EFT Descriptions of Dark Matter


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Deducing the nature of dark matter from direct and indirect detection experiments in the absence of collider signatures of new physics
Beltran, Hooper, Kolb, Krusberg *Phys. Rev. D* **80,** 043509, (2009)

Maverick dark matter at colliders
Beltran, Hooper, Kolb, Krusberg, Tait *JHEP* 1009, 037 (2010)

Probing dark matter couplings to top and bottom at the LHC
Lin, Kolb, Wang *Phys. Rev. D* **88,** 063510 (2013)

Gamma-ray constraints on dark-matter annihilation to electroweak gauge and Higgs bosons
Fedderke, Kolb, Lin, Wang *JCAP* **01,** 001 (2014)

The Fermionic Dark Matter Higgs Portal: an effective field theory approach
Fedderke, Chen, Kolb, Wang JHEP to appear (2014)

Particle Dark Matter Bestiary

- sub-eV mass neutrinos (WIMPs exist!) (hot)
- sterile neutrinos, gravitini (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

} thermal relics or decay of or oscillation from thermal relics

- Bose-Einstein condensates
- axions, axion clusters
- solitons (Q-balls, B-balls, …)

} from phase transitions

- supermassive wimpzillas — from inflation

} nonthermal relics

Mass

10^{-22} eV (10^{-56} g) Bose-Einstein

$10^{-8} M_{\odot}$ (10^{+25} g) axion clusters

Interaction Strength

only gravitational: wimpzillas

strongly interacting: B balls

Fermi National Accelerator Laboratory

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May 1977

Cosmological Lower Bound on Heavy Neutrino Masses

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ABSTRACT

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29}g/cm^3, the lepton mass would have to be greater than a lower bound of the order of 2 GeV.

**On leave 1976-7 from Harvard University.

*Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

Ben Lee (1935 — June 1977)

Steve Weinberg

Physical Review Letters – 25 July 1977
Volume 39, Issue 4

LETTERS

Elementary Particles and Fields

- **Cosmological Lower Bound on Heavy-Neutrino Masses**
  Benjamin W. Lee and Steven Weinberg
  pp. 165-168 [**View** Page Images or PDF (569 kB)]

- **Cosmological Upper Bound on Heavy-Neutrino Lifetimes**
  Duane A. Dicus, Edward W. Kolb, and Vigdor L. Teplitz
  pp. 168-171 [**View** Page Images or PDF (642 kB)]

Heavy Neutrino?

GeV mass neutrinos

Motivated by an *incorrect* experimental result (high-y anomaly)

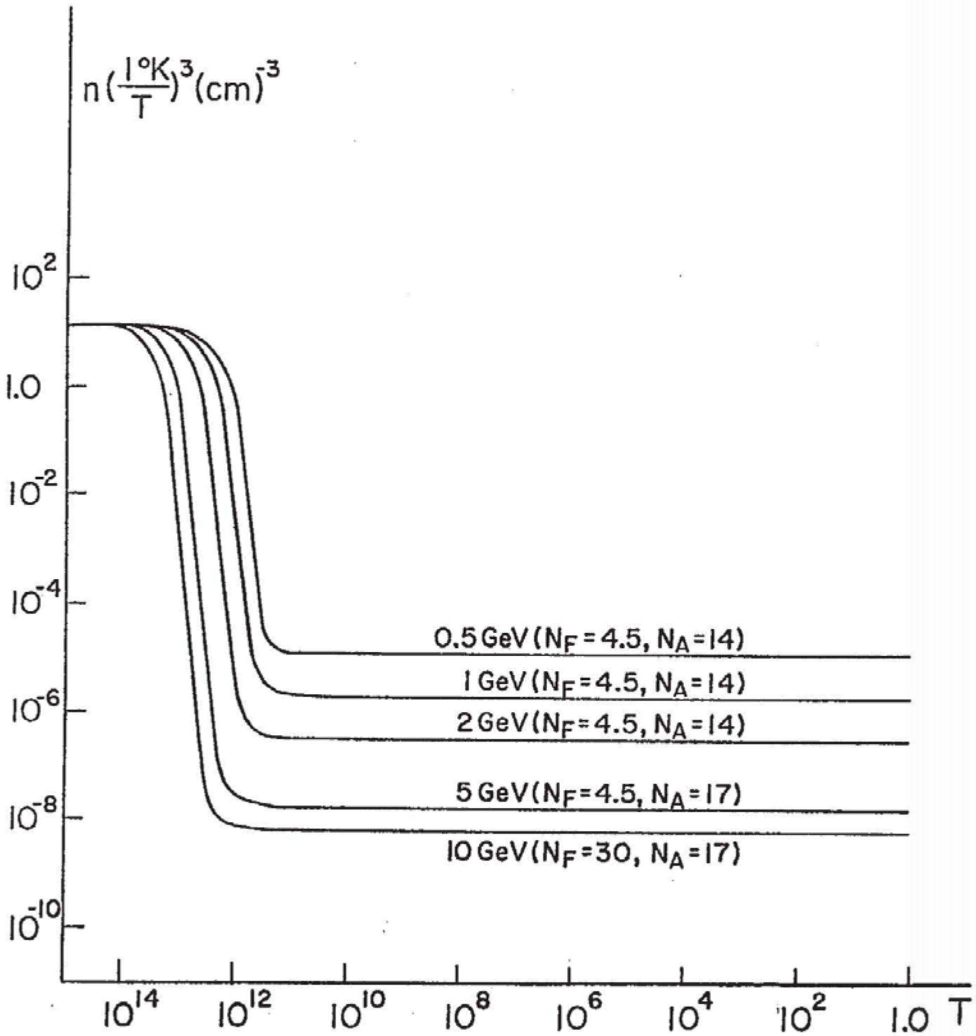


FIG. 1

$$\langle \sigma v \rangle = G_F^{\,2} m_L^{\,2} N_A / 2\pi$$

an effective field theory

Model ruled out by
- direct detection
- LEP ν counting

$$\frac{dn}{dt} = -\frac{3\dot{R}}{R}n - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_0^{\,2} . \qquad (2)$$

Here n is the actual number density of heavy neutrinos at time t; R is the cosmic scale factor; $\langle\sigma v\rangle$ is the average value of the $L^0\bar{L}^0$ annihilation cross-section times the relative velocity and n_0 is the number density of heavy neutrinos in thermal (and chemical) equilibrium[6]:

$$n_0(T) = \frac{2}{(2\pi)^3}\int_0^\infty 4\pi p^2 dp\left[\exp\left((m_L^{\,2}+p^2)^{\frac{1}{2}}/kT\right)+1\right]^{-1} . \qquad (3)$$

(We use units with $\hbar$=c=1 throughout.)

$$\frac{dn}{dt} = -\frac{3\dot{R}}{R}n - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_0^{\,2}$$

where ρ is the energy density

$$\rho = N_F a T^4 = N_F \pi^2 (kT)^4/15 \qquad (5)$$

with N_F an effective number of degrees of freedom, counting ½ and 7/16 respectively for each boson or fermion species and spin state. For temperatures in the range of 10-100 MeV (which most concern us here) we must include just $\gamma, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, e^-$, and e^+, so N_F = 4.5, a value we will adopt for most purposes. However, if current ideas about the strong interactions are correct, then N_F rises steeply at a temperature of order 500 MeV to a value[7] $N_F \approx 30$.

To estimate $\langle\sigma v\rangle$, we note that the heavy neutrinos must be quite non-relativistic at the temperature T_f where they freeze

$\langle \sigma v \rangle$ = NR annihilation cross section × Møller flux (thermal avg.)

$$\Omega h^2 \approx 0.11 \times \frac{10^{-36}\ \text{cm}^2}{\langle \sigma v \rangle}$$

$$10^{-36}\ \text{cm}^2 = \frac{\alpha^2}{(150\ \text{GeV})^2}$$

weak scale!

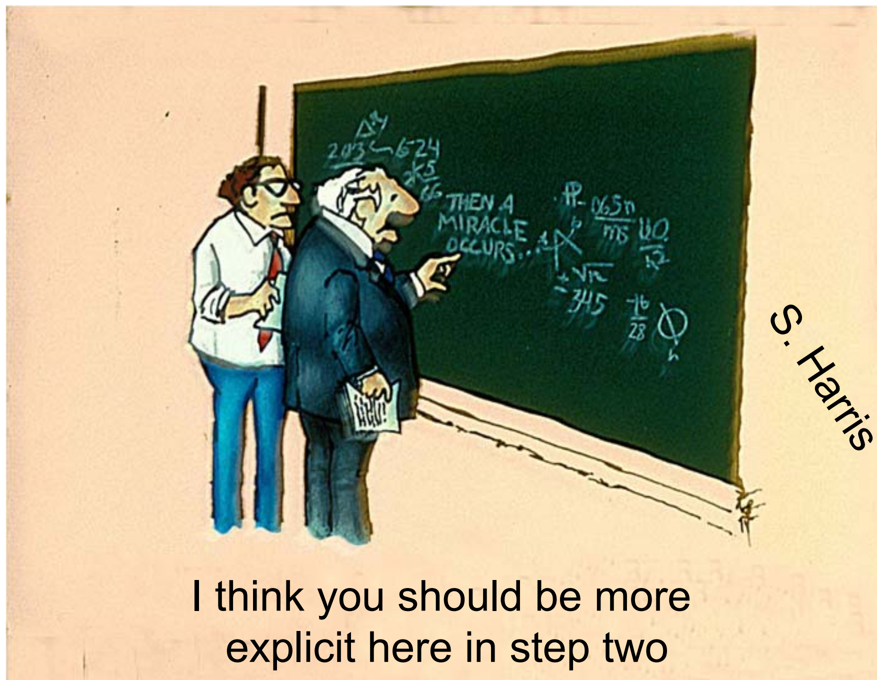
Not quite so clean:

- velocity dependence
- resonances
- co-annihilation
- log dependence on M
- decay production
- spin-dependence
- asymmetries
- …

Dark Matter Has "Weak-Scale" Interactions
Weakly-Interacting Massive Particle: WIMP

The WIMP “Miracle”

1 : an extraordinary
divine interventio



encyclopedia

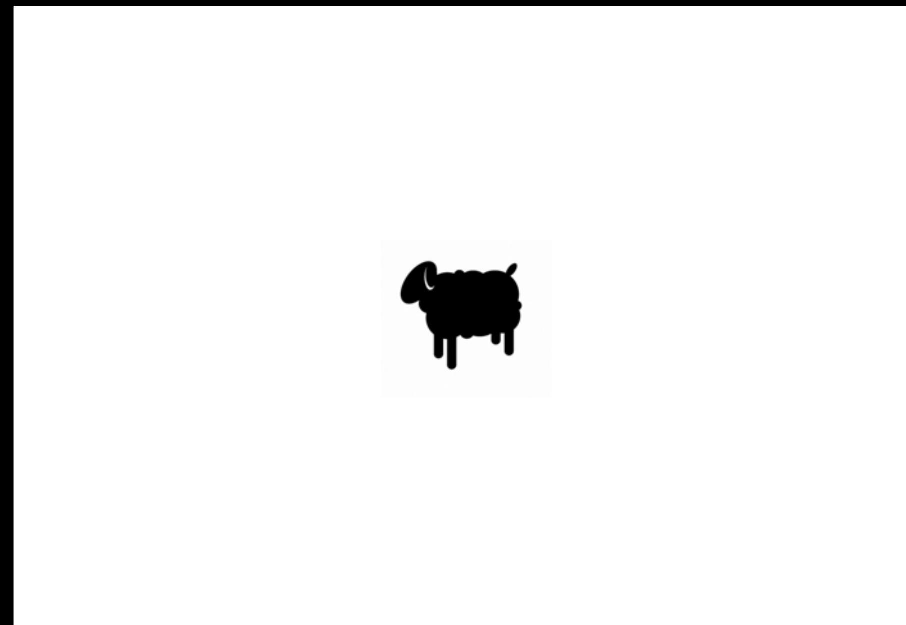
. often used to give an
npression of great and
nusual value in a trivial
ontext …

WIMPs: **BSM (but not far BSM)**
Interact with Standard Model particles (weakly)

WIMPs Couple to SM Particles

WIMPs: Social or Maverick Species?

Social WIMP

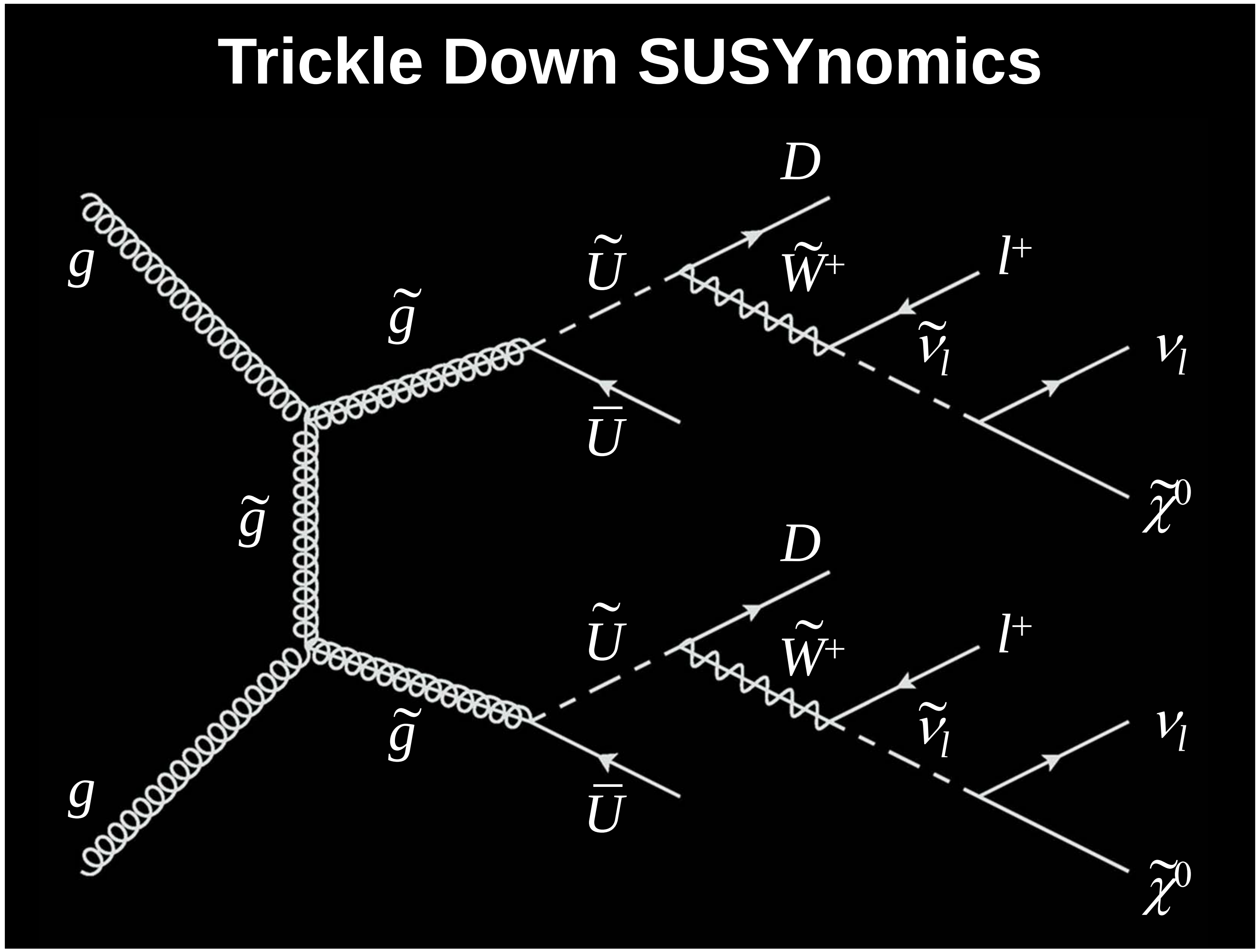


Maverick WIMP

Social WIMPs are part of a social network
Pals around with new un-WIMPy particles
Part of a larger theoretical framework
Top down
Generally UV complete
Find the WIMP by finding its friends
Example: SUSY

Maverick WIMPs have no social network
Not friended by any new particles
Larger theoretical framework unspecified
Bottom up
Not UV complete
Find the WIMP through what is not seen
Example: Neutrinos before late 1960s

SUSY WIMPs



Complicated decay chain—very model dependent

SUSY WIMPs

SUSY WIMPs (choose 105 SUSY parameters):

- Any limits very model dependent $\rightarrow$ pick a SUSY model
- Collider & direct detection limits:
  - CMSSM surviving on life support
  - MSSM running a high fever
  - Low-energy SUSY just called in sick
- As push SUSY scale high $\rightarrow$
  - cross section too small for correct relic abundance, unless ... resonant annihilation, co-annihilation, etc.

Maverick WIMPs

- Assume WIMP the only non-SM particle with weak-scale mass
- Other particles are heavy compared to weak scale
- Integrate out heavy particles and form an *Effective Field Theory*

Example: low-energy ($E \ll m_Z$) neutrino physics

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \bar{\nu}\gamma^{\mu}(1-\gamma_5)\nu \cdot \bar{q}\gamma_{\mu}\left(g_V^q - g_A^q\gamma_5\right)q$$

- Assume $\mathcal{L} = M_*^{-n} \; J_{\mathrm{DM}} \cdot J_{\mathrm{SM}}$ $\quad J_{\mathrm{DM}}$ and J_{SM} are SM singlets
- J_{DM} contains scalars ϕ or fermions χ

Examples: $J_{\mathrm{DM}} = \phi^{\dagger}\partial^{\mu}\phi + h.c.$ or $J_{\mathrm{DM}} = \bar{\chi}\gamma^{\mu}\chi$

- J_{SM} contains SM fermions or electroweak gauge/Higgs bosons

Examples: $J_{\mathrm{SM}} = \bar{q}\gamma_{\mu}q$ or $J_{\mathrm{SM}} = B_{\lambda\mu}Y_H H^{\dagger}D^{\lambda}H + h.c.$

Maverick WIMPs

Assumptions:

1. Dark matter is a cold thermal relic (WIMP)
2. Only one WIMP
3. Only one relevant operator dominates DM—SM couplings
4. WIMP is a SM singlet
5. DM sector does not participate in EWSB*
6. Relic density $\Omega h^2 = 0.11$ or 0.12
7. No post-freeze-out entropy release
8. No Super-WIMPs
9. No co-annihilation, resonances, or other chicanery
10. 2DM $\rightarrow$ 2SM annihilation only
11. WIMP is either a
    complex scalar, or
    self-conjugate or non-self-conjugate fermion

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* For the opposite approach, see Cotta et al. 1210.0525

Maverick WIMPs Coupling to Quarks

Maverick WIMPs Coupling to Quarks

Dirac fermion Maverick WIMP, χ

$$\mathcal{L} = \sum_q \frac{1}{M_*^2} \left[\overline{\chi}\, \Gamma_i\, \chi \right] \cdot \left[\overline{q}\, \Gamma_j\, q \right]$$

$$\Gamma_{i,j} = \left\{ 1, \gamma^5, \gamma^\mu, \gamma^{\mu 5}, \gamma^{\mu\nu} \right\}$$

Expect Yukawa-like (S,P) couplings $\propto m_q$ (MFV)

Some terms vanish for Majorana χ

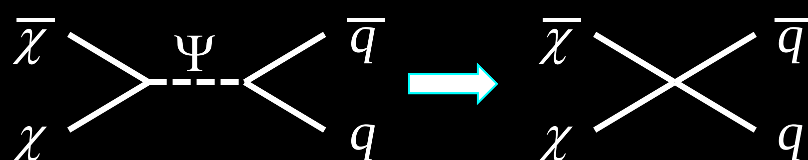
Complex scalar Maverick WIMP, ϕ

$$\mathcal{L} = \sum_q \frac{1}{M_*^n} \begin{bmatrix} \phi^\dagger \phi \\ \phi^\dagger \partial^\mu \phi + h.c. \\ i\left(\phi^\dagger \partial^\mu \phi - h.c. \right) \end{bmatrix} \cdot \left[\overline{q}\, \Gamma_j\, q \right]$$

Maverick WIMPs Coupling to Quarks

	operator	annih.	direct detec.
Scalar WIMPs	$\phi^\dagger \phi \; \bar{q} q$	1	SI
	$\phi^\dagger \phi \; \bar{q}\gamma^5 q$	1	v^2
	$(\phi^\dagger \partial^\mu \phi + h.c.) \; \bar{q}\gamma_\mu q$	0	SI
	$(\phi^\dagger \partial^\mu \phi + h.c.) \; \bar{q}\gamma_{\mu 5} q$	m_q^2/M^2	SD
	$i(\phi^\dagger \partial^\mu \phi - h.c.) \; \bar{q}\gamma_\mu q$	v^2	SI
	$i(\phi^\dagger \partial^\mu \phi - h.c.) \; \bar{q}\gamma_{\mu 5} q$	v^2	SD
Fermion WIMPs	$\bar{\chi}\chi \; \bar{q} q$	v^2	SI
	$\bar{\chi}\chi \; \bar{q}\gamma^5 q$	v^2	v^2
	$\bar{\chi}\gamma^5\chi \; \bar{q} q$	1	SI
	$\bar{\chi}\gamma^5\chi \; \bar{q}\gamma^5 q$	1	v^2
	~~$\bar{\chi}\gamma^\mu\chi \; \bar{q}\gamma_\mu q$~~	~~1~~	~~SI~~
	$\bar{\chi}\gamma^{\mu 5}\chi \; \bar{q}\gamma_\mu q$	v^2	SI
	~~$\bar{\chi}\gamma^\mu\chi \; \bar{q}\gamma_{\mu 5} q$~~	~~1~~	~~SD~~
	$\bar{\chi}\gamma^{\mu 5}\chi \; \bar{q}\gamma_{\mu 5} q$	$v^2, m_q^2/M^2$	SD
	~~$\bar{\chi}\gamma^{\mu\nu}\chi \; \bar{q}\gamma_{\mu\nu} q$~~	~~1~~	~~SD~~

- Possible WIMP—gluon couplings
- Some terms vanish for Majorana fermions
- Possible "light" mediators (not a true Maverick)
- Range where effective field theory valid

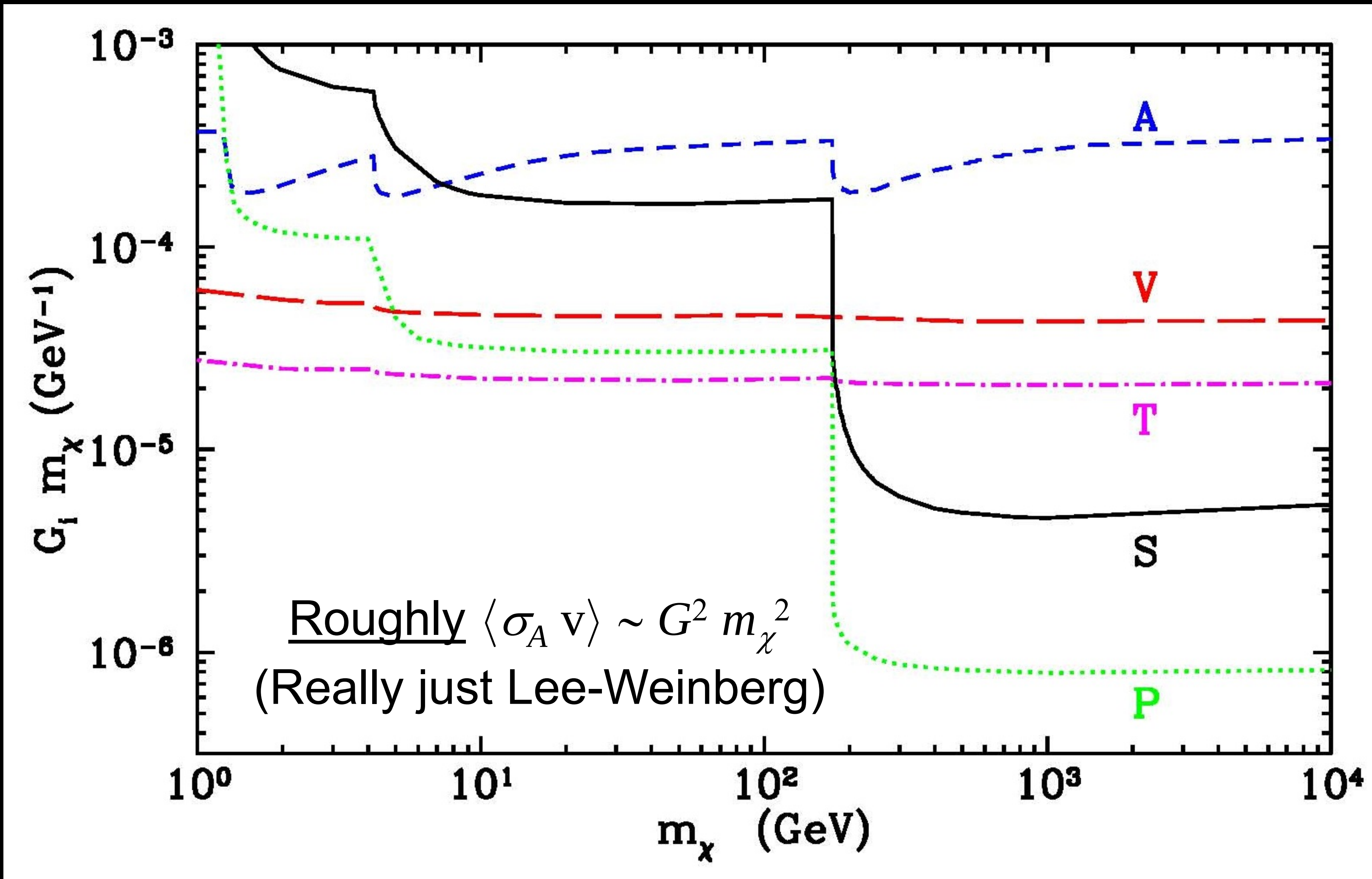


$$\frac{g_\chi g_q}{p^2 - M_\Psi^2} \rightarrow \frac{G}{\sqrt{2}}$$

- Could also include couplings to leptons

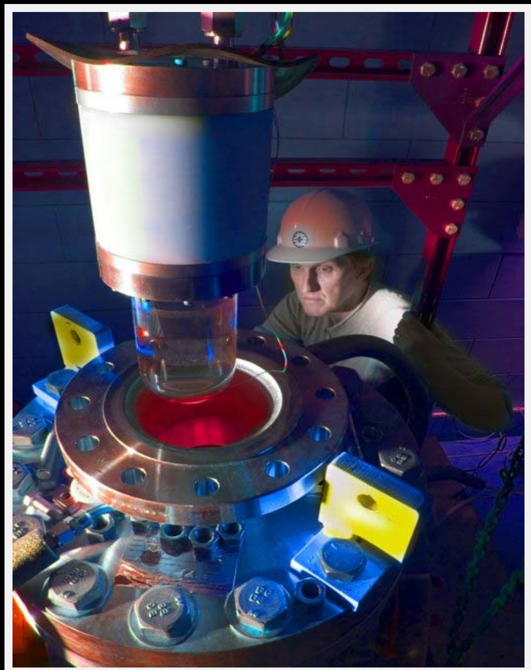
Maverick WIMPs

Values of G to give correct dark matter density

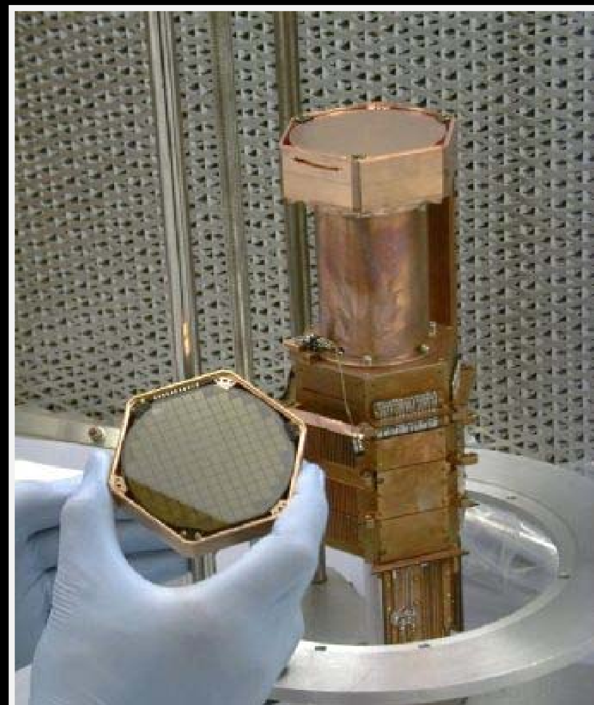


Direct Detection

COUPP



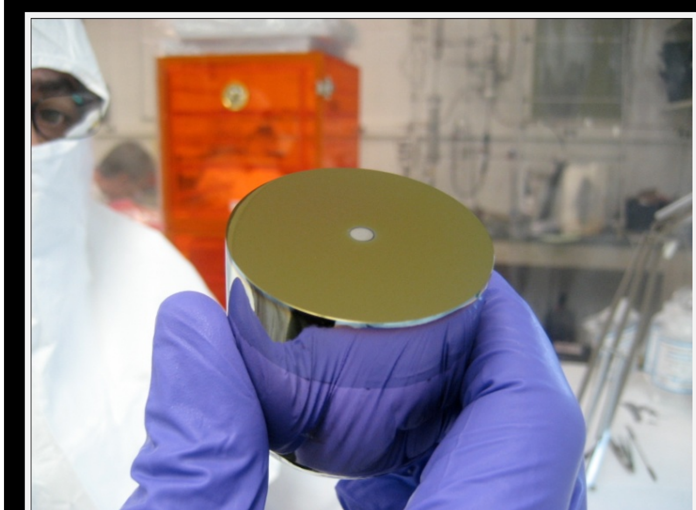
CDMS



CRESST

Xenon

CoGeNT



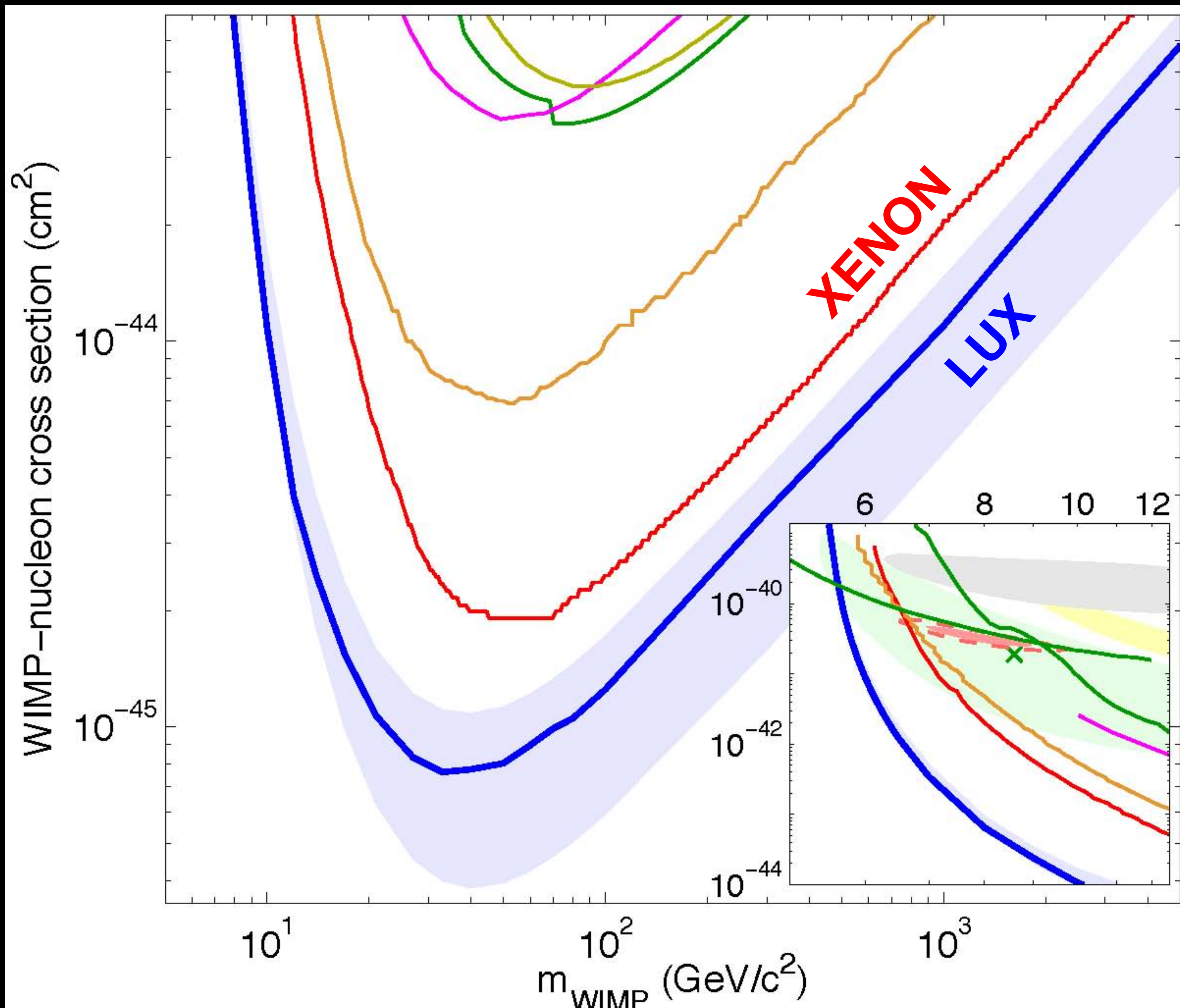
(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, LUX, ARDM, ANAIS, CDEX PandaX, DarkSide, DAMA/LIBRA …)

Direct Detection

Direct Detection Low-Velocity Limits:

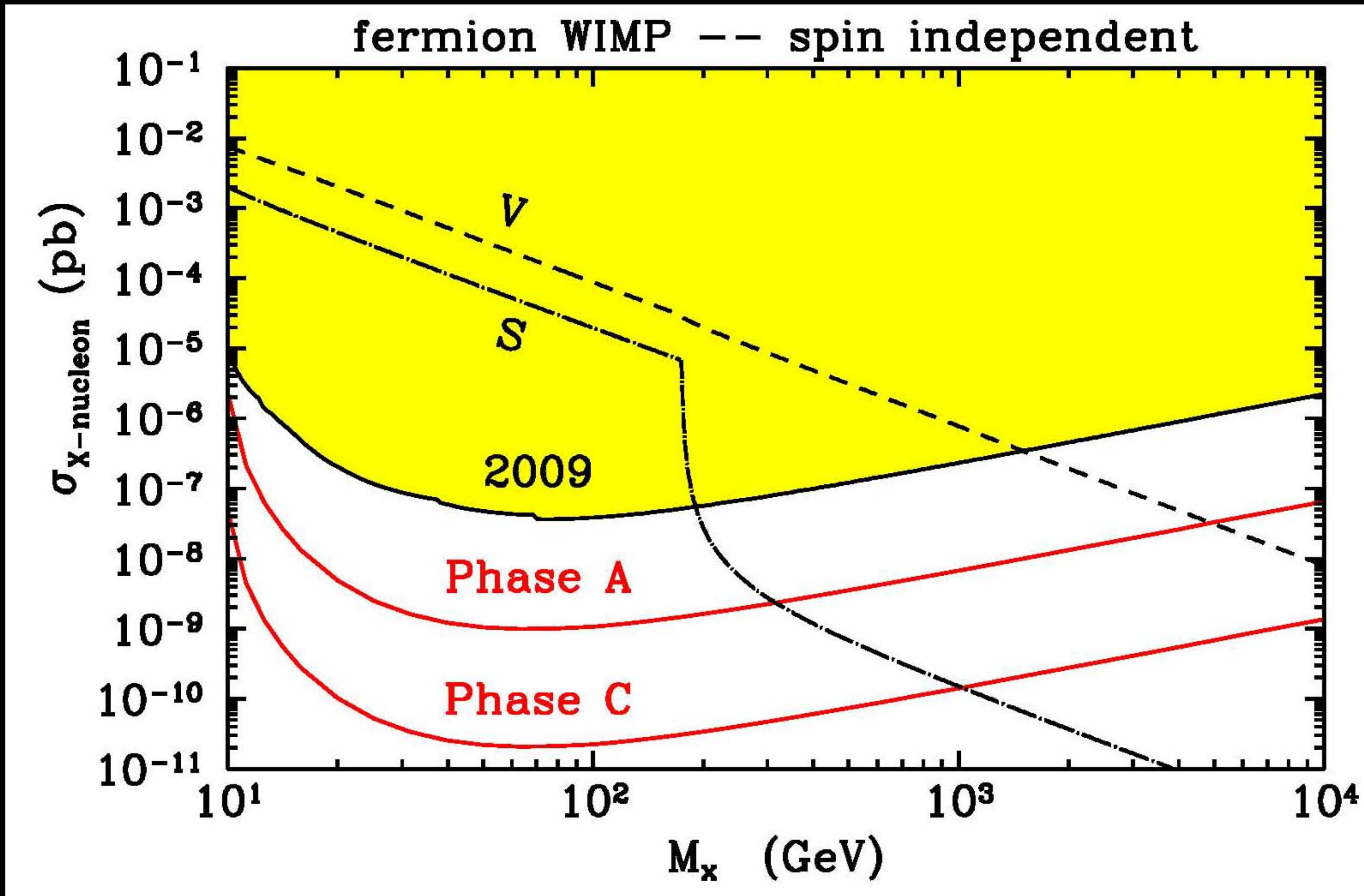
1. Spin-independent (coherent) scattering: $\sigma \propto A^2$
2. Spin-dependent (incoherent) scattering: $\sigma \propto J$
3. Velocity-dependent scattering $\sigma \propto \mathrm{v}^2$

LUX (arXiv:1310.8214)



Direct Detection

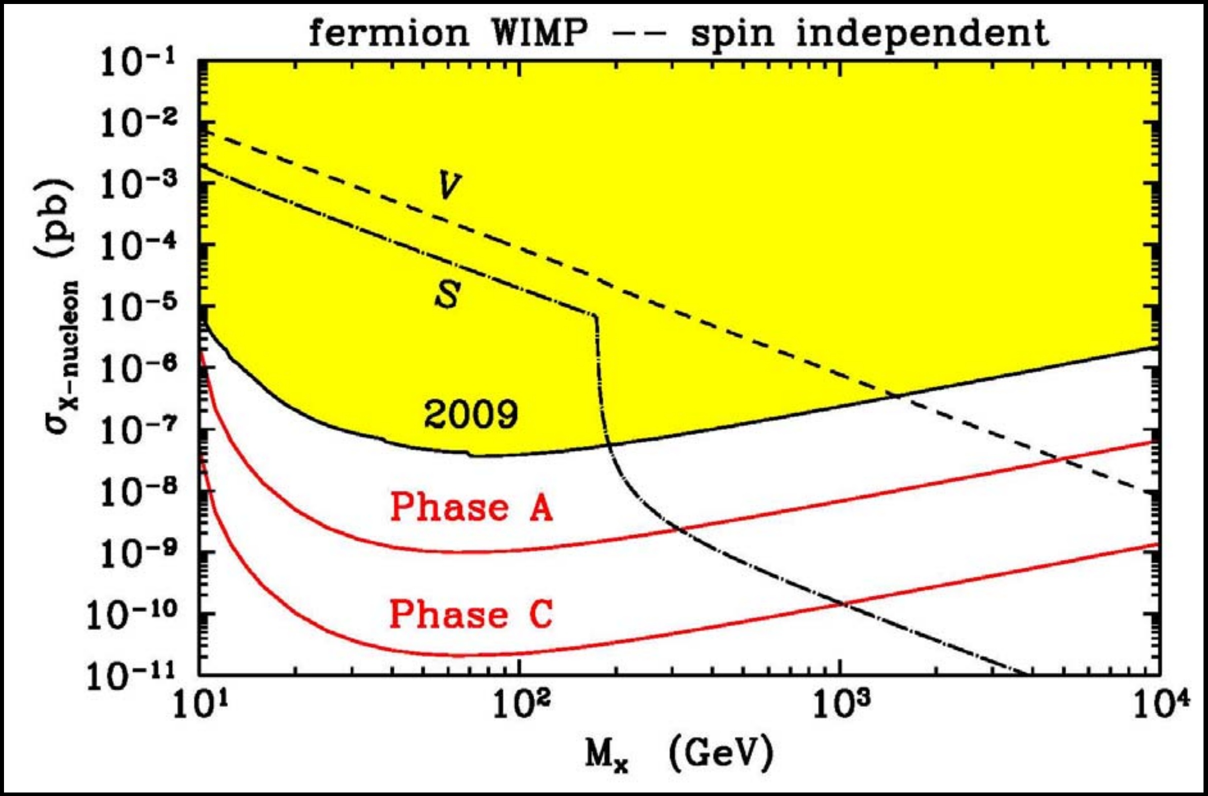
spin-independent



For $m \geq 10$ GeV or so $\sigma \leq 10^{-9}$ pb

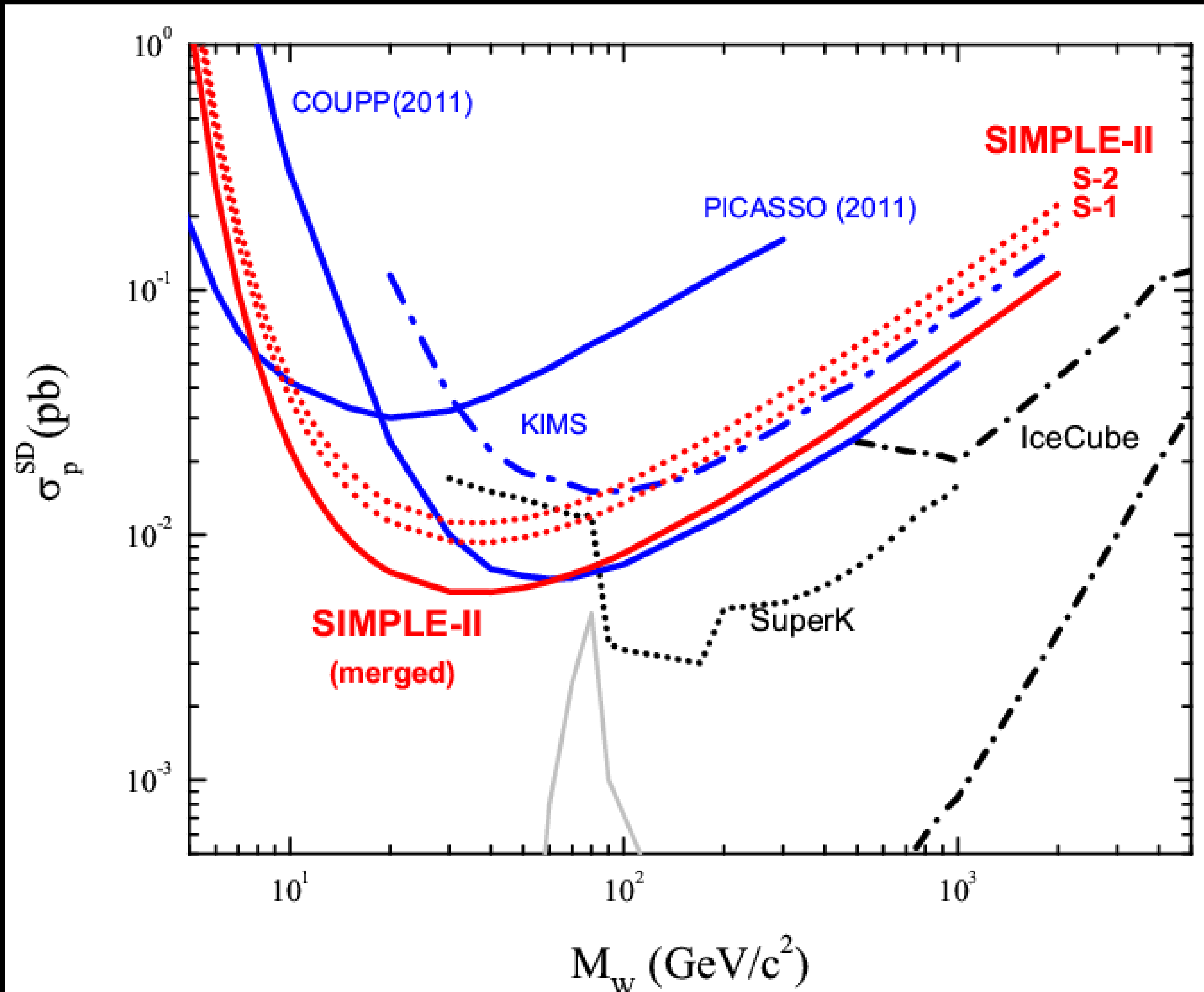
Around a few GeV $\sigma \leq 10^{-6}$ pb

Direct Detection



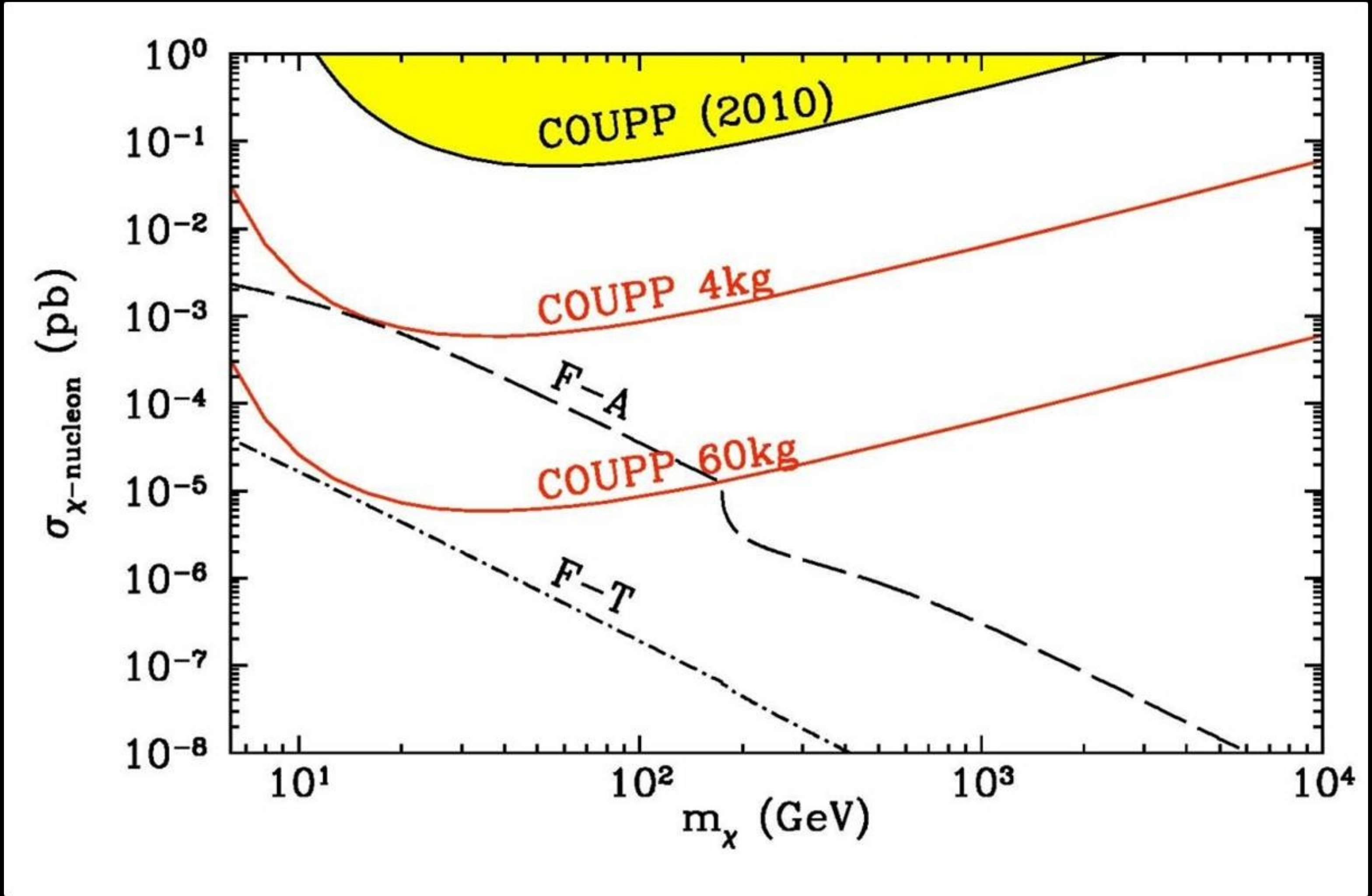
- Coupling $\propto m_q$ is very important effect
- Including couplinsg to leptons is subdominant effect
- Usual Super-WIMP trick not in Maverick spirit

SIMPLE (PRL 2012 arXiv:1106.3014)



Direct Detection

spin-dependent



σ can be as large as 10^{-3} pb to 10^{-6} pb

Direct Detection

Maverick WIMPs (for given M, choose $\Lambda \rightarrow$ relic abundance):

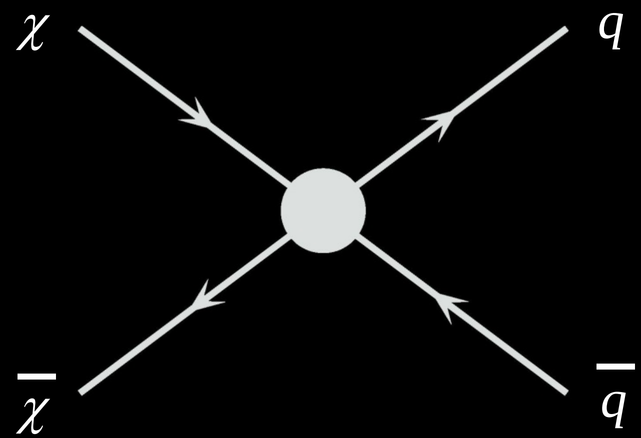
Vector couplings excluded in range $10\ \mathrm{GeV}$ to $2000\ \mathrm{GeV}$

Scalar couplings excluded in range $10\ \mathrm{GeV}$ to $200\ \mathrm{GeV}$

Axial & Tensor couplings spin-dependent weak or no limits

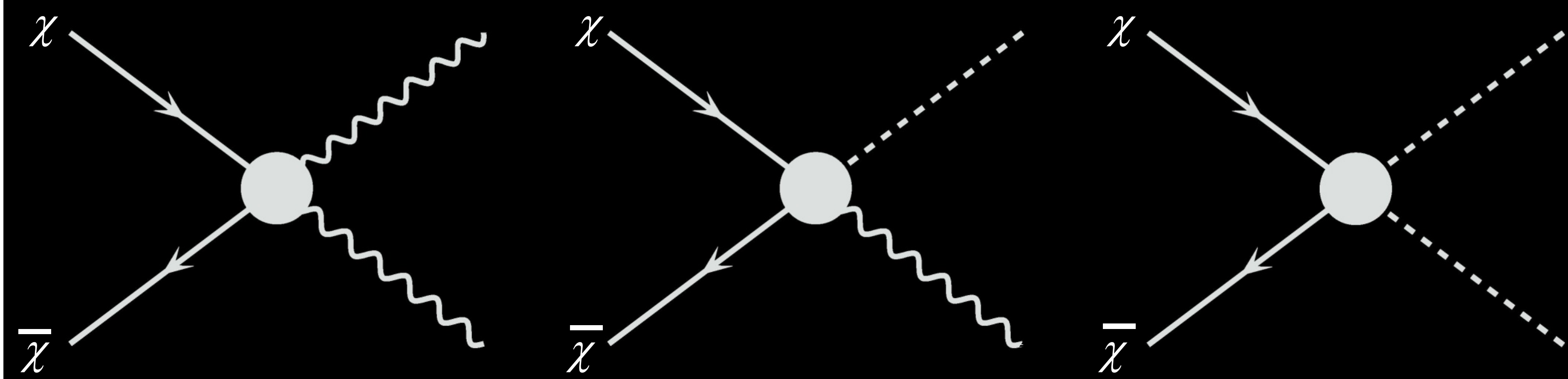
Pseudoscalar couplings velocity suppressed $\rightarrow$ no limits

Maverick WIMPs Coupling to EWK Gauge and Higgs Bosons



Well-studied
Direct detection limits

Why not…



$= \gamma, W^{\pm}, Z$ $= h$

Maverick WIMPs Coupling to EWK Gauge and Higgs Bosons

J_{SM} is a SM neutral combination of $B_{\mu\nu}$, $W^a{}_{\mu\nu}$, and H

UV-complete models on the market: e.g., Jackson et al. 2010

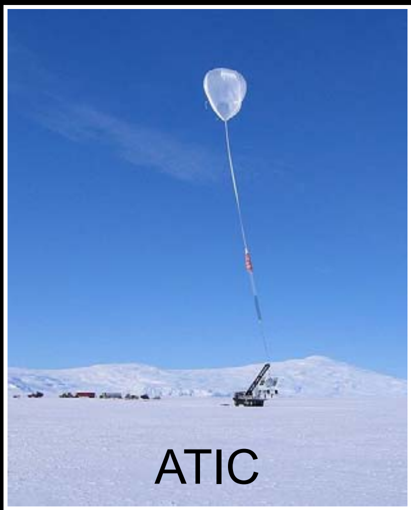
Use indirect detection, esp. for γ lines

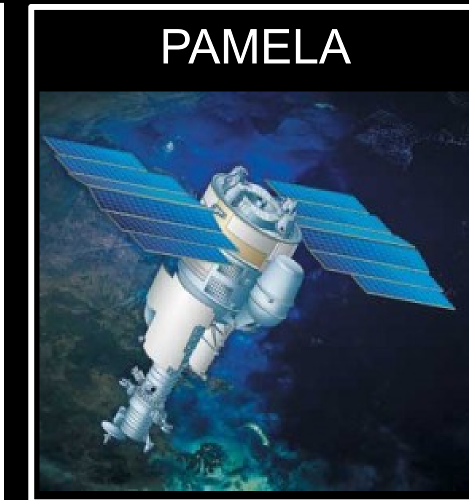
EDM operators must be suppressed (CP violation limits)

Direct detection relevant only for electric or magnetic dipole operators, Banks et al, 1007.5515

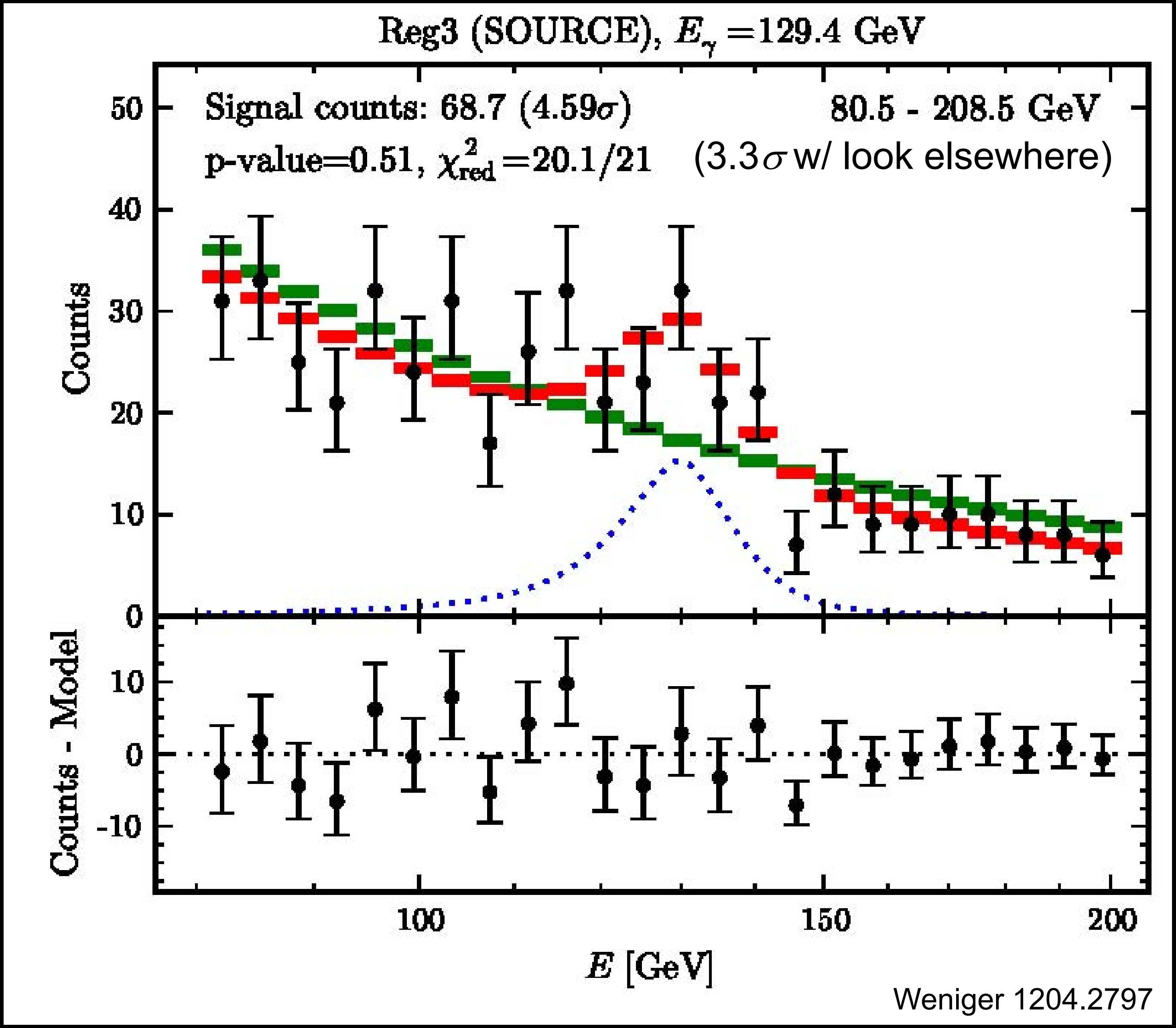
(Collider limits to come)

Indirect Detection



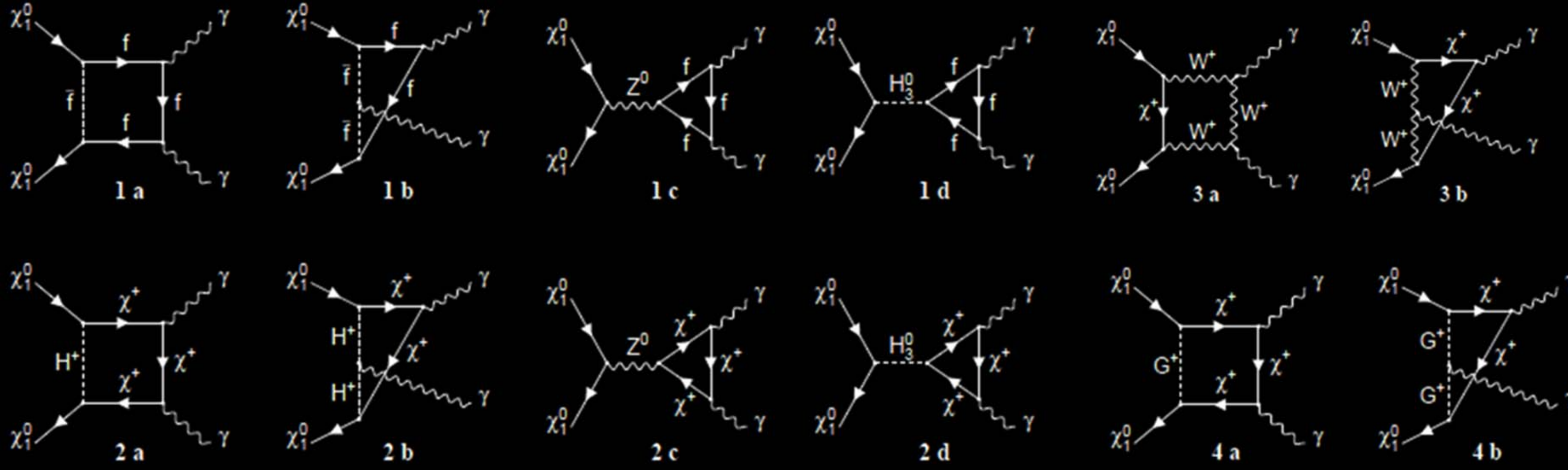


Fermi/GLAST Line



Fermi/GLAST Line(s)

- WIMP−charged particle coupling $\rightarrow$ annihilates to $\gamma\gamma + \gamma Z + ZZ + ...$).



Bergstrom & Ullio 97

- But also annihilates at tree-level to W's and Z's, e^+e^-, quarks, …, producing "continuum" γ-ray background. Loop smaller than tree by $\mathcal{O}(\alpha^2/4\pi)$.
- Inner bremsstrahlung also produces γ's, only suppressed $\mathcal{O}(\alpha)$.
- Continuum constrained by observations, BR($\gamma\gamma$) must be $\mathcal{O}(1)$.
- Models with no tree-level annihilation: *e.g.,* Jackson *et al*. 0912.0004

DM Couples to EWK Gauge & Higgs

Chen, Kolb, Wang

- Most analyses assume WIMPs couple to fermions, untenable if see γ lines
- Effective Field Theory analysis of gauge/Higgs di-boson couplings
- Assume $\mathcal{L}_{\text{EFT}} = J_{\text{DM}} \cdot J_{\text{SM}}$ and each J is an $\text{SU}_3 \times \text{SU}_2 \times \text{U}_1$ singlet
- 50 possible dimension-6, 7, & 8 operators. 34 operators survive $\text{v} \to 0$ limit.
- Different final states (energy spectrum of γ-ray lines) and continuum

DM Couples to EWK Gauge & Higgs

Chen, Kolb, Wang

SCALAR

$$\left.\begin{array}{r}\phi^\dagger\phi \\ \bar\chi\chi \\ \bar\chi i\gamma^5\chi\end{array}\right\}\times\begin{cases} H^\dagger H & \text{with final state } hh \\ B_{\mu\nu}\,B^{\mu\nu} & \text{with final states } \gamma\gamma,\,\gamma Z,\,ZZ \\ B_{\mu\nu}\,\widetilde{B}^{\mu\nu} & \text{with final states } \gamma\gamma,\,\gamma Z,\,ZZ \\ W^a_{\mu\nu}\,W^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\,\gamma Z,\,ZZ,\,W^+W^- \\ W^a_{\mu\nu}\,\widetilde{W}^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\,\gamma Z,\,ZZ,\,W^+W^- \end{cases}$$

TENSOR

$$\bar\chi\gamma^{\mu\nu}\chi\times\begin{cases} B_{\mu\nu} & \text{with final states } Zh,\,W^+W^-,\,f\bar f \\ \widetilde{B}_{\mu\nu} & \text{with final states } Zh,\,W^+W^-,\,f\bar f \\ B_{\mu\nu}Y_H\,H^\dagger H & \text{with final states } \gamma h,\,Zh,\,W^+W^-,\,f\bar f \\ \widetilde{B}_{\mu\nu}Y_H\,H^\dagger H & \text{with final states } \gamma h,\,Zh,\,W^+W^-,\,f\bar f \\ W^a_{\mu\nu}H^\dagger t^a H & \text{with final states } \gamma h,\,Zh,\,W^+W^-,\,f\bar f \\ \widetilde{W}^a_{\mu\nu}H^\dagger t^a H & \text{with final states } \gamma h,\,Zh,\,W^+W^-,\,f\bar f \end{cases}$$

DM Couples to EWK Gauge & Higgs

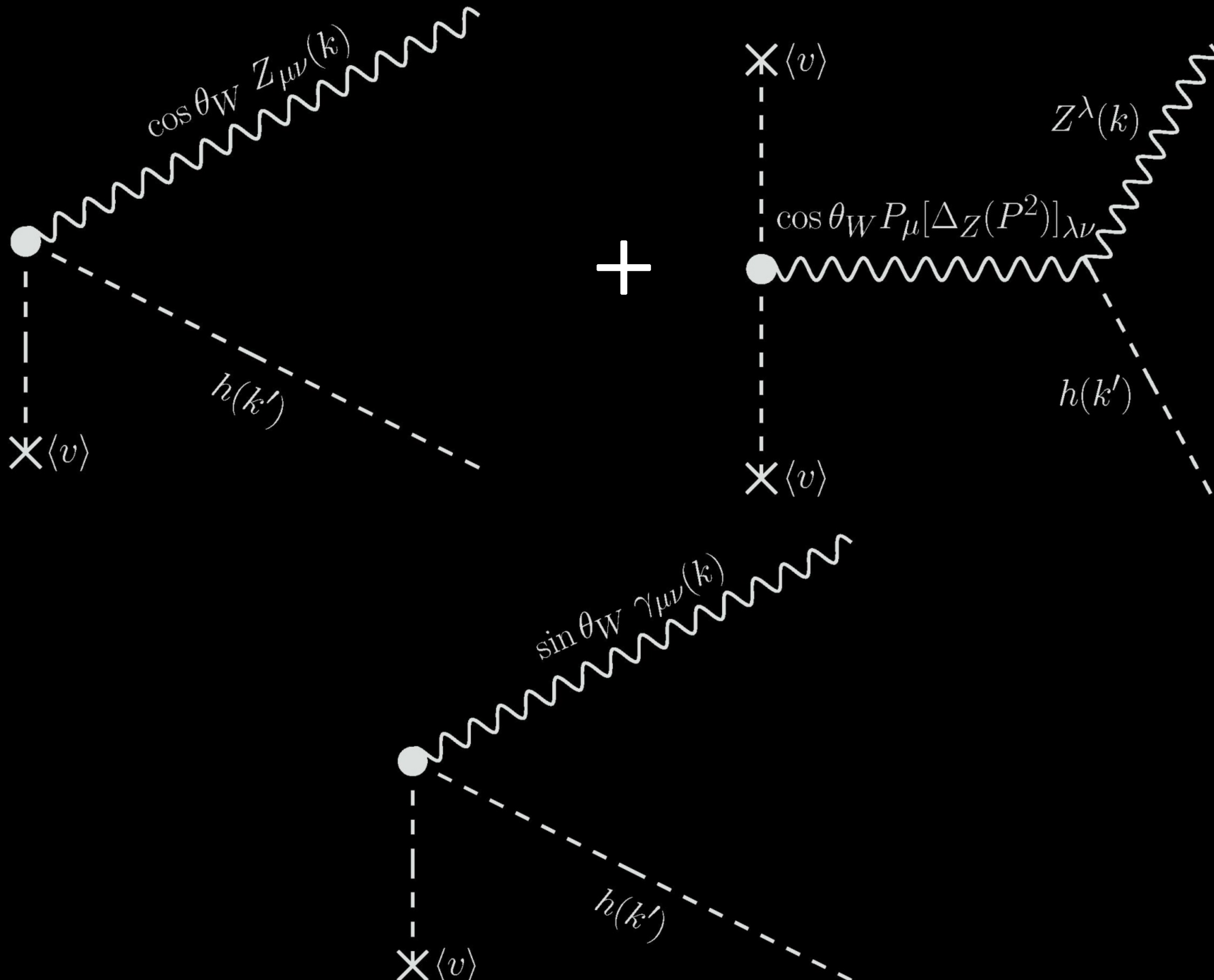
Chen, Kolb, Wang

VECTOR

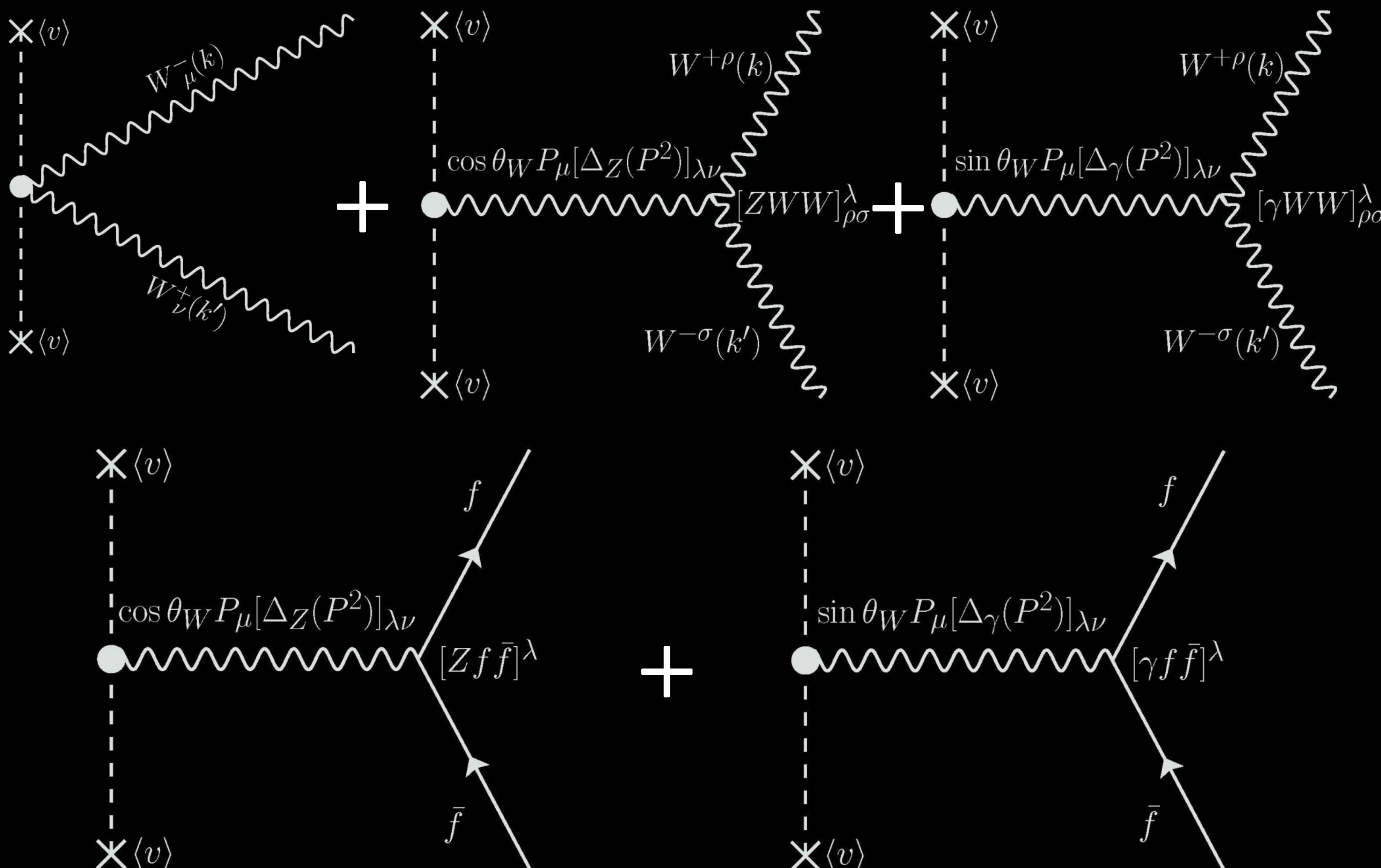
$$(\phi^\dagger\partial^\mu\phi + h.c.) \times \begin{cases} \left(B_{\lambda\mu}Y_H\, H^\dagger D^\lambda H + h.c.\right) & \text{with final state } Zh \\ \left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) & \text{with final state } Zh \\ i\left(B_{\lambda\mu}Y_H\, H^\dagger D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ \\ i\left(\widetilde{B}_{\lambda\mu}Y_H\, H^\dagger D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ \\ i\left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ,\, W^+W^- \\ i\left(\widetilde{W}^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ,\, W^+W^- \end{cases}$$

$$\left.\begin{matrix} i\left(\phi^\dagger\partial^\mu\phi - h.c.\right) \\ \bar{\chi}\gamma^\mu\chi \\ \bar{\chi}\gamma^{\mu 5}\chi \end{matrix}\right\} \times \begin{cases} \left(B_{\lambda\mu}Y_H\, H^\dagger D^\lambda H + h.c.\right) & \text{with final states } \gamma h,\, Zh \\ \left(\widetilde{B}_{\lambda\mu}Y_H\, H^\dagger D^\lambda H + h.c.\right) & \text{with final states } \gamma h,\, Zh \\ i\left(B_{\lambda\mu}Y_H\, H^\dagger D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ \\ i\left(\widetilde{B}_{\lambda\mu}Y_H\, H^\dagger D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ \\ \left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) & \text{with final states } \gamma h,\, Zh,\, W^+W^- \\ \left(\widetilde{W}^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) & \text{with final states } \gamma h,\, Zh,\, W^+W^- \\ i\left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ,\, W^+W^- \\ i\left(\widetilde{W}^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) & \text{with final states } \gamma Z,\, ZZ,\, W^+W^- \end{cases}$$

$$W^a_{\mu\nu}\ H^\dagger\, t^a\, H$$



$$W^a_{\mu\nu}\ H^\dagger t^a H$$



DM Couples to EWK Gauge & Higgs

Chen, Kolb, Wang

For a given operator

1. Possible final states determined by *gauge structure*
2. Branching ratios determined by *gauge structure*
3. Unknown parameters for given operator are M and Λ
4. For a given M, Λ determined to give correct relic density

DM Couples to EWK Gauge & Higgs

Chen, Kolb, Wang

- Assume operator leads to 130 GeV line
- Λ from dark matter density constraint
- σ v in units of $10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

Operators	If 130GeV line from $\gamma\gamma$ final state	If 130GeV line from γZ final state
$\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ B_{\mu\nu}B^{\mu\nu}$ $\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ B_{\mu\nu}\widetilde{B}^{\mu\nu}$	15	6
$\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ W^a_{\mu\nu}W^{a\ \mu\nu}$ $\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ W^a_{\mu\nu}\widetilde{W}^{a\ \mu\nu}$	0.7-0.8	3-4
comments	$M = 130\mathrm{GeV}$ extra line at 114GeV due to γZ final state	$M = 144\mathrm{GeV}$ extra line at 144GeV due to $\gamma\gamma$ final state

$$\gamma Z : \gamma\gamma \quad 0.4\ \ B_{\mu\nu}B^{\mu\nu} \qquad 4.5\ \ W^{a\mu\nu}W^{a}{}_{\mu\nu}$$

DM Couples to EWK Gauge & Higgs

Fedderke, Kolb, Lin, Wang

Photon Flux

$$\frac{d\Phi}{dE\,d\Omega} = \frac{\langle \sigma \mathrm{v} \rangle}{16\pi M^2} \times J(\theta) \times \frac{dN}{dE}$$

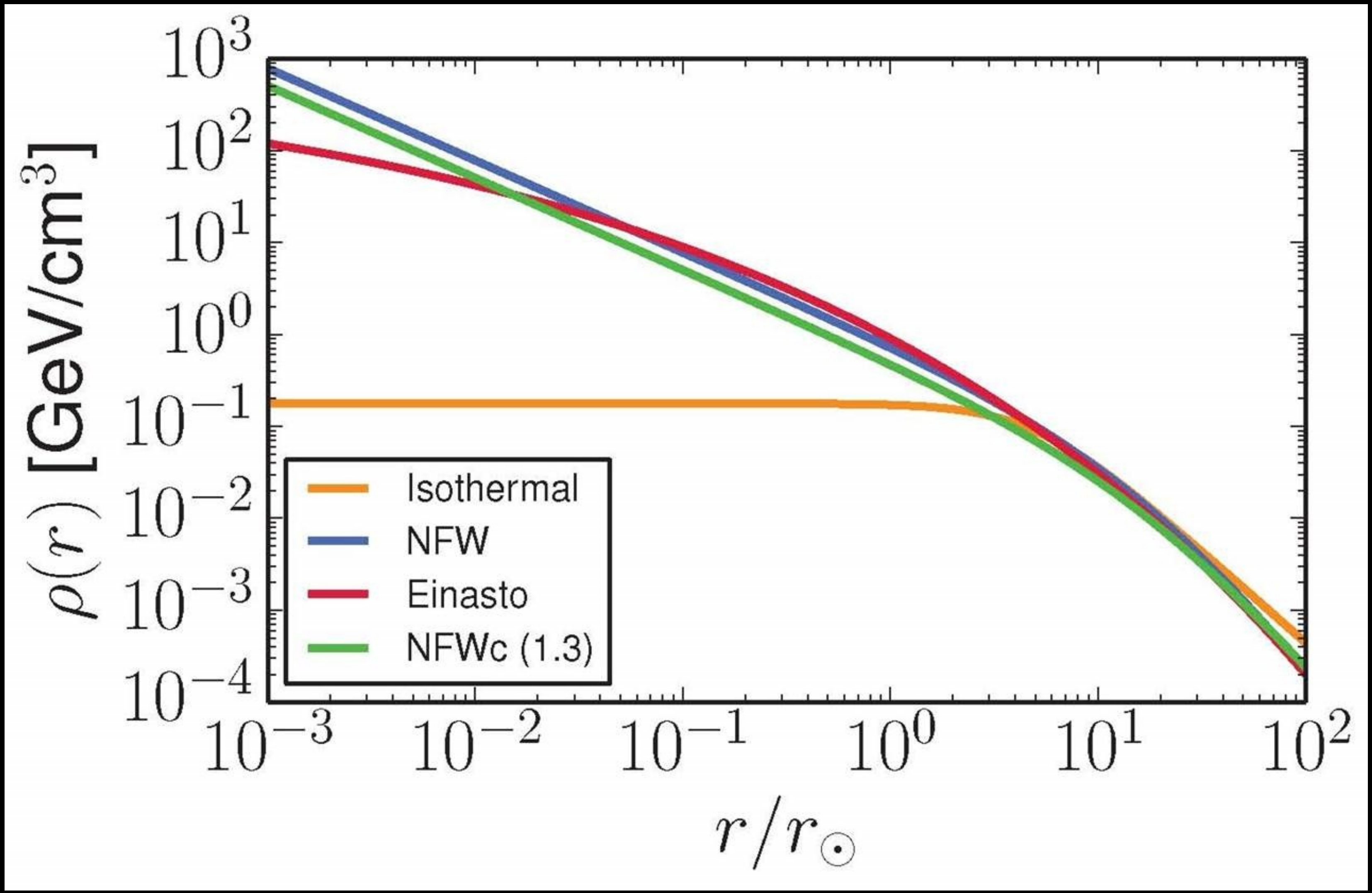
$$J(\theta) \equiv \int_{LOS} \rho^2 \left[r(s,l,b) \right] ds$$

dark matter profile

per annihilation photon spectrum (Pythia 8.176)

DM Couples to EWK Gauge & Higgs

Fedderke, Kolb, Lin, Wang



Uncertainty in DM profile → large systematic error

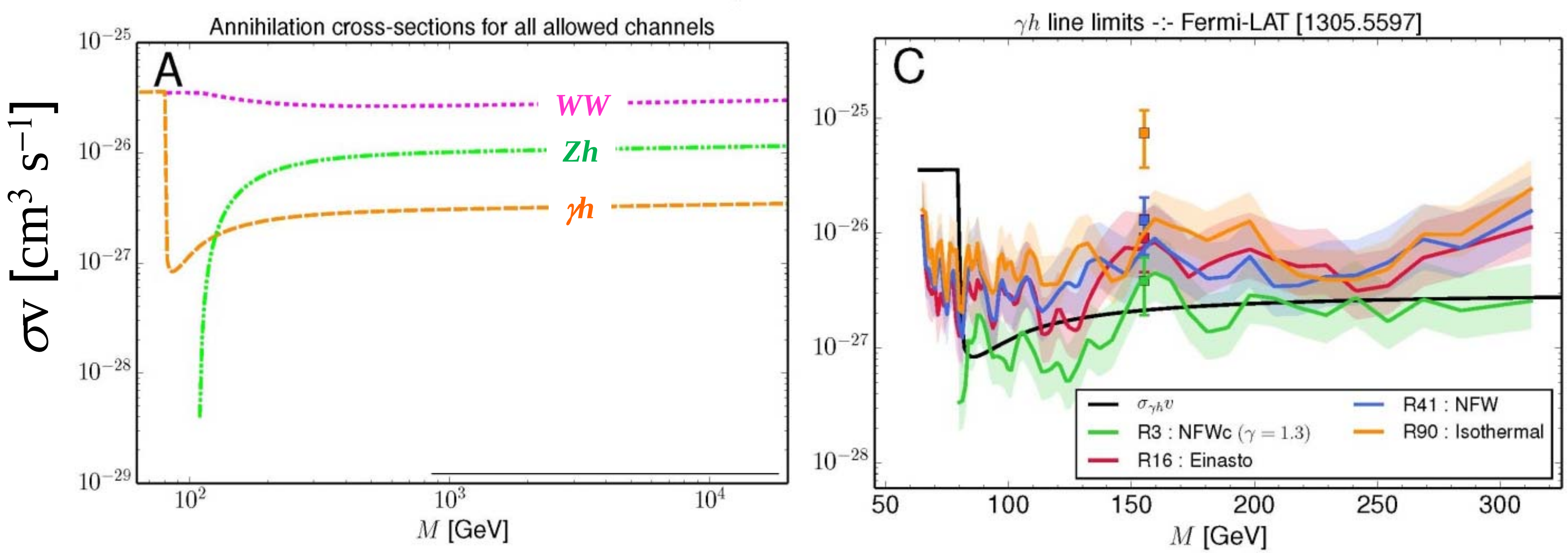
DM Couples to EWK Gauge & Higgs

Fedderke, Kolb, Lin, Wang

- Gamma-ray observations for this case play the role of direct detection for coupling to quarks
- Fifty operators/34 without velocity suppression
  - DM+DM → $\gamma\gamma$, γZ, γh, W^+W^-, ZZ, Zh, hh, ff
  - For each operator calculate photon spectrum (lines+continuum)
  - Compare to various constraints

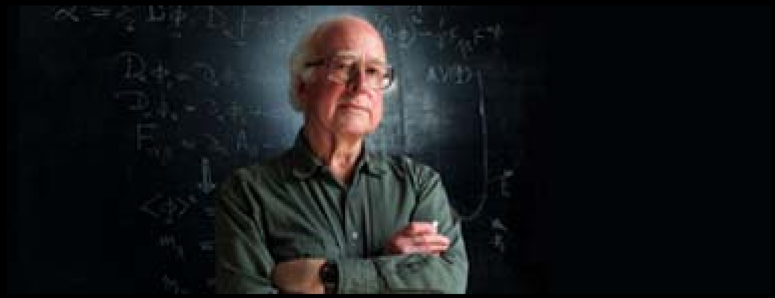
} Thirteen different classes

$$\Lambda^{-4}\bar{\chi}\gamma^{\mu}\chi(\widetilde{W}^{a}_{\lambda\mu}H^{\dagger}t^{a}D^{\lambda}H + h.c.)$$



DM—SM Through the Higgs Portal

Fedderke, Chen, Kolb, Wang



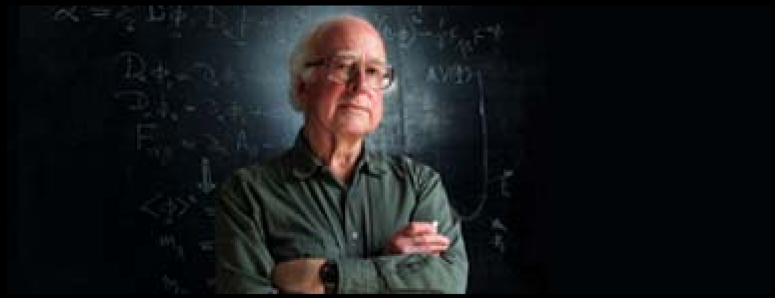
Pre-EWSB: DM couples to SM through Higgs Portal

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}\,(i\partial\!\!\!/ - M_0)\,\chi + \Lambda^{-1}\left(\cos\theta\,\overline{\chi}\,\chi + \sin\theta\,\overline{\chi}\,i\gamma_5\,\chi\right) H^{\dagger}H$$

- Pre-EWSB parameters: M_0, Λ, θ
- Post-EWSB: $H^{\dagger}H \rightarrow \frac{1}{2}\langle v^2\rangle + \langle v\rangle h + \frac{1}{2}h^2$
- EWSB contributes a mass term; if $\sin\theta \neq 0$ have to perform chiral rotation to obtain real mass term
- Scalar/pseudoscalar couplings scrambled
- Important because velocity dependence of $\langle \sigma \mathrm{v}\rangle$

DM—SM Through the Higgs Portal

Fedderke, Chen, Kolb, Wang



Post-EWSB: DM couples to SM through Higgs Portal

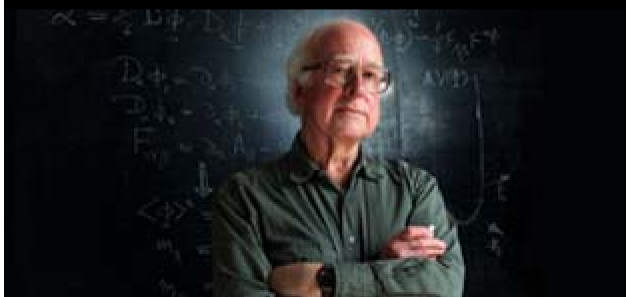
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}\,(\,i\partial - M\,)\,\chi$$
$$+ \Lambda^{-1}\left(\cos\xi\ \bar{\chi}\chi + \sin\xi\ \bar{\chi}\,i\gamma_5\,\chi\right)\left(\langle v\rangle h + \tfrac{1}{2}h^2\right)$$

Post-EWSB parameters (M, ξ) are complicated functions of pre-EWSB parameters (M_0, θ , Λ)

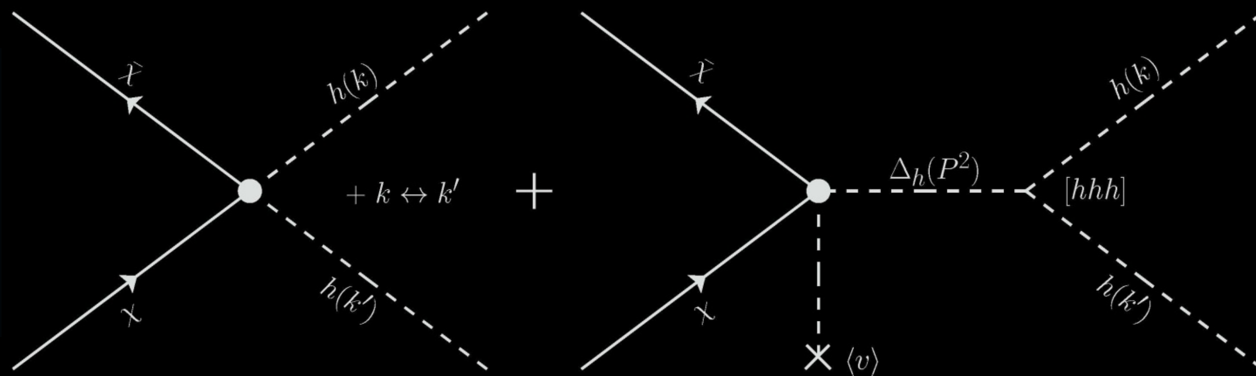
Mapping from (M, ξ) to (M_0, θ) is Λ-dependent and not single-valued

DM—SM Through the Higgs Portal

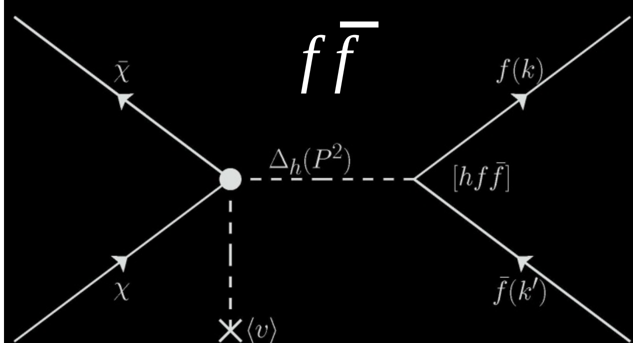
Fedderke, Chen, Kolb, Wang



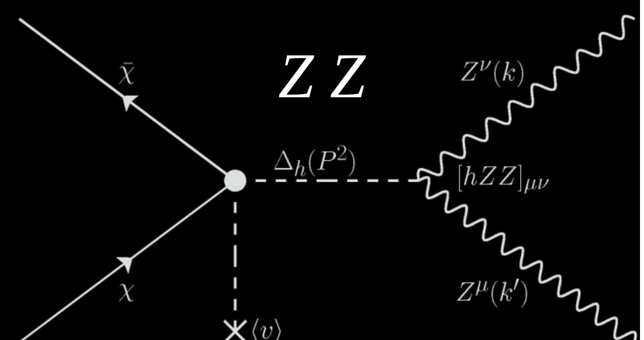
hh



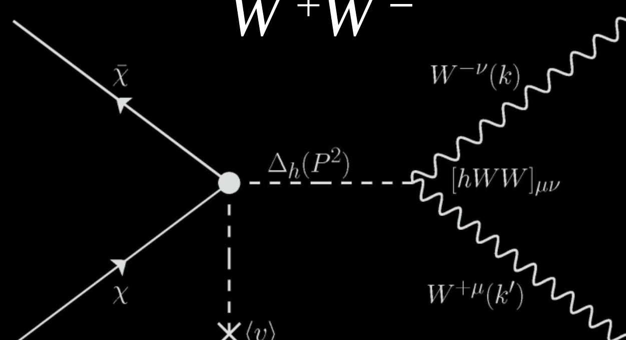
$f\bar{f}$



$Z\,Z$

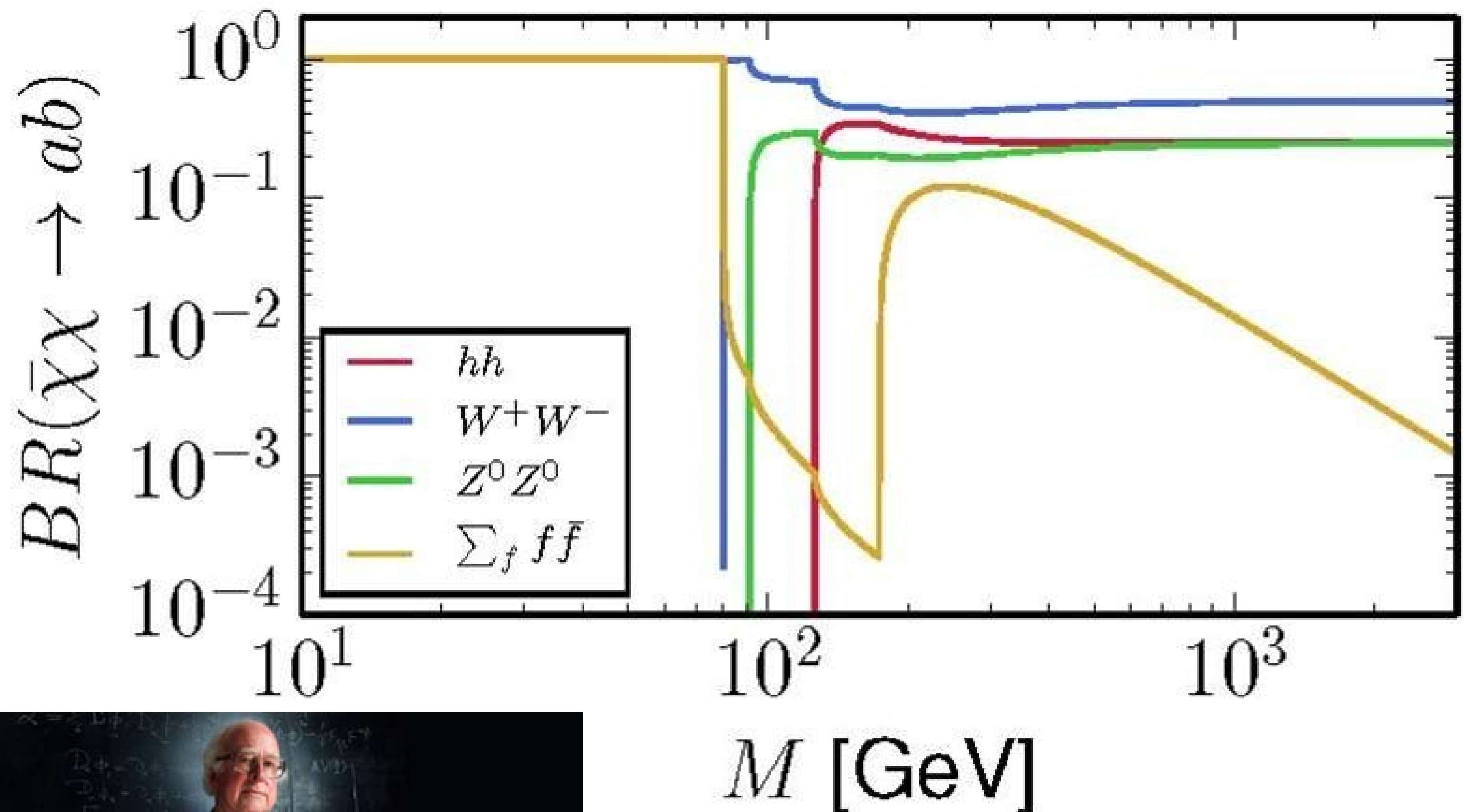


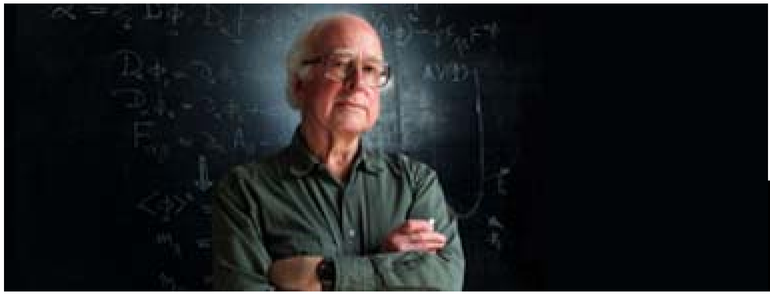
W^+W^-



DM—SM Through the Higgs Portal

Fedderke, Chen, Kolb, Wang

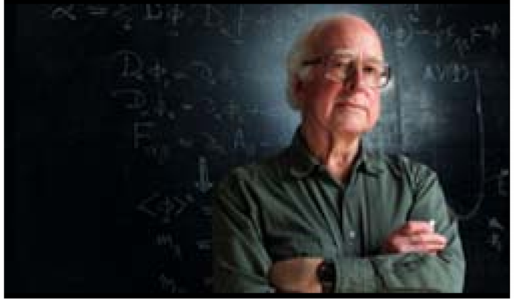


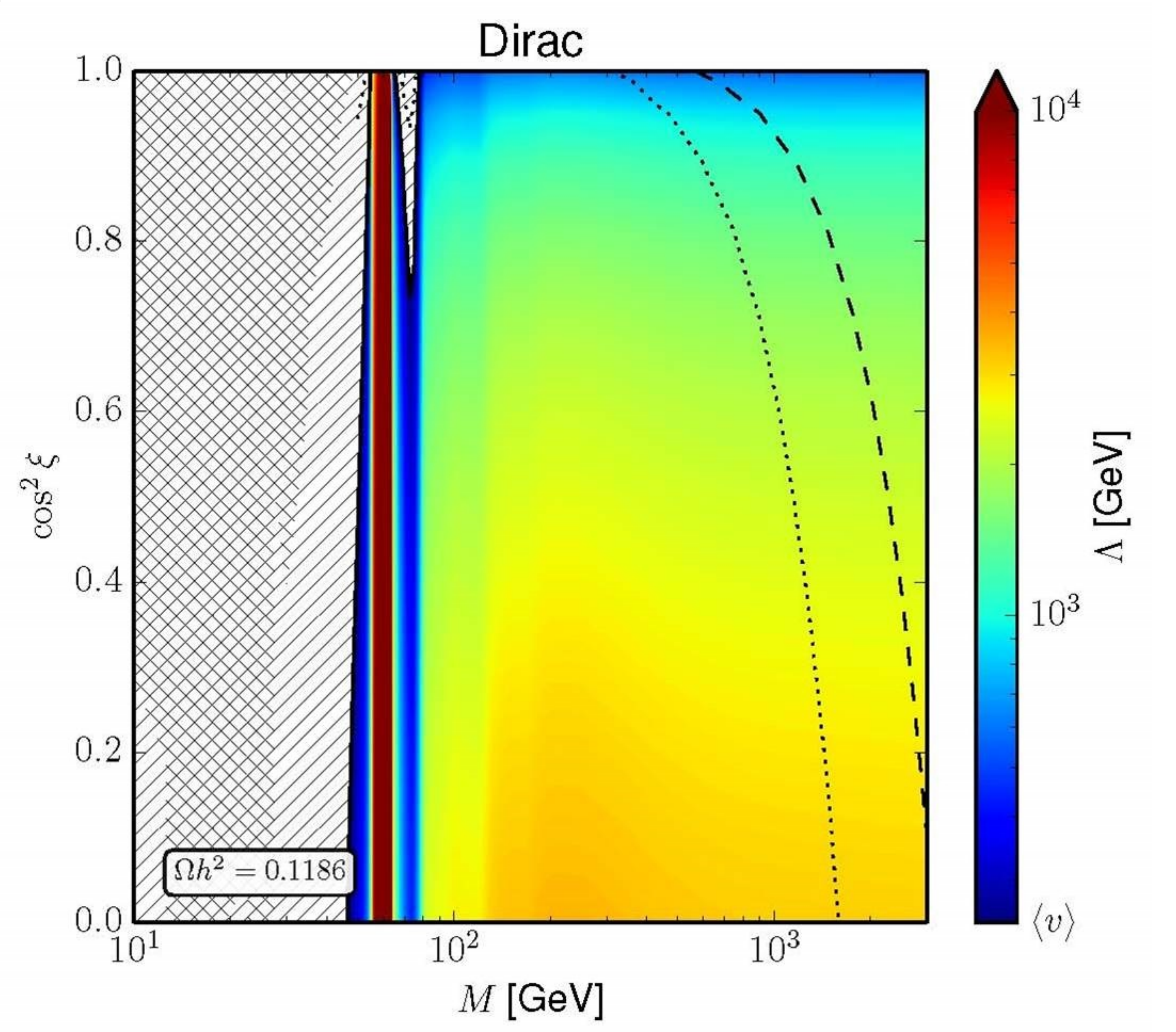


DM—SM Through the Higgs Portal

Fedderke, Chen, Kolb, Wang

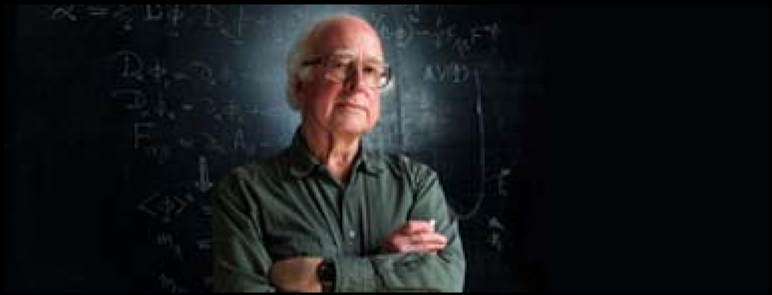
Λ to give DM abundance





DM—SM Through the Higgs Portal

Fedderke, Chen, Kolb, Wang



Collider limits on "invisible" (non-SM) width of the Higgs:

$$\frac{\Gamma_{h\to\bar{\chi}\chi}}{\Gamma_{\mathrm{SM}}+\Gamma_{h\to\bar{\chi}\chi}}\leq 0.19$$

$$\Gamma_{\mathrm{SM}}=4\ \mathrm{MeV}$$

$$\Gamma_{h\to\bar{\chi}\chi}=\frac{m_h}{8\pi}\frac{\langle v^2\rangle}{\Lambda^2}\sqrt{1-\frac{4M^2}{m_h^2}}\left[1-\frac{4M^2}{m_h^2}\cos^2\xi\right]$$

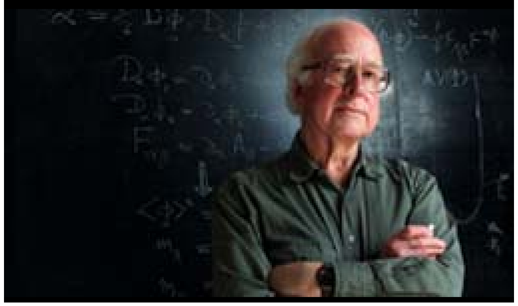
$$=\left(300\ \mathrm{MeV}\right)\times\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2\sqrt{1-\frac{4M^2}{m_h^2}}\left[1-\frac{4M^2}{m_h^2}\cos^2\xi\right]$$

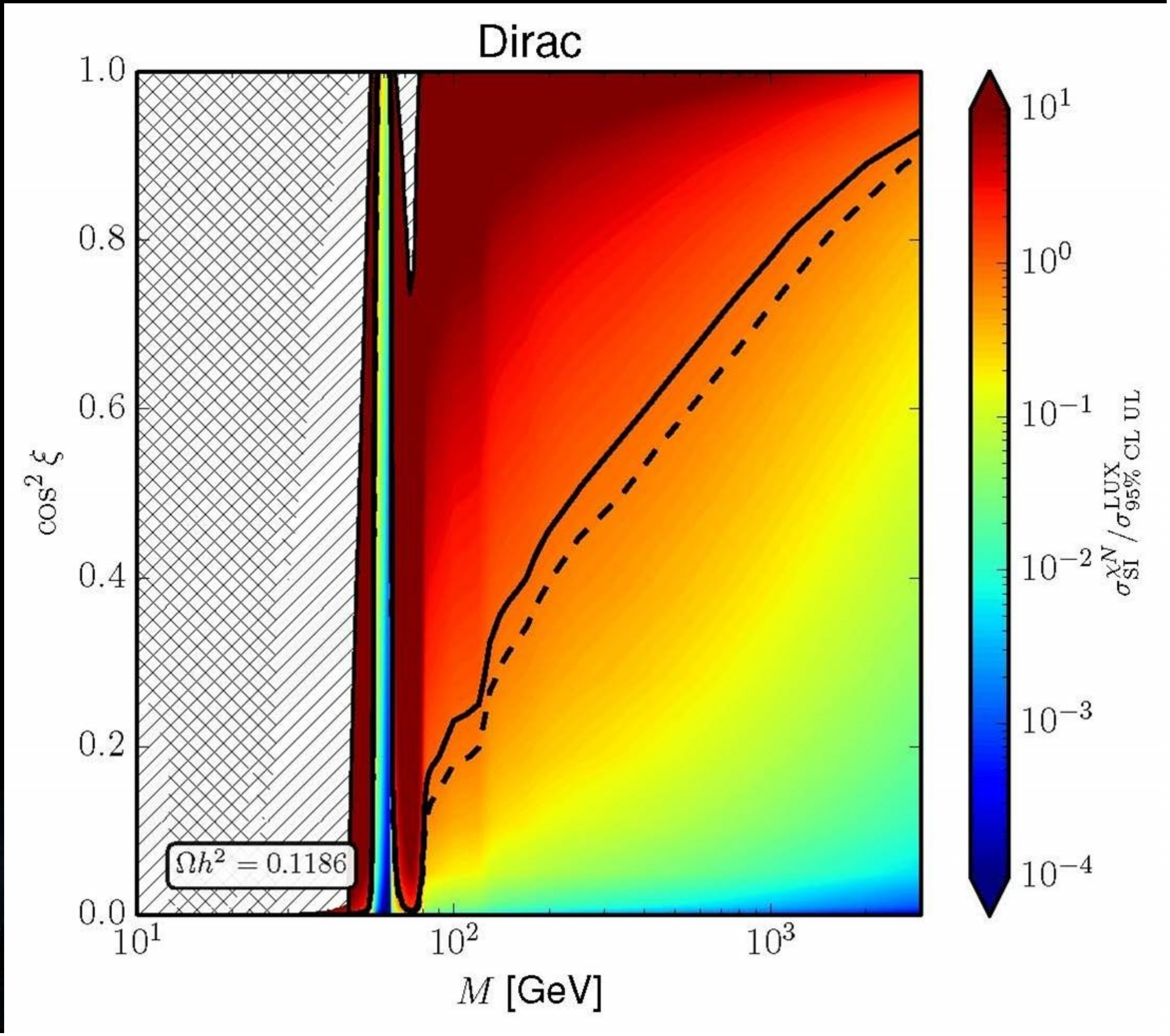
Very restrictive above threshold for $h\to\bar{\chi}\chi$ (63 GeV)

DM—SM Through the Higgs Portal

Fedderke, Chen, Kolb, Wang

direct detection limits

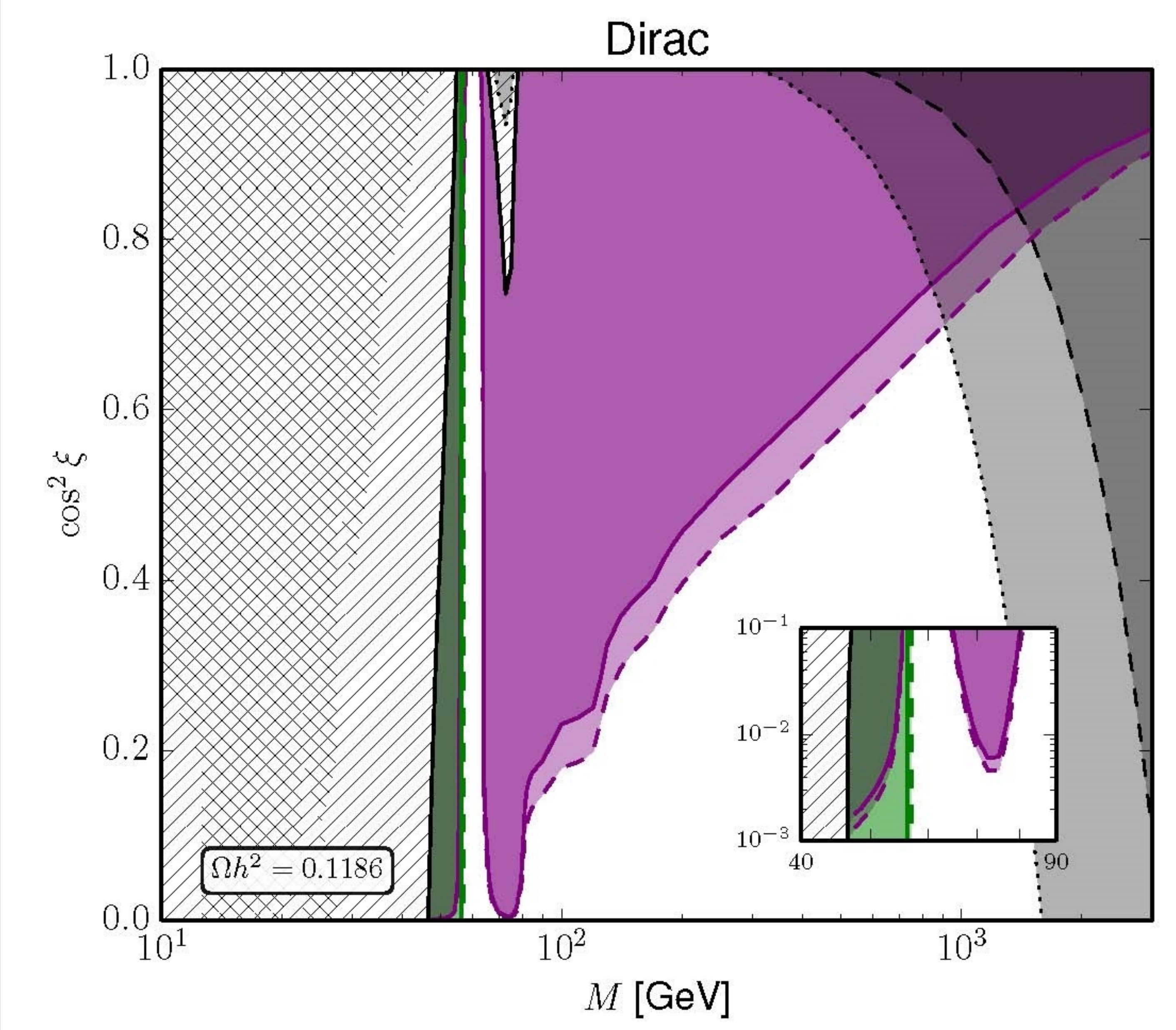


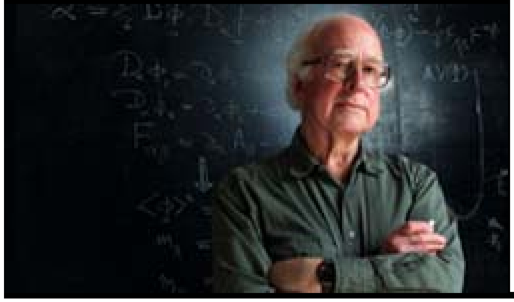


DM—SM Through the Higgs Portal

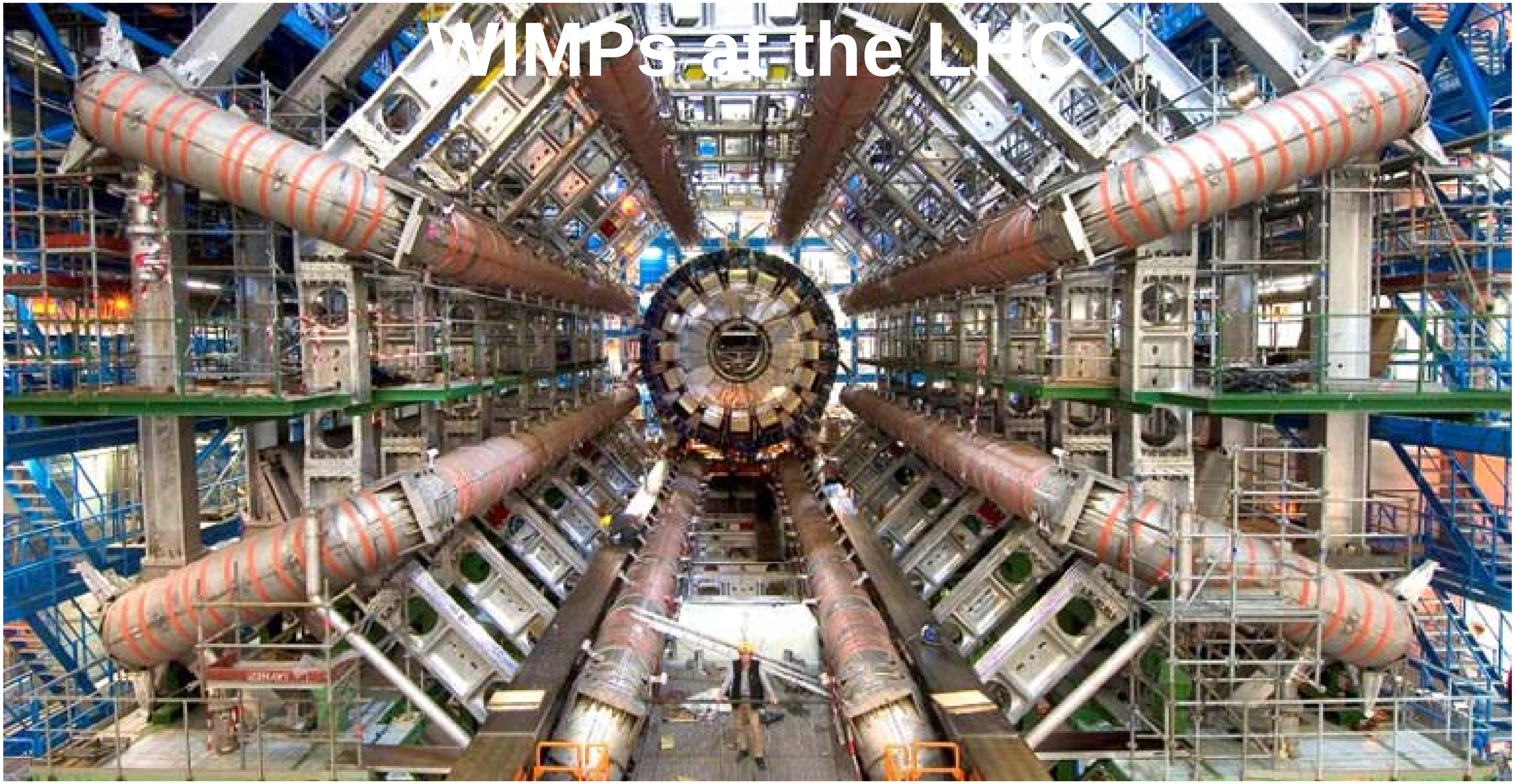
Fedderke, Chen, Kolb, Wang

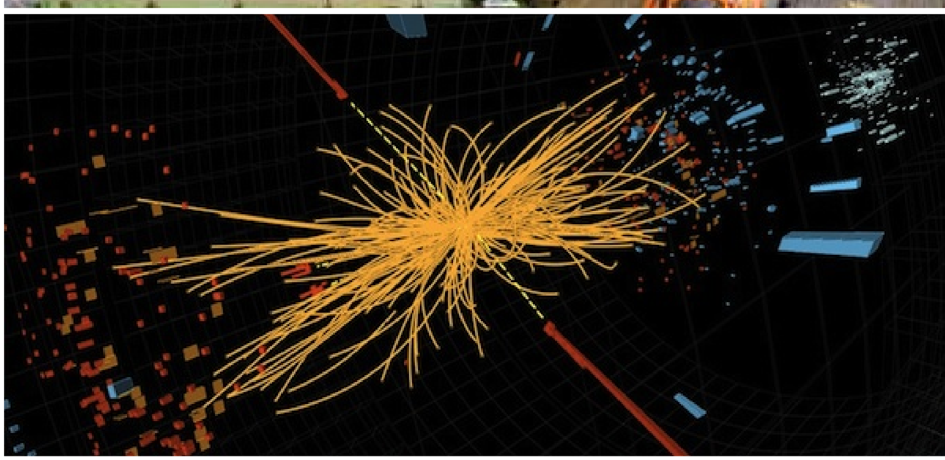
exclusion plot





WIMPs at the LHC





Looking for an
invisible
needle in a haystack

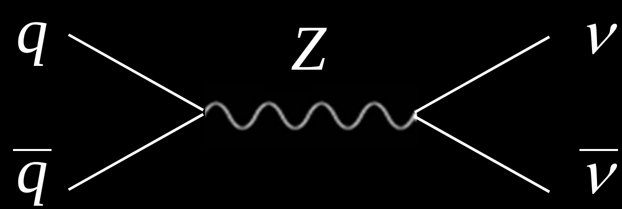
Maybe, just maybe, SUSY won't be seen at the LHC, and dark matter is not the LSP.

Neutrino Background for Mavericks

Once thought that $\nu\,\overline{\nu}$ background

Renormalizible

$$q+\overline{q}\rightarrow Z\rightarrow\ \nu+\overline{\nu}$$

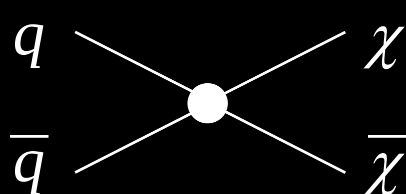


$\sigma\propto s^{-1}$ (parton level)

Would swamp WIMP signal

Nonrenormalizible

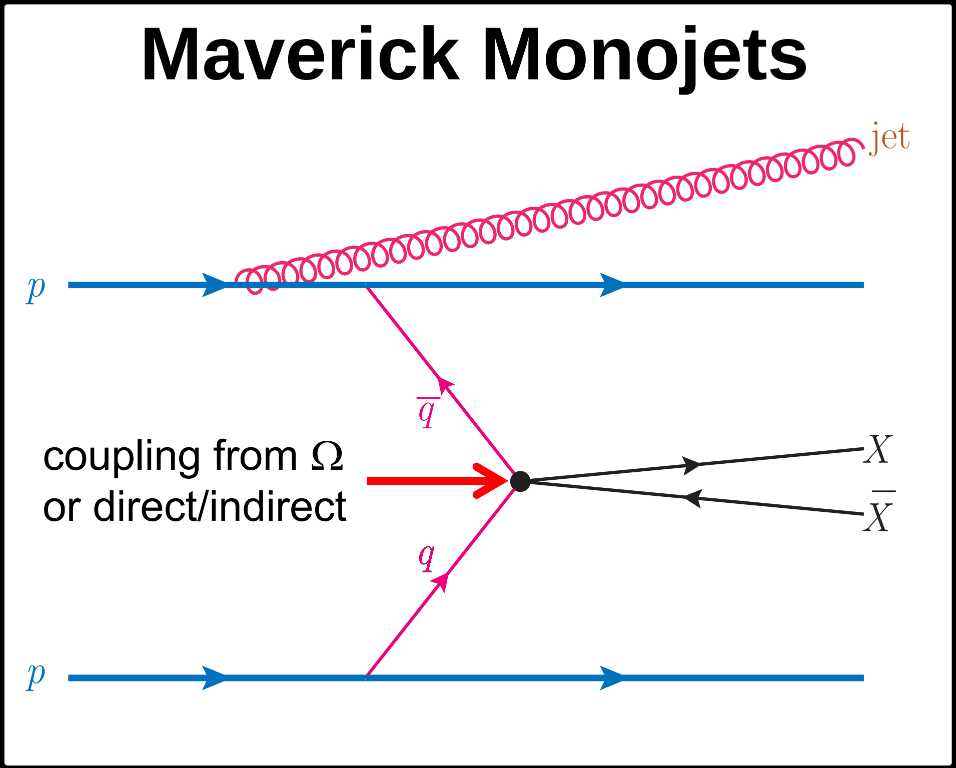
$$q+\overline{q}\rightarrow\chi+\overline{\chi}$$



$\sigma\propto s$ (parton level)

Judicious cuts on MET can pull out signal

Collider Searches for Maverick WIMPs



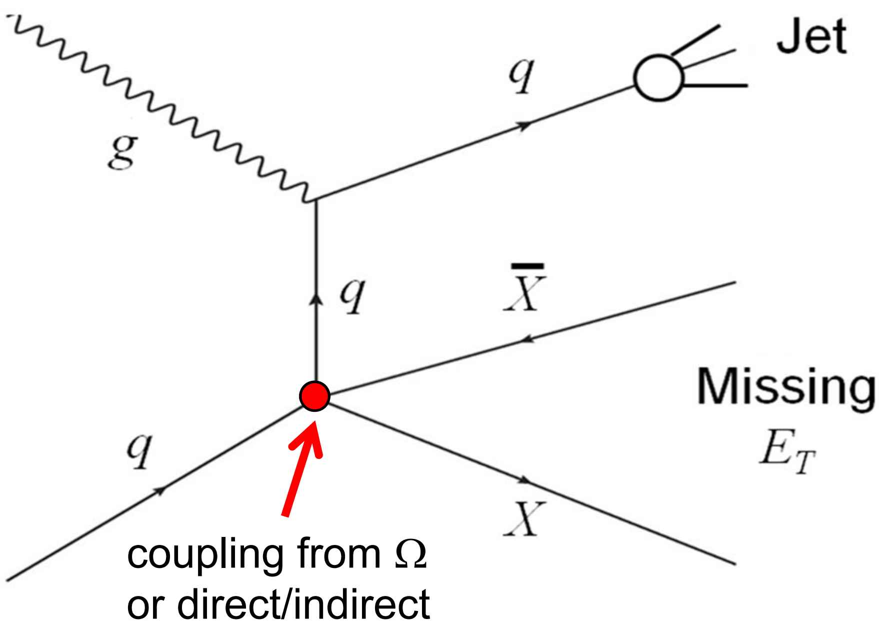
Backgrounds (neutrinos, QCD, …)
Only signal (other than mono-γ)
Largely model independent

- Monojets are Nature's garbage can
- Monophotons, mono-Z's also
- SM background extremely well modeled and understood

Beltran, Hooper, Kolb, Krusberg, Tait 2009
Goodman, Ibe, Rajaraman, Shepard, Tait, Yu 2010
Rajaraman, Shepherd, Tait, Wijangco
Bai, Fox, Harnik; Fox, Harnik, Kopp, Tsai
CDF, CMS, ATLAS

Collider Searches for Maverick WIMPs

Maverick Monojets

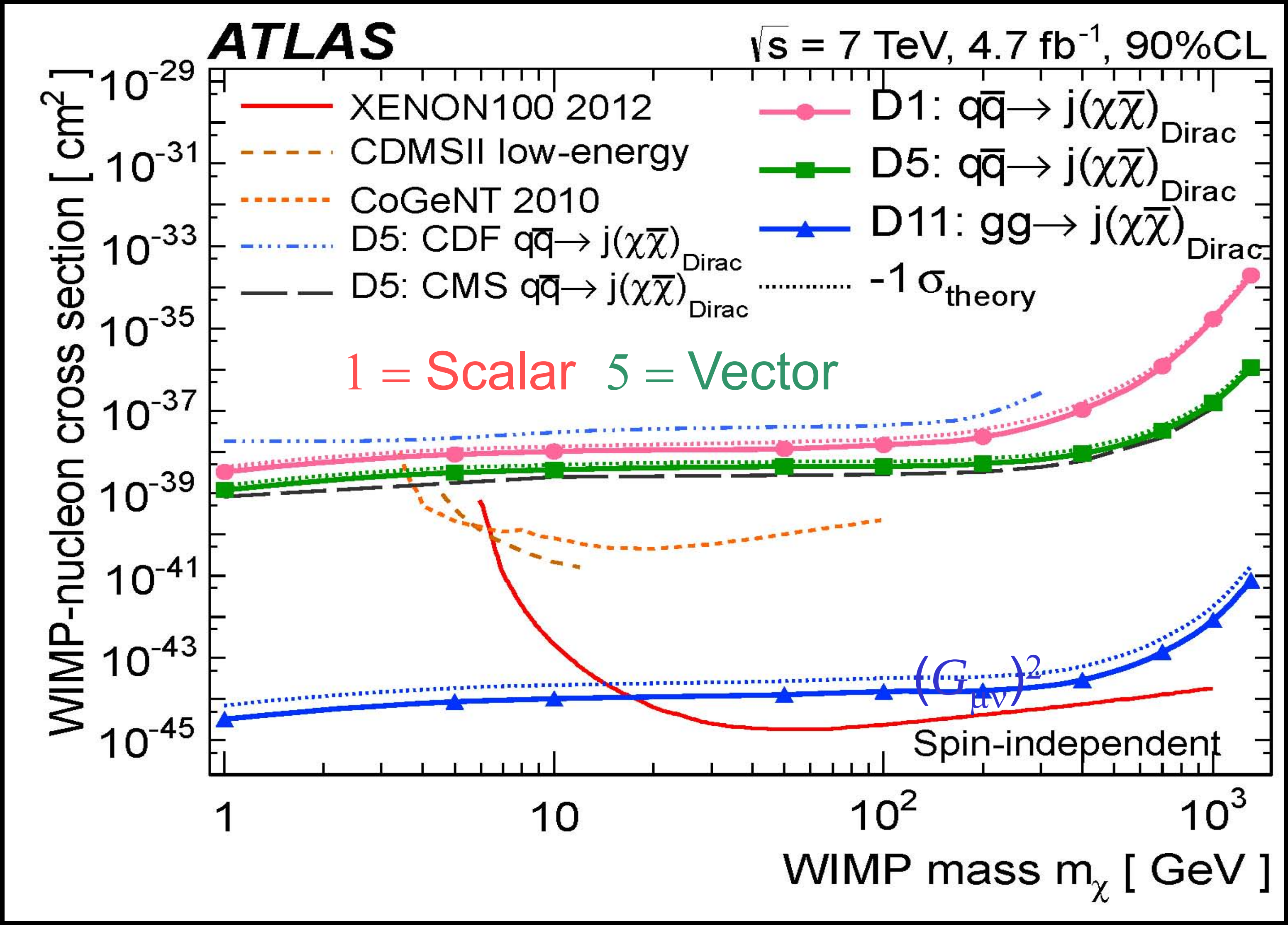


Backgrounds (neutrinos, QCD, …)
Only signal (other than mono-γ)
Largely model independent

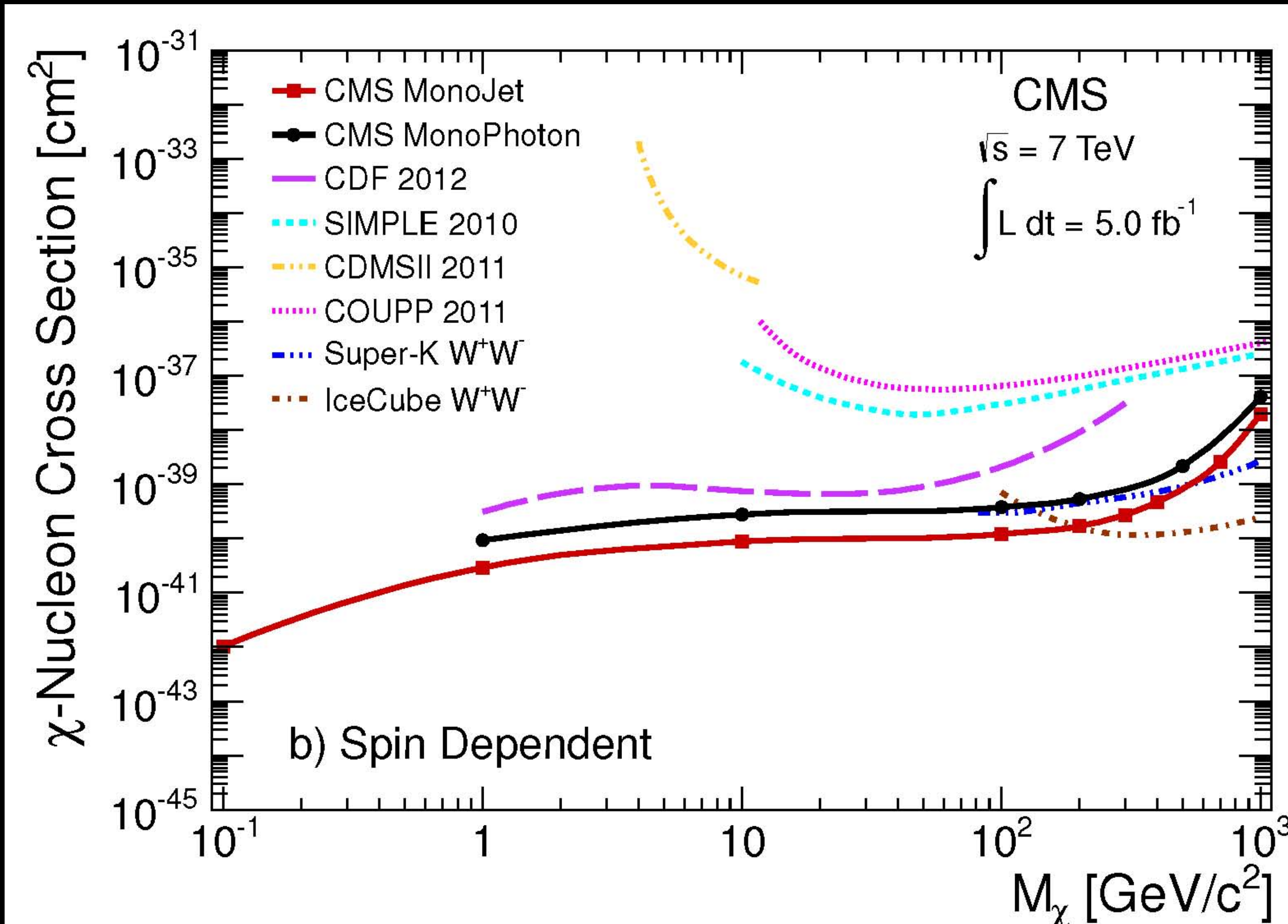
- MadGraph/MadEvent:
  Feynman diagrams,
  cross sections,
  parton-level events
- Pythia:
  Hadron-level events
  via Monte Carlo showering
- PGS:
  Reconstructed events
  at collider

Beltran, Hooper, Kolb, Krusberg, Tait 2009
Goodman, Ibe, Rajaraman, Shepard, Tait, Yu 2010
Rajaraman, Shepherd, Tait, Wijangco
Bai, Fox, Harnik; Fox, Harnik, Kopp, Tsai

ATLAS Analysis 1210.4491



CMS Analysis JHEP 2012

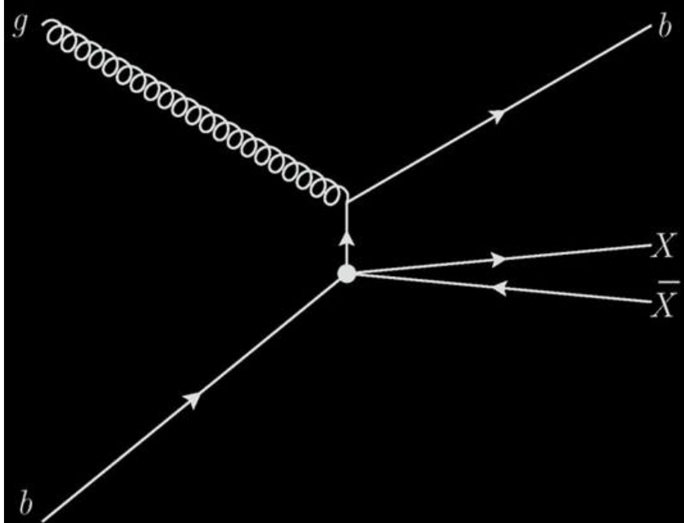


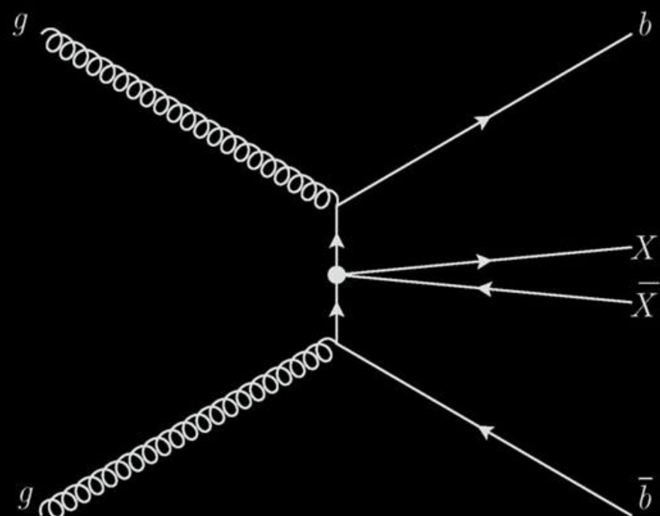
Take Advantage of Largest Yukawas

(Lin, Kolb, Wang 13036638)

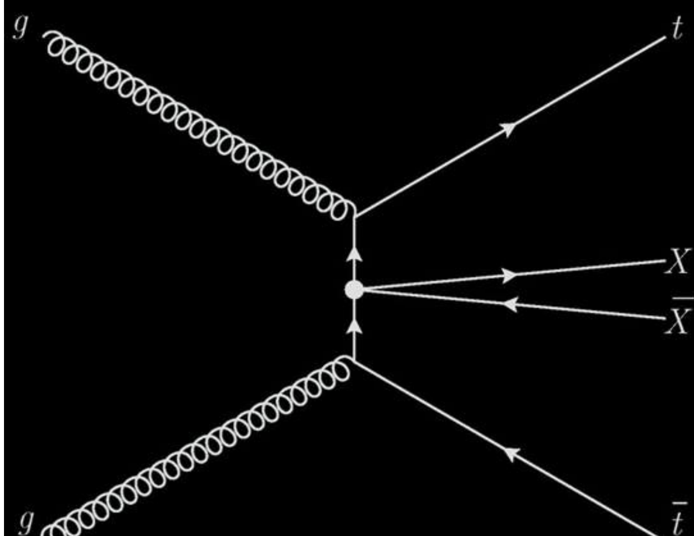
S & P couplings $\propto m_q$ (Minimal Flavor Violation) $m_c : m_b : m_t :: 1 : 3.3 : 135$

So far, analysis includes only c (b PDF smaller than c PDF) but $m_t \gg m_b > m_c$





Take advantage of b tagging

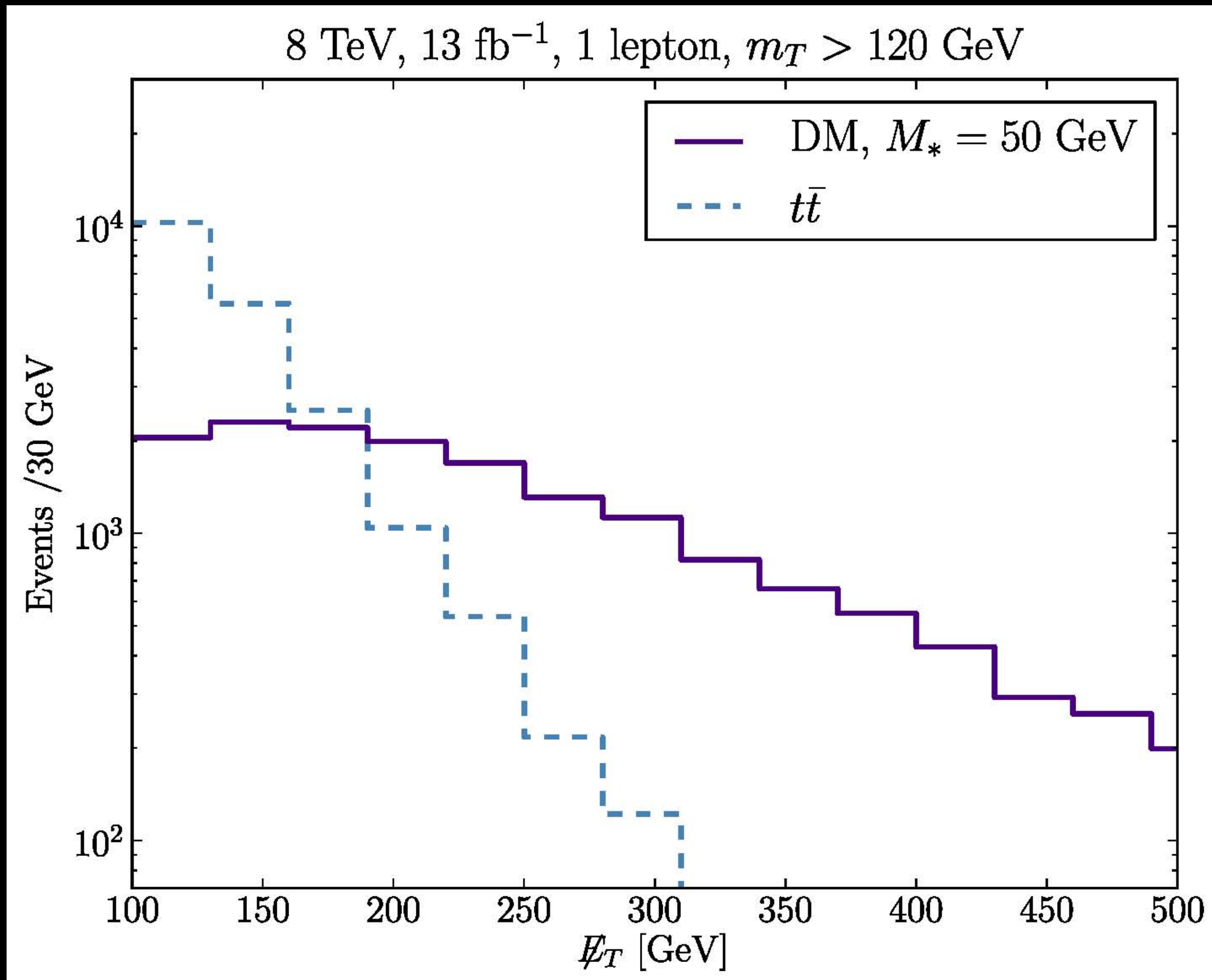


Top PDF small (& very uncertain) but m_t huge

Looks like stop signal—use stop search limits

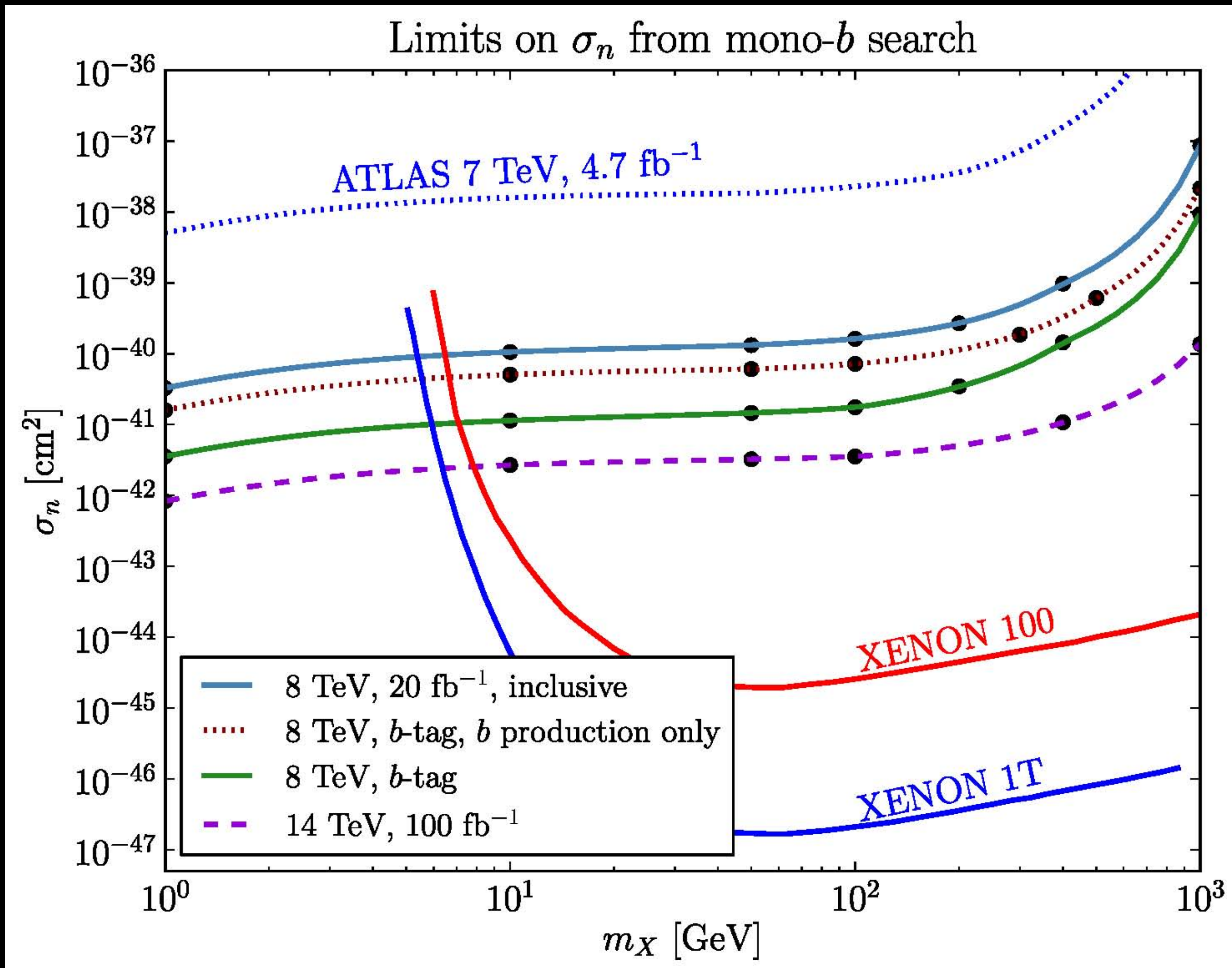
Take Advantage of Largest Yukawas

(Lin, Kolb, Wang 13036638)

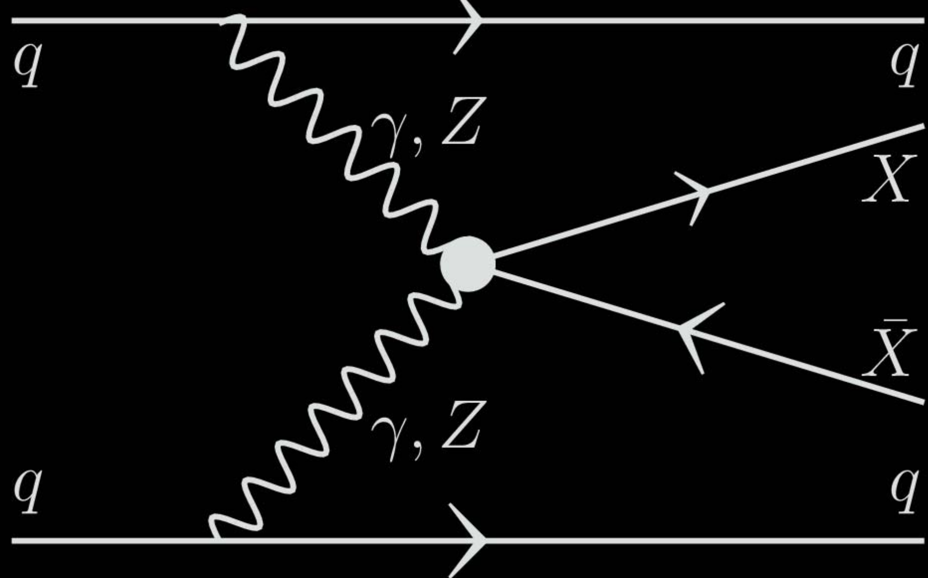


Take Advantage of Largest Yukawas

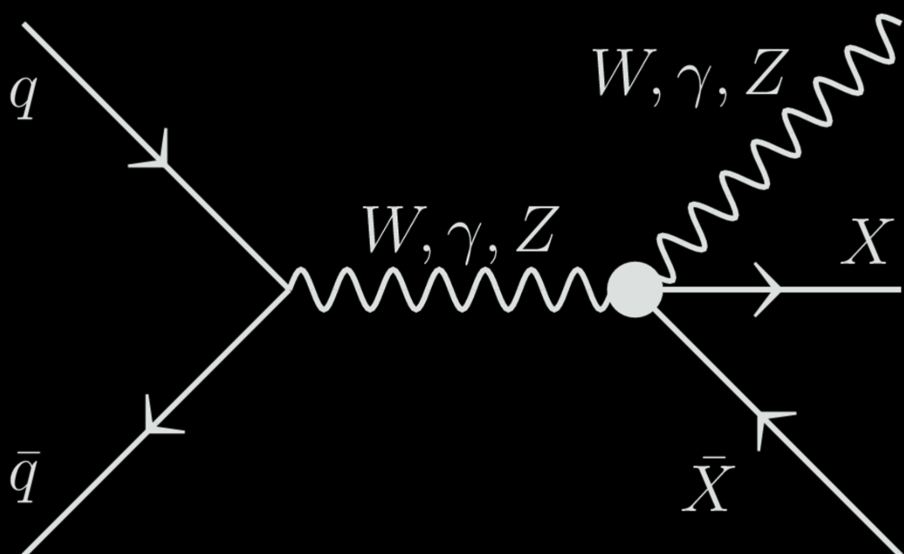
(Lin, Kolb, Wang 13036638)



LHC:DM Couples to EWK Gauge & Higgs



Cohen et al JHEP 2012



Carpenter PRD 2013

Effective Field Theory Descriptions of Dark Matter

Ultimate goal: discover nature of dark matter, including how it fits into a theoretical framework (Inner Space / Outer Space)

Most desirable is discovery of (say) SUSY @ LHC and neutralino is the WIMP

Theoretical framework may be beyond reach, in the interim use EFT!

Rocky Kolb—University of Chicago

Edinburgh—June 2014

INFLATION
Gravitation
DARK ENERGY
COSMO 2014
AUGUST 25-29, 2014
CHICAGO, IL