Experimental challenges for SUSY (and other new physics) searches at the LHC13/14

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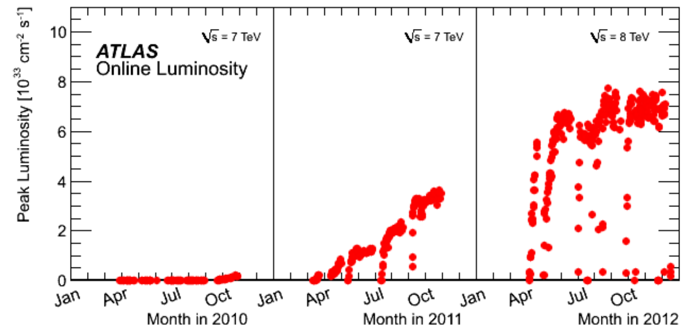
(disclaimer: most plots from ATLAS, but CMS results are equally beautiful)

LHC Run 2: starting out from a very successful Run 1

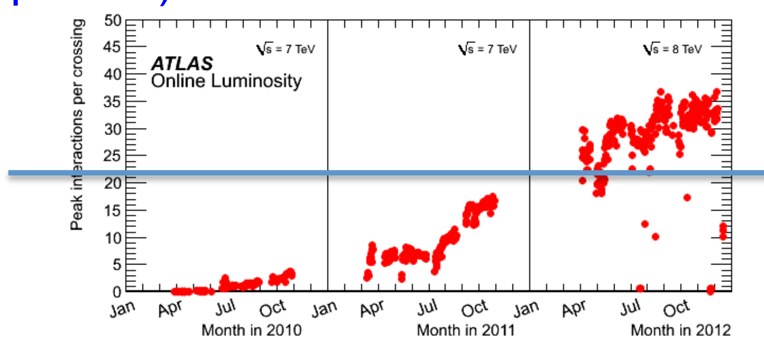


Big effort paid off

LHC worked beautifully (modulo 2008 accident)
- luminosity already almost nominal
- machine behaves as in simulation: understood
- experimental backgrounds generally low
- few issues: UFOs, SEU, 25 ns electron cloud, beam induced heating

ATLAS p-p run: April-Sept. 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.3	99.5	97.0	99.6	99.9	99.8	99.9	99.9	99.7	99.2
All good for physics: 93.7%										

Experiments performed very well
- >95% of channels work
- >93% of delivered lumi on tape
- operating in pile-up conditions worse than expected
- resolutions basically as designed
- amount of material in detector well known
- detector simulations pretty accurate (but not perfect)
- able to trigger at higher rates than foreseen,
  and selecting the right events
- data analysis model and GRID work



GREAT PHYSICS RESULTS

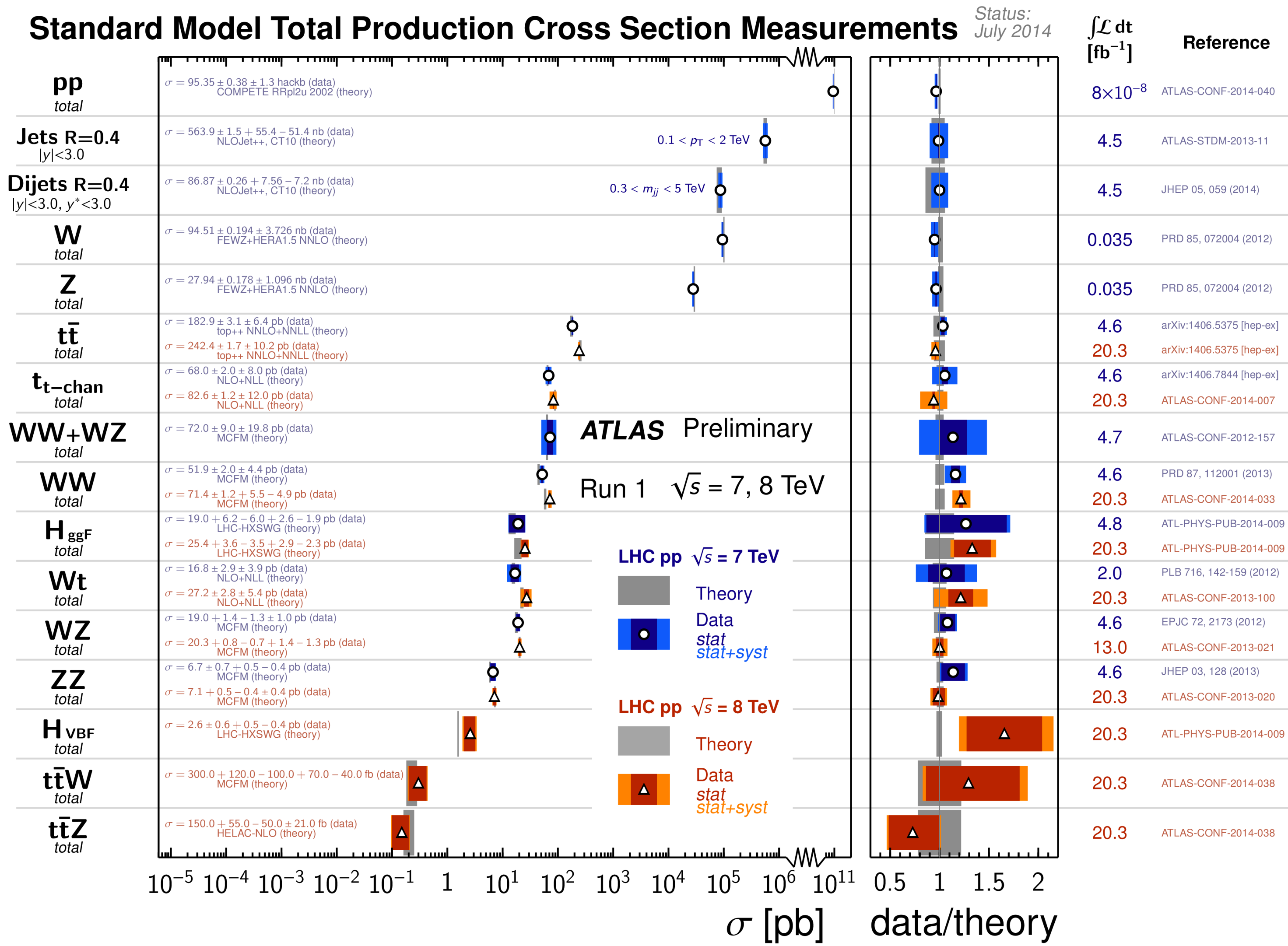
GREAT PHYSICS RESULTS

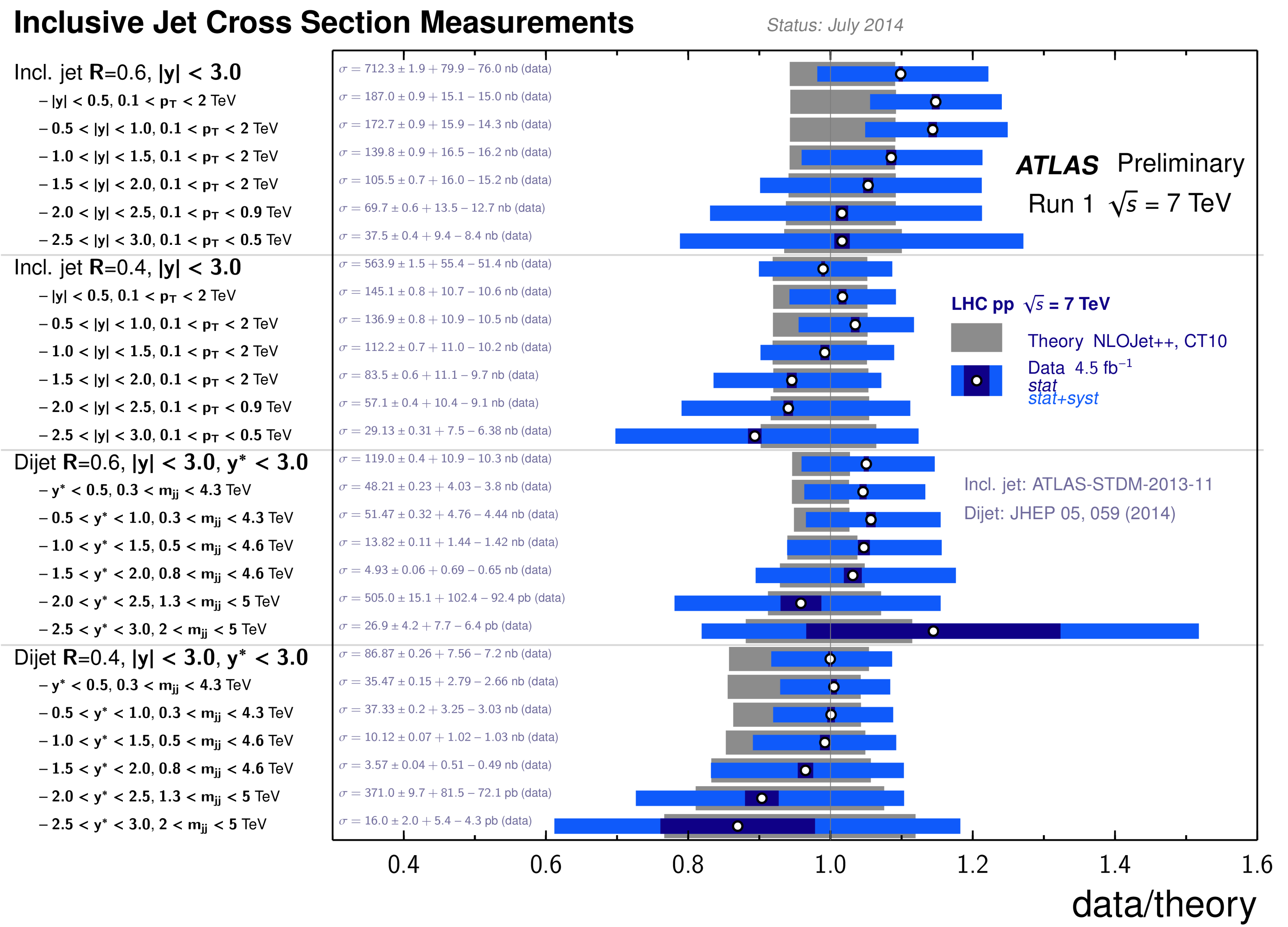
Discovery of a new scalar boson at 125 GeV in the Higgs search

SM Cross Sections

again a triumph for the SM

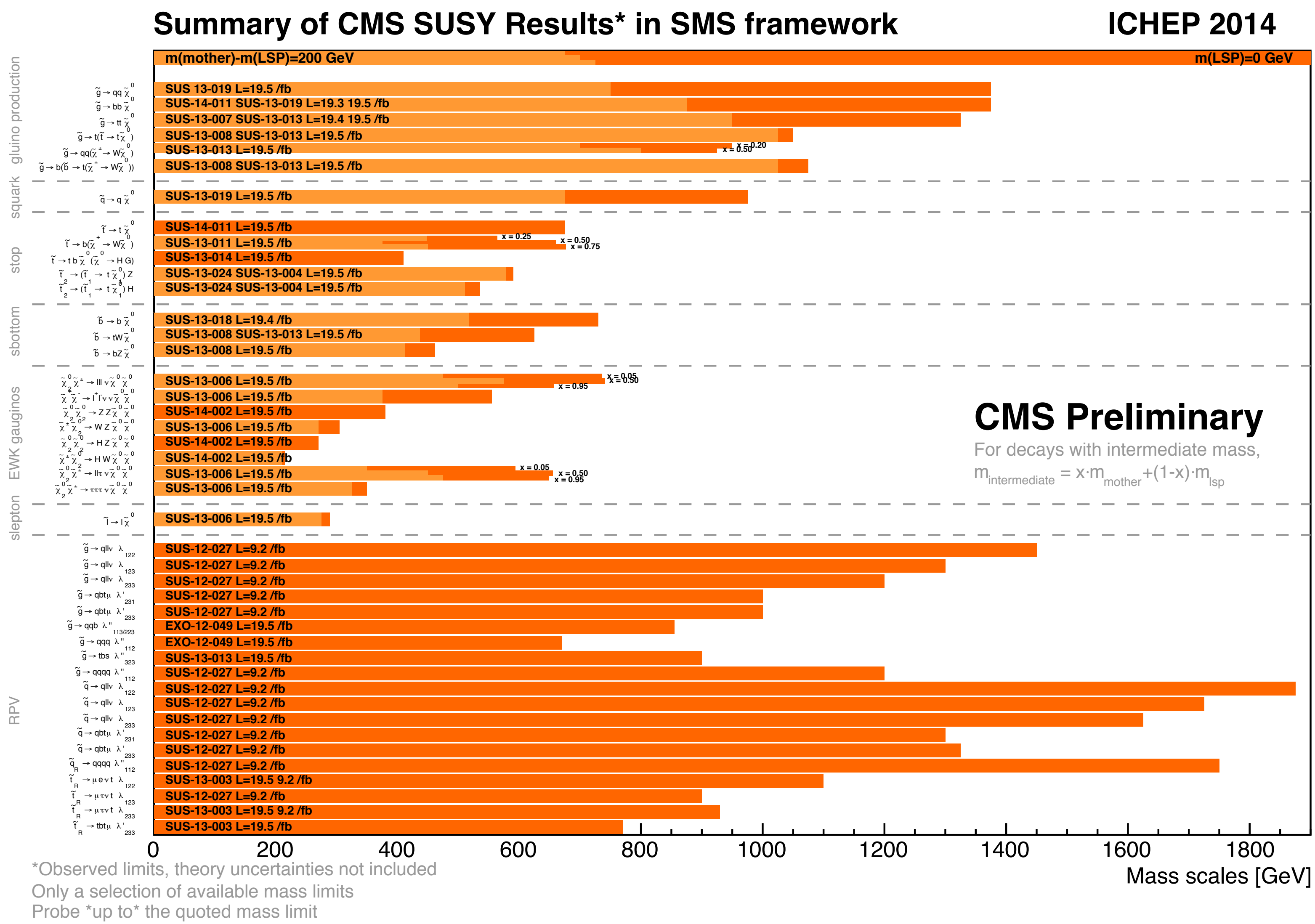
and for advanced theory calculations!





Who would have expected this before the LHC started?
Theory calculations with jets: (at least) NLO + PS matching is the standard

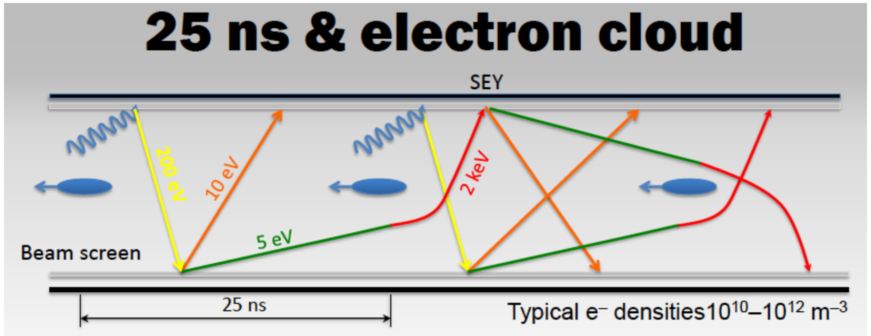
But no new physics, despite huge efforts



With significant consequences for BSM theories
Some despair here and there, but certainly premature

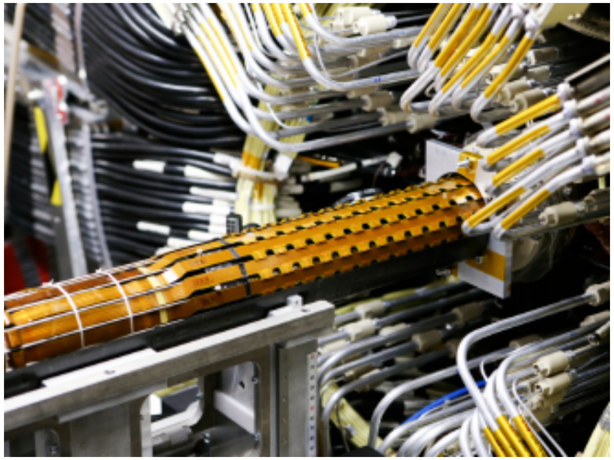
The first challenge of Run 2 will be to do as good, or better

LHC: new energy
should move from 50ns to 25ns
worry about electron cloud



Detectors: some recommissioning involved
CMS: new muon chambers, HCAL photodetectors, trigger/DAQ
ATLAS: new layer of pixels, muon chambers, trigger/DAQ

Some early pioneers have left
(moved on in their career)
Need to build a new pool of experts



Expectations:

1 fb^{-1} for EPS Vienna? (still 50 ns operation)
3 fb^{-1} for lepton-photon Ljubljana? (but very uncertain, 25 ns will be tried)
15 fb^{-1} by the end of the year?

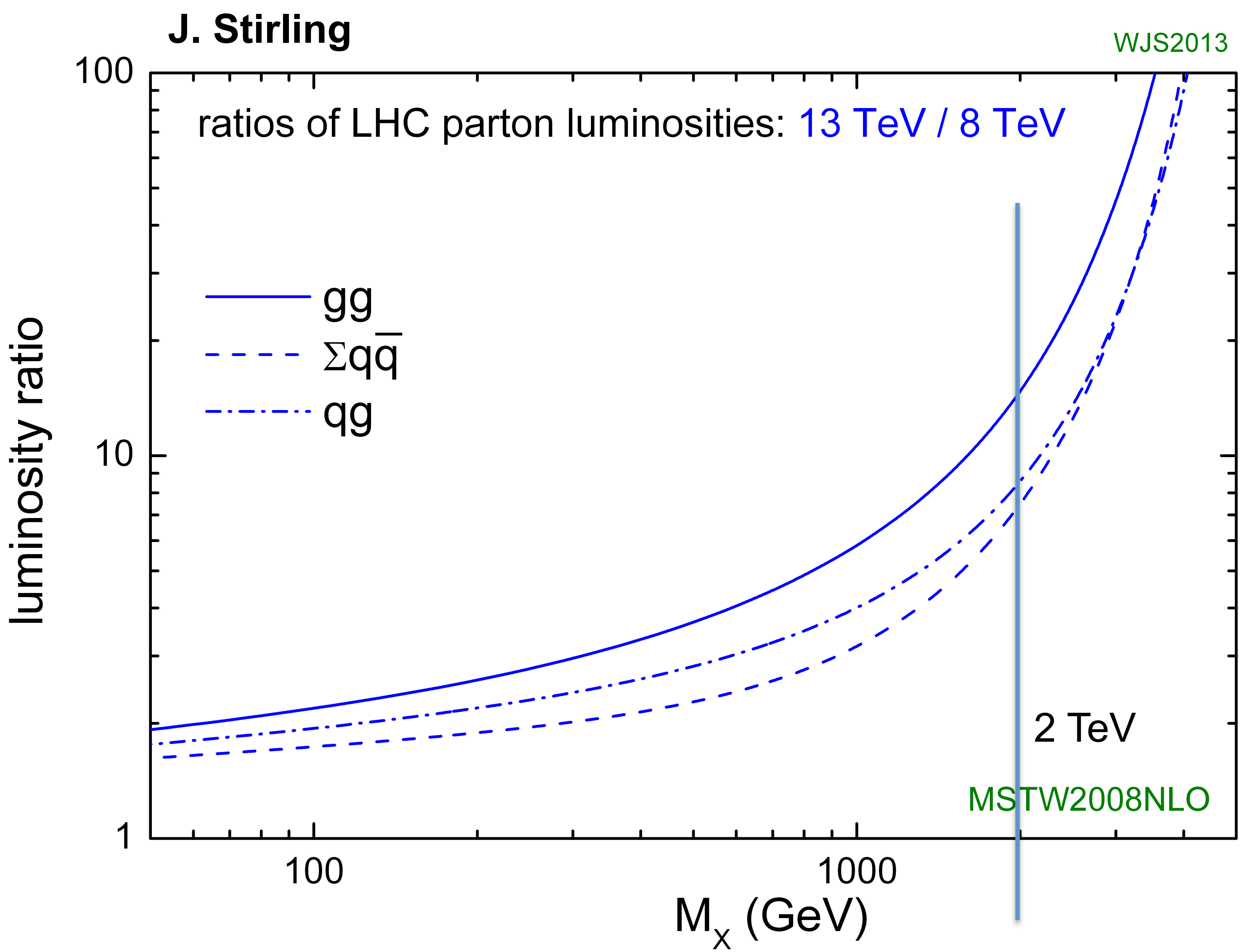
The 125 GeV scalar boson will determine the research program quite a bit

Some BSM aspects:

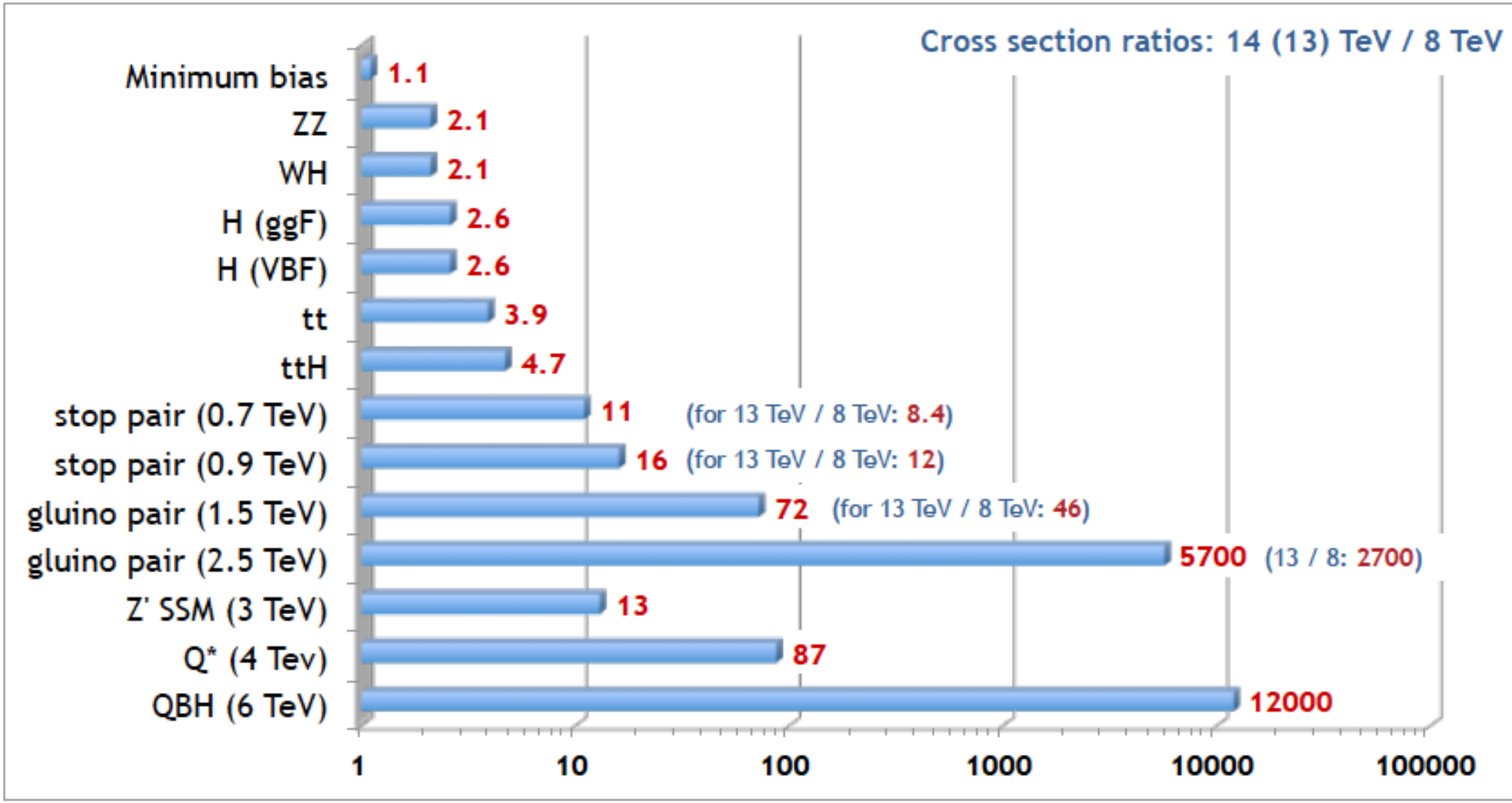
- is it elementary or composite ?
- are there multiple Higgs bosons?   Doublets? Singlets?
- couplings SM-like or not?
- does it regularize WW scattering or not?
- production by top-loops in ggF, or new vector-like quarks?
- is it a portal to dark matter?
- is the electroweak phase transition related to matter/antimatter asymmetry?
- is it related to inflation?
- are there non-SM production or decay mechanisms?
  (e.g. neutralino2 → higgs + neutralino1)

But the search for heavy new particles profits more from the higher $\sqrt{s}$

Higher √s very important for search for heavy particles

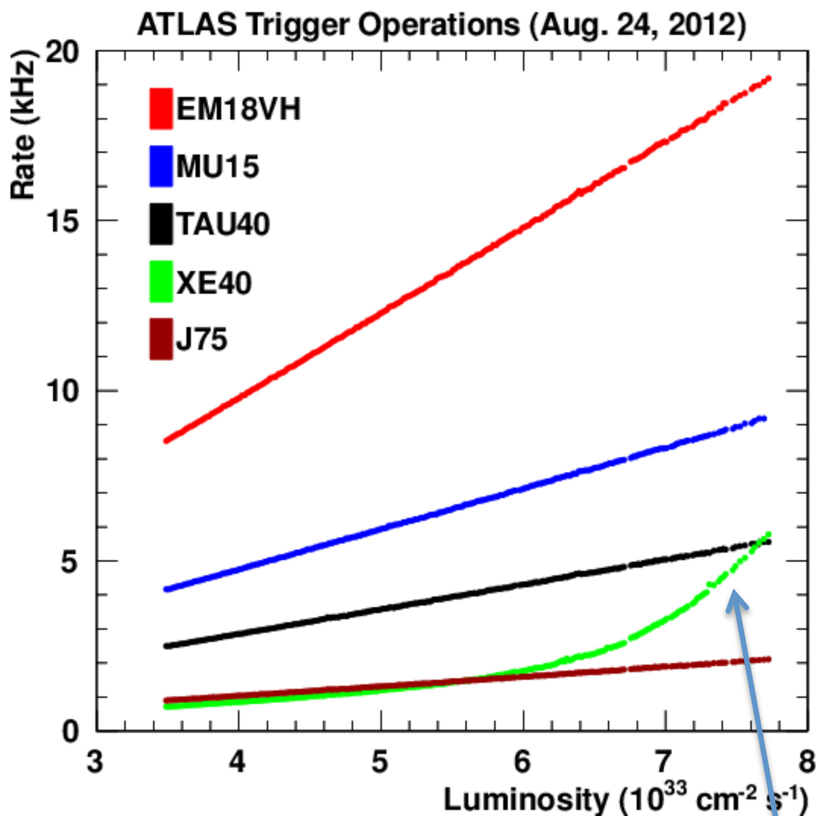


Hugely increased potential for discovery of heavy particles at 13~14 TeV

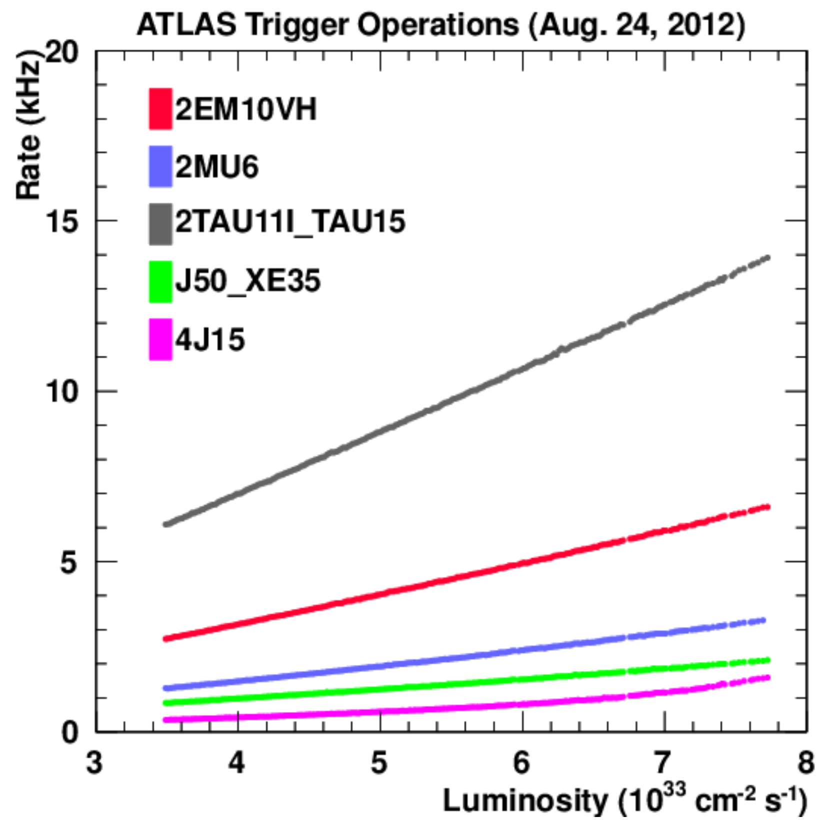


A. Höcker

Trigger challenge



single object triggers



multi-object triggers

missing ET trigger: non-linear behaviour due to pile-up

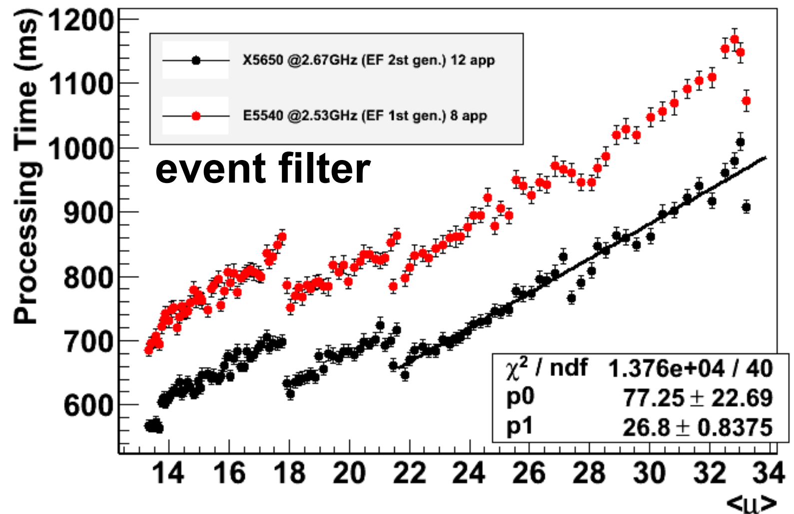
13 TeV: higher cross sections
higher trigger rates: x 1.5-2 for leptons
x 2-3 for photons
x 4 or more for jets, MET

target instantaneous luminosity x 2 → rates x 2

Acceptable L1-accept rate 100 kHz
Only single lepton triggers would saturate bandwidth already
Something must be done!

Lots of activities in CMS & ATLAS
new calibration methods, noise reduction,
pile-up reduction
new and faster algorithms
topological trigger at level-1
Rate to tape 400 Hz → 1 kHz

2012: too slow!



Expect only modest increase in single object trigger thresholds
More emphasis on multi-object triggers, use of topology in L1 trigger

Excellent new ideas in 2012:
data scouting, parked/delayed triggers

Challenges specific to SUSY (and new physics) searches

Not knowing the right underlying physics model:
a huge range of possible different final states: where do we look?

Heavy particles: cross sections are very small
Effects show up in the tail of distributions

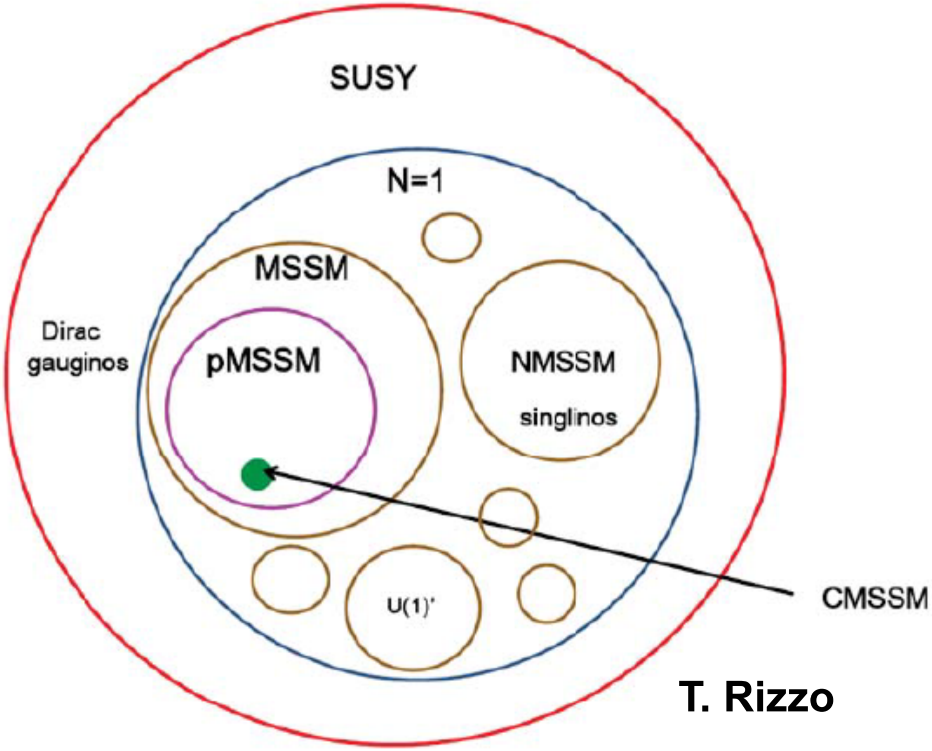
or: they could be light with small mass gaps
Hidden in background, or untriggerable

or: very peculiar final states
probably triggerable, but trigger needs to be designed

SM backgrounds need to be understood and modeled well

Where do we look?

The possibilities
are endless



T. Rizzo

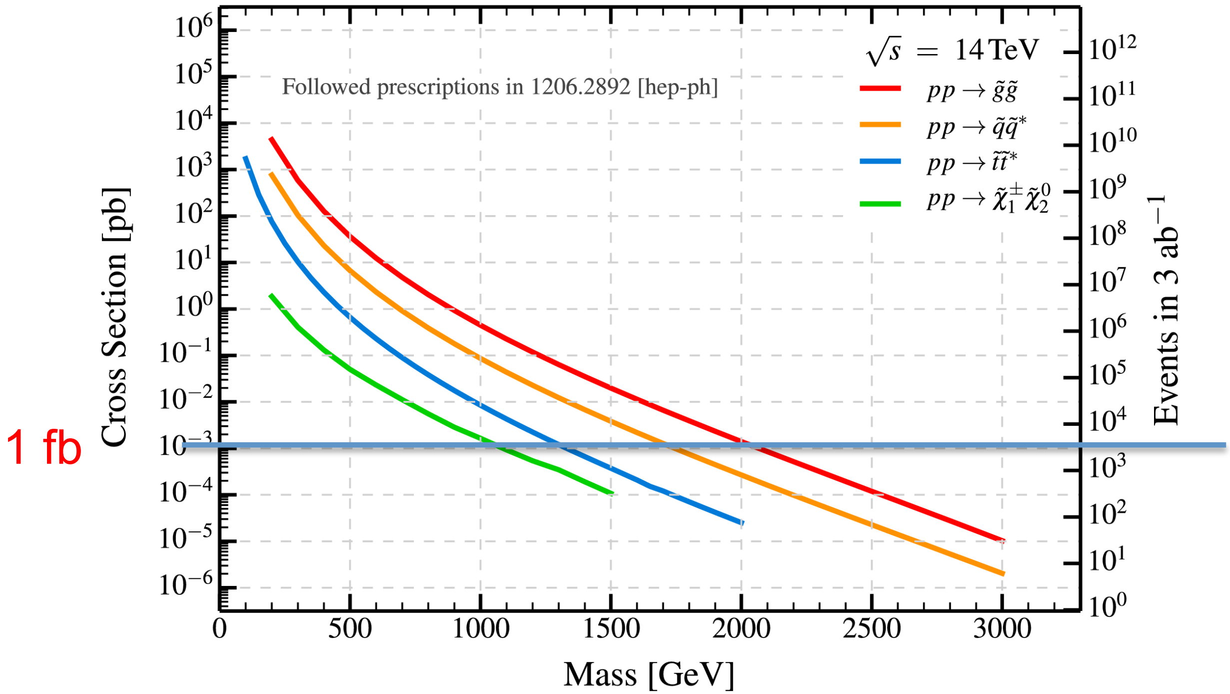
We have a lamp post called LHC

It is easy to look under the light, but more fun to look far away from the light

Theory motivations like naturalness are good to have, but will never dictate the program

We try what we can (but there are priorities)

Cross sections: low cross sections determine the limits at high M_{susy}



Most of the limits at high mass are simply due to running out of events

But: another ingredient: mass splittings

squark

LSP

0

soft jets & leptons
little MET

BAD for trigger
LOTS of background

EASY **HARD**

Background modeling

Pure MC

For rare processes where detector simulation can be trusted
e.g.: diboson, triboson, ttbar+W/Z   uncertainties ≥ 50%
Still OK now, may become a problem for very rare signals

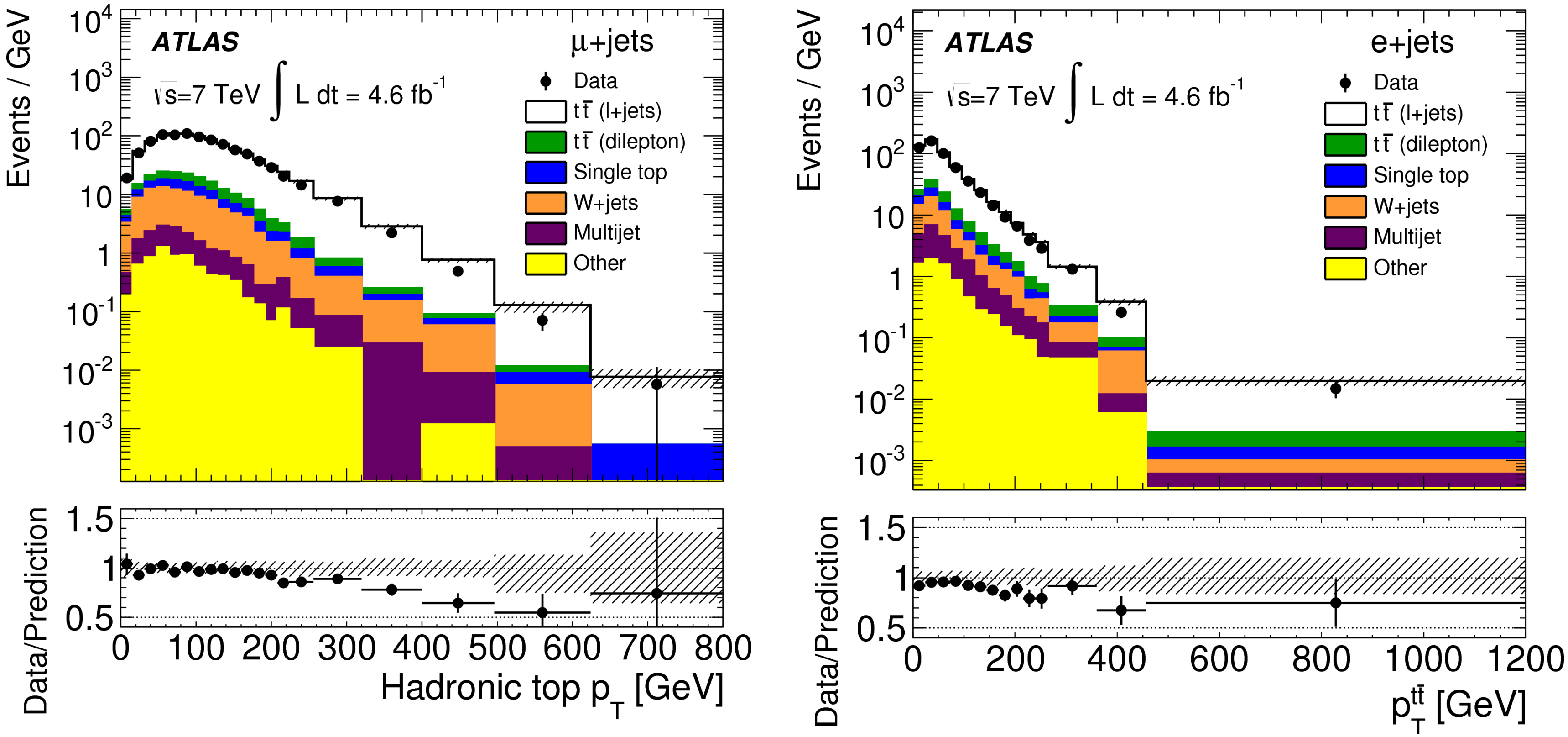
MC+data mix (semi data-driven)

take MC distribution but scale it to data in a control region (CR)
even better: correct MC shape using control region
transfer CR→SR →systematic uncertainty
send message to MC authors if MC/data disagree

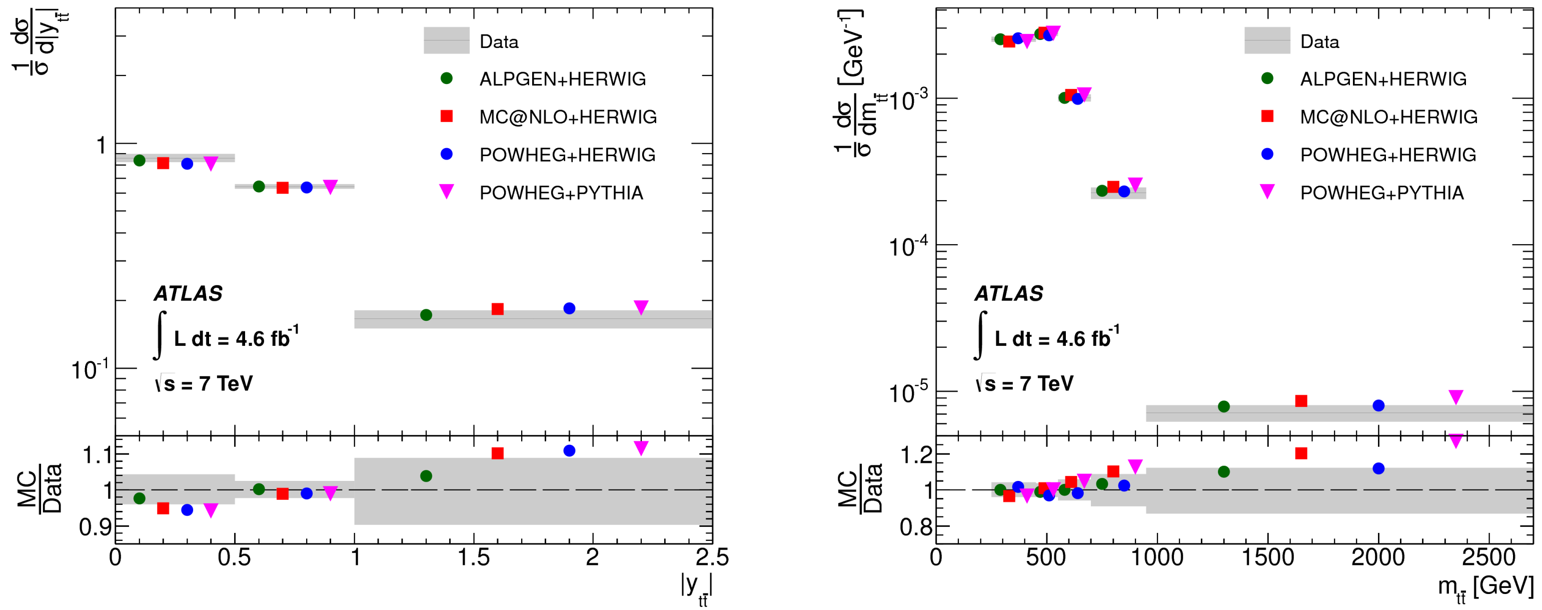
Fully data-driven

Large backgrounds like multi-jets
Or difficult to simulate: jets faking leptons
Preferable but not always easy, limited statistics

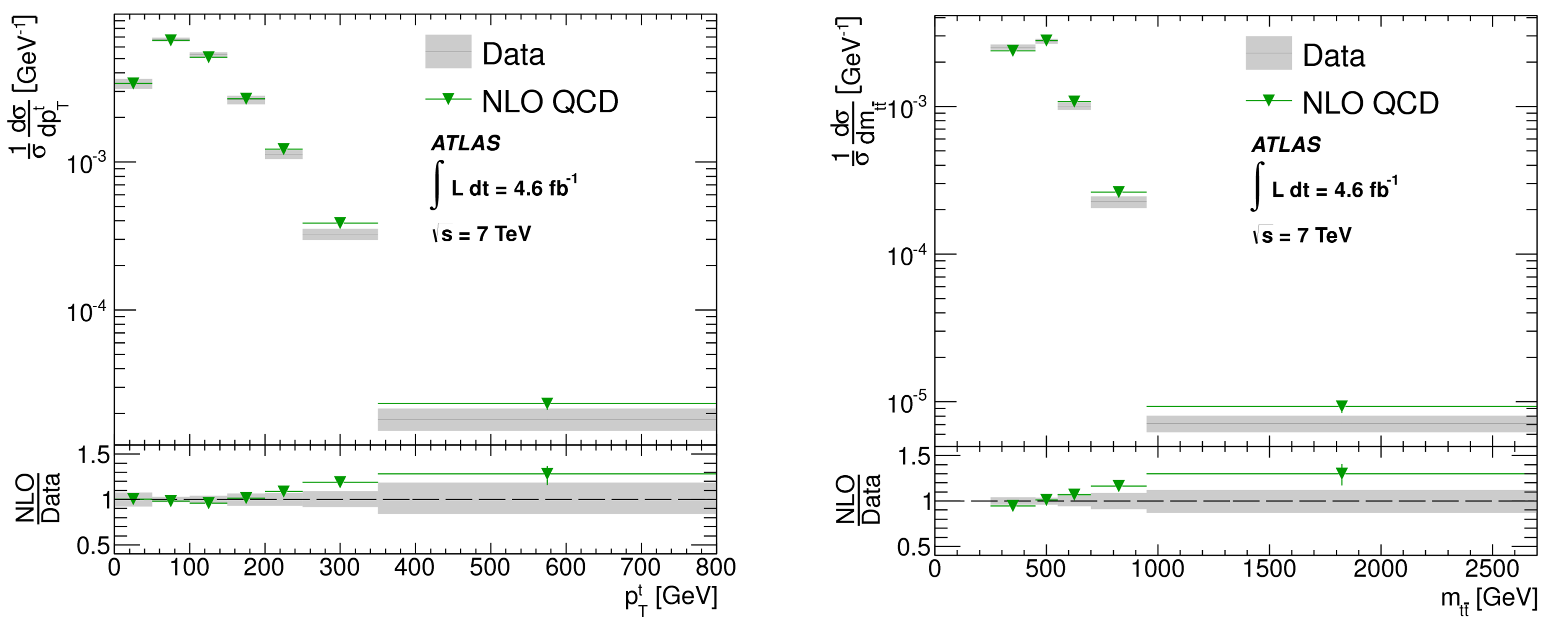
Example of issue in semi data-driven background modeling:



Observe ttbar simulation to have a problem to model top p_T, ttbar mass and p_T (simulation is harder than data)



More than one Monte Carlo generator, and also compared to NLO theory

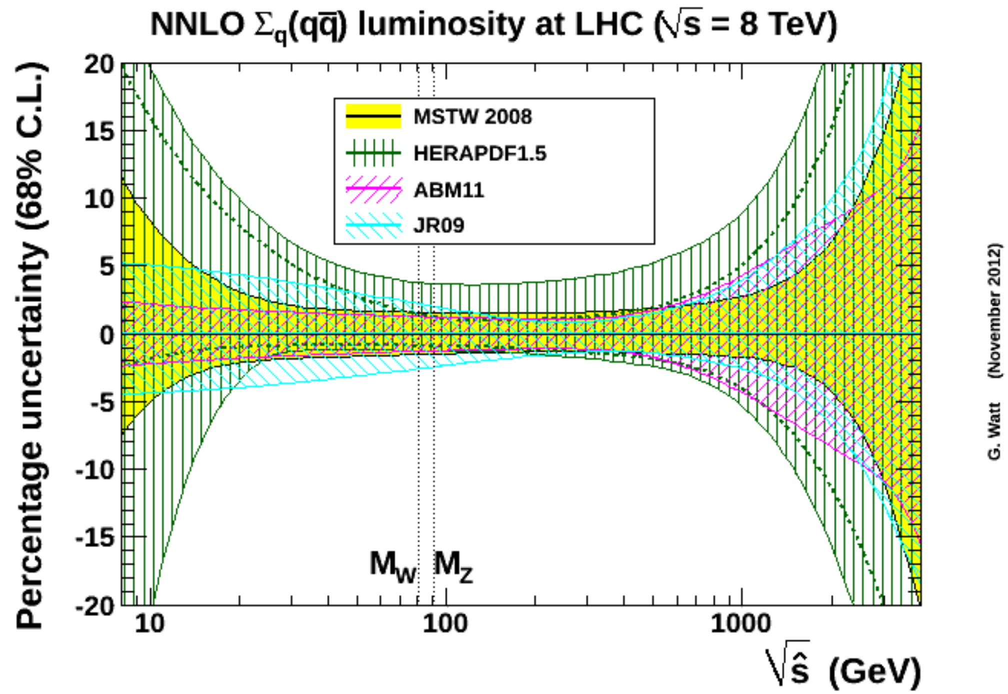


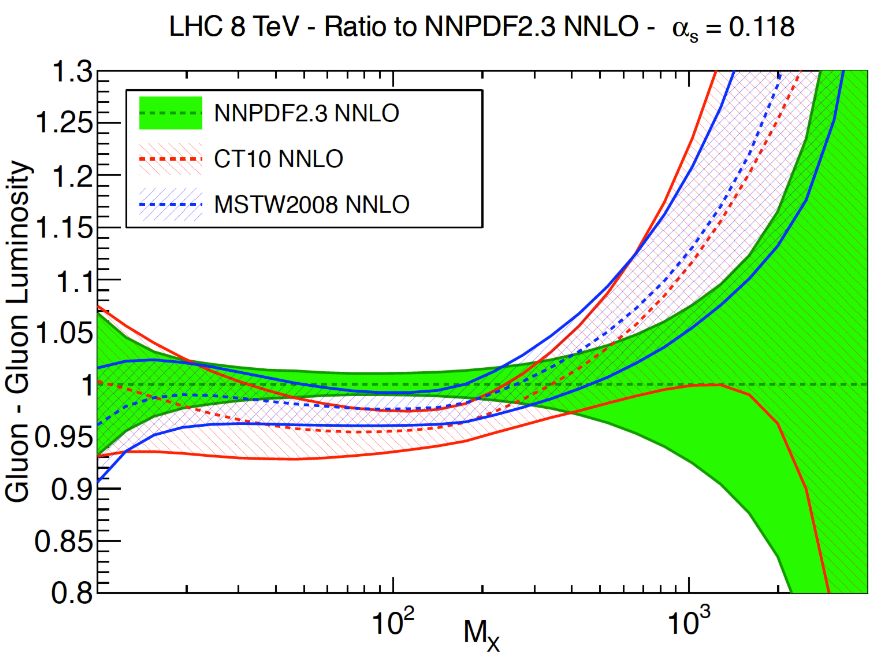
Use control regions in data to correct Monte Carlo shape

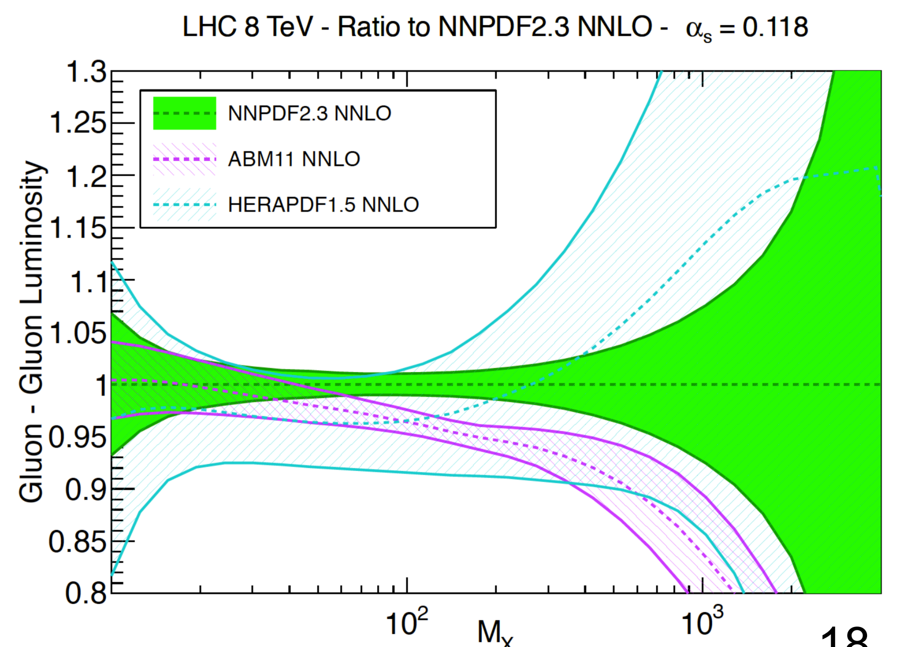
Parton distribution functions

Typically not a big deal for backgrounds

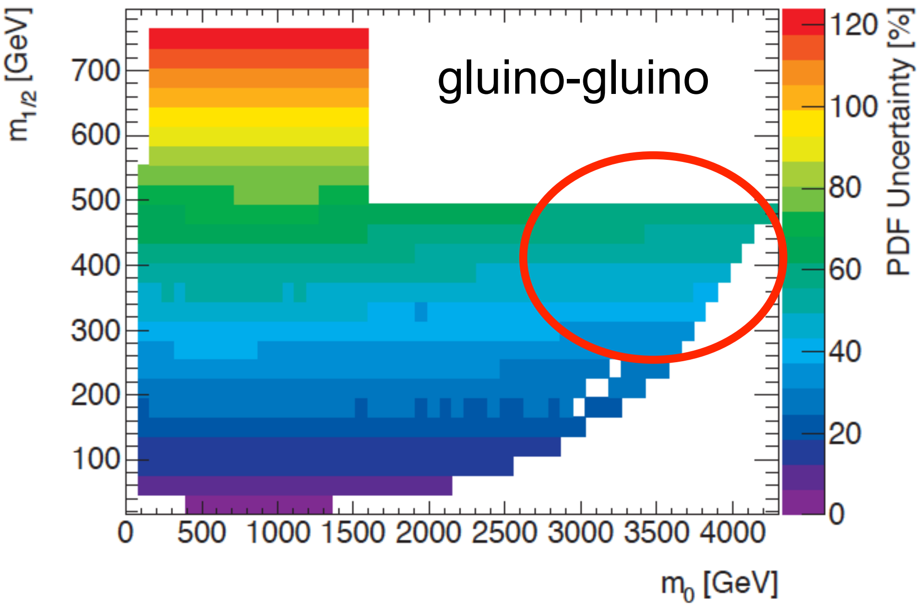
But BSM signals with heavy particles now probe into uncertain region

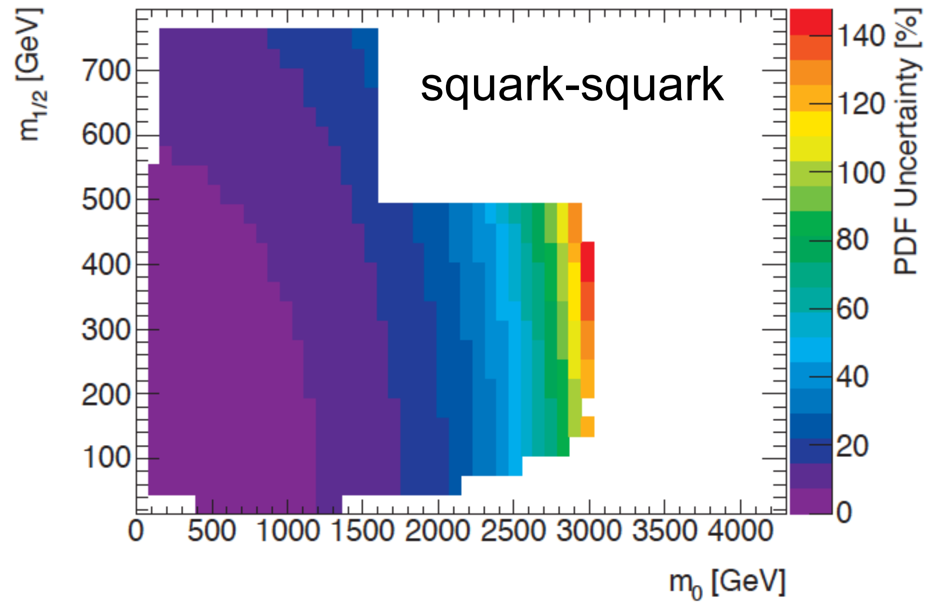






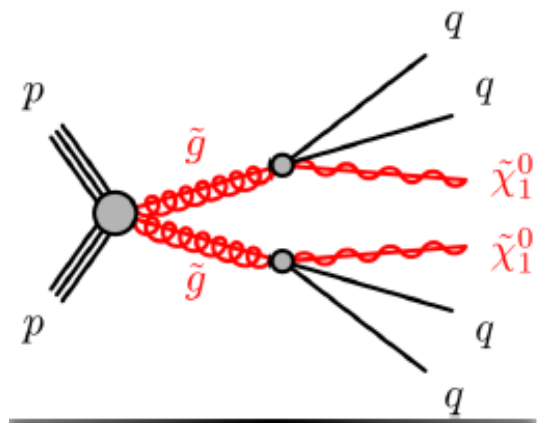
Effects of PDF uncertainties (CTEQ6) on MSUGRA/CMSSM





In extreme parts of phase space ~ 50%
Not a showstopper for SUSY (yet)

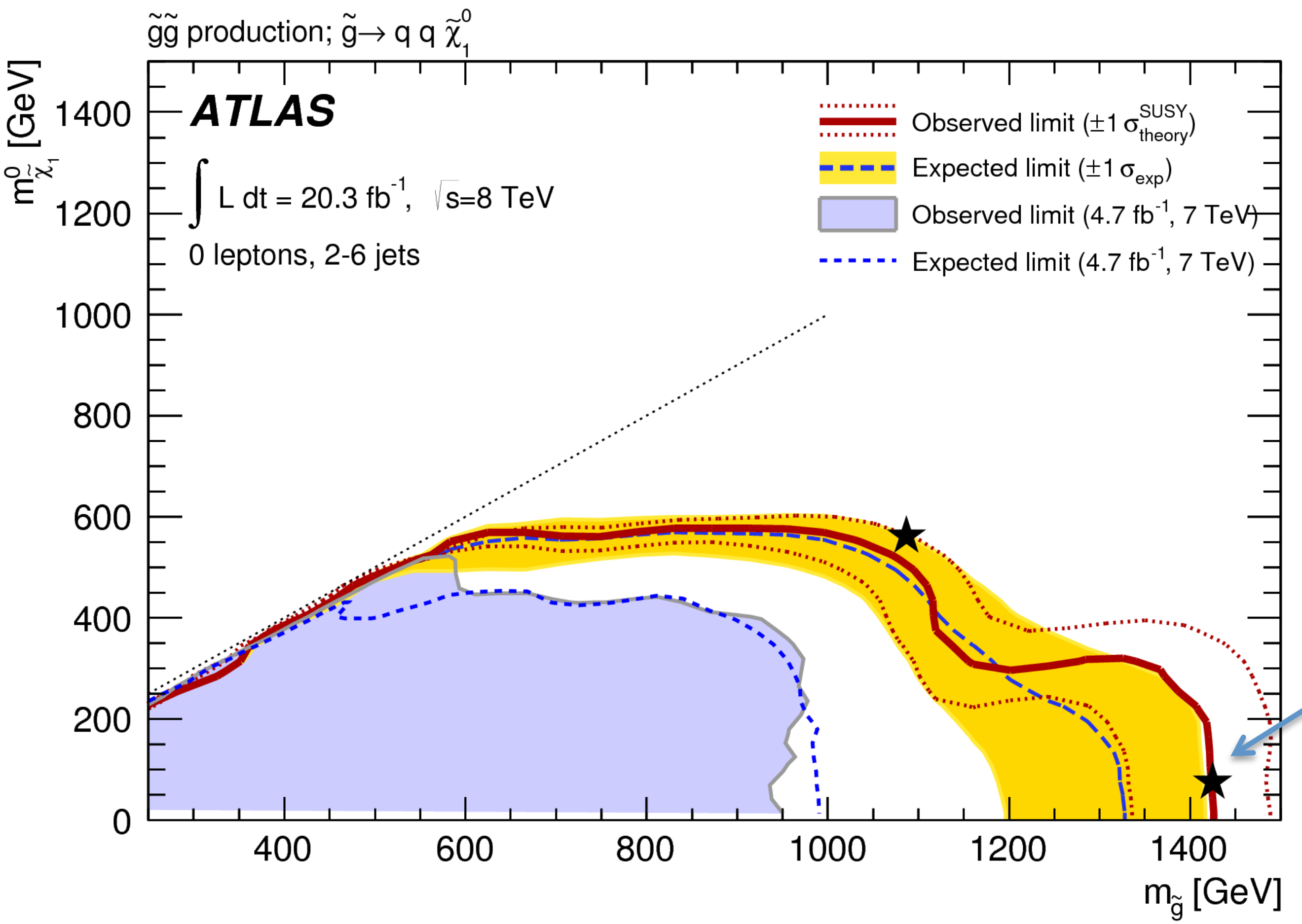
What can we expect in the early 2015 LHC run?



SUSY strong production: squarks and gluinos

Will benefit a lot from increased beam energy

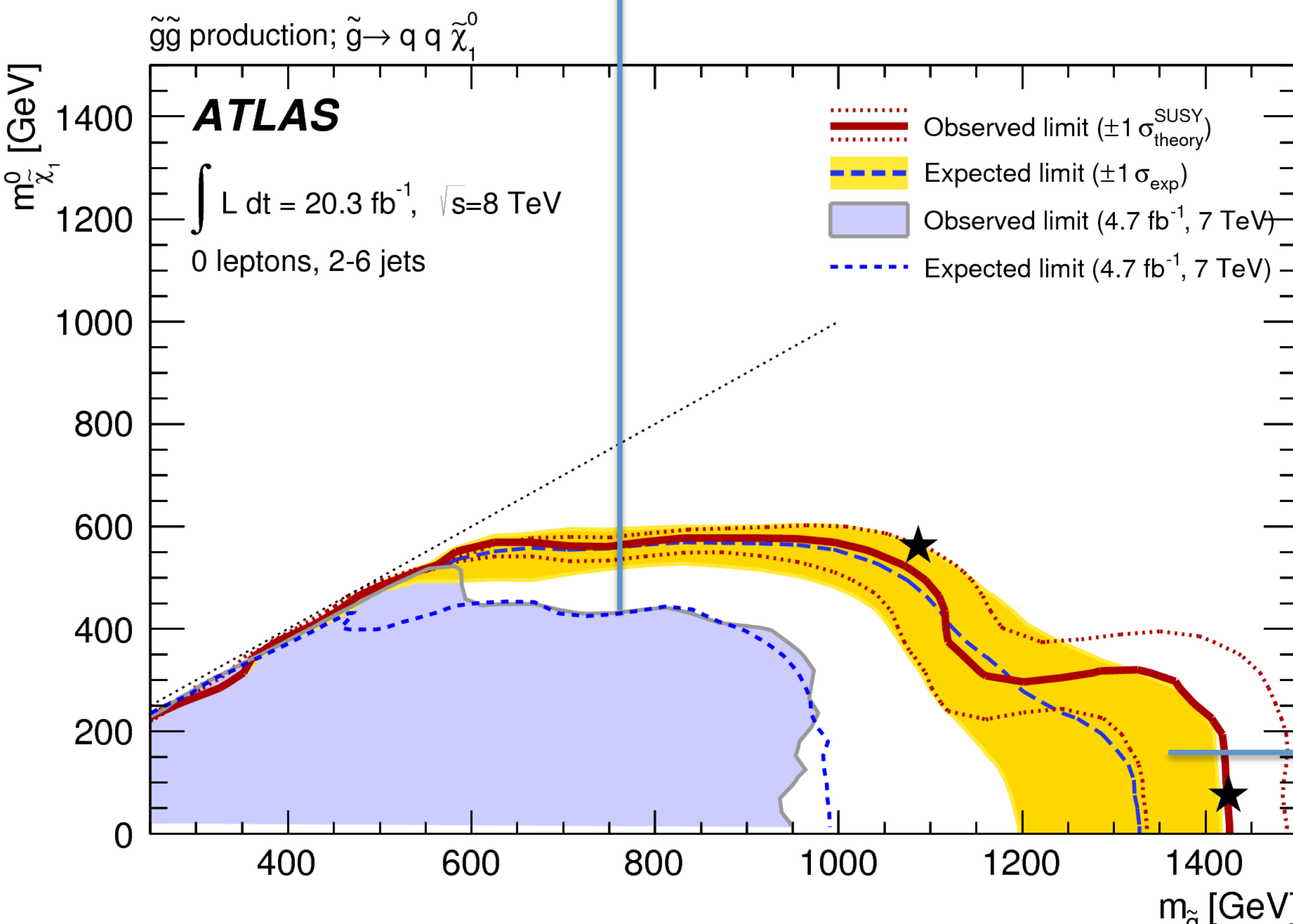
>= 4 jets + MET



at m_{gluino} = 1400 GeV
1 fb^{-1} at 13 TeV
= 20 fb^{-1} at 8 TeV

compressed spectrum
low p_T jets, low MET

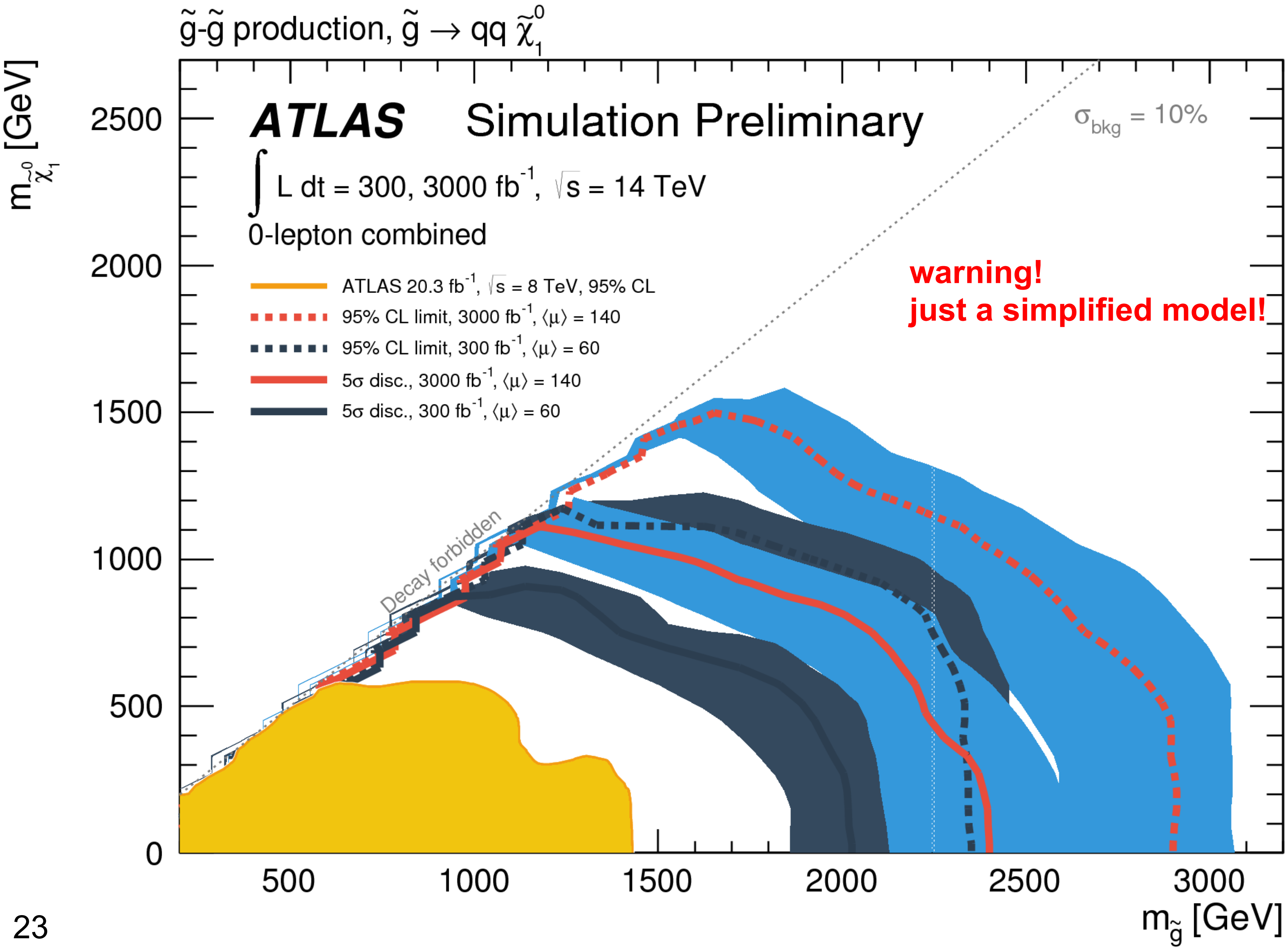
difficult to trigger
large backgrounds
tag with ISR jet
ISR systematics



limited by cross section
easy to trigger
some background
modeling systematics

large mass splitting
high p_T jets, large MET

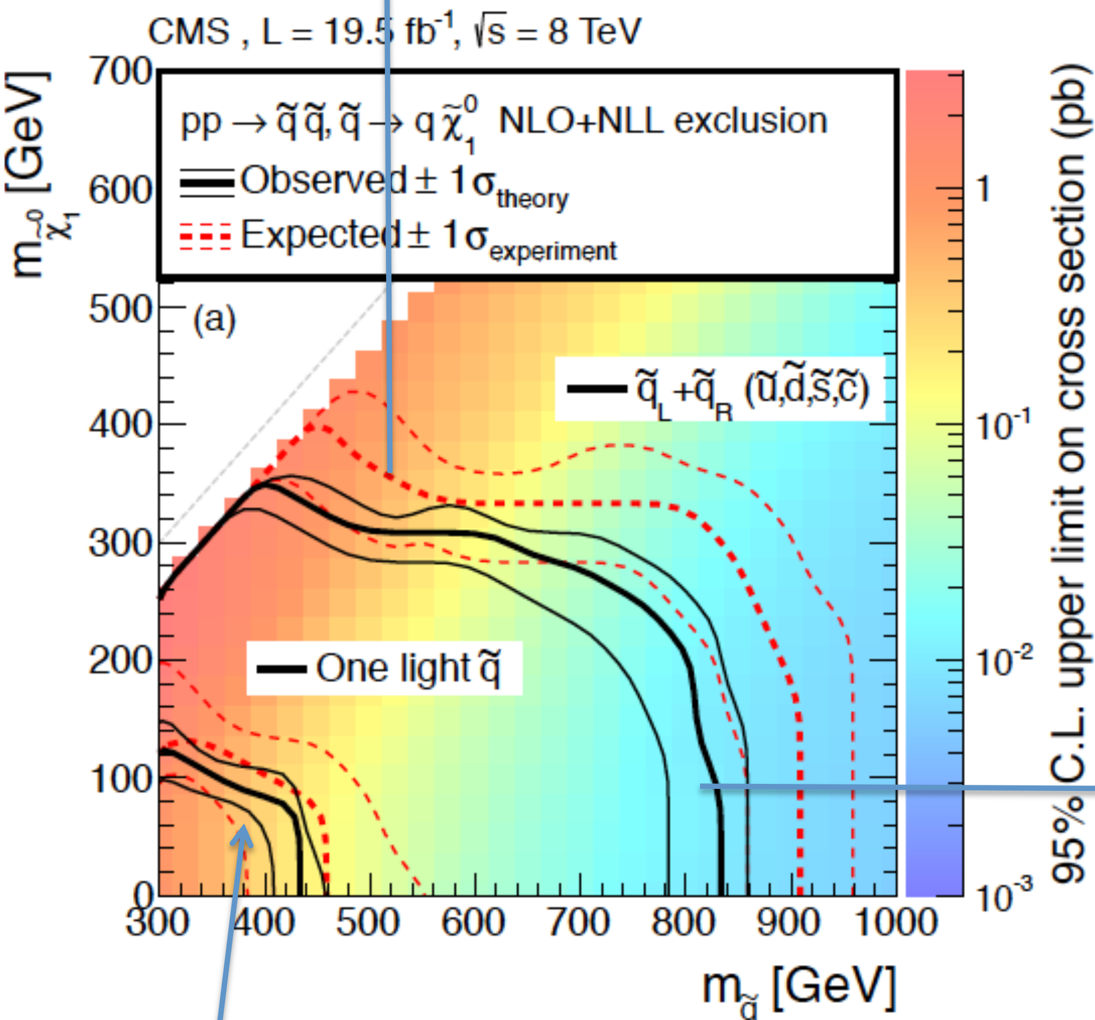
WARNING: predictions are difficult, in particular about the future

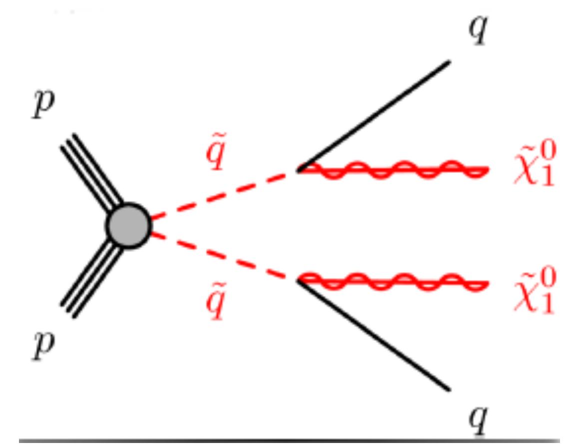


g̃-g̃ production, $\tilde{g} \rightarrow qq\,\tilde{\chi}_1^0$
ATLAS Simulation Preliminary
$\int L\,dt$ = 300, 3000 fb^{-1}, $\sqrt{s}$ = 14 TeV
0-lepton combined
ATLAS 20.3 fb^{-1}, $\sqrt{s}$ = 8 TeV, 95% CL
95% CL limit, 3000 fb^{-1}, $\langle\mu\rangle$ = 140
95% CL limit, 300 fb^{-1}, $\langle\mu\rangle$ = 60
5σ disc., 3000 fb^{-1}, $\langle\mu\rangle$ = 140
5σ disc., 300 fb^{-1}, $\langle\mu\rangle$ = 60
σ_{bkg} = 10%
warning!
just a simplified model!
Decay forbidden
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
0
500
1000
1500
2000
2500
3000

even more difficult compressed spectrum

squark-squark production



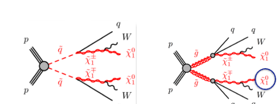


2-jets + MET

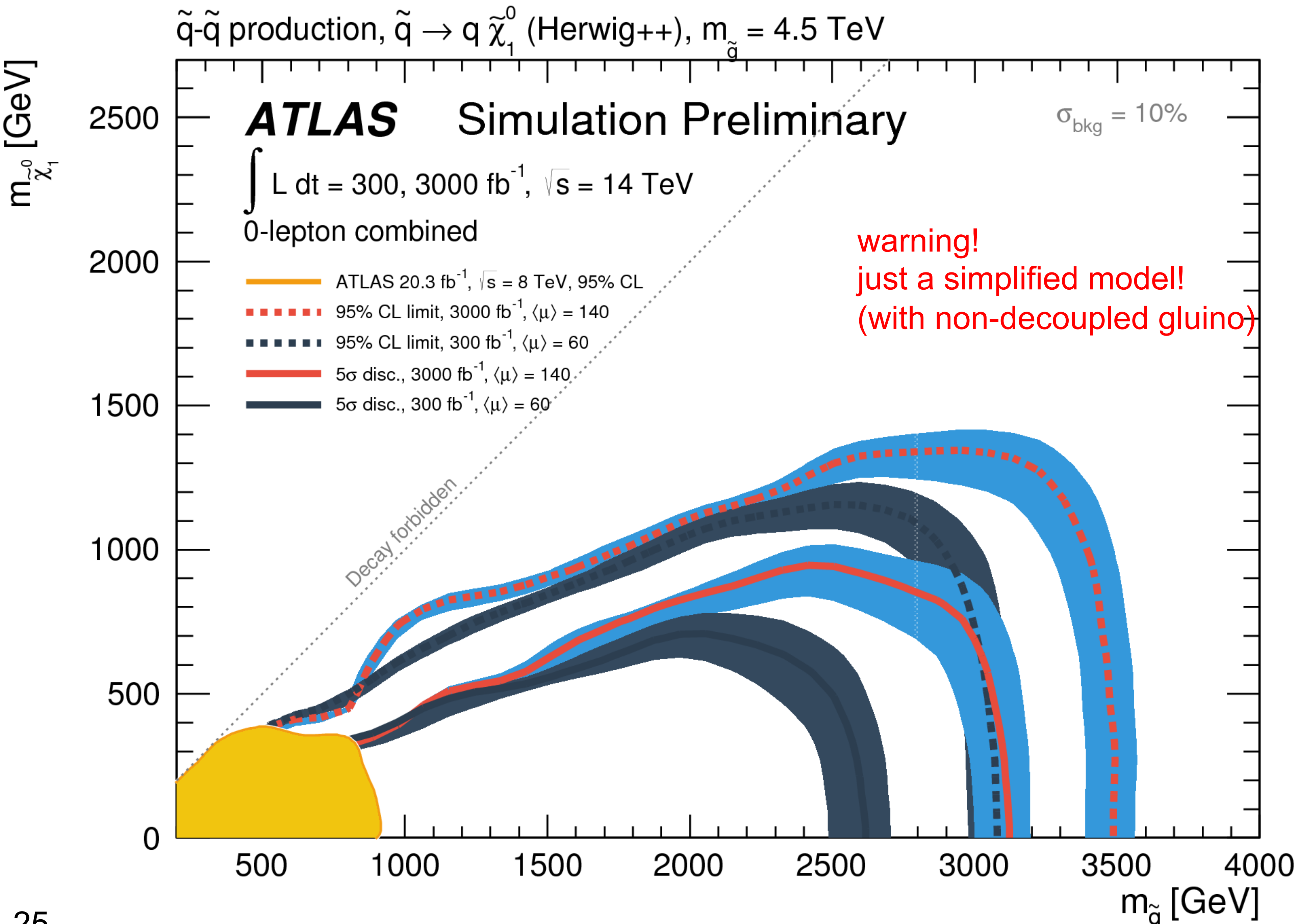
cross section limited very high p_T jets + MET

Note how the limit changes with only one light squark species!

The basis of simplified models is much larger than shown here…

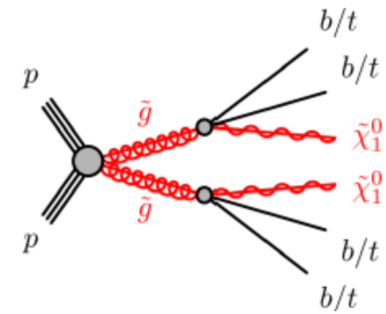


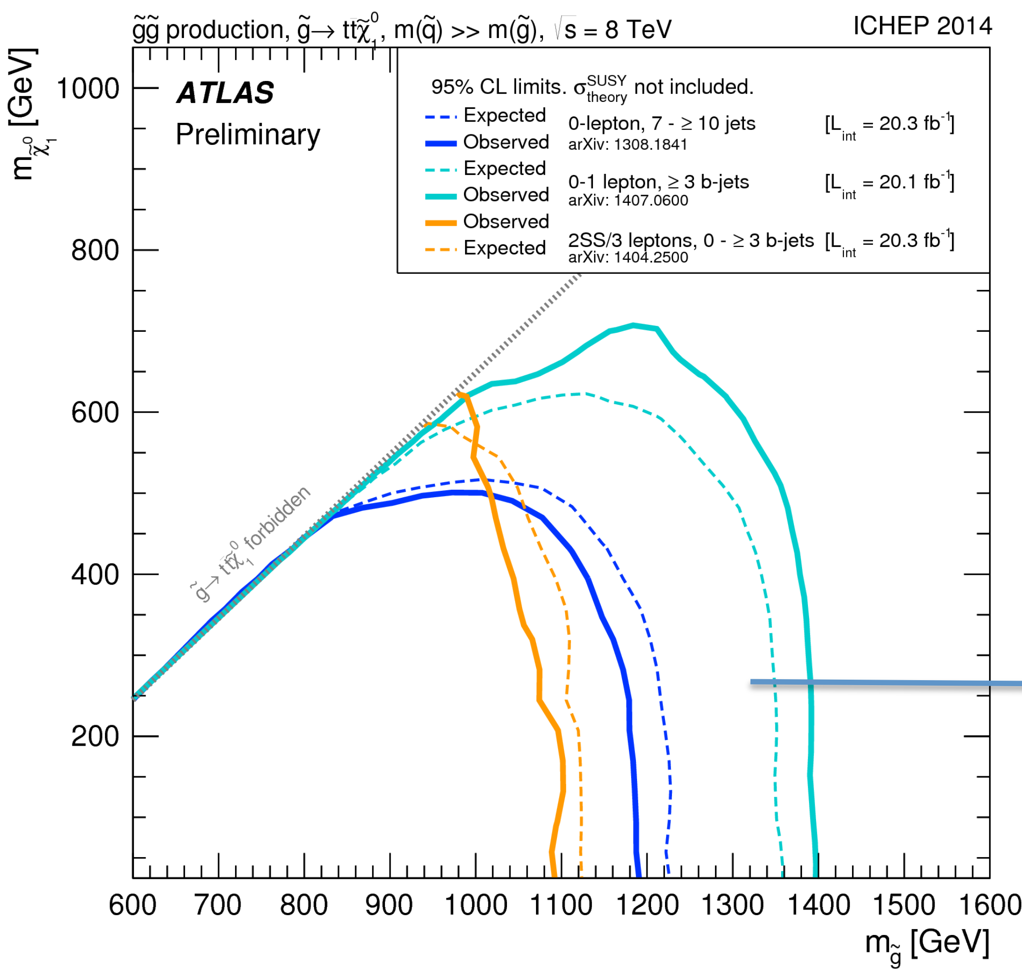
…



q̃-q̃ production, q̃ → q $\tilde{\chi}_1^0$ (Herwig++), $m_{\tilde{g}}$ = 4.5 TeV
ATLAS Simulation Preliminary
$\int L\,dt$ = 300, 3000 fb^{-1}, $\sqrt{s}$ = 14 TeV
0-lepton combined
σ_{bkg} = 10%
ATLAS 20.3 fb^{-1}, $\sqrt{s}$ = 8 TeV, 95% CL
95% CL limit, 3000 fb^{-1}, ⟨μ⟩ = 140
95% CL limit, 300 fb^{-1}, ⟨μ⟩ = 60
5σ disc., 3000 fb^{-1}, ⟨μ⟩ = 140
5σ disc., 300 fb^{-1}, ⟨μ⟩ = 60
warning!
just a simplified model!
(with non-decoupled gluino)
Decay forbidden
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{q}}$ [GeV]
0
500
1000
1500
2000
2500
500
1000
1500
2000
2500
3000
3500
4000

Gluino-mediated production of 3rd generation quarks (can easily dominate over light quarks through a light stop mediator)



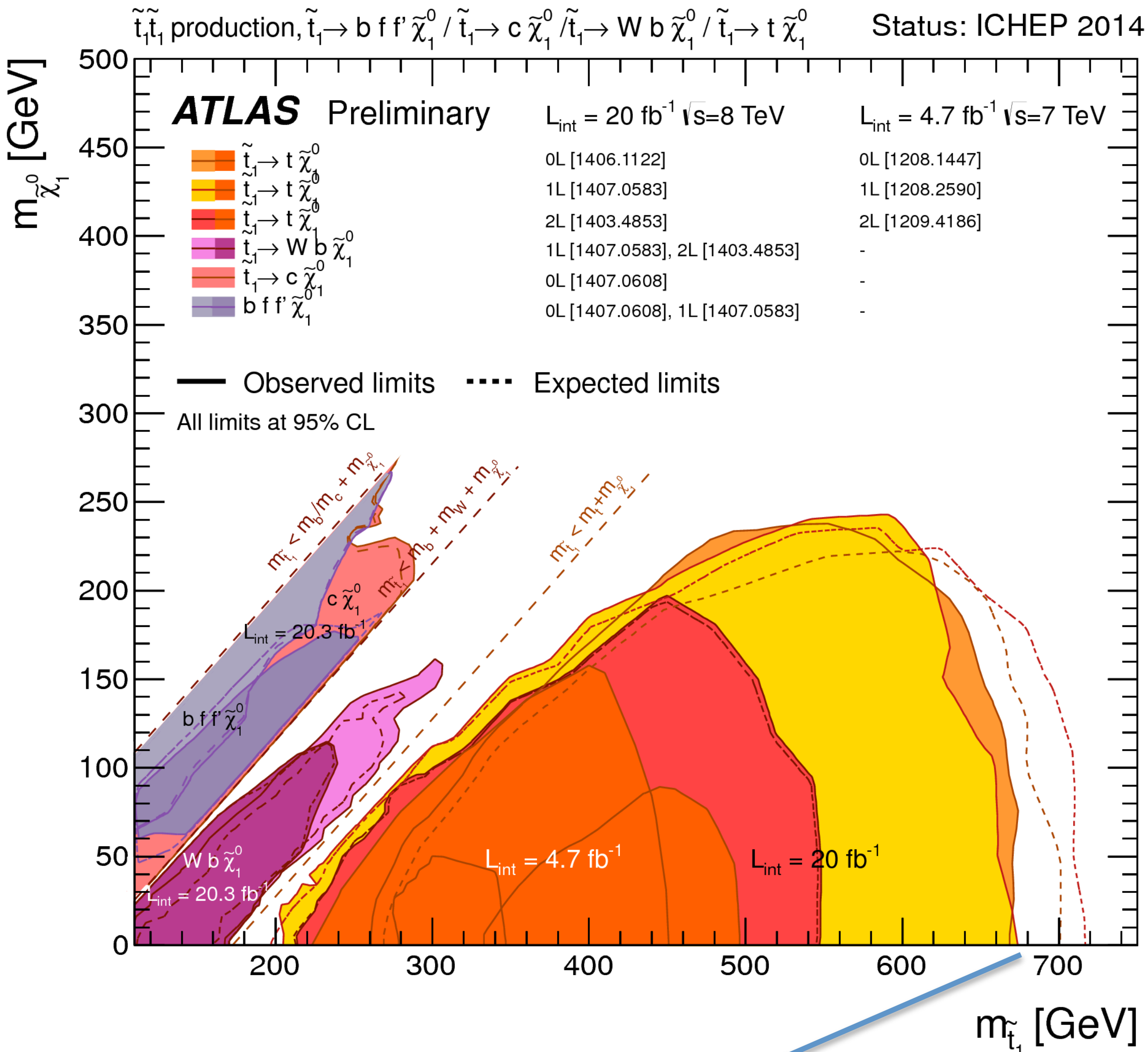


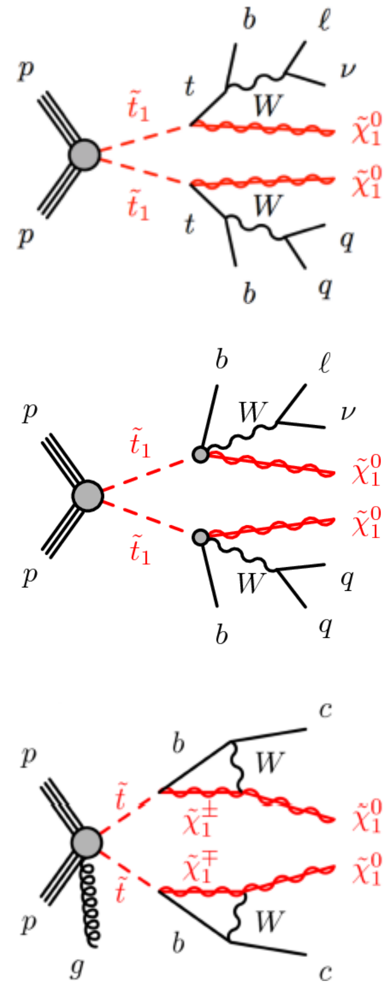
4-tops: multi b-jet search

cross section limited
``top-taggers''
high p_T top quarks,
boosted decay products

top squark pair production

Watch out: many decay modes
Simplified models simplify…



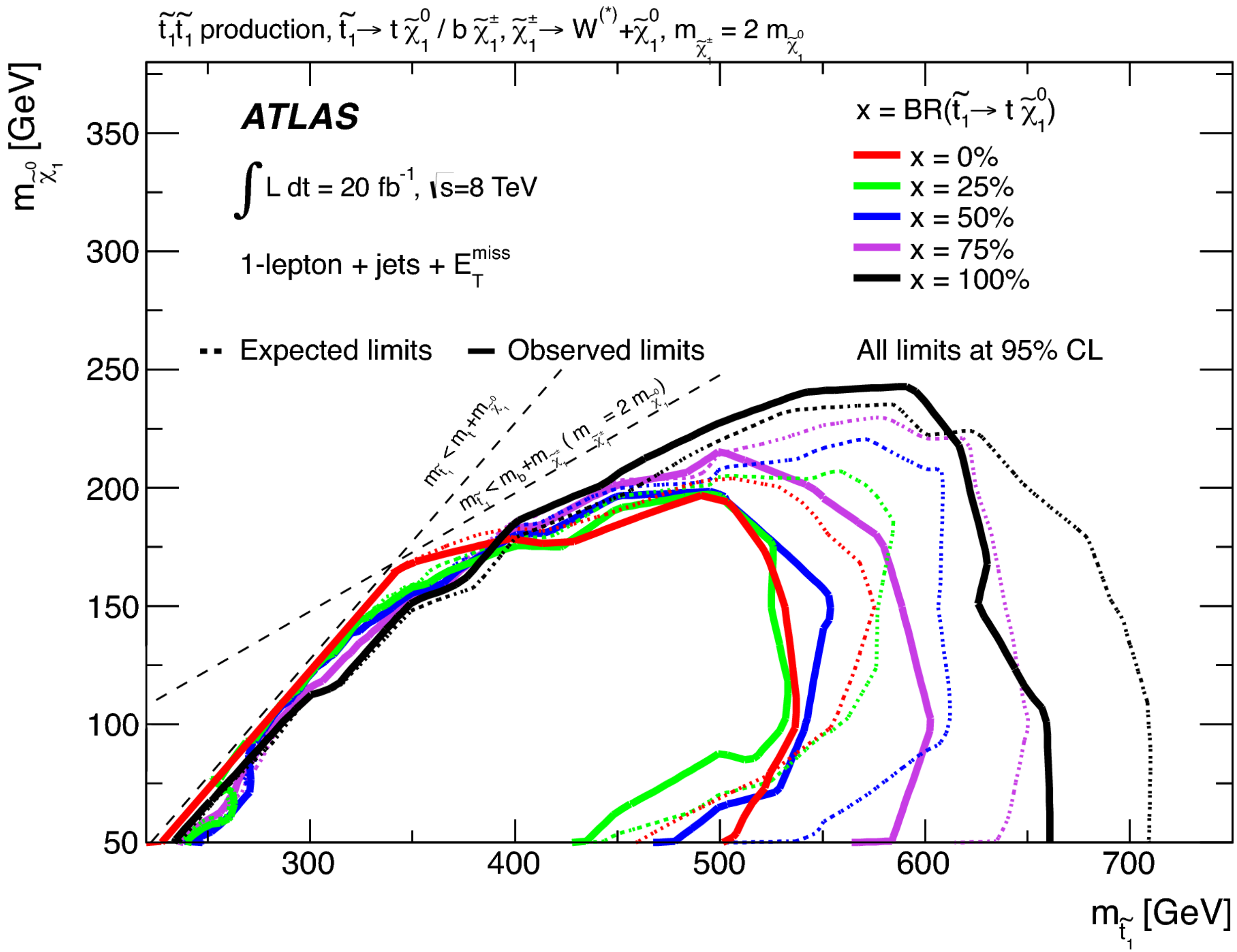


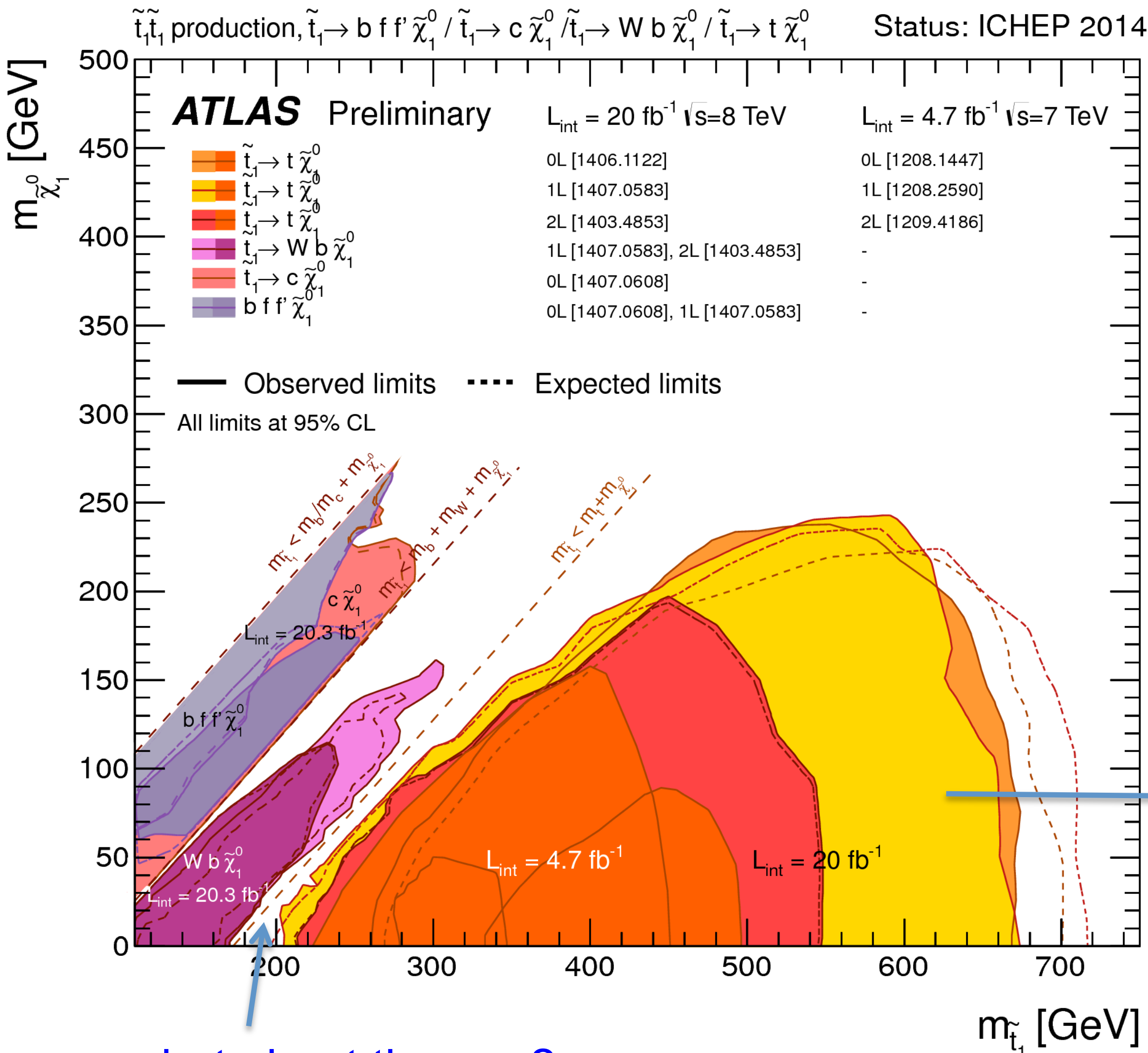
…

at m_{stop} = 700 GeV, 3.5 fb^{-1} at 13 TeV = 22 fb^{-1} at 8 TeV

Intermezzo: relax simplified model assumptions on branching fraction

Effect of changing branching fraction to top+neutralino (x) vs b+chargino (1-x)





what about the gap?

stop hiding behind the top is being ruled out
(accurate top cross section prediction)

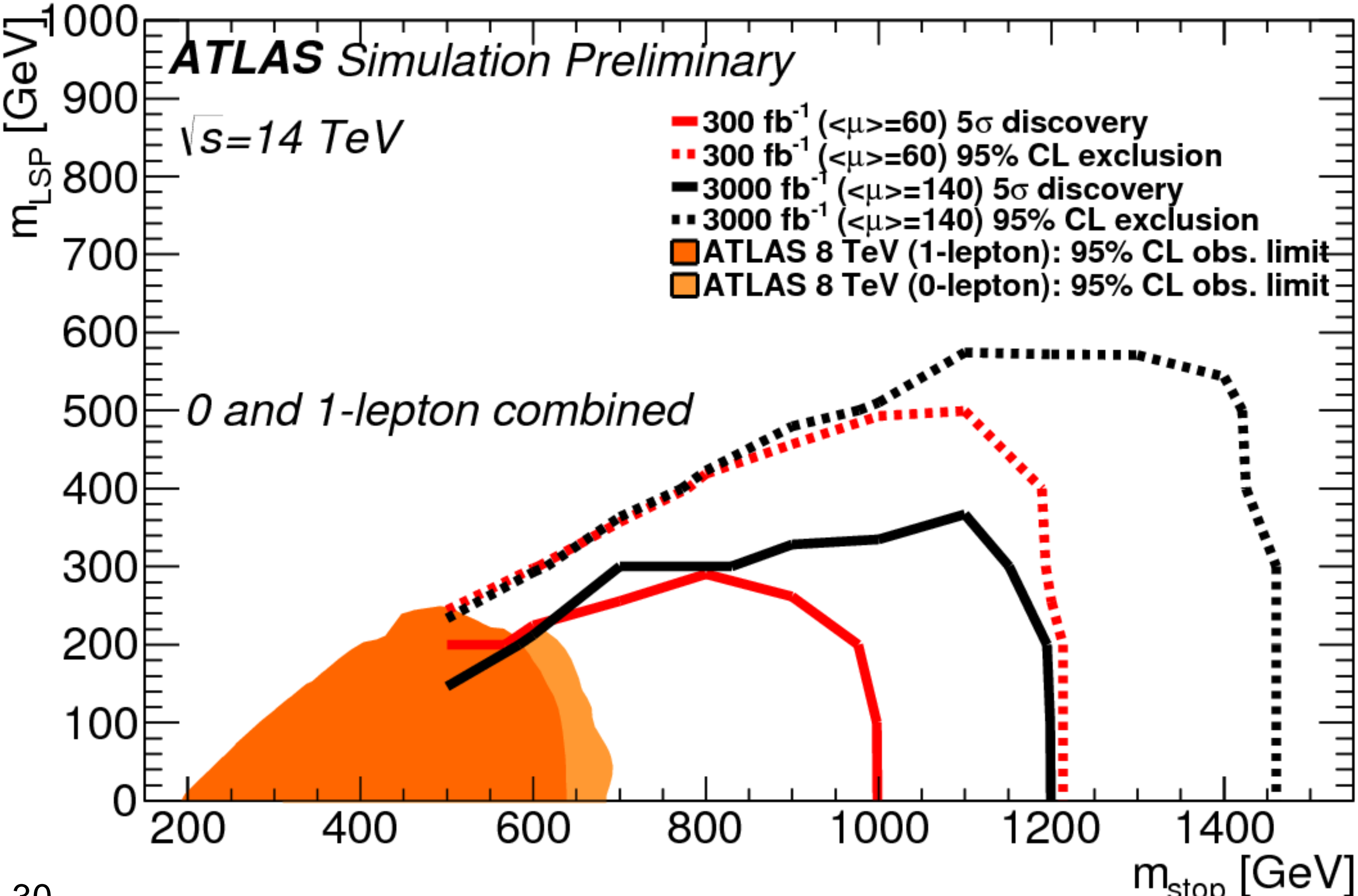
cross section limited

but also: boosted tops overlapping decay prods.

boosted decay tagging

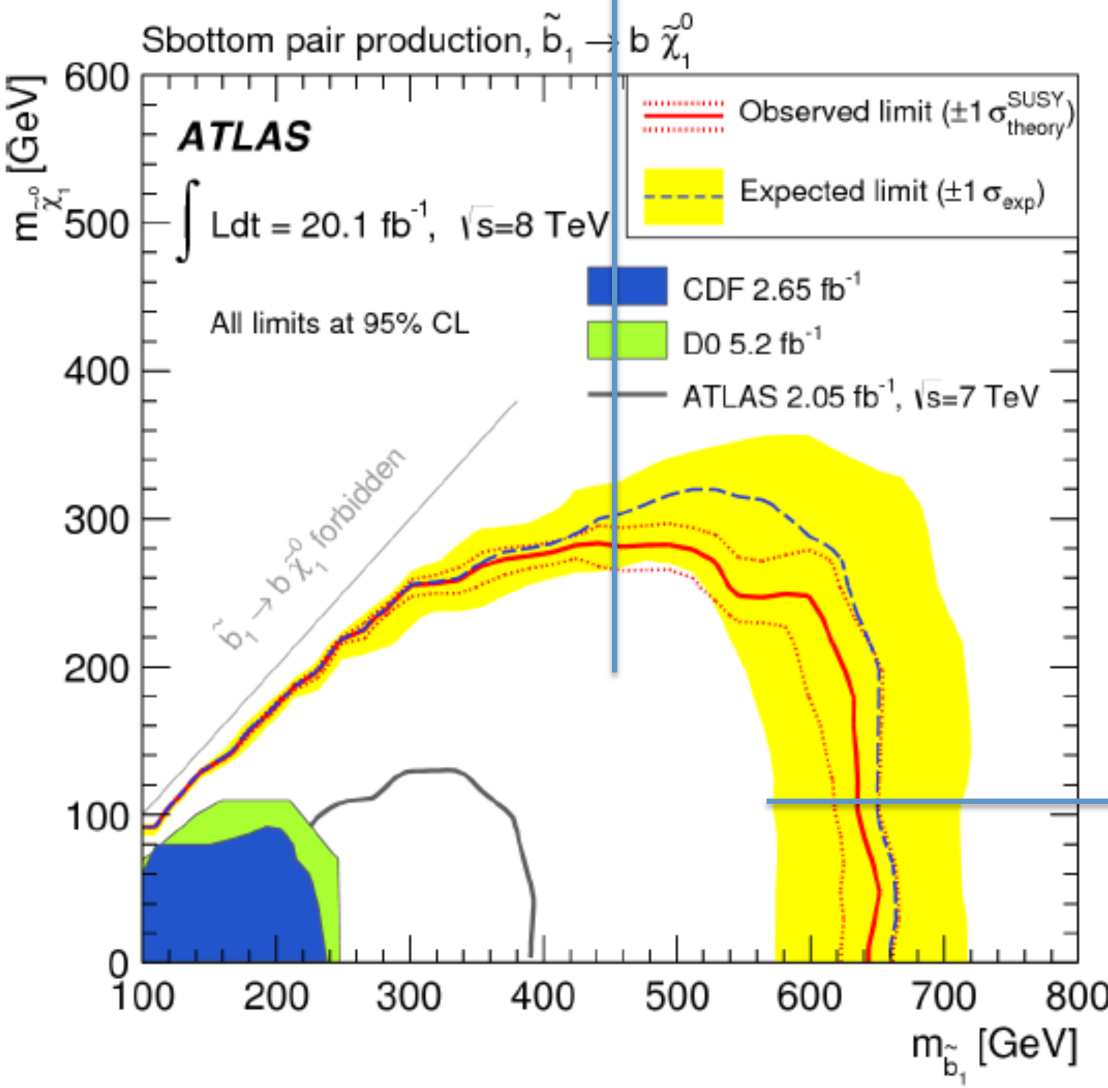
top background modeling

stop → top + neutralino outlook



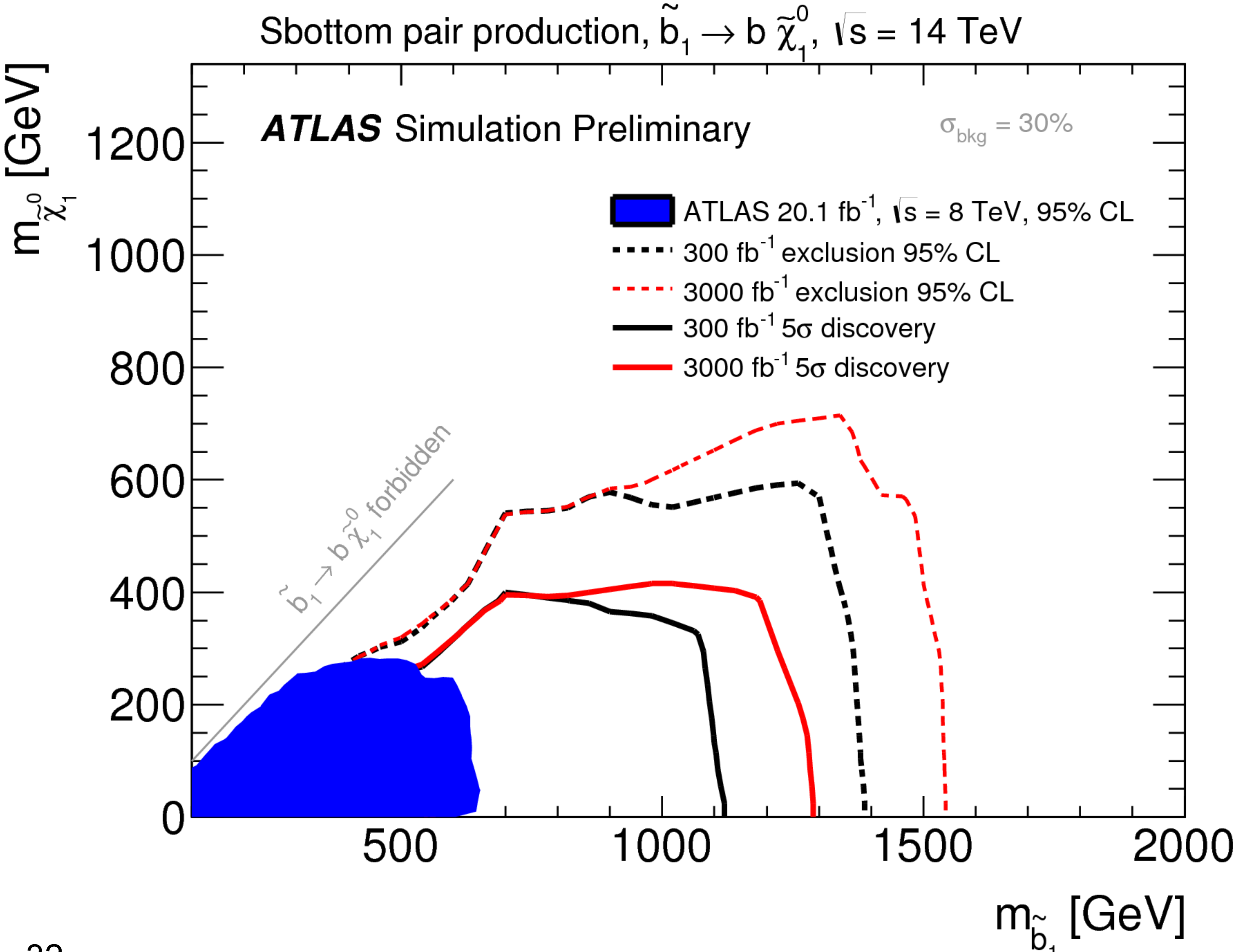
sbottom pair production

soft b-jets: triggering challenge

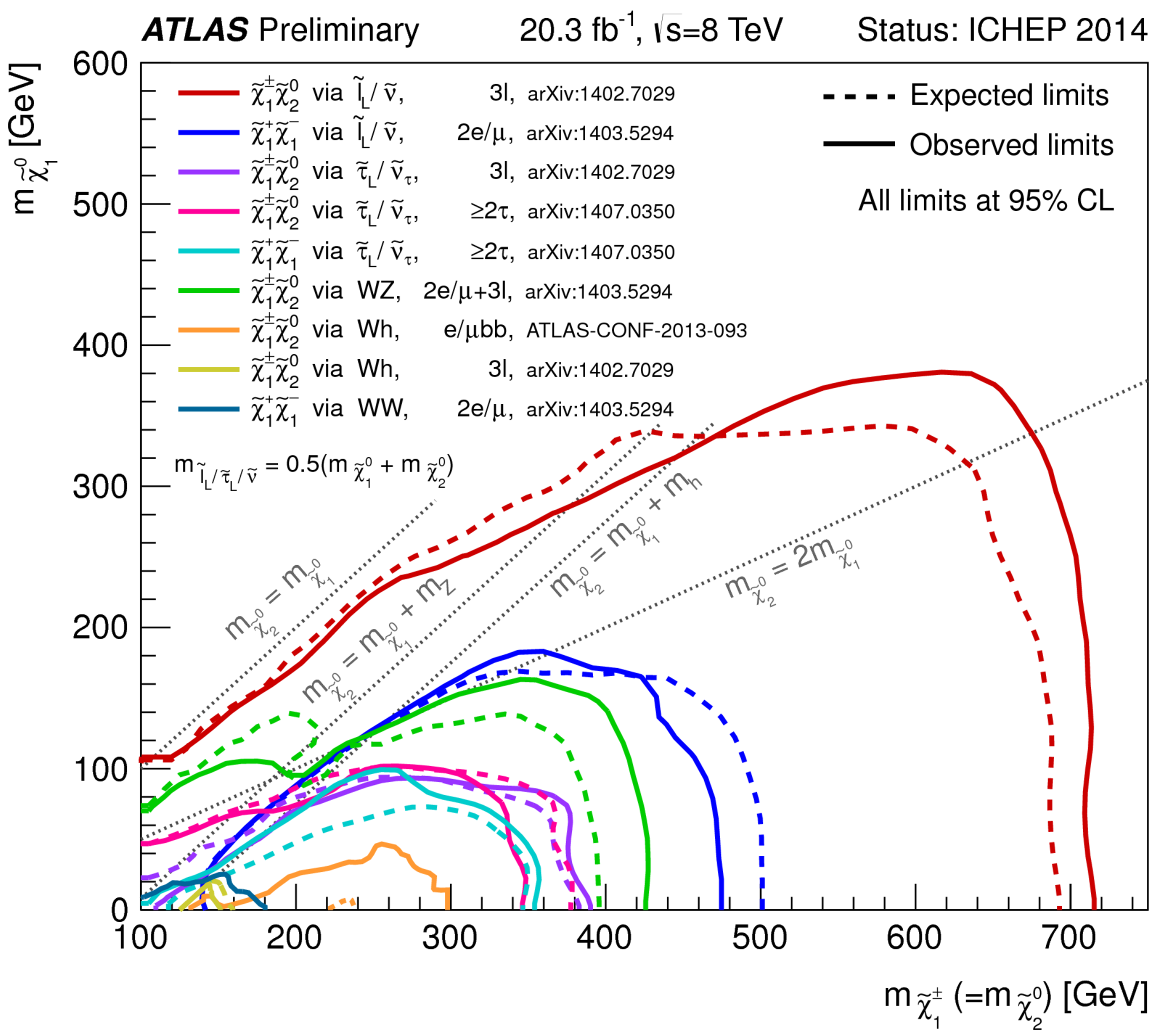


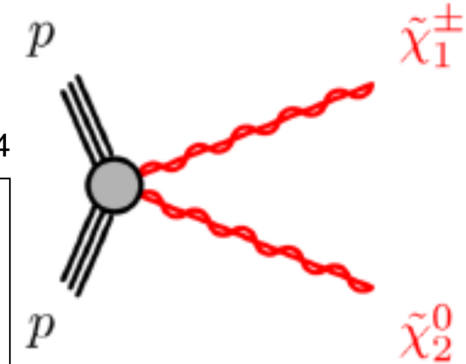
reduction of b-tagging efficiency;
b's fly beyond first pixel layers

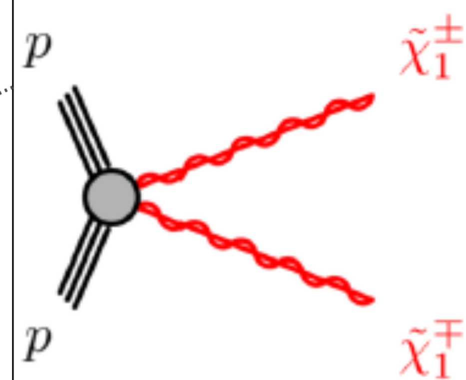
very high p_T b-jets


Sbottom pair production, $\tilde{b}_1 \rightarrow b\, \tilde{\chi}_1^0$, $\sqrt{s}$ = 14 TeV
ATLAS Simulation Preliminary
σ_{bkg} = 30%
ATLAS 20.1 fb^{-1}, $\sqrt{s}$ = 8 TeV, 95% CL
300 fb^{-1} exclusion 95% CL
3000 fb^{-1} exclusion 95% CL
300 fb^{-1} 5σ discovery
3000 fb^{-1} 5σ discovery
$\tilde{b}_1 \rightarrow b\, \tilde{\chi}_1^0$ forbidden
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{b}_1}$ [GeV]
0
200
400
600
800
1000
1200
500
1000
1500
2000

(electroweak) gauginos

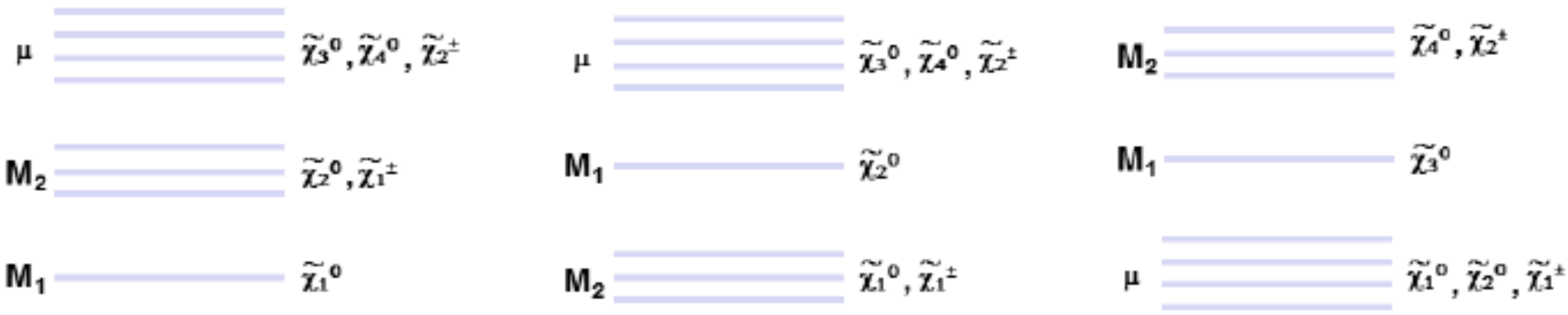






Warning! These simplified models can fool the reader quite a bit! Read the small print!

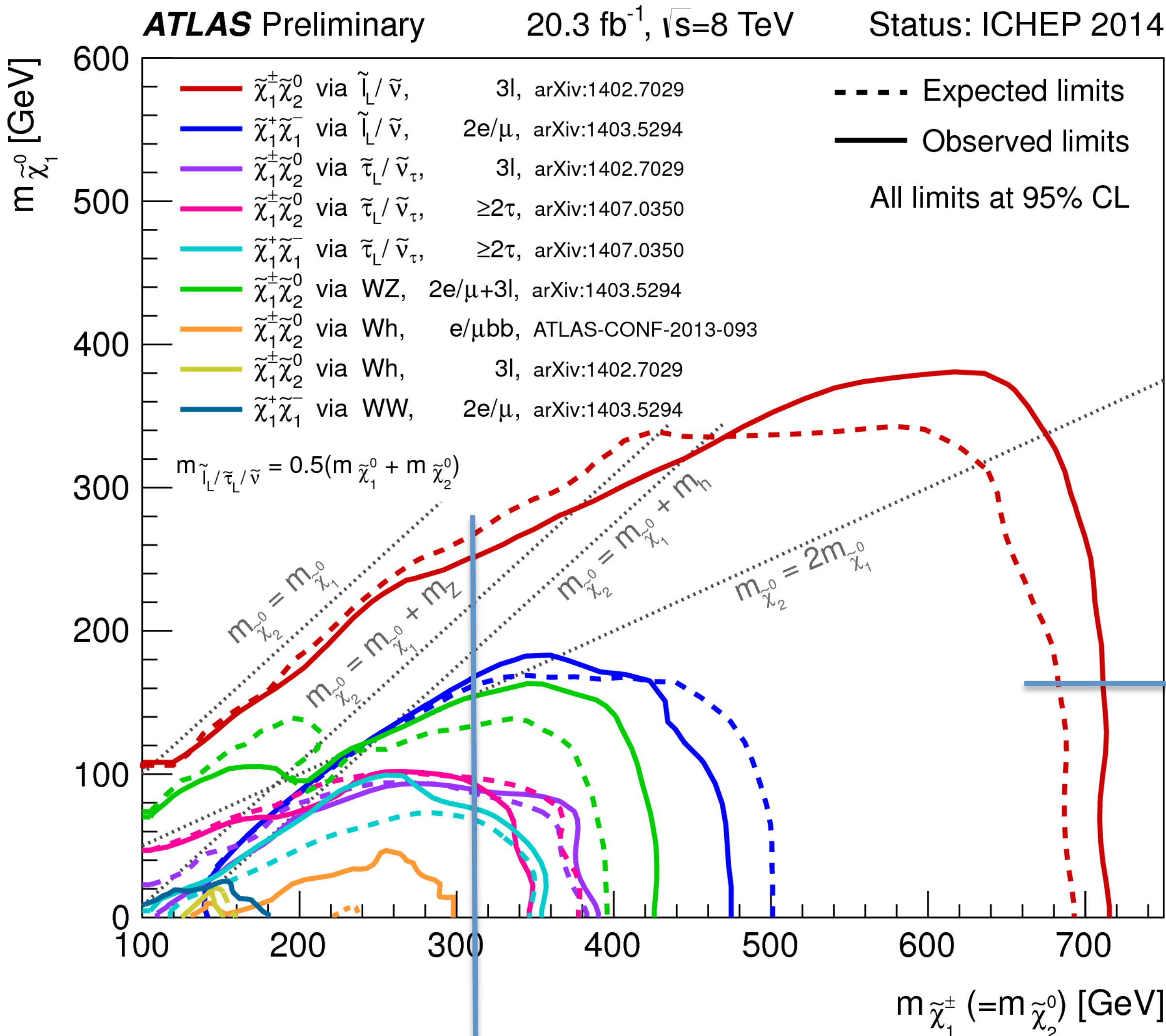
Three scenarios for gaugino contents:



bino-like **wino-like** **higgsino-like**

Preferred by naturalness
Degenerate lightest gauginos
Much more difficult, few results so far
Long-lived charginos, soft leptons,…

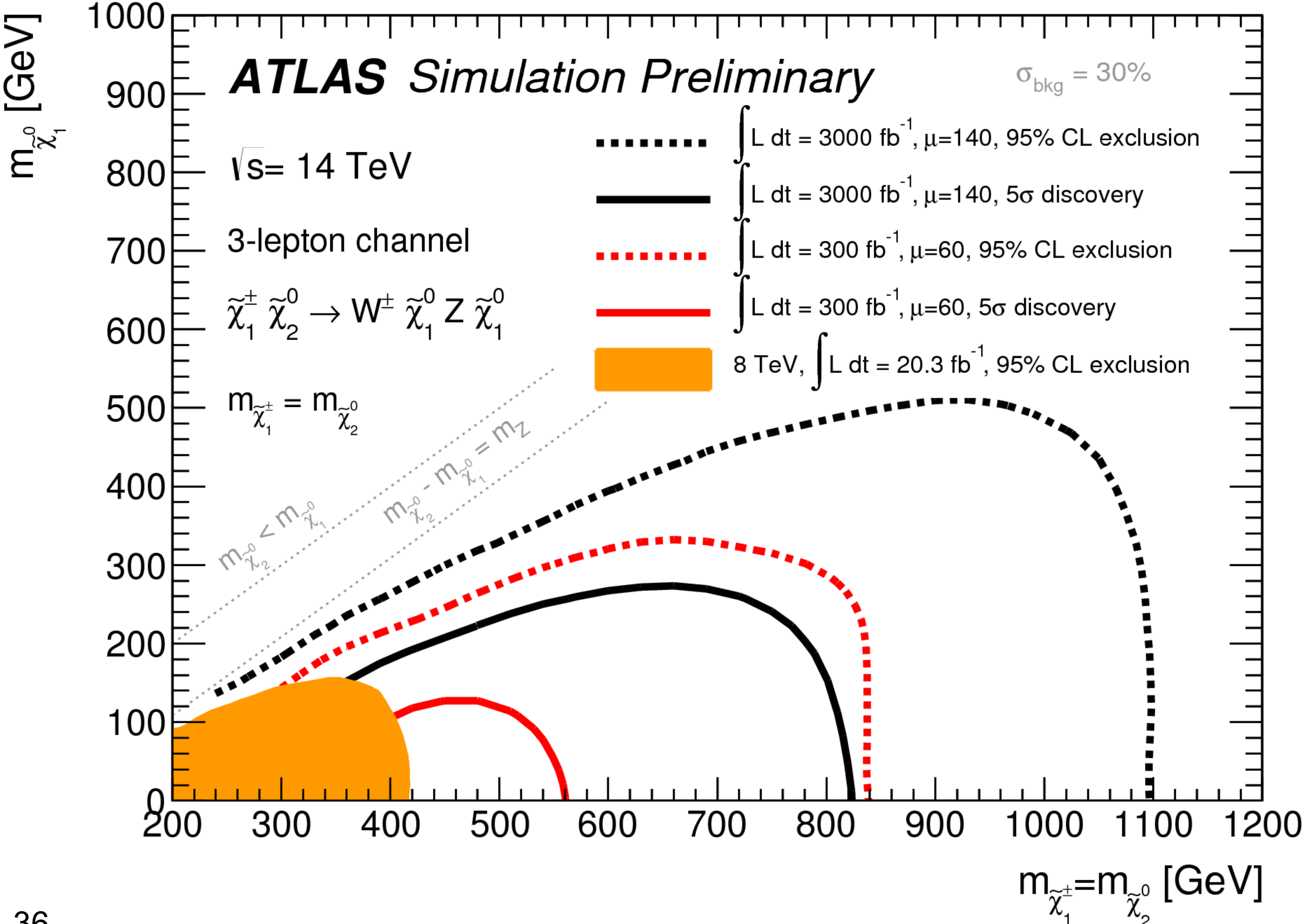
Mostly used so far.
Significant mass gap between (degenerate) chargino1/neutralino2 and neutralino1
Best limits obtained assuming light sleptons, mediating decay to leptons
More realistic scenarios with W,Z decay have poorer limits
Some limits on neutralino2 → higgs + neutralino1



Need more effort on higgsinos and heavier gauginos

cross section-limited

soft leptons: triggering, reconstruction, backgrounds



ATLAS Simulation Preliminary
σ_{bkg} = 30%
$\sqrt{s}$= 14 TeV
3-lepton channel
$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 \rightarrow W^{\pm} \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
$\int L\,dt$ = 3000 fb^{-1}, μ=140, 95% CL exclusion
$\int L\,dt$ = 3000 fb^{-1}, μ=140, 5σ discovery
$\int L\,dt$ = 300 fb^{-1}, μ=60, 95% CL exclusion
$\int L\,dt$ = 300 fb^{-1}, μ=60, 5σ discovery
8 TeV, $\int L\,dt$ = 20.3 fb^{-1}, 95% CL exclusion
$m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = m_Z$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^{\pm}}=m_{\tilde{\chi}_2^0}$ [GeV]
0
100
200
300
400
500
600
700
800
900
1000
200
300
400
500
600
700
800
900
1000
1100
1200

Some personal conclusions:

Don't get fooled by simplified model limits. There is phase space out there for SUSY. The gaugino sector is hardly scratched. Even 500 GeV squarks are not generally ruled out.

Expect more effort on gaugino sector, especially higgsinos. Difficult!

Non-vanilla SUSY: special final states (V. Mitsou talk)

Many BSM aspects of Higgs to be studied: anomalous decays, but also anomalous production mechanisms.

Regardless of new particles or not, there is a whole program of precision physics measurements to do, for example of top and vector boson production/decay

The LHC is the right machine. But who said it would be easy?


CHALLENGE
YOURSELF
AND
HAVE FUN !