Searches for New Physics in the LHC era

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Laboratori Nazionali di Frascati

Research Seminar @ University of Milan, Milan, Italy

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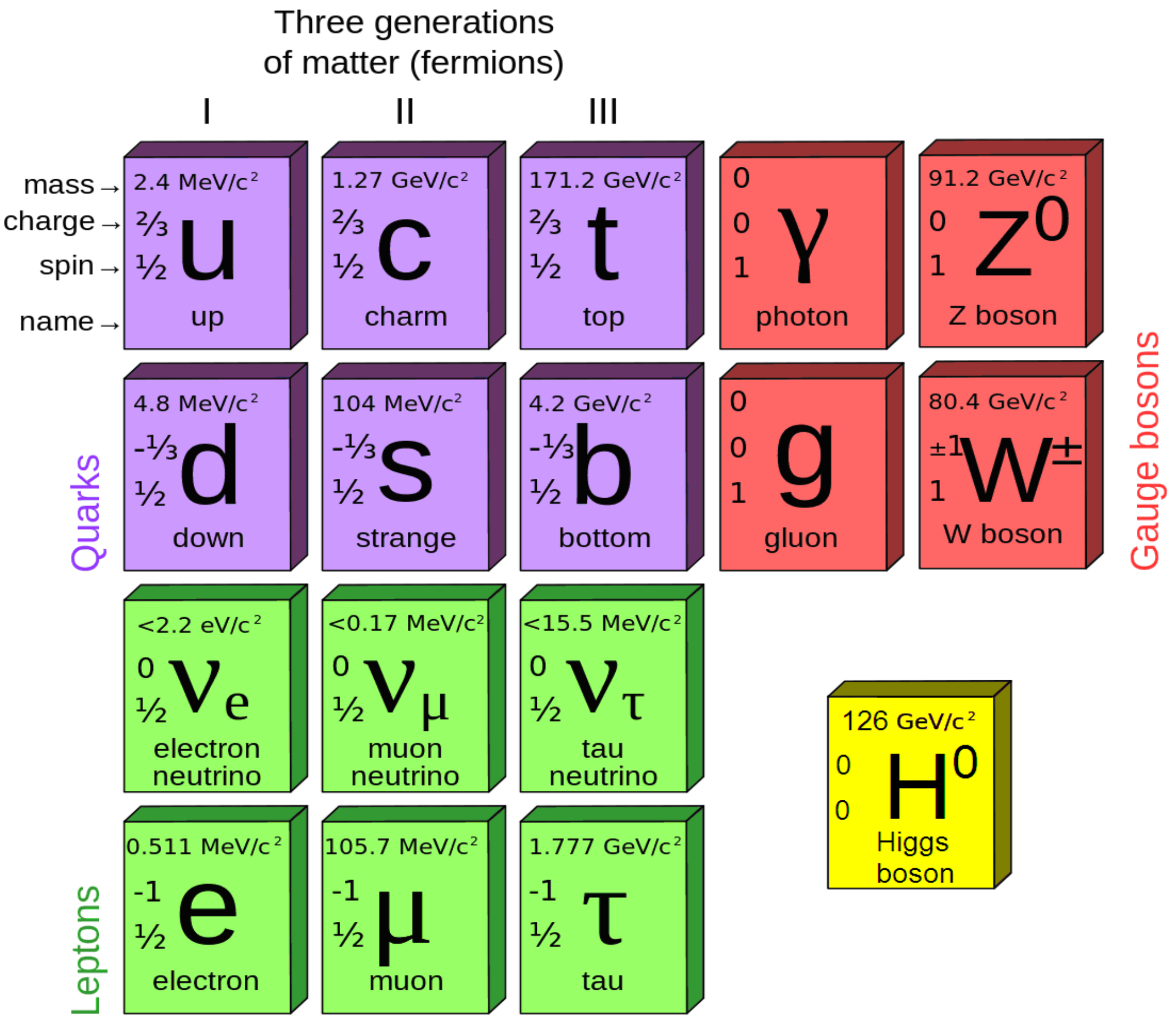
The Standard Model



Three generations of matter (fermions)

mass →
charge →
spin →
name →

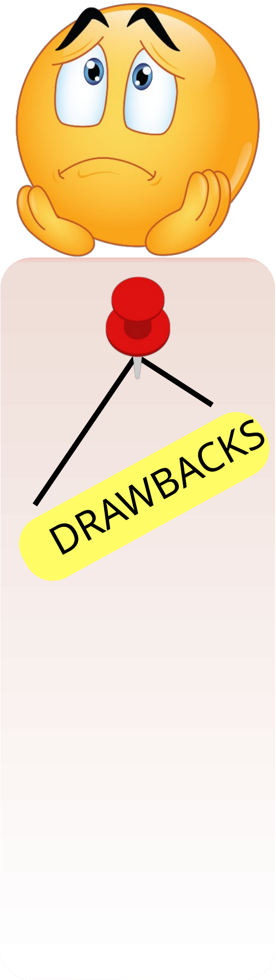
	I	II	III		
Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	91.2 GeV/c^2 0 1 Z^0 Z boson
Quarks	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino		
Leptons	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau		

Gauge bosons

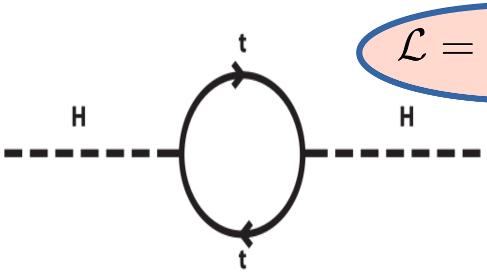
126 GeV/c^2
0
0
H^0
Higgs boson

V. D. Barger et.al., Collider Physics (1996)

Drawbacks of the Standard Model



✦The Higgs mass instability problem in the Electroweak (EW) sector



$$\mathcal{L} = -\lambda_t H\bar{t}t$$

$$\Delta m_H^2 = \frac{-|\lambda_t|^2}{8\pi^2}\Lambda_{UV}^2 + \underbrace{\dots} \longrightarrow \propto m_t^2 log\Lambda_{UV}$$

✦The Strong CP Problem

$$\underbrace{\mathcal{L} = \bar{\theta}\frac{g^2}{32\pi^2}F_a^{\mu\nu}\tilde{F}_{a\mu\nu} \text{ ; Neutron electric dipole moment } < 2.9\times 10^{-26}ecm}$$

From Exp.

$$\longrightarrow \bar{\theta} < 10^{-9} - 10^{-10}$$

✦The Axion quality Problem

Inclusion of quantum gravity ruins the $U(1)_{PQ}$ solution to the Strong CP problem

✦Existence of Dark Matter

✦Masses of Neutrino

M. Bauer et. al., Lect.Notes Phys. (2019)
A. Hook, PoS TASI2018
S.P. Martin, Adv.Ser.Direct.High Energy Phys. (2010)
V. D. Barger et.al., Collider Physics (1996)

Addressing the Drawbacks

🟪 DRAWBACKS
🟨 SOLUTIONS
🟥 PHENOMENOLOGY

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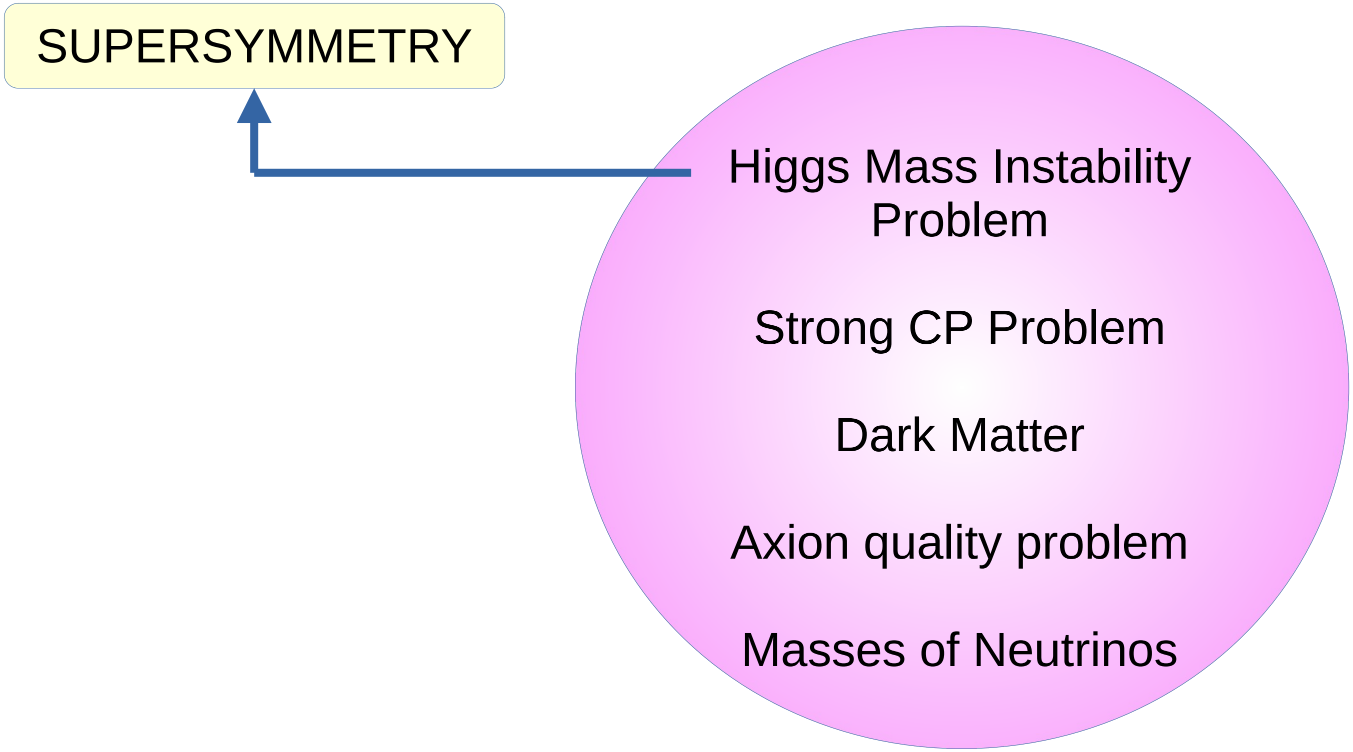

SUPERSYMMETRY

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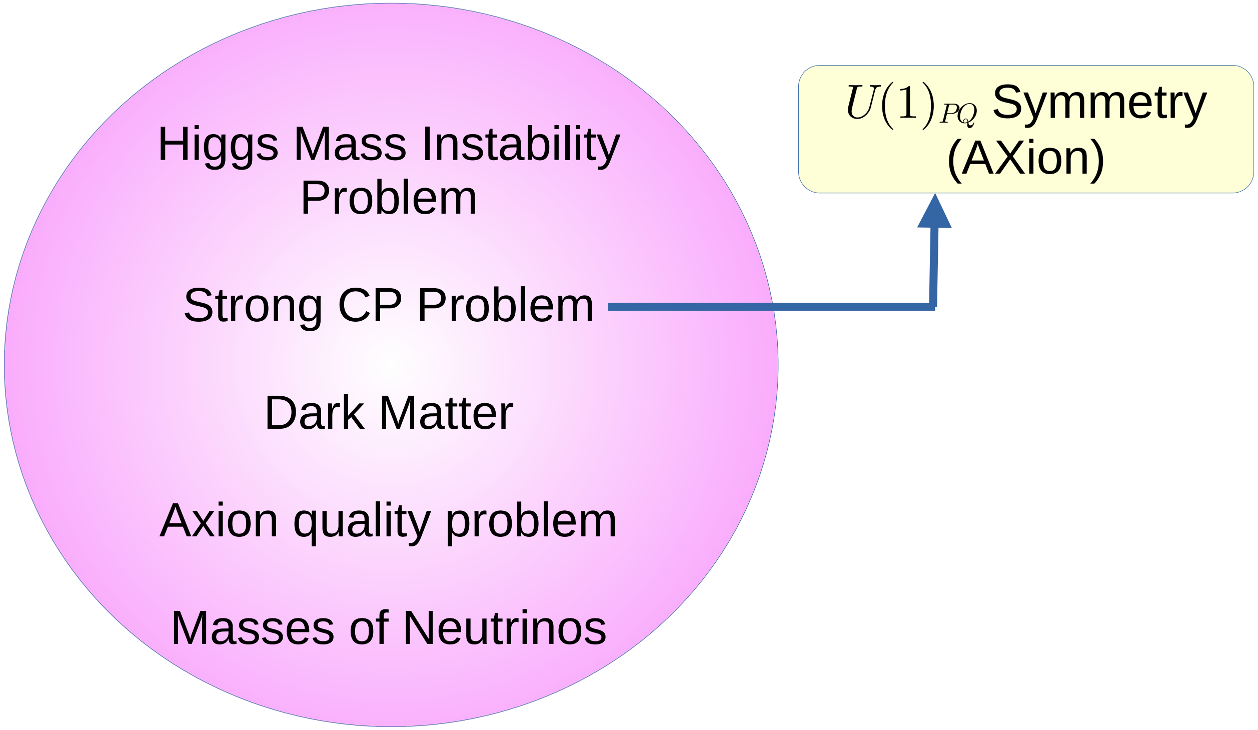

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$U(1)_{PQ}$ Symmetry (AXion)

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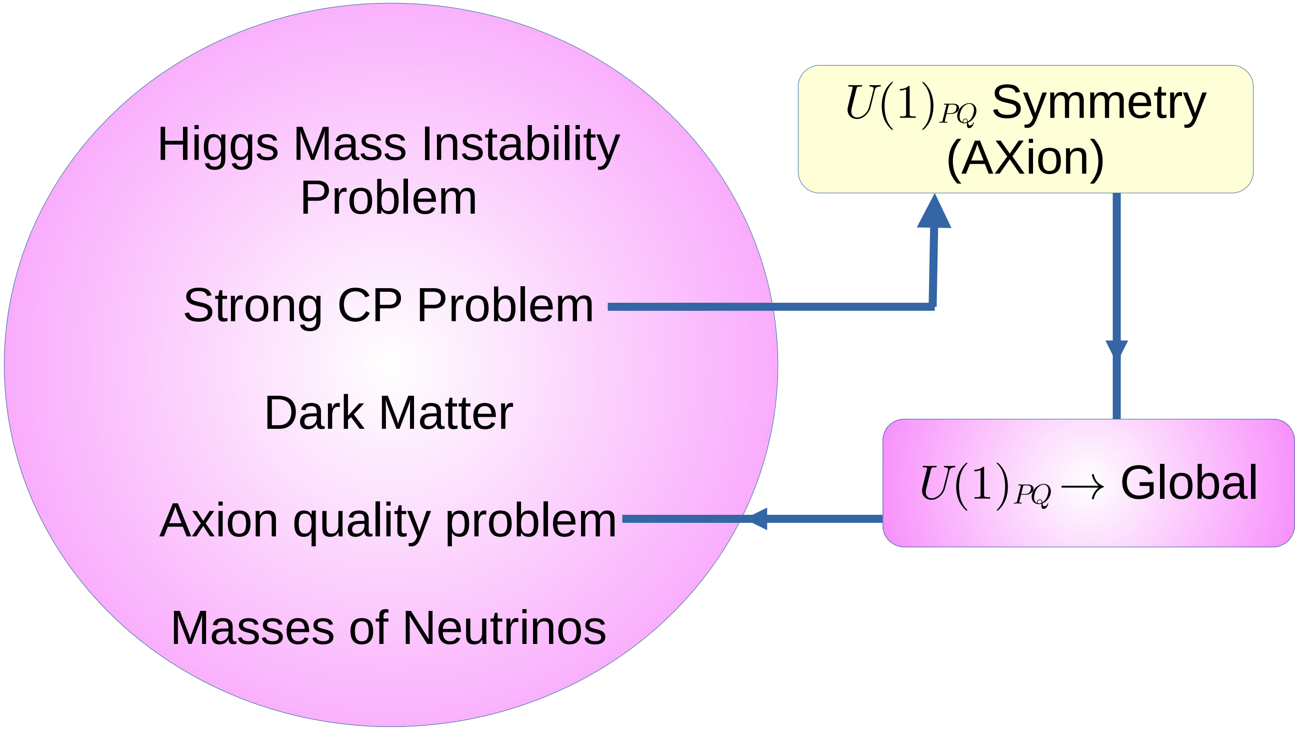

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$U(1)_{PQ}$ Symmetry (AXion)

$U(1)_{PQ} \to$ Global

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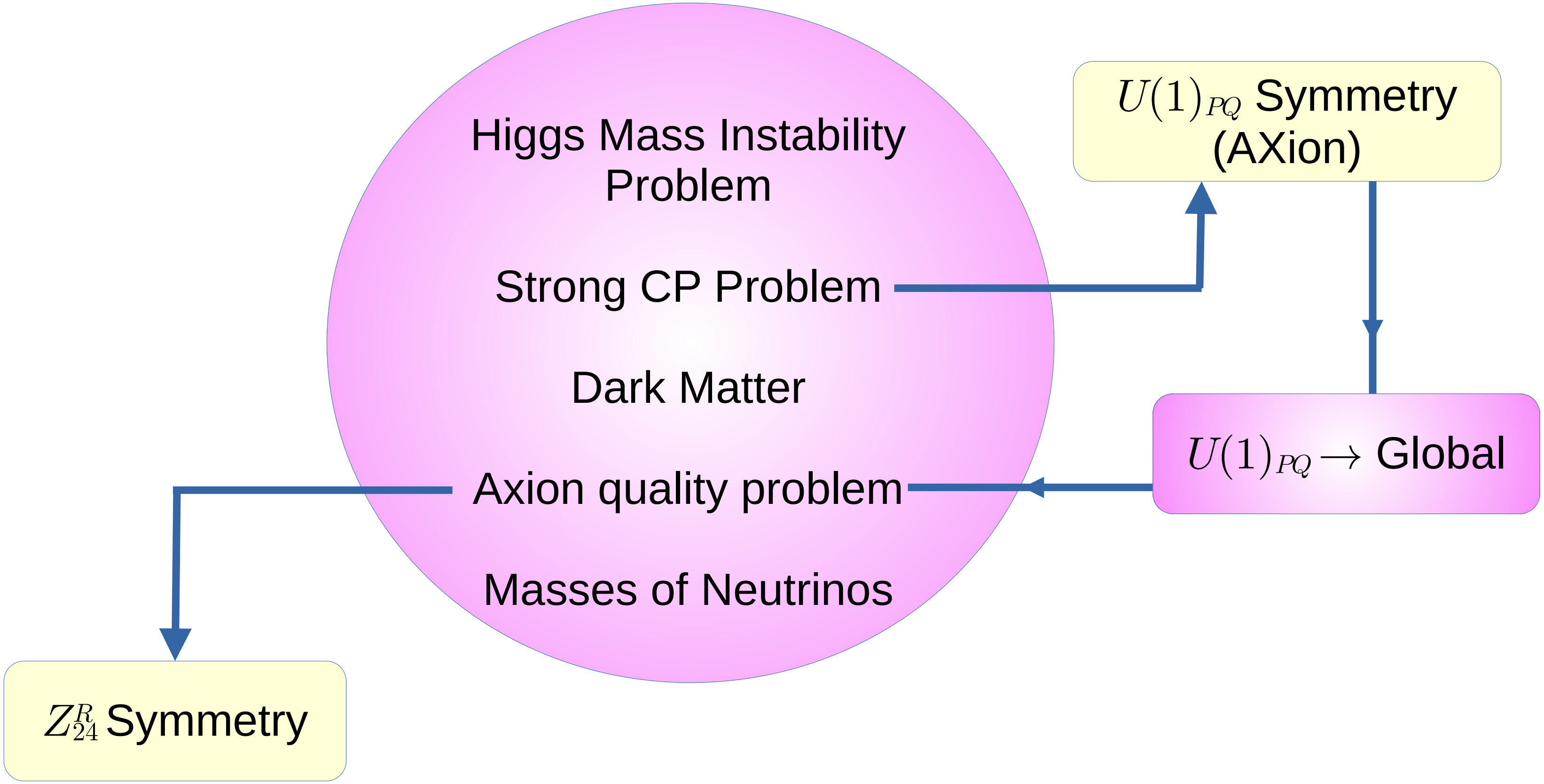

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Z_{24}^{R} Symmetry

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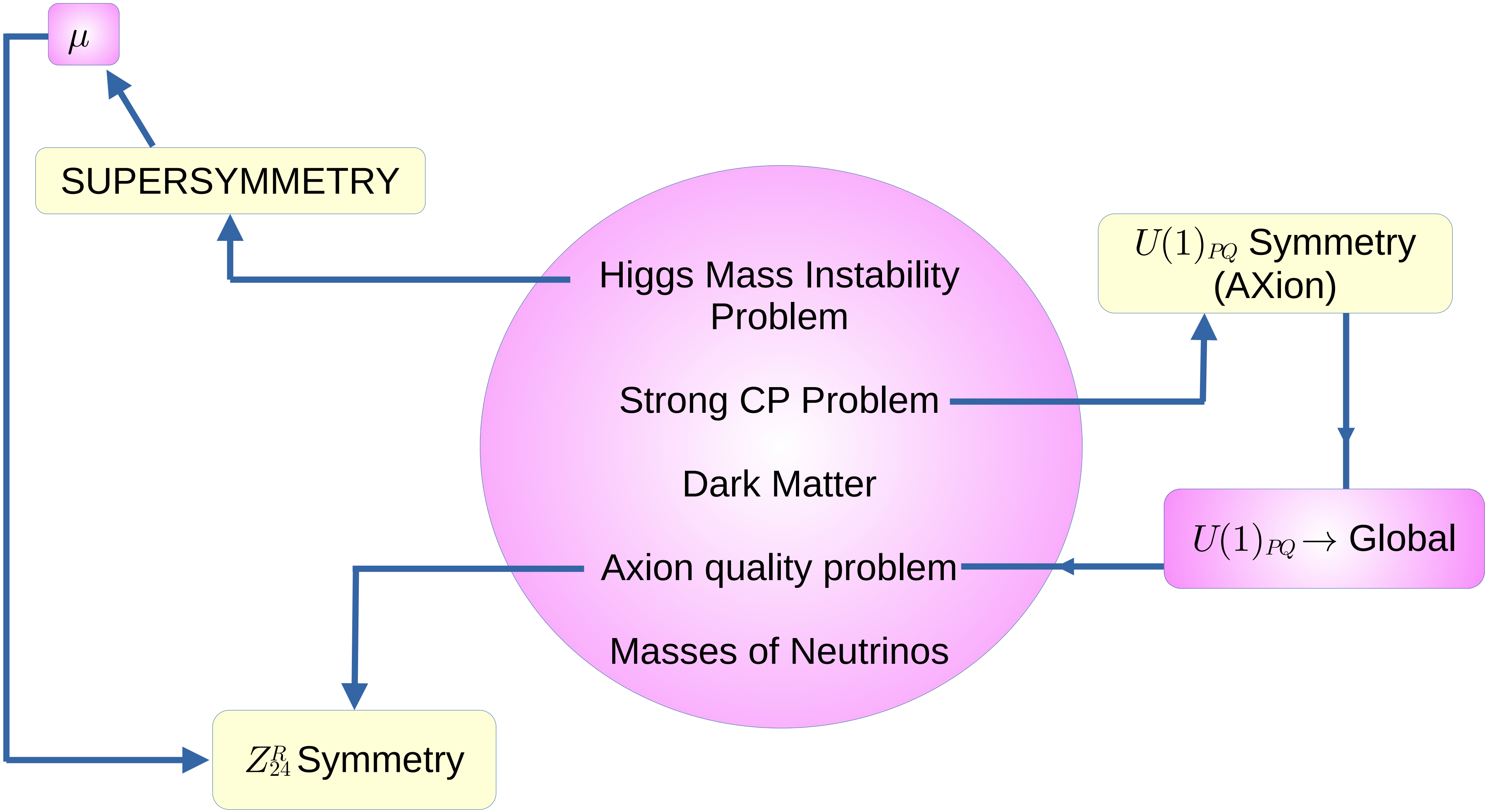

μ

SUPERSYMMETRY

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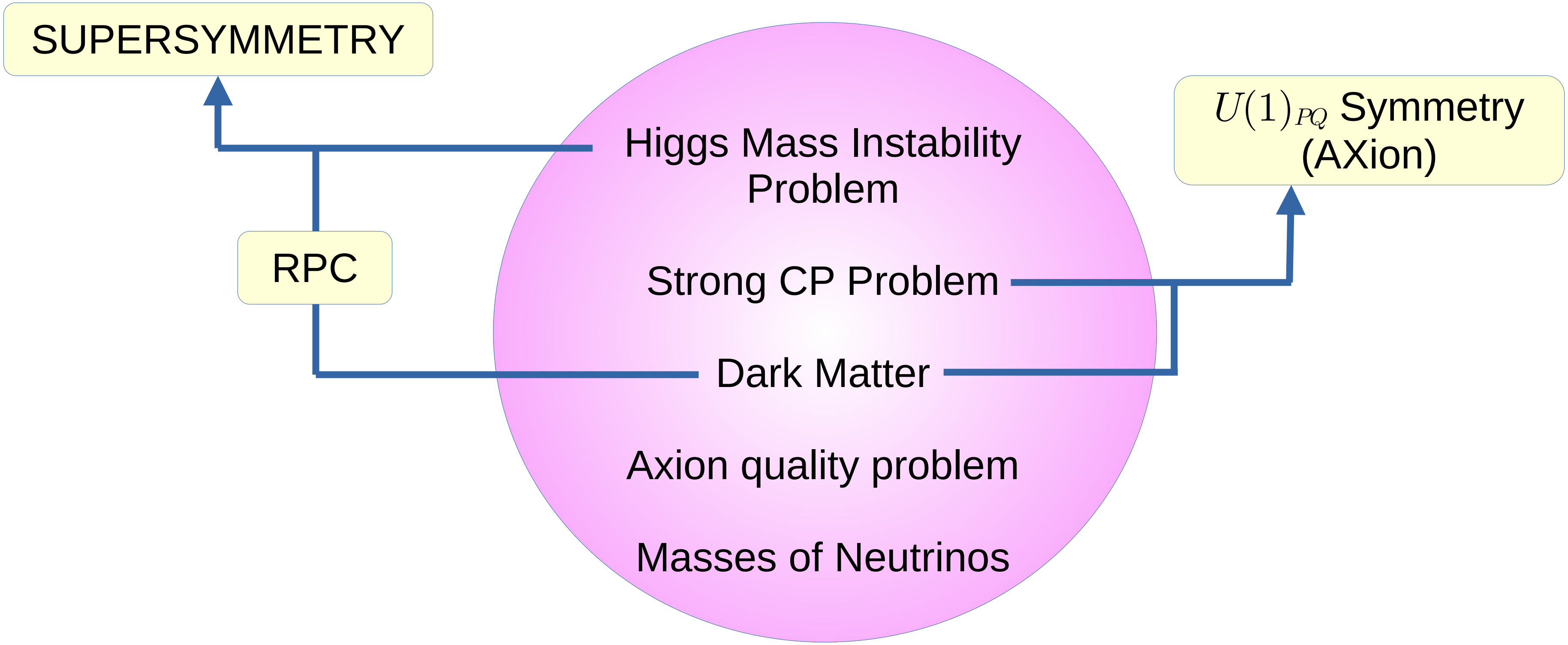

SUPERSYMMETRY

RPC

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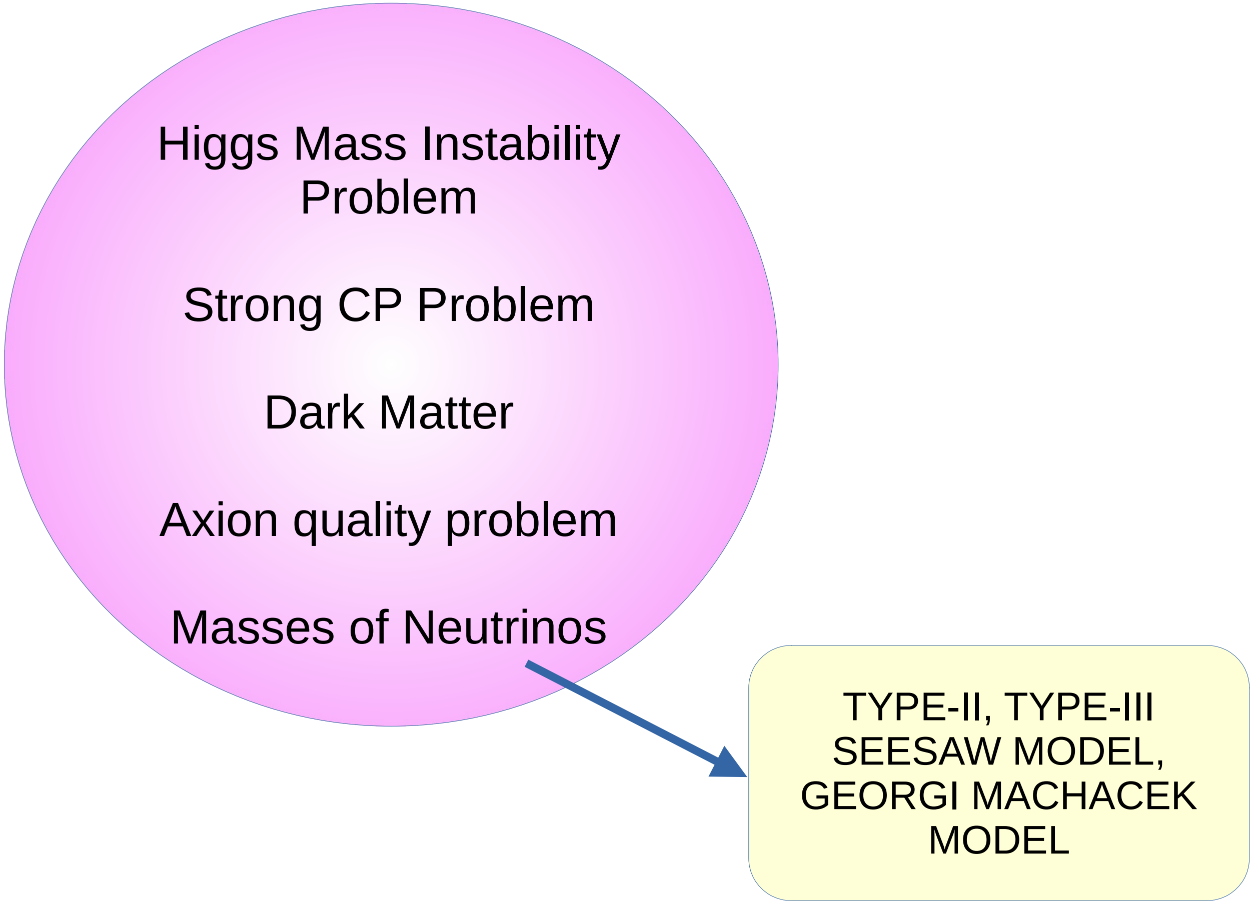

Higgs Mass Instability Problem

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TYPE-II, TYPE-III SEESAW MODEL, GEORGI MACHACEK MODEL

Addressing the Drawbacks

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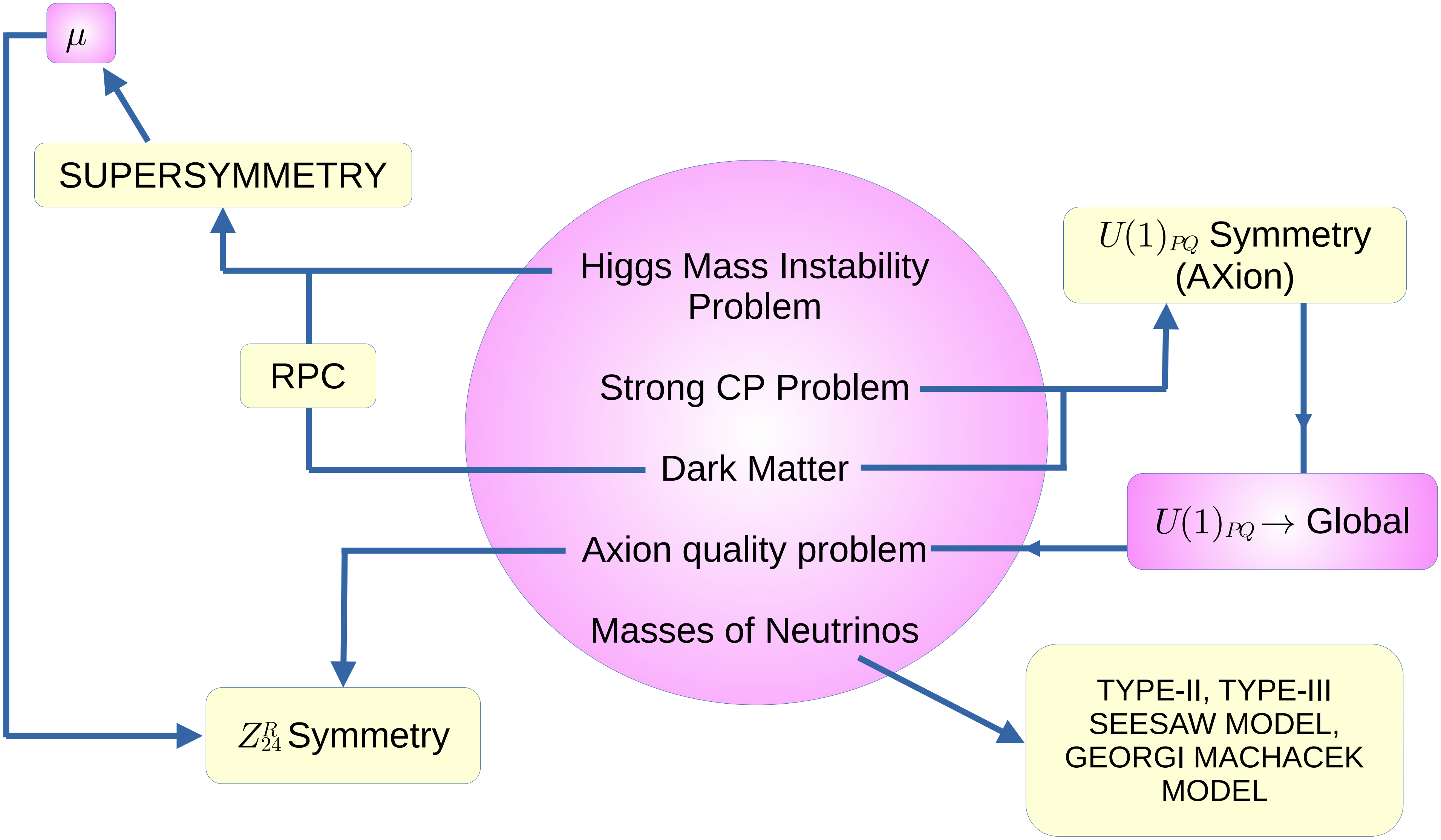

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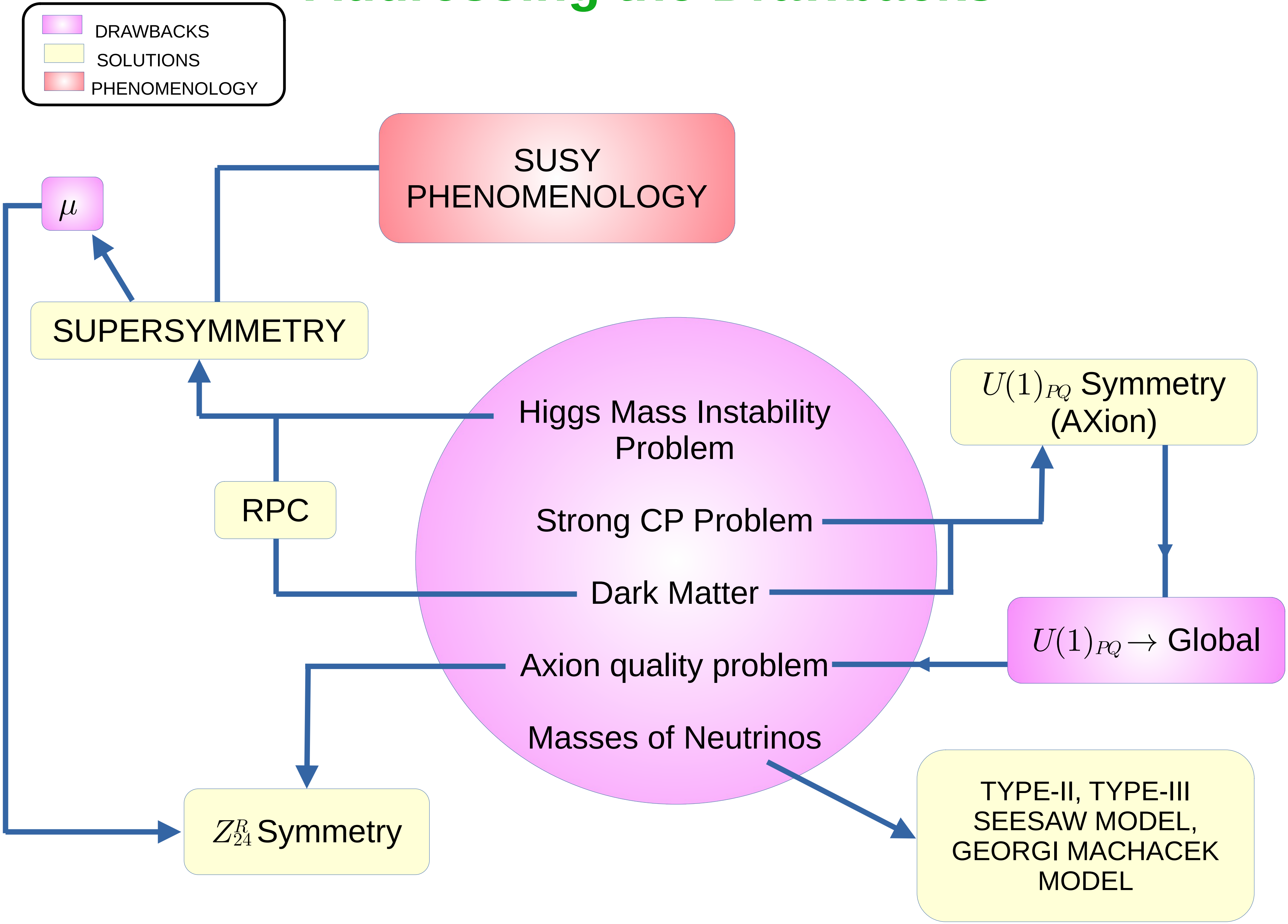

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SUSY PHENOMENOLOGY

μ

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A BSM Scenario: Supersymmetry (SUSY)

SUSY = SM + Superpartner with spin = spin(SM) ± 1/2 → **MINIMAL SUPERSYMMETRIC STANDARD MODEL (MSSM)**

H. Baer et. al., Cambridge University Press, 2006.
S.P. Martin, Adv.Ser.Direct.High Energy Phys. (2010)

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SM Boson:
W_1, W_2, W_3
B
Gluon
Higgs
Graviton

→

SUPERPARTNER

Fermion:
Wino
Bino
Gluino
Higgsino
Gravitino

SM Fermion:
Quarks
Leptons

→

SUPERPARTNER

Boson:
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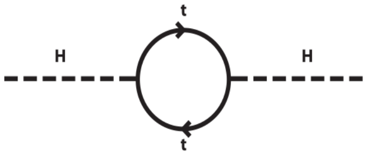
Main Motivation: *Cancellation of Quadratic Divergence in Higgs Mass*



$$\Delta m_H^2 = \frac{-|\lambda_t|^2}{8\pi^2}\Lambda_{UV}^2 + \underbrace{\ldots}_{} \longrightarrow \propto m_t^2 log\Lambda_{UV}$$

$$\Delta m_H^2 = \frac{|\lambda_t|^2}{8\pi^2}\Lambda_{UV}^2 + \underbrace{\ldots}_{} \longrightarrow \propto m_{\tilde{t}}^2 log\Lambda_{UV}$$

Quadratic divergences must be canceled to stabilize the Higgs mass in the ultraviolet complete theory

H. Baer et. al., Cambridge University Press, 2006.
S.P. Martin, Adv.Ser.Direct.High Energy Phys. (2010)

Naturalness in SUSY

No **SPARTICLES** yet!

$$m_{sparticles} \gg m_{SM particles}$$

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LHC Limits : $m_{\tilde{g}} > 2.2\, TeV$, $m_{\tilde{t}_1} > 1.1\, TeV$

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Notion of Practical Naturalness :

An Observable $\mathcal{O}$ *is natural if all independent contributions to* $\mathcal{O}$ *are comparable to or less than* $\mathcal{O}$.

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$$\Delta_{\mathrm{EW}} = \max_i |C_i| / (M_Z^2/2)$$

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u\left(\tilde{t}_{1,2}\right)$$

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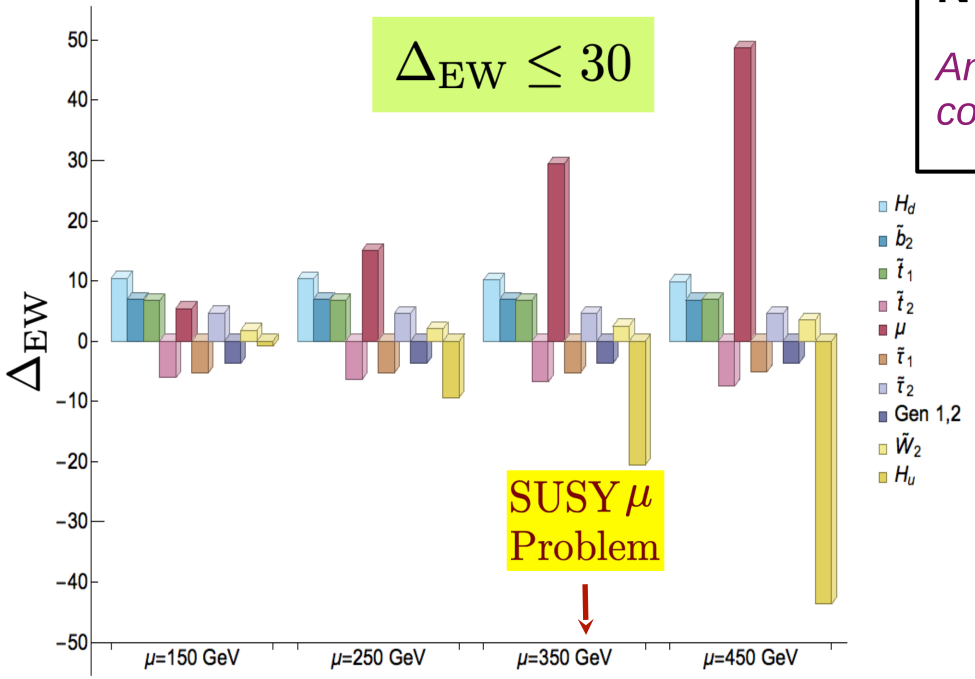

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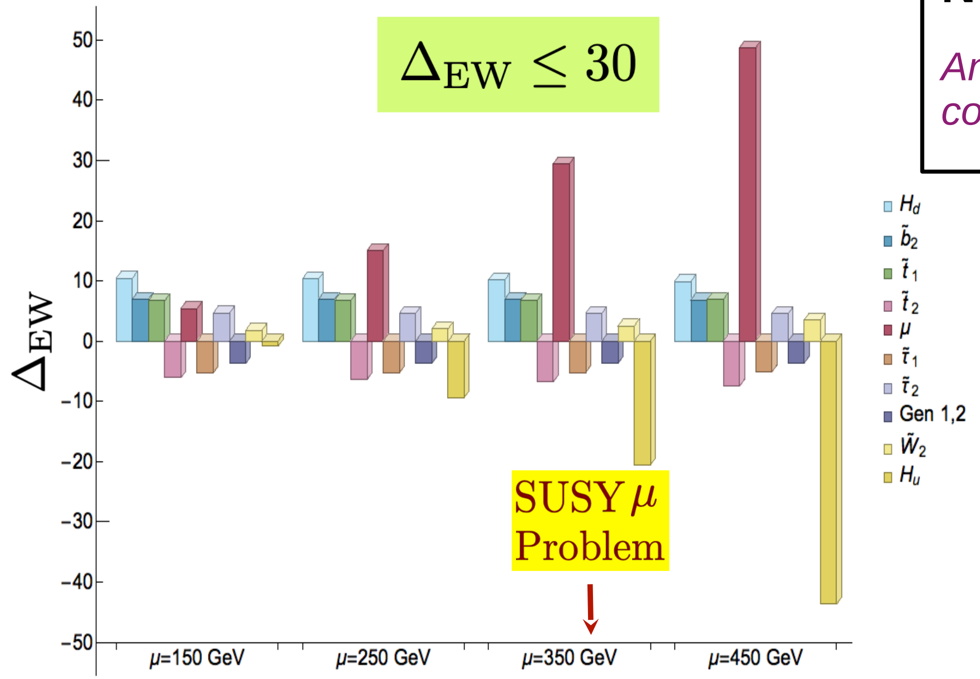

$\Delta_{\rm EW} \leq 30$

SUSY μ
Problem

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$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u\,(\tilde{t}_{1,2})$$

$$\mathcal{L}_{MSSM} \leftarrow \mu H_u H_d$$

H. Baer et. al., Cambridge University Press, 2006.

$\Delta_{EW} < 30$?

$\Delta_{EW} < 30$ → Anthropic requirements needed to sustain life

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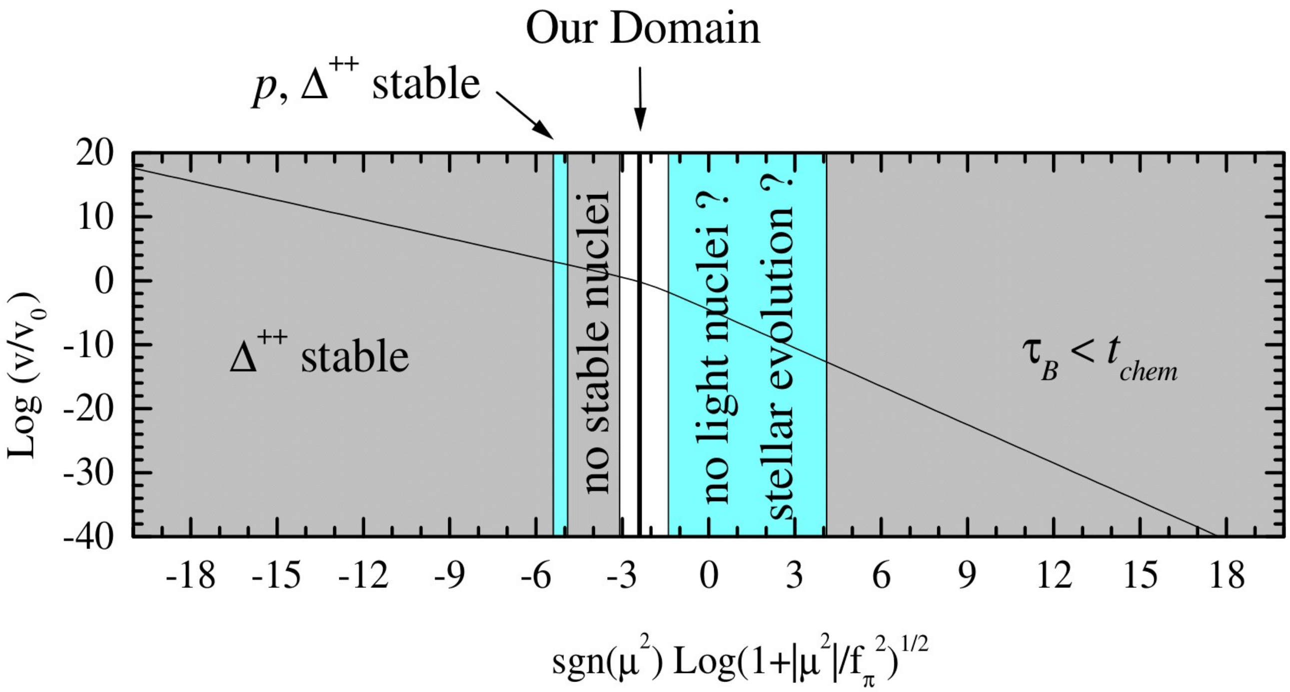

V. Agrawal et. al. Phys. Rev. D 57, 5480

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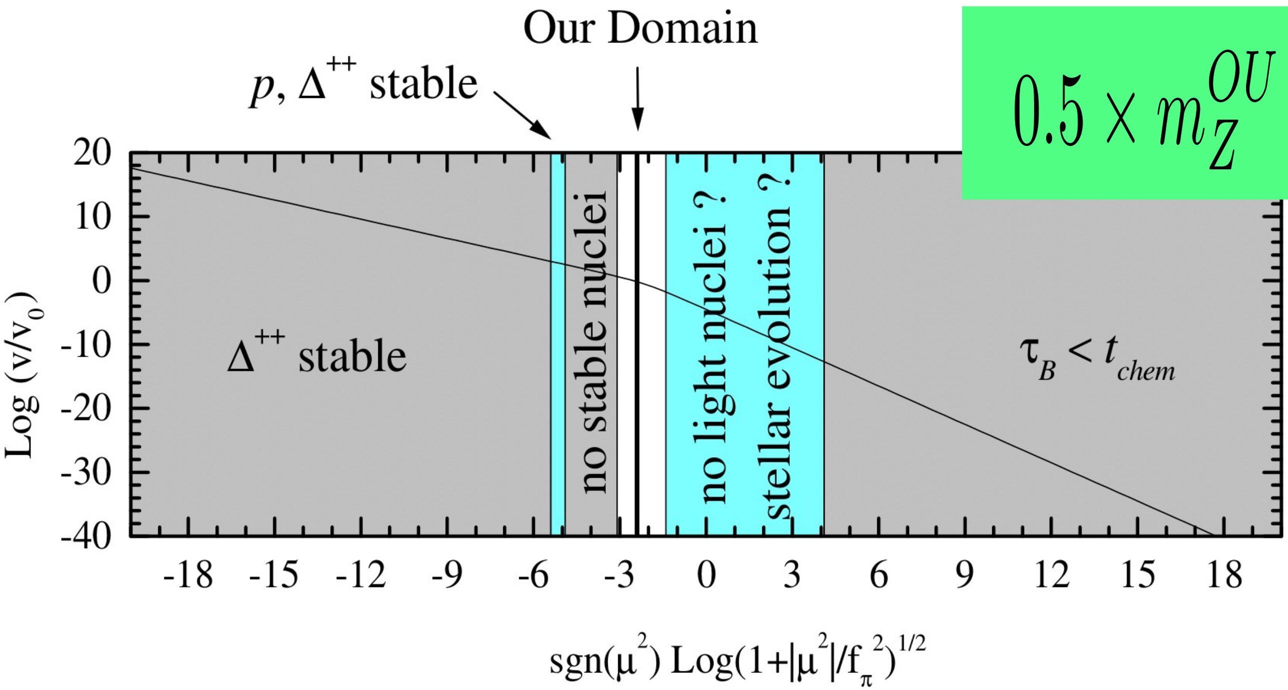

$$0.5 \times m_Z^{OU} \leq m_Z^{PU} \leq 5 \times m_Z^{OU}$$

V. Agrawal et. al. Phys. Rev. D 57, 5480

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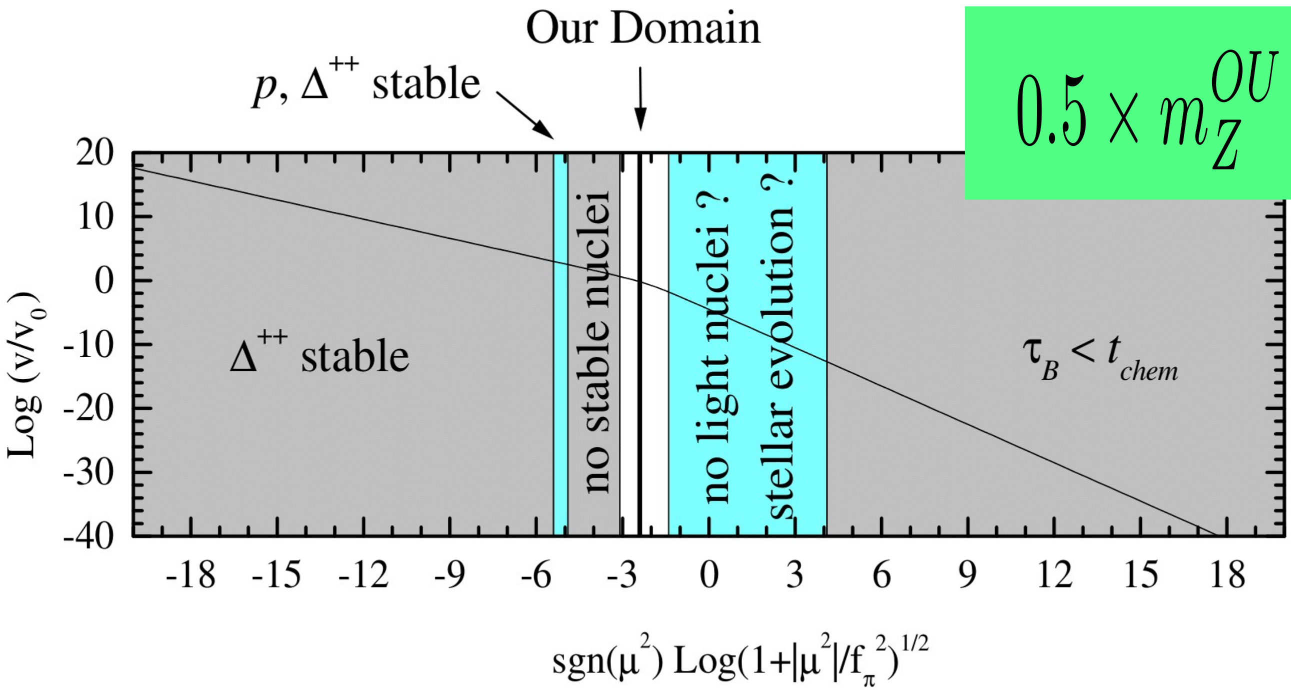
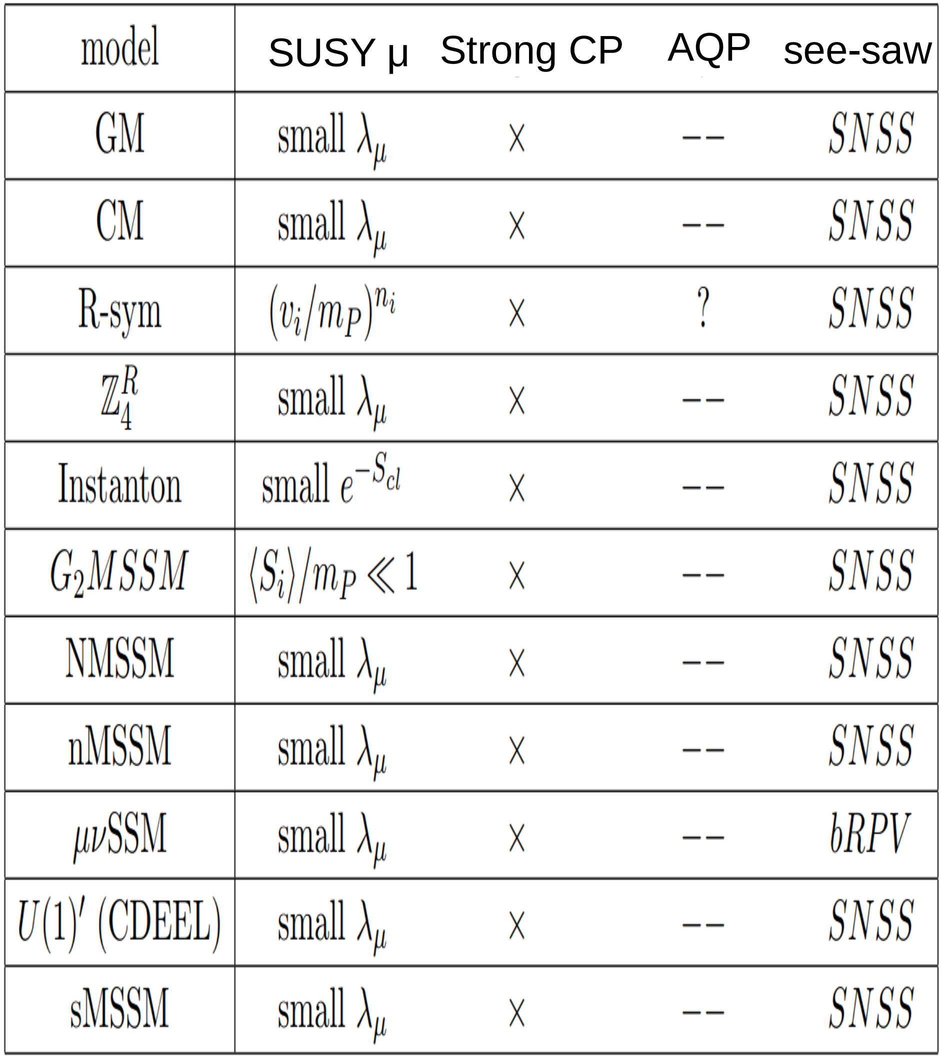


$$0.5 \times m_Z^{OU} \leq m_Z^{PU} \leq 5 \times m_Z^{OU}$$

$$\Delta_{EW} = 30 \rightarrow 4 \times m_Z^{OU}$$

V. Agrawal et. al. Phys. Rev. D 57, 5480

Solutions to the SUSY μ problem



model	SUSY μ	Strong CP	AQP	see-saw
GM	small λ_μ	$\times$	$--$	$SNSS$
CM	small λ_μ	$\times$	$--$	$SNSS$
R-sym	$(v_i/m_P)^{n_i}$	$\times$	?	$SNSS$
Z_4^R	small λ_μ	$\times$	$--$	$SNSS$
Instanton	small $e^{-S_{cl}}$	$\times$	$--$	$SNSS$
G_2MSSM	$\langle S_i\rangle/m_P \ll 1$	$\times$	$--$	$SNSS$
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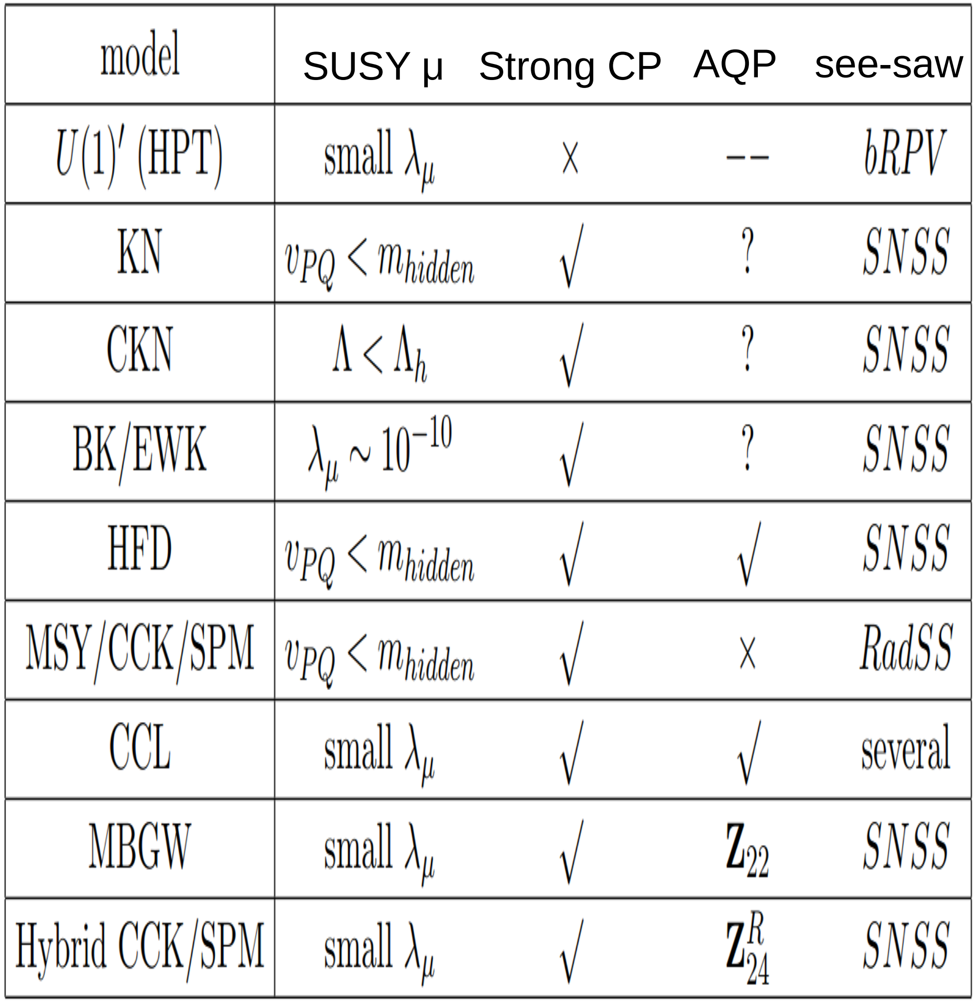
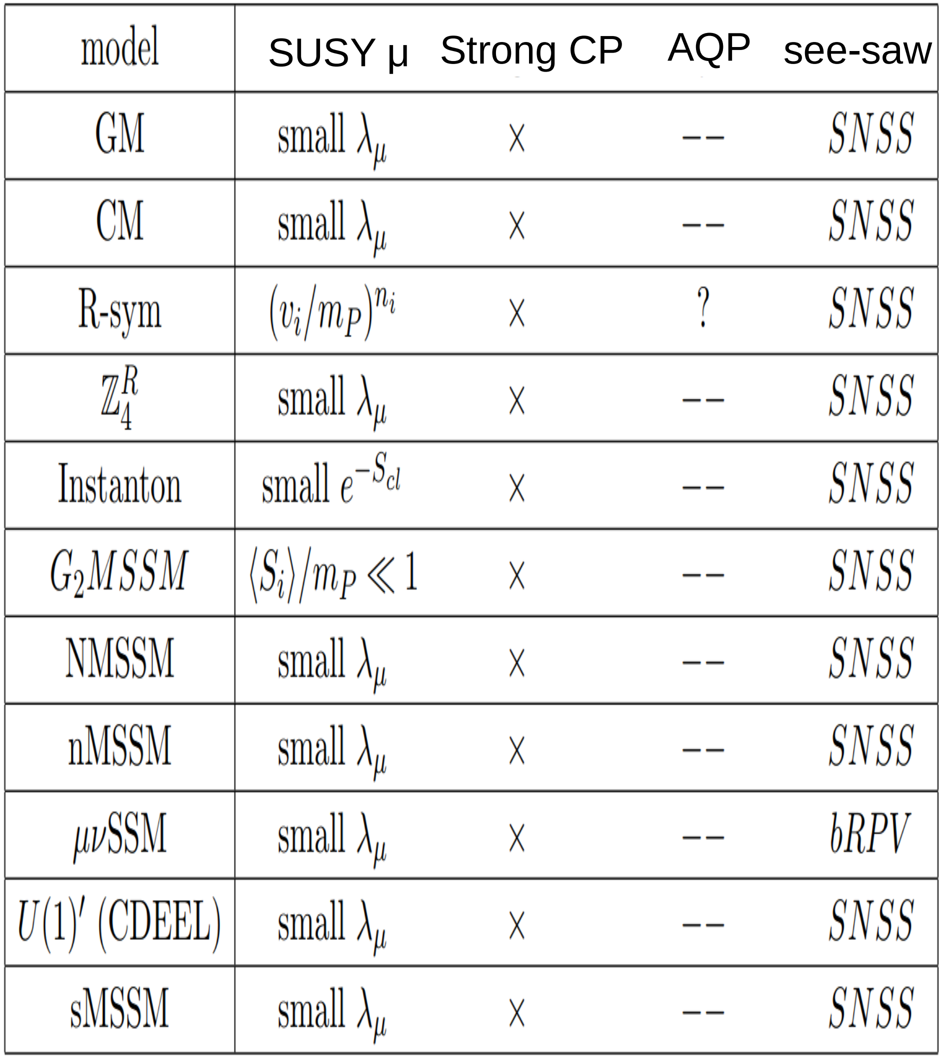
$U(1)'$ (CDEEL)	small λ_μ	$\times$	$--$	$SNSS$
sMSSM	small λ_μ	$\times$	$--$	$SNSS$



model	SUSY μ	Strong CP	AQP	see-saw
$U(1)'$ (HPT)	small λ_μ	$\times$	$--$	$bRPV$
KN	$v_{PQ} < m_{hidden}$	$\surd$	?	$SNSS$
CKN	$\Lambda < \Lambda_h$	$\surd$	?	$SNSS$
BK/EWK	$\lambda_\mu \sim 10^{-10}$	$\surd$	?	$SNSS$
HFD	$v_{PQ} < m_{hidden}$	$\surd$	$\surd$	$SNSS$
MSY/CCK/SPM	$v_{PQ} < m_{hidden}$	$\surd$	$\times$	$RadSS$
CCL	small λ_μ	$\surd$	$\surd$	several
MBGW	small λ_μ	$\surd$	$\mathbf{Z}_{22}$	$SNSS$
Hybrid CCK/SPM	small λ_μ	$\surd$	$\mathbf{Z}_{24}^R$	$SNSS$

K. J. Bae, H. Baer, V. Barger, **D. S.**, Phys. Rev. D 99 (2019) no.11, 115027

Solutions to the SUSY μ problem



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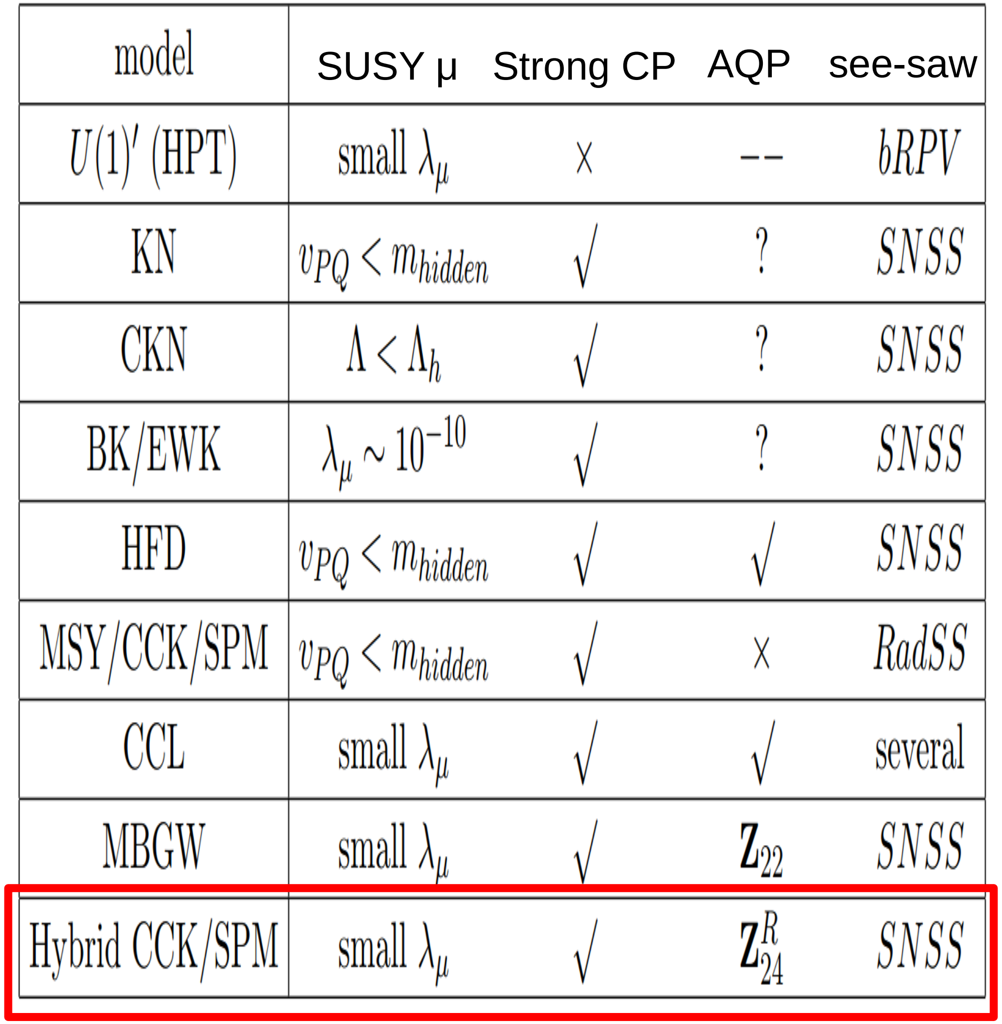

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K. J. Bae, H. Baer, V. Barger, **D. S.**, Phys. Rev. D 99 (2019) no.11, 115027

Supersymmetry Breaking

$$m_{sparticles} \gg m_{SM particles}$$

BROKEN IN HIDDEN SECTOR

H. Baer et. al., Cambridge University Press, 2006.

Supersymmetry Breaking

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BROKEN IN HIDDEN SECTOR

SUSY BREAKING EFFECTS MEDIATED TO VISIBLE SECTOR VIA:

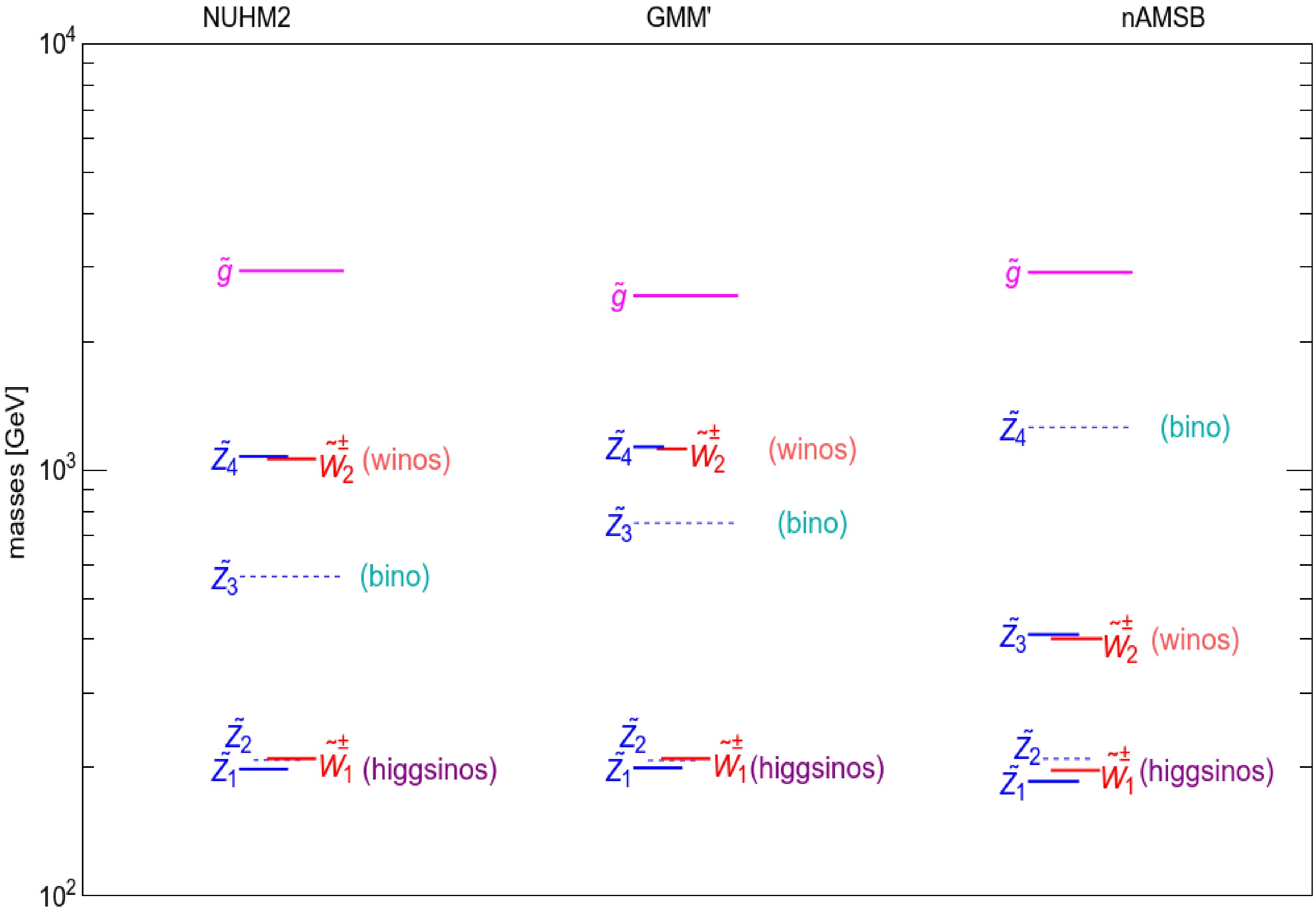
- Gravity-Mediation
- Anomaly-Mediation
- Mirage-Mediation = Anomaly + Gravity Mediation

- Gauge-Mediation
- Gaugino-Mediation

} → **UNNATURAL**

H. Baer et. al., Cambridge University Press, 2006.

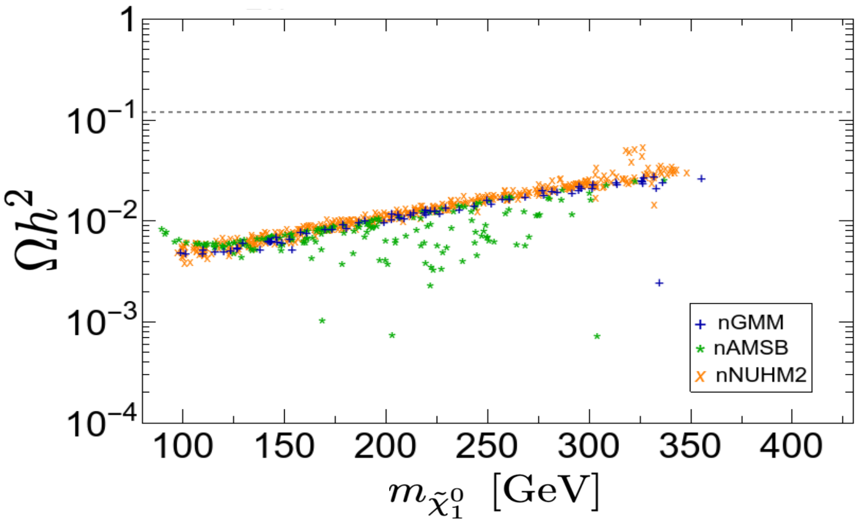
Typical Mass Spectra of Natural SUSY Models

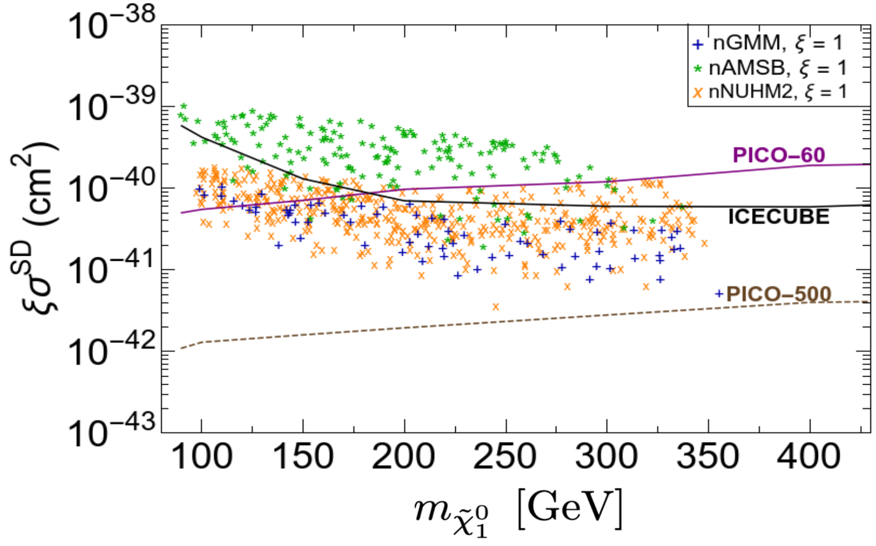


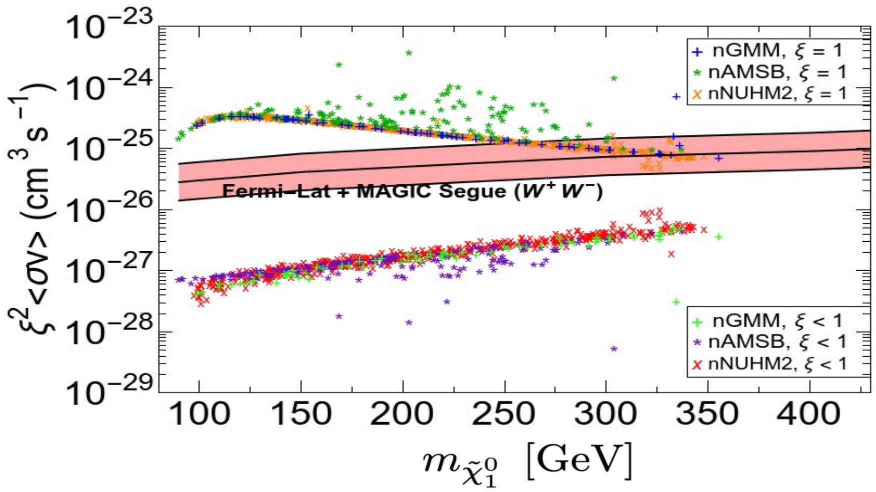
H. Baer, V. Barger, S. Salam, **D.S.** and K. Sinha, Eur.Phys.J.ST 229 (2020) 21, 3085-3141

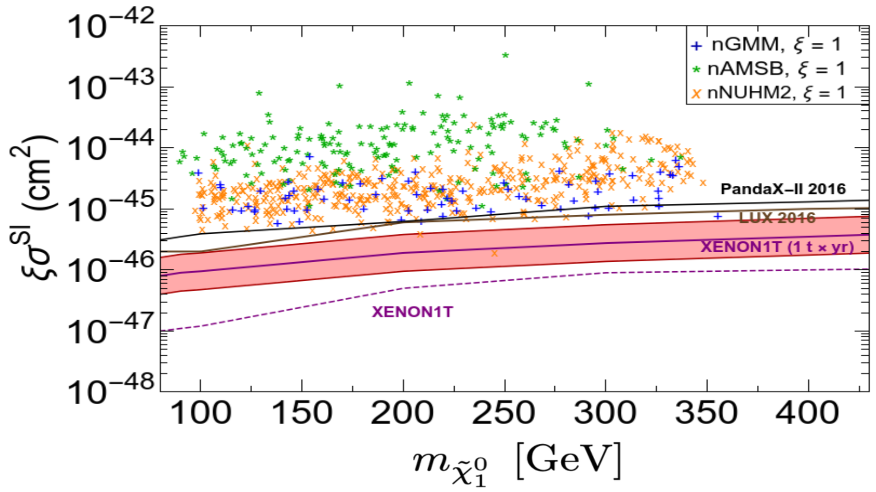
Dark Matter in SUSY

$$\Delta_{\rm EW} < 30 \;\&\; 122 < m_h < 128 \text{ GeV}$$









Dark matter = LSP from RPC SUSY+Axion

H. Baer, V. Barger, **D. S.**, and X. Tata, Eur. Phys. J. C 78 (2018) 10, 838

Strong CP Problem and its Solution

✦The Strong CP Problem

From Exp.

$\mathcal{L} = \bar{\theta}\frac{g^2}{32\pi^2}F_a^{\mu\nu}\tilde{F}_{a\mu\nu}$; Neutron electric dipole moment < $2.9 \times 10^{-26} ecm$

$$\bar{\theta} < 10^{-9} - 10^{-10}$$

R. D. Peccei et. al., Phys. Rev. Lett. (1977)

A. Hook, PoS TASI2018

Strong CP Problem and its Solution

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$$\rightarrow \bar{\theta} < 10^{-9} - 10^{-10}$$

✦The Peccei-Quinn Solution

Adding axion a and a coupling f_a to the SM $\longrightarrow \mathcal{L} \supset (a/f_a + \bar{\theta})\ \dfrac{1}{32\pi^2}F\tilde{F}$.

Axion follows an anomalous symmetry ($U(1)_{PQ}$) :

$$a \to a + \alpha f_a \qquad \bar{\theta} \to \bar{\theta} - \alpha$$

Axion Potential:

$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right)}.$$

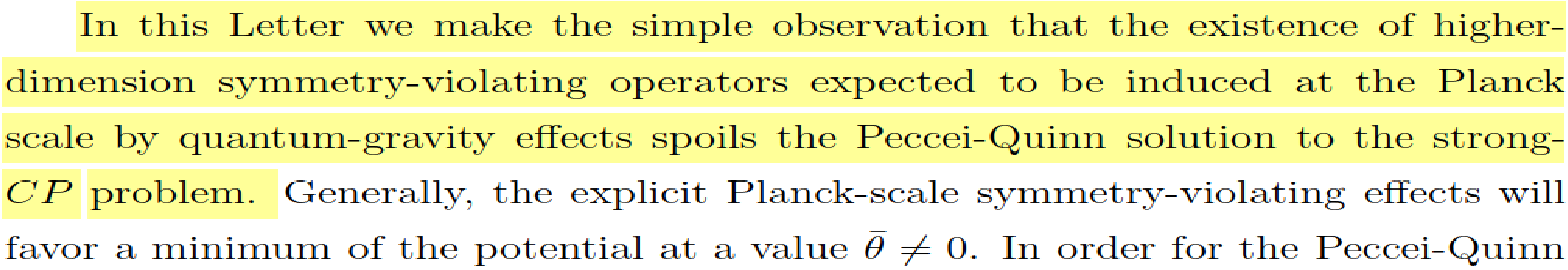
$V \to V_{min}$ when $<a>$ = $-\bar{\theta} f_a$

Neutron electric dipole moment $\propto \dfrac{a}{f_a} + \bar{\theta} \longrightarrow$ 0

R. D. Peccei et. al., Phys. Rev. Lett. (1977)

A. Hook, PoS TASI2018

Axion Quality Problem and its Solution



In this Letter we make the simple observation that the existence of higher-dimension symmetry-violating operators expected to be induced at the Planck scale by quantum-gravity effects spoils the Peccei-Quinn solution to the strong-CP problem. Generally, the explicit Planck-scale symmetry-violating effects will favor a minimum of the potential at a value $\bar{\theta} \neq 0$. In order for the Peccei-Quinn

M. Kamionkowski et. al. Phys. Lett. B 282 (1992) 137

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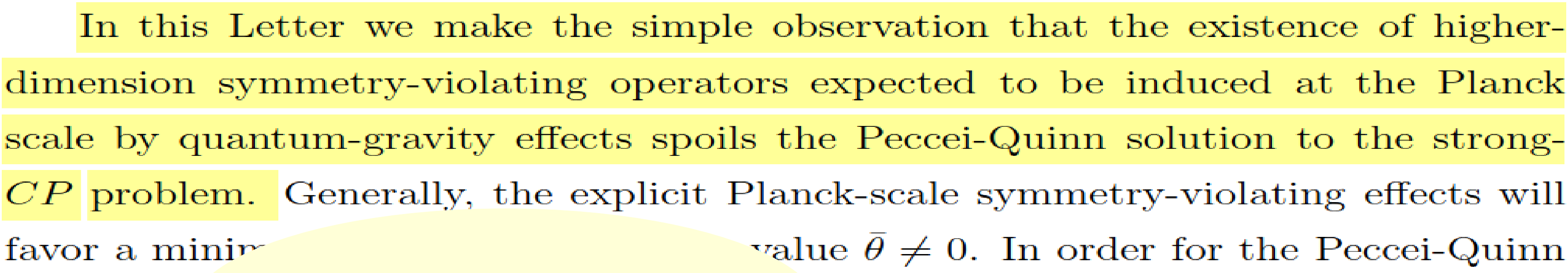

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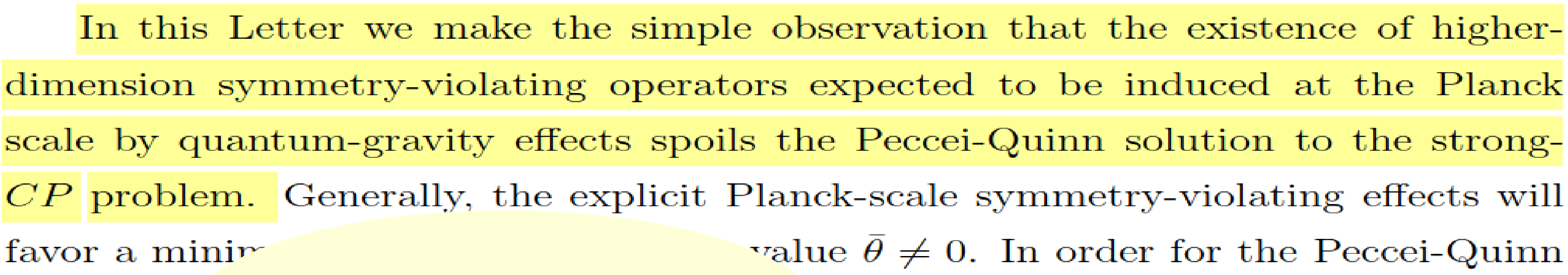

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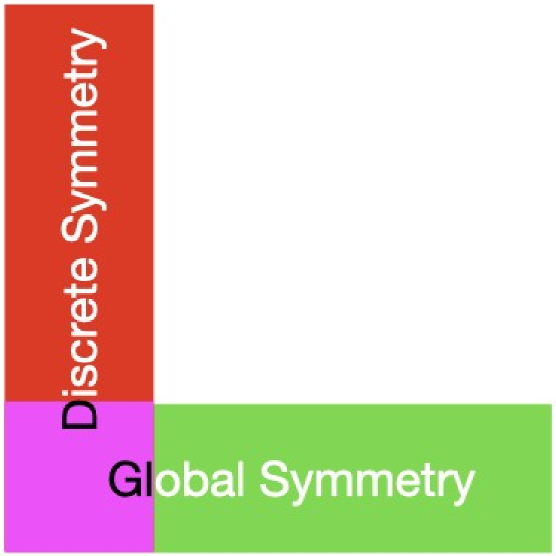
Solution to Axion quality problem



Replace $U(1)_{PQ}$ global symmetry by a discrete symmetry as the fundamental symmetry and $U(1)_{PQ}$ arises accidentally from that discrete symmetry

MBGW Model

proposed by K.S. Babu, I. Gogoladze and K. Wang and seperately by S.P. Martin

Fundamental Symmetry: Z_{22} discrete gauge symmetry **SOLVES AQP !**

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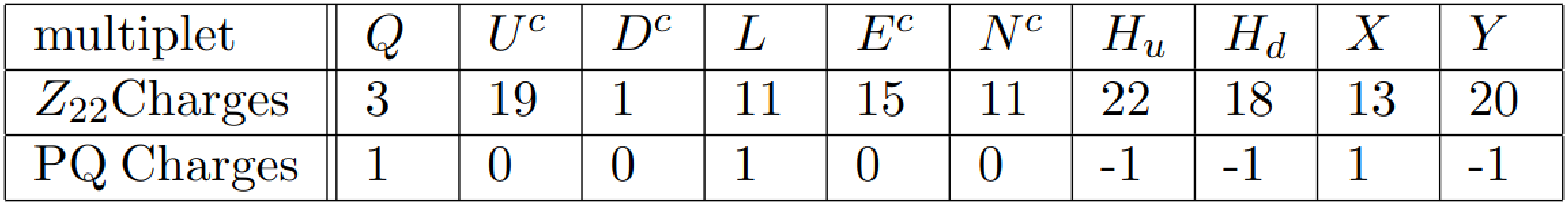

multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
Z_{22}Charges	3	19	1	11	15	11	22	18	13	20
PQ Charges	1	0	0	1	0	0	-1	-1	1	-1

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$$V = (\lambda_2 C \phi_X^2 \phi_Y^2 / m_P + h.c.) + m_X^2 |\phi_X|^2 + m_Y^2 |\phi_Y|^2 \longrightarrow$$ **SSB Terms**

$$+4\lambda_2 |\phi_X \phi_Y|^2 / m_P^2 \left(|\phi_X|^2 + |\phi_Y|^2\right) \longrightarrow$$ **F-Terms**

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CHARGE ASSISGNMENTS INCONSISTENT WITH GUT

ORIGINATES FROM CONDENSATION OF A FIELD OF CHARGE $22e$ → HIGHLY IMPLAUSIBLE

S. P. Martin, Phys. Rev. D 62 (2000) 095008

K. S. Babu, I. Gogoladze and K. Wang, Phys. Lett. B 560 (2003) 214.

Fundamental R Symmetries

$$\mathcal{L} \supset \int W d^2\theta \longrightarrow$$

Non-trivial R charge : +1 (simplest)

Superpotential: must carry R-charge **2 + nN** for the $\mathcal{L}$ **to be invariant under** Z_N^R ; (n = any integer)

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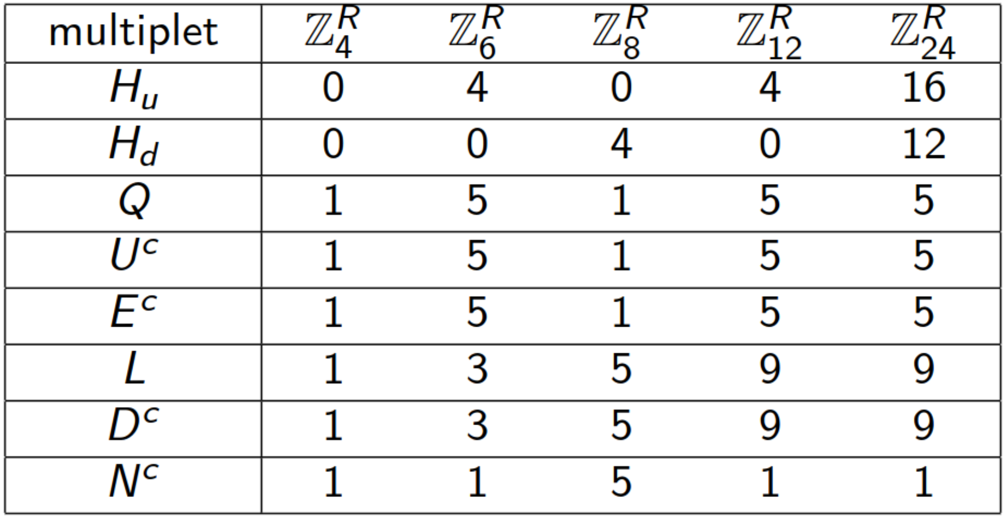

multiplet	$\mathbb{Z}_4^R$	$\mathbb{Z}_6^R$	$\mathbb{Z}_8^R$	$\mathbb{Z}_{12}^R$	$\mathbb{Z}_{24}^R$
H_u	0	4	0	4	16
H_d	0	0	4	0	12
Q	1	5	1	5	5
U^c	1	5	1	5	5
E^c	1	5	1	5	5
L	1	3	5	9	9
D^c	1	3	5	9	9
N^c	1	1	5	1	1

These R-symmetries were shown to be anomaly-free and consistent with GUT

Lee et al. in arXiv : 1102.3595

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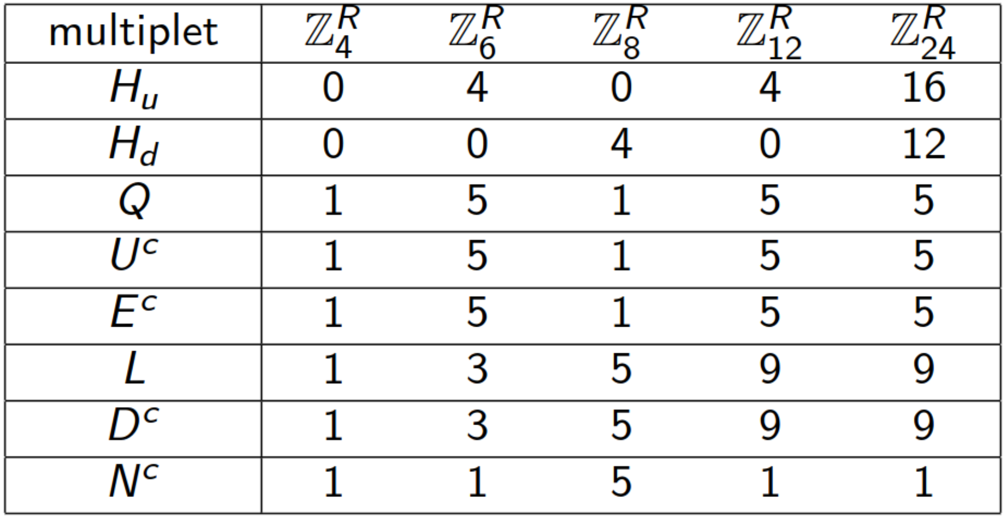
Z_{24}^R



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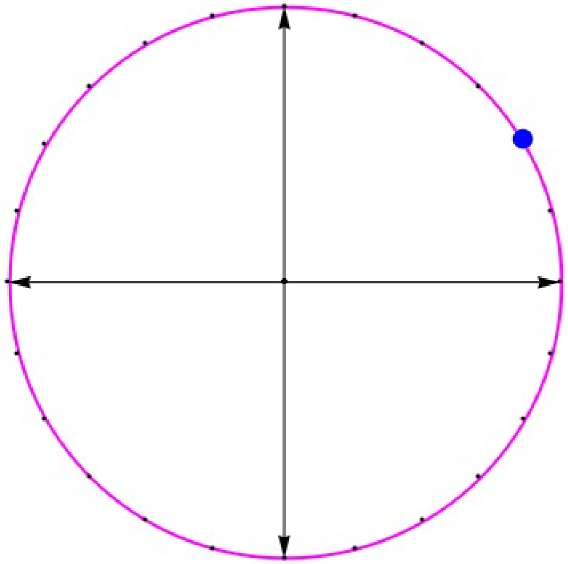

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All terms in superpotential (W) must have R charge : 2 + 24n (n = integer)

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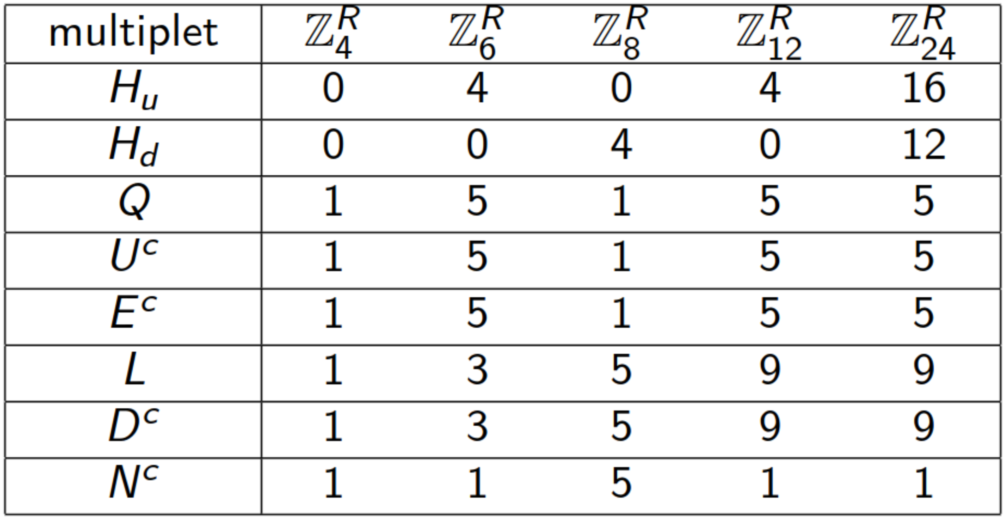
$$Z_{24}^R$$



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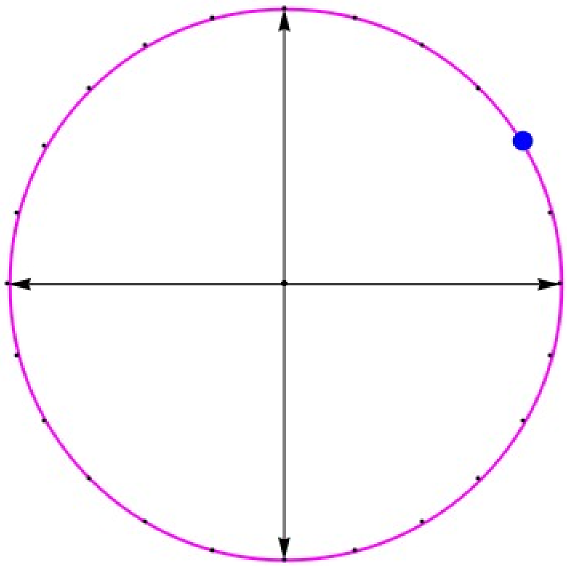

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MBGW MODEL DOES NOT SOLVE AQP WITH ANY OF THESE R SYMMETRIES

Lee et al. in arXiv : 1102.3595

Radiative PQ breaking Scenarios

MSY MODEL

$$W_{PQ} \ni \frac{1}{2} h_{ij} X N_i^c N_j^c + \frac{f}{m_P} X^3 Y + \frac{g_{MSY}}{m_P} XYH_u H_d$$

Murayama et. al. Phys. Lett. B 291 (1992) 418.

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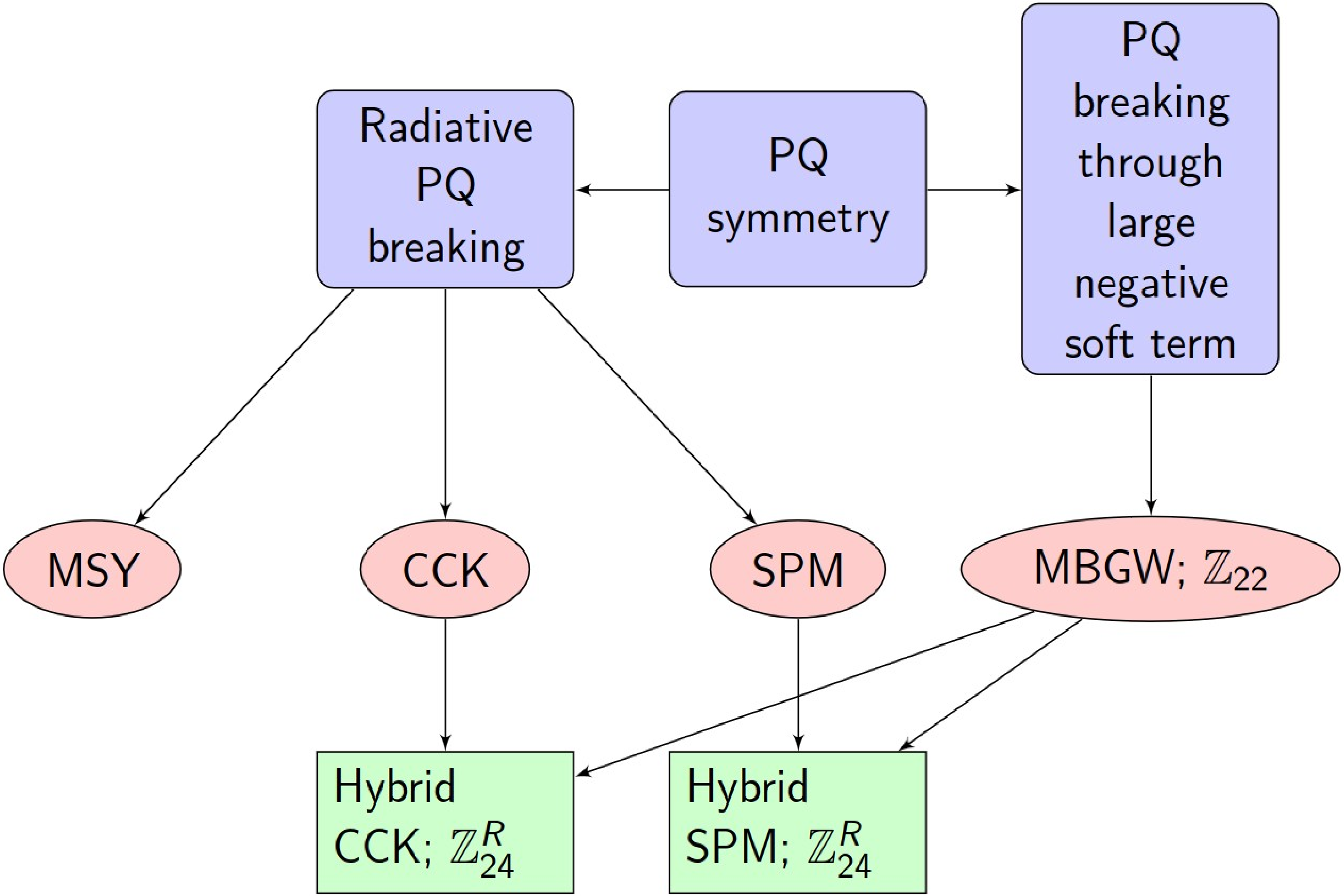
DOES NOT SOLVE AQP WITH ANY R SYMMETRIES MENTIONED EARLIER

Hybrid Model



PQ symmetry

Radiative PQ breaking

PQ breaking through large negative soft term

MSY

CCK

SPM

MBGW; $\mathbb{Z}_{22}$

Hybrid CCK; $\mathbb{Z}_{24}^{R}$

Hybrid SPM; $\mathbb{Z}_{24}^{R}$

H. Baer, V. Barger, and **D. S.**, Phys. Lett. B 790 (2019) 58-63

Hybrid CCK

$$W_{PQ} \ni \frac{f}{m_P} X^3 Y + \frac{\lambda_\mu}{m_P} X^2 H_u H_d$$

multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
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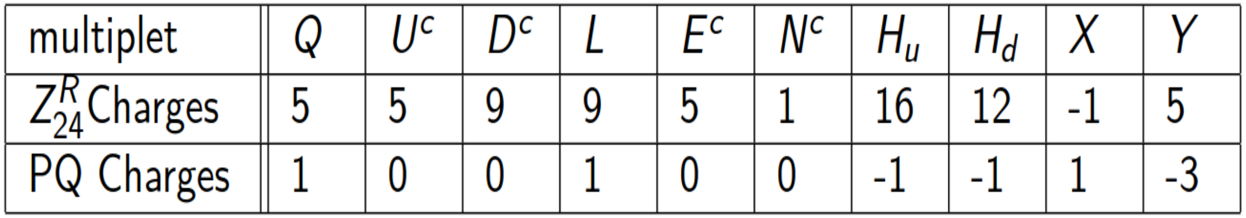

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Lowest order PQ-violating terms in W_{PQ} :

$$X^8 Y^2 / m_P^7 \, , \, X^4 Y^6 / m_P^7 \quad \text{and} \quad Y^{10} / m_P^7$$

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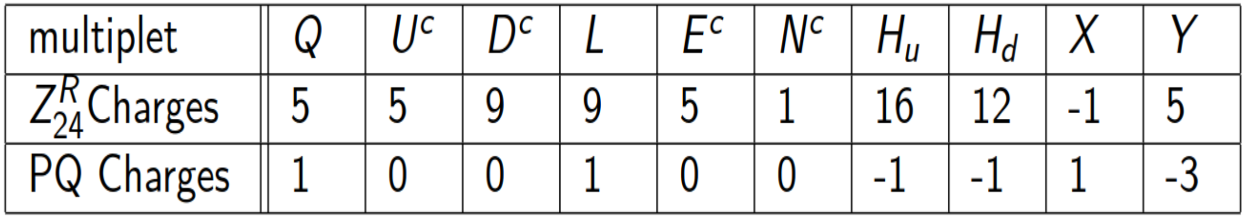

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$$\begin{aligned} W \ni\ & f_u Q H_u U^c + f_d Q H_d D^c + f_\ell L H_d E^c + f_\nu L H_u N^c \\ +\ & f X^3 Y/m_P + \lambda_\mu X^2 H_u H_d/m_P + M_N N^c N^c/2 \end{aligned}$$

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$$V = [f A_f \frac{\phi_X^3 \phi_Y}{m_P} + h.c.] + m_X^2|\phi_X|^2 + m_Y^2|\phi_Y|^2 + \frac{f^2}{m_P^2}[9\phi_X^4\phi_Y^2 + \phi_X^6]$$

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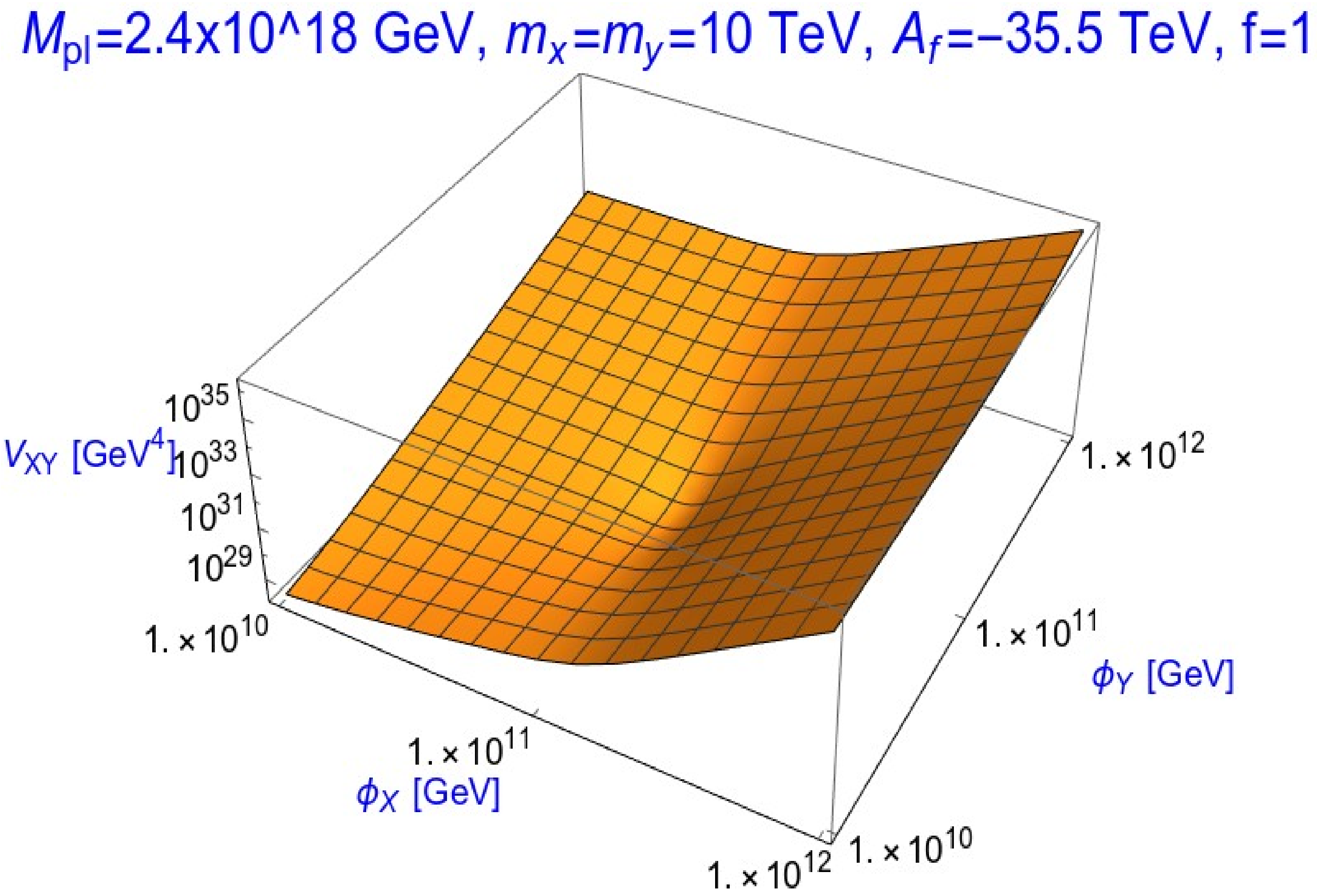

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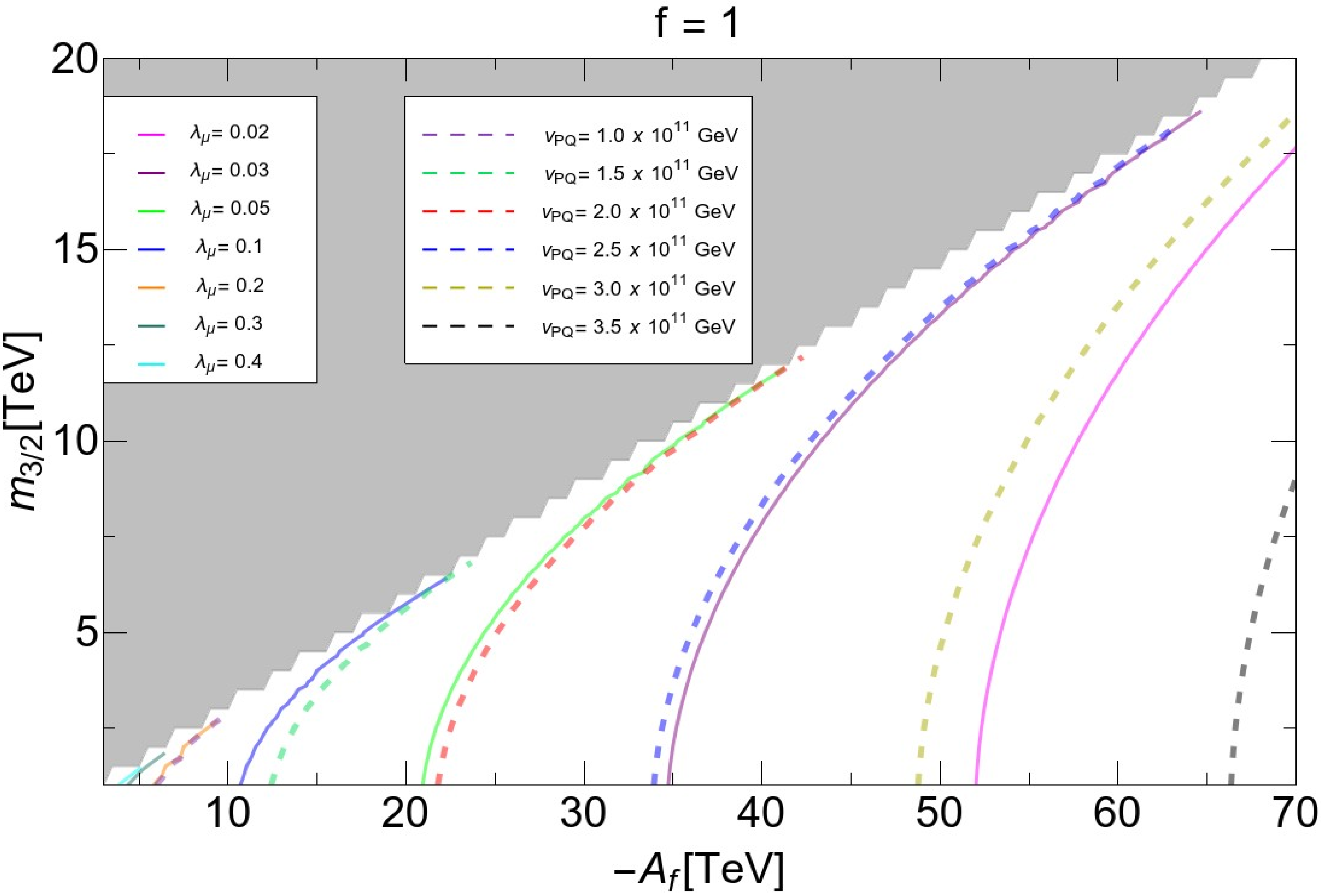

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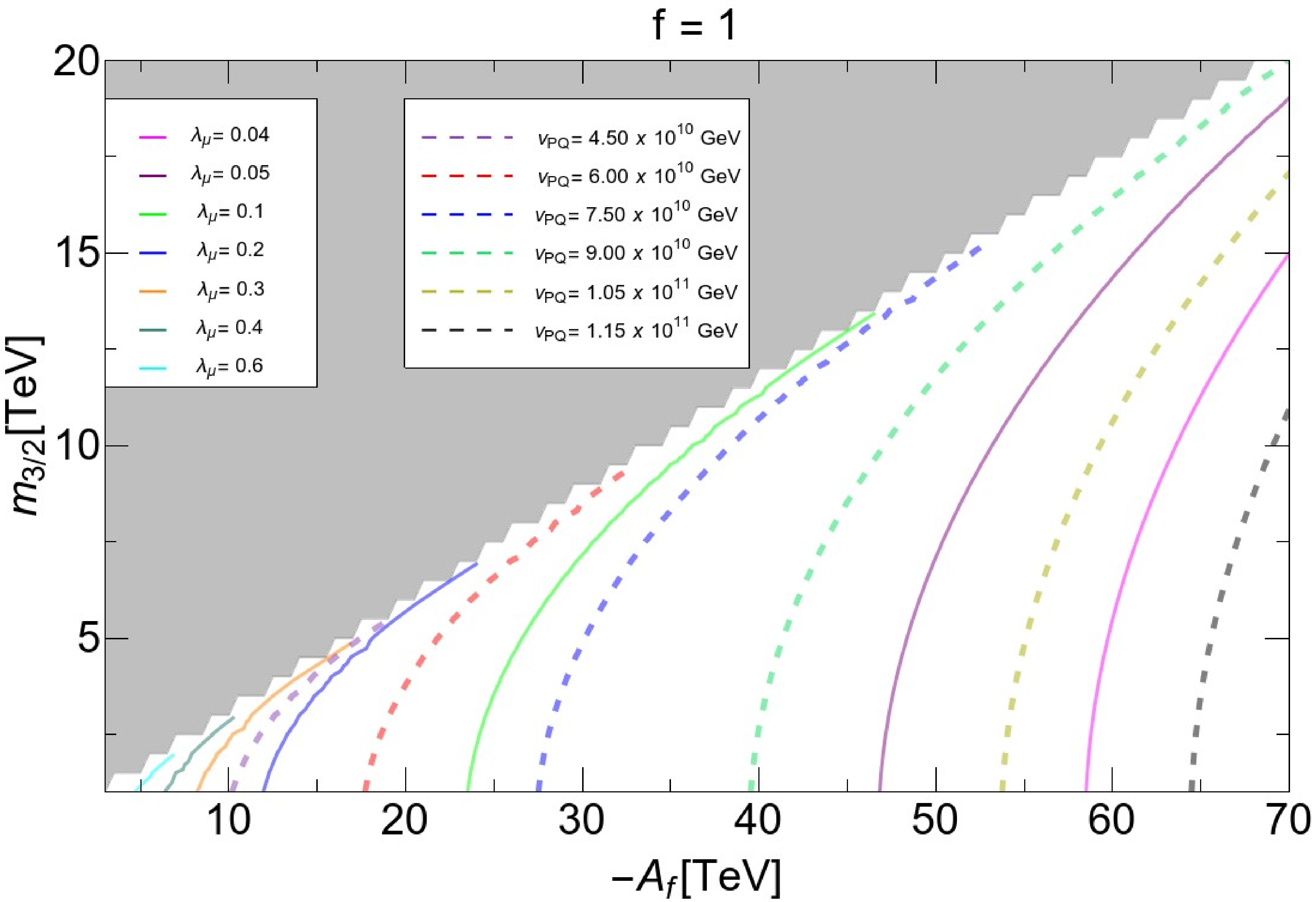
Hybrid SPM



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Kill Three Birds with One Stone

$\mu_{eff} \sim m_{weak}$

Solves the Axion-quality Problem because no terms with suppression less than $1/m_P^8$ are allowed in the scalar potential

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Added Advantages

~~R-Parity Violating Operators~~

~~Dim-5 Proton Decay Operators~~

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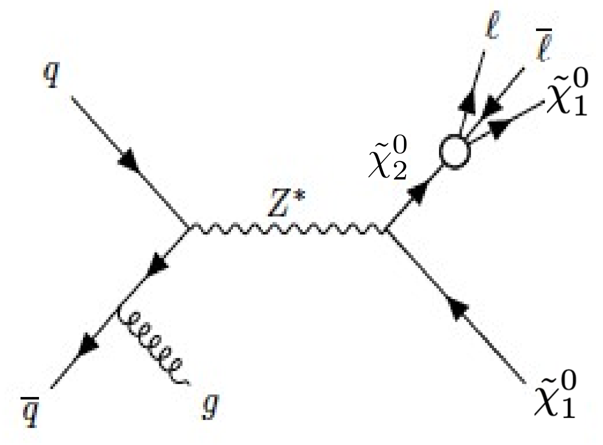
Higgsino Pair-Production at LHC



H. Baer, V. Barger, **D. S.** and Xerxes Tata Phys. Rev. D 105 (2022) 9, 095017

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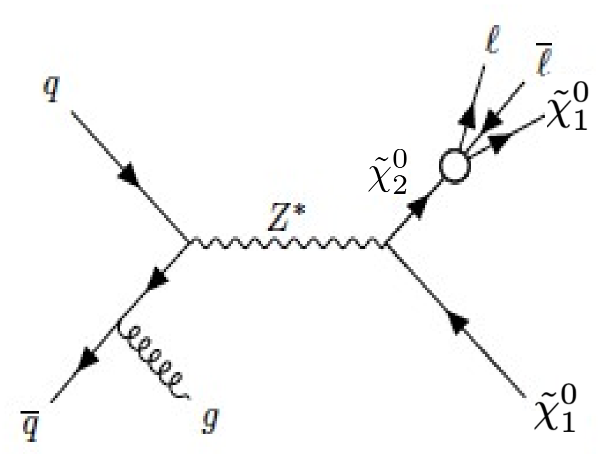


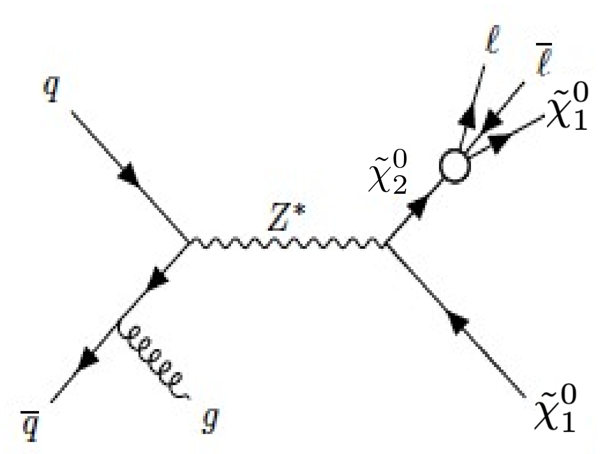
SM Backgrounds: $\tau\bar{\tau}j$, $t\bar{t}$, WWj, $W\ell\bar{\ell}j$, $Z\ell\bar{\ell}j$

BENCHMARK POINTS

- BM1 (NUHM2): $m_{\tilde{\chi}_2^0} = 157.6$ GeV, $m_{\tilde{\chi}_1^0} = 145.4$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 12.2$ GeV, $\Delta_{EW} = 13.9$
- BM2 (NUHM2):$m_{\tilde{\chi}_2^0} = 310.1$ GeV, $m_{\tilde{\chi}_1^0} = 293.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 16.4$ GeV, $\Delta_{EW} = 21.7$
- BM3 (GMM'): $m_{\tilde{\chi}_2^0} = 207.0$ GeV, $m_{\tilde{\chi}_1^0} = 202.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 4.3$ GeV, $\Delta_{EW} = 26.0$

H. Baer, V. Barger, **D. S.** and Xerxes Tata Phys. Rev. D 105 (2022) 9, 095017

Higgsino Pair-Production at LHC



BASIC CUTS

$p_T(j) >$ 80 GeV, $p_T(\ell) >$ 1 GeV, $\Delta R(\ell\bar{\ell}) >$ 0.01,

$m(\ell\bar{\ell}) >$ 1 GeV for the backgrounds $\gamma^*, Z^* \to \ell\bar{\ell}$

SM Backgrounds: $\tau\bar{\tau}j$, $t\bar{t}$, WWj, $W\ell\bar{\ell}j$, $Z\ell\bar{\ell}j$

BENCHMARK POINTS

- BM1 (NUHM2): $m_{\tilde{\chi}_2^0} = 157.6$ GeV, $m_{\tilde{\chi}_1^0} = 145.4$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 12.2$ GeV, $\Delta_{EW} = 13.9$
- BM2 (NUHM2):$m_{\tilde{\chi}_2^0} = 310.1$ GeV, $m_{\tilde{\chi}_1^0} = 293.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 16.4$ GeV, $\Delta_{EW} = 21.7$
- BM3 (GMM'): $m_{\tilde{\chi}_2^0} = 207.0$ GeV, $m_{\tilde{\chi}_1^0} = 202.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 4.3$ GeV, $\Delta_{EW} = 26.0$

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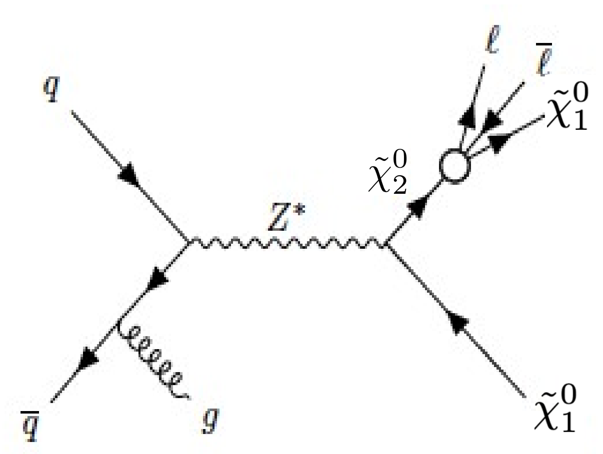
Higgsino Pair-Production at LHC



BASIC CUTS

$p_T(j) >$ 80 GeV, $p_T(\ell) >$ 1 GeV, $\Delta R(\ell\bar{\ell}) >$ 0.01,

$m(\ell\bar{\ell}) >$ 1 GeV for the backgrounds $\gamma^*, Z^* \to \ell\bar{\ell}$

SM Backgrounds: $\tau\bar{\tau}j$, $t\bar{t}$, WWj, $W\ell\bar{\ell}j$, $Z\ell\bar{\ell}j$

BENCHMARK POINTS

- BM1 (NUHM2): $m_{\tilde{\chi}_2^0} = 157.6$ GeV, $m_{\tilde{\chi}_1^0} = 145.4$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 12.2$ GeV, $\Delta_{EW} = 13.9$
- BM2 (NUHM2):$m_{\tilde{\chi}_2^0} = 310.1$ GeV, $m_{\tilde{\chi}_1^0} = 293.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 16.4$ GeV, $\Delta_{EW} = 21.7$
- BM3 (GMM'): $m_{\tilde{\chi}_2^0} = 207.0$ GeV, $m_{\tilde{\chi}_1^0} = 202.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 4.3$ GeV, $\Delta_{EW} = 26.0$

C1-Cuts

- require two OS/SF isolated leptons with $p_T(\ell) > 5$ GeV, $|\eta(\ell)| < 2.5$,
- $n(jets) \geq 1$ with $p_T(j1) > 100$ GeV for identified calorimeter jets,
- $\Delta R(\ell\bar{\ell}) > 0.05$ (for $\ell = e$ or μ),
- $\not{E}_T > 100$ GeV and
- $n(b - jet) = 0$.

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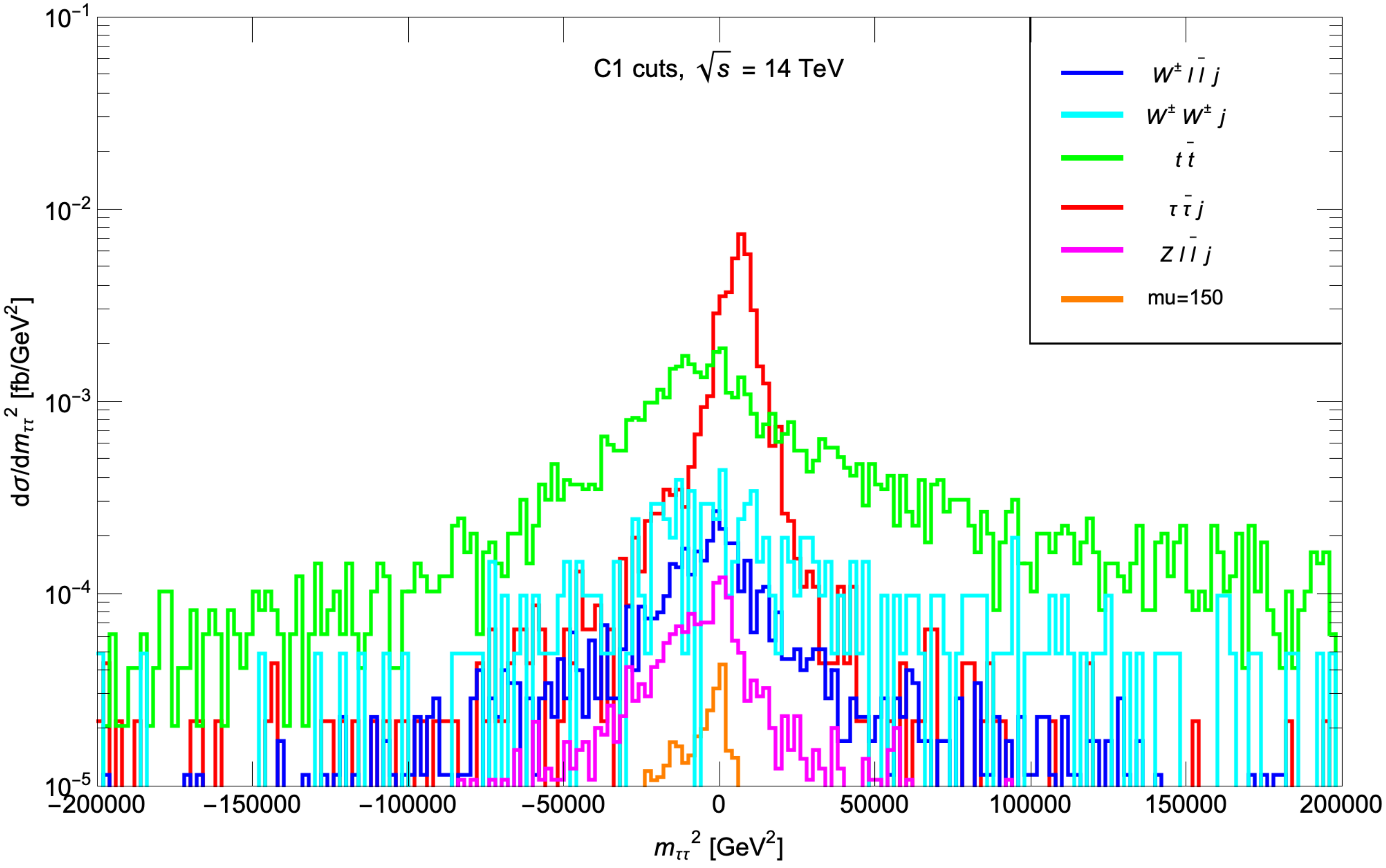
Cuts

$$m^2_{\tau\tau} = (1+\xi_1)(1+\xi_2)m^2_{\ell\ell}$$

$$-\sum_{jets}\vec{p}_T(j) = (1+\xi_1)\vec{p}_T(\ell_1) + (1+\xi_2)\vec{p}_T(\ell_2)$$



$$\boxed{m^2_{\tau\tau} < 0}$$

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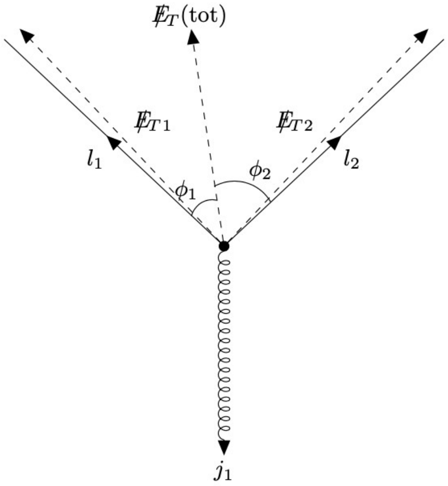
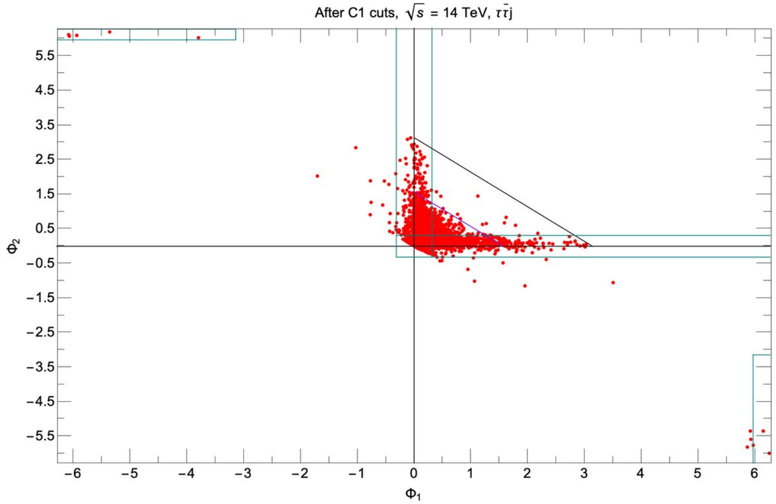
Angle Cuts

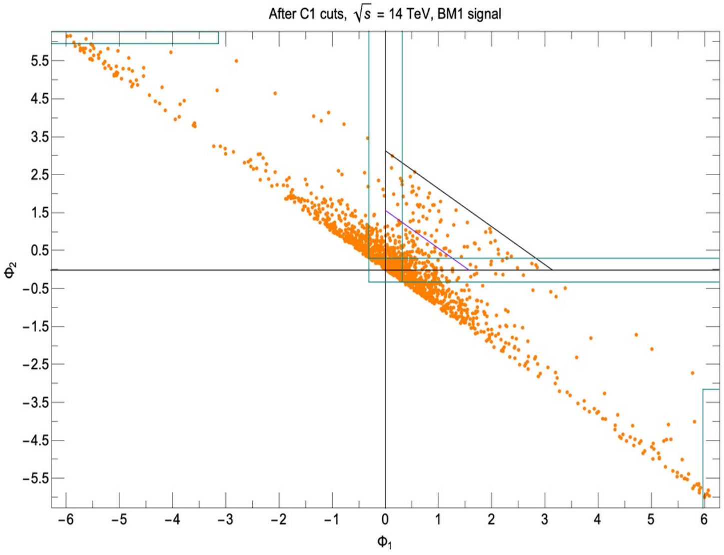


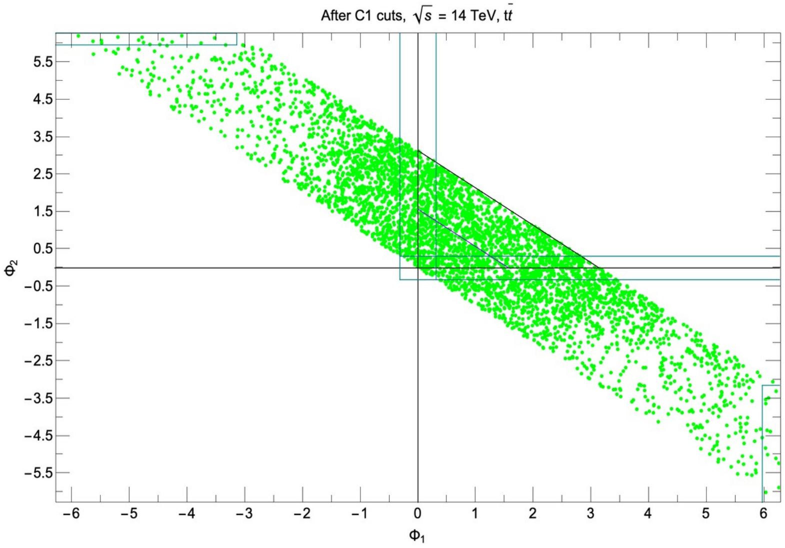


Veto: $\varphi_1, \varphi_2 > 0$, $\varphi_1 + \varphi_2 < \pi/2$

Veto: $|\varphi_{1,2}| < \pi/10$

Veto: Corner strips





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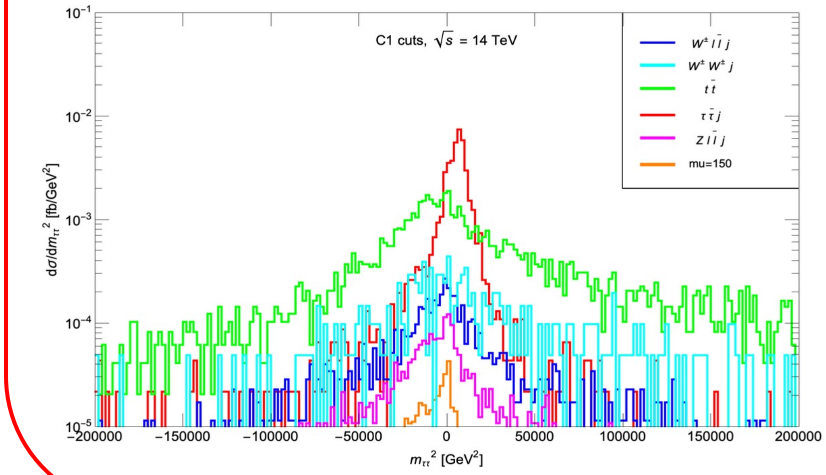
Cuts

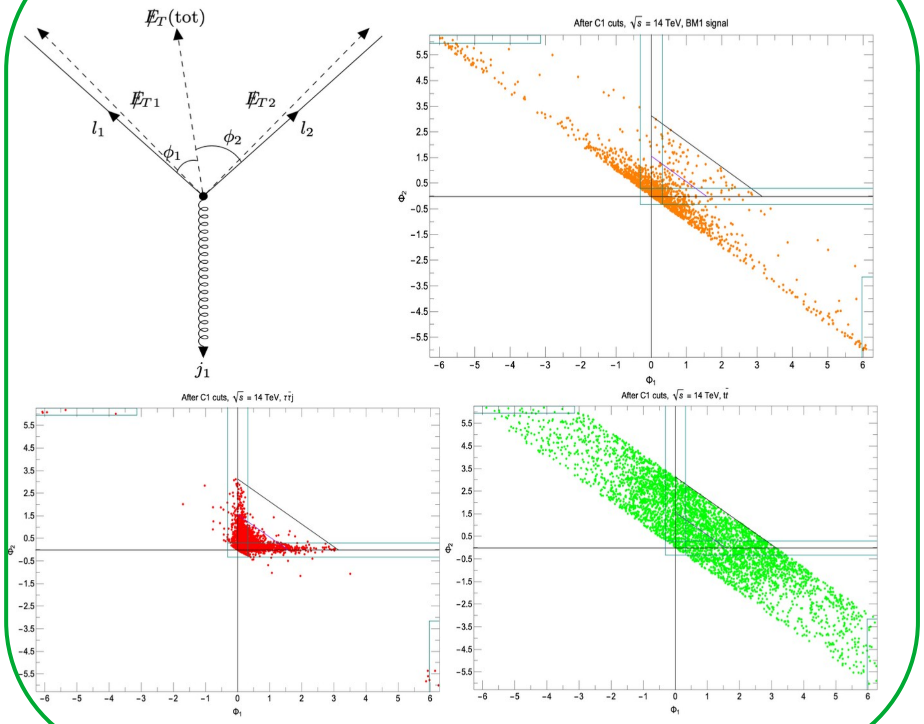
$m^2_{\tau\tau}$

$$m^2_{\tau\tau} = (1+\xi_1)(1+\xi_2)m^2_{\ell\ell}$$

$$-\sum_{jets}\vec{p}_T(j) = (1+\xi_1)\vec{p}_T(\ell_1) + (1+\xi_2)\vec{p}_T(\ell_2)$$



Angle Cuts



cuts/process	$BM1$	$BM2$	$BM3$ GMM'	$\tau\bar{\tau}j$	$t\bar{t}$	WWj	$W\ell\bar{\ell}j$	$Z\ell\bar{\ell}j$
BC	83.1	9.3	31.3	43800.0	41400	9860.0	1150.0	311
$C1$	1.2	0.19	0.07	94.2	179	35.9	14.7	5.9
$C1 + m^2_{\tau\tau} < 0$	0.92	0.13	0.043	23.1	75.6	12.8	7.7	3.2
$C1 + angle$	0.68	0.12	0.04	1.8	130	22	11.0	4.9

Table: Cross sections (in fb) for signal benchmark points and the various SM backgrounds listed in the text after various cuts.

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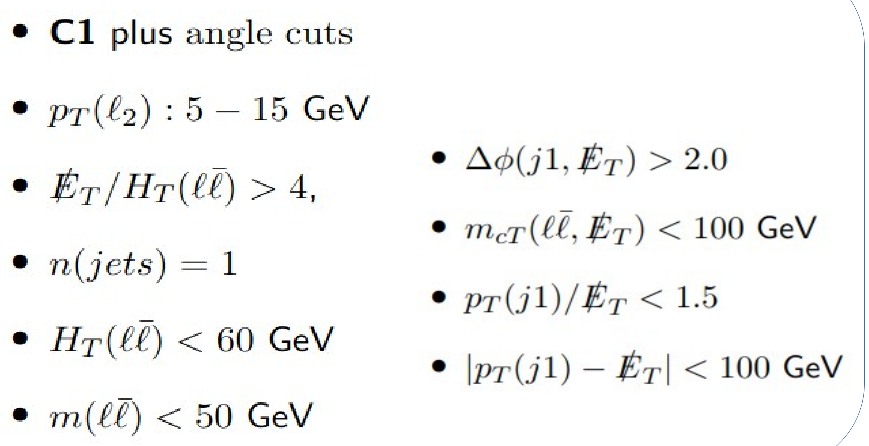
Cuts

C3-Cuts



- **C1** plus angle cuts
- $p_T(\ell_2) : 5 - 15$ GeV
- $\not{E}_T/H_T(\ell\bar{\ell}) > 4,$
- $n(jets) = 1$
- $H_T(\ell\bar{\ell}) < 60$ GeV
- $m(\ell\bar{\ell}) < 50$ GeV
- $\Delta\phi(j1, \not{E}_T) > 2.0$
- $m_{cT}(\ell\bar{\ell}, \not{E}_T) < 100$ GeV
- $p_T(j1)/\not{E}_T < 1.5$
- $|p_T(j1) - \not{E}_T| < 100$ GeV

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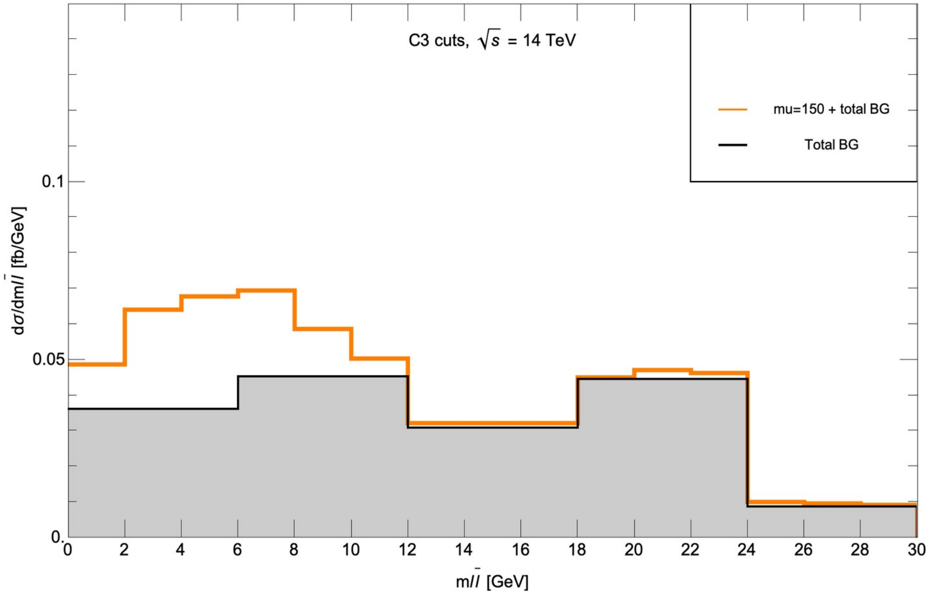
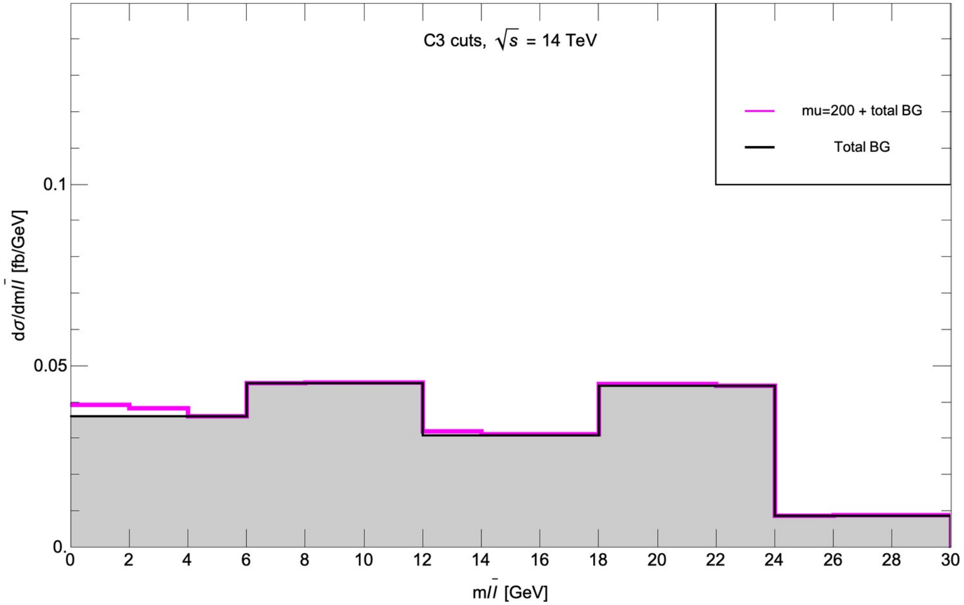
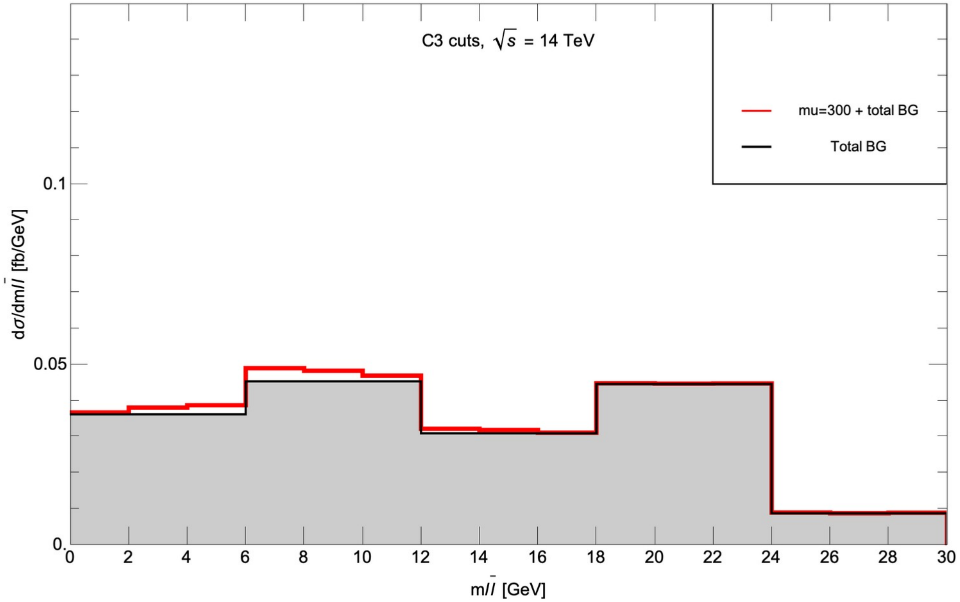
Cuts

C3-Cuts

- **C1** plus angle cuts
- $p_T(\ell_2) : 5 - 15$ GeV
- $\not{E}_T / H_T(\ell\bar{\ell}) > 4,$
- $n(jets) = 1$
- $H_T(\ell\bar{\ell}) < 60$ GeV
- $m(\ell\bar{\ell}) < 50$ GeV
- $\Delta\phi(j1, \not{E}_T) > 2.0$
- $m_{cT}(\ell\bar{\ell}, \not{E}_T) < 100$ GeV
- $p_T(j1)/\not{E}_T < 1.5$
- $|p_T(j1) - \not{E}_T| < 100$ GeV







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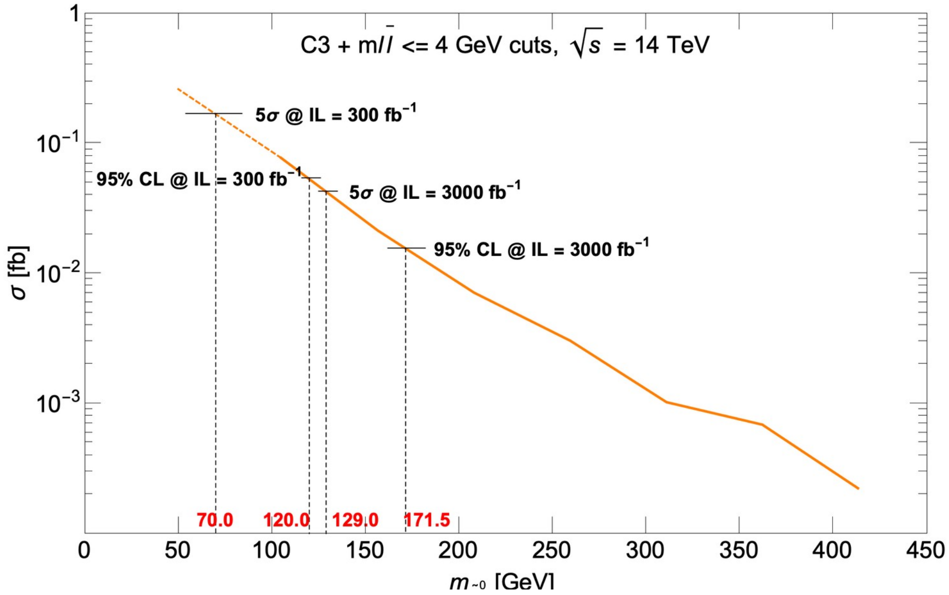
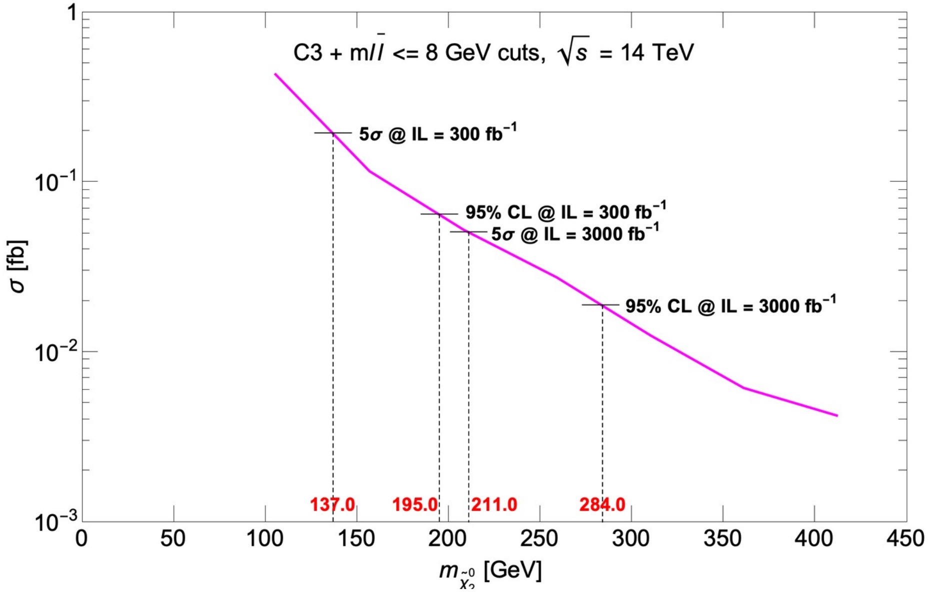
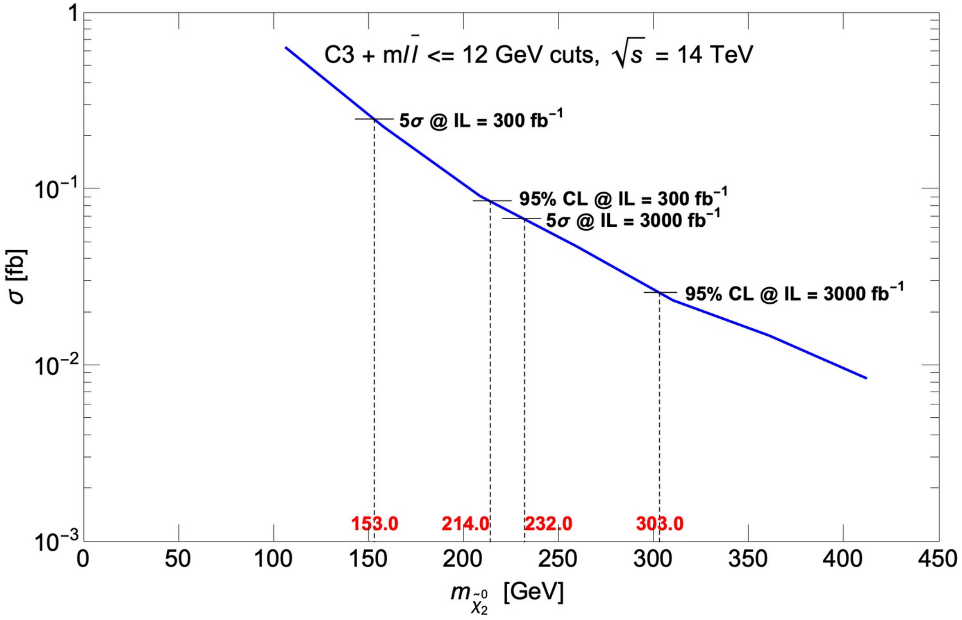
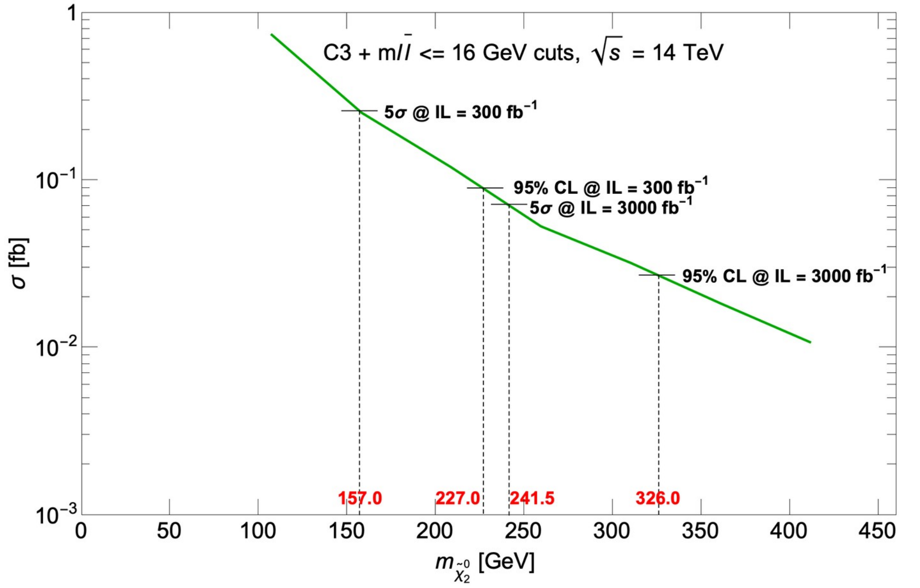
Mass Reach









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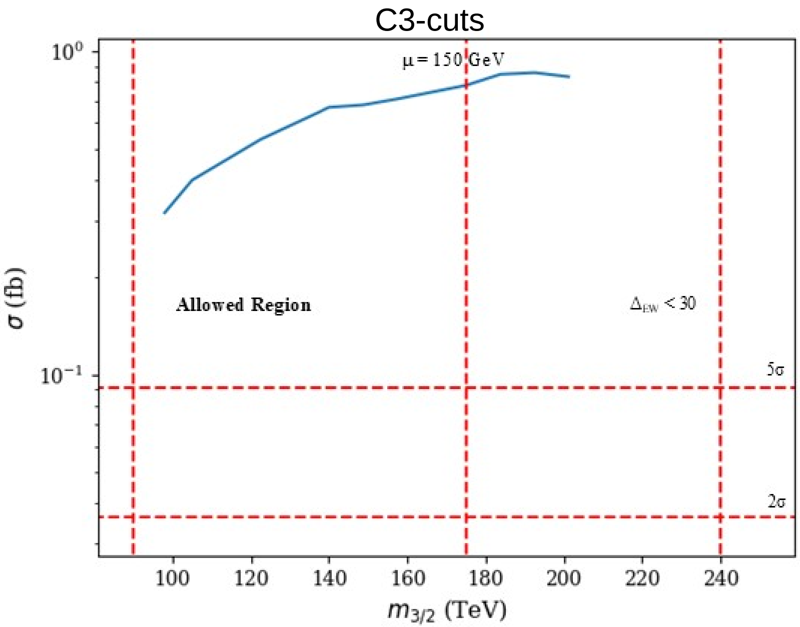
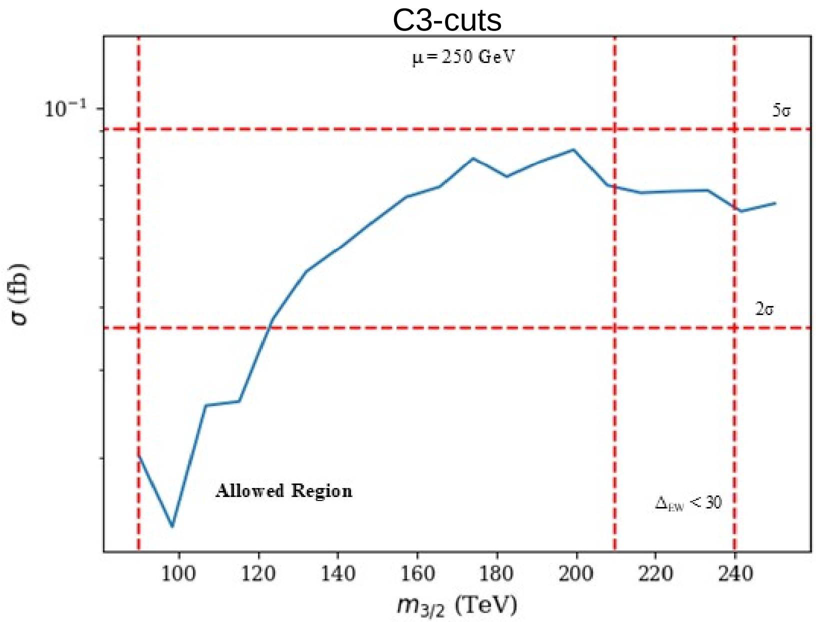
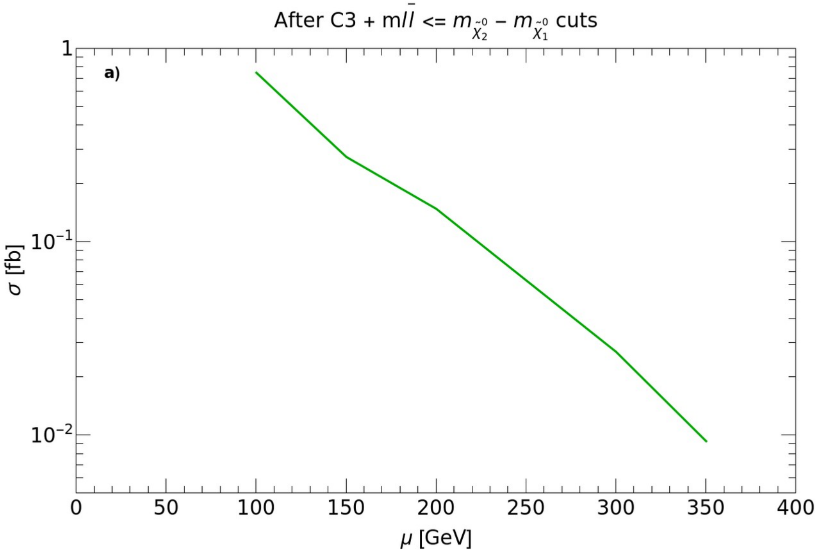
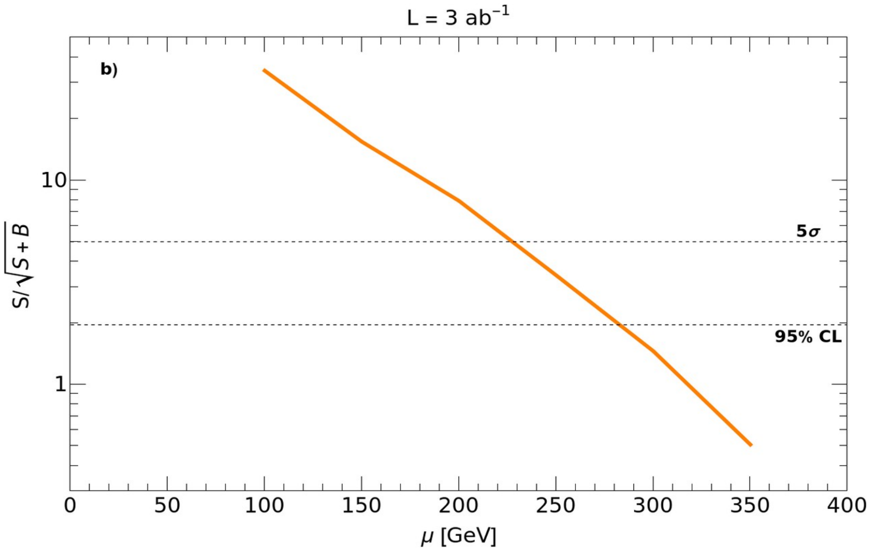
Mass Reach (nAMSB model)

Model Line: $m_0\left(3\right)=m_{3/2}/35, m_0\left(1,2\right)=2m_0\left(3\right), A_0=1.2m_0\left(3\right), tan\beta=10, m_A=2TeV$


C3-cuts

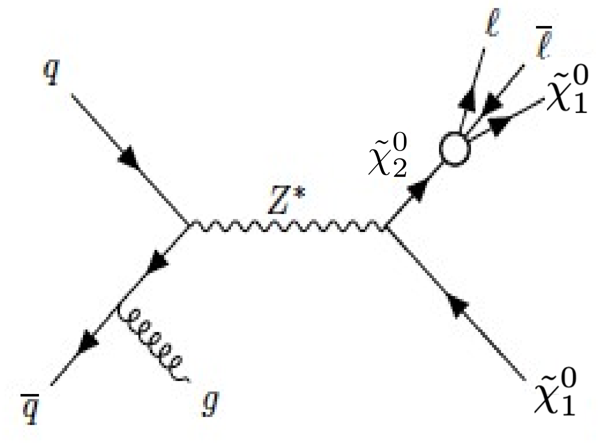

C3-cuts

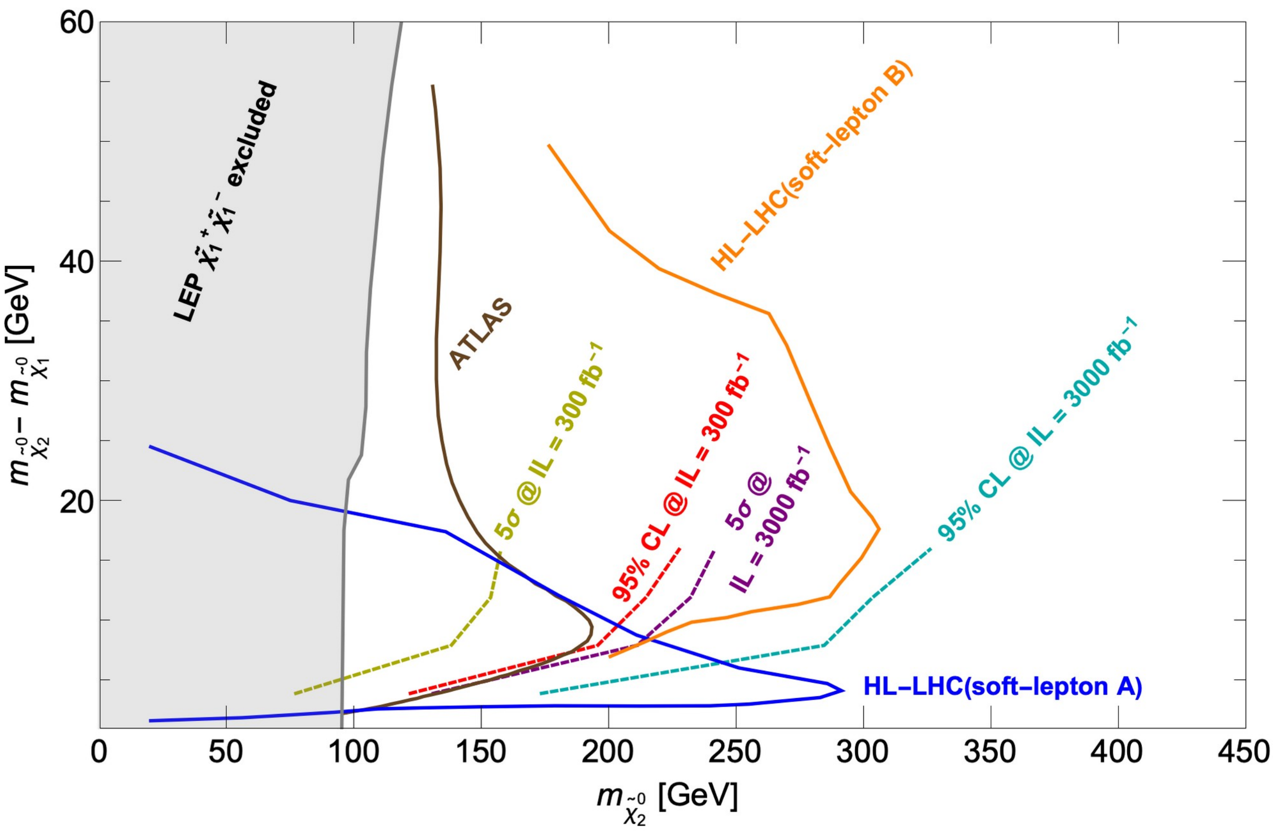

After C3 + $m l\bar{l} <= m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ cuts


L = 3 ab^{-1}

H. Baer, V. Barger, J. Bolich, J. Dutta, **D.S.**, ArXiv: 2408.03276 [hep-ph]

Higgsino Pair-Production at LHC



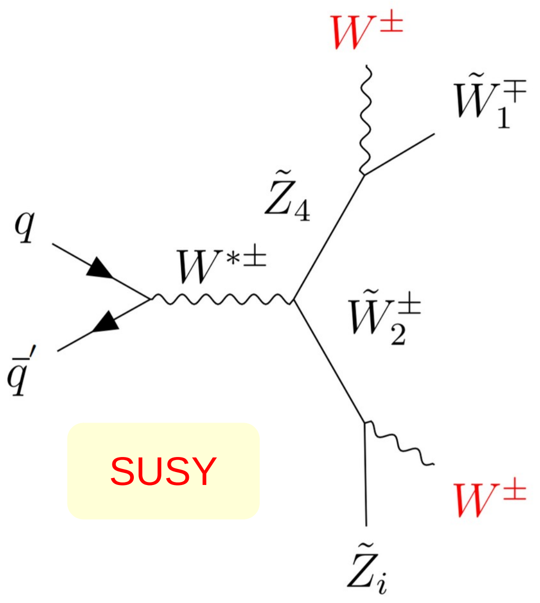


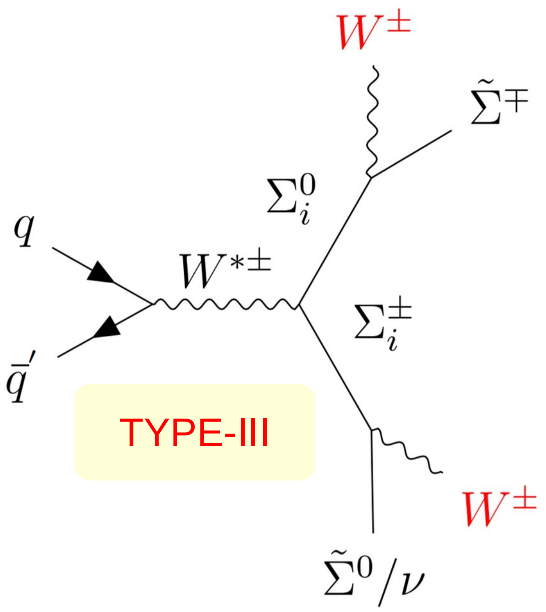
Natural SUSY: Higgsinos at $\sqrt{s}$ = 14 TeV and $\mathcal{L}$ = 3 ab^{-1}

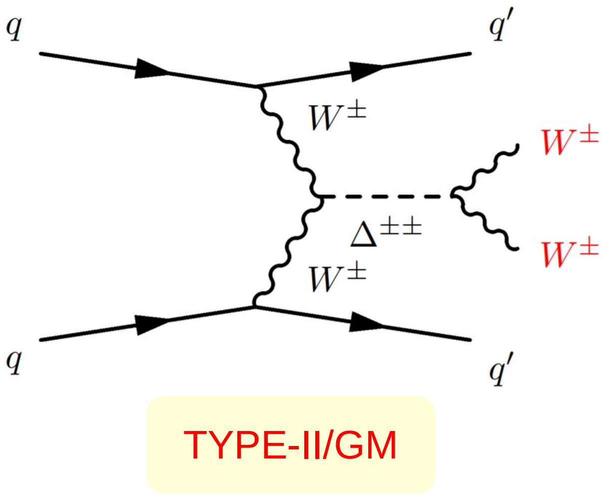
Snowmass report in 2021

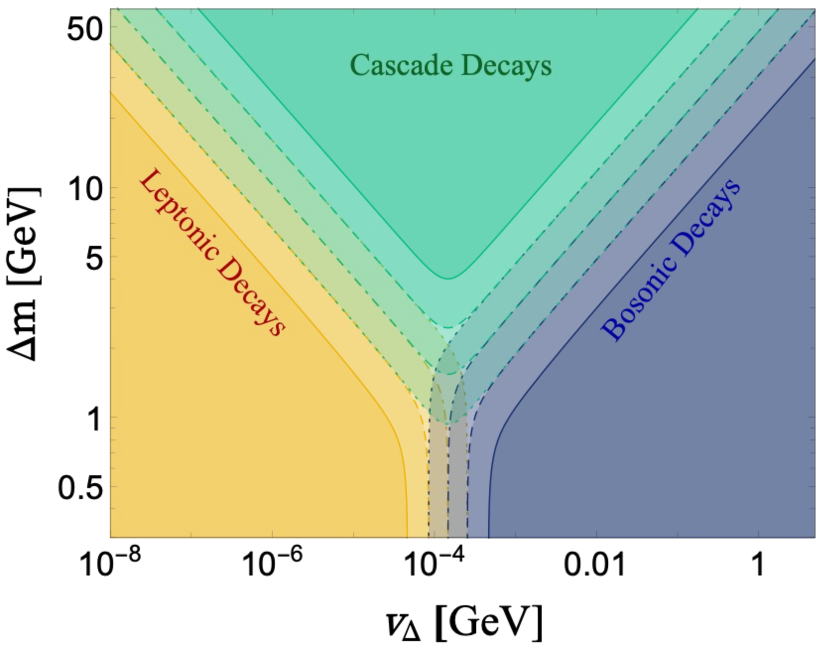
H. Baer, V. Barger, **D. S.** and Xerxes Tata Phys. Rev. D 105 (2022) 9, 095017

Same-Sign Diboson + $\not{E}_T$









$W^\pm W^\pm + \not{E}_T$

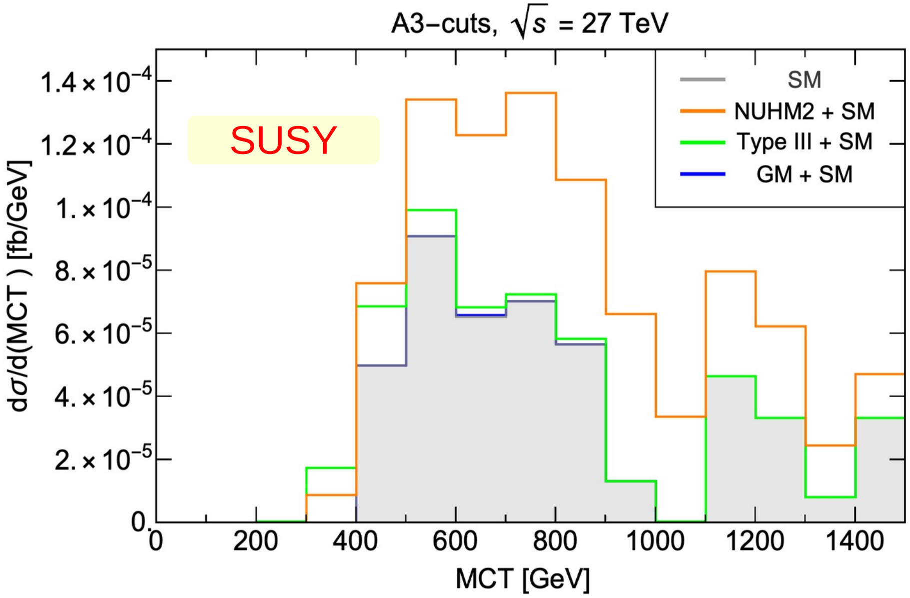
Natural SUSY: Wino pair production

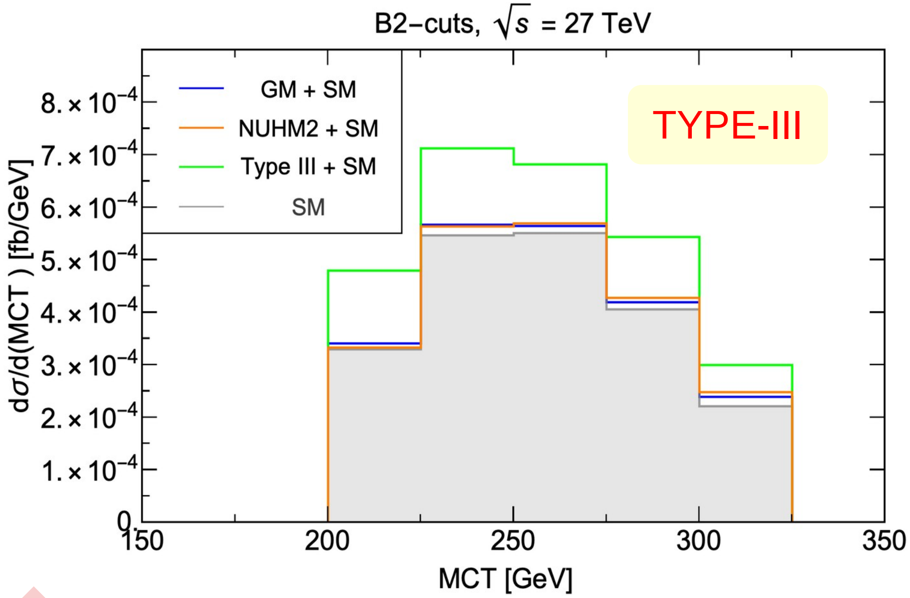
Type - III Seesaw model: Associated production of 2nd/3rd generation $\Sigma^\pm$ and Σ^0

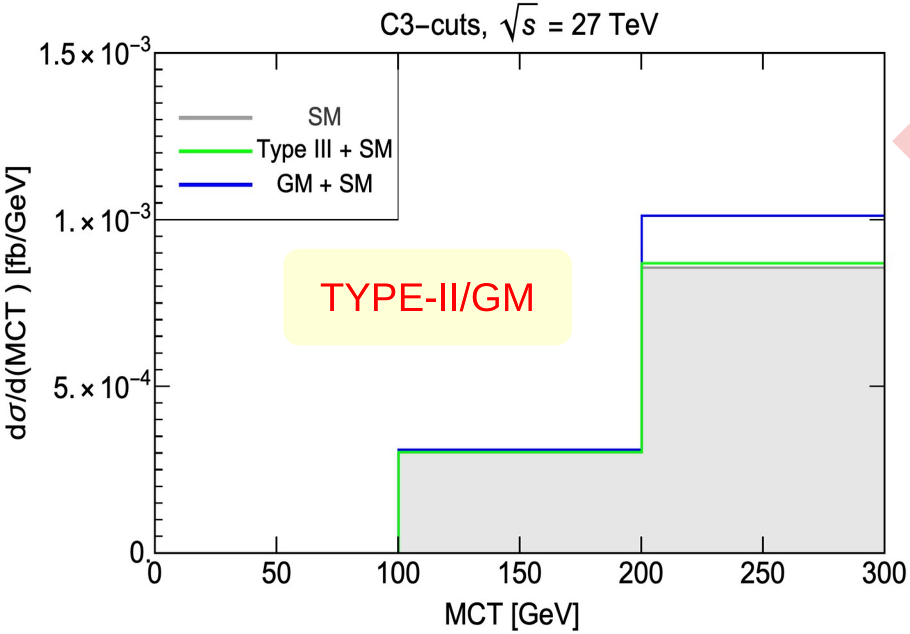
Type - II Seesaw model/ Georgi-Machacek model: Production of $\Delta^{\pm\pm}$ via vector boson fusion

C.W. Chiang, S. Jana**, D. S**. Phys. Rev. D 105 (2022) 5, 055014

Same-Sign Diboson + $\not{E}_T$







$W^{\pm}W^{\pm} + \not{E}_T$

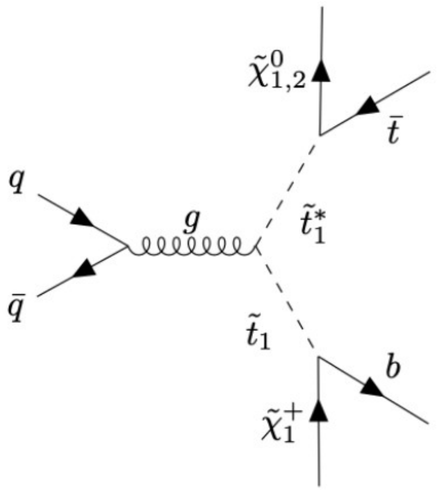
Natural SUSY: Winos at √s = 27 TeV and $\mathcal{L}$ = 3 ab^{-1}

Type - III Seesaw model: Lightest exotic fermions ($\Sigma^{\pm,0}$) at √s =27 TeV and $\mathcal{L}$ = 15 ab^{-1}

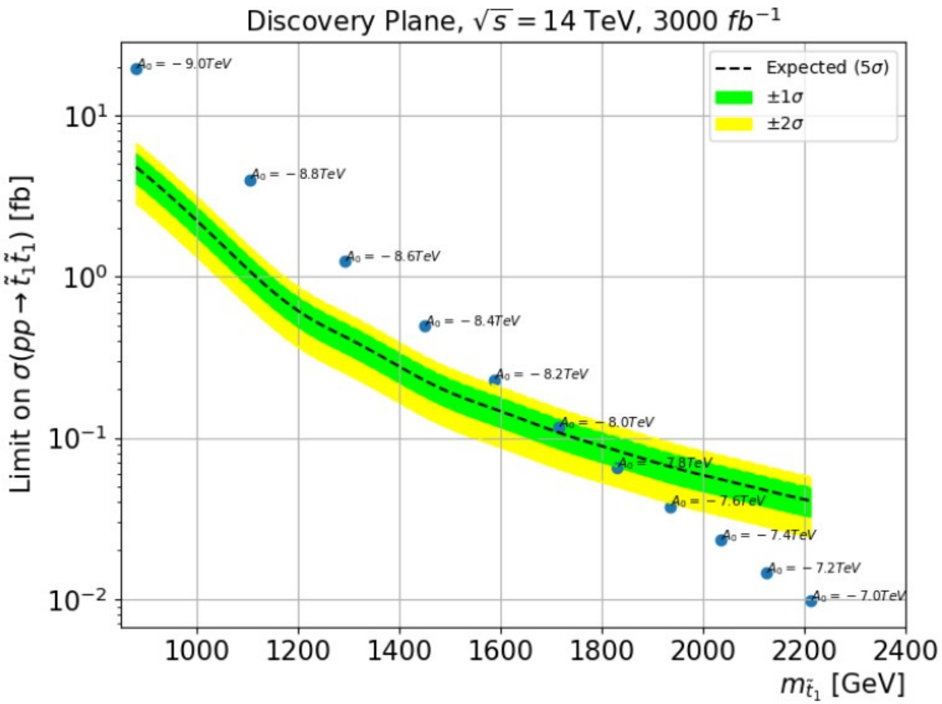
Type - II Seesaw model/ Georgi-Machacek model: $\Delta^{\pm\pm}$ at √s =27 TeV and $\mathcal{L}$ = 15 ab^{-1}

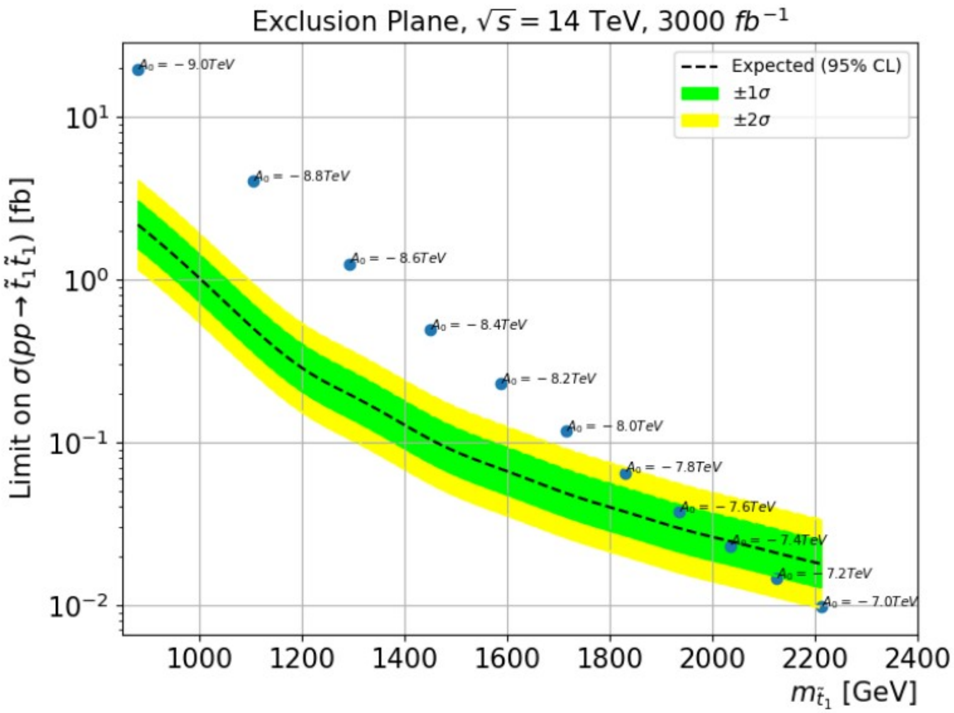
C.W. Chiang, S. Jana, **D. S**. Phys. Rev. D 105 (2022) 5, 055014

Top squark searches



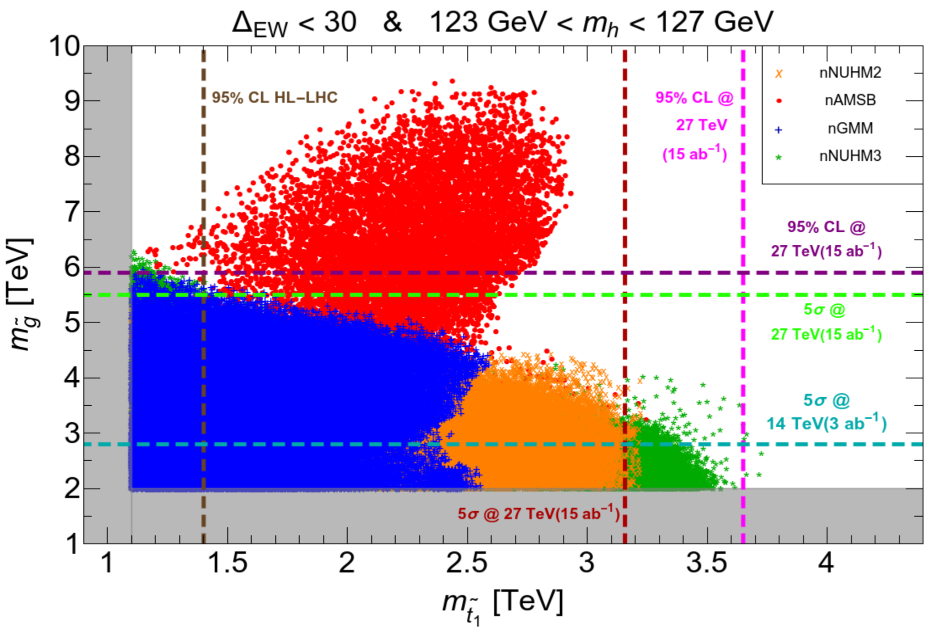
Model Line: $m_0 = 5$ TeV, $m_{1/2} = 1.2$ TeV, $tan\,\beta = 10$,
$\mu = 250$ GeV, $m_A = 2$ TeV,
$A_0 =$ -7 TeV to -9 TeV

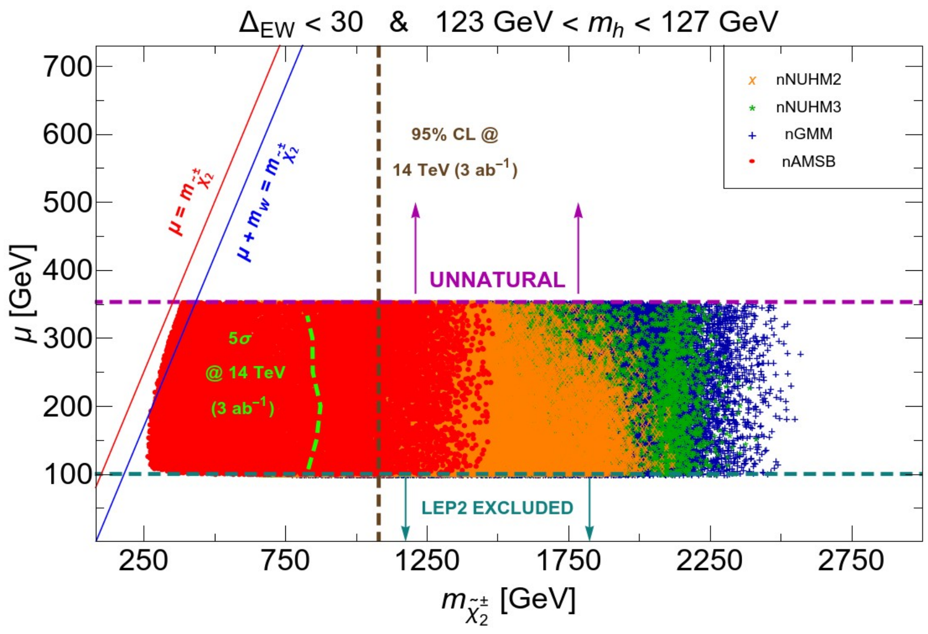


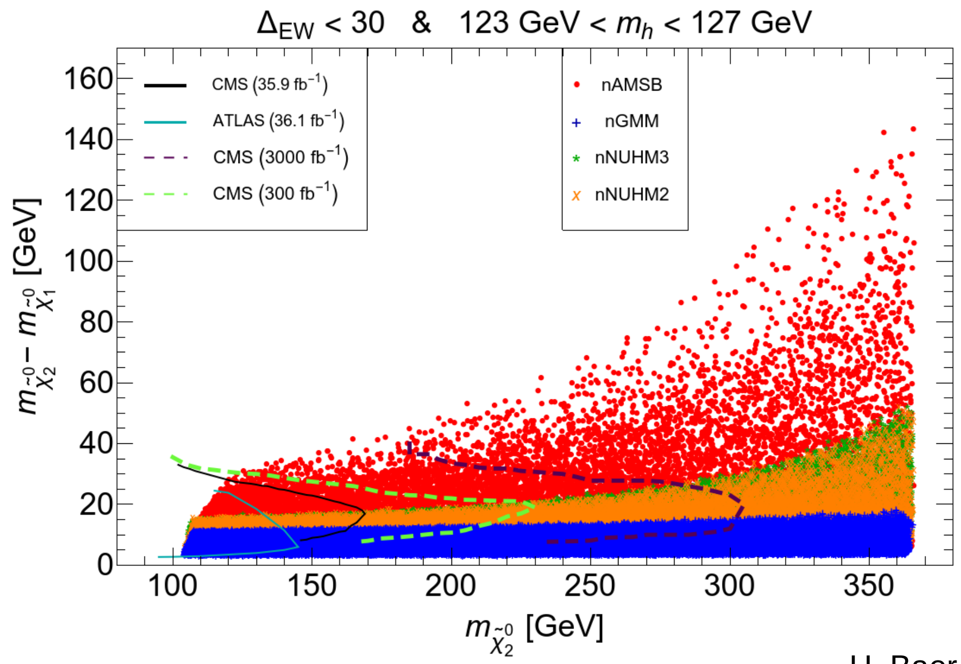


H. Baer, V. Barger, J. Dutta, **D.S.**, K. Zhang, Phys.Rev.D 108 (2023) 7

LHC Confronts SUSY







Exploration of Parameter Space of Natural Supersymmetric models

↓

Higgsinos at HL-LHC

Gluinos and top squarks and winos at HE-LHC

European strategy update report in 2018

H. Baer, V. Barger, J.S. Gainer, **D. S.**, H. Serce Phys. Rev. D 98 (2018) 7, 075010

Phenomenology

Natural SUSY: Higgsinos at $\sqrt{s}$ = 14 TeV and $\mathcal{L}$ = 3 ab^{-1}

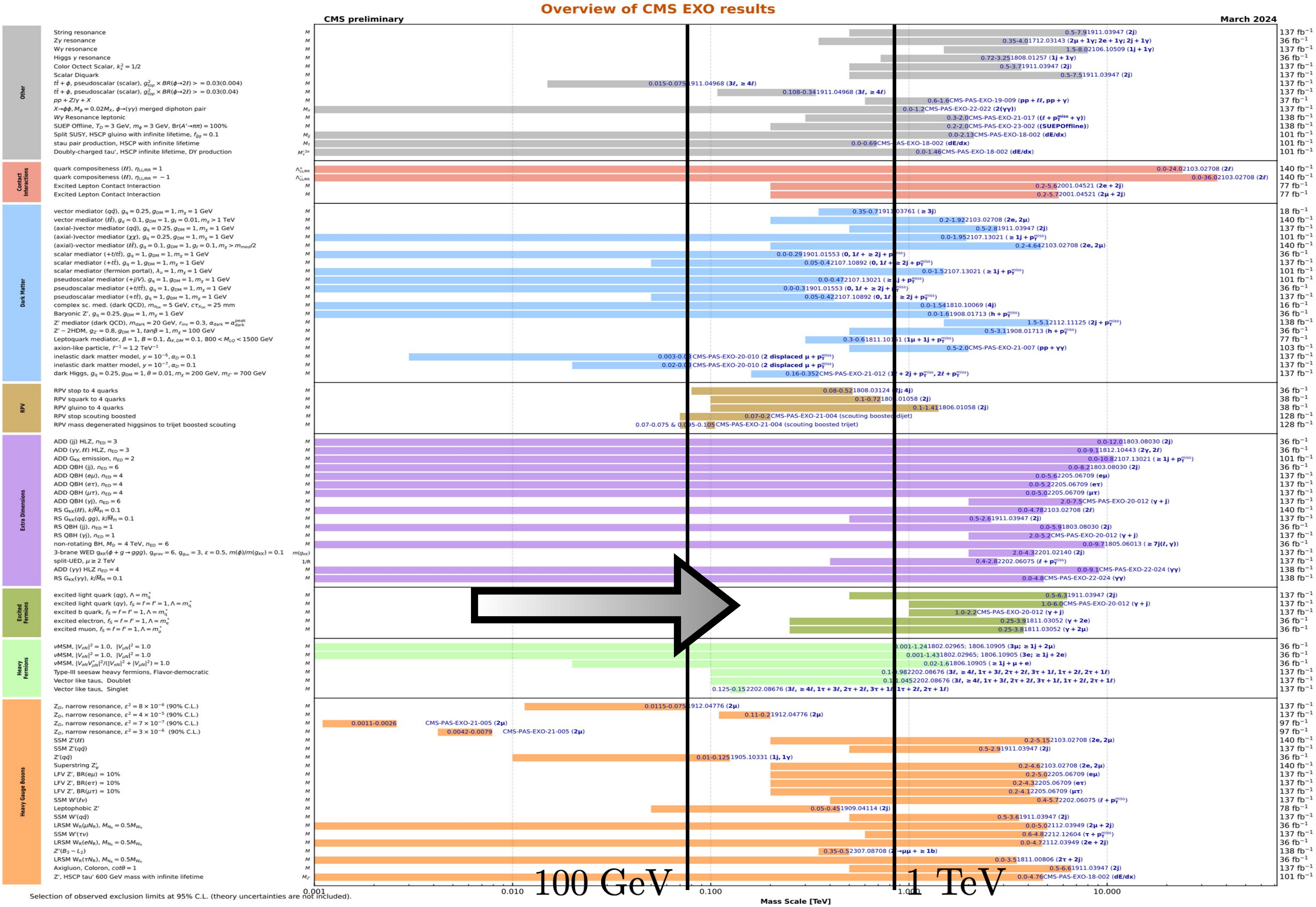
Natural SUSY: Winos at $\sqrt{s}$= 27 TeV and $\mathcal{L}$ = 3 ab^{-1}

Natural SUSY: Stop and Gluinos at $\sqrt{s}$ = 27 TeV and L = 15 ab^{-1}

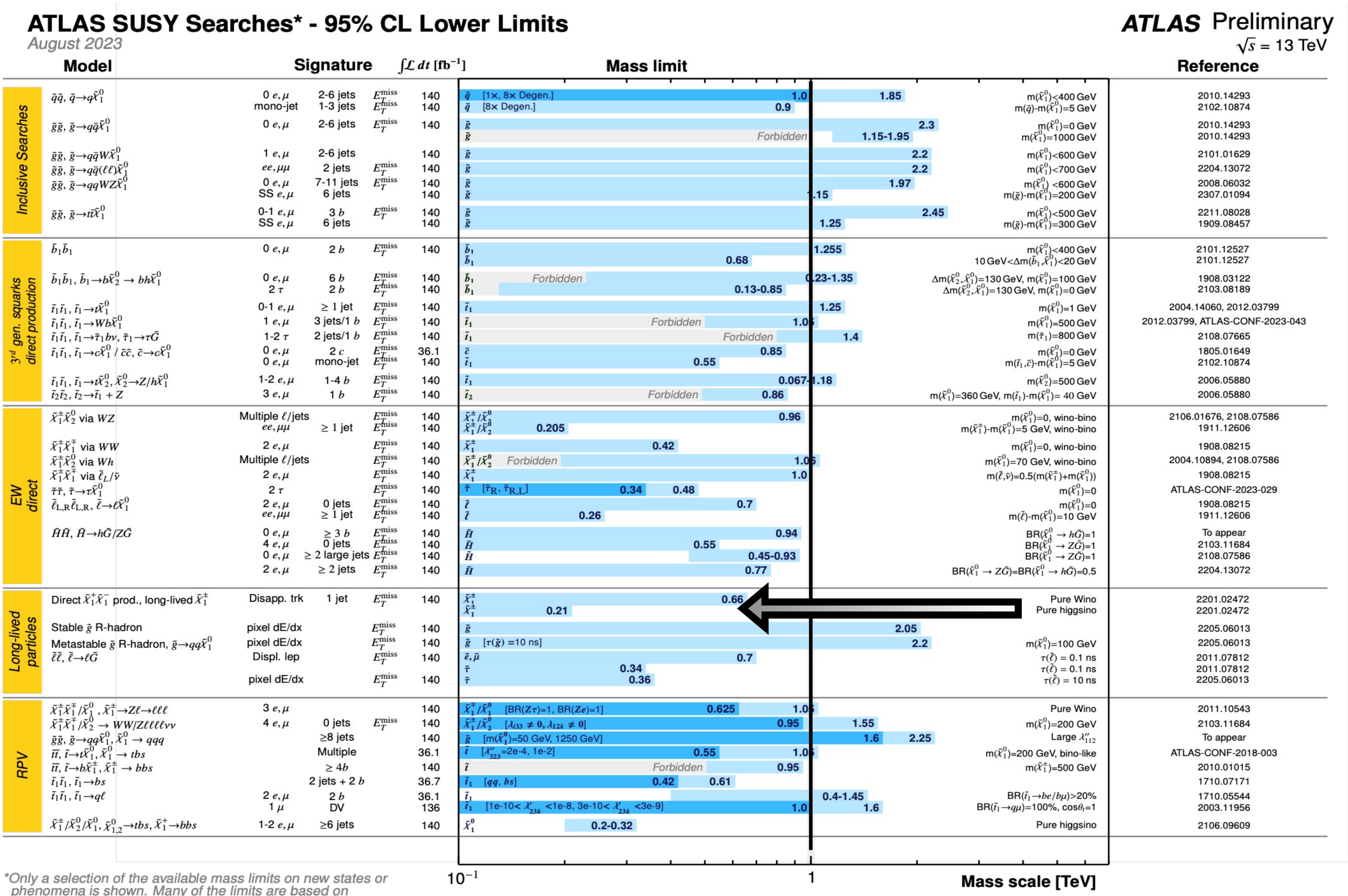
Type - III Seesaw model: Lightest exotic fermions ($\Sigma^{\pm,0}$) at $\sqrt{s}$ =27 TeV and $\mathcal{L}$ = 15 ab^{-1}

Type - II Seesaw model/ Georgi-Machacek model: $\Delta^{\pm\pm}$ at $\sqrt{s}$ =27 TeV and $\mathcal{L}$ = 15 ab^{-1}

Has LHC excluded Light new Physics?

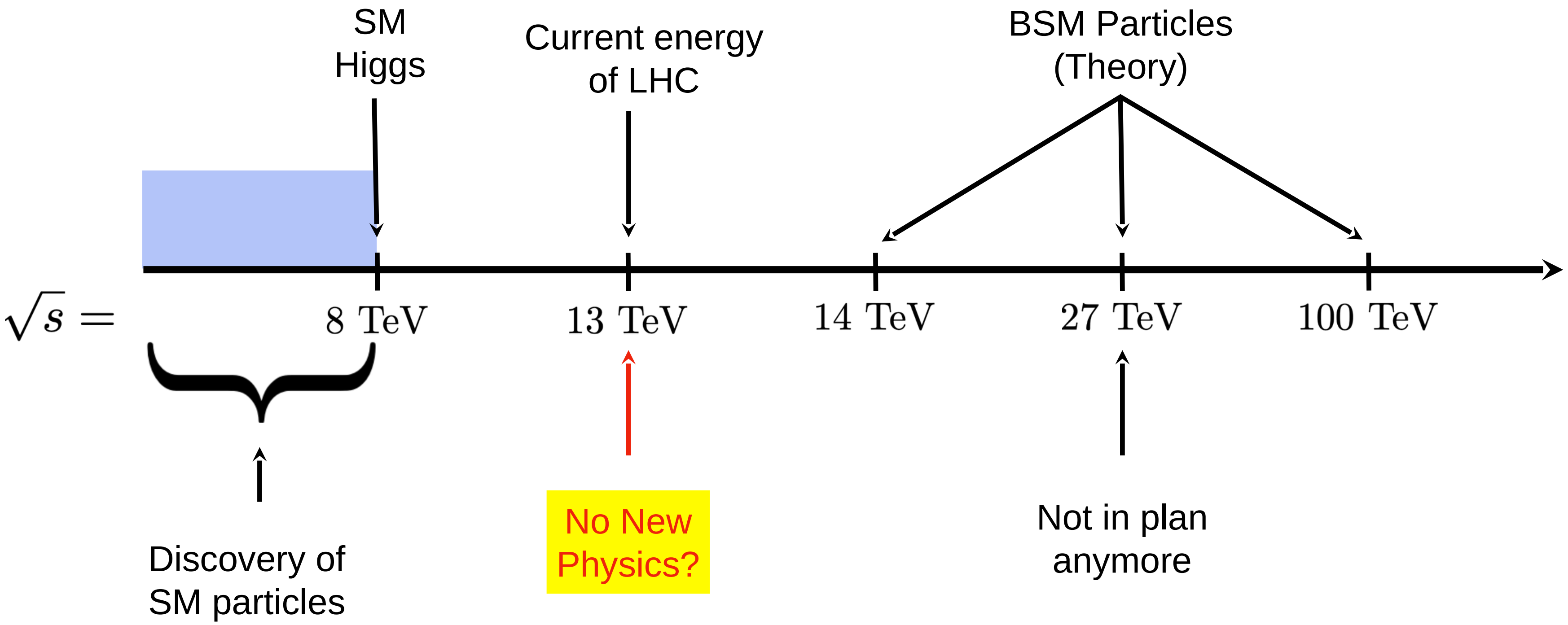


Has LHC excluded Light new Physics?



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

New Physics: Light or Heavy?



SM Higgs

Current energy of LHC

BSM Particles (Theory)

$\sqrt{s} =$ 8 TeV, 13 TeV, 14 TeV, 27 TeV, 100 TeV

Discovery of SM particles

No New Physics?

Not in plan anymore

Energy line of SM and BSM particles

Searches for new physics → Future colliders

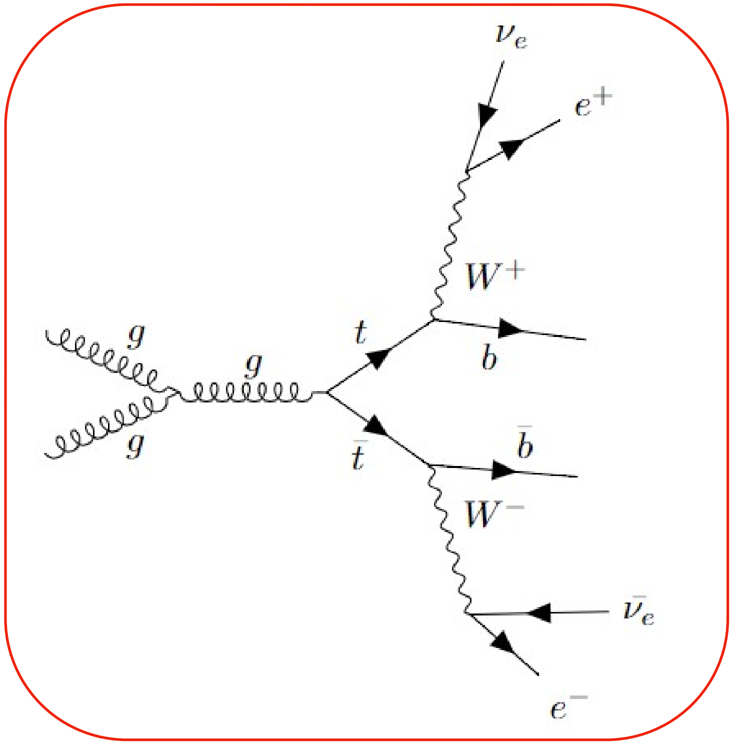
Our proposal: Study well-known observables to reveal New Physics

This work: Precise measurement of top quark observables

Light New Physics from $t\bar{t}$

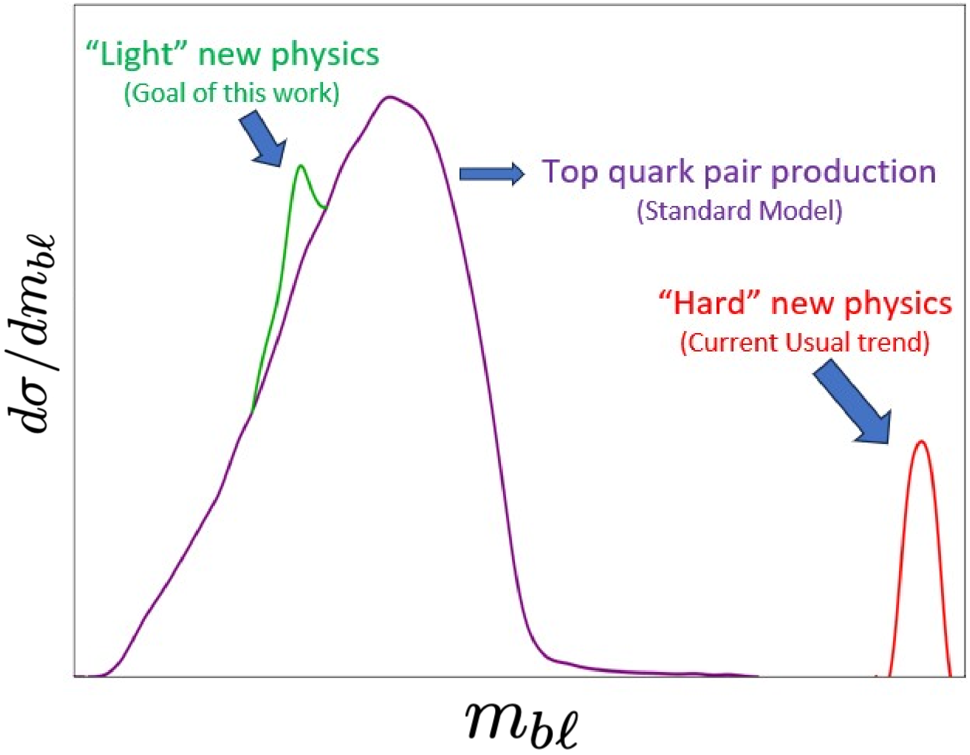
The **LHC**, being a **“top quark factory”**, helps in precise measurement of various properties of the top quark

SM Process



Pair-production of top quarks with each top t decaying to b and $W^\pm$ which further decays leptonically

Invariant mass of the b -jet and the lepton ($m_{b\ell}$)



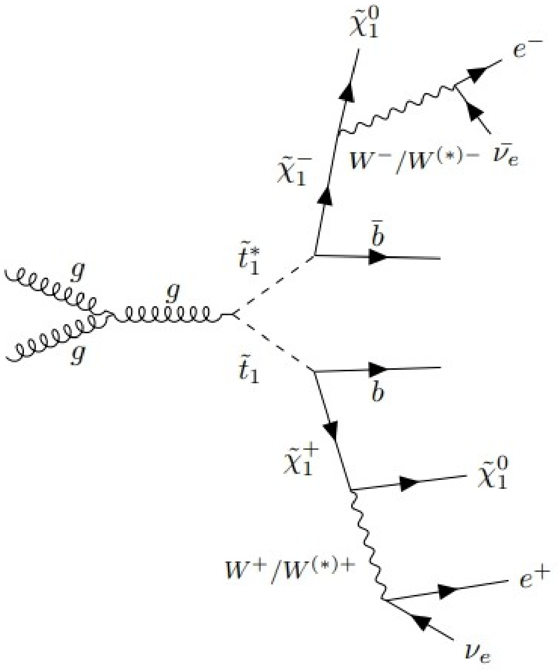
E. Bagnaschi, G. Corcella, R. Franceschini, **D.S.** Phys.Rev.Lett. 133 (2024) 6, 06180

Targeted New Physics Scenario

Any BSM scenario with final state: opposite sign dileptons + 2 b -jets + $\not{E}_T$

Example: Minimal supersymmetric standard model (MSSM)

MSSM Process



Several parameter space points generated using SPheno - 4.0.3 interfaced with SARAH -4.15.1

$$m_{\tilde{t}_1} = 180, 200, 220 \text{ GeV}$$
$$M_1 : 5 \text{ GeV} - 1 \text{ TeV}$$
$$\mu : 100 \text{ GeV} - m_{\tilde{t}_1}$$

$$m_{\tilde{q}} \approx m_{\tilde{l}} \approx 3.5 \text{ TeV} \neq m_{\tilde{t}_1}$$
$$m_{\tilde{g}} \approx 3.6 \text{ TeV}$$
$$122 \text{ GeV} \leq m_h \leq 128 \text{ GeV}$$

Pair-production of the lightest stop $\tilde{t}_1$, with each $\tilde{t}_1$ decaying to the lightest chargino $\tilde{\chi}_1^\pm$ and b, and each $\tilde{\chi}_1^\pm$ decaying to the lightest SUSY particle (LSP) $\tilde{\chi}_1^0$ leptonically via a real or a virtual $W^\pm$ boson

Lightest SUSY Particle (LSP) : $\tilde{\chi}_1^0$
Next-to-Lightest SUSY Particle (NLSP) : $\tilde{\chi}_1^\pm$

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Bounds from Experiments

Important!

A new physics scenario should not be excluded by

→ experimental searches **SPECIFICALLY** designed for this scenario, **AS WELL AS**

→ experimental searches **NOT** designed for this scenario

https://smodels.github.io/
https://smodels.readthedocs.io/en/stable/
https://indico.cern.ch/event/1375202/ - April 25th 2024 - Roberto Franceschini - LHC top WG
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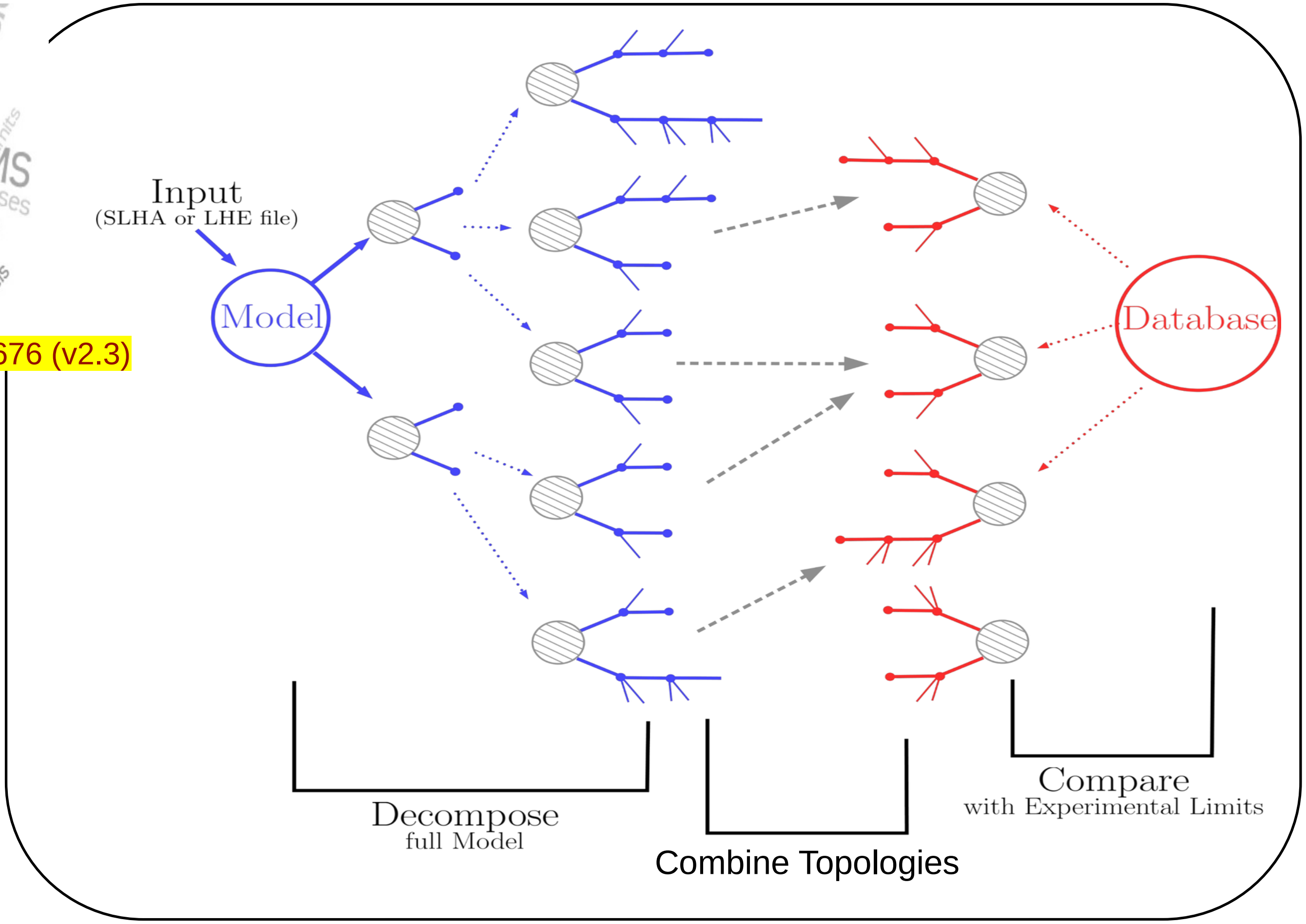

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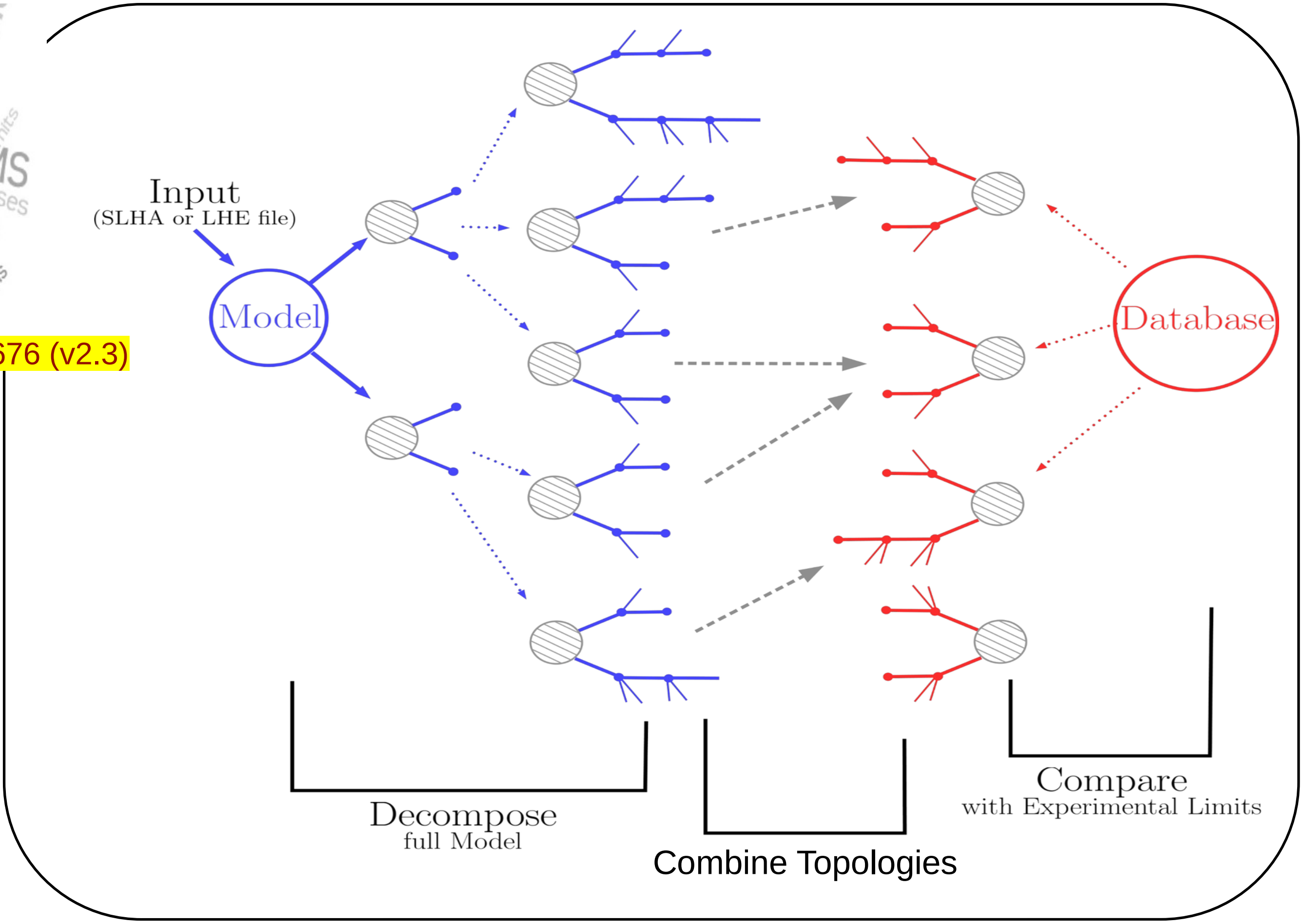
$r > 1$
Excluded

$r < 1$
Not Excluded



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Simulation

All the parameter space points are simulated with Pythia — 8.3 with PDF=NNPDF2.3 QCD+QED LO.

Cuts imposed (motivated by experimental papers)

$$p_T(\ell) \geq 25 \text{ GeV}, \ |\eta(\ell)| < 2.5, \ R(j) = 0.4, \ p_T(j) \geq 25 \text{ GeV}, \ |\eta(j)| < 2.5,$$
$$\Delta R(\ell j) > 0.2, \ \Delta R(\ell\ell) > 0.1, \ \Delta R(jj) > 0.4$$

Jet clustering: Anti-k_T jet algorithm

From $m_{b\ell}$ distribution :

$$\text{Significance} = \sqrt{\sum_i \left[S_i / \left(B_i \times u_{B_i}\right)\right]^2} \quad \text{at } \mathcal{L} = 139 \ fb^{-1}$$

$S_i = \text{No. of signal events in the } i^{th} \text{ bin}$

$B_i = \text{No. of background events in the } i^{th} \text{ bin}$

$u_{B_i} = \text{Relative uncertainty in the background in the } i^{th} \text{ bin}$

(extracted from ATLAS and CMS)

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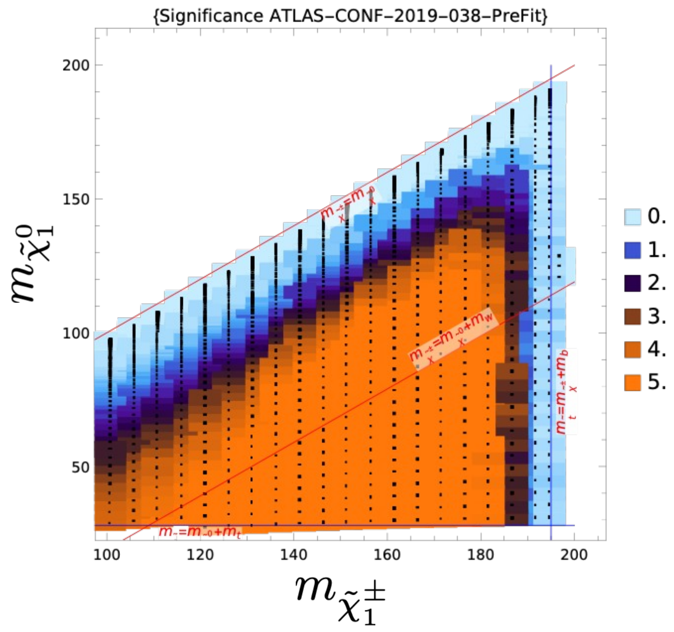
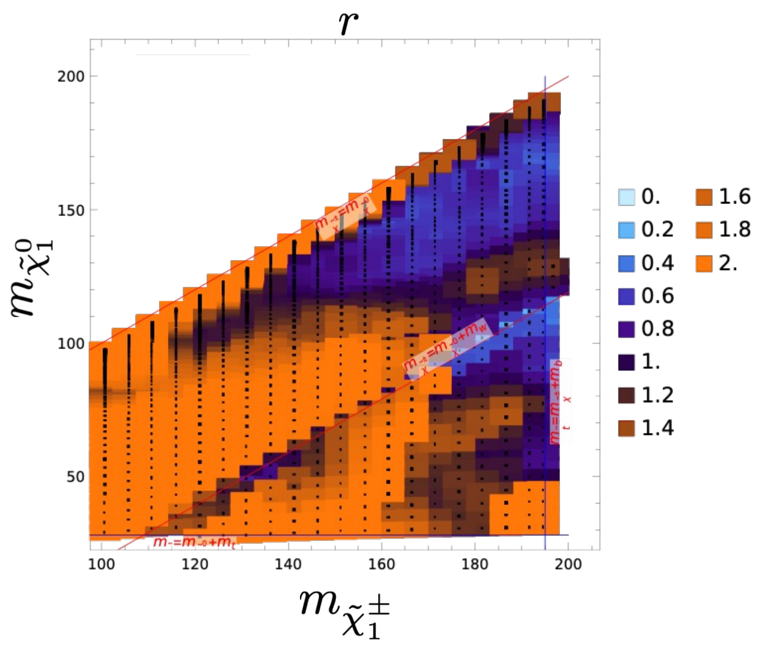
Tech. Rep. ATLAS-CONF-2019-038
M. Aaboud et. al. (ATLAS), Eur. Phys. J. C 78, 129 (2018)
A. M. Sirunyan et. al. (CMS), Eur. Phys. J. C 79, 368 (2019)

Benchmark Points $\left(m_{\tilde{t}_1} = 200\ \text{GeV}\right)$



Significance with u_B from ATLAS

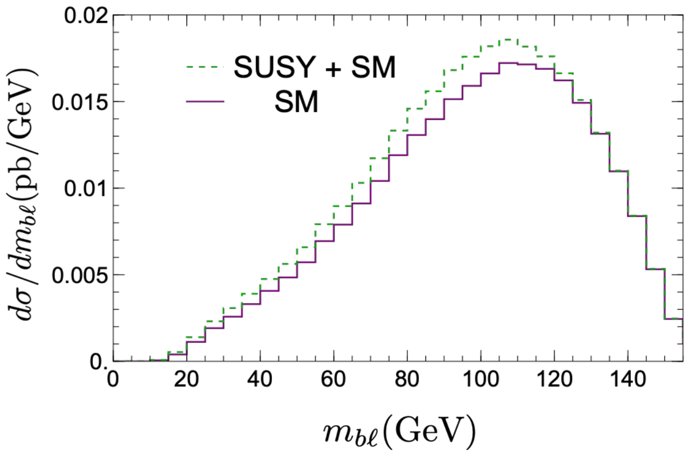


Values of r calculated using SModelS — 2.3.3

$\text{Significance} \geq 5$

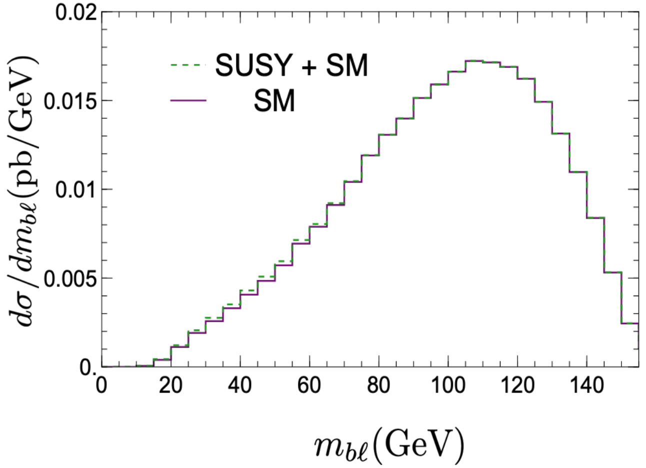
DISCOVERY!!

$m_{\tilde{t}_1} = 200\text{GeV}, m_{\tilde{\chi}_1^\pm} = 136.2\text{GeV}, m_{\tilde{\chi}_1^0} = 49.9\text{GeV}, r = 0.83$



Significance with u_B from ATLAS ~ 10.8

$m_{\tilde{t}_1} = 200\text{GeV}, m_{\tilde{\chi}_1^\pm} = 156.42\text{GeV}, m_{\tilde{\chi}_1^0} = 123.3\text{GeV}, r = 0.72$



Significance with u_B from ATLAS~ 2.6

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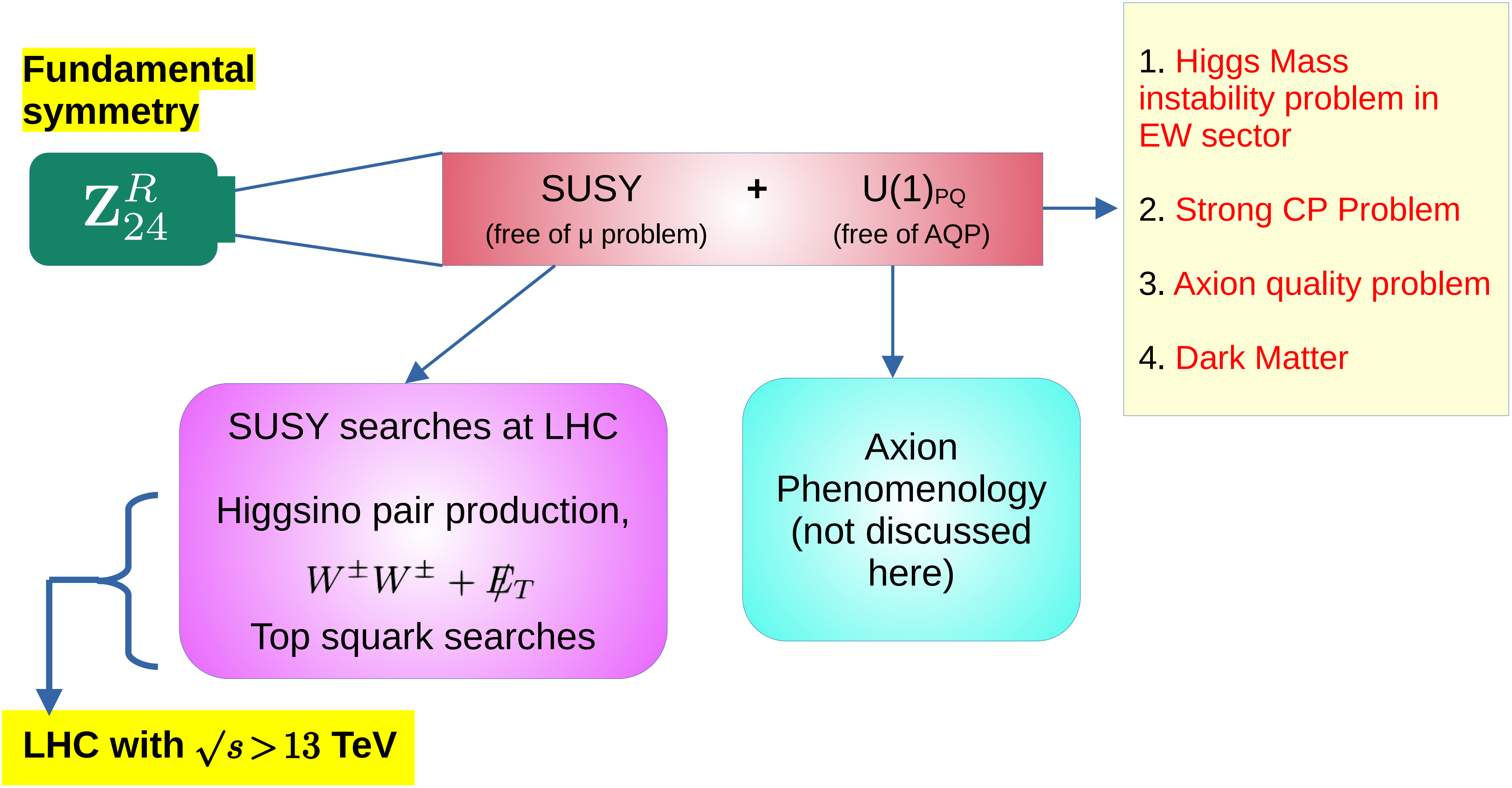
Conclusion



Fundamental symmetry

$\mathbf{Z}_{24}^{R}$

SUSY (free of μ problem) + U(1)$_{PQ}$ (free of AQP)

1. Higgs Mass instability problem in EW sector
2. Strong CP Problem
3. Axion quality problem
4. Dark Matter

SUSY searches at LHC

Higgsino pair production,

$W^{\pm}W^{\pm} + \not{E}_T$

Top squark searches

Axion Phenomenology (not discussed here)

LHC with $\sqrt{s} > 13$ TeV

A thorough study of well-known/well-measured observable such as $m_{b\ell}$ can hint towards new physics in the top-quark sample.

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Jessica Bolich (U. Oklahoma)

Robert W. Deal (U. Wisconsin Madison)

Kairui Zhang (Nebraska U.)

Naturalness in SUSY, SUSY μ problem, Z_{24}^{R} symmetry

Phenomenology of Natural SUSY models,

SUSY from String Landscape

Cheng-Wei Chiang (NTU Taiwan)

Sudip Jana (MPIK, Heidelberg)

$W^{\pm}W^{\pm} + \not{E}_T$ from Natural SUSY, Type-III seesaw, Type-II seesaw/GM model

Gennaro Corcella (INFN Frascati)

Emanuele Bagnaschi (INFN Frascati)

Roberto Franceschini (INFN Roma Tre)

Light new physics from $t\bar{t}$

THANK YOU