Experimental SUSY Searches

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U.S. DEPARTMENT OF ENERGY

Office of Science

About this talk (1)

- Not a full compendium of SUSY results from the LHC
- Only on R-parity conserving (RPC) SUSY. Why?
  - Without RPC SUSY loses one of its most compelling motivation (dark matter), and becomes yet-another-BSM theory
  - The space of RPV theories is becomes so vast that just about any search you can think of is an RPV (almost)
- When showing results, almost exclusively use CMS
  - Because I am on CMS and I know them better
  - Because it does not really matter for the points I want to make
  - For each plot/result from CMS you can imagine that there is a similar one from ATLAS

About this talk (2)

- Leave the theory out (covered elsewhere in this workshop)
- Leave statistics out (ditto)
- Not about detectors
- Aimed at graduate students/young postdocs
  - Not (yet) experts in the field

Outline

- A few comments about searches
- Pre LHC expectations
- SUSY cross-sections
- Models
- Limits
- A case study
- Future

New Physics Searches, Ingredients (not just SUSY!)

3 + 1 ingredients

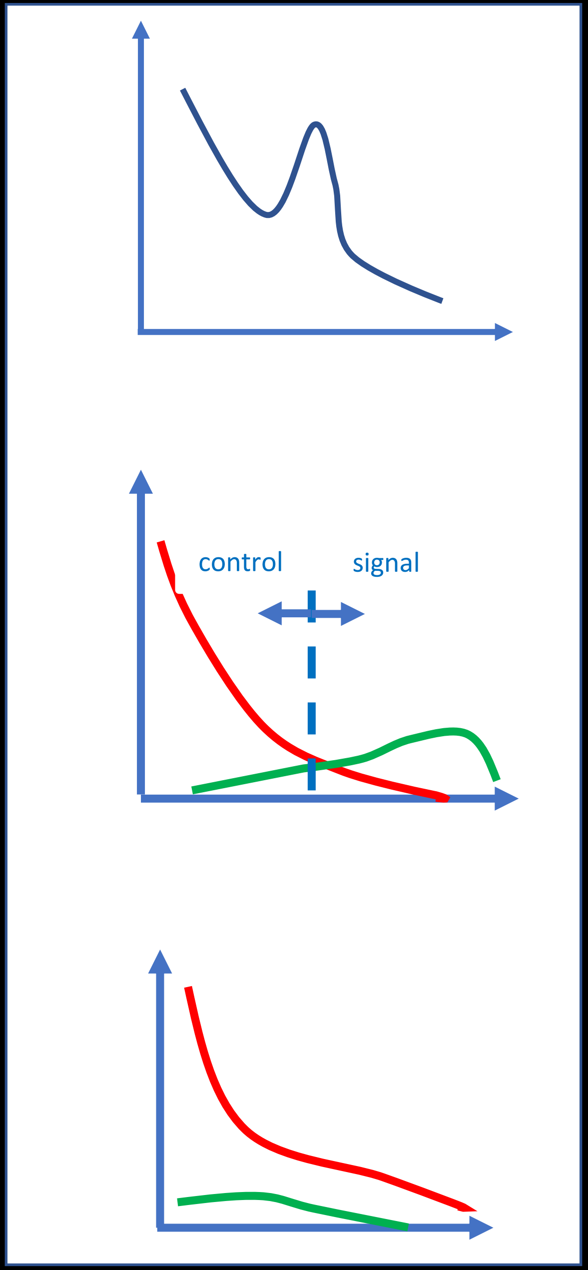
0. **Detector and machine**
1. **Trigger:** *If you didn't trigger on it, it never happened*
   - Will mostly not talk about it
2. **Backgrounds:** *Background is everything*
   - Need to understand SM and instrumental backgrounds
3. **Ideas (or luck):** *If you look for something, you may not find it. But if you don't look, you will never find it*
   - Model independent vs model dependent searches

Roadmap for a search

- **A search is most often an analysis of BG**
- Decide what to look for (!)
  - Pay attention to theory guidance, but don't go overboard
- Define trigger/event selection
  - Most often with MC of signal and BG
- Do not over-tune on a particular signal model
  - Unless you are looking for very specific signal
- Keep it simple
  - Esp. if the 1st time and/or "next year" you get more data
- Think carefully about BG estimate at every step
  - Avoid blind use of MC if you can

Roadmap for a search (cont.)

- Don’t forget very rare (maybe never seen?) SM processes. They can add up.
  - UA1 “found” SUSY in 1984 because of this (!)
  - Here sometimes all you have is MC
- If it is a mass peak it sounds easy (!)
- If you can separate, use control region plus MC or other tricks to extrapolate
  - If counting instead of fitting, careful about sig. contamination
- If on top of each other, difficult
  - Need good control of shape and/or normalization of SM
- Blind analysis



Searches

- Categorized by final state
  - $0\ell,\quad 1\ell,\quad 2\ell$ (same-sign, opposite-sign), $\quad > 2\ell,$ photons
  - With/without τ's
  - Measure of hadronic activity
    - $N_{jets},\quad H_T = \sum P_T^{jets}$
  - With/without *b*-quarks
  - Boosted objects?
  - Some measure of P_T^{miss} (of course, for RPC)
- Searches have evolved to categorize events finely in kinematical properties
  - Especially CMS, 100's of "Signal Regions"
    - Will see an example in the "Case Study" later on

Why Many Signal Regions (SR)

- Comprehensive coverage of unknown signals
- Improved sensitivity also for a particular signal
  - Shape analysis vs. counting experiment
- Searches become almost ”signature based”
  - Can be used to constrain (or discover!) something that you were not necessarily looking for
- There ”better motivated” targets where a very focused search makes sense
  - But even then, many SR help

Arguments for model-independent searches

Return to Rationale(s)

1. Have a robust and predictive hypothesis to test- the Standard Model- testing it is classic science.
2. Emphasis should be on understanding and improving the detector performance on SM predictions- time spent elsewhere is very costly (zero sum game for time and $)
3. Exptl papers dependent on a model do not age well- 20 years later one could use the data, but the comparisons with models are junk, and diminish the paper (e.g Trion-ProtoDynamics)
4. Particle theorists do it better- experimentalists should concentrate on communicating results to them and working together
5. Students learn the wrong lessons from poorly-motivated limit setting- complacency on $,time

H. Frisch, Pheno 2009

Before LHC turn-on.....

Discovery "assumed"

How to sort out details?

- Publicity…
- Papers…
- Workshops…
- Olympics…

Physics Letters B
Volume 677, Issues 1–2, 15 June 2009, Pages 48-53

Supersymmetry, the ILC, and the LHC inverse problem

C.F. Berger[a, 1], J.S. Gainer[b, 2], J.L. Hewett[b], B. Lillie[c, d, 3], T.G. Rizzo[b 2]

Show more

7.5. Look-Alikes at the Moment of Discovery

Using the techniques outlined above, it is quite possible that LHC experiments will make a 5σ missing energy discovery with the first 100 pb^{-1} of well-understood data.

At the moment of discovery a large number of theory models will be instantly ruled out because, even within conservative errors for the backgrounds and systematics, they give the wrong excess. However a large number of models will remain as missing energy *look-alikes*, defined as models that predict the same inclusive missing energy excess, within some tolerance, in the same analysis in the same detector, for a given integrated luminosity. The immediate challenge for LHC physicists will then be to begin disambiguating the look-alikes.

Solving the LHC inverse problem with dark matter observations

Baris Altunkaynak, Michael Holmes and Brent D. Nelson
Department of Physics, Northeastern University, Boston, MA 02115, U.S.A.
E-mail: altunkaynak.i@neu.edu, holmes.mi@neu.edu, b.nelson@neu.edu

LHC Inverse Workshop

Workshop Home | Scientific Program | Registration | Travel Information | Accommodations | MCTP

April 12-15, 2006
University of Michigan, Ann Arbor

Theory Space, LHC and the Inverse Problem

Bobby Acharya (ICTP, Trieste)
INFN Monte Carlo Workshop, Frascati
28th February, 2006

Supersymmetry and the LHC inverse problem

Nima Arkani-Hamed,[a] Gordon L. Kane,[b] Jesse Thaler[a] and Lian-Tao Wang[a]
[a] *Jefferson Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, U.S.A.*
[b] *Physics Department, University of Michigan and MCTP Ann Arbor, Michigan 48109, U.S.A.*
E-mail: arkani@physics.harvard.edu, gkane@umich.edu, jthaler@jthaler.net, liantaow@schwinger.harvard.edu

4th LHC  **Workshop**

Princeton, 22 March, 2007

Resolving the existence of Higgsinos in the LHC inverse problem

Sunghoon Jung
School of physics, Korea Institute for Advanced Study, Seoul, Korea
E-mail: nejsh21@kias.re.kr

Expectations quickly met reality

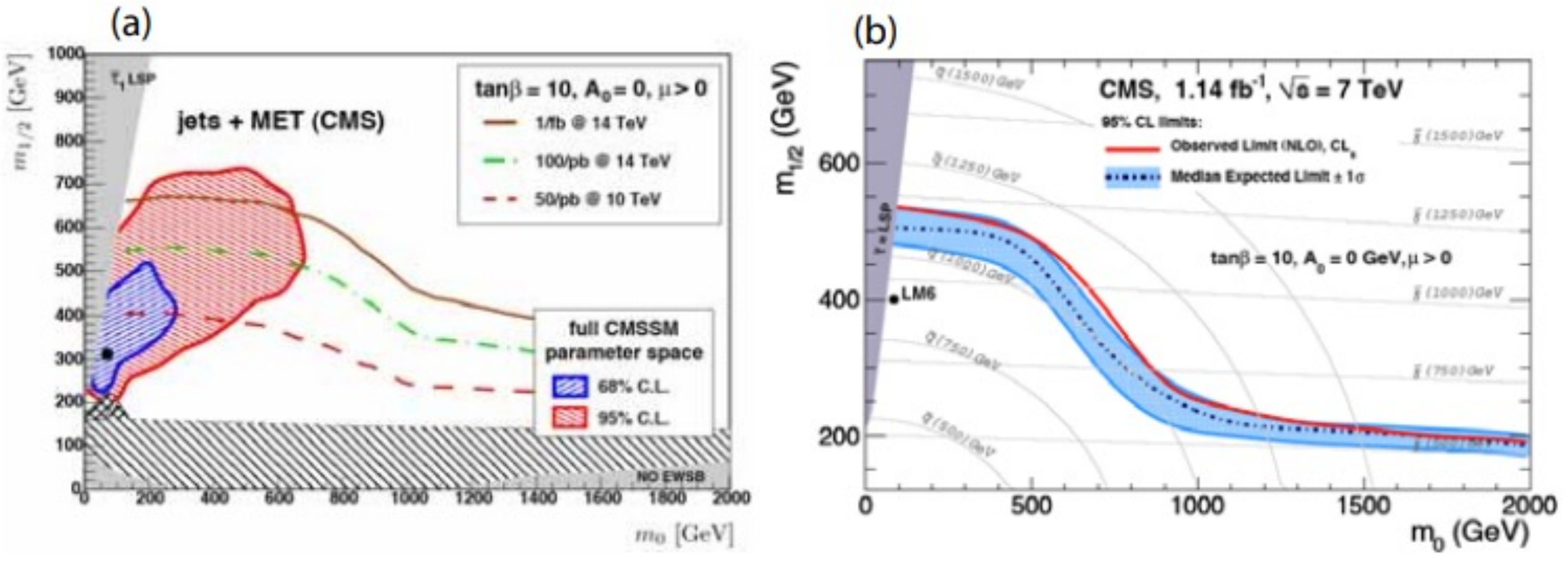
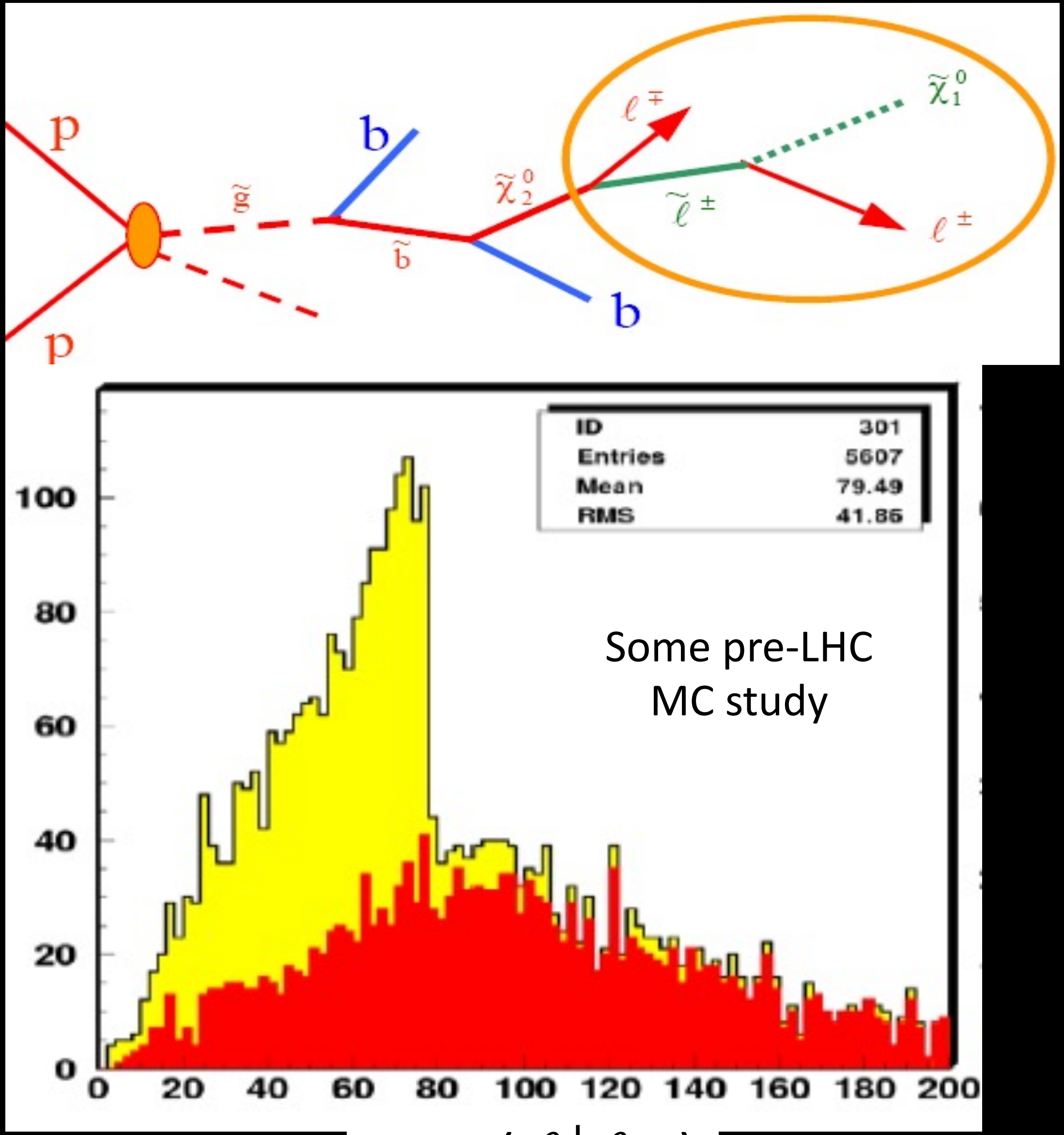


Figure 33: (a) Prediction of [126] at 68% and 95% confidence of the unified supersymmetry-breaking parameters $(m_0, m_{1/2})$ of the constrained Minimal Supersymmetric Standard Model. (b) 95% confidence exclusion region in the parameters $(m_0, m_{1/2})$ in the α_T search for supersymmetry presented by CMS at LP11 [127].

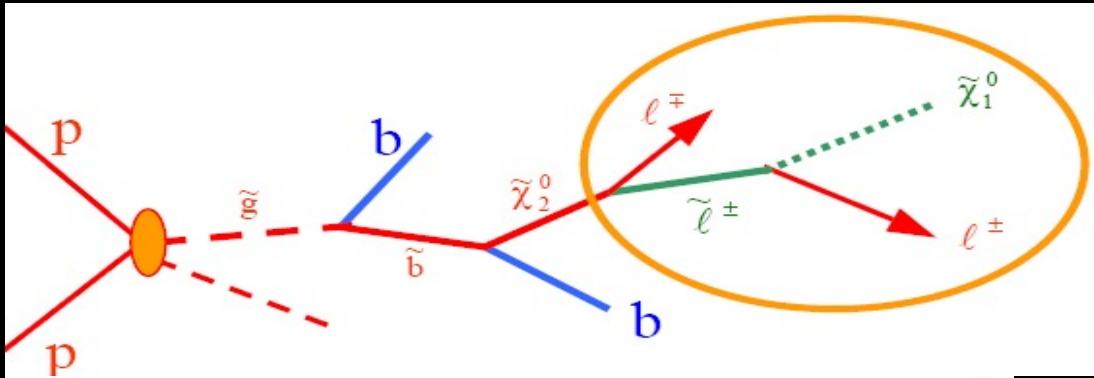
Peskins, Summary of Lepton-Photon 2011
https://arxiv.org/abs/1110.3805

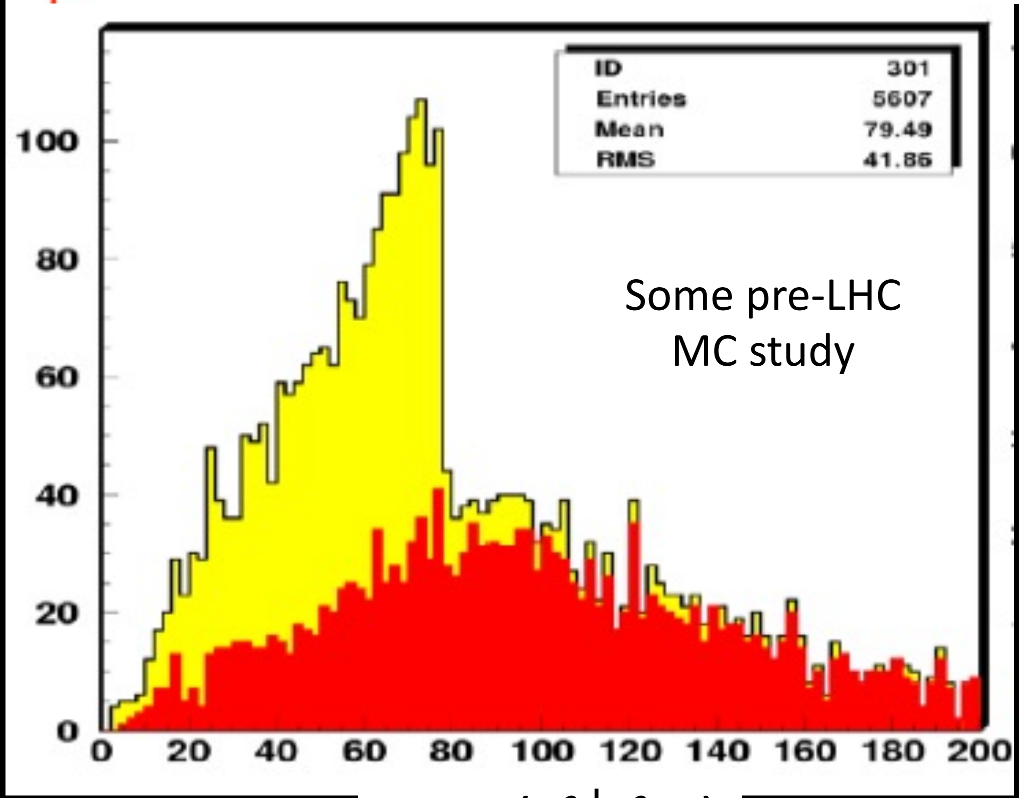
Some SUSY searches looked really easy



Mass($\ell^+\ell^-$)

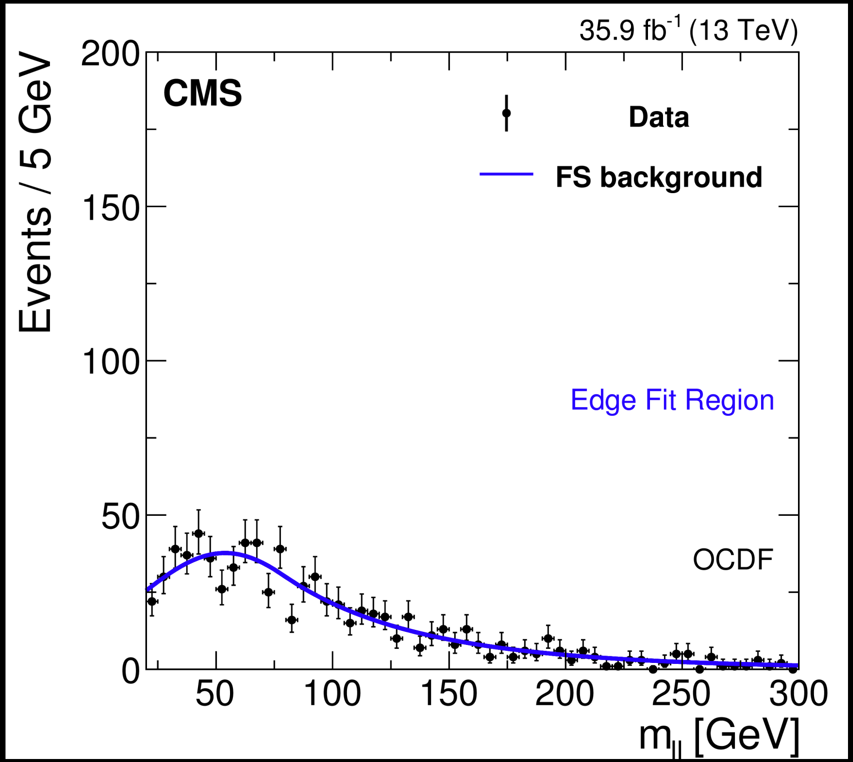
Some SUSY searches looked really easy



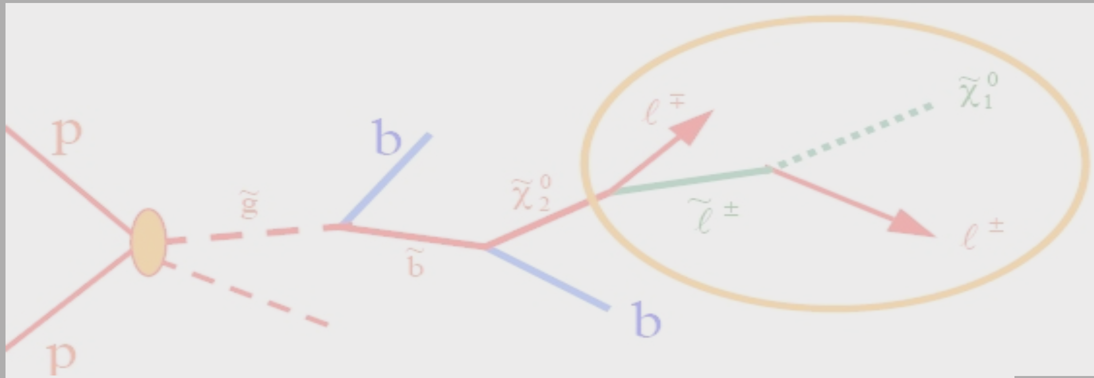


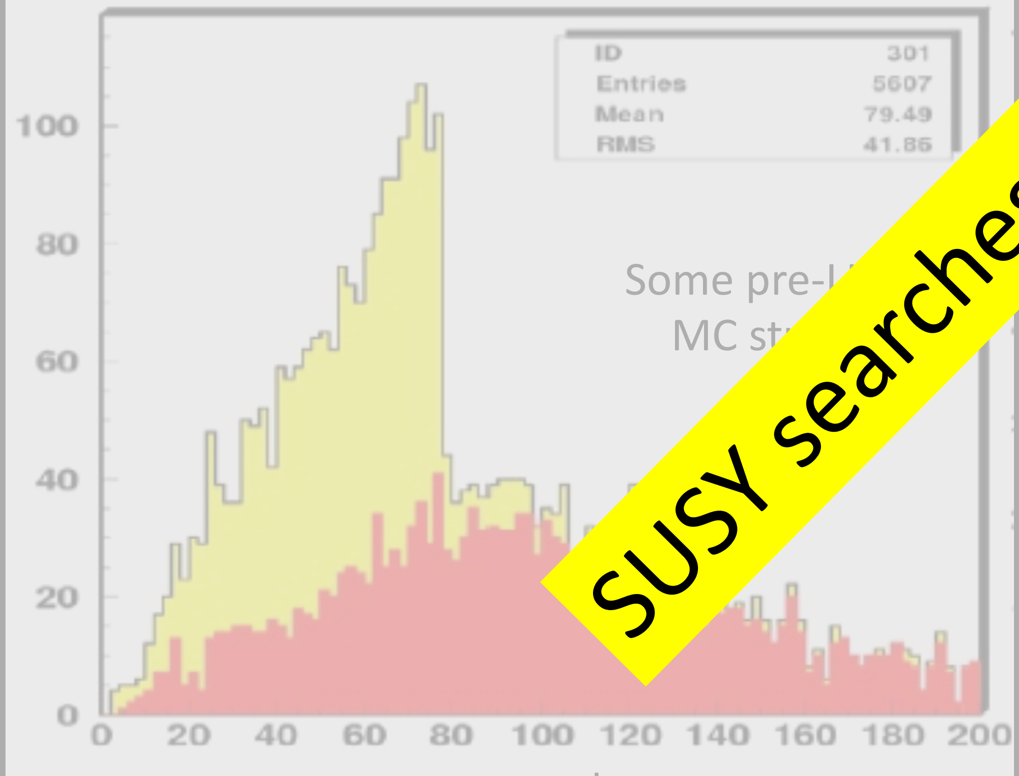
Mass($\ell^+\ell^-$)

Did not turn out that way…..



Some SUSY searches looked really easy



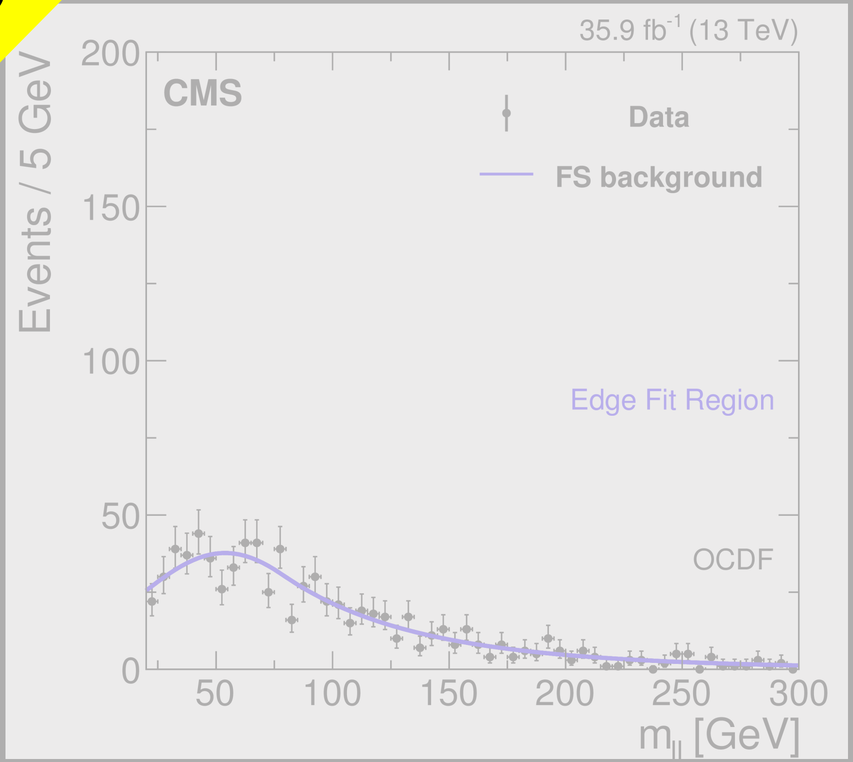


Mass($\ell^+\ell^-$)

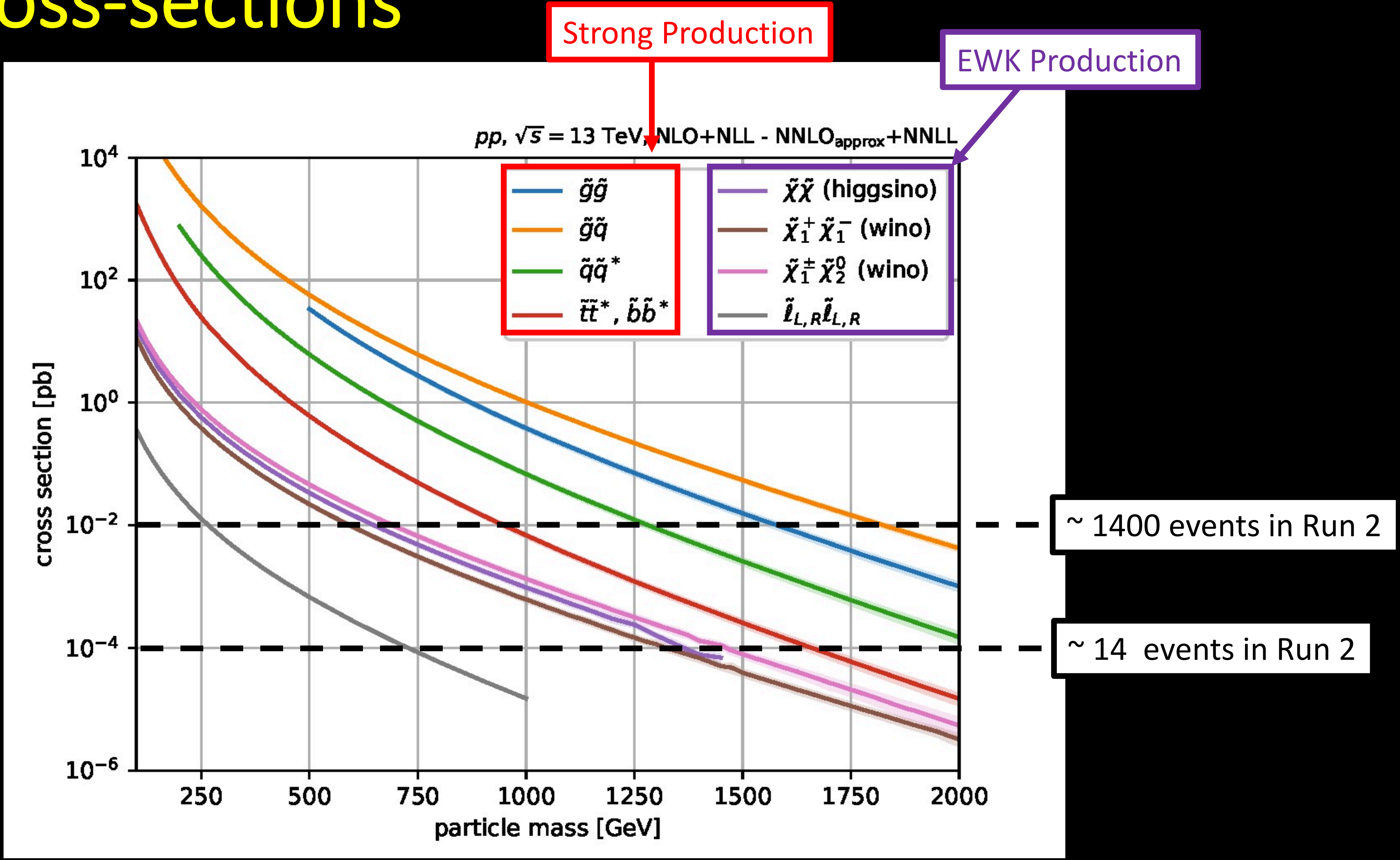
Some pre-L…
MC st…

SUSY searches are not "simple"

Did n… rn out that way.....



SUSY cross-sections



Why the fall off

- Parton-parton x-section, i+j → X:

$$\hat{\sigma}_{ij}(\hat{s}) \text{ at } E_{CM} = \sqrt{\hat{s}}$$

- σ for pp→X:

$$\sigma = \sum \int dx_i dx_j f_i(x_i) f_j(x_j) \hat{\sigma}_{ij}$$

$$\hat{s} = x_i x_j s \quad \text{and} \quad \tau \equiv \frac{\hat{s}}{s}$$

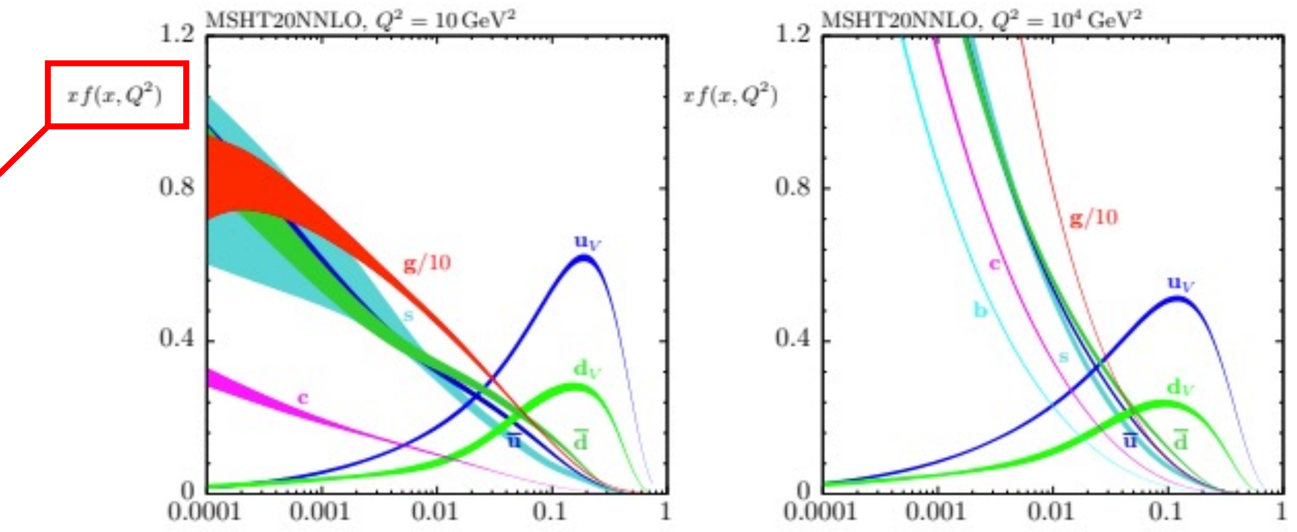


Figure 1: MSHT20 NNLO PDFs at $Q^2 = 10\ \mathrm{GeV}^2$ and $Q^2 = 10^4\ \mathrm{GeV}^2$, with associated 68% confidence-level uncertainty bands.

https://arxiv.org/abs/2012.04684

- Rewrite it as:

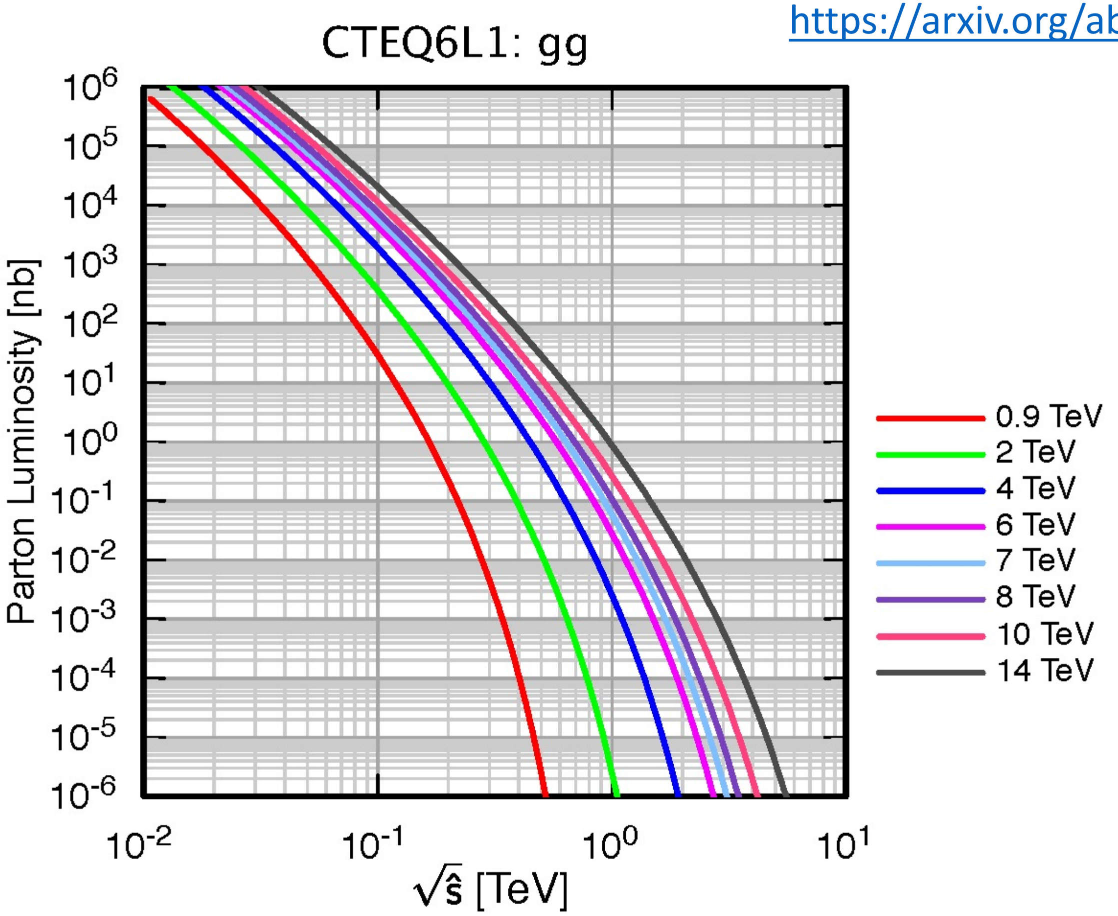
$$\sigma(s) = \sum \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}} \frac{dL_{ij}}{d\tau} \cdot [\hat{s}\hat{\sigma}_{ij}(\hat{s})]$$

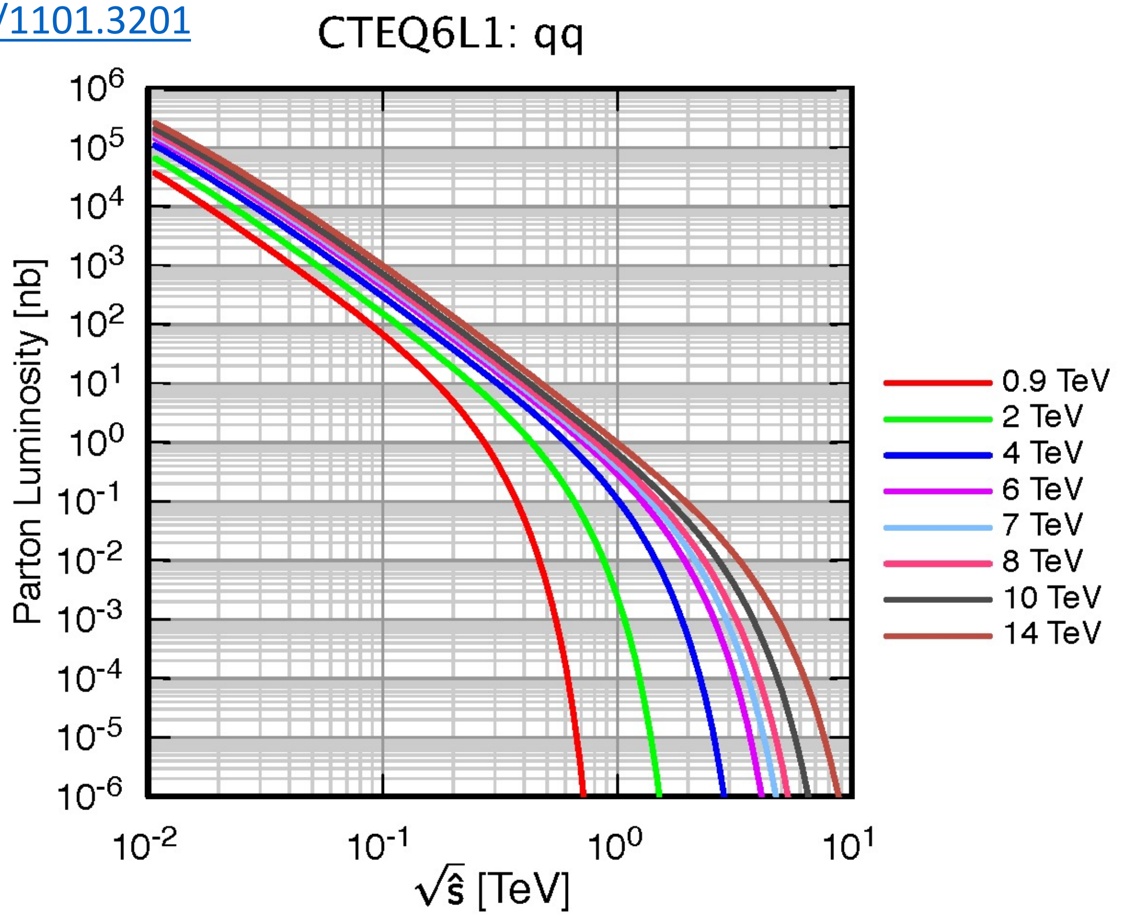
$$\frac{dL_{ij}}{d\tau} \equiv \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{dx}{x} [f_i(x) f_j(\frac{\tau}{x}) + f_j(x) f_i(\frac{\tau}{x})]$$

EHLQ: https://doi.org/10.1103/RevModPhys.56.579

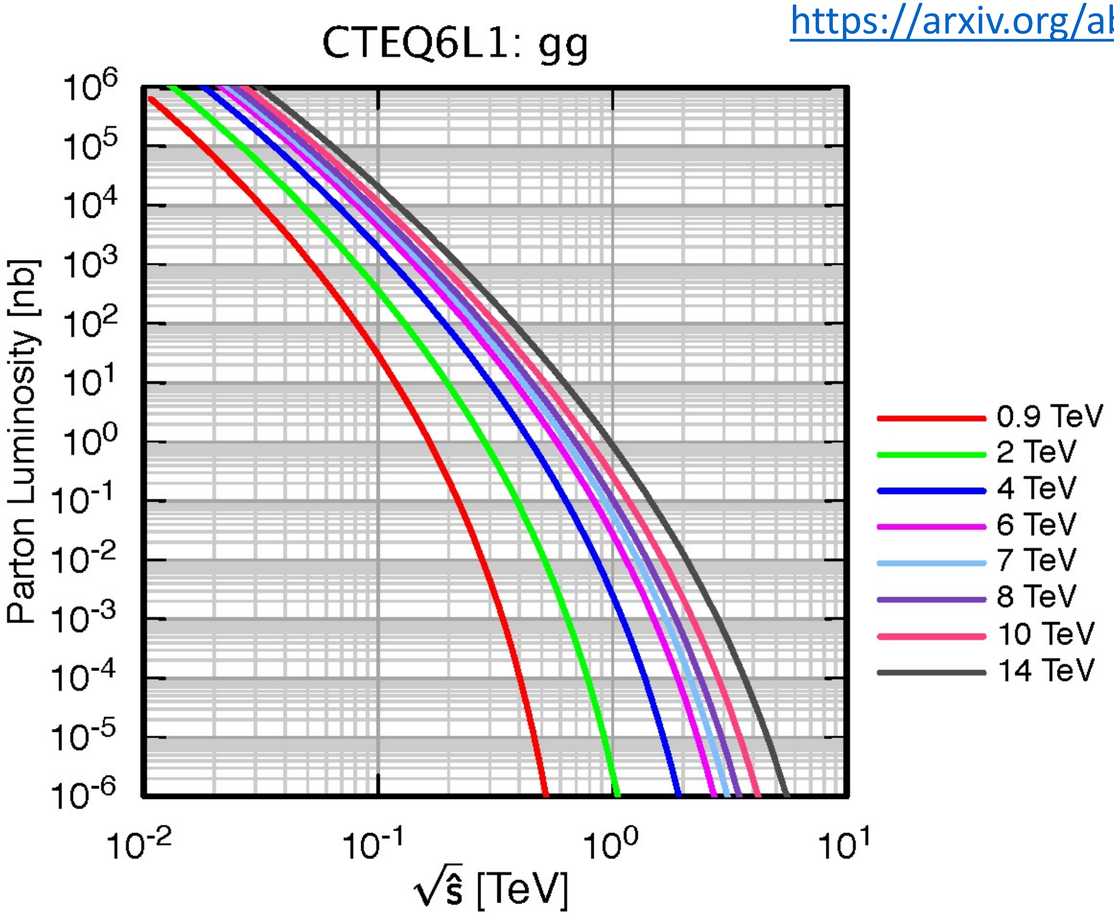
Luminosity for parton-parton collisions.
Dimensionless, function of parton-parton $\hat{s}$
Multiply by $\frac{\tau}{\hat{s}} = \frac{1}{s}$ to get units of x-section

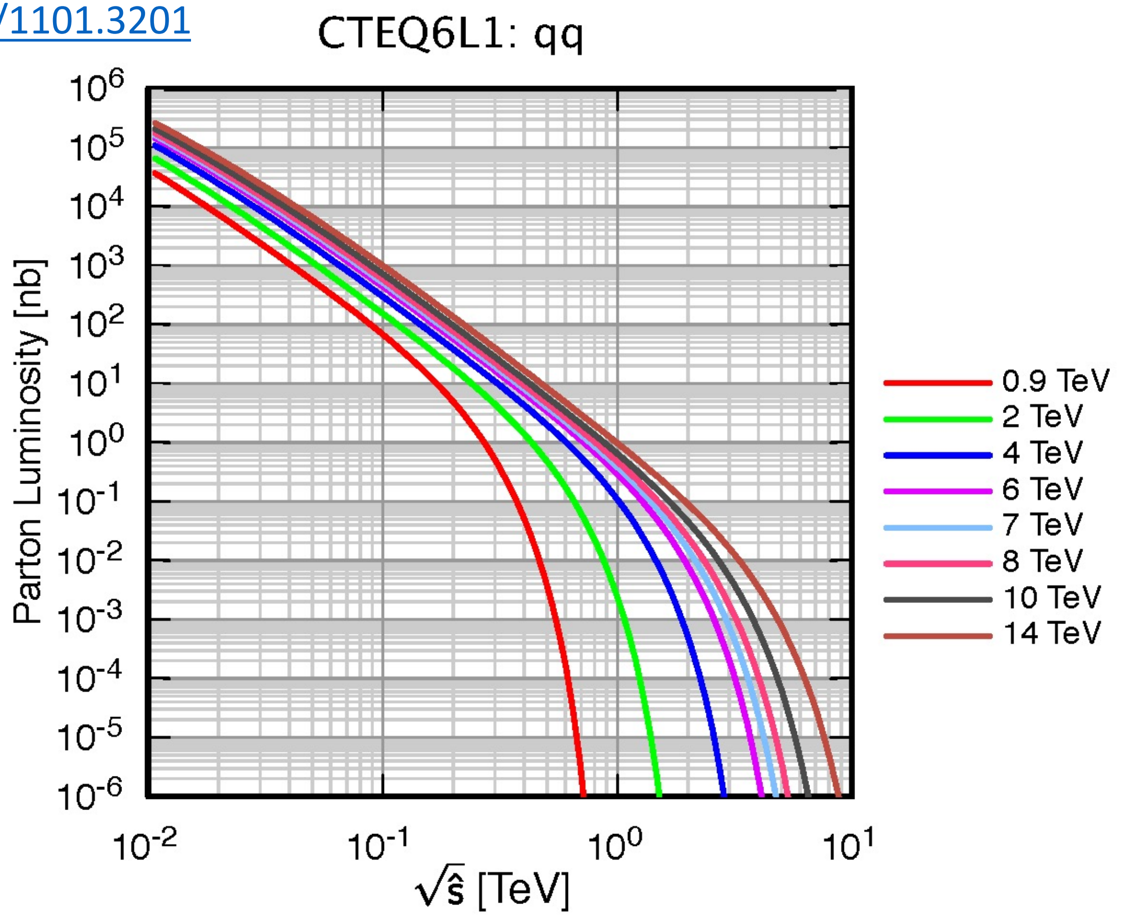
https://arxiv.org/abs/1101.3201



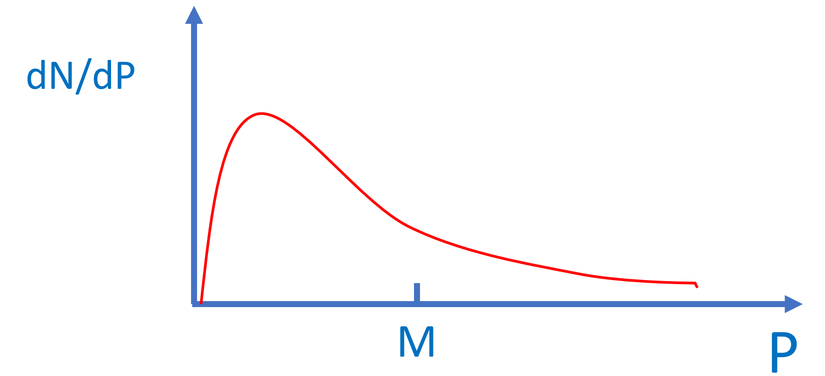


https://arxiv.org/abs/1101.3201





As a consequence, most of the production is near threshold. Good to keep it in mind.



SUSY models

- Not a unique theory
- A family of models
- “Benchmarks”

Eur.Phys.J.C25:113-123,2002
2002, very old

952 citations
Check out the mass scales (!)

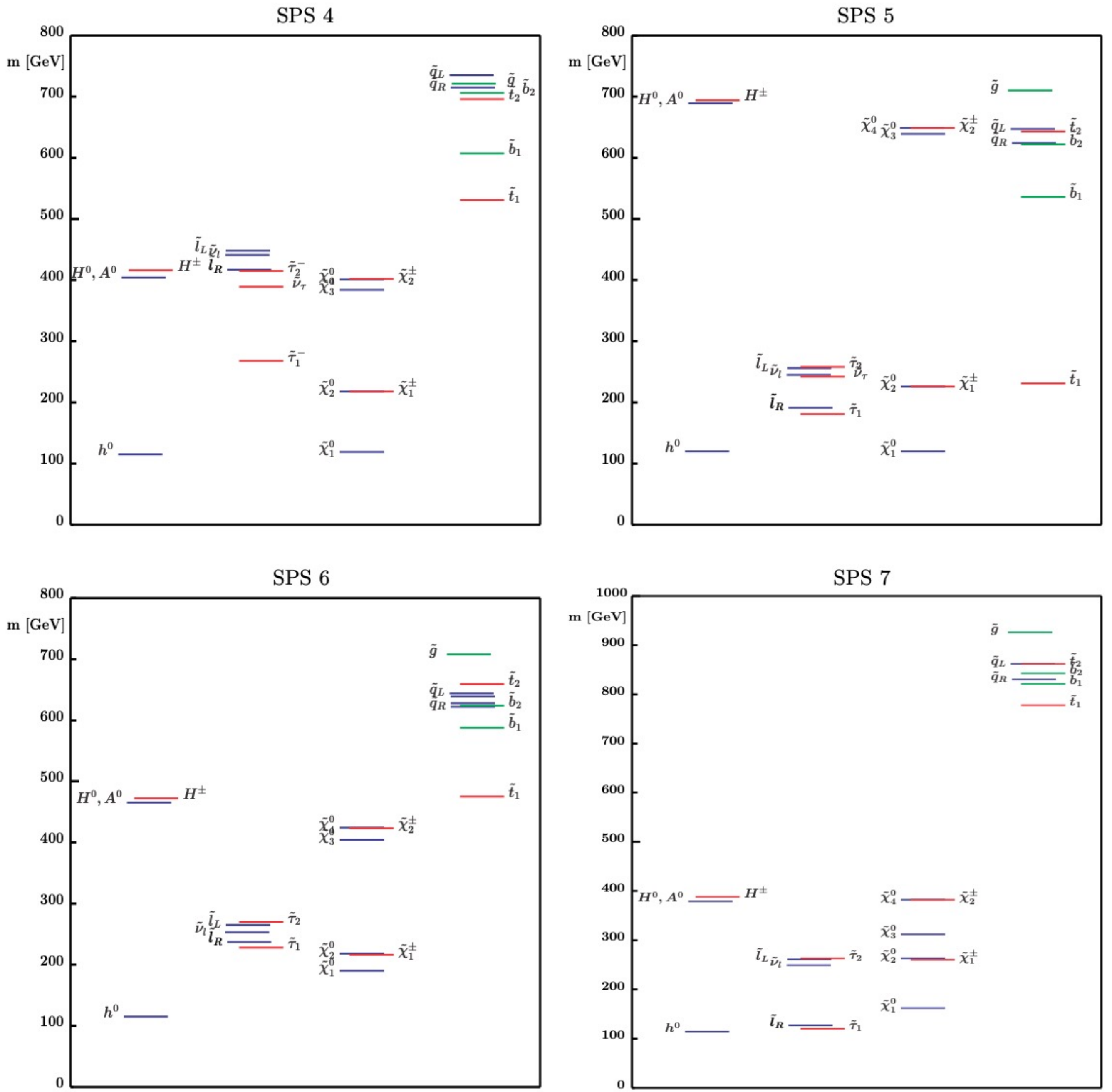


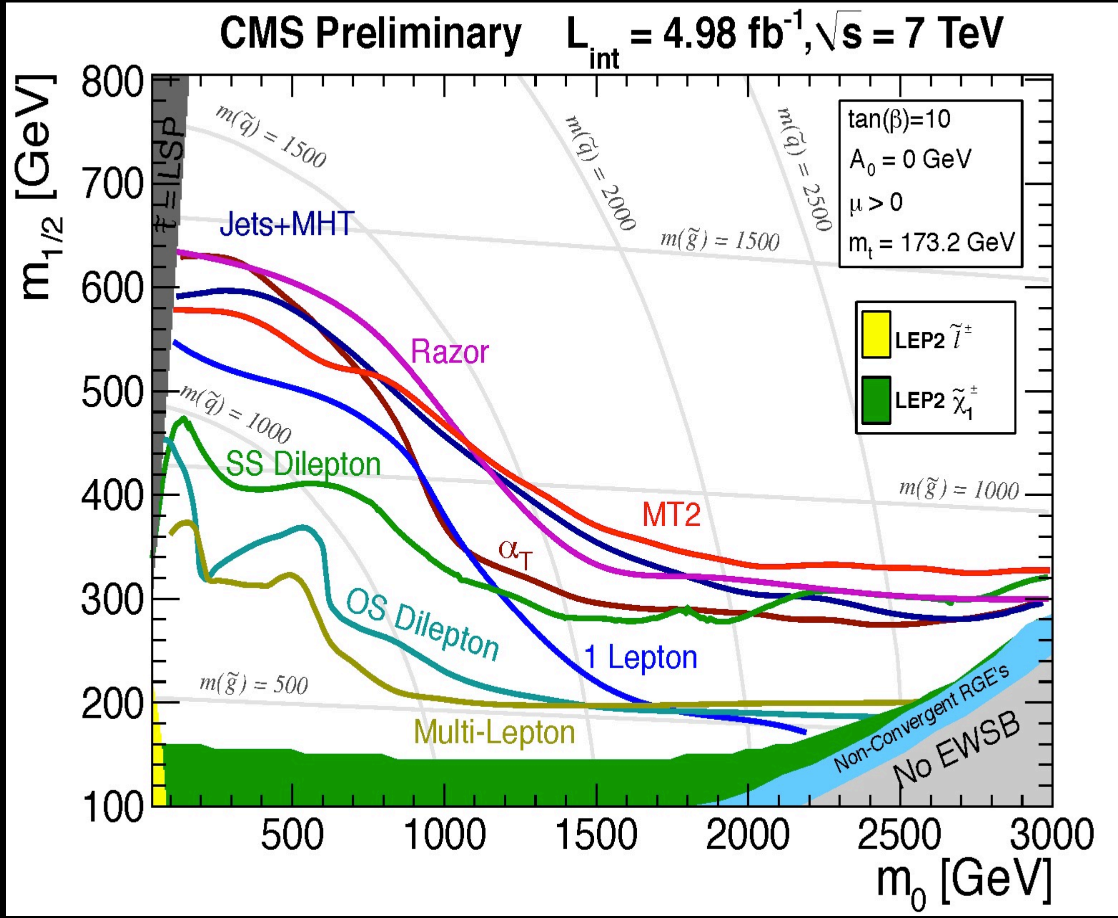
FIG. 2: The SUSY particle spectra for the benchmark points corresponding to SPS 4, SPS 5, SPS 6 and SPS 7 as obtained with *ISAJET 7.58* (see Ref. [33]).

Constrained Minimal SUSY SM (CMSSM) extension

<u>Five parameters:</u>

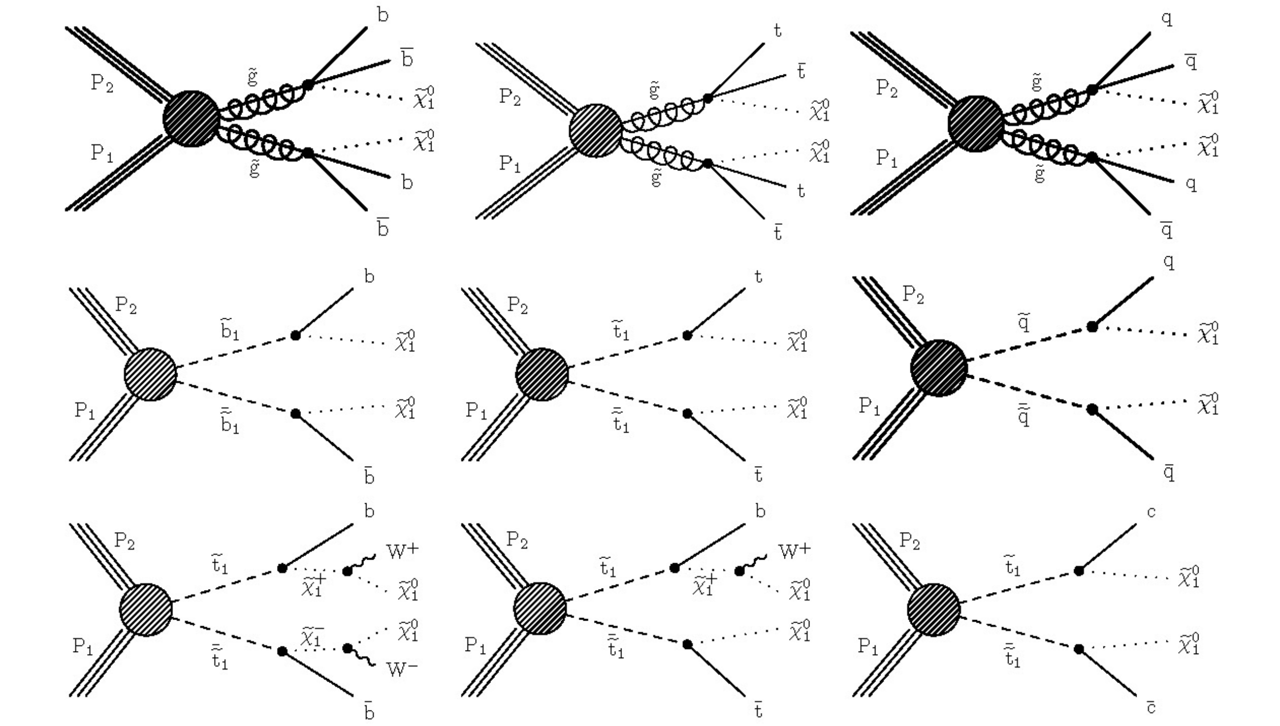
- Universal scalar/gaugino masses: $m_0, m_{1/2}$
- Soft breaking parameter: A_0
- Ratio of Higgs doublets vev: $\tan\beta$
- Sign of Higgs mix. parameter: μ

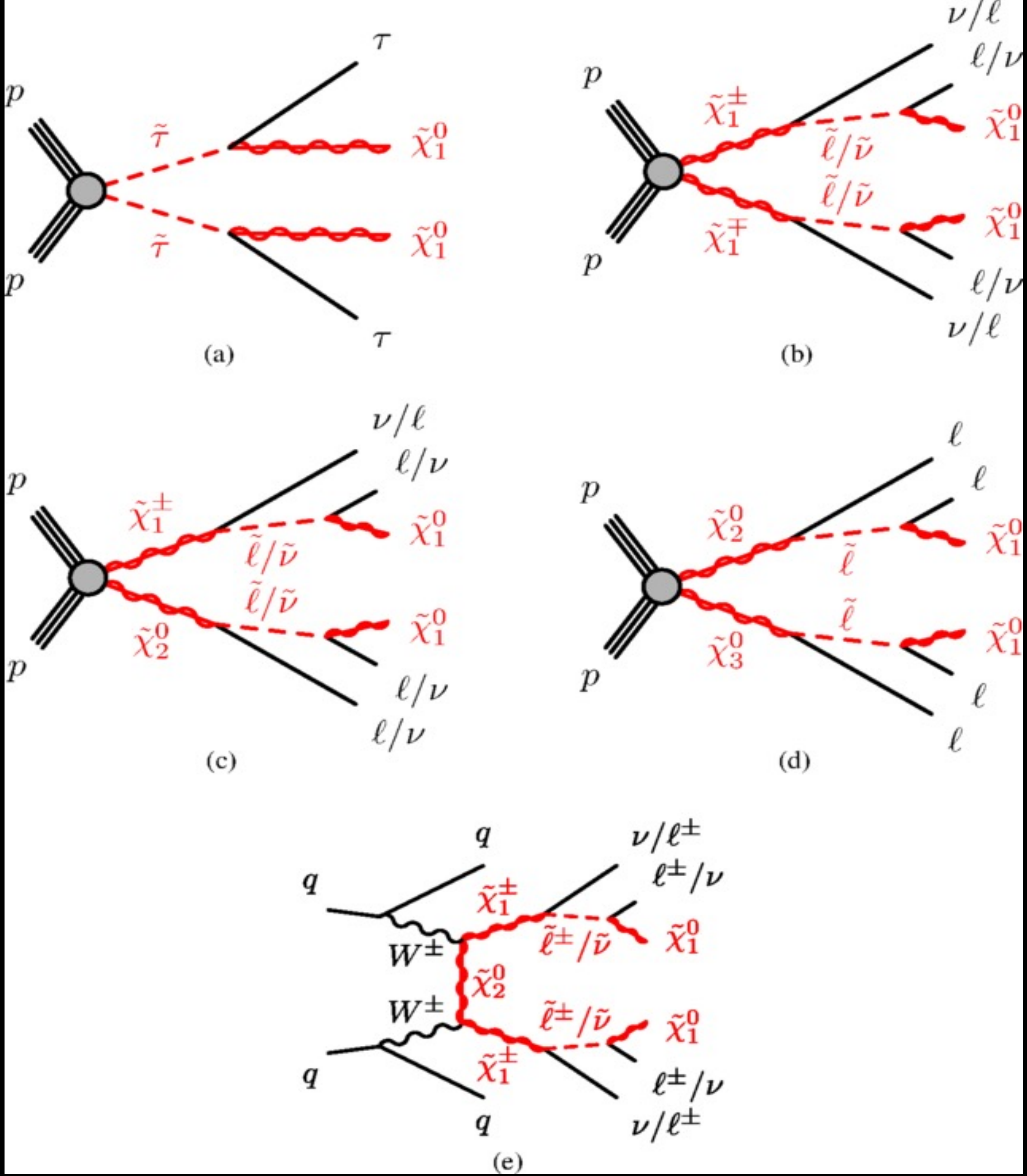
- This way of "interpreting" results was soon abandoned in favor of ***Simplified Models***



Simplified Models

- Production of SUSY particles with well defined x-sections
- Almost always 100% BR
- Almost always neglecting spin factors, matrix element dynamic in production and decay

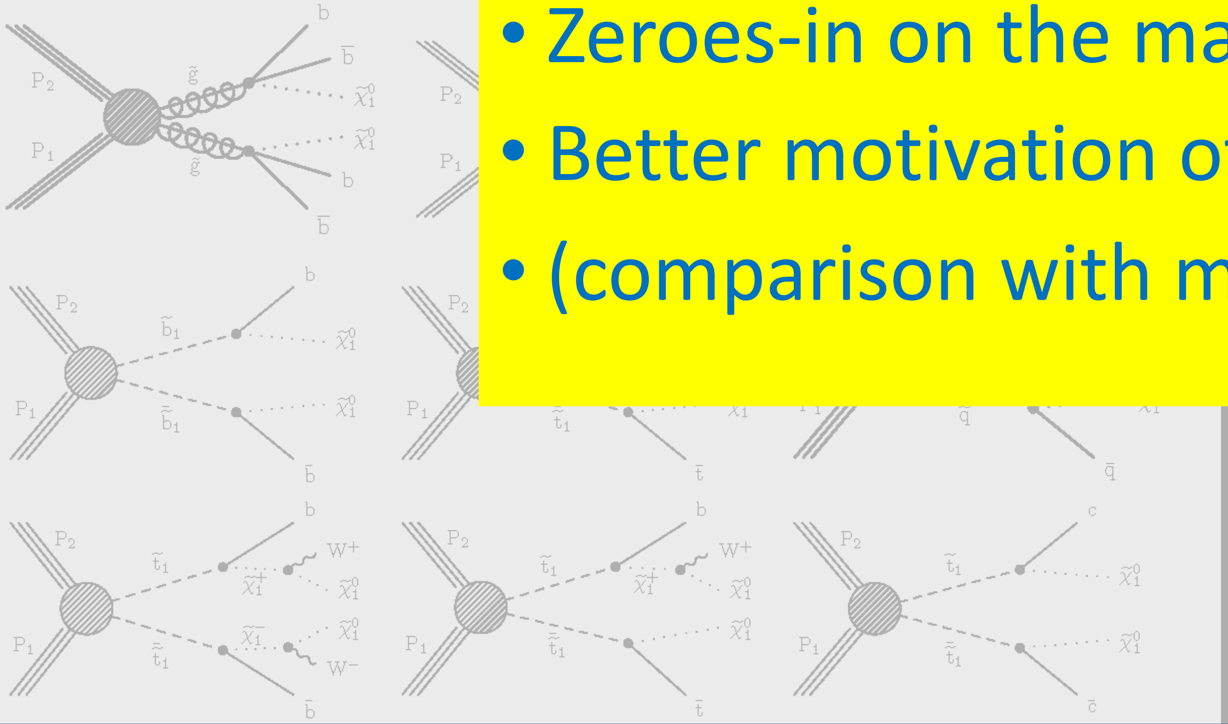


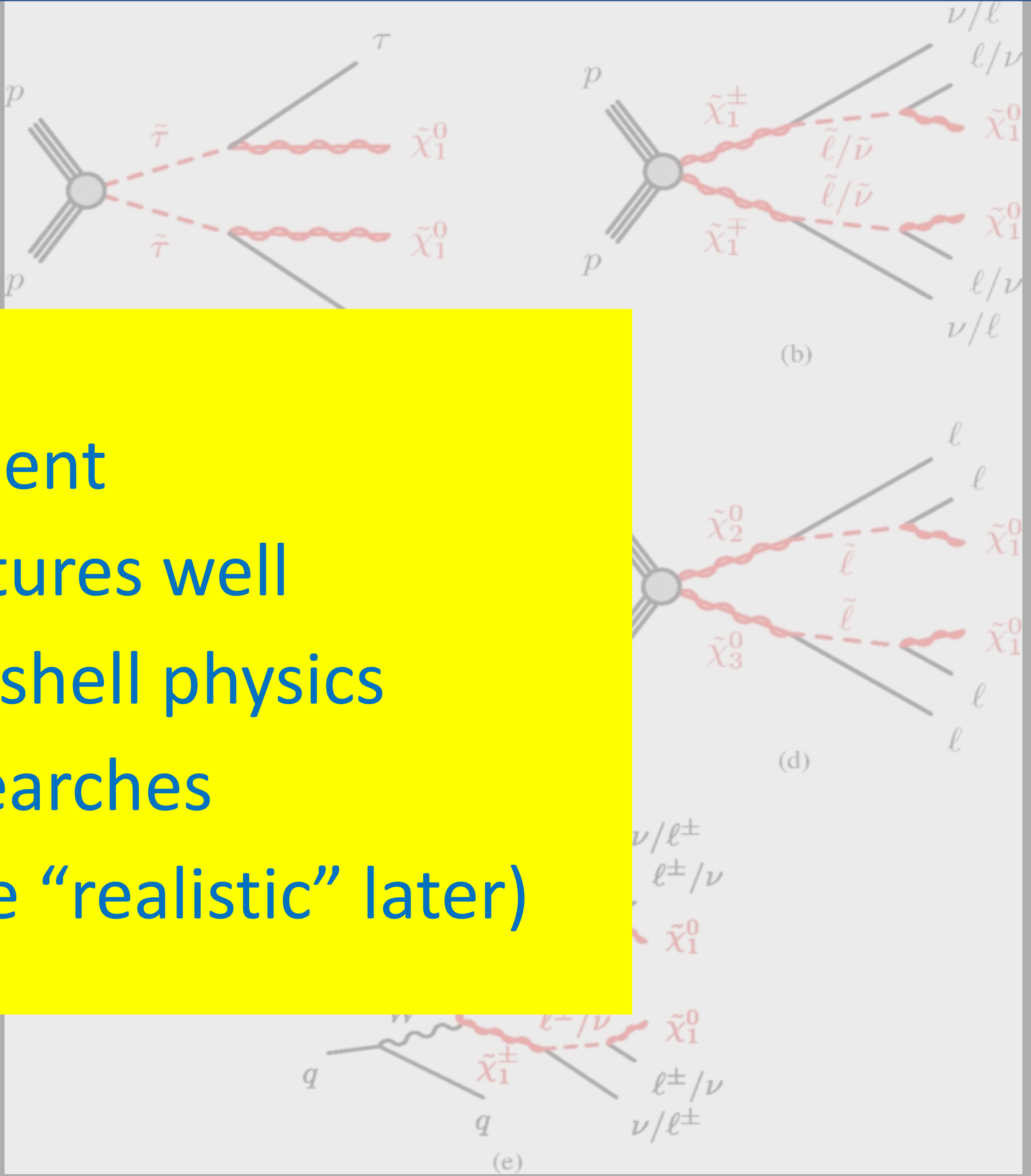


Simplified Models

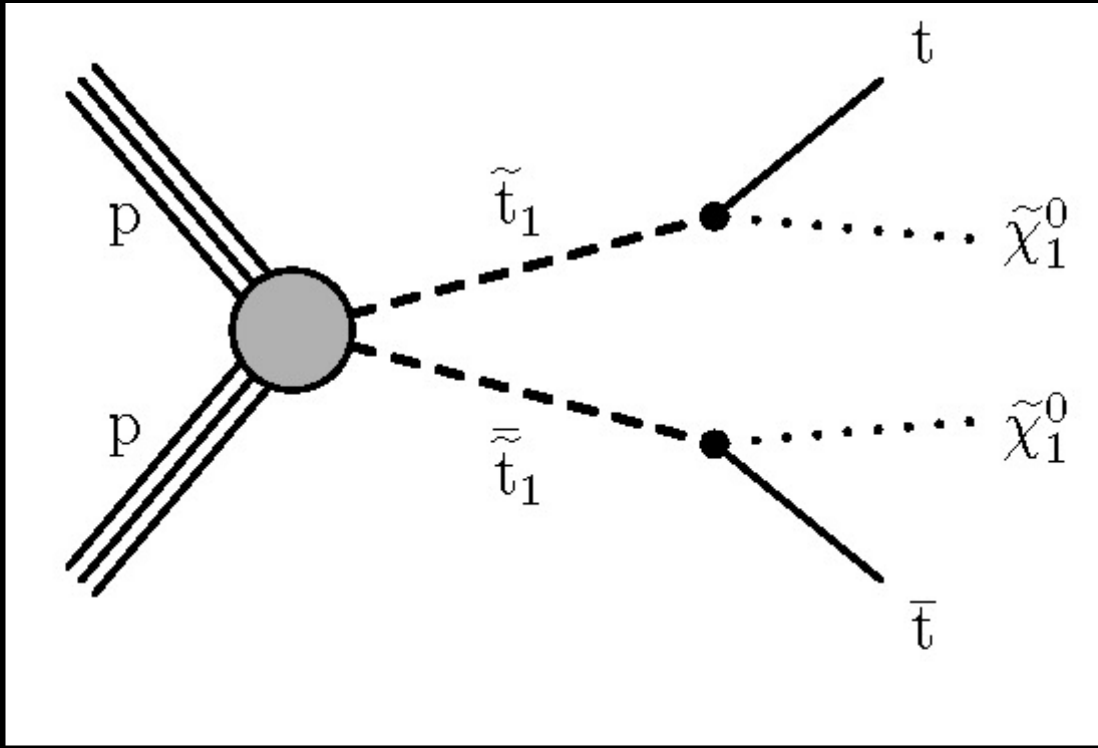
- Production of SUSY particles with well defined x-sections
- Almost always
- Almost always matrix elemen and decay

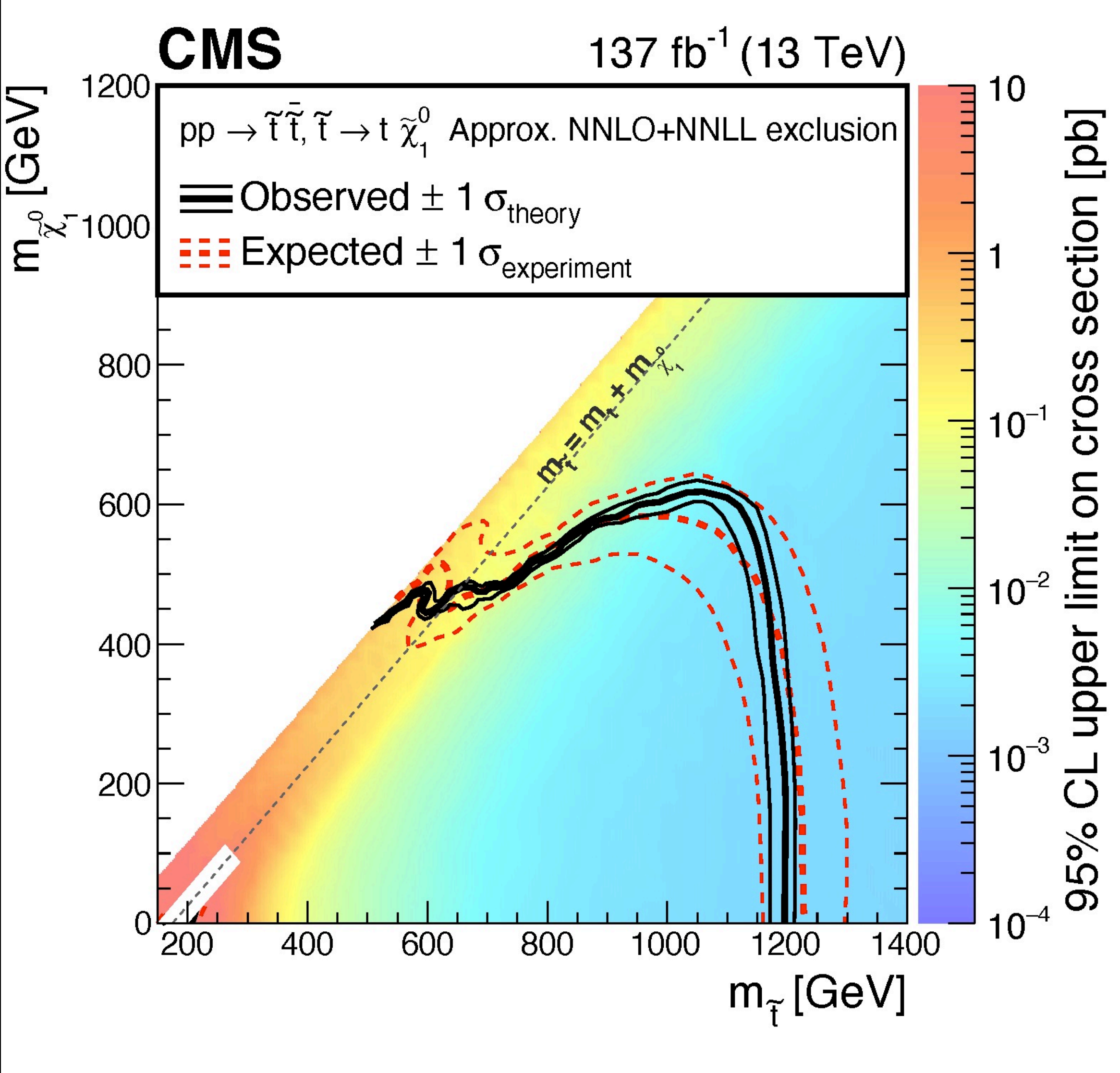
- Unrealistic
- But less model dependent
- Captures the gross features well
- Zeroes-in on the mass-shell physics
- Better motivation of searches
- (comparison with more “realistic” later)





Anatomy of a Simplified Model limit plot





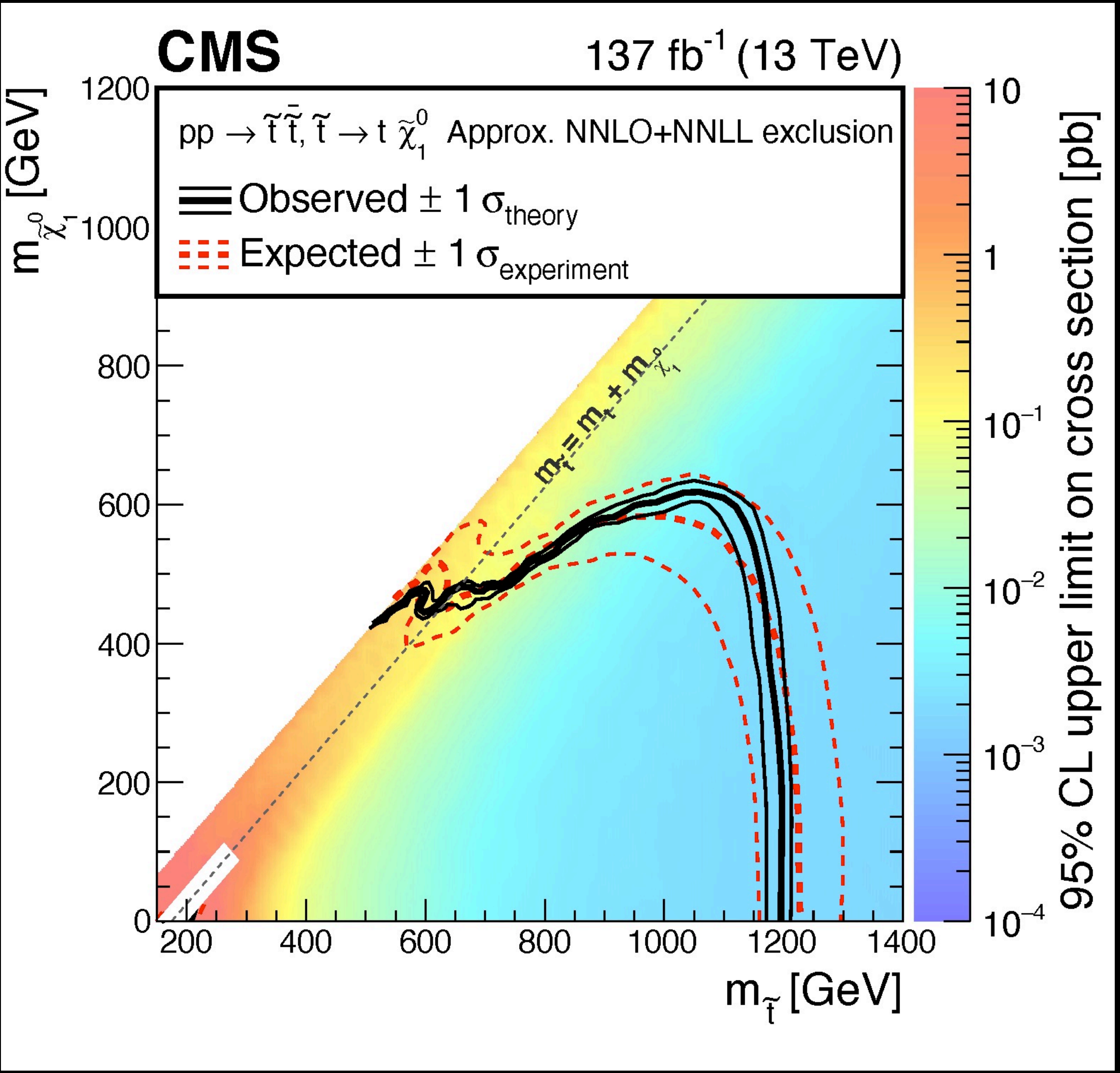
$t\bar{\tilde{t}} \rightarrow t\chi^0\ \bar{t}\chi^0 \rightarrow Wb\, W\bar{b} \rightarrow q\bar{q}b\ \ell\nu\bar{b}$

Anatomy of a Simplified Model limit plot

- The color map gives the cross section limit in pb as a function of $m(\tilde{t}), m(\chi^0)$
  - Kin properties vary across plane

- Everything to the left of the black lines is excluded (observed) using the the theoretical calculation of the production cross-section

- Everything to the left of the red line is expected to be excluded, on average

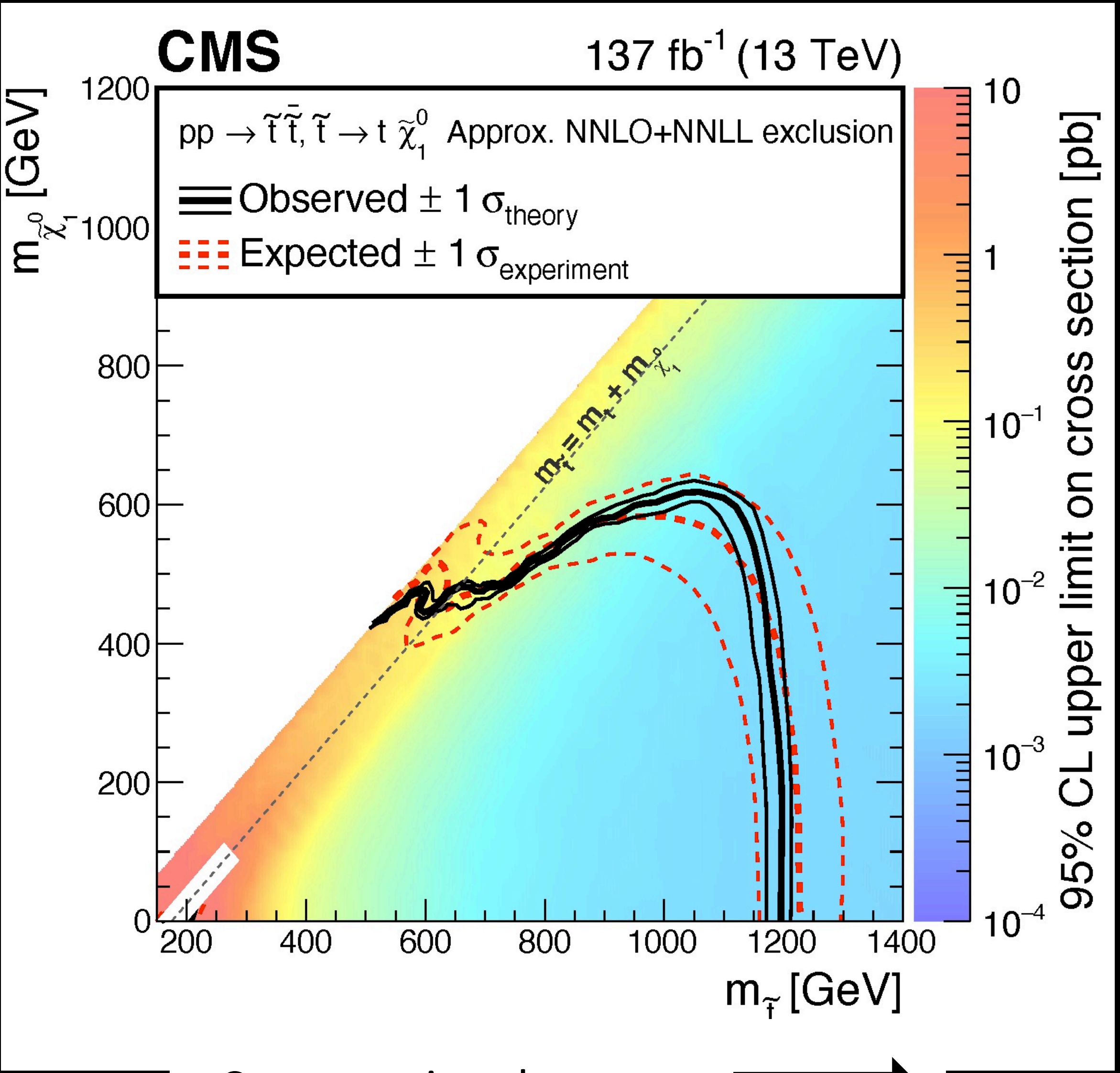


$$t\bar{\tilde{t}} \rightarrow t\chi^0\ \bar{t}\chi^0 \rightarrow Wb\,W\bar{b} \rightarrow q\bar{q}b\ \ell\nu\bar{b}$$

Anatomy of a Simplified Model limit plot

The theoretical cross section decreases as $m(\tilde{t})$ increases

- At some point run out of events



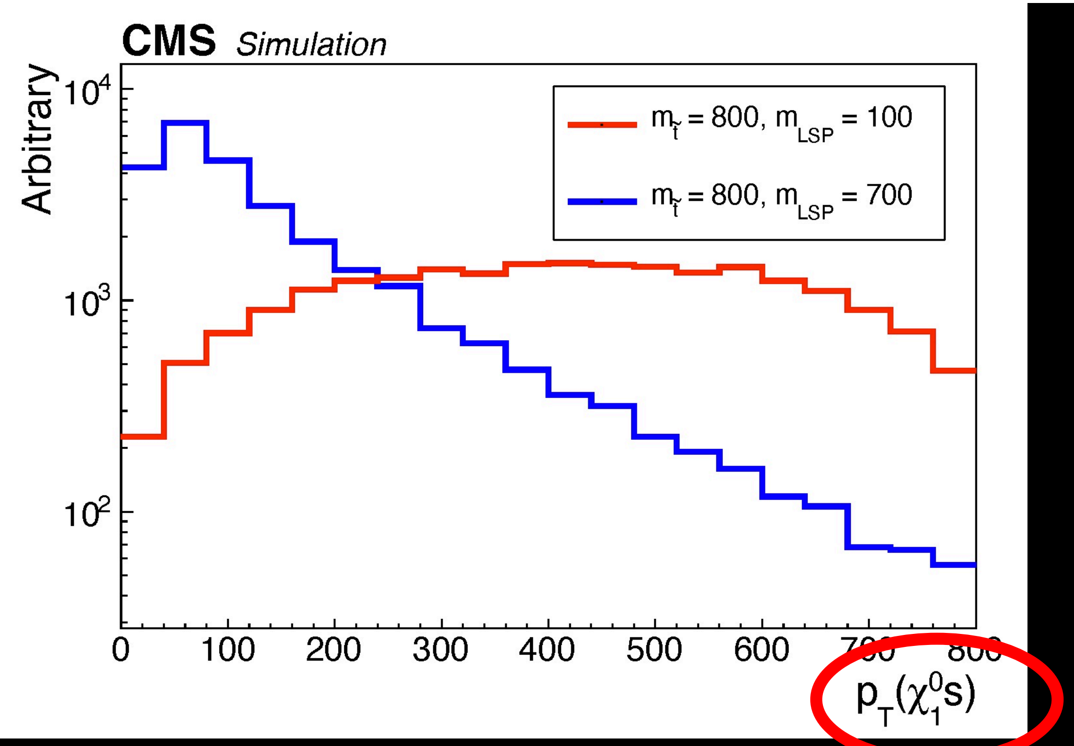
Cross section decreases →

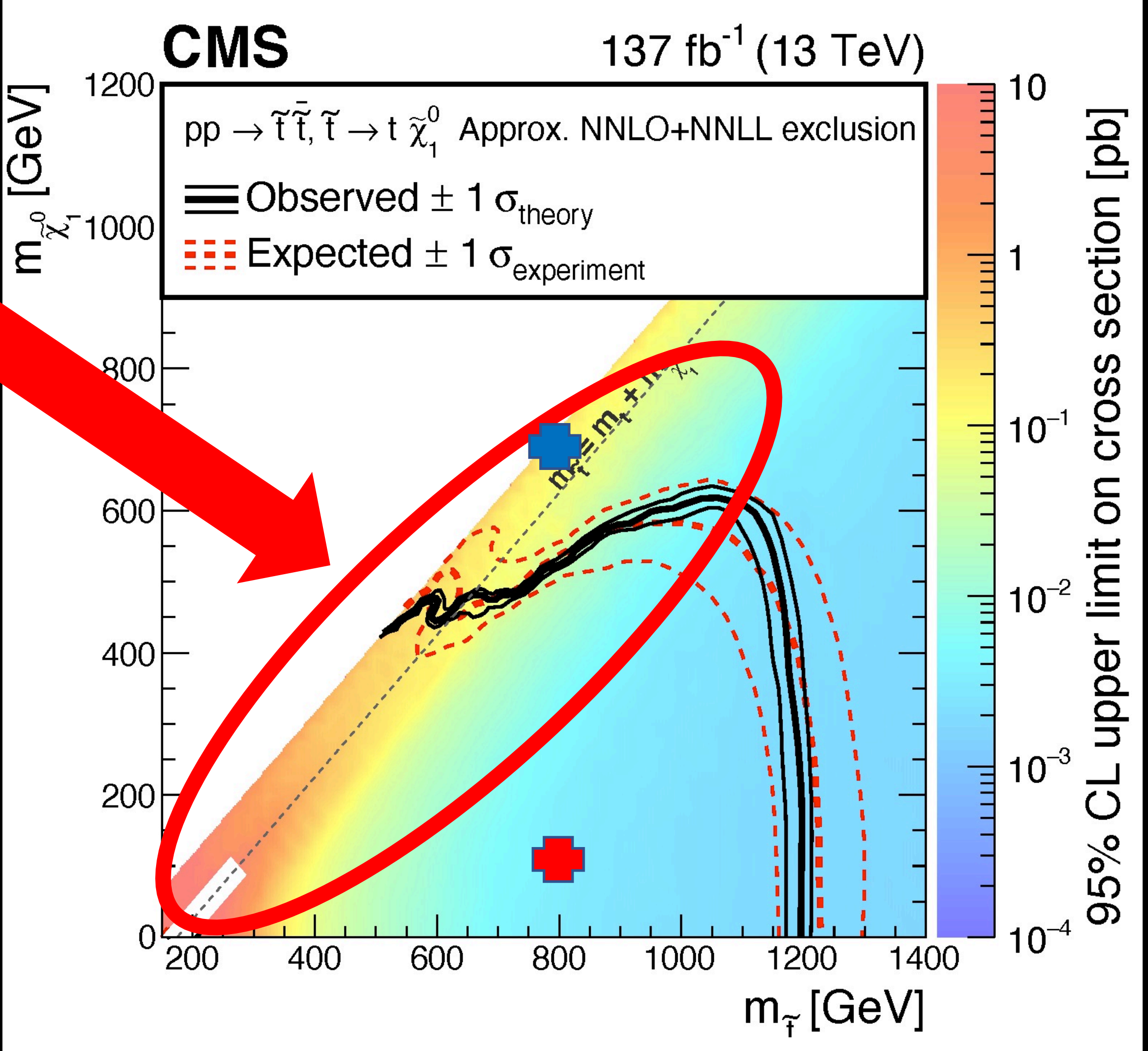
$$t\bar{\tilde{t}} \rightarrow t\chi^0\ \bar{t}\chi^0 \rightarrow Wb\ W\bar{b} \rightarrow q\bar{q}b\ \ell\nu\bar{b}$$

Anatomy of a Simplified Model limit plot

"Compressed":

- Small $\Delta m = m(\tilde{t}) - m(t) - m(\chi^0)$
- Analysis becomes more difficult





Cross section decreases

$$t\bar{\tilde{t}} \rightarrow t\chi^0\ \bar{t}\chi^0 \rightarrow Wb\, W\bar{b} \rightarrow q\bar{q}b\, \ell\nu\bar{b}$$

Anatomy of a Simplified Model limit plot

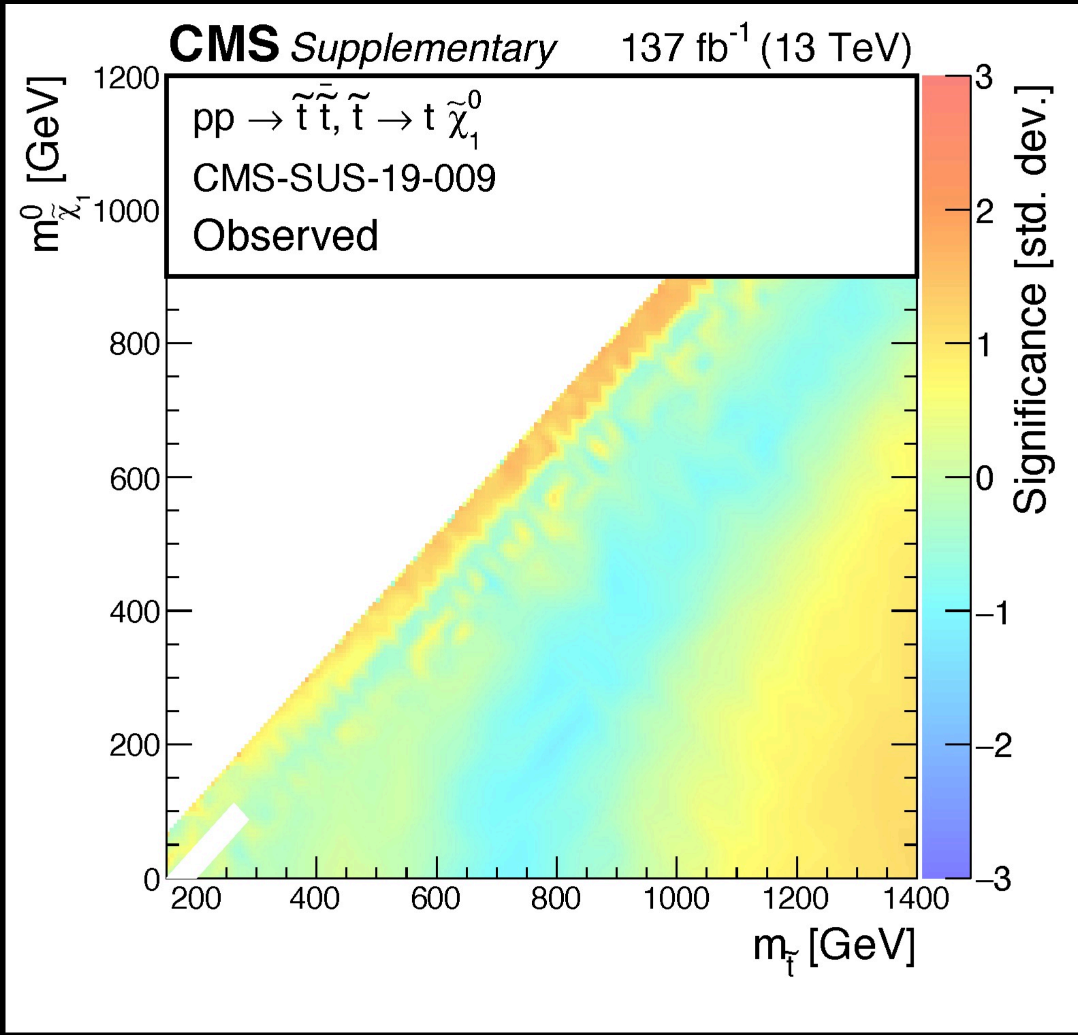
The "standard" limit plot is not the full story

There can be localized excesses in the data that are not large enough to be consistent with the particular SUSY model

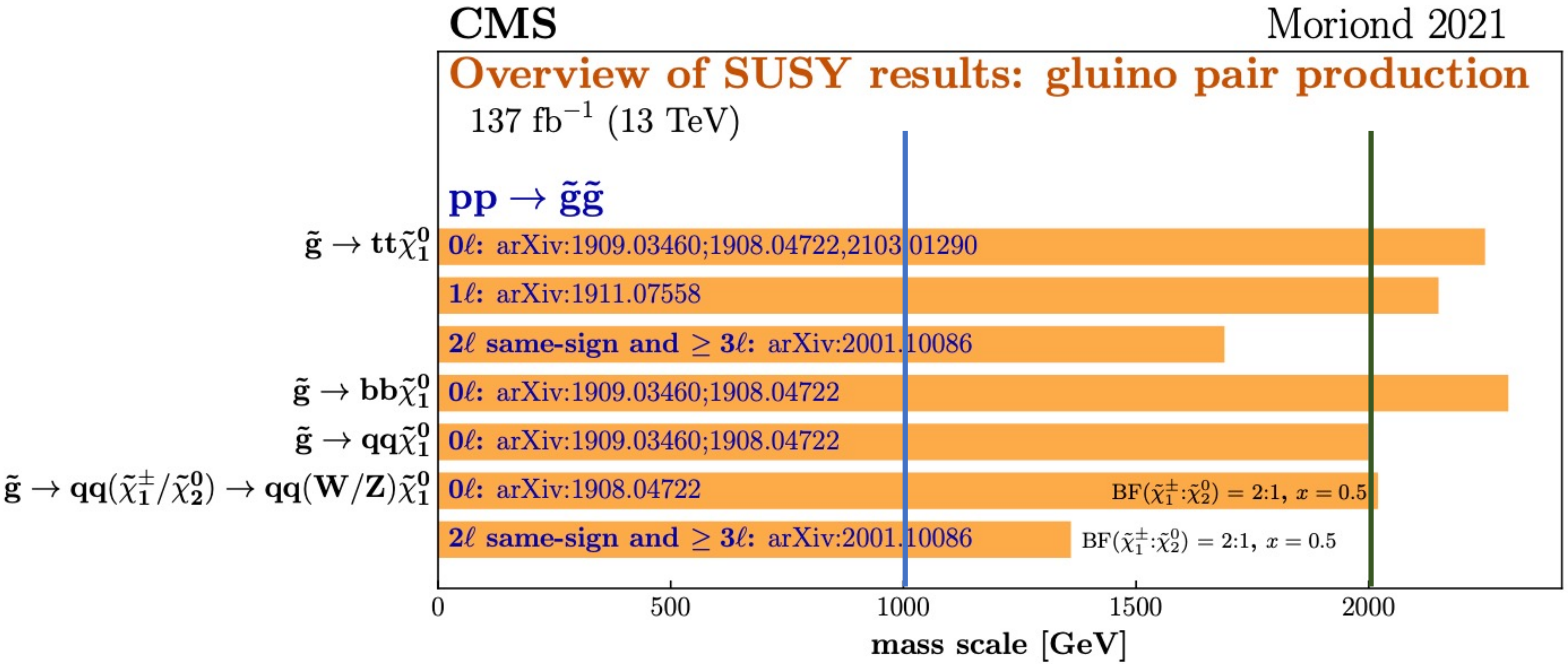
- Remember, BTW, that BRs are set to 100%

The excesses could come to some other lower x-section BSM process. **PAY ATTENTION!!!**

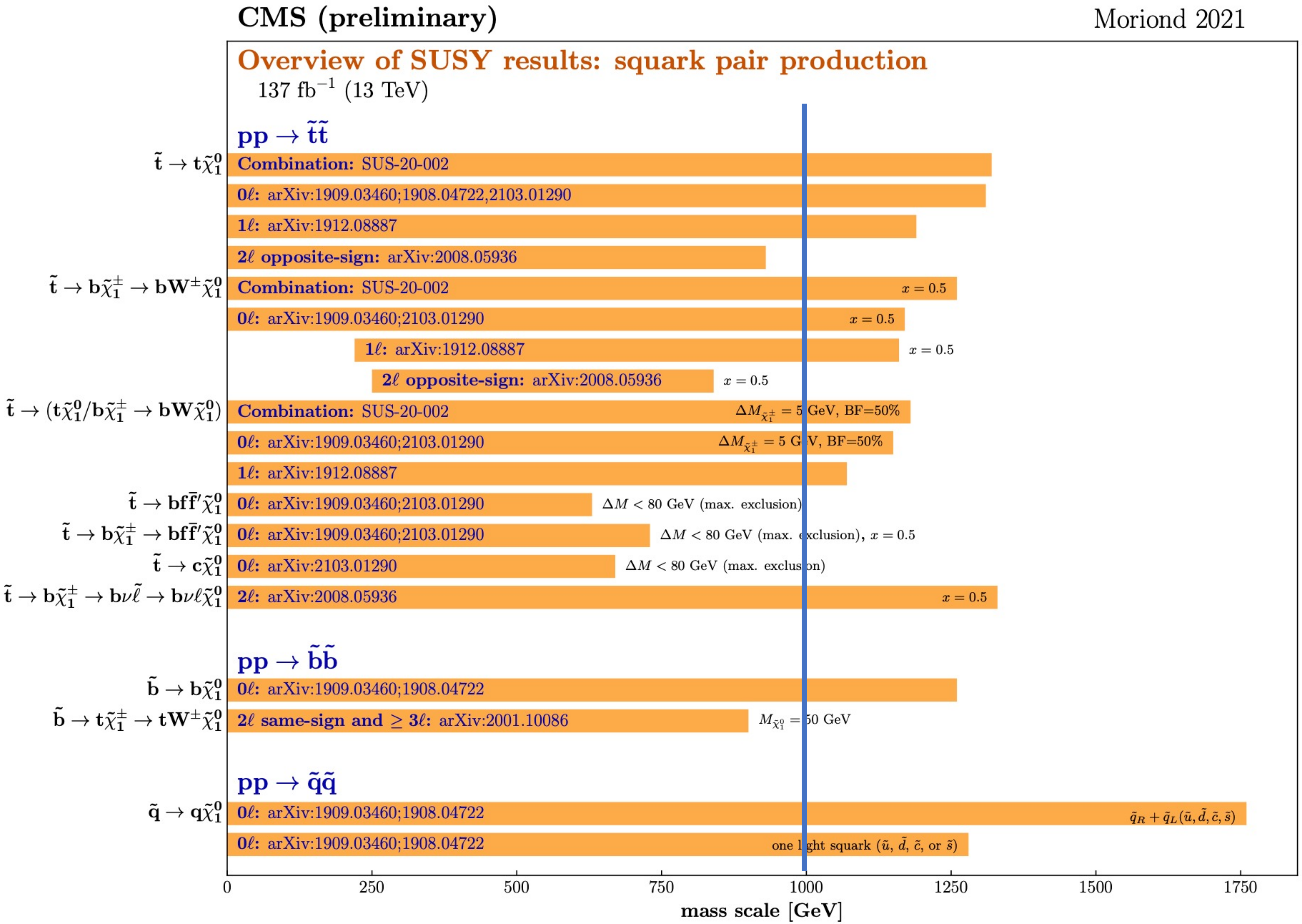
Deficits are interesting to: maybe something is wrong with what you have done



$$t\bar{\tilde{t}} \rightarrow t\chi^0 \ \bar{t}\chi^0 \rightarrow Wb\, W\bar{b} \rightarrow q\bar{q}b\ \ell\nu\bar{b}$$



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



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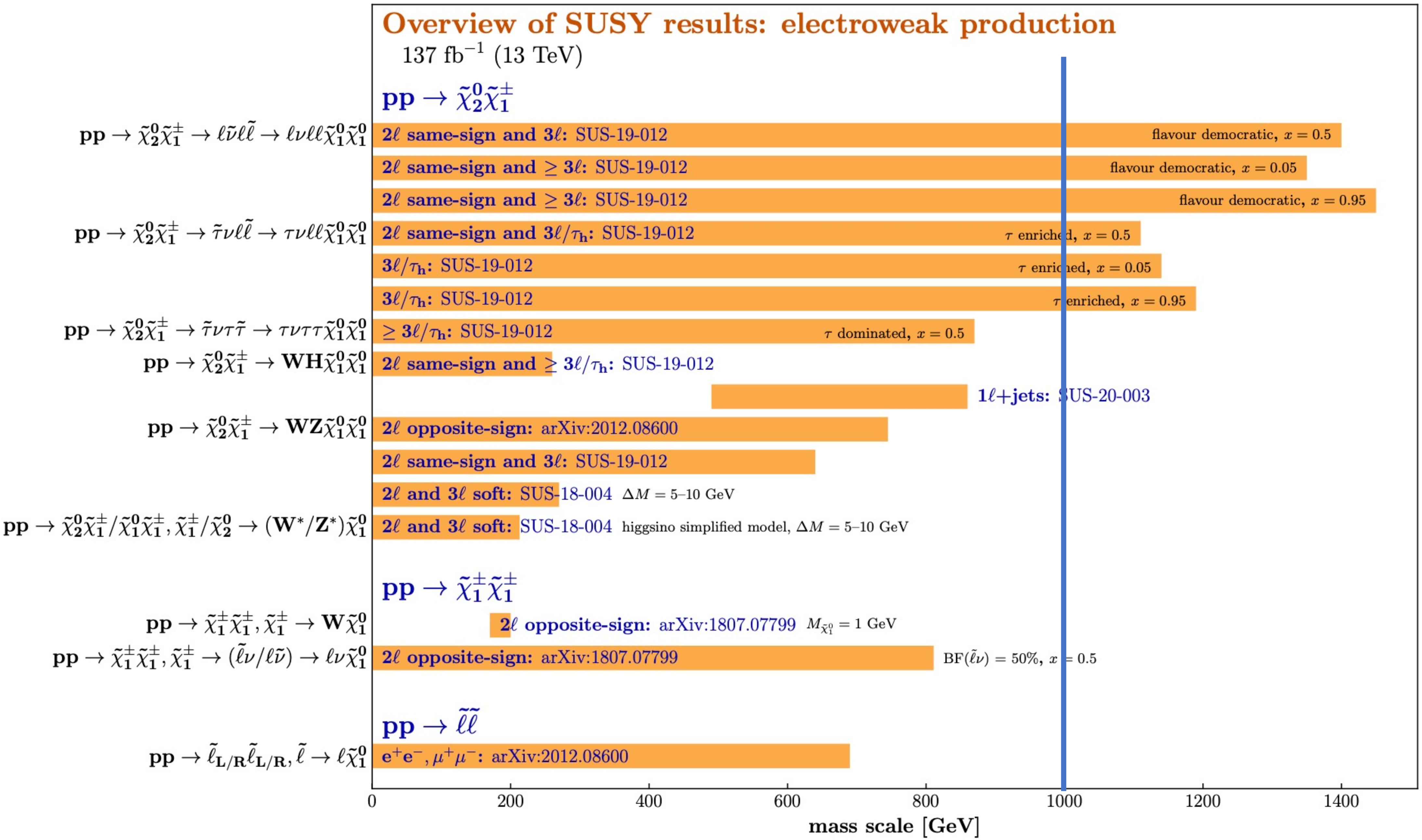
CMS (preliminary) Moriond 2021



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

How ”real” are limits from simplified models?

pMSSM:

- R-parity conserving
- no new CP violation
- Minimal Flavor Violation
- LSP = lightest neutralino
- First two q and ℓ generations mass-degenerate
- 19 parameters
- 310K pMSSM models confronted with Run 1 search results (ATLAS)

JHEP

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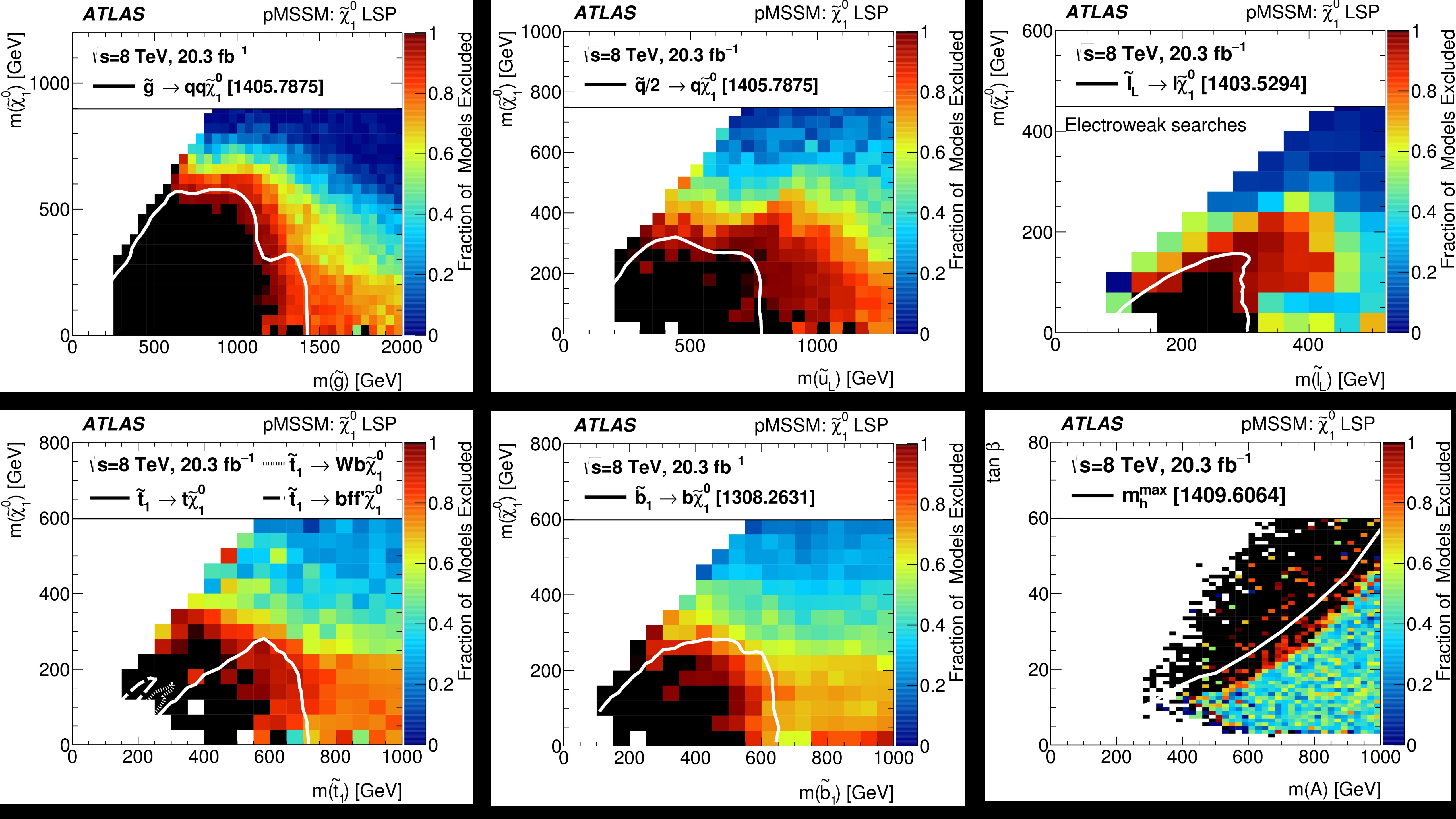
Published: *October 21, 2015*

Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM

10.1007/JHEP10(2015)134


ATLAS
pMSSM: $\tilde{\chi}_1^0$ LSP
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$ [1405.7875]
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{g})$ [GeV]
Fraction of Models Excluded
ATLAS
pMSSM: $\tilde{\chi}_1^0$ LSP
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
$\tilde{q}/2 \rightarrow q\tilde{\chi}_1^0$ [1405.7875]
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{u}_L)$ [GeV]
Fraction of Models Excluded
ATLAS
pMSSM: $\tilde{\chi}_1^0$ LSP
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
$\tilde{l}_L \rightarrow l\tilde{\chi}_1^0$ [1403.5294]
Electroweak searches
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{l}_L)$ [GeV]
Fraction of Models Excluded
ATLAS
pMSSM: $\tilde{\chi}_1^0$ LSP
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
$\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$
$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$
$\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{t}_1)$ [GeV]
Fraction of Models Excluded
ATLAS
pMSSM: $\tilde{\chi}_1^0$ LSP
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ [1308.2631]
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{b}_1)$ [GeV]
Fraction of Models Excluded
ATLAS
pMSSM: $\tilde{\chi}_1^0$ LSP
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
m_h^{max} [1409.6064]
tan β
m(A) [GeV]
Fraction of Models Excluded

New (non SUSY) Physics from SUSY searches?

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *October 23, 2017*
ACCEPTED: *November 22, 2017*
PUBLISHED: *November 28, 2017*

Digging deeper for new physics in the LHC data

Pouya Asadi, Matthew R. Buckley, Anthony DiFranzo, Angelo Monteux and David Shih

Applying our technique to the two CMS jets+MET SUSY searches, we identify a set of previously overlooked $\sim 3\sigma$ excesses. Among these, four excesses survive tests of inter- and intra-search compatibility, and two are especially interesting: they are largely overlapping between the jets+MET searches and are characterized by low jet multiplicity, zero b-jets, and low MET and H_T. We find that resonant color-triplet production decaying to a quark plus an invisible particle provides an excellent fit to these two excesses and all other data

10.1007/JHEP11(2017)194

New (non SUSY) Physics from SUSY searches?

Not confirmed by new data

JHEP

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Digging deeper for ne… …in the LHC data

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10.1007/JHEP11(2017)194

Importance of providing information for further study

SciPost Phys. 9, 022 (2020)

Reinterpretation of LHC results for new physics: status and recommendations after run 2

The LHC BSM Reinterpretation Forum

https://scipost.org/SciPostPhys.9.2.022

Simplified simulation
Efficiency maps
Aggregate Regions
Background Covariance Matrices

A Case Study:

Inclusive search for BSM Physics (mostly SUSY) in a fully hadronic (ie: no leptons) sample with missing transverse momentum

Eur. Phys. J. C (2020) 80:3
https://doi.org/10.1140/epjc/s10052-019-7493-x

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Searches for physics beyond the standard model with the M_{T2} variable in hadronic final states with and without disappearing tracks in proton–proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration*

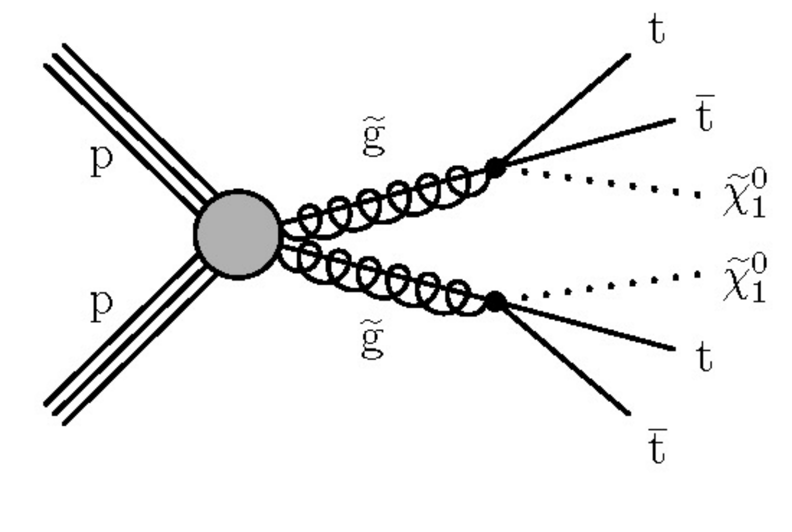
CERN, 1211 Geneva 23, Switzerland

Received: 8 September 2019 / Accepted: 15 November 2019 / Published online: 3 January 2020

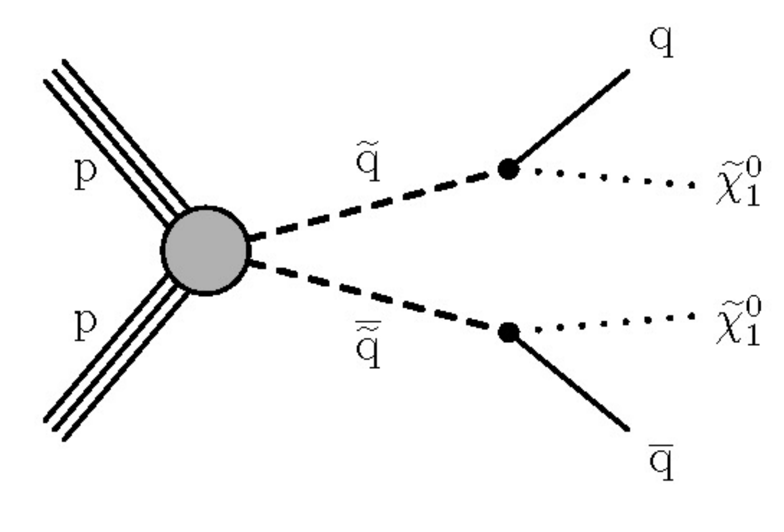
https://doi.org/10.1140/epjc/s10052-019-7493-x

Inclusive search. How to characterize the events?

Many jets.
remember:
$t \rightarrow Wb \rightarrow q\bar{q}b$



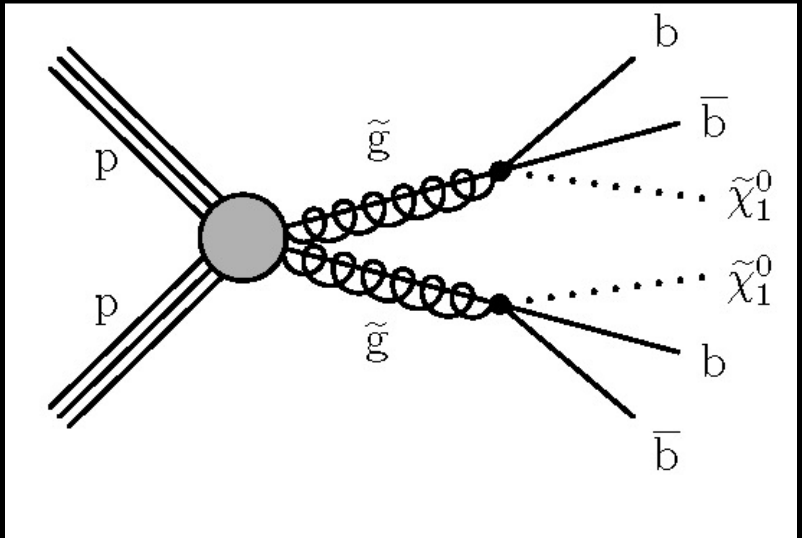
Few jets



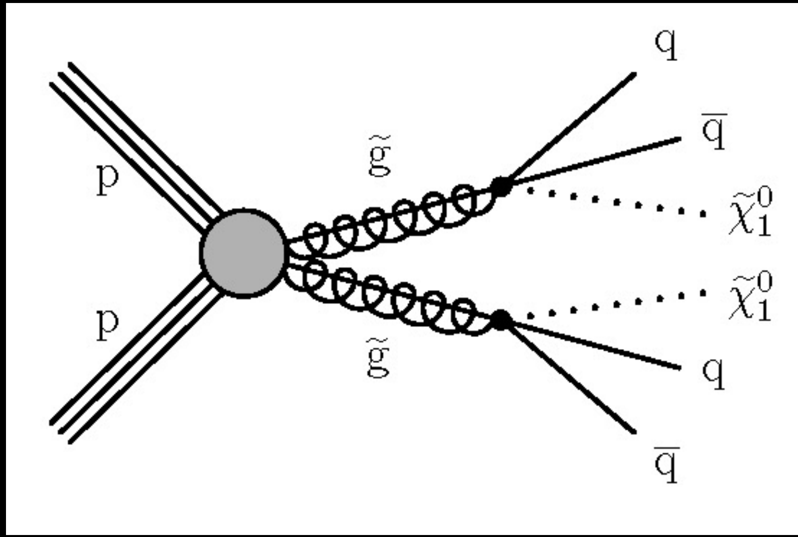
N_{jets}

Inclusive search. How to characterize the events?

Many b-tagged jets.

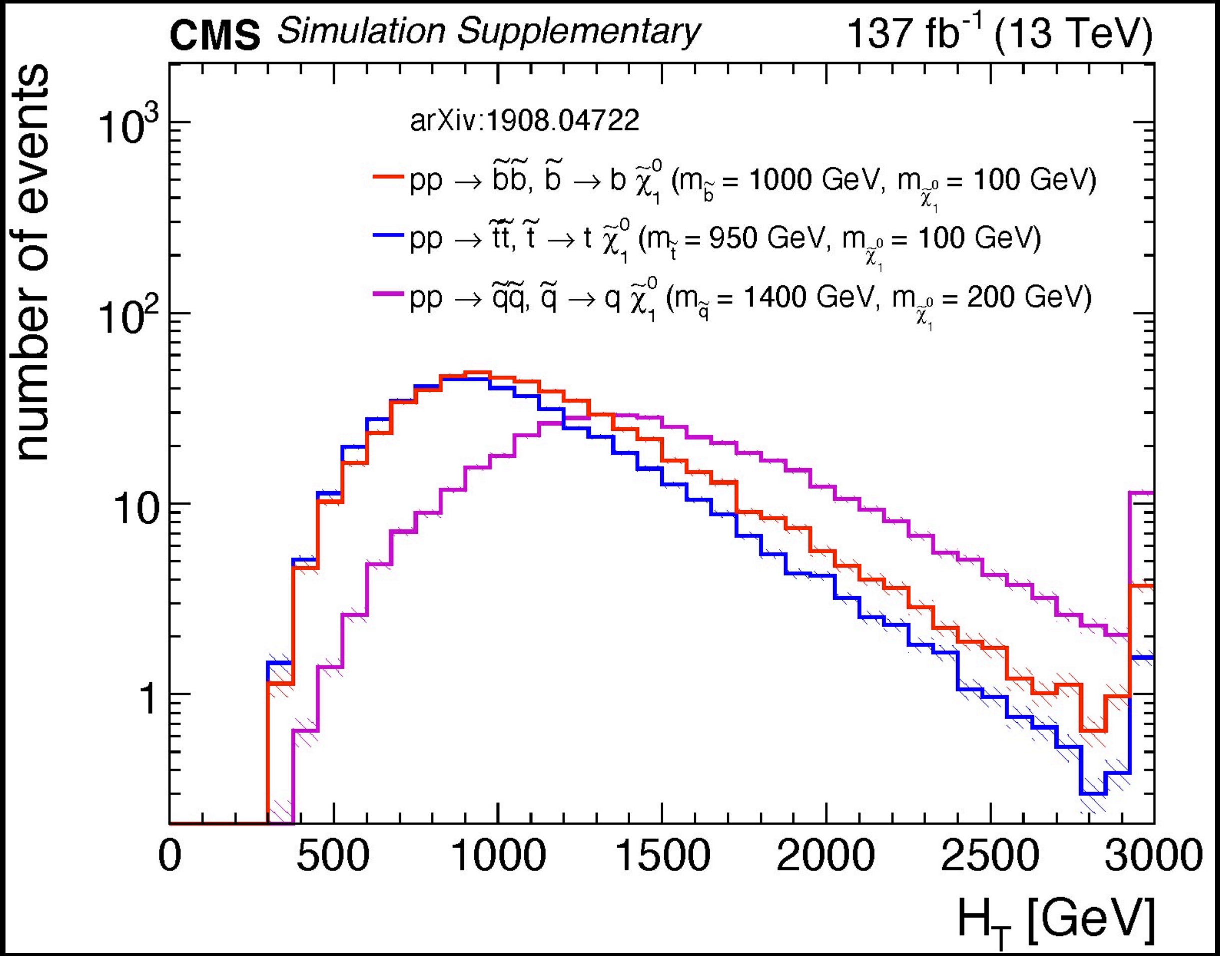


Few b-tagged jets



N_b

Inclusive search. How to characterize the events?

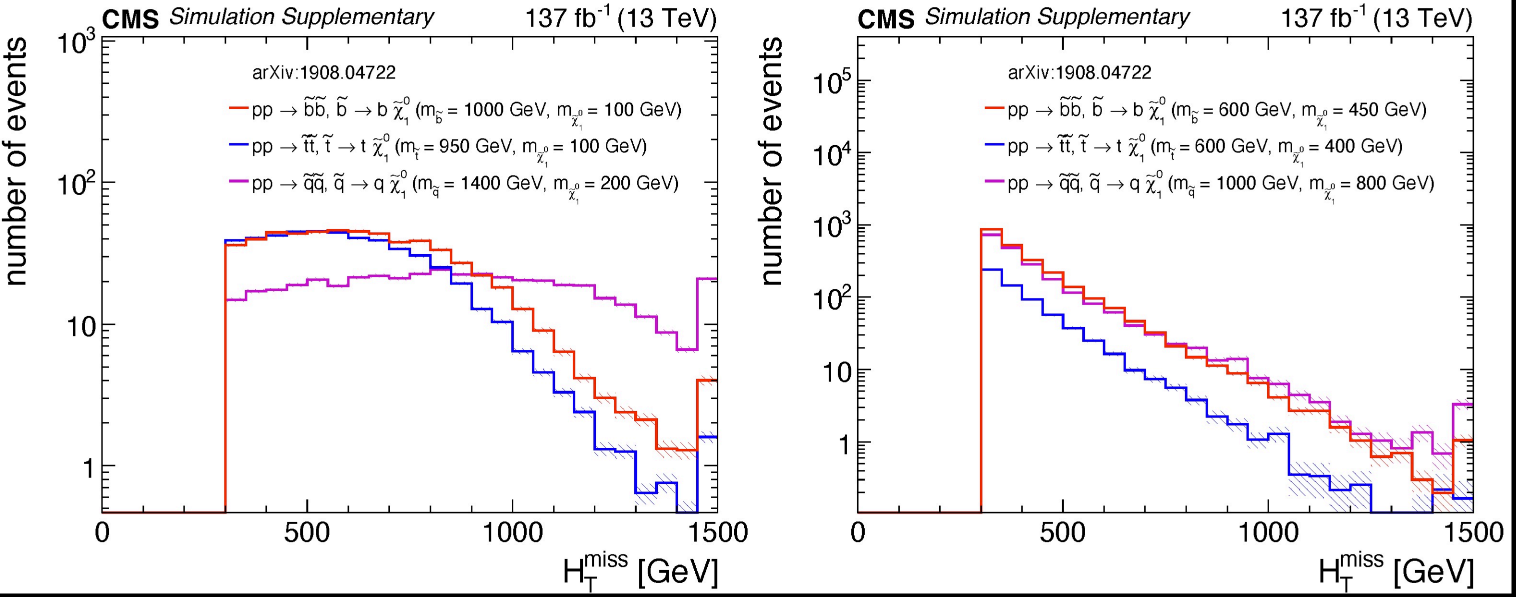


$$H_T = \sum P_T^{jet}$$

Inclusive search. How to characterize the events?

Not “compressed”
$m(\tilde{q}) \gg m(\chi_0)$

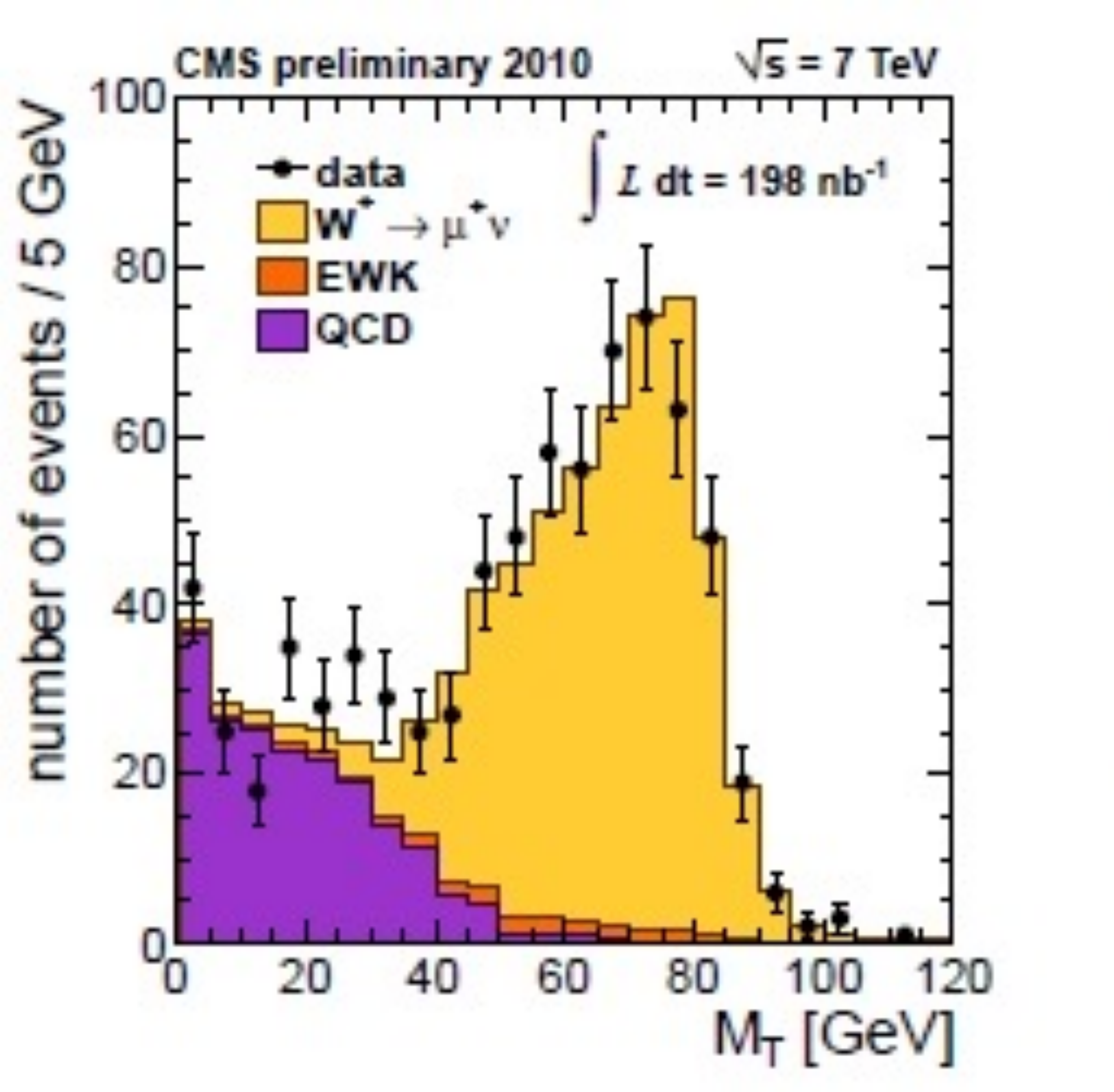
“Compressed”
$m(\tilde{q}) \sim m(\chi_0)$



P_T^{miss}
or
H_T^{miss}
or
M_{T2}

What is M_{T2}?

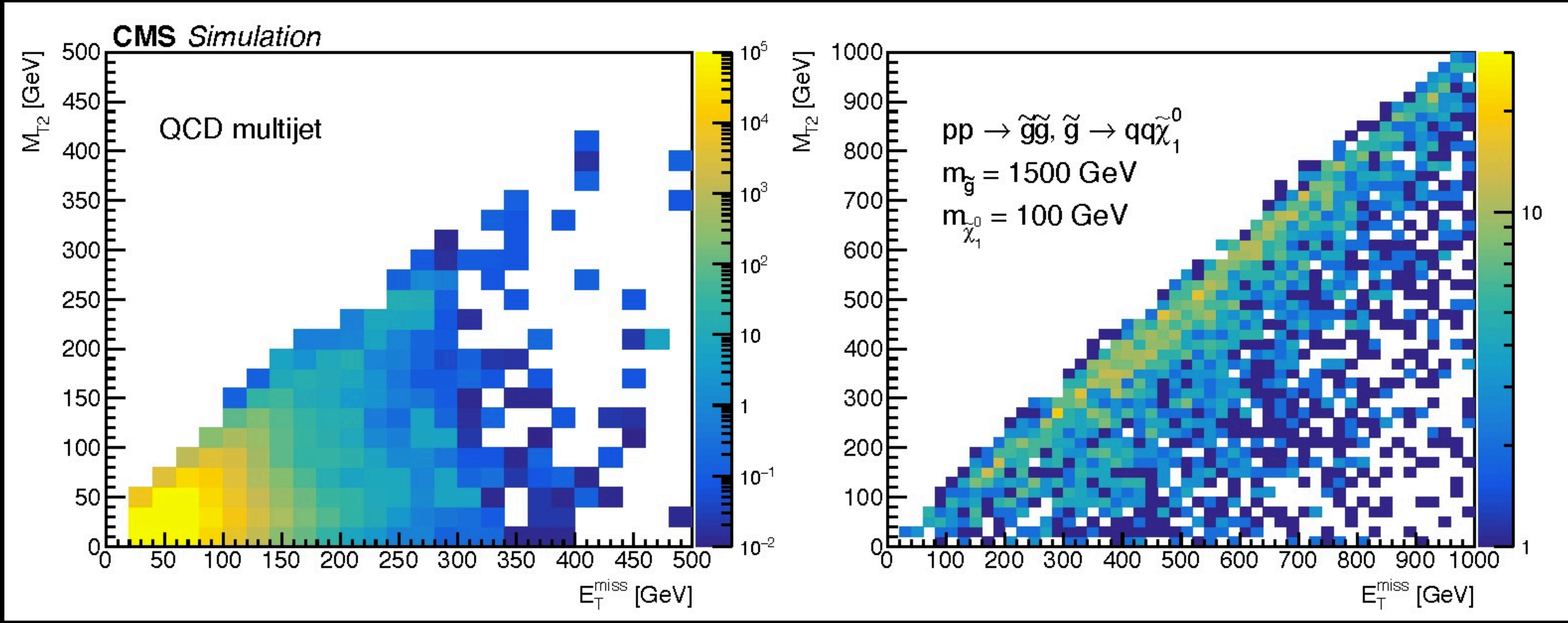
- Decay of one particle into visible + invisible, e.g., $W \to \mu\nu$
- Identify $\vec{P}_T^{\nu} = \vec{P}_T^{miss}$.
- Cannot say anything about P_z^{ν}.
- Construct pseudo-invariant mass (aka transverse mass) M_T using only the transverse components.
- M_T is bound by the mass of the parent particle



What is M_{T2}?

- Now imagine that we have $pp \to \tilde{q}\bar{\tilde{q}} \to q\chi^0\bar{q}\chi^0$
- Now $\vec{P}_T^{miss} = \vec{P}_T^{\chi(1)} + \vec{P}_T^{\chi(2)}$, so cannot uniquely build $M_{T(1)}$ and $M_{T(2)}$
- Build an infinite number of ($M_{T(1)}$, $M_{T(2)}$) pairs subject to $\vec{P}_T^{miss} = \vec{P}_T^{\chi(1)} + \vec{P}_T^{\chi(2)}$
- Define $M_{T2} = min\ \{ max\ (M_{T(1)}\ ,\ M_{T(2)})\ \}$ over all pairs
- M_{T2} is such that $M_{T2} < m(\tilde{q})$
- M_{T2} was invented to measure the mass of SUSY particles
- It turns out that the M_{T2} variable is a little bit better than P_T^{miss} to discriminate events with real P_T^{miss} (eg: SUSY) from QCD backgrounds (see next page)

What is M_{T2}?



Technical details:

- For multijet events, group jets by hemisphere into two jet-like objects
- $M_{T(1)}$ and $M_{T(2)}$ are calculated with all masses set to zero.

Event characherization and binning

- Four variables: H_T N_J N_b M_{T2}
- Four "orthogonal" properties:
  - Total hadronic energy
  - Jet multiplicity
  - b-quark content
  - P_T^{miss}
- Total of 282 signal regions (!)
- Other choices are also possible

Dissecting jets and missing energy searches using n-body extended simplified models

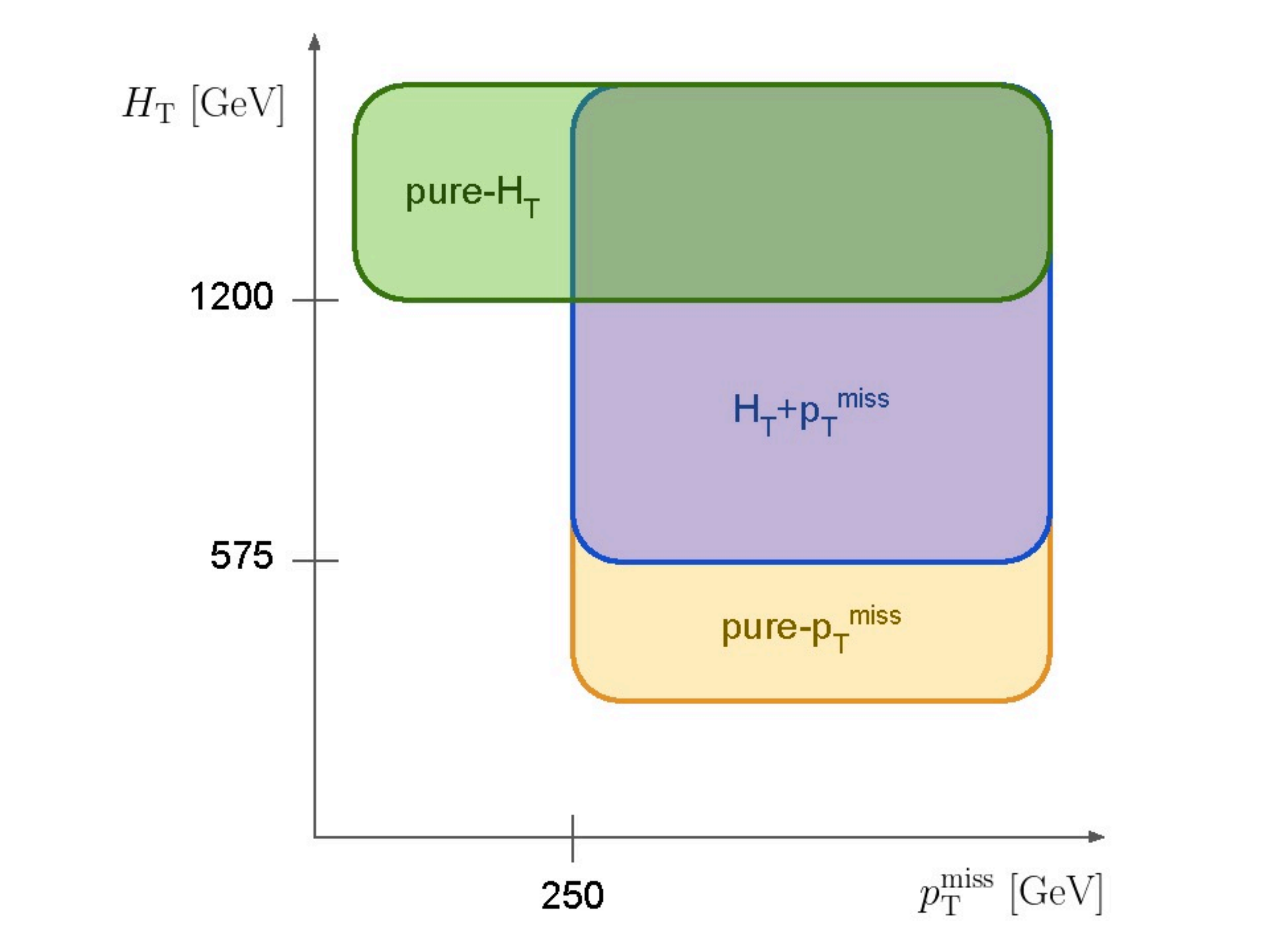
Timothy Cohen,[a] Matthew J. Dolan,[b] Sonia El Hedri,[c] James Hirschauer,[d] Nhan Tran[d] and Andrew Whitbeck[d]

A large number of variables were considered: H_T, $\not{H}_T$, $\not{H}_T/\sqrt{H_T}$, N_j, M_J, m_{eff}, Razor, M_{T2}, and M_{T2}^{CMS}. As was expected and shown in figure 6, no variable can do the job alone. A winning strategy derives from placing cuts on maximally uncorrelated observables in order to generate signal regions where background events are very rare. Boosted Decision

10.1007/JHEP08(2016)038

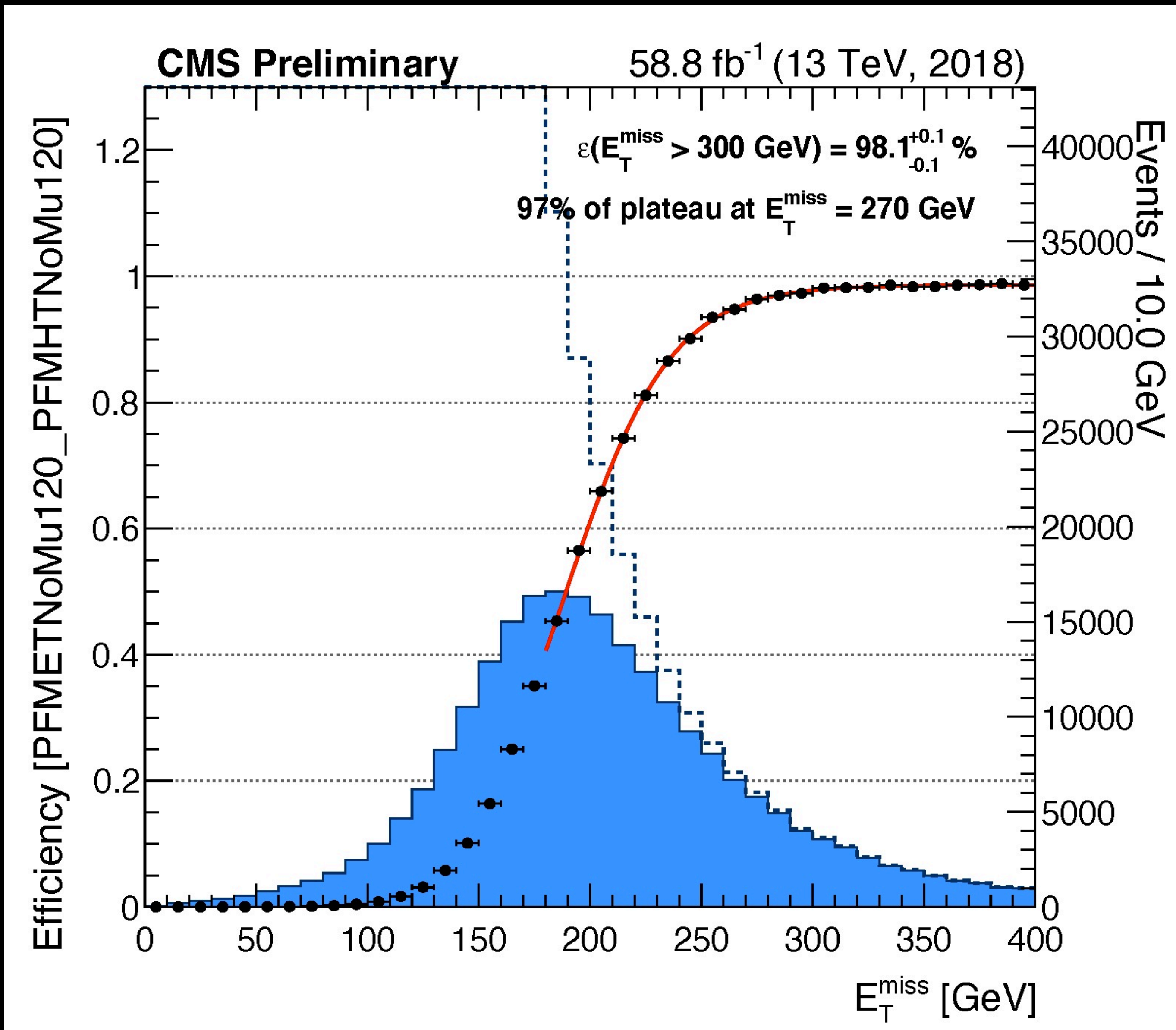
Triggers

- Thresholds driven by rate that can be sustained
- Other triggers used for various control region studies
- Including some “prescaled” triggers



Trigger Efficiency example

P_T^{miss} trigger efficiency measured from muon triggered events

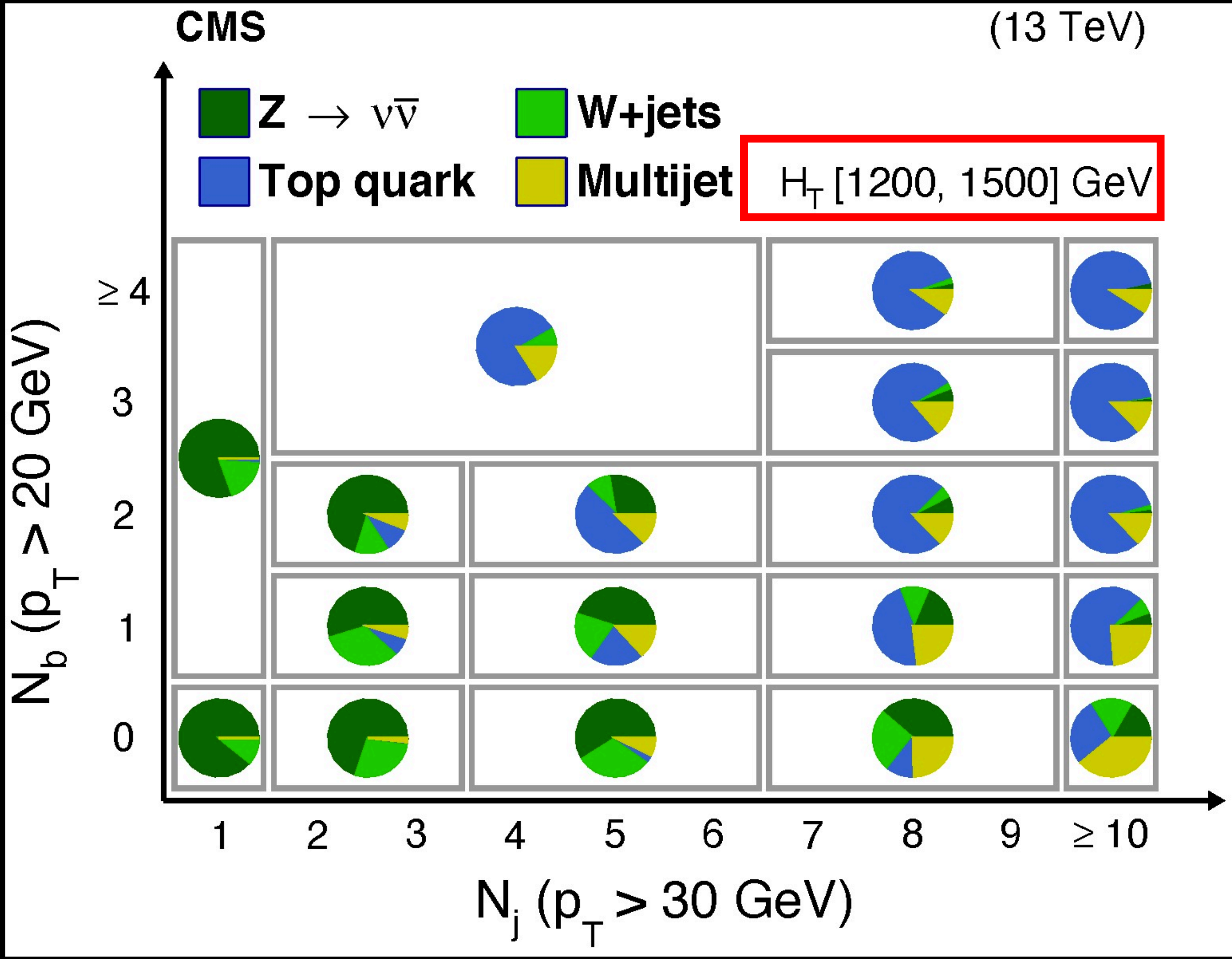


Event Selection, in a nutshell

- Reject events with identified noise in the detector
- H_T and P_T^{miss} in trigger "plateaus"
- Reject events with isolated e, μ, τ
  - Against leptonic decays of W, which result in neutrinos, and therefore P_T^{miss}
- $\vec{P}_T^{miss}$ must point away from 4 highest P_T jets
  - Against P_T^{miss} from mismeasured jets
- P_T^{miss} not too different from H_T^{miss}
  - Against "trouble" from unclustered energy (noise?), very forward unbalanced activity
- M_{T2} > 200 GeV (low H_T) or 400 GeV (high H_T)
  - Against multijet QCD events

Example binning

- One of 5 H_T bins
- Each "square" is subdivided into several (3 to 6, in this case) M_{T2} bins
- The pie charts show the relative composition of the SM backgrounds



How are the bins chosen

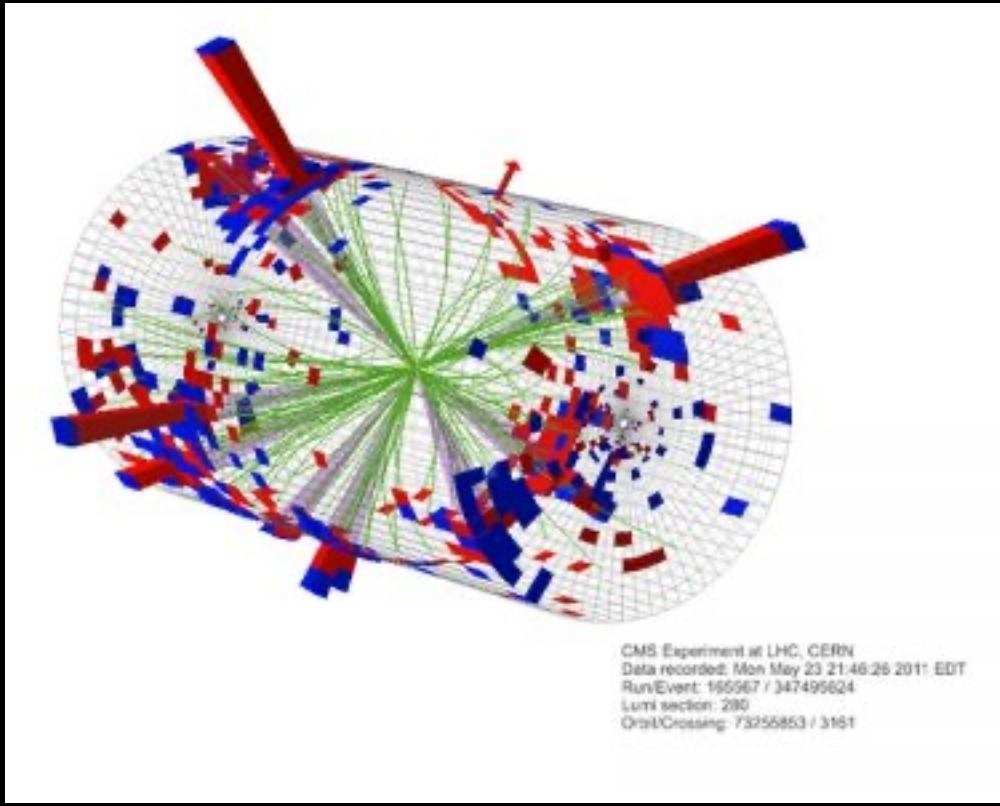
- Science or art?
- H_T binning: go down as far as allowed by trigger; 1200 GeV boundary is where pure H_T trigger kicks in
  - [250-450] [450-575] [575-1200] [1200-1500] [1500-∞]
- N_b binning: typically 0,1,2,≥3
  - 0 removes top BG. ≥3 very small BG: $t\bar{t}$ only has 2 b quarks
- N_j binning: typically group by 2 (2-3, 4-5,..). Go as high as makes sense at given H_T
- M_{T2} binning:
  - Starts at 200 GeV, except at H_T>1500 where we start at 400 GeV to reduce QCD
  - Binsize ~ 100 GeV, but merge bins with expected BG < 1 event (no point in going finer)
  - Highest M_{T2} bin such that O(1) BG event is expected

Backgrounds

- QCD multijet
- "Z invisible", $Z \to \nu\nu$
- "Lost leptons": $W \to \ell\nu$ where the lepton is not found
  - Could be from $pp \to W$ but also $pp \to t\bar{t} \to WWb\bar{b}$ etc. etc.

QCD multijet

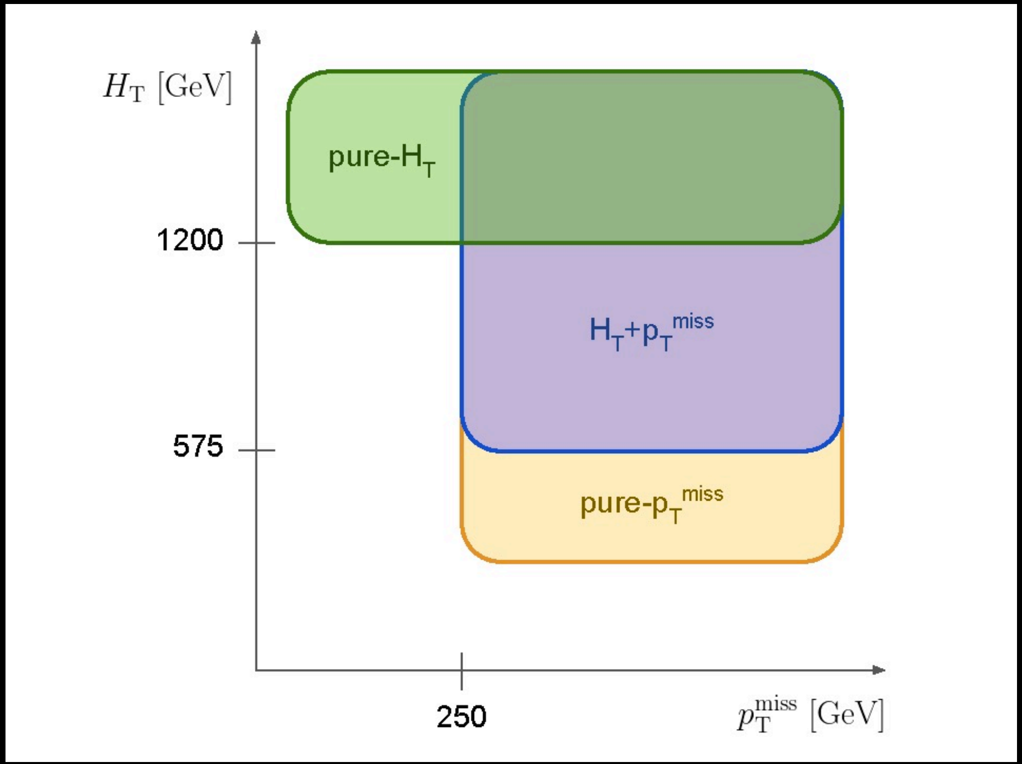
- <u>**The scariest background**</u>
- Extreme “tail” of very high cross-section process
- Very difficult to come up with robust data-driven estimation method
- Prohibitively CPU expensive to simulate
  - Trust the <u>simulation</u> of very unlikely events?
  - Trust the detailed <u>generation</u> of events with several jets? (High order QCD)
- **Rebalance and Smear**
  - Hybrid data-driven and MC method
- Fortunately BG turns out to be subdominant, does not need to be known too precisely

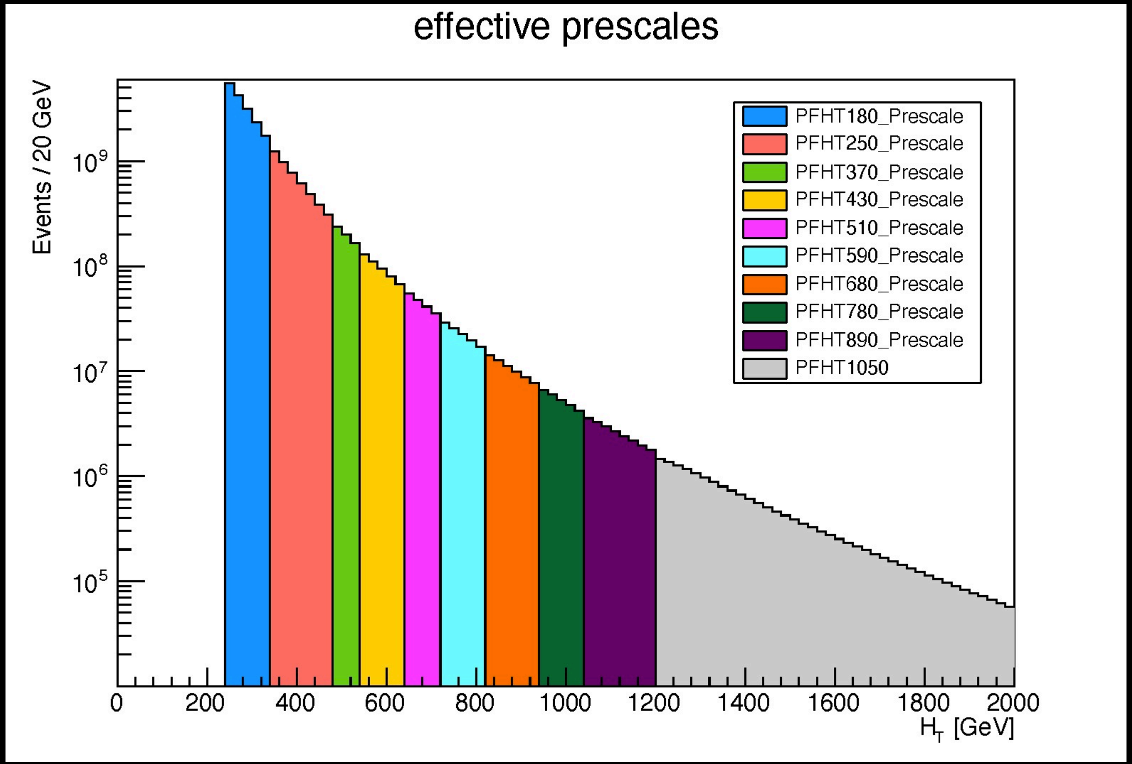


Rebalance and Smear (R&S) in a Nutshell

- Select multijet events in data
- They have non-zero $\vec{P}_T^{miss}$
- **Rebalance:** shift (re-fit) the jet energies within resolutions so that $\vec{P}_T^{miss} \sim 0$
  - Obtain a **data-driven** model of the physics of multijet events
- **Smear:** use **MC** jet energy resolution templates to perform (**by hand**) equivalent of full detector simulation
  - Can repeat this many times on each rebalanced event (large stat, little CPU time)
  - Can easily change templates to assess systematics
- **The rebalanced-and-smeared events, properly normalized, are used to predict the backgrounds in the various signal regions.**

R&S: selection of multijet events, pure H_T triggers



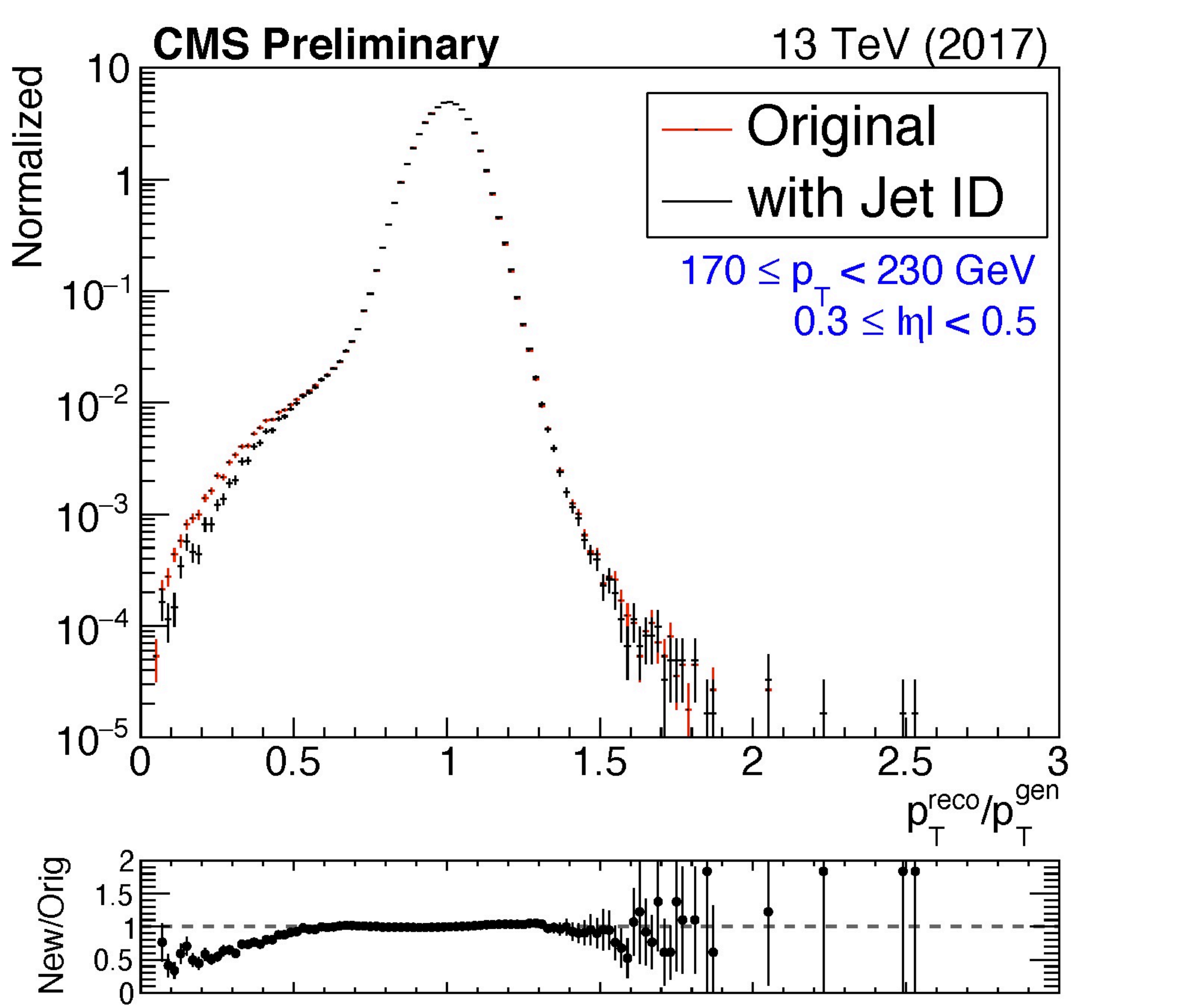


For $H_T < 1200$ GeV need to rely on prescaled triggers

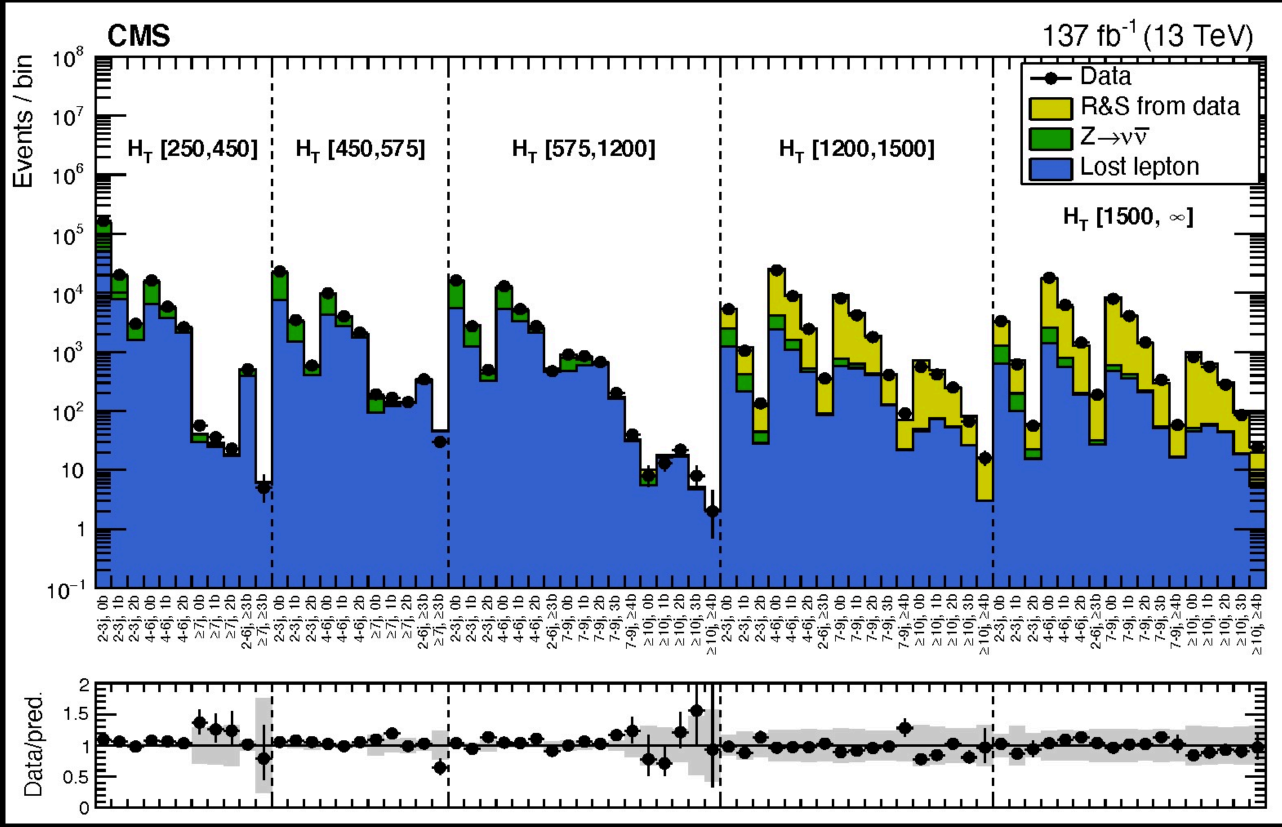
H_T spectrum, with prescaled triggers. Note: events with ν, eg, $W \to \ell\nu$ must be carefully removed

R&S: example jet resolution template from MC

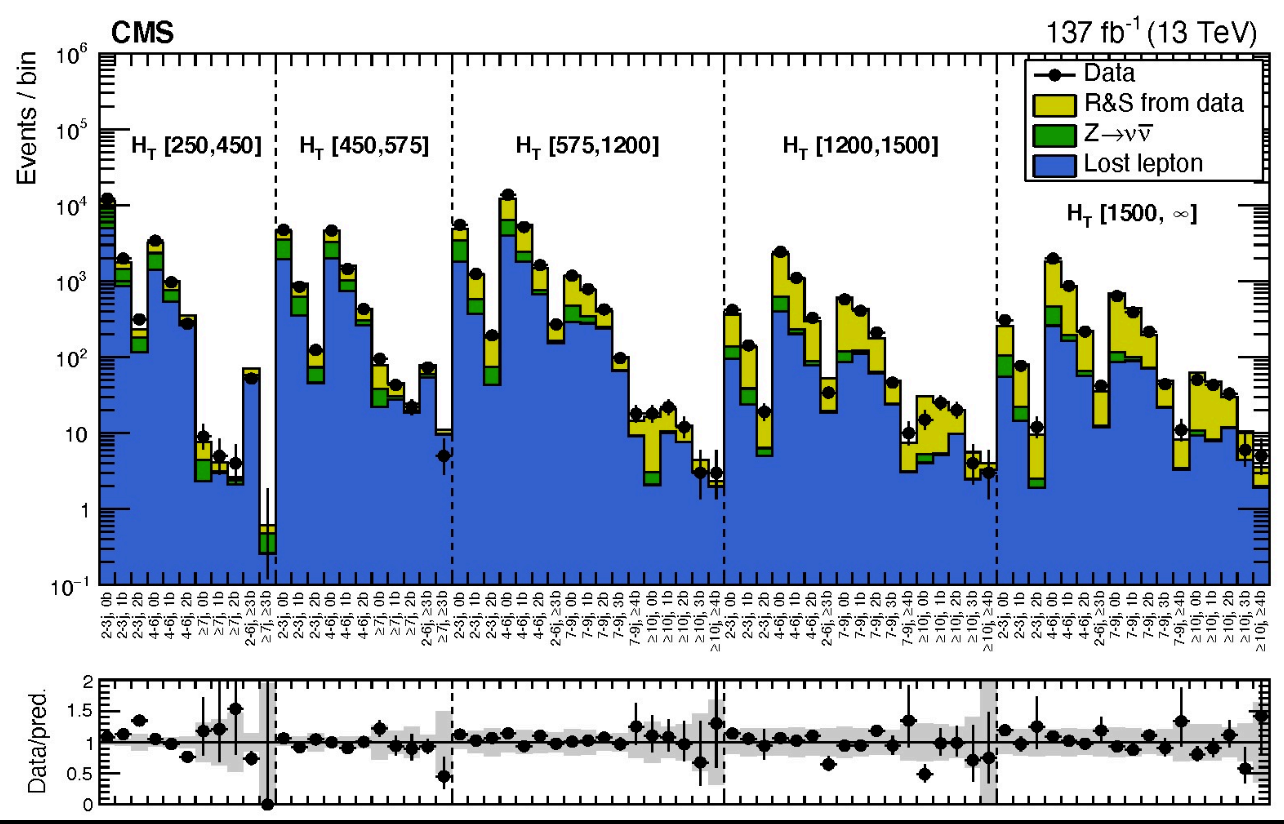
- Note the asymmetric tail
- Template extraction from full simulation delicate. Far tails, which are the most important can be affected by
  - Jet merging/splitting
  - Simulation of dead cells
  - Simulation of pileup
  - Simulation of “noise cleaning”
  - etc



R&S: Checks in data sidebands



100 < M_{T2} < 200 GeV

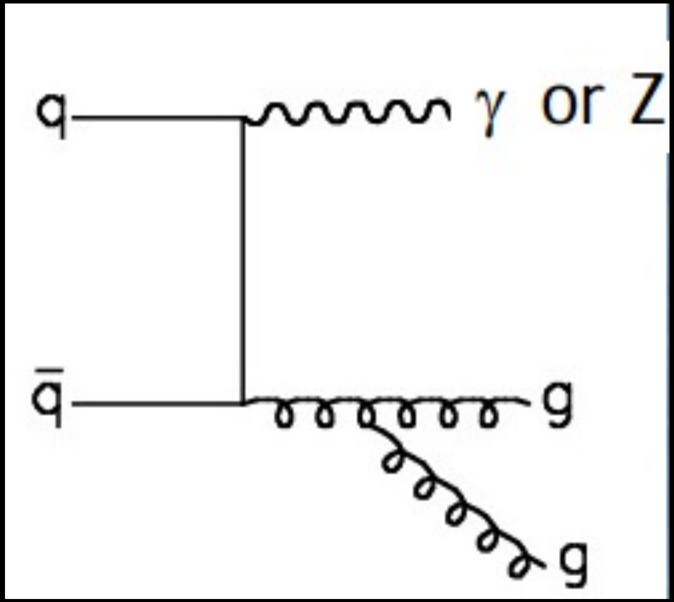


$\vec{P}_T^{miss}$ points in the direction of a jet

Z invisible. $(Z \to \nu\nu)$

Two possible methods

1. Exploit the similarities between γ+jets and Z+jets



2. Extrapolate from observed $Z \to \ell\ell$

$$\frac{\mathrm{BR}(Z \to \nu\nu)}{\mathrm{BR}(Z \to ee \text{ or } \mu\mu)} = 4.5$$

Z invisible from $Z \to ee/\mu\mu$

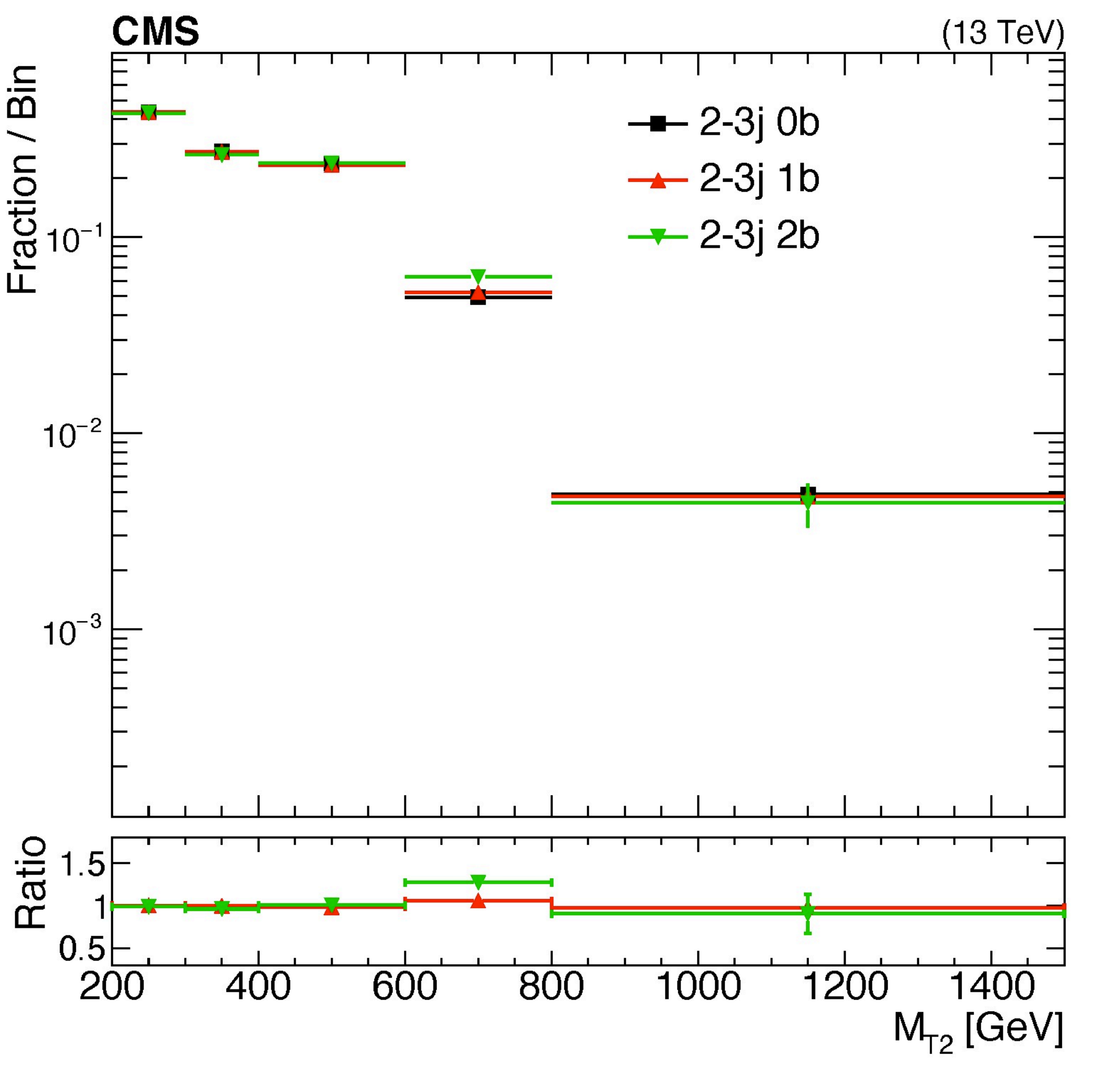
- Measure $Z \to ee/\mu\mu$ in various kinematical regions
- Subtract off contributions from other processes such as $t\bar{t} \to ee + X$
  - Use, e.g., $t\bar{t} \to e\mu + X$
- Rescale by $\frac{1}{\epsilon(\ell)^2}$ x $\frac{1}{Acc(\ell\ell)}$ and ratio of $Z \to \nu\nu$ to $Z \to ee/\mu\mu$ branching ratios
- $\overrightarrow{P_T^{\ell\ell}} + \overrightarrow{P_T^{miss}}$ in $\ell\ell$ events is estimate of $\overrightarrow{P_T^{miss}}$ in $\nu\nu$ events

- **Challenge: the branching ratio for $\nu\nu$ is > than for $\ell\ell$**
- **Lack of statistics! Must extrapolate into tails!**

Z invisible extrapolation

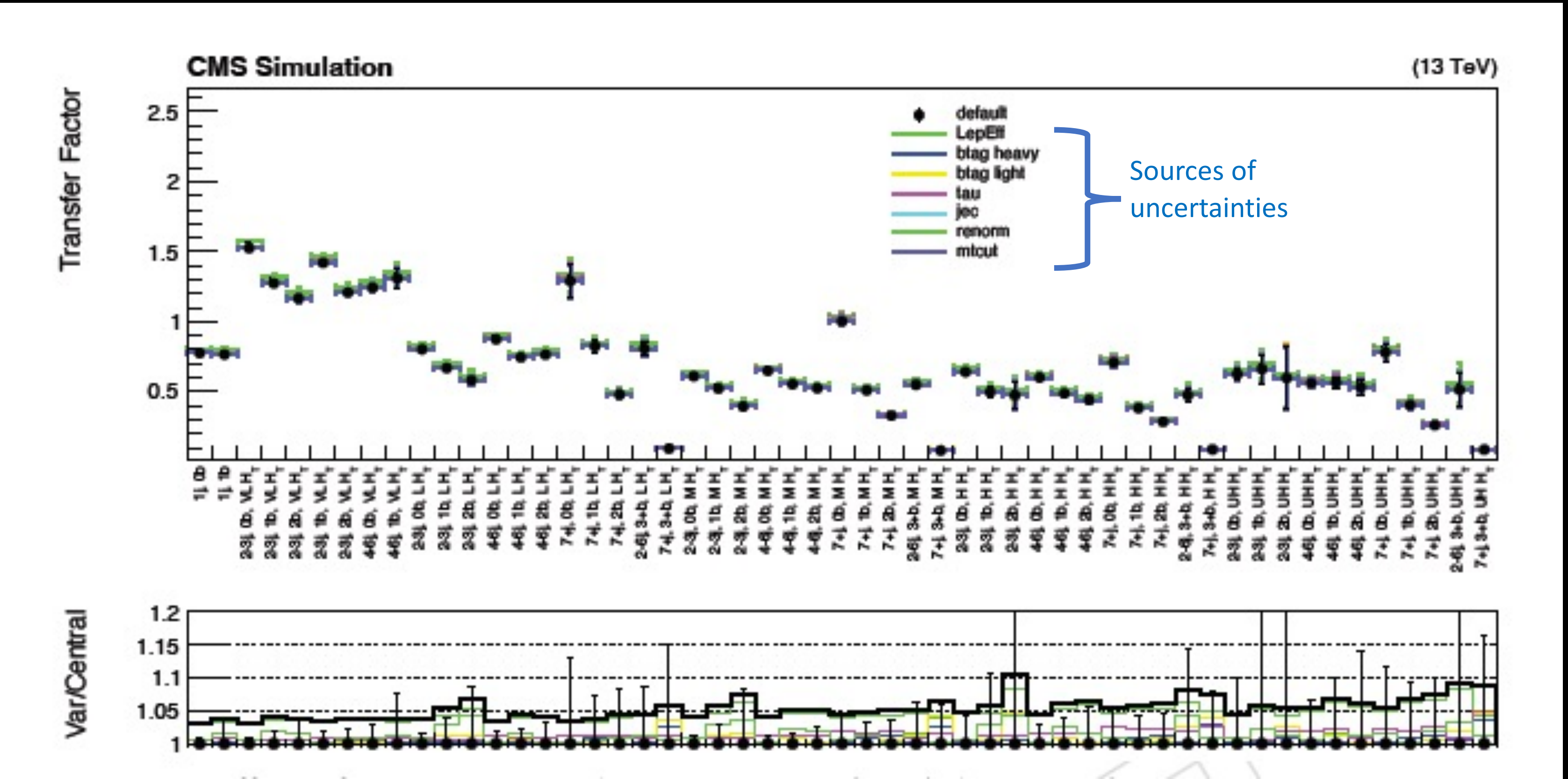
- The $\ell\ell$ data is used to predict the $\nu\nu$ BG as a function of (H_T N_J N_b) integrated over M_{T2}
- BG is then distributed between M_{T2} bins assuming
  - M_{T2} **shape** does not depend on N_b (most of the Z invisible has no b quarks anyway!)
  - First, merge low statistics M_{T2} bins together to get the total BG in the merged bins
  - Then, split the BG prediction across merged bins according to the MC
- MC is then used, but its effect is minimized.
  - Use MC shapes (not normalization) and only in limited regions and/or where BG is tiny

Example MC M_{T2} shape vs b-multiplicity



“Lost lepton”: $W \rightarrow \ell\nu$ where the lepton is not found

- First try to suppress it as much as possible by looking very hard for leptons
- Then use MC to obtain *Transfer Factor (TF)* as ratio of lost-to-found
  - ”Lost” includes “out of geometrical acceptance”.
  - “Found” are events in Control Region with one lepton
- Similar type of extrapolations as in Z invisible case are needed in the tails because of low statistics



One last wrinkle

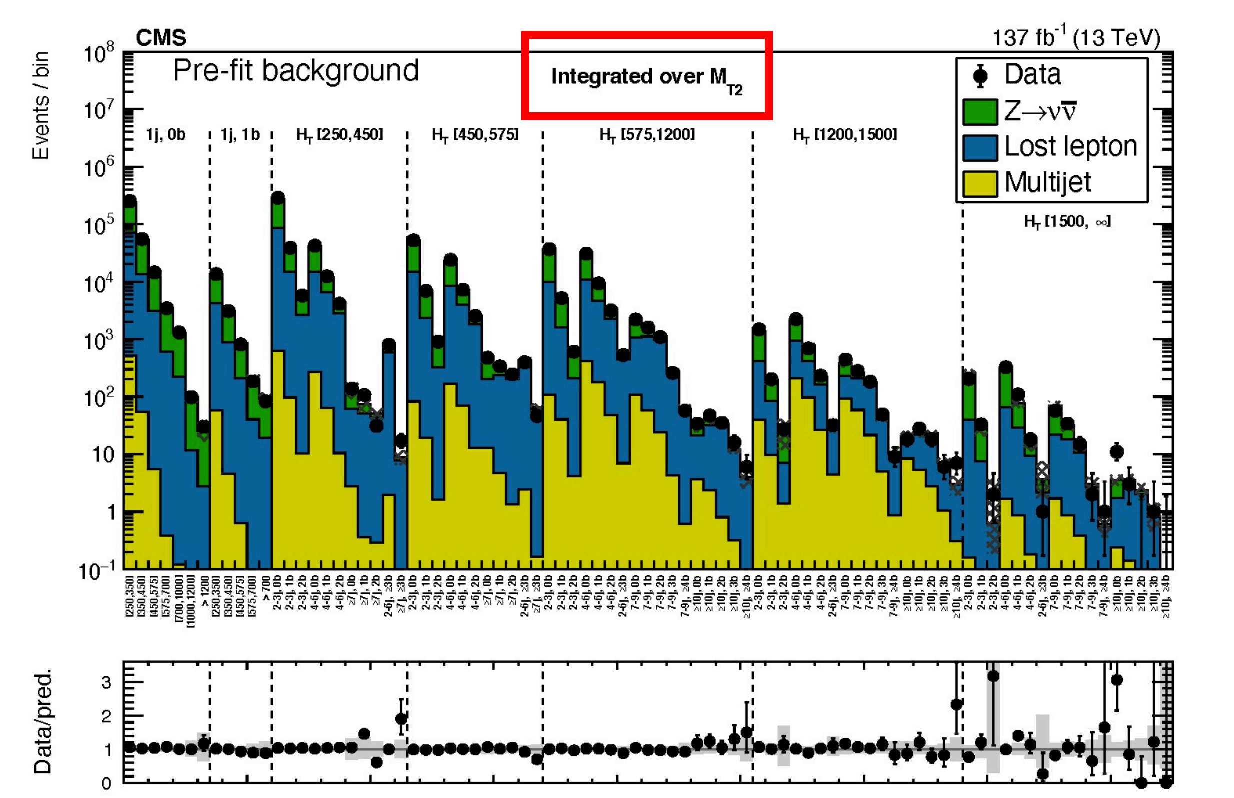
- Some of the Control Regions, e.g., the "One Lepton Control Region" can include SUSY events
  - e.g.: $\tilde{t} \to t\chi^0 \to Wb\chi^0 \to \ell\nu b\chi^0$
- Leads to overestimate of Standard Model background
- Can deal in two ways
  1. The right way: joint fit of S+B in Signal and Control Regions
     - Doubles or triples the complexity of the statistical analysis
  2. Treat the overestimate of the BG to be subtraced as a loss of efficiency
     - Since the effects in this analysis are small from none to at most 5-10%, this is what was done

Systematics

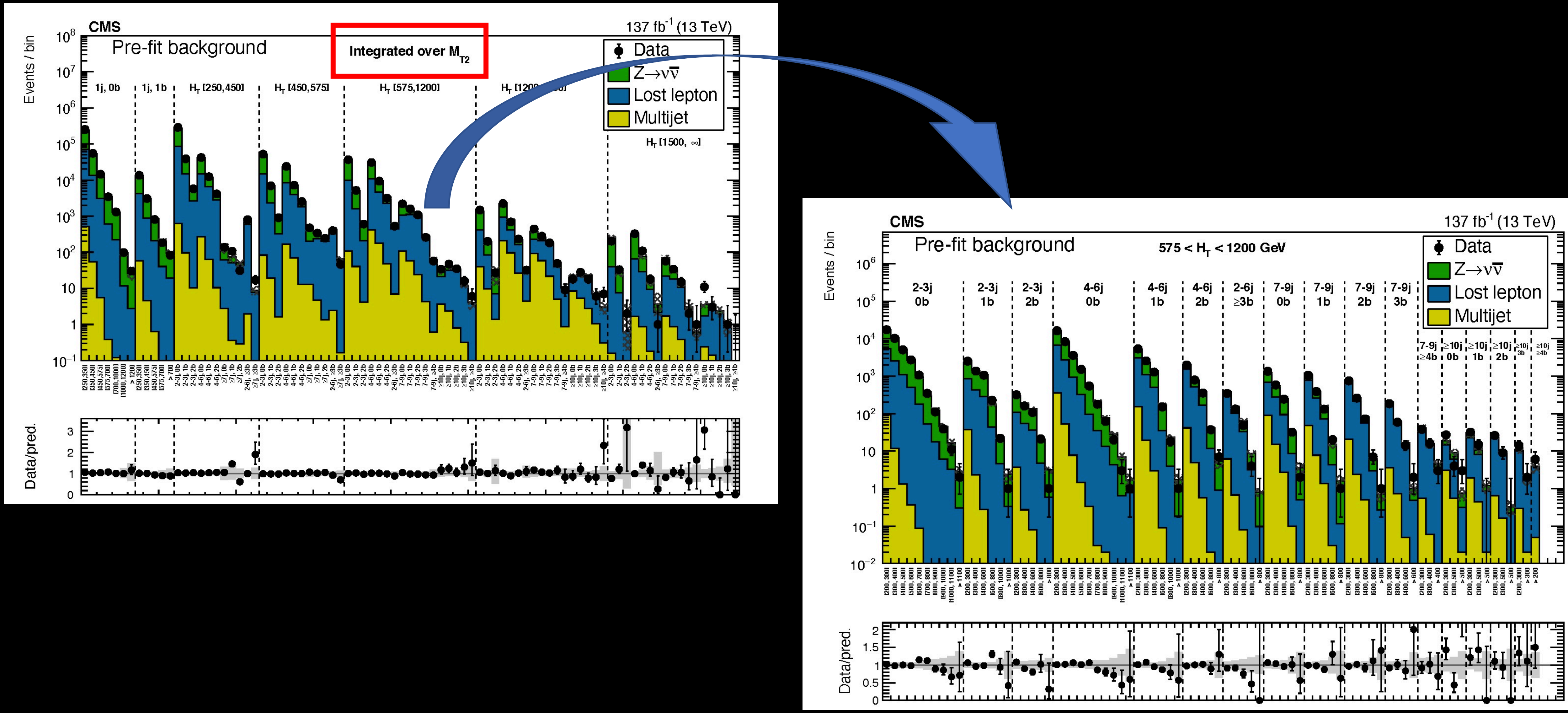
- Most important are on BG prediction: range from few % to O(100%) depending on signal region
  - Statistics of control regions
  - Transfer factor uncertainties from various effects
  - Extrapolations

- Uncertainties on signal efficiency also included.
  - Signal region by signal region
  - By signal model (final state eg. $\tilde{q}\,\tilde{\bar{q}} \rightarrow q\bar{q}\chi^0\chi^0$ and pairs of SUSY masses)
  - B tagging efficiency
  - Jet energy scale
  - M_{T2} resolution

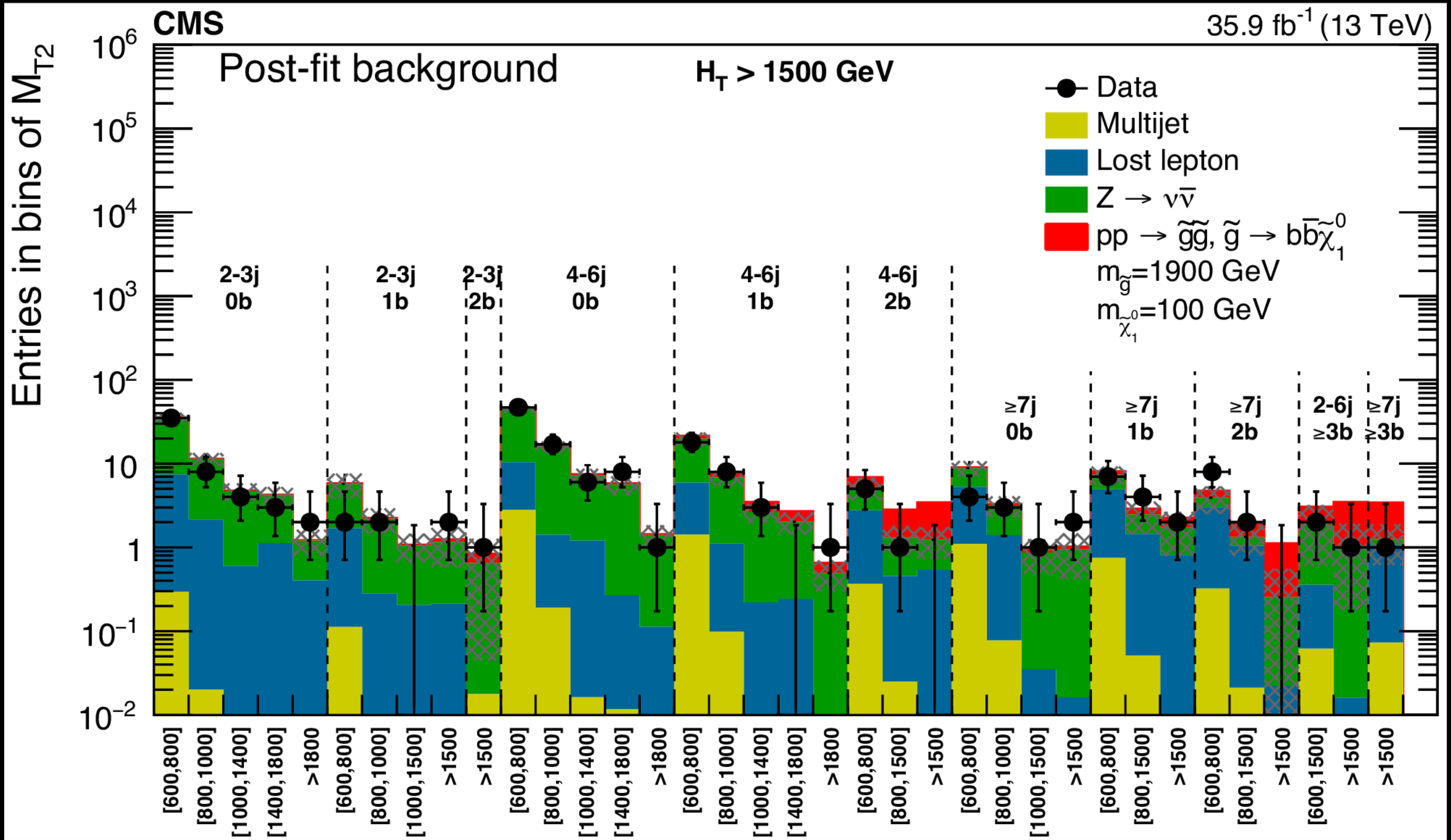
Sample of results



Sample of results



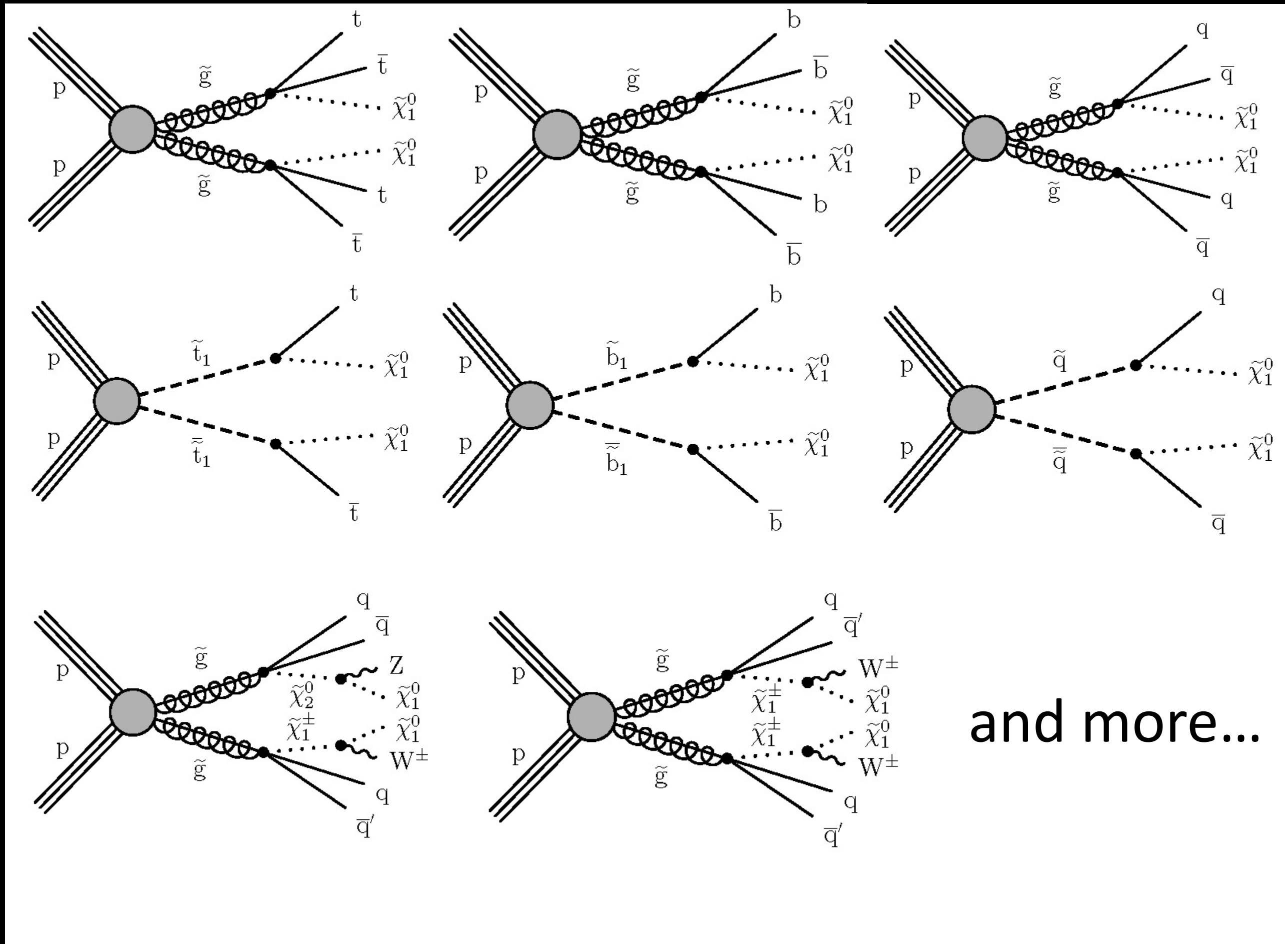
SUSY signal would be spread over subset of bins

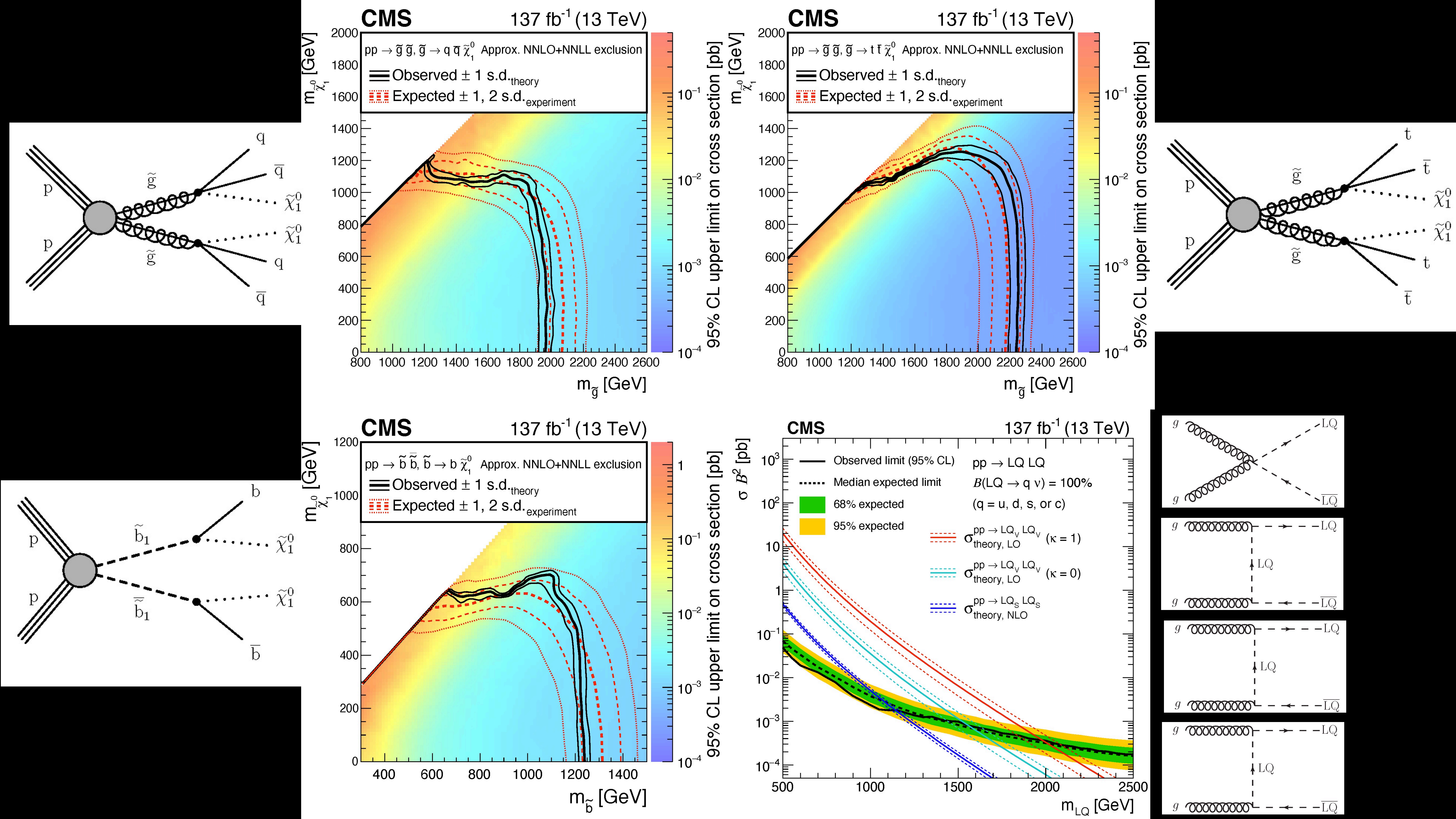


NB: this is a plot with only about ¼ of the total luminosity

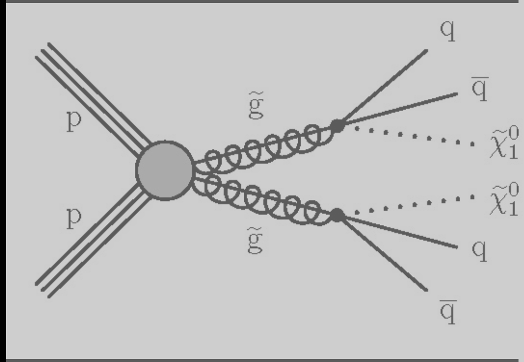
Next step: set upper limits on SUSY cross-section

- Done for each signal model
- Grid of mass pairs, eg, $m(\tilde{t}), m(\chi^0)$

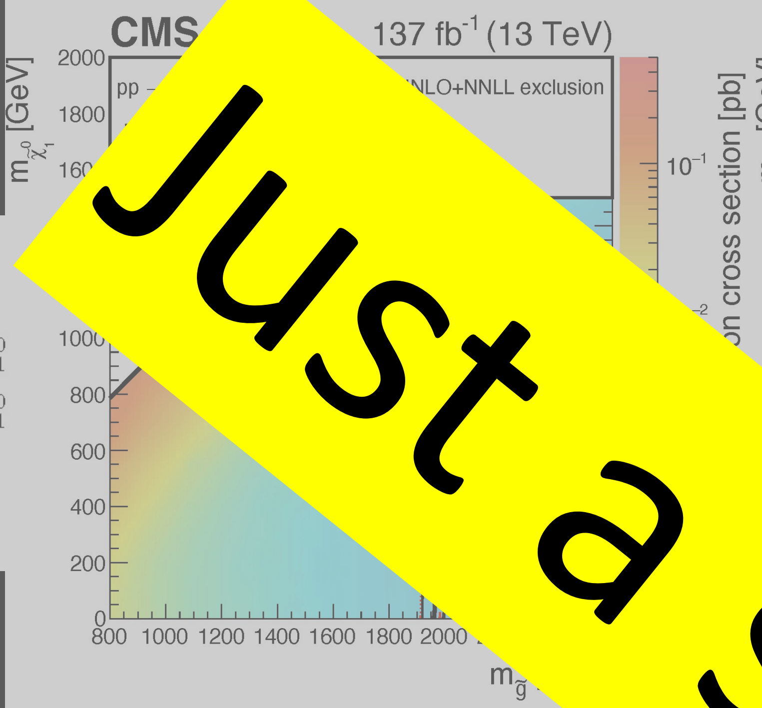




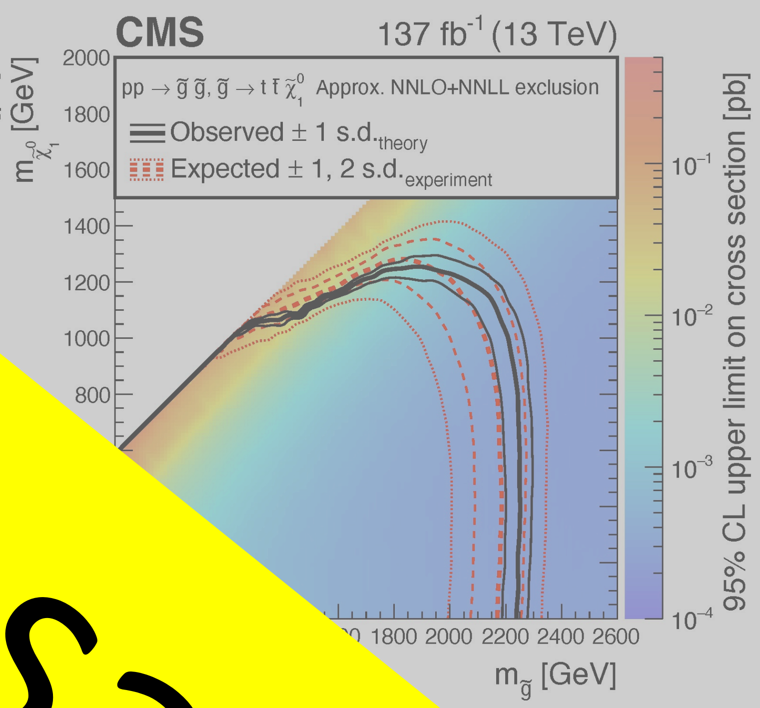
CMS
137 fb^{-1} (13 TeV)
pp → $\tilde{g}\tilde{g}$, $\tilde{g}$ → q $\bar{q}$ $\tilde{\chi}^0_1$ Approx. NNLO+NNLL exclusion
Observed ± 1 s.d.$_{theory}$
Expected ± 1, 2 s.d.$_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]
pp → $\tilde{g}\tilde{g}$, $\tilde{g}$ → t $\bar{t}$ $\tilde{\chi}^0_1$ Approx. NNLO+NNLL exclusion
pp → $\tilde{b}\bar{\tilde{b}}$, $\tilde{b}$ → b $\tilde{\chi}^0_1$ Approx. NNLO+NNLL exclusion
$m_{\tilde{b}}$ [GeV]
Observed limit (95% CL)
Median expected limit
68% expected
95% expected
pp → LQ LQ
B(LQ → q ν) = 100%
(q = u, d, s, or c)
$\sigma^{pp \to LQ_V LQ_V}_{theory, LO}$ (κ = 1)
$\sigma^{pp \to LQ_V LQ_V}_{theory, LO}$ (κ = 0)
$\sigma^{pp \to LQ_S LQ_S}_{theory, NLO}$
σB^2 [pb]
m_{LQ} [GeV]



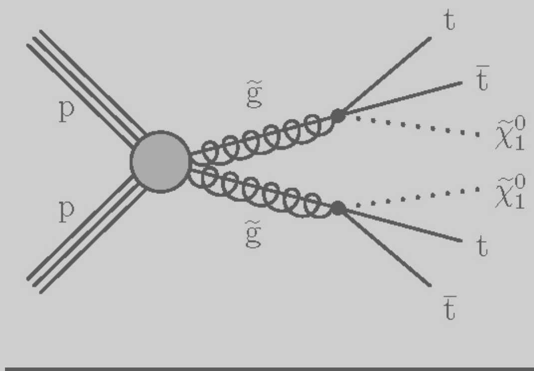
p
p
g̃
g̃
q
q̄
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
q
q̄



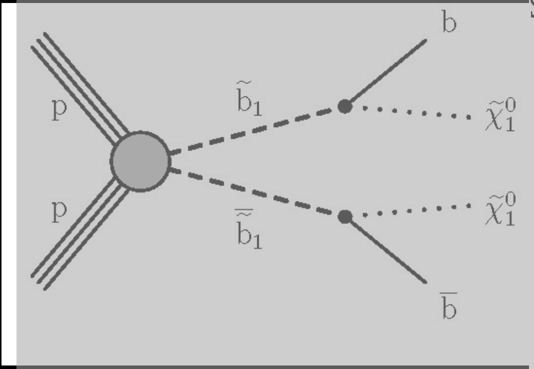
CMS
137 fb^{-1} (13 TeV)
NNLO+NNLL exclusion
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$



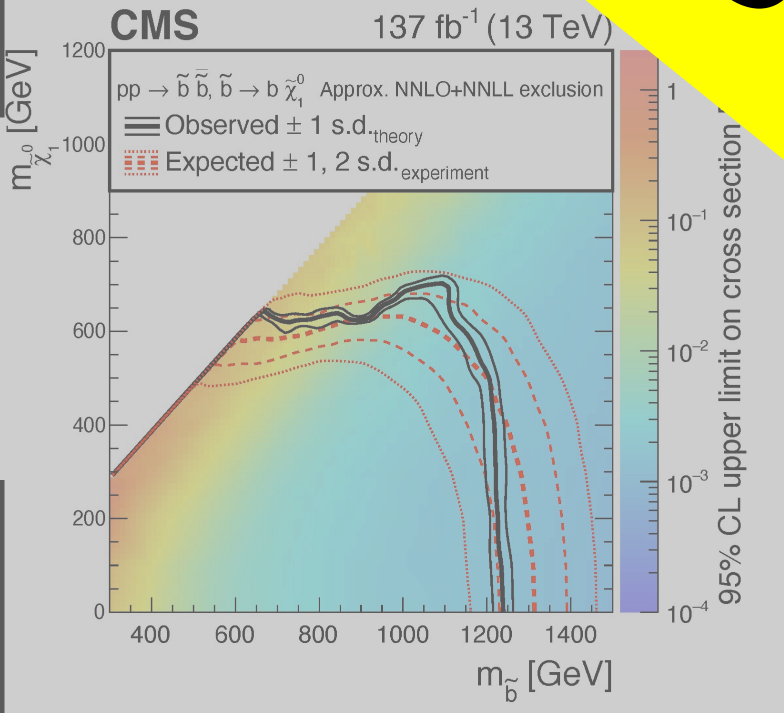
CMS
137 fb^{-1} (13 TeV)
pp → g̃ g̃, g̃ → t t̄ $\tilde{\chi}_1^0$ Approx. NNLO+NNLL exclusion
Observed ± 1 s.d.$_{\text{theory}}$
Expected ± 1, 2 s.d.$_{\text{experiment}}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]



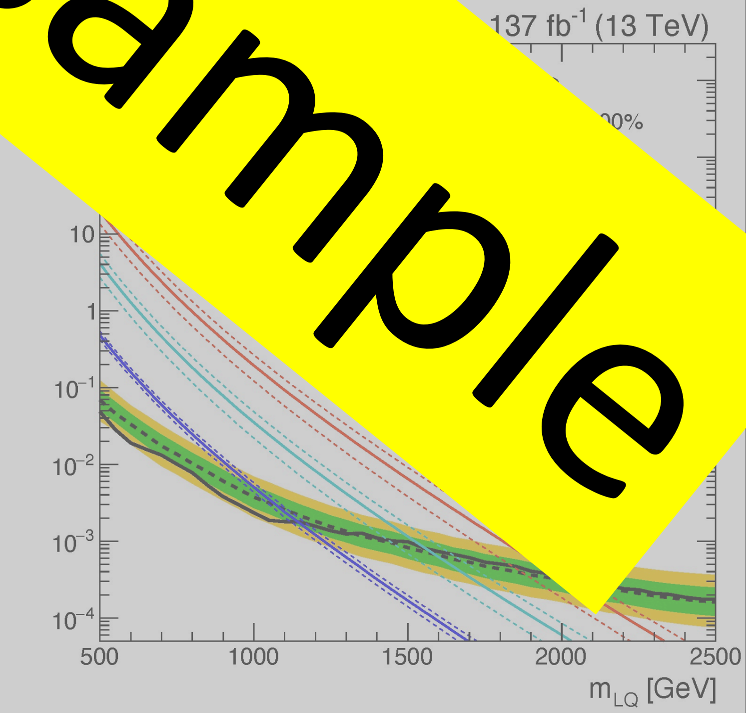
p
p
g̃
g̃
t
t̄
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
t
t̄



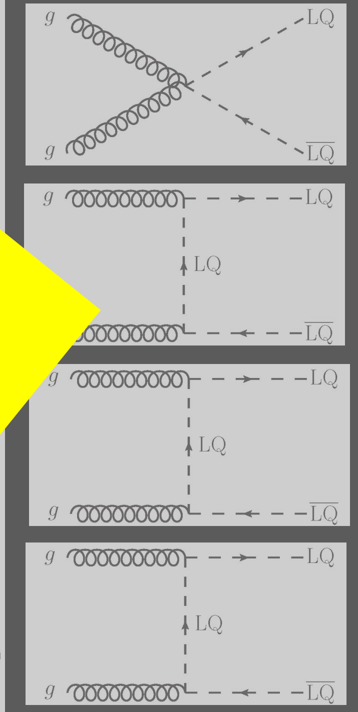
p
p
$\tilde{b}_1$
$\bar{\tilde{b}}_1$
b
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
b̄



CMS
137 fb^{-1} (13 TeV)
pp → b̃ b̃, b̃ → b $\tilde{\chi}_1^0$ Approx. NNLO+NNLL exclusion
Observed ± 1 s.d.$_{\text{theory}}$
Expected ± 1, 2 s.d.$_{\text{experiment}}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{b}}$ [GeV]
95% CL upper limit on cross section



137 fb^{-1} (13 TeV)
m_{LQ} [GeV]



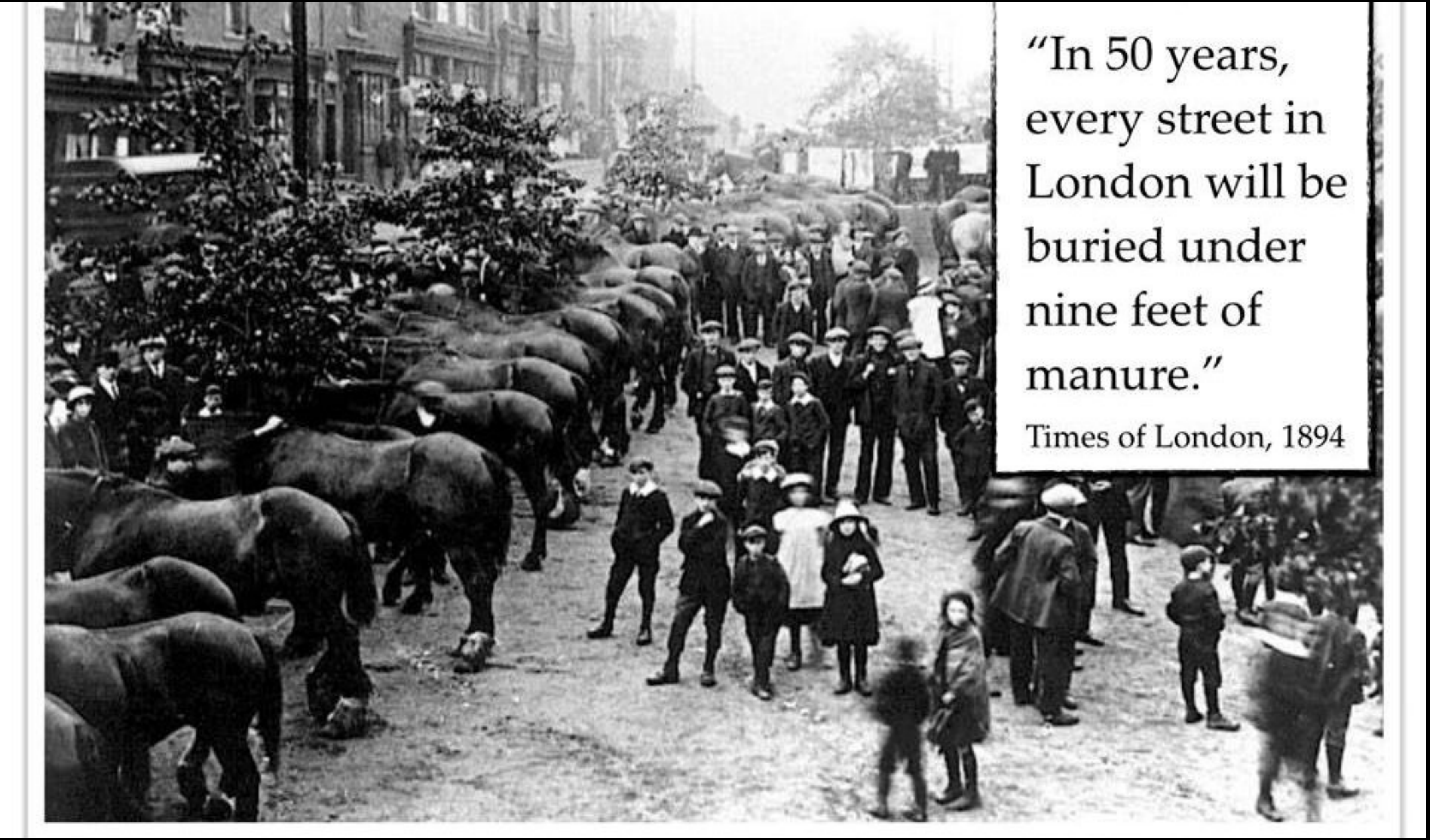
g
LQ
$\overline{\text{LQ}}$

Exclusions

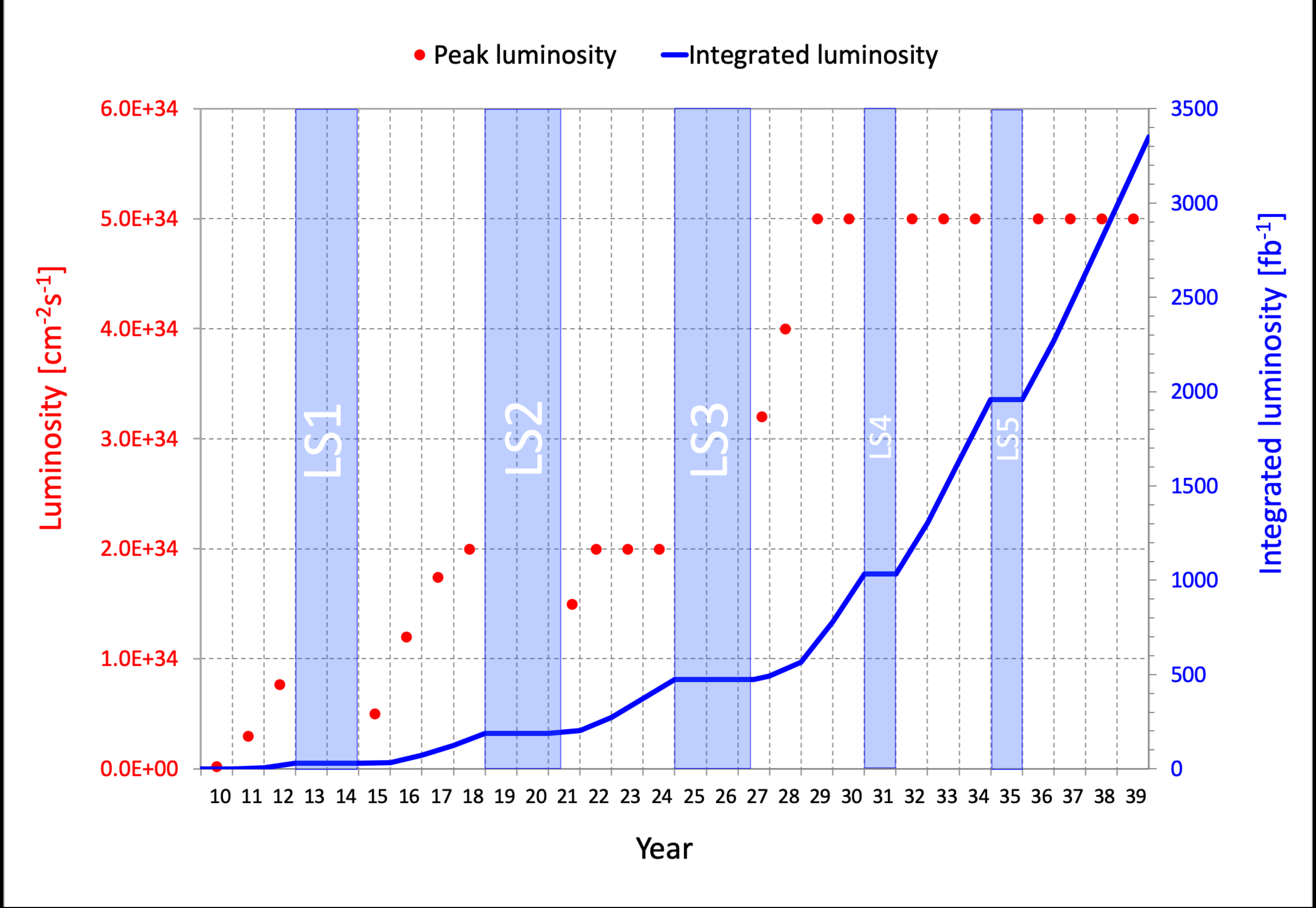
- Gluino masses up to ~ 2250 GeV
- Neutralino masses up to ~ 1525 GeV (in gluino scenarios)
- Stop, Sbottom, Squark masses up to ~ 1710, 1240, 1200 GeV
- Neutralino masses up to ~ 870, 700, 580 GeV (in squark scenarios)
- LQ decaying to qν or bν or tν up to masses ~ 1200-2100 GeV

Future?

Predicting the future is hard….



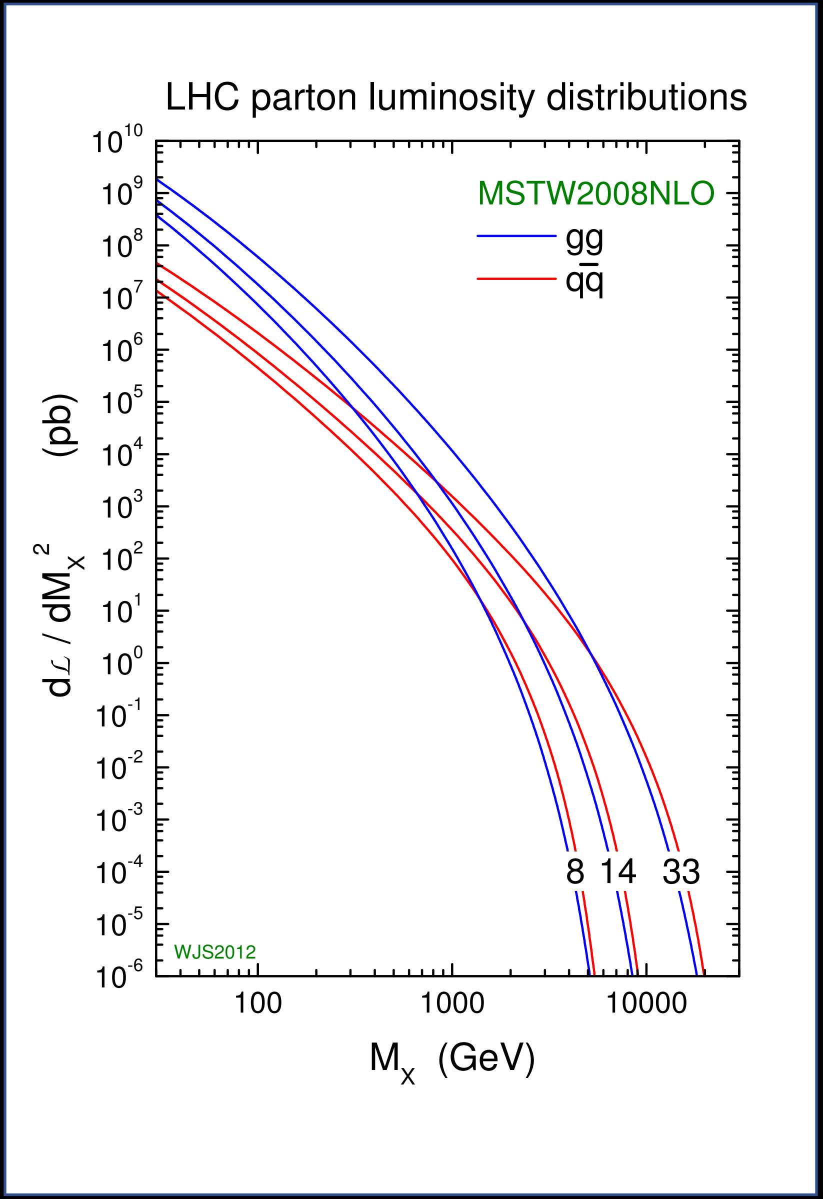
The great horse manure crisis of 1894



Not the latest one, shift by ~ one year

Future of SUSY (and other BSM Searches)

- Expected increase in size of data set will not have a significant effect on mass reach for discovering new particles
- More data + better ideas to look in "difficult" corner of parameter space?



Is SUSY dead?

- It cannot be killed because it is not one theory but a framework

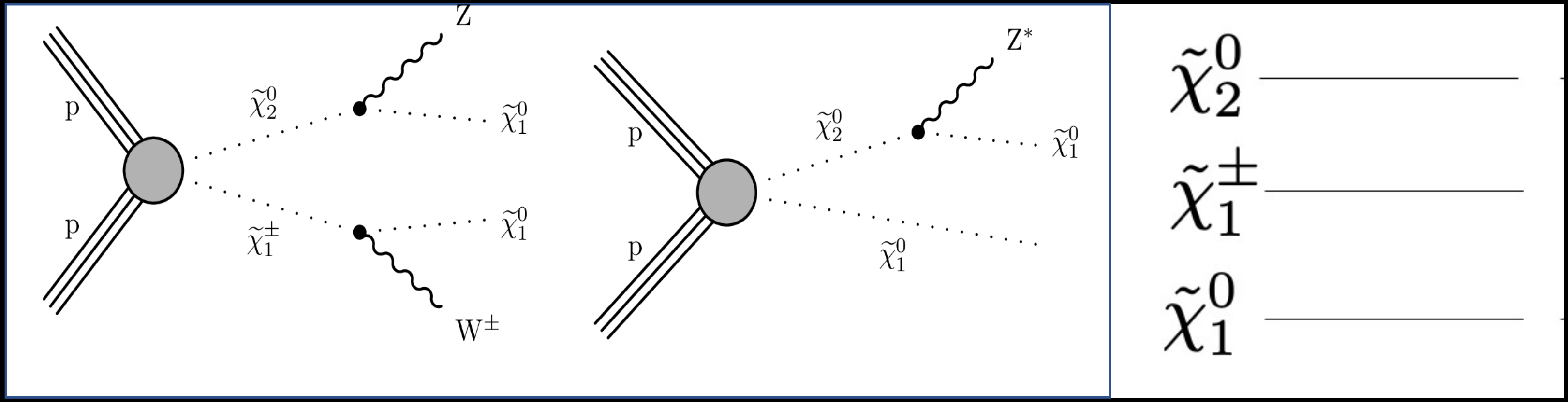
- Can always push masses higher than current LHC reach

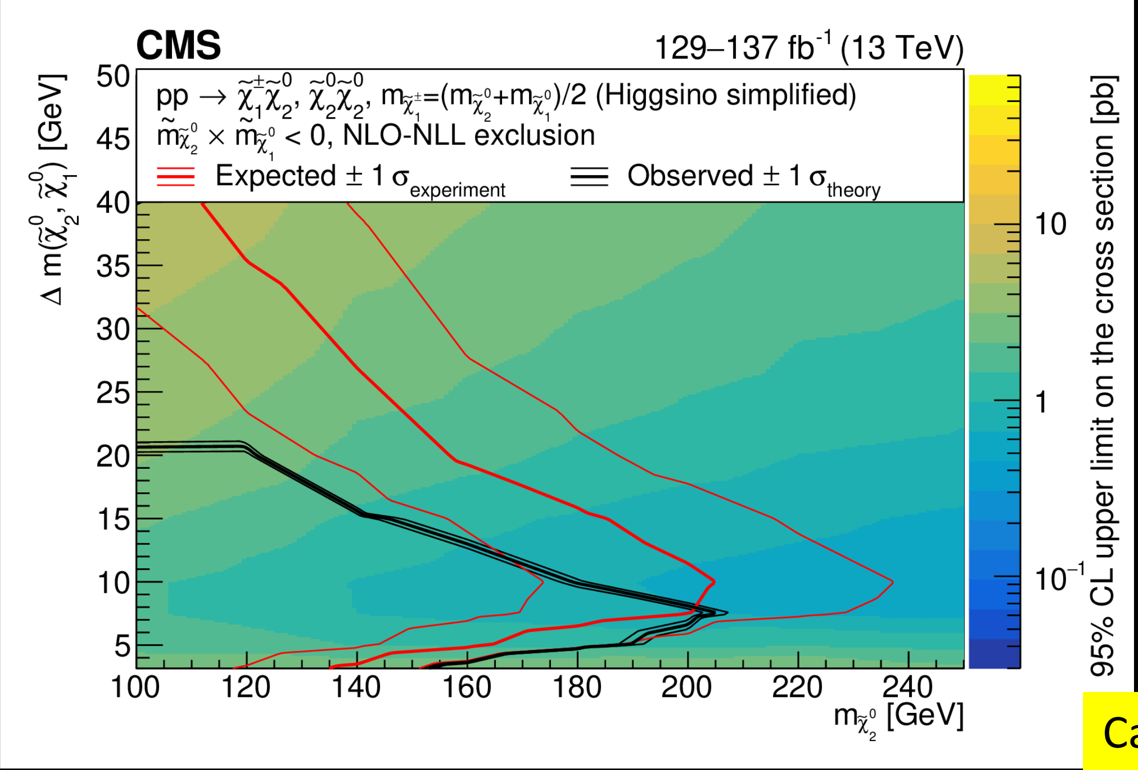
- But TeV-scale SUSY to solve the naturalness problem is on life support

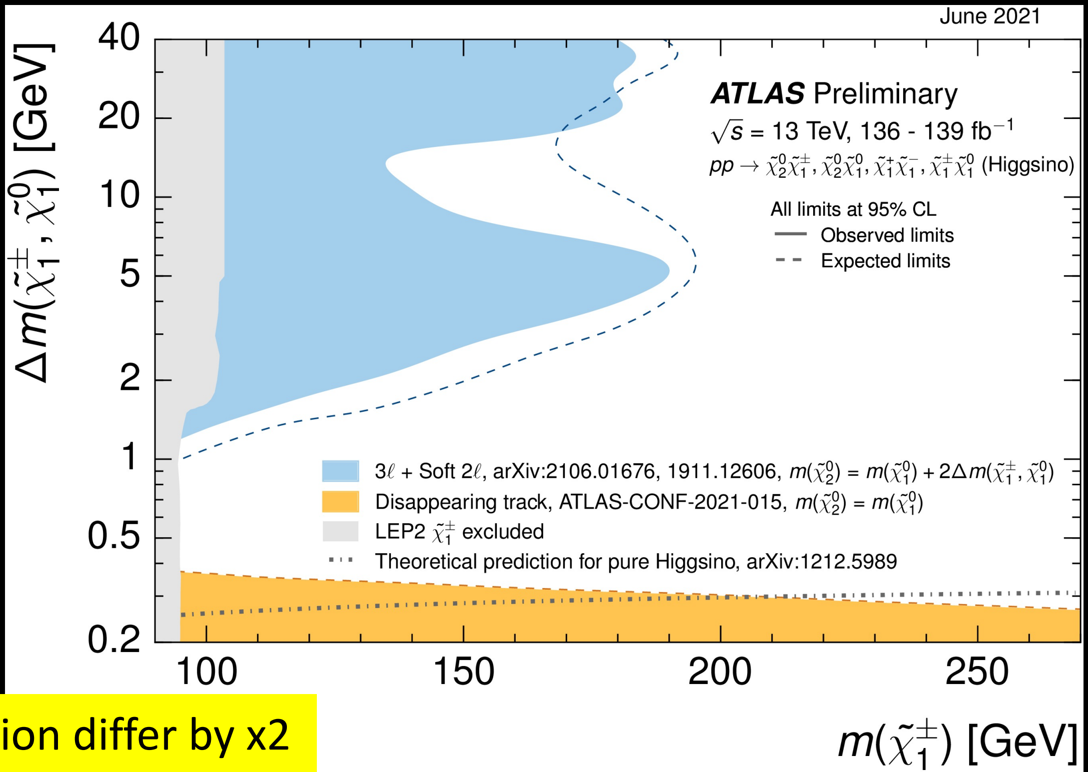
Hossenfelder

Higgsinos: best hope to rescue Naturalness?

- Low cross section
- Compressed spectrum
- Jet recoil
- Low P_T leptons







Careful: Δm definition differ by x2

Some theorists are confused

The trouble is that it's not clear when to give up on supersymmetry. True, as more data arrives from the LHC with no sign of superpartners, the heavier they would have to be if they existed, and the less they solve the problem. But there's no obvious point at which one says 'ah well, that's it – now supersymmetry is dead'. Everyone has their own biased point in time at which they stop believing, at least enough to stop working on it. The LHC is still going and there's still plenty of effort going into the search for superpartners, but many of my colleagues have moved on to new research topics. For the first 20 years of my scientific career, I cut my teeth on figuring out ways to detect the presence of superpartners in LHC data. Now I've all but dropped it as a research topic.

Ben Allanach, Cambridge

Some theorist are more hopeful

WIMPs remain promising because they are one of only a few dark matter candidates to predict their own existence, and also a candidate where that prediction is strongly correlated with discovery prospects.

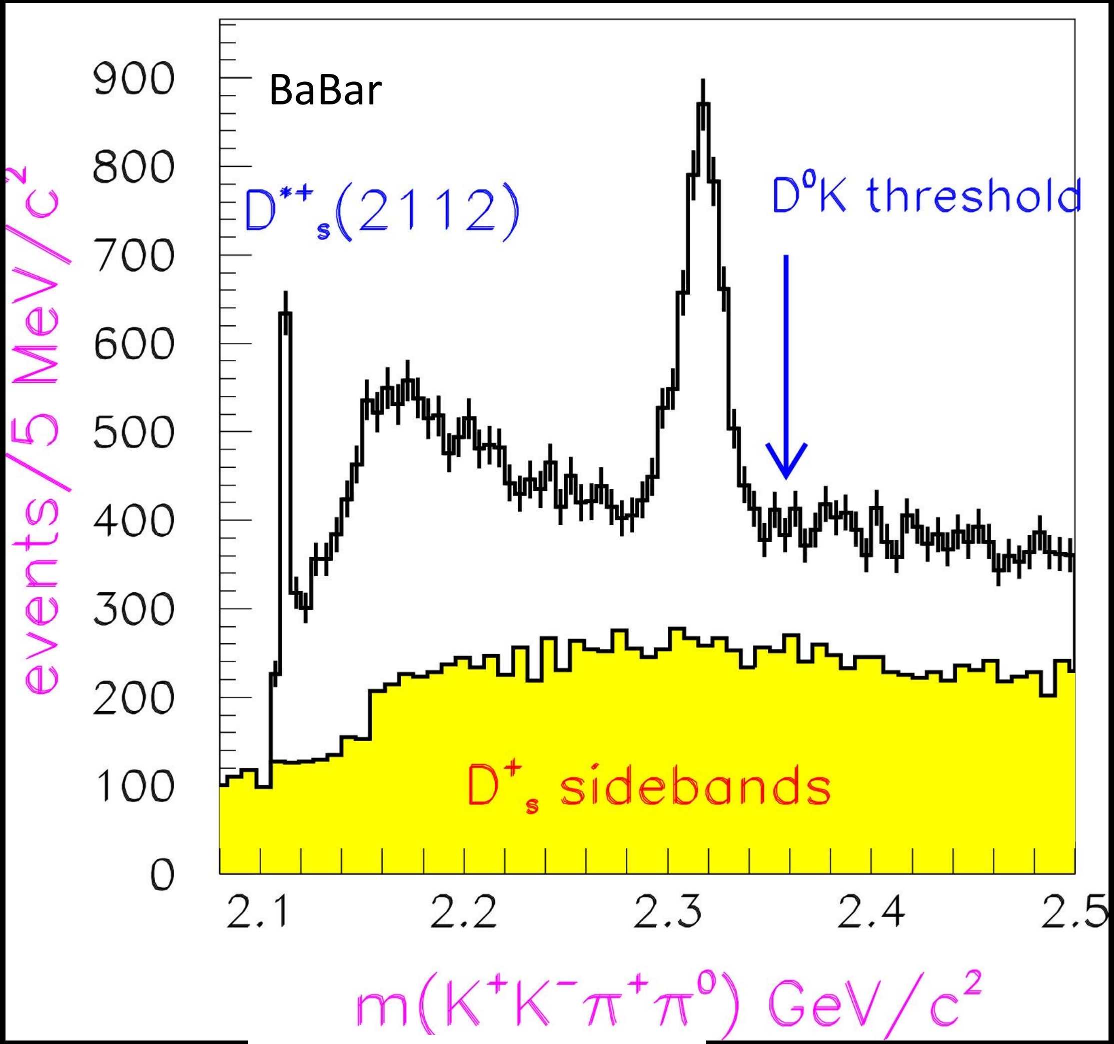
Nathaniel Craig, UCSB

Lessons from experience with searches

- Conventional wisdom on what New Physics should be has failed
  - Do not listen to theorists too much
- More emphasis on unconventional signatures
  - Delayed, long-lived, crazy stuff
- Look where we did not look before or with better sensitivity using new techniques
- Because of Dark Matter P_T^{miss} can still be an effective approach
- Higgs is special
- Test the SM

Caution: we can only find what we look for

- This huge signal had been in various data sets for many years
- Nobody looked because its mass was supposed to be above DK threshold, and therefore was supposed to be very broad



PRL90 242001 (2003)

Personal note: what I work on these days

Sensitivity to millicharged particles in future proton-proton collisions at the LHC with the milliQan detector

A. Ball,[1] J. Brooke,[2] C. Campagnari,[3] M. Carrigan,[4] M. Citron,[3] A. De Roeck,[1] M. Ezeldine,[5] B. Francis,[4] M. Gastal,[1] M. Ghimire,[6] J. Goldstein,[2] F. Golf,[7] A. Haas,[6] R. Heller,[3,*] C. S. Hill,[4] L. Lavezzo,[4] R. Loos,[1] S. Lowette,[8] B. Manley,[4] B. Marsh,[3] D. W. Miller,[9] B. Odegard,[3] R. Schmitz,[3] F. Setti,[3] H. Shakeshaft,[1] D. Stuart,[3] M. Swiatlowski,[9,†] J. Yoo,[3,‡] and H. Zaraket[5]

Search for long-lived particles decaying into two muons in proton-proton collisions at $\sqrt{s} = 13$ TeV using data collected with high rate triggers

The CMS Collaboration

Evidence for off-shell Higgs boson production and first measurement of its width

The CMS Collaboration

Measurements of *$t\bar{t}H$* Production and the *CP* Structure of the Yukawa Interaction between the Higgs Boson and Top Quark in the Diphoton Decay Channel

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

Conclusions

- The first ten years of the LHC program have seriously challenged the SUSY paradigm
- The experiments and the data analyses have been exceeded expectations….
- …. but Nature has not been kind
- The additional luminosity that we will be collecting is unlikely to lead to significant progress (discovery!) with the same type of "standard" searches
  - I will be thrilled to be proven wrong
- Future LHC emphasis:
  a) SM measurements, particularly Higgs-related
  b) Exploration **must** continue. Look everywhere, do not rely on theoretical prejudice