Effective Field Theory and WIMP Observables

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Effective Field Theory

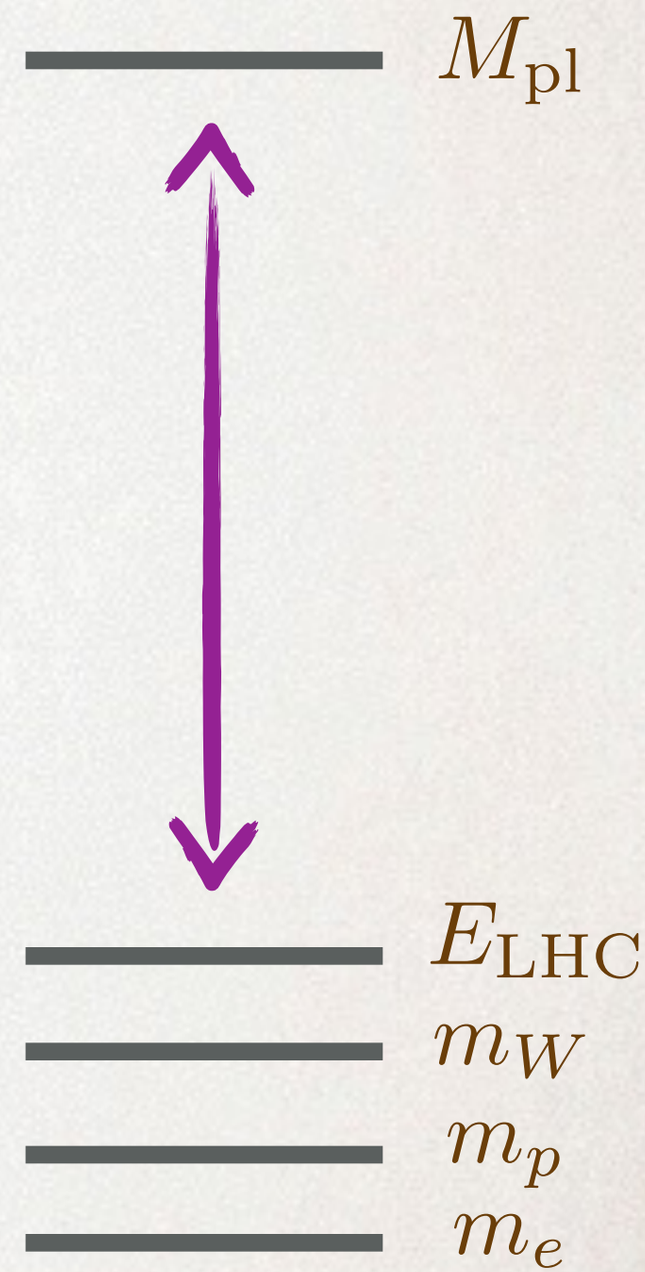
Formalizes physics of reductionism.

Large separation of scales ⇨ integrate out irrelevant effects.

Work with relevant degrees of freedom.

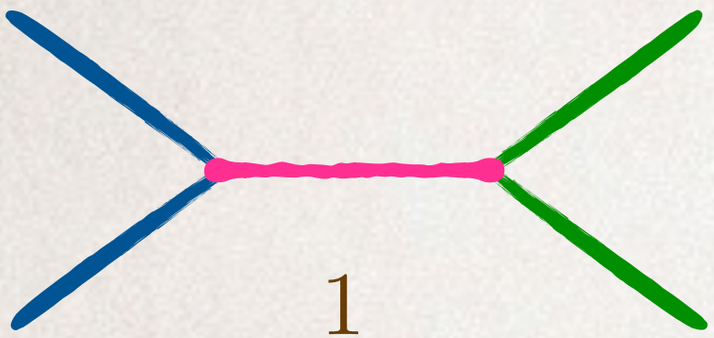
Symmetry and **power counting** constraints EFT.

$E_{\rm LHC}/M_{\rm pl} \ll 1$:
Integrate out gravitational effects for LHC calculations.



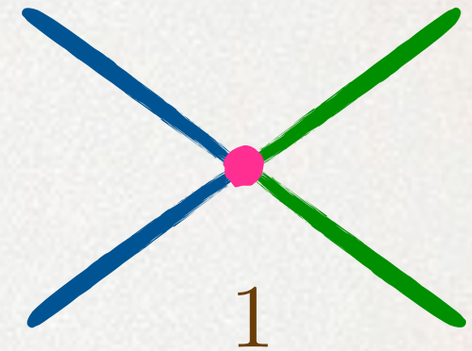
In Practice

Tree-level



$$\frac{1}{E_{\rm CM}^2 - M^2}$$

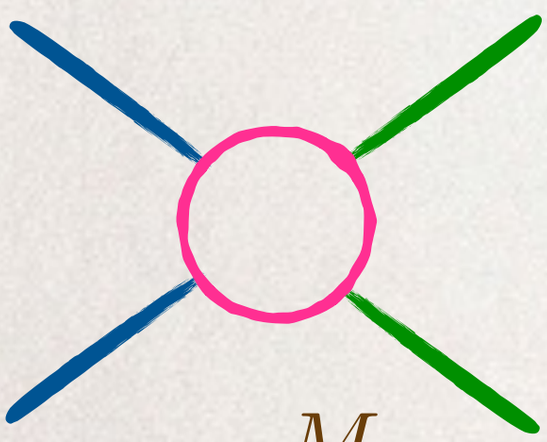
$$E_{\rm CM}/M \ll 1$$



$$\frac{1}{M^2}$$

Contact operators: polynominal in M.

Loop-level



$$\log \frac{M}{E_{\rm CM}}$$

divergence

$$E_{\rm CM}/M \ll 1$$

$$\log \frac{M}{E_{\rm CM}} \gg 1$$

spoils perturbation theory…

Renormalization group evolution to the rescue!

Examples

EFT at the LHC

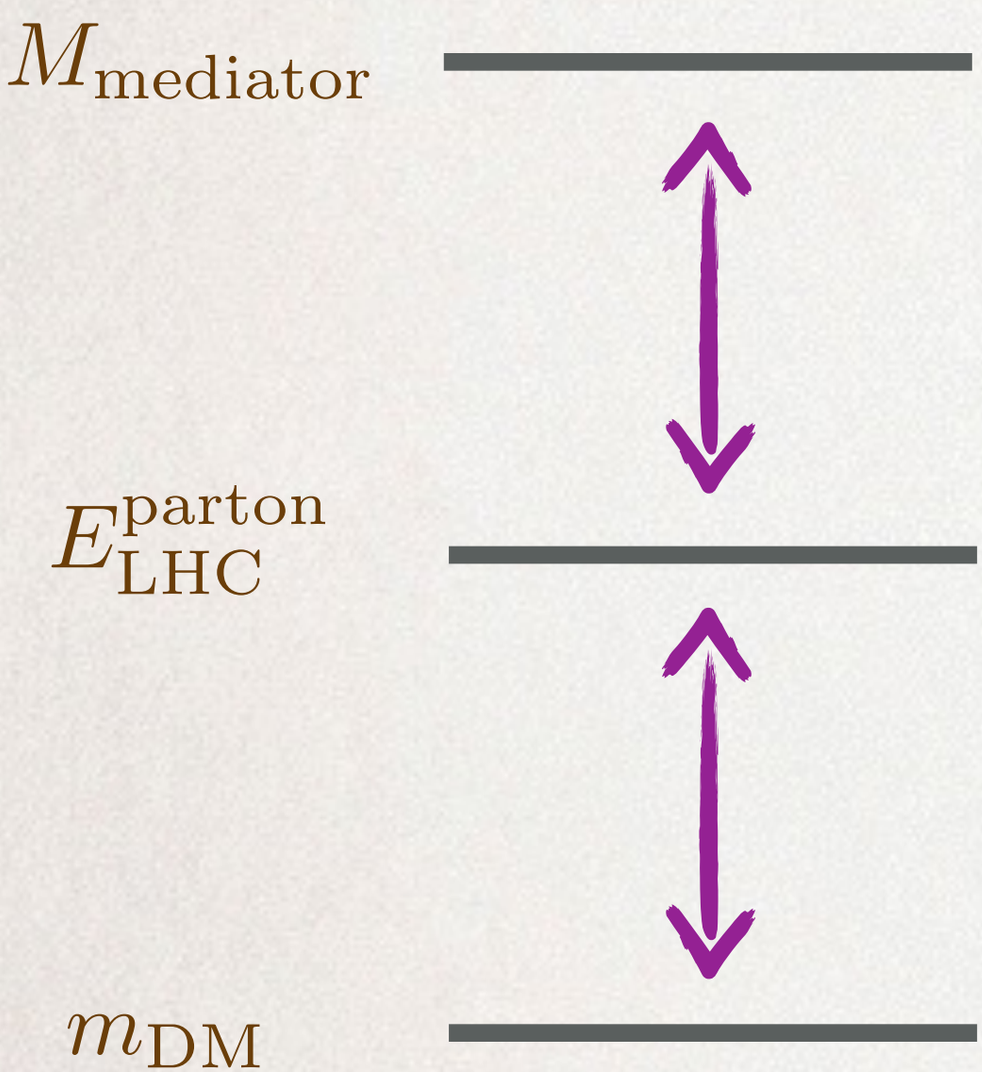
EFT for Heavy WIMP Annihilation

EFT at the LHC

Operator List

Organized using symmetry and mass dimension.

$$(\mathrm{DM} \times \mathrm{DM})(\mathrm{SM} \times \mathrm{SM})$$



Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu [arXiv:1008.1783];
Fox, Harnik, Kopp, Tsai [arXiv:1109.4398]

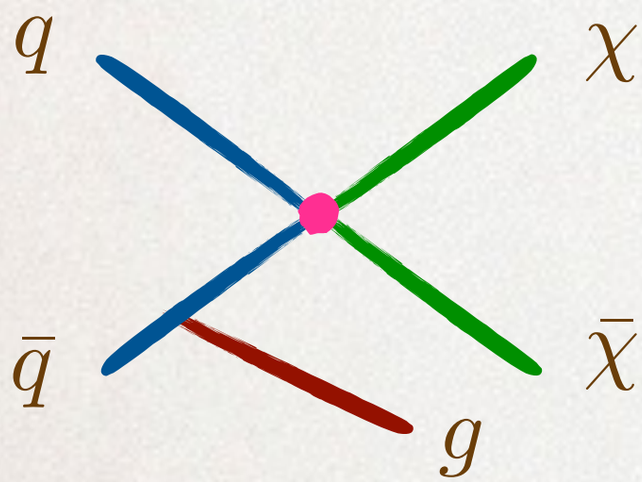
"Model Independence"

For concreteness, take:

$$(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)$$

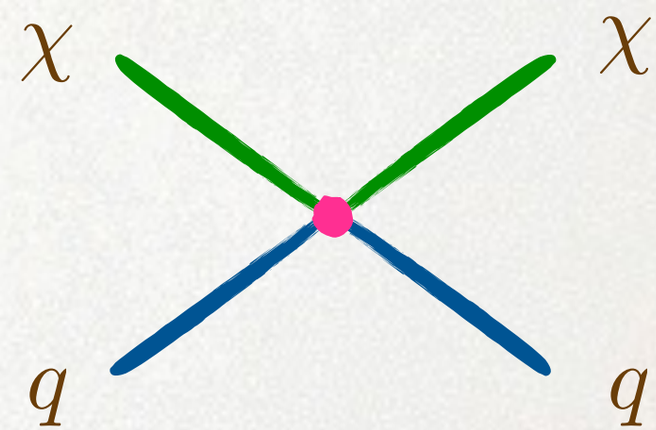
Test this operator?

LHC:



"Mono-jet searches"

Direct-detection:



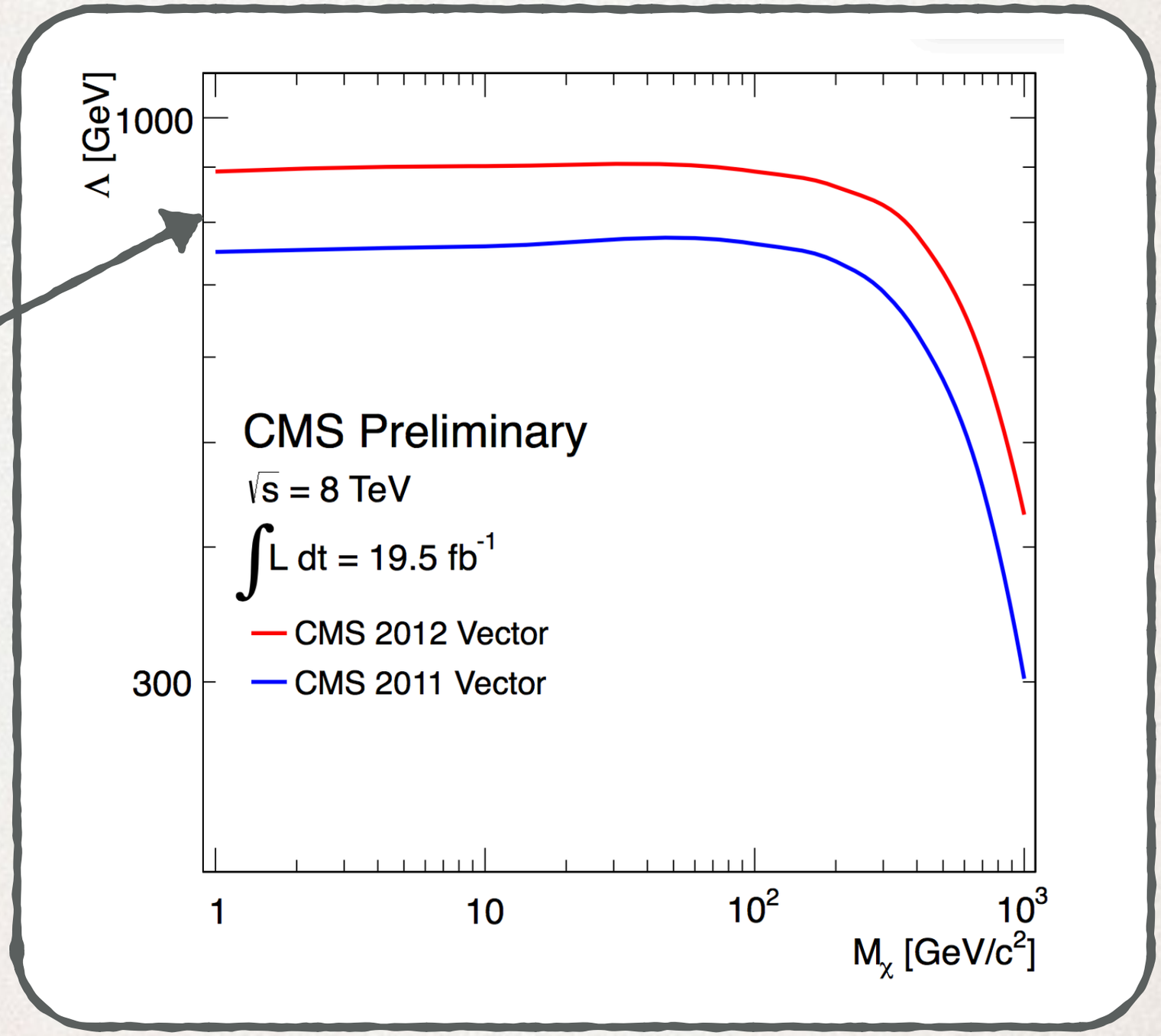
Spin-independent DD

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu [arXiv:1008.1783];
Fox, Harnik, Kopp, Tsai [arXiv:1109.4398]

Constraints

$$\mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$$

Scale close to parton energy



CMS Collaboration: CMS EXO-12-048

EFT for LHC

No large separation of scales…

Contact operator approximation breaks down:

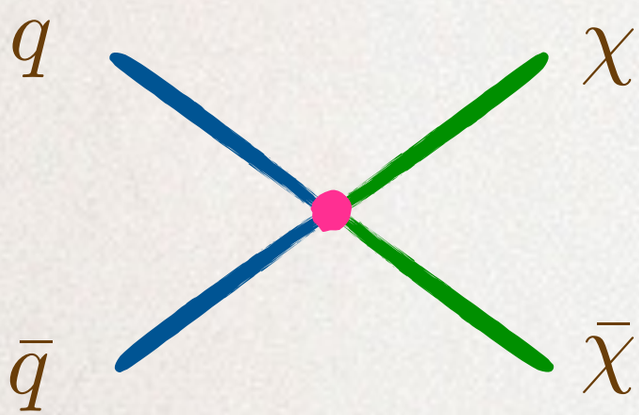
$$\frac{E_{\rm LHC}^{\rm parton}}{M_{\rm mediator}} \sim 1$$

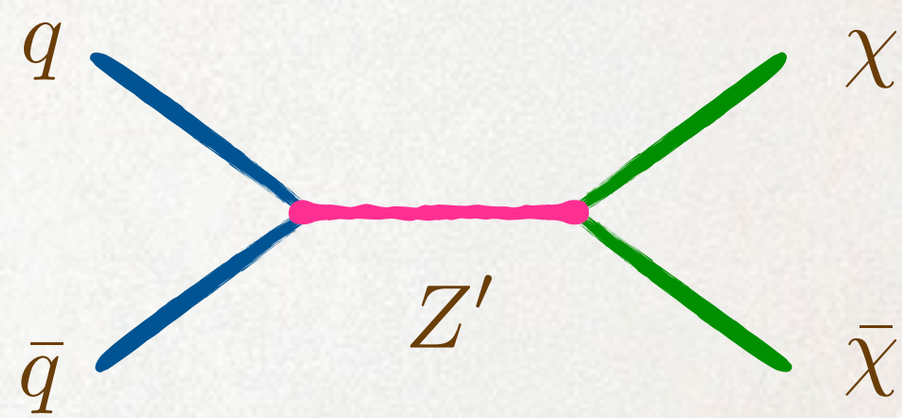
Integrate in Mediator

Example operator: $(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)$

Pick a state to integrate in.

Example: vector mediator.





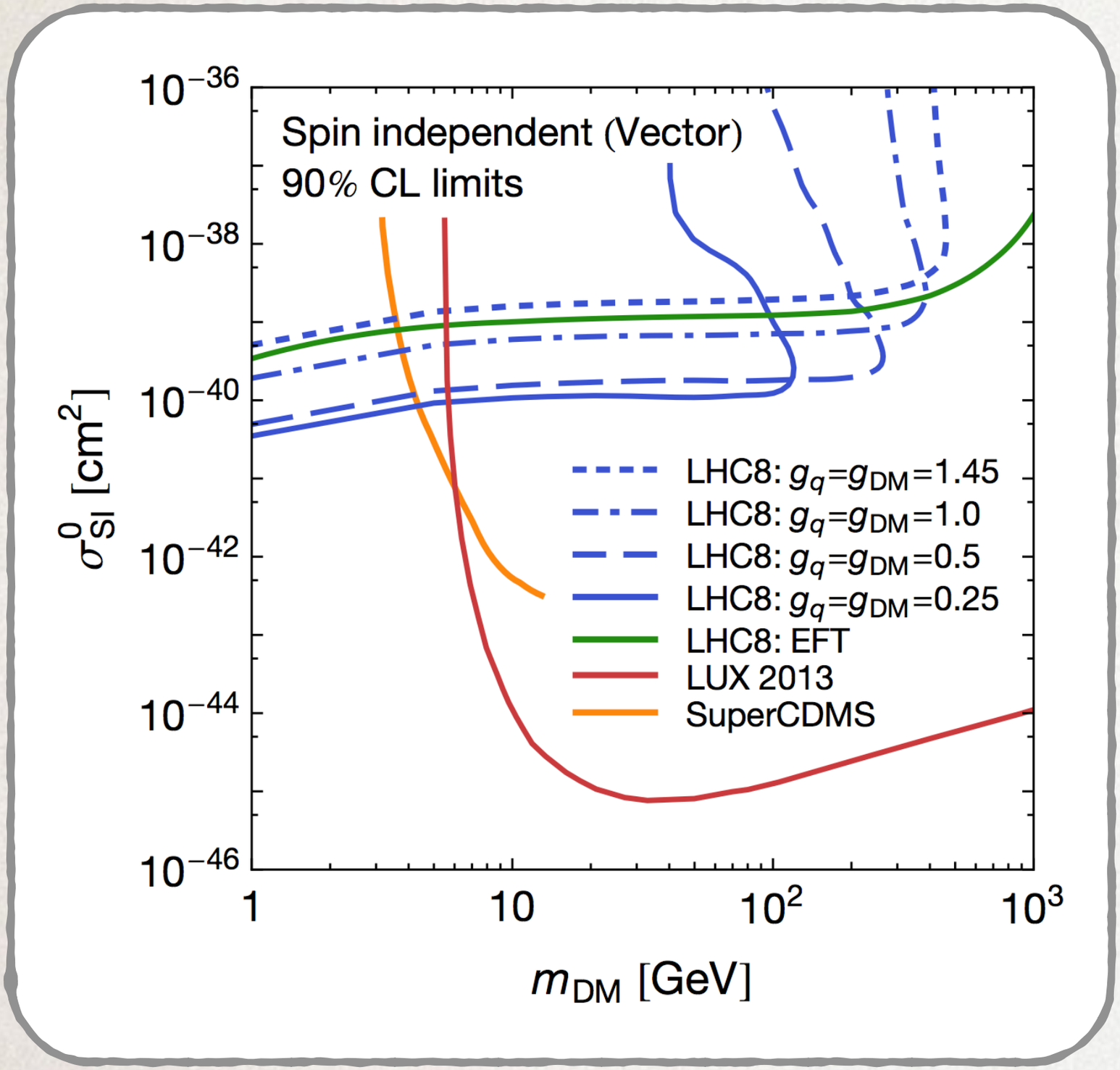
Model parameters expanded:

vector and axial couplings to quarks and dark matter.

Note: other UV completions exist.

Recent reviews of these issues: arXiv:1409.2893 and 1409.4075.

Contact Operator Approximation



Fixed cross section:

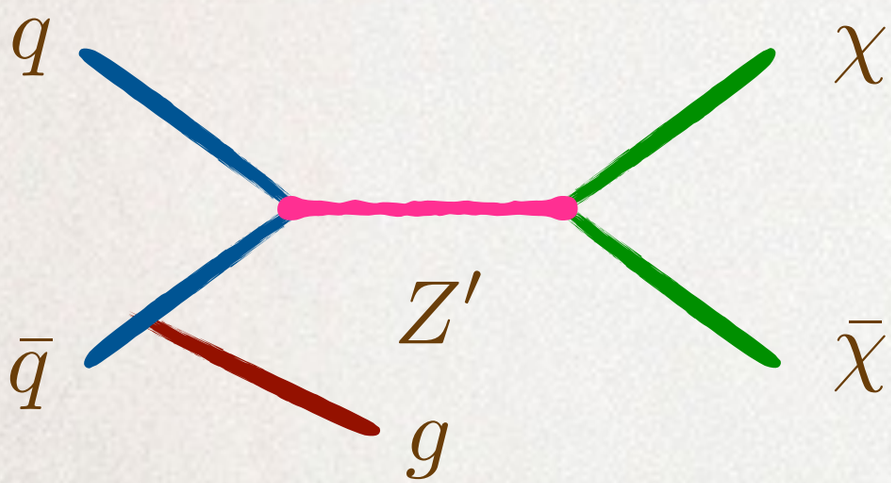
$$\frac{g^2}{M_{Z'}} \text{ is constant.}$$

Bigger coupling, better approx.

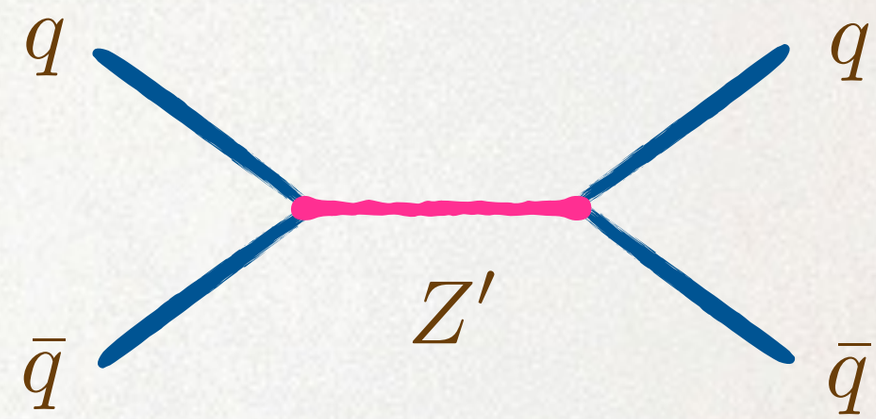
Malik et. al. [arXiv:1409.4075]

Additional Channels

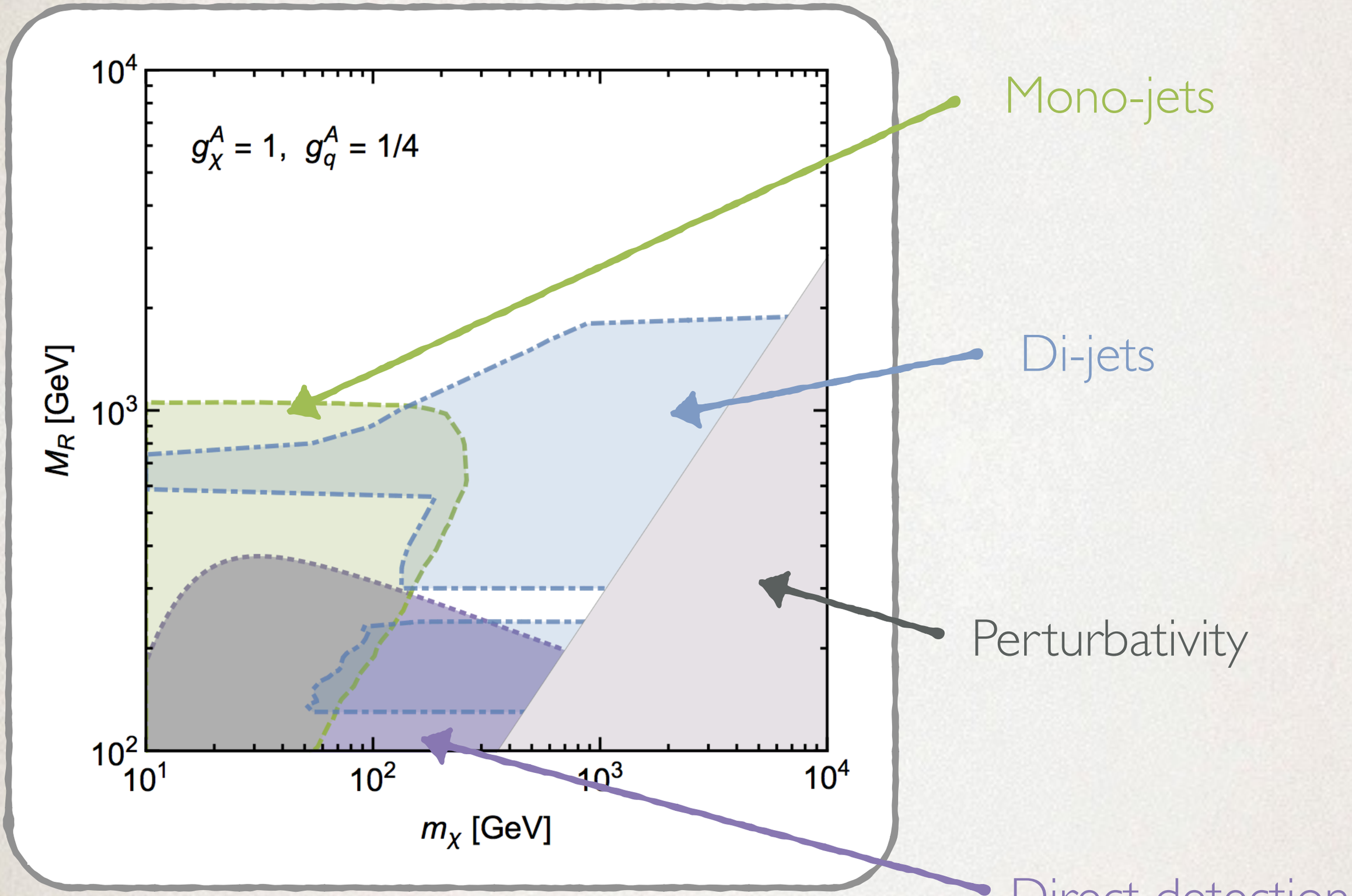
Mono-jet



Di-jet

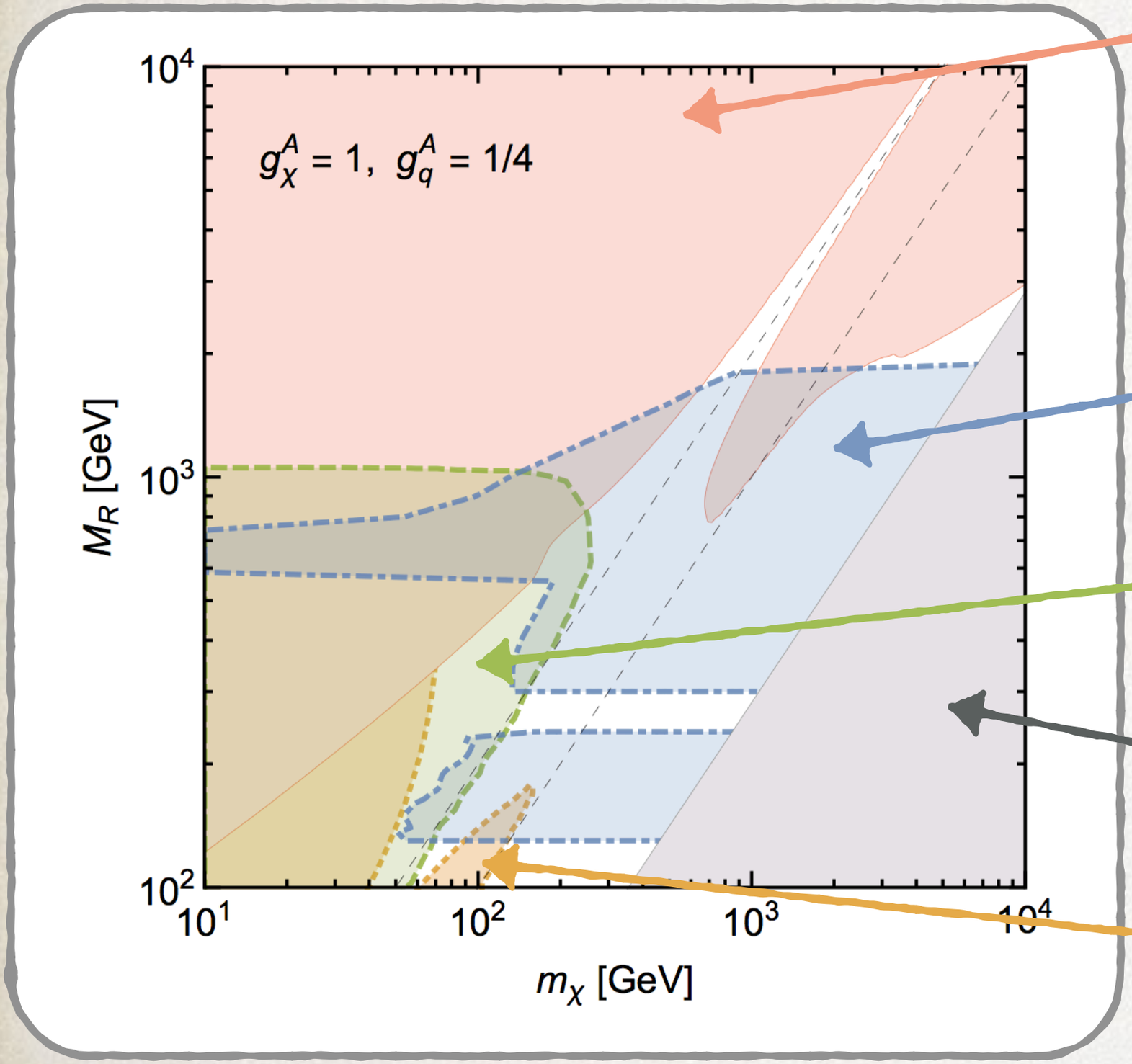


Impact of Additional Channels



Chala, Khlheofer, McCullough, Nardini, Schmidt-Hoberg [arXiv:1503.05916]

Add Relic Density Information



Overclosure

Di-jets

Mono-jet

Perturbativity

LUX (rescaled by computed relic density)

Chala, Khlheofer, McCullough, Nardini, Schmidt-Hoberg [arXiv:1503.05916]

Comments

Most important goal:

Don't miss the signal of new physics!

Also important:

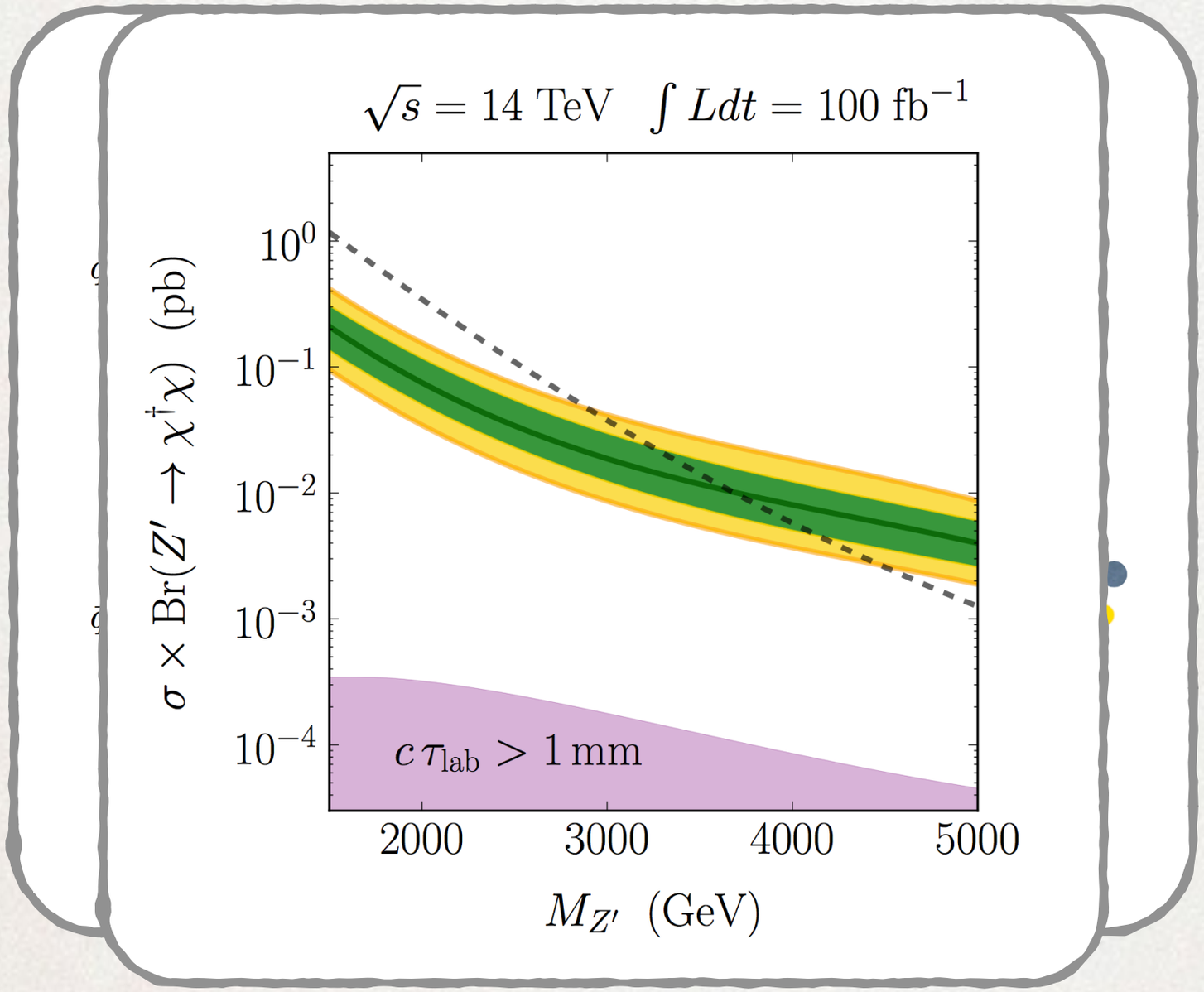
Don't waste time and money.

For Example (shameless plug)

Semi-visible Jets

Visible hadronic jets aligned with MET;

current LHC searches have low efficiency for this signal.



TC, Lisanti, Lou [arXiv:1503.00009];
see also “Hidden Valleys” Strassler and Zurek [arXiv:hep-ph/0604261];
Han, Si, Zurek, Strassler [arXiv: 0712.2041]

EFT for Heavy WIMP Annihilation

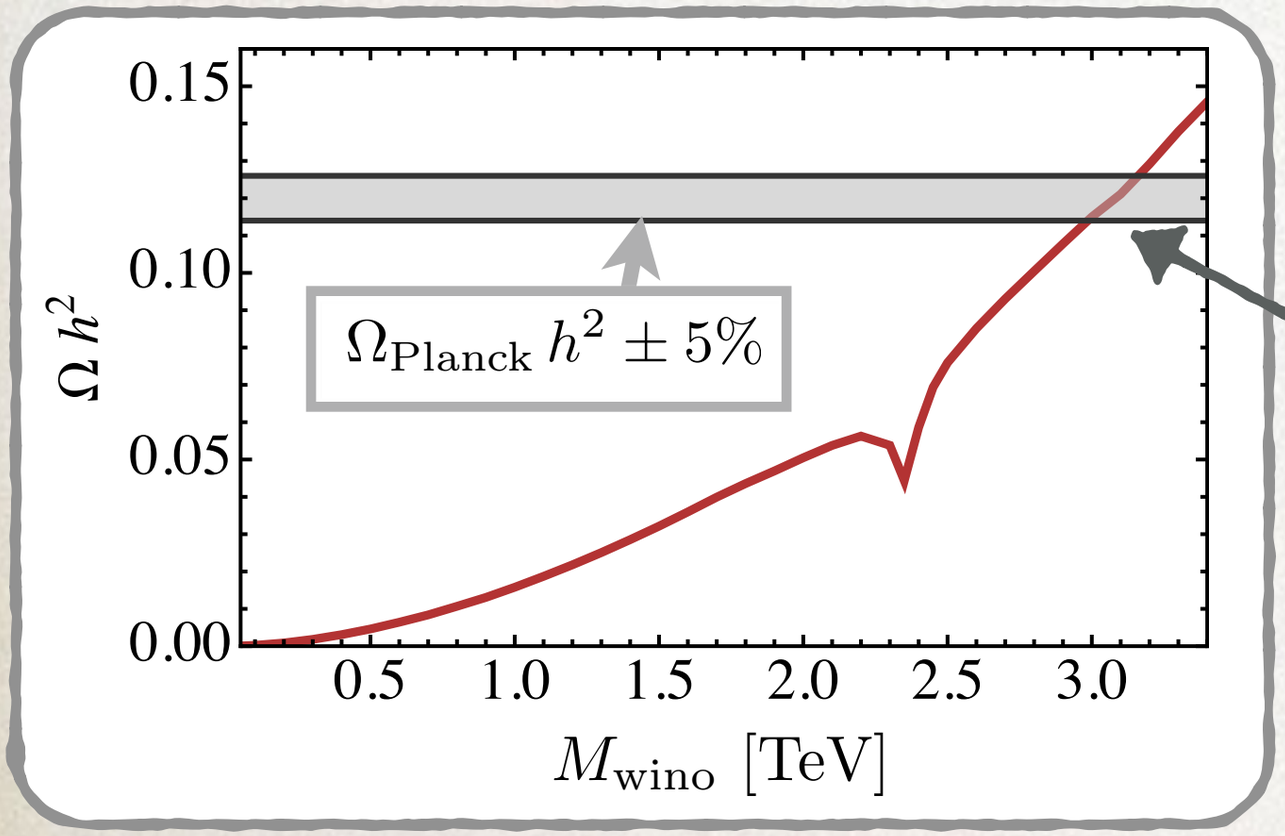
Wino as a Heavy WIMP

Minimally extend SM by adding EW triplet fermion.
(Additional motivation from SUSY.)

One free parameter, $M_{\rm wino}$.
Spectrum: $\chi^0, \chi^\pm$.

EW loops yield $\simeq 0.17\ \mathrm{GeV}$ mass splitting.

Ibe, Matsumoto, Sato [arXiv:1212.5989]



Thermal relic:
$$\chi\,\chi \to W^+\,W^-$$

$$M_{\rm wino} \simeq 3\ \mathrm{TeV}$$

Hisano, Matsumoto, Nagai, Saito, Senami [arXiv:hep-ph/0610249]

Planck Collaboration [arXiv:1303.5076]

Observable?

Want to reach $M_{\rm wino} \simeq 3\ {\rm TeV}$.

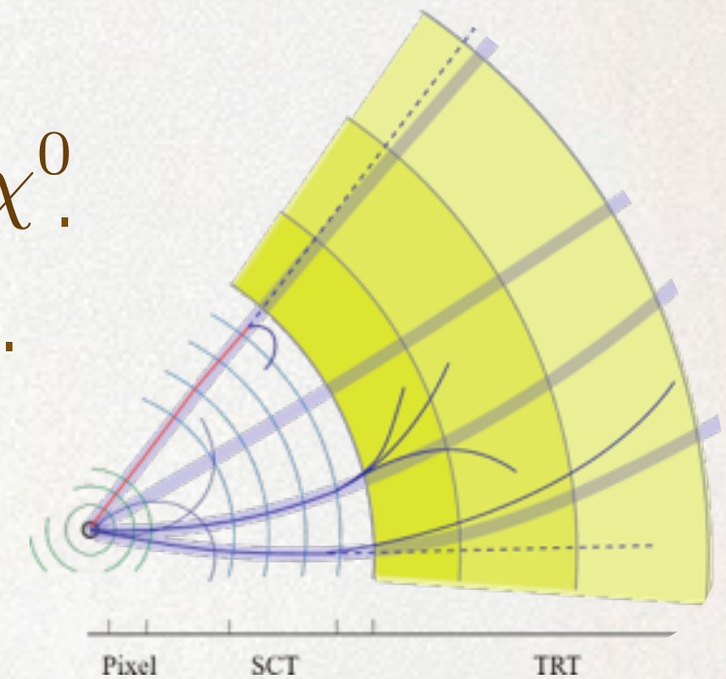
LHC:

Search for charged wino decay to $\pi^{\pm} + \chi^{0}$.

Lifetime just right to leave charged stub.

ATLAS limit: 280 GeV.

ATLAS Colloberation [arXiv:1310.3675]



Direct-Detection:

$$\sigma_{\rm SI}^{\rm wino} = 8^{+6+3}_{-3-3} \times 10^{-48} {\rm cm}^2$$

Hill and Solon [arXiv:1409.8290]

Just above the neutrino background?

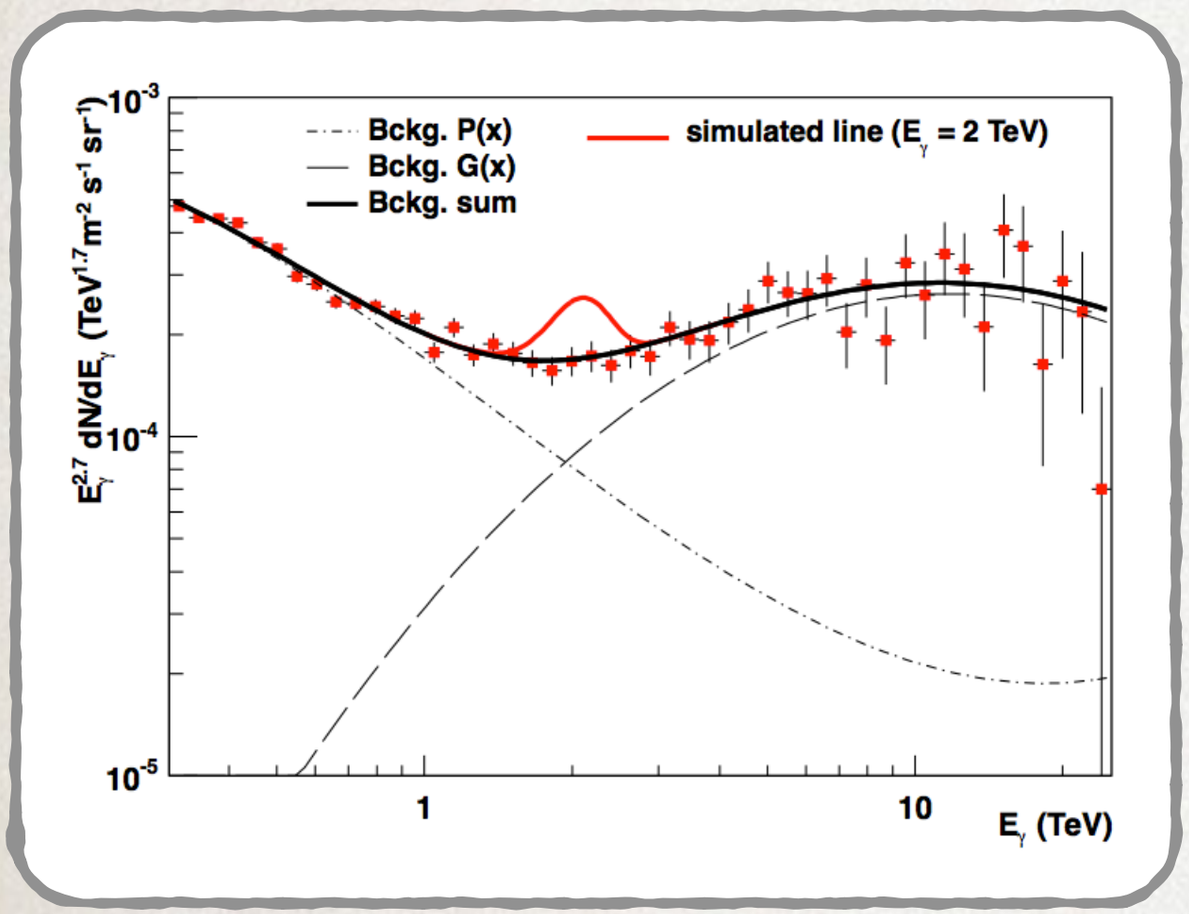
Indirect detection?

H.E.S.S.

Line search at the galactic center.

Extends to 20 TeV.

$$\chi\chi \to \gamma\gamma$$



H.E.S.S. Collaboration [arXiv:1301.1173]

(Sommerfeld enhanced) tree-level 3 TeV wino line cross section:

$$\sigma_{\rm line} \simeq 4 \times 10^{-26} {\rm cm}^3/s$$

H.E.S.S exclusion at 3 TeV:

$$\sigma_{\rm excluded} \simeq 3 \times 10^{-27} {\rm cm}^3/s$$

Thermal wino (naively) excluded by order of magnitude.

TC, Lisanti, Pierce, Slatyer [arXiv:1307.4082]; Fan and Reece [arXiv:1307.4400]

Uncertainties

Halo profile:

Many orders of uncertainty.

TC, Lisanti, Pierce, Slatyer [arXiv:1307.4082]

Improvements coming from observation and simulation.

Prediction for cross section:

Explicit 1-loop calculation yields

Note "log squared"

$$\log^2 \frac{2\, m_{\rm wino}}{m_W} \gg 1$$

Hryczuk and Iengo [arXiv:1111.2916]

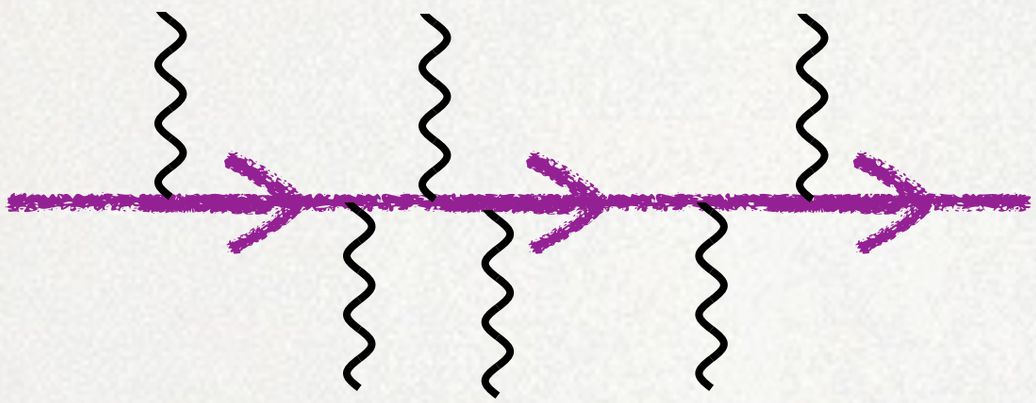
How to improve prediction for cross section?

Need EFT to "resum large logs"!

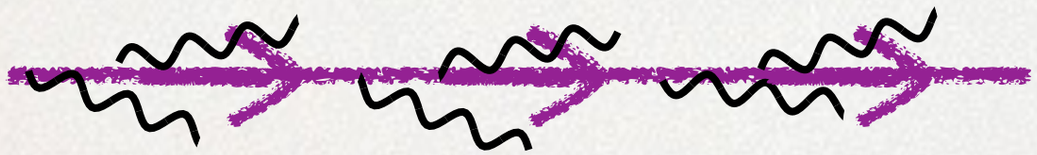
Soft Log x Collinear Log

Log due to IR divergences in gauge theory.

Infinite probability to radiate "zero energy" photon:
soft divergence ⇨ soft log.



Infinite probability to radiate aligned photon:
collinear divergence ⇨ collinear log.



Restricted Phase Space

IR divergences cancel in physical processes.

BUT

Restricted phase space $\Rightarrow$ logs become physical.

By choosing the process

$$\chi\,\chi \to \gamma\,\gamma$$

No additional soft or collinear photons emitted.

Effective restriction of phase space.

EFT for Annihilation

$\mu \sim 2M$ — Full relativistic field theory

Heavy particle EFT &
EW symmetric SCET

↓ SCET RGE

$\mu \sim m_W$ — Heavy particle EFT &
EW broken SCET

Quantum Mechanics

Split gauge boson:
soft modes
and
collinear modes

Integrate out all other degrees of freedom.

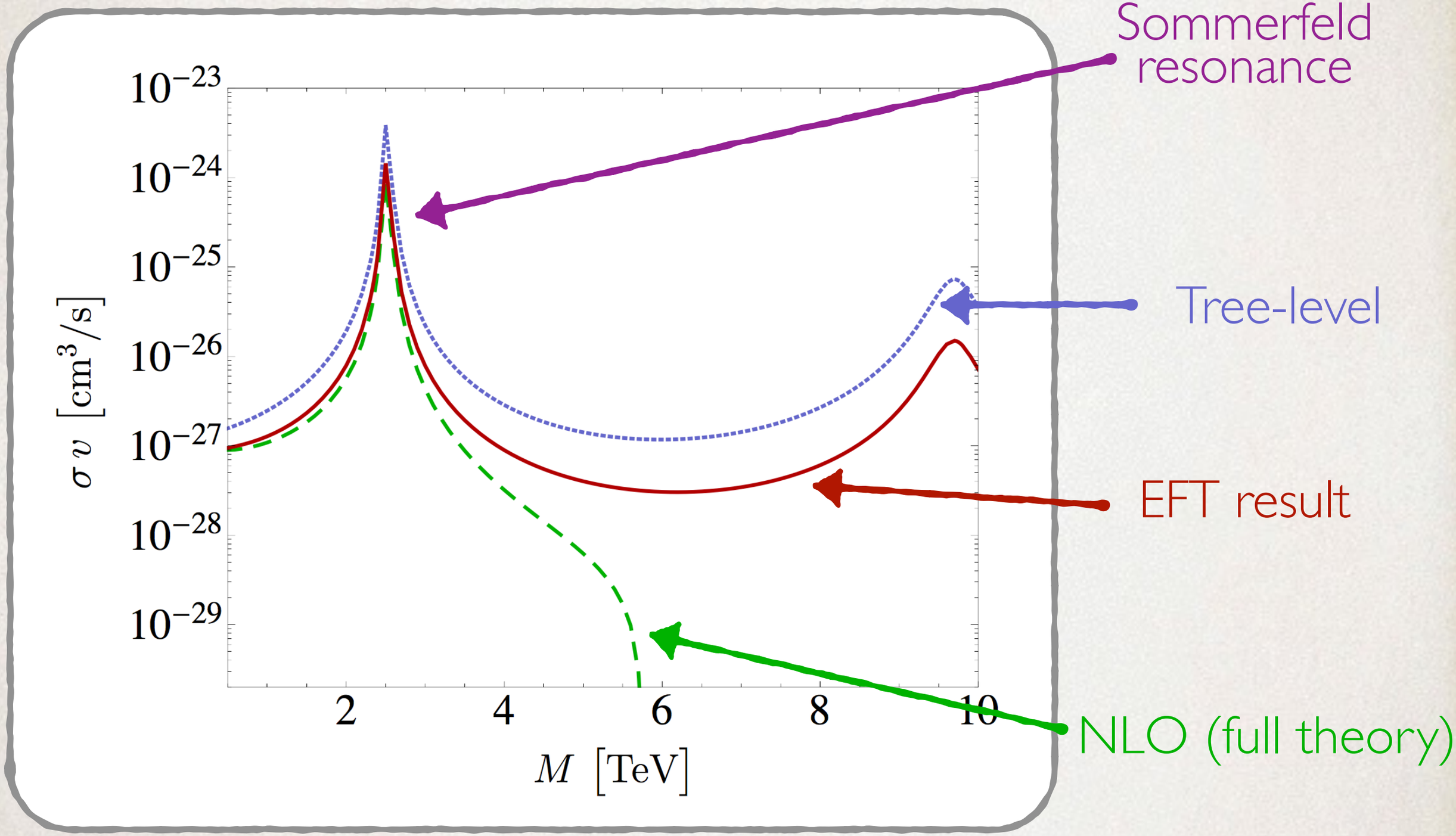
Can use renormalization group to resum large double logs.

Bauer, TC, Hill, Solon [arXiv:1409.7392]

$$\mathcal{O}_{\rm ann} \sim \underbrace{\chi\,\chi}_{\text{Non-relativistic Wino}}\,\underbrace{\mathcal{A}_\mu\,\mathcal{A}^\mu}_{\text{"Collinear" Photon}}$$

Bauer, Fleming, Luke [arXiv:hep-ph/0005275];
Bauer, Fleming, Pirjol, Stewart [arXiv:hep-ph/0011336]
,...

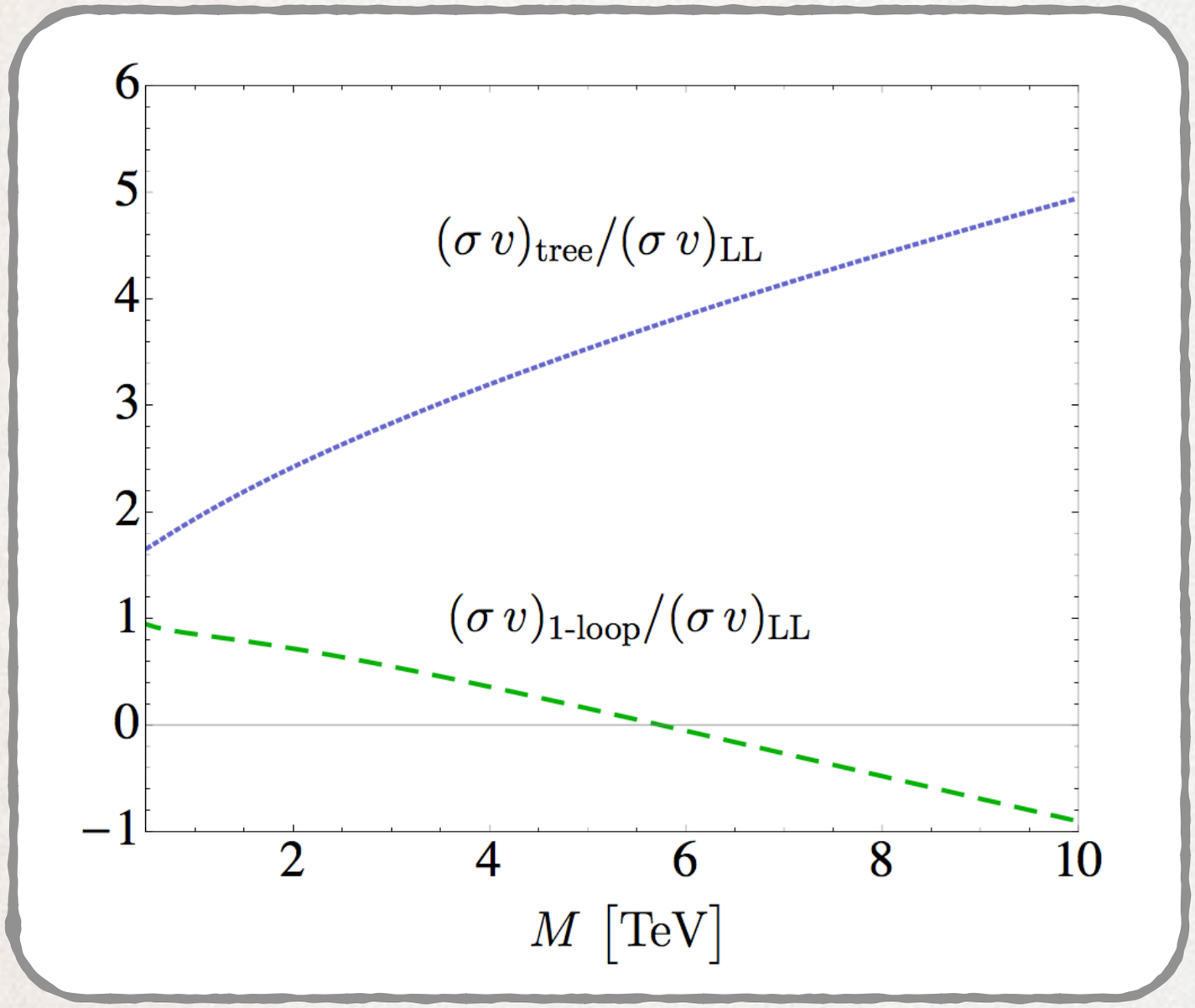
Robust Prediction



Bauer, TC, Hill, Solon [arXiv:1409.7392];
see also Ovanesyan, Slatyer, Stewart [arXiv:1409.8294], and
Baumgart, Rothstein, Vaidya [arXiv:1412.8698]

Impact of EFT Calculation

H.E.S.S. limits weakened by factor of ~ 3.



"LL" = leading log = EFT calculation.

Bauer, TC, Hill, Solon [arXiv:1409.7392];
see also Ovanesyan, Slatyer, Stewart [arXiv:1409.8294], and
Baumgart, Rothstein, Vaidya [arXiv:1412.8698]

Wrap-up

EFTs and WIMPs

Modern EFT techniques relevant for dark matter detection.

Tree-level: Contact operator.

Loop-level: (Possible) large logs and RGE improvement.

LHC searches

UV completion dependent.

Heavy WIMP Annihilation

Resumming large logs yields robust prediction for annihilation to line photons.

Factor of 3 less than tree prediction.