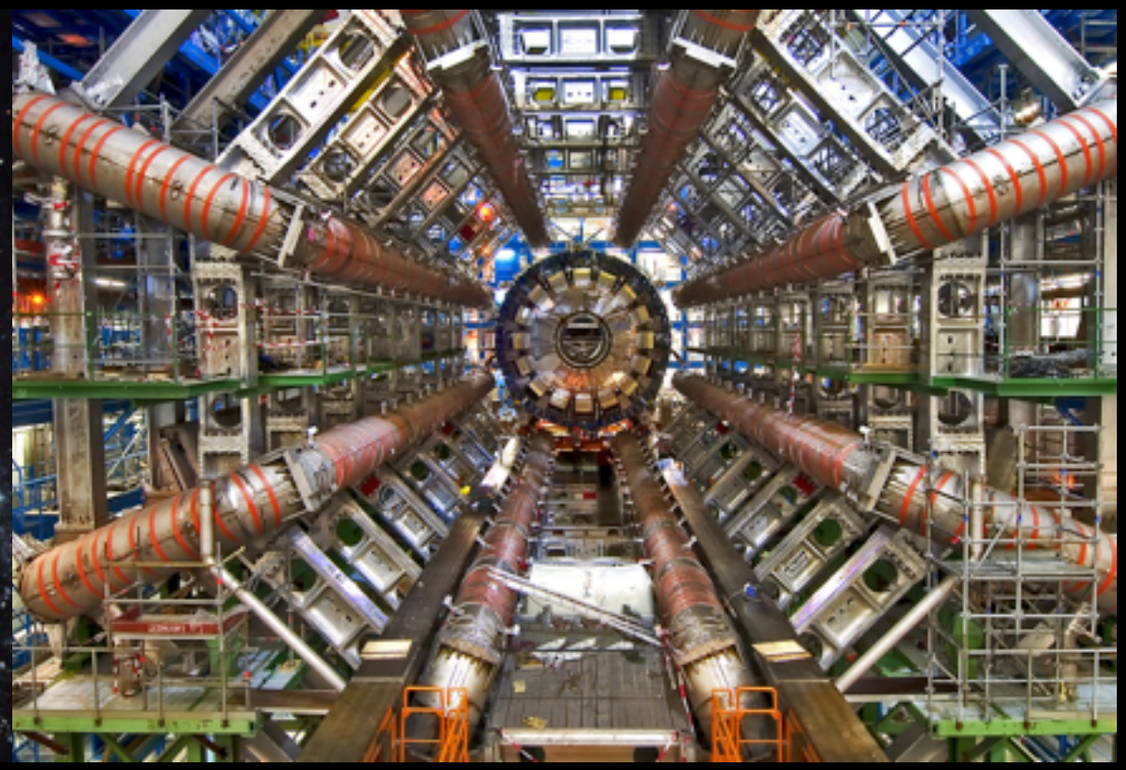
The Galactic Center Excess from the *Bottom* Up



Gordan Krnjaic
Perimeter Institute

with Eder Izaguirre and Brian Shuve

1404.2018, PRD D90 (2014) 055002

TRIUMF, Sept. 10, 2014

Overview

What is the excess?

Is it astrophysics or DM?

If DM, what kind?

Can the LHC teach us more?

The Fermi Excess

2009: Goodenough & Hooper spot feature in FGST data near ~1-3 GeV

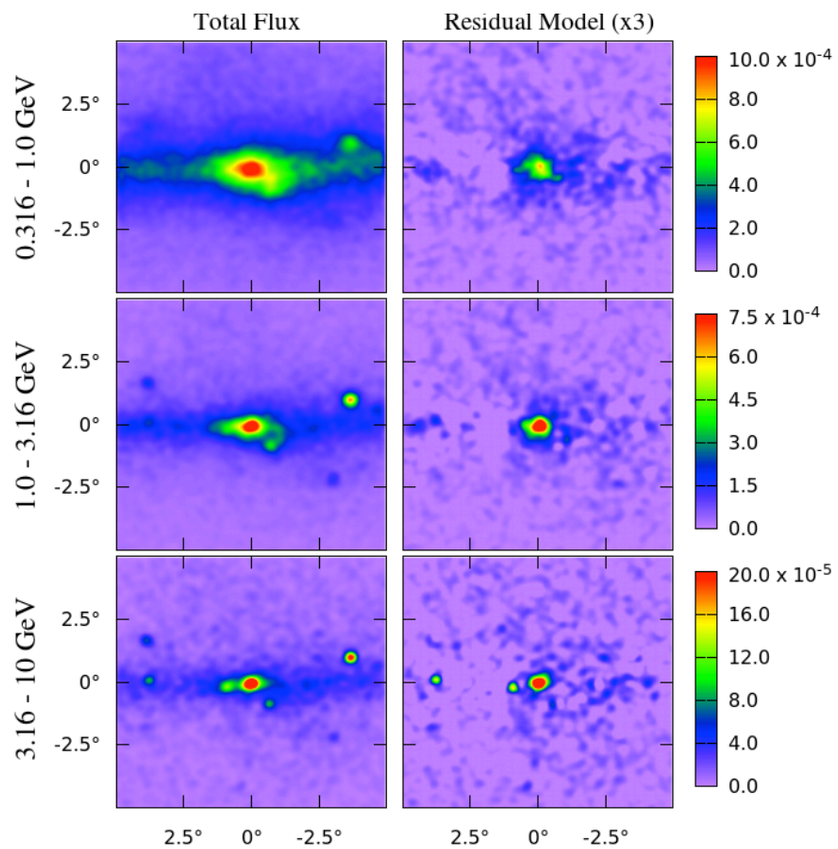
Localized to few deg. near GC w/ very large statistical significance

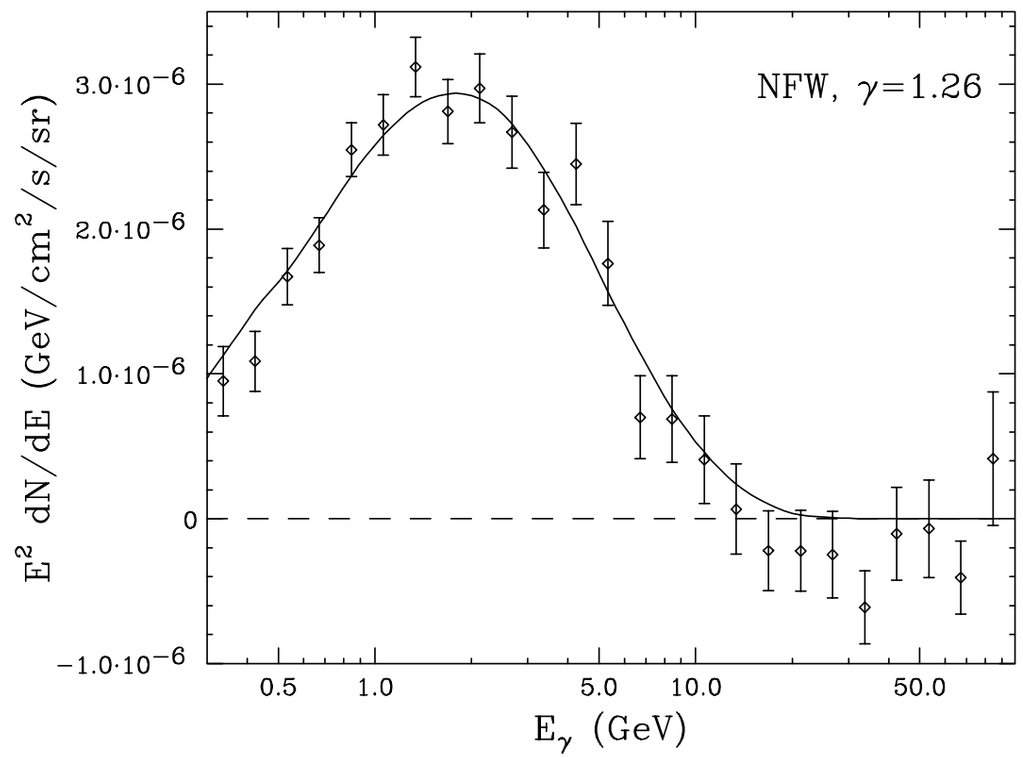
Can be resolved at large angles above galactic plane

2009-2014: Several groups analyzing same data agree on basic features
(Abazajian et al, Dayan et. al., Linden et. al, Boyarski et. al., Macias et. al., Kaplinghat et. al.)

Appears to be good evidence for some striking phenomena despite our incomplete knowledge of GC emission

What's observed?





Dayan *et. al.* 1402.6703

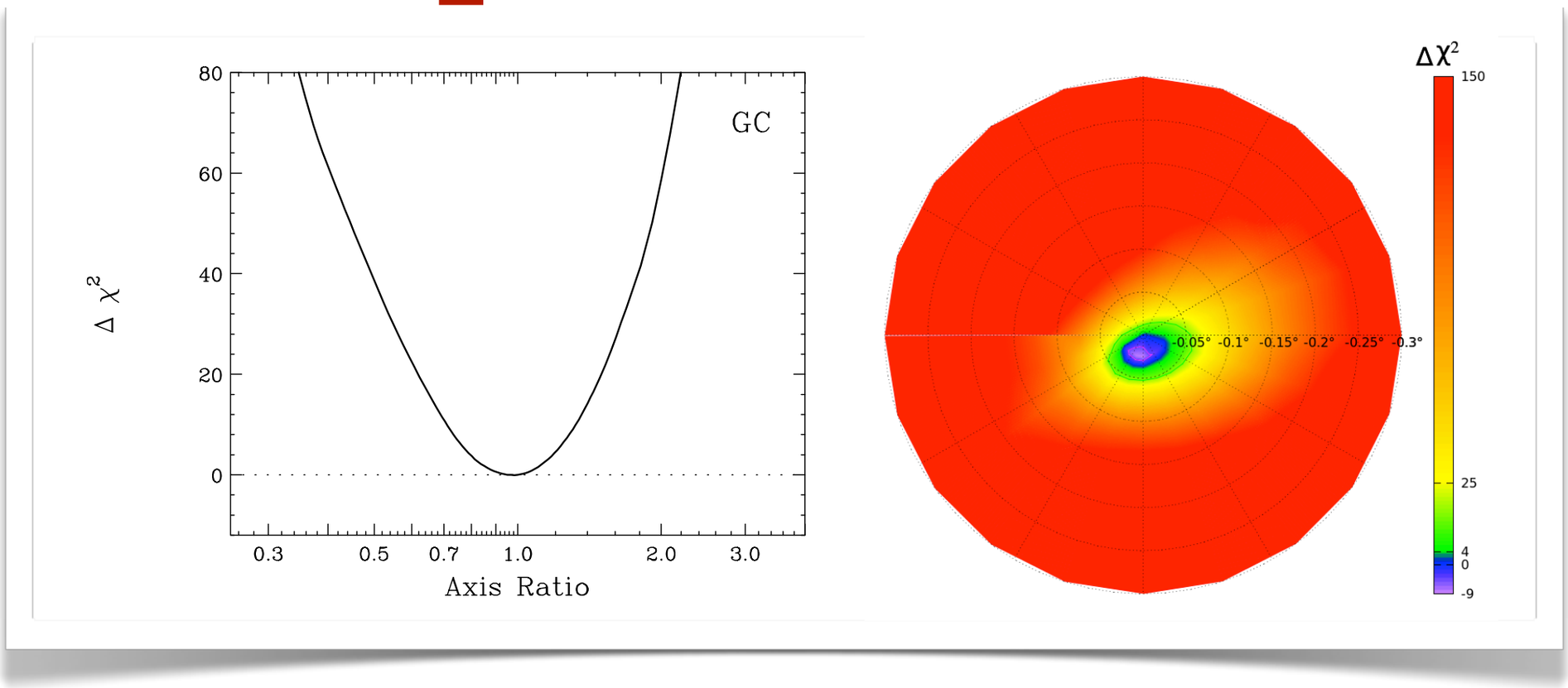
Based on Fermi Pass 7 data (2008-2013)

Including CTBCORE cuts to improve angular reconstruction

Remove galactic plane, known pt. srcs, dust maps

subtract gamma spectrum from Fermi's Galactic Diffuse BG Model

Shape and Location

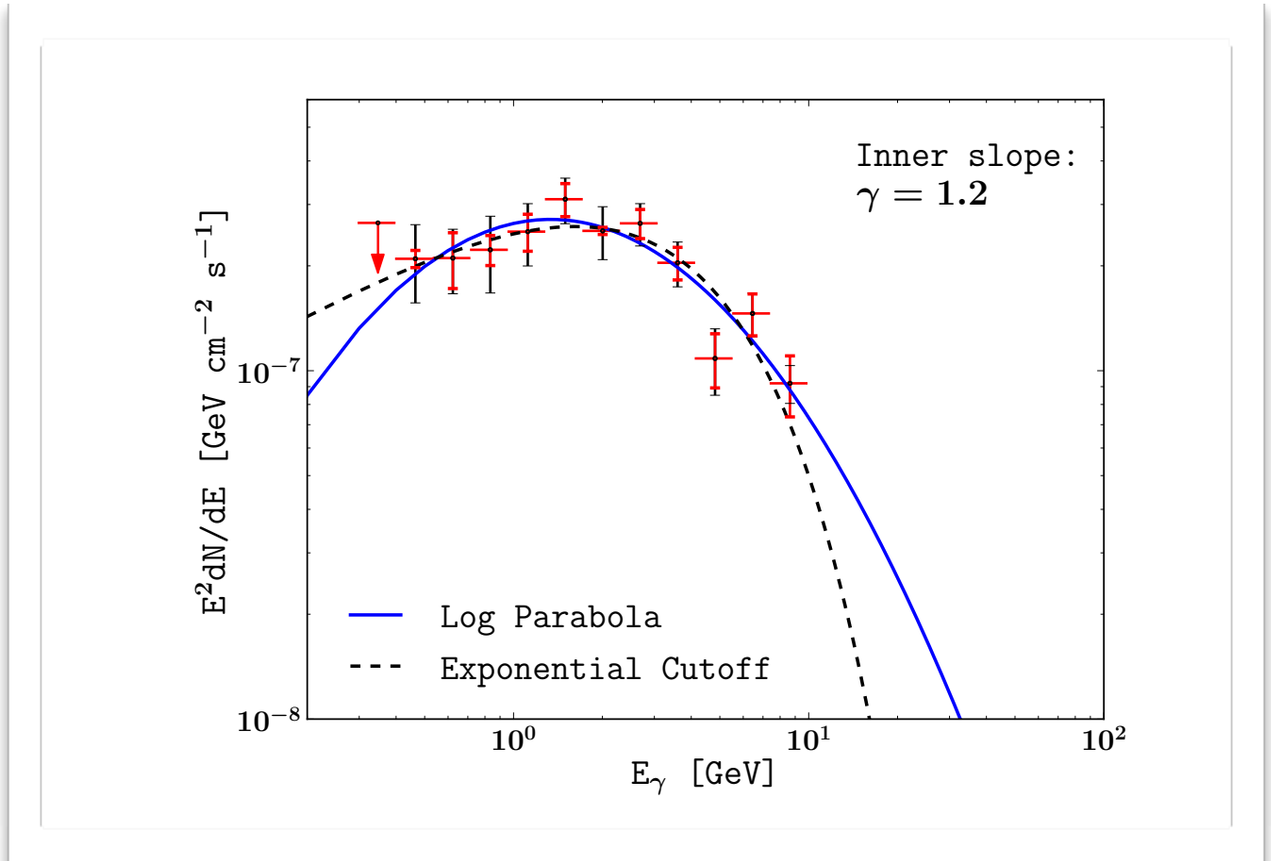


Shape is uncorrelated with galactic gas profile

Axes of residual emission appear spherical to good approx

Center of excess is within ~0.03 deg. of GC

Millisecond Pulsars?



Macias, Gordon 1306.5725

Empirical model of MSP spectrum

$$\frac{dN}{dE} = K \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{\rm cut}}\right)$$

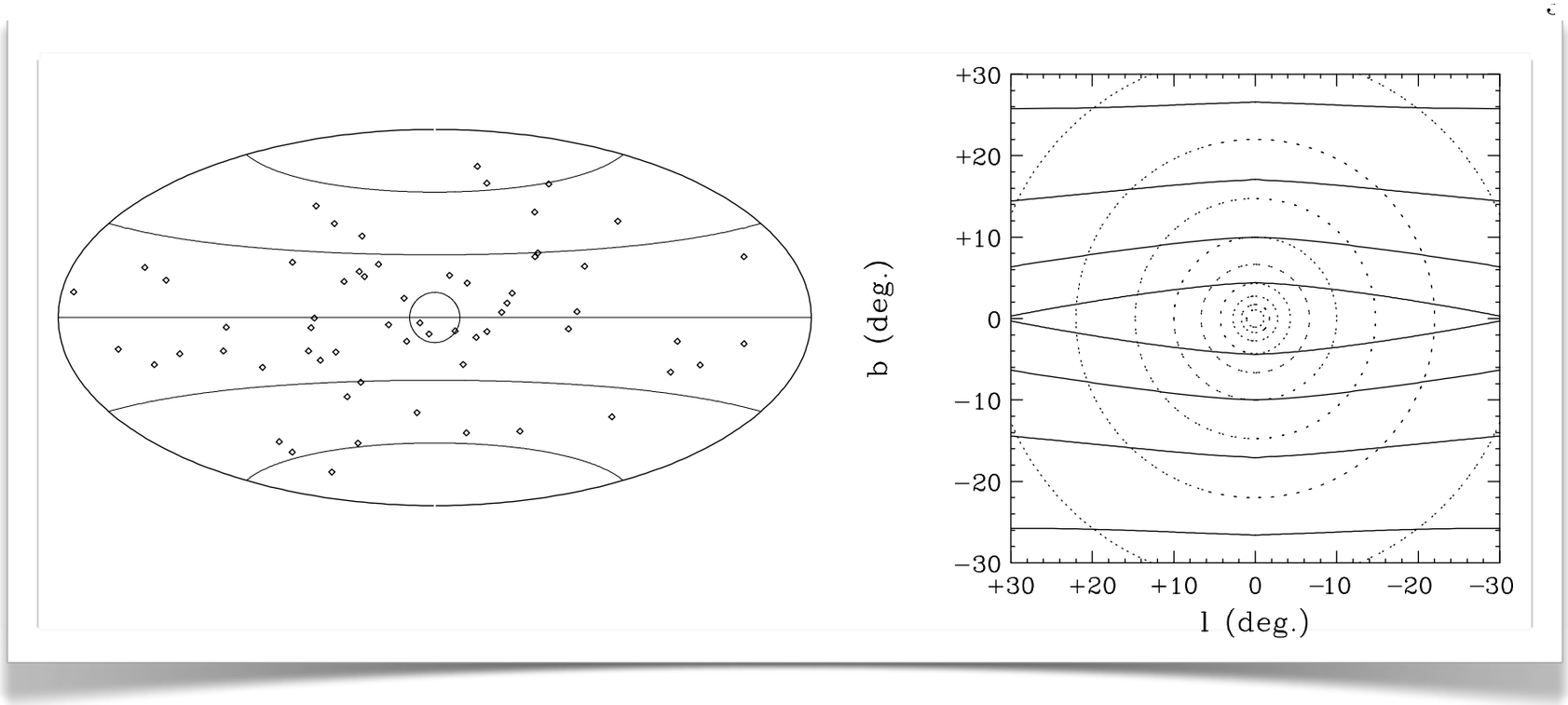
"exponential cutoff model"

Confirm basic features of excess

Fix spectrum using known ~ 30-40 MSP src. (now ~60)

Assume ~ 1000 MSPs in NFW profile

Millisecond Pulsars?



Cholis, Hooper, Linden 1407.5625

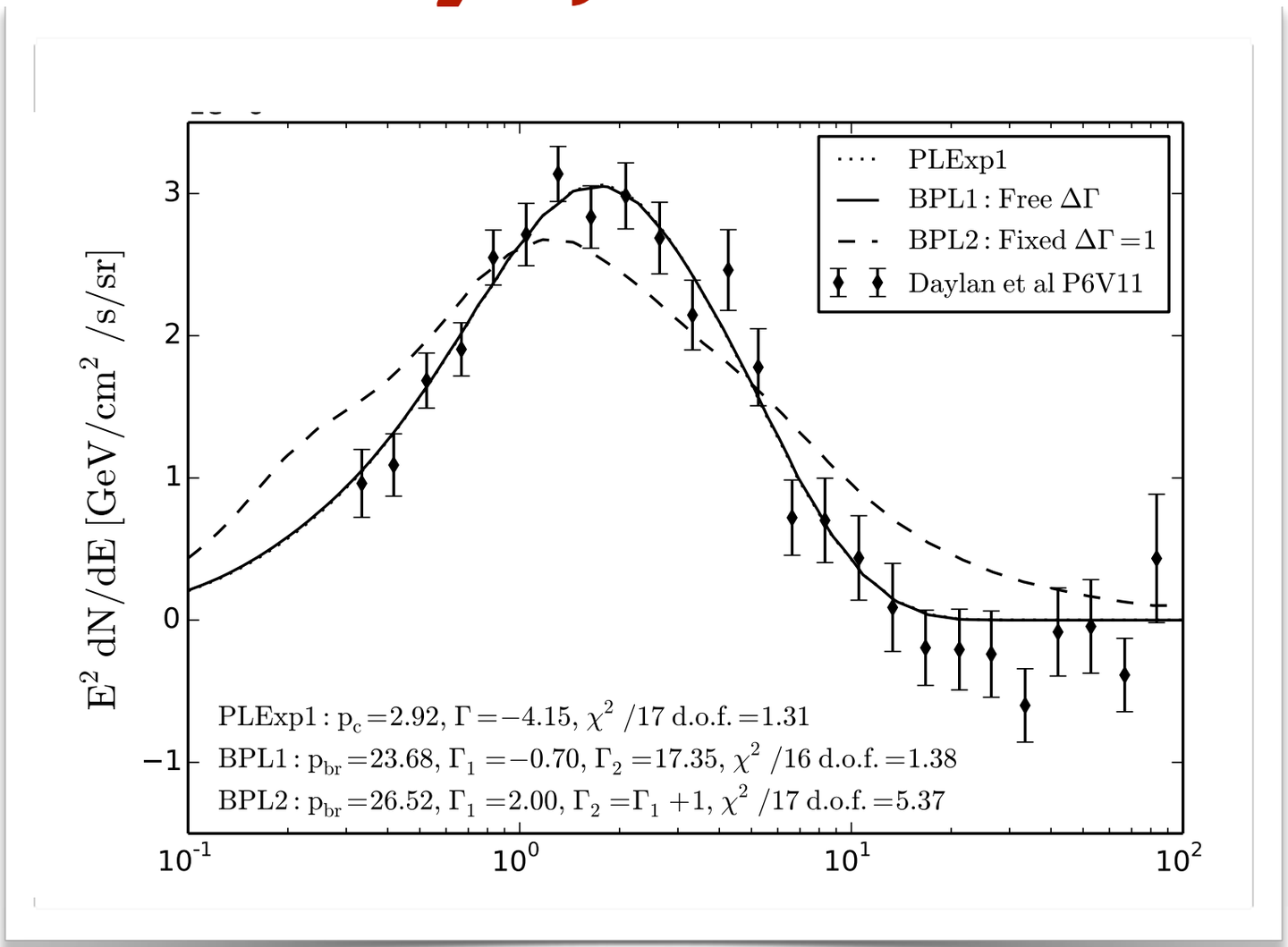
Estimate unresolved pulsar population from X-ray binaries
(correlated precursors of MSPs)

If MSP, FGST should have seen more point sources
Must be unusual population

Existing spectra should have radically different spatial extent

Stacked MSP spectra from known sources bad fit for $E < 1$ GeV

Cosmic Rays, SN Remnants?



$\sim 10^{52}$ erg **bursts of CR from SN ~ 1,000,000 yr. timescales**

Recent injection ~ 1 kyr ago accounts for inner GC intensity

Gamma rays from CR proton emission spectra provide good fit

Cosmic Rays, SN Remnants?

However:

***Requires CR protons with monochromatic spectrum**
Incompatible with more realistic "broken power law" model

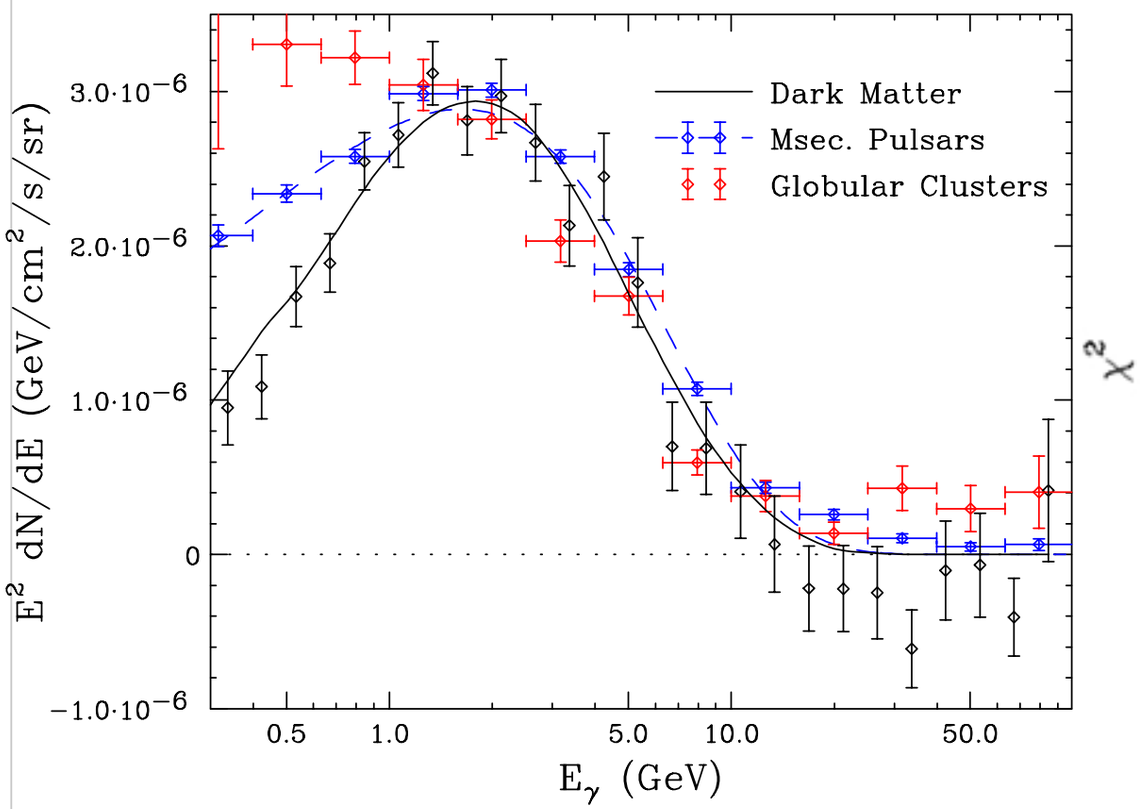
***If dominated by protons?**
Scatter off galactic gas distribution, profile becomes less spherical

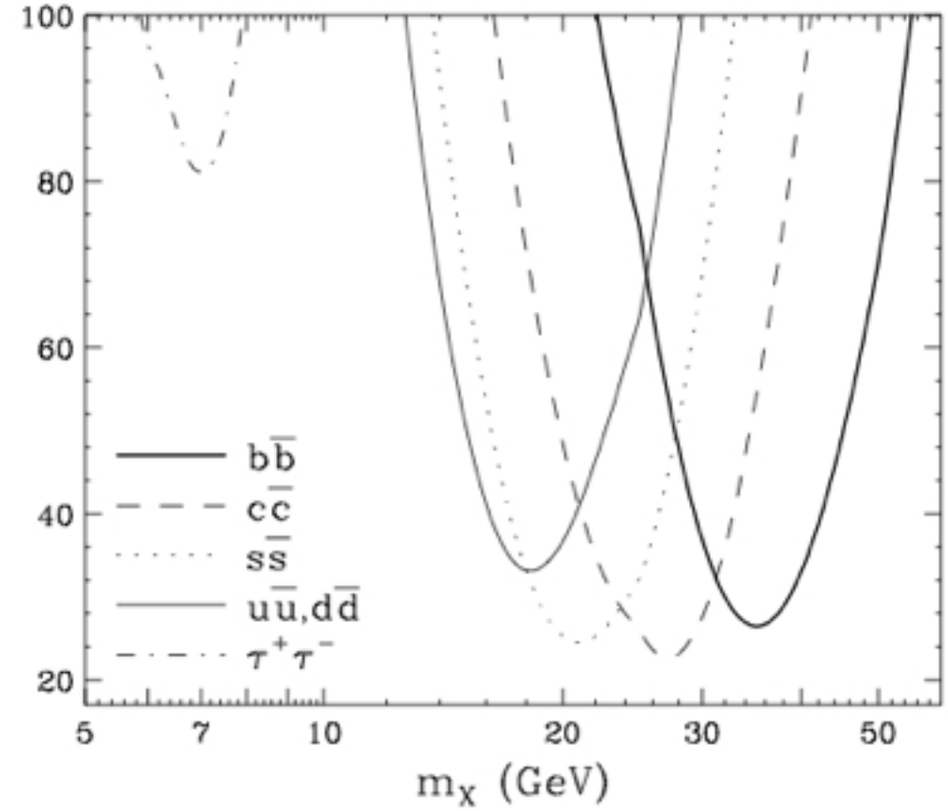
***If dominated by electrons?**
Gamma emission more spherical, but Bremsstrahlung is not

*claims from Cholis, Hooper, Linden 1407.5625

Verdict: Astrophysical mechanisms may be viable, but it's currently unclear

Dark Matter?





$$\Phi(E_\gamma, \psi) = \frac{\sigma v}{8\pi m_X^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \int_{\mathrm{los}} \rho^2(r)\, \mathrm{d}l, \qquad \rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

Direct annihilation favors b or tau final states

30 GeV DM for b, 10 GeV for tau (slightly worse)

Model Building Challenges

Need s-wave annihilation cross section

$$v_{DM,GC} \sim 10^{-2} - 10^{-3}$$

Couple preferentially to b's and/or taus*

Higgs portal? (see Jessie's talk)

Suppressed direct detection signals

Hide from LUX, need loop and/or spin dependence

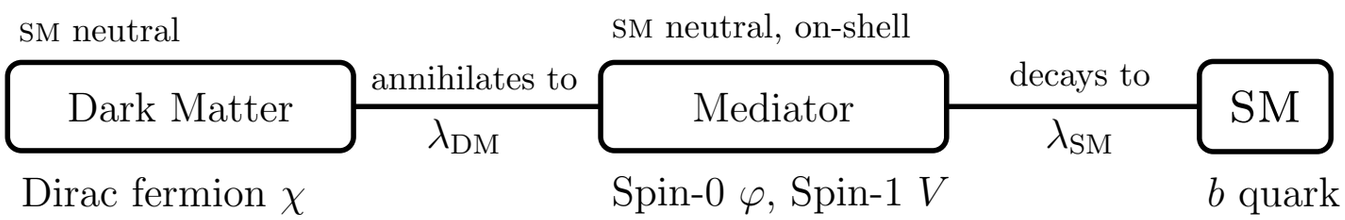
Evade mono-photon & mono-jet searches

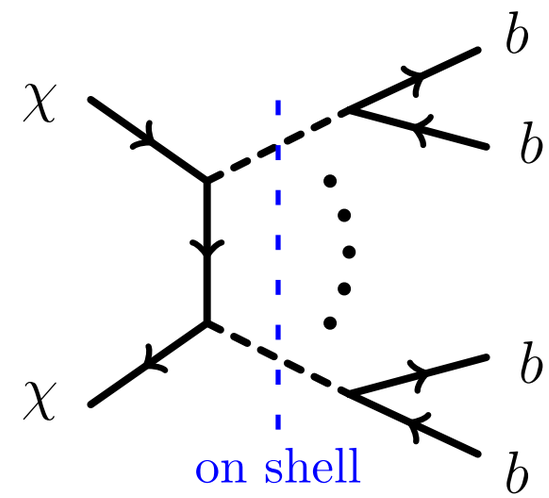
Straightforward if mostly coupled to 3rd gen (esp. b)

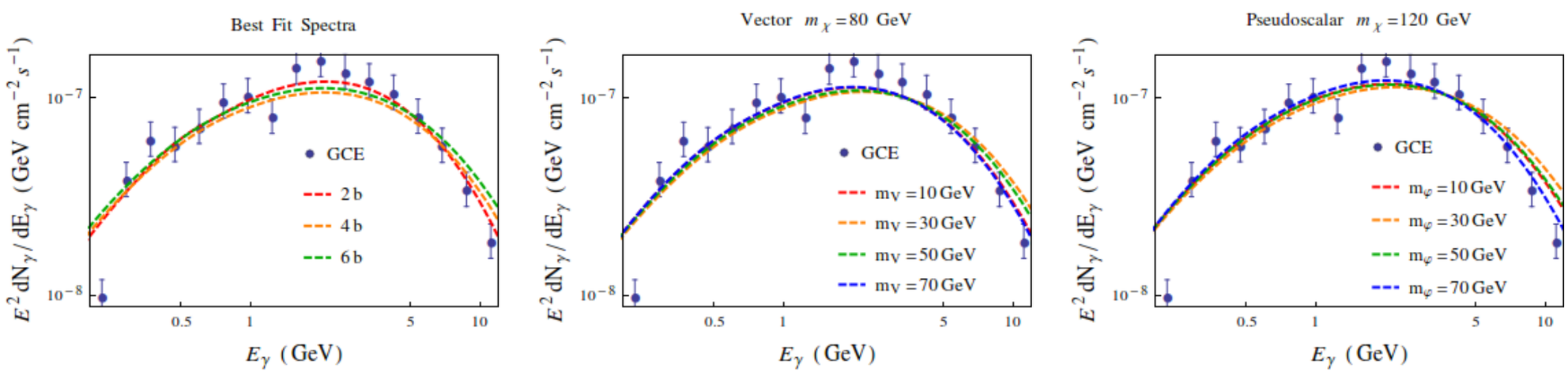
Caveat: "Tough" Scenario

Annihilate to on-shell Dark Mediator

Rajaraman, Tait, Tanedo, et. al. 1404.6528
Martin, Unwin, Shelton 1405.0272







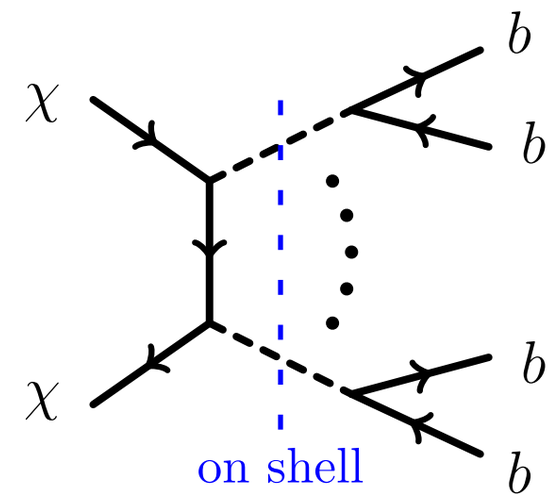
(a) Comparison (b) Spin-1 (c) Spin-0

Great fit, but…

Caveat: "Tough" Scenario

Annihilate to on-shell Dark Mediator

… feature or bug:



DM mass can be (almost) anything

SM-mediator coupling (relatively) unconstrained

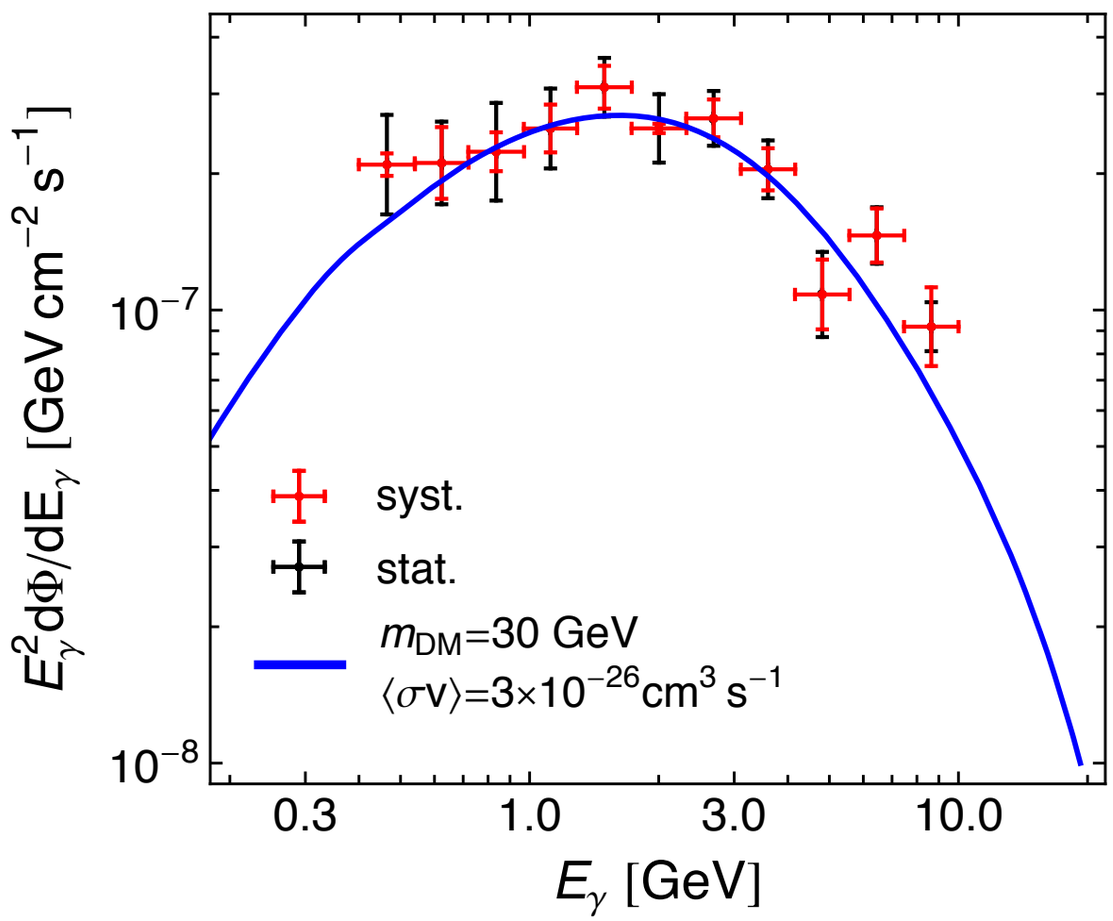
Coupling to b-quarks further suppresses mediator production @ LHC

Mediator is SM singlet > 10 GeV, hard to see in dark force searches

Caveat: "Nightmare" Scenario

"Coy" Dark Matter

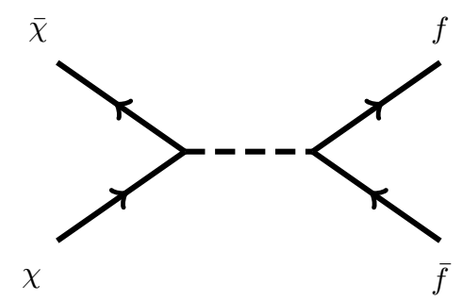
Boehm, Dolan et. al. 1401.6458



DM is a thermal relic fermion

Yukawa weighted couplings

Annihilates mainly to $\bar{b}b$



"Light" pseudoscalar mediator

$$m_a < 2m_\chi$$

$$\mathcal{L} \supset -i\frac{g_{\rm DM}}{\sqrt{2}}a\bar{\chi}\gamma^5\chi - i\sum_f \frac{g_f}{\sqrt{2}}a\bar{f}\gamma^5 f + \text{h.c.}$$

Viable, minimal* model

Great fit, but…

Caveat: "Nightmare" Scenario

"Coy" Dark Matter

Direct Detection:

Spin-dep. & yukawa suppression at LUX

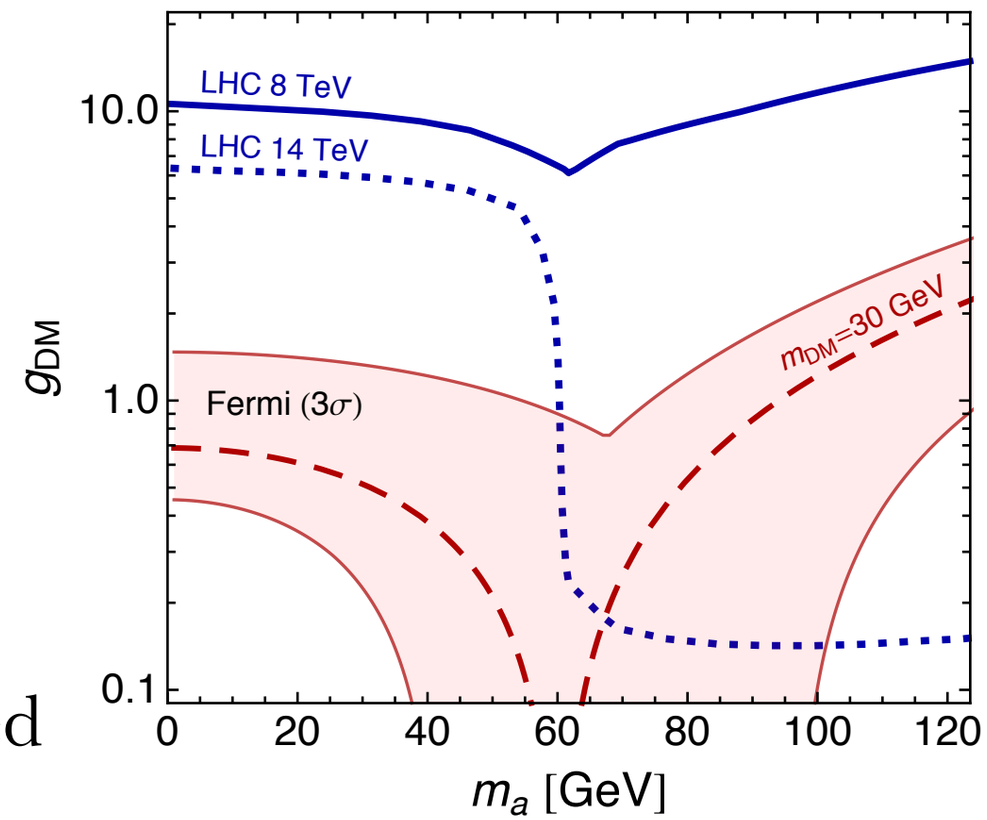
LHC signatures:

Small SM-mediator coupling

3rd gen. couplings, production suppressed

Mediator can't decay to MET

Inv. mass below dijet search thresholds



Boehm, Dolan et. al. 1401.6458

Verdict: we may never know (not snark, this was their point)

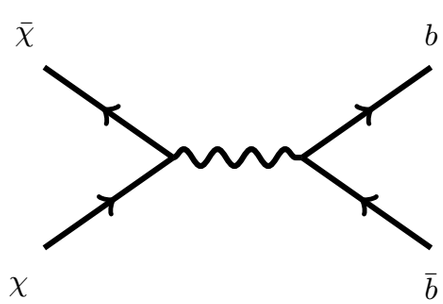
Discovery/ Debunking Strategy

Take quoted best fits (for *b*-annihilation) at face value:

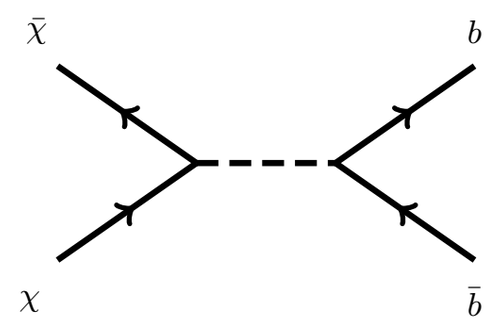
$$\begin{aligned} \langle \sigma v \rangle &= (5.1 \pm 2.4) \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1} \quad , \\ m_\chi &= 39.4\ (^{+3.7}_{-2.9}\ \mathrm{stat.})(\pm 7.9\ \mathrm{sys.})\ \mathrm{GeV} \end{aligned}$$

Fermionic* DM and singlet mediators coupled only to *b***

$$m_{med} > 2m_\chi \quad \text{(un-“coy”)}$$



$$\begin{aligned} \mathcal{L}_U &= \left(g_\chi \bar{\chi}\gamma^\mu\gamma^5\chi + g_b \bar{b}\gamma^\mu\gamma^5 b\right) U_\mu \\ \mathcal{L}_V &= \left(g_\chi \bar{\chi}\gamma^\mu\chi + g_b \bar{b}\gamma^\mu b\right) V_\mu \quad , \\ \mathcal{L}_a &= i\left(g_\chi \bar{\chi}\gamma^5\chi + g_b \bar{b}\gamma^5 b\right) a \quad , \end{aligned}$$



Agnostic about cosmology, other couplings etc…

Analysis applies to any viable direct-annihilation scenario

How do we learn more?

More GC Data?

No: Already huge statistical significance > 40 sigma

"I don't even know if I exist to a 40-sigma confidence" - Tim Tait

Dwarf Galaxies?

Not yet: takes many years, large astrophysical uncertainties in profiles

If BH in dwarves, it's already dead Profumo et. al. 1406.2424

Similar issue w/ Sgr A* & DM "spikes" Fields, Shapiro, Shelton 1406.4856

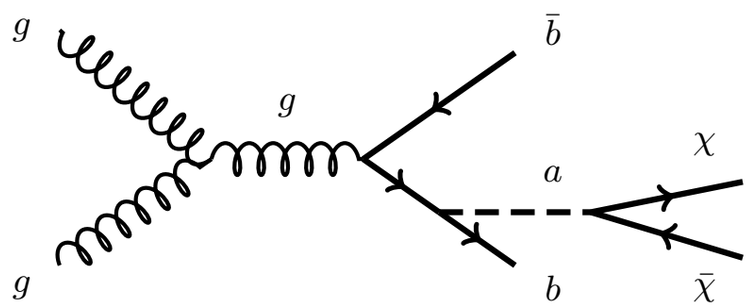
Direct Detection?

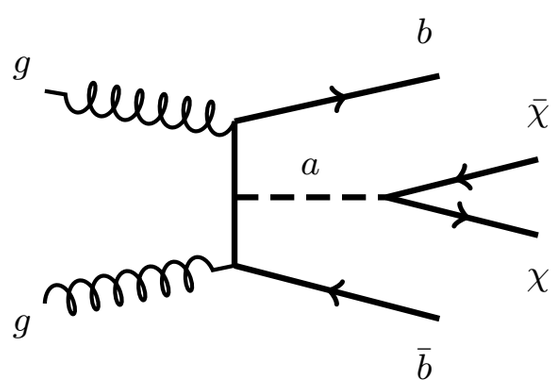
Yes: By stipulation, the signal is tiny, but it's not impossible to learn more here

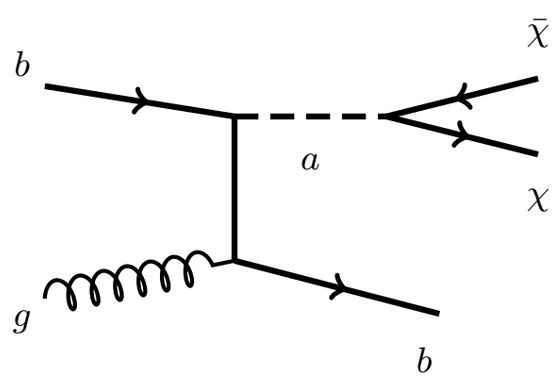
LHC?

Yes: need optimized 3rd gen searches for more model independent searches

LHC Production







Similar processes for *U*&*V* and b-jet decays

Mediator yields DM (MET)

$$pp \;\rightarrow\; (U/V/a \rightarrow \chi\bar{\chi}) + X_{\rm sm},$$

Sbottom signature

$$X_{\rm sm} = b\bar{b}$$

Mono-b signature

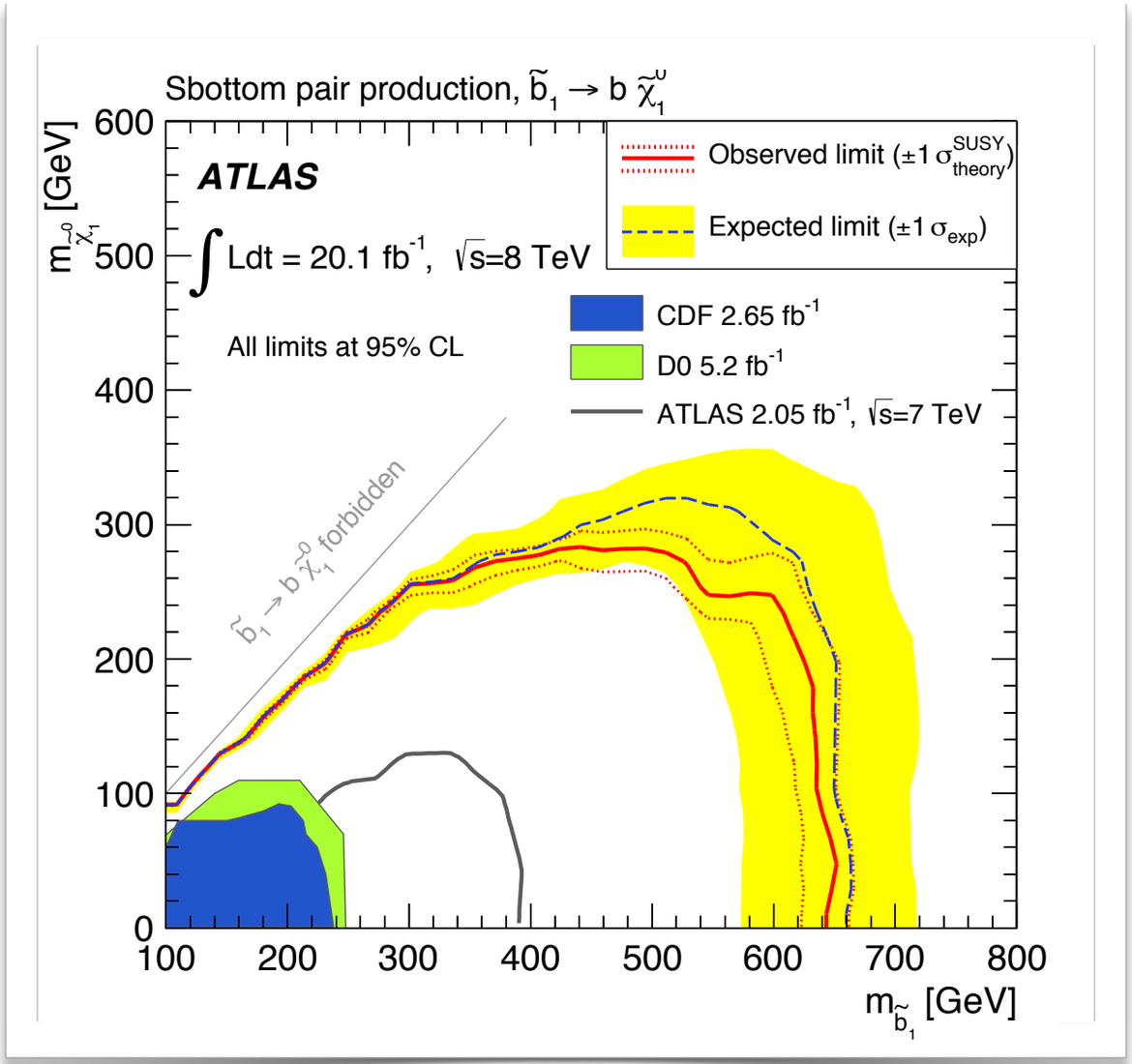
$$X_{\rm sm} = \not{E}_T + b$$

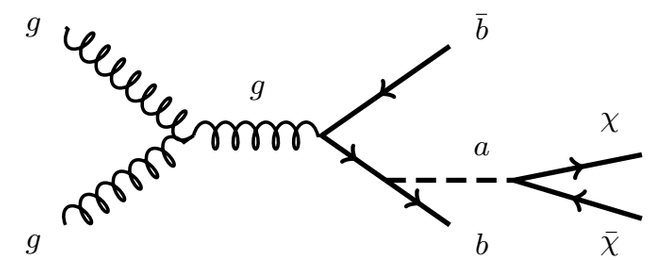
Mediator yields b-jets:

$$pp \;\rightarrow\; (U/V/a \rightarrow b\bar{b}) + b \text{ jets.}$$

Higgs signautre

Existing ATLAS Sbottom Search



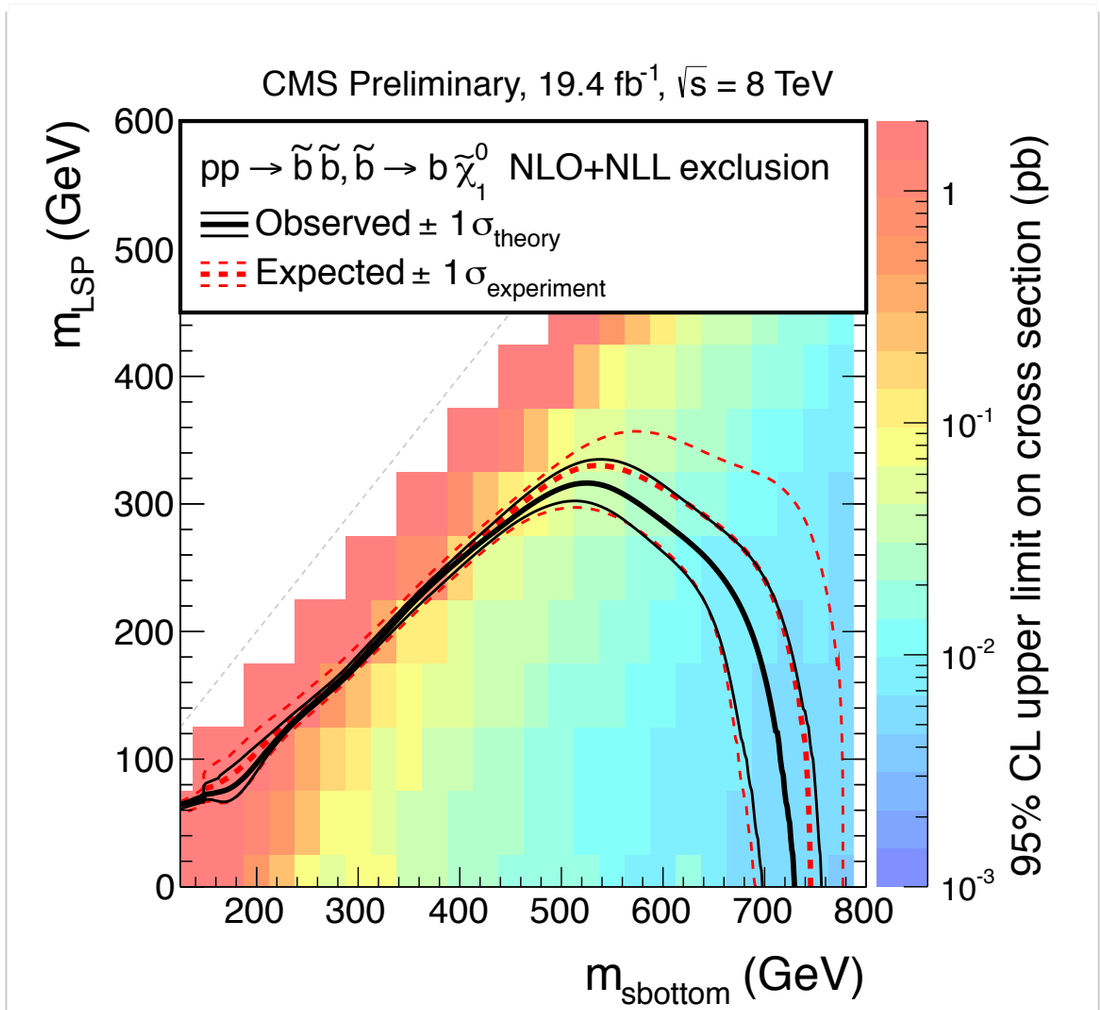


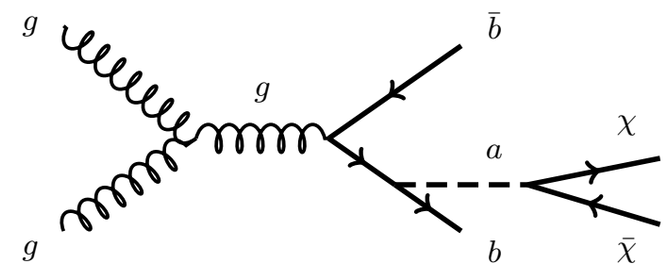
Description	Signal Regions	
	SRA	SRB
Event cleaning	Common to all SR	
Lepton veto	No e/μ after overlap removal with $p_{\mathrm{T}} > 7(6)$ GeV for $e(\mu)$	
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 250 GeV
Leading jet $p_{\mathrm{T}}(j_1)$	> 130 GeV	> 150 GeV
Second jet $p_{\mathrm{T}}(j_2)$	> 50 GeV,	> 30 GeV
Third jet $p_{\mathrm{T}}(j_3)$	veto if > 50 GeV	> 30 GeV
$\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, j_1)$	-	> 2.5
b-tagging	leading 2 jets ($p_{\mathrm{T}} > 50$ GeV, $\lvert\eta\rvert < 2.5$)	2nd- and 3rd-leading jets ($p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 2.5$)
	$n_{b\text{-jets}} = 2$	
$\Delta\phi_{\mathrm{min}}$	> 0.4	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(k)$	$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(2) > 0.25$	$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(3) > 0.25$
m_{CT}	$> 150, 200, 250, 300, 350$ GeV	-
$H_{\mathrm{T},3}$	-	< 50 GeV
m_{bb}	> 200 GeV	-

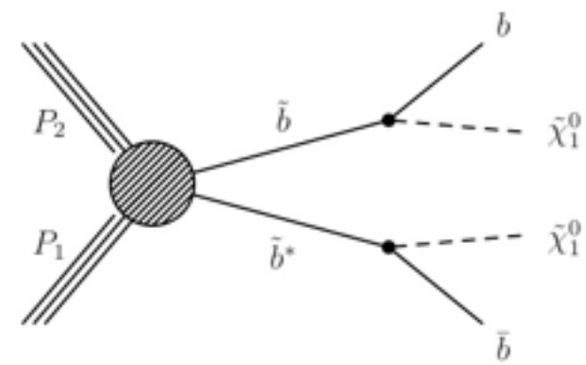
hep-ex/1308.2631

$$m_{\mathrm{CT}}^2(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\boldsymbol{p}_{\mathrm{T}}(v_1) - \boldsymbol{p}_{\mathrm{T}}(v_2)]^2$$

Existing CMS Sbottom Search



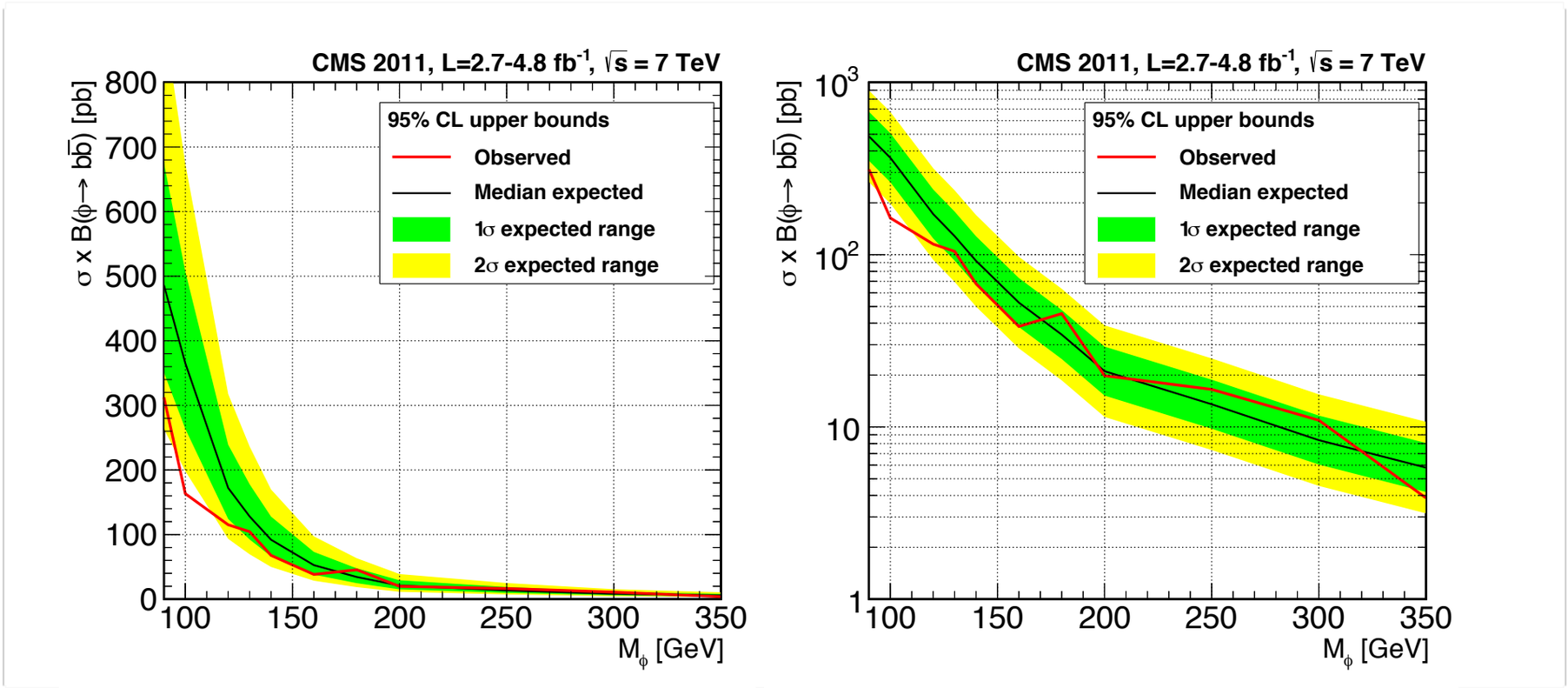


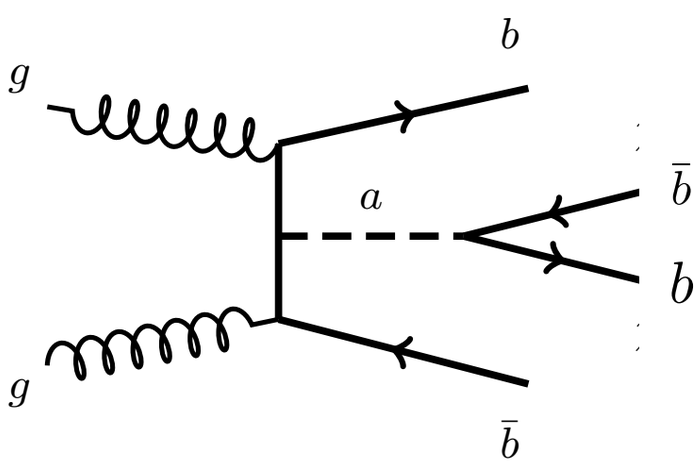


Requirements			
Jet	Lepton	b-jet	Kinematics
Signal region			
Two Central Jets Veto 3rdjet, p_T >50 GeV	lepton(e and μ) veto Isolated Track veto	$N_{\text{b-jets}}$=1,2 Medium WP	$M_T(J_2, E_T^{miss}) > 200$ GeV, $H_T > 250$ GeV $E_T^{miss} > 175$ GeV and $\Delta\phi(J_1, J_2) < 2.5$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13018

Existing CMS Higgs multi-*b* Search





Hardest 3 bjets satisfy

$$p_T > 46, 38, 60 \text{ GeV}, \quad (60, 53, 20 \text{ GeV})$$

Leading 2 jet separation

$$\Delta R > 1$$

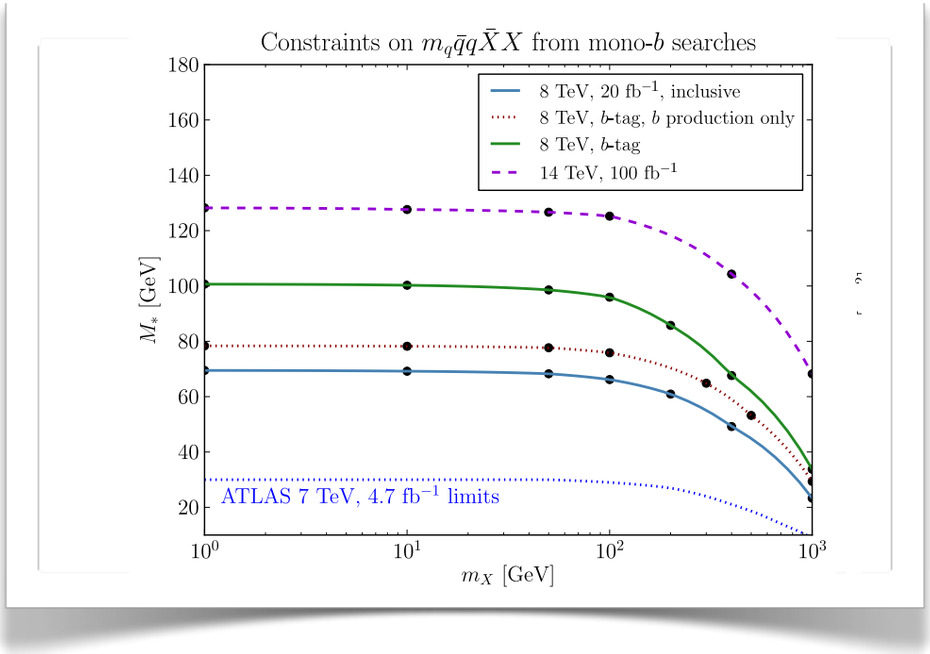
Other *b*-rich Higgs searches subdominant

Proposed Mono-*b* Search

Lin, Kolb, Wang 1303.6638

$$\mathcal{O} = \frac{m_q}{M_*^3}\bar{q}q\bar{X}X,$$

EFT proof of principle



Proposed selection criteria:

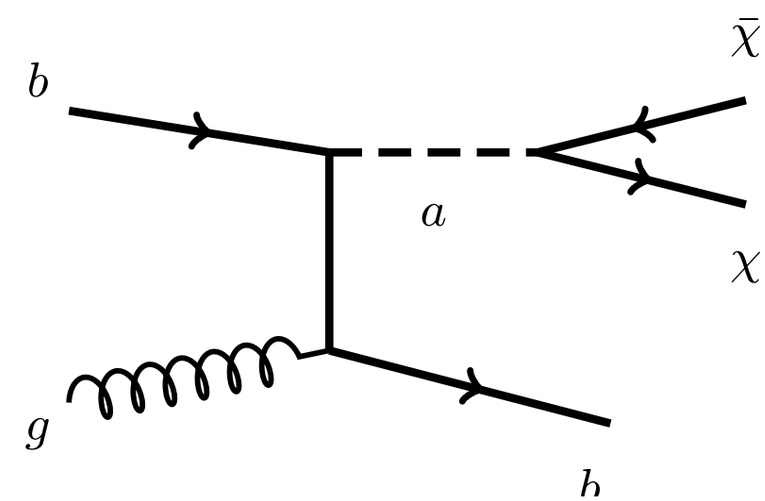
Leading b-jet: $p_T > 100$ GeV, $|\eta| < 2.5$,

Large MET: $\not{E}_T > 350$ GeV,

< 3 additional, softer jets: $p_T > 50$ GeV.

Suppress mismeasured dijet BG: $\Delta\phi(\not{E}_T, p_T^{j_2}) > 0.4$,

No isolated leptons



MC Simulation

Partonic LHC events generated using MadGraph 5

Hadronization/Parton Shower in Pythia 6

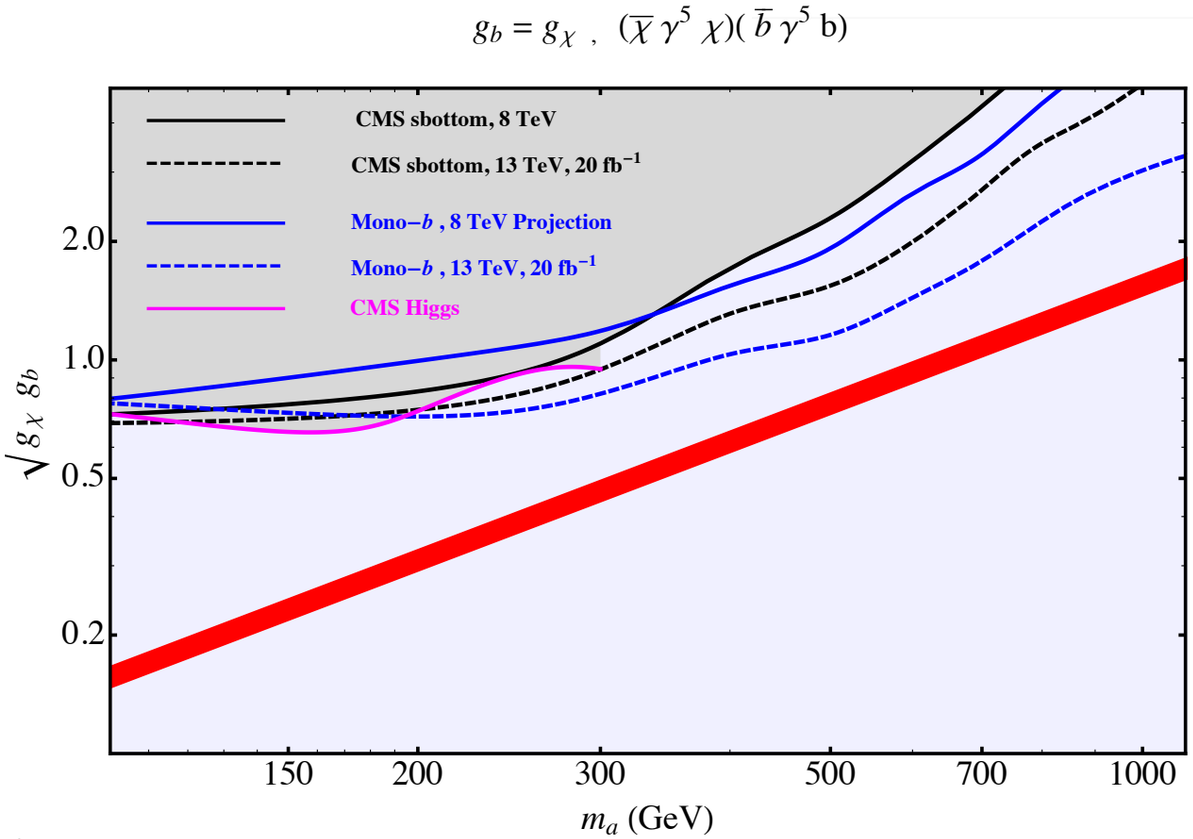
ATLAS/CMS Detector Simulations in PGS

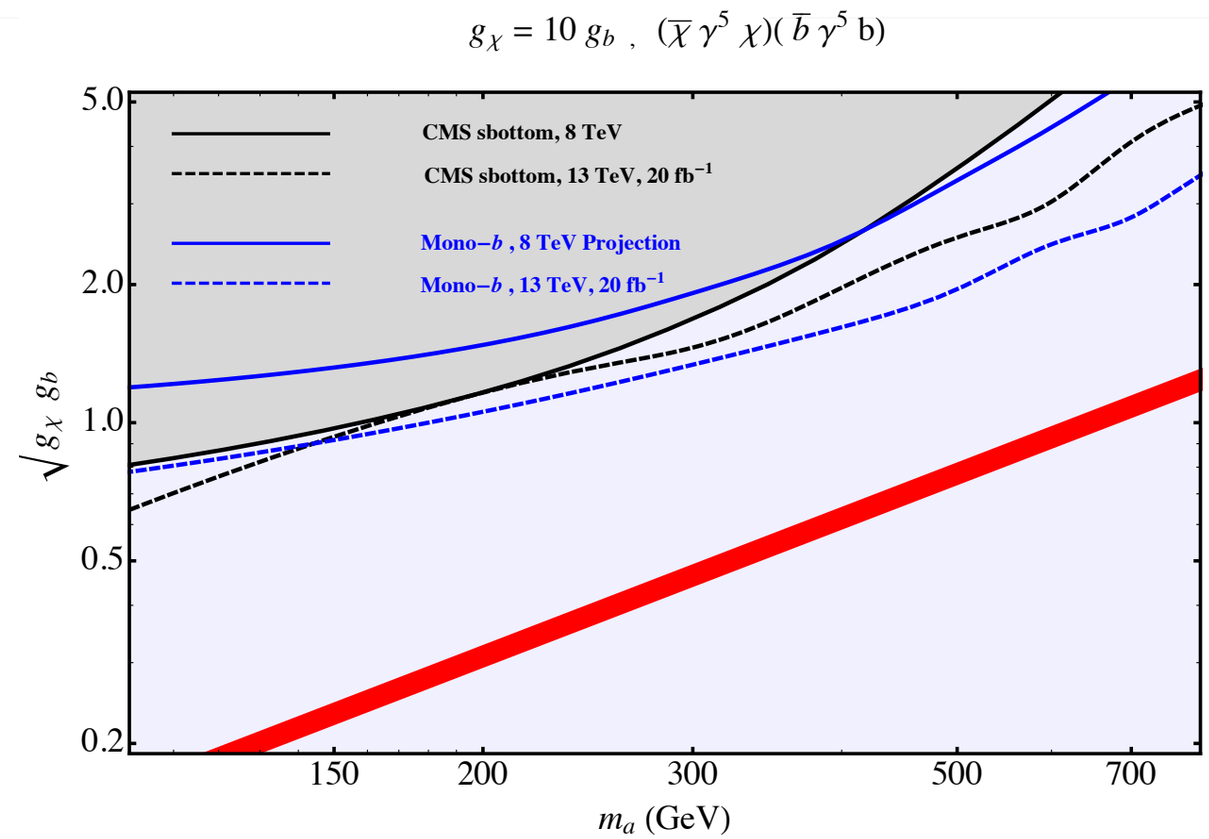
BG NLO K-factors calculated in MCFM

Full on-shell mediator production and decay

LHC Limits & Projections

Pseudoscalars Remain elusive post upgrade





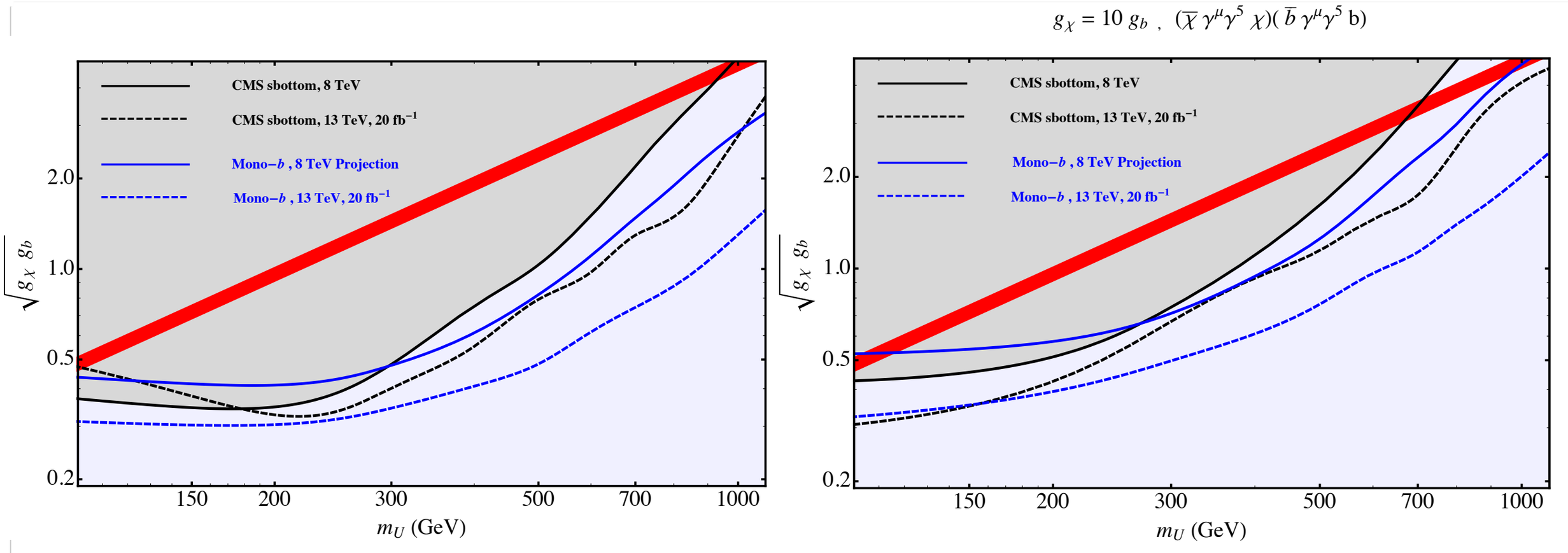
GC favored region

$$\begin{aligned} \langle \sigma v \rangle &= (5.1 \pm 2.4) \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1} \quad , \\ m_\chi &= 39.4\ (^{+3.7}_{-2.9}\ \mathrm{stat.})(\pm 7.9\ \mathrm{sys.})\ \mathrm{GeV} \end{aligned}$$

$$\langle \sigma v \rangle_a \simeq \frac{N_c}{2\pi} \frac{(g_\chi g_b)^2\, m_\chi^2 \sqrt{1 - m_b^2/m_\chi^2}}{\left(m_a^2 - 4m_\chi^2\right)^2 + m_a^2 \Gamma_a^2}$$

LHC Limits & Projections

Axial-vector mediator



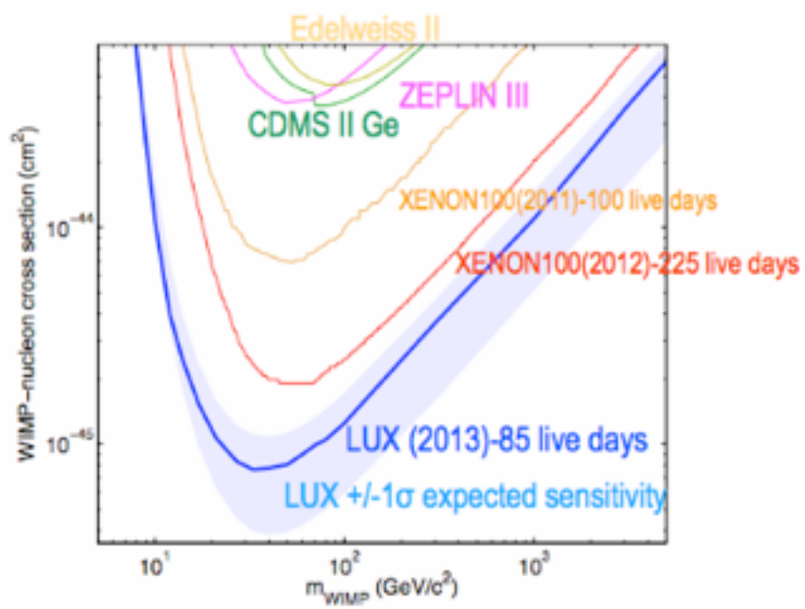
GC favored region

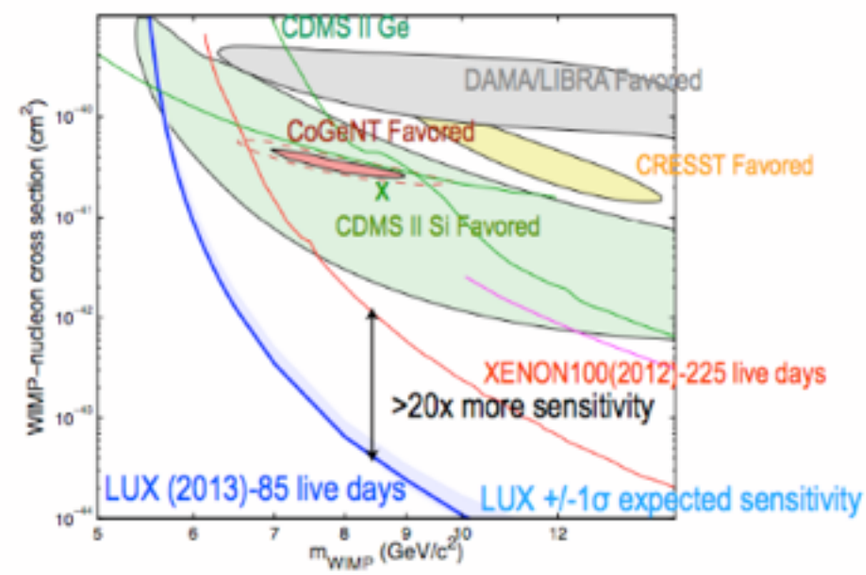
$$\langle \sigma v \rangle = (5.1 \pm 2.4) \times 10^{-26}\ \mathrm{cm^3 s^{-1}} \ ,$$
$$m_\chi = 39.4\ (^{+3.7}_{-2.9}\ \mathrm{stat.})(\pm 7.9\ \mathrm{sys.})\ \mathrm{GeV}$$

$$\langle \sigma v \rangle_U \simeq \frac{N_c}{2\pi} \frac{(g_\chi g_b)^2 m_b^2 (1 - 4m_\chi^2/m_U^2)^2 \sqrt{1 - m_b^2/m_\chi^2}}{\left(m_U^2 - 4m_\chi^2\right)^2 + m_U^2 \Gamma_U^2} ;$$

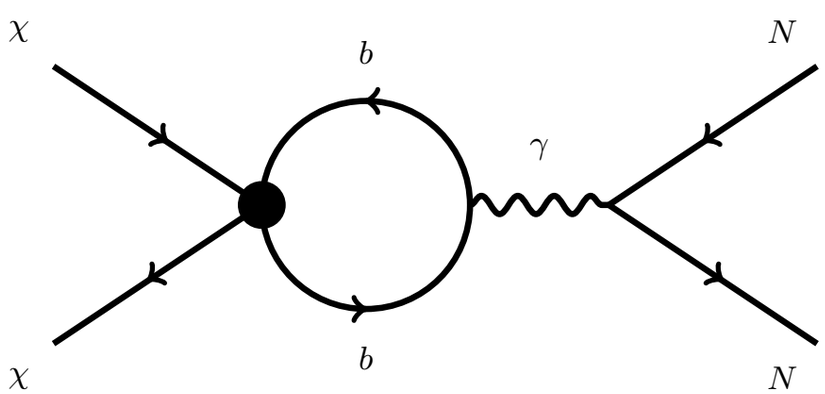
Direct Detection Aside

Bad news for vectors





Loop level recoils signals in the simplified model



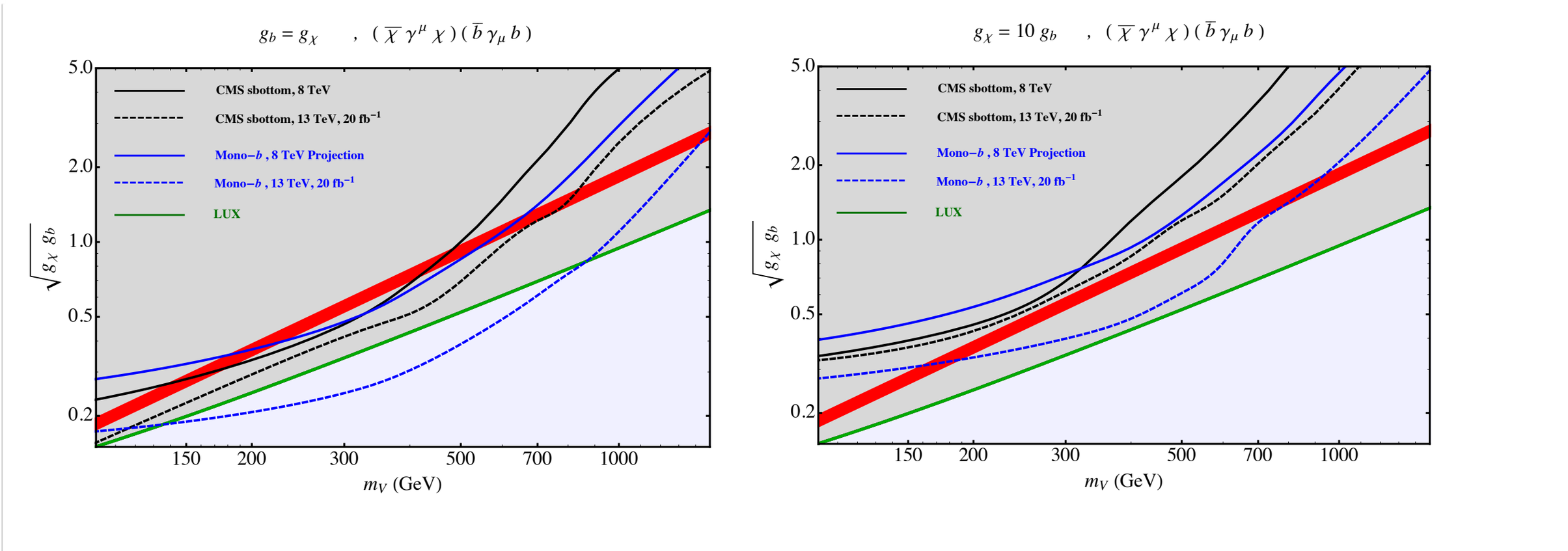
$$\frac{d\sigma}{dE} = \frac{(g_b g_\chi)^2\, m_{\rm T}}{18\pi v^2\, m_V^4} \left(\frac{\alpha Z}{\pi}\right)^2 F^2(E) \left[\log\left(\frac{m_b^2}{m_V^2}\right)\right]^2$$

$$\frac{dR}{dE} = \frac{\rho_\chi}{m_\chi m_{\rm T}} \int_{v_{\rm min}(E)}^{v_{\rm esc}} d^3v\, f_\odot(\vec{v}, v_0)\, v\, \frac{d\sigma}{dE}$$

For *a* & *U*, loop traces to zero

LHC Limits & Projections

Vector Mediator



GC favored region

$$\begin{aligned} \langle \sigma v \rangle &= (5.1 \pm 2.4) \times 10^{-26}\ \mathrm{cm^3 s^{-1}} \quad , \\ m_\chi &= 39.4\ (^{+3.7}_{-2.9}\ \mathrm{stat.})(\pm 7.9\ \mathrm{sys.})\ \mathrm{GeV} \end{aligned}$$

$$\langle \sigma v \rangle_V \simeq \frac{N_c}{\pi} \frac{(g_\chi g_b)^2\, m_\chi^2 (1 + m_b^2/2m_\chi^2)\sqrt{1 - m_b^2/m_\chi^2}}{\left(m_V^2 - 4m_\chi^2\right)^2 + m_V^2 \Gamma_V^2}$$

Outlook

Excess still unexplained & DM remains a good fit!

Independently: it's a good benchmark for future DM-3rd gen coupling searches

Many simplified models in tension w LHC or LUX

pseudoscalar mediator strongly favored over alternatives & very hard to kill (c'est la vie)

Sbottom searches *already* powerful @ 7 & 8 TeV

surprisingly set strongest limits using existing data

Proposed mono-b comparable @ 8 TeV

verifies proof of principle beyond EFT, motivates 14 TeV searches

Upgrade can probe interesting parameter space

searches will greatly improve reach

Thanks/Merci!