Composite BSM at run-2

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Ideology

Run-1 discovery of **SM-like Higgs** is a **revolution** in HEP

Pre-Higgs

Guaranteed Discoveries.

Ensured by **No-Lose Theorems:**

- Beyond the Fermi Theory (the W)
- Beyond the Bottom quark (the Top)
- Beyond the EW Theory (the Higgs)

Post-Higgs

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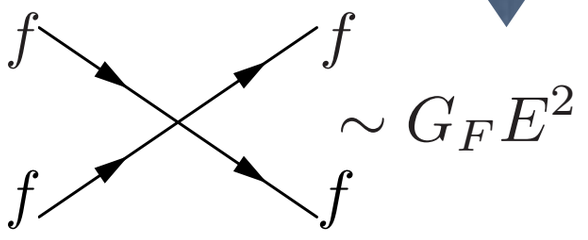
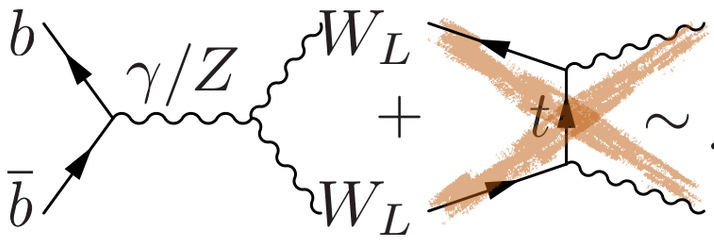


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v$$



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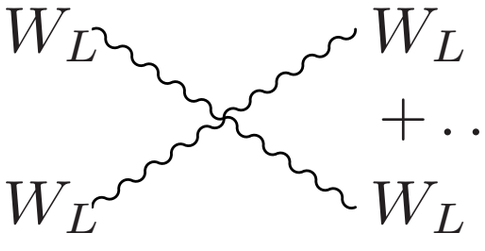

$$+\ldots \sim g_W^2 E^2/m_W^2 < 16\pi^2 \rightarrow m_H < 4\pi v$$

Due to non-renormalizable operators, signalling nearby new physics

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Renormalizable theory of **EW/Strong** Interactions.

The only, impractical, No-Lose Theorem is Q.G. below $M_{\rm P}$!

No Guaranteed Discovery

$$\frac{1}{G_N}\sqrt{g}R \rightarrow \sim G_N E^2 \simeq E^2/{M_{\rm P}}^2 < 16\pi^2 \rightarrow \Lambda_{\rm SM} \lesssim M_{\rm P}$$

Moreover:

1. with measured values of SM parameters no coupling explodes below $M_{\rm P}$.
2. we do have experimental evidences of BSM, but none necessarily requires light/strongly-coupled enough new physics

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Relevant questions to ask data, e.g.

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

If **relevant** enough, even negative answer is progress

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However, searching for answer to specific questions should be accompanied by **open-minded exploration effort.**

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High-energy physics is not **validation** anymore,
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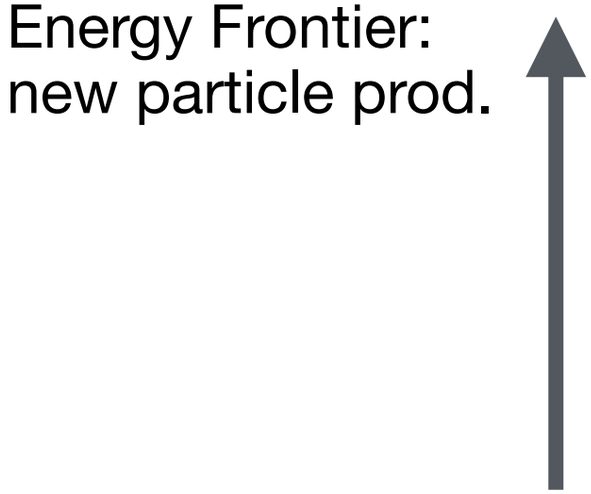

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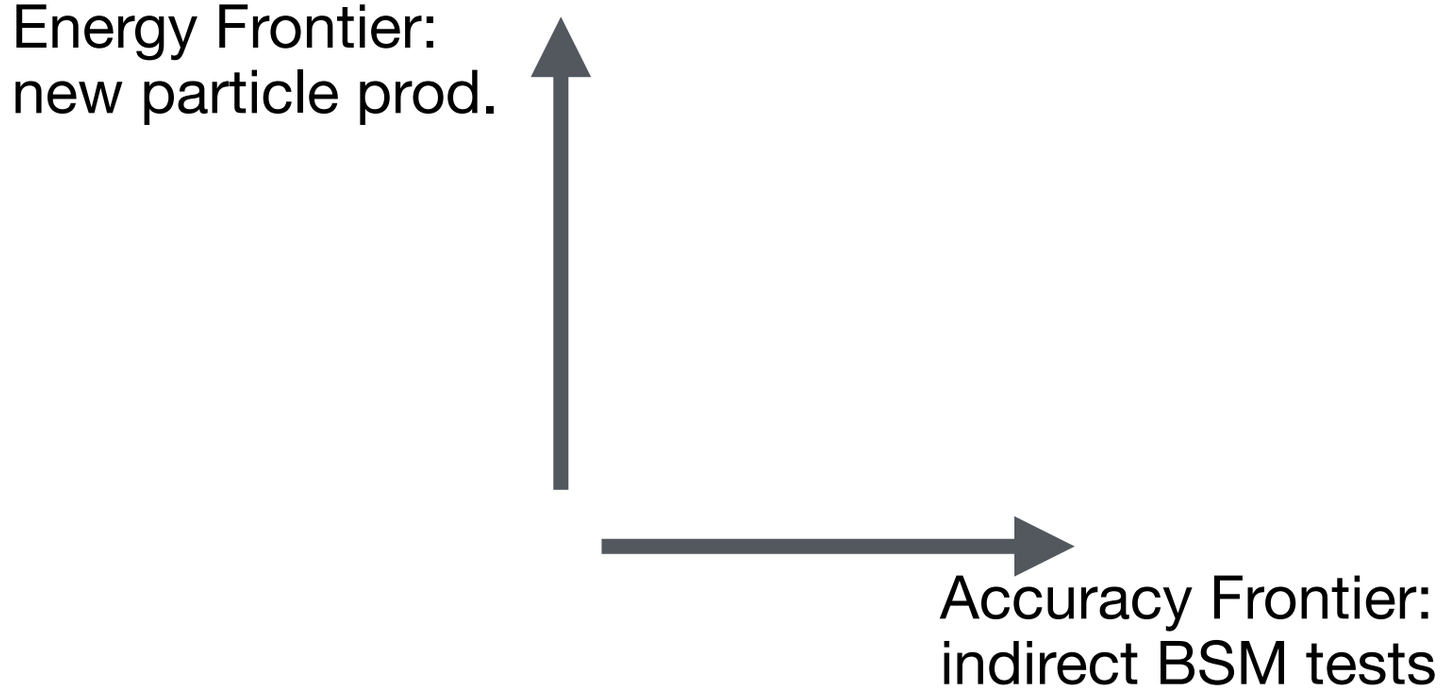

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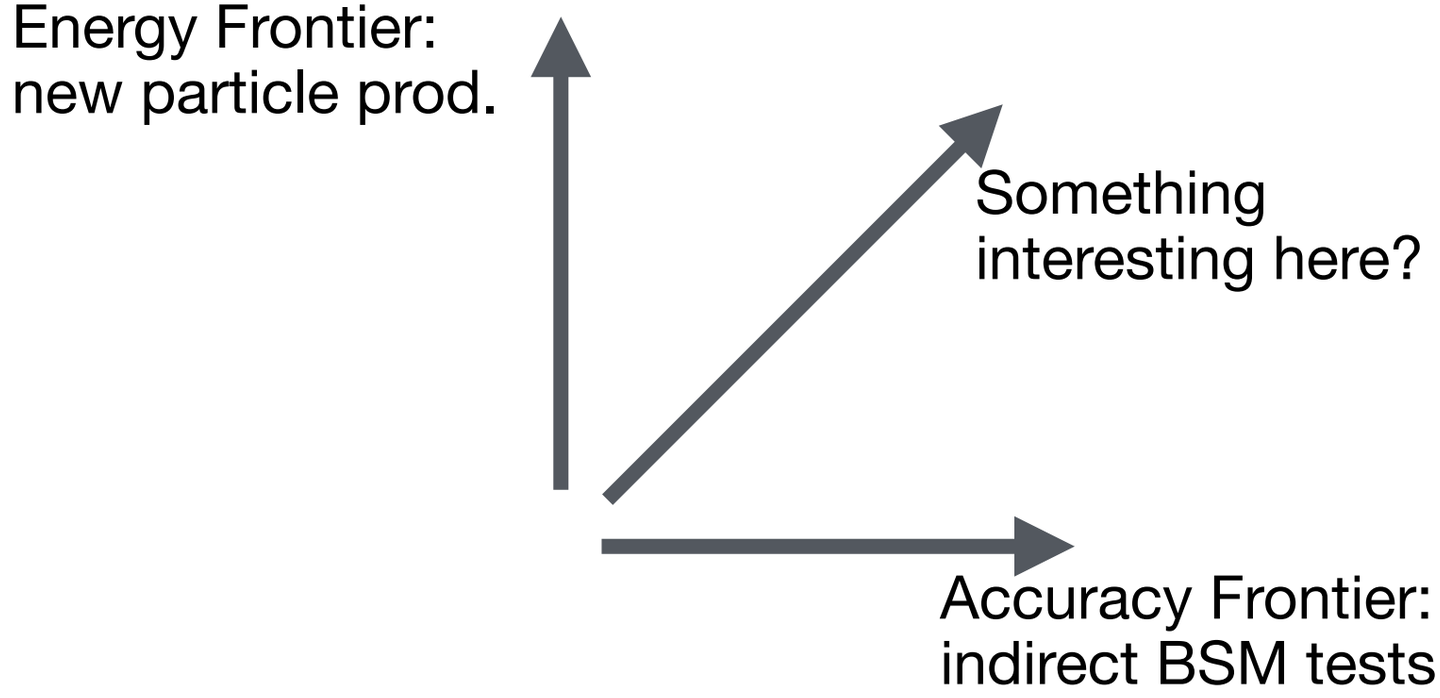

Naturalness

Two orthodox approaches to the Naturalness Problem:

Low-energy SUSY

you all know about it

Composite Higgs

- Higgs is bound state of new (strong) composite sector
- Higgs is a **Goldstone Boson**
- Important CS parameters:
  CS mass scale: m_*
  CS coupling: $g_* = m_*/f$
- Minimal source of tuning:

$$\xi = \frac{v^2}{f^2}\,, \quad \Delta \geq 1/\xi$$

"Natural" frameworks to discuss LHC implications on the Naturalness Problem.

Direct Searches I: Top Partners

$$\Delta \geq \left(\frac{\Lambda_{\rm SM}}{500\,{\rm GeV}} \right)^2$$

$\Lambda_{\rm SM}$ = “generic BSM scale”

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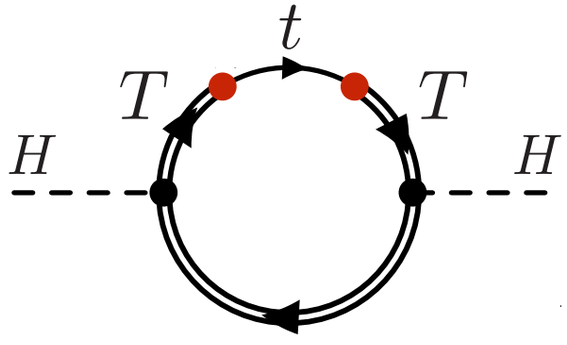
concretely:

Composite Higgs

$\Lambda_{\rm SM}$ = **fermionic Top Partners** mass

$m_H^2 \sim$ 

run-1 limits ~**800/900 GeV**.
Maybe more due to single production

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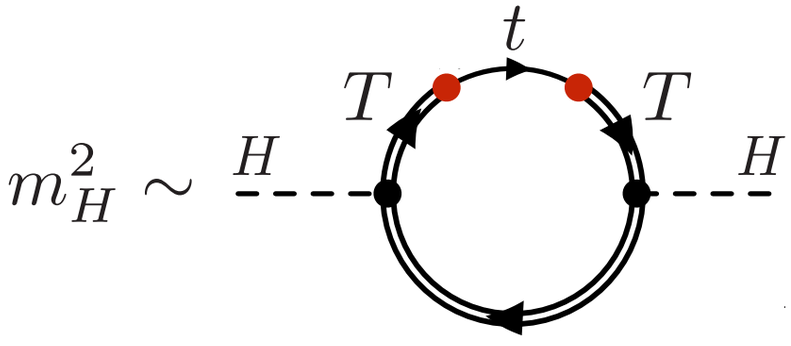

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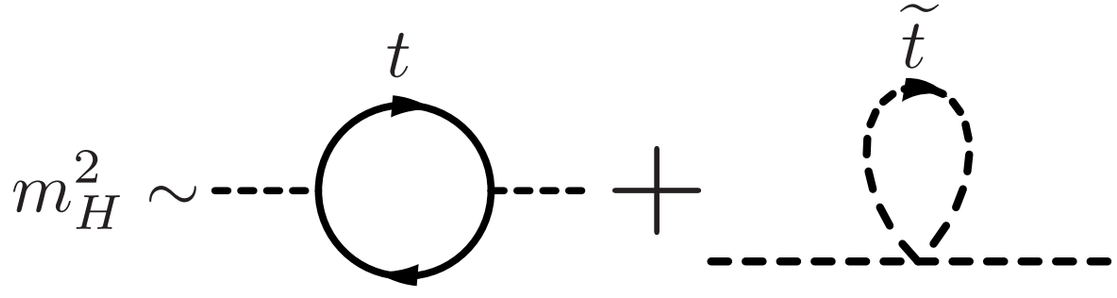
Supersymmetry

[if ~~SUSY~~ low, otherwise large logs]

$\Lambda_{\rm SM}$ = **Stop** mass



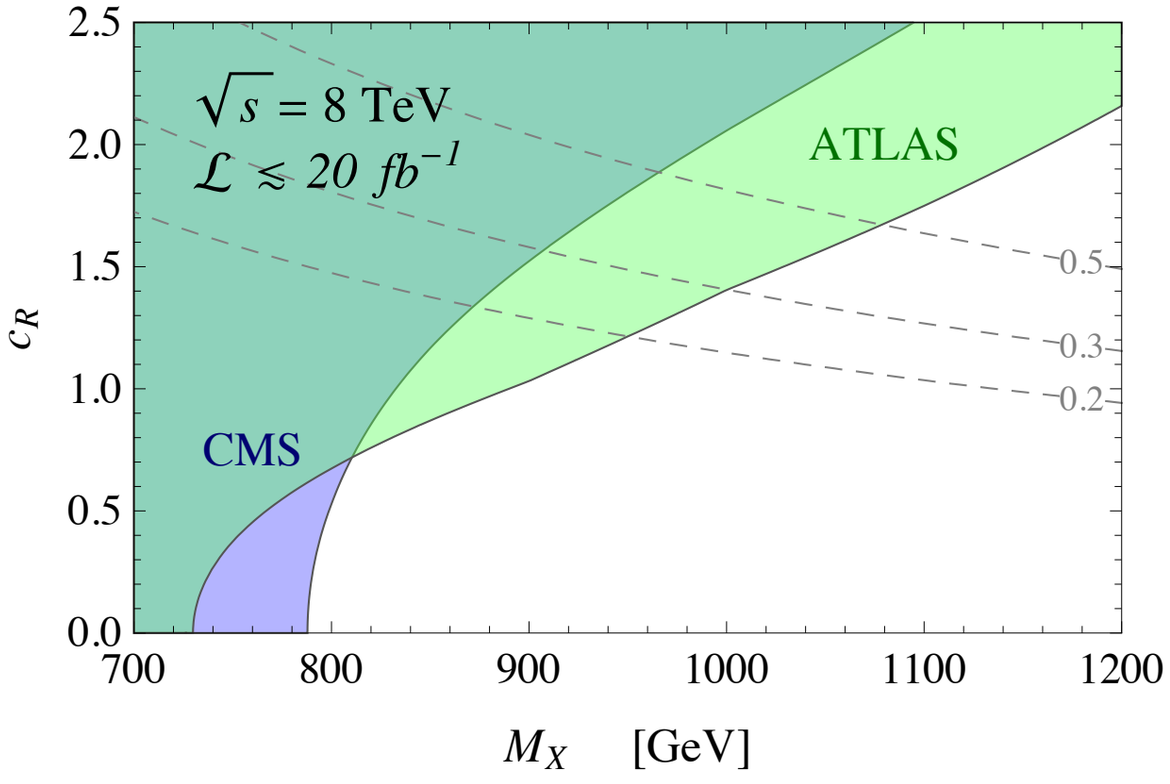
run-1 limits ~**700 GeV** [model dep.]
Gluinos > 1 TeV also matter for Δ

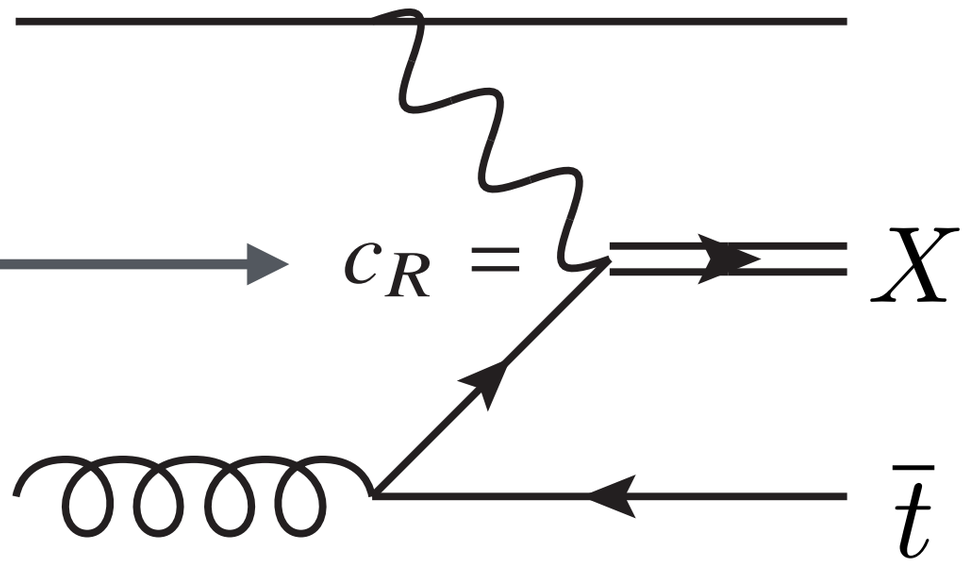
Direct Searches I: Top Partners

[Matsedonskyi, Panico, AW, 2015]

Plenty of opportunities at run-2

run-1 limits on Top Partners





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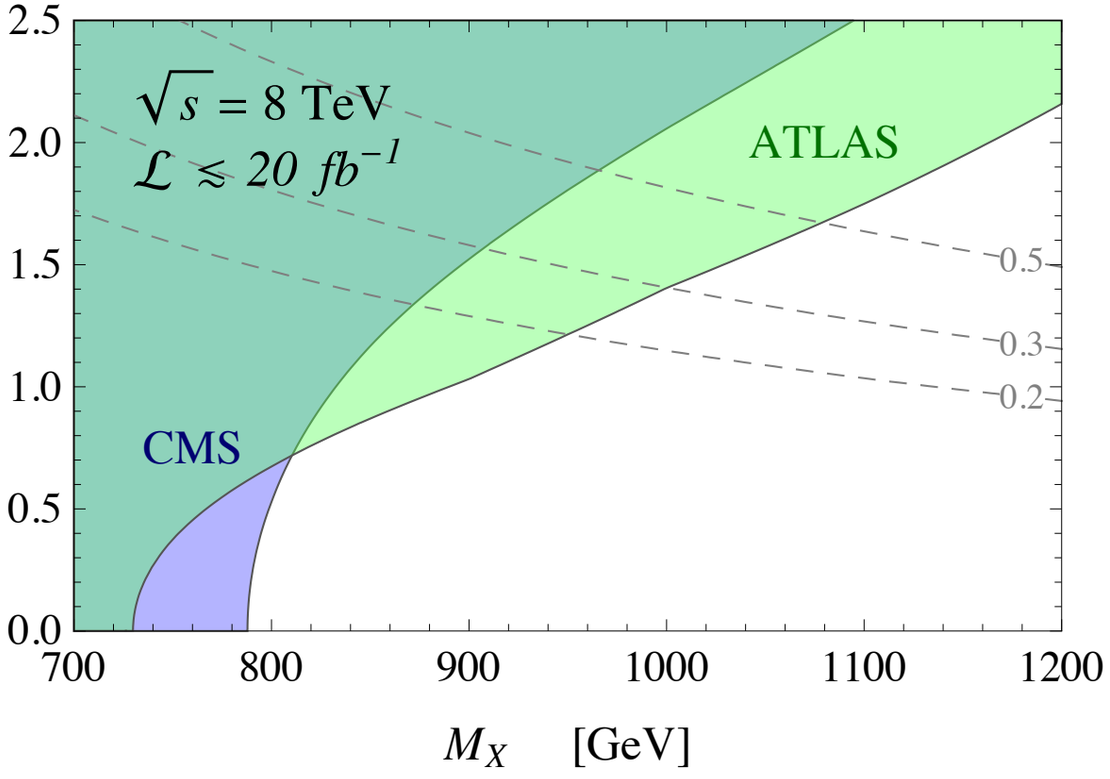
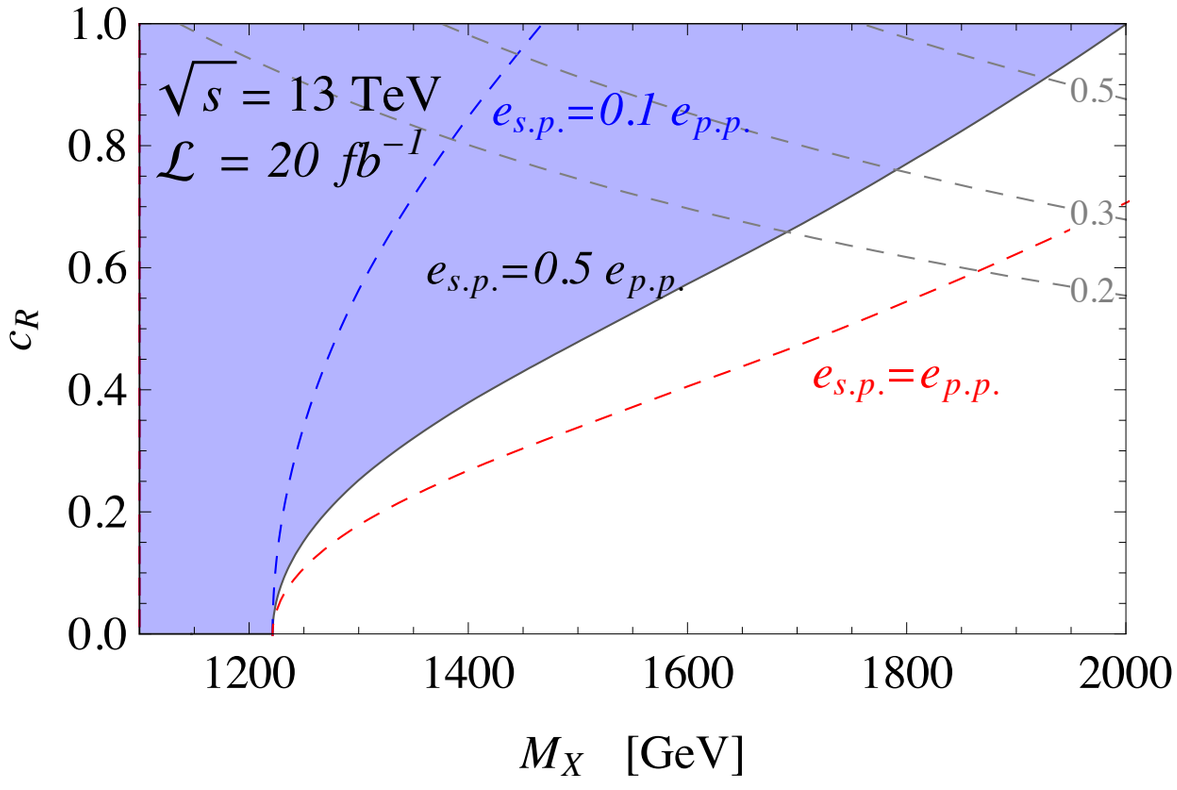


run-2 sensitivity



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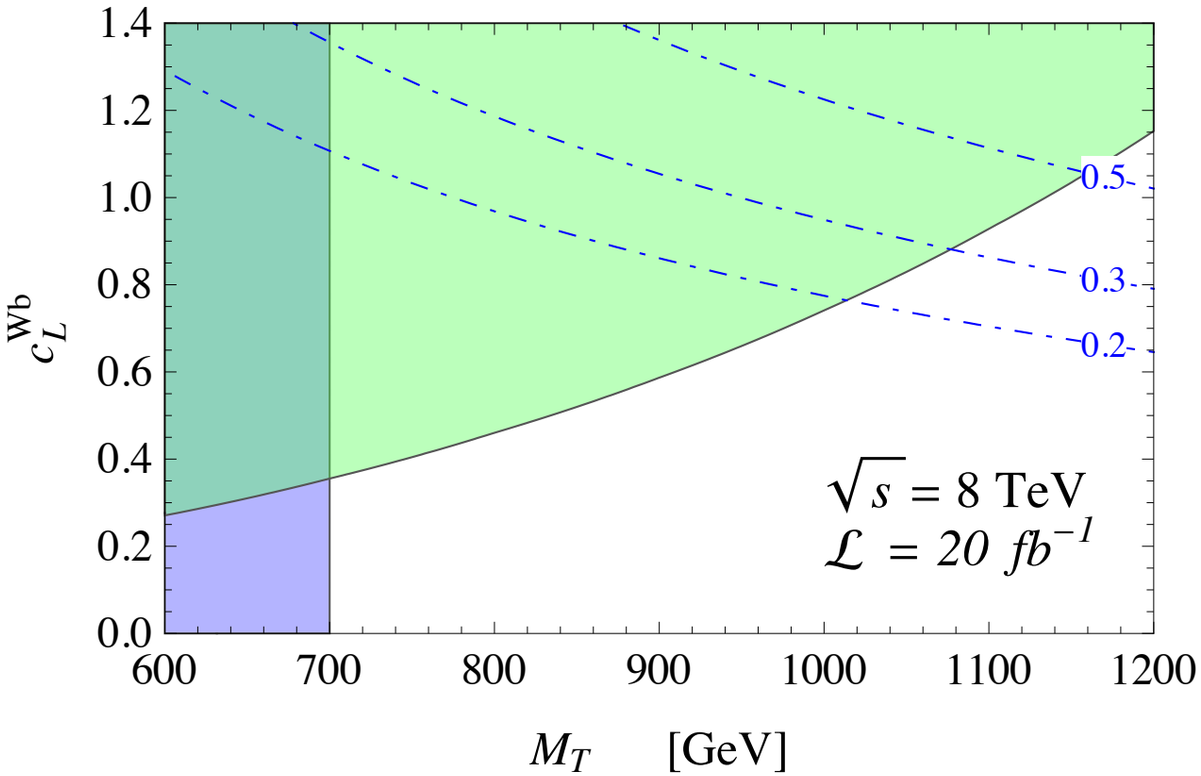

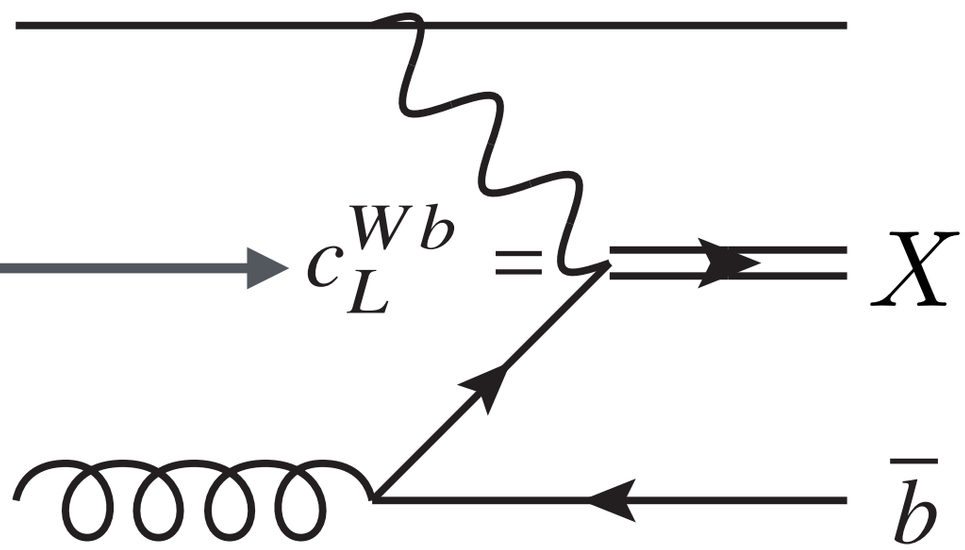

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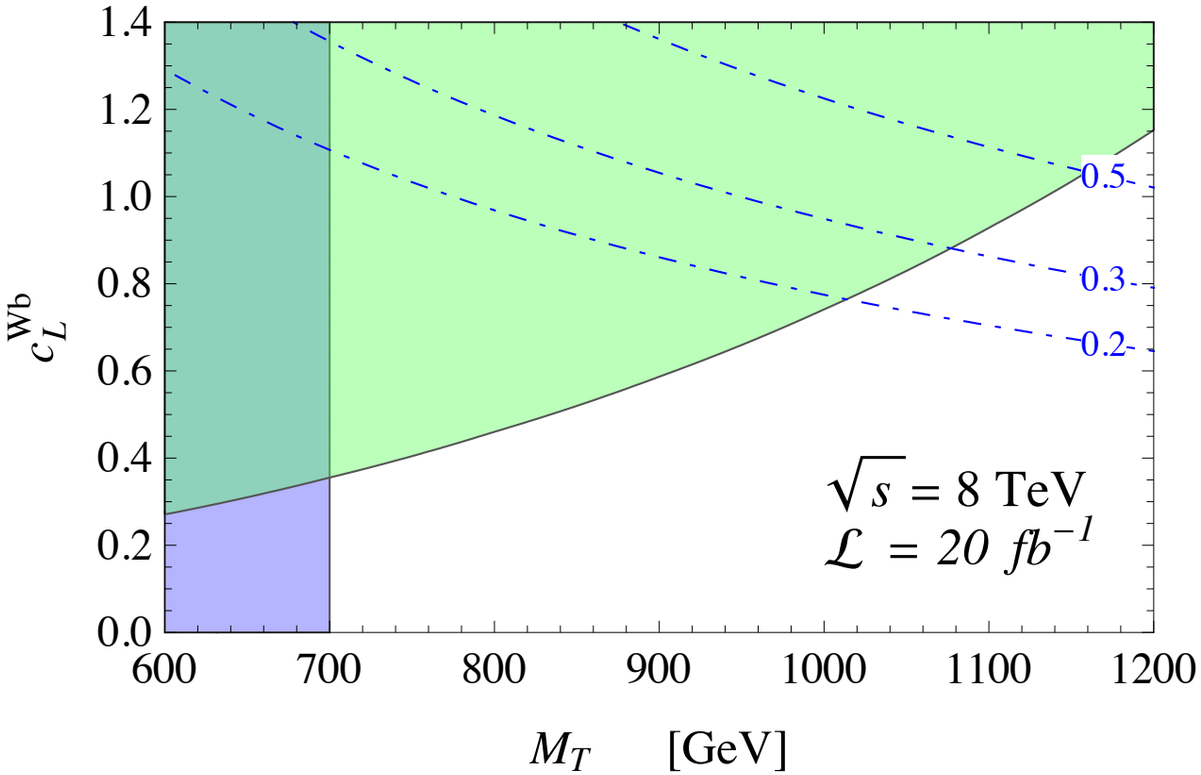

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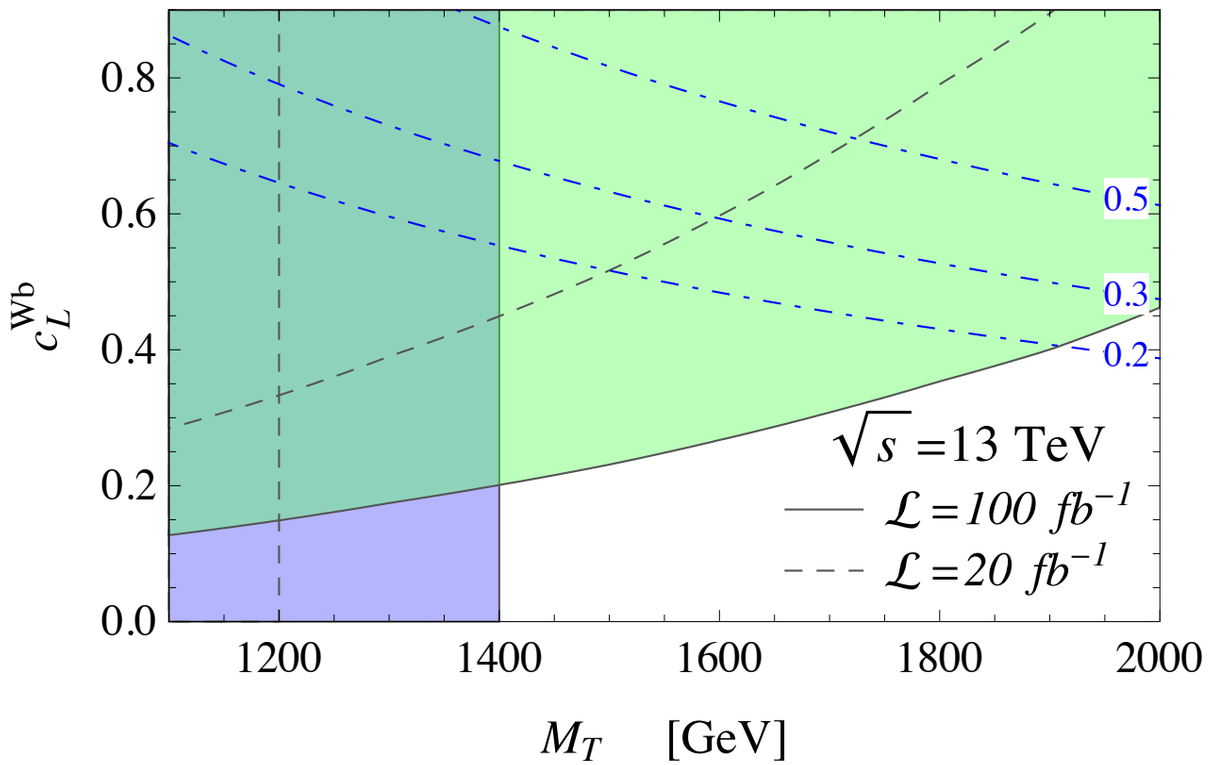

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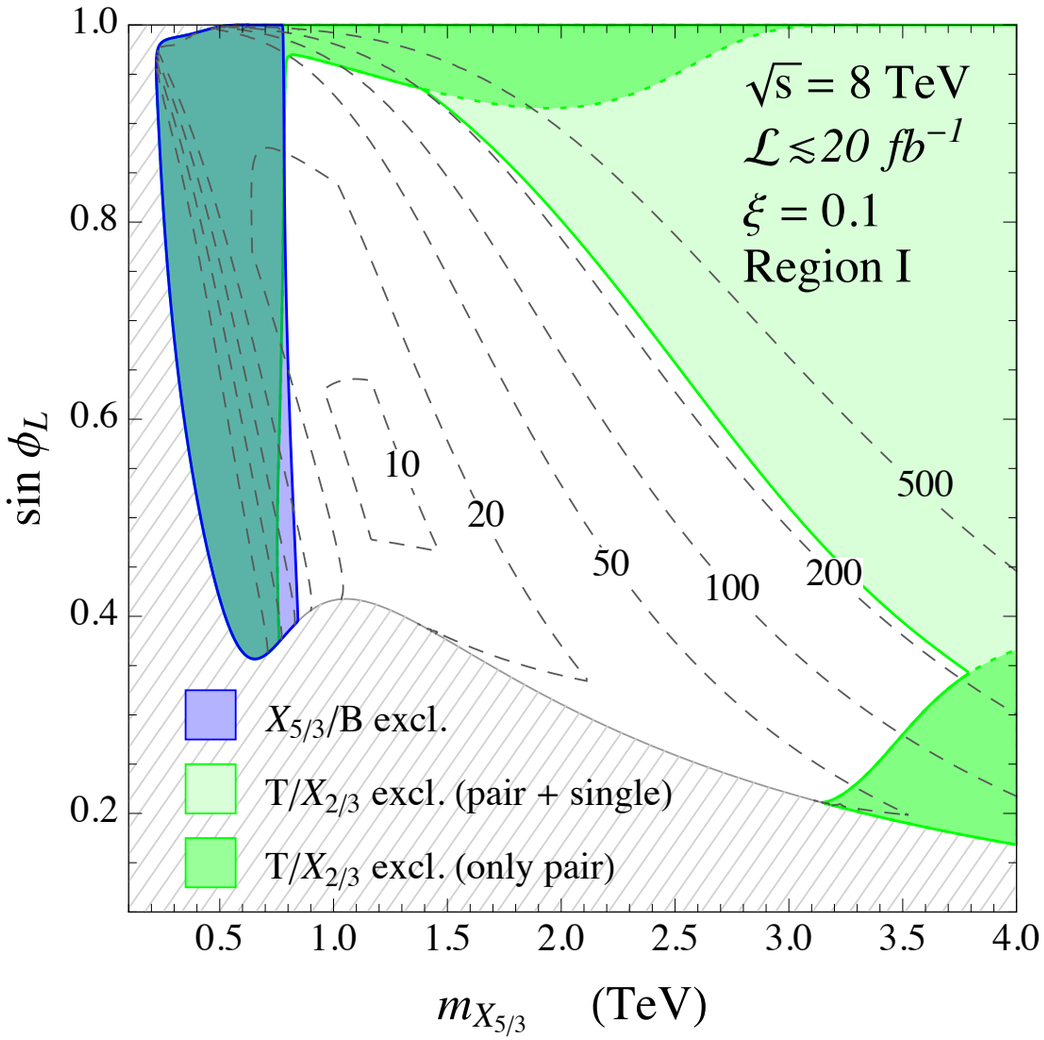
Example: run-1 limits on one explicit Composite Higgs model



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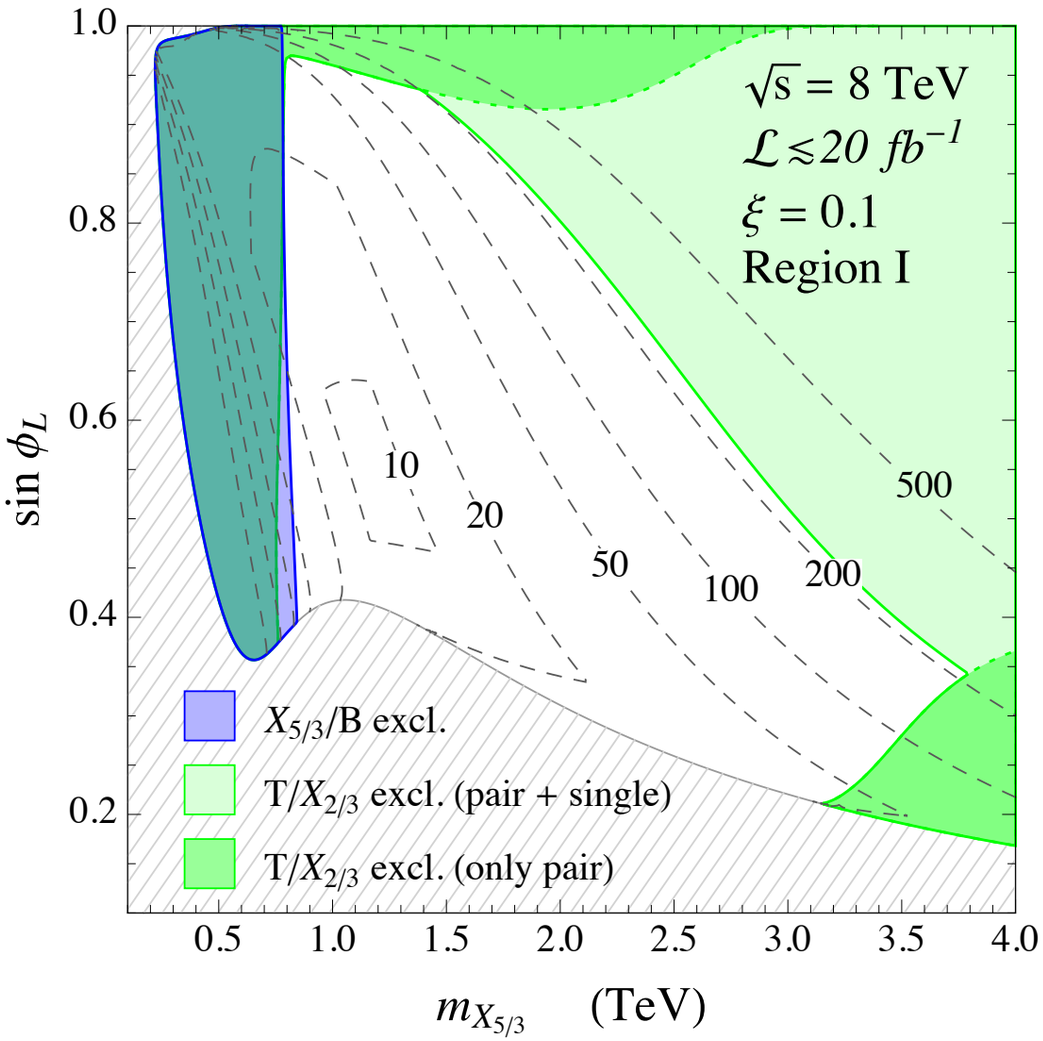
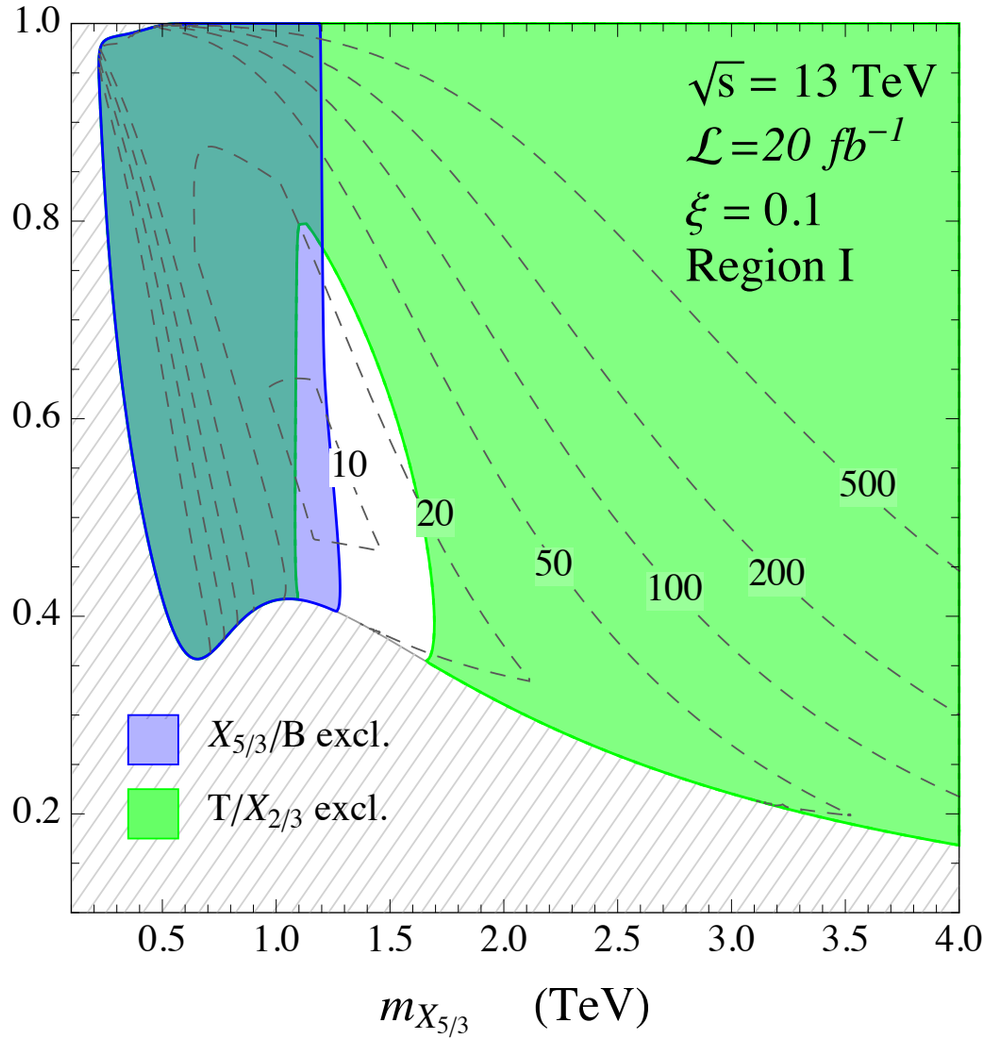


Big change at run-2: searches improve, measurements not much



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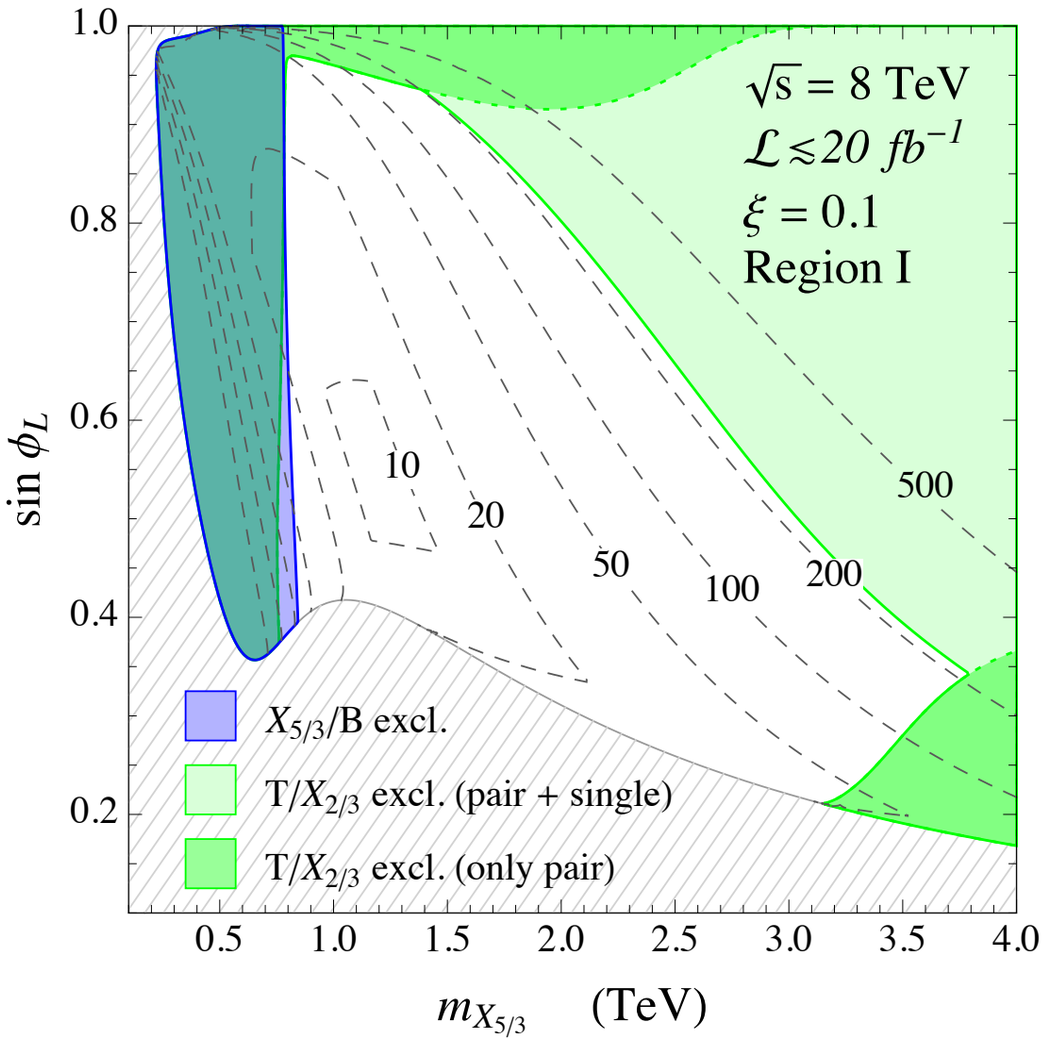

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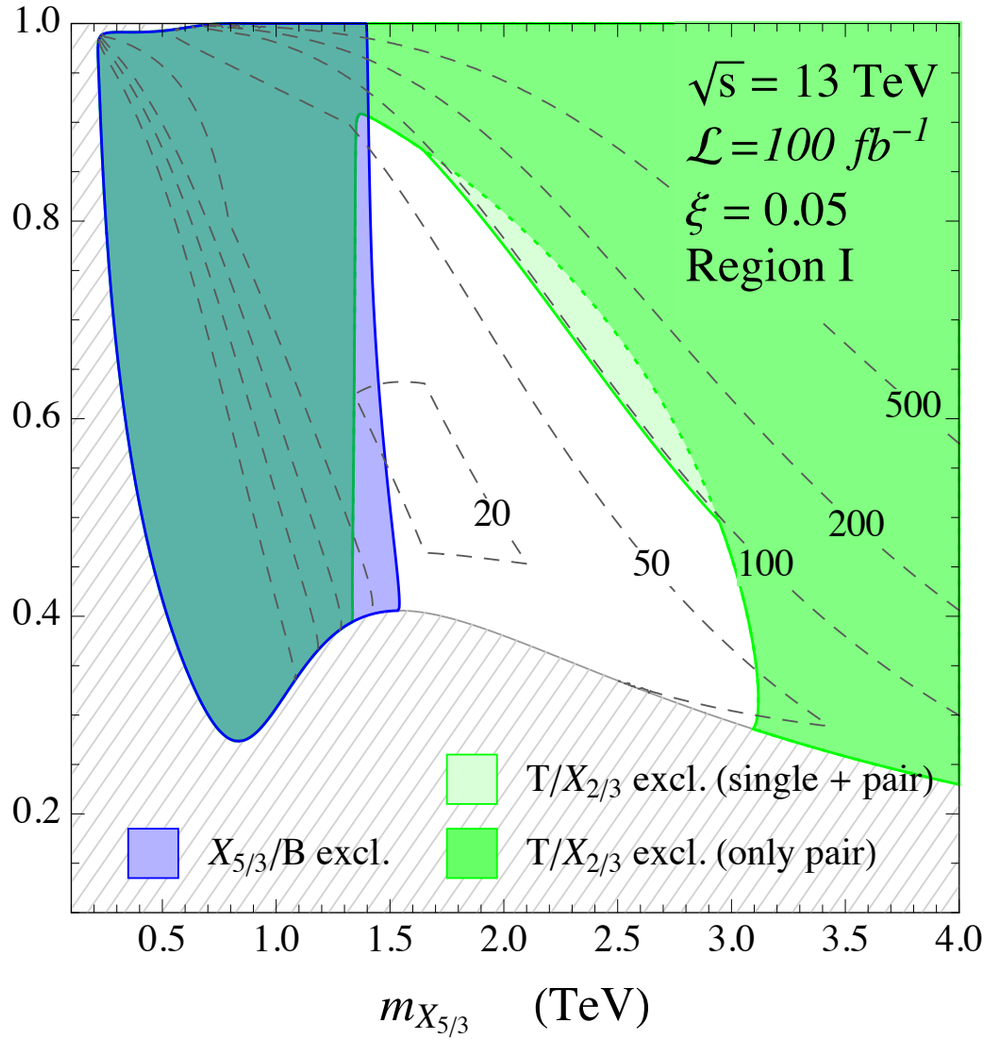

Direct Searches II: Vectors

[Pappadopulo, Torre, Thamm, AW, 2014]

Unavoidably present in CH models

Global group of the new "composite sector"

$$\mathcal{G} \supset \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

Associated conserved global currents

$$J^{\mathcal{G}}_\mu \supset J^{\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}_\mu = \mathbf{3_0} \oplus \mathbf{1_0}$$

Triplet plus **singlet** are unmistakably present.

A.K.A **techinrho,** present in TC, CH, Little Higgs, Dilaton Higgs

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New gauge forces (W', LR models) are also a motivation

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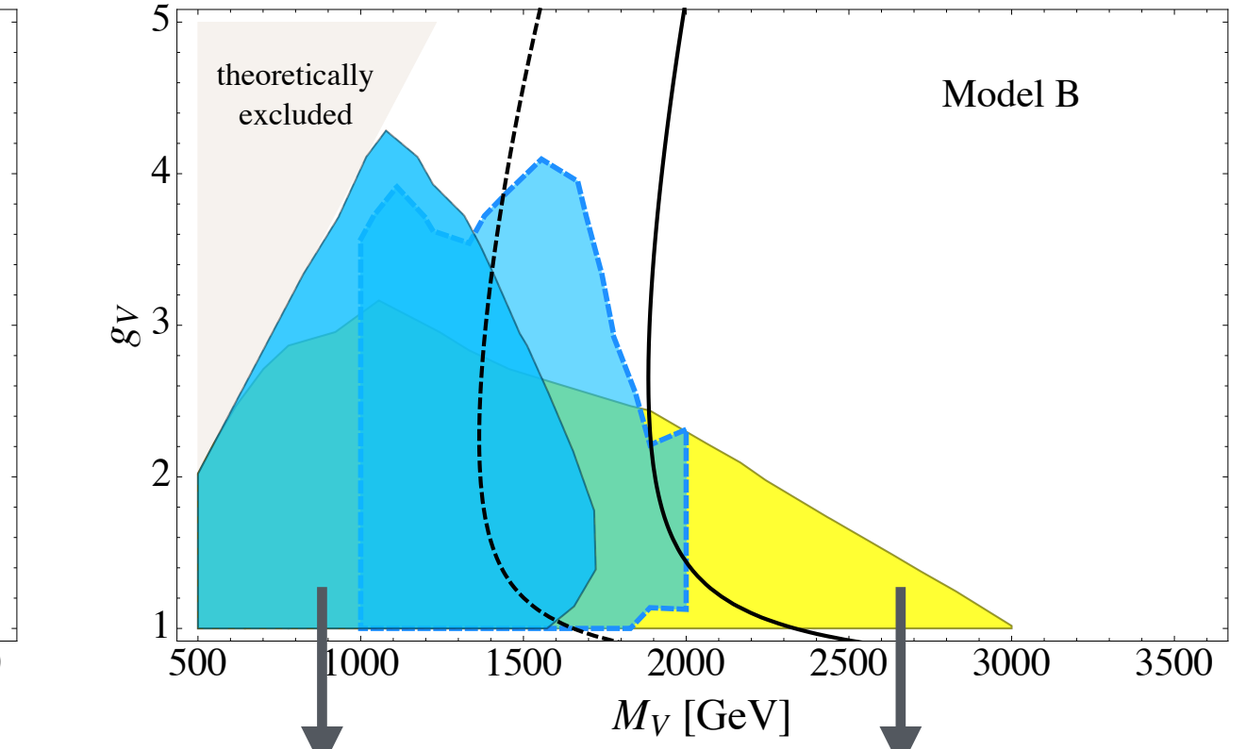
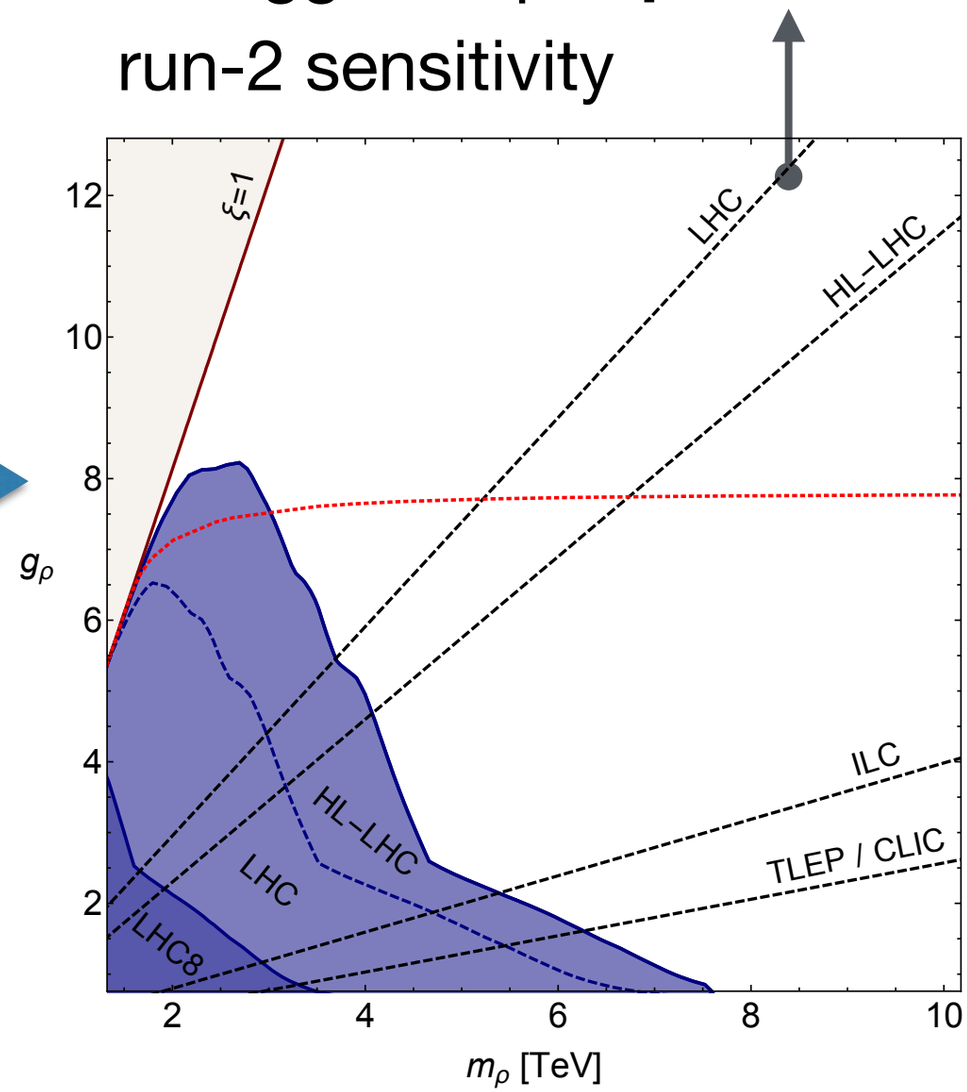
run-1 limits on Composite HVT



Diboson (WZ)

2-leptons (lv)

from Higgs coup., **qualitative** run-2 sensitivity



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

Indirect Searches: Higgs Couplings

Model-independent prediction, from **symmetries**

Direct connection with **tuning:**

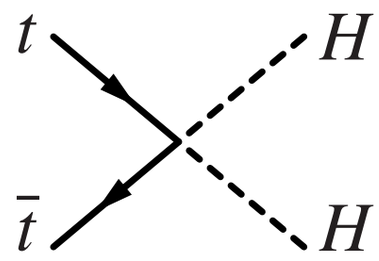
$$\xi = \frac{v^2}{f^2} \qquad\qquad \Delta \geq \frac{1}{\xi}$$

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:

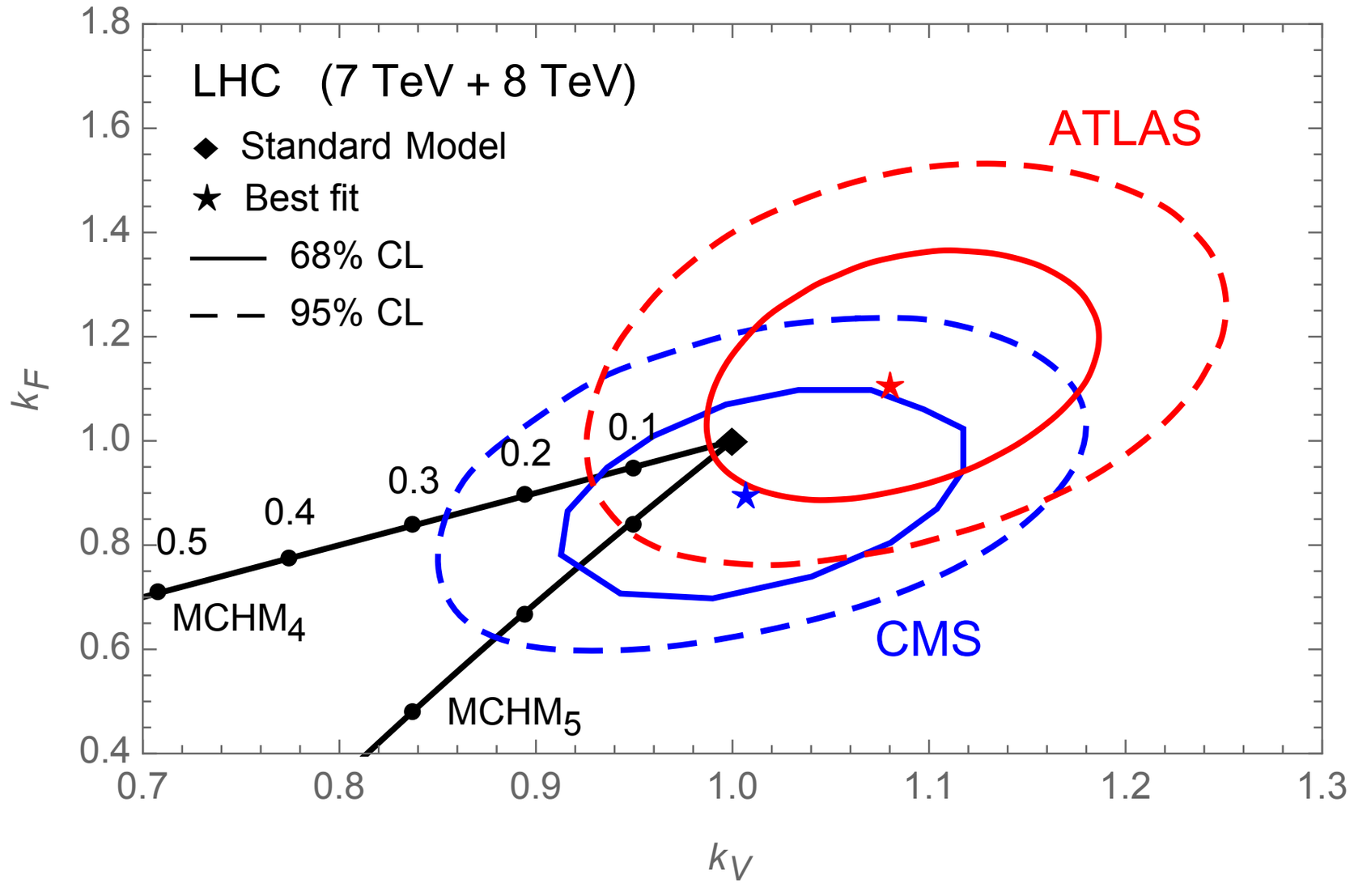


1) Easy to encounter $k_t \neq k_b$
2) Easy to find **extra Goldstone scalars** that contribute by mixing
3) **New couplings** are also there

(see e.g. arXiv:1205.5444)

Indirect Searches: Higgs Couplings

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**

Beyond Higgs Couplings

Slow progresses on Higgs couplings at run-2:

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

from CERN-CMS-NOTE-2012-006

Close to the threshold due to systematics

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 stat.

High energy EW processes
- larger effects at high energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$
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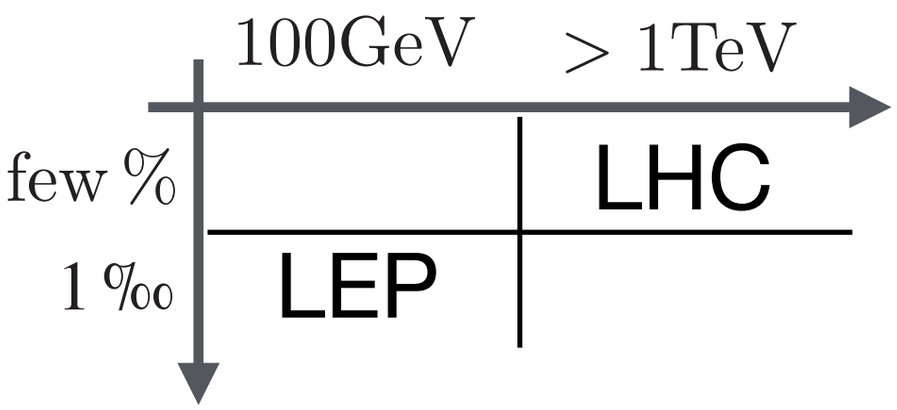

LHC better than LEP on some EWPT par.?

Plus of course measuring operators not constrained by LEP

Oblique Parameters at the LHC

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]

Drell-Yan: currently measured at 10% at 1TeV
Syst.=2%, much better stat. at run-2 at high mass

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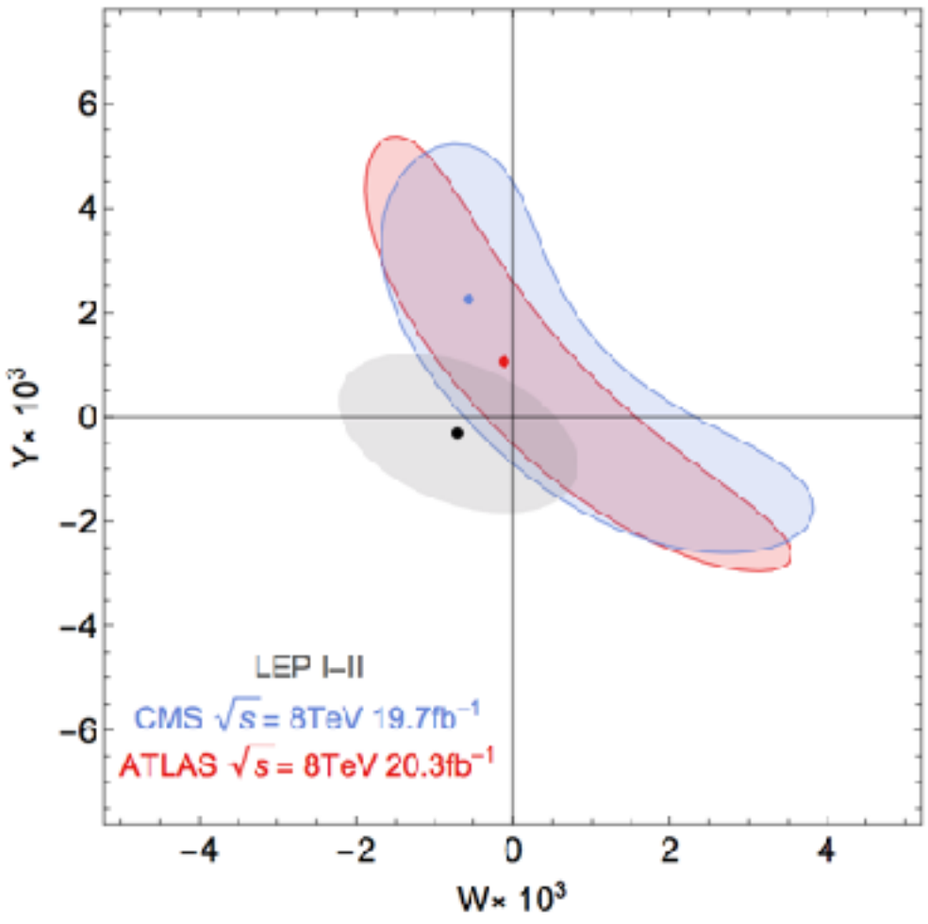

Neutral DY @ **run-1** is **competitive with LEP**

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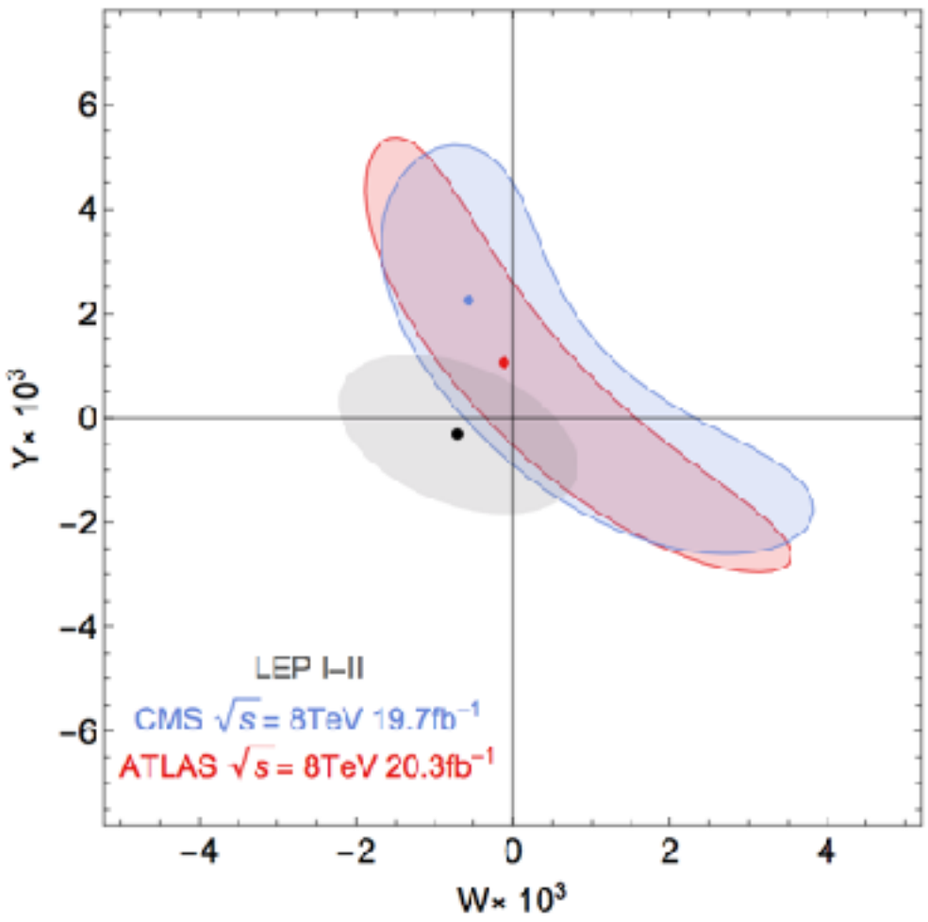

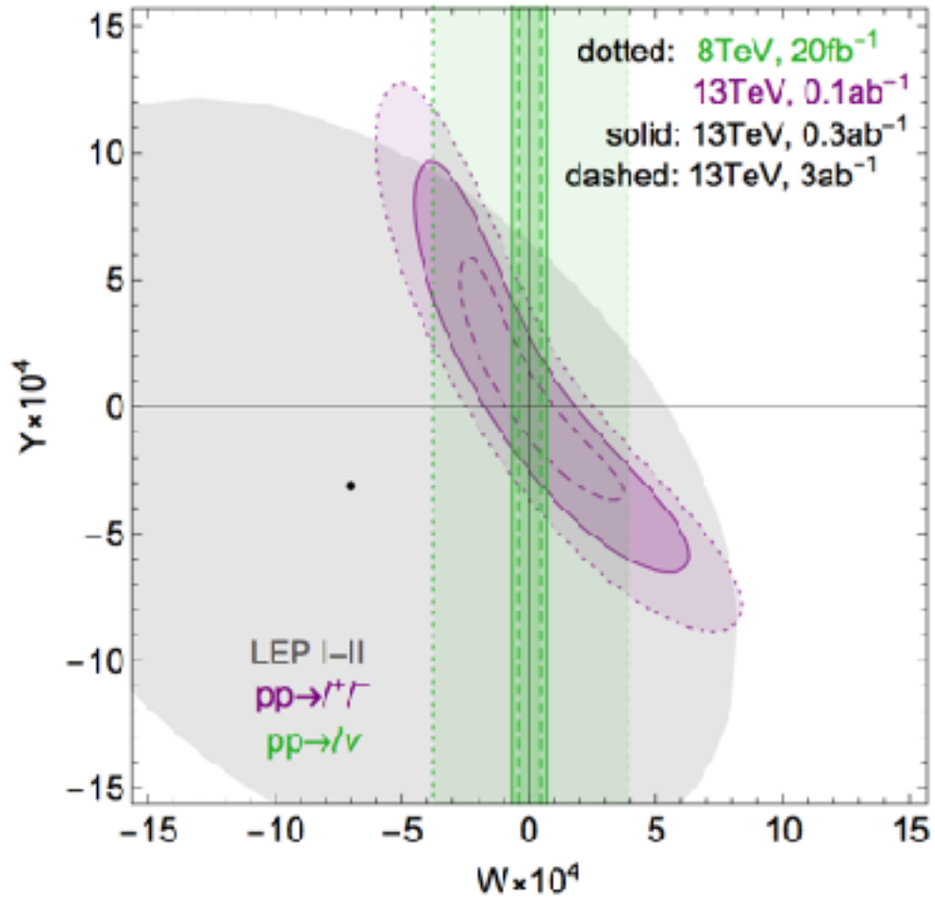

Neutral DY @ **run-1** is **competitive with LEP**

Charged DY @ **run-1 would surpass LEP**

→ No measurement available, extrapolation assumes (conservative) 5% systematic

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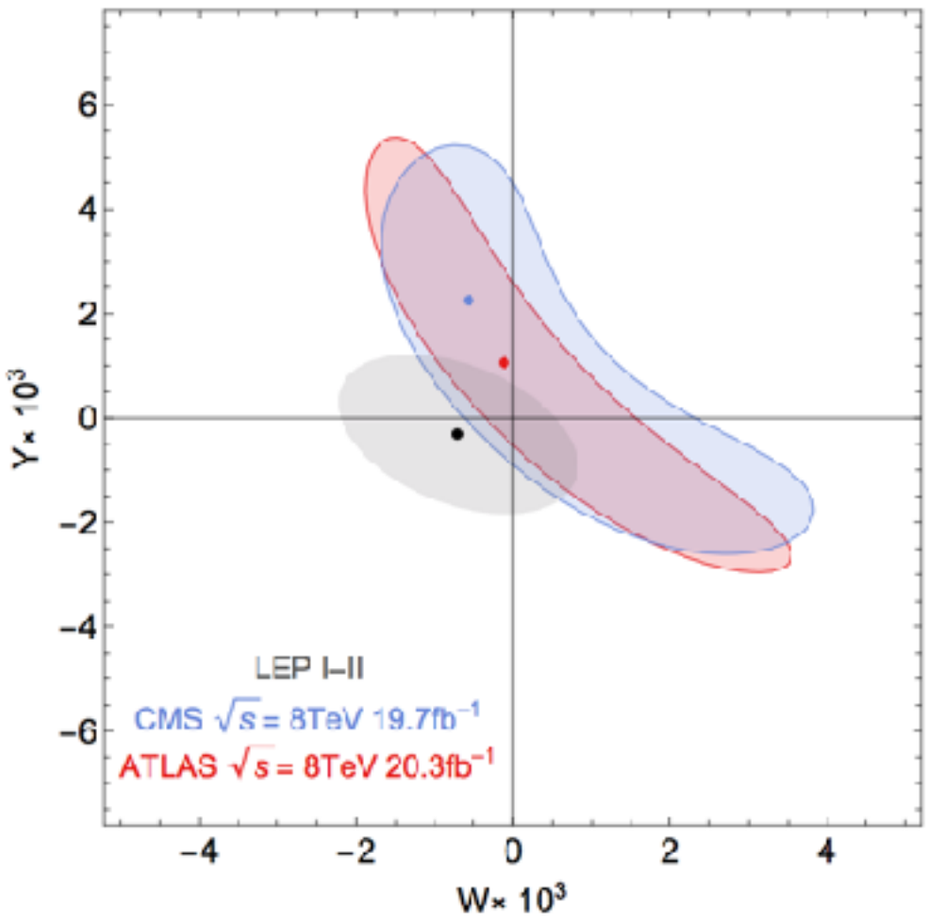
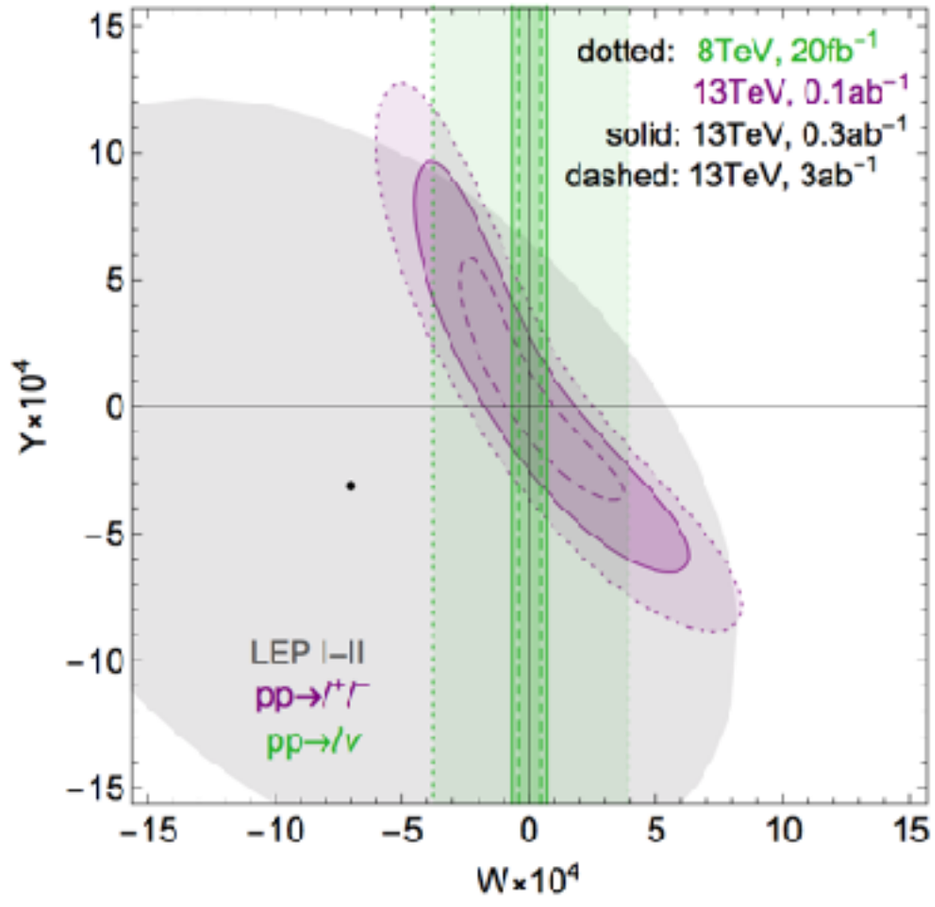
Syst.=2%, much better stat. at run-2 at high mass





Neutral DY @ **run-1** is **competitive with LEP**

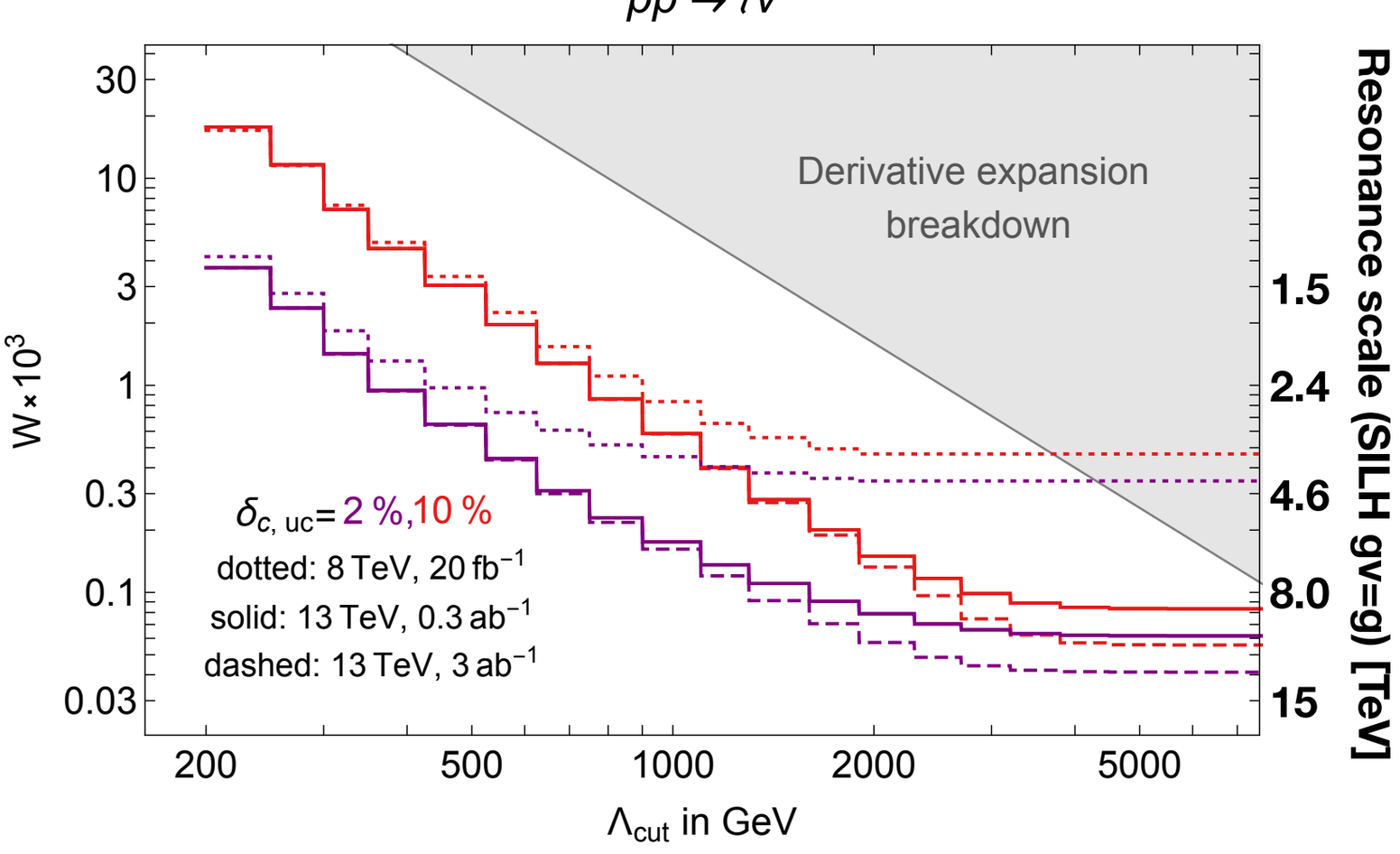
Charged DY @ **run-1 would surpass LEP**

Neut./Ch. DY @ **run-2/3 is much better than LEP**

Oblique Parameters at the LHC

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]

Basic Sanity Check: Limit from scales (2-3 TeV) well below cutoff



Mass limit competitive or stronger than direct searches for small-coupling SILH realisation or for W-compositeness “remedios” power-counting

More model-independent limits, better from “exploration” view-point.

Summary

Top Partner Searches:

- strongly connected with tuning
- however light Top Partners avoided in peculiar “Twin Higgs” models

Vector Searches:

- less directly related to tuning (but still, higher mass-reach …)
- apply to broader class of comp. models (TC, TH, W-comp.)

Higgs Couplings:

- very model-independent and very strong.
- part of a broad (“SM”) exploration program
- slow progresses at run-2

Energy and Accuracy:

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- looking for other channels with similar performances. **Diboson?**