Prospectus
For the Discovery
of Dark Matter @ LHC

Joseph Lykken

Fermilab

this is not a CMS talk

Prospectus for Discovery?

OPPENHEIMER

Discovery Fund

Summary Prospectus January 28, 2013, as revised May 17, 2013

NYSE Ticker Symbols

Class A	**OPOCX**
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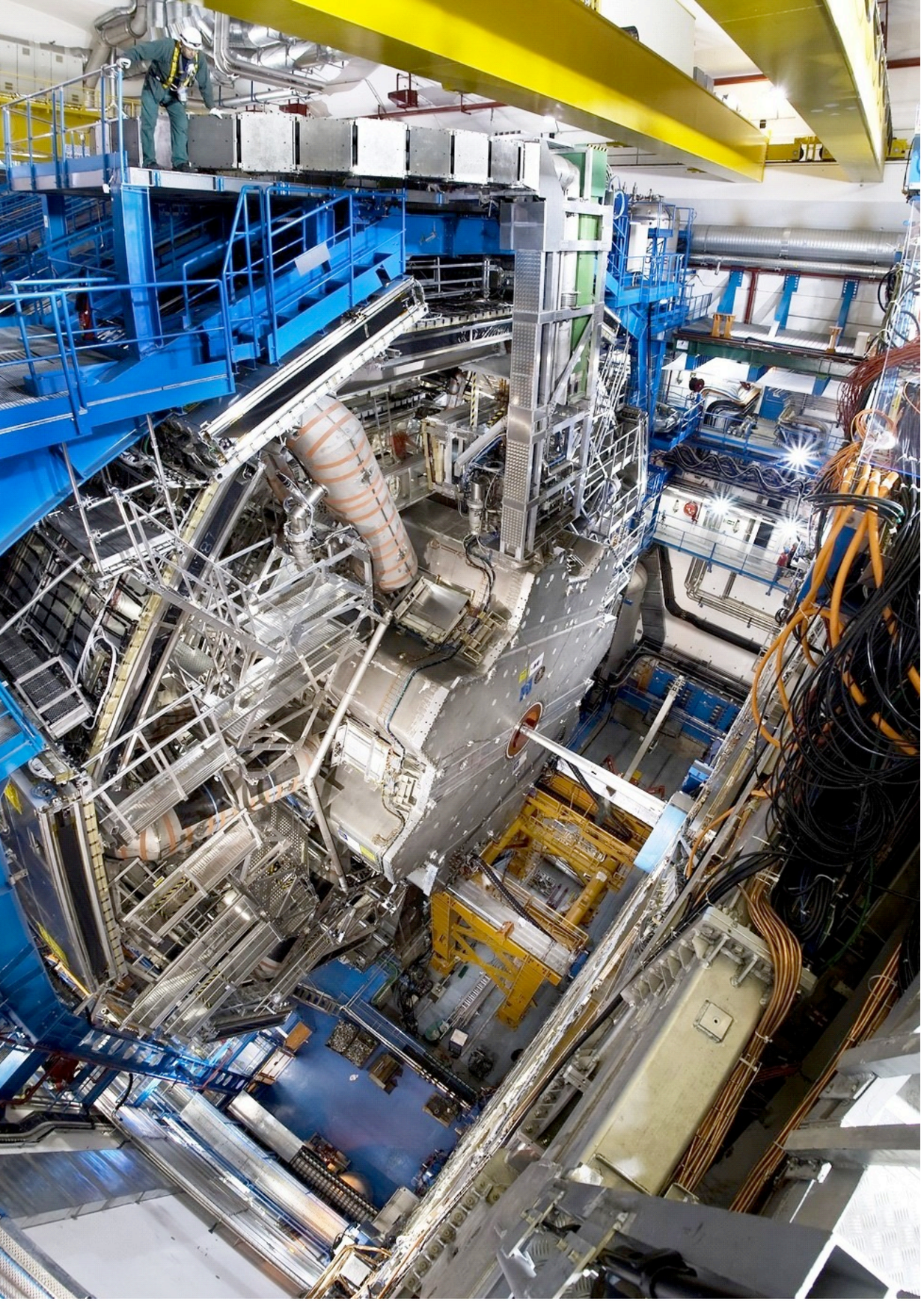
PROSPECTUS
APRIL 30, 2013

NEW ALTERNATIVES FUND, INC.
Ticker: NALFX

Past Performance is No Guarantee of Future Results

Past performance does not guarantee future results for startups, venture capitalists, accelerator programs, the media, individual founders, or any other



Dark Matter @ LHC
The Dream

- Produce dark matter candidate particles in LHC collisions
- Produce heavier relatives of these particles
- Figure out quantum numbers and interactions of DM particles with SM, and of DM particles with themselves
- Close the circle with what you see in direct and indirect detection

How to make DM particles at LHC

- Direct production: $\chi\chi$ + SM particles
  - Includes monojet, monophoton, mono-b, mono-Z, mono-W, mono-Higgs
- Associated production with a heavier exotic: χ + E, then E-> χ + SM
- Pair of heavier exotics: E + E, then both E's-> χ + SM
- SM decays to χ: Z -> $\chi\chi$, h-> $\chi\chi$, t -> c$\chi\chi$
- Exotic resonance decays: E -> $\chi\chi$
- Heavier metastable exotic, decay of E-> χ not seen in the detector

SUSY models give lots of examples of all of these, so this is not a bad place to start, *even if DM has nothing to do with SUSY*

Mediators at the LHC?

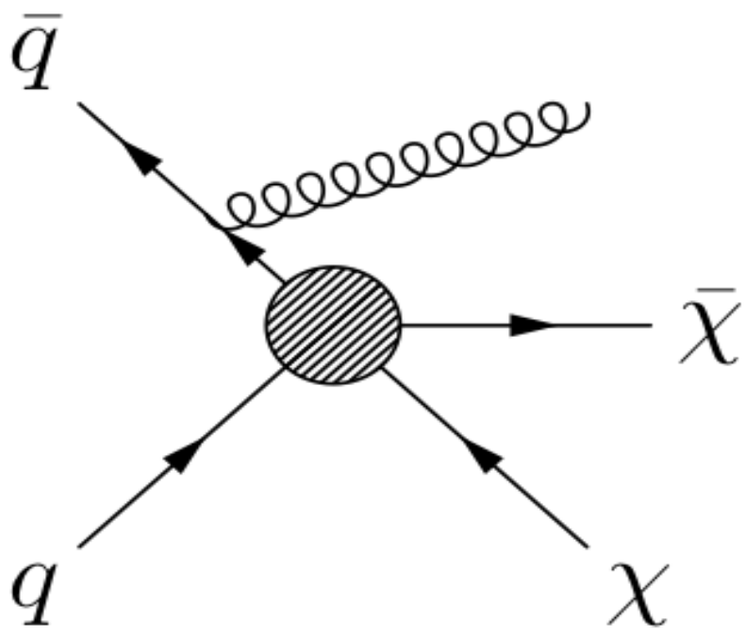
- Besides heavier unstable relatives of the DM particle, we are also interested in the particle/particles that mediate the non-gravitational interactions of dark matter with SM matter
- The only candidate SM mediators are the Z boson and the Higgs boson
- Exotic mediators may be very heavy, in which case think about DM-SM interactions in terms of effective operators
- If mediators are lighter, produce and identify them at LHC, not necessarily in association with DM particles, e.g. heavy Higgses in SUSY
- If they are really light, produce and identify them in lower energy experiments

Dark Matter @ LHC
Run 1 results

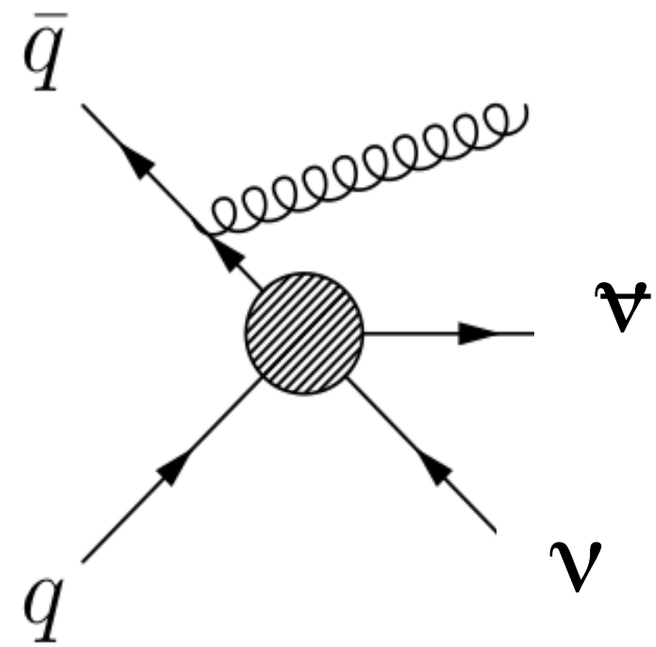
- A very broad and powerful program of MET-related searches at ATLAS and CMS. These are “SUSY” searches
- Strong results from monojet and monophoton searches. These are “Exotics” searches
- Weak constraints on invisible decays of the Higgs boson

Monojets

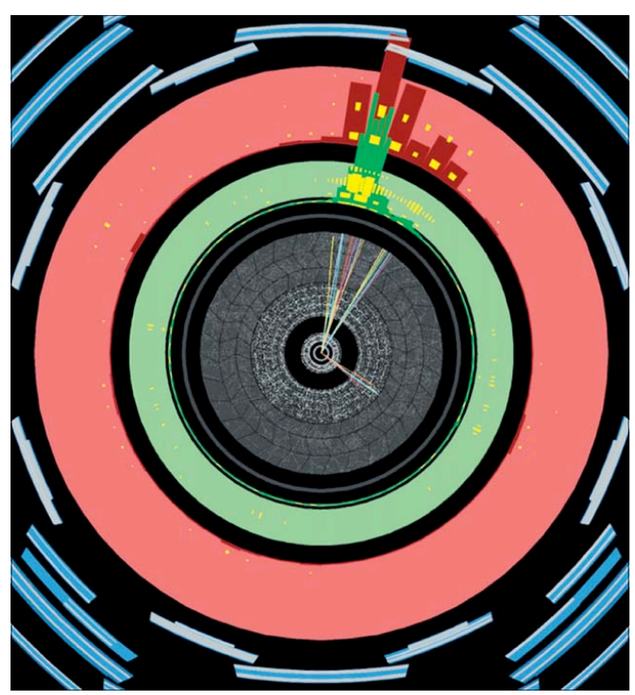
Direct production of DM particles, or Nature's garbage collector?



DM signal



Z(→νν) background



A Brief History of Monojets
1984: SUSY discovered at UA1

SLAC–PUB–3551
LBL–18990
January 1985
(T/E)

IMPLICATIONS OF A SYSTEMATIC STUDY OF THE CERN MONOJETS FOR SUPERSYMMETRY*

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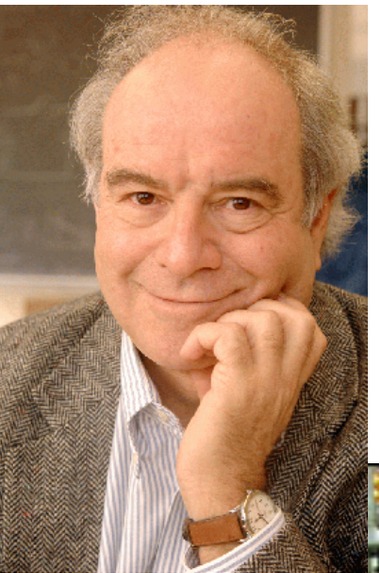
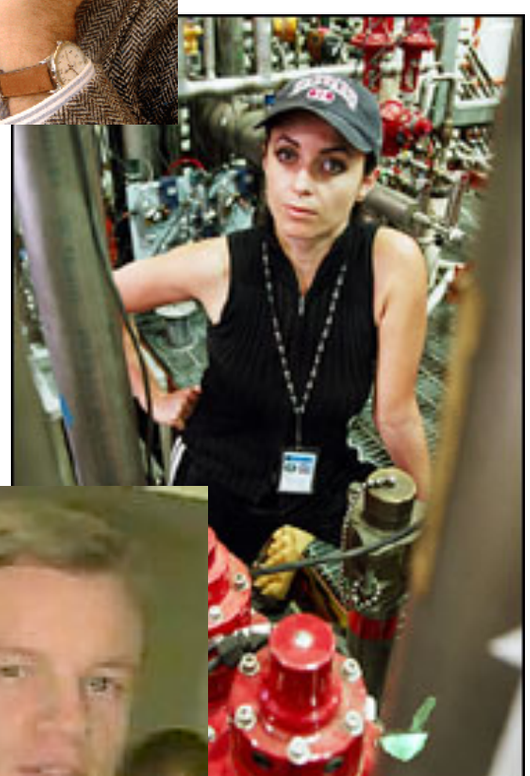
Submitted to *Physical Review Letters*

ABSTRACT

We report on a comprehensive study of supersymmetric processes which could give events similar to those observed at the CERN $S\bar{p}p.S$ collider. The present limited data seem to suggest a gluino mass $\lesssim$ 20 GeV and a scalar-quark mass of 100 – 120 GeV, although certain other supersymmetric masses are not yet excluded. With this choice of masses we also predict that other events with different characteristics should be observed. An essential ingredient of our analysis is the inclusion of events originating from a perturbatively generated gluino distribution function inside the proton.

A Brief History of Monojets
The Tevatron/U. Chicago Revolution





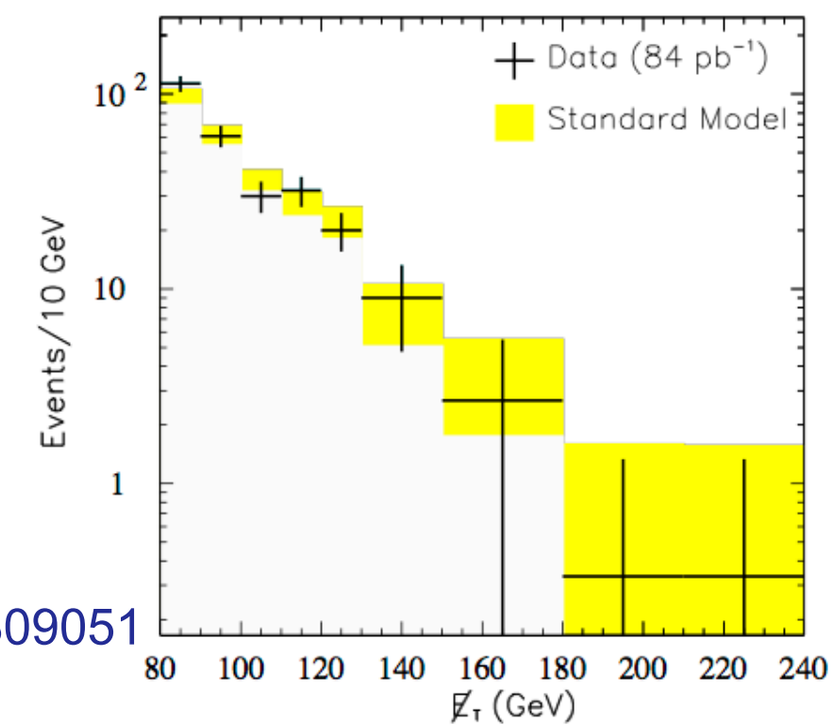
Percentage of monojet events, AFTER cleanup, coming from badly mismeasured jets:

Run 0: 60%

Run 1: 8%

TABLE II: The predicted number of events in the final sample from standard model sources and the number observed in the data.

Background Source	Predicted Events
$Z(\rightarrow \nu\bar{\nu})$+jets	160.2 ± 11.5
$W(\rightarrow \tau\nu)$+jets	46.6 ± 5.5
$W(\rightarrow \mu\nu)$+jets	23.8 ± 5.0
$W(\rightarrow e\nu)$+jets	18.1 ± 4.3
QCD	21.7 ± 6.7
$t\bar{t}$, single t, dibosons	3.9 ± 0.3
Total predicted	274.1 ± 15.9
Observed	284



CDF Tevatron Run II, hep-ex/0309051

A Brief History of Monojets
Precision Monojets at LHC

Percentage of monojet events, AFTER cleanup, coming from badly mismeasured jets:

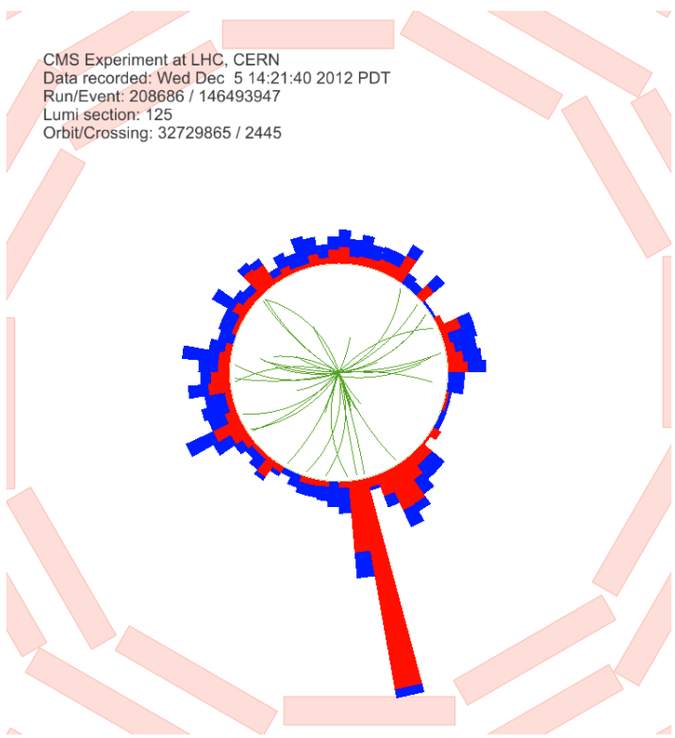
Tevatron Run 0: 60%

Tevatron Runs 1,2: 8%

LHC Run 1: 1%

	SR1	SR2	SR3	SR4
$Z \to \nu\nu + jets$	63000 ± 2100	5300 ± 280	500 ± 40	58 ± 9
$W \to \tau\nu + jets$	31400 ± 1000	1853 ± 81	133 ± 13	13 ± 3
$W \to e\nu + jets$	14600 ± 500	679 ± 43	40 ± 8	5 ± 2
$W \to \mu\nu + jets$	11100 ± 600	704 ± 60	55 ± 6	6 ± 1
tt, single t	1240 ± 250	57 ± 12	4 ± 1	–
Multijets	1100 ± 900	64 ± 64	8^{+9}_{-8}	–
Non-coll. Background	575 ± 83	25 ± 13	–	–
$Z/\gamma^* \to \tau\tau + jets$	421 ± 25	15 ± 2	2 ± 1	–
Di-Boson	302 ± 61	29 ± 5	5 ± 1	1 ± 1
$Z/\gamma^* \to \mu\mu + jets$	204 ± 19	8 ± 4	–	–
Total Background	124000 ± 4000	8800 ± 400	750 ± 60	83 ± 14
Measured Events	124703	8631	785	77

ATLAS arXiv:1210.4491



For results stay tuned for talks by Steven Schramm and Sarah Malik

SUSY searches already in many different topologies

- **MET + jets (ie, quarks/gluons)**
- **MET + b-quarks**
- **MET + jets + 1 lepton (e or μ)**
- **MET + jets + 2 leptons (same sign)**
- **MET + jets + 2 leptons (opposite sign)**
- **MET + single jet**
- **MET + jets + 1 lepton + b-quarks**
- **MET + jets + 2 leptons + b-quarks**
- **MET + jets + Z-boson**
- **MET + 3 or 4 leptons**
- **MET + jets + 1 photon**
- **MET + jets + 2 photons**
- **MET + leptons and no jets**
- **etc etc etc**

- **<u>Broad program to leave no stone unturned</u>**
- Started with the "easiest" most obvious searches

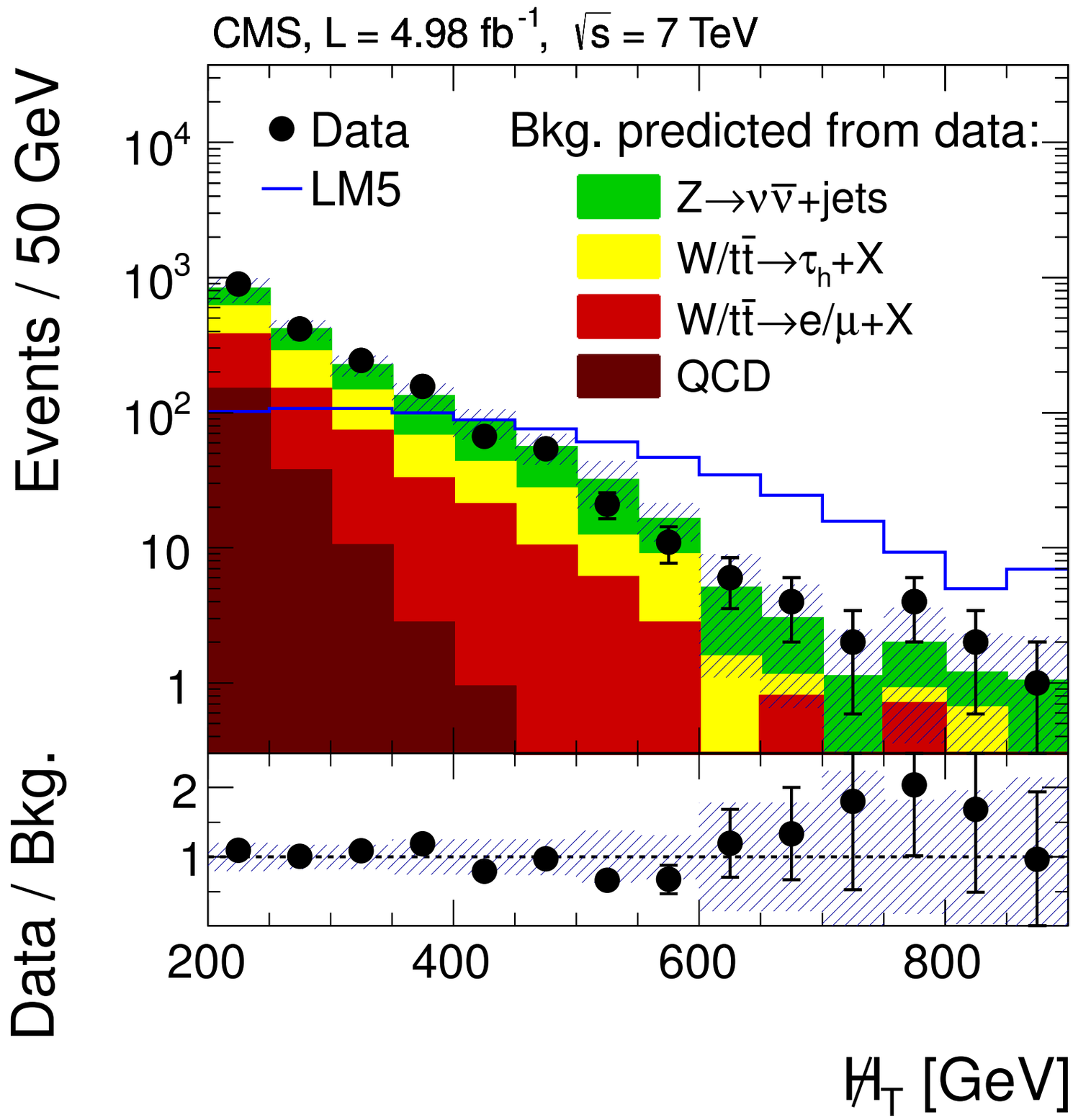
Slide stolen from Claudio Campagnari

It's the background, stupid!

- All the work goes in estimating the background
- "Instrumental backgrounds", eg, fake leptons, are clearly data driven.
- CMS has gone to great lengths to minimize reliance on Monte Carlo also for "physics backgrounds", ie, for tail of SM physics processes

Slide stolen from Claudio Campagnari

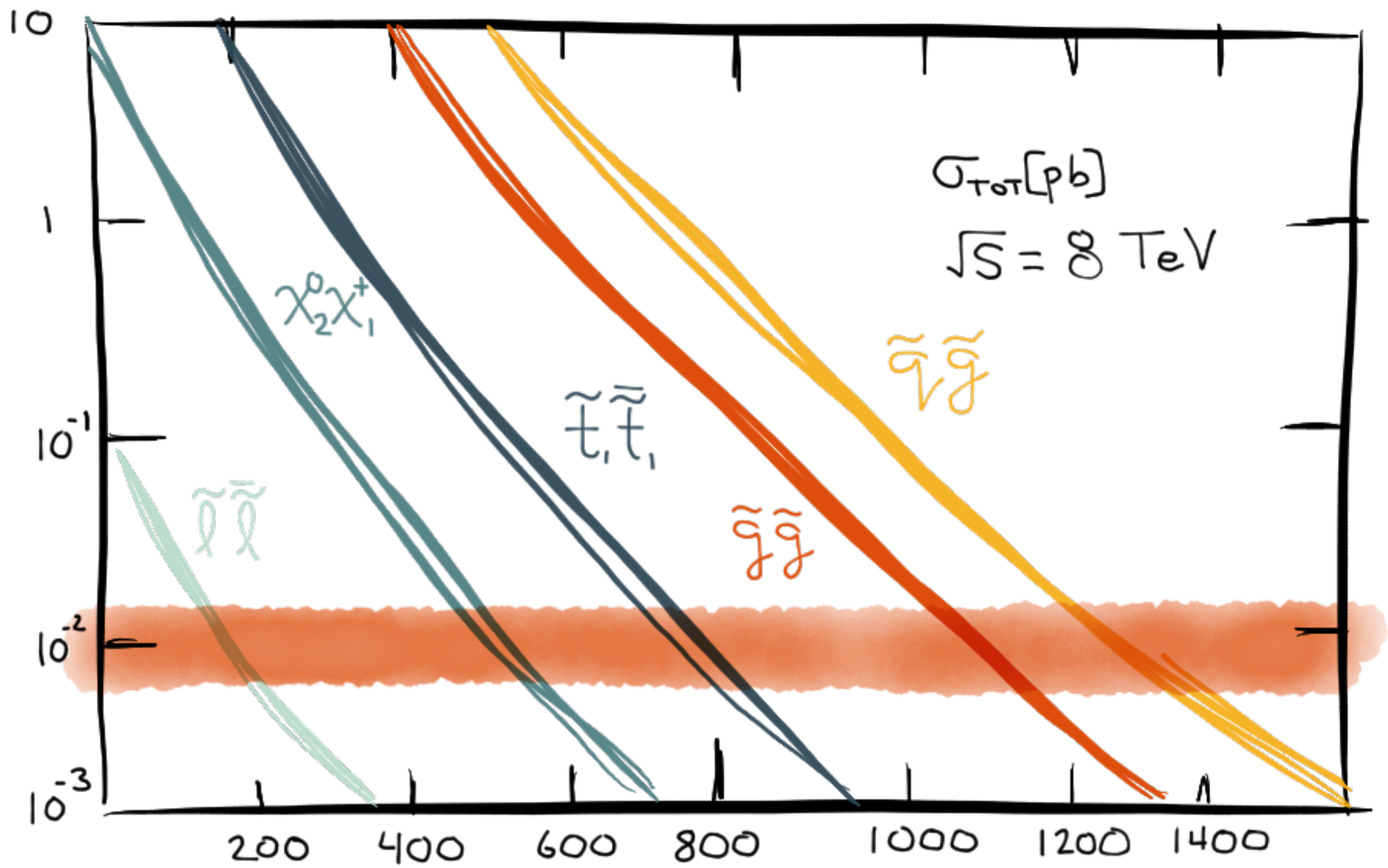
Signal? Fluctuation? Not enough Monte Carlo?



Cross sections in picobarns for superpartner production at 8 TeV

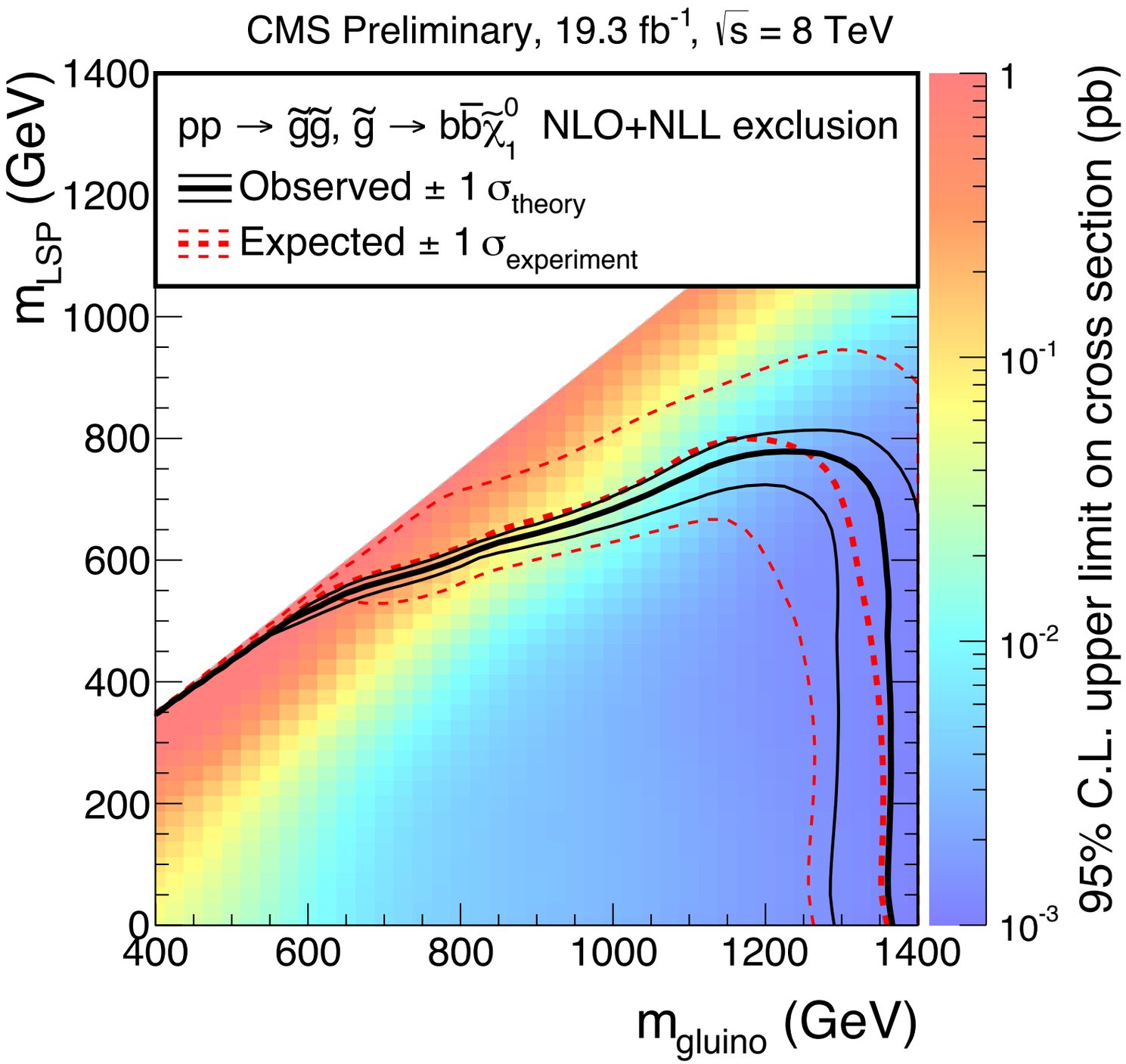
1 picobarn

1 femtobarn



Nathaniel Craig, arXiv 1309.0528

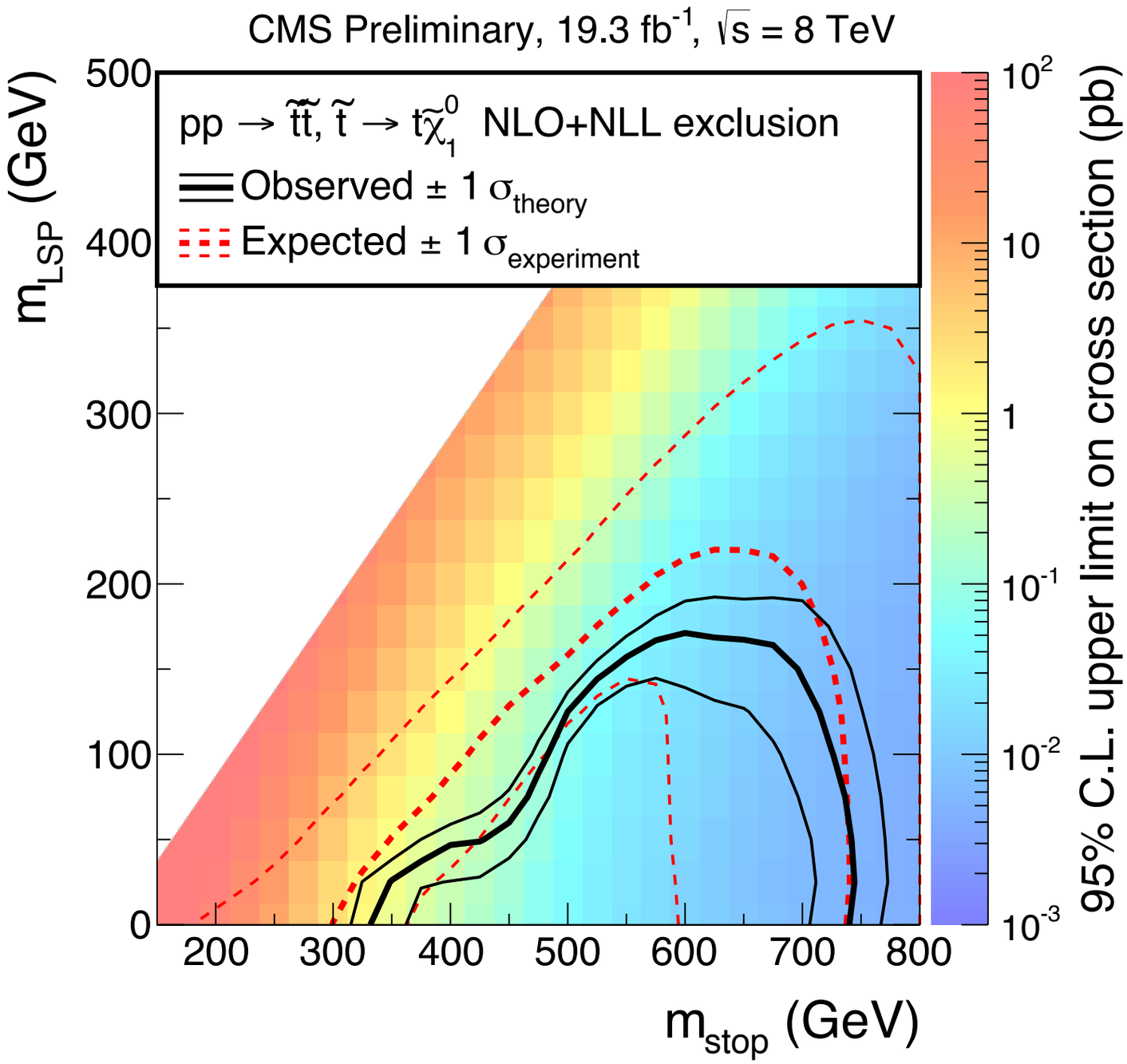
Razor-b: the most sensitive CMS SUSY search so far



- Fully inclusive except for requirement of >= 1 b-tag
- The exclusion at gluino mass 1.35 TeV corresponds to only 8 signal events after a 30% efficient selection
- This corresponds to signal cross section x BR of 1.3 fb
- For comparison the Higgs boson cross section x BR to diphotons is about 10 fb

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13004

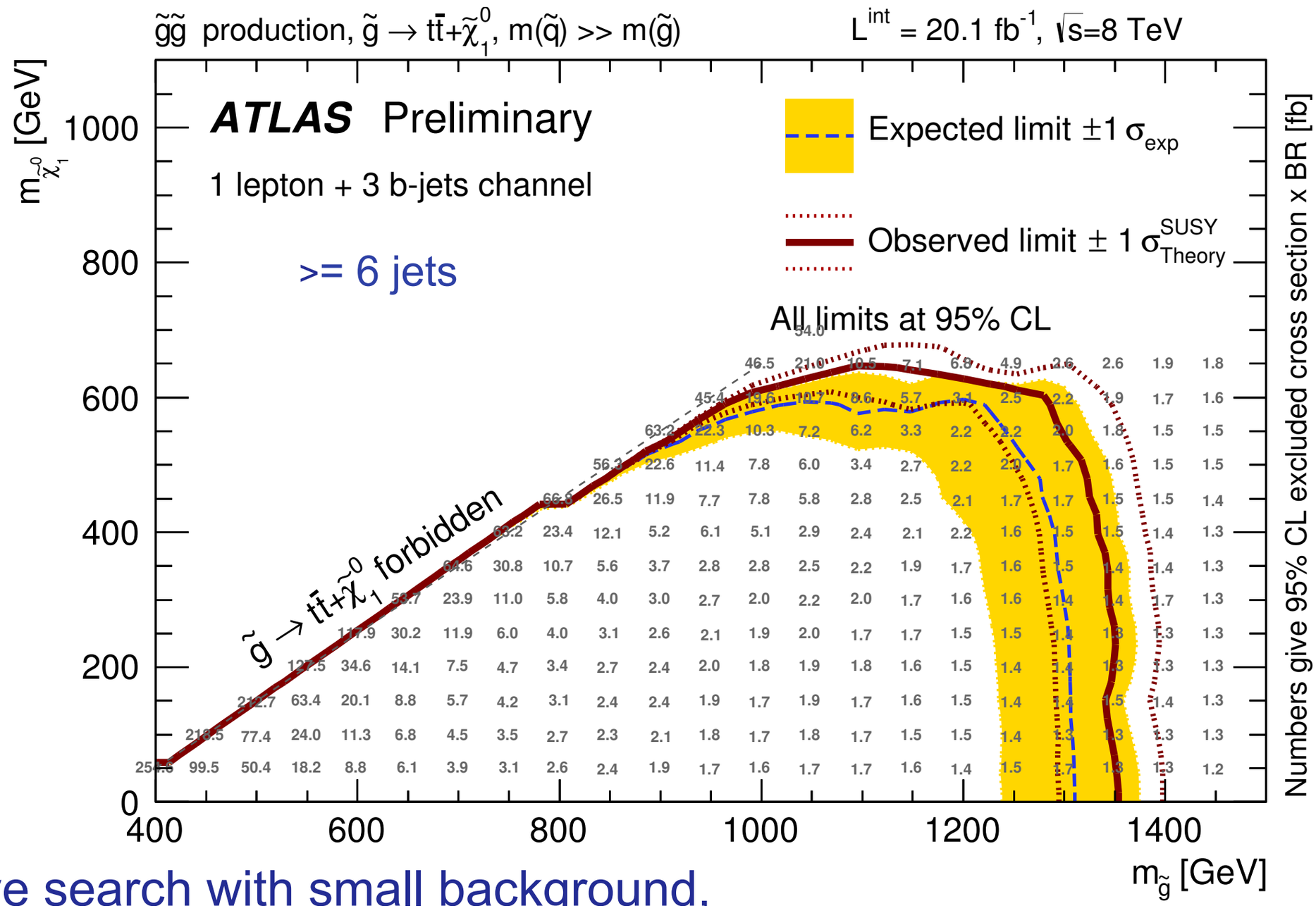
Razor-b: the most sensitive SUSY search so far



- Fully inclusive except for requirement of >= 1 b-tag
- The exclusion at stop mass 740 GeV corresponds to only 30 signal events after a 30% efficient selection
- This corresponds to signal cross section x BR of 5 fb
- For comparison the Higgs boson cross section x BR to diphotons is about 10 fb

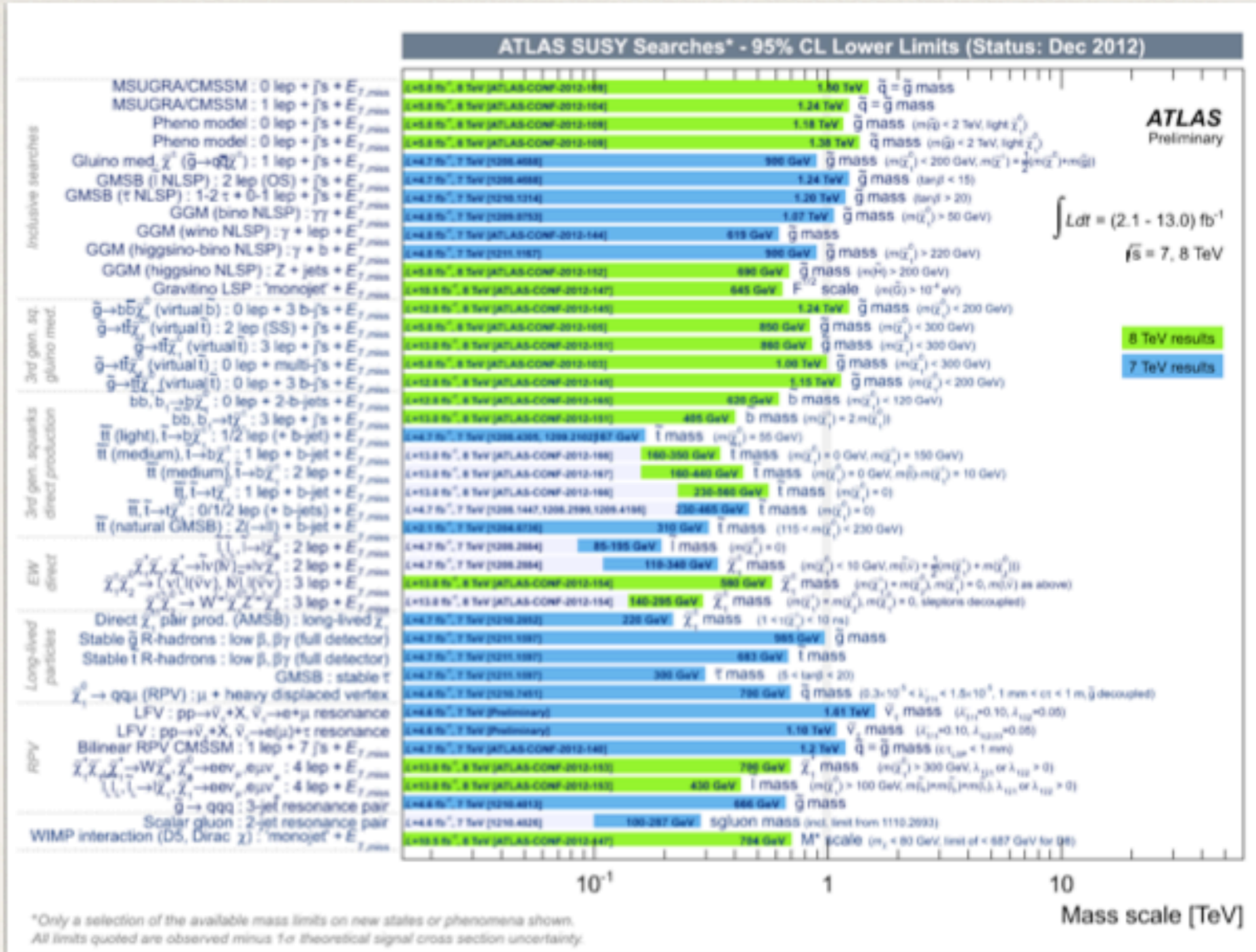
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13004

The most sensitive ATLAS SUSY search so far

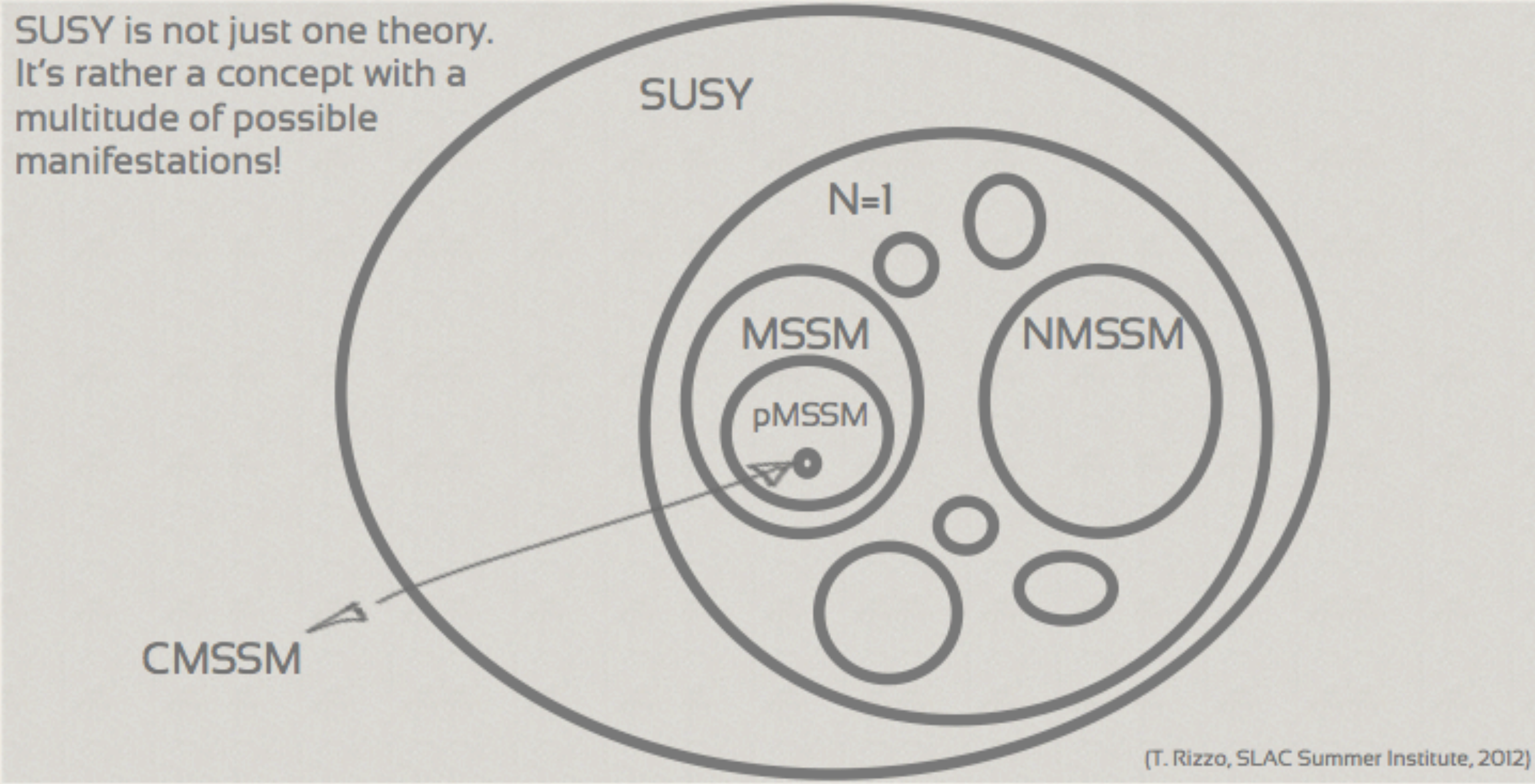


Exclusive search with small background,
but also excludes cross section x BR as small as 1.3 fb

ATLAS-CONF-2013-061



Need to read the fine print when interpreting SUSY exclusion limits



LHC searches at 7 and 8 TeV have so far excluded about 1/3 of the parameter space of the pMSSM

Too soon to tell from LHC exclusions if SUSY is related to the electroweak scale and dark matter

"Natural" SUSY predictions

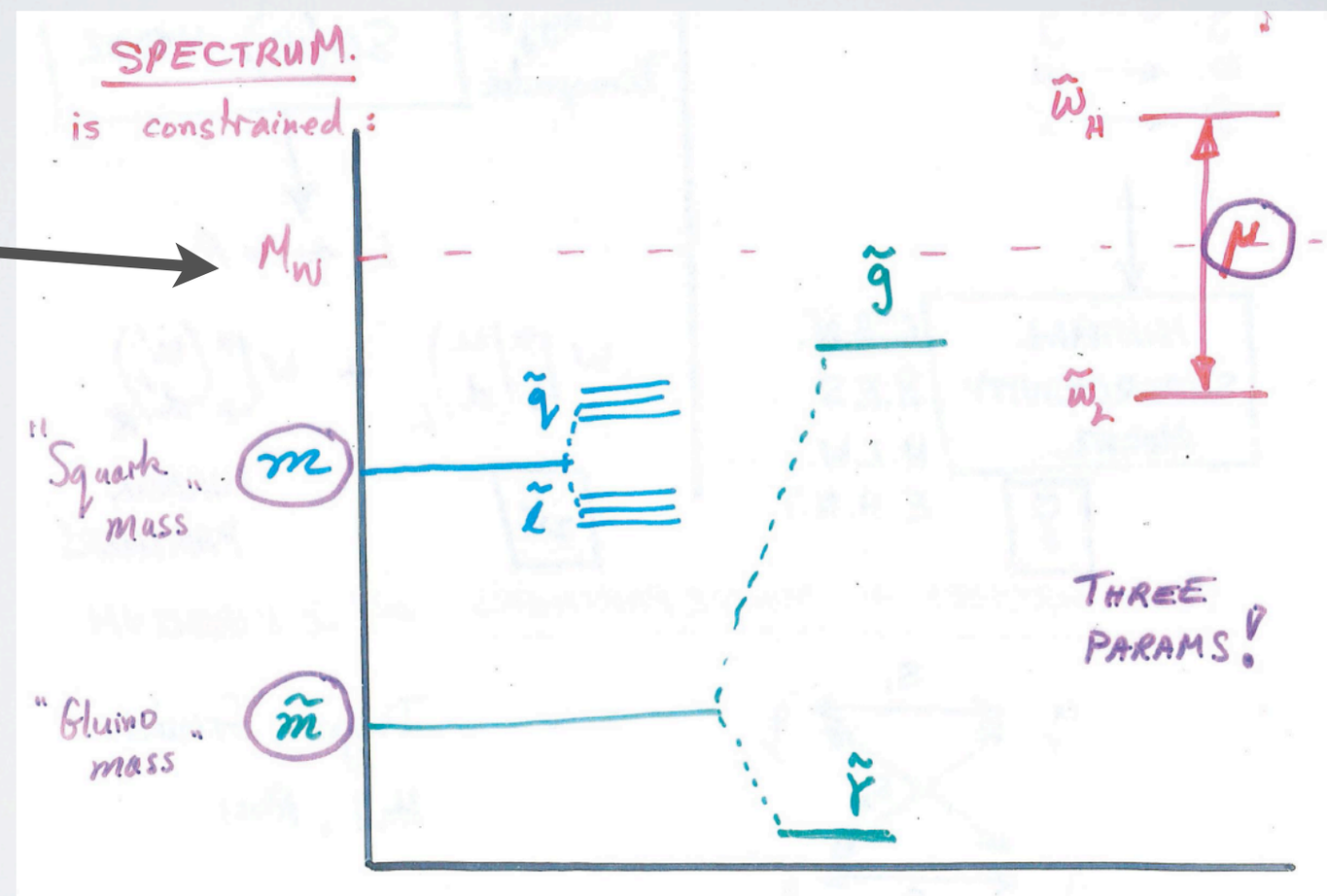
NATURAL SUSY, 1984

From Lawrence Hall's talk at SavasFest

W boson near the top of the spectrum....

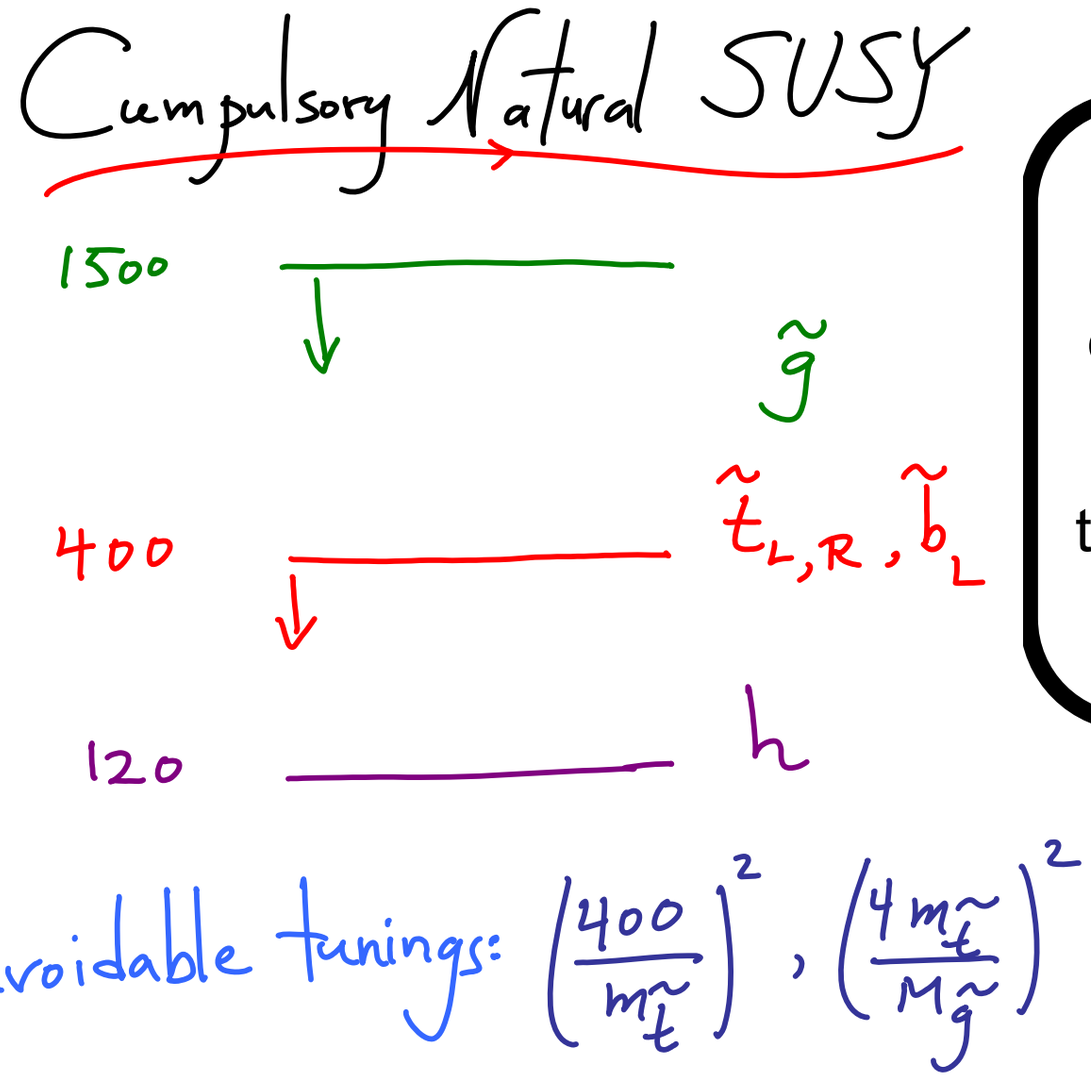
1984 was a utopian year for SUSY.

Times have changed!



Slide stolen from Matt Reece

“Natural” SUSY predictions

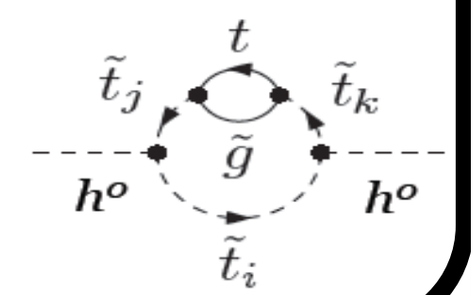


For 10% tuning:

Giudice ‘95
Dimopulus

one loop: stops<600GeV

two loops: gluinos<1400GeV



Natural SUSY is almost, but not quite, dead, dead, dead

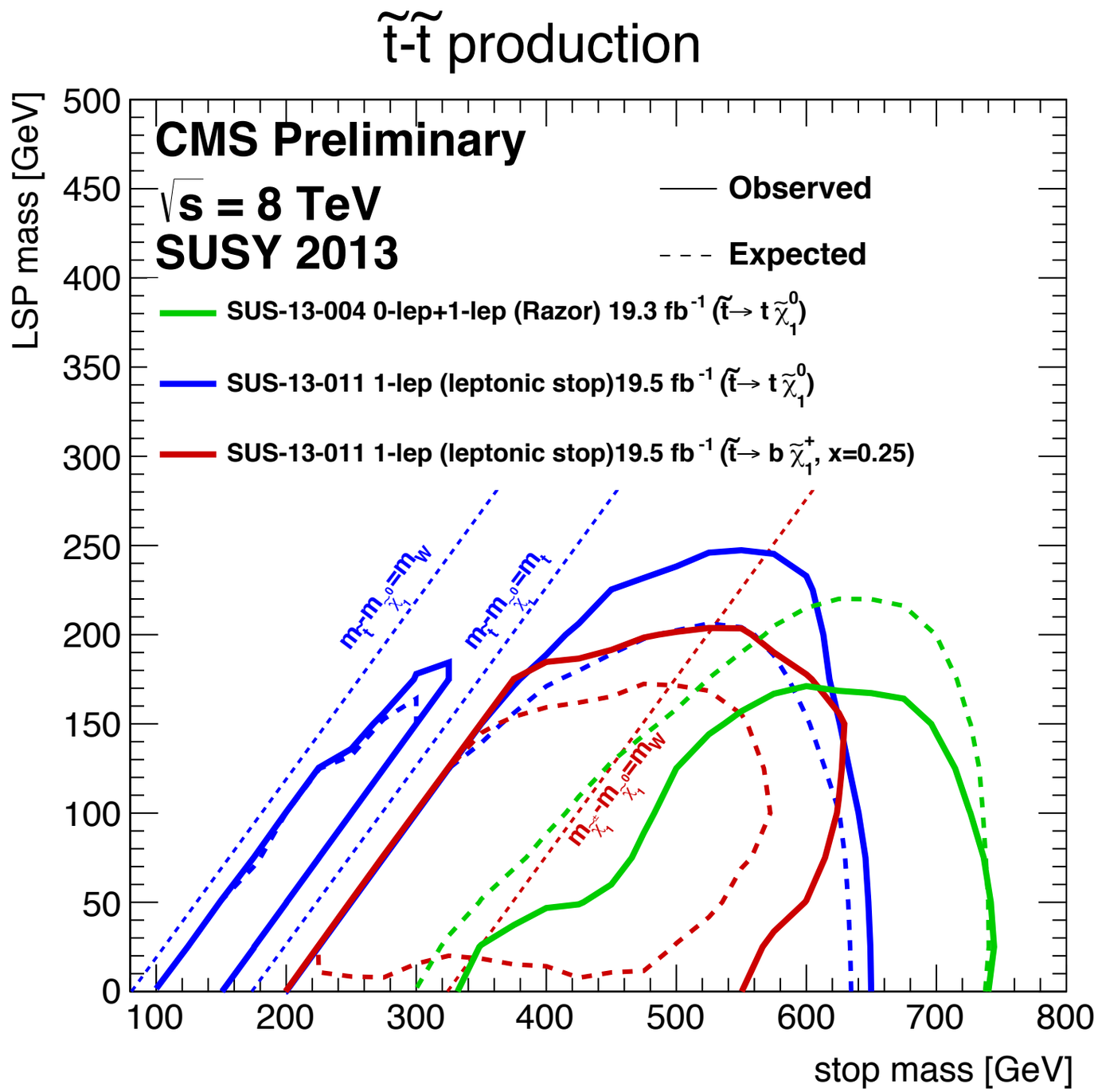
N. Arkani-Hamed talk at CERN Oct. 2012

The Naturalness Dogma:

quem deus vult perdere, dementat prius

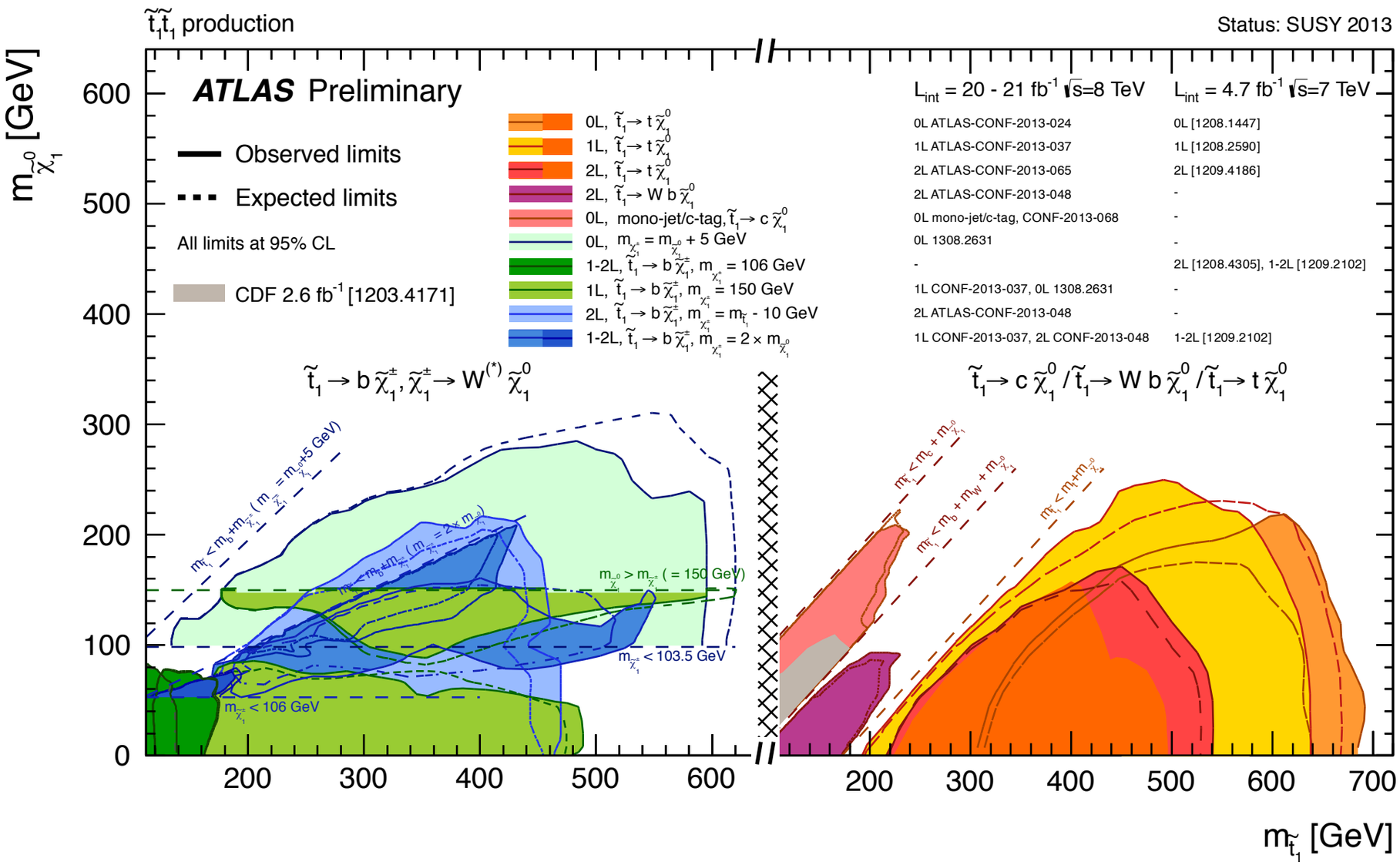
- If superpartners are discovered at LHC, we will figure out what kind of SUSY model we actually have, and shed light on the “small” tuning issues
- But it is interesting already to question whether the mighty cathedral of BSM built up over 30 years may rest on shaky foundations...
- At the very least, should free up our thinking about what are plausible dark matter candidates

Are superpartners hiding?



Maybe, but the gaps are closing…

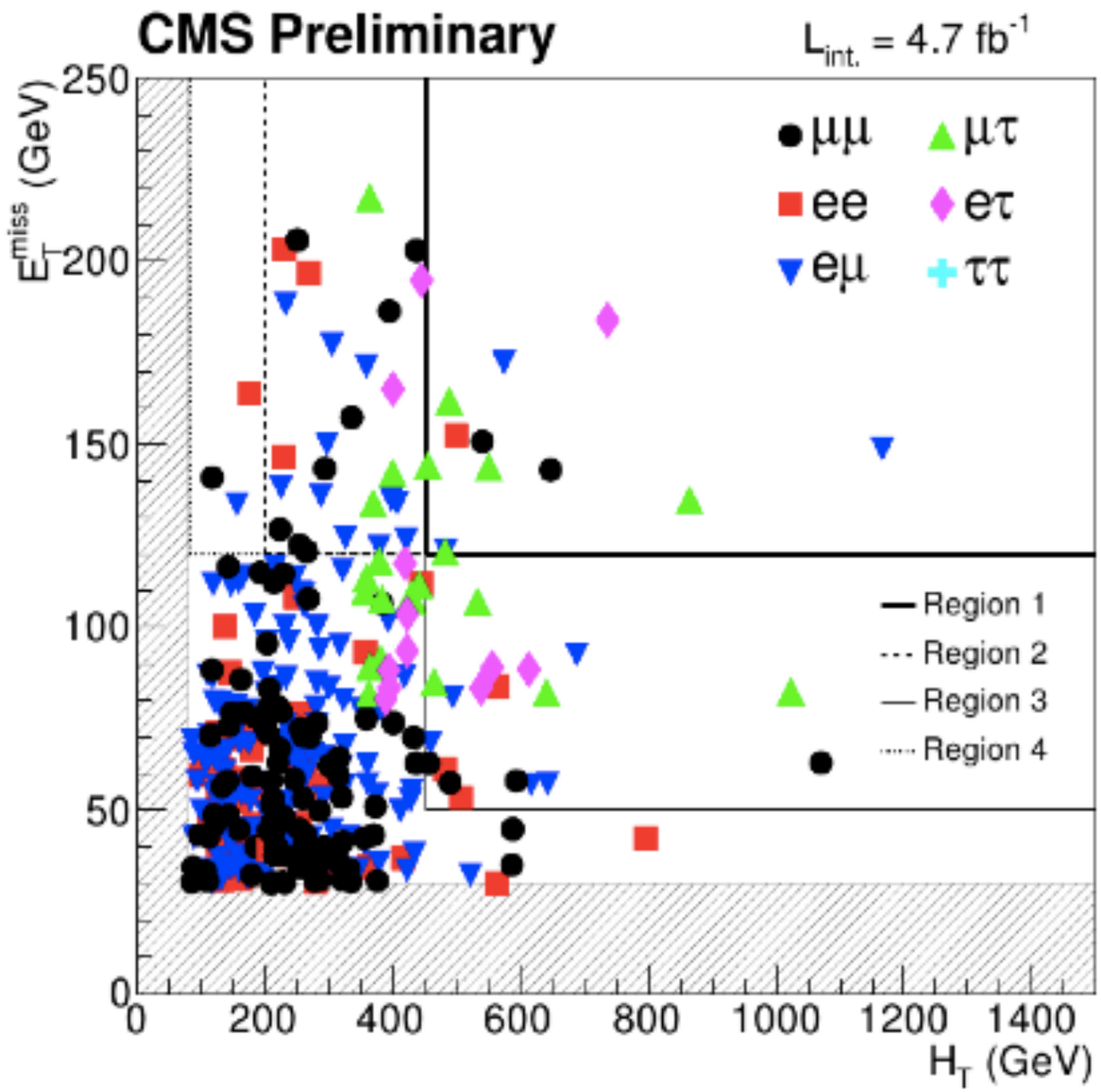
Are superpartners hiding?



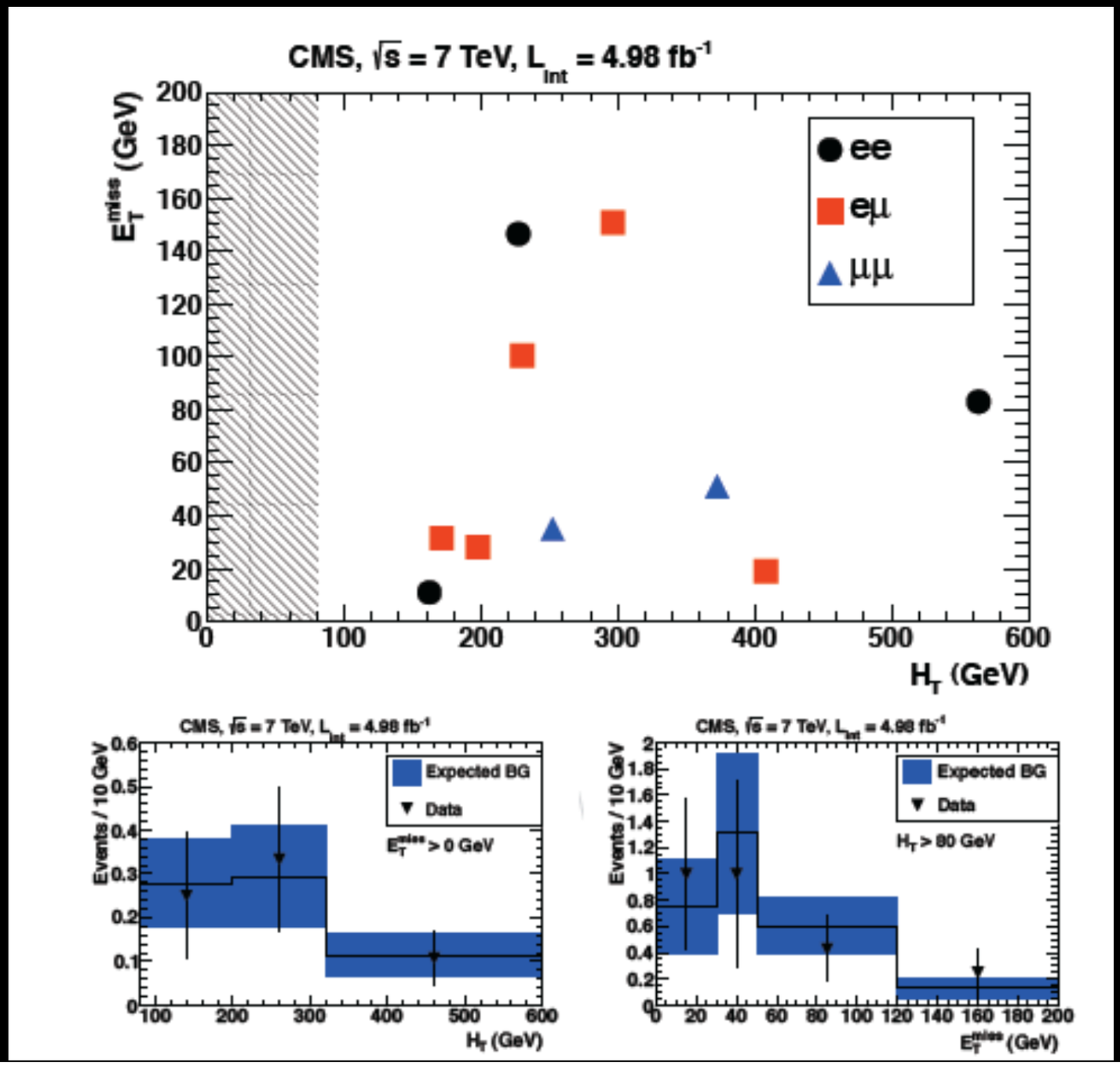
Maybe, but the gaps are closing…

Search with Same-Sign Dileptons

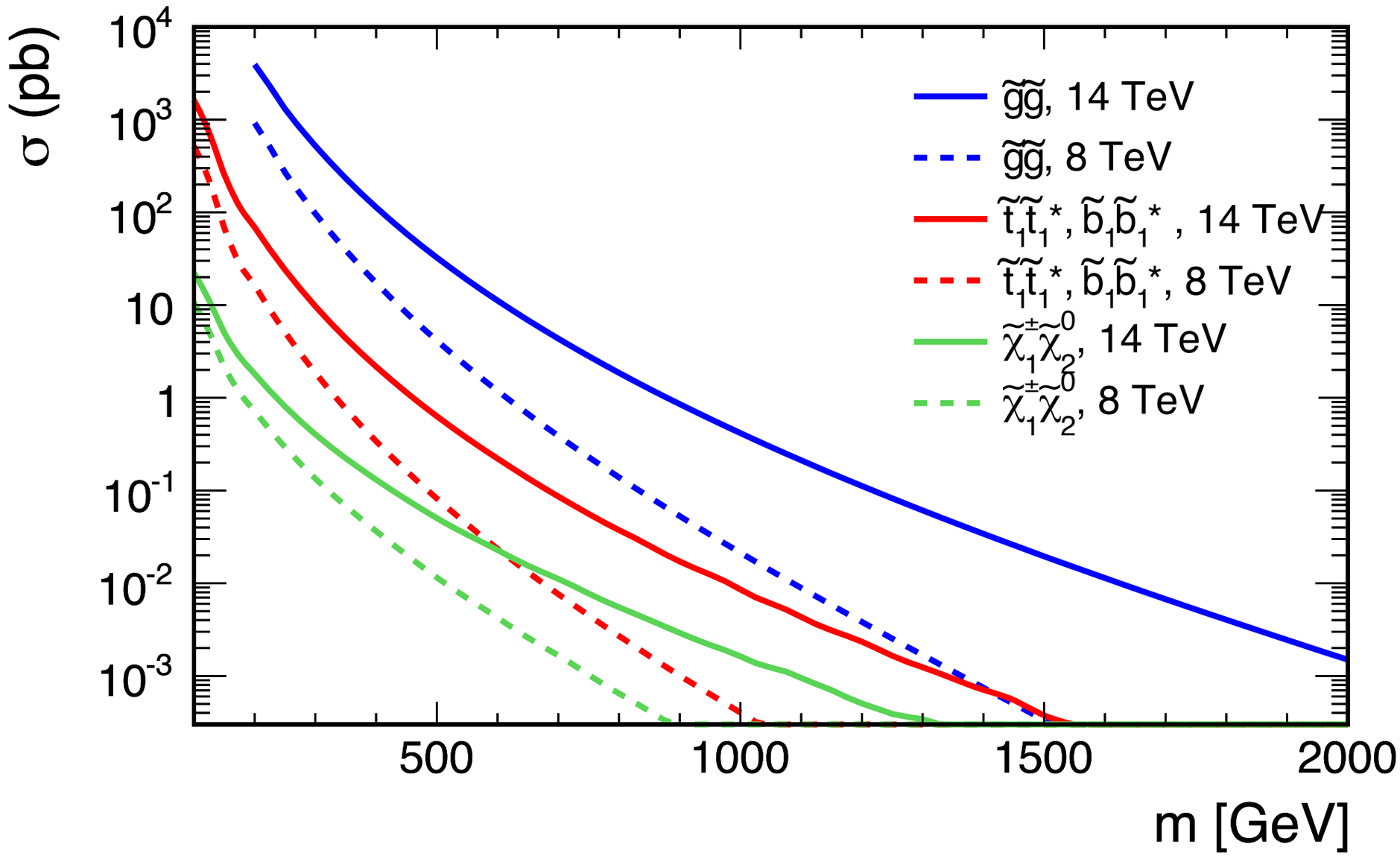
CMS-SUS-11-010



SS + 2 btags results

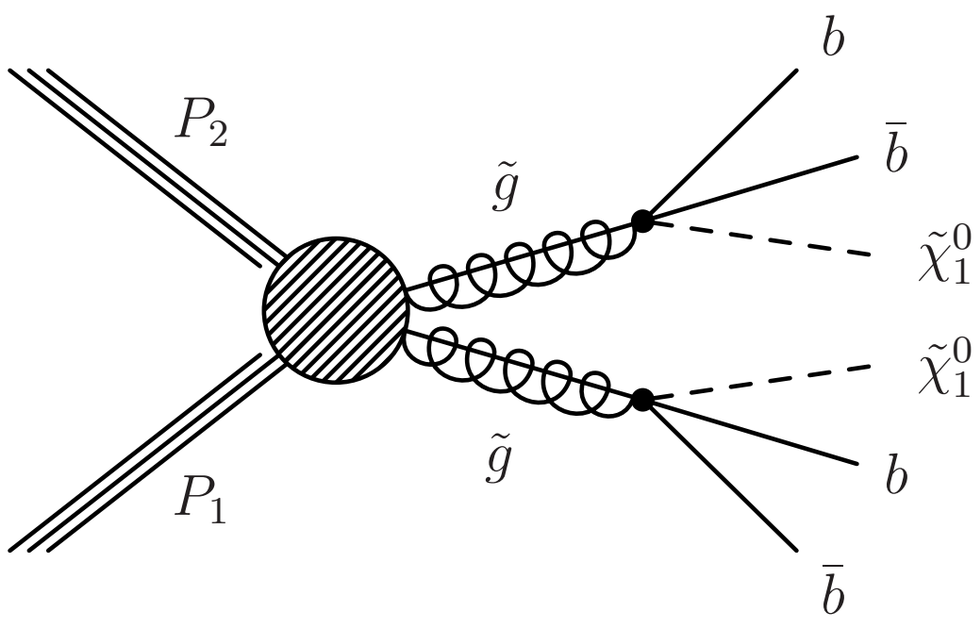


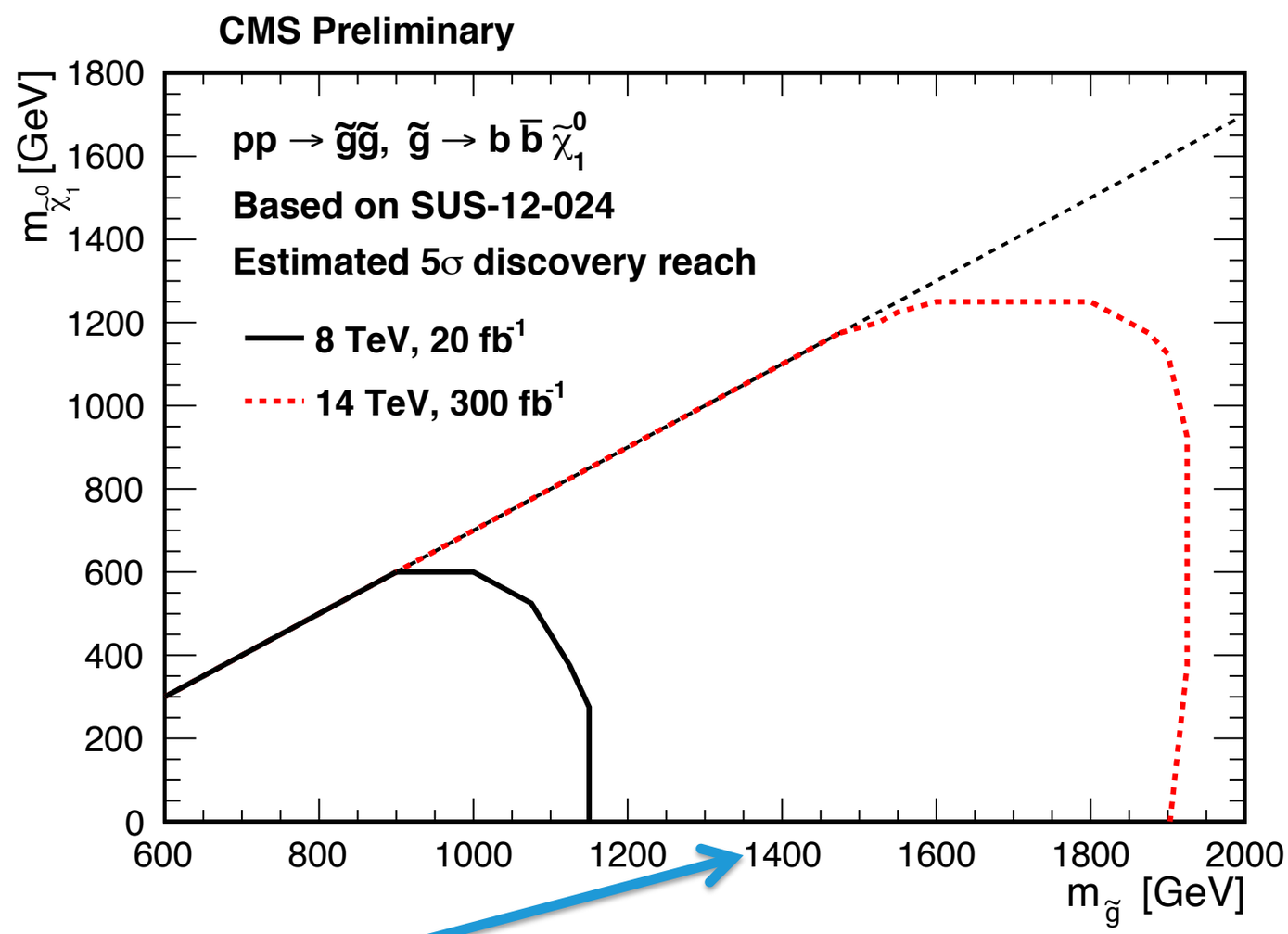
LHC SUSY searches: The Future



CMS Snowmass white paper arXiv 1307.7135

Predictions are hard, especially about the future

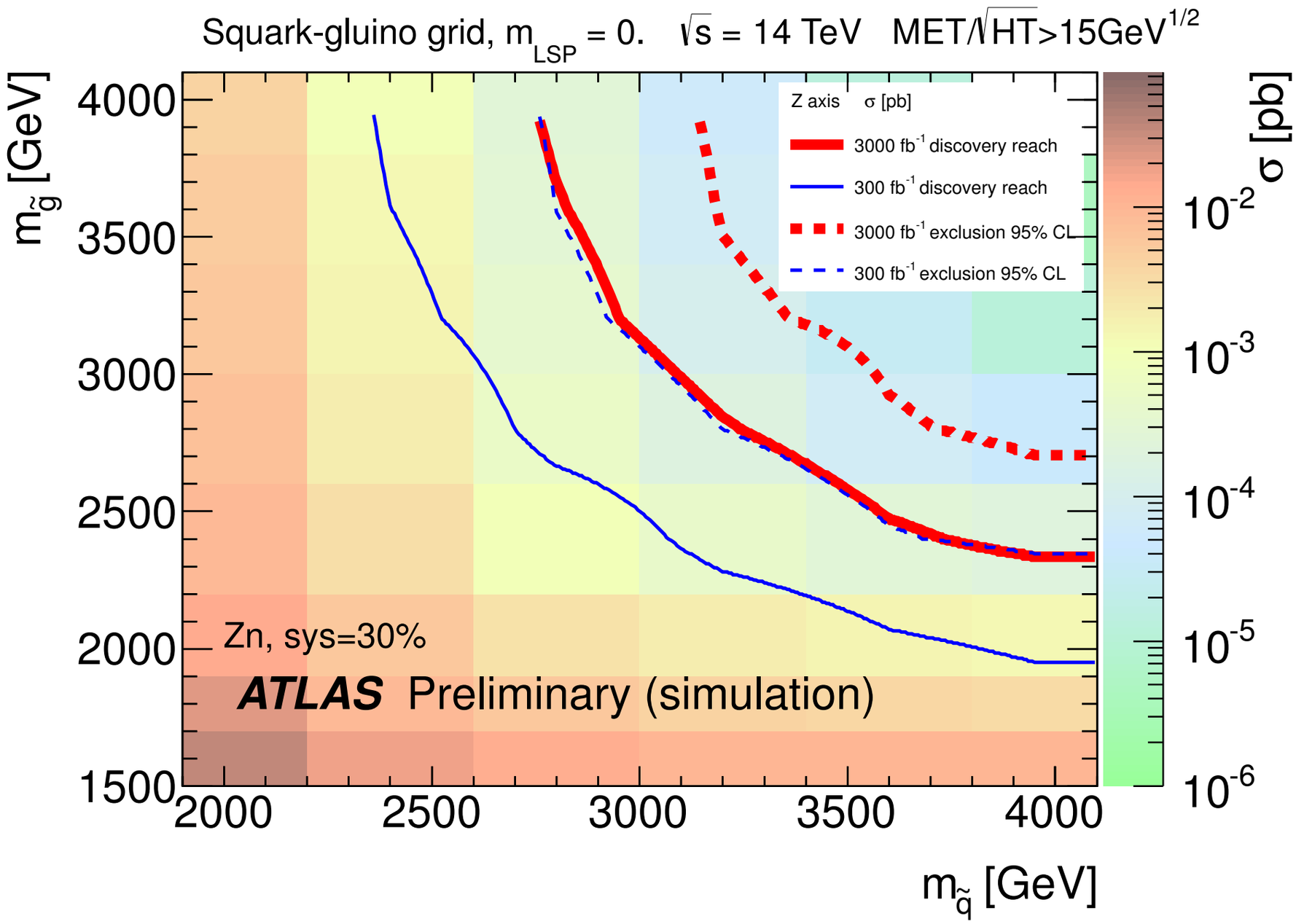




Already we are here!

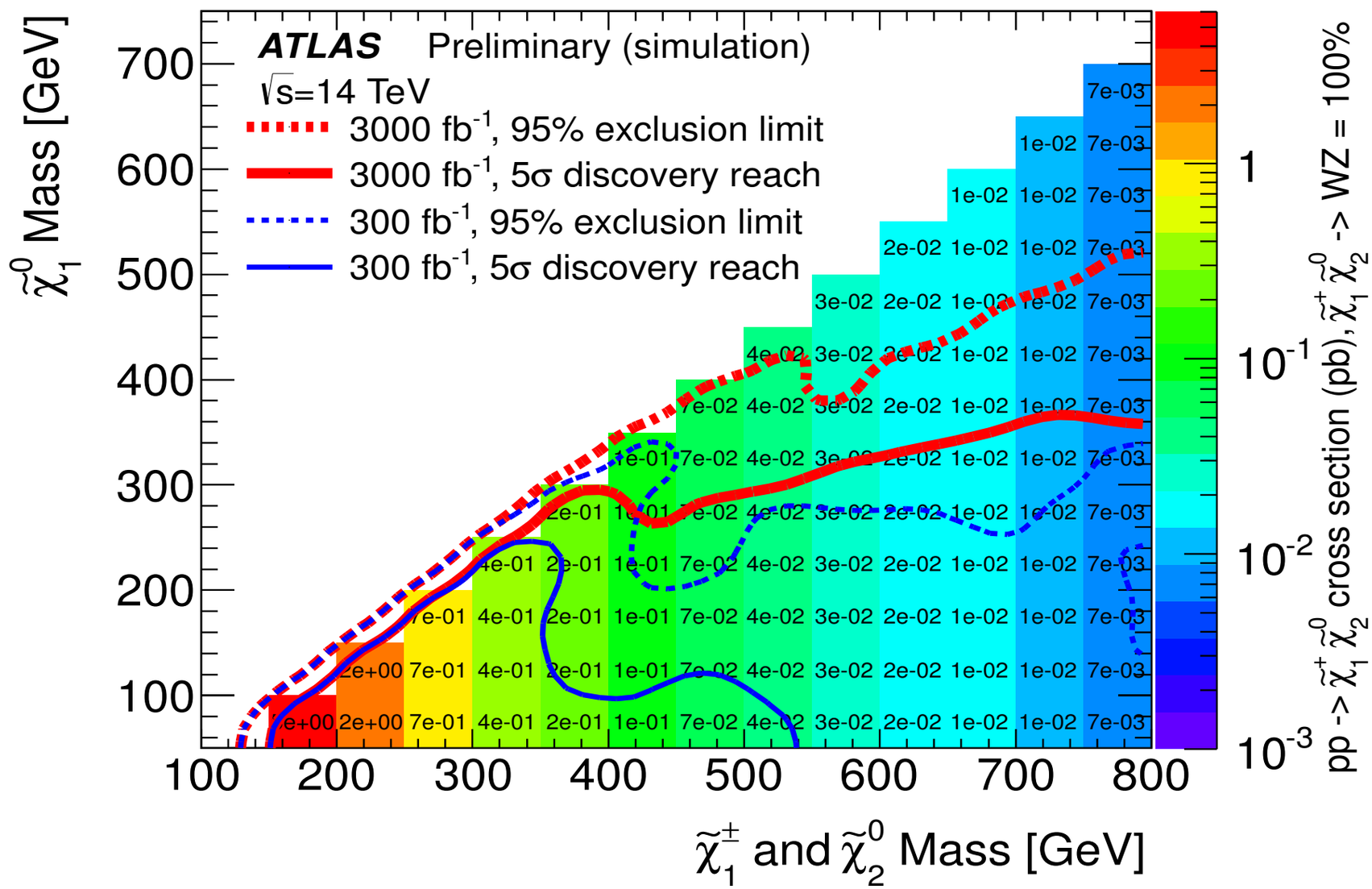
CMS Snowmass white paper arXiv 1307.7135

Ultimate LHC reach for SUSY?



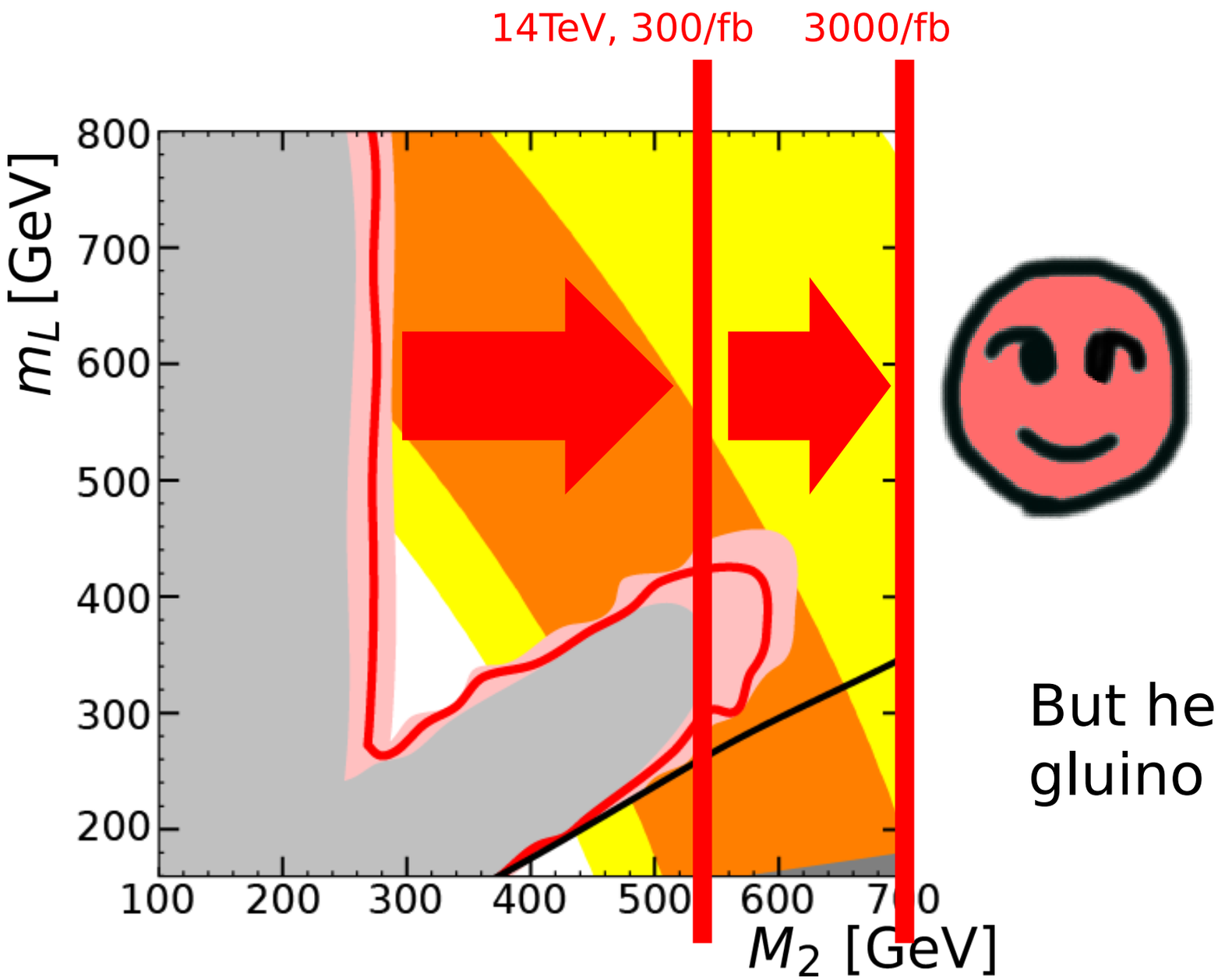
ATLAS projections from ATL-PHYS-PUB-2013-002

Ultimate LHC reach for Electroweakino production



ATLAS projections from ATL-PHYS-PUB-2013-002

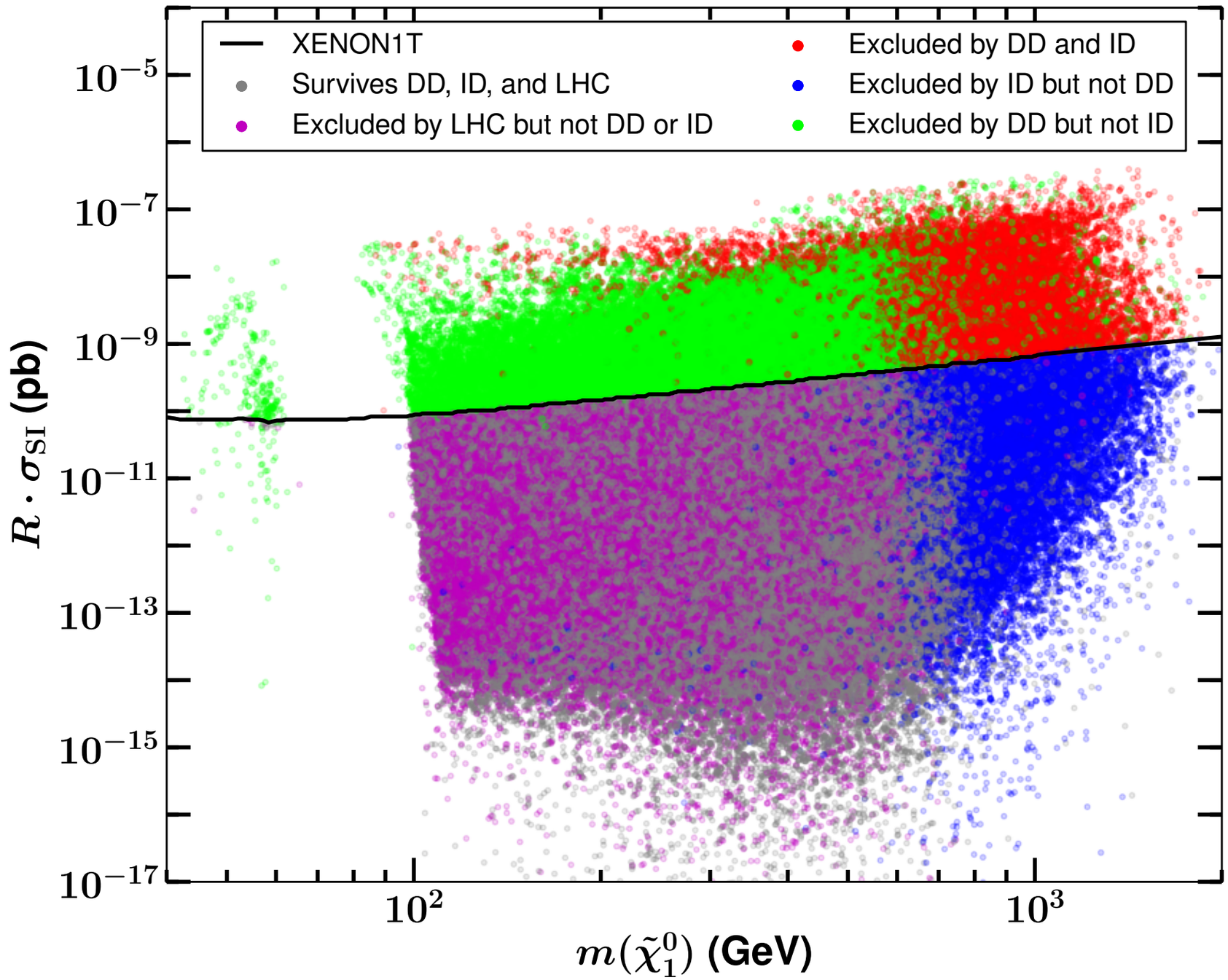
The most-discussed LHC projection at the SUSY 2013 conference



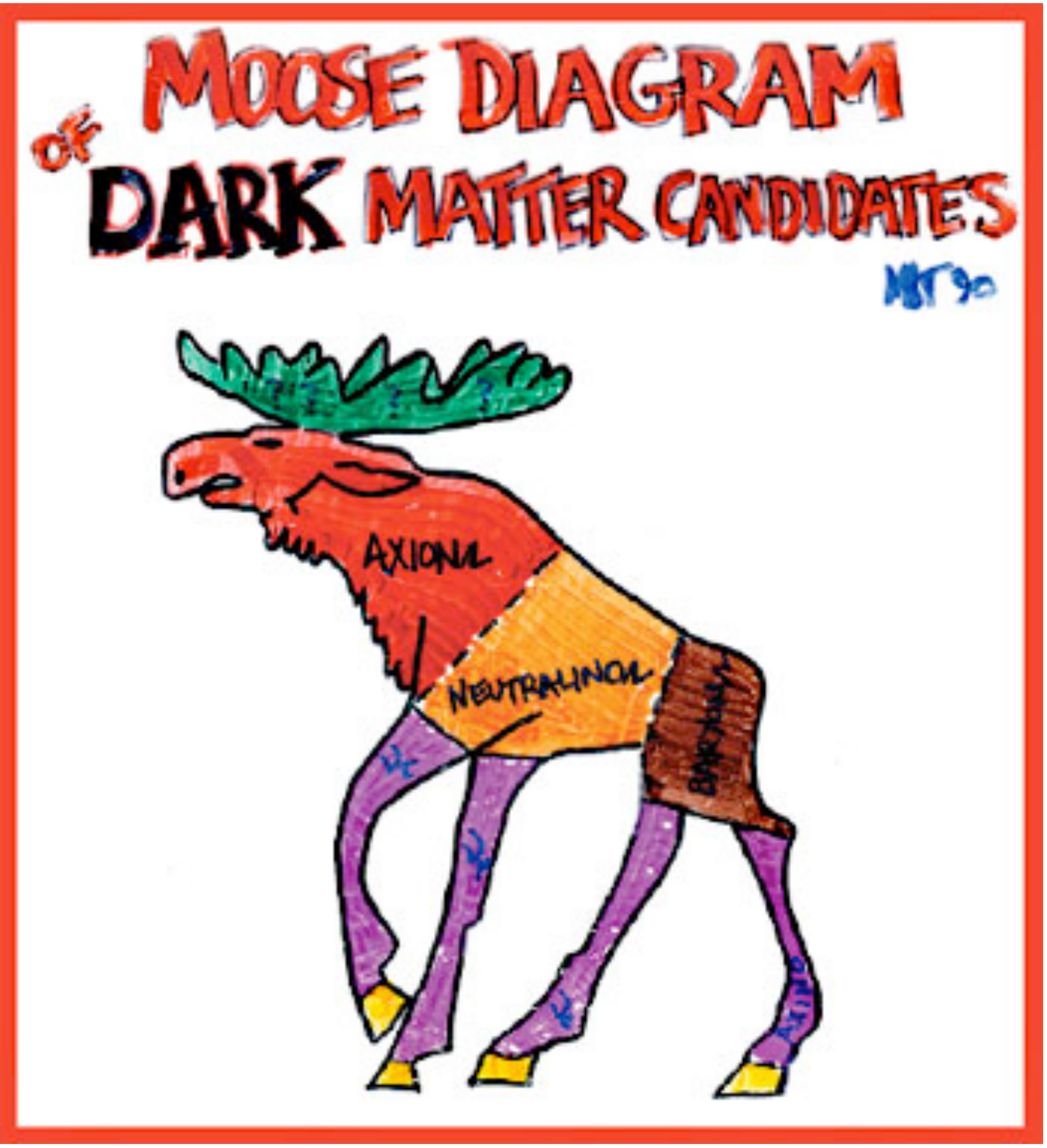
But here
gluino is required.

S. Iwamoto, SUSY 2013 Trieste

Complementarity of LHC vs DD vs ID searches: pMSSM model scan



M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, S. Funk, J. Hewett, A. Ismail, T. Rizzo, M. Wood, arXiv:1305.6921



Dark Matter @ LHC
The Dream

- Discovering the identity of dark matter may be the biggest science accomplishment of your generation
- This is not to suggest that it will be a quick or easy task
- There will be surprises
- The full story of dark matter will be richer than we imagine, pointing us in new directions for particle physics and for cosmology