Searching for Dark Matter at the LHC

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UCIrvine Seminar
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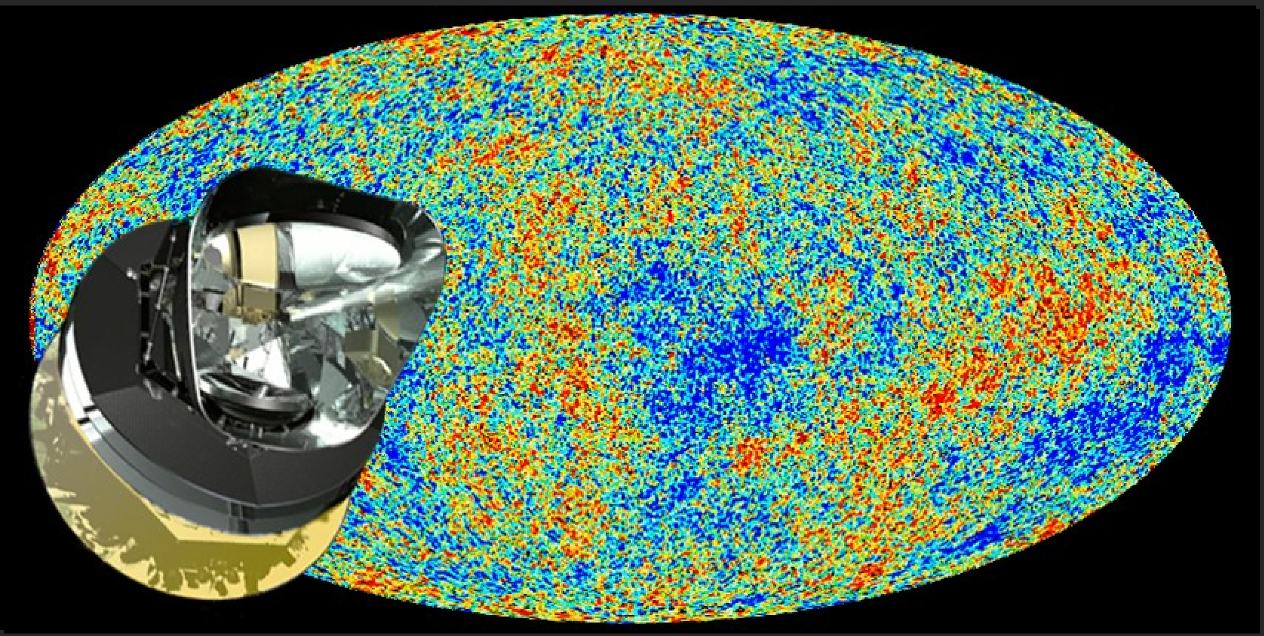
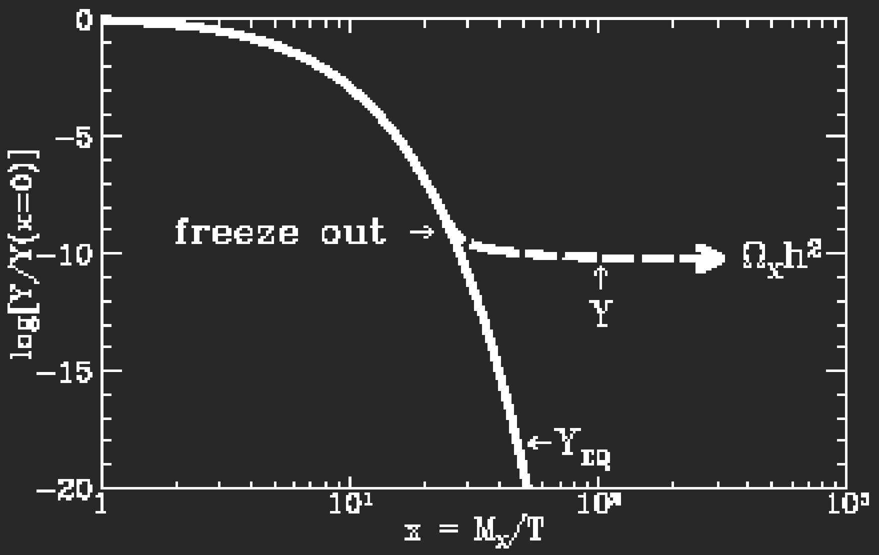
Dark matter, 2014

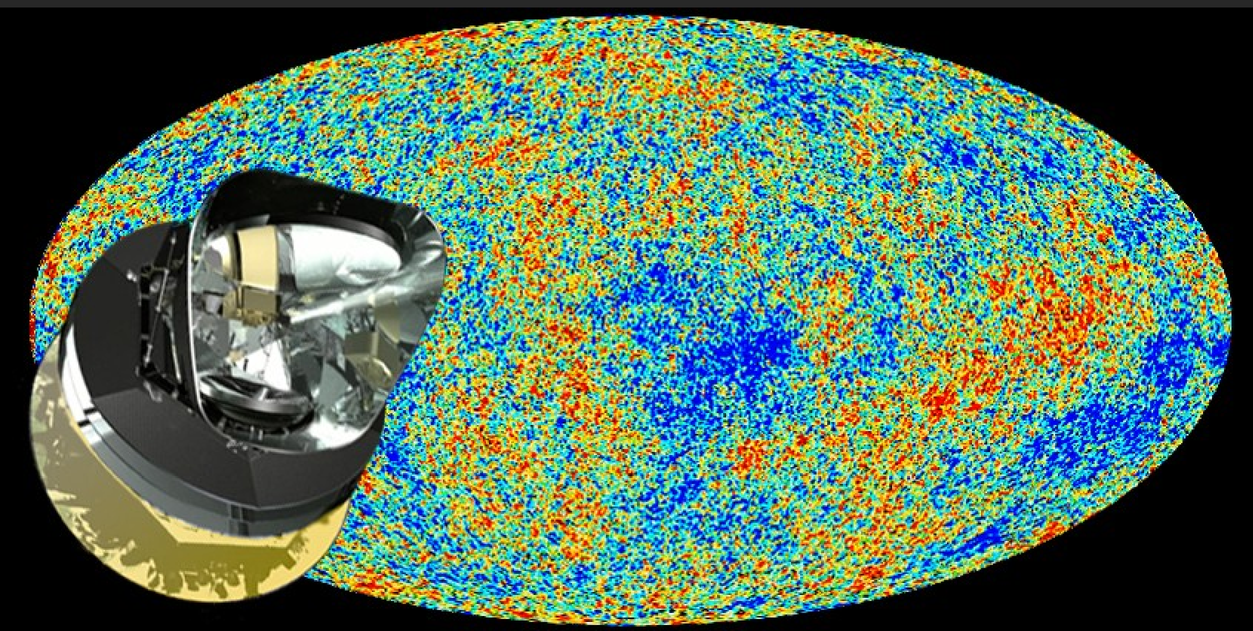


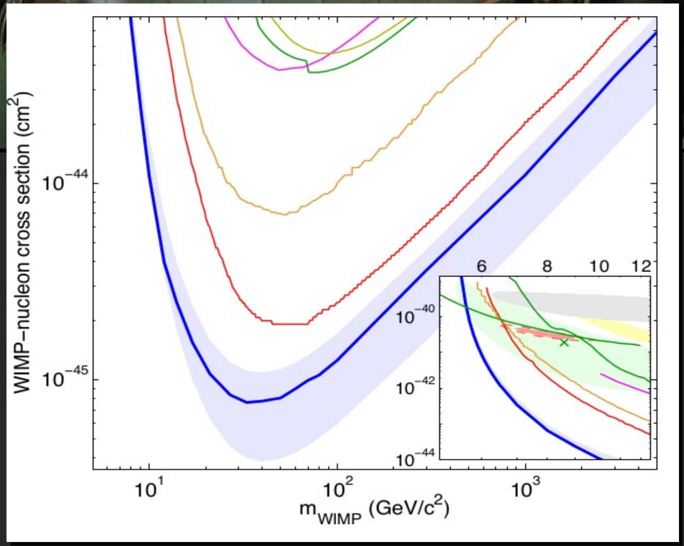
WIMP Miracle

Weak-scale annihilation cross section gets you in the right ballpark to get the right thermal relic abundance



Dark matter, 2014



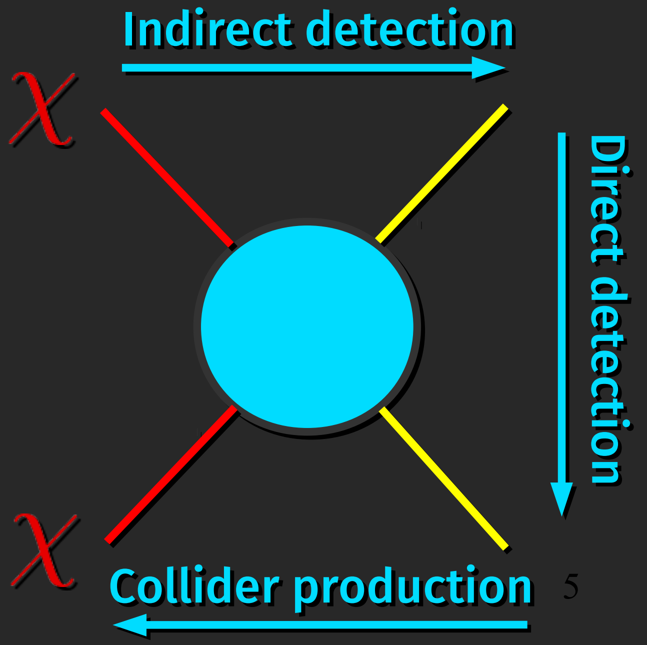


The LHC

- LHC Run 1, 2011-2012
  - 7 and 8 TeV, combined 25/fb
  - Higgs discovery!
- 2015-202?
  - 13-14 TeV, expected 50-100/fb per year
  - SUSY? Dark matter? Something else?

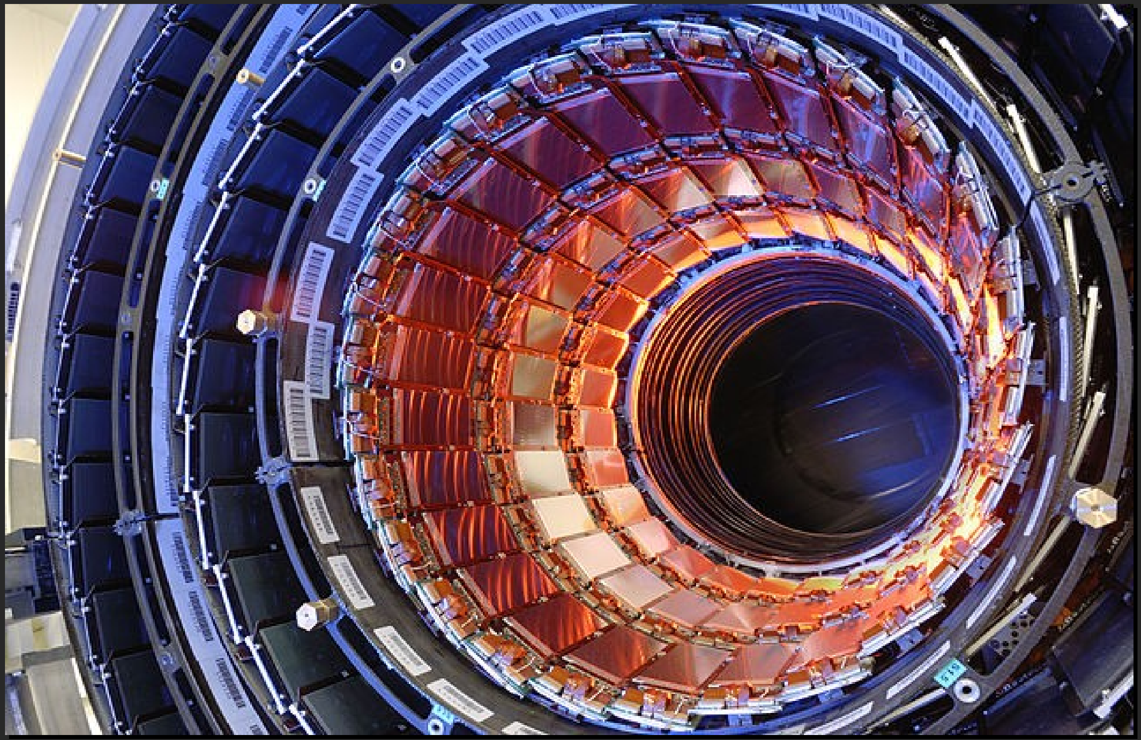
Why dark matter at LHC?

- WIMP miracle?
  - WIMP miracle suggestive of M ~ 100 GeV – 1 TeV
- Connection with new weak scale physics?
  - e.g. natural candidate from SUSY
- Complementarity
  - Cosmic dark matter needs to be detected more than one way!



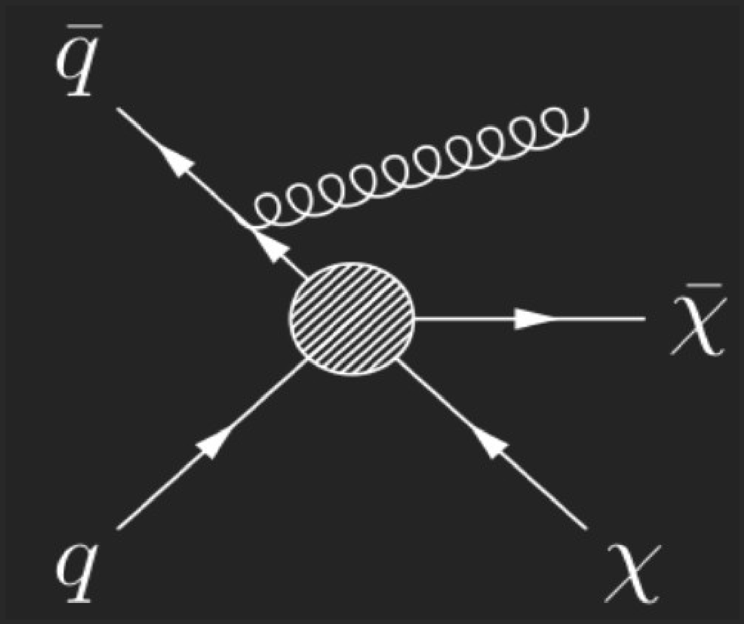
Looking for dark matter at the LHC: new directions

- Contact operator, monojets
  - Assume DM is only new particle relevant at LHC
- Simplified models
  - Study DM plus additional mediator particles



CMS Tracker

“Monojet” searches



Contact operator limit: all new physics at high scale (related to M*), not accessible

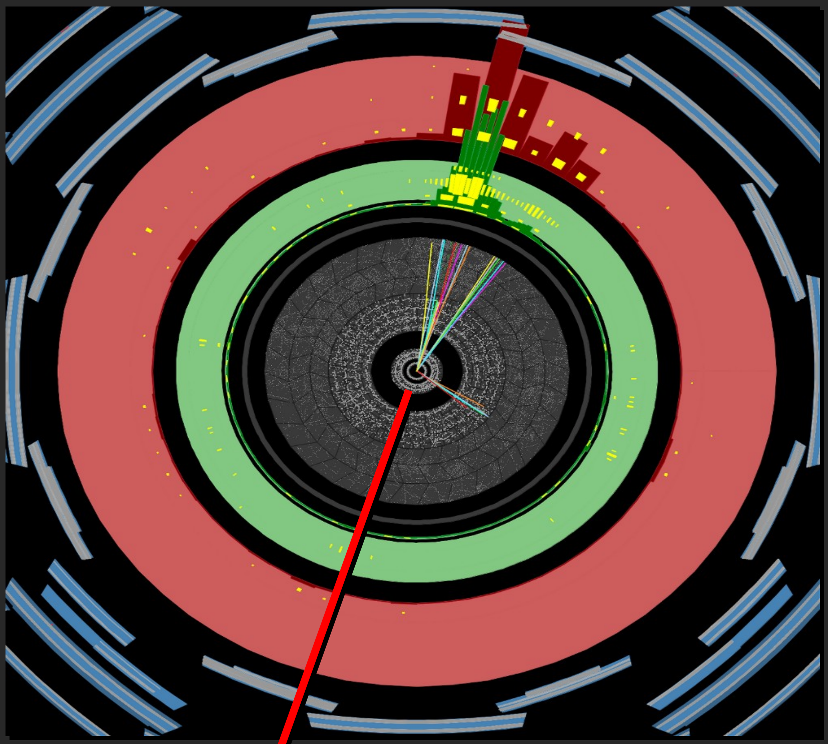
$$\mathcal{O} = \sum_q \frac{m_q}{M_*^3} \bar{q} q \bar{X} X$$

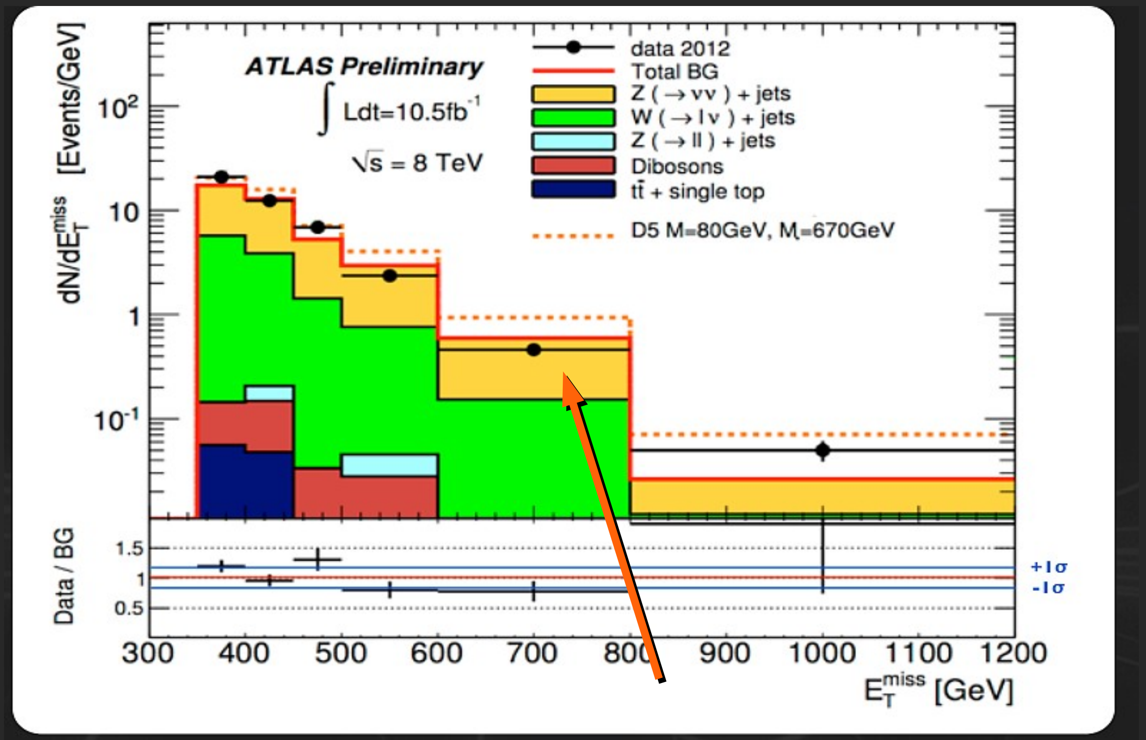
Assume also that DM is a SM gauge singlet

- Simple relation between collider, direct detection, and relic abundance
- Systematic study of contact operators coupled to quarks, gluons, etc.

e.g. Goodman et al., Beltran et al.
Fox, Harnik, Kopp, Tsai

Monojets





Z+jets

MET > 350, 500 GeV

ATLAS monojet event

Note: 8 TeV / CMS searches allow more than one hard jet.

Choices

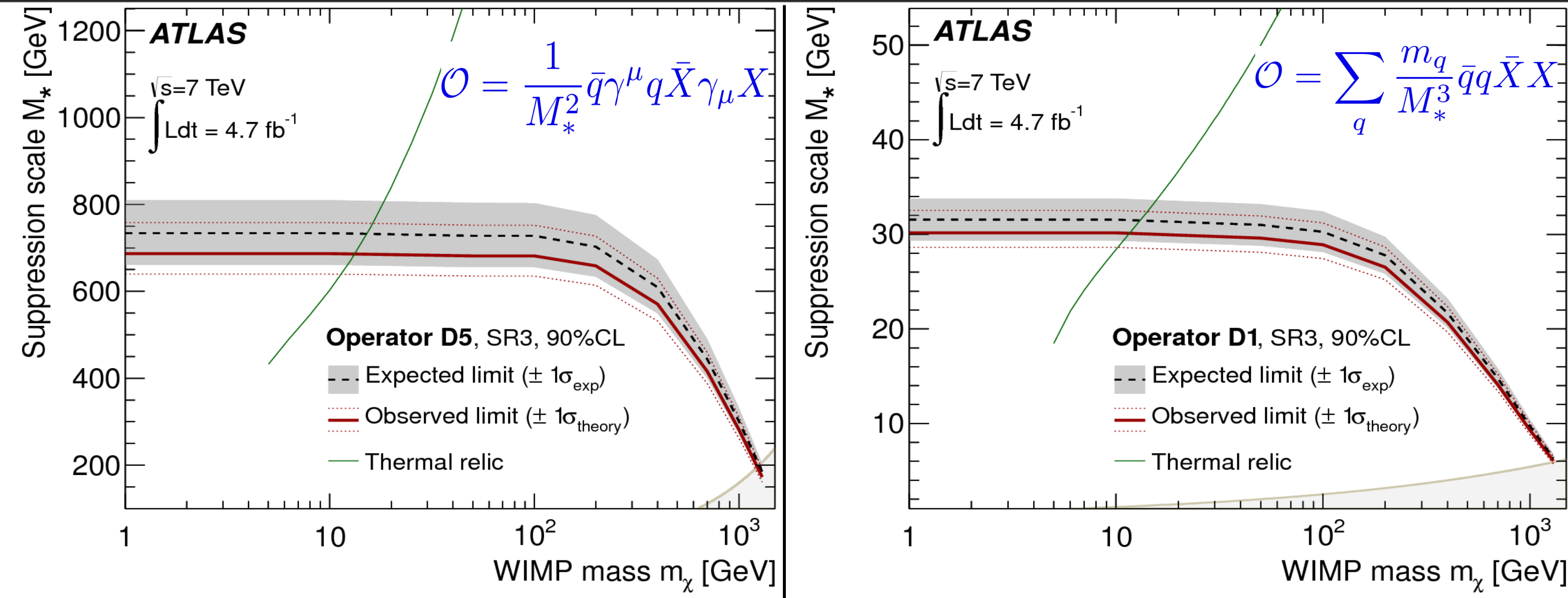
- Fermion/Scalar, Real/Complex
- Lorentz structure
- Quarks, gluons

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu

Limits



Constraints for operators are not very sensitive to specific tensor structure

Only some are relevant for direct detection →

Spin-independent

Spin-dependent

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
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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	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
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C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
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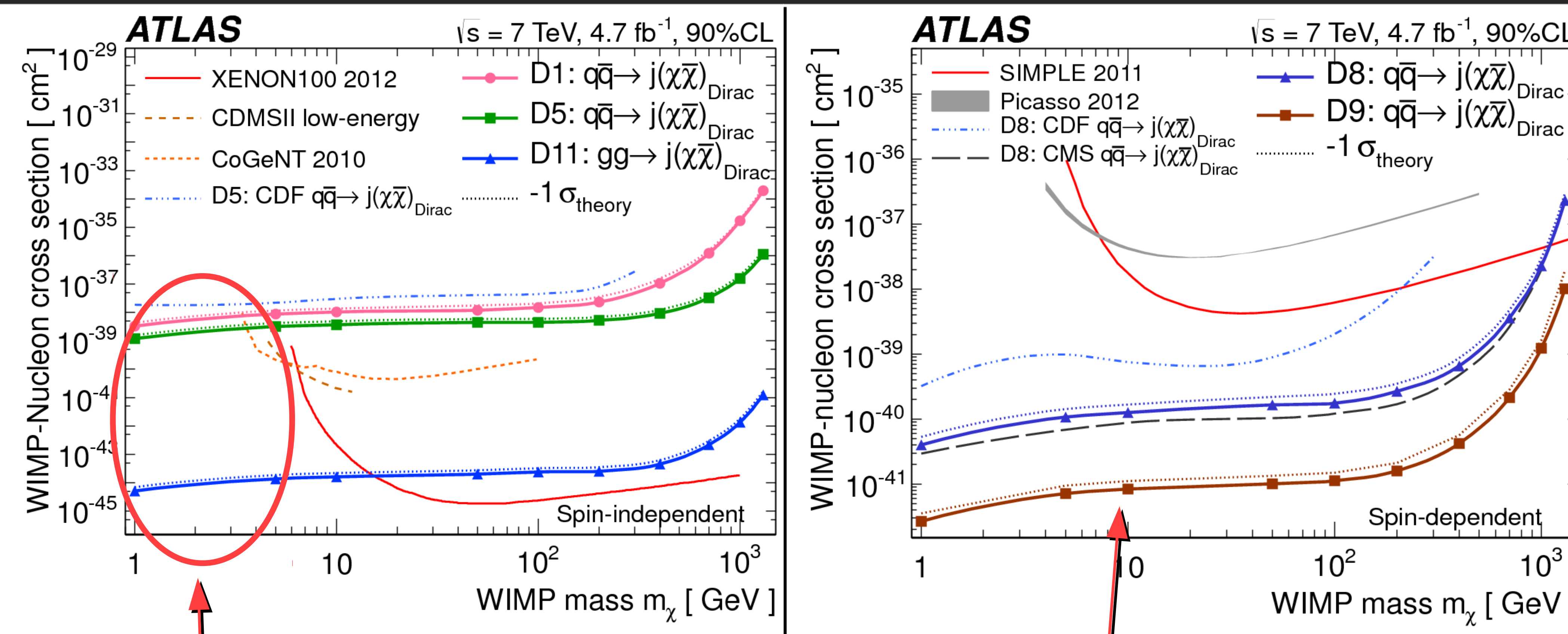
The LHC vs. direct detection



Effective for low mass

Effective vs. spin-dependent

Cost: ~$10 billion vs. ~$10 million (LUX)

BUT, there will be important modifications to this story...

The mono-something field

- Mono-photon
- Mono-W/Z
- Mono-quark vs. mono-gluon
- Mono-*b*, mono-top
- Mono-higgs

- Razor analysis
- NLO corrections

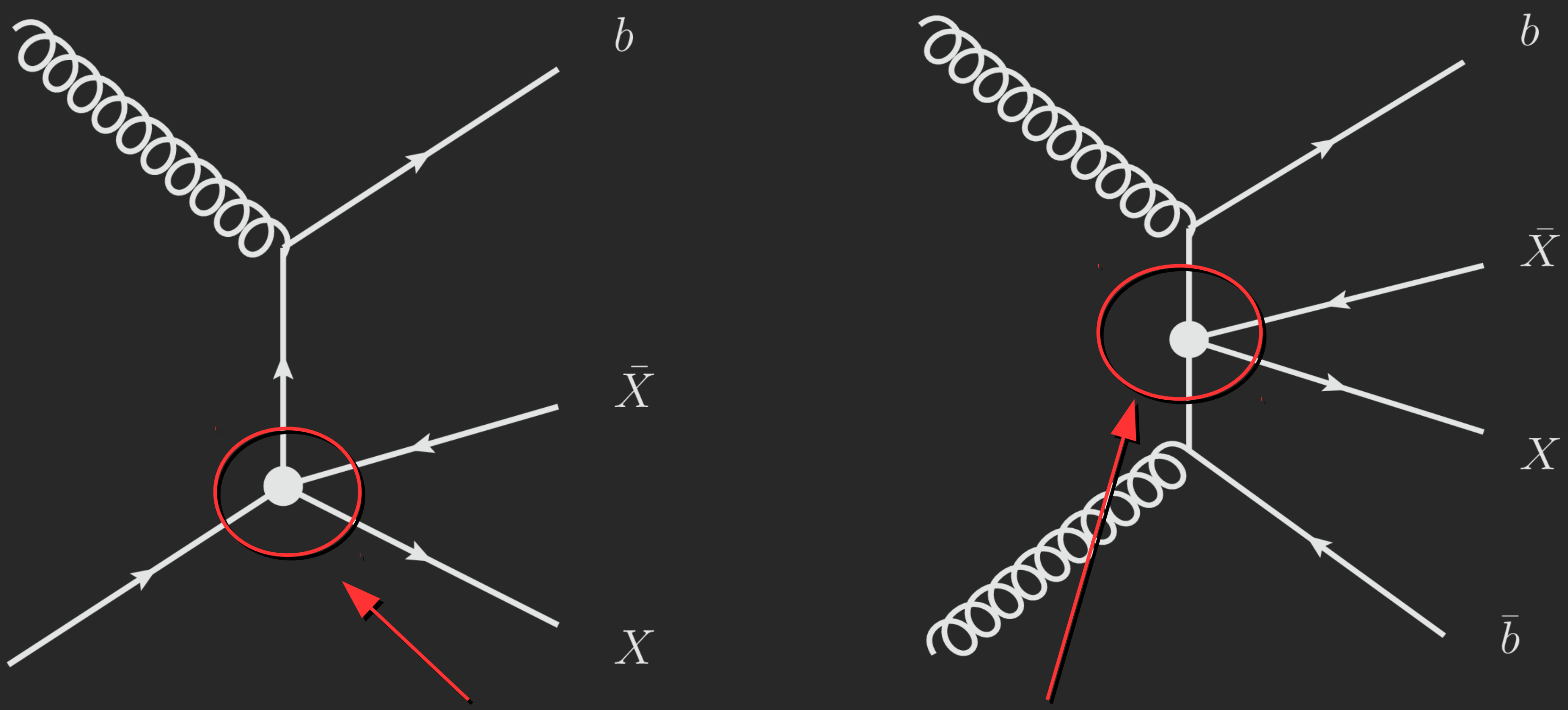
TL, Kolb, Wang, 1303.6638

Mono-b

Scalar operator with MFV form of coupling to quarks

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

Production mechanisms for b-quarks plus MET:



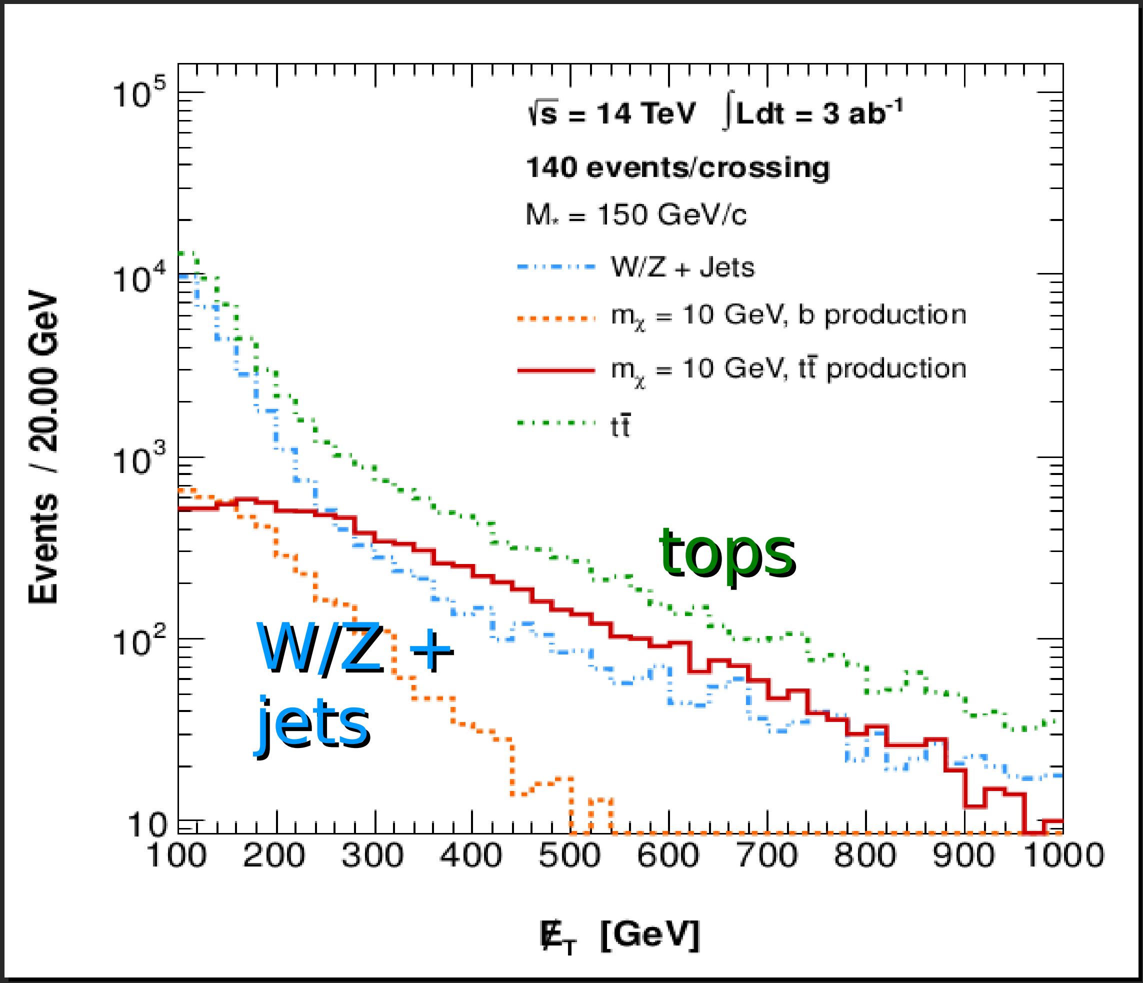
Small b-quark pdf/production is made up by large couplings to b-quarks.

LHC "mono-*b*" search

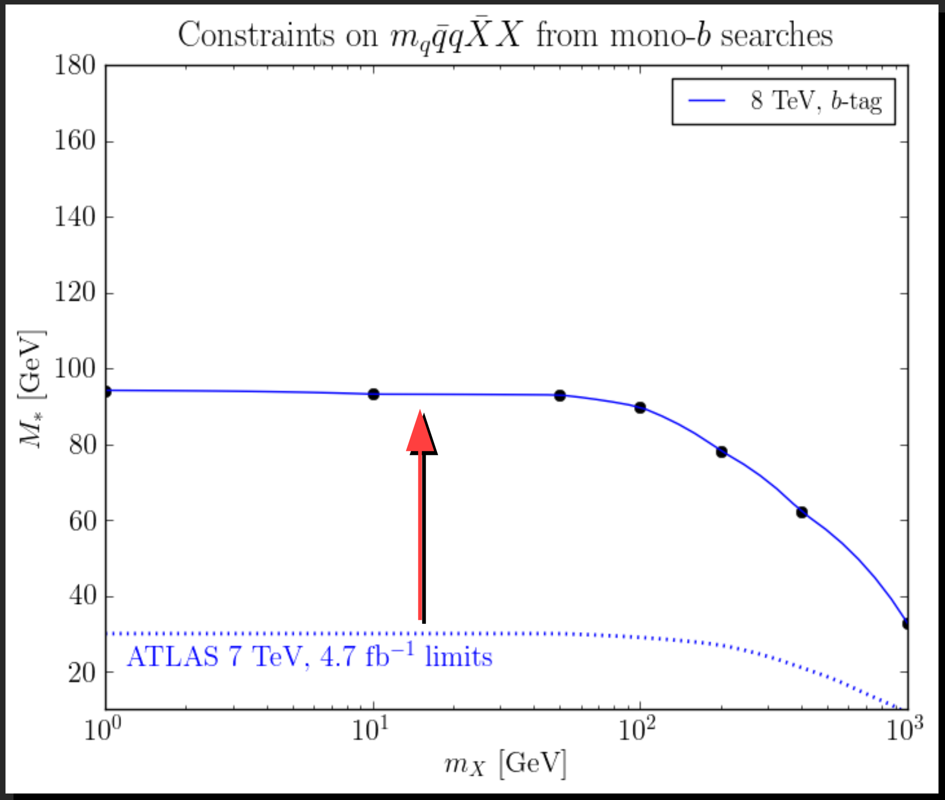
b-enriched final state: improve on monojet analysis by requiring a *b*-tag (~60-70% efficiency). Also cuts backgrounds significantly.

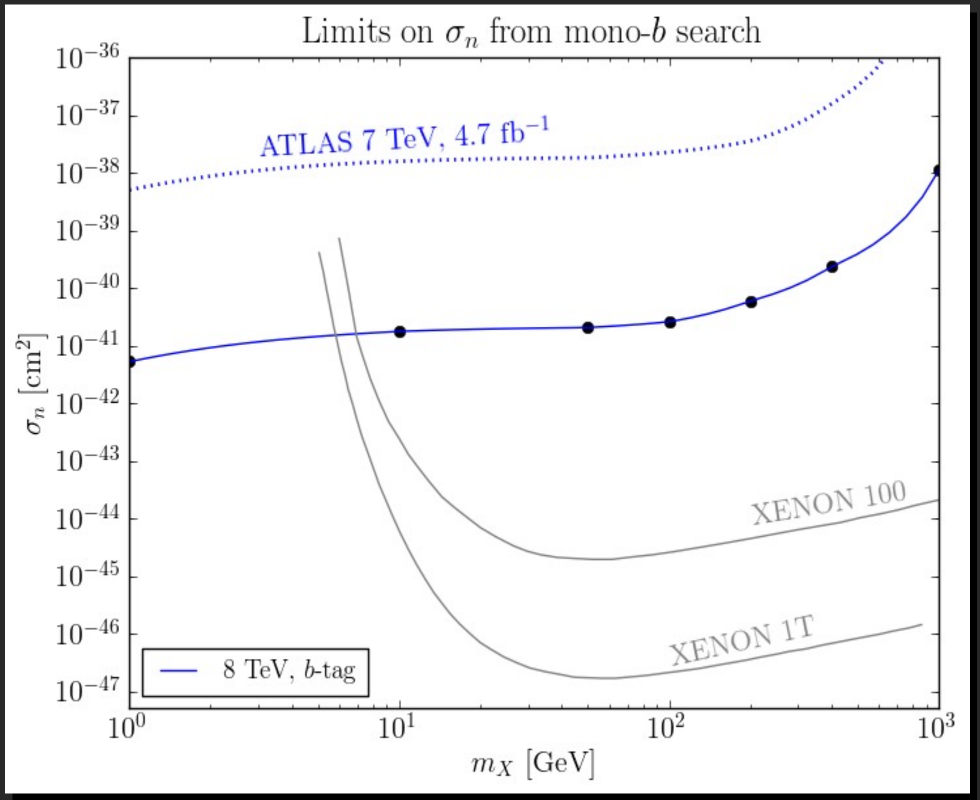
This is a new signal region!

ATLAS analysis of 8 TeV data in progress.



Projected limits for 8 TeV run



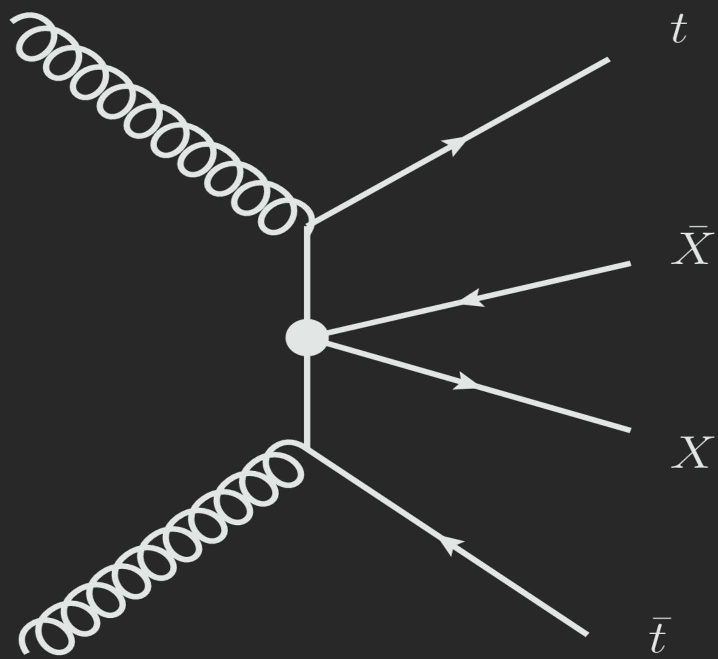


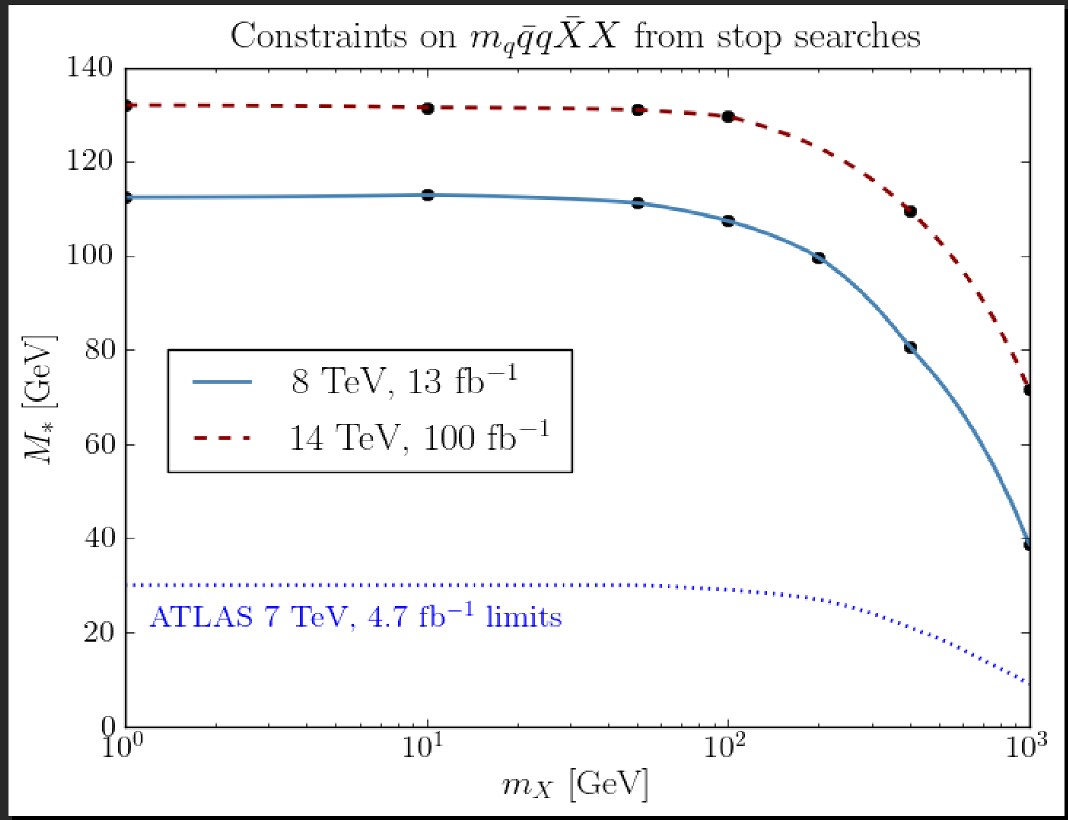
Spin-independent scattering:

$$\sigma_n = \frac{(0.38 m_n)^2 \mu_X^2}{\pi M_*^6} \approx 2 \times 10^{-38} \mathrm{cm}^2 \left(\frac{30\ \mathrm{GeV}}{M_*} \right)^6$$

tops + MET search

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

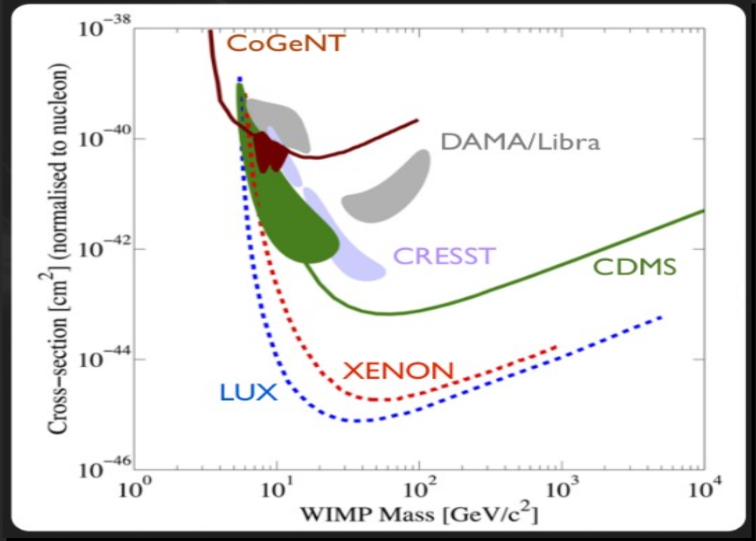


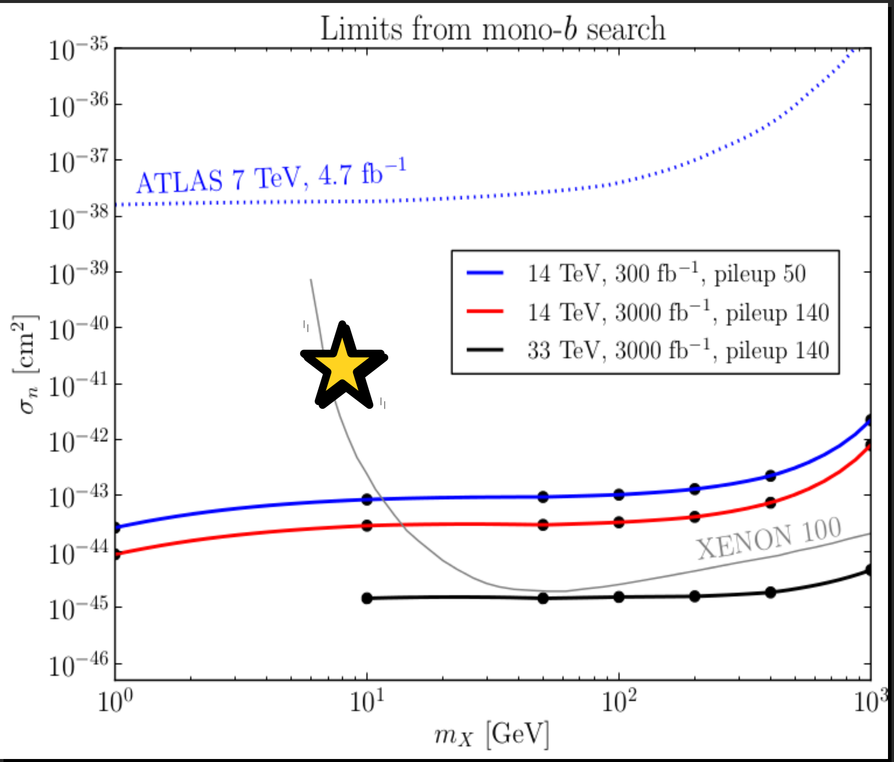


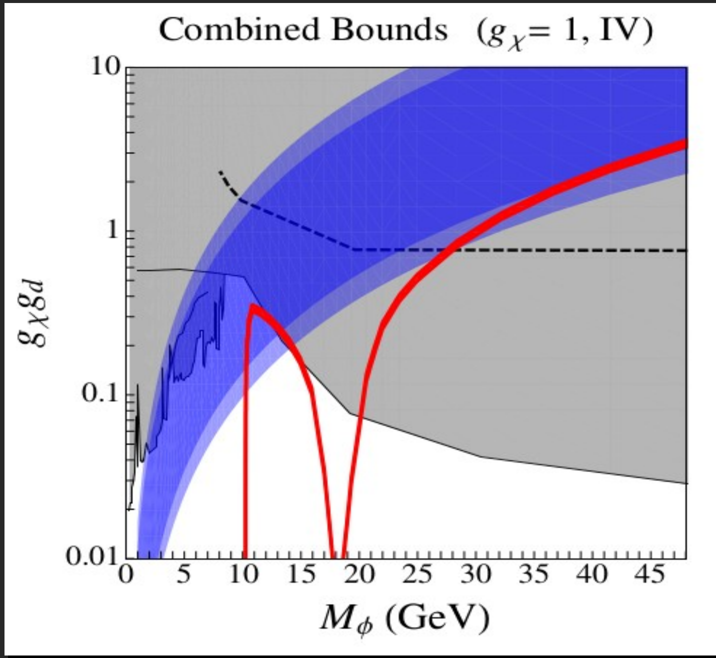
- Factor of ~10 larger than *b* production
- Unlike monojets, *tt+XX* signal not from ISR
- Projection – recast limits from SUSY stop search

14 TeV projections

For MFV couplings of DM to quarks, DM+heavy quark searches have sensitivity for CDMS/CoGeNT preferred region







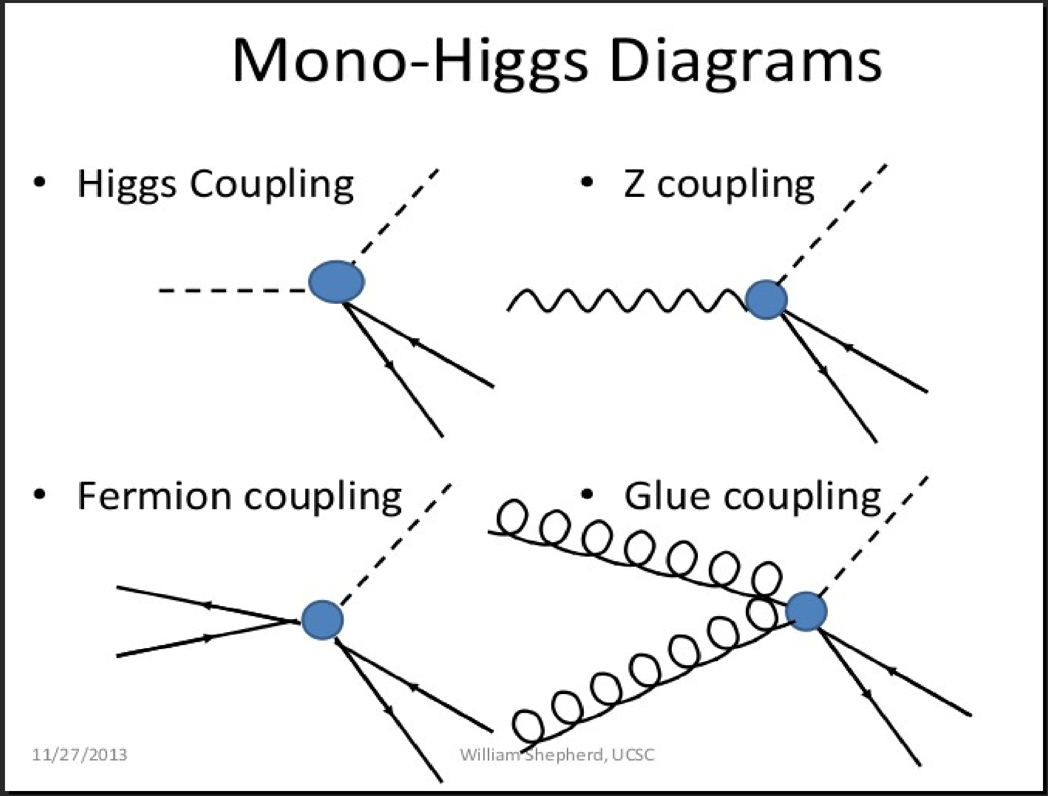
Cotta, Rajaraman, Tait, Wijangco

mono-Higgs (Higgs + MET)

Found SM-like Higgs!

Potential for a new signal channel for probing dark matter couplings?

See also: Higgs invisible decay



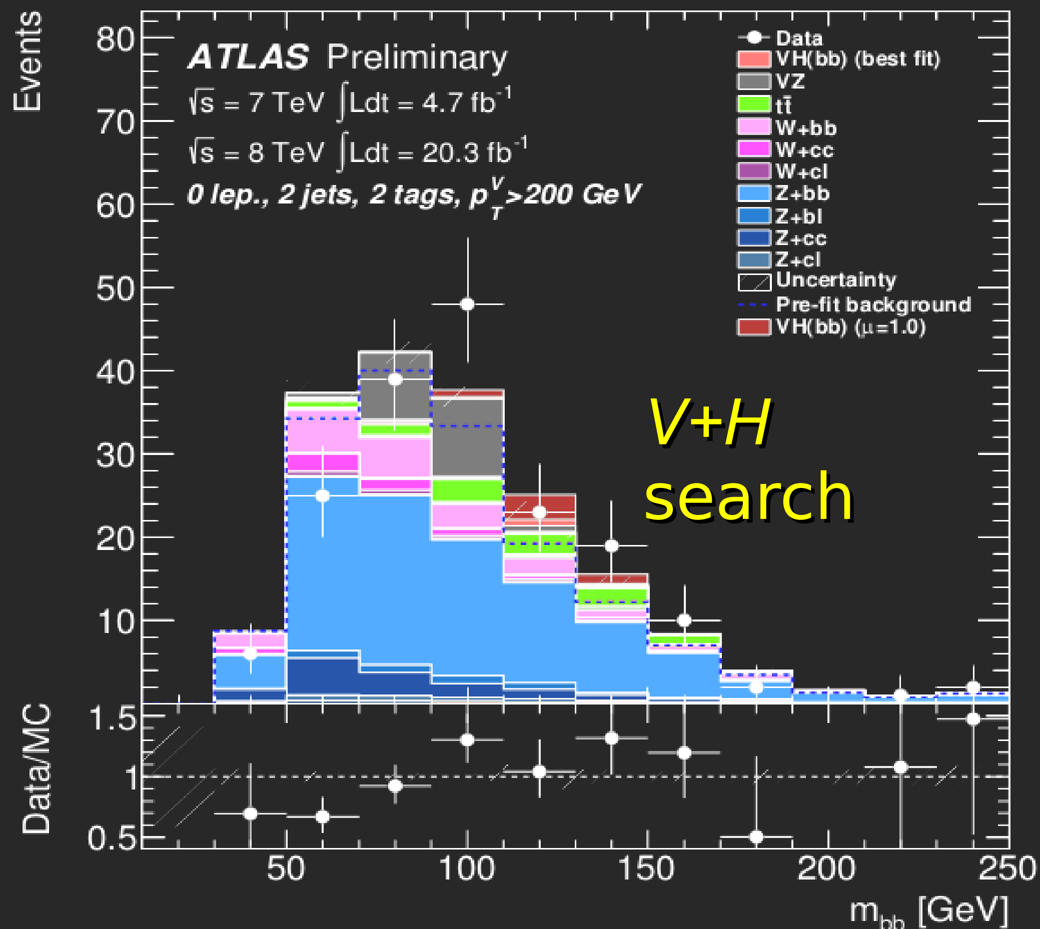
Graphic from William Shepherd

Petrov and Shepherd 2013
Carpenter, DiFranzo, Mulhearn, Shimmin, Tulin, Whiteson 2013
Berlin, TL, Wang, *to appear*

mono-Higgs channels

$\mathrm{Br}(h \to b\bar{b}) \approx 0.58$

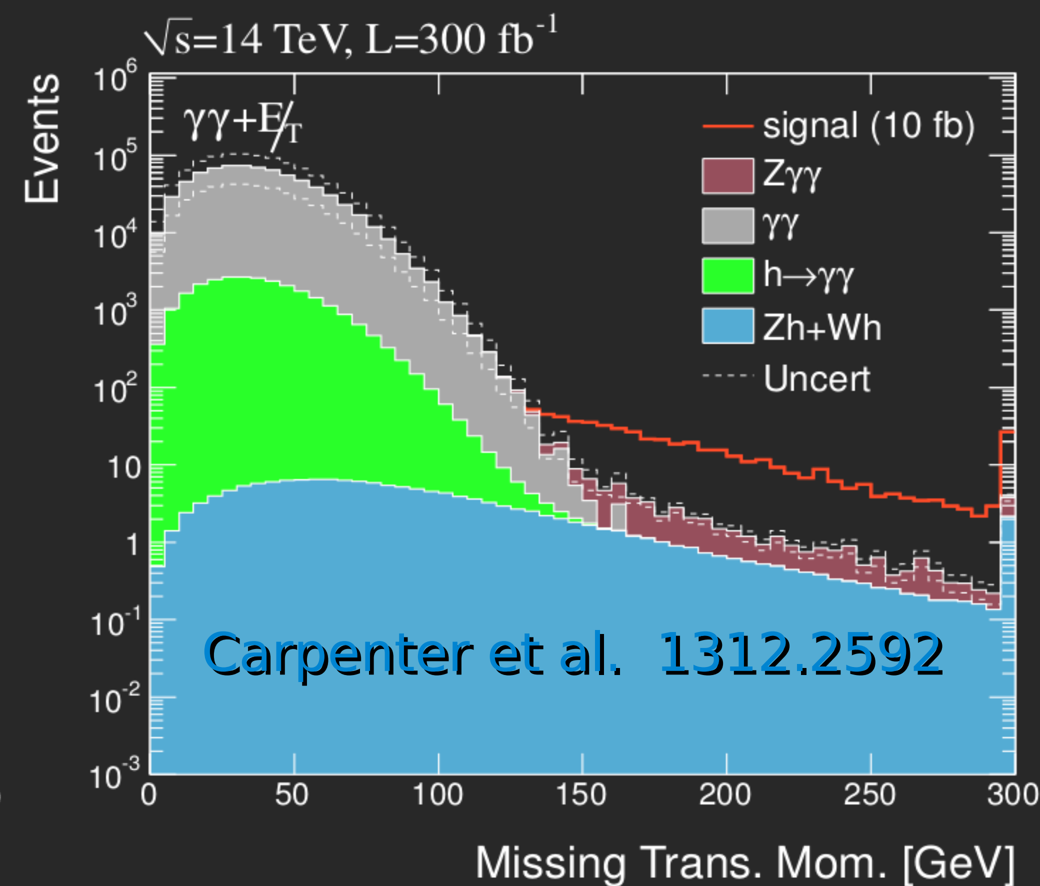
Limit setting with 8 TeV data:



LHC Run 1,
Combined 7+8 TeV, 25/fb

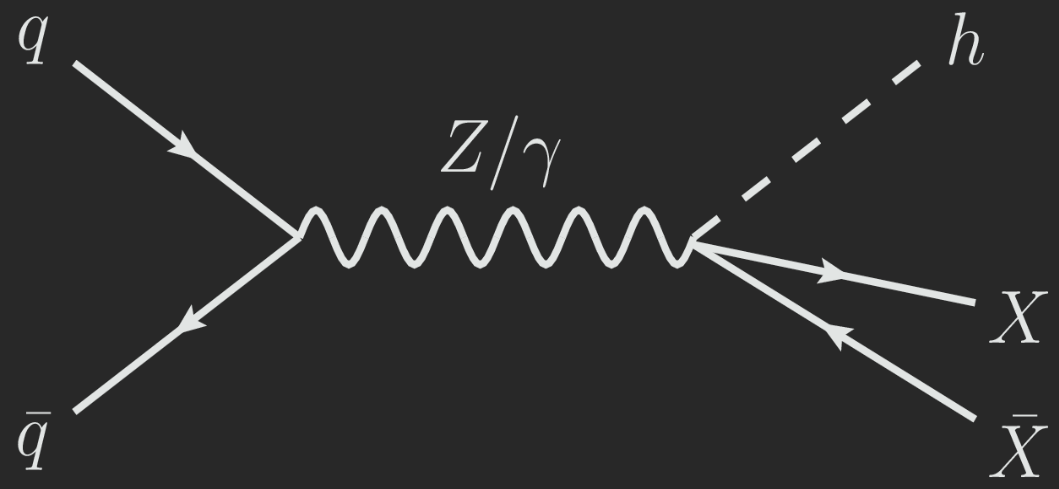
$\mathrm{Br}(h \to \gamma\gamma) \approx 3 \times 10^{-3}$

A new, clean signal channel for 14 TeV?



mono-Higgs in EFT

Operators where dominant production is through mono-Higgs?



Dimension 6, fermion DM

$$\frac{1}{\Lambda^2}\bar{X}\gamma^\mu X \times i(H^\dagger D_\mu H - \text{h.c.})$$

Dimension 7, fermion DM

$$\frac{1}{\Lambda^3}\bar{X}\gamma^{\mu\nu} X \times i\left[(D_\mu H)^\dagger D_\nu H - \text{h.c.}\right]$$

Dimension 8, scalar or fermion DM

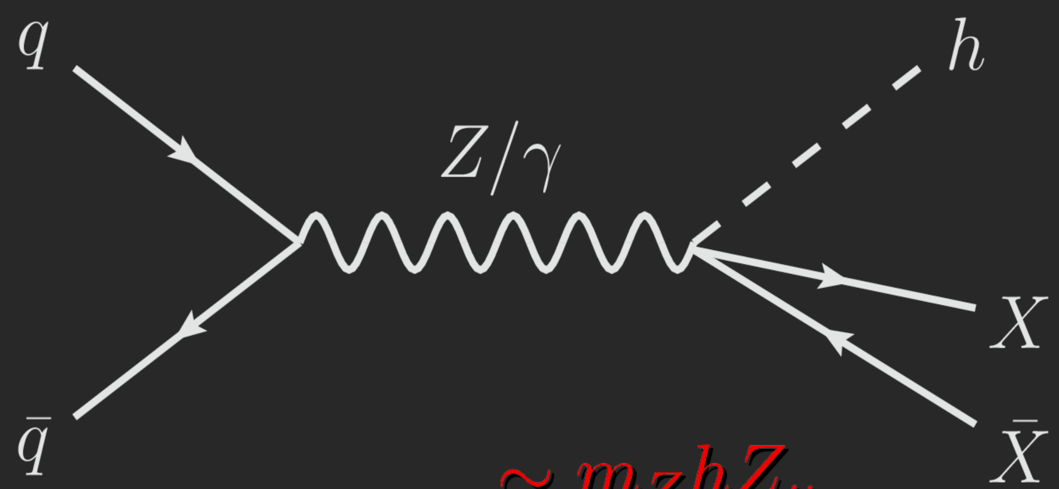
$$\frac{1}{\Lambda^4}\frac{1}{2}(\phi^\dagger\partial^\mu\phi + \text{h.c.})\ (B_{\nu\mu}H^\dagger D^\nu H + \text{h.c.})$$

$$\frac{1}{\Lambda^4}\bar{X}\gamma^\mu X\ (W^a_{\nu\mu}H^\dagger t^a D^\nu H + \text{h.c.})$$

See also: Chen, Kolb, Wang; Fedderke, Kolb, TL, Wa

mono-Higgs in EFT

Operators where dominant production is through mono-Higgs?



Dimension 6, fermion DM

$$\frac{1}{\Lambda^2}\bar{X}\gamma^\mu X \times i(H^\dagger D_\mu H - \text{h.c.})$$

$\sim m_Z h Z_\mu$

Dimension 7, fermion DM

$$\frac{1}{\Lambda^3}\bar{X}\gamma^{\mu\nu} X \times i\left[(D_\mu H)^\dagger D_\nu H - \text{h.c.}\right]$$

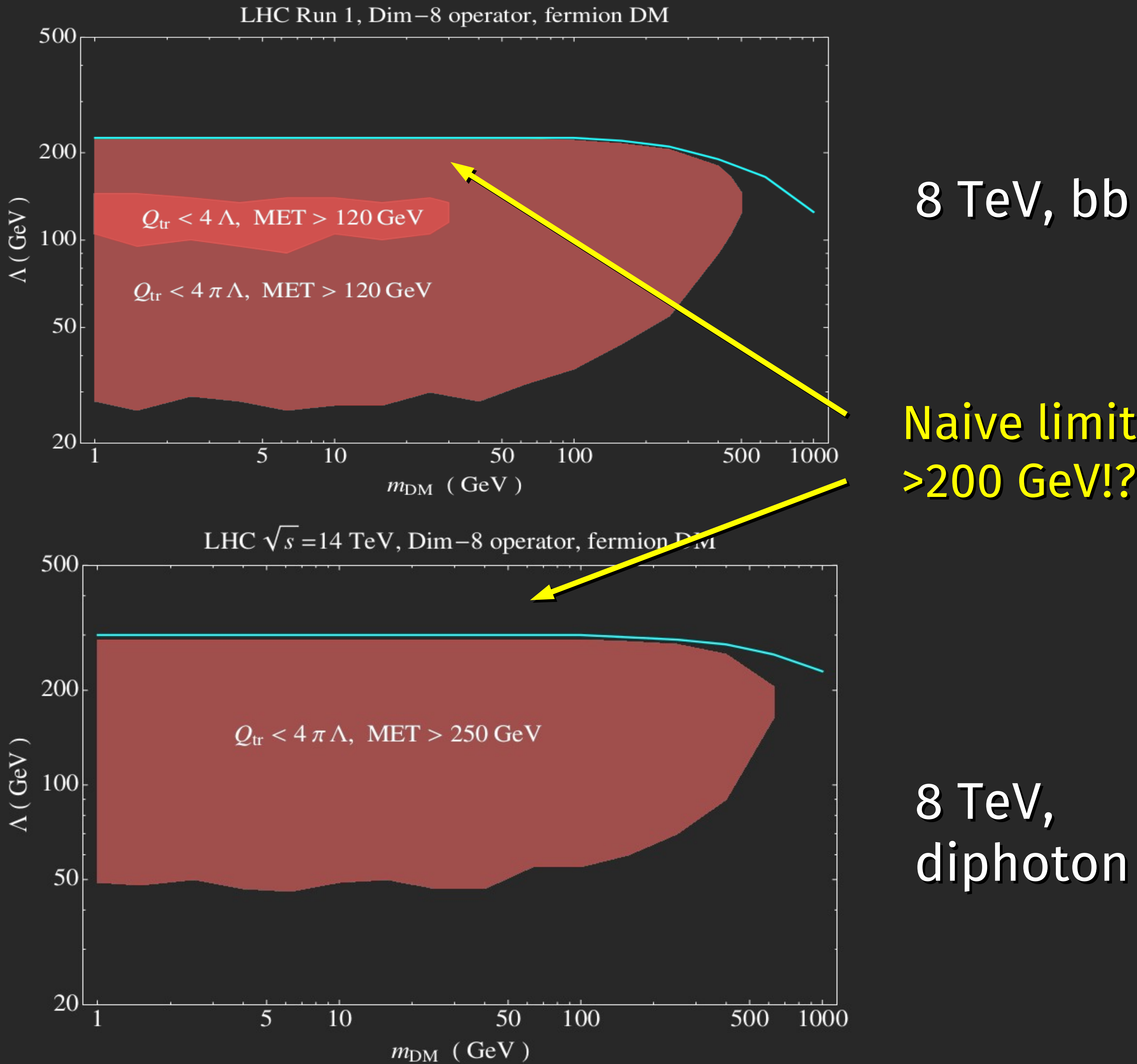
$\sim m_Z Z_\mu \partial_\nu h$

Dimension 8, scalar or fermion DM

$$\frac{1}{\Lambda^4}\frac{1}{2}(\phi^\dagger \partial^\mu \phi + \text{h.c.})\,(B_{\nu\mu} H^\dagger D^\nu H + \text{h.c.})$$

$$\frac{1}{\Lambda^4}\bar{X}\gamma^\mu X\,(W^a_{\nu\mu} H^\dagger t^a D^\nu H + \text{h.c.})$$

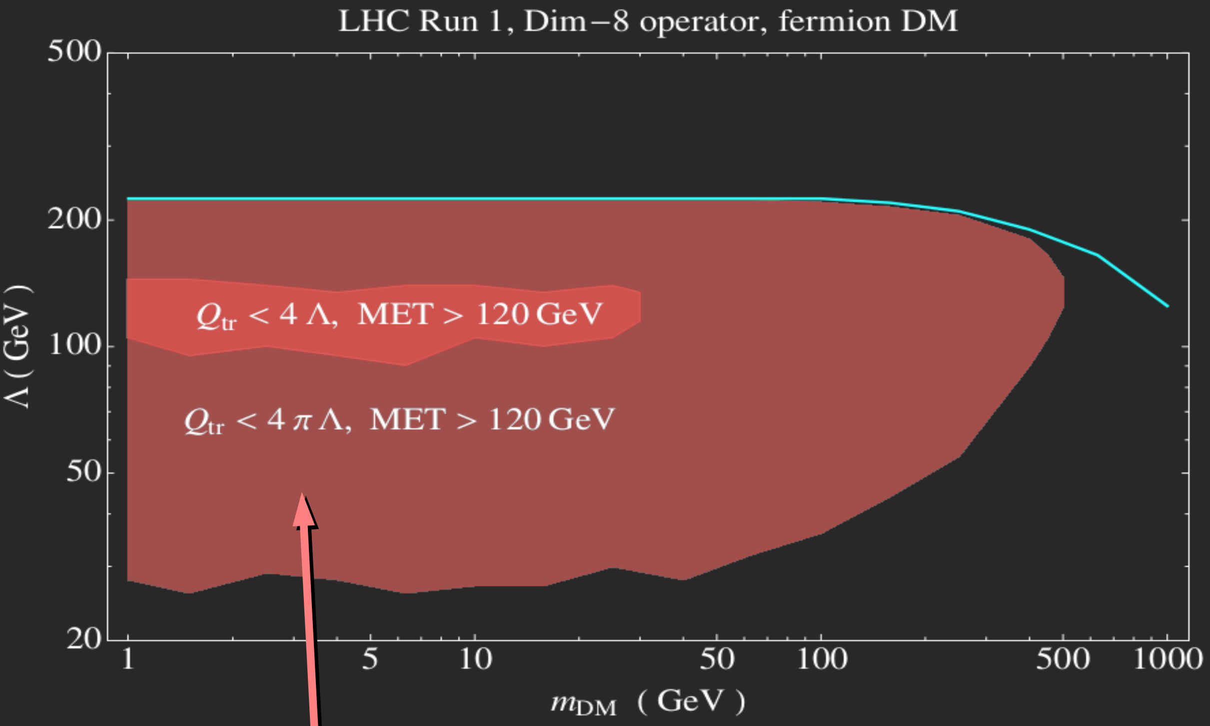
$\sim \langle v \rangle Z_{\mu\nu} \partial^\nu h$

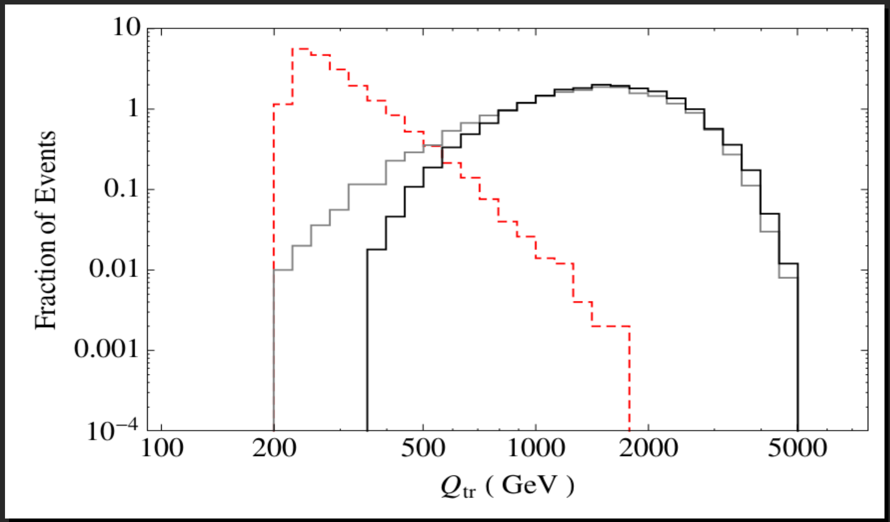


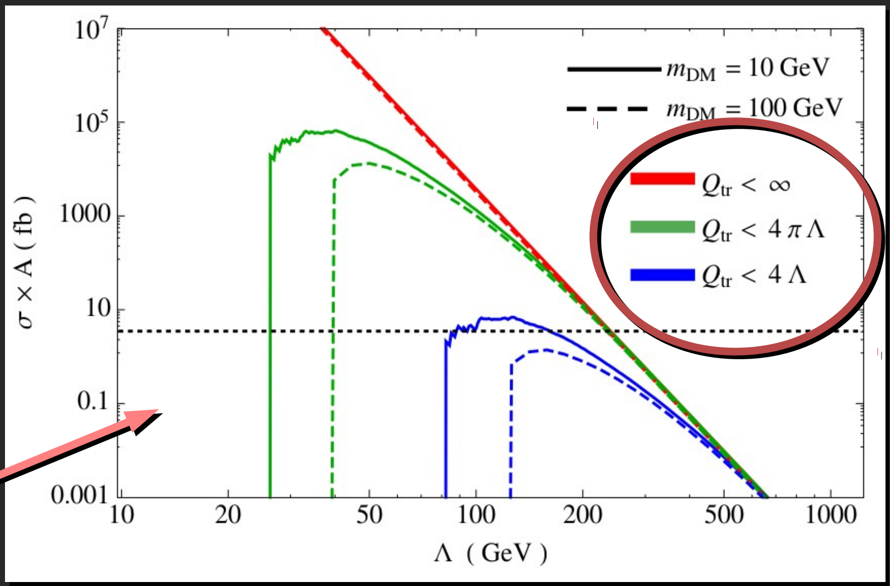
LHC Run 1, Dim−8 operator, fermion DM
Λ (GeV)
m_{DM} (GeV)
$Q_{tr} < 4\,\Lambda$, MET > 120 GeV
$Q_{tr} < 4\,\pi\,\Lambda$, MET > 120 GeV
LHC $\sqrt{s}$ =14 TeV, Dim−8 operator, fermion DM
$Q_{tr} < 4\,\pi\,\Lambda$, MET > 250 GeV
8 TeV, bb
Naive limit
>200 GeV!?
8 TeV,
diphoton

Distribution of momentum transfer Qtr skewed towards very large values

$$\sigma \propto \frac{m_W^2 E^4}{\Lambda^8}$$





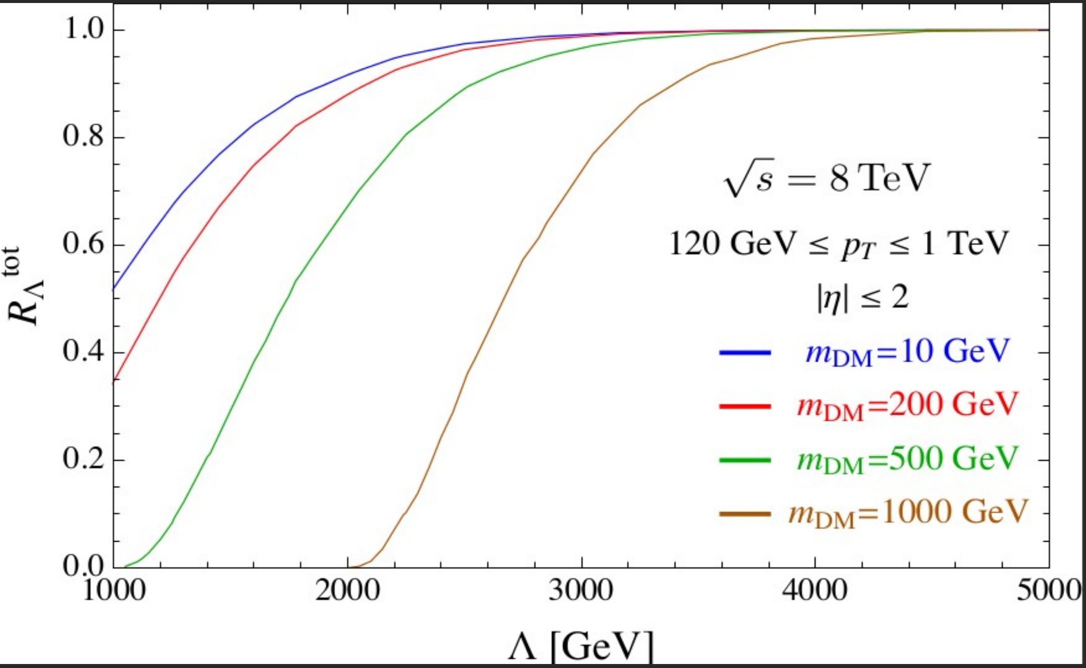


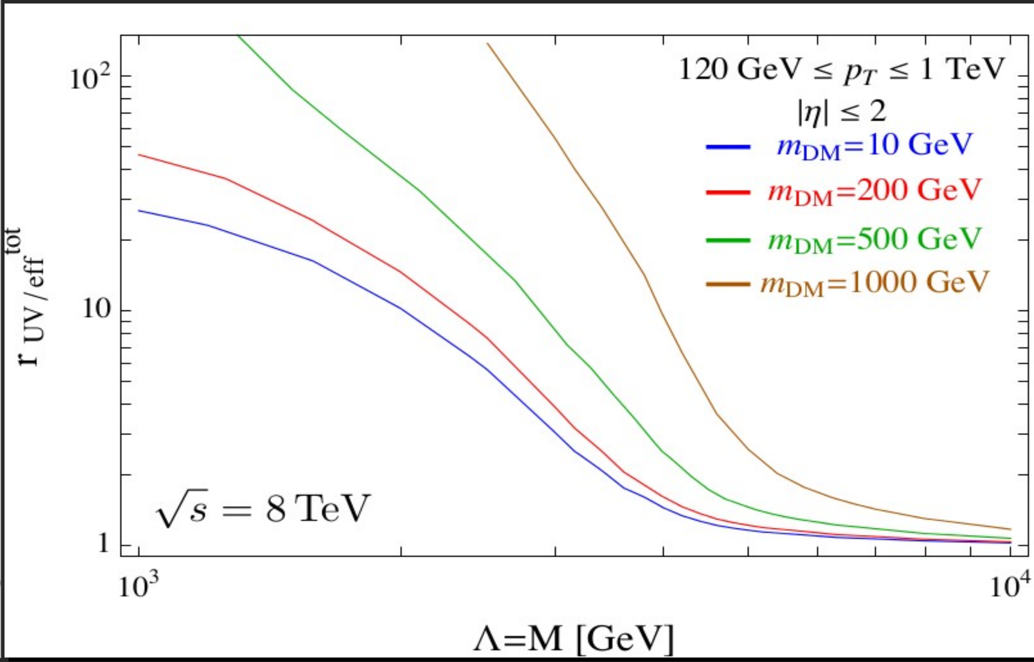
Imposing "unitarity" conditions on Qtr

Validity of EFT

In general, many events violate unitarity

EFT limits conservative, in some sense



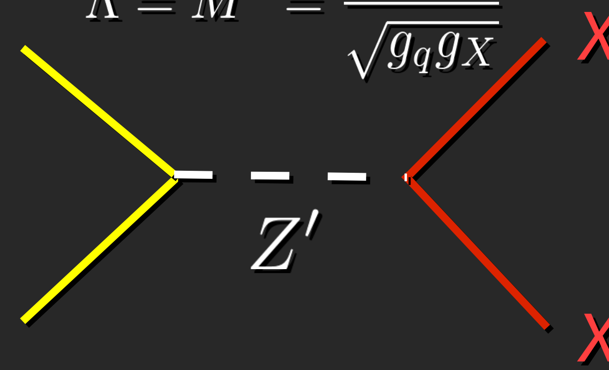


Busoni, de Simone, Morgante, Riotto + Gramling et al.

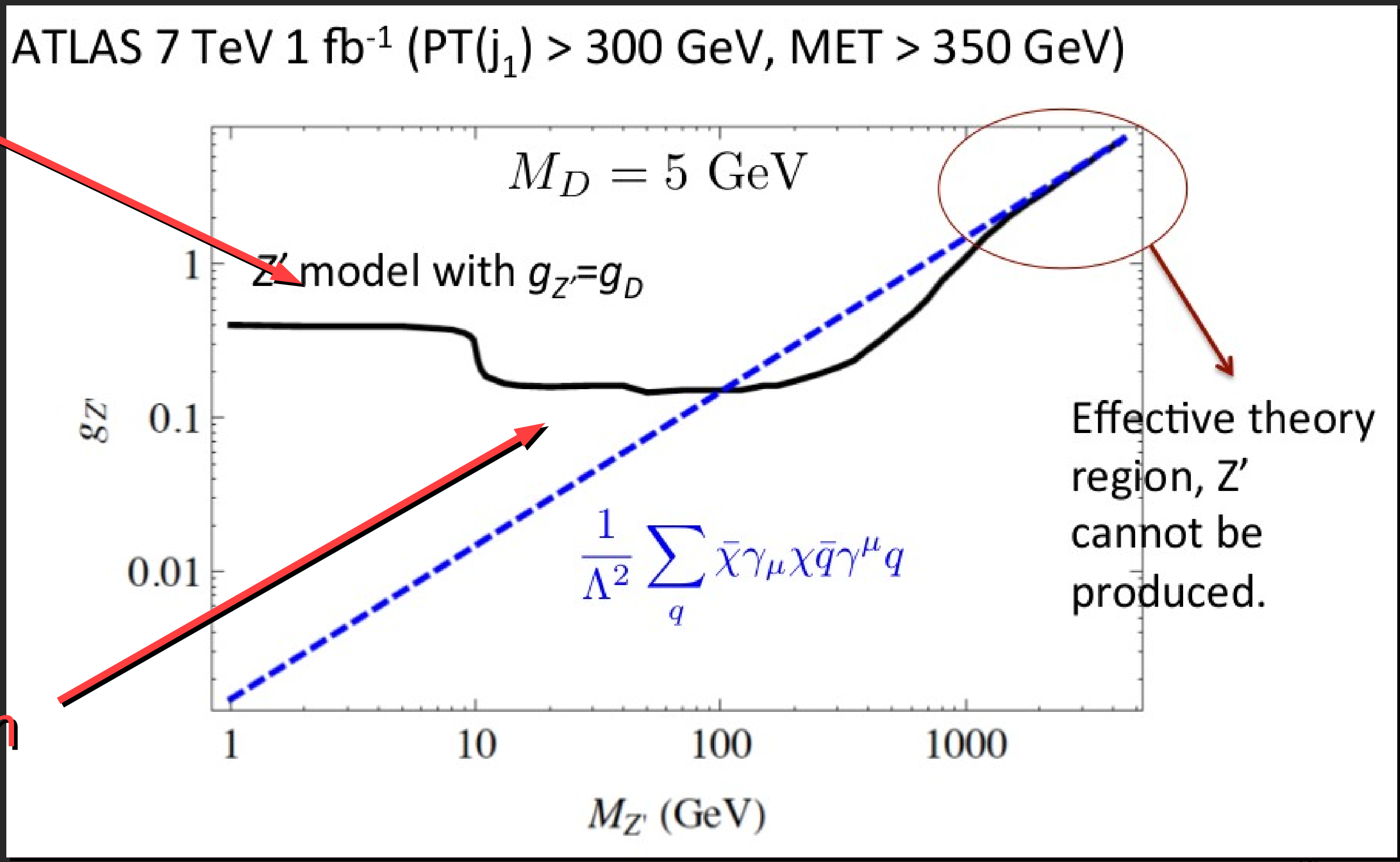
- Putting cuts on Qtr doesn't fully address the question.

Limitations of Monojets

$$\Lambda = M^* = \frac{M_{Z'}}{\sqrt{g_q g_X}}$$



Light mediators

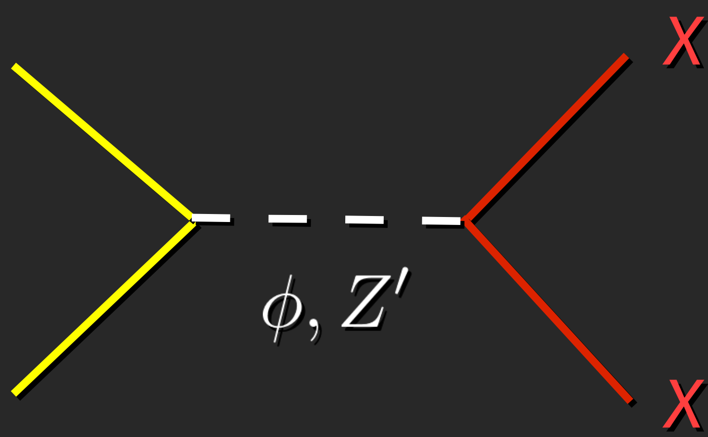


On-shell production of Z'

Slide from Haipeng A

Simplified Models: *s-channel*

Away from the contact operator limit, there may be a new "mediator" particle accessible at colliders.



- *s*-channel mediator, SM singlet
- Basic data:

g_q	coupling to quarks
g_X	coupling to dark matter
$M_{Z'}$	mediator mass
$M_{\rm DM}$	dark matter mass

An, Ji, Wang; Cotta et al, Goodman and Shepherd, etc

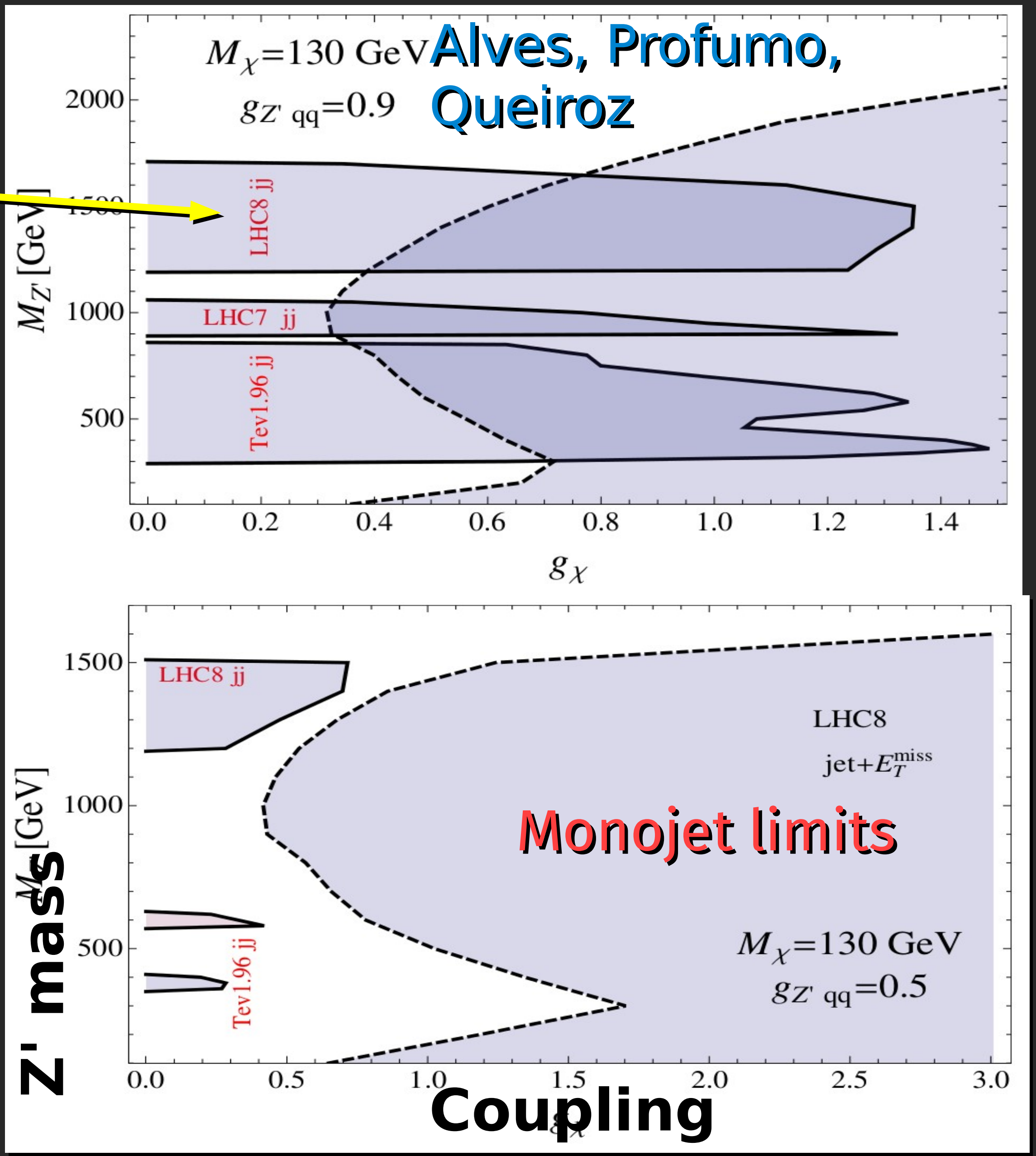
$$M_* = \frac{M_{Z'}}{\sqrt{g_q g_X}}$$

For EFT limit, coupling needs to be large.

Lessons from Z' studies

Dijet resonance searches

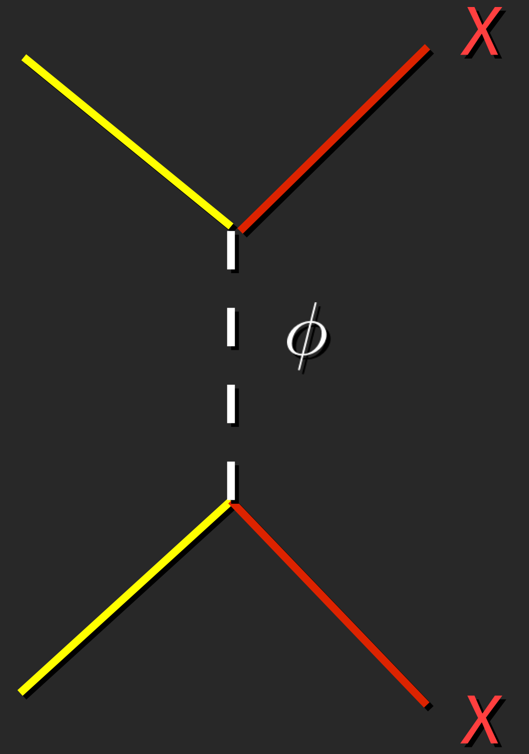
Relative strength of dijet vs. monojet depends on Z' branching to visible or invisible final states



Simplified Models: *t-channel*
(flavored dark matter)

- *t*-channel mediator, charged under SM gauge group
- Basic data:

λ	coupling
m_ϕ	mediator mass
$m_{\rm DM}$	dark matter mass



top-flavored dark matter

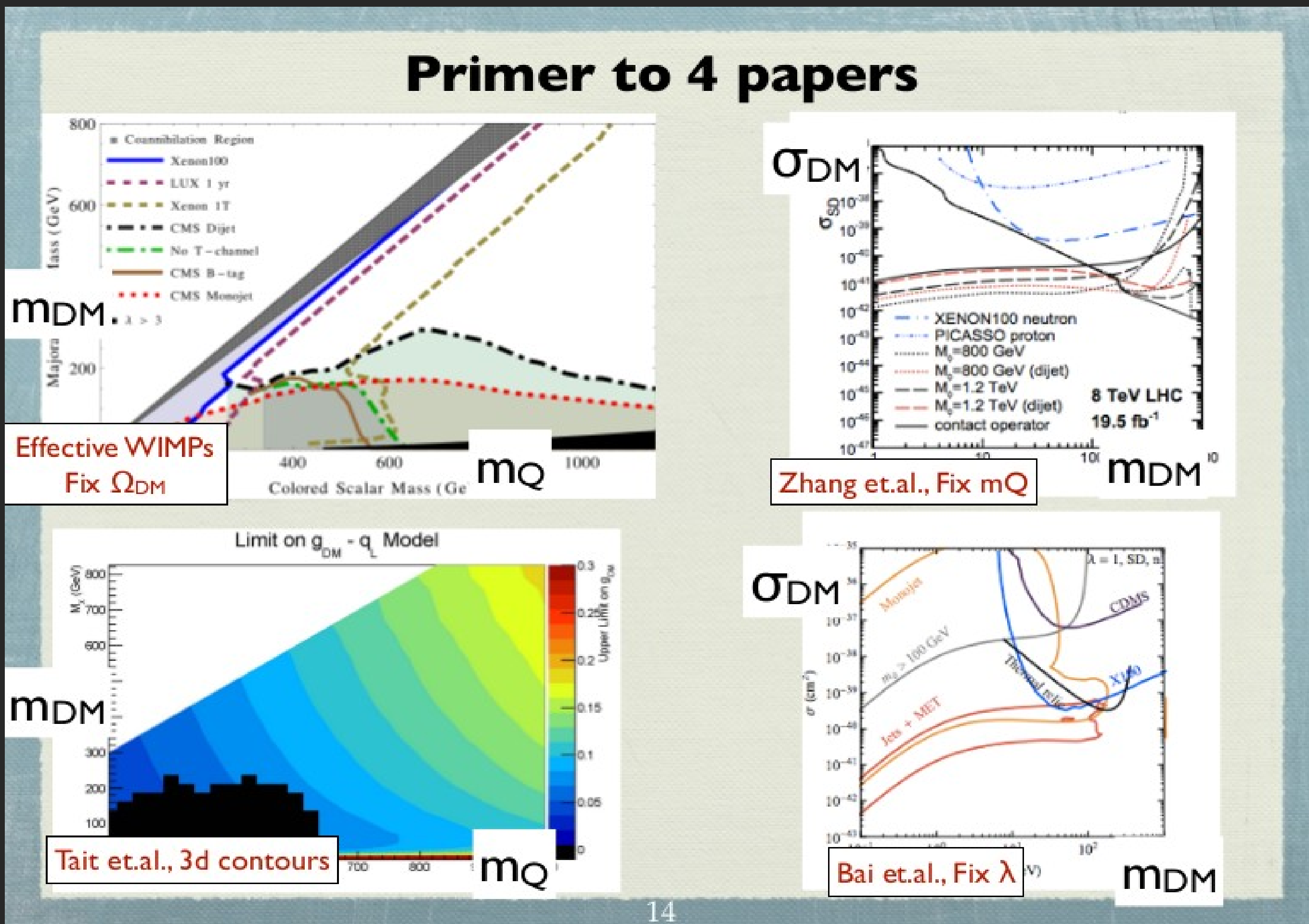
$$\lambda_t \bar{\chi}_t t_R \phi + \text{h.c.}$$

Stability from flavor, UV completion in MFV SUSY

Batell, TL, Wang, 1309.4462

An et al.,
Chang et al.,
Bai and Berger,
DiFranzo et al.,

There are many more examples



LHC constraints more important for Majorana DM

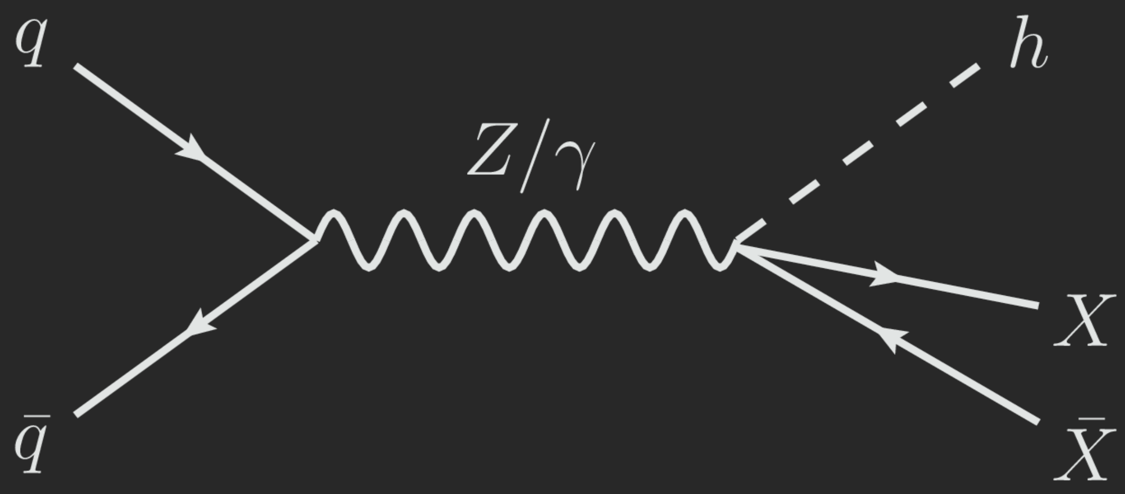
Pair production, associated production of mediator.

Kinematics not exactly the same as squarks.

Slide from Spencer Chang

See also: Papucci, Vichi, Zurek

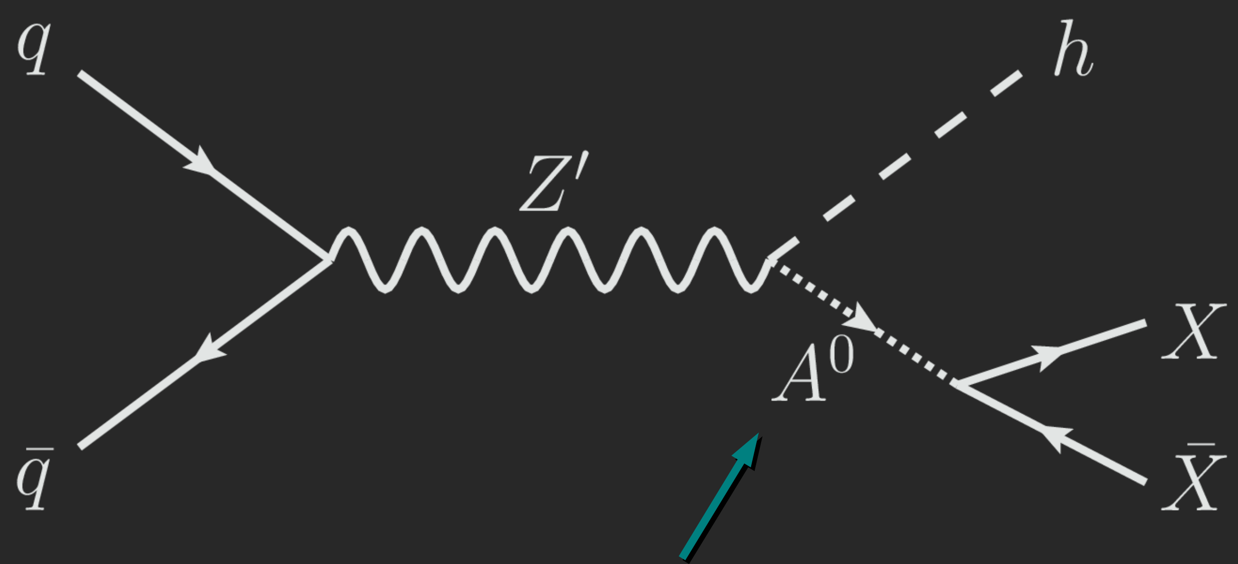
mono-Higgs – a simplified model?



$$\frac{1}{\Lambda^4}\bar{X}\gamma^\mu X \; (W^a_{\nu\mu} H^\dagger t^a D^\nu H + \mathrm{h.c.})$$

mono-Higgs – a simplified model?

Model with resonant production of Z':



Pseudoscalar of Type II two-Higgs doublet mode

	Φ_d	Φ_u	Q_L	d_R	u_R
$U(1)_{Z'}$	0	1/2	0	0	1/2

Avoid dilepton resonance constraints

Z – Z' mass mixing

Constraints on model

- *Z-Z′* mass mixing

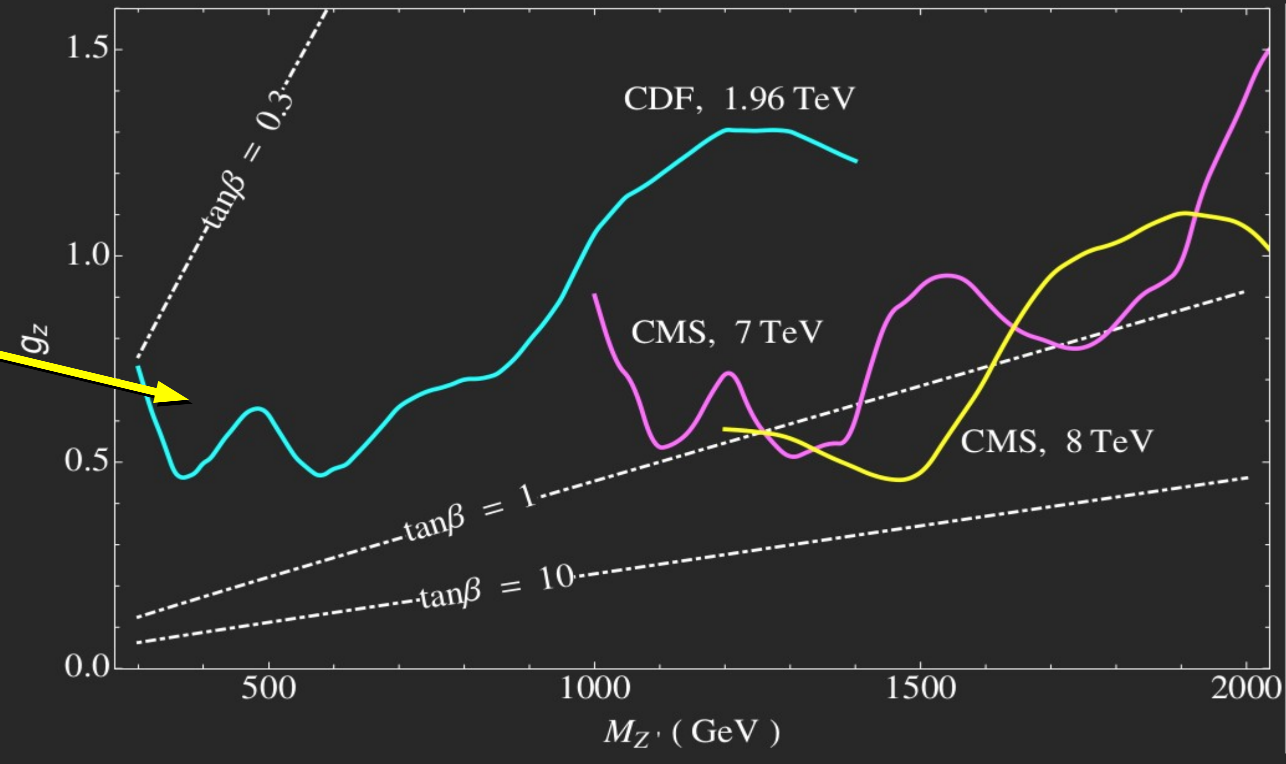
$$M_Z^2 \approx (M_Z^0)^2 - \epsilon^2 \left[(M_{Z'}^0)^2 - (M_Z^0)^2\right] \qquad \epsilon = \frac{(M_Z^0)^2}{M_{Z'}^2 - M_Z^2} \frac{2g_z \cos\theta_w}{g} z_u \sin^2\beta$$

$$\rho_0 = 1 + \epsilon^2 \left(\frac{M_{Z'}^2 - M_Z^2}{M_Z^2}\right) \leq 1.0009$$

- Limits on dijet resonances

  - Important at low tanβ, large M$_{Z'}$

$$\tan\beta = \frac{v_u}{v_d}$$

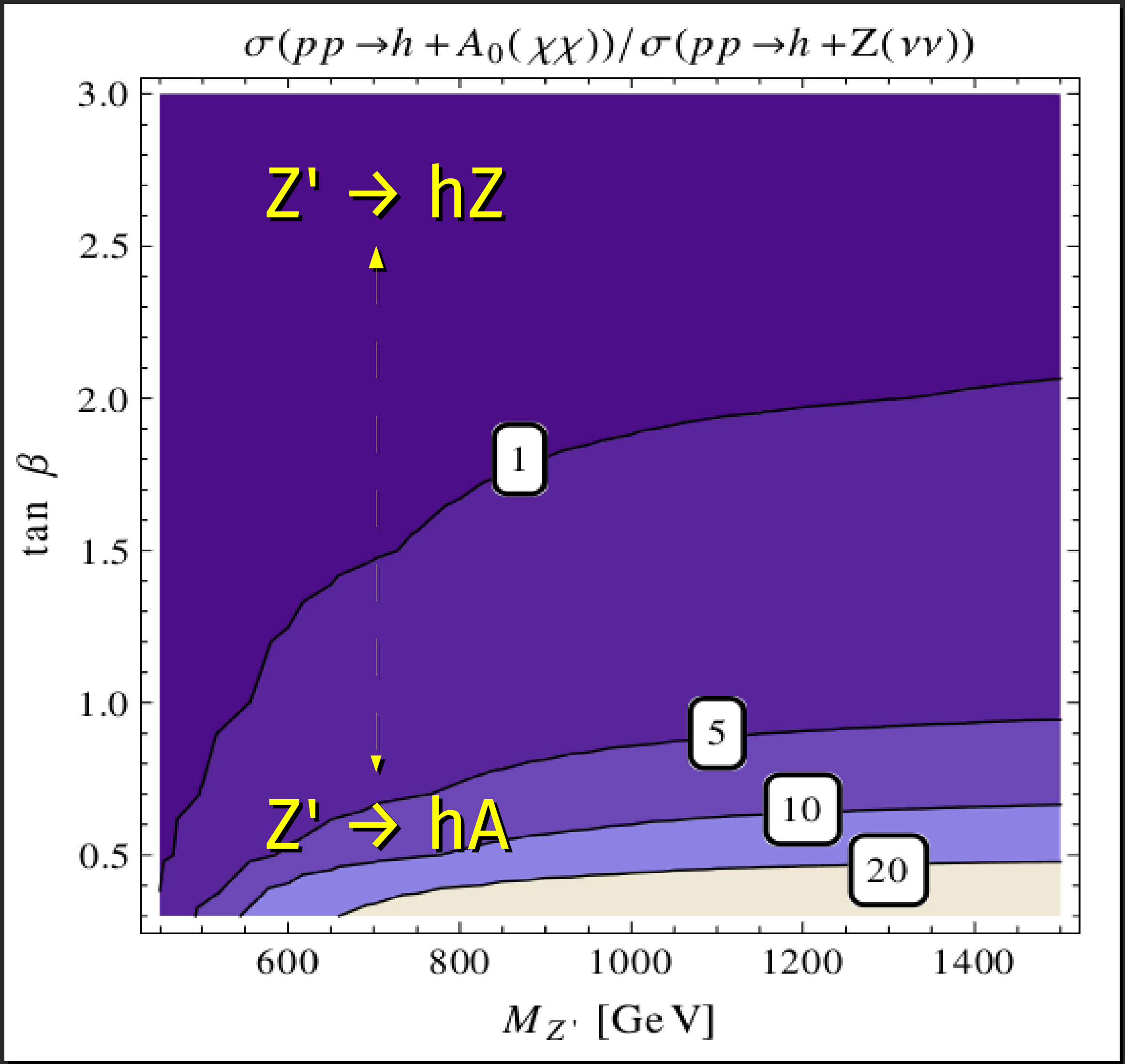


Higgs + MET

- Two sources:
  - *Z' → hA, A → XX* (with 100% BR)
  - *Z' → hZ, Z → νν*

Assumptions

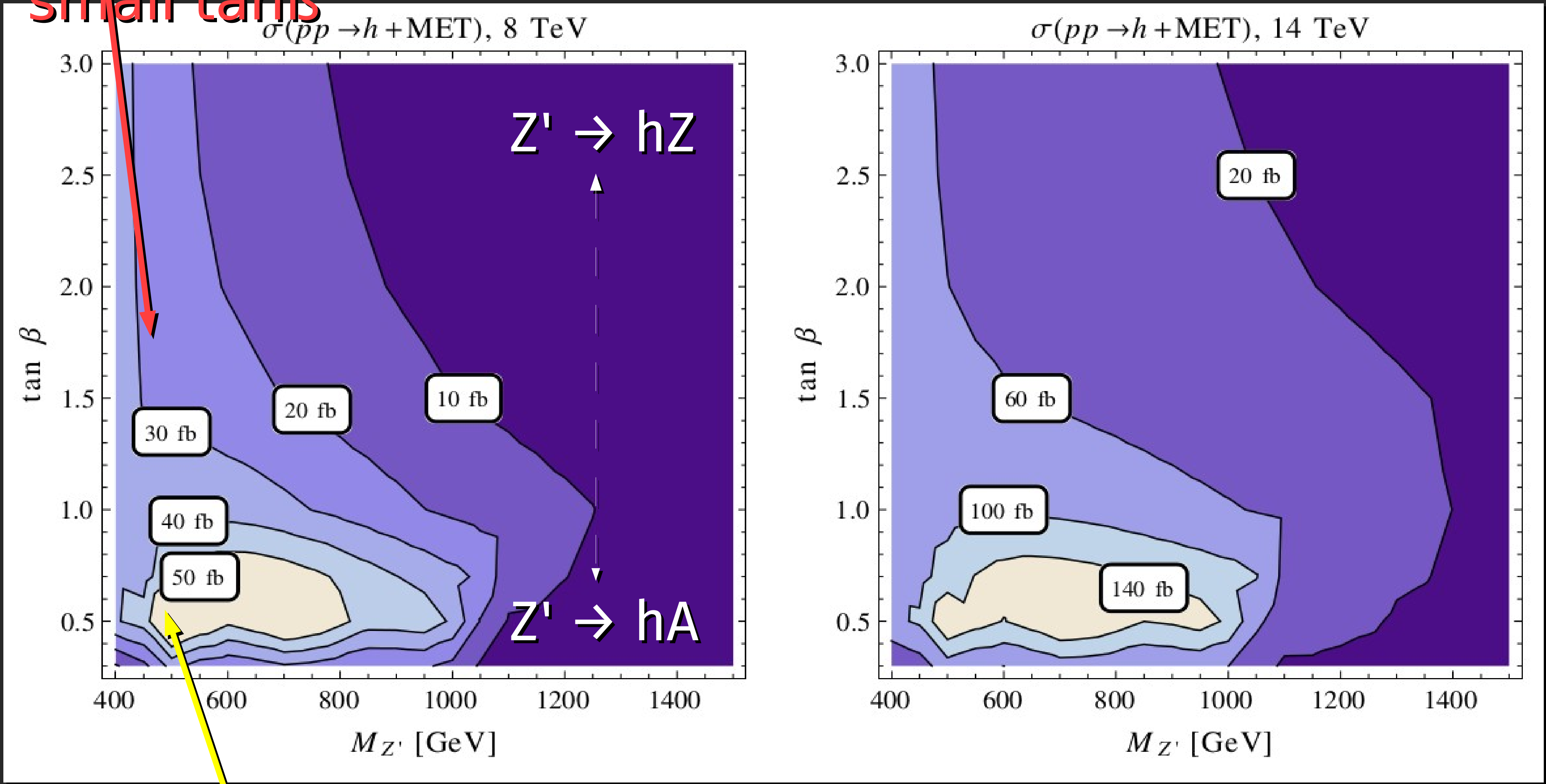
- mA, mH > 300 GeV
- Alignment limit (*h* has SM couplings to fermions)



Higgs + MET

(Subject to constraints on coupling)

Allowed coupling increases with large Mz', small tanß

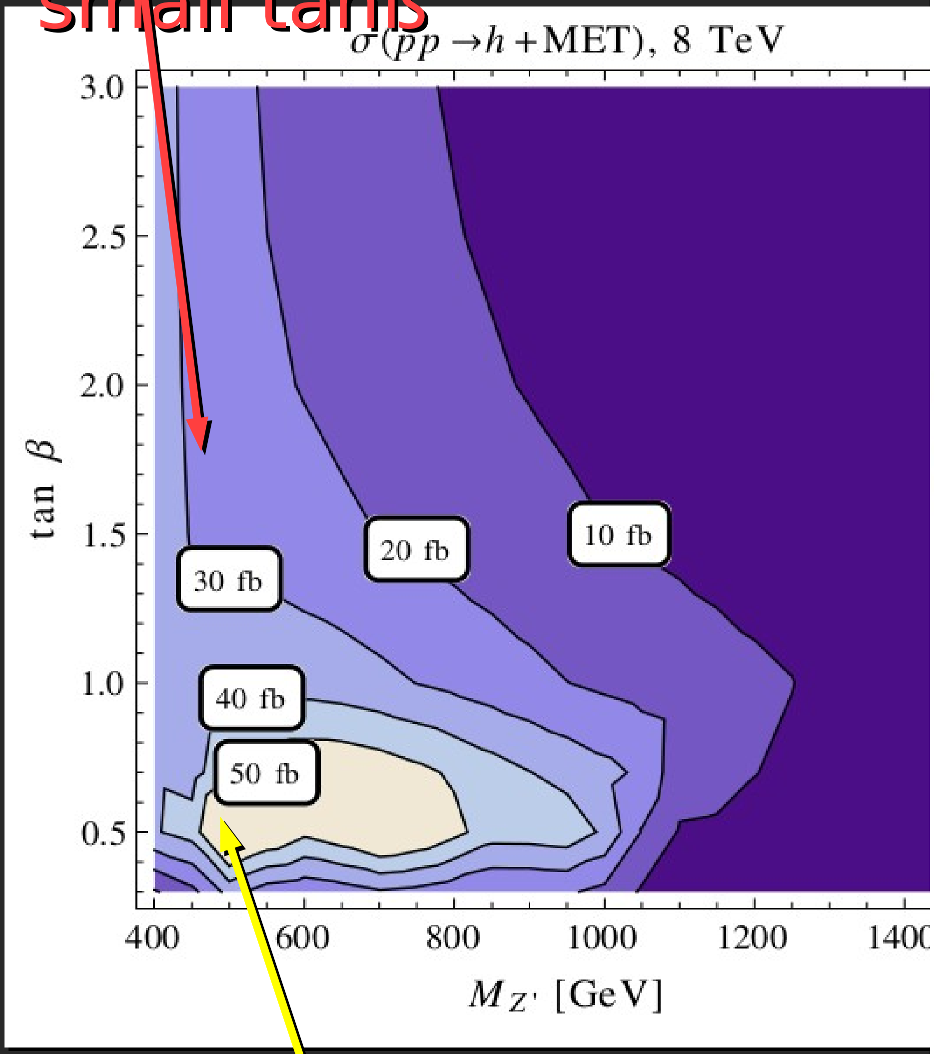


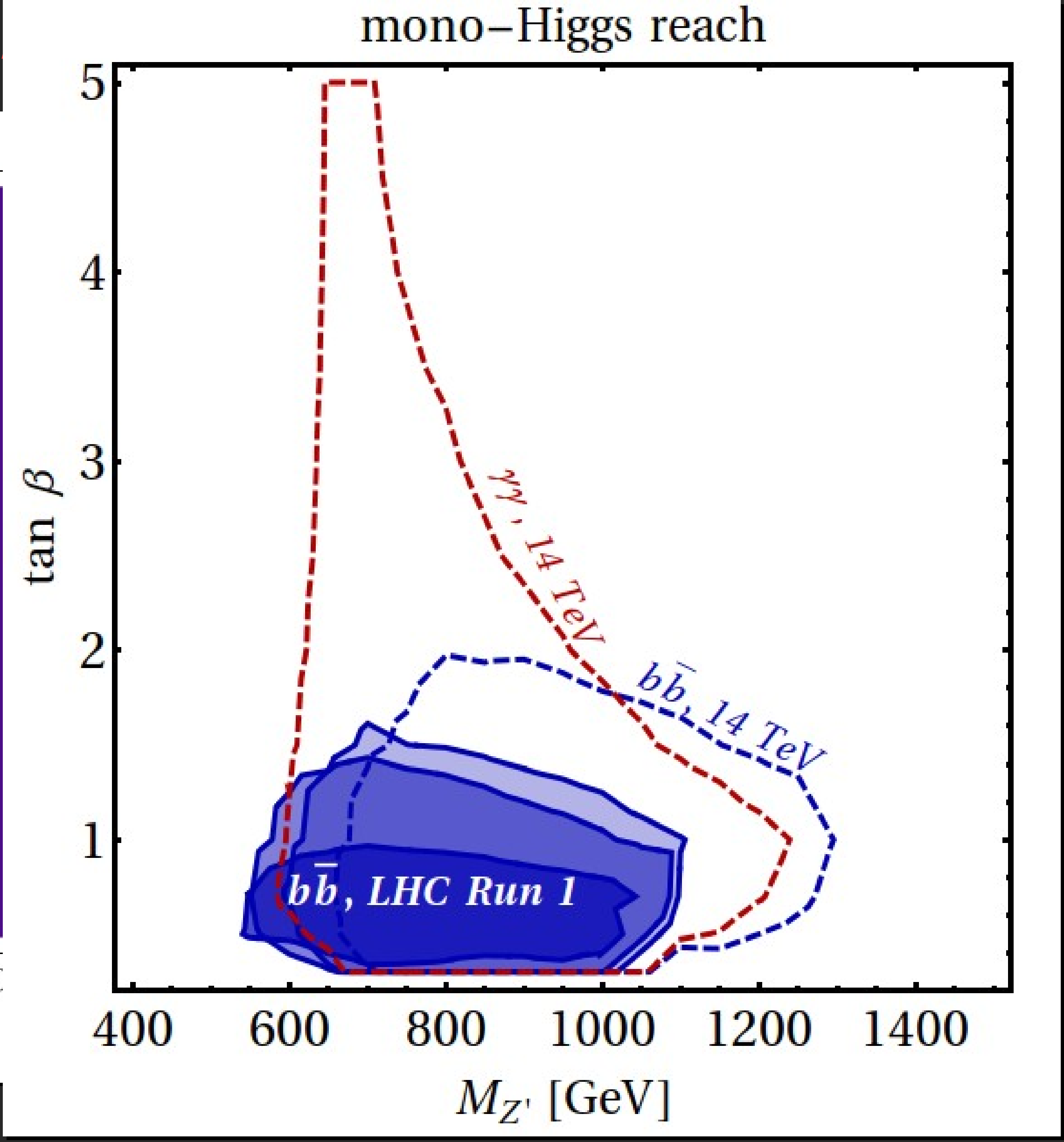
$$\Gamma(Z' \to hA^0) \propto \sin^2(2\beta)$$

$$\tan\beta = \frac{v_u}{v_d}$$

Allowed coupling increases with large Mz', small tanß

Higgs + MET





$$\Gamma(Z' \to hA^0) \propto \sin^2(2\beta)$$

Coupling to dark matter

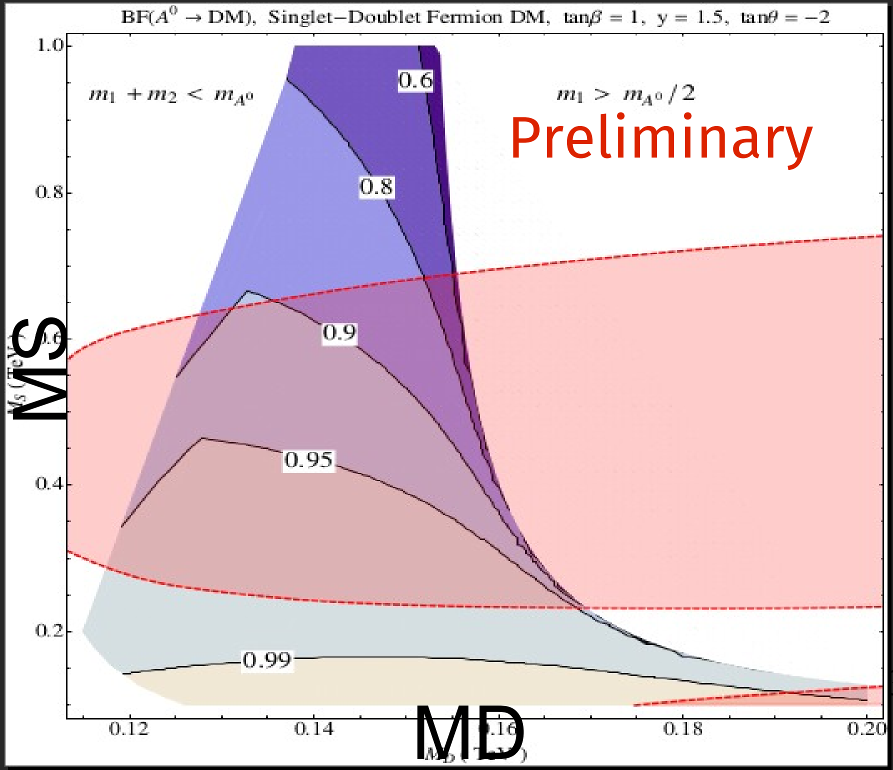
See also: Cohen et al.
Cheung and Sanford.

- Singlet-doublet model

$$\frac{1}{2}M_S^2 S^2 + M_D D_1 D_2 + y_1 S H_d D_1 + y_2 S H_d^\dagger D_2 + \text{h.c.}$$

has fermion DM coupling to pseudoscalar *A*

- *A* → *XX* dominates
- Can satisfy *LUX*

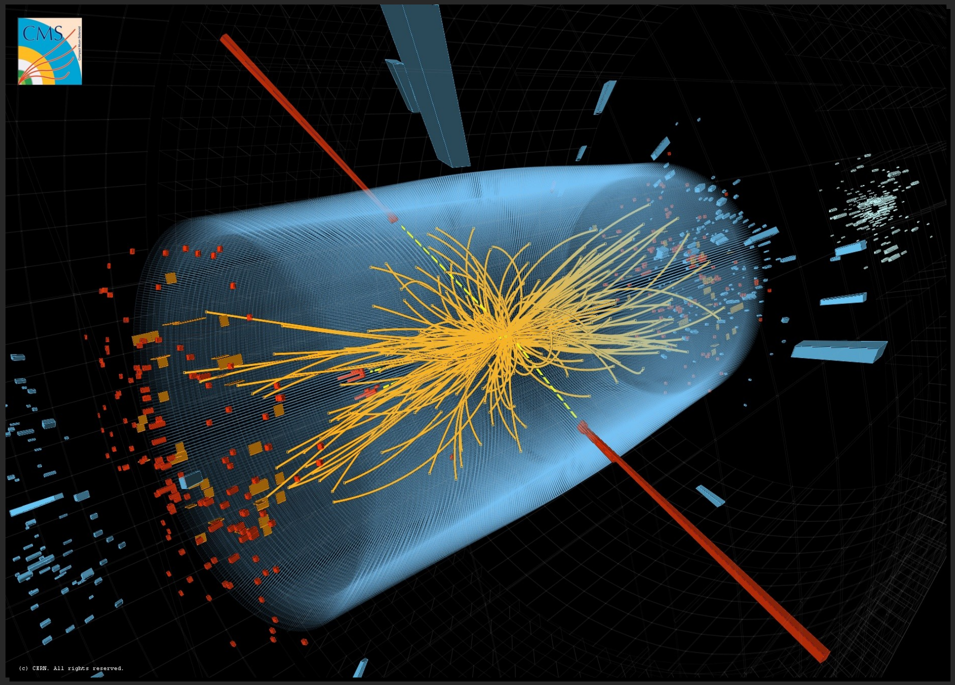


Study in progress. Model may also be interesting beyond mono-Higgs.

Bino-Higgsino in the MSSM, but parameter space more narrowly defined.

The road from monojets

- EFT framework
- Many operators!
  - Mono-something
- Simplified models with mediators
  - Z', t-channel
  - Need to develop dedicated analyses
- More to do...



theorists & experimentalists wanted!

Conclusions and Outlook

- New signal regions
  - Mono-*b*
  - Mono-*h* (diphoton) plus MET
  - Different kinematic regions
- New models
  - Not just SUSY-like, though SUSY models/searches are a good place to start
- Many opportunities with next LHC run
- We need to keep looking!