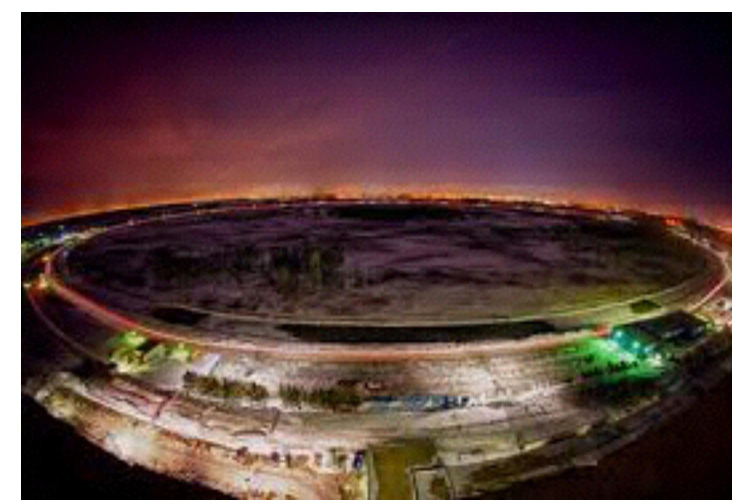
Cosmic Frontier-Collider Complementarity

Patrick Fox

Fermilab



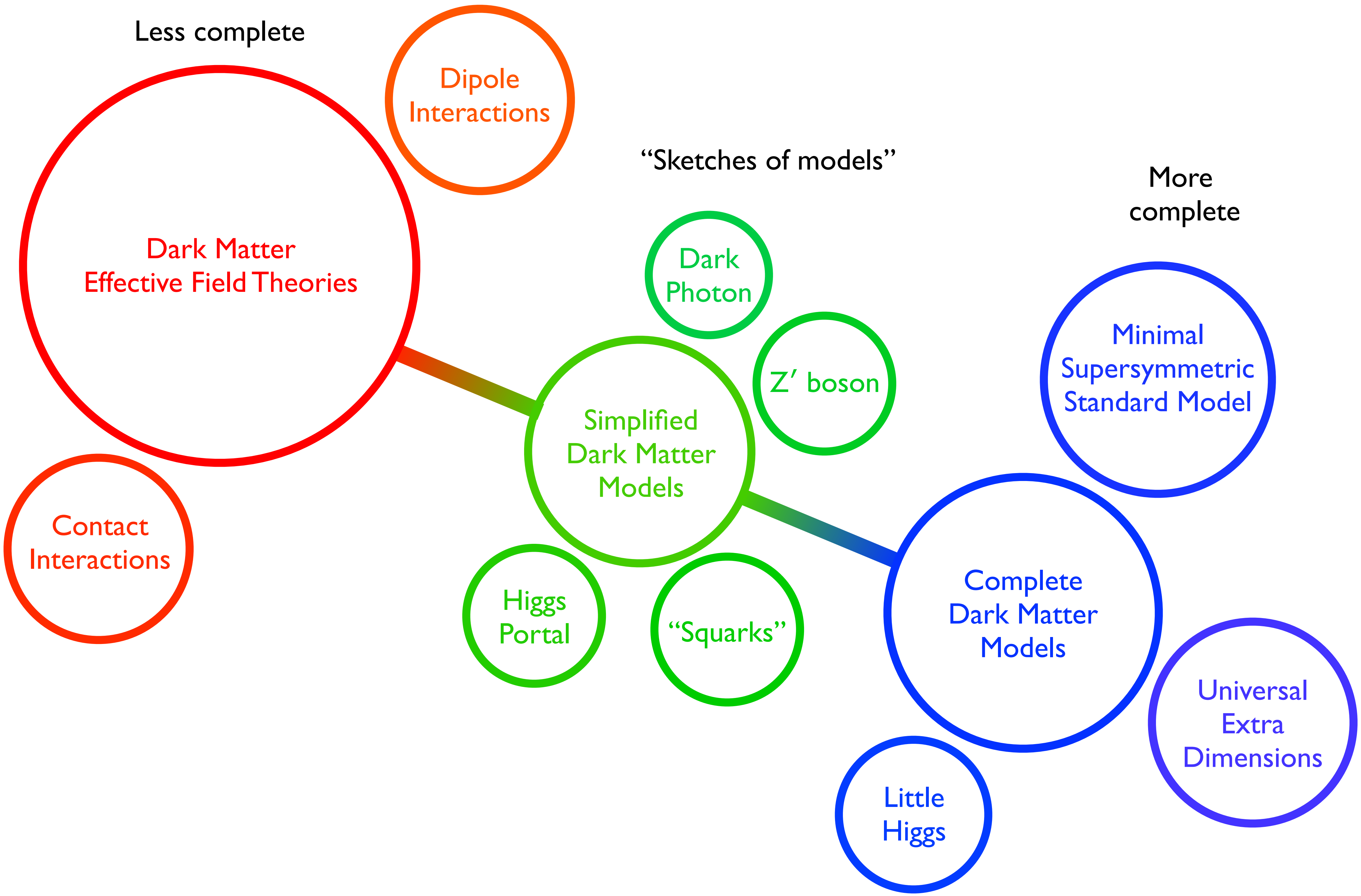
Outline

- Overview of dark matter's properties
- Overview of WIMP's properties
- Direct, Indirect searches
- Collider searches

Lecture II

- Electroweakinos, a case study
- Light mediators, light dark matter
- Conclusions

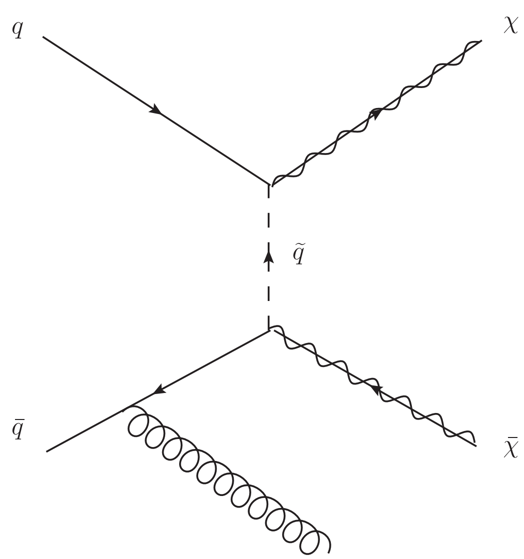
Ways to search for DM at colliders



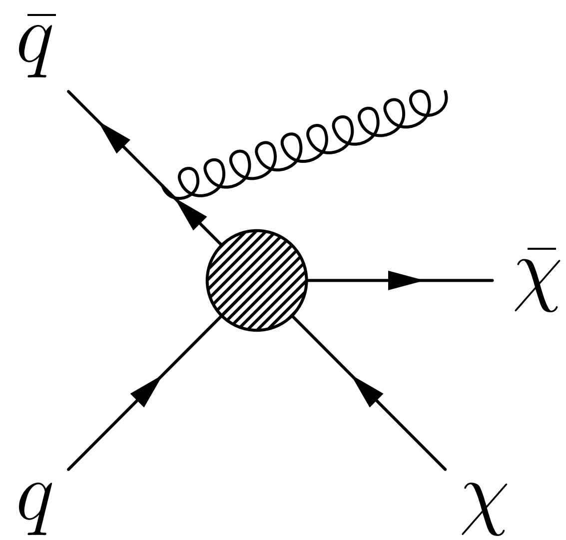
Simplified Models

"Integrate in" the mediator

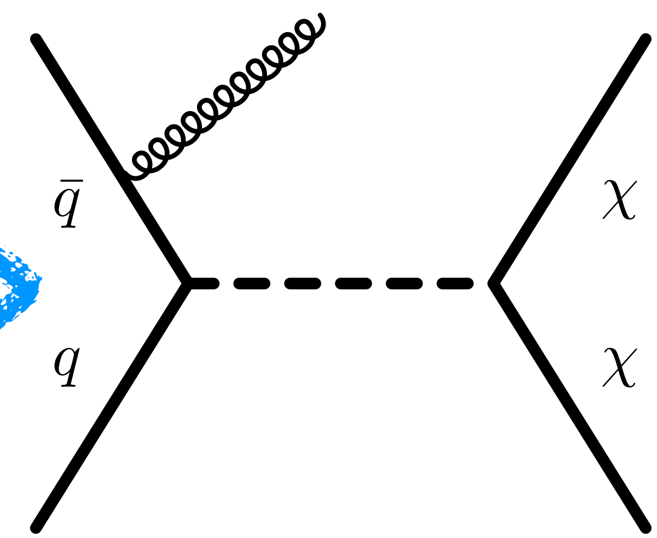
t-channel



EFT



s-channel

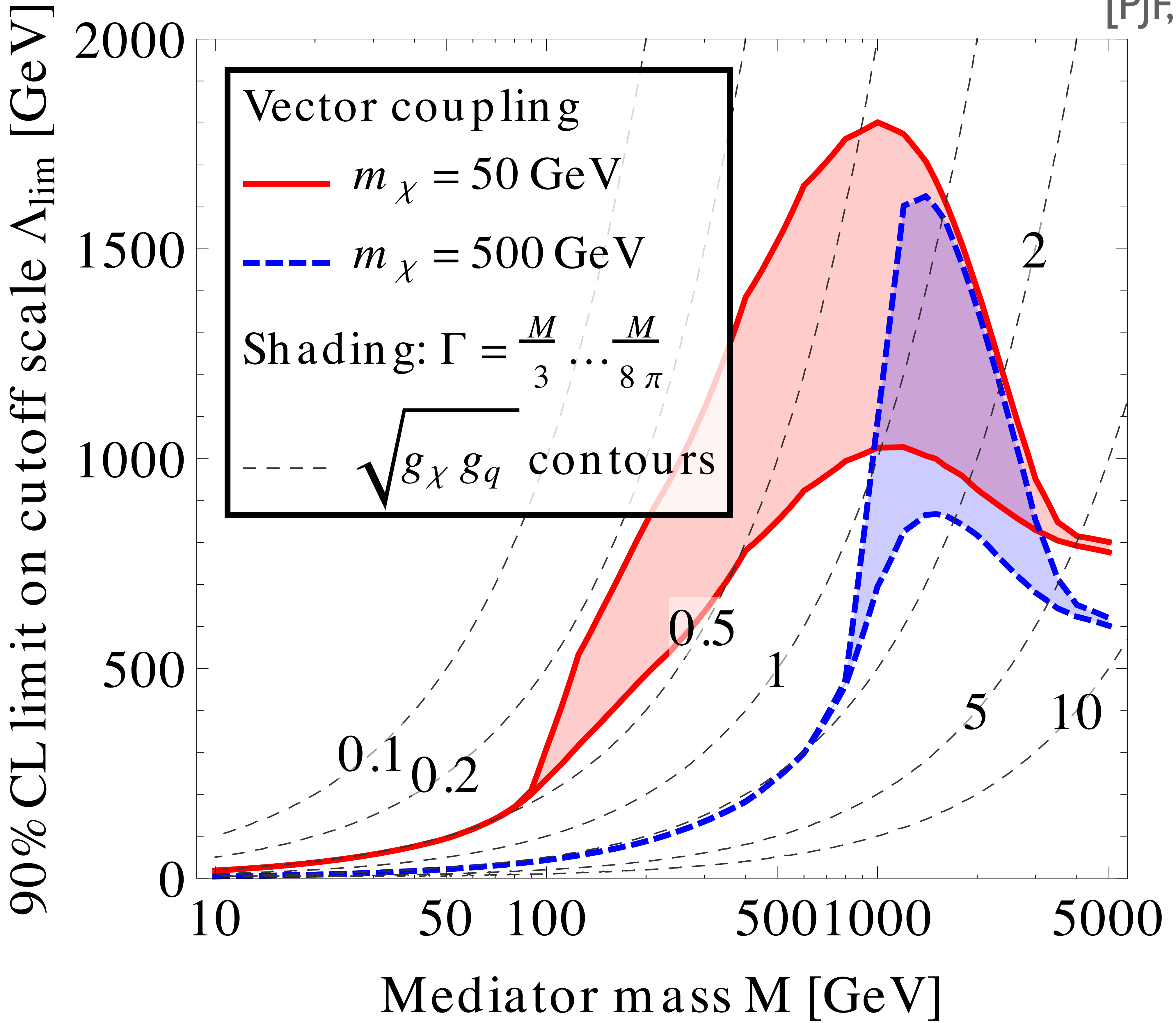


$$\Lambda,\ m_\chi \longrightarrow m_\chi,\ M,\ \Gamma,\ \sqrt{g_q g_\chi}$$

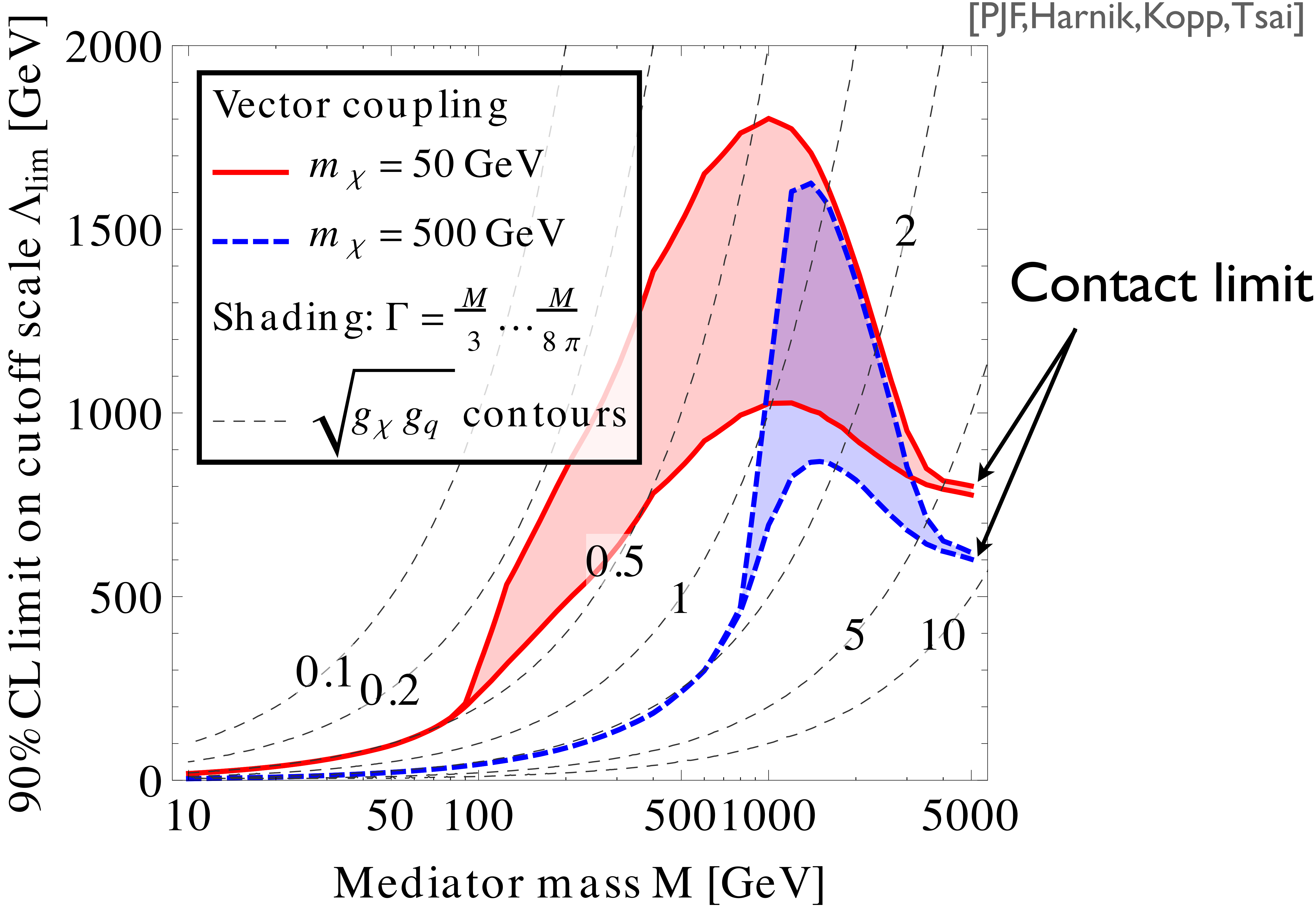
New channels to search for!

Collider only sensitive to all 4 parameters over a narrow range

But mapping collider constraints to direct/indirect detection now requires assumptions



90% CL limit on cutoff scale Λ_{lim} [GeV]
2000
1500
1000
500
0
Vector coupling
$m_\chi = 50$ GeV
$m_\chi = 500$ GeV
Shading: $\Gamma = \frac{M}{3} \ldots \frac{M}{8\pi}$
$\sqrt{g_\chi g_q}$ contours
0.1
0.2
0.5
1
2
5
10
10
50
100
500
1000
5000
Mediator mass M [GeV]



[PJF,Harnik,Kopp,Tsai]
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Contact limit
90% CL limit on cutoff scale $\Lambda_{\rm lim}$ [GeV]
Mediator mass M [GeV]
0.1
0.2
0.5
1
2
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2000
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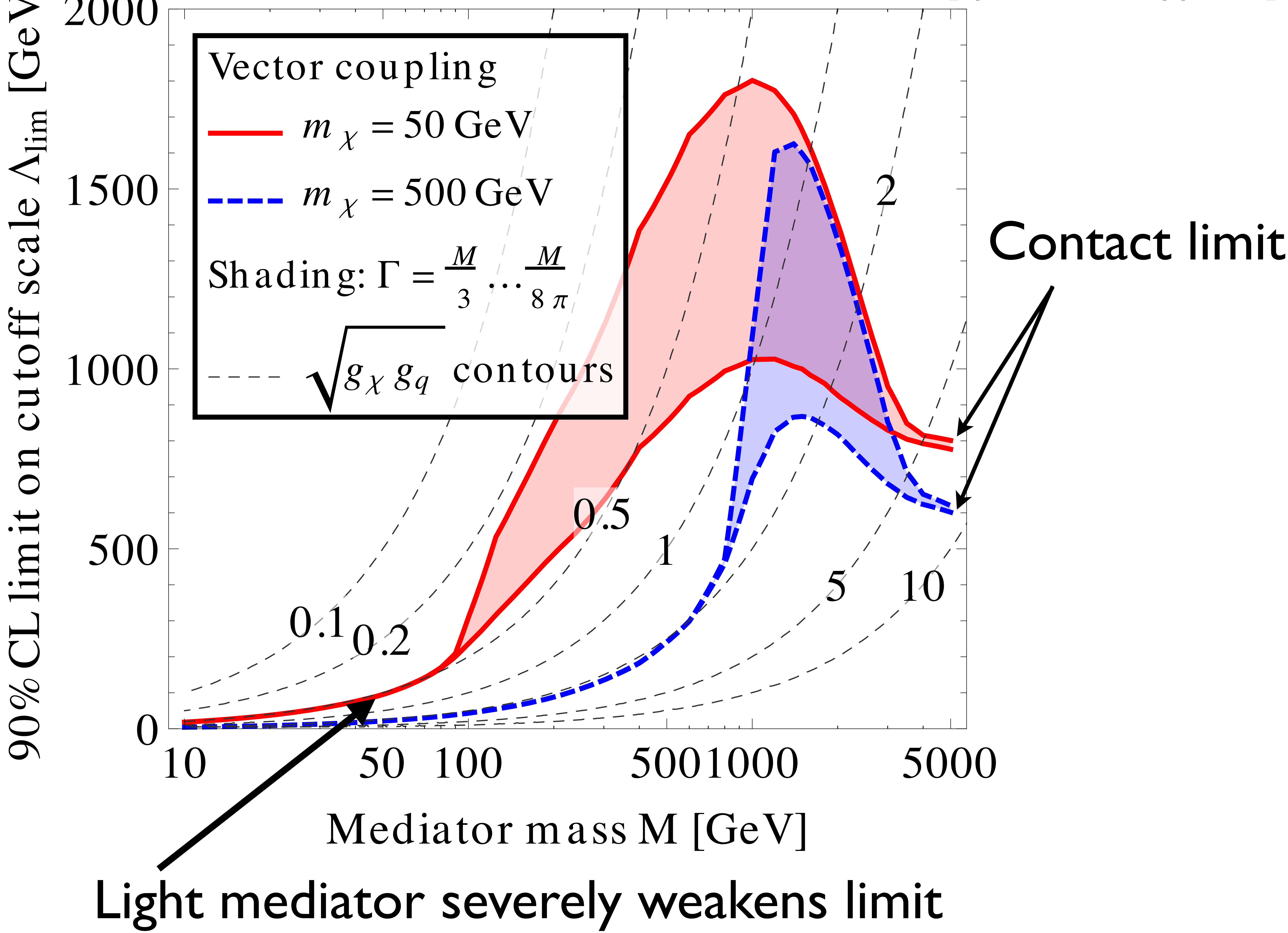
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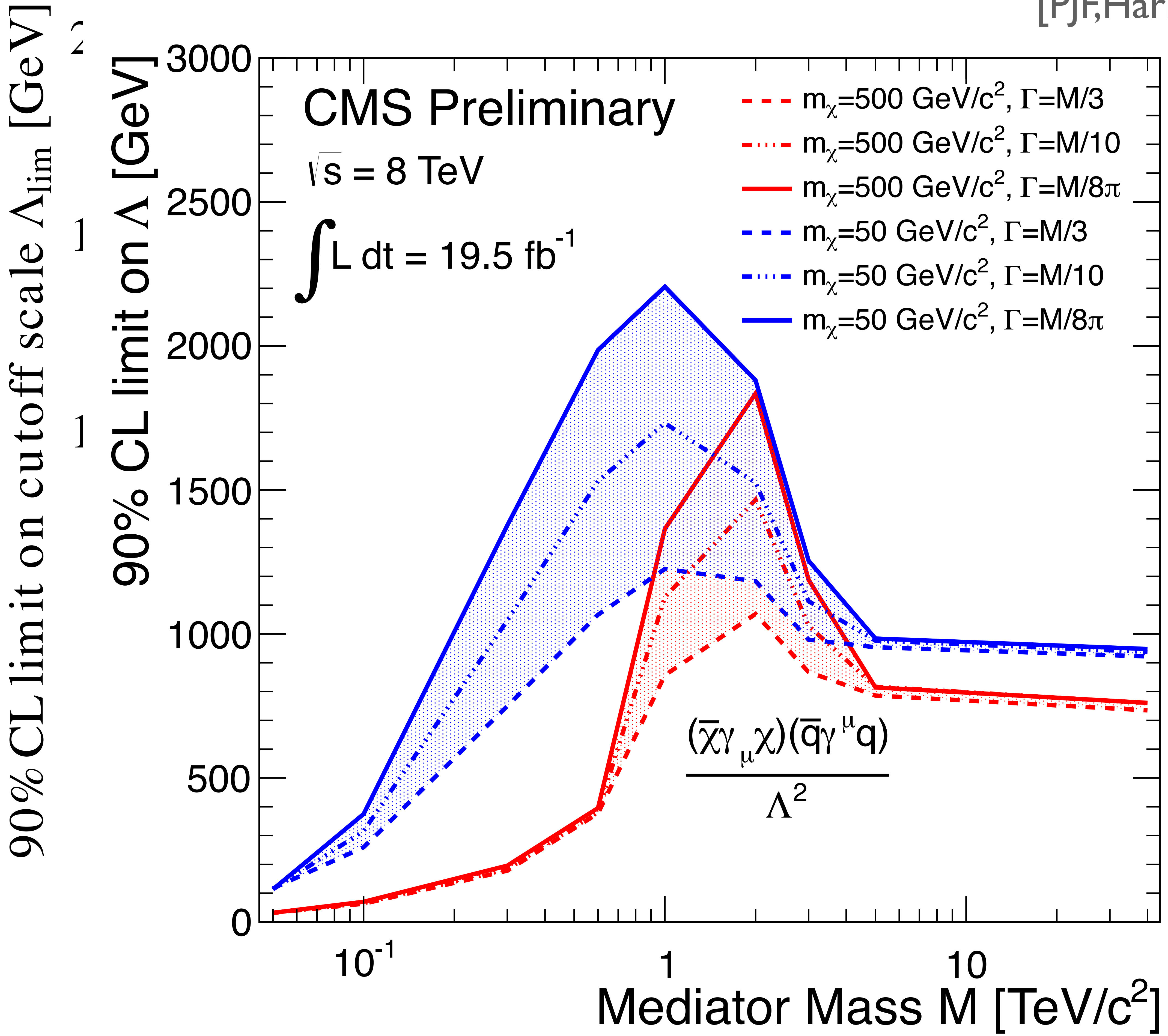
Contact limit
Light mediator severely weakens limit

[PJF,Harnik,Kopp,Tsai]

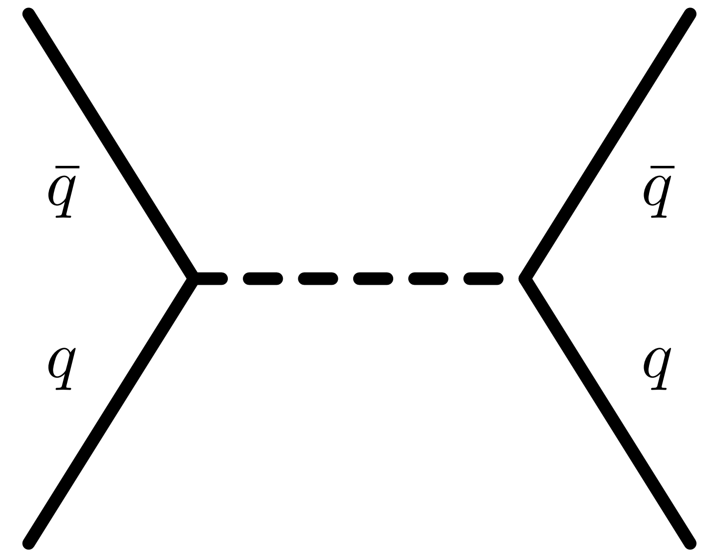


ntact limit

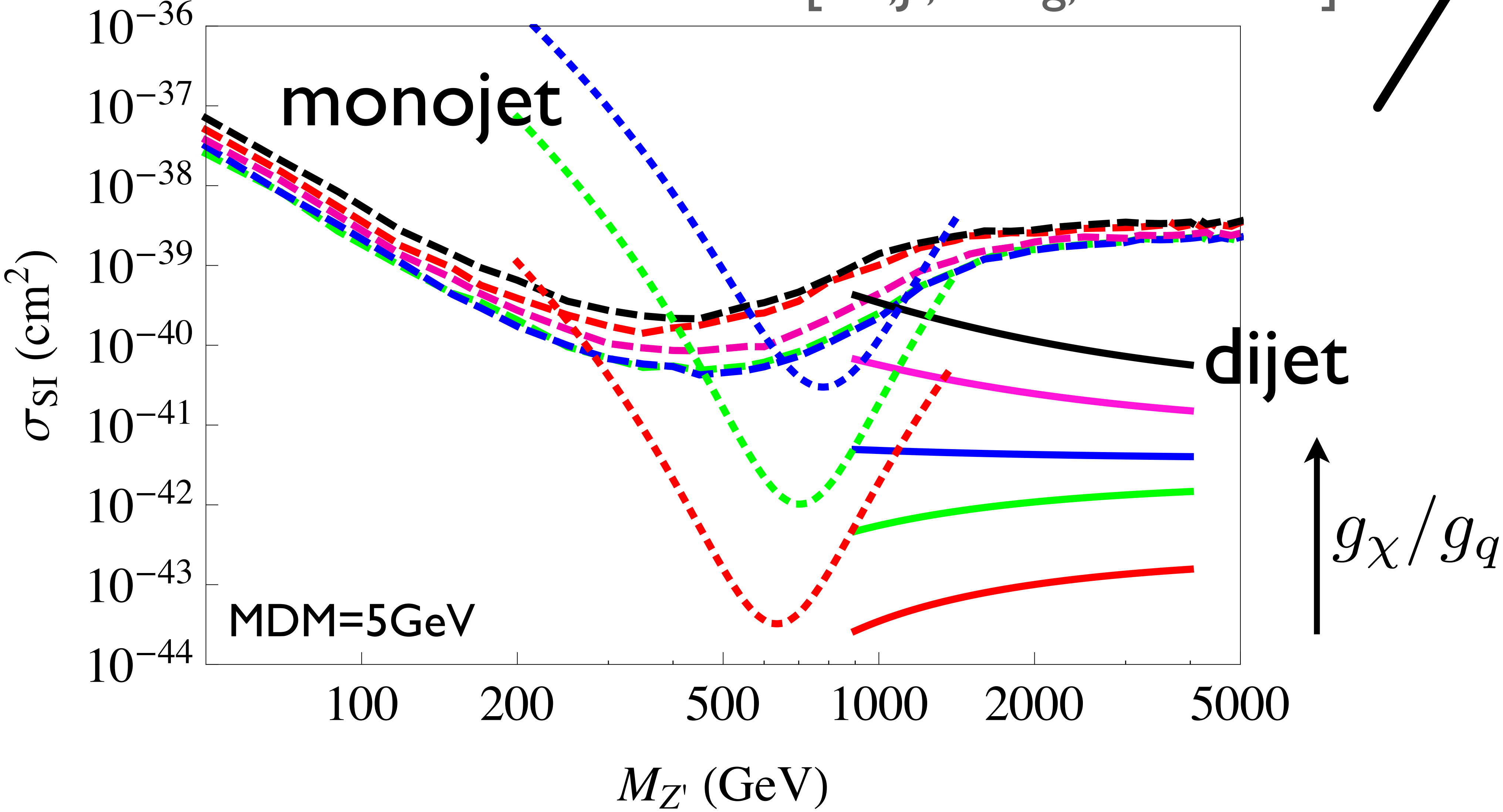
Light Mediators

[An,Ji,Wang:1202.2894;March-Russell, Unwin,West: 1203.4854]

Look for the light mediator directly-dijet resonance/angular distributions



[An,Ji,Wang, 1202.2894]



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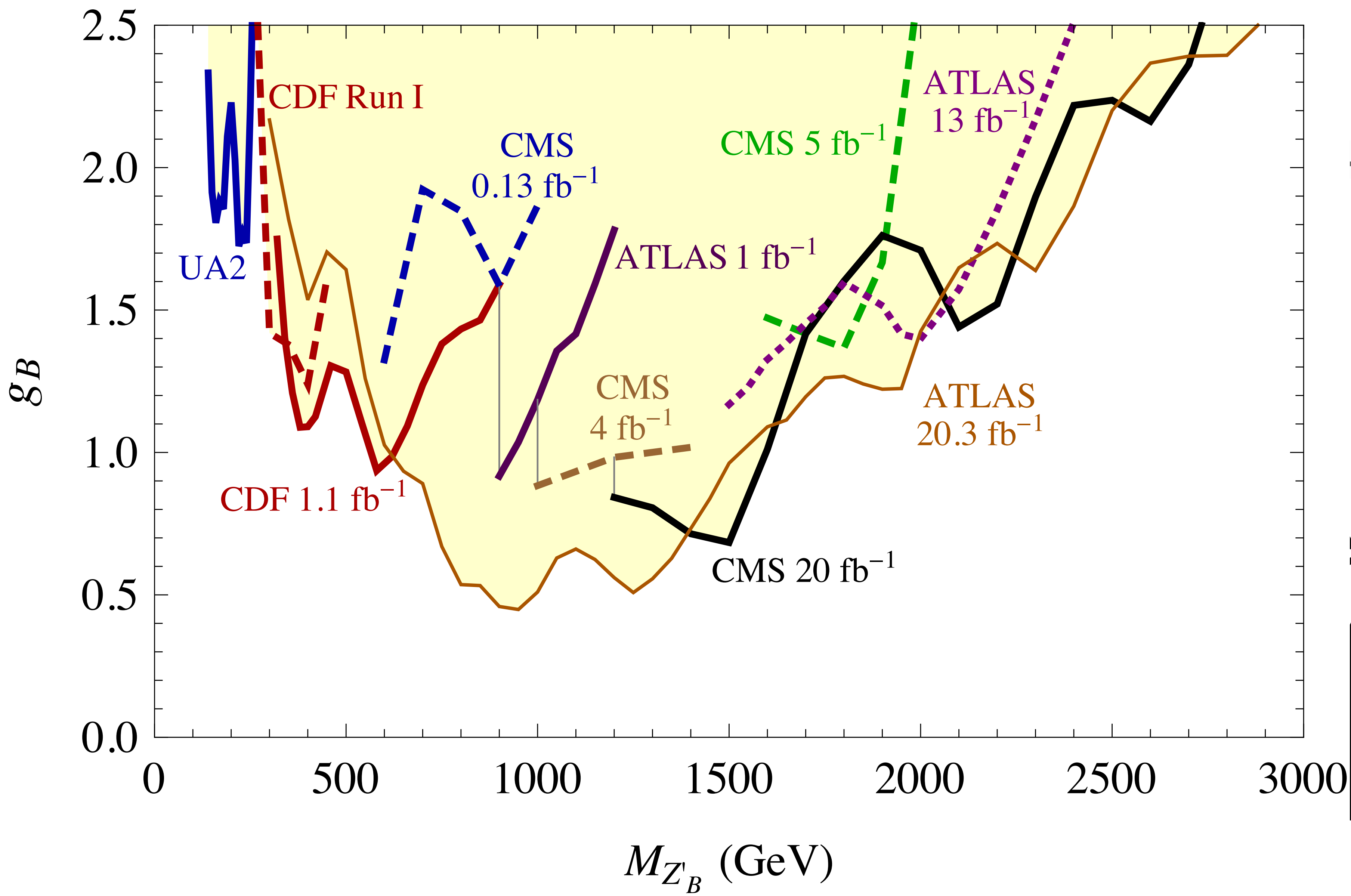

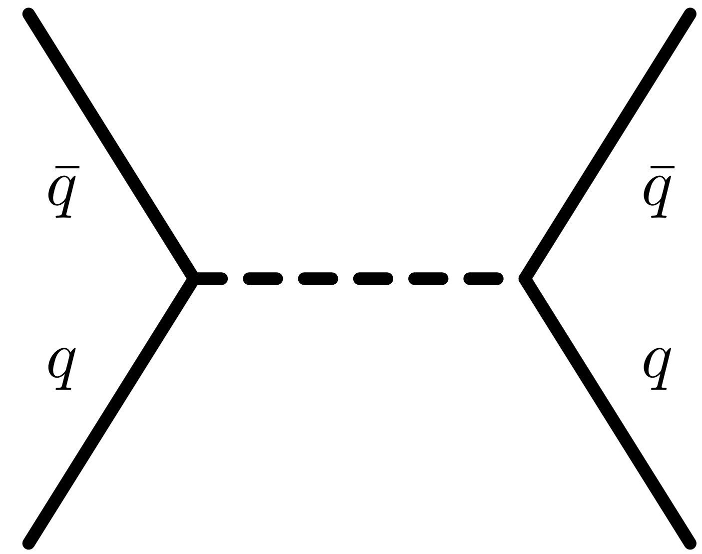

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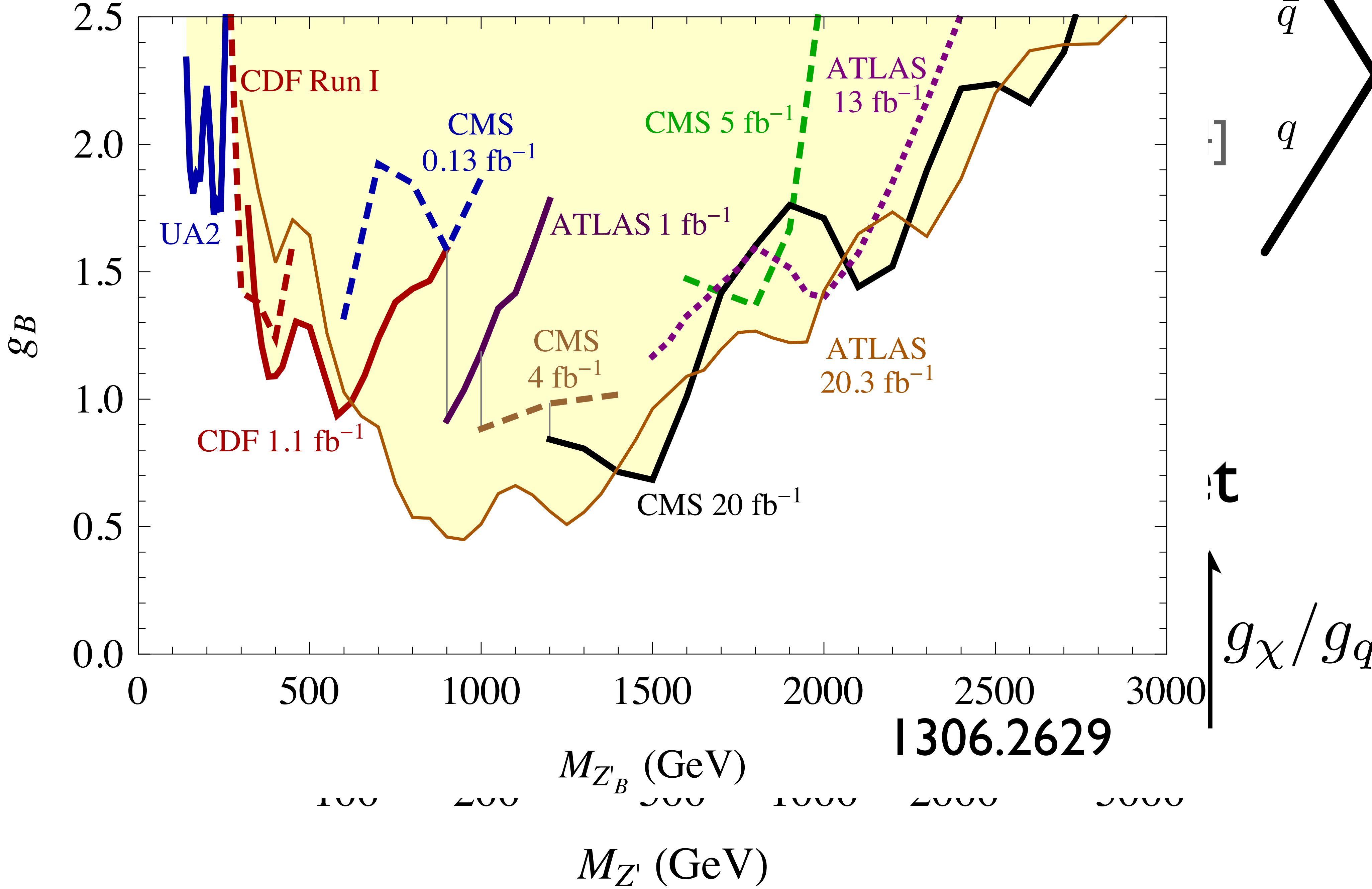
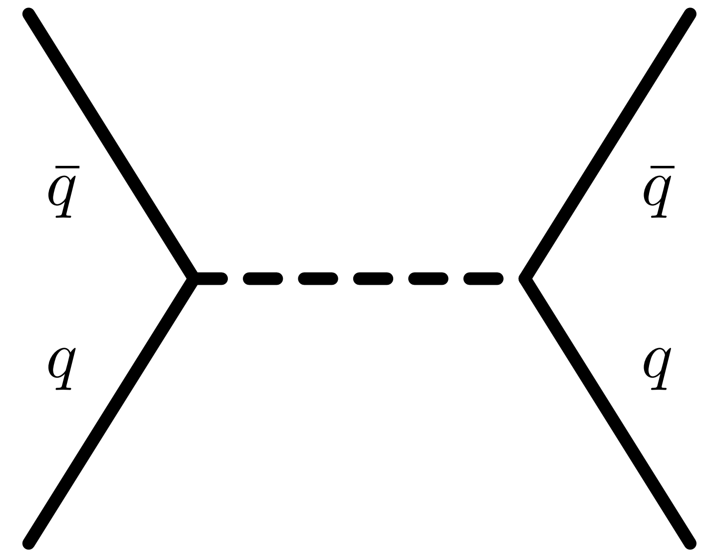


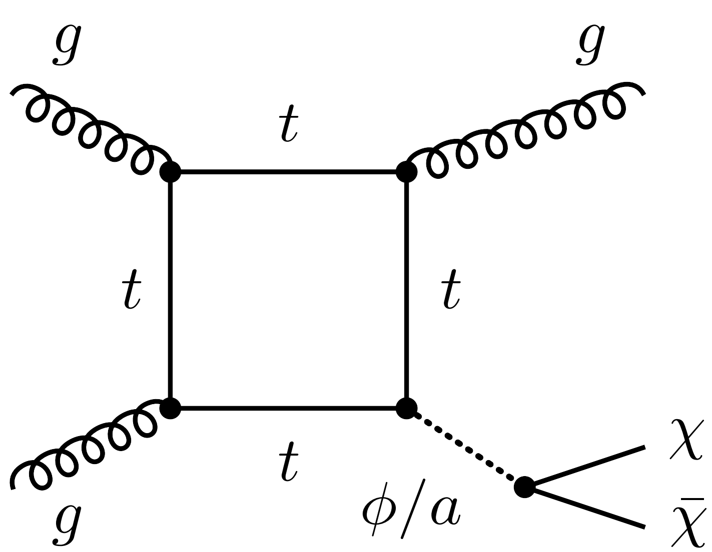
1306.2629



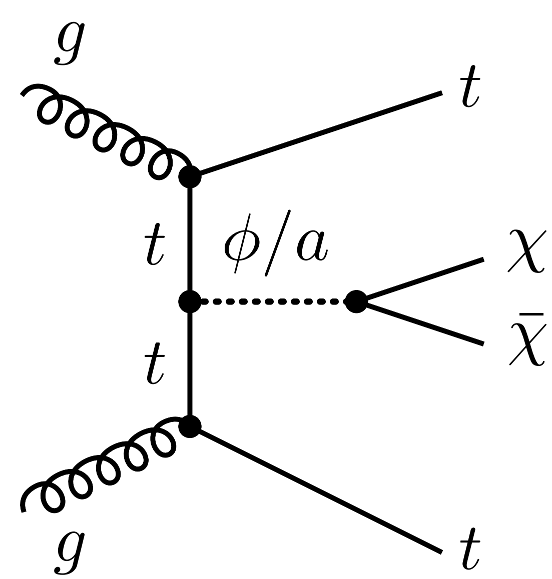
Types of Simplified models

s-channel scalar/psuedo-scalar

MFV: $\lambda_\chi \phi \bar{\chi}\chi + \lambda_U \phi \left(Y_U^{ij} Q_i H U_j^c \right)$ Physics dominated by top



monojet



tops + MET

- Scalars have helicity suppressed annihilation, and SI DD
- Pseudo scalars do not, and have SD momentum suppressed DD

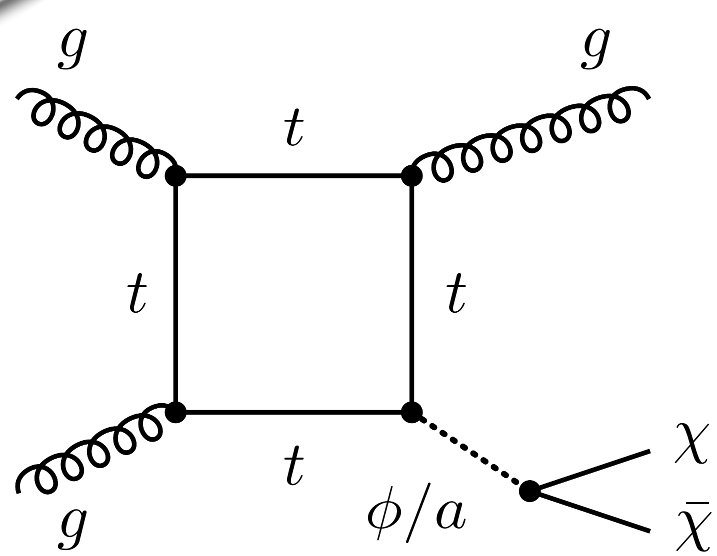
Types of Simplified models

s-channel scalar/ … -scalar

See talk by Jure Zupan

MFV: … $\phi \left(Y_U^{ij} Q_i H U_j^c \right)$

Physics dominated by top



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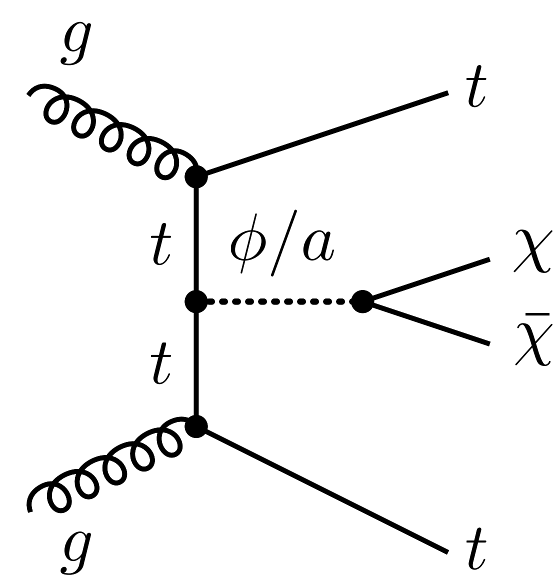

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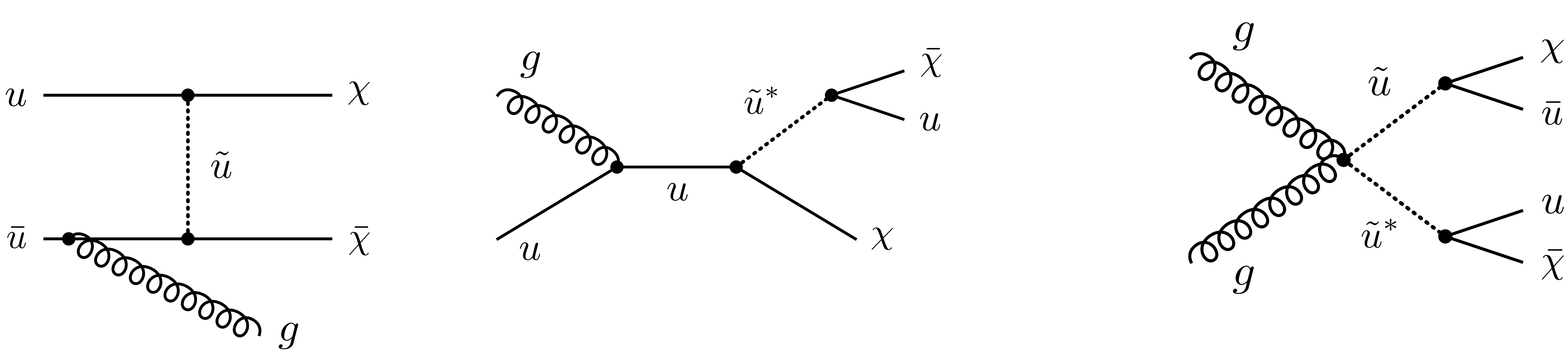
Types of Simplified models

t-channel scalar/psuedo-scalar

MFV requires DM or mediator to carry flavour $\lambda \phi_i \bar{\chi} q_i$

(Like in SUSY MFV allows for separation of 1,2 from 3 gen.)



monojet

jets+MET

Majorana has only SD, Dirac has both

Dirac cannot be a thermal relic, Majorana can if > 100 GeV

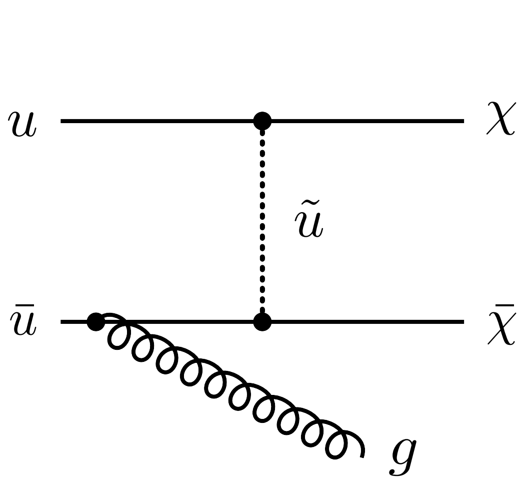
Types of Simplified models

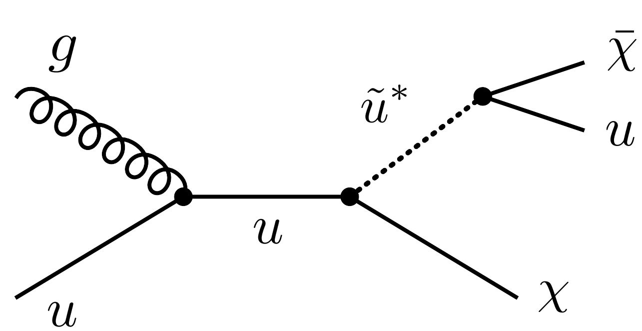
t-channel scalar/psuedo-scalar

“squarks” w/o SUSY prior

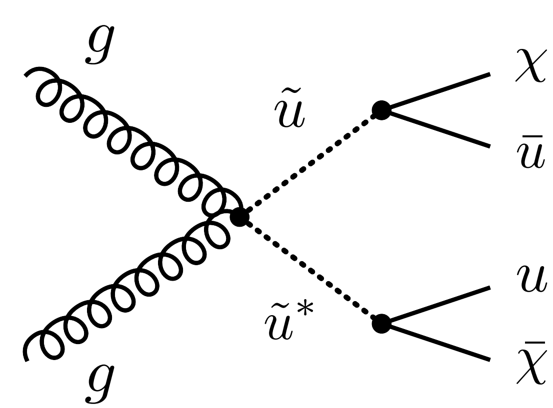
MFV requires DM or mediator to c[...] flavour $\lambda \phi_i \bar{\chi} q_i$

(Like in SUSY MFV allows for separation of 1,2 from 3 gen.)





monojet



jets+MET

Majorana has only SD, Dirac has both
Dirac cannot be a thermal relic, Majorana can if > 100 GeV

Types of Simplified models

s-channel vector/axial-scalar

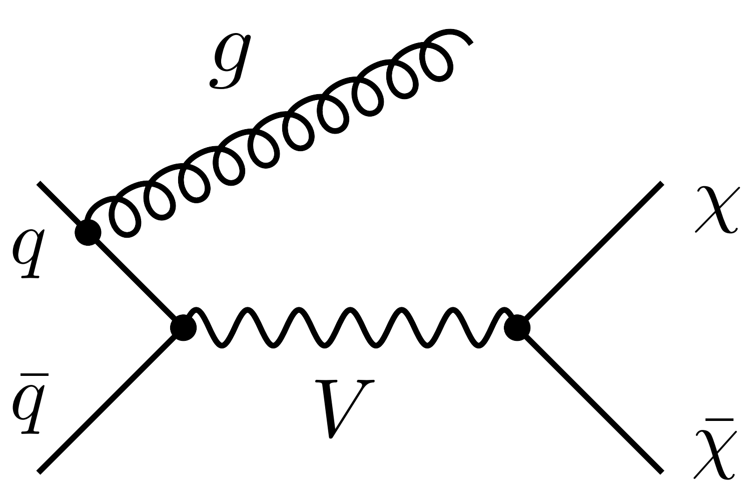
Spontaneously broken $U(1)'$

(Higgs mode may be accessible, can alter physics)

Consistency of model? How does DM get mass, anomalies…

$$m_\chi \lesssim \frac{\sqrt{4\pi}}{g_\chi^A} M_V$$

Bounds on dileptons, leptophobic Z'



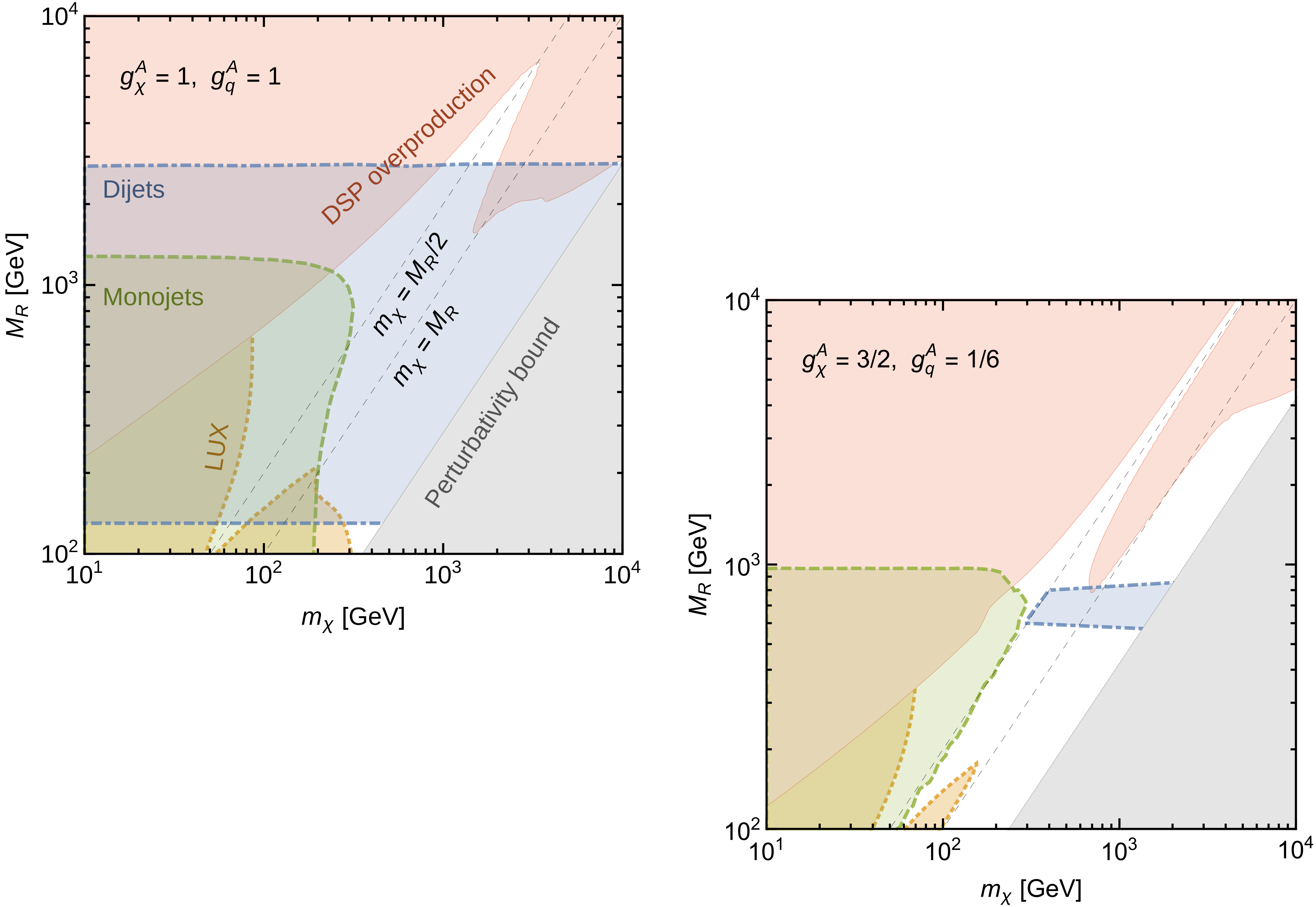
monojet

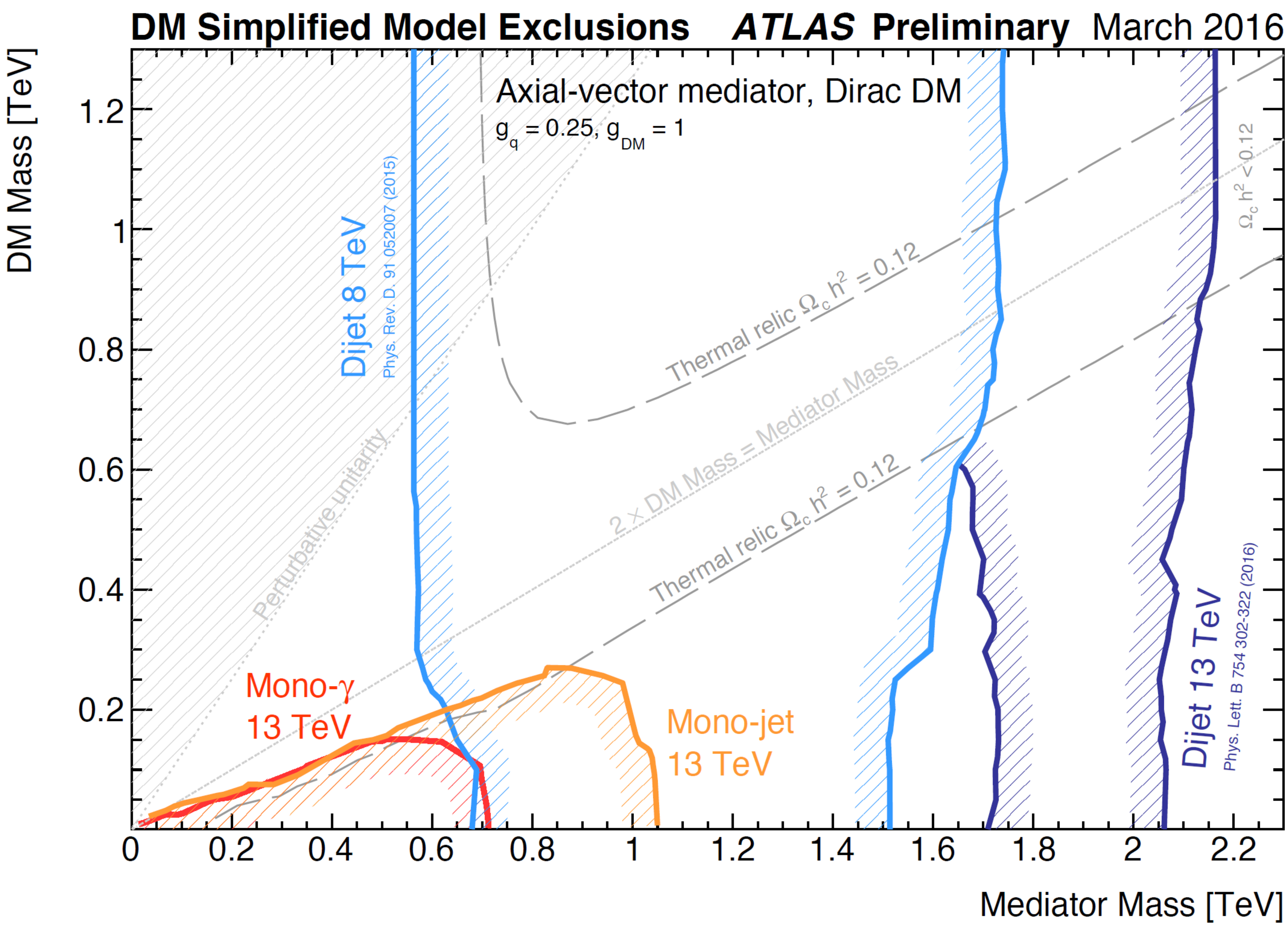
- Vectors are SI
- Axial vectors SD
- If thermal often underproduced

Types of Simplified models

- Landscape of simplified models is broad and varied
- Spin/parity of DM and mediator
- MFV
- Kinetic mixing
- Higgs portal
- Vector DM
- Other dark sector states alter thermal history & BRs
- Electroweak-inos, singlet-doublet DM, etc

[Chala, Kahlhoefer, McCullough, Nardini, Schmidt-Hoberg]




DM Simplified Model Exclusions ATLAS Preliminary March 2016
Axial-vector mediator, Dirac DM
g_q = 0.25, g_DM = 1
DM Mass [TeV]
Mediator Mass [TeV]
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Perturbative unitarity
Thermal relic Ω_c h² = 0.12
2 × DM Mass = Mediator Mass
Ω_c h² < 0.12
Mono-γ
13 TeV
Mono-jet
13 TeV
Dijet 13 TeV
Phys. Lett. B 754 302-322 (2016)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2

Higgs and DM

[Fox, Harnik, Kopp, Tsai]

- The Higgs exists. DM exists.
- The Higgs is a motivated candidate for mediator of DM interaction. a.k.a. the **Higgs Portal**.
- Assuming Standard Higgs production:

Limit on invisible Higgs.

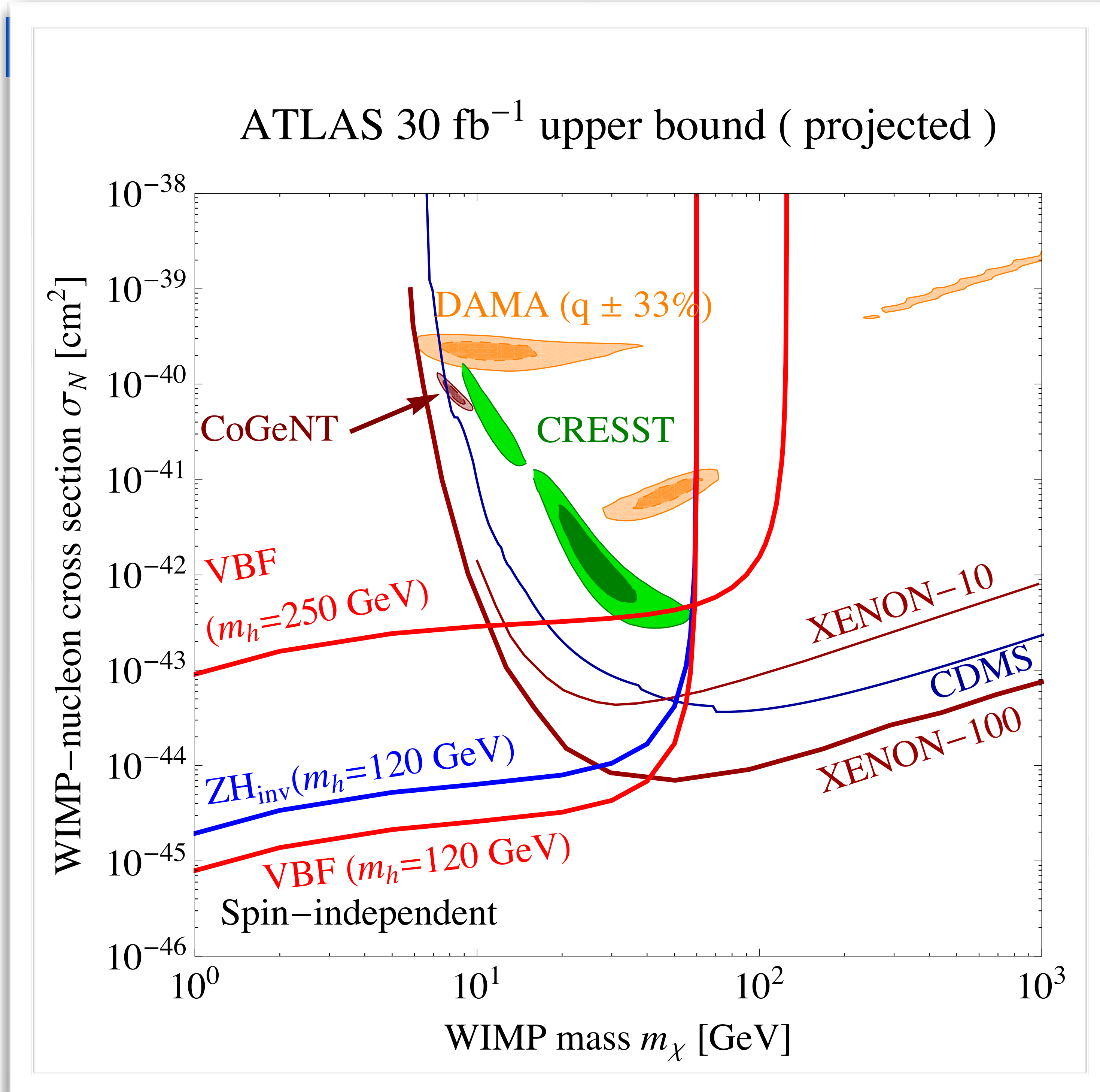
↓

Limit on Higgs-DM coupling.

↓

Limit on direct detection.

[Fox, Harnik, Kopp, Tsai]



or mediator of DM

:

Higgs.

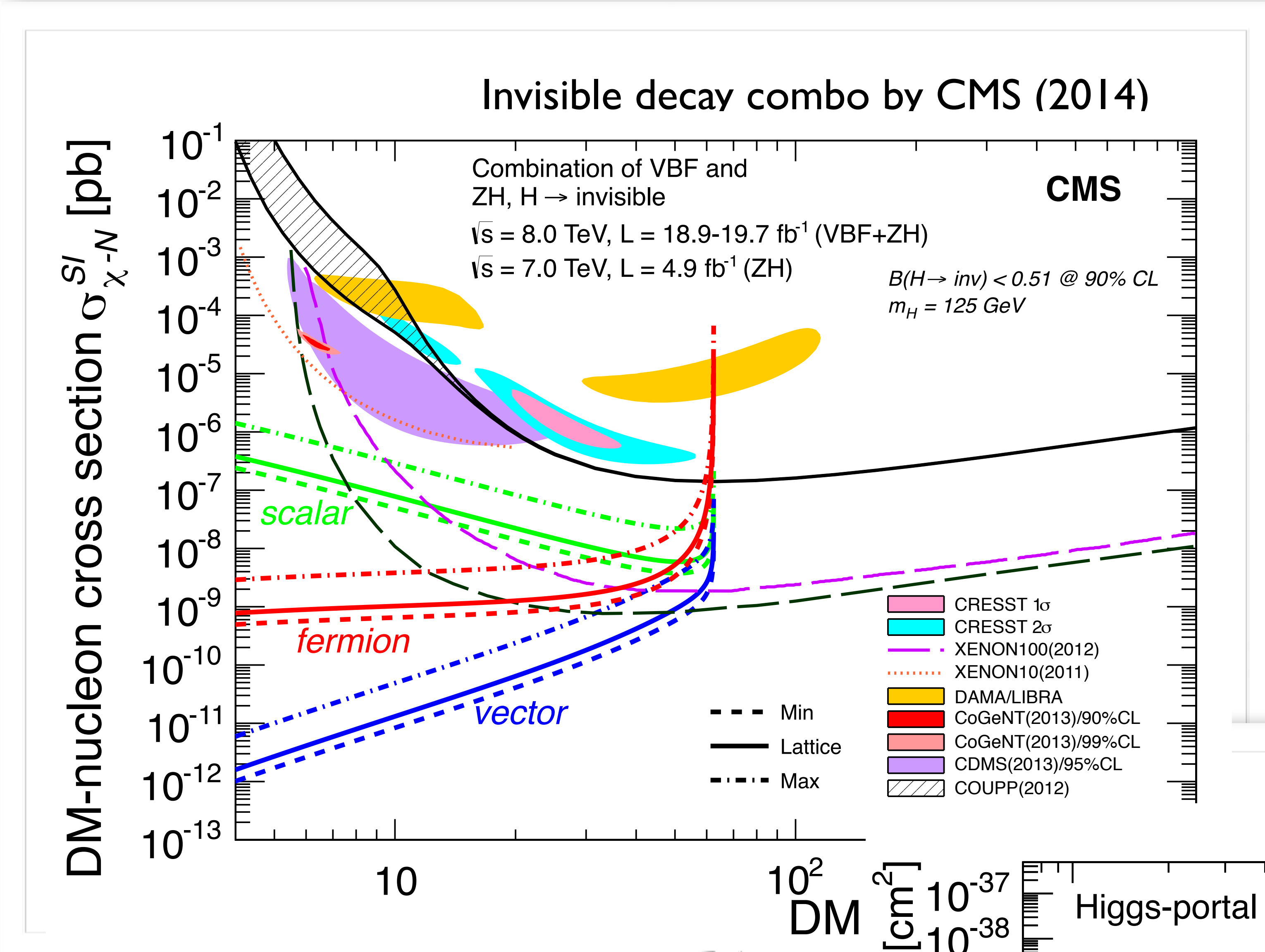
Limit on Higgs-DM coupling.

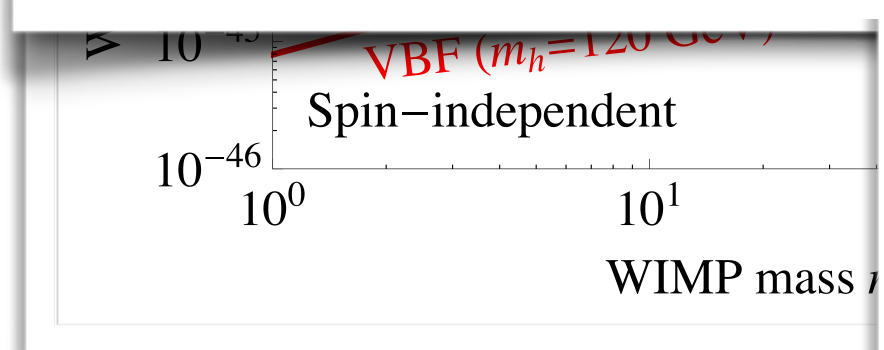
↓

Limit on direct detection.

[Fox, Harnik, Kopp, Tsai]

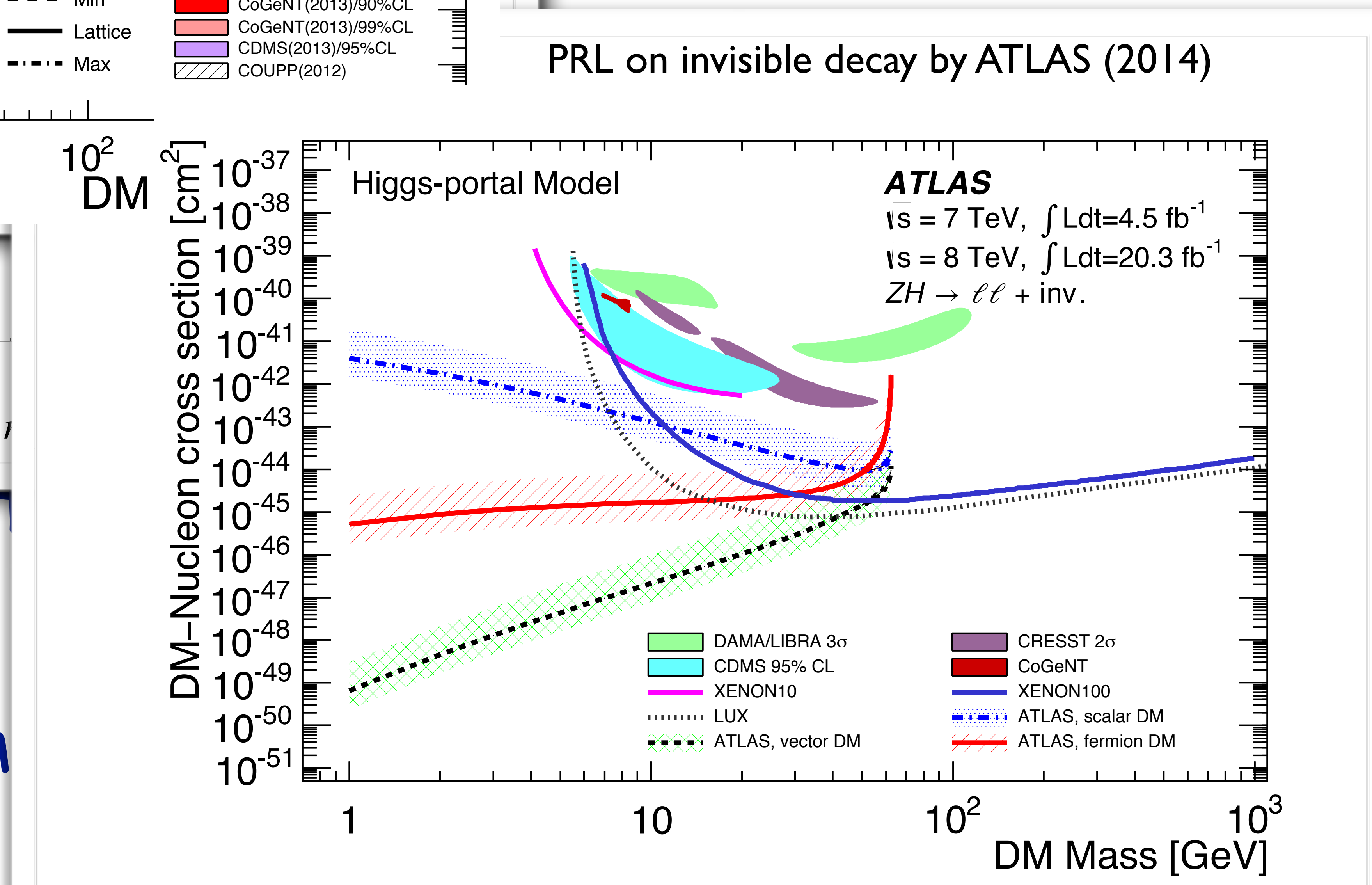
r mediator of DM





Limi

Lim



What next?

"Mono" searches: $\Delta\phi(j_1, j_2) < 2.5 \quad N_{jet} \leq 2$

LHC is a jets "factory", can we do better?

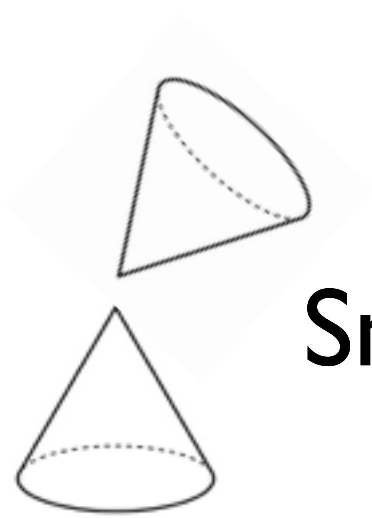
Steal from SUSY jets+MET analyses

[Rogan 1006.2727]

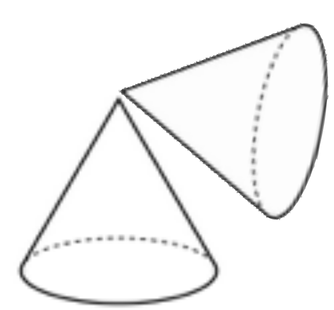
$$M_R = \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_R^T = \sqrt{\frac{\not{E}_T(p_T^{j_1} + p_T^{j_2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

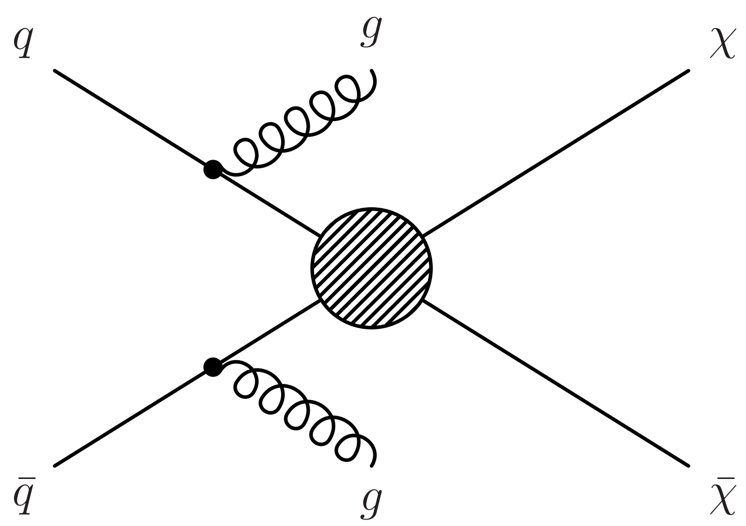
$$R = \frac{M_R^T}{M_R}$$



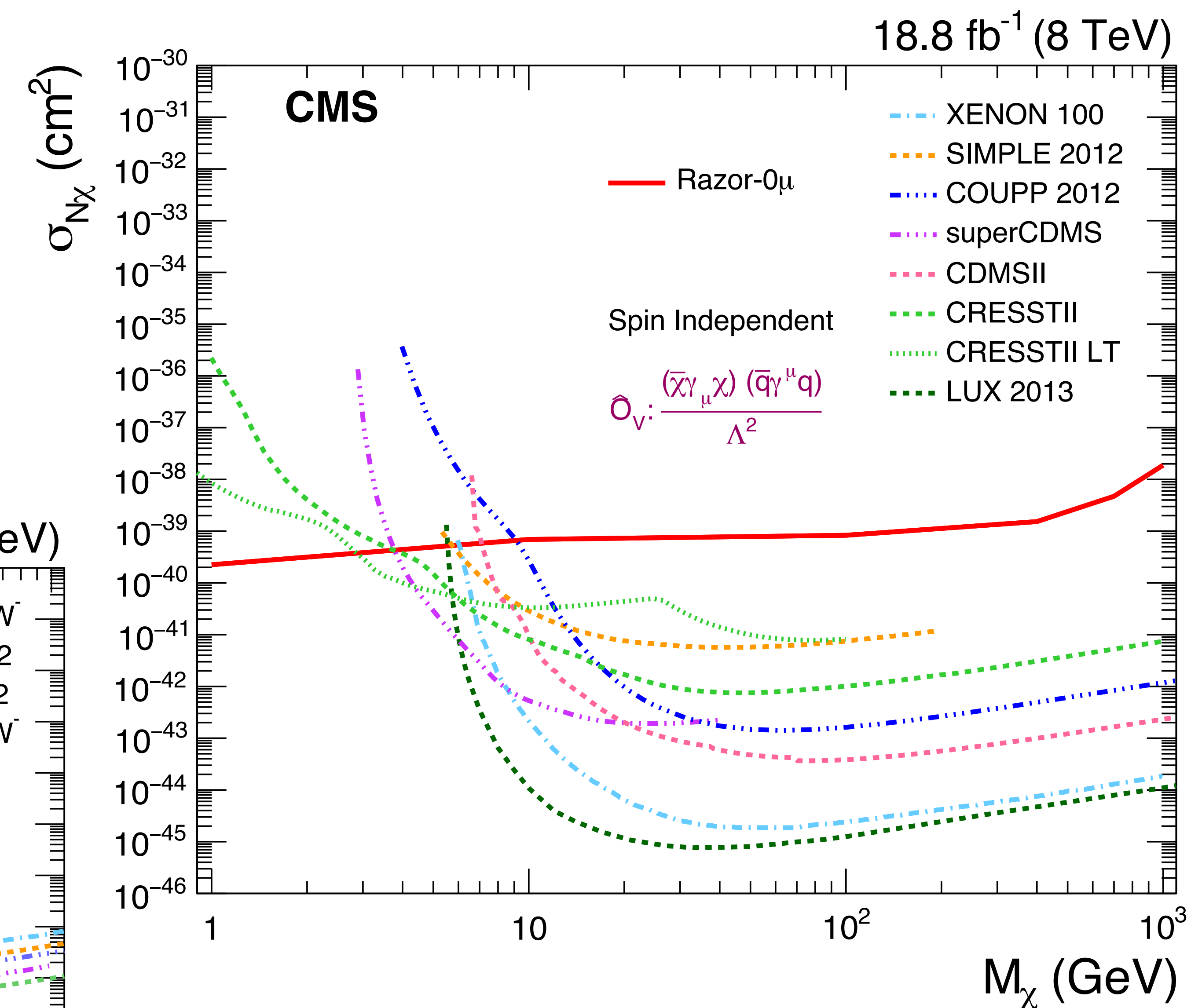
Small R

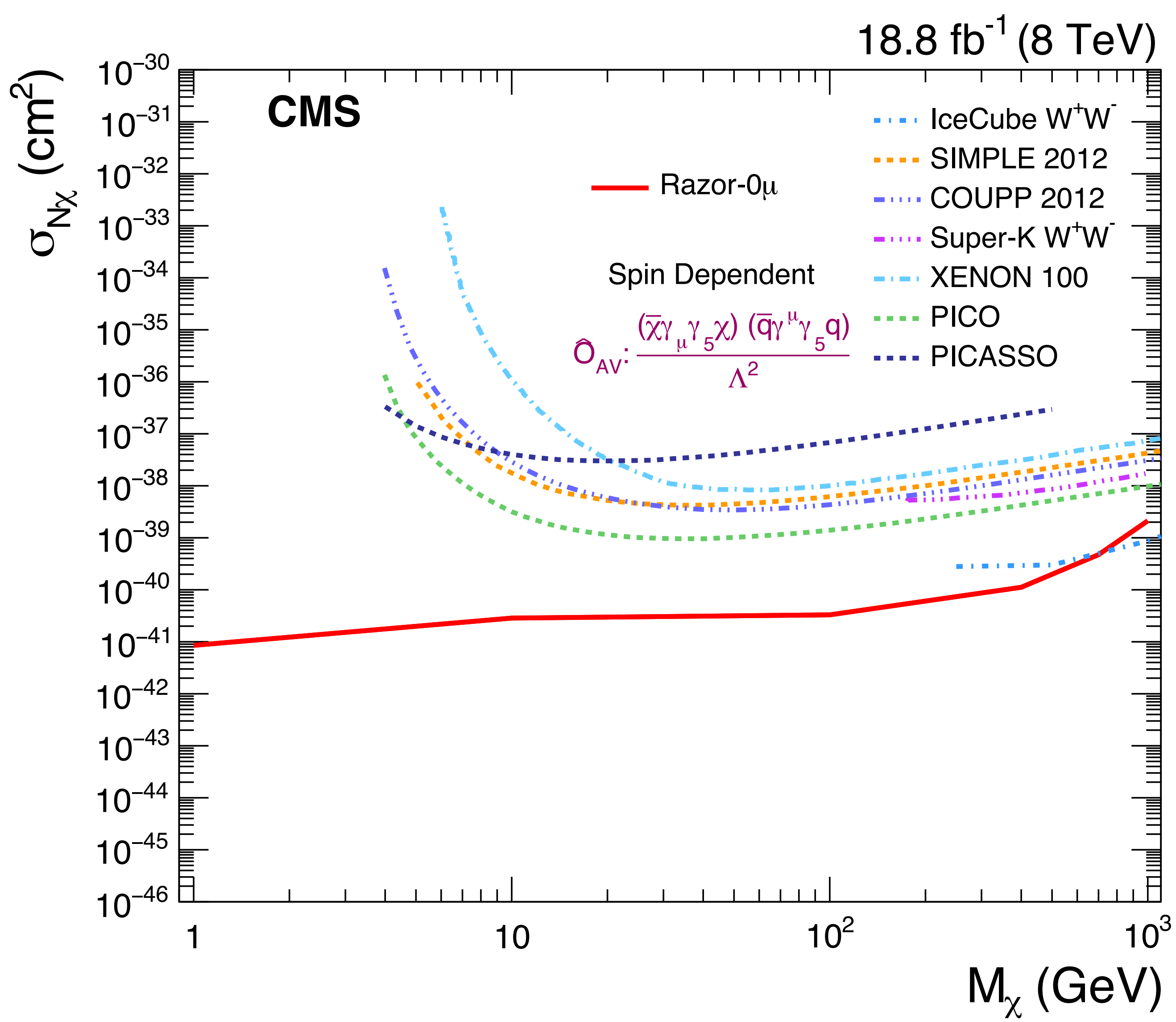


Large R



CMS dedicated razor DM search



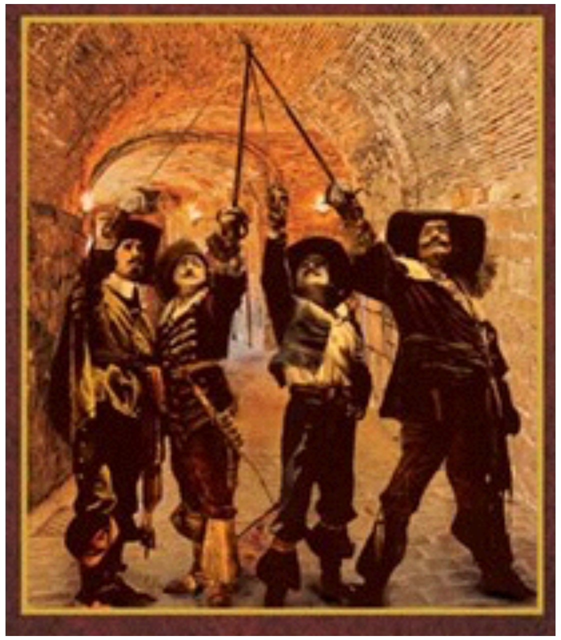


Similar sensitivity but more inclusive set of events

Complementarity

- Direct detection limited to DM above GeV, needs DM nearby moving in the right way
- No upper limit on mass probed, learn about DM in cosmos
- Indirect detection very sensitive to astrophysics
- Halo shapes can probe DM-DM interactions
- Collider searches have kinematic upper limit, no astrophysics systematics, but many others

Complementary taken together provide complete picture



Complementarity

Many exciting new ideas for probing light DM e.g. scattering off electrons in semi/super conductors

- Direct detection ...
- ... mass probed, learn about DM in cosmos
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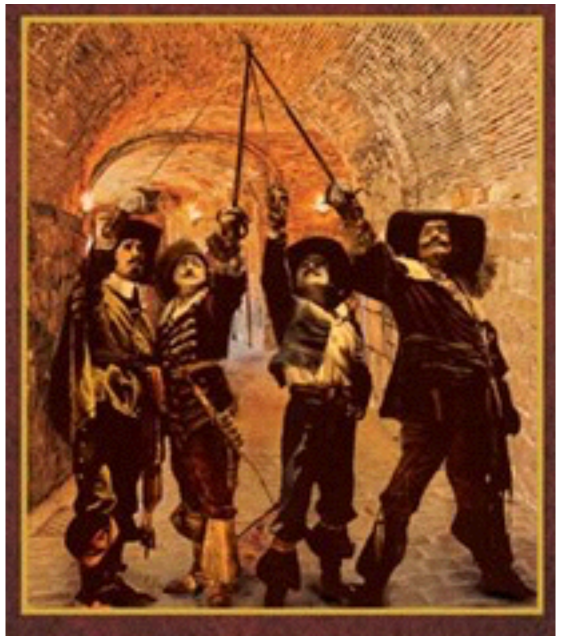

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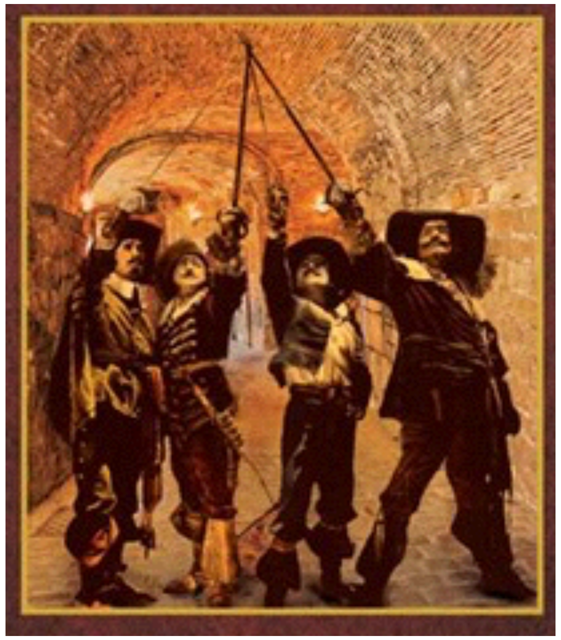

Slightly less simple—electroweakinos

Higgsinos, Wino, Bino admixtures

Charginos (Higgsinos, Winos) $(\widetilde{W}^+,\ \widetilde{H}_u^+,\ \widetilde{W}^-,\ \widetilde{H}_d^-)$

$$\mathbf{X} \;=\; \begin{pmatrix} M_2 & g v_u \\ g v_d & \mu \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta\, m_W \\ \sqrt{2} c_\beta\, m_W & \mu \end{pmatrix}$$

Neutralinos $\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$

$$\mathbf{M}_{\widetilde{N}} \;=\; \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}.$$

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Neutralinos

$$\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$$

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & [illegible] & [illegible] \\ 0 & [illegible] & [illegible] & s_\beta \, c_W \, m_Z \\ [illegible] & [illegible] & 0 & -\mu \\ [illegible] & -s_\beta \, c_W \, m_Z & -\mu & 0 \end{pmatrix}.$$

4 parameters: mu, M1, M2, tanbeta

Electroweakinos general strategies

[Low and Wang]

[Gori, Jung, Wang, Wells]

[Cirelli, Sala, Taoso]

Monojet

Hard ISR jet boosts chargino/neutralino system

VBF

Tag forward jets with rapidity gap

Disappearing tracks

Pure Higgsino/Wino have small (loop) splittings. Long lived charginos. Sensitive to higher order operators

Soft leptons

e.g. Production of Wino NLSP and chargino. Possible to find relic Higgsino if Wino NLSP< 3TeV

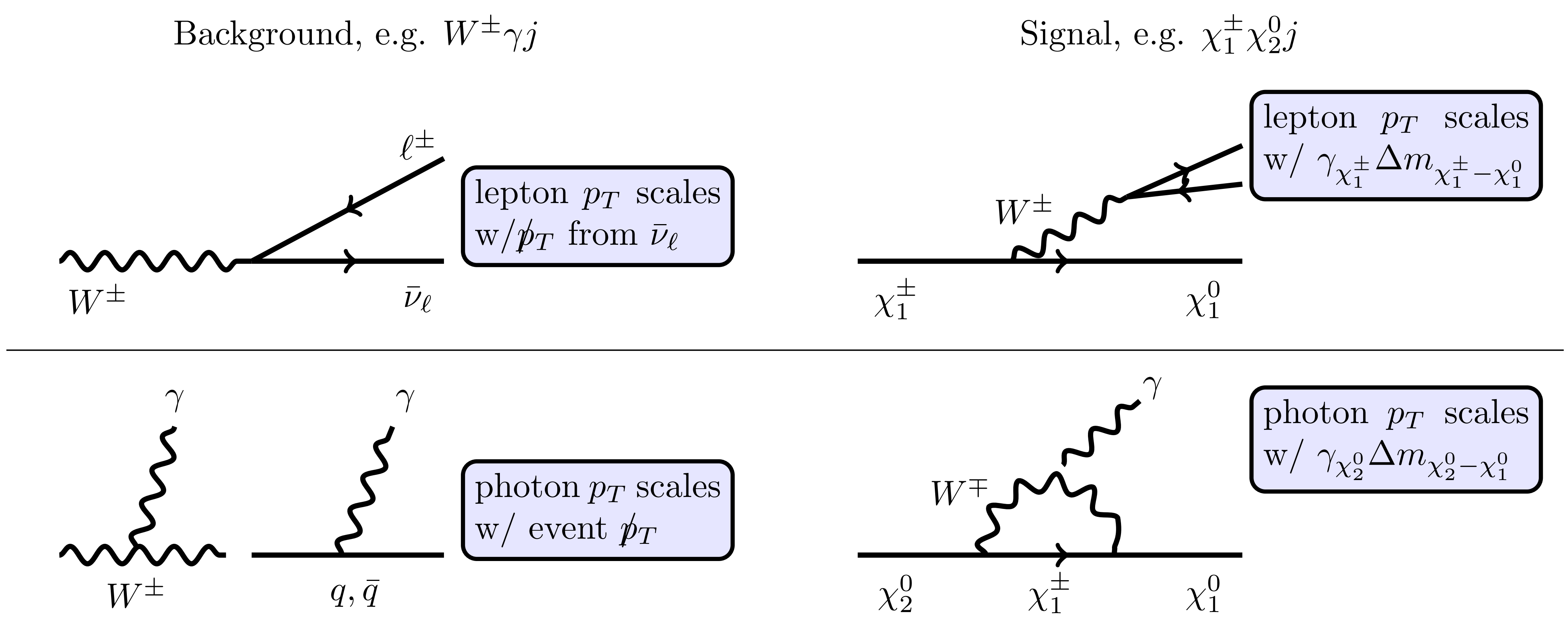
Electroweakinos at 100 TeV

$$pp \to \chi_2^0 \chi_1^\pm j \to (\gamma \chi_1^0)\ (\ell^\pm \nu \chi_1^0)\ j$$

Small splittings mean that decays involve soft photons and leptons

ISR to boost system and get large MET (and trigger!)

Background and signal scale very differently with pT



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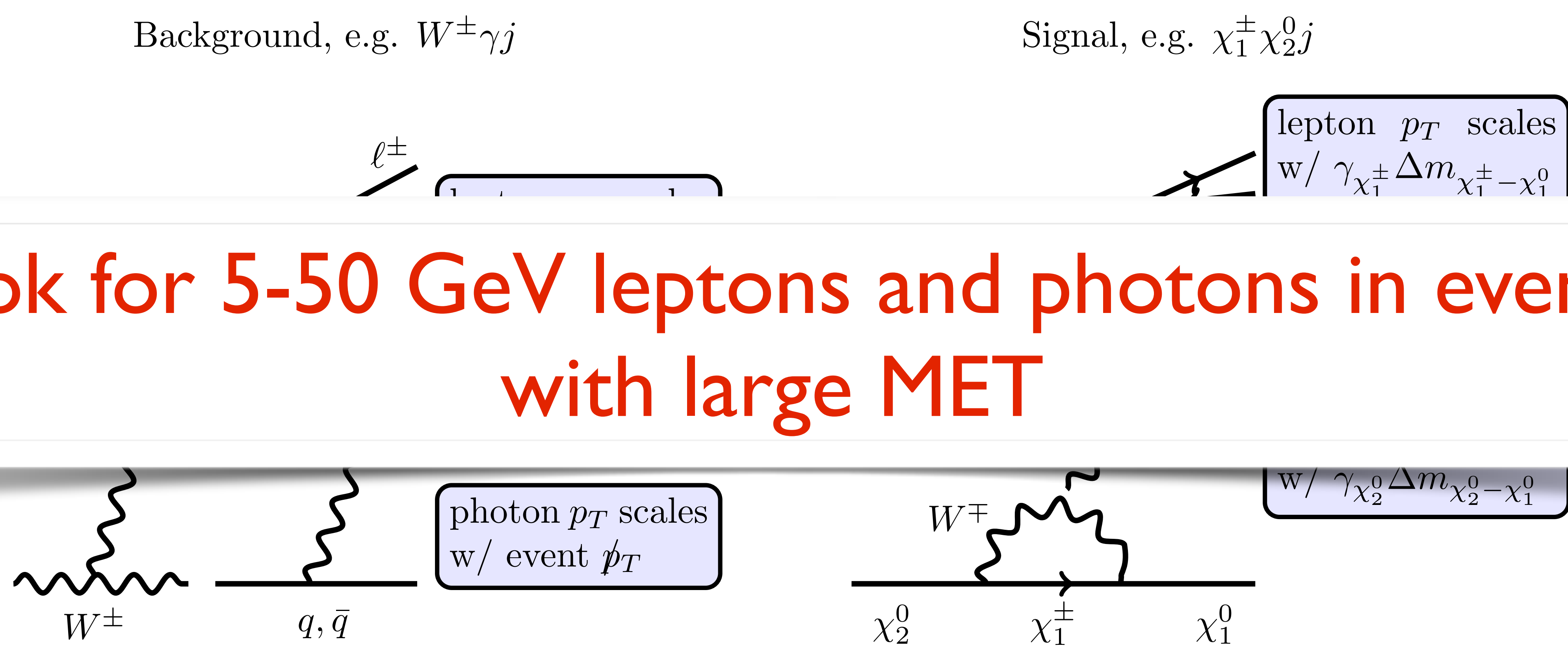
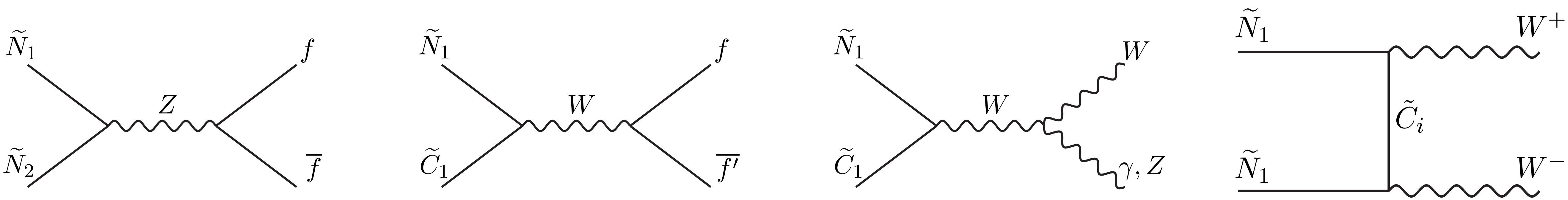
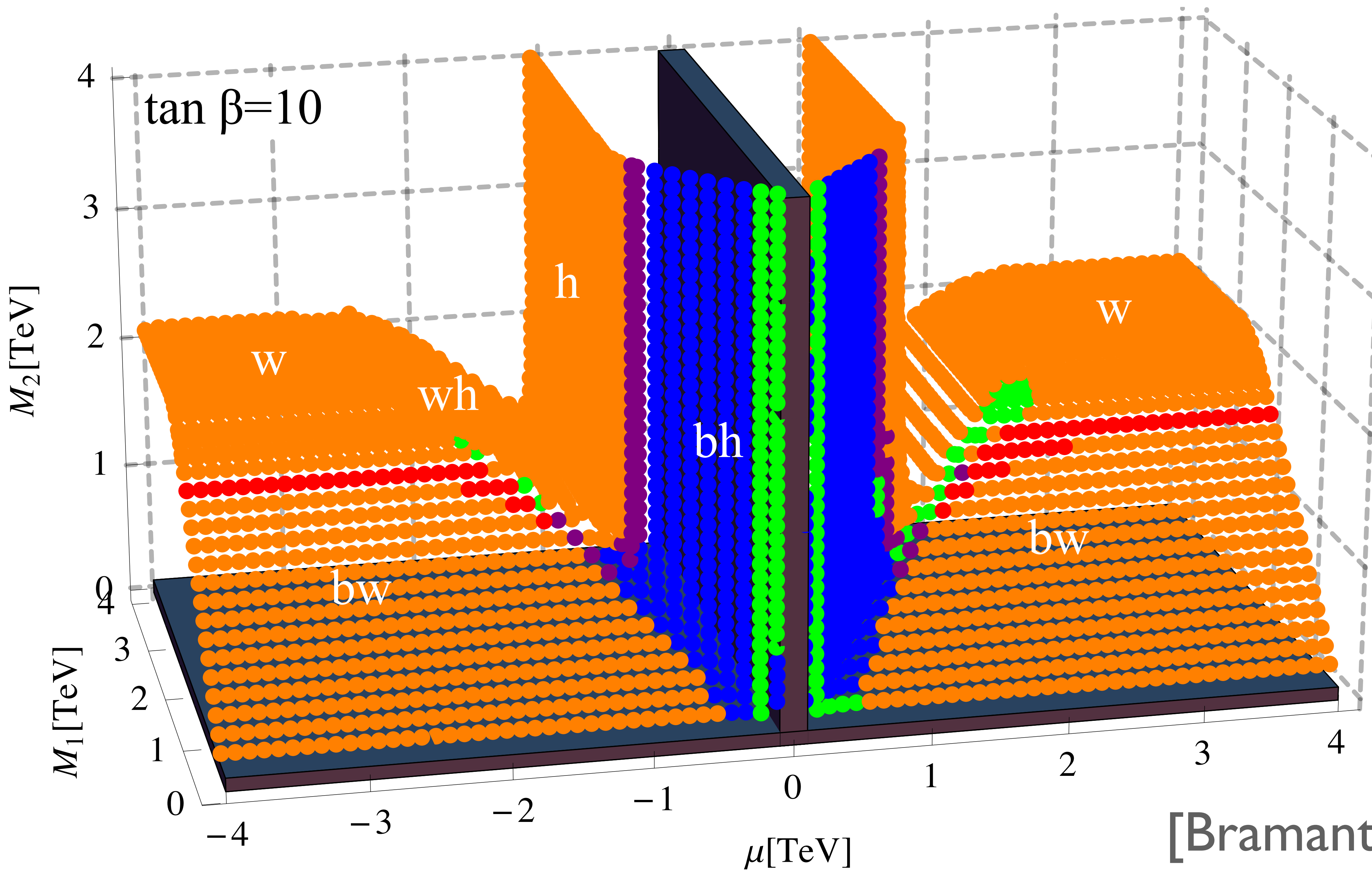


Look for 5-50 GeV leptons and photons in events with large MET

Relic abundance

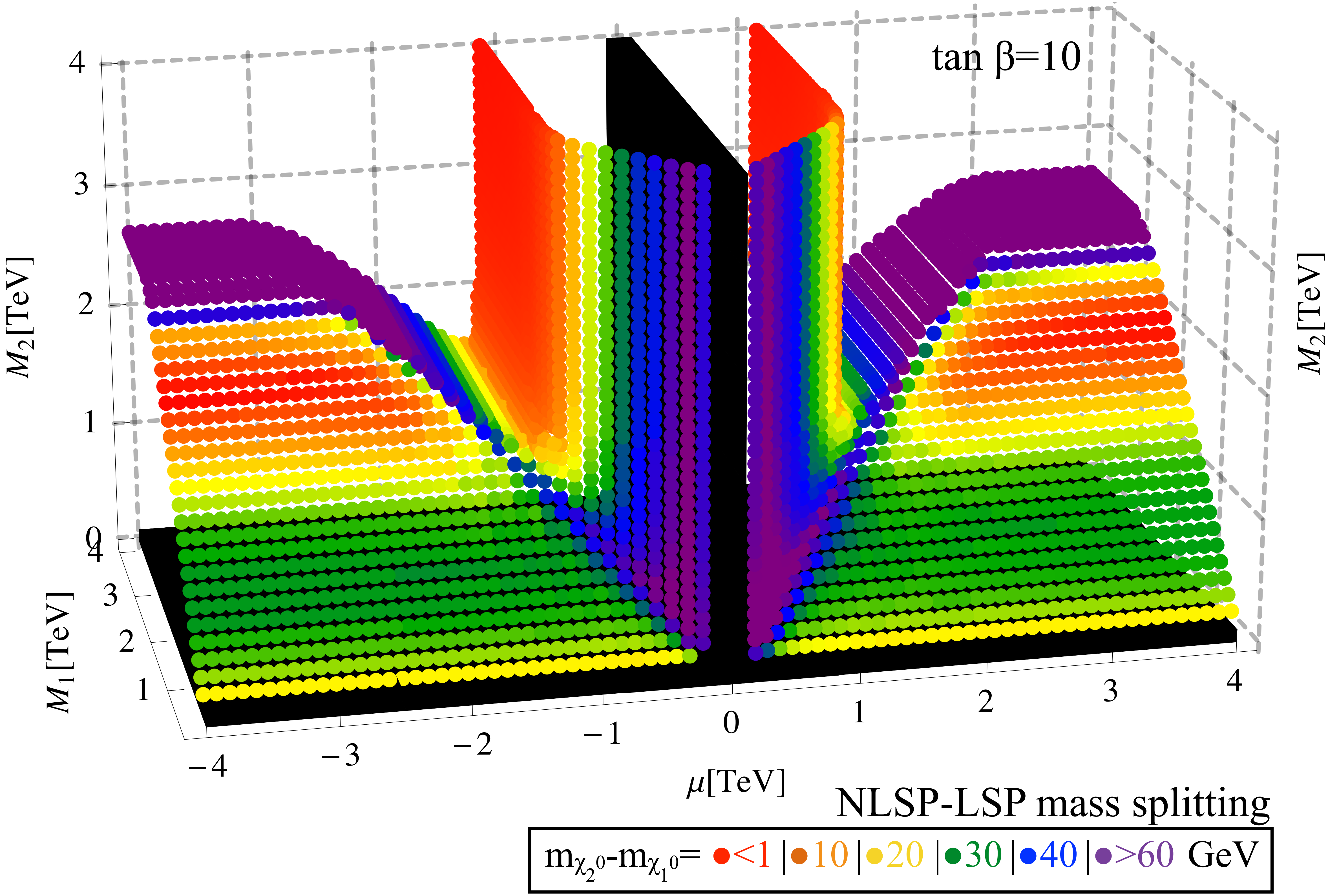




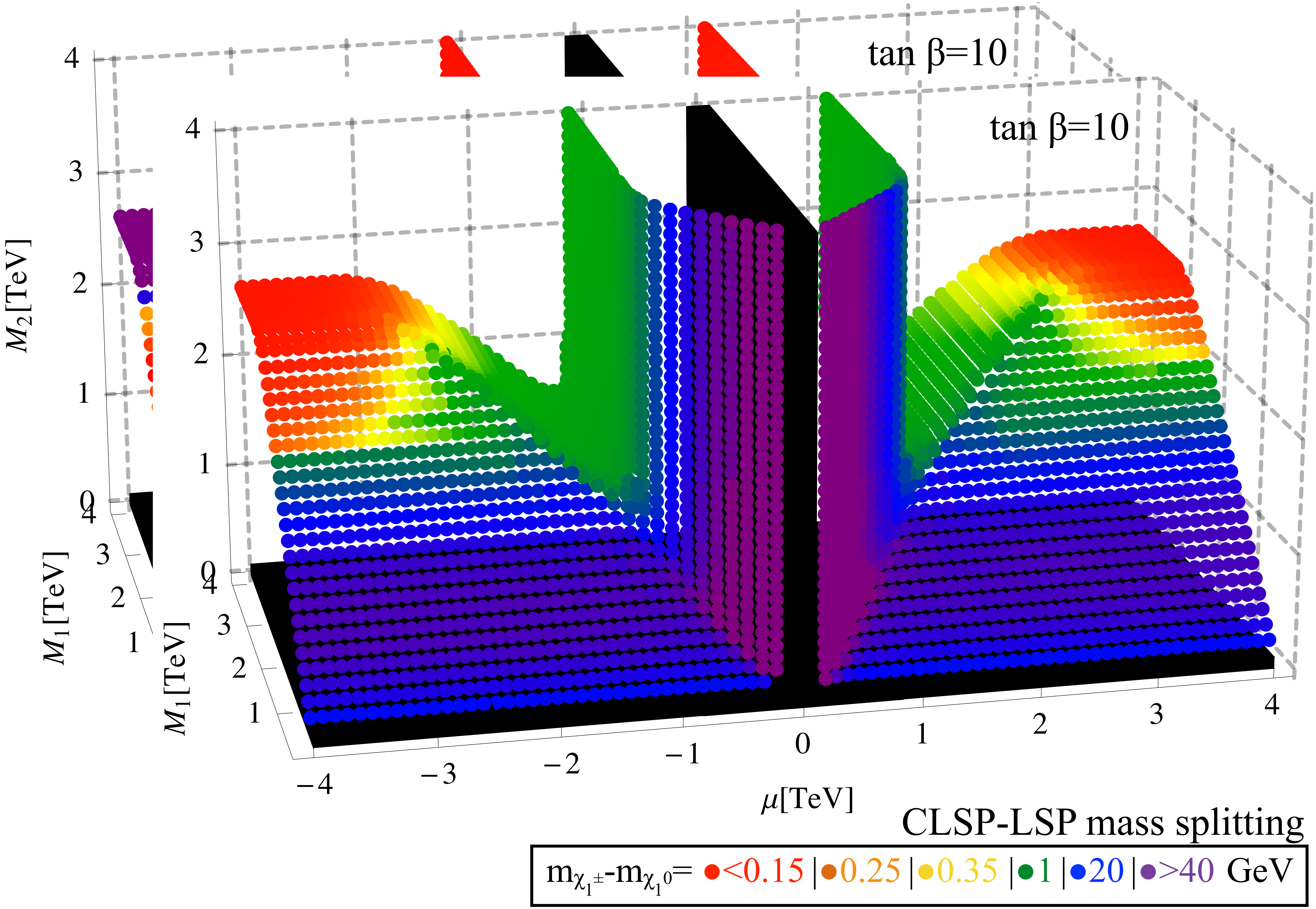
[Bramante, PJF, et al.]

●$t\bar{t}$,$b\bar{b}$ || ●$u\bar{d}$,$c\bar{s}$ || ●$t\bar{b}$ || ●W^+W^- || ●W^+W^+

Mass splittings

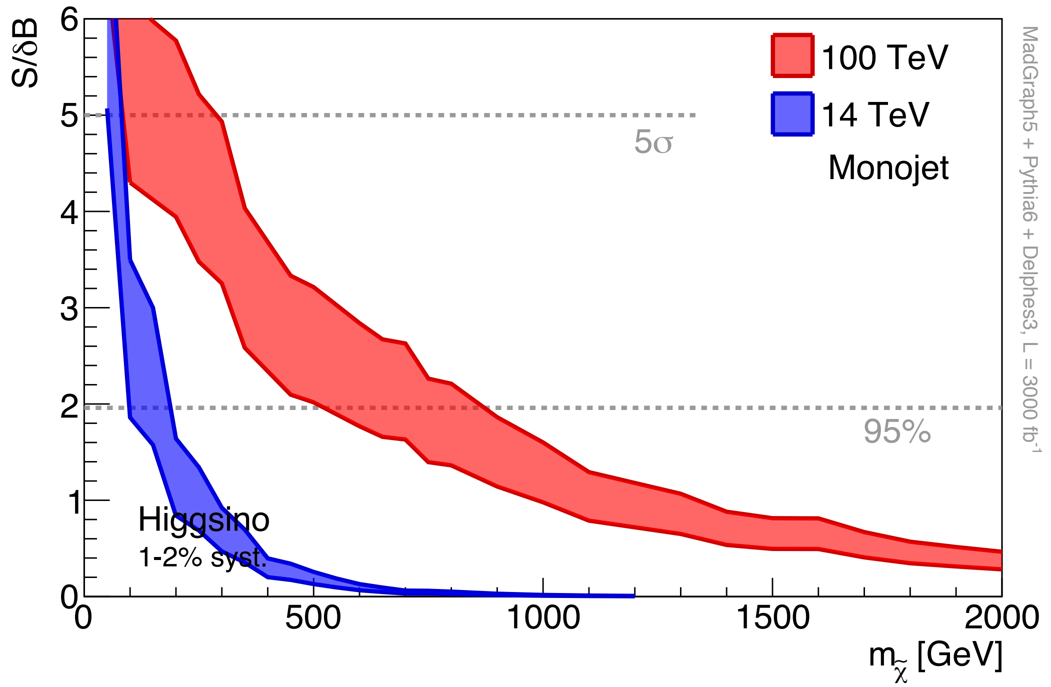


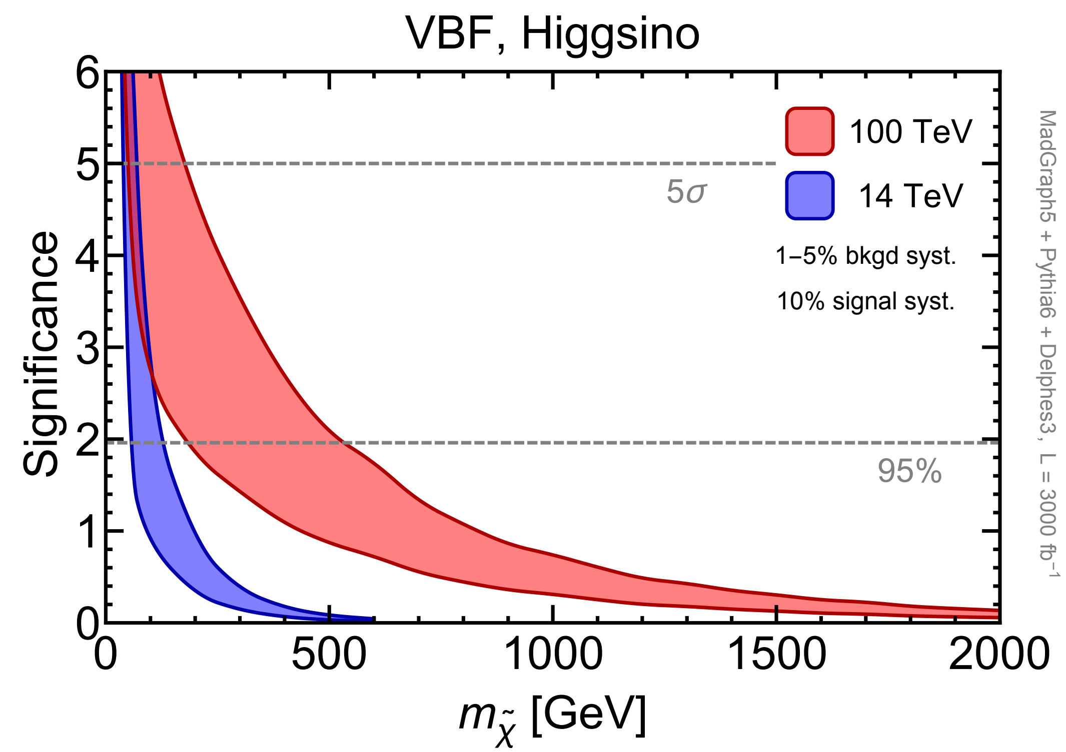
Mass splittings

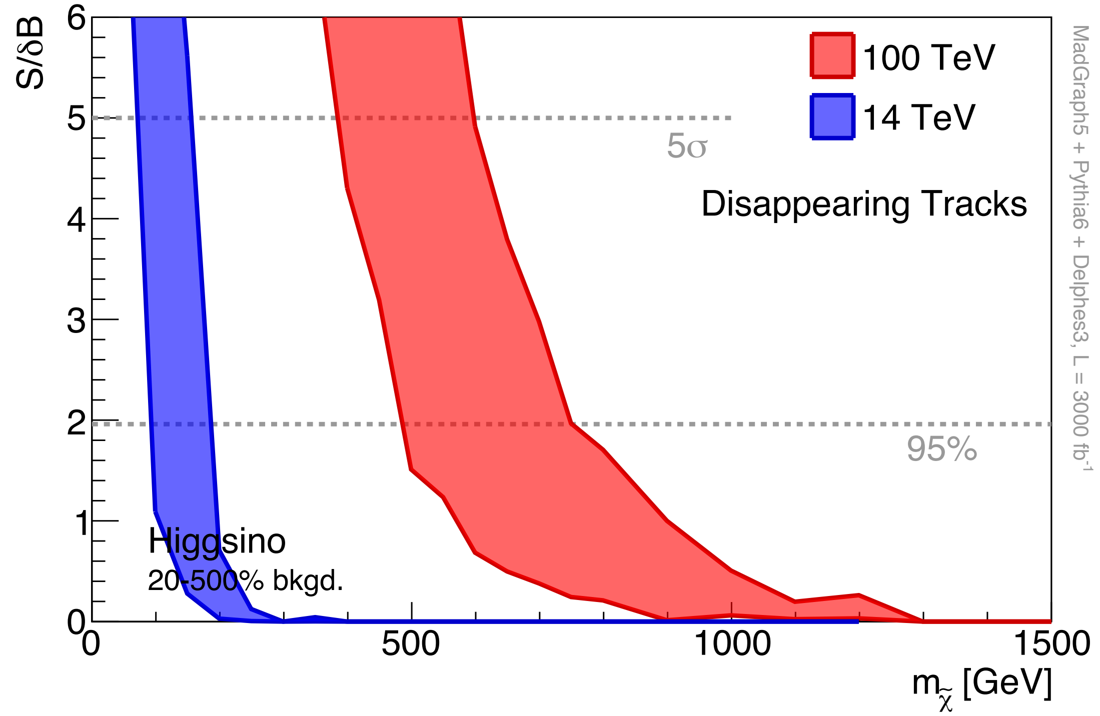


Higgsinos~1 TeV

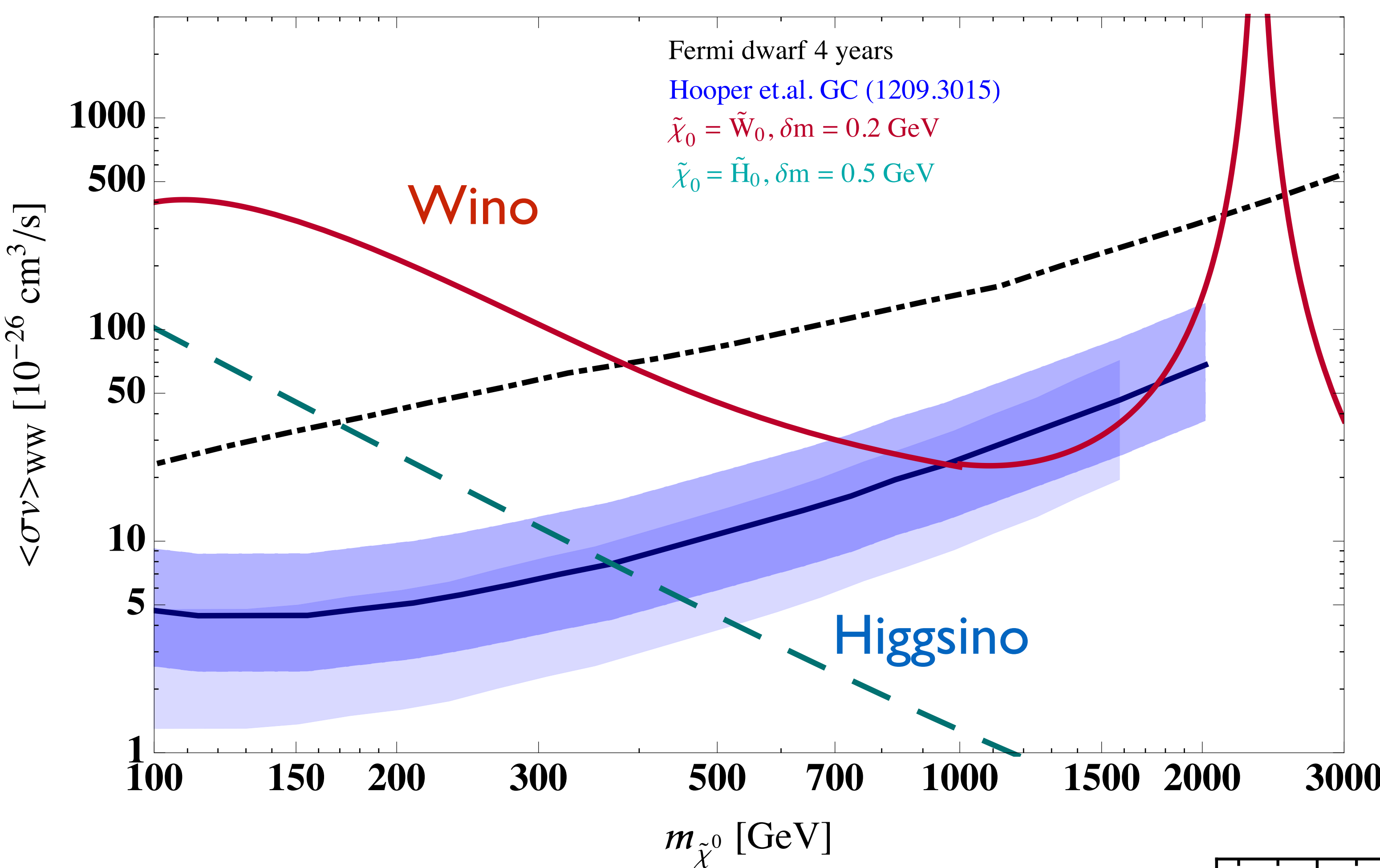
[Low and Wang]



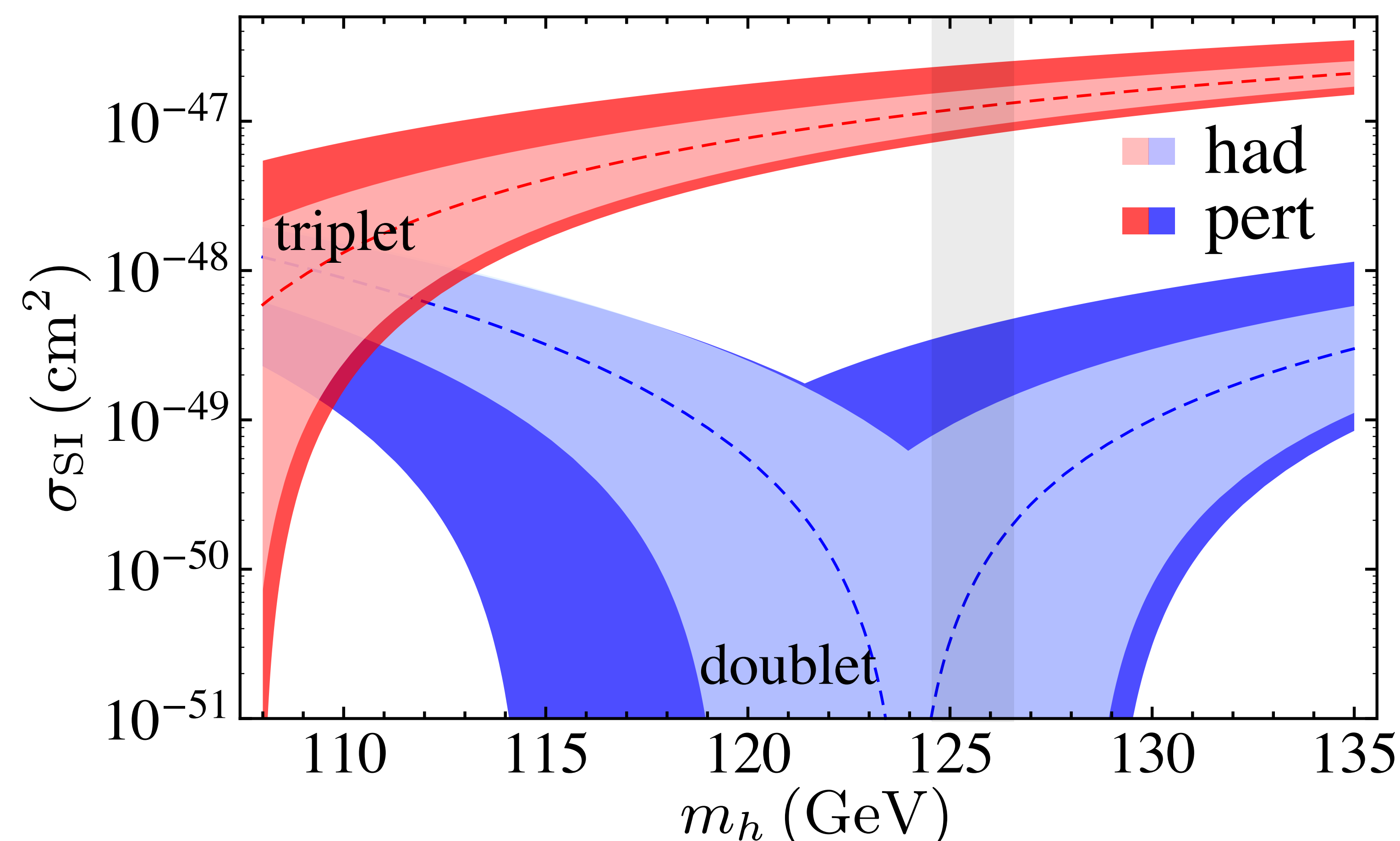




[Fan and Reece, see also Cohen et al.]



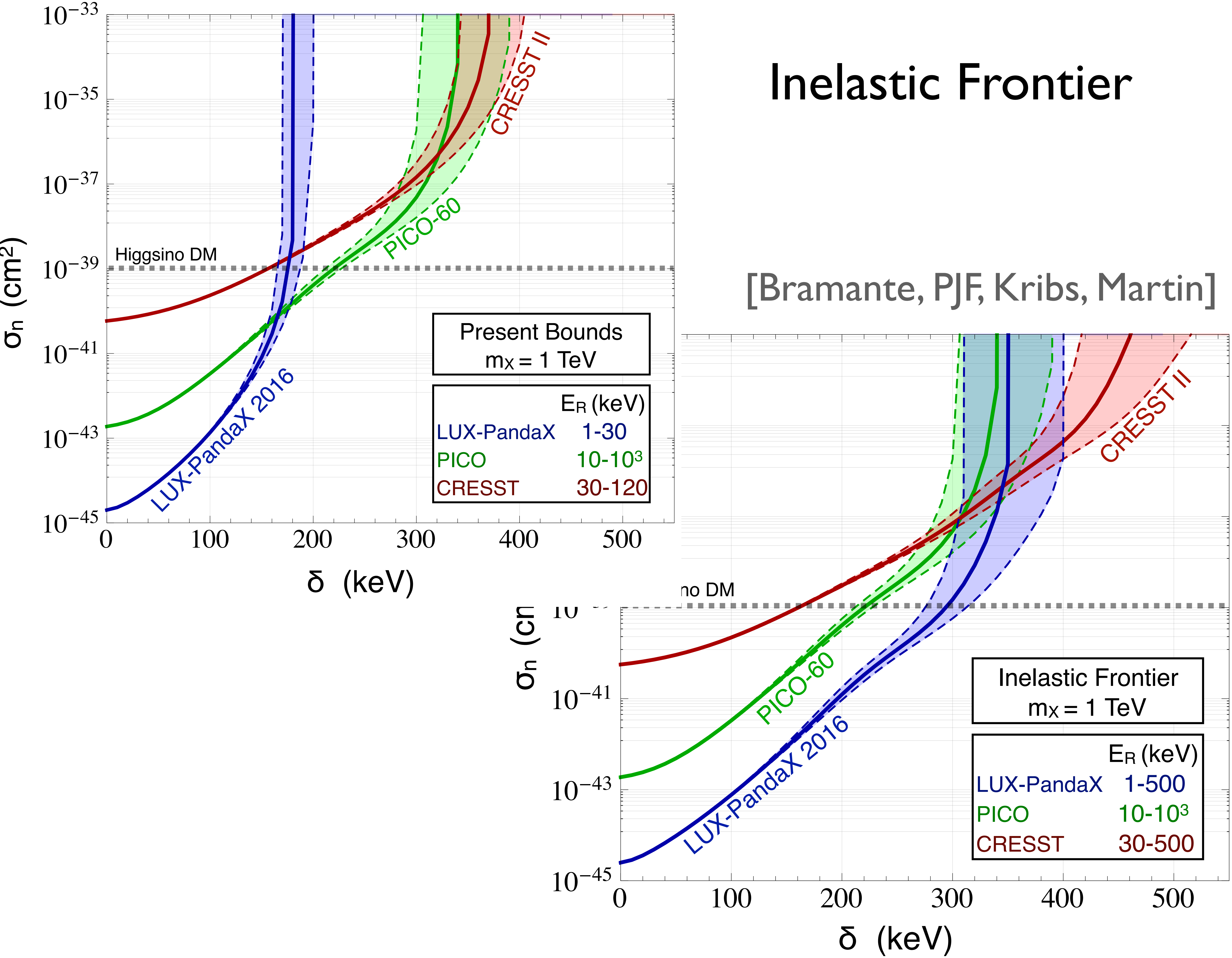
[Hill and Solon]



Thermal Higgsino DM will be tough to find

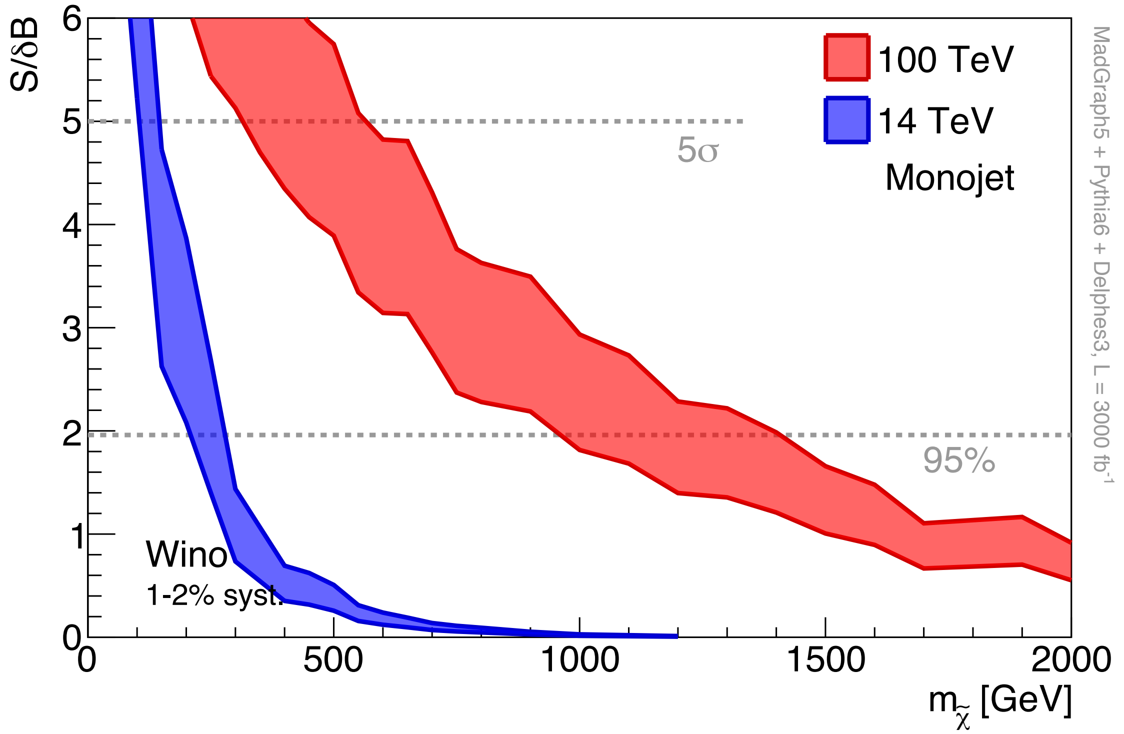
Inelastic Frontier

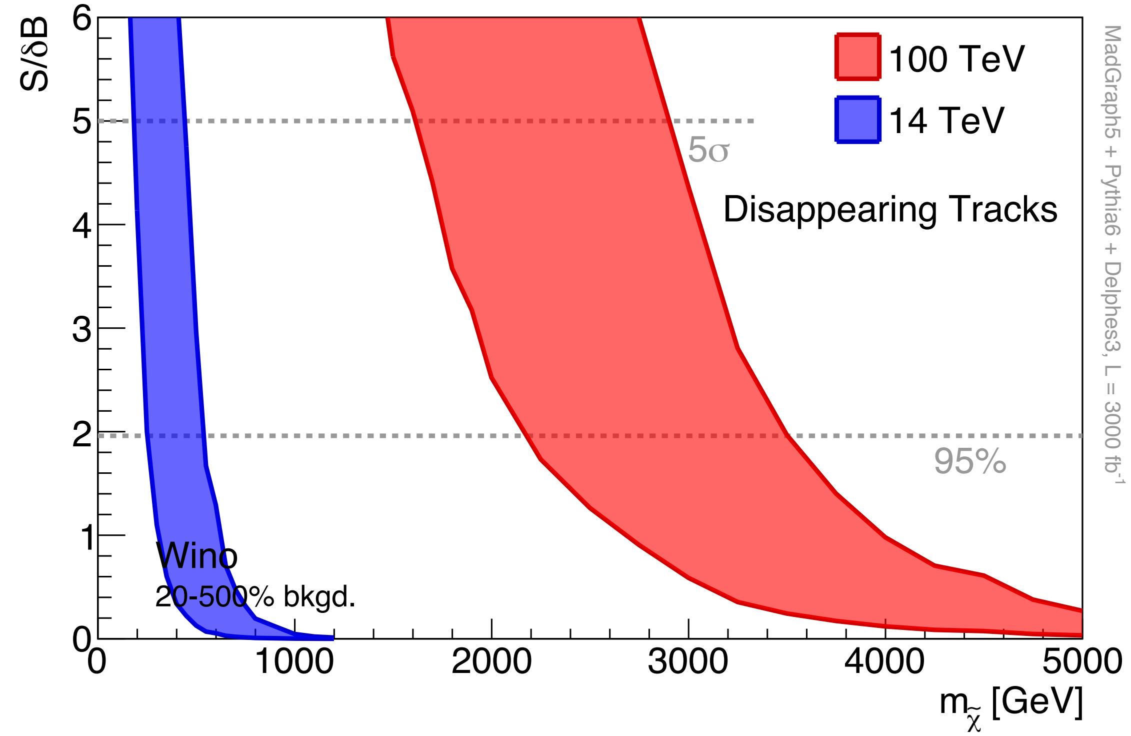
[Bramante, PJF, Kribs, Martin]



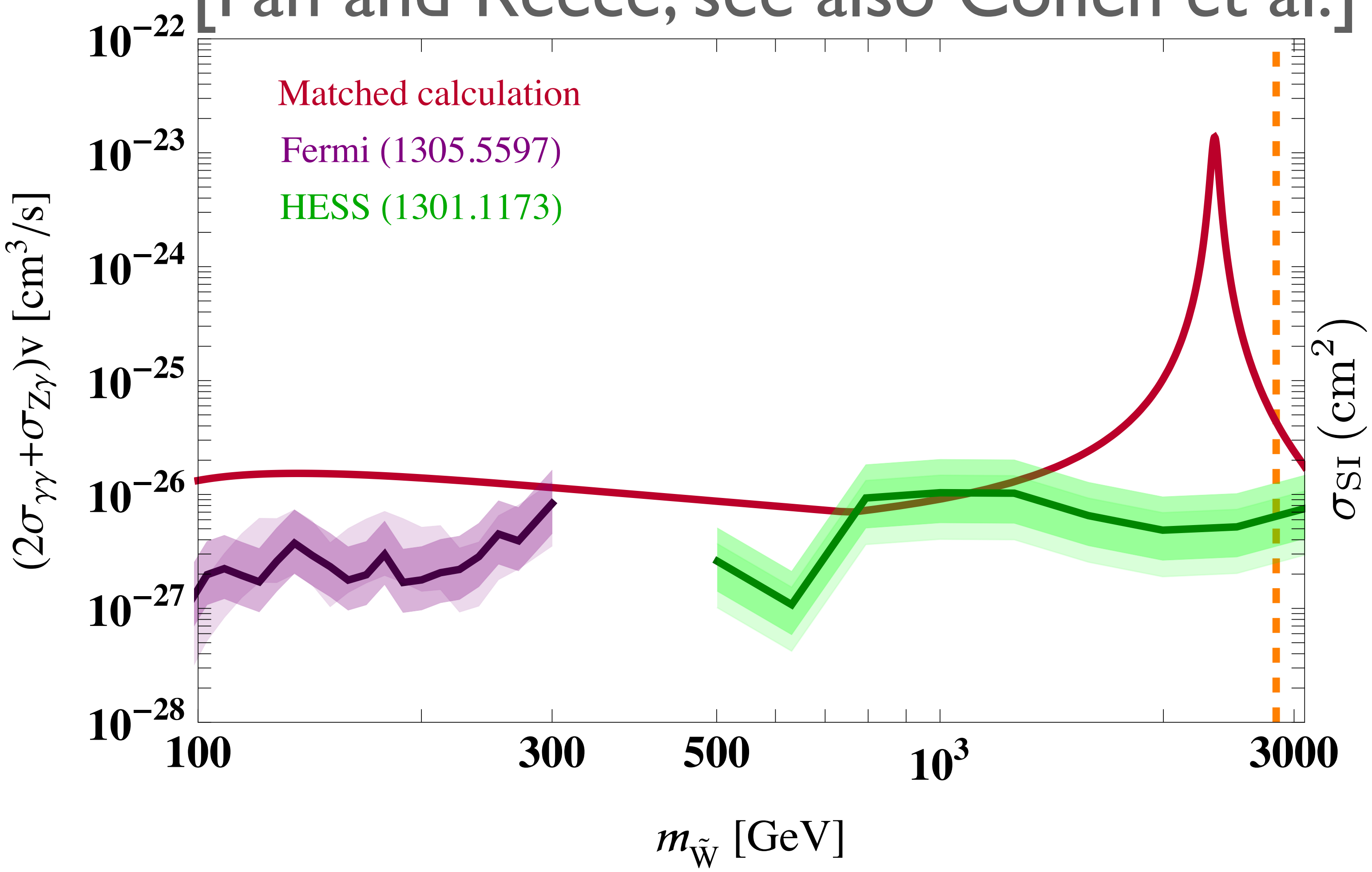
Winos~3 TeV

[Low and Wang, see also Cirelli et al.]

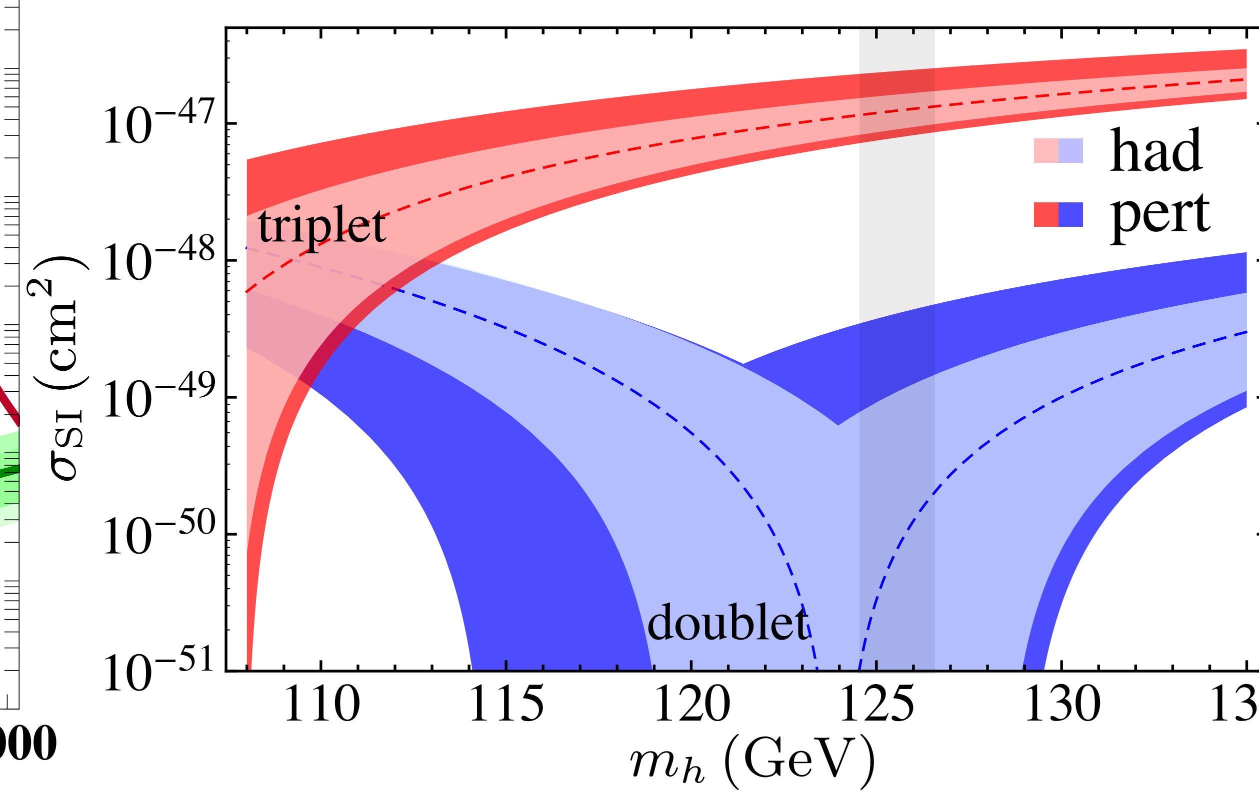




[Fan and Reece, see also Cohen et al.]

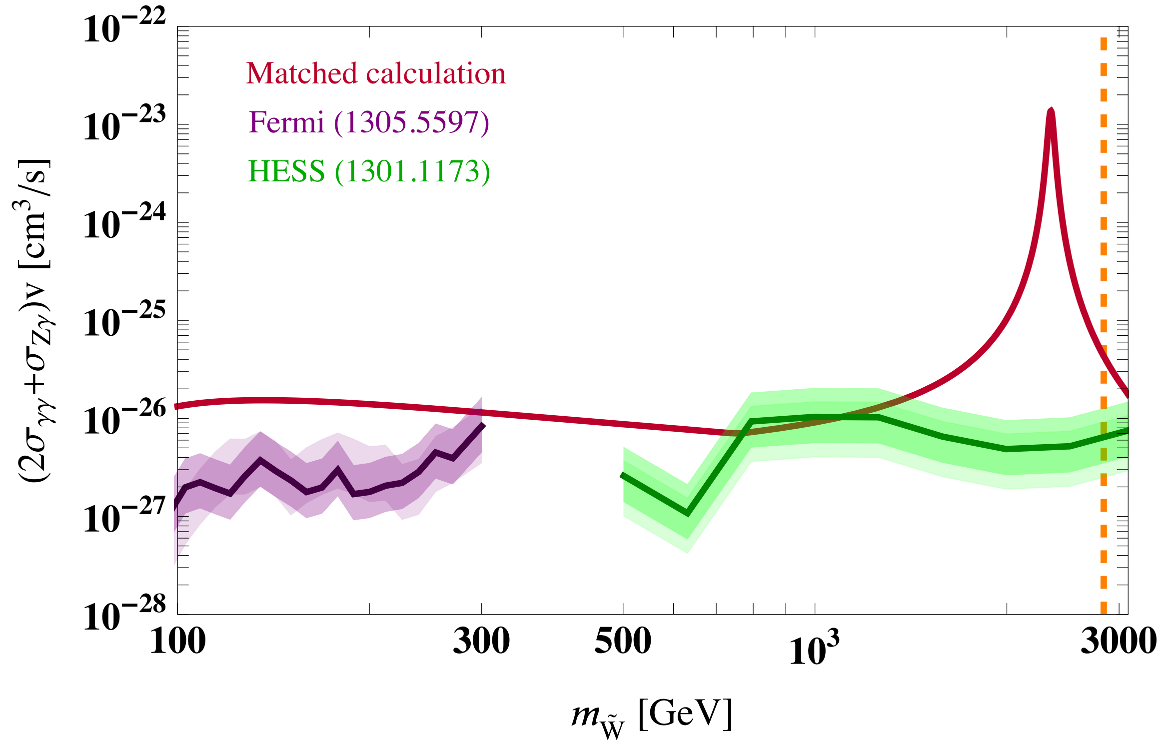


[Hill and Solon]

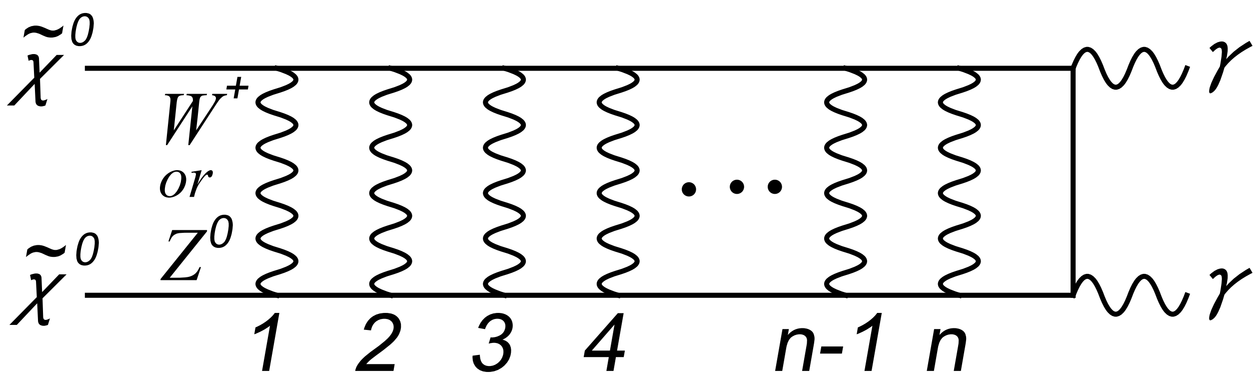


[Hisano et al.]

Sommerfeld enhancement



For heavy DM W,Z exchange becomes a "long range" force

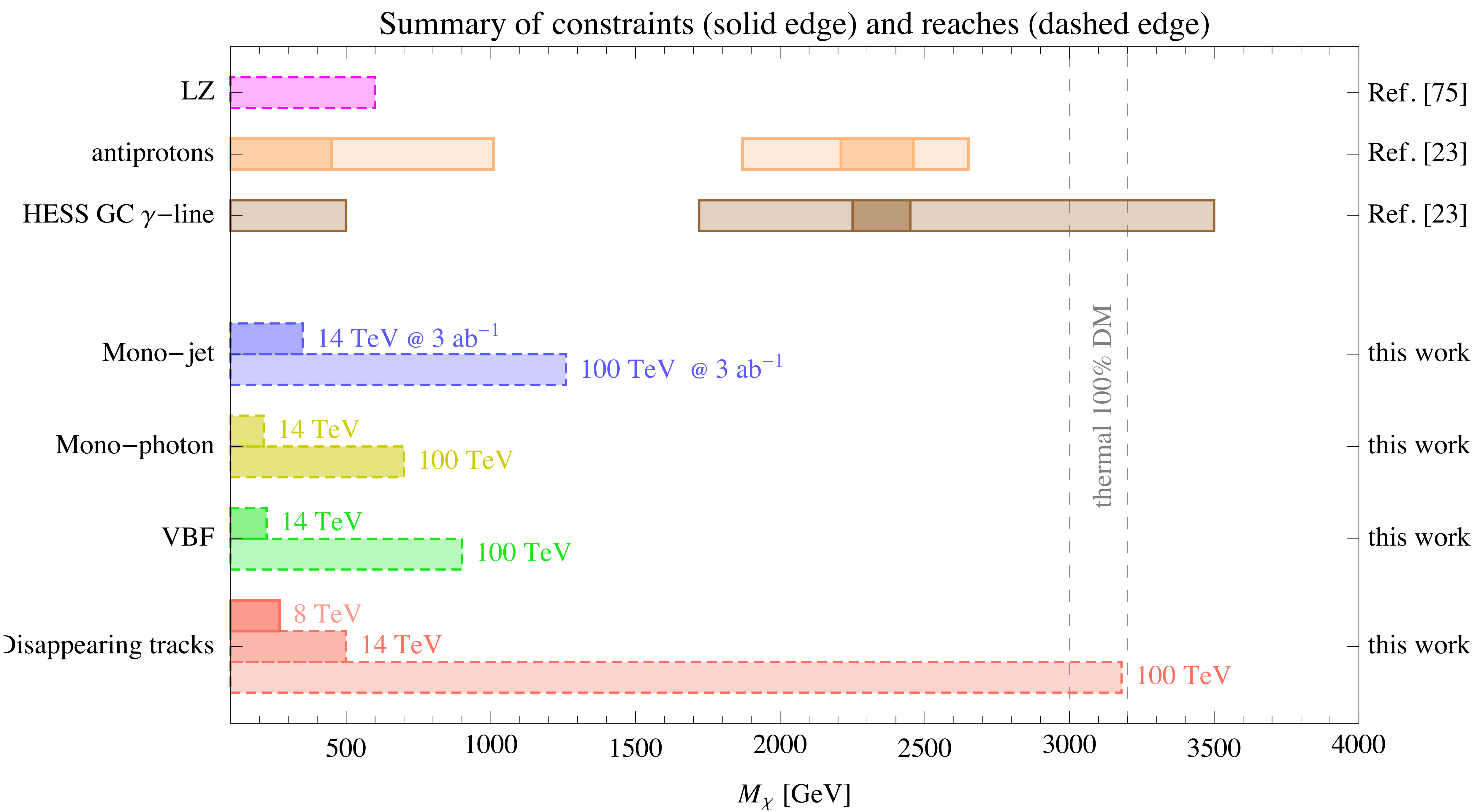


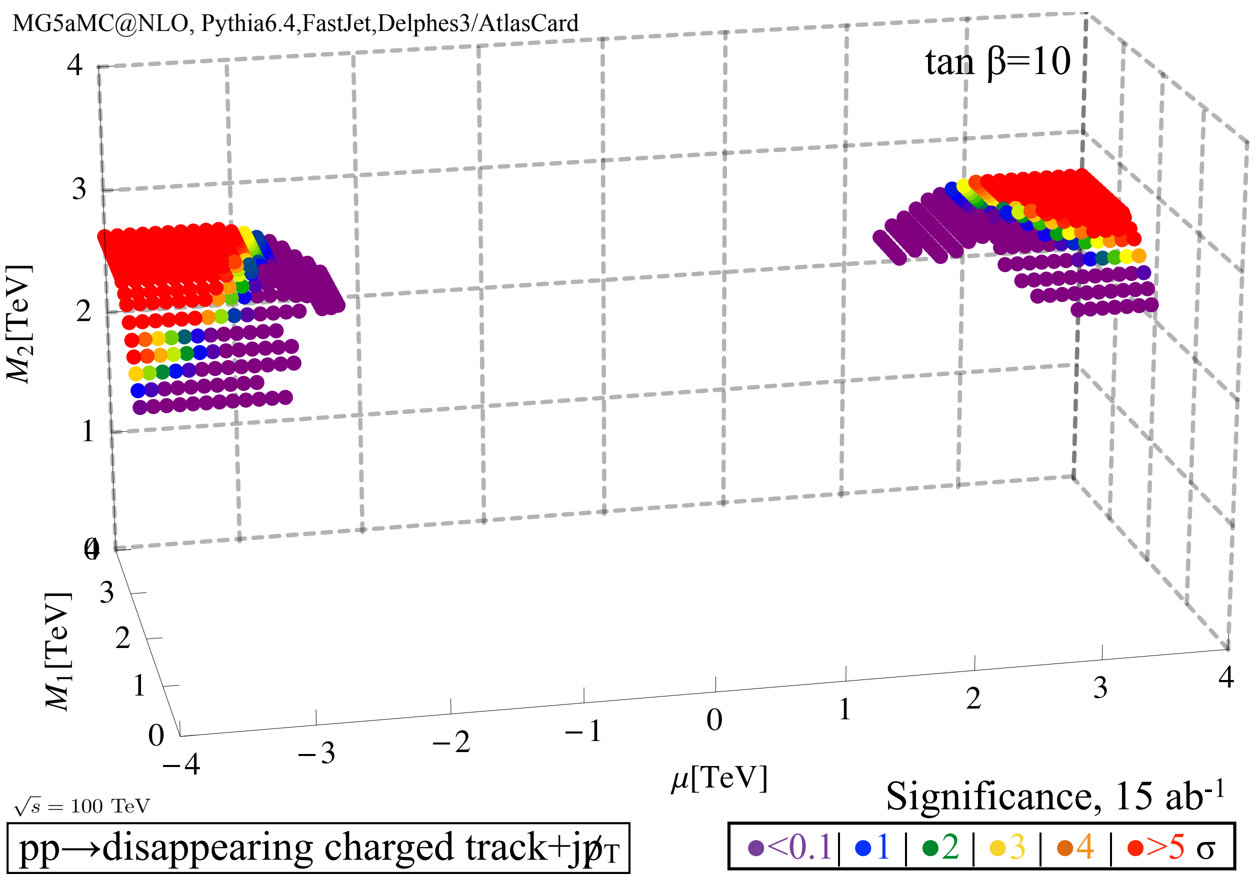
$$\frac{1}{M_W} > \frac{1}{\alpha_W m_\chi}$$

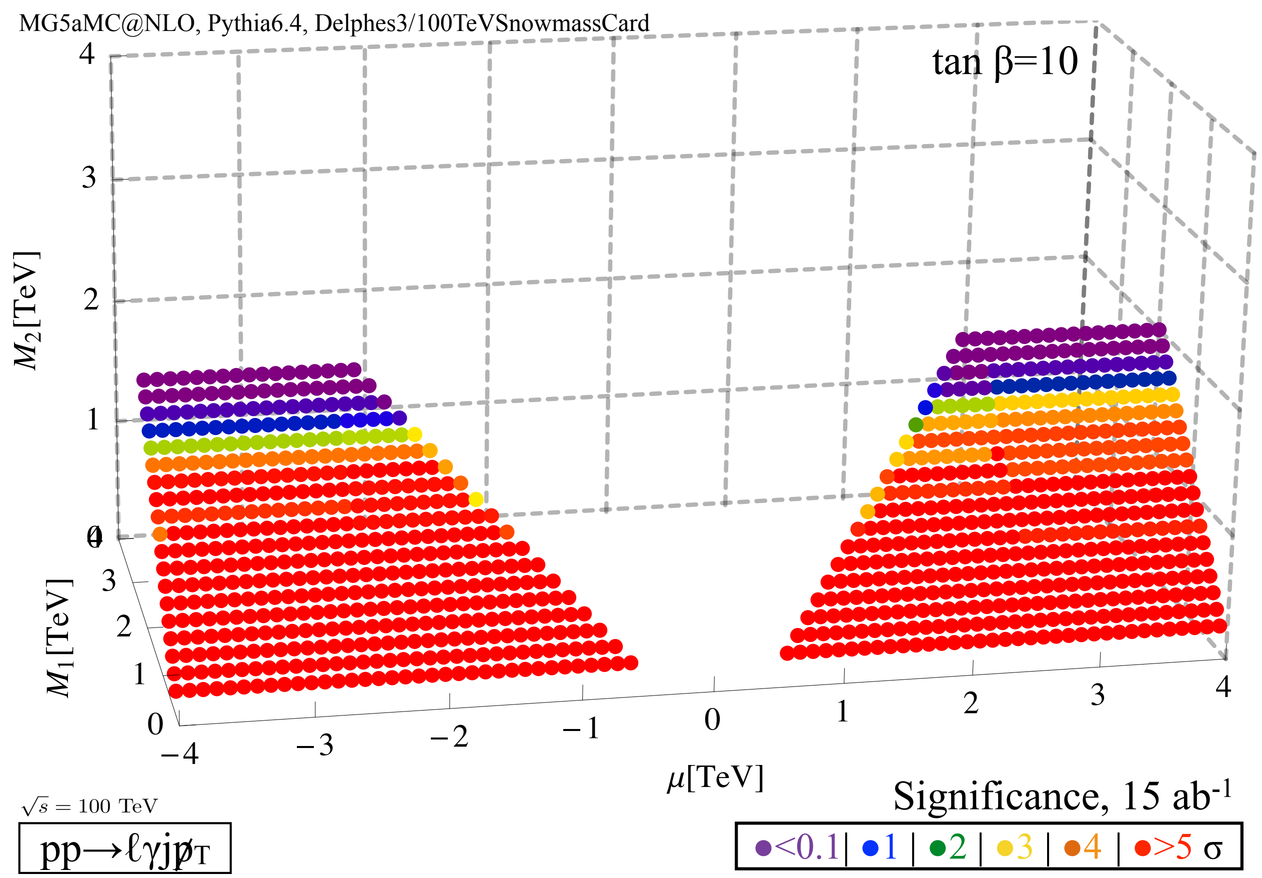
Zero energy bound states increase annihilation cross section

Complementarity, again

[Cirelli, Sala, Taoso]







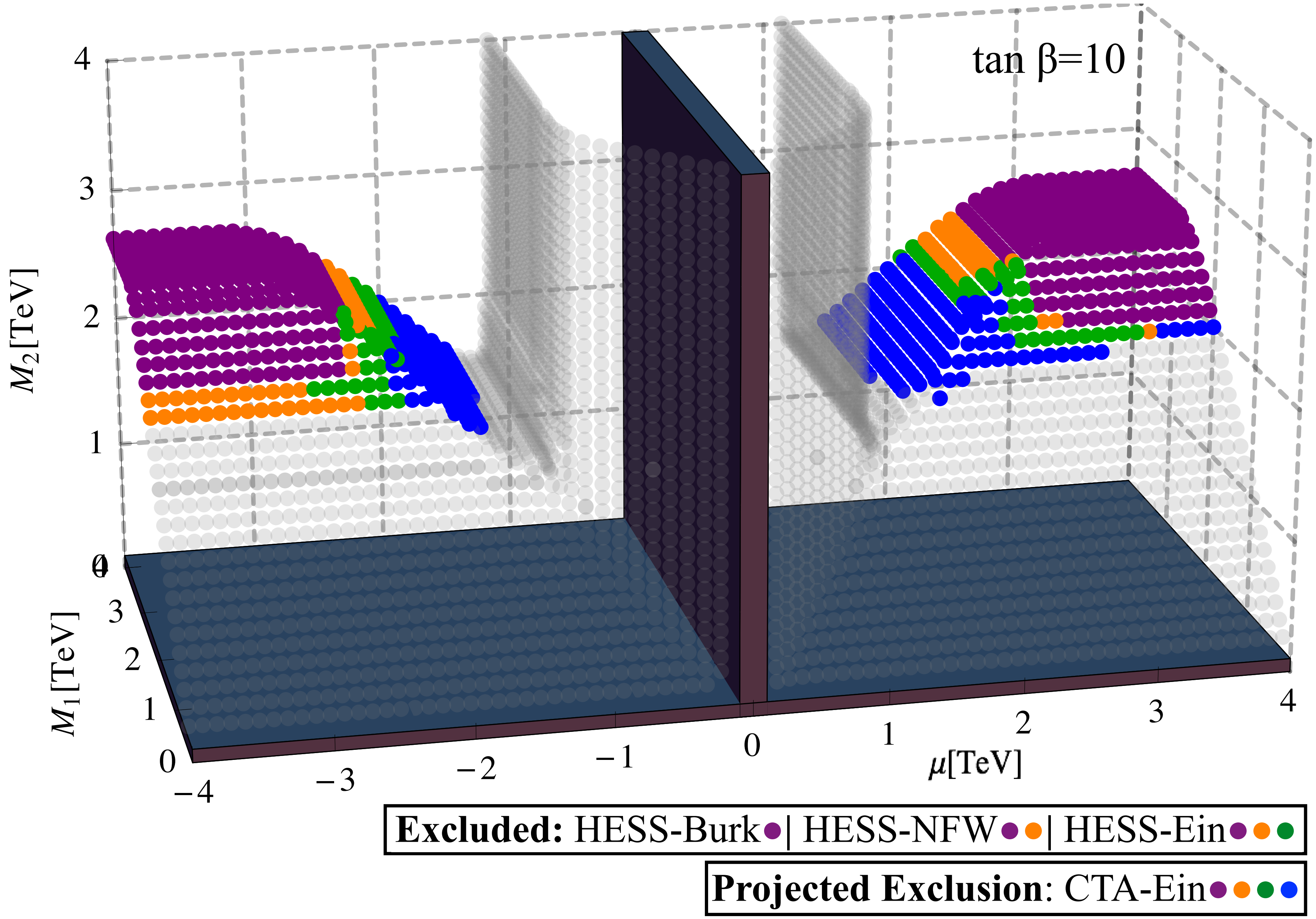
$$p_{T,\ell} = [10 - 60]\ \text{GeV} \qquad |\eta_\ell| < 2.5$$

$$p_{T,\gamma} = [10 - 60]\ \text{GeV} \qquad |\eta_\gamma| < 2.5 \qquad \Delta R_{\ell\gamma} > 0.5$$

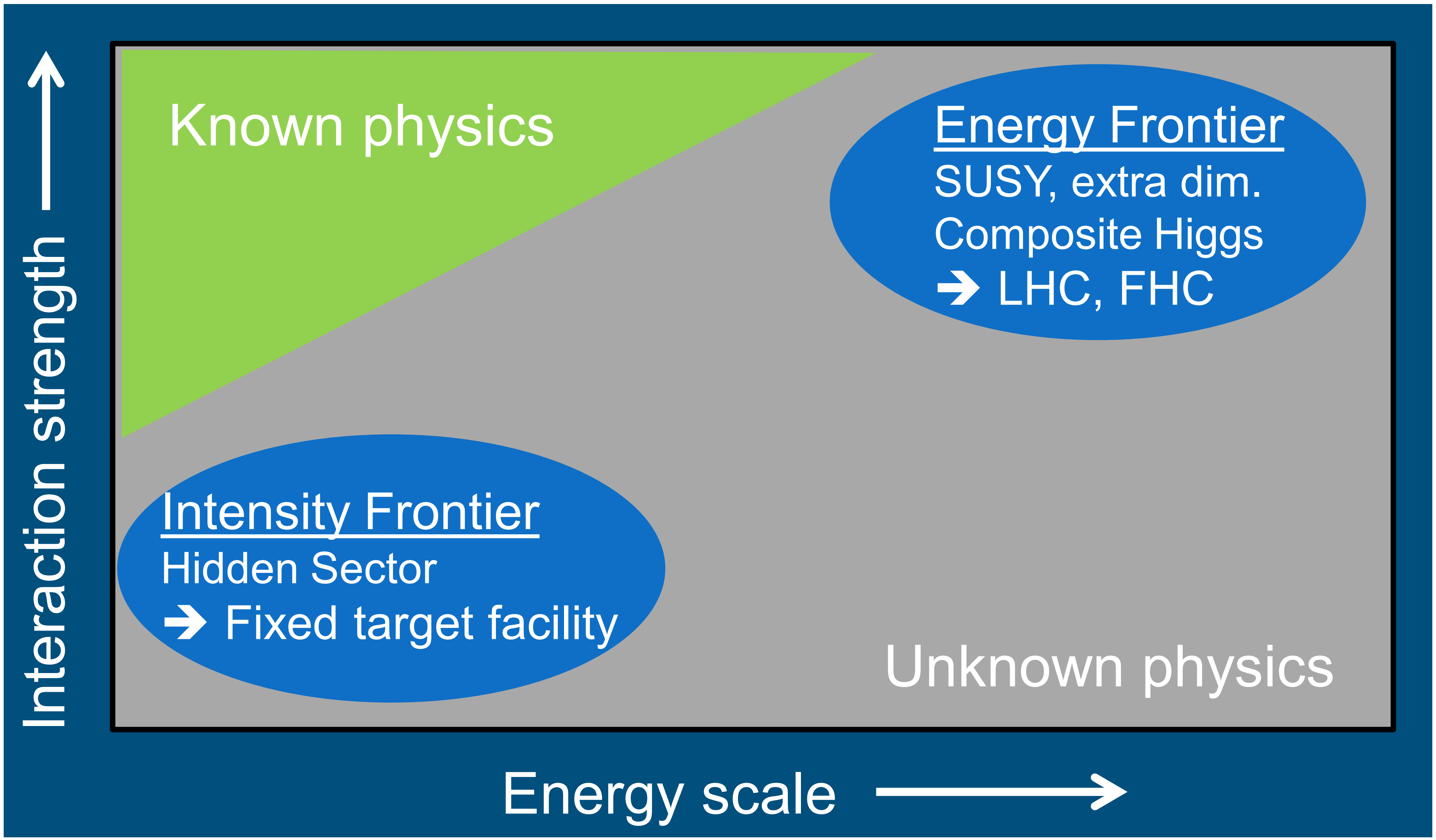
$$p_{T,j} > 0.8\ \text{TeV} \qquad |\eta_j| < 2.5 \qquad M_{T2}^{(\gamma,\ell)} < 10\ \text{GeV}$$

$$\not{p}_T > 1.2\ \text{TeV}\ .$$

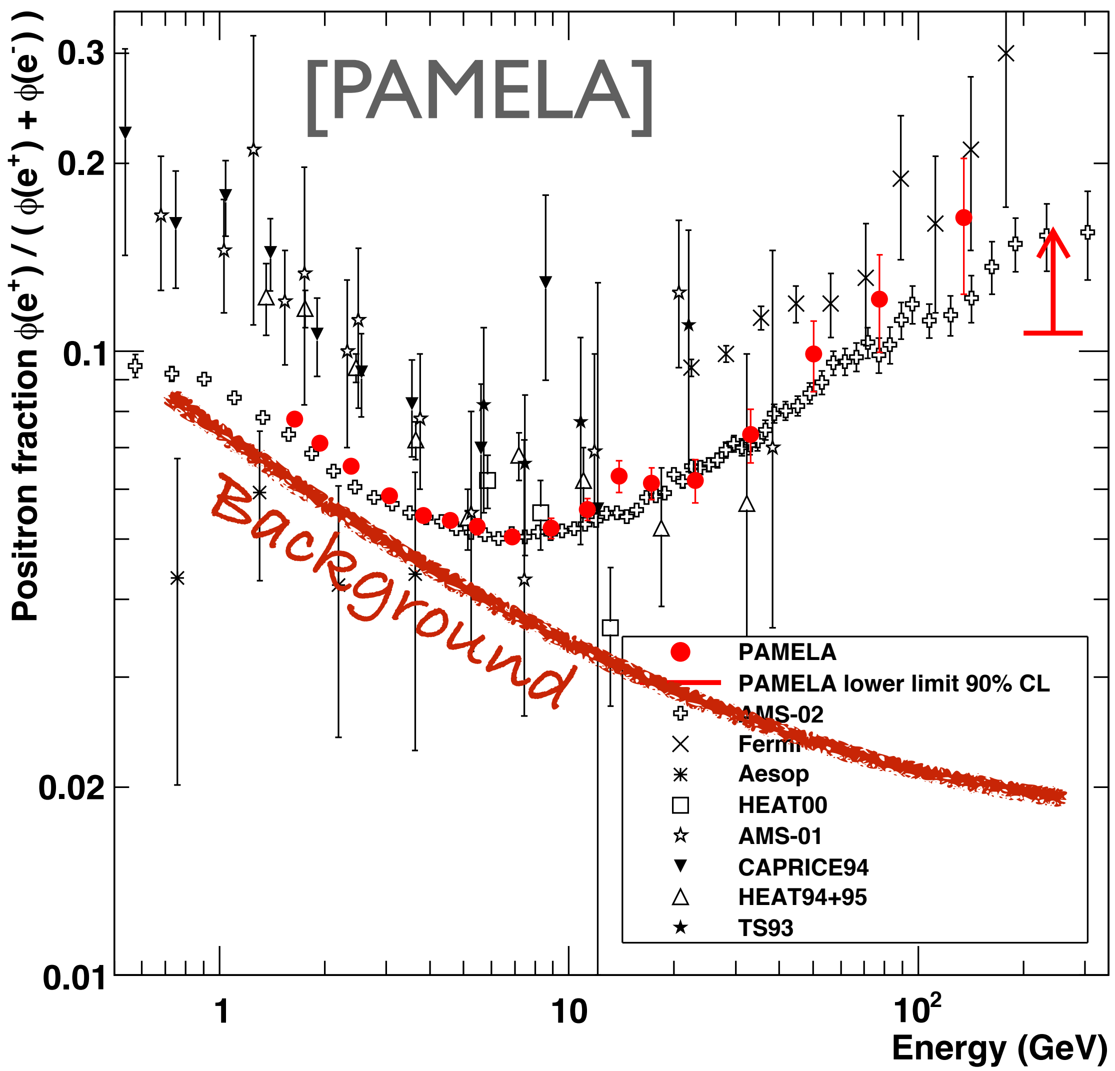
veto if Njets >2

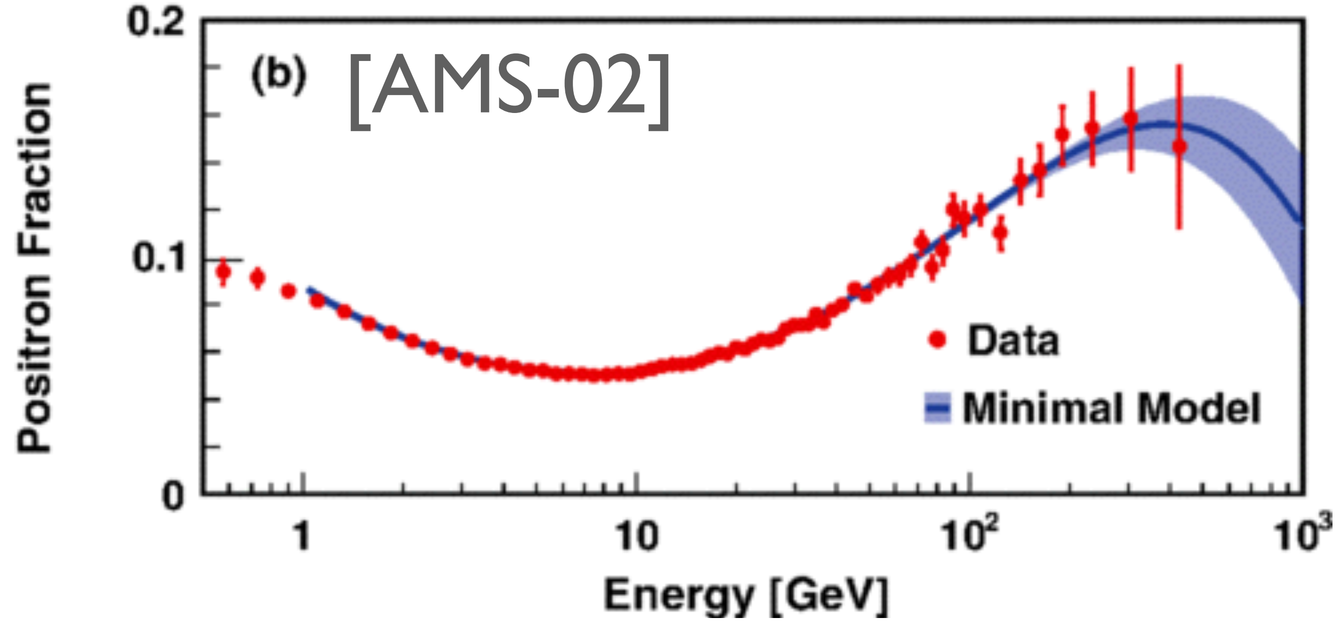

tan β=10
4
3
2
1
0
M_2[TeV]
4
3
2
1
0
M_1[TeV]
−4
−3
−2
−1
0
1
2
3
4
μ[TeV]
Excluded: HESS-Burk | HESS-NFW | HESS-Ein
Projected Exclusion: CTA-Ein

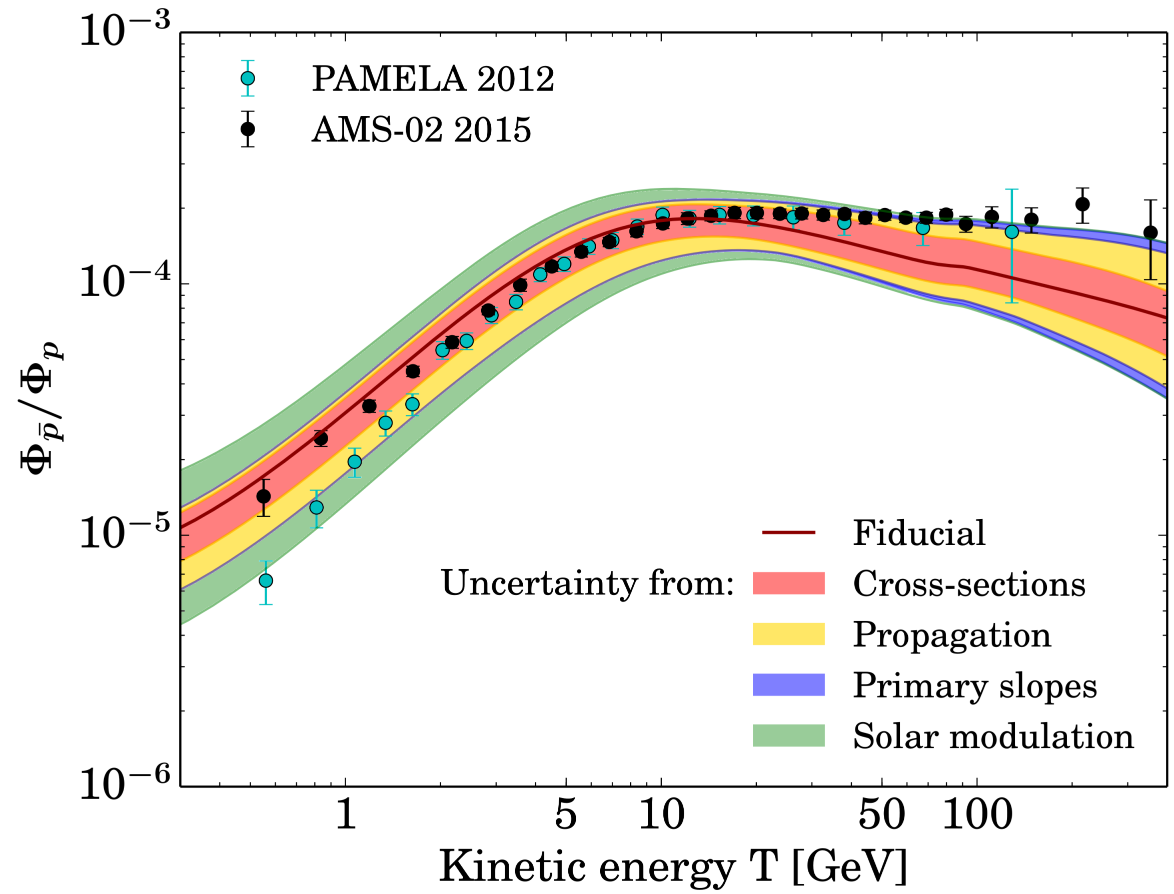
Dark Sectors and Dark Mediators



PAMELA excess



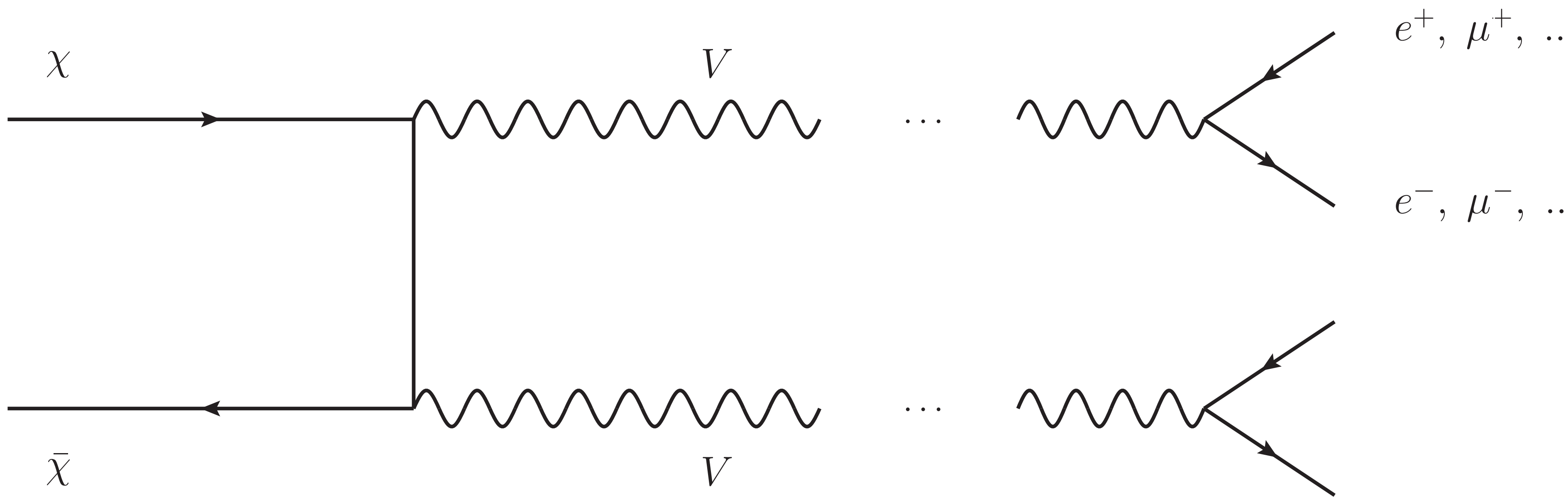




Could this be DM annihilating?

1. Why only positron excess, not antiproton
2. Rate is 100x relic annihilation cross section

DM annihilates to light V, antiprotons kinematically forbidden



V exchange gives Sommerfeld enhancement!

Two step process also sequesters DM from SM, no direct detection

Predicts DM self interactions, core-cusp, missing satellites, too big to fail, N-body simulations, etc

Kinetic mixing

No SM fields charged under U(1)'

$$-\frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} = A'_\mu \times (e\epsilon)J_\mu^{\mathrm{EM}}$$

Dark photon (Z'?) couples proportional to charge

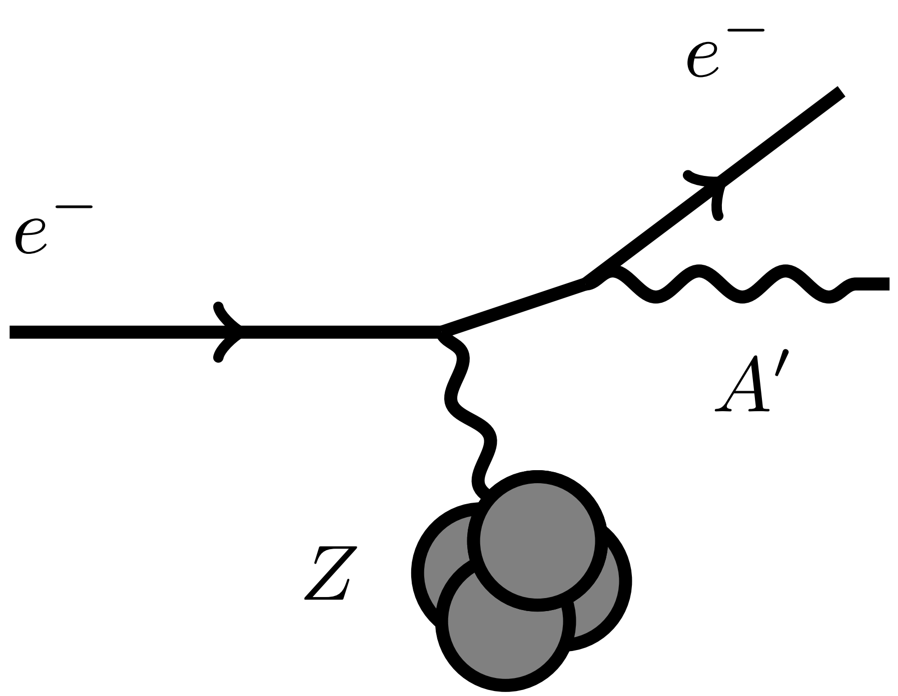
Kinetic mixing allows multiple ways to search for light mediator:
production at proton colliders, lepton colliders, beam dump, fixed target, neutrino experiments, beams in front of DM experiments

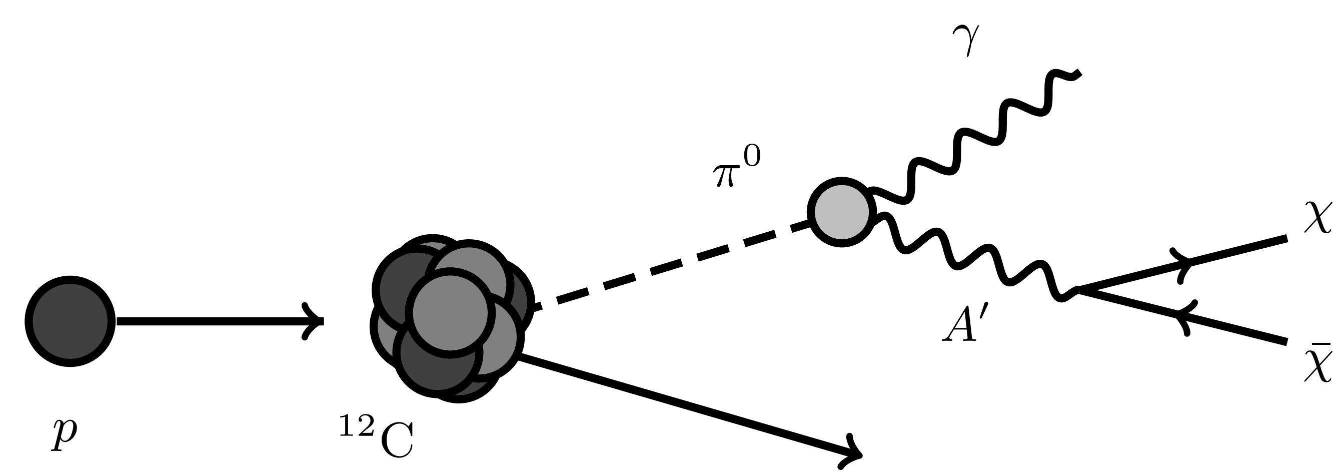
Kinetic mixing

No SM fields charged under U(1)'

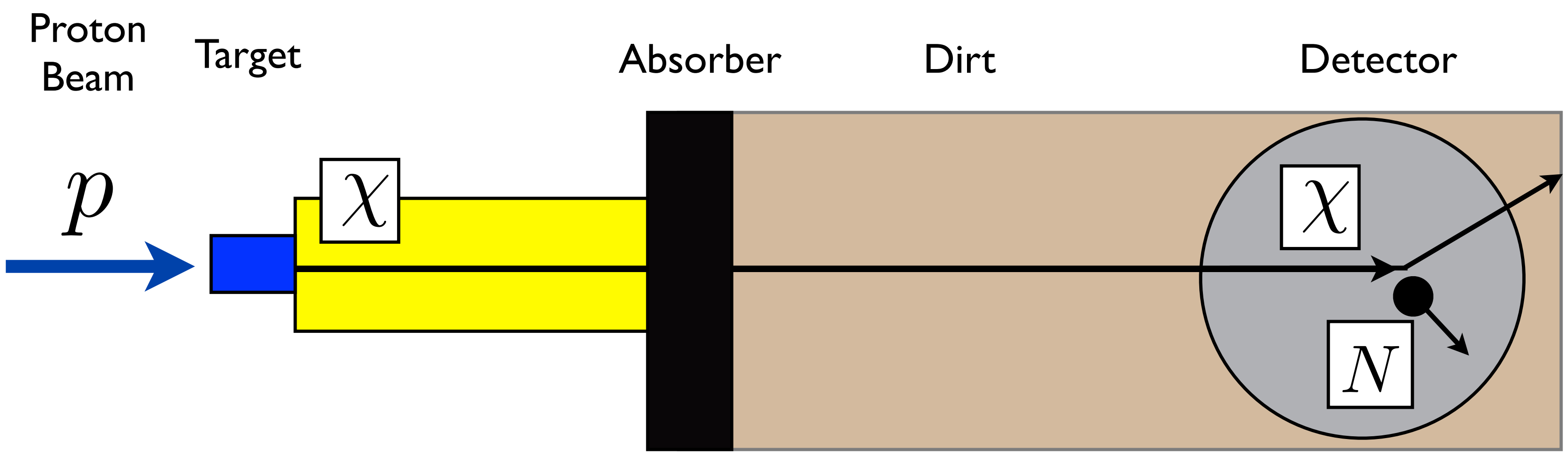
$$-\frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} = A'_\mu \times (e\epsilon)J^{\mathrm{EM}}_\mu$$

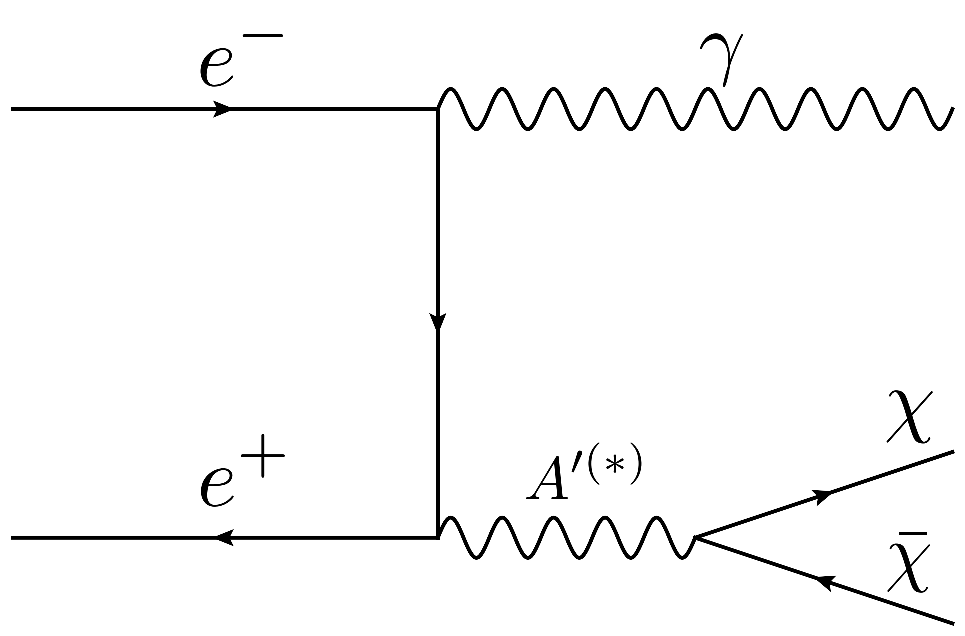
Dark photon (Z'?) couples proportional to charge

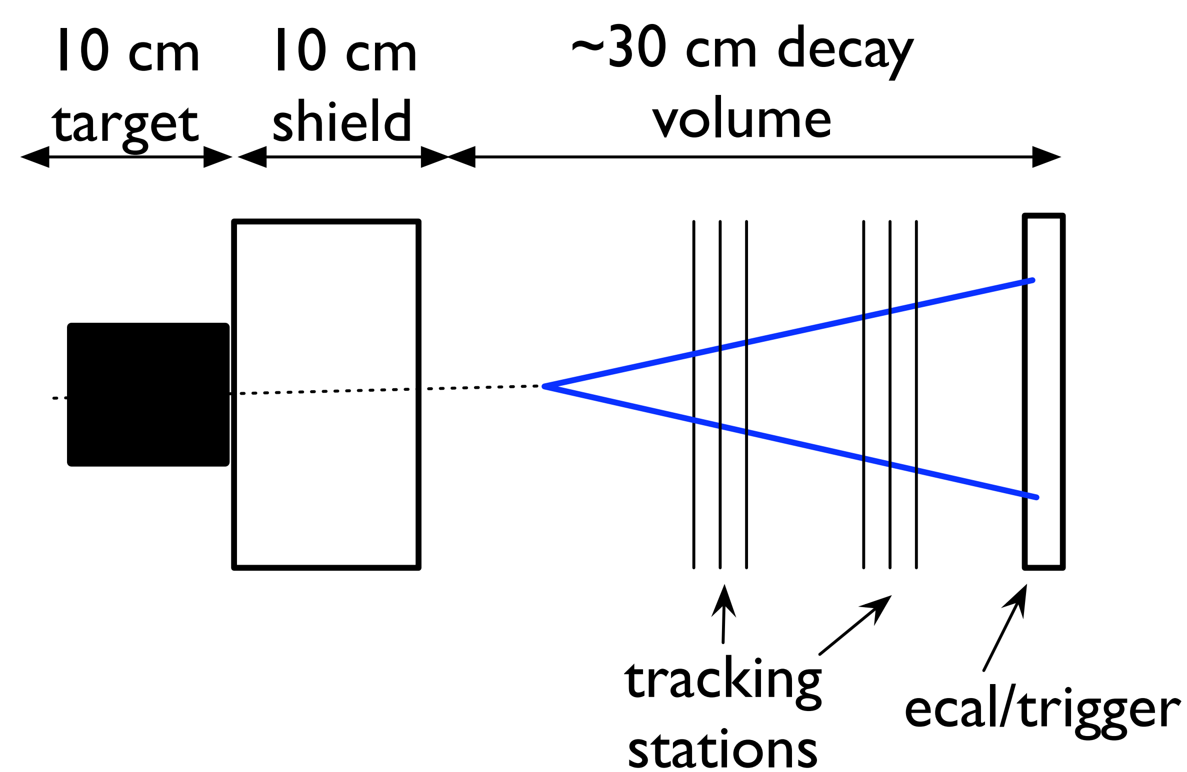




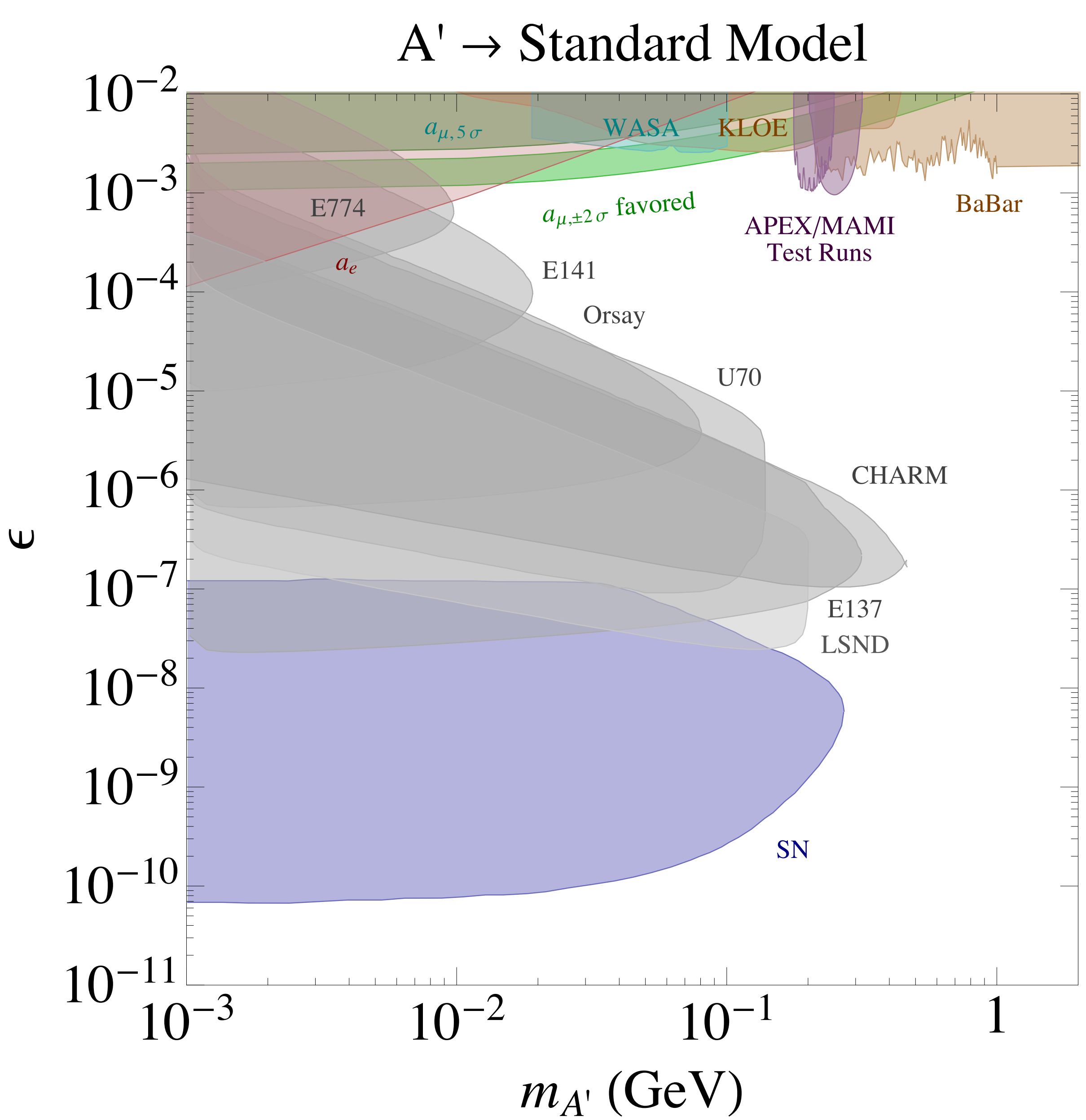
Can decay back to SM or to DM, depending on mass

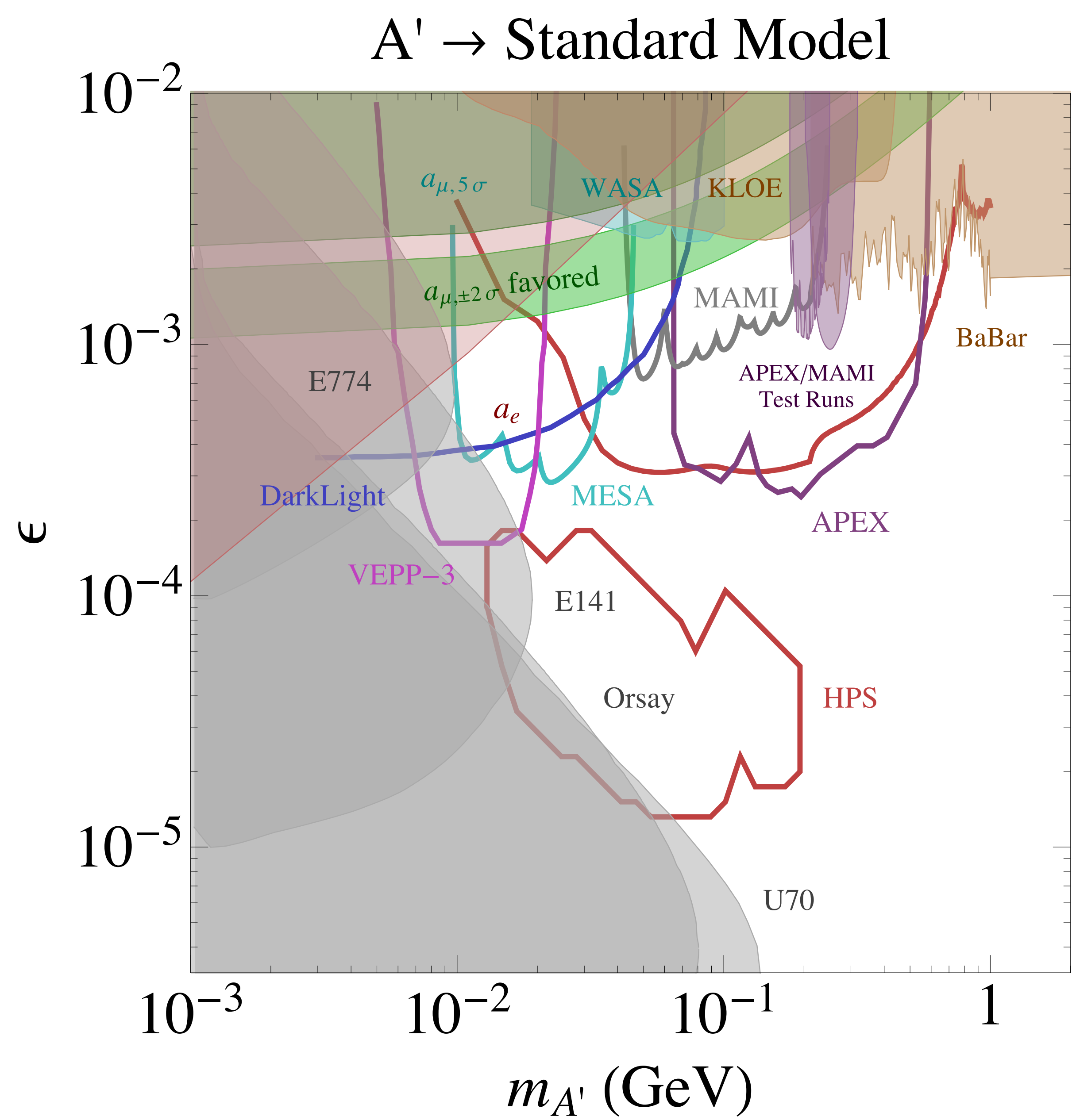




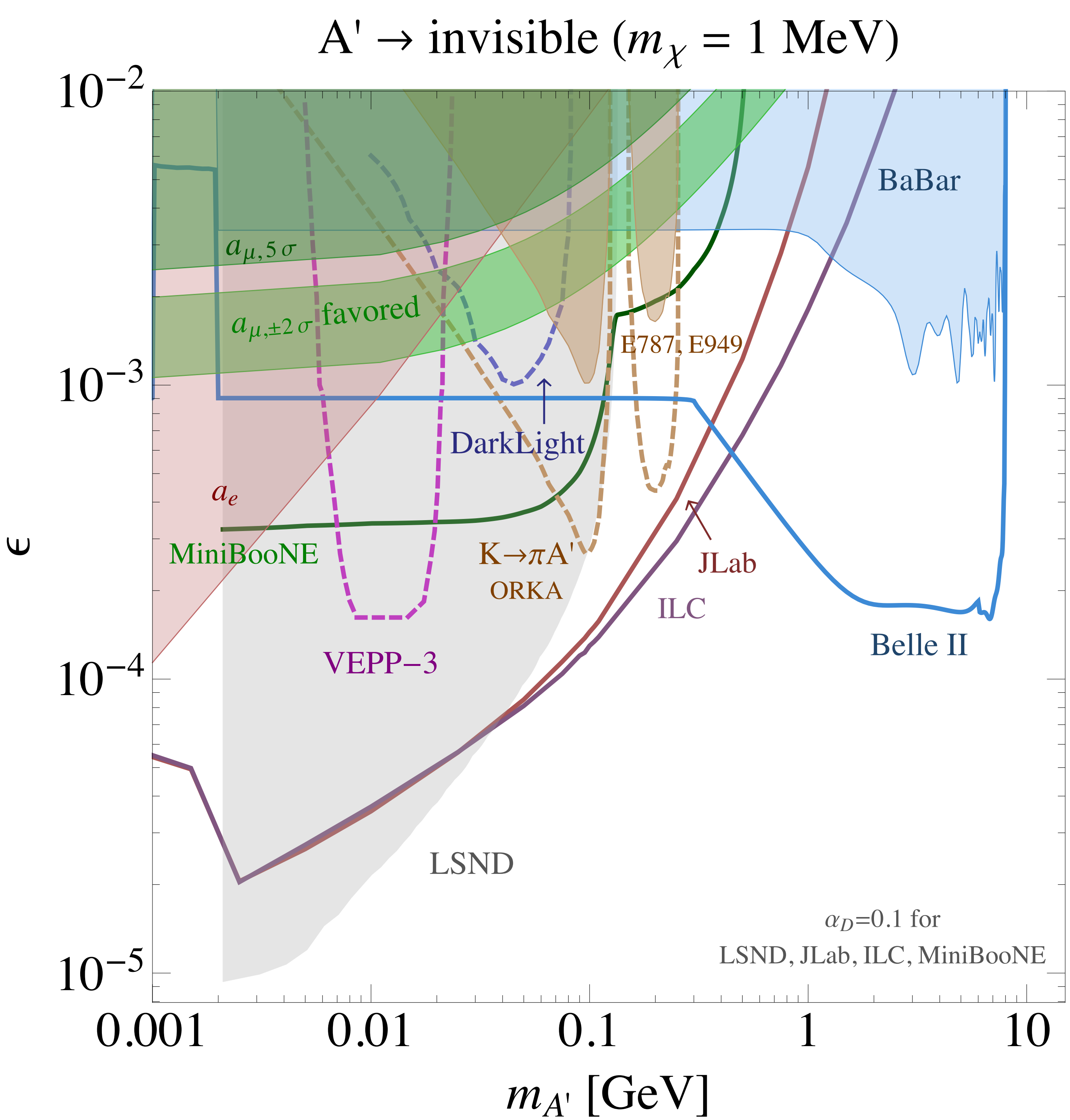


Assuming DM heavier than vector





Vector decays invisibly, DM can scatter downstream of production, or show up as MET



Have seen DM through its gravitational interactions

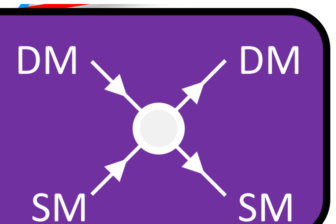
IT IS NEW PHYSICS

Should try to learn as much as possible about it

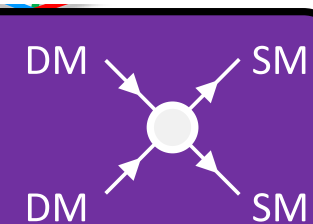
Everyone has their part to play

Exciting times ahead!

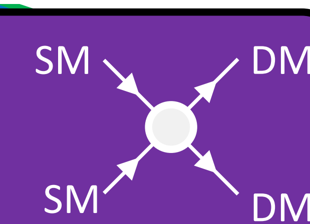
Direct Detection



Indirect Detection



Particle Colliders



Astrophysical Probes