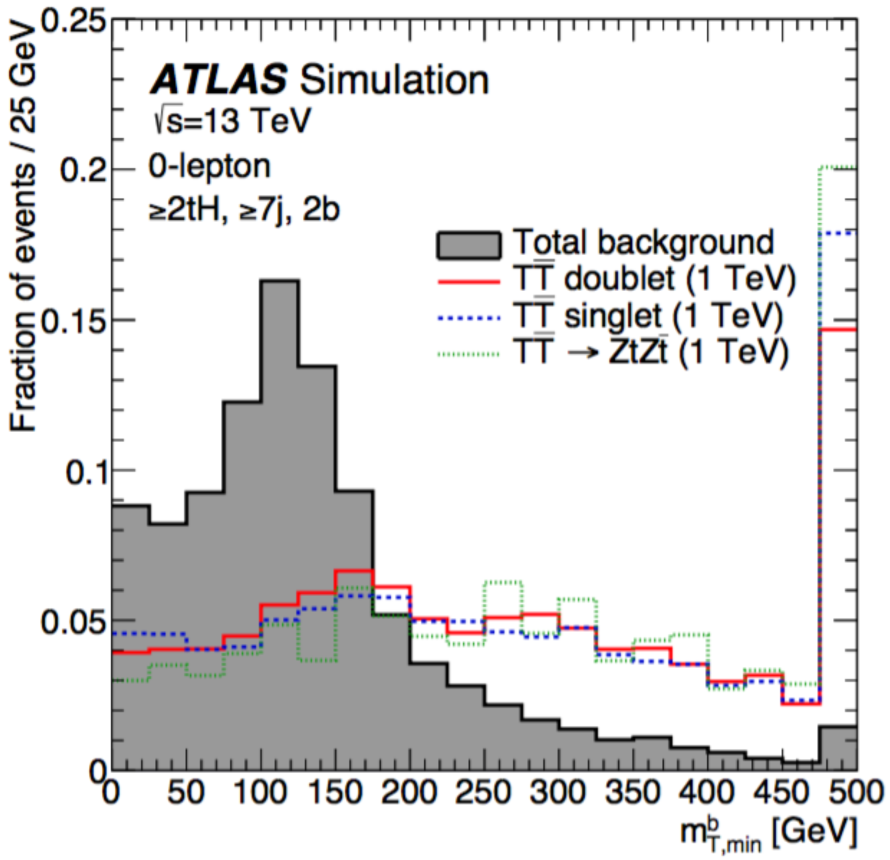
Searches for New Particles at the LHC



M. E. Peskin

April 2018

No new particles have been discovered yet at the LHC.

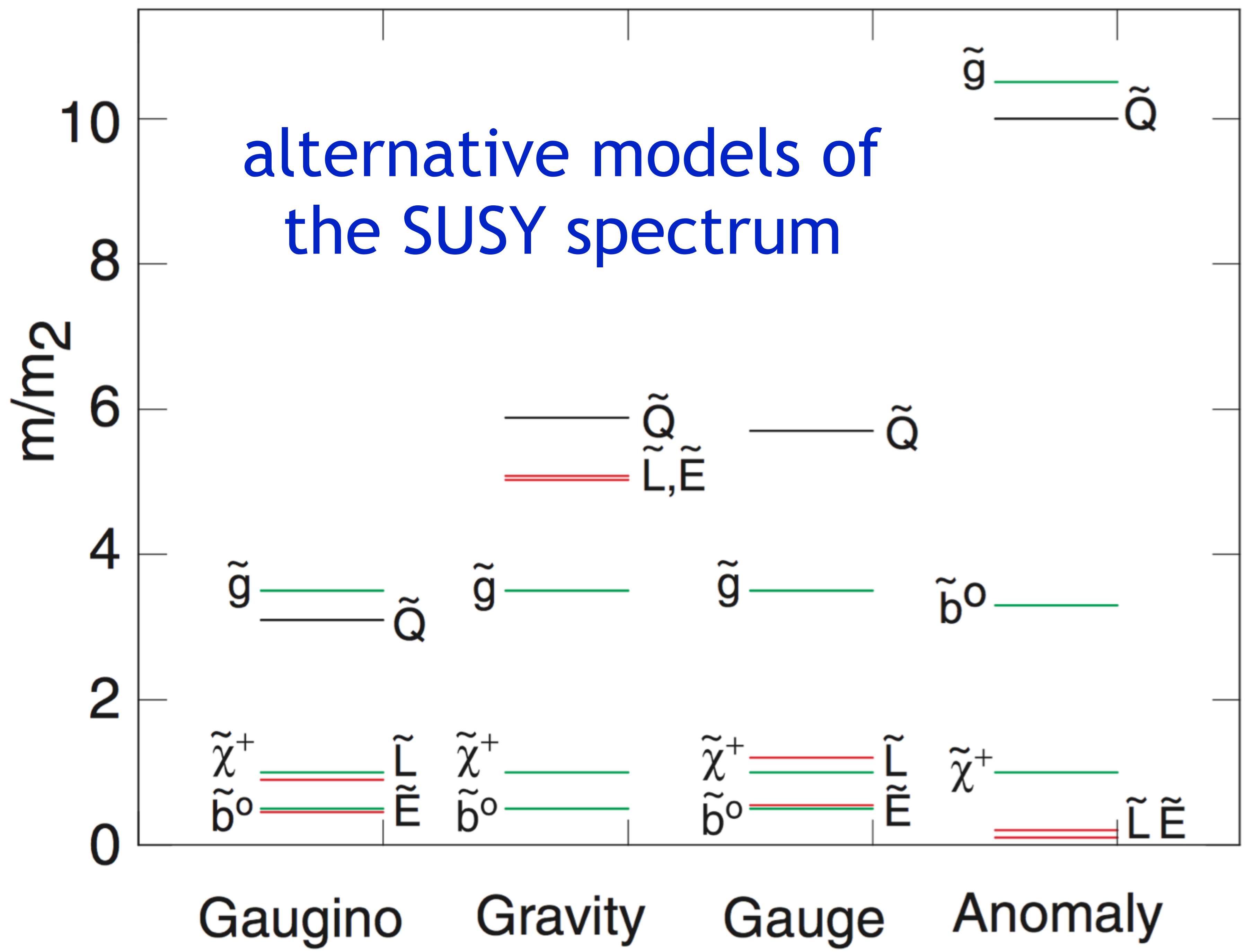
This is not for lack of persistence and ingenuity. The search for new particles at the LHC has many layers of difficulty, and these have been overcome by a variety of fascinating techniques. In this lecture, I will describe these, layer by layer.

For string theorists, the most attractive model of new particles and forces is supersymmetry.

Here is a quote from Brian Green’s book “The Elegant Universe”:

"The masses and charges of the superpartner particles would reveal the detailed way in which supersymmetry is incorporated into the laws of nature. String theorists would then face the challenge of seeing whether this implementation can be fully realized or explained by string theory."

I quoted this in a talk that I gave at the KITP in 2001.
Here is a figure from that talk:



We expected: $m_2 \approx m_h \approx 100 \text{ GeV}$

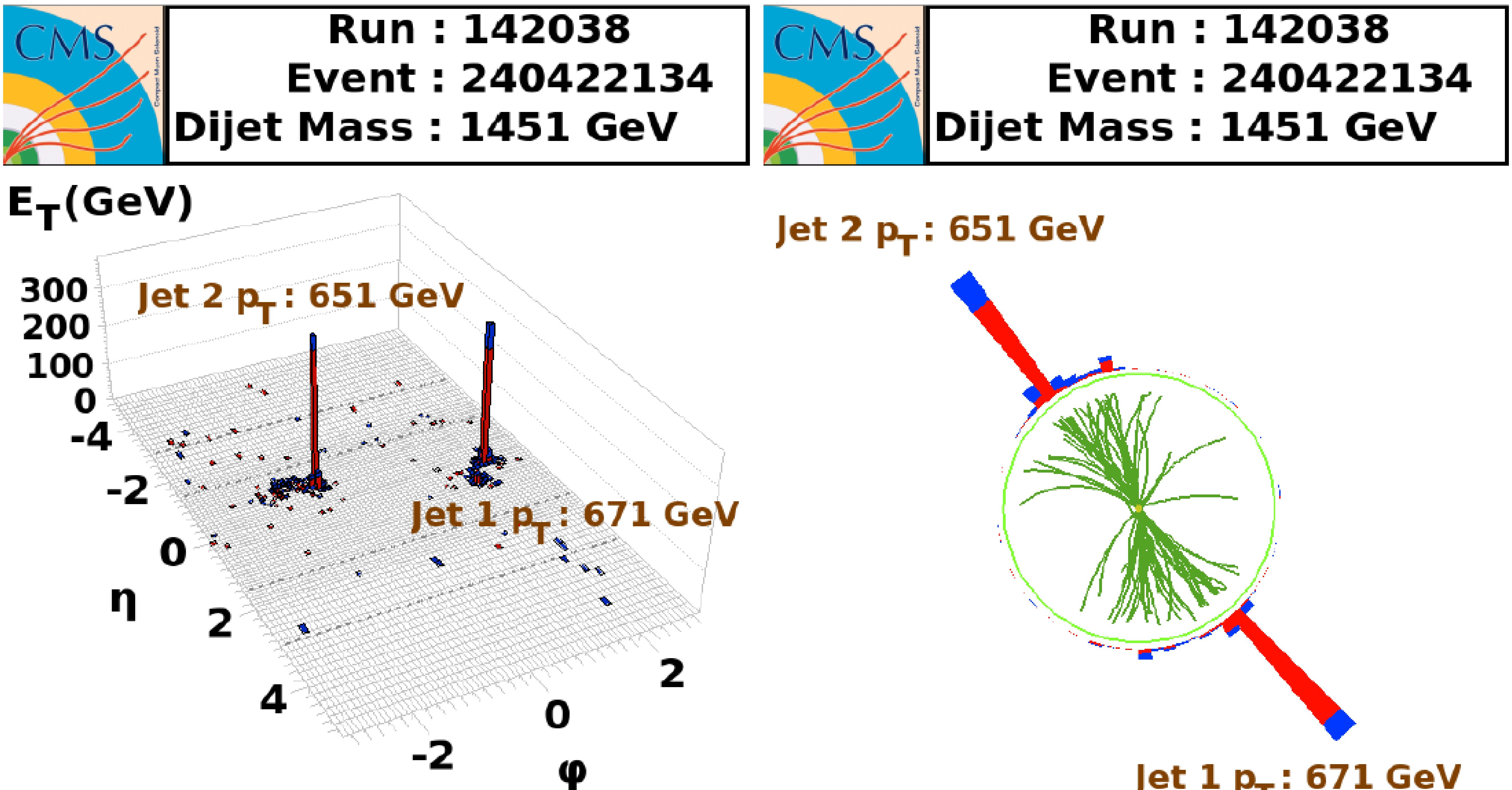
At first sight, it seems not so hard to discover SUSY at the LHC.

It is difficult to avoid conservation of R-parity:

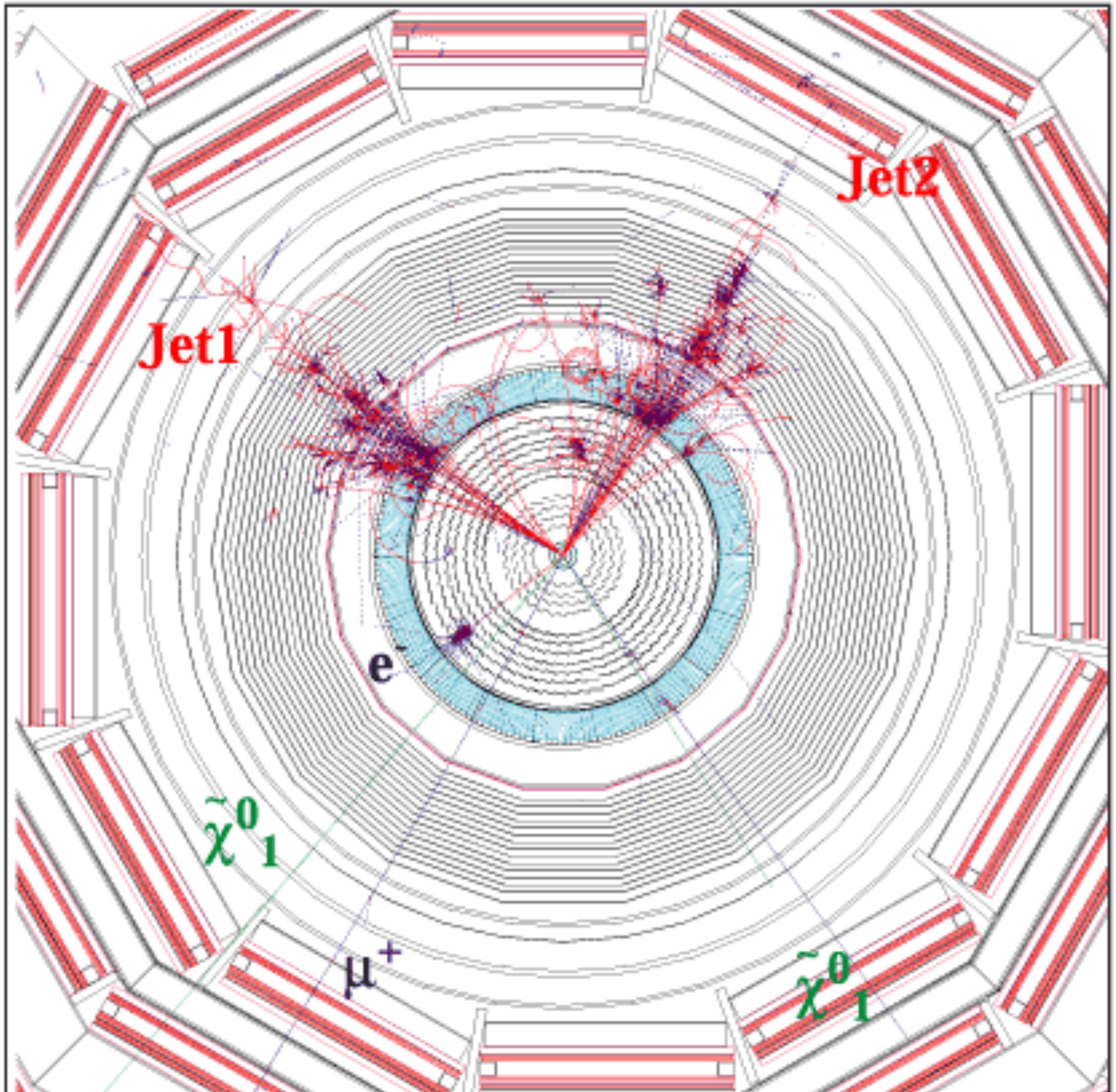
$$R = (-1)^{B-L+2J}$$

This implies that the lightest superpartner is stable. If it is also neutral and weakly coupled — other options are ruled out by cosmology — it is invisible to LHC detectors. Then we look for events with large activity and unbalanced visible momentum.

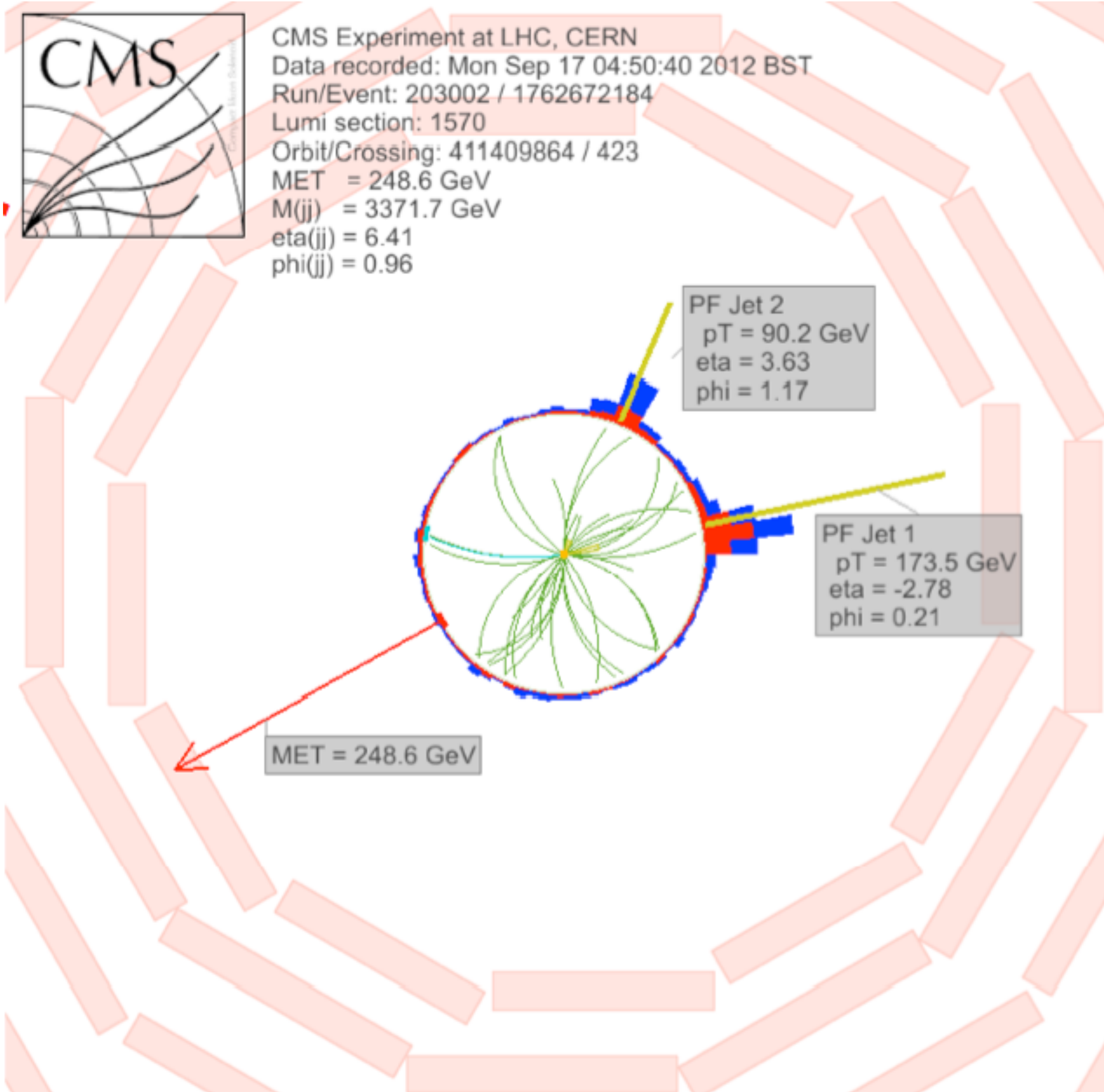
R parity also makes the lightest superpartner a good dark matter candidate. This makes a very attractive picture.

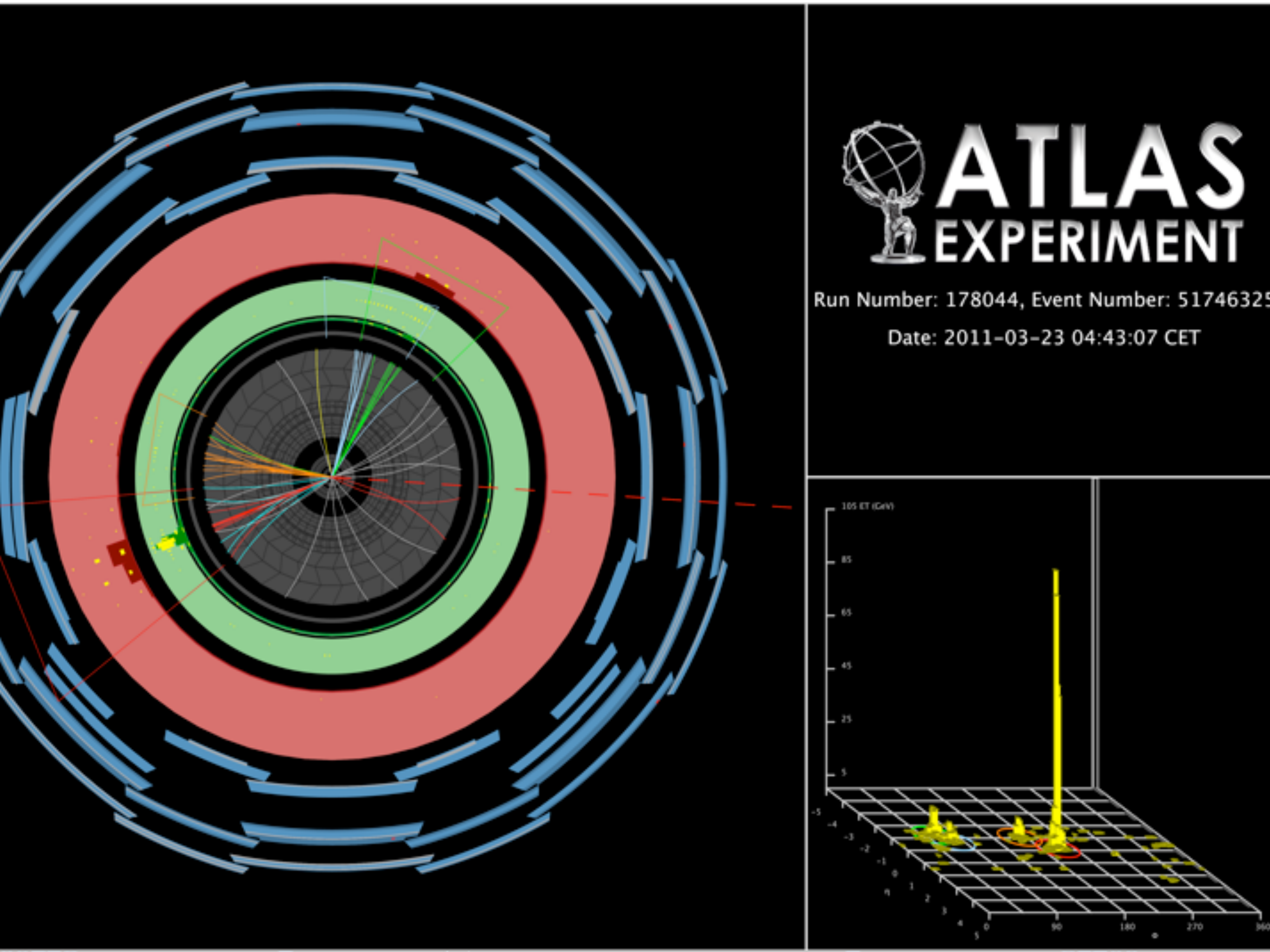


Run : 142038
Event : 240422134
Dijet Mass : 1451 GeV
E_T(GeV)
300
200
100
0
Jet 2 p_T : 651 GeV
Jet 1 p_T : 671 GeV
η
φ
-4
-2
0
2
4
Run : 142038
Event : 240422134
Dijet Mass : 1451 GeV
Jet 2 p_T : 651 GeV
Jet 1 p_T : 671 GeV



CMS simulation


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Sep 17 04:50:40 2012 BST
Run/Event: 203002 / 1762672184
Lumi section: 1570
Orbit/Crossing: 411409864 / 423
MET = 248.6 GeV
M(jj) = 3371.7 GeV
eta(jj) = 6.41
phi(jj) = 0.96
PF Jet 2
pT = 90.2 GeV
eta = 3.63
phi = 1.17
PF Jet 1
pT = 173.5 GeV
eta = -2.78
phi = 0.21
MET = 248.6 GeV

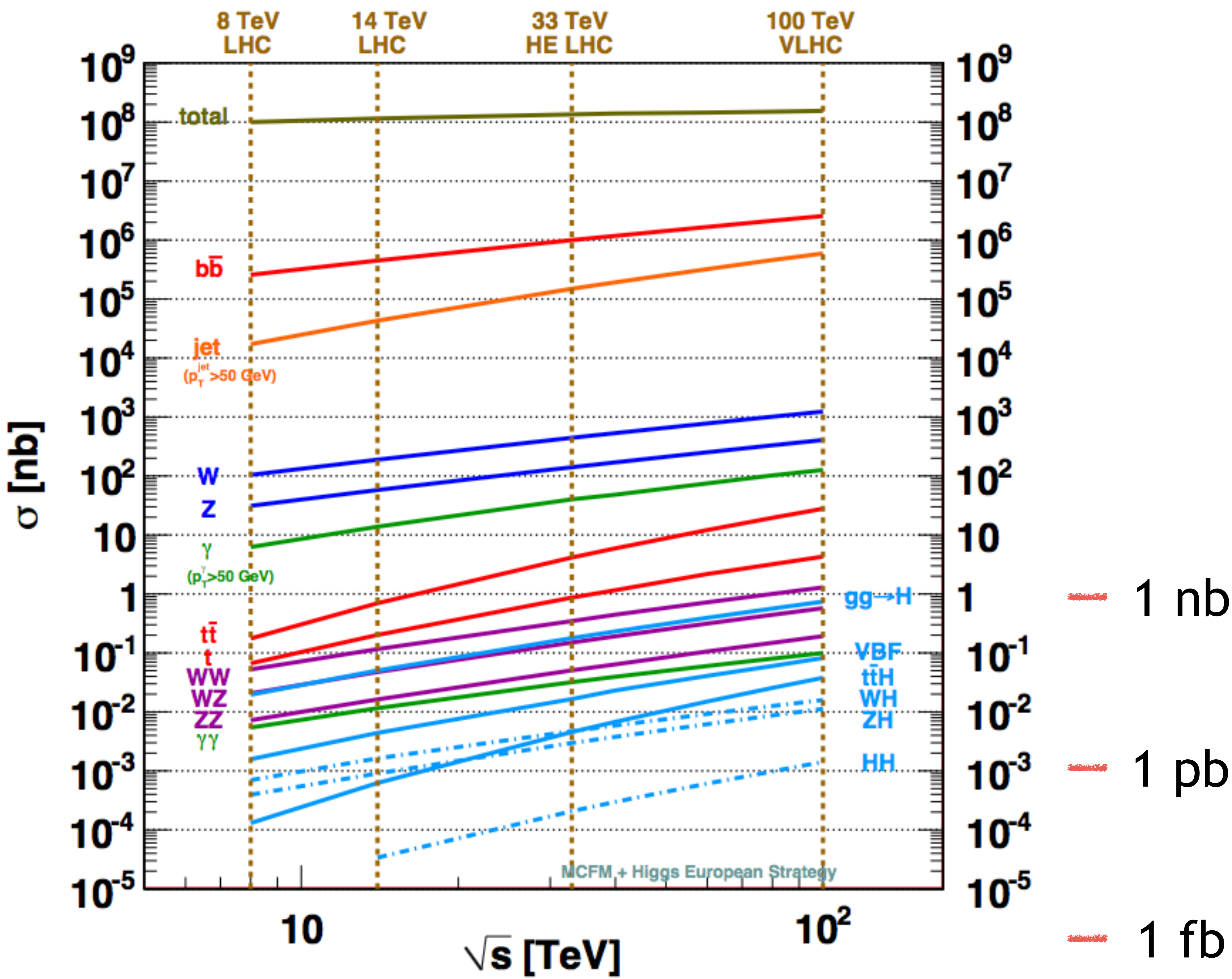

ATLAS
EXPERIMENT
Run Number: 178044, Event Number: 51746325
Date: 2011-03-23 04:43:07 CET
105 ET (GeV)
85
65
45
25
5
0
90
180
270
360

In fact, searches for SUSY and other models of new physics at the LHC must face many levels of difficulty:

Low event rates under overwhelming backgrounds

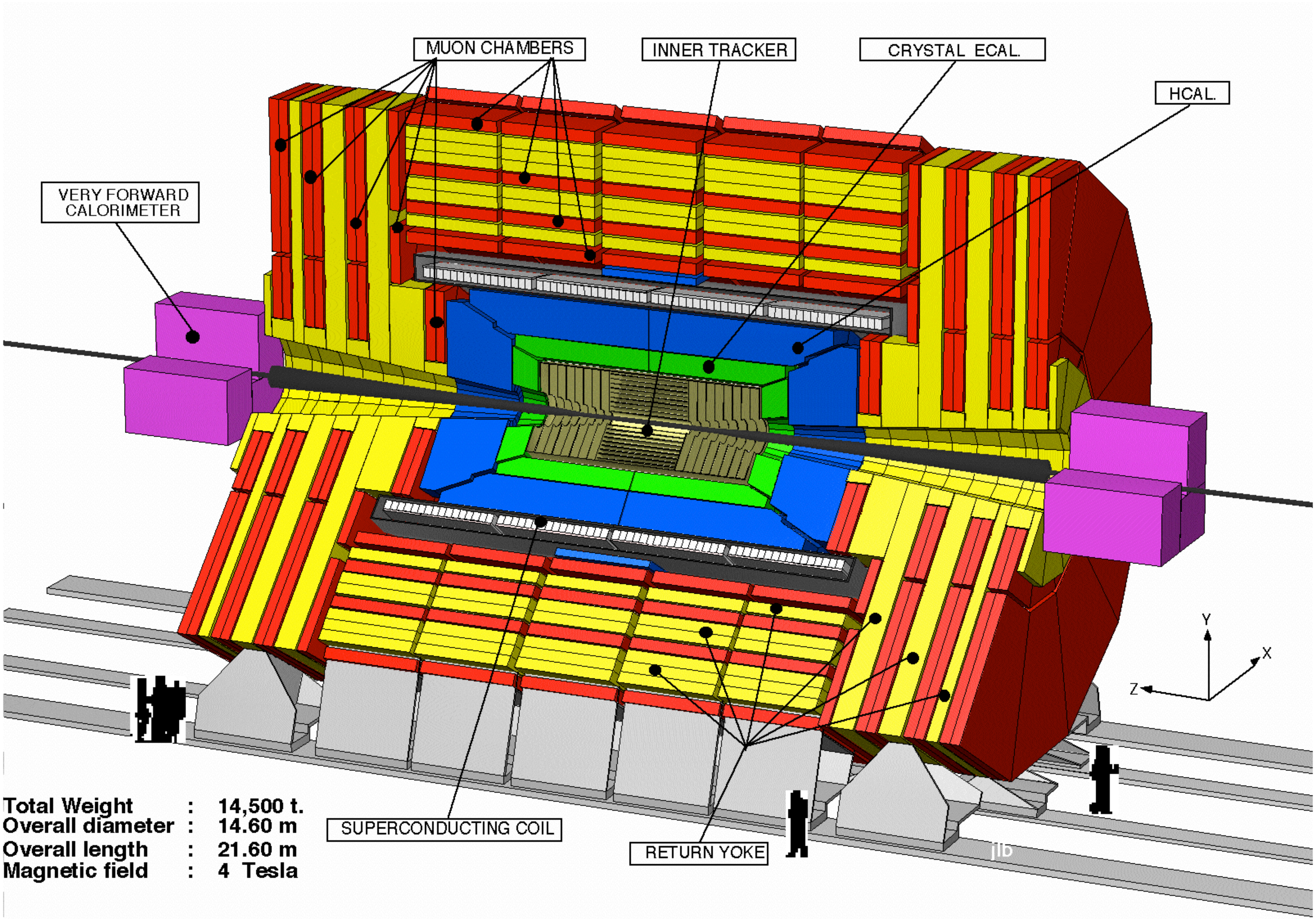
Complexity of multijet processes in the Standard Model

Difficulty of inferring momenta and identities of parent particles in an event

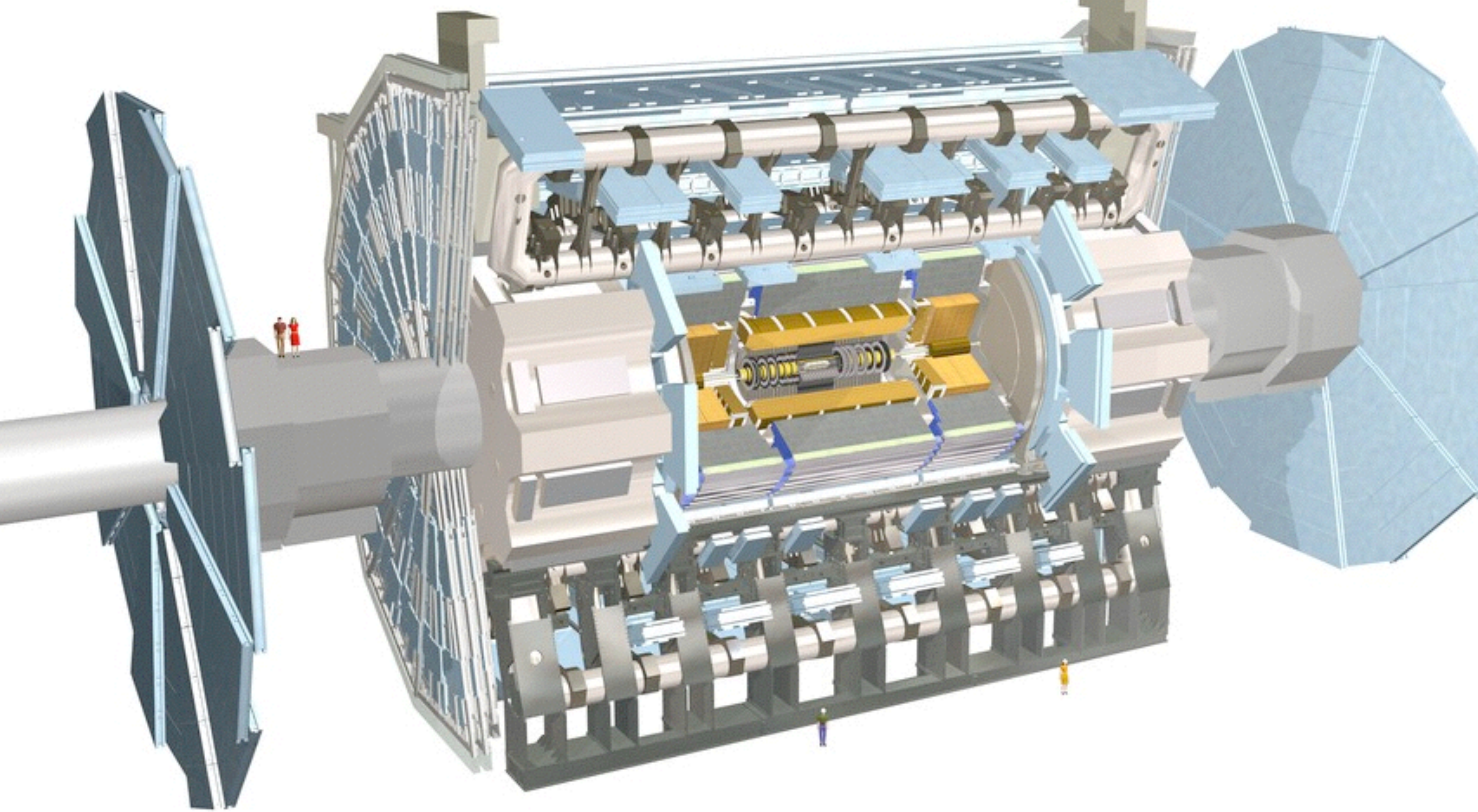


8 TeV LHC
14 TeV LHC
33 TeV HE LHC
100 TeV VLHC
total
$b\bar{b}$
jet
(p_T^{jet}>50 GeV)
W
Z
γ
(p_T^{γ}>50 GeV)
$t\bar{t}$
t
WW
WZ
ZZ
γγ
gg→H
VBF
$t\bar{t}$H
WH
ZH
HH
MCFM + Higgs European Strategy
σ [nb]
√s [TeV]
1 nb
1 pb
1 fb

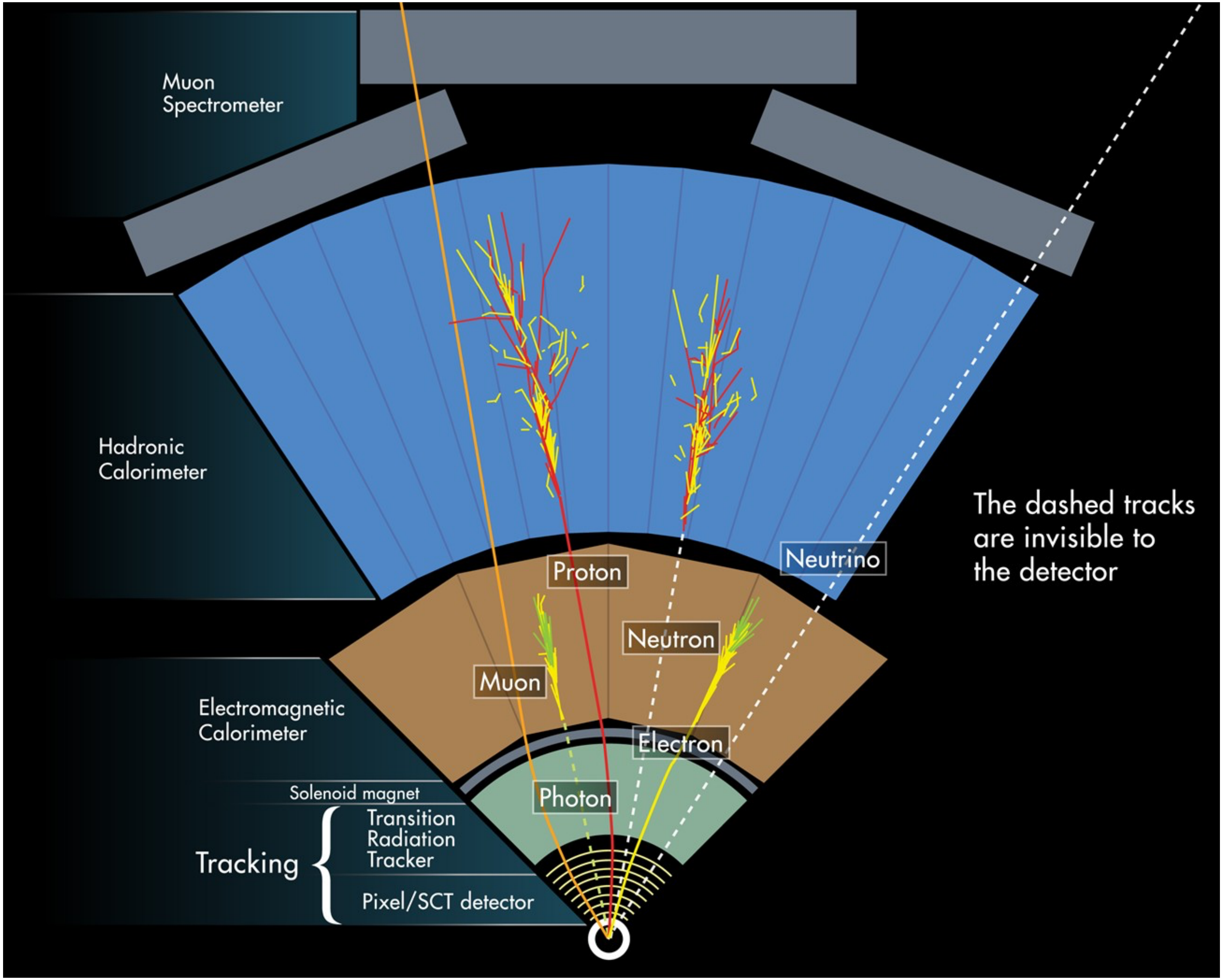
A Compact Solenoidal Detector for LHC

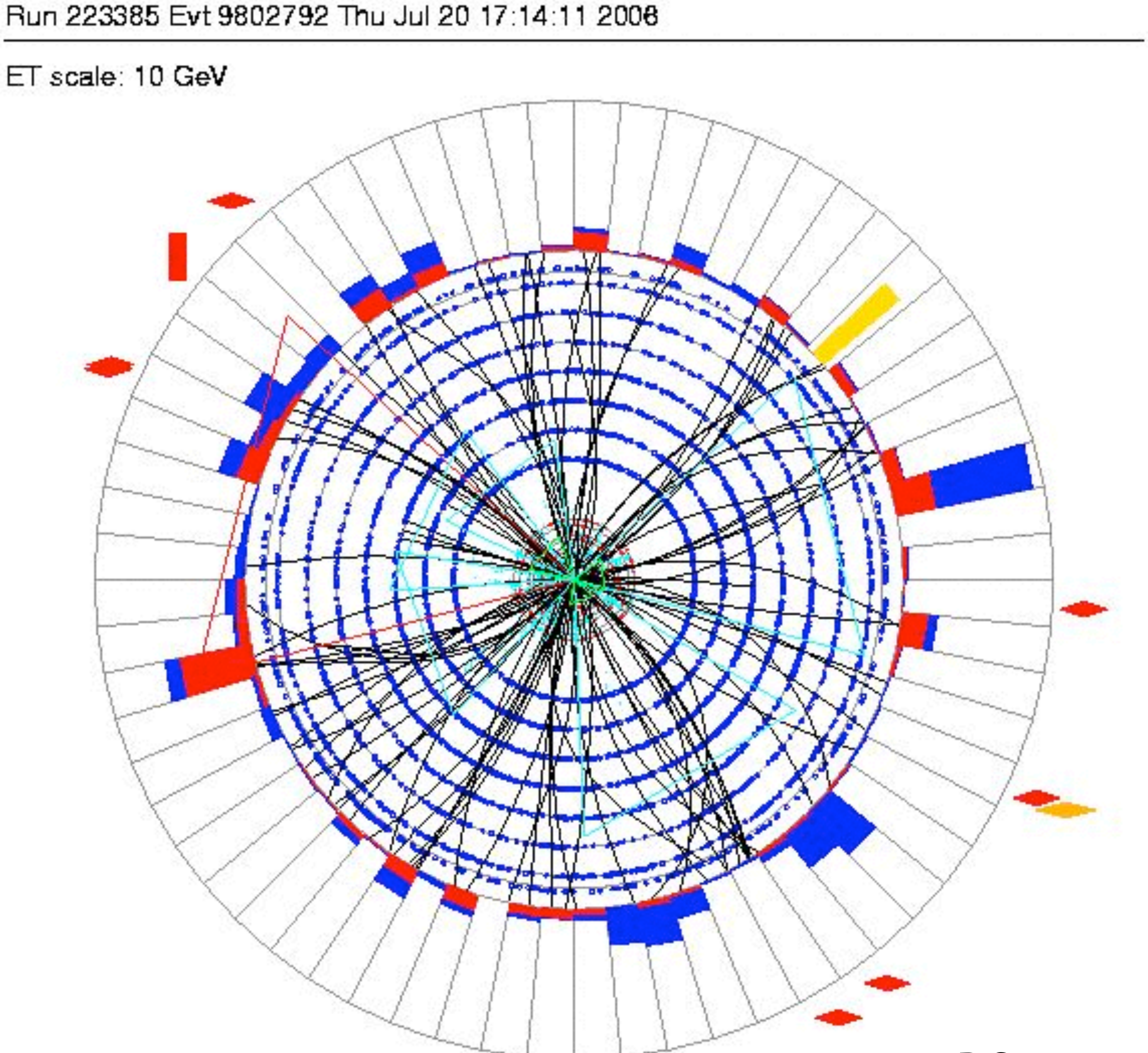


Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

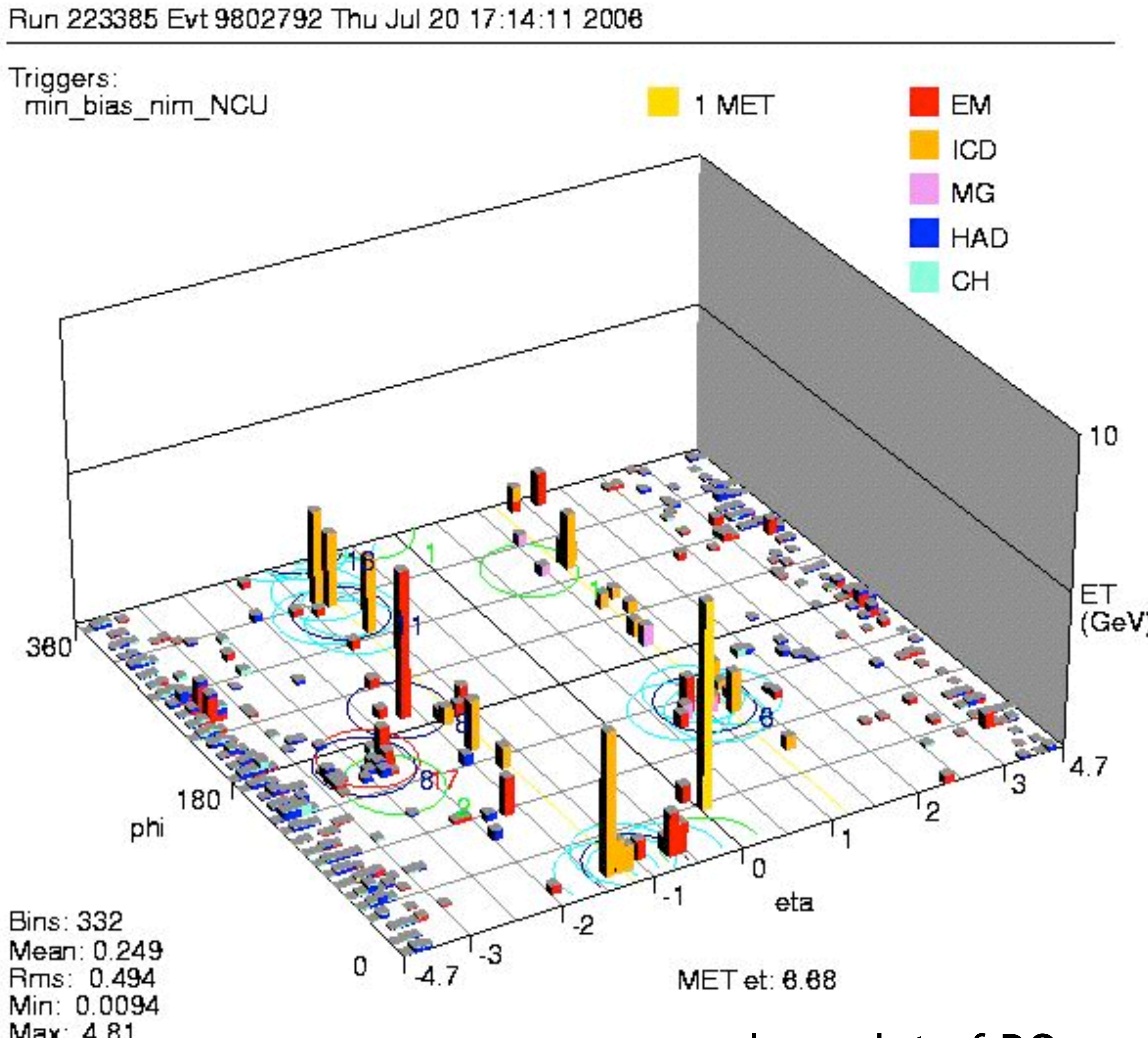


the ATLAS experiment


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector



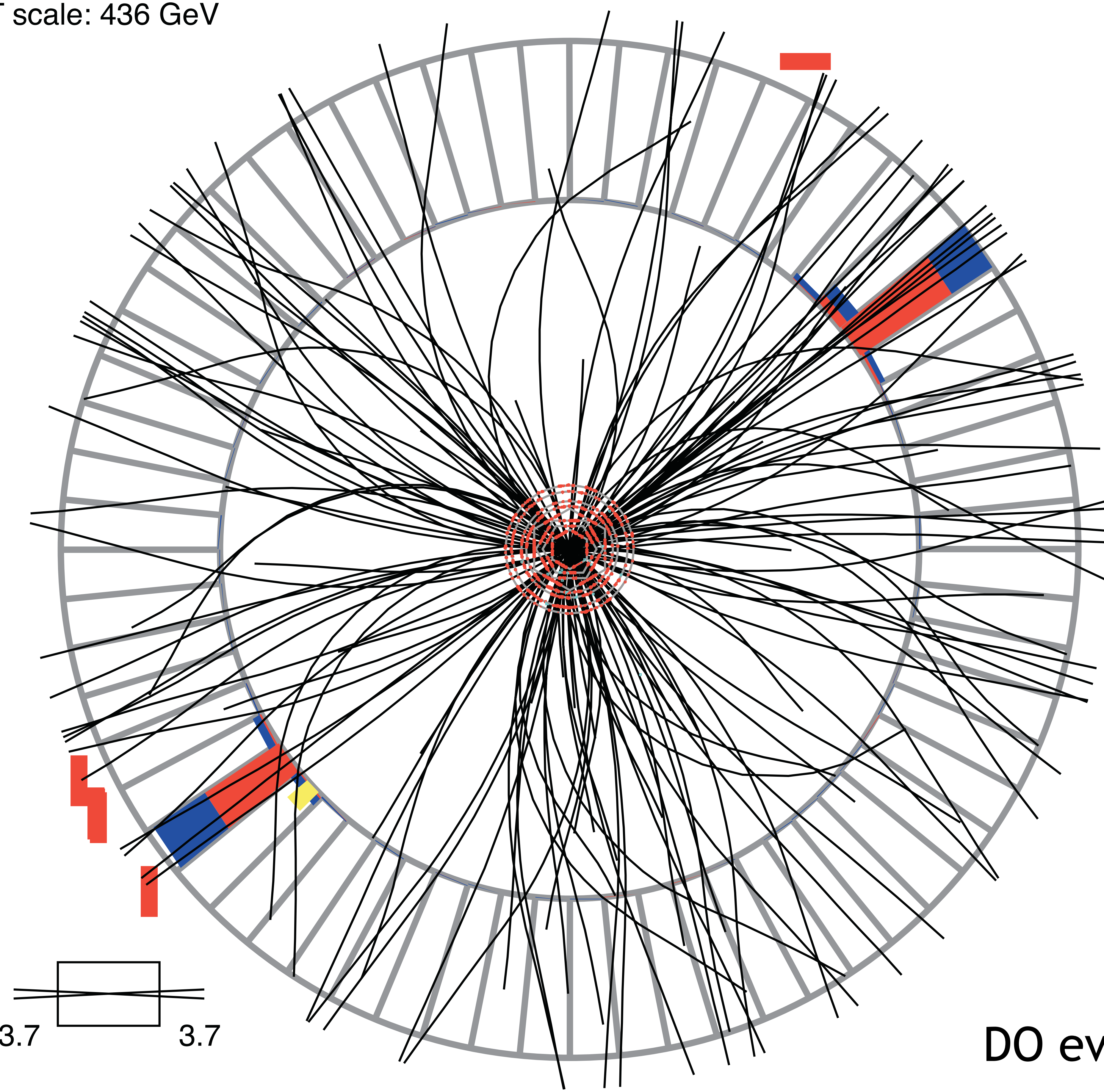
DO event



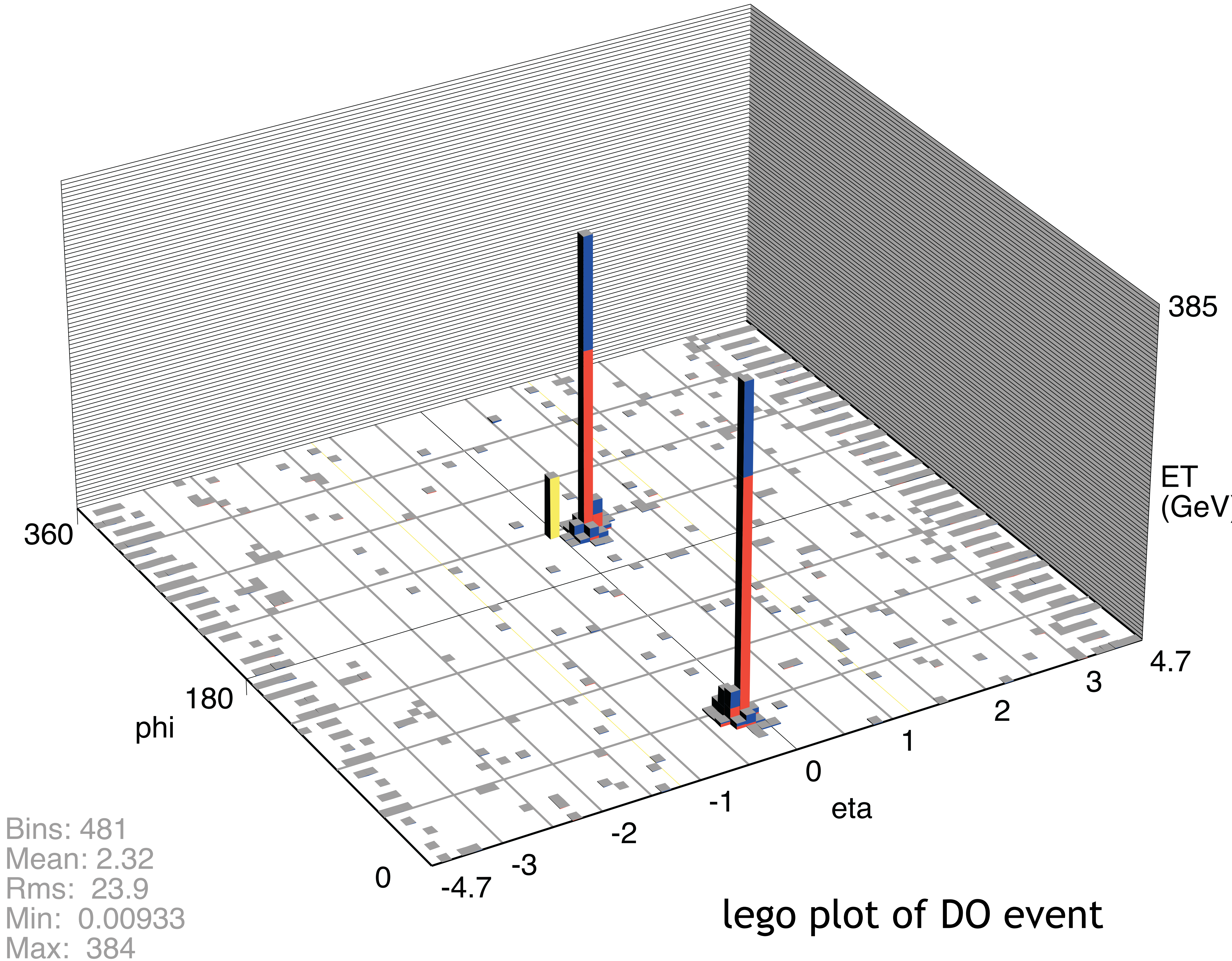
lego plot of DO event

Run 178796 Event 67972991 Fri Feb 27 08:34:15 2004

ET scale: 436 GeV



DO event


385
ET
(GeV)
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
Bins: 481
Mean: 2.32
Rms: 23.9
Min: 0.00933
Max: 384
lego plot of DO event

The LHC experiments record a few hundred events/sec , compared to the bunch crossing rate of $40 \times 10^6/\mathrm{sec}$.

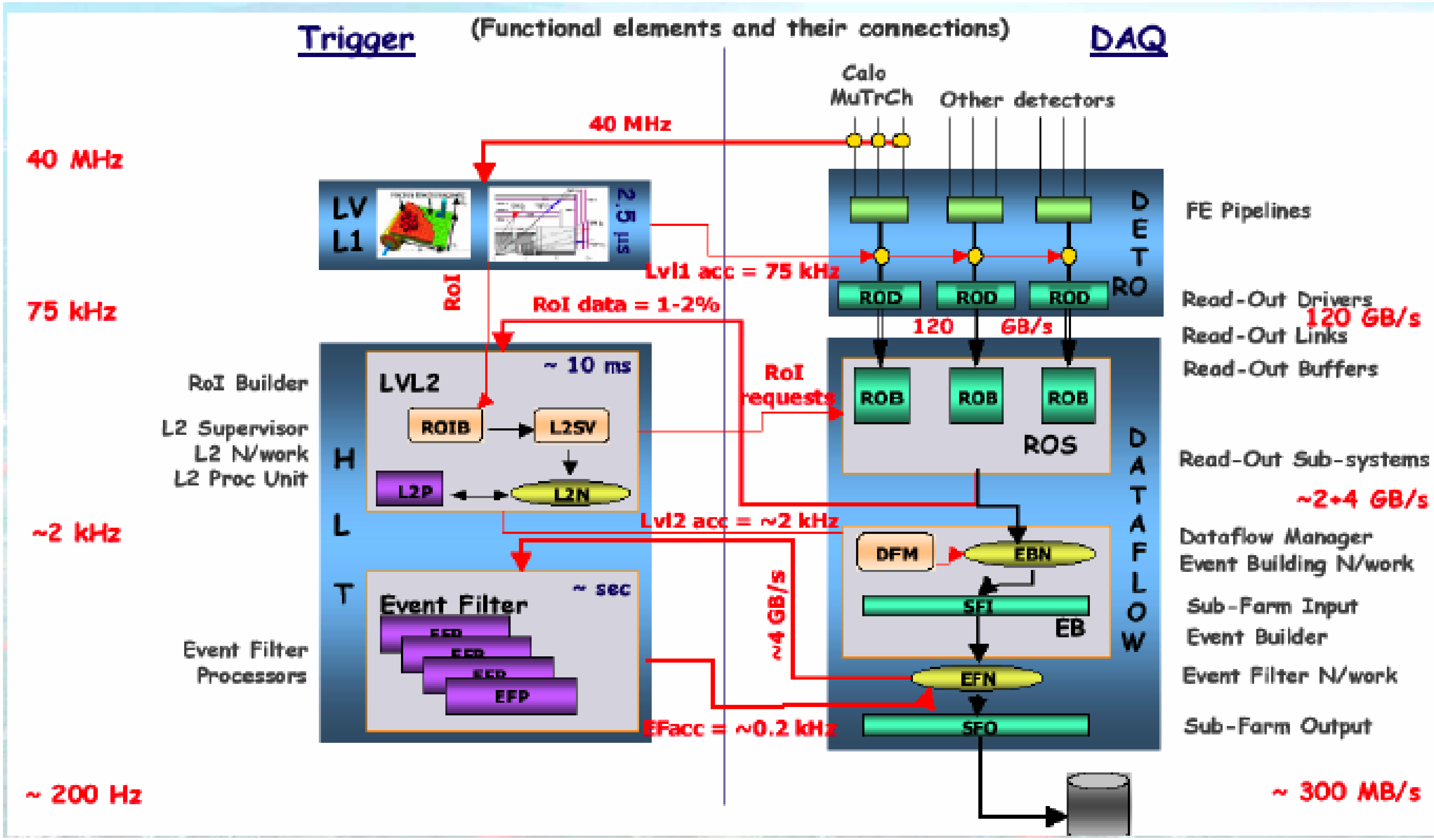
At about 3 Mb/event, this gives a database of 10 Pb / yr.

The reduction from 40 MHz to 300 Hz must be done automatically. This is done by the trigger, a network of computers and data pipelines. In ATLAS, the trigger has 3 levels. Conceptually,

	allowed rate	decision time
Level 1	1 MHz	100 microsec
Level 2	30 kHz	10 msec
Level 3	300 Hz	1 sec

The data from each bunch collision is stored in a pipeline and thrown away if that collision is rejected by the trigger.

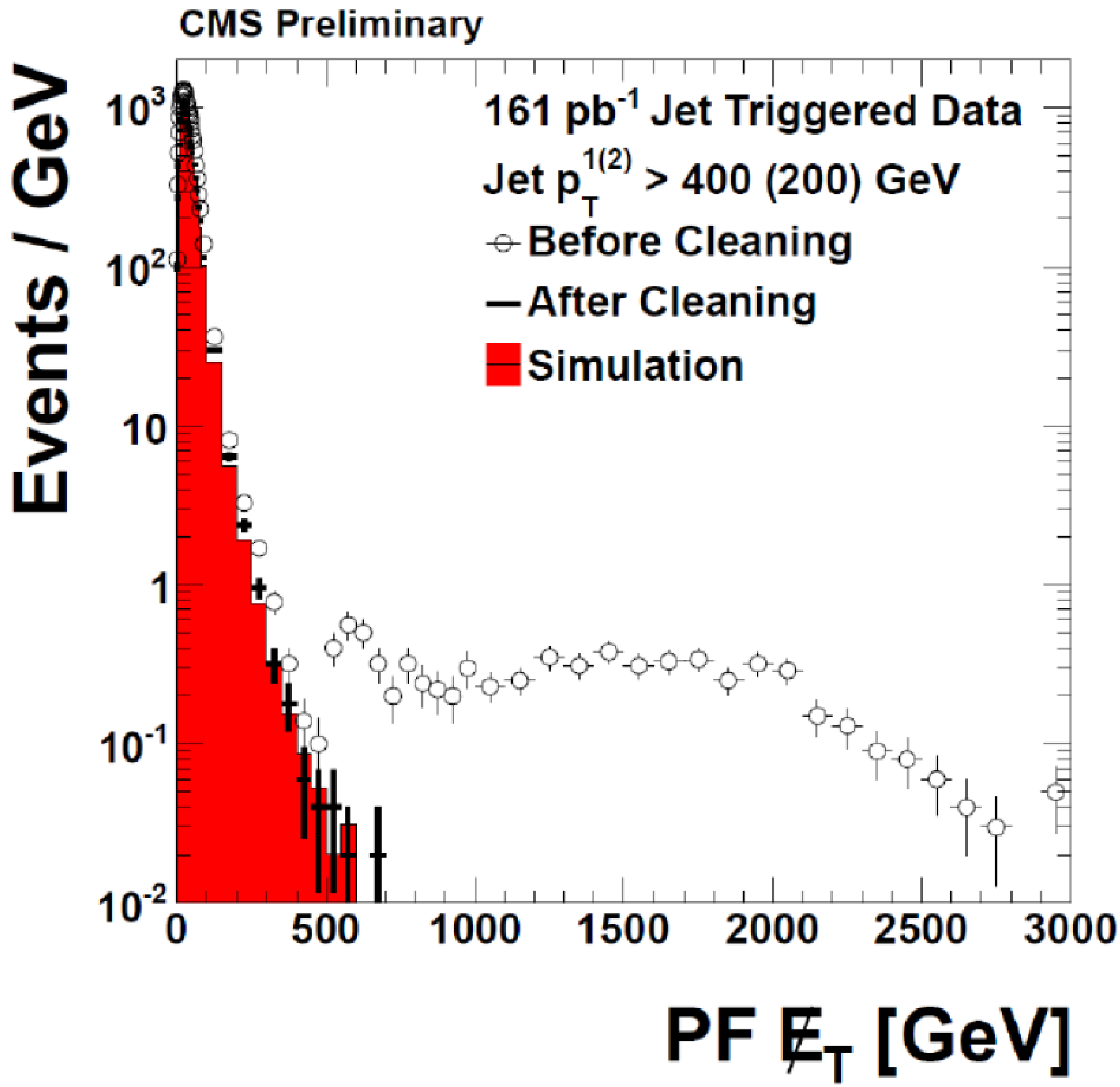
more precisely:



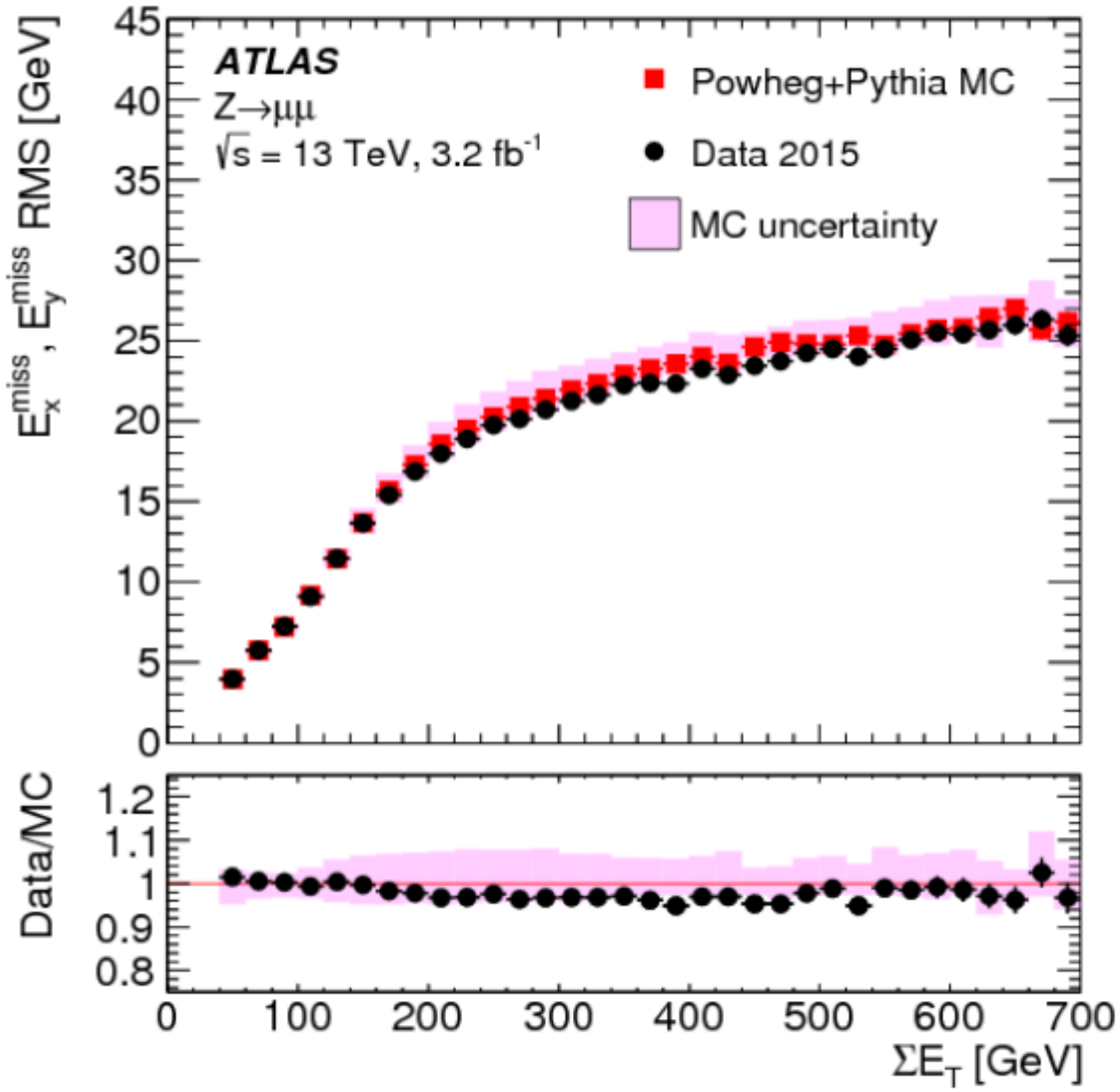
N. Ellis, ATLAS

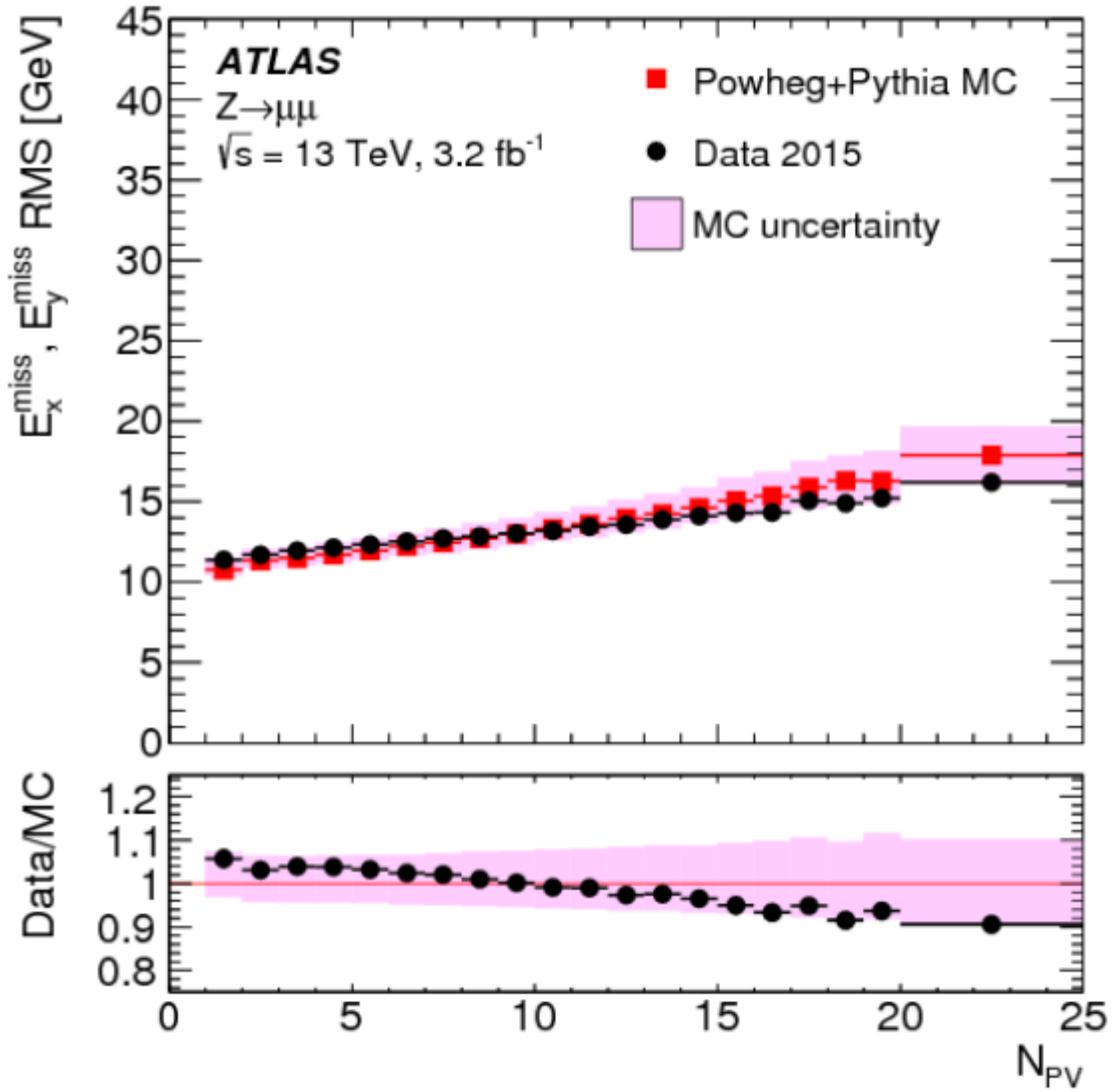
Missing momentum is a tricky variable to understand. If part of the detector is not working, we will observe spurious missing momentum.

It is thus necessary to carefully qualify each element of the hadron calorimeter, correcting for dead or hyperactive regions.



ATLAS missing ET performance at 13 TeV (2015 data)





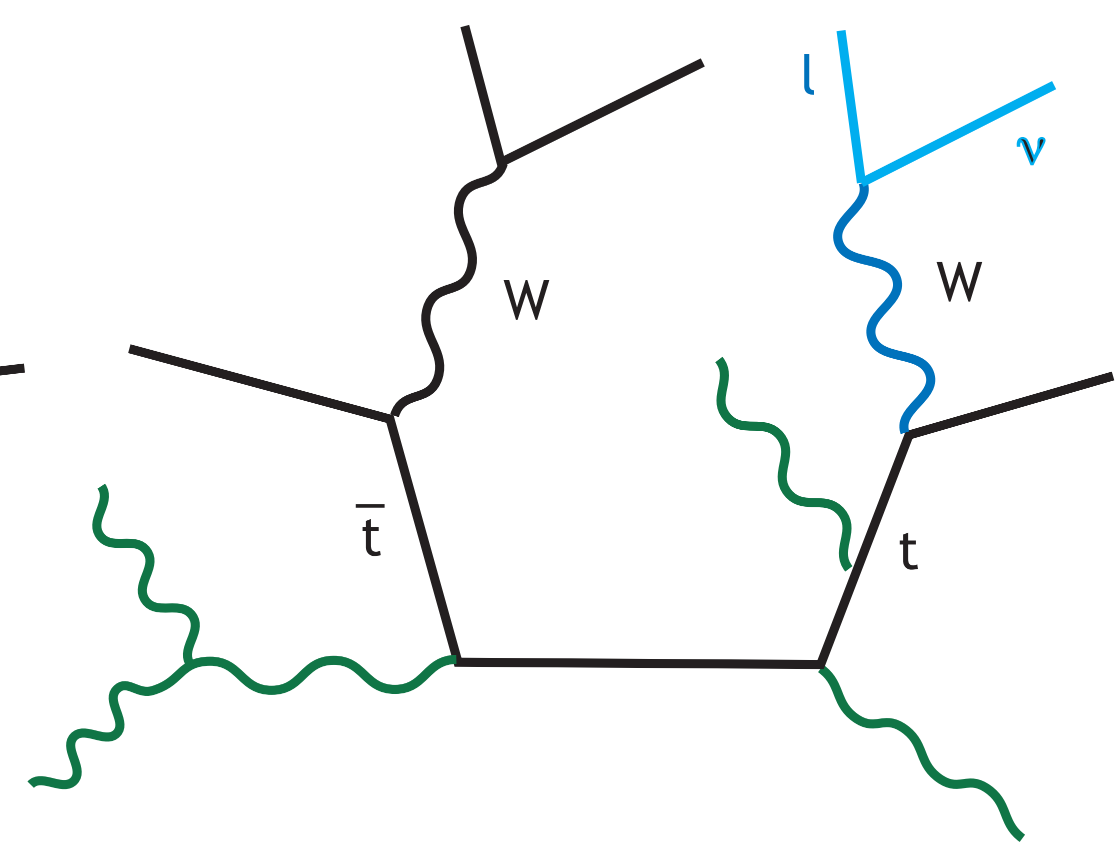
After solving all of these problems, we come to the dominant sources of background in actual analyses that search for new particles.

These are Standard Model reactions that produce the known heavy particles -$W, Z, t\bar{t}$ - plus extra jets from QCD radiation.

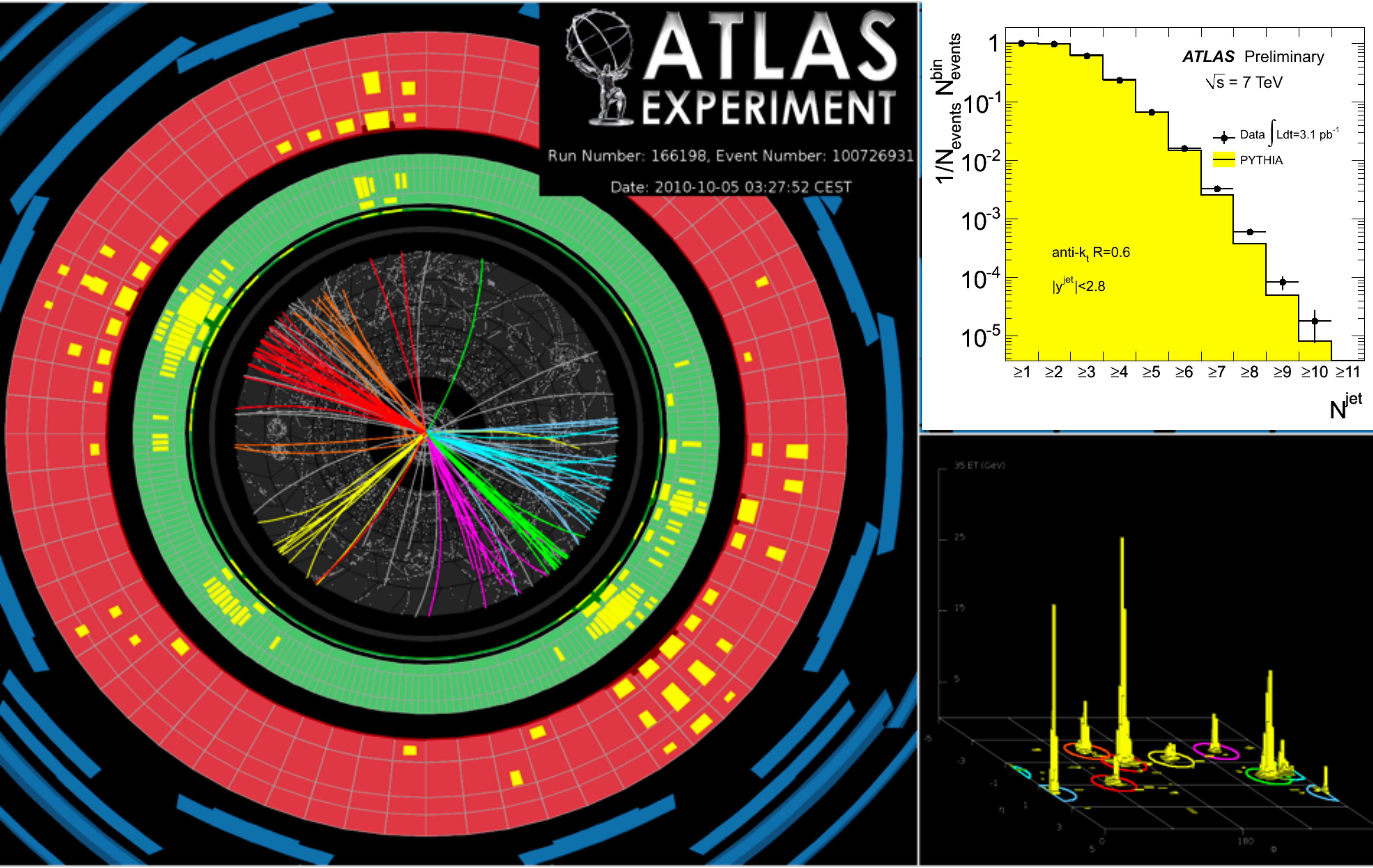
These reactions already offer missing energy, leptons, and and multiple jets. The cross sections are still large compared to our signals:

$$\begin{array}{rl} W(\to \ell\nu) & 10 \text{ nb} \\ Z(\to \ell^+\ell^-) & 1 \text{ nb} \\ t\bar{t}(\to \ell\nu jjj) & 0.3 \text{ nb} \\ \text{new particles} & 10^{-3} \text{ nb} \end{array}$$

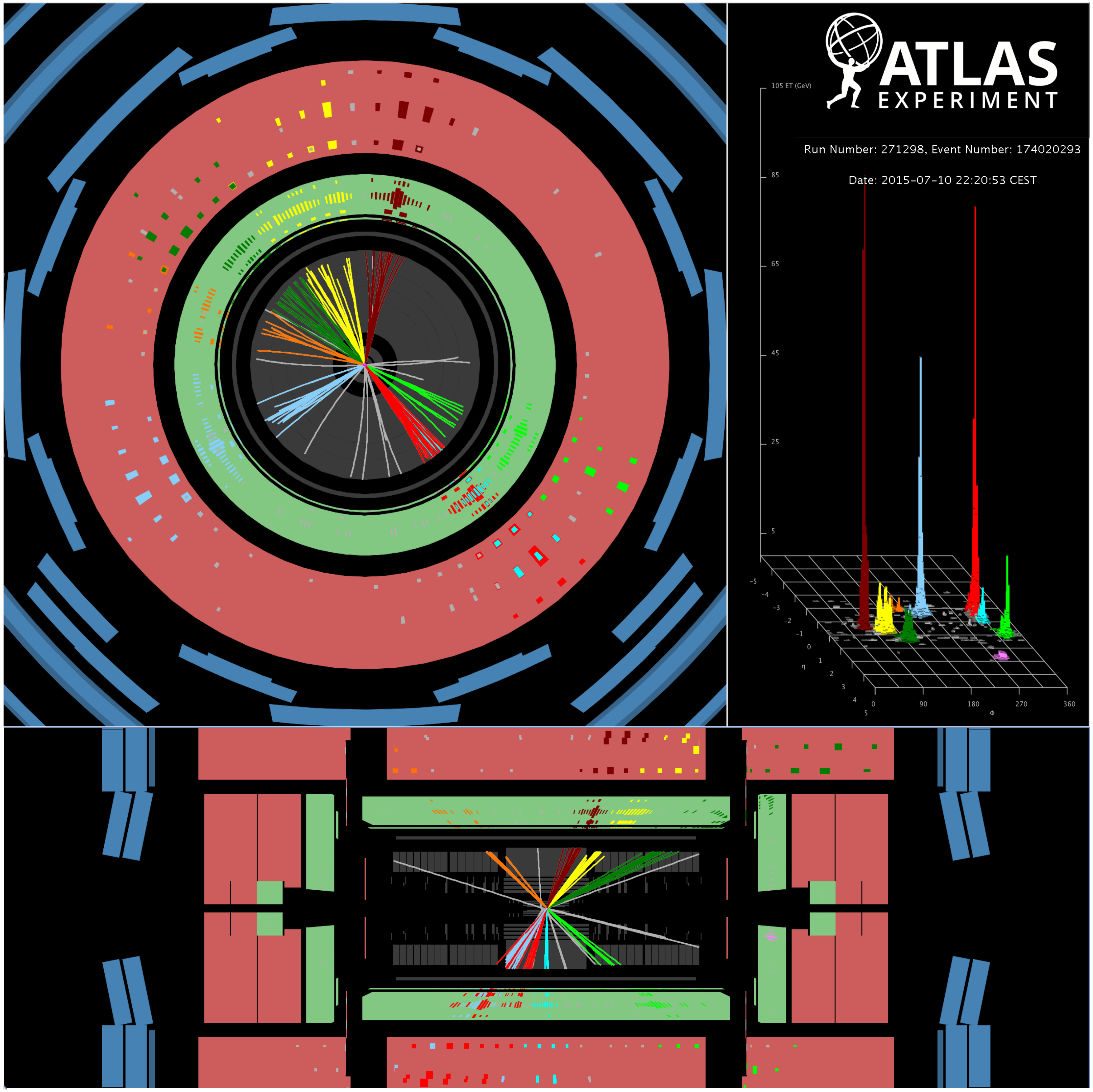
This is genuinely scary. Processes such as



have cross sections comparable to the SUSY signal and might compete with it.

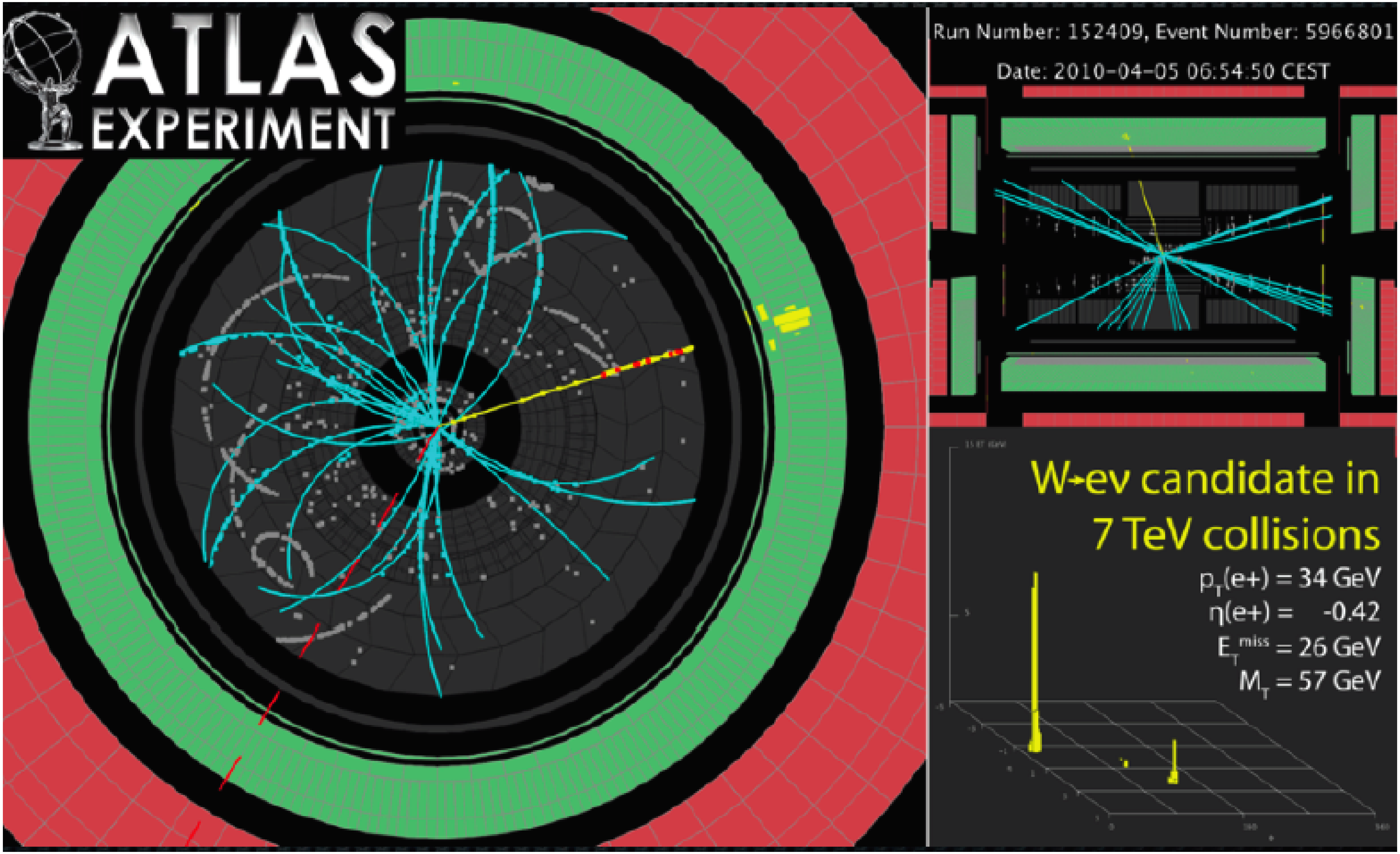

ATLAS
EXPERIMENT
Run Number: 166198, Event Number: 100726931
Date: 2010-10-05 03:27:52 CEST
ATLAS Preliminary
√s = 7 TeV
Data ∫Ldt=3.1 pb⁻¹
PYTHIA
anti-k_t R=0.6
|y^jet|<2.8
1/N_events N^bin_events
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
≥1 ≥2 ≥3 ≥4 ≥5 ≥6 ≥7 ≥8 ≥9 ≥10 ≥11
N^jet

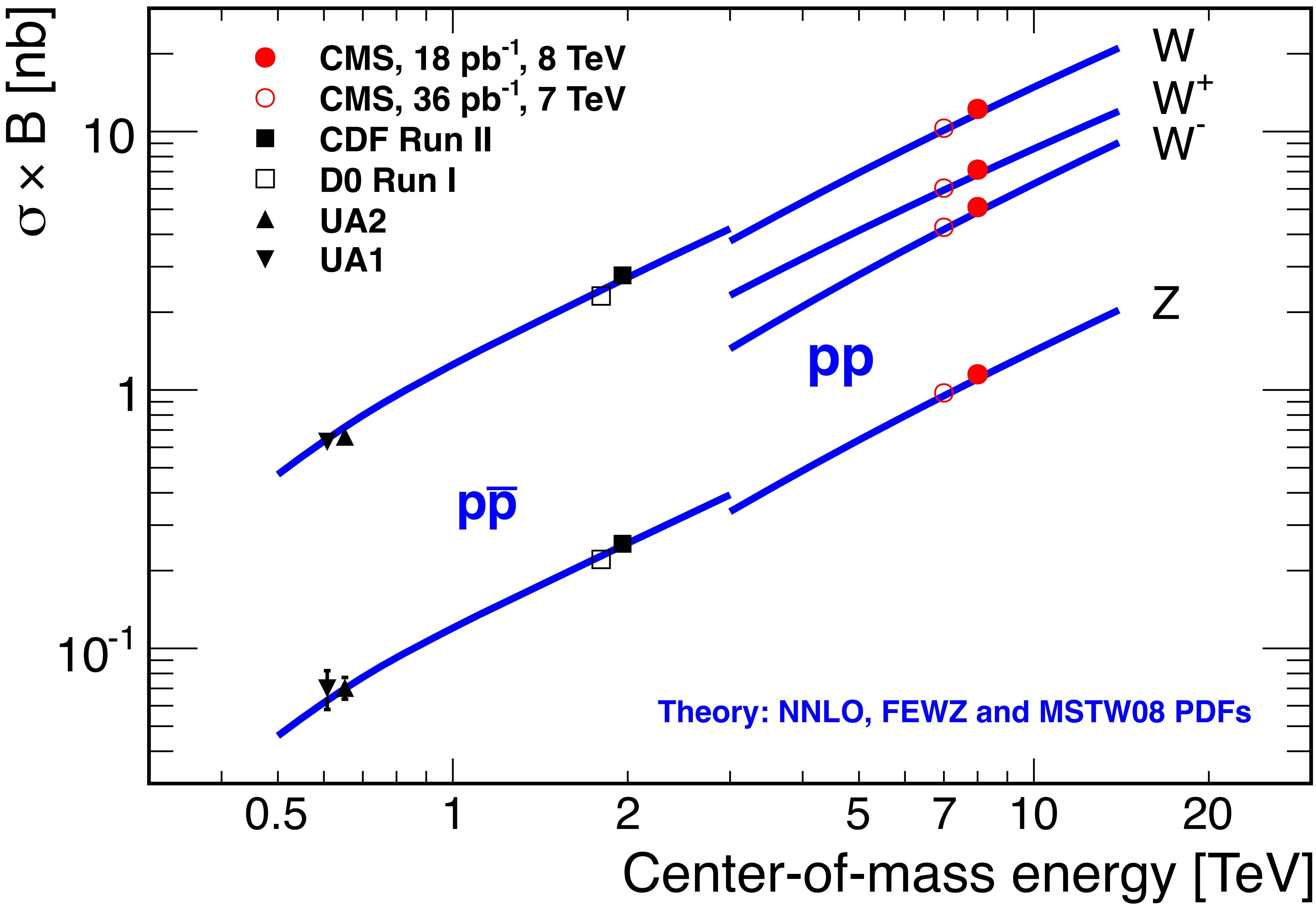
8-jet event

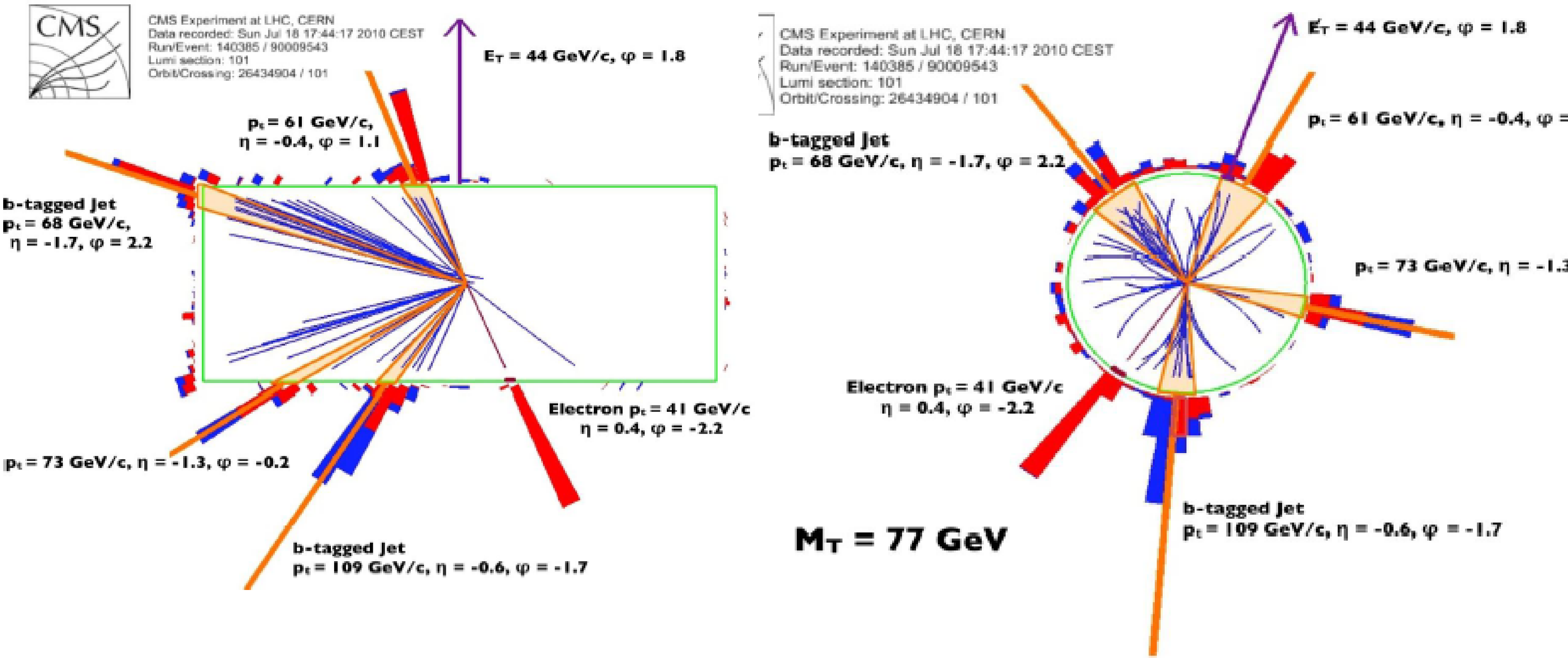


ATLAS 13 TeV   9 jet event

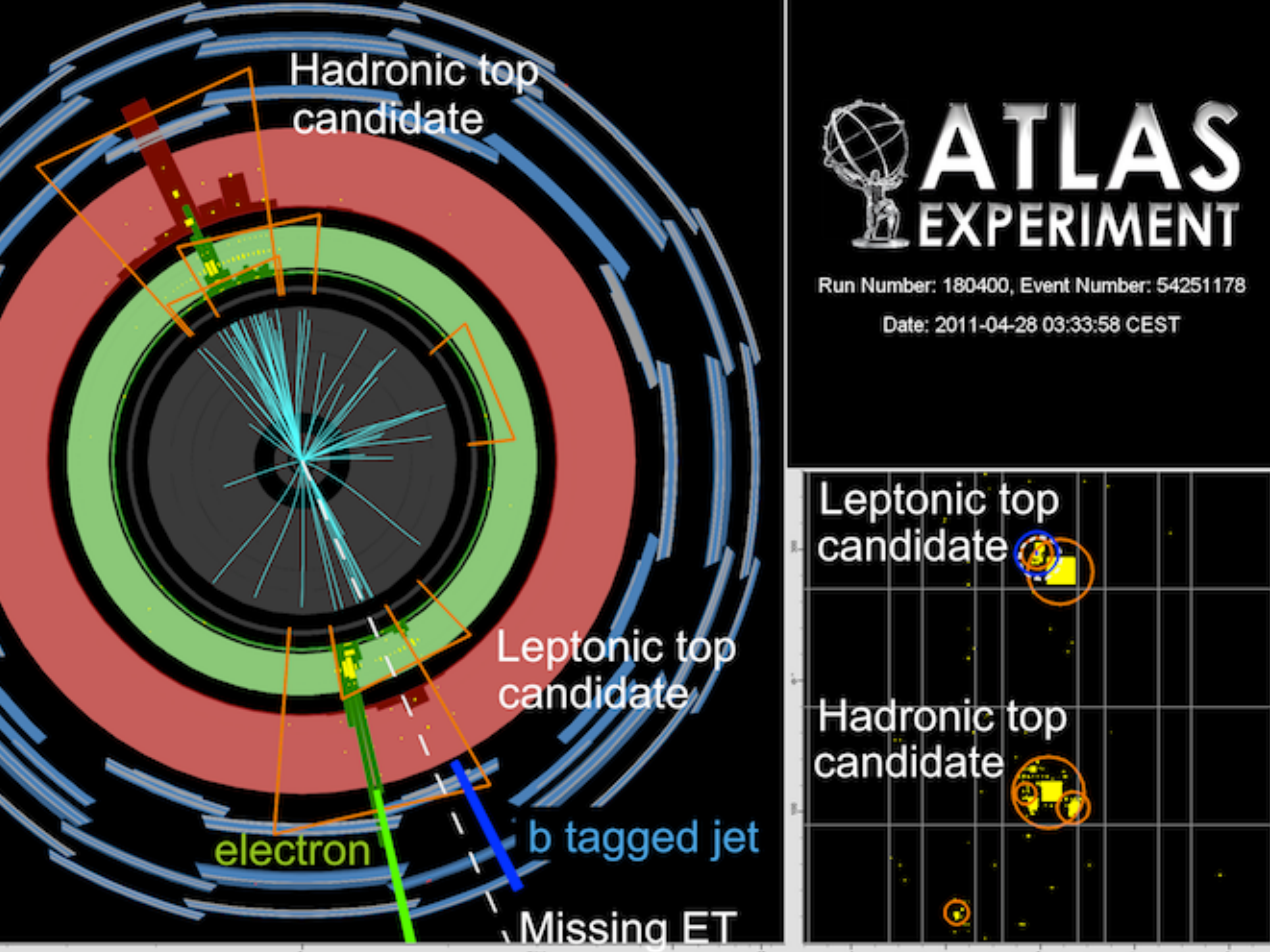
At least, we can discover heavy particles of the Standard Model that are known to be there.


ATLAS EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in 7 TeV collisions
$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

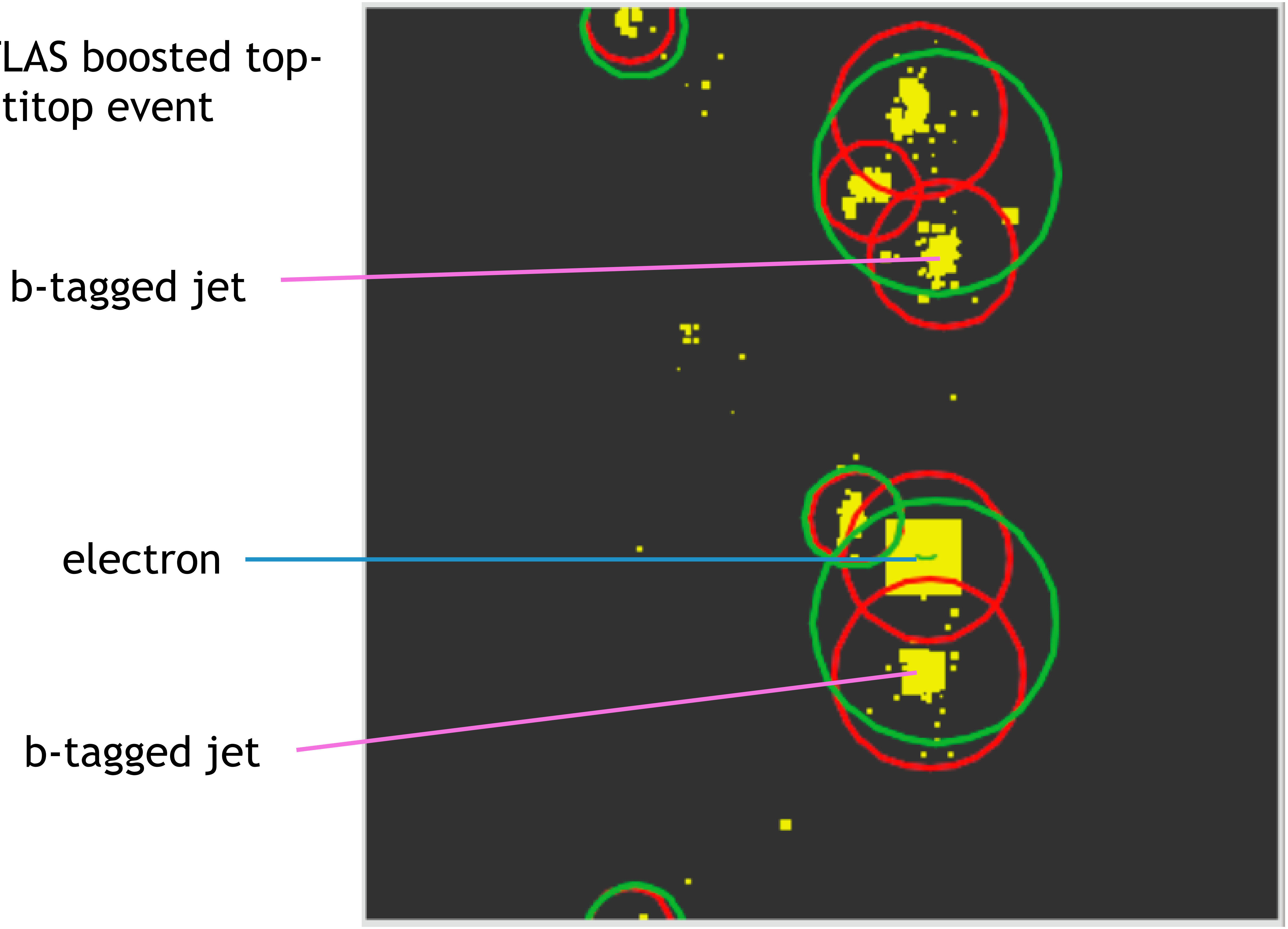

CMS, 18 pb^{-1}, 8 TeV
CMS, 36 pb^{-1}, 7 TeV
CDF Run II
D0 Run I
UA2
UA1
W
W$^+$
W$^-$
Z
pp
p$\bar{\text{p}}$
Theory: NNLO, FEWZ and MSTW08 PDFs
$\sigma \times B$ [nb]
Center-of-mass energy [TeV]
10
1
10^{-1}
0.5
1
2
5
7
10
20

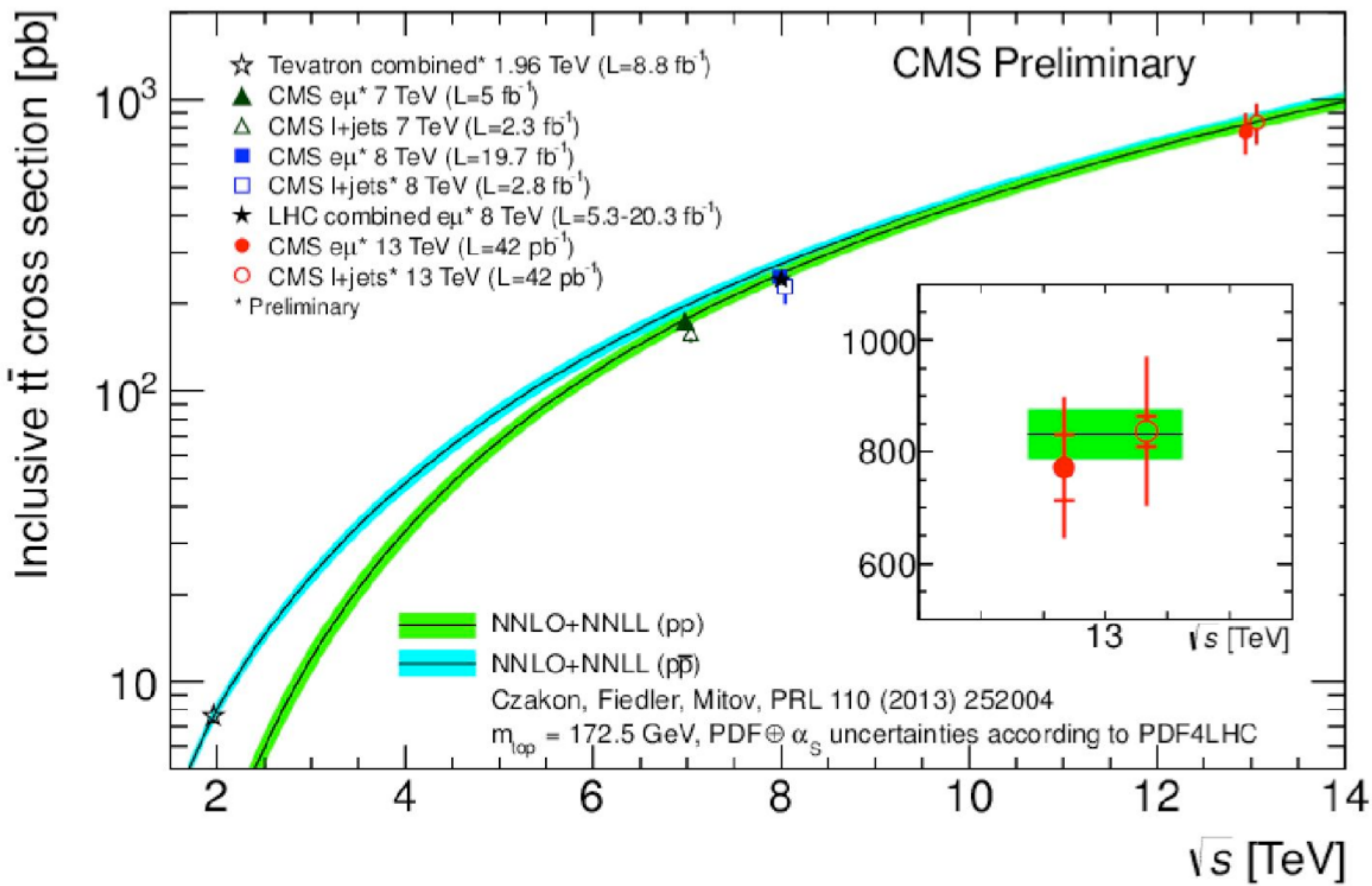


CMS t tbar candidate in e + MET + 4 jets

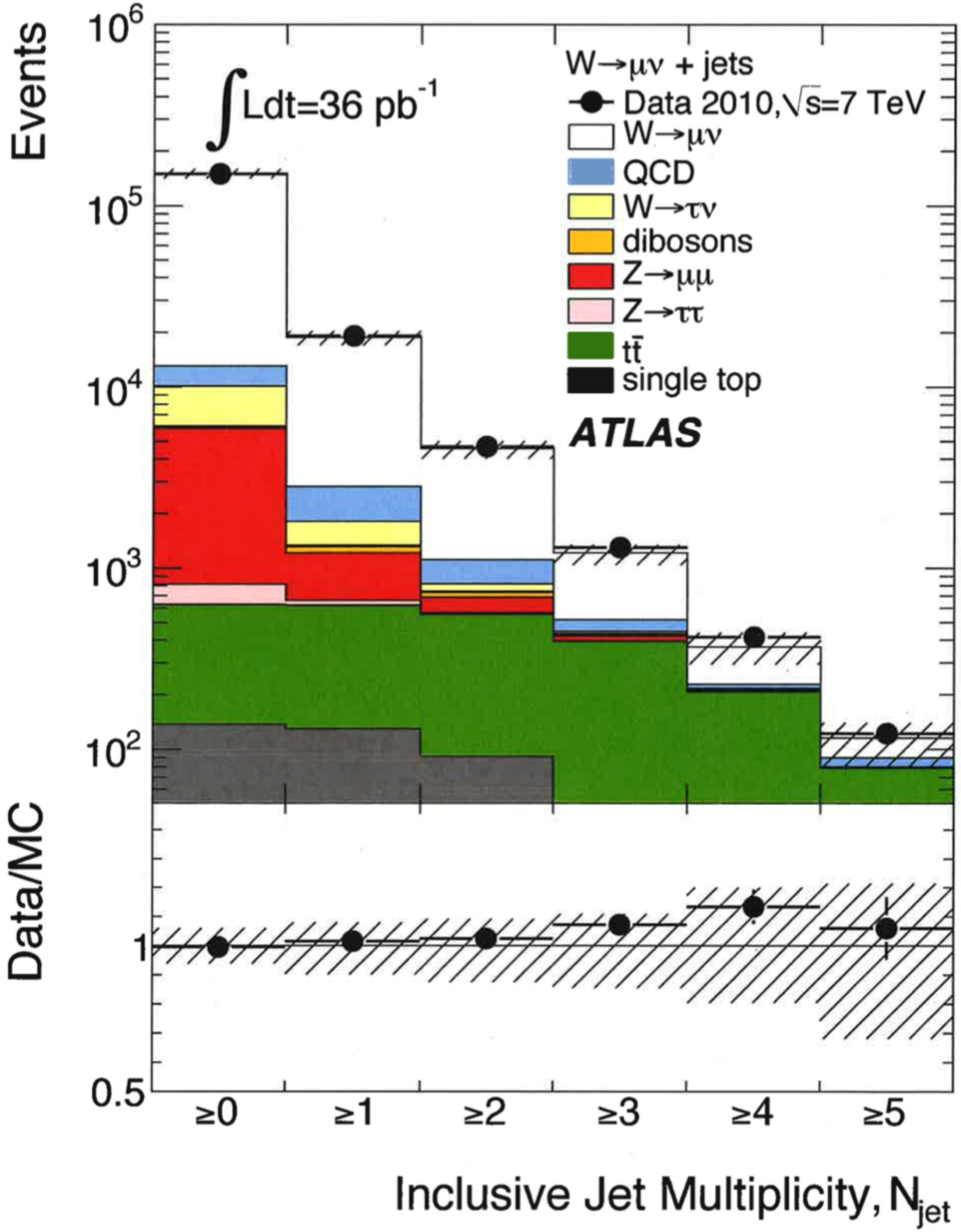

Hadronic top candidate
ATLAS EXPERIMENT
Run Number: 180400, Event Number: 54251178
Date: 2011-04-28 03:33:58 CEST
Leptonic top candidate
Hadronic top candidate
Leptonic top candidate
b tagged jet
electron
Missing ET

ATLAS boosted top-antitop event

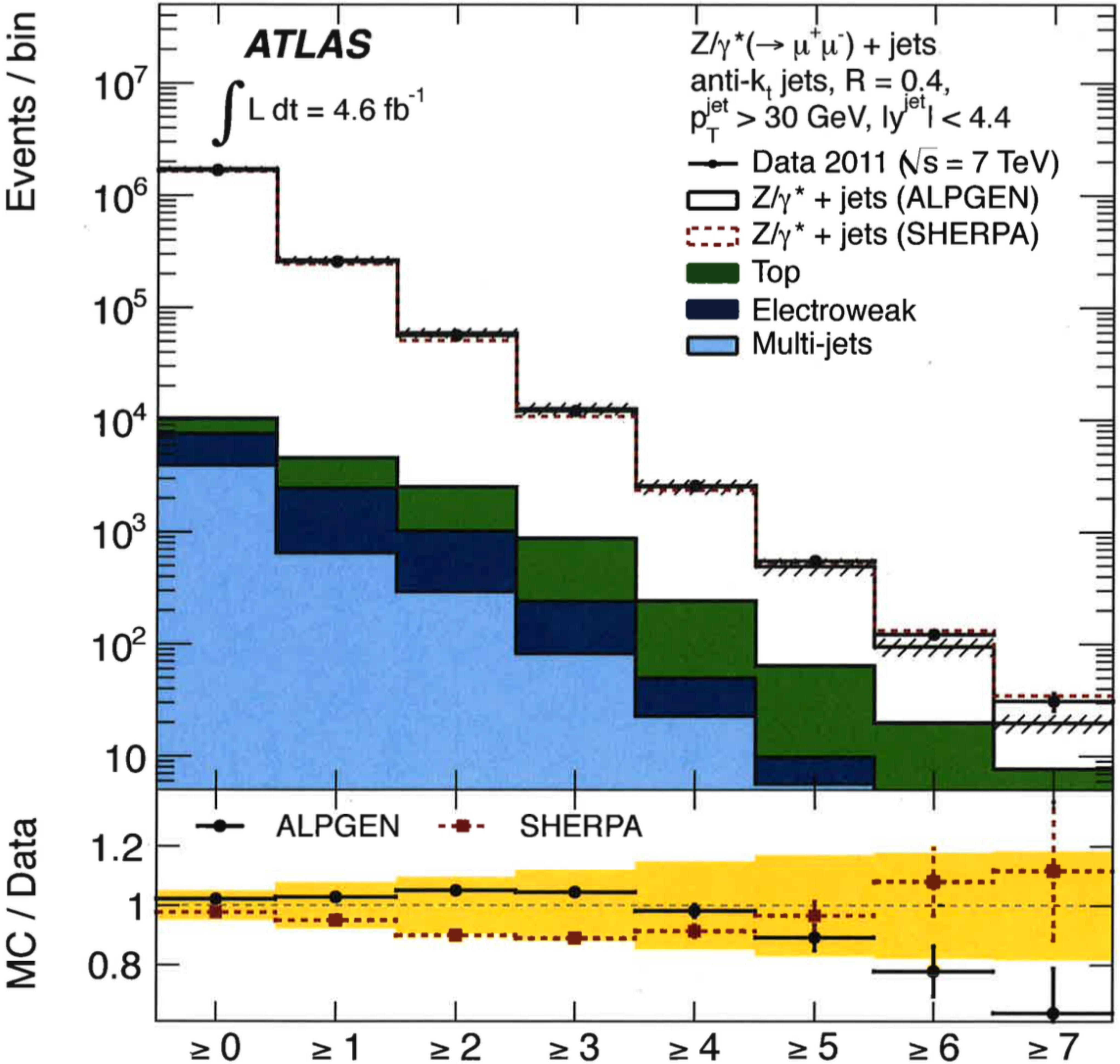




Inclusive $t\bar{t}$ cross section [pb]
CMS Preliminary
Tevatron combined* 1.96 TeV (L=8.8 fb^{-1})
CMS eμ* 7 TeV (L=5 fb^{-1})
CMS l+jets 7 TeV (L=2.3 fb^{-1})
CMS eμ* 8 TeV (L=19.7 fb^{-1})
CMS l+jets* 8 TeV (L=2.8 fb^{-1})
LHC combined eμ* 8 TeV (L=5.3-20.3 fb^{-1})
CMS eμ* 13 TeV (L=42 pb^{-1})
CMS l+jets* 13 TeV (L=42 pb^{-1})
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL ($p\bar{p}$)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_{top} = 172.5 GeV, PDF$\oplus\alpha_S$ uncertainties according to PDF4LHC
$\sqrt{s}$ [TeV]



Events
$\int Ldt=36\ pb^{-1}$
W→μν + jets
Data 2010, √s=7 TeV
W→μν
QCD
W→τν
dibosons
Z→μμ
Z→ττ
$t\bar{t}$
single top
ATLAS
Data/MC
≥0
≥1
≥2
≥3
≥4
≥5
Inclusive Jet Multiplicity, N_{jet}



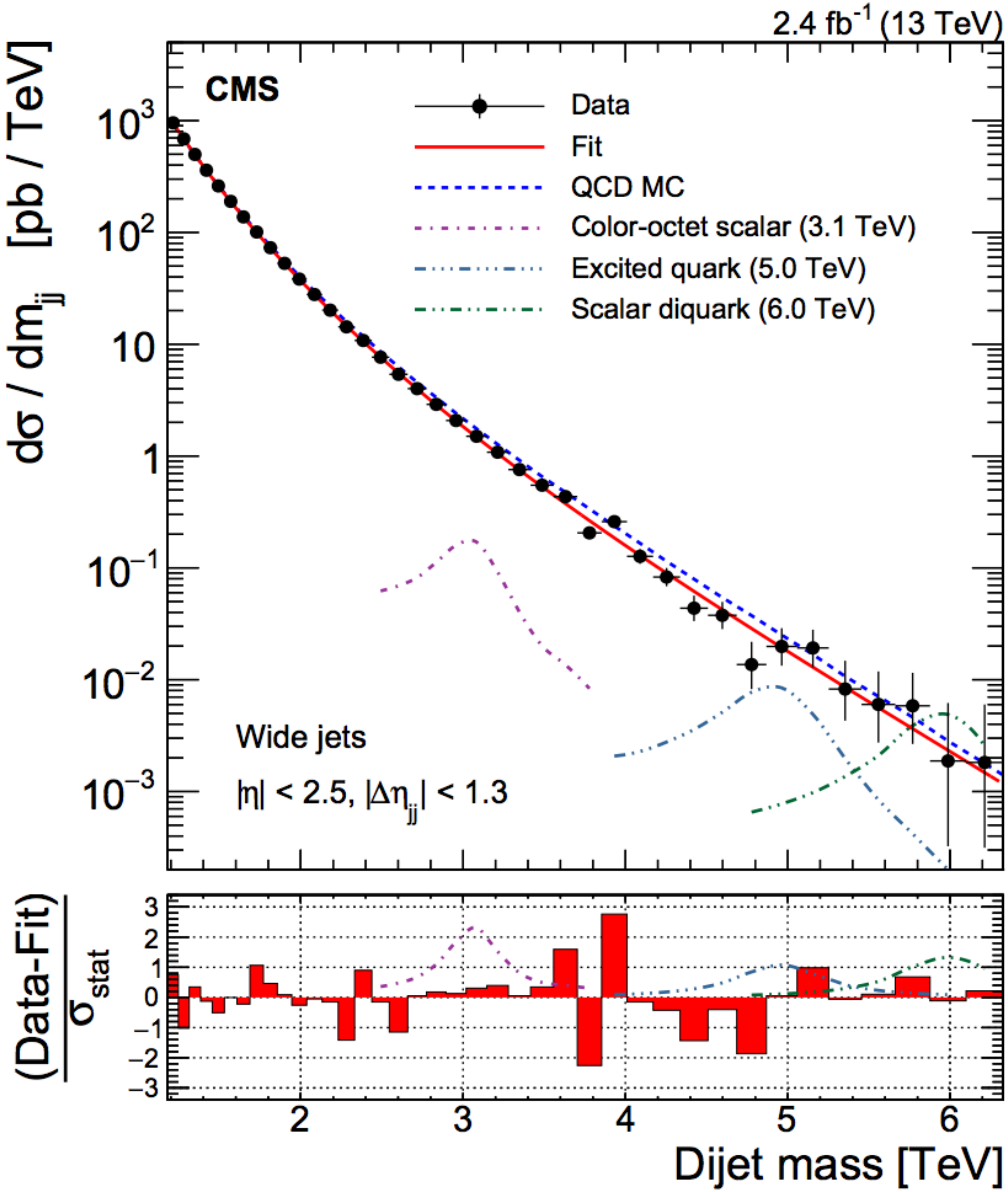
ATLAS
$\int L\,dt = 4.6\ \text{fb}^{-1}$
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$ + jets
anti-k_t jets, R = 0.4,
$p_T^{jet} > 30$ GeV, $|y^{jet}| < 4.4$
Data 2011 ($\sqrt{s}$ = 7 TeV)
Z/γ^* + jets (ALPGEN)
Z/γ^* + jets (SHERPA)
Top
Electroweak
Multi-jets
Events / bin
ALPGEN
SHERPA
MC / Data
≥ 0
≥ 1
≥ 2
≥ 3
≥ 4
≥ 5
≥ 6
≥ 7

N_{jet}

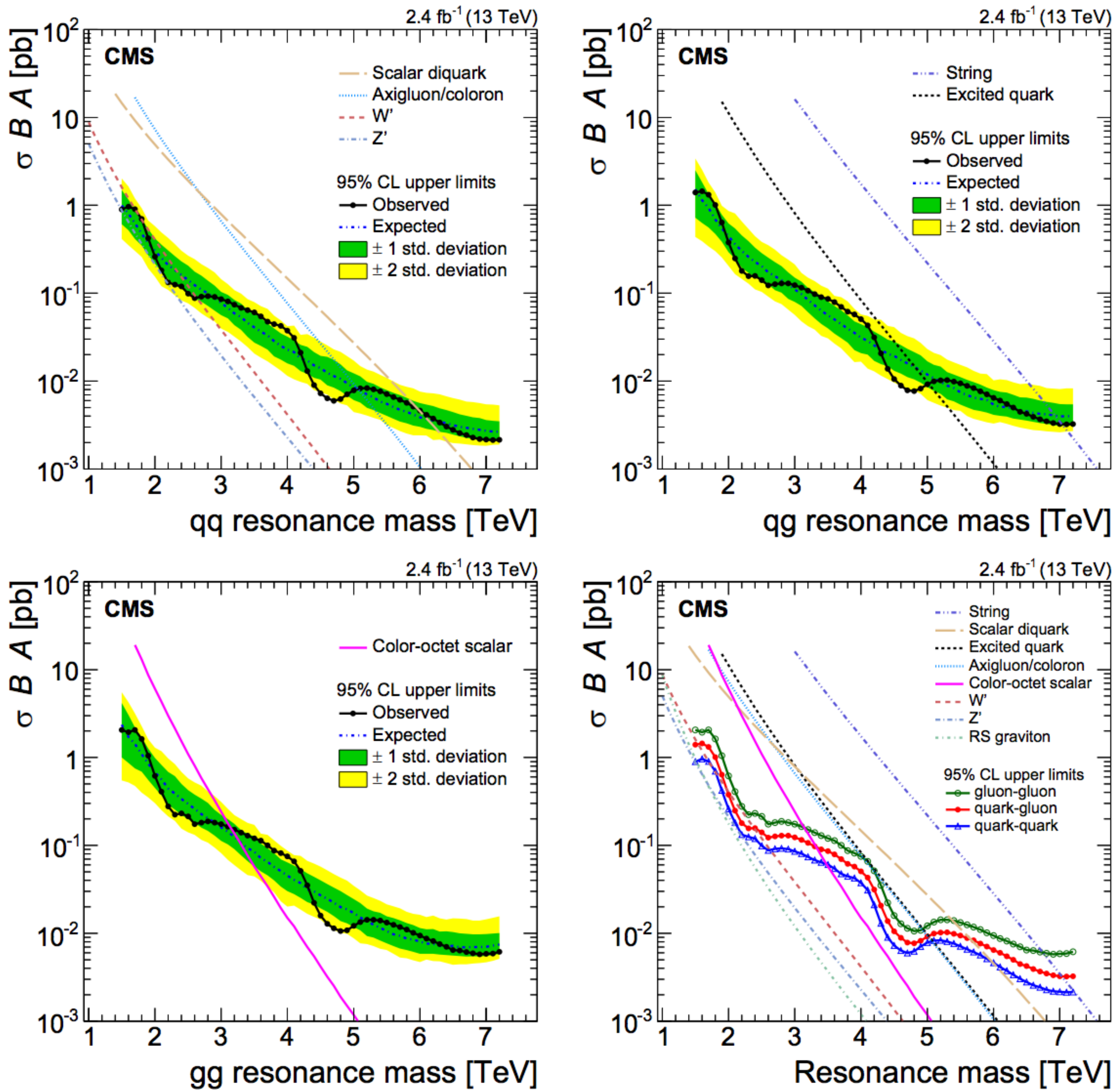
Now we can look into various particle searches, from easy to difficult.

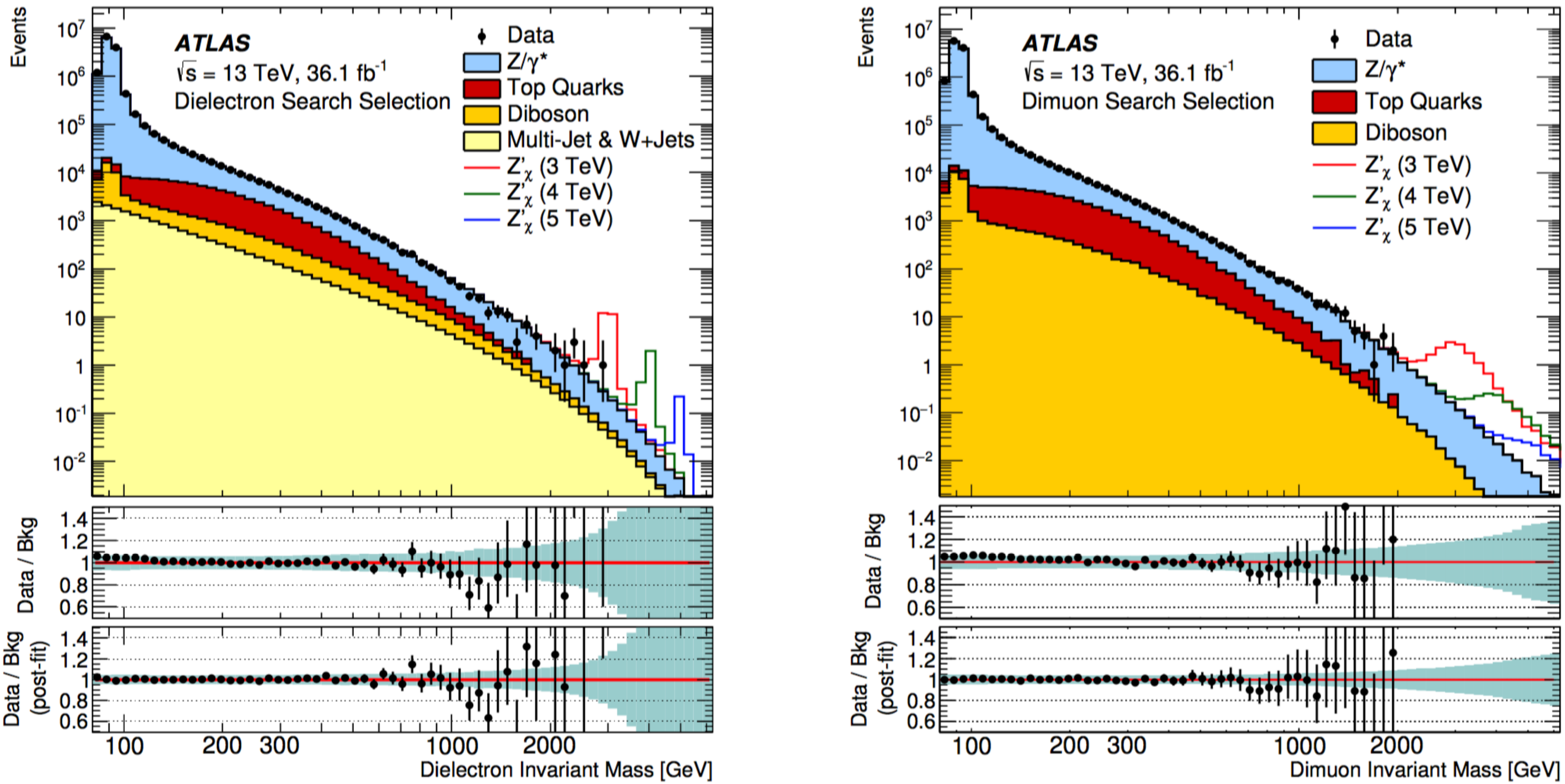
The easiest searches are resonance searches in 2-jet or 2-lepton events at the highest energy.   These events are easily triggered.

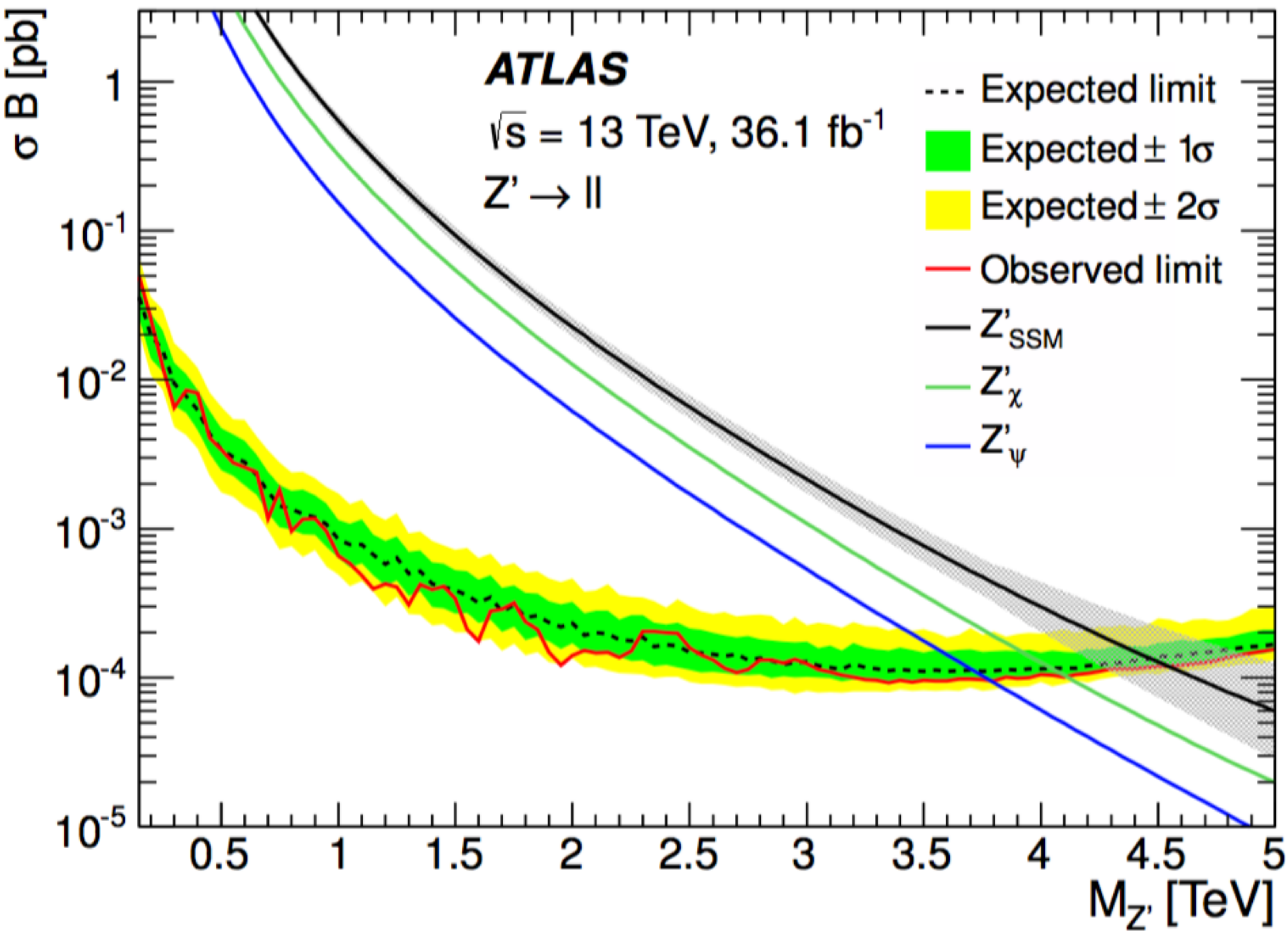
The main difficulty is in the measurement of ET for the jets and the energy/sign measurement for the leptons.



2.4 fb^{-1} (13 TeV)
CMS
Data
Fit
QCD MC
Color-octet scalar (3.1 TeV)
Excited quark (5.0 TeV)
Scalar diquark (6.0 TeV)
Wide jets
$|\eta| < 2.5$, $|\Delta\eta_{jj}| < 1.3$
$d\sigma / dm_{jj}$ [pb / TeV]
$\frac{(Data-Fit)}{\sigma_{stat}}$
Dijet mass [TeV]


2.4 fb⁻¹ (13 TeV)
CMS
σ B A [pb]
Scalar diquark
Axigluon/coloron
W'
Z'
95% CL upper limits
Observed
Expected
± 1 std. deviation
± 2 std. deviation
qq resonance mass [TeV]
2.4 fb⁻¹ (13 TeV)
CMS
σ B A [pb]
String
Excited quark
95% CL upper limits
Observed
Expected
± 1 std. deviation
± 2 std. deviation
qg resonance mass [TeV]
2.4 fb⁻¹ (13 TeV)
CMS
σ B A [pb]
Color-octet scalar
95% CL upper limits
Observed
Expected
± 1 std. deviation
± 2 std. deviation
gg resonance mass [TeV]
2.4 fb⁻¹ (13 TeV)
CMS
σ B A [pb]
String
Scalar diquark
Excited quark
Axigluon/coloron
Color-octet scalar
W'
Z'
RS graviton
95% CL upper limits
gluon-gluon
quark-gluon
quark-quark
Resonance mass [TeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
Dielectron Search Selection
Data
Z/γ*
Top Quarks
Diboson
Multi-Jet & W+Jets
Z'χ (3 TeV)
Z'χ (4 TeV)
Z'χ (5 TeV)
Events
Data / Bkg
Data / Bkg (post-fit)
Dielectron Invariant Mass [GeV]
ATLAS
√s = 13 TeV, 36.1 fb-1
Dimuon Search Selection
Data
Z/γ*
Top Quarks
Diboson
Z'χ (3 TeV)
Z'χ (4 TeV)
Z'χ (5 TeV)
Events
Data / Bkg
Data / Bkg (post-fit)
Dimuon Invariant Mass [GeV]


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Z' → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'_{SSM}
Z'_{χ}
Z'_{ψ}
σ B [pb]
$M_{Z'}$ [TeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

It is possible to do a parallel search for single production of a W' boson, i.e., $q\bar{q} \to \ell\nu$

Here it is not possible to reconstruct a resonance, since the neutrino is not observed. The pT of the neutrino can be measured as the missing ET of the rest of the event. However, the longitudinal momentum of the ν is lost.

However, there is a tool to make the distribution sharper. Write the lepton momenta in terms of rapidity as

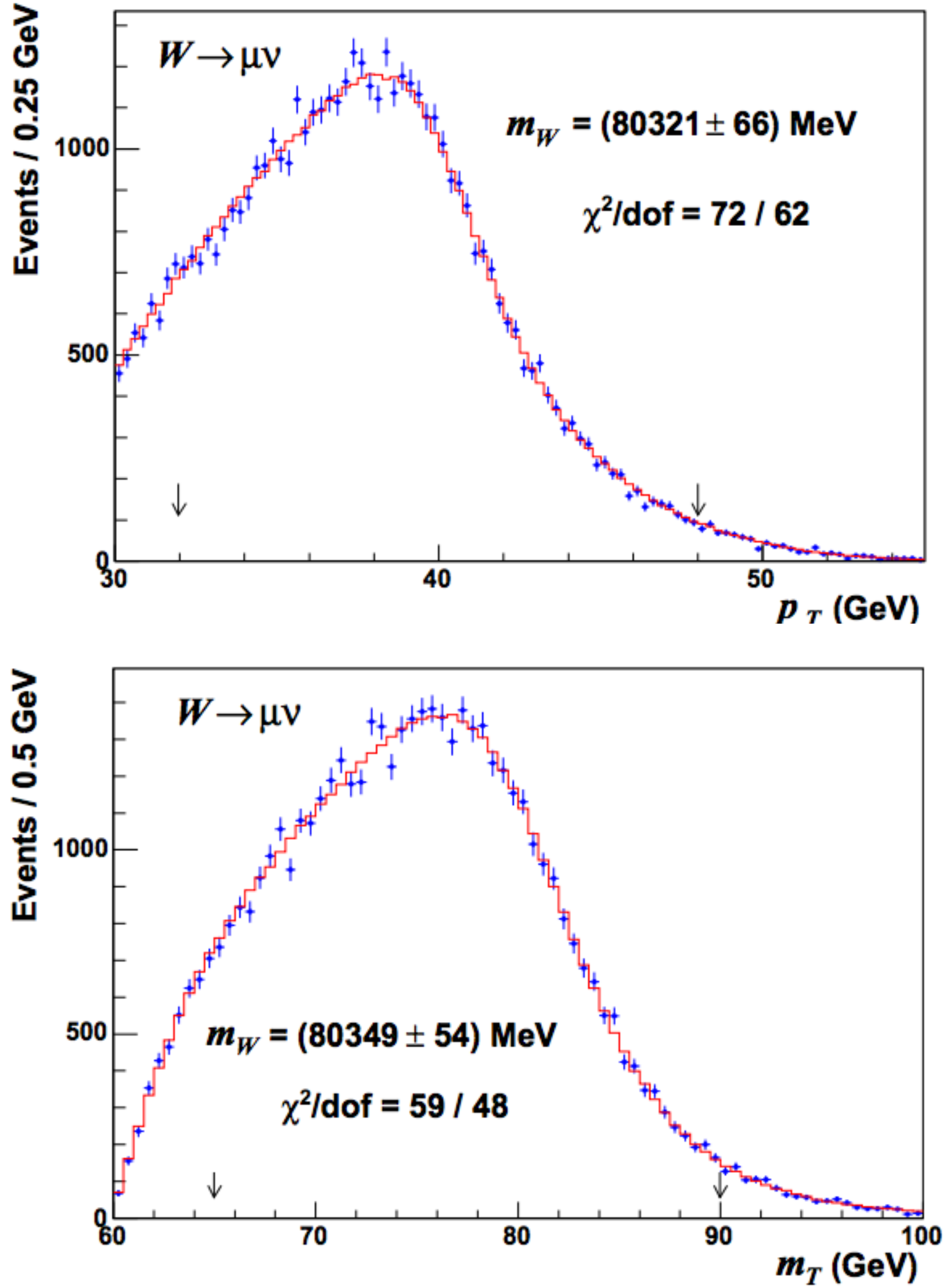
$$p_\ell = (p_{T\ell} \cosh \eta_\ell, p_{T\ell} \hat{n}_\ell, p_{T\ell} \sinh \eta_\ell)$$
$$p_\nu = (p_{T\nu} \cosh \eta_\nu, p_{T\nu} \hat{n}_\nu, p_{T\nu} \sinh \eta_\nu)$$

The mass of the parent is then

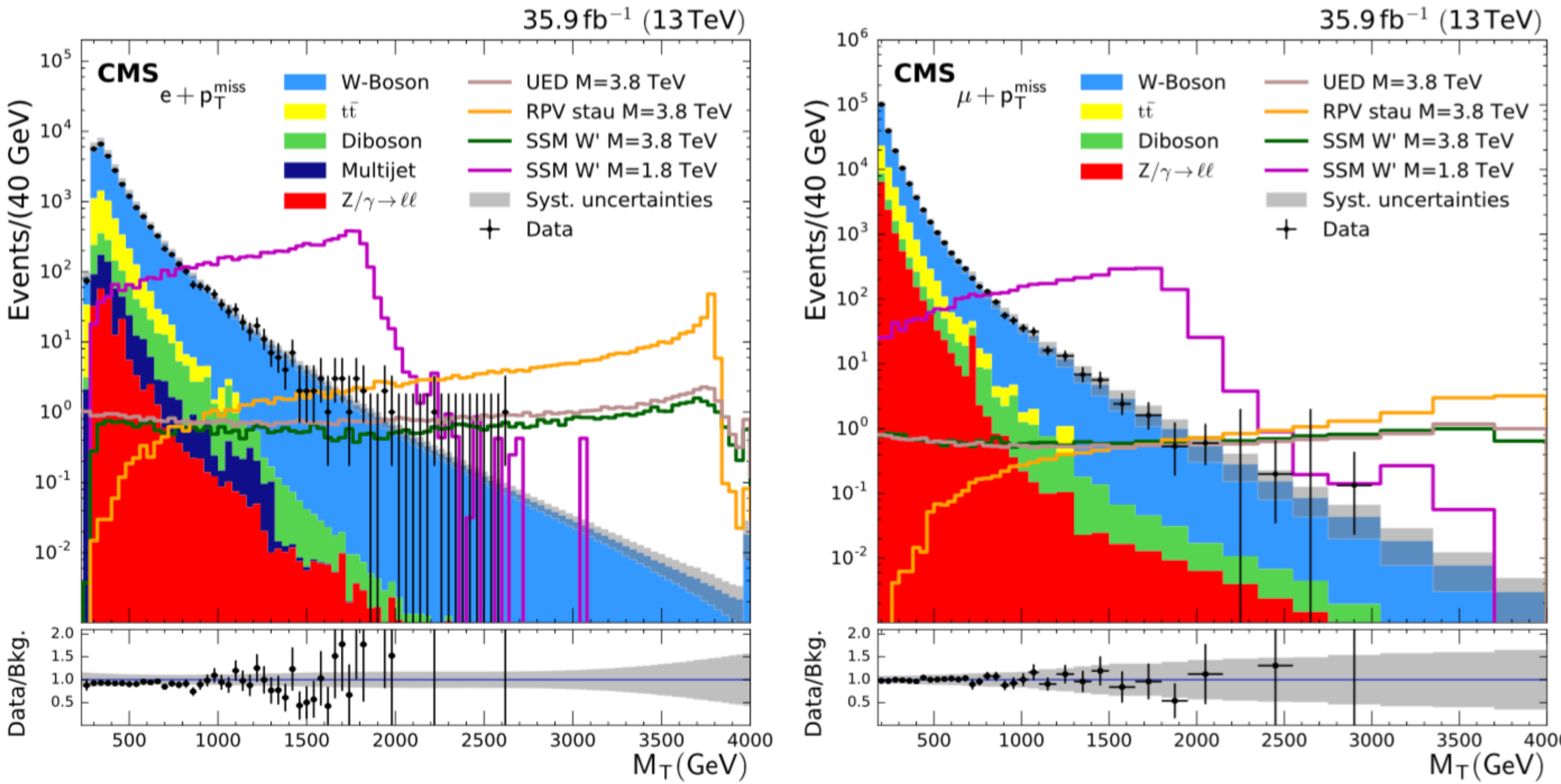
$$\begin{aligned} m_{W'}^2 &= 2 p_\ell \cdot p_\nu \\ &= 2 p_\ell p_\nu (\cosh(\eta_\ell - \eta_\nu) - \hat{n}_\ell \hat{n}_\nu) \\ &\geq 2 p_\ell p_\nu (1 - \hat{n}_\ell \hat{n}_\nu) \end{aligned}$$

It makes sense to define the transverse mass of the W' as

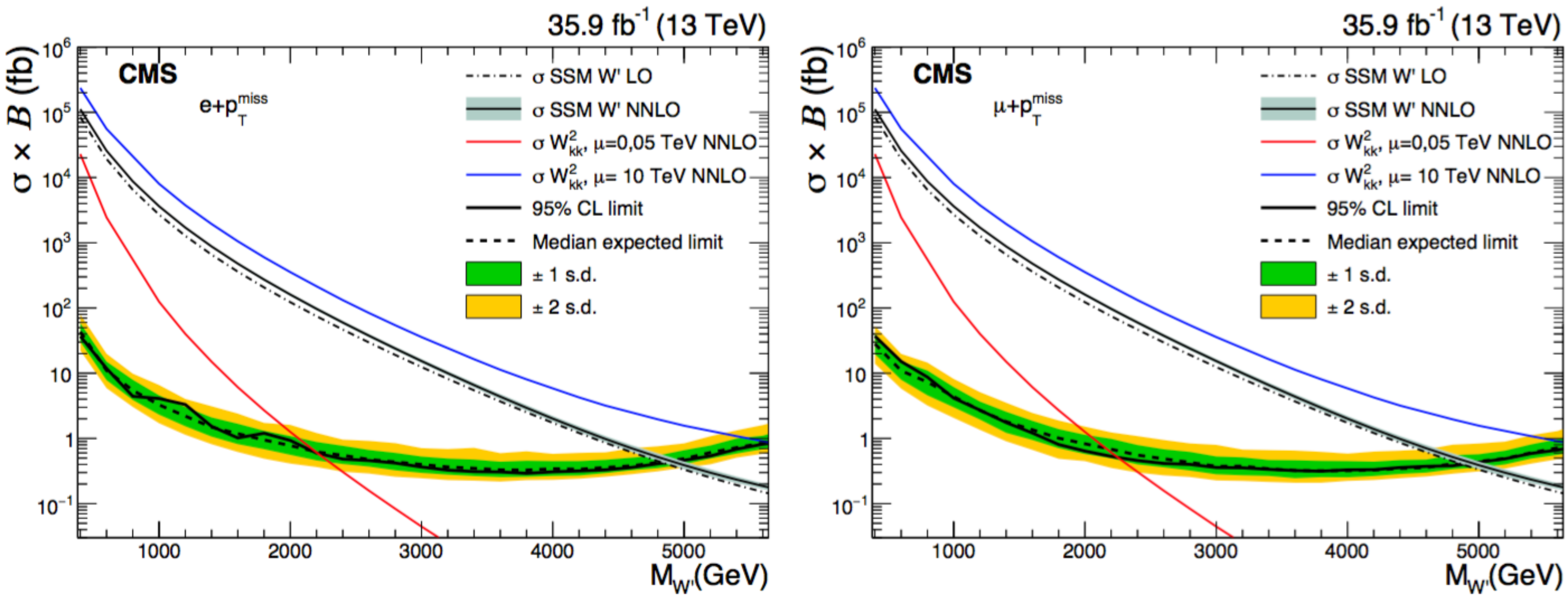
$$m_T^2 = 2 p_\ell p_\nu (1 - \hat{n}_\ell \hat{n}_\nu)$$



CDF
W mass
measurement
2007



35.9 fb^{-1} (13 TeV)
CMS
$e + p_T^{miss}$
W-Boson
$t\bar{t}$
Diboson
Multijet
$Z/\gamma \rightarrow \ell\ell$
UED M=3.8 TeV
RPV stau M=3.8 TeV
SSM W' M=3.8 TeV
SSM W' M=1.8 TeV
Syst. uncertainties
Data
Events/(40 GeV)
Data/Bkg.
M_T (GeV)
35.9 fb^{-1} (13 TeV)
CMS
$\mu + p_T^{miss}$
W-Boson
$t\bar{t}$
Diboson
$Z/\gamma \rightarrow \ell\ell$
UED M=3.8 TeV
RPV stau M=3.8 TeV
SSM W' M=3.8 TeV
SSM W' M=1.8 TeV
Syst. uncertainties
Data
Events/(40 GeV)
Data/Bkg.
M_T (GeV)



35.9 fb^{-1} (13 TeV)
CMS
e+p_T^{miss}
σ SSM W' LO
σ SSM W' NNLO
σ W_{kk}^2, μ=0,05 TeV NNLO
σ W_{kk}^2, μ= 10 TeV NNLO
95% CL limit
Median expected limit
± 1 s.d.
± 2 s.d.
σ × B (fb)
$M_{W'}$(GeV)
35.9 fb^{-1} (13 TeV)
CMS
μ+p_T^{miss}
σ SSM W' LO
σ SSM W' NNLO
σ W_{kk}^2, μ=0,05 TeV NNLO
σ W_{kk}^2, μ= 10 TeV NNLO
95% CL limit
Median expected limit
± 1 s.d.
± 2 s.d.
σ × B (fb)
$M_{W'}$(GeV)

Now turn to SUSY searches.   In this discussion, I will assume R parity conservation, so that the lightest SUSY particle is absolutely stable.   This being so, it must be neutral; then it will be weakly interacting and exit the detector with no signal.

The generic signature of SUSY would be production of an energetic event including production of a high-momentum invisible particle.

How do we impose quantitative restrictions on candidate events ?

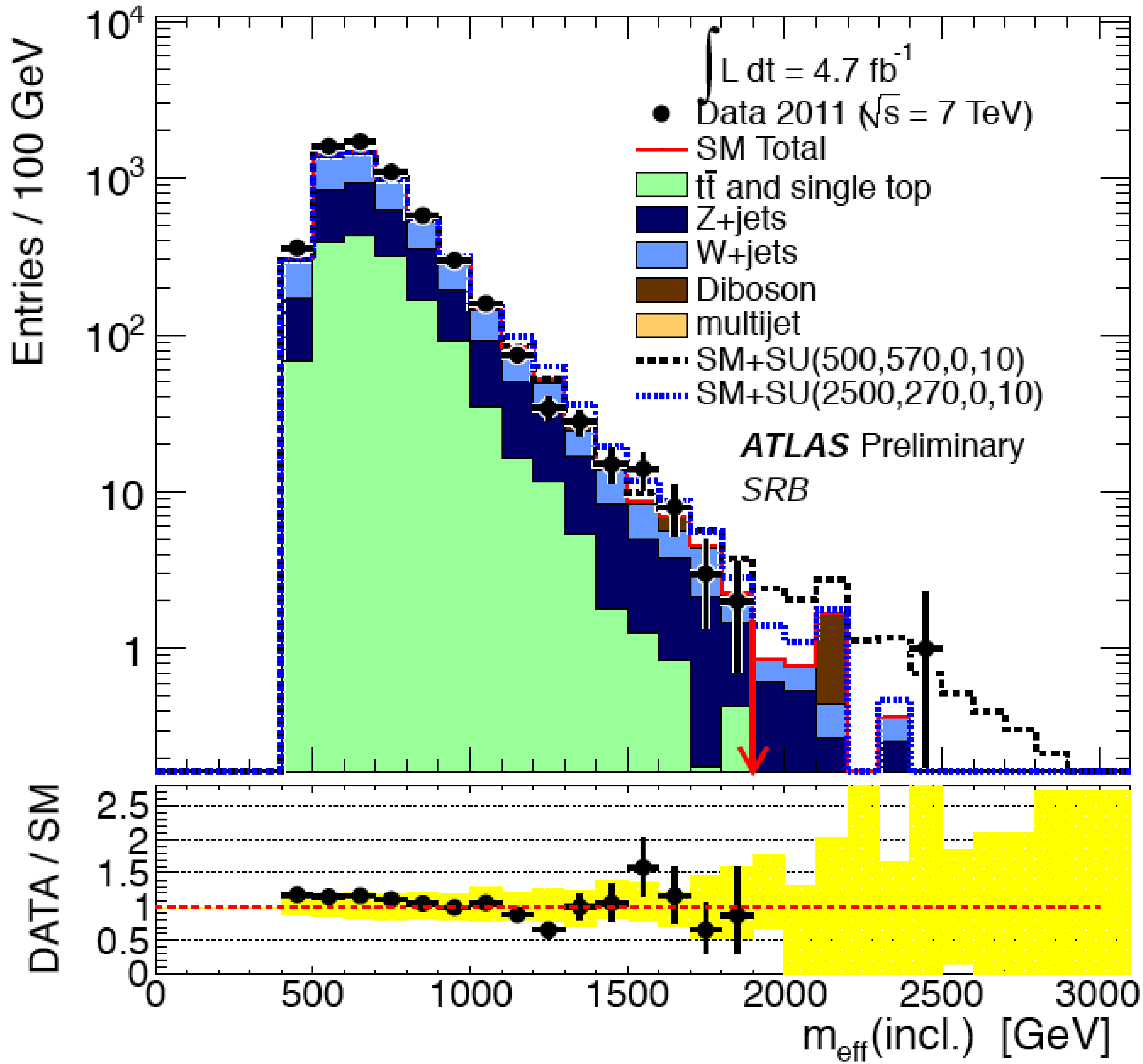
Longitudinal momentum imbalance cannot be measured. Work with transverse variables:

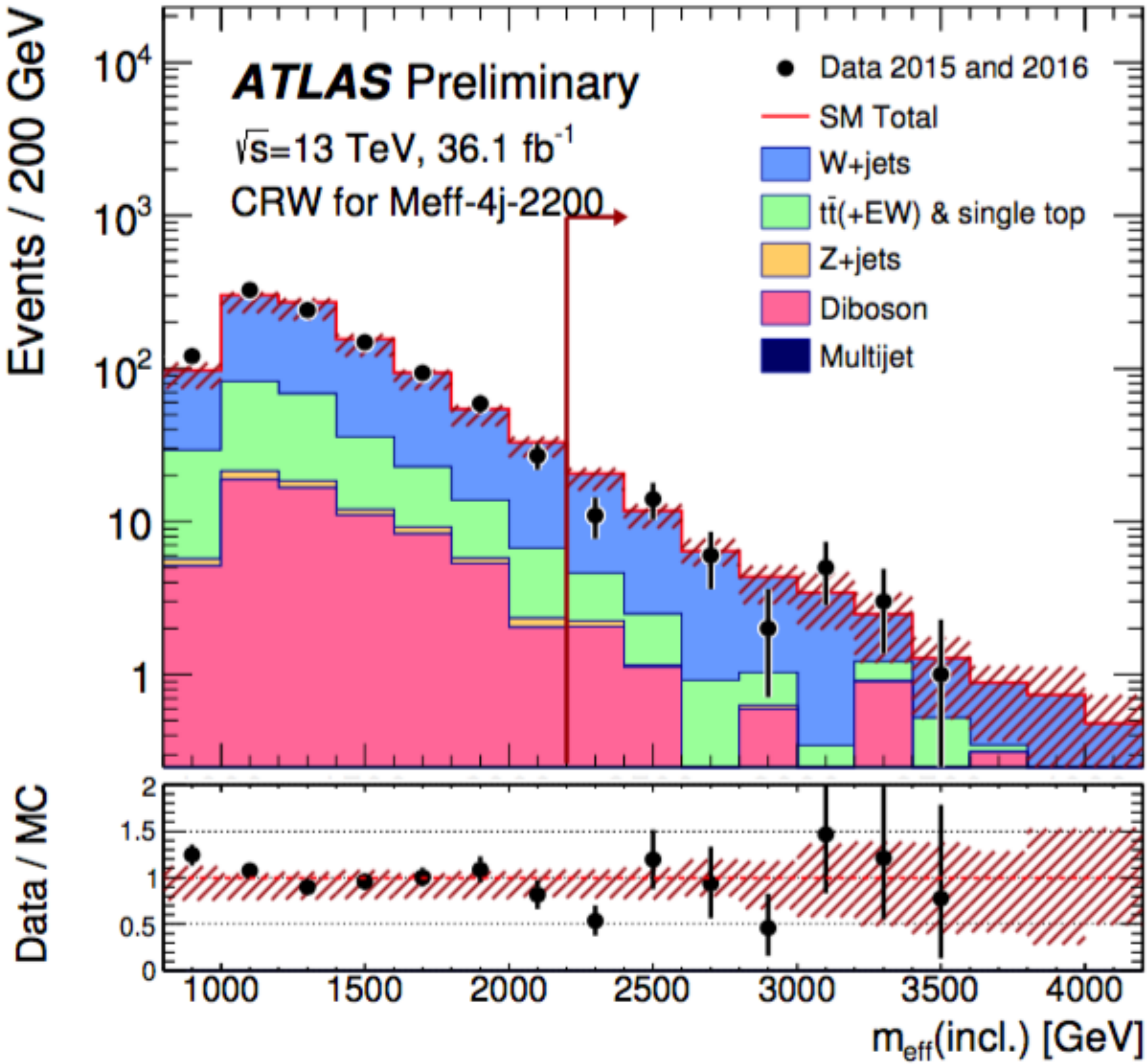
$$\not{E}_T = -\sum \vec{E}_{Ti} \qquad \text{(MET)}$$

$$H_T = \sum_i E_{Ti}$$

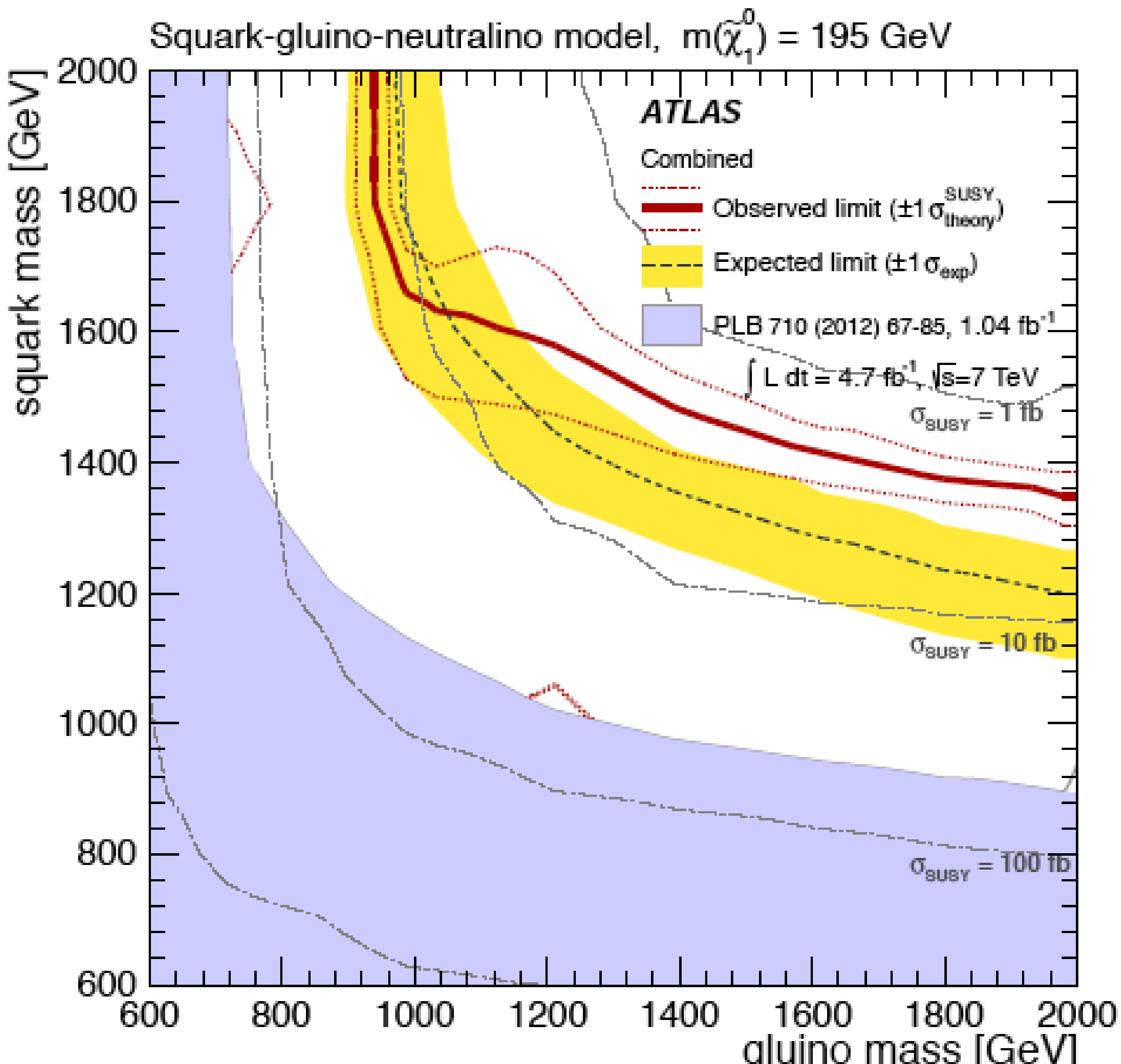
$$m_{eff} = \sum_{i=1}^{4} E_{Ti} + \not{E}_T$$

example: ATLAS 2011





ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
CRW for Meff-4j-2200
Data 2015 and 2016
SM Total
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Multijet
Events / 200 GeV
Data / MC
meff(incl.) [GeV]

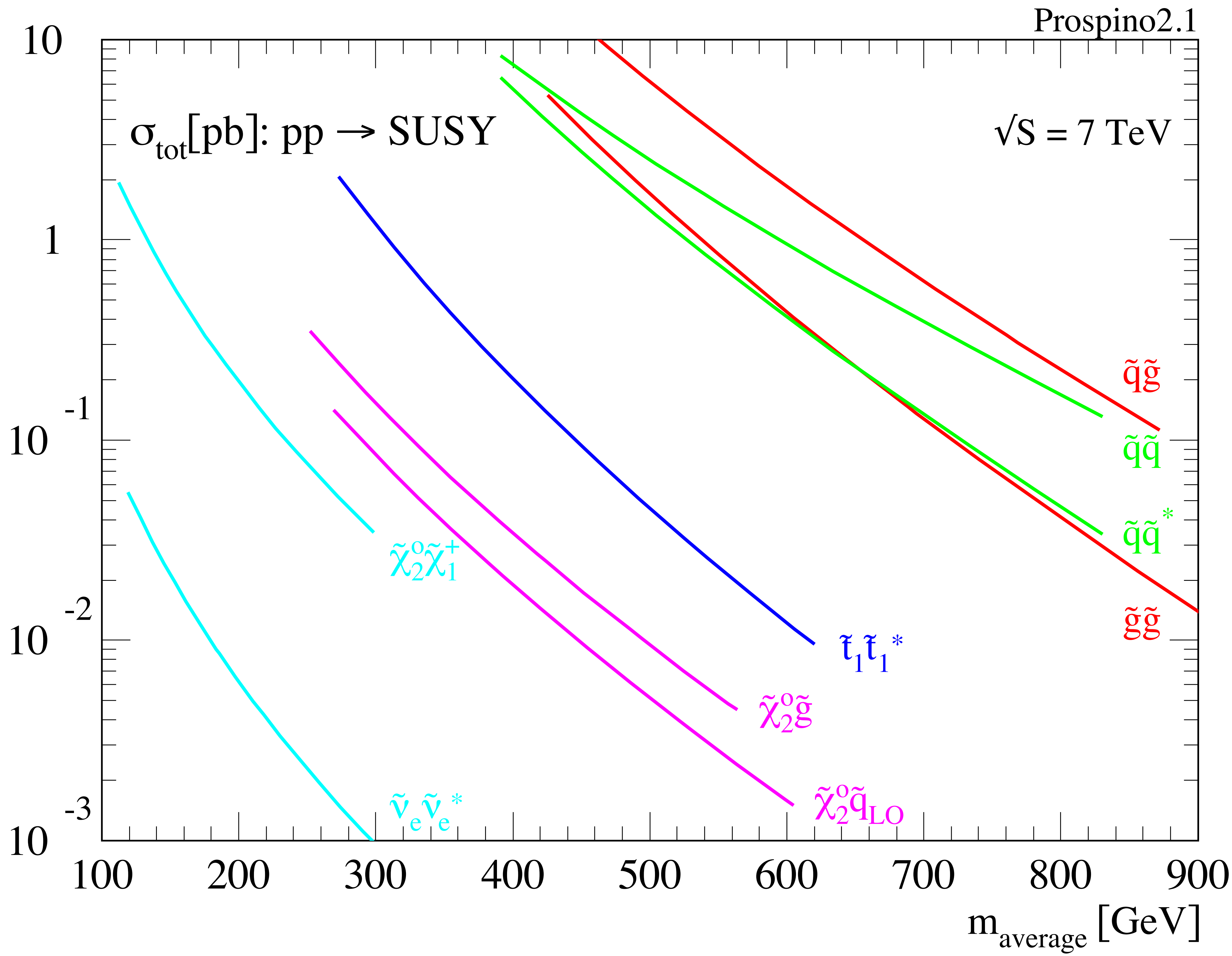


Squark-gluino-neutralino model, $m(\tilde{\chi}_1^0)$ = 195 GeV
ATLAS
Combined
Observed limit ($\pm 1 \sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1 \sigma_{exp}$)
PLB 710 (2012) 67-85, 1.04 fb^{-1}
$\int L\,dt = 4.7\ fb^{-1}$, $\sqrt{s}$=7 TeV
σ_{SUSY} = 1 fb
σ_{SUSY} = 10 fb
σ_{SUSY} = 100 fb
squark mass [GeV]
gluino mass [GeV]
600
800
1000
1200
1400
1600
1800
2000

An important assumption of this plot is the description of the SUSY spectrum with a small number of parameters using grand unification.

This implies that all 12 squarks have roughly the same mass.

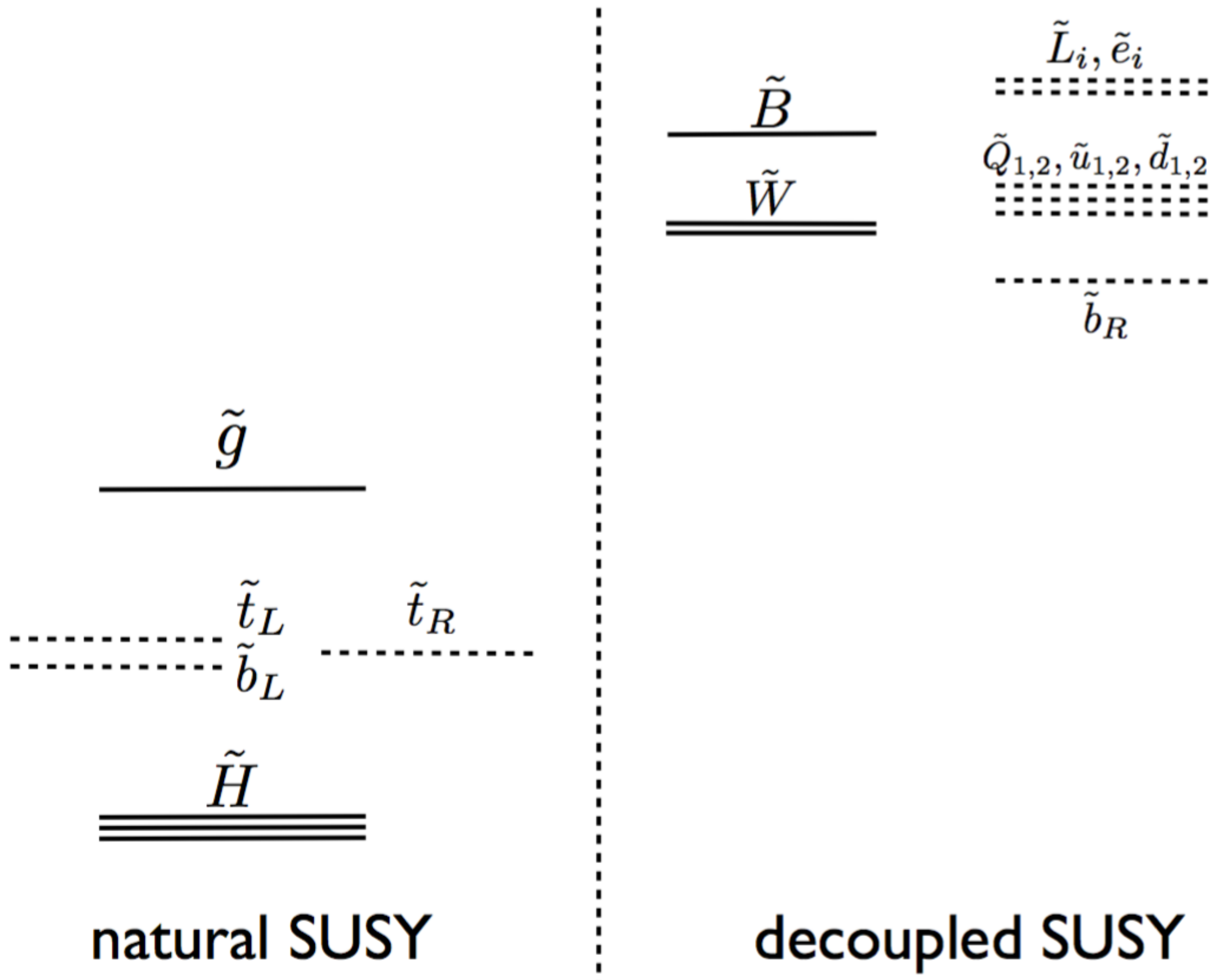
Note that the production cross sections for u and d squarks are much larger than those for squarks of 2nd, 3rd generations.



Prospino: Beenacker, Plehn, Spira et al.

An influential paper (2011):

Papucci, Ruderman, Weiler: “Natural SUSY Endures”

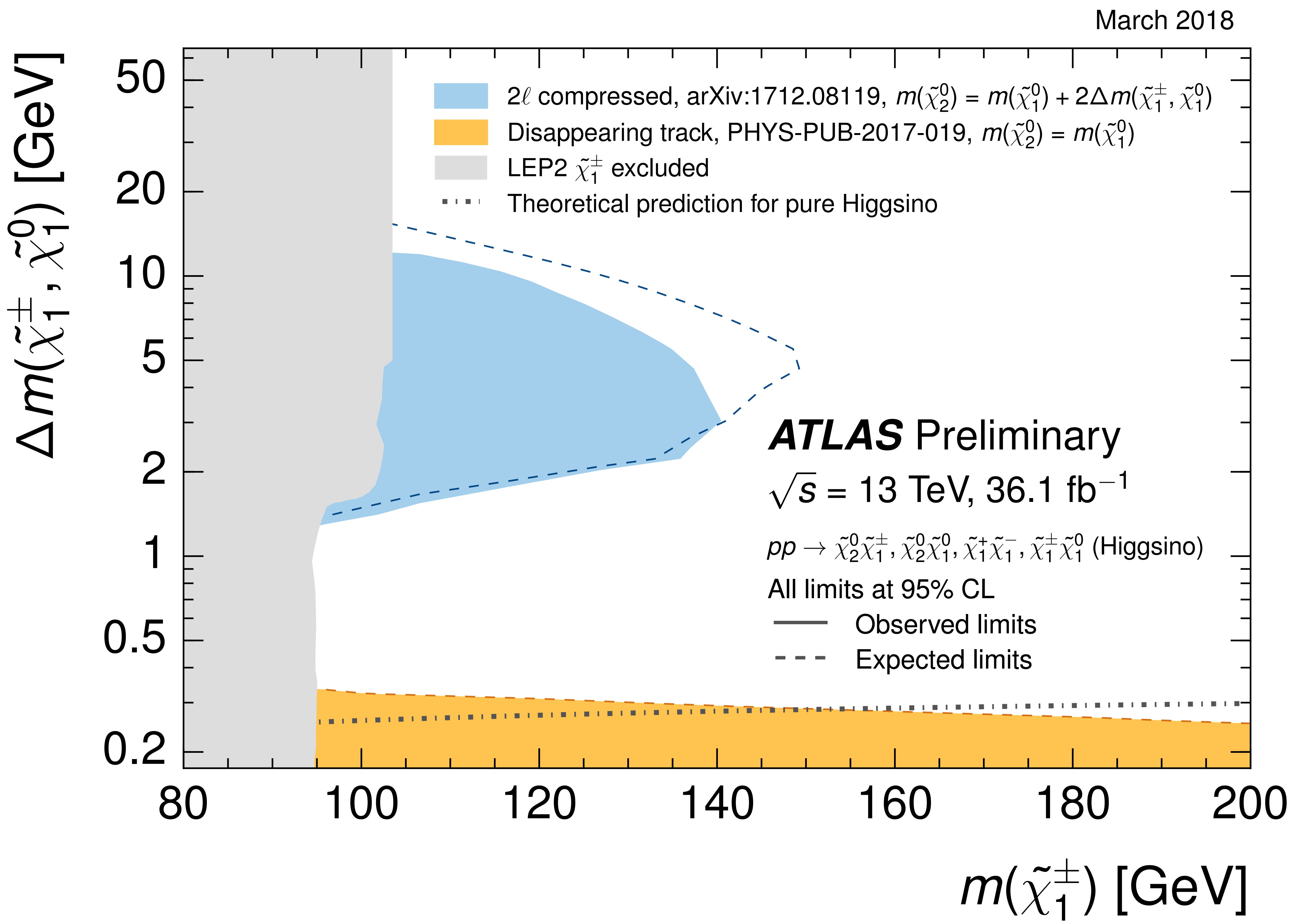


spectrum orig. proposed by Cohen, Kaplan, Nelson (1996)

PRW minimal requirements for natural SUSY theory:

- two stops and one (left-handed) sbottom, both below $500 - 700$ GeV.
- two higgsinos, *i.e.*, one chargino and two neutralinos below $200 - 350$ GeV. In the absence of other chargino/neutralinos, their spectrum is quasi-degenerate.
- a not too heavy gluino, below 900 GeV $- 1.5$ TeV.

This changes the game. These stops and Higgsinos are very difficult to discover at the LHC. Stops are difficult not only at large mass but also when $m(\widetilde{t}) \approx m_t$.



March 2018
2ℓ compressed, arXiv:1712.08119, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$
Disappearing track, PHYS-PUB-2017-019, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0)$
LEP2 $\tilde{\chi}_1^\pm$ excluded
Theoretical prediction for pure Higgsino
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm, \tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_1^0$ (Higgsino)
All limits at 95% CL
Observed limits
Expected limits
$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]
50
20
10
5
2
1
0.5
0.2
80
100
120
140
160
180
200
$m(\tilde{\chi}_1^\pm)$ [GeV]

Another tool to sharpen the SUSY signal
(Lester and Summers (1999))

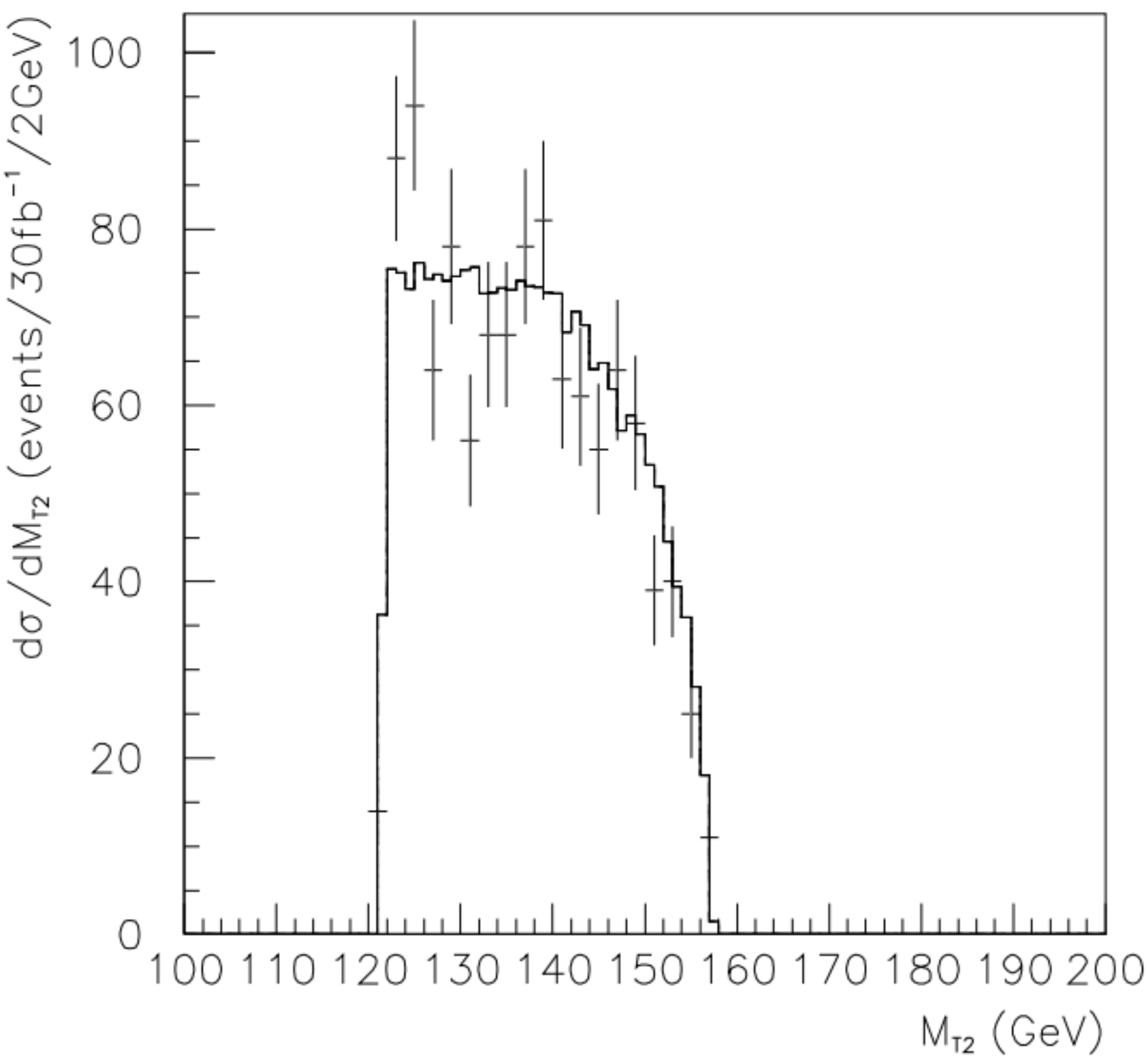
Consider $pp \to 2 \text{ jets} + \not{E}_T$
or, if there are more jets, cluster these into 2 hemispheres

Decompose the MET into 2 transverse vectors

$$\vec{\not{p}}_T = \vec{\not{p}}_{T1} + \vec{\not{p}}_{T2}$$

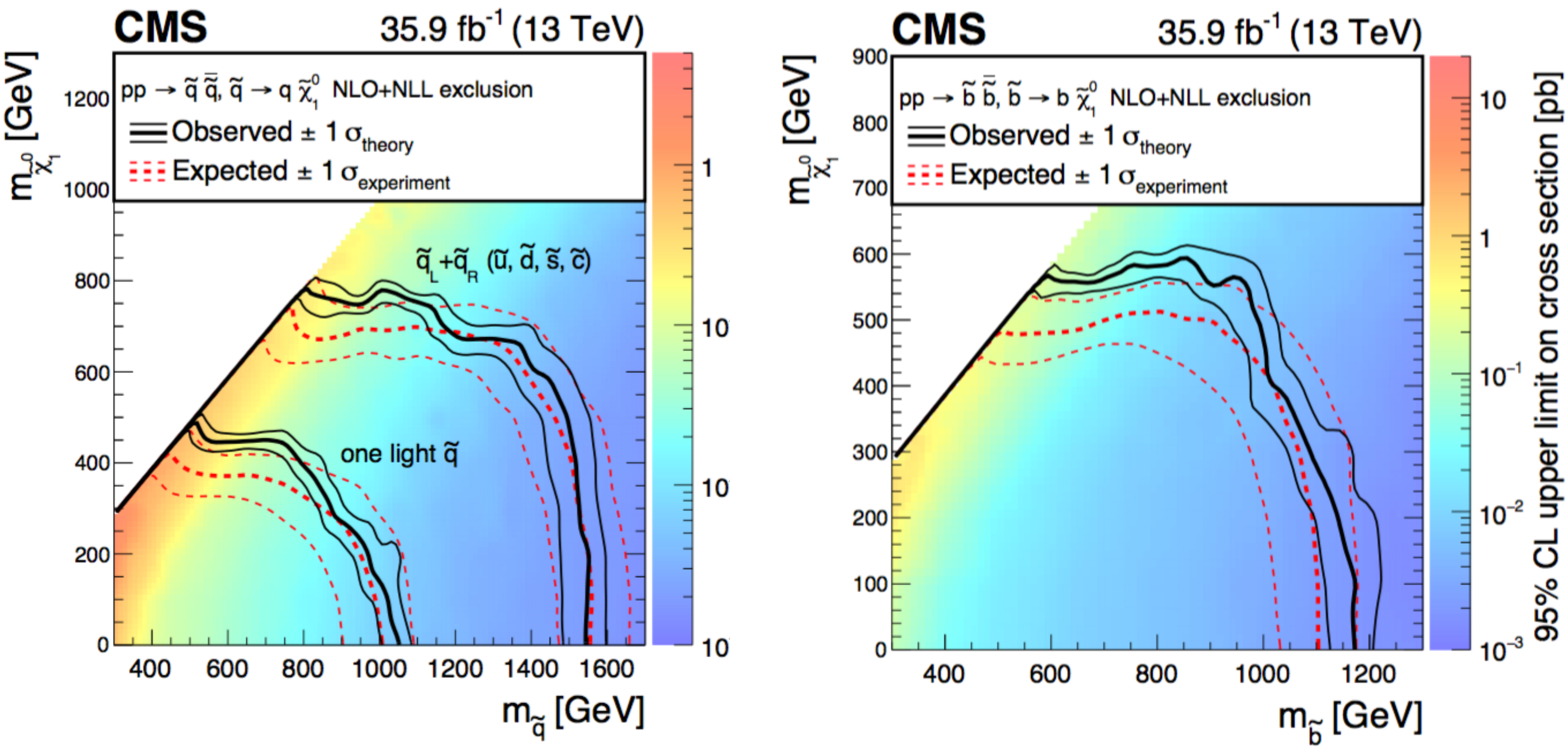
Define $$M_{T2} = \min_{\vec{\not{p}}_{T1} + \vec{\not{p}}_{T2}} [\max(M_{T1}, M_{T2})]$$

(where the tranverse mass calculation includes an assumed mass for the missing particle). Then M_{T2} is bounded above by the mass of the parent, and typical values tend to be close to that bound.



$$pp \to X + \widetilde{\ell}^+ \widetilde{\ell}^- \to X + \ell^+ \ell^- N^0 N^0$$

Lester and Summers

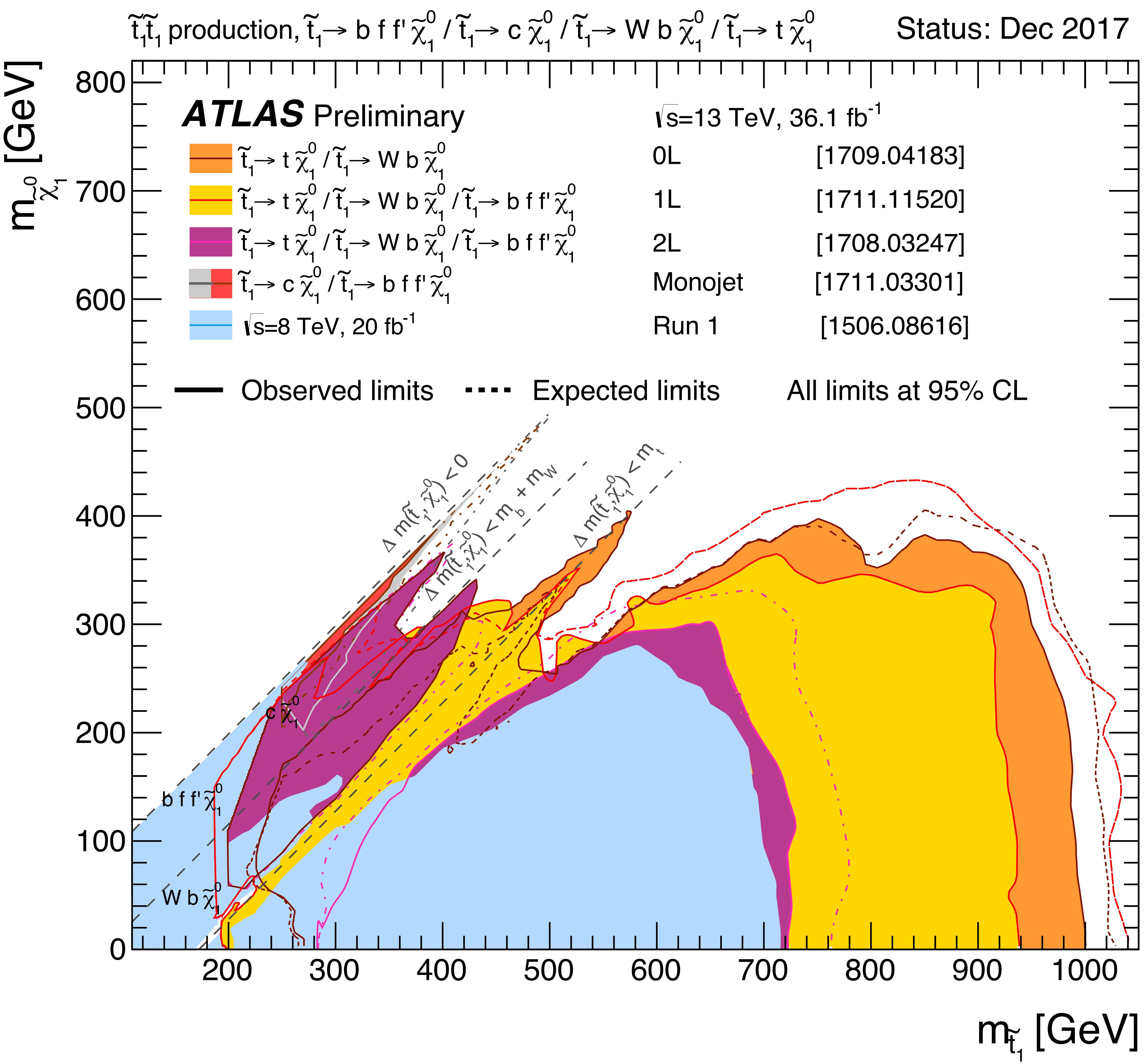


CMS
35.9 fb^{-1} (13 TeV)
pp → $\tilde{q}\bar{\tilde{q}}$, $\tilde{q} \rightarrow q \tilde{\chi}^0_1$ NLO+NLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$\tilde{q}_L + \tilde{q}_R$ ($\tilde{u}$, $\tilde{d}$, $\tilde{s}$, $\tilde{c}$)
one light $\tilde{q}$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{q}}$ [GeV]
CMS
35.9 fb^{-1} (13 TeV)
pp → $\tilde{b}\bar{\tilde{b}}$, $\tilde{b} \rightarrow b \tilde{\chi}^0_1$ NLO+NLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{b}}$ [GeV]
95% CL upper limit on cross section [pb]

A sophisticated literature has grown up around M_{T2} .
In particular, in a model with multi-stage SUSY decay.

For example, in $pp \to \widetilde{t t^*} \to N^0 N^0 t \bar{t} \to \cdots$
it is possible to tailor M_{T2} according to which final jets and leptons are well-measured.

A number of different M_{T2} definitions and corresponding event selections are used to cover all accessible regions in the stop parameter space.

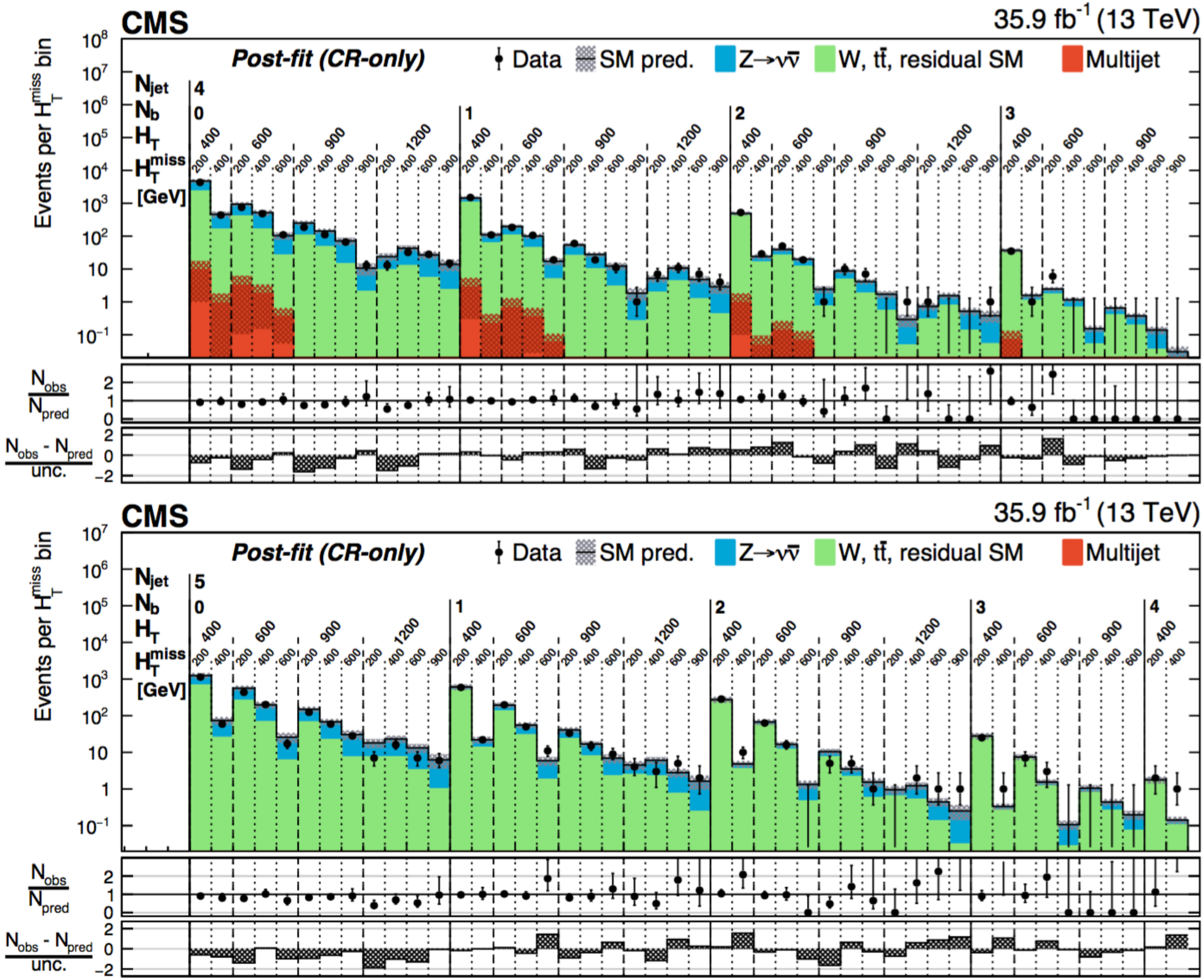


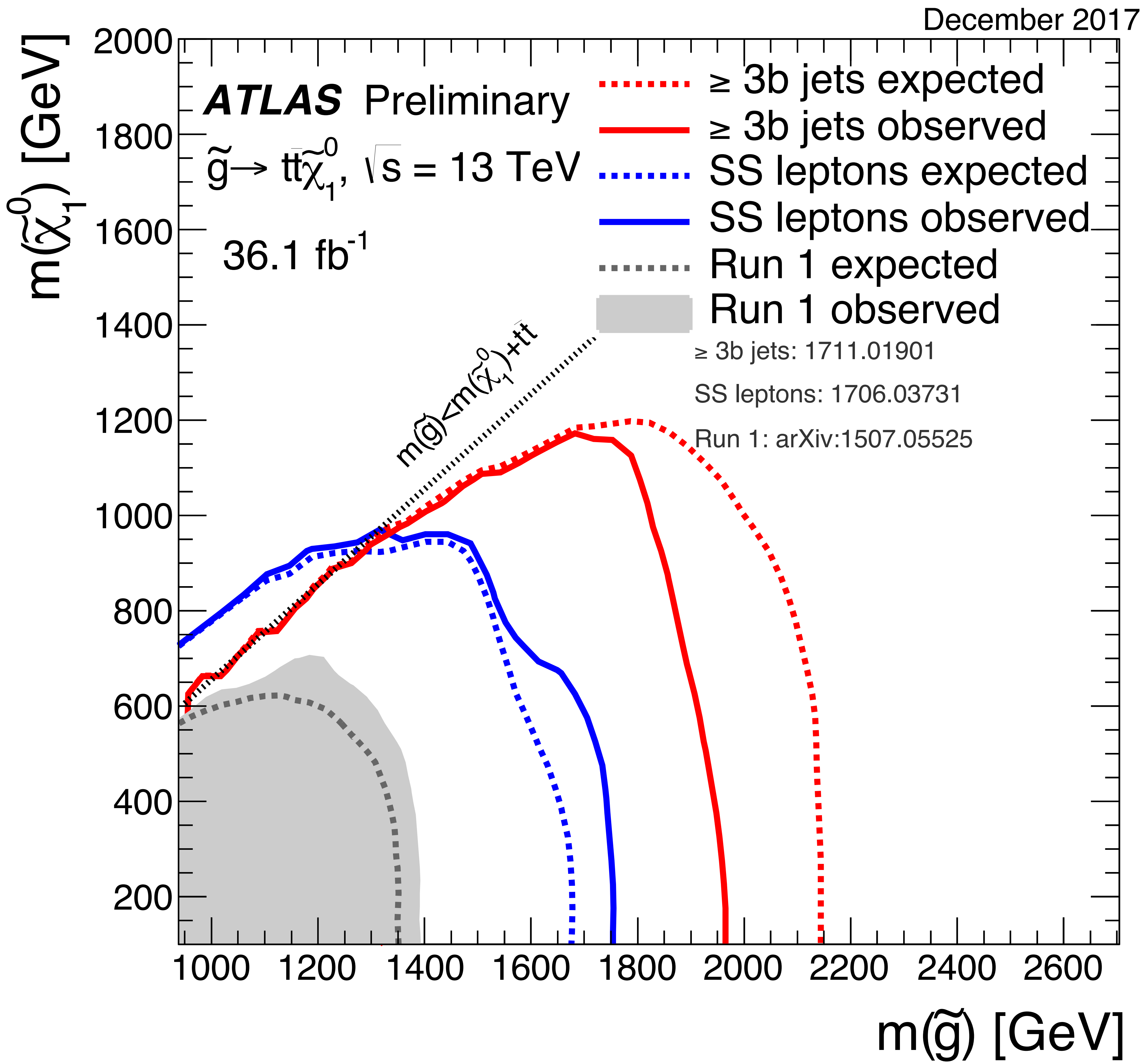
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
Status: Dec 2017
ATLAS Preliminary
$\sqrt{s}$=13 TeV, 36.1 fb^{-1}
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ 0L [1709.04183]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ 1L [1711.11520]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ 2L [1708.03247]
$\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ Monojet [1711.03301]
$\sqrt{s}$=8 TeV, 20 fb^{-1} Run 1 [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < 0$
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_b + m_W$
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_t$
$c \tilde{\chi}_1^0$
$b f f' \tilde{\chi}_1^0$
$W b \tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
100
200
300
400
500
600
700
800
900
1000

Oddly, though, the logic that makes the squark search harder makes the gluino search easier.

Since the stop and sbottom are the lightest squarks in “natural SUSY”, the gluino decays to these particles (real or virtual) and through them to 3rd generation quarks.

Thus, we can search for gluinos by using the standard variables $m_{eff}, \not{E}_T$ together with selections for a large number of b-tagged jets.


CMS
35.9 fb-1 (13 TeV)
Post-fit (CR-only)
Data
SM pred.
Z→νν̄
W, tt̄, residual SM
Multijet
Events per HTmiss bin
Njet
Nb
HT
HTmiss
[GeV]
Nobs / Npred
Nobs - Npred / unc.
CMS
35.9 fb-1 (13 TeV)
Post-fit (CR-only)
Data
SM pred.
Z→νν̄
W, tt̄, residual SM
Multijet
Events per HTmiss bin
Njet
Nb
HT
HTmiss
[GeV]
Nobs / Npred
Nobs - Npred / unc.



December 2017
ATLAS Preliminary
$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$, $\sqrt{s}$ = 13 TeV
36.1 fb^{-1}
≥ 3b jets expected
≥ 3b jets observed
SS leptons expected
SS leptons observed
Run 1 expected
Run 1 observed
≥ 3b jets: 1711.01901
SS leptons: 1706.03731
Run 1: arXiv:1507.05525
$m(\tilde{g}) < m(\tilde{\chi}_1^0) + t\bar{t}$
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{g})$ [GeV]

If we give up on SUSY, the “gauge hierarchy problem” is still with us. I like to say, more physically, that we are still obligated to explain the symmetry-breaking form of the Higgs potential.

Why is the point $\langle h \rangle = 0$ unstable?

In SUSY models, we derive the Higgs potential by integrating out the system: $(\widetilde{t}_L, \widetilde{t}_R, \phi_u)$

In composite Higgs or extra-dimensional models, we derive the Higgs potential by integrating out the system:

$$(t_L, T, \phi)$$

where T is a heavy quark with vectorlike couplings.

So, we ought to give attention to searches for T.

In the simplest scheme, T is an SU(2) singlet that coupling to (t_L, b_L) through

$$\delta L = g\,\overline{T}\phi^* \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

Then the decay scheme of T is

$$\begin{aligned} T &\to th \qquad (25\%) \\ &\to tZ \qquad (25\%) \\ &\to bW^+ \quad (50\%) \end{aligned}$$

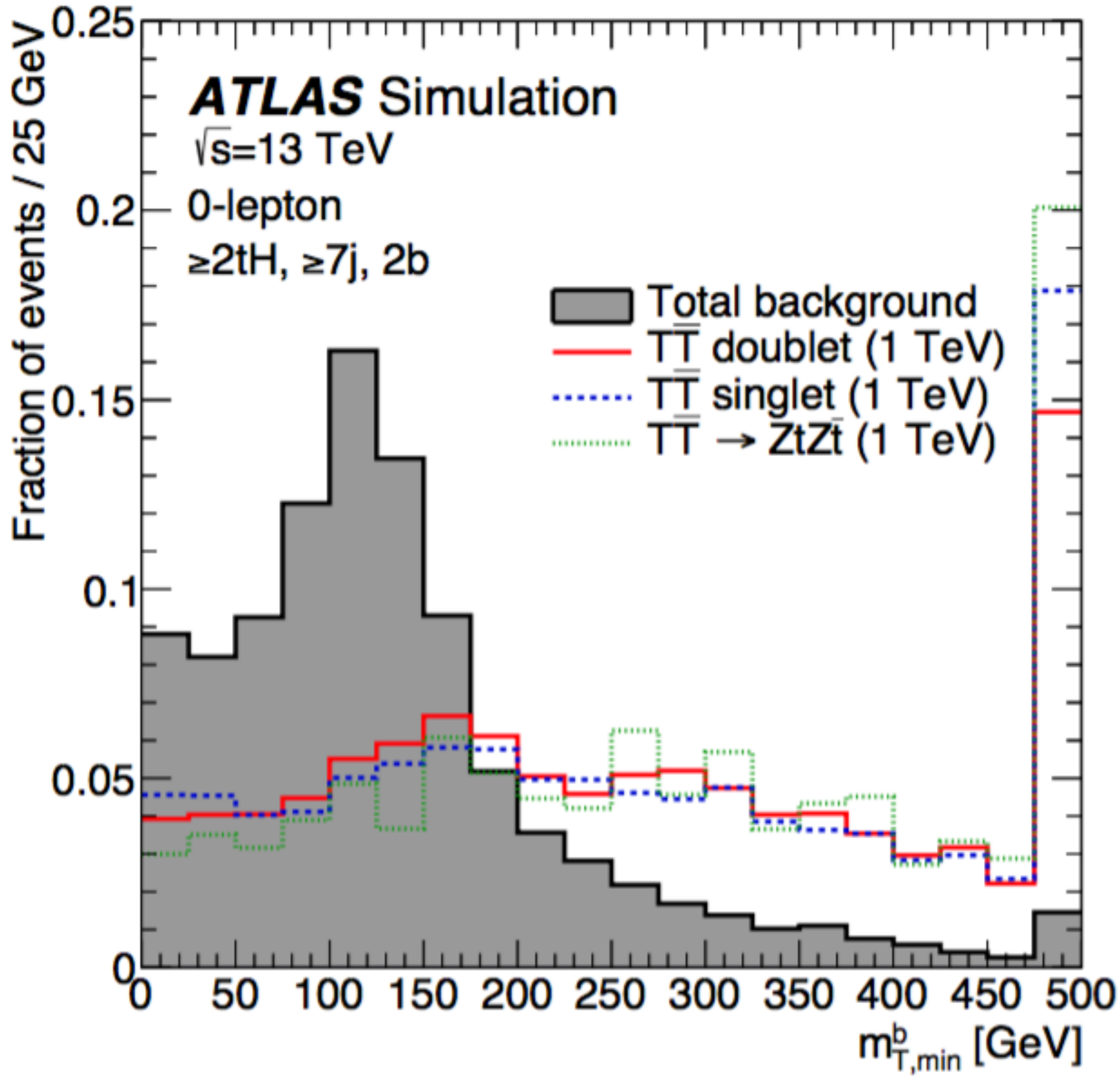
The branching ratios are different in different models, so we should search systematically for all three decays, independently on the two sides of a pair-production event.

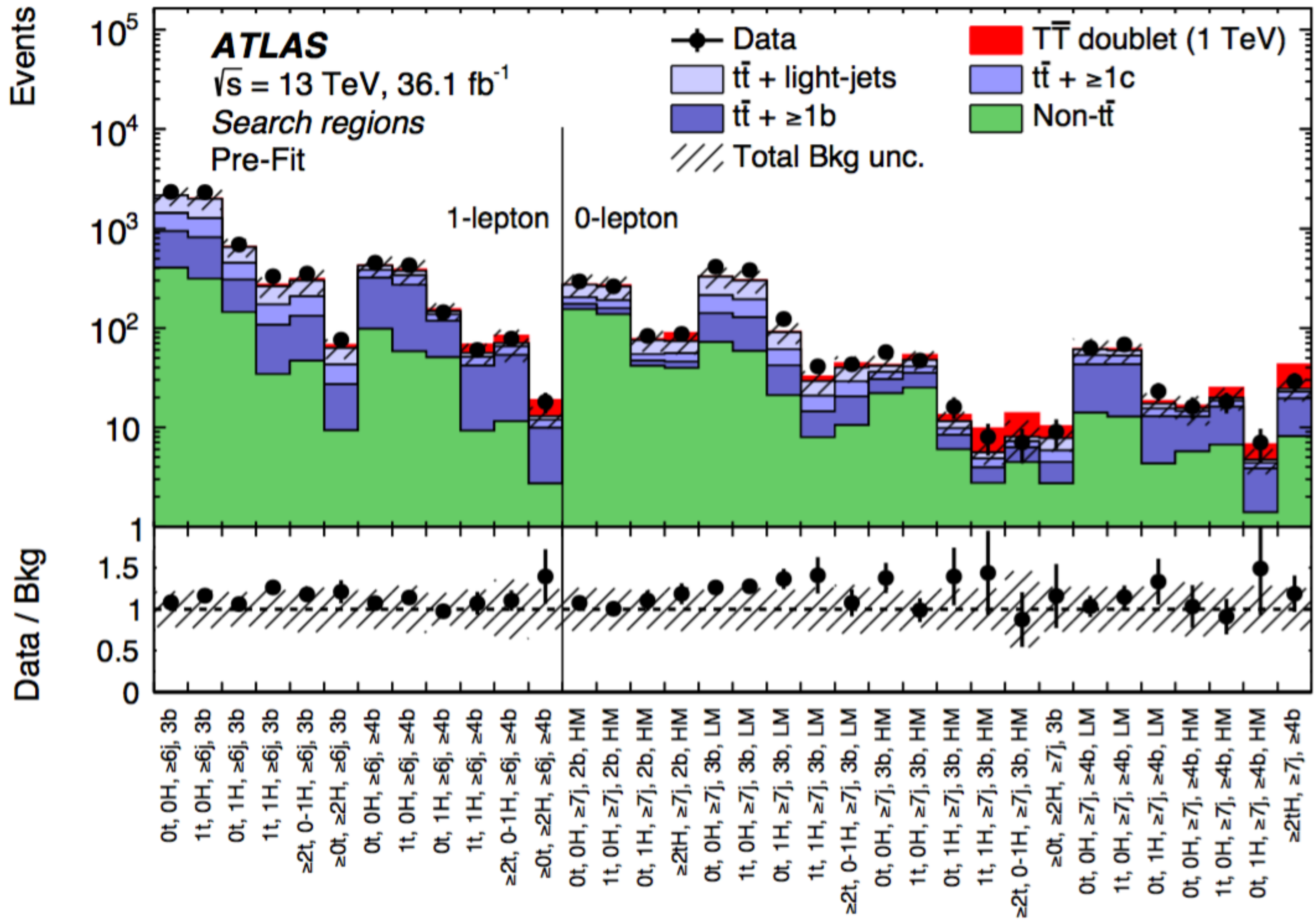
ATLAS search for T in

$$pp \to T\overline{T} \to tZtZ- > t + b + \not{E}_T$$

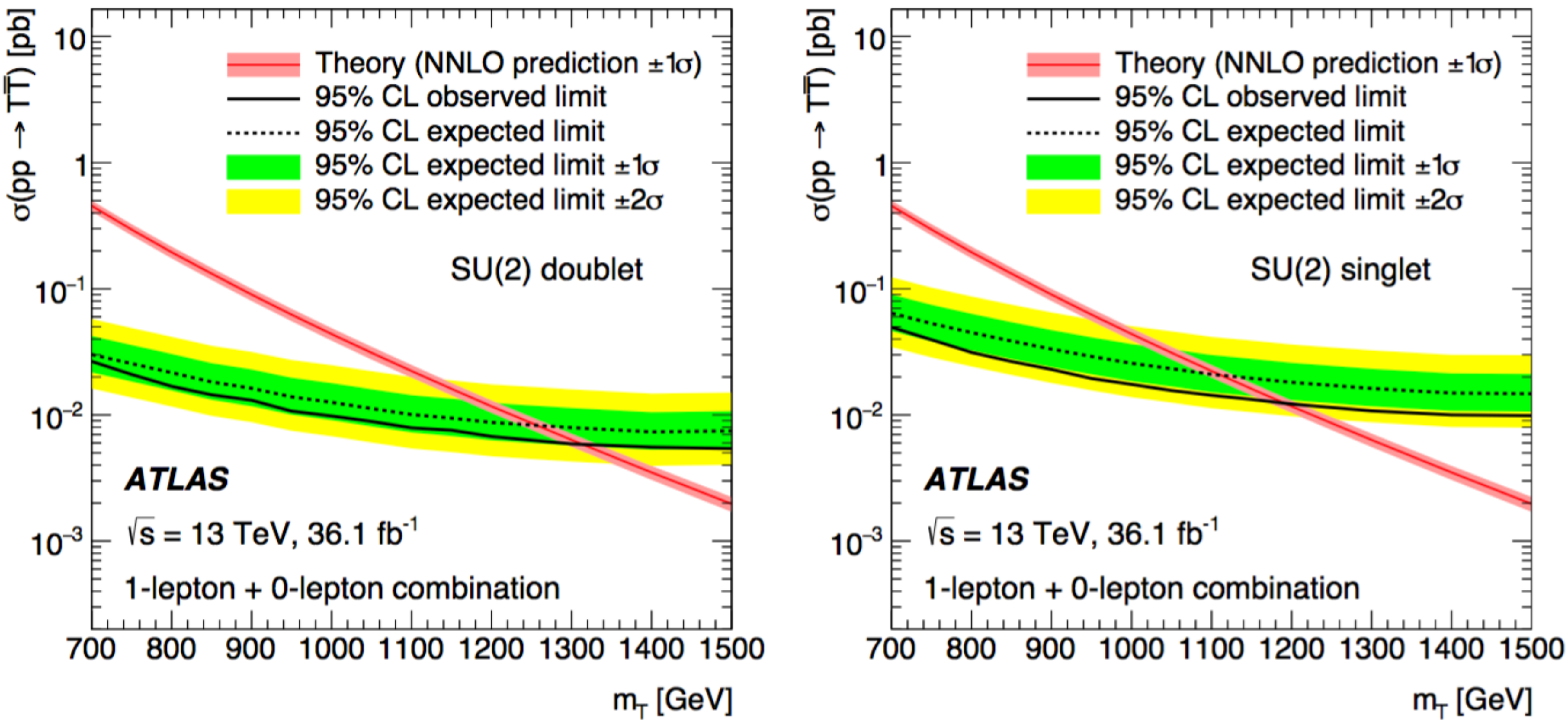
using

$$\min M_{T2}(b + \not{E}_T)$$

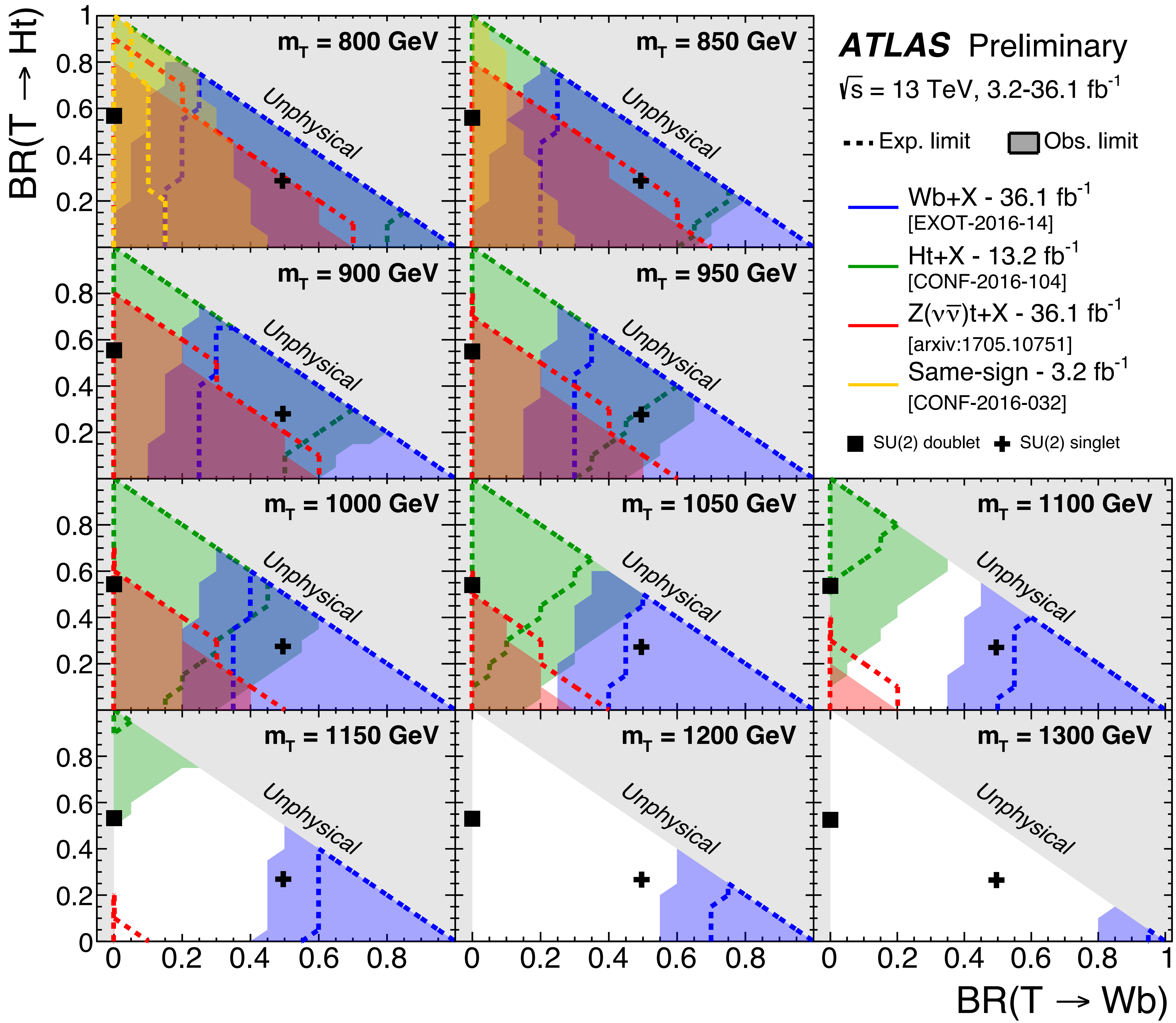




ATLAS
√s = 13 TeV, 36.1 fb-1
Search regions
Pre-Fit
Data
TT̄ doublet (1 TeV)
tt̄ + light-jets
tt̄ + ≥1c
tt̄ + ≥1b
Non-tt̄
Total Bkg unc.
1-lepton
0-lepton
Events
Data / Bkg
0t, 0H, ≥6j, 3b
1t, 0H, ≥6j, 3b
0t, 1H, ≥6j, 3b
1t, 1H, ≥6j, 3b
≥2t, 0-1H, ≥6j, 3b
≥0t, ≥2H, ≥6j, 3b
0t, 0H, ≥6j, ≥4b
1t, 0H, ≥6j, ≥4b
0t, 1H, ≥6j, ≥4b
1t, 1H, ≥6j, ≥4b
≥2t, 0-1H, ≥6j, ≥4b
≥0t, ≥2H, ≥6j, ≥4b
0t, 0H, ≥7j, 2b, HM
1t, 0H, ≥7j, 2b, HM
0t, 1H, ≥7j, 2b, HM
≥2tH, ≥7j, 2b, HM
0t, 0H, ≥7j, 3b, LM
1t, 0H, ≥7j, 3b, LM
0t, 1H, ≥7j, 3b, LM
1t, 1H, ≥7j, 3b, LM
≥2t, 0-1H, ≥7j, 3b, LM
0t, 0H, ≥7j, 3b, HM
1t, 0H, ≥7j, 3b, HM
0t, 1H, ≥7j, 3b, HM
1t, 1H, ≥7j, 3b, HM
≥2t, 0-1H, ≥7j, 3b, HM
≥0t, ≥2H, ≥7j, 3b
0t, 0H, ≥7j, ≥4b, LM
1t, 0H, ≥7j, ≥4b, LM
0t, 1H, ≥7j, ≥4b, LM
0t, 0H, ≥7j, ≥4b, HM
1t, 0H, ≥7j, ≥4b, HM
0t, 1H, ≥7j, ≥4b, HM
≥2tH, ≥7j, ≥4b



Theory (NNLO prediction ±1σ)
95% CL observed limit
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
SU(2) doublet
ATLAS
√s = 13 TeV, 36.1 fb-1
1-lepton + 0-lepton combination
σ(pp → TT̄) [pb]
m_T [GeV]
Theory (NNLO prediction ±1σ)
95% CL observed limit
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
SU(2) singlet
ATLAS
√s = 13 TeV, 36.1 fb-1
1-lepton + 0-lepton combination
σ(pp → TT̄) [pb]
m_T [GeV]



ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 3.2-36.1 fb^{-1}
Exp. limit
Obs. limit
Wb+X - 36.1 fb^{-1}
[EXOT-2016-14]
Ht+X - 13.2 fb^{-1}
[CONF-2016-104]
Z($\nu\bar{\nu}$)t+X - 36.1 fb^{-1}
[arxiv:1705.10751]
Same-sign - 3.2 fb^{-1}
[CONF-2016-032]
SU(2) doublet
SU(2) singlet
m_T = 800 GeV
m_T = 850 GeV
m_T = 900 GeV
m_T = 950 GeV
m_T = 1000 GeV
m_T = 1050 GeV
m_T = 1100 GeV
m_T = 1150 GeV
m_T = 1200 GeV
m_T = 1300 GeV
Unphysical
BR(T → Ht)
BR(T → Wb)

A huge amount of ingenuity has gone into these searches, with no payoff so far.

However, we have still not solved the problem of the origin of the Higgs VEV and the electroweak mass scale.

The LHC has current analyzed about 40 $\mathrm{fb}^{-1}$of data per experiment. The goal of the high-luminosity phase of LHC is 3000 fb^{-1}, that is, about 100 x more data.

However, it is much easier to extend particle searches with higher energy, not higher luminosity. ATLAS estimates the ultimate limit of its searches at 13 TeV as

~ 6000 GeV for W'
~ 2500 GeV for gluino
~ 1600 GeV for T

Other targets, in particular, those with electroweak production, may get as much as a factor 2 improvement. But, already, we see the need for either a much higher energy accelerator or a genuinely new strategy (e.g. Higgs precision measurements) to make progress.