Some Physics Opportunities at HL-LHC

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Disclaimer

Any guess on what the relevant physics will be at HL-LHC unavoidably relies on:

1) Present-day theoretical understanding
2) Absence of new physics at the LHC

Since we expect (or hope for) progresses on both sides, don't make too detailed plans too in advance.

Outline

If no discovery, same priorities as today:

Higgs/Top properties

Higgs/Top couplings

Top mass (width?)

Exotic decays

Higgs to light matter

… …. ….

Naturalness

Non-minimal SUSY

Composite Higgs

- Higgs couplings
- heavy vectors
- top partners

Dark Matter

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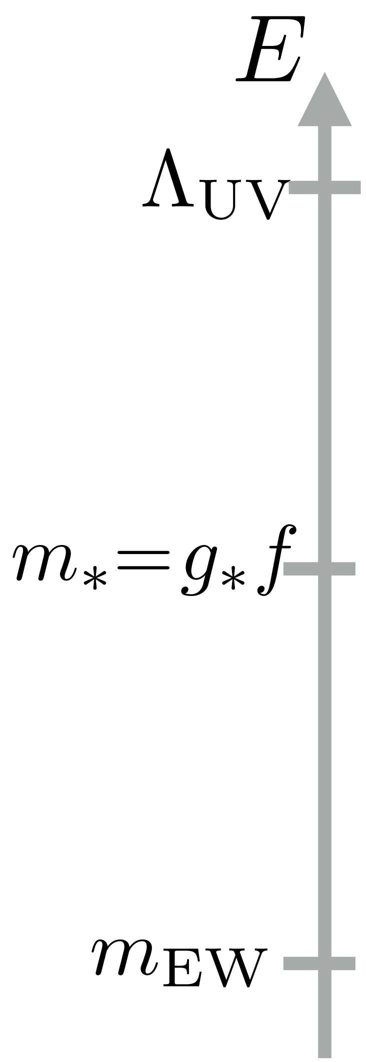
Dark Matter

- heavy-mediator WIMP

This Talk

Composite Higgs Definition



- Big Hierarchy from new CS
- Nambu-Goldstone Higgs:

$$G \xrightarrow{f} H \qquad \xi = \frac{v^2}{f^2} \ll 1$$

- SM gauge and matter from ES
- Coupled by Partial Compositeness

Composite Higgs Signatures

- Higgs Couplings Modifications
- EW-charged vector resonances
- Fermionic Top-Partners

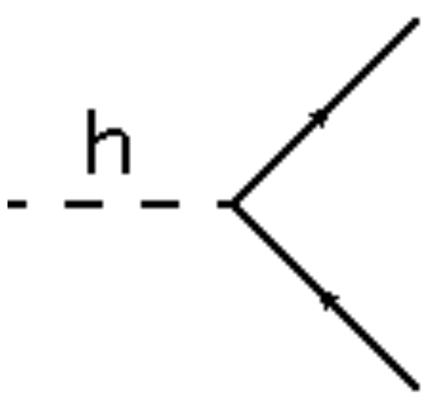
Higgs Couplings

Low energy Higgs physics from **symmetries**

$$\mathcal{L}_\pi = \frac{f^2}{4} d^i_\mu d^\mu_i = \frac{1}{2}(\partial h)^2 + \frac{g^2}{4} f^2 \sin^2 \frac{h}{f} \left(|W|^2 + \frac{1}{2c_w^2} Z^2 \right)$$

$$g_{HVV} = i\,\frac{g^2}{4} v \sqrt{1-\xi} \qquad \xi \equiv \frac{v^2}{f^2} = \sin^2 \frac{\langle h \rangle}{f}$$

Fermion couplings are less sharply predicted



$$= i\,\frac{m_f}{v} c$$

MCHM_5 $\quad c = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

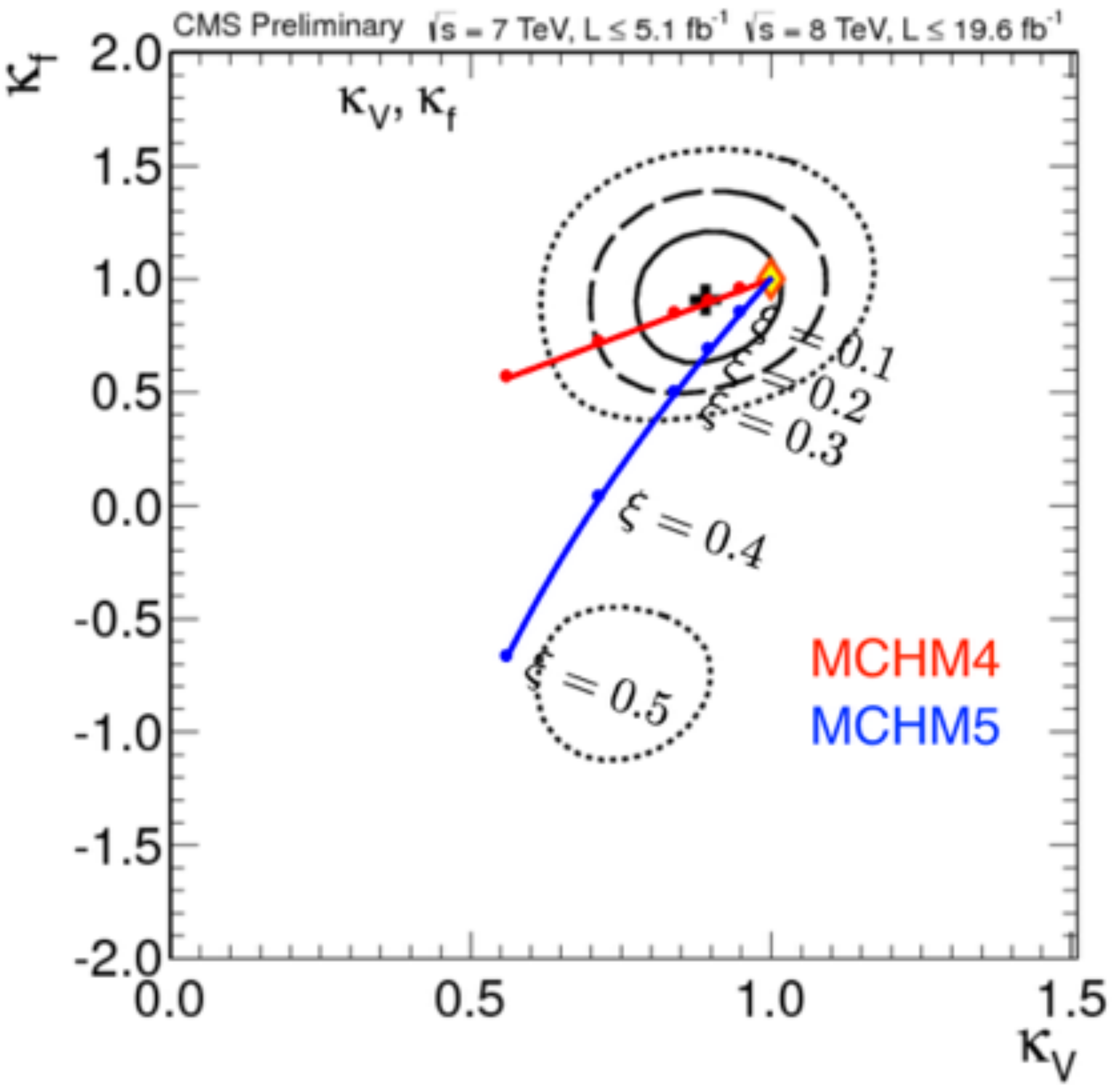
MCHM_4 $\quad c = \sqrt{1-\xi}$

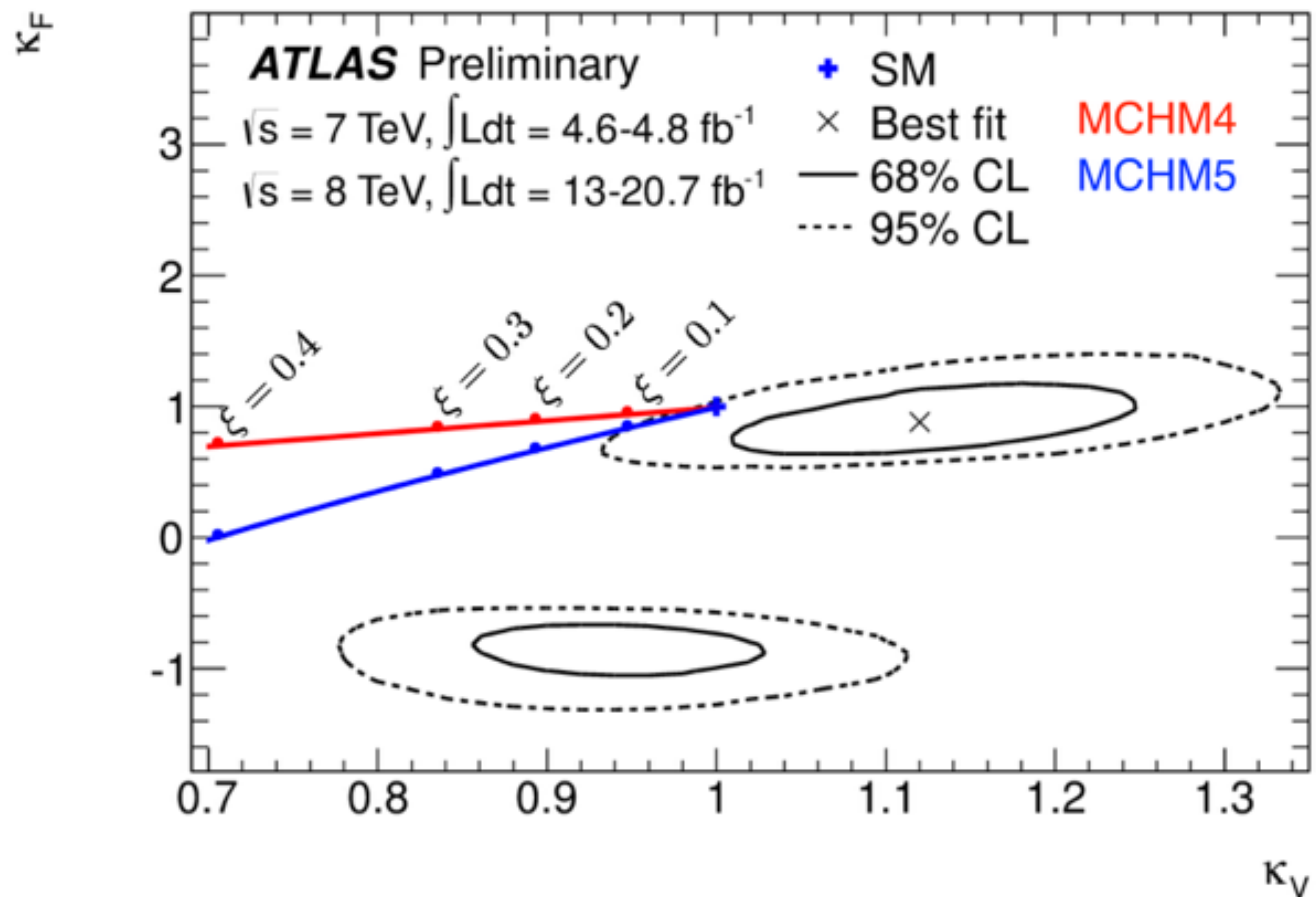
MCHM_{10} $\quad \cdots$

Do depend on fermionic operator representations

Higgs Couplings

A rough comparison with data:





Higgs Couplings

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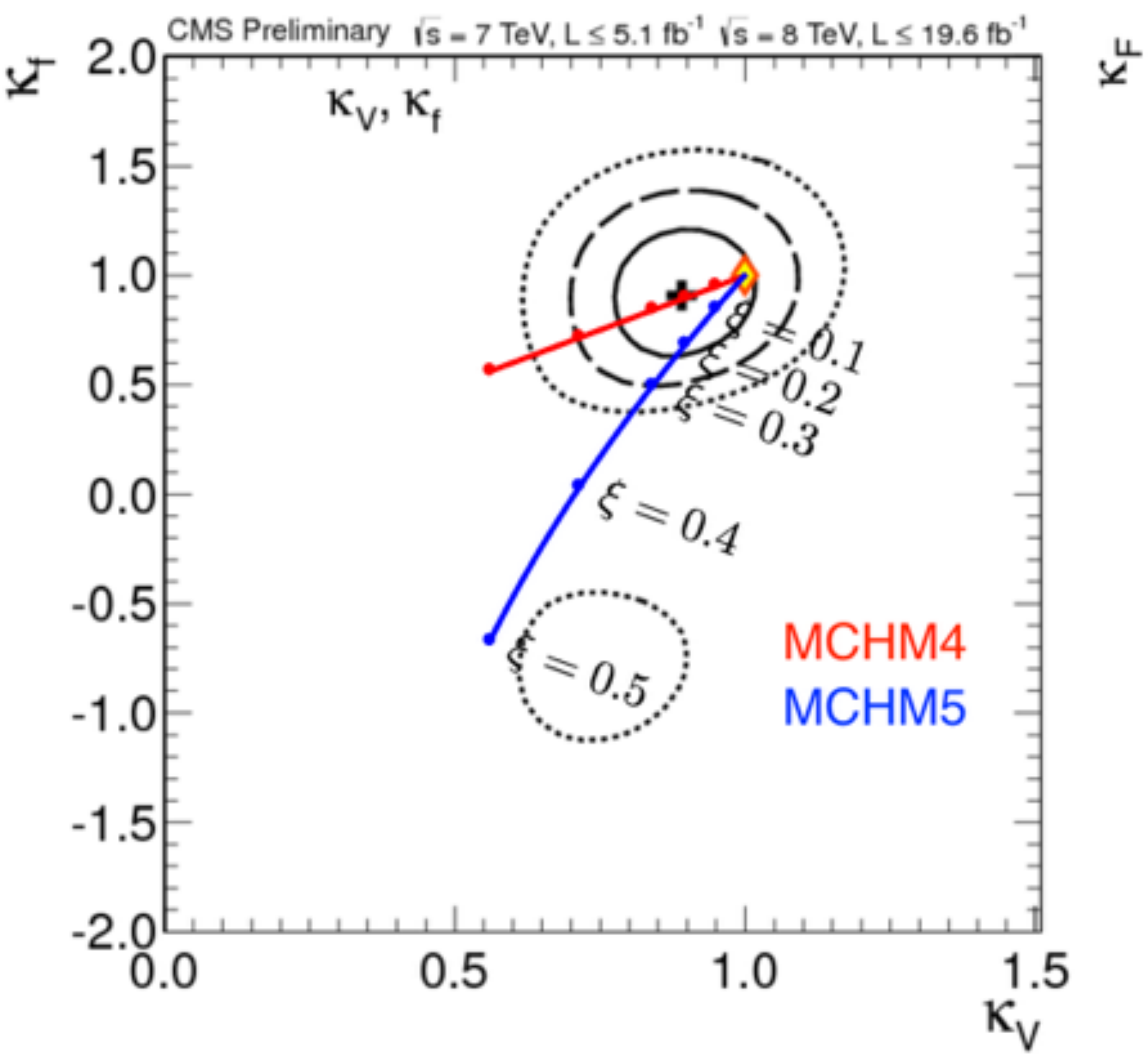
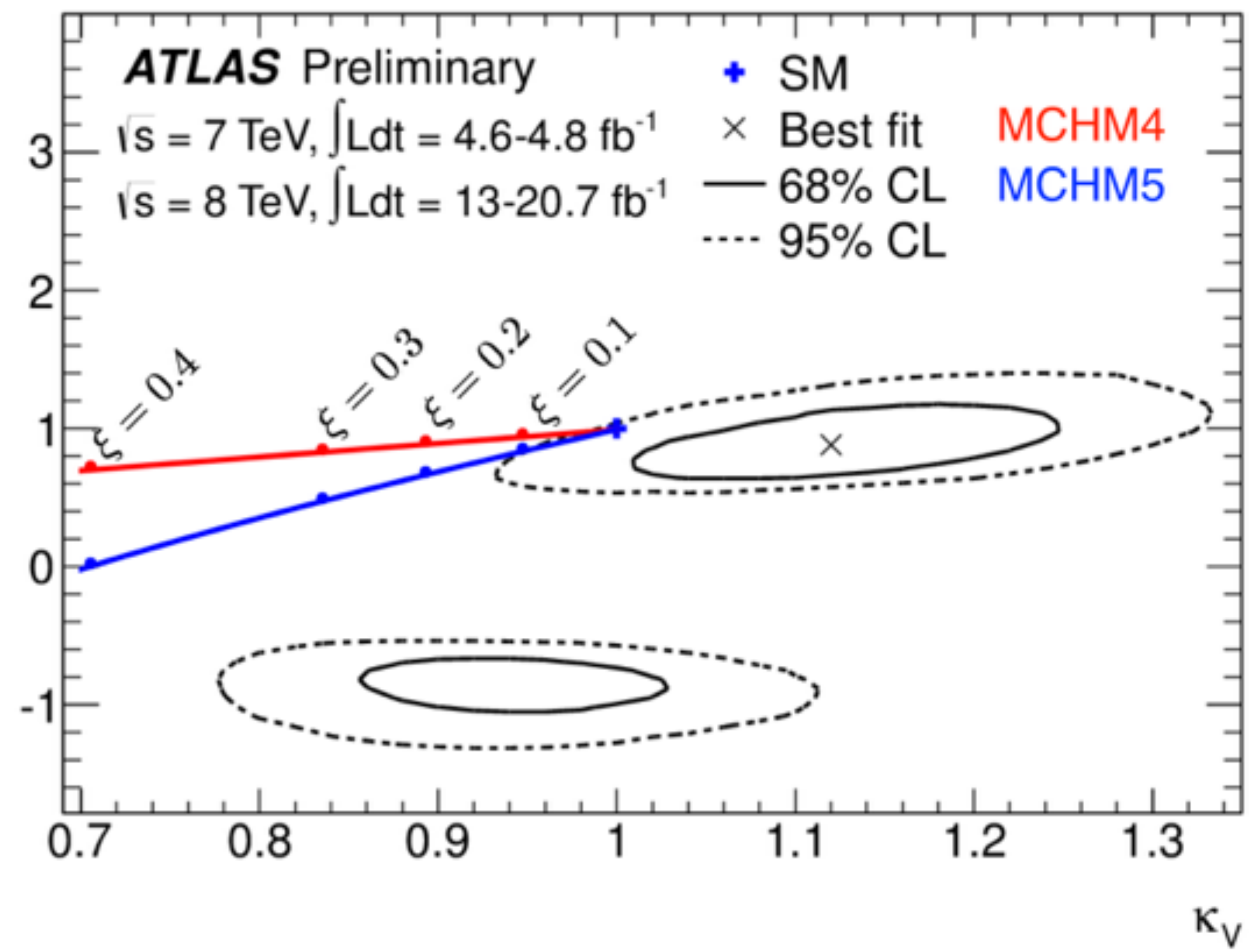




Projections:

Collider	Energy	Luminosity	ξ $[1\sigma]$	References
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$	[60–62]
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$	[60–62]

Plausible reach:

$$\xi \sim 0.1$$

Vector Resonances

A "very direct" direct signature:

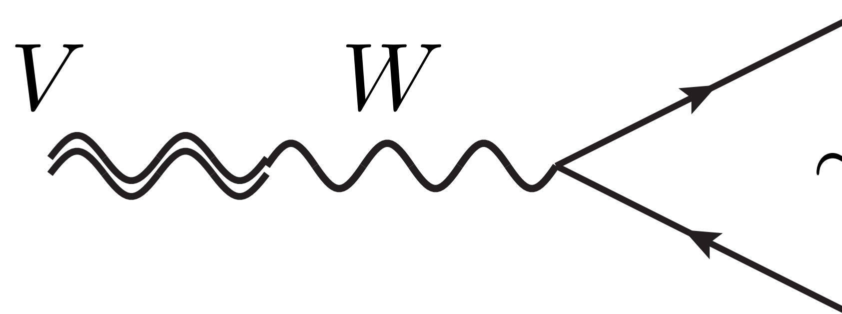
$$J_\mu^{SO(4)} = (\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3})$$

The W partners 

Two-Parameter modelling:

Typical Composite Sector scale: m_*

Typical Composite Sector Coupling: $g_* = m_*/f$



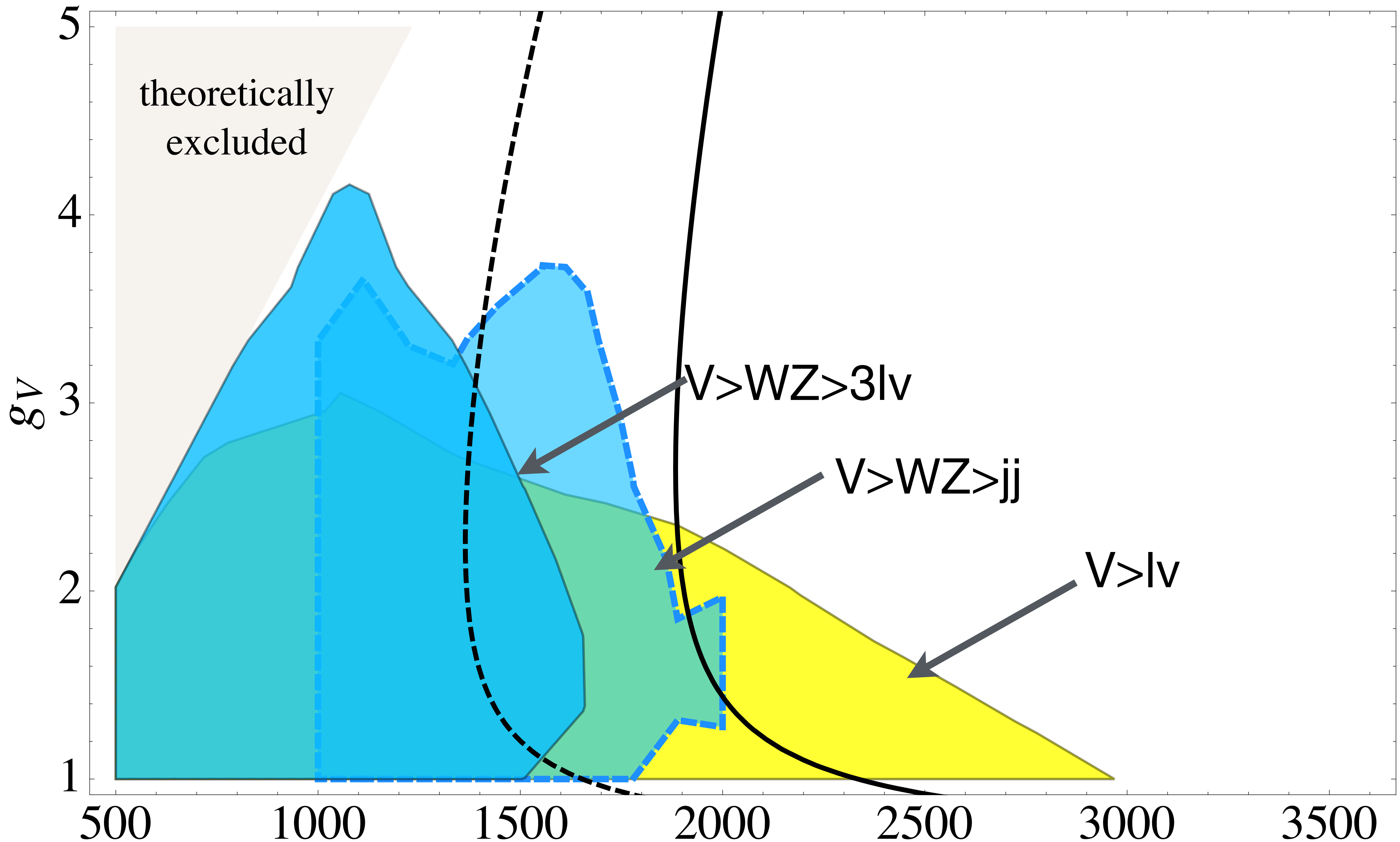
$$\sim g_W \frac{g_W}{g_*}$$

For large g_*: reduced DY, reduced quark and leptons BR

Vector Resonances

[Pappadopulo, Torre, Thamm, AW, 2014]

Current Limits on W partners:



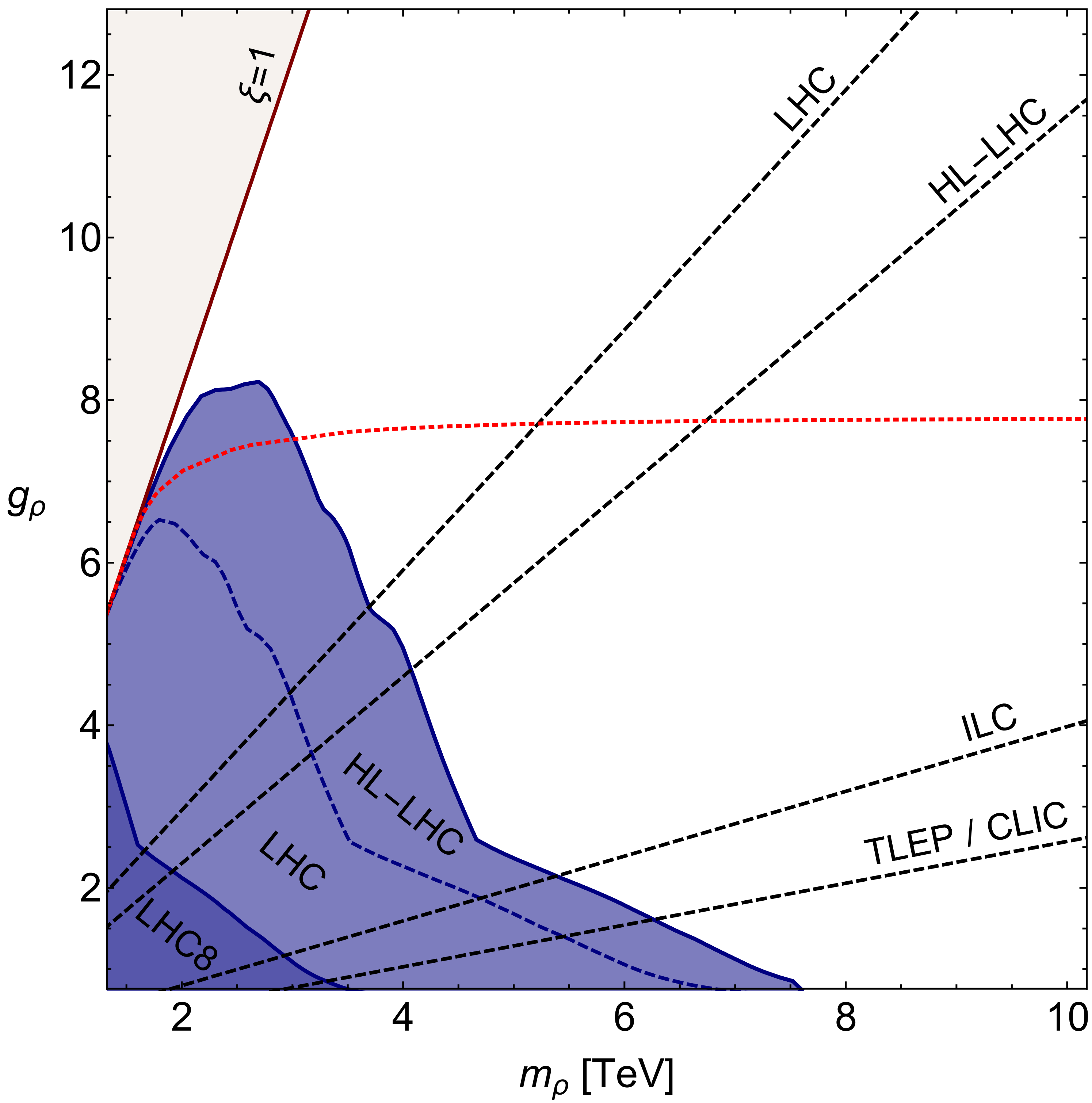
Even weaker if Top Partner decays open

[Contino et al. 2012; Greco et.al., 2013; Chala et al. 2014;]

Vector Resonances

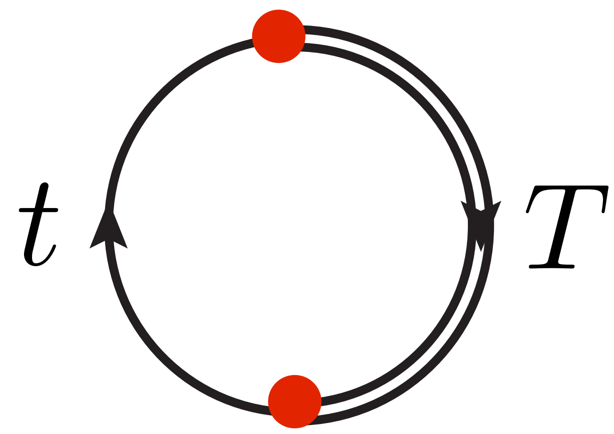
[Torre, Thamm, AW, 2015.]

Direct versus Indirect @ LHC



Top Partners

Top Partners generate
Higgs potential and mass:



$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\ \mathrm{GeV}}{m_h}\right)^2 \left(\frac{M_P}{500\ \mathrm{GeV}}\right)^2$$

M_P = mass of the **Top Partner** that cancels the divergence

Light Higgs plus **Low Tuning** need **Light Partners**

SUSY:

light stops

pNGB Higgs:

light top partners

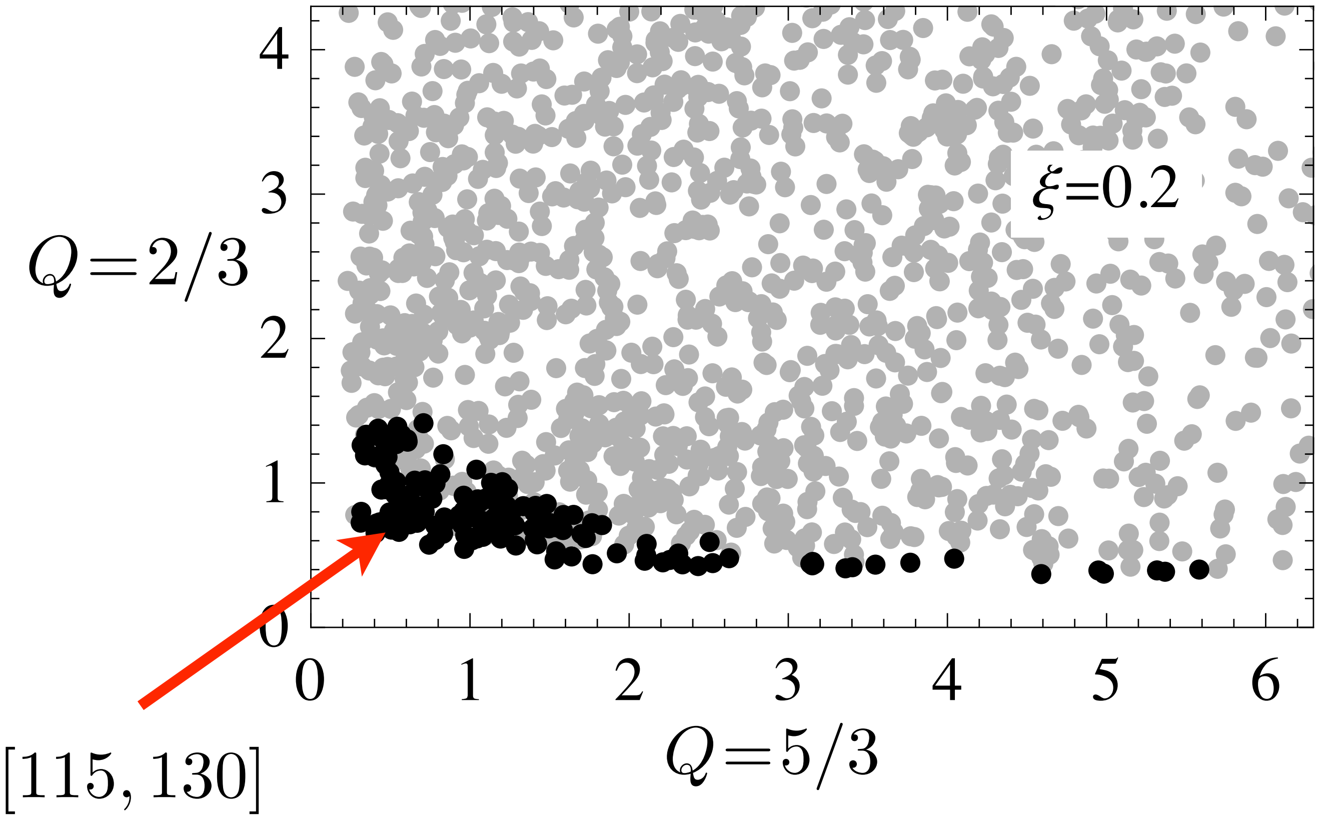
Top Partners

[Matsedonsky,i Panico, AW 2012]

In a class of explicit CH models

$$\mathrm{MCHM}_{4,5,10}$$

$\xi = 0.2:$ (low tuning)



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Top Partners

[Matsedonsky,i Panico, AW 2012]

In a class of explicit CH models

$\mathrm{MCHM}_{4,5,10}$

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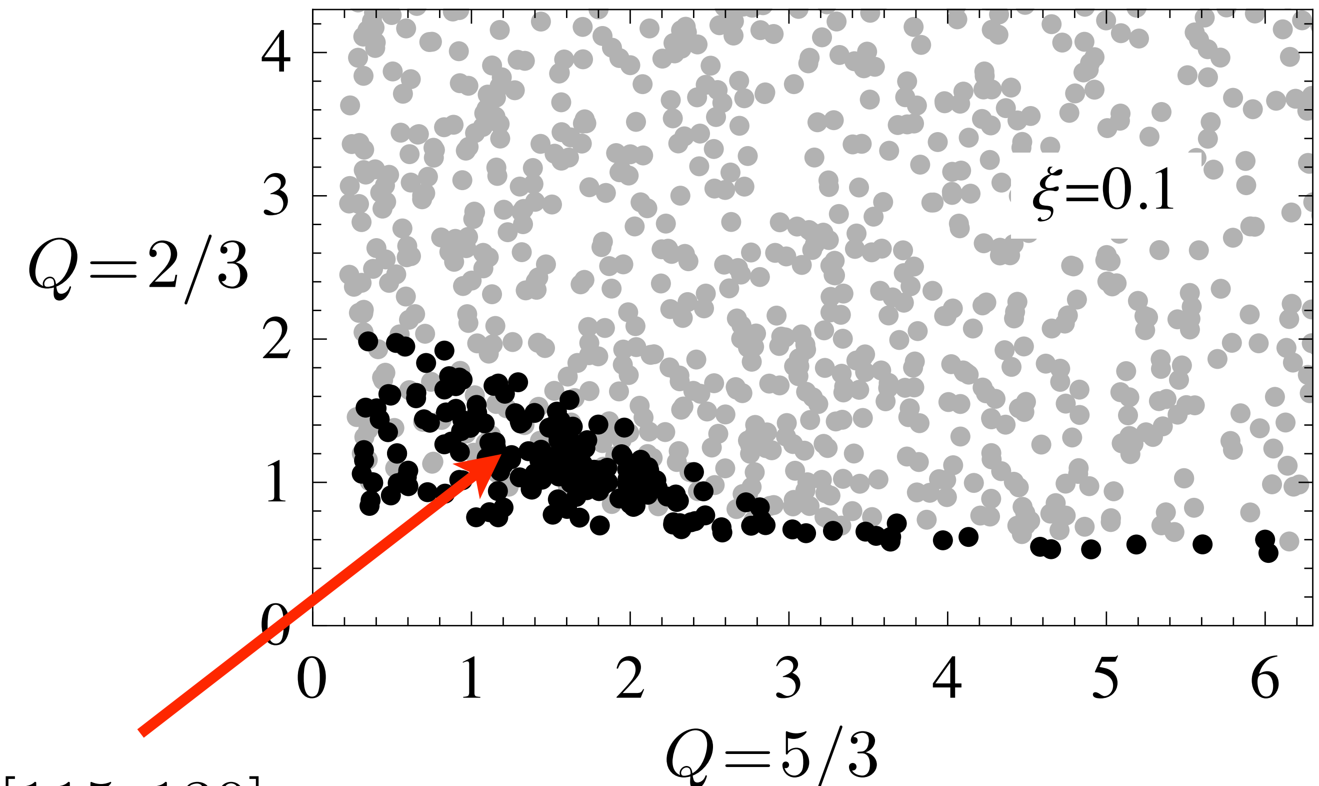

$m_H \in [115, 130]$

Light Higgs plus **Low Tuning** need **Light Partners**

SUSY:

light stops

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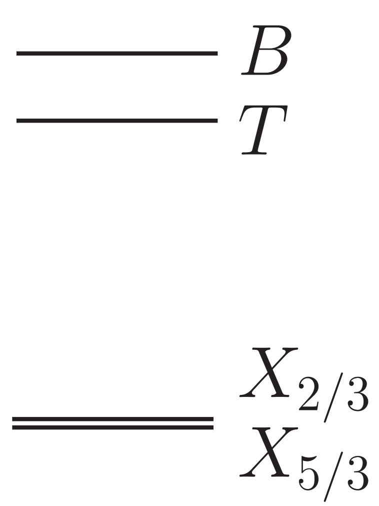
Top Partners

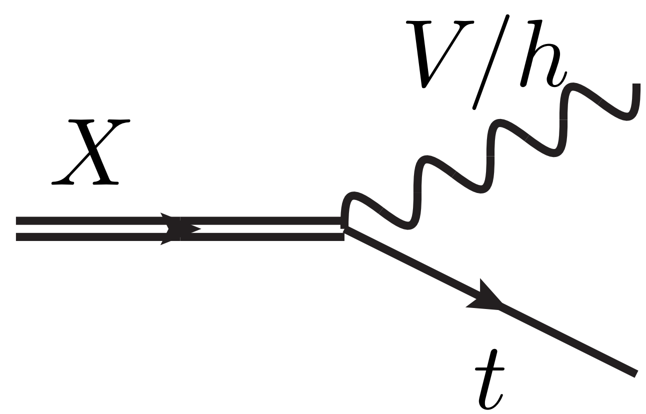
[De Simone, Matsedonsky, Rattazzi, AW, 2012]

Fourplet of custodial $\mathrm{SO}(4)$ $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$

Spectrum:



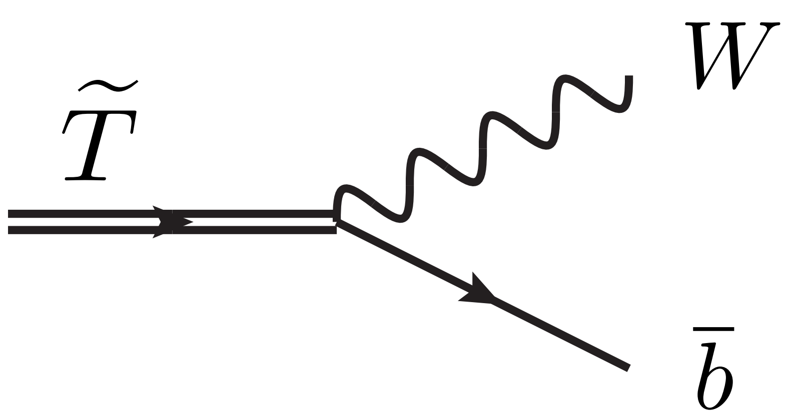
Couplings:



$\sim M_X/f$

generically large Top coupling

Singlet of custodial $\mathrm{SO}(4)$ $\widetilde{T}$

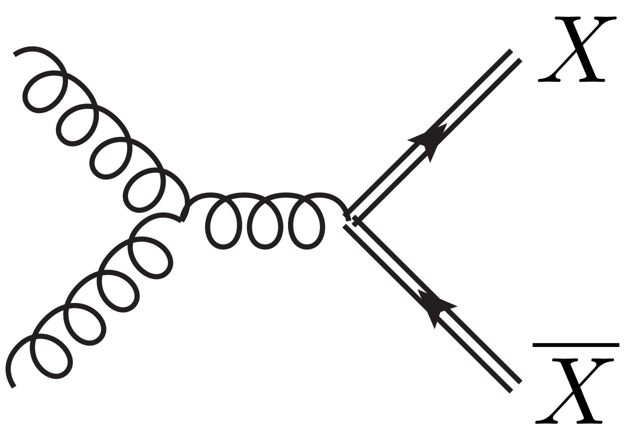


sizable coupling with the bottom quark

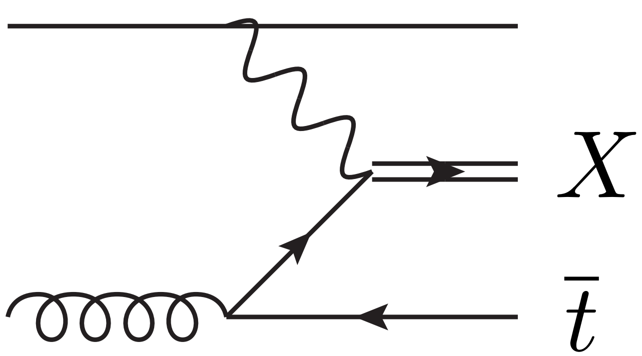
Top Partners

[De Simone, Matsedonsky, Rattazzi, AW, 2012]

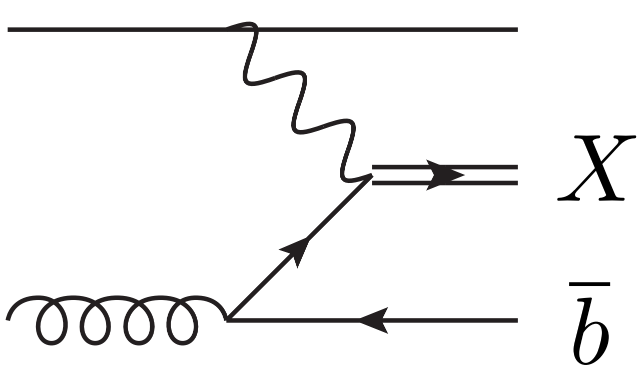
Three possible production mechanisms



QCD **pair prod**.
model indep.,
relevant at low mass



single prod. with **t**
model dep. coupling
pdf-favoured at high mass



single prod. with **b**
favoured by small b mass
dominant when allowed

Top Partners

[De Simone, Matsedonsky, Rattazzi, AW, 2012]

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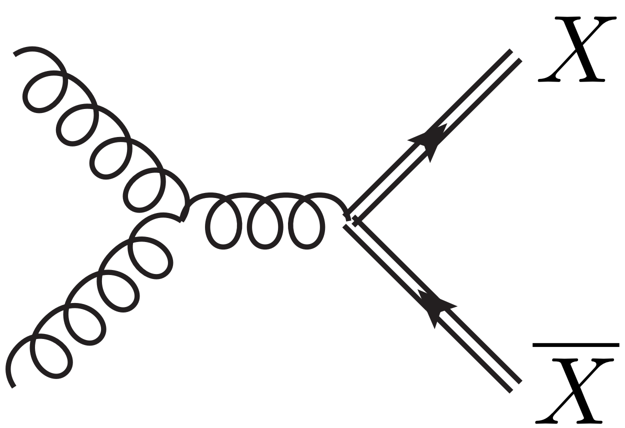

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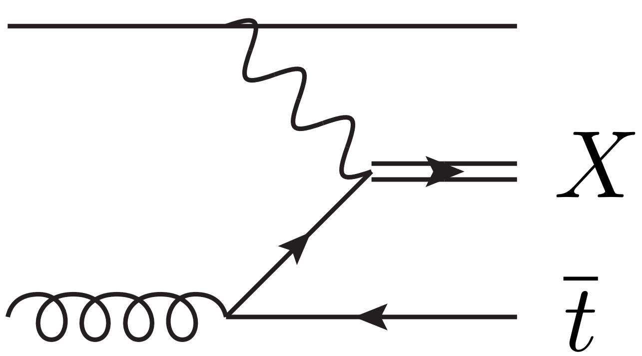
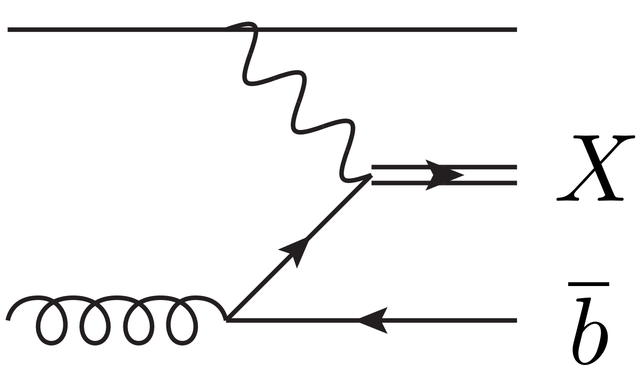


single prod. with **t**
model dep. couplin
pdf-favoured at higl



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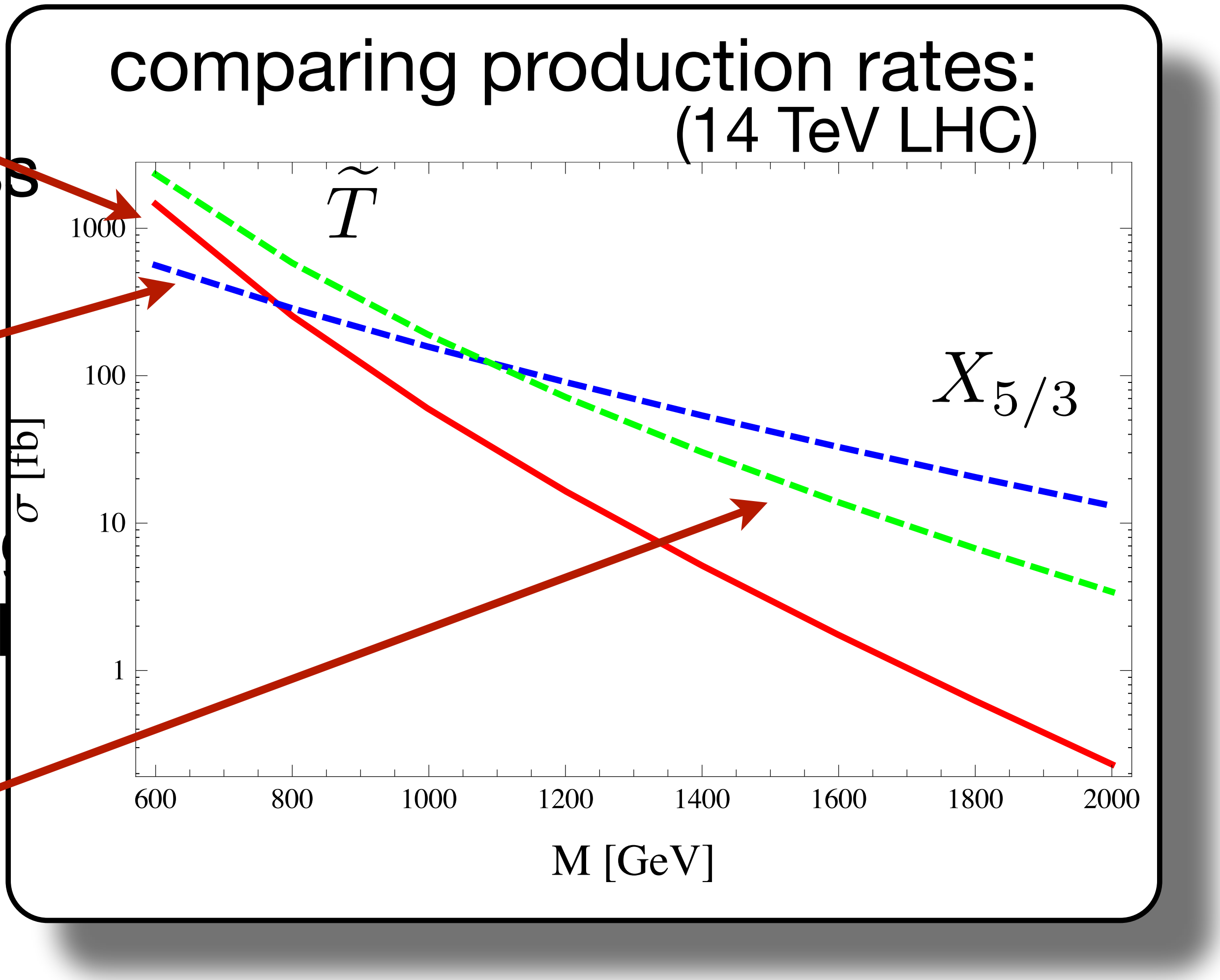

Top Partners

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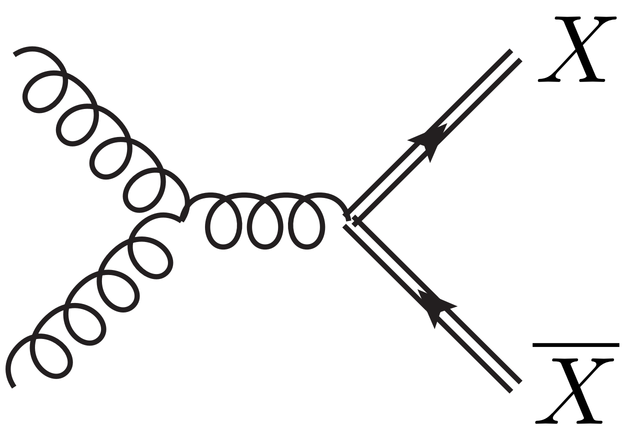

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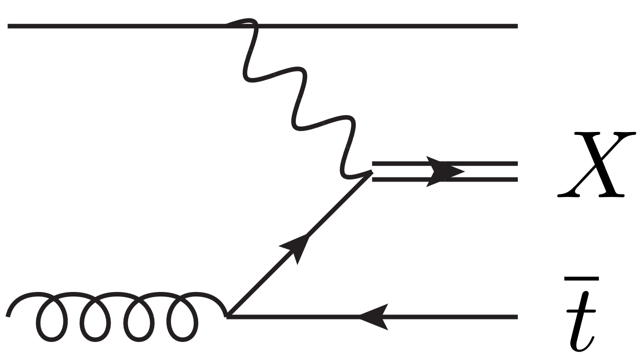

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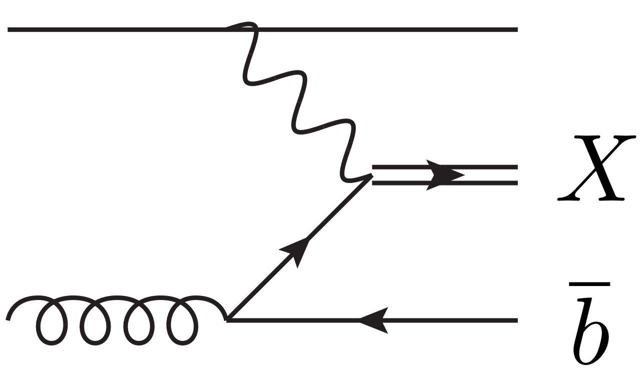

single prod. with **b**
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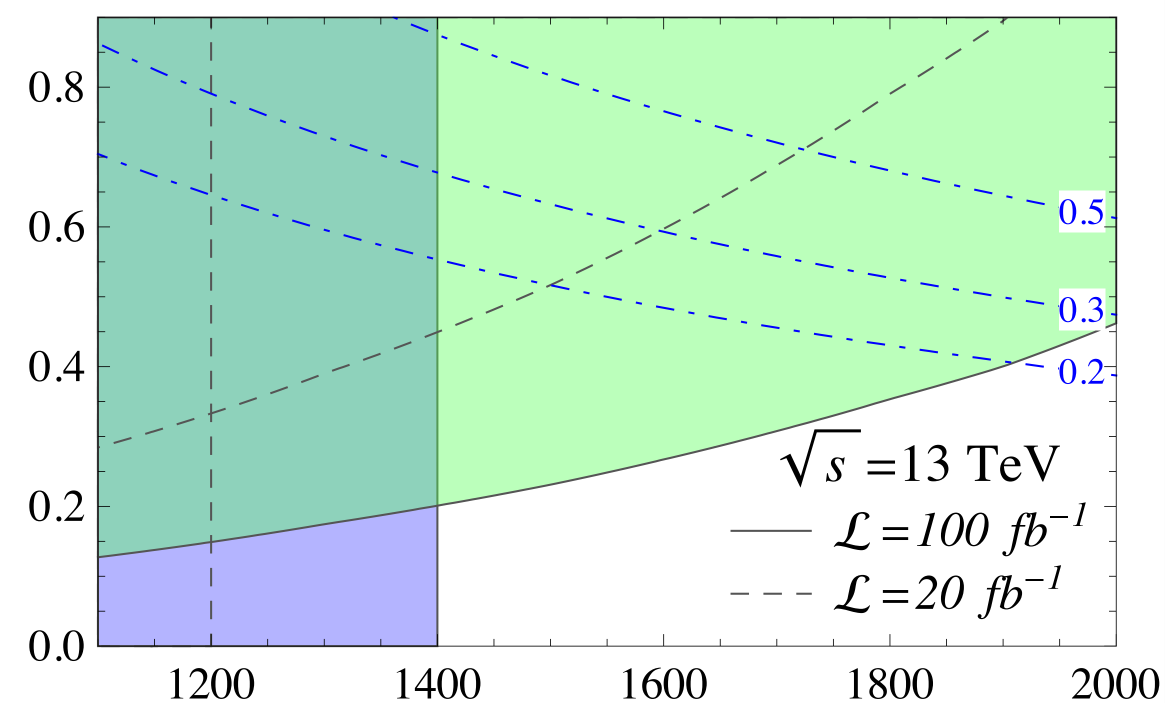
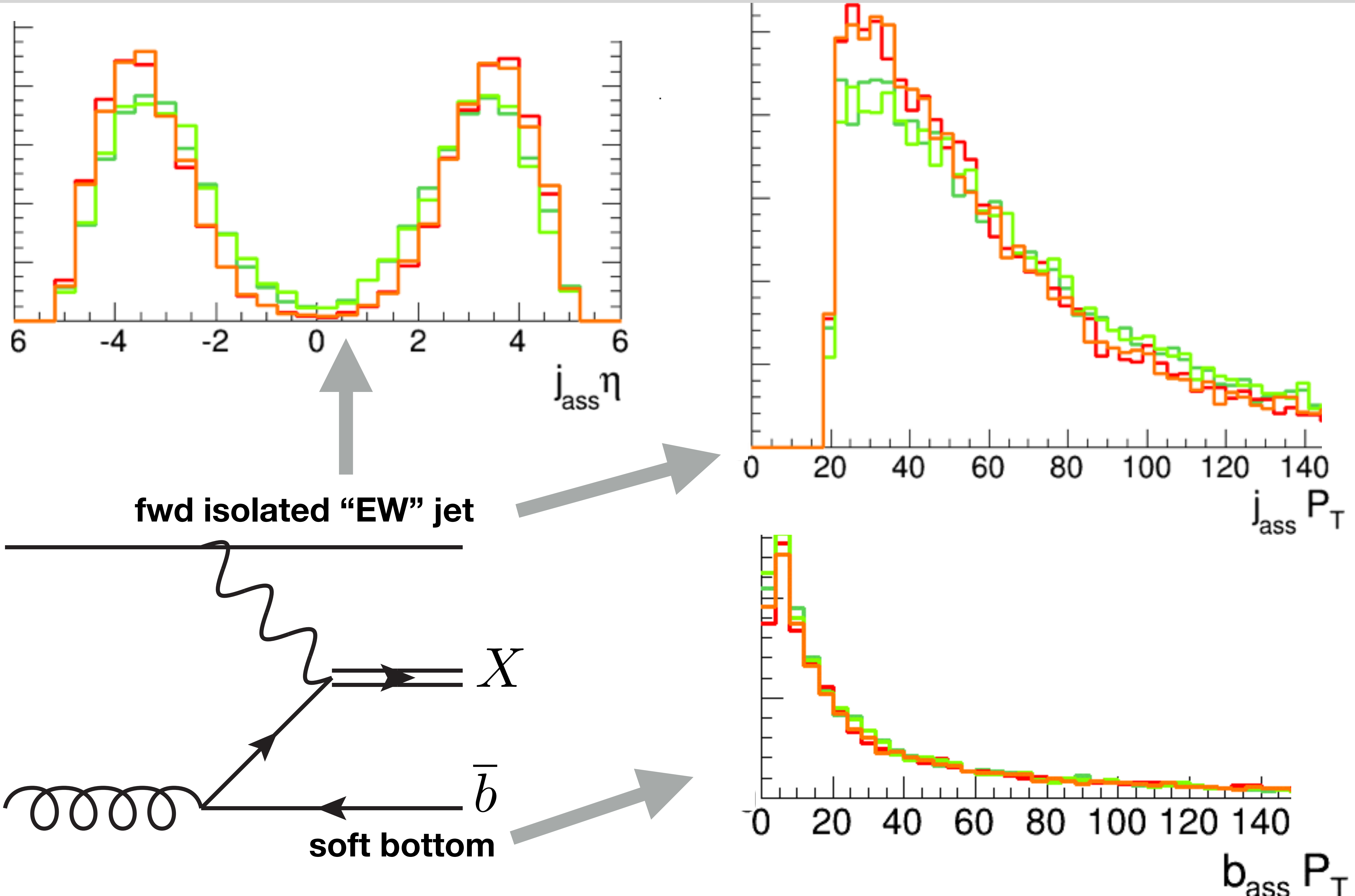
mass-reach improvement
from $\widetilde{T}$ single production:



A good signal for detector studies?



Dark Matter

Heavy-Mediator hypothesis: DM to SM from high scale dynamics

$$M_{\rm Med} \gg m_{\rm DM}$$

Can we fully test this hypothesis in a model-independent way?

Dark Matter

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In the appropriate kinematical region, EFT can do the job

$$\mathcal{L}_{\rm int} = \frac{1}{M_*^2} \sum_i c_i \, O_i$$

EFT definitely applies to low-momentum reaction:
$\left\{ \begin{array}{l} \text{1) thermal relic calculation} \\ \text{2) direct search limits} \\ \text{3) indirect search limits} \end{array} \right.$

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what instead about … 4) collider limits ??

Dark Matter

[Racco, AW, Zwirner, to appear]

EFT only holds below its cutoff $M_{\rm cut} \sim M_{\rm Med}$

All reactions occurring above are unpredictable within the EFT
All reactions occurring below are perfectly predictable

Restricting the signal to the predictable region sets lower bound on the "true" signal, which holds for any mediator model

$$\sigma^S_{EFT}\Big|_{E_{\rm cm}<M_{\rm cut}} \leq \sigma^S_{\rm true} < \sigma_{\rm exc}$$

compared with exclusion upper bound, model indep. limit is set

Dark Matter

[Racco, AW, Zwirner, to appear]

ATLAS mono-jet recast, for $\mathcal{L}_{\rm int} = -\frac{1}{M_*^2} \left(\overline{X}\gamma^\mu\gamma^5 X\right) \left(\sum_q \overline{q}\gamma_\mu\gamma^5 q\right)$

counting in four SR

signal region	SR1	SR2	SR3	SR4
$p_T^{\rm jet}$ and MET	>120	>220	>350	>500
$\sigma_{\rm exc}$[pb]	2.7	0.15	$4.8\,10^{-2}$	$1.5\,10^{-2}$

restricted signal definition:

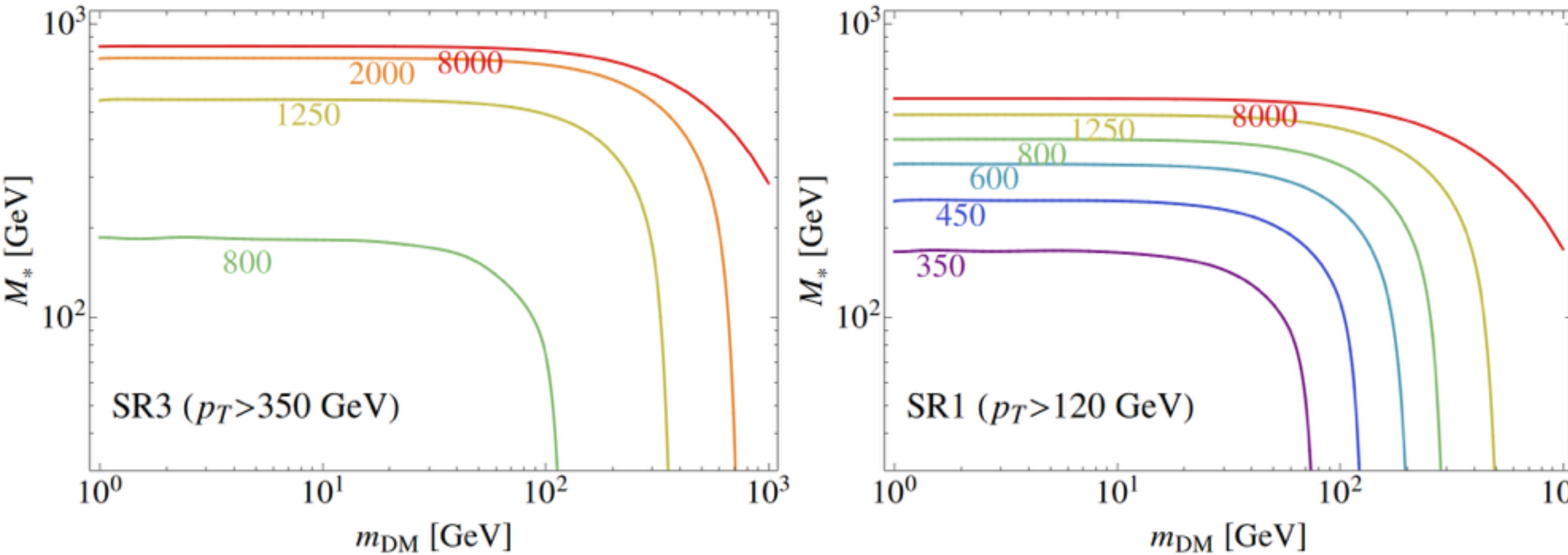
$$\sigma_{{\rm SR}i}(M_*, m_{DM}, M_{\rm cut}) = \sigma(M_*, m_{DM}, M_{\rm cut}) \times A_i(m_{DM}, M_{\rm cut}) \times \epsilon$$

NOTE: the EFT has **three** parameters

1) $m_{\rm DM}$
2) M_*
3) $M_{\rm cut}$ (as physical as the other two)

Dark Matter

[Racco, AW, Zwirner, to appear]



Hard signal regions are favored at high cutoff (naive EFT)

But rapidly loose sensitivity: the cut makes distributions softer

Dark Matter

[Racco, AW, Zwirner, to appear]

Theoretical connection among M_* and $M_{\rm cut}$:

$$M_{\rm cut} = g_*\, M_*$$

estimated mediator coupling

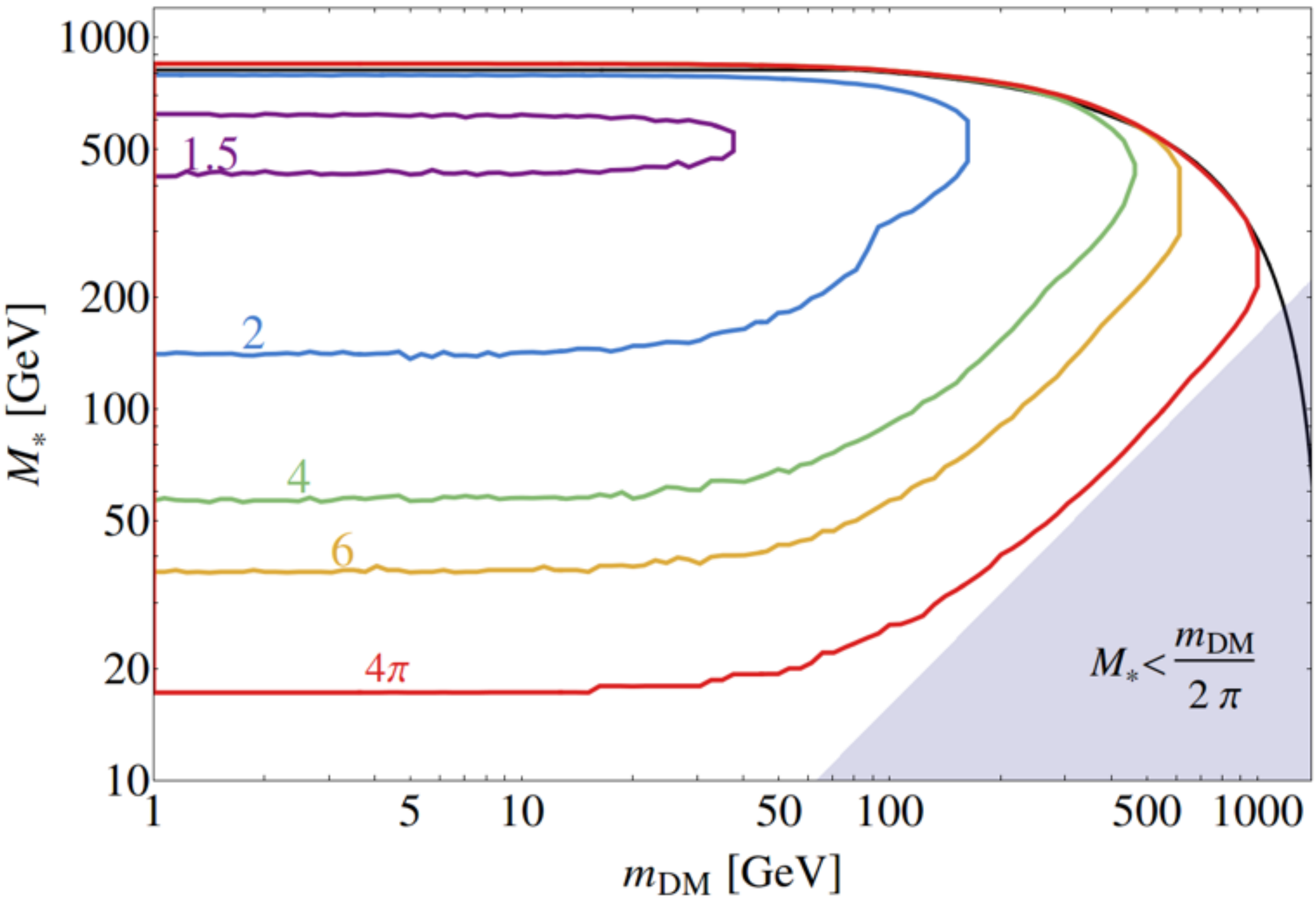
We know for sure that: $g_* < 4\pi$

Expected for a WIMP: $g_* \sim 1$

Dark Matter

[Racco, AW, Zwirner, to appear]

Fixed g_* limits:



Dark Matter

Message:

work is needed on mono-X, especially in the soft region

Question:

two fwd ISR jets, from same IP, plus nothing and little MET
(also good for H>invisible or WW>invisible)
unthinkable even with upgrade?

Conclusions

- CH is a playground for (Un-)Naturalness tests
    1. Higgs couplings modifications
    2. Vector or fermion resonances

- Top Partners single prod. deserves particular attention

- Heavy-mediator DM is far from fully tested
    could we do better with HL and new detectors?