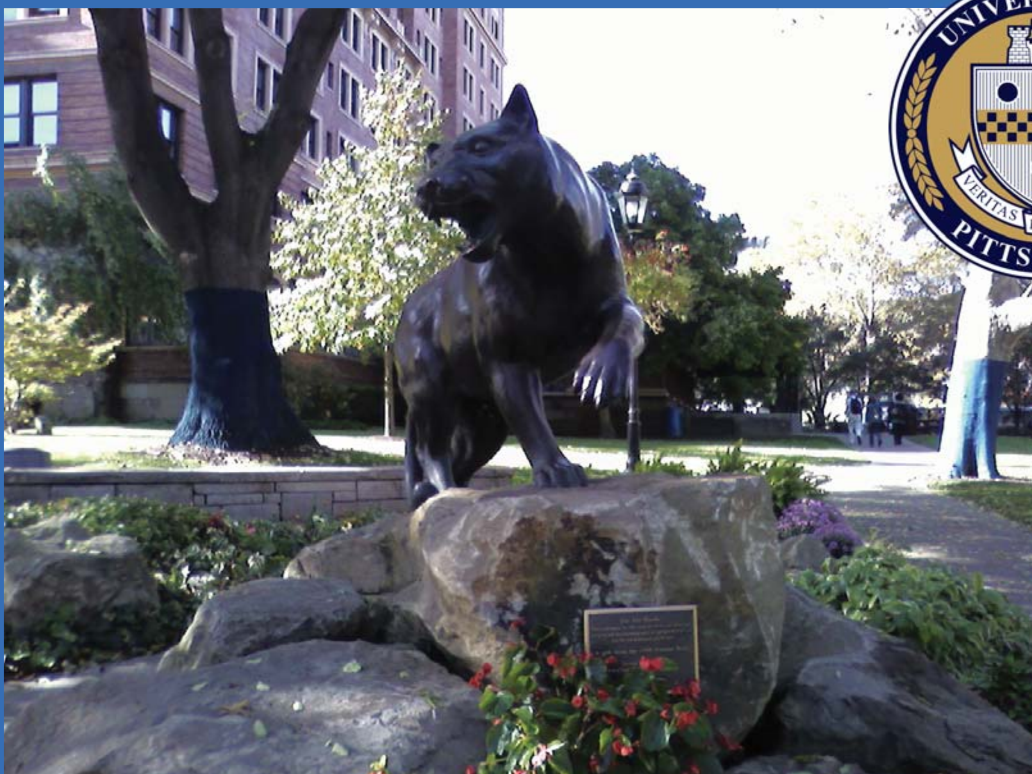
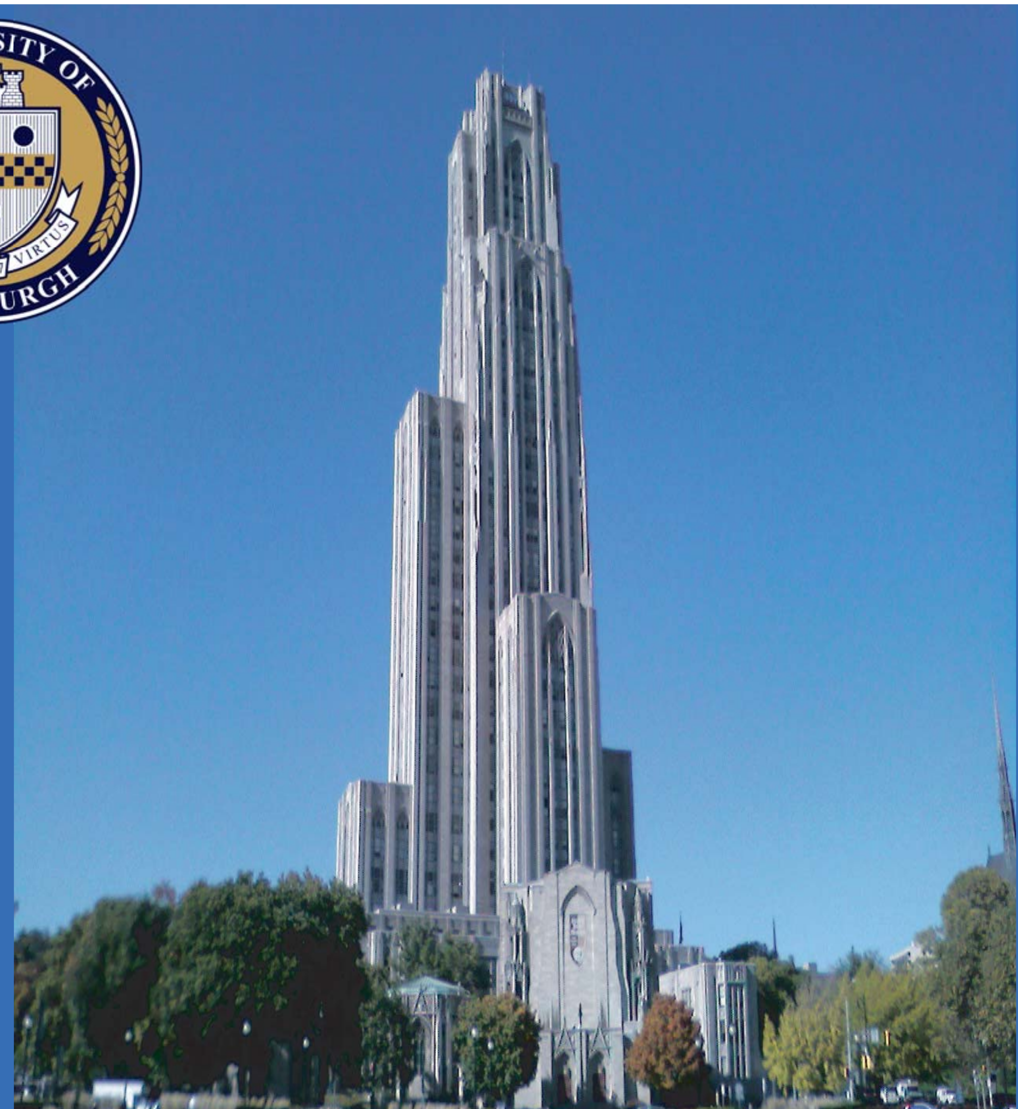
Vladimir Savinov (University of Pittsburgh)

Searches for Heavy Neutrinos, Lepton Number Violation (and more stuff) with the ATLAS detector at the LHC





From Majorana to LHC: Workshop on the Origin of Neutrino Mass

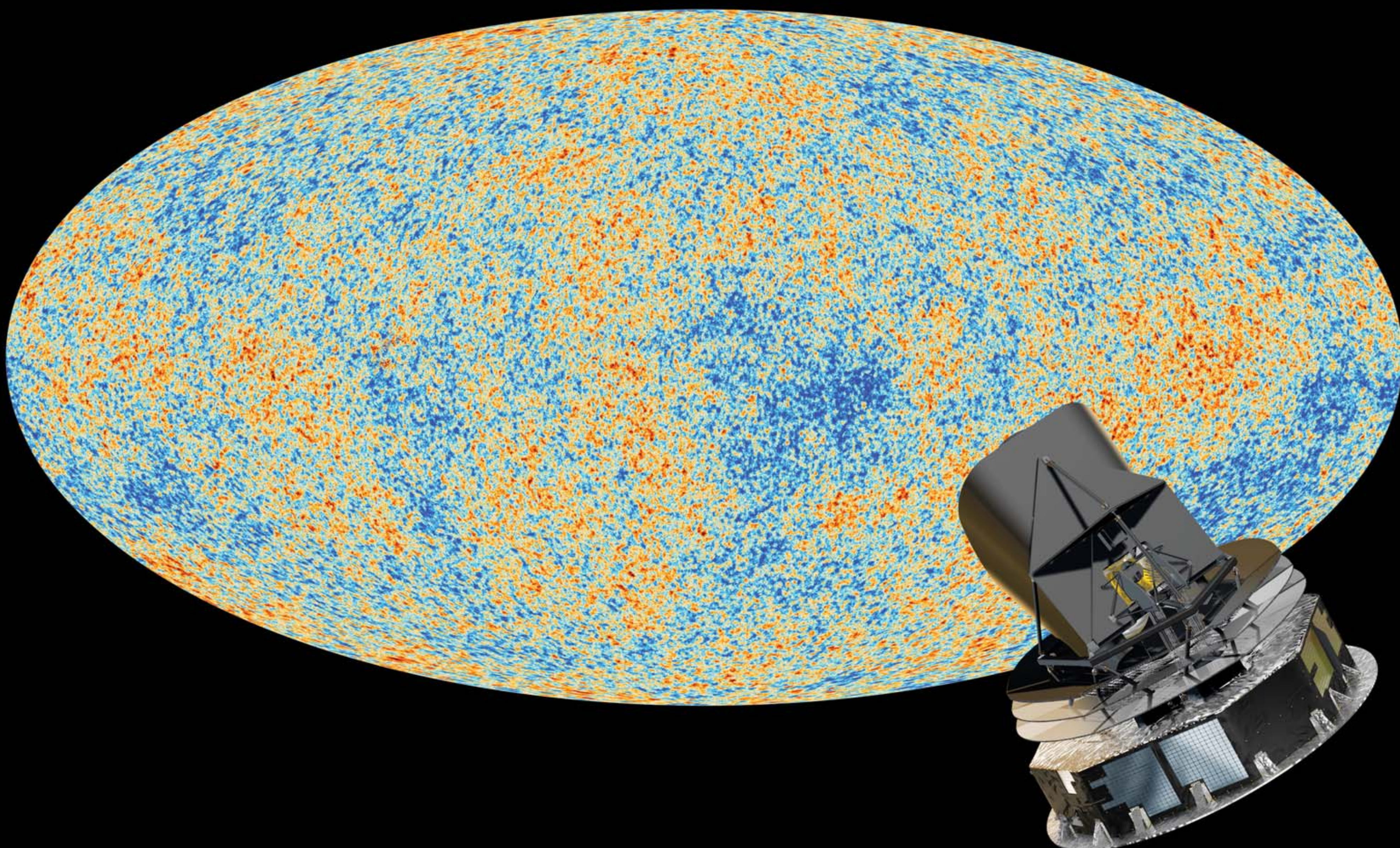
2 - 5 October 2013

Miramare, Trieste, Italy

The Abdus Salam International Centre for Theoretical Physics

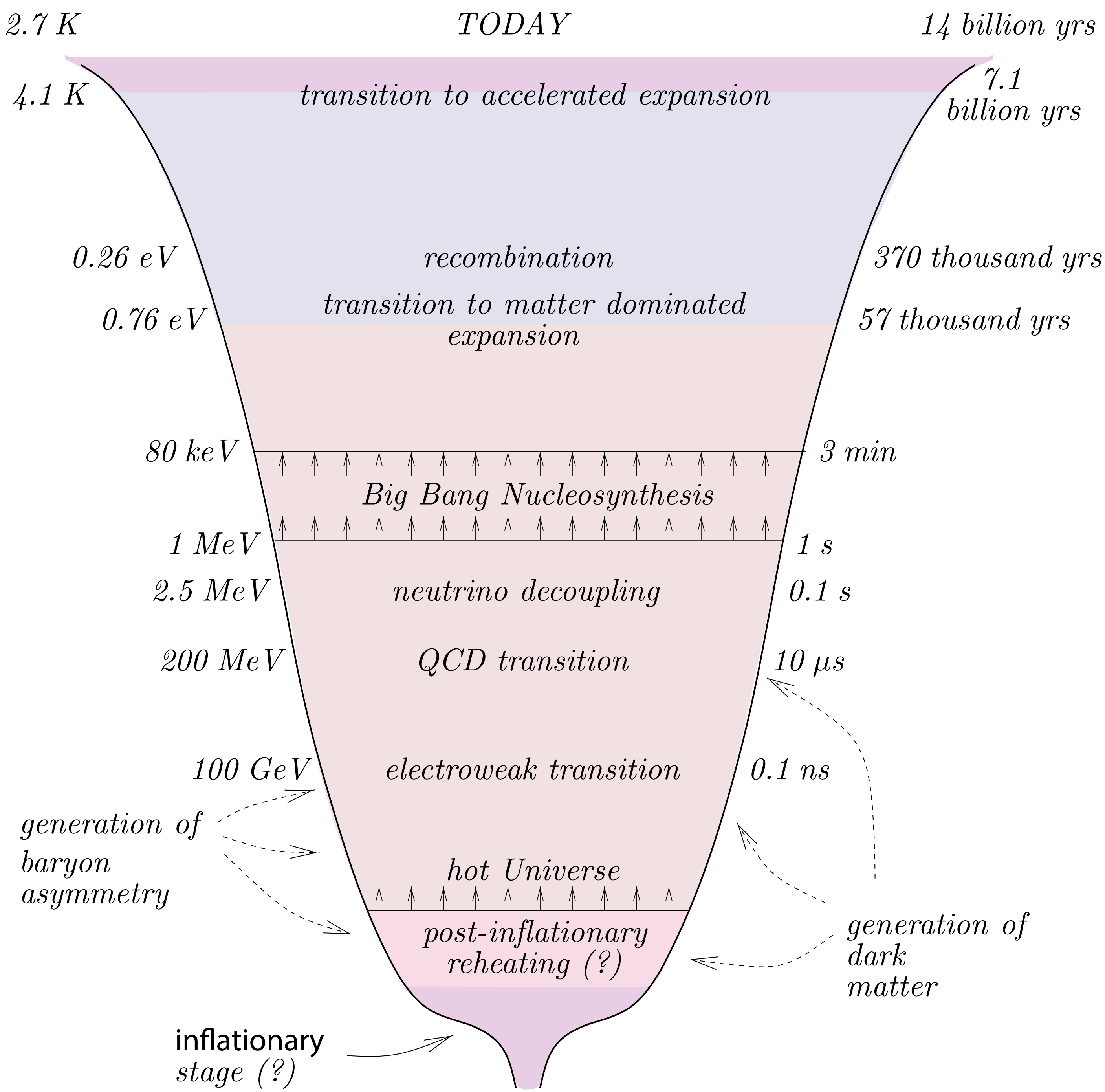
www.ictp.it

The anisotropies of the Cosmic microwave background (CMB) as observed by Planck. The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380 000 years old. It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today.



In 1967 Andrei Sakharov formulated three necessary conditions for baryogenesis, i.e., asymmetry between matter and anti-matter:

1. Baryon number violation
2. C asymmetry is due to CP violation
3. Departure from thermal equilibrium



(from Gorbunov and Rubakov, "Introduction to the Theory of the Early Universe: Hot Big Bang Theory")

Have to focus on:

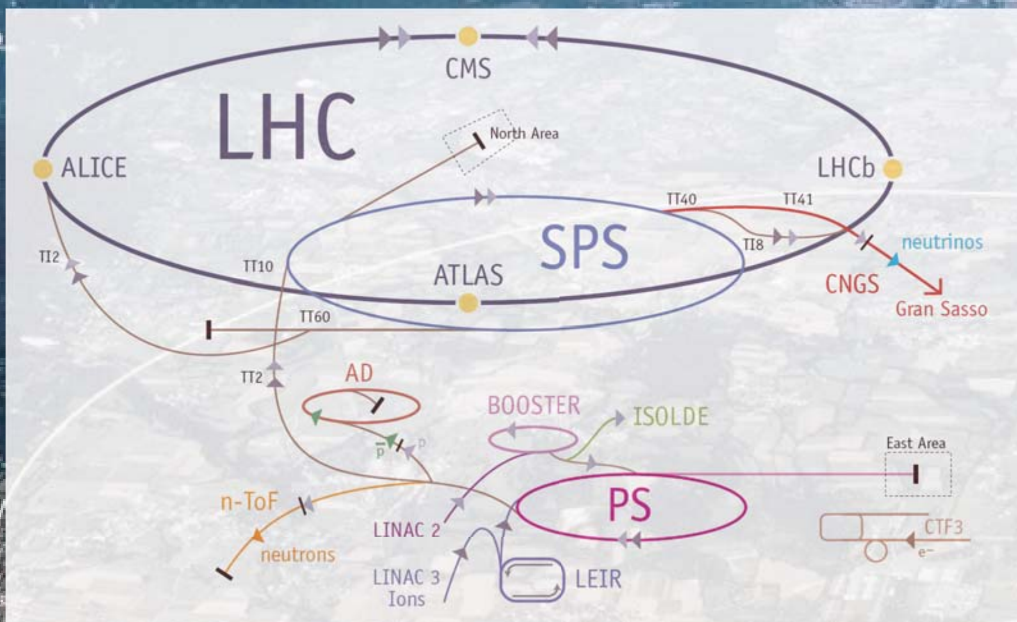
1. Non-conservation of baryon and lepton numbers
2. Violation of charge-parity symmetry
3. Properties of electroweak vacuum

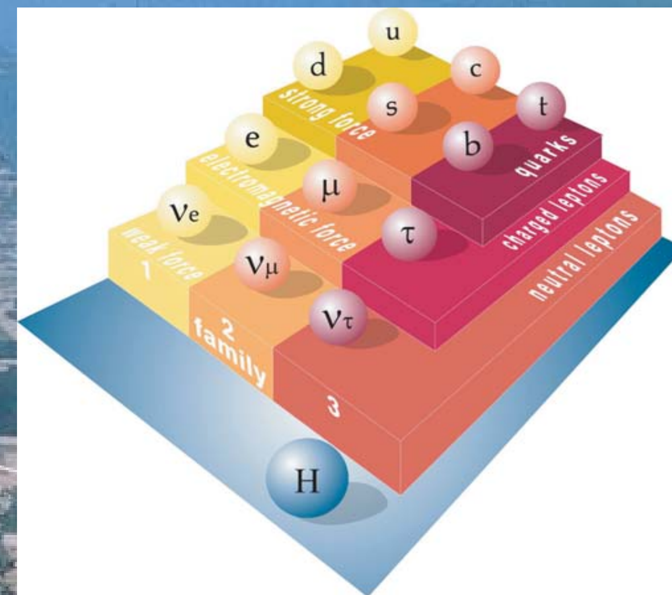
Some of these matters could be investigated

at the LHC experiments (but not only there!)

Successfully searched for and found the "missing piece" of this puzzle

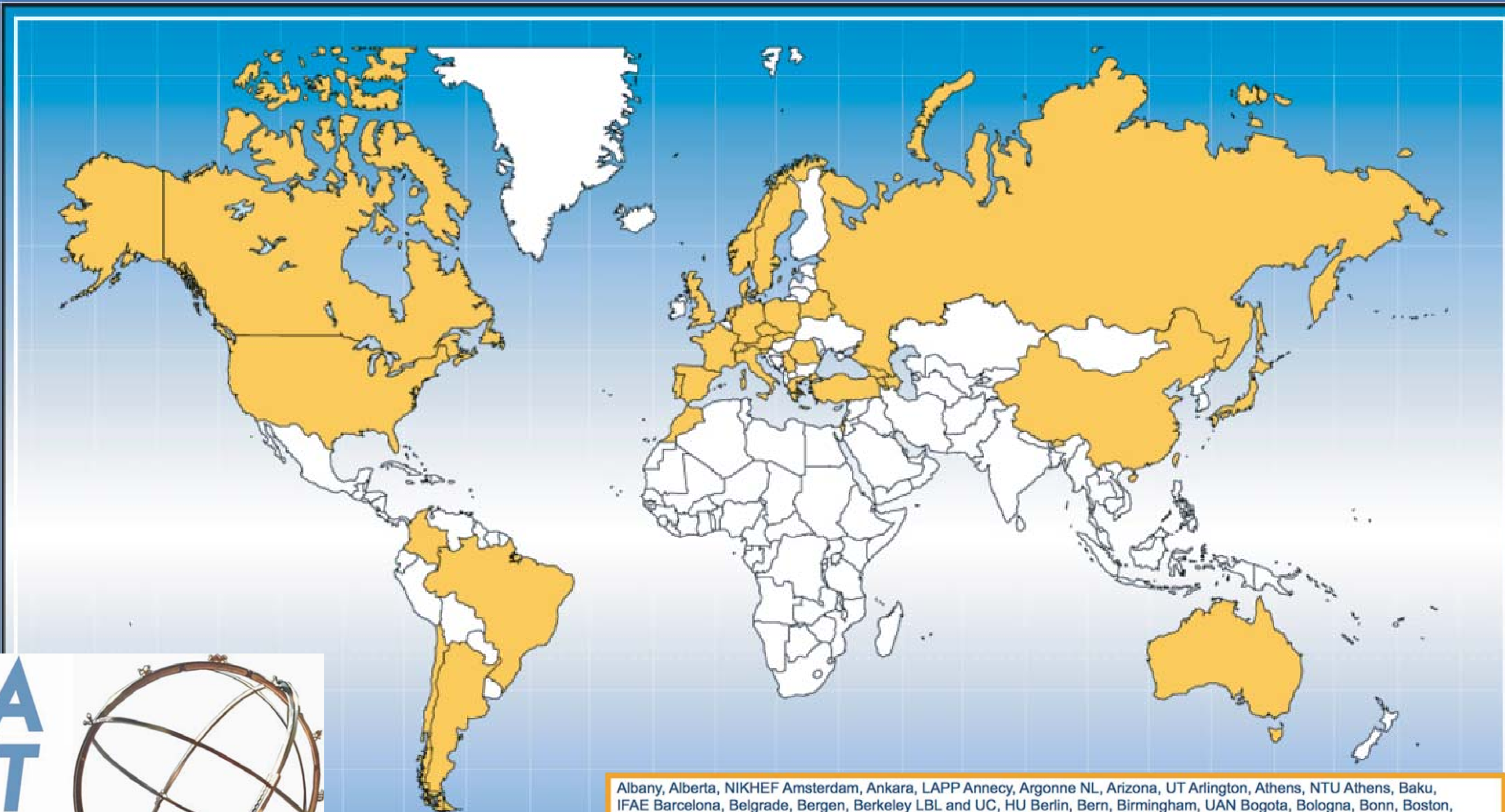
The Large Hadron Collider at CERN

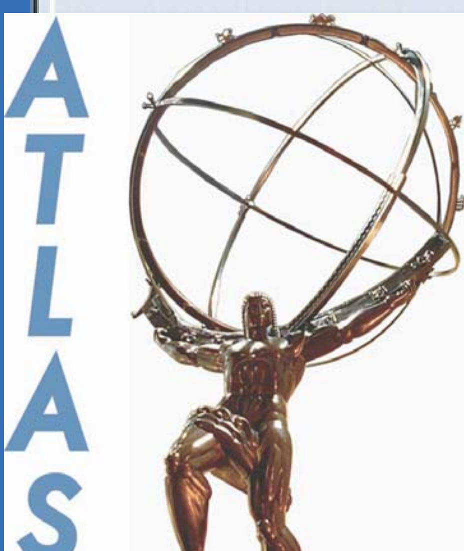




"Sooner or later we will find something else also"

The ATLAS Collaboration at the LHC: (like) 3,000 Happy Little Elves

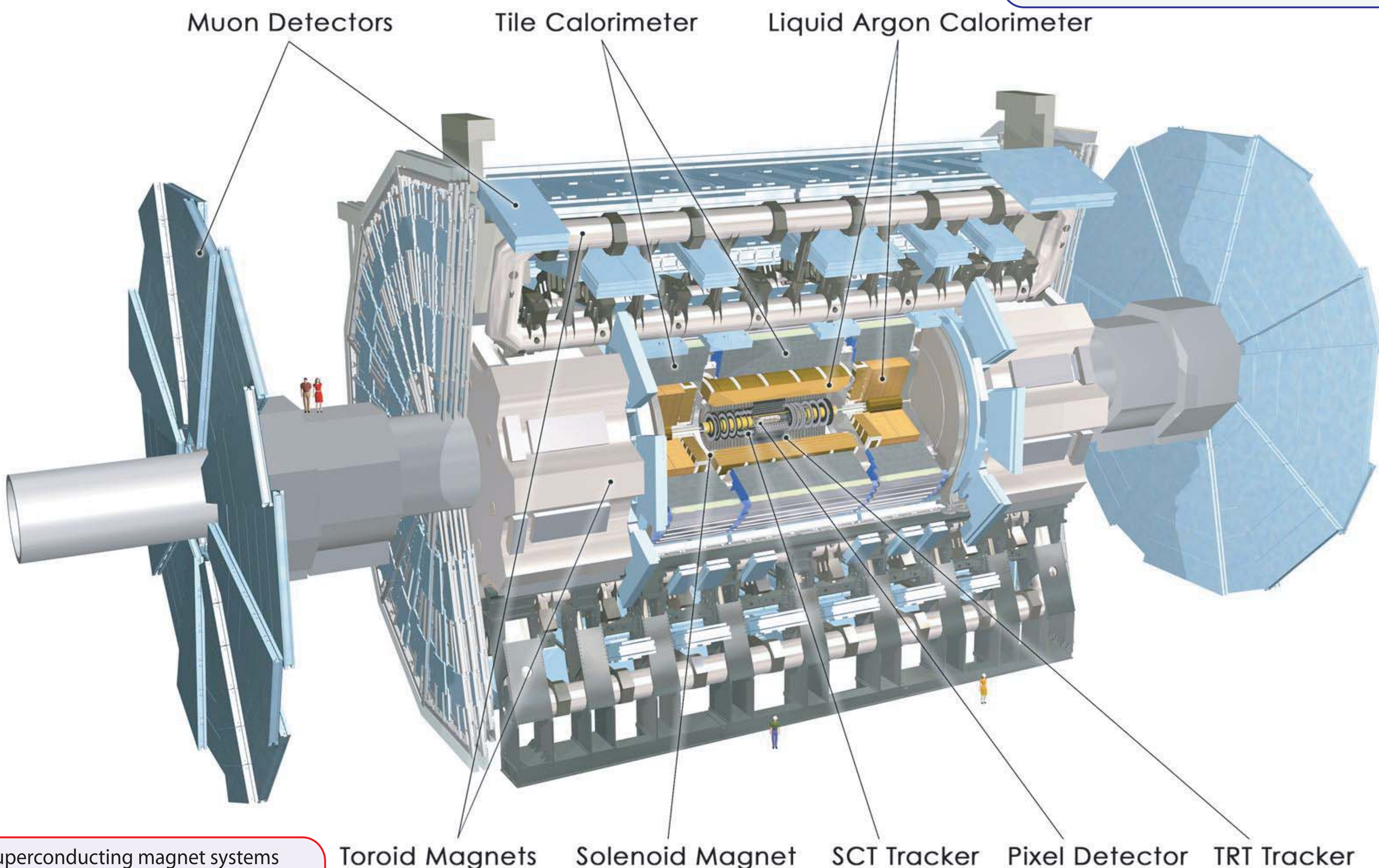




Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

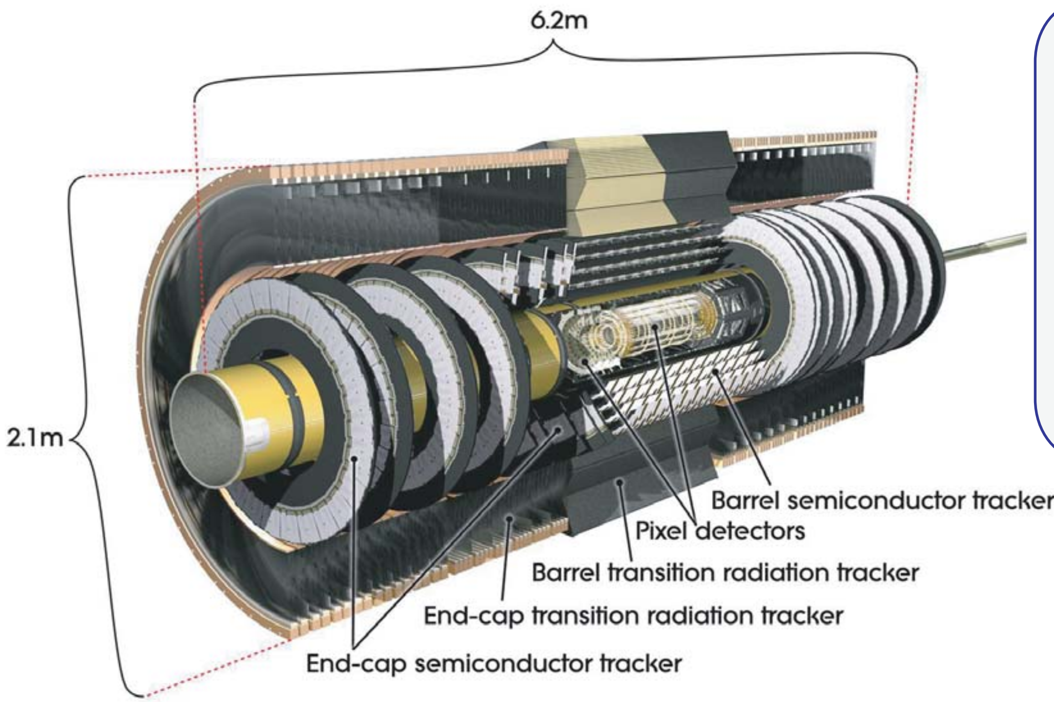
ATLAS (A Toroidal LHC ApparatuS)

Mass ~ 7000 tons
Length ~ 46m, barrel toroids: ~26m
Diameter ~ 25m
~100 million channels of electronics
~3000 km of cables



3 superconducting magnet systems
10 major particle detector technologies
20 years in the making

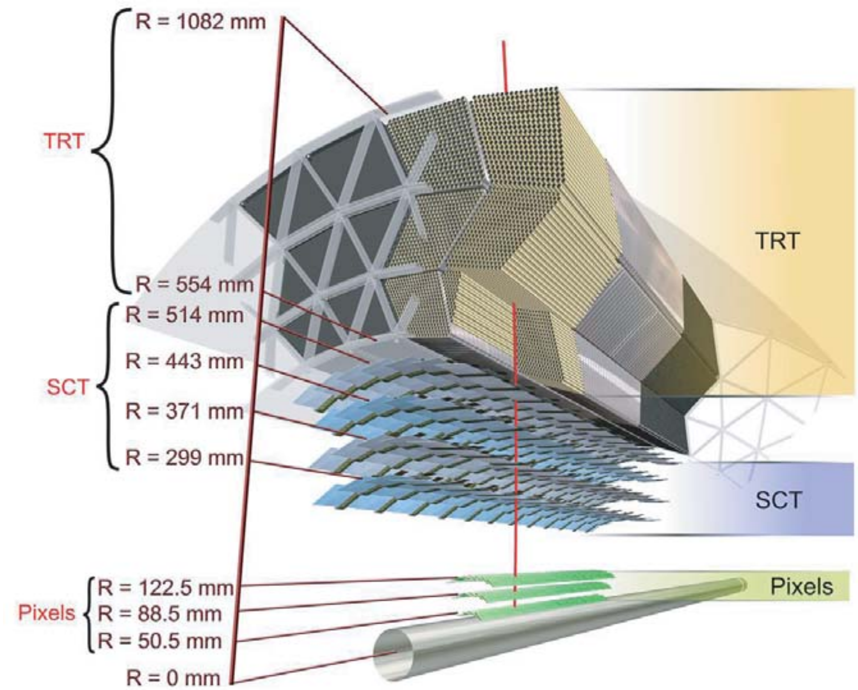
Inner Detector: silicon pixels, silicon microstrips and transition radiation tracker



Angular coverage and the measurements:

Silicon pixels and strips: $\eta=-\ln\tan(\Theta/2) < 2.5$
Pixels: up to 3/3 hits in barrel ($|\eta|<1$) / endcap
SCT: up to 8/9 hits in the barrel/endcap parts

TRT: $\eta=-\ln\tan(\Theta/2) < 2.0$, 73/160 layers in the barrel / each endcap, >30 hits per track at $\eta=0$



Resolutions of individual subsystems (in R-ϕ/z)

Pixel detector:	10 / 115 μm
Silicon microstrips (SCT):	17 / 580 μm
Straw tubes (TRT):	130 μm

Tracking, vertexing, e/π separation

Momentum and impact parameter resolutions (almost there using just cosmics and minbias!):

$$\sigma(p_\perp)/p_\perp \simeq 3.8\times10^{-4}\, p_\perp \oplus 0.015 \ (p_\perp \text{ in GeV})$$

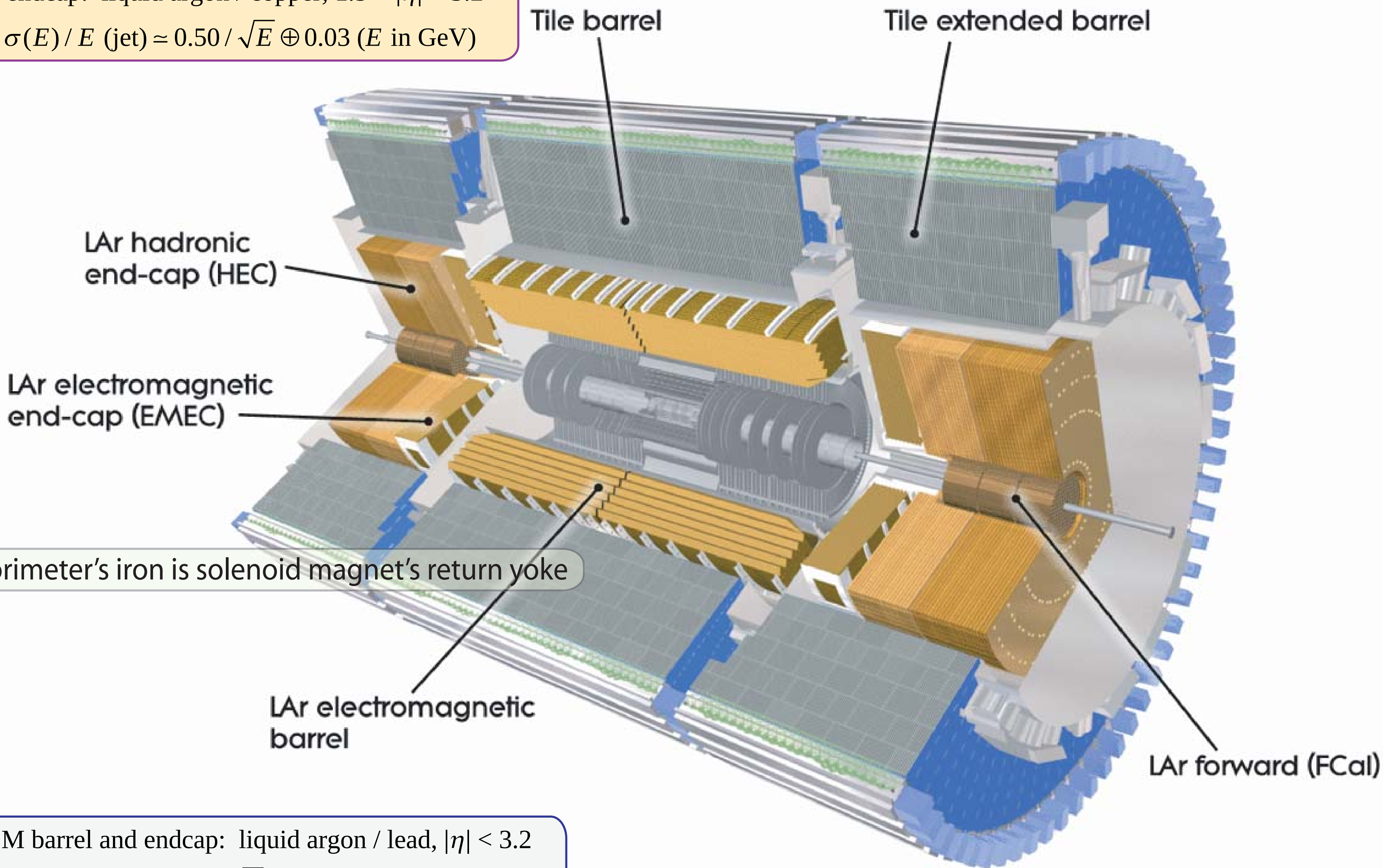
$$\sigma(d_0) \simeq 10 \oplus 140/p_\perp(\text{GeV})\ \mu\text{m}$$

The detectors are inside 2T solenoid field

ATLAS (sampling) calorimeters

Hadronic barrel (+extended): plastic scintillator tiles / iron,
$|\eta| < 1.7$, 3 layers, $\sigma(E)/E$ (jet) $\simeq 0.50/\sqrt{E} \oplus 0.03$ (E in GeV)

Hadronic endcap: liquid argon / copper, $1.5 < |\eta| < 3.2$
4 layers, $\sigma(E)/E$ (jet) $\simeq 0.50/\sqrt{E} \oplus 0.03$ (E in GeV)



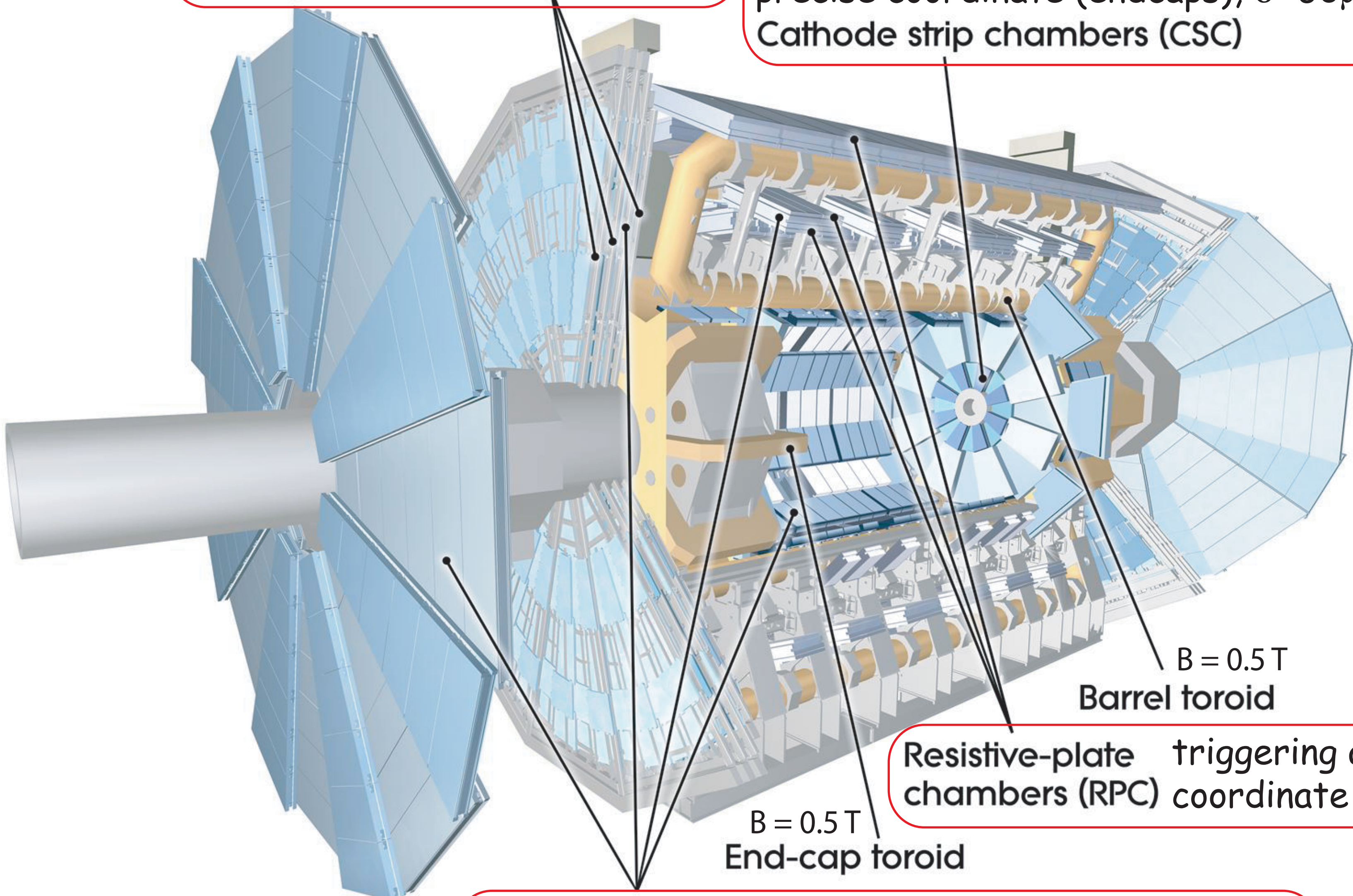
Tile calorimeter's iron is solenoid magnet's return yoke

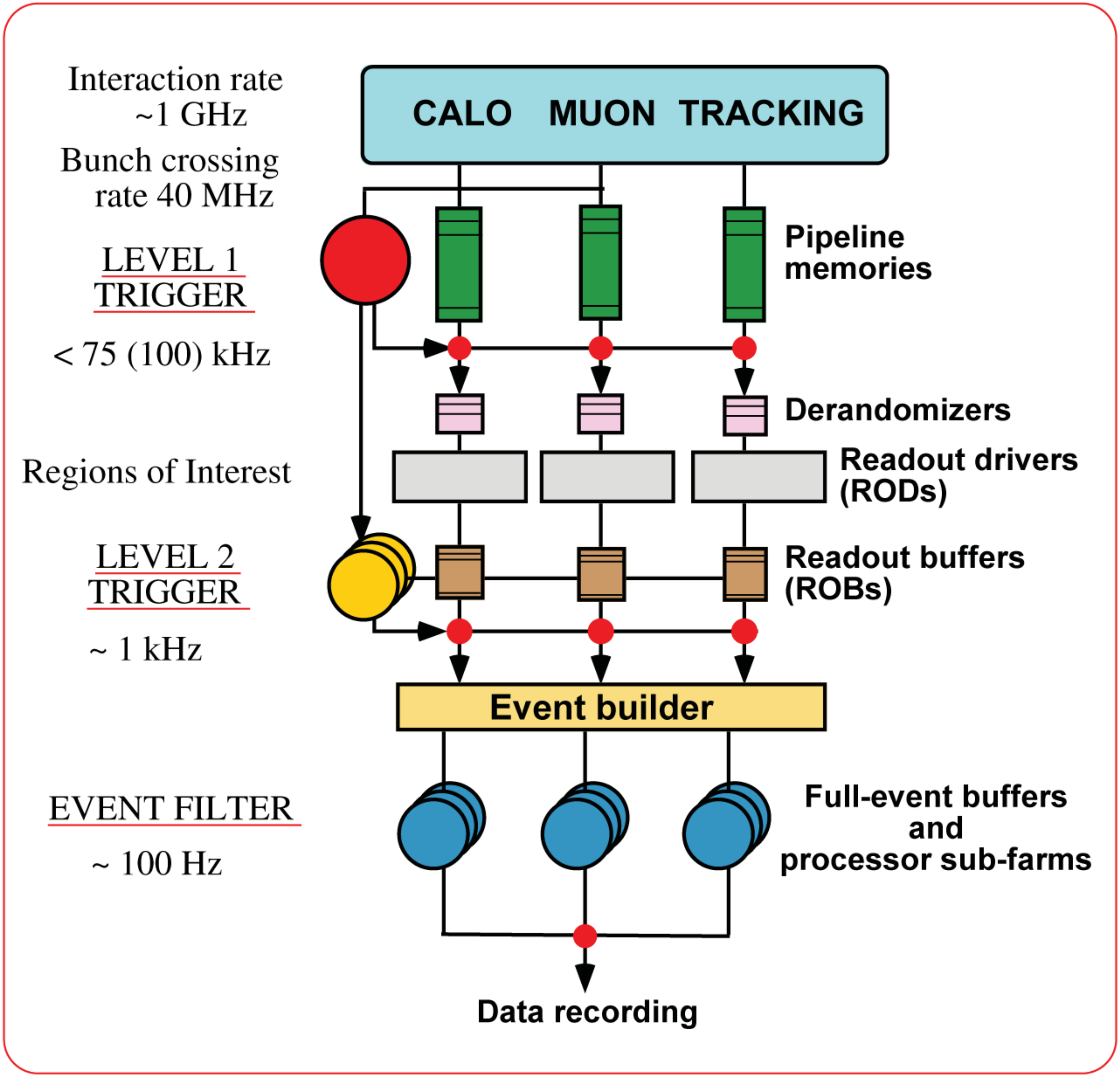
EM barrel and endcap: liquid argon / lead, $|\eta| < 3.2$
$\sigma(E)/E$ (e/γ) $\simeq 0.10/\sqrt{E} \oplus 0.007$ (E in GeV)
presampler ($|\eta| < 1.8$) + 3 layers (2 for $|\eta| > 2.5$)

Hadronic (EM) forward: liquid argon / tungsten (copper),
$3.1 < |\eta| < 4.9$, $\sigma(E)/E$ (jet) $\simeq 1.0/\sqrt{E} \oplus 0.10$ (E in GeV)
1 EM + 2 hadronic layers

Muon Spectrometer

Muon trigger and momentum resolution and coverage
$|\eta| < 2.7$, $\sigma(p_\perp)/p_\perp \leq 0.10$ ($p_\perp$ in GeV, up to ~ TeV)





Interaction rate
~1 GHz
Bunch crossing
rate 40 MHz
LEVEL 1
TRIGGER
< 75 (100) kHz
Regions of Interest
LEVEL 2
TRIGGER
~ 1 kHz
EVENT FILTER
~ 100 Hz
CALO MUON TRACKING
Pipeline
memories
Derandomizers
Readout drivers
(RODs)
Readout buffers
(ROBs)
Event builder
Full-event buffers
and
processor sub-farms
Data recording

The Price of the Higgs

16 SEPTEMBER 2011 VOL 333 SCIENCE www.sciencemag.org
Published by AAAS

Particle Physicists' New Extreme Teams

Life at the world's biggest atom smasher is an odd combination of selfless cooperation and intense competition

by Adrian Cho

The United States has gone to great lengths to keep its scientists integrated in the far-away experiments—for example, by establishing a remote center for CMS at Fermi National Accelerator Laboratory in Batavia, Illinois. Nevertheless, many make personal sacrifices to be here. Vivek Sharma of the University of California, San Diego, is co-leader of the working group within the CMS team that's searching for the Higgs boson. He spends 8 weeks at CERN for every week at home with his wife and their 7-year-old daughter.

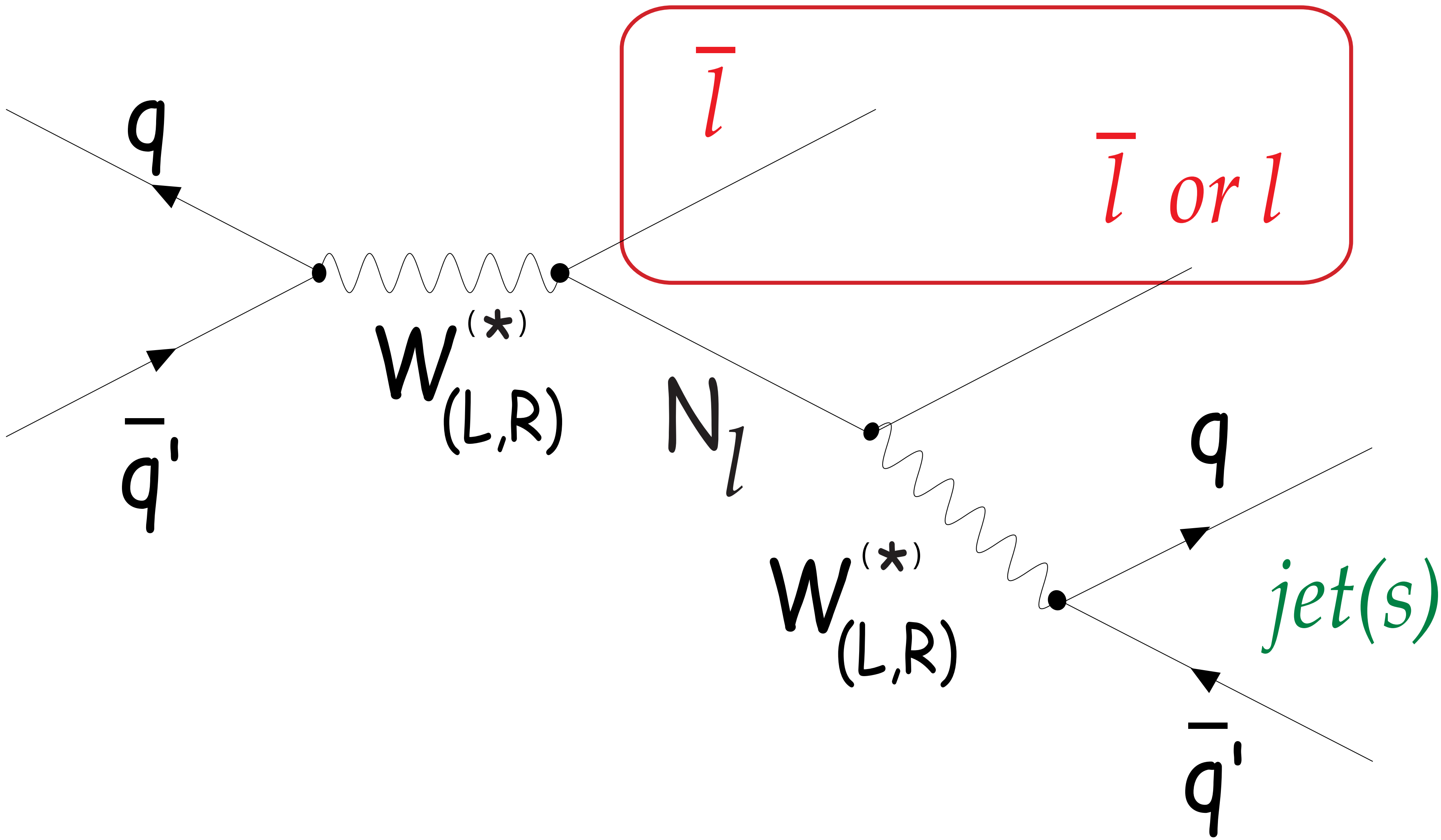
"It's more of a sacrifice for them," Sharma says. On weekends, he says, he and his family rely on Internet video links to "be" together: "When they wake up, we just put on the cameras. They go about their things and I go about mine, and we have conversations." **–A.C.**

"I don't look at it as a big collaboration, but as a small world. … It's perfect being here."
—MARTIJN MULDERS, CERN

"If you ask any physics analysis group in ATLAS, they will tell you they need more people, even with 3000 of us."
—SARA STRANDBERG, STOCKHOLM UNIVERSITY

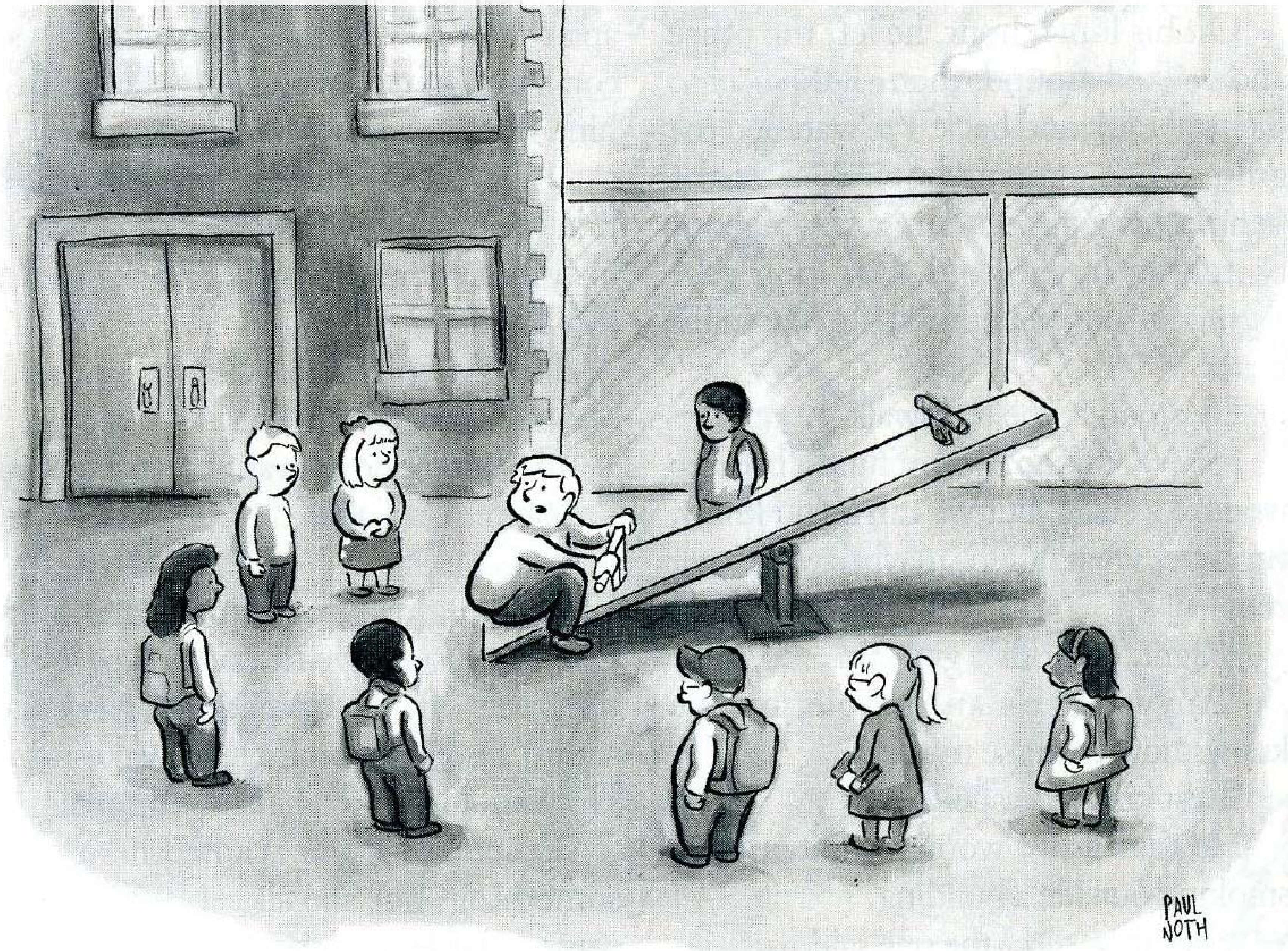
"There is the good-citizen approach, and then there is the approach 'I am better than you and I'm going to kill you.'"
—MAURIZIO PIERINI, CERN

Search for Lepton Number Violation at the LHC



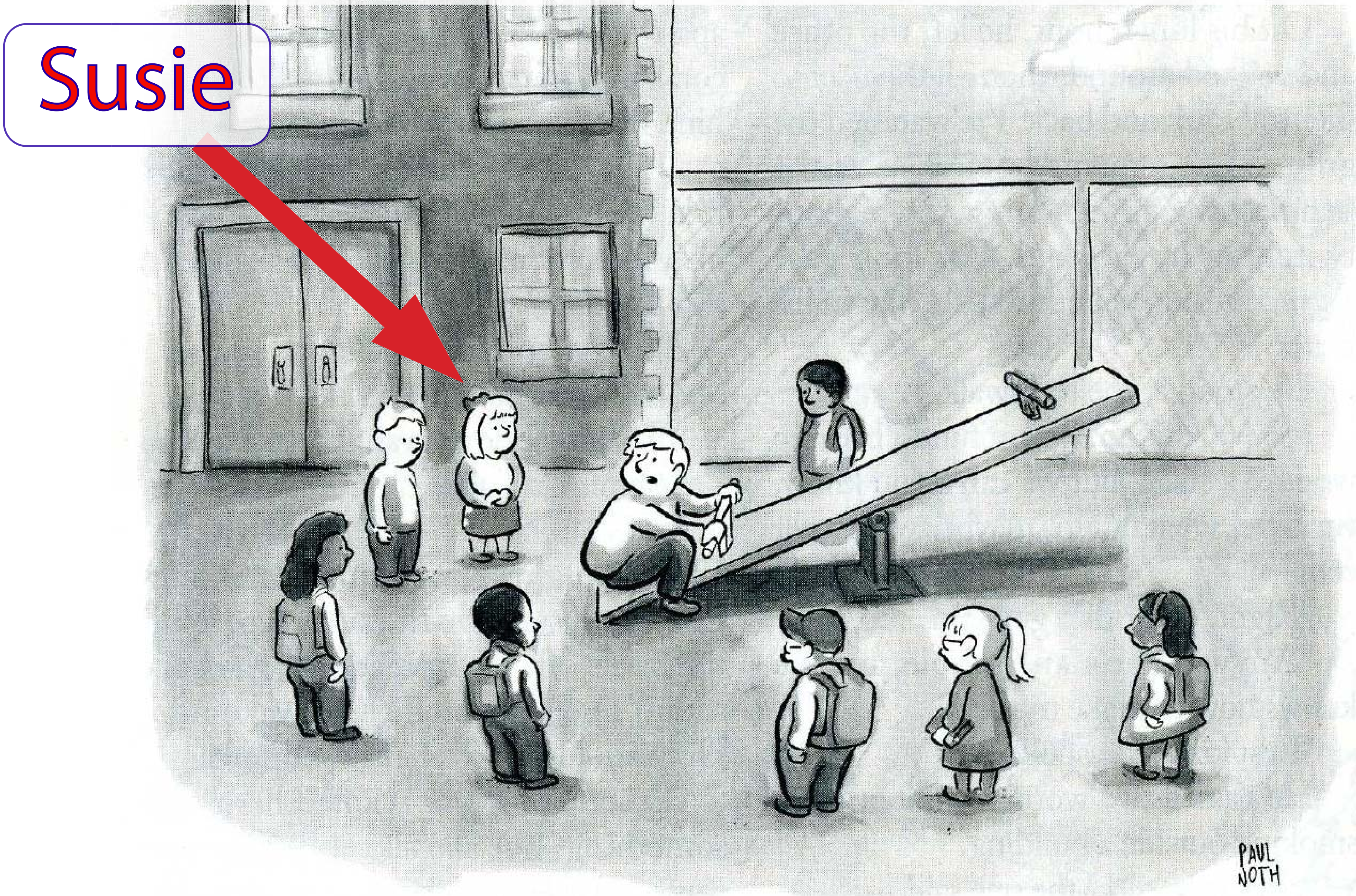
One particularly interesting (but not the only one!) scenario is Left Right Symmetry: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

The seesaw mechanism in action



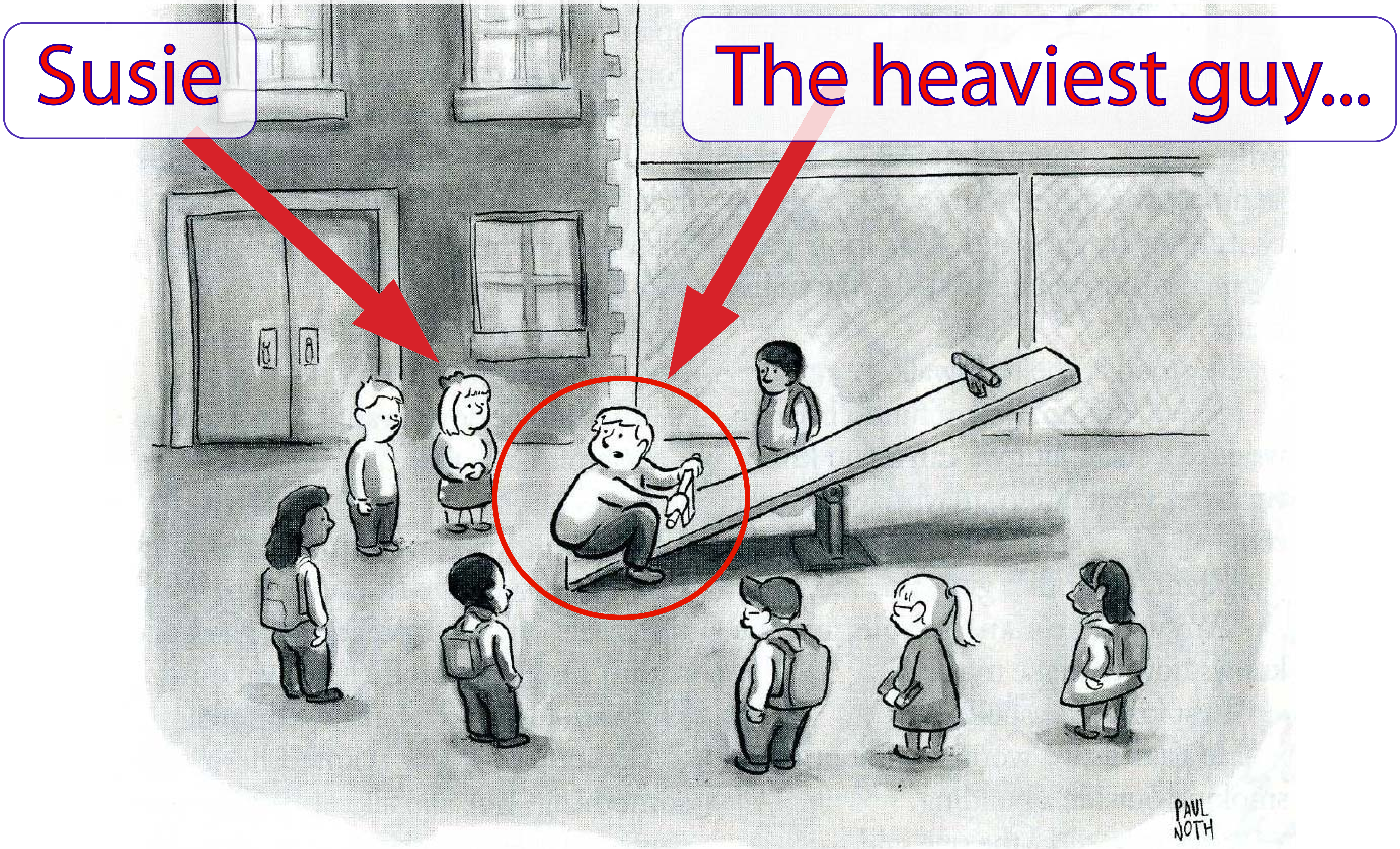
"O.K., now, when a teacher comes out, everybody look straight up."

The seesaw mechanism in action



"O.K., now, when a teacher comes out, everybody look straight up."

The seesaw mechanism in action



"O.K., now, when a teacher comes out, everybody look straight up."

R. N. Mohapatra and G. Senjanovic, *Neutrino Mass and Spontaneous Parity Violation*, Phys.Rev.Lett. **44** (1980) 912.

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F. del Aguila, S. Bar-Shalom, A. Soni, J. Wudka, *Heavy Majorana Neutrinos in the Effective Lagrangian Description: Application to Hadron Colliders*, arXiv:0806.0876 [hep-ph], Phys.Lett.B670:399-402, 2009

M. Nemevsek, G. Senjanovic, and V. Tello, *Connecting Dirac and Majorana Neutrino Mass Matrices in the Minimal Left-Right Symmetric Model*, arXiv:1211.2837 [hep-ph], PRL 110, 151802 (2013)

Our work is based on many important theoretical ideas developed before some of the LHCers were born!

Many other important papers should likely be added to this very incomplete list!

My apologies if I missed to include such papers.

Search for heavy neutrinos and right-handed W bosons in events with two leptons and jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

$2.1\ \mathrm{fb}^{-1}$

The ATLAS Collaboration*

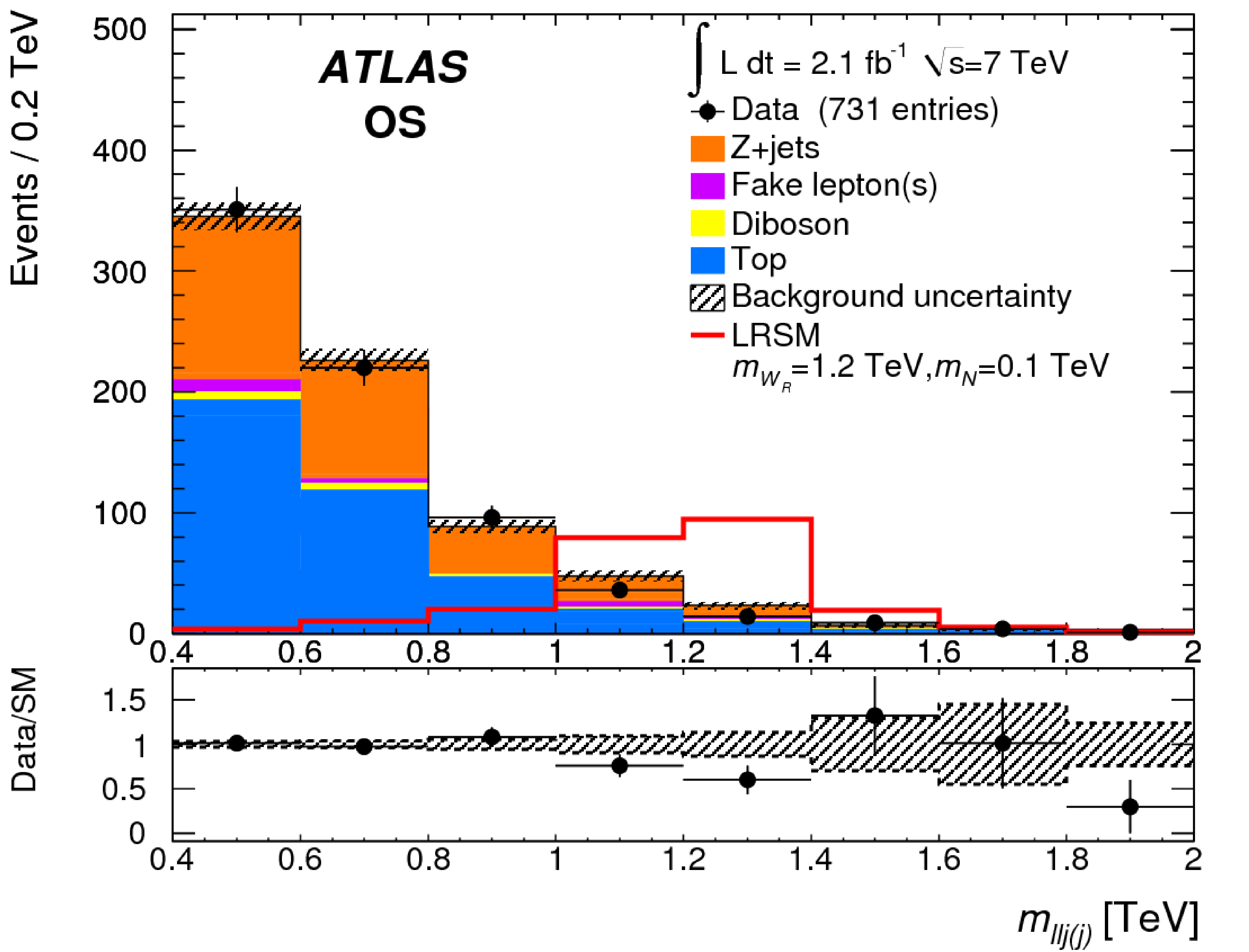
CERN, 1211 Geneva 23, Switzerland

Eur. Phys. J. C (2012) 72:2056

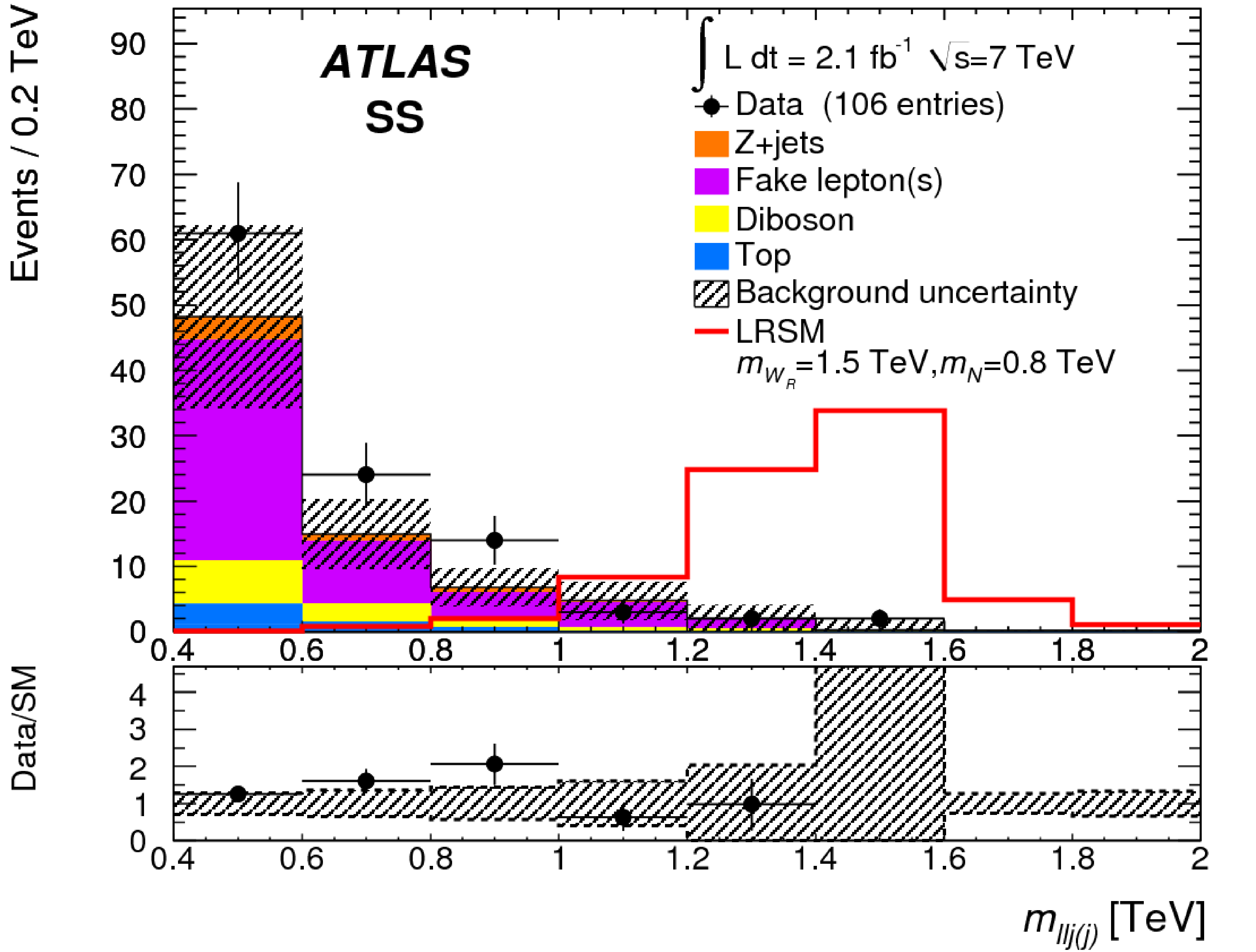
Received: 24 March 2012 / Revised: 17 May 2012 / Published online: 3 July 2012

Table 2 Summary of the expected background yields and observed numbers of events for the SS dilepton channels. The top part of the table shows the numbers obtained for events with two leptons, ≥ 1 jet and $m_{\ell\ell} > 110$ GeV. The bottom part of the table shows the numbers for the final LRSM selection, where an additional requirement $m_{\ell\ell j(j)} \geq 400$ GeV is imposed. The quoted uncertainties include statistical and systematic components, excluding the luminosity uncertainty of ± 3.7 %. The latter is relevant for all backgrounds except for the fake lepton(s) background, which is measured using data

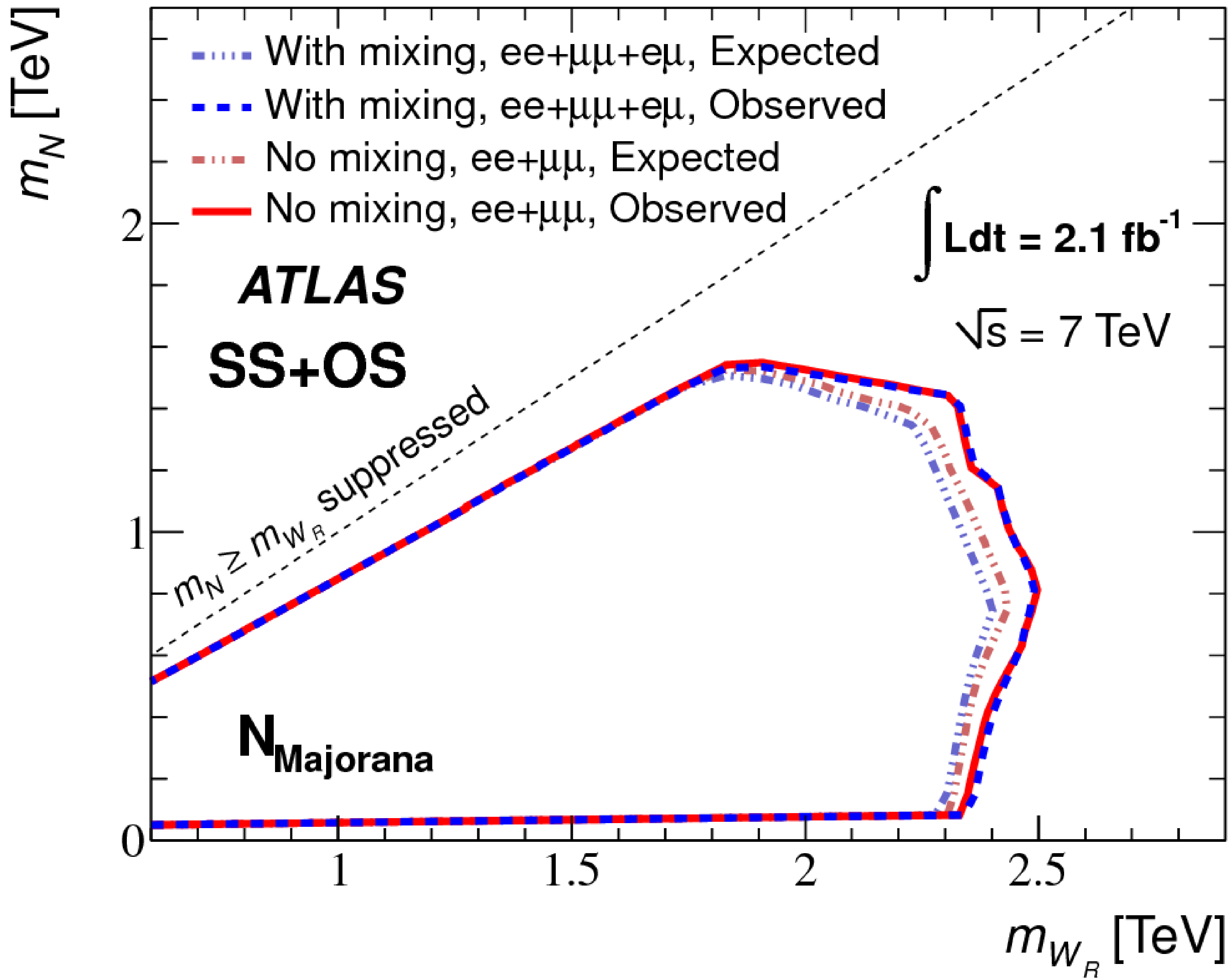
Physics processes	$e^\pm e^\pm$	$\mu^\pm\mu^\pm$	$e^\pm\mu^\pm$	Total
$Z/\gamma^* +$ jets	26.1 ± 5.6	$0.0^{+1.6}_{-0}$	1.2 ± 0.7	27 ± 6
Diboson	12.7 ± 2.3	7.2 ± 1.7	18.8 ± 3.0	39 ± 6
Top	5.8 ± 1.3	0.7 ± 0.3	6.8 ± 1.6	13 ± 3
Fake lepton(s)	93.6 ± 35.7	3.1 ± 1.6	53.8 ± 20.3	151 ± 50
Total background	138.3 ± 36.5	$11.0^{+2.9}_{-2.5}$	80.7 ± 20.8	230 ± 52
Observed events	155	14	99	268
	$m_{\ell\ell j(j)} \geq 400$ GeV			
Total background	48.4 ± 16.1	$4.4^{+2.1}_{-1.3}$	24.6 ± 7.6	77 ± 21
Observed events	59	8	39	106



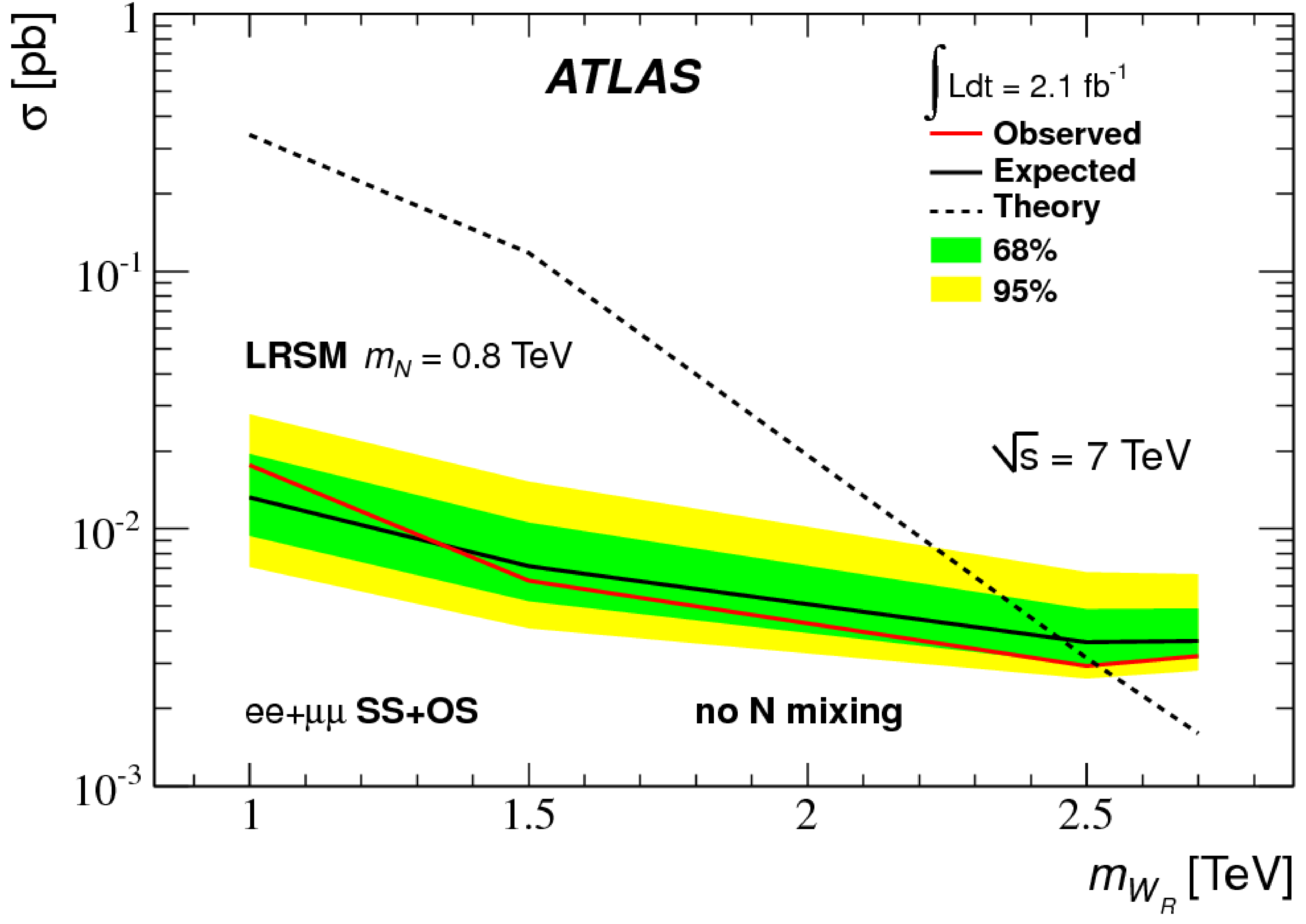
ATLAS
OS
∫ L dt = 2.1 fb-1 √s=7 TeV
Data (731 entries)
Z+jets
Fake lepton(s)
Diboson
Top
Background uncertainty
LRSM
mWR=1.2 TeV,mN=0.1 TeV
Events / 0.2 TeV
Data/SM
mllj(j) [TeV]



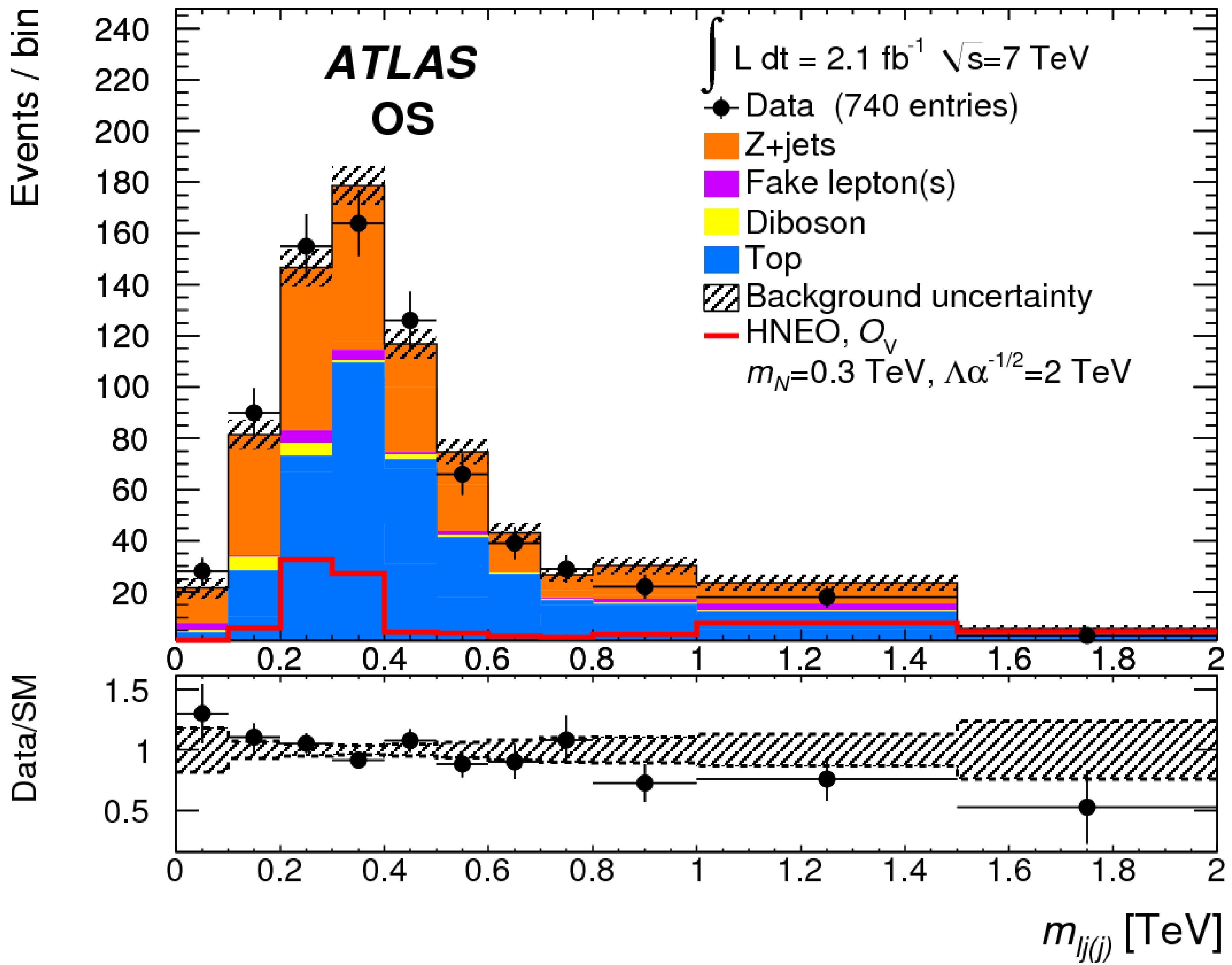
ATLAS
SS
∫ L dt = 2.1 fb-1 √s=7 TeV
Data (106 entries)
Z+jets
Fake lepton(s)
Diboson
Top
Background uncertainty
LRSM
m_{W_R}=1.5 TeV,m_N=0.8 TeV
Events / 0.2 TeV
Data/SM
$m_{llj(j)}$ [TeV]
0
10
20
30
40
50
60
70
80
90
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



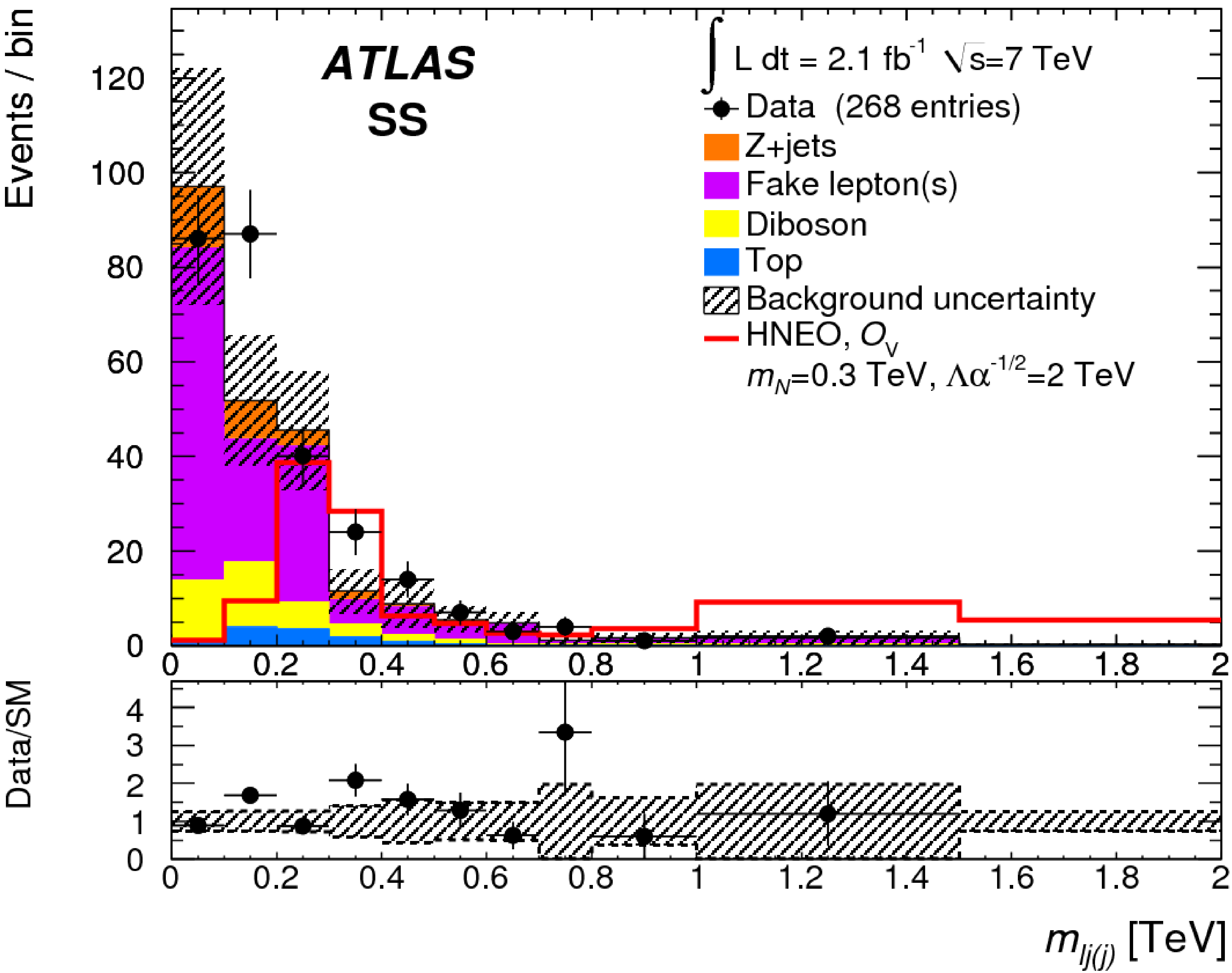
With mixing, ee+μμ+eμ, Expected
With mixing, ee+μμ+eμ, Observed
No mixing, ee+μμ, Expected
No mixing, ee+μμ, Observed
ATLAS
SS+OS
$\int$ Ldt = 2.1 fb^{-1}
$\sqrt{s}$ = 7 TeV
$m_N \geq m_{W_R}$ suppressed
N$_{Majorana}$
m_N [TeV]
m_{W_R} [TeV]
0
1
2
1
1.5
2
2.5



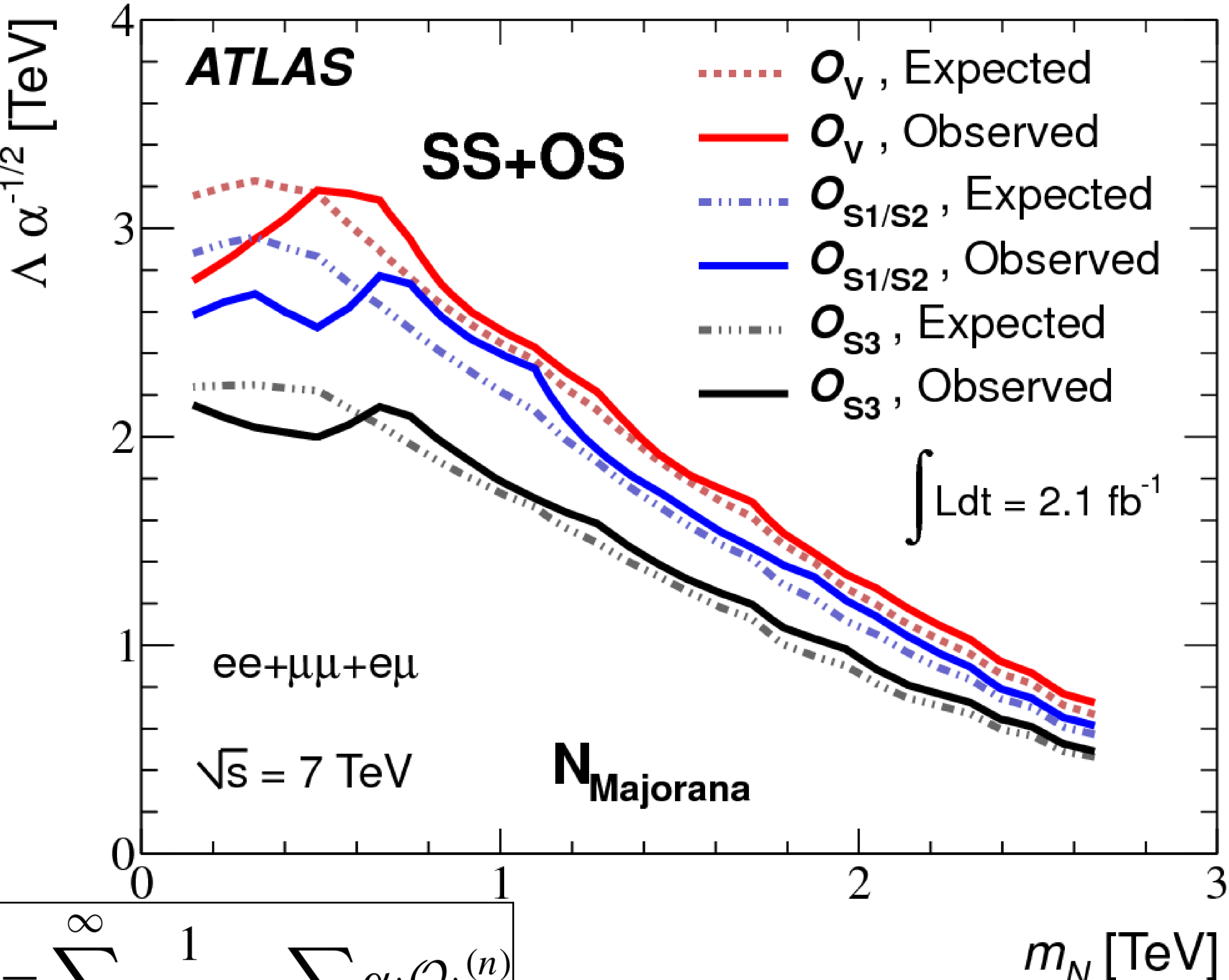
ATLAS
∫Ldt = 2.1 fb-1
Observed
Expected
Theory
68%
95%
LRSM m_N = 0.8 TeV
√s = 7 TeV
ee+μμ SS+OS
no N mixing
σ [pb]
m_{W_R} [TeV]
1
10-1
10-2
10-3
1
1.5
2
2.5



ATLAS
OS
∫ L dt = 2.1 fb^-1 √s=7 TeV
Data (740 entries)
Z+jets
Fake lepton(s)
Diboson
Top
Background uncertainty
HNEO, O_V
m_N=0.3 TeV, $\Lambda\alpha^{-1/2}$=2 TeV
Events / bin
Data/SM
$m_{lj(j)}$ [TeV]



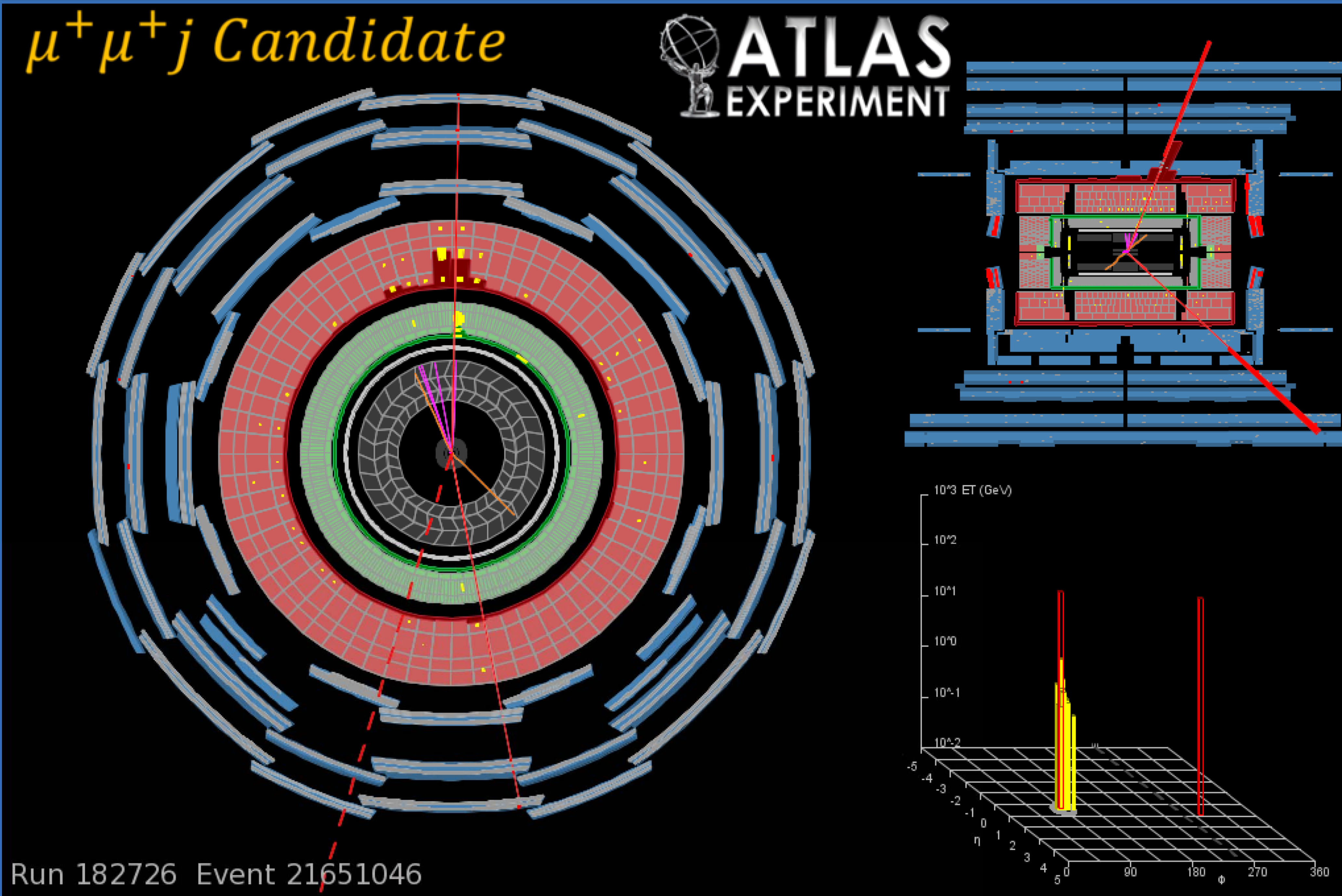
Events / bin
ATLAS
SS
$\int L\,dt = 2.1\ fb^{-1}$ $\sqrt{s}$=7 TeV
Data (268 entries)
Z+jets
Fake lepton(s)
Diboson
Top
Background uncertainty
HNEO, O_V
m_N=0.3 TeV, $\Lambda\alpha^{-1/2}$=2 TeV
0
20
40
60
80
100
120
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Data/SM
0
1
2
3
4
$m_{lj(j)}$ [TeV]



$$\mathcal{L} = \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \cdot \sum_i \alpha_i \mathcal{O}_i{}^{(n)}$$

F. Aguila, S. Bar-Shalom, A. Soni, J. Wudka, Phys. Lett. B **670**, 399 (2009)

The higher momentum muon has a PT of 187 GeV and an (eta,phi) of (-0.39,1.55). The subleading muon has PT of 183 GeV and an (eta,phi) of (0.93,-1.38). The jet has PT of 149 GeV and an (eta,phi) of (0.46,1.59). The dimuon invariant mass is 383 GeV and m(lljj) = 512 GeV. Only tracks with PT > 3 GeV are displayed.



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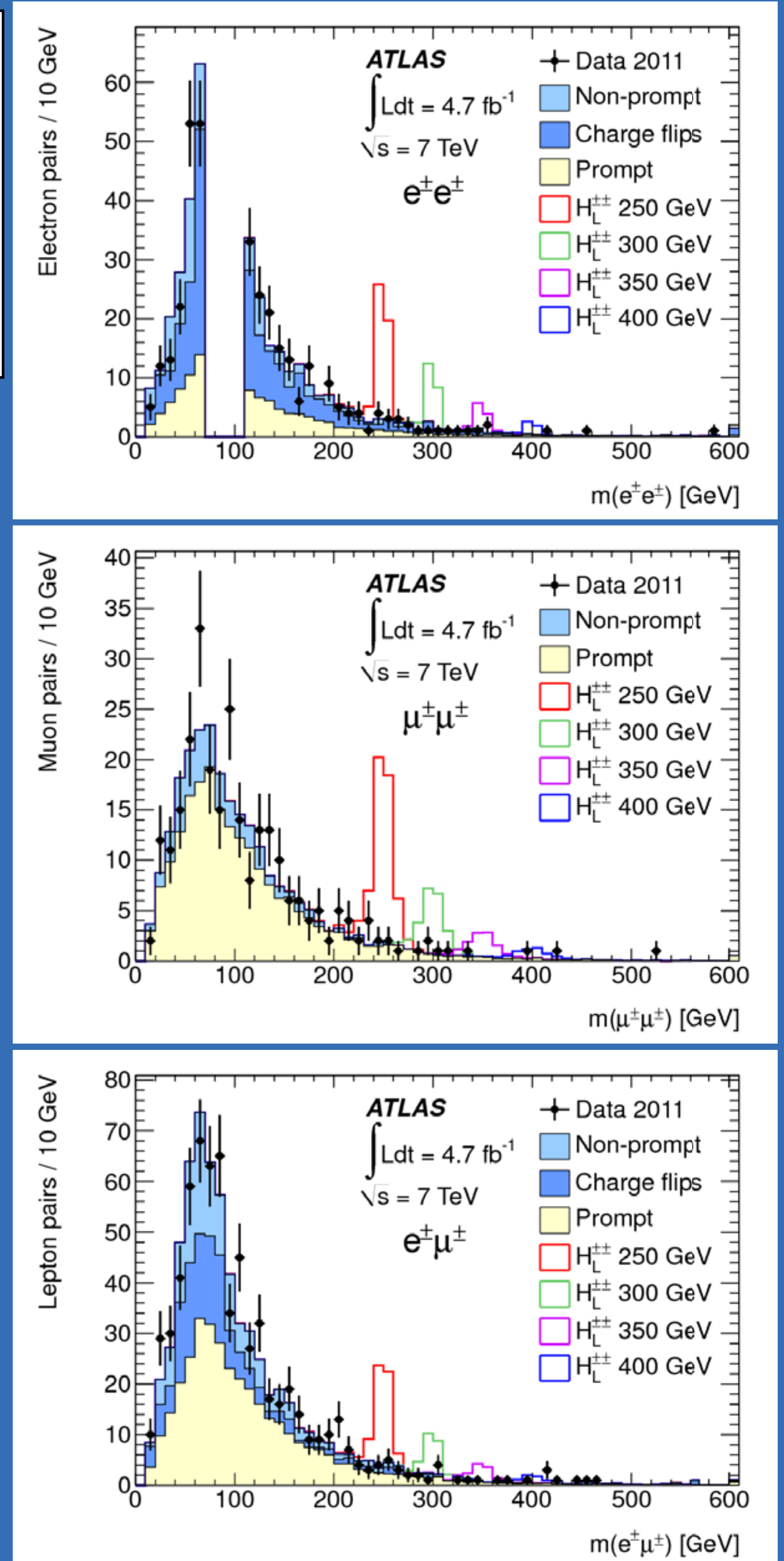
Eur. Phys. J. C (2012) 72:2244

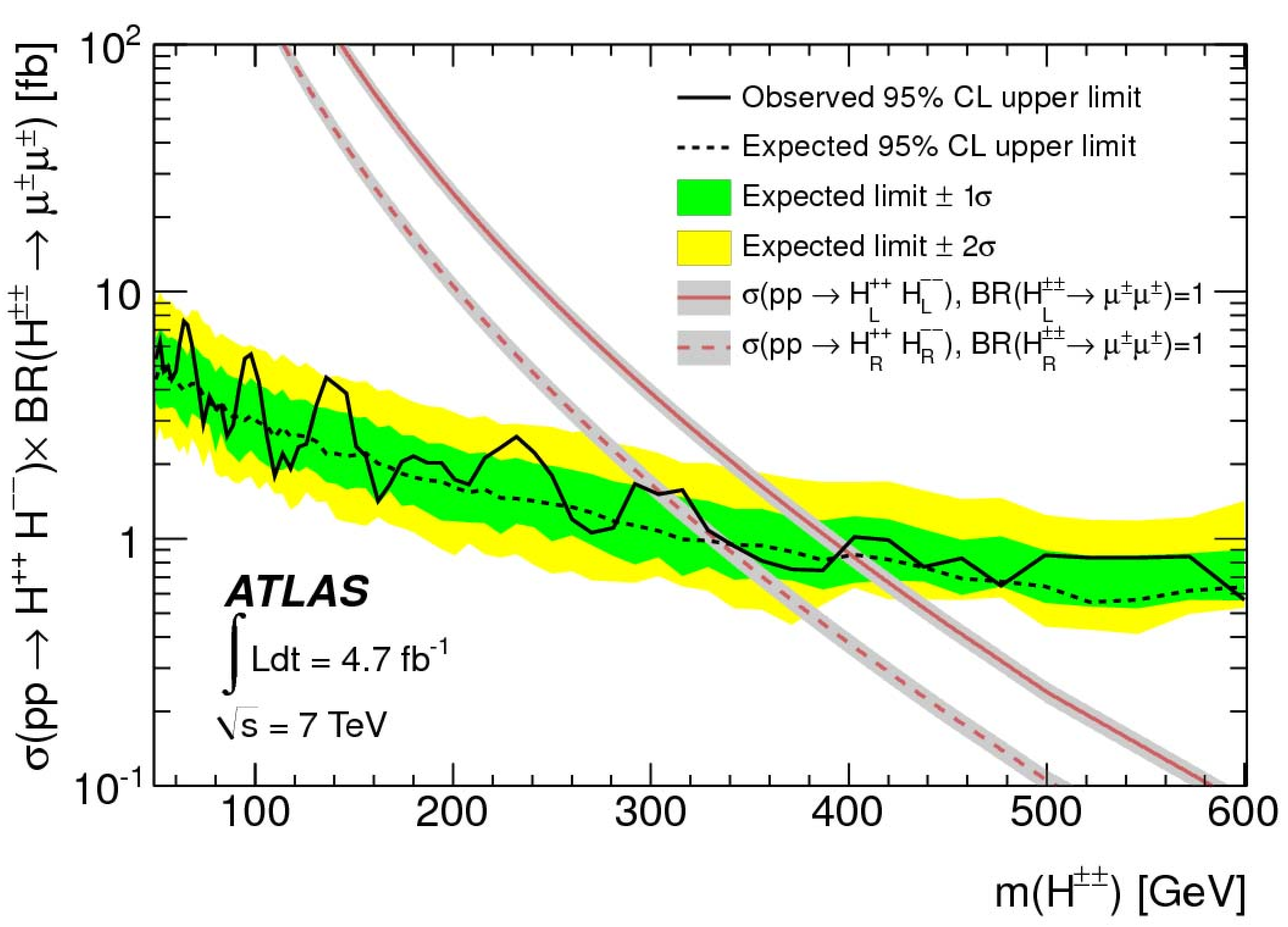
Search for doubly charged Higgs bosons in like-sign dilepton final states at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration*

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$
$$\downarrow$$
$$SU(2)_L \otimes U(1)_Y$$
$$\downarrow$$
$$U(1)_{em}$$

Abstract A search for doubly charged Higgs bosons decaying to pairs of electrons and/or muons is presented. The search is performed using a data sample corresponding to an integrated luminosity of 4.7 fb^{-1} of pp collisions at $\sqrt{s}$ = 7 TeV collected by the ATLAS detector at the LHC. Pairs of prompt, isolated, high-p_T leptons with the same electric charge ($e^\pm e^\pm$, $e^\pm\mu^\pm$, $\mu^\pm\mu^\pm$) are selected, and their invariant mass distribution is searched for a narrow resonance. No significant excess over Standard Model background expectations is observed, and limits are placed on the cross section times branching ratio for pair production of doubly charged Higgs bosons. The masses of doubly charged Higgs bosons are constrained depending on the branching ratio into these leptonic final states. Assuming pair production, coupling to left-handed fermions, and a branching ratio of 100 % for each final state, masses below 409 GeV, 375 GeV, and 398 GeV are excluded for $e^\pm e^\pm$, $e^\pm\mu^\pm$, and $\mu^\pm\mu^\pm$, respectively.





Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit ± 1σ
Expected limit ± 2σ
σ(pp → H$_L^{++}$ H$_L^{--}$), BR(H$_L^{\pm\pm}$→ μ±μ±)=1
σ(pp → H$_R^{++}$ H$_R^{--}$), BR(H$_R^{\pm\pm}$→ μ±μ±)=1
ATLAS
∫Ldt = 4.7 fb^{-1}
√s = 7 TeV
σ(pp → H^{++} H^{--})× BR(H$^{\pm\pm}$ → μ±μ±) [fb]
m(H$^{\pm\pm}$) [GeV]

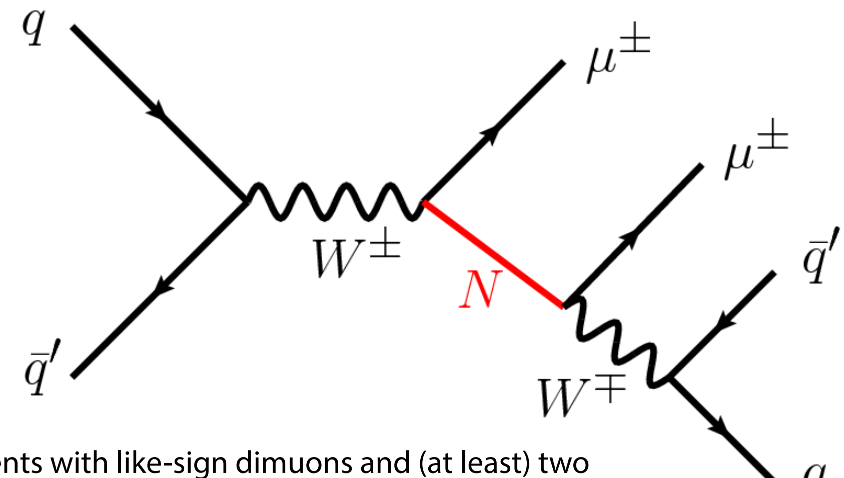
ATLAS NOTE

ATLAS-CONF-2012-139

September 25, 2012

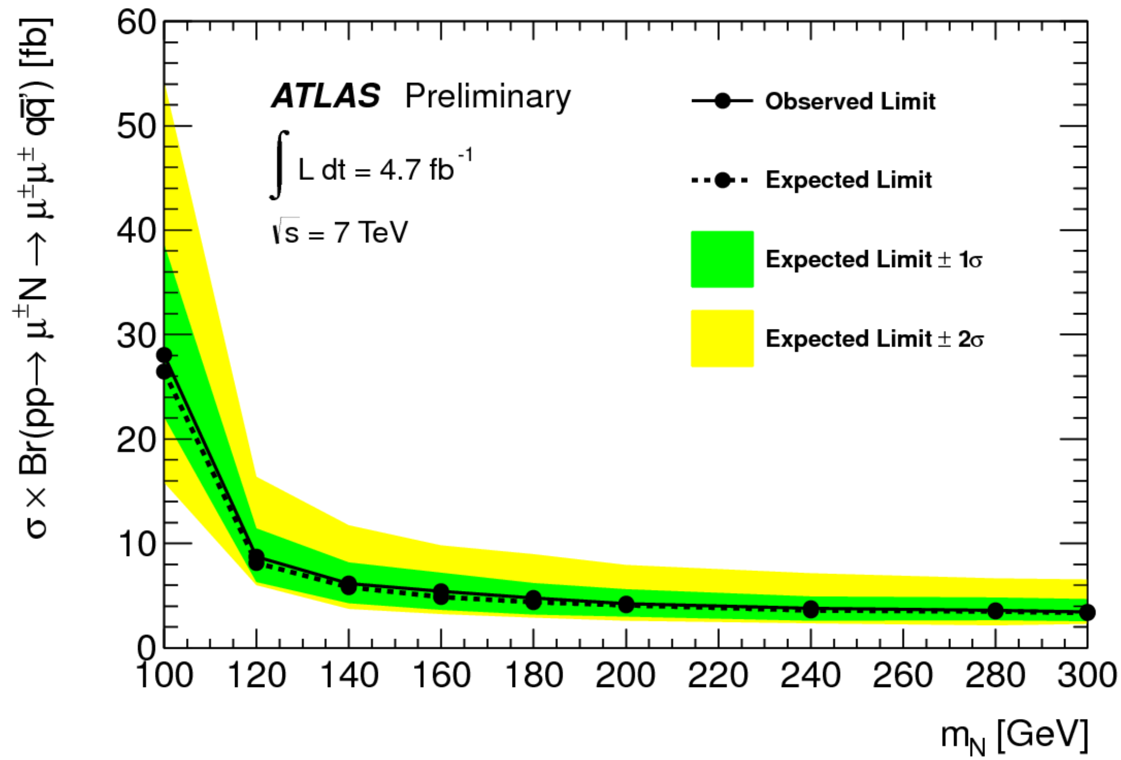
Search for Majorana neutrino production in pp collisions at $\sqrt{s} = 7$ TeV in same-sign dimuon final states with the ATLAS detector

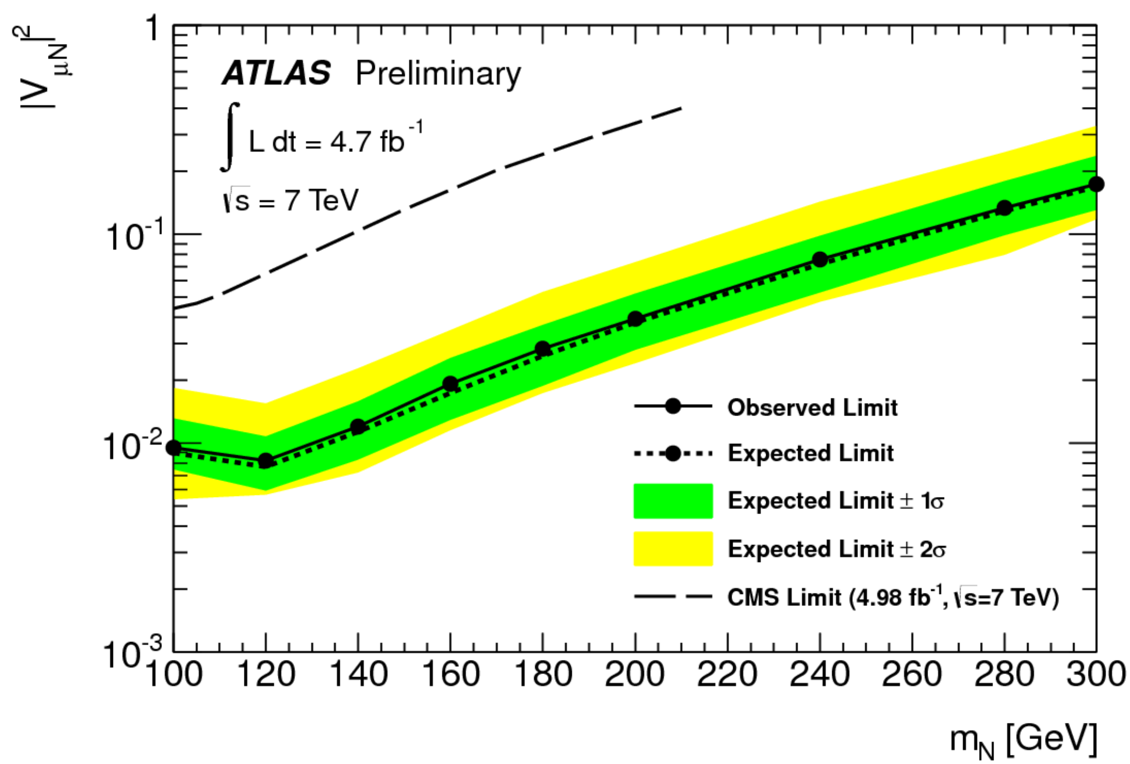
A search for a heavy Majorana neutrino decaying into a W boson and a muon has been performed using the ATLAS detector at the LHC. The search is performed using events with two same-sign muons, at least two jets and low missing transverse momentum. The data used in the search were collected in pp collisions at $\sqrt{s} = 7$ TeV in 2011 and correspond to an integrated luminosity of 4.7 fb^{-1}. No excess of events above the background prediction is observed and 95% confidence level upper limits are set on the cross section times branching ratio for the production of heavy Majorana neutrinos. The observed limits range from 28 to 3.4 fb for heavy neutrino masses between 100 and 300 GeV.



Events with like-sign dimuons and (at least) two jets (with the invariant mass around W) are selected

Source	$\mu^{\pm}\mu^{\pm}$
WZ	$1.0 \pm 0.2 \pm 0.3$
ZZ	$0.22 \pm 0.05\,^{+0.07}_{-0.06}$
$W^{\pm}W^{\pm}$	$0.15 \pm 0.04 \pm 0.08$
$t\bar{t} + V$	$0.23 \pm 0.04 \pm 0.12$
Charge mis-measurement	< 0.03
Non−prompt	$1.1 \pm 0.5\,^{+0.6}_{-0.5}$
Total background	$2.7 \pm 0.5\,^{+0.7}_{-0.6}$
Data	3





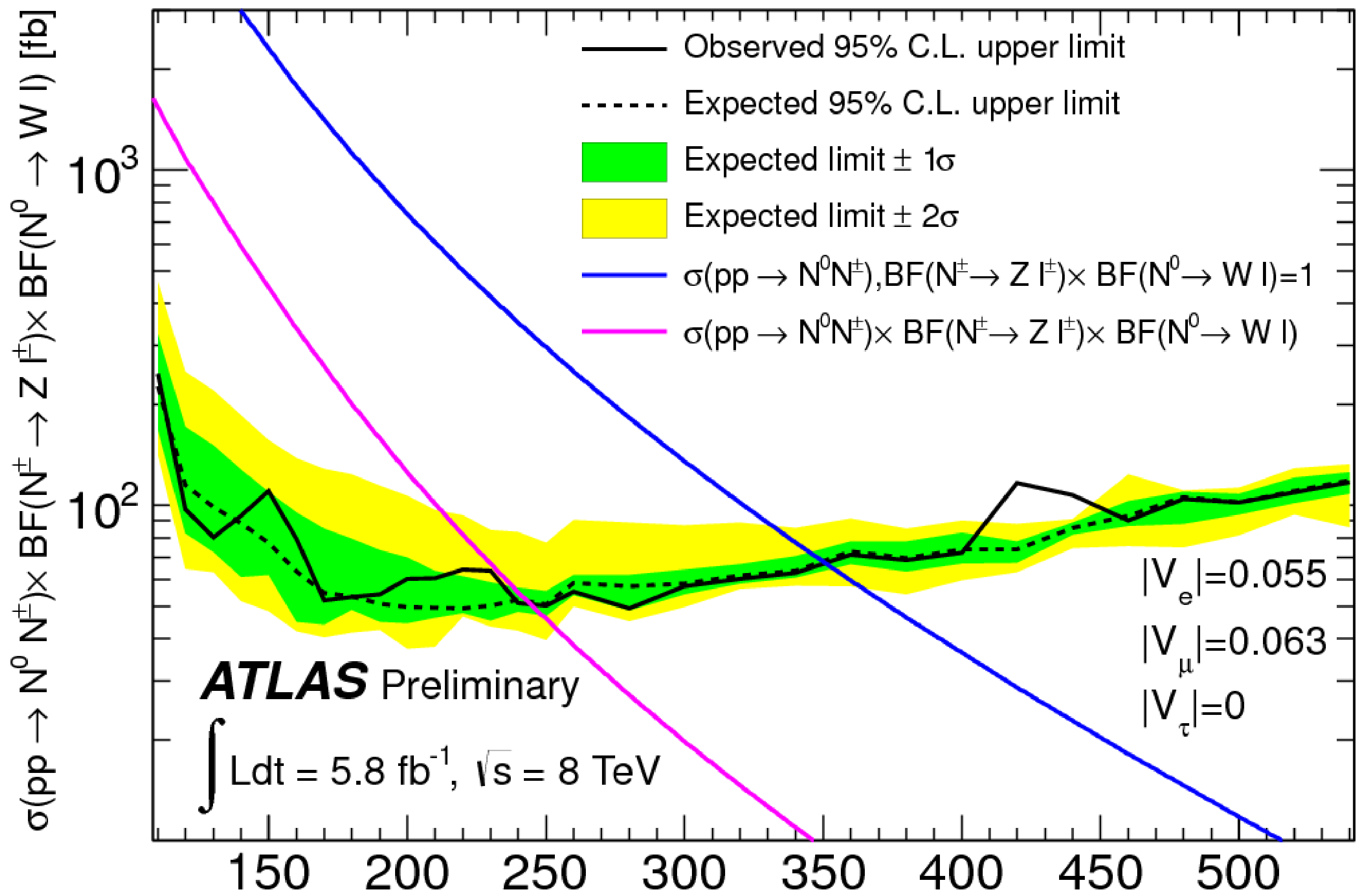
ATLAS NOTE

ATLAS-CONF-2013-019

March 7, 2013

Search for Type III Seesaw Model Heavy Fermions in Events with Four Charged Leptons using 5.8 fb^{-1} of $\sqrt{s}$ = 8 TeV data with the ATLAS Detector

A search for Type III Seesaw model heavy fermions is presented. The search is performed in a data sample corresponding to 5.8 fb^{-1} of integrated luminosity collected in 2012 in pp collisions at $\sqrt{s}$ = 8 TeV by the ATLAS detector at the LHC. Charged heavy fermions, $N^{\pm}$, are reconstructed in the channel $Z(\ell\ell)+\ell^{\pm}$ together with an additional charged lepton from the decay of a partner heavy fermion, $N^{0/\mp} \to \ell X$, where $\ell = e, \mu$. No evidence of the $N^{\pm}$ is observed. Upper limits at 95% confidence level are set on the production cross section of $N^{+}N^{0}$ times the branching fraction to the examined four lepton final states. When interpreted in the context of the Type III Seesaw model, the results translate into a lower limit on the mass of the N states of 245 GeV at 95% confidence level.



Assuming the maximal allowed mixing angles between the SM leptons and the new heavy states, i.e. using parameters |Ve|=0.055 and |Vmu|=0.063, while the mixing angle for tau leptons (|Vtau|) is taken to be 0.

ATLAS NOTE

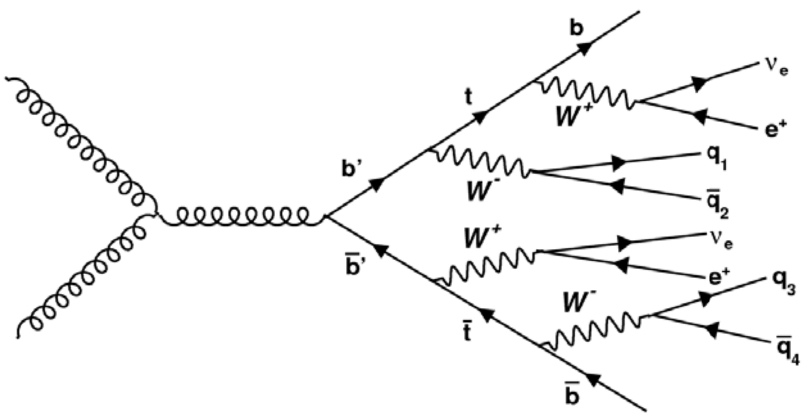
ATLAS-CONF-2013-051

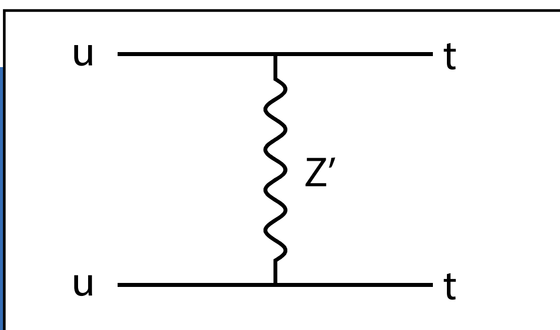
May 17, 2013

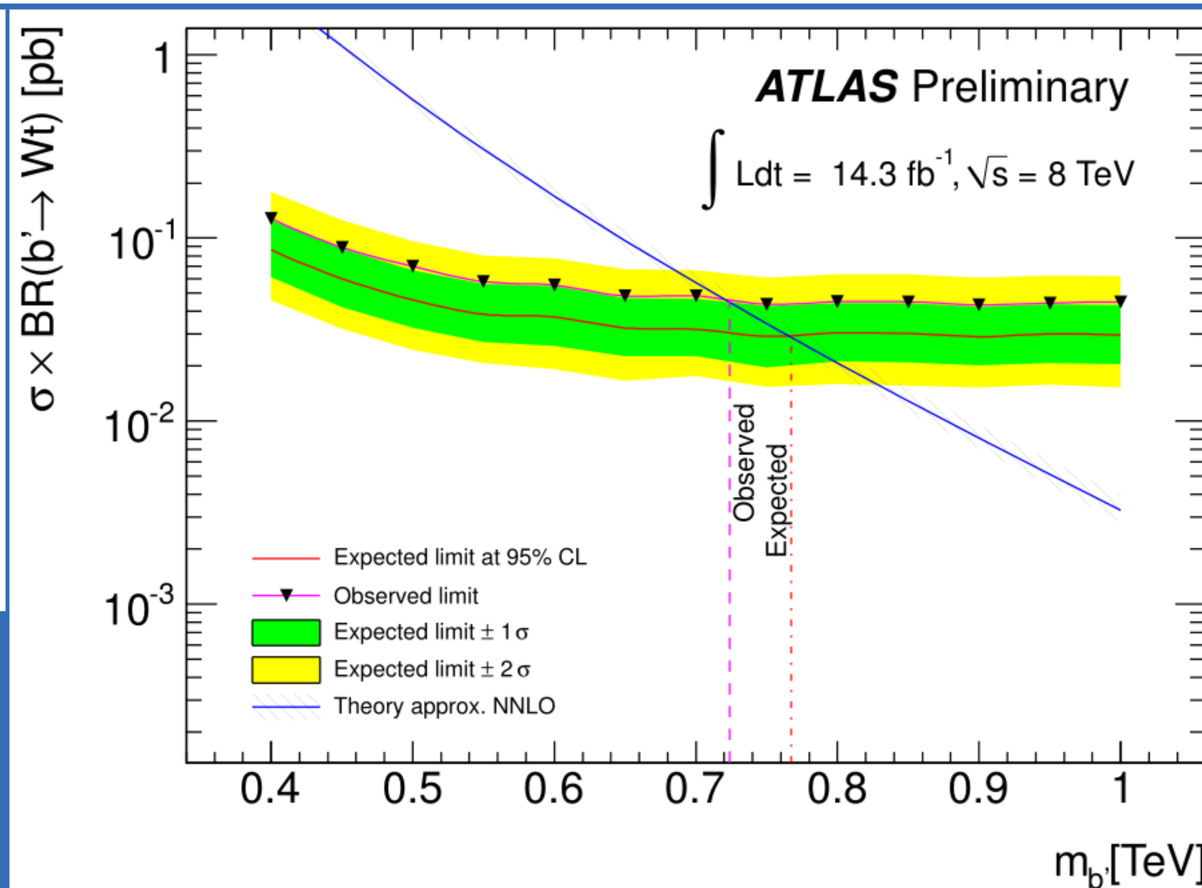
Search for anomalous production of events with same-sign dileptons and b jets in 14.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

A search is presented for exotic processes that result in final states containing jets including at least one b jet, sizable missing transverse momentum, and a pair of leptons with the same electric charge. There are several models that predict an enhanced rate of production of such events beyond the expectations of the Standard Model (SM); the ones considered in this note are pair production of chiral b' quarks, pair production of vector-like quarks, enhanced four top quark production and production of two positively-charged top quarks. Using a sample of 14.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV recorded by the ATLAS detector at the Large Hadron Collider, with selection criteria optimised for each signal, no significant excess of events over the background expectation is observed. This observation is interpreted as constraining the signal hypotheses, and it is found at 95% confidence level that: the mass of the b', assuming 100% branching fraction to Wt, must be > 0.72 TeV; the mass of a vector-like B (T) quark, assuming branching ratios to W, Z, and H decay modes consistent with the B or T being a singlet, must be > 0.59 (0.54) TeV; the four top production cross section must be < 85 fb in the SM and < 59 fb for production via a contact interaction; the mass of an sgluon must be > 0.80 TeV; in the context of models with two universal extra dimensions the inverse size of the extra dimensions must be > 0.90 TeV; and the cross section for production of two positively-charged top quarks must be < 210 fb.

Pair production of 4th generation (b') quarks, pair production of vector-like quarks, enhanced production of four top quarks, production of two positively-charged top quarks.







PHYSICAL REVIEW D **83**, 115014 (2011)

Limits on the left-right symmetry scale and heavy neutrinos from early LHC data

Miha Nemevšek,[1,2] Fabrizio Nesti,[3] Goran Senjanović,[1] and Yue Zhang[1]
[1]*ICTP, Trieste, Italy*
[2]*Jožef Stefan Institute, Ljubljana, Slovenia*
[3]*Università di Ferrara, Ferrara, Italy*
(Received 24 March 2011; published 13 June 2011)

We use the early Large Hadron Collider data to set the lower limit on the scale of left-right symmetry, by searching for the right-handed charged gauge boson W_R via the final state with two leptons and two jets, for 33 pb^{-1} integrated luminosity and 7 TeV center-of-mass energy. This signal is kinematically observable for right-handed neutrino lighter than W_R. In the absence of a signal beyond the standard model background, we set the bound $M_{W_R} \gtrsim 1.4$ TeV at 95% C.L.. This result is obtained for a range of right-handed neutrino masses of the order of few 100 GeV, assuming no accidental cancellation in right-handed lepton mixings.

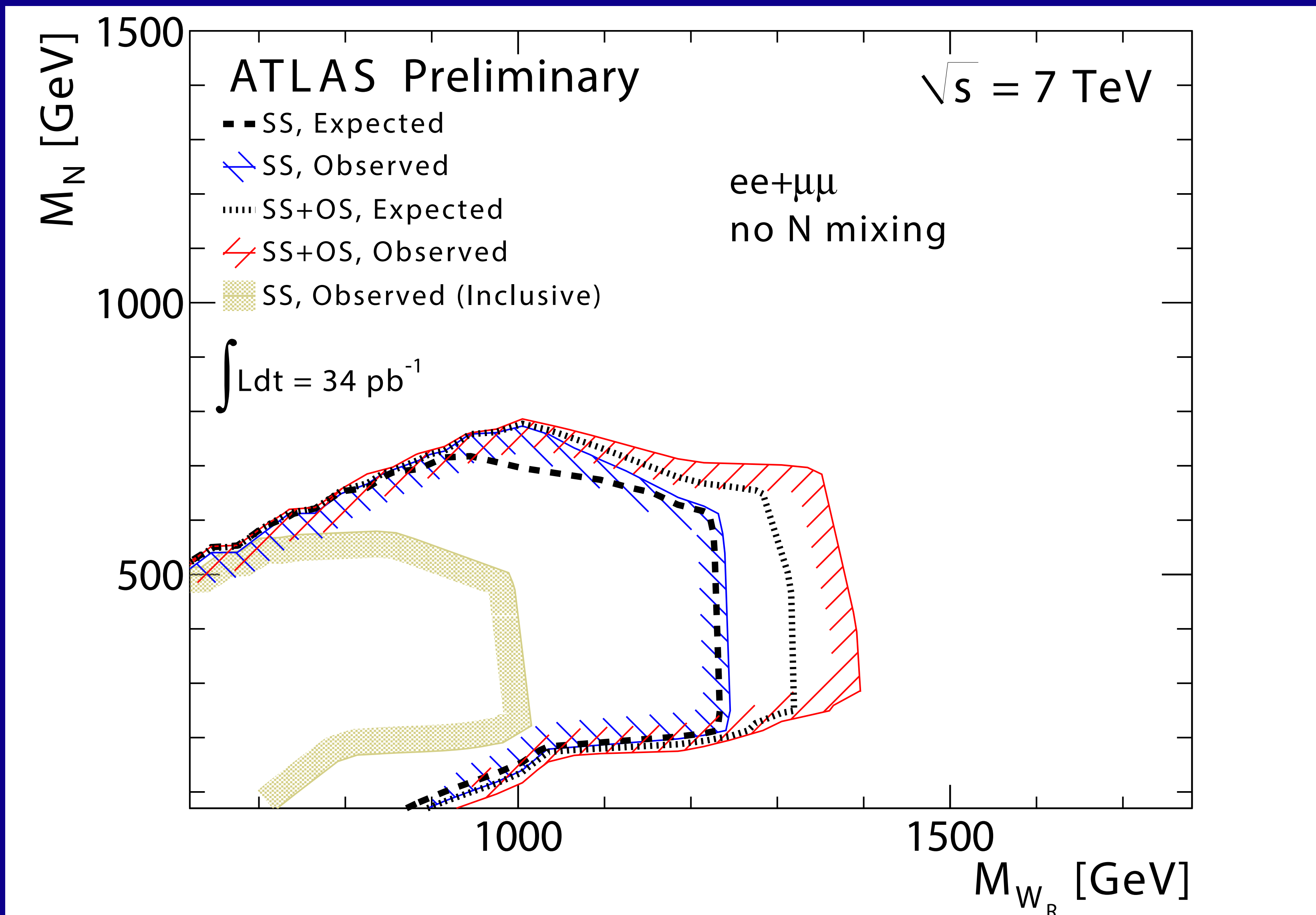
ATLAS NOTE

ATLAS-CONF-2011-115

August 2, 2011

Search for heavy Majorana neutrino and W_R in dilepton plus jets events with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration



Search for anomalous production of prompt like-sign lepton pairs at sqrt(s) = 7 TeV with the ATLAS detector

arXiv:1210.4538
JHEP12(2012)007

The ATLAS Collaboration

A search for anomalous production of like-sign lepton pairs has been presented using $4.7\,\mathrm{fb}^{-1}$ of pp collision data at $\sqrt{s} = 7\,\mathrm{TeV}$ recorded by the ATLAS experiment at the LHC. The data are found to agree with the background expectation in $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, and $\mu^{\pm}\mu^{\pm}$ final states both in overall rate and in the kinematic distributions. The data are used to constrain new physics contributions to like-sign lepton pairs within a fiducial region of two isolated leptons with large transverse momentum within the pseudorapidity range of the tracking system ($|\eta| < 2.5$). The 95% confidence level upper limits on the cross section of new physics processes within this fiducial region range between 1.7 fb and 64 fb for $\ell^{\pm}\ell^{\pm}$ pairs depending on the dilepton invariant mass and flavour combination.

This analysis (3rd generation shown today) is all that's needed to discover NP in events with two well-isolated like-sign leptons!

If *your* model predicts events with at least two well-isolated like-sign leptons, these results is all you need to estimate limits!

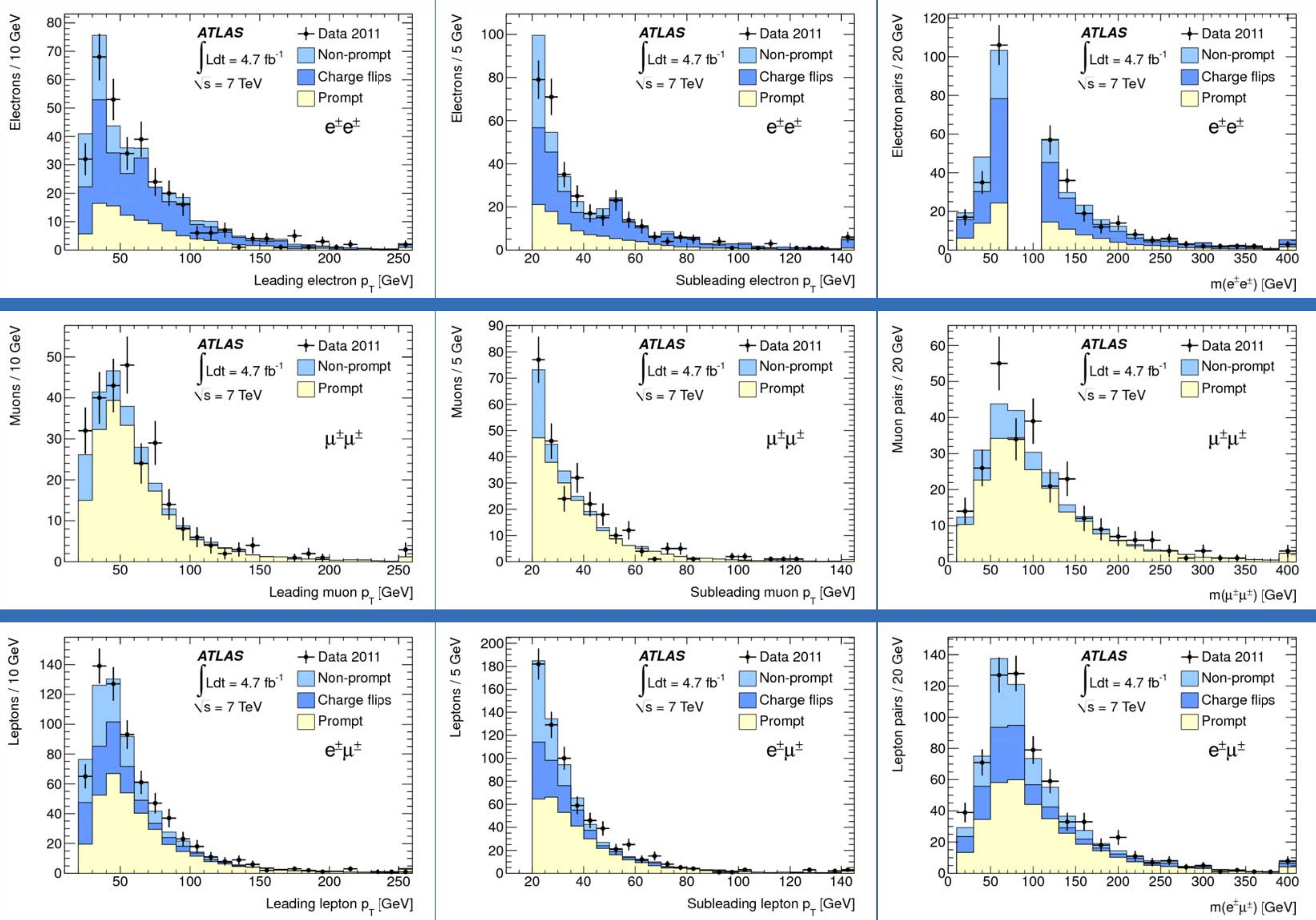
	Electron requirement	Muon requirement
Leading lepton p_T	$p_T > 25$ GeV	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 20$ GeV	$p_T > 20$ GeV
Lepton η	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	$\|\eta\| < 2.5$
Isolation	$p_T^{cone0.3}/p_T < 0.1$	$p_T^{cone0.4}/p_T < 0.06$ and $p_T^{cone0.4} < 4\text{ GeV} + 0.02 \times p_T$

For $m(\ell^\pm\ell^\pm) > 15$ GeV in the $e^\pm e^\pm$ channel, the fiducial efficiencies range from 43% for models with low-p_T leptons to 65% for models with high-p_T leptons. The primary reason for this dependence is that the electron identification efficiency varies by about 15% over the relevant p_T range [60]. The model dependence introduced by not emulating the calorimeter isolation in the definition of the fiducial region is $< 1\%$. For the $e^\pm\mu^\pm$ channel, ε_{fid} ranges from 55% to 70%, and for the $\mu^\pm\mu^\pm$ final state it varies between 59% and 72%. For the higher dilepton mass thresholds the efficiencies are slightly larger than for the lower mass thresholds. The efficiencies are also derived for $\ell^+\ell^+$ and $\ell^-\ell^-$ pairs separately and found to be independent of the charge. For the same new physics models, the fraction of events satisfying the experimental selection originating from outside the fiducial region ranges from $< 1\%$ to about 9%, depending on the final state and the model considered.

To derive the upper limit on the fiducial cross section, the lowest efficiency values are taken for all mass thresholds, i.e. 43% for the $e^\pm e^\pm$, 55% for the $e^\pm\mu^\pm$, and 59% for the $\mu^\pm\mu^\pm$ analysis.

Check the paper when applying to your model!

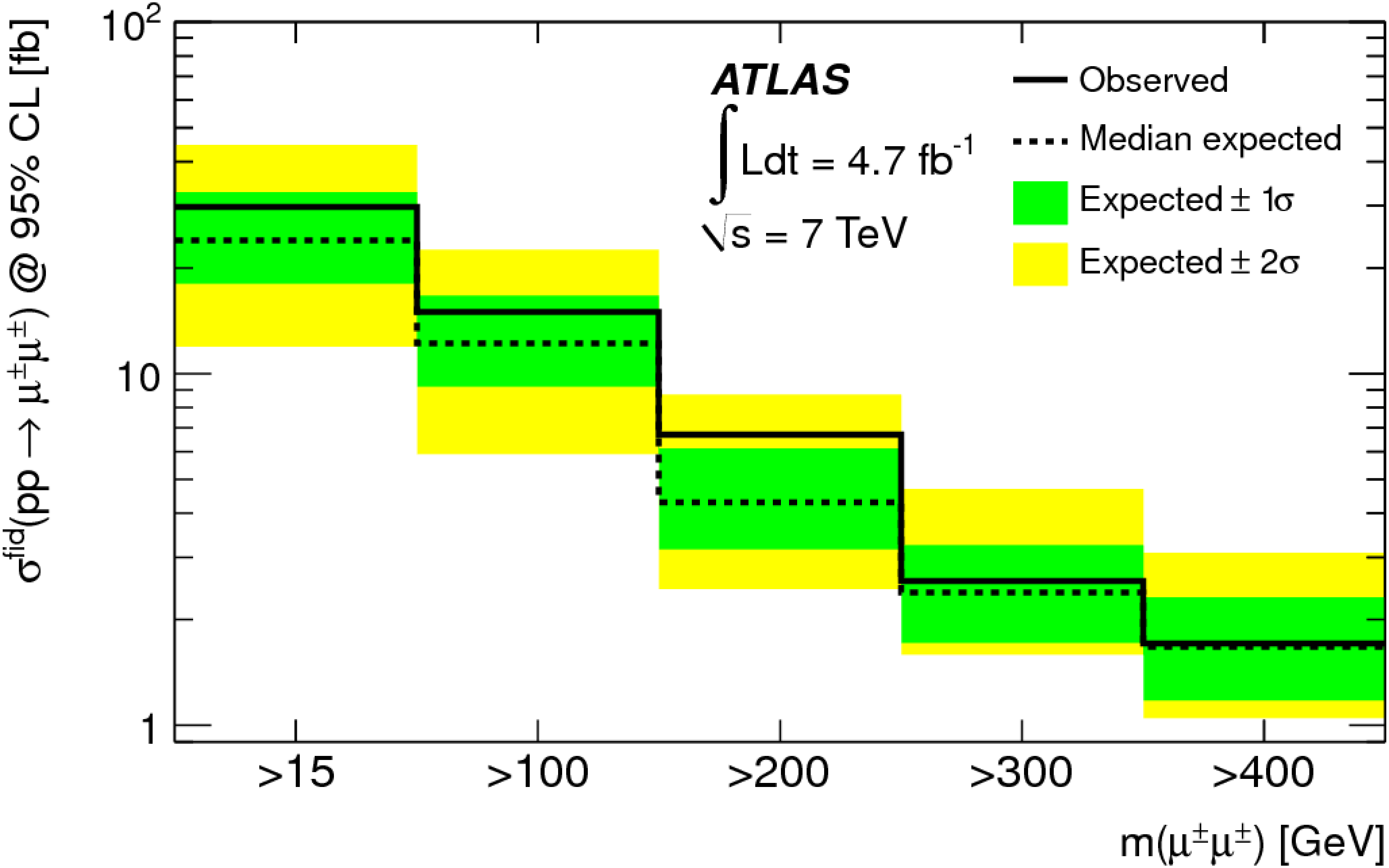
ATLAS, arXiv:1210.4538 [hep-ex], JHEP12(2012)007



Sample	Number of electron pairs with $m(e^{\pm}e^{\pm})$				
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV	> 400 GeV
Prompt	101 ± 13	56.3 ± 7.2	14.8 ± 2.0	4.3 ± 0.7	1.4 ± 0.3
Non-prompt	75 ± 21	28.8 ± 8.6	5.8 ± 2.5	$0.5^{+0.8}_{-0.5}$	$0.0^{+0.2}_{-0.0}$
Charge flips and conversions	170 ± 33	91 ± 16	22.1 ± 4.4	8.0 ± 1.7	3.4 ± 0.8
Sum of backgrounds	346 ± 44	176 ± 21	42.8 ± 5.7	12.8 ± 2.1	4.8 ± 0.9
Data	329	171	38	10	3
	Number of muon pairs with $m(\mu^{\pm}\mu^{\pm})$				
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV	> 400 GeV
Prompt	205 ± 26	90 ± 11	21.8 ± 2.8	5.8 ± 0.9	2.2 ± 0.4
Non-prompt	42 ± 14	12.1 ± 4.6	1.0 ± 0.6	$0.0^{+0.3}_{-0.0}$	$0.0^{+0.3}_{-0.0}$
Charge flips	$0.0^{+4.9}_{-0.0}$	$0.0^{+2.5}_{-0.0}$	$0.0^{+1.8}_{-0.0}$	$0.0^{+1.7}_{-0.0}$	$0.0^{+1.7}_{-0.0}$
Sum of backgrounds	247^{+30}_{-29}	102 ± 12	$22.8^{+3.4}_{-2.9}$	$5.8^{+1.9}_{-0.9}$	$2.2^{+1.7}_{-0.4}$
Data	264	110	29	6	2
	Number of lepton pairs with $m(e^{\pm}\mu^{\pm})$				
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV	> 400 GeV
Prompt	346 ± 43	157 ± 20	36.6 ± 4.7	10.8 ± 1.5	3.9 ± 0.6
Non-prompt	151 ± 47	45 ± 13	9.2 ± 4.1	2.6 ± 1.1	1.0 ± 0.6
Charge flips and conversions	142 ± 28	33 ± 7	10.5 ± 2.8	2.9 ± 1.2	2.2 ± 1.1
Sum of backgrounds	639 ± 71	235 ± 25	56.4 ± 7.0	16.3 ± 2.3	7.0 ± 1.4
Data	658	259	61	17	7

Sample	Number of lepton pairs with $m(\ell^{\pm}\ell^{\pm})$				
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV	> 400 GeV
	e^+e^+ pairs				
Sum of backgrounds	208 ± 28	112 ± 14	28.6 ± 4.0	8.5 ± 1.4	3.3 ± 0.7
Data	183	93	26	6	1
	e^-e^- pairs				
Sum of backgrounds	138 ± 21	63.3 ± 8.5	14.2 ± 2.3	4.4 ± 0.8	$1.54^{+0.4}_{-0.3}$
Data	146	78	12	4	2
	$\mu^+\mu^+$ pairs				
Sum of backgrounds	147 ± 17	$63.7^{+7.7}_{-7.6}$	$14.5^{+2.1}_{-1.9}$	$4.1^{+1.1}_{-0.6}$	$1.6^{+0.9}_{-0.3}$
Data	144	60	16	4	2
	$\mu^-\mu^-$ pairs				
Sum of backgrounds	100 ± 12	$38.4^{+5.0}_{-4.8}$	$8.3^{+1.5}_{-1.2}$	$1.7^{+0.9}_{-0.3}$	$0.6^{+0.9}_{-0.1}$
Data	120	50	13	2	0
	$e^+\mu^+$ pairs				
Sum of backgrounds	381 ± 42	142 ± 15	33.8 ± 5.3	9.8 ± 1.5	4.2 ± 0.9
Data	375	149	39	9	4
	$e^-\mu^-$ pairs				
Sum of backgrounds	259 ± 31	93 ± 10	22.6 ± 3.0	6.5 ± 1.3	2.9 ± 1.0
Data	283	110	22	8	3

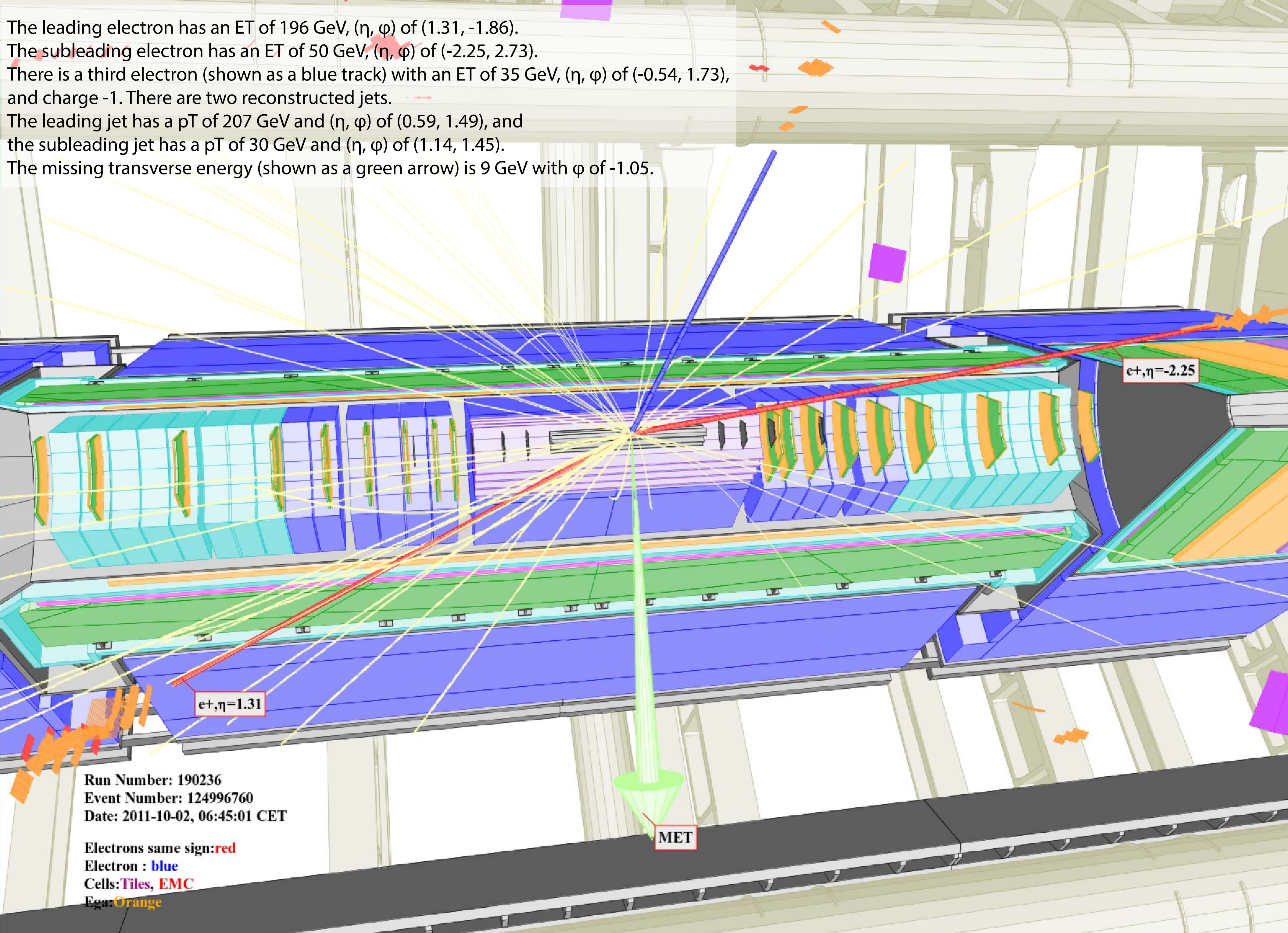
ATLAS, arXiv:1210.4538 [hep-ex], JHEP12(2012)007



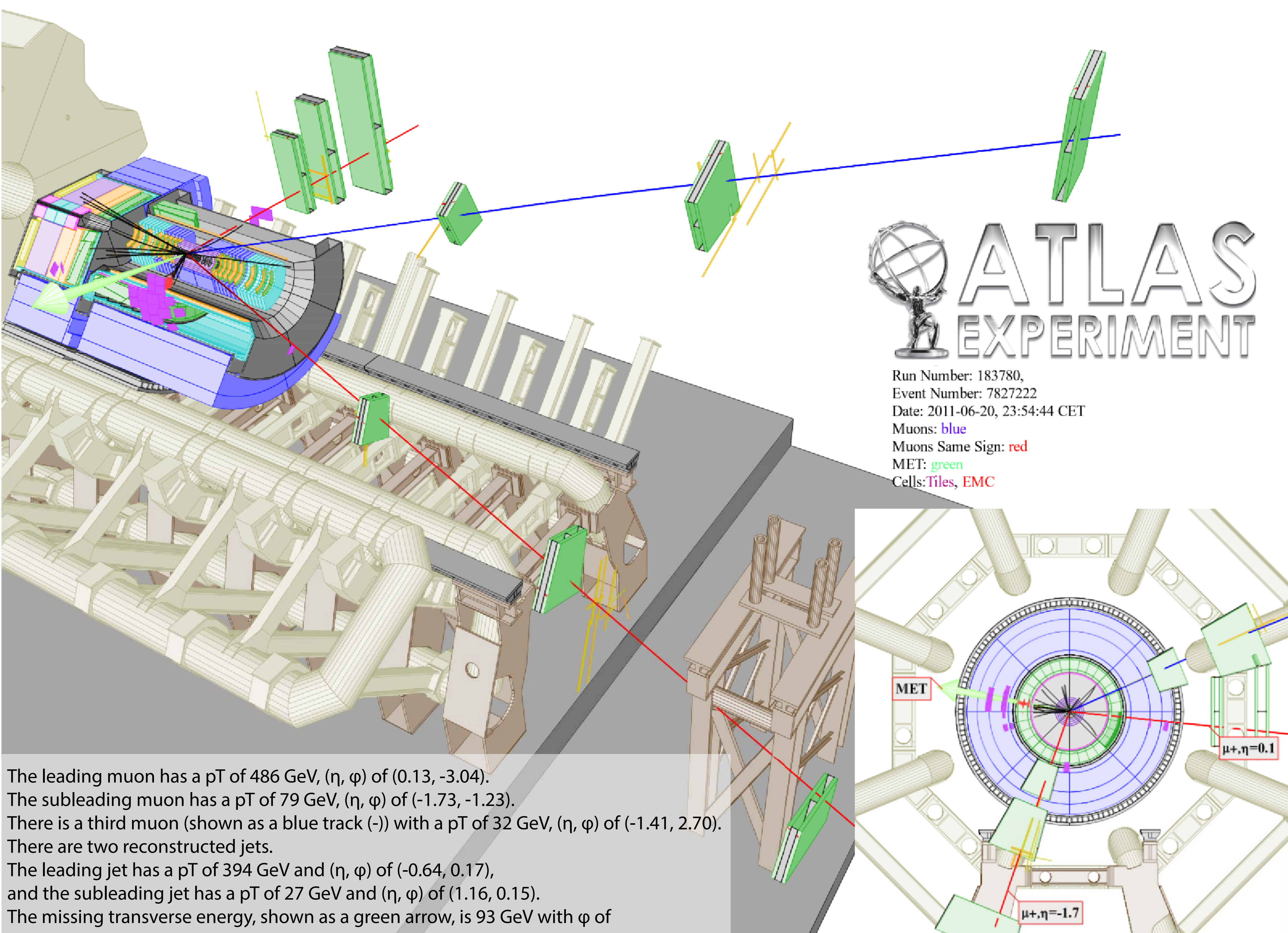
An example of a 95% CL upper limit on NP cross section in fiducial region

Mass range	$e^{\pm}e^{\pm}$ expected	$e^{\pm}e^{\pm}$ observed	$e^{\pm}\mu^{\pm}$ expected	$e^{\pm}\mu^{\pm}$ observed	$\mu^{\pm}\mu^{\pm}$ expected	$\mu^{\pm}\mu^{\pm}$ observed
	95% C.L. upper limit [fb]					
$m > 15$ GeV	46^{+15}_{-12}	42	56^{+23}_{-15}	64	$24.0^{+8.9}_{-6.0}$	29.8
$m > 100$ GeV	$24.1^{+8.9}_{-6.2}$	23.4	$23.0^{+9.1}_{-6.7}$	31.2	$12.2^{+4.5}_{-3.0}$	15.0
$m > 200$ GeV	$8.8^{+3.4}_{-2.1}$	7.5	$8.4^{+3.4}_{-1.7}$	9.8	$4.3^{+1.8}_{-1.1}$	6.7
$m > 300$ GeV	$4.5^{+1.8}_{-1.3}$	3.9	$4.1^{+1.8}_{-0.9}$	4.6	$2.4^{+0.9}_{-0.7}$	2.6
$m > 400$ GeV	$2.9^{+1.1}_{-0.8}$	2.4	$3.0^{+1.0}_{-0.8}$	3.1	$1.7^{+0.6}_{-0.5}$	1.7
	$e^{+}e^{+}$		$e^{+}\mu^{+}$		$\mu^{+}\mu^{+}$	
$m > 15$ GeV	$29.1^{+10.2}_{-8.6}$	22.8	$34.9^{+12.2}_{-8.6}$	34.1	$15.0^{+6.1}_{-3.3}$	15.2
$m > 100$ GeV	$16.1^{+5.9}_{-4.3}$	12.0	$15.4^{+5.9}_{-4.1}$	18.0	$8.4^{+3.2}_{-2.4}$	7.9
$m > 200$ GeV	$7.0^{+2.9}_{-2.2}$	6.1	$6.6^{+3.5}_{-1.8}$	8.8	$3.5^{+1.6}_{-0.7}$	4.3
$m > 300$ GeV	$3.7^{+1.4}_{-1.0}$	2.9	$3.2^{+1.2}_{-0.9}$	3.2	$2.0^{+0.8}_{-0.5}$	2.1
$m > 400$ GeV	$2.3^{+1.1}_{-0.6}$	1.7	$2.4^{+0.9}_{-0.6}$	2.5	$1.5^{+0.6}_{-0.3}$	1.8
	$e^{-}e^{-}$		$e^{-}\mu^{-}$		$\mu^{-}\mu^{-}$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7	$26.2^{+10.6}_{-7.6}$	34.4	$12.1^{+4.5}_{-3.5}$	18.5
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7	$11.5^{+4.2}_{-3.5}$	16.9	$6.0^{+2.3}_{-1.9}$	10.1
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0	$4.6^{+2.1}_{-1.2}$	4.5	$2.7^{+1.1}_{-0.7}$	4.4
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7	$2.7^{+1.1}_{-0.6}$	3.5	$1.5^{+0.8}_{-0.3}$	1.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3	$2.3^{+0.8}_{-0.5}$	2.5	$1.2^{+0.4}_{-0.0}$	1.2

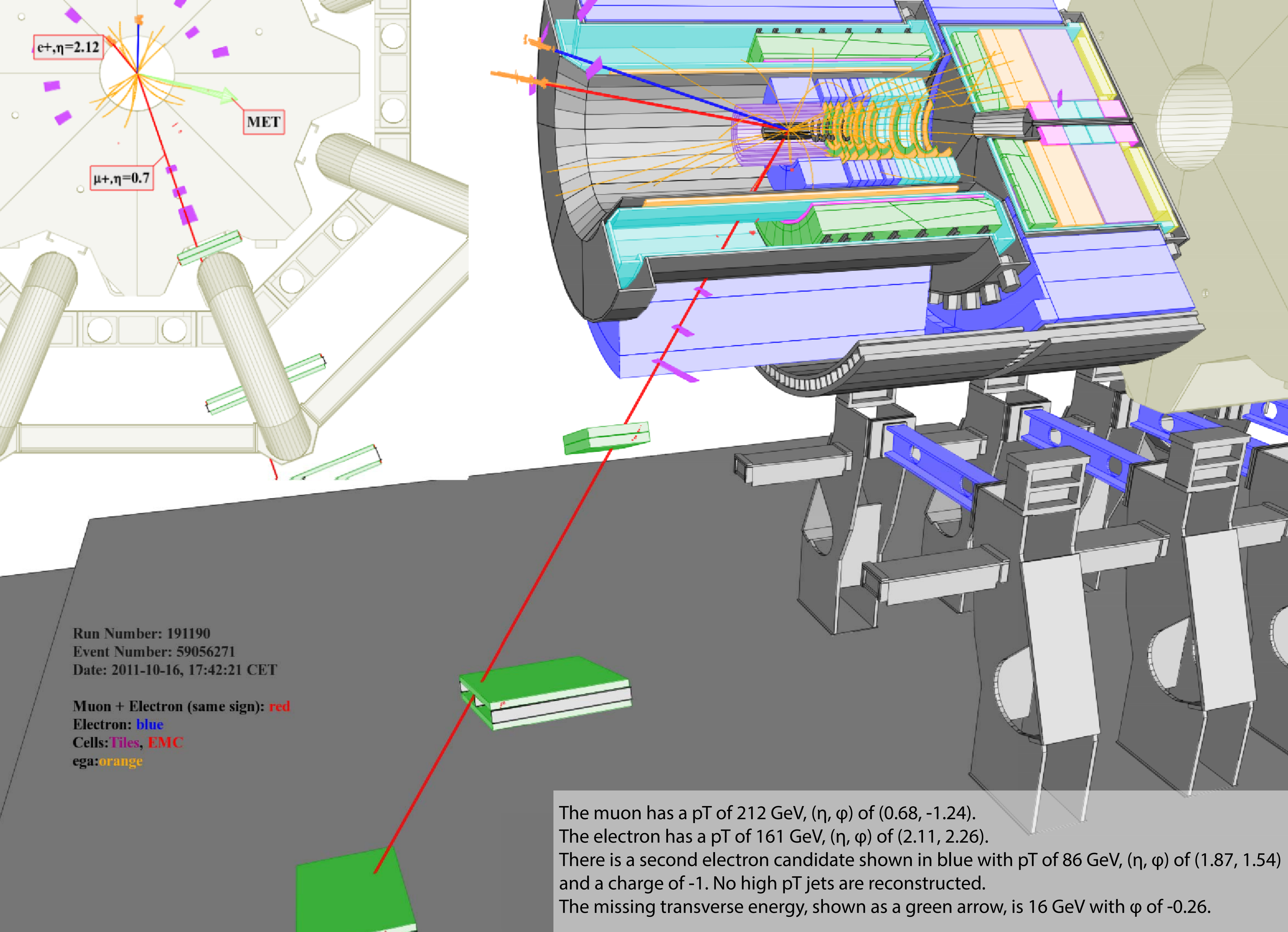
The leading electron has an ET of 196 GeV, (η, φ) of (1.31, -1.86).
The subleading electron has an ET of 50 GeV, (η, φ) of (-2.25, 2.73).
There is a third electron (shown as a blue track) with an ET of 35 GeV, (η, φ) of (-0.54, 1.73), and charge -1. There are two reconstructed jets.
The leading jet has a pT of 207 GeV and (η, φ) of (0.59, 1.49), and the subleading jet has a pT of 30 GeV and (η, φ) of (1.14, 1.45).
The missing transverse energy (shown as a green arrow) is 9 GeV with φ of -1.05.



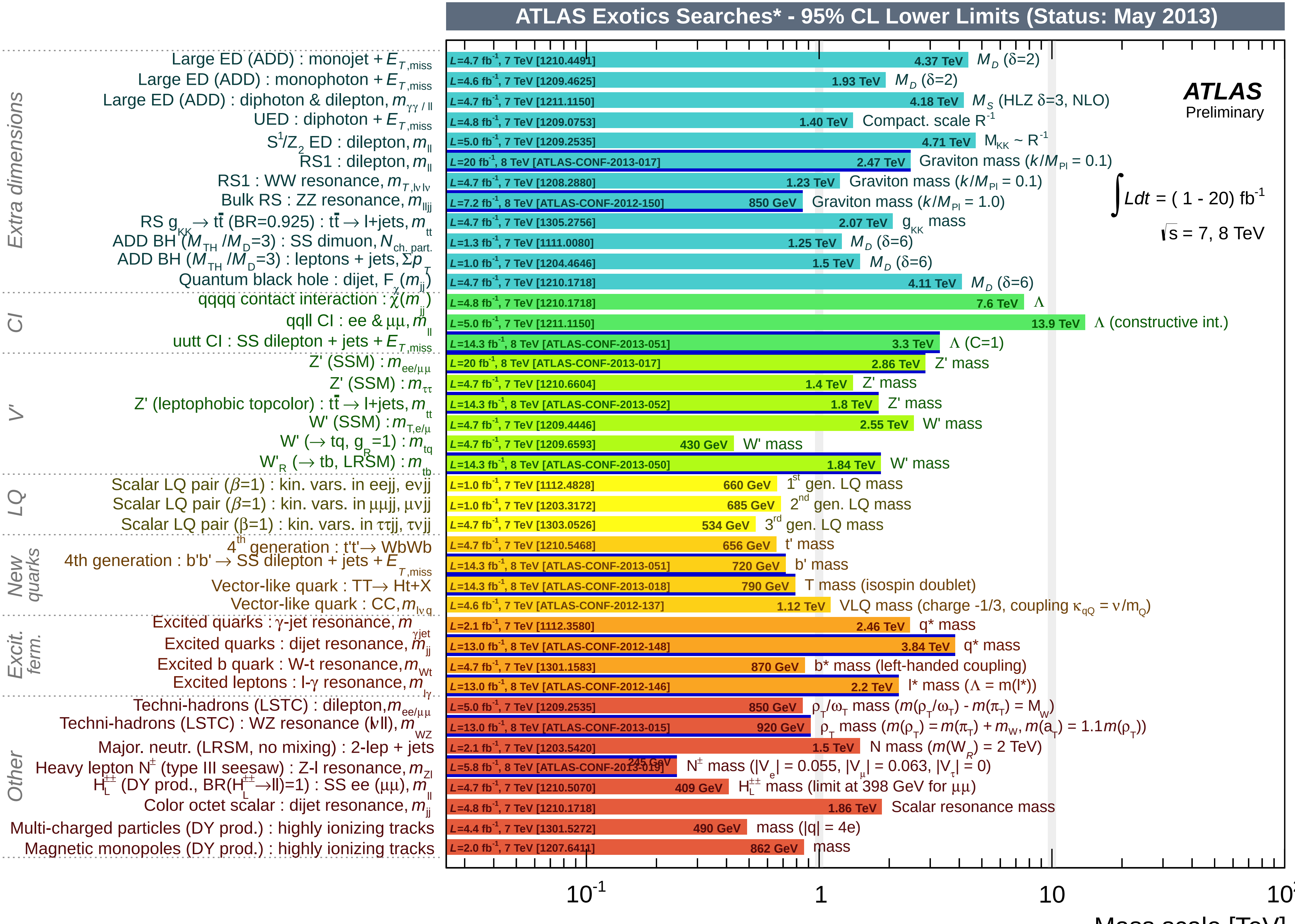
Event display of the ee (++) event with the highest invariant mass (589 GeV).



Event display of the μμ (++) event with the highest invariant mass (522 GeV).



Event display of the eμ (++) event with the highest invariant mass (464 GeV).



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

We searched for violation of lepton and lepton flavor numbers in exclusive and inclusive dilepton channels.

In all reported analyses we observe a good agreement with SM predictions.

From our measurements we estimated upper limits on production cross sections of various BSM processes and lower limits on masses of new hypothetical particles.

A discovery of heavy Majoranas would have explained neutrino masses and baryogenesis via violation of lepton number and more CP violation! Wishful thinking, hahaha...

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