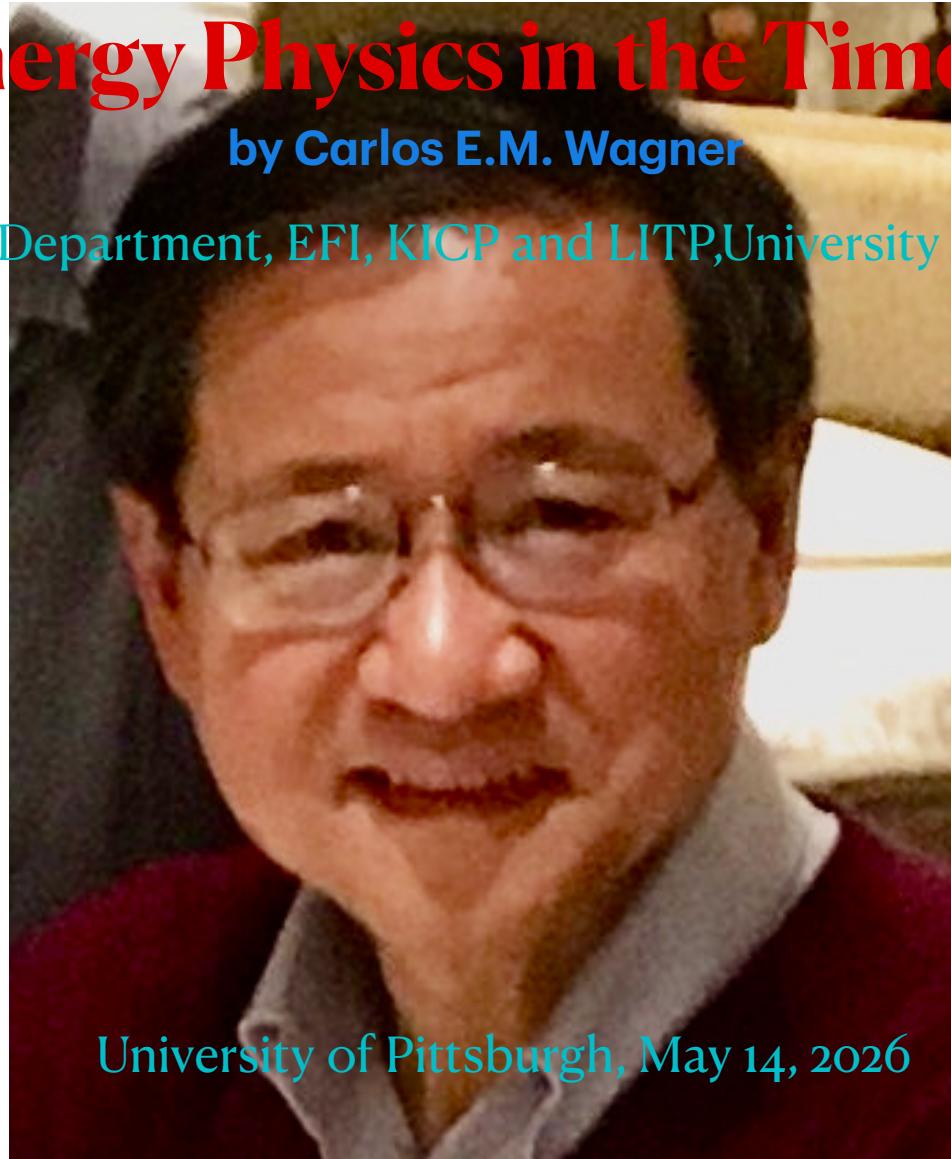


# High Energy Physics in the Times of Tao

by Carlos E.M. Wagner

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University of Pittsburgh, May 14, 2026

# Replacing Marcela



## Salient Qualities of Tao Han

- High Quality Scientific and Pedagogical Capabilities

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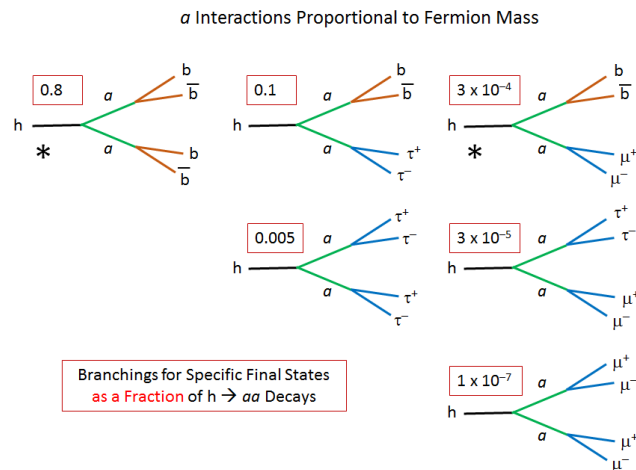
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- Strong Influence in the Chinese Academic Community
- First class Chinese Opera Singer

# Paper with Tao

## Higgs Signals in $H \rightarrow aa$ at Hadron colliders

- Marcela Carena, Tao Han, Gui-Yu Huang, Carlos E.M. Wagner, 0712.2466
- Standard search analysis these days, but this was back in 2007
- We considered the possibility of a decaying into bottoms or taus



	parameters	representative value	considered range
masses	$m_h$	120	90–130
	$m_a$	30	20–60
coupling	$\kappa_{hVV}^2$	0.7	0.5–1.0
branching fractions	$BR(h \rightarrow aa)$	0.85	0.8–1.0
	$BR(a \rightarrow b\bar{b})$	0.92	0.95–0.50
	$BR(a \rightarrow \tau^+\tau^-)$	0.08	0.05–0.50

# Tevatron and LHC were analyzed

- We found, of course good prospects at the Tevatron, but with large statistical limitations.
- At the LHC, those limitations were lifted and prospect for discovery in the  $b\bar{b}b\bar{b}$  and  $b\bar{b}\tau\tau$  channels were excellent, provided the luminosity was larger than  $10 \text{ inverse fb}$ .
- Today, we have significant larger luminosities and this decay channel is therefore heavily constrained.
- One thing I noticed is that we did not discussed the possibility of 4 Tau production
- There were good reasons for that, in part the small rates and in part the **danger of producing 4 Taos**. Imagine you are invited for dinner and when you sit down at the table you find this :



4 Tao Production



4 Tao Production

2 of them must be Anti-Taos !

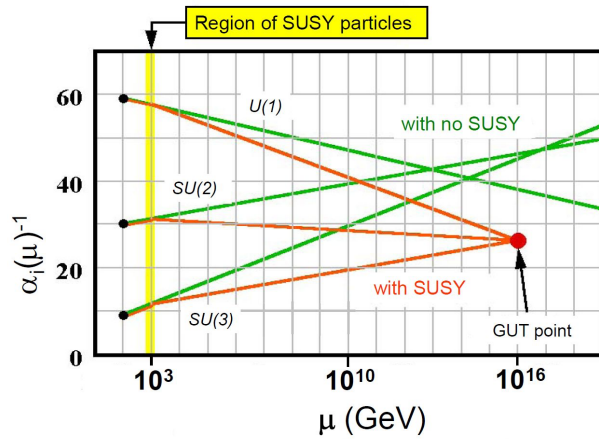
# LHC and Scalars at the Time of Tao



My own perspective

## Consequences of SUSY

### Unification



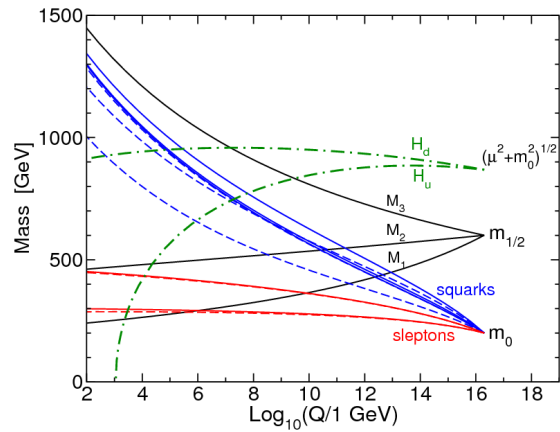
### SUSY Algebra

$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma_{\alpha\dot{\alpha}}^\mu P_\mu$$

$$[Q_\alpha, P_\mu] = [\bar{Q}_{\dot{\alpha}}, P_\mu] = 0$$

### Quantum Gravity ?

### Electroweak Symmetry Breaking



If R-Parity is Conserved the Lightest SUSY particle is a good Dark Matter candidate

## Stop Searches : MSSM Guidance ?

Lightest SM-like Higgs mass strongly depends on:

\* CP-odd Higgs mass  $m_A$                       \*  $\tan \beta = \frac{v_u}{v_d}$                       \* the top quark mass

\* the stop masses and mixing                      
$$\mathbf{M}_{\tilde{t}}^2 = \begin{pmatrix} \mathbf{m}_Q^2 + \mathbf{m}_t^2 + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}_U^2 + \mathbf{m}_t^2 + \mathbf{D}_R \end{pmatrix}$$

$M_h$  depends logarithmically on the averaged stop mass scale  $M_{SUSY}$  and has a quadratic and quartic dep. on the stop mixing parameter  $X_t$ . [and on sbottom/stau sectors for large  $\tan \beta$ ]

For moderate to large values of  $\tan \beta$  and large non-standard Higgs masses

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left( \frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_3 \right) (\tilde{X}_t t + t^2) \right]$$

$$t = \log(M_{SUSY}^2 / m_t^2) \quad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2} \left( 1 - \frac{X_t^2}{12M_{SUSY}^2} \right) \quad \underline{X_t = A_t - \mu / \tan \beta} \rightarrow \text{LR stop mixing}$$

Carena, Espinosa, Quiros, C.W.'95,96

Analytic expression valid for  $M_{SUSY} \sim m_Q \sim m_U$

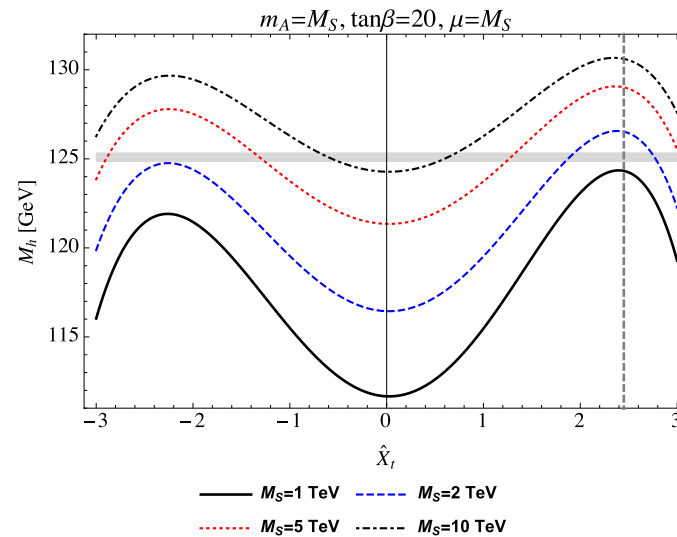
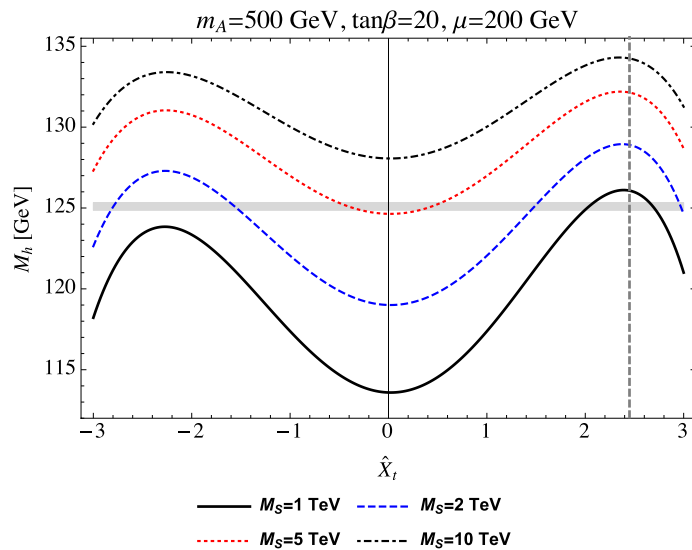
LHC

# MSSM Guidance: Stop Masses above about 1 TeV lead to the right Higgs Mass

P. Slavich, S. Heinemeyer et al, arXiv:2012.15629

P. Draper, G. Lee, C.W.'13, Bagnaschi et al' 14, Vega and Villadoro '14, Bahl et al'17

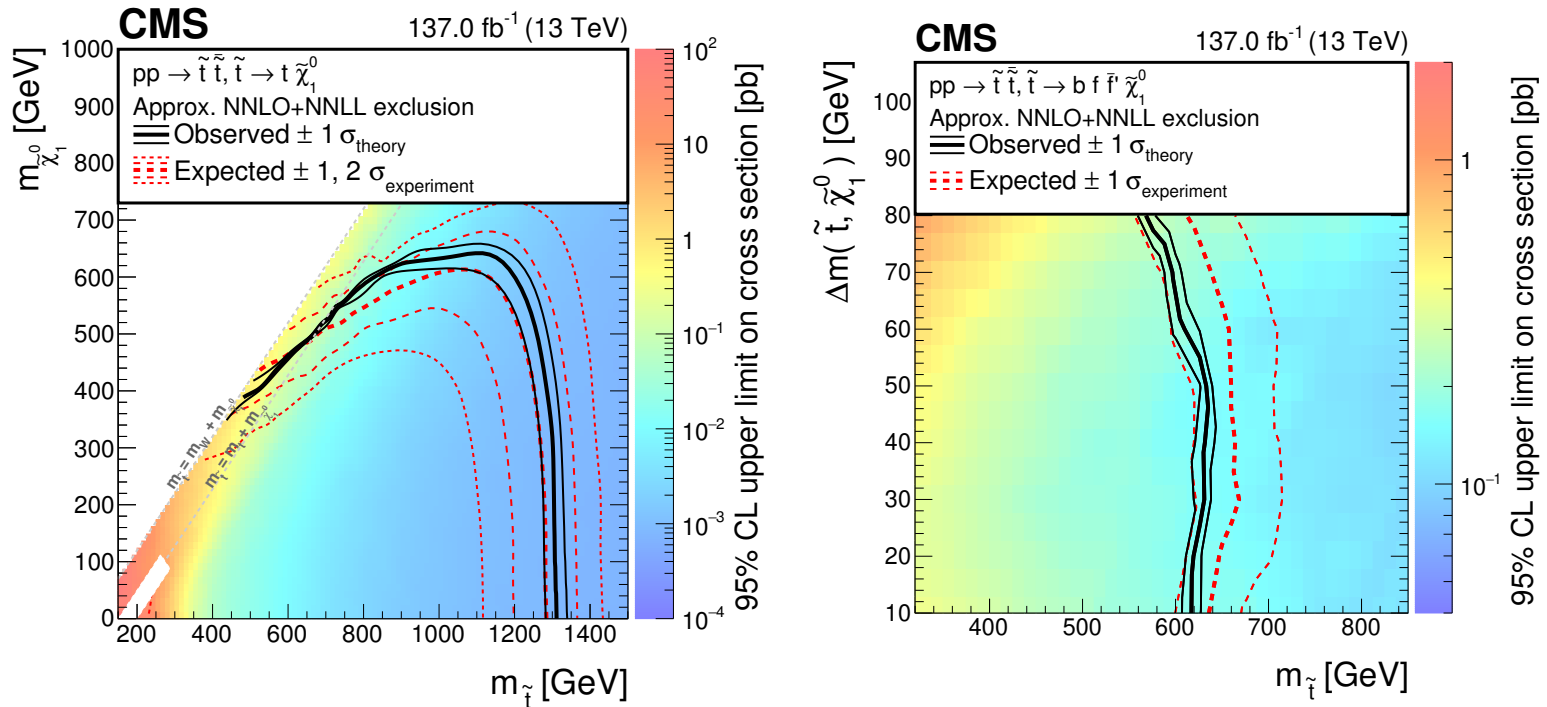
G. Lee, C.W. arXiv:1508.00576



Necessary stop masses increase for lower values of  $\tan\beta$ , larger values of  $\mu$  smaller values of the CP-odd Higgs mass or lower stop mixing values.

Lighter stops demand large splittings between left- and right-handed stop masses

# Stop Searches



Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for sbottoms and 600 GeV for stops. Islands in one search are covered by other searches.

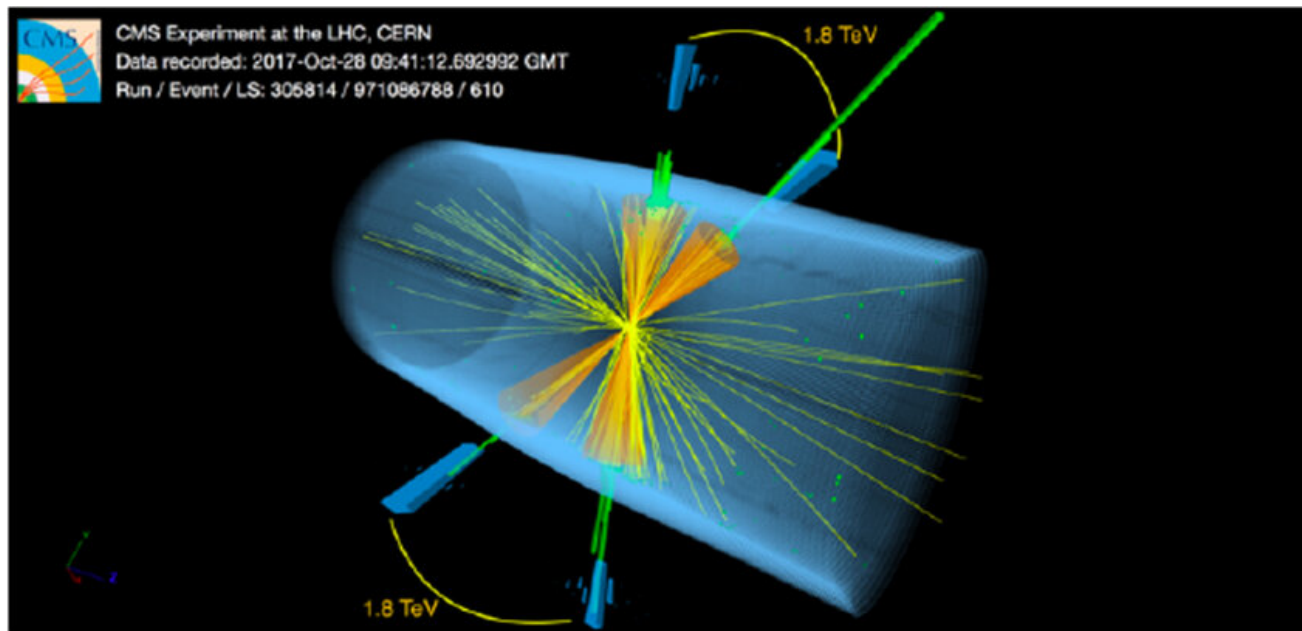
We are starting to explore the mass region suggested by the Higgs mass determination !

# Heavy Squarks and 4-jet events at CMS

2 events with Total 4-jet Invariant Mass : 8 TeV . Very large, considering the parton pdfs  
Di-jet invariant Mass : 2 TeV.

Consistent with Production of a heavy 8 TeV resonance decaying to pairs of lighter 2 TeV resonances,  
decaying to di-jets

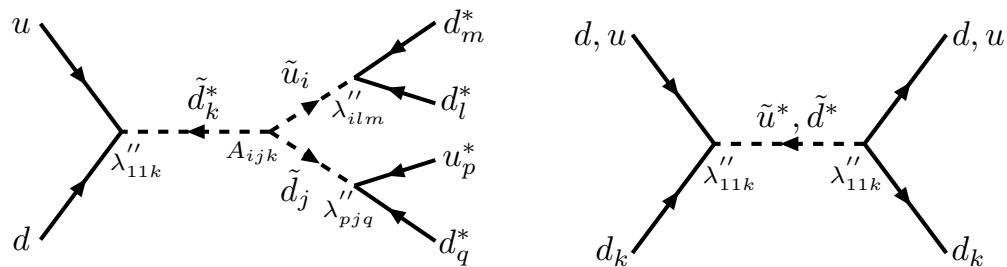
CMS Collaboration, arXiv:2206.09997, 2507.17885



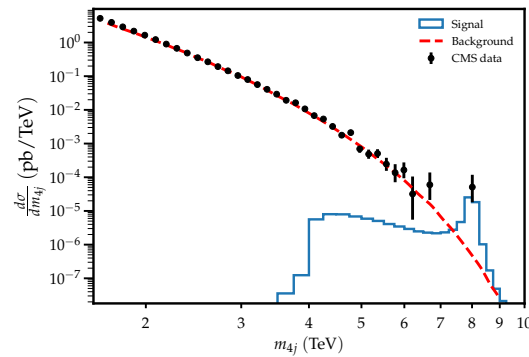
Possible Interpretation in terms of Di-quarks, necessary to generate such large energy particles :  
 Bogdan Dobrescu, arXiv:2411.04121, Ioana Duminica et al. arXiv:2503.17031

May be also explained by Supersymmetry with R-Parity Violation  
 Consistent with Wagner's Conjecture

Pedro Bittar, Subhojit Roy and C.W. , arXiv:2509.09062



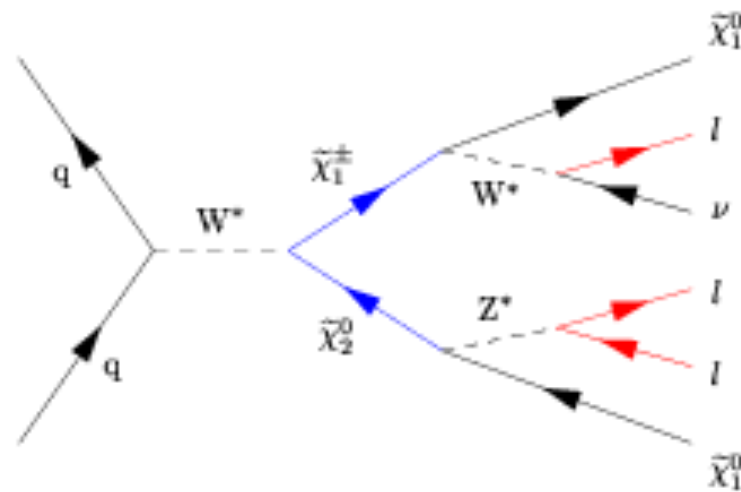
About 1.2 events expected from on-shell and off-shell squark production



Quantity	Value
Parent mass	$m_{\tilde{d}_k} = 8 \text{ TeV}$
Daughter masses	$m_{\tilde{u}_i}, m_{\tilde{d}_j} \simeq 2 \text{ TeV}$
Couplings	$\lambda''_{11k} = 0.3, \quad A_{11k} = 4 \text{ TeV}$
Branching ratio	$\text{BR}(\tilde{d}_k^* \rightarrow \tilde{u}_i \tilde{d}_j) \simeq 0.7$
Total width	$\Gamma_{\tilde{d}_k} \simeq 97.6 \text{ GeV} (\sim 4.9\%)$
Signal cross section	$\sigma(pp \rightarrow \tilde{d}_k^* \rightarrow 4j) \simeq 6.0 \times 10^{-2} \text{ fb}$
Acceptance (4j)	$A \simeq 0.30$
$N_{4j} @ 139 \text{ fb}^{-1}$	$\simeq 2.51 \text{ events}$
On/off-shell split @ $139 \text{ fb}^{-1}$	$\sim 1.19 \text{ on-shell} + \sim 1.32 \text{ off-shell}$

$k = 3$  (bottoms) due to bounds from di-jet production as well as di-nucleon decays.  
 Third generation 8 TeV squarks consistent with 125 Higgs mass generation via loop effects.

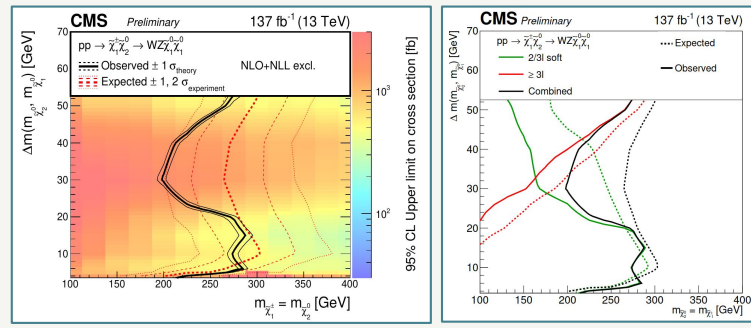
## Chargino-Neutralino Production



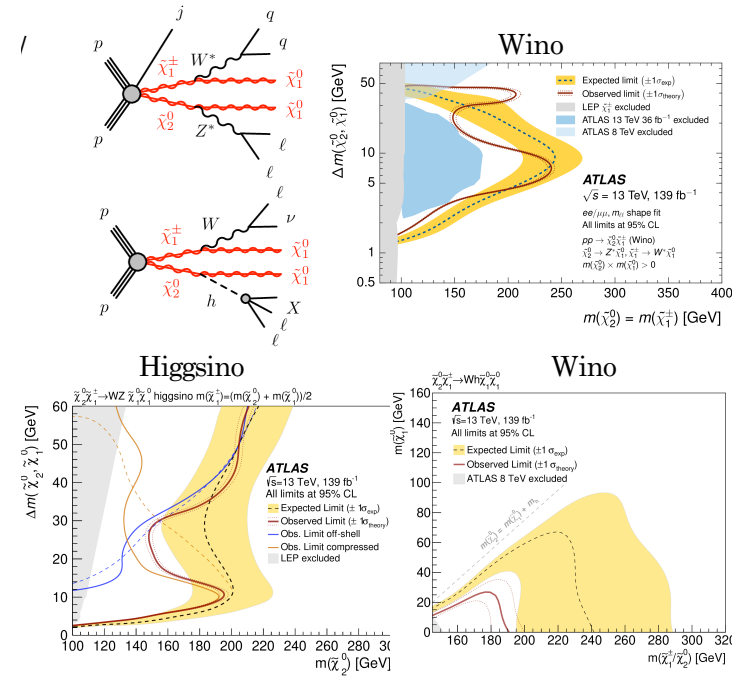
- For values of the wino and Higgsino masses larger than the weak scale, the mixing between them is small.
- Winos, in the adjoint representation of  $SU(2)$ , are produced at a stronger rate than Higgsinos.
- The cross section for **Wino production is about a factor 4 larger** than the one for **Higgsino production**.
- Mixing increases for smaller mass differences, leading to a reduction of the wino cross section, and to the **addition of new channels, some of them mixed “Wino-Higgsino”**.

# There may be surprises at the LHC in the compressed region

- The 2/3l soft and  $\geq 3l$  analyses complement each other in the compressed region
  - Orthogonal lepton  $p_T$  ranges but different selections (e.g. MET for 2/3l soft)
    - Challenging to be fully optimal in the crossover regime



Excesses in regions consistent with co-annihilating Dark Matter

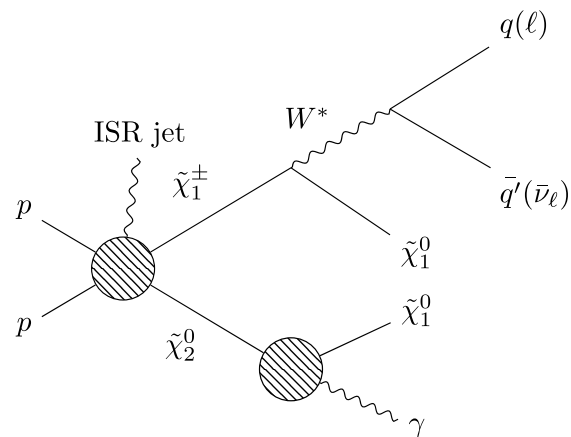


First weak evidences of SUSY electroweakino sector ?  
Eagerly waiting for Run3 results :)

Consistency : Combined analysis : M. Chakraborti, S. Heinemeyer, I. Saha, 2403.14759

## New Search Channel

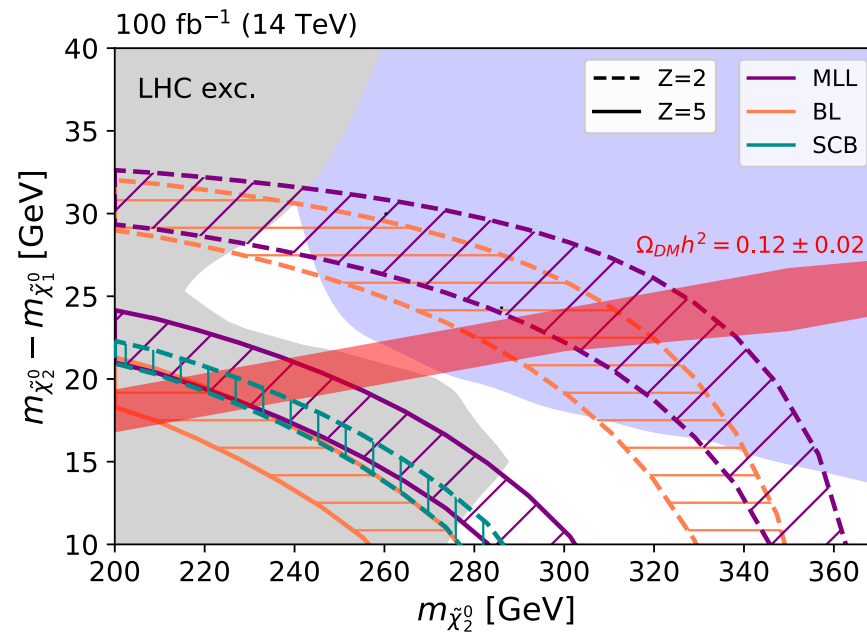
We propose to search for electroweakinos in this new search channel



One can trigger in events with sufficient Missing  $E_T$  and a somewhat hard photon in the final state

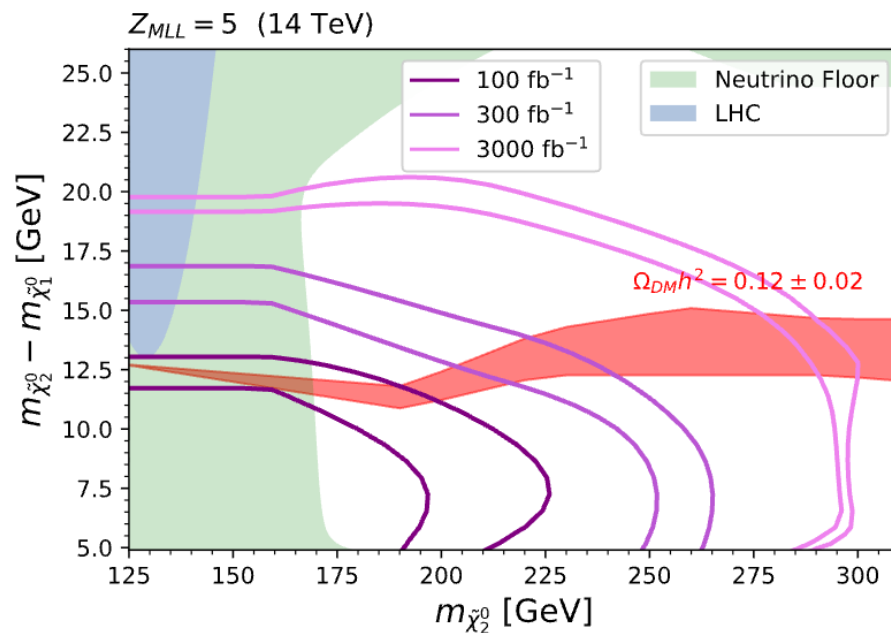
# Results of the ML Analysis

Arganda, Carena, De Los Rios, Perez, Rocha, Sanda Seoane, C.W., 2410.13799



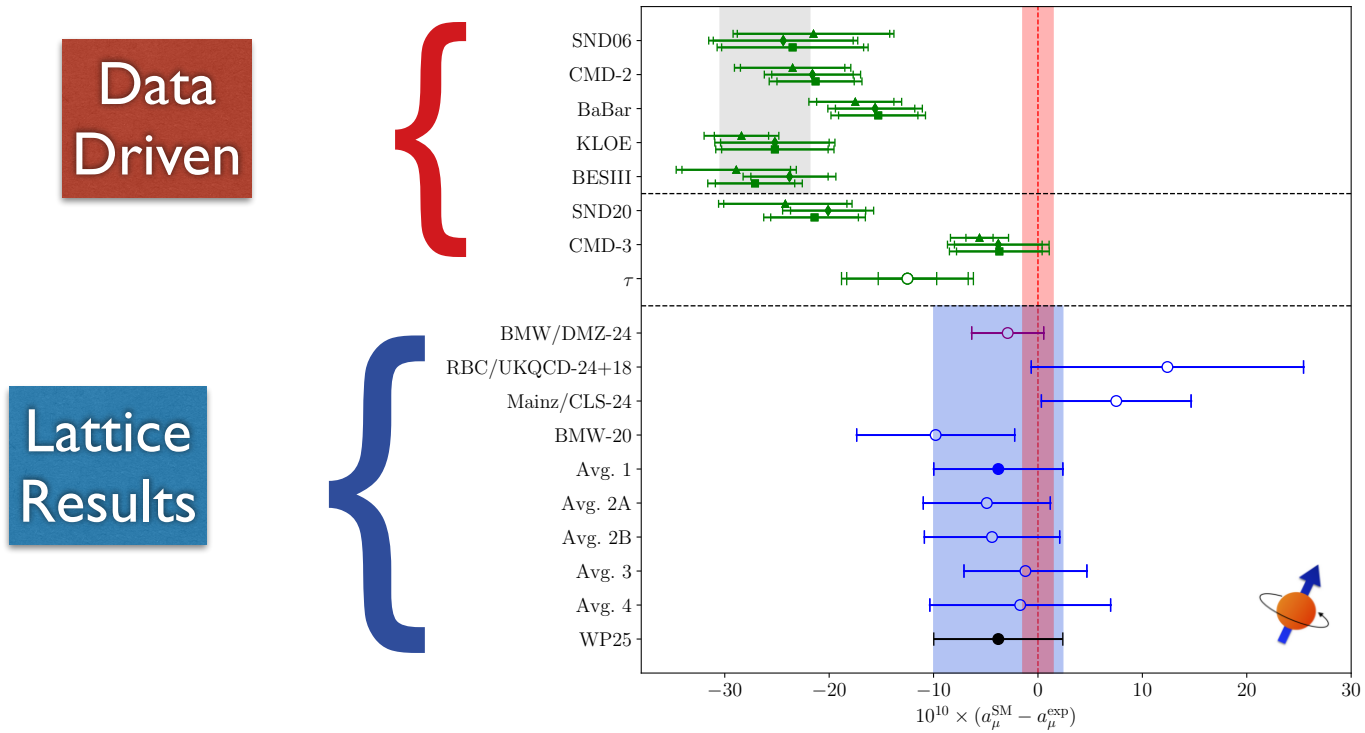
Results are optimistic, ignoring probable systematic errors.  
One can probe currently allowed parameter space, although discovery will demand higher luminosities.

## Reach of ML Analysis in the NMSSM



Higgsino Cross section is smaller than in the Wino case.  
Photon signatures enhanced in this region of parameters  
Multilepton limits degraded due to the increase in radiative decays  
Blind Spot region degrades also the power of direct detection

The anomalous magnetic moment of the muon in the Standard Model: an update

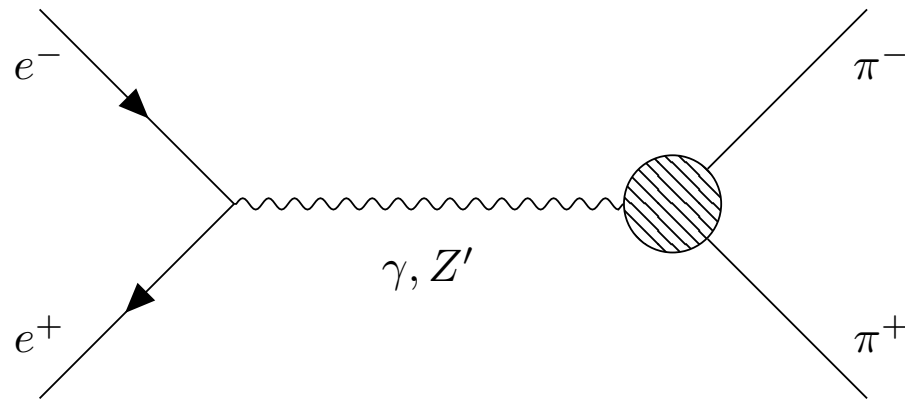


## Resolving the tensions.

- Tension of the lattice results with the data driven ones may be resolved by some unaccounted systematic error in the lattice evaluations. However, it should be shared by many different lattice collaborations, which agree in a value that leads to consistency with experiment. In this case, the tension between experiment and theory is at the level of 5 sigma, implying new physics.
- Tension of experiment with data driven and lattice results could be resolved by a large systematic error in the cross sections evaluation. Again, it should be shared by many different experiments, besides perhaps CMD3.
- Lattice result should be considered a SM result. Data driven determination could be affected by new physics in the hadronic cross sections.
- HPV effects would have an impact on the variation of the fine structure constant, affecting precision measurements at  $M_Z$ , and any correction from the current values should be limited to energies below 0.9 GeV.

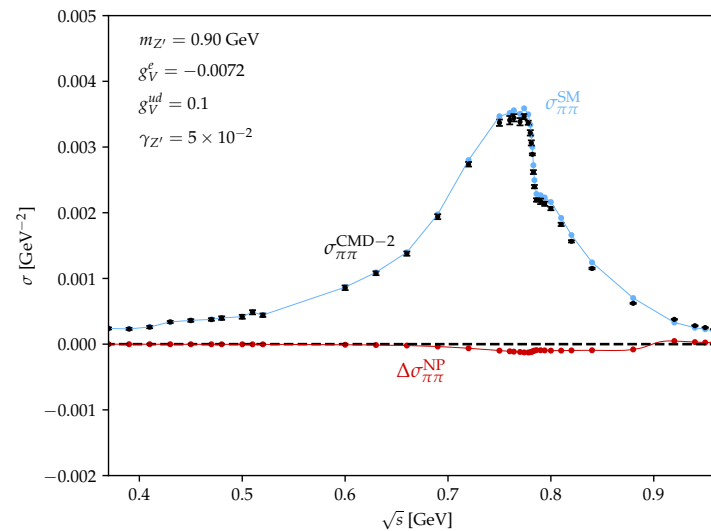
Crivellin et al, 2003.04886; Kezhavarzi, Marciano, Passera, Sirlin, arXiv: 2006.12666

## New Contributions to the Hadronic Cross Section



# Extra Width Contributions

N. Coyle, C.W. arXiv:2305.02354



$$\gamma_{Z'} = \Gamma_{Z'}/m_{Z'}$$

With an additional contribution to the width the feature disappears. Dark sector challenge. A possible model was presented in the quoted article.

# Benchmarks

N. Coyle, C.W. arXiv:2305.02354 (JHEP)

Benchmark	$m_{Z'}$ (GeV)	$g_V^{ud}$	$g_V^e \times 10^3$			
			CMD-2	KLOE	SND	BaBar
1	0.60	0.08	7.5	8.3	8.5	8.1
2	0.60	0.07	8.6	9.4	9.7	9.2
3	0.65	0.08	7.6	7.8	7.1	7.7
4	0.65	0.07	8.6	8.9	8.1	8.7
5	0.65	0.06	10.0	10.4	9.4	10.2
6	0.90	0.09	-8.0	-8.3	-7.9	-8.2
7	0.90	0.08	-9.0	-9.4	-8.9	-9.2

Example benchmark points with an enhanced width of  $\gamma_{Z'} = 5 \times 10^{-2}$  that satisfy  $\Delta a_\mu^{\text{HVP}} = 1.44 \times 10^{-9}$  for the respective listed experiment.

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They were asking what was the best time of one's life.

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I wish you many years more of a happy and scientifically productive life !

