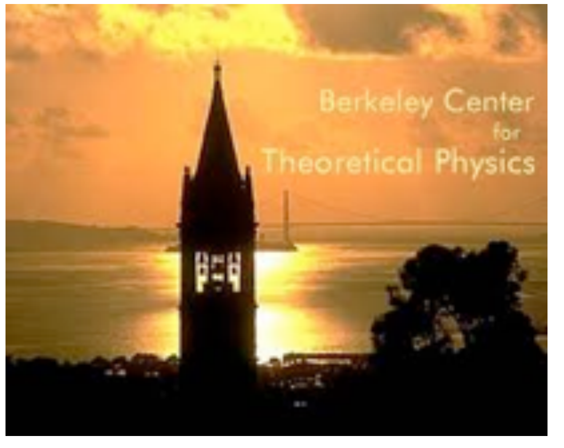
KATHRYN ZUREK

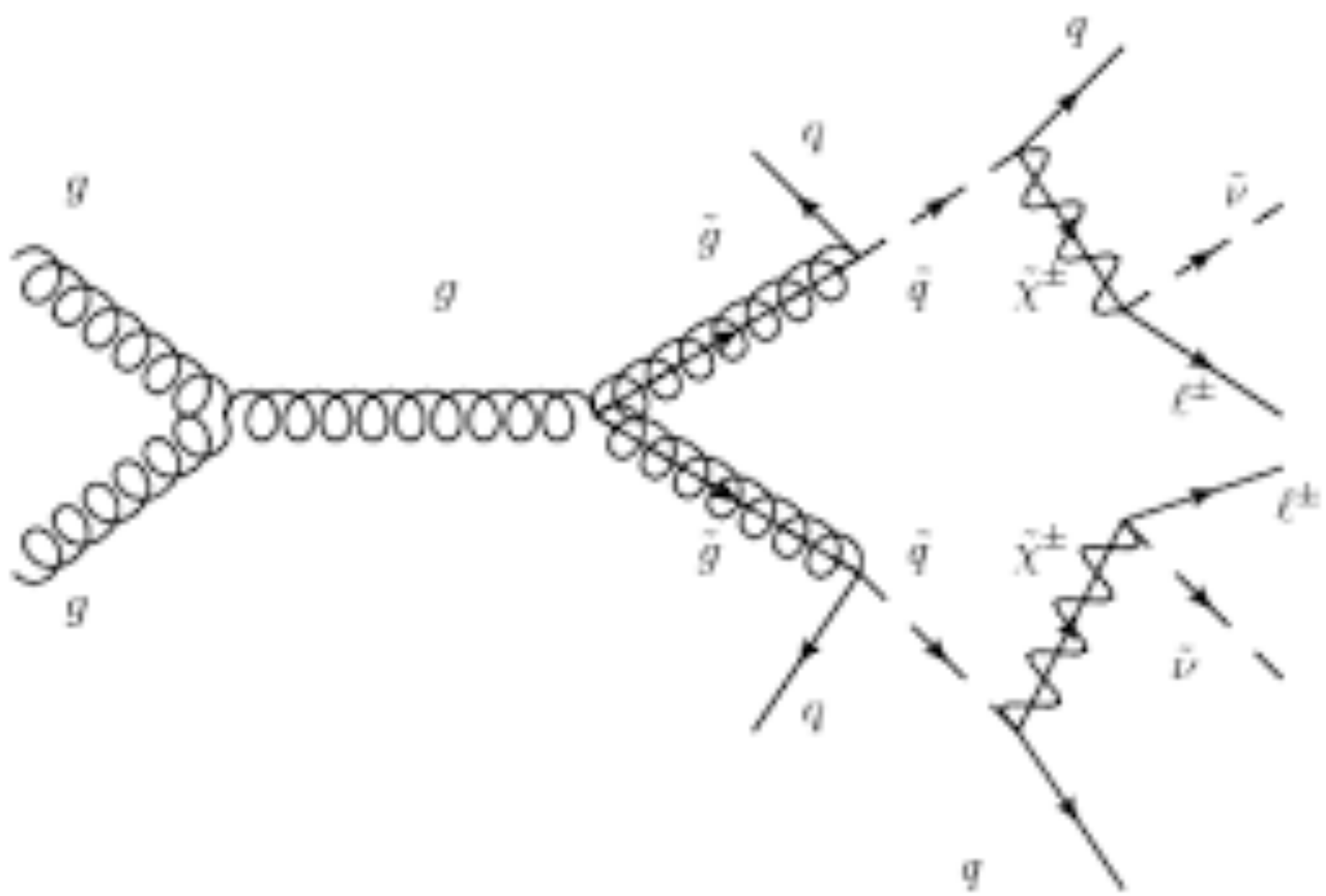
DARK MATTER AT COLLIDERS

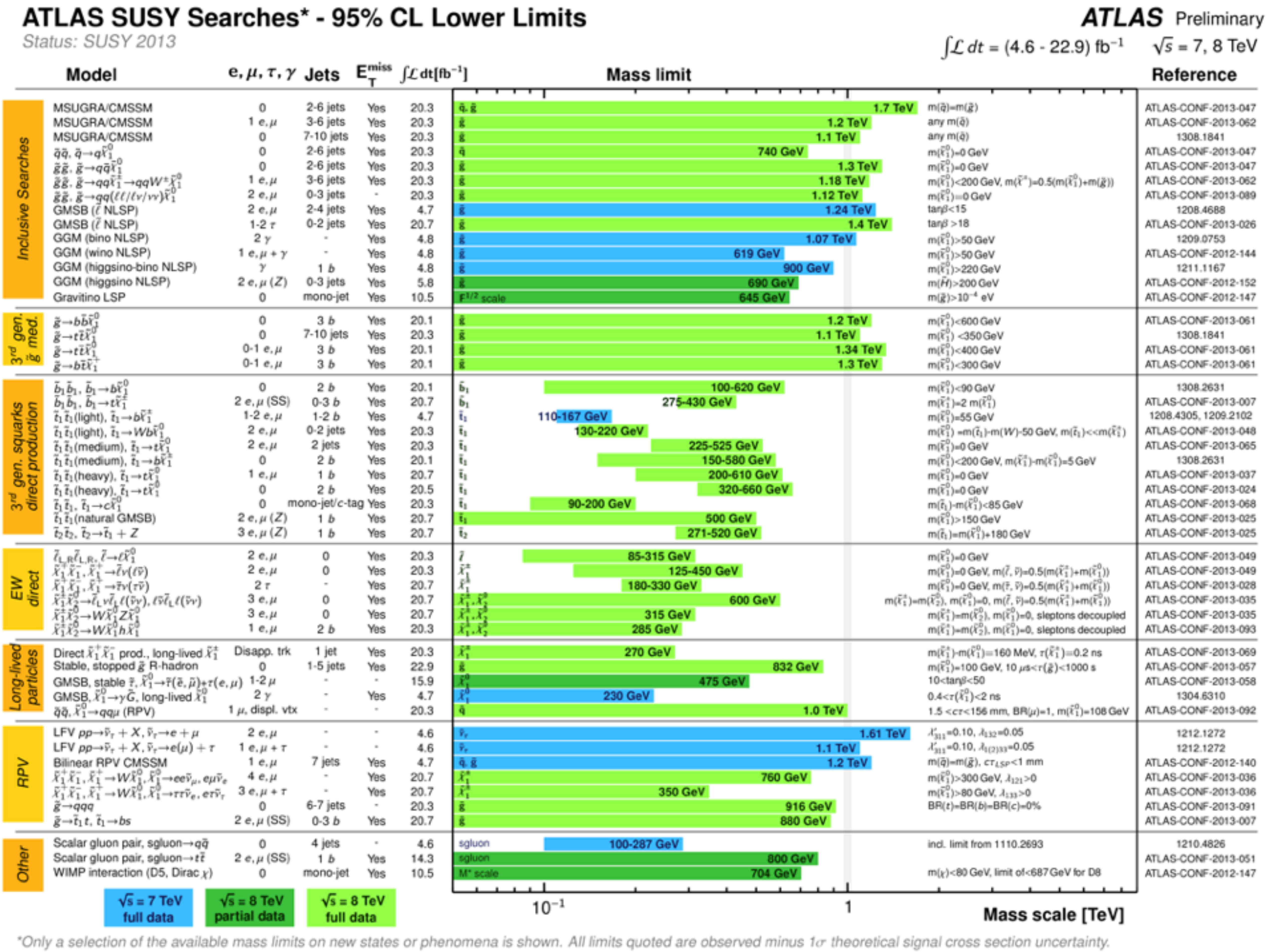
LBL Berkeley



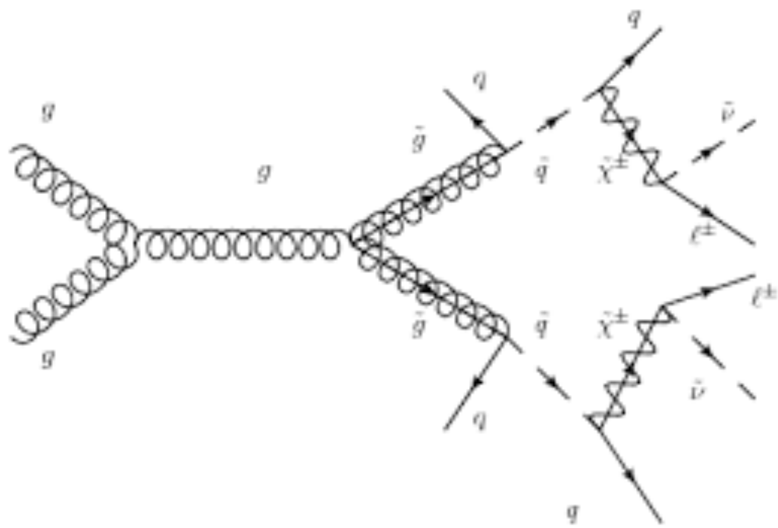
LHC AS DARK MATTER MACHINE?

- LHC is a mediator machine, not a dark matter machine



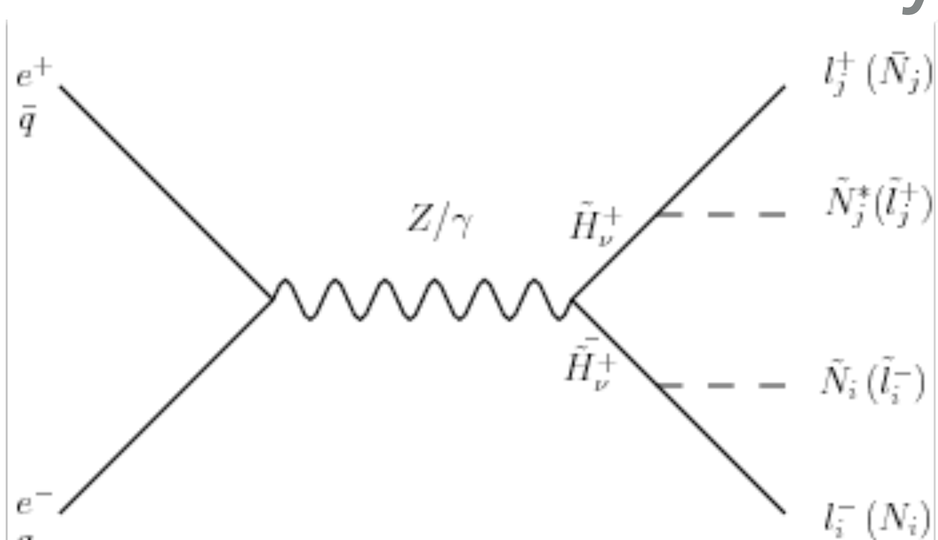

ATLAS SUSY Searches* - 95% CL Lower Limits
Status: SUSY 2013
ATLAS Preliminary
$\int \mathcal{L} dt$ = (4.6 - 22.9) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L} dt$[fb^{-1}]
Mass limit
Reference
Inclusive Searches
MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | q̃, g̃ | 1.7 TeV | m(q̃)=m(g̃) | ATLAS-CONF-2013-047
MSUGRA/CMSSM | 1 e, μ | 3-6 jets | Yes | 20.3 | g̃ | 1.2 TeV | any m(q̃) | ATLAS-CONF-2013-062
MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | g̃ | 1.1 TeV | any m(q̃) | 1308.1841
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | q̃ | 740 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | g̃ | 1.3 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm \to qqW^\pm\tilde{\chi}_1^0$ | 1 e, μ | 3-6 jets | Yes | 20.3 | g̃ | 1.18 TeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+m(g̃)) | ATLAS-CONF-2013-062
$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 e, μ | 0-3 jets | - | 20.3 | g̃ | 1.12 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-089
GMSB ($\tilde{\ell}$ NLSP) | 2 e, μ | 2-4 jets | Yes | 4.7 | g̃ | 1.24 TeV | tanβ<15 | 1208.4688
GMSB ($\tilde{\tau}$ NLSP) | 1-2 τ | 0-2 jets | Yes | 20.7 | g̃ | 1.4 TeV | tanβ >18 | ATLAS-CONF-2013-026
GGM (bino NLSP) | 2 γ | - | Yes | 4.8 | g̃ | 1.07 TeV | $m(\tilde{\chi}_1^0)$>50 GeV | 1209.0753
GGM (wino NLSP) | 1 e, μ + γ | - | Yes | 4.8 | g̃ | 619 GeV | $m(\tilde{\chi}_1^0)$>50 GeV | ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 4.8 | g̃ | 900 GeV | $m(\tilde{\chi}_1^0)$>220 GeV | 1211.1167
GGM (higgsino NLSP) | 2 e, μ (Z) | 0-3 jets | Yes | 5.8 | g̃ | 690 GeV | $m(\tilde{H})$>200 GeV | ATLAS-CONF-2012-152
Gravitino LSP | 0 | mono-jet | Yes | 10.5 | $F^{1/2}$ scale | 645 GeV | m(g̃)>10^{-4} eV | ATLAS-CONF-2012-147
3rd gen. g̃ med.
$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 20.1 | g̃ | 1.2 TeV | $m(\tilde{\chi}_1^0)$<600 GeV | ATLAS-CONF-2013-061
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | g̃ | 1.1 TeV | $m(\tilde{\chi}_1^0)$ <350 GeV | 1308.1841
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 e, μ | 3 b | Yes | 20.1 | g̃ | 1.34 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | ATLAS-CONF-2013-061
$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 e, μ | 3 b | Yes | 20.1 | g̃ | 1.3 TeV | $m(\tilde{\chi}_1^0)$<300 GeV | ATLAS-CONF-2013-061
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.1 | $\tilde{b}_1$ | 100-620 GeV | $m(\tilde{\chi}_1^0)$<90 GeV | 1308.2631
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$ | 2 e, μ (SS) | 0-3 b | Yes | 20.7 | $\tilde{b}_1$ | 275-430 GeV | $m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$ | ATLAS-CONF-2013-007
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 1-2 e, μ | 1-2 b | Yes | 4.7 | $\tilde{t}_1$ | 110-167 GeV | $m(\tilde{\chi}_1^0)$=55 GeV | 1208.4305, 1209.2102
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ | 2 e, μ | 0-2 jets | Yes | 20.3 | $\tilde{t}_1$ | 130-220 GeV | $m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-m(W)-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^\pm)$ | ATLAS-CONF-2013-048
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 2 e, μ | 2 jets | Yes | 20.3 | $\tilde{t}_1$ | 225-525 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-065
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 0 | 2 b | Yes | 20.1 | $\tilde{t}_1$ | 150-580 GeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV | 1308.2631
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 1 e, μ | 1 b | Yes | 20.7 | $\tilde{t}_1$ | 200-610 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-037
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.5 | $\tilde{t}_1$ | 320-660 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-024
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet/c-tag | Yes | 20.3 | $\tilde{t}_1$ | 90-200 GeV | $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV | ATLAS-CONF-2013-068
$\tilde{t}_1\tilde{t}_1$(natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.7 | $\tilde{t}_1$ | 500 GeV | $m(\tilde{\chi}_1^0)$>150 GeV | ATLAS-CONF-2013-025
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$ | 3 e, μ (Z) | 1 b | Yes | 20.7 | $\tilde{t}_2$ | 271-520 GeV | $m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV | ATLAS-CONF-2013-025
EW direct
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\ell}$ | 85-315 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-049
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm$ | 125-450 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$) | ATLAS-CONF-2013-049
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 τ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ | 180-330 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$) | ATLAS-CONF-2013-028
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 e, μ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ | 600 GeV | $m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$) | ATLAS-CONF-2013-035
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$ | 3 e, μ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ | 315 GeV | $m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled | ATLAS-CONF-2013-035
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$ | 1 e, μ | 2 b | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ | 285 GeV | $m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled | ATLAS-CONF-2013-093
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^\pm$ | 270 GeV | $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns | ATLAS-CONF-2013-069
Stable, stopped g̃ R-hadron | 0 | 1-5 jets | Yes | 22.9 | g̃ | 832 GeV | $m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<τ(g̃)<1000 s | ATLAS-CONF-2013-057
GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 μ | - | - | 15.9 | $\tilde{\chi}_1^0$ | 475 GeV | 10<tanβ<50 | ATLAS-CONF-2013-058
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 γ | - | Yes | 4.7 | $\tilde{\chi}_1^0$ | 230 GeV | 0.4<τ($\tilde{\chi}_1^0$)<2 ns | 1304.6310
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV) | 1 μ, displ. vtx | - | - | 20.3 | q̃ | 1.0 TeV | 1.5 <cτ<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV | ATLAS-CONF-2013-092
RPV
LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e+\mu$ | 2 e, μ | - | - | 4.6 | $\tilde{\nu}_\tau$ | 1.61 TeV | λ'_{311}=0.10, λ_{132}=0.05 | 1212.1272
LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu)+\tau$ | 1 e, μ + τ | - | - | 4.6 | $\tilde{\nu}_\tau$ | 1.1 TeV | λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05 | 1212.1272
Bilinear RPV CMSSM | 1 e, μ | 7 jets | Yes | 4.7 | q̃, g̃ | 1.2 TeV | m(q̃)=m(g̃), $c\tau_{LSP}$<1 mm | ATLAS-CONF-2012-140
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 e, μ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ | 760 GeV | $m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0 | ATLAS-CONF-2013-036
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 e, μ + τ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ | 350 GeV | $m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0 | ATLAS-CONF-2013-036
$\tilde{g}\to qqq$ | 0 | 6-7 jets | - | 20.3 | g̃ | 916 GeV | BR(t)=BR(b)=BR(c)=0% | ATLAS-CONF-2013-091
$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$ | 2 e, μ (SS) | 0-3 b | Yes | 20.7 | g̃ | 880 GeV | | ATLAS-CONF-2013-007
Other
Scalar gluon pair, sgluon→$q\bar{q}$ | 0 | 4 jets | - | 4.6 | sgluon | 100-287 GeV | incl. limit from 1110.2693 | 1210.4826
Scalar gluon pair, sgluon→$t\bar{t}$ | 2 e, μ (SS) | 1 b | Yes | 14.3 | sgluon | 800 GeV | | ATLAS-CONF-2013-051
WIMP interaction (D5, Dirac χ) | 0 | mono-jet | Yes | 10.5 | M* scale | 704 GeV | m(χ)<80 GeV, limit of<687 GeV for D8 | ATLAS-CONF-2012-147
$\sqrt{s}$ = 7 TeV full data
$\sqrt{s}$ = 8 TeV partial data
$\sqrt{s}$ = 8 TeV full data
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

- Strong constraints on strongly interacting particles



> 1 TeV

- Weak constraints on weakly interacting particles



> few hundred GeV

WEAKLY INTERACTING DARK MATTER

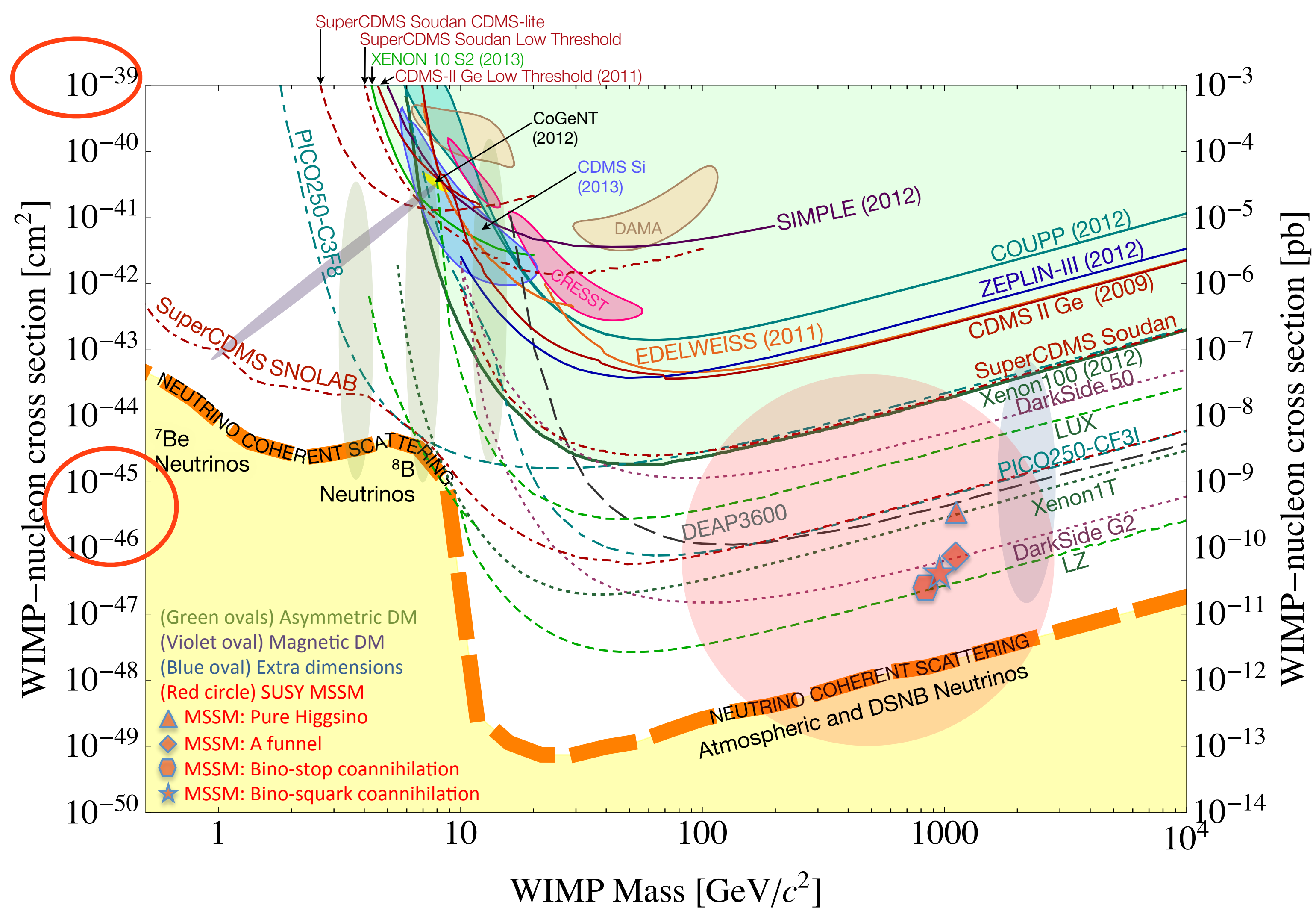
- Direct/Indirect detection does well here

$$\sigma_n \sim 10^{-39}\ \mathrm{cm}^2$$

Scattering via the Z boson

$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

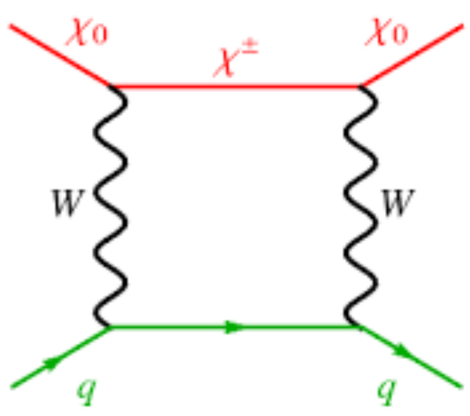
Scattering via the Higgs boson



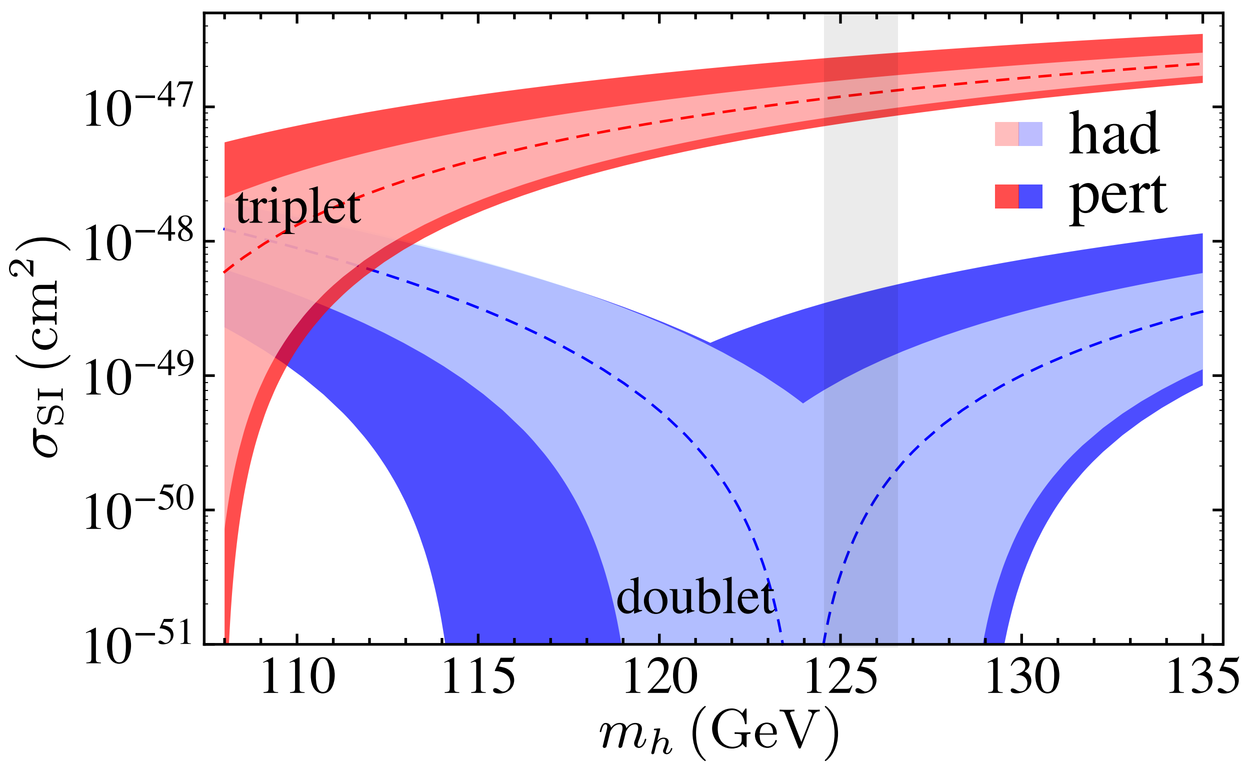
WEAKLY INTERACTING DARK MATTER

- Scattering cross-sections so large that even 1-loop suppressed processes detectable

EW doublet and triplet:



Hill and Solon



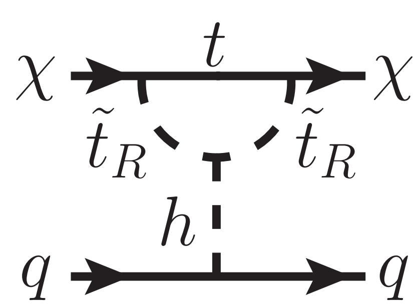
WEAKLY INTERACTING DARK MATTER

- Scattering cross-sections so large that even 1-loop suppressed processes detectable

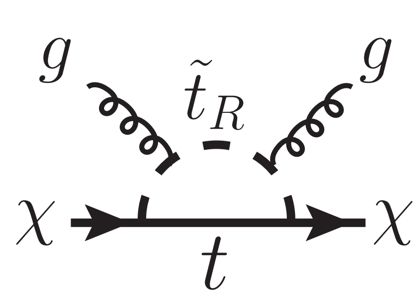
Berlin, Robertson, Solon, KZ 1511.05964

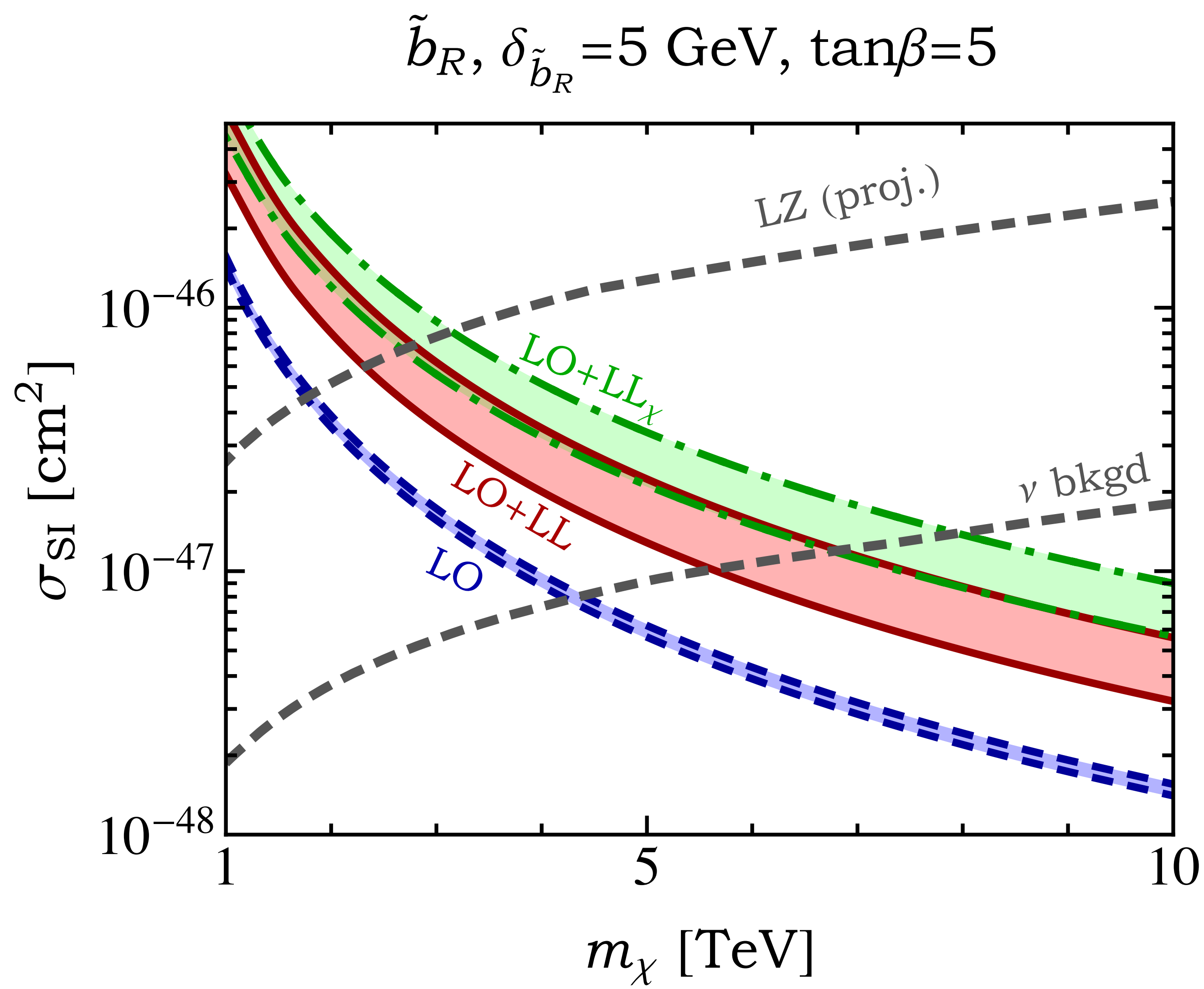
EW singlet:

$\mathcal{O}(\alpha_w^2)$:



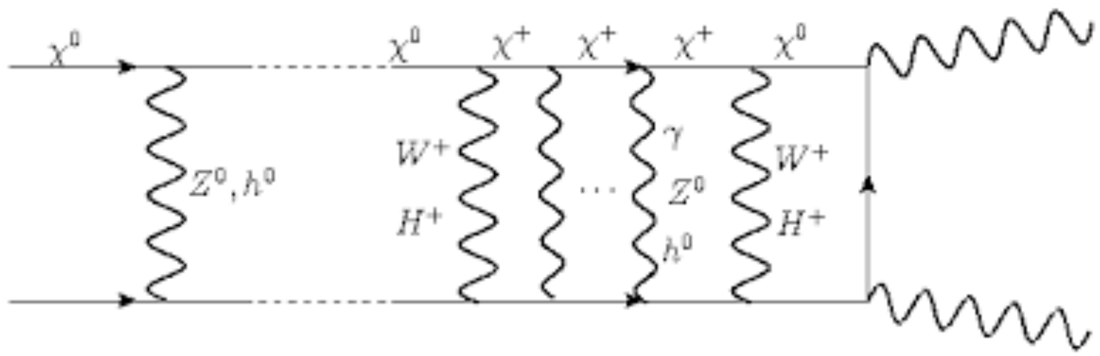
$\mathcal{O}(\alpha_w \alpha_s)$:



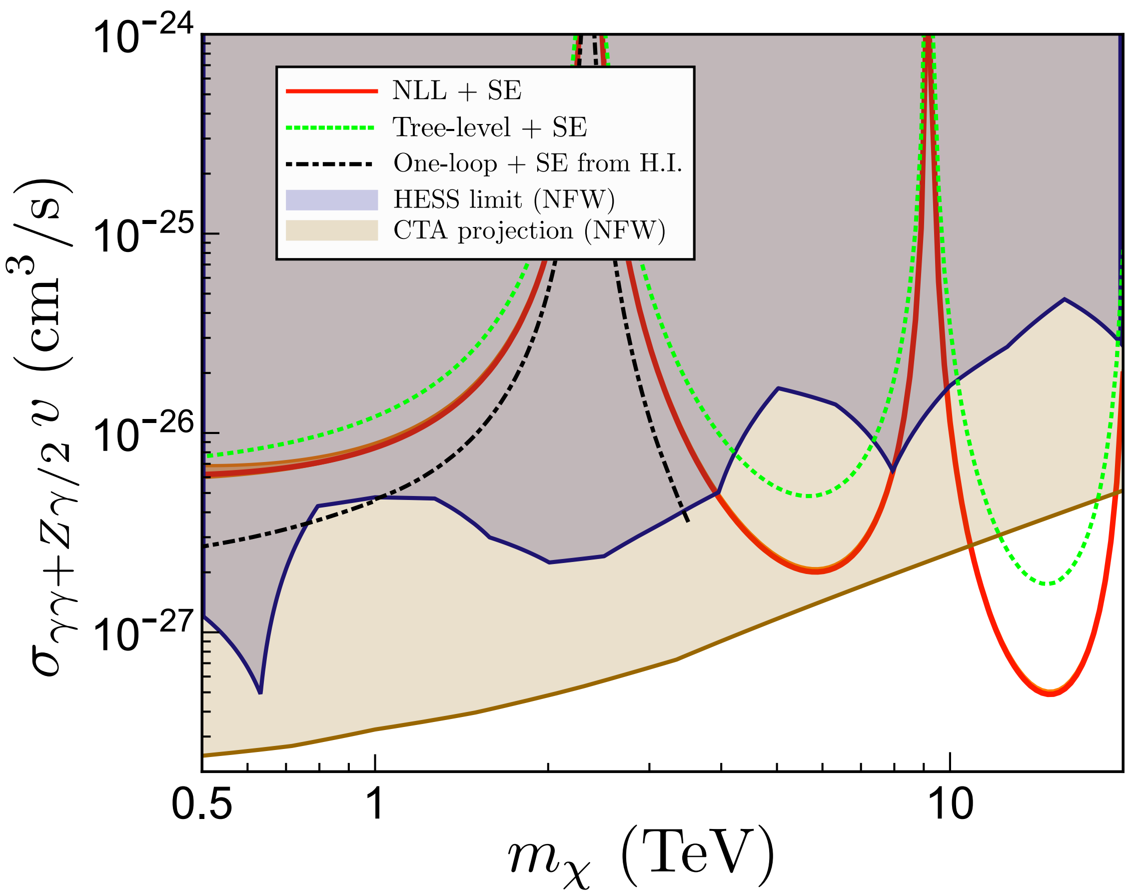


WEAKLY INTERACTING DARK MATTER

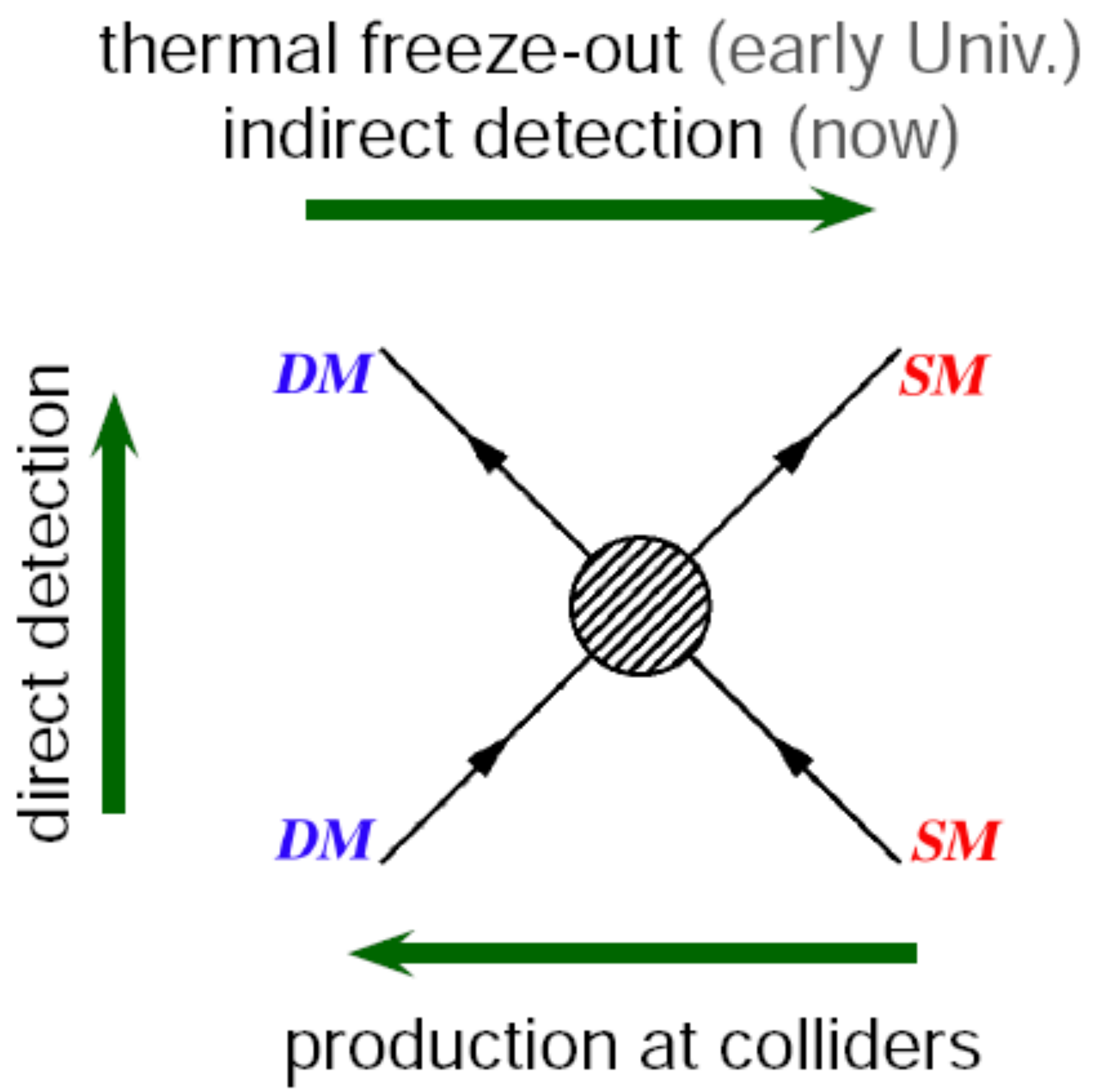
- Electroweak triplet has a big annihilation rate to photons



Ovanesyan, Slatyer, Stewart

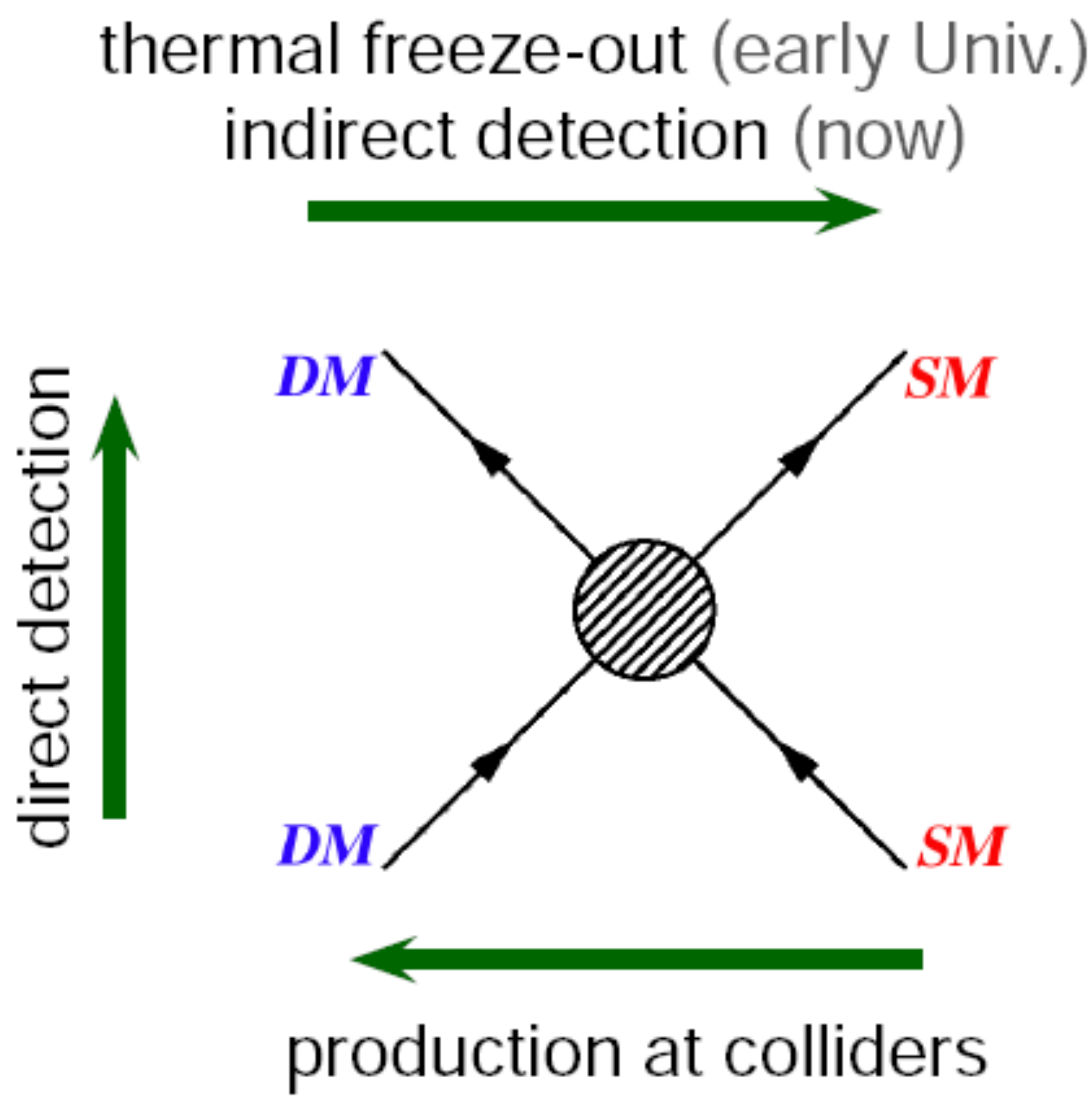


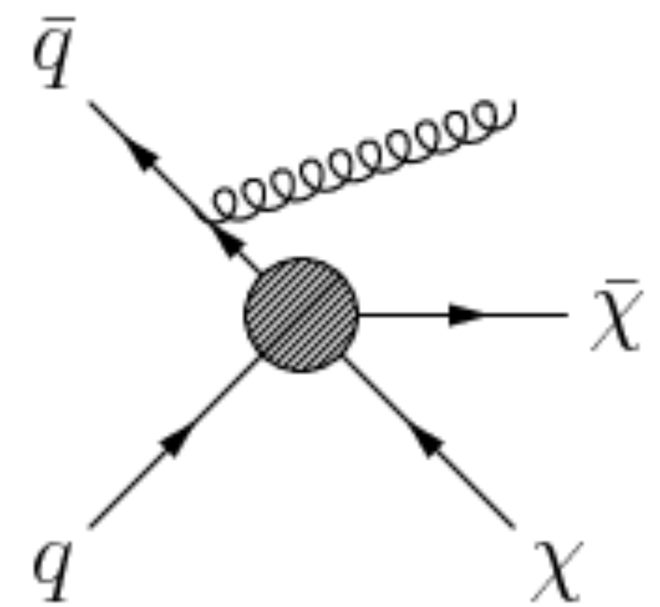
COLLIDER AS DM MACHINE



COLLIDER AS DM MACHINE

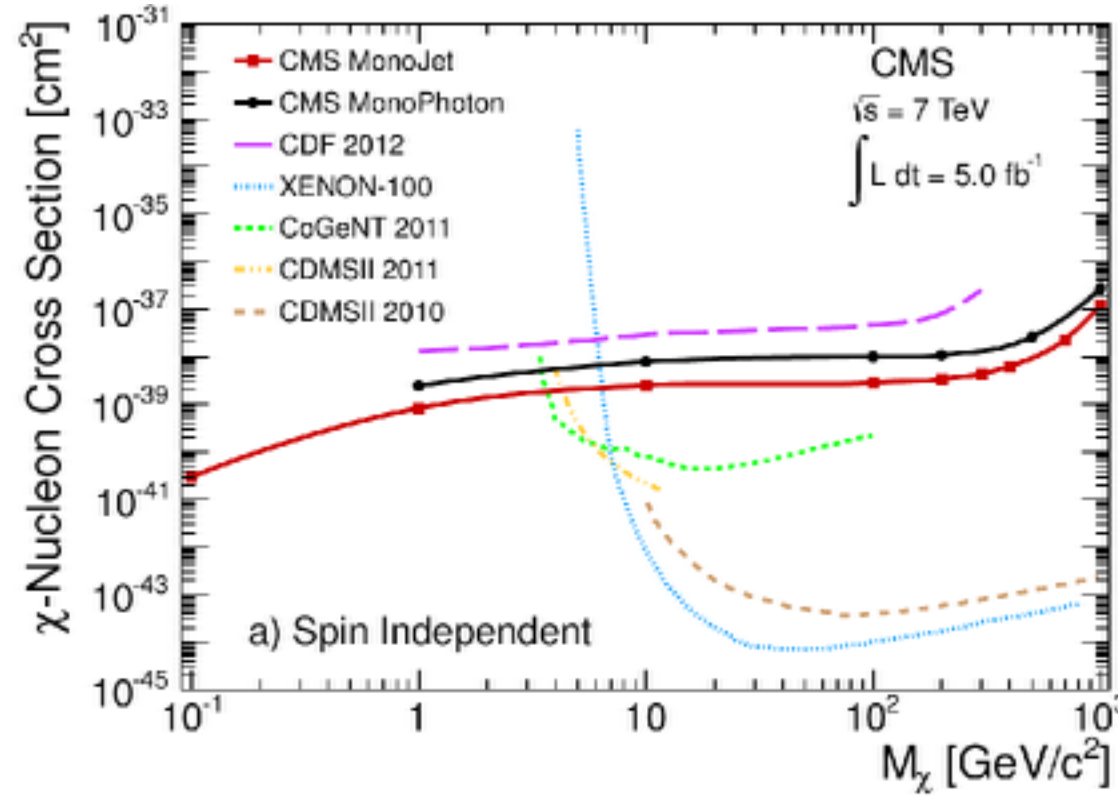
- Mono-X is "collider as DM machine"

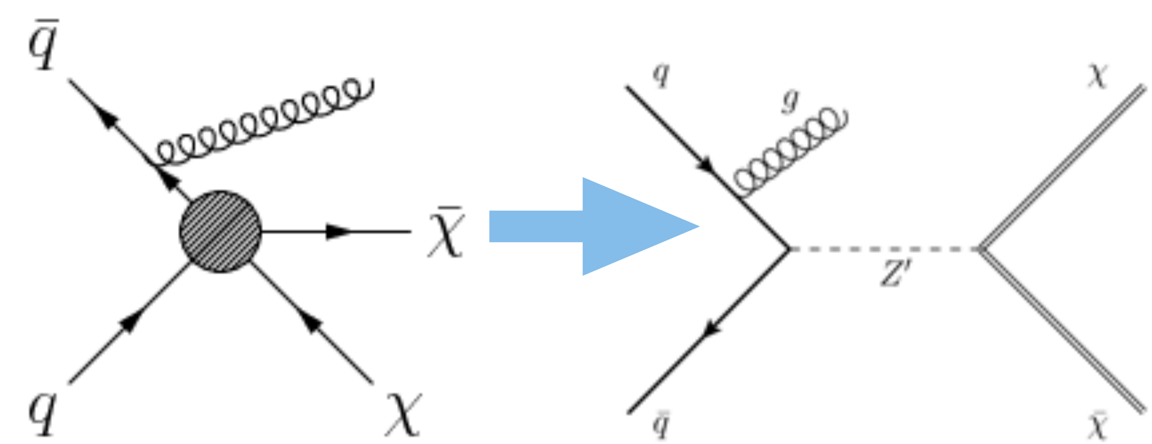




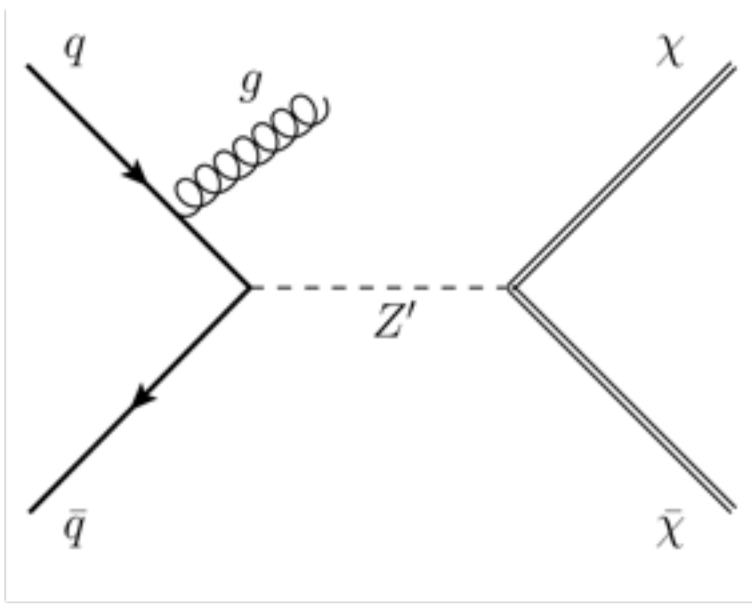
COMPARE LHC TO DIRECT DETECTION CONSTRAINTS?

- Important theory dependence in these plots!
- Inappropriate use of higher dimension operators
- Failure to take into account direct searches for mediator

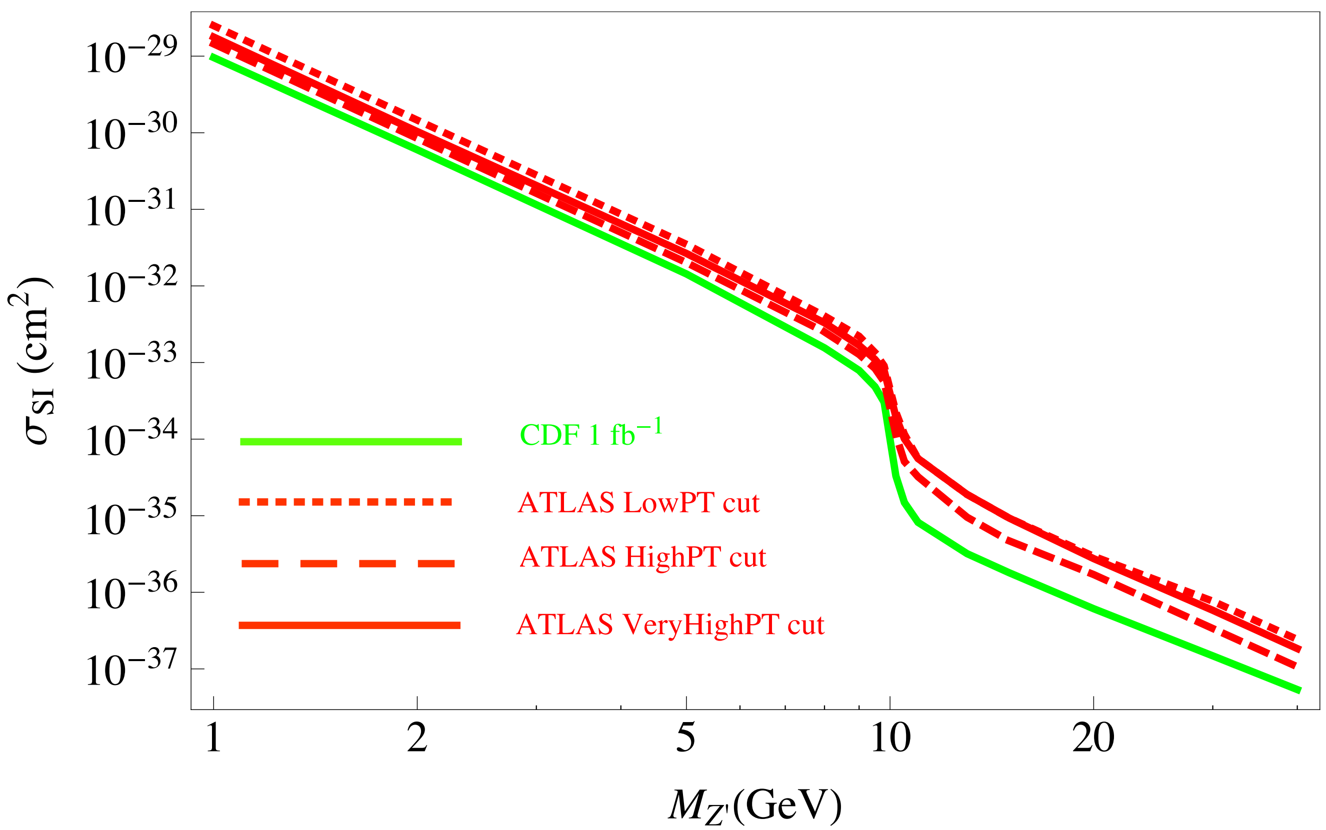




INAPPROPRIATE USE OF HIGHER DIMENSION OPERATORS



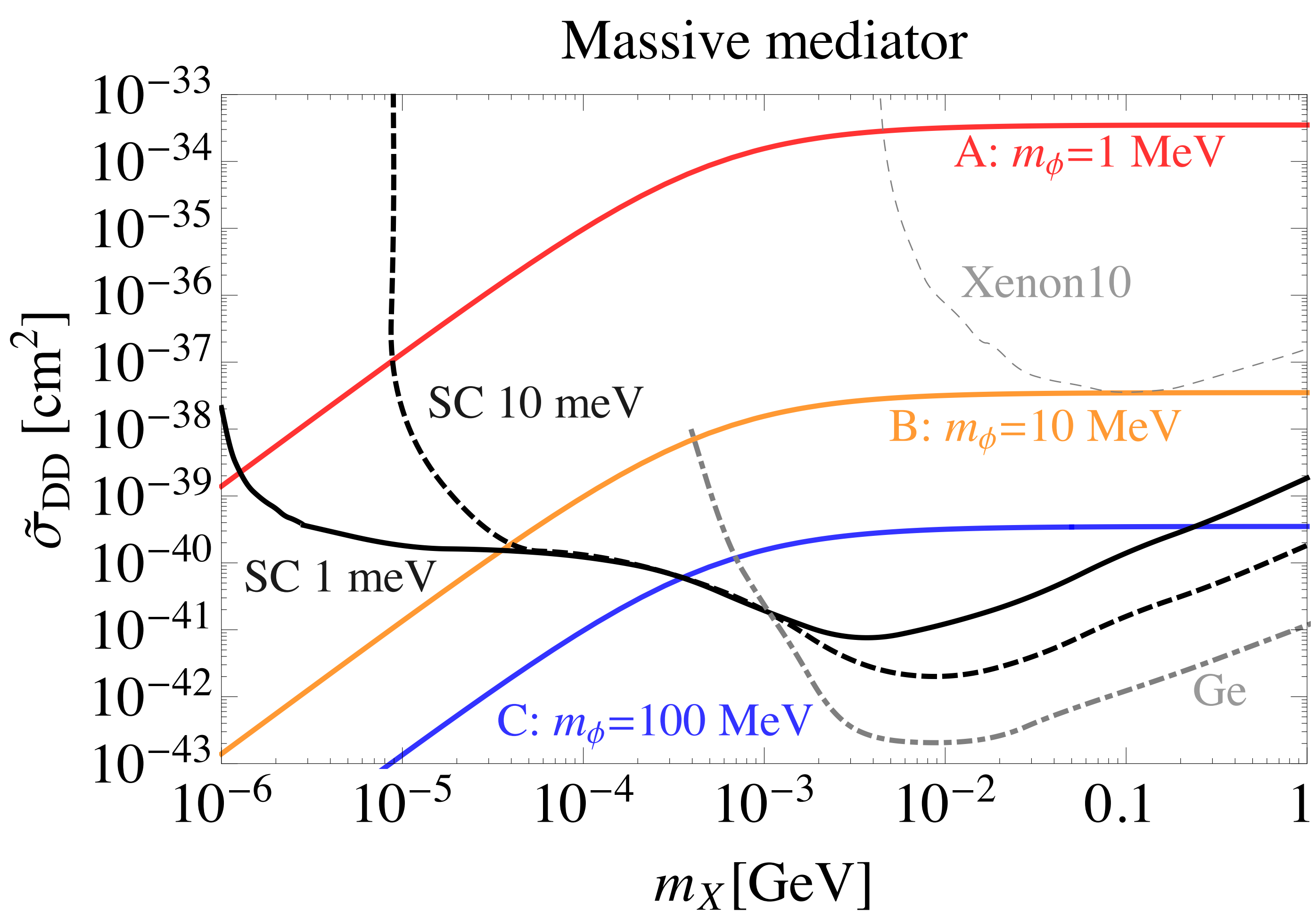
$$\sigma \sim \frac{s}{(s-m_M^2)^2 + m_M^2\Gamma^2}$$



An, Ji, Wang

DIRECT DETECTION MORE EFFECTIVE WITH LIGHT MEDIATORS

- And light dark matter.

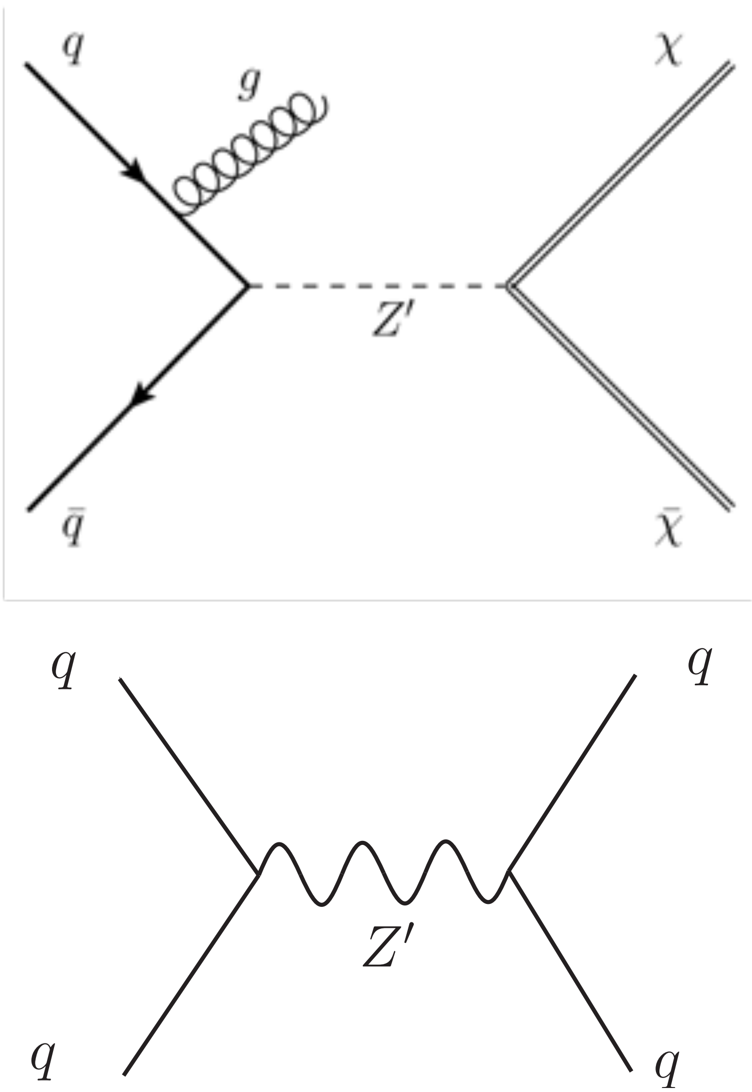


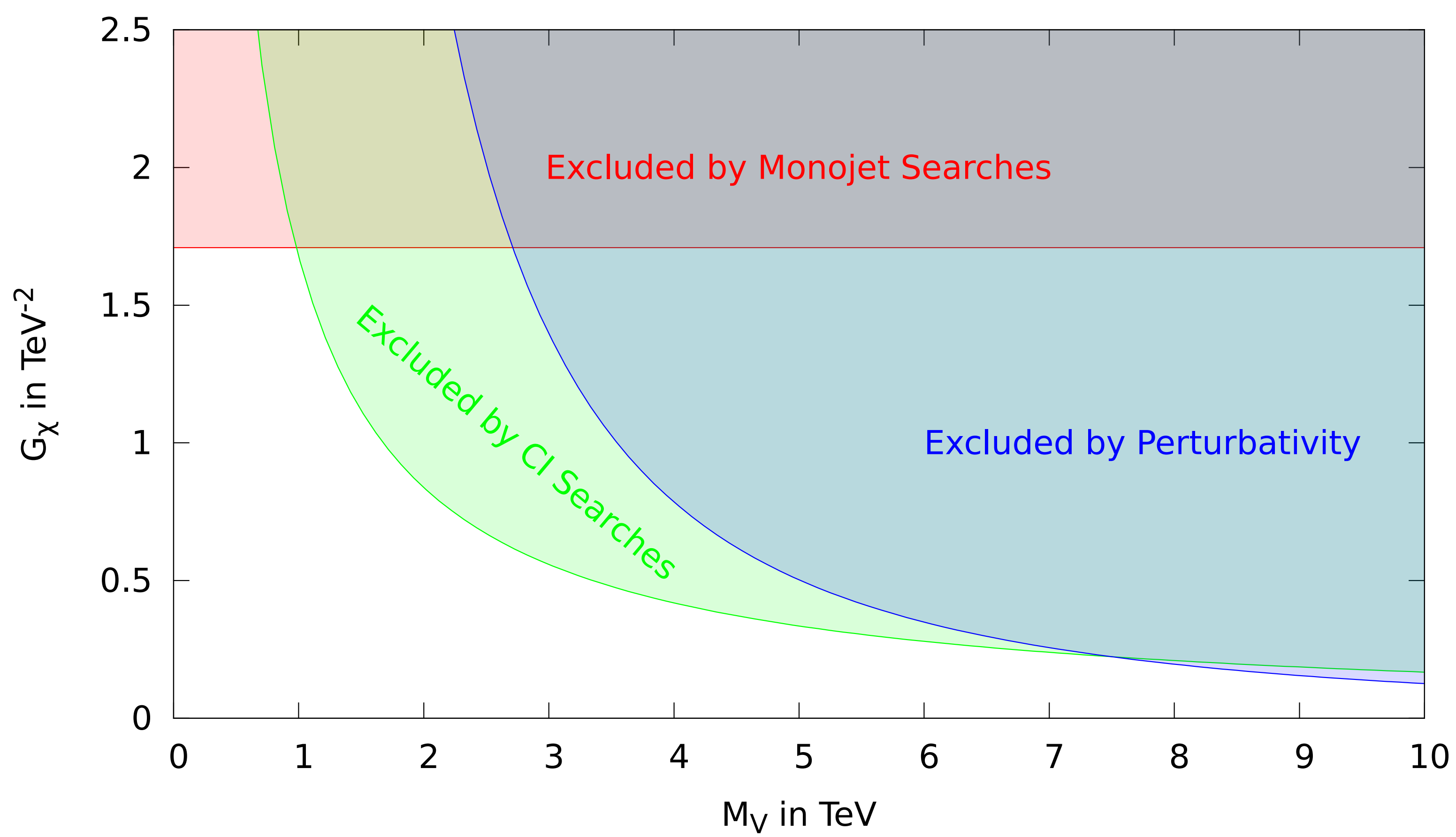
- See talk later on direct detection of sub-GeV dark matter

DIRECT SEARCH MODES

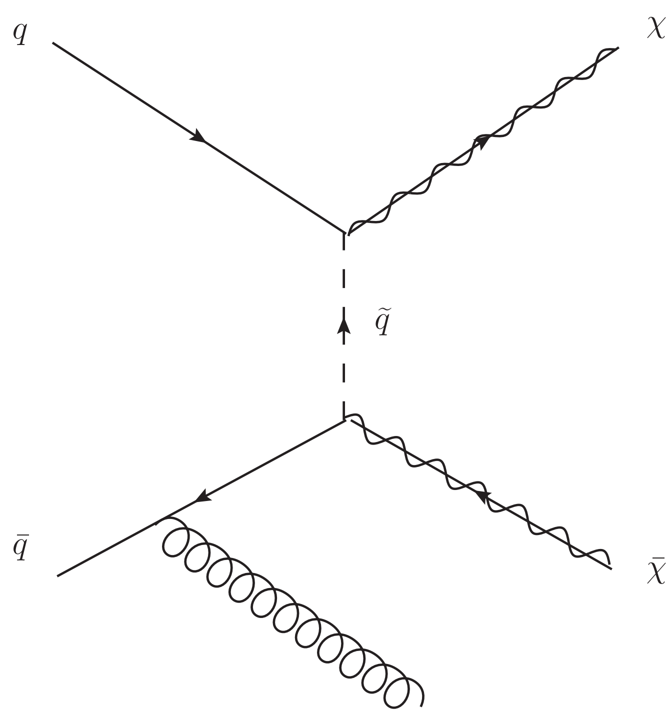
- Dijet constraints

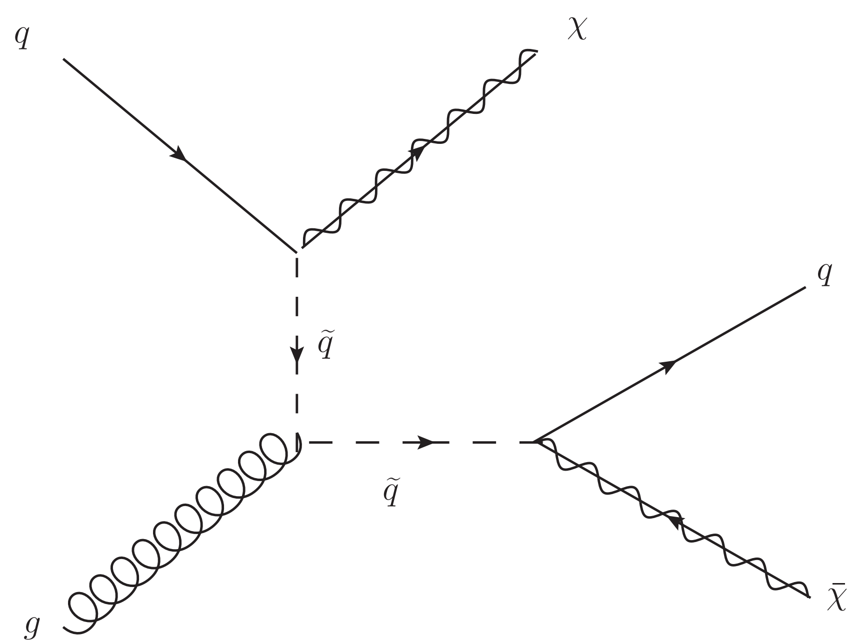
Dreiner et al 1303.3348



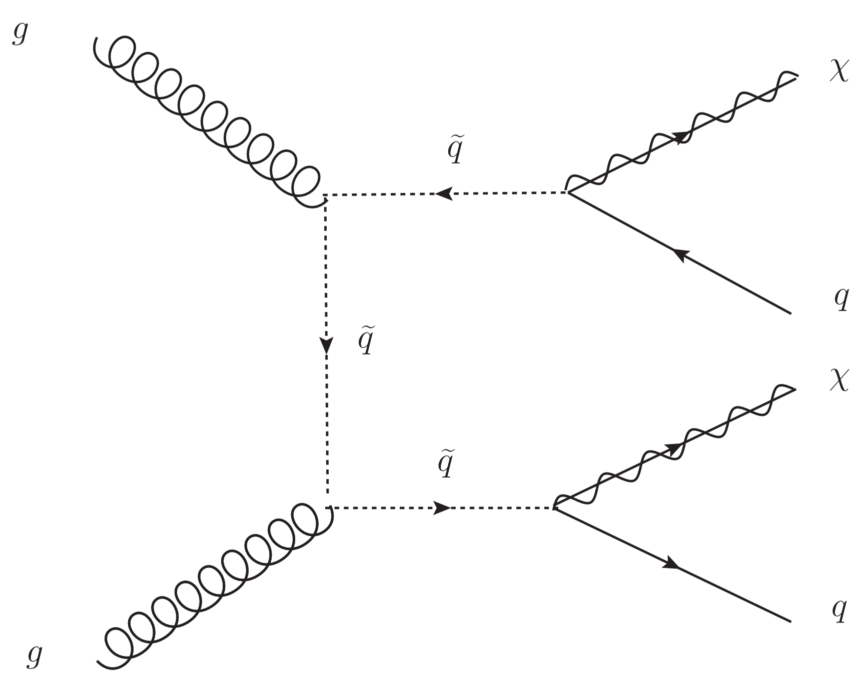


T-CHANNEL MODEL



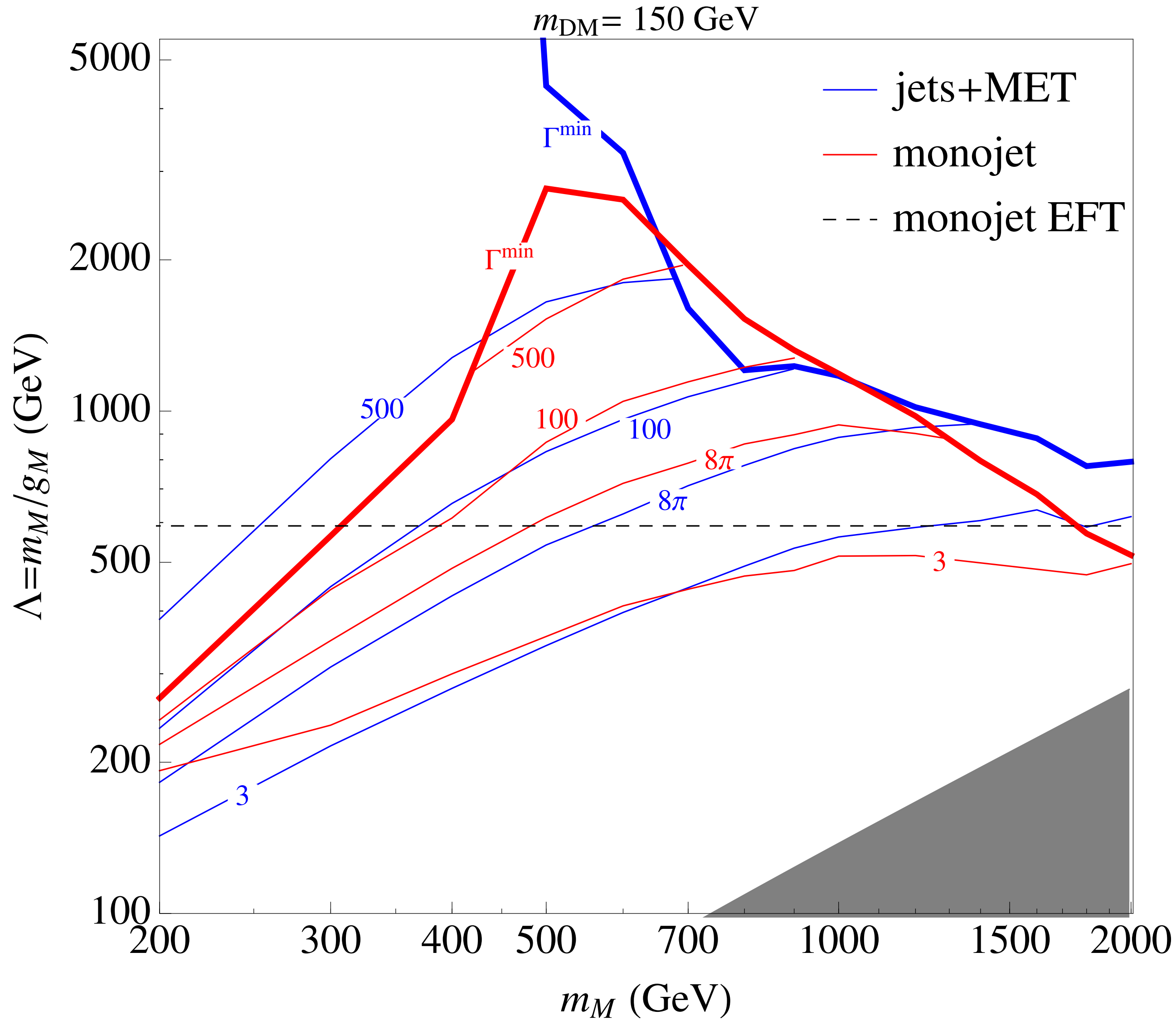


- Other channels:



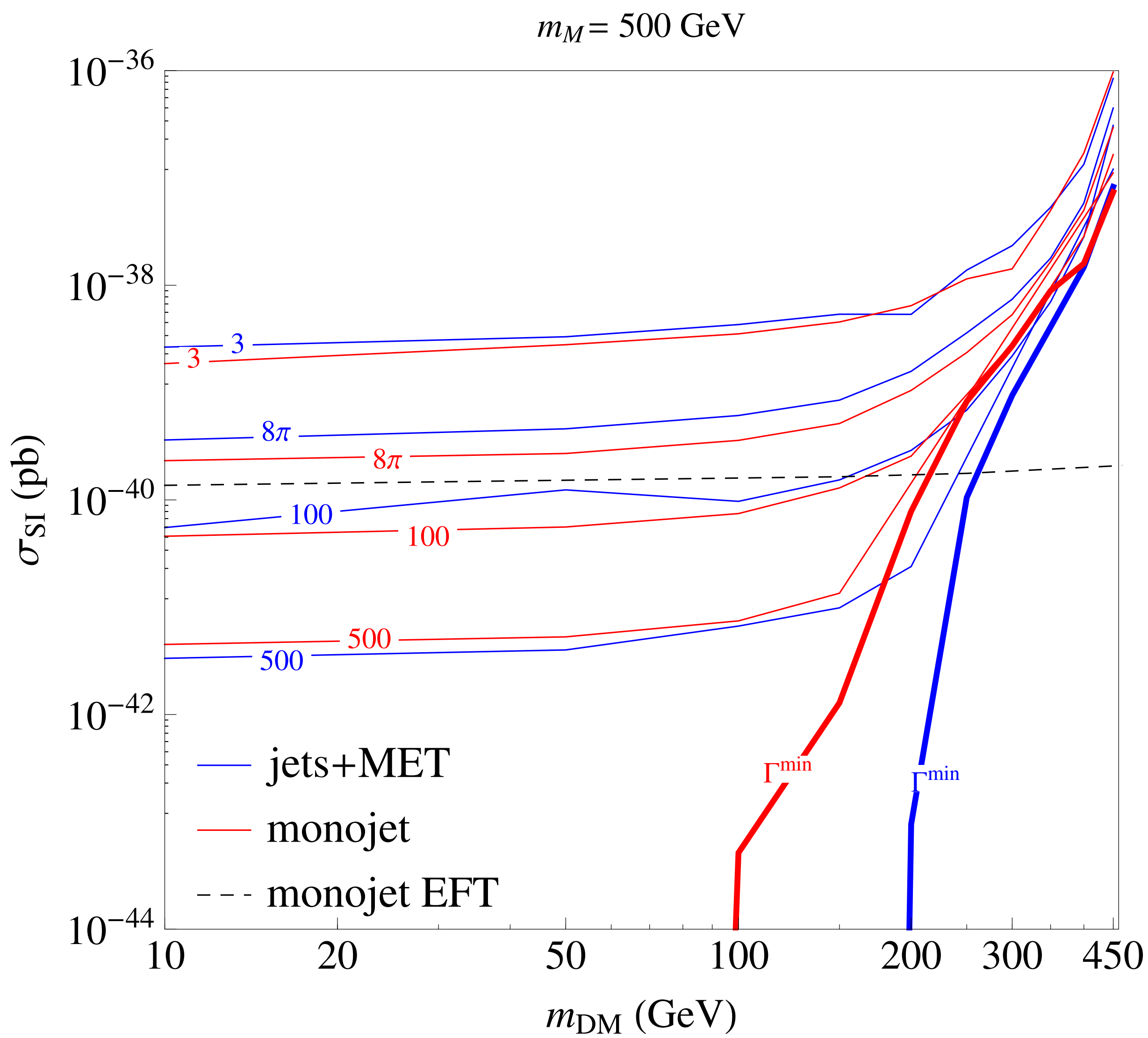
T-CHANNEL MODEL

- Compare monojet to traditional SUSY search: dijet+MET
- True constraints are stronger or weaker than EFT constraint
- EFT limit not reached until mediator 2 TeV or heavier



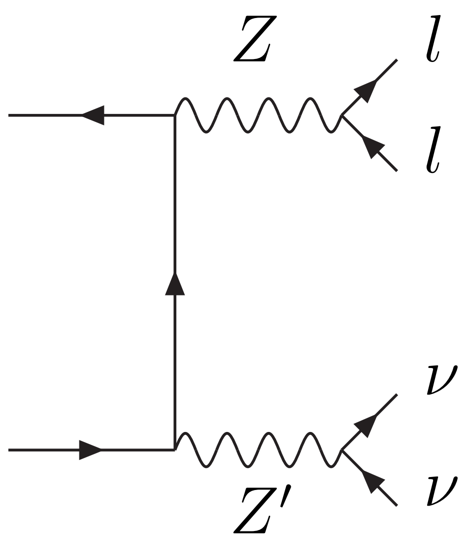
T-CHANNEL MODEL

- Compare monojet to traditional SUSY search: dijet+MET
- Look at direct detection plane
- Constraints obviously model dependent!

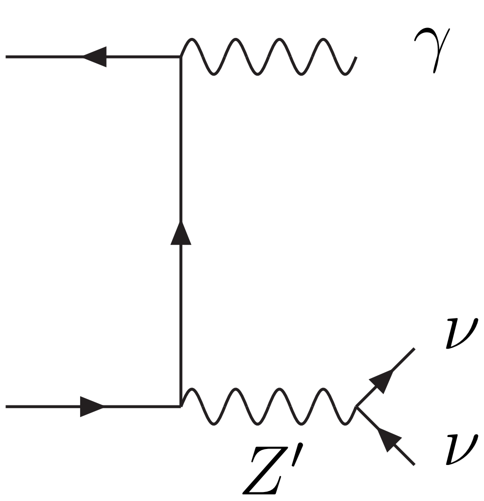


OTHER PARTICLES THAN JETS

- Not restricted to jets as Initial State Radiation
- Earliest studies used Z bosons because cleaner signature



Petriello, Quackenbush, KZ
0803.4005

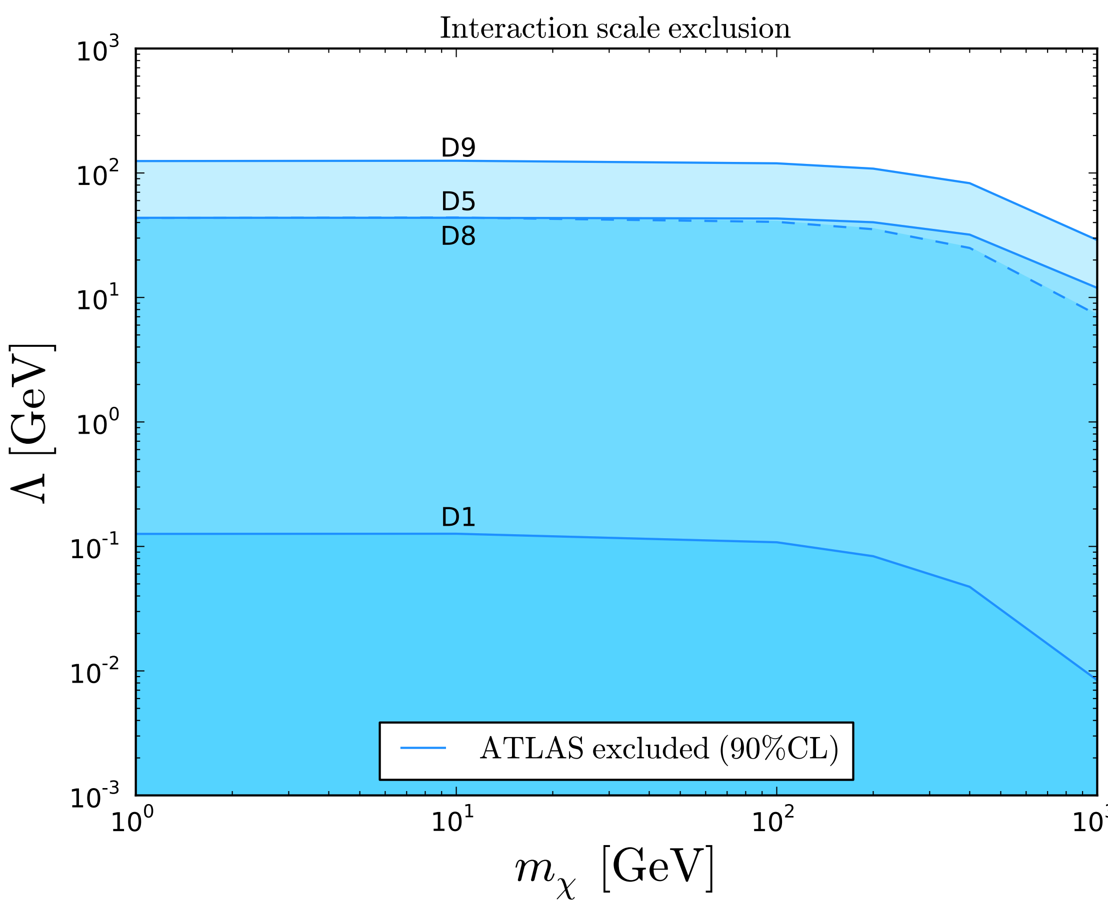


Gershtein, Petriello, Quackenbush, KZ
0809.2849

- Z/W/Higgs/photon

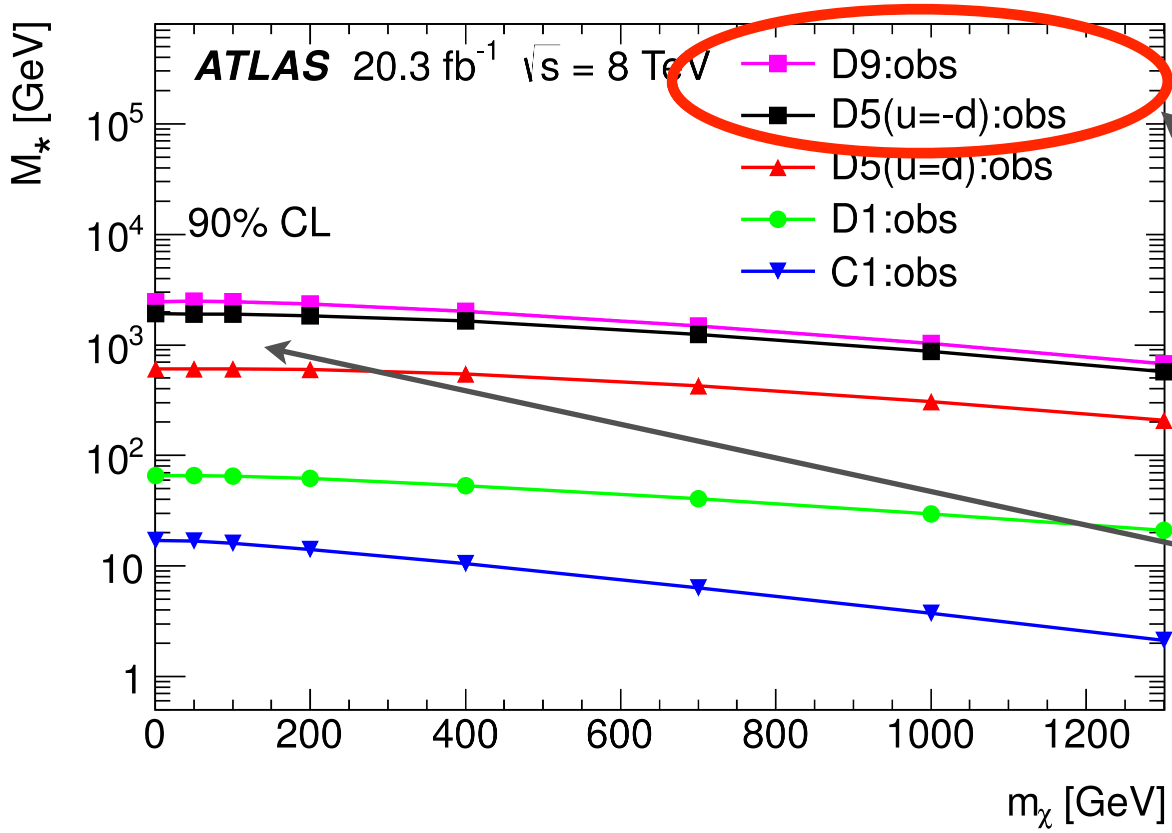
CONSTRAINTS TOO WEAK TO JUSTIFY EFT APPROACH

Carpenter et al, 1212.3352



$$\Lambda = m_M / \sqrt{g_q g_\chi}$$

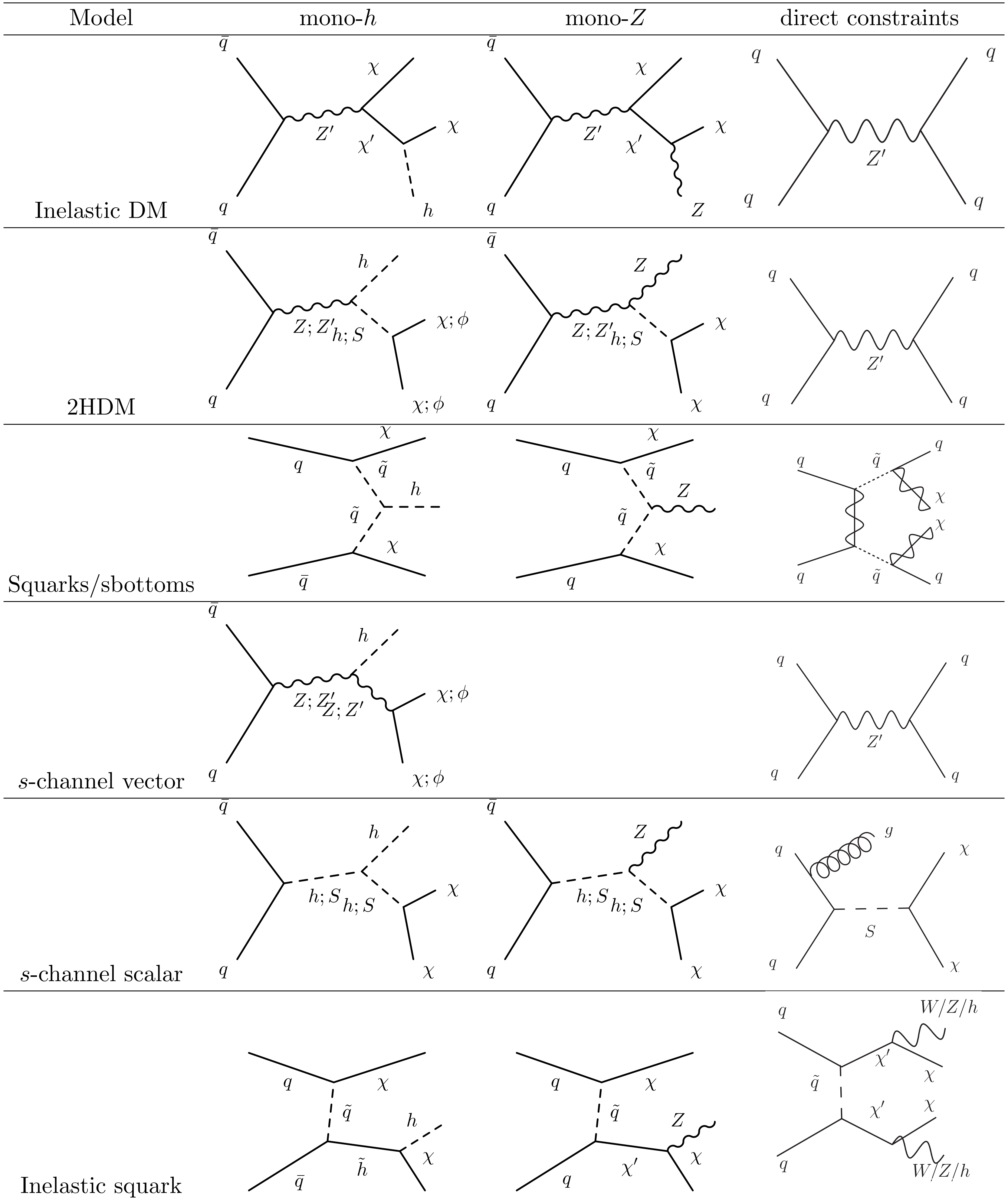
CONSTRAINTS TOO WEAK TO JUSTIFY EFT APPROACH



(Artificially) high scale, better than monojets

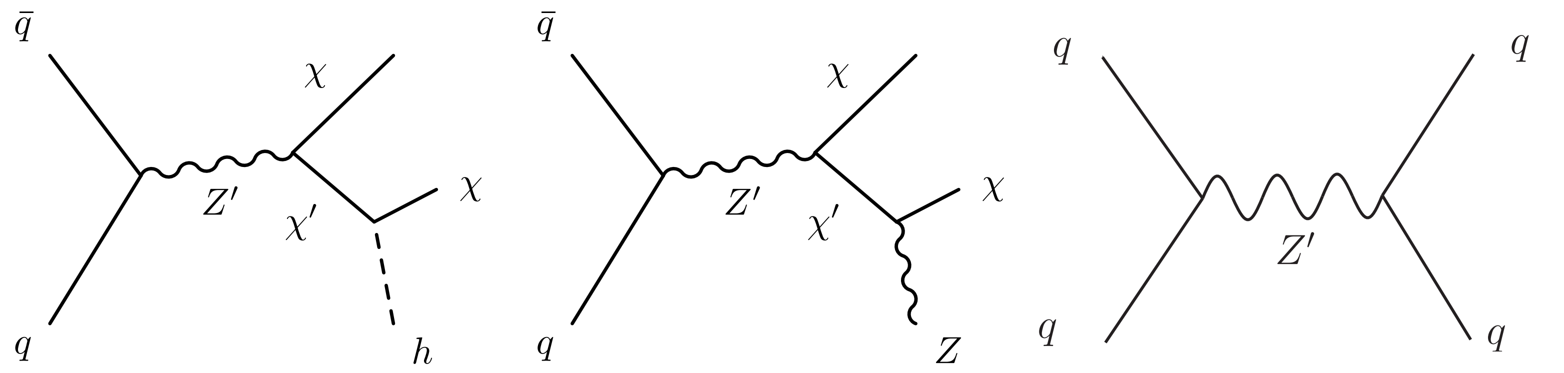
D5(u=-d) $\frac{1}{M^2}(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d)(\bar{\chi}\sigma^{\mu\nu}\chi) \rightarrow \frac{H^\dagger \tau^a H}{\Lambda^4}(\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{\chi}\sigma^{\mu\nu}\chi)$

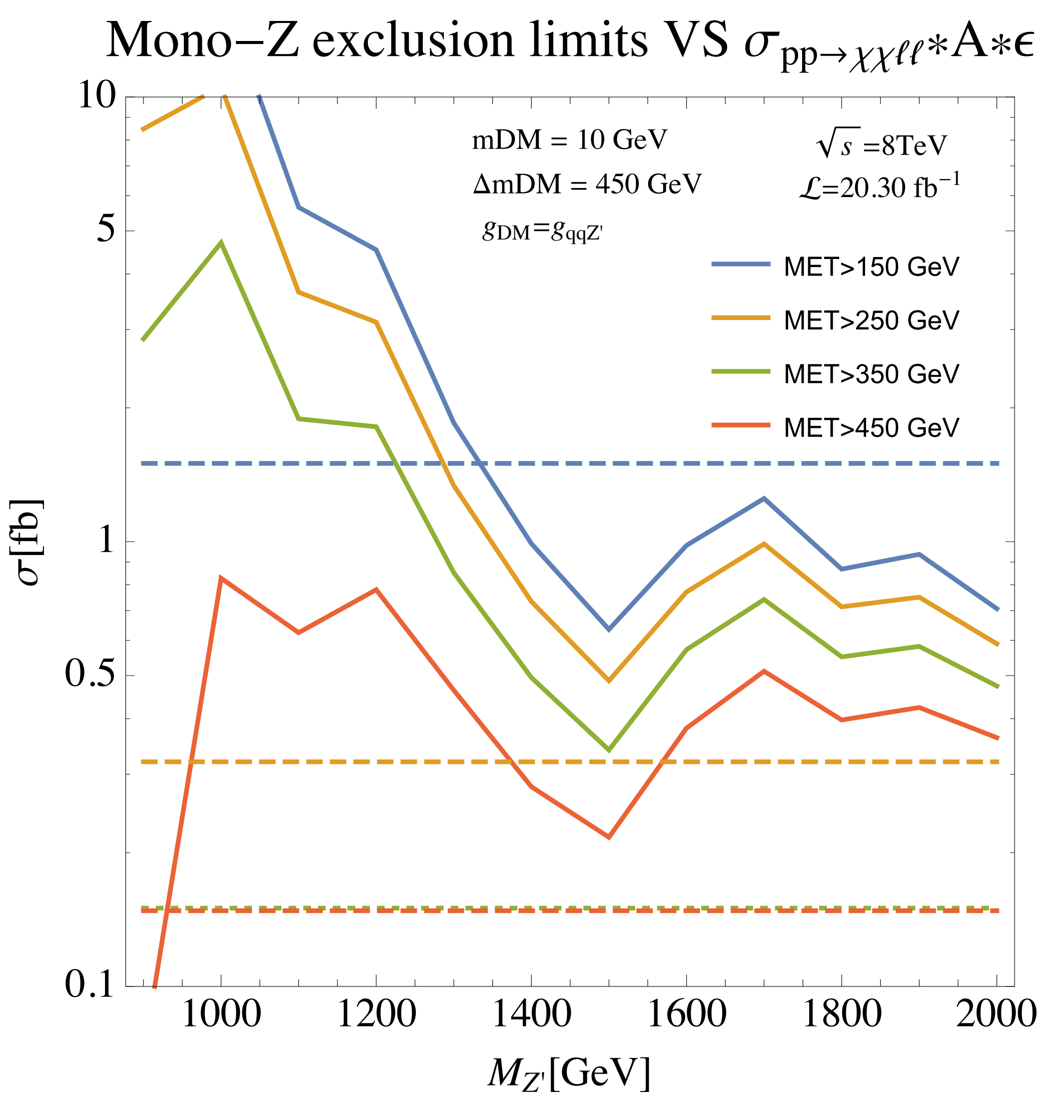
D9 $\frac{1}{M^2}(\bar{q}\sigma^{\mu\nu} q)(\bar{\chi}\sigma^{\mu\nu}\chi) \rightarrow \frac{v}{\Lambda^3}(\bar{q}_L \sigma^{\mu\nu} q_R)(\bar{\chi}\sigma^{\mu\nu}\chi)$

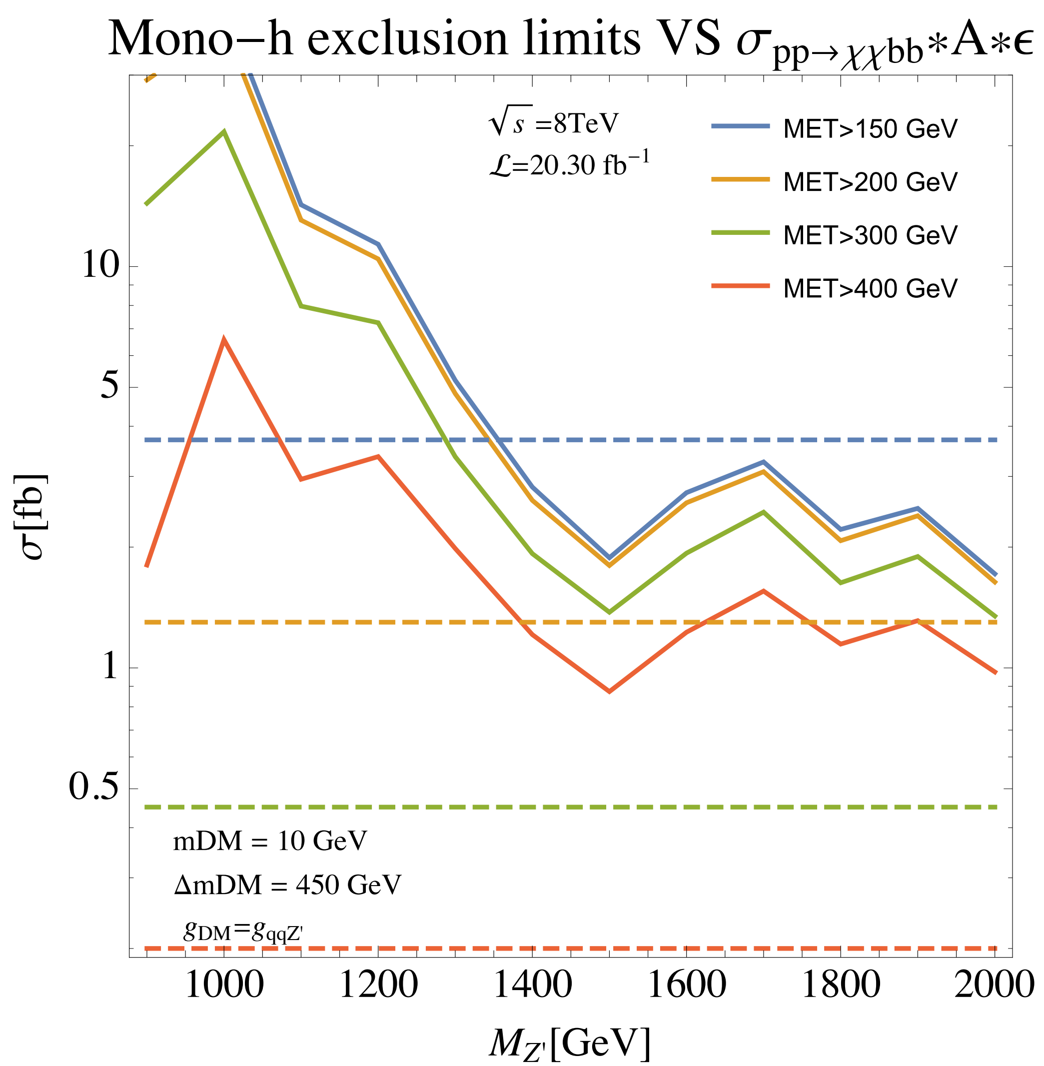


Liew, Papucci, Vichi, KZ

EFFECTIVE PROBE IN INELASTIC MODELS

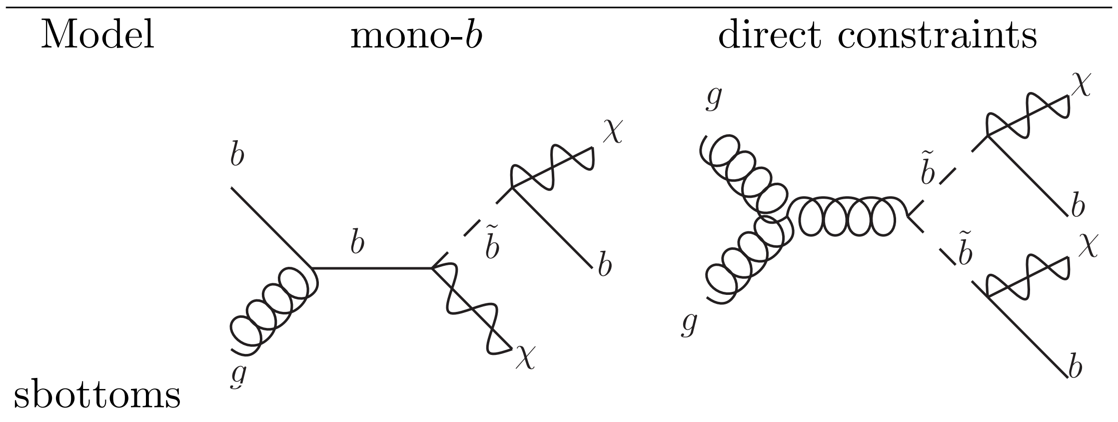


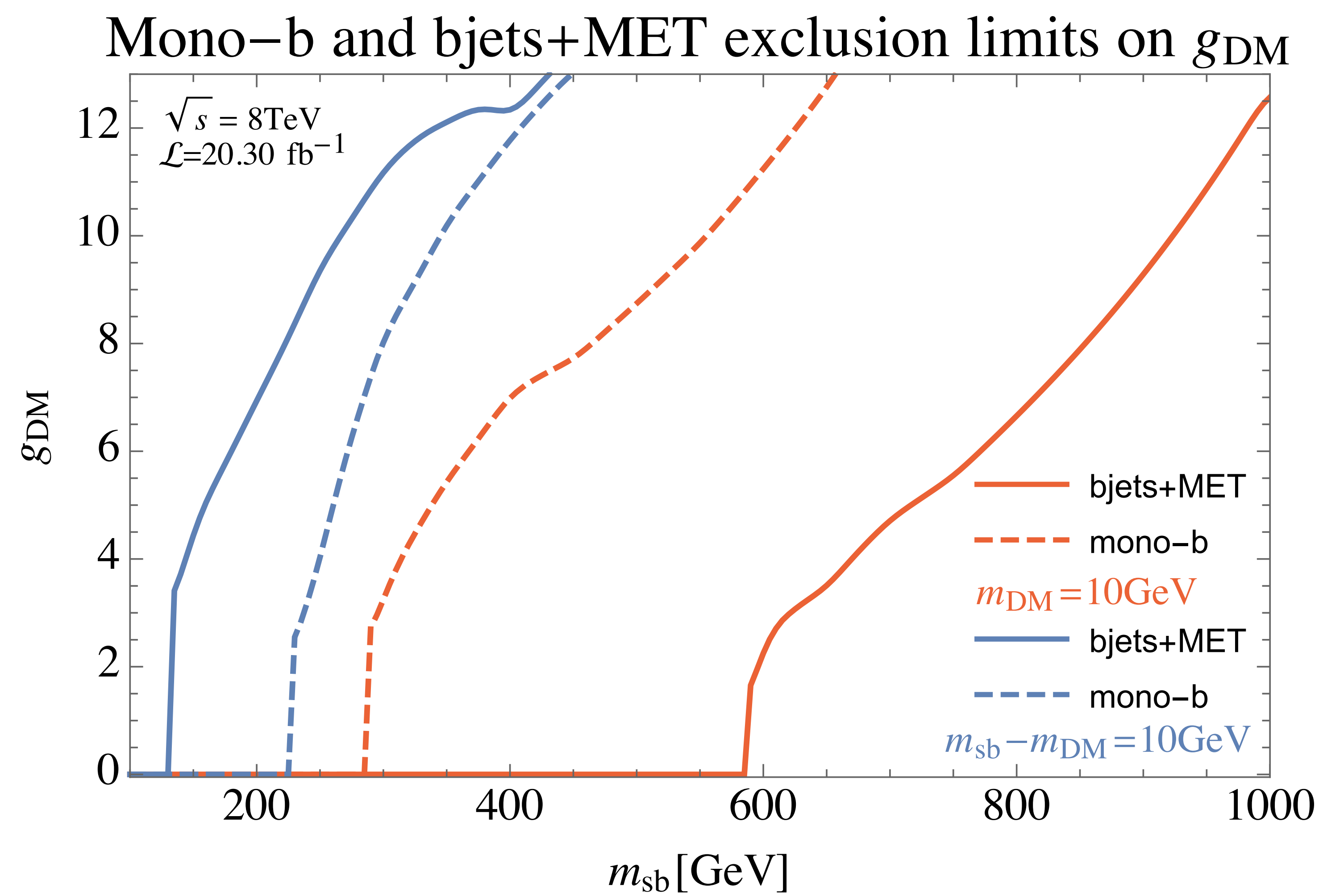




MONO-B

- Even here traditional SUSY searches are more powerful

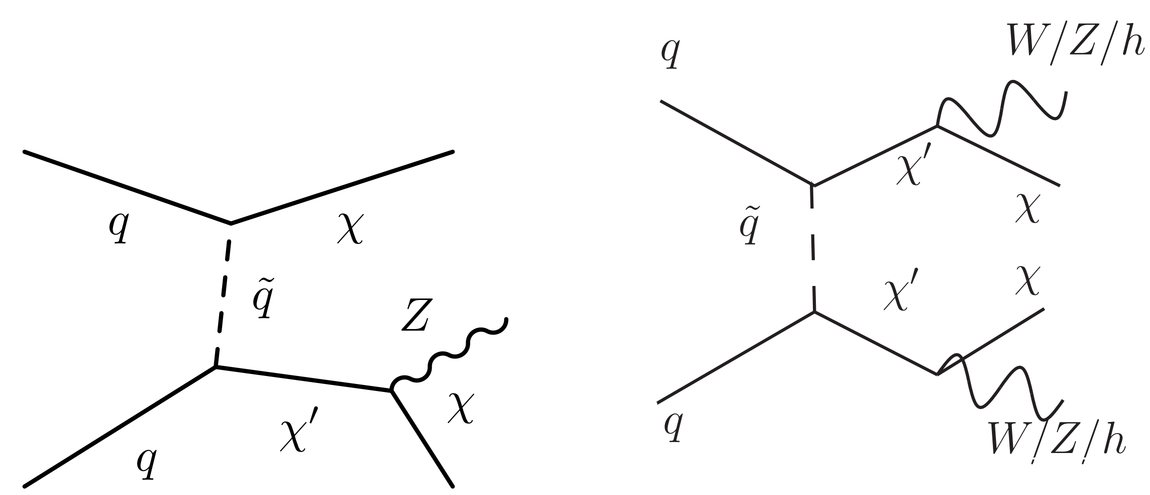


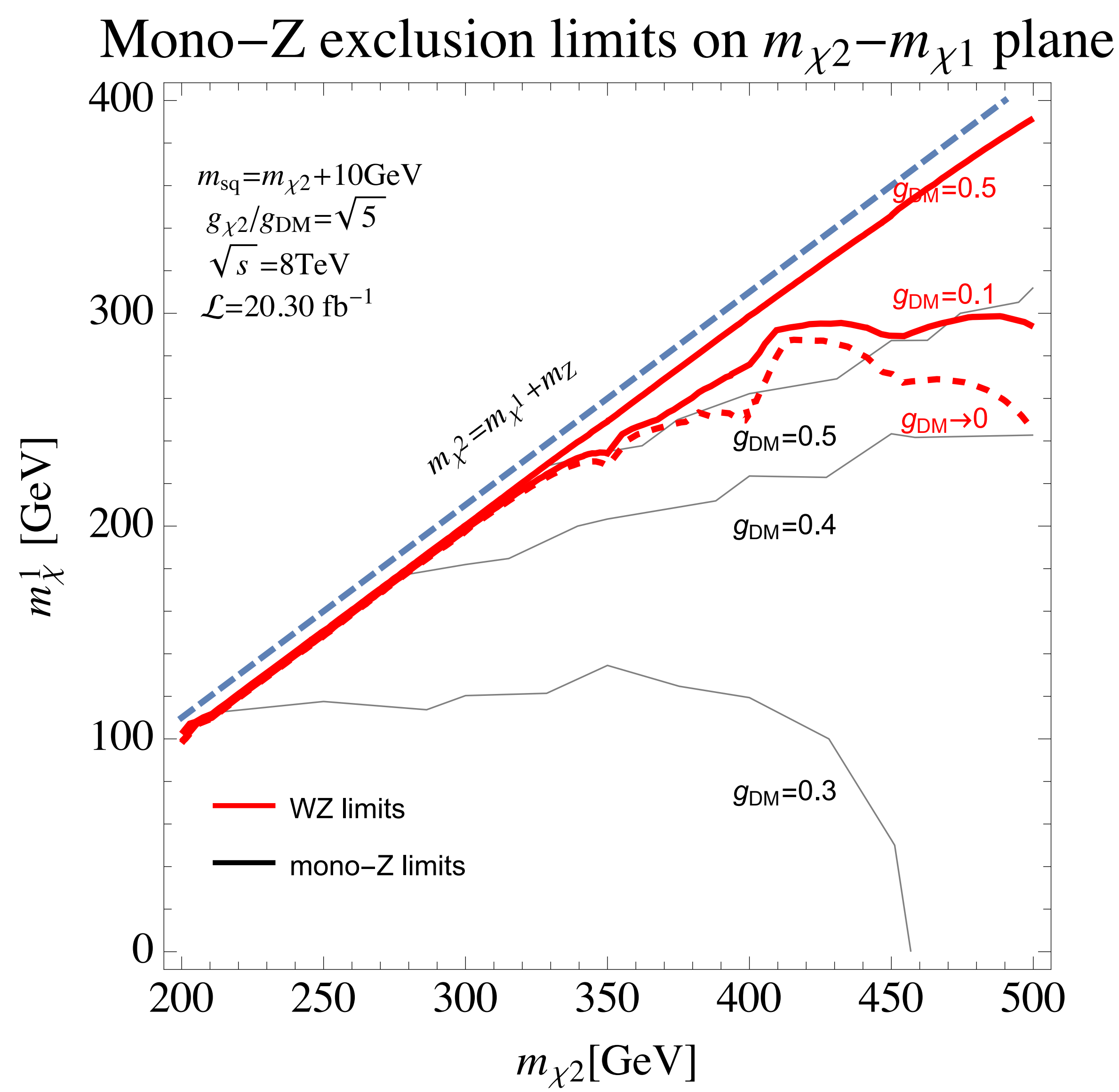


Liew, Papucci, Vichi, KZ, to appear

MONO-Z VS DIBOXON+MET

- Even here traditional SUSY searches are more powerful



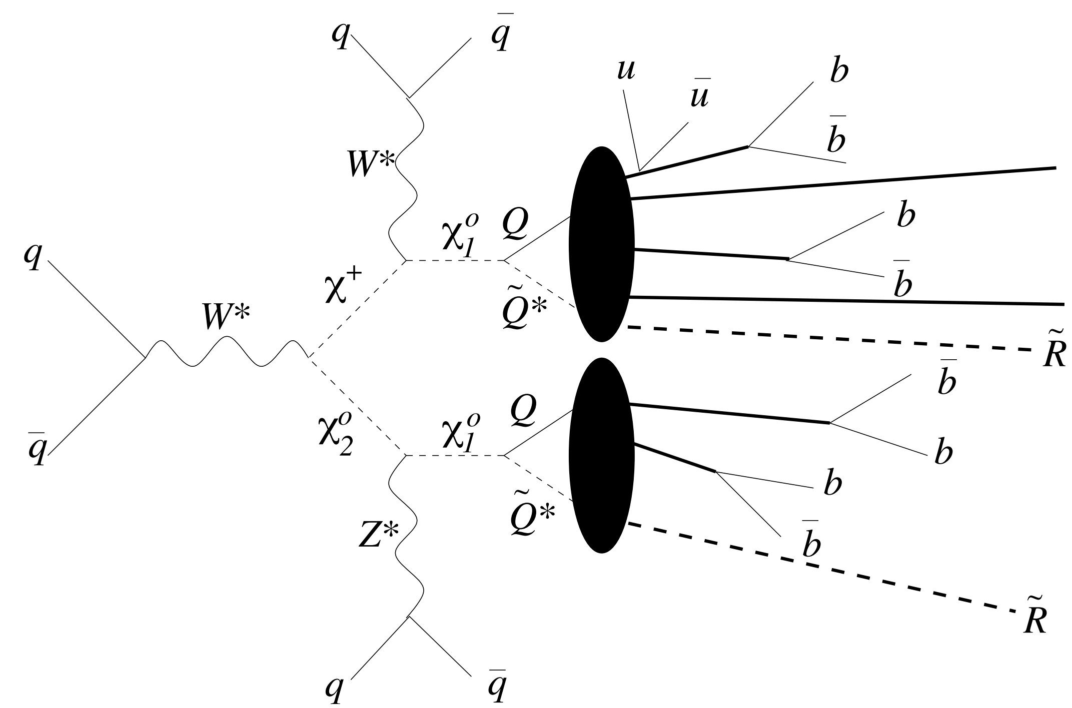


Moral

- Keep an eye on direct searches for SUSY as well as searches for the mediators (e.g. dijets, dileptons, dijets + MET, Z + jets + MET, etc)
- Monojet is generally not a new physics discovery mode; helpful later on in reconstructing the Lagrangian of the new physics, including coupling to DM

HIDDEN SECTOR DARK MATTER AT LHC

- Gives rise to extended decay chains at LHC
- LSP is not stable!
- Reduced MET, additional jets



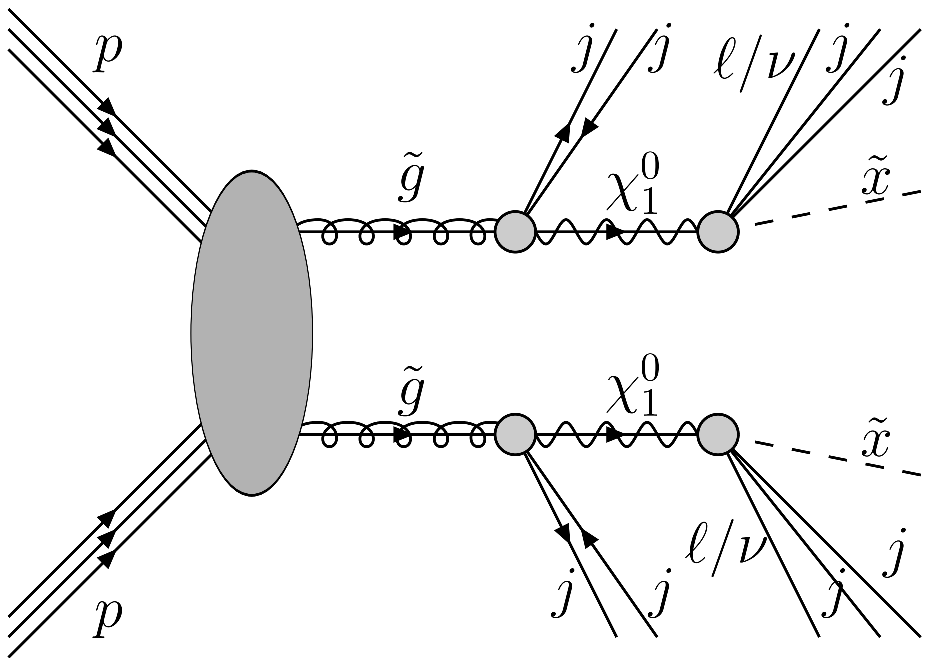
Hidden Valley, Strassler, KZ 2006

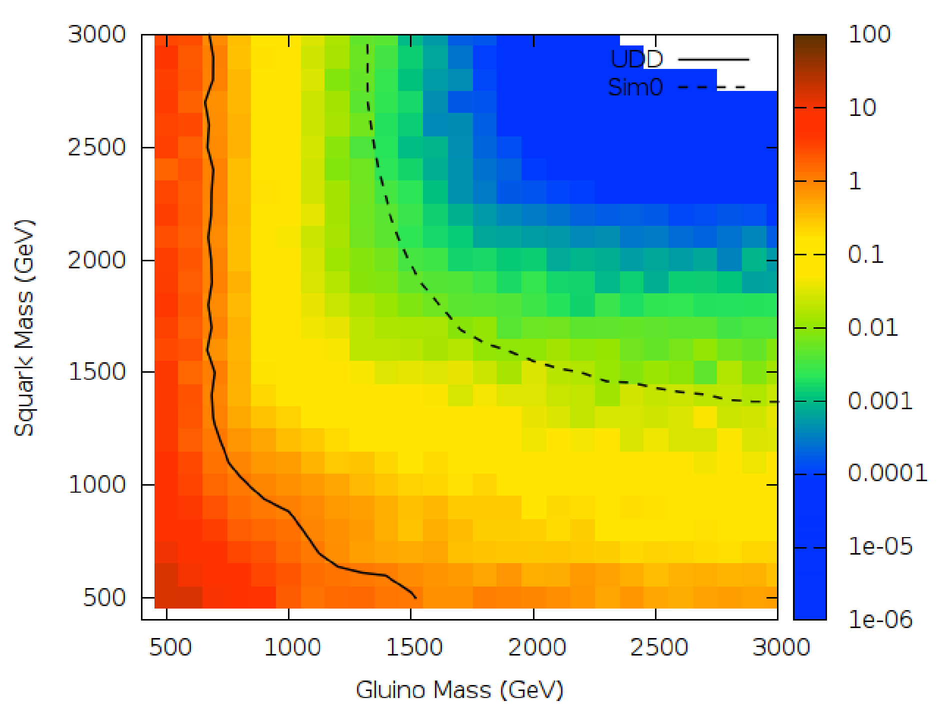
HIDDEN SECTOR DARK MATTER AT LHC

- Gives rise to extended decay chains at LHC
- LSP is not stable!
- Reduced MET, additional jets
- Weakened constraints

$$W_{\rm ADM} = X\ell H, \quad \frac{X u^c_i d^c_j d^c_k}{M_{ijk}}, \quad \frac{X q_i \ell_j d^c_k}{M_{ijk}}, \quad \frac{X \ell_i \ell_j e^c_k}{M_{ijk}}$$

arXiv:1310.2617





(a) 0 lepton analysis for $m_{\chi^0_1} = 100$ GeV

SEARCHING FOR DM AT COLLIDERS

- LHC is strongest probe for weak scale *mediators* decaying dominant visibly, especially if those states carry color
- If there is DM at the bottom of the decay chain, one has an excellent chance of seeing it. But in these cases it is usually accompanied by additional *structure*. (i.e. not mono-anything.)
- Direct and indirect detection experiments are excellent intensity experiments, and will cover *much* of the parameter space for EW dark matter

IT'S AN IMPORTANT YEAR FOR PHYSICS BSM AT LHC