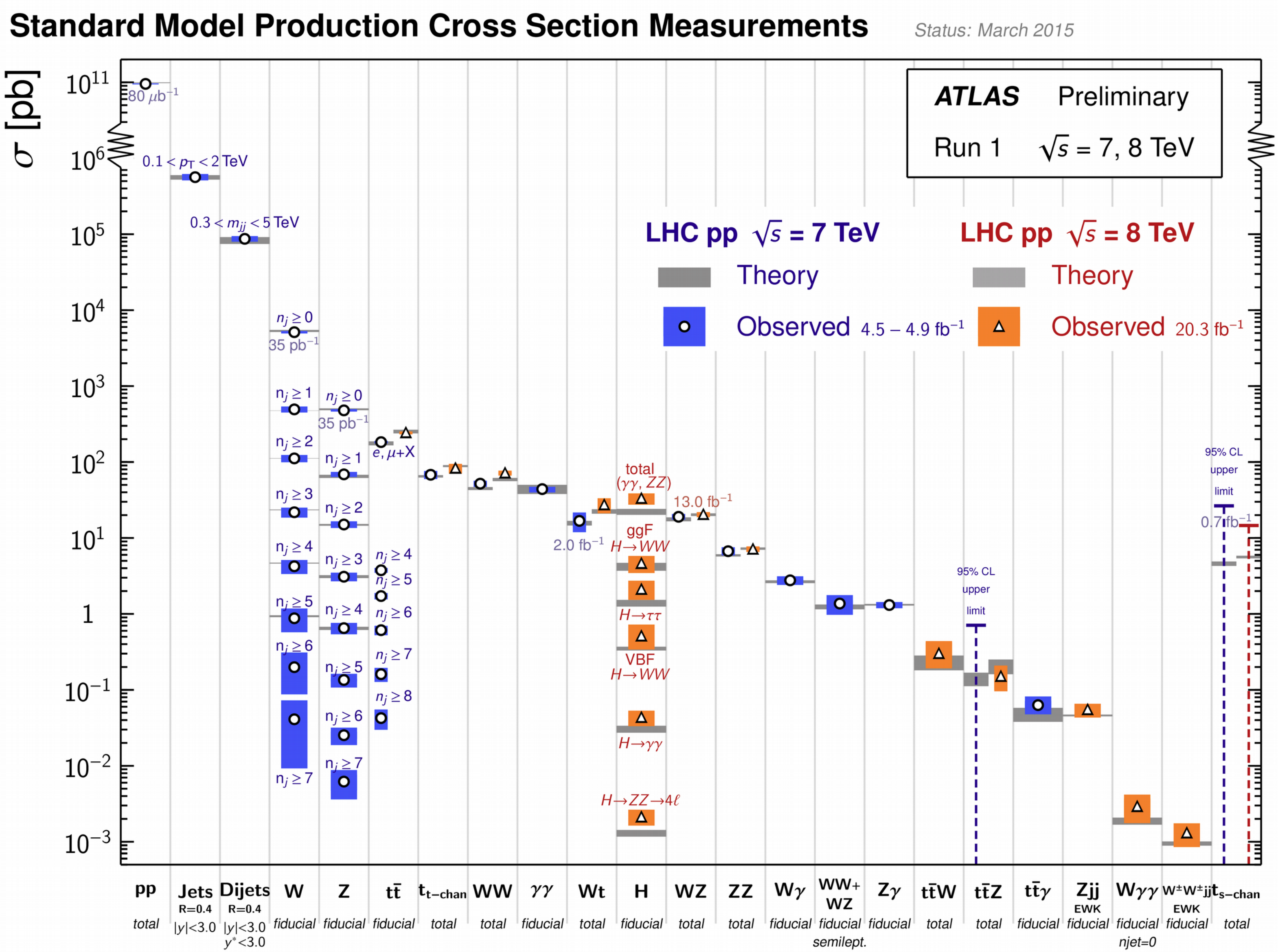
New Physics? Old Questions...

Ian Hinchliffe

After LHC Run 1

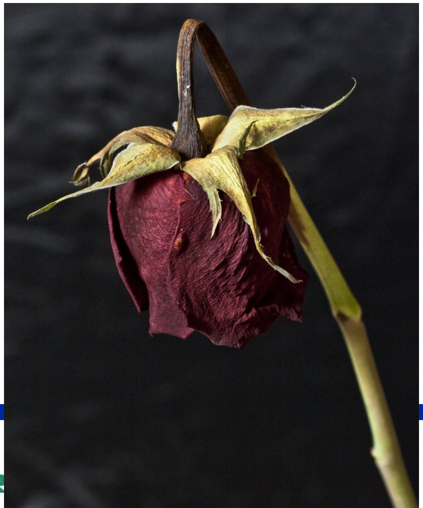
- Phenomenal success of Standard Model
  - Both calculational and experimental
    - Rates over 10 orders of magnitude
    - Precision of ppm
- Higgs boson has been found
  - Properties are consistent with standard model expectations
- Nothing missing
- No other new particles have been seen
- Cue party…..

After LHC Run 1



Everything is not rosy

- **Experimental**
  - Neutrinos oscillate:
    - Can be accomodated by straightforward modifications
  - (g-2)μ does not agree with predictions
    - Errors underestimated (both theory and experiment)?
    - Hint of new physics?
  - Dark Matter
    - If it's a particle, there is no candidate
- **Theoretical (philosophical?)**



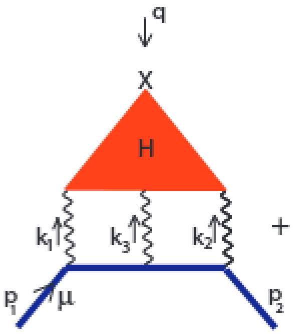
Issues with Standard model

- **Experimental**
  - **0.5(g-2)$_\mu$**

    http://arxiv.org/abs/1311.2198 For summary

    - **Very precise measurement: (116592089)x10^{-11}**

- *Theory-experiment=(287 or 261)x10^{-11}(250 ppm)*
- *Experimental error 63x10^{-11} (0.54 ppm)*
- *Calculational error (light by light scattering): 49x10^{-11}*
- *So what?*
  - » *Theorists: "supersymmetry might explain it"*
  - » *Experimenters: "need better experiment"*
  - » *Me: "need smaller credible errors"*

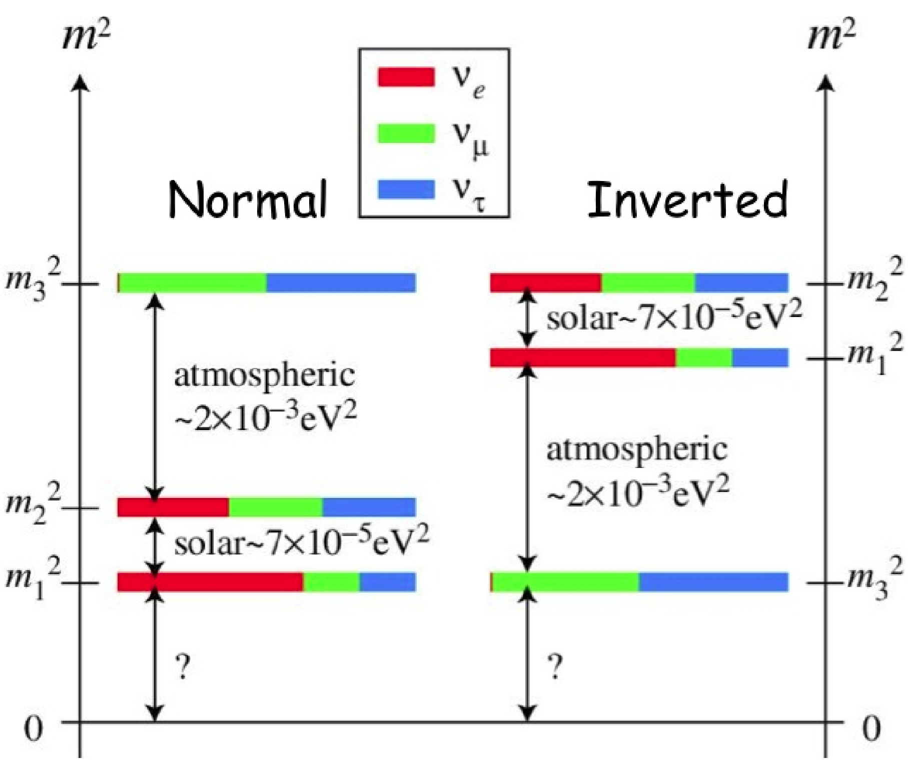


Issues with Standard model

Neutrino masses and mixings

- **Does not fit into SM**
  - But easily accomodated

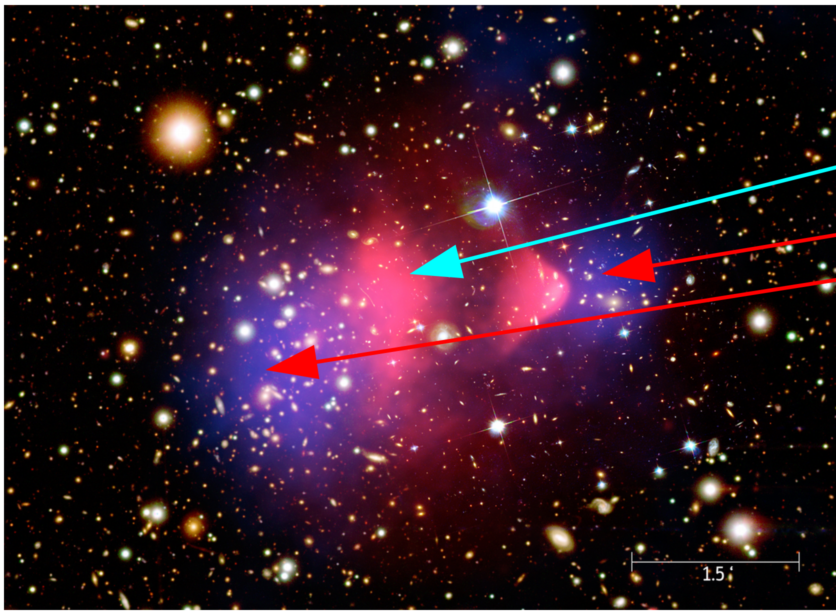
Summary from Steve King

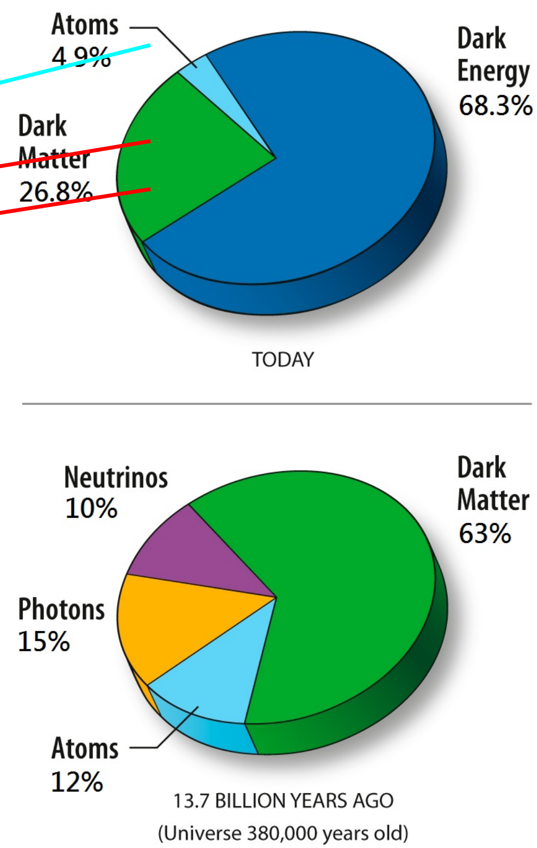


- *Which ordering?*
- *CP Violation?*
  - *Is there any?*
  - *Can it explain universe baryon excess*
- *Dirac or Majorana*
  - *Neutrinoless double beta decay*

Mostly experimental issues

Issues with Standard model





No dark matter candidate in SM

Dark matter inferred from star motion and gravitational lensing

Issues with Standard model

- Theoretical (philosophical?)
  - 18 parameters
  - No understanding of particle masses
    - All blamed on Higgs couplings
  - Measured CP violation (quark sector) too small to explain excess of matter over anti-matter
    - Could be related to neutrino problem (above)
  - Higgs mass is “unnatural” (fine tuned)
    - Or why is $M_H << M_P$
    - Gravity problem or Weak interaction problem

Making progress

- Someone comes up with a good theory
  - Must predict something measurable and definitive
    - Sadly lacking at present
- New Experimental information
  - More information about neutrinos
    - CP violation?
    - Mass structure
    - Important but unlikely by itself so be critical
  - Discovery of some new state(s)
    - Everything changes

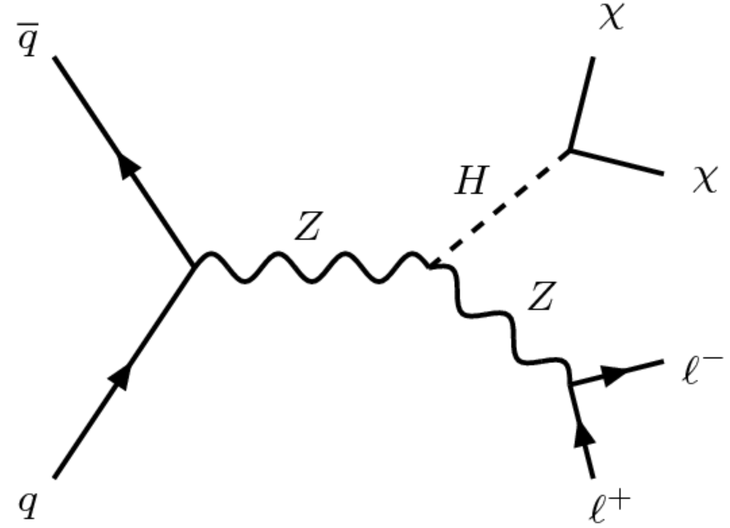
Could Higgs be related to Dark Matter?

- Higgs is rather odd
  – Non universal couplings, Spin 0
  – Could it be coupling to Dark matter?
    - DM particles only couple to matter via Higgs ("Higgs Portal")
  – $M_{DM}<M_H/2$ has bound on coupling to Higgs
    - Higgs decays to pairs of DM particles
    - Invisible width limited by experiment

"Higgs portal models"

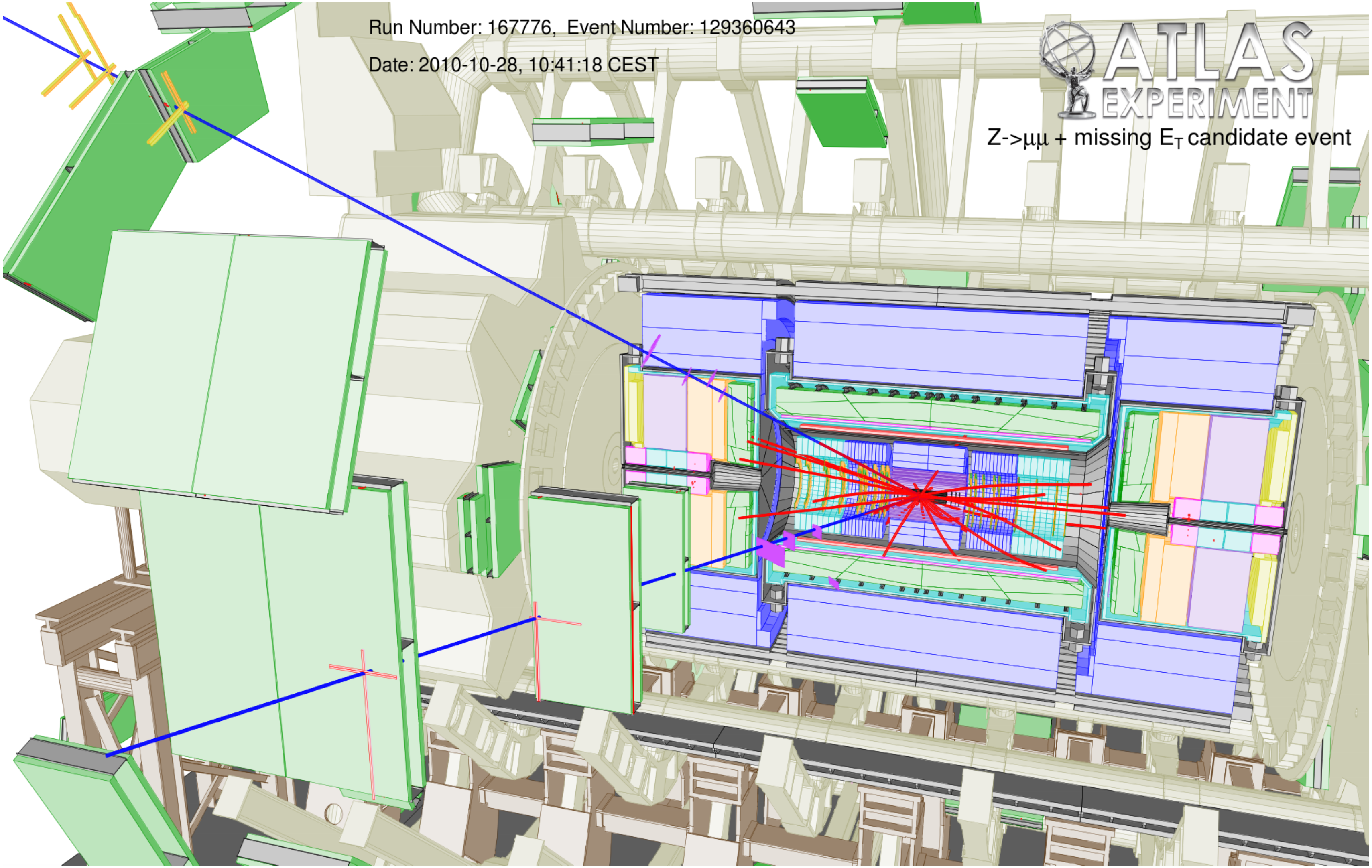
Higgs to “invisible” search at LHC

- Uses production of Z+Higgs
- Trigger and Detect Z to leptons
  - (Can also use Z to bbar)

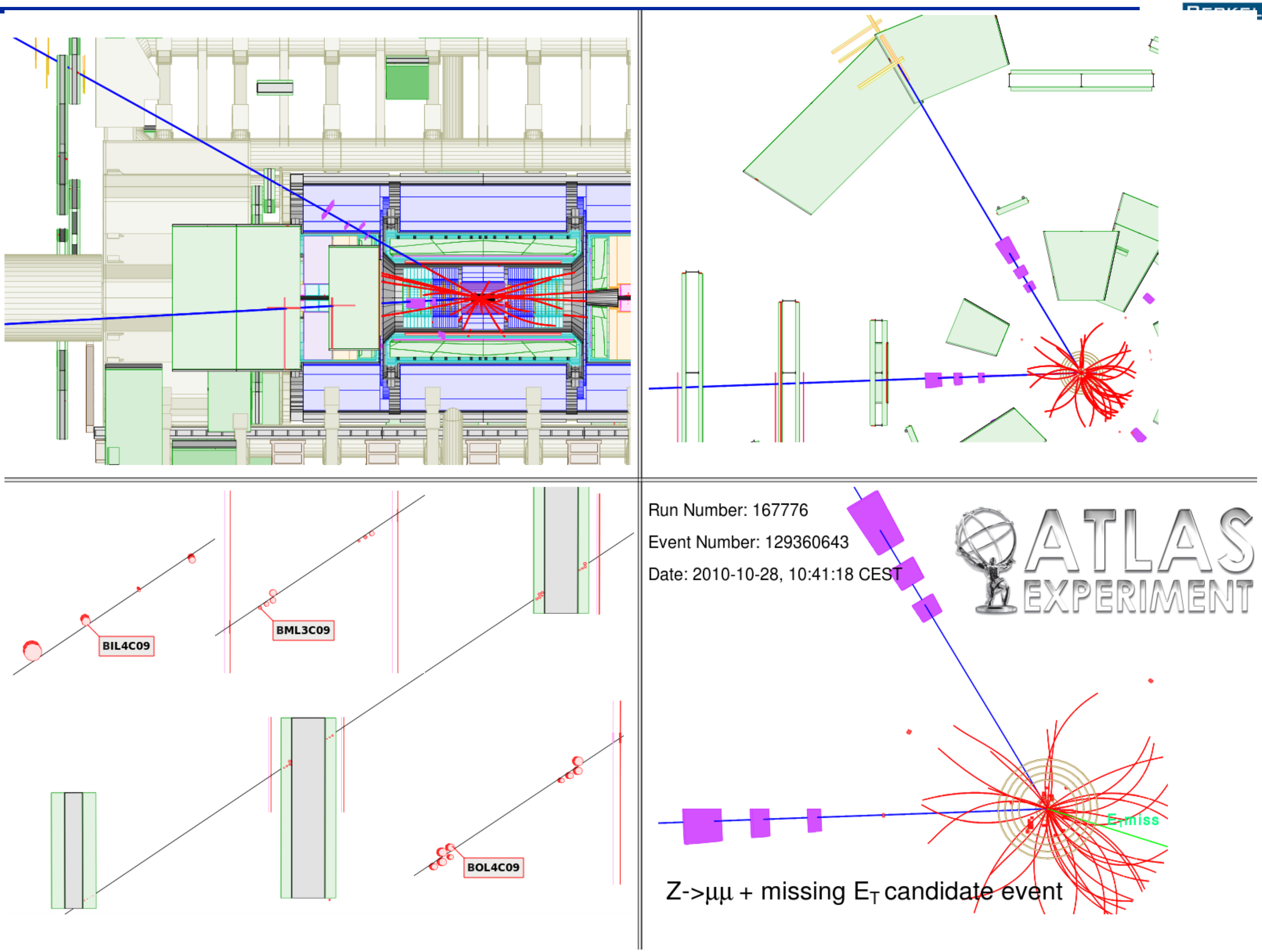


Phys. Rev. Lett. 112, 201802

Z+Missing ET event



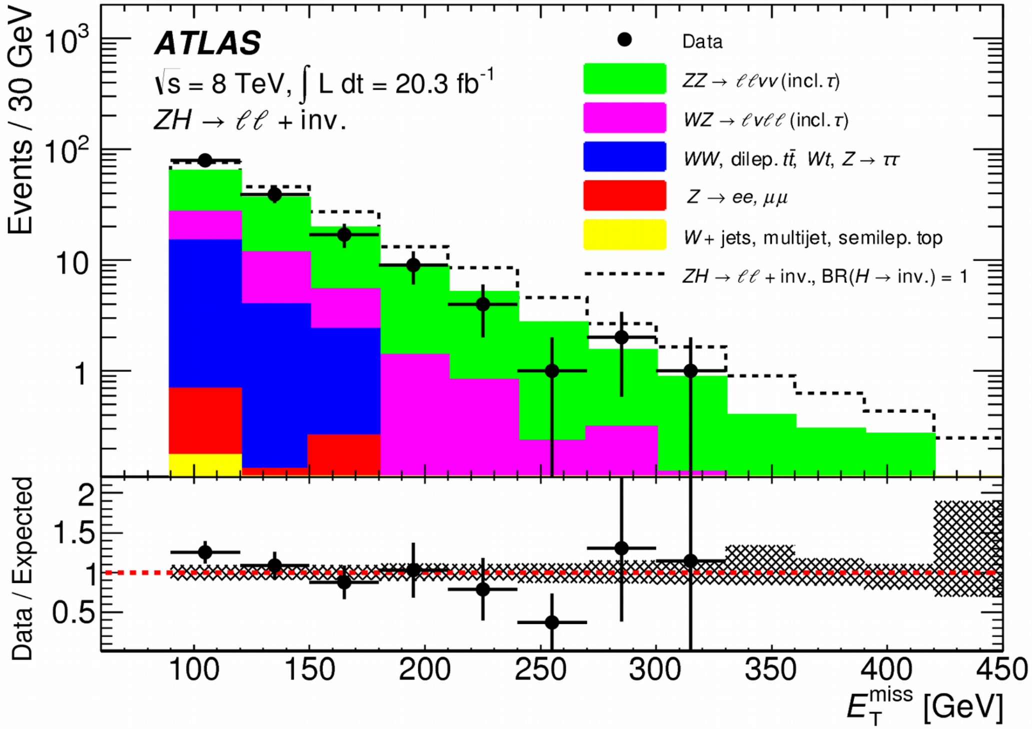
Z+Missing ET event



Higgs to "invisible": Backgrounds

- **ZZ, WZ from MC.:Validated from data**
- **WW, ttbar, Wt from MC and data:**
  - **These make eμ final states: signal does not**
- **Z+jets with jet mismeasured or lost**
  - **Data driven using $\Delta\Phi(Z$,Etmiss) and |Etmiss – p_{TZ}|/p_{TZ}**
    - **Use regions outside of selections**
  - **Agrees within 10% with pure MC estimate**
- **Final background dominated by ZZ**
  - **Note that Higgs discovery itself validates this background.**

Invisible Higgs decay: Result



"Signal" assumes H> invisible dominates decays

Sensitive to large BR

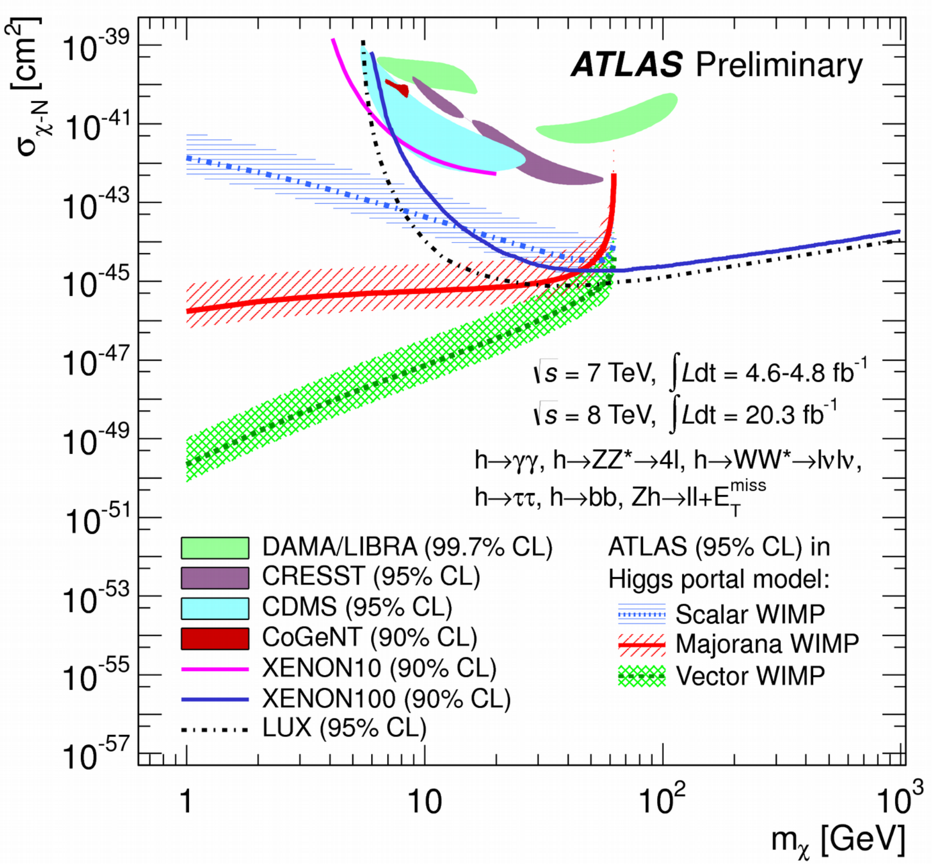
Combined with 7 TeV data: BR(H> invisible)<75%

See also ATLAS-CONF-2015-004

Looks unimpressive but….

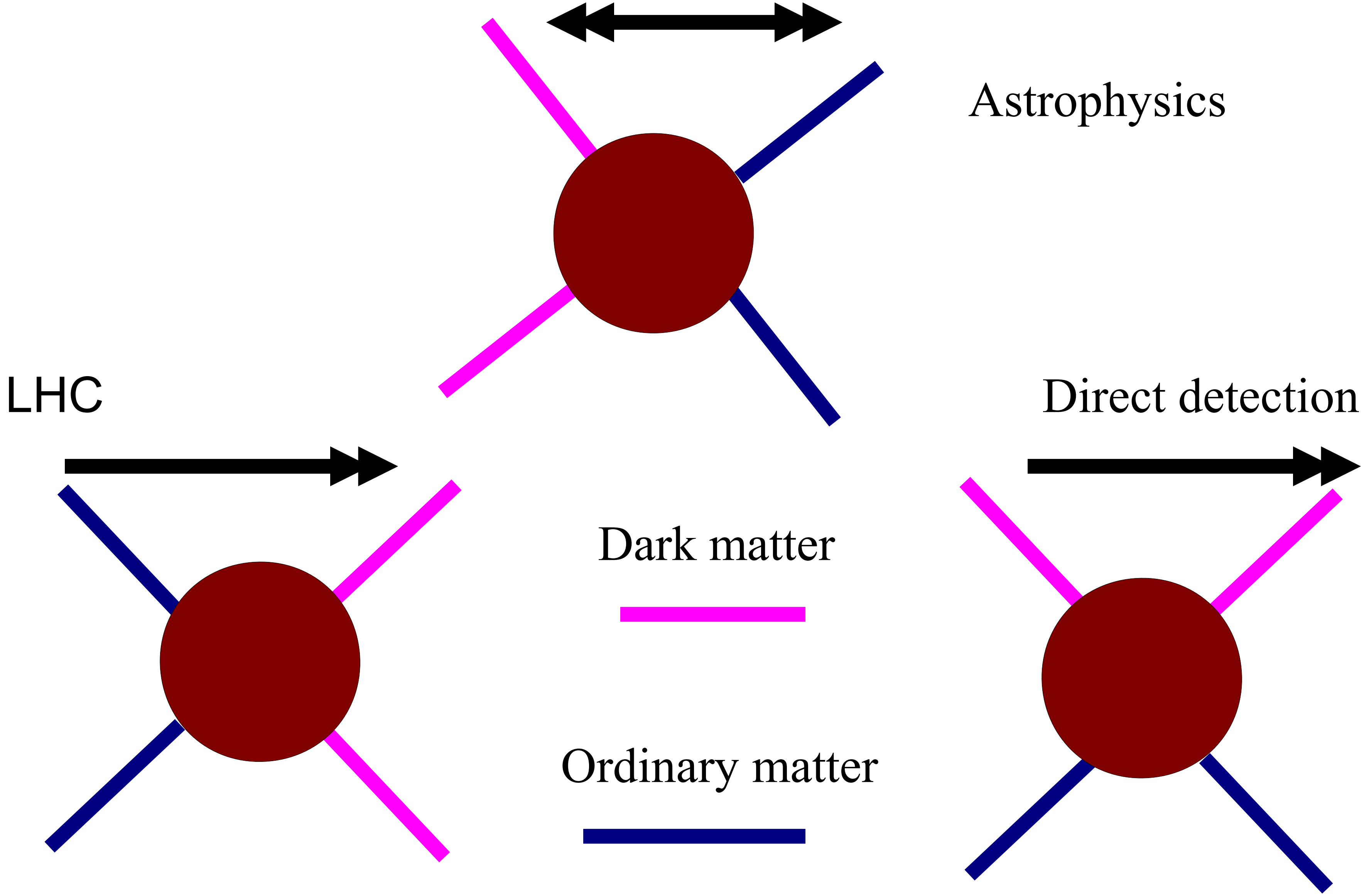
Invisible Higgs: Global fit

- **Can compare to other laboratory searches in simple model**
  - Not bad for a "byproduct"



Similar result from CMS

Generic approach



Generic production

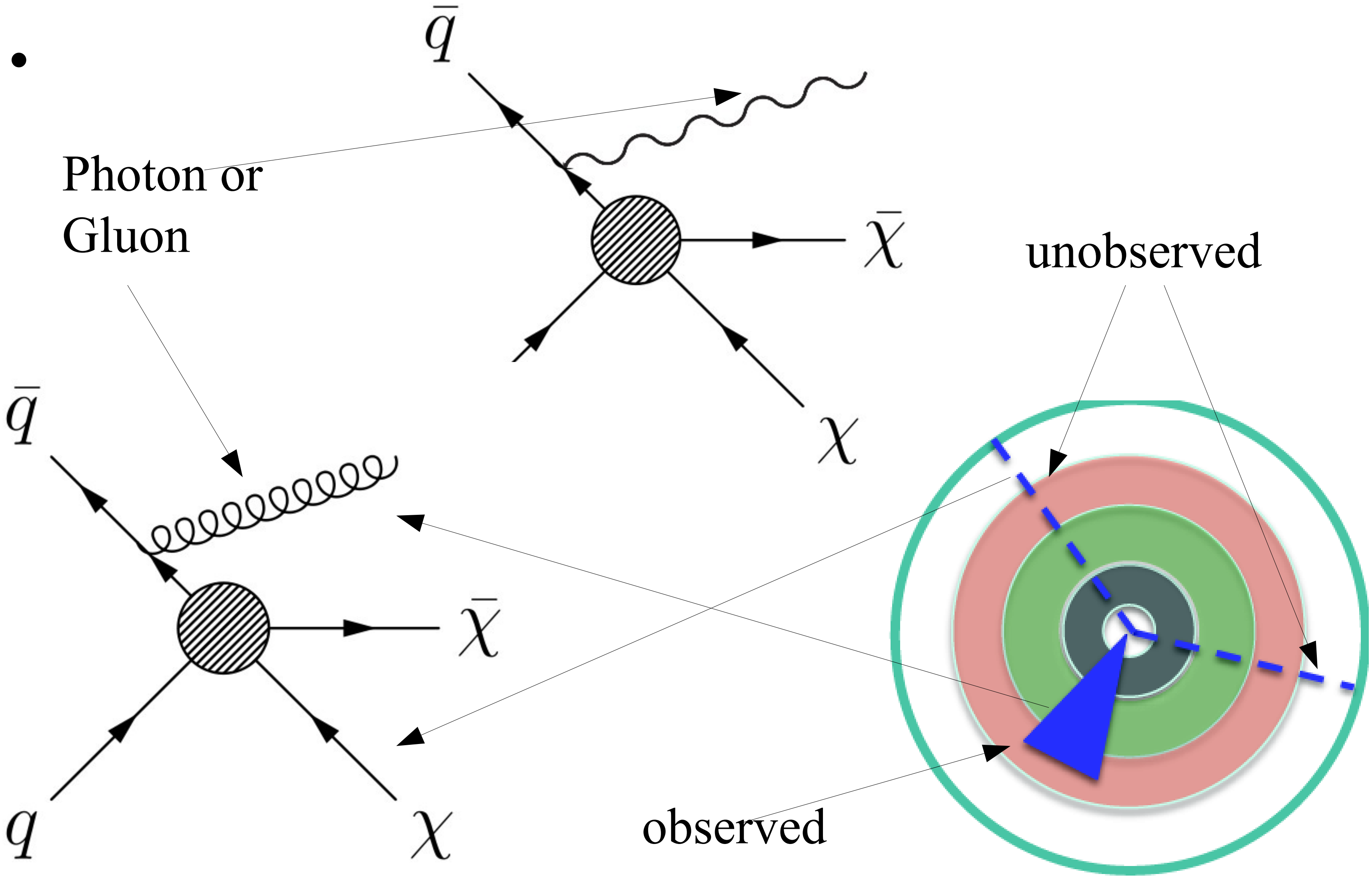
- **Parameterized by**
  - **DM mass**
  - **Interaction strength (M*)**
- **Assumptions**
  - **Only SM and DM produced**
    - **No other new particles**
  - **Interaction is treated as point**
    - **M*> kinematics of production**
- **Need something else in the event to observe**
  - **Get this by QCD or QED radiation.**
  - **Only small fraction of total production observable**

M*

Energy of collision

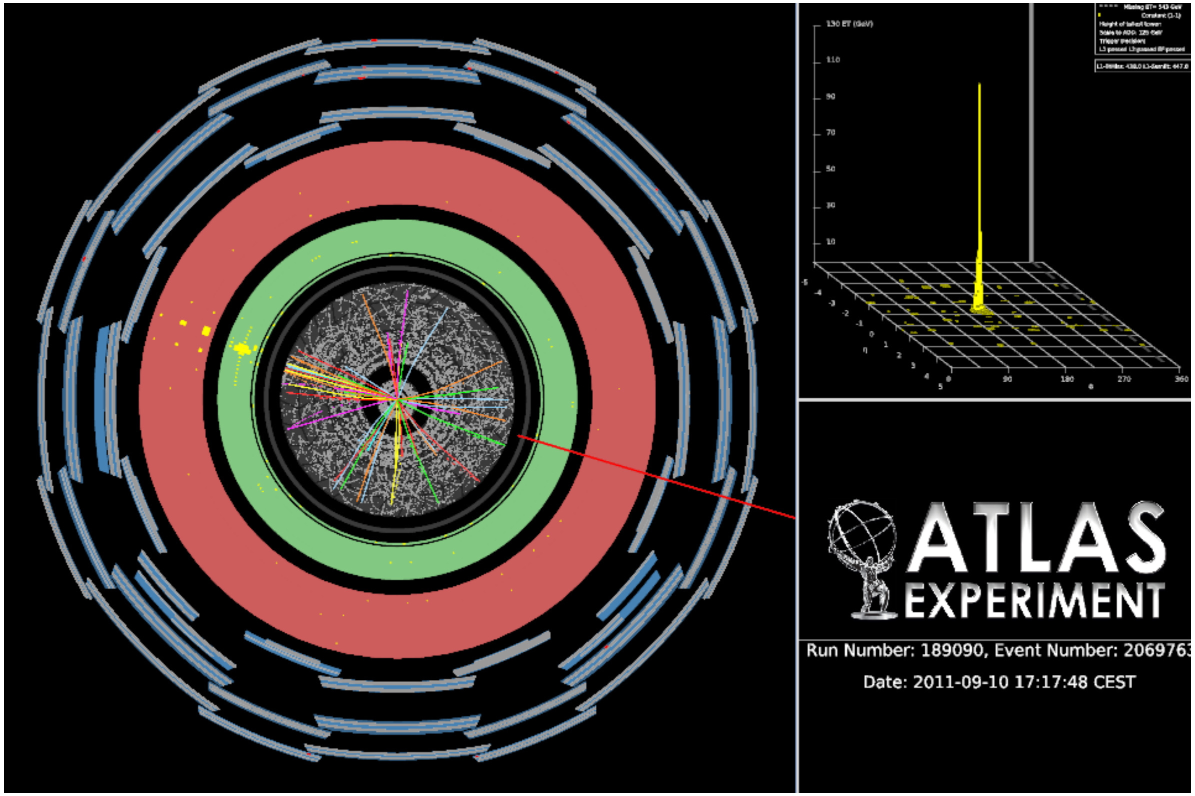
m(wimp)

•


Photon or
Gluon
$\bar{q}$
$\bar{\chi}$
χ
q
unobserved
observed

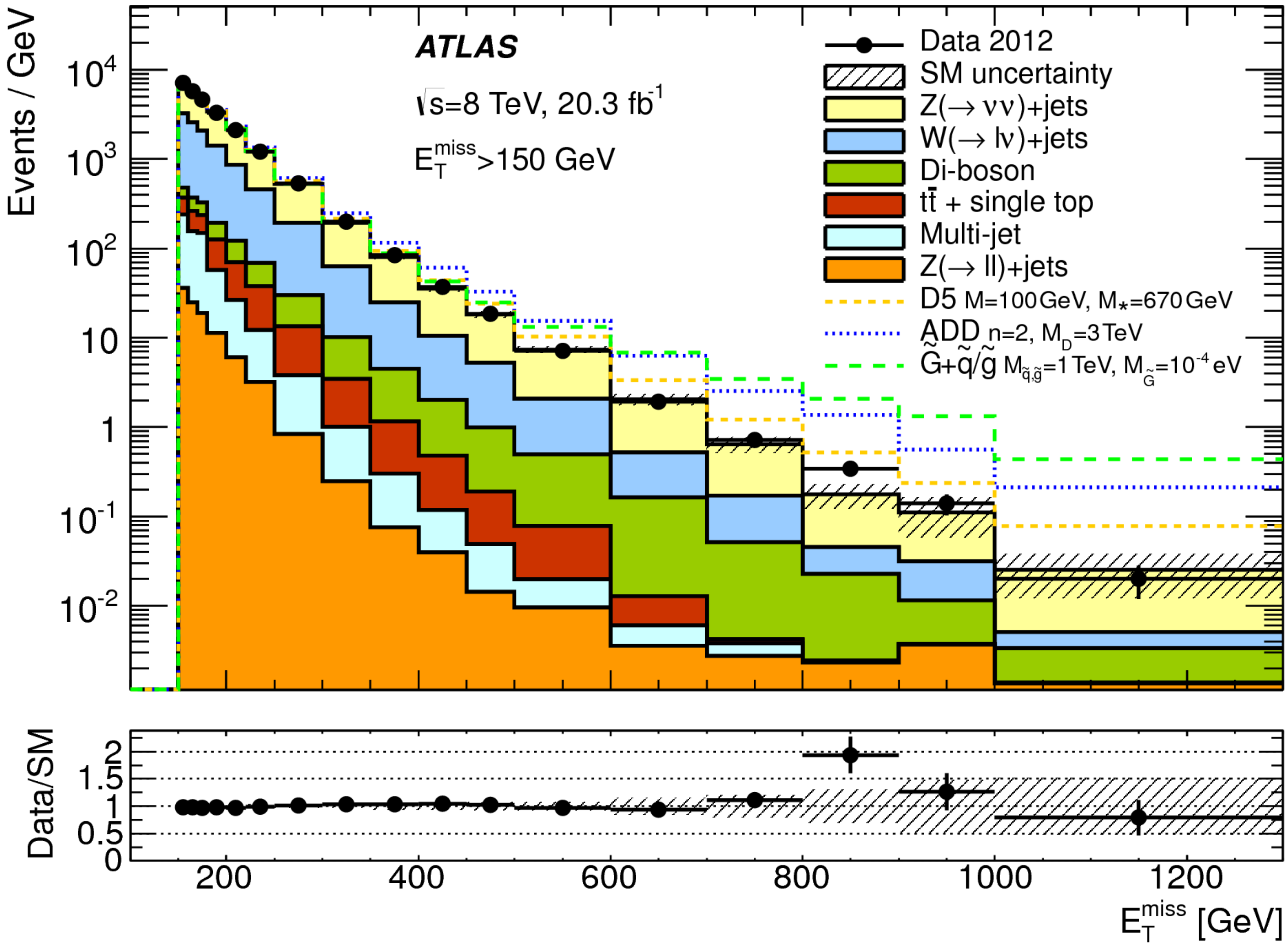
Event display of "monojet"

Search for Event with Jets+nothing
Determine expected background



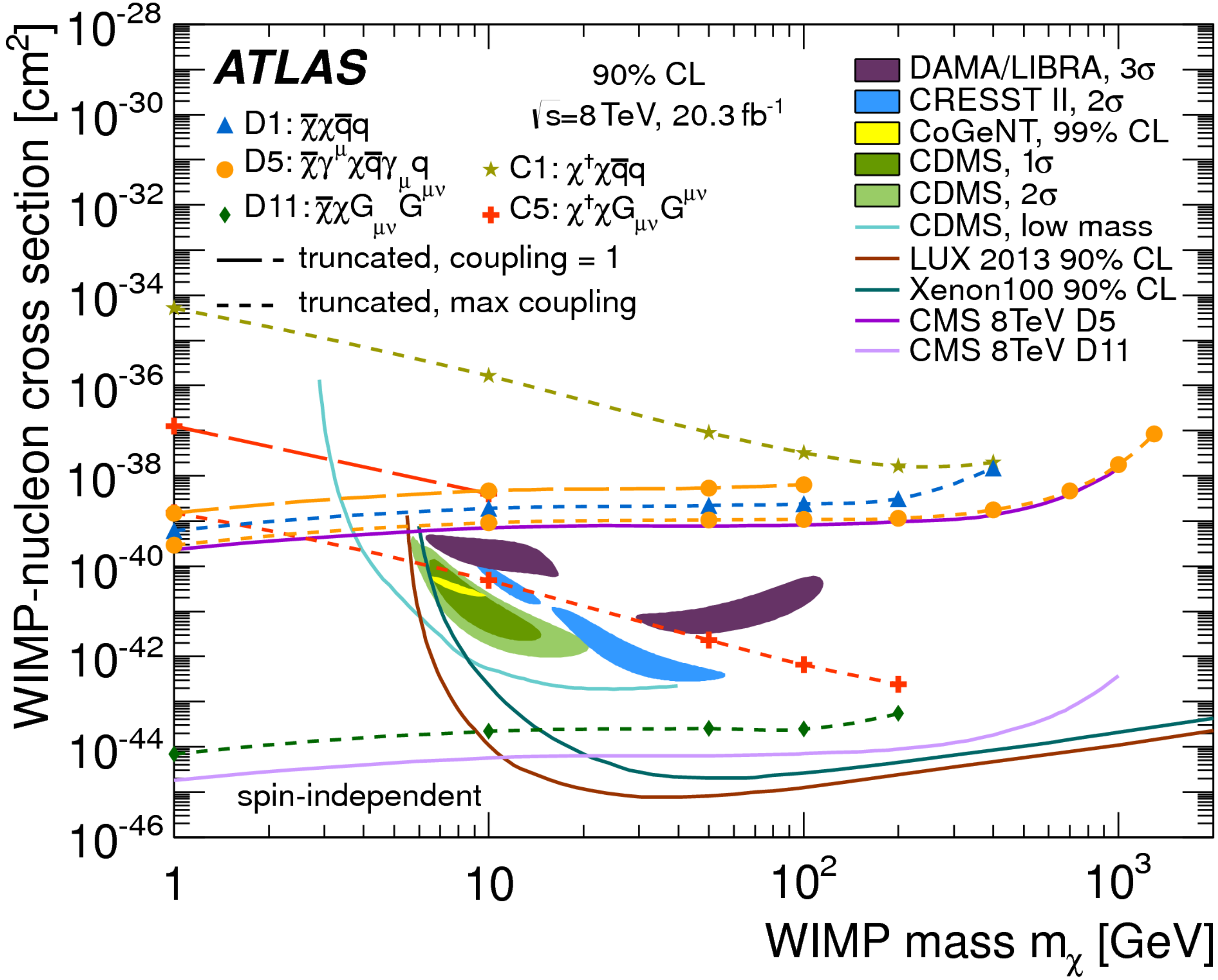
Lack of Signal

New physics examples show excess at large values



Comparisons

Excluded regions above lines



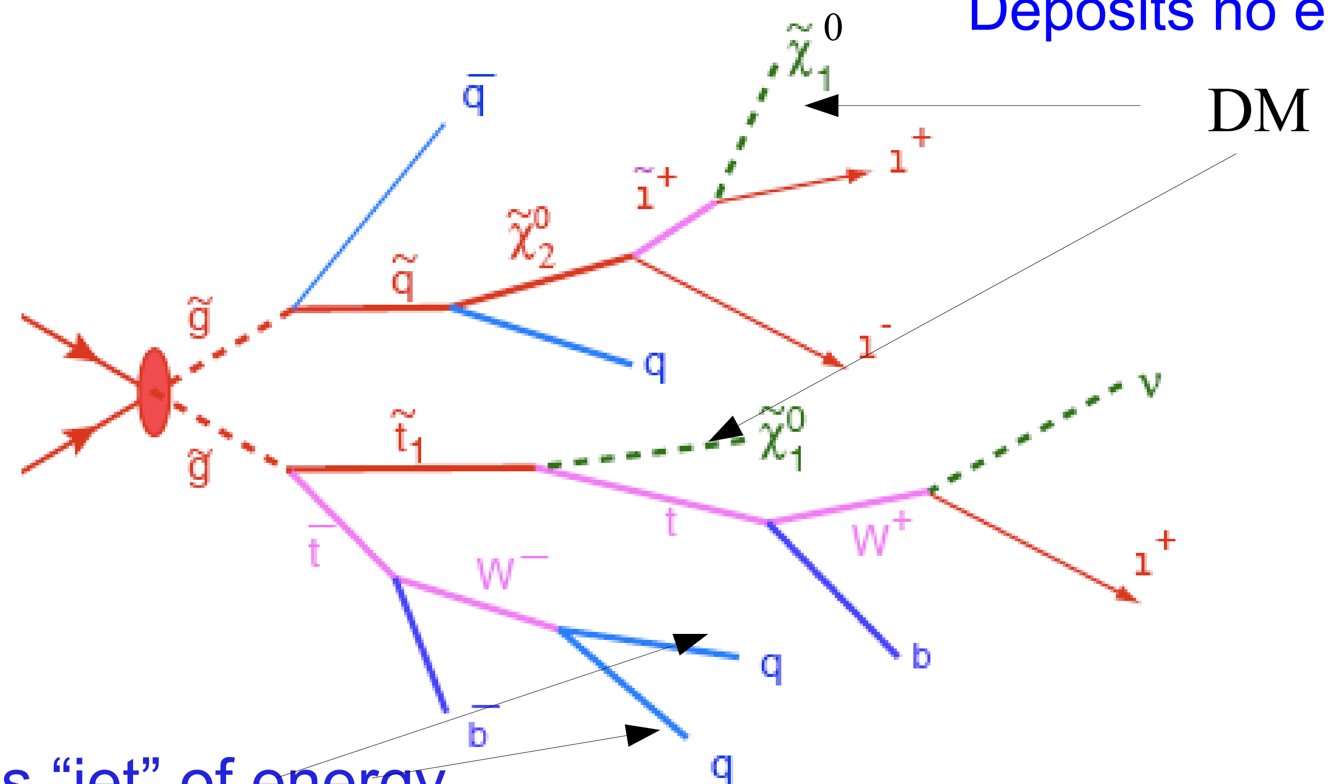
SUSY and Dark Matter

- Supersymmetry models can provide dark matter candidates
  - R parity conservation --> Lightest SUSY particle (LSP) stable
    - Must be Neutral and probably weakly interacting
- Models have strongly interacting SUSY particles
  - Heavier than LSP
  - But production rates might be larger at LHC
- Generic searches for SUSY particles cannot be easily interpreted as Dark Matter constraints
  - Direct production of LSP small (but not negligible)
- Searches within fully defined model can provide constraints
- General statements impossible

SUSY and Dark Matter

- **Typically complicated decay at LHC**
  - **Electrons, muons, jets....**

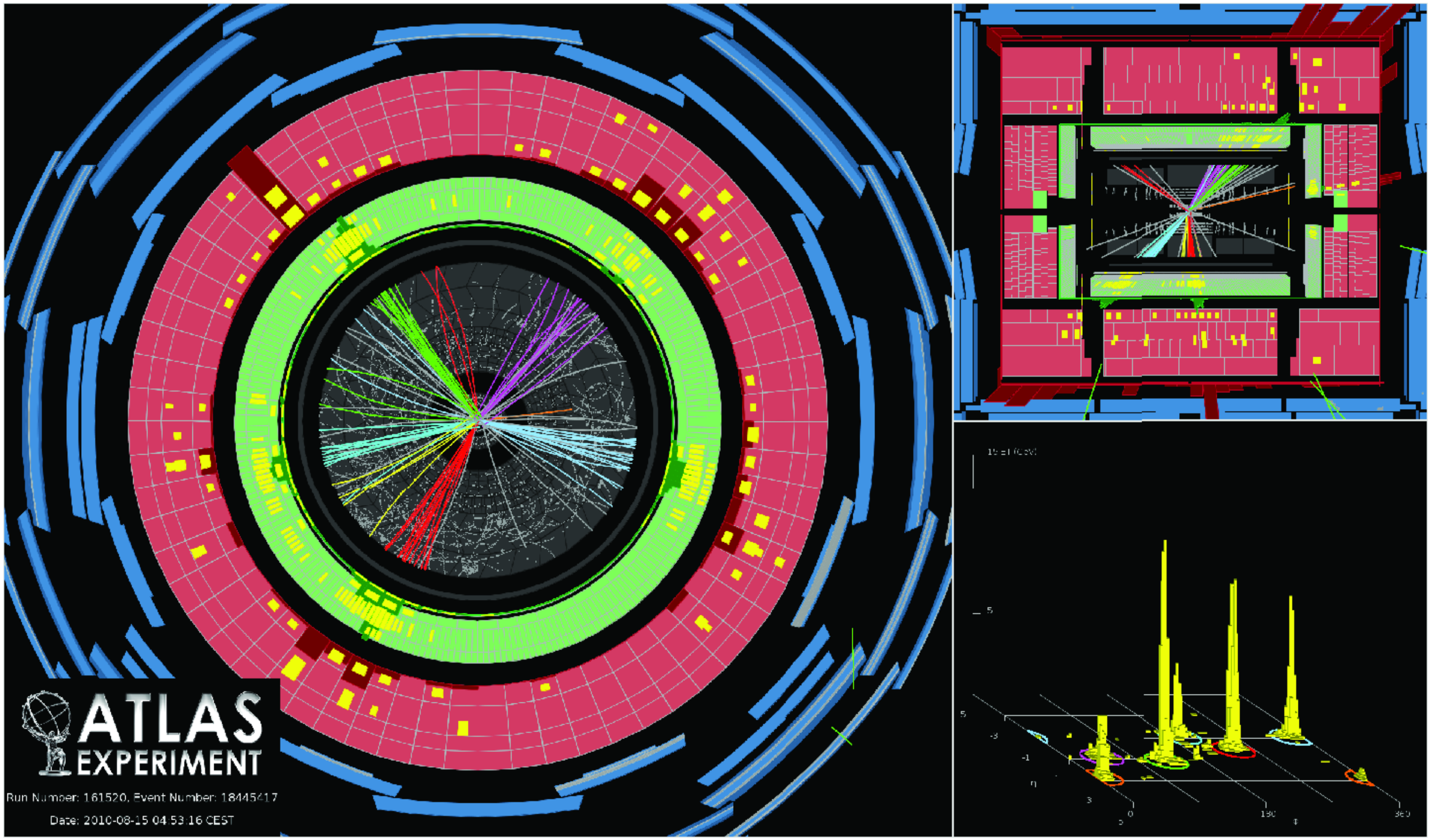
Deposits no energy



Observed as “jet” of energy

Many searches in many models: nothing seen

Events of this type



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$	250 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$) = m(c)	1411.1559
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<300 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	1.32 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV; 230-460 GeV	m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	90-191 GeV; 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$	210-640 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	250 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$	1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	435 GeV	2<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e + \mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e(\mu) + \tau$	1 e,μ + τ	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{121}\neq$0	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq$0	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	490 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

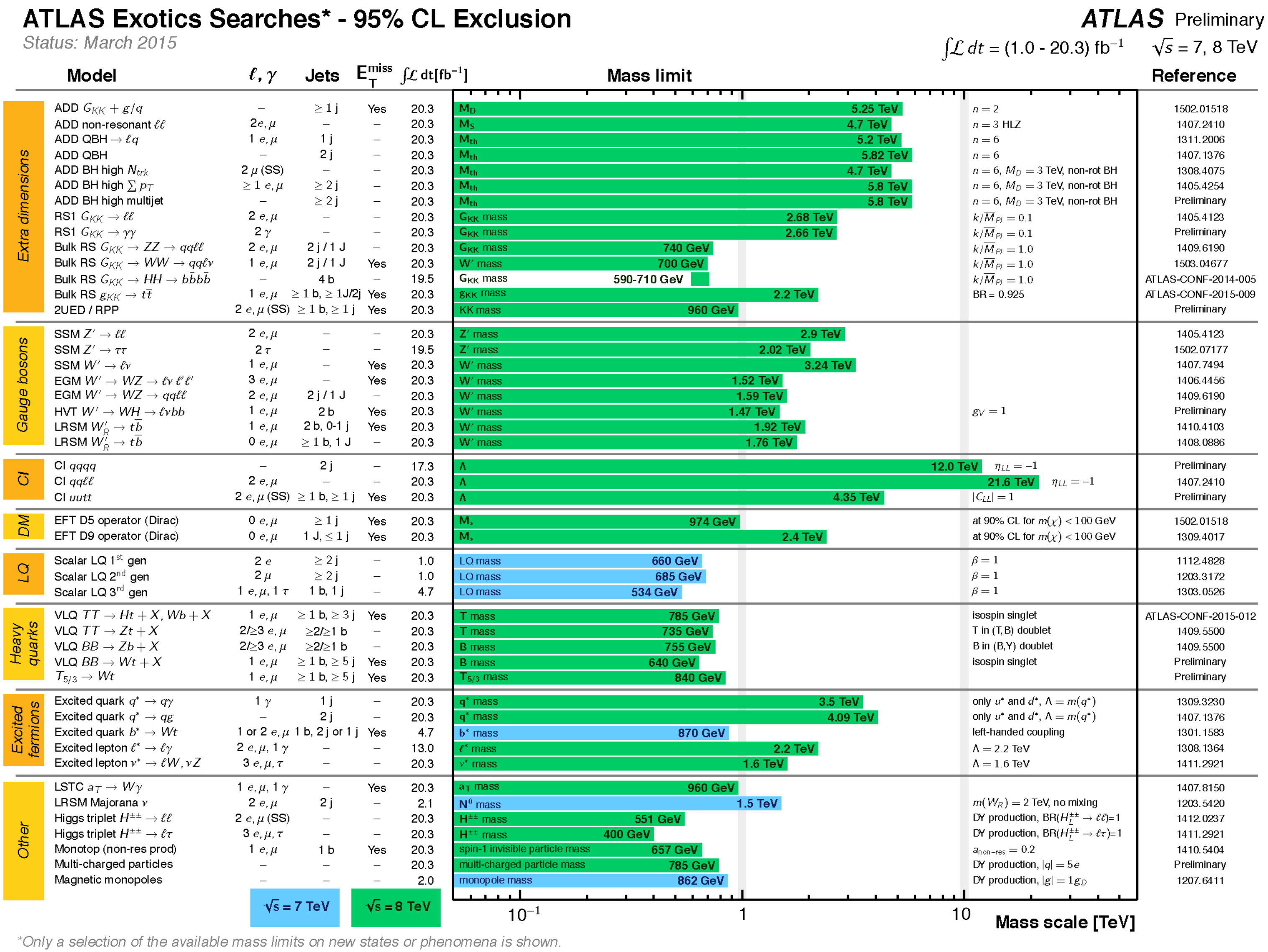
10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Supersymmetry has not been seen

- **Proponents say this makes discovery more likely**
  - **But they are Beyesians on the issue**
  - **Cannot really be killed (just push up mass scales..)**

Nothing else seen either



Where to look now?

- **13 TeV LHC**
  - **Search range doubled approx**
- **People tend to “look under favorite lampposts”**
  - **With that in mind……….**

Suggestions where Roger should look