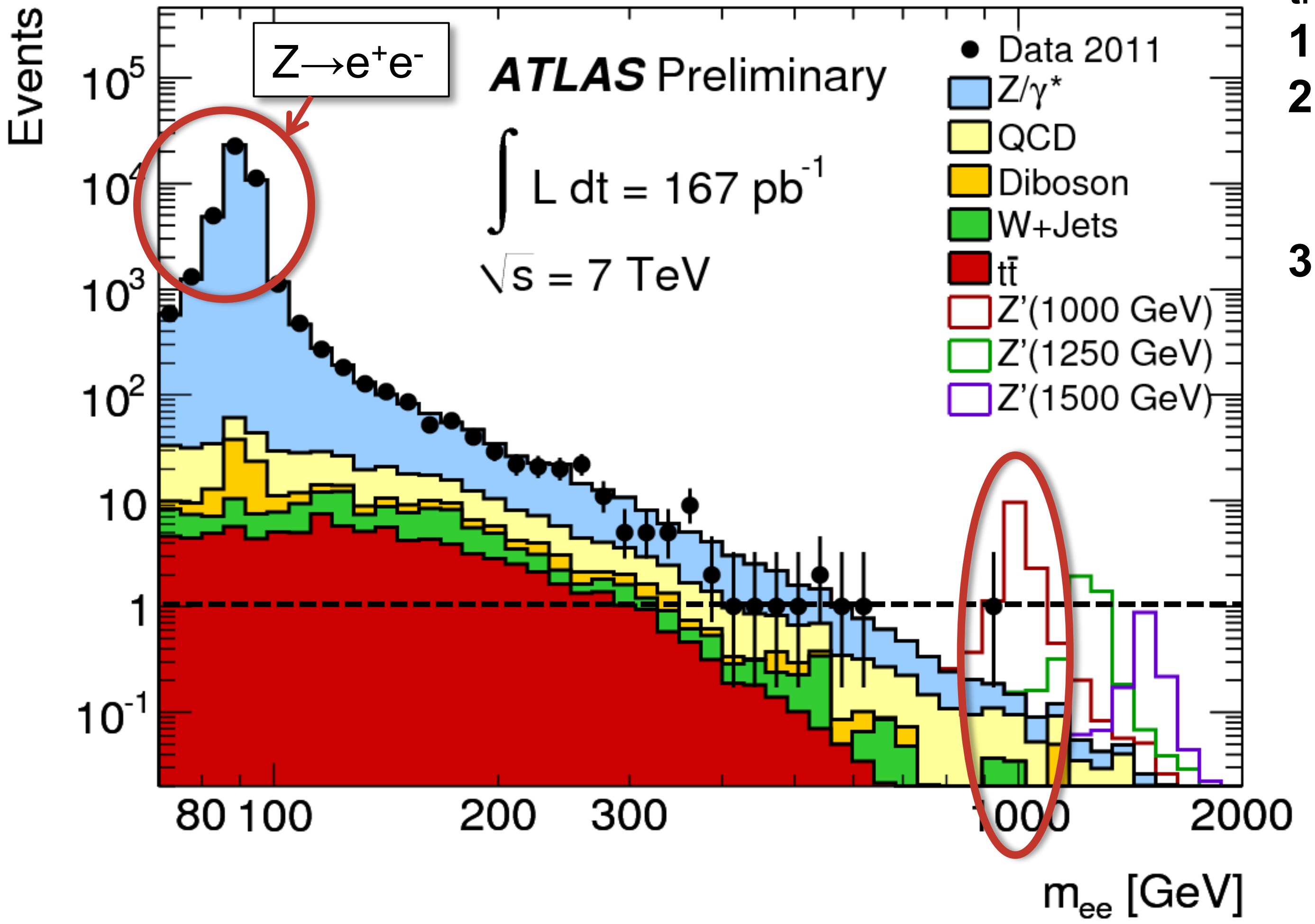


Select 2 electron candidates and plot their invariant mass for:

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

SEARCH FOR A NEW HEAVY Z'

- Like Z->ee but at higher mass.



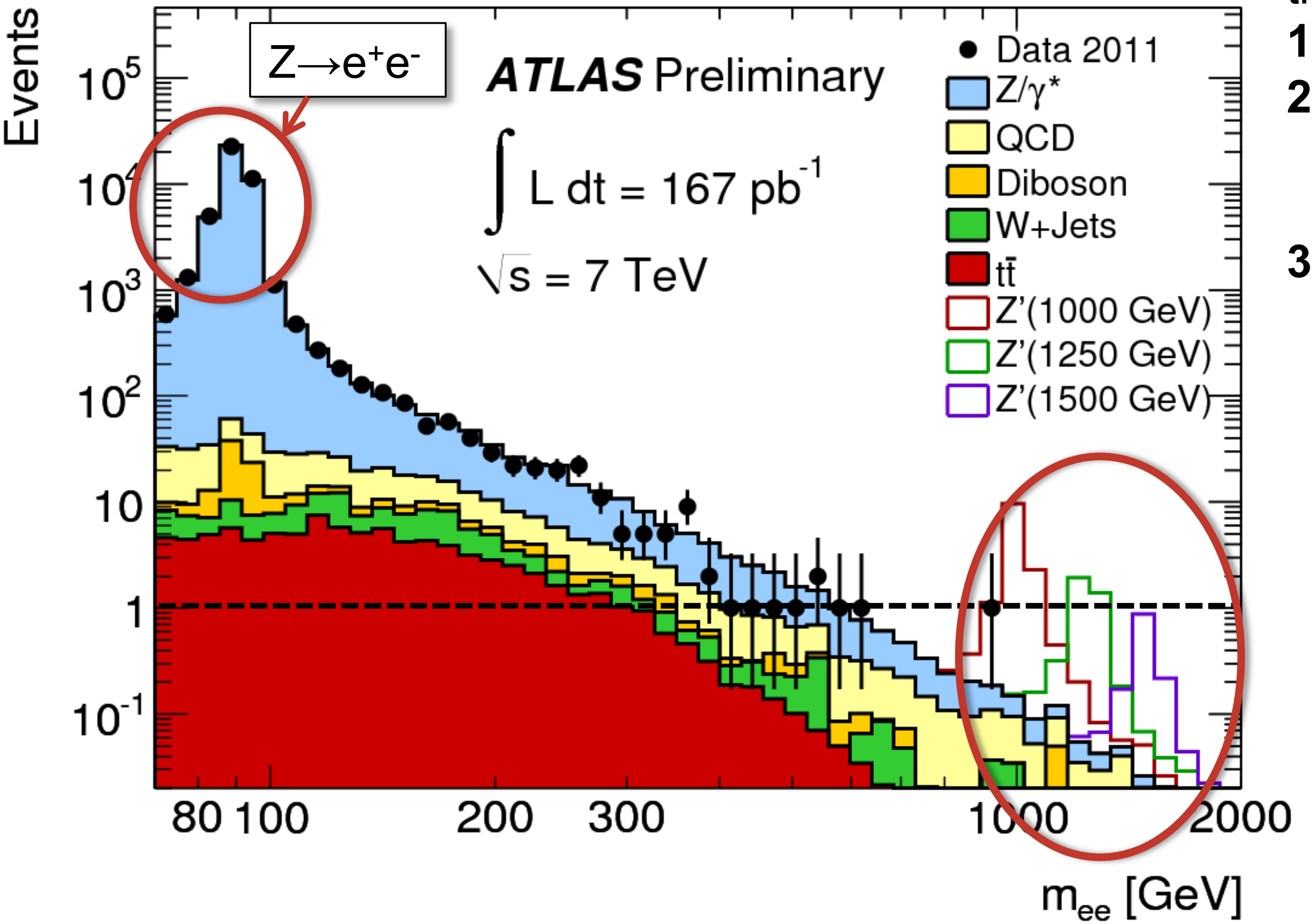
Select 2 electron candidates and plot their invariant mass for:

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.**



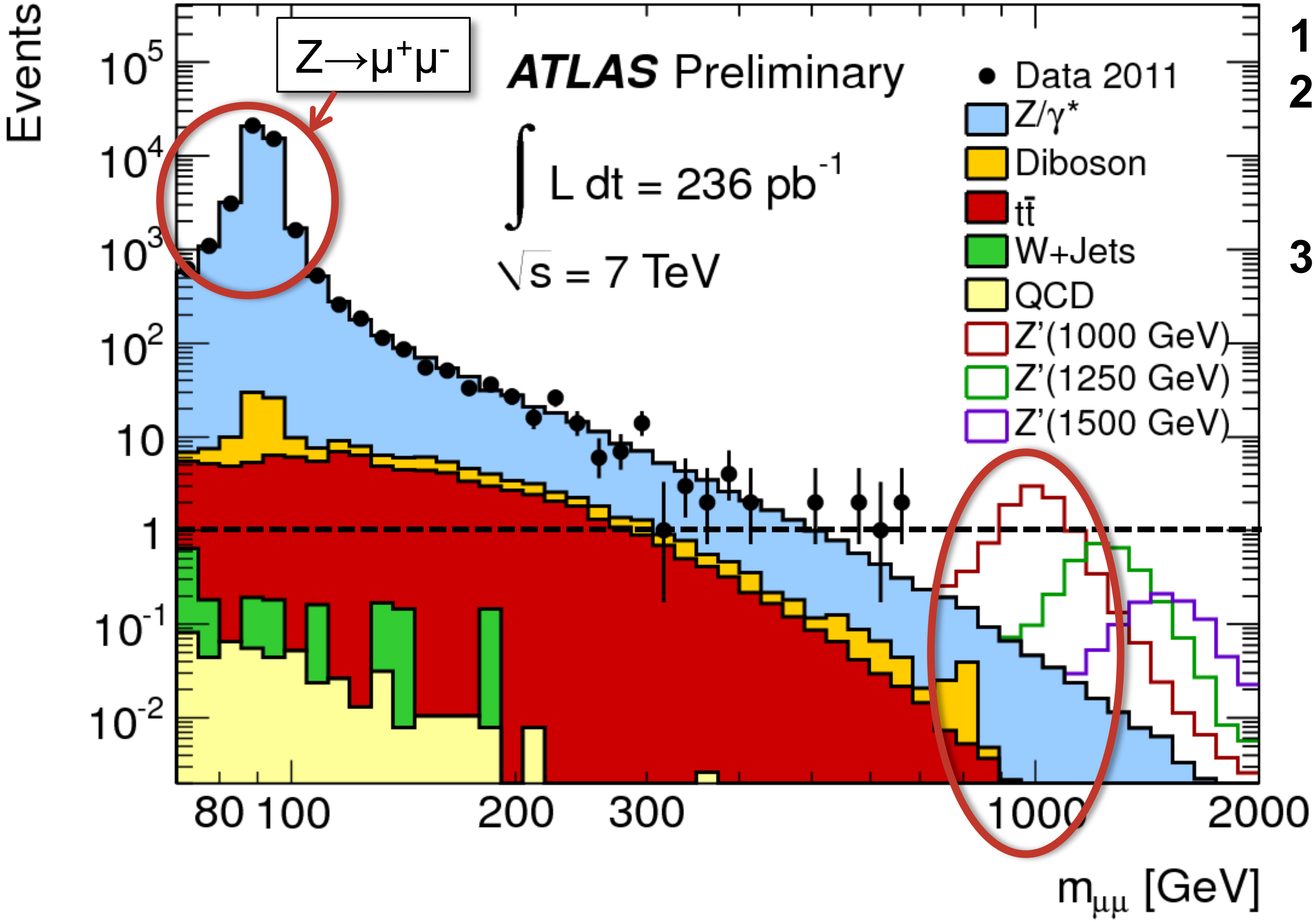
Select 2 electron candidates and plot their invariant mass for:

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**

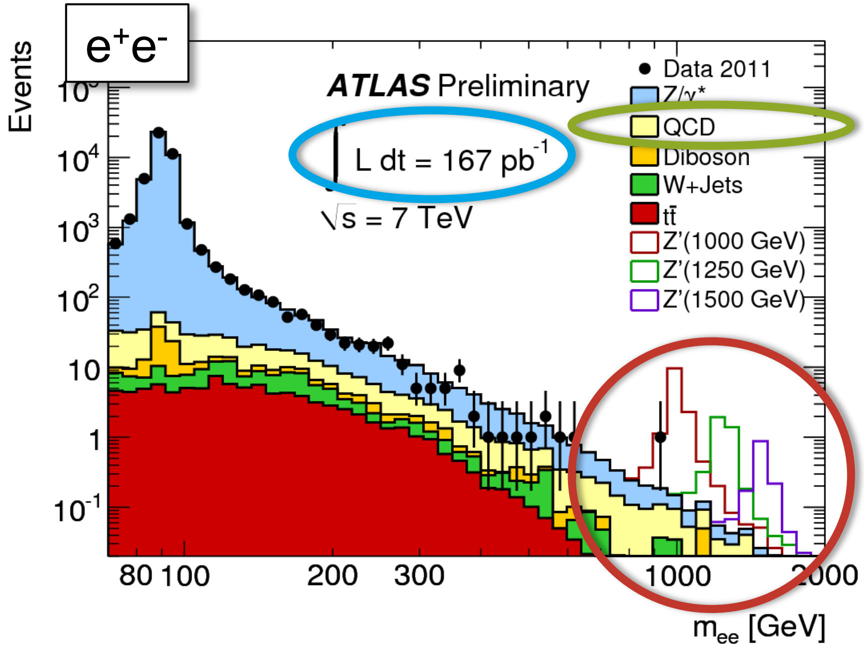


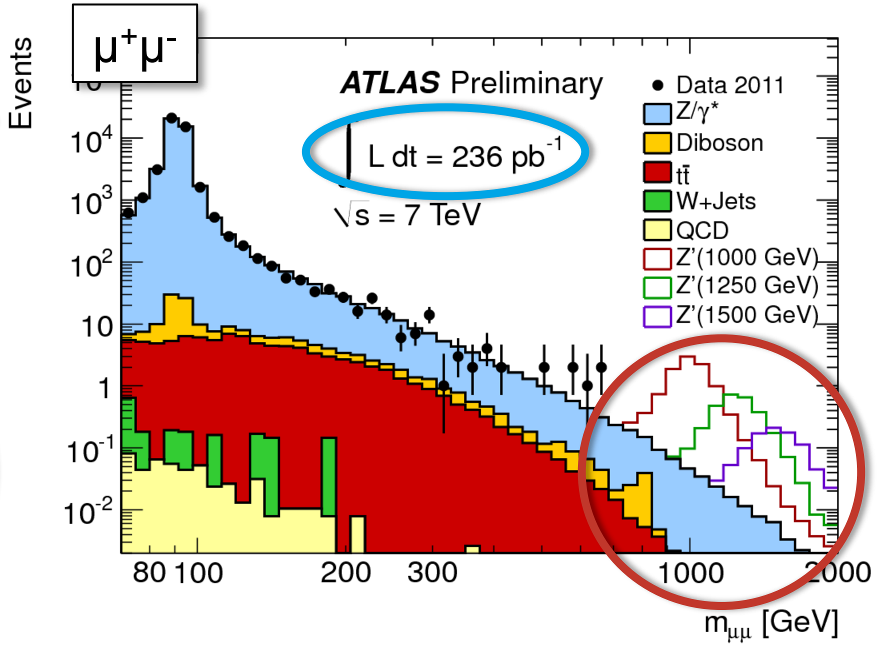
Select 2 muon candidates and plot their invariant mass for:

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

Data inconsistent with a 1TeV Z'

A SMALL COMPARISON

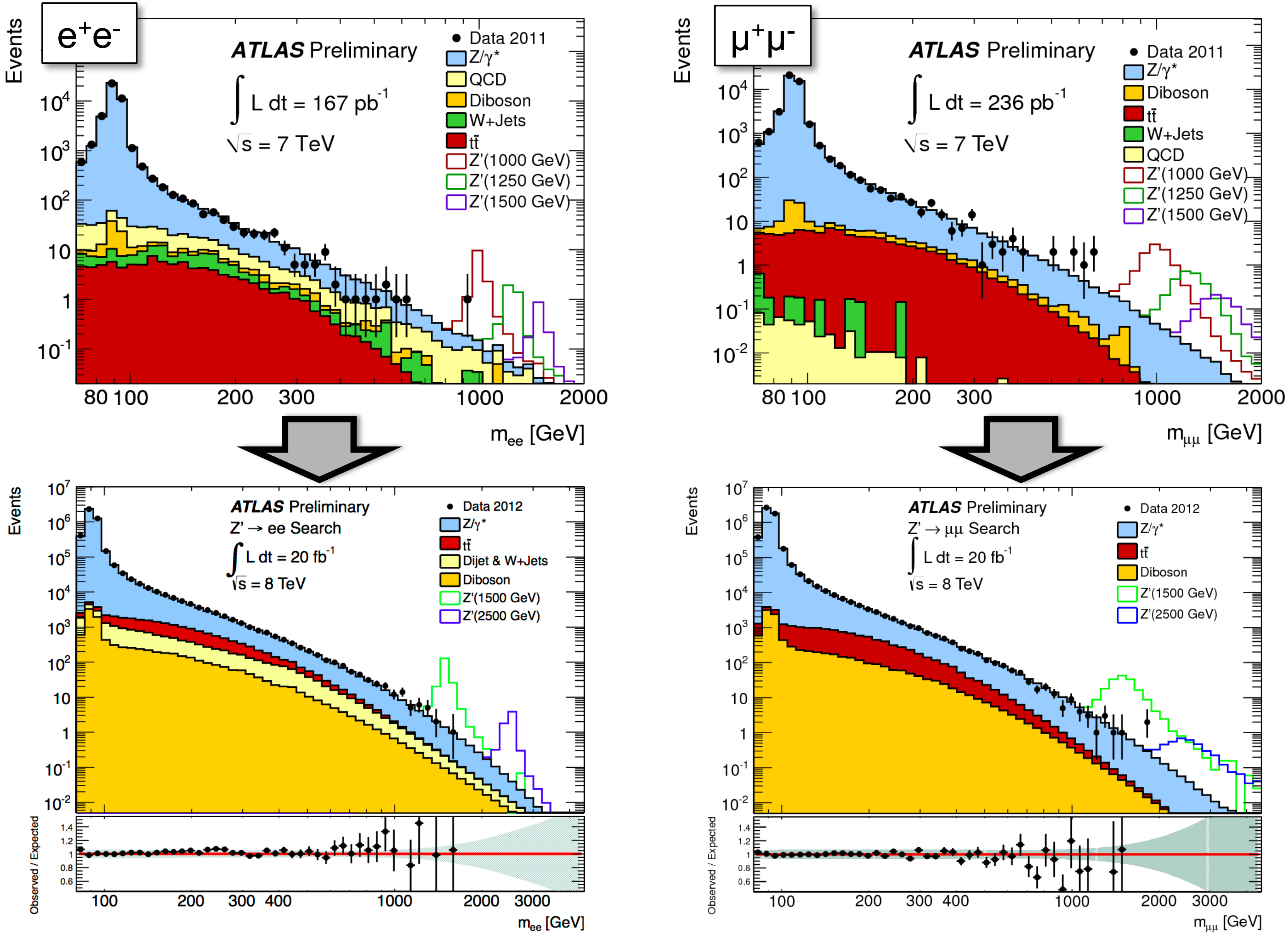




Differences in:

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

EVOLUTION...

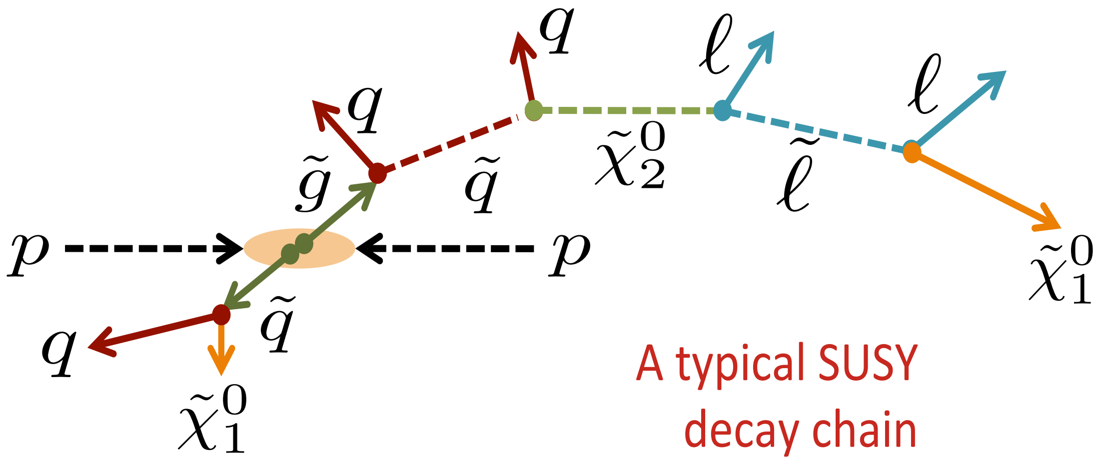

e+e-
μ+μ-
Events
ATLAS Preliminary
∫ L dt = 167 pb-1
√s = 7 TeV
Data 2011
Z/γ*
QCD
Diboson
W+Jets
tt̄
Z'(1000 GeV)
Z'(1250 GeV)
Z'(1500 GeV)
m_ee [GeV]
∫ L dt = 236 pb-1
m_μμ [GeV]
10^4
10^3
10^2
10
1
10^-1
10^-2
80 100
200
300
1000
2000
Z' → ee Search
Z' → μμ Search
∫ L dt = 20 fb-1
√s = 8 TeV
Data 2012
Dijet & W+Jets
Z'(1500 GeV)
Z'(2500 GeV)
10^7
10^6
10^5
Observed / Expected
1.4
1.2
1
0.8
0.6
100
400
3000

THANK YOU MARIO!

BUT OUR PRINCESS IS IN
ANOTHER CASTLE!

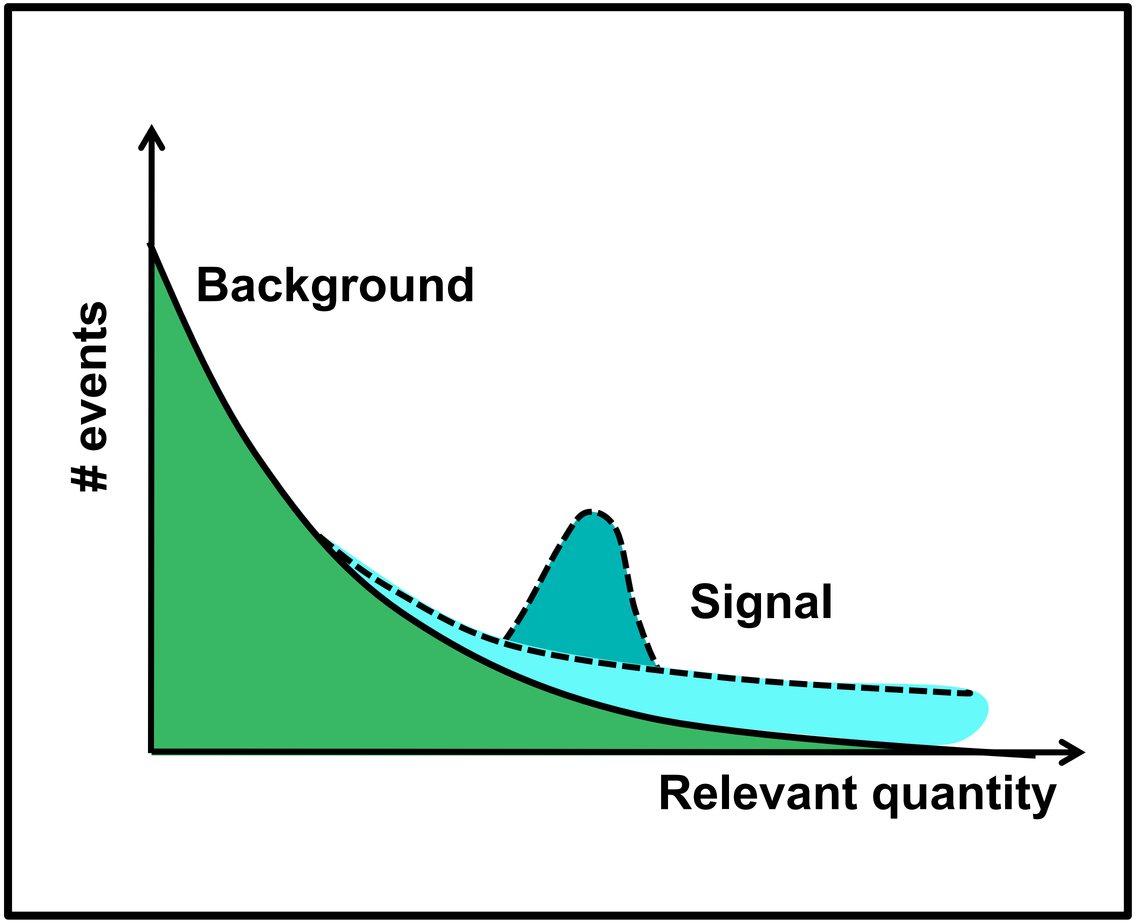
AND A MORE COMPLICATED EXAMPLE:

SEARCH FOR SUSY IN EVENTS WITH LARGE JET MULTIPLICITIES

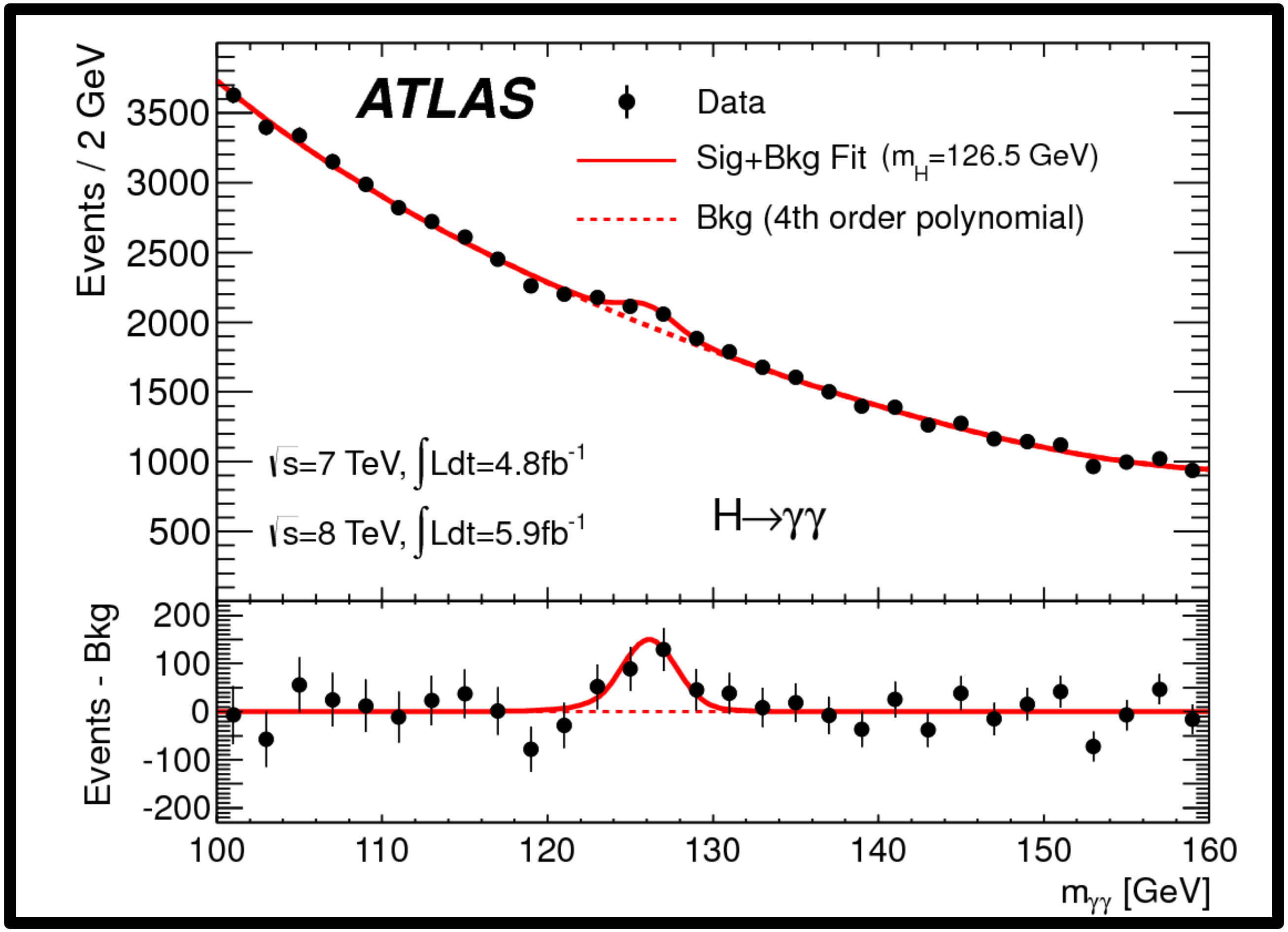


A typical SUSY decay chain

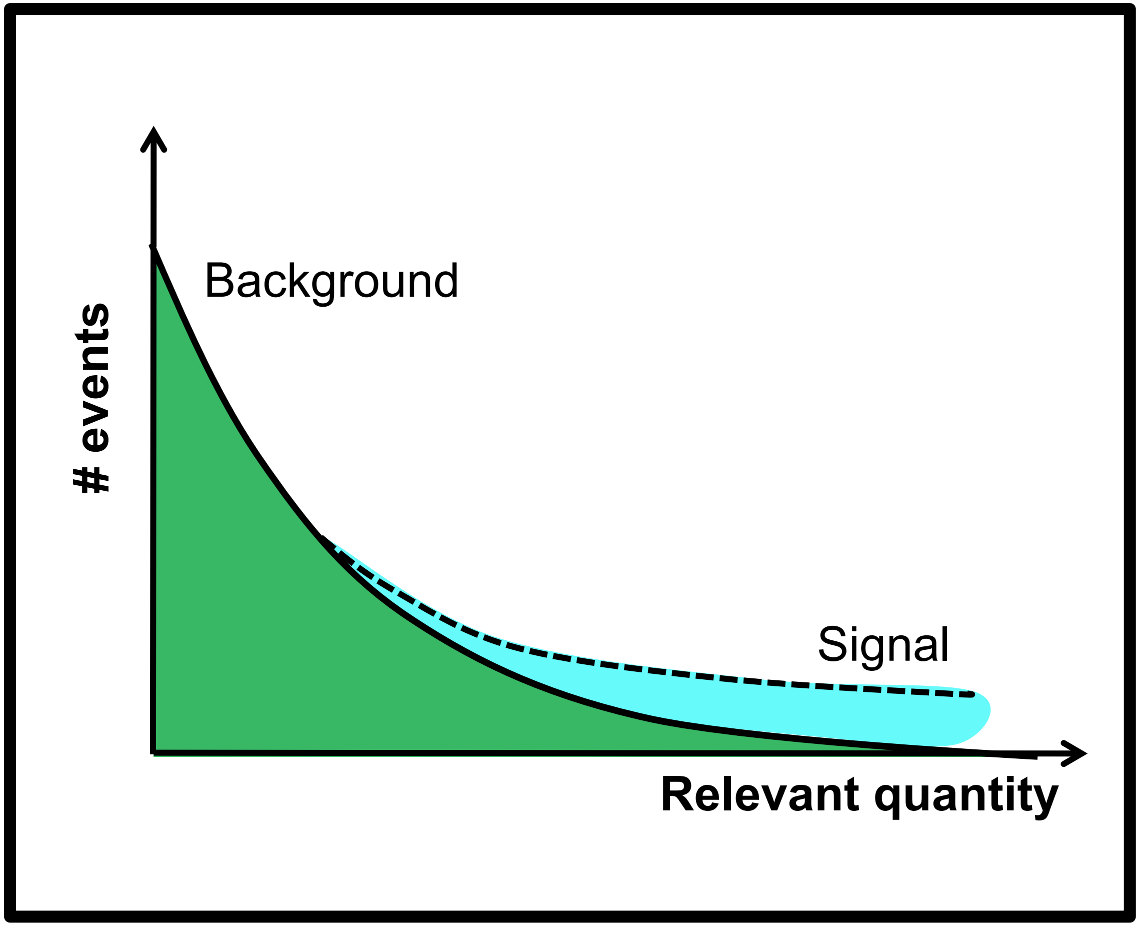
SEARCHES...



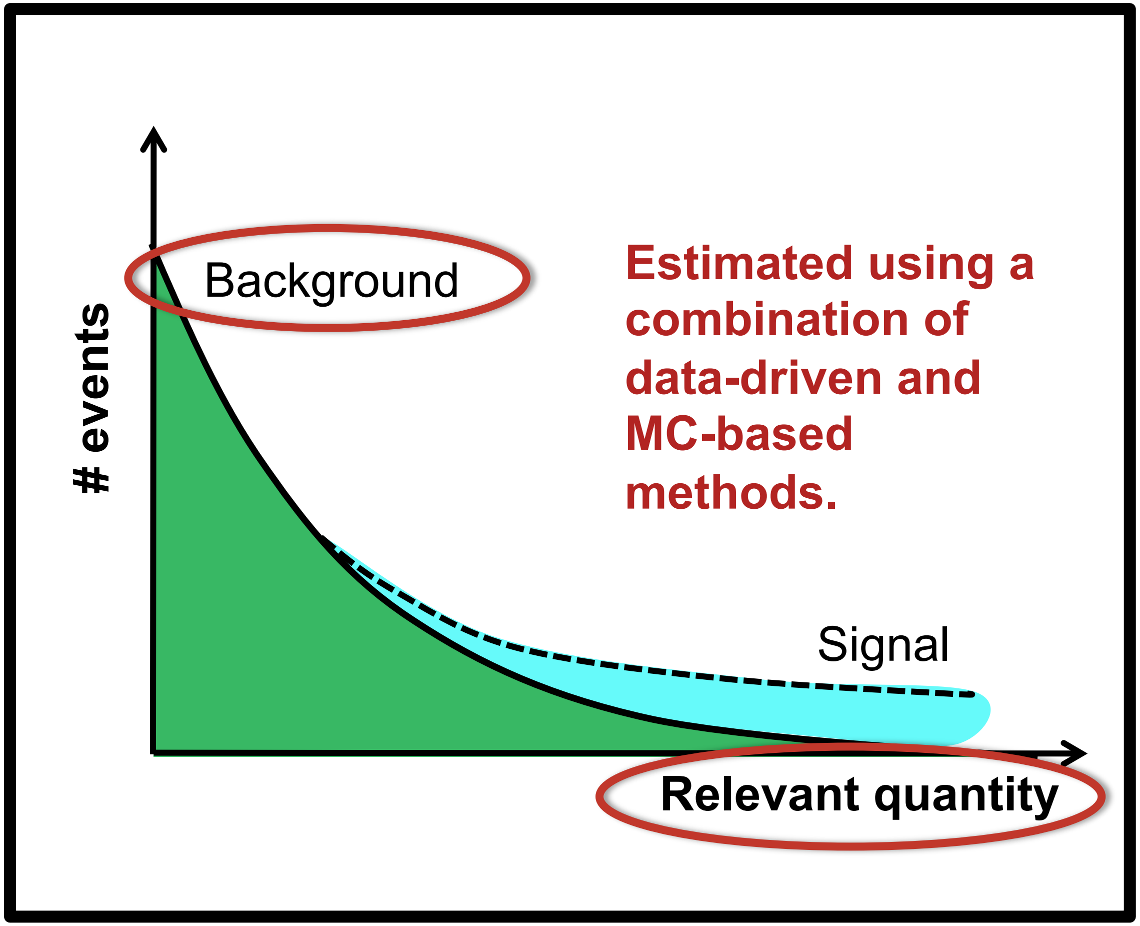
A “WELL KNOWN” BUMP SEARCH



TYPICAL SUSY SEARCHES



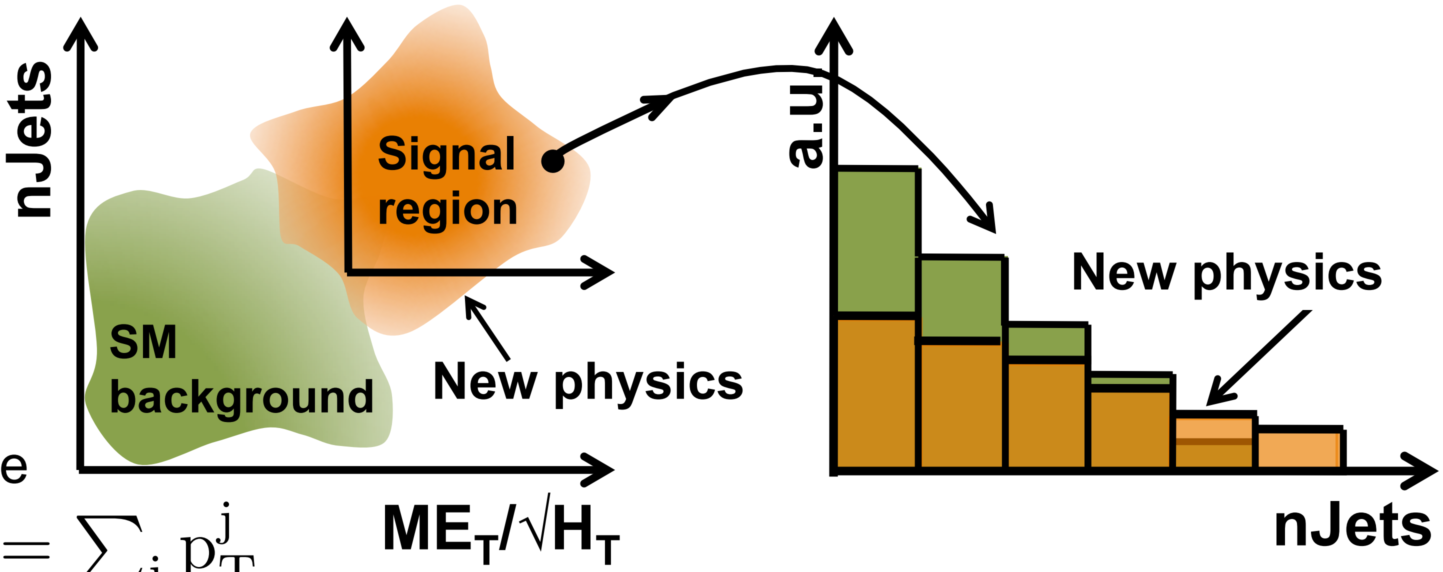
TYPICAL SUSY SEARCHES



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

E.g. MET

THE SUSY MULTIJET SEARCH



where

$$H_T = \sum_j p_T^j$$

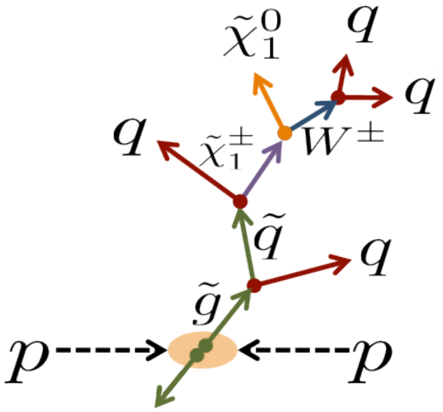
Dominant background: SM multijet production; fake MET from jet mis-measurements. Estimated using a combination of data-driven methods and Monte-Carlo based methods. Validated in control regions. ***Typical treatment of (SUSY) searches.***

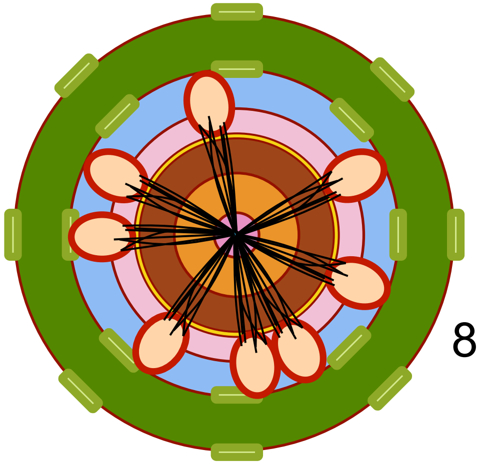
Why $ME_T/\sqrt{H_T}$?
⇒ a measure of ME_T in units of standard deviations of the fake ME_T

$$\frac{\sigma_{p_T}}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C$$

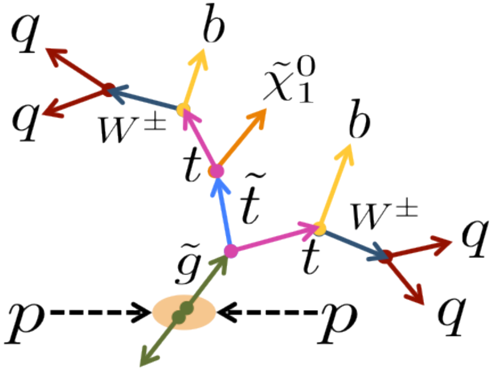
EVENT SELECTIONS

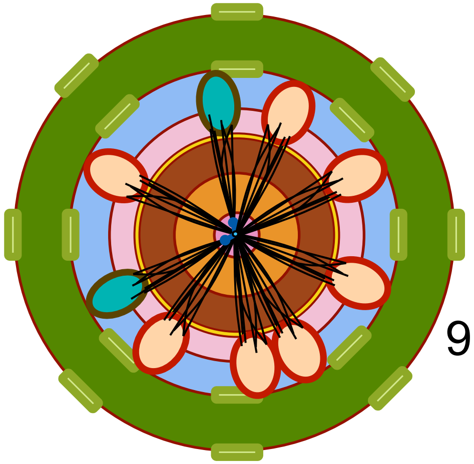
“b-jet stream”





8 jets, 0 b-jets



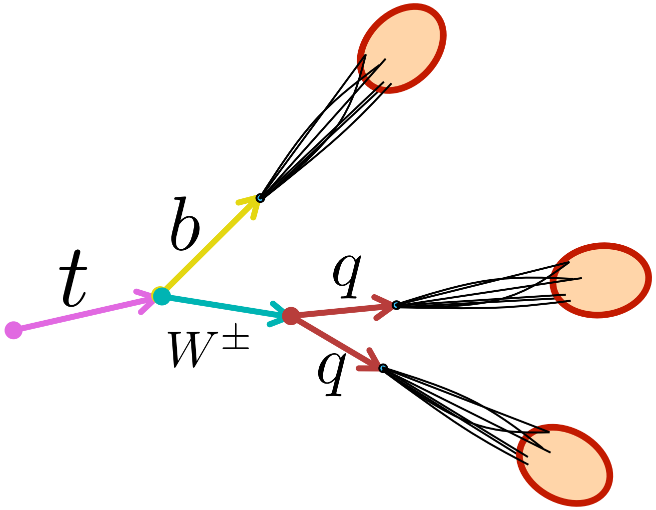


9 jets, ≥2 b-jets

13 signal regions overall ranging in jet p_T and jet & b-jet multiplicity.

EVENT SELECTIONS

“fat-jet stream”



EVENT SELECTIONS

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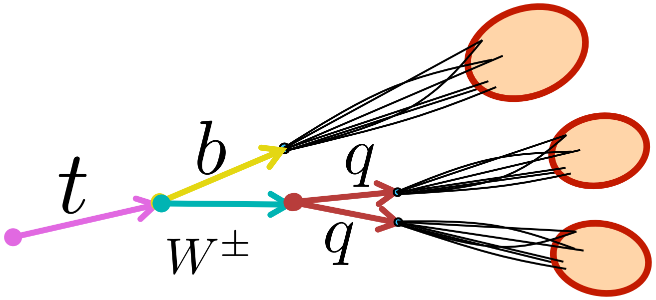

EVENT SELECTIONS

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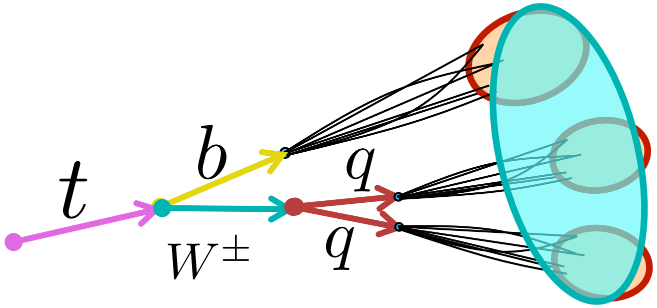

EVENT SELECTIONS

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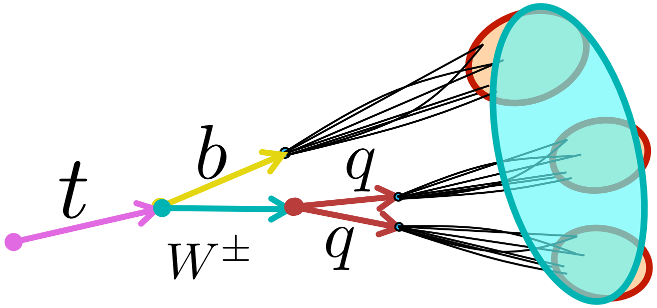
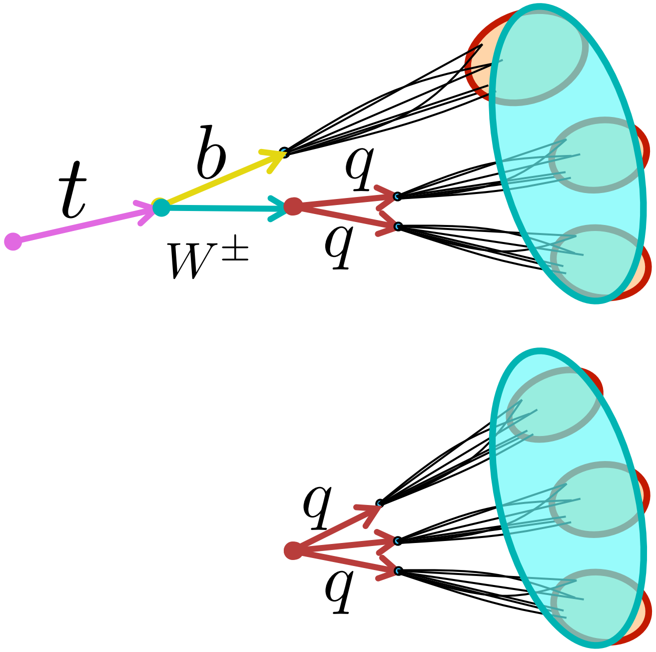


Fat-jets are a key signature in searches for boosted objects, e.g. boosted tops.

EVENT SELECTIONS

“fat-jet stream”

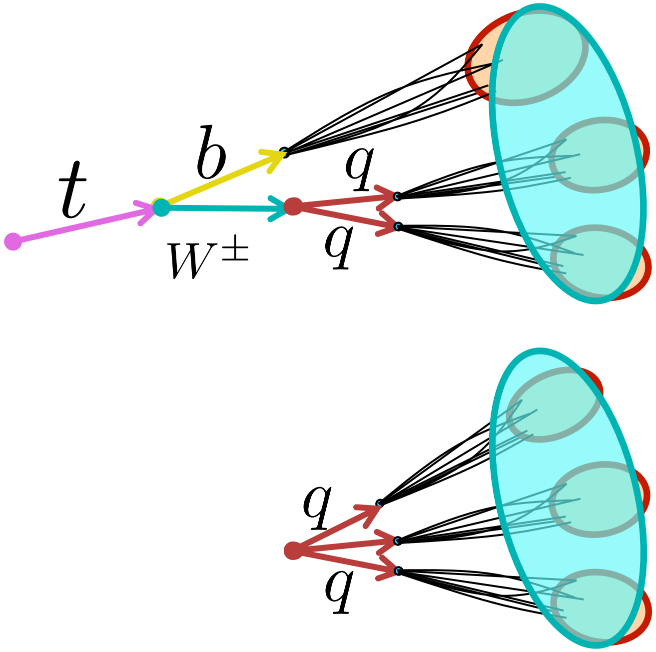


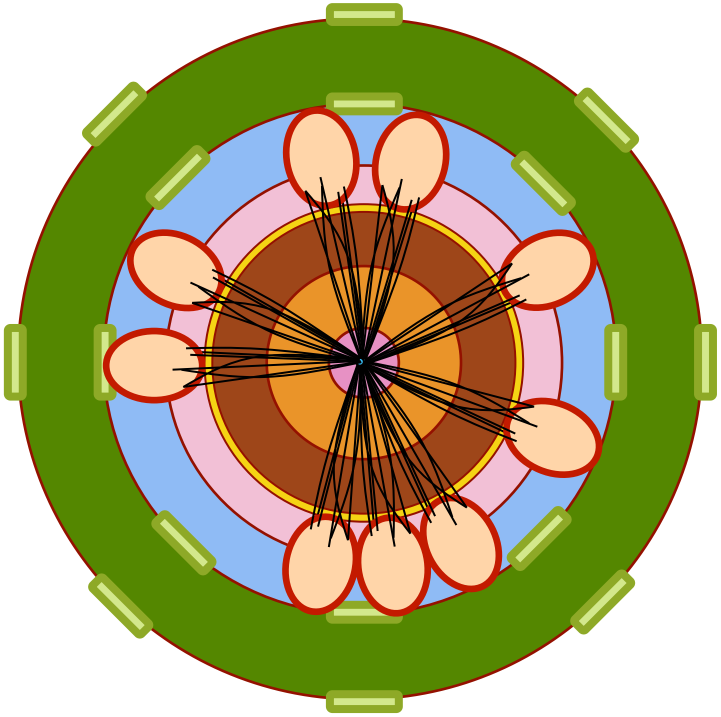
$$m_j\ (\mathrm{QCD}) < m_j\ (\mathrm{SUSY})$$

Proposed in arXiv:1202.0558

EVENT SELECTIONS

“fat-jet stream”





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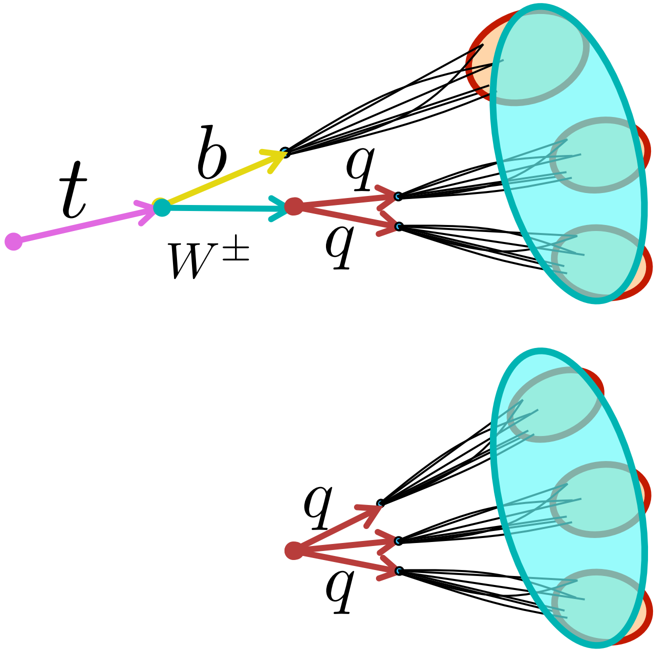
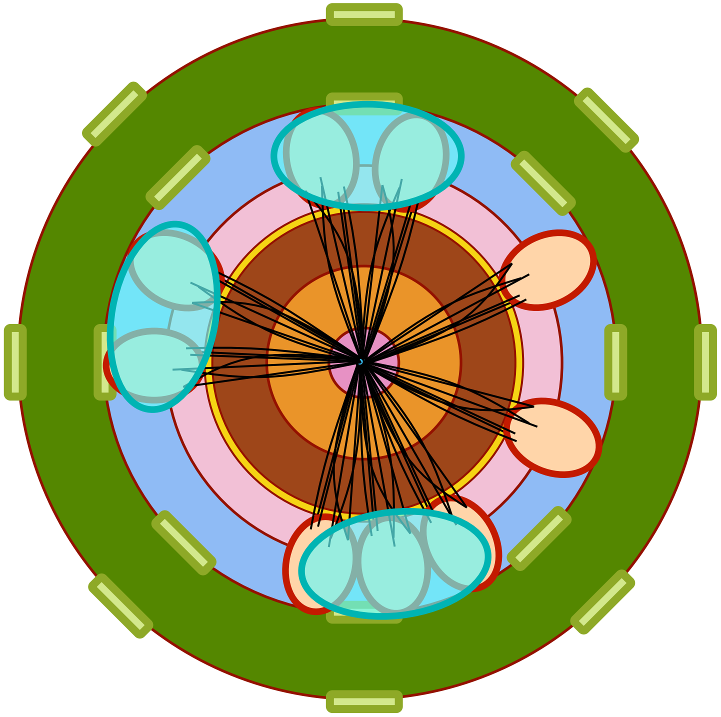




$m_j\ (\mathrm{QCD}) < m_j\ (\mathrm{SUSY})$

Proposed in arXiv:1202.0558

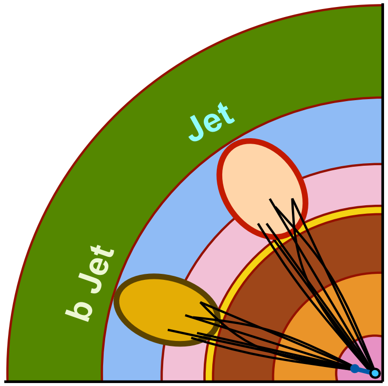
$$M_J^\Sigma = \sum_{i=1}^{nJ} m_{j_i}$$

6 signal regions overall ranging in jet multiplicity and M_J^Σ cuts.

EVENT SELECTIONS

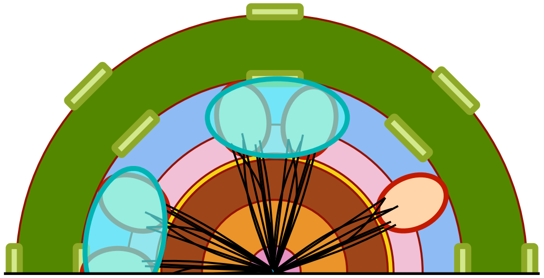
“b-jet stream”

ID	8j50			9j50			≥10j50	7j80			≥8j80		
Jet $\|\eta\|$	< 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
$\mathrm{ME}_T/\sqrt{H_T}$	> 4 GeV ½												



“fat-jet stream”

ID	≥8j50		≥9j50		≥10j50	
Jet $\|\eta\|$	< 2.8					
Jet p_T	50 GeV					
Jet count	≥8		≥9		≥10	
M_J^{Σ} (GeV)	>340	>420	>340	>420	>340	>420
$\mathrm{ME}_T/\sqrt{H_T}$	> 4 GeV ½					



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

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
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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
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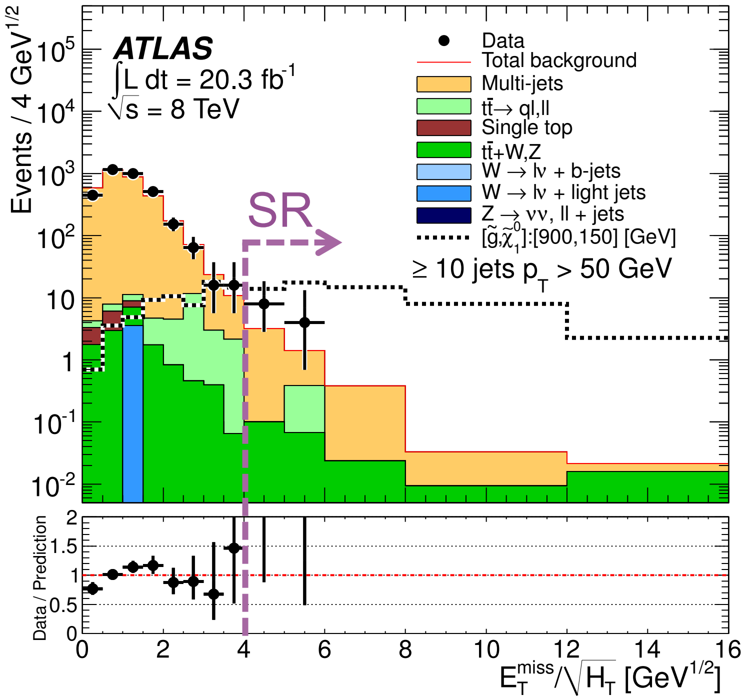
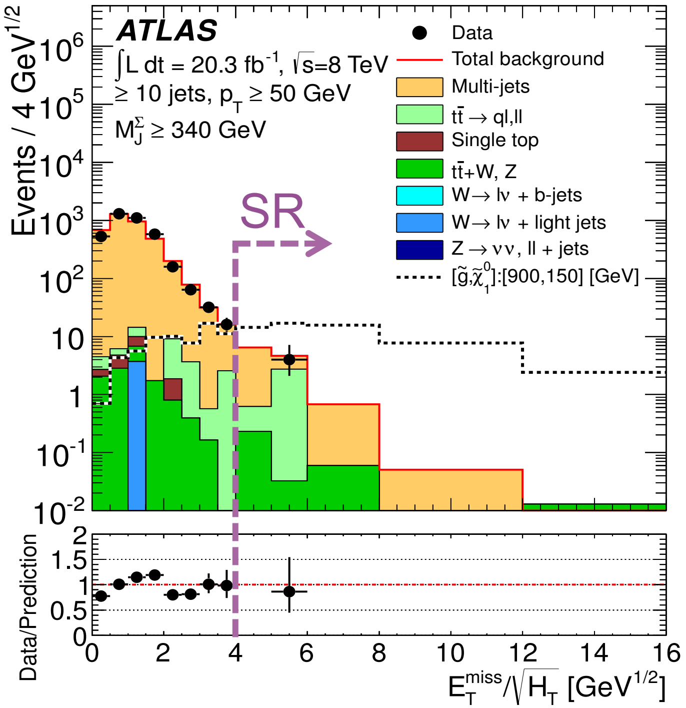
Significance (σ)	-0.27	-0.6	-0.6	-0.34	-0.8	-0.6

RESULTS

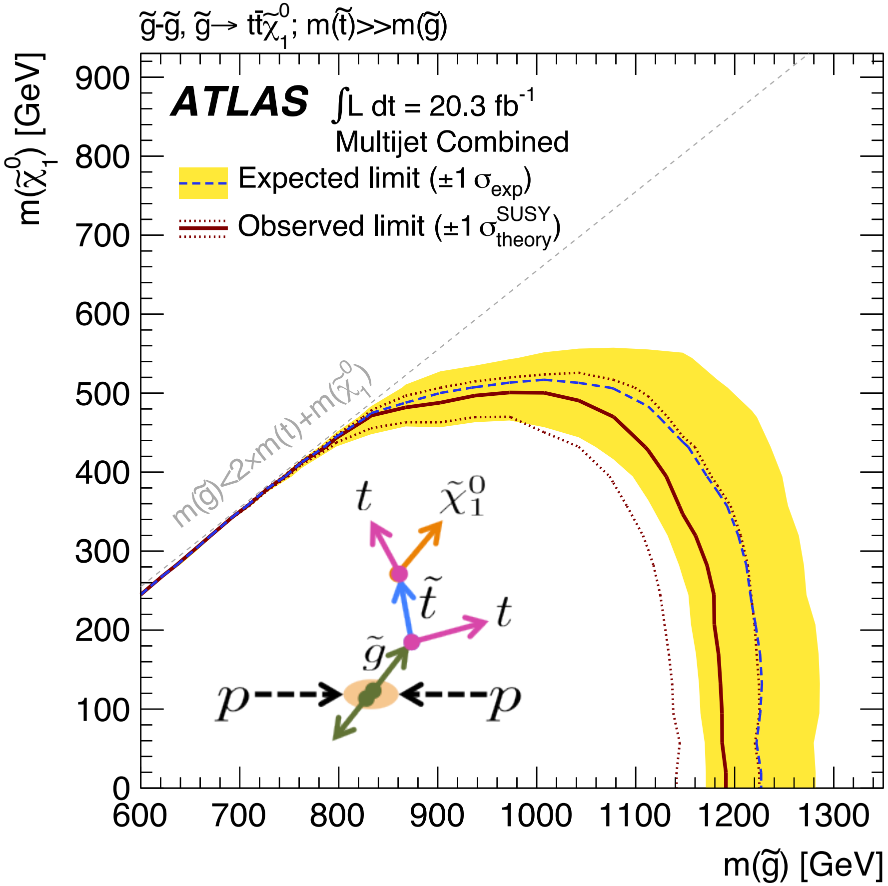

ATLAS
∫L dt = 20.3 fb^{-1}
√s = 8 TeV
● Data
Total background
Multi-jets
$t\bar{t} \to$ ql,ll
Single top
$t\bar{t}$+W,Z
W → lν + b-jets
W → lν + light jets
Z → νν, ll + jets
[$\tilde{g}$,$\tilde{\chi}_1^0$]:[900,150] [GeV]
≥ 10 jets p$_T$ > 50 GeV
SR
Events / 4 GeV$^{1/2}$
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
Data / Prediction
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]


ATLAS
∫L dt = 20.3 fb^{-1}, √s=8 TeV
≥ 10 jets, p$_T$ ≥ 50 GeV
M_J^{Σ} ≥ 340 GeV
● Data
Total background
Multi-jets
$t\bar{t} \to$ ql,ll
Single top
$t\bar{t}$+W, Z
W→ lν + b-jets
W→ lν + light jets
Z → νν, ll + jets
[$\tilde{g}$,$\tilde{\chi}_1^0$]:[900,150] [GeV]
SR
Events / 4 GeV$^{1/2}$
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
Data/Prediction
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]

INTERPRETATIONS

<u>Real or Simplified models</u>

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



INTERPRETATIONS

<u>Real or Simplified models</u>

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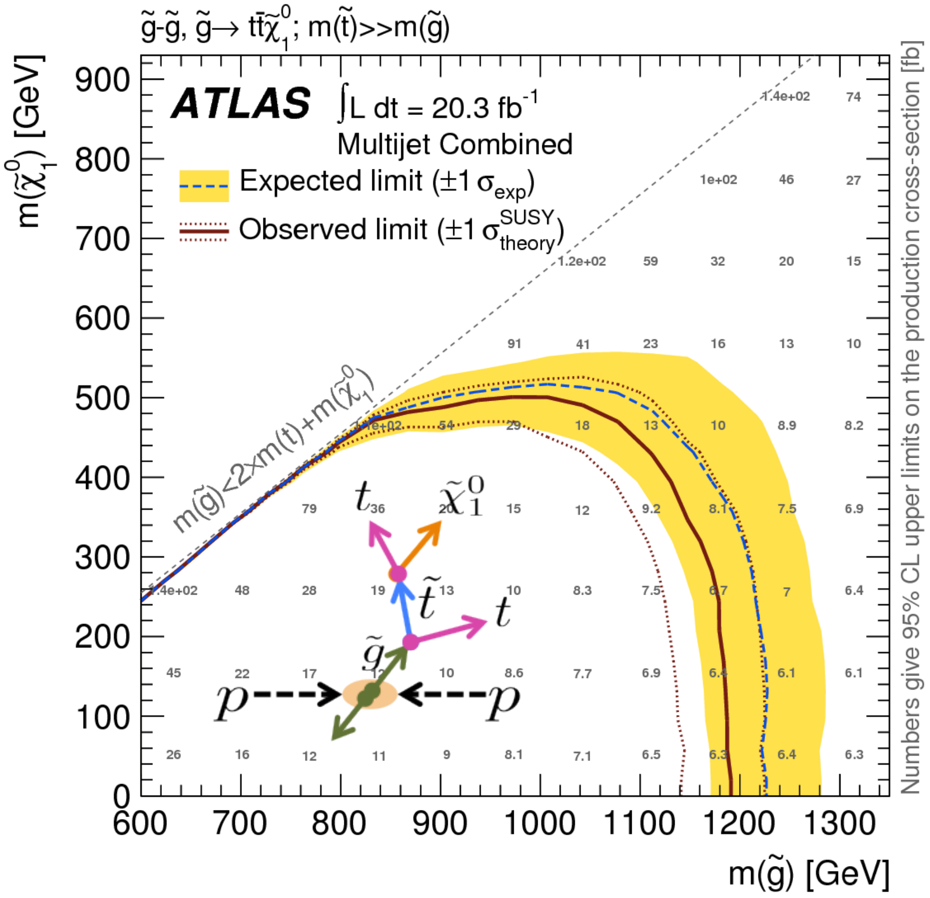
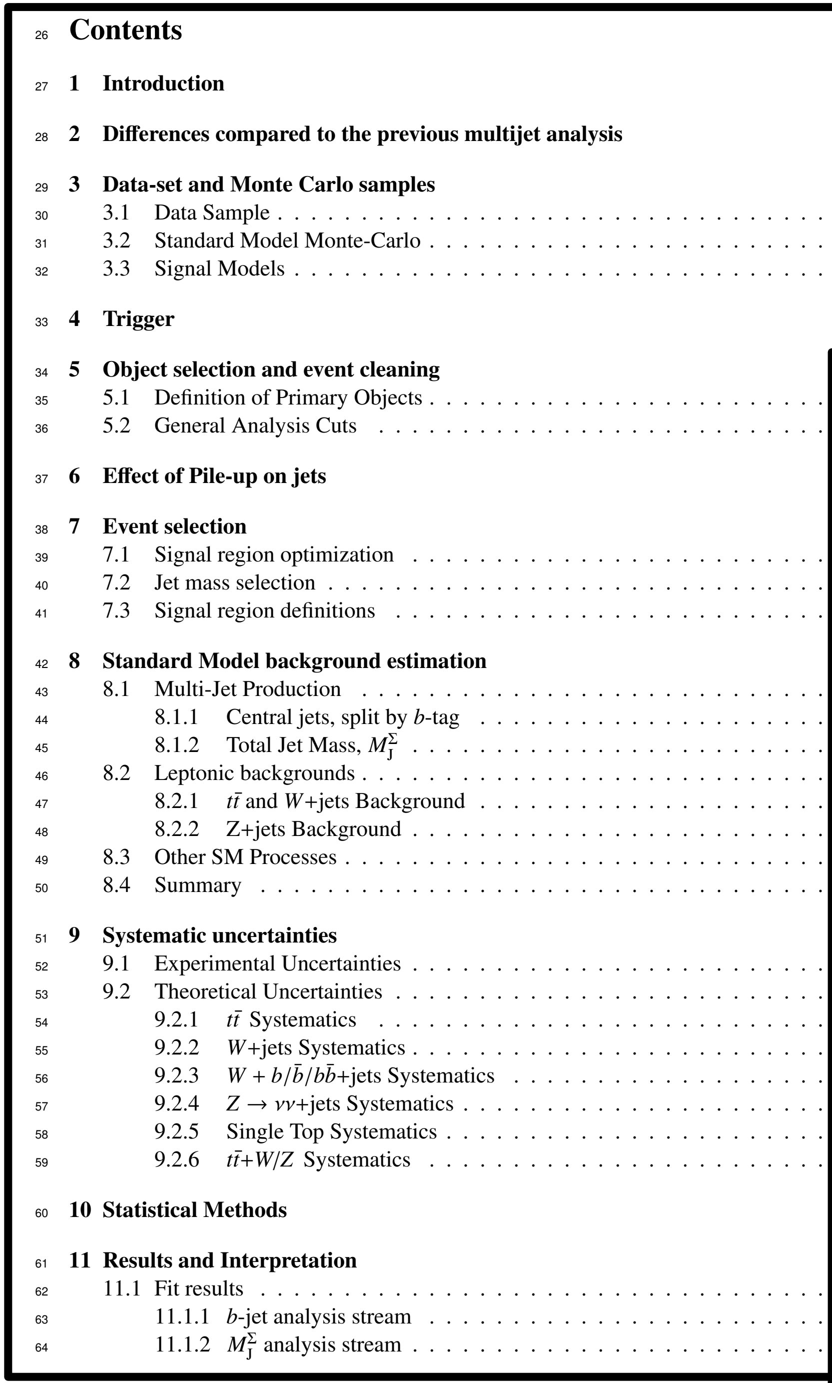
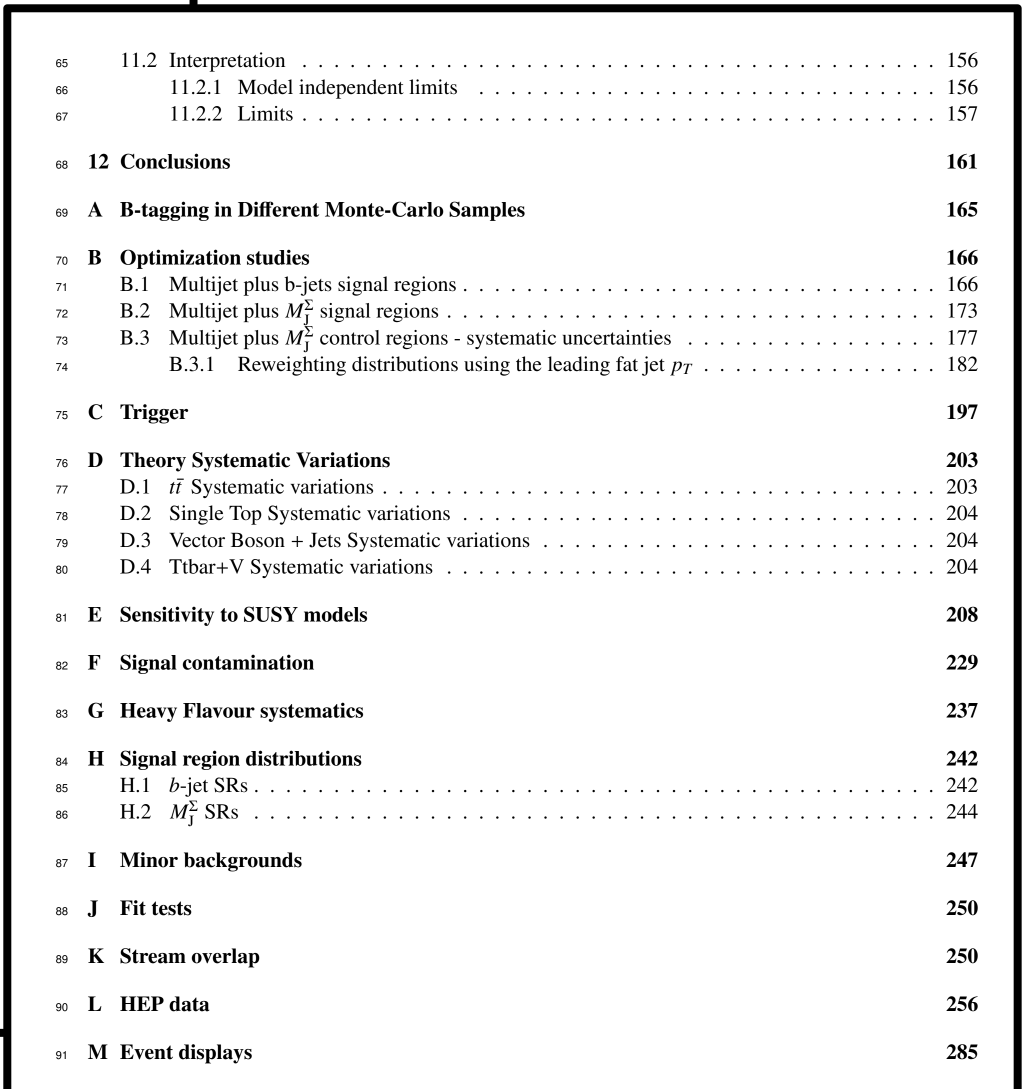


CONTENTS OF A RANDOM SEARCH INTERNAL DOCUMENTATION



Contents



COMPONENTS OF A PHYSICS ANALYSIS

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

COMPONENTS 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.

COMPONENTS OF A PHYSICS ANALYSIS

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

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.

COMPONENTS OF A PHYSICS ANALYSIS

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Backg
- 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**”.

COMPONENTS OF A PHYSICS ANALYSIS

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

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.

COMPONENTS OF A PHYSICS ANALYSIS

- Data-set and Monte Carlo
- Trigger
- Object definitions and eve
- Background determinatio
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

- 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.

COMPONENTS OF A PHYSICS ANALYSIS

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and even
- Background determinatio
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

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.

COMPONENTS OF A PHYSICS ANALYSIS

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

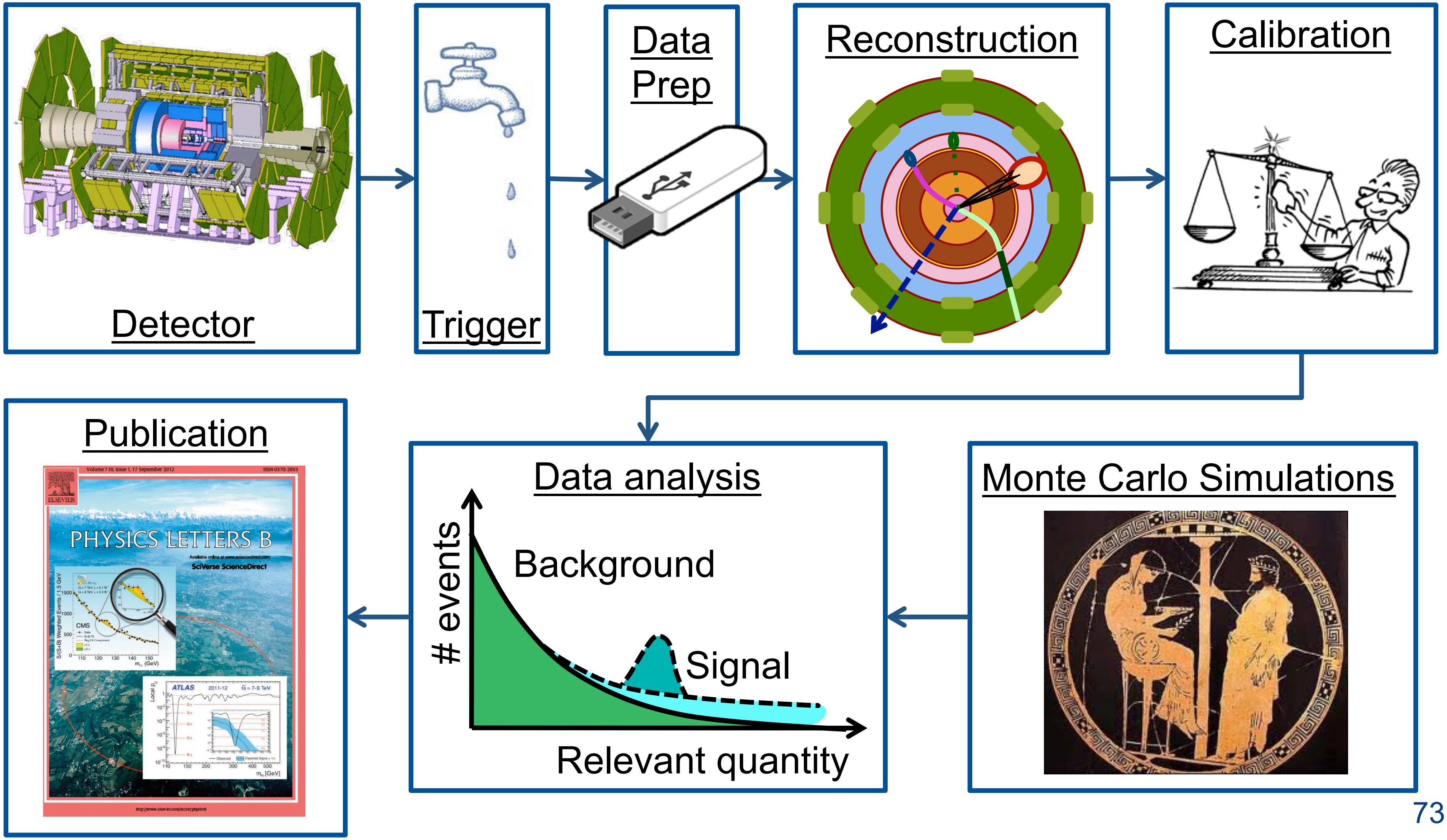
Produce the results in tables and plots. These include details of what is found in the signal region.

COMPONENTS OF A PHYSICS ANALYSIS

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

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

CONCLUSIONS



Detector

Trigger

Data Prep

Reconstruction

Calibration

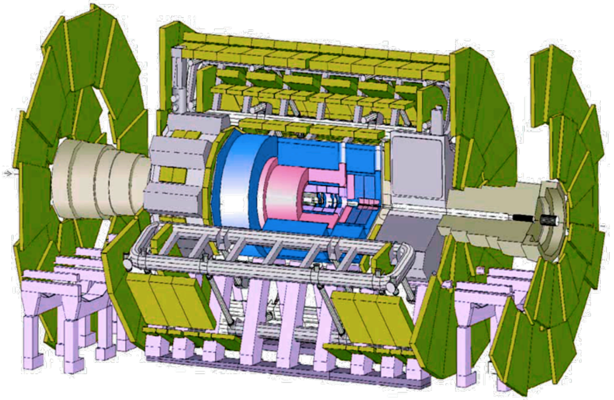
Monte Carlo Simulations

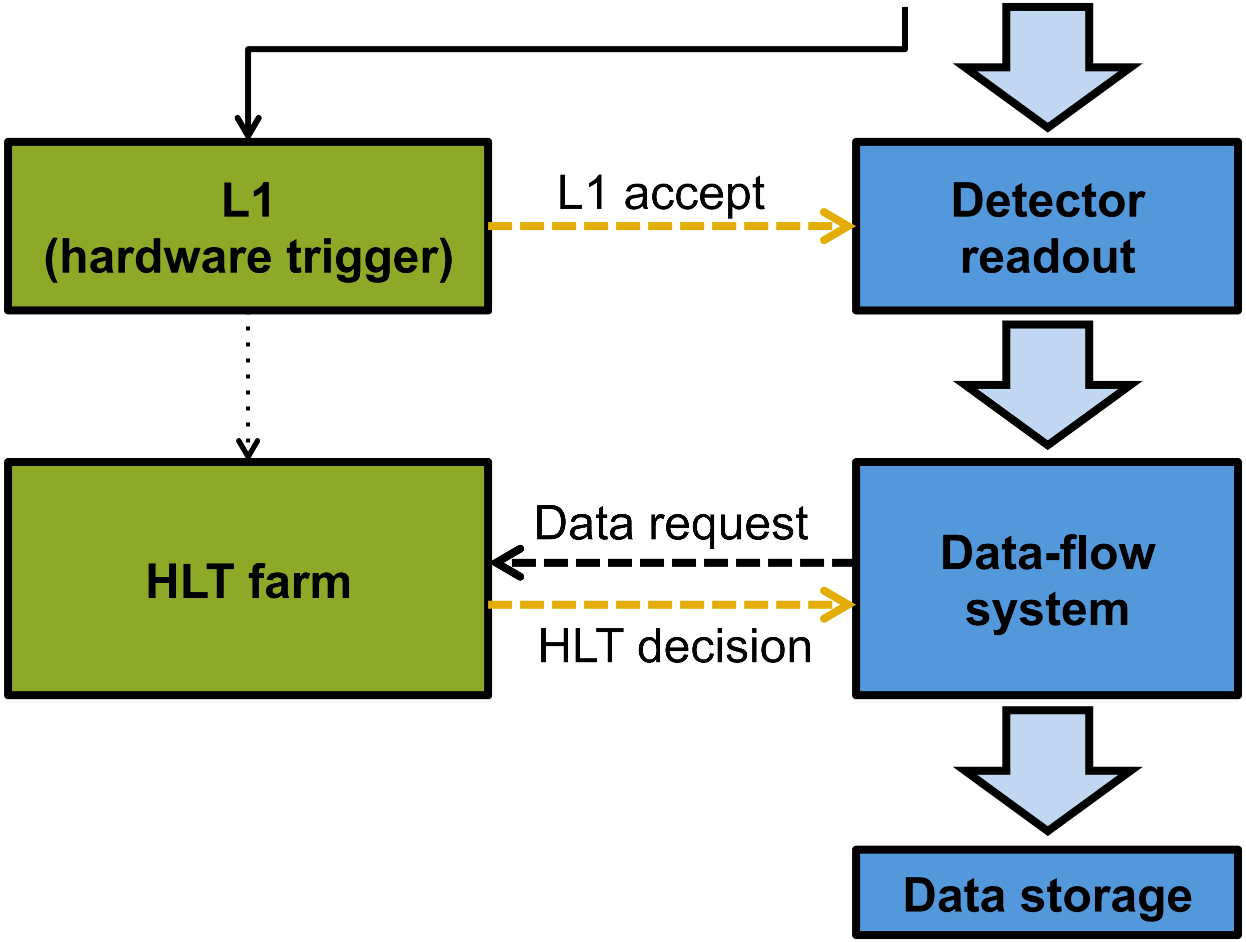
Data analysis

Publication

BACKUP

THE DATA ACQUISITION





L1 (hardware trigger)

L1 accept

Detector readout

HLT farm

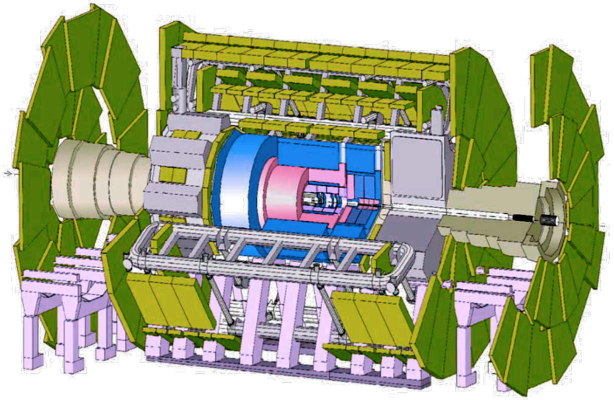
Data request

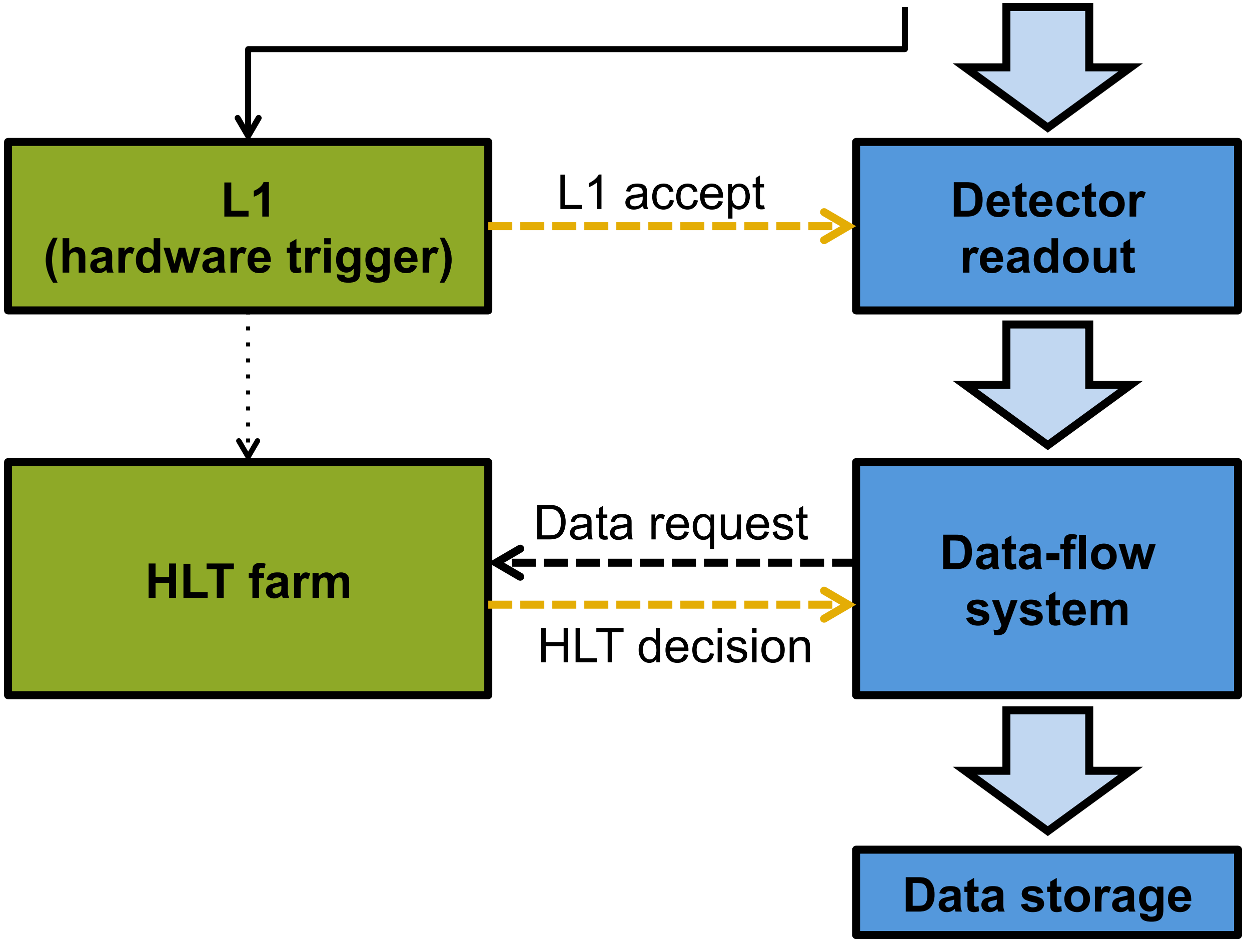
HLT decision

Data-flow system

Data storage

THE DATA ACQUISITION





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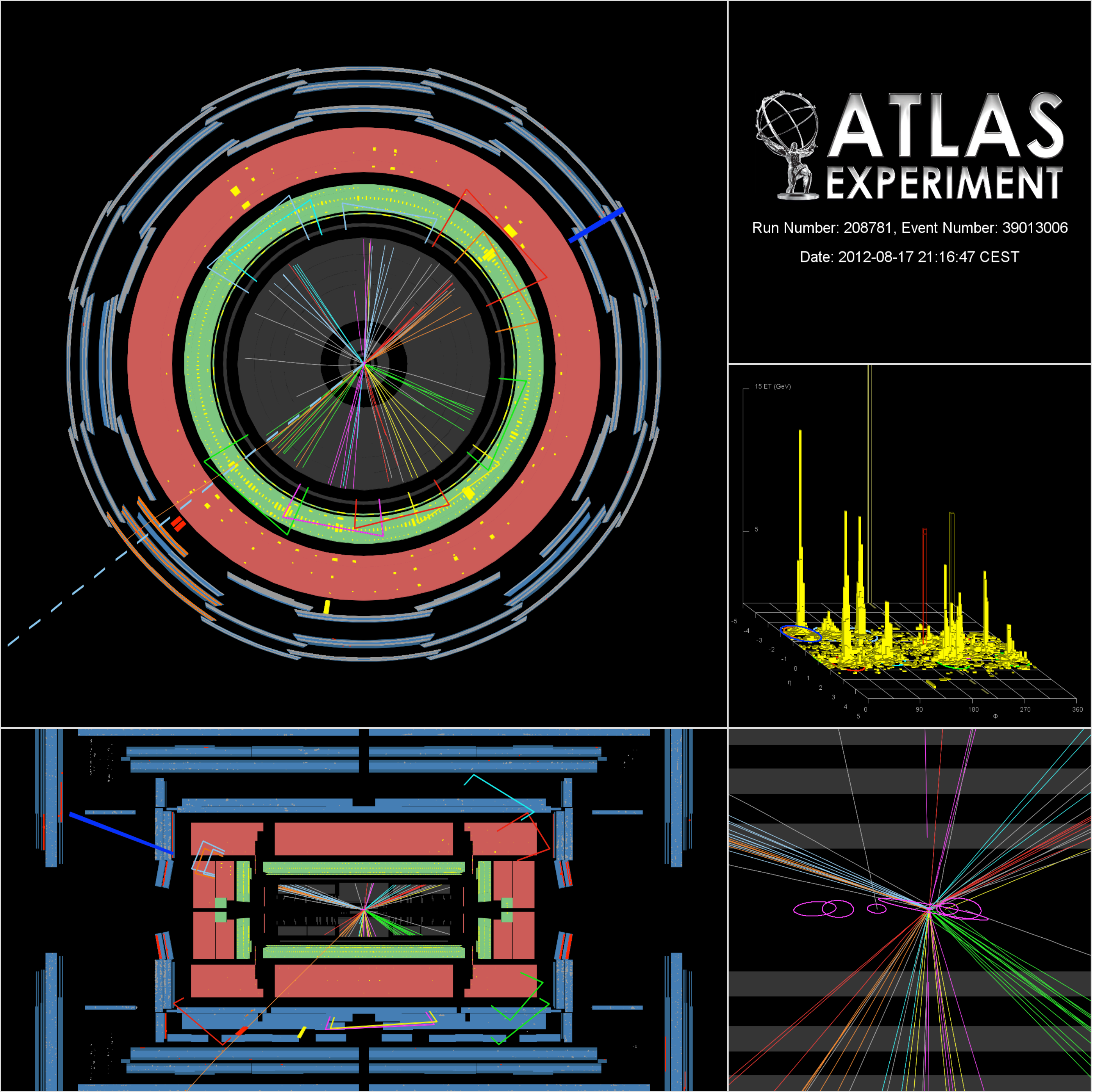
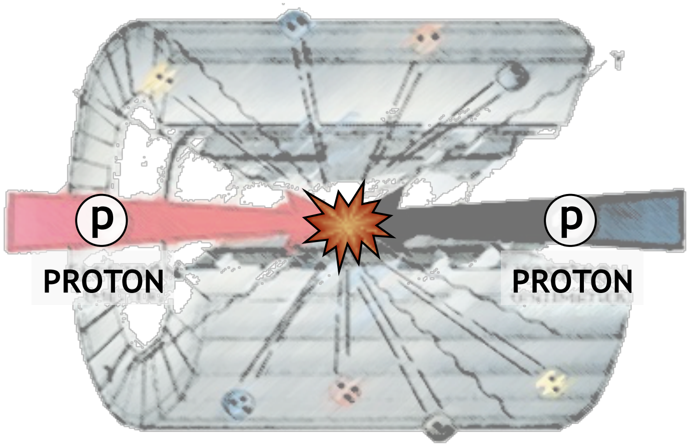
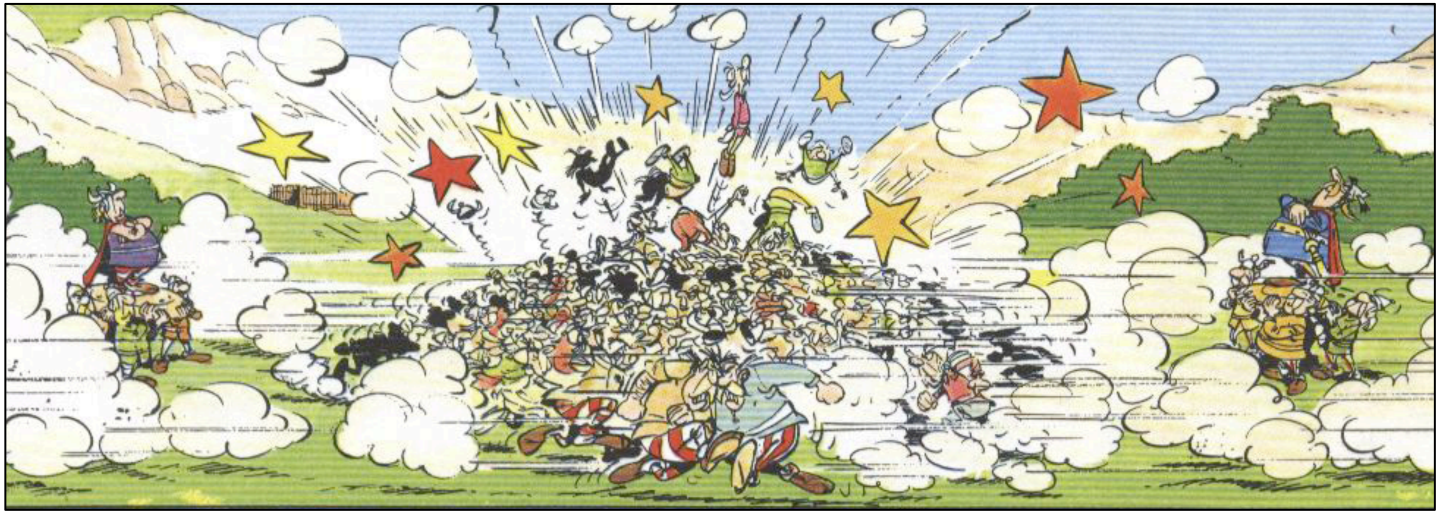


10 jets
with pT > 50GeV
ME_T = 120 GeV

IN A P-P COLLISION





MISSING TRANSVERSE MOMENTUM

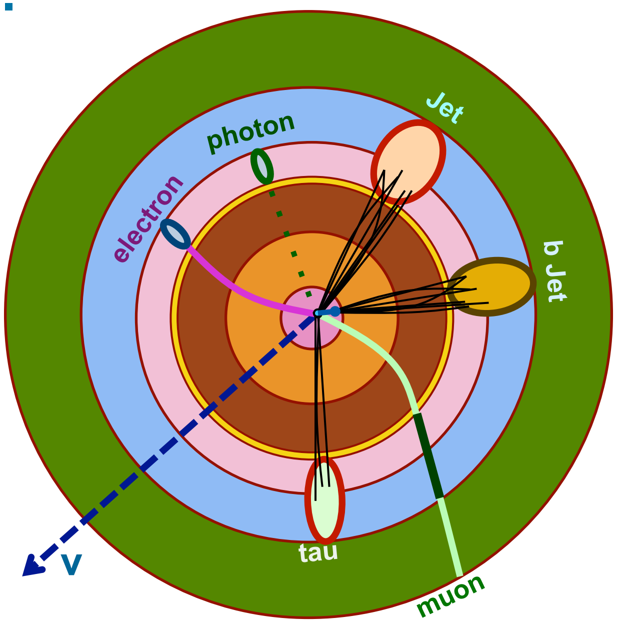
Impossible to measure particles that don't interact in the detector.

➲ Instead, measure everything else & require momentum conservation in the transverse plane.

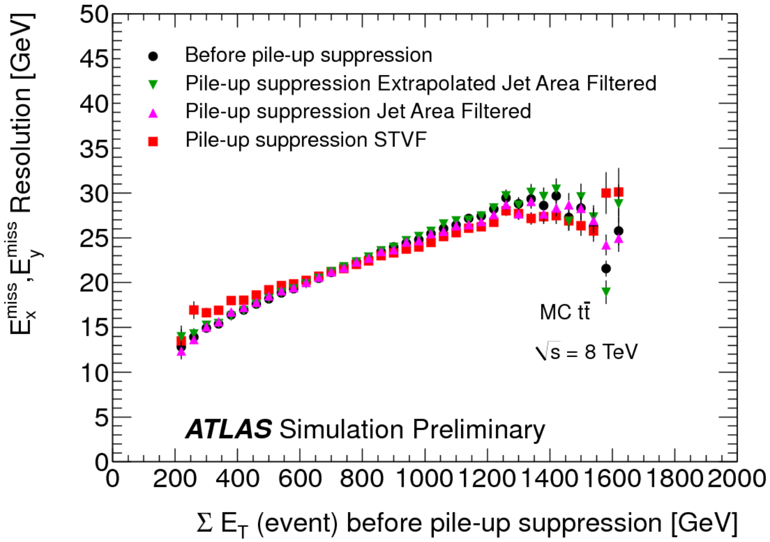
- Sensitive to pile-up and detector problems.

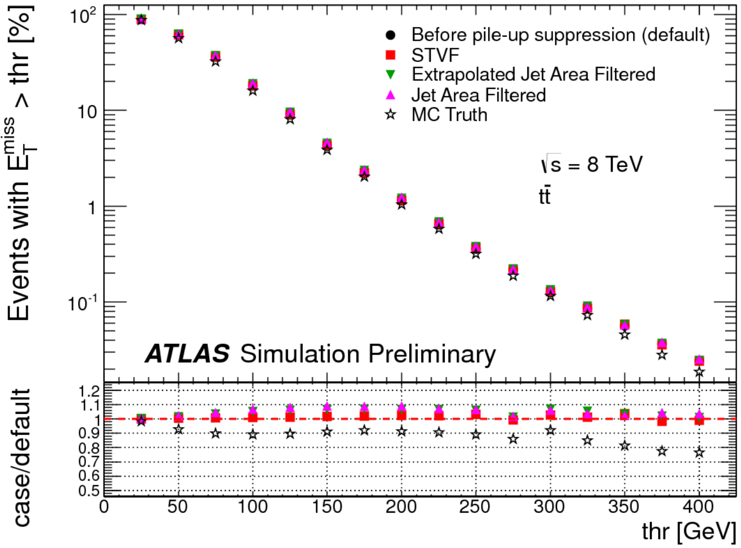
Only as good as its inputs.

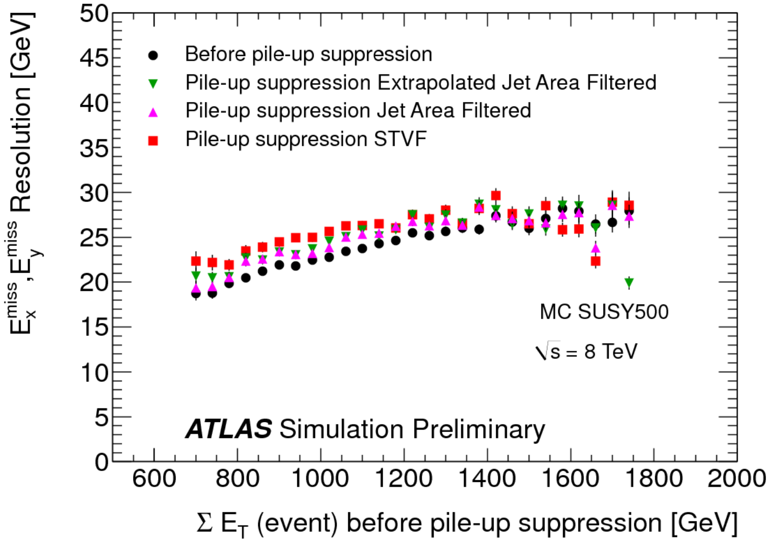
- Use calibrated physics objects: electrons, photons, muons, taus, jets.
- Add remaining soft energy.

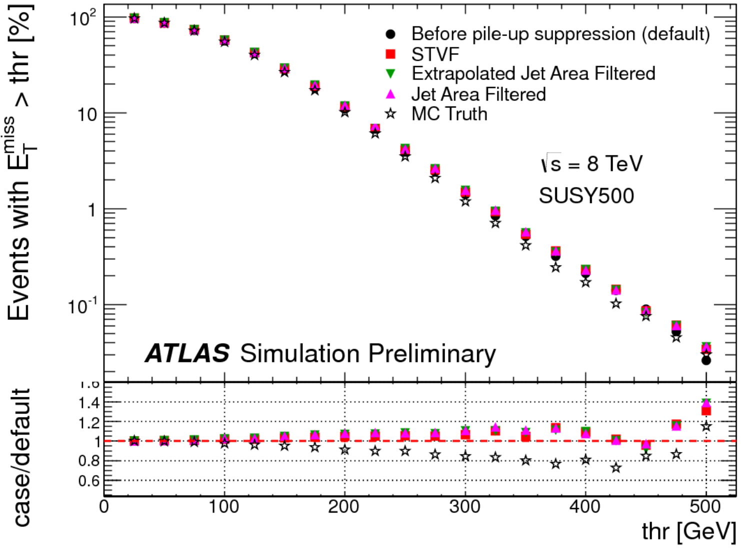


MISSING ET – PILEUP & TAILS

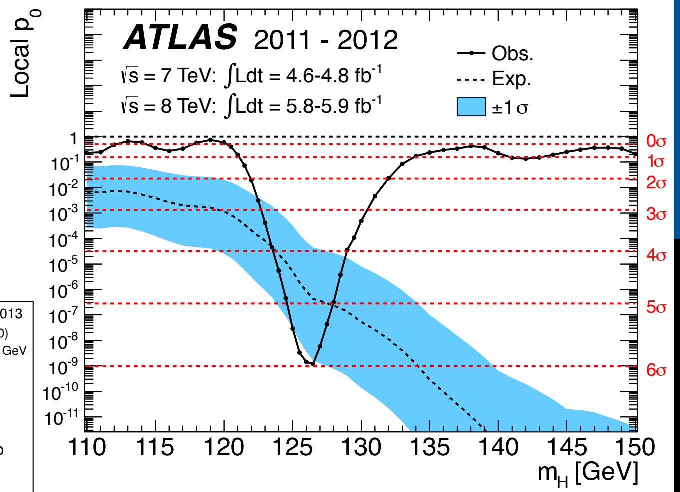


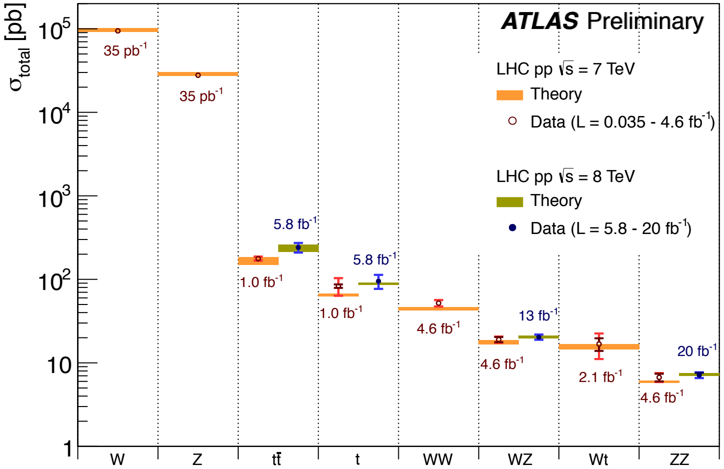


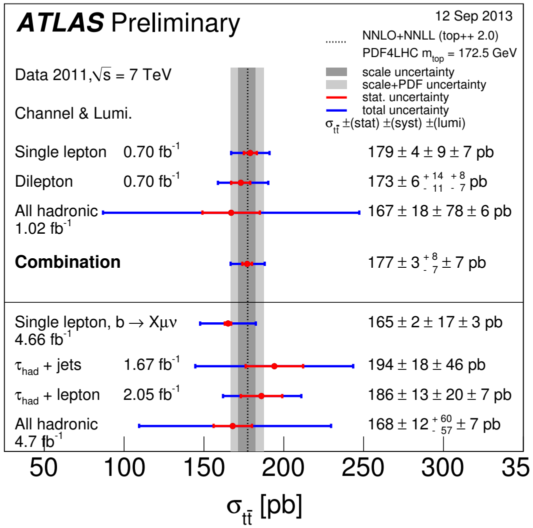


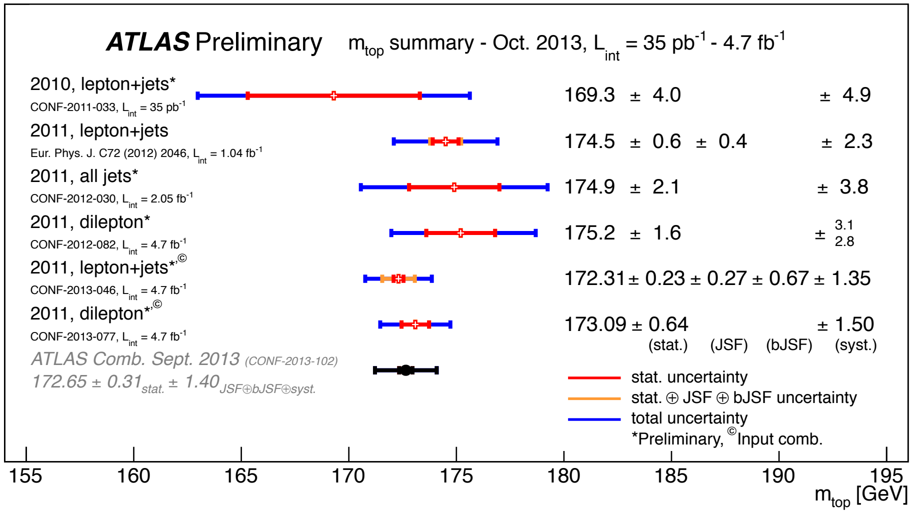


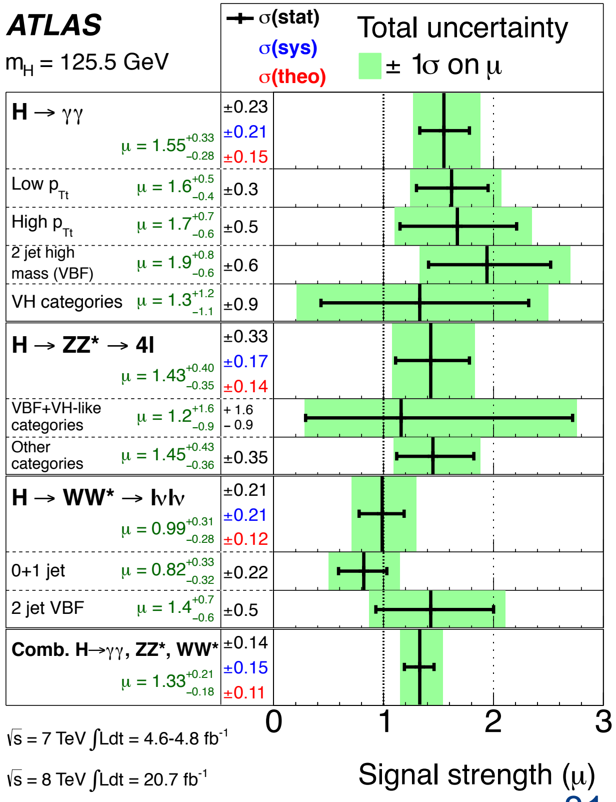
GRAND ATLAS (non-BSM) PHYSICS SUMMARY



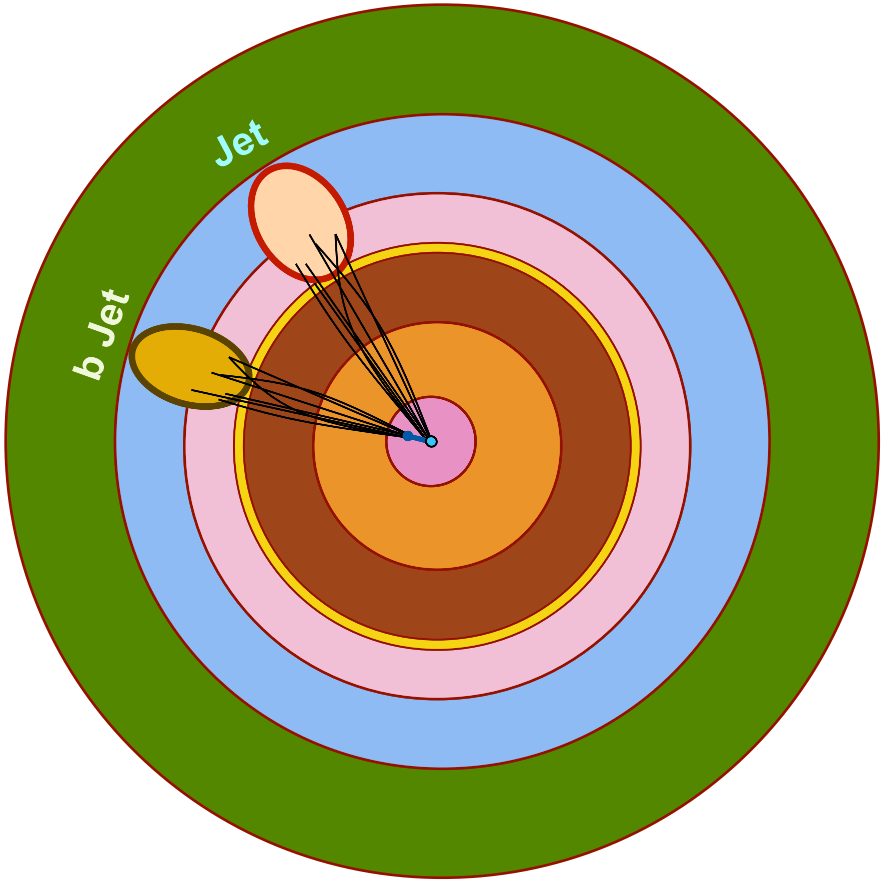








B-JET



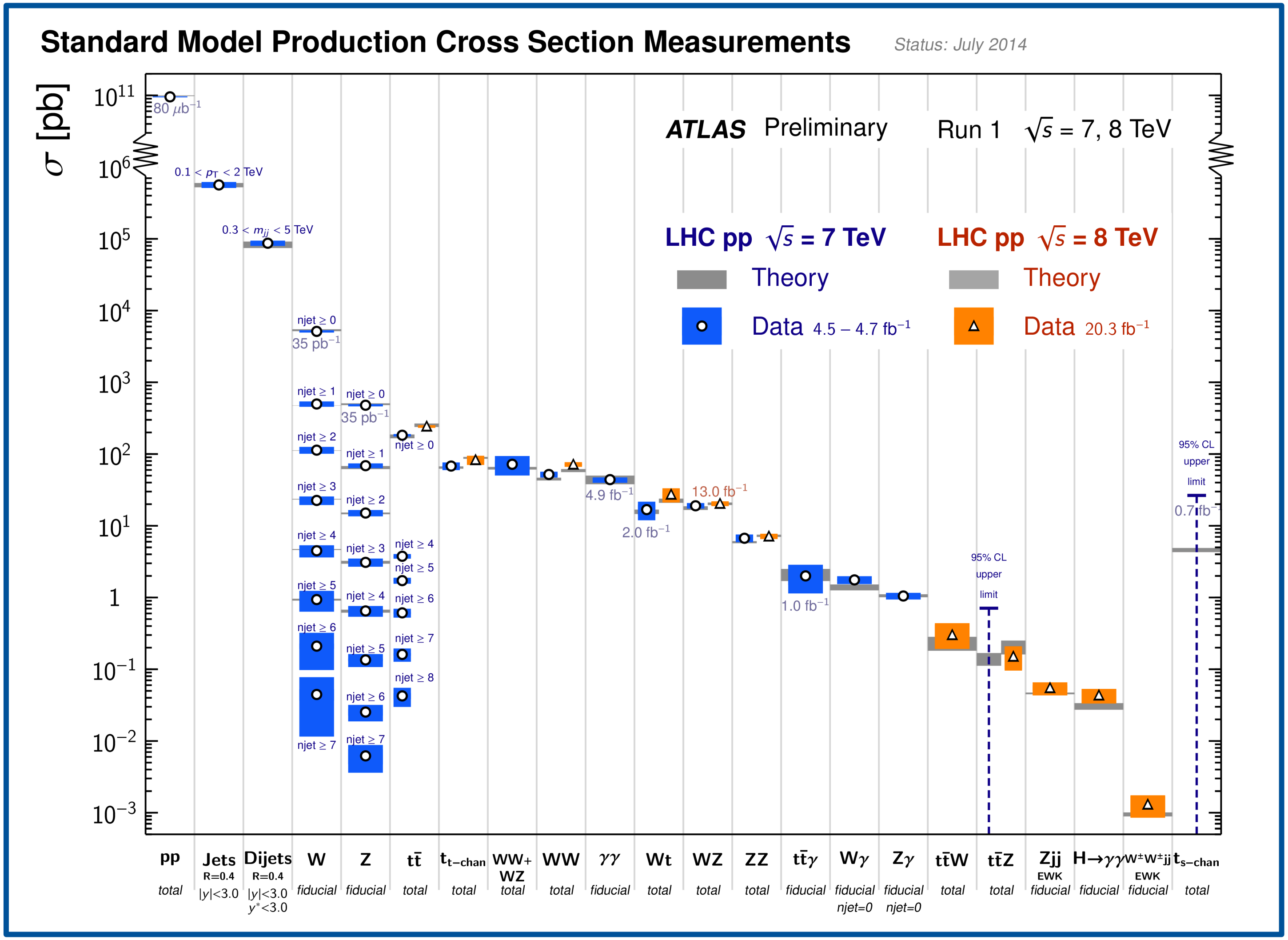
TRIGGER MENUS FOR SUSY

Selection	**EF trigger election**	**EF Avg. Rate (Hz)** $L_{\mathrm{avrg}}=5\mathrm{e}33/\mathrm{cm}^2\mathrm{s}$
Single jet & $E_{\mathrm{T}}^{\mathrm{miss}}$	Jet E_{T} >145 GeV & EF-only $E_{\mathrm{T}}^{\mathrm{miss}}$ >70 GeV	8
Single jet & $E_{\mathrm{T}}^{\mathrm{miss}}$ & $\Delta\phi(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}})$	Jet E_{T} >80 GeV & $E_{\mathrm{T}}^{\mathrm{miss}}$ >70 GeV & $\Delta\phi$ >1.0 rad	8
H_{T}	>700 GeV	8
Single electron & $E_{\mathrm{T}}^{\mathrm{miss}}$	Electron p_{T} >25 GeV & EF-only $E_{\mathrm{T}}^{\mathrm{miss}}$ >35 GeV	26
Single muon & single jet & $E_{\mathrm{T}}^{\mathrm{miss}}$	Muon p_{T} >24 GeV & jet E_{T} >65 GeV & EF-only $E_{\mathrm{T}}^{\mathrm{miss}}$ >40 GeV	15
Single photon & $E_{\mathrm{T}}^{\mathrm{miss}}$	Photon p_{T} >40 GeV & EF-only $E_{\mathrm{T}}^{\mathrm{miss}}$ >60 GeV	5
3 electrons	$p_{\mathrm{T}} > 18, 2\times7$ GeV	<1
3 muons	$p_{\mathrm{T}} > 18, 2\times4$ GeV	<1
3 electrons & muons	$p_{\mathrm{T}} > 2\times7\ (e), 6\ (\mu)$ GeV	<1
	$p_{\mathrm{T}} > 7\ (e), 2\times6\ (\mu)$ GeV	<1

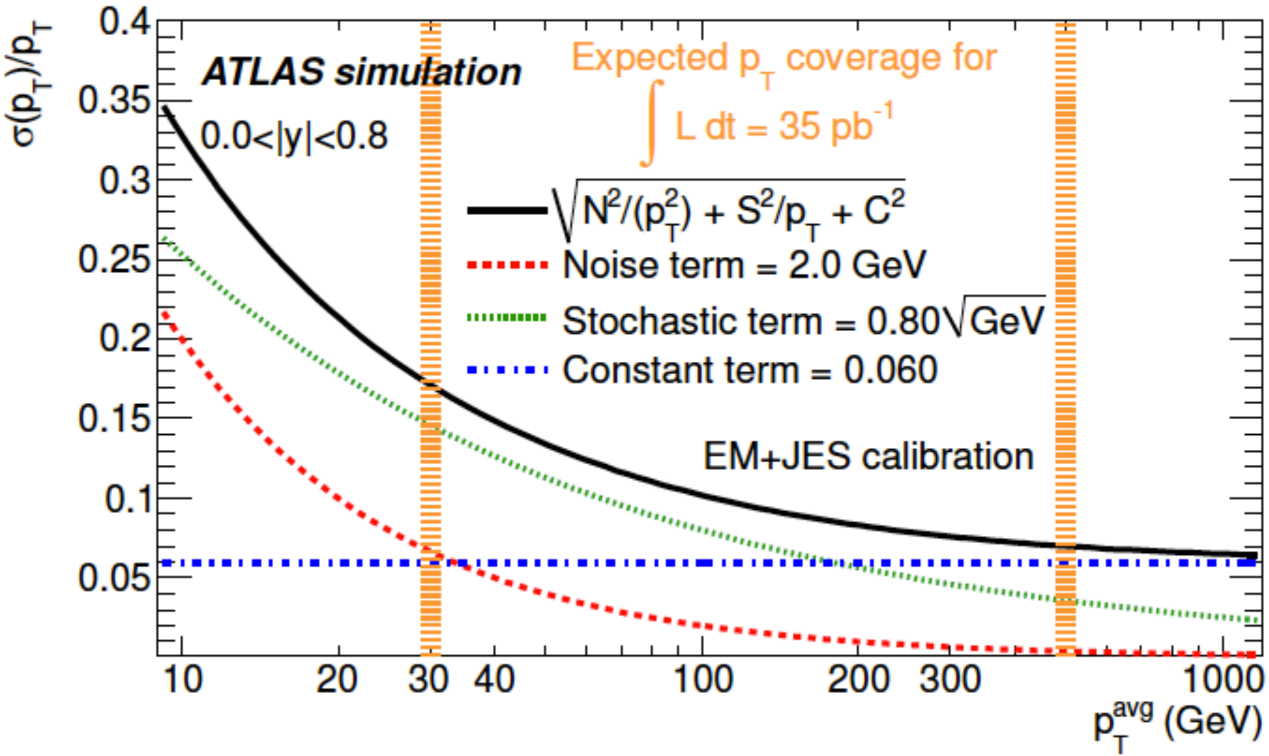
‘DELAYED’ TRIGGERS

Trigger	**EF trigger Selection**	
	Prompt Stream	**Delayed Stream**
Multi-jets	4×80 GeV	4×65 GeV
	5×55 GeV	5×45 GeV
	6×45 GeV	
H_T	700 GeV	500 GeV
Single jet (R = 1.0)	460 GeV	360 GeV
E_T^{miss}	80 GeV	60 GeV

STANDARD MODEL SUMMARY



THE SUSY MULTIJET SEARCH



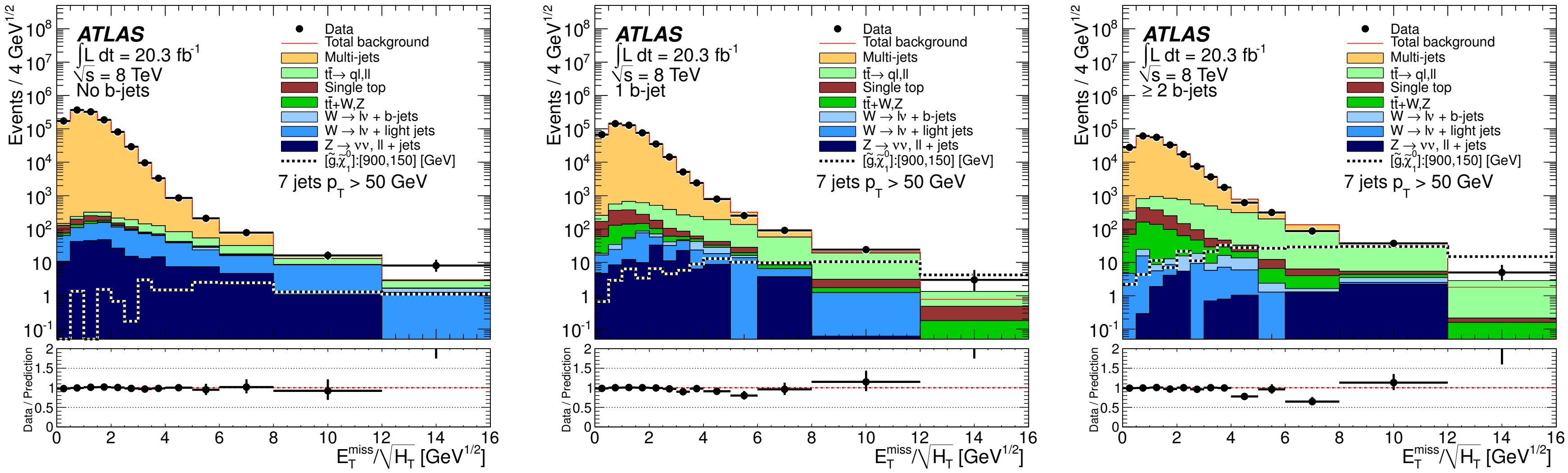
ATLAS-PERF-2011-04-001

Why $ME_T/\sqrt{H_T}$?
⇒ a measure of ME_T in units of standard deviations of the fake ME_T

$$\frac{\sigma_{p_T}}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C$$

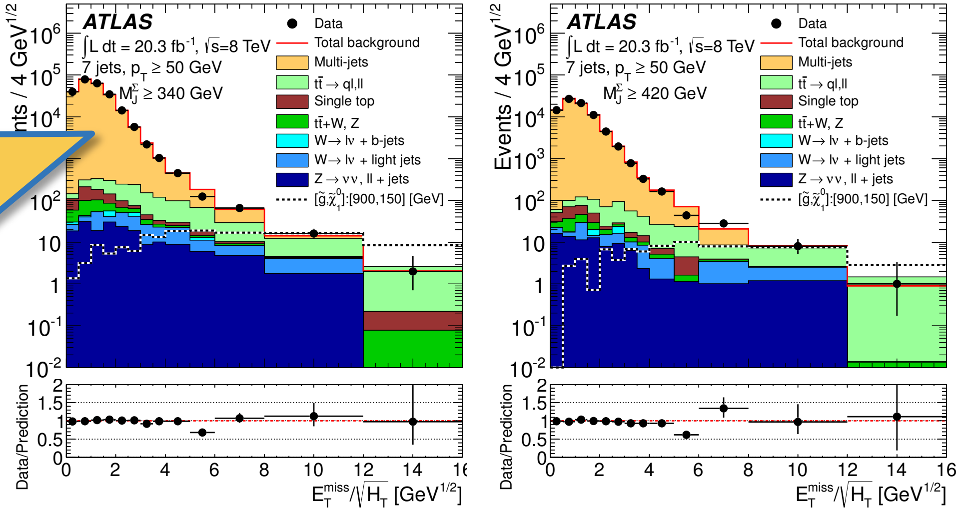
MULTI-JET BACKGROUND

Flavour stream



MJ stream

Template extracted from '6j50' and validated in '7j50'



Discrepancies in control regions become uncertainties – dominant, on top of heavy flavour and 'leptonic' backgrounds.

LEPTONIC BACKGROUNDS

- **ttbar (non-full-hadronic) + jets and W/Z + jets.**
- **Scale MC in control regions in data (through a multi-bin fit).**

Single-lepton validation region	
Lepton p_{T}	$> 25\,\mathrm{GeV}$
Lepton multiplicity	Exactly one, $\ell \in \{e,\, \mu\}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 30\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	$> 2.0\ \mathrm{GeV}^{1/2}$
m_{T}	$< 120\,\mathrm{GeV}$
Jet p_{T}	As for signal regions (table 1)
Jet multiplicity	
b-jet multiplicity	
M_J^{Σ}	

Control region (additional criteria)	
Jet multiplicity	Unit increment if $p_{\mathrm{T}}^{\ell} > p_{\mathrm{T}}^{\mathrm{min}}$
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}\ (+p_{\mathrm{T}}^{\ell})}$	$> 4.0\ \mathrm{GeV}^{1/2}$

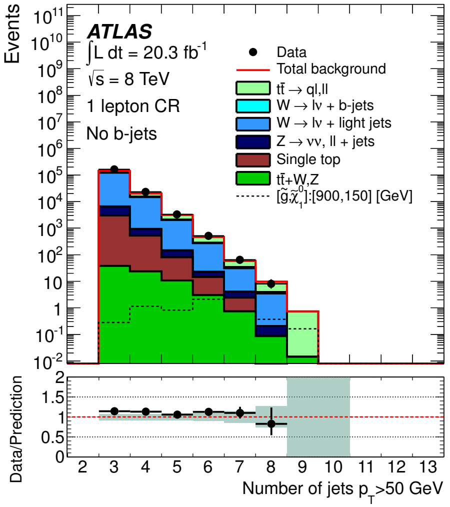
Two-lepton validation region	
Lepton p_{T}	$> 25\,\mathrm{GeV}$
Lepton multiplicity	Exactly two, $e\,e$ or $\mu\,\mu$
$m_{\ell\ell}$	$80\,\mathrm{GeV}$ to $100\,\mathrm{GeV}$
Jet p_{T}	As for signal regions (table 1)
Jet multiplicity	
b-jet multiplicity	
M_J^{Σ}	

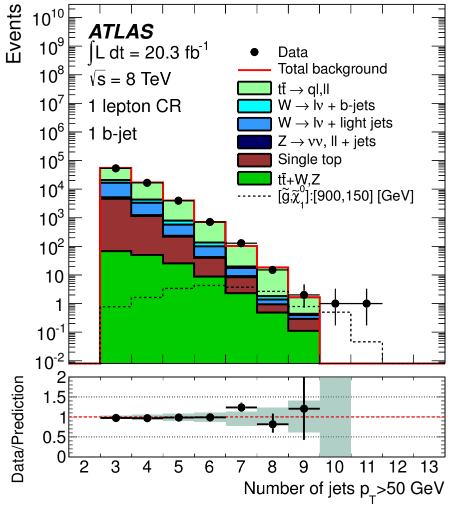
Control region (additional criteria)	
$\lvert \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}^{\ell_1} + \mathbf{p}_{\mathrm{T}}^{\ell_2} \rvert/\sqrt{H_{\mathrm{T}}}$	$> 4.0\ \mathrm{GeV}^{1/2}$

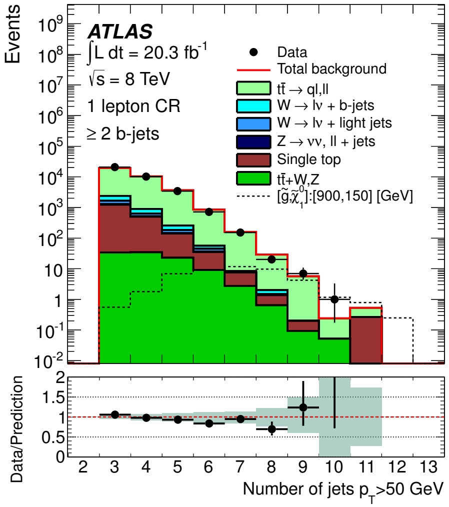
- **Uncertainties dominating the leptonic background determination: JES/JER, b-tagging, pile-up and theory.**

LEPTONIC BACKGROUND

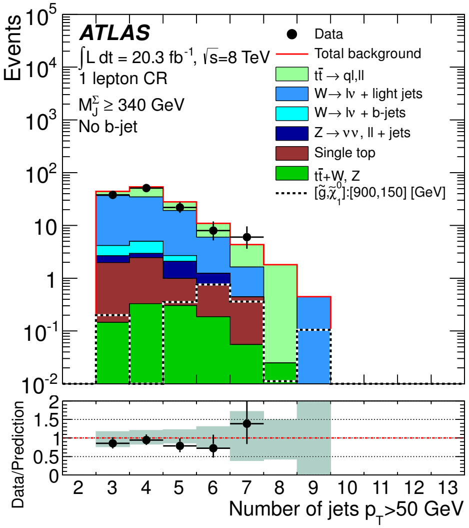
Flavour stream

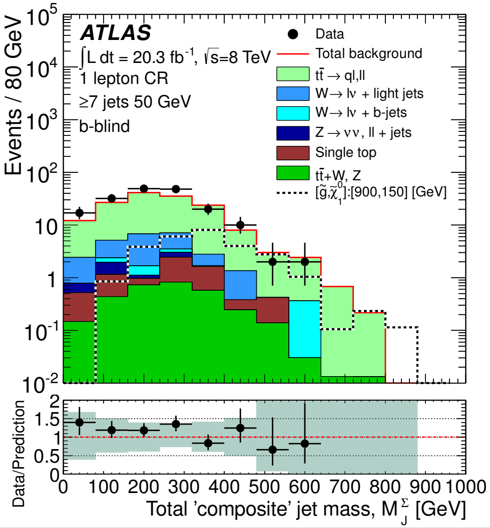






MJ stream





Uncertainties dominating the leptonic background determination: JES/JER, b-tagging, pile-up and theory.

THE STATISTICAL TREATMENT

Flavour stream

Simultaneous fit in the ‘j50’ and ‘j80’ signal regions separately.

- **ttbar & W+jets:** one control region per signal region. **Normalization allowed to vary freely in the fit.**
- **Other less significant backgrounds;** determined using MC. **Constrained by their uncertainties.**
- **Multijet background;** not constrained by control regions. **Constrained by its uncertainties.**

MJ stream

A fit performed in each signal region to adjust the normalization of ttbar and W backgrounds.

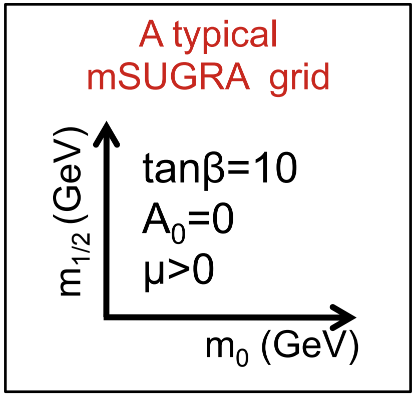
INTERPRETATIONS

‘Real models’

◎ **A minimal model, Constraint Minimal SUSY (CMSSM) (mSugra, i.e. gravity-mediated, based) only has 5 free parameters:**

- Scalar mass parameter, $\mathbf{m_0}$
- Gaugino mass parameter, $\mathbf{m_{1/2}}$
- Trilinear Higgs-sfermion-sfermion coupling, $\mathbf{A_0}$
- Ratio of Higgs vaccum expectation values, **tanβ**
- Sign of SUSY Higgs parameter, **sign(μ)**

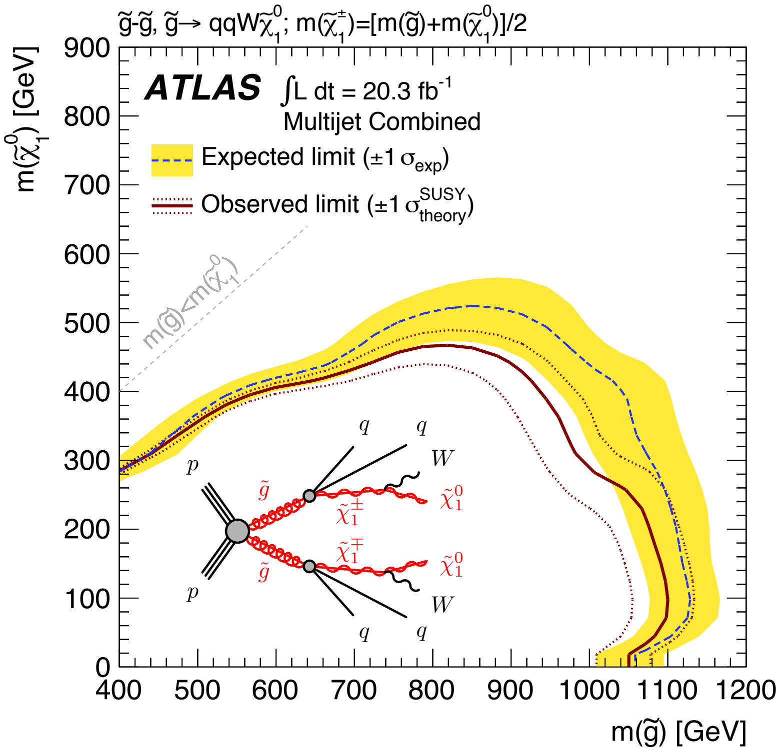
A typical mSUGRA grid

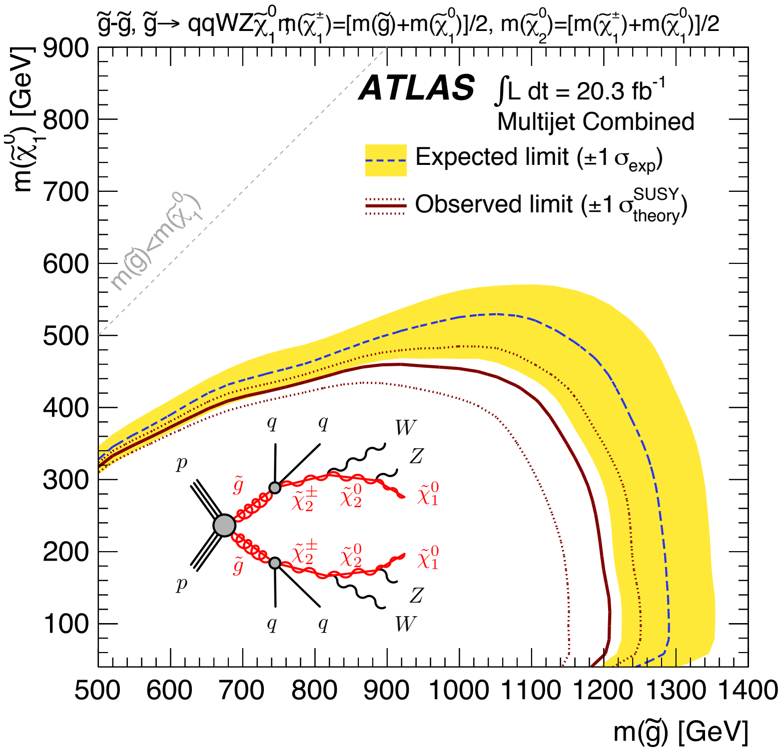


‘Simplified models’

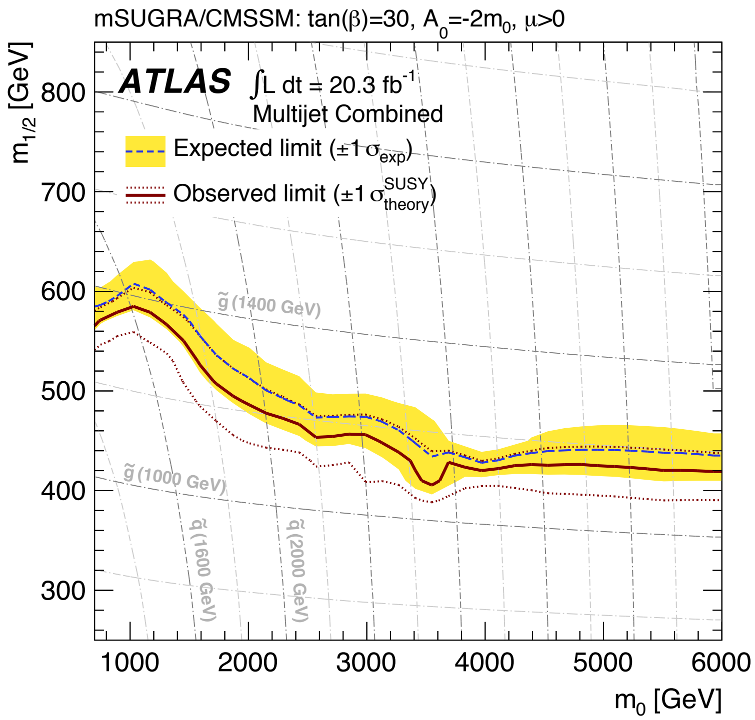
◎ **Simplified topologies with typically one production and one decay process. Provide useful information for theorists.**

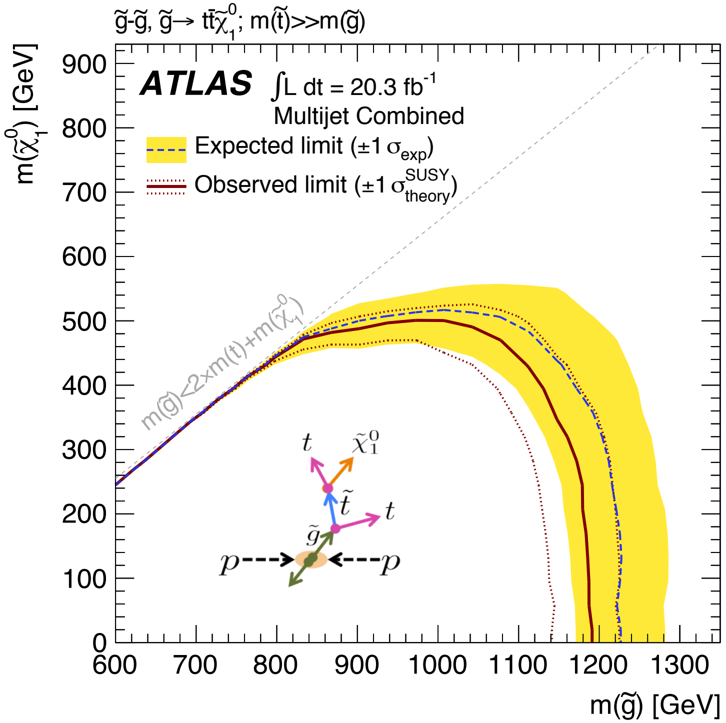
INTERPRETATIONS



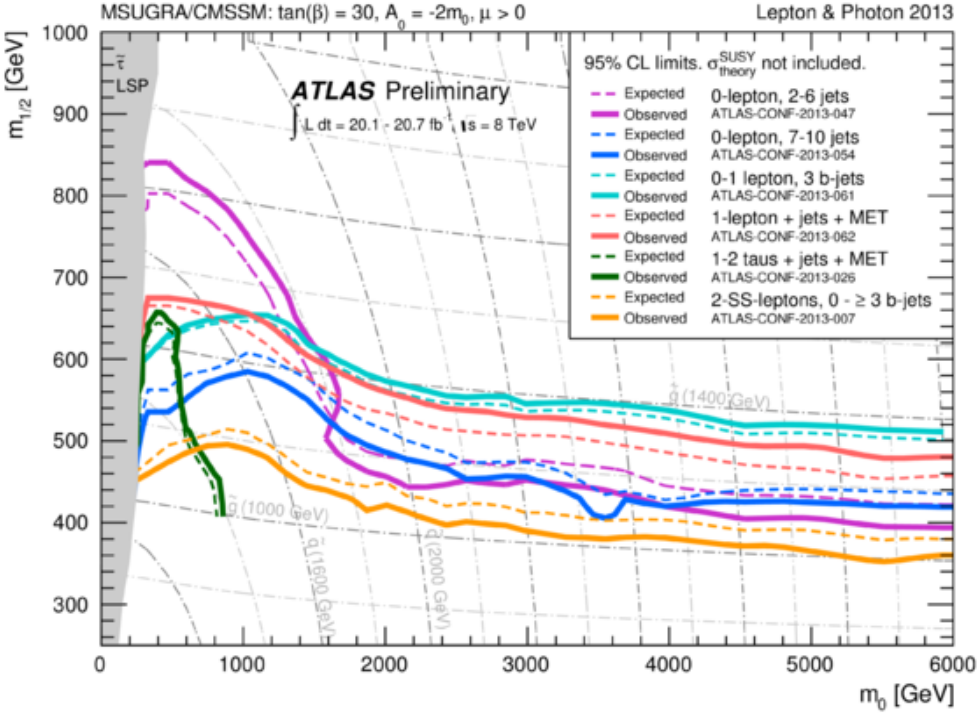


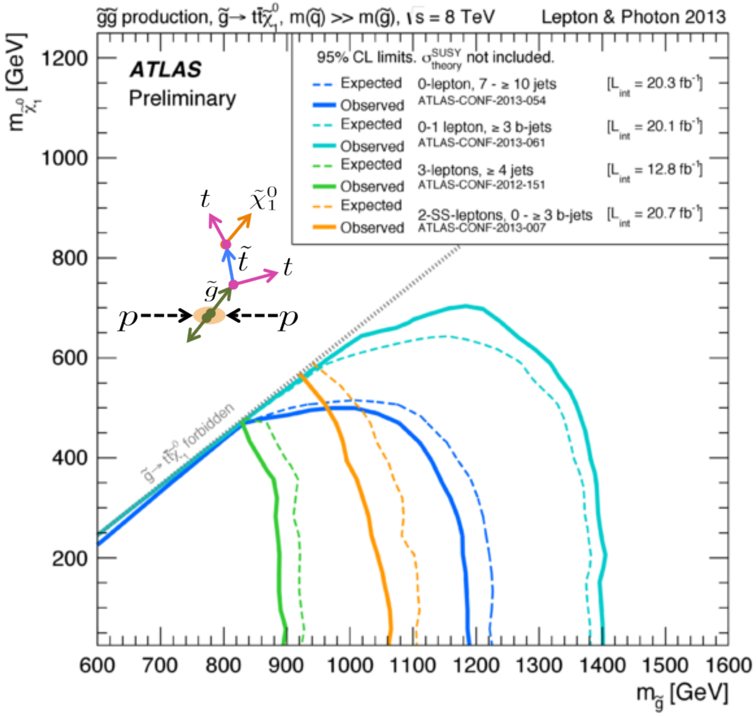
INTERPRETATIONS





INTERPRETATIONS





- Note that the multijet analysis is not optimized for a specific model, it is built to be as model-independent as possible.
- Multijet analysis is strong in other simplified models, e.g. gluino pair production via 2-step decay to 12 jets.

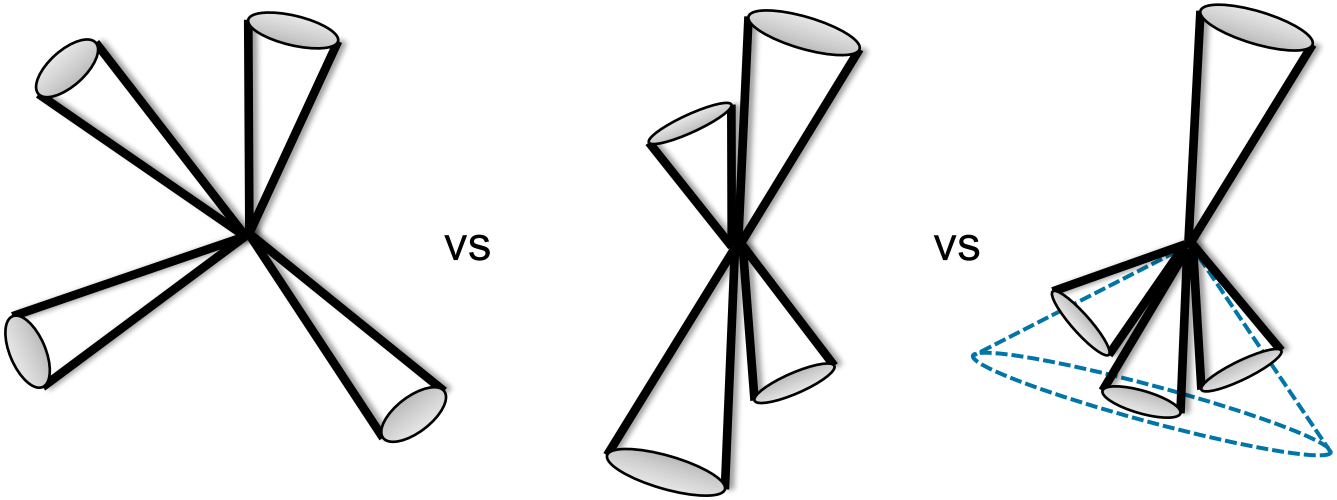
QCD BACKGROUNDS IN SUSY

All (SUSY) analyses use data-driven methods for assessing multi-jet SM production.

Monte Carlo can not be used when large multiplicities are involved:

- Inclusive multi-jet / multi-parton samples provided by Monte Carlo generators recently only.
  - E.g. only very latest Sherpa release provides NLO calculations up to four jets.
- Monte Carlo predictions have not yet been validated with multi-jet data.
- **Detailed comparisons between data and various Monte Carlo generators and theoretical predictions would provide extremely useful input to the theory community in understanding QCD.**
  - They would also provide a great understanding of a dominant SUSY background in view of run2.

E.G. FOUR-JET TOPOLOGIES & OBSERVABLES

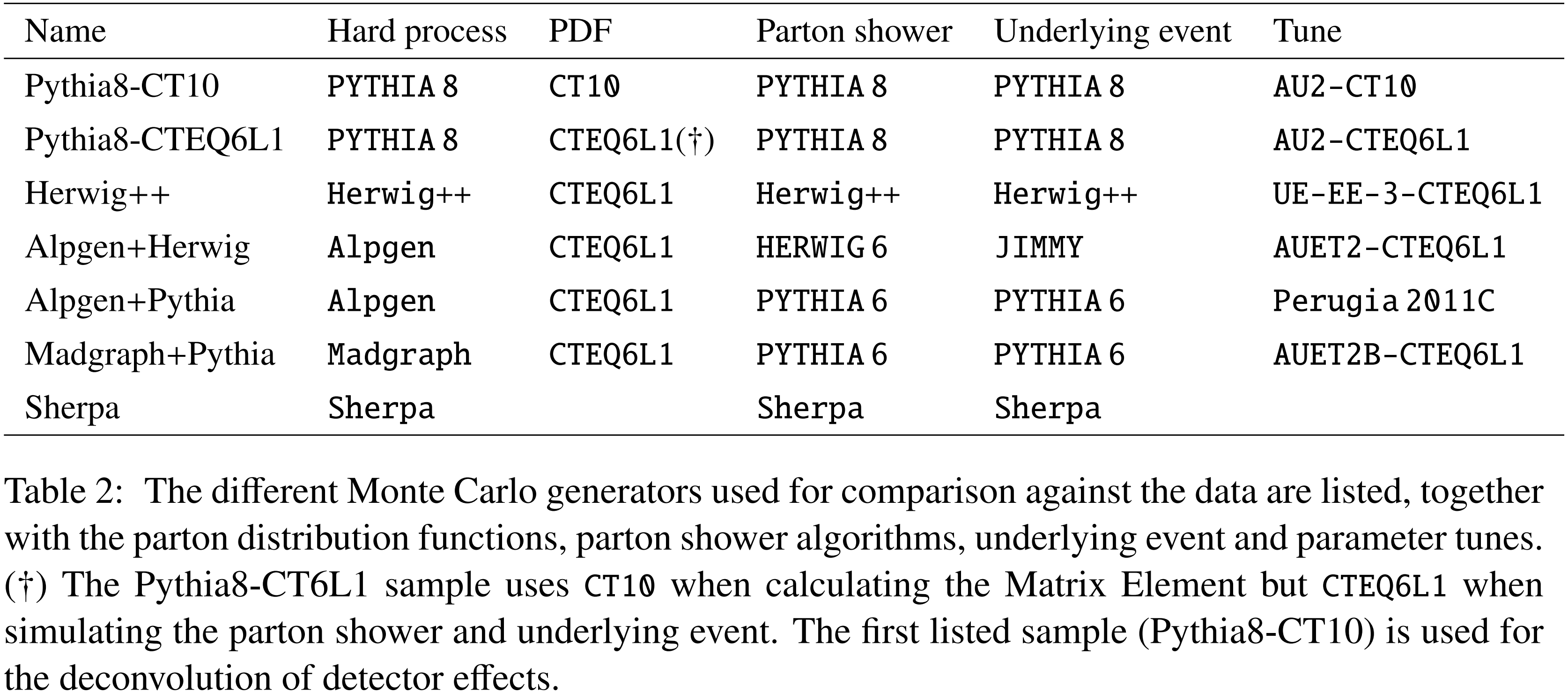


Category	**Variable**
Simple kinematic & ratios	p_T, η, φ, H_T, p_{Ti}/p_{Tj}
Angles	$\Delta\eta_{ij}$, $\Delta\varphi_{ij}$, ΔR_{ij}
Masses & ratios	m_{ij}, m_{ijk}, m_4, m_i/m_{ij}, m_i/m_{ijk}, m_i/m_4
Event shapes	$\Sigma\, p_T^2 / \Sigma\, p^2$

E.G. FOUR-JET TOPOLOGIES & OBSERVABLES

Name	Definition	Comment
$p_{\mathrm{T}i}$	Transverse momentum of the ith jet	Sorted descending in p_{T}
Y_i	Rapidity of the ith jet	
H_{T}	$\sum_{i=1}^{4} p_{\mathrm{T}i}$	Scalar sum of the p_{T} of the four jets
M_{jjjj}	$\left(\sum_{i=1}^{4} E_i\right)^2 - \left(\sum_{i=1}^{4} \mathbf{p}_i\right)^2$	Invariant mass of the four jets
$M_{\mathrm{jj}}^{\mathrm{min}}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\left(E_i + E_j\right)^2 - \left(\mathbf{p}_i + \mathbf{p}_j\right)^2\right)$	Minimum invariant mass of any two jets
$\Delta\phi_{ij}^{\mathrm{min}}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\lvert\phi_i - \phi_j\rvert\right)$	Min azimuthal separation of two jets
$\Delta Y_{ij}^{\mathrm{min}}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\lvert Y_i - Y_j\rvert\right)$	Min rapidity separation of two jets
$\Delta\phi_{ijk}^{\mathrm{min}}$	$\min_{\substack{i,j,k\in[1,4]\\ i<j<k}} \left(\lvert\Delta\phi_{ij}\rvert + \lvert\Delta\phi_{jk}\rvert\right)$	Min azimuthal separation between three jets
$\Delta Y_{ijk}^{\mathrm{min}}$	$\min_{\substack{i,j,k\in[1,4]\\ i<j<k}} \left(\lvert\Delta Y_{ij}\rvert + \lvert\Delta Y_{jk}\rvert\right)$	Min rapidity separation between three jets
$\Delta Y_{ij}^{\mathrm{max}}$	$\Delta Y_{ij}^{\mathrm{max}} = \max_{i,j\in[1,4]} \left(\lvert Y_i - Y_j\rvert\right)$	Max rapidity difference between two jets
$\Sigma p_{\mathrm{T}}^{\mathrm{central}}$	Sum of p_{T} of the two central-rapidity jets	Excludes jets having $\Delta Y_{ij}^{\mathrm{max}}$

E.G. FOUR-JET MONTE CARLO SAMPLES



Name	Hard process	PDF	Parton shower	Underlying event	Tune
Pythia8-CT10	PYTHIA 8	CT10	PYTHIA 8	PYTHIA 8	AU2-CT10
Pythia8-CTEQ6L1	PYTHIA 8	CTEQ6L1(†)	PYTHIA 8	PYTHIA 8	AU2-CTEQ6L1
Herwig++	Herwig++	CTEQ6L1	Herwig++	Herwig++	UE-EE-3-CTEQ6L1
Alpgen+Herwig	Alpgen	CTEQ6L1	HERWIG 6	JIMMY	AUET2-CTEQ6L1
Alpgen+Pythia	Alpgen	CTEQ6L1	PYTHIA 6	PYTHIA 6	Perugia 2011C
Madgraph+Pythia	Madgraph	CTEQ6L1	PYTHIA 6	PYTHIA 6	AUET2B-CTEQ6L1
Sherpa	Sherpa		Sherpa	Sherpa	

Table 2: The different Monte Carlo generators used for comparison against the data are listed, together with the parton distribution functions, parton shower algorithms, underlying event and parameter tunes. (†) The Pythia8-CT6L1 sample uses CT10 when calculating the Matrix Element but CTEQ6L1 when simulating the parton shower and underlying event. The first listed sample (Pythia8-CT10) is used for the deconvolution of detector effects.

THE ATLAS TRIGGER SYSTEM

Rate (2012 conditions)

Hardware

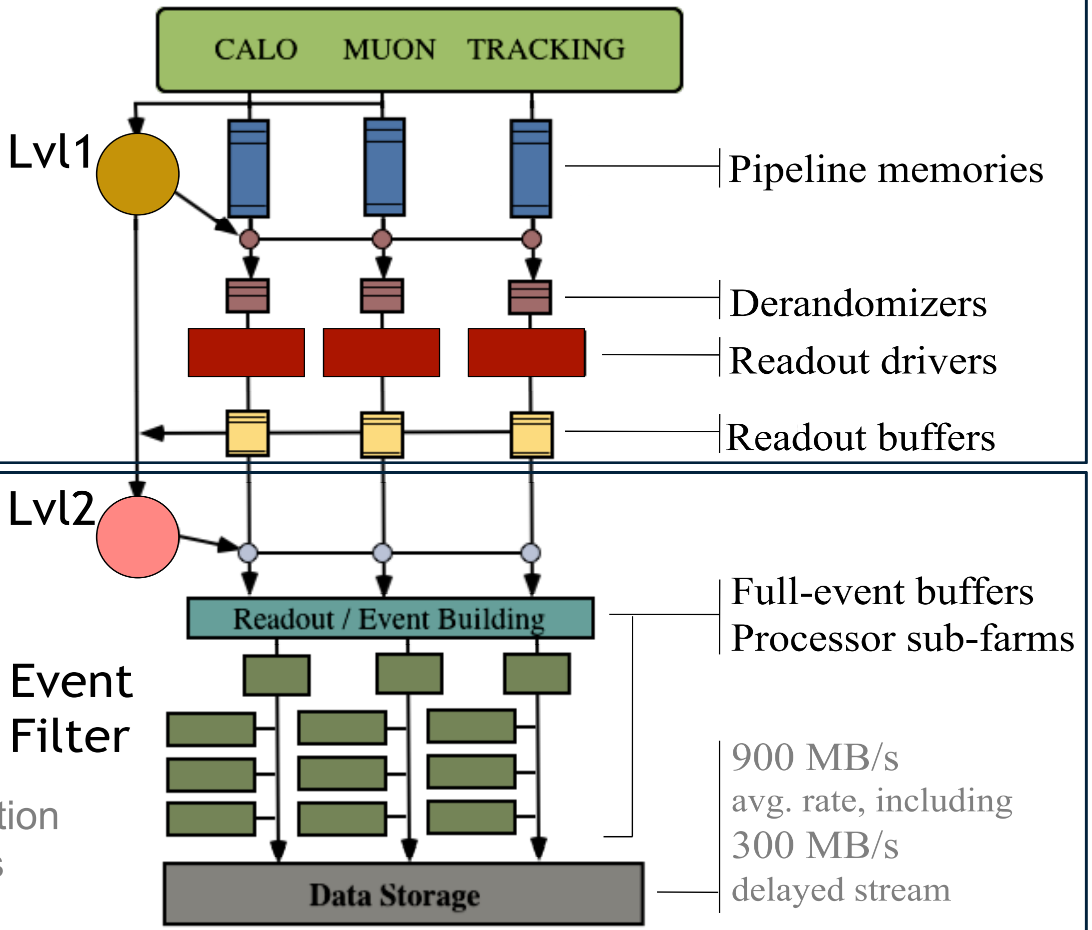
20 MHz
Bunch crossing rate
6.4×10^8
Interactions/s

75 kHz
Peak rate

Software

6 kHz
Peak rate

600 Hz
Avg. rate, including
200 Hz delayed stream
(stored for later reconstruction
when computing resources
available)



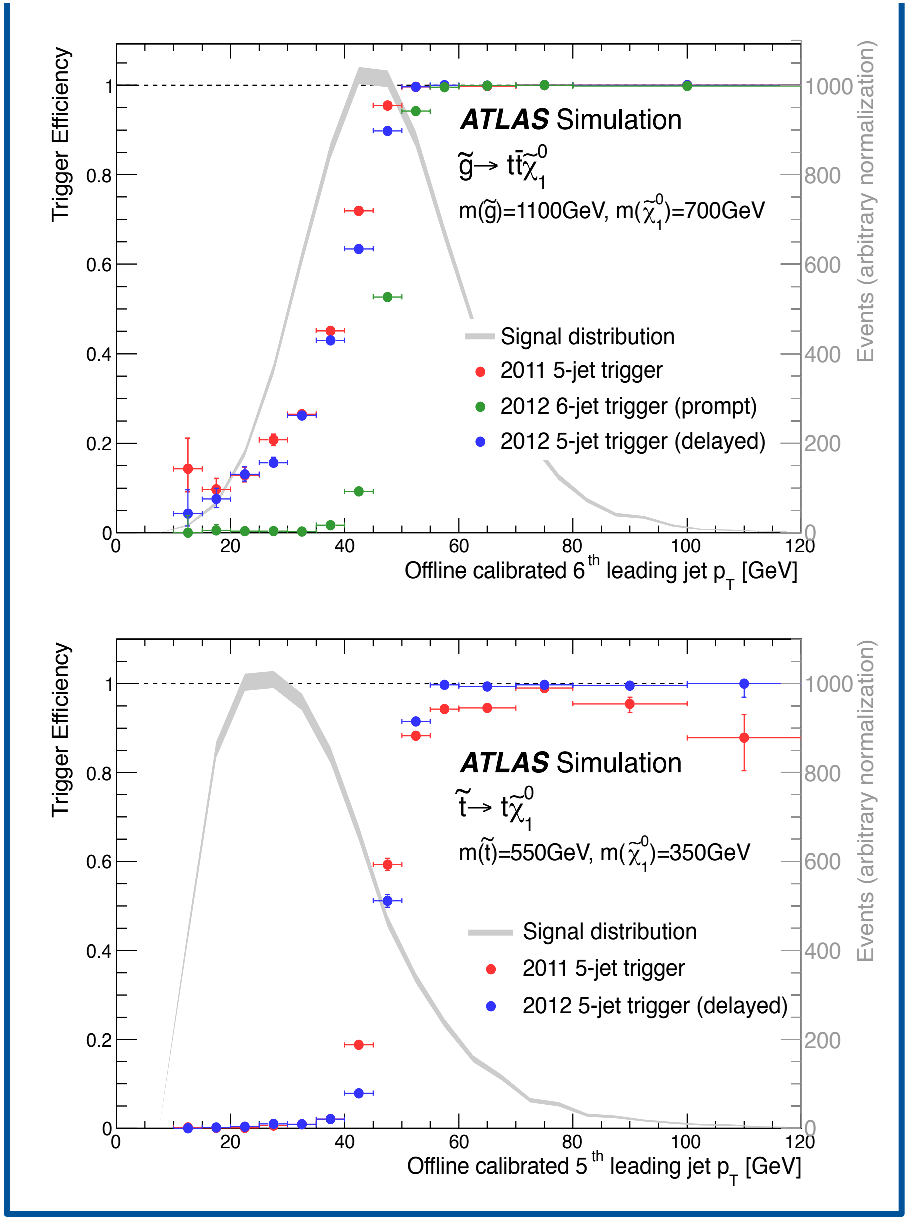
900 MB/s
avg. rate, including
300 MB/s
delayed stream

TRIGGER

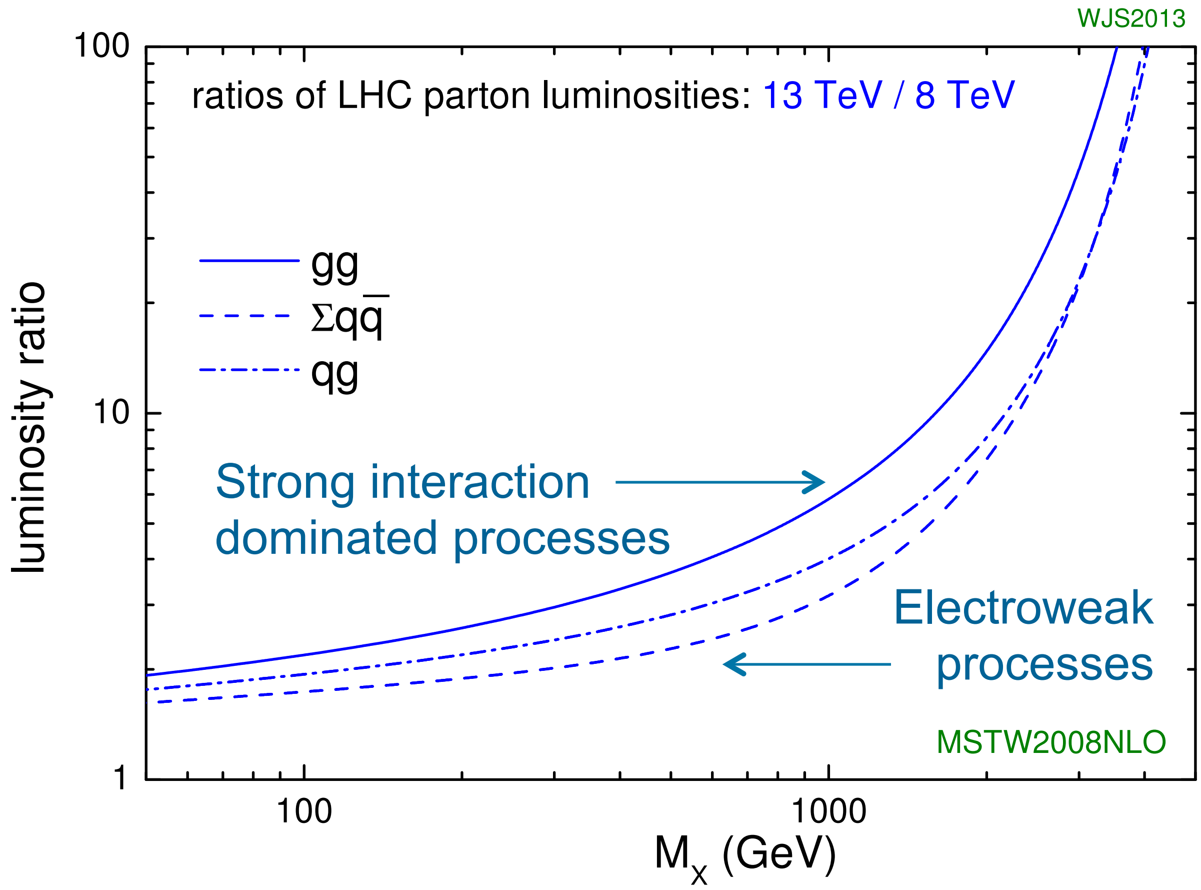
<table>
<tr><th colspan="3">Signal triggers</th></tr>
<tr><th>Jet Multiplicity</th><th>pT cut</th><th>|η|</th></tr>
<tr><td>6</td><td>45</td><td rowspan="2">3.2</td></tr>
<tr><td>5</td><td>55</td></tr>
</table>

<table>
<tr><th colspan="2">Background/support triggers</th></tr>
<tr><th>Type</th><th>Purpose</th></tr>
<tr><td>Multijet (prescaled)</td><td>Efficiencies & Control regions</td></tr>
<tr><td>Single lepton</td><td>Control regions</td></tr>
</table>

Multijet trigger improvements in 2012



THE BENEFITS



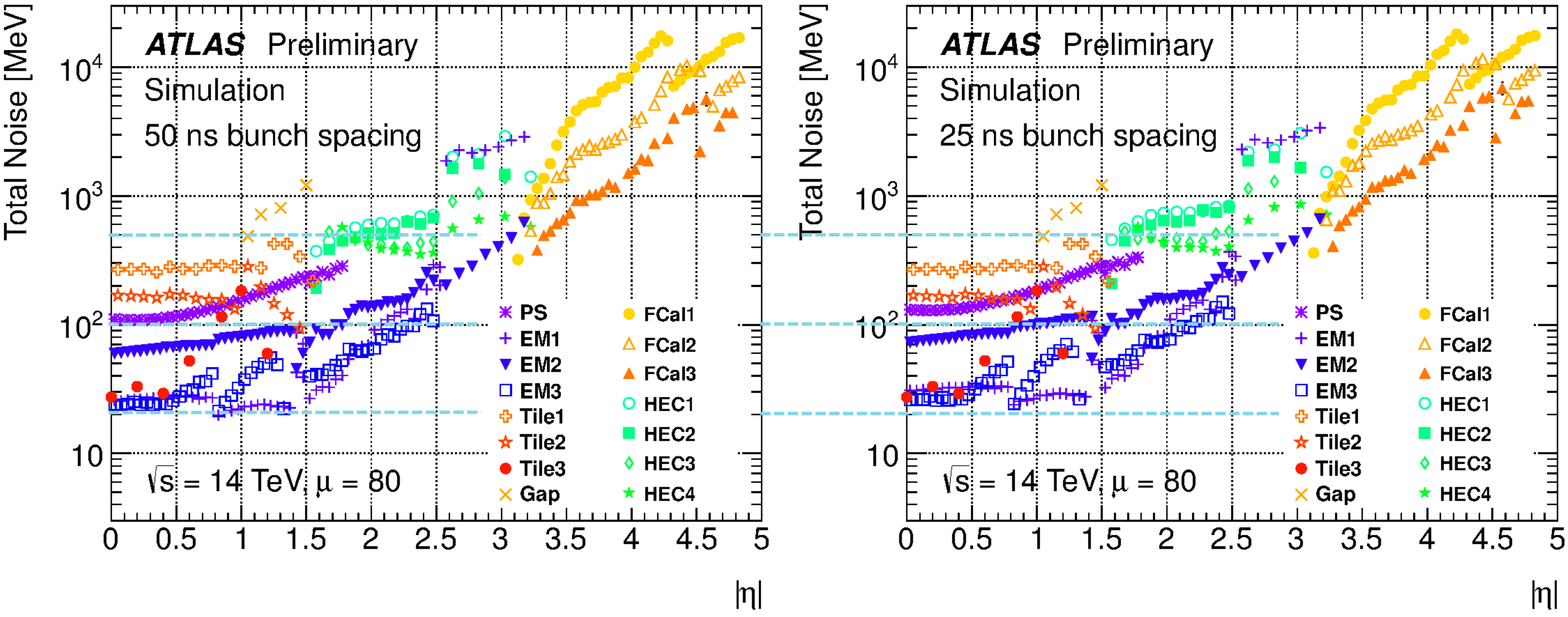
Strong interaction dominated processes

Electroweak processes

THE CHALLENGES

The calorimeter

Simulated noise in the Liquid Argon and Tile calorimeters at the electron scale



THE ‘SOLUTIONS’

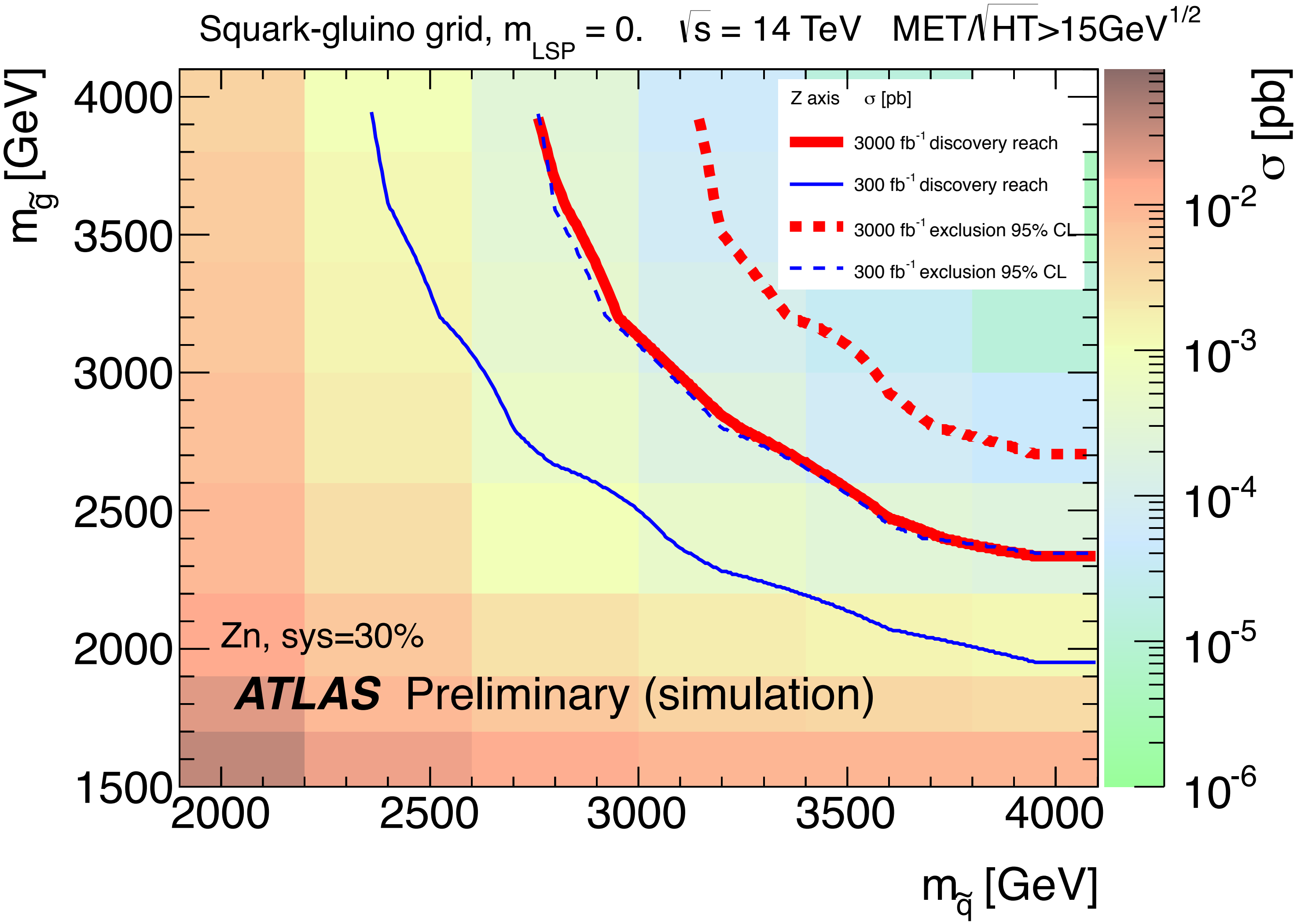
Detector extensions, e.g. extra muon chambers at $1.0<|\eta|<1.3$.

Ongoing trigger upgrade that will:

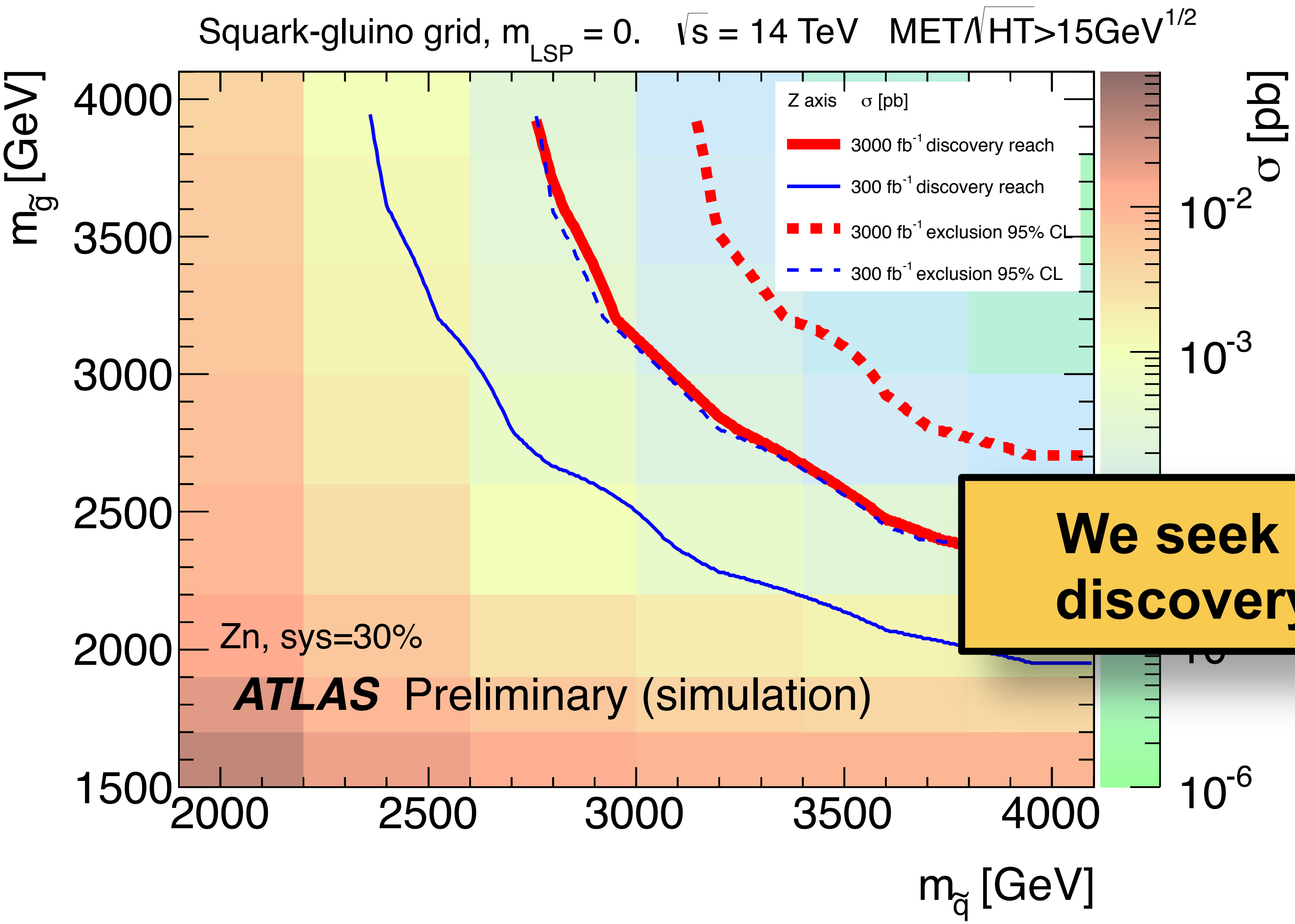
- Increase the peak L1 rate to 100kHz.
- Provide possibility to select on combined L1 quantities (angles, masses, etc).
- Provide tracks at the input of the HLT for better object ID.
- Ensure more efficient and flexible HLT reconstruction with a merged (L2 & EF) HLT.

Clever ideas for better & more robust object reconstruction.

THE PROSPECTS



THE PROSPECTS



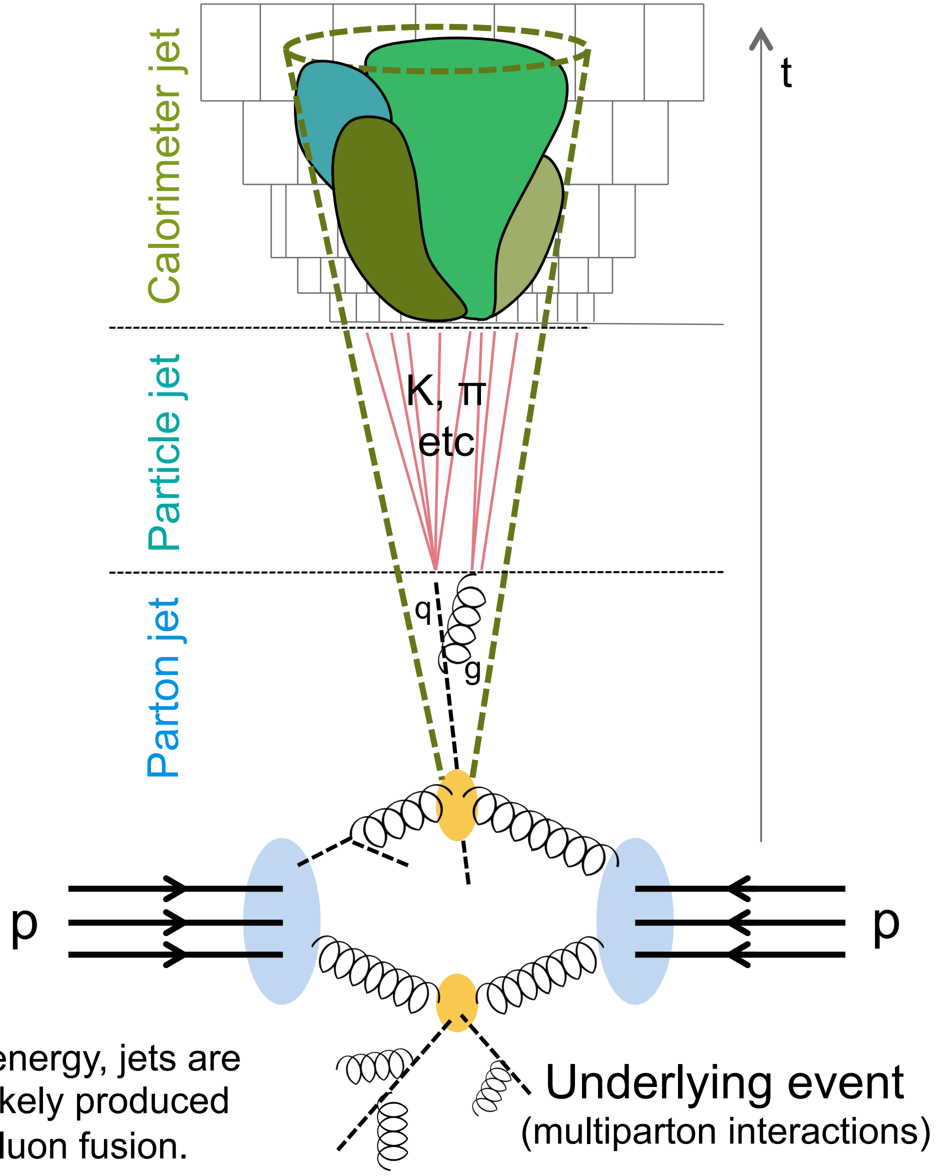
We seek a discovery.

JETS

Detector inefficiencies
‘Pile-up’
Electronic noise
Clustering, noise suppression
Dead material losses
Detector response
Algorithm efficiency

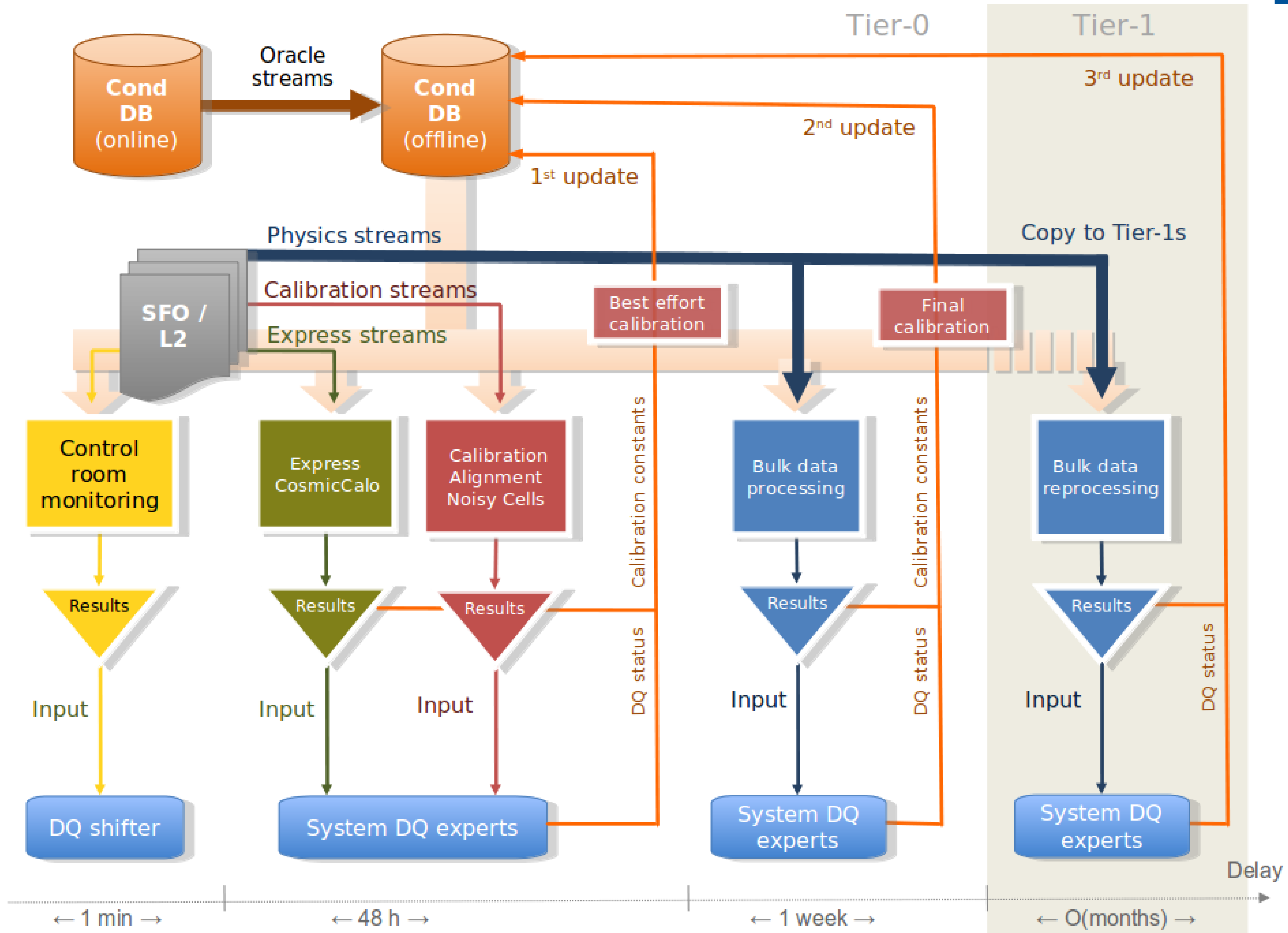
Algorithm efficiency
‘Pile-up’
‘Underlying event’

Physics process of interest



At low energy, jets are more likely produced by gluon fusion.

Underlying event
(multiparton interactions)



Tier-0

Tier-1

Cond DB (online)

Oracle streams

Cond DB (offline)

3rd update

2nd update

1st update

Physics streams

Copy to Tier-1s

SFO / L2

Calibration streams

Express streams

Best effort calibration

Final calibration

Control room monitoring

Express CosmicCalo

Calibration Alignment Noisy Cells

Calibration constants

Bulk data processing

Calibration constants

Bulk data reprocessing

Results

Results

Results

Results

Results

DQ status

DQ status

DQ status

Input

Input

Input

Input

Input

DQ shifter

System DQ experts

System DQ experts

System DQ experts

Delay

← 1 min →

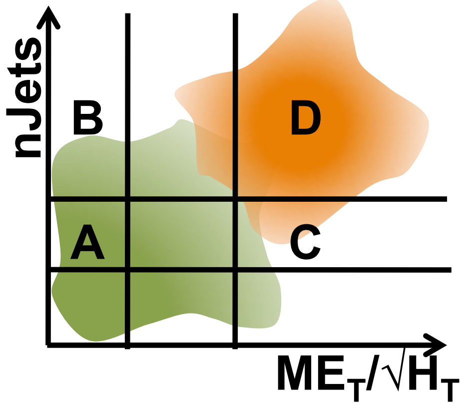
← 48 h →

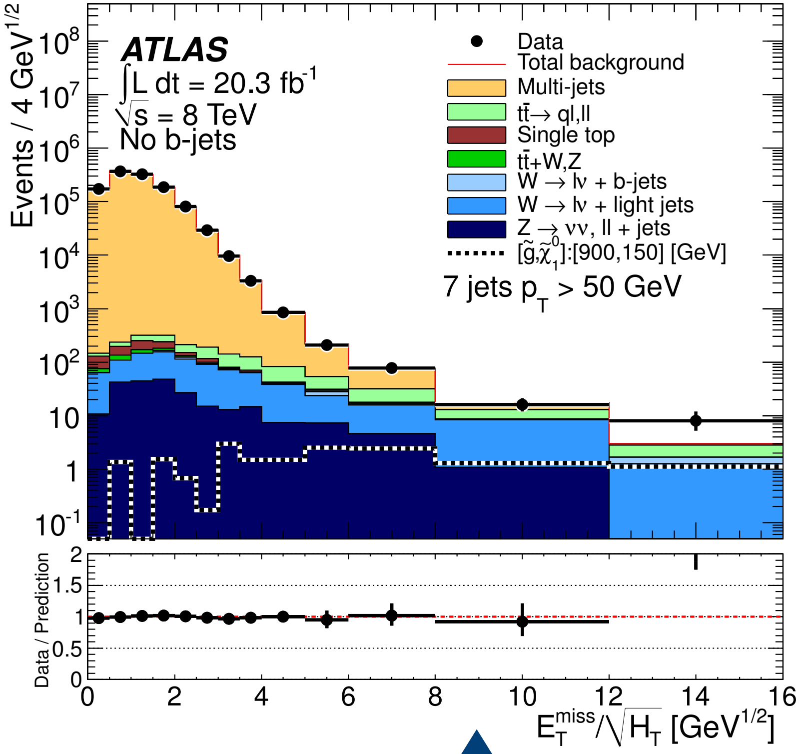
← 1 week →

← O(months) →

BACKGROUNDS & DETERMINATION

QCD & Hadronic ttbar

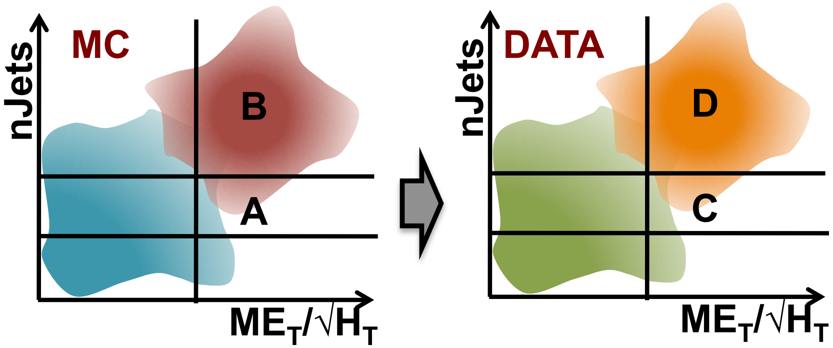


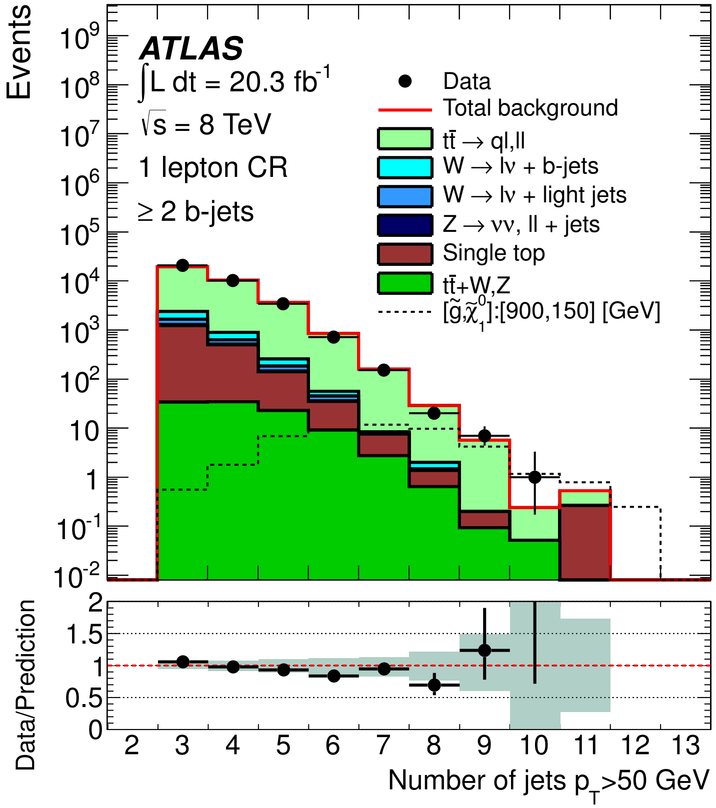


- ◎ Template extracted from '6j50' and validated in '7j50'.
- ◎ Discrepancies in control regions become uncertainties; dominant, on top of heavy flavor and 'leptonic' backgrounds.

BACKGROUNDS & DETERMINATION

Non-full hadronic ttbar & V+jets





- Extracted from MC normalized on data.
- Uncertainties: JES/JER, b-tagging, pile-up and theory.