Constraints from other experiments

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University of Cincinnati

KITP, Experimental Challenges for the LHC Run II
Santa Barbara, April 25th 2016

SUSY at low energy

Historically, an important
constraint on SUSY breaking

Flavor/CP transitions

- Quark sector
- Lepton sector

Dark Matter

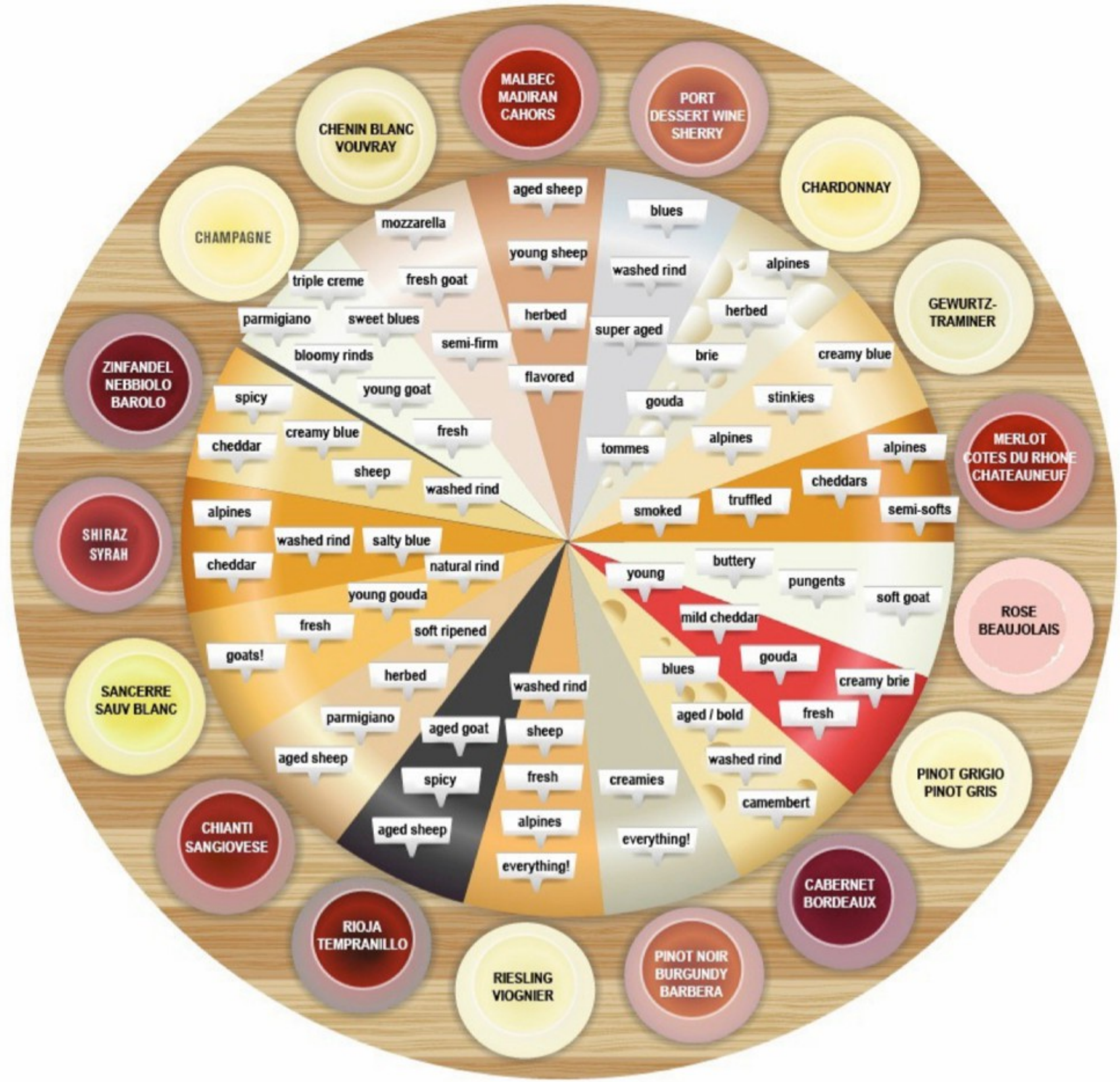
- Direct detection
- Indirect detection
- Collider searches

Hidden scenarios

Historically, a virtue of SUSY
with R-parity.
Now, rather interesting
experimental probes

Electroweak precision
measurements

SUSY & Flavor

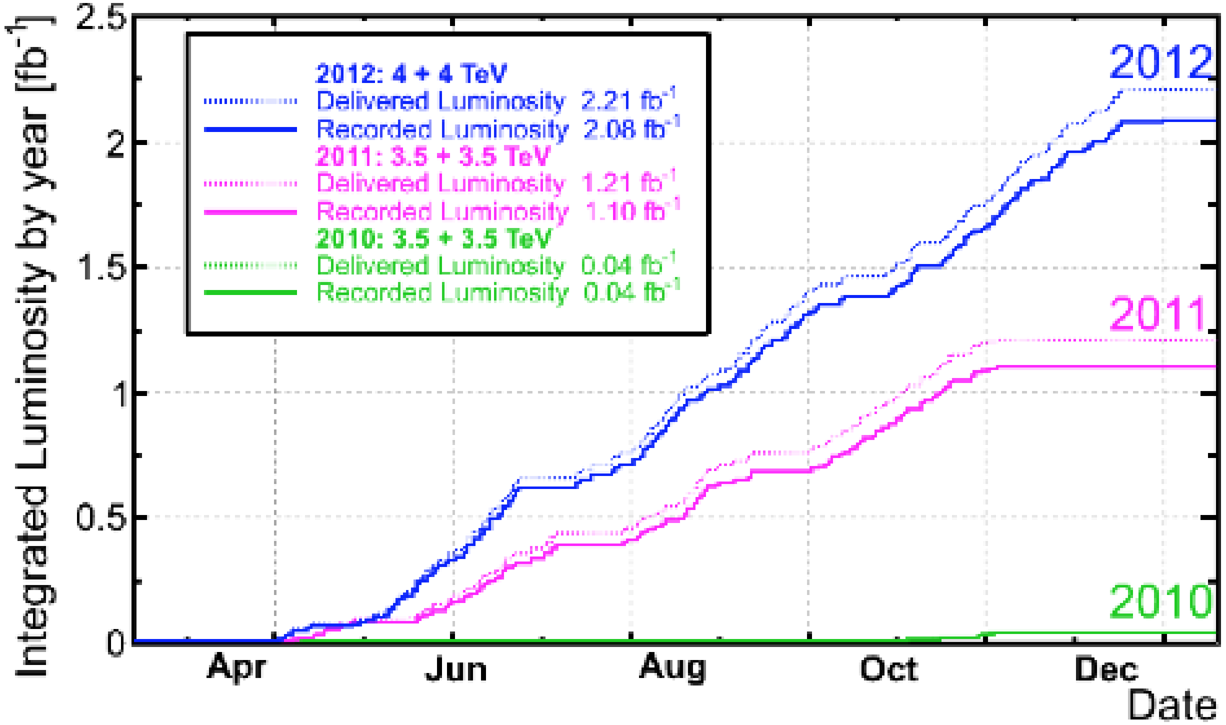


MALBEC MADIRAN CAHORS
PORT DESSERT WINE SHERRY
CHARDONNAY
GEWURTZ-TRAMINER
MERLOT COTES DU RHONE CHATEAUNEUF
ROSE BEAUJOLAIS
PINOT GRIGIO PINOT GRIS
CABERNET BORDEAUX
PINOT NOIR BURGUNDY BARBERA
RIESLING VIOGNIER
RIOJA TEMPRANILLO
CHIANTI SANGIOVESE
SANCERRE SAUV BLANC
SHIRAZ SYRAH
ZINFANDEL NEBBIOLO BAROLO
CHAMPAGNE
CHENIN BLANC VOUVRAY
aged sheep
young sheep
herbed
flavored
blues
washed rind
super aged
gouda
tommes
smoked
alpines
herbed
brie
creamy blue
stinkies
alpines
alpines
cheddars
truffled
semi-softs
young
buttery
pungents
soft goat
mild cheddar
gouda
creamy brie
fresh
blues
aged / bold
washed rind
camembert
creamies
everything!
washed rind
sheep
fresh
alpines
everything!
aged goat
spicy
aged sheep
herbed
parmigiano
aged sheep
soft ripened
young gouda
fresh
goats!
natural rind
salty blue
washed rind
cheddar
alpines
washed rind
sheep
creamy blue
cheddar
spicy
fresh
young goat
bloomy rinds
parmigiano
sweet blues
semi-firm
triple creme
fresh goat
mozzarella

Tremendous progress in flavor physics

… in the last years

The LHC is a b-factory



10^{12} b quarks produced in the LHCb detector, during Run I;
~two times more expected for Run II.

+ interesting results coming from B-factories (Belle + Babar)

 S.Gori

Probing high scales

Meson mixing observables probe generic New Physics at very high scales.

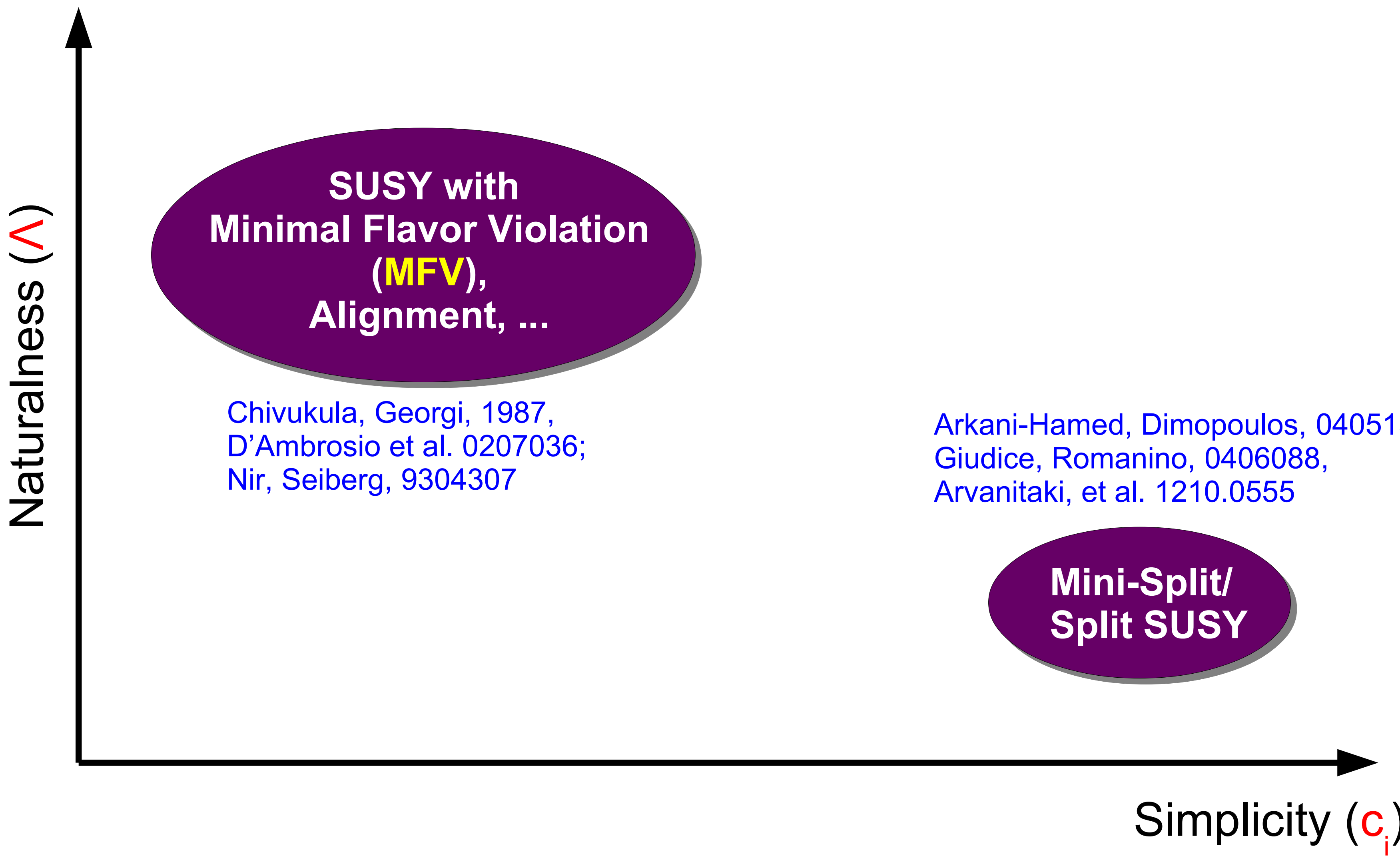
$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Operator	Λ in TeV ($c_{\text{NP}} = 1$)		Bounds on c_{NP} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\|q/p\|, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\|q/p\|, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Isidori, 1507.00867
Update from Isidori, Nir, Perez, 1002.0090

Different approaches to SUSY

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$



Sources of flavor/CP violation in SUSY

Soft SUSY breaking terms of the sfermions generically break flavor $M^2_{\tilde{q}},\ M^2_{\tilde{\ell}},\ A^2_{\tilde{q}},\ A^2_{\tilde{\ell}}$

Plethora of free parameters!

$$
\begin{aligned}
M^2_{\tilde{q}} &= \tilde{m}^2_q(\mathbb{1} + \delta_q),\\
M^2_{\tilde{\ell}} &= \tilde{m}^2_\ell(\mathbb{1} + \delta_\ell),\\
A_{\tilde{q}} &= \tilde{A}_q(\mathbb{1} + \delta_{A_q}),\\
A_{\tilde{\ell}} &= \tilde{A}_\ell(\mathbb{1} + \delta_{A_\ell})
\end{aligned}
$$

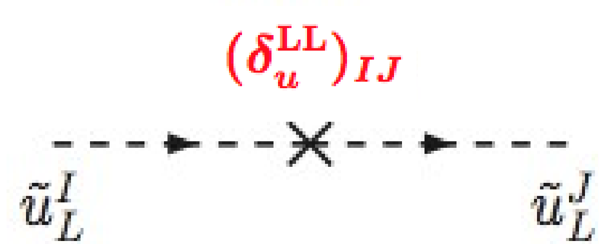
Ideally,
we would have liked δ ~ O(1).

→ **Mini-Split SUSY**

Misalignment between quarks and squarks in flavor space

→ Mass Insertions

Flavor change through mass insertions along squark propagators



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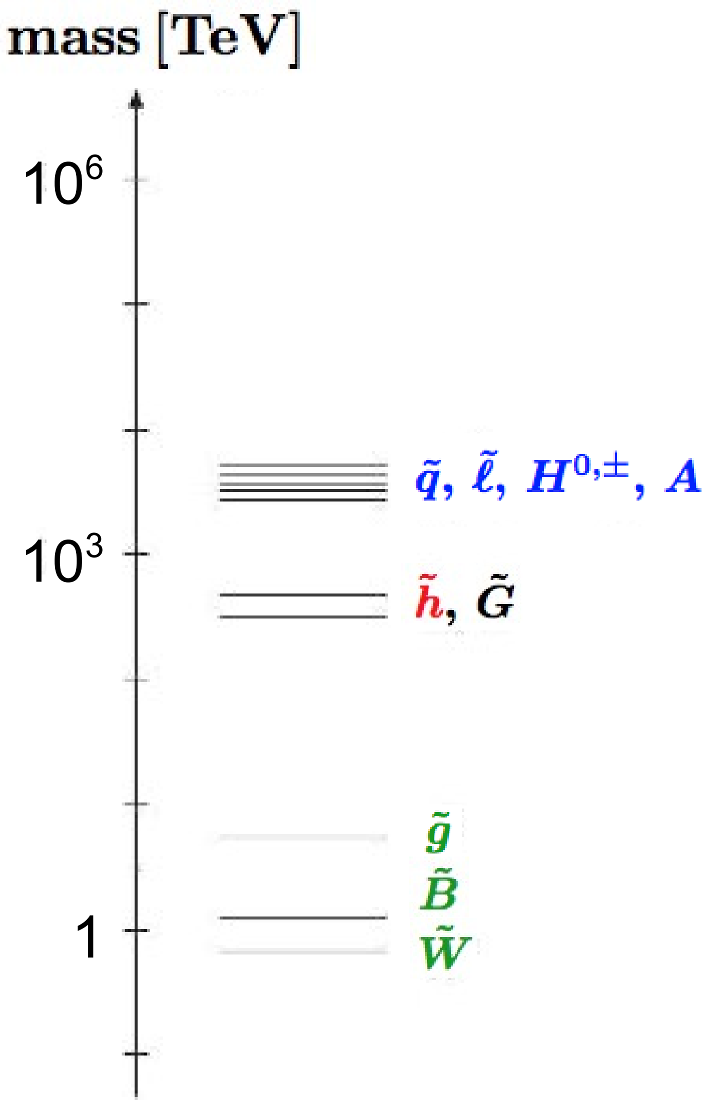
Mini - Split SUSY



$$\mathcal{L}_{SB} \supset \frac{1}{M_*^2}\int d^4\theta (X^\dagger X)(\Phi^\dagger\Phi + H_u H_d)$$

$$-\frac{\alpha_i b_i}{4\pi}\frac{m_{3/2}}{2}\lambda_i\lambda_i - \frac{m_{3/2}}{2}\tilde{G}\tilde{G} + \int d^4\theta (H_u H_d)$$

- scalar masses of order $F_X/M_* \gtrsim F_X/M_{Pl} = m_{3/2}$

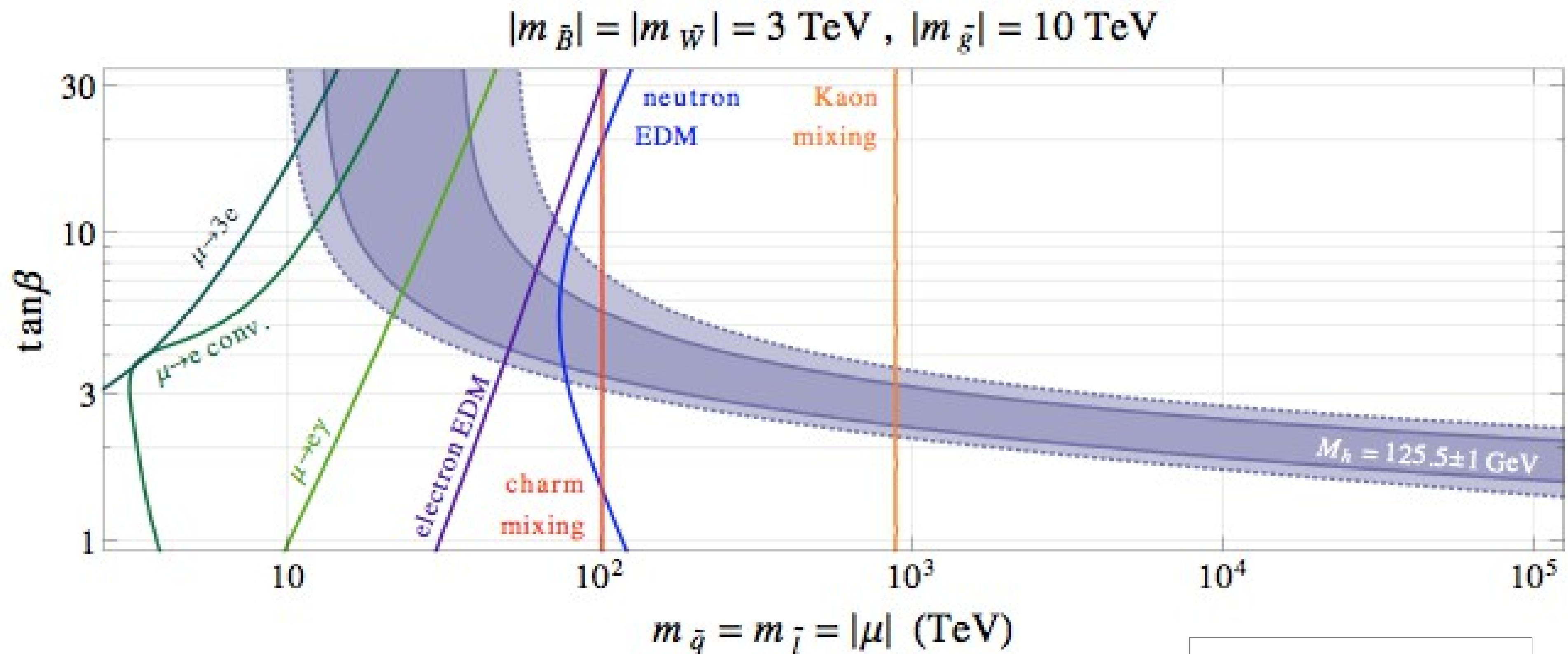
- gaugino masses from anomaly mediation, 1-loop factor below the gravitino mass

- Higgsino mass model dependent: could be order gravitino mass or additionally suppressed

Arkani-Hamed, Dimopoulos, 0405159
Giudice, Romanino, 0406088,
Arvanitaki, et al. 1210.0555

Constraints on "heavy SUSY"

Altmannshofer, Harnik, Zupan, 1308.3653



SUSY flavor problem

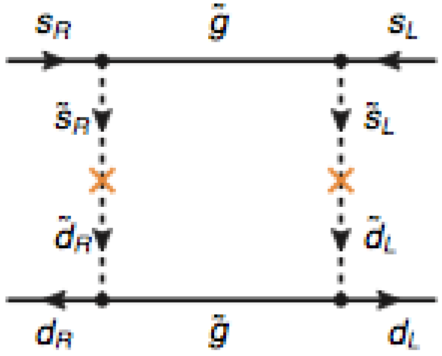
Assumptions for the plot:

- all relevant mass insertions **$|\delta_{ij}|=0.3$**
- all relevant phases $\sin(\varphi_i) = 1$
- no large cancelations between the various contributions

Mini-Split SUSY

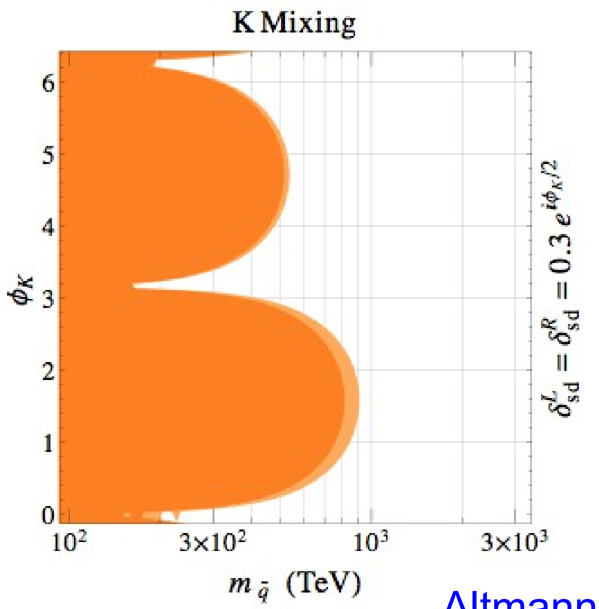
Meson mixing & squark spectra

Kaon mixing



Mini-Split SUSY

$$M_{12}^K \propto \frac{\alpha_s^2}{m_{\tilde{q}}^2}\left(\delta_{sd}^L \delta_{sd}^R\right)$$



Altmannshofer, Harnik, Zupan, 1308.3653

Contributions depend to an excellent approximation only on the squark masses

Meson mixing & squark spectra

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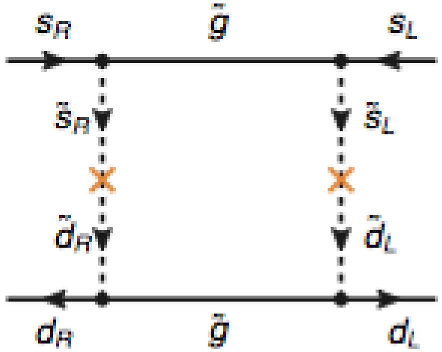
Mini-Split SUSY



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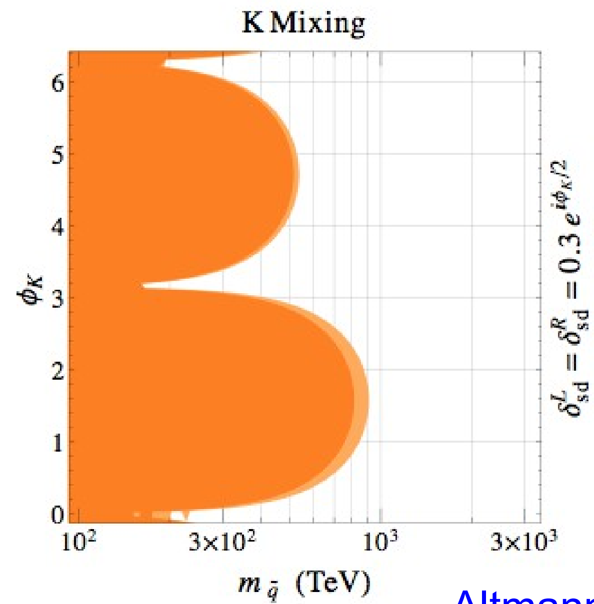
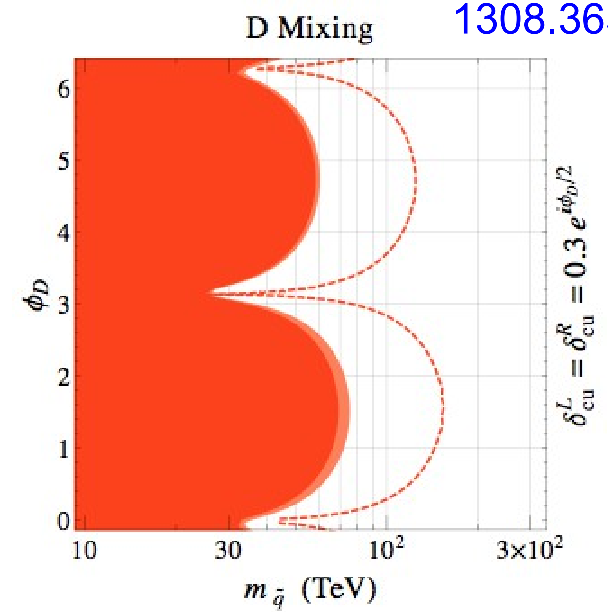


Contributions depend to an excellent approximation only on the squark masses

Altmannshofer, Harnik, Zupan, 1308.3653

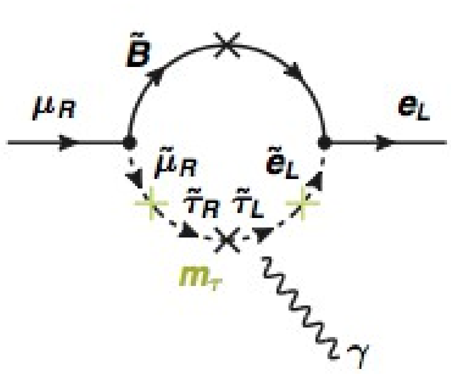
Similar contributions for D-meson mixing:



Even more interesting:
For charm mixing,
experimental bounds on CPV in charm mixing can still improve substantially (LHCb and Belle II)

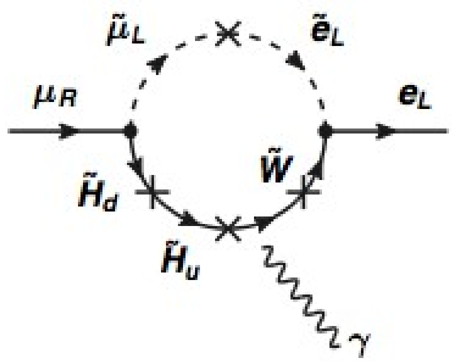
μ → eγ & slepton-gaugino-Higgsino spectra

Mini-Split SUSY



$$\mathcal{A}^{\tilde{B}}_{L,R} \propto \frac{\alpha_1}{4\pi}\frac{m_\tau}{m_\mu}\frac{\mu m_{\tilde{B}}}{m^4_{\tilde{\ell}}}\tan\beta\,(\delta^{L,R}_{\mu\tau}\delta^{L,R}_{\tau e})$$

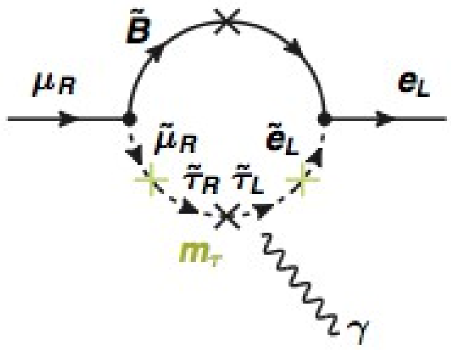
It can probe
Bino-slepton-Higgsino spectra



$$\mathcal{A}^{\tilde{W}}_{L} \propto \frac{\alpha_2}{4\pi}\frac{1}{m^2_{\tilde{\ell}}}\frac{m_{\tilde{W}}}{\mu}\tan\beta\,(\delta^{L}_{\mu e})\log\left(\frac{m^2_{\tilde{W}}}{m^2_{\tilde{\ell}}}\right)$$

It can probe
Wino-slepton-Higgsino spectra

μ → eγ & slepton-gaugino-Higgsino spectra



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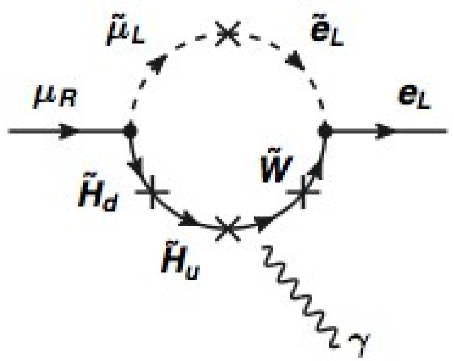

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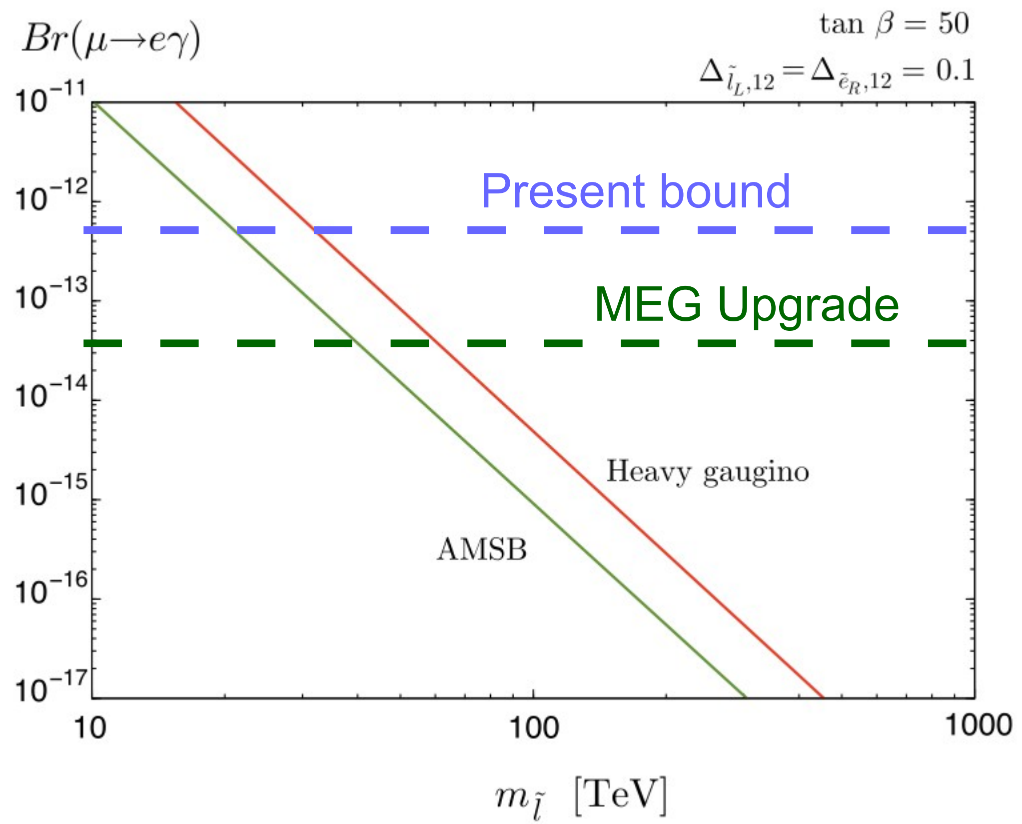
It can probe
Wino-slepton-Higgsino spectra

Mini-Split SUSY

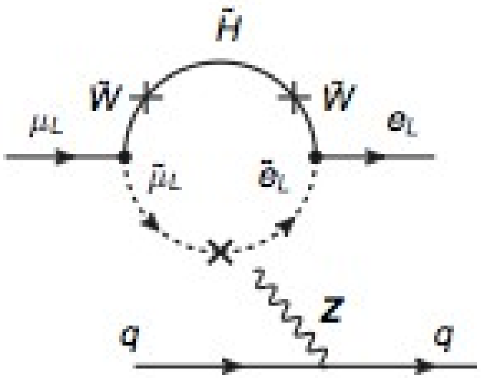
Moroi and Nagai, 1303.0668



BR bound can be improved by one order of magnitude with a MEG upgrade

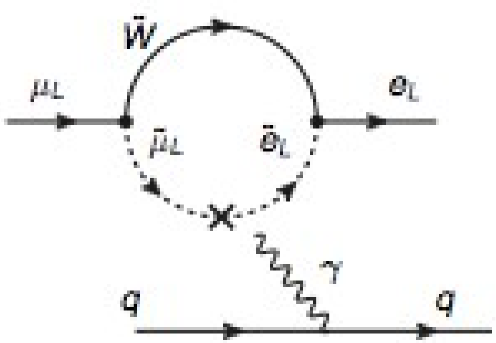
μ to e conversion

Mini-Split SUSY



$$\mathcal{A}^Z \propto \frac{\alpha_2^2}{m_{\tilde{\ell}}^2} (\delta^L_{\mu e}) \log\left(\frac{\mu^2}{m_{\tilde{\ell}}^2}\right)$$

Enhanced for light Higgsinos

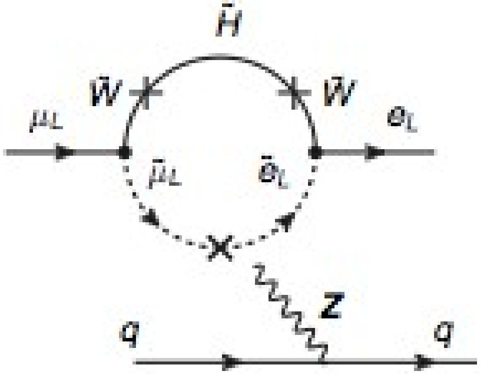


$$\mathcal{A}^\gamma \propto \frac{\alpha_{em}\alpha_2}{m_{\tilde{\ell}}^2} (\delta^L_{\mu e}) \log\left(\frac{m_{\tilde{W}}^2}{m_{\tilde{\ell}}^2}\right)$$

Enhanced for light Winos

Dominant contributions at low values of tanβ. Otherwise dipole operators

μ to e conversion



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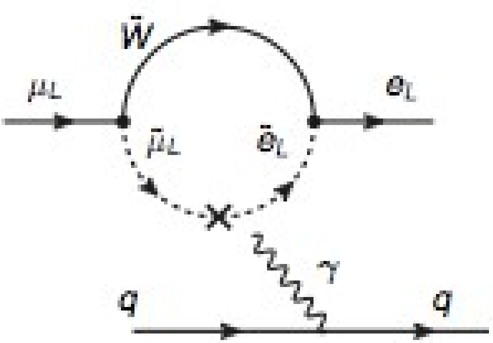
Enhanced for light Higgsinos

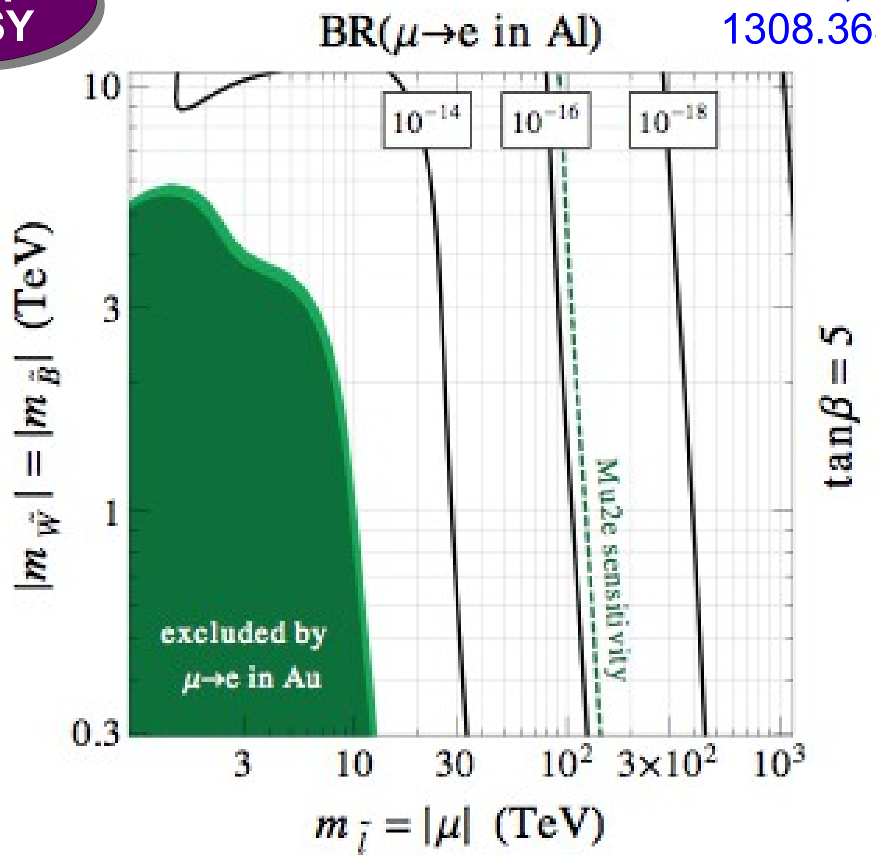


$$\mathcal{A}^\gamma \propto \frac{\alpha_{em}\alpha_2}{m_{\tilde{\ell}}^2} (\delta^L_{\mu e}) \log\left(\frac{m_{\tilde{W}}^2}{m_{\tilde{\ell}}^2}\right)$$

Enhanced for light Winos

Mini-Split SUSY

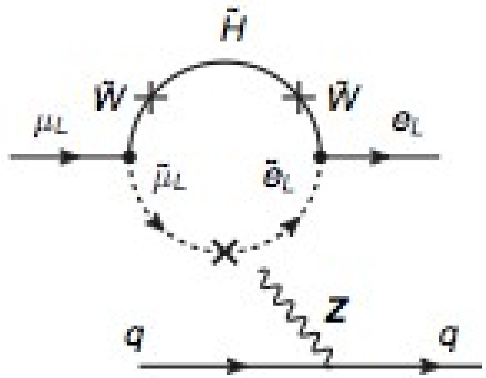
Altmannshofer, Harnik, Zupan, 1308.3653



The Mu2e collaboration hopes to improve the μ → e reach by four order of magnitude

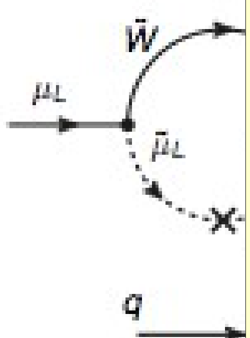
Dominant contributions at low values of tanβ. Otherwise dipole operators

μ to e conversion



$$\mathcal{A}^Z \propto \frac{\alpha_2^2}{m_{\tilde\ell}^2} (\delta^L_{\mu e}) \log\left(\frac{\mu^2}{m^2_{\tilde\ell}}\right)$$

Enhanced for

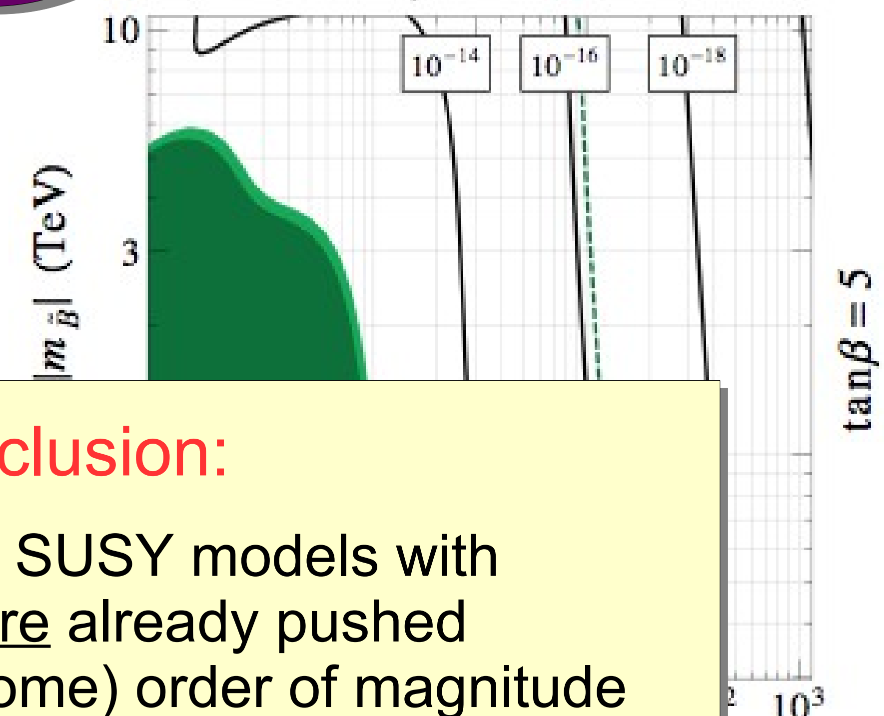


$$\mathcal{A}^\gamma \propto \frac{\alpha_{em}\alpha_2}{m_{\tilde\ell}^2}$$

Enhanced for light Winos

Mini-Split SUSY

Altmannshofer, Harnik, Zupan, 1308.3653



Conclusion:

Flavor constraints on SUSY models with <u>generic flavor structure</u> already pushed the mass reach to (some) order of magnitude above the TeV scale:

- squarks → O(10^3 TeV) meson mixing
- Wino, Higgsino, slepton → O(10 TeV) LFV

hopes
ach by

Dominant contributions at low values of tanβ. Otherwise dipole operators

Inserting a flavor structure: MFV

SUSY with Minimal Flavor Violation (MFV):
soft breaking terms are highly non-generic

$$m_Q^2 = \tilde{m}_Q^2 \left(\mathbb{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + \right.$$
$$\left. + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + \ldots \right)$$
$$m_U^2 = \tilde{m}_U^2 \left(\mathbb{1} + b_4 Y_u^\dagger Y_u + \ldots \right)$$
$$m_D^2 = \tilde{m}_D^2 \left(\mathbb{1} + b_5 Y_d^\dagger Y_d + \ldots \right)$$
$$A_u = \tilde{A}_u \left(\mathbb{1} + b_6 Y_d Y_d^\dagger + b_7 Y_u Y_u^\dagger + \ldots \right) Y_u$$
$$A_d = \tilde{A}_d \left(\mathbb{1} + b_8 Y_u Y_u^\dagger + b_9 Y_d Y_d^\dagger + \ldots \right) Y_d$$

In SUSY with MFV:

- meson mixing is SM like
- Lepton sector processes are SM-like

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$$\left. + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + \ldots \right)$$
$$m_U^2 = \tilde{m}_U^2 \left(1\!\!1 + b_4 Y_u^\dagger Y_u + \ldots \right)$$
$$m_D^2 = \tilde{m}_D^2 \left(1\!\!1 + b_5 Y_d^\dagger Y_d + \ldots \right)$$
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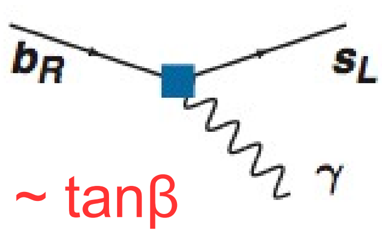
In SUSY with MFV:

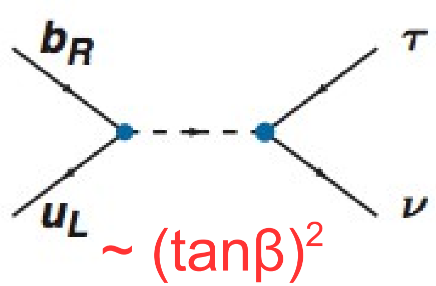
- meson mixing is SM like
- Lepton sector processes are SM-like

SUSY with Minimal Flavor Violation (MFV)

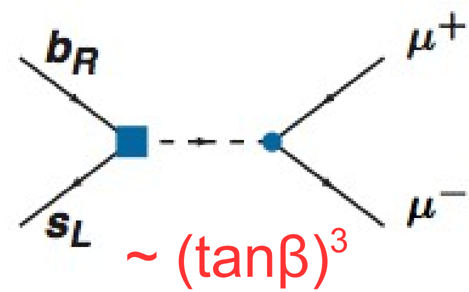
Visible deviations are possible in helicity suppressed processes:



$b \to s\gamma$

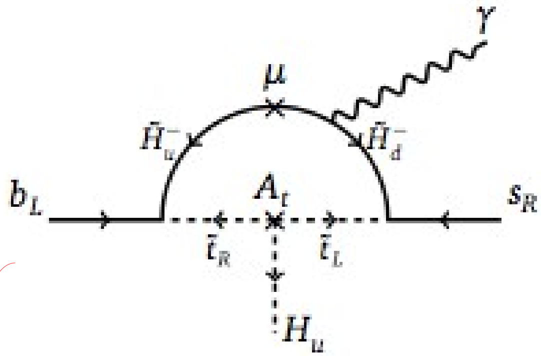


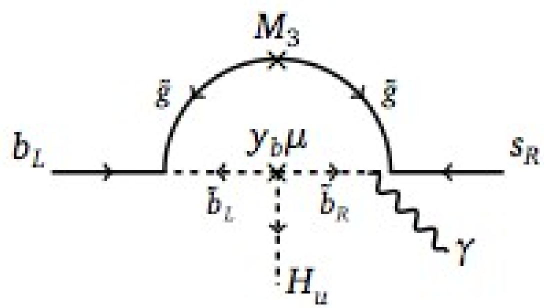
$B^+ \to \tau^+ \nu$



$B_{s,d} \to \mu^+ \mu^-$

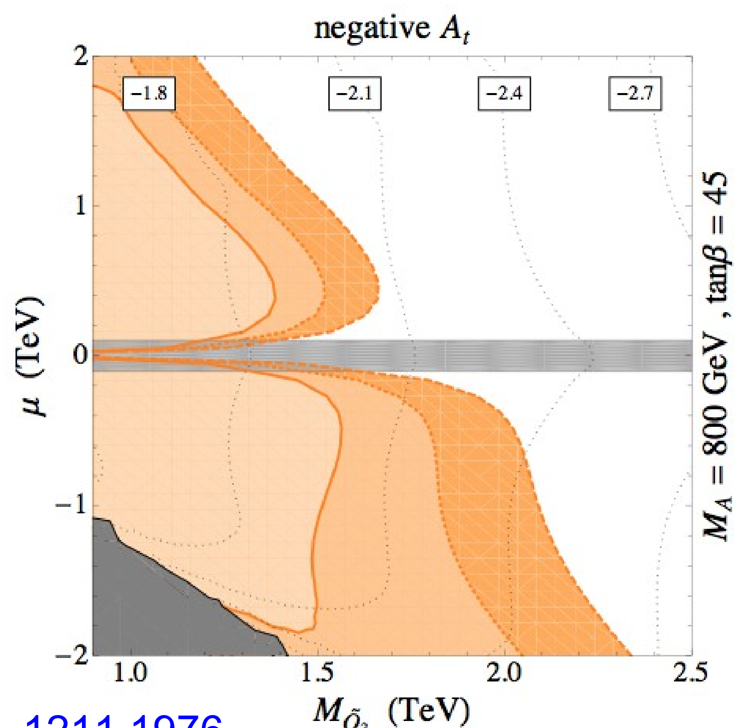
b → sγ in the "natural regime"





These are the two dominant contributions in a typical SUSY natural spectrum

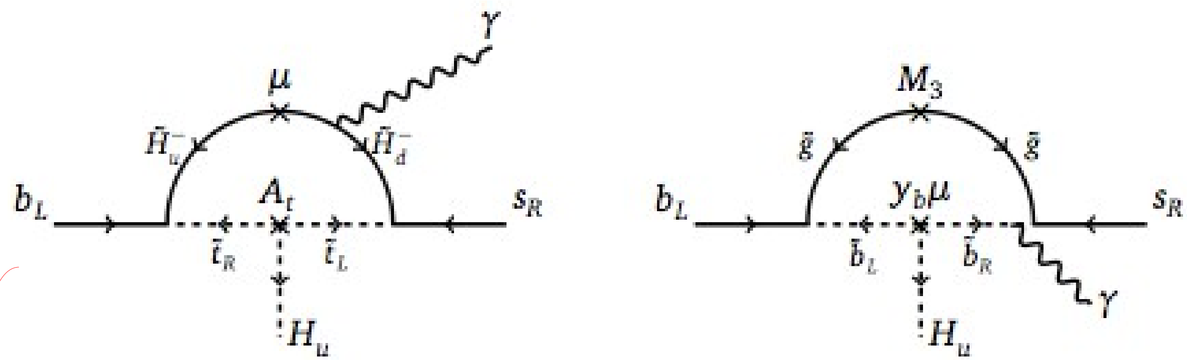
$$\mathcal{M}(b \to s\gamma)_{\tilde{H},\tilde{t}} \sim \frac{A_t \mu}{m_{\tilde{t}}^4} \tan\beta$$



Altmannshofer et al., 1211.1976

SUSY with Minimal Flavor Violation (MFV)

b → sγ in the "natural regime"



+ Wino loop
+ charged Higgs loop

$$m_{H^\pm} \geq 450\,\mathrm{GeV}$$

in a Type II 2HDM
Misiak et al., 1503.01789

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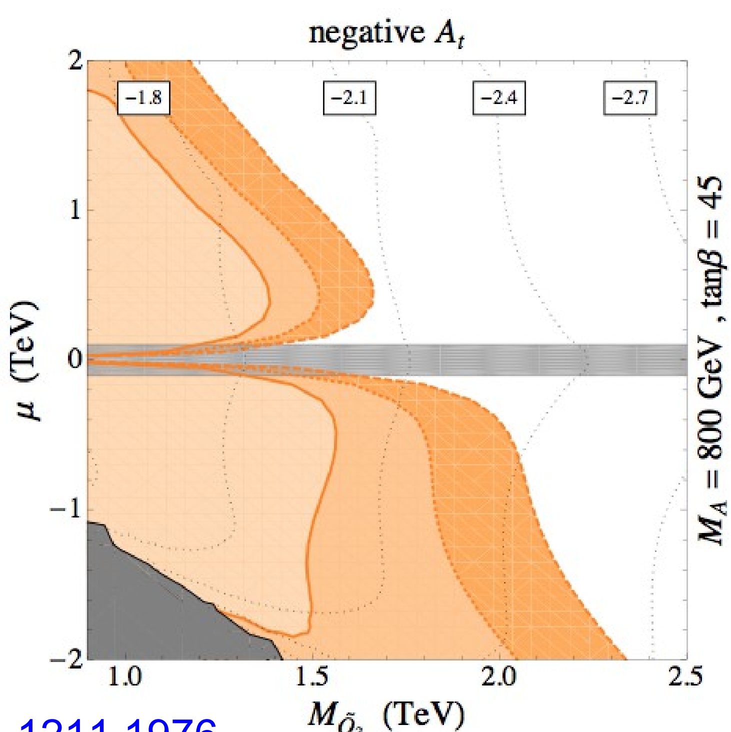


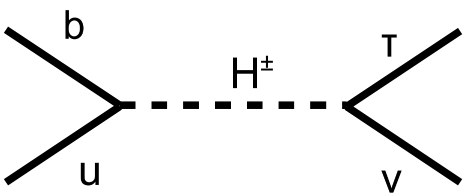
Altmannshofer et al., 1211.1976

SUSY with Minimal Flavor Violation (MFV)

$B \to \tau\nu$

In type II 2HDMs light charged Higgs are strongly constrained

SUSY with Minimal Flavor Violation (MFV)

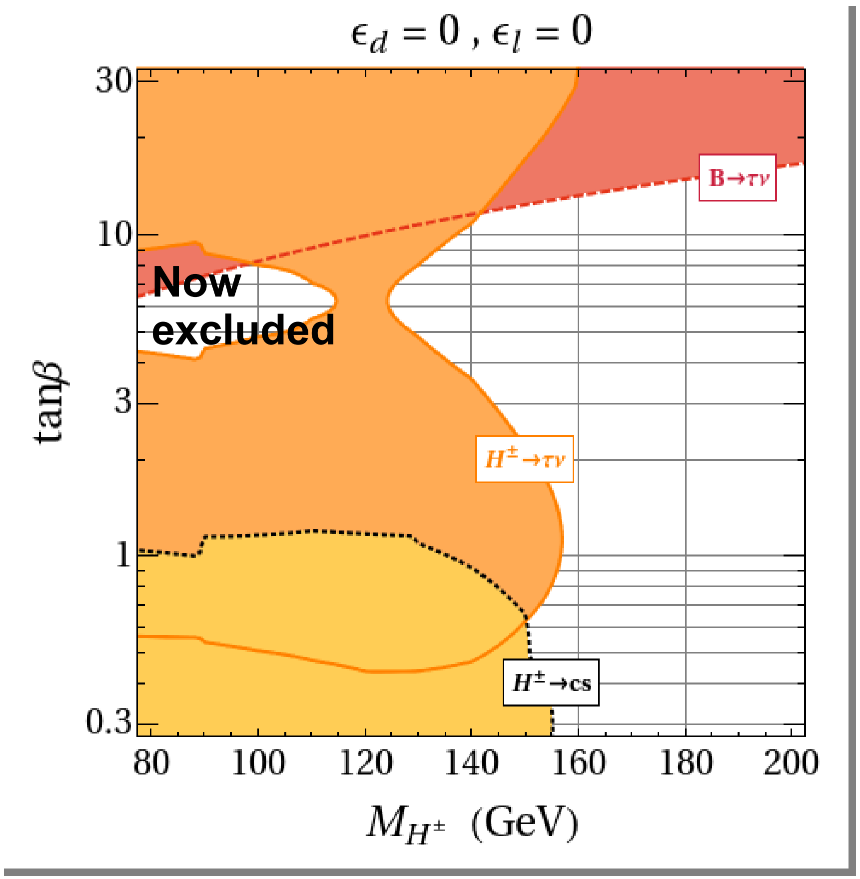


$$\frac{\mathrm{BR}}{\mathrm{BR}_{\mathrm{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} t_\beta^2\right)^2$$

In SUSY, we should keep into account non-holomorphic contributions: "wrong Yukawa terms" $\mathcal{L} \sim \epsilon_b H_u^\dagger Q b^c$

$$\frac{\mathrm{BR}}{\mathrm{BR}_{\mathrm{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} \frac{t_\beta^2}{(1+\epsilon_d t_\beta)(1+\epsilon_\tau t_\beta)}\right)^2$$

Complementarity with direct searches of charged Higgses:

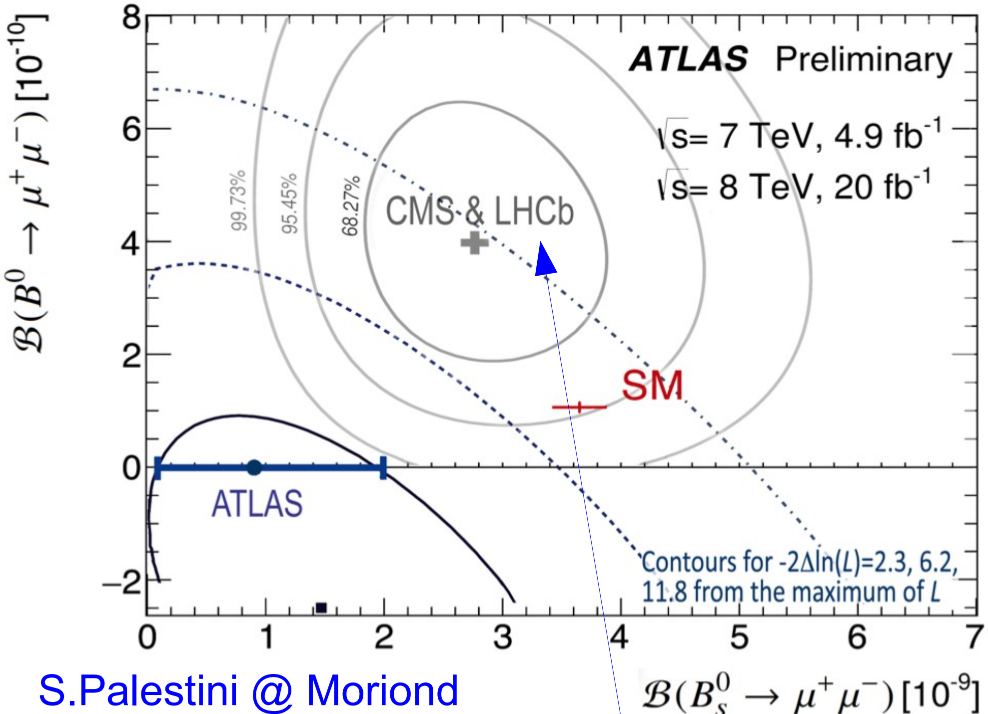


Altmannshofer, SG, Kribs, 1210.2465

B decays to two muons & MFV theories

SUSY with Minimal Flavor Violation (MFV)

Recent experimental result:



S.Palestini @ Moriond

From 1411.4413

LHCb + CMS

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathrm{BR}(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

ATLAS

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$
$$\mathrm{BR}(B_d \to \mu^+\mu^-) < 4.2 \times 10^{-10}$$

SM

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$
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Bobeth et al., 1311.0903

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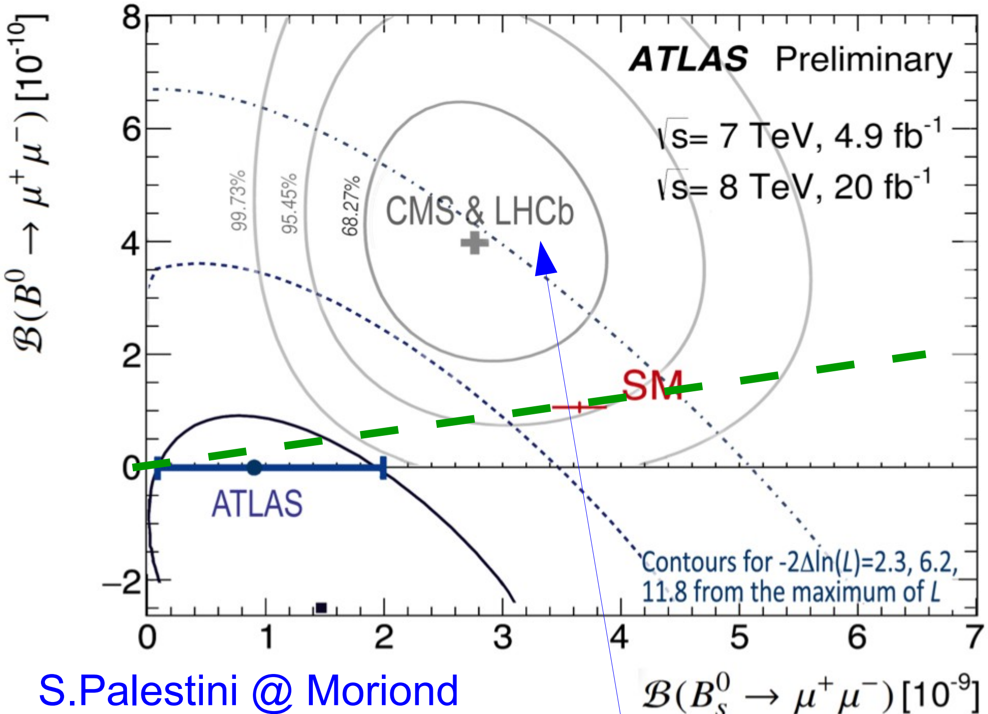

S.Palestini @ Moriond

From 1411.4413

SUSY with Minimal Flavor Violation (MFV)

In all generality, MFV theories lead to

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} \sim \left|\frac{V_{ts}}{V_{td}}\right|^2$$

See for example Buras, Carlucci, SG, Isidori, 1005.5310

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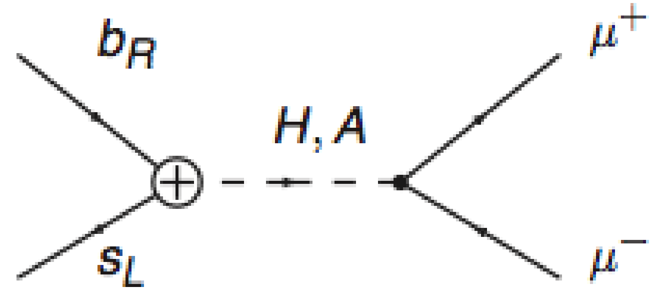
Bobeth et al., 1311.0903

B decays to two muons: SUSY implications

Dominant SUSY effects
come from the Higgs penguins:



$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}}$$

$$\simeq |A|^2 + |A+1|^2 \geq \frac{1}{2}$$

This lower bound does not
have impact yet

$$A^{\tilde{H}} \propto \frac{y_t^2}{16\pi^2} \frac{\mu A_t}{m_{\tilde{t}}^2} \frac{\tan\beta^3}{M_A^2}$$

SUSY with
Minimal Flavor Violation
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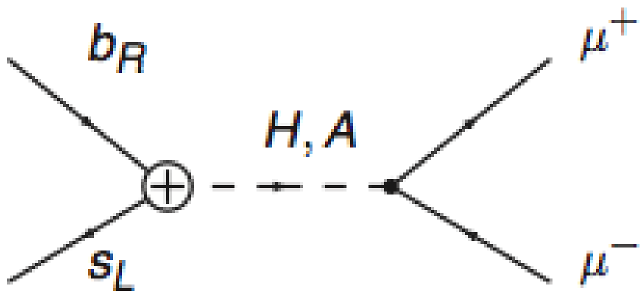

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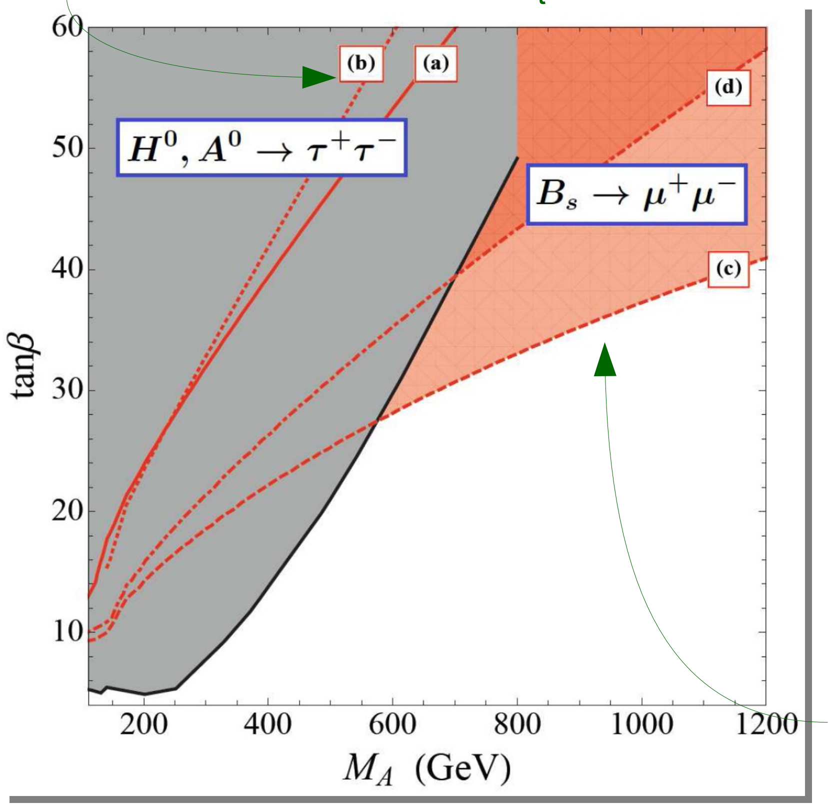
Destructive interference, $\mu A_t > 0$



Constructive interference, $\mu A_t < 0$

Altmannshofer, Carena, Shah, Yu, 1211.1976

SUSY with Minimal Flavor Violation (MFV)

Beyond constraints: flavor anomalies

An (incomplete) list:

~3.5σ enhanced $B \rightarrow D(*)\, \tau\, \nu$ rates (Babar)

~3.5σ suppressed branching ratio of $B_s \rightarrow \varphi\, \mu^+ \mu^-$ (LHCb)

(2-3)σ anomaly in $B \rightarrow K^* \mu^+ \mu^-$ angular distributions (LHCb, CMS, ATLAS)

~2.5σ lepton flavor non universality in $B \rightarrow K\, \mu^+ \mu^-$ vs. $B \rightarrow K\, e^+ e^-$ (LHCb)

~ 2σ non zero $h \rightarrow \tau\, \mu$ decay (CMS)

In all generality, these anomalies
do not point towards SUSY
(or at least towards a minimal SUSY scenario)

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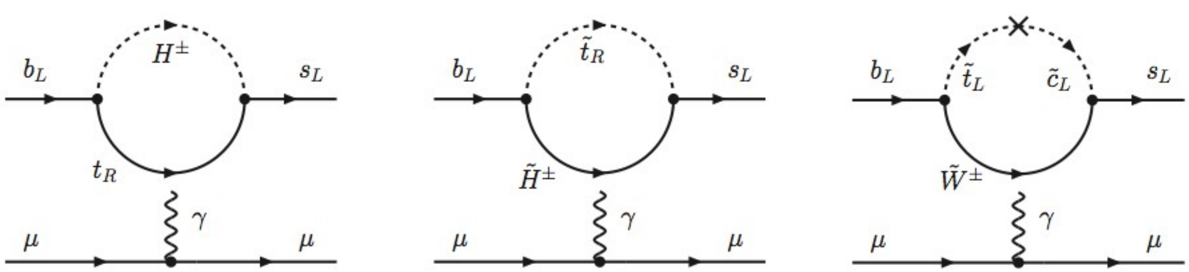
Need a sizable contribution to

$$C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu),\ C_9 \sim \frac{1}{(30\,\mathrm{TeV})^2}$$



Very (< 100 GeV) light SUSY spectrum would be needed

Altmannshofer, Straub, 1308.1501

Beyond constraints: flavor anomalies

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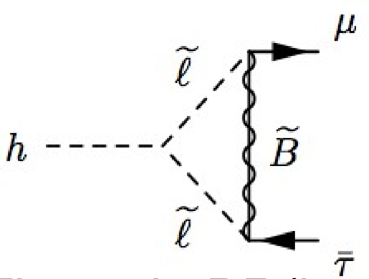
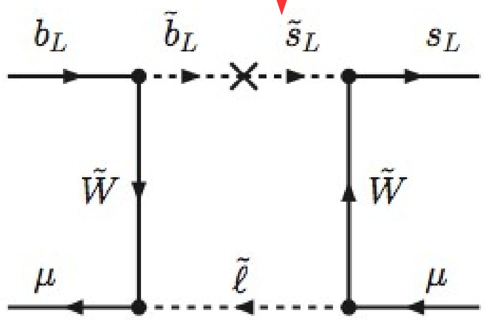


Aloni, Nir, Stamou, 1511.00979

"The ratio $BR(h \to \tau\mu)/BR(h \to \tau\tau)$ can be enhanced by about three orders of magnitude above the estimate from naive dimensional analysis, but still about two orders of magnitude below the present bound."



Need very light smuons, with huge mass splitting with selectrons.
Also Winos need to be very light

Altmannshofer, Straub, 1308.1501

SUSY
&
Dark Matter

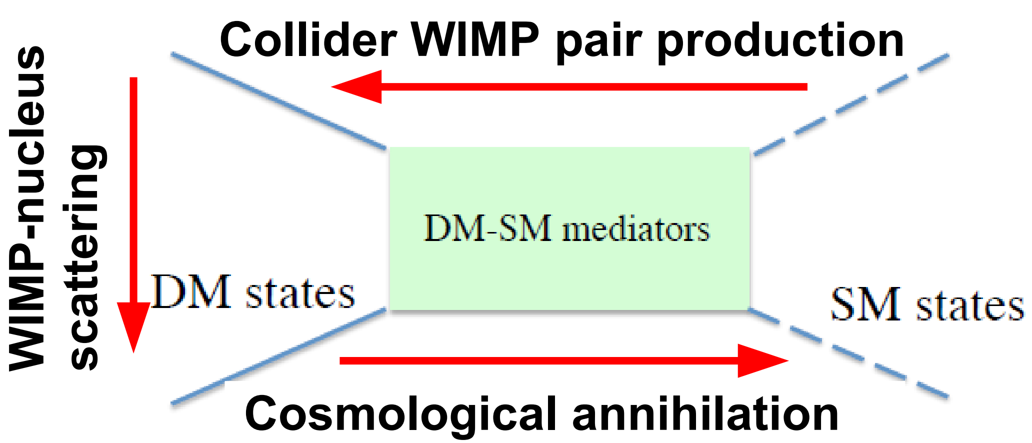
(SUSY) WIMP Dark Matter

The Lamp post of the last decade(s)

The WIMP paradigm has been the primary guide for the current dark matter experimental program

Assumptions:

- Single Particle
- Weakly Interacting
- Mass ~$10^{2\text{-}3}$ GeV



 S.Gori

(SUSY) WIMP Dark Matter

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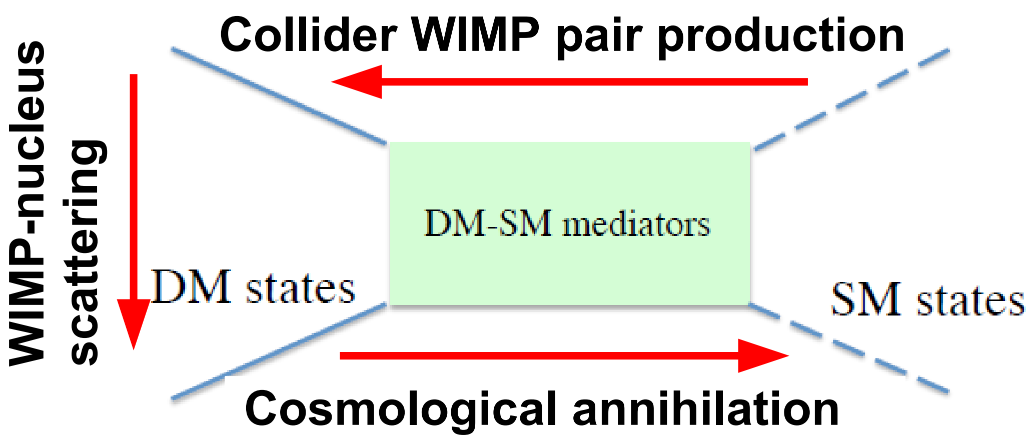


(Minimal) SUSY candidates:

- Bino
- Higgsino
- Wino

For this talk:

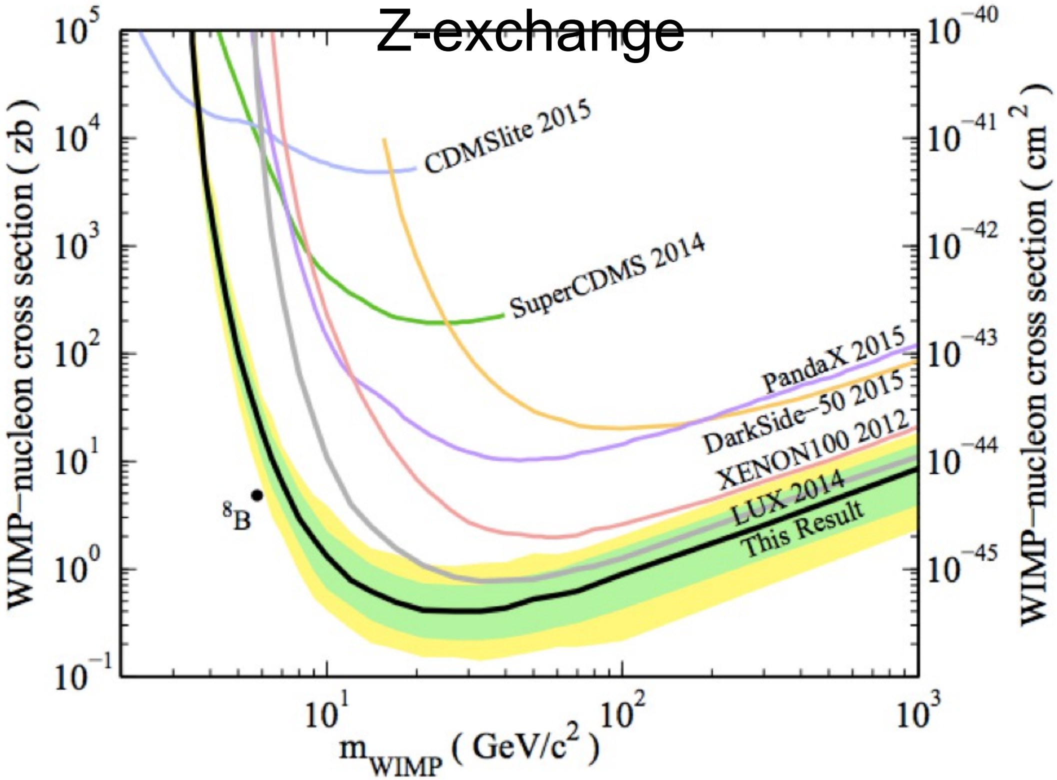
- Latest bounds on WIMP Dark Matter
- Blind spots (Cheung et al., 1211.4873)
- Pure DM states, in particular Higgsino Dark Matter

More and more experimental constraints...

… on this simple set-up

Direct detection experiments

Z-exchange



LUX collaboration, 1512.03506,
Phys.Rev.Lett. 116 (2016) 161301

Probing Higgs-exchange region

More and more experimental constraints...

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Direct detection experiments

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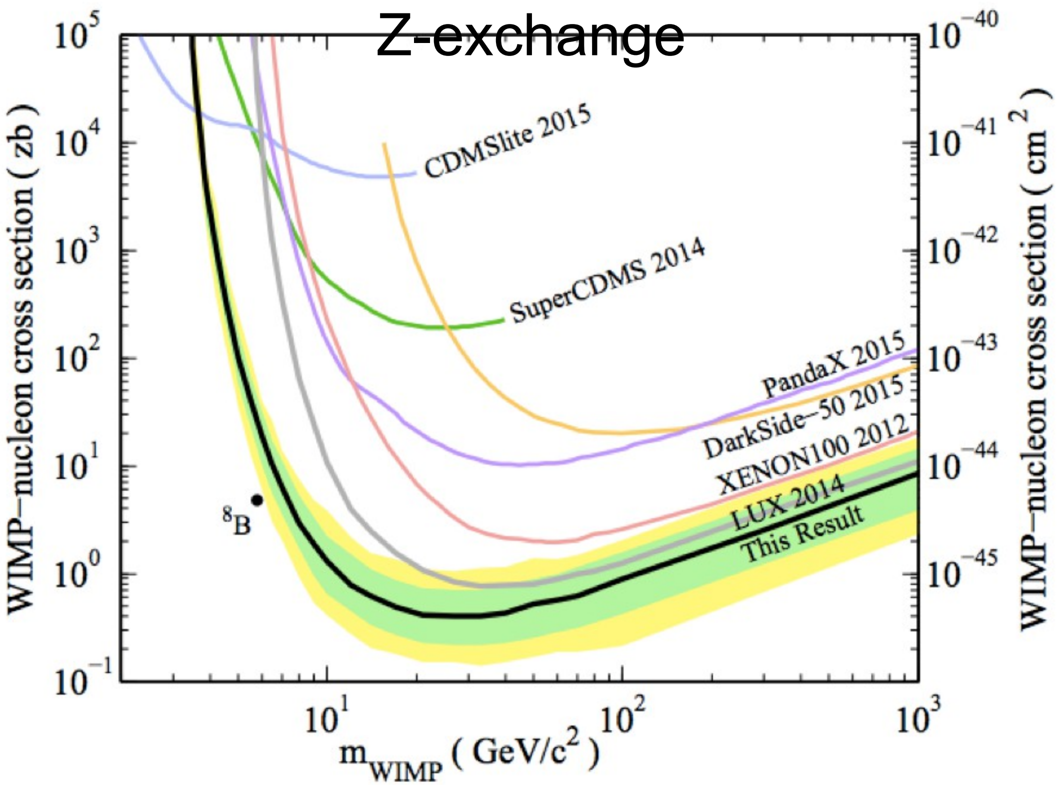
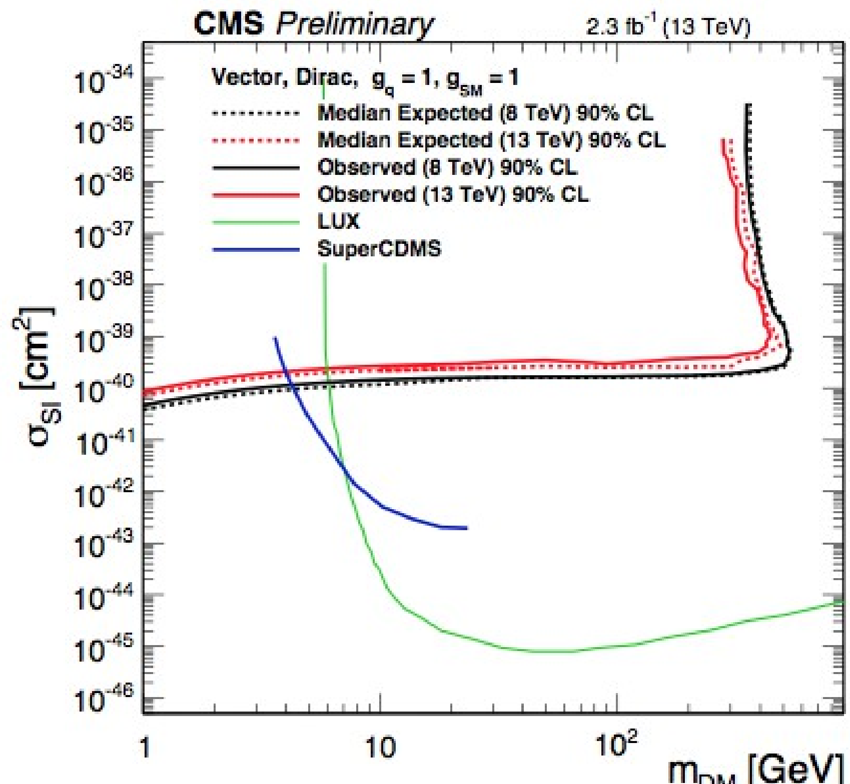


LUX collaboration, 1512.03506,
Phys.Rev.Lett. 116 (2016) 161301

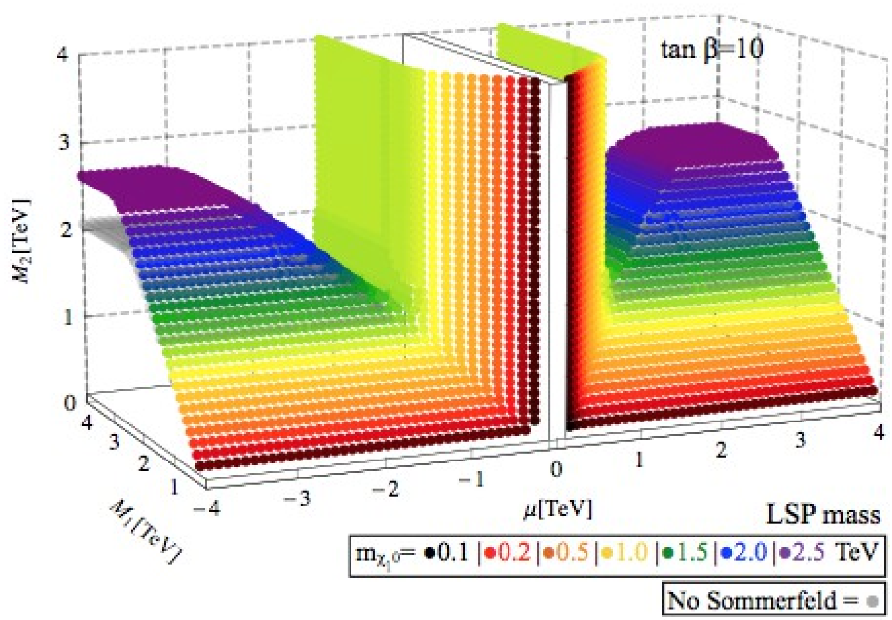
Collider searches



CMS-EXO-16-013

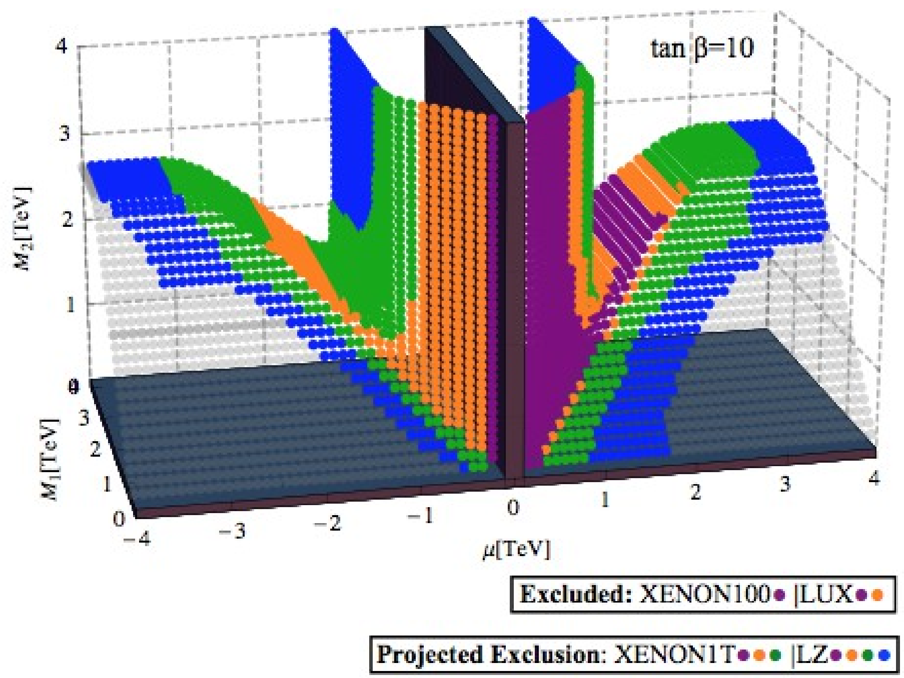
Probing Higgs-exchange region

SUSY constraints and blind spots



Combinations of neutralino mass parameters M_1, M_2, μ that produce the correct relic abundance

"Well tempered" neutralinos are (and will be) well probed by our direct detection experimental program



Bramante, et al. 1510.03460

How to probe generalized blind spots for which the tree-level contribution from the light Higgs exchange cancels the contribution from the heavy Higgs?

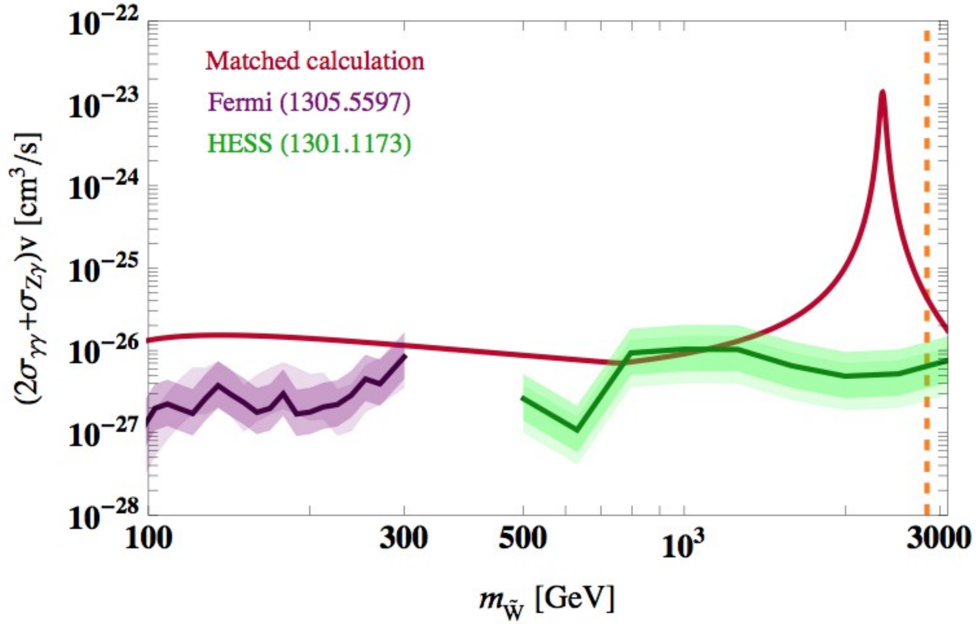
Huang, Wagner, 1404.0392

SUSY DM pure state (Wino)

Thermal scenario with mass at about **2.8 TeV**

See also
Beneke et al.,
1601.04718

Indirect detection



Fan, Reece, 1307.4400

Constraint on Wino annihilation into photon(s)

See also
Cohen et al., 1307.4082
Baumgart et al., 1412.8698

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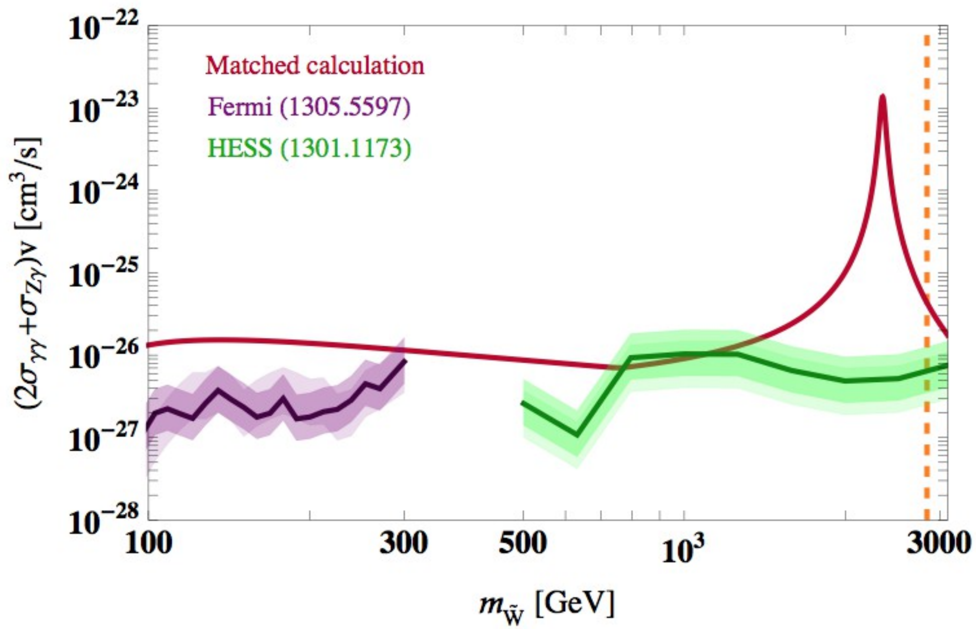

Fan, Reece, 1307.4400

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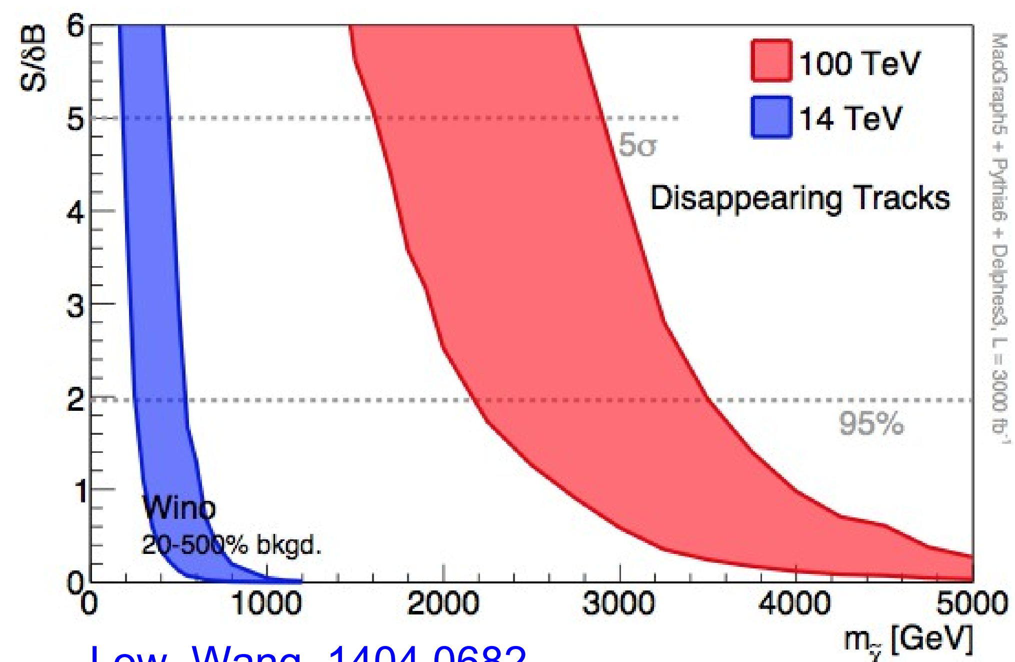
(Future) colliders



Low, Wang, 1404.0682

Constraints from disappearing tracks searches

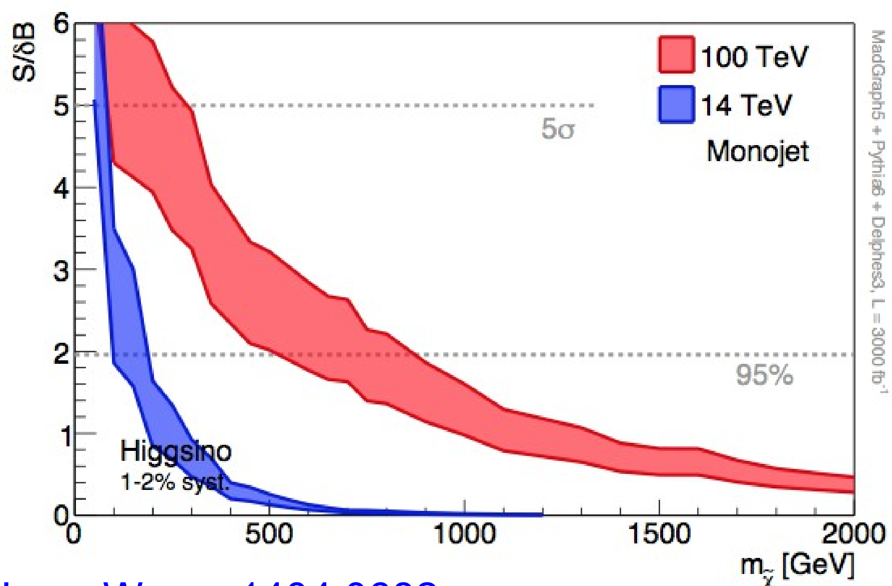
The challenge comes from the fact that we have a squeezed spectrum

SUSY DM pure state (Higgsino)

Thermal scenario with mass at about **1 TeV**

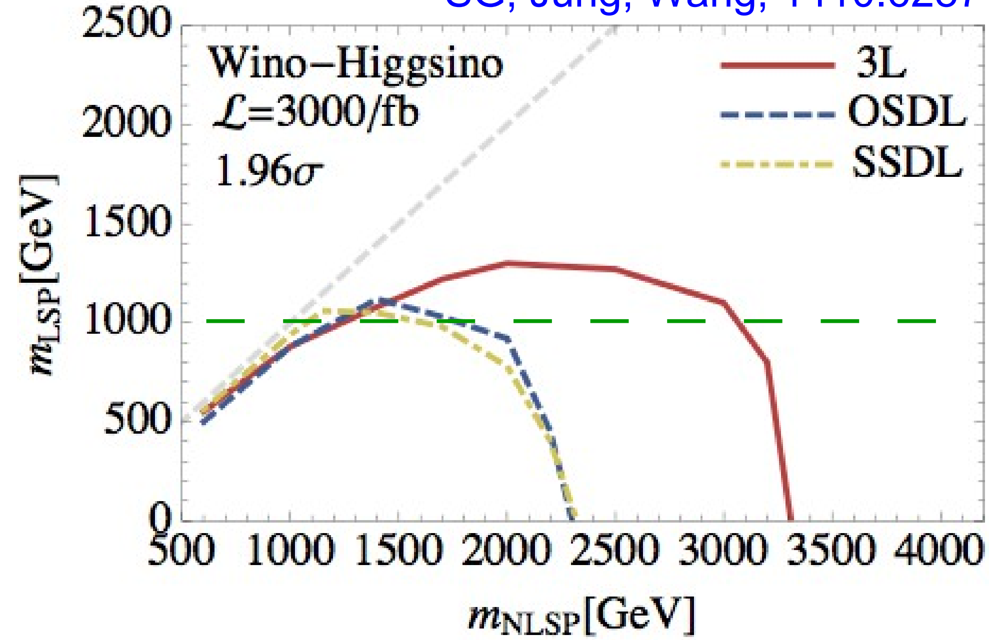
Spin-independent scattering cross-section is near/below the neutrino floor

(Future) colliders



Low, Wang, 1404.0682

SG, Jung, Wang, 1410.6287



Disappearing track searches are less powerful.
Best tested by mono-jet searches

Indirect probe if Winos are not too heavy

The challenge comes from the fact that we have a squeezed spectrum

Conclusions/discussion

SUSY LHC direct searches are complementary to

Mini-Split SUSY

Low energy flavor measurements

- Very stringent constraints on a general SUSY flavor violation setup
- SUSY with MFV is still a viable possibility, even with SUSY at ~TeV scale
- Flavor anomalies calling for SUSY?

SUSY with Minimal Flavor Violation (MFV)

DM searches

- Good coverage of the most vanilla SUSY scenarios
- How to optimize our chance to discover blind spots?
- How to probe SUSY DM pure state? In particular Higgsino states...