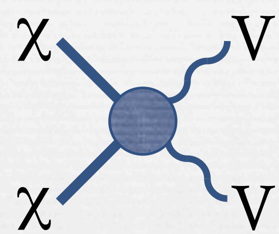
Bounds on Dark Matter Interactions with Electroweak Gauge Bosons



Randy Cotta

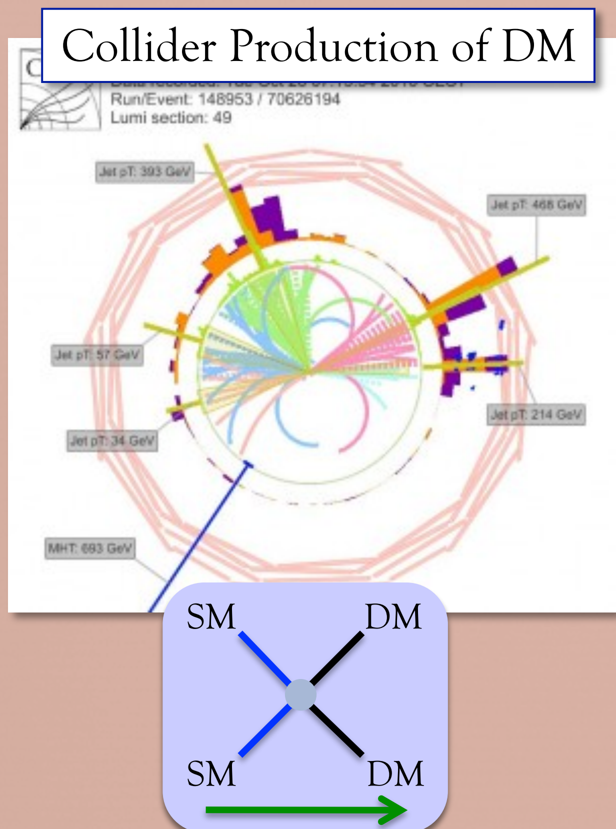
Based on arXiv:1209:XXXX

with: JoAnne Hewett, My Phuong Le
and Tom Rizzo

SLAC NATIONAL ACCELERATOR LABORATORY

WIMP Dark Matter
Provides a Fantastic Opportunity:

DM Made in the Lab:



DM From the Milky Way DM Halo:

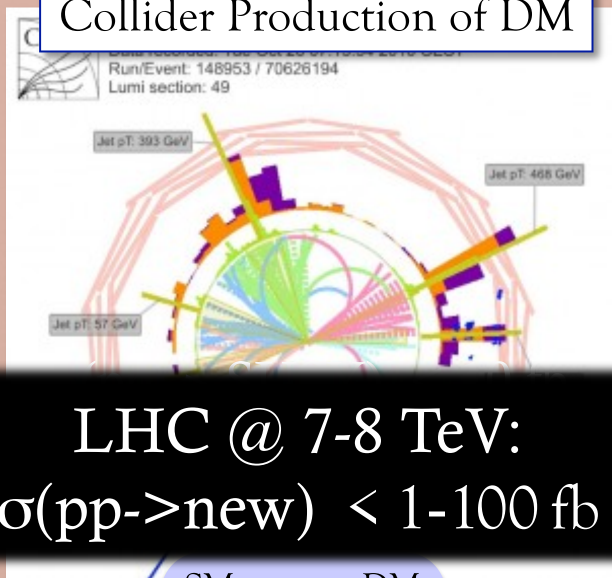
Observations are related,

Although the same process is measured in very different contexts.

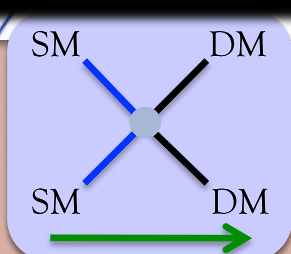
WIMP Dark Matter
Provides a Fantastic Opportunity:

DM Made in the Lab:

Collider Production of DM

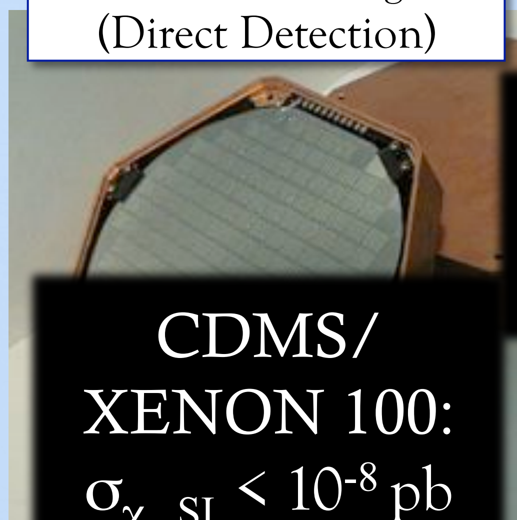


LHC @ 7-8 TeV:
σ(pp->new) < 1-100 fb

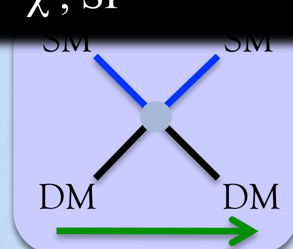


DM From the Milky Way DM Halo:

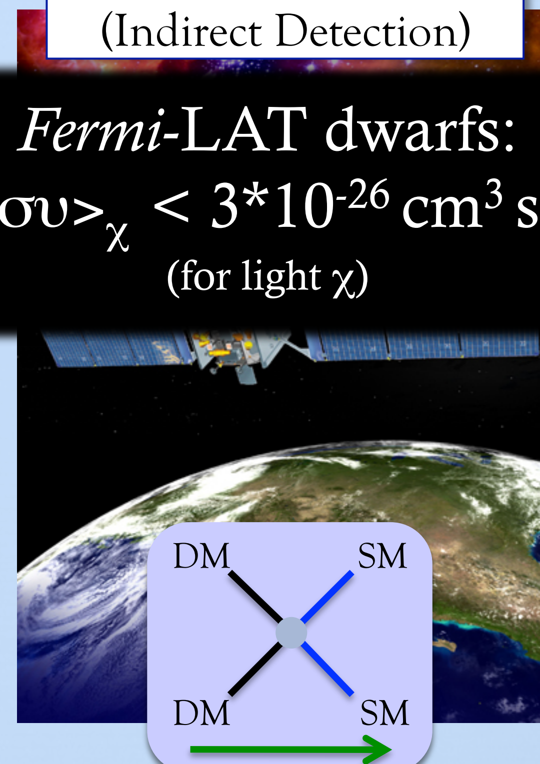
DM Scattering
(Direct Detection)



CDMS/
XENON 100:
$\sigma_{\chi\,,\,\mathrm{SI}} < 10^{-8}$ pb



DM Annihilation
(Indirect Detection)



Fermi-LAT dwarfs:
$\langle\sigma\upsilon\rangle_\chi < 3{*}10^{-26}\ \mathrm{cm^3\,s^{-1}}$
(for light χ)

Observations are related,
Although the same process is measured in very different contexts.

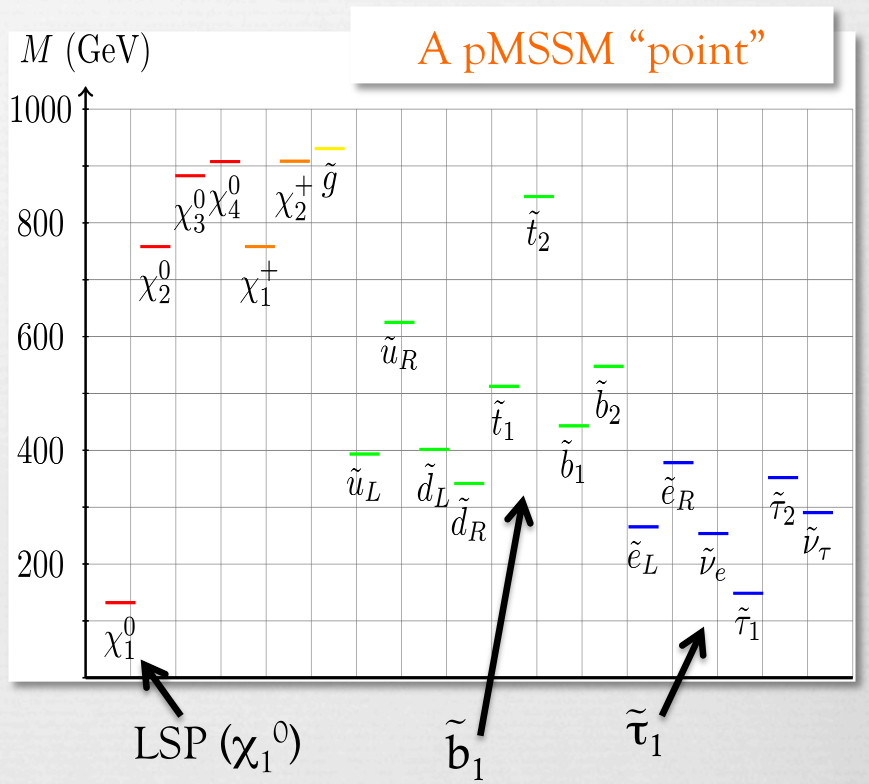
Which WIMPs?

<u>The Top Down Approach:</u>

Historically: WIMPs come from <u>theoretical frameworks</u> designed to solve other problems (e.g., SUSY or Extra Dimensions).

Get new particles with weak-scale masses. If stable, neutral ones (typically partners of EWGBs) can be WIMP DM

Any signature can be calculated <u>exactly</u> for example models in theory space…



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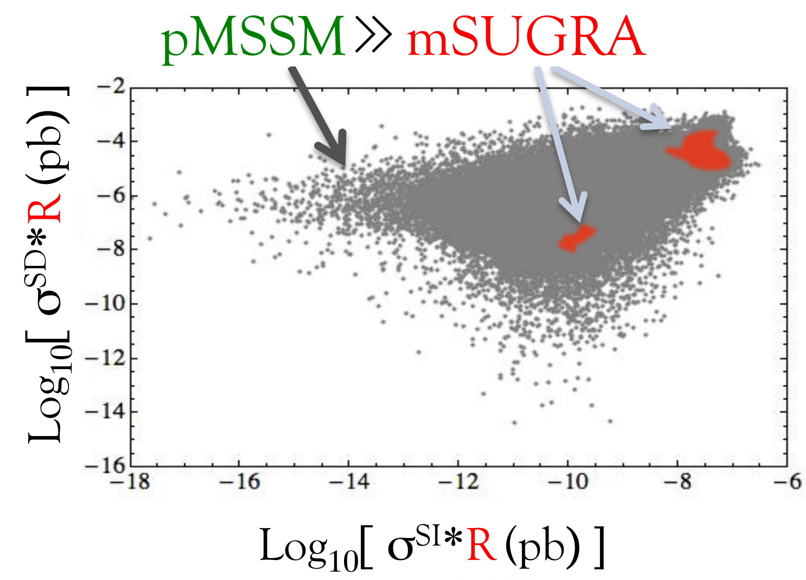
Any signature can be calculated exactly for example models in theory space…

…But theory space is BIG and exact calculations take time.



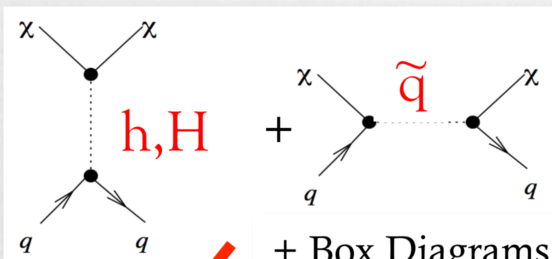
mSUGRA: see e.g. Barger etal. (0806.1962)

Which WIMPs?

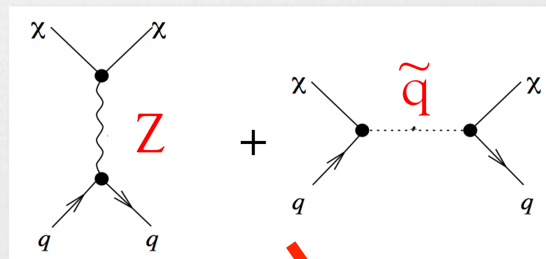
<u>The Bottom Up Approach:</u>

Try to categorize and study the DM-SM interactions, independent of their theoretical origins.

e.g., in SUSY, the full details of any SUSY "point" are necessary to calculate…



+ Box Diagrams



$$\sigma^{\mathrm{SI}}: (1/\Lambda)\bar{\chi}\chi\bar{q}q$$

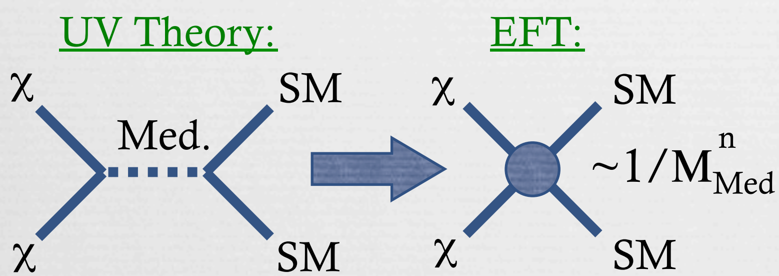
$$\sigma^{\mathrm{SD}}: (1/\Lambda')\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q$$

… just a few numbers that determine
spin-dependent/independent χ-nucleon scattering.

Dark Matter Effective Theory

We expect that DM (χ) is lighter than
the particles that mediate DM-SM interactions
(stability, experimental bounds, RG)

So we imagine an effective theory whose only IR degrees of freedom are SM+χ :



There are a small number of operators
that connect DM to the SM
consistent with Lorentz and gauge
symmetry
at any given order in E/Λ.

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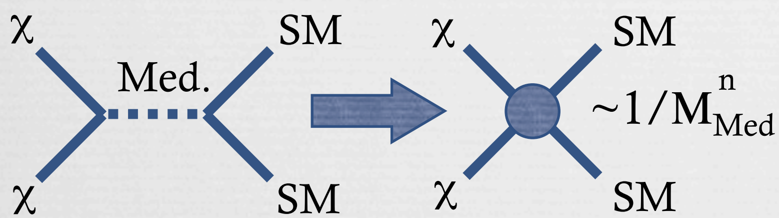
UV Theory: EFT:



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that connect DM to the SM
consistent with Lorentz and gauge
symmetry
at any given order in E/Λ.

“Maverick Dark Matter”

Beltran, Hooper Kolb, Krusberg, Tait
(1002.4137)

Previous Work…

DM EFT formalism has been used to great effect:

Beltran, Hooper, Kolb, Krusberg, Tait (1002.4137)

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (1005.1286)

Bai, Fox, Harnik (1005.3797)

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (1008.1783)

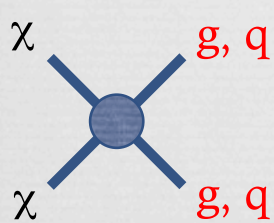
Fox, Harnik, Kopp, Tsai (1103.0240)

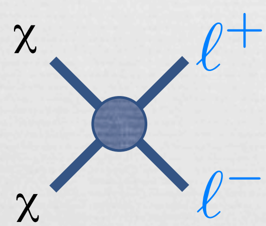
Rajaraman, Shepherd, Tait, Wijangco (1108.1196)

Fox, Harnik, Kopp, Tsai (1109.4398)

Cheung, Tseng, Tsai, Yuan (1201.3402)

Fox, Harnik, Primulando, Yu (1203.1662)





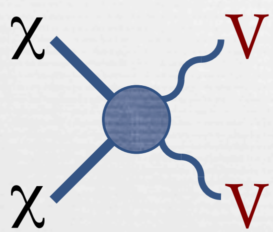
Early work focused on DM interactions with colored SM particles
(largest rates at hadron colliders, potential strong connection to scattering)

…or DM interactions with leptons
(large rates at lepton colliders)

Our Work

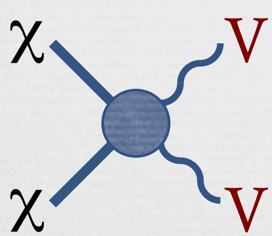
(RCC, J. Hewett, M-P Le, T. Rizzo)

Bounding DM interactions with EW gauge bosons:



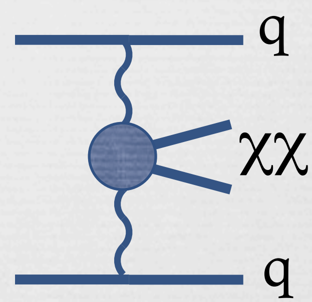
Where: $V = \gamma, Z, W^{\pm}$ (or B, W^a)

Via:



Cosmic Annihilation Products

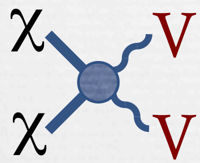
And:

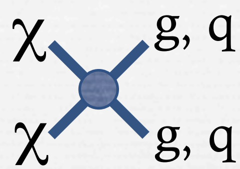


Weak Boson Fusion at the LHC

See also:
Rajaraman, etal. (1205.4723), Frandsen, etal. (1207.3971) and Bell etal., 1209.0231

Motivation:

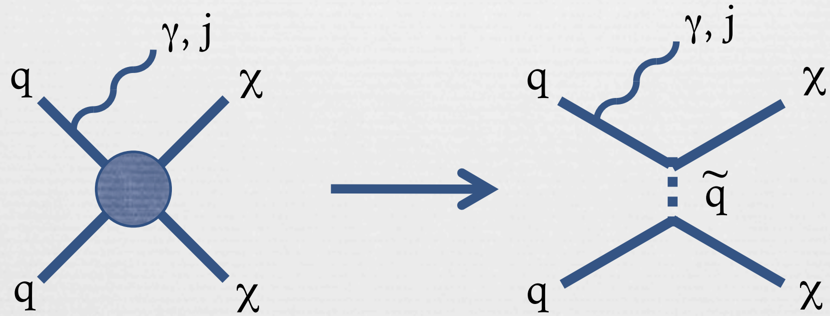
- 

may dominate


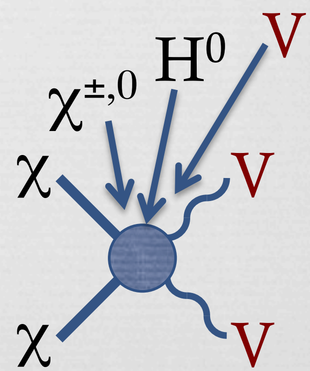
in nature…

Especially without new colored particles in current LHC data:

EFT Picture: A (Squark) UV Completion



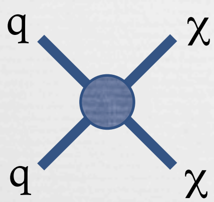
- We directly study our **WI**MP's connection to the physics of the weak scale:



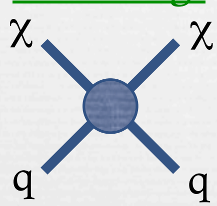
Dark Matter Effective Theory

Easy to study complementarity:

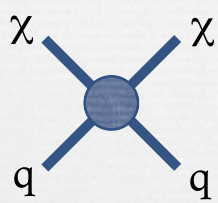
Production:



Scattering:

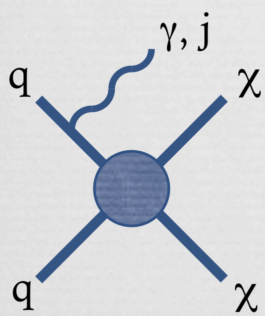


Annihilation:

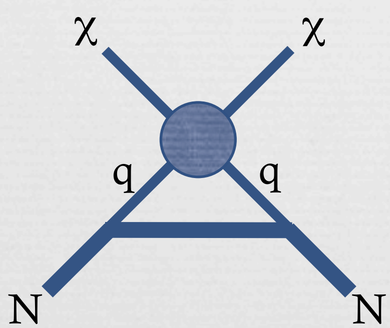


Assuming the same operator dominates in all cases, e.g.,

Mono-stuff @ LHC:



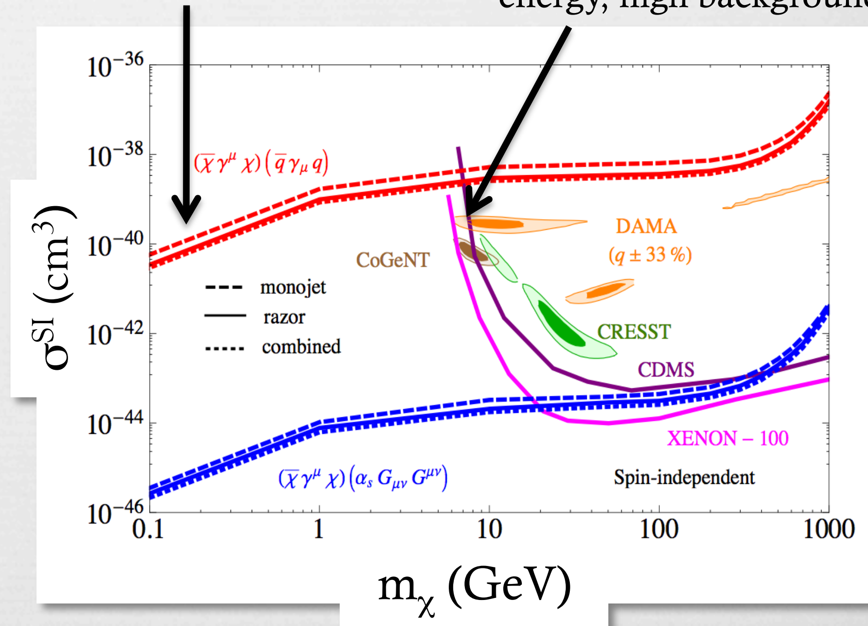
Scattering on nuclei:



Searches are complementary:

In accelerators, a lighter WIMP just means more missing energy

Direct Detection searches have a hard time constraining light WIMPs (low recoil energy, high background)

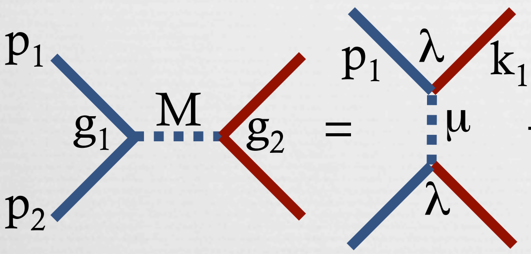


Fox, Harnik, Primulando and Yu (1203.1662)

EFT Efficacy

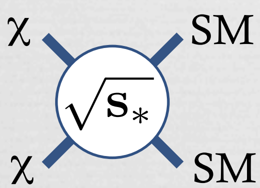
*The weakness of the EFT approach is that it is NOT universally valid

Many UV theories give the same effective operator at lowest order in p/M_{med}:



$+ \mathcal{O}(p^2/M^2)$

Roughly, EFT useful when…



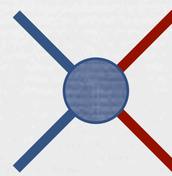
$\sqrt{s_*} < M_{med.}$

Scattering: $M_{\mathrm{med.}} > |q| \ll m_\chi$

Annihilation: $\sim m_\chi$

Production: $\sim p_T$

Even so… Results have been interpreted for light mediators and possibly resonant production…



$$\sim \frac{1}{\Lambda^2} = \frac{g_1 g_2}{M^2} = \frac{g_1 g_2}{\Gamma M}$$

Heavy mediator w/ O(1) cplgs.

Or… Light mediator, weakly coupled

Or… Narrow light mediator produced on-shell ($M>2m_\chi$)

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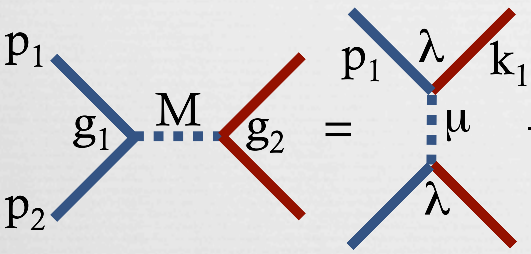

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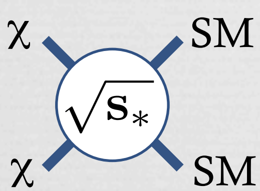

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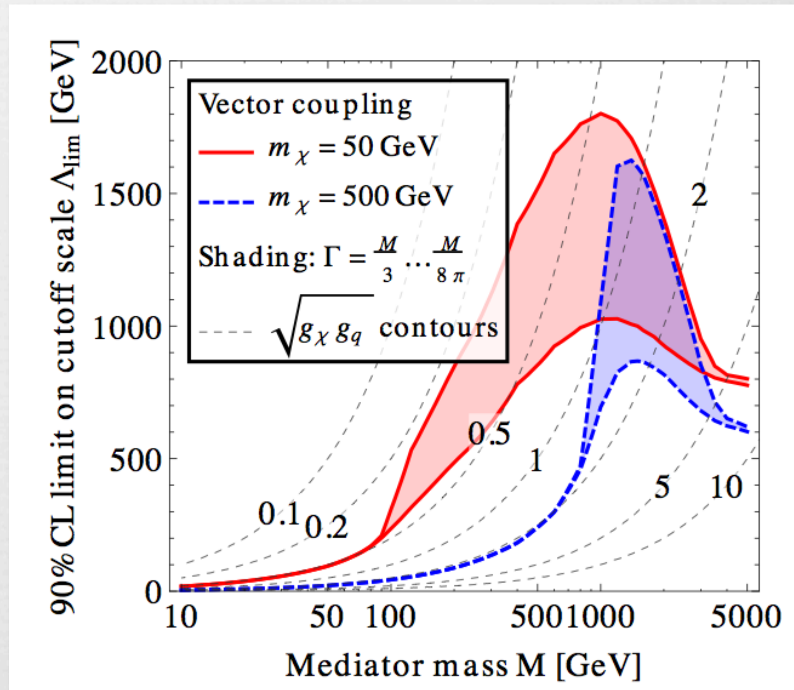

Fox, Harnik, Kopp, Tsai (1109.439)

EFT Efficacy

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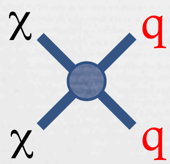
Perturbative UV Completion…

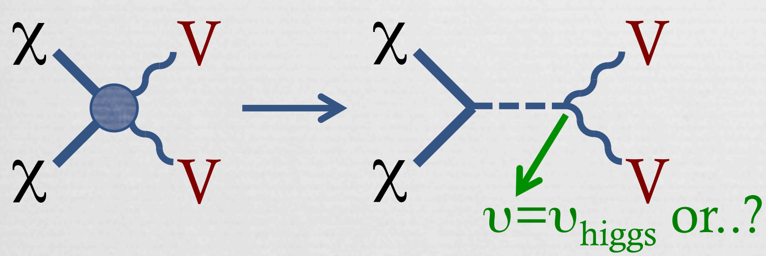
dim=6: 

$$\sim \frac{1}{\Lambda^2} = \frac{g_1 g_2}{M^2}$$

Require: $\alpha_i \equiv g_i^2/(4\pi) < 1$
$M > 2m_\chi$

Then: $\Lambda \geq (m_\chi/\sqrt{\pi})$

For us this is more subtle…

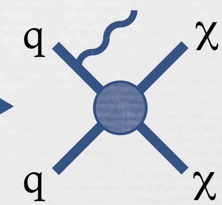


UV completion with dimensionful couplings → UV Model dependence

Unitarity…

Shoemaker, Vecchi (1112.5457)

In any given event…

$\sqrt{\hat{s}} \rightarrow$  $\rightarrow \sqrt{s_*}$

Amplitude grows with $\sqrt{s_*}$, unitarity gives smallest possible Λ such that events can be described in the EFT.

$$|a_0(W_L W_L \rightarrow \chi\chi)| < (1/2)$$

We will plot curves in Λ vs. m_χ such that 99%, 90% and 50% of WBF events obey this unitarity limit.

Our Operators

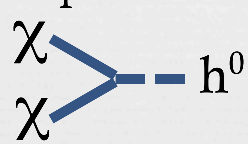
Basic Assumptions about χ:

1) χ is spin-1/2 Dirac (Majorana related by sym. factors and some operators vanish)

2) χ may be:

   i) an EW singlet or
   ii) in a non-chiral EW rep.

➔ Avoids renormalizable Higgs coupling:



3) Operators Satisfy: $U(1)_{EM}$

Not Necessarily: $SU(2)_L \otimes U(1)_Y$

➔ Allows UV completions Which have already undergone EWSB, e.g., the Higgs portal: $\frac{1}{\Lambda}\bar{\chi}\chi Z^\mu Z_\mu$

"Scalar" (Higgs Portal)

$$D5a: \quad \bar{\chi}\chi V^{a\mu}V^a_\mu$$
$$D5b: \quad \bar{\chi}i\gamma_5\chi V^{a\mu}V^a_\mu$$

Weak Dipole Moments

$$D5c: \quad \bar{\chi}\sigma_{\mu\nu}t^a\chi V^{a\mu\nu}$$
$$D5d: \quad \bar{\chi}\sigma_{\mu\nu}t^a\chi \widetilde{V}^{a\mu\nu}$$

"Vector" (Z')

$$D6a: \quad \bar{\chi}\gamma_\mu t^a D_\nu\chi V^{a\mu\nu}$$
$$D6b: \quad \bar{\chi}\gamma_\mu\gamma_5 t^a D_\nu\chi V^{a\mu\nu}$$

Loop Process

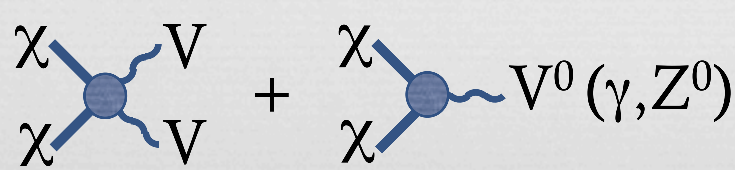
$$D7a: \quad \bar{\chi}\chi V^{\mu\nu}V_{\mu\nu}$$
$$D7b: \quad \bar{\chi}i\gamma_5\chi V^{\mu\nu}V_{\mu\nu}$$
$$D7c: \quad \bar{\chi}\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$$
$$D7d: \quad \bar{\chi}i\gamma_5\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$$

($V = \gamma, Z, W^\pm, B, W^a$)

Important Details…

Name	Expression	Norm.	Vertices	Sub-Procs.	Ann.
$dim = 5$:					
D5a	$\bar{\chi}\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	v^2
D5b	$\bar{\chi}i\gamma_5\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	1
D5c	$\bar{\chi}\sigma_{\mu\nu}t^a\chi V^{a\mu\nu}$	Λ^{-1}	3/4pt	A,Z,WW	1
D5d	$\bar{\chi}\sigma_{\mu\nu}t^a\chi\widetilde{V}^{a\mu\nu}$	Λ^{-1}	3/4pt	A,Z,WW	1 (VV), v^2 $(f\bar{f})$
$dim = 6$:					
D6a	$\bar{\chi}\gamma_\mu t^a D_\nu\chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1
D6b	$\bar{\chi}\gamma_\mu\gamma_5 t^a D_\nu\chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1 (VV), v^2 $(f\bar{f})$
$dim = 7$:					
D7a	$\bar{\chi}\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7b	$\bar{\chi}i\gamma_5\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1
D7c	$\bar{\chi}\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7d	$\bar{\chi}i\gamma_5\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1

Operators with odd # of field strengths give two topologies:



The 3-point vertices change phenomenology dramatically…

Important Details…

Name	Expression	Norm.	Vertices	Sub-Procs.	Ann.
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D5a	$\bar{\chi}\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	v^2
D5b	$\bar{\chi}i\gamma_5\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	1
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D5d	$\bar{\chi}\sigma_{\mu\nu}t^a\chi \widetilde{V}^{a\mu\nu}$	Λ^{-1}	3/4pt	A,Z,WW	1 (VV), v^2 $(f\bar{f})$
$dim = 6$:					
D6a	$\bar{\chi}\gamma_\mu t^a D_\nu \chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1
D6b	$\bar{\chi}\gamma_\mu\gamma_5 t^a D_\nu \chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1 (VV), v^2 $(f\bar{f})$
$dim = 7$:					
D7a	$\bar{\chi}\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7b	$\bar{\chi}i\gamma_5\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1
D7c	$\bar{\chi}\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7d	$\bar{\chi}i\gamma_5\chi V^{\mu\nu}\widetilde{V}_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1

Canonical Normalization

Generic UV theory: Mixture of AA, AZ, ZZ and WW. (and A,Z for 3-pt.) Allowed sub-processes satisfy $U(1)_{EM}$

Some annihilations are velocity suppressed ($\upsilon \sim 10^{-3}c$)

Sub-process Combinations

Generic UV theory: combination of AA, AZ, ZZ, WW sub-processes.

DM annihilation: V's in the final state: sub-proc's are independent

In WBF: V's are virtual states => $\sigma_{\text{tot.}}$ Is a coherent sum of sub-processes

But: error in using incoherent sum is << than syst. uncertainty on BGs.

To be concrete,
we set bounds on the combinations:

"Scalar" (Higgs Portal)

$$\frac{1}{\Lambda}\bar{\chi}\chi\left(\frac{Z^\mu Z_\mu}{2}+W^{+\mu}W^-_\mu+h.c.\right)$$

$$\frac{1}{\Lambda}\bar{\chi}i\gamma_5\chi\left(\frac{Z^\mu Z_\mu}{2}+W^{+\mu}W^-_\mu+h.c.\right)$$

Weak Dipole Moments

$$\frac{g_w}{\Lambda}\left(\bar{\chi}\sigma_{\mu\nu}t^3\chi W^{3\mu\nu}+\frac{s_w}{c_w}\frac{Y}{2}\bar{\chi}\sigma_{\mu\nu}\chi B^{\mu\nu}\right)$$

$$\frac{g_w}{\Lambda}\left(\bar{\chi}\sigma_{\mu\nu}t^3\chi \widetilde{W}^{3\mu\nu}+\frac{s_w}{c_w}\frac{Y}{2}\bar{\chi}\sigma_{\mu\nu}\chi \widetilde{B}^{\mu\nu}\right)$$

"Vector" (Z')

$$\frac{g_w}{\Lambda^2}\left(\bar{\chi}\gamma_\mu t^3 D_\nu\chi W^{3\mu\nu}+\frac{s_w}{c_w}\frac{Y}{2}\bar{\chi}\gamma_\mu D_\nu\chi B^{\mu\nu}\right)$$

$$\frac{g_w}{\Lambda^2}\left(\bar{\chi}\gamma_5\gamma_\mu t^3 D_\nu\chi W^{3\mu\nu}+\frac{s_w}{c_w}\frac{Y}{2}\bar{\chi}\gamma_5\gamma_\mu D_\nu\chi B^{\mu\nu}\right)$$

cancels $\chi\chi A$

Loop Process

$$\frac{1}{\Lambda^3}\bar{\chi}\chi W^{a\mu\nu}W^a_{\mu\nu}$$

$$\frac{1}{\Lambda^3}\bar{\chi}i\gamma_5\chi W^{a\mu\nu}W^a_{\mu\nu}$$

$$\frac{1}{\Lambda^3}\bar{\chi}\chi W^{a\mu\nu}\widetilde{W}^a_{\mu\nu}$$

$$\frac{1}{\Lambda^3}\bar{\chi}i\gamma_5\chi W^{a\mu\nu}\widetilde{W}^a_{\mu\nu}.$$

Before we go on…

Milli-Charged DM:

3-point $\chi\chi V$ coupling could be $\chi\chi A$ => DM is milli-charged

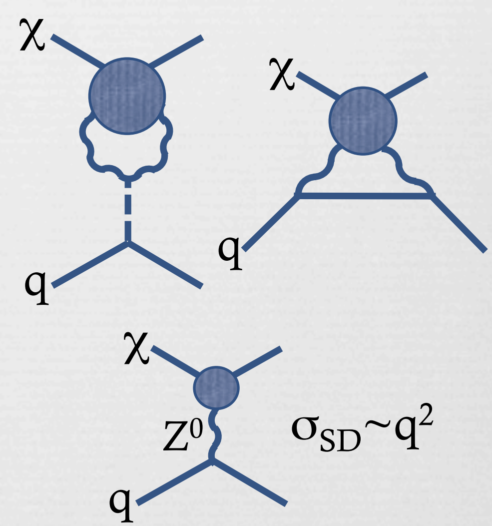
Such scenarios are strongly constrained (e.g., McDermott etal., 1101.2907)

Here: tune all operators so the $\chi\chi A$ coupling vanishes.

Direct Detection:

4-point operators only => scatter at higher order.
This is estimated to give $\lesssim 10^{-10}$ pb level SI rates.
(Hisano etal. 1104.0228, Frandsen, etal., 1207.3971)

With $\chi\chi A$ cancelled, the only other possibility is SD scattering via the $\chi\chi Z$ vertex. But all ops giving $\chi\chi Z$ have derivatives => Negligible scattering (momentum suppressed).

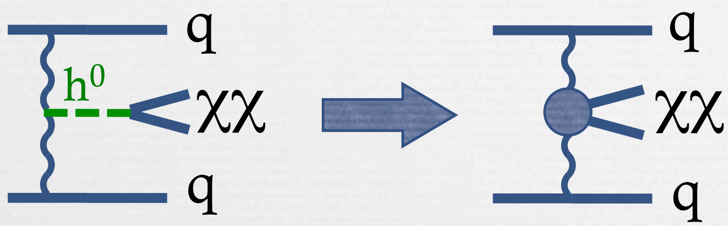


Z^0 Invisible Width Constraint:

The $\chi\chi Z$ vertex contributes to $\Gamma_{Z,\text{inv.}}$ for $m_\chi < m_Z/2$.
We show excluded ($\Gamma_{Z,\text{inv.}}$ >2 MeV) regions in what follows…

Bounds from Weak Boson Fusion at the LHC

WBF analysis similar to invisible Higgs search: (Eboli, Zeppenfeld hep-ph/0009158):



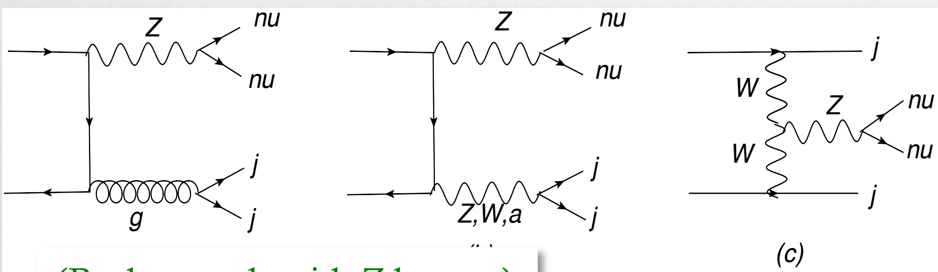
Require two well-separated high-rapidity jets + missing transverse energy to beat backgrounds:

$$p_T^j > 40GeV, \quad |\eta_j| < 5.0 \quad (j \in 1,2)$$

$$|\eta_1 - \eta_2| > 4.4, \quad \eta_1 \cdot \eta_2 < 0$$

$$p_T^{miss} > 100\,\mathrm{GeV} \quad M_{1,2} > 1200\,\mathrm{GeV}$$

$$\Delta\phi = |\phi_1 - \phi_2| < 1. \quad \text{+Central Jet Veto}$$



(Backgrounds with Z bosons)

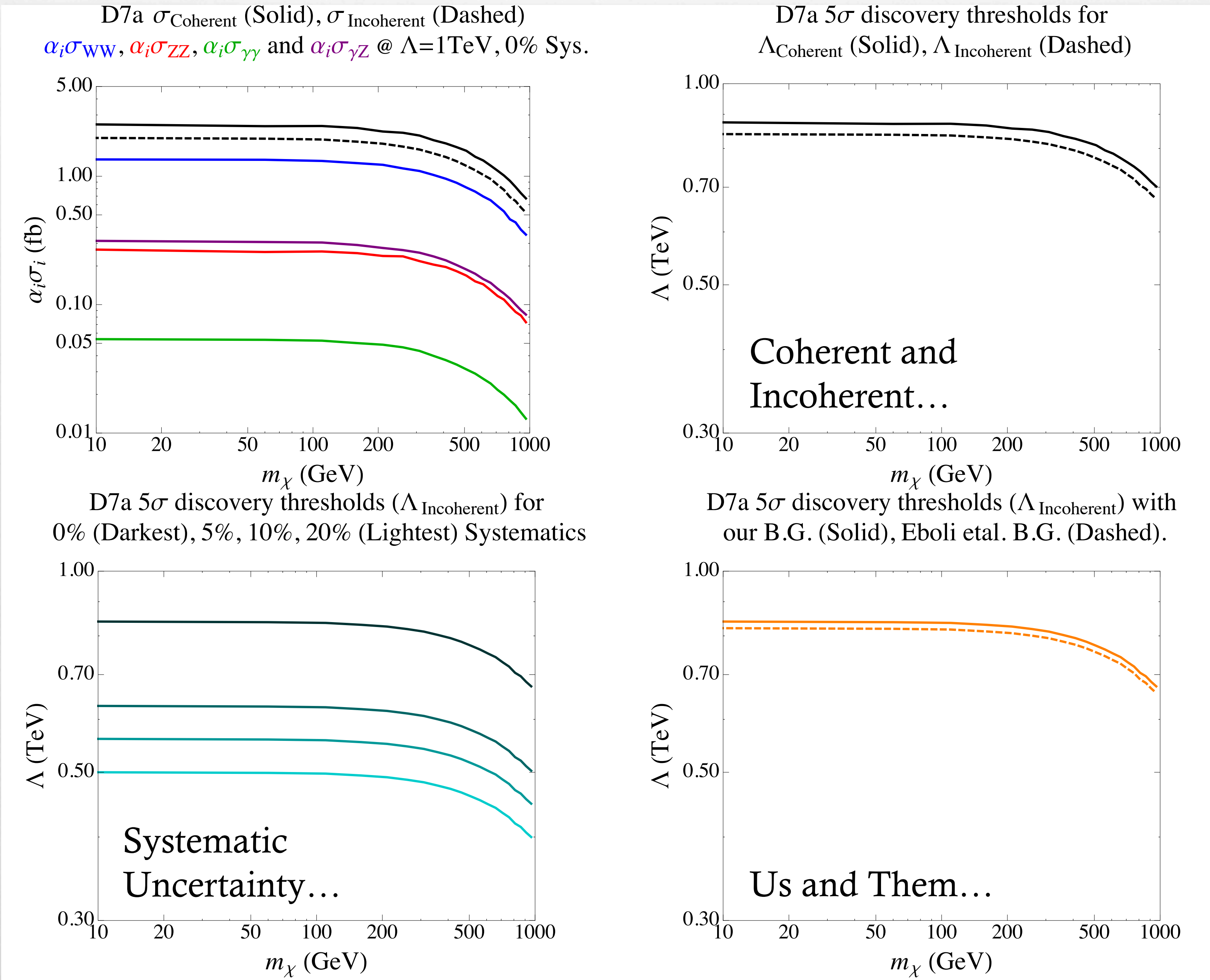
Comparing with previous analysis… (Eboli, Zeppenfeld hep-ph/0009158):

σ (fb)	QCD Zjj		QCD Wjj		EW Zjj		EW Wjj		Total	
	[41]	Here	[41]	Here	[41]	Here	[41]	Here	[41]	Here
Eqs. (6-8)	1254	1055	1284	906	151	148	101	85	2790	2194
Eqs. (6-9) + C.J.V.	71.8	56.6	70.2	47.3	14.8	14.6	9.9	8.2	167	127

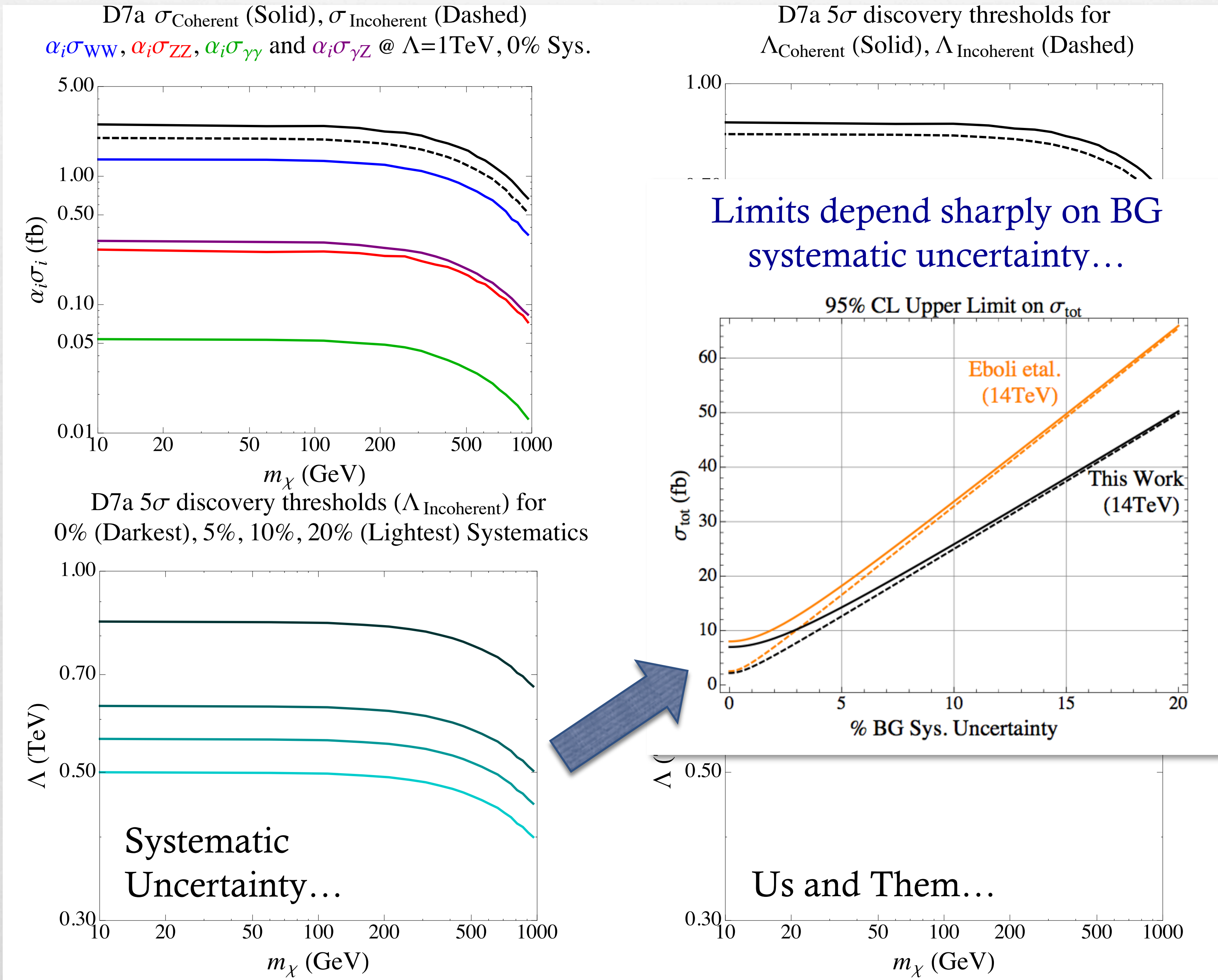
Use FeynRules and Madgraph v5 for both signal and background

We Present results for 14TeV 100fb^{-1} and 8TeV 25 fb^{-1} LHC data sets

Sources of Error/Uncertainty



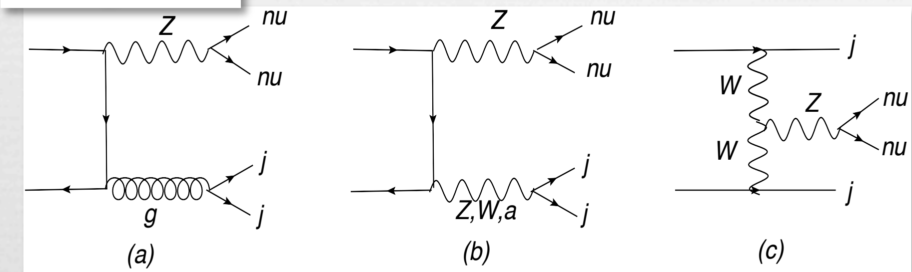
Sources of Error/Uncertainty



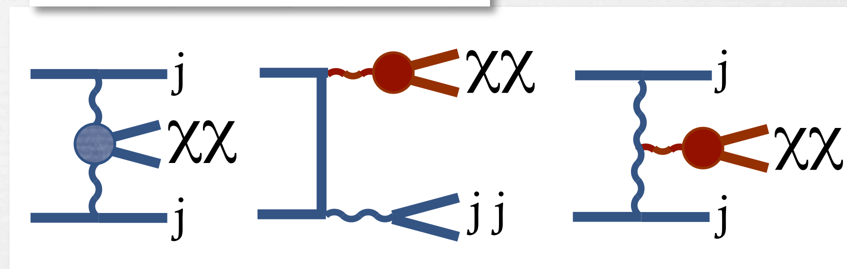
Not all operators have the same cut efficiencies…

3-point Vertices give tagging jet distributions that look like BG ones:

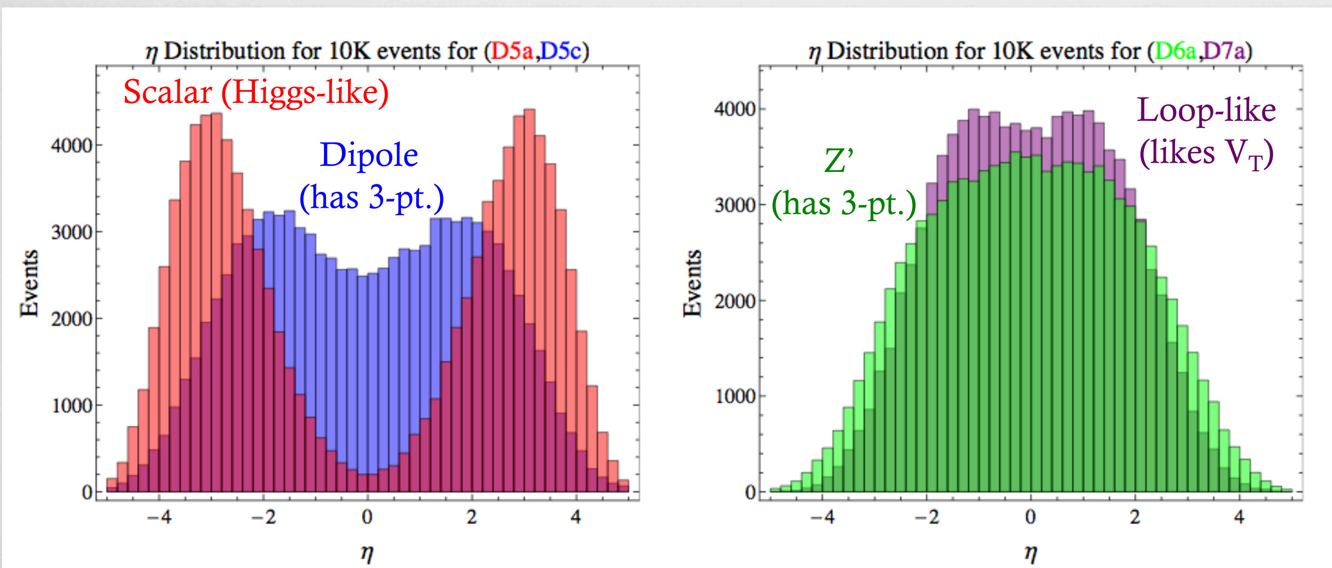
Background:



Signal (with 3-pt. vertices):

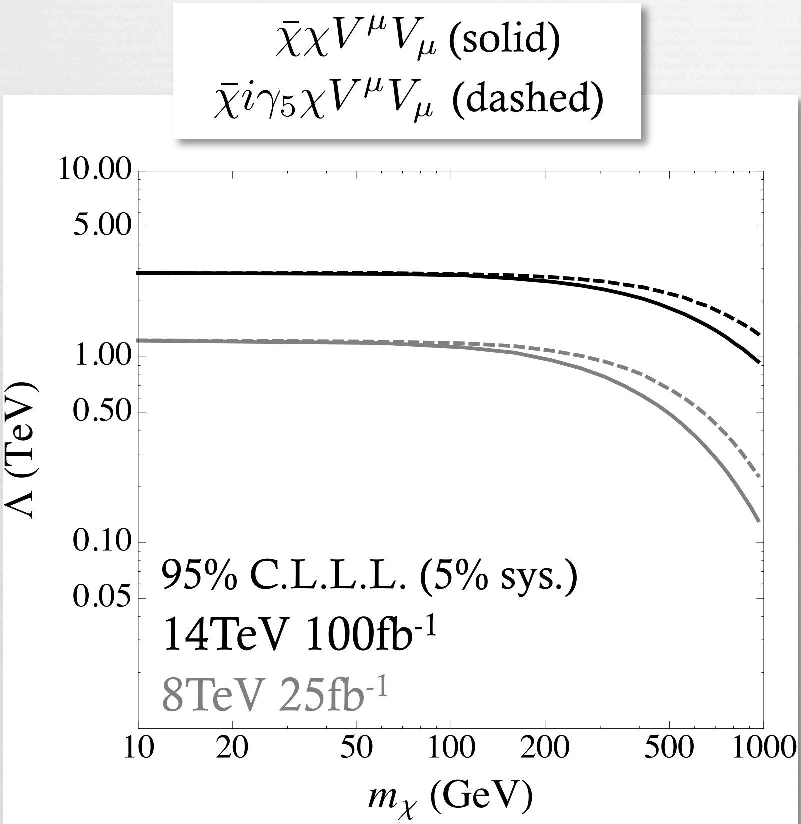


Operators that favor Transversely Polarized V's (D7a-d) also have much more central tagging jet distributions…

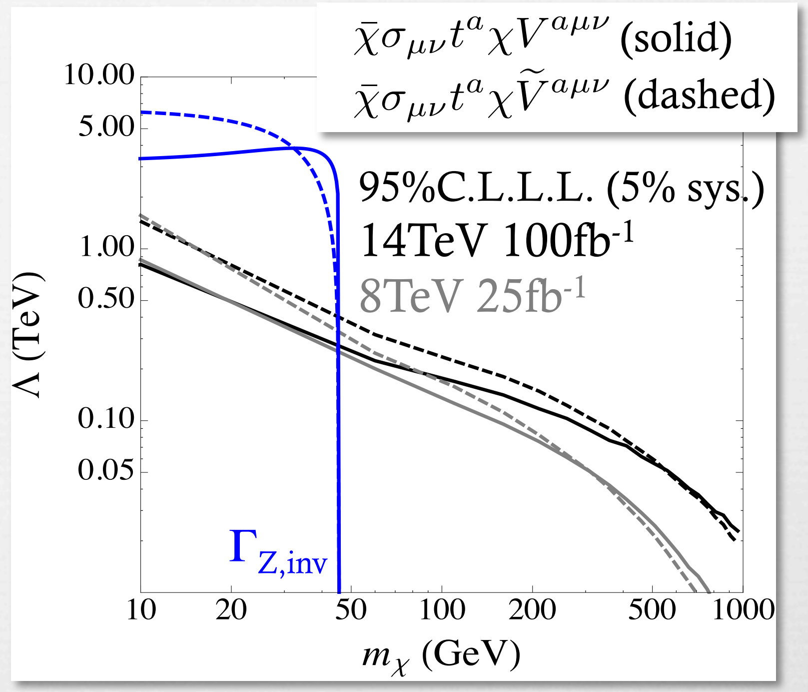


We lose Signal-BG discrimination that we usually get from forward/backward and central jet veto cuts

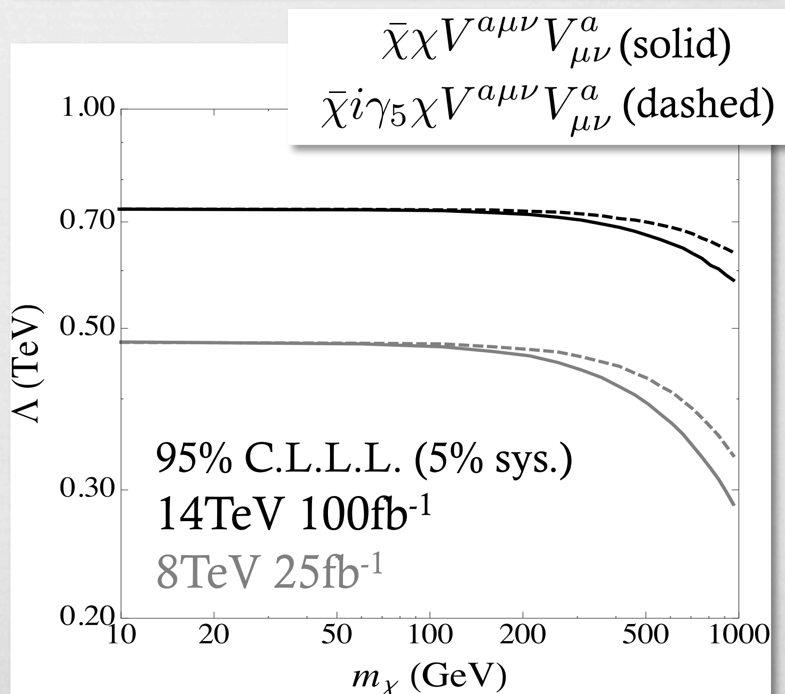
WBF Results…



$\bar{\chi}\chi V^{\mu}V_{\mu}$ (solid)
$\bar{\chi}i\gamma_5\chi V^{\mu}V_{\mu}$ (dashed)
10.00
5.00
1.00
0.50
0.10
0.05
Λ (TeV)
95% C.L.L.L. (5% sys.)
14TeV 100fb-1
8TeV 25fb-1
10
20
50
100
200
500
1000
m_χ (GeV)



$\bar{\chi}\sigma_{\mu\nu}t^a\chi V^{a\mu\nu}$ (solid)
$\bar{\chi}\sigma_{\mu\nu}t^a\chi\widetilde{V}^{a\mu\nu}$ (dashed)
10.00
5.00
1.00
0.50
0.10
0.05
Λ (TeV)
95%C.L.L.L. (5% sys.)
14TeV 100fb-1
8TeV 25fb-1
$\Gamma_{Z,\mathrm{inv}}$
10
20
50
100
200
500
1000
m_χ (GeV)



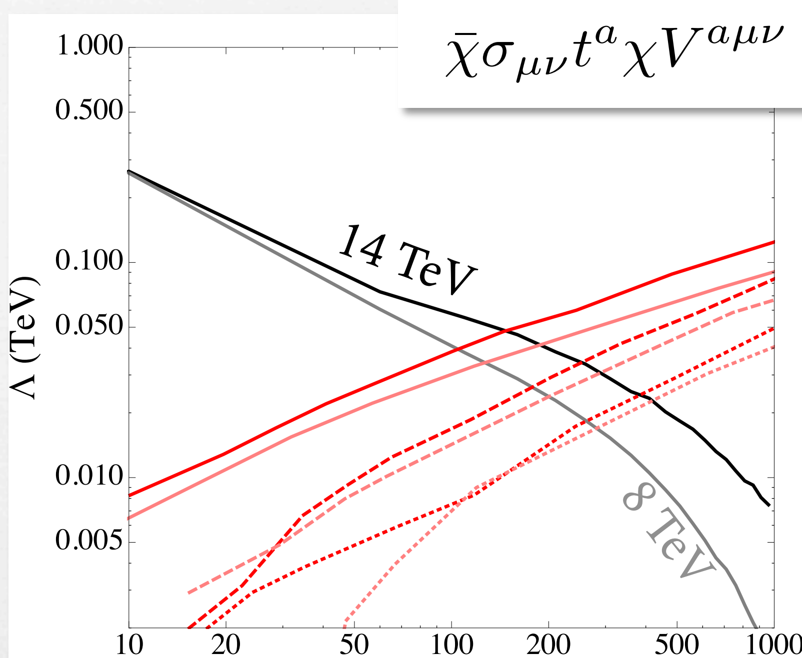
$\bar{\chi}\chi V^{a\mu\nu}V^a_{\mu\nu}$ (solid)
$\bar{\chi}i\gamma_5\chi V^{a\mu\nu}V^a_{\mu\nu}$ (dashed)
1.00
0.70
0.50
0.30
0.20
Λ (TeV)
95% C.L.L.L. (5% sys.)
14TeV 100fb-1
8TeV 25fb-1
10
20
50
100
200
500
1000
m_χ (GeV)

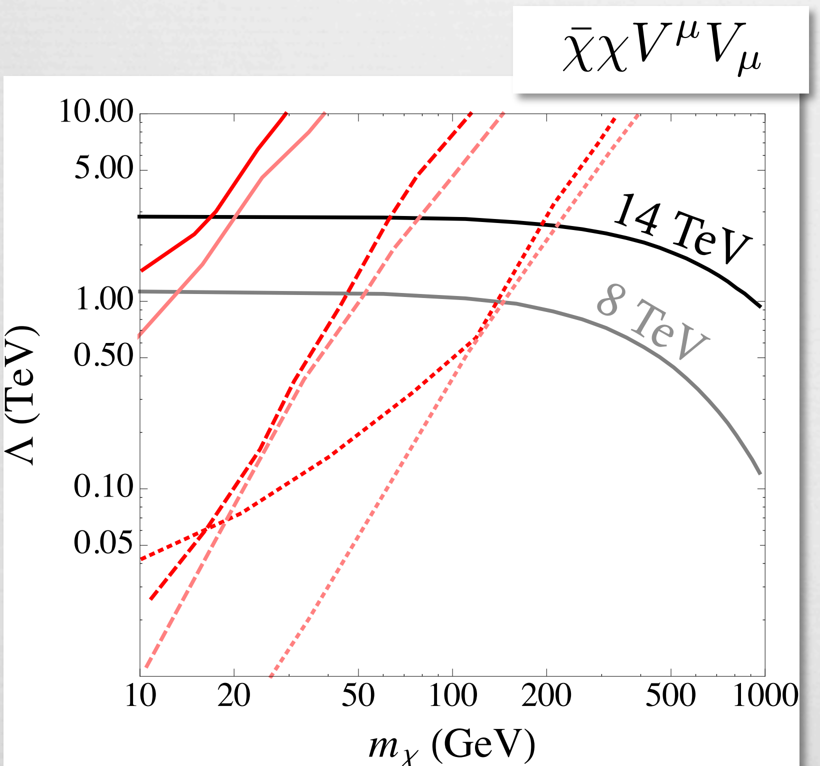
WBF Unitarity…

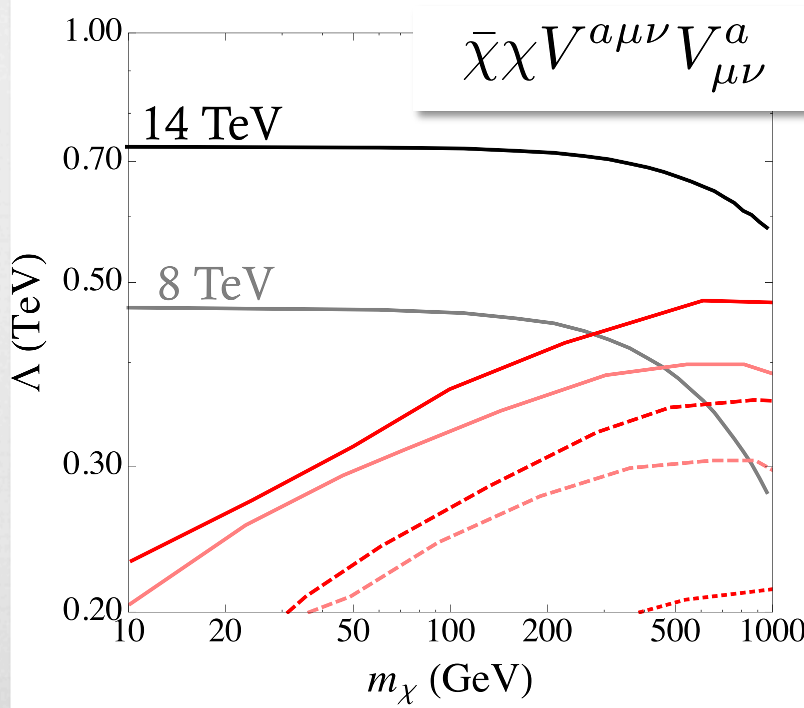
Calculated for $W_L W_L \to \chi\chi$
Using the Effective-W Approx.

14 TeV
- 99% events unitary
- 90% events unitary
- 50% events unitary

8 TeV
- 99% events unitary
- 90% events unitary
- 50% events unitary

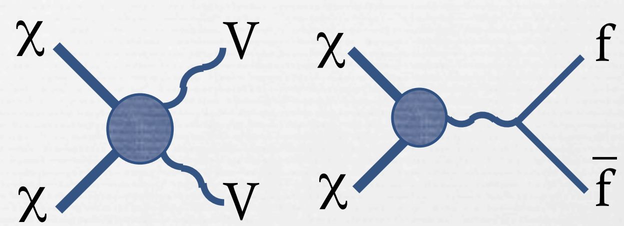






Bounds from Indirect Detection

Our operators allow DM annihilation into the $\gamma\gamma$, γZ, ZZ, WW and $f\bar{f}$ final states ($f\bar{f}$ from 3-point ops.):



Can bound Λ with some assumptions…

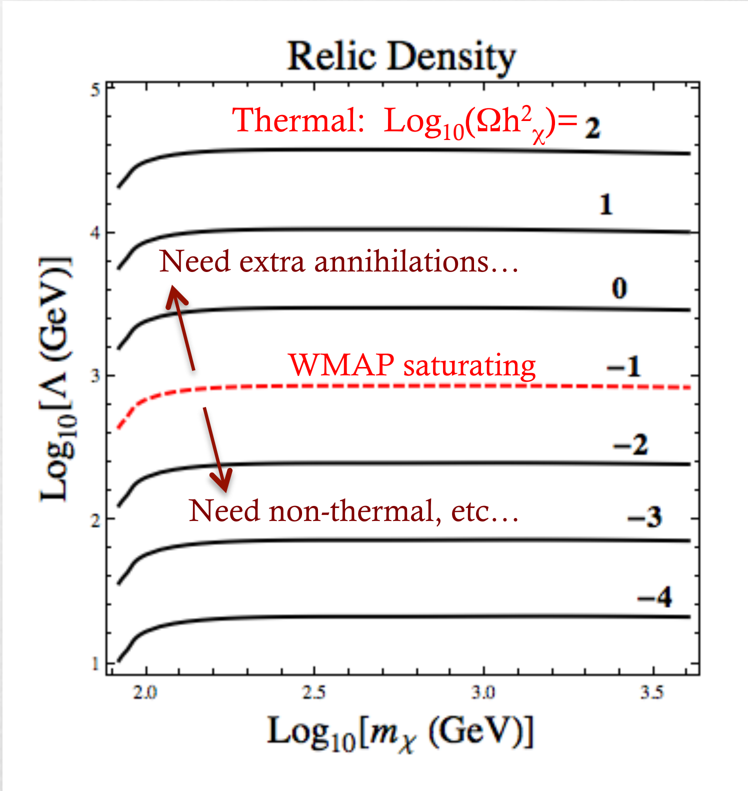
i) The dominant annihilation channel is through our operator

ii) χ makes up all of DM,
i.e., has relic abundance: $\Omega h^2_\chi \approx 0.11$

*Suppose this can be arranged by details of the dark sector (co-annihilating states, non-thermal cosmology, etc.)

*In Figs. we show relic density contours calculated assuming thermal cosmology and *only* our operator is involved

iii) Assume χ and $\bar{\chi}$ have equal abundance.



Dwarf Spheroidal Bounds:

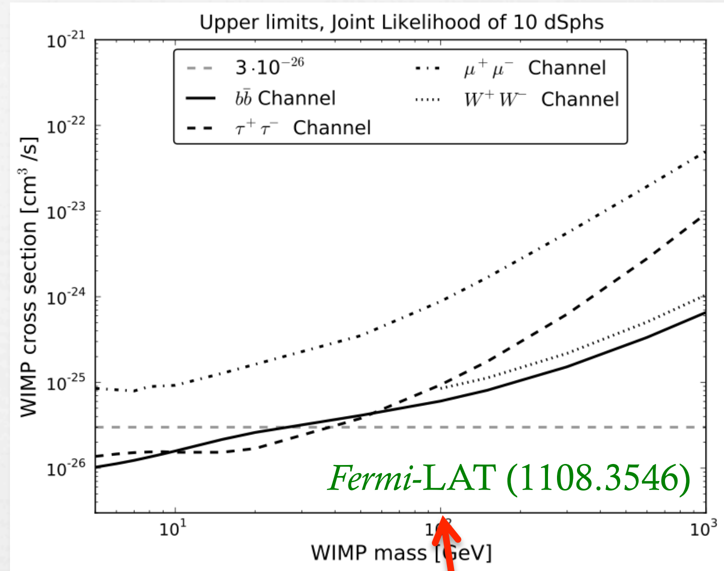
- Bounds from *Fermi*-LAT and VERITAS observations of dwarf spheroidal galaxies:

- 95% C.L. exclusions on pure-channel annihilations ($b\bar{b}$, $\tau\bar{\tau}$, $\mu\bar{\mu}$, W^+W^-)

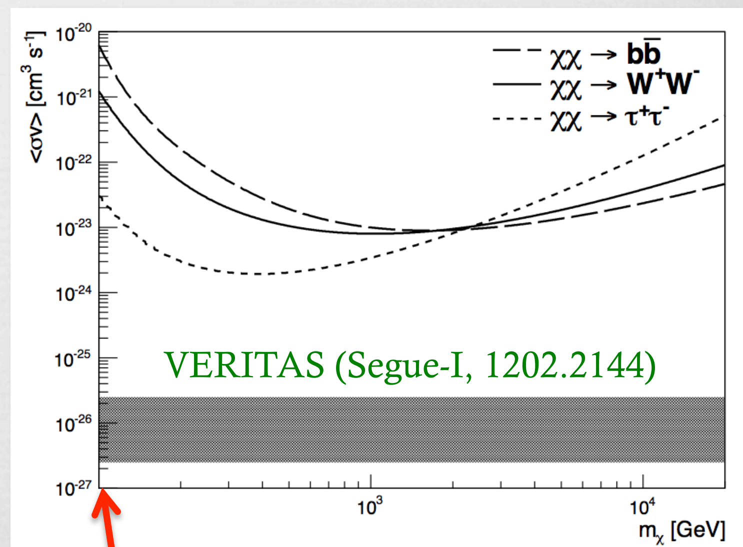
- γ spectra for all light quarks similar to $b\bar{b}$ spectrum. γ's for Z^0Z^0 similar to W^+W^-…

  => We set limits on their sums.

- LAT limits dominate for $m_\chi < 1$ TeV, VERITAS for $m_\chi > 1$ TeV



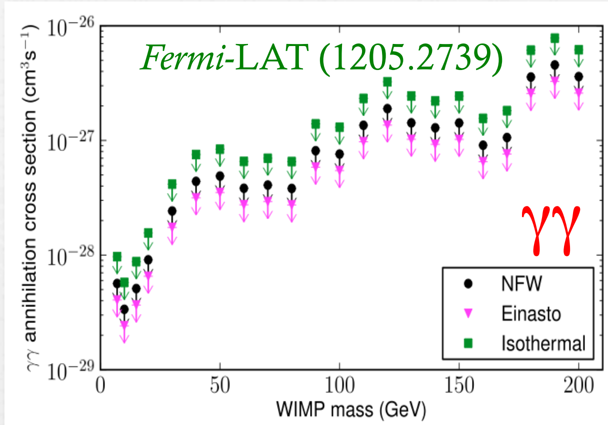
m_χ=100 GeV

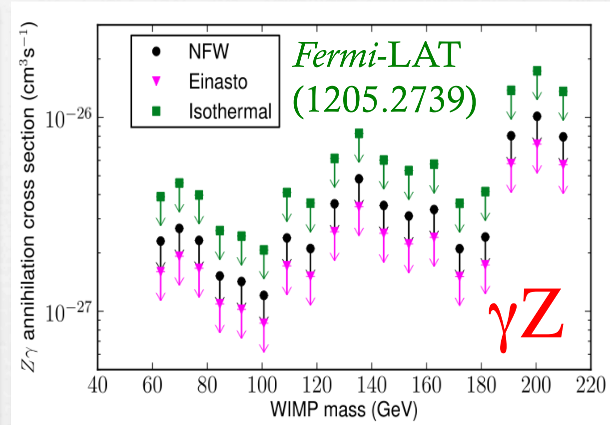


m_χ=100 GeV

γ-ray Line Search:

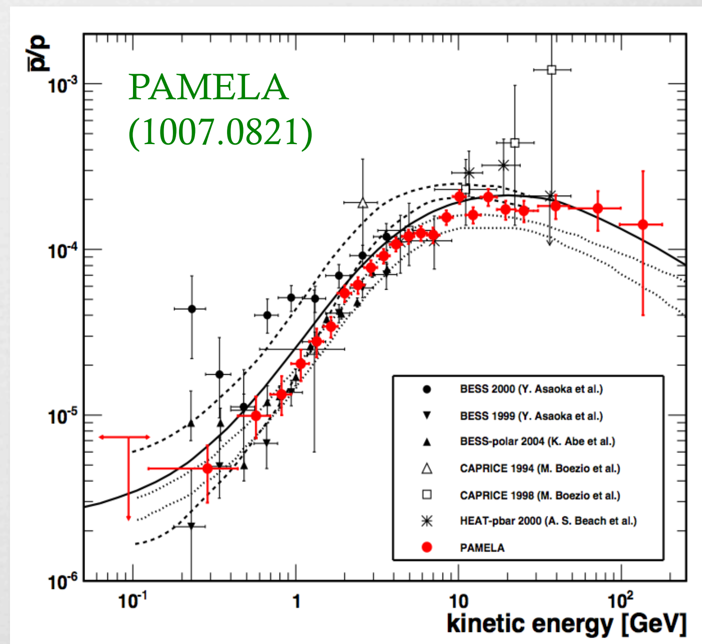
- Bounds from *Fermi*-LAT γ-ray line searches
- We use 95% C.L. exclusions assuming NFW DM profile





Antiproton Cosmic Rays:

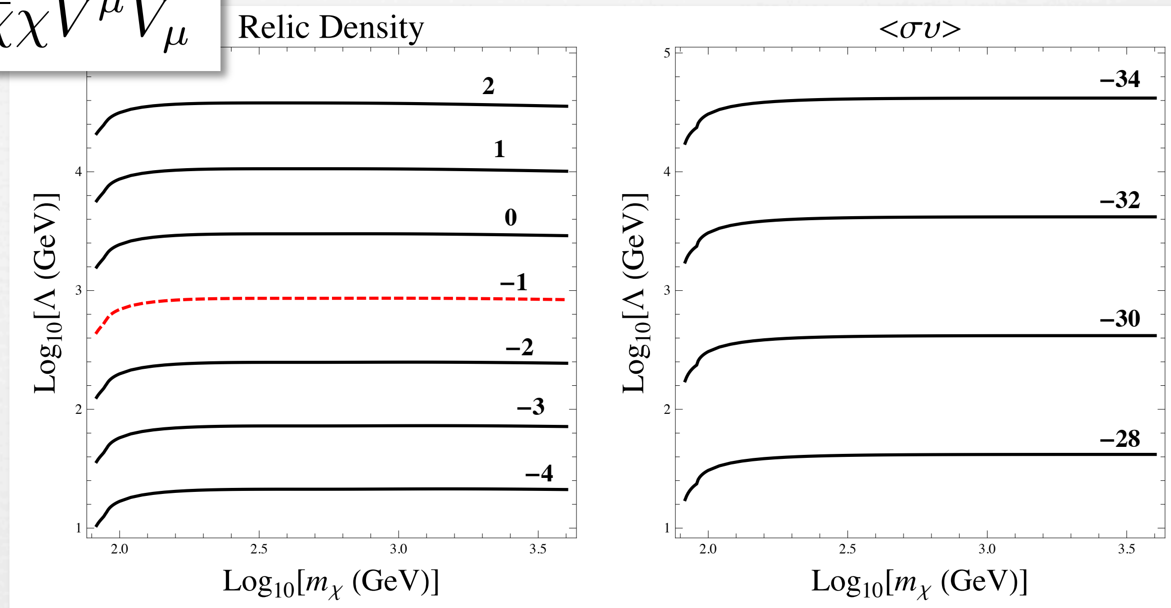
- Bounds from PAMELA measurement of the cosmic-ray antiproton/proton flux ratio
- Assume NFW profile and use GALPROP to propagate signal, add to well-measured CR proton spectrum
- Omit background (secondary) $\bar{p}$'s to calculate conservative χ^2



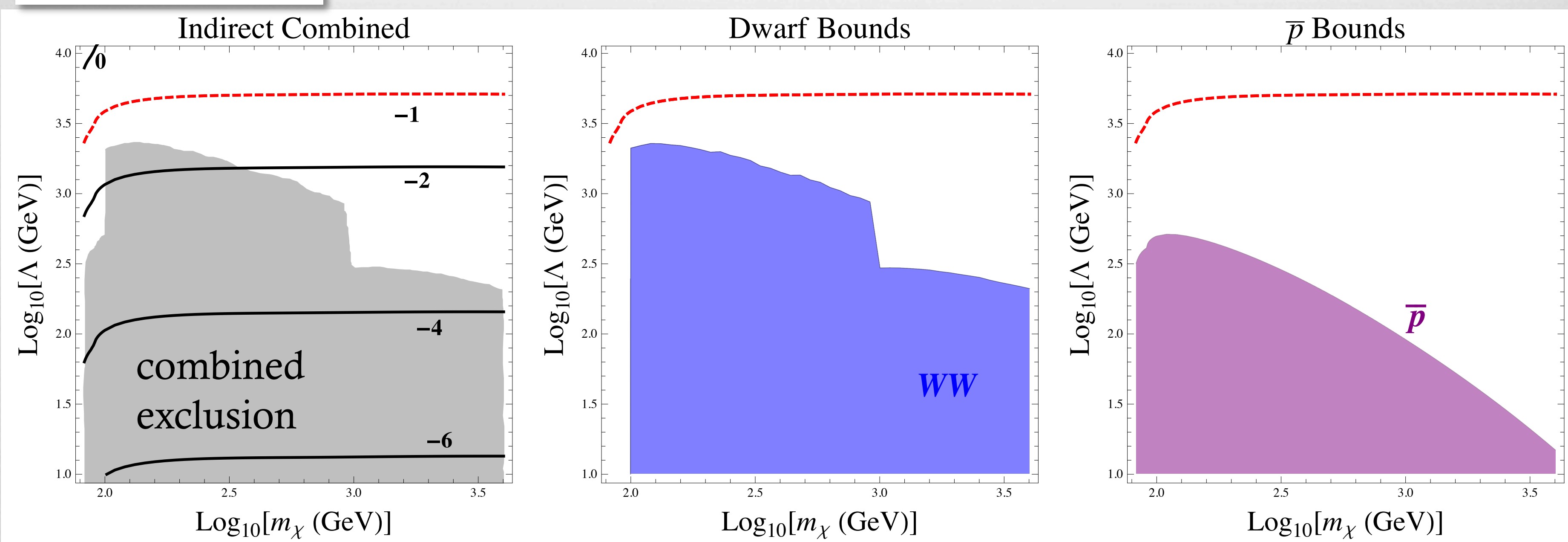
Indirect Detection Results:

$\bar{\chi}\chi V^{\mu}V_{\mu}$

No ID Bounds!
(Velocity Suppressed)

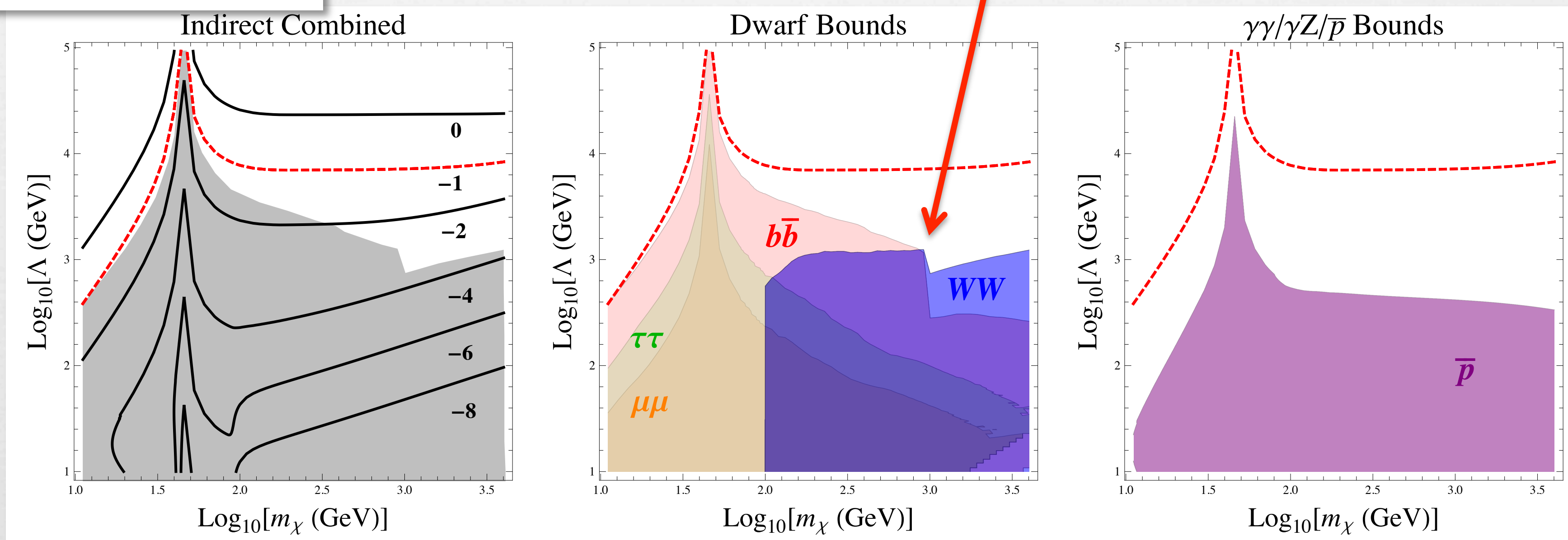


$\bar{\chi}i\gamma_5\chi V^{\mu}V_{\mu}$



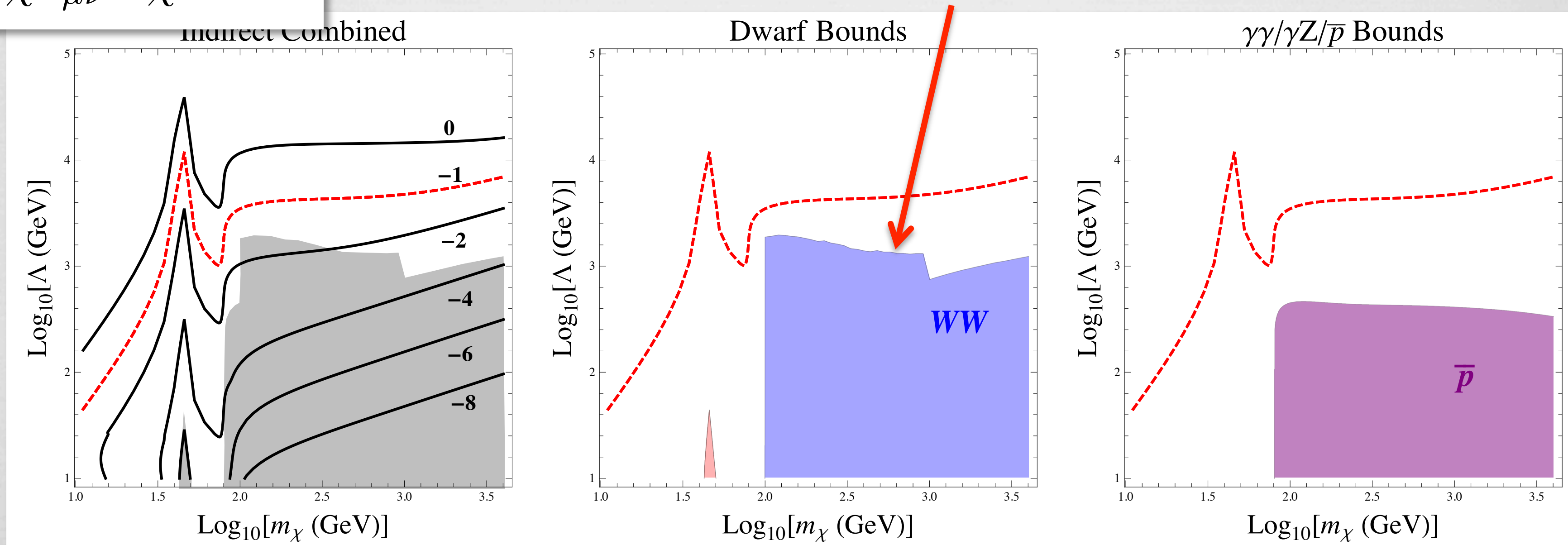
$\bar{\chi}\sigma_{\mu\nu}t^a\chi V^{a\mu\nu}$

Fermi-LAT / VERITAS changeover

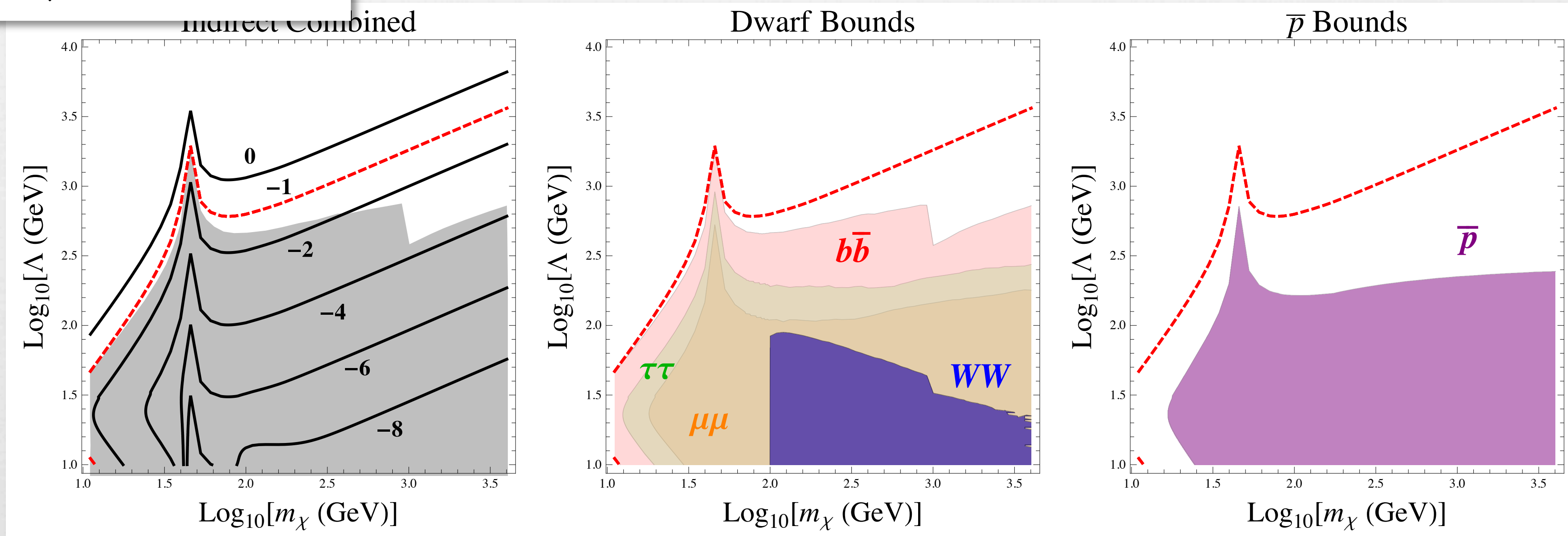


$\bar{\chi}\sigma_{\mu\nu}t^a\chi\widetilde{V}^{a\mu\nu}$

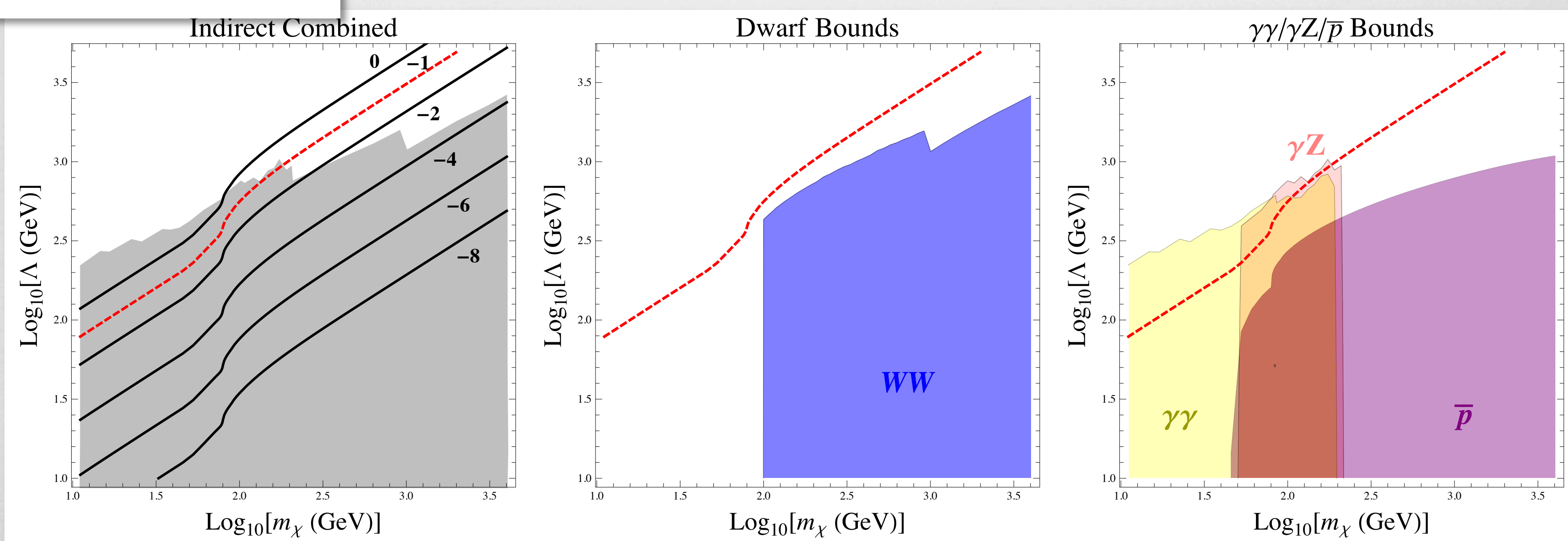
$\bar{\mathrm{f}}\mathrm{f}$ is suppressed, WW is not.



$$\bar{\chi}\gamma_\mu t^a D_\nu \chi V^{a\mu\nu}$$



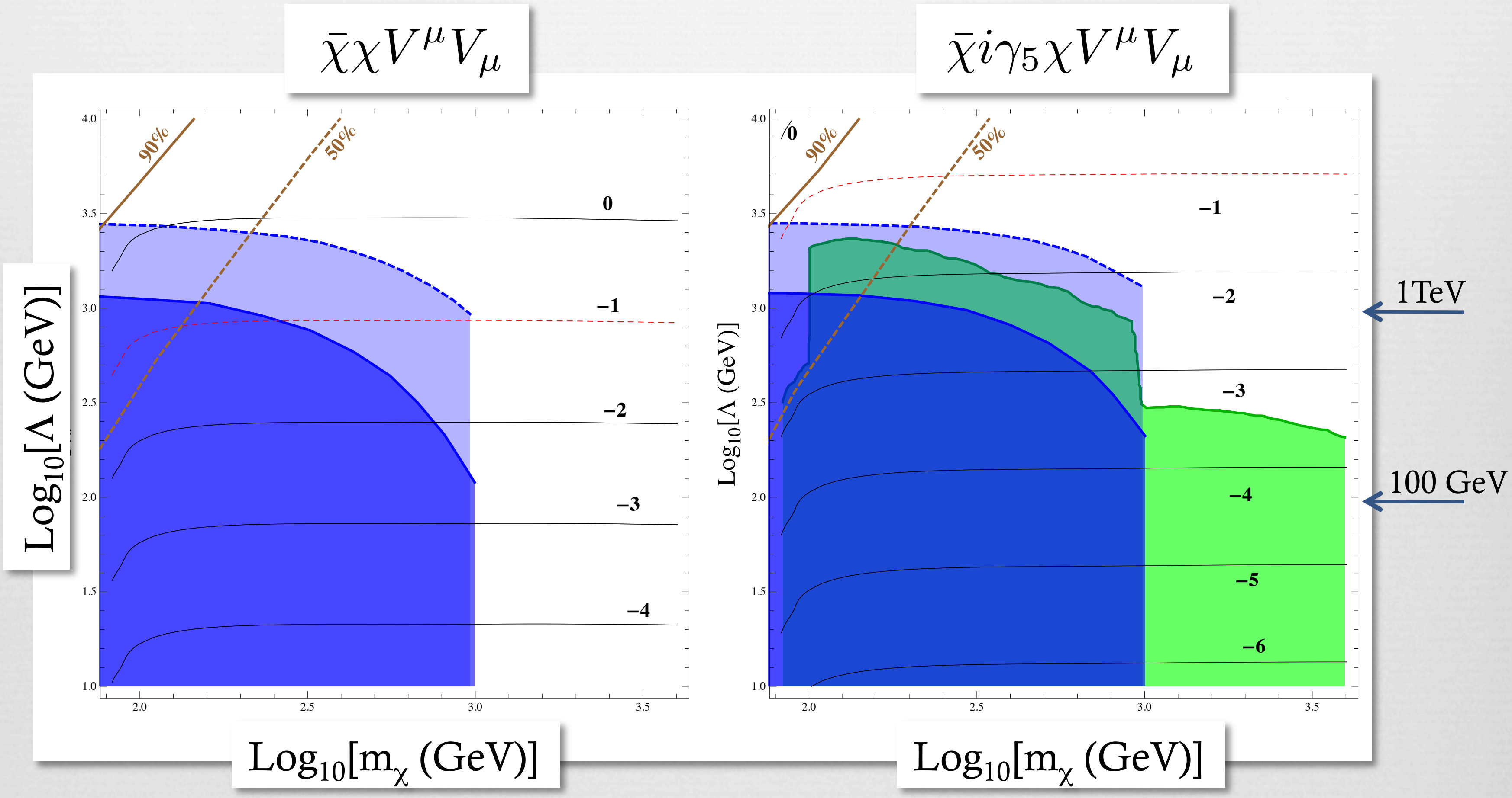
$$\bar{\chi} i\gamma_5 \chi V^{a\mu\nu} V^a_{\mu\nu}$$



Combined Results

8/14 TeV LHC Excl.

Indirect Excl.

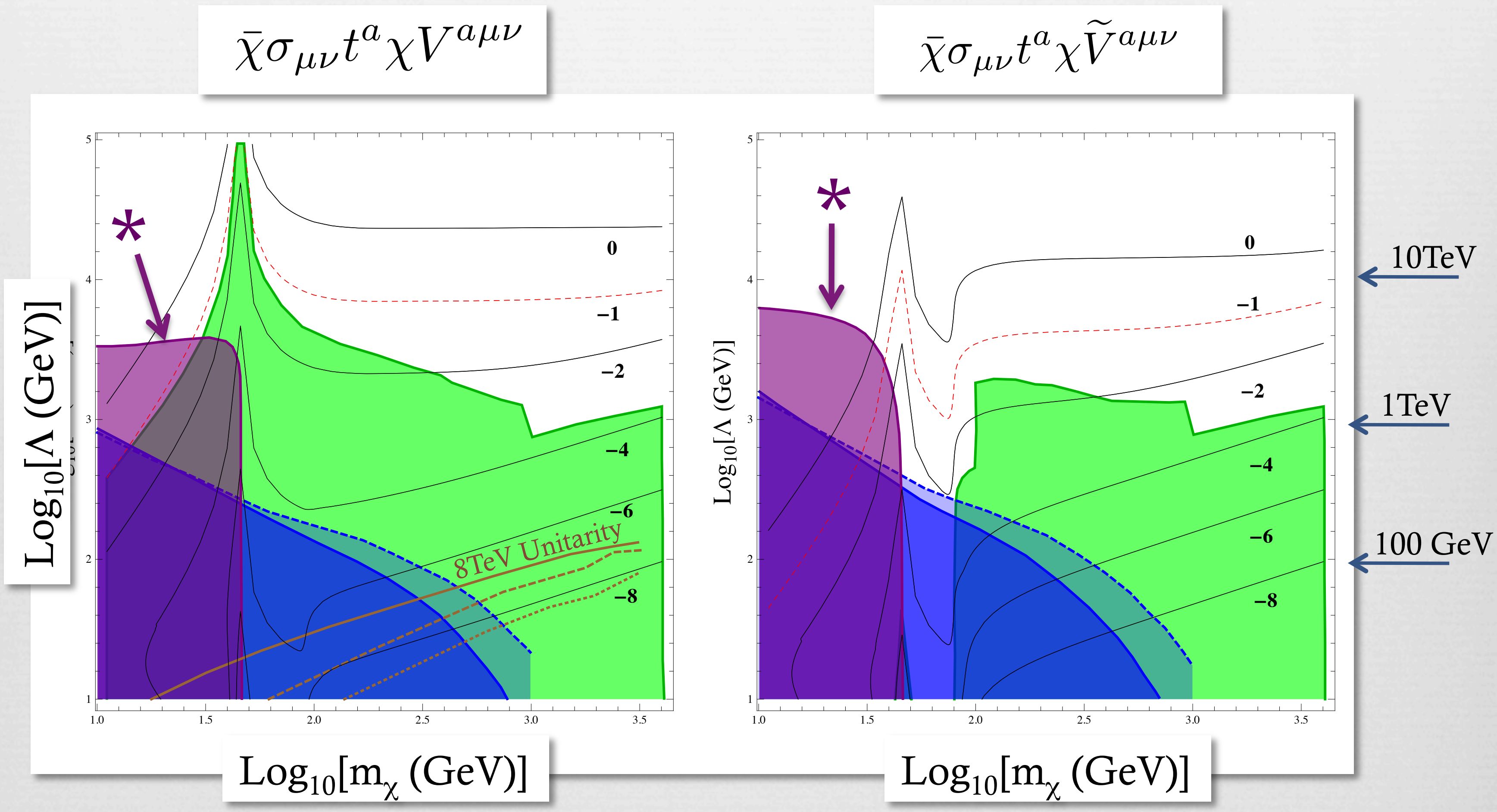


Combined Results

8/14 TeV LHC Excl.

Indirect Excl.

$\Gamma_{Z,inv}$ Excl.



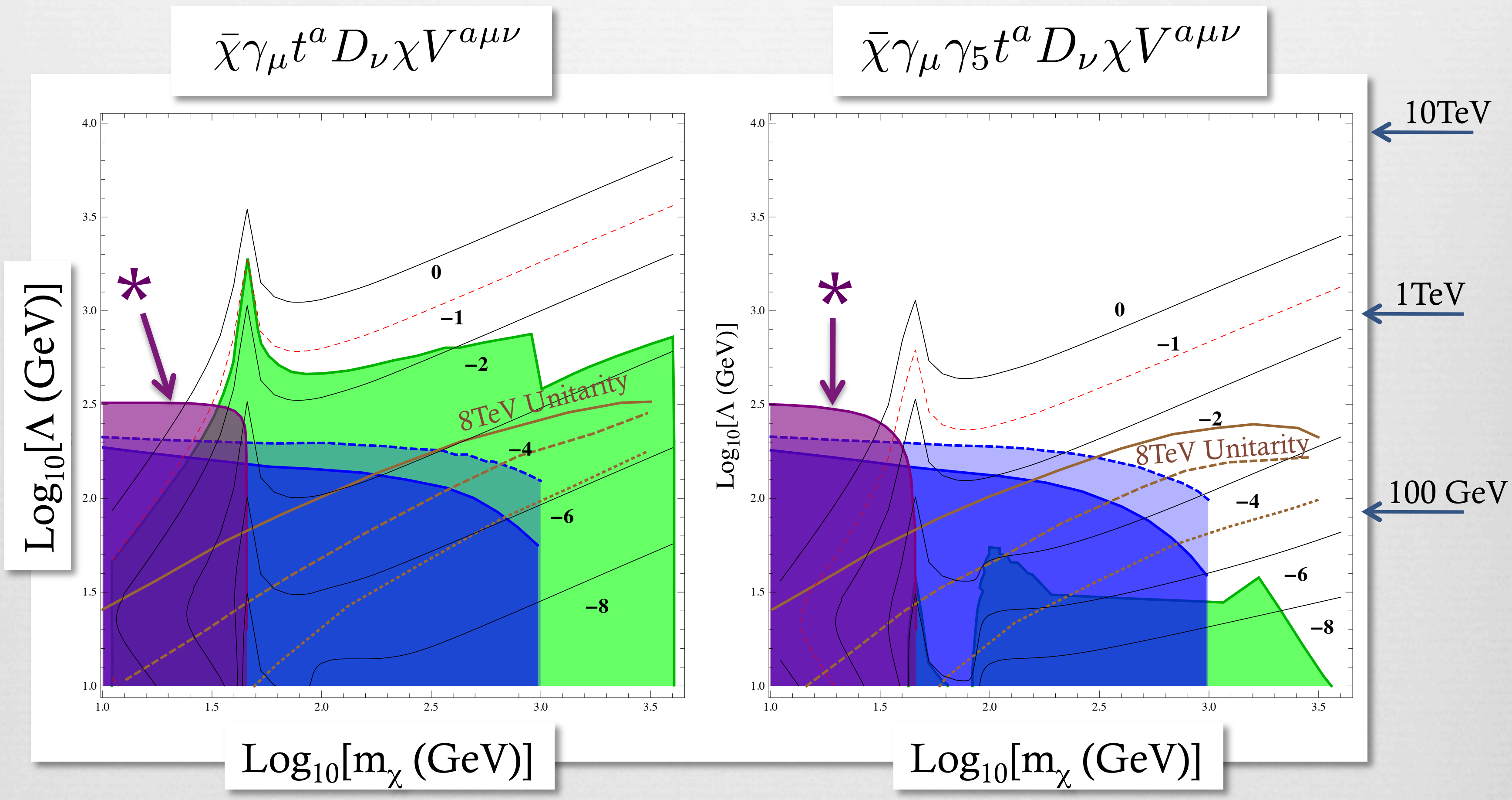
* $\Gamma_{Z,inv}$ Excludes single op. $\chi\chi VV$ below $m_\chi \sim mZ/2$

Combined Results

8/14 TeV LHC Excl.

Indirect Excl.

$\Gamma_{Z,inv}$ Excl.

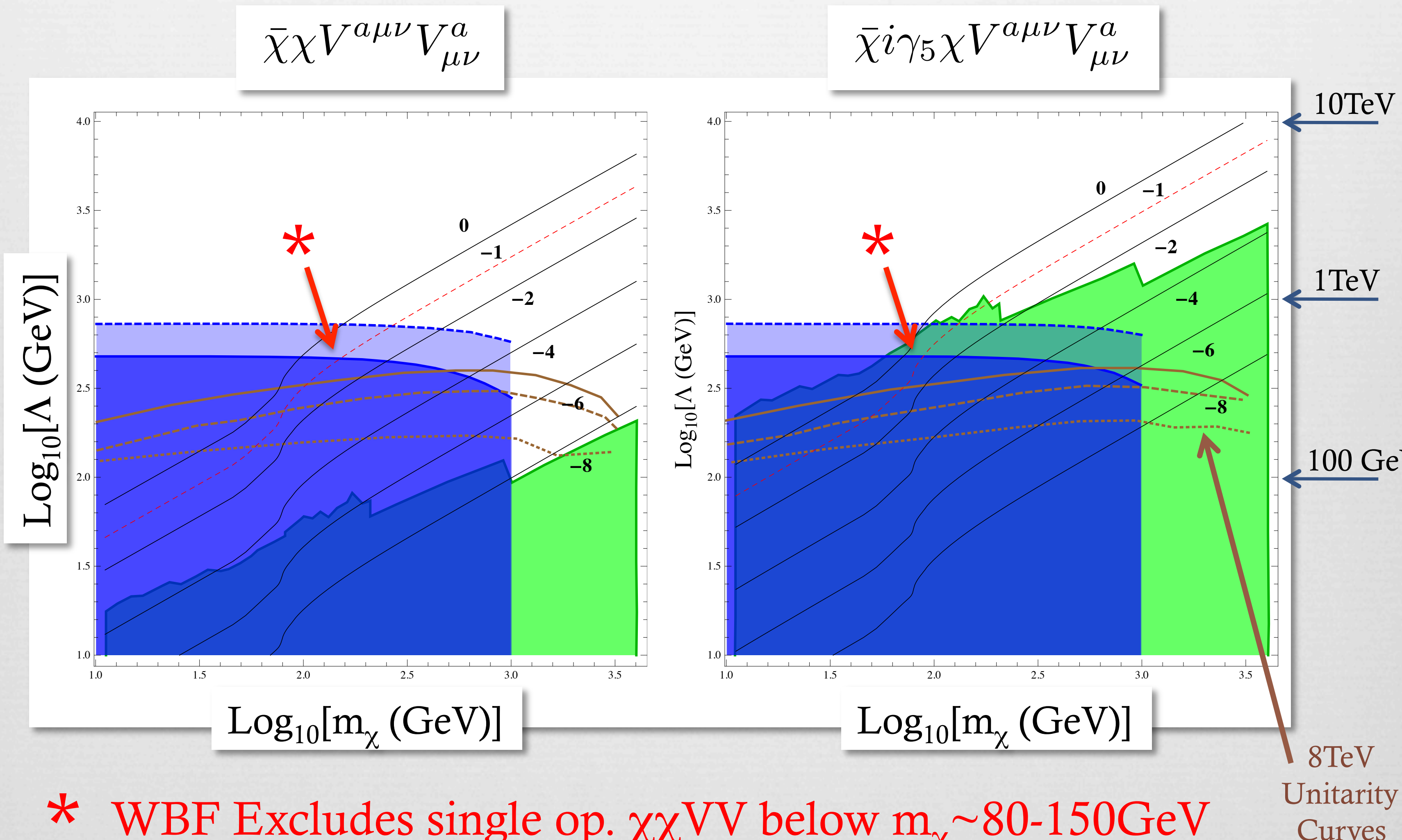


* $\Gamma_{Z,inv}$ Excludes single op. $\chi\chi VV$ below $m_\chi \sim mZ/2$

Combined Results

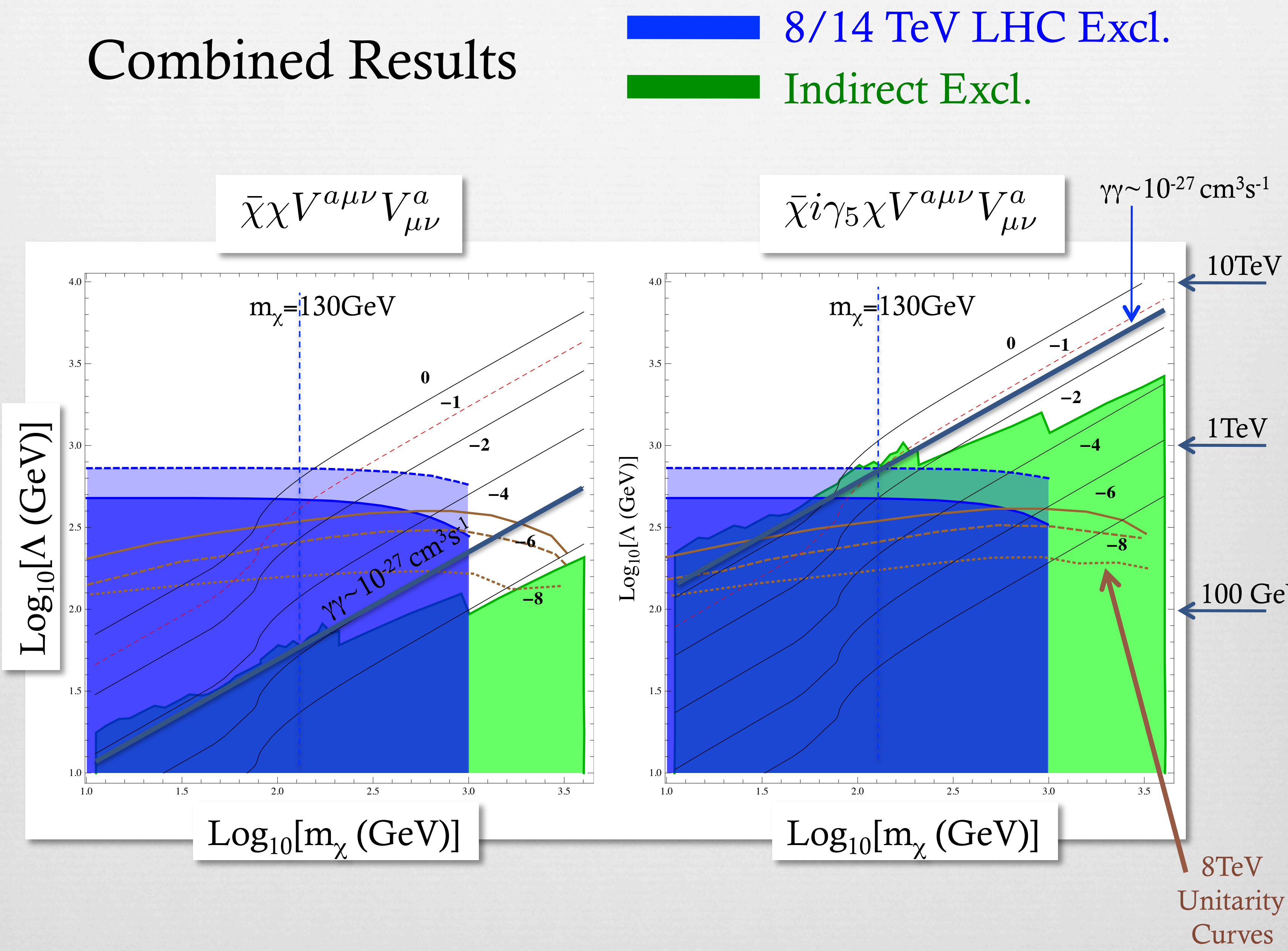
8/14 TeV LHC Excl.

Indirect Excl.



* WBF Excludes single op. χχVV below m_χ~80-150GeV

Combined Results



Summary

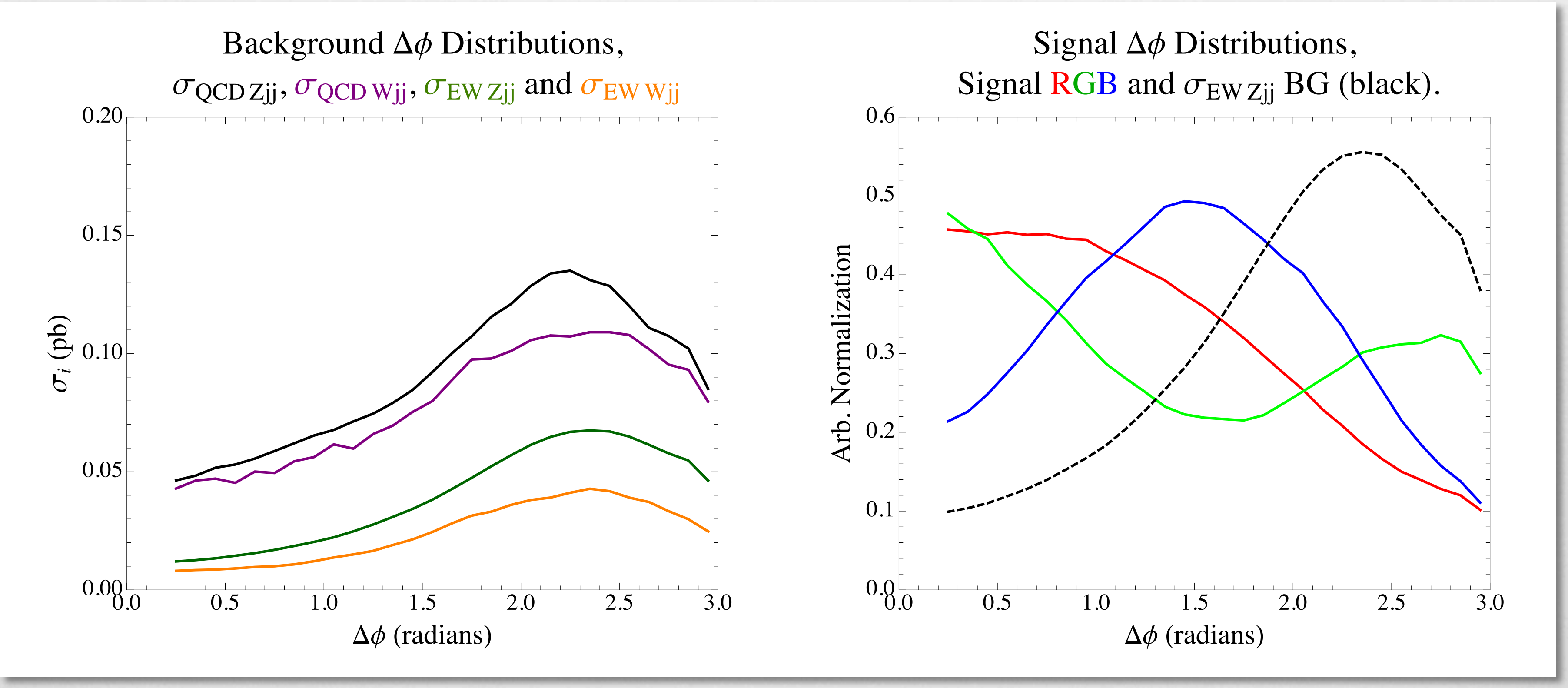
DM in EFT language allows simple and UV model-independent study of search complementarity, provided assumptions are satisfied.

We find bounds on DM that interacts with the SM primarily via electroweak gauge bosons that reach generally to weak scale values (~TeV) of Λ.

For most of our operators, extra operators or dark sector structure are necessary for light DM to avoid over-closing the universe.

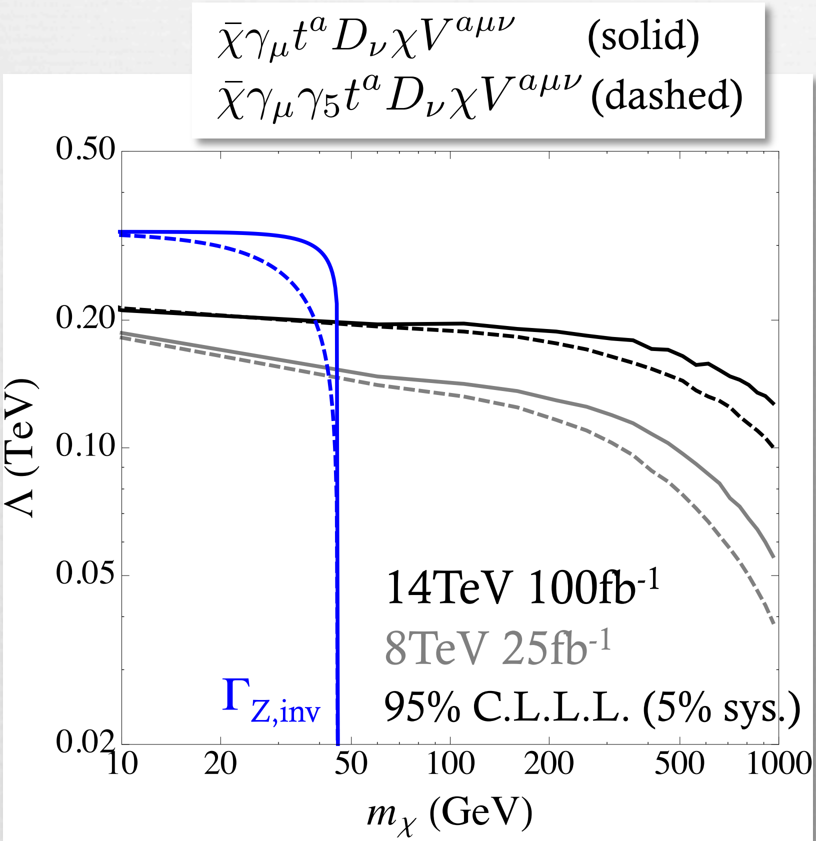
~Backup~

Not all signals have same azimuthal distr's. either…

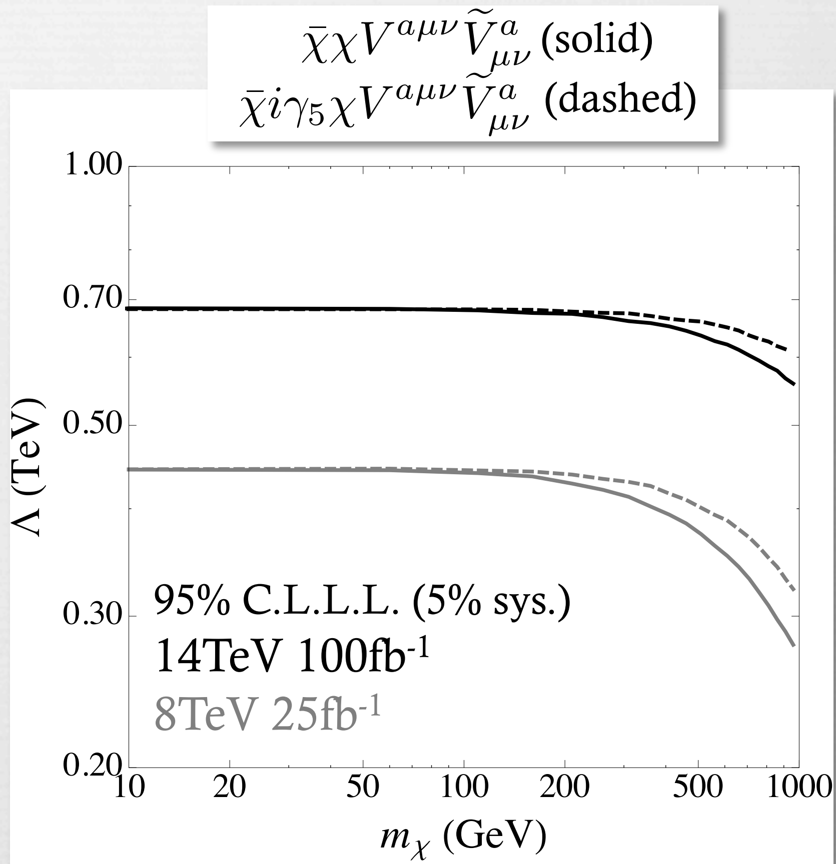


(Not as important as the tagging jet rapidity distributions)

WBF Results…

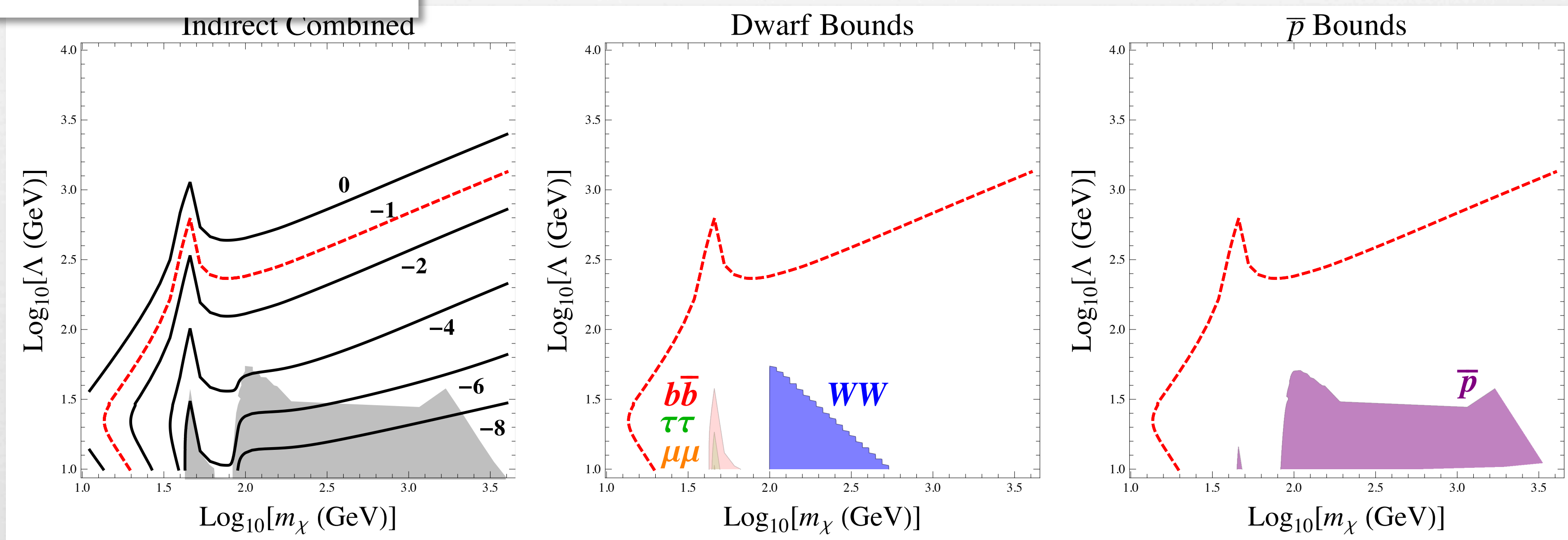


$\bar{\chi}\gamma_\mu t^a D_\nu \chi V^{a\mu\nu}$ (solid)
$\bar{\chi}\gamma_\mu\gamma_5 t^a D_\nu \chi V^{a\mu\nu}$ (dashed)
0.50
0.20
0.10
0.05
0.02
10
20
50
100
200
500
1000
Λ (TeV)
m_χ (GeV)
$\Gamma_{Z,inv}$
14TeV 100fb^{-1}
8TeV 25fb^{-1}
95% C.L.L.L. (5% sys.)

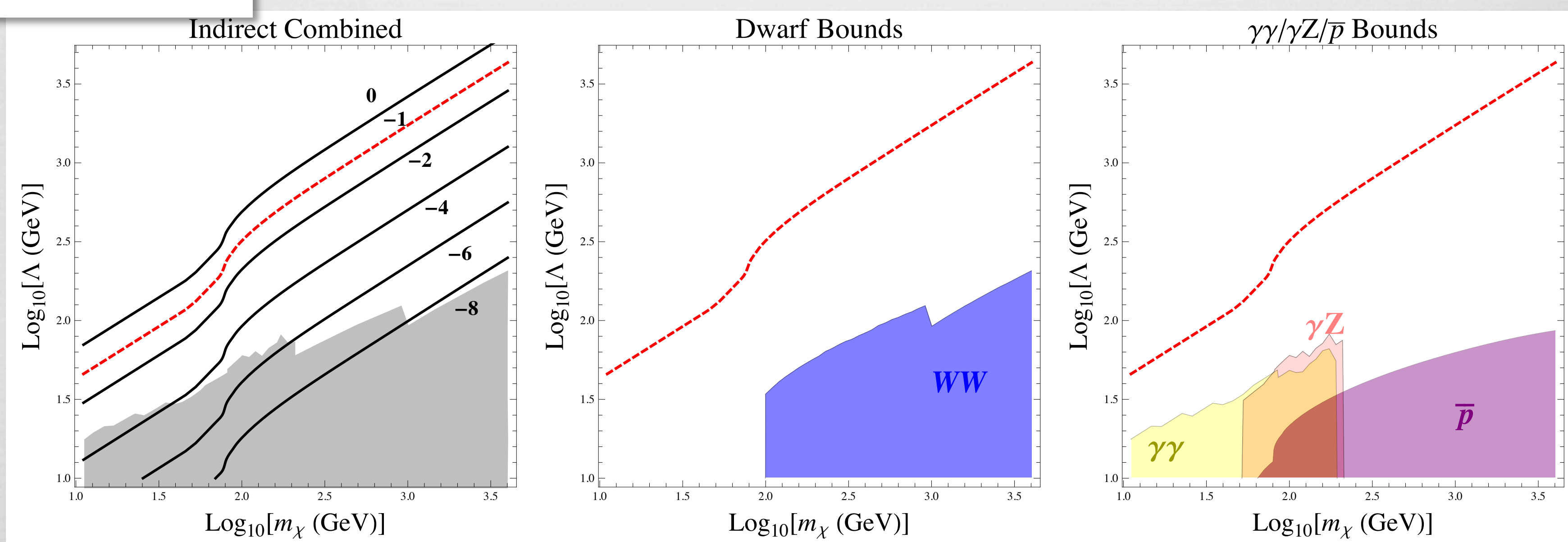


$\bar{\chi}\chi V^{a\mu\nu}\widetilde{V}^a_{\mu\nu}$ (solid)
$\bar{\chi}i\gamma_5\chi V^{a\mu\nu}\widetilde{V}^a_{\mu\nu}$ (dashed)
1.00
0.70
0.50
0.30
0.20
10
20
50
100
200
500
1000
Λ (TeV)
m_χ (GeV)
95% C.L.L.L. (5% sys.)
14TeV 100fb^{-1}
8TeV 25fb^{-1}

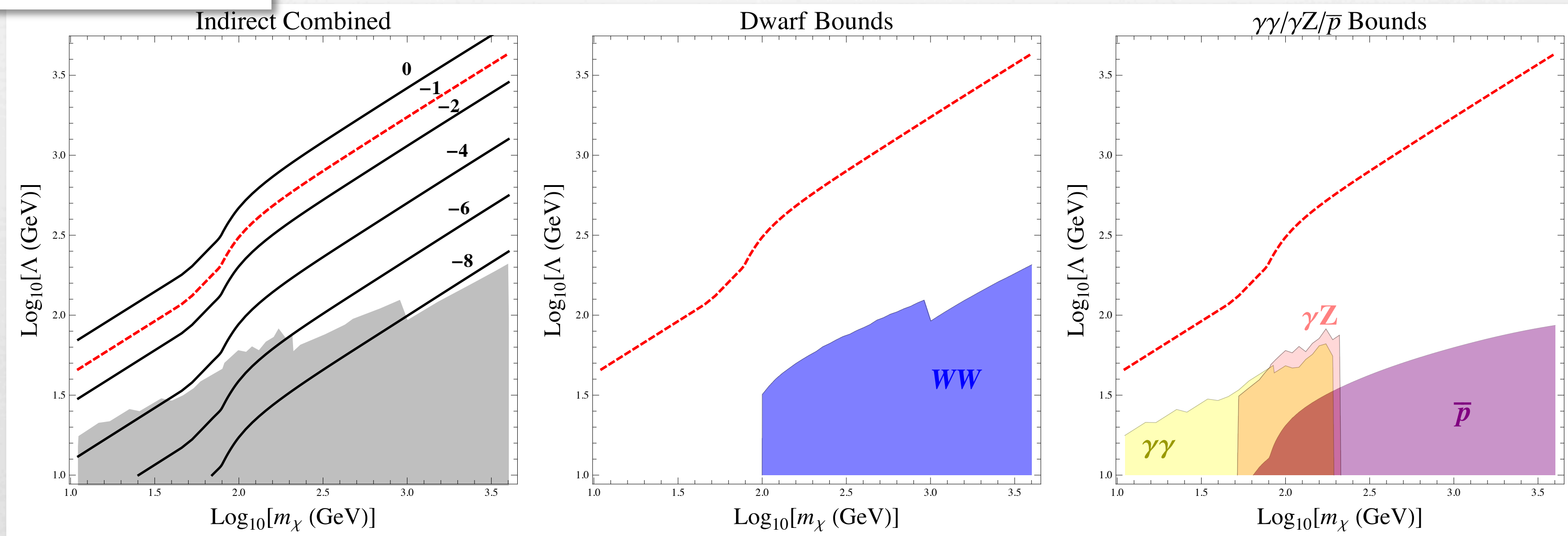
$$\bar{\chi}\gamma_\mu\gamma_5 t^a D_\nu \chi V^{a\mu\nu}$$



$$\bar{\chi}\chi V^{a\mu\nu} V^a_{\mu\nu}$$



$$\bar{\chi}\chi V^{a\mu\nu}\widetilde{V}^{a}_{\mu\nu}$$



$$\bar{\chi}i\gamma_5\chi V^{a\mu\nu}\widetilde{V}^{a}_{\mu\nu}$$