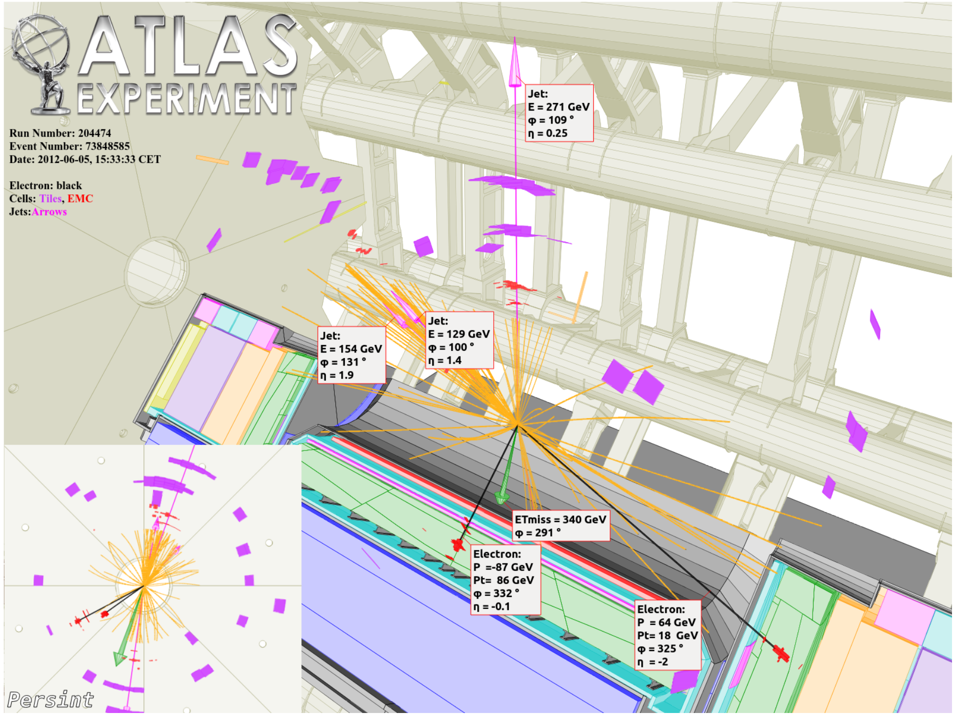
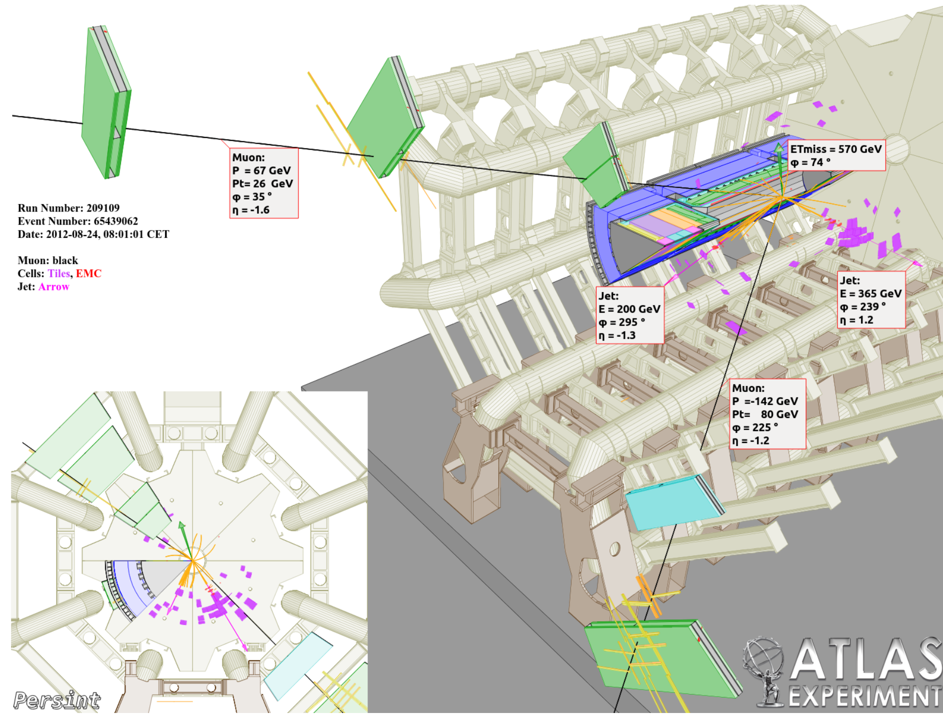




Searching for SUSY in Big Data @ the LHC

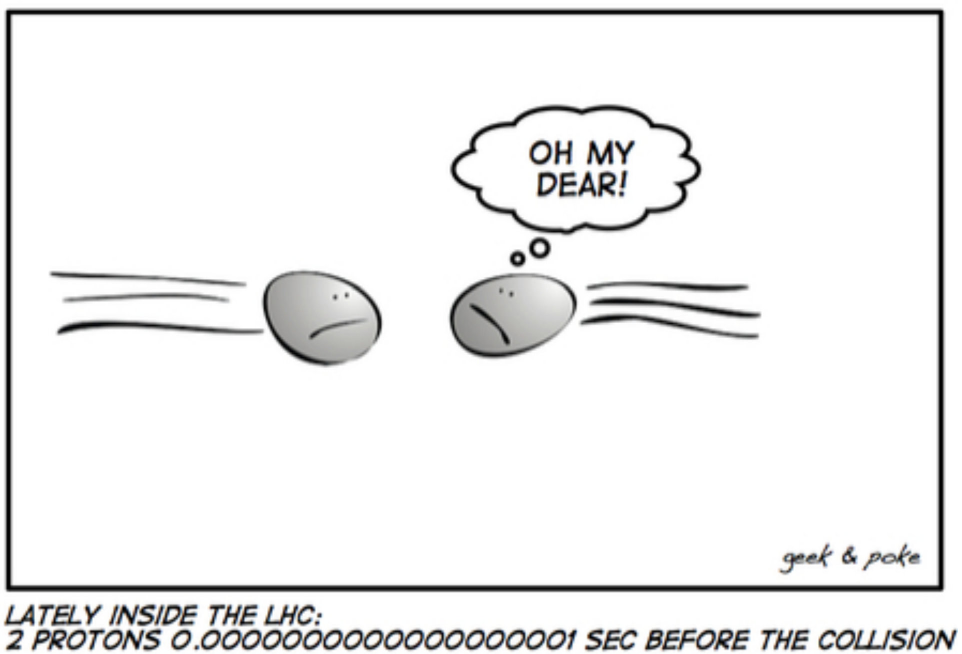
Zach Marshall (LBNL)

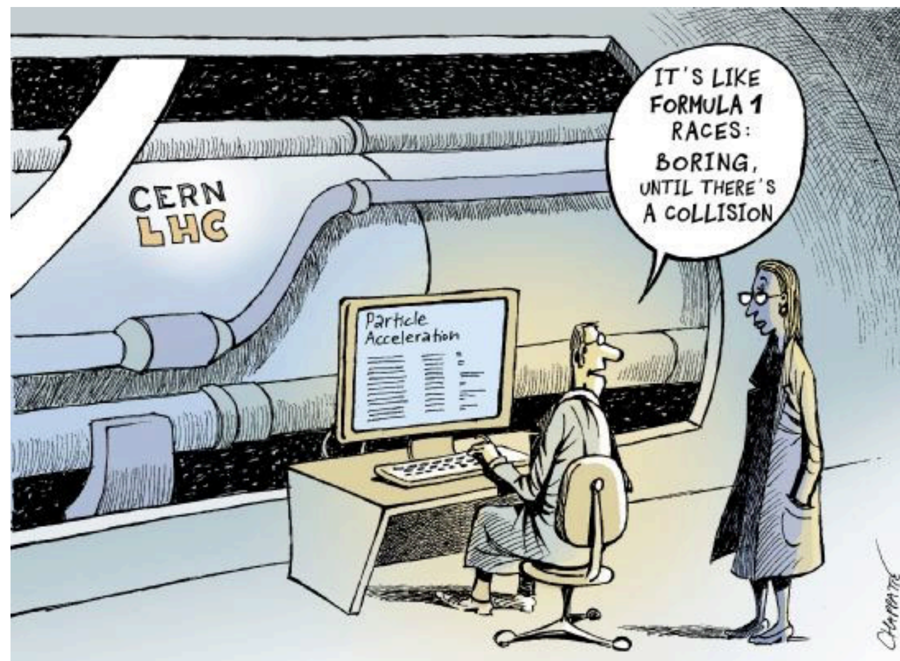
DPNC Seminar

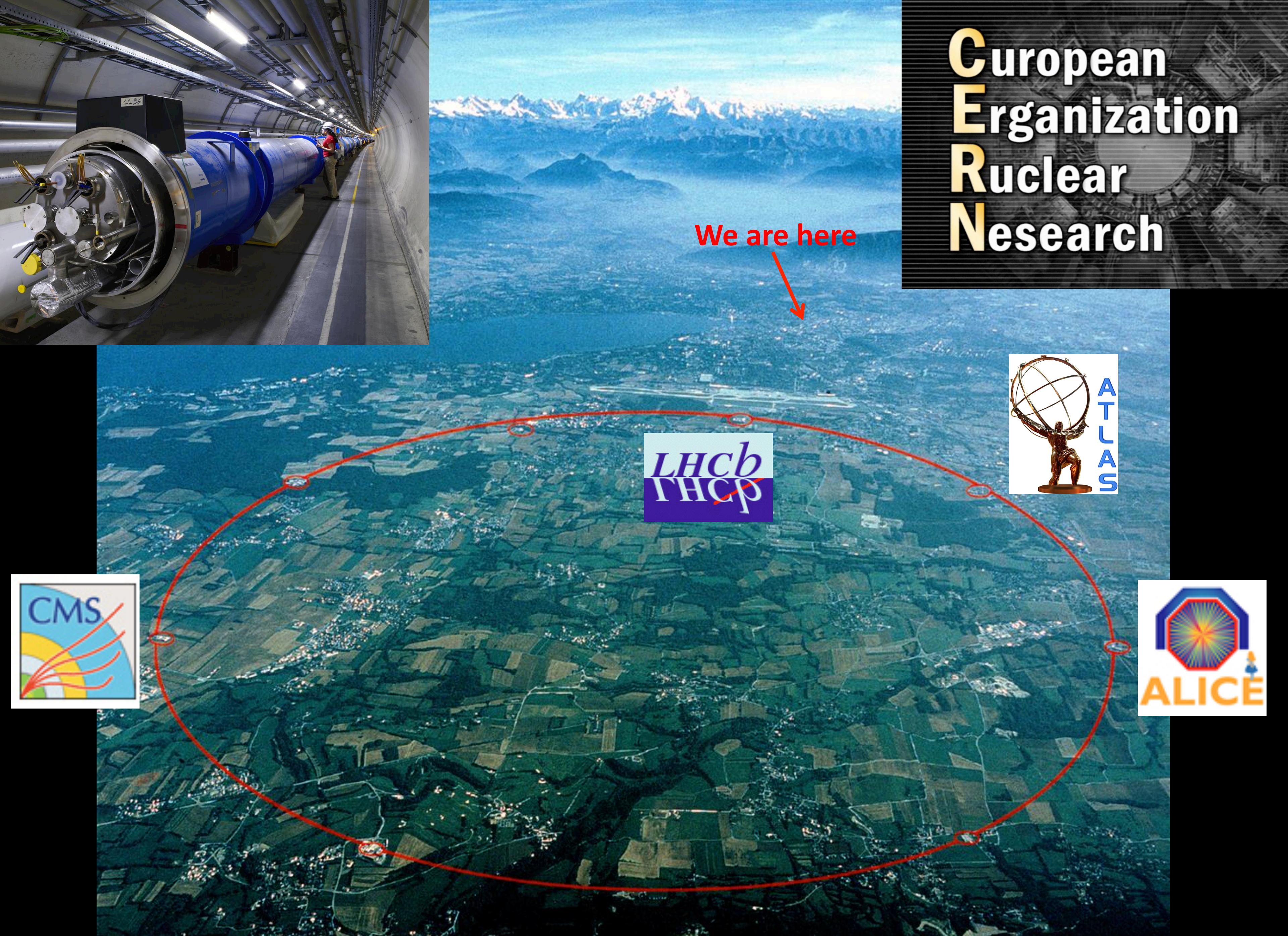
29 September 2017

Outline

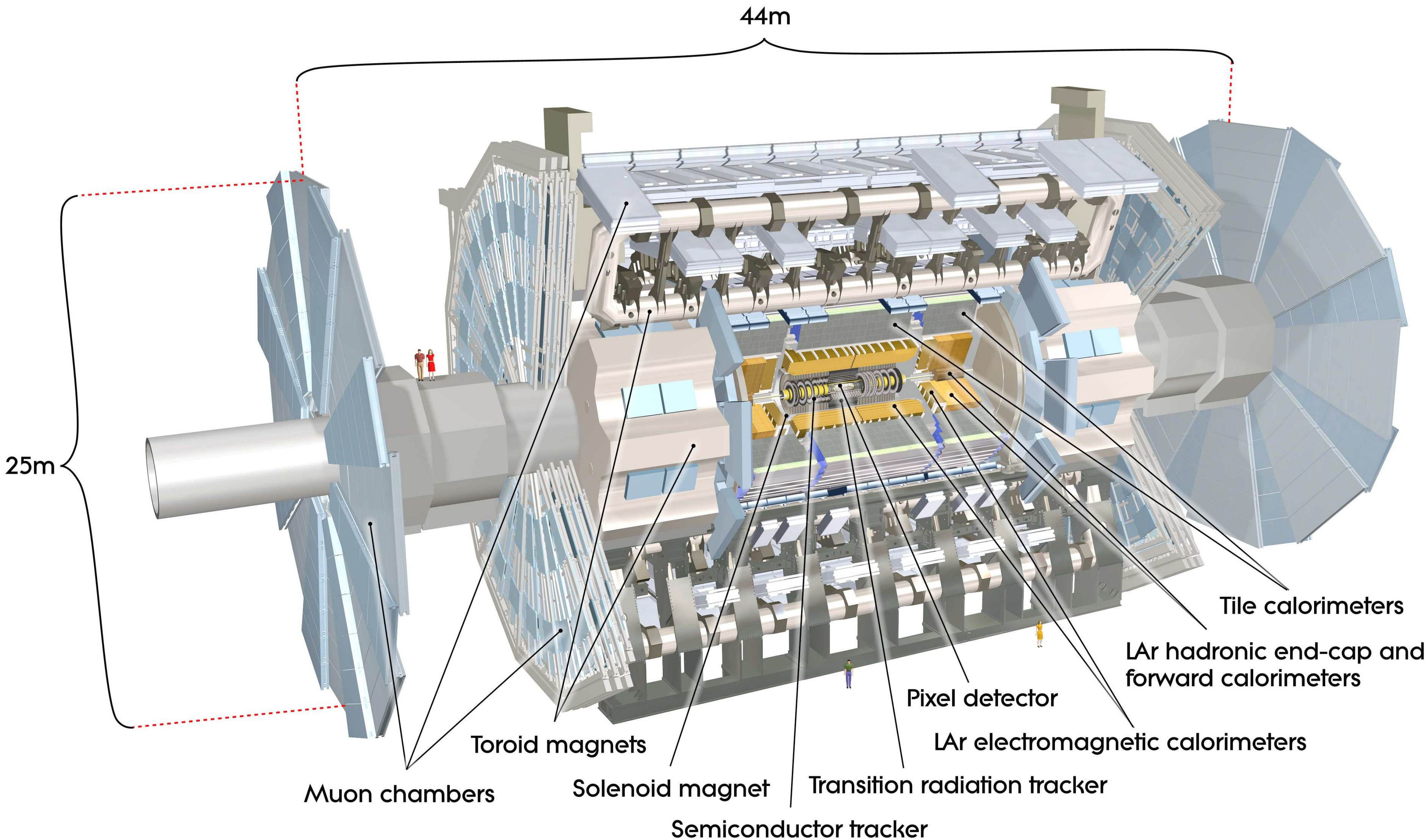
- Quick introduction to ATLAS and the LHC
- Computing at the LHC
- Searching for something **new:** Supersymmetry
- The latest on Supersymmetry from ATLAS and CMS
- A little outlook for the future

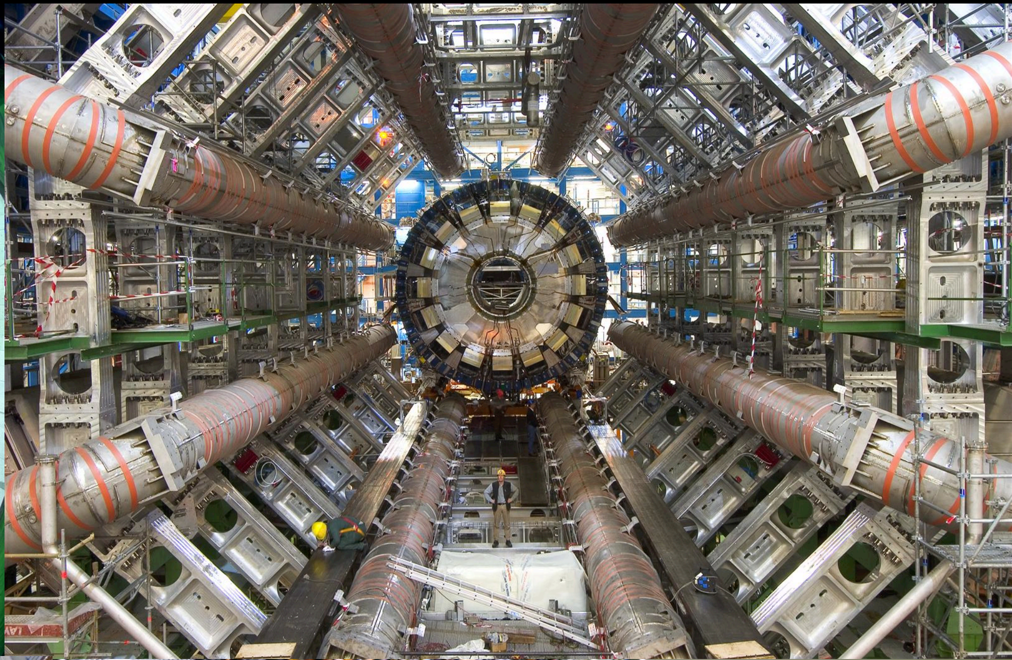
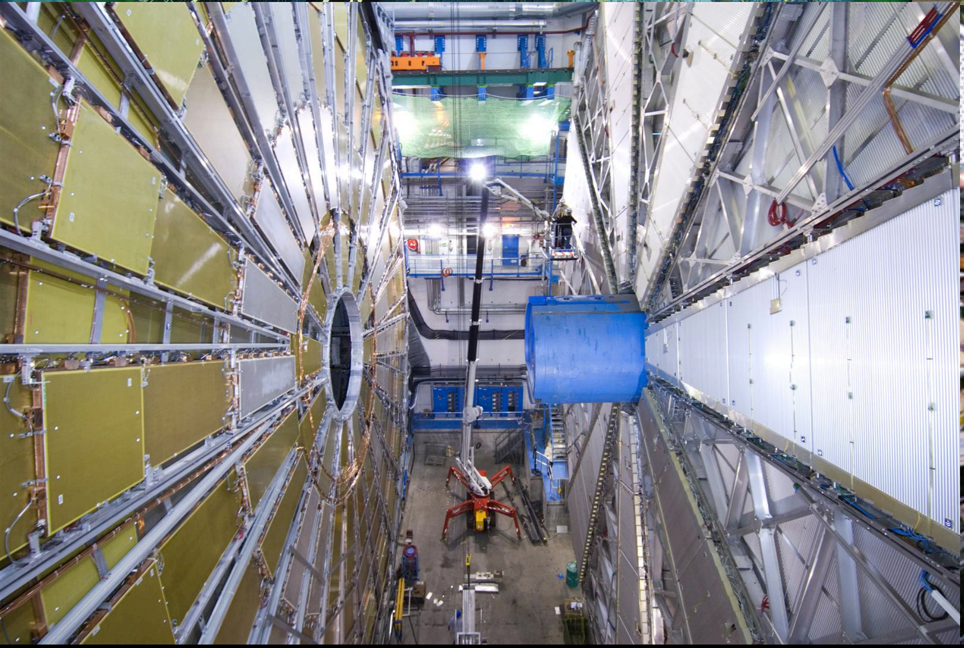
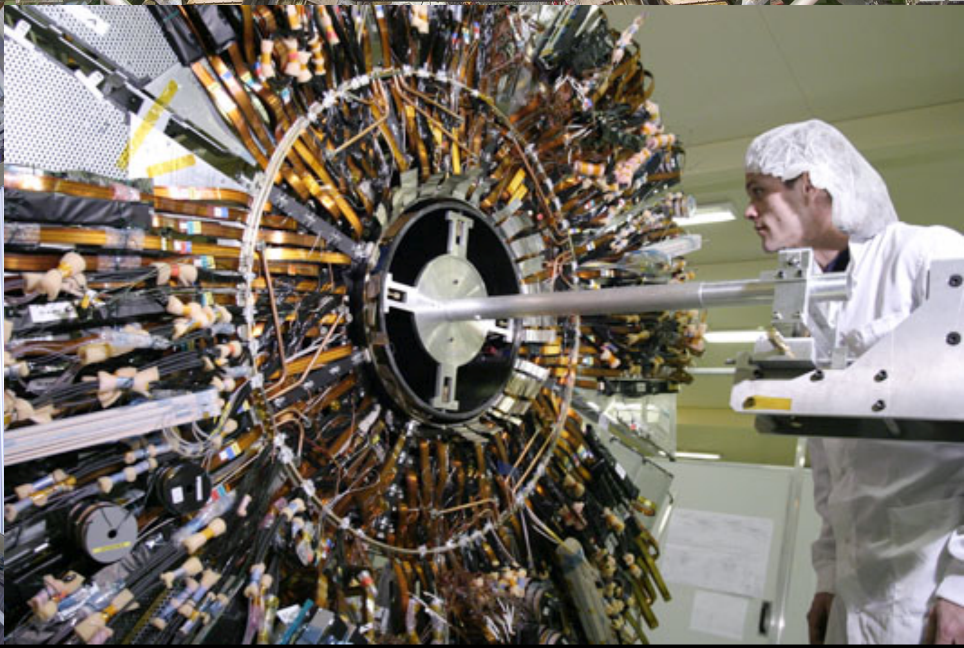





Curopean
Erganization
Ruclear
Nesearch
We are here
LHCb
ATLAS
CMS
ALICE

ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

A Quick History Reminder

1980s	1990s	2000s	2010s

First LHC workshop

ATLAS "Founded"

ATLAS Cavern

First Data!

Higgs!

Today

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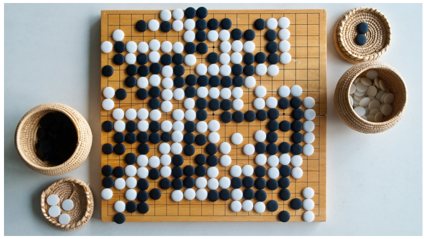

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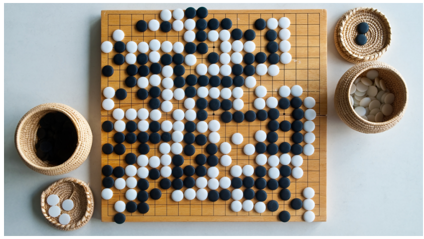

Today

2020s	2030s	2040s

HL-LHC Upgrade

End of LHC Running?

First collisions at the next collider?

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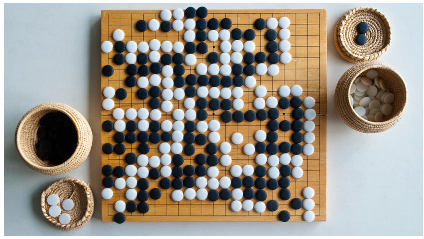


Singularity?

2020s	2030s	2040s

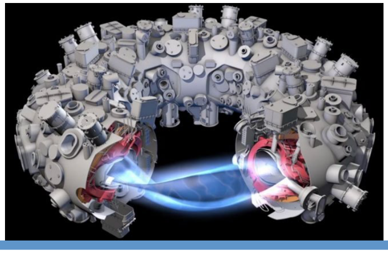
HL-LHC Upgrade

End of LHC Running?

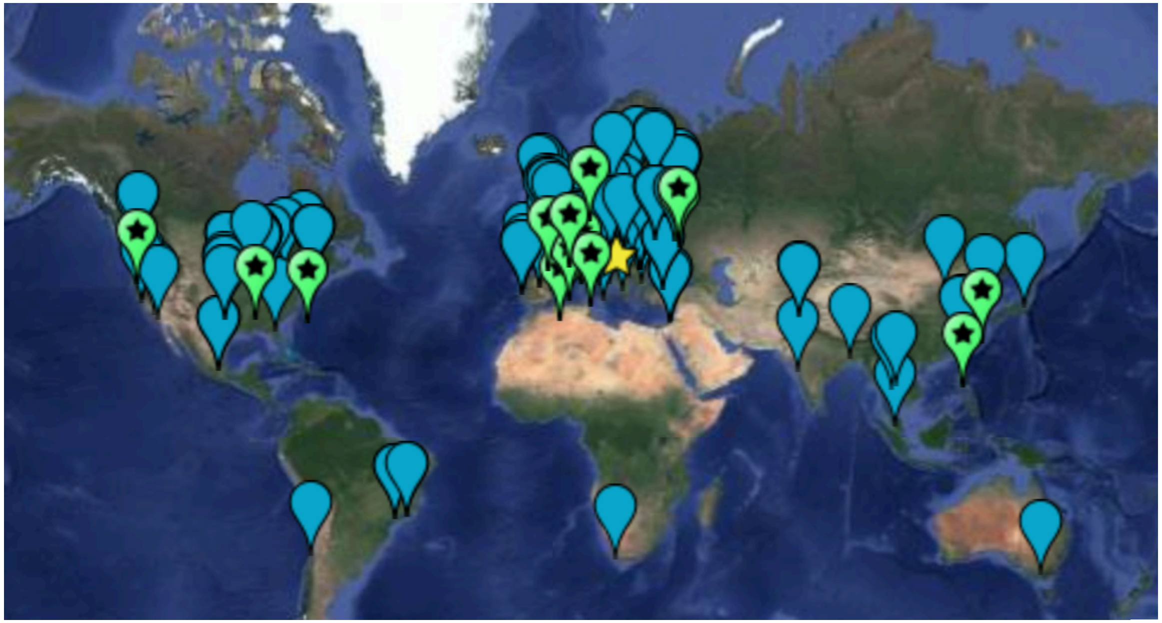
First collisions at the next collider?

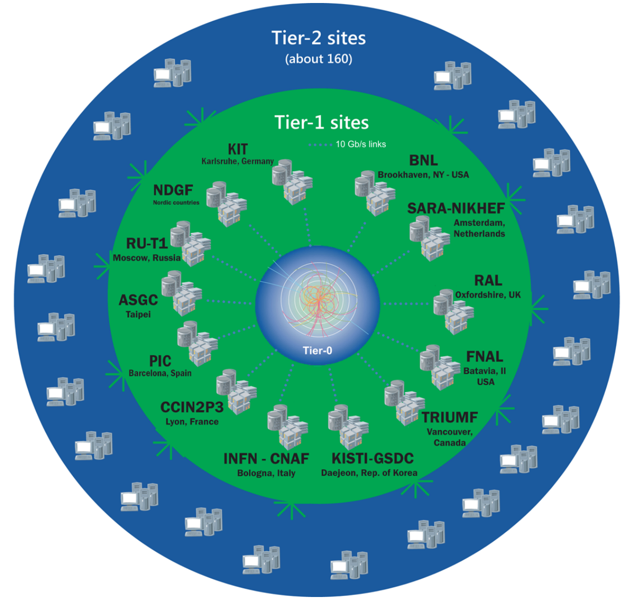
$1000 brain

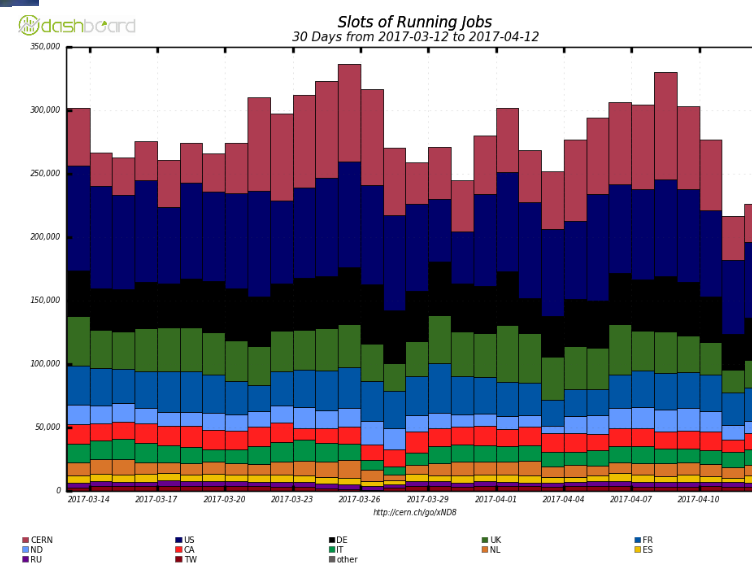
~~**Moore's Law?**~~



Computing



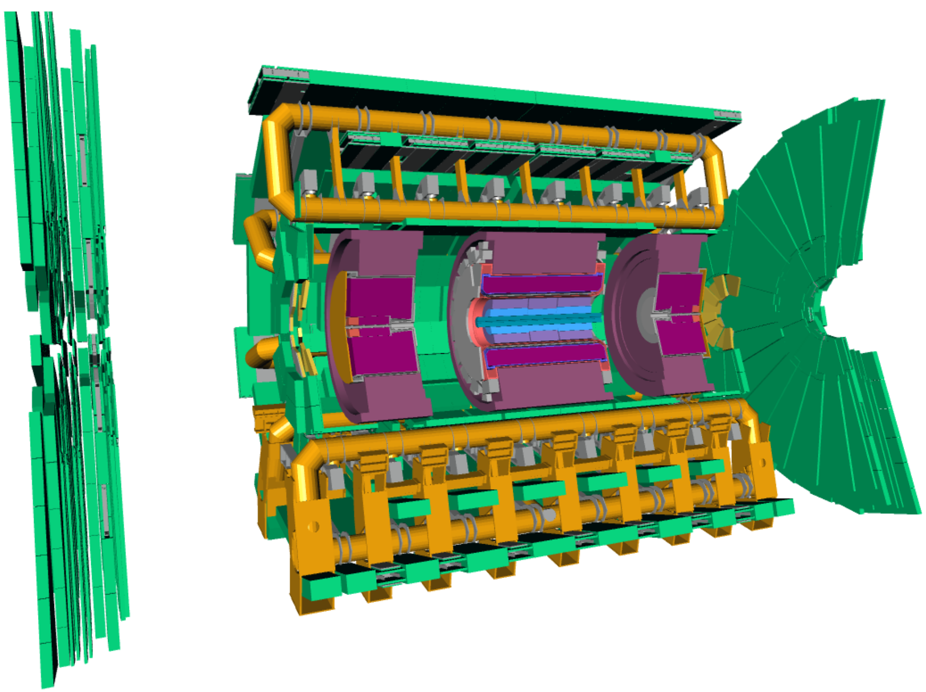


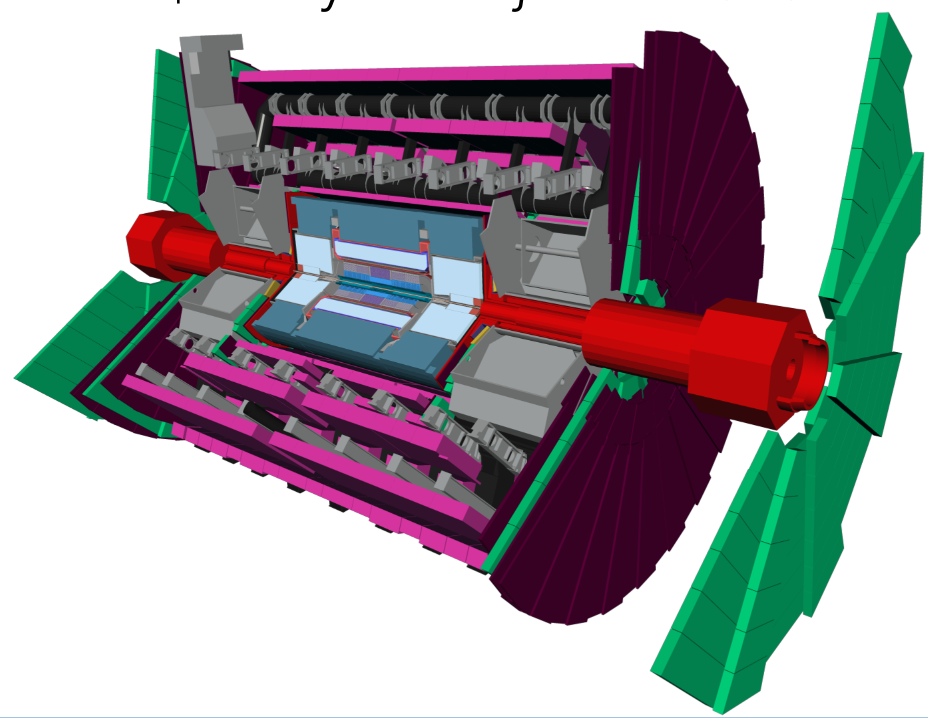


- We use the Worldwide LHC Computing Grid for all our computing needs
- Constantly running 200-300k jobs
  - There is a lot of science to do!

Simulation

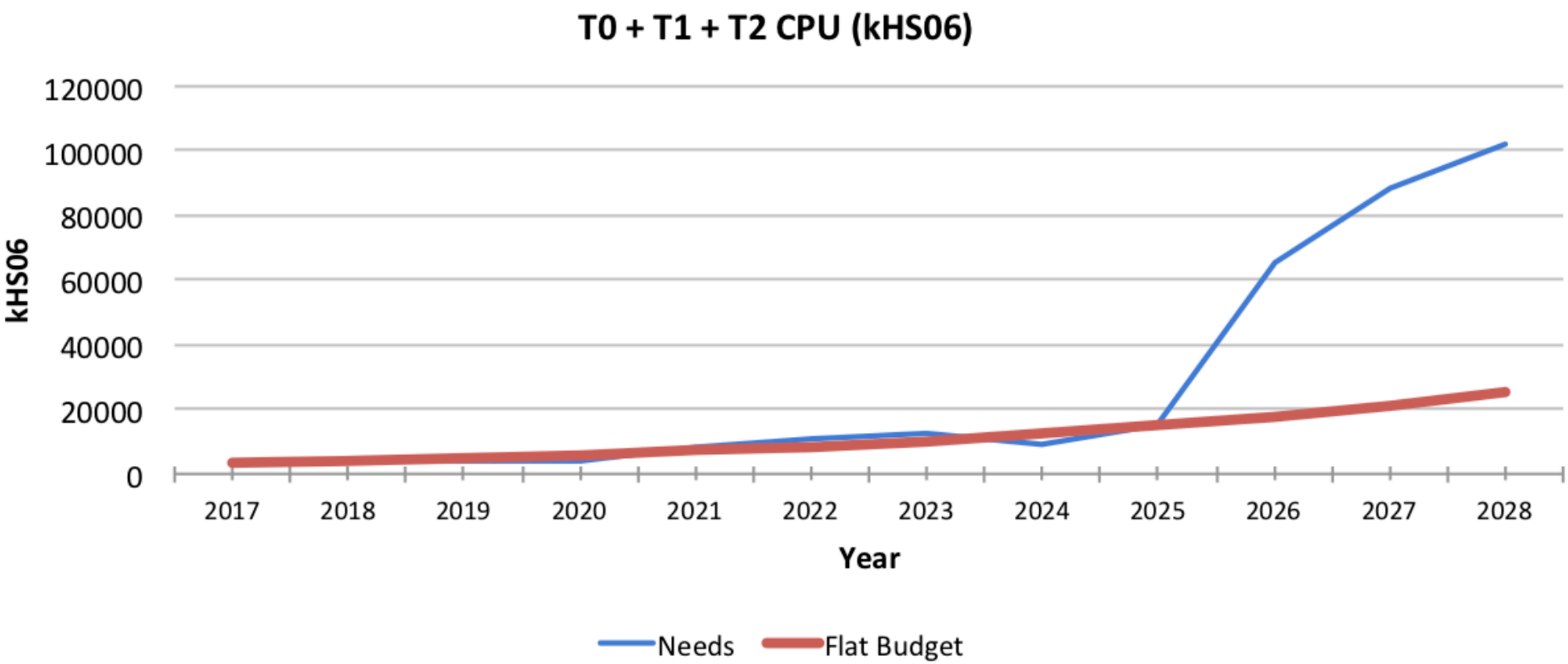
- We have an extraordinarily detailed model of our detector
  - That model can do a **lot** of things
- Think of this as the "hypothesis" step of the Scientific Method
- It's also a rather expensive step
  - A bit more than half of our total computing time
  - On Amazon Cloud computing, it'd be ~$15M/year for *just* the CPU





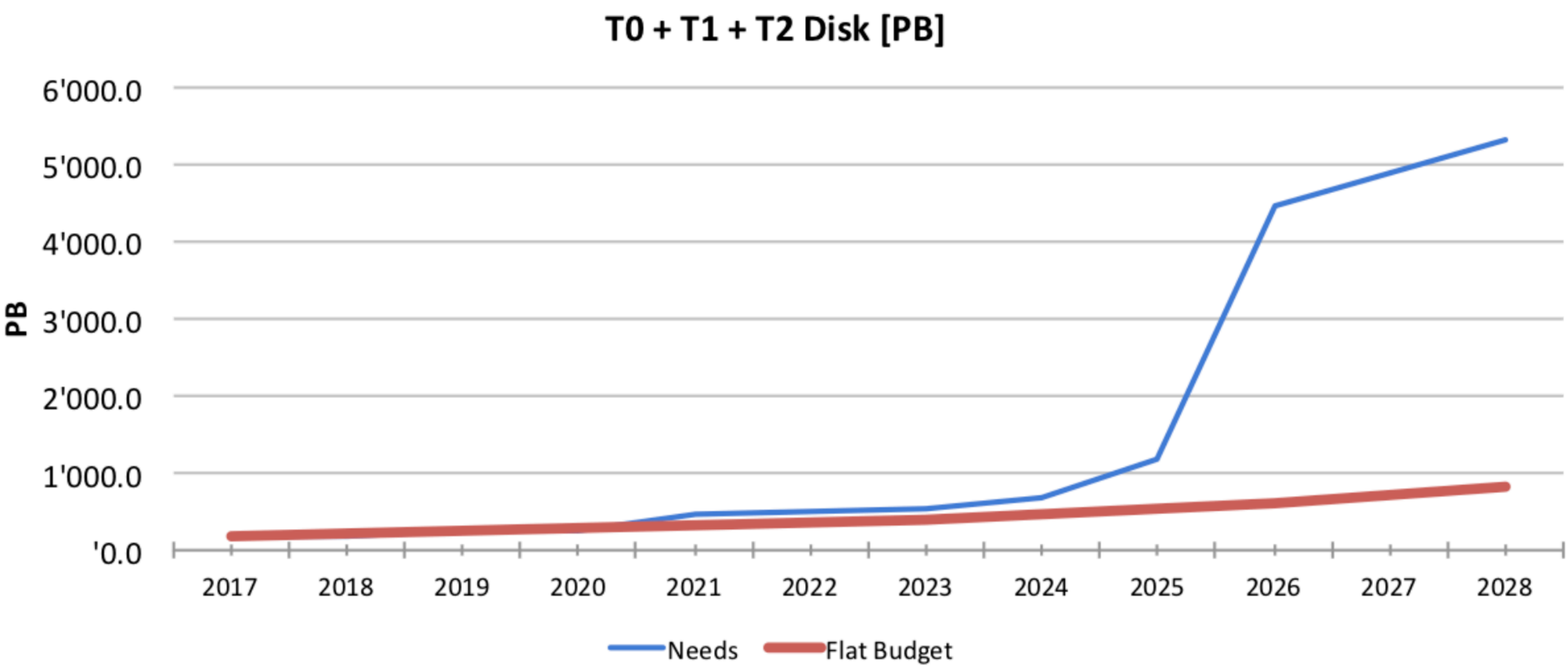
The Data are Coming!

- Traditional computing is not keeping up with our needs…
- We're going to be needing much more soon!
  - 10x jump in CPU need and data volume in ~2024

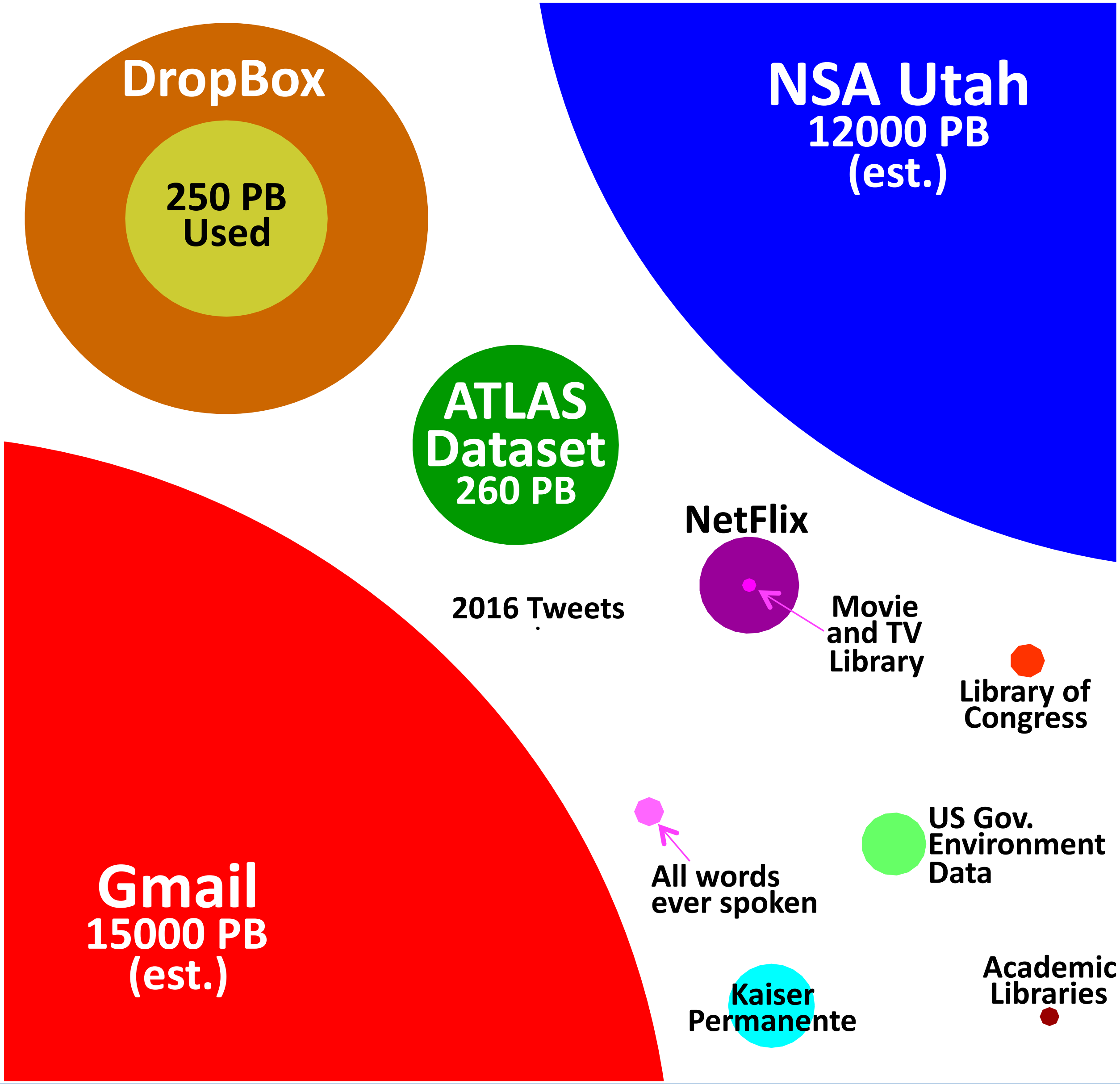


The Data are Coming!

- We're also pretty big now in terms of **storage**!
  - 15 PB of data processed by analyses each week, not counting private clusters, laptops…
- Simple projection shows a **~1BCHF shortfall** by 2025-6



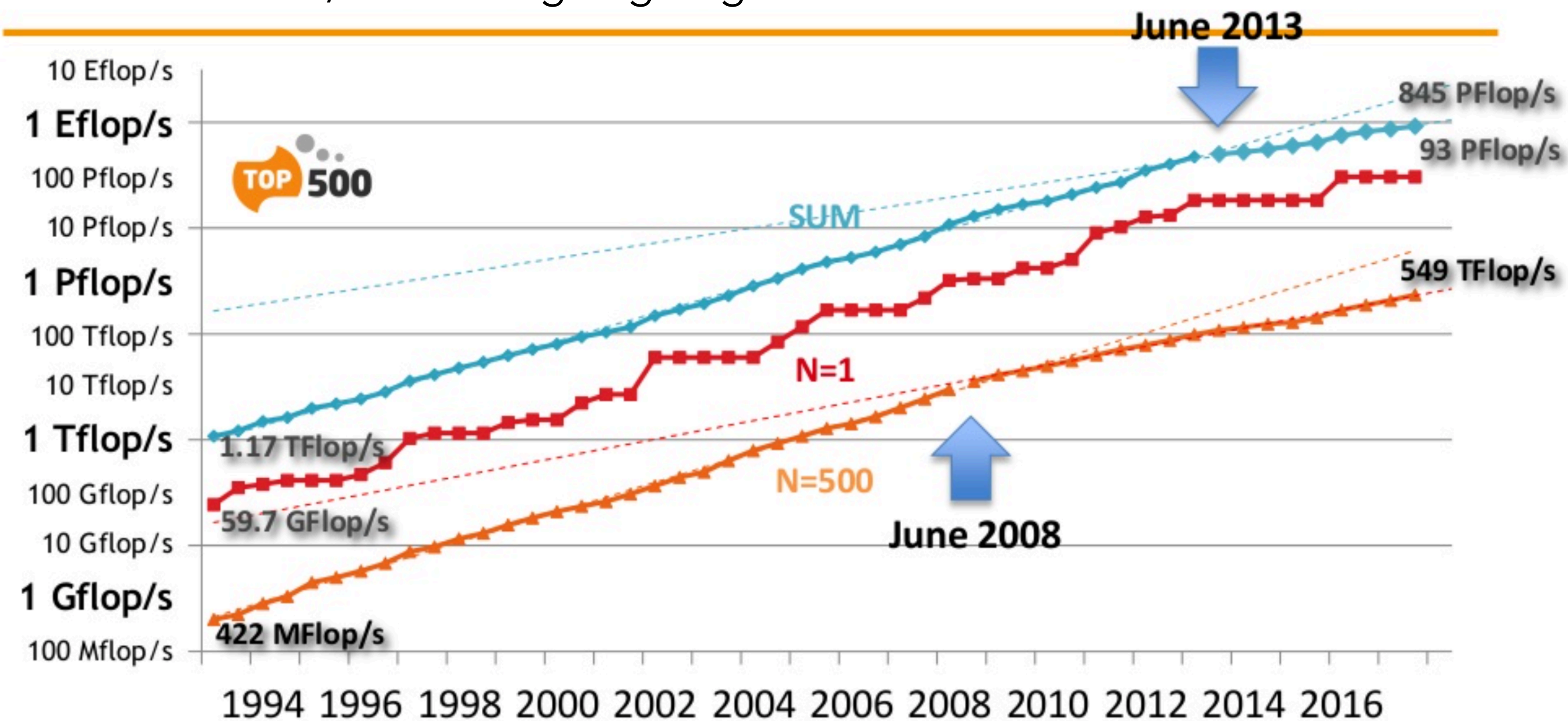
How BIG are we really?



Estimates: ZM, XKCD, NASA, NOAA, DropBox, Kaiser, Amazon, Netflix, Twitter, and Google

Follow the Leader

- A model for the future: High Performance Computing centers
- They might keep up with the expanding demand of the LHC!
  - We are actually **not** that big compared to most of these machines!
  - Of course, we aren't going to get one to ourselves…



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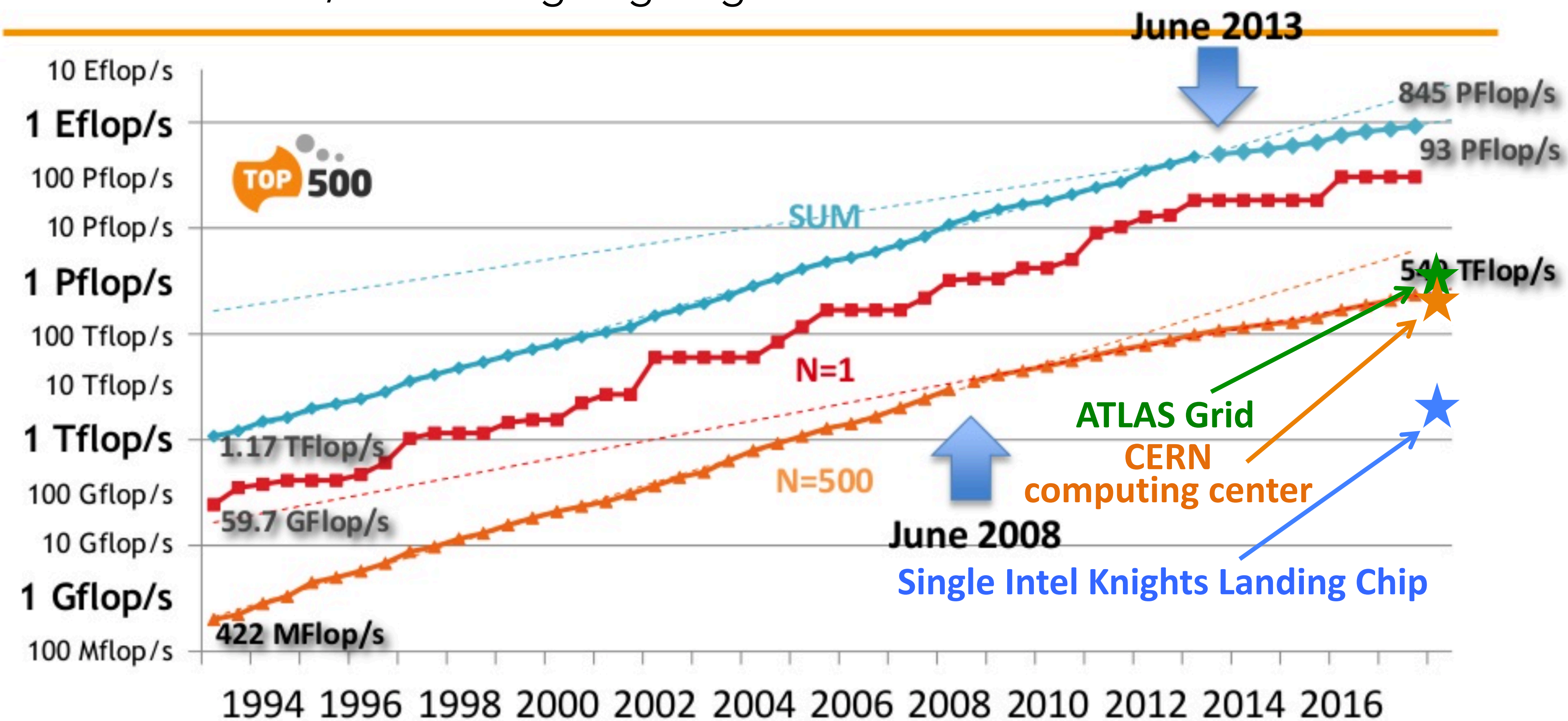
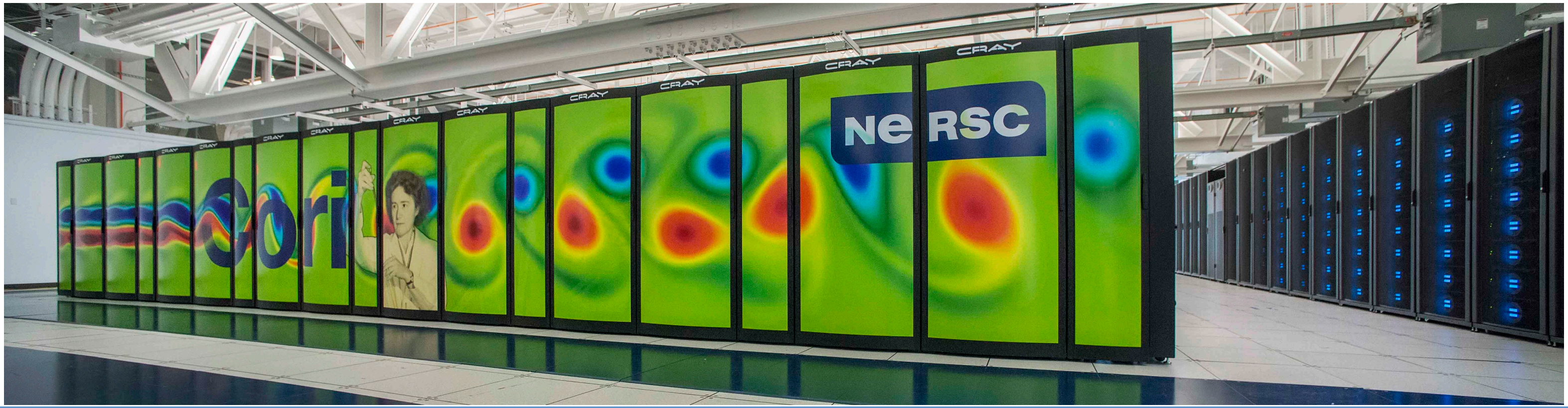


Our Local Beast

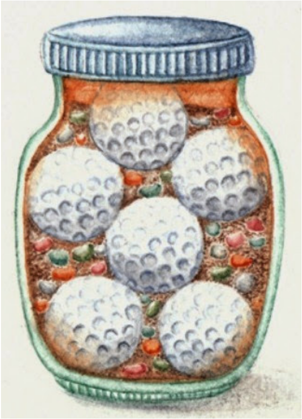
Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway , NRCPC National Supercomputing Center in Wuxi China	10,649,600	93,014.6	125,435.9	15,371
2	**Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P , NUDT National Super Computer Center in Guangzhou China	3,120,000	33,862.7	54,902.4	17,808
3	**Piz Daint** - Cray XC50, Xeon E5-2690v3 12C 2.6GHz, Aries interconnect , NVIDIA Tesla P100 , Cray Inc. Swiss National Supercomputing Centre (CSCS) Switzerland	361,760	19,590.0	25,326.3	2,272
4	**Gyoukou** - ZettaScaler-2.2 HPC system, Xeon D-1571 16C 1.3GHz, Infiniband EDR, PEZY-SC2 700Mhz , ExaScaler Japan Agency for Marine-Earth Science and Technology Japan	19,860,000	19,135.8	28,192.0	1,350
5	**Titan** - Cray XK7, Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x , Cray Inc. DOE/SC/Oak Ridge National Laboratory United States	560,640	17,590.0	27,112.5	8,209
6	**Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom , IBM DOE/NNSA/LLNL United States	1,572,864	17,173.2	20,132.7	7,890
7	**Trinity** - Cray XC40, Intel Xeon Phi 7250 68C 1.4GHz, Aries interconnect , Cray Inc. DOE/NNSA/LANL/SNL United States	979,968	14,137.3	43,902.6	3,844
8	**Cori** - Cray XC40, Intel Xeon Phi 7250 68C 1.4GHz, Aries interconnect , Cray Inc. DOE/SC/LBNL/NERSC United States	622,336	14,014.7	27,880.7	3,939

New as of June 2017

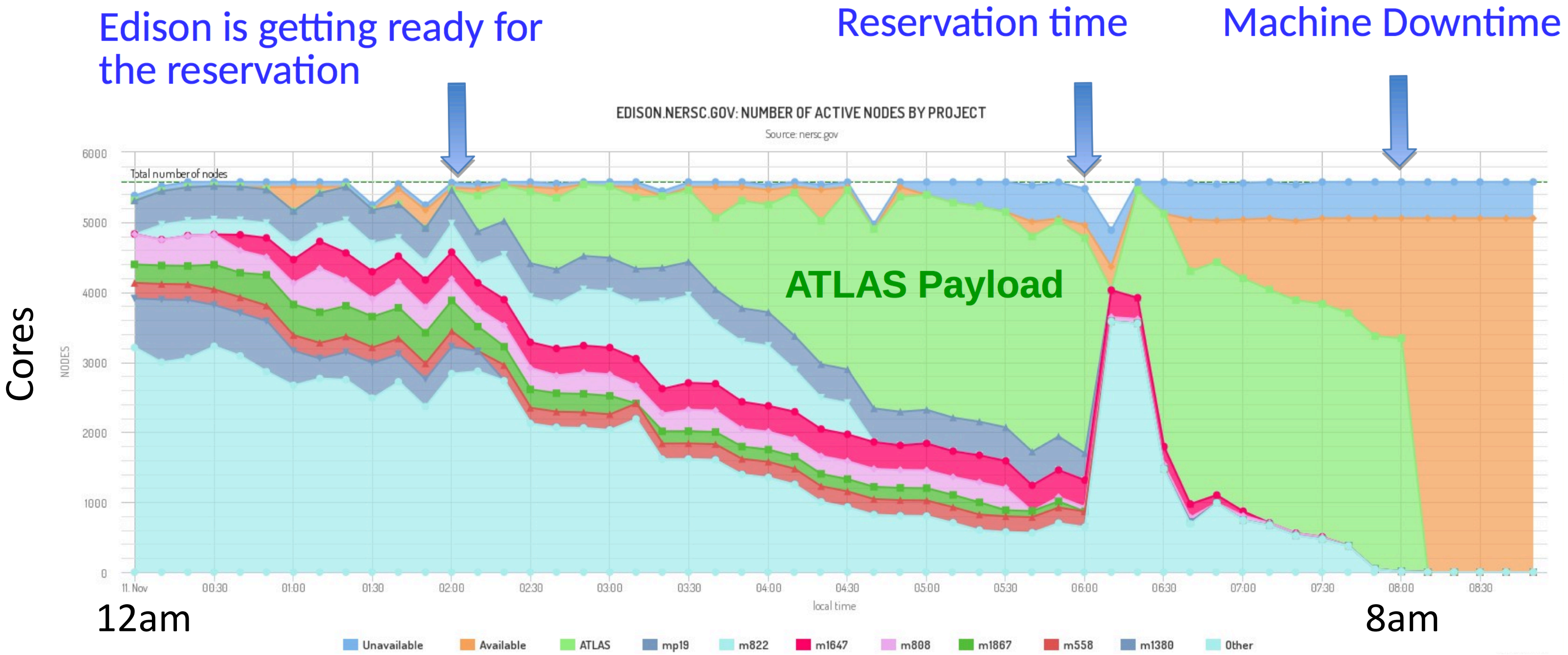
New as of Nov 2017



Use All the Space



- It can be tough to get many hours on these machines – they are often full
- What "full" means depends on what you're filling, and what you are filling it with
- Clever and dynamic job scheduling means "free" CPU!



BOINC!

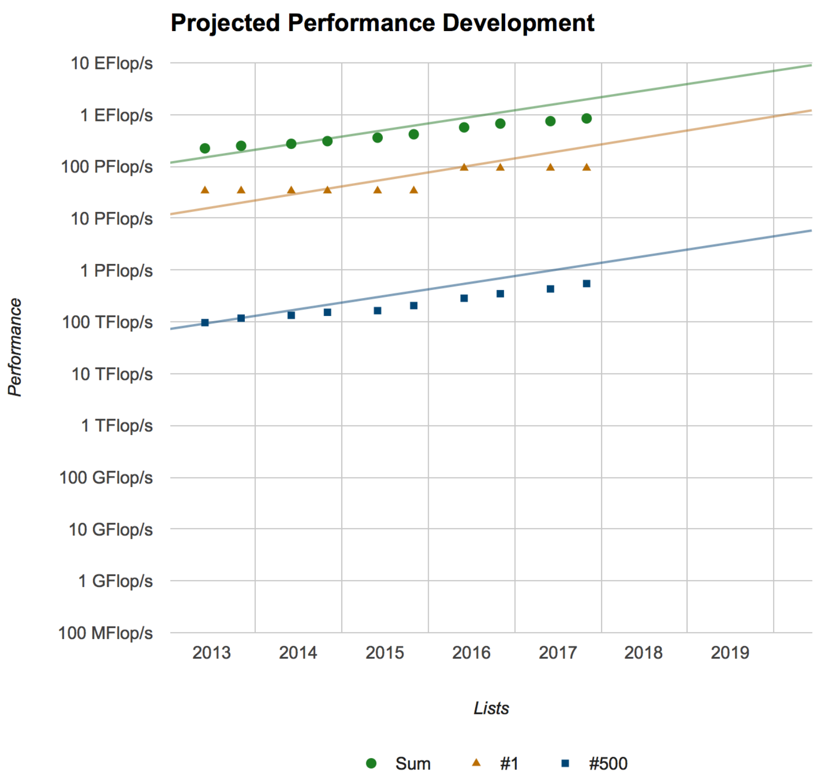
		CMS		Theory		ATLAS	
Rank	Name	Average	Total	Average	Total	Average	Total
1	MPI für Physik	0.00	0	0.00	0	211,662.72	3,322,116
2	Andrej Filipcic	0.00	0	0.00	0	66,009.16	1,261,757
3	Toby Broom	26,050.86	4,022,187	45,855.60	16,294,936	53,713.75	1,312,048
4	Yeti	1,335.42	123,619	1,398.98	1,990,312	53,119.42	1,192,022
5	hartmut	53,605.98	15,498,209	6,647.69	6,899,874	44,424.50	944,219
6	rbpeake	1,520.11	151,354	53.00	535	35,750.73	765,305
7	gorinie	0.00	0	187.03	12,683	35,178.61	744,207
8	Claus Varming Lund	2,336.10	282,981	1,651.21	1,171,971	33,094.87	661,020
9	Ravkin	1,475.84	203,838	2,416.71	399,529	29,113.56	619,466
10	Tom*	449.49	4,734	4,662.88	4,181,427	22,296.07	452,077

http://lhcathome.cern.ch

- You can volunteer your computer if you'd like!
  - Or your cluster, or your school…
- We get almost 10k cores!
  - That's as big as some of the computing centers

Will It Keep Up?

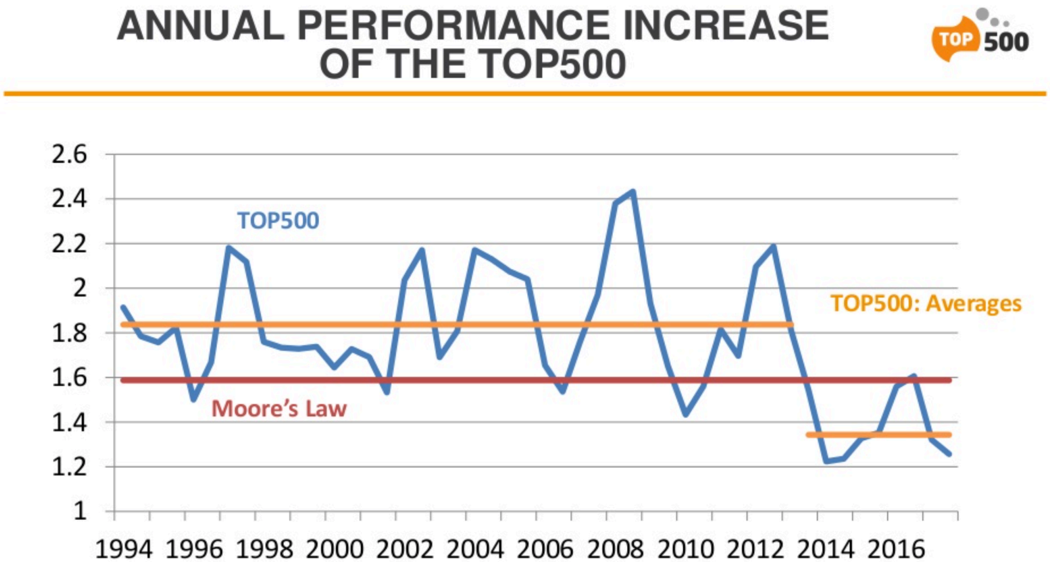
- If we look at just the last few years of HPC centers, the scaling doesn't seem to be so great
  - Moore's law now projected to run out around 2022-5
- It is not clear ***yet*** what advances will take us there; it could be that the future is not quite so rosy

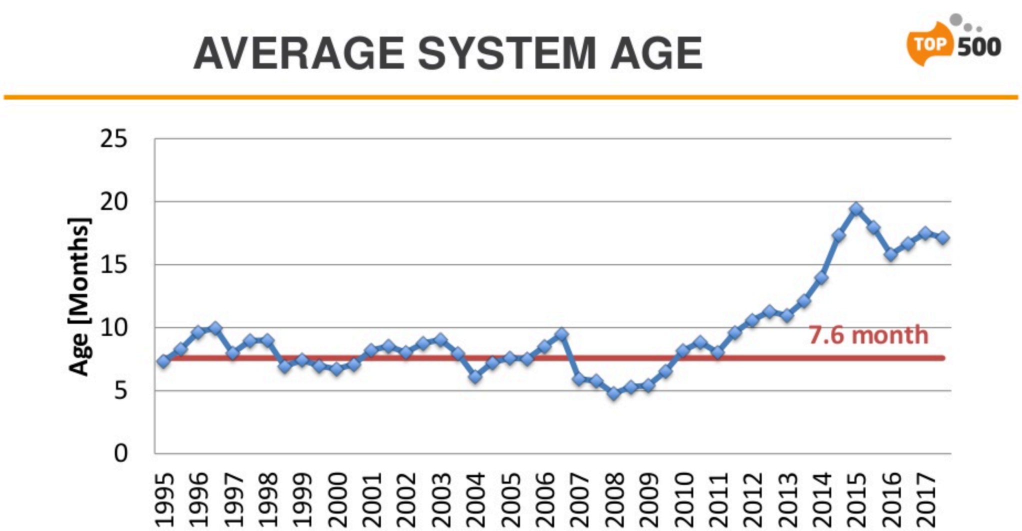


Still technology innovations to come, e.g.:
- Tensor processing units (Google), and "Deep-Learning Units" (Fujitsu)
- Ways to overcome the van Neumann bottleneck (the memory wall; Intel)

With all advances, we have to decide whether to lead or follow!
- The choice is about *investment* – we get 'free money' once these are well-understood technologies

CPU Really Isn't Free…





- Some folks have pointed out that the increases aren't even tracking Moore's law any more
- Seems to be related more to *power consumption* than anything else
  - If your data center can't handle the power, you have to build a new data center, which takes a lot longer than building a new machine!
- Power targets for exascale machines may mean that they will be *very rare*

A Brief Aside: You Can Help!!

Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context

Recommendation 29: Strengthen the global cooperation among laboratories and universities to address computing and scientific software needs, and provide efficient training in next-generation hardware and data-science software relevant to particle physics. Investigate models for the development and maintenance of major software within and across research areas, including long-term data and software preservation.

High Energy Physics Forum for Computational Excellence: Working Group Reports

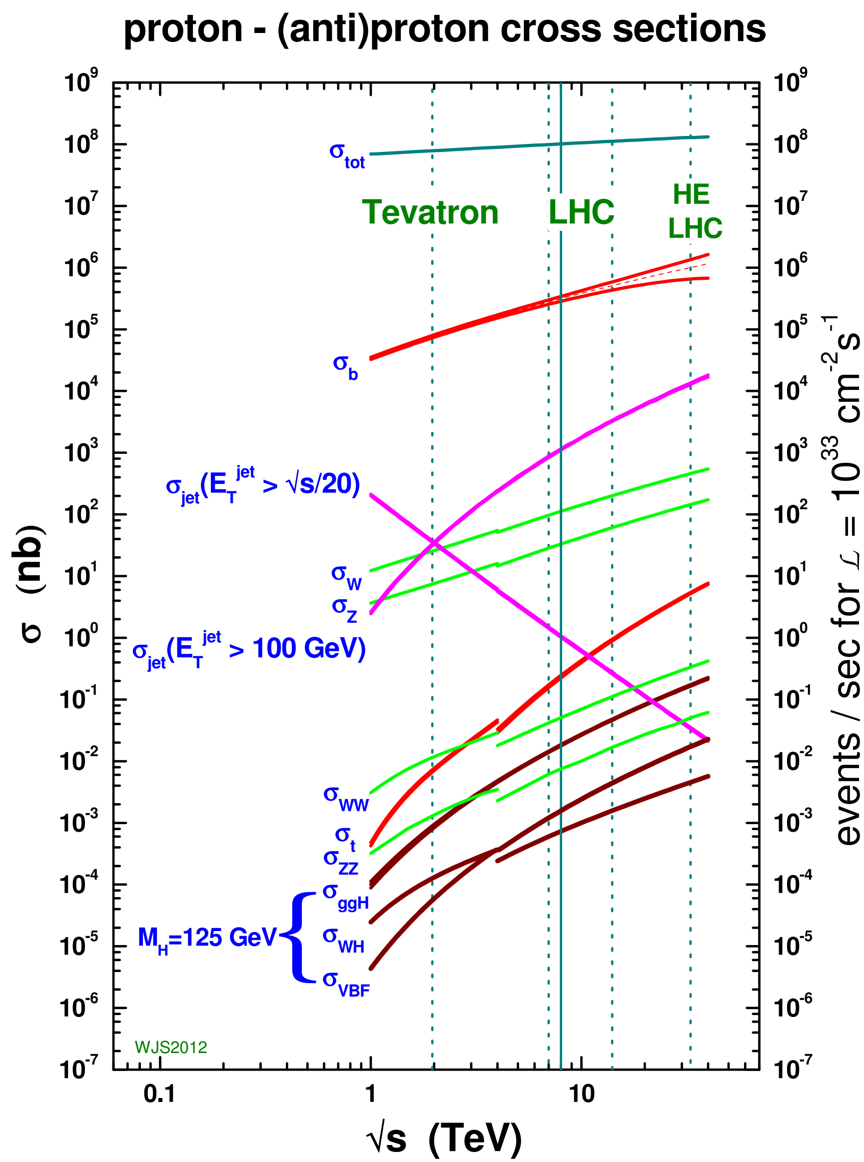
Finally, given the scale of modern software development, it was considered beneficial to recognize a significant community-level software commitment as a technical undertaking at times on par with major detector R&D.

Make sure you take software training seriously!

If you wouldn't just drop a student in front of a detector test stand, don't just drop them in front of a laptop!

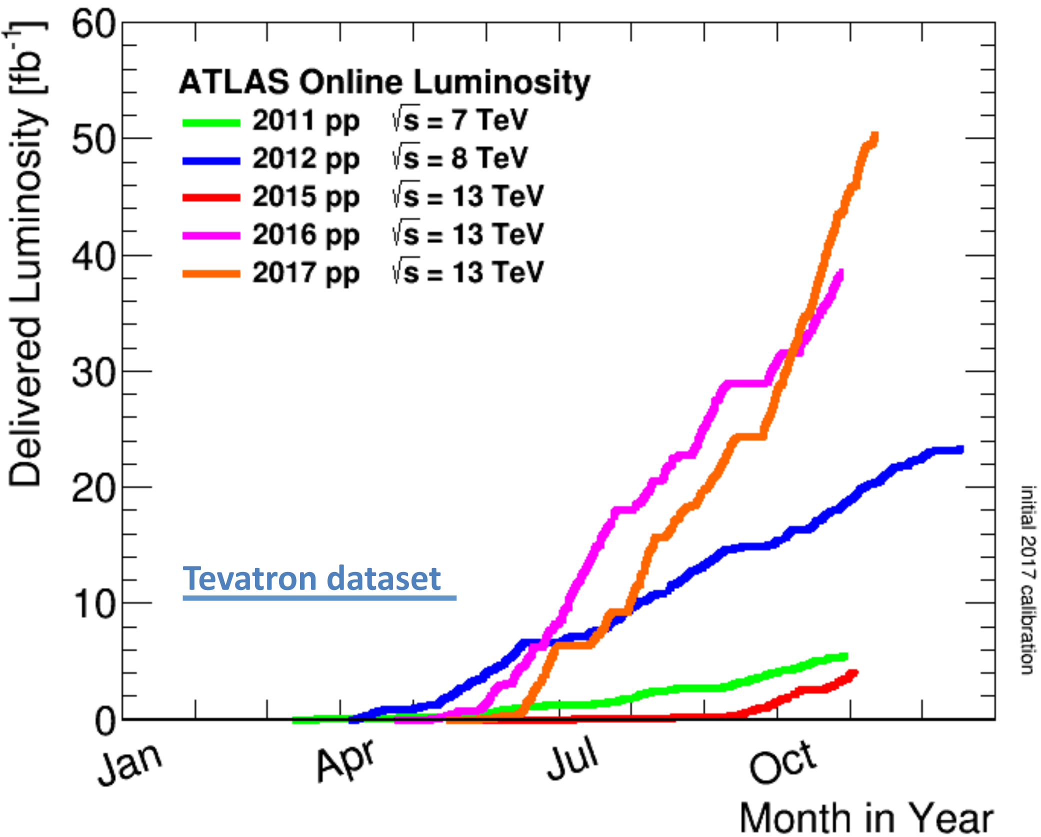
What We Measure and Search For

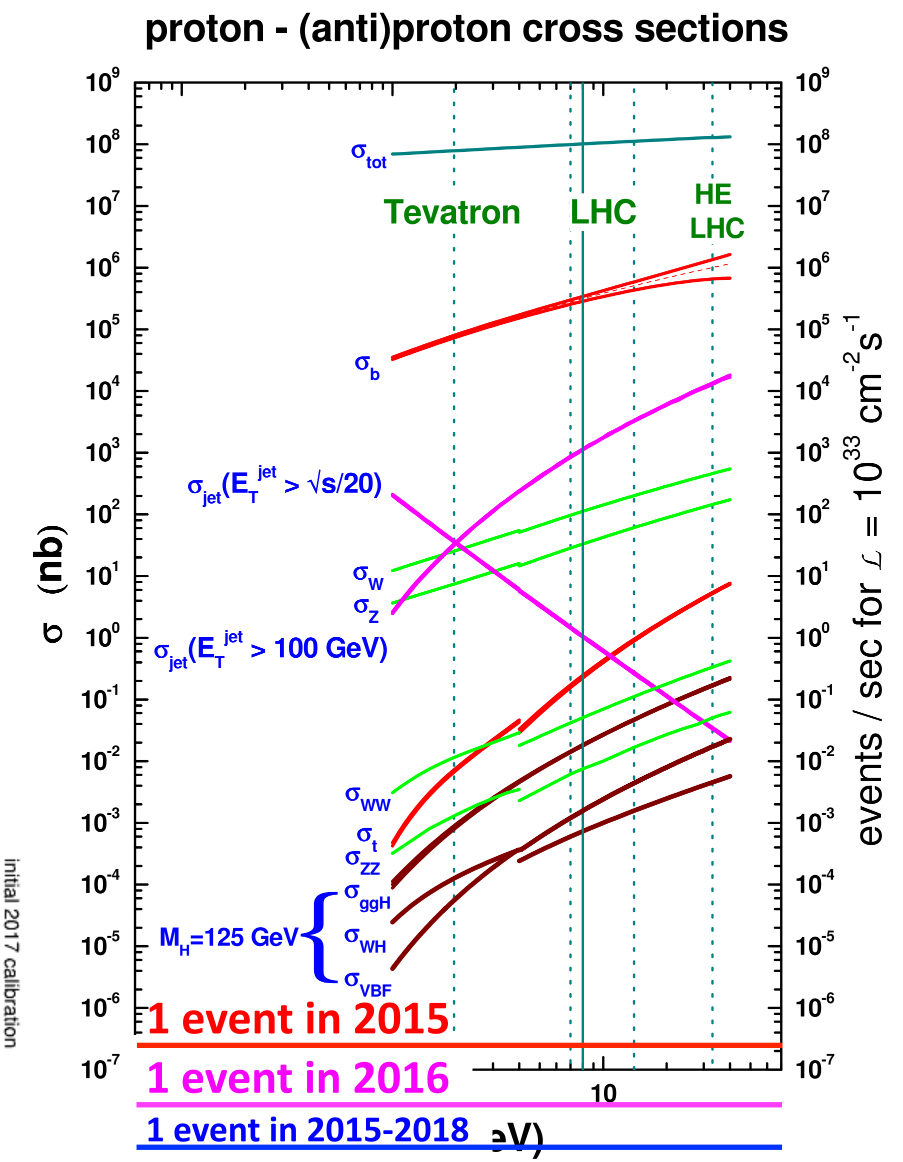
- The Standard Model gives us predictions of how many of a certain kind of event we will see for each proton-proton collision
- 1 Higgs boson in 10^{10} collisions
- In 2017 we peaked at about **3 billion** collisions **per second**
- In a **very** good year, we could run for about 10^7 seconds
  - 3 million Higgs bosons per year – so Higgs physics is easy, right?



Data Sets

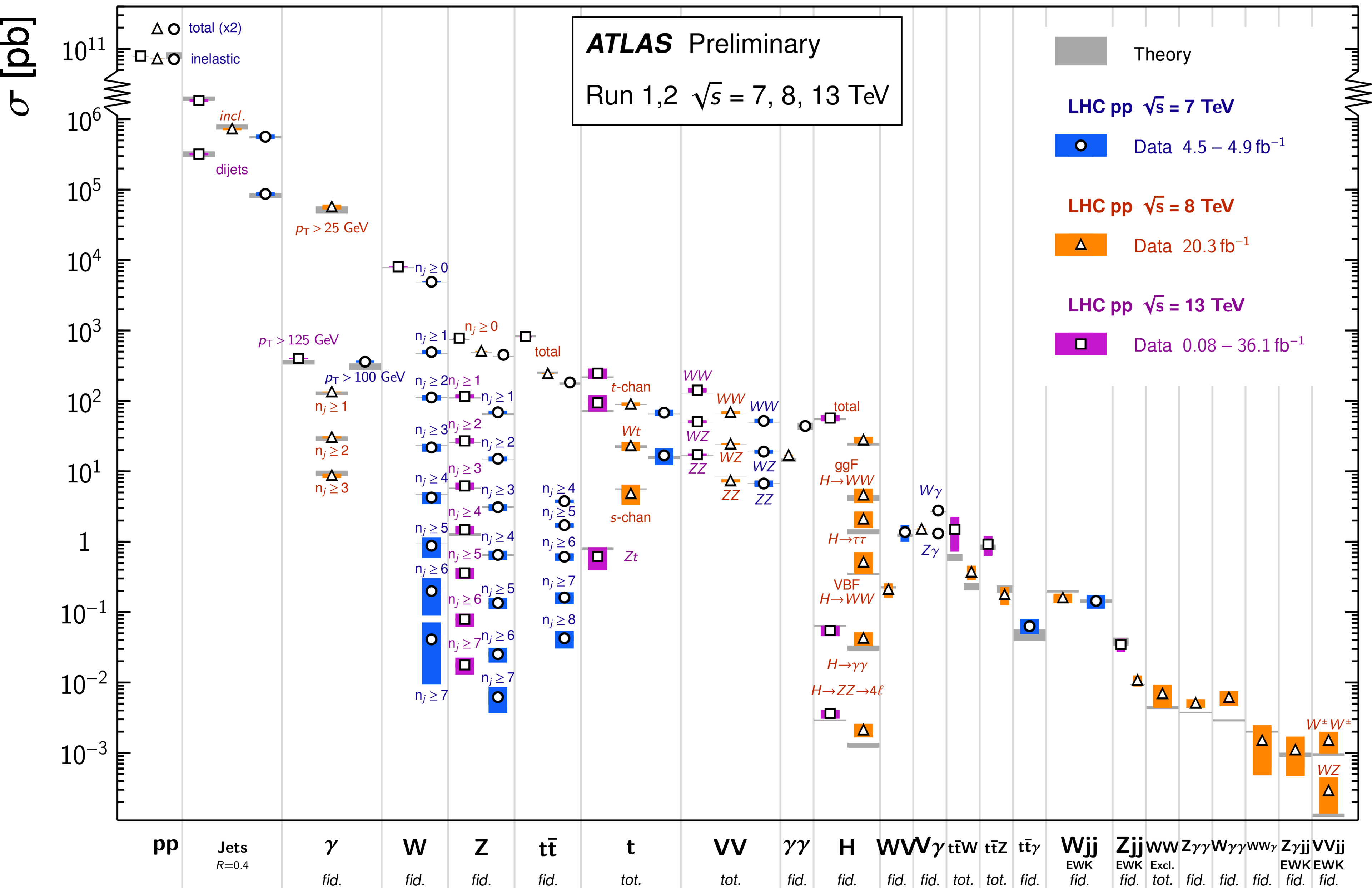
- We measure our data in units of inverse cross section
- Easy to figure out event **counts**

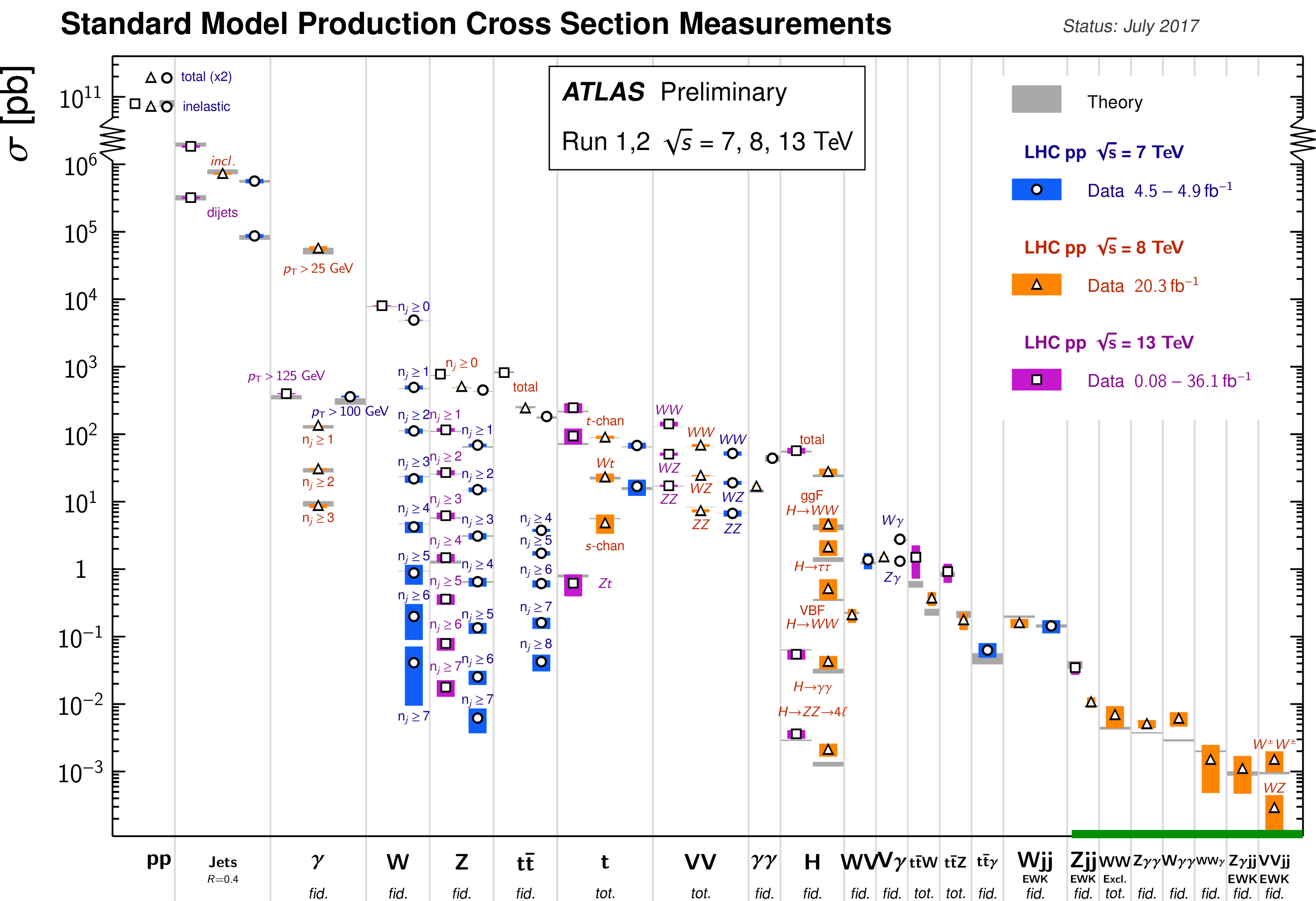




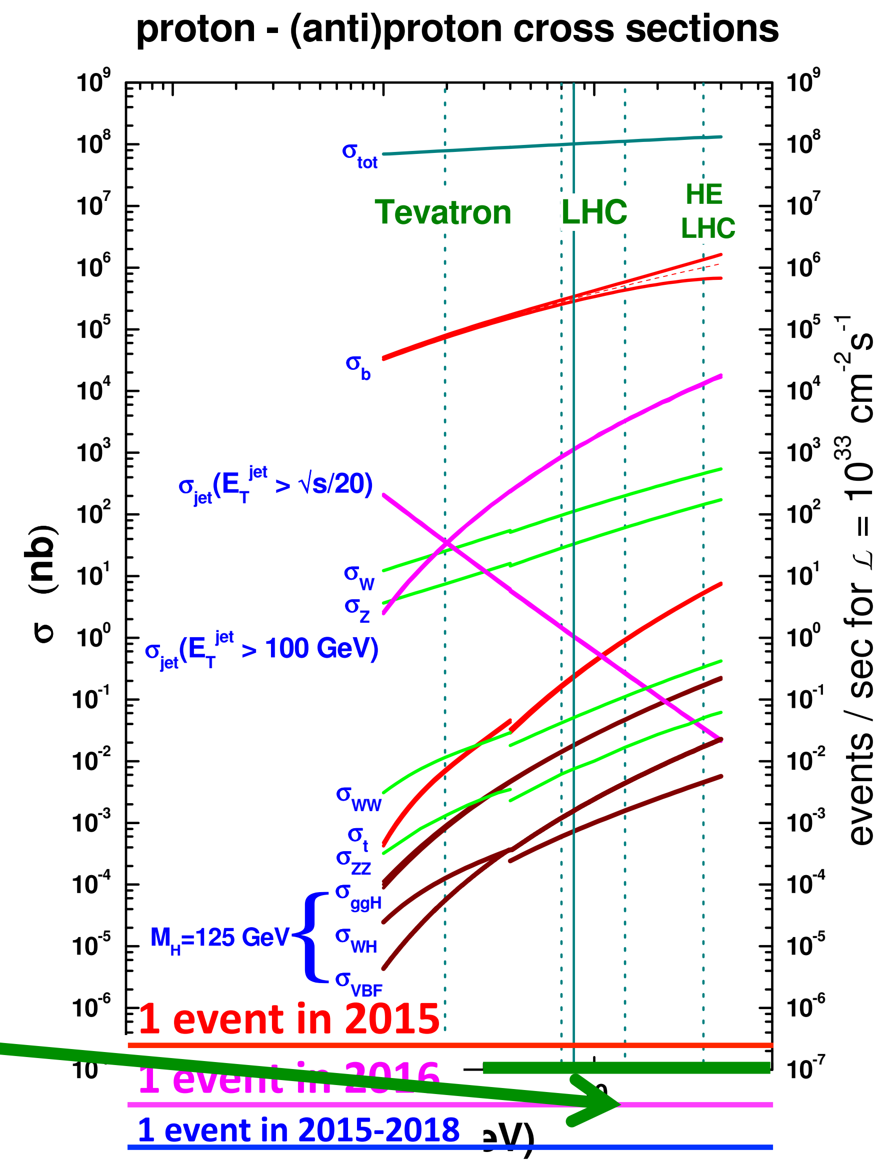
Standard Model Production Cross Section Measurements

Status: July 2017

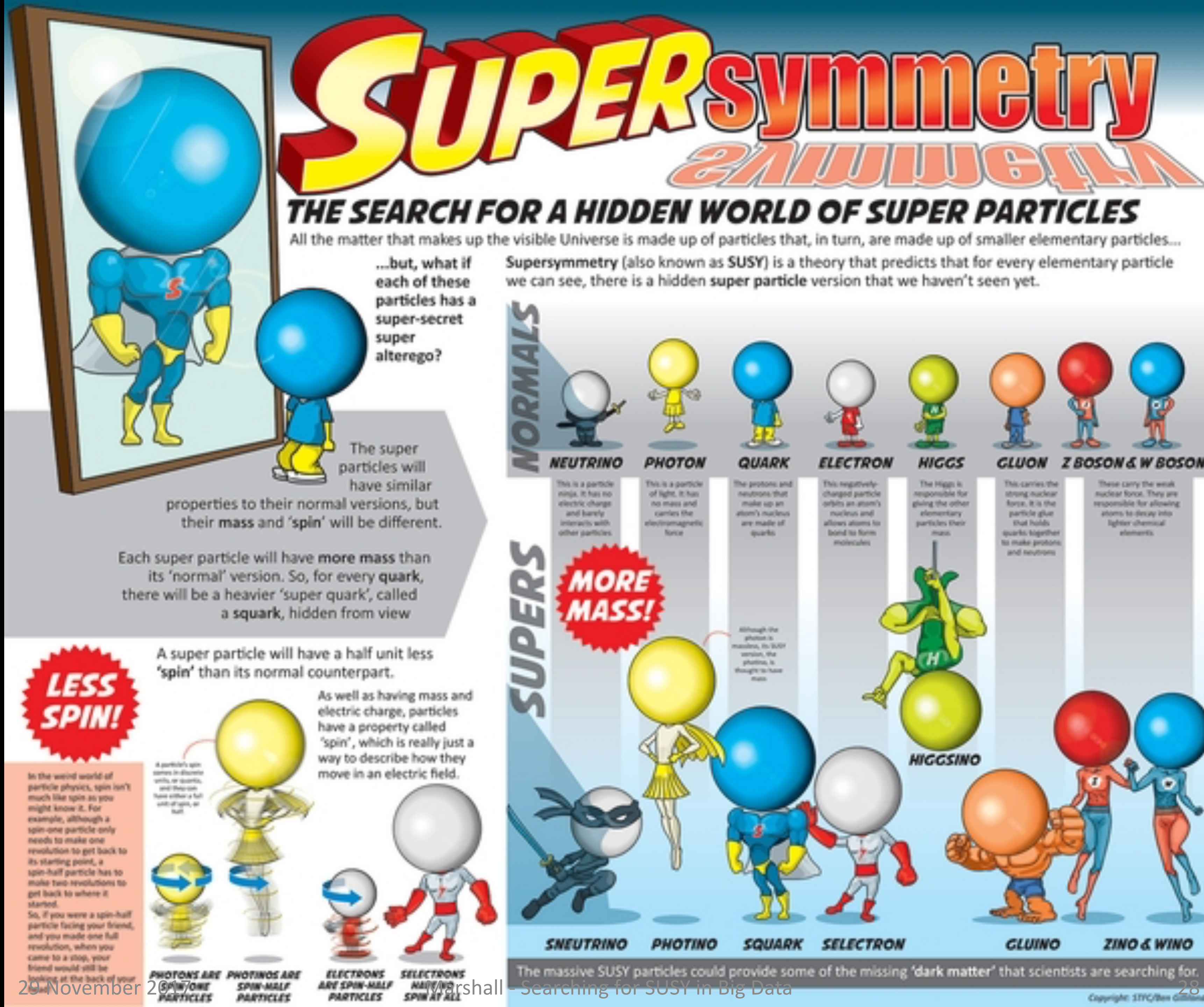



Standard Model Production Cross Section Measurements
Status: July 2017
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 36.1 fb⁻¹
σ [pb]
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
WV fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Wjj EWK fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
Wγγ fid.
WWγ fid.
Zγjj EWK fid.
VVjj EWK fid.

Data Sets

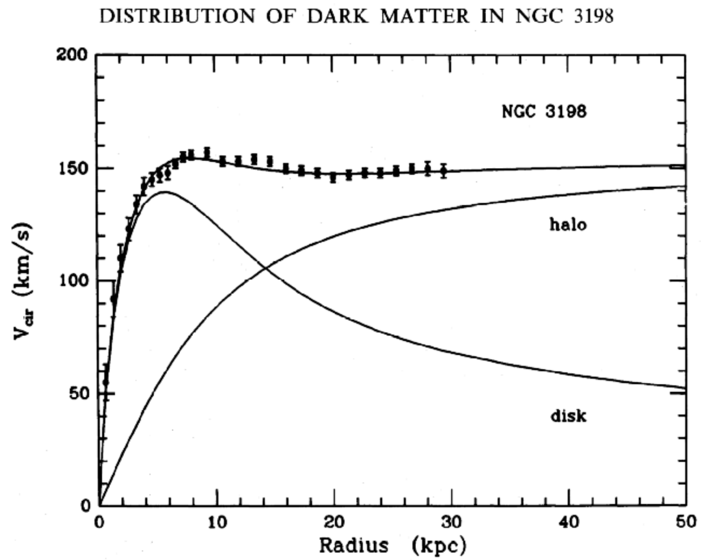


So what else is down here???


SUPERsymmetry
THE SEARCH FOR A HIDDEN WORLD OF SUPER PARTICLES
All the matter that makes up the visible Universe is made up of particles that, in turn, are made up of smaller elementary particles...
...but, what if each of these particles has a super-secret super alterego?
Supersymmetry (also known as SUSY) is a theory that predicts that for every elementary particle we can see, there is a hidden super particle version that we haven't seen yet.
The super particles will have similar properties to their normal versions, but their mass and 'spin' will be different.
Each super particle will have more mass than its 'normal' version. So, for every quark, there will be a heavier 'super quark', called a squark, hidden from view
LESS SPIN!
A super particle will have a half unit less 'spin' than its normal counterpart.
As well as having mass and electric charge, particles have a property called 'spin', which is really just a way to describe how they move in an electric field.
PHOTONS ARE SPIN-ONE PARTICLES
PHOTINOS ARE SPIN-HALF PARTICLES
ELECTRONS ARE SPIN-HALF PARTICLES
SELECTRONS HAVE NO SPIN AT ALL
NORMALS
NEUTRINO
PHOTON
QUARK
ELECTRON
HIGGS
GLUON
Z BOSON & W BOSON
SUPERS
MORE MASS!
HIGGSINO
SNEUTRINO
PHOTINO
SQUARK
SELECTRON
GLUINO
ZINO & WINO
The massive SUSY particles could provide some of the missing 'dark matter' that scientists are searching for.

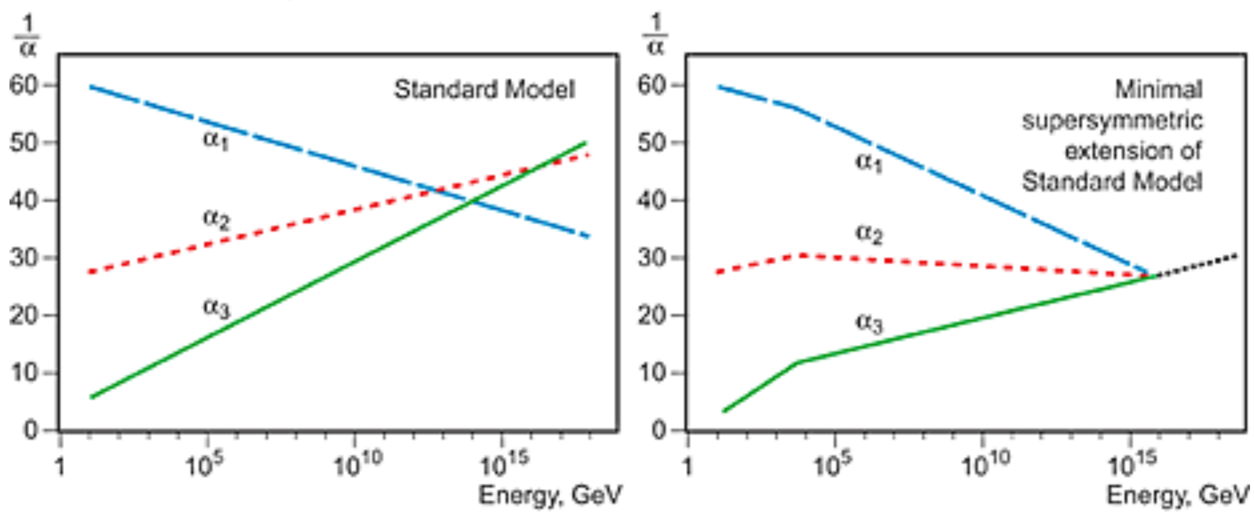
Why SUSY?

SUSY **could** help explain dark matter



If there is R-Parity in nature…

SUSY **could** help with force unification



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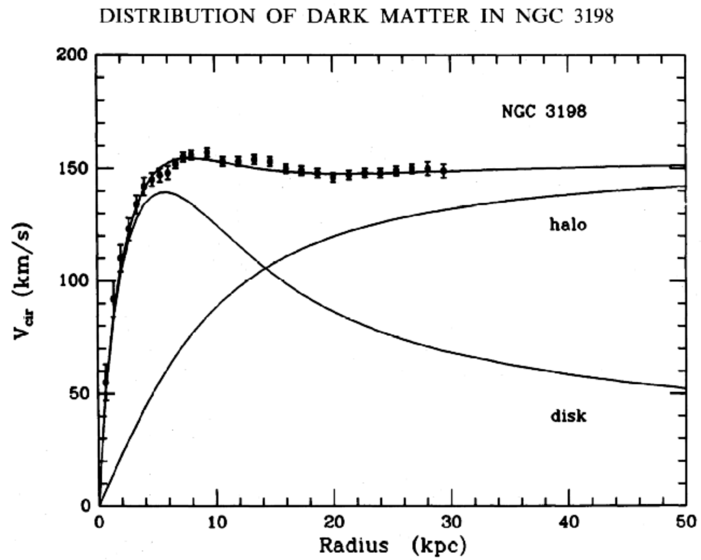

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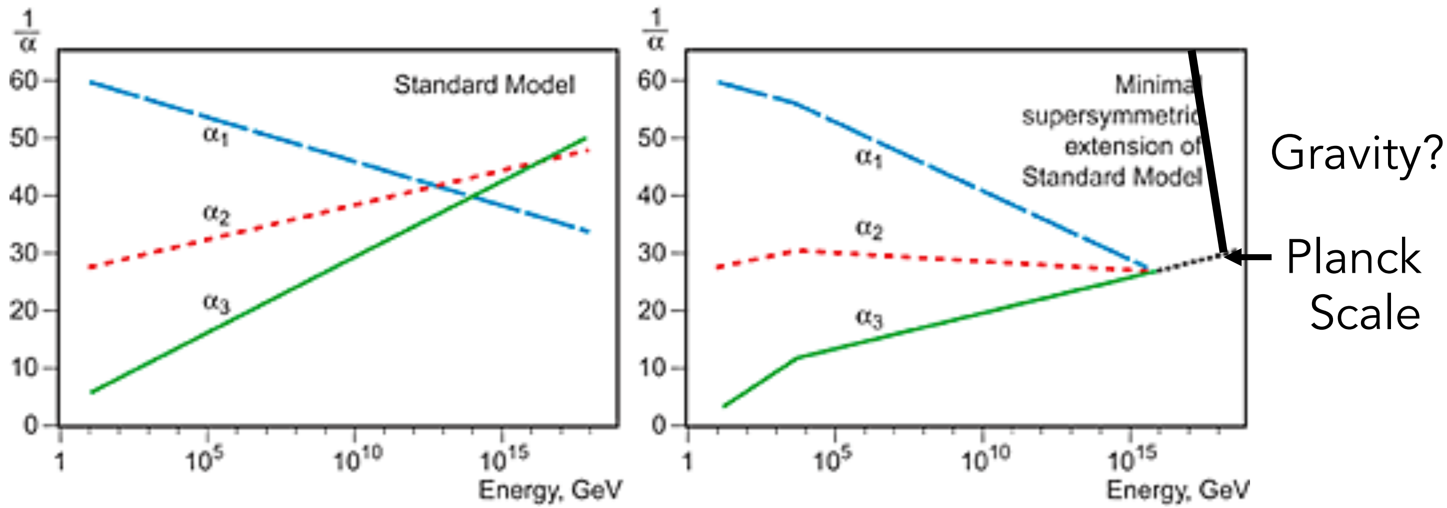


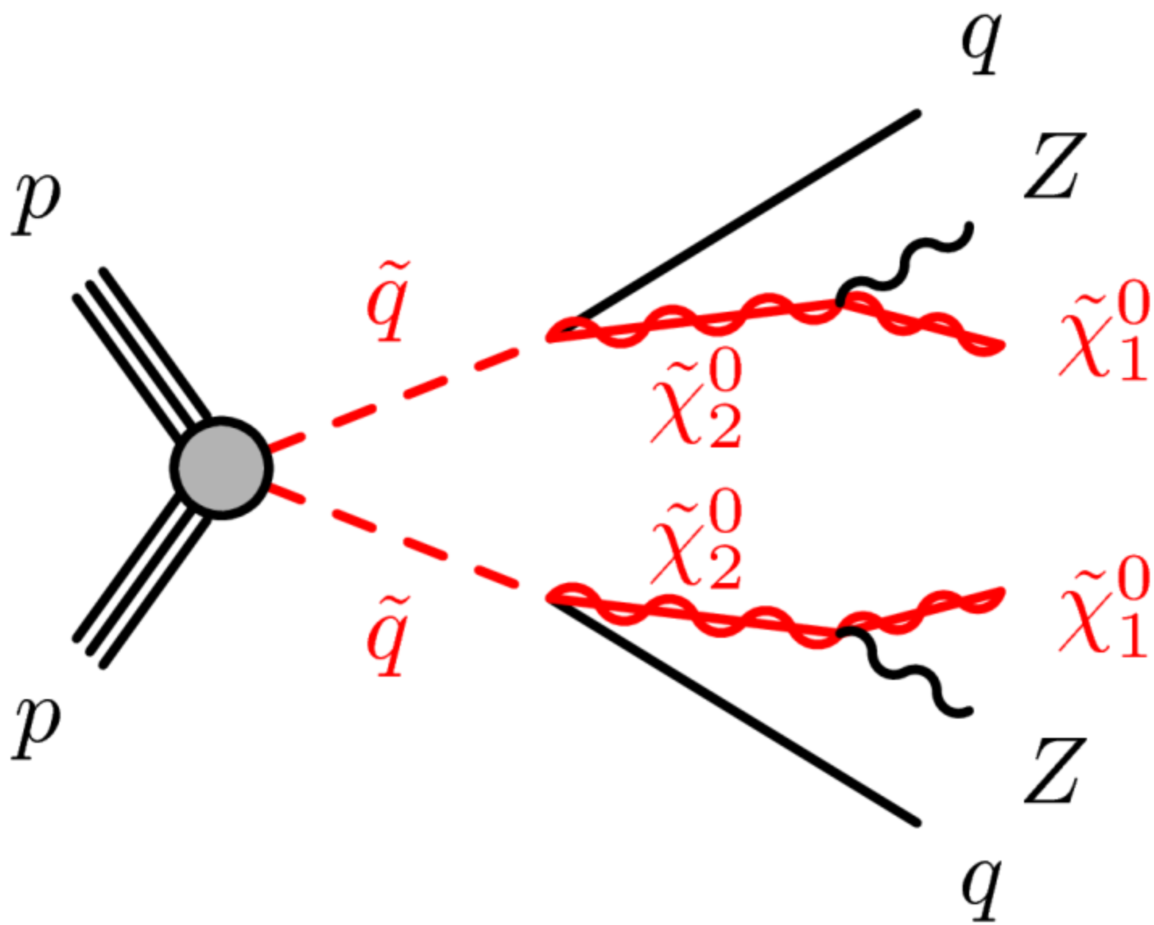
Wouldn't it be nice???

It's Not All Good

- That's a lot of particles!
- Lots of different scenarios
  - Which is lighter than which
  - How do they decay
- It's a bit complicated

Modern World: Simplified Models

- This is (an example of) a simplified model



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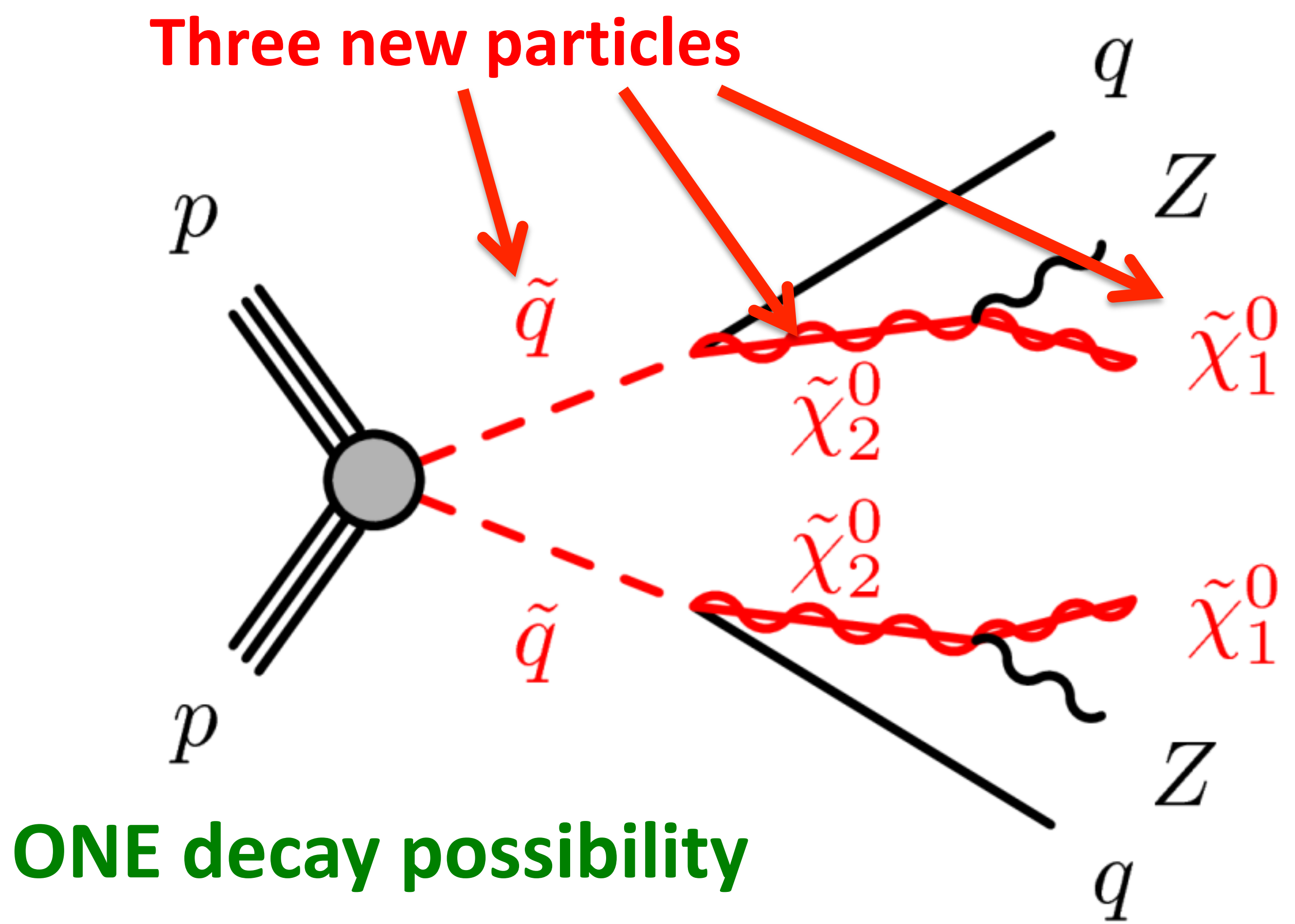

I can search for that ☺

Modern World: Simplified Models

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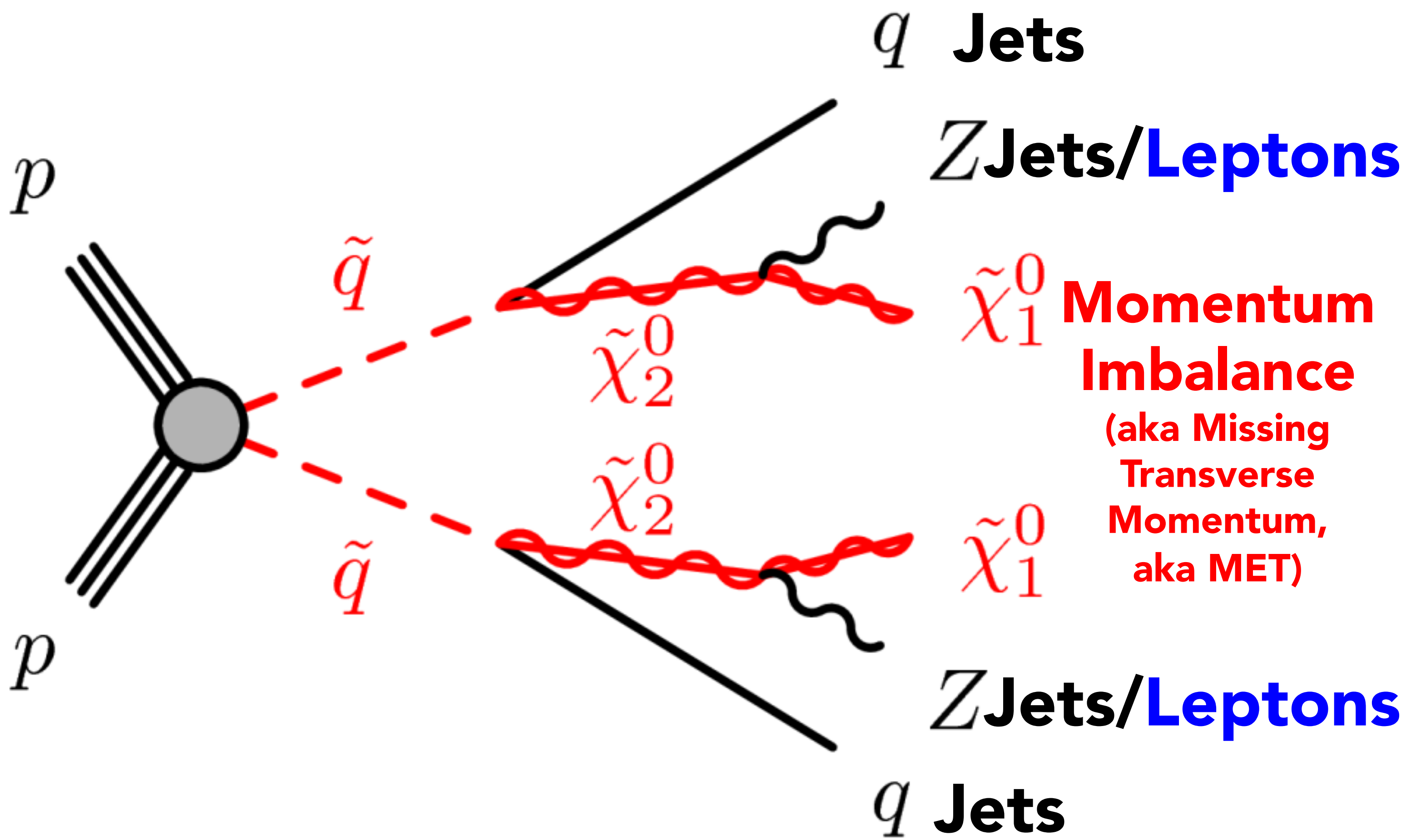
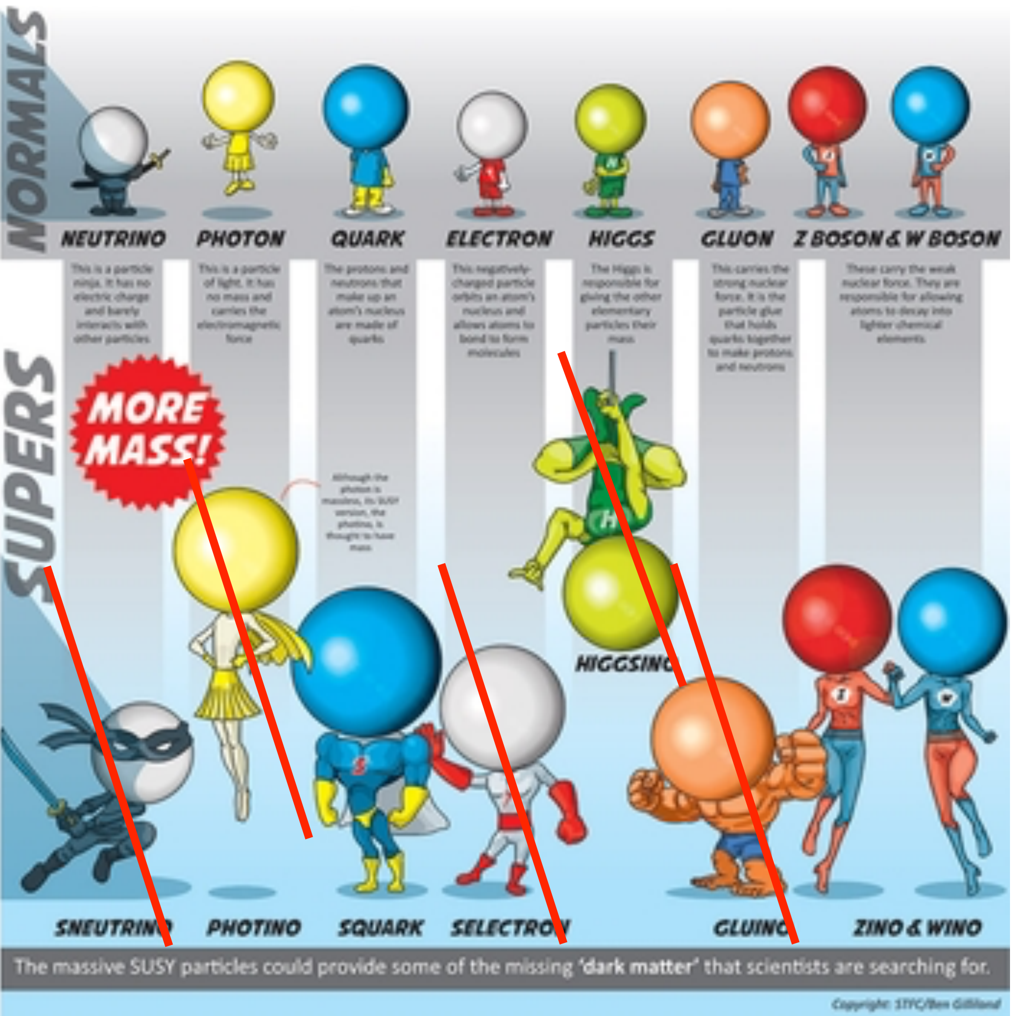


I can search for that ☺

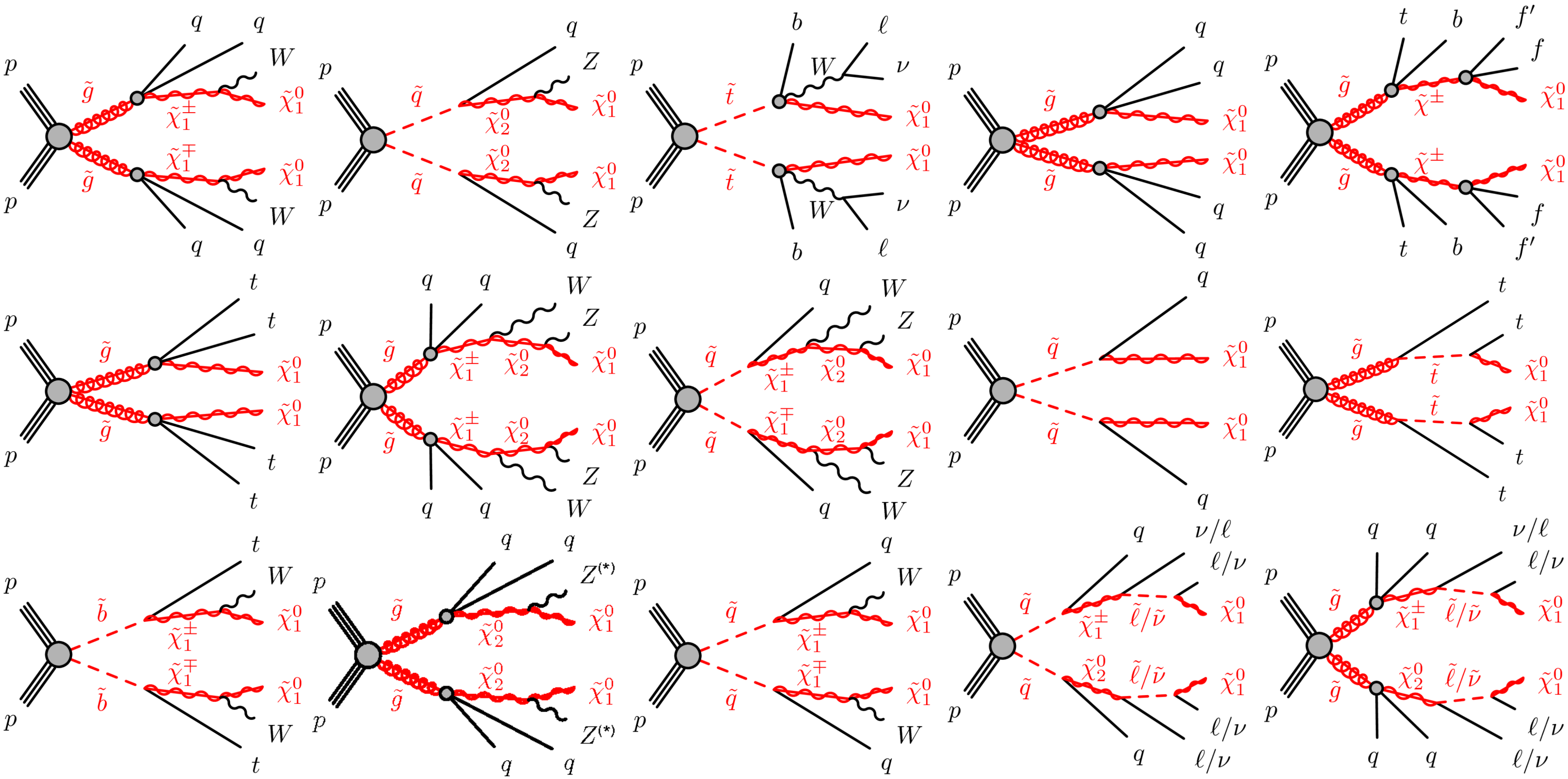
Unfortunately…



- We killed a lot of particles that could be there if SUSY is realized in nature
- We will have to think about how those assumptions affect our conclusions!

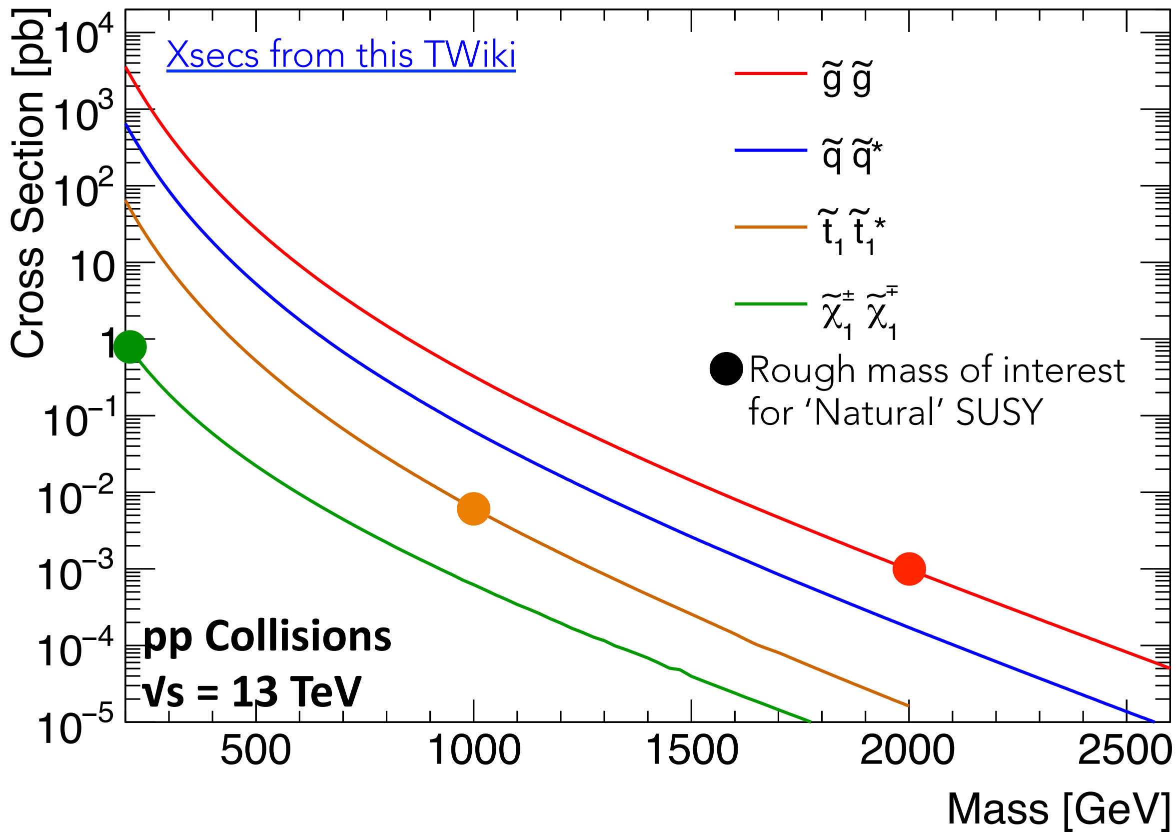
So Many Options!

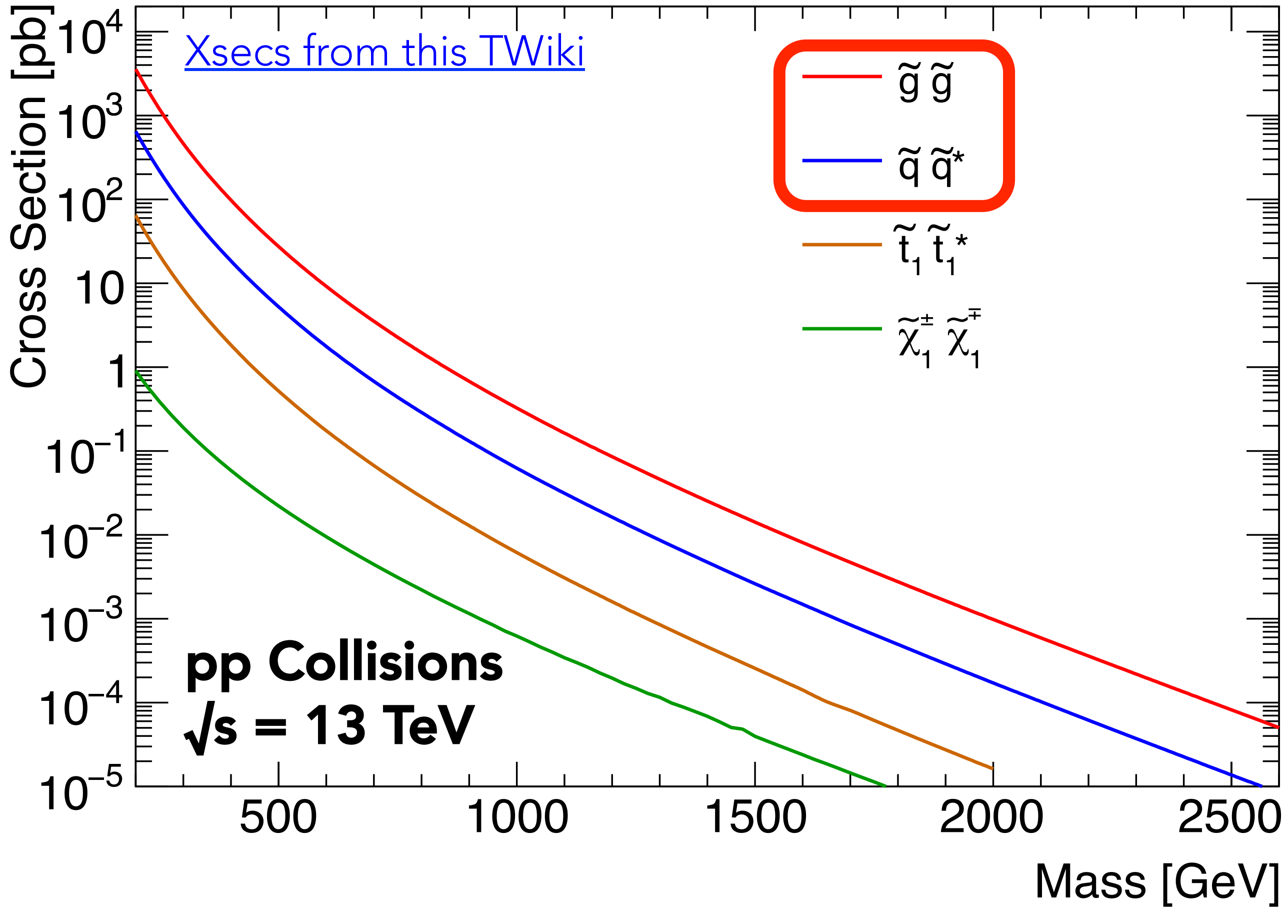
Now we have to choose ***which*** Supersymmetry to look for



Organizing the Searches

- SUSY final states are quite **diverse**!
- We tend to search from easiest to hardest
  - From **strong** to **electroweak** production
  - From "bulk" into "corners"



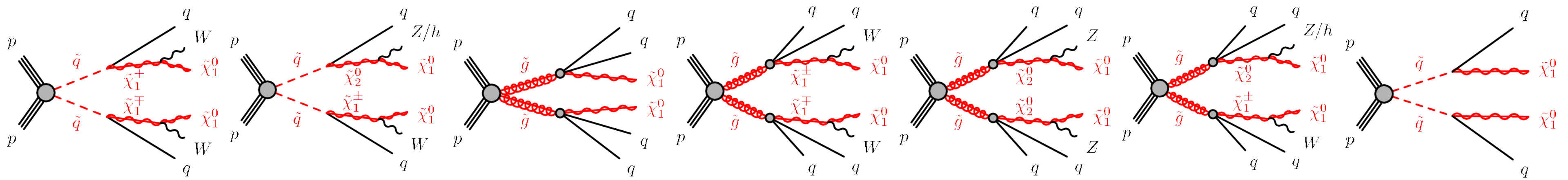


STRONG PRODUCTION

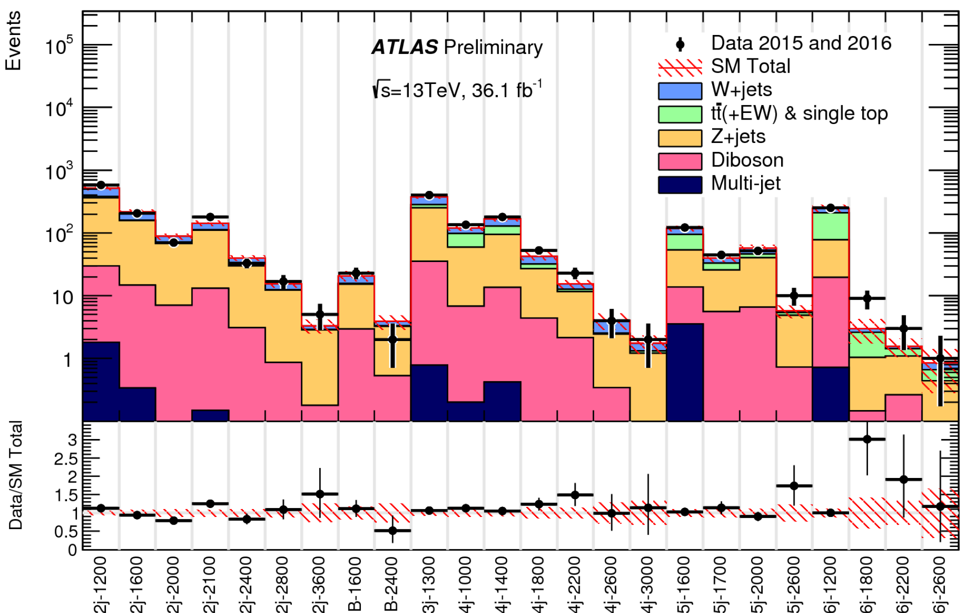
SEARCHES WITH JETS, MISSING TRANSVERSE MOMENTUM (MET) AND (SOMETIMES) LEPTONS

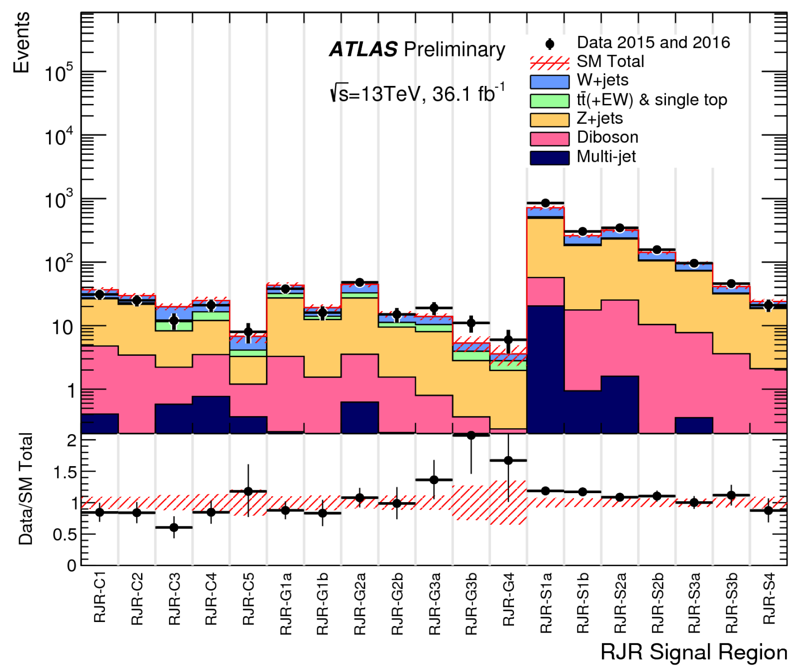
ATLAS 0L Strong Production

- MET in the Standard Model likes to come with **leptons**
- Workhorse search **vetoes leptons**, covers a variety of models



- 46 signal regions with many different targets

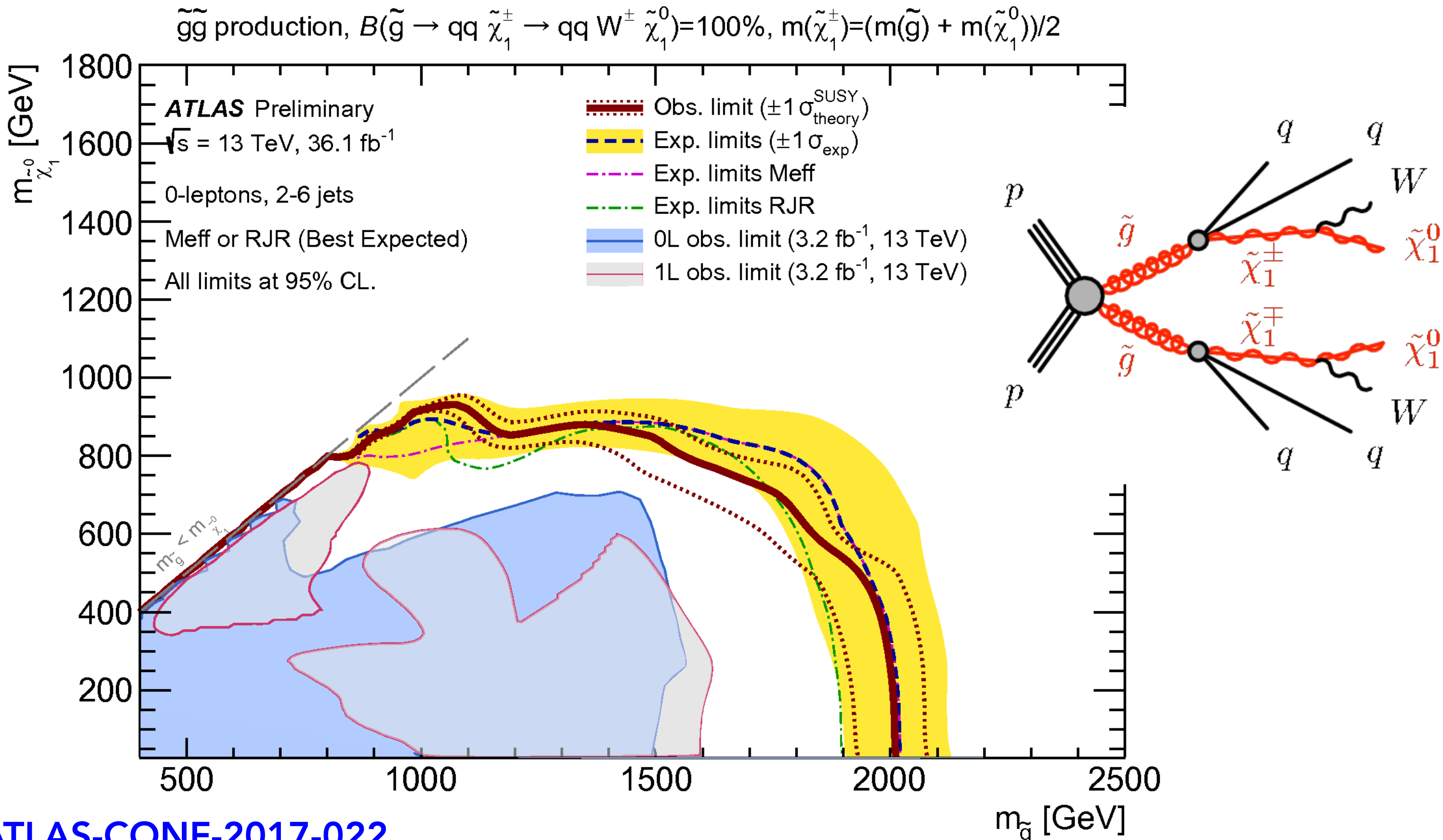




ATLAS-CONF-2017-022

ATLAS 0L Strong Production (II)

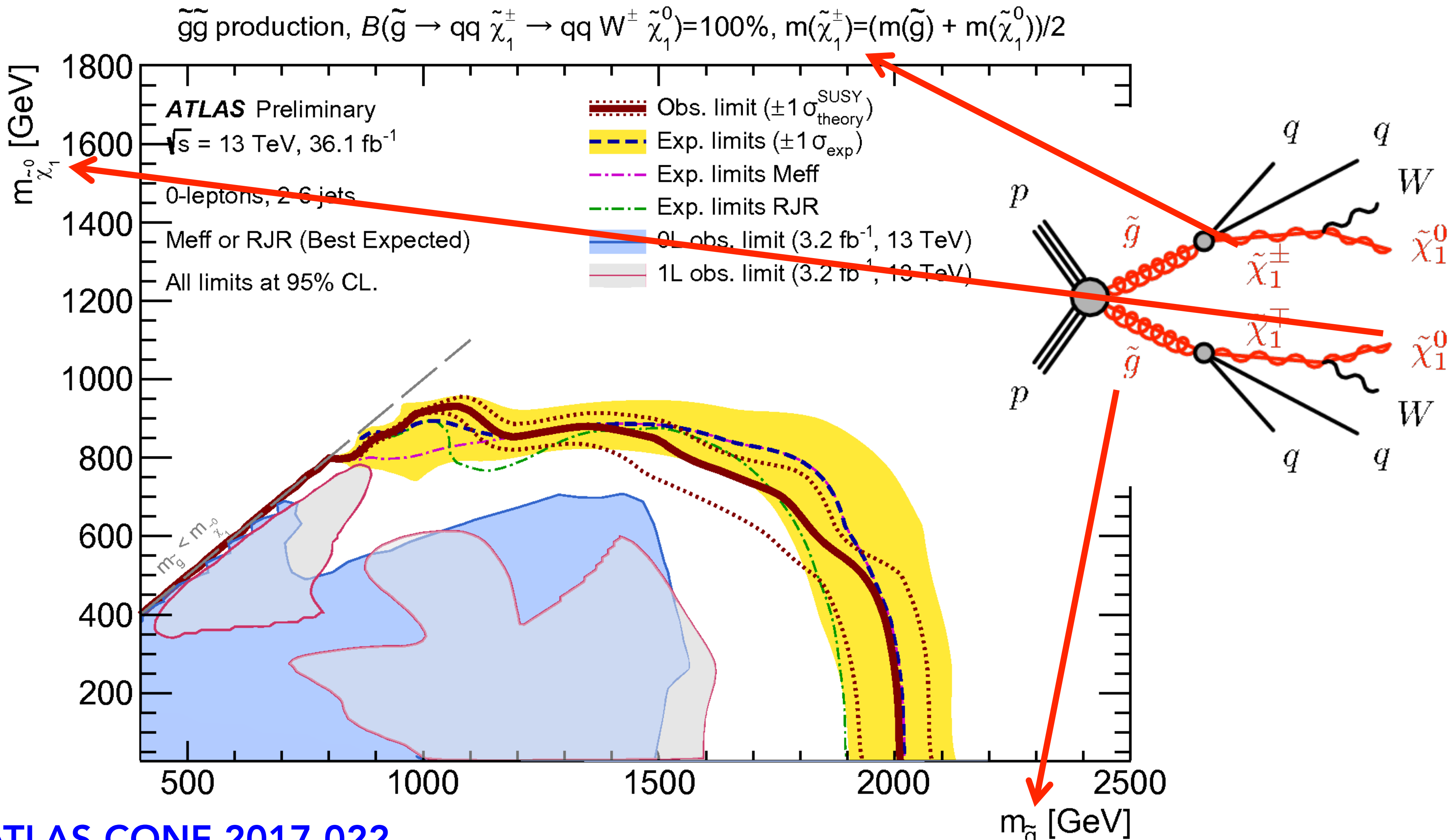
Limits set on a variety of simplified models like this one:



ATLAS-CONF-2017-022

ATLAS 0L Strong Production (II)

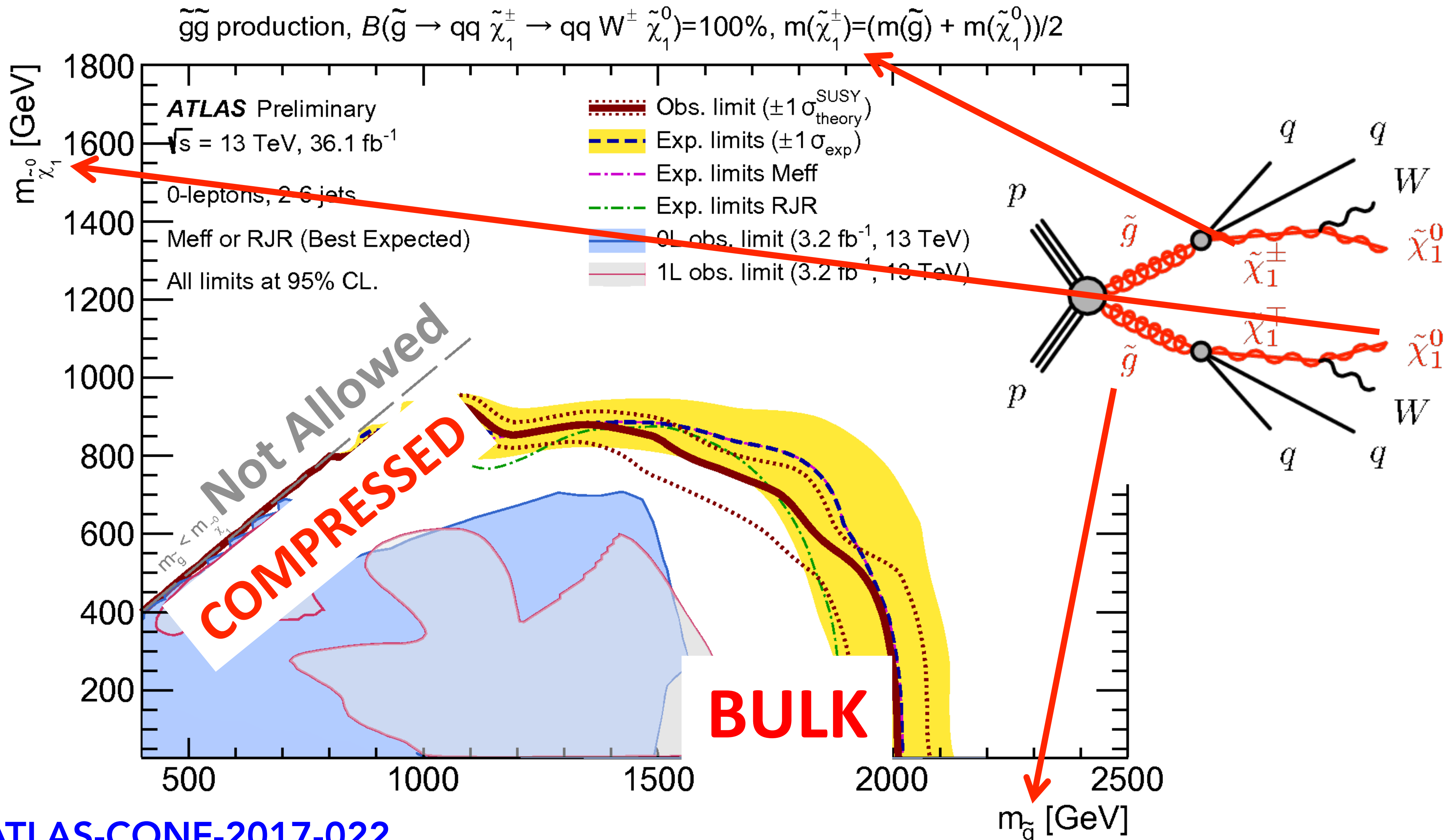
Limits set on a variety of simplified models like this one:



[ATLAS-CONF-2017-022]()

ATLAS 0L Strong Production (II)

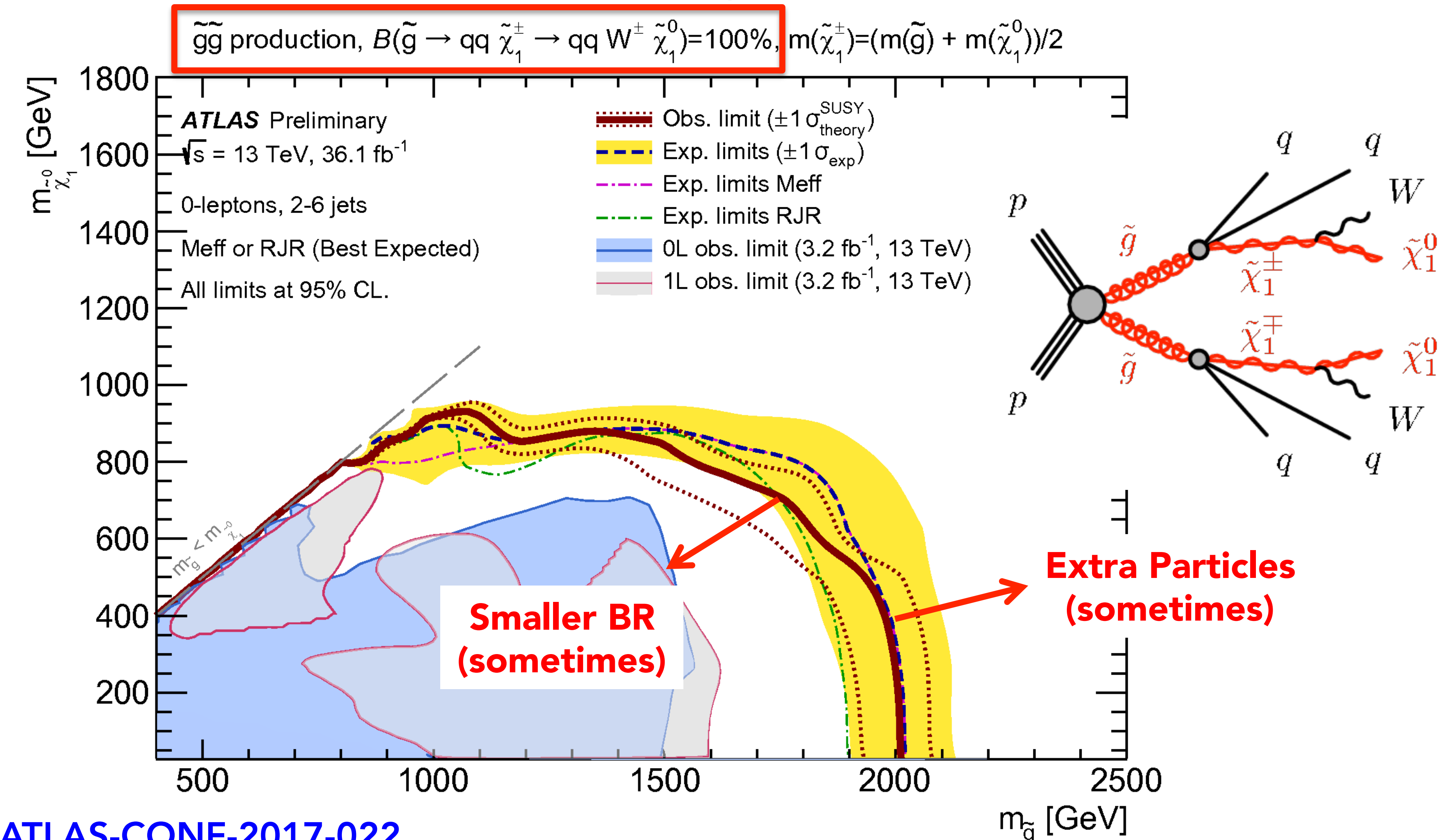
Limits set on a variety of simplified models like this one:



[ATLAS-CONF-2017-022]

ATLAS 0L Strong Production (II)

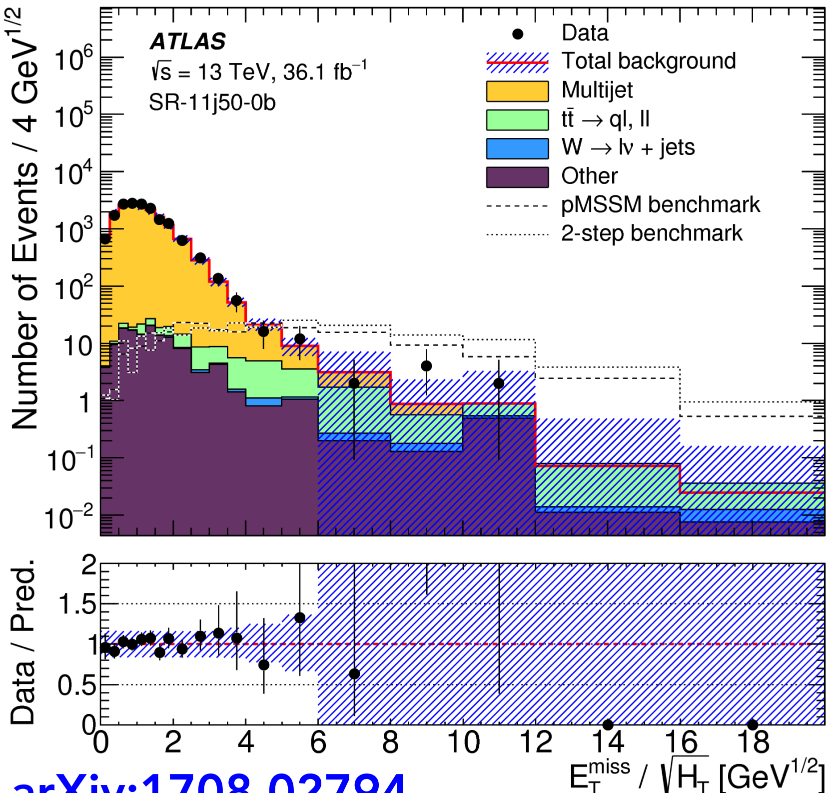
Limits set on a variety of simplified models like this one:

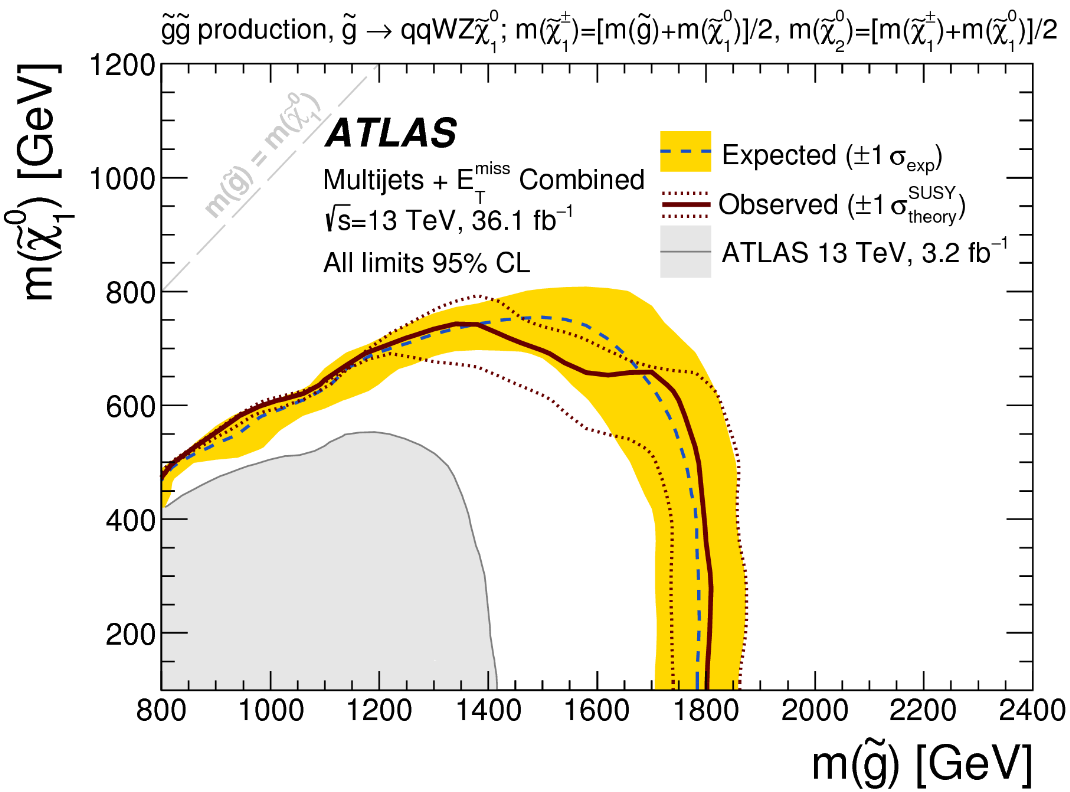


ATLAS-CONF-2017-022

ATLAS Multi-Jet

- Long SUSY decay chains produce many jet final states
- Search in events with many (7-11) jets
- Uses a 'template' method to estimate QCD background
  - MET significance approximately invariant in jet multiplicity

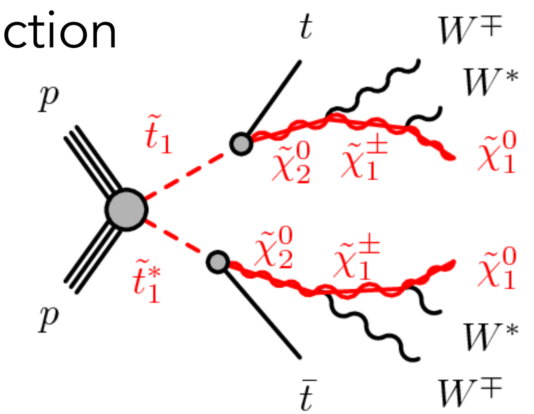


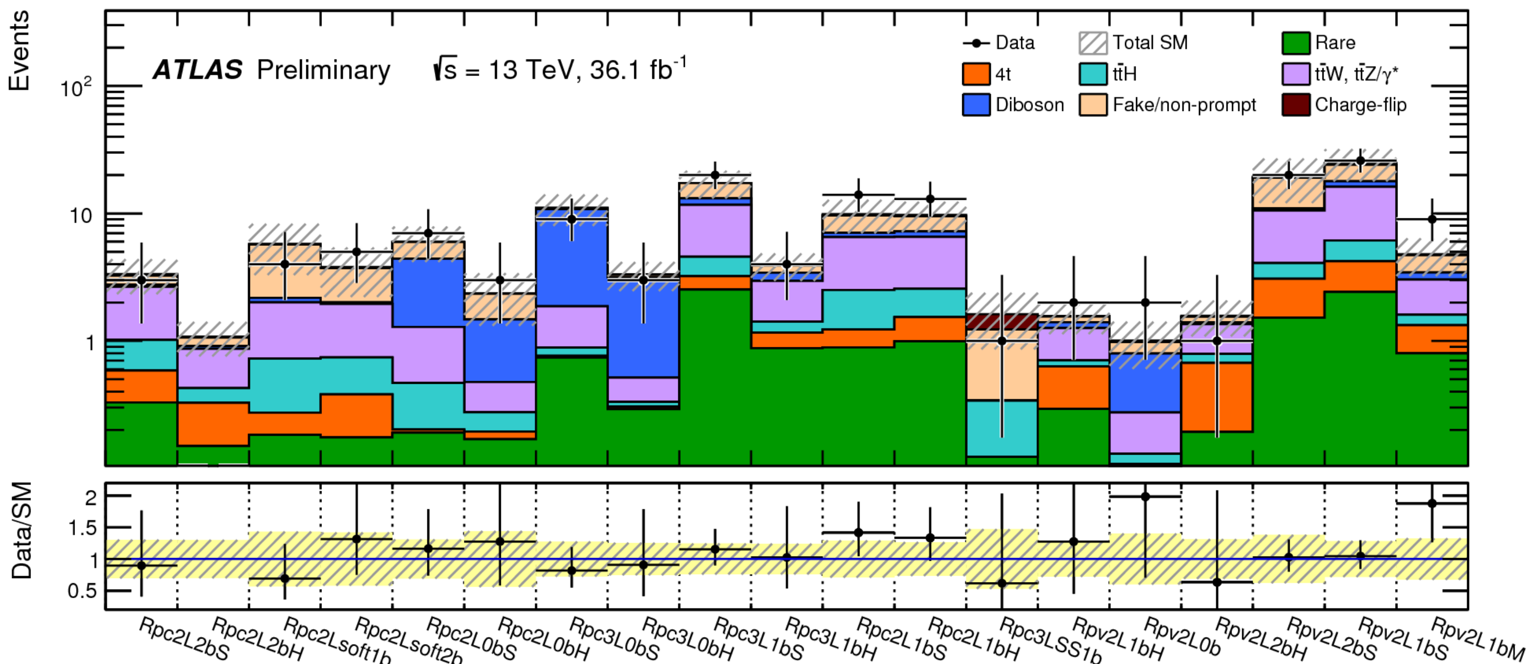


[arXiv:1708.02794](https://arxiv.org/abs/1708.02794)

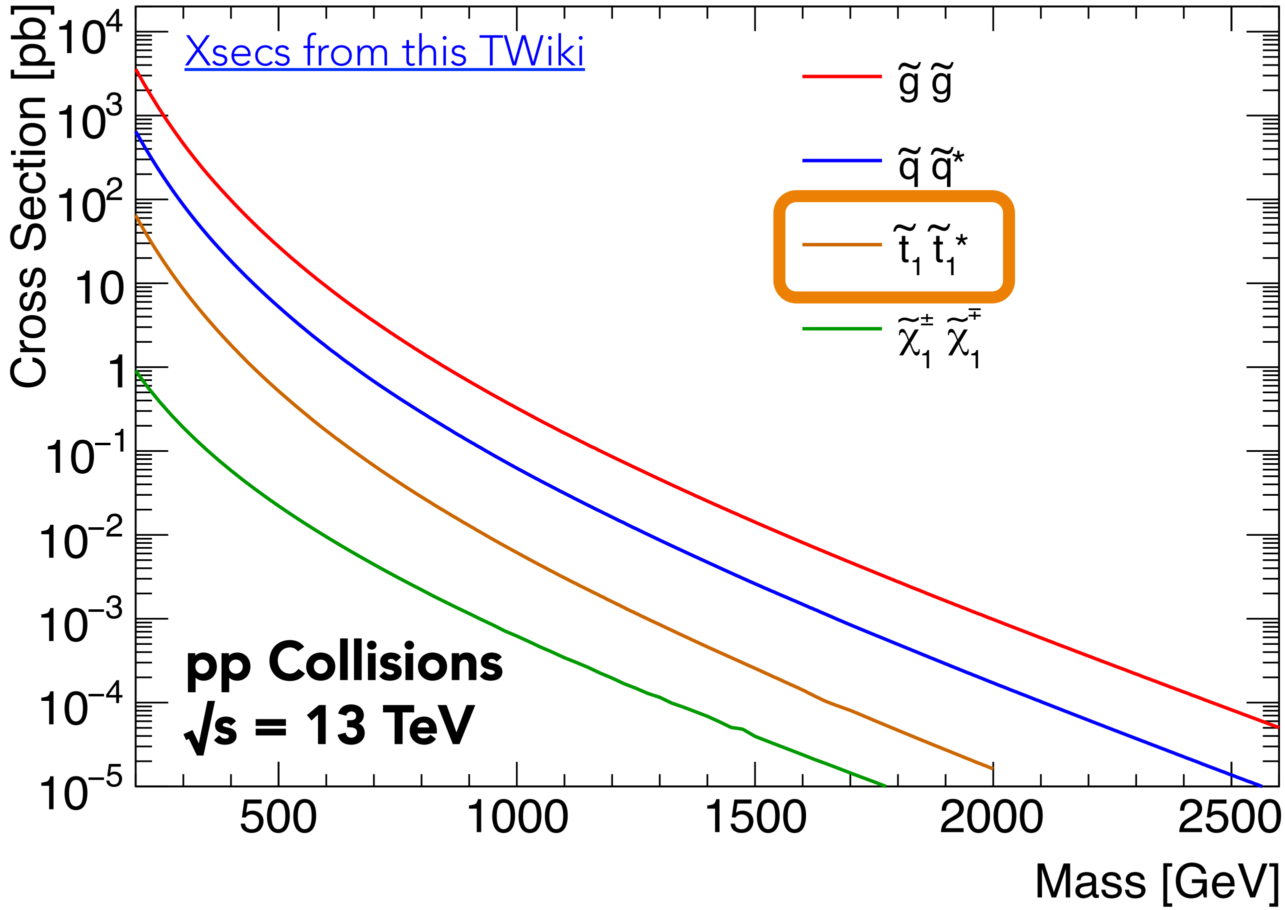
ATLAS SS/3L

- Because of the independent gluino decays, **same-sign leptons** are a powerful way to constrain strong production
  - This search targets 12 different SUSY scenarios!
- Large diboson (theory) and non-prompt lepton background uncertainties
- Good target for improvement with more data!





arXiv:1706.03731

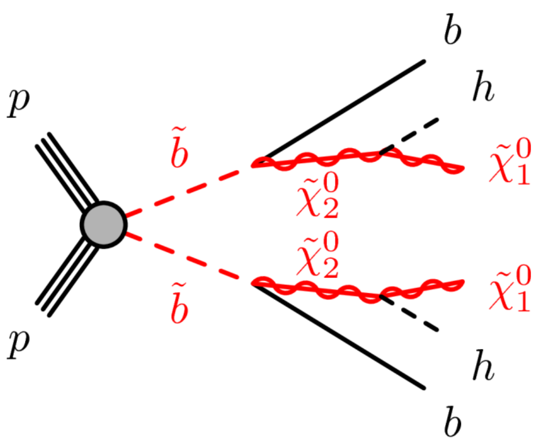


3RD GENERATION SUSY

SEARCHES WITH HEAVY-FLAVOUR JETS, MET, AND (SOMETIMES) LEPTONS

CMS Sbottom+Higgs

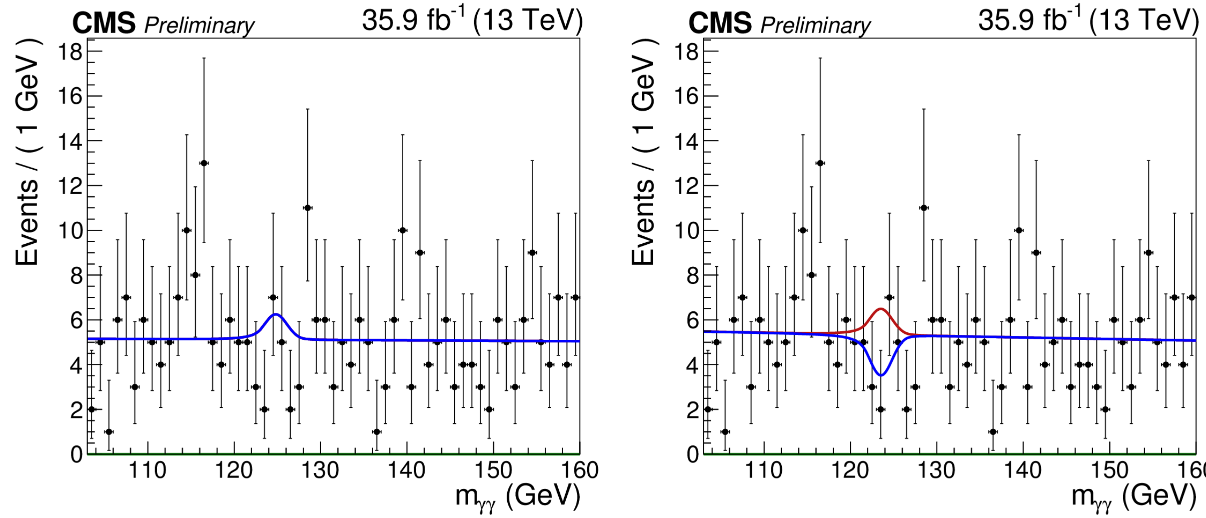
- **Higgs bosons** in the decay chain (H→γγ)
- Fitting the **diphoton mass spectrum** in many bins



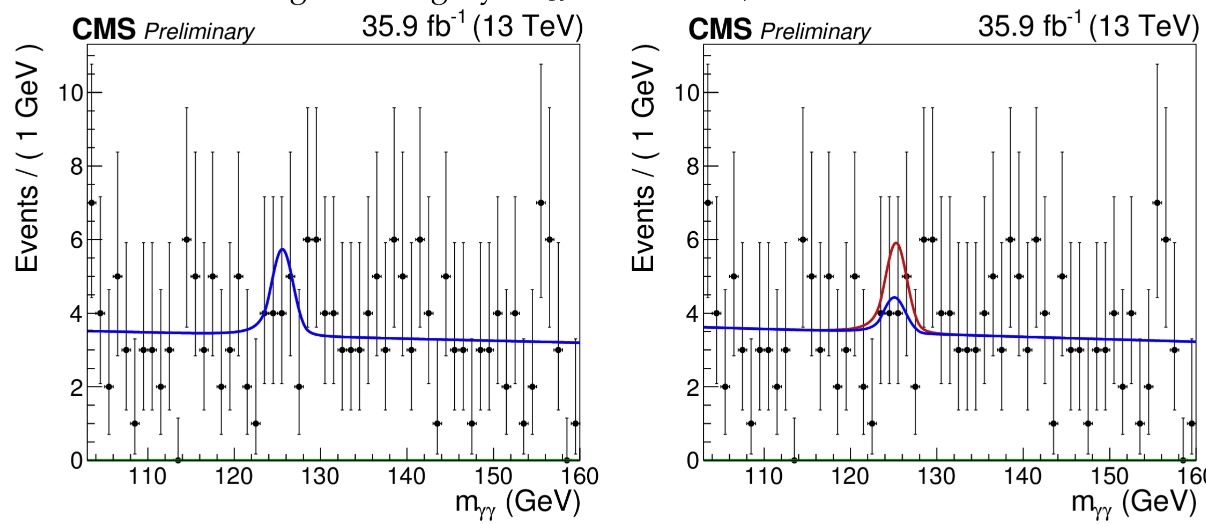
arXiv:1709.00384

Background-only / Signal+Background

HighPt Category: $150 < M_R < 600\,\text{GeV}, R^2 > 0.13$

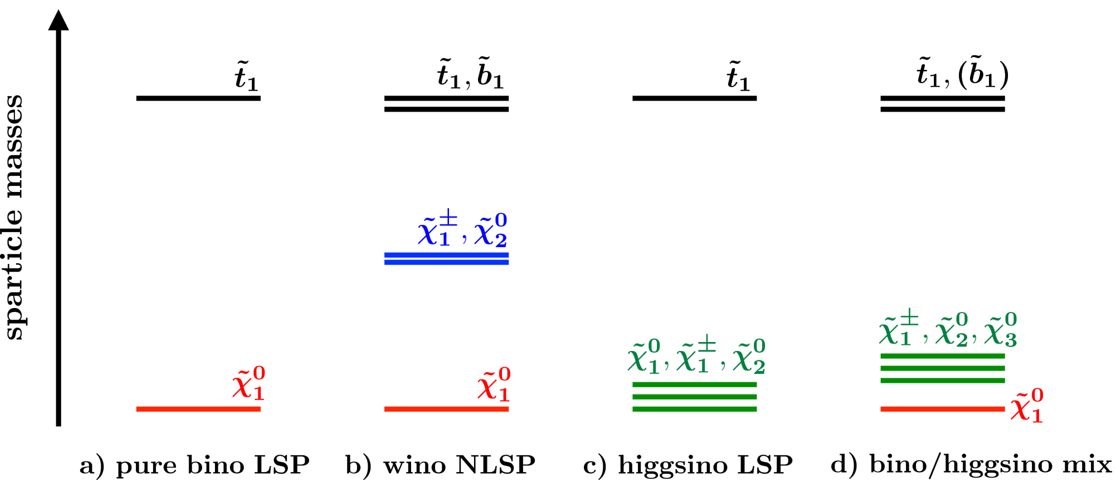


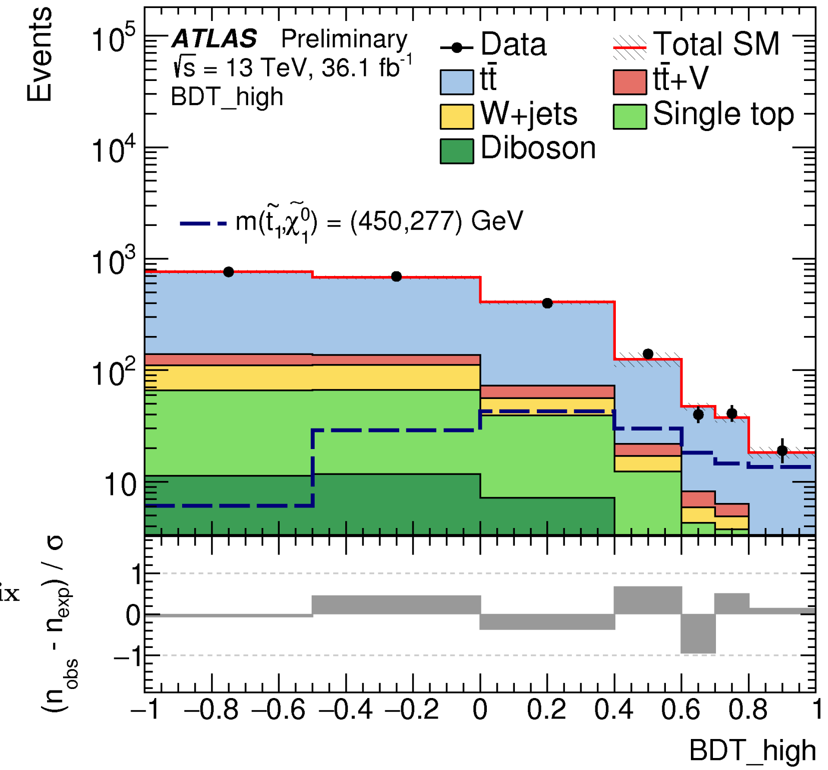
HighPt Category: $M_R > 1250\,\text{GeV}, 0 < R^2 < 0.025$



ATLAS Stop 1L

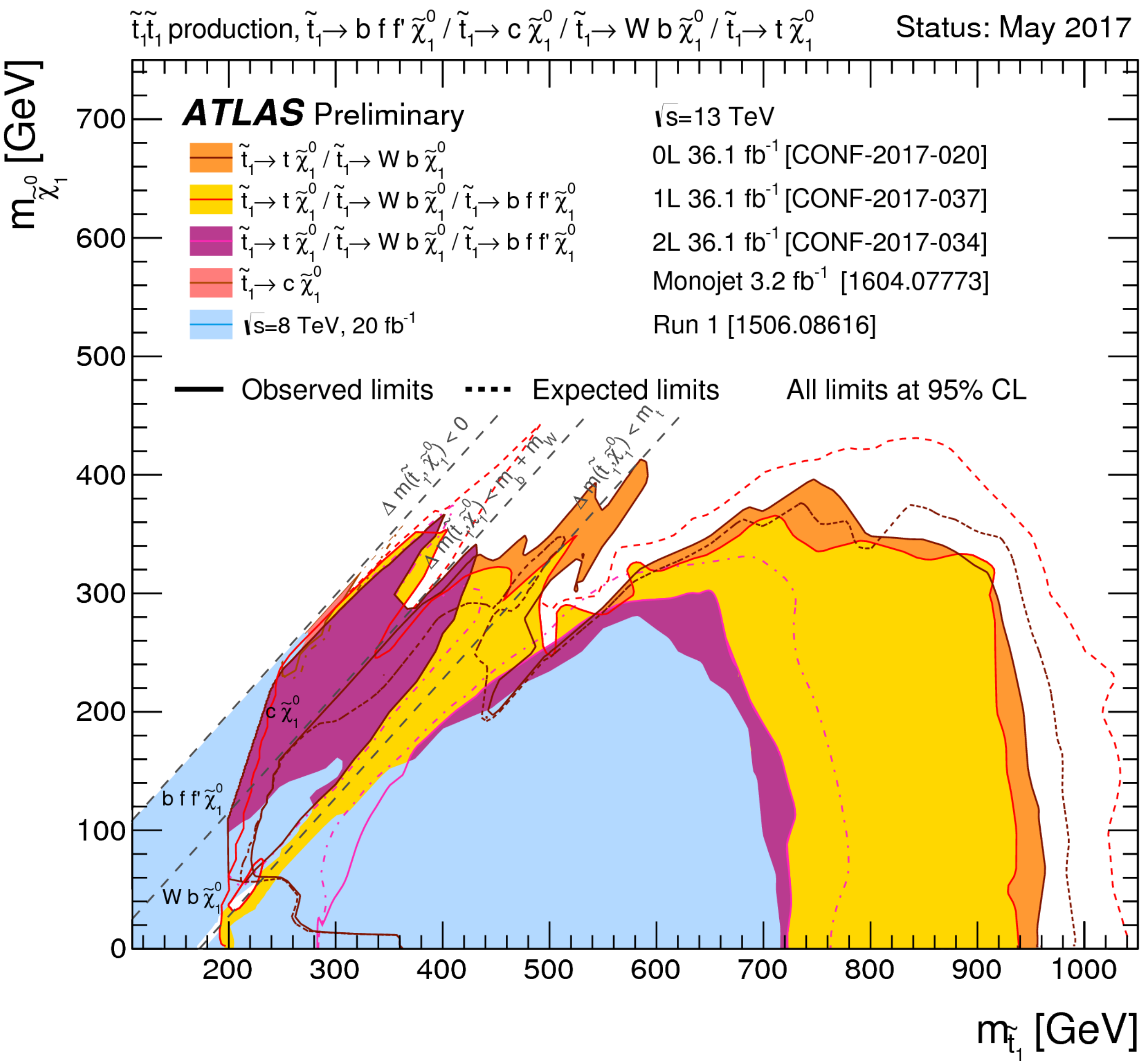
- Searching for stop in several scenarios (motivated by pMSSM)
  - Includes the first **BDT**-based SUSY analyses from ATLAS
- **Many variables** to reduce specific backgrounds
  - am_{T2}, m_T, $m_{top}^{recl.}$, $\Delta R(b,l)$, m^{τ}_{T2} (tau veto), $MET_{\perp}$, $\Delta\phi$(jet,MET), $H_{T,miss}^{sig}$



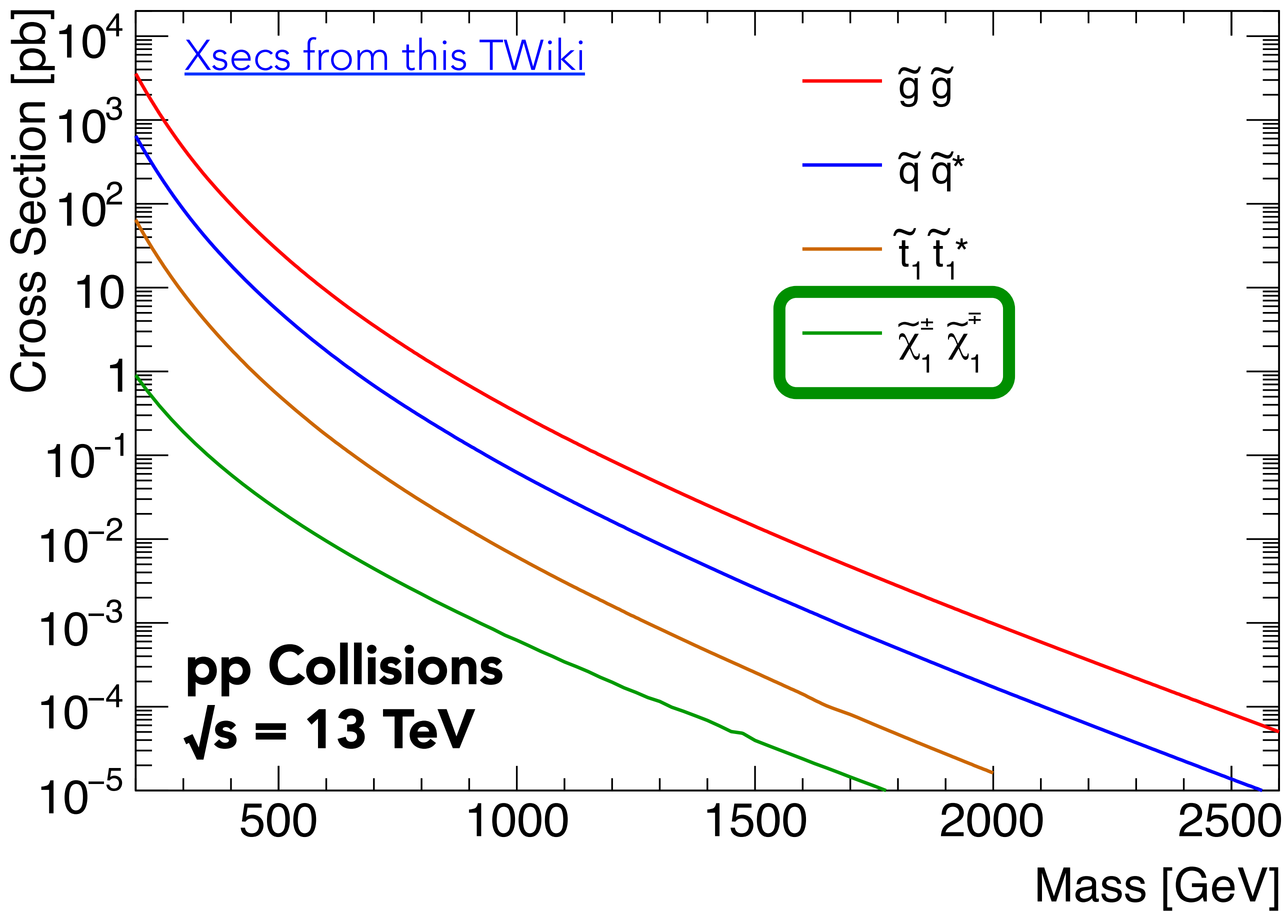


ATLAS-CONF-2017-037

ATLAS Stop Summary



- Low-mass stop phase space rapidly closing
- **Gaps** that we used to point to are **being closed** by clever tricks and new searches
- Several searches "**deepen**" the exclusion
- Expect more **combinations** in the near future

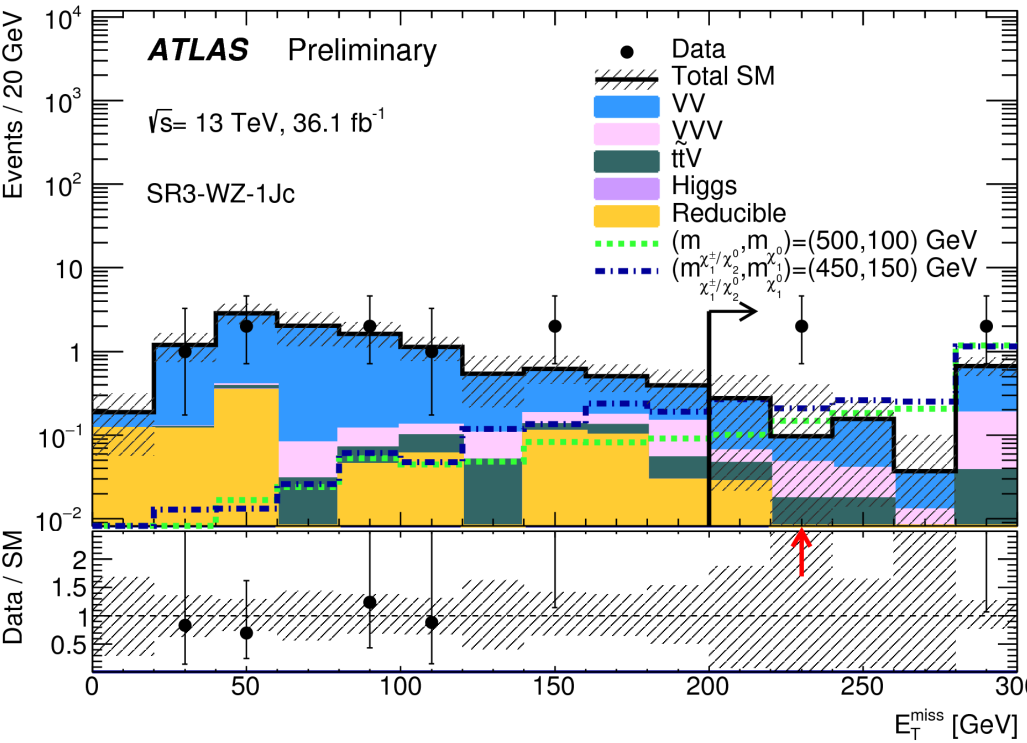


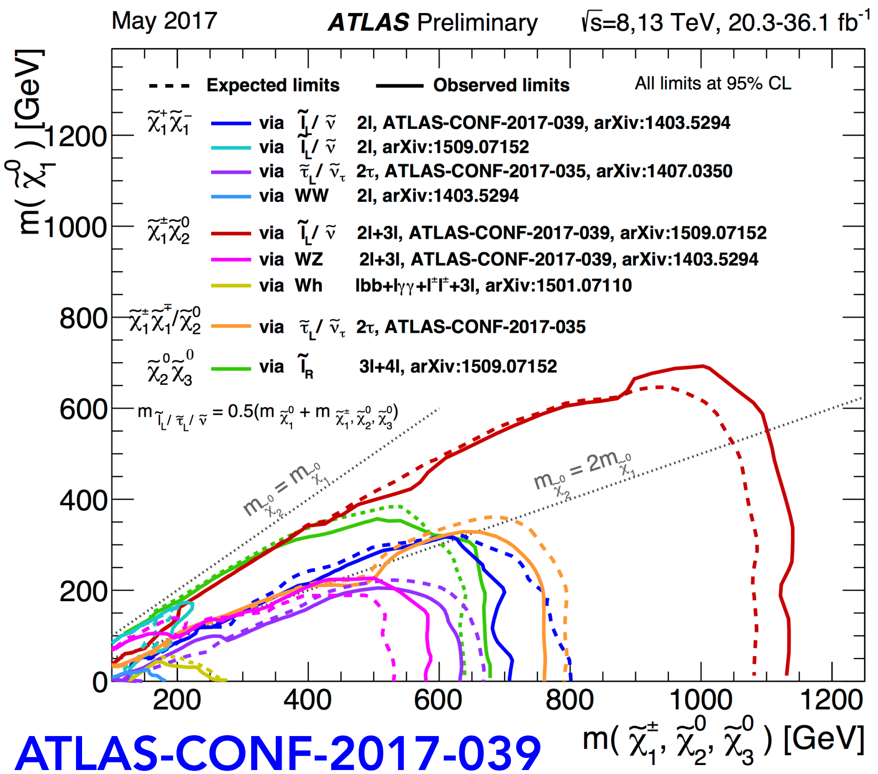
ELECTROWEAK SUSY

SEARCHES WITH MET, AND (SOMETIMES) LEPTONS, AND USUALLY WITHOUT JETS

ATLAS 2/3L Electroweak

- Search for a variety of electroweak processes
- Difficult to control detector-induced backgrounds
  - Z+jets with a jet veto and "fake" MET, jets identified as leptons
- Highest limits to date in many simplified models

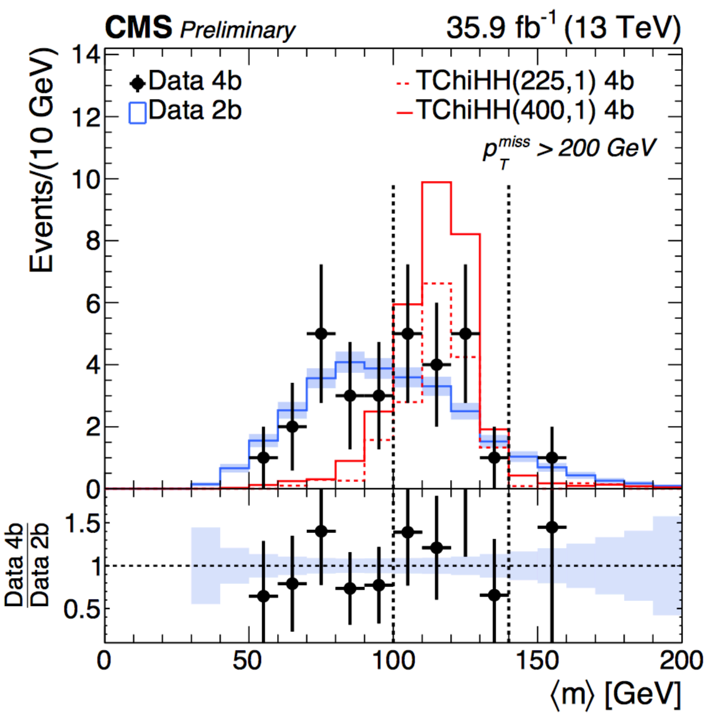


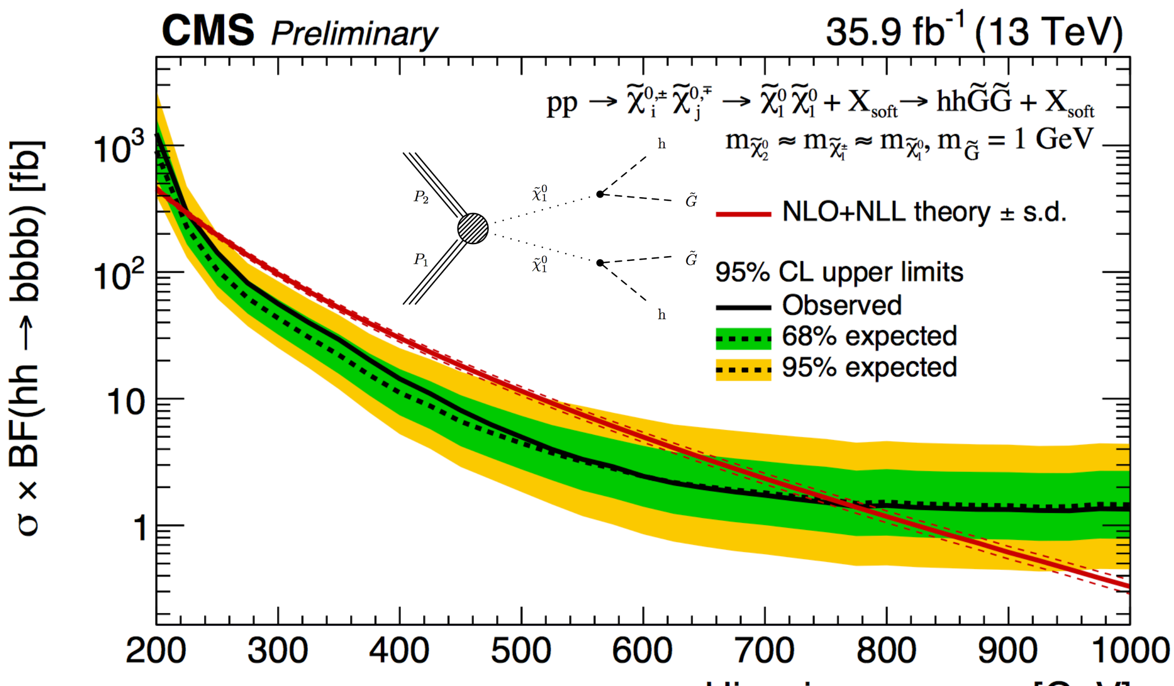


[ATLAS-CONF-2017-039]

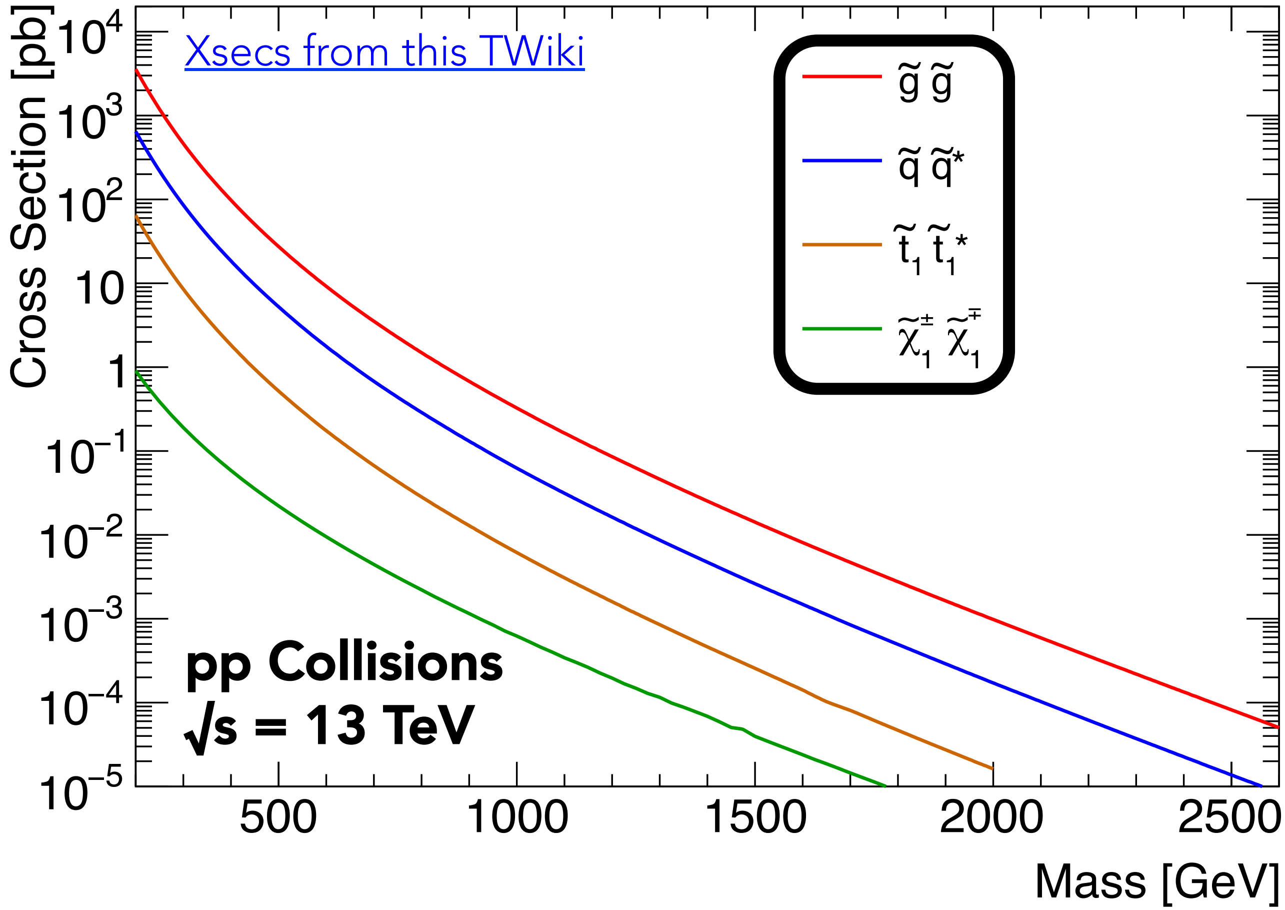
CMS Higgsino (4b)

- Higgsinos are the last (hardest) critical piece of **natural SUSY**
- Searching in **compressed scenarios** for decays to Higgs+Goldstino for MET and (up to) four b-jets using a **deep learning b-tagging algorithm**
  - Compressed scenario keeps final state but increases prod. cross section
- Excludes most interesting high-mass Higgsinos space in these scenarios
  - "Bare" Higgsino searches are still a way off, but are in progress



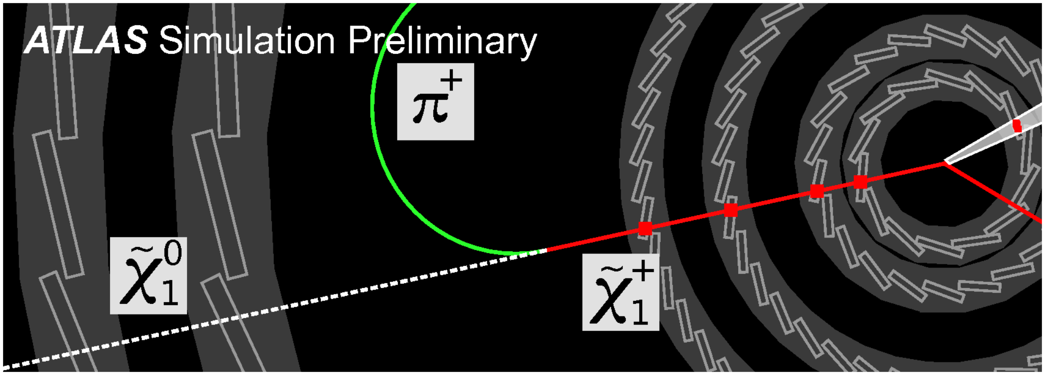


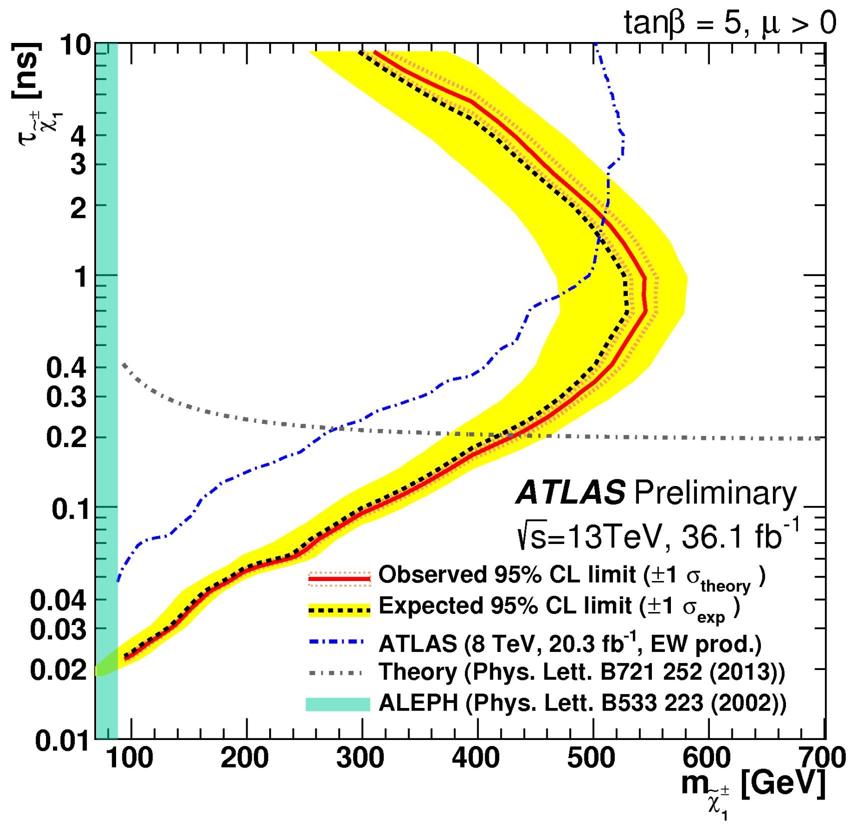
[CMS-PAS-SUS-16-044]



LONG-LIVED SUSY

ATLAS Disappearing Track



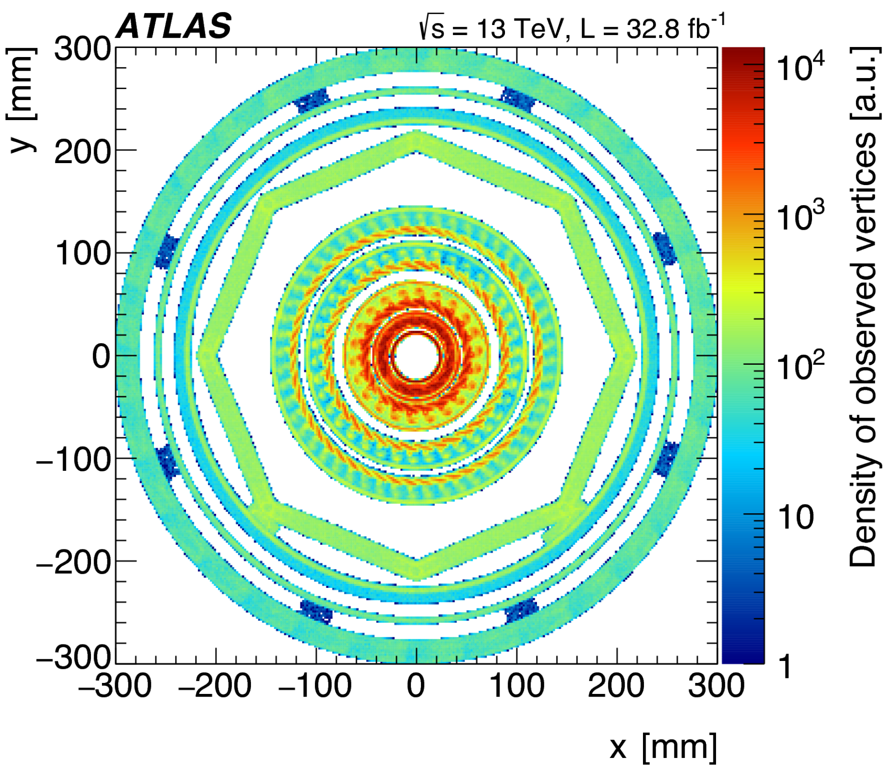


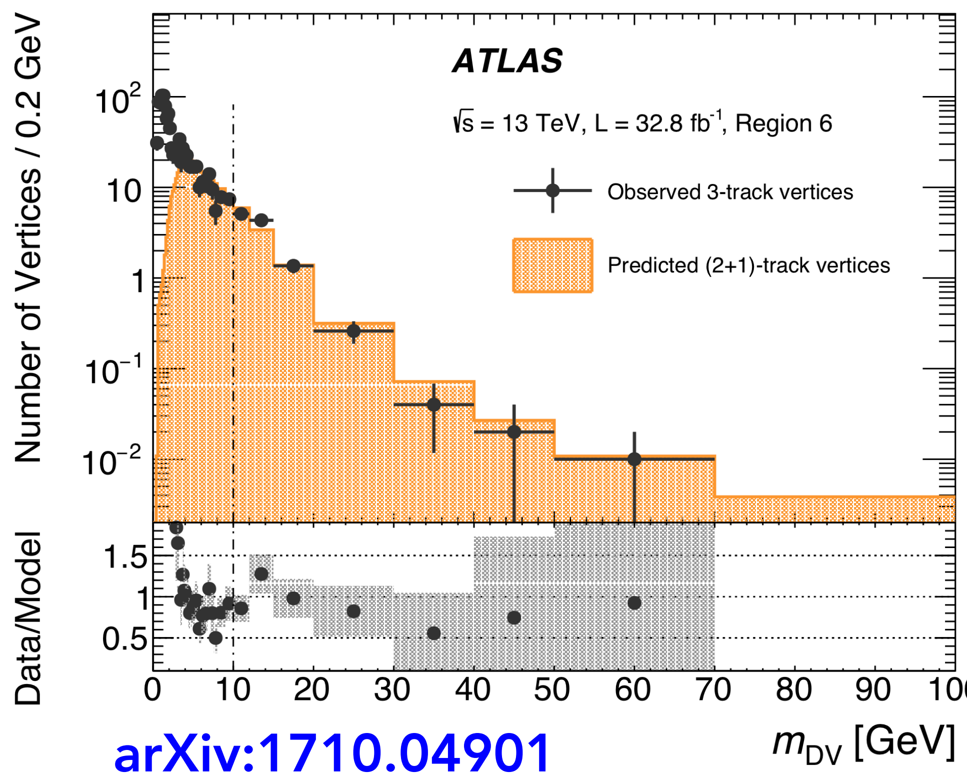
- In **highly-compressed** scenarios, common to have a 'disappearing track' type signature
  - Very common in the MSSM for Higgsino and Wino LSPs
- Small chargino-neutralino mass spliting makes **chargino long-lived**
- Extended to strong production with the chargino in a cascade

ATLAS-CONF-2017-017

ATLAS Displaced Vertex

- Search for R-hadrons (stable, hadronized squarks and gluinos) that decay in the detector
  - Demands excellent understanding of **detector material**
- Search in decay **vertex mass** and charged particle **multiplicity**
- Limits on gluinos up to 2.2 TeV (!!) for lifetimes of 0.05-1 ns

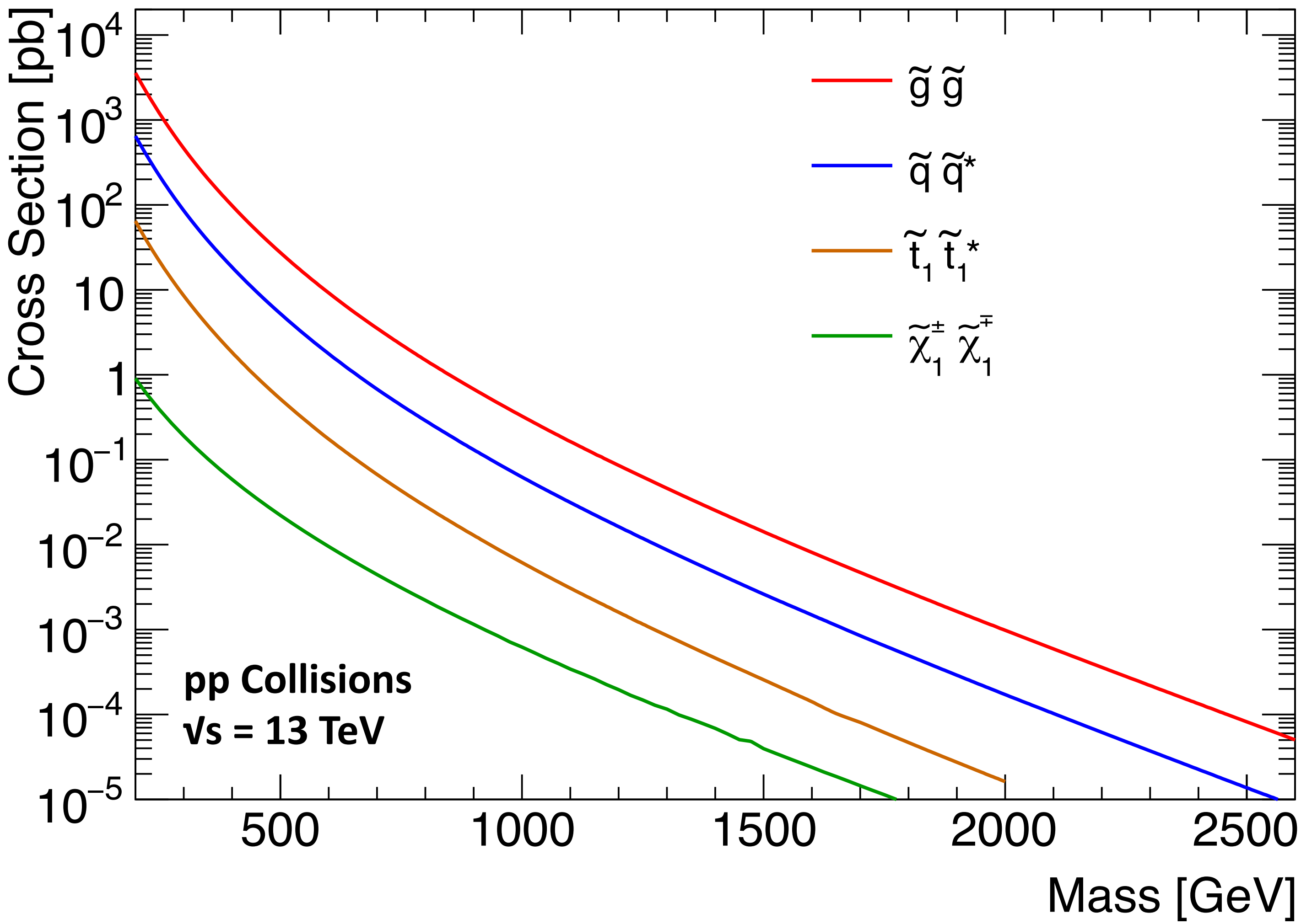




arXiv:1710.04901

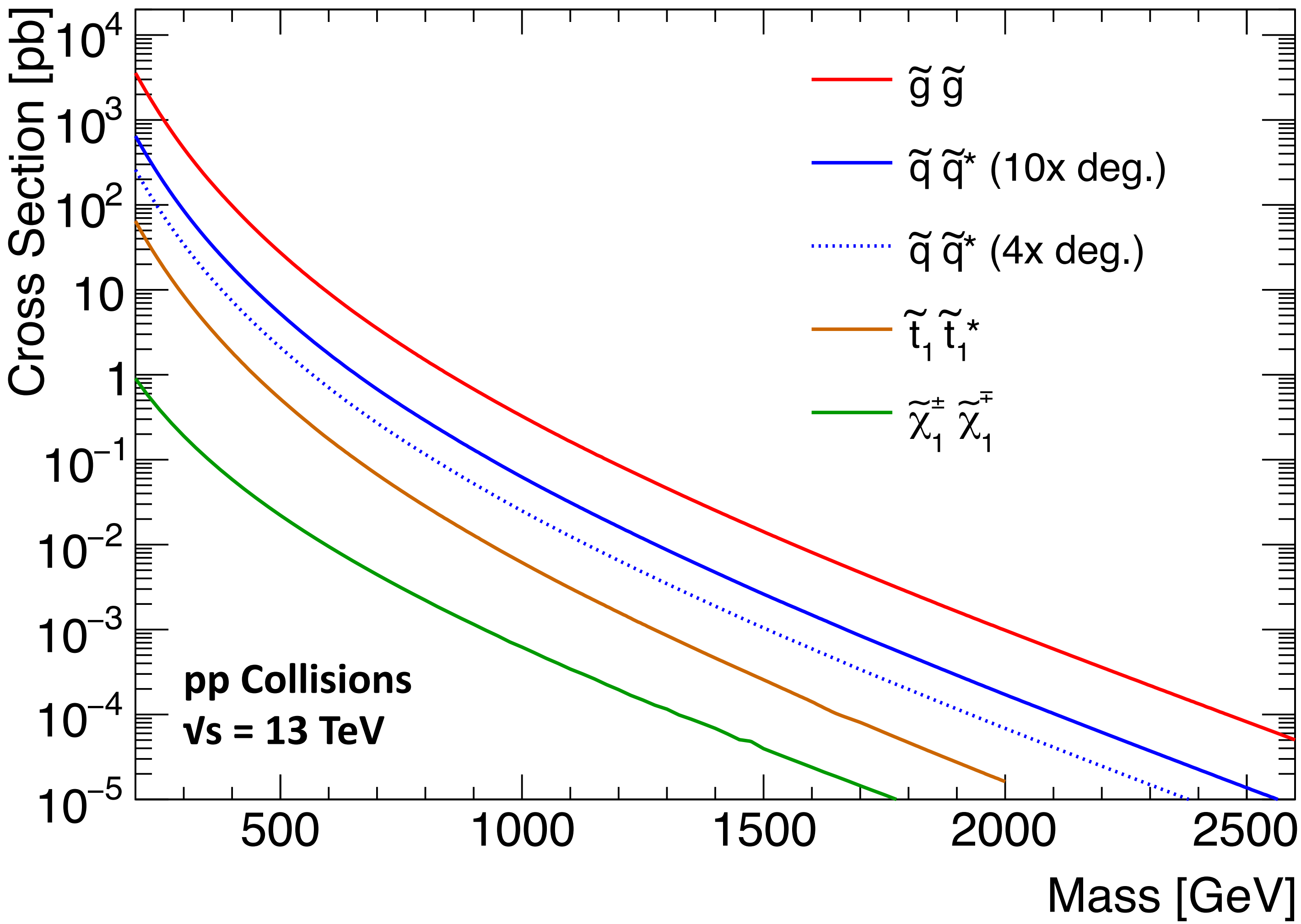
Where to Next?

- There is still a lot of work to be done!
- Many manifestations of Supersymmetry to look for



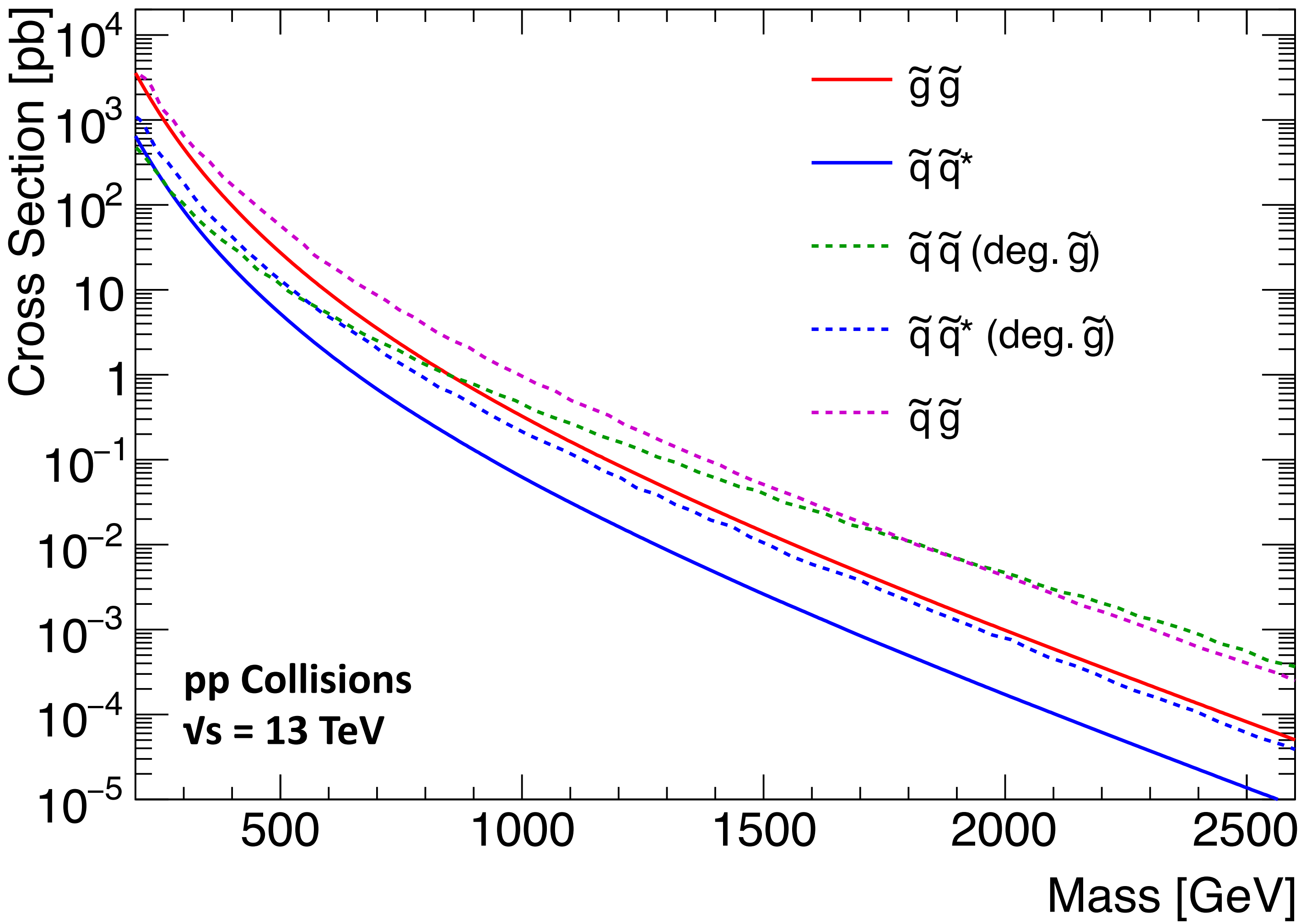
Where to Next?

- We should make our limits *deeper* at low masses!



Where to Next?

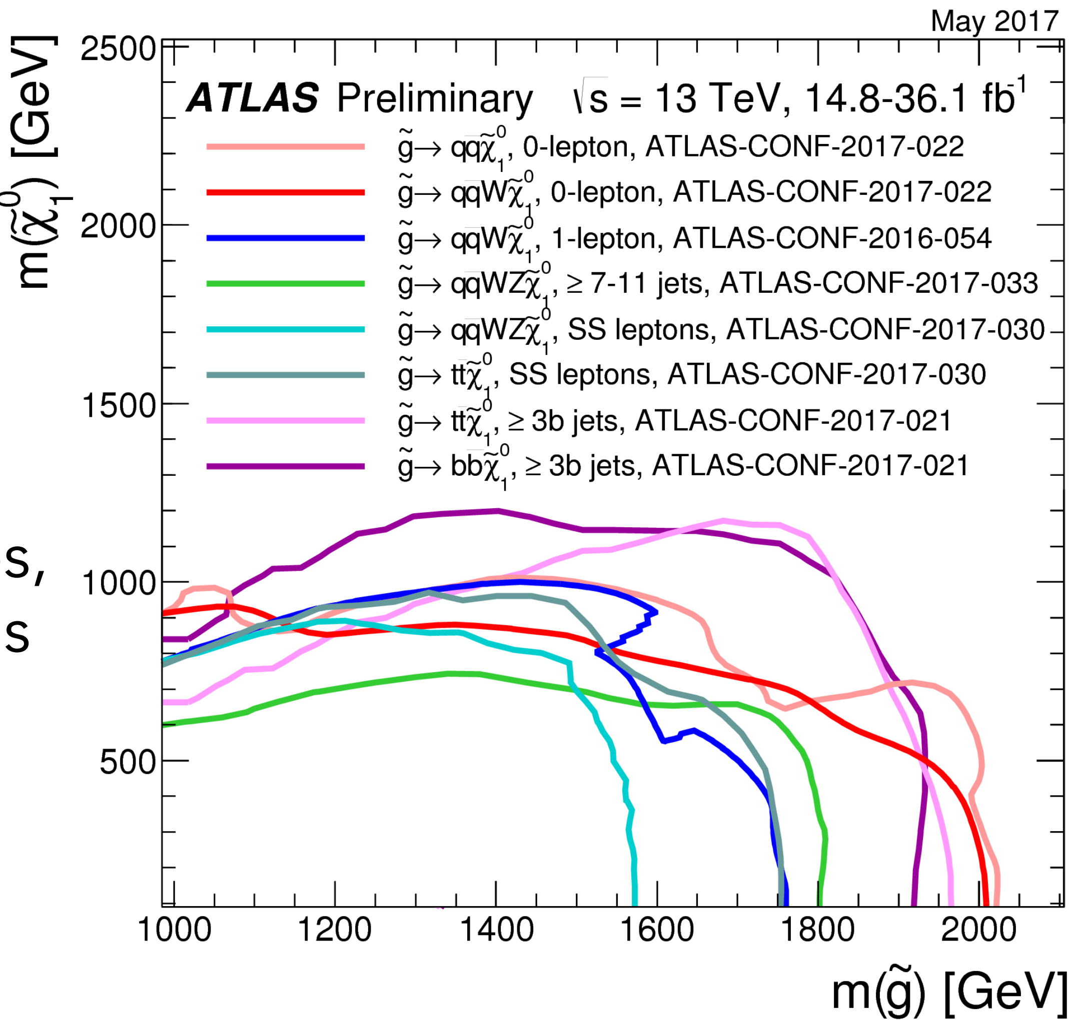
- Don't assume that adding particles makes the limit weaker, though ☺



Where to Next?

- Work on *combinations* of analyses and of simplified models

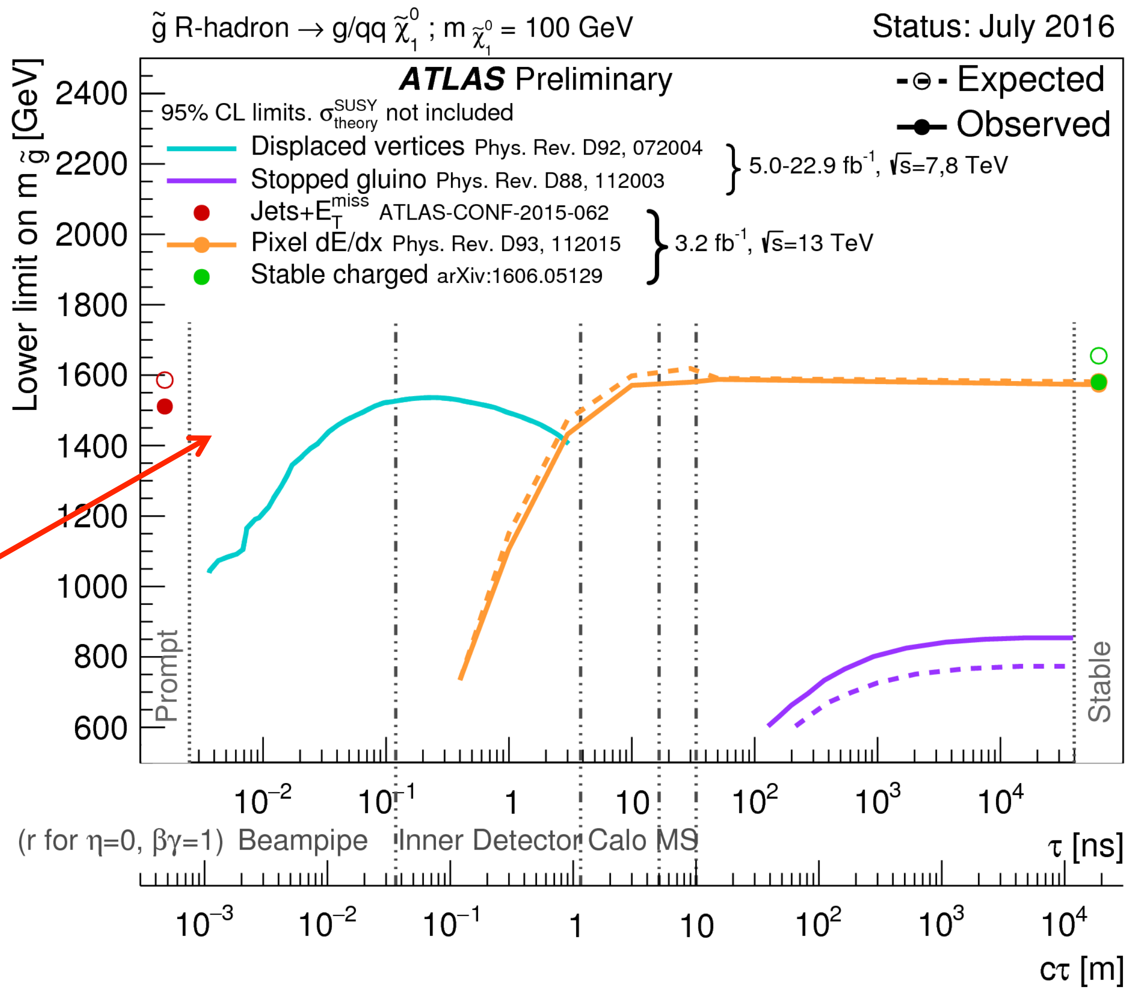
Lots of wiggles, but no obvious **holes** (yet)



Where to Next?

- Check the robustness of our limits in many dimensions, not just the obvious ones!

Not a hole



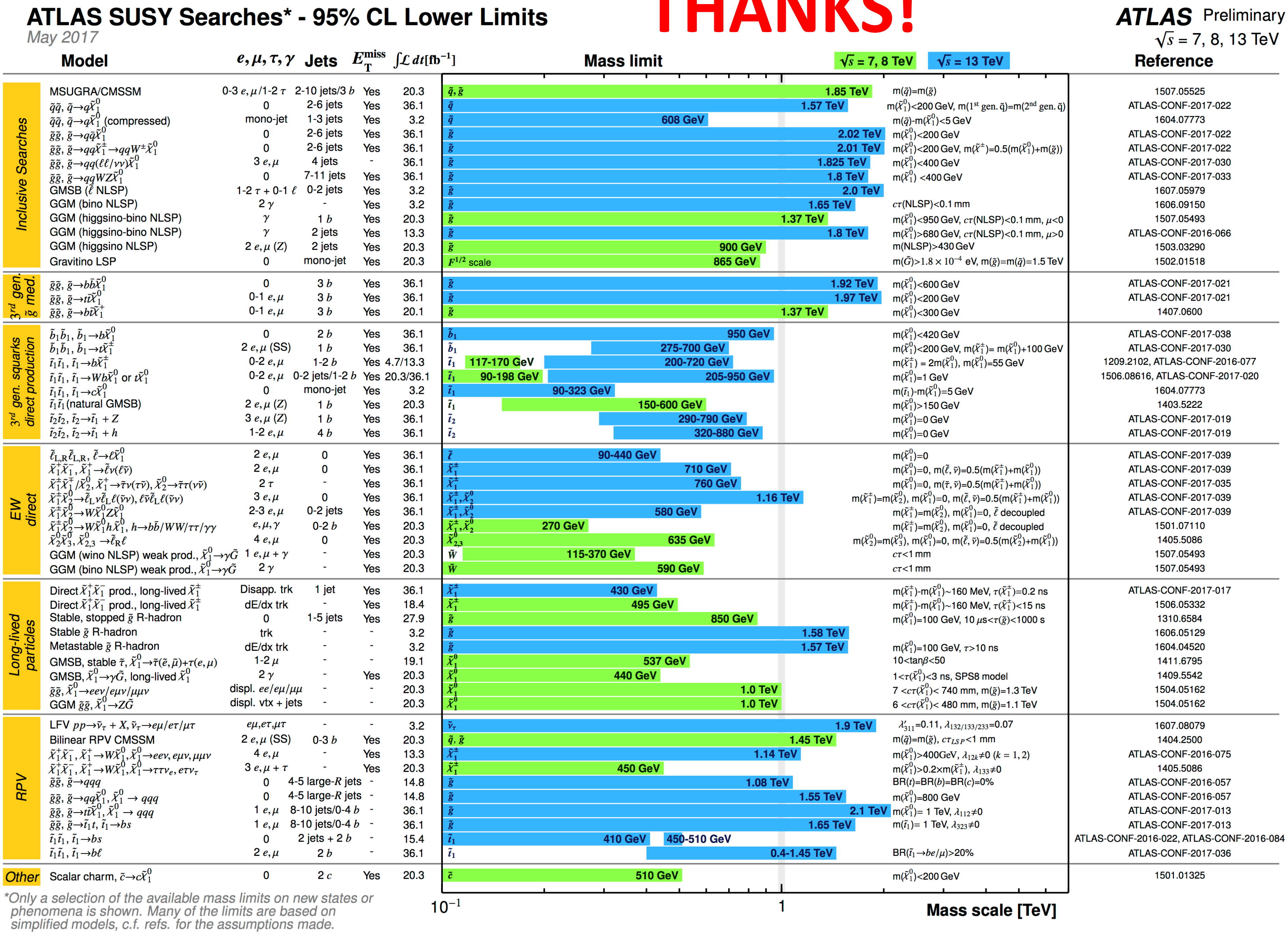
Summary

- Lots of searches! But no sign of SUSY yet
  - Consider more SUSY models that only solve *most* of our theory problems
  - Bulk of region for "natural SUSY" covered
  - But don't forget our **assumptions** and watch for **false negatives**!

Next up:

- Many more manifestations of Supersymmetry to look for
  - Make those simplified models ***less simple*** (e.g. multiple decay modes)!
  - Push into **corners** of the models where SUSY is hard to find!
  - Use the **Higgs** (properties and in our decays) and look for **Higgsinos**
- More searches for **strange-looking** and **Electroweak SUSY**
  - Displaced vertices (see extras), stopped particles, disappearing tracks…
- Start on search **combinations**
  - Find ways to beat the 'simple' statistics increases – the time for dataset doubling is getting much longer!
- Start **dreaming**
  - BDTs? NNs? CNNs? ME analysis? Imagine having your own supercomputer!

THANKS!



ATLAS SUSY Searches* - 95% CL Lower Limits
May 2017
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV
Model | e, μ, τ, γ | Jets | E_T^{miss} | $\int \mathcal{L}\, dt[fb^{-1}]$ | Mass limit | $\sqrt{s}$ = 7, 8 TeV | $\sqrt{s}$ = 13 TeV | Reference
Inclusive Searches
MSUGRA/CMSSM | 0-3 e,μ/1-2 τ | 2-10 jets/3 b | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.85 TeV | $m(\tilde{q})=m(\tilde{g})$ | 1507.05525
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{q}$ 1.57 TeV | $m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$) | ATLAS-CONF-2017-022
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | $\tilde{q}$ 608 GeV | $m(\tilde{q})-m(\tilde{\chi}_1^0)$<5 GeV | 1604.07773
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.02 TeV | $m(\tilde{\chi}_1^0)$<200 GeV | ATLAS-CONF-2017-022
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.01 TeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | ATLAS-CONF-2017-022
$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$ | 3 e,μ | 4 jets | - | 36.1 | $\tilde{g}$ 1.825 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | ATLAS-CONF-2017-030
$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 0 | 7-11 jets | Yes | 36.1 | $\tilde{g}$ 1.8 TeV | $m(\tilde{\chi}_1^0)$ <400 GeV | ATLAS-CONF-2017-033
GMSB ($\tilde{\ell}$ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 3.2 | $\tilde{g}$ 2.0 TeV | | 1607.05979
GGM (bino NLSP) | 2 γ | - | Yes | 3.2 | $\tilde{g}$ 1.65 TeV | $c\tau$(NLSP)<0.1 mm | 1606.09150
GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 20.3 | $\tilde{g}$ 1.37 TeV | $m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0 | 1507.05493
GGM (higgsino-bino NLSP) | γ | 2 jets | Yes | 13.3 | $\tilde{g}$ 1.8 TeV | $m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0 | ATLAS-CONF-2016-066
GGM (higgsino NLSP) | 2 e,μ (Z) | 2 jets | Yes | 20.3 | $\tilde{g}$ 900 GeV | m(NLSP)>430 GeV | 1503.03290
Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $F^{1/2}$ scale 865 GeV | $m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV | 1502.01518
3rd gen. $\tilde{g}$ med.
$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 36.1 | $\tilde{g}$ 1.92 TeV | $m(\tilde{\chi}_1^0)$<600 GeV | ATLAS-CONF-2017-021
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 e,μ | 3 b | Yes | 36.1 | $\tilde{g}$ 1.97 TeV | $m(\tilde{\chi}_1^0)$<200 GeV | ATLAS-CONF-2017-021
$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 e,μ | 3 b | Yes | 20.1 | $\tilde{g}$ 1.37 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 | 36.1 | $\tilde{b}_1$ 950 GeV | $m(\tilde{\chi}_1^0)$<420 GeV | ATLAS-CONF-2017-038
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$ | 2 e,μ (SS) | 1 b | Yes | 36.1 | $\tilde{b}_1$ 275-700 GeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_1^0)$+100 GeV | ATLAS-CONF-2017-030
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 0-2 e,μ | 1-2 b | Yes | 4.7/13.3 | $\tilde{t}_1$ 117-170 GeV 200-720 GeV | $m(\tilde{\chi}_1^\pm)=2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV | 1209.2102, ATLAS-CONF-2016-077
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 e,μ | 0-2 jets/1-2 b | Yes | 20.3/36.1 | $\tilde{t}_1$ 90-198 GeV 205-950 GeV | $m(\tilde{\chi}_1^0)$=1 GeV | 1506.08616, ATLAS-CONF-2017-020
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet | Yes | 3.2 | $\tilde{t}_1$ 90-323 GeV | $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$=5 GeV | 1604.07773
$\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 e,μ (Z) | 1 b | Yes | 20.3 | $\tilde{t}_1$ 150-600 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 | 36.1 | $\tilde{t}_2$ 290-790 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2017-019
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$ | 1-2 e,μ | 4 b | Yes | 36.1 | $\tilde{t}_2$ 320-880 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2017-019
EW direct
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 e,μ | 0 | Yes | 36.1 | $\tilde{\ell}$ 90-440 GeV | $m(\tilde{\chi}_1^0)$=0 | ATLAS-CONF-2017-039
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 e,μ | 0 | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 710 GeV | $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ | ATLAS-CONF-2017-039
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$ | 2 τ | - | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 760 GeV | $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ | ATLAS-CONF-2017-035
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 e,μ | 0 | Yes | 36.1 | $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 1.16 TeV | $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ | ATLAS-CONF-2017-039
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$ | 2-3 e,μ | 0-2 jets | Yes | 36.1 | $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 580 GeV | $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled | ATLAS-CONF-2017-039
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$ | e,μ,γ | 0-2 b | Yes | 20.3 | $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 270 GeV | $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ 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 | $\tilde{\chi}_{2,3}^0$ 635 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
GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$ | 1 $e,\mu+\gamma$ | - | Yes | 20.3 | $\tilde{W}$ 115-370 GeV | $c\tau$<1 mm | 1507.05493
GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$ | 2 γ | - | Yes | 20.3 | $\tilde{W}$ 590 GeV | $c\tau$<1 mm | 1507.05493
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 430 GeV | $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns | ATLAS-CONF-2017-017
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | dE/dx trk | - | Yes | 18.4 | $\tilde{\chi}_1^\pm$ 495 GeV | $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns | 1506.05332
Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | $\tilde{g}$ 850 GeV | $m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s | 1310.6584
Stable $\tilde{g}$ R-hadron | trk | - | - | 3.2 | $\tilde{g}$ 1.58 TeV | | 1606.05129
Metastable $\tilde{g}$ R-hadron | dE/dx trk | - | - | 3.2 | $\tilde{g}$ 1.57 TeV | $m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns | 1604.04520
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 | $\tilde{\chi}_1^0$ 440 GeV | 1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to eev/e\mu v/\mu\mu v$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV | 1504.05162
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$ | displ. vtx + jets | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV | 1504.05162
RPV
LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | - | - | 3.2 | $\tilde{\nu}_\tau$ 1.9 TeV | λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079
Bilinear RPV CMSSM | 2 e,μ (SS) | 0-3 b | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.45 TeV | $m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm | 1404.2500
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to eev, e\mu v, \mu\mu v$ | 4 e,μ | - | Yes | 13.3 | $\tilde{\chi}_1^\pm$ 1.14 TeV | $m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2) | ATLAS-CONF-2016-075
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau v_e, e\tau v_\tau$ | 3 $e,\mu+\tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 450 GeV | $m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$ | 1405.5086
$\tilde{g}\tilde{g}, \tilde{g}\to qqq$ | 0 | 4-5 large-R jets | - | 14.8 | $\tilde{g}$ 1.08 TeV | BR(t)=BR(b)=BR(c)=0% | ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$ | 0 | 4-5 large-R jets | - | 14.8 | $\tilde{g}$ 1.55 TeV | $m(\tilde{\chi}_1^0)$=800 GeV | ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$ | 1 e,μ | 8-10 jets/0-4 b | - | 36.1 | $\tilde{g}$ 2.1 TeV | $m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$ | ATLAS-CONF-2017-013
$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$ | 1 e,μ | 8-10 jets/0-4 b | - | 36.1 | $\tilde{g}$ 1.65 TeV | $m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$ | ATLAS-CONF-2017-013
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | 0 | 2 jets + 2 b | - | 15.4 | $\tilde{t}_1$ 410 GeV 450-510 GeV | | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$ | 2 e,μ | 2 b | - | 36.1 | $\tilde{t}_1$ 0.4-1.45 TeV | BR($\tilde{t}_1\to be/\mu$)>20% | ATLAS-CONF-2017-036
Other
Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2 c | Yes | 20.3 | $\tilde{c}$ 510 GeV | $m(\tilde{\chi}_1^0)$<200 GeV | 1501.01325
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.