PART 4

SMARTHEP
REAL-TIME ANALYSIS FOR
SCIENCE AND INDUSTRY

WHAT WILL THIS LECTURE BE ABOUT?

INTRODUCTION

- Definitions and basic concepts

INPUT TO THE PHYSICS

- The data: trigger, data preparation
- The theory: Monte carlo simulations
- Reconstruction, or how to translate detector signals to particles

PHYSICS ANALYSES

- **Through example, step-by-step**
- **Discussion of analysis methods**

SMARTHEP
REAL-TIME ANALYSIS FOR
SCIENCE AND INDUSTRY

Is there a topic you would like to add to this material?
If so: please let me know at the end of this lecture and I will see if I can add it!

LHC PHYSICS

AN ANALYSIS
STEP-BY-STEP

PHYSICS ANALYSES

Measurements

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

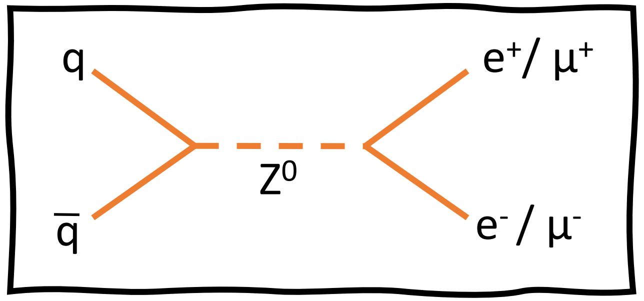
“Systematic” uncertainties are introduced by inaccuracies in the methods used to perform the measurement.

Searches

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

SIMPLE EXAMPLE:
MEASURING THE Z^0 CROSS-SECTION AT LHC

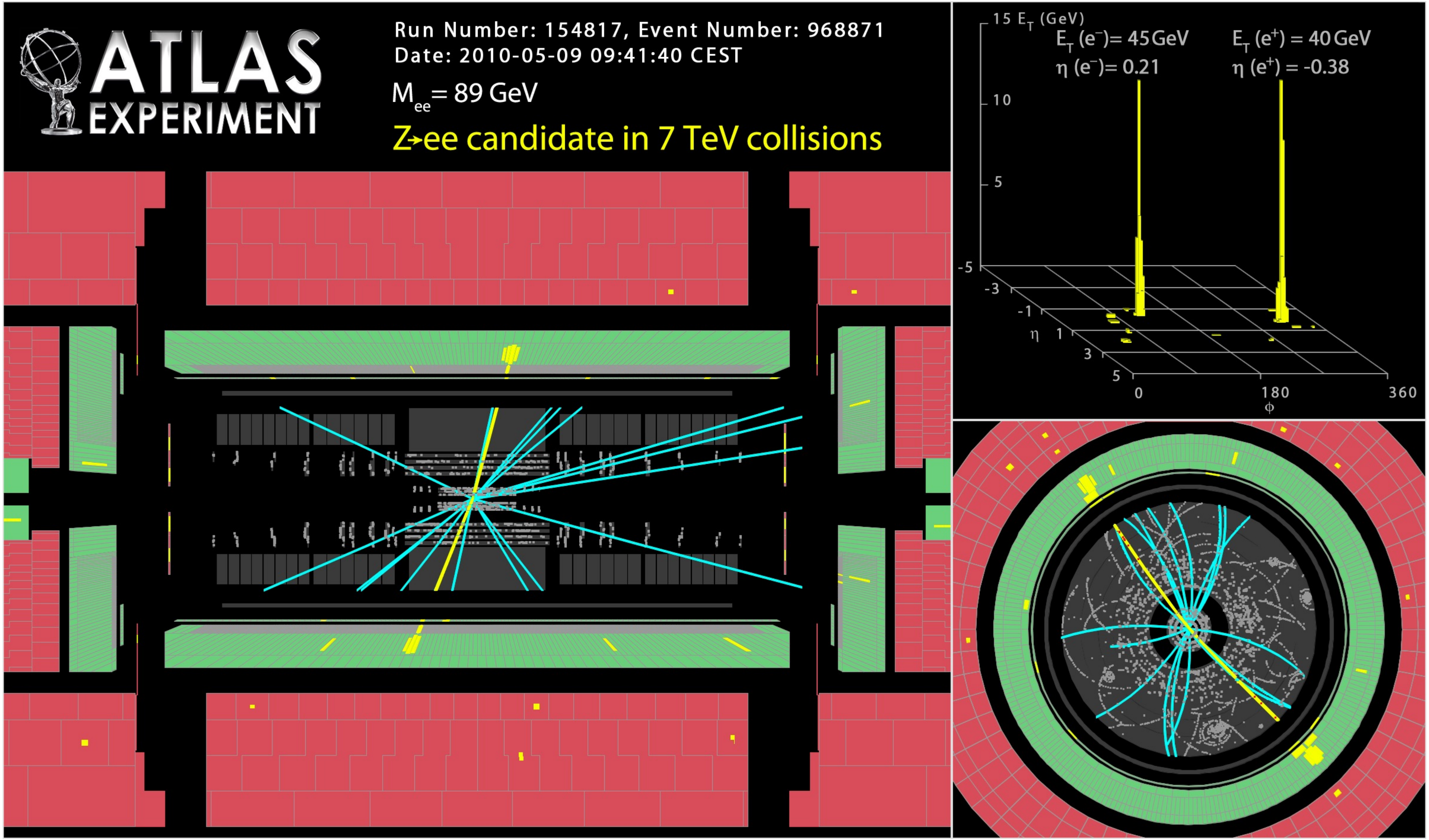
- **Z^0 boson decays to lepton or quark pairs**
  - We can reconstruct it in the e^+e^- or $\mu^+\mu^-$ decay modes



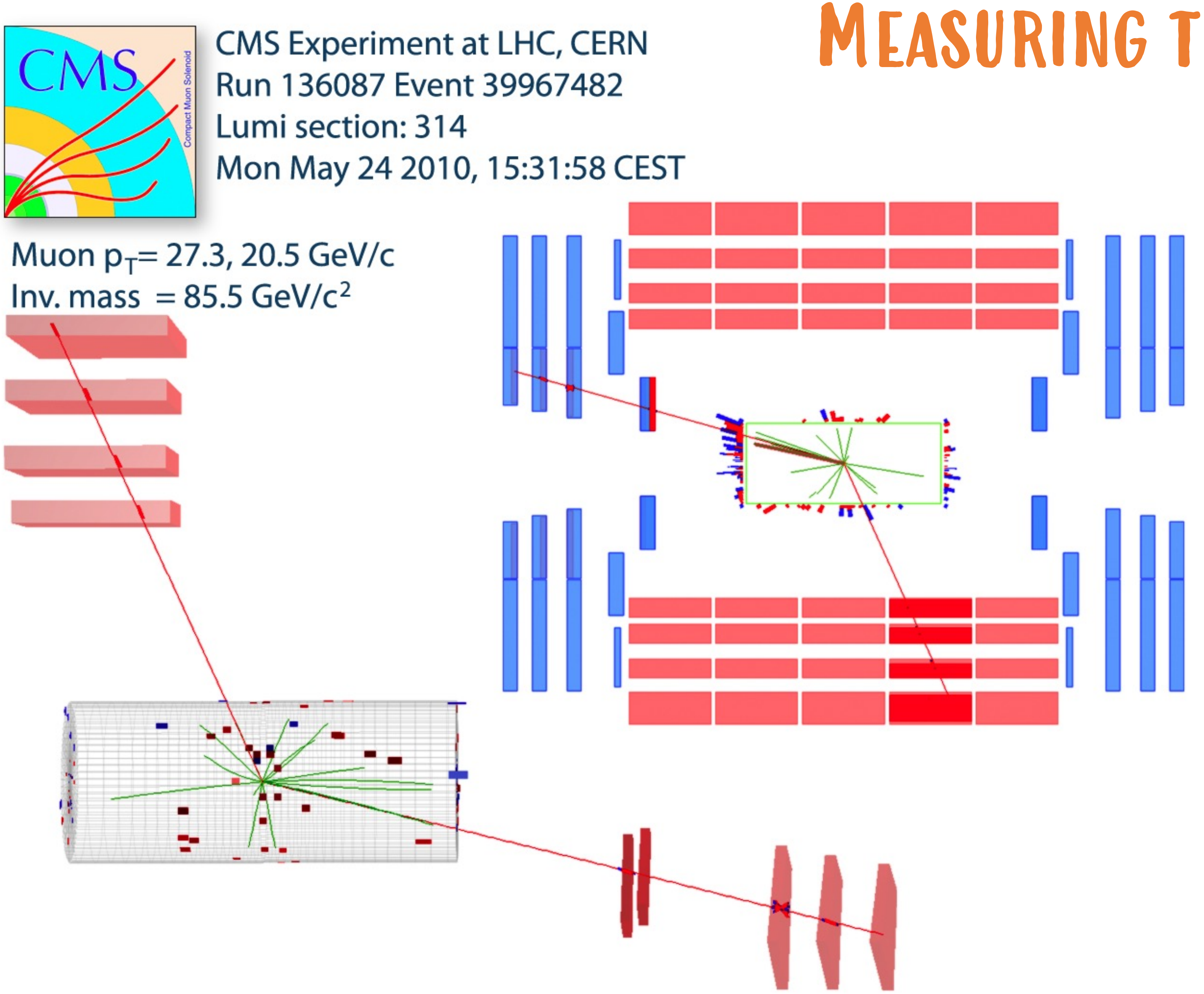
- Discovery and study of the Z^0 boson was a critical part of understanding the electroweak force.

- 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!

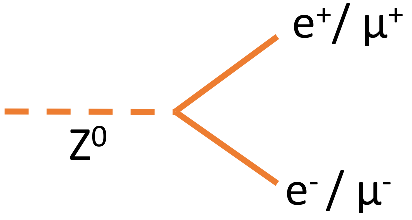
MEASURING THE Z^0 CROSS-SECTION AT LHC



MEASURING THE Z^0 CROSS-SECTION AT LHC



RECONSTRUCTING Z^0'S



STEP-1: IDENTIFY THE OBSERVABLE OF INTEREST

- Identify Z decays using the invariant mass of the 2 leptons

$M^2 = (L_1+L_2)^2$ where $L_i = (E_i,\underline{\boldsymbol{p}}_i)$ = 4-vector for lepton i

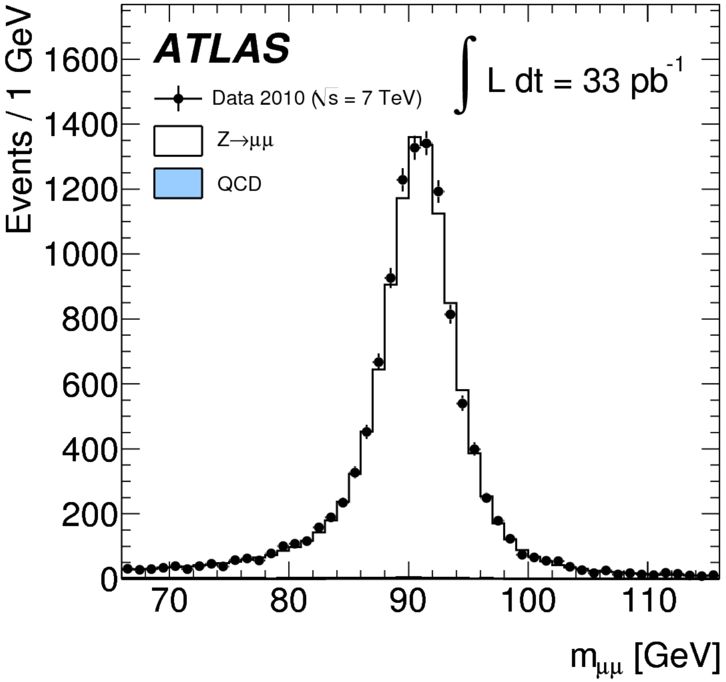
- Under assumption that lepton is massless compared to mass of Z^o

=> $M^2 = 2\, E_1\, E_2\, (1\text{-}\cos\theta_{12})$ where θ_{12}= angle between the leptons

STEP-2: SELECT Z^0 EVENTS WITH 'ANALYSIS CUTS':

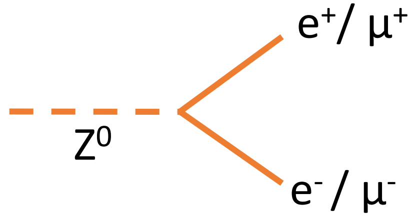
- Events with 2 high momentum electrons or muons
- Require the electrons or muons are of opposite charge
- With di-lepton mass close to the Z^o mass

(e.g. $70<m_{l+l-}<110$ GeV)



Very little background in Z^o mass region!

Reconstructing Z^0's



Step-1: Identify the observable of interest

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

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

Step-2: Select Z^0 events with 'analysis cuts':

- Events with 2 high momentum electrons or muons
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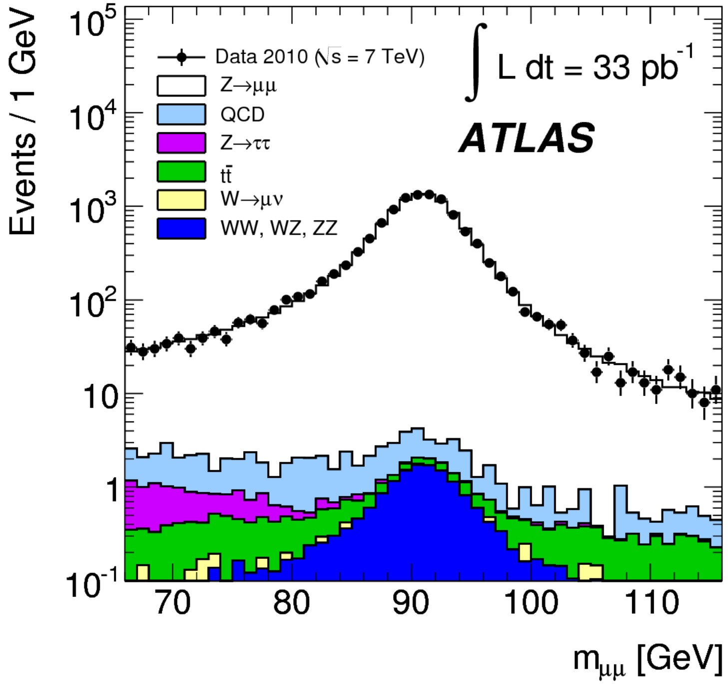
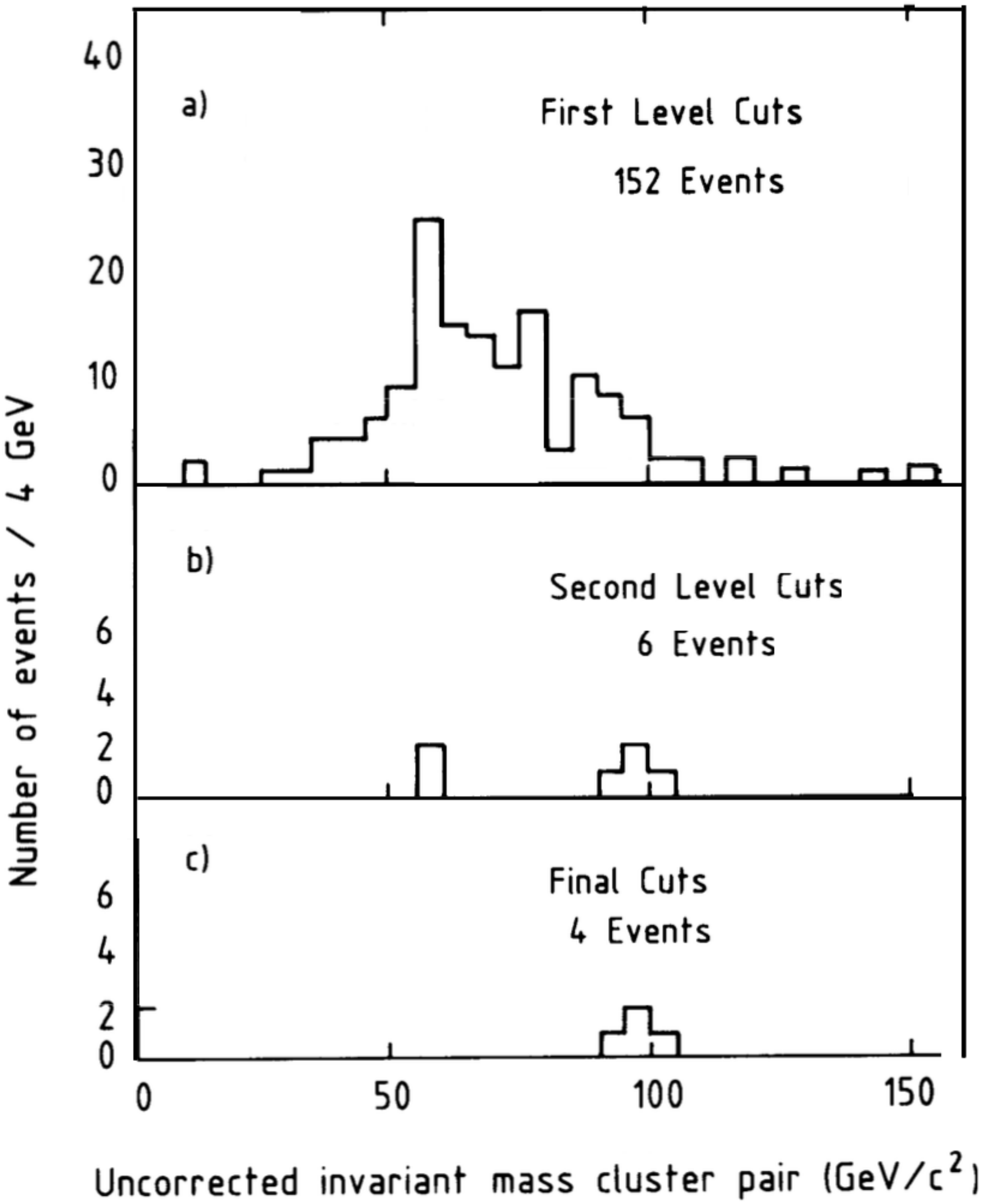
  (e.g. $70<m_{l+l-}<110$ GeV)



Very little background in Z^0 mass region!

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.

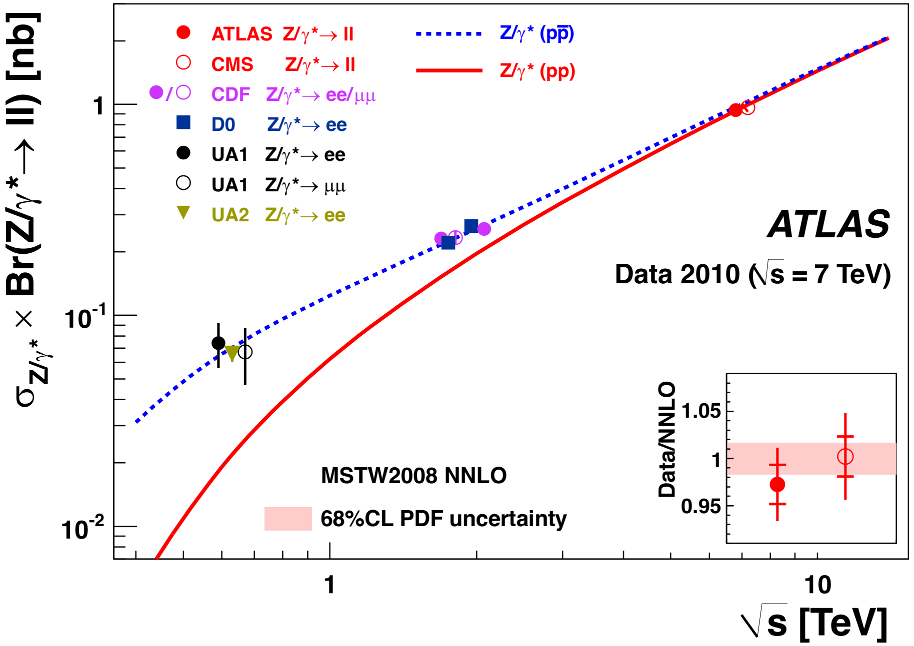
A second cluster has also an isolated track.

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

MEASURING Z^0 CROSS-SECTION

THEORETICALLY

Cross-section calculated for:
- ◎ Specific production mechanism (pp, pp, e^+e^-)
- ◎ Centre-of-Mass of the collisions (7, 8, 13 TeV at LHC)



EXPERIMENTALLY

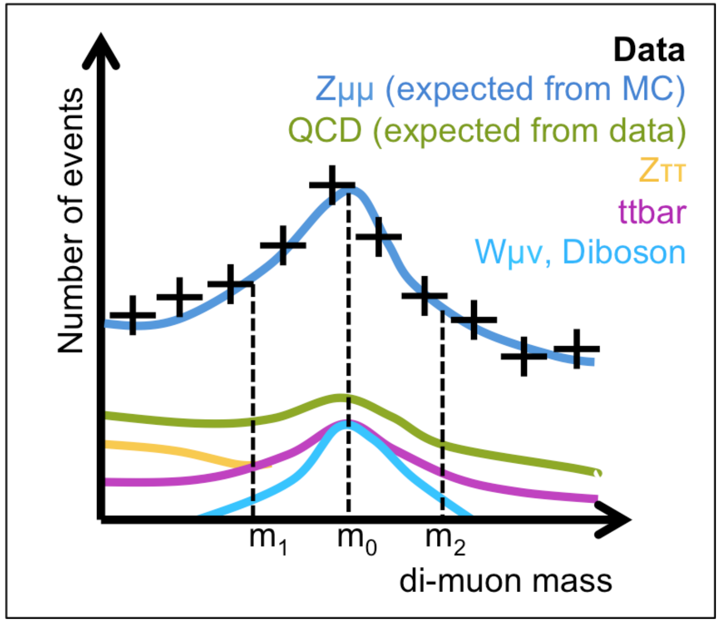
$$\sigma \cdot \mathrm{BR} = \frac{\text{Number of events}}{\alpha \cdot \epsilon \cdot \mathrm{L}}$$

N of events: N of events on data – N of expected background events

α – acceptance: fraction of events passing selection requirements

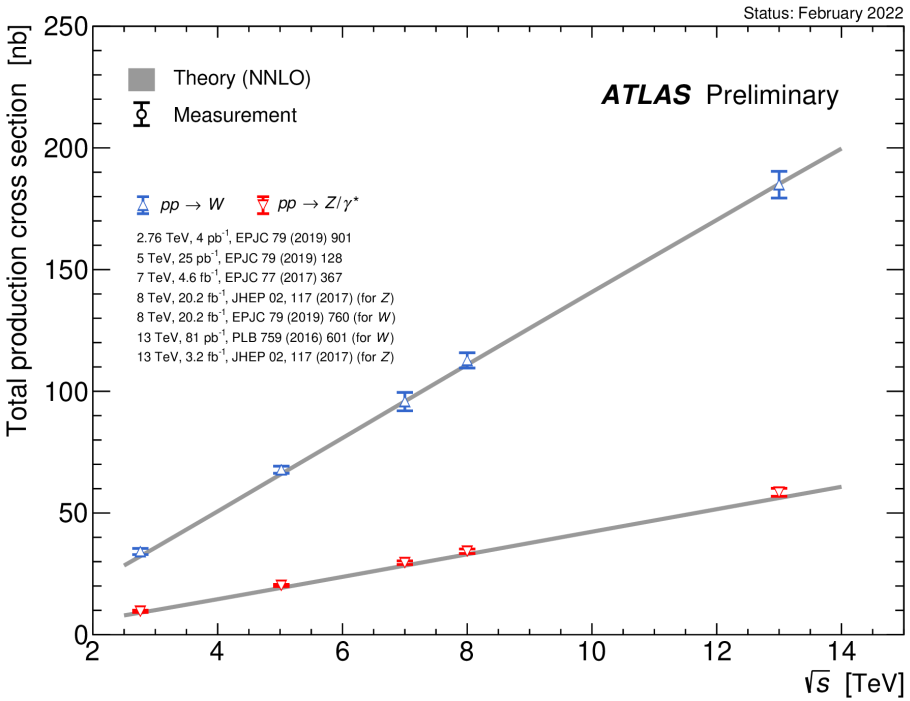
ε – efficiency: reconstruction efficiency of relevant objects

L – luminosity



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

MEASURING Z^0 CROSS-SECTION



THEORETICALLY

Cross-section calculated for:

- Specific production mechanism (pp, pp, e^+e^-)
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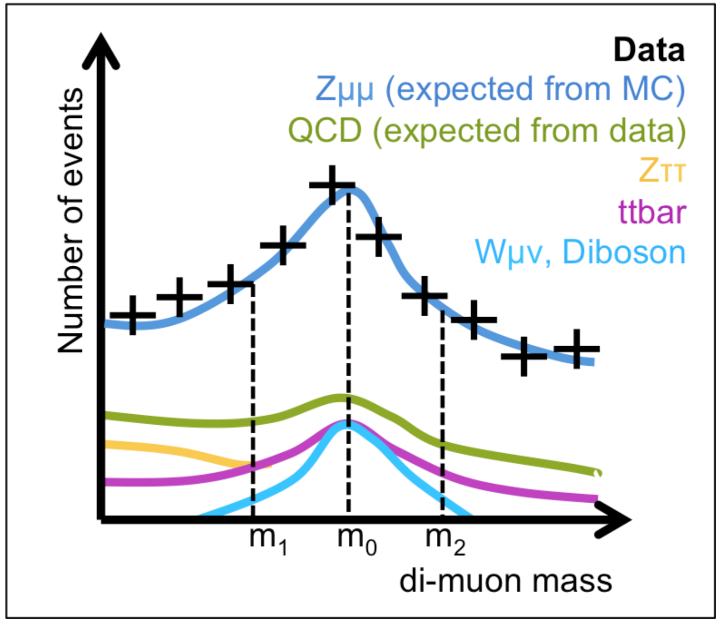

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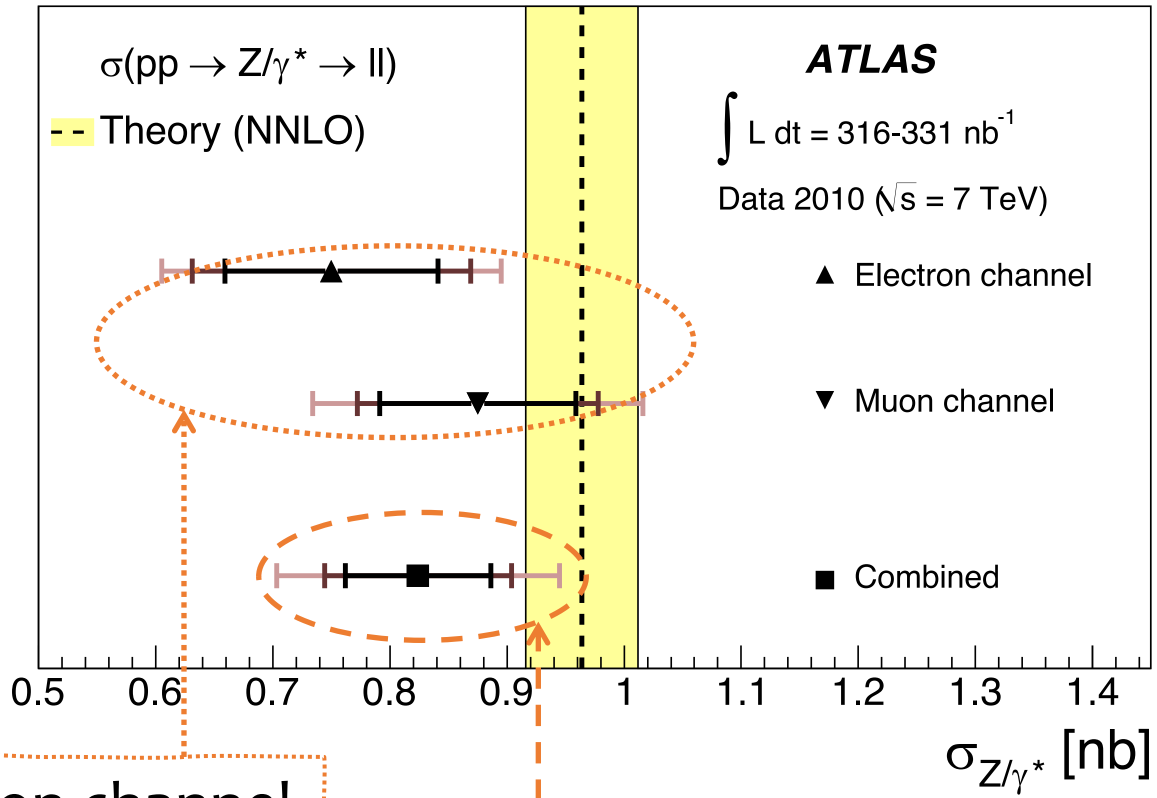
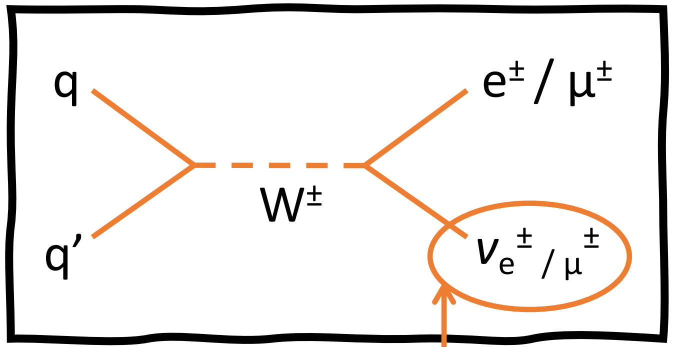
MEASURING Z^0 CROSS-SECTION



Electron and Muon channel agree within uncertainties

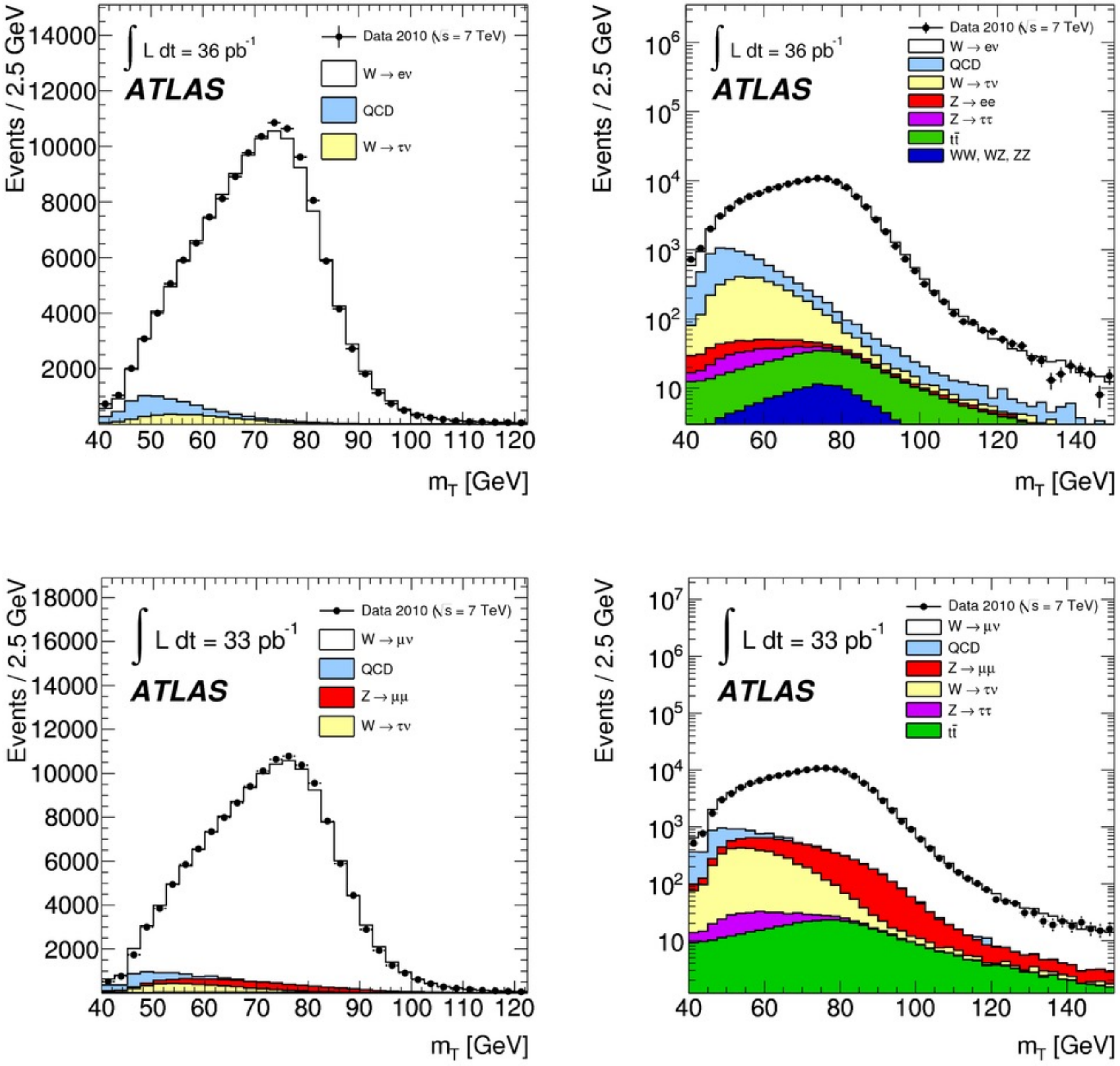
Measurement consistent with prediction within uncertainties

MEASURING W CROSS-SECTION

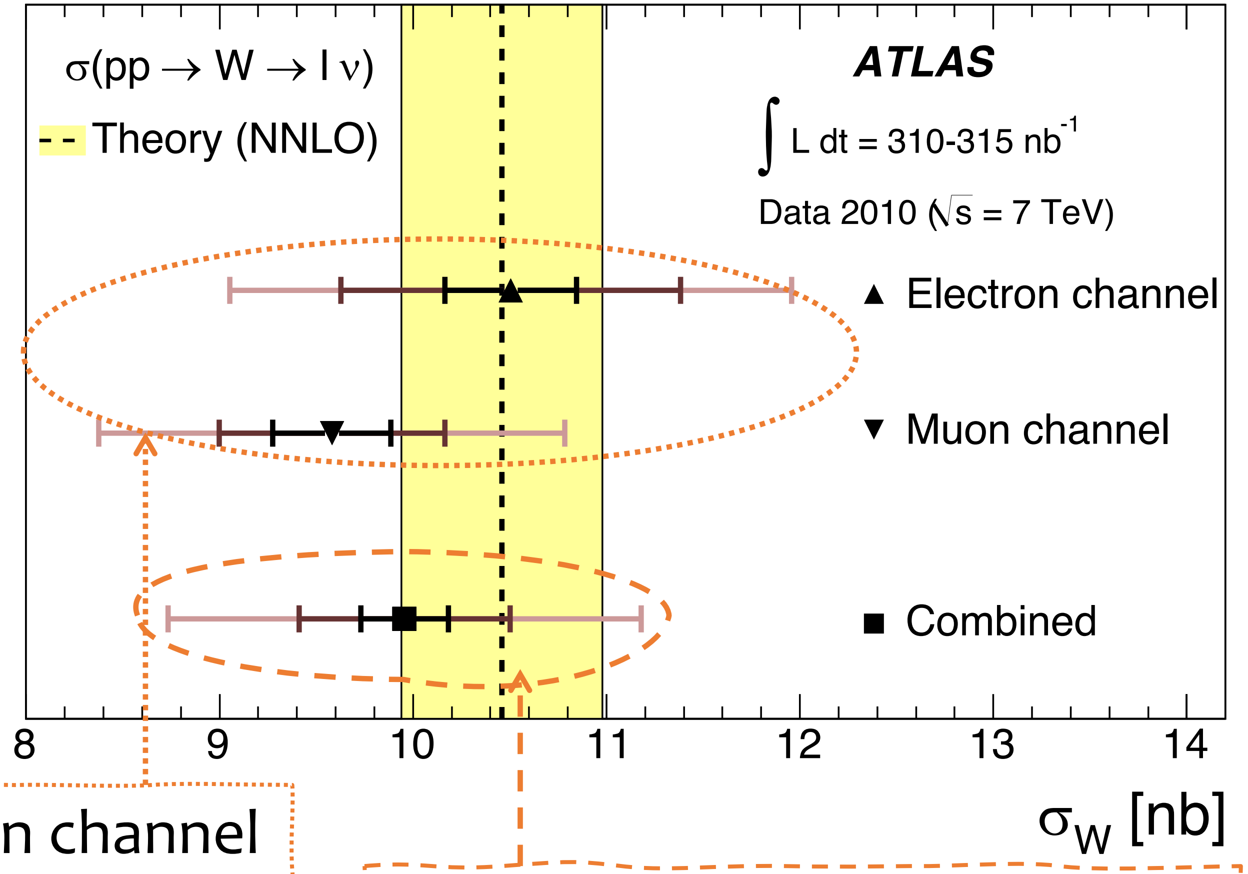


Available in the transverse plane only!

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



MEASURING W CROSS-SECTION



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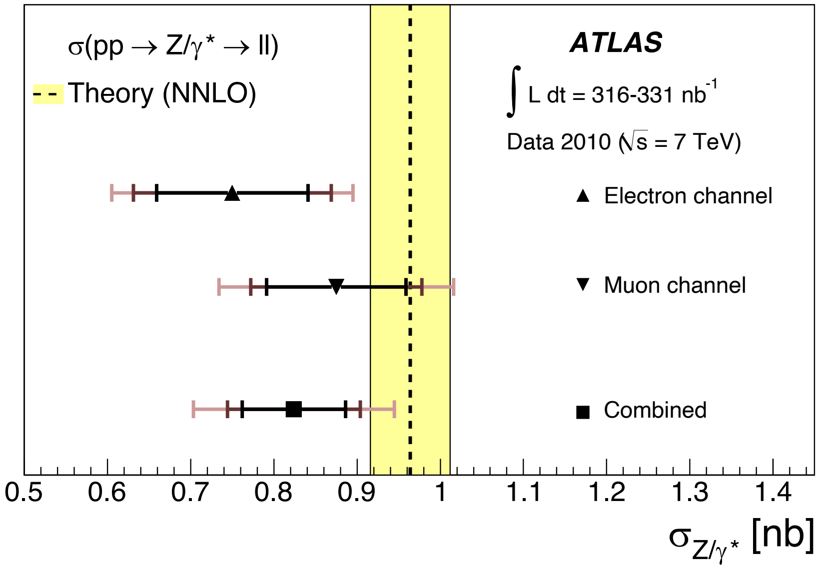
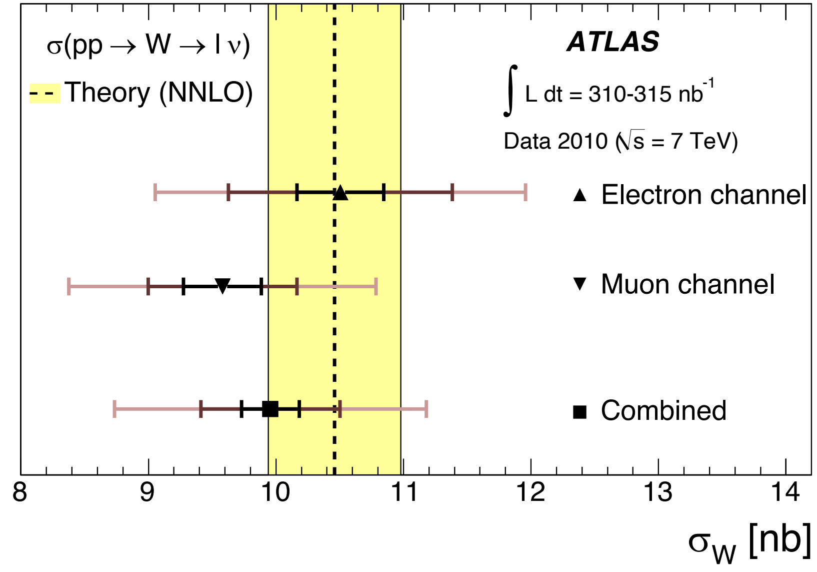
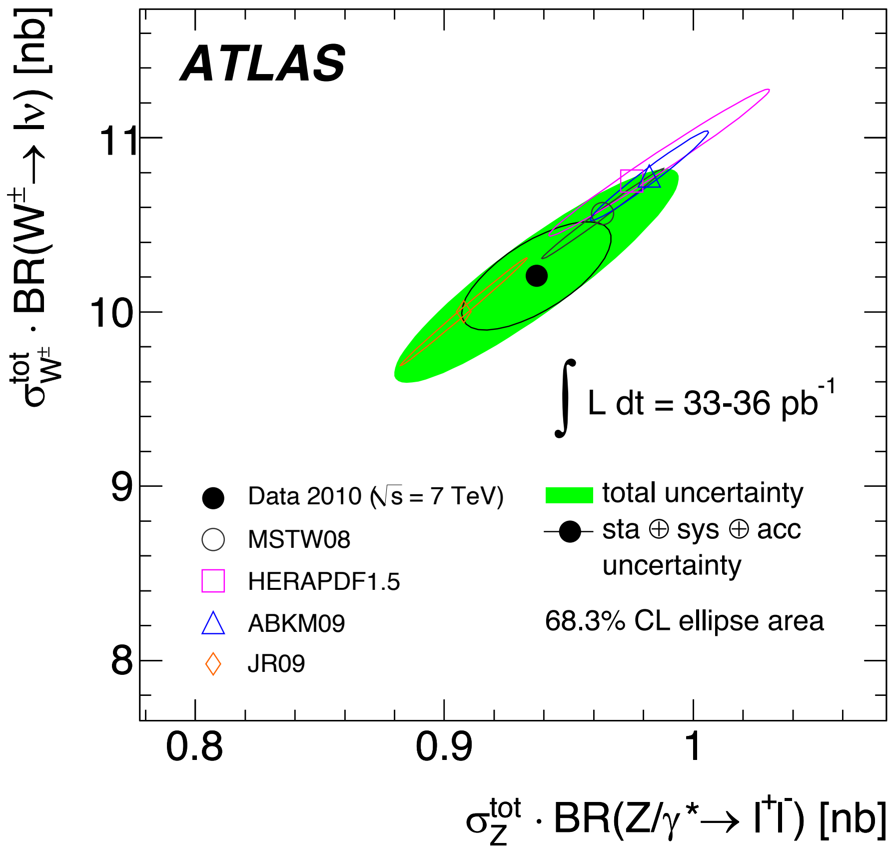
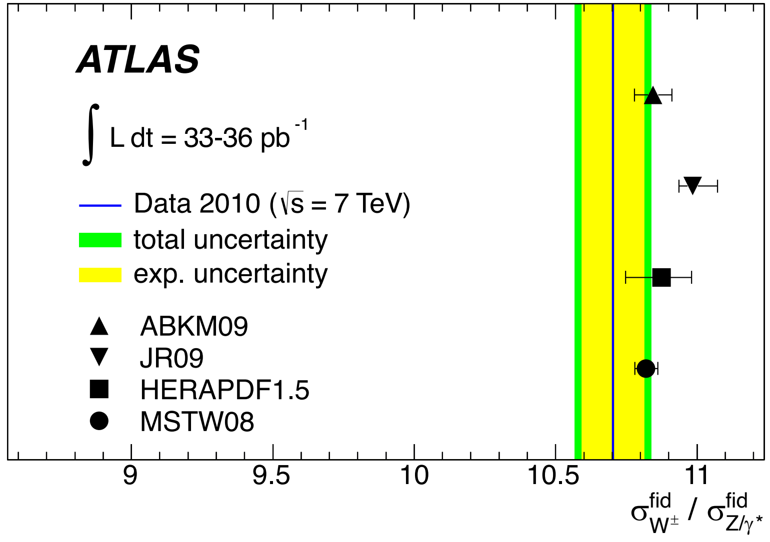
MEASURING CROSS-SECTIONS





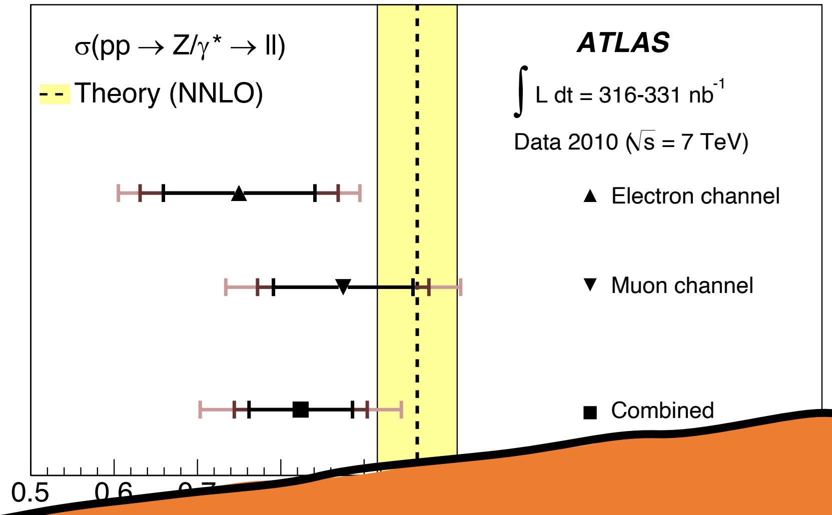
RATIOS

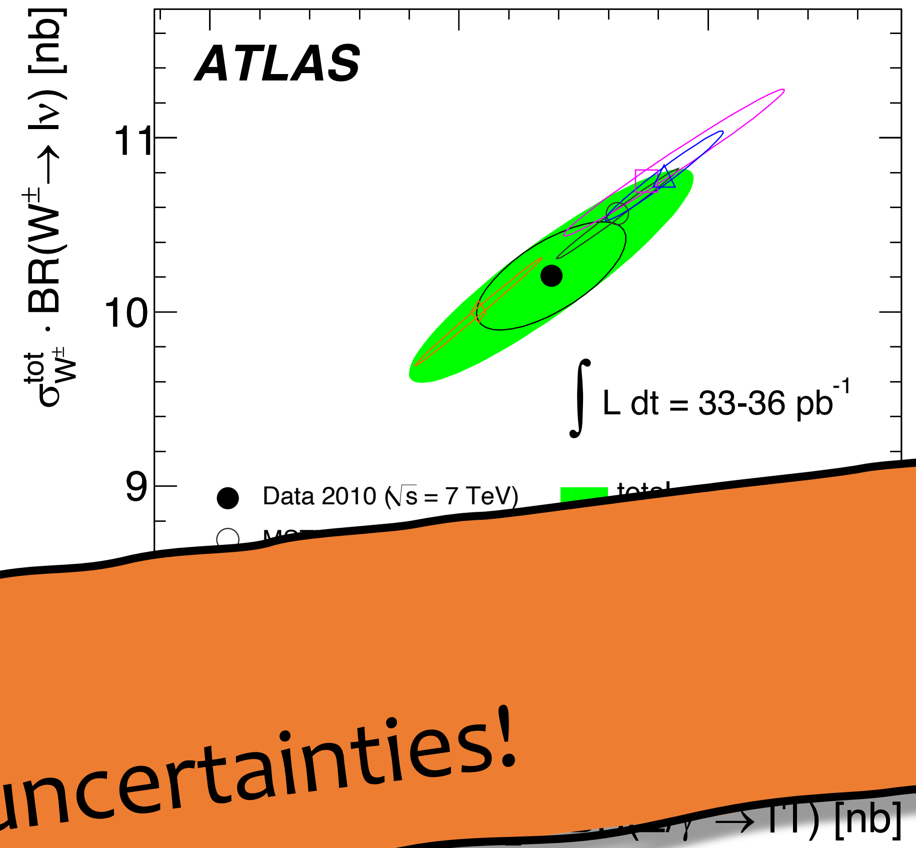




Measuring cross-sections

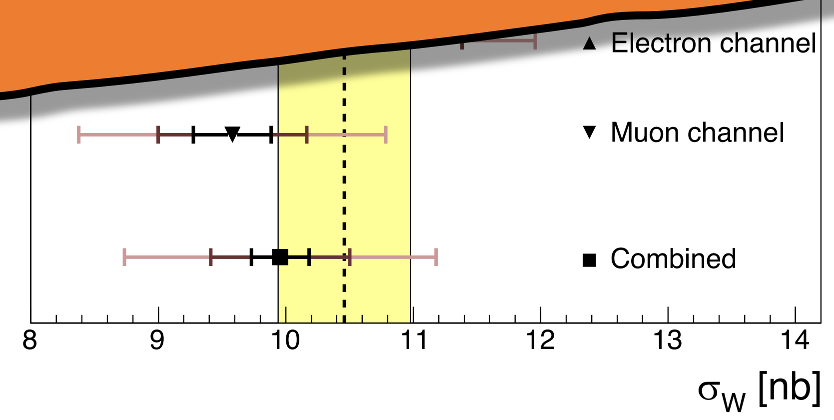
Ratios

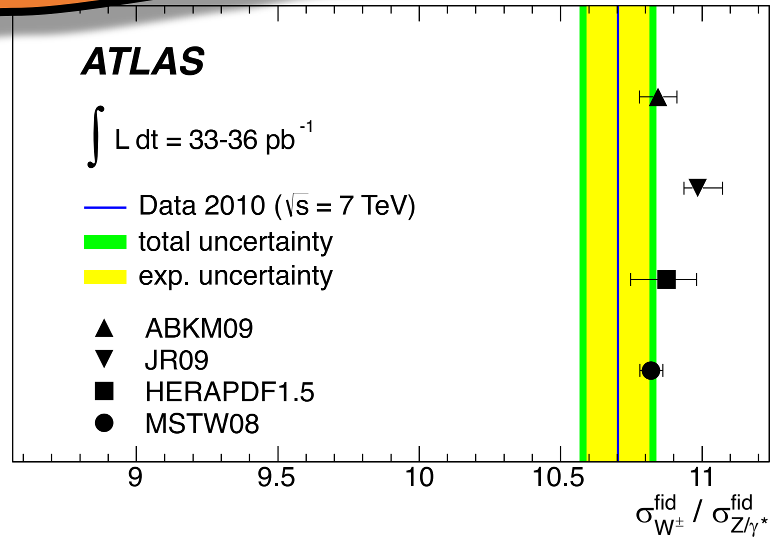




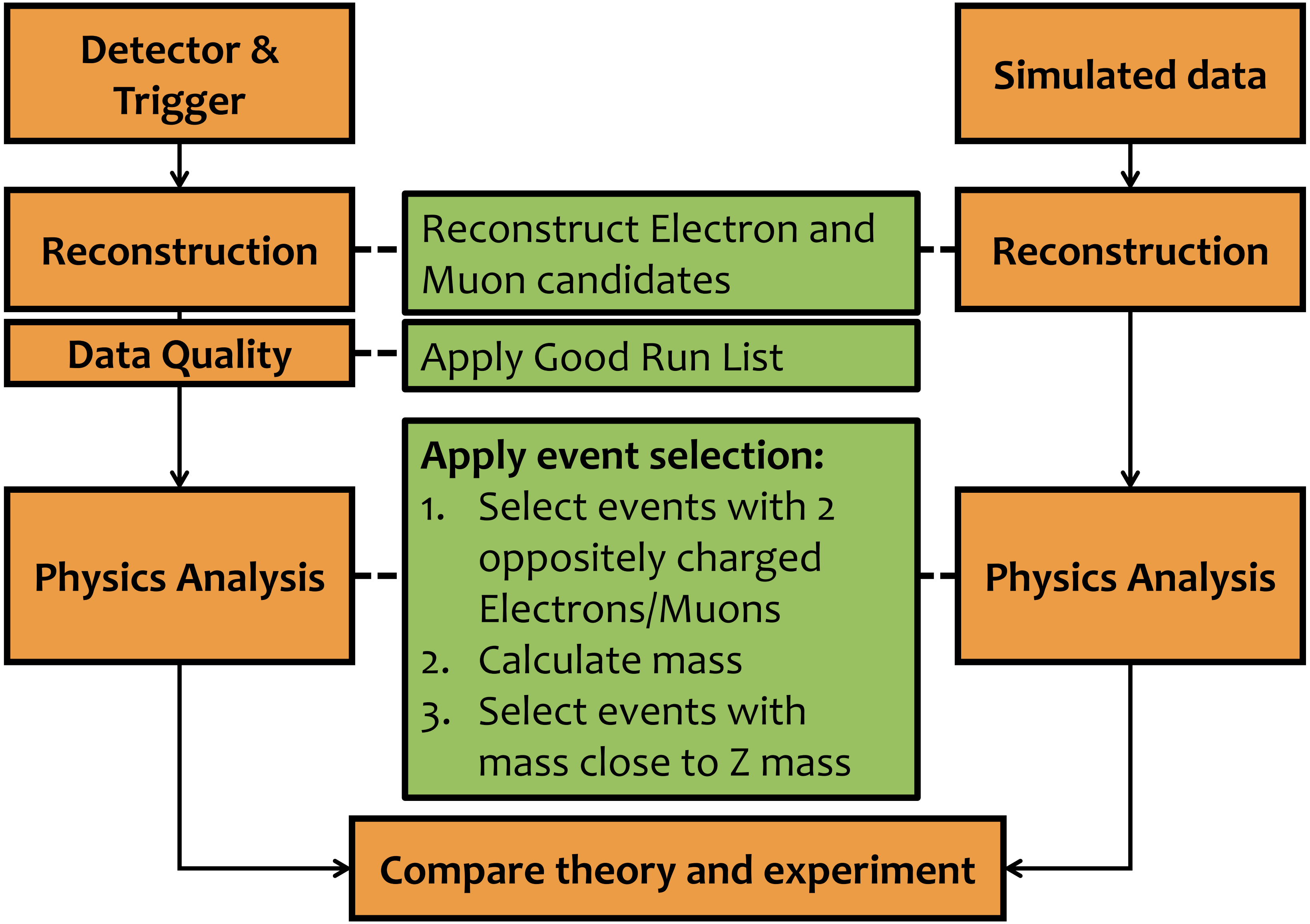
General aim:

find ways to reduce the uncertainties!





ANALYSIS FLOW – E.G. CROSS-SECTION MEASUREMENT



Detector & Trigger

Reconstruction

Data Quality

Physics Analysis

Simulated data

Reconstruction

Physics Analysis

Reconstruct Electron and Muon candidates

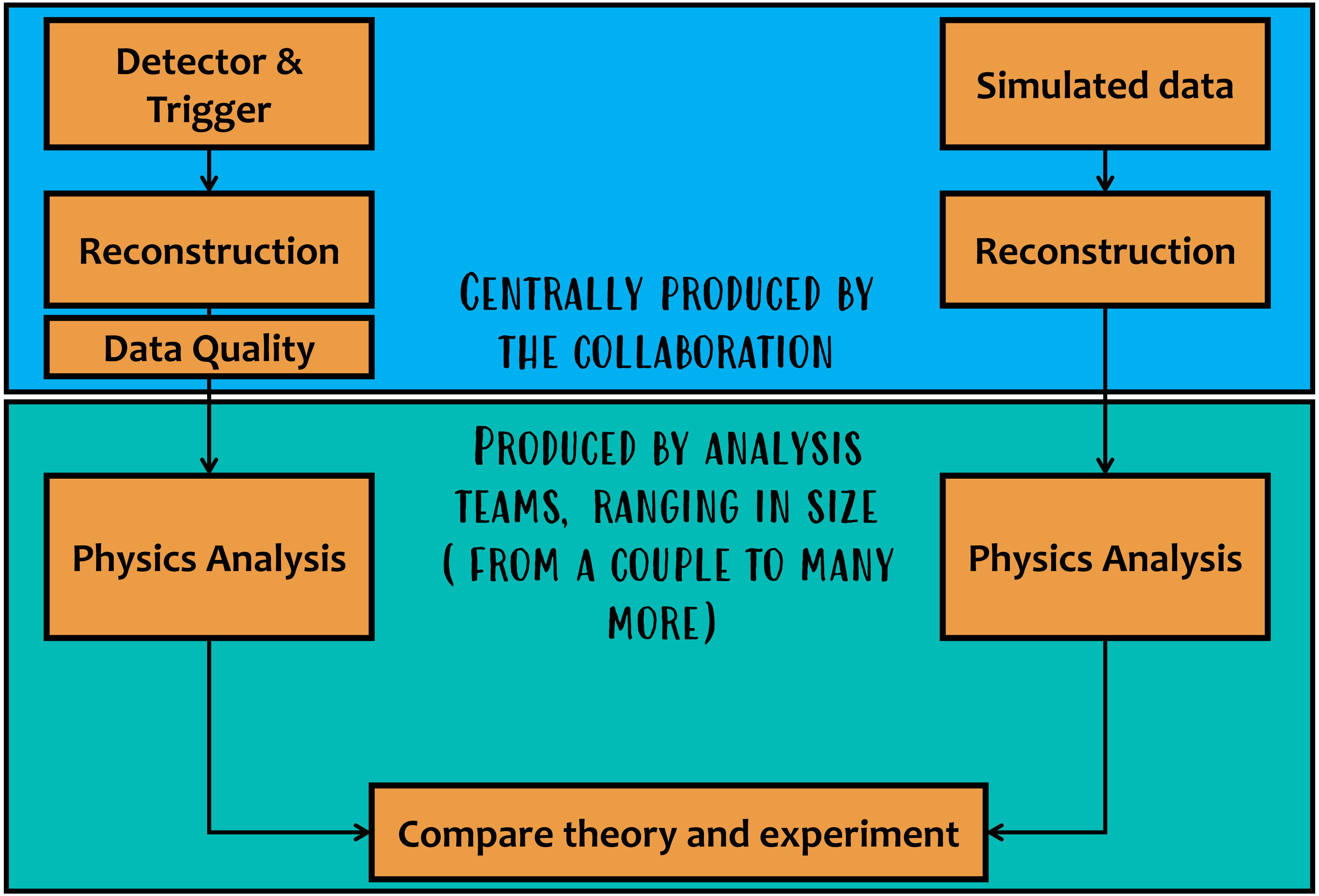
Apply Good Run List

Apply event selection:

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

Compare theory and experiment

ANALYSIS FLOW – E.G. 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

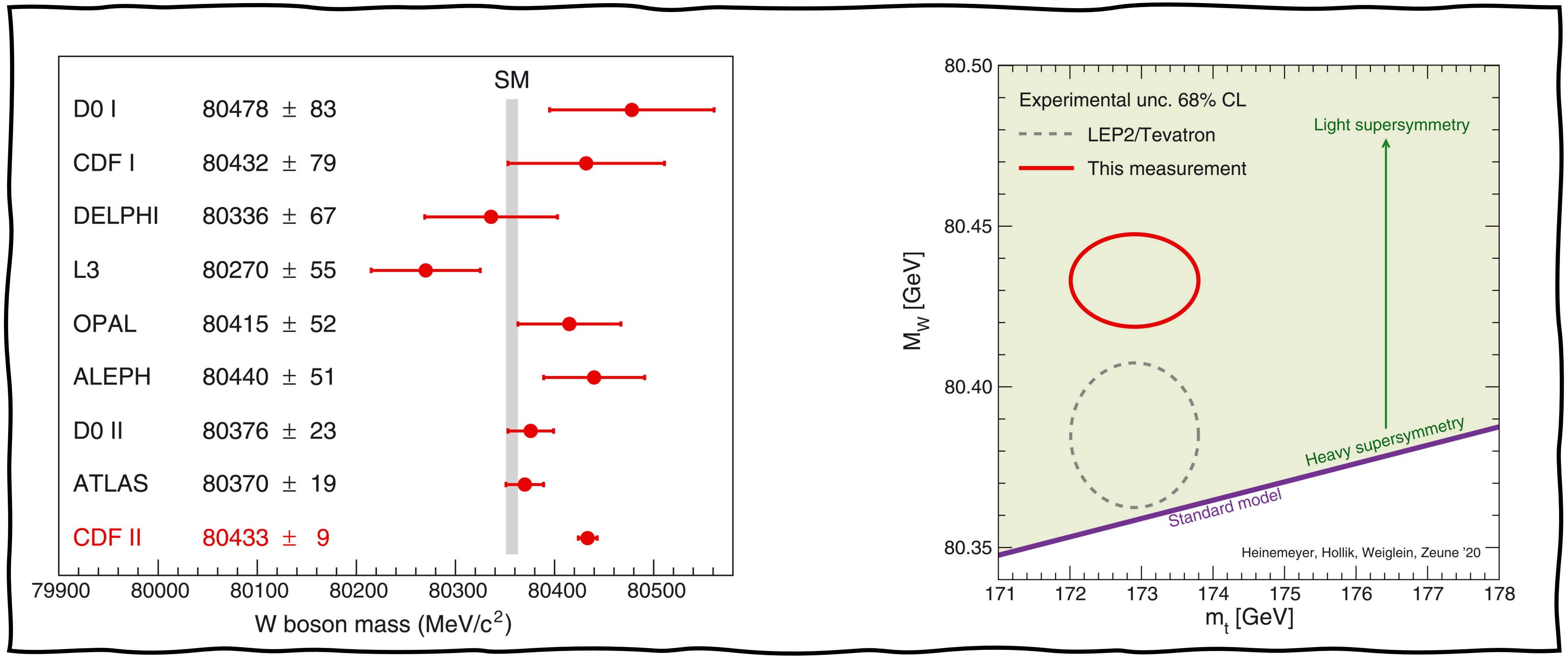
Physics Analysis

Compare theory and experiment

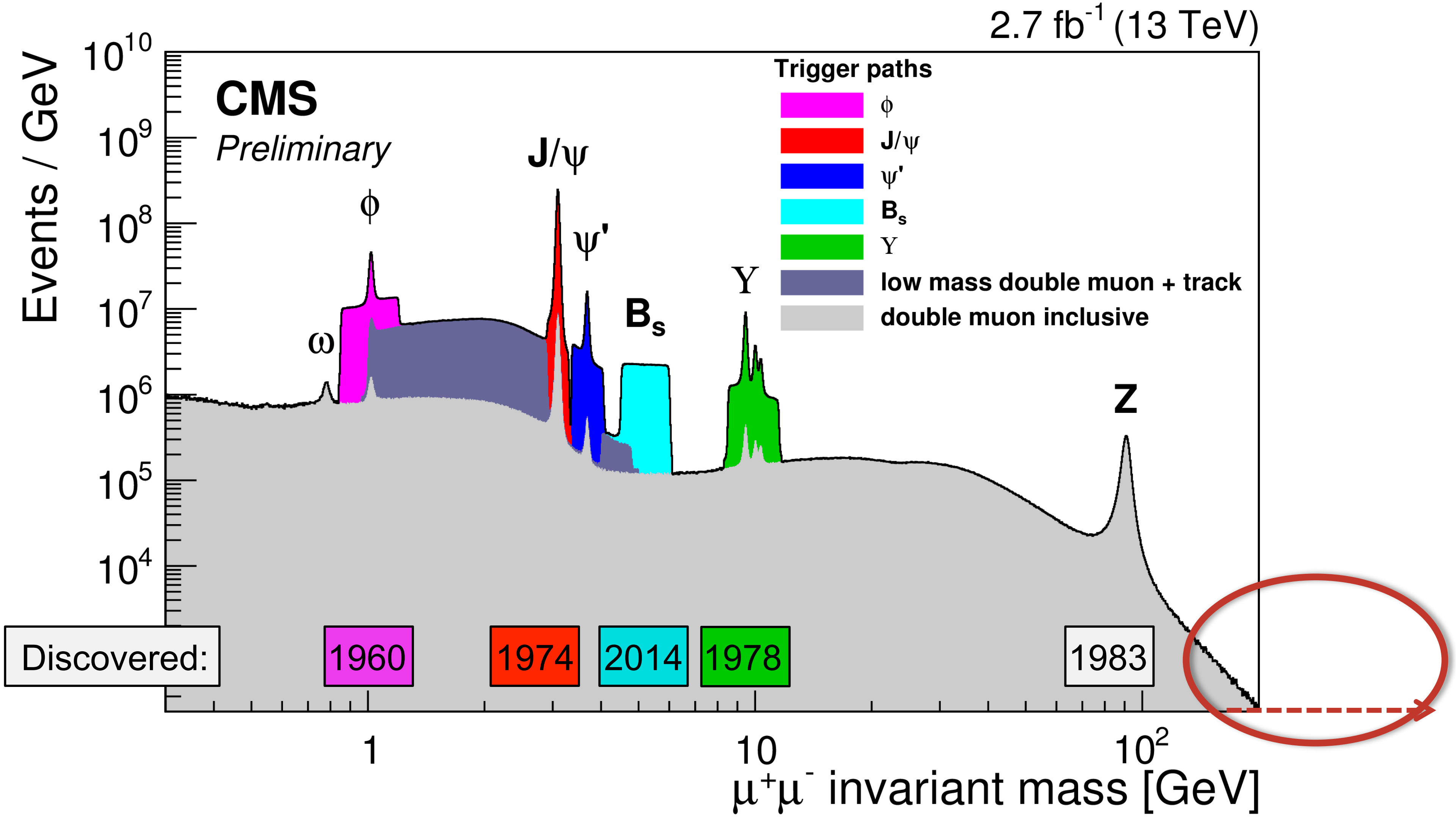
MASSES – RECENT NEWS ! (NOT FROM THE LHC)

Following up from discussion in class…

> “
>
> **This measurement, M_W=80,433.5±9.4 MeV, is more precise than all previous measurements of M_W combined.**
>
> **A comparison with the SM expectation of M_W=80,357±6 MeV […] yields a difference with a significance of 7.0σ and suggests the possibility of improvements to the SM calculation or of extensions to the SM.**
>
> ”



https://www.science.org/doi/10.1126/science.abk1781

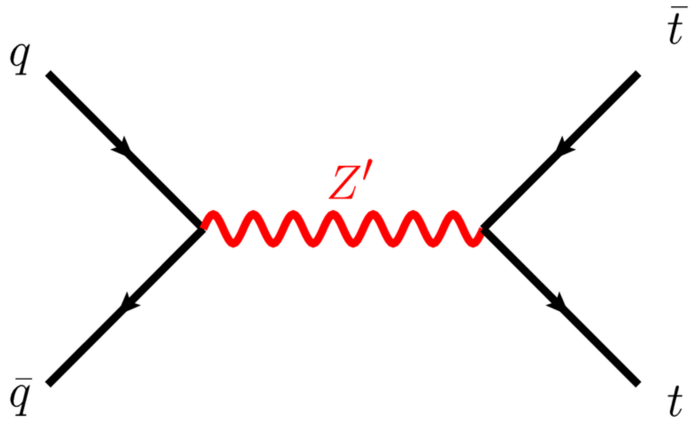


What's out there?

WHAT "NEW PHYSICS" CAN CREATE BUMPS?

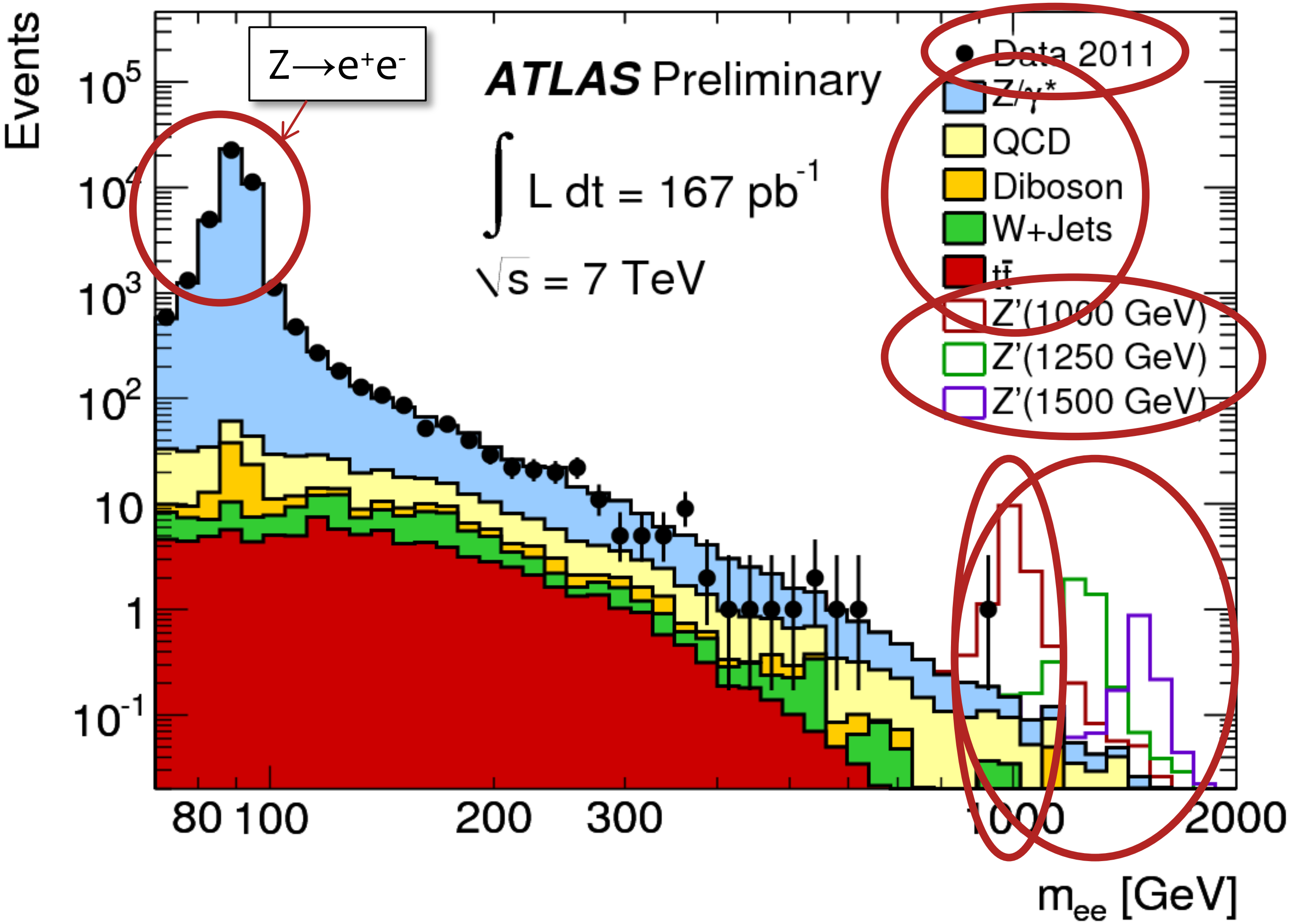
Many models giving answers to the SM problems include new heavy particles with short lifetime that appear as resonances

- Heavy bosons e.g. in grand unified and additional gauge symmetries
- High mass states, gravitons, e.g. in 'randall-sundrum' models
- Heavy quark partners, excited leptons, leptoquarks
- Composite Higgs
- Dark matter candidates



SIMPLE SEARCH EXAMPLE:
SEARCH FOR A HEAVY Z'

- Like Z->ee but at higher mass



Select 2 electron candidates and plot their invariant mass for:

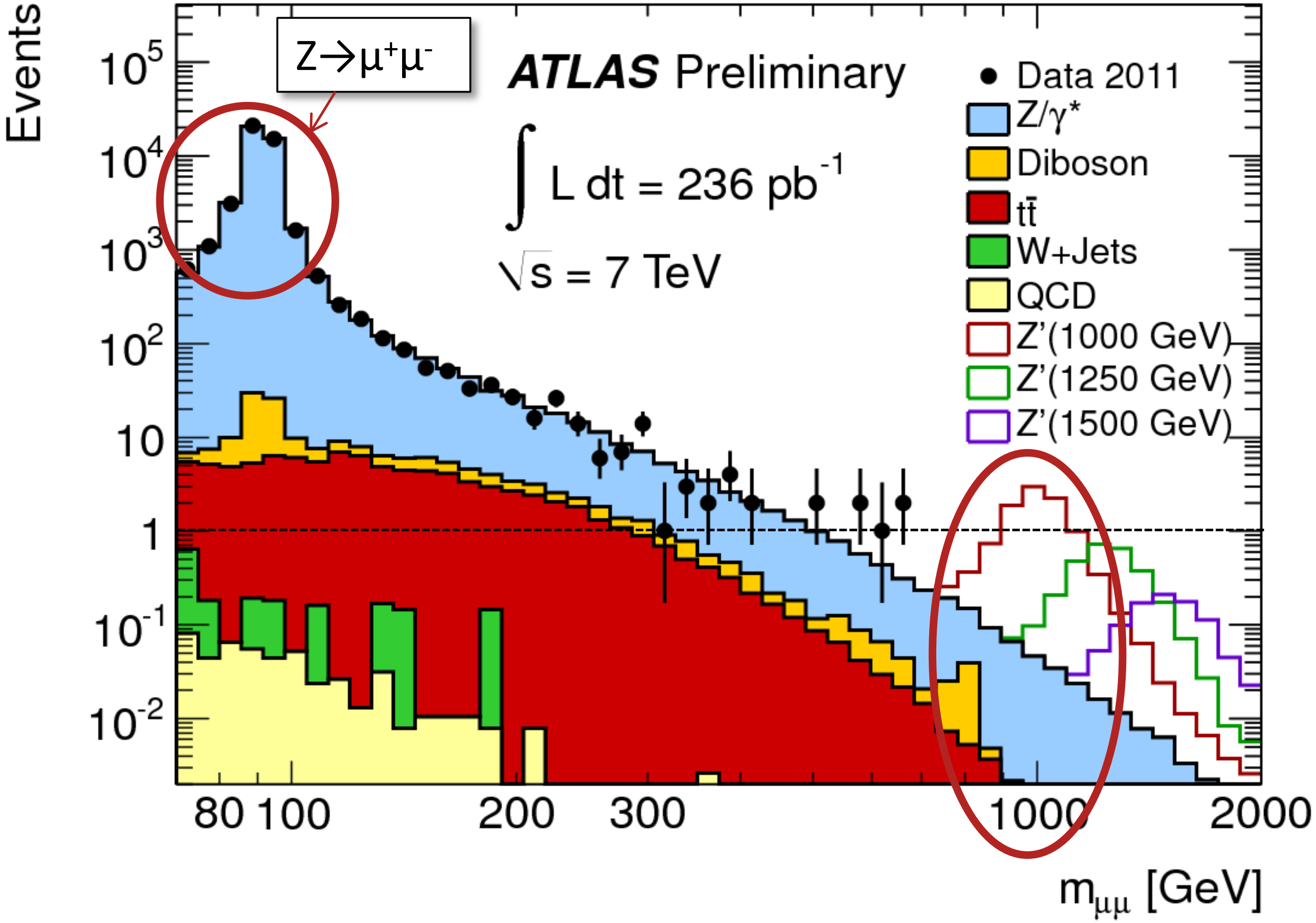
1. **Data**
2. **Simulated background events**
3. **Simulated signal with different masses**

Data inconsistent with a 1TeV Z'

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

SIMPLE SEARCH EXAMPLE:
SEARCH FOR A HEAVY Z'

- And similar for muons



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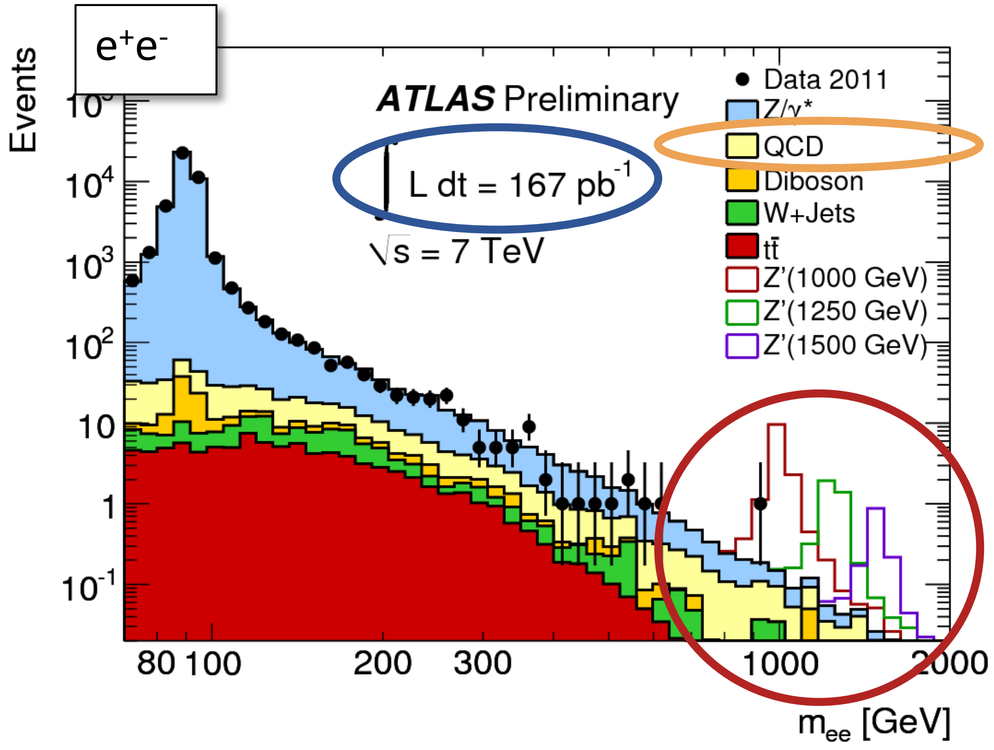
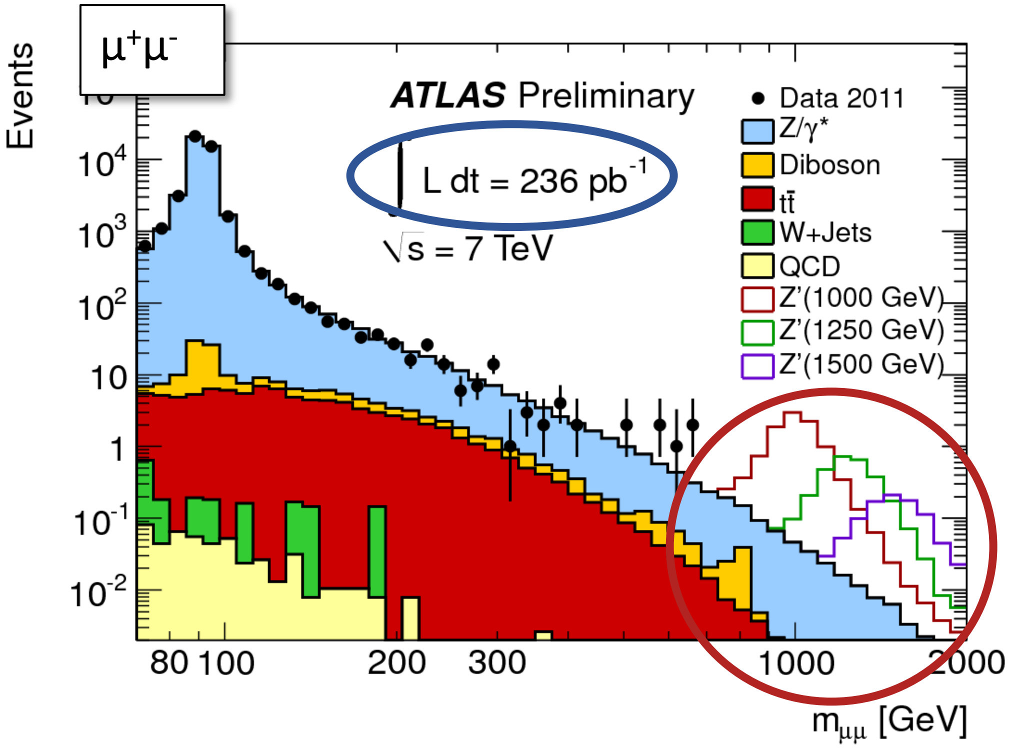
A SMALL COMPARISON

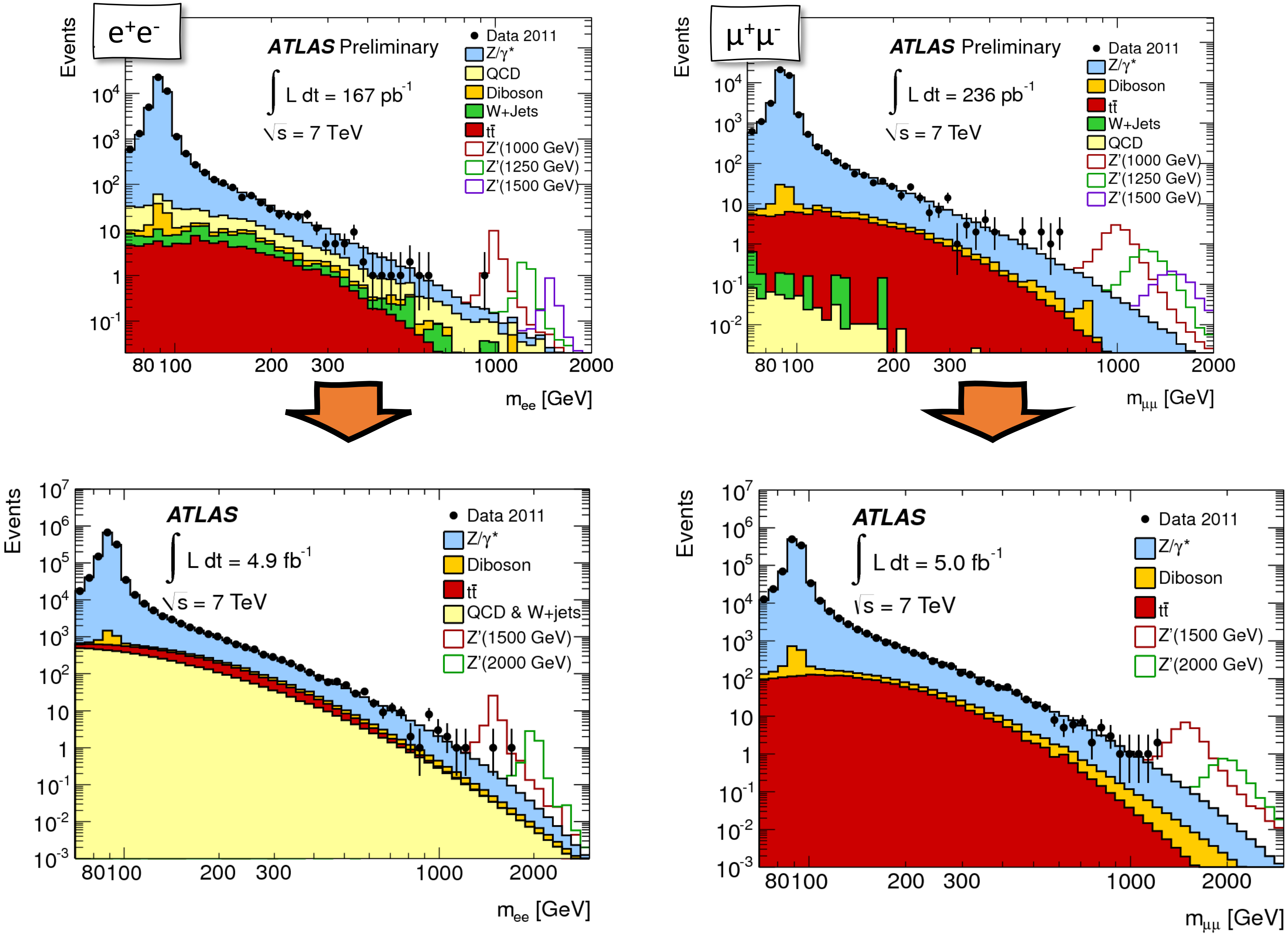




Differences in:

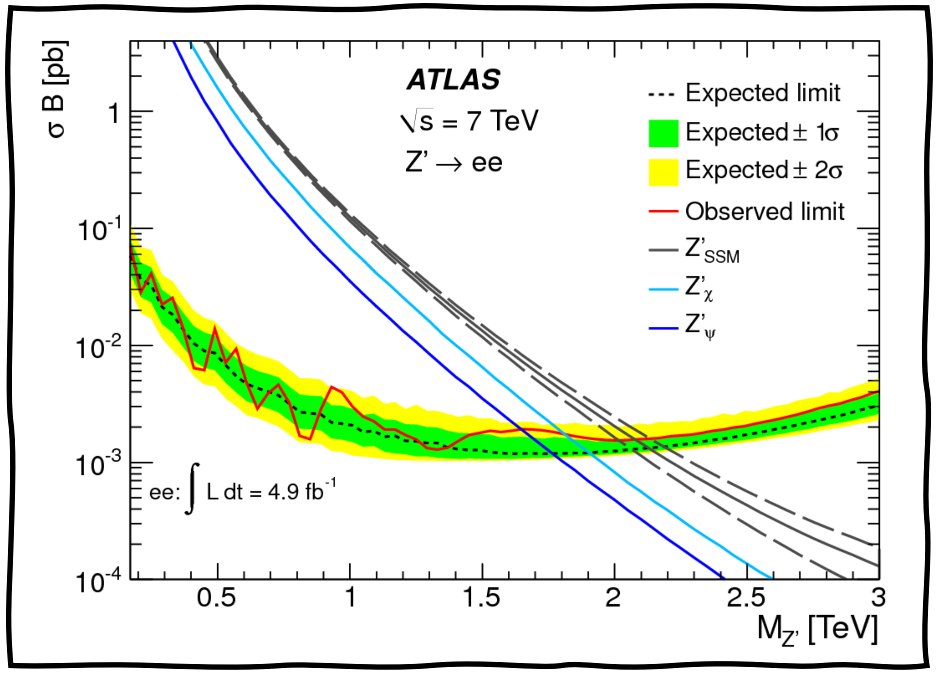
- ◎ **Resolution**
- ◎ **Background composition**
- ◎ **Dataset**

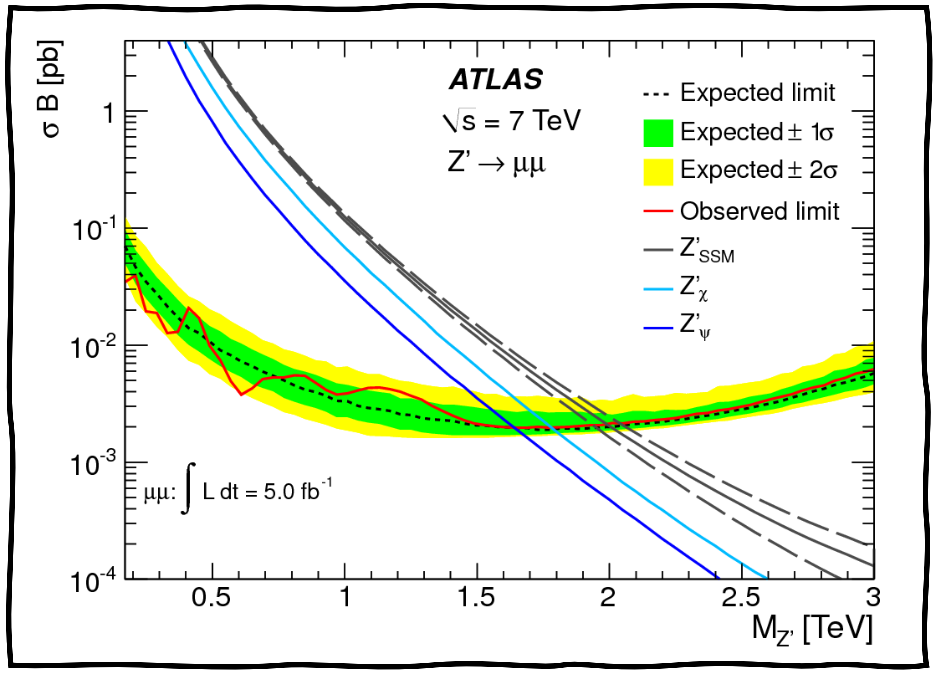
Evolution...

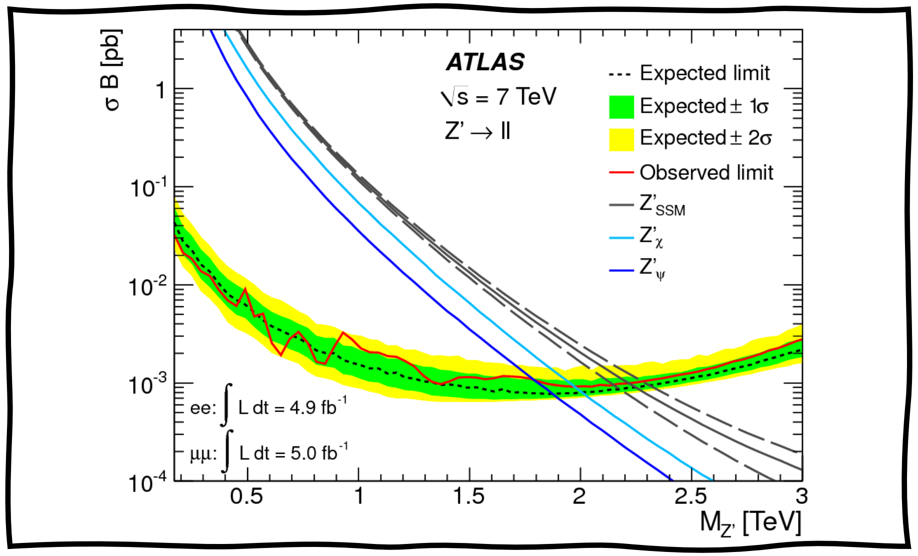


arXiv:1209.2535

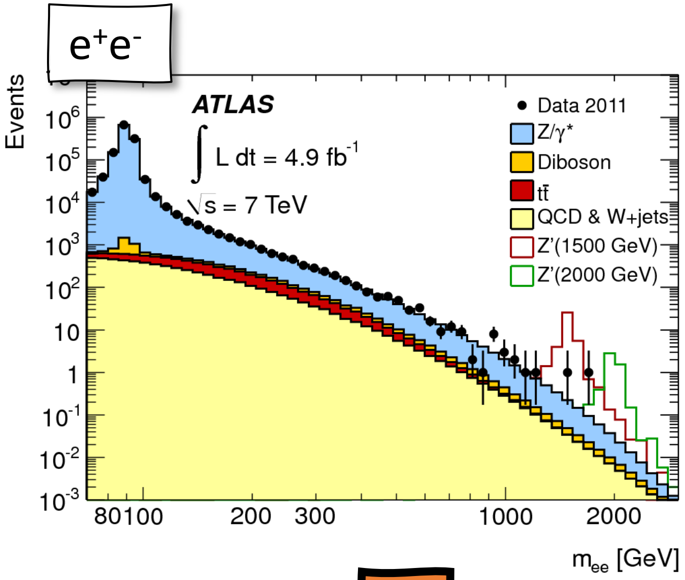
EXCLUSION LIMITS

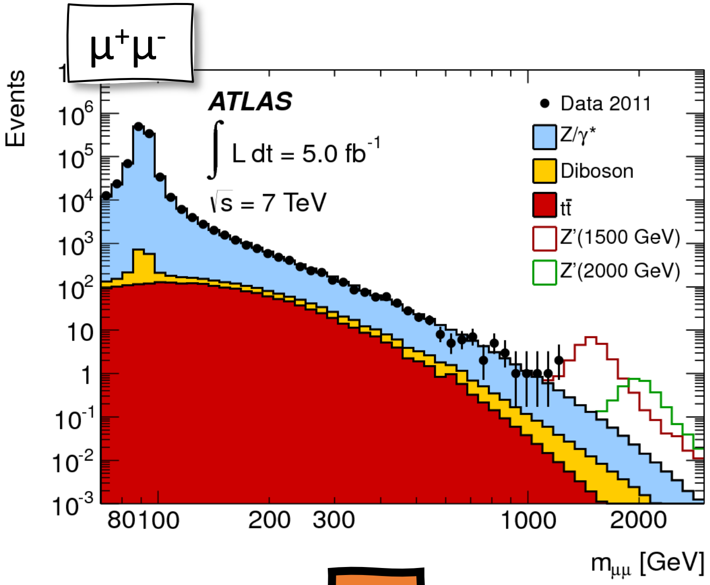


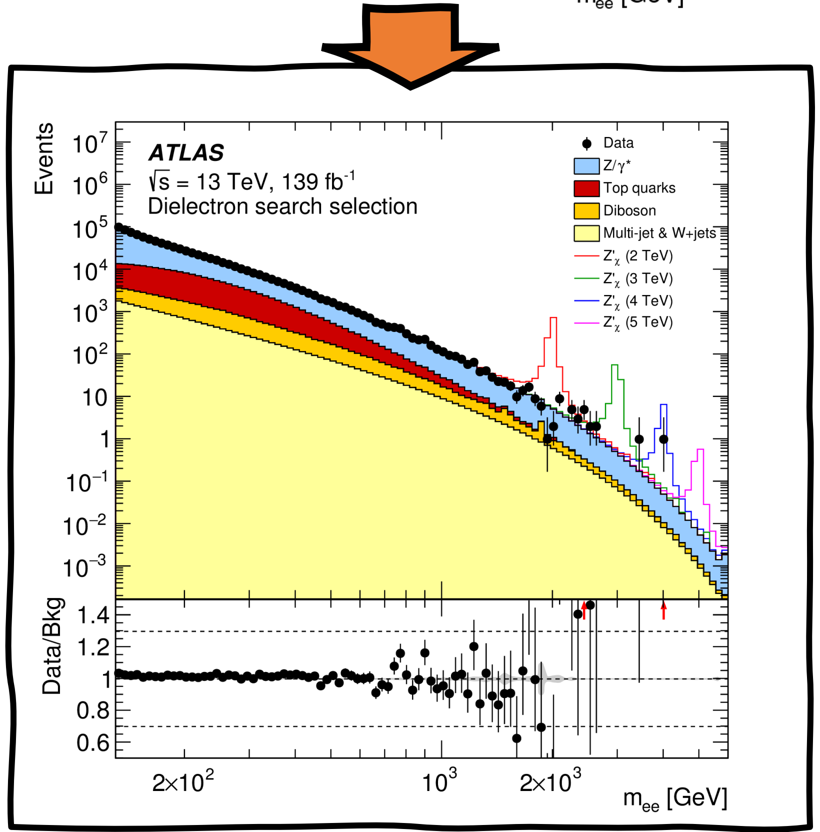


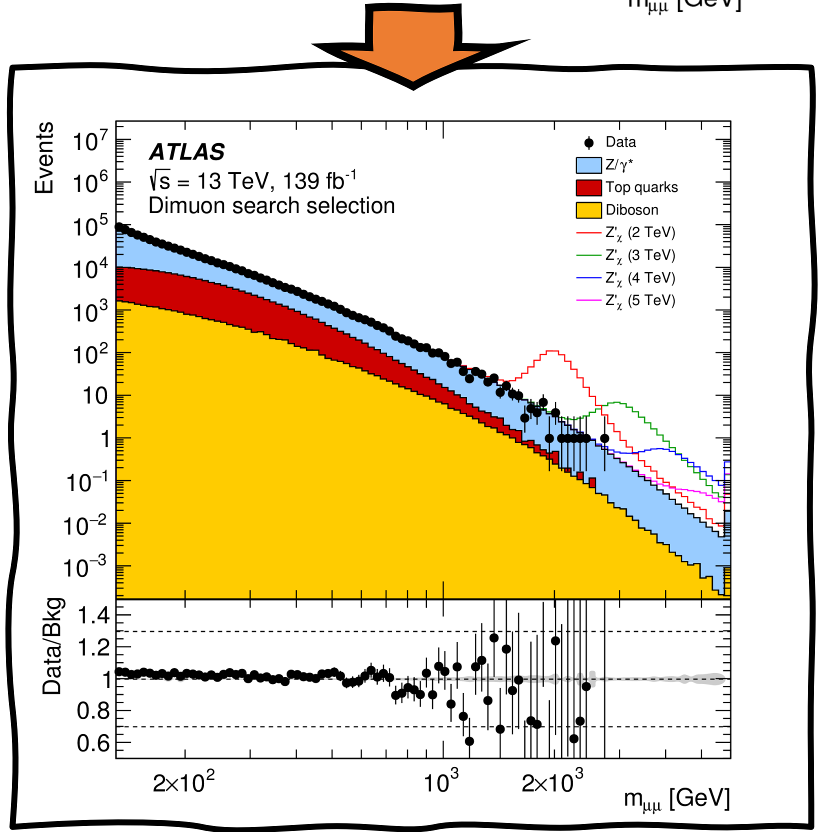


EVOLUTION…



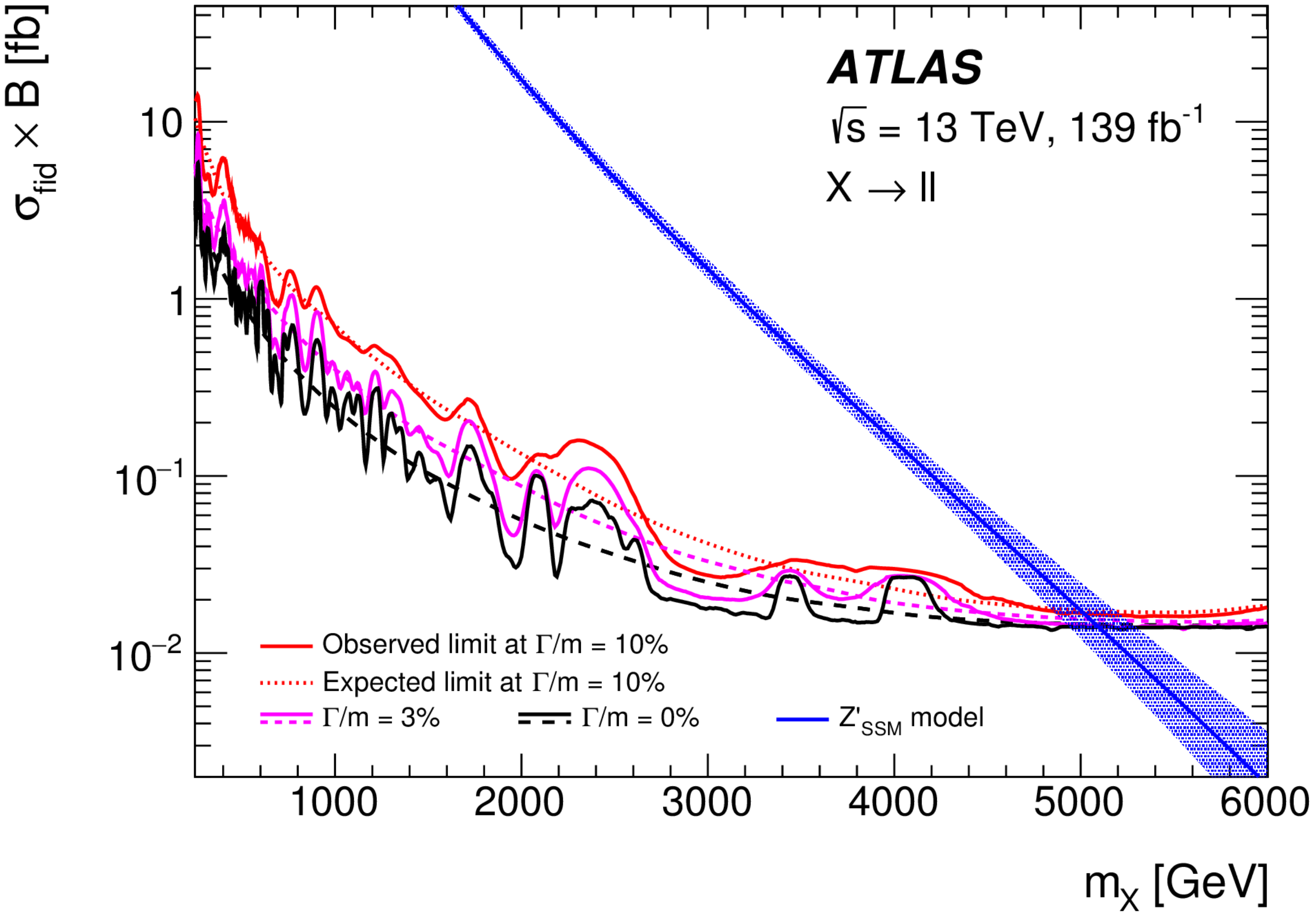




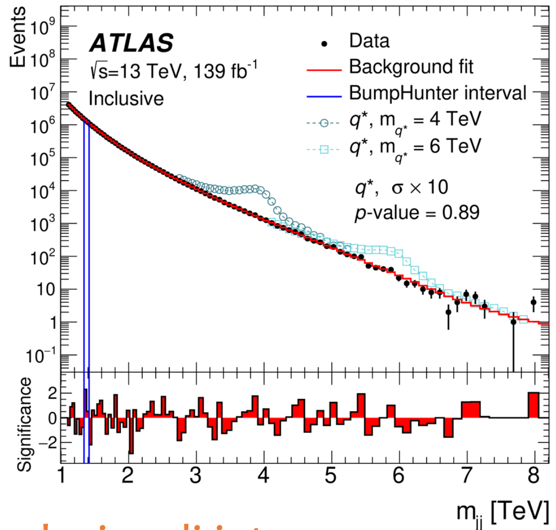


arXiv:1903.06248

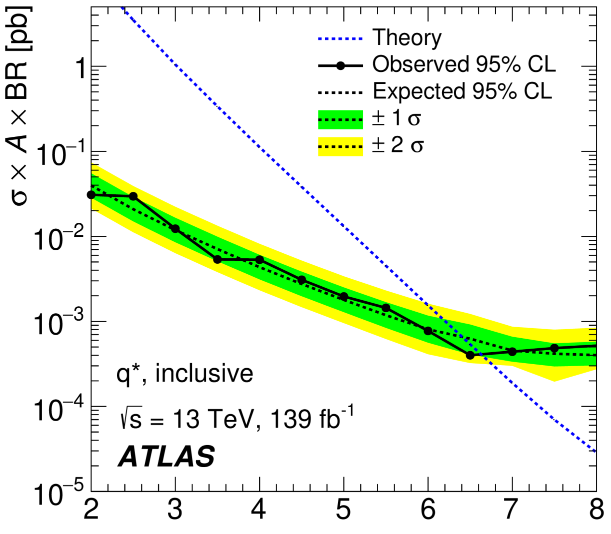
EXCLUSION LIMITS



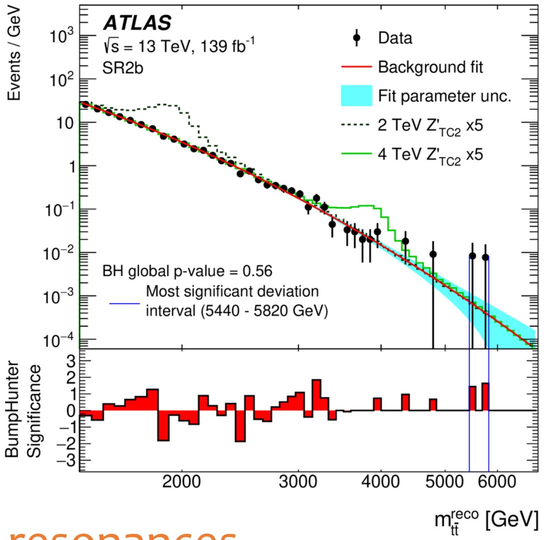
HIGH MASS RESONANCES



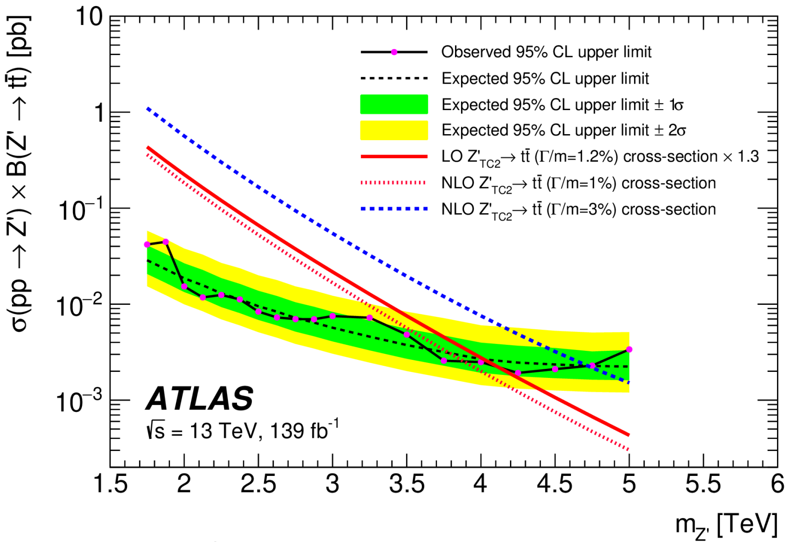
inclusive di-jet



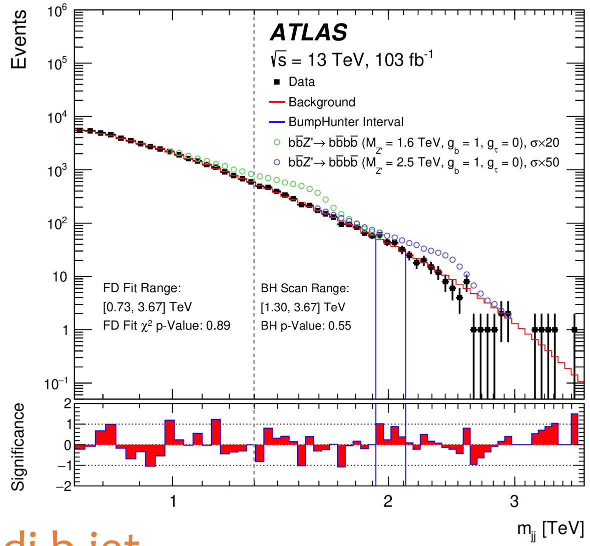
arXiv:1910.08447



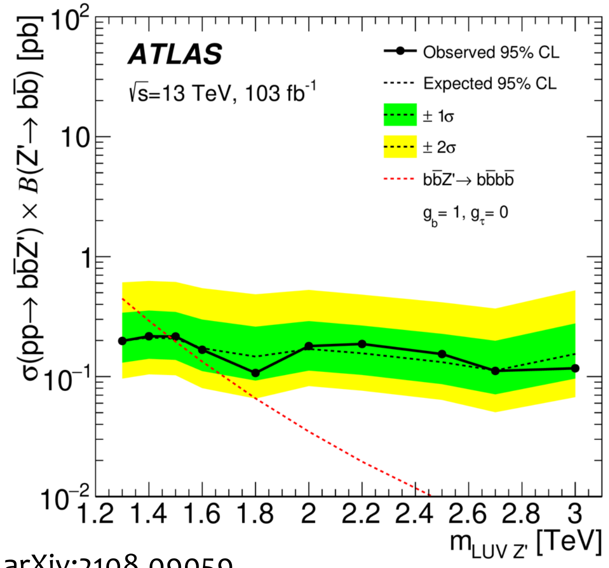
ttbar resonances



arXiv:2005.05138

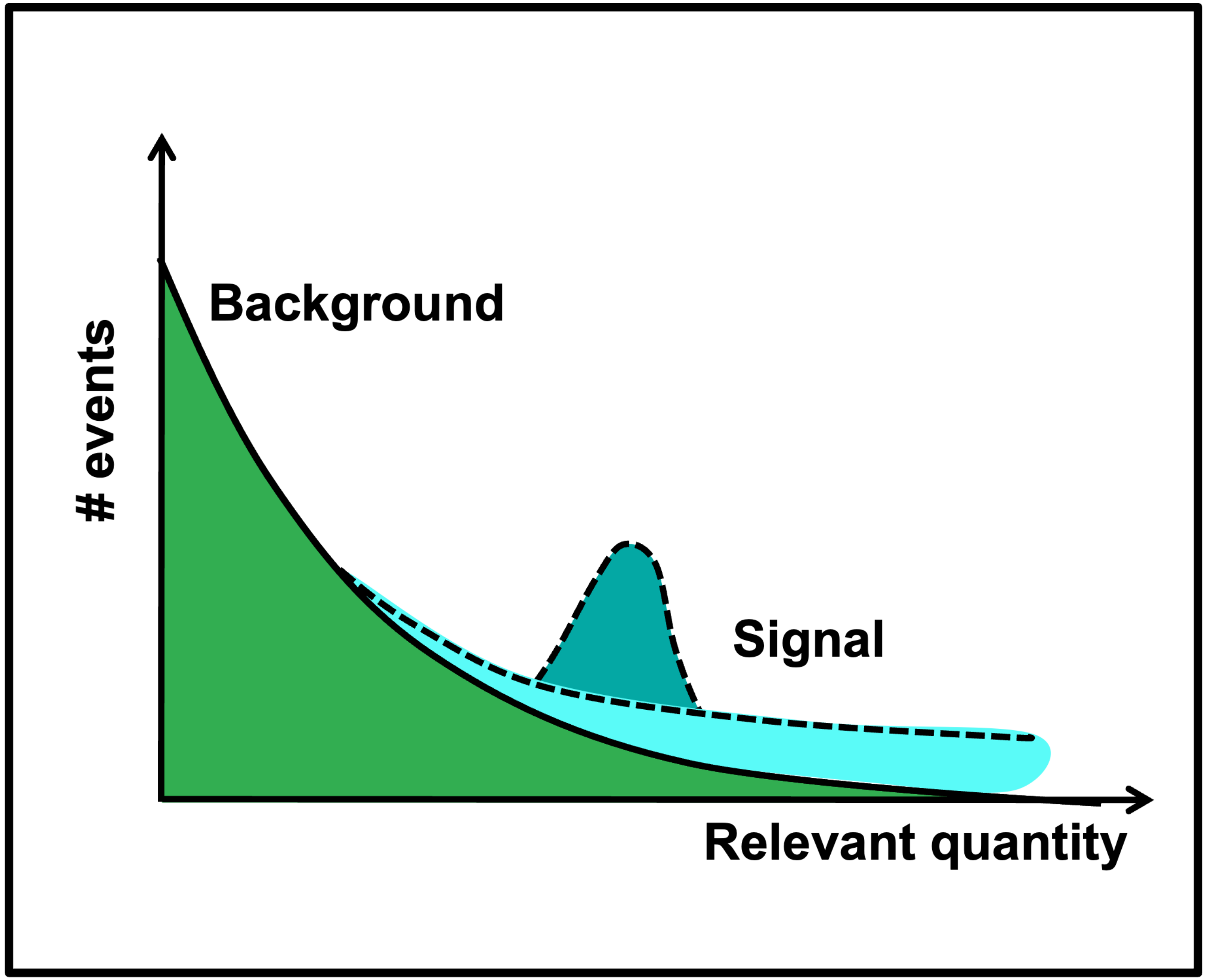


di-b-jet

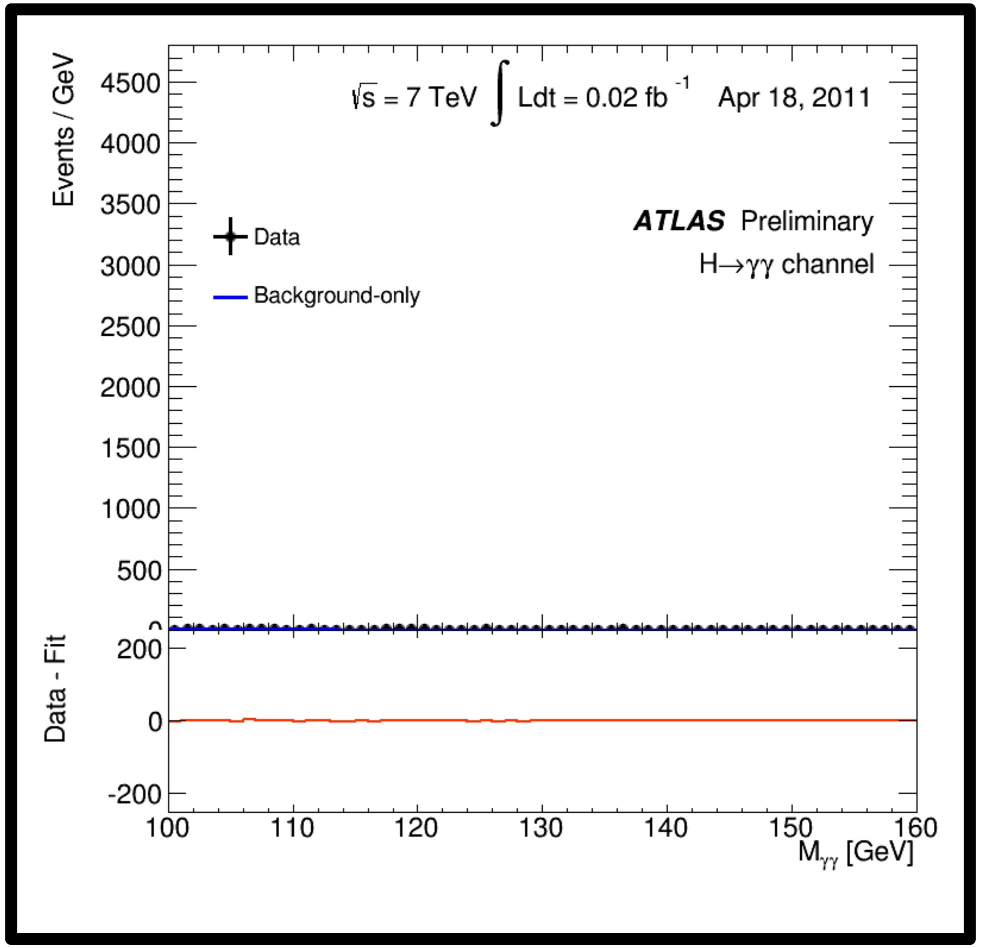


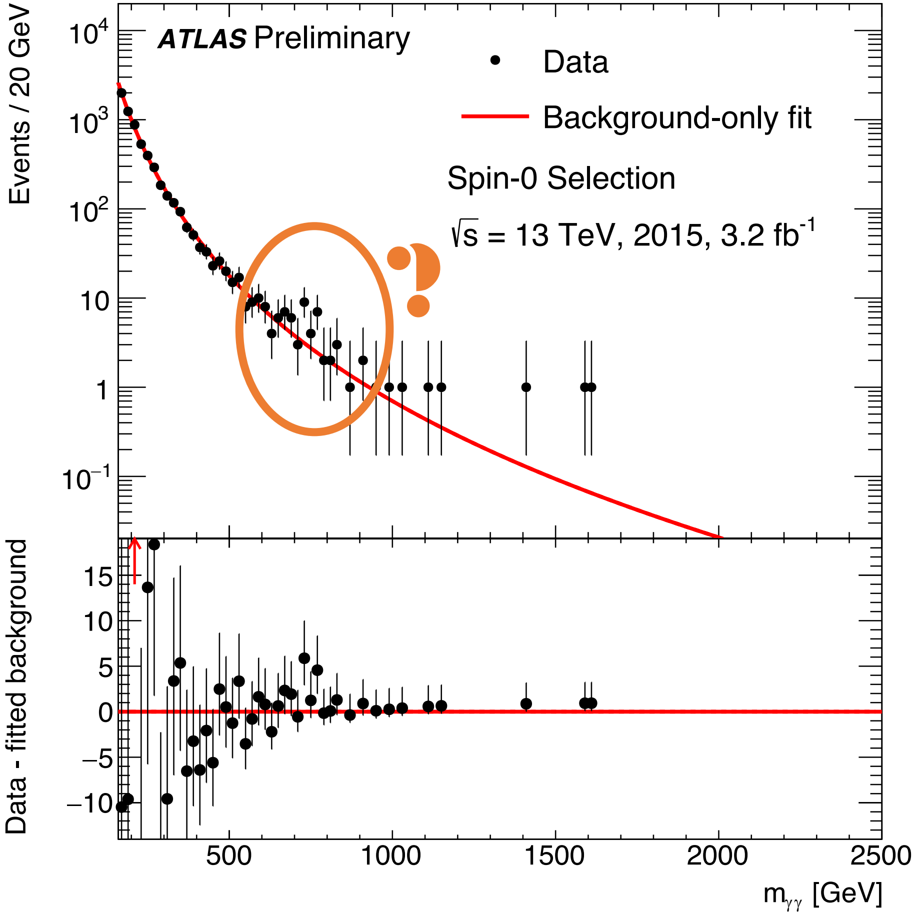
arXiv:2108.09059

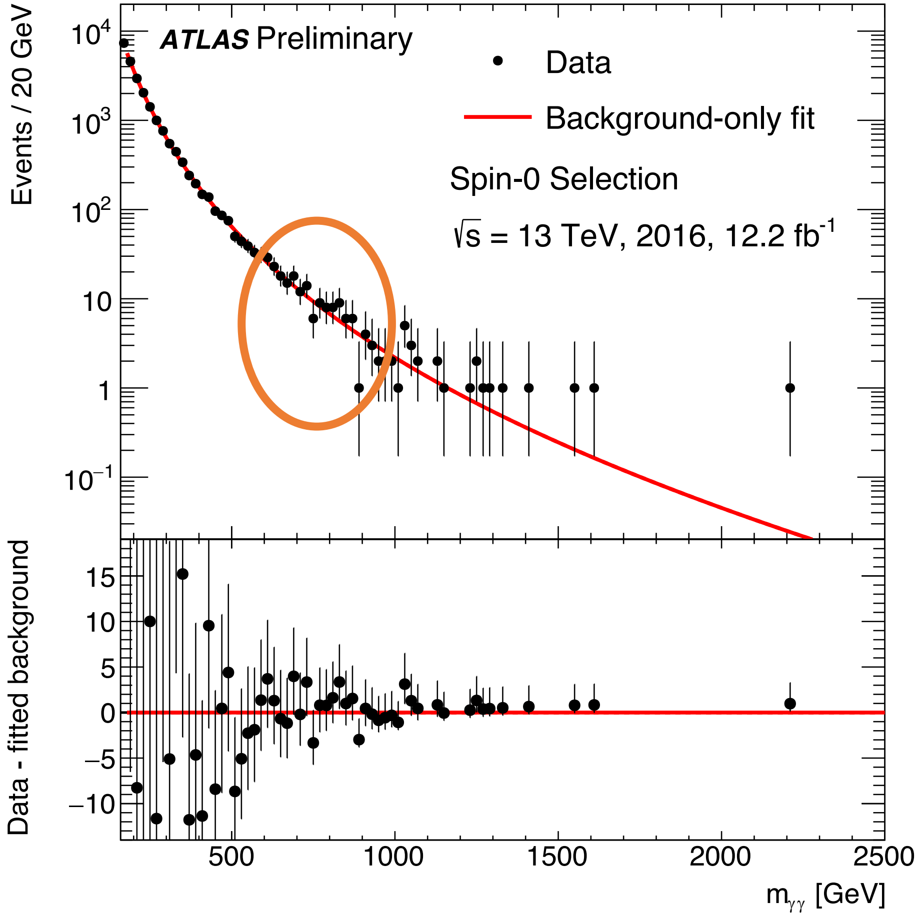
SEARCHES



A WELL-KNOWN BUMP SEARCH




ATLAS Preliminary
Data
Background-only fit
Spin-0 Selection
√s = 13 TeV, 2015, 3.2 fb^{-1}
?
Events / 20 GeV
10^4
10^3
10^2
10
1
10^{-1}
Data - fitted background
15
10
5
0
−5
−10
500
1000
1500
2000
2500
m$_{\gamma\gamma}$ [GeV]


ATLAS Preliminary
Data
Background-only fit
Spin-0 Selection
√s = 13 TeV, 2016, 12.2 fb⁻¹
Events / 20 GeV
10⁴
10³
10²
10
1
10⁻¹
Data - fitted background
15
10
5
0
−5
−10
500
1000
1500
2000
2500
m_γγ [GeV]

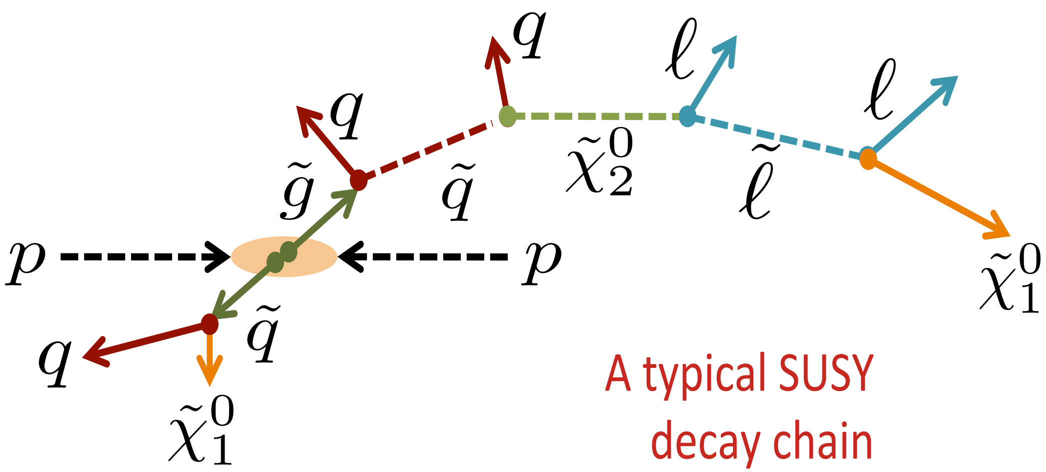
THANK YOU MARIO!

BUT OUR PRINCESS IS IN
ANOTHER CASTLE!

LHC Physics

OTHER SEARCHES

ANOTHER SEARCH EXAMPLE:
SEARCH FOR SUSY IN EVENTS WITH LARGE JET MULTIPLICITIES



A typical SUSY decay chain

Disclaimer:

<u>This is only an example!</u>

There are numerous such searches!

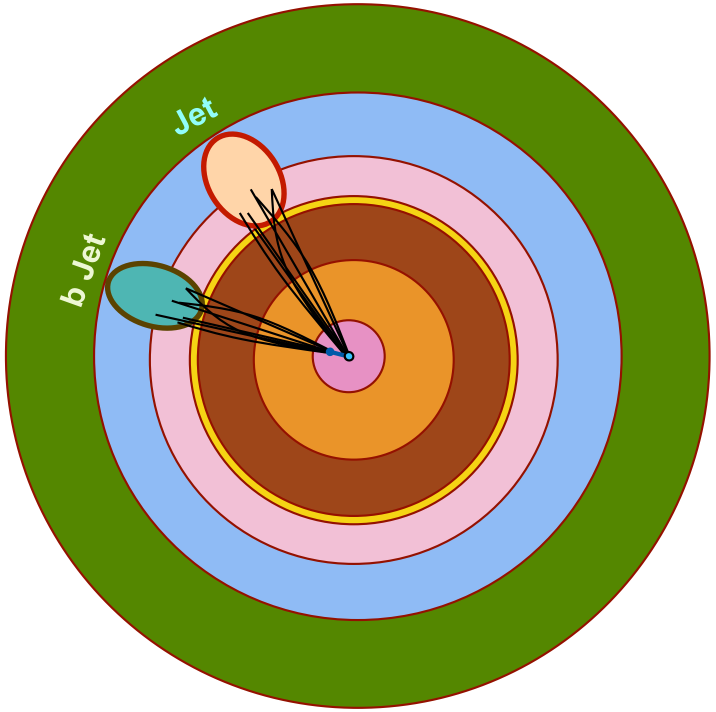
Each of them differs in

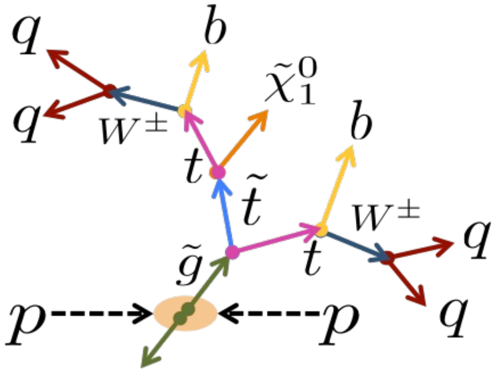
- event selections,
- background determinations,
- methodology

SEARCHING FOR NEW PHYSICS IS FUN!

EVENT SELECTIONS

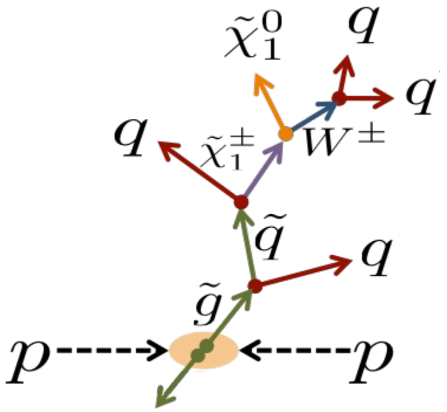
b-jets

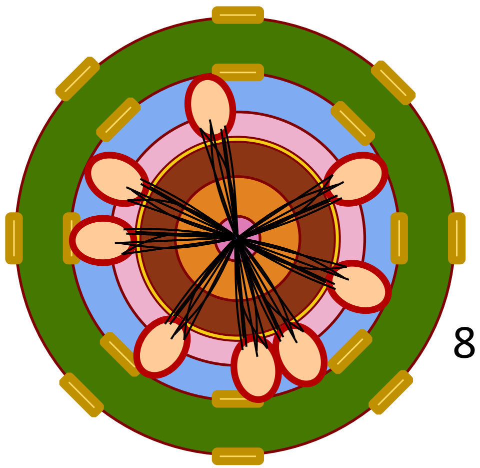




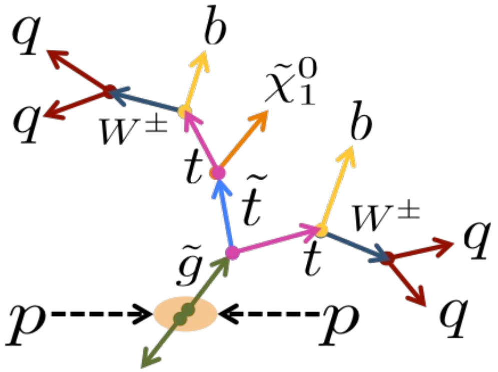
EVENT SELECTIONS

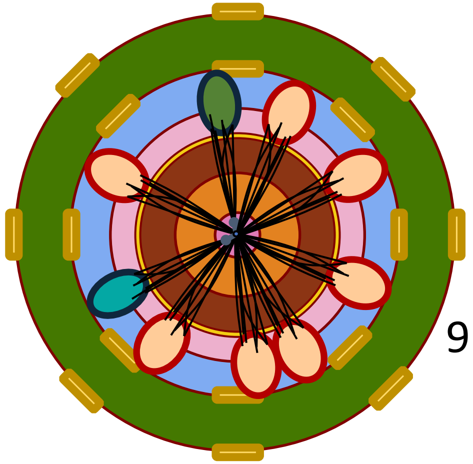
b-jets





8 jets, 0 b-jets



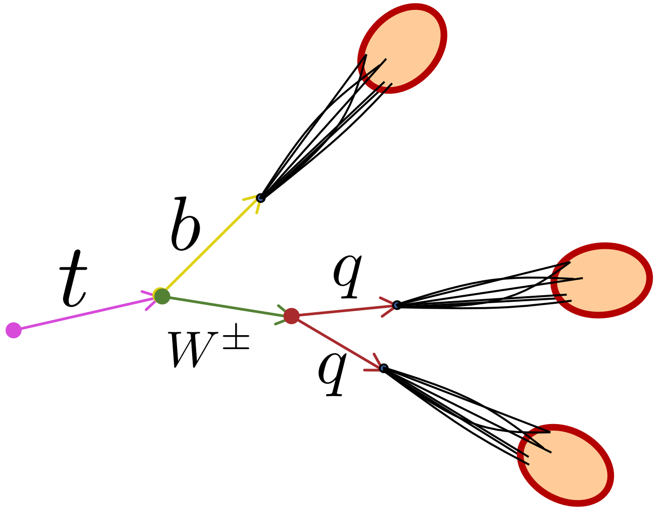


9 jets, ≥2 b-jets

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

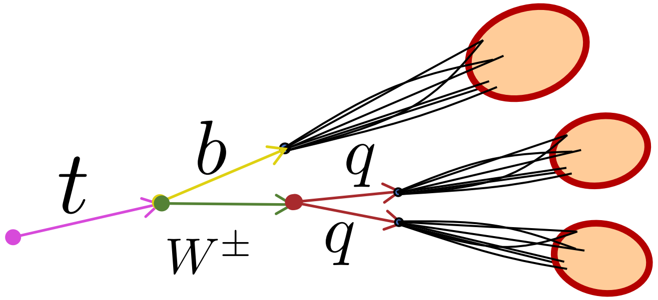
EVENT SELECTIONS

“fat-jets”



EVENT SELECTIONS

“fat-jets”



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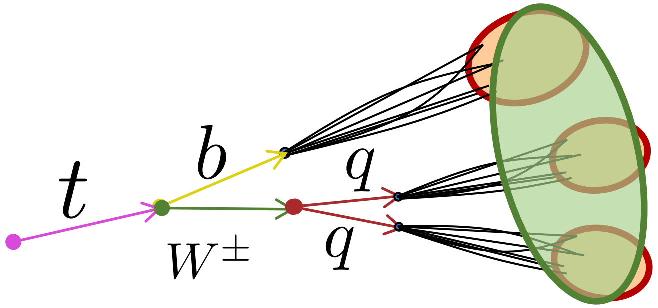
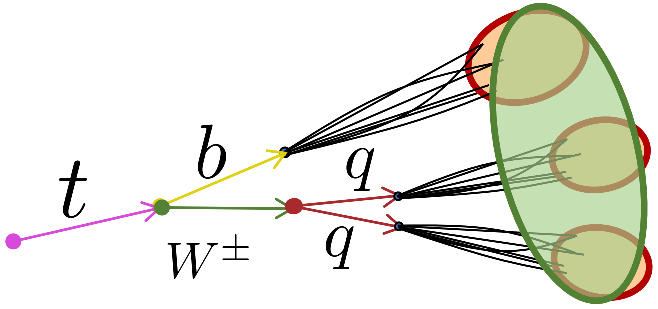


EVENT SELECTIONS

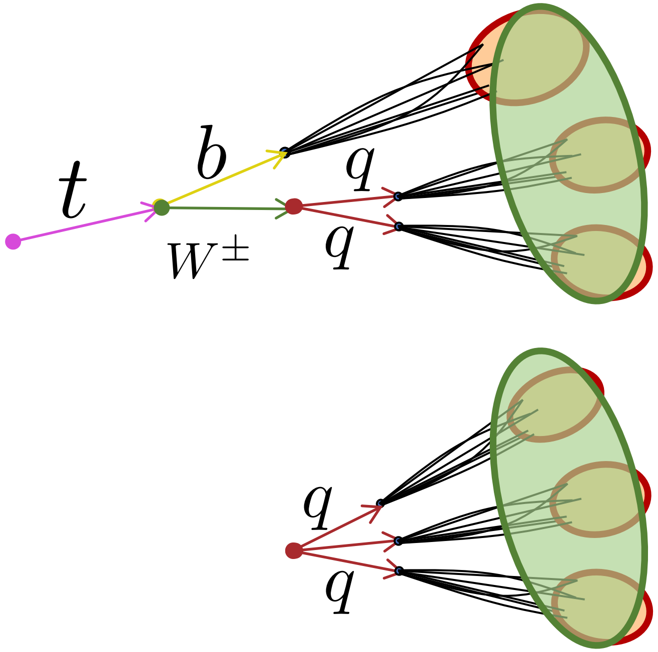
“fat-jets”



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

EVENT SELECTIONS

“fat-jets”

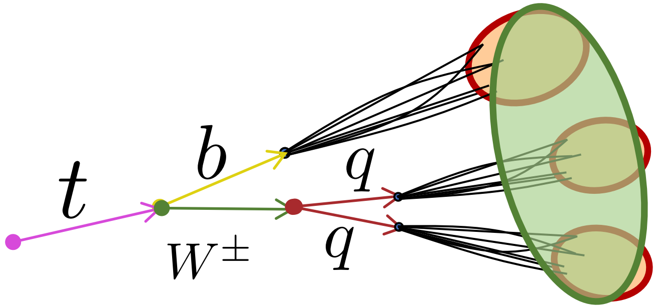


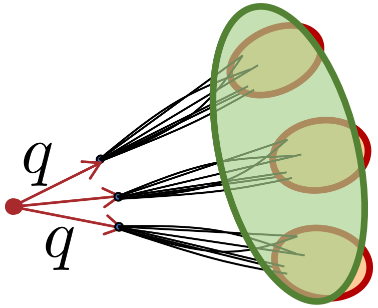
$$m_j \text{ (QCD)} < m_j \text{ (SUSY)}$$

Proposed in arXiv:1202.0558

EVENT SELECTIONS

“fat-jets”





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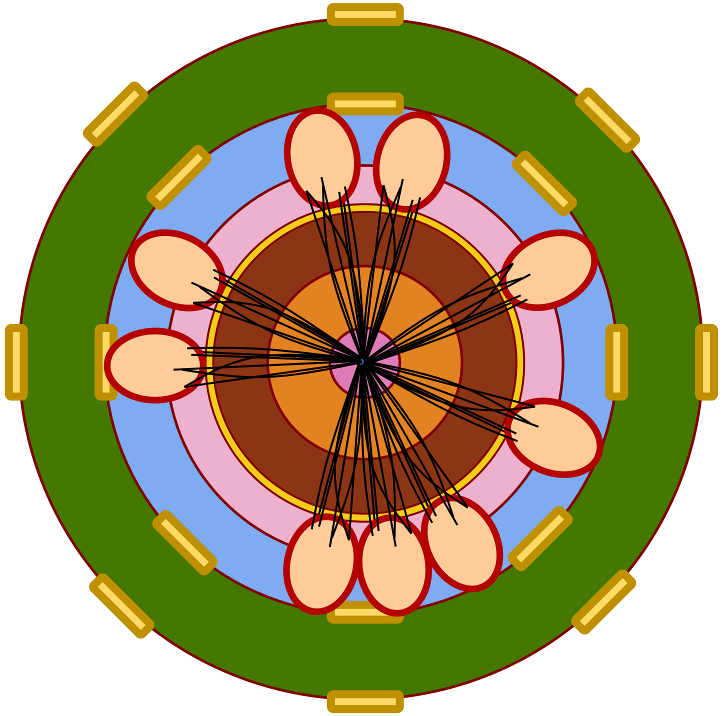

EVENT SELECTIONS

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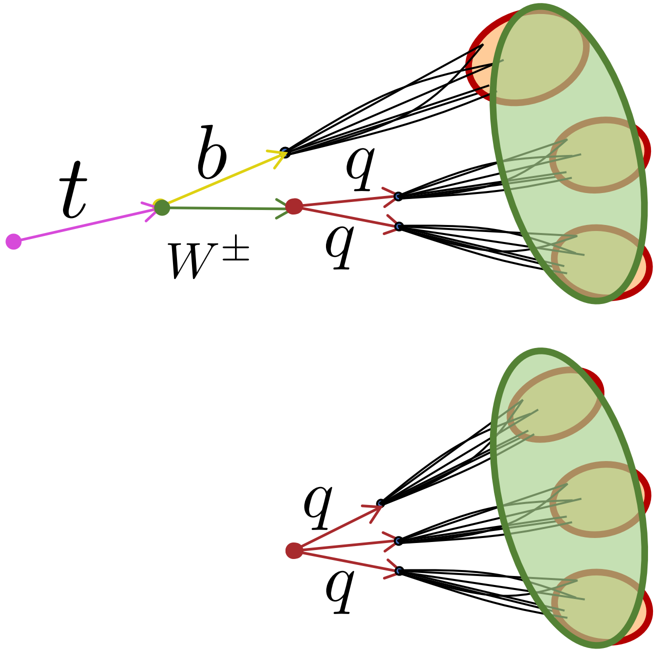

$$m_j\ (\text{QCD}) < m_j\ (\text{SUSY})$$

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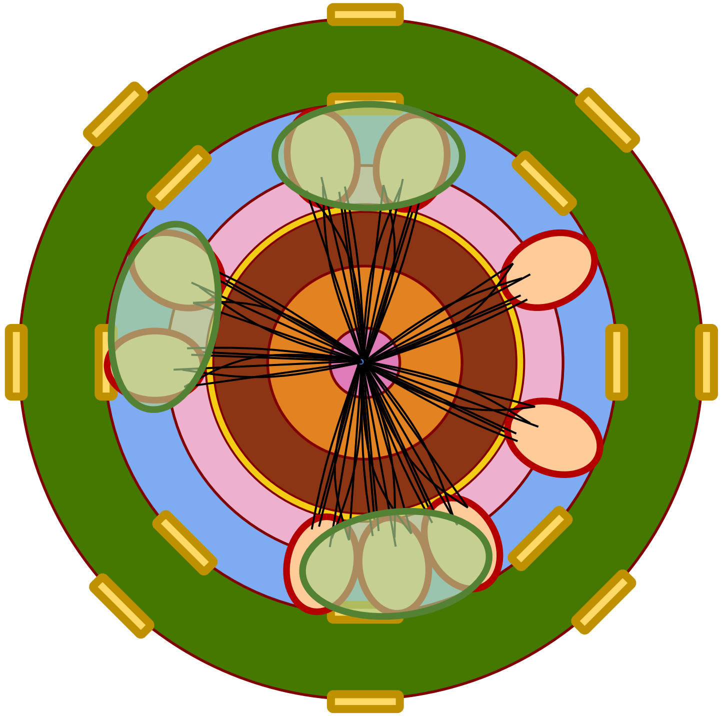


$$M_J^{\Sigma} = \sum_{i=1}^{nJ} m_{j_i}$$

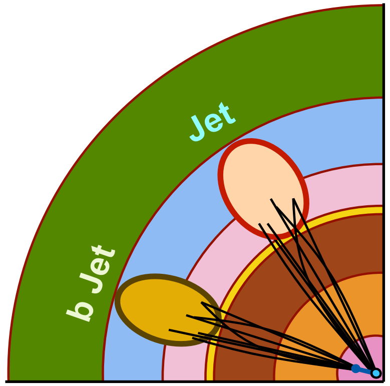
Signal regions can range in jet multiplicity and M_J^{Σ} cuts.

EVENT SELECTIONS

An example of a search

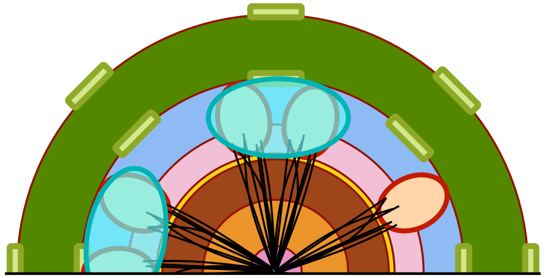
“b-jet stream”

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
$ME_T/\sqrt{H_T}$	> 4 GeV$^{1/2}$												



“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
$ME_T/\sqrt{H_T}$	> 4 GeV$^{1/2}$					



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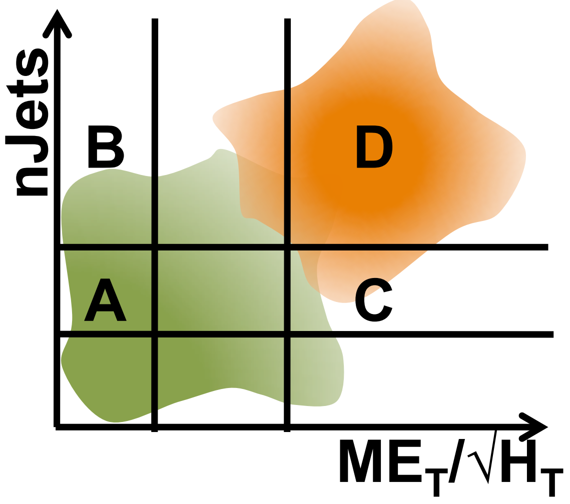
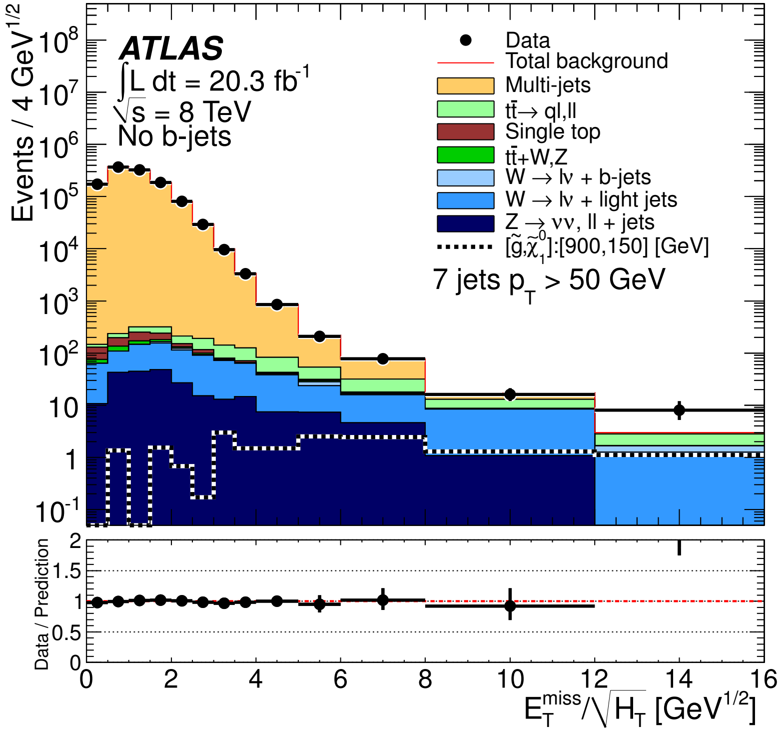
$$M_J^{\Sigma} = \sum_{i=1}^{nJ} m_{j_i}$$

BACKGROUND DETERMINATION



where $H_T = \sum_j p_T^j$

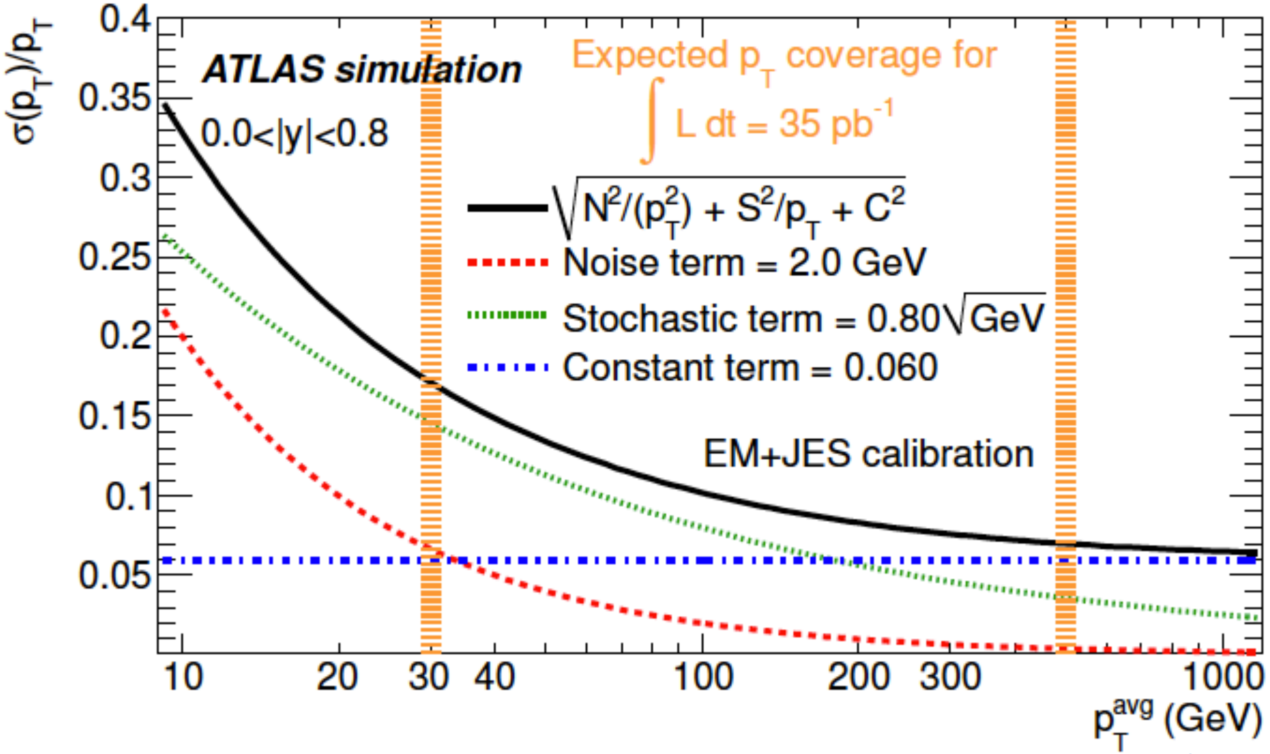


Why $ME_T/\sqrt{H_T}$?

⇒ a measure of ME_T in units of standard deviations of the fake ME_T

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

BACKGROUND DETERMINATION



ATLAS-PERF-2011-04-001

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

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
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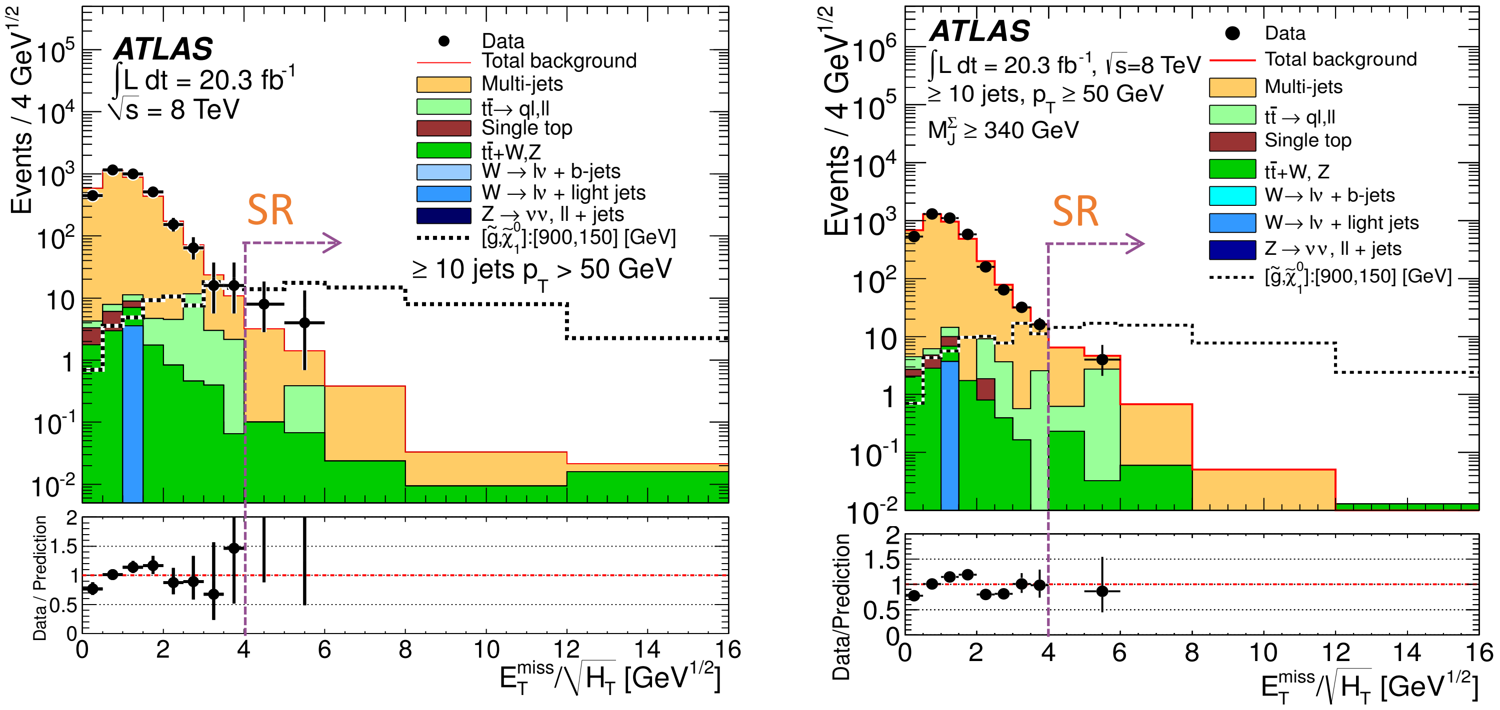
RESULTS


ATLAS
∫L dt = 20.3 fb⁻¹
√s = 8 TeV
Data
Total background
Multi-jets
tt̄→ ql,ll
Single top
tt̄+W,Z
W → lν + b-jets
W → lν + light jets
Z → νν, ll + jets
[g̃,χ̃⁰₁]:[900,150] [GeV]
≥ 10 jets p_T > 50 GeV
SR
Events / 4 GeV^1/2
Data / Prediction
E_T^miss/√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
tt̄ → ql,ll
Single top
tt̄+W, Z
W→ lν + b-jets
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Z → νν, ll + jets
[g̃,χ̃⁰₁]:[900,150] [GeV]
SR
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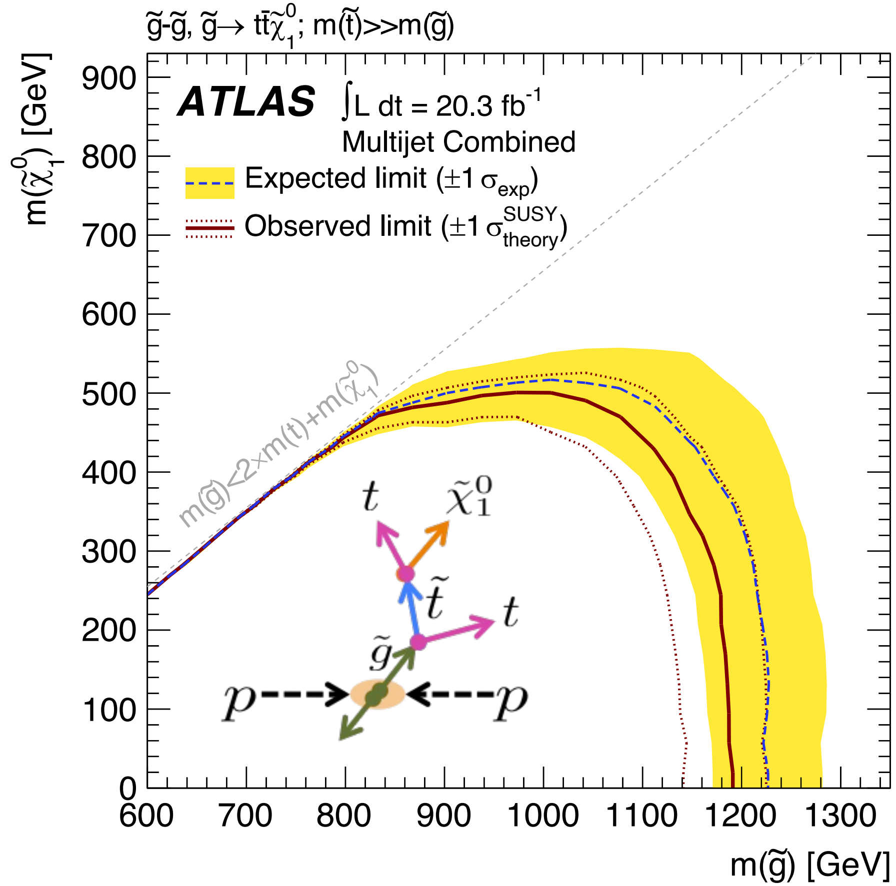
INTERPRETATIONS

Real or Simplified models

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



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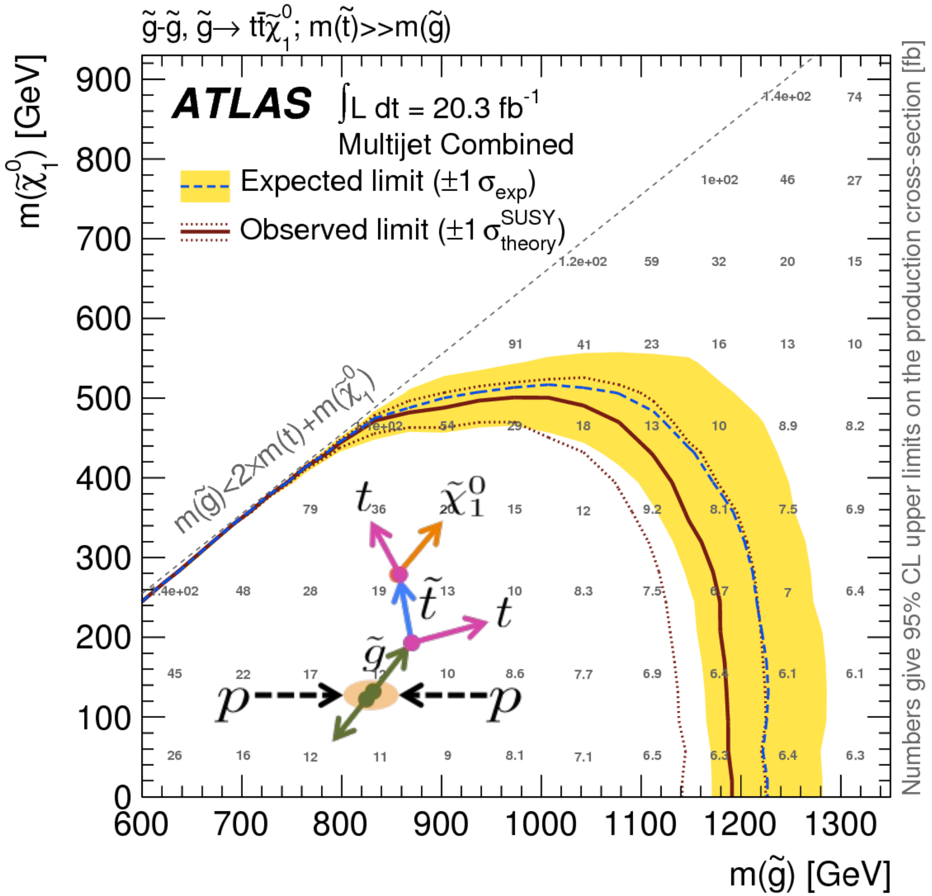
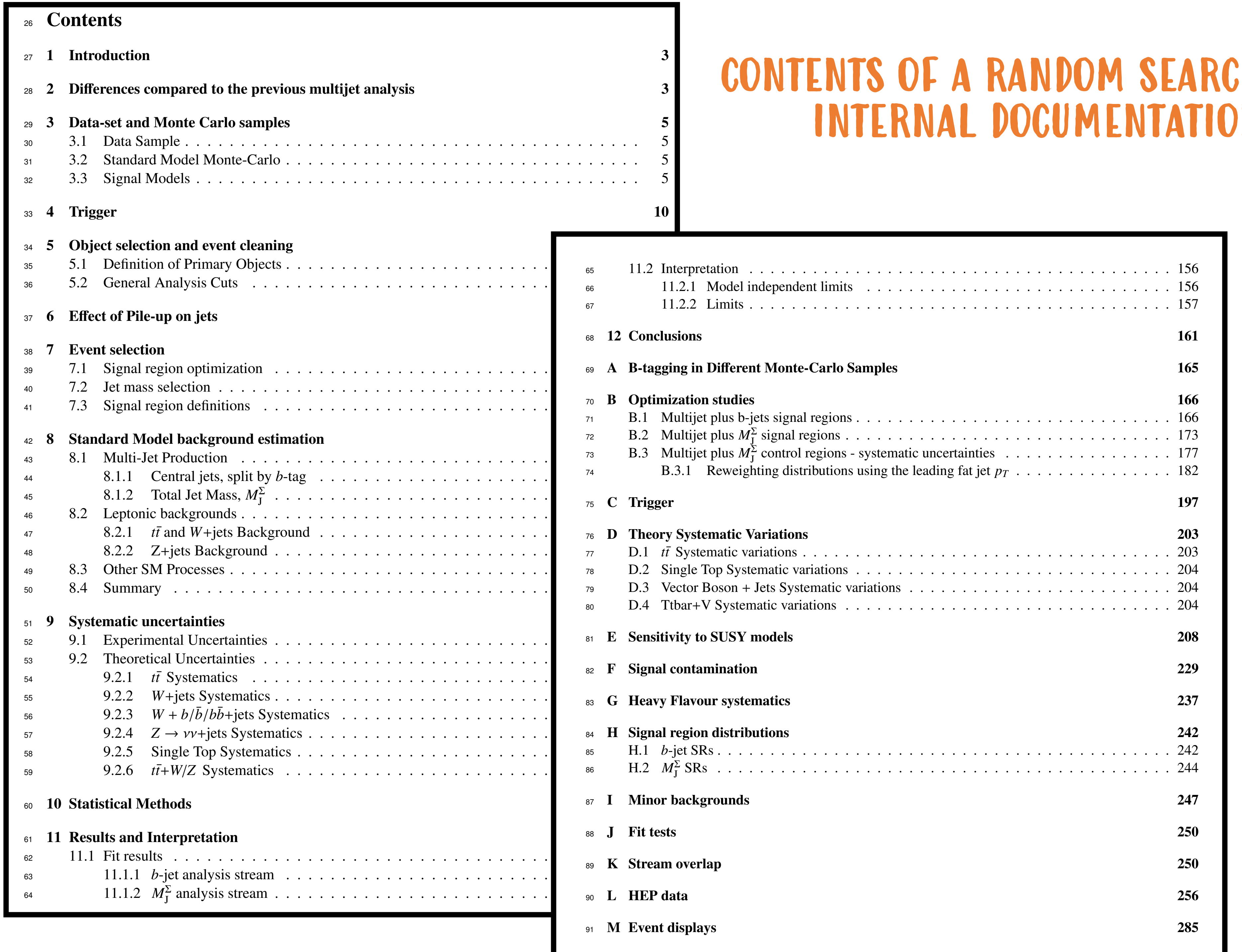


CONTENTS OF A RANDOM SEARCH INTERNAL DOCUMENTATION



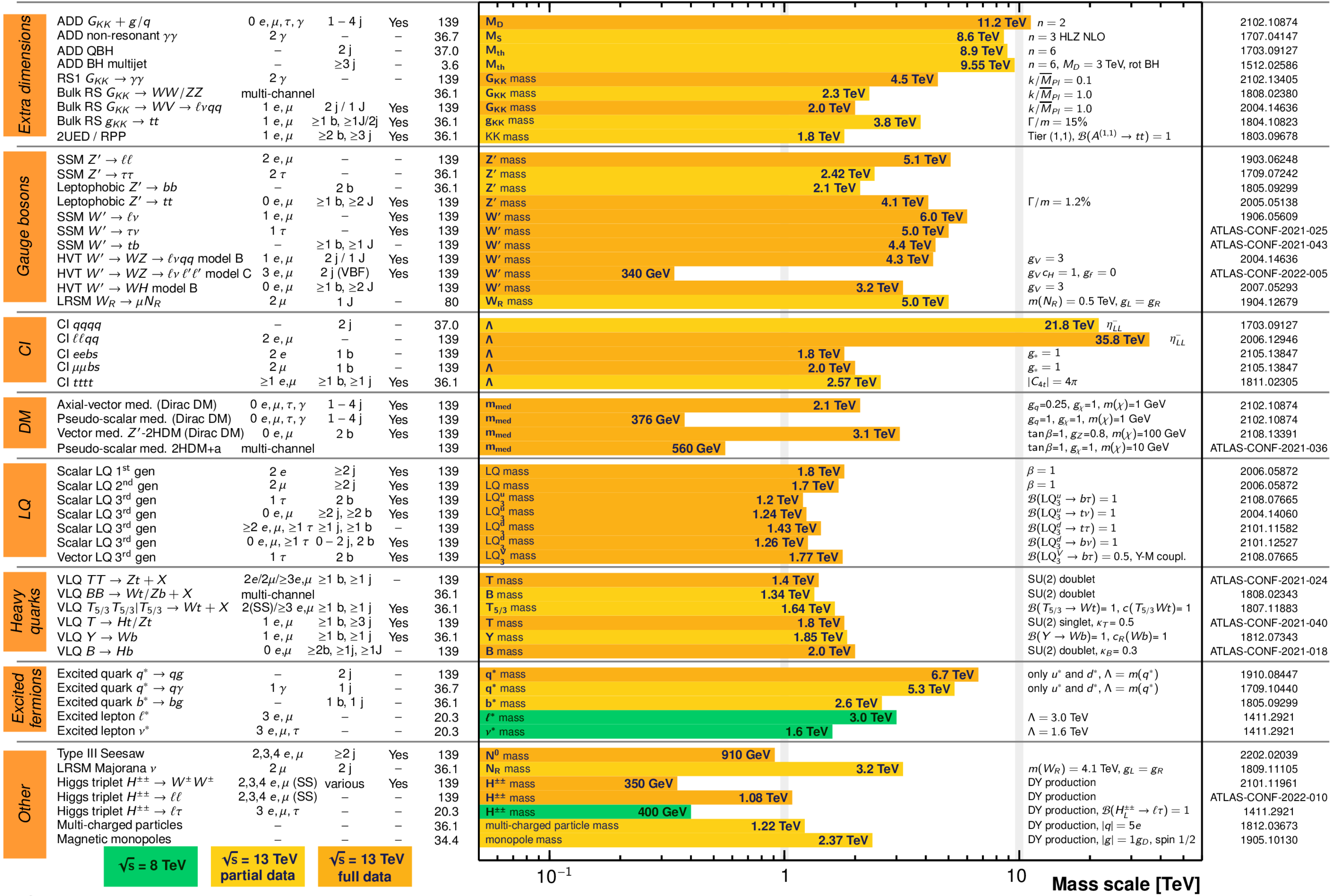
Contents

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2022

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	$1\ e, \mu$	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\, \ell'\ell'$ model C	$3\ e, \mu$	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH$ model B	$0\ e, \mu$	≥1 b, ≥2 J		139	W' mass 3.2 TeV	$g_V = 3$	2007.05293
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	$\geq 1\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	m_{med} 3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med} 560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass 1.2 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	$\geq 2\ e, \mu, \geq 1\ \tau$	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu, \geq 1\ \tau$	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^V mass 1.77 TeV	$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Heavy quarks	VLQ $TT \to Zt + X$	$2e/2\mu/\geq 3e,\mu$	≥1 b, ≥1 j	–	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	$2(SS)/\geq 3\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$2,3,4\ e, \mu$	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	$2,3,4\ e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2,3,4\ e, \mu$ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

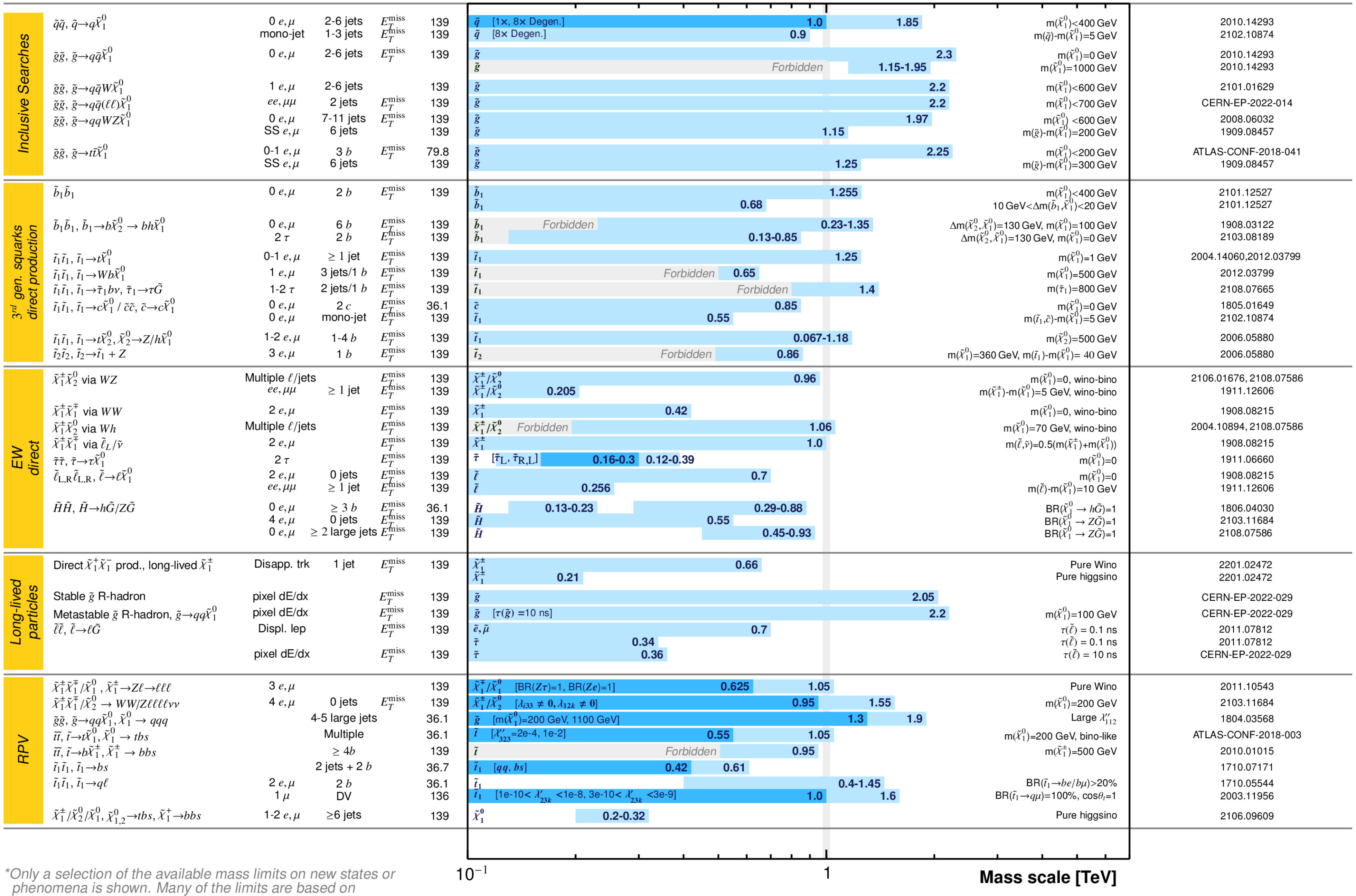
†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2022

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[1×, 8× Degen.]	1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$		2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden	1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$		2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	139	$\tilde{g}$		2.2	m($\tilde{\chi}^0_1$)<700 GeV	CERN-EP-2022-014
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$		1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$		1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$		2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$		1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$		1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$		0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden	0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$		0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$		1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden	0.65	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden	1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$		0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$		0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$		0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden	0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$		0.96	m($\tilde{\chi}^0_1$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$		0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$		0.42	m($\tilde{\chi}^0_1$)=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden	1.06	m($\tilde{\chi}^0_1$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$		1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$	[$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$		0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$		0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$		0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$		0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	$E_T^{\rm miss}$	139	$\tilde{H}$		0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$		0.66	Pure Wino	2201.02472
						$\tilde{\chi}^\pm_1$		0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{g}$		2.05		CERN-EP-2022-029
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}^0_1$)=100 GeV	CERN-EP-2022-029
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	139	$\tilde{e},\tilde{\mu}$		0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$		0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})$ = 10 ns	CERN-EP-2022-029
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$	[BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	[$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large jets		36.1	$\tilde{g}$	[m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		139	$\tilde{t}$	Forbidden	0.95	m($\tilde{\chi}^\pm_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$		0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}^0_1$		0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

From Raw Data to Physics

INSTEAD OF SUMMARY:

COMPONENTS OF AN ANALYSIS

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]

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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
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- ◎ Background de
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- ◎ Results
- ◎ [Interpretations]

The trigger used to collect the data with.

Trigger specifics:

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

COMPONENTS OF A PHYSICS AN

- Data-set and Monte Carlo sa
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- [Interpretations]

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

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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.

COMPONENTS 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.

COMPONENTS OF A PHYSICS ANALYSI

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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!

COMPONENTS 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.

COMPONENTS OF A PHYSICS ANALYSIS

- Data-set and Monte Carlo samples
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Put the results into context:
interpret them in theoretical models.

https://xkcd.com/1838/

EXCITING TIMES COMING UP IN HEP

GOOD LUCK IN YOUR RESEARCH!

Please get in touch for question, comments,
or simply feedback on this lecture
anna.sfyrla@unige.ch