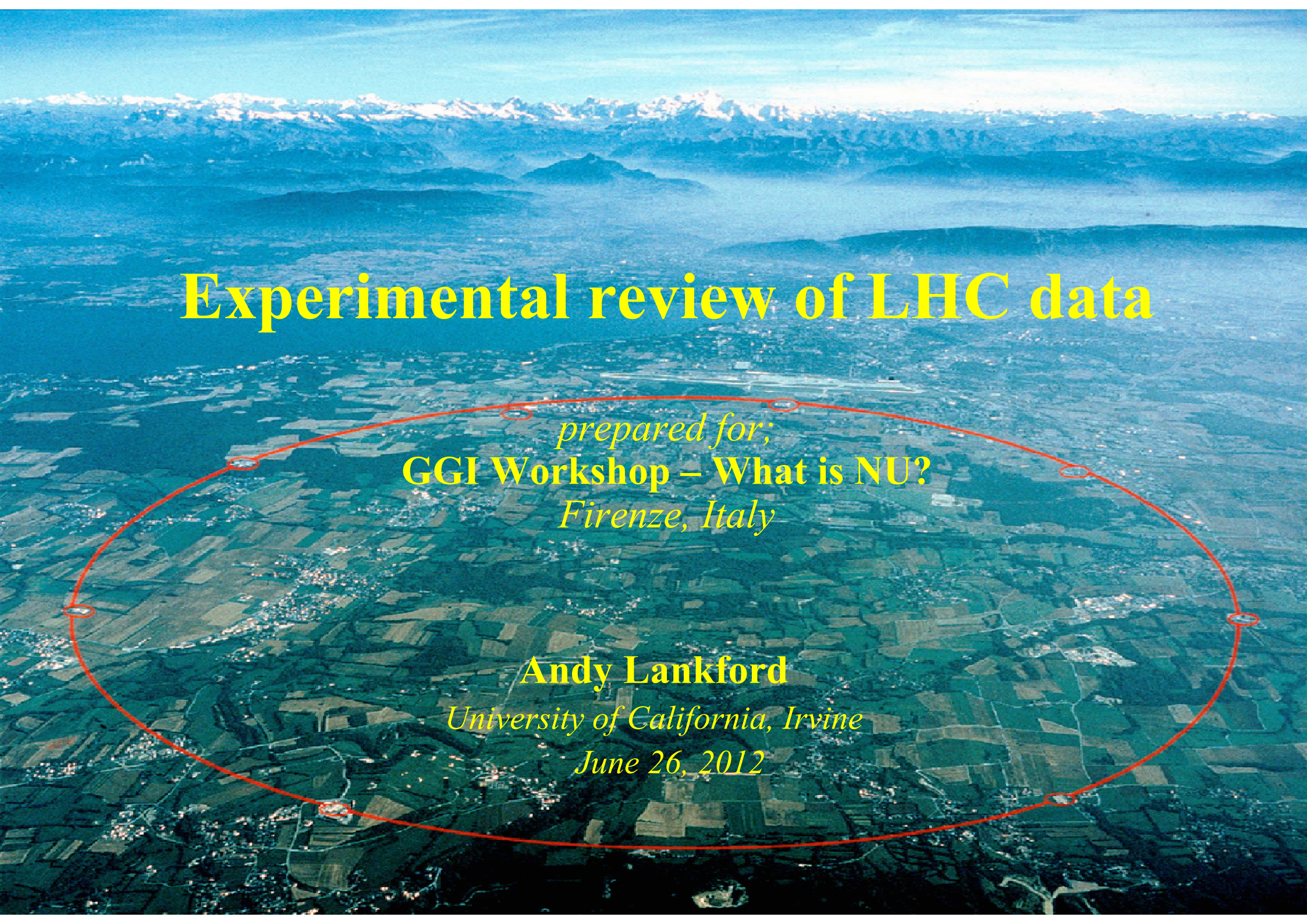


Experimental review of LHC data

prepared for;

GGI Workshop – What is NU?

Firenze, Italy

Andy Lankford

University of California, Irvine

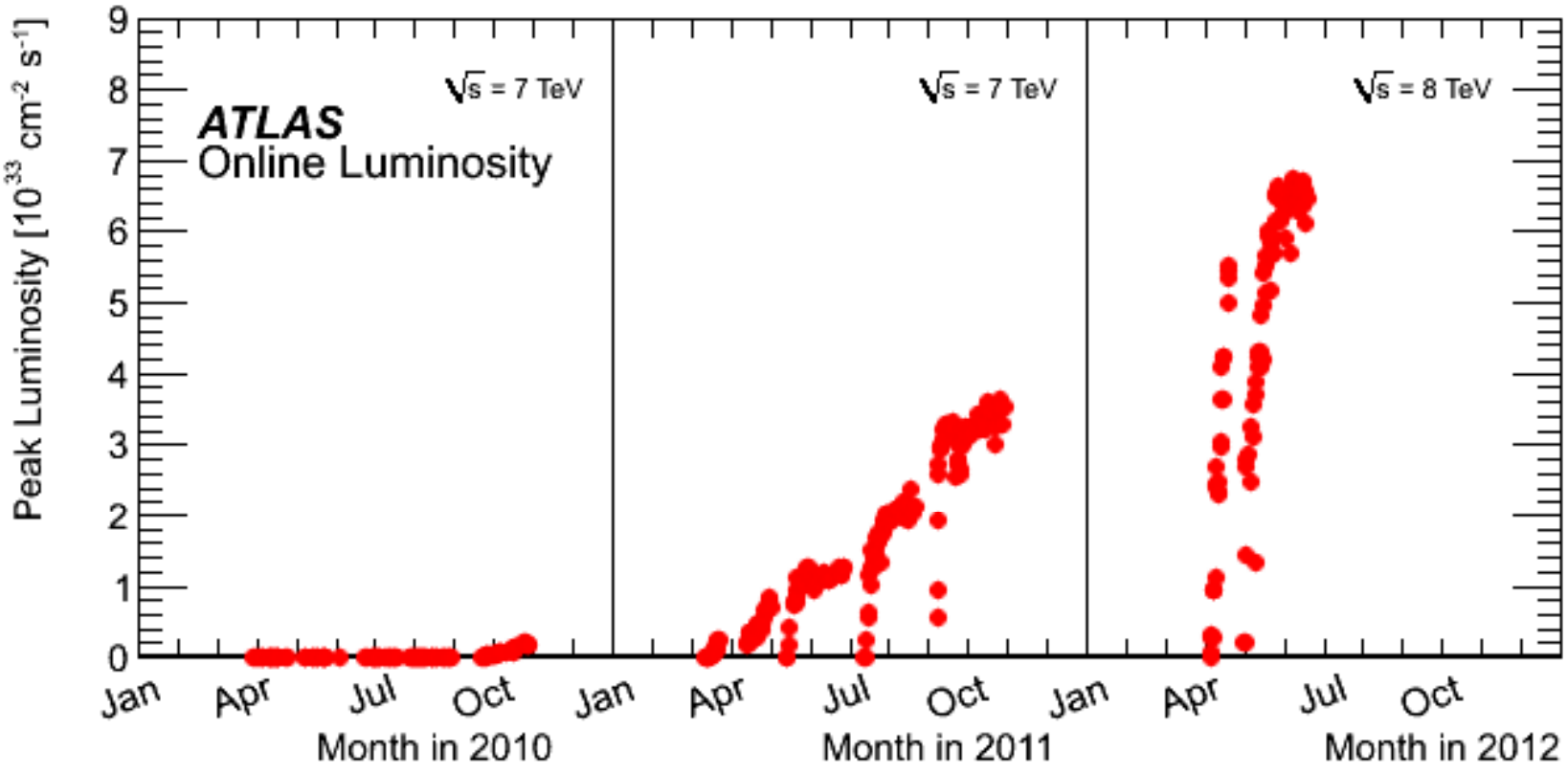
June 26, 2012

Experimental review of LHC data

Outline:

- Where is the LHC now?
- Laying the groundwork
- Exploring for new physics
- Summary and prospects

LHC instantaneous luminosity



The LHC continues to surprise with its outstanding performance.

2009 – 1st physics collisions at injection energy late in year

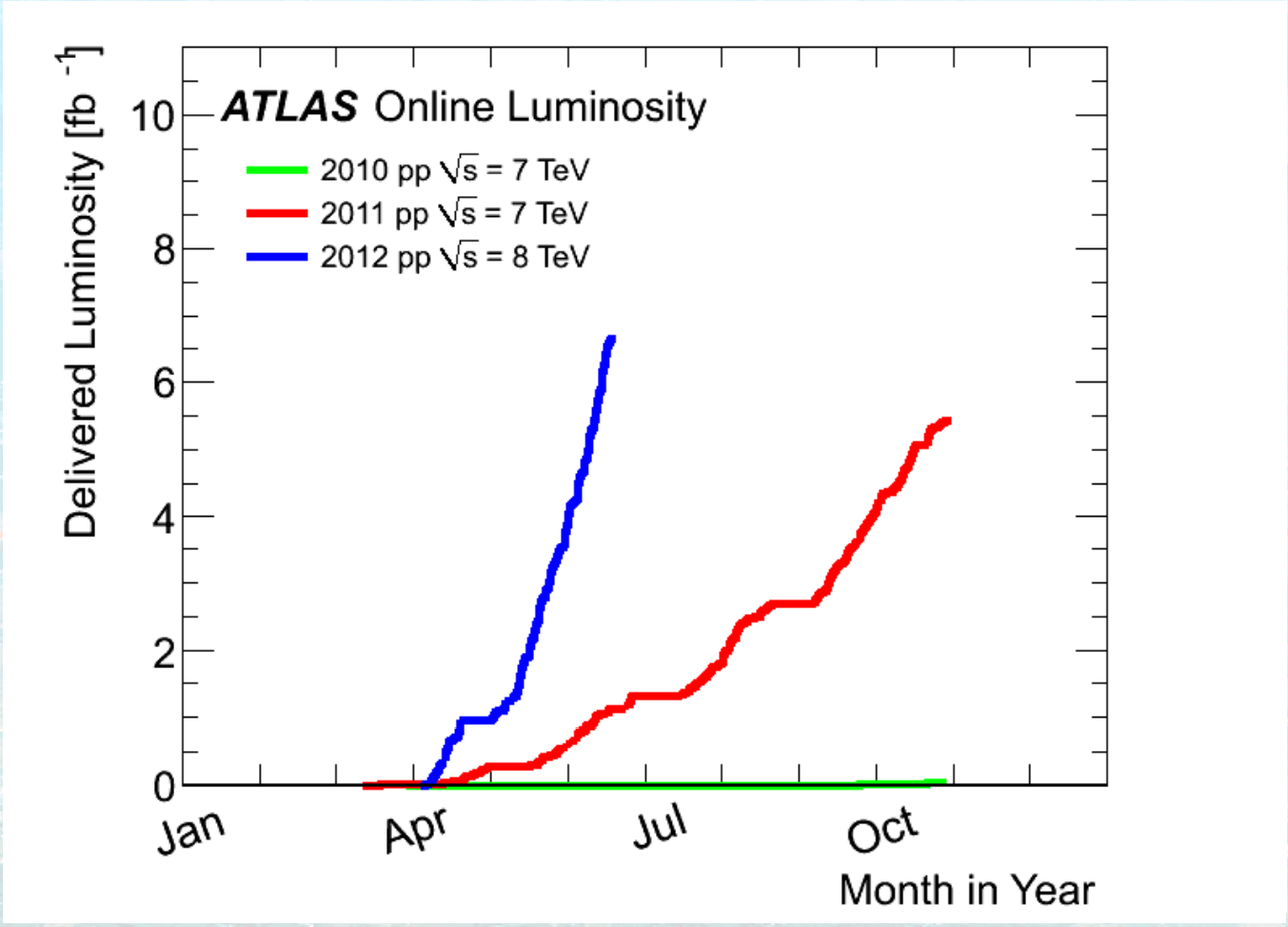
2010 – 1st full year of physics data taking, at 7 TeV E_{cm}

2011 – improving luminosity as bunches added to ring; peak $3.65x10^{33}$

2012 – further improvements; 8 TeV E_{cm}; peak to date $6.76x10^{33}$

Design luminosity at 14 TeV = 10^{34}; expect better in future

LHC integrated luminosity



The LHC continues to surprise with its outstanding performance.

2010 – 45 pb^{-1} recorded; 7 TeV

2011 – 5.25 fb^{-1} recorded; 7 TeV

2012 – 6.28 fb^{-1} recorded to date; 8 TeV; target for 2012 ~15 fb^{-1}

Where is the LHC today?

~1/3 of way thru 2nd year of 2-yr run at 7-8 TeV

- **Already recorded slightly more data than in all of 1st year**
- **Expect to quadruple 1st year data sample**

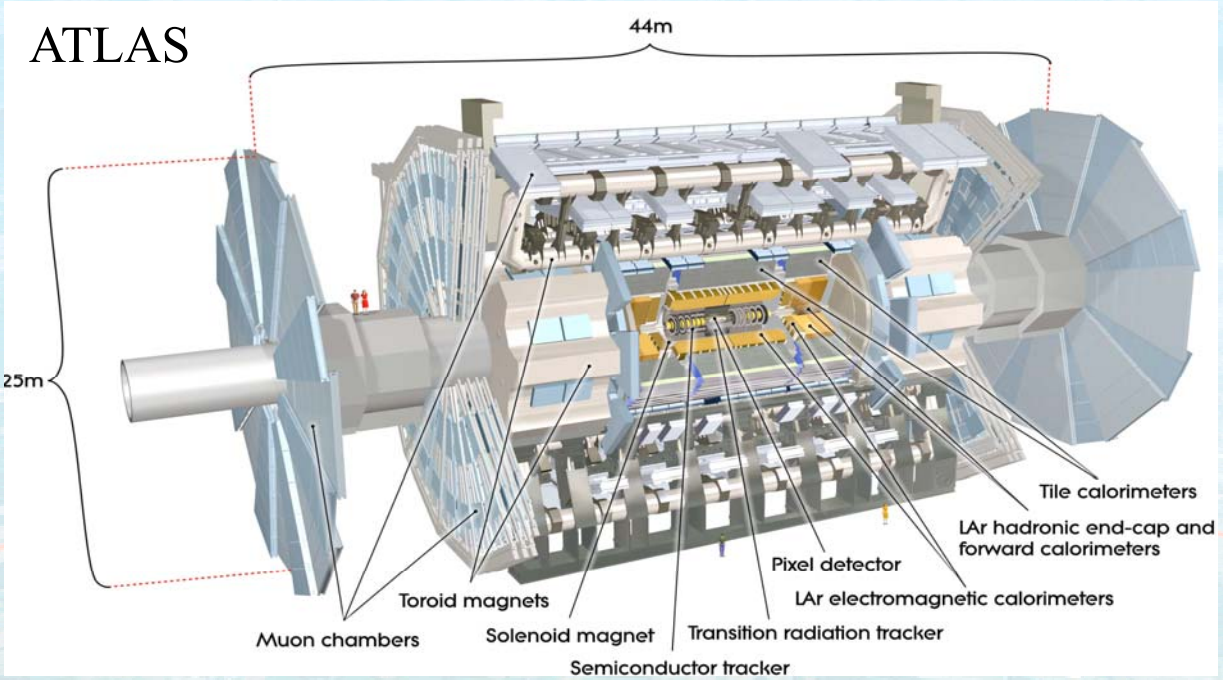
Late 2012 – start "long shutdown 1"

- **for magnet "consolidation"** (replace splices)
- **until Autumn 2014**

Return to operations in late 2014

- **train SC magnets for 13-13.5 TeV**
- **prepare for full design luminosity (and more)**

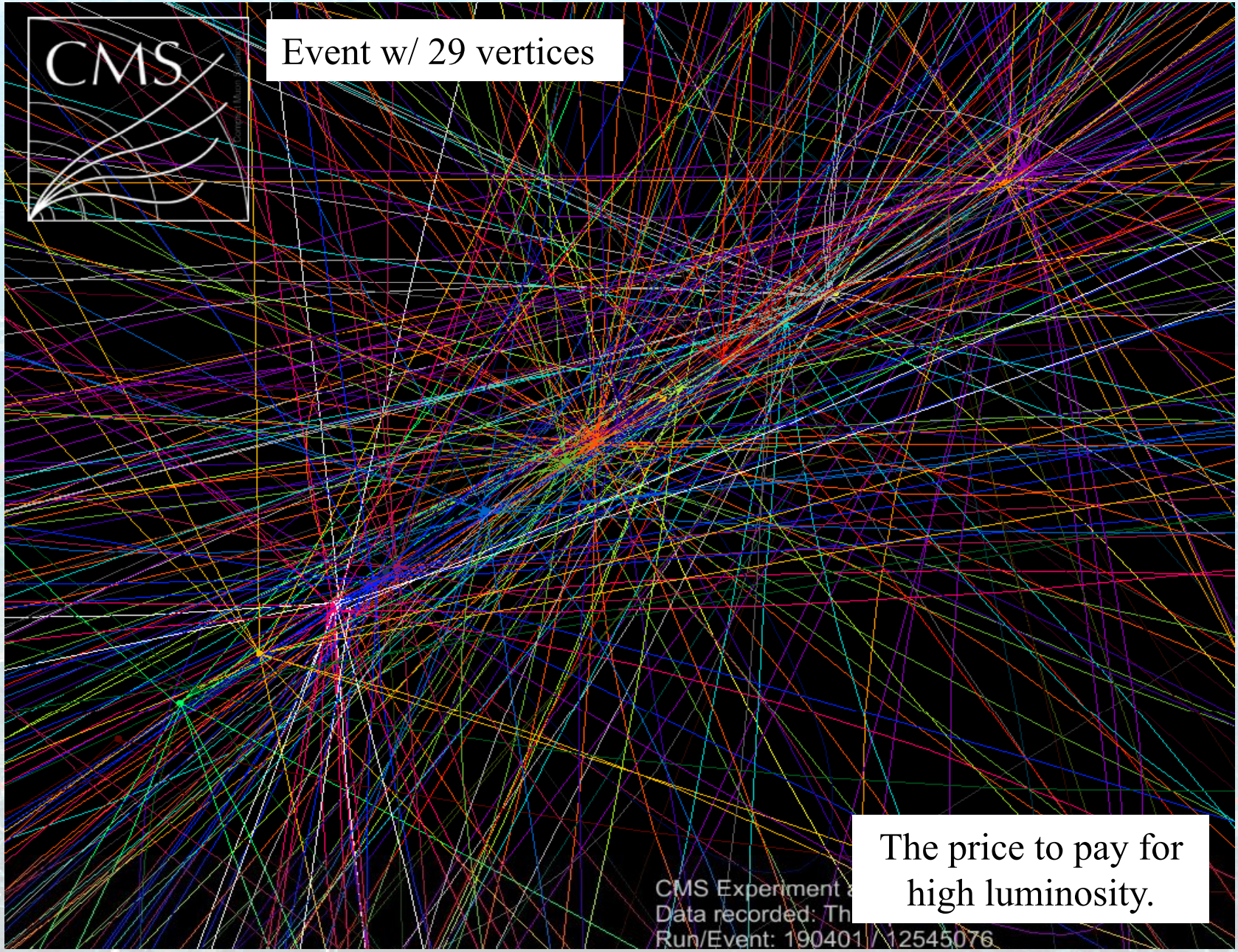
The experiments



- **Goal – detect all particles produced in each pp collision**
- **The experiments detect, identify, and measure physics objects:**

  e, μ, τ, γ, jets, b-jets, ν (missing E_T)
- **The experimental conditions are somewhat challenging.**
  - **~10^9 interactions/sec → ~10^2 recorded/sec (select ~1 per 10^7)**
  - **~10^8 readout channels; radiation tolerance; limited access, etc.**
  - **~ 50μm point precision over ~ 50m detector;** (~5μm near vertex)
  - **Multiple interactions per crossing.**

Event pileup - multiple interactions per crossing



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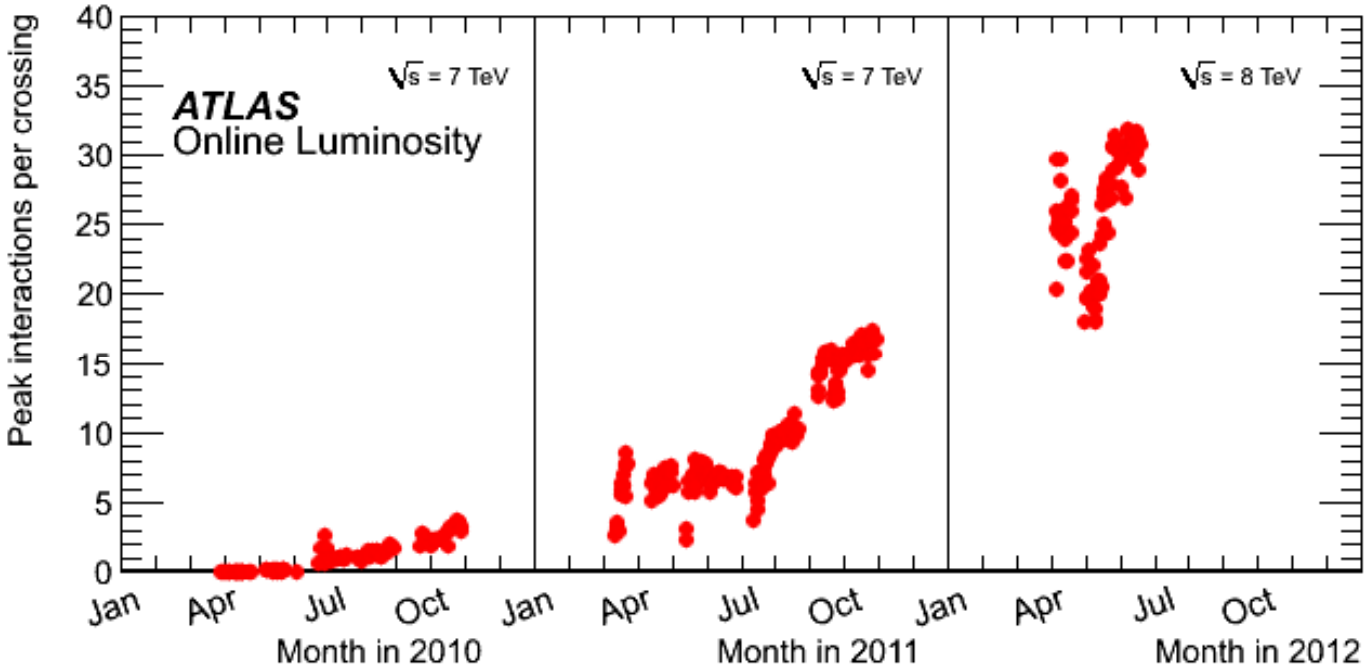
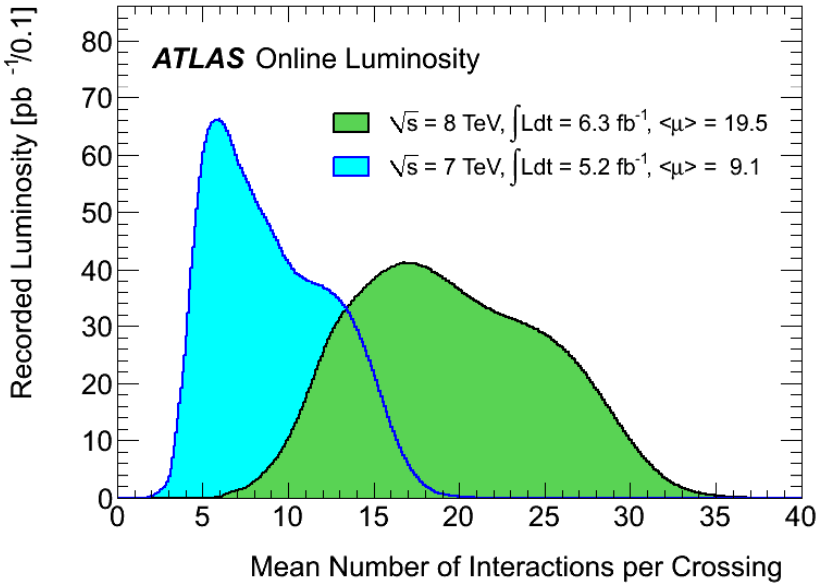
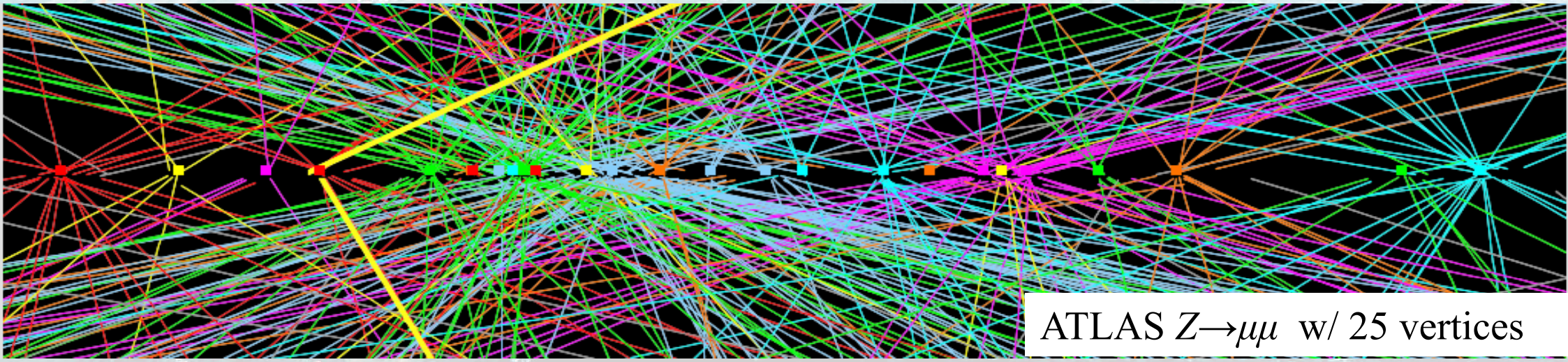
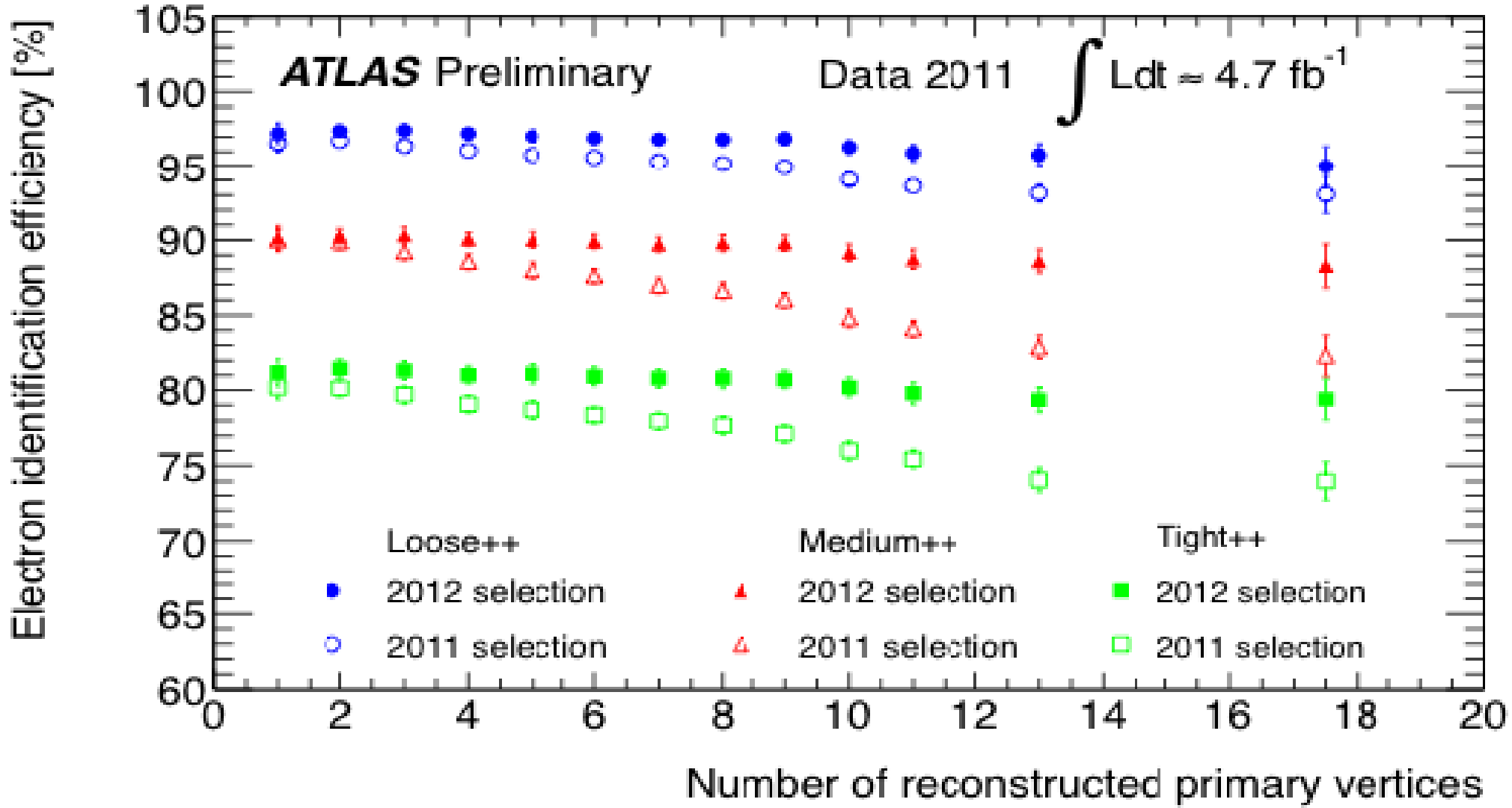




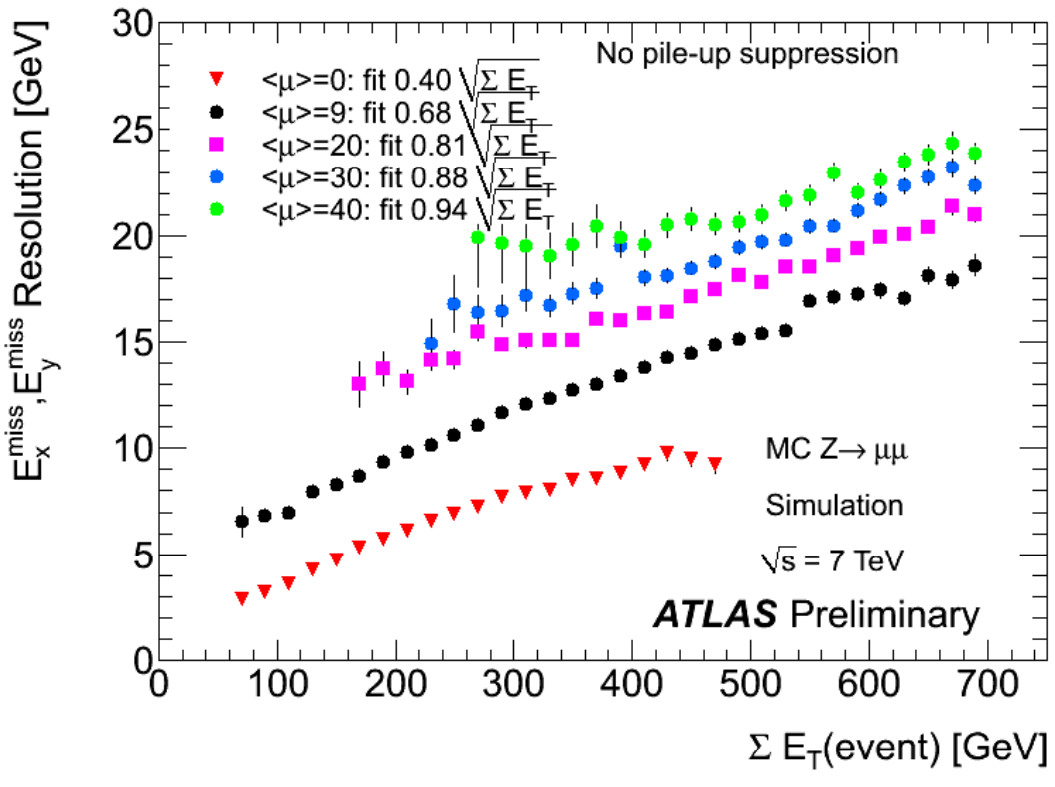


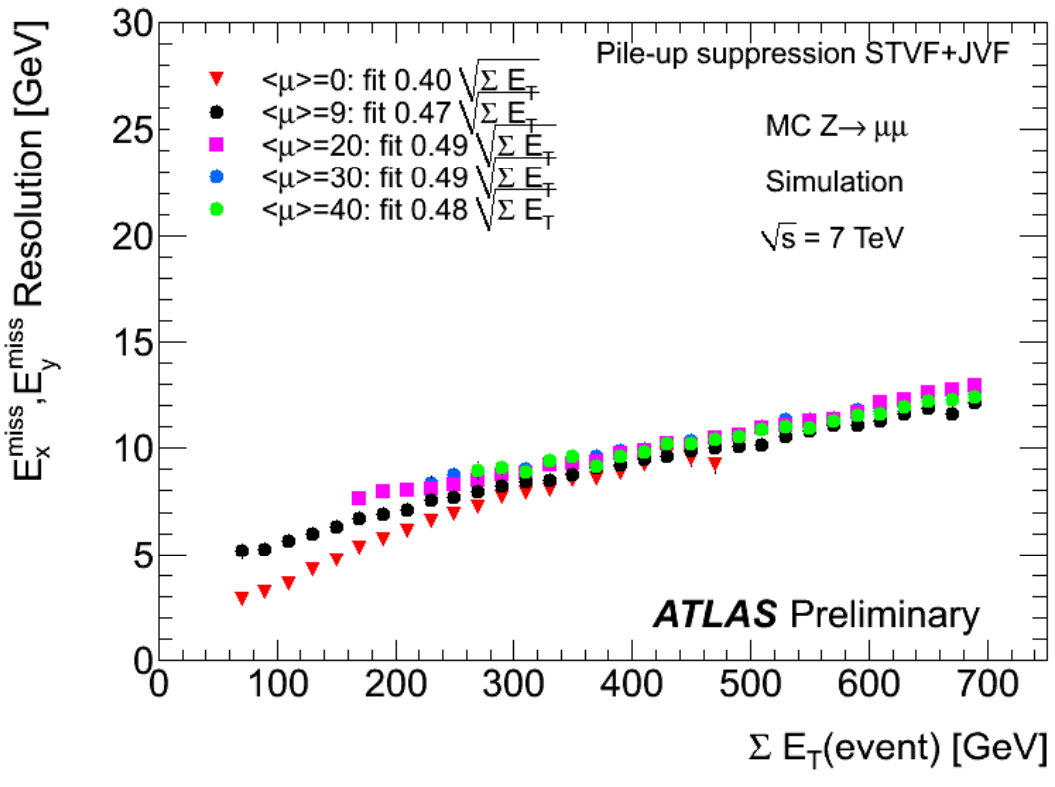
ATLAS $Z \rightarrow \mu\mu$ w/ 25 vertices

Improving electron id for high pileup



Improving missing E_T measurement for high pileup





LHC physics

4 major experiments: ATLAS, CMS, LHCb, ALICE

(I will focus on ATLAS & CMS, for their interest to today's theme.)

Rich physics program: CMS physics groups (ATLAS very similar):

- **Forward & small-x QCD physics**
- **B physics & quarkonium**
- **Standard Model physics**
- **Top physics**
- **Higgs physics**
- **Supersymmetry**
- **Exotica**
- **Heavy ion physics**

ATLAS & CMS each have published >150 papers by this time.

I must select just a few topics to report here.

All results will be based on 2011 data at 7 TeV, often less than the full 5 fb^{-1}

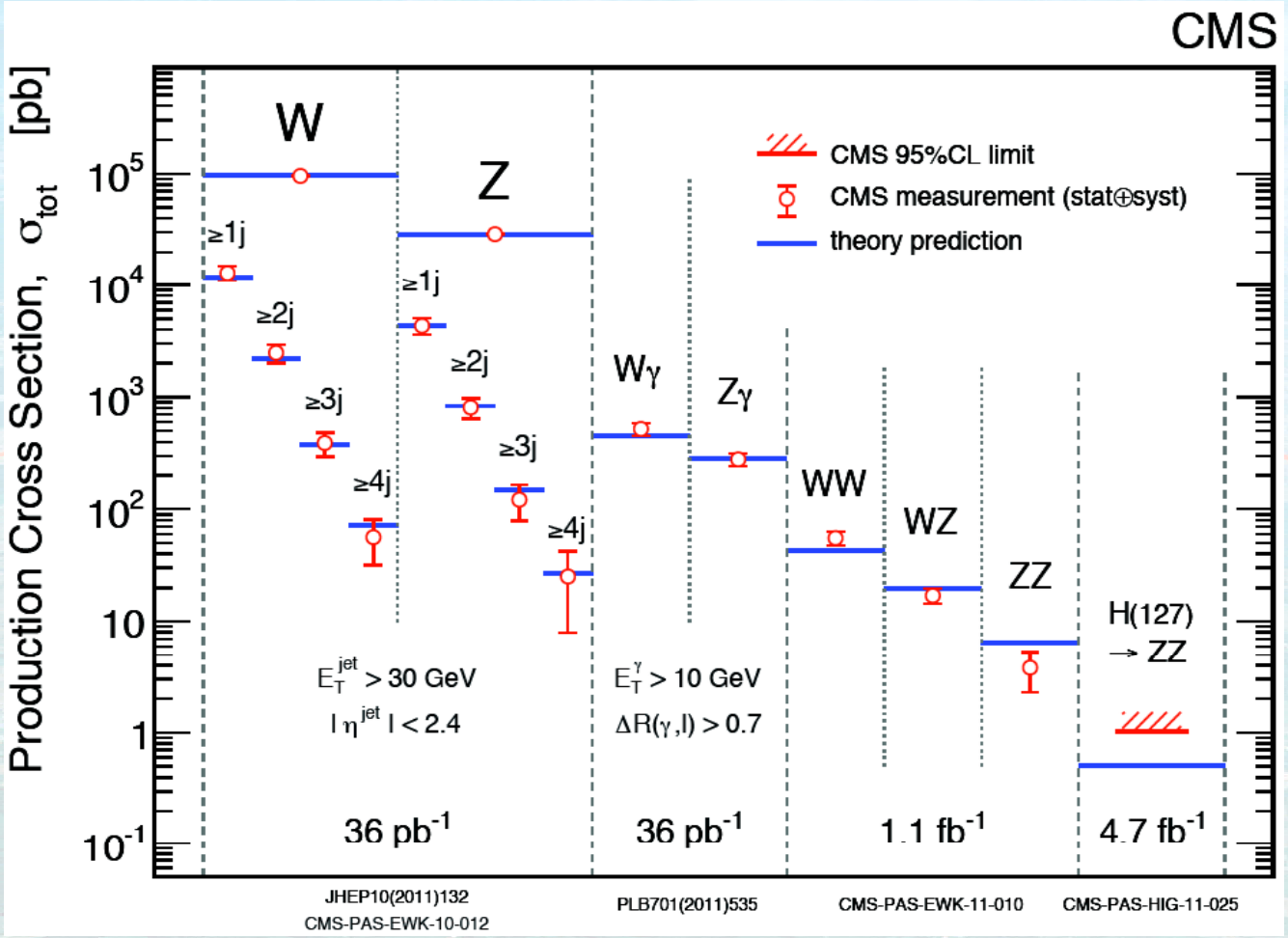
There will be many new results next week at ICHEP:

many more 5 fb^{-1} analyses,

some 2012 8 TeV analyses (even some w/ data recorded thru last Monday)

SM processes are backgrounds to many searches

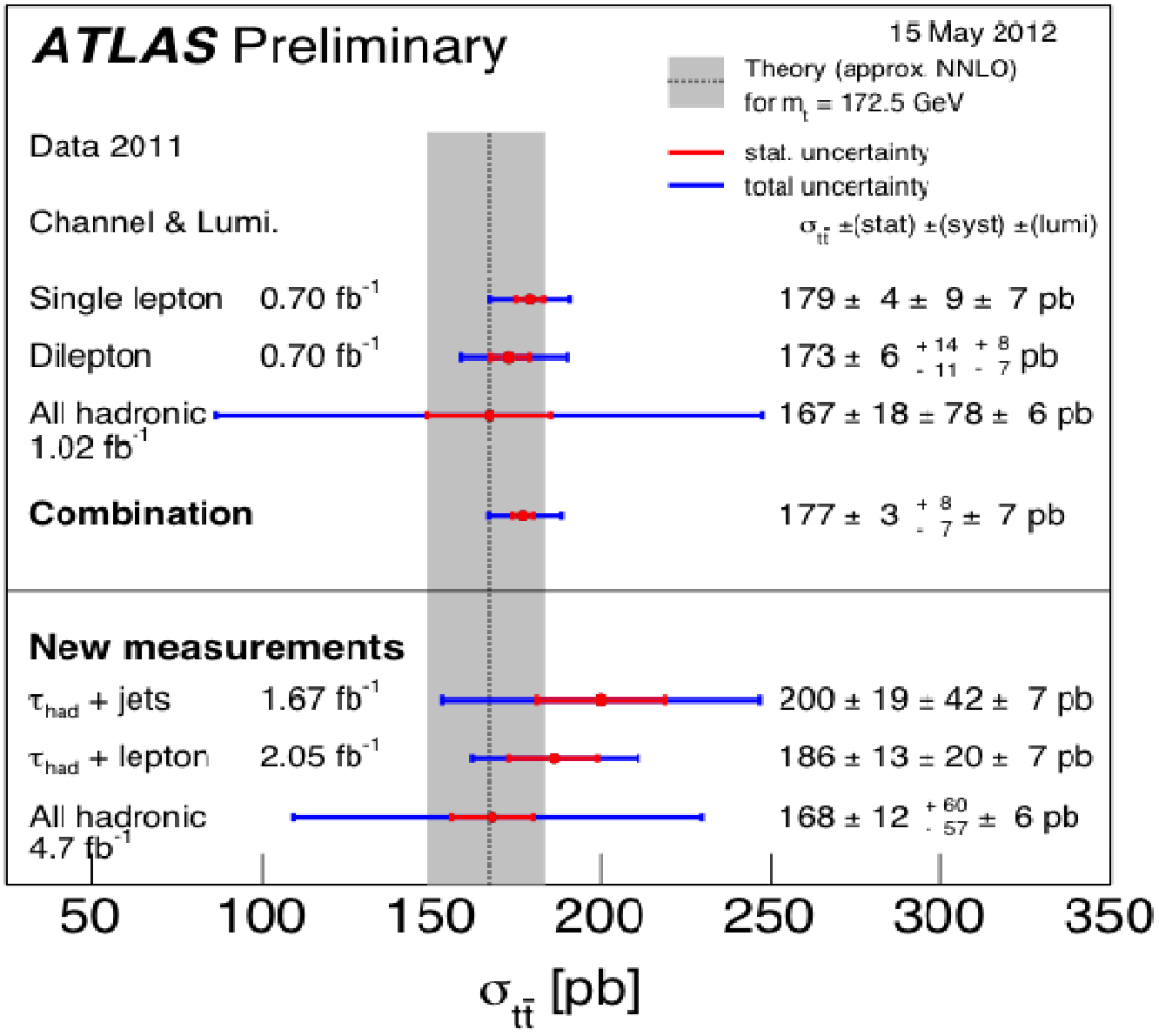
Standard Model is being studied and tested in detail.



Agreement of theory & experiment illustrates quality of:

- **Theoretical background calculations/models**
- **Understanding of detector performance**

Top is also a background to many searches



Top pair cross-sections measured in all important modes.

Differential cross-sections measured as well.

Searching for the SM Higgs

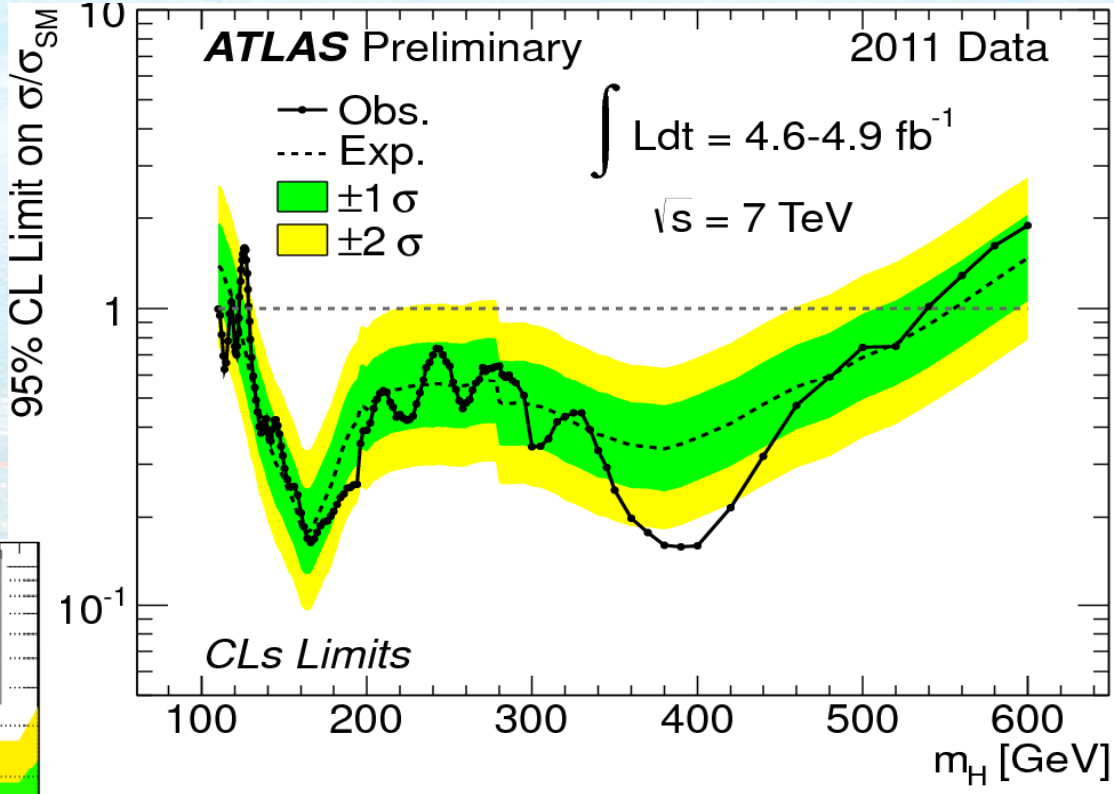
Wide continuous 95% CL exclusion range at **high mass**

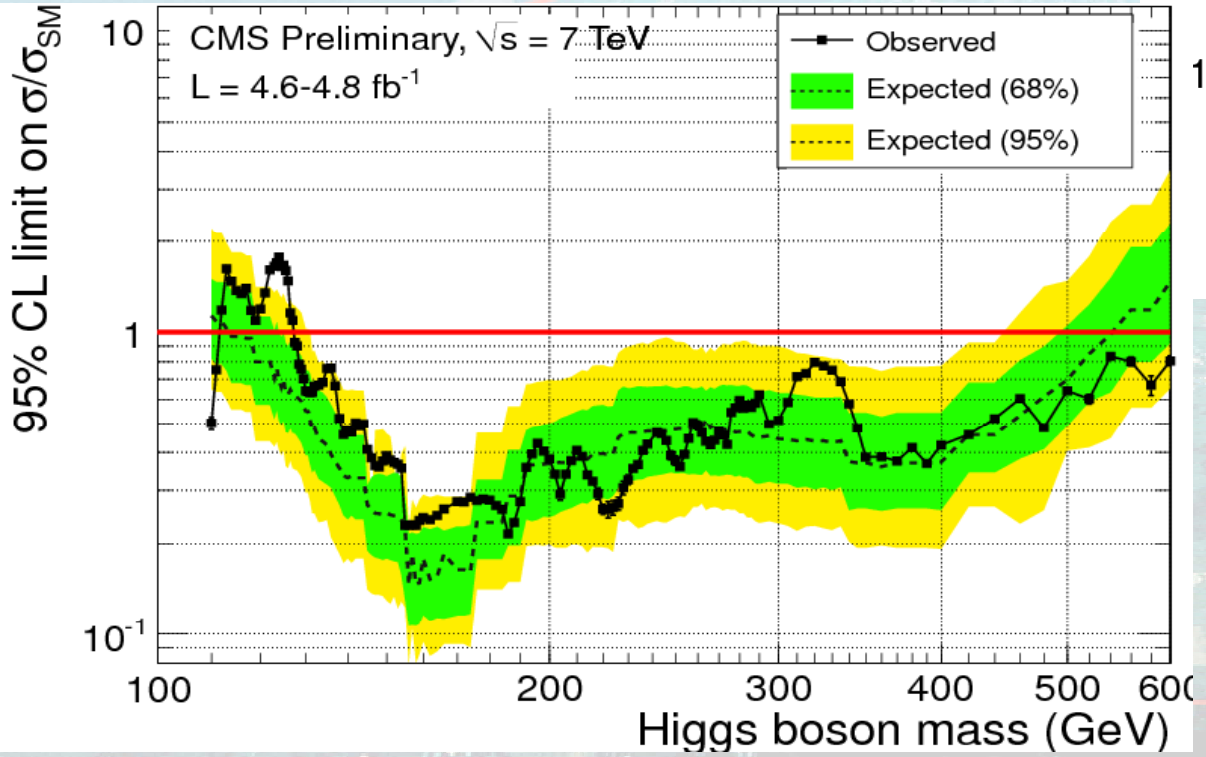
ATLAS: 129-539 GeV

Expect 120-555 GeV

CMS: 127.5-600 GeV

Expect 114.5-543 GeV





Even at 99% CL, exclude:

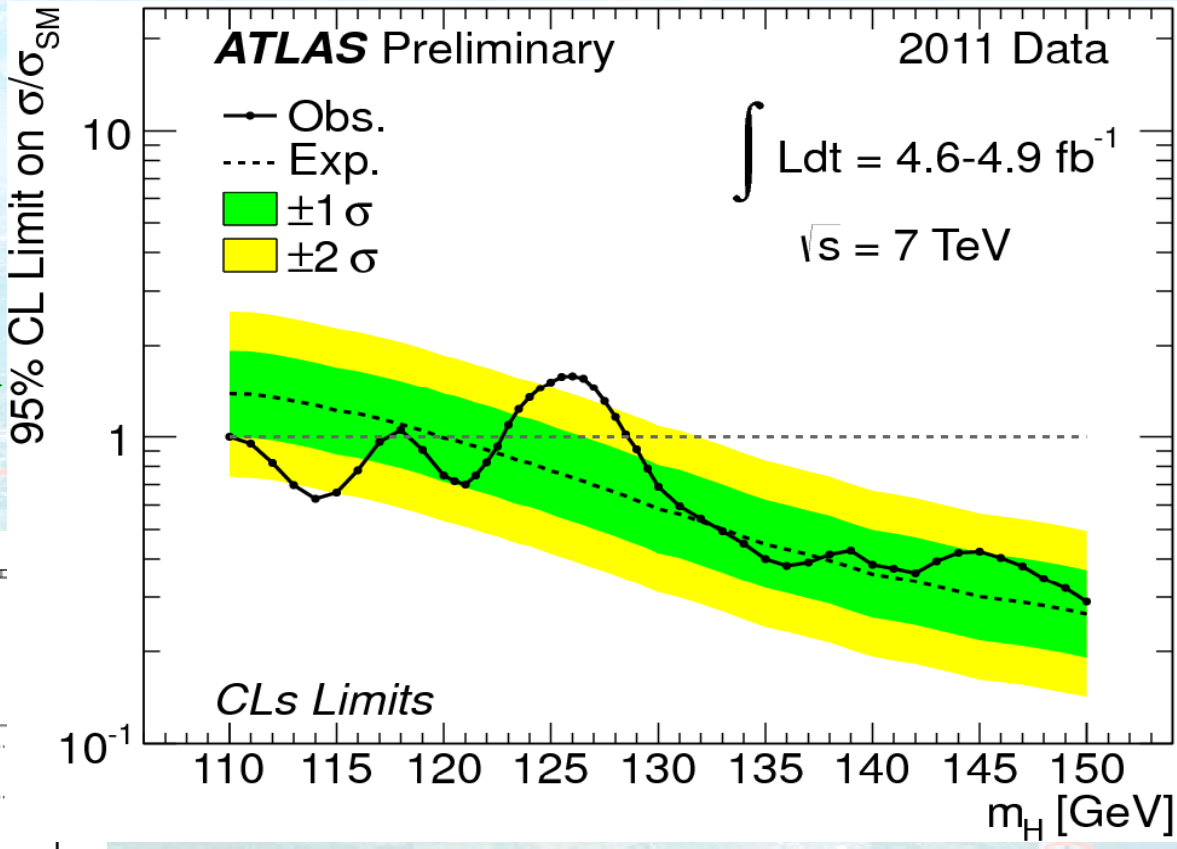
ATLAS: 130-486 GeV

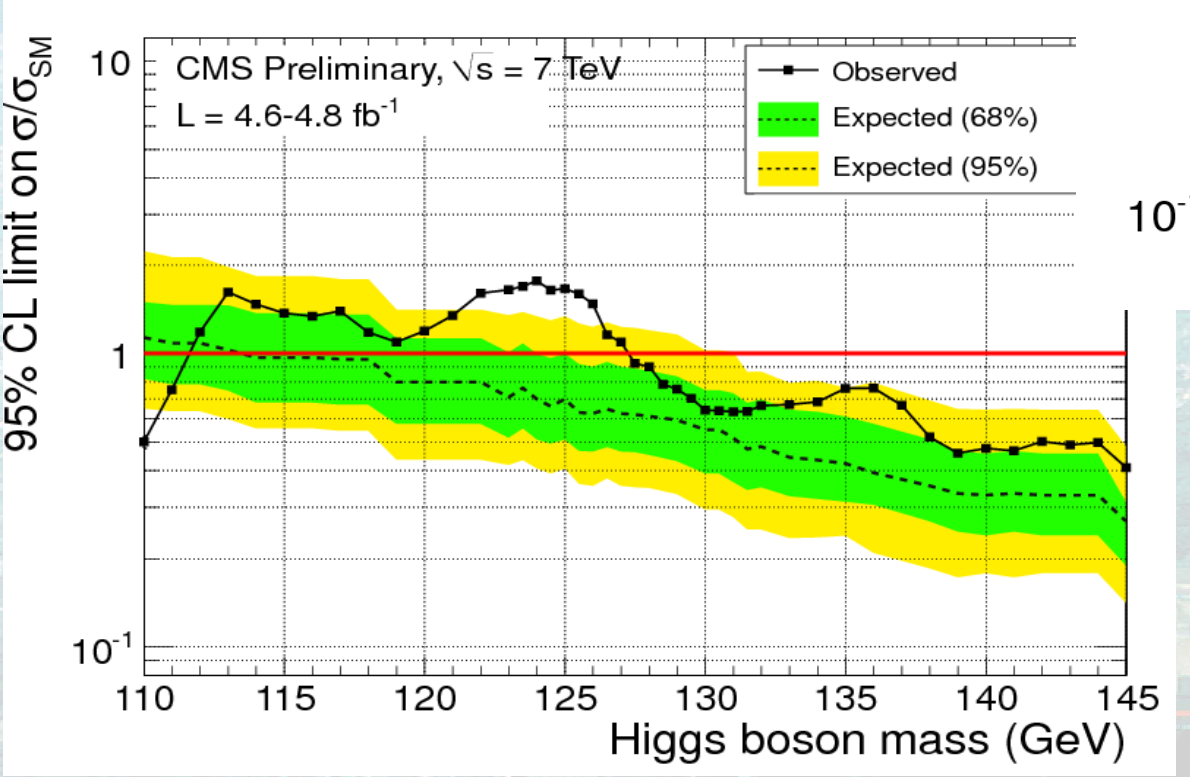
CMS: 129-525 GeV

Searching for the SM Higgs

Low-mass range below 130 GeV
some excesses in data "spoil"
expected exclusions

ATLAS exclude at 95% CL
110-117.5 and 118.5-122.5 GeV



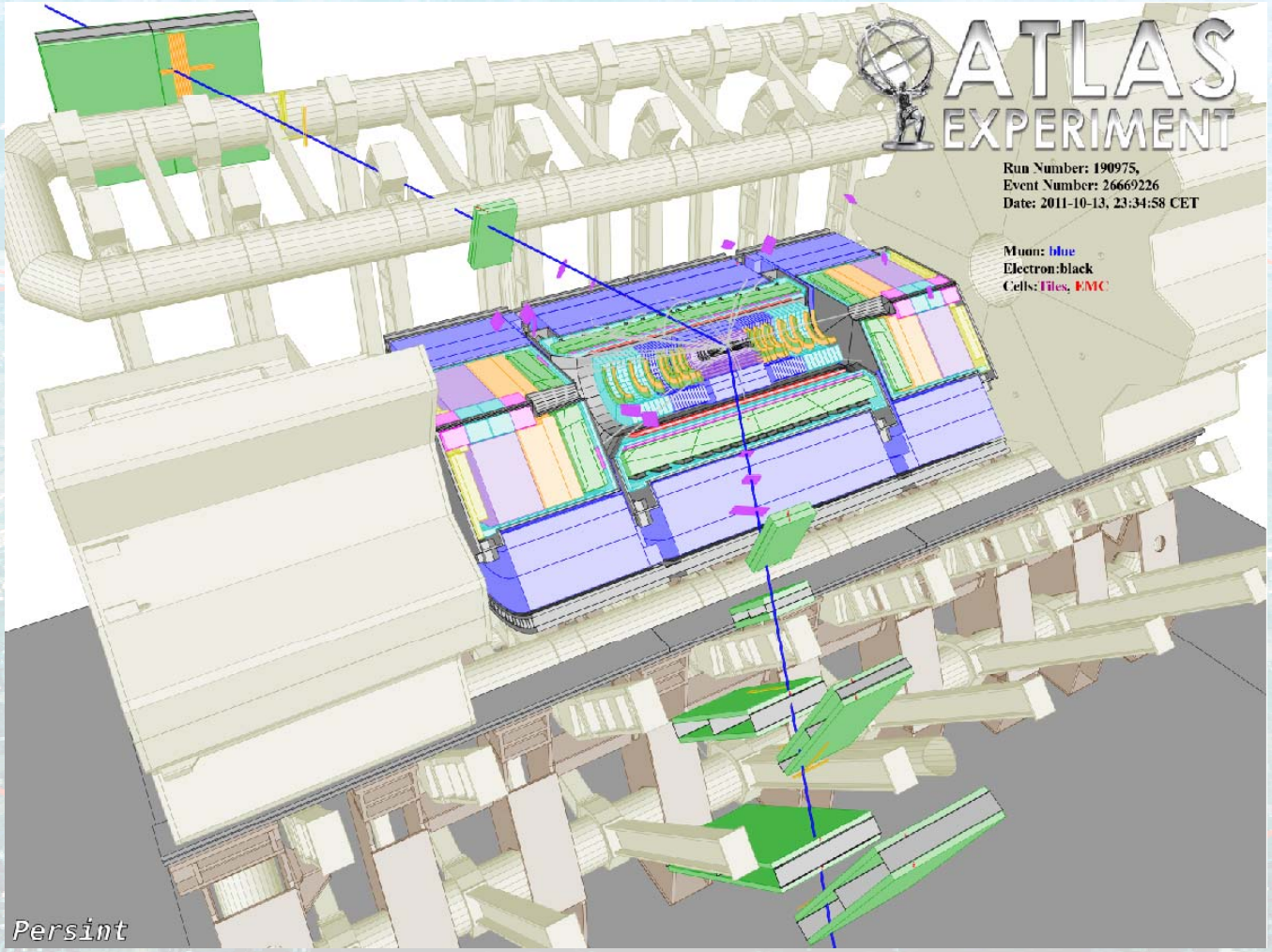


CMS expected exclusion at 95% CL
114.5 up to 543 GeV

Experiments have now doubled their data samples. Will excesses grow or diminish?

New Gauge Bosons - Z'

- Searches in di-electrons and di-muons in both CMS & ATLAS with similar sensitivity
- Comparison of data with expectations of: Z'_{ssm} of Sequential SM; Z'_{ψ} & Z'_{χ} of E_6 GUT; G^* or G_{KK} of Randall-Sundrum; Z'_{St} of Stueckelberg extension.
- Experimental signatures are clean



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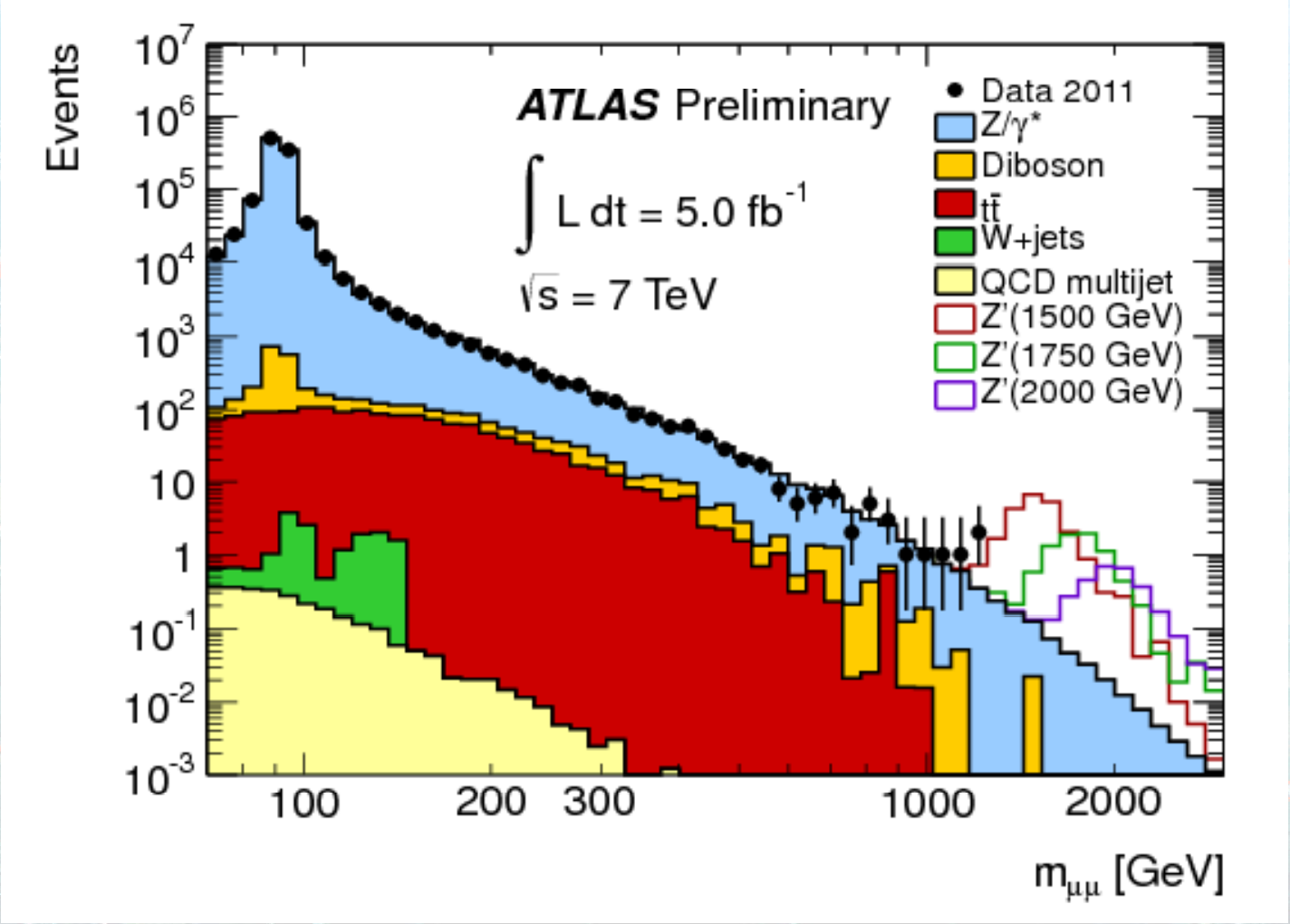
- Experimental signatures are clean, but Drell-Yan backrounds are irreducible.



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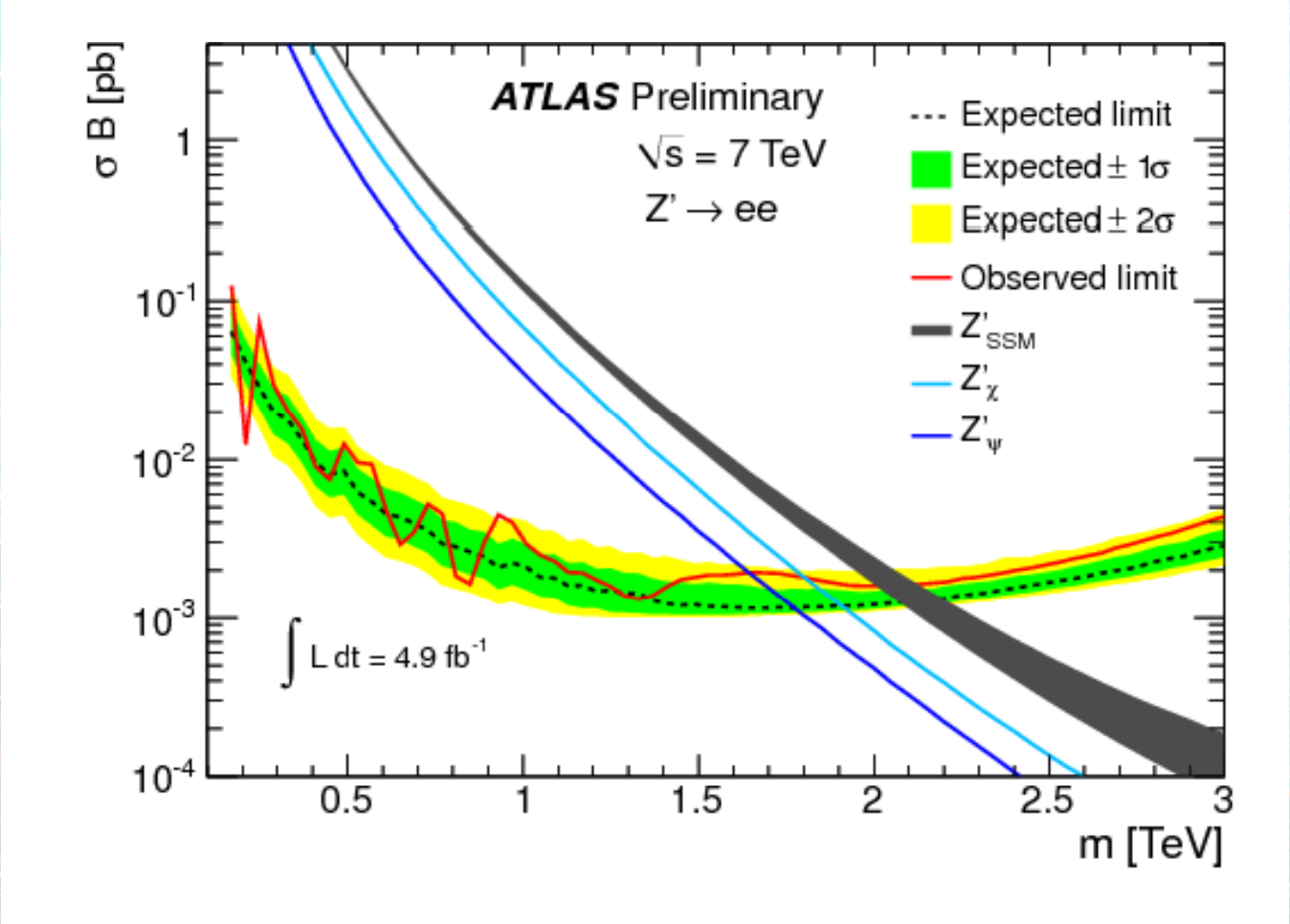

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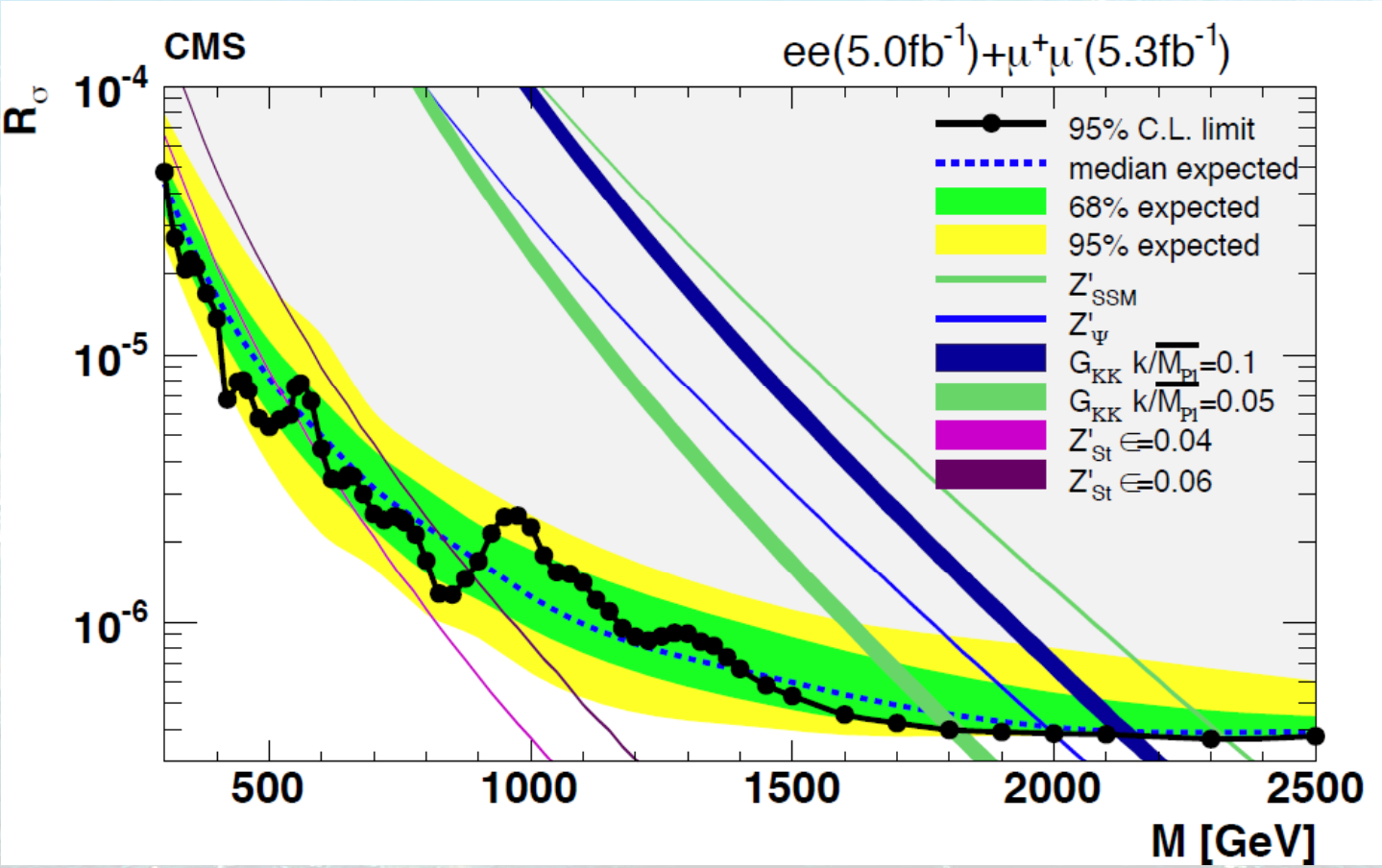
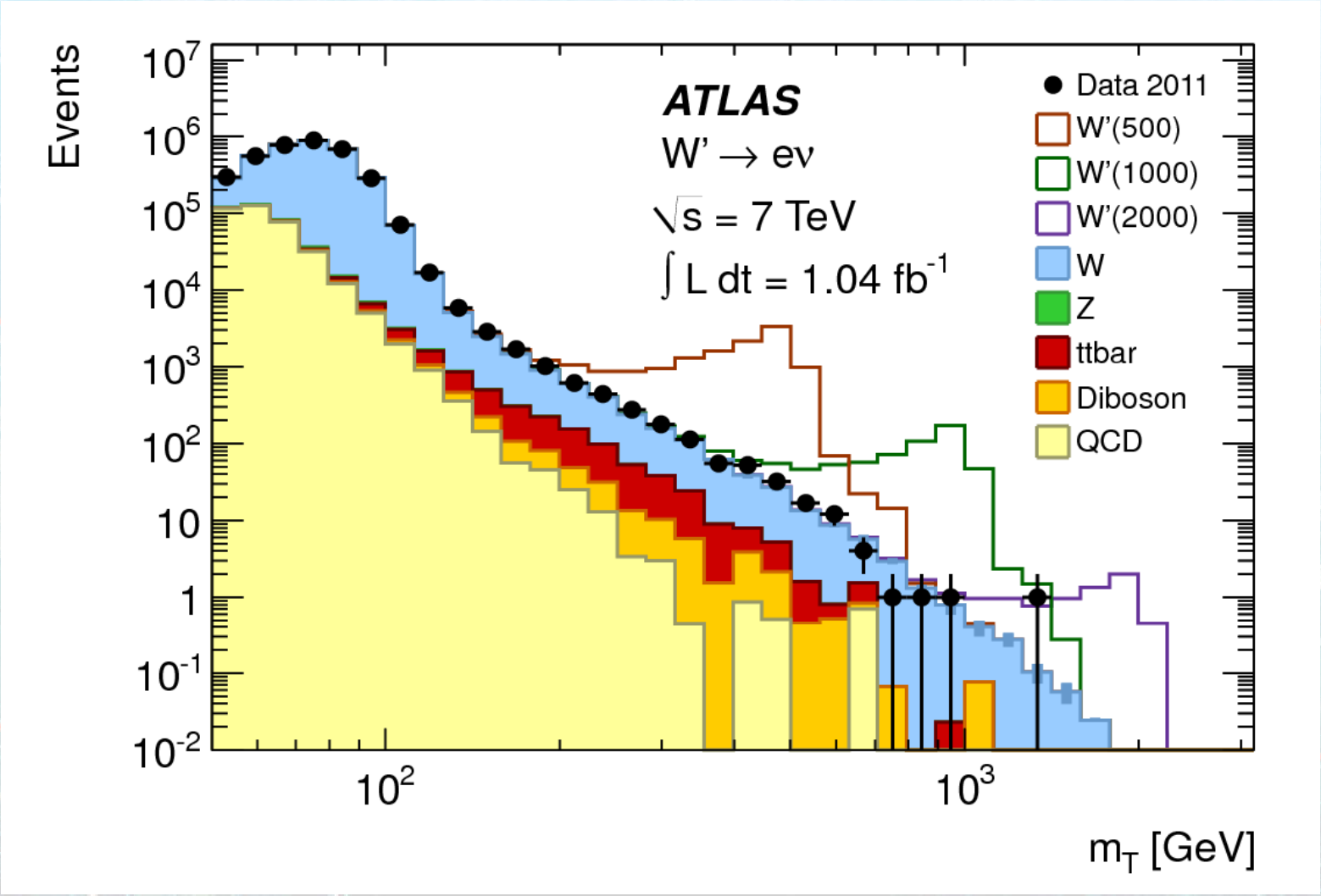


CMS constraints are presently most stringent $m(Z'_{SSM}) > 2.3$ TeV

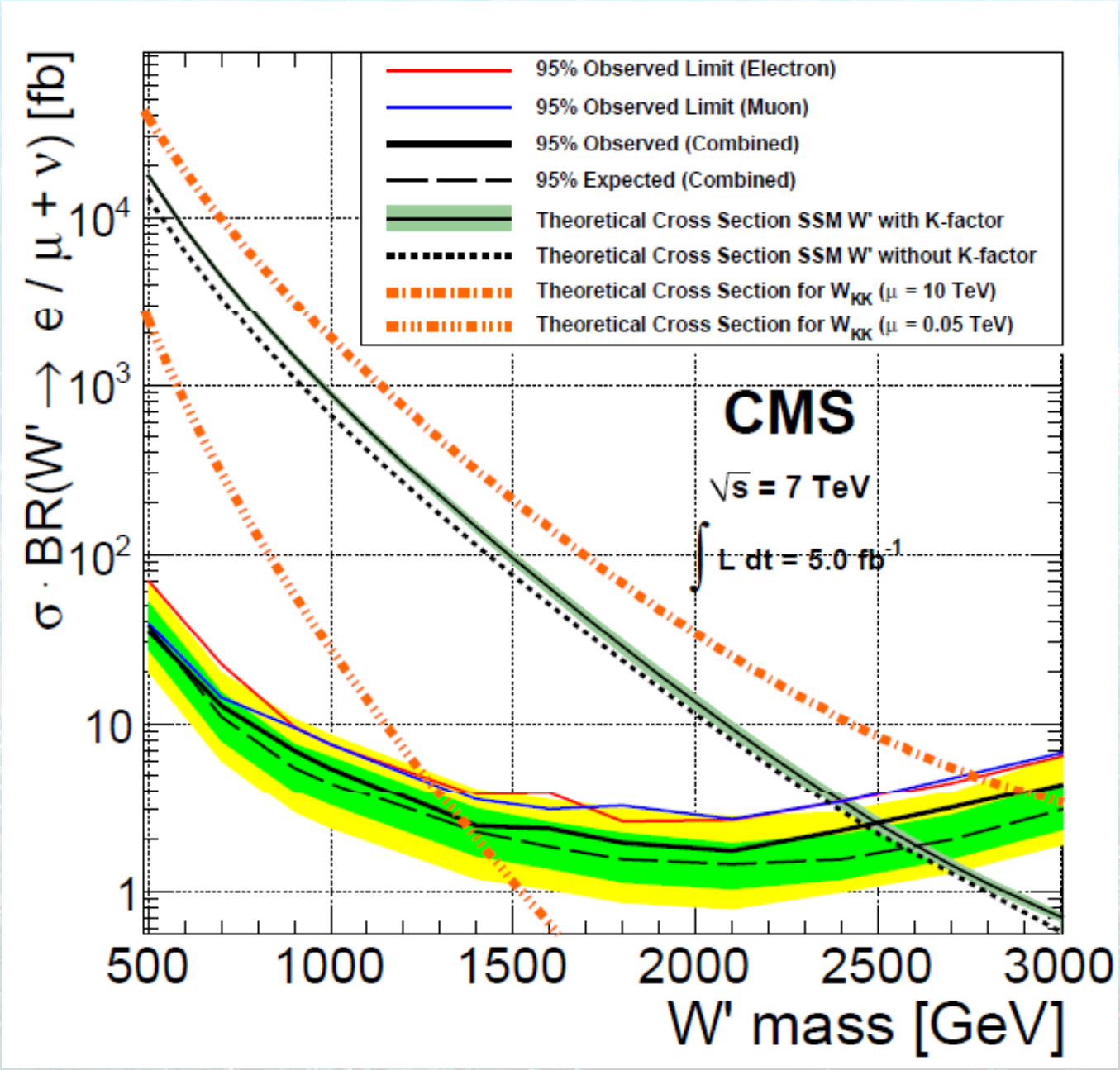
R_σ is ratio of σB(Z') to σB(Z)

New Gauge Bosons - W'

- Decay channel is *lepton* + *missing* E_T
- Signature is excess above background in transverse mass distribution.
- Dominant, irreducible background is W decays.



New Gauge Bosons - W'



CMS

$m(W'_R) > 2.5$ TeV

@95%CL w/ 5 fb^{-1}

(assuming a light decay neutrino)

ATLAS

$m(W'_R) > 2.15$ TeV

@95%CL w/ 1 fb^{-1}

(assuming a light decay neutrino)

CMS also has limits on:

- W'_L with & w/o interference
- W'_{KK} for various values of bulk mass parameter μ

ATLAS (1 fb^{-1}) & CMS (5 fb^{-1}) have also studied *WZ* production

Heavy neutrino & right-handed *W*

Both ATLAS & CMS

- Search in $2l + 2j$

- CMS - 5.0 fb^{-1} – μ *only*

  Left-right symmetric model

  $qq' \rightarrow W_R \rightarrow \mu N_\mu \rightarrow \mu(\mu\, W_R^*) \rightarrow \mu(\mu jj)$

- ATLAS - 2.1 fb^{-1} – e *or* μ

  Left-right symmetric model

  $qq' \rightarrow W_R \rightarrow lN \rightarrow l(l\, W_R^*) \rightarrow l(ljj)$

  Heavy neutrino effective operators

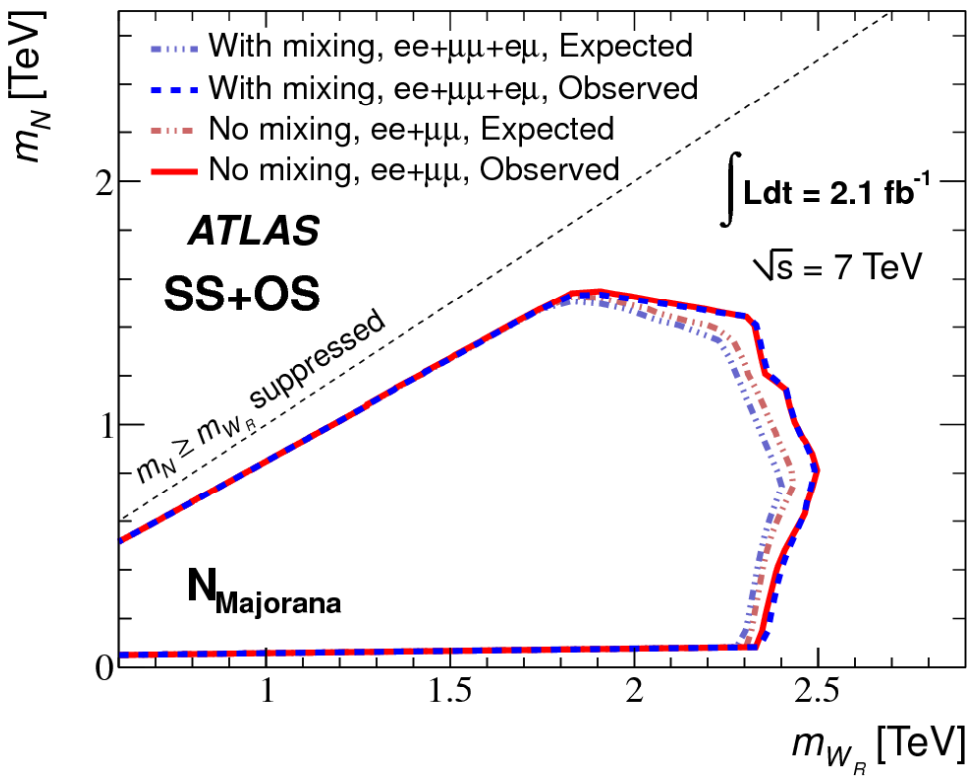
  $qq' \rightarrow lN \rightarrow l(ljj)$

- Opposite sign *l*'s for Dirac *N*

  dominant background: t-tbar

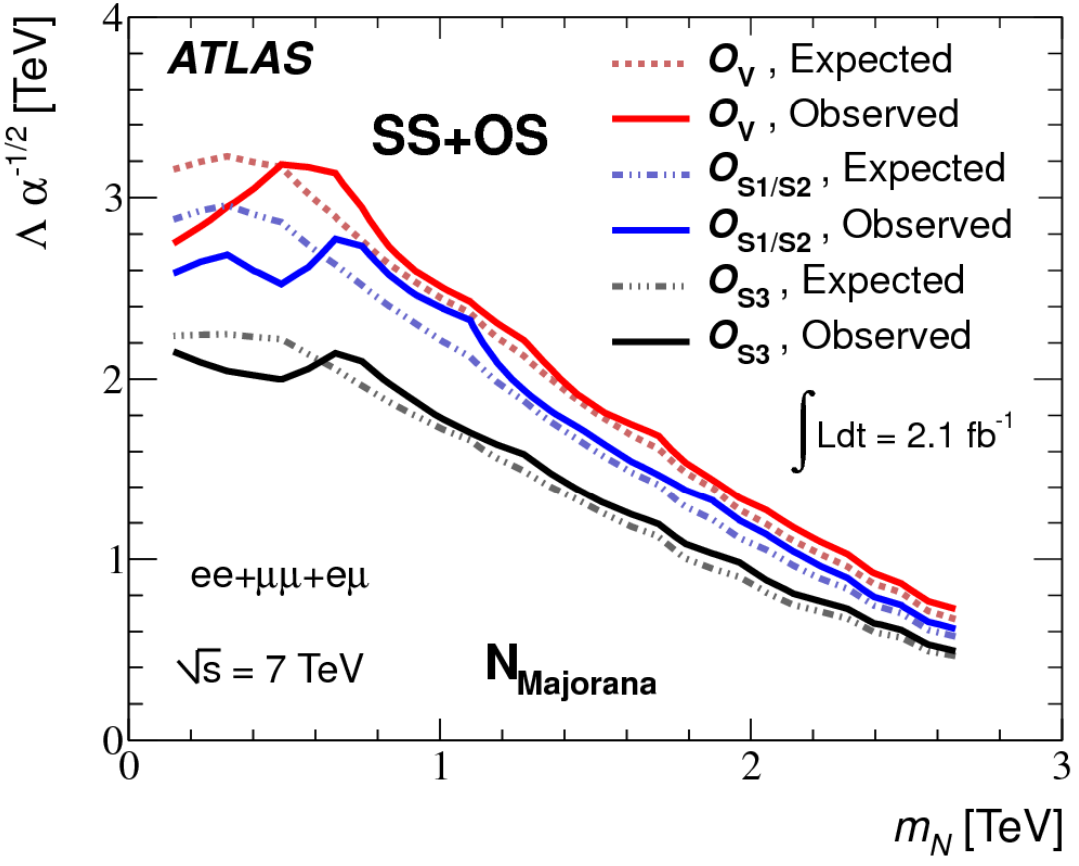
- Same sign *l*'s allowed if Majorana *N*

  dominant background: fake lepton(s)

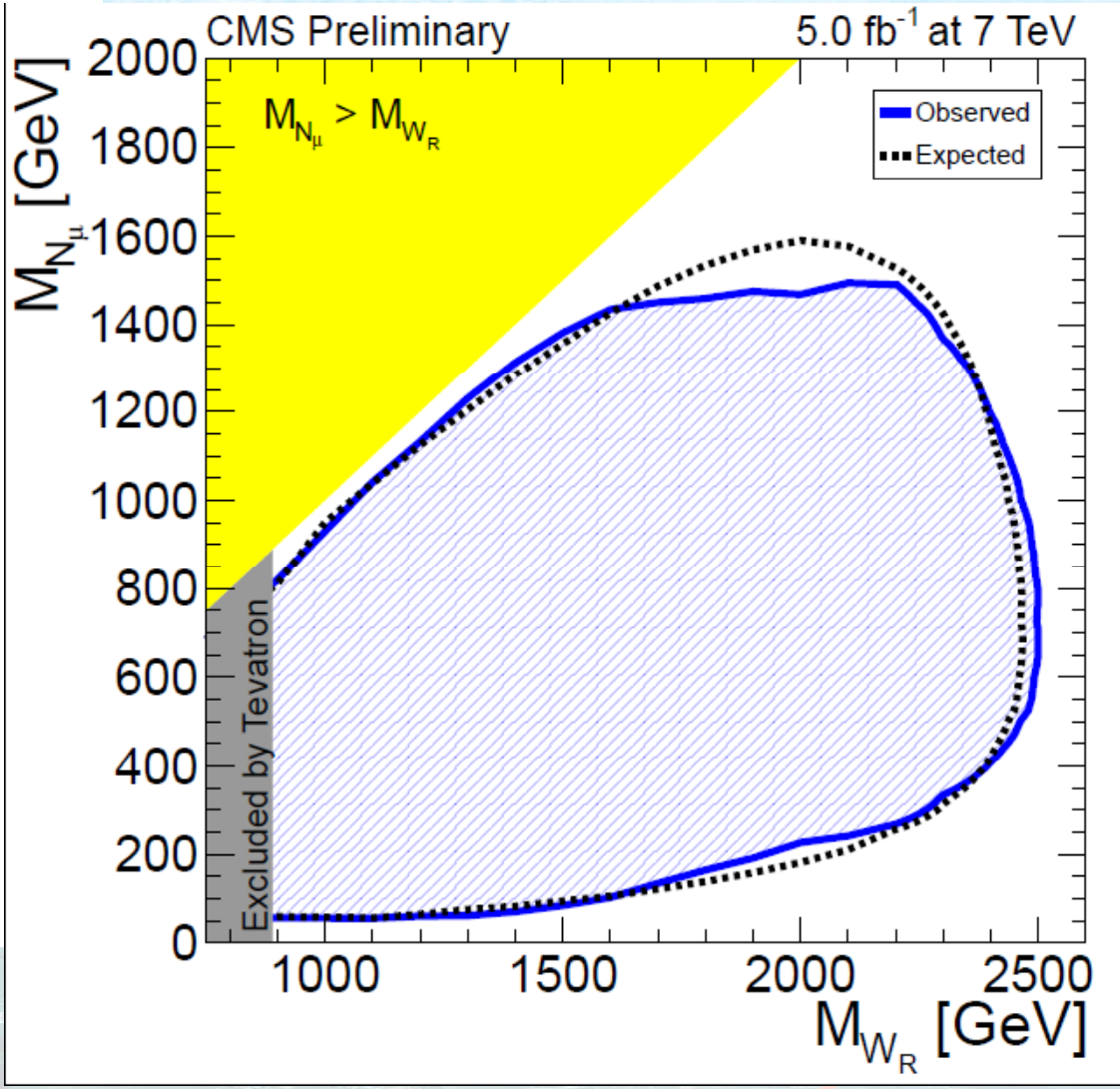


95% C.L. upper limits on the heavy neutrino and W_R for the Majorana case in no-mixing and maximal-mixing scenarios

Heavy neutrino & right-handed *W*



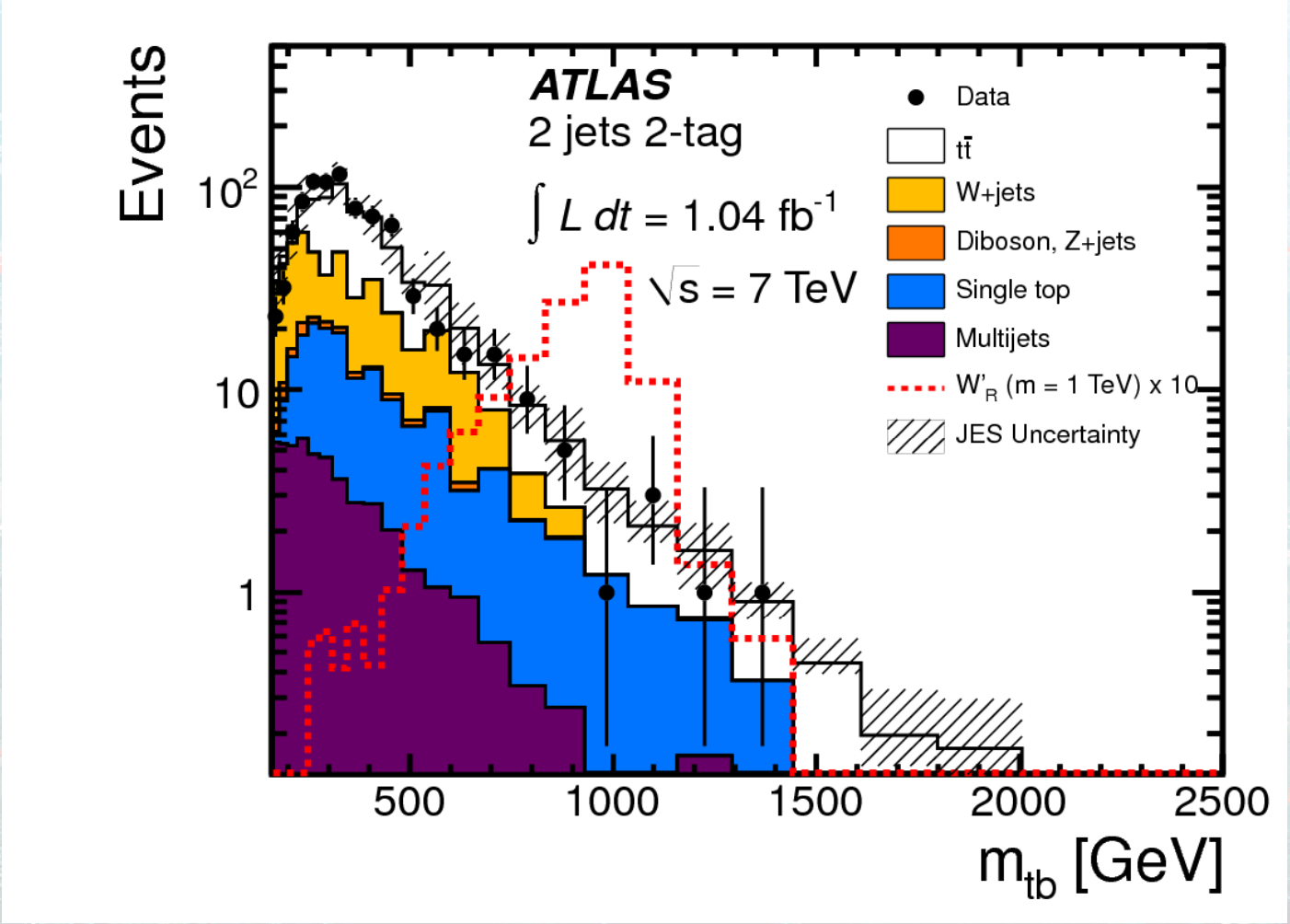
95% C.L. upper limits on $\Lambda/\sqrt{\alpha}$ (scale Λ & coupling α) as a function of the mass of the heavy neutrino for three different operators in the effective Lagrangian formalism for the Majorana scenario.



95% C.L. exclusion region for the μ channel as a function of the mass of the W_R and the N_μ, for equal coupling in the L & R sectors and N_μ as only *l* decay.

New Gauge Bosons - W'→ tb

- Previous search depends on m(W_R) > m(N) for $W_R \rightarrow l\,N$ decay.
- $W' \rightarrow tb$ decay channel is open even if m(N) > m(W_R).
- Signature is *lepton* + ≥ 2 *jets* + *missing* E_T, with ≥ 1 jet tagged as a b jet.
- Dominant backgrounds are ttbar and $W(\rightarrow l\,\nu)$+*jets*.



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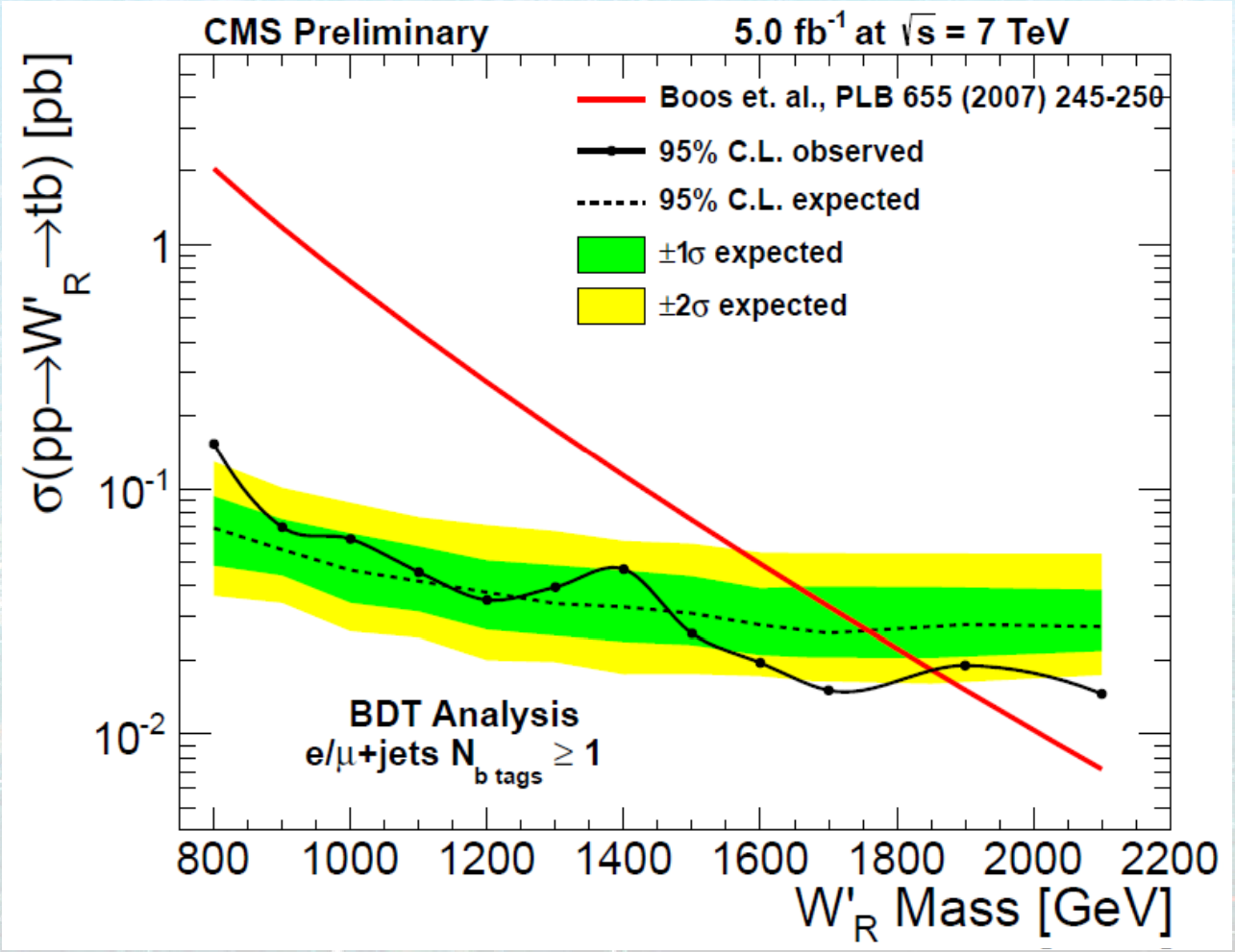


CMS analysis using multivariate techniques:

m(W'_R) > 1.85 TeV

@95%CL

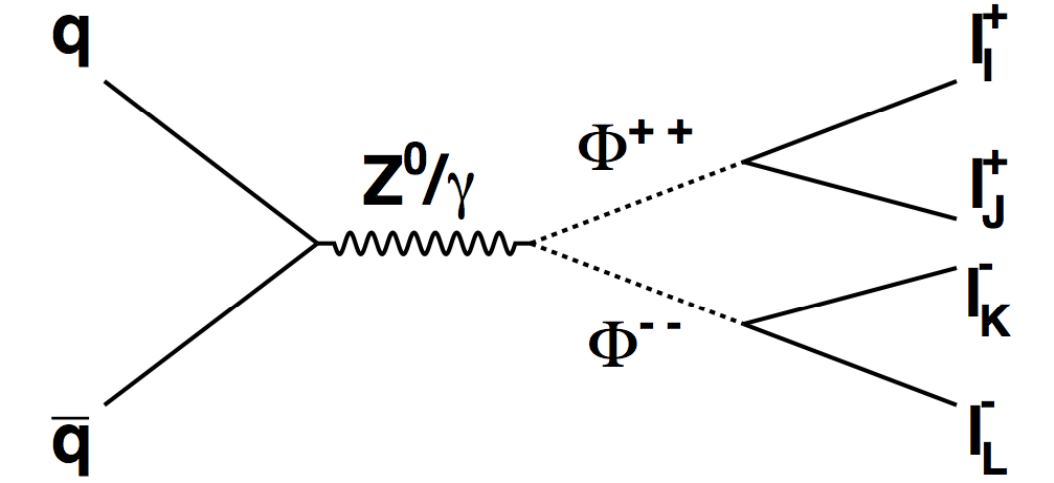
ATLAS

m(W'_R) > 1.13 TeV

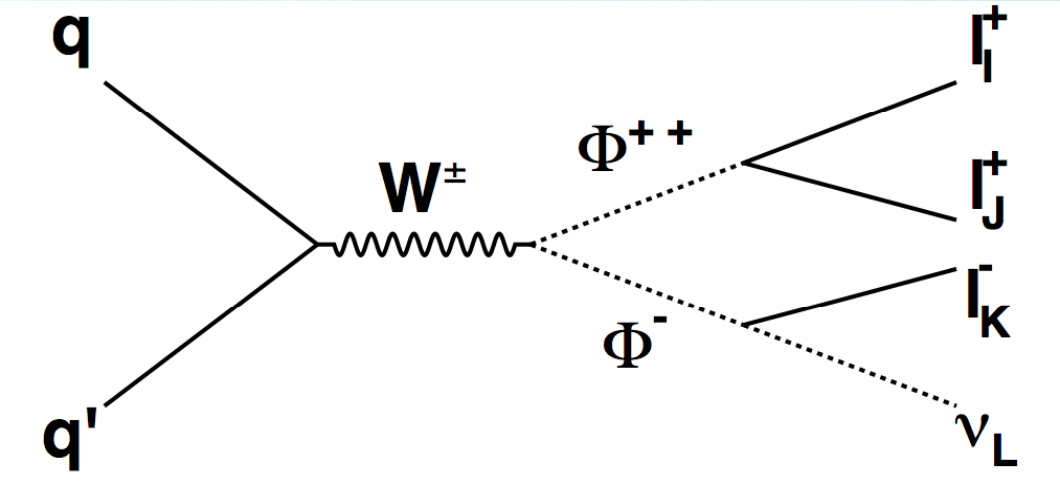
@95%CL w/ 1 fb^{-1}

CMS has also performed a search for $W' \rightarrow td$, in $dg \rightarrow t\,W' \rightarrow t\,td$

Doubly-charged Higgs - $H^{\pm\pm}$



pair production - 4 *l*



associated production - 3 *l* + *v*

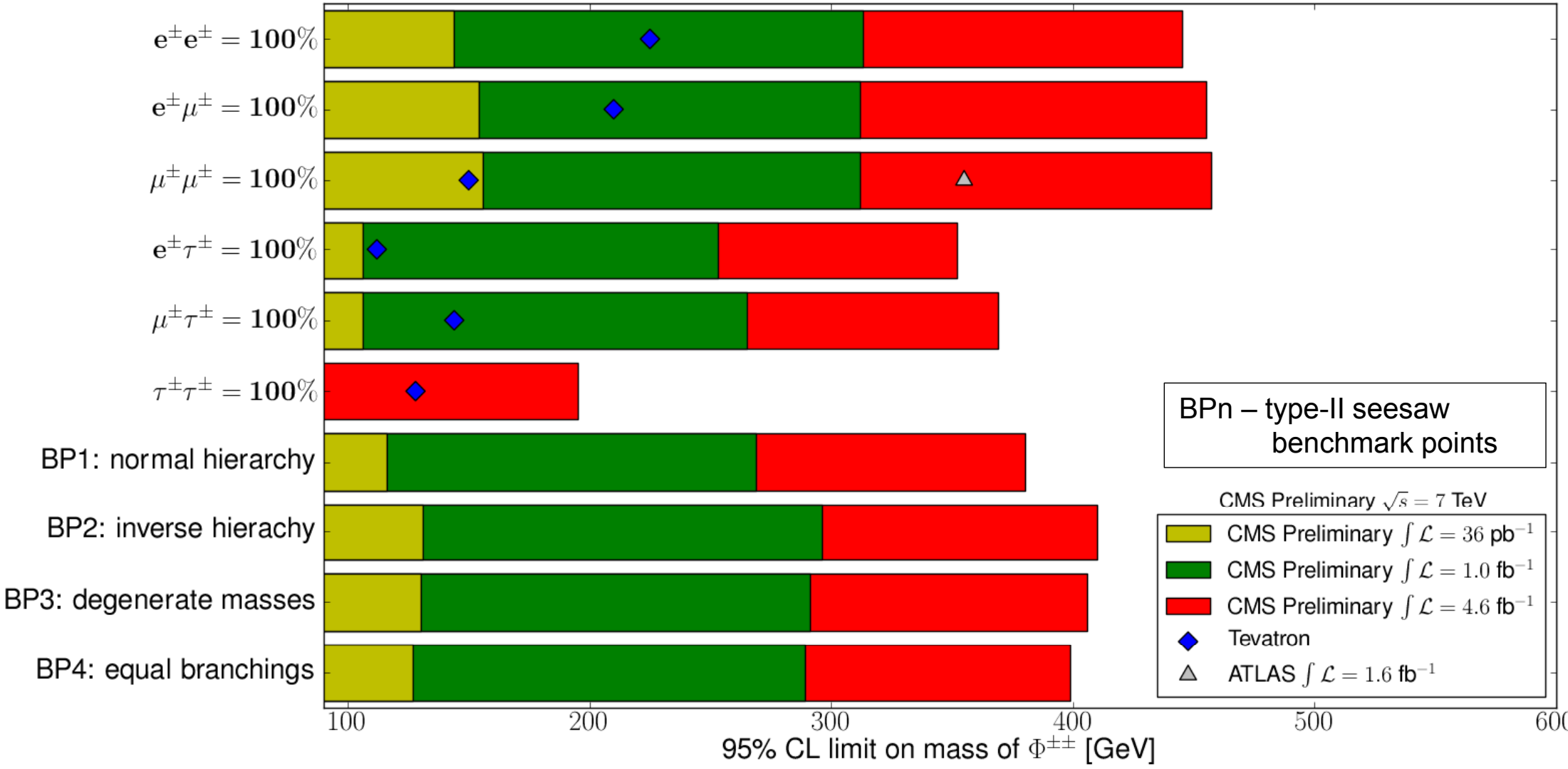
- Production produces multi-lepton final states, w/ same-sign lepton pairs.

- ATLAS searches (1.0-1.6 fb^{-1}):
  - Same-sign μ pairs – m($\mu^{\pm}\mu^{\pm}$)
  - ≥ 3 leptons (e, μ) – counting, pair
  - = 4 leptons (e, μ) – counting, pair

- CMS searches (4.6 fb^{-1}) :
  - ≥ 3 leptons (e, μ, τ) – m($l^{\pm}l^{\pm}$)
  - ≥ 3 leptons (e, μ, τ) – counting

CMS mass search is now the most sensitive.

Doubly-charged Higgs - $H^{\pm\pm}$

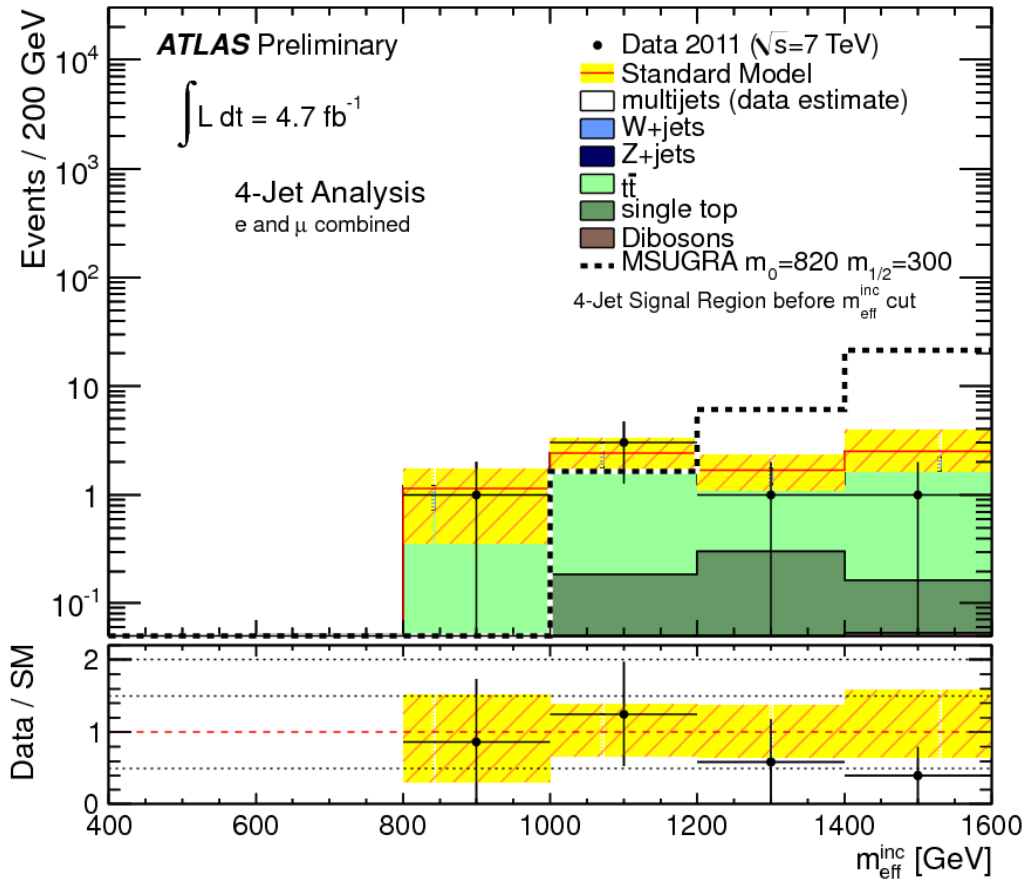


1 *lepton* + 4 *jets* + missing E_T

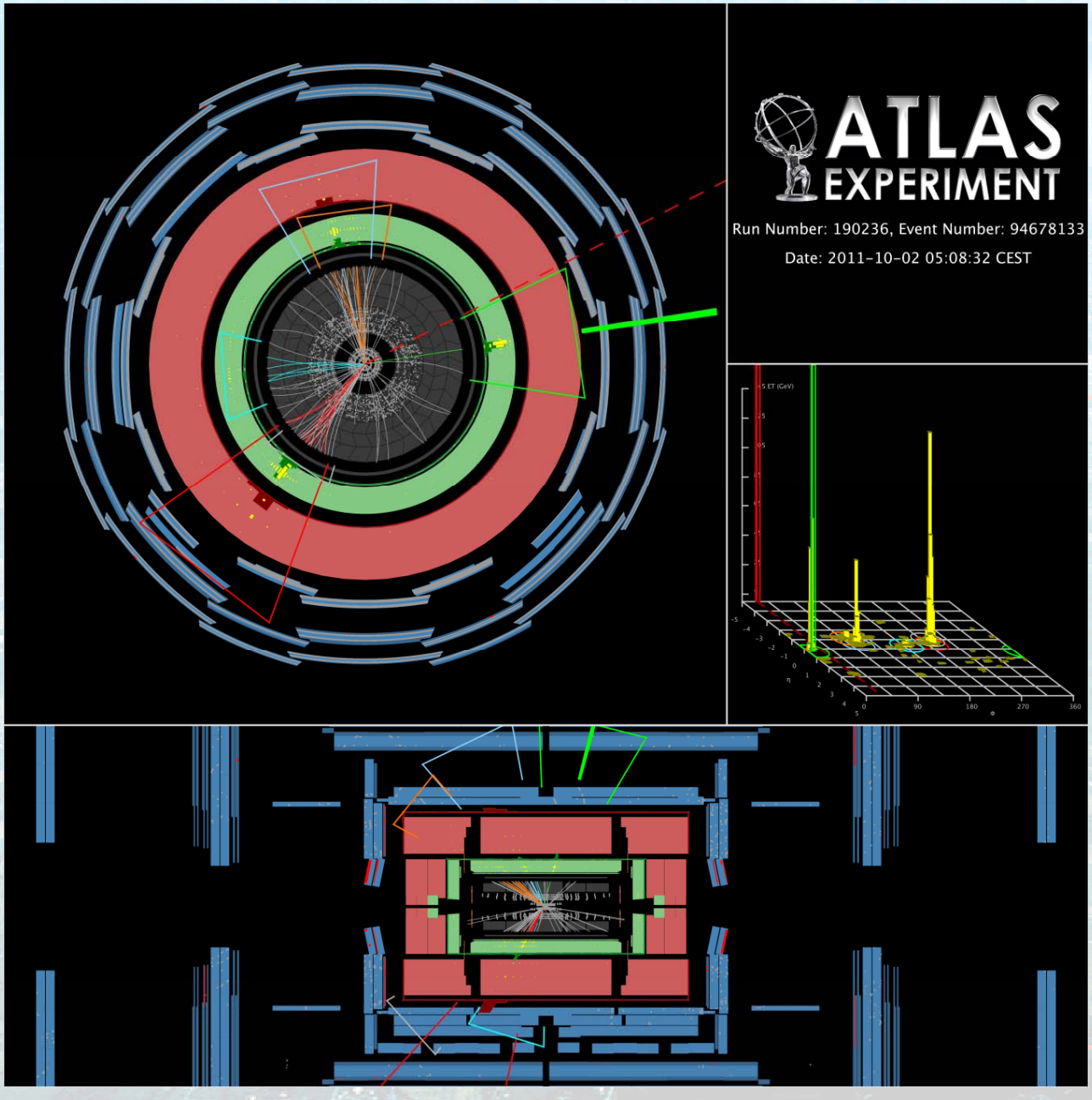
- Search usually performed in SUSY context
  - and often as $1l + \geq 3\, j + MET$
- But consider Type-III Seesaw (fermion triplet)

  $qq' \rightarrow \Sigma^+\Sigma^0 \rightarrow \nu W^+ W^{\pm} l^{-/+} \rightarrow MET + 4\, j + l$

- ATLAS: 4.7 fb^{-1}
  - 1 l , $p_T > 25$ (20) GeV e (μ)
  - ≥ 4 *jets* , $p_T > 80$ GeV
  - $MET > 250$ GeV
    - $m_T(l,MET) > 100$ GeV
    - (scalar) $m_{eff}(l,4j,MET) > 800$ GeV
    - $MET/m_{eff} > 0.2$
  - Background: top dominates; W/Z+jets
  - Observe 6 events; Expect 8.3±3.1
  - $\langle \varepsilon\sigma \rangle$ <1.5 fb @ 95% CL

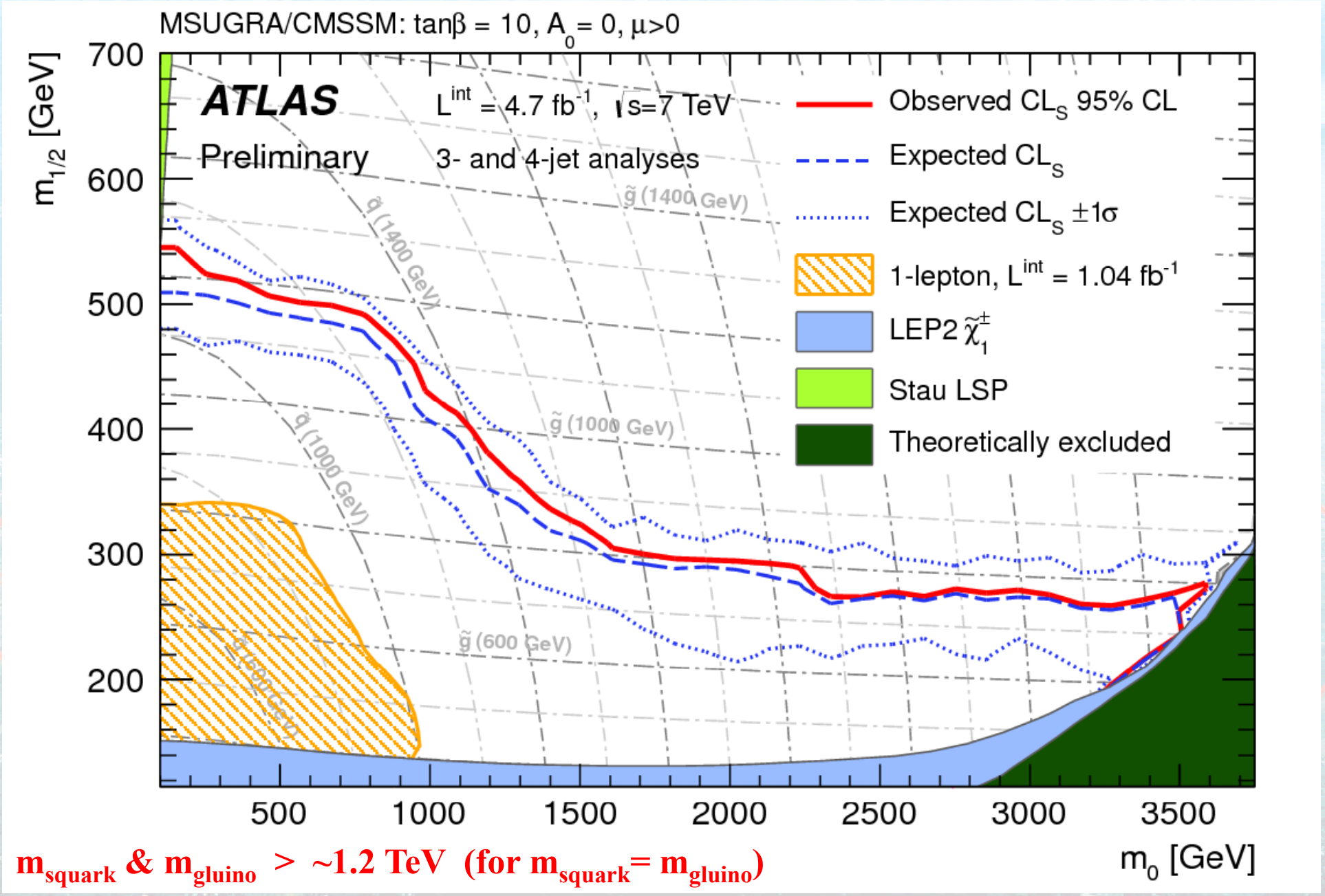


1 *lepton* + 4 *jets* + *missing* E_T



$p_T(e) = 265$ GeV
$p_T(j) = 690, 254, 117, 84, (36)$ GeV
MET = 381 GeV
$m_{eff} = 1827$ GeV

1 lepton + 4 jets + missing E_T



m_{squark} & m_{gluino} > ~1.2 TeV (for $m_{squark} = m_{gluino}$)

Search for anomalous production of multilepton events

Selection	N(τ)=0		N(τ)=1		N(τ)=2	
	obs	expect	obs	expect	obs	expect
4ℓ Lepton Results						
4ℓ (DY0) S_T(High)	0	0.0010 ± 0.0009	0	0.01 ± 0.09	0	0.18 ± 0.07
4ℓ (DY0) S_T(Mid)	0	0.004 ± 0.002	0	0.28 ± 0.10	2	2.5 ± 1.2
4ℓ (DY0) S_T(Low)	0	0.04 ± 0.02	0	2.98 ± 0.48	4	3.5 ± 1.1
4ℓ (DY1, no Z) S_T(High)	1	0.009 ± 0.004	0	0.10 ± 0.07	0	0.12 ± 0.05
4ℓ (DY1, Z) S_T(High)	1	0.09 ± 0.01	0	0.51 ± 0.15	0	0.43 ± 0.15
4ℓ (DY1, no Z) S_T(Mid)	0	0.07 ± 0.02	1	0.88 ± 0.26	1	0.94 ± 0.29
4ℓ (DY1, Z) S_T(Mid)	0	0.45 ± 0.11	5	4.1 ± 1.2	3	3.4 ± 0.9
4ℓ (DY1, no Z) S_T(Low)	0	0.09 ± 0.04	7	5.5 ± 2.2	19	13.7 ± 6.4
4ℓ (DY1, Z) S_T(Low)	2	0.80 ± 0.34	19	17.7 ± 4.9	95	60 ± 31
4ℓ (DY2, no Z) S_T(High)	0	0.02 ± 0.01	–	–	–	–
4ℓ (DY2, Z) S_T(High)	0	0.89 ± 0.34	–	–	–	–
4ℓ (DY2, no Z) S_T(Mid)	0	0.20 ± 0.09	–	–	–	–
4ℓ (DY2, Z) S_T(Mid)	3	7.9 ± 3.2	–	–	–	–
4ℓ (DY2, no Z) S_T(Low)	1	2.4 ± 1.1	–	–	–	–
4ℓ (DY2, Z) S_T(Low)	29	29 ± 12	–	–	–	–
3ℓ Lepton Results						
3ℓ (DY0) S_T(High)	2	1.14 ± 0.43	17	11.2 ± 3.2	20	22.5 ± 6.1
3ℓ (DY0) S_T(Mid)	5	7.4 ± 3.0	113	97 ± 31	157	181 ± 24
3ℓ (DY0) S_T(Low)	17	13.5 ± 4.1	522	419 ± 63	1631	2018 ± 253
3ℓ (DY1, no Z) S_T(High)	6	3.5 ± 0.9	10	13.1 ± 2.3	–	–
3ℓ (DY1, Z) S_T(High)	17	18.7 ± 6.0	35	39.2 ± 4.8	–	–
3ℓ (DY1, no Z) S_T(Mid)	32	25.5 ± 6.6	159	141 ± 27	–	–
3ℓ (DY1, Z) S_T(Mid)	89	102 ± 31	441	463 ± 41	–	–
3ℓ (DY1, no Z) S_T(Low)	126	150 ± 36	3721	2983 ± 418	–	–
3ℓ (DY1, Z) S_T(Low)	727	815 ± 192	17631	15758 ± 2452	–	–
Total 4ℓ	37	42 ± 13	32.0	32.1 ± 5.5	124	85 ± 32
Total 3ℓ	1021	1137 ± 198	22649	19925 ± 2489	1808	2222 ± 255
Total	1058	1179 ± 198	22681	19957 ± 2489	1932	2307 ± 257

CMS 5 fb^{-1}

classify events by:

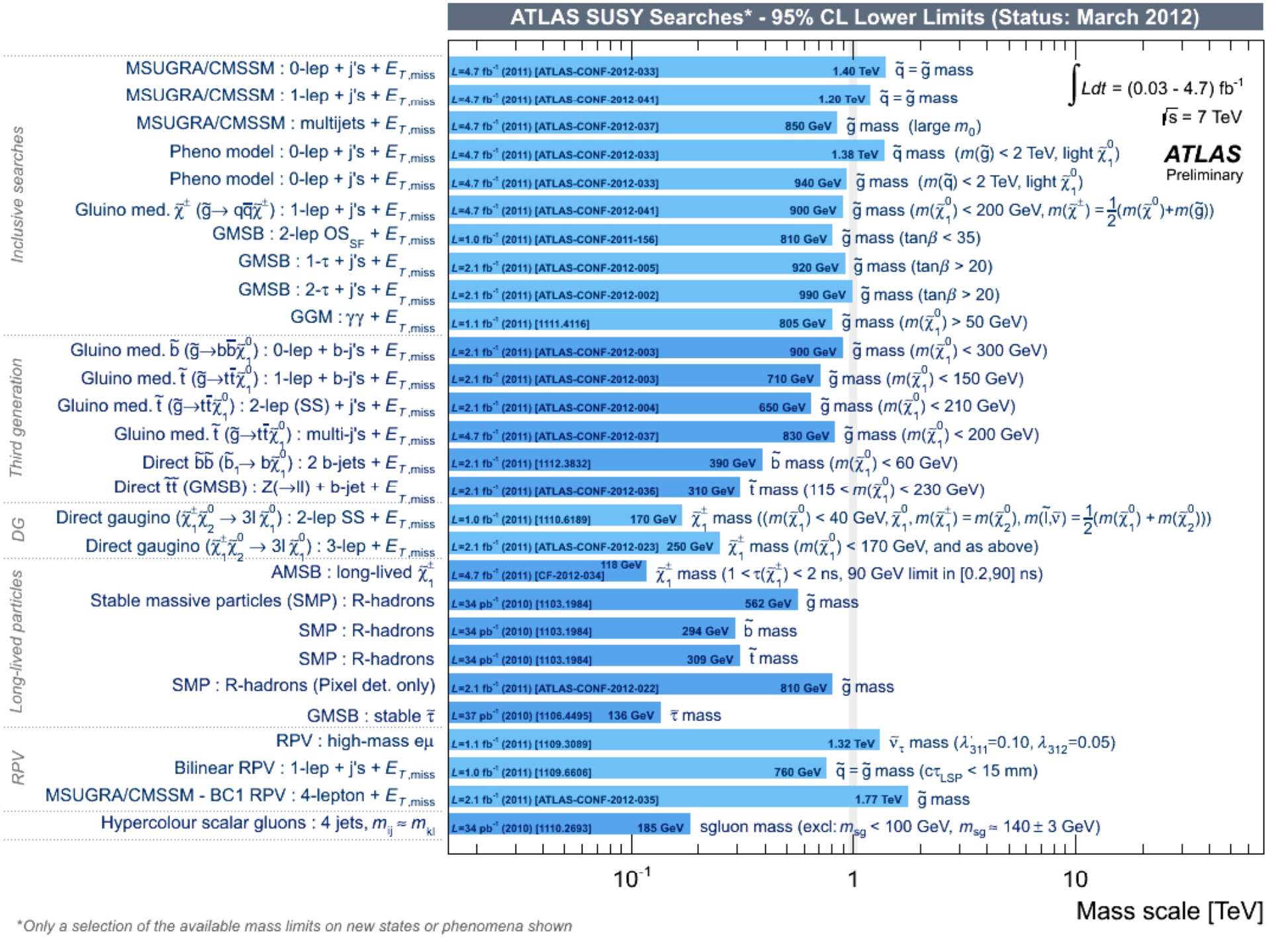
- # leptons
- # τ
- # Drell-Yan pairs
- whether Z excluded
- H_T *or* S_T

- Models can be compared to numbers of events in all categories.
- Models explored include RPV scenarios.

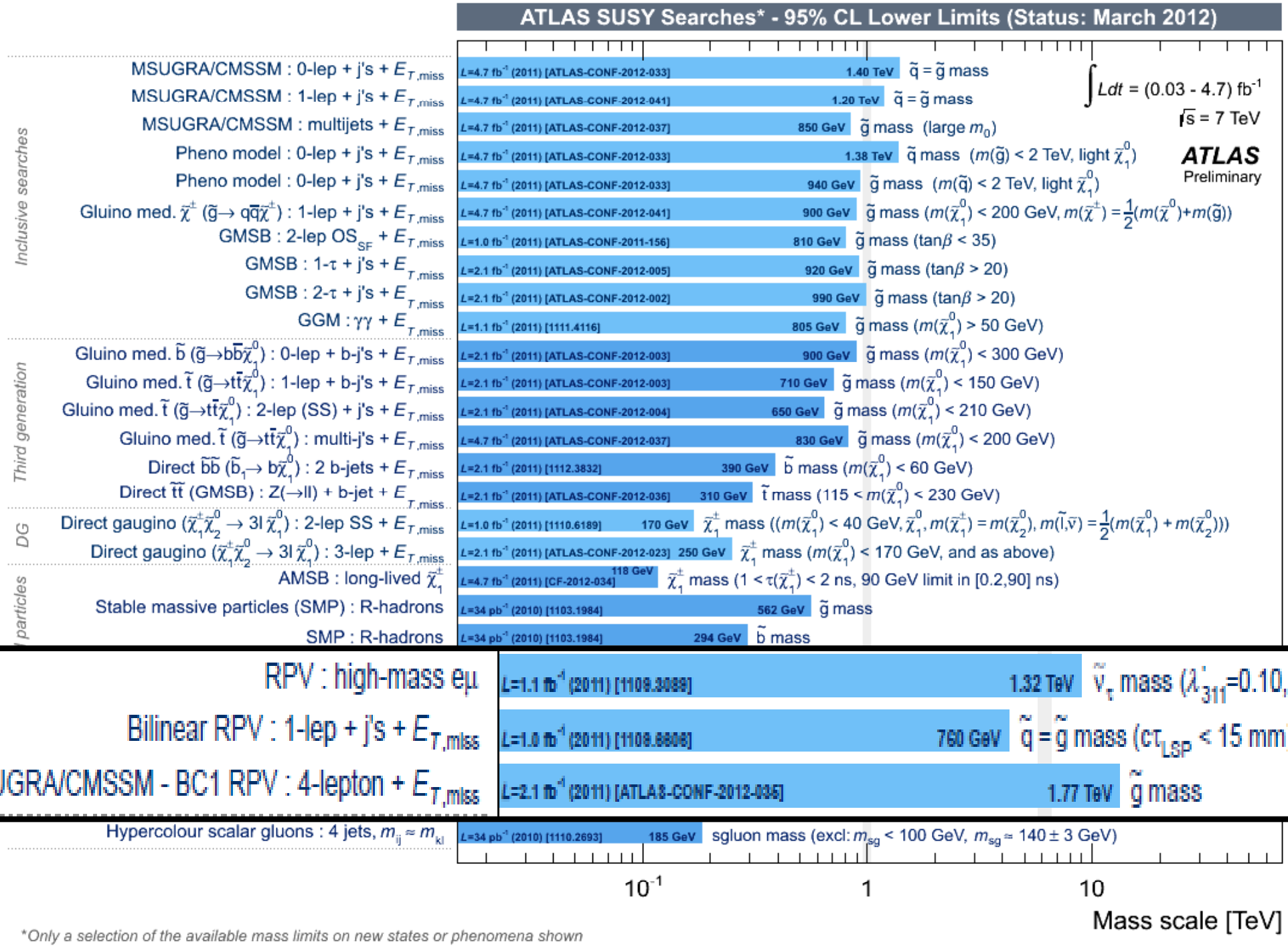
ATLAS $\geq 4l$ 2 fb^{-1}

cross-section upper limit

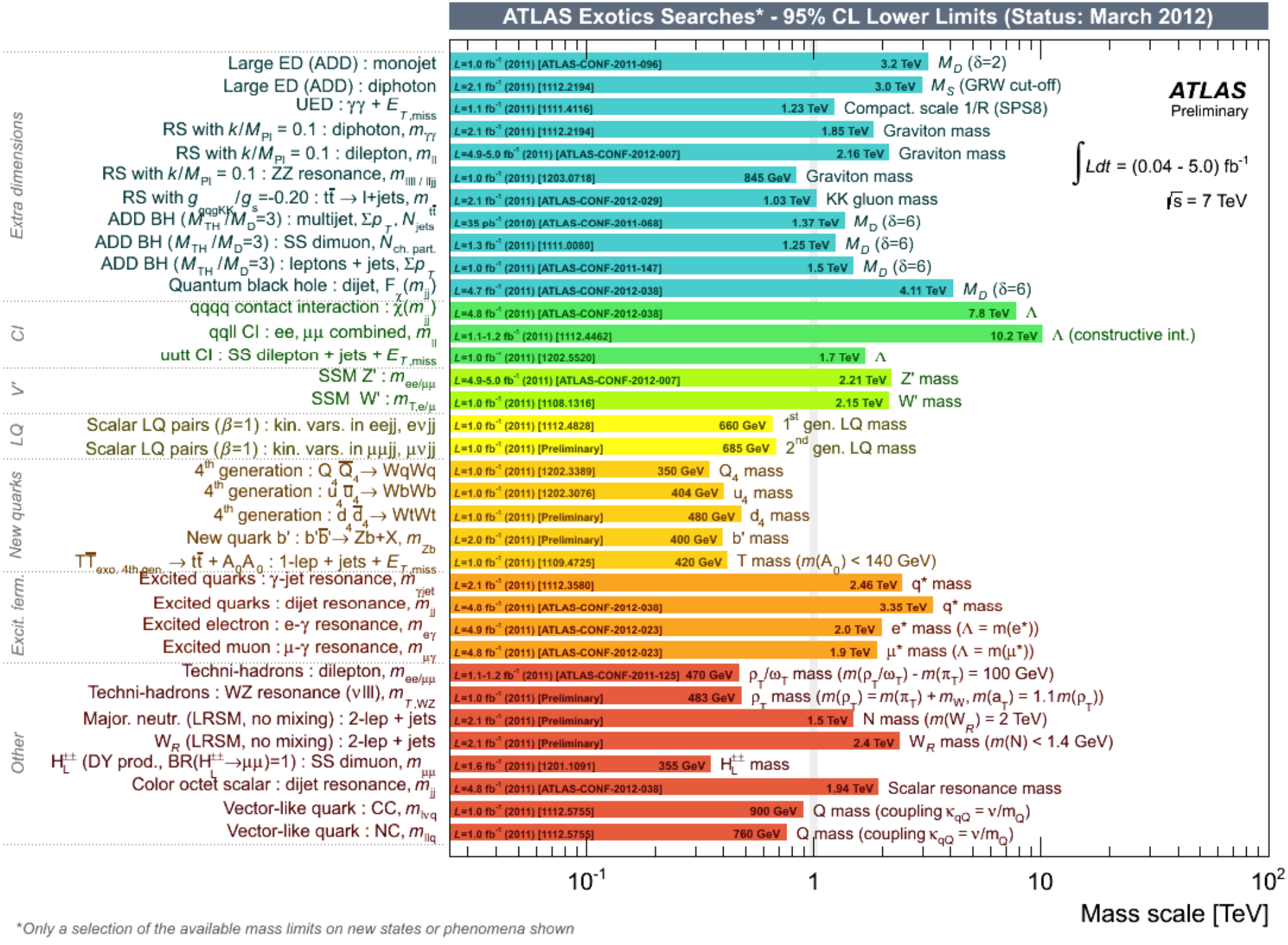
3.5 fb w/o Z, 1.5 fb w/ Z



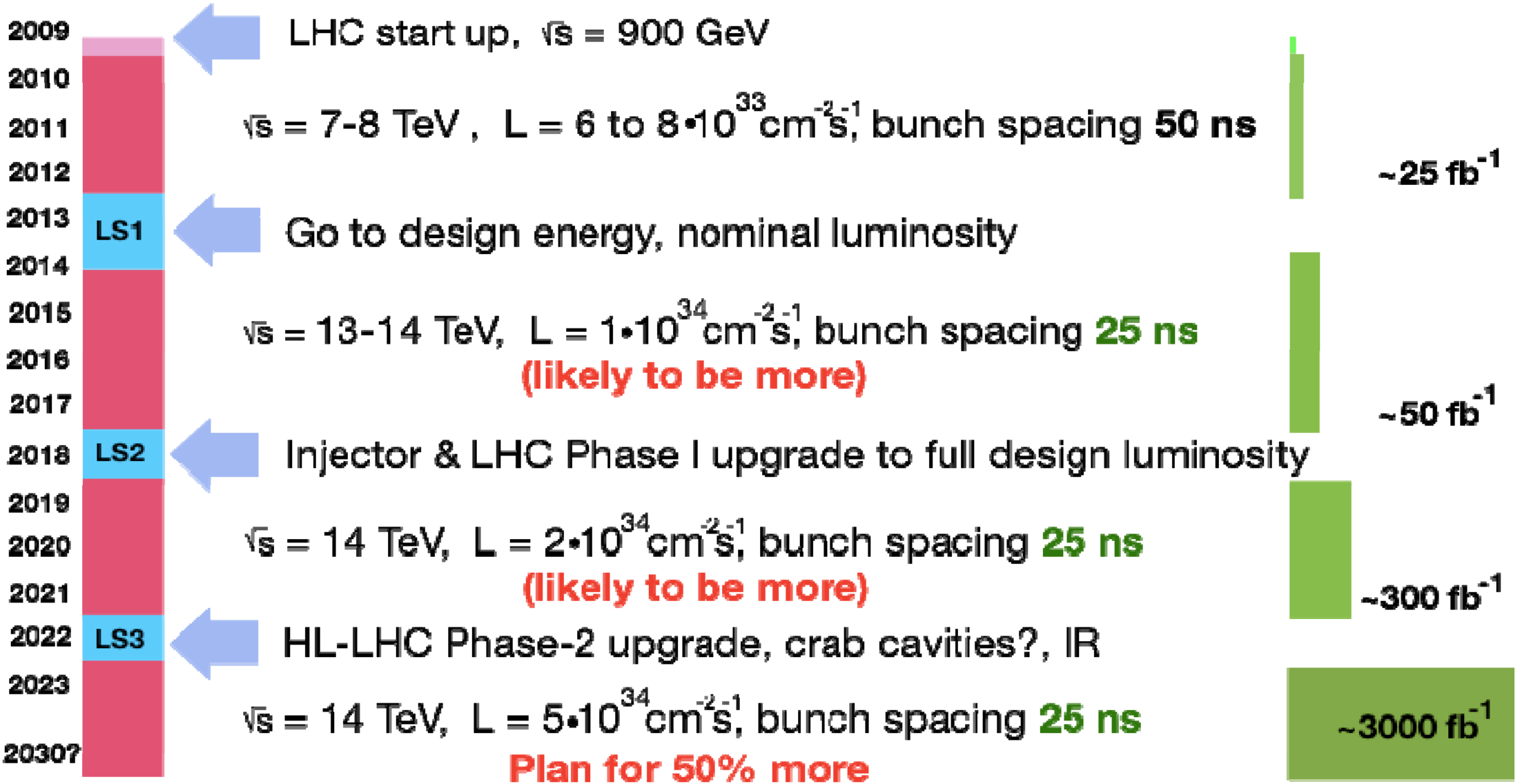
*Only a selection of the available mass limits on new states or phenomena shown



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


ATLAS Exotics Searches* - 95% CL Lower Limits (Status: March 2012)
ATLAS
Preliminary
∫Ldt = (0.04 - 5.0) fb-1
√s = 7 TeV
Extra dimensions
Large ED (ADD) : monojet
Large ED (ADD) : diphoton
UED : γγ + E T,miss
RS with k/M Pl = 0.1 : diphoton, m γγ
RS with k/M Pl = 0.1 : dilepton, m ll
RS with k/M Pl = 0.1 : ZZ resonance, m llll / lljj
RS with g qqgKK /g s =-0.20 : tt̄ → l+jets, m tt̄
ADD BH (M TH /M D =3) : multijet, Σp T , N jets
ADD BH (M TH /M D =3) : SS dimuon, N ch. part.
ADD BH (M TH /M D =3) : leptons + jets, Σp T
Quantum black hole : dijet, F χ (m jj)
CI
qqqq contact interaction : χ(m jj)
qqll CI : ee, μμ combined, m ll
uutt CI : SS dilepton + jets + E T,miss
V'
SSM Z' : m ee/μμ
SSM W' : m T,e/μ
LQ
Scalar LQ pairs (β=1) : kin. vars. in eejj, eνjj
Scalar LQ pairs (β=1) : kin. vars. in μμjj, μνjj
New quarks
4th generation : Q Q̄ 4 → WqWq
4th generation : u u 4 → WbWb
4th generation : d d 4 → WtWt
New quark b' : b'b̄' → Zb+X, m Zb
TT̄ exo. 4th gen. → tt̄ + A 0 A 0 : 1-lep + jets + E T,miss
Excit. ferm.
Excited quarks : γ-jet resonance, m γjet
Excited quarks : dijet resonance, m jj
Excited electron : e-γ resonance, m eγ
Excited muon : μ-γ resonance, m μγ
Other
Techni-hadrons : dilepton, m ee/μμ
Techni-hadrons : WZ resonance (νlll), m T,WZ
Major. neutr. (LRSM, no mixing) : 2-lep + jets
W R (LRSM, no mixing) : 2-lep + jets
H L±± (DY prod., BR(H L±± →μμ)=1) : SS dimuon, m μμ
Color octet scalar : dijet resonance, m jj
Vector-like quark : CC, m lνq
Vector-like quark : NC, m llq
L=1.0 fb-1 (2011) [ATLAS-CONF-2011-096] 3.2 TeV M D (δ=2)
L=2.1 fb-1 (2011) [1112.2194] 3.0 TeV M S (GRW cut-off)
L=1.1 fb-1 (2011) [1111.4116] 1.23 TeV Compact. scale 1/R (SPS8)
L=2.1 fb-1 (2011) [1112.2194] 1.85 TeV Graviton mass
L=4.9-5.0 fb-1 (2011) [ATLAS-CONF-2012-007] 2.16 TeV Graviton mass
L=1.0 fb-1 (2011) [1203.0718] 845 GeV Graviton mass
L=2.1 fb-1 (2011) [ATLAS-CONF-2012-029] 1.03 TeV KK gluon mass
L=35 pb-1 (2010) [ATLAS-CONF-2011-068] 1.37 TeV M D (δ=6)
L=1.3 fb-1 (2011) [1111.0080] 1.25 TeV M D (δ=6)
L=1.0 fb-1 (2011) [ATLAS-CONF-2011-147] 1.5 TeV M D (δ=6)
L=4.7 fb-1 (2011) [ATLAS-CONF-2012-038] 4.11 TeV M D (δ=6)
L=4.8 fb-1 (2011) [ATLAS-CONF-2012-038] 7.8 TeV Λ
L=1.1-1.2 fb-1 (2011) [1112.4462] 10.2 TeV Λ (constructive int.)
L=1.0 fb-1 (2011) [1202.5520] 1.7 TeV Λ
L=4.9-5.0 fb-1 (2011) [ATLAS-CONF-2012-007] 2.21 TeV Z' mass
L=1.0 fb-1 (2011) [1108.1316] 2.15 TeV W' mass
L=1.0 fb-1 (2011) [1112.4828] 660 GeV 1st gen. LQ mass
L=1.0 fb-1 (2011) [Preliminary] 685 GeV 2nd gen. LQ mass
L=1.0 fb-1 (2011) [1202.3389] 350 GeV Q 4 mass
L=1.0 fb-1 (2011) [1202.3076] 404 GeV u 4 mass
L=1.0 fb-1 (2011) [Preliminary] 480 GeV d 4 mass
L=2.0 fb-1 (2011) [Preliminary] 400 GeV b' mass
L=1.0 fb-1 (2011) [1109.4725] 420 GeV T mass (m(A 0) < 140 GeV)
L=2.1 fb-1 (2011) [1112.3580] 2.46 TeV q* mass
L=4.8 fb-1 (2011) [ATLAS-CONF-2012-038] 3.35 TeV q* mass
L=4.9 fb-1 (2011) [ATLAS-CONF-2012-023] 2.0 TeV e* mass (Λ = m(e*))
L=4.8 fb-1 (2011) [ATLAS-CONF-2012-023] 1.9 TeV μ* mass (Λ = m(μ*))
L=1.1-1.2 fb-1 (2011) [ATLAS-CONF-2011-125] 470 GeV ρ T /ω T mass (m(ρ T /ω T) - m(π T) = 100 GeV)
L=1.0 fb-1 (2011) [Preliminary] 483 GeV ρ T mass (m(ρ T) = m(π T) + m W , m(a T) = 1.1m(ρ T))
L=2.1 fb-1 (2011) [Preliminary] 1.5 TeV N mass (m(W R) = 2 TeV)
L=2.1 fb-1 (2011) [Preliminary] 2.4 TeV W R mass (m(N) < 1.4 GeV)
L=1.6 fb-1 (2011) [1201.1091] 355 GeV H L±± mass
L=4.8 fb-1 (2011) [ATLAS-CONF-2012-038] 1.94 TeV Scalar resonance mass
L=1.0 fb-1 (2011) [1112.5755] 900 GeV Q mass (coupling κ qQ = v/m Q)
L=1.0 fb-1 (2011) [1112.5755] 760 GeV Q mass (coupling κ qQ = v/m Q)
10-1
1
10
102
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

LHC plans



LS = Long Shutdown

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http://cms.web.cern.ch/org/cms-papers-and-results

New gauge bosons - Z'
- ATLAS-CONF-2012-007
- CMS: arXiv:1206.1849

New gauge bosons - W'
- ATLAS: Phys.Lett. B705 (2011) 28-45
- CMS: arXiv:1204.4764

Heavy neutrinos and right-handed *W*'s
- ATLAS: arXiv:1203.5420 (accepted by EPJC)
- CMS PAS EXO-11-091

W' → tb
- ATLAS: arXiv:1205.1016
- CMS PAS EXO-12-001

W' → td
- CMS PAS EXO-11-056

W' → WZ
- ATLAS: arXiv:1204.1648
- CMS-EXO-11-041

Doubly-charged Higgs – H^{++}
- ATLAS: arXiv:1201.1091
- ATLAS-CONF-2011-144
- ATLAS-CONF-2011-158
- CMS PAS HIG-12-005
- CMS-SUS-11-013

1 *l* + 4 *jets* + *MET*
- ATLAS-CONF-2012-041

Multileptons
- ATLAS-CONF-2012-001
- CMS: arXiv:1204.5341

Summary

LHC is midway in its first long successful run.

- **The accelerator and experiments are performing extremely well.**

Standard model and Top are measured and understood.
Modeling of backgrounds is excellent.

Searches for excesses beyond SM being performed in many channels.

- **No significant excesses observed (yet)**
- **Results expressed as:**
  - (fiducial) **cross-section limits,**
  - **limits on new particle masses in specific models.**

Expect limits on new physics to improve

increased statistics (this year, and after)

increased energy (in 2015) – a doubling!