Exotic Signals of Compositeness

Daniele Barducci

w/ A. Azatov, C. Delaunay, S. Banerjee, G. Belanger, L. Panizzi

arXiv:1511:01101, arXiv:1606:09013 and work in progress

The same old story…

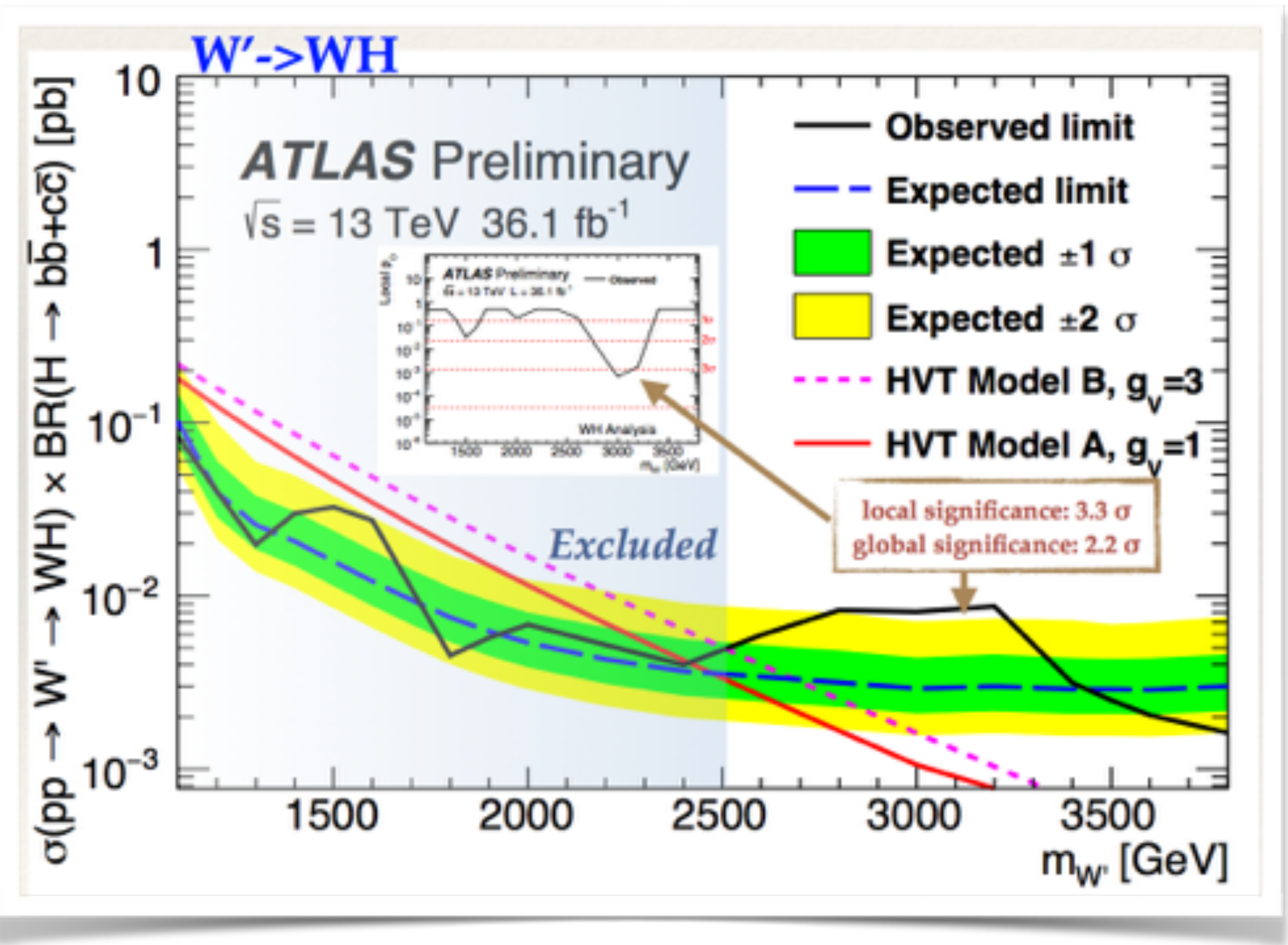
LHC Run-2 - Almost 40/fb

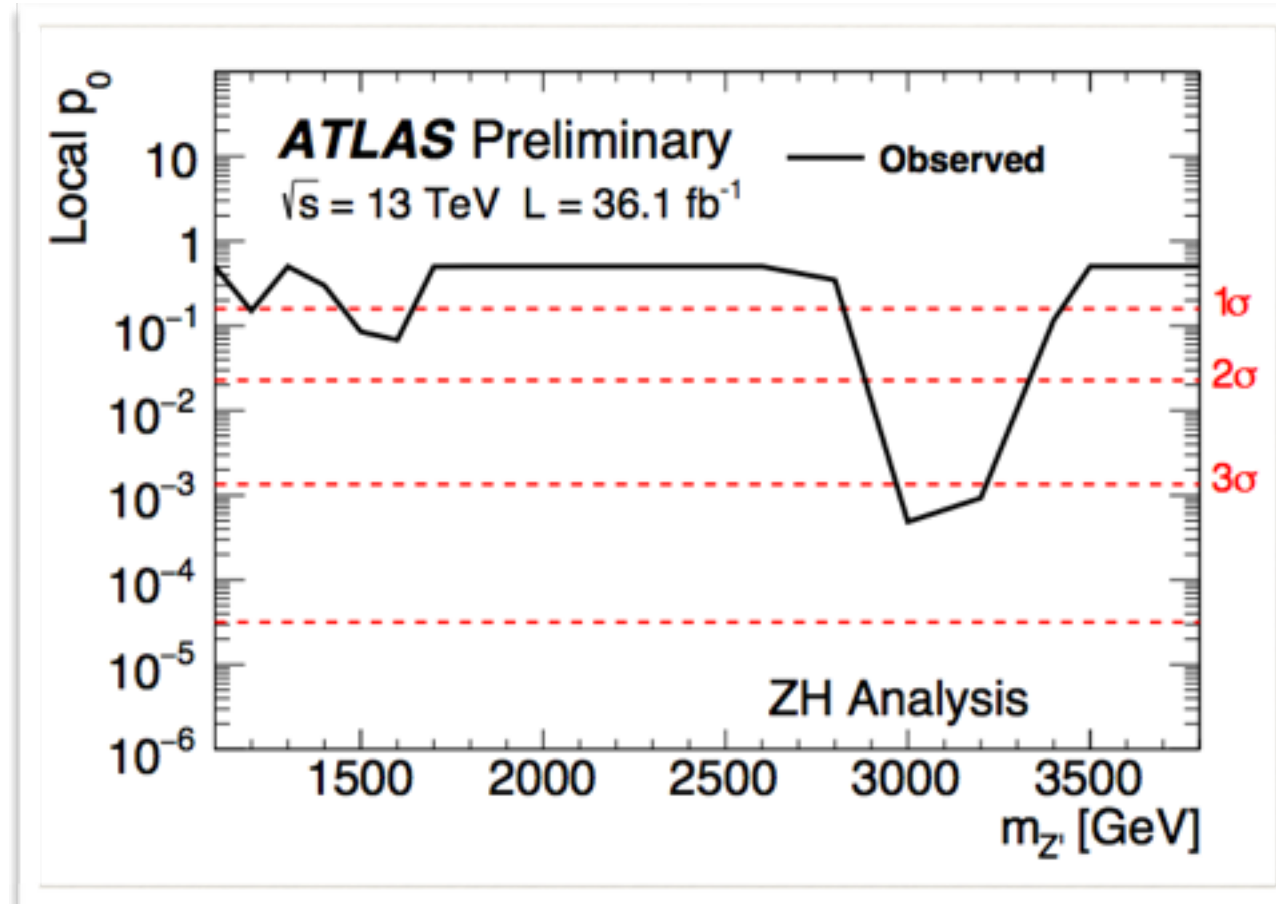
LHC is running at its default energy and has delivered ~40/fb

Great expectation for results to be presented in Moriond next week

Maybe something new is waiting us behind the corner

LHC Run-2 - Almost 40/fb





local significance: 3.3 σ
global significance: 2.2 σ

Diboson revival?

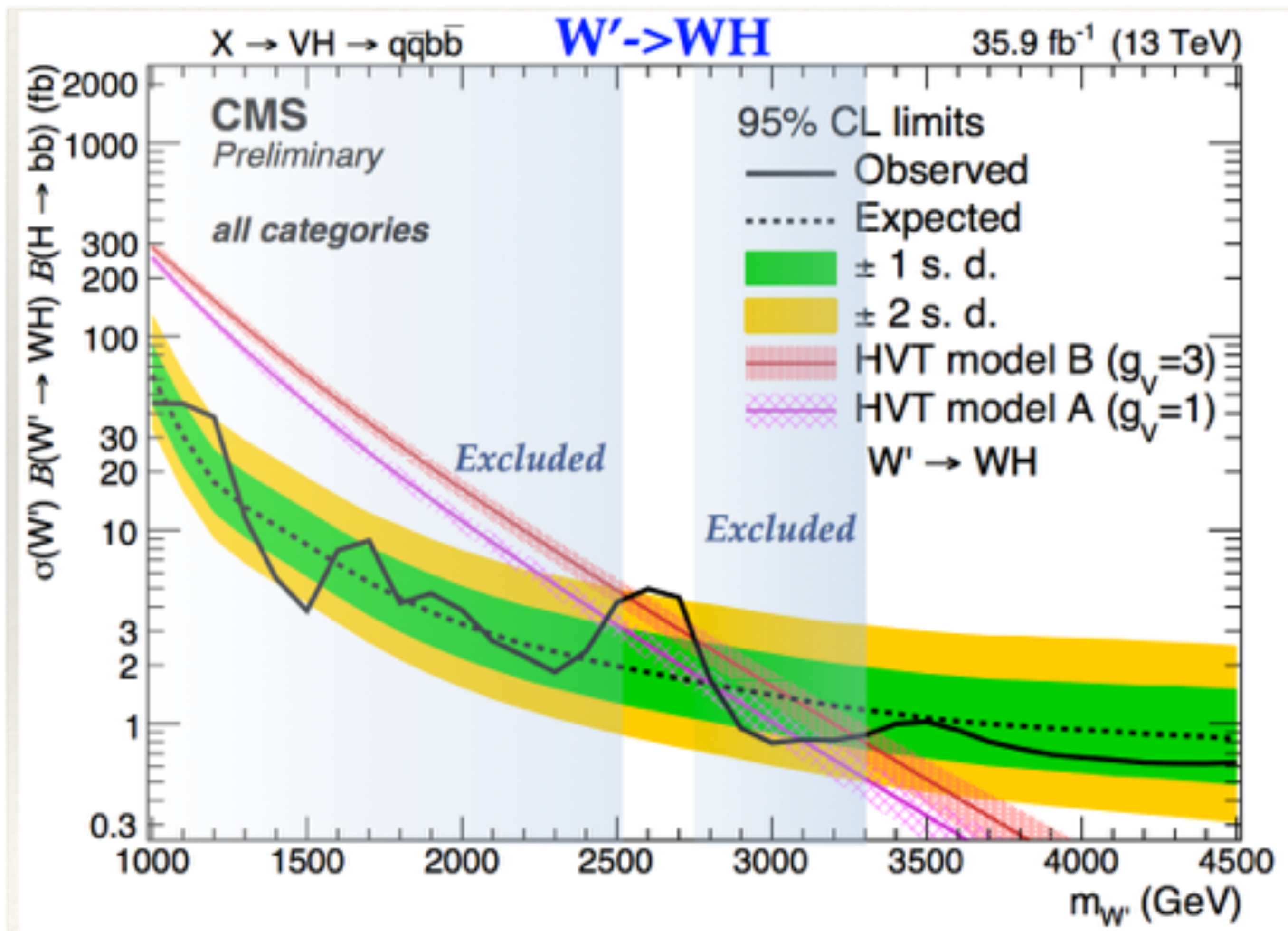
[8 TeV diboson was 3.4 and 2.5 sigma for 2 TeV mass]

LHC Run-2 - Almost 40/fb

We need however to be prepared for puzzling (disappointing) results!

But we are kind of used to…

LHC Run-2 - Almost 40/fb



❖ **The excess observed by ATLAS with a local significance of 3.3 σ at ~3.0 TeV is not observed at CMS.**

There is actually a downward fluctuation at the mass of the ATLAS excess

Where is TeV scale

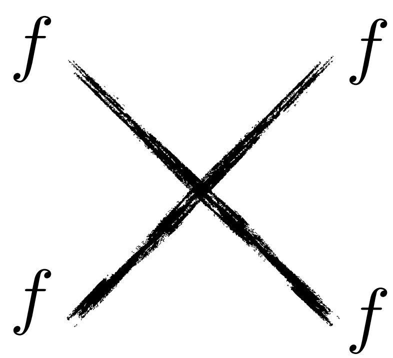
New Physics?

Why we are looking

for TeV scale

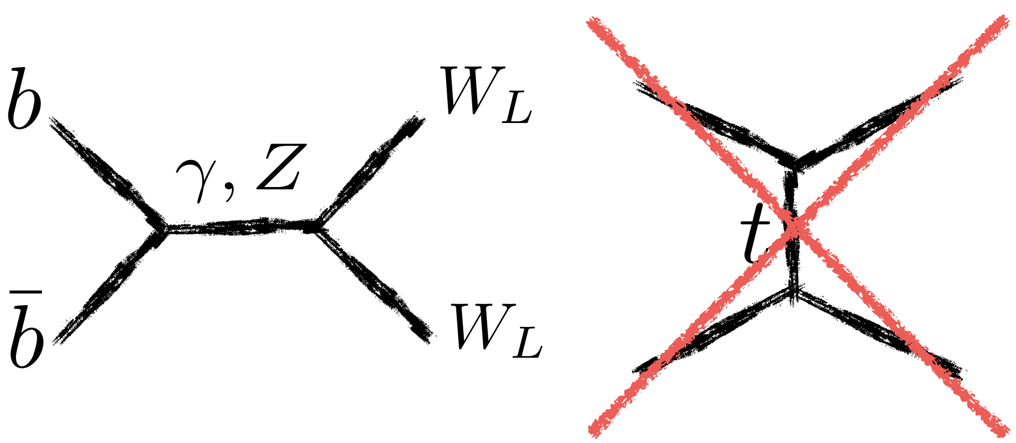
New Physics?

We always had a strong guidance hinting to new physics



$\sim G_F E^2 \sim E^2/v^2 < 16\pi^2$

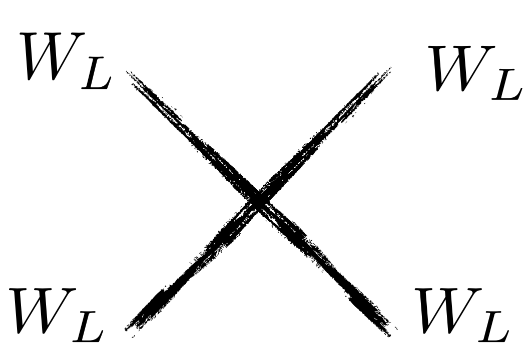
$m_W < 4\pi v$



$\sim g_W^2 E^2/m_W^2 < 16\pi^2$

$m_t < 4\pi v$

And lastly



$g_W^2 E^2/m_W^2 < 16\pi^2$

$m_H < 4\pi v$

If we didn't find the Higgs we would have been sure that some kind of new physics should have appeared somewhere

No matter what, we would have kept investigating the mechanism of electro-weak symmetry breaking by pushing higher and higher the energy of our colliders

However it seems that Nature has chosen an elementary weakly coupled Higgs to unitarise longitudinal gauge boson scattering

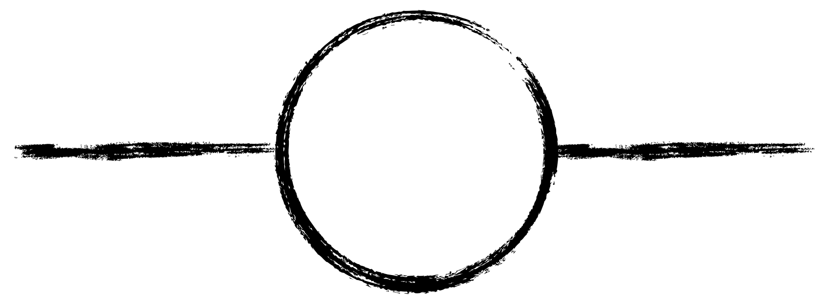
This scalar states seems consistent with the prediction of the Glashow-Weinberg-Salam theory

There is no guarantee of a future discovery for the first time in ~50 years!

Q: How are we motivating the search for TeV scale New Physics?

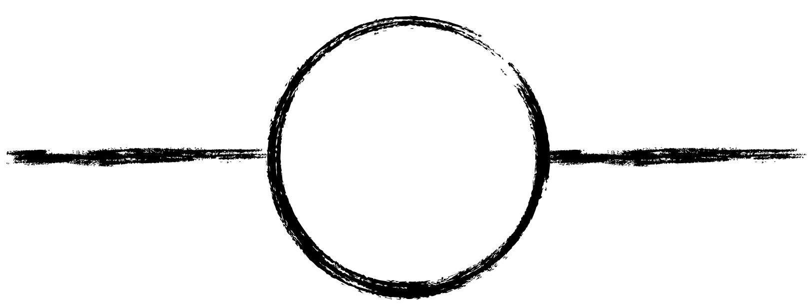
The search for TeV scale New Physics

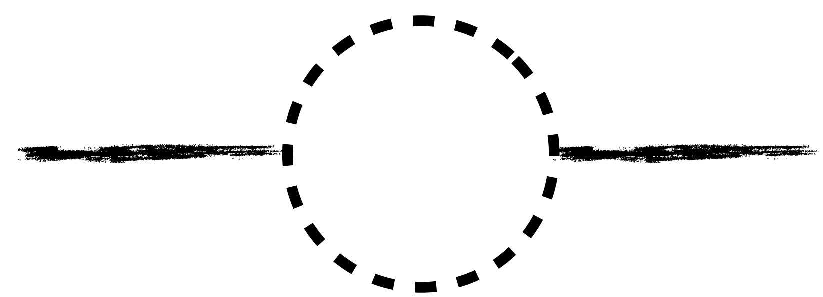
In the Standard Model no symmetries are protecting the Higgs mass



$$\sim \Lambda^2$$

A symmetry protecting it brings NP required to stabilize the EW scale





$$\sim 0$$

For $\delta m_H^2 \ll m_h^2$ New Physics is expected at the TeV scale

Naturalness of the weak scale is the only quasi-no-loose theorem we have

Outline

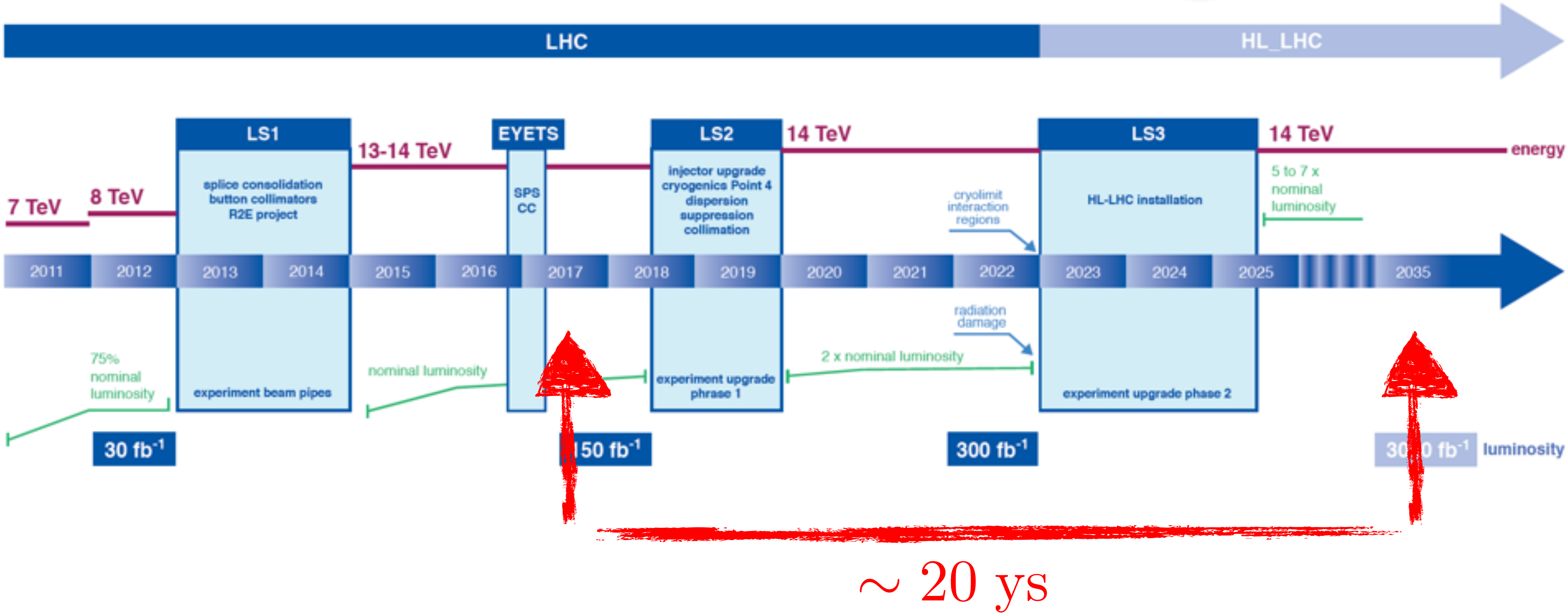
Why despite null results we should keep looking for NP at the TeV scale?

I'll try to answer this with motivations within the Composite Higgs paradigm

Standard CHM searches for heavy resonances

Exotic CHM searches for heavy resonances

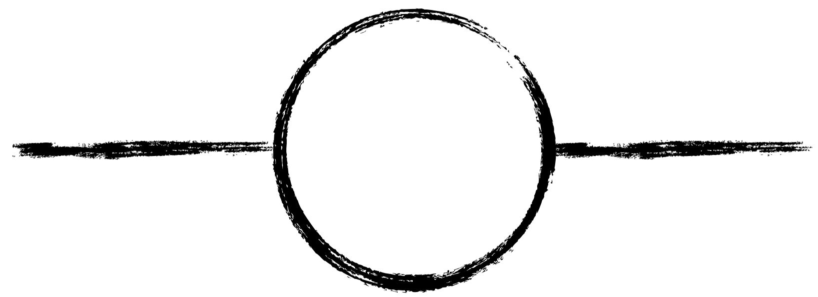
LHC / HL-LHC Plan



The LHC might represent our last chance of high energy proton collisions

- Precision measurements of SM properties
- Flavour physics - anomalies as guide for NP searches?
- Coverage of “all” BSM possibilities

The composite Higgs idea



$\sim \Lambda^2$

SUSY stabilizes the Fermi scale with an elementary Higgs

What about the possibility of the Higgs as a composite state?

A composite state would "solve" the hierarchy problem

All the scalar we know are (QCD) bound states

Composite Higgs assumes the 125 GeV boson to be a bound state of a new strongly interesting sector

[Terazawa et al. '77, Dimopolous et al. '79, 't Hooft '80]

How to get a light Higgs from a strongly interacting sector which should lie at a scale greater than the Fermi one?

Assume the Higgs to be a pseudo Golstone boson of a spontaneously broken global symmetry

The prototype of this paradigm are QCD pions

[Georgi and Kaplan ‘84]

$$G \to H$$

$n = \dim(G) - \dim(H)$ massless bosons due to NG shift symmetry

An explicit breaking of the global symmetry will provide a mass to the Higgs

General implications of CHMs

GBs action can be described by the CCWZ formalism

$$U = e^{i\frac{\Pi}{f}} U_0 \qquad \Pi = \sqrt{2} h^{\hat{a}} T^{\hat{a}} \qquad U_0 = (0, 0, ...1)$$

$$\mathcal{L} = \frac{f^2}{2} D^\mu U D_\mu U$$

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Pion matrix

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G broken generators

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Explicit breaking of global symmetry

Assume a potential that breaks the EW symmetry $\langle \mathbf{h} \rangle = (0, ..., 0, \langle h \rangle)$

$$m_W^2 = \frac{g^2 f^2}{4} \xi^2 \qquad \xi = \frac{v^2}{f^2}$$

$$g_{VVh} = g_{VVh}^{\text{SM}} \times f(\xi)$$

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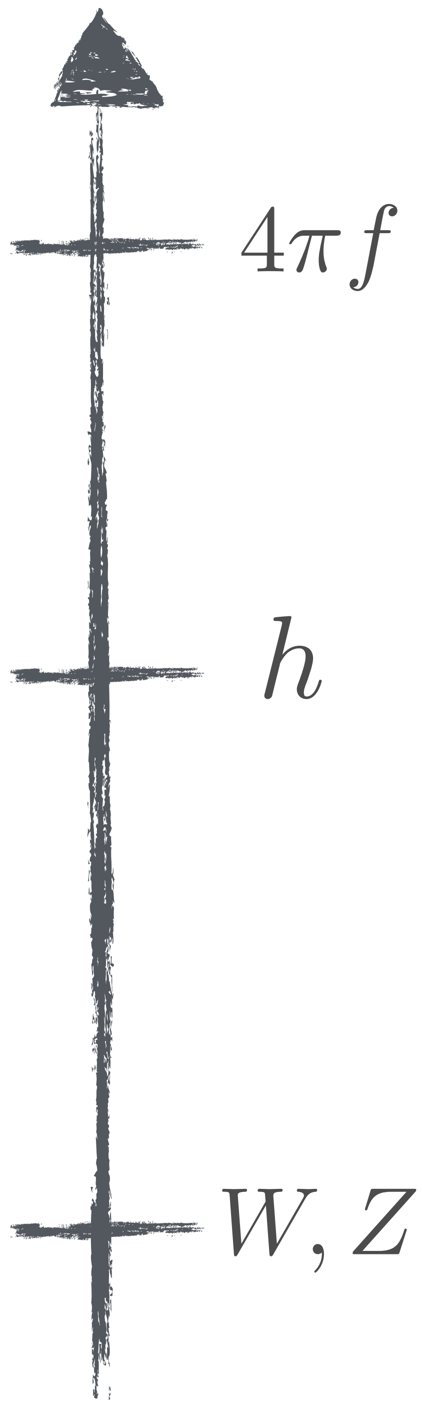
Modification of Higgs couplings

General implications of CHMs



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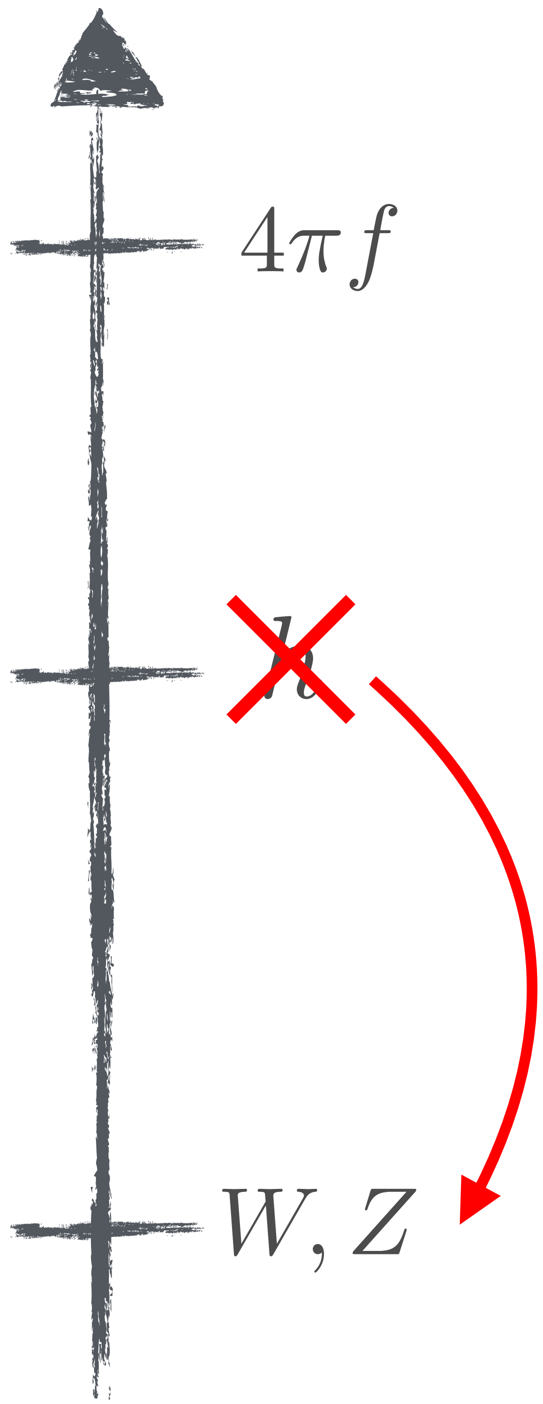

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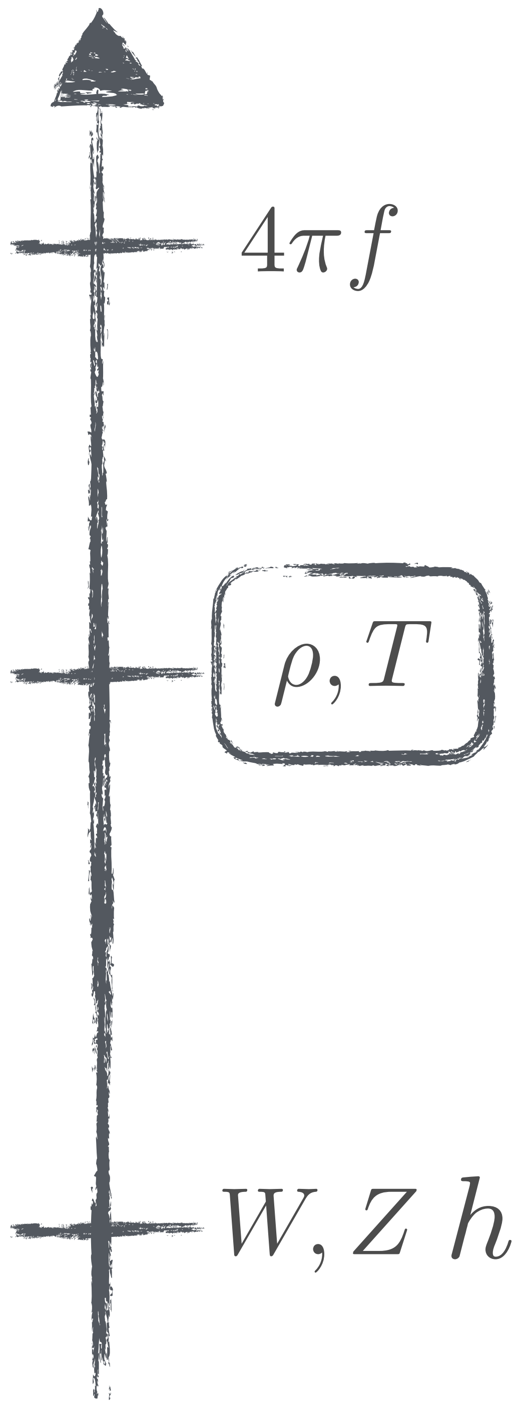

A composite dynamics will generate resonances at the scale f

- Top partners are an essential ingredient to provide mass to the top quark through partial compositeness mechanisms
- They guarantee a mexican-hat radiatively generated Higgs potential

[Panico and Wulzer ’15 for a review]

$$m_h \sim y_t \frac{m_T}{f} v$$

Light resonances arise naturally in CHMs!

[De Curtis et al. ‘11]

The minimal composite Higgs model

$$G \to H$$ identified with $$SO(5) \to SO(4)$$

4 GBs in the fundamental of $SO(4) \sim SU(2)_L \times SU(2)_R$

- Minimum number of GBs
- Custodial symmetry

$$SU(2)_L \times SU(2)_R$$

Two isotriplets of vector

$$\rho^0_{L,R},\ \rho^\pm_{L,R}$$

A bidoublet of top partners

$$\Psi = \begin{bmatrix} (X_{5/3} & X_{2/3}) \\ (T_{2/3} & B_{-1/3}) \end{bmatrix}$$

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SU(2) doublet with exotic (hyper)charge

The minimal composite Higgs model - MCHM

$$\mathcal{L} \supset \frac{f^2}{2} D_\mu U D^\mu U$$

Pion Lagrangian

$$\mathcal{L} \supset \bar{\Psi}(i\hat{D} - M_\Psi)\Psi + ic_1 \bar{\Psi}_R \, \hat{d} \, t_R + y_L f \bar{Q}_L U \Psi_R + y_L c_2 f \bar{Q}_L U t_R$$

Mass term allowed for VLQ

Partial compositeness - top mass

[d^μ and e^μ CCWZ symbols ensuring non linear SO(5) realisation]

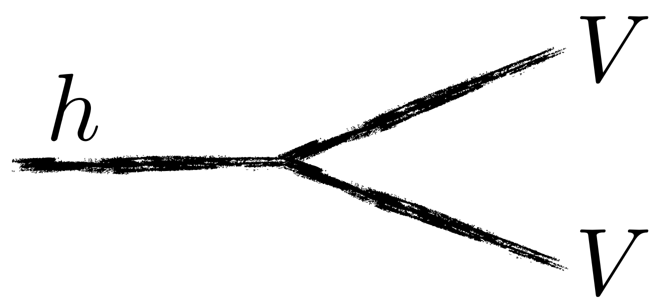
$$\mathcal{L} \supset -\frac{1}{4}\rho^{\mu\nu}\rho_{\mu\nu} + \frac{m_\rho^2}{2g_\rho^2}(g_\rho \rho_\mu - e_\mu)^2 + c_3 \bar{\Psi}\gamma^\mu (g_\rho \rho_\mu - e_\mu)\Psi$$

Resonances interactions

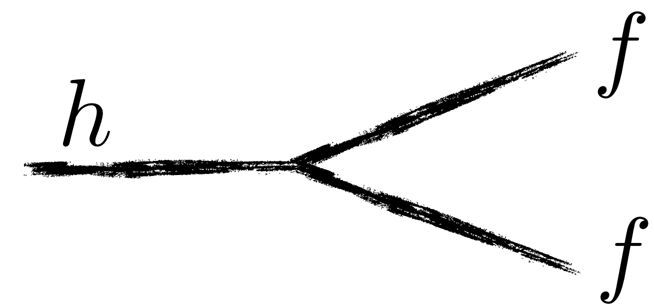
MCHM Explicit realization that allows phenomenological studies

[Agashe et al. '05]

Constraints from Higgs measurements

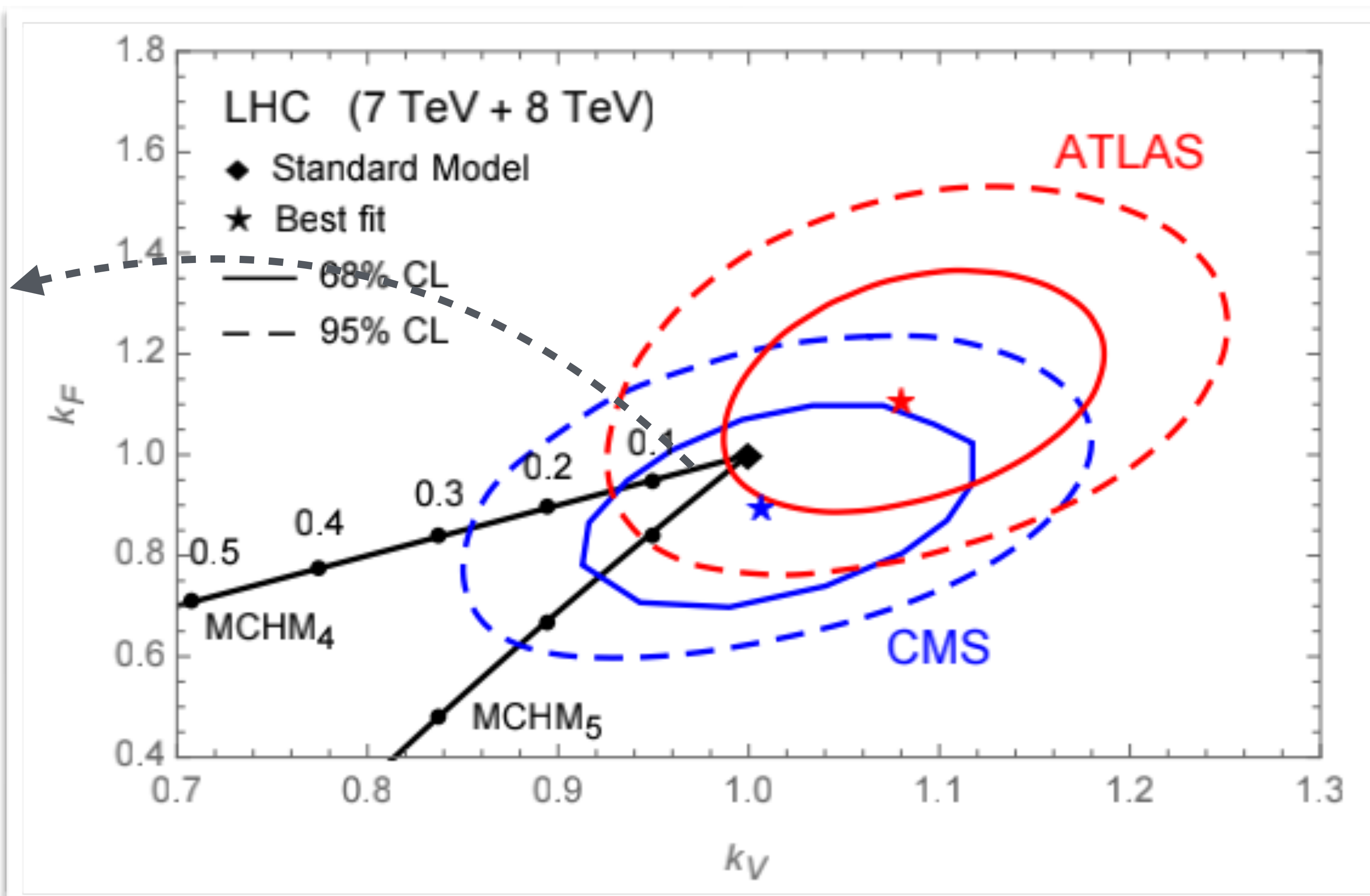


$$\frac{\delta g}{g} = \sqrt{1-\xi}$$



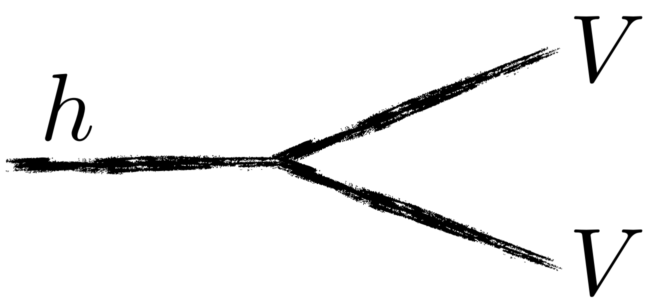
$$\frac{\delta g}{g} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

$$\xi = \frac{v^2}{f^2}$$



CMS: f>550 GeV
ATLAS: f>770 GeV

Constraints from Higgs measurements



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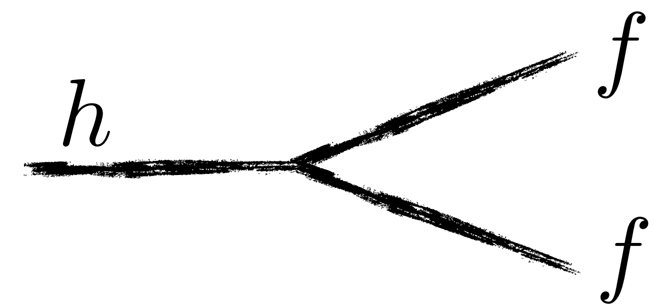

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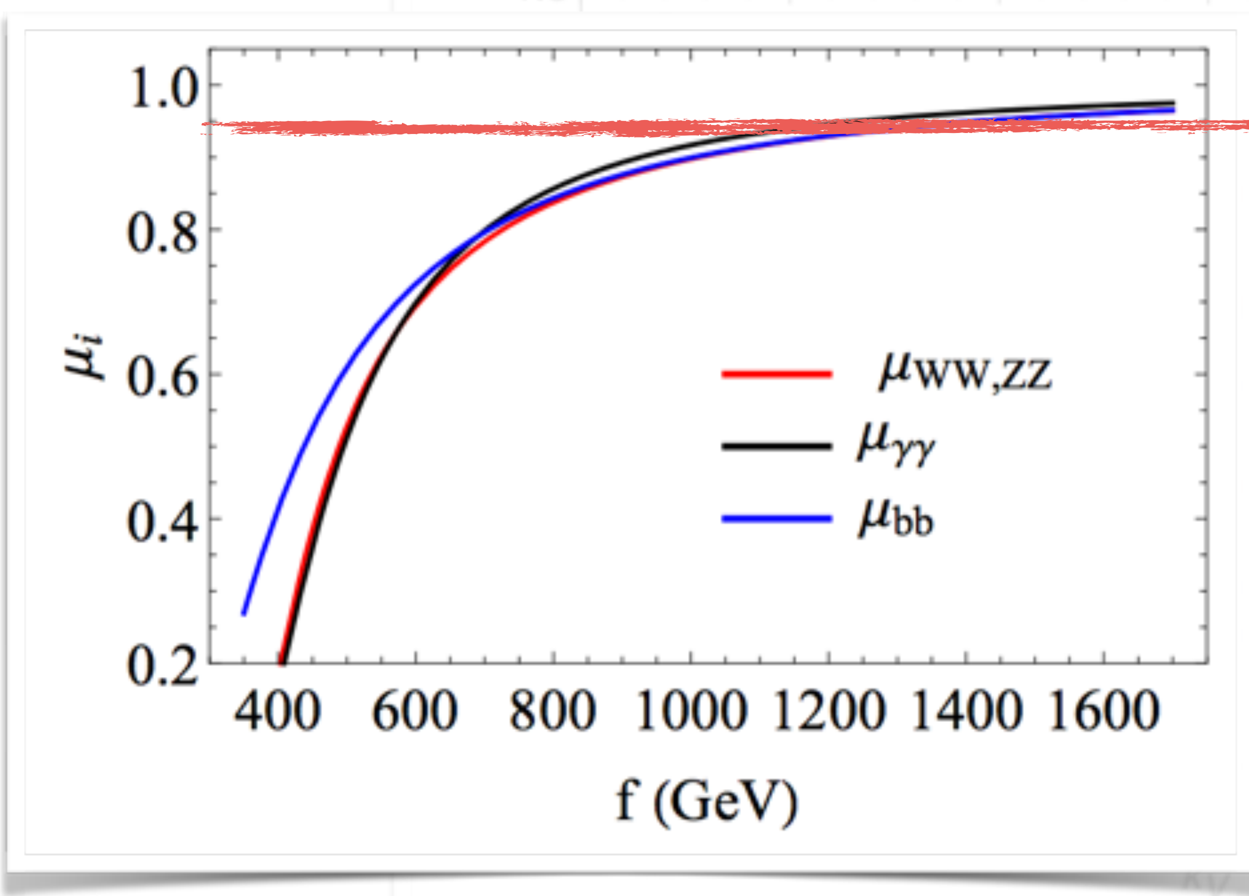


5% Expected precision on Higgs couplings

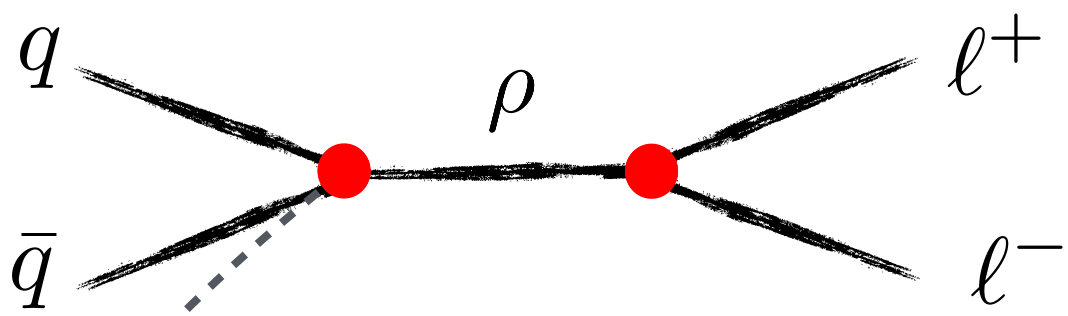
Precision measurements of Higgs coupling have a floor at f~1.2 TeV

Higgs precision not the most effective way to test CHMs

The Search for Vector Resonances

Drell-Yan production is the prince channel for heavy resonances searches

- Precise theoretical predictions for the SM background
- Good resolution for high mass dilepton pairs



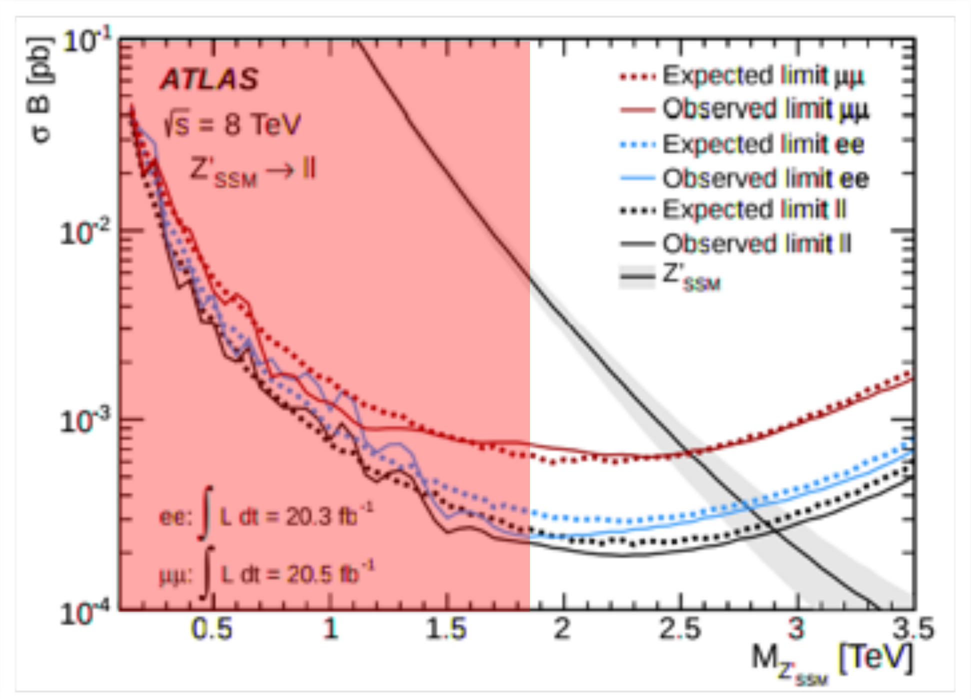
$$m_\rho \sim f g_\rho$$

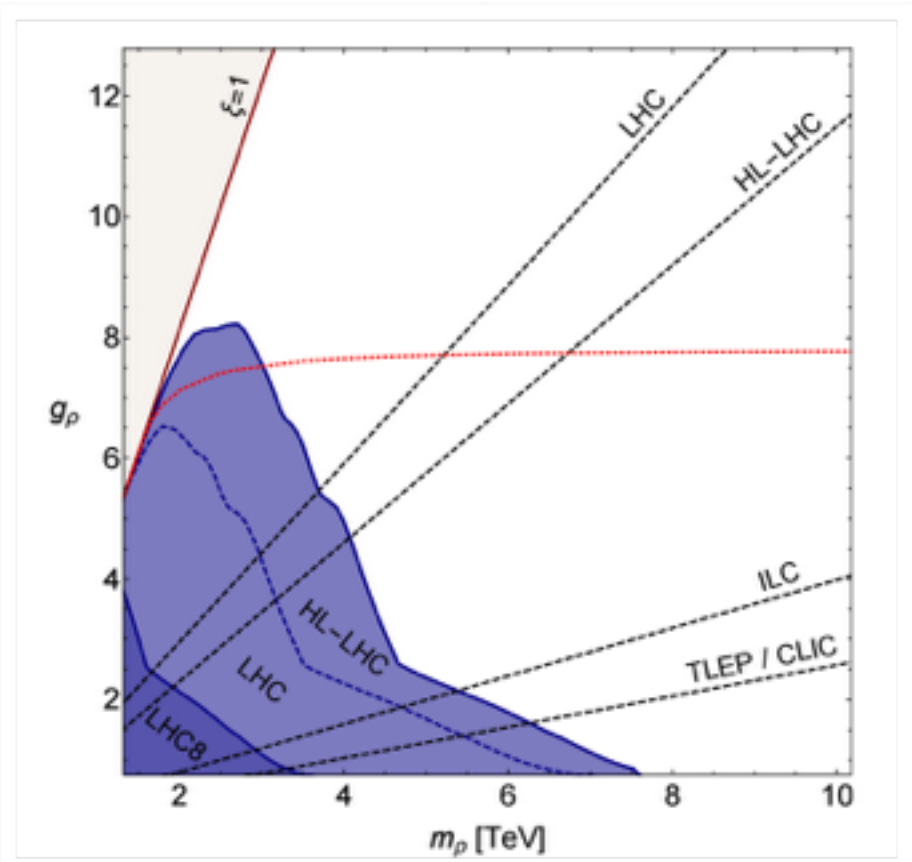
$$\frac{m_\rho^2}{2 g_\rho^2}(g_\rho \rho_\mu - e_\mu)^2$$

$$g \sim g_W s_\theta \sim \frac{g_W^2}{g_\rho}$$

Coupling to SM current from $Z - \rho$ mixing → Bounds from EWPT S-parameter ~2 TeV

The Search for Vector Resonances





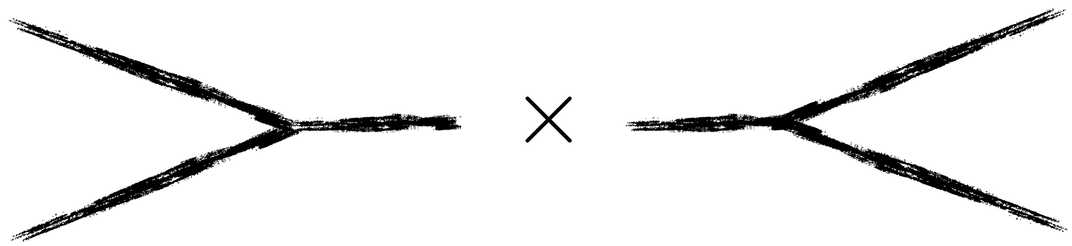
Limits on sequential SM needs to be rescaled by the CHM coupling

8 TeV reach around 1.7 TeV
similar reach for early 13 TeV data

Up to ~5 TeV resonance can be tested for moderate value of g_ρ

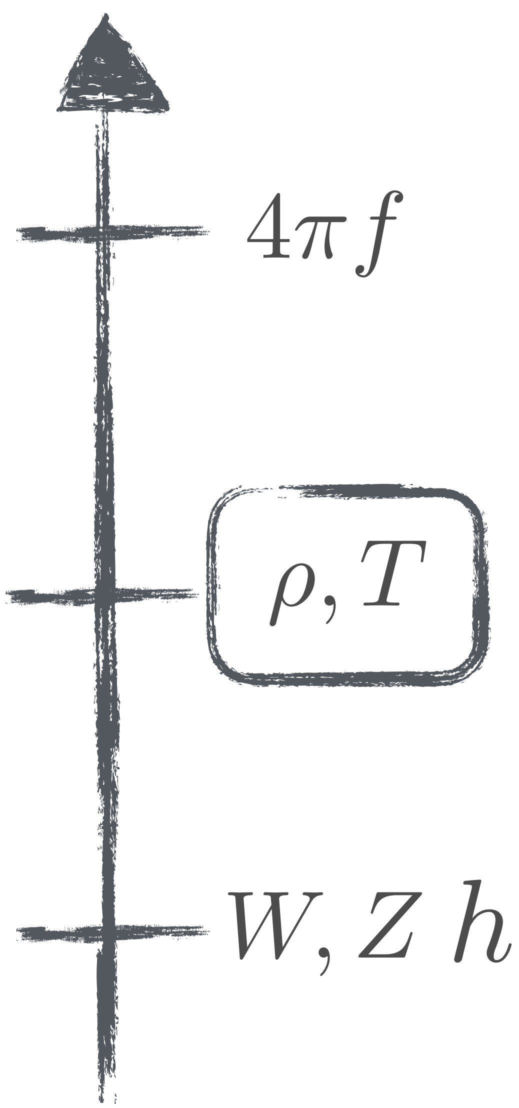
[Thamm et al. ’15]

Search strategies strongly relies on a high leptonic decay rate



$$\sigma \times \mathrm{BR}$$

There is however a small hierarchy in the resonance spectrum

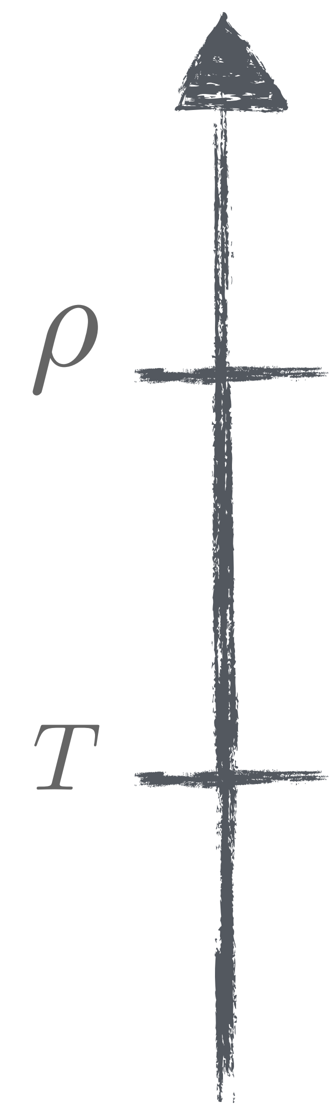


EWPT requires ~ 2 TeV ρ

[Contino and Salvarezza '15]

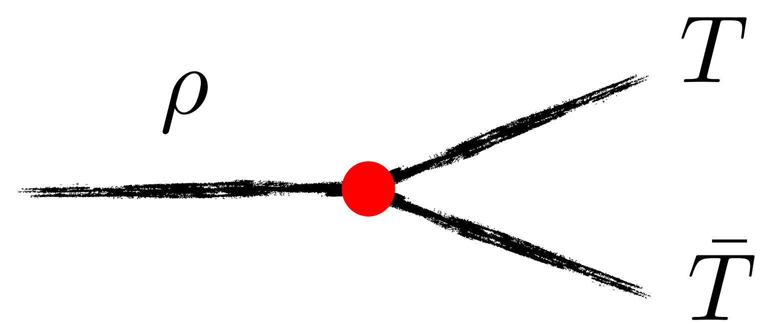
A light Higgs requires
~1 TeV top partners

[Matsedonskyi et al '12]



Naturalness, Higgs and LEP data point to a specific spectrum configuration

$$\mathcal{L} \sim \bar{\Psi}\gamma^{\mu}(g_\rho \rho_\mu - e_\mu)\Psi$$



$\sim g_\rho \gg g_W s_\theta$

- If kinematically allowed the decay in a pair of top partners will dominate

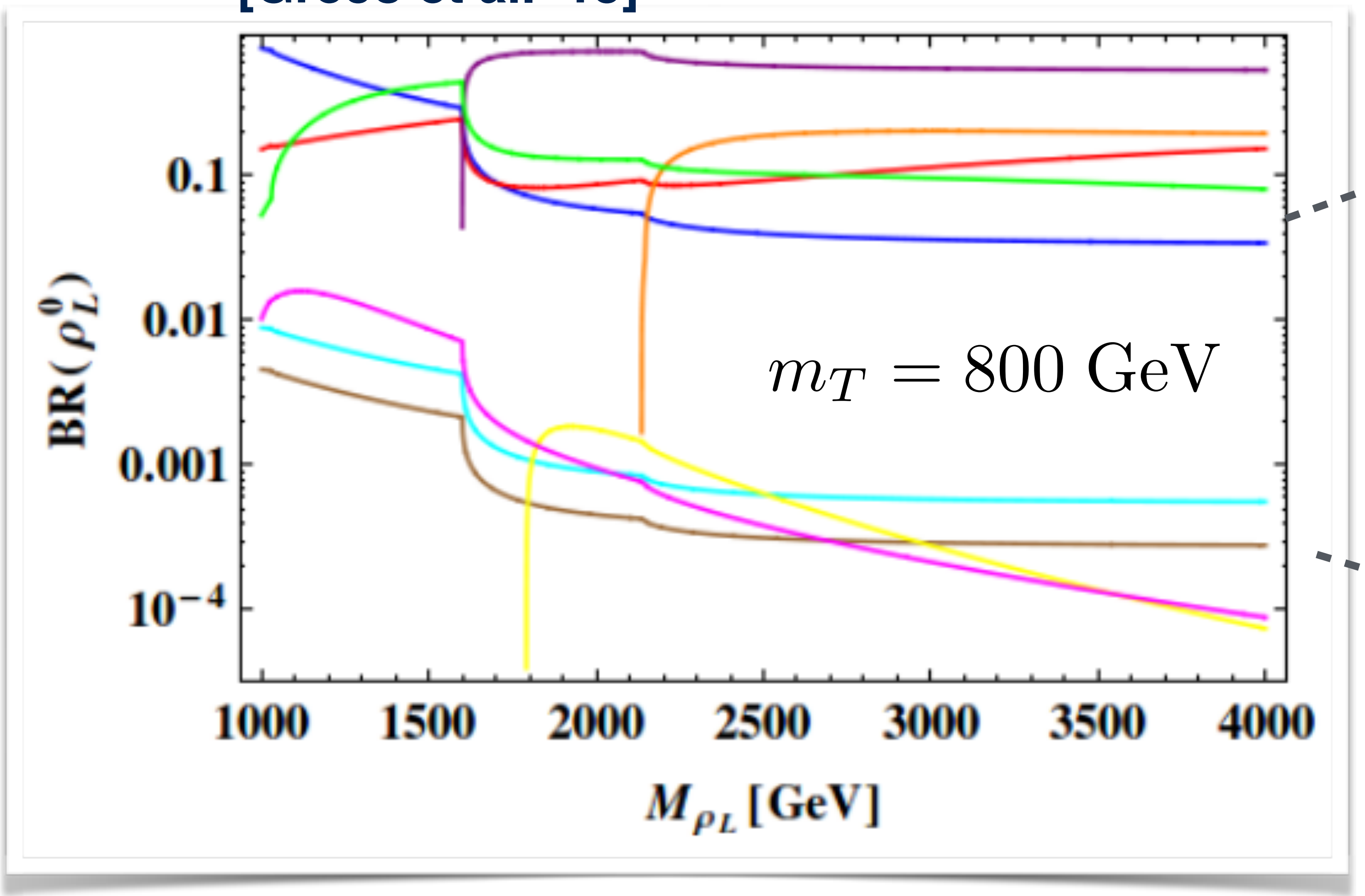
$$\sigma(pp \to \rho \to \ell^+\ell^-) \ll \sigma(pp \to \rho \to T\bar{T})$$

- Stronger limits will be set by the S-parameter **[DB et al. ’12, Greco et al. ’15]**

- This configuration allows for a different production mode for top partners

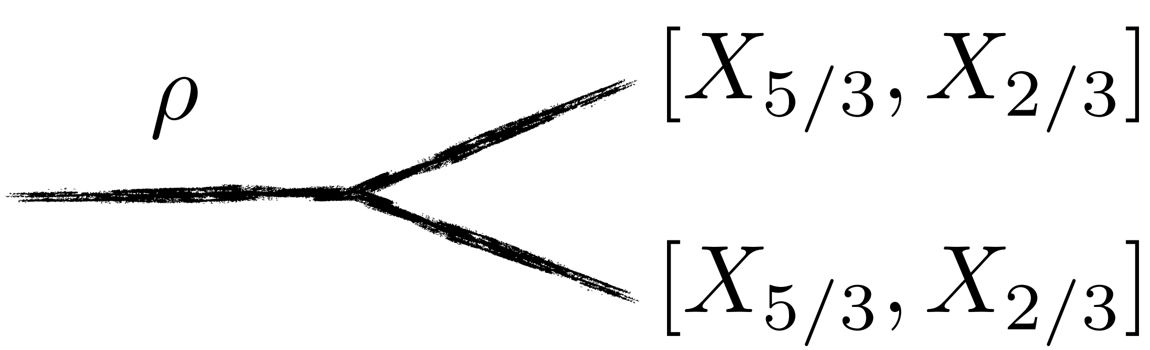
Can we exploit this decay pattern to search composite vector resonances?

[Greco et al. '15]



Dominant decay into top partners

Suppressed SM decay



In MCHM the typical decay pattern is into the exotic quark doublet

The exotic $X_{5/3}$ quark has a particular decay pattern: only charged current

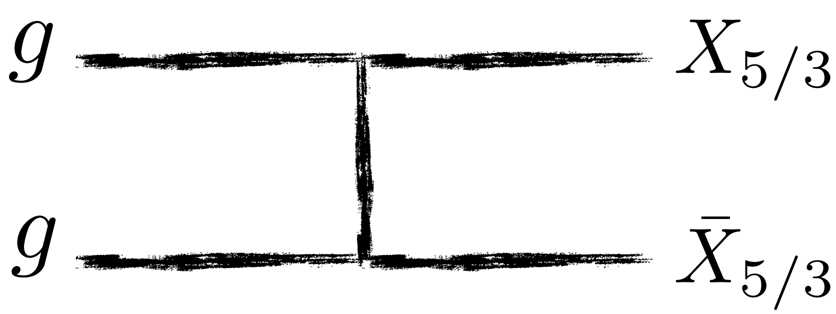
Leptonic decaying W give rise to a same-sign dilepton signature

- Pay the price of a double leptonic W : BR~0.04
- Process with a small Standard Model background

Many LHC searches look for a same-sign dilepton final state

- SUSY searches, with high $E_T^{\rm miss}$
- Exotic searches, with low $E_T^{\rm miss}$ requirement

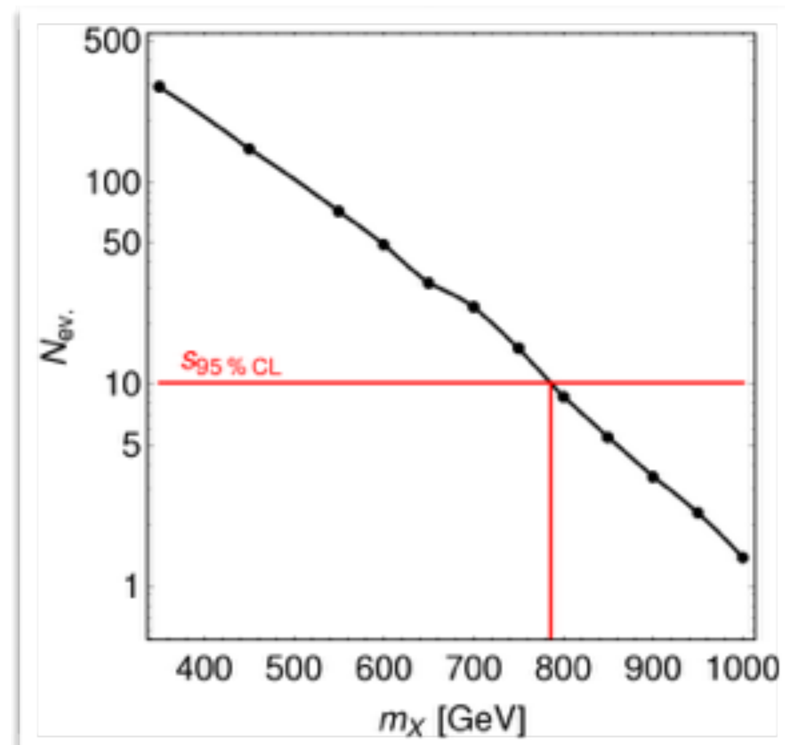
We recast a CMS search for pair produced top partners in SS2L final state
[Recast publicly available at the MadAnalysis5 web-page]



$4W2b$ final state

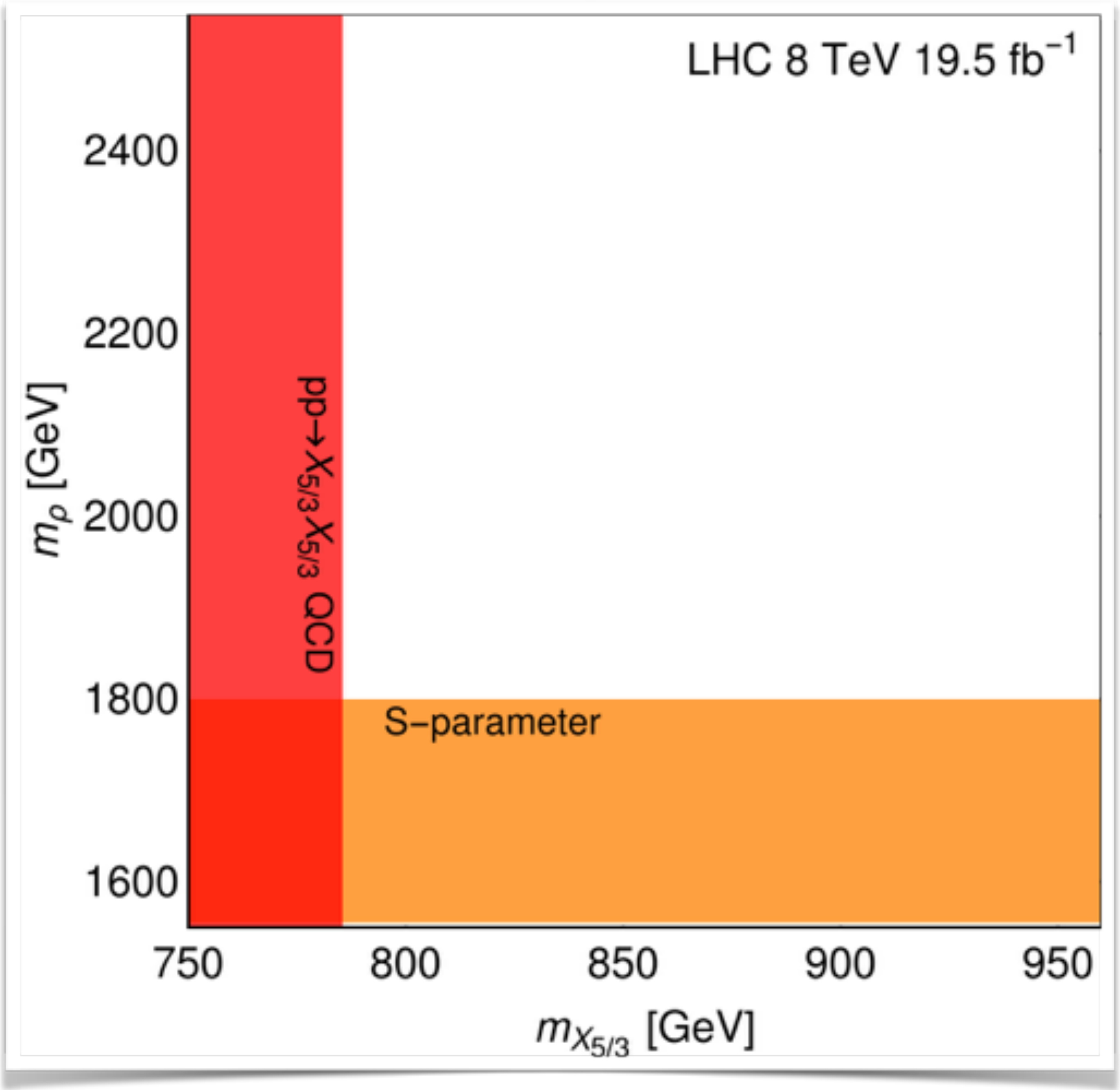
- 2 same-sign lepton
- high p_T leptons
- 5 jets
- high p_T jets

Signal Region	CMS official results	MA5 results
ee	2.1	2.3
$\mu\mu$	2.8	2.1
$e\mu$	4.7	4.2

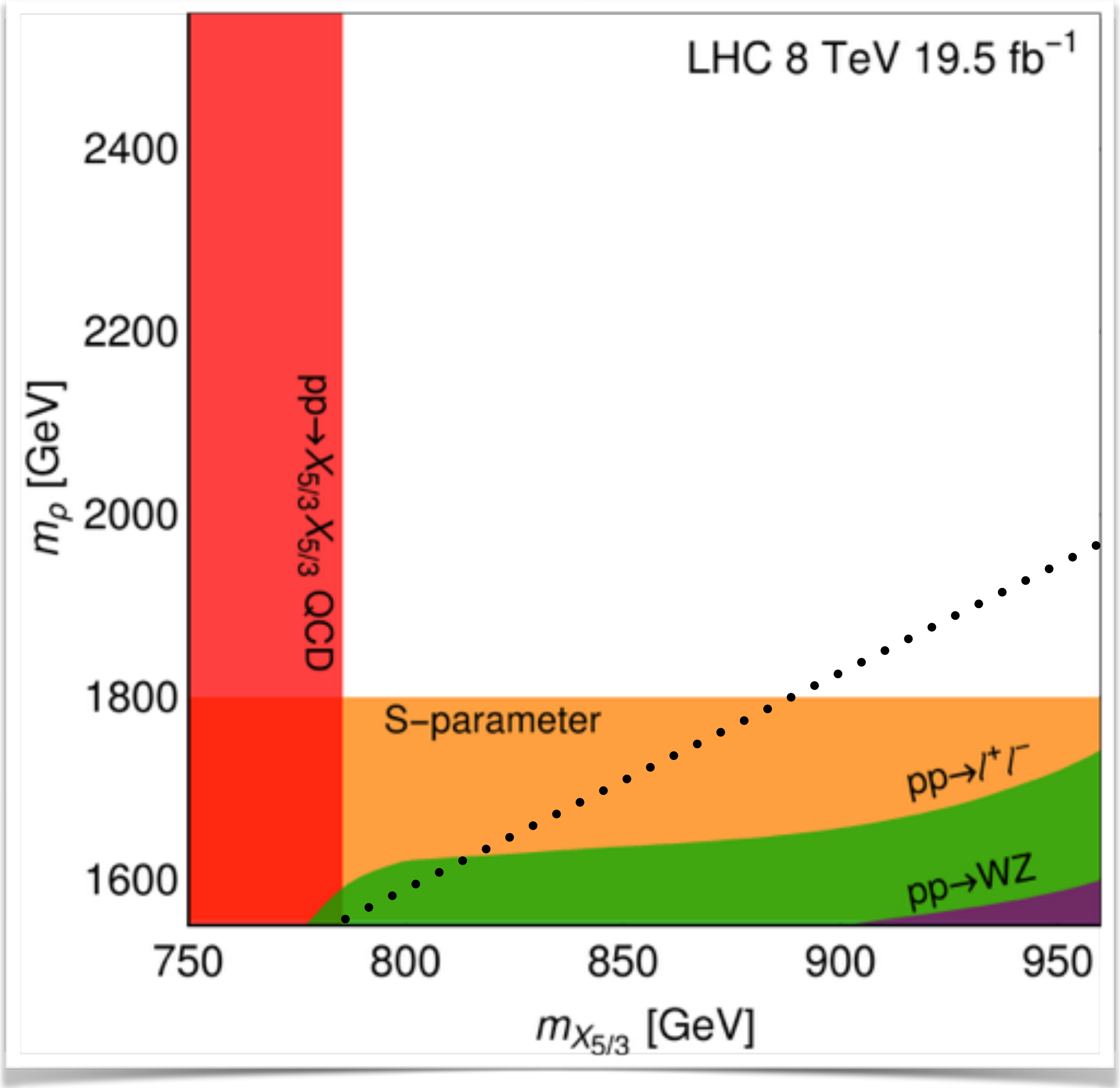


Consistent with ~800 GeV bound from CMS

We can apply this analysis to our Composite Higgs scenario



[DB and Delaunay '15]

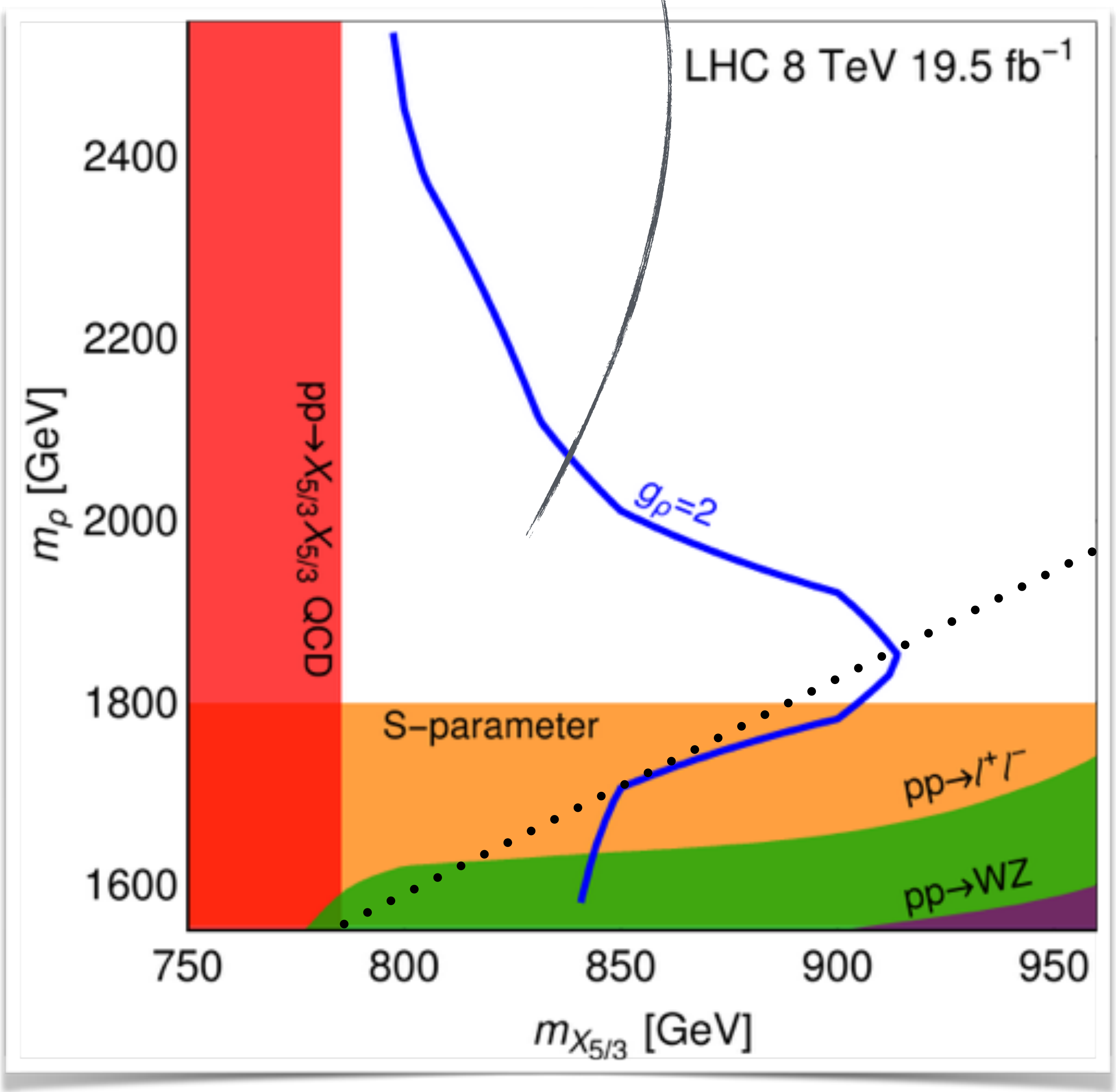


[DB and Delaunay '15]

$m_\rho = 2m_T$

Direct searches not effective if $m_\rho > 2m_T$

Exotic decay strong probe for this unconstrained regime



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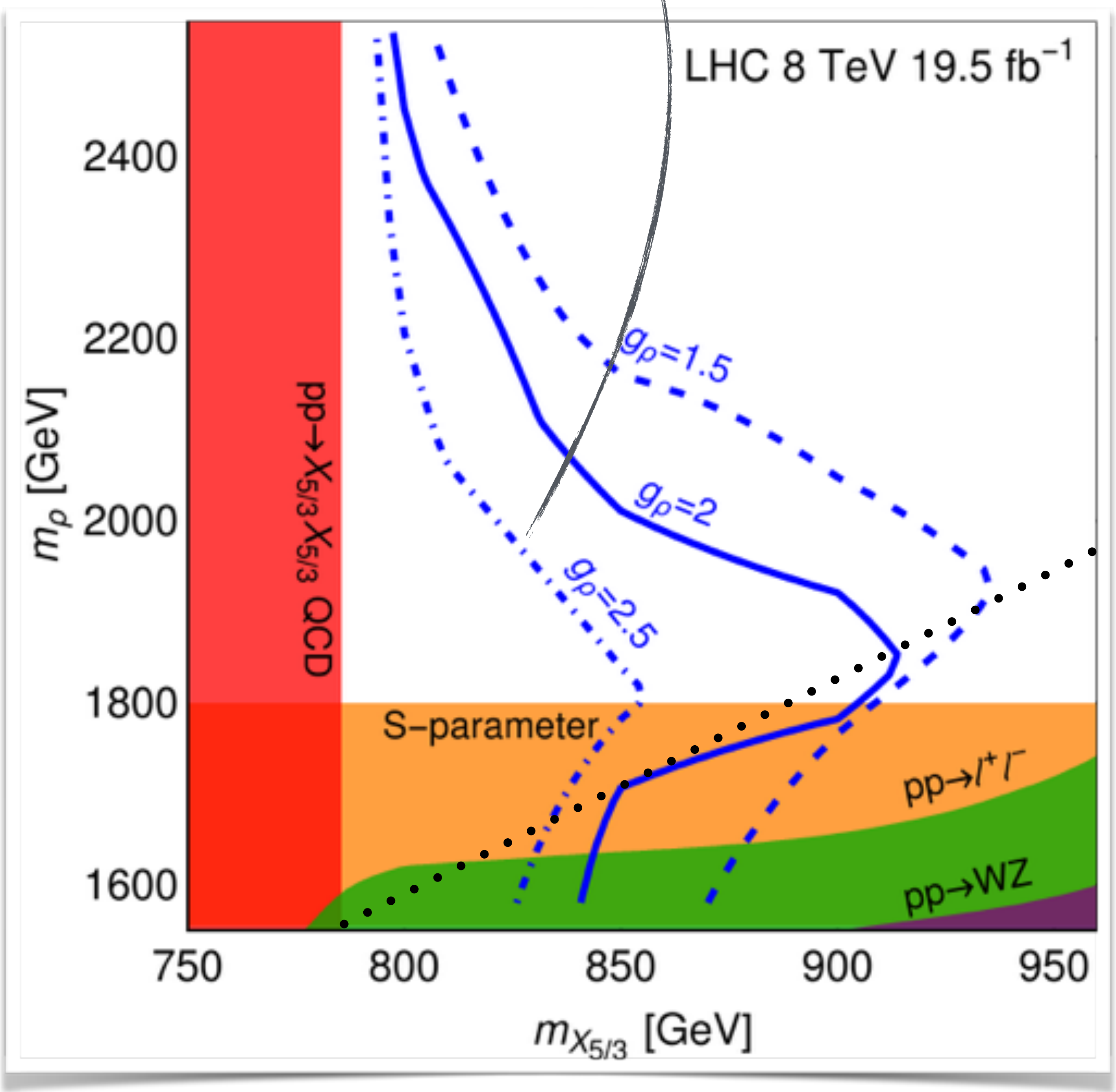

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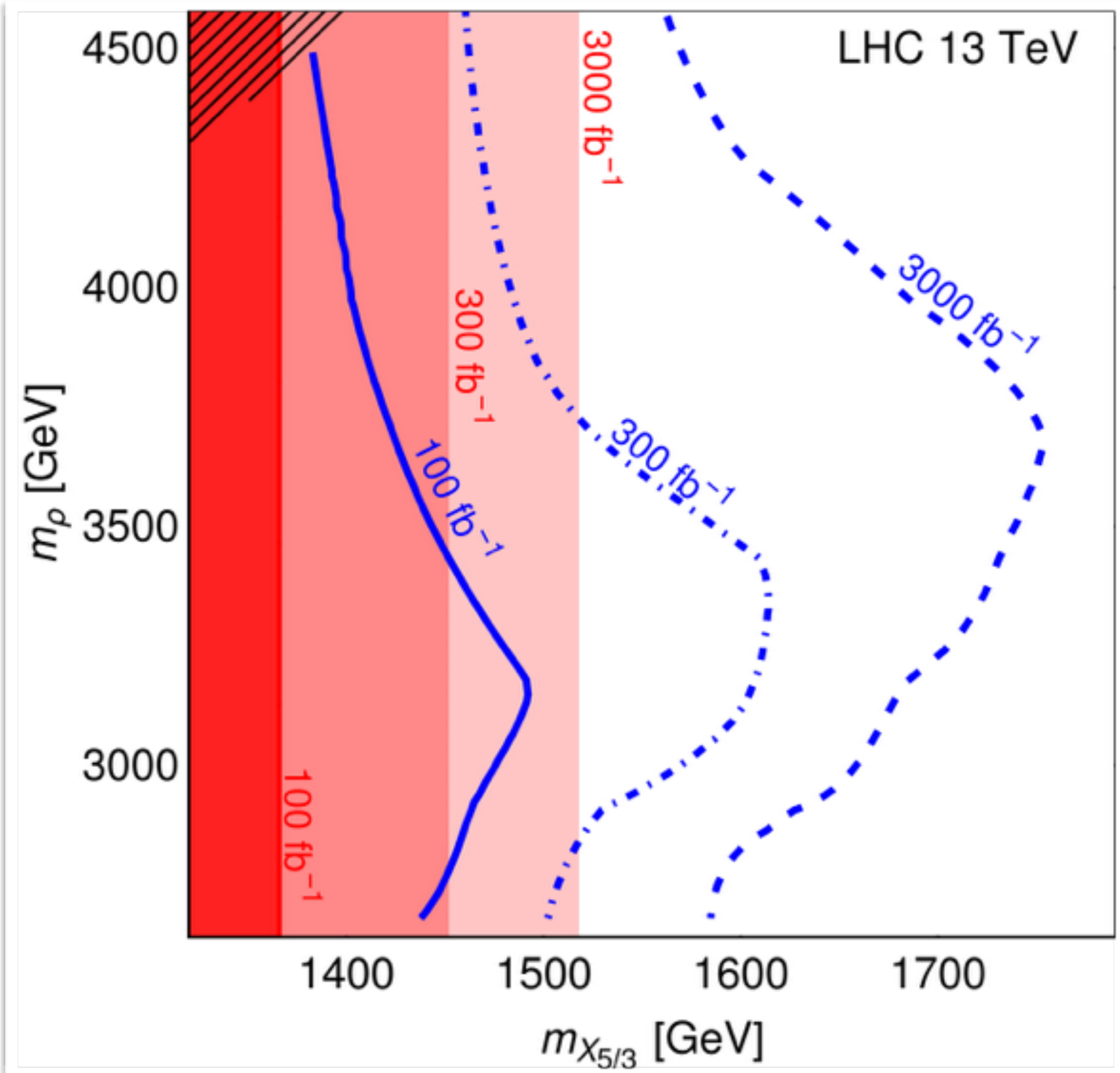

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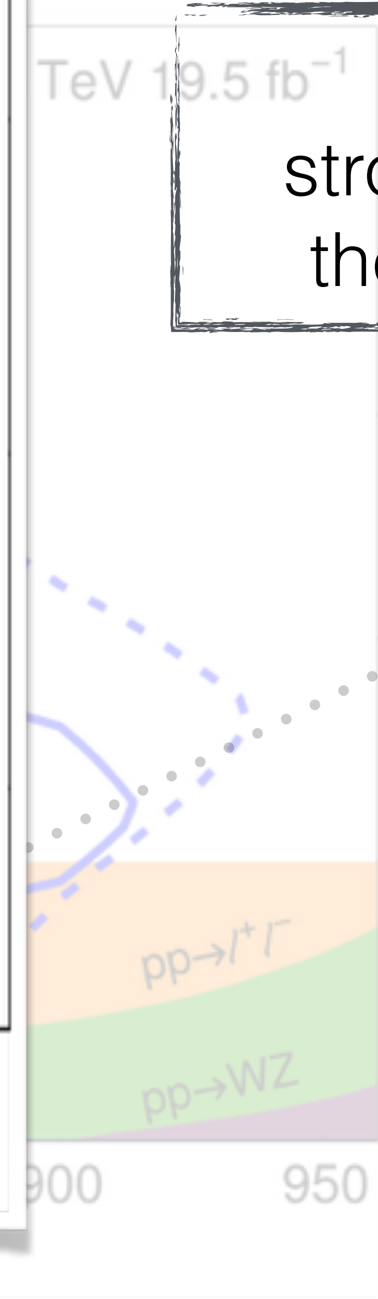

LHC-13 will strongly increase the mass reach

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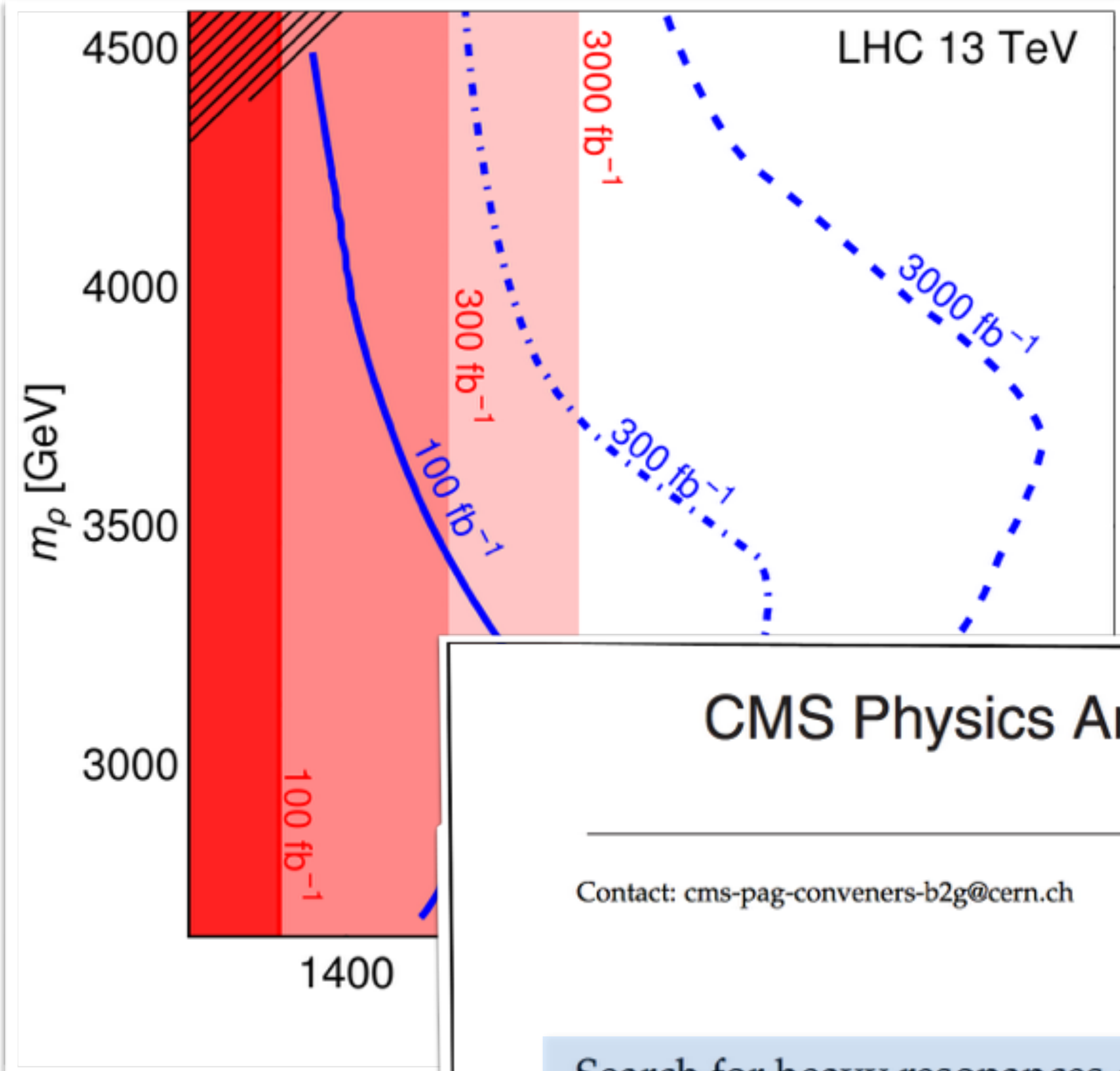

[DB and Delaunay '15]

nconstrained regime

TeV 19.5 fb^{-1}

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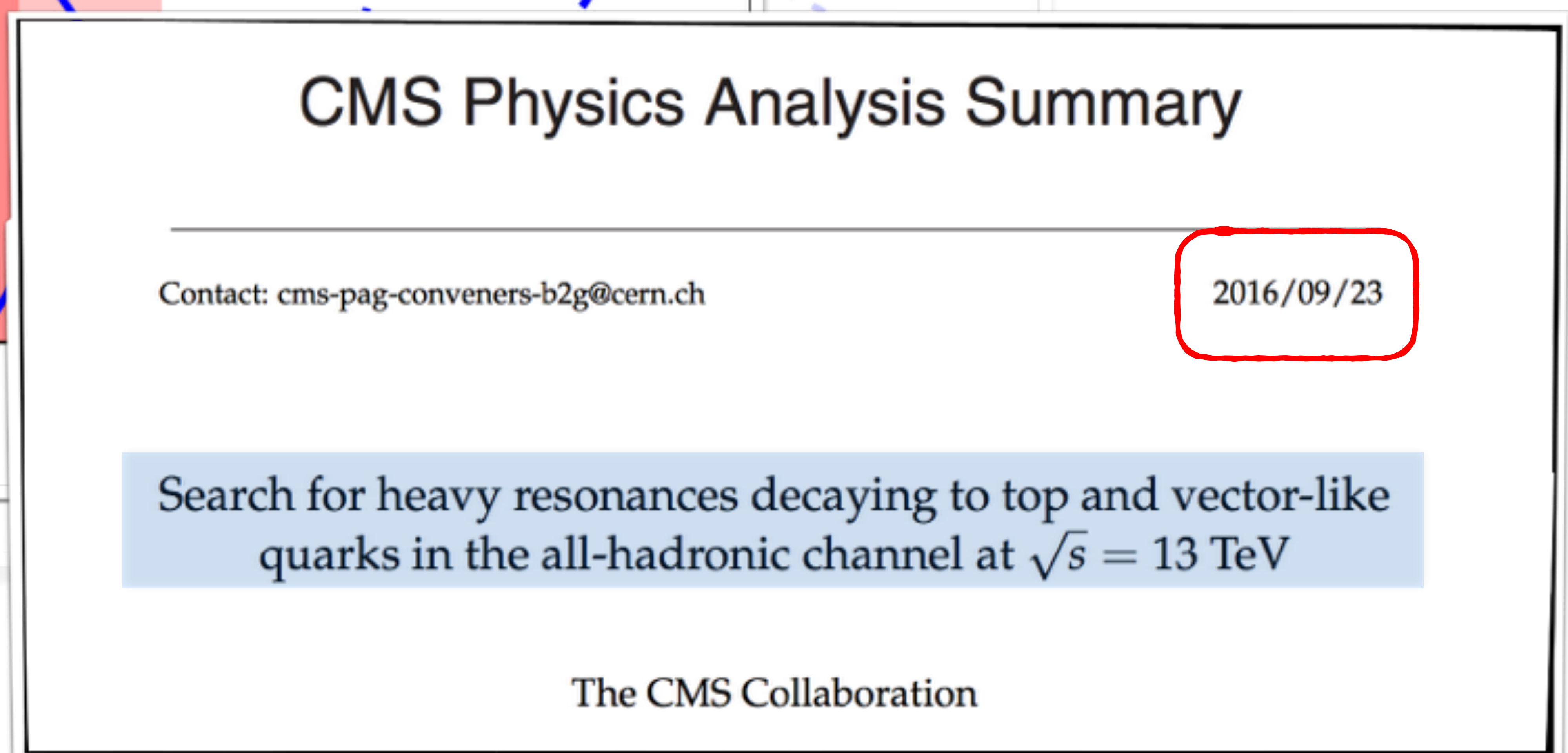


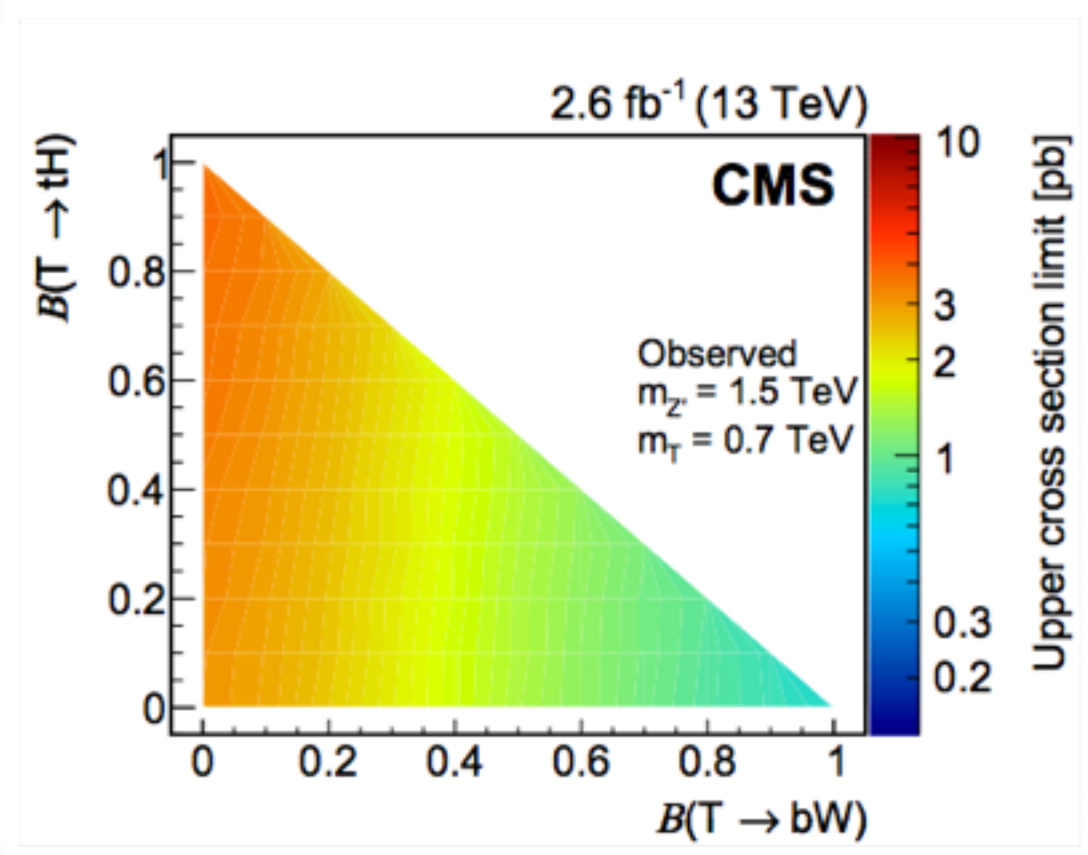
CMS Physics Analysis Summary

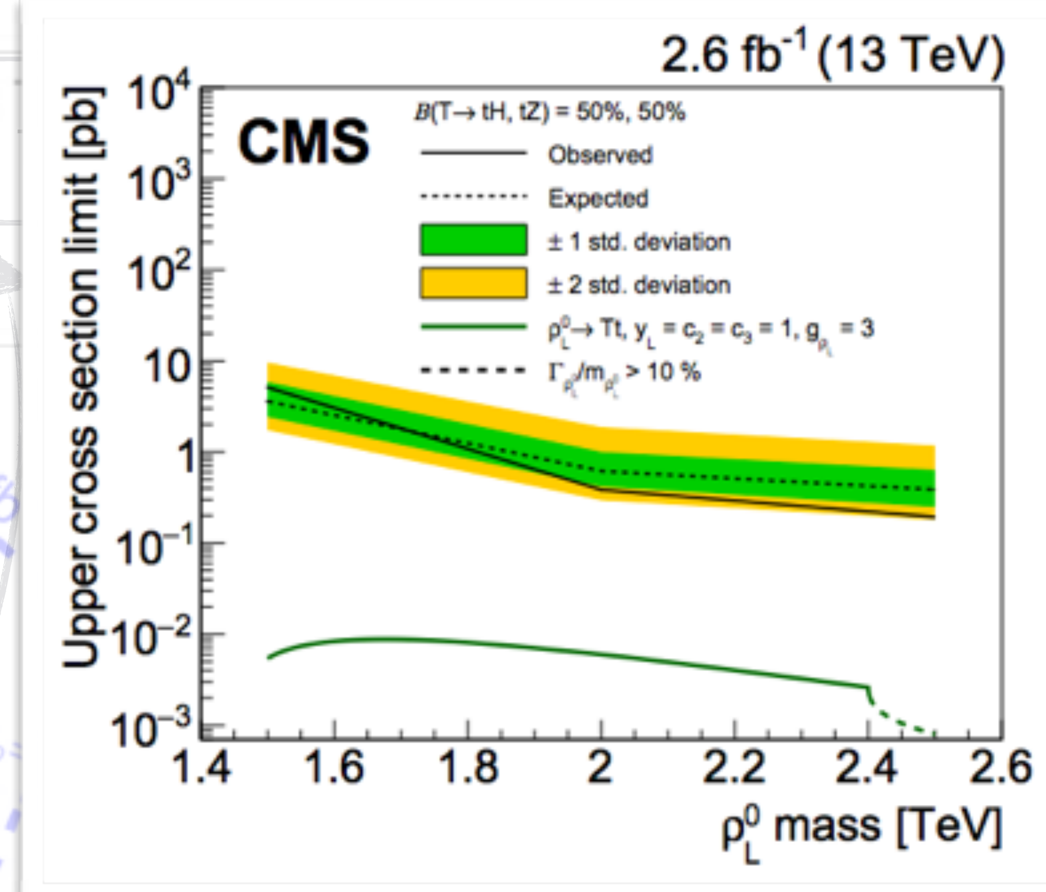
Contact: cms-pag-conveners-b2g@cern.ch

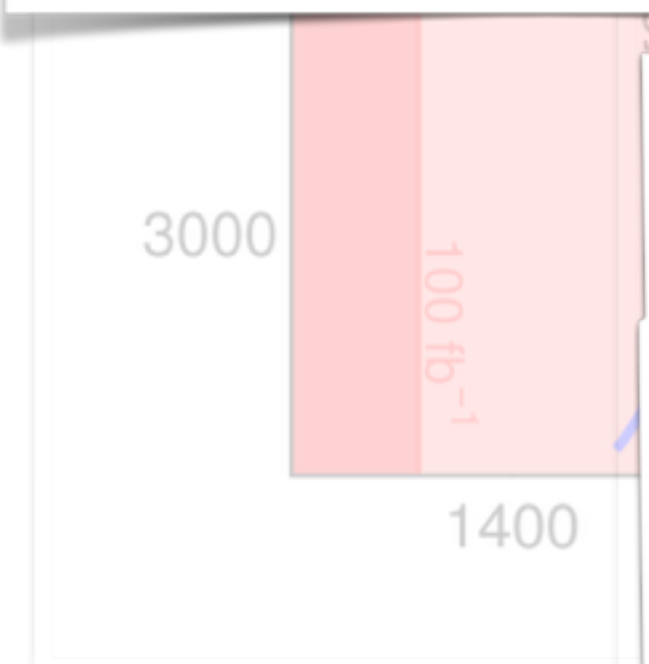
2016/09/23

Search for heavy resonances decaying to top and vector-like quarks in the all-hadronic channel at $\sqrt{s} = 13$ TeV

The CMS Collaboration







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Contact: cms-pag-conveners-b2g@cern.ch

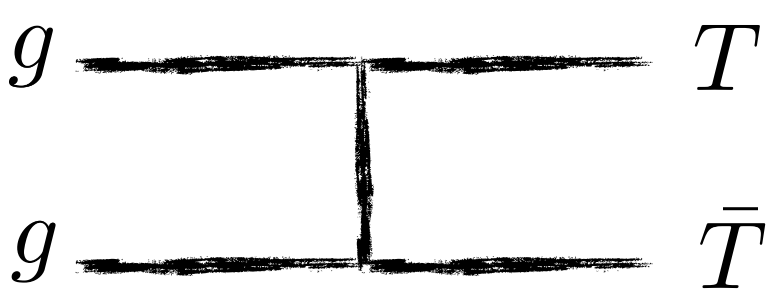
2016/09/23

Search for heavy resonances decaying to top and vector-like quarks in the all-hadronic channel at $\sqrt{s} = 13$ TeV

The CMS Collaboration

The Search for Top Partners

QCD pair production main channel for top partners production



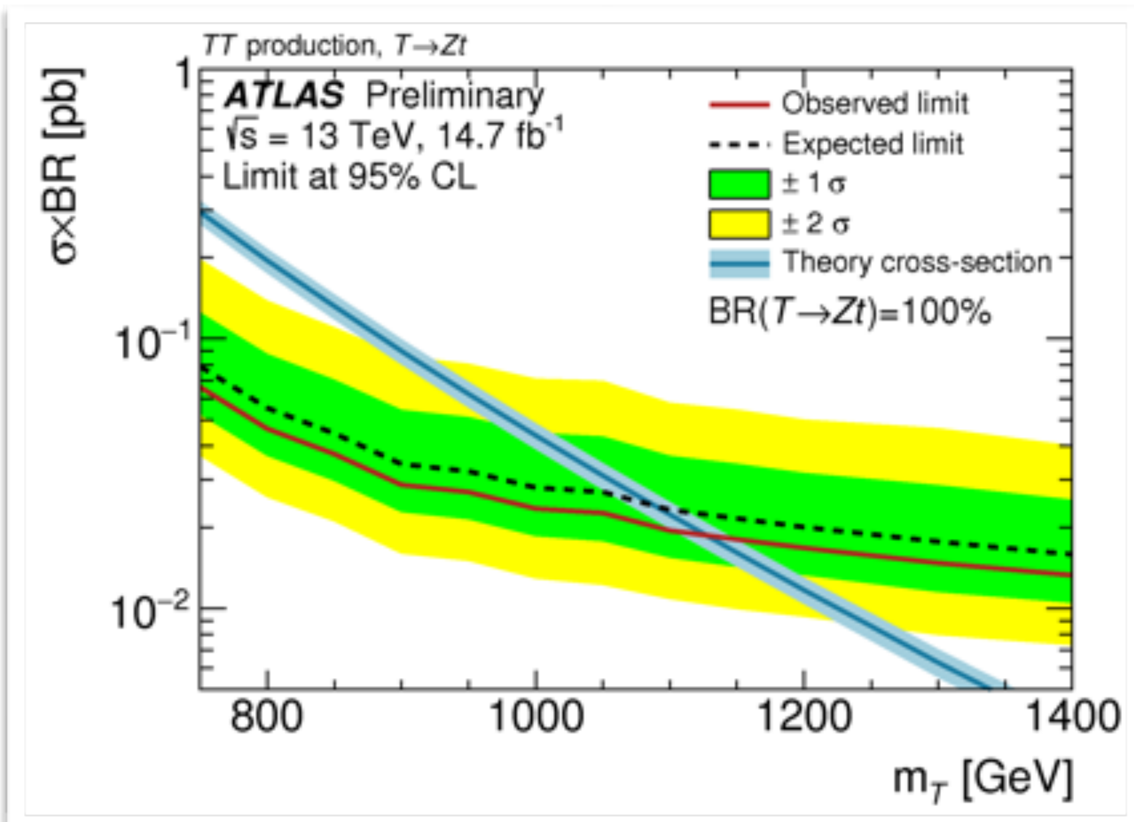
Single production can become important at high masses

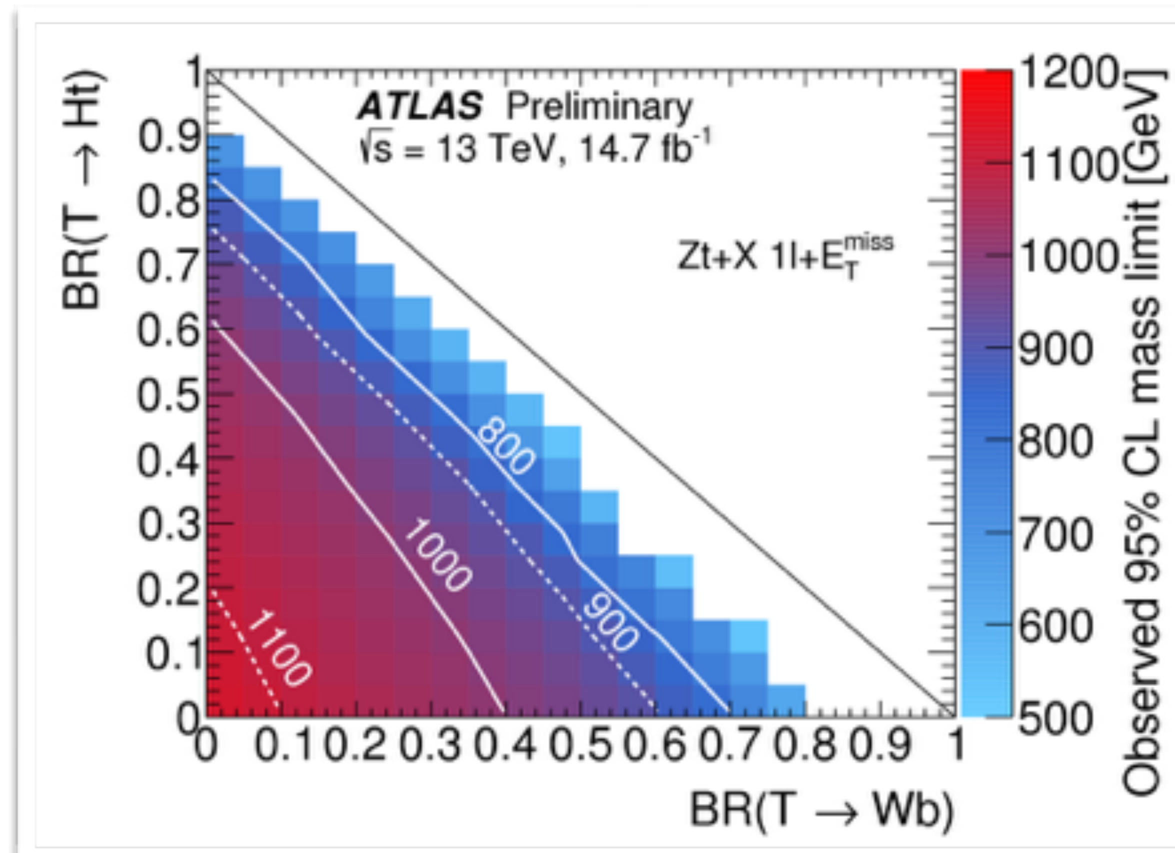
In CHMs heavy quarks generally decay into 3rd generation SM quarks

All channels are now covered by LHC searches

The Search for Top Partners

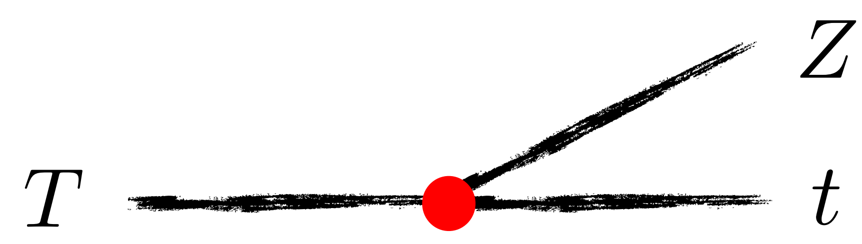
Strongest limits with ~13/fb around 1.1 TeV for top partners masses





Limits on charged 5/3 top partners ~1.1 TeV with 3.2/fb

The limits depends on the chirality of the coupling between top-partners and SM states



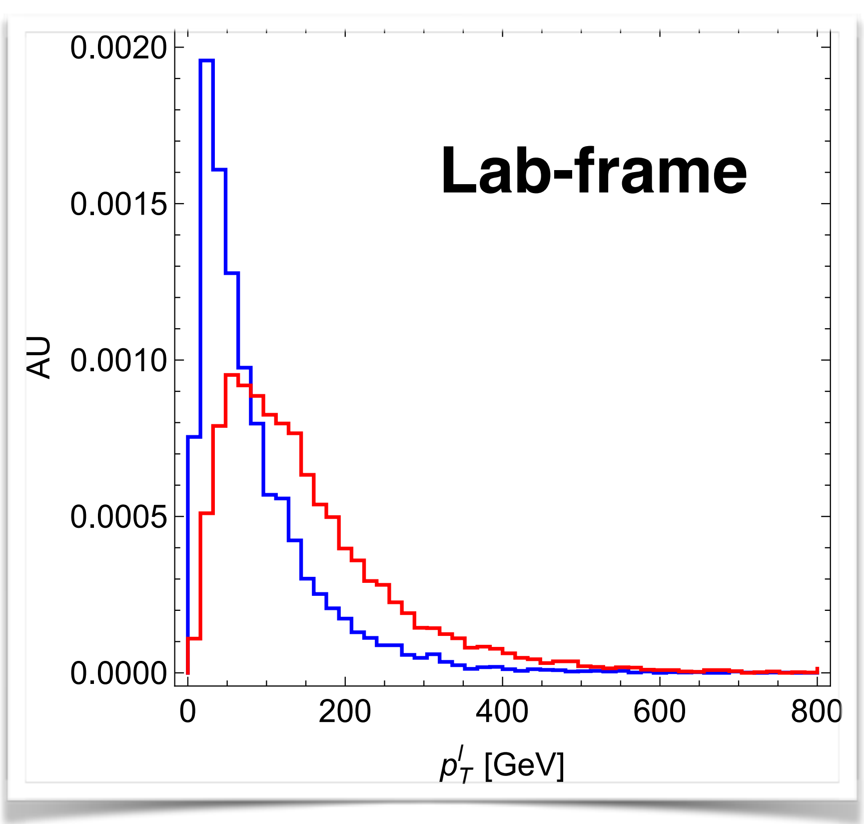
$g_L \gg g_R$

or

$g_R \gg g_L$

[Cacciapaglia et al. ’12]

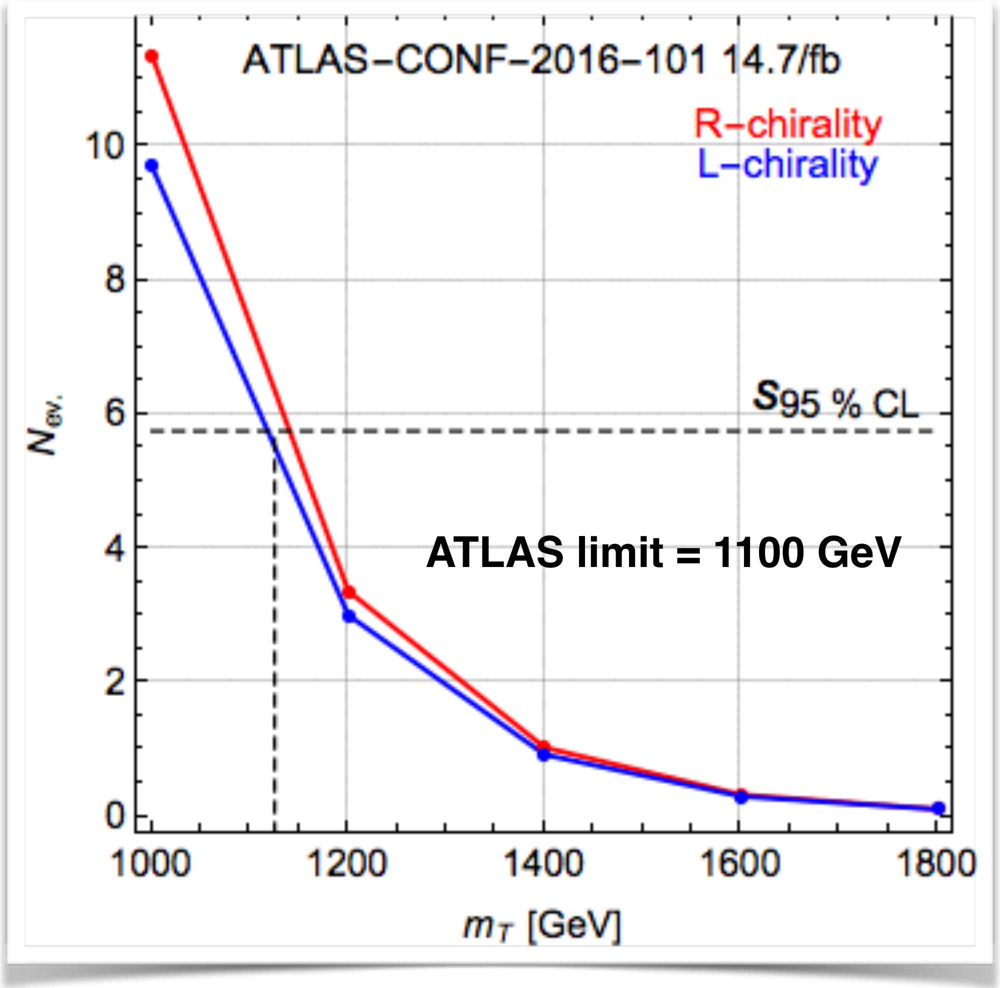
Leptons momentum forward/backward (wrt to top momentum) for positive/negative pol. top quarks



Right coupling

Left coupling

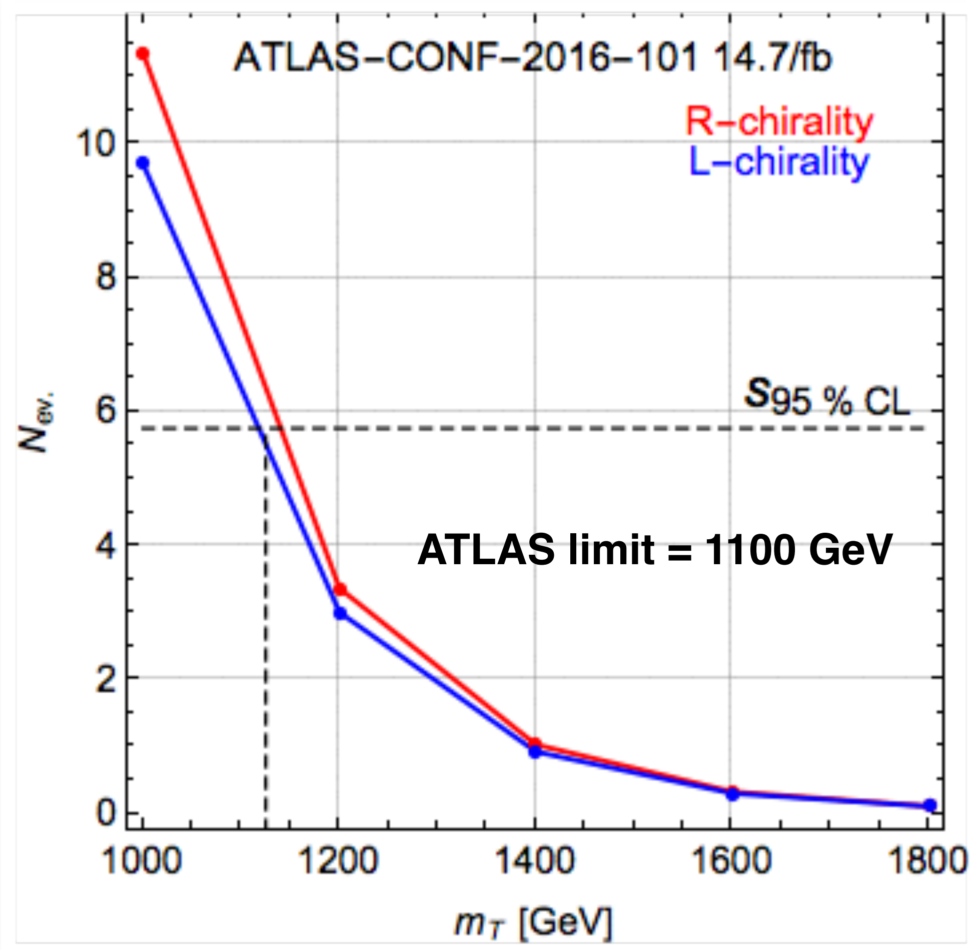
Easier for lepton in the right case to pass selection cuts



[Recast soon available at the MadAnalysis5 web-page]

Mild difference in mass reach

However should a top partner be discovered we can use the shape difference to test L against R hypothesis



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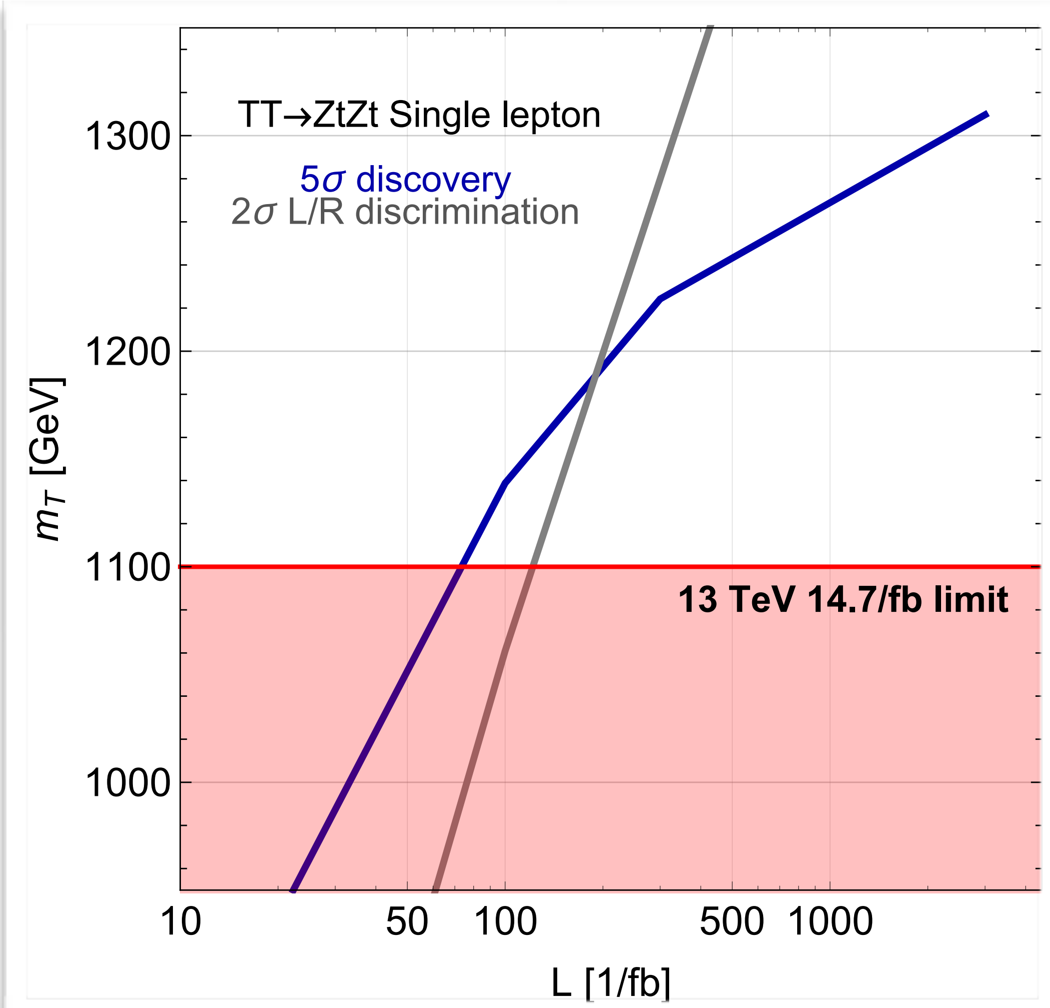
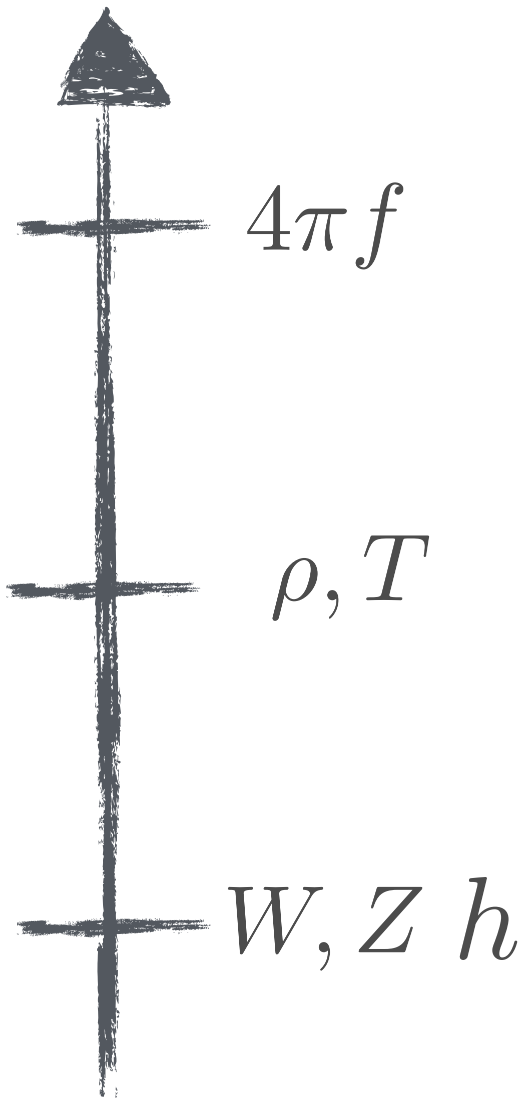
Possible to disentangle L and R coupling structure

This can give a discrimination power with respect to different CHM models which predict different chirality



[DB and Panizzi, in progress]

Also top partners searches are strongly affected by the minimal experimental assumptions of a single BSM resonance in the spectrum



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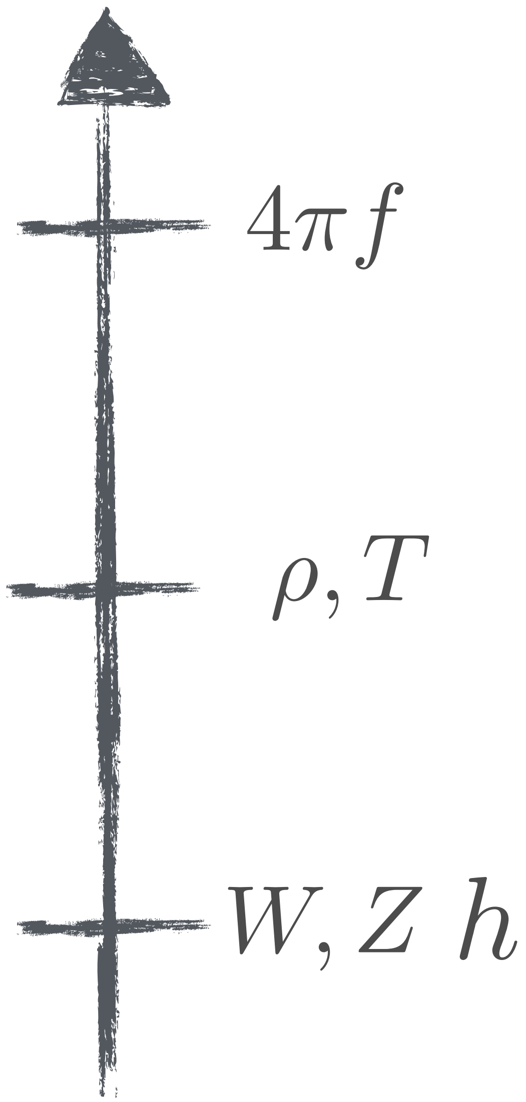

A non minimal symmetry breaking pattern in CHMs can give rise to additional pNGB

$SO(6)/SO(5)$ provides an additional scalar singlet **[Redi, Tesi '12]**

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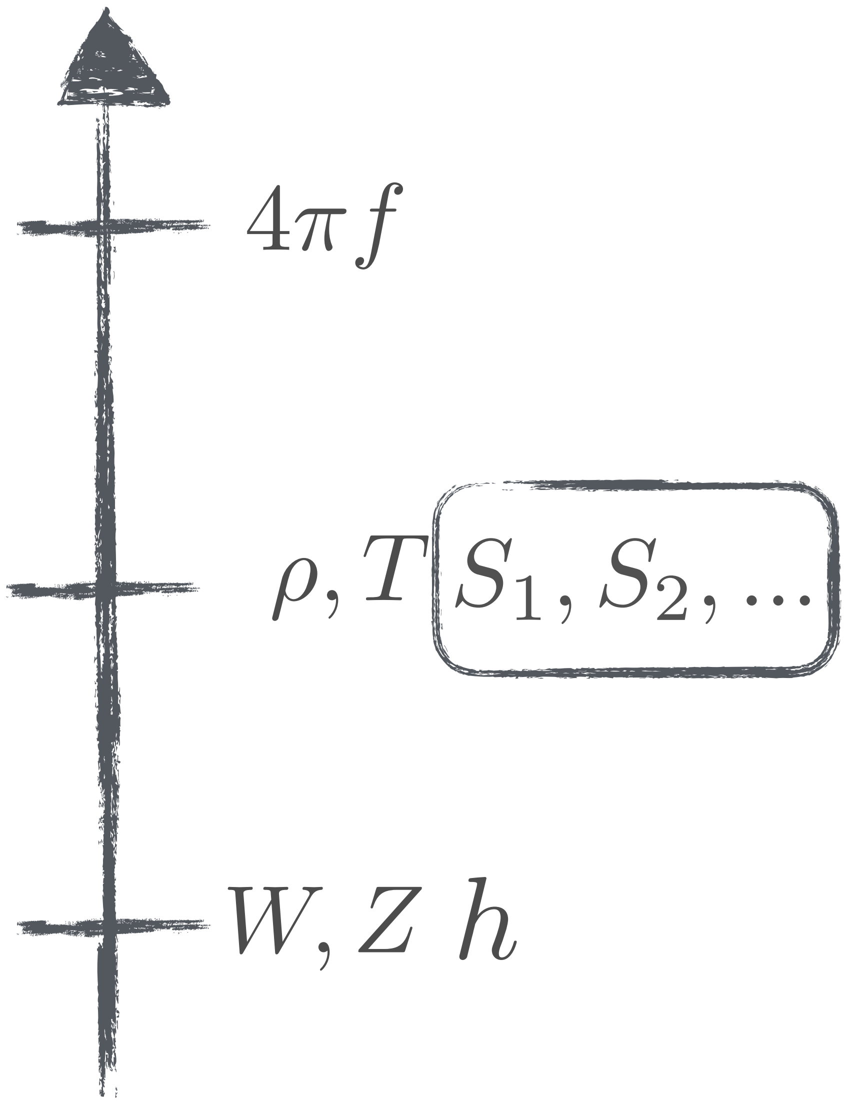

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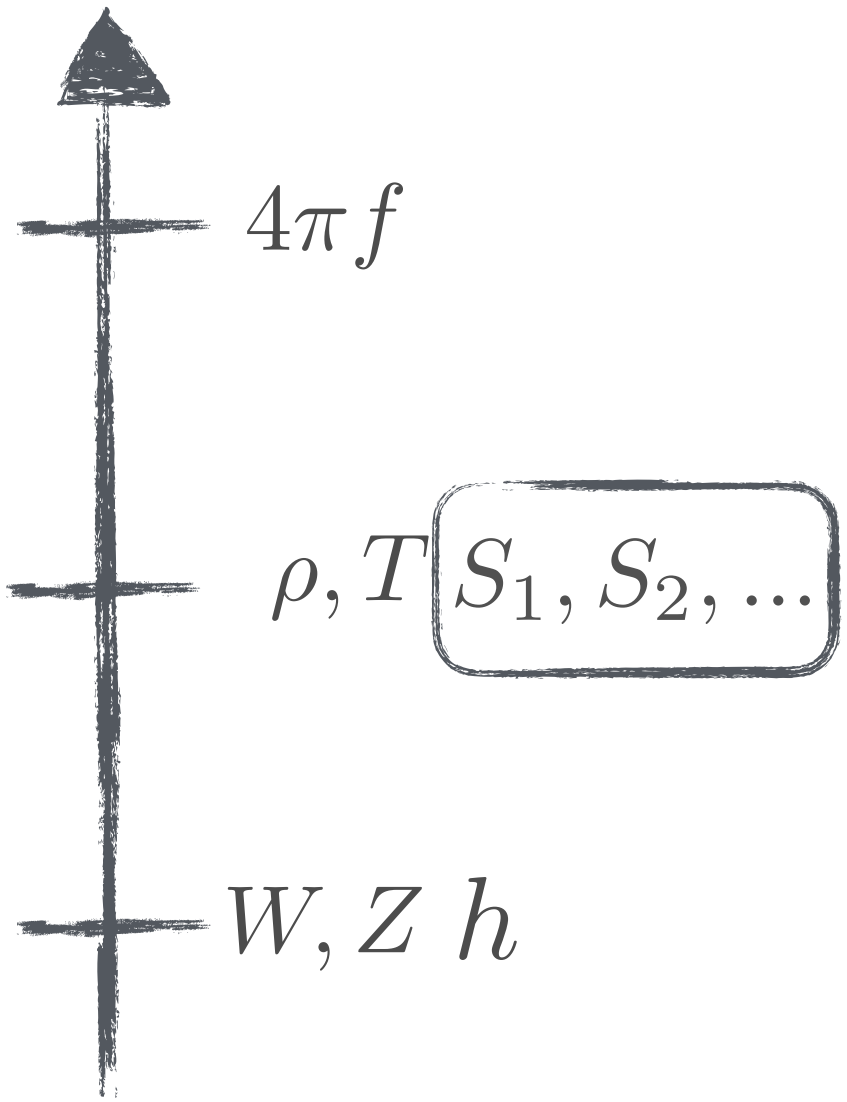

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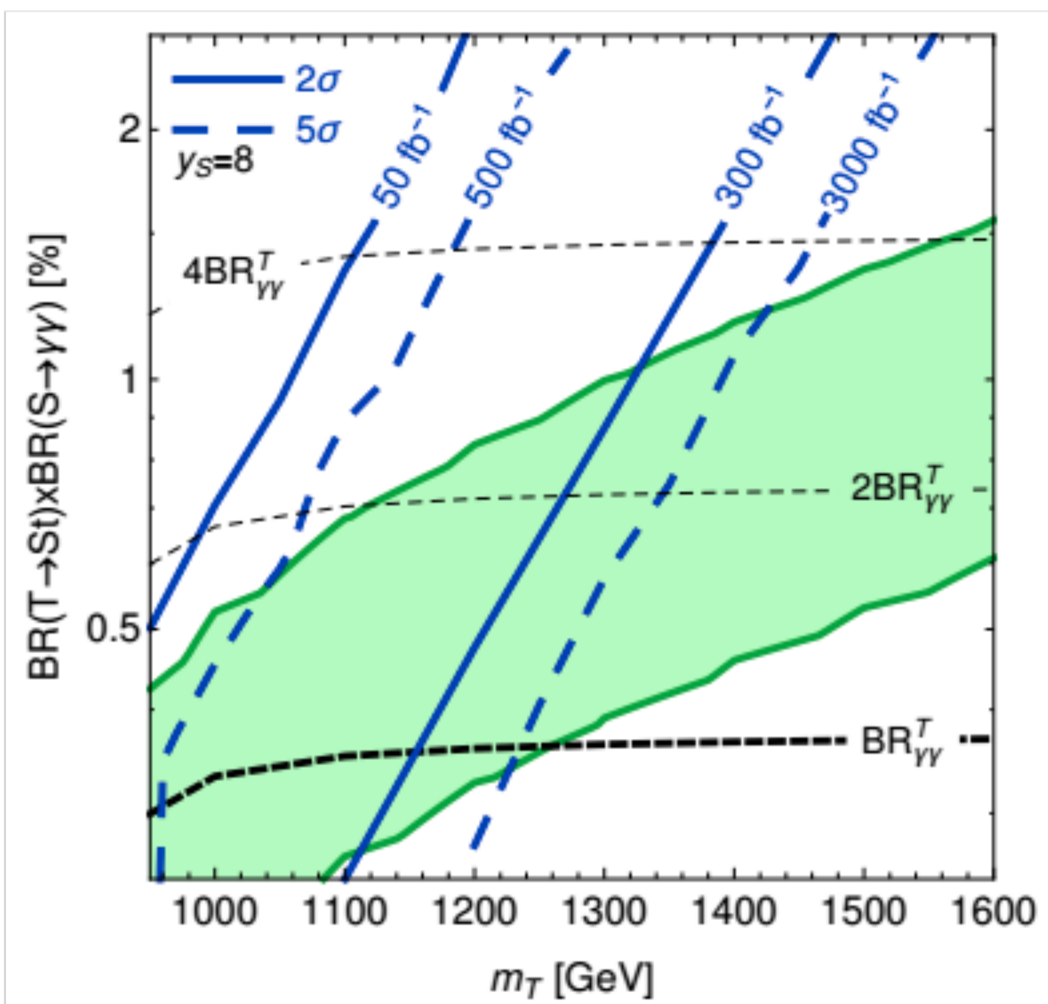
This decay channel could be a striking signature of compositeness

…back the glorious day of the 750 GeV resonance…

$$\frac{\mathrm{BR}(T \to St)}{\mathrm{BR}(T \to Zt)} \sim \frac{y_S^2}{g_W^2}$$

$$\mathcal{L} \supset -y_S S \bar{T}_L T_R - m \bar{t} T_L$$



[DB et al. '15]

Exotic decay of a top-partner could have been a strong probe of a composite nature of the digamma excess

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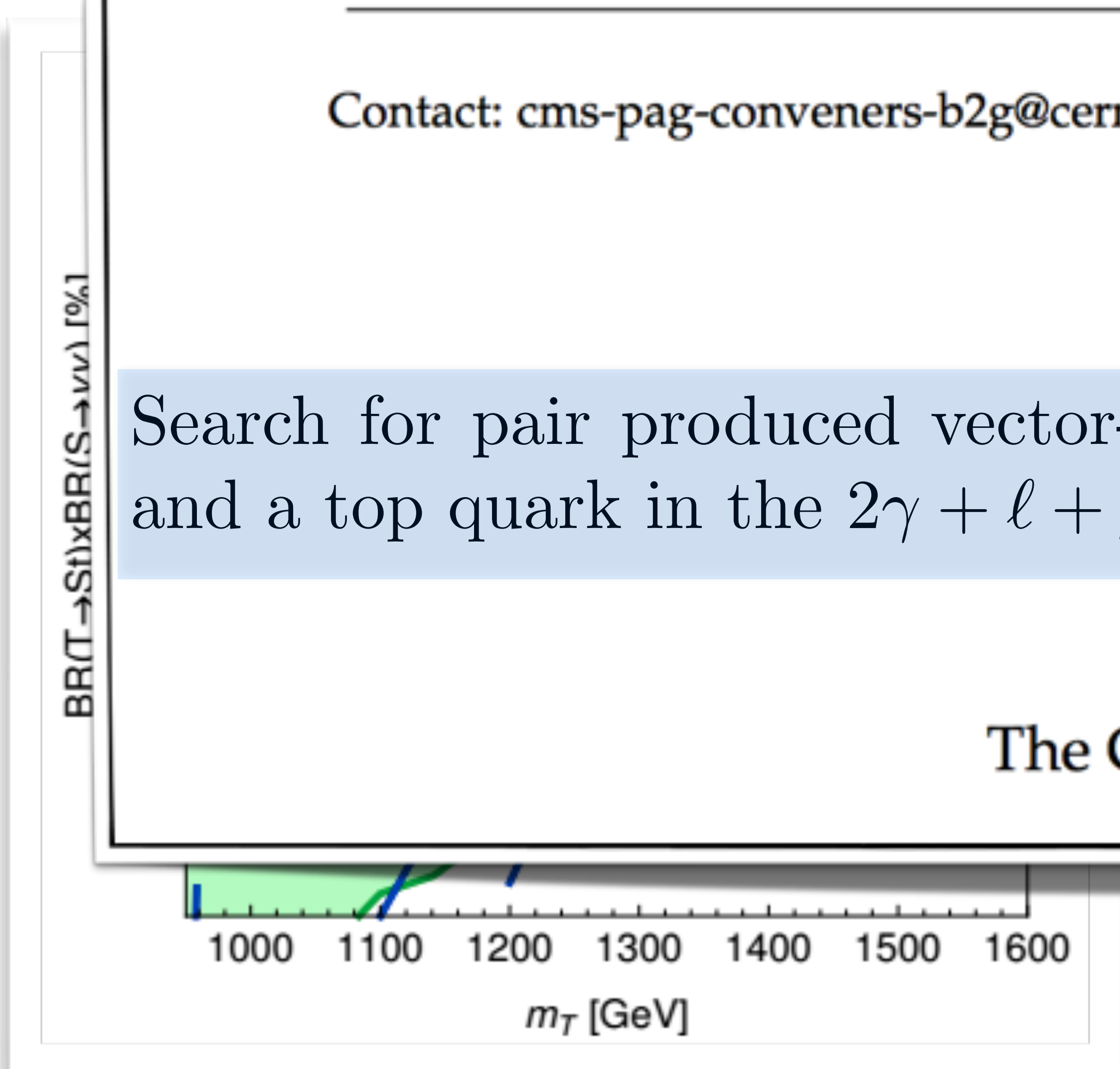

CMS Physics Analysis Summary

Contact: cms-pag-conveners-b2g@cern.ch

2016/09/23

Search for pair produced vector-like quarks decaying into the F^{750} resonance and a top quark in the $2\gamma + \ell + j$ final state at $\sqrt{s}$=13 TeV

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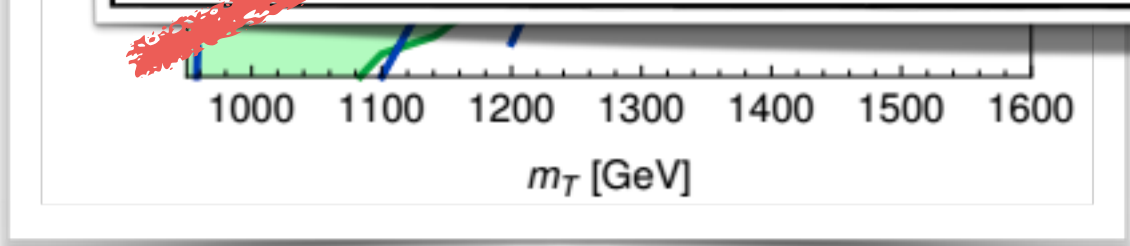

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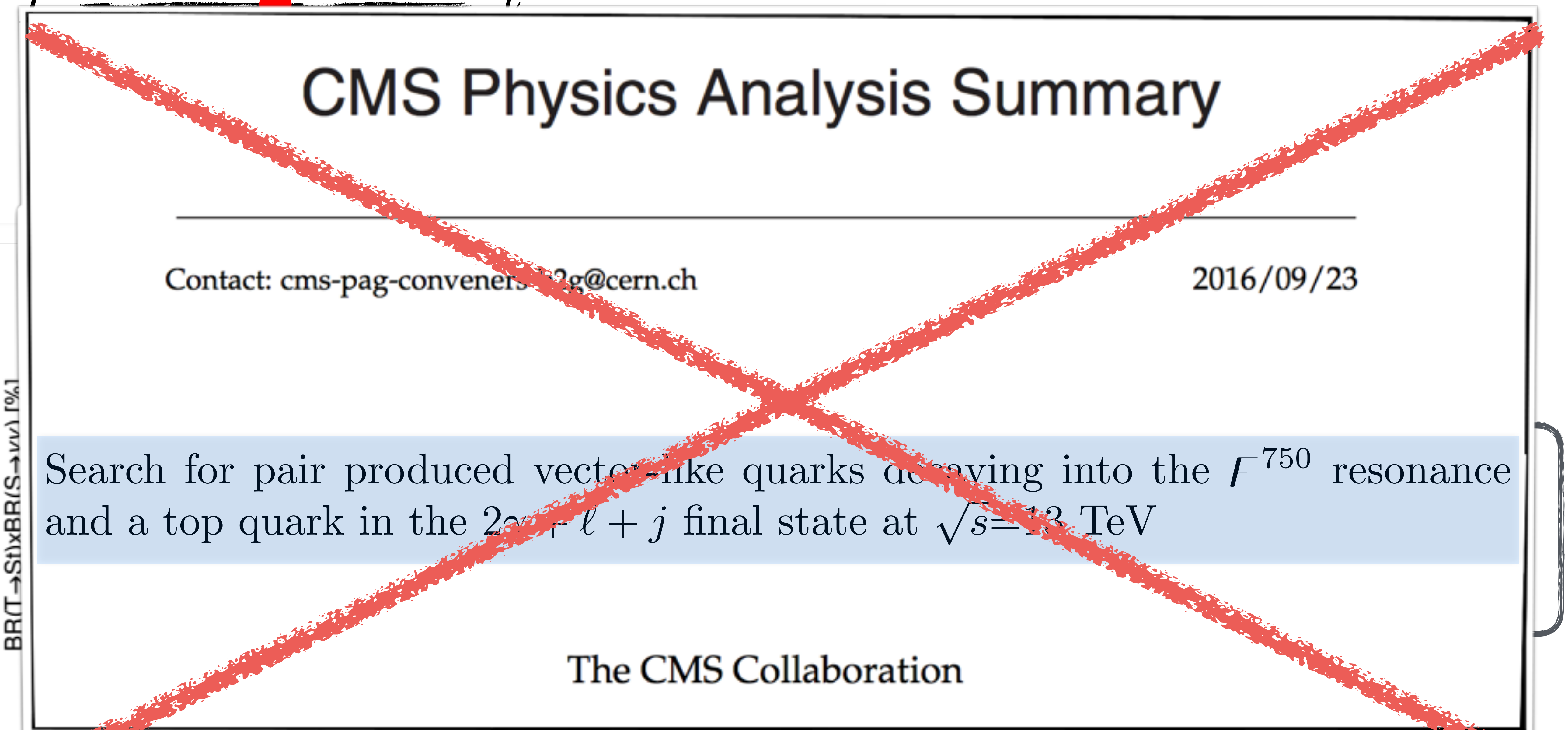

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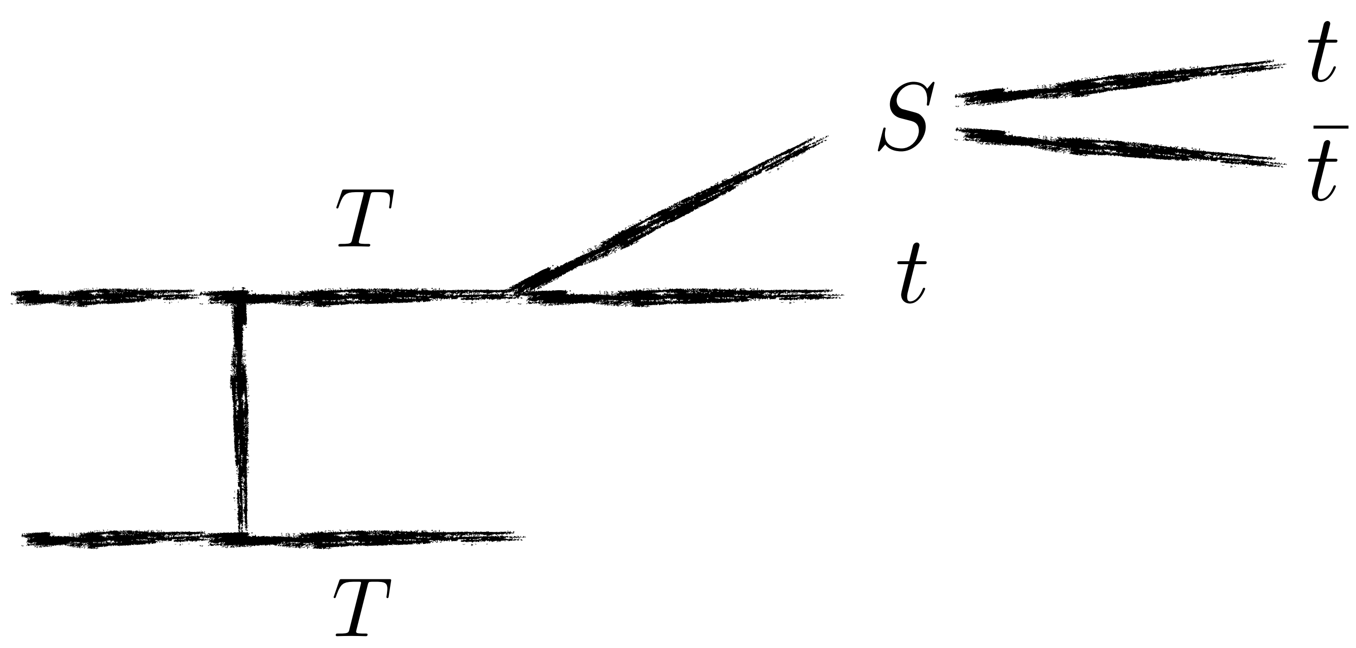
The CMS Collaboration

Despite the disappearance of the excess exotic decays are still interesting

A sizable $t\bar{t}$ coupling will provide a multi-top final state



$3t3\bar{t}$ signature

Does this happen in Composite Higgs models?

A gauge singlet spin-1 resonance is present in many CHMs

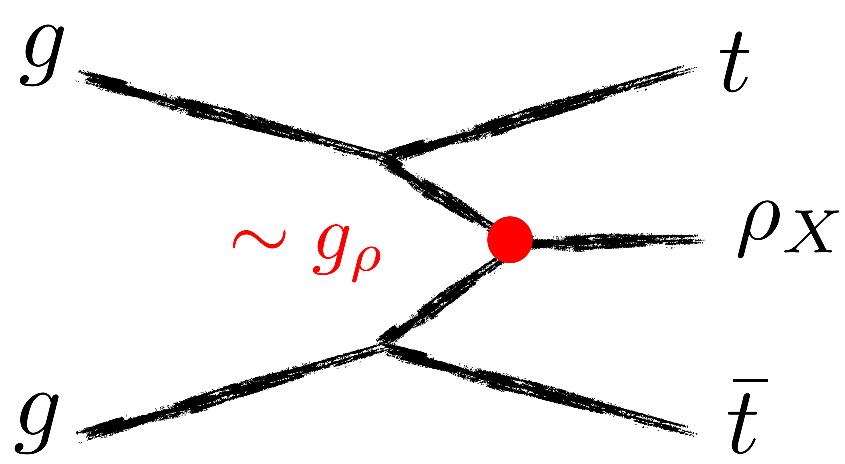
In the MCHM the breaking pattern is $SO(5) \times U(1)_X \rightarrow SO(4) \times U(1)_X$

Needed for correct Y assignment of SM fermions

$$\mathcal{L}_{\rho_X} = -\frac{1}{4}\rho^X_{\mu\nu}\rho^{X\mu\nu} + \frac{m^2_{\rho_X}}{2g^2_{\rho_X}}(g_{\rho_X}\rho^X_\mu - g'_{el}B_\mu)^2 + c\,\bar{t}_R\gamma^\mu(g_{\rho_X}\rho^X_\mu - g'_{el}B_\mu)t_R$$

Interaction with a composite t_R

The $t\bar{t}$ resonance can be produced via $t\bar{t}$ scattering



[Da Liu and Mahbubani, '15]

The six top final state can provide an extra handle

$$3t3\bar{t} \to 3W^+3W^-3b3\bar{b}$$

Clean multileptonic final state
- Same-sign 3-lepton
- 4-lepton with 3 same-sign

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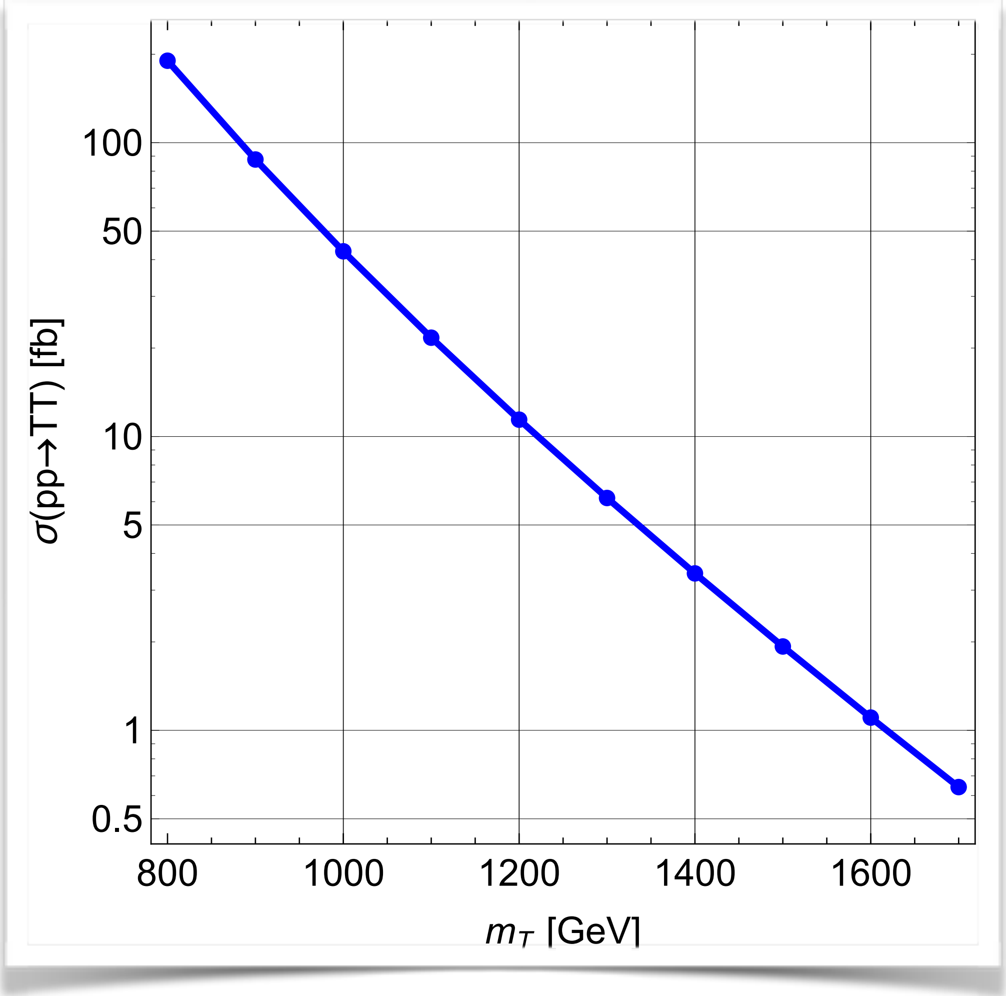


Same-sign 3 leptons

$$0.2^3 \times 2 = 2 \times 10^{-2}$$

$$m_T = 1200 \text{ GeV} \quad L = 300/fb$$

$$N_{ev} = 66$$

4 leptons

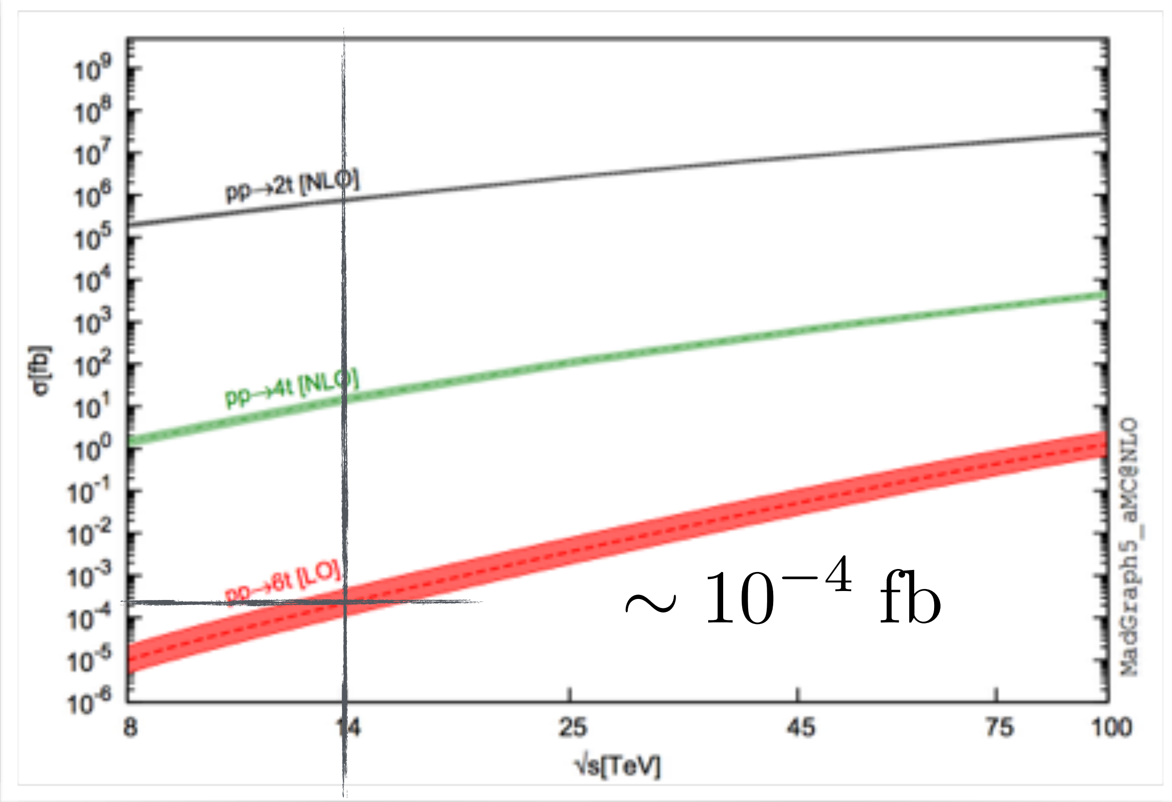
$$0.2^3 \times 0.2 \times 3 \times 2 = 1 \times 10^{-2}$$

$$m_T = 1200 \text{ GeV} \quad L = 300/fb$$

$$N_{ev} = 33$$

3 same-signs leptons final state has a small Standard Model background

Negligible SM 6-tops



Negligible 3SS-leptons

Channel	$\sigma \times BR$ (pb)
ZZW	1.05×10^{-5}
ZZW	5.57×10^{-6}
ZWt	1.79×10^{-6}
ZWW	6.28×10^{-7}
ZZt	4.8×10^{-7}
Wtt	1.83×10^{-8}
Ztt	1.02×10^{-8}
WWW	6.89×10^{-9}

Heavy flavor decay removed with isolated leptons

$$Zb\bar{b}, t(b)b, Wb\bar{b}, Zt\bar{b}, \ldots$$

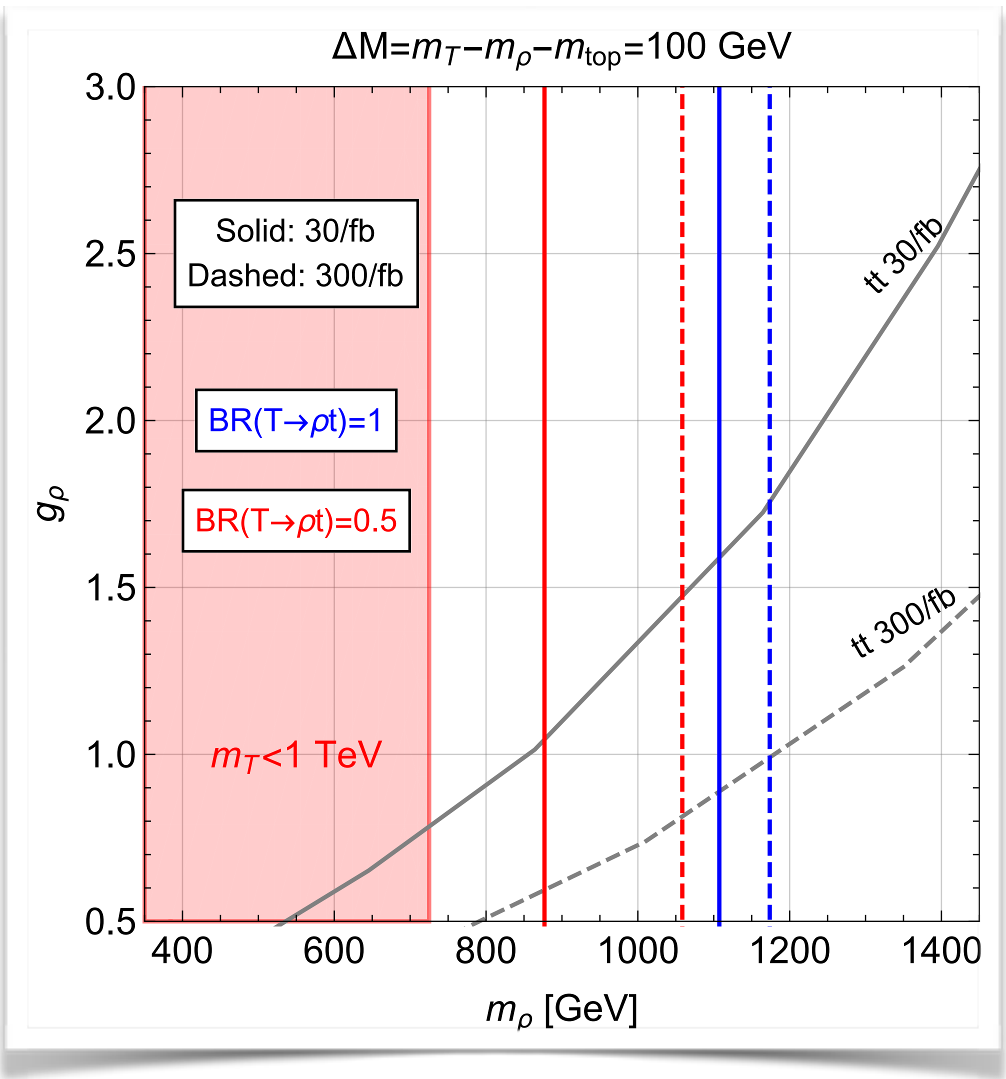
Main contributions charge mis-ID from multi-lepton

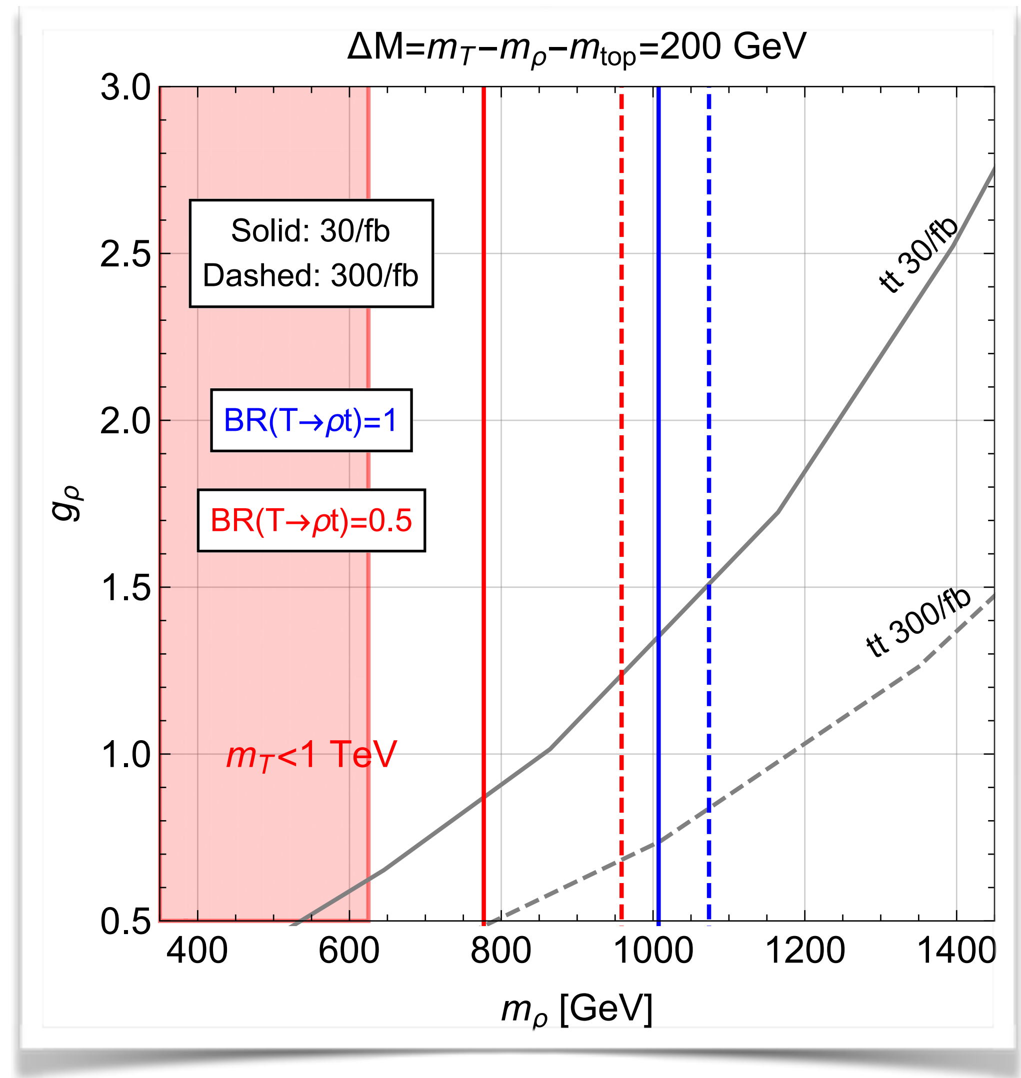
$$\sigma \sim 3 \times 10^{-2} \text{ fb}$$

$$L = 300/fb \quad N_{\text{ev}} \sim 15$$

$$3t3\bar{t} \to 3W^{+}3W^{-}3b3\bar{b} \to 3\ell^{+} + 12j$$

Just ask for high hadronic activity





[Azatov and DB, in progress]

6-top final state unexplored at the LHC

Composite Higgs models provide motivations for this challenging scenario

Conclusions

The lack of TeV scale NP could have three answers

There is no TeV scale NP: the concept of fine-tuning has misguided us
Need to reconsider the naturalness paradigm

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All three options deserve deep investigation

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- Non minimal scenarios where NP can manifest itself deserve deep investigation given the null results of LHC new physics search and the lack of indication from complementary experiment (flavour physics, astrophysics)

- Exotic decay patterns can from one side hide signatures of commonly studied new physics scenario, from the other side provide stronger handles to investigate new physics models

- Experimental efforts already going in this direction; need to fully exploit the potentiality of the LHC which might provide our last chance to investigate high energy proton collisions!!!

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Thank you for the attention!