Learning from run-2

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Disclaimer

The **Higgs** was the **last guided discovery**

Right now, we are not sure of what we should search for

Experimental research now is **exploration**, not **validation**

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We **do have** theoretical questions to be asked to data, e.g.

- **Naturalness:** a proper **microscopic** origin of EW scale?
- **Dark Matter: must** be there. **Can** be a WIMP?

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We **do have** theoretical questions to be asked to data, e.g.

- **Naturalness:** a proper **microscopic** origin of EW scale?
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However, searching for specific signals dictated by those questions should be accompanied by theory-independent exploration effort. [This holds now and, if nothing is seen at future coll.]

Higgs Couplings in CH

Model-independent prediction, from **symmetries**

Direct connection with **tuning:**

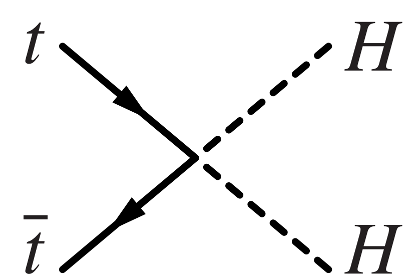
$$\xi = \frac{v^2}{f^2} \qquad\qquad \Delta \geq \frac{1}{\xi}$$

Higgs-Vectors coupling modification: $k_V = \sqrt{1-\xi}$

Few discrete possibilities for fermion couplings:

$$\begin{cases} \mathrm{MCHM}_5 & k_F = \dfrac{1-2\xi}{\sqrt{1-\xi}} \\ \mathrm{MCHM}_4 & k_F = \sqrt{1-\xi} \\ \mathrm{MCHM}_{10} & \cdots \end{cases}$$

CAVEATS:

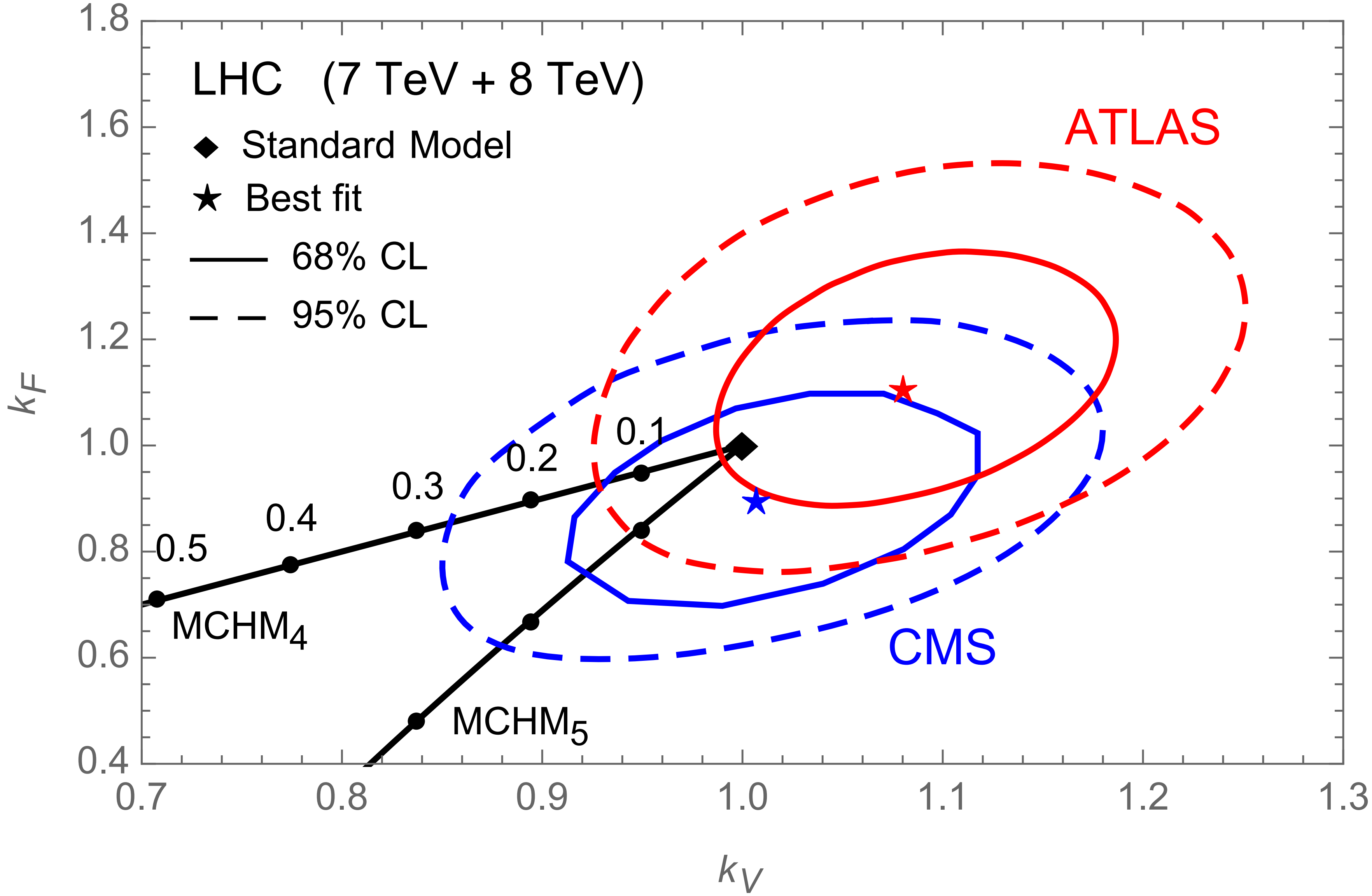


(see e.g. arXiv:1205.5444)

1) Easy to encounter $k_t \neq k_b$
2) Easy to find **extra Goldstone scalars** that contribute by mixing
3) **New couplings** are also there

Higgs Couplings in CH

Current bound (from ATLAS) is $\xi < 0.12$.



Expected LHC-300 reach (with SM central value): $\xi < 0.1$.

No much space for **improvement** at **run-2**

Higgs Couplings in the MSSM

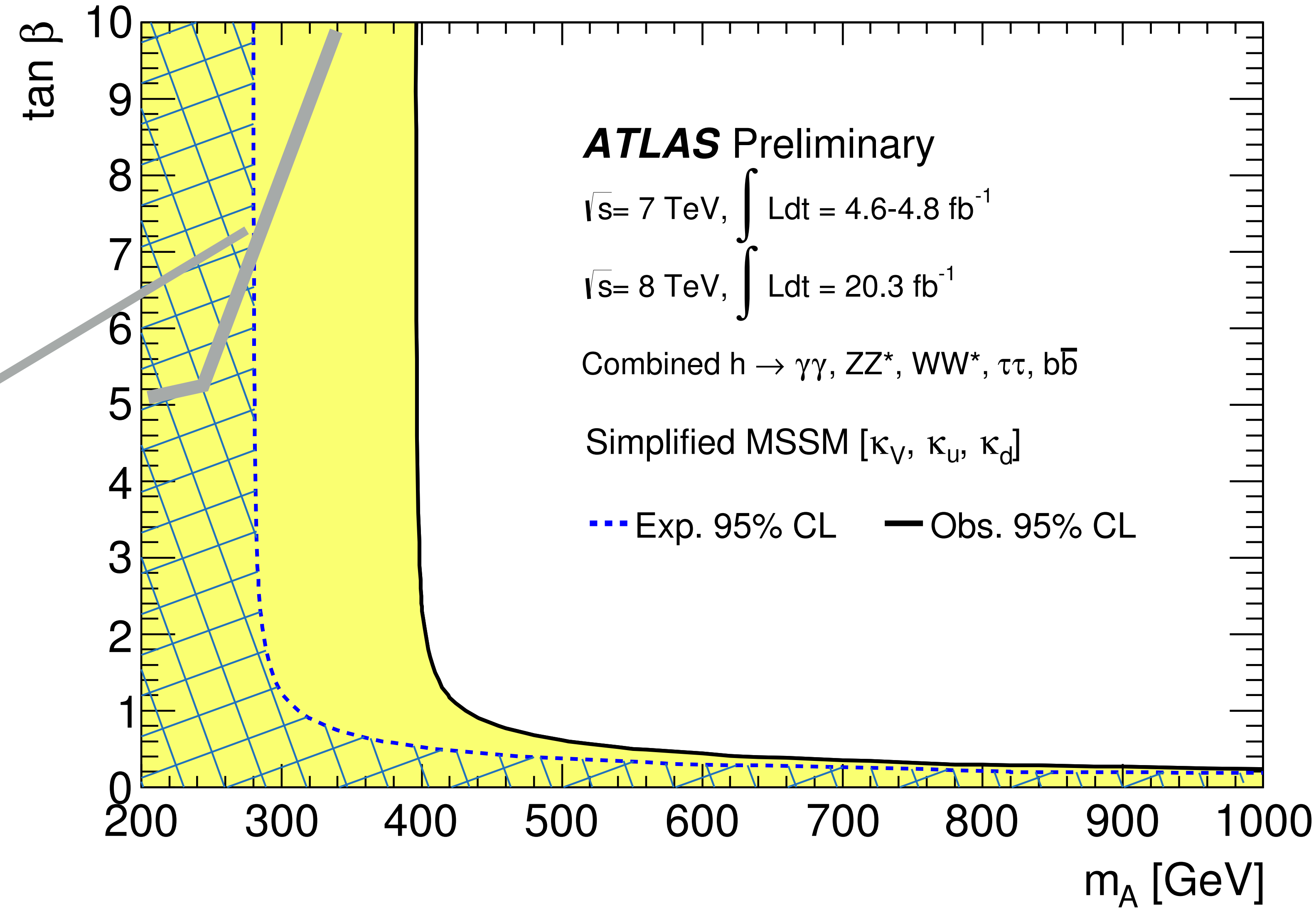
Higgs coupling modifications expected (a priori) from second doublet mixing:

$$k_b \simeq 1 + \frac{t^2}{1+t^2}\epsilon \qquad t = \tan\beta$$

$$k_t \simeq 1 - \frac{1}{1+t^2}\epsilon \qquad \epsilon \sim \frac{m_h^2}{m_A^2}$$

$$k_V \simeq 1 - \mathcal{O}(\epsilon^2)$$

Direct H,A searches
[from Barbieri et. al, 2013]



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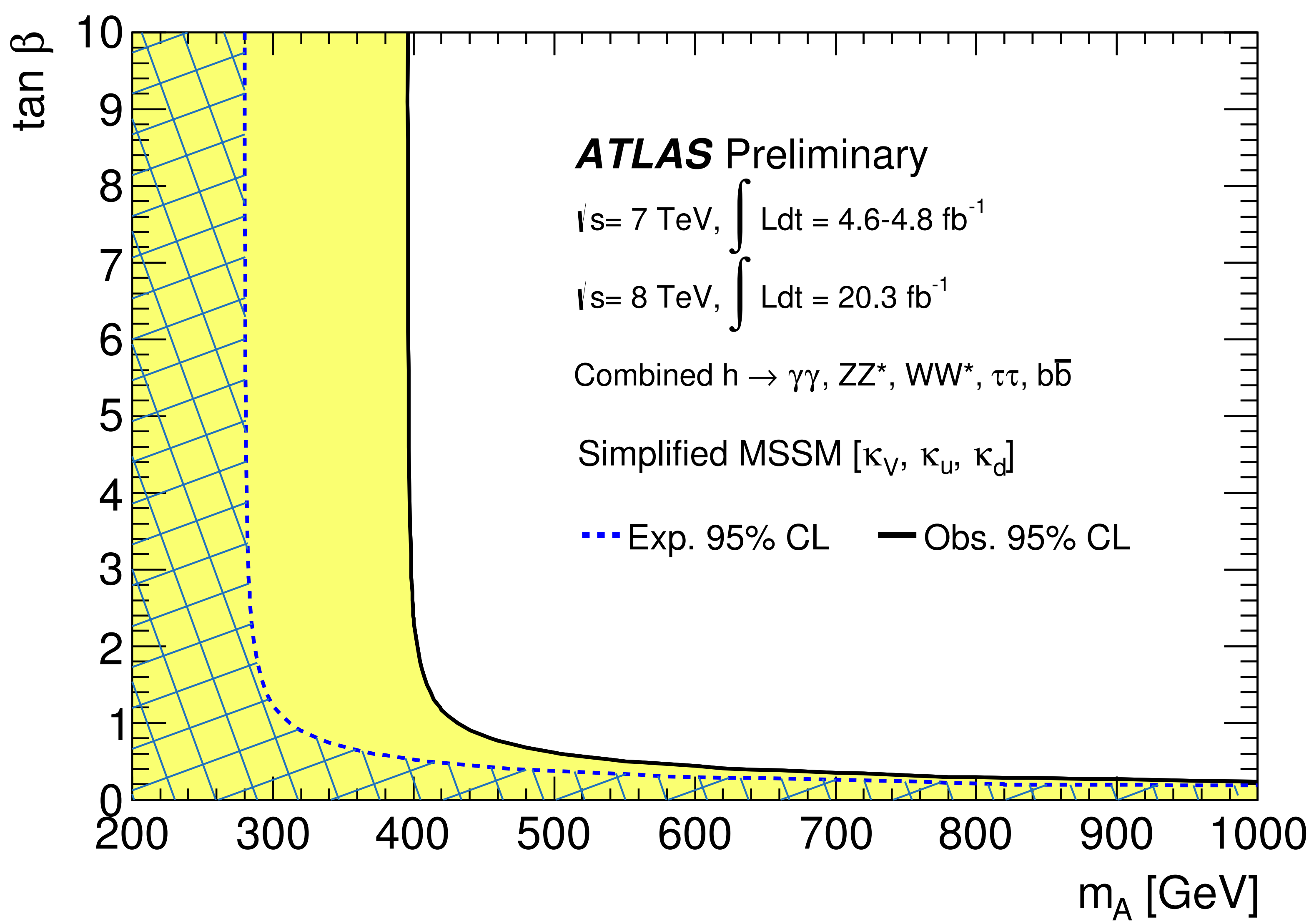
However ....

$$\frac{m_Z^2}{2} \simeq \frac{m_A^2}{t^2} - \widetilde{m}_u^2$$
$$\widetilde{m}_u^2 = \mu^2 + m_u^2 + \delta$$

$$\Delta^{\text{tree}} \simeq \left(\frac{6}{t}\right)^2 \left(\frac{m_A}{400\,\text{GeV}}\right)^2$$



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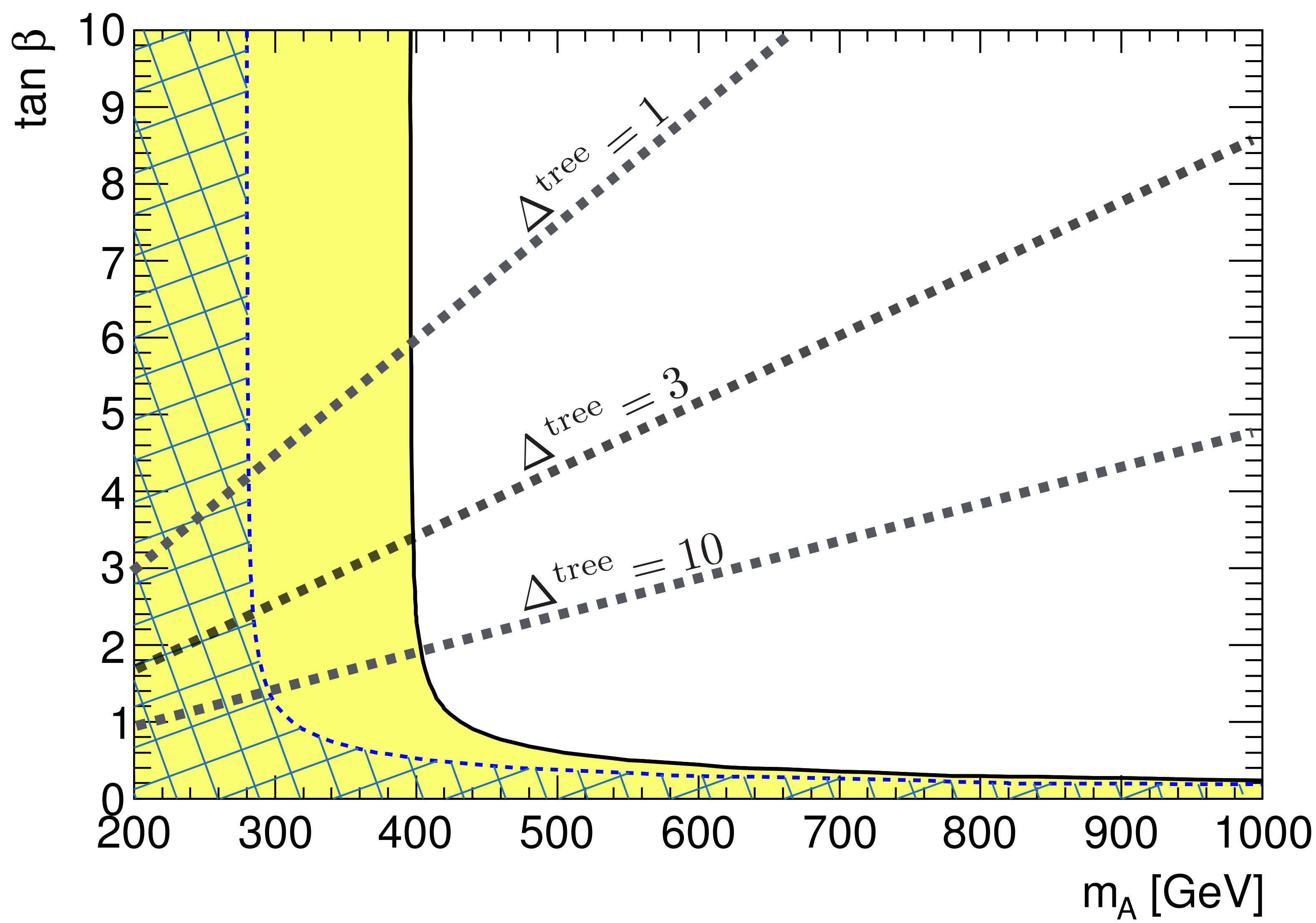
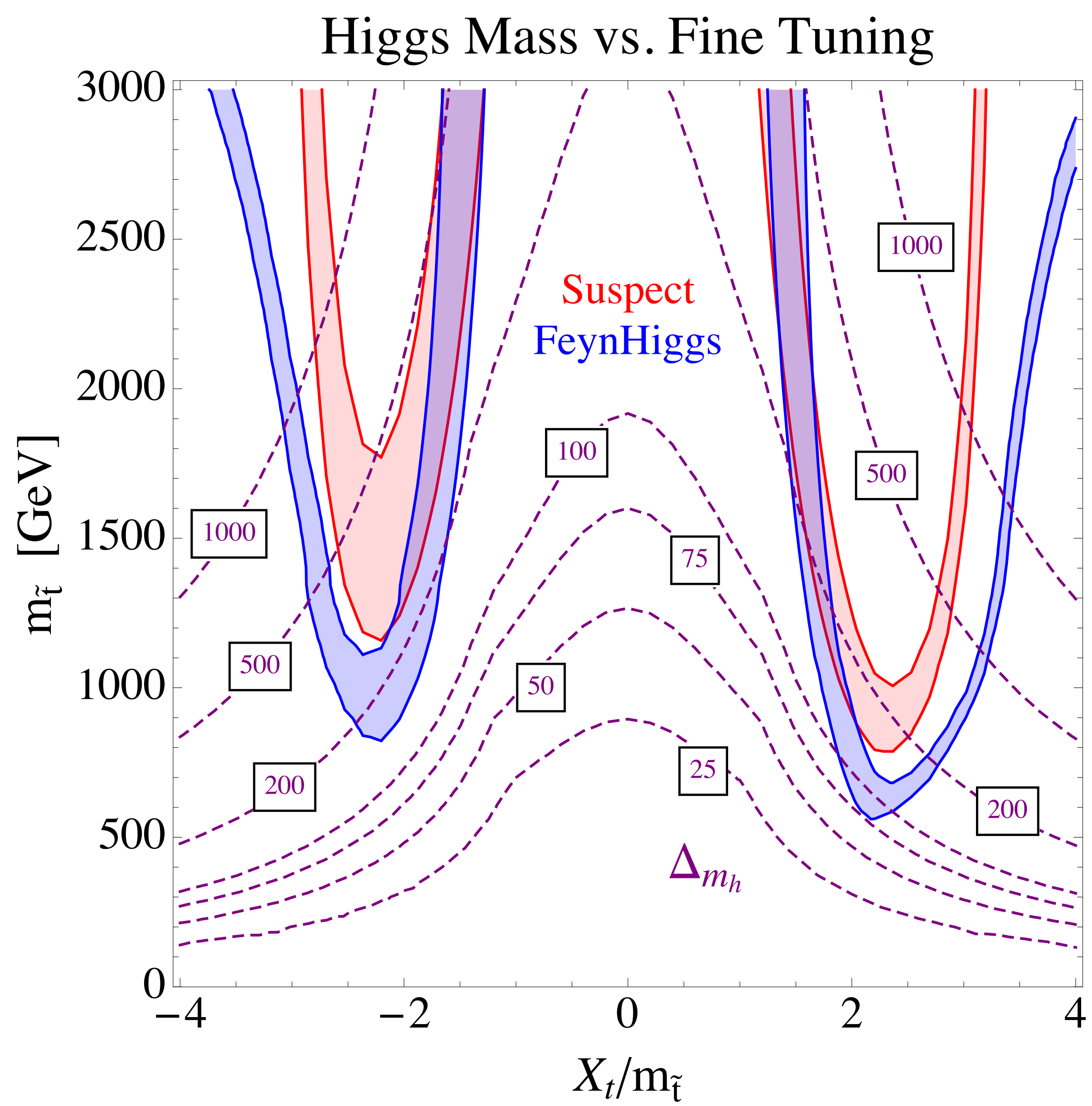
No Tuning/coupling connection in MSSM



Higgs Couplings in the MSSM

Natural MSSM is fine with couplings, but **killed by mass**

$m_H^2 > m_Z^2$ → Exponentially heavy stops → Exponentially large tuning



$$\Delta \gtrsim 100$$

Less Minimal SUSY (λ-SUSY)

[Barbieri et al. 2006, Hall et al. 2012, Barbieri et al. 2013]

Adding extra singlet is sufficient to avoid heavy stops

$$W_\lambda = \lambda S H_u H_d \longrightarrow m_h^2 \sim m_Z^2 \left(\frac{1-t^2}{1+t^2}\right)^2 + 4\lambda^2 v^2 \frac{t^2}{(1+t^2)^2}$$

The framework requires large λ and moderate $\tan\beta$

No decoupling limit. Tuning set by scalar masses, e.g.

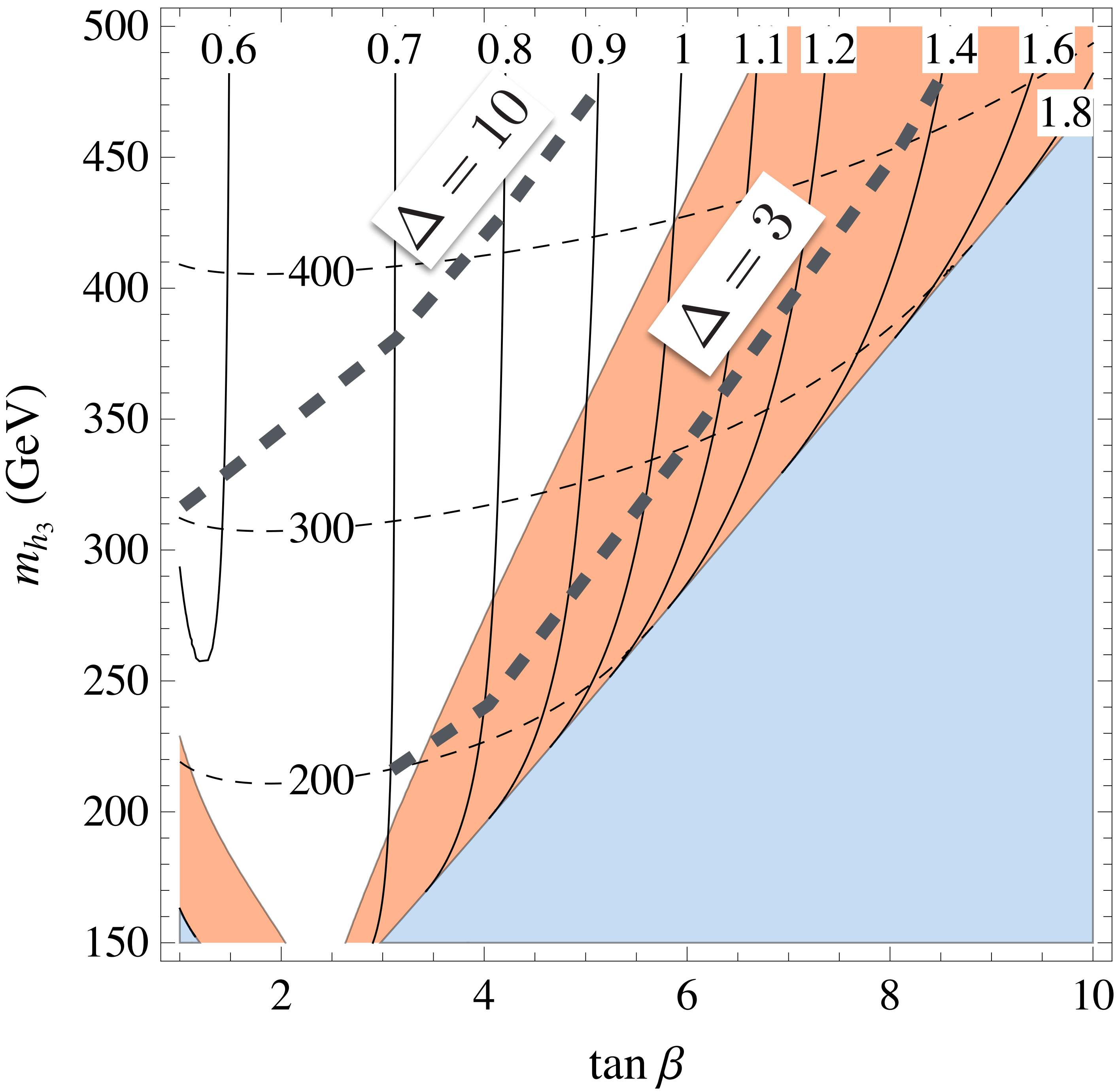
$$\Delta \geq \frac{1}{\lambda^2}\left(\frac{m_{H^\pm}}{170\,\mathrm{GeV}}\right)^2$$

Direct Tuning/Scalar sector connection in λ-SUSY.

Less Minimal SUSY (λ-SUSY)

[Barbieri et al. 2006, Hall et al. 2012, Barbieri et al. 2013]

Higgs coupling bounds (singlet decoupled): current



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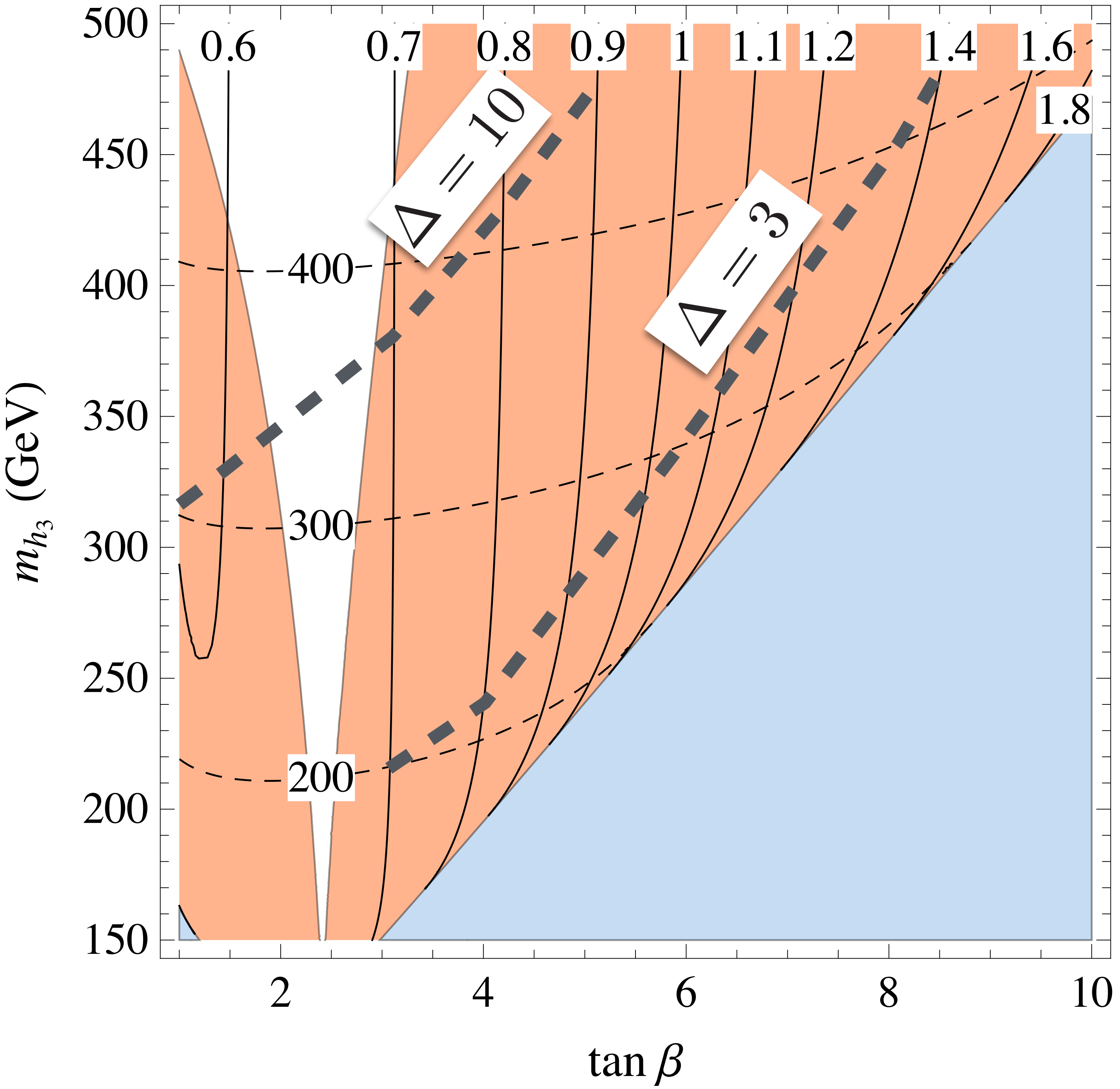
Higgs coupling bounds (singlet decoupled): LHC-300

(improved $H\tau\tau$)



Beyond Higgs Couplings

Physics modifying couplings also affects other EW obs.

In EFT description: (appropriate if BSM is heavy)

EFT

e.g. $\mathcal{L}^{d=6}$

→

Higgs coupling modifications

- dominated by systematics
- no much benefit from larger run-2 rate

High energy EW processes

- larger effects at high energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$
- possible improvement at run-2

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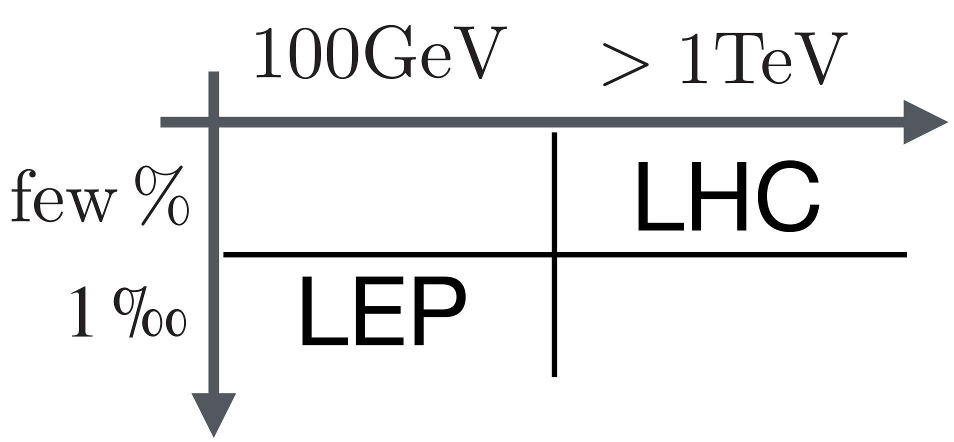


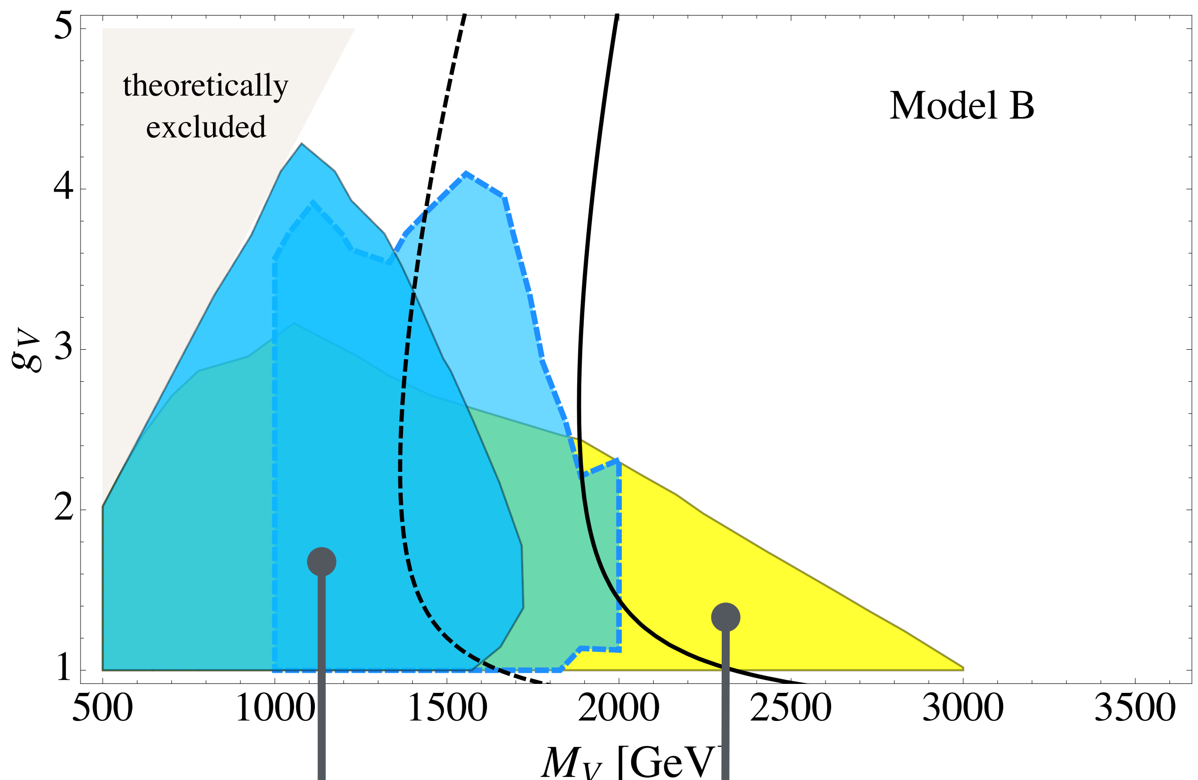
LHC better than LEP on some EWPT par.?

Plus of course measuring operators not constrained by LEP

Resonances

Plenty of opportunities at run-2

run-1 limits on Composite HVT



VV/VH final states

ll/lv final states

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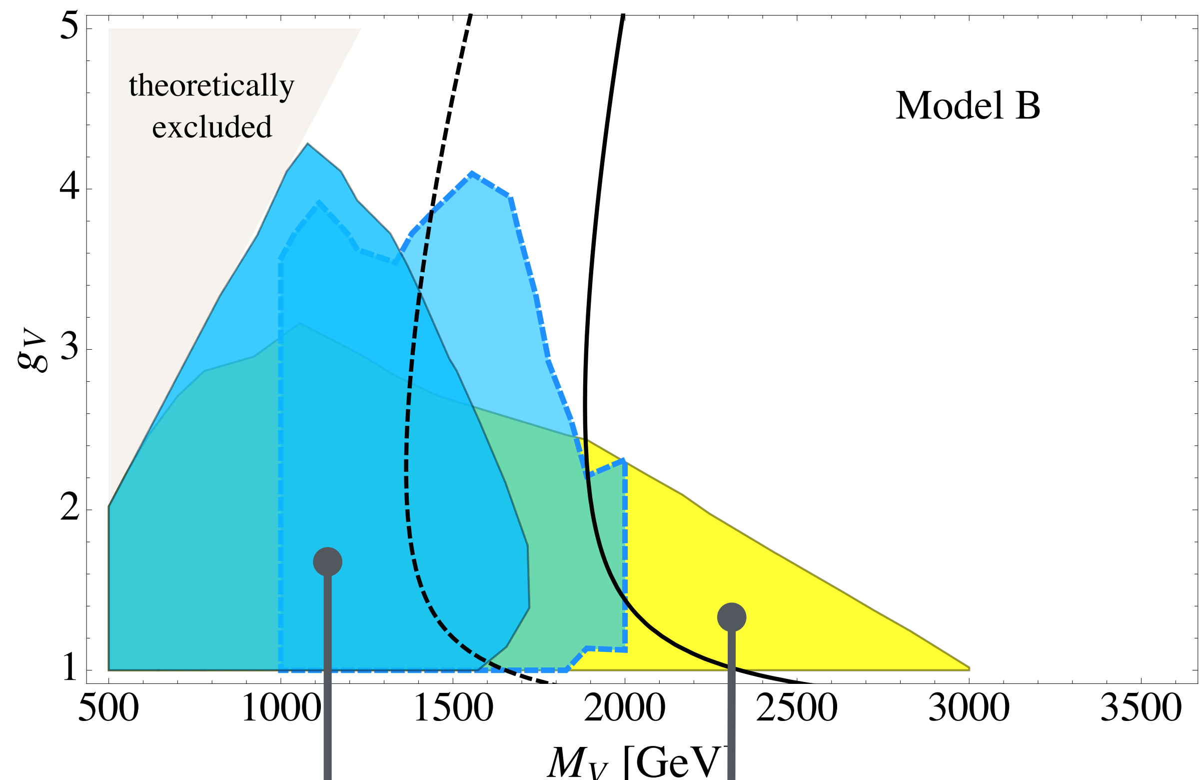
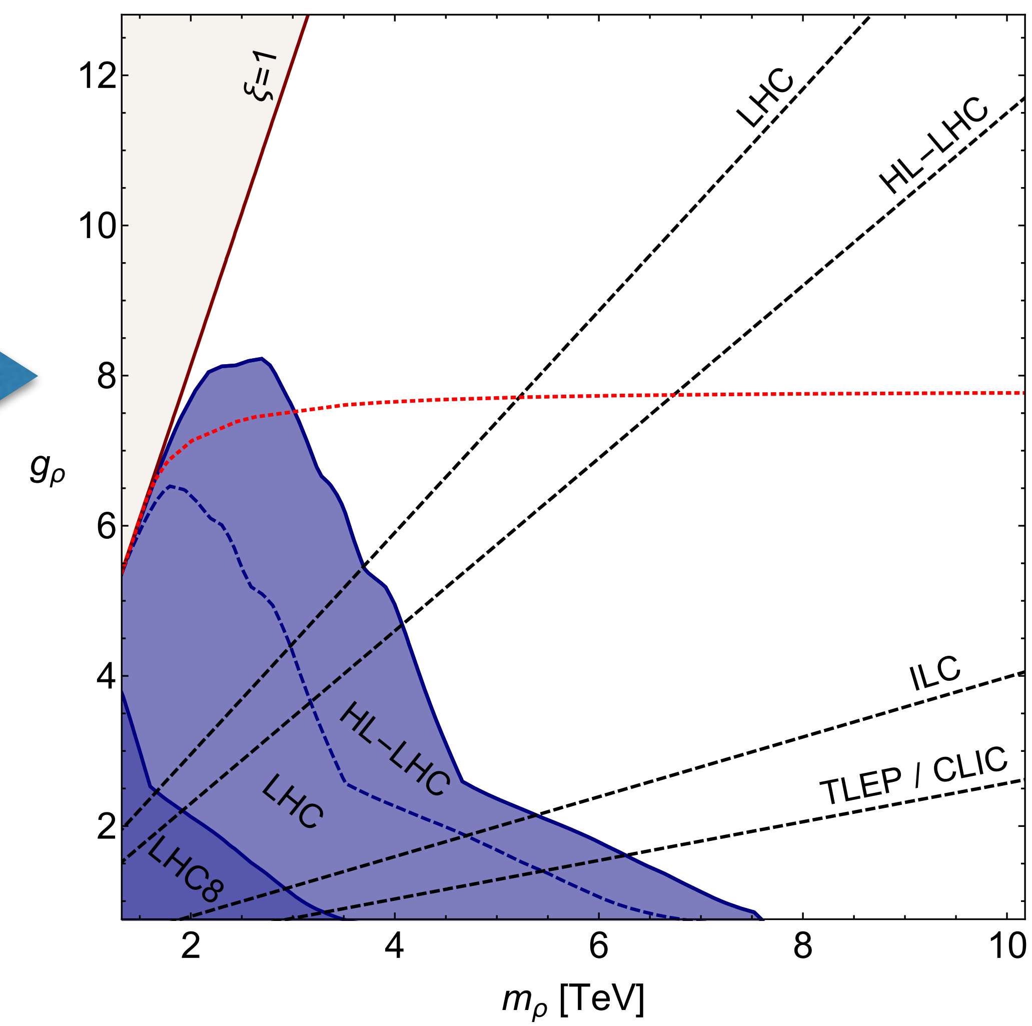


VV/VH final states

ll/lν final states

run-2 sensitivity



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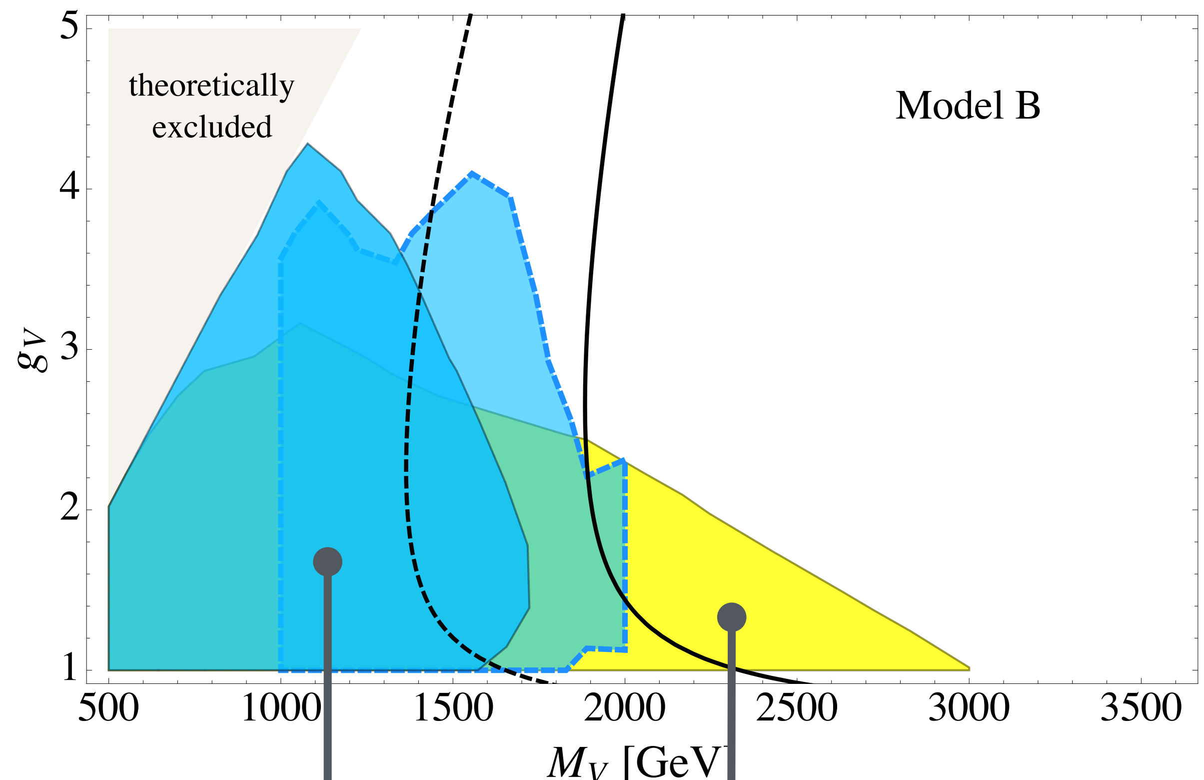
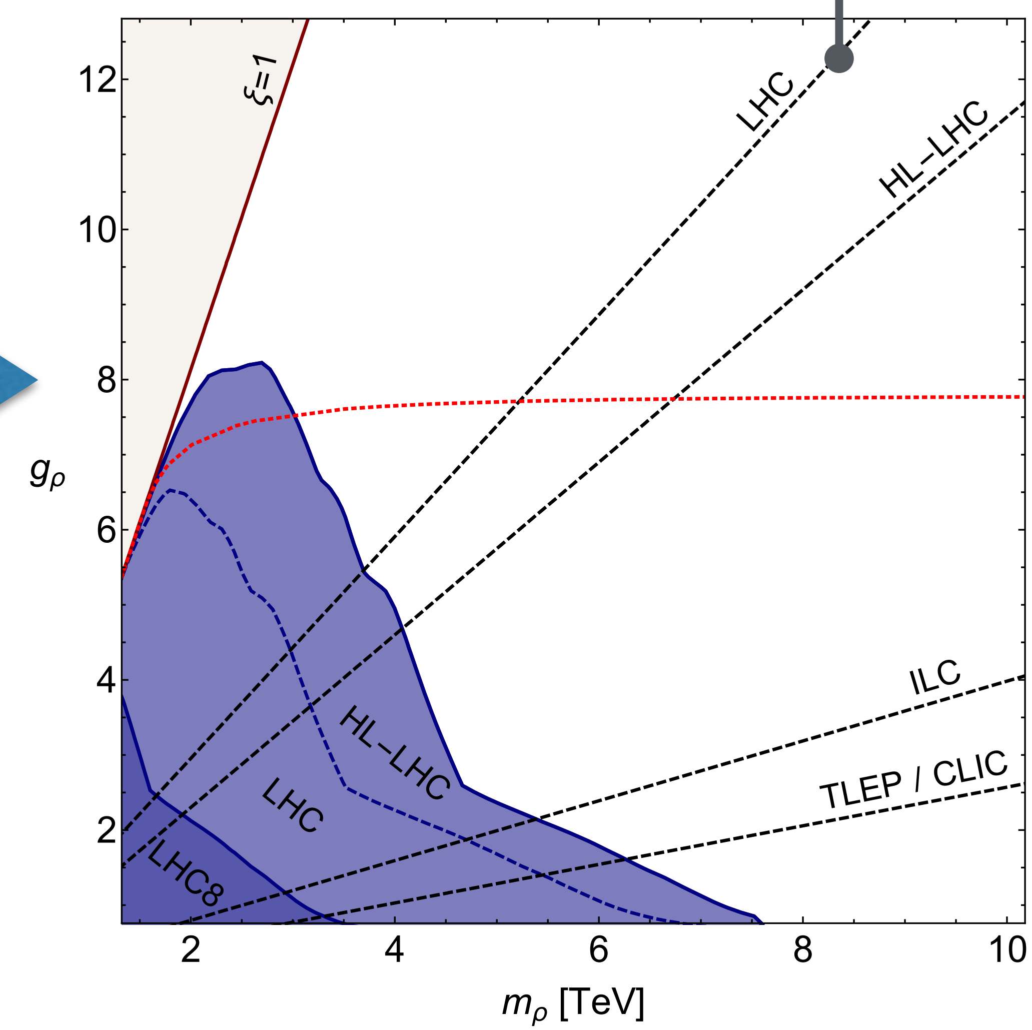


from Higgs coup., **qualitative**

run-2 sensitivity



VV/VH final states

ll/lν final states

Direct + indirect limit ~ 3 TeV @LHC, > 4 TeV @HL-LHC

Resonances

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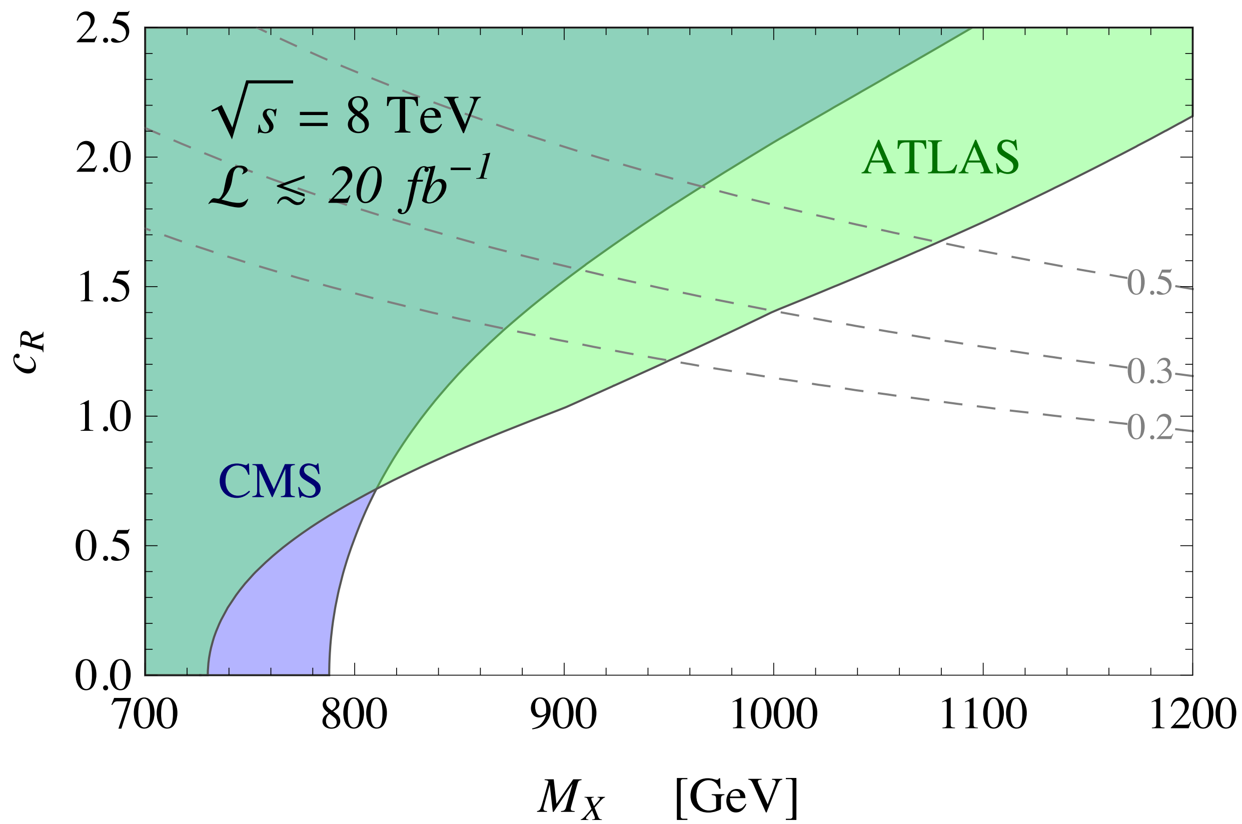
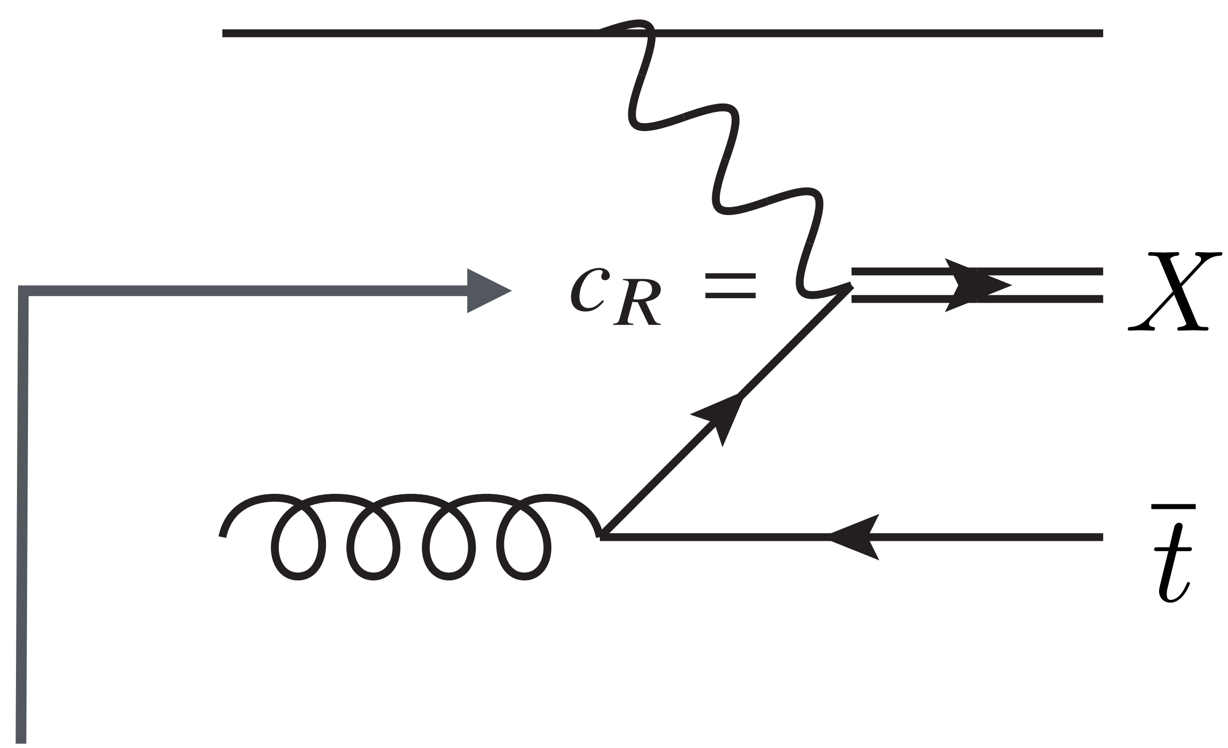
run-1 limits on Top Partners





Charge 5/3, including **single production**

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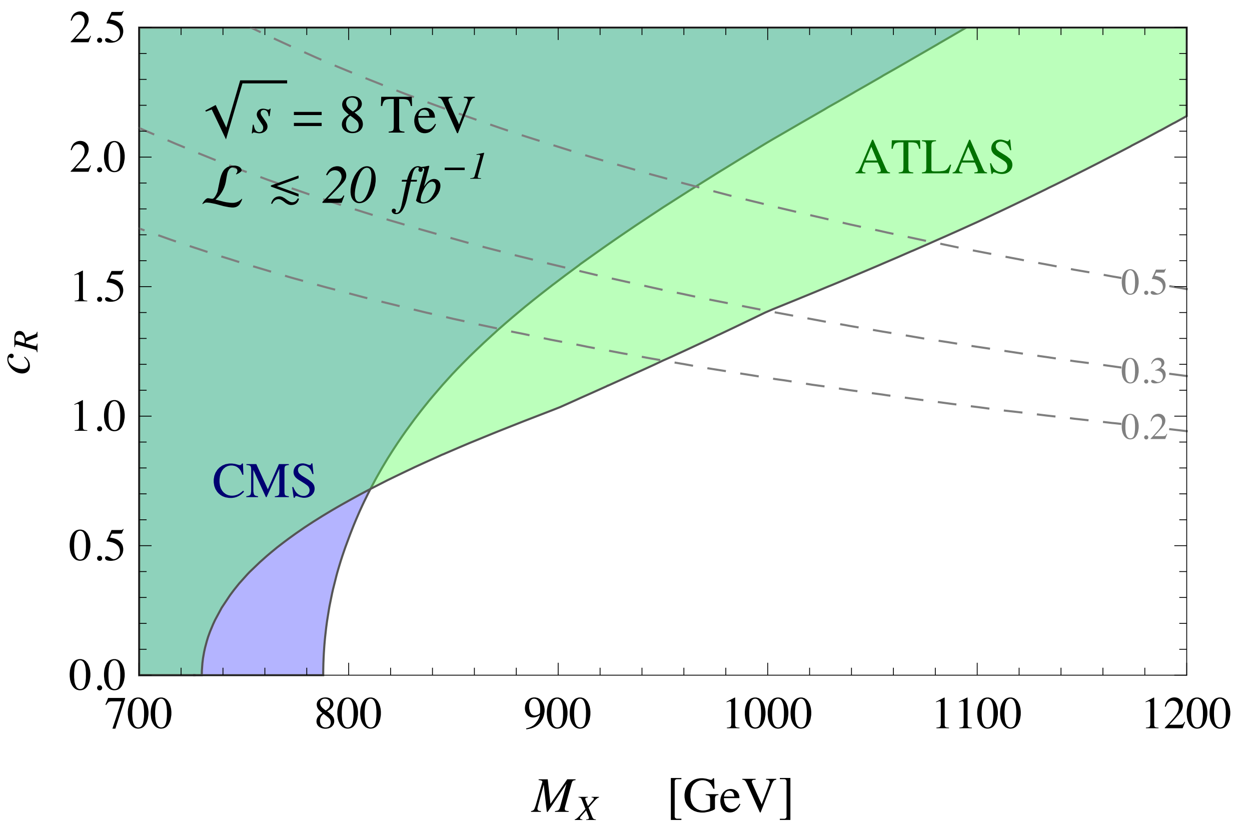
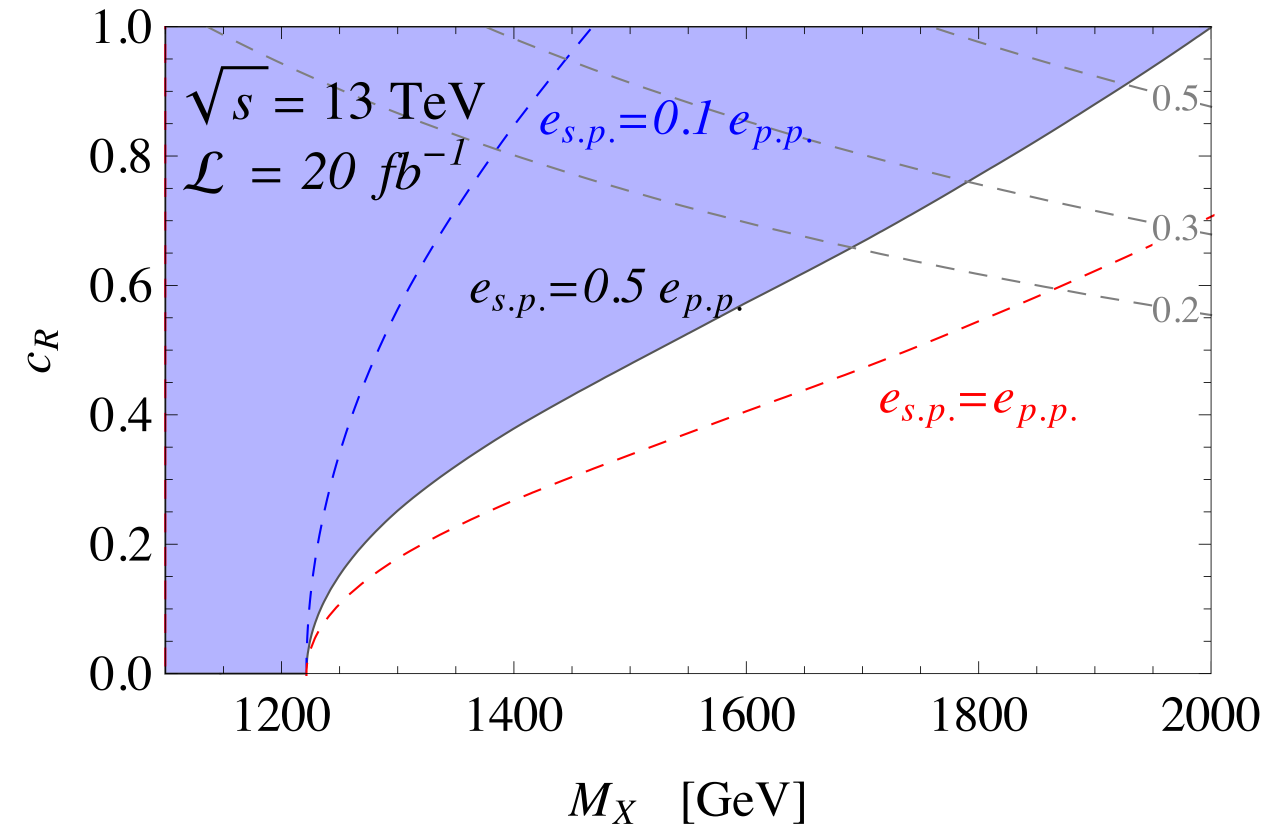


run-2 sensitivity



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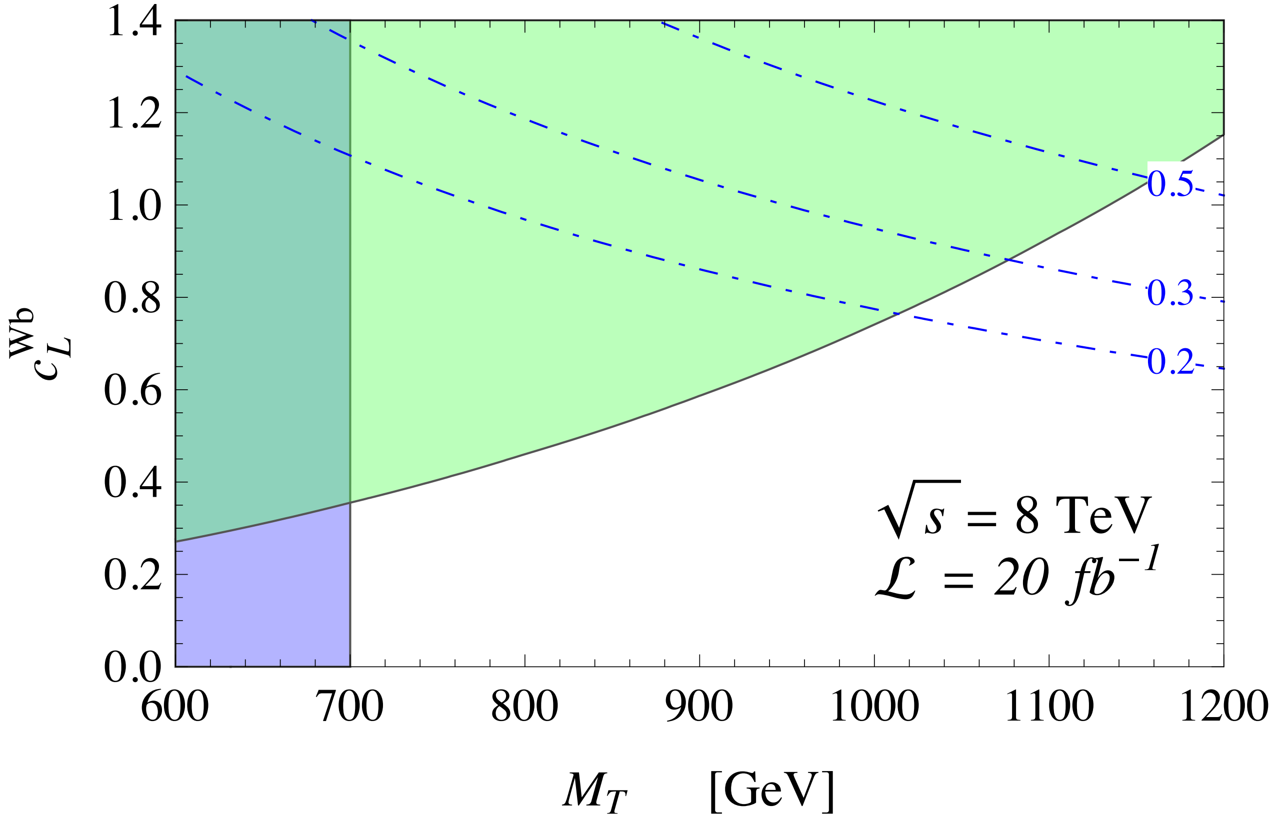
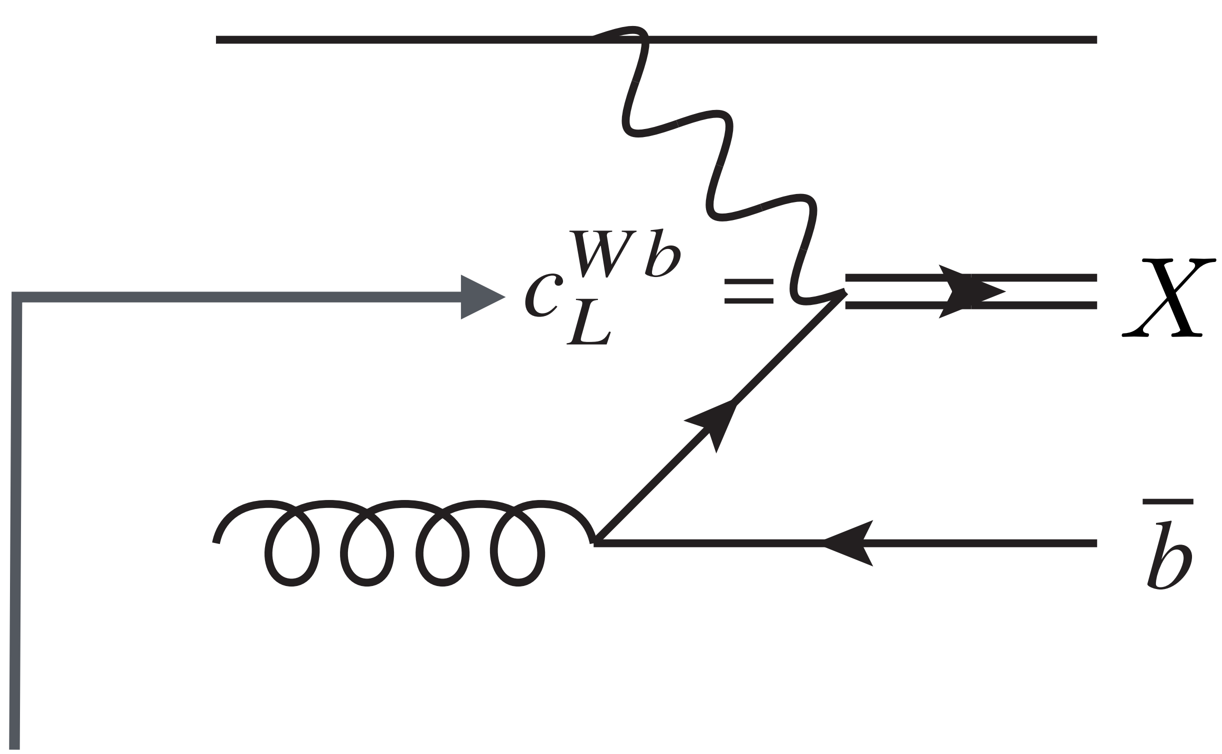


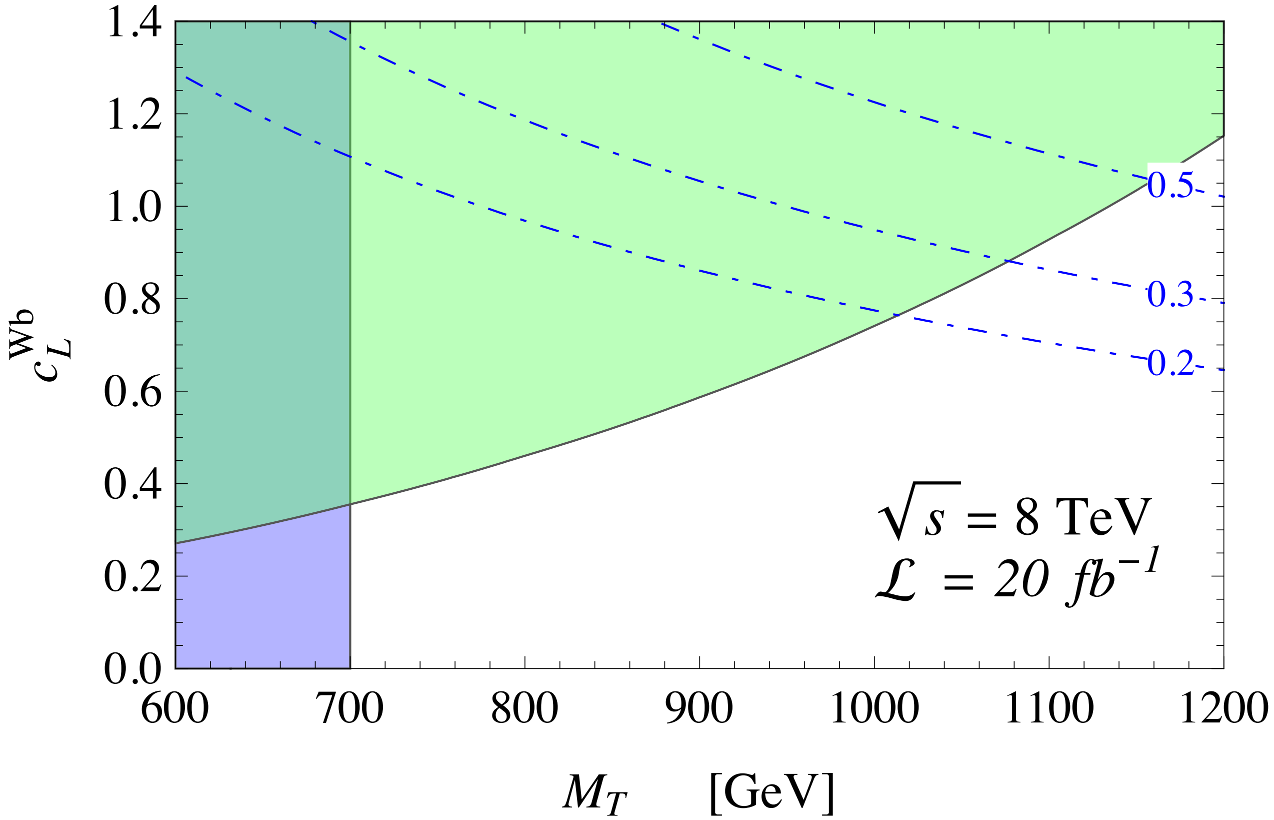


Charge 2/3, including **single production**

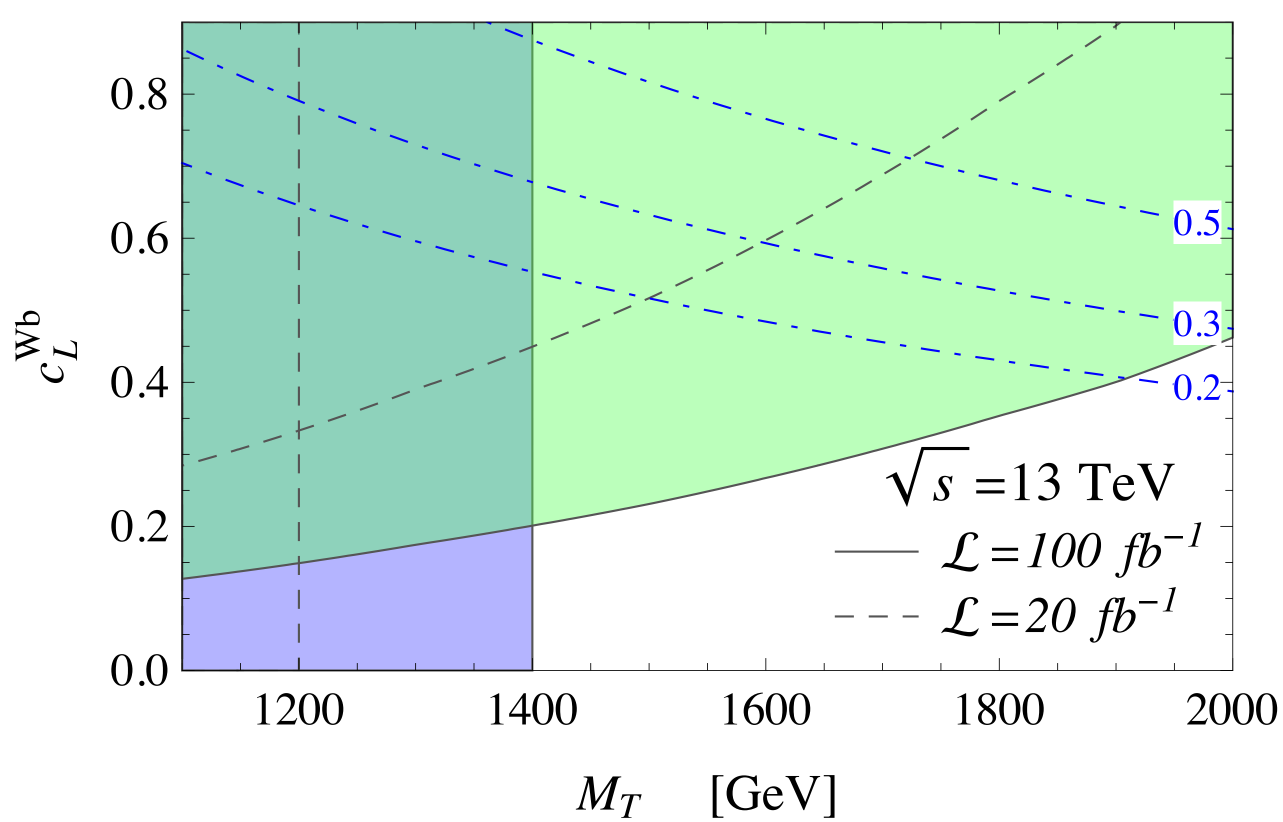
Resonances

Plenty of opportunities at run-2

run-1 limits on Top Partners



run-2 sensitivity



Charge 2/3, including **single production**

Resonances

Plenty of opportunities at run-2

Top Partner searches on a table:

Decay

Production

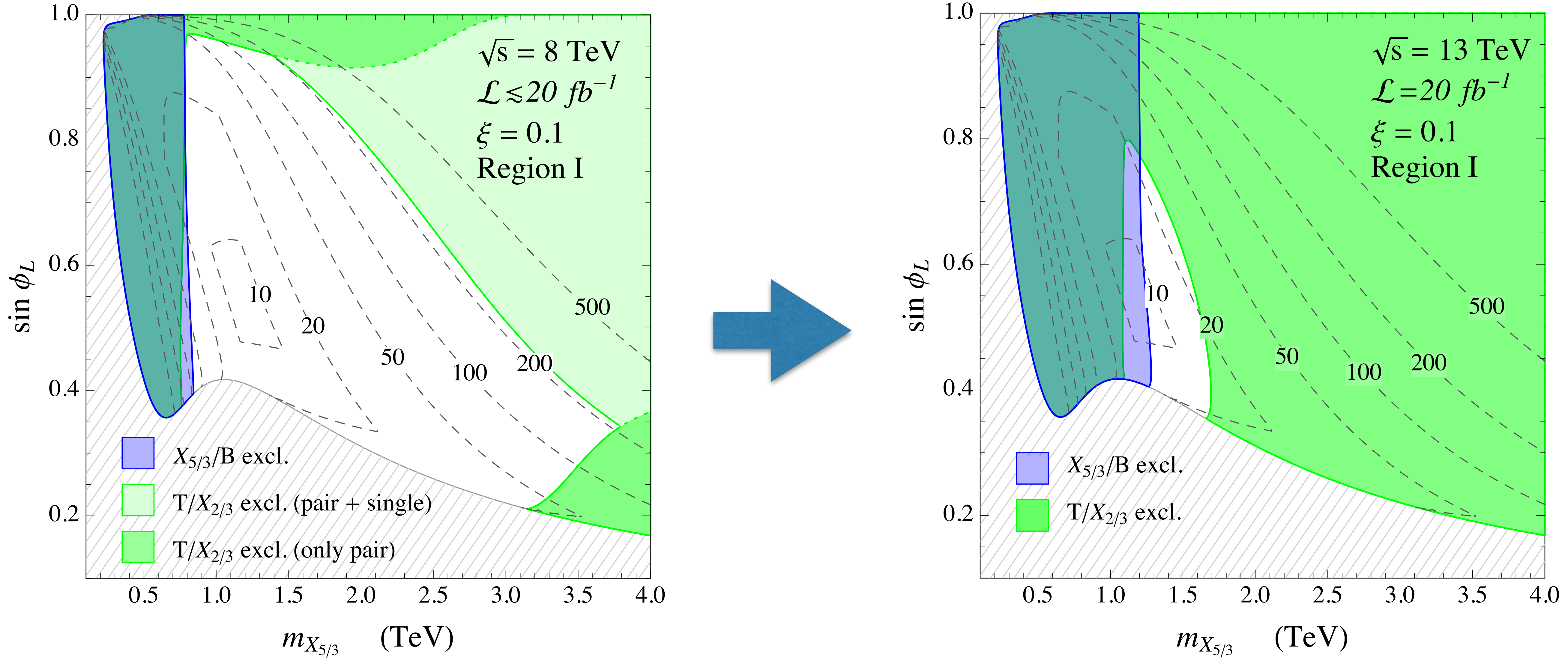
	$W+t$	$W+b$	$Z/h+t$
Pair Production	$X_{5/3}, B$	$\widetilde{T}$	$X_{2/3}, T, \widetilde{T}$
Single + top	$X_{5/3}, B$		$X_{2/3}, T$
Single + bottom		$\widetilde{T}$	$\widetilde{T}$

Resonances

Plenty of opportunities at run-2

Top Partners mass robustly connected with **tuning**

$$\Delta \sim \left(\frac{M_{\text{T.P.}}}{450\ \text{GeV}}\right)^2 \quad \text{(same as SUSY stops)}$$



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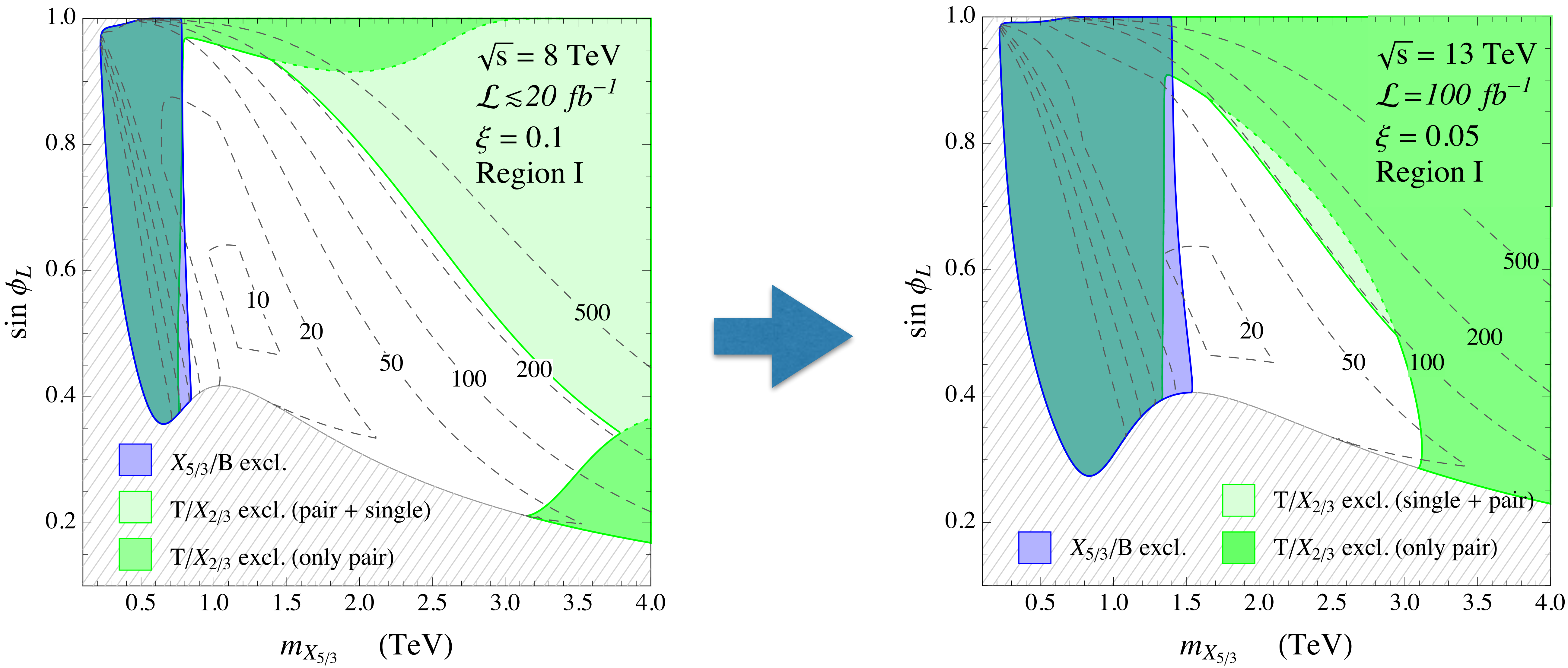

Dark Matter

DM could be anything. Mod.-indep. is **mandatory**

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IF DM/SM coupling from high scale: $M_{\rm Med} \gg m_{\rm DM}$
Model-independent description, by EFT:

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

The EFT has **three** parameters (little paradigm shift)

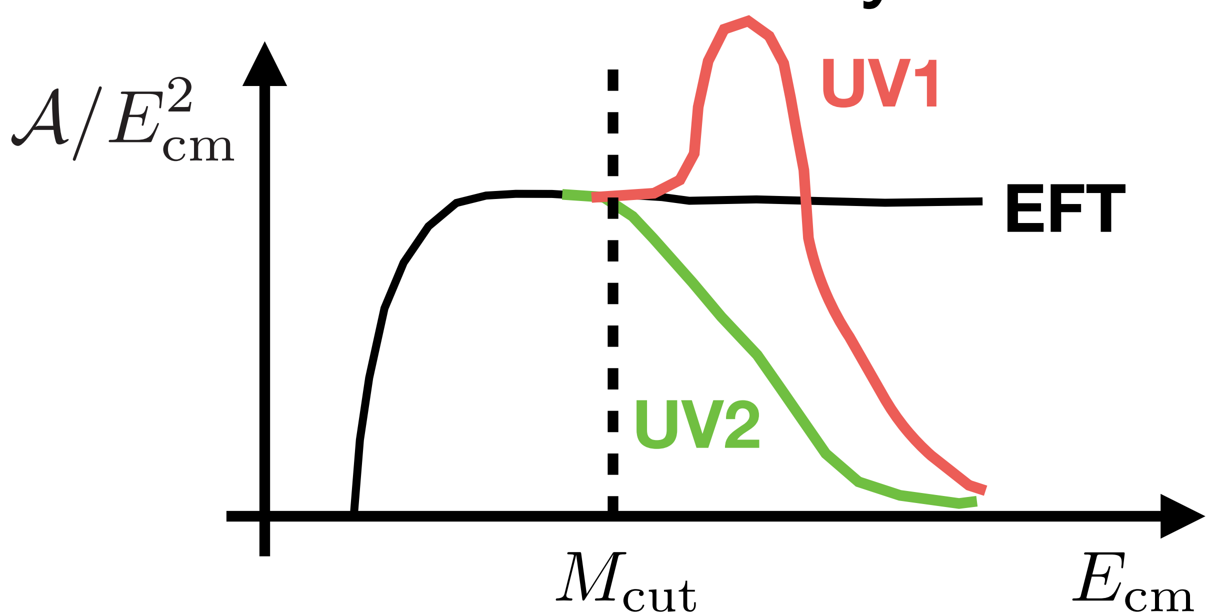
1) Dark Matter mass $m_{\rm DM}$
2) Effective coupling strength M_*
3) EFT **cutoff** $M_{\rm cut}$ (indep. of M_*)

Huge variety of models encapsulated in these parameters

Dark Matter

[De Simone et al., 2014 ; AW et al., 2015]

Debated **problem**: LHC can carry us above the cutoff.



Solution: (obvious if $M_{\rm cut}$ is par.) restricting signal to the predictable region sets lower bound on the "true" signal

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

compared with exclusion upper bound, we get a mod. indep. limit that holds for any mediator model

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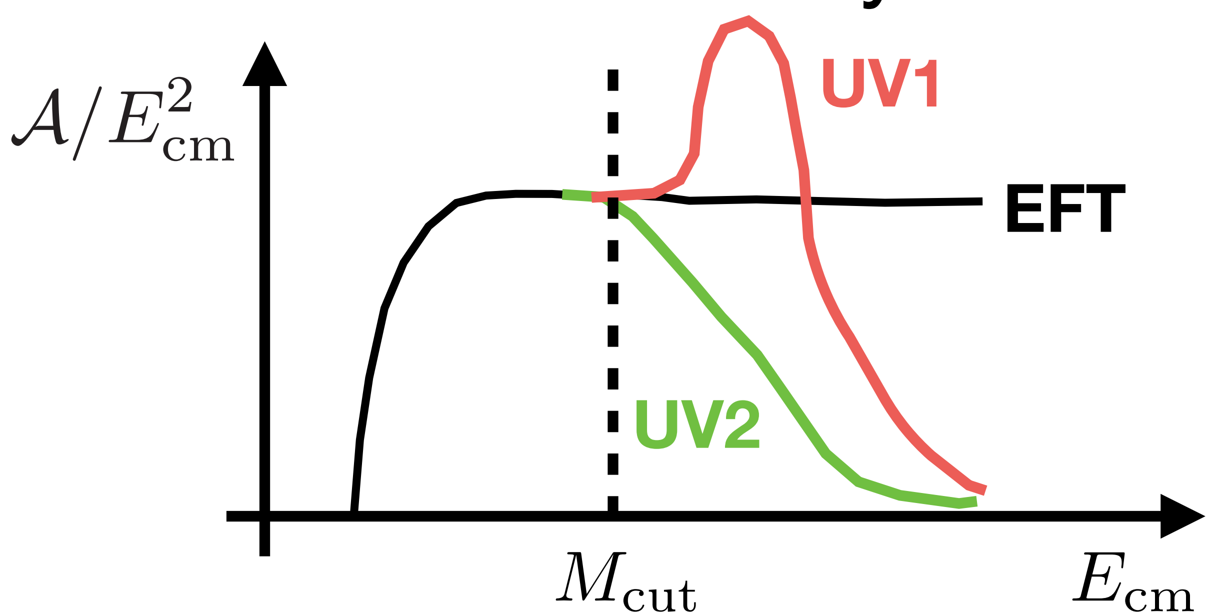


Solution: (obvious if $M_{\rm cut}$ is par.) restricting signal to the predictable region sets lower bound on the "true" signal

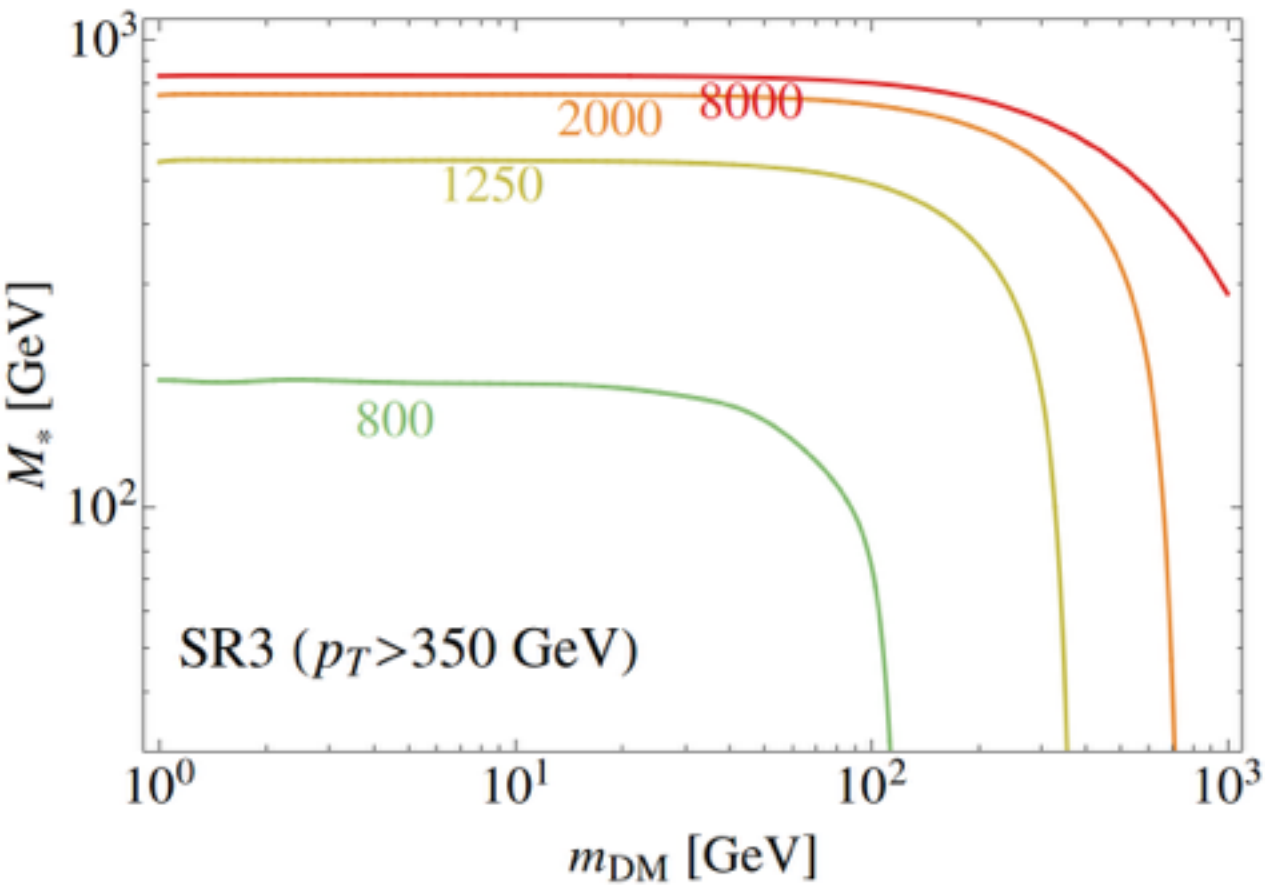
Alternative solution: (obvious if not understanding EFT's) **give up** (trend of recent analyses, exception is ATLAS mono-photon)

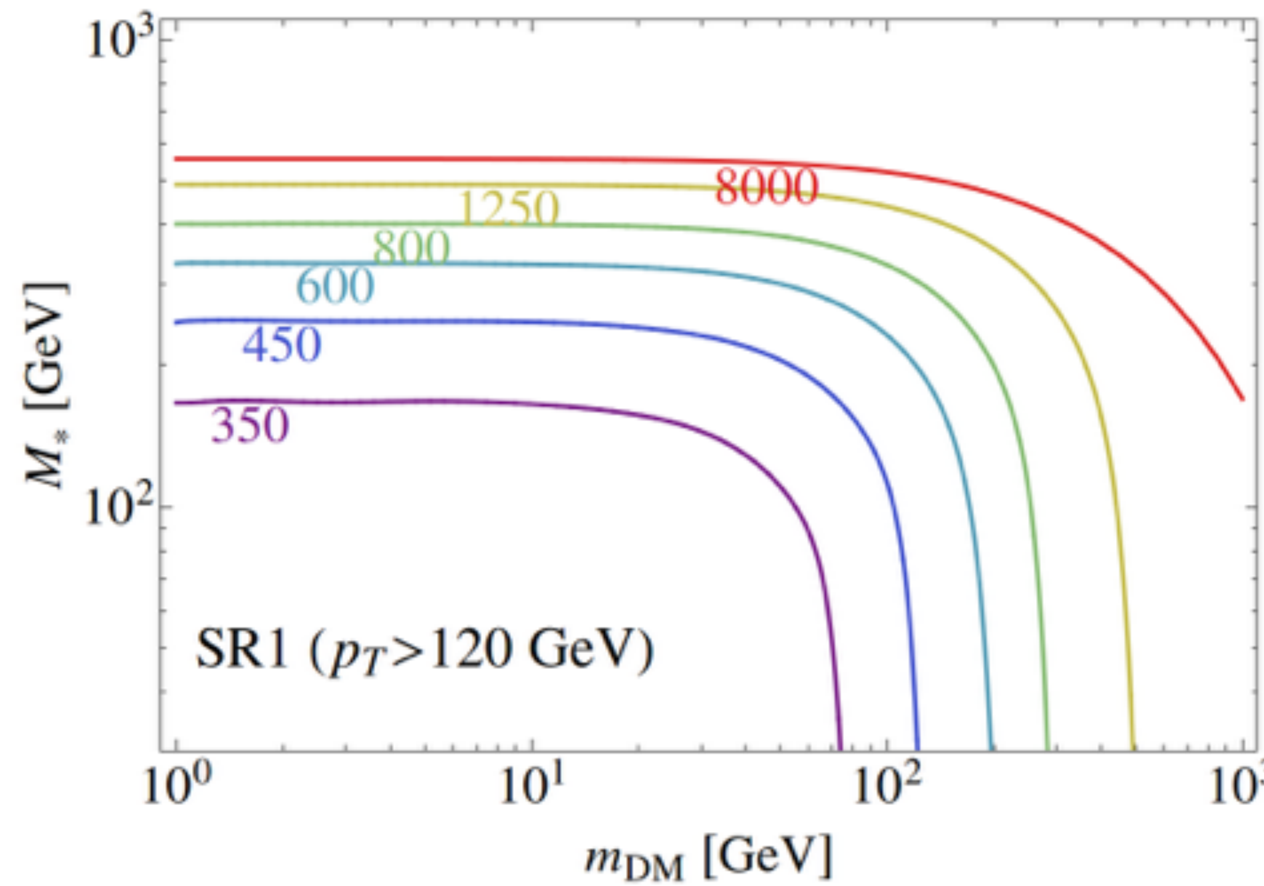
Dark Matter

[De Simone et al., 2014 ; AW et al., 2015]

Presenting limit in 3-d parameter space:

ATLAS mono-j recast



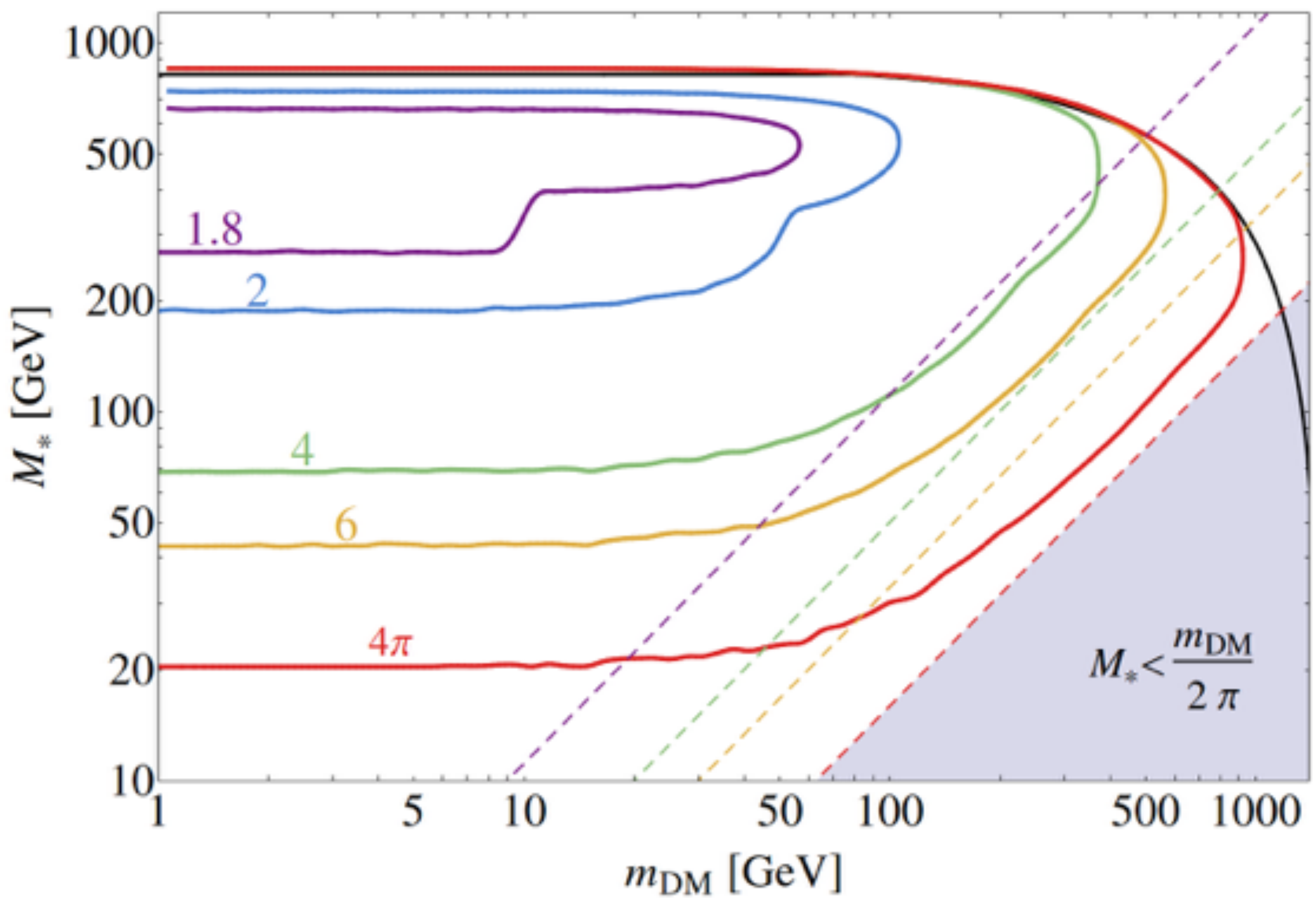


Plot outlines the need of a better exploration of soft region

Dark Matter

[De Simone et al., 2014 ; AW et al., 2015]

A smarter plot: $g_* \equiv M_{\rm cut}/M_*$, mediator sector **coupling**



“WI”MP hypothesis far from fully tested

Dark Matter

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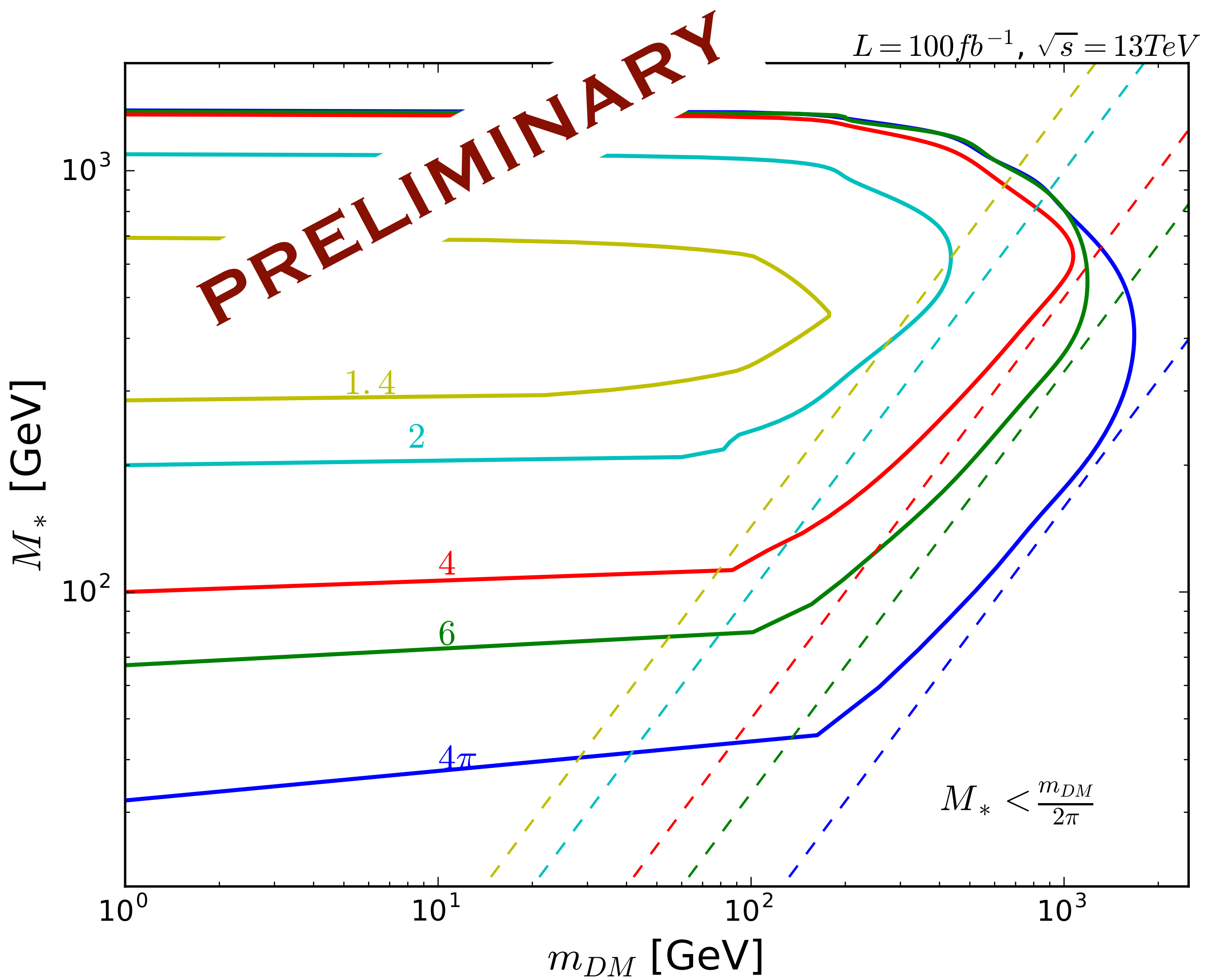

Only a bit better at run-2. Unavoidable because $\sigma \propto 1/M_*^4$

Dark Matter

EFT limits get **weak** (**not inconsistent!**) at low M_{cut}

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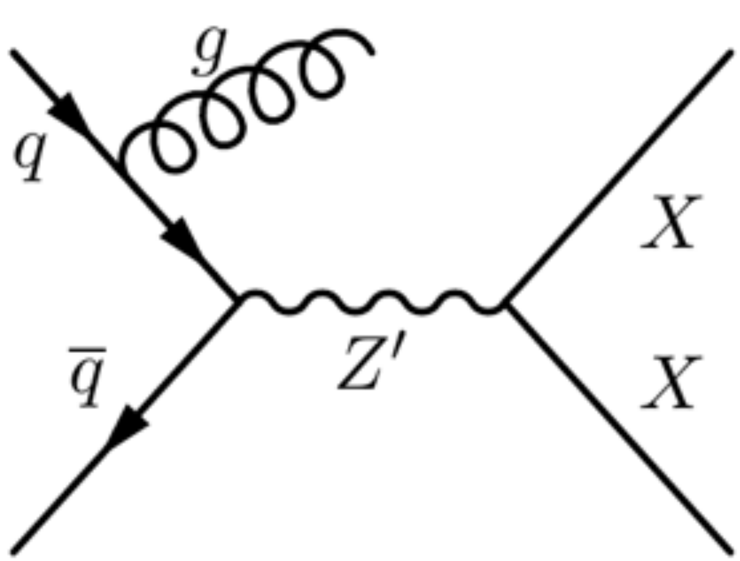
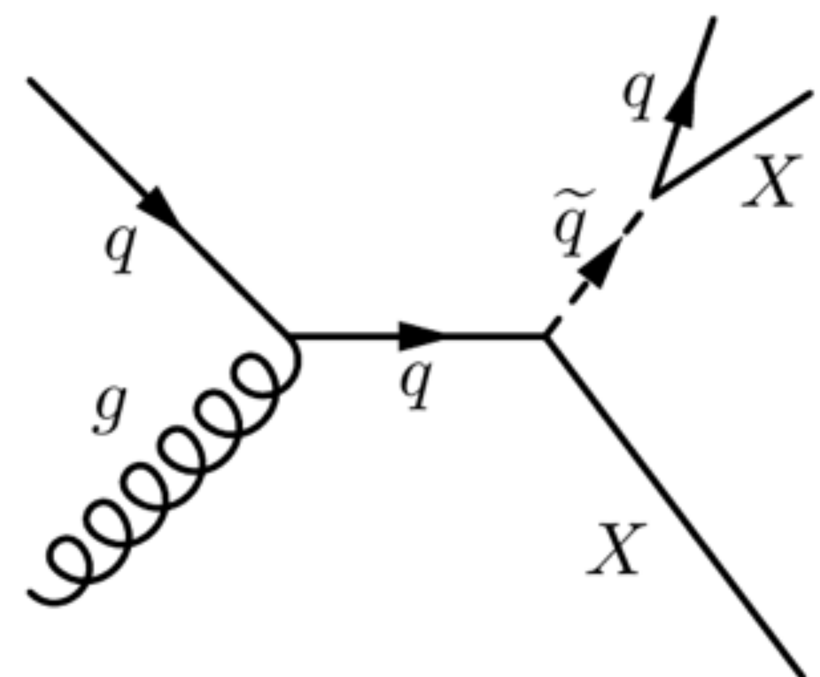
But $M_{\rm cut} \simeq M_{\rm med}$: produce **on-shell mediators** at low $M_{\rm cut}$





DM search turns into mediator search in this regime

Dark Matter

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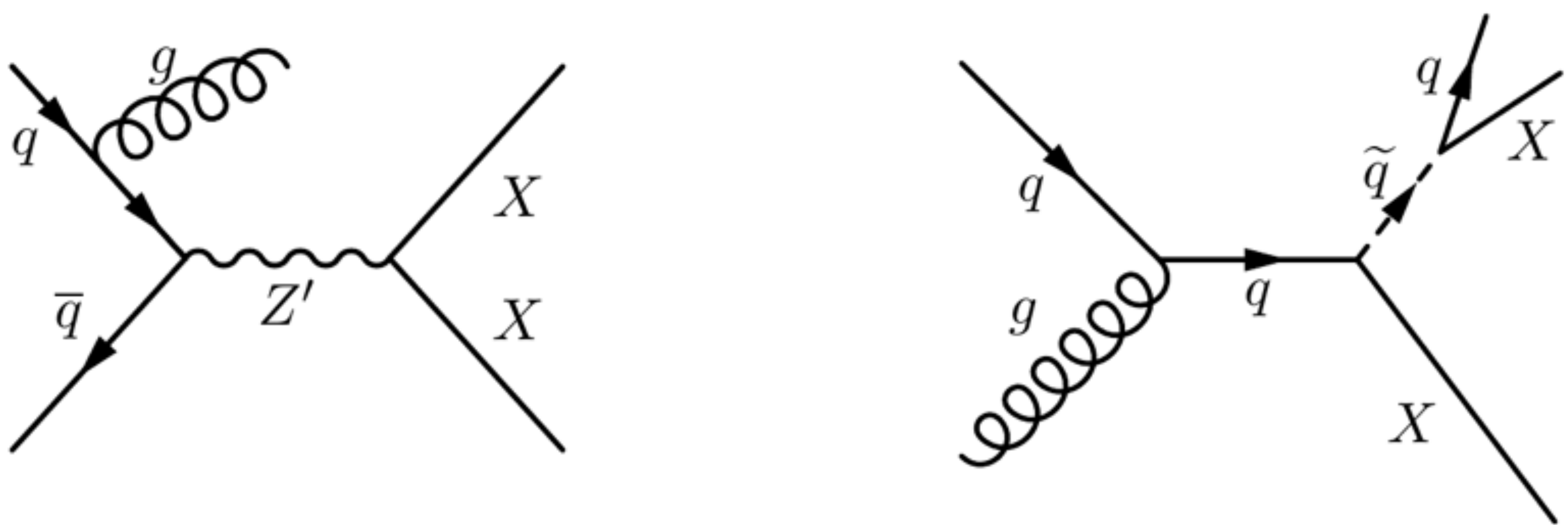
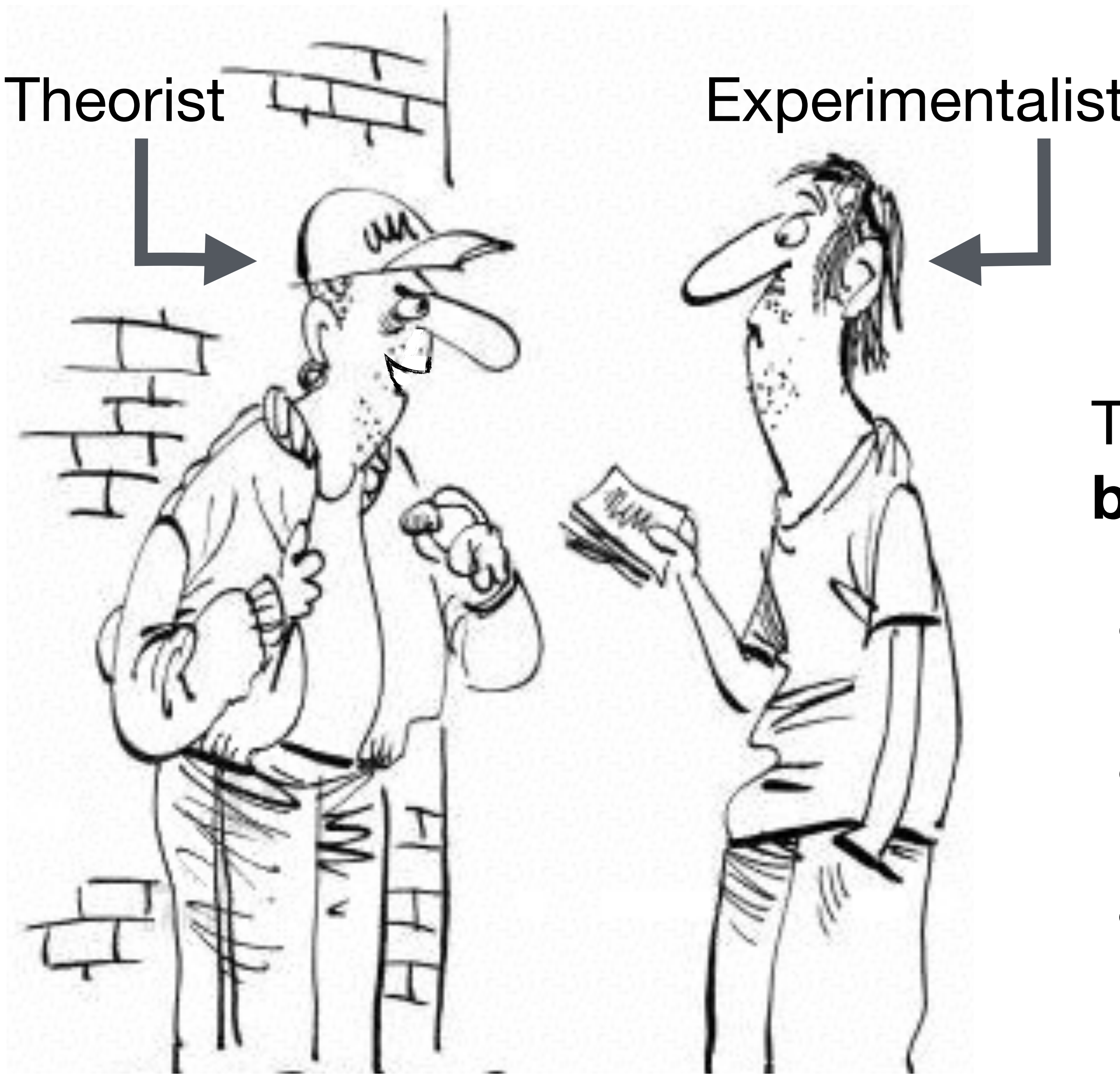


DM search turns into mediator search in this regime

More difficult to maintain sufficient degree of mod.-indep.

Dark Matter

Mediator searches, how **not to** proceed: by **benchmarks**



"it's the ideal benchmark …"

Too specific, often **conventional benchmark models** produce:

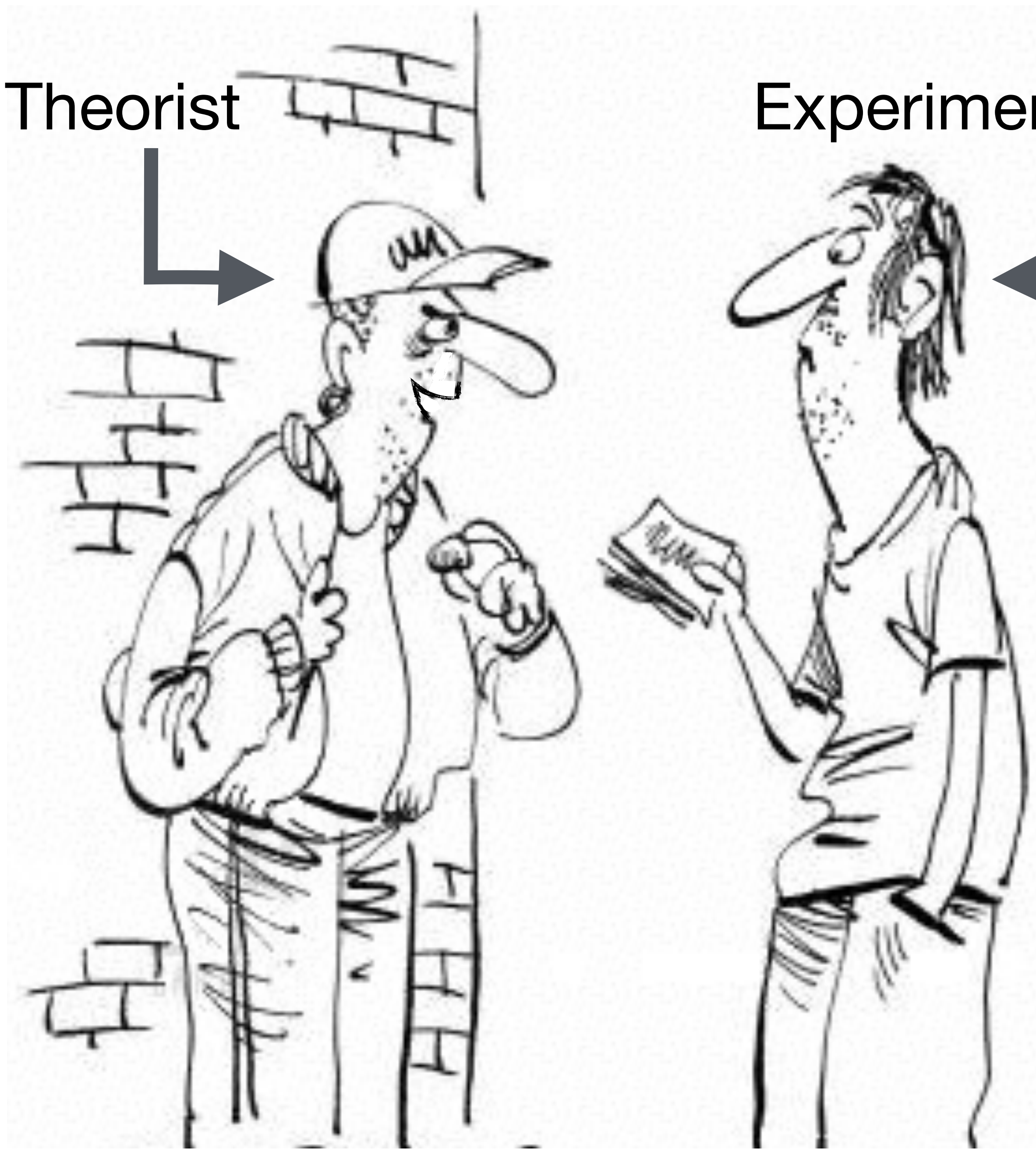
- extremely **partial exploration** of the theoretical possibilities
- **exclusions** which are **impossible to reuse** in any other model
- **no result in case of discovery.** Since the benchmark has no chance to be true

Dark Matter

Mediator searches, how **not to** proceed: by **benchmarks**

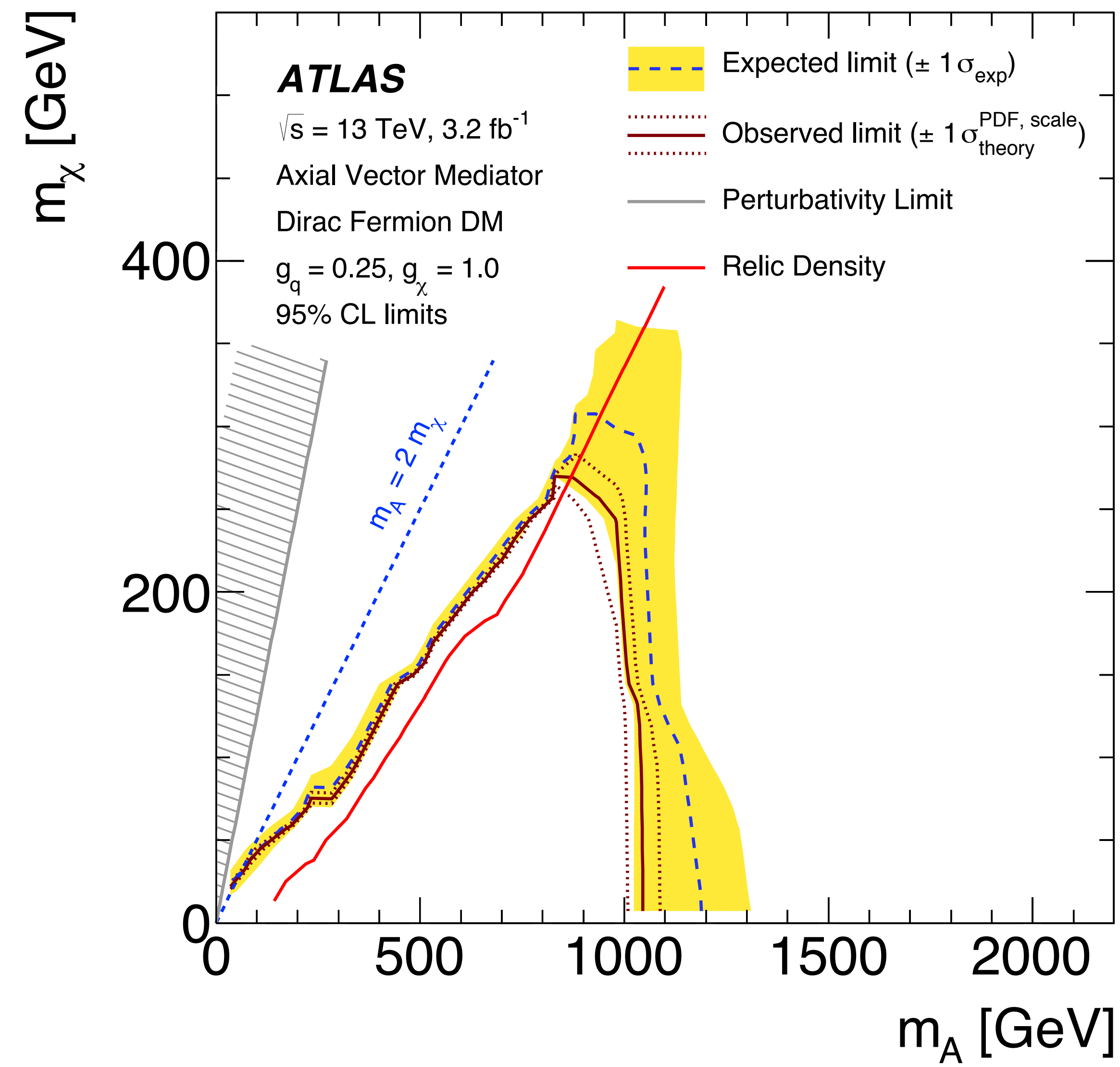
Theorist

Experimentalist



"it's the ideal benchmark …"

Is really this plot …



… the best one to report limits on a Z'>invisible??

Diphoton

Can be real:

ATLAS/CMS@run-2/1 compatible **if gg or bb production** [Gof>10%]

Not in tension with other channels **if weakly coupled to leptons**

RS graviton is (almost) the only excluded case …

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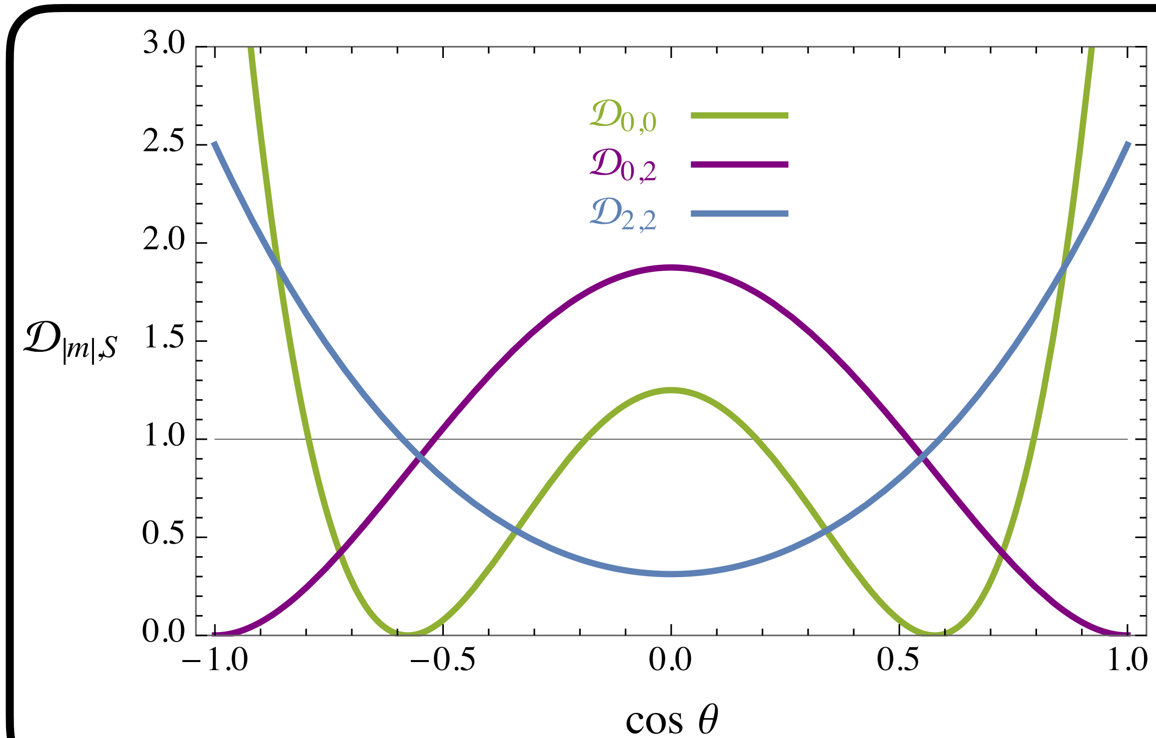

Spin 0 = flat

Spin 2 from gg = linear combination of 3 distributions.

Spin 2 from qq = linear combination of 4 distributions.

RS graviton = 1 particular case

Diphoton

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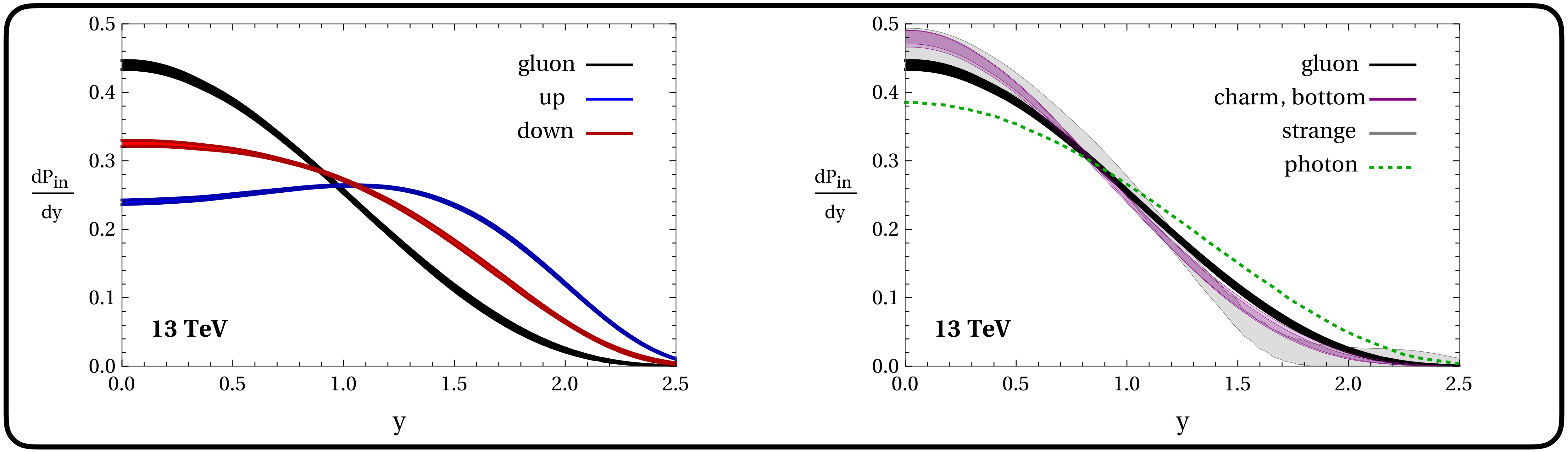

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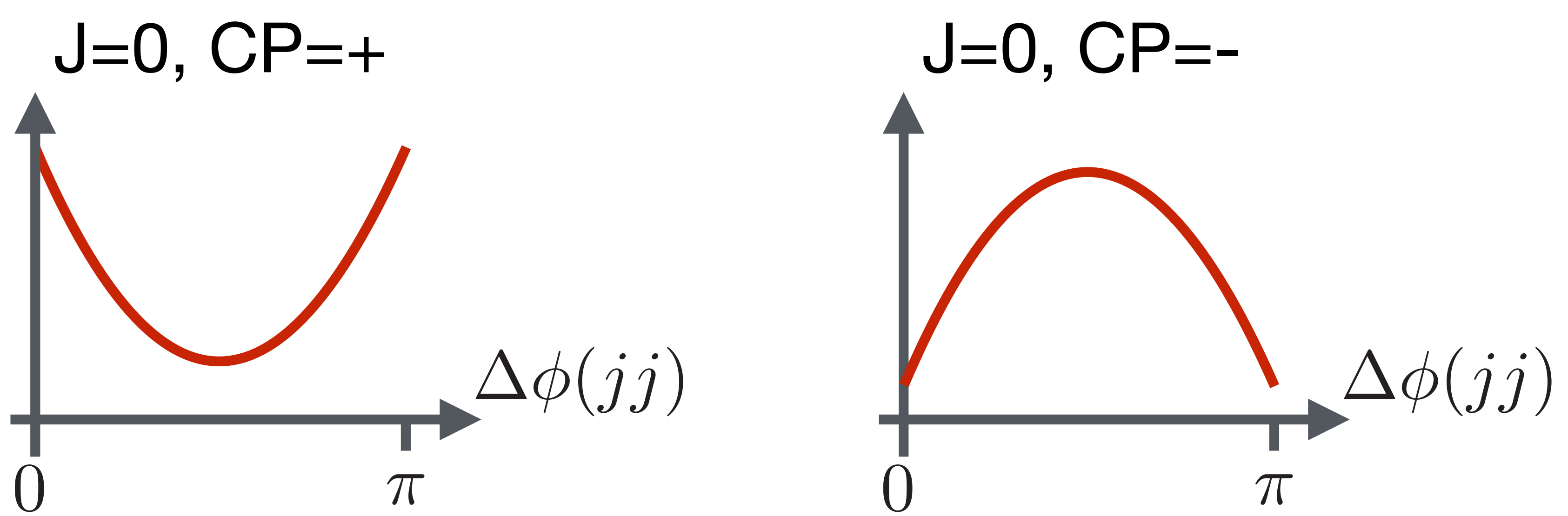
- Conclusive result on CP from QCD collinear radiation

$$pp > \mathcal{R}jj$$



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2) see it in **other channels** [$Z\gamma$ seems good candidate]

$c_W \mathcal{R} W W + c_B \mathcal{R} B B$ ➡ Only **one channel** among $WW,\ ZZ,\ Z\gamma$ can be suppressed

Diphoton

Can be real:

ATLAS/CMS@run-2/1 compatible **if gg or bb production** [Gof>10%]
Not in tension with other channels **if weakly coupled to leptons**
RS graviton is (almost) the only excluded case …

IF it is real: ToDo List

1) characterise its **properties**: (have a look at arXiv:1603.04248)
- Spin from $\cos\theta_{\rm c.m.}$ distribution
- Production mode from $y_{\rm c.m.}$ distribution (+ searching for soft b's)
- Conclusive result on CP from QCD collinear radiation

2) see it in **other channels** [$Z\gamma$ seems good candidate]

3) **Find all the rest:** cannot be alone!

Diphoton

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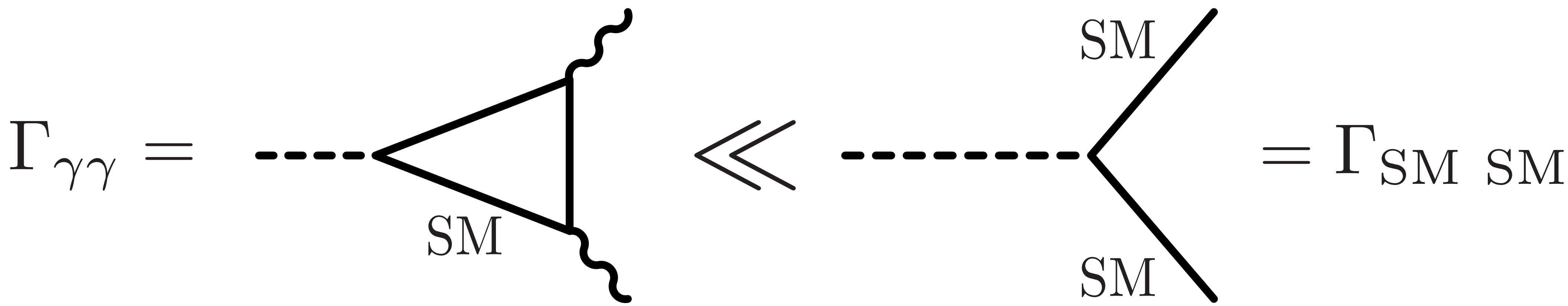

If only SM particles in the loop, we would have seen it in other channels.

A **new sector** of BSM particles is responsible for its decay!

2)

3) **Find all the rest:** cannot be alone!

Diphoton

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If real, **diphoton = revolution** in particle physics!

Conclusions

1) Moderate progress on Higgs couplings. Better if enlarging the scope to high-energy EW processes? [in any case, not for early run-2]

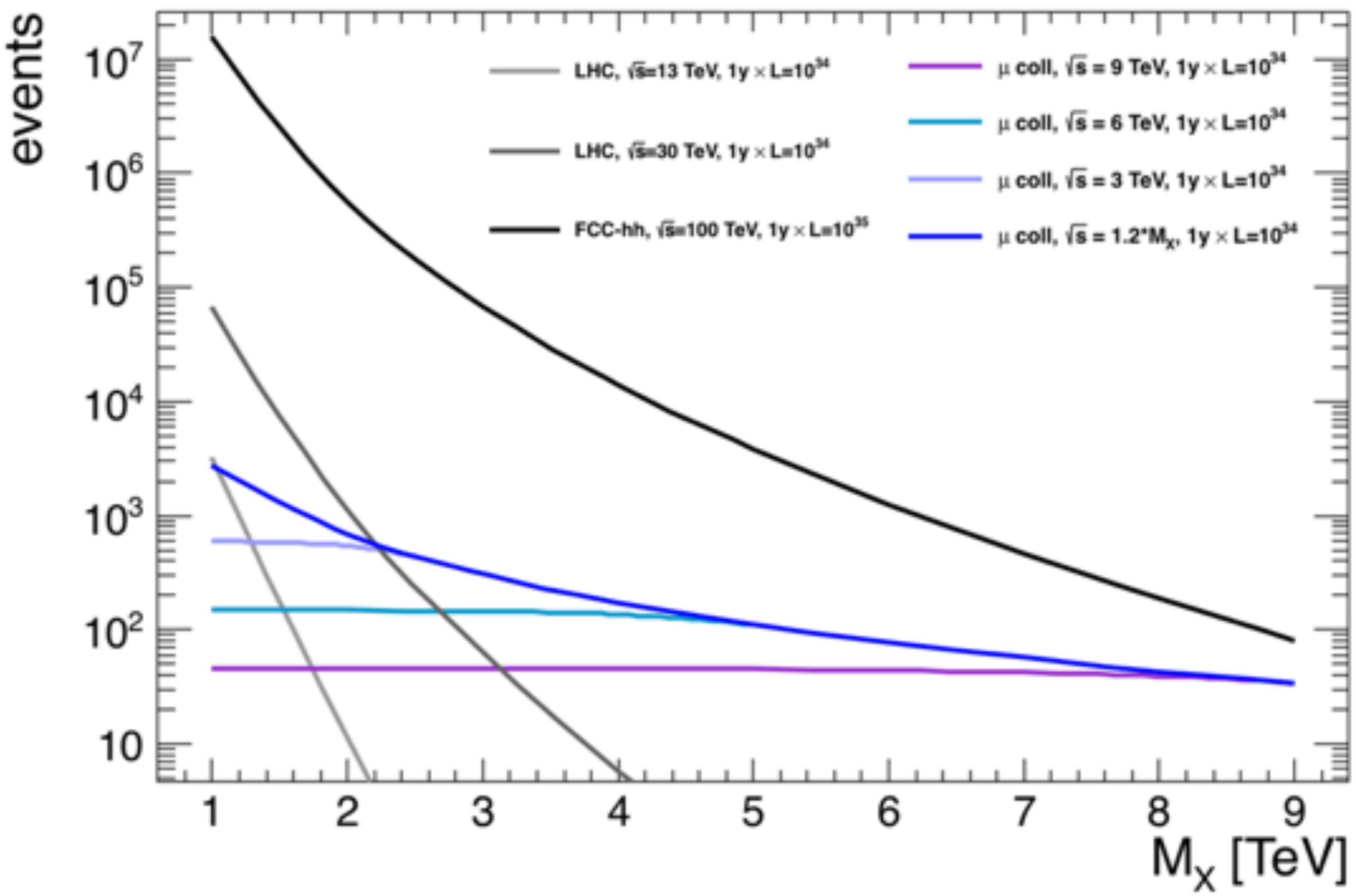
2) Fast progresses on resonance searches.

3) Dark Matter: figure of merit (i.e., interpretation plane) not clear enough to assess run-2 progresses.

4) Diphoton:
The mere fact that it **can be true** illustrates **how little we know** about the TeV scale.
Its **potentially revolutionary** nature shows **capital run-2 importance**

Muon collider

Good for **direct** exploration?



Good for **indirect** exploration?

	$100\,\mathrm{GeV}$	$> 1\,\mathrm{TeV}$
few %		LHC
1 ‰	LEP	mu?