Experimental BSM Physics

Lecture 2 of 3

CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

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BROWN

18th HCPSS

CERN, August 26, 2023

Model-Independent Searches

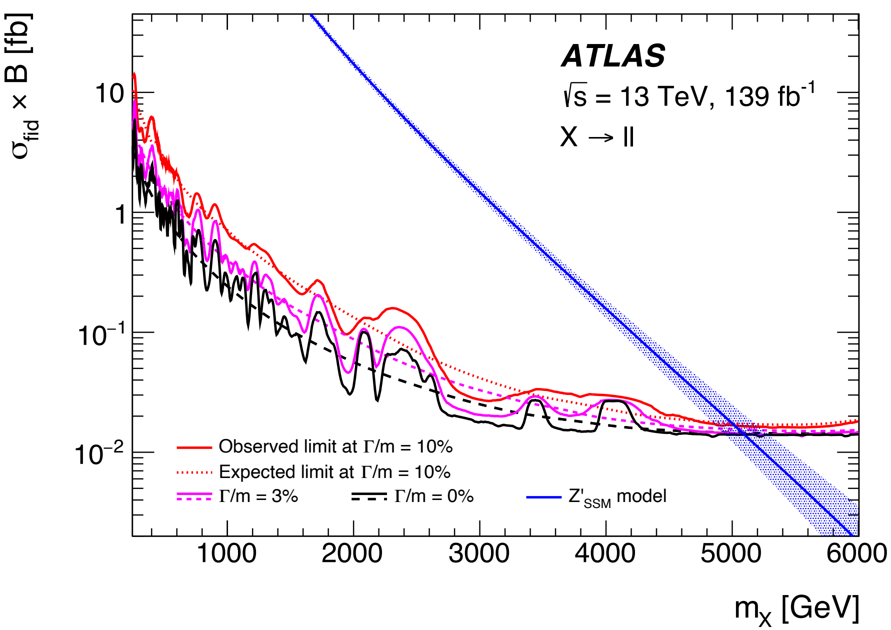
- It is very tempting to try optimizing a search for an arbitrary signal
  - ★ Unfortunately, this is not mathematically possible, as has been shown by Pearson in 1930-ies
  - ★ Only the likelihood ratio (e.g., L(S+B)/L(B)) possess well-defined properties; while individual likelihoods change property under transformation of variables
    - ✤ That means that "optimizing" in, e.g., p_T or p_T^2 yields completely different results
  - ★ Unfortunately, this is largely underappreciated in the HEP community, and every few years there is another attempt to reinvent the wheel and do "model-independent optimization", which is simply mathematically impossible (latest attempts use unsupervised machine learning)
- What can be done is what's typically done in SUSY searches: create a large number of independent or overlapping search categories ("signal regions", SRs) and look for the maximum excess of events over the respective background prediction among them

Look-Elsewhere Effect

- This brings us to a concept of the look-elsewhere effect (LEE)
  - ★ If one rolls a dice, a probability to get six is $1/6 \approx 0.17$
  - ★ If one rolls three dices, a probability that one of them will have six is $1 - (5/6)^3 = 0.42$
  - ★ The ratio $r = 0.42/0.17 \approx 2.5$ is the *trial factor*
- Similarly, if one looks for a signal in multiple search regions, the local p-value of the largest excess among them needs to be multiplied by a trial factor in order to get the *global p-value* of an excess
  - ★ The trial factor is usually estimated with pseudo-experiments, but there are also analytical asymptotic methods [Gross and Vitells, Eur. Phys. J. C 70 (2010) 525]
- Therefore, the more SRs one has, the larger the trial factor is, and the lower the global p-value is, compared to the local one
- Consequently these model-independent searches [e.g., D0's Sleuth, PRL 86 (2001) 3712, ; ATLAS, Eur. Phys. J. C 79 (2019) 120; CMS' MUSiC, EPJC 81 (2021) 629] are inherently less powerful than model-specific searches that can be properly optimized without paying the trial factor price
  - ★ They are good as a grand finale kind of thing: e.g., have we missed anything interesting in the LHC Run 2 data, despite all the model-specific searches we published?
  - ★ While fun to conduct, they are unlikely to become a discovery tool

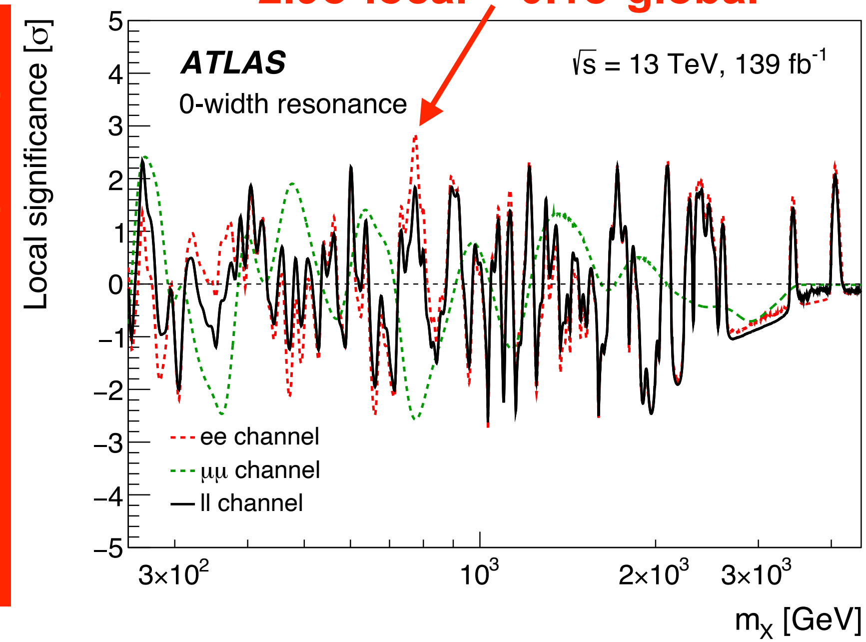
An LEE Example

- Typically, LEE is very pronounced in searches in a high-resolution channel
  - ★ An infamous X(750) was a classic example of people underestimating LEE
- Roughly speaking the trial factor is approximately equal to the search range divided by the average resolution, i.e., how many non-overlapping signals one could "fit" in the mass spectrum probed
- In the case of ATLAS dielectron X(ee) search, the trial factor is ~50



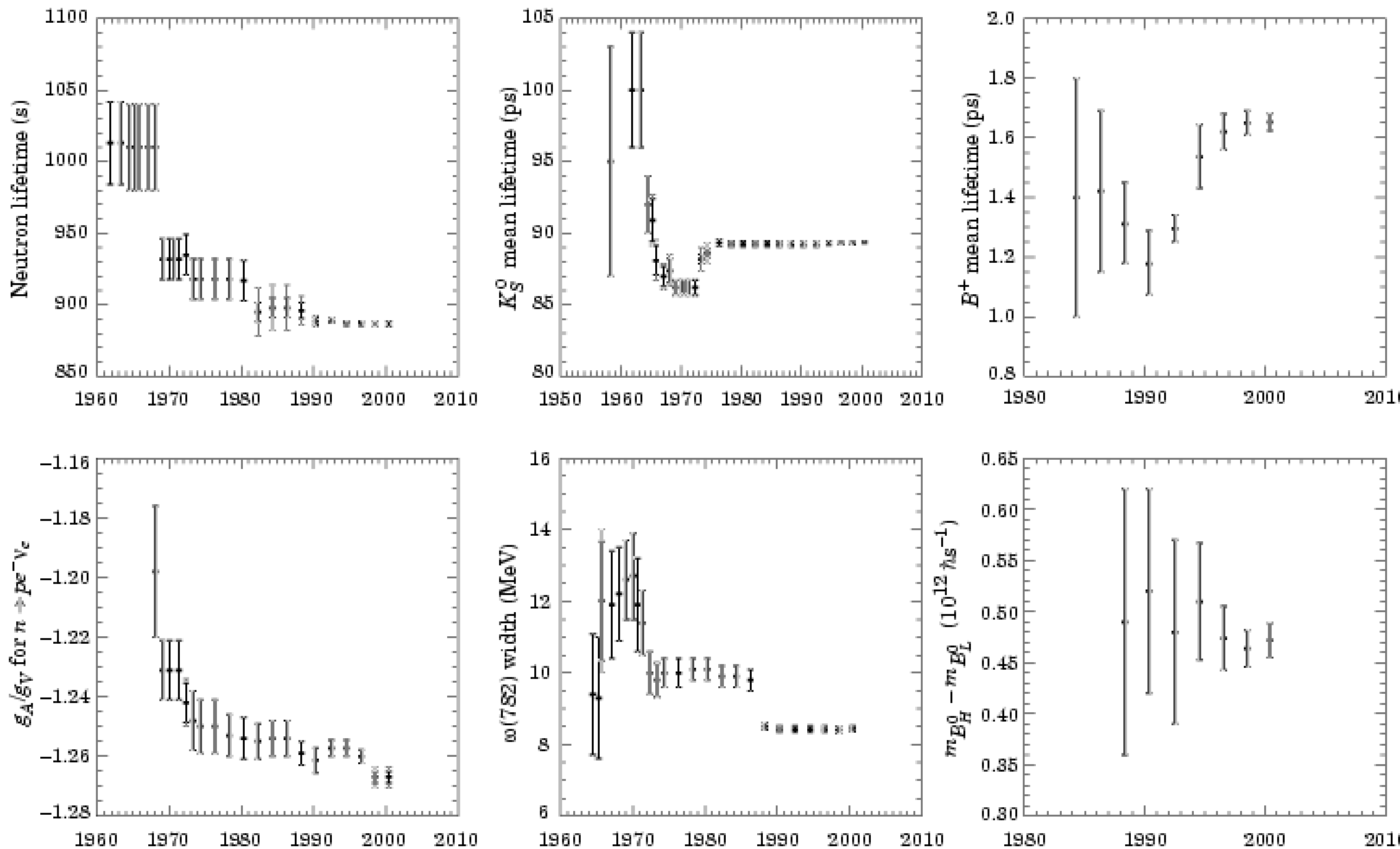
ATLAS PLB 796 (2019) 68

2.9σ local = 0.1σ global



Blind Analysis

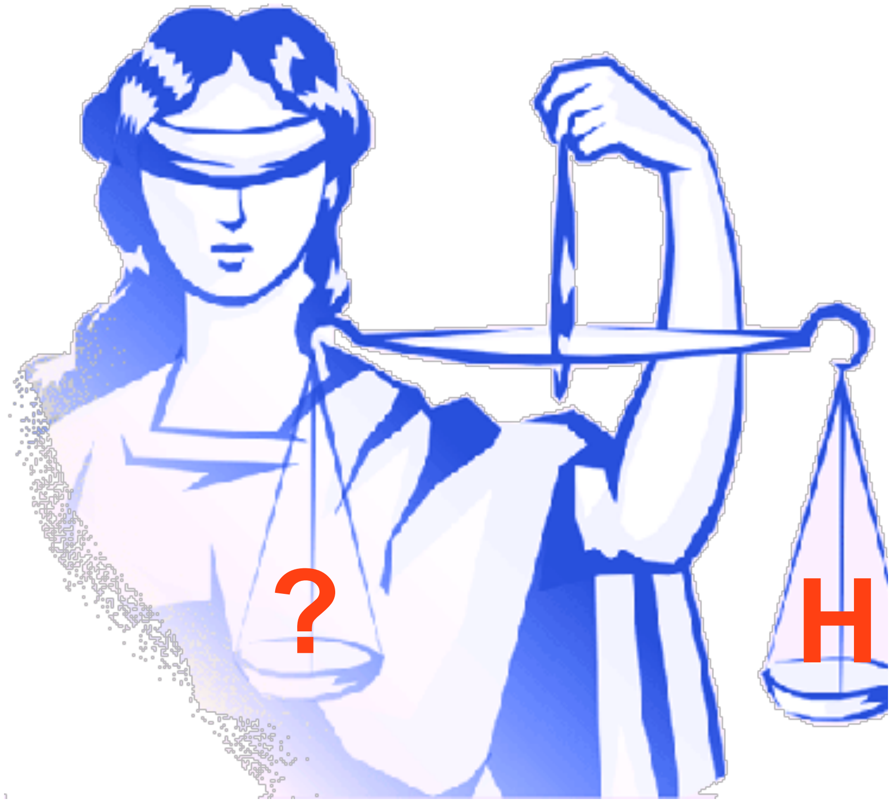
- Removes (often subconscious!) bias of an observer
- Many examples in particle physics, biology, medicine

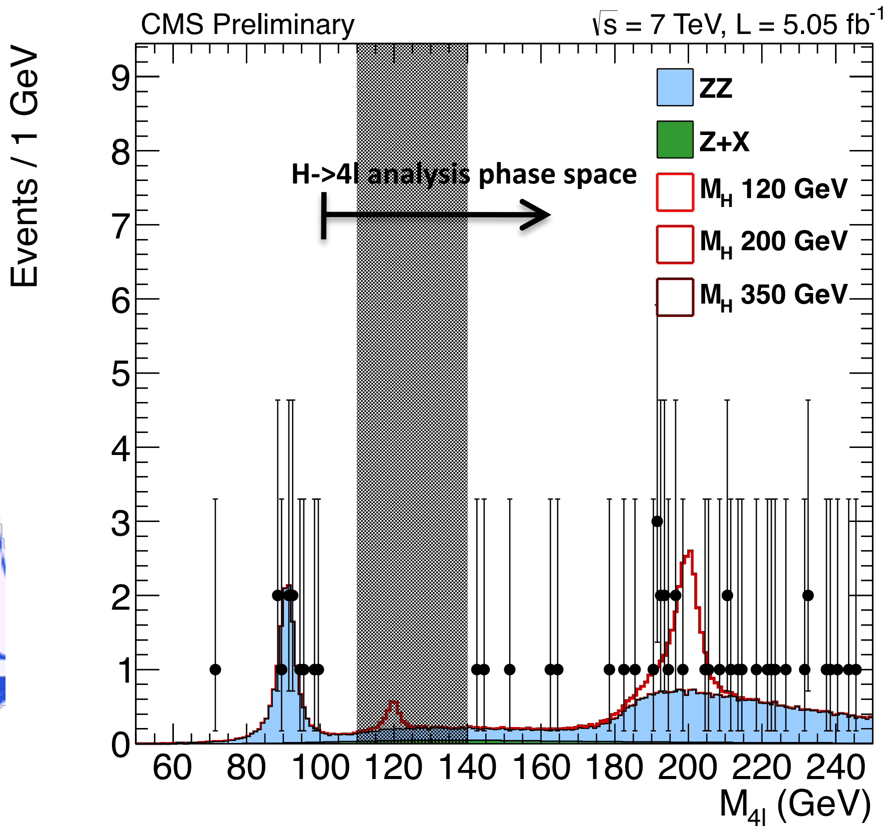


History of some of the measurements, P.F. Harrison, J. Phys. G28 (2002) 2679

Justice is Blind...

- Optimization of the analysis is done exclusively in the control regions
- “Peeking” in the signal region is strictly not allowed
- Example: $H \rightarrow ZZ \rightarrow 4l$: [110,140] GeV mass region is blinded





CMS Unblinding Event

- The unblinding of all the Higgs channel took place at a special event on June 15, 2012, with roughly 80% of total statistics - no changes in any of the analyses after unblinding

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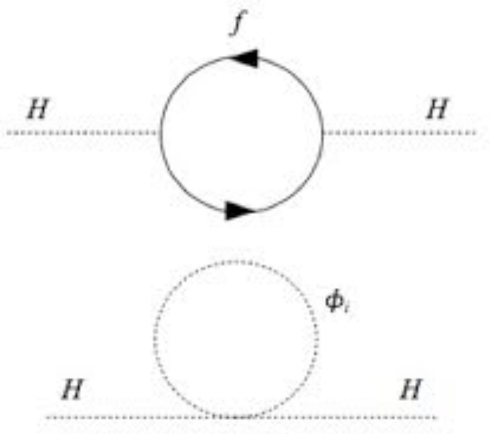
SUSY Searches

Looking for SUSY

- Everything you always wanted to know about SUSY but were afraid to ask:
  - ★ What is SUSY? - Answered for you by Tim
  - ★ Three SUSY miracles
  - ★ Supersymmetric particle zoo - Answered for you by Tim
  - ★ “Natural” SUSY
- SUSY and Higgs - the marriage made in heaven
  - ★ What did we learn about SUSY in the aftermath of the Higgs discovery?

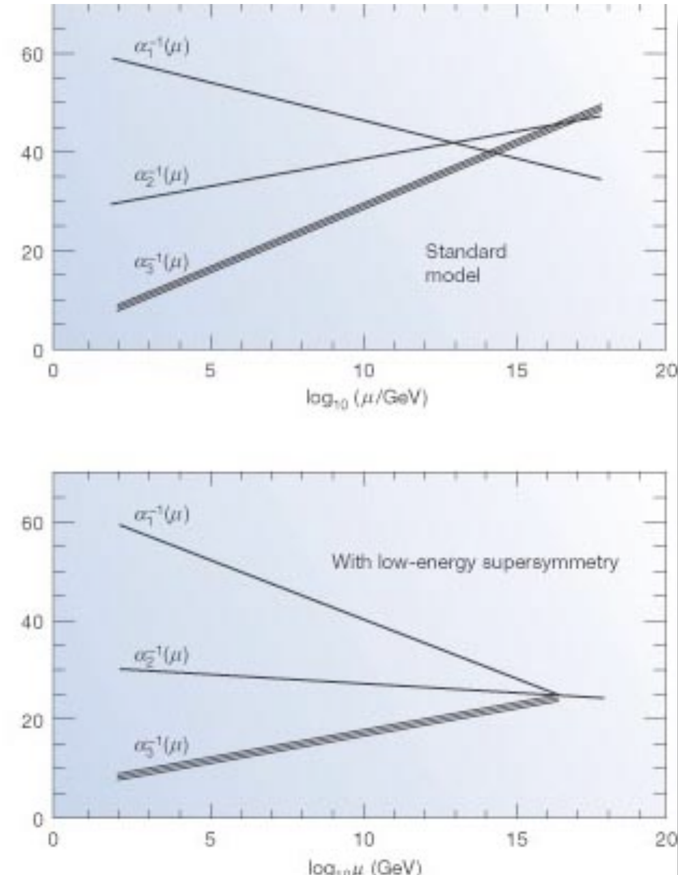
Three Miracles of SUSY



$$\Delta M_H^2 \sim \frac{\lambda_f^2}{4\pi^2}[(m_f^2 - m_S^2)\log(\frac{\Lambda}{m_S})]$$

- Elegant solution to the hierarchy problem (via the cancellation of fermionic loops with bosonic ones)

✦ Gauge unification



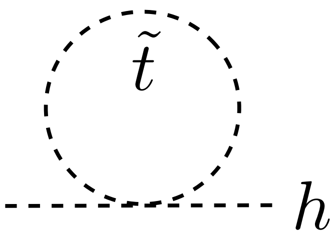
✦ Dark matter candidate with the right abundance

Fine-Tuning in (p)MSSM

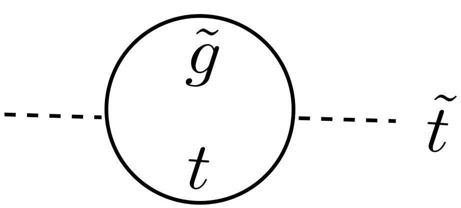
- **Fine-tuning: cancellation of two or more large numbers**
- **In pMSSM:** $m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \frac{2}{\tan^2\beta}(m_{H_d}^2 - m_{H_u}^2) + \mathcal{O}(1/\tan^4\beta)$

|μ| is small → light higgsinos

m^2_{Hu} is small → lights stops (at one-loop level) and gluinos (at two-loop level)



$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(\underbrace{m_{Q_3}^2 + m_{u_3}^2}_{\text{stops}} + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$



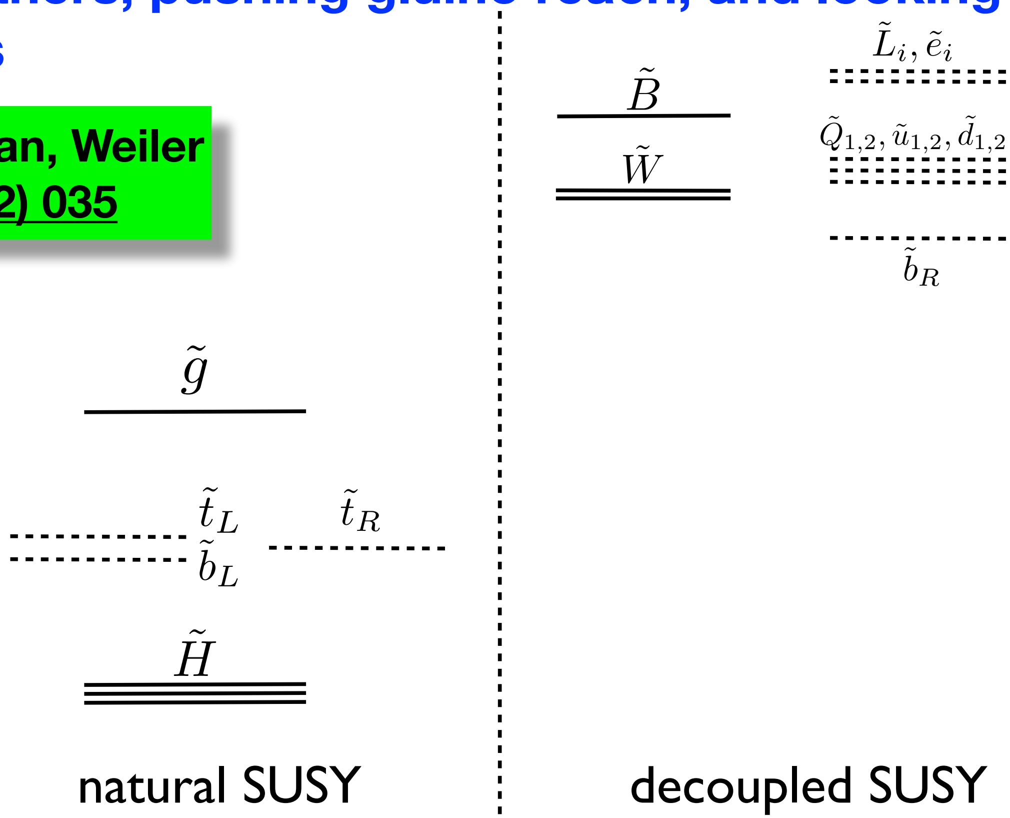
gluino-top loop drives the stop mass further up

Greg Landsberg - Experimental BSM Physics - HCPSS 2023 - 08/23

Natural SUSY

- If SUSY is natural, we should find it soon:
  - ★ And we most likely will find it by observing 3rd generation SUSY particles first
- Requires shifting of the SUSY search paradigm: going for the third-generation partners, pushing gluino reach, and looking for EW boson partners

Papucci, Ruderman, Weiler
JHEP 09 (2012) 035



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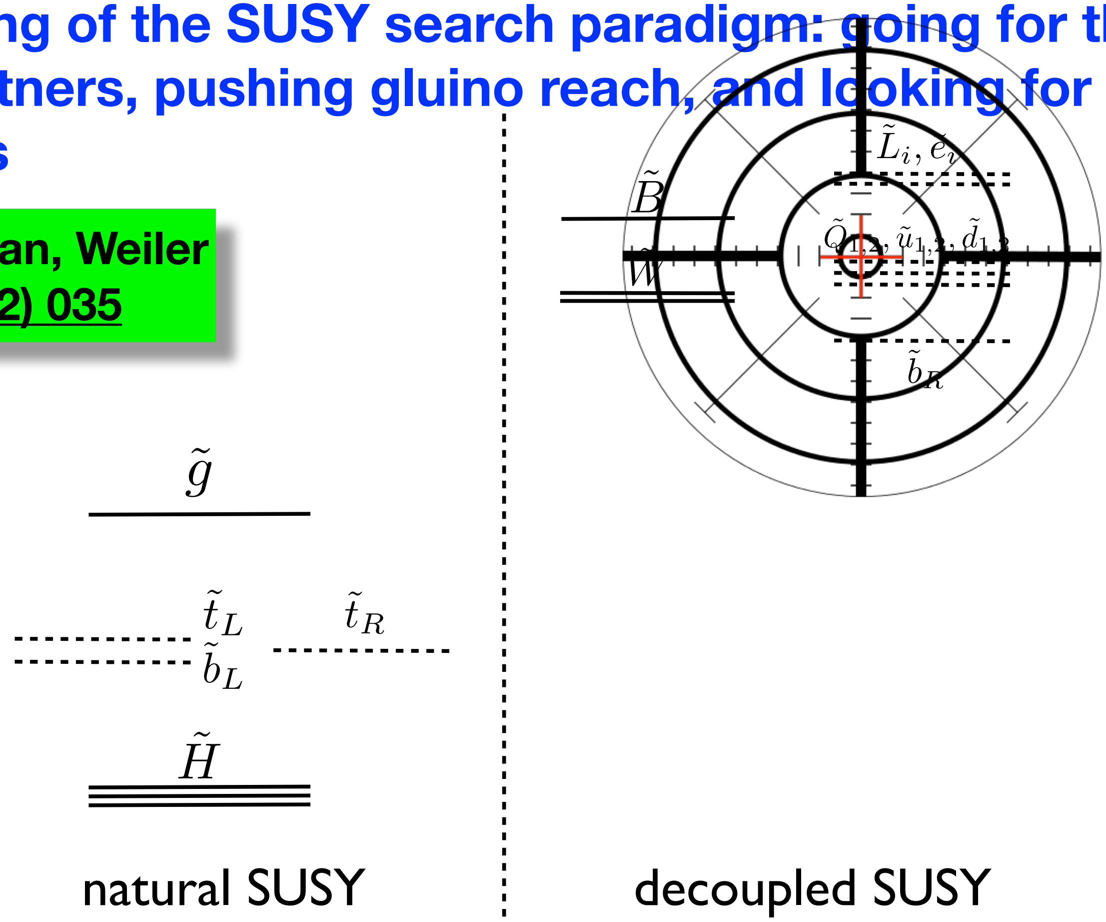

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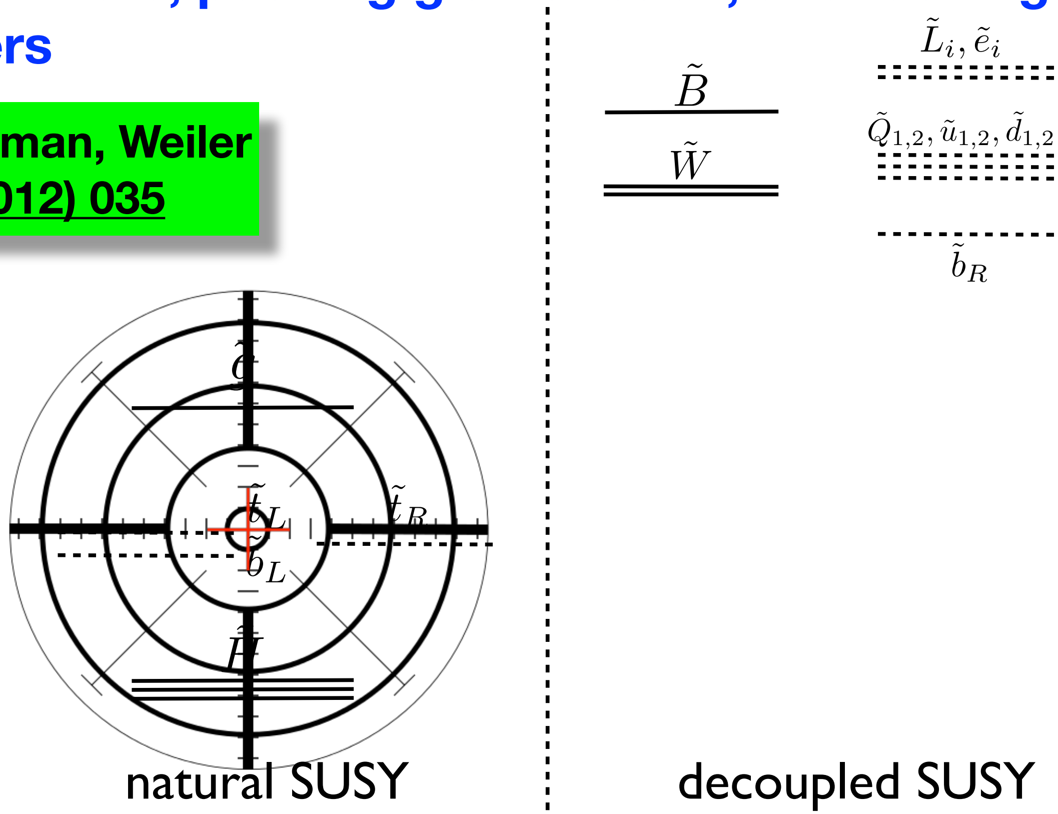


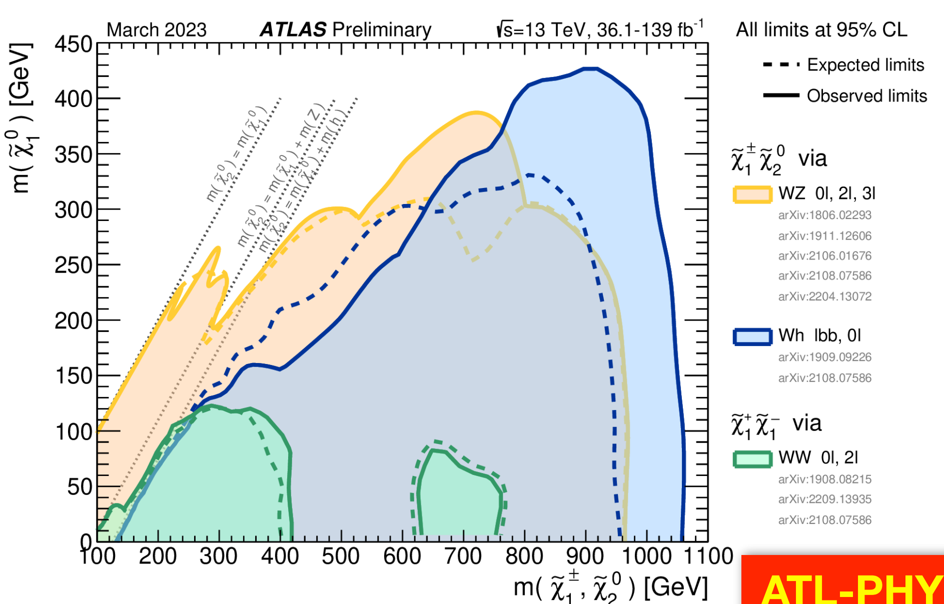
SUSY Searches: General Approach

- Given that the SUSY signal is typically seen in multiple channels, hard to find good control regions that are signal free
- Also, given the landscape of SUSY models, the signal can be present at various multiplicities of different particles and in different kinematic regions
- Common to all R-parity conserving scenarios: generally large amount of ME_T due to the LSPs
- Hence, a search is typically done *by signatures* (e.g., jets + ME_T, 1l + jets + ME_T, etc.)
- The phase space is diced into *multiple rectangular search regions*, often O(100) per search (e.g., 3 jets, ≥1 b jet, ME_T > 300 GeV)
- Backgrounds are determined from a mixture of simulation and control regions targeting specific backgrounds
- The search often targets the main backgrounds via dedicated kinematic variables

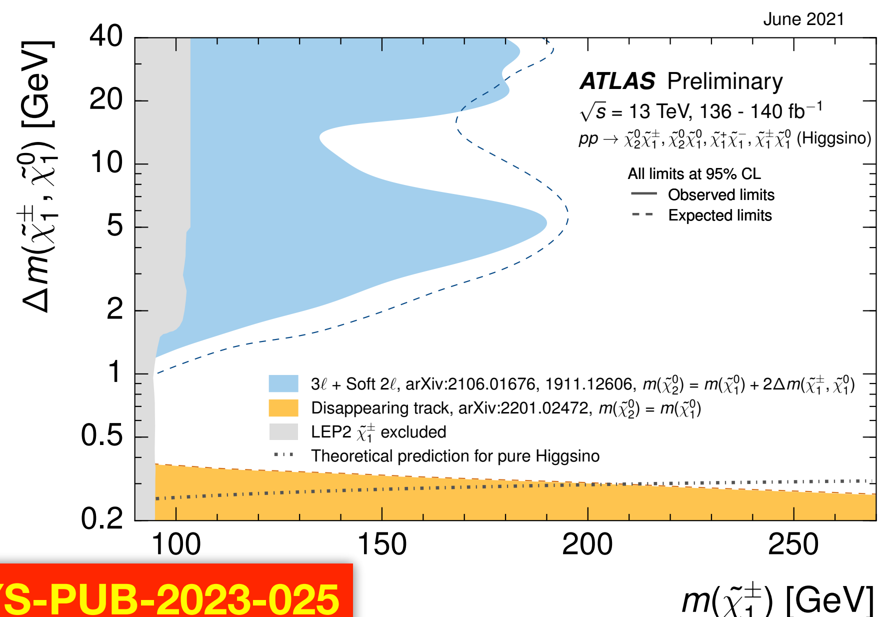
Electroweakino Production

- **In natural SUSY, the lightest Higgsino is light, so it's a natural particle to search for**
  - ★ **Unfortunately, it's most often an LSP, i.e. undetectable**
  - ★ **It is also produced with EW cross section, i.e., feebly**
  - ★ **Additionally, if the chargino-neutralino mass difference is small, searches are complicated because of soft final-state particles and small amount of ME_T**

Wino-like neutralino



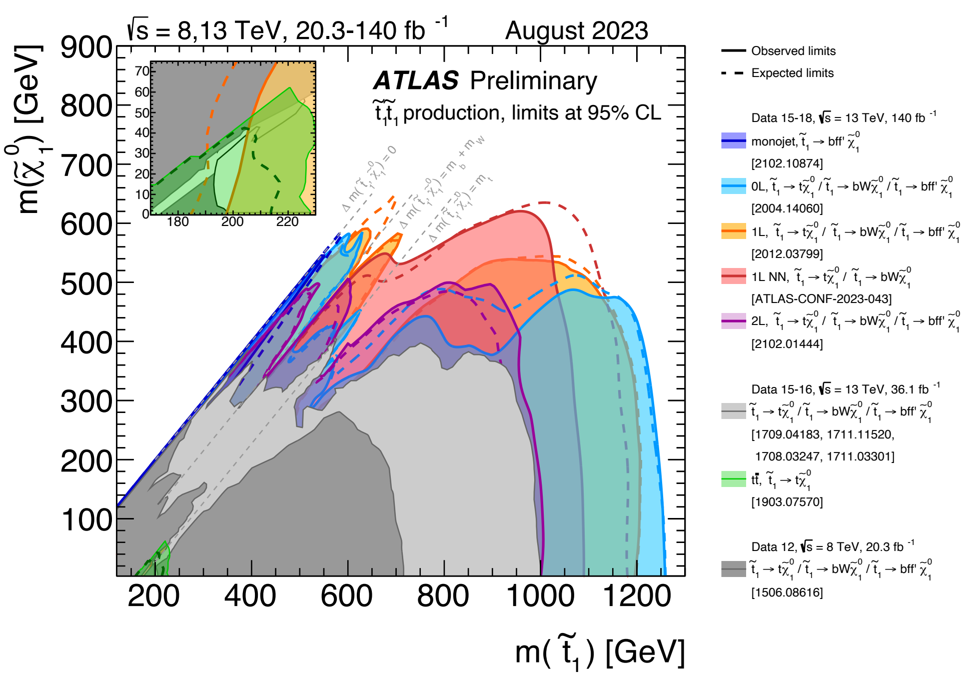
Pure higgsino neutralino

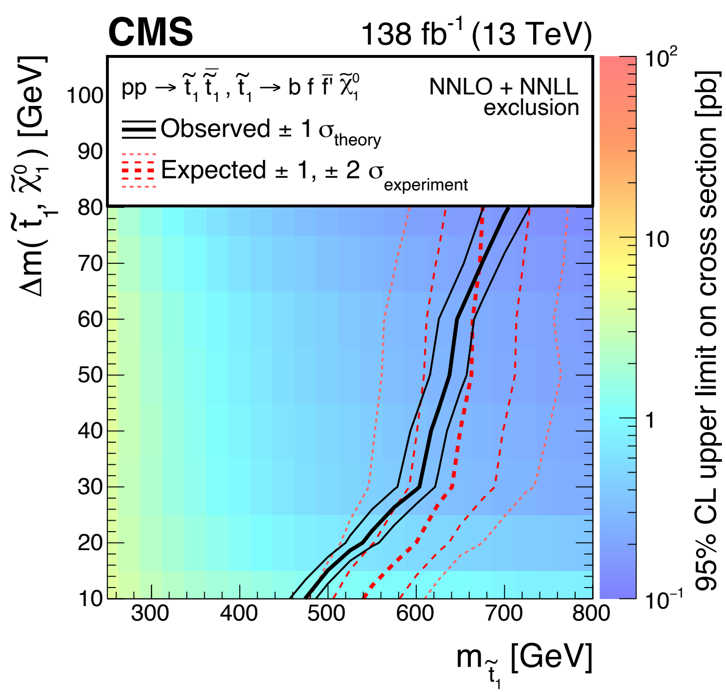


ATL-PHYS-PUB-2023-025

Pulling all the Stops!

- **Top quark partner ("stop") is expected to be light, if SUSY offers a natural solution to the hierarchy problem**
  - ★ **Not surprisingly, a lot of effort went into top squark searches**
- **With the top squark masses excluded as high as ~1 TeV, a paradigm shift in filling gaps at low masses, via challenging 3- and 4-body decays**





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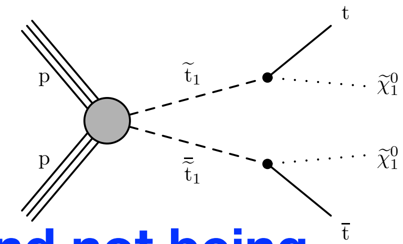
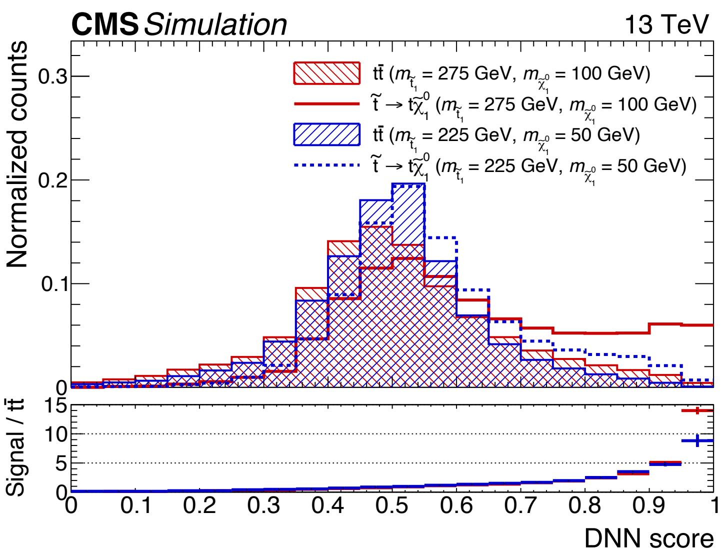
CMS JHEP 06 (2023) 060

Search for Light Top Squarks

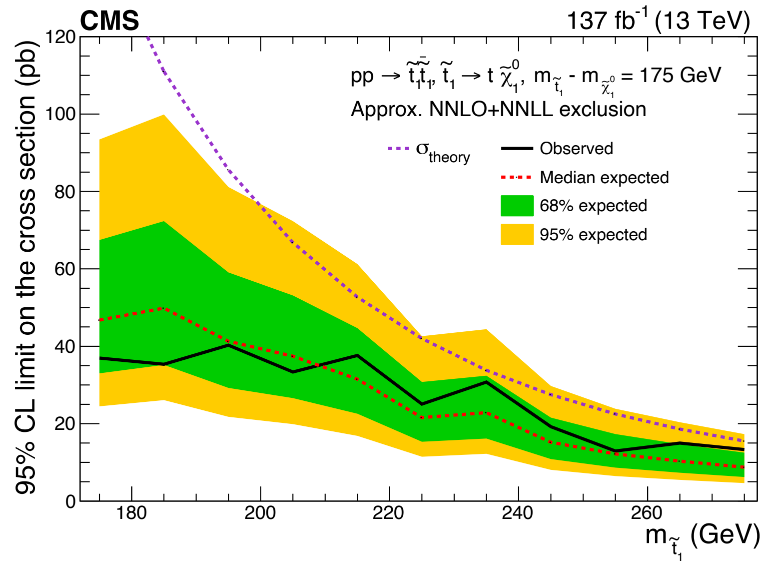
- A particularly challenging case is when the mass of the top squark is nearly degenerate with the sum of the top quark and neutralino masses: $(m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \simeq m_t)$



- In this case the neutralino is produced nearly at rest and not being detected, does not contribute to the missing transverse momentum
  - ★ Consequently, the process looks just like top quark pair production!
- The new analysis in the dilepton channel looks for an excess of events above the dominant background using shape differentiation offered by a DNN based on M_T-like variable (M_{T2}) & dilepton mass, ME_T, and H_T



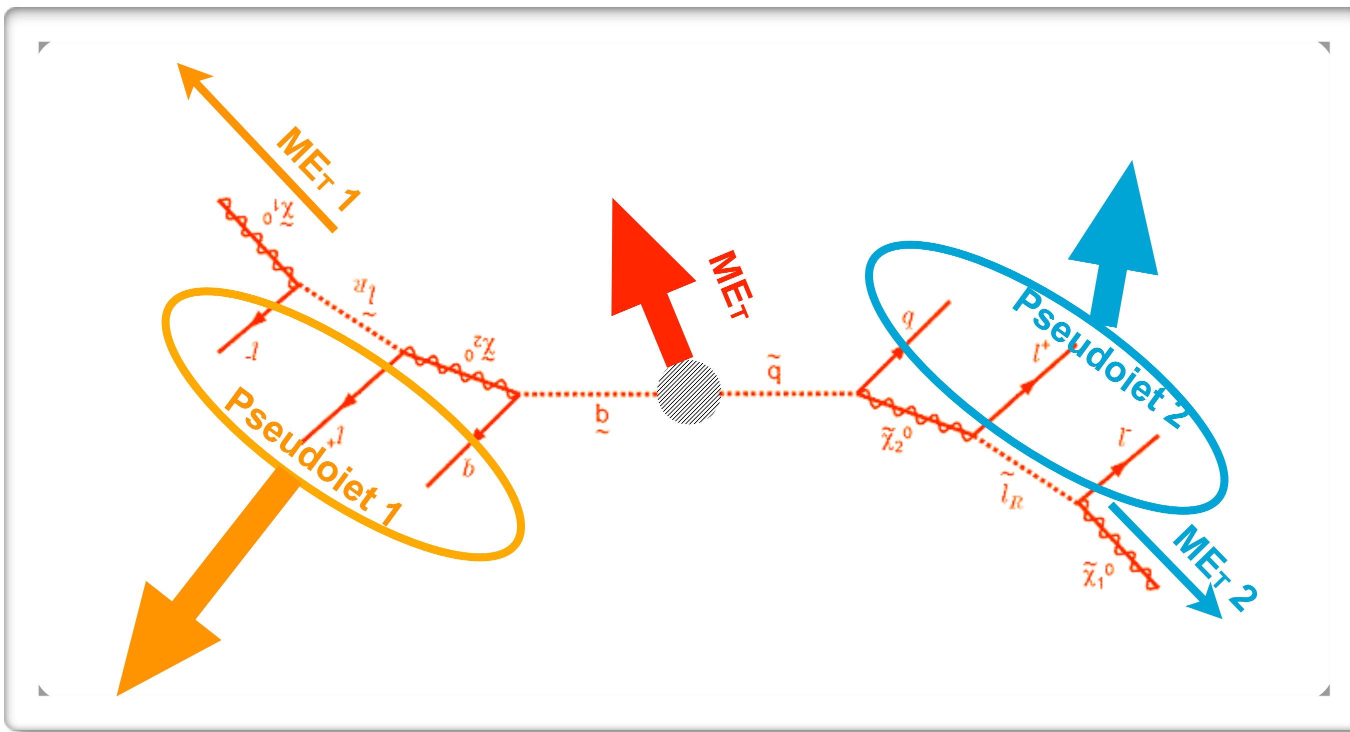
CMS EPJC 81 (2021) 11



Designer Variables

SUSY Kinematics

- Look for pair-produced particles that cascade-decade with invisible particle emission
  - ★ Generally can cluster all visible products in each hemisphere to form "pseudojets", resulting in a dijet + ME_T topology
- How to optimize the search to reduce backgrounds and at the same time retain information about characteristic SUSY masses?
  - ★ CMS explored a number of different kinematic variables to optimize SUSY searches



The α_T Variable

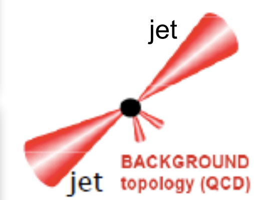
- Alternative approach to requiring large ME_T in the event; does not rely on ME_T reconstruction and tails

Randall & Tucker-Smith, PRL 101 (2008) 221803

- Combine visible decay products in the event into two (pseudo)jets:

$$H_T = \sum_{i=1}^{N_{\text{jet}}} E_T$$

$$\not{H}_T = \left| \sum_{i=1}^{N_{\text{jet}}} \vec{p}_T \right|$$

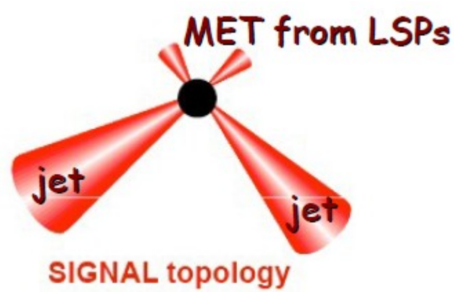


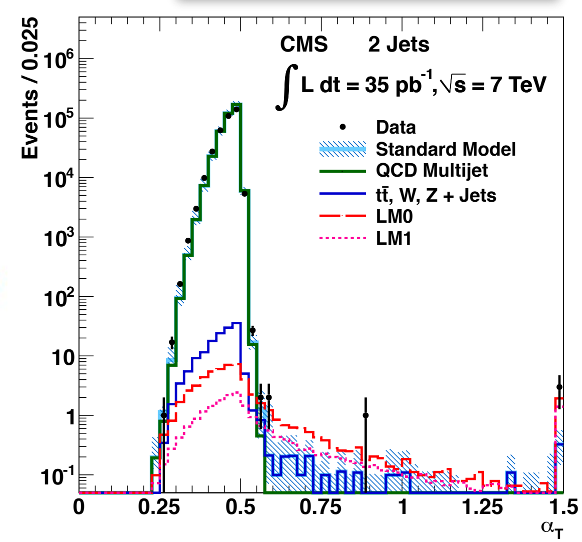
$$\alpha_T = E_T^{j_2} / M_T = E_T^{j_2} / \sqrt{H_T^2 - \not{H}_T^2}$$

CMS
PLB 698 (2011) 196

- For a perfectly balanced dijet event, $\alpha_T = 0.5$
- For QCD events with mismeasured ME_T, $\alpha_T < 0.5$
- For signal, long tail of $\alpha_T > 0.5$

$$\alpha_T \equiv E_T^{j_2} / M_T(j_1 j_2) = \frac{\sqrt{E_T^{j_2} / E_T^{j_1}}}{\sqrt{2(1 - \cos\Delta\varphi)}}$$





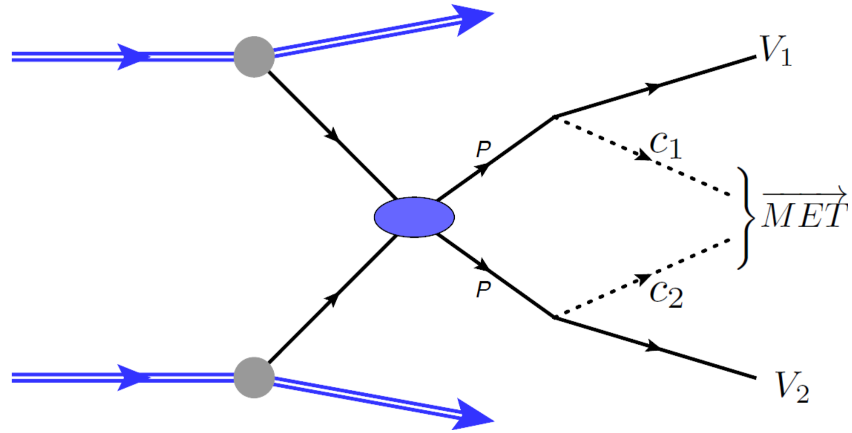
The M_{T2} Variable

- M_{T2}: ***"stransverse mass"*** **- a generalization of the transverse mass in case of a pair of invisible particles**
- **For a simplified case of no extra jets and zero masses for visible and invisible systems:**

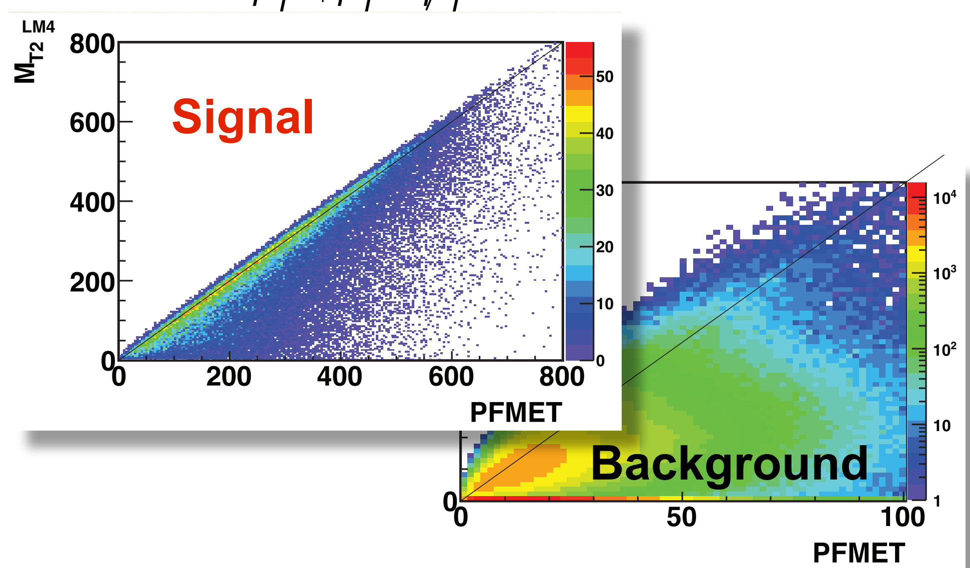
$$(M_{T2})^2 \simeq 2p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$

  - ★ **$M_{T2} \sim ME_T$ for symmetric SUSY-like topologies**
- **M_{T2} kills QCD background very efficiently:**
  - ★ **$M_{T2} \sim 0$ for dijets**
  - ★ **$M_{T2} < ME_T$ in case of mismeasured dijets**

Lesters & Summers, PLB 463 (1999) 99

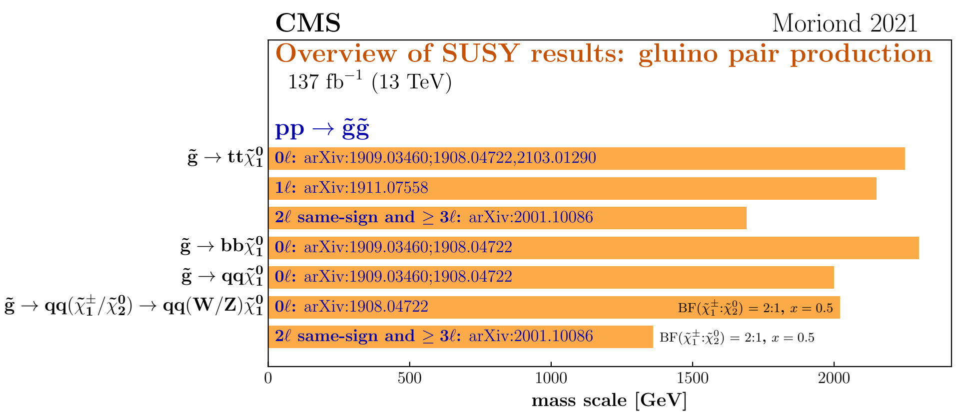


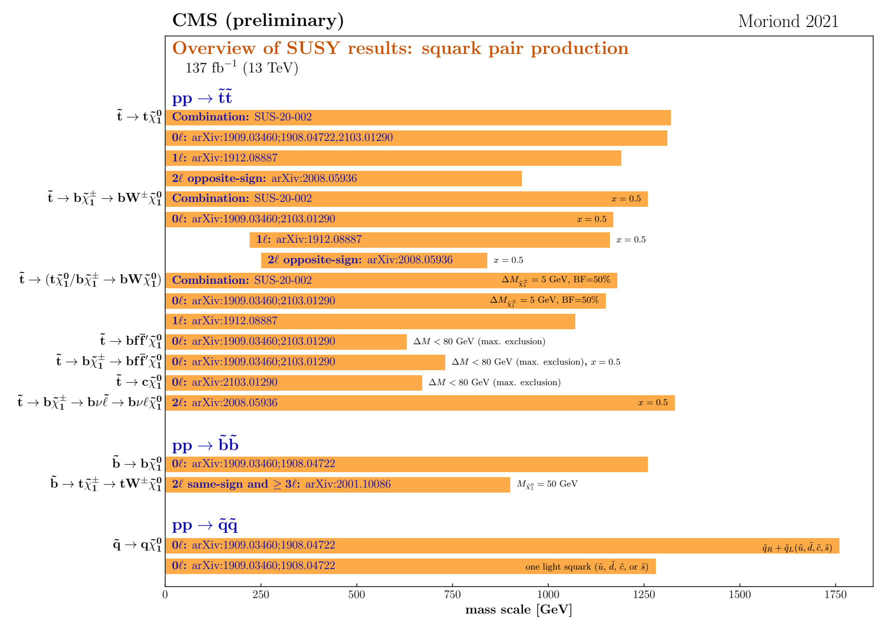
$$M_{T2} = \min_{p_T^{c1}+p_T^{c2}=\not{p}_T} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$



Supercemetery?

- At first glance, the TeV scale SUSY is simply not there: strongly produced superpartners of gluons and quarks, gluinos and squarks, have been excluded to ~2 and ~1 TeV, respectively…





Read the Fine Print!

- Keep in mind that:
  - ★ Searches typically assume 100% branching fraction in a particular channel, which does not have to be the case
  - ★ Many searches assume mass degeneracy between various SUSY particles, e.g., squarks of different generation
  - ★ Interpretation is usually done via simplified model framework, not in the full model

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