Collider Phenomenology of Composite Higgs Models

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

MITP, Mainz, April 13, 2016

Composite Dynamics:
from Lattice to the LHC Run II

Mainz Institute for Theoretical Physics

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Composite Dynamics:
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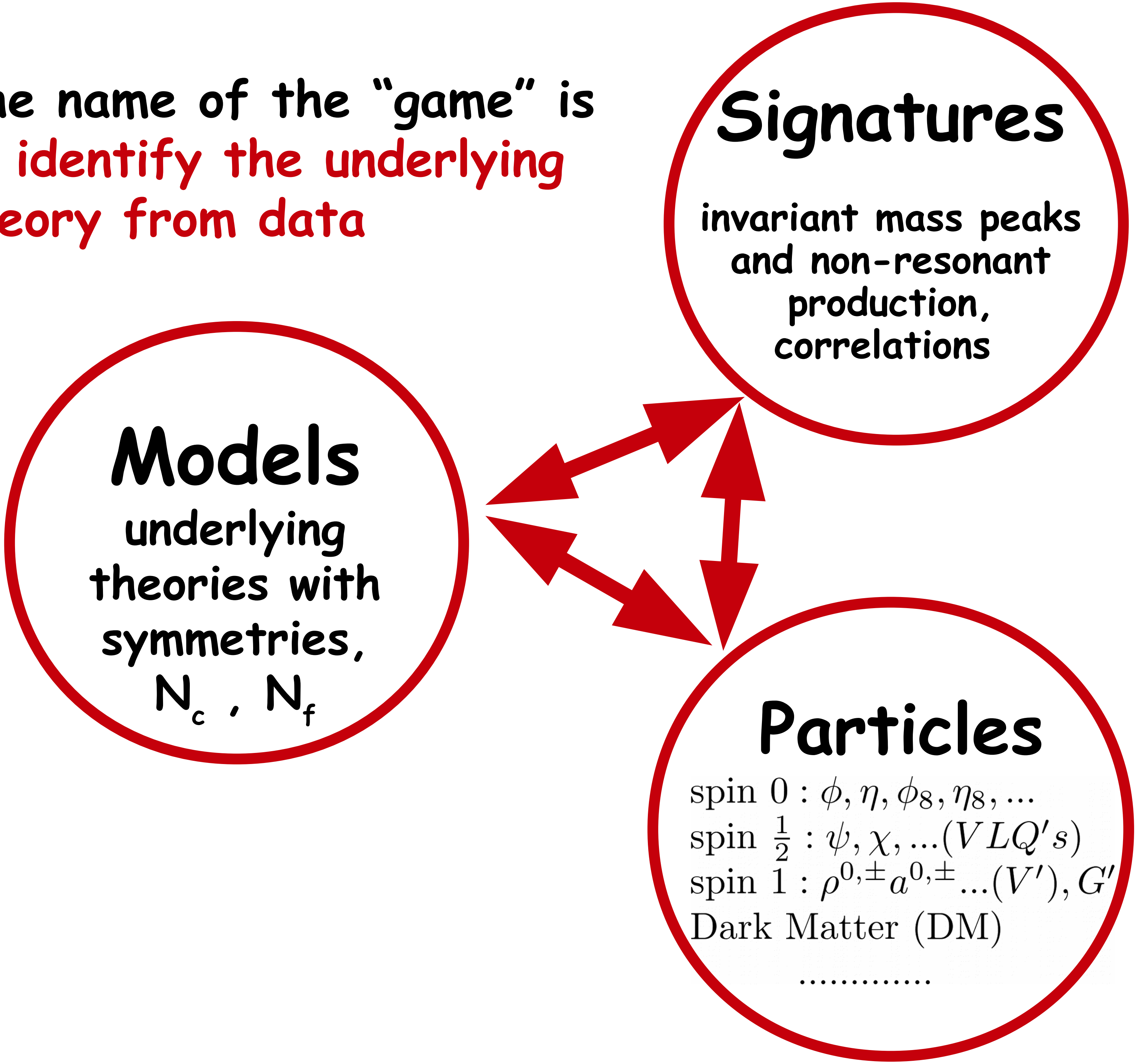
Thanks to the organisers for the great weather during weekend!

The name of the "game" is **to identify the underlying theory from data**



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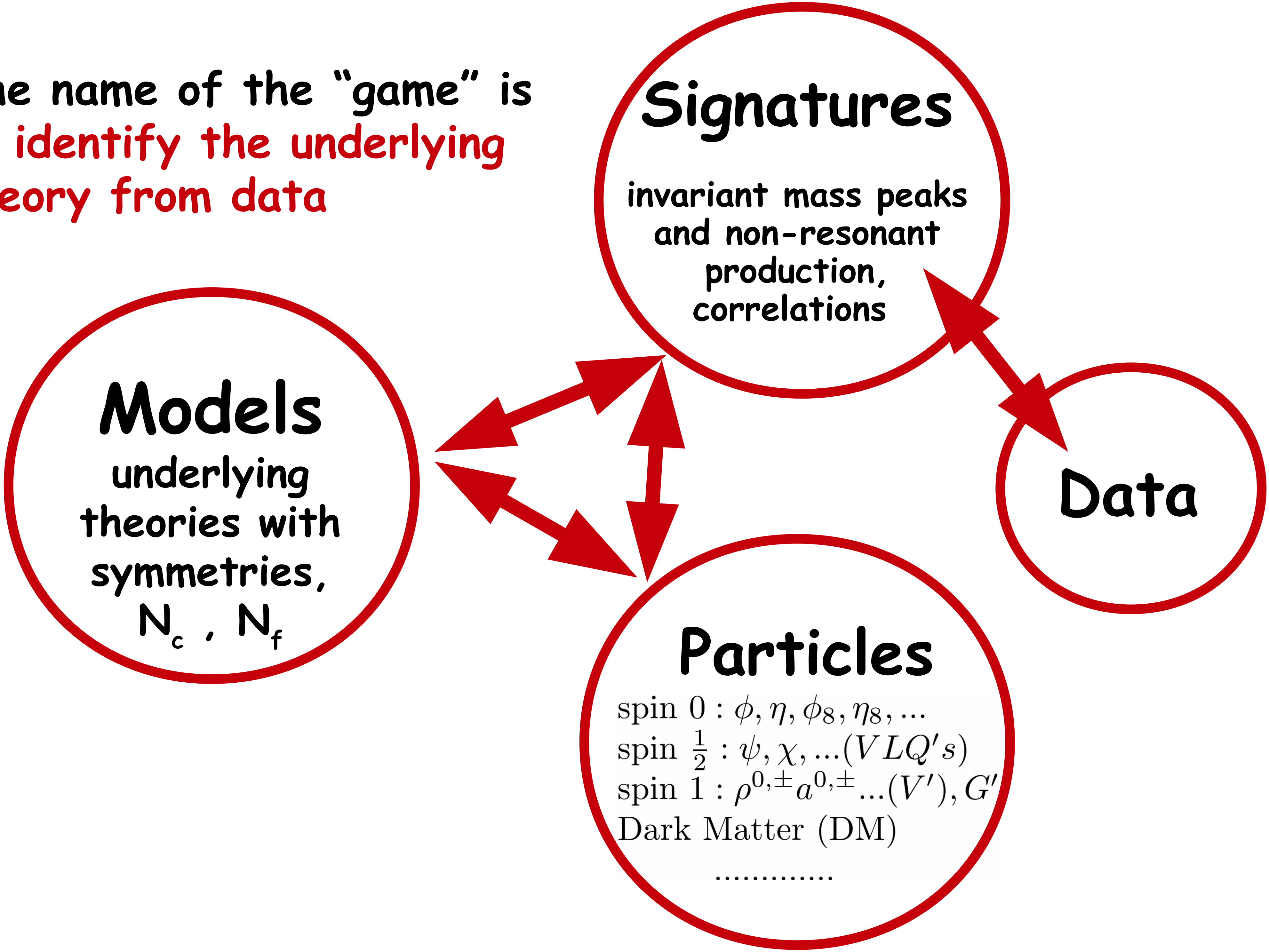
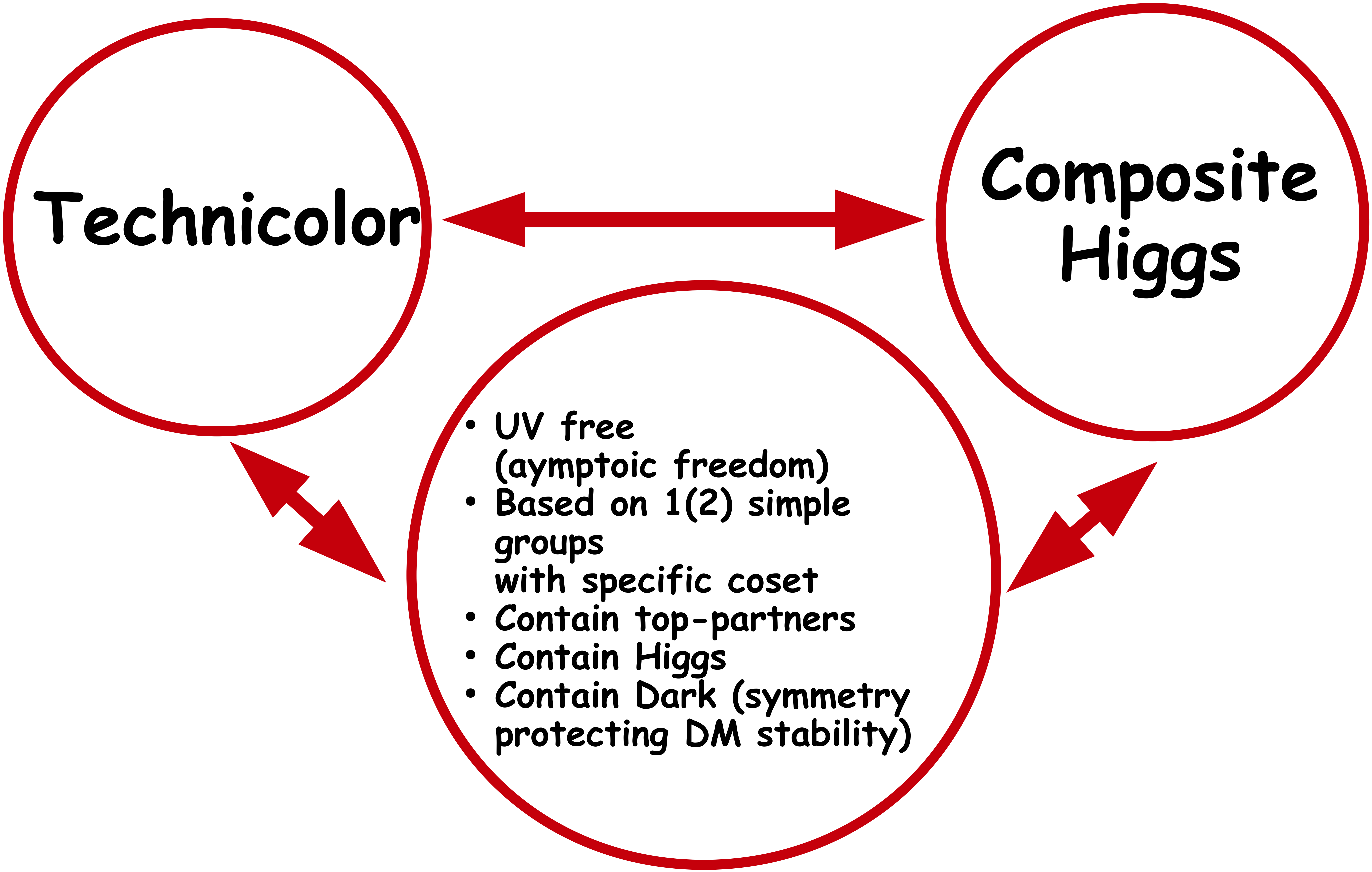


Models


Technicolor
Composite Higgs
• UV free
(aymptoic freedom)
• Based on 1(2) simple groups
with specific coset
• Contain top-partners
• Contain Higgs
• Contain Dark (symmetry protecting DM stability)

New Strong Dynamics: TC vs CH

m_σ^{TC}

- **The Technicolor Composite Higgs**
  - 'Higgs' is the lightest scalar isospin-0 resonance of strong dynamics
  - Compare with the $f_0(500)$ in QCD

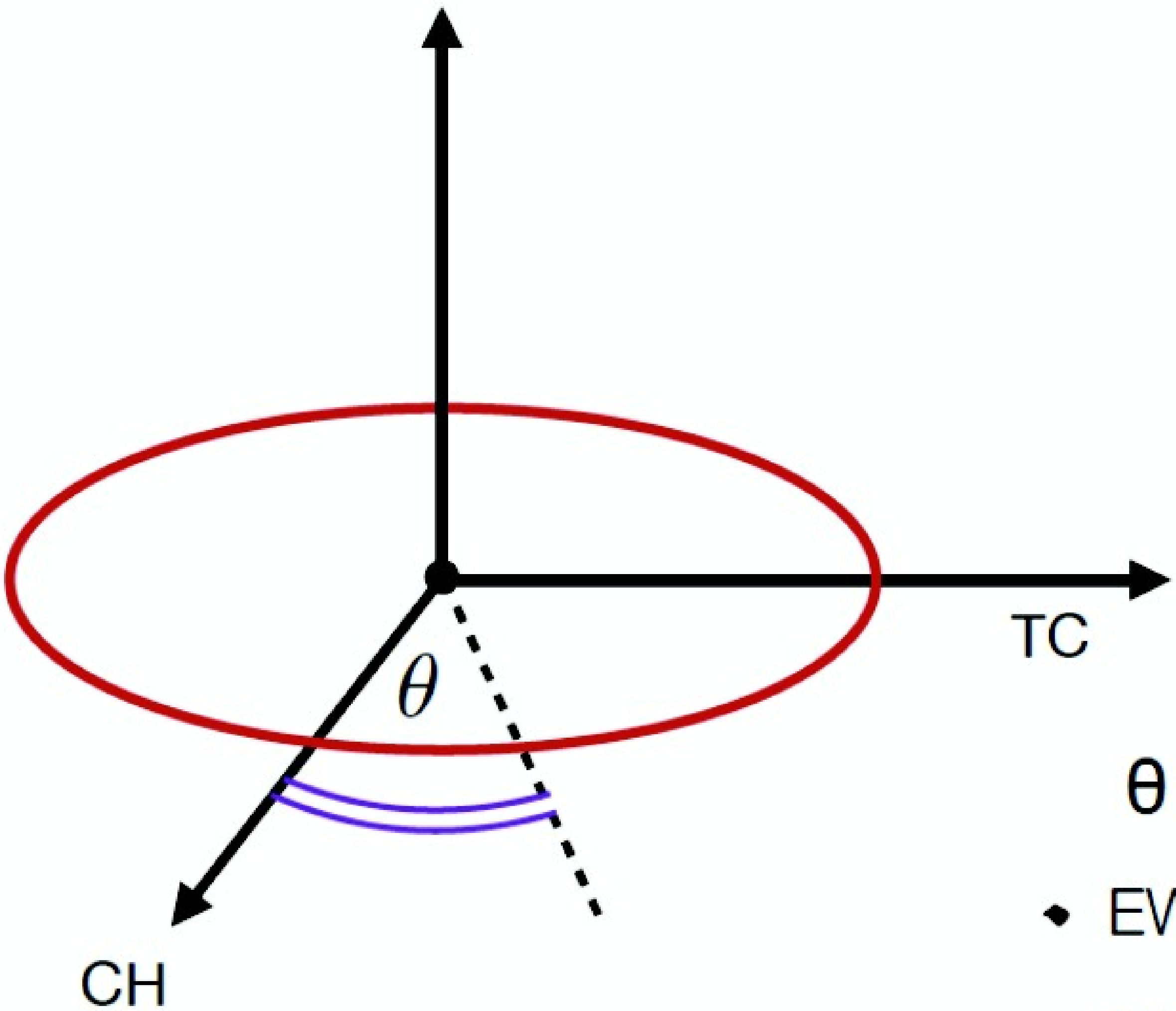
m_h^{obs}

- **The *Composite Higgs* Composite Higgs**
  - The Higgs doublet arises as goldstone bosons of global symmetry breaking
  - Electroweak symmetry breaks through vacuum misalignment

m_h^{CH}

New Strong Dynamics: TC vs CH

(Galloway, Evans, Tacchi & Luty '10
G. Cacciapaglia & F. Sannino '14)



$\theta = 0$

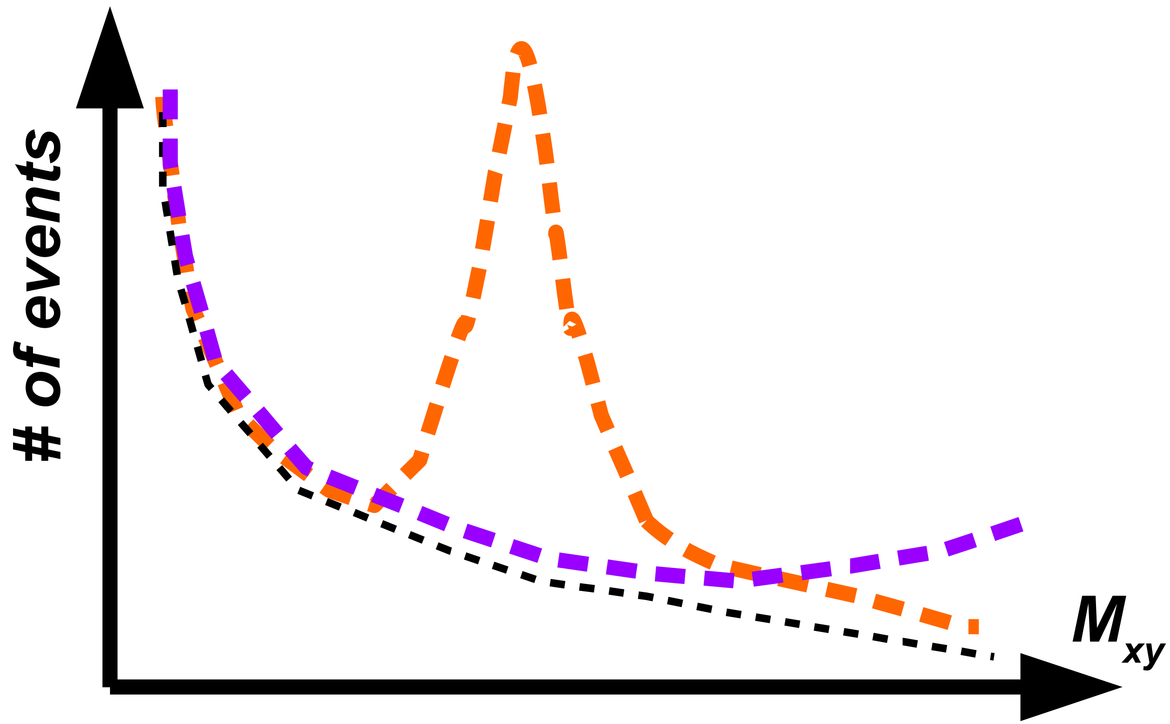
- EW does not break
- Higgs is exact GB

$\theta = \pi/2$

- EW breaks
- Higgs is massive excitation

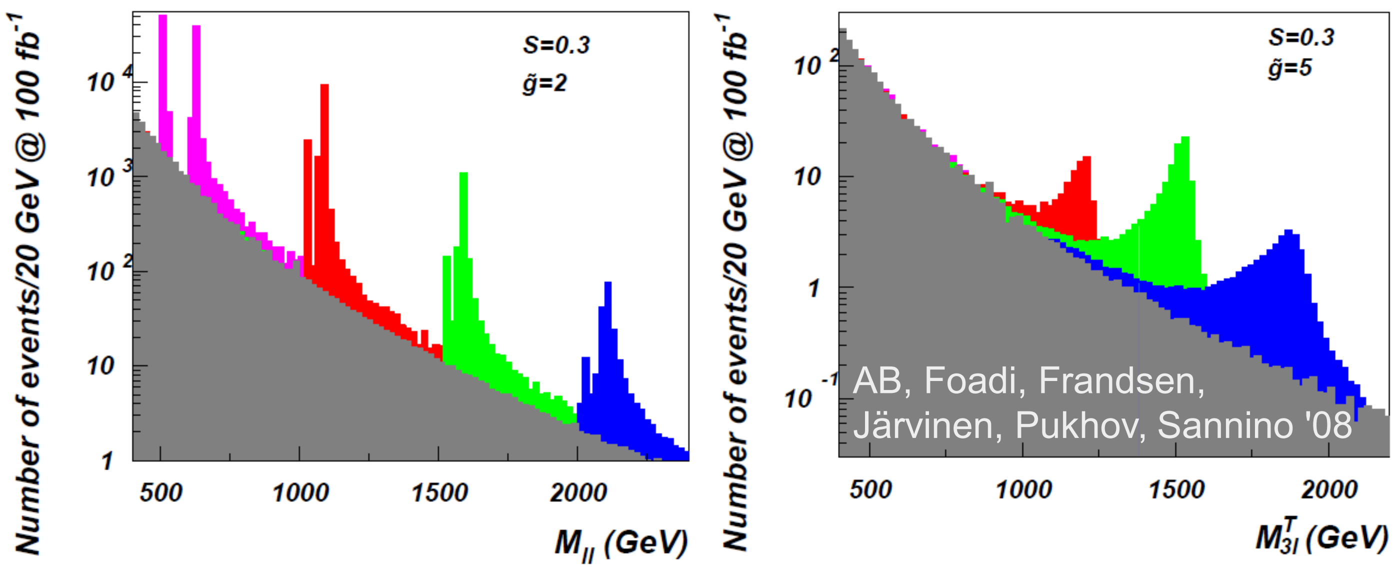
Signatures and Strategies

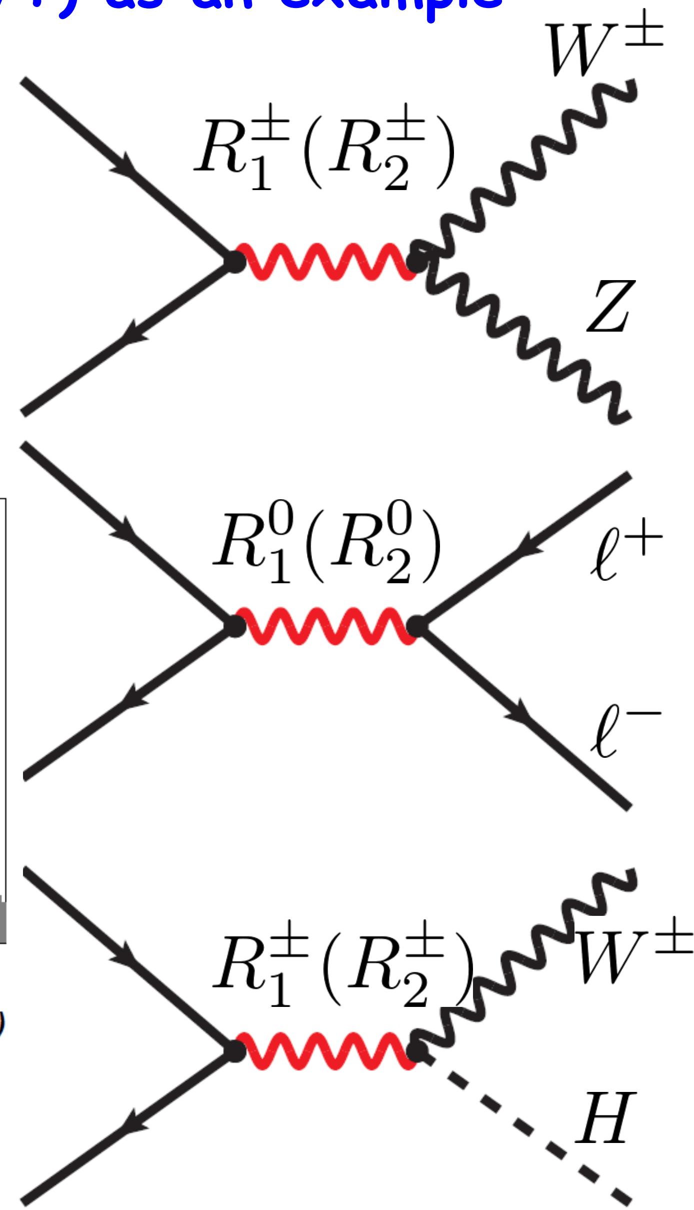
- There are two main classes of signatures
  - resonant – single or several bumps
  - non-resonant – typically effects in the tails of distributions



V' resonances and "no-loose" strategy

- Next to Minimal Walking Technicolor (NMWT) as an example
- N_c = 3, N_f = 2 (two-index symmetric reps)
  $SU(2)_L$ X $SU(2)_R$ -> $SU(2)_V$: two triplets of heavy mesons $R_1^0(R_2^0)$ and $R_1^\pm(R_2^\pm)$
- Use of di-lepton + tri-lepton (di-boson) signatures sets no-loose strategy



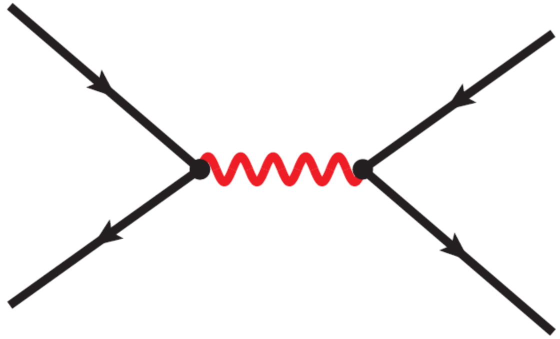


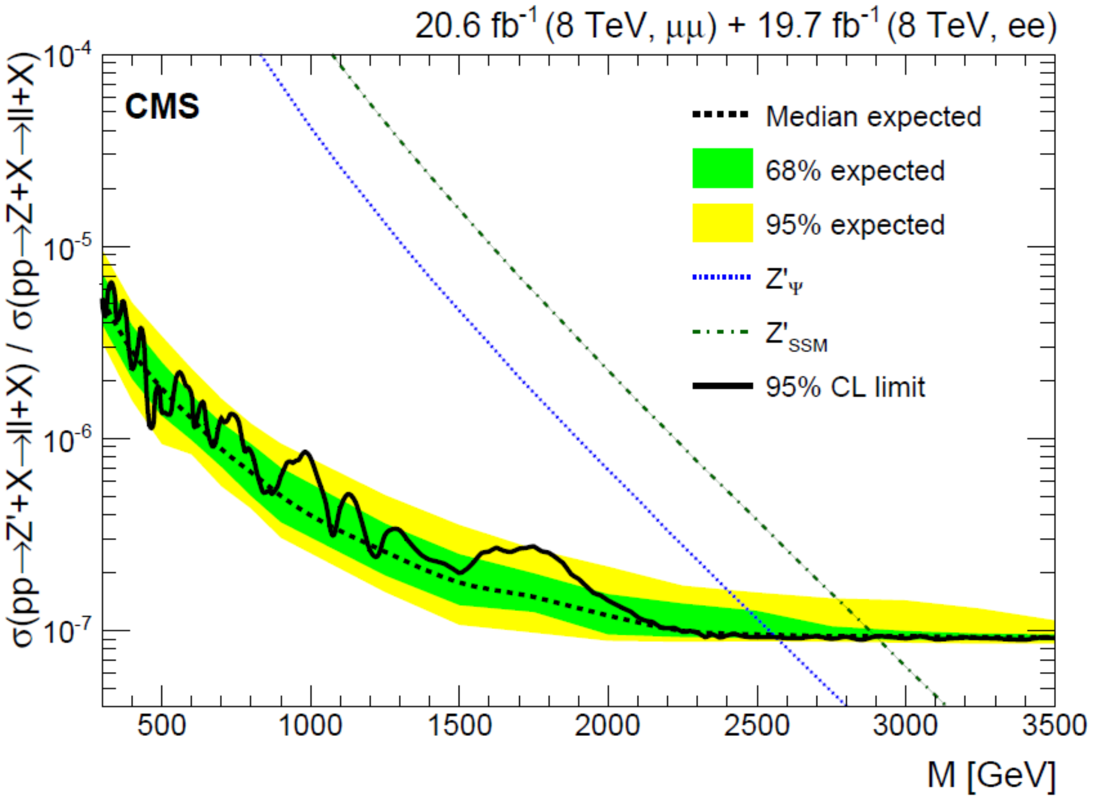
- additional WH signature from R resonance can further complement no-loose strategy

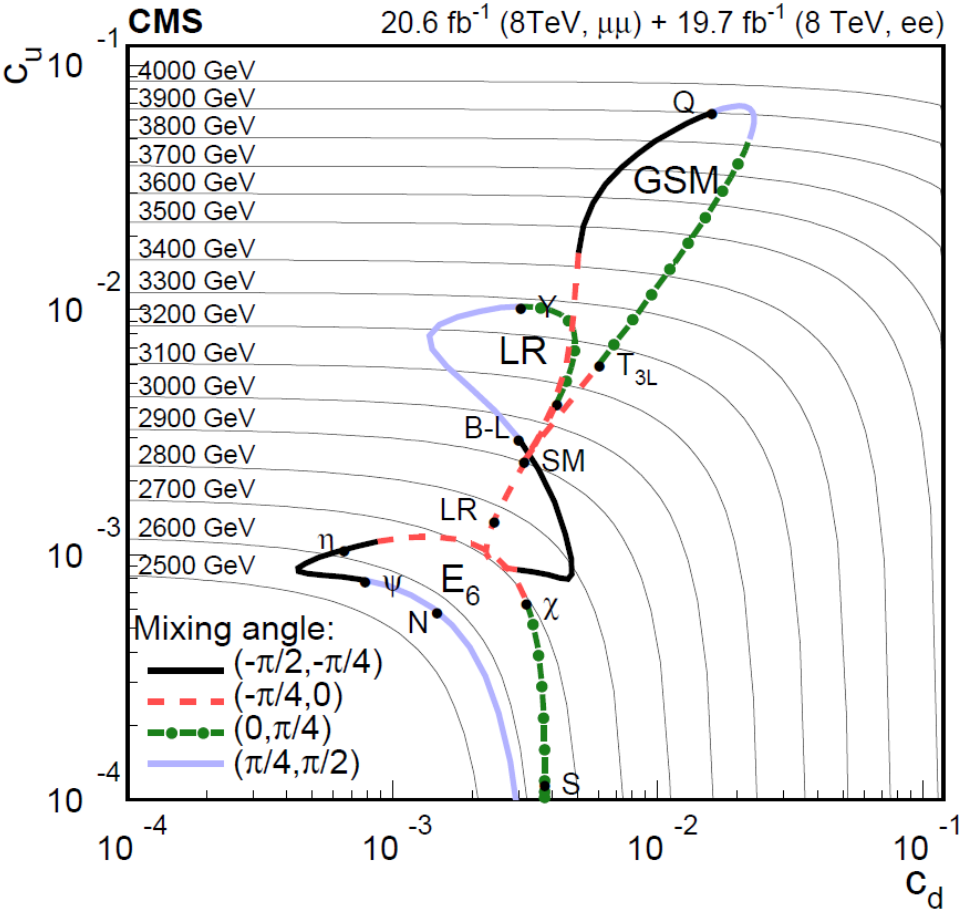
Experimental limits on V'(di-lepton signature)

~ 3 TeV limit for SSM Z' @ 8 TeV

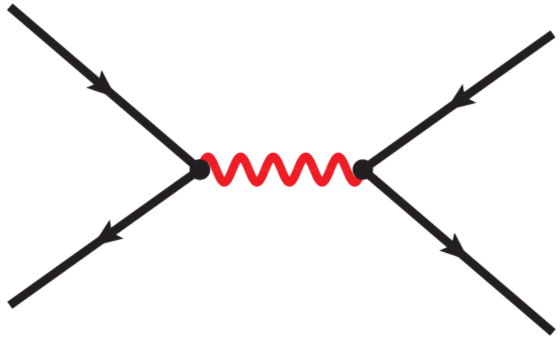
arXiv:1412.6302





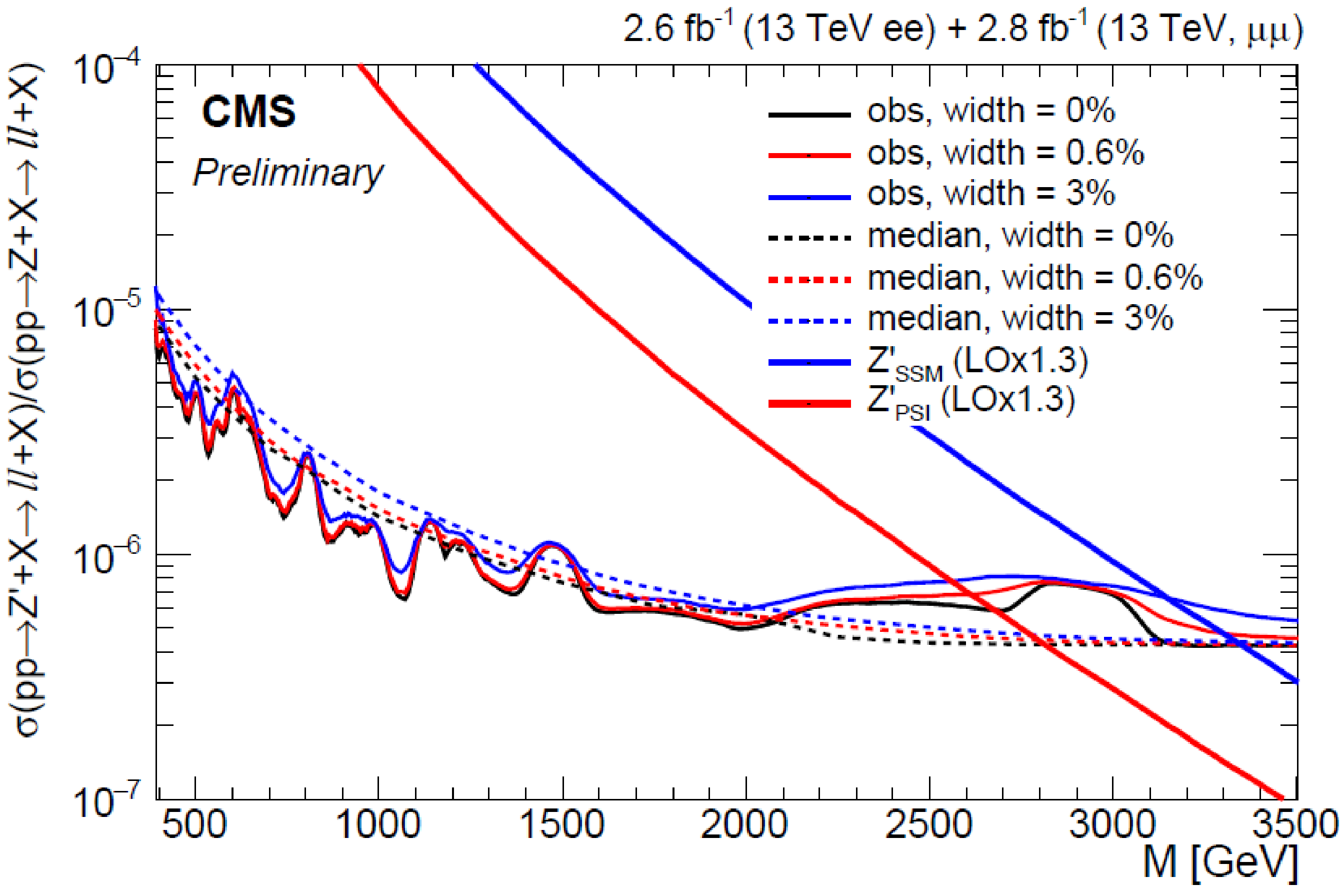


Experimental limits on V'(di-lepton signature)



~ 3.5 TeV limit for SSM Z' @ 13 TeV

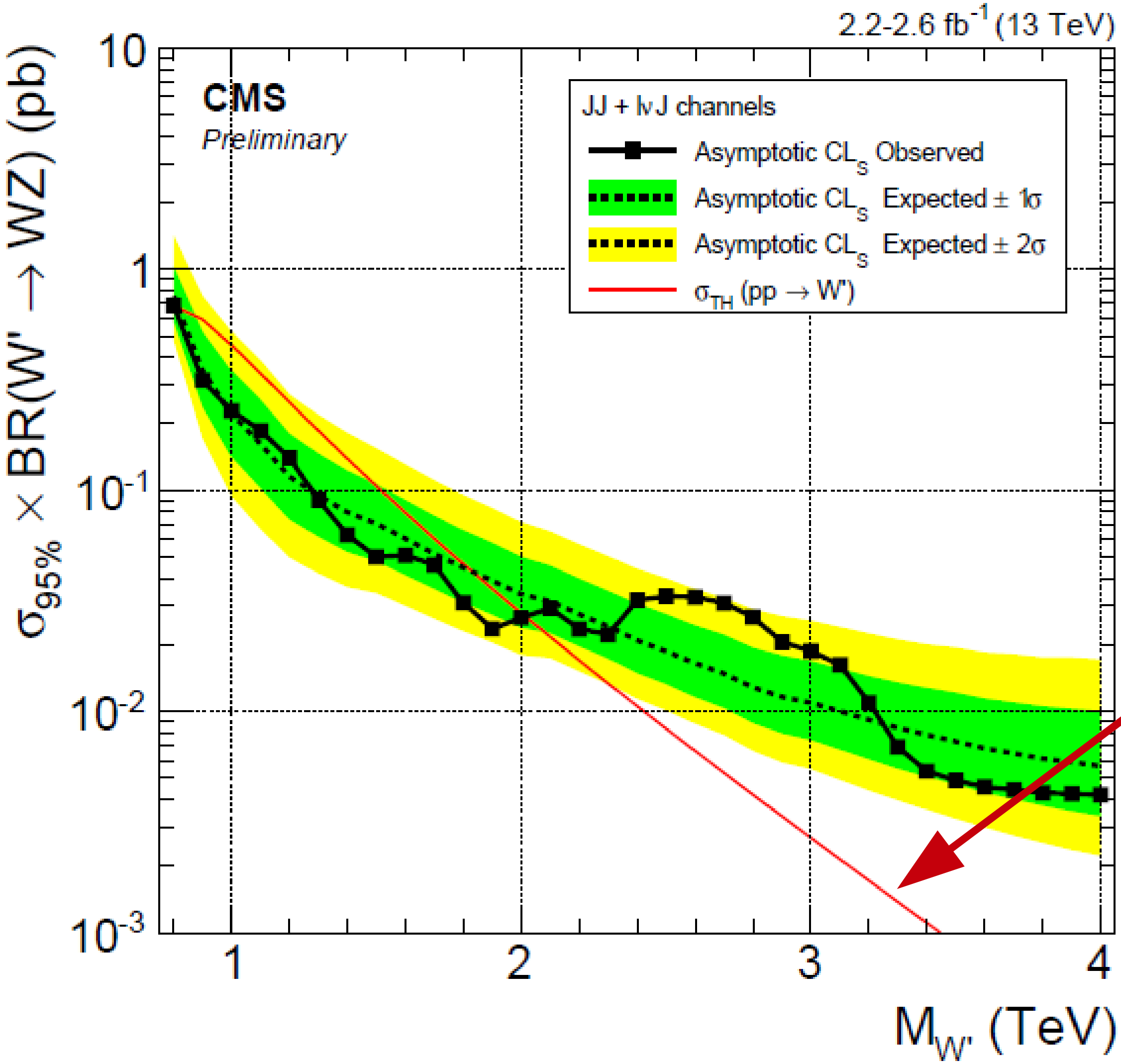
CMS-PAS-EXO-15-005

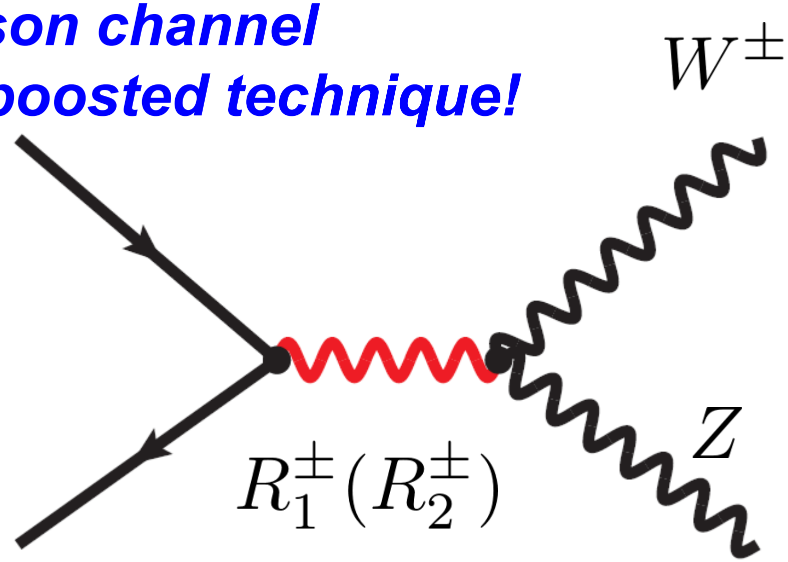


Experimental limits on V'(di-boson)

~ 2 TeV limit for HVT W' @ 13 TeV in di-boson channel
an example of the effective application of boosted technique!

CMS-PAS-EXO-15-002



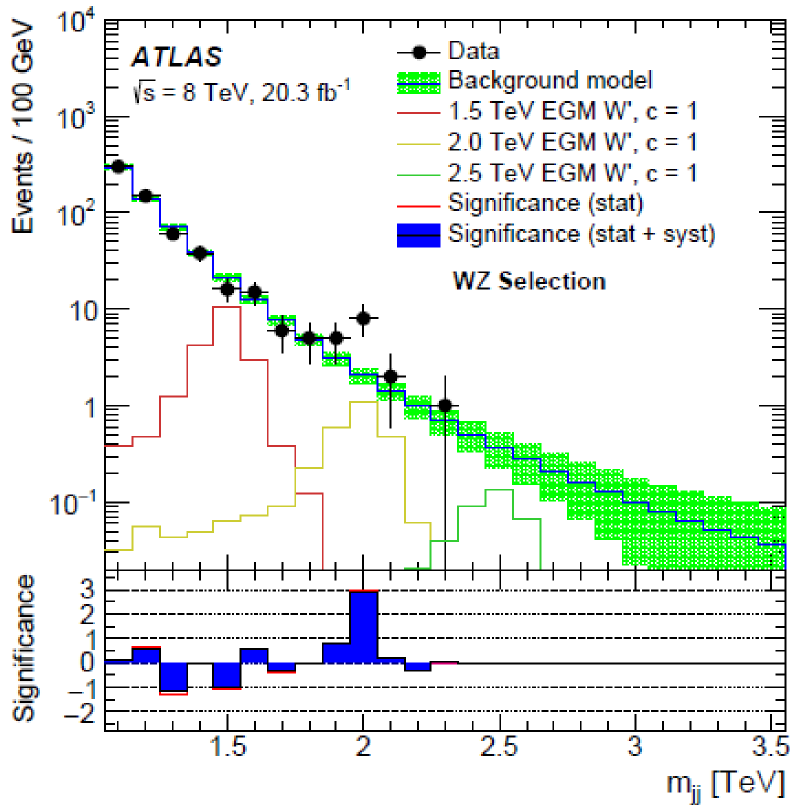


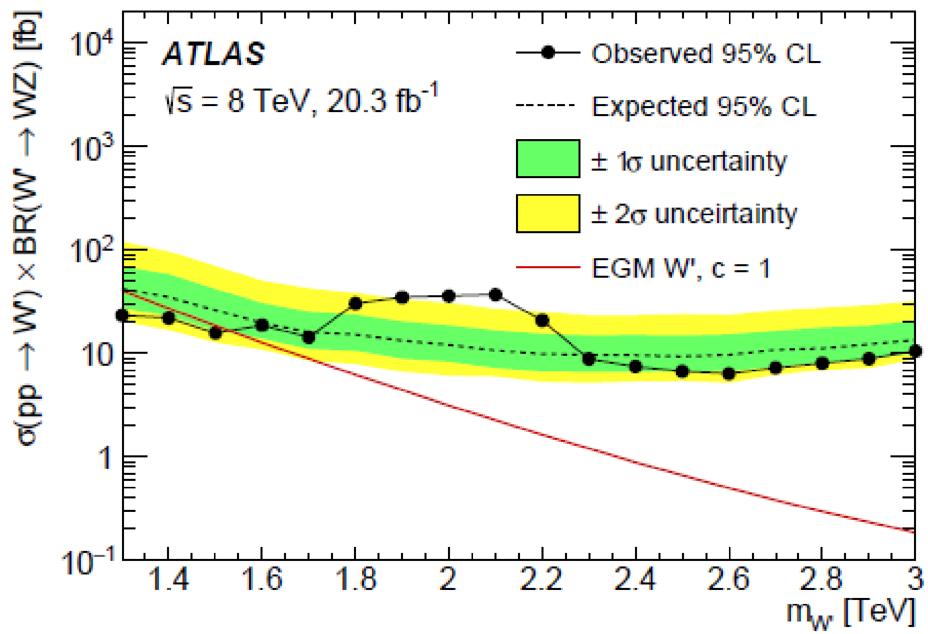
the composite heavy vector triplet (HVT) model
Duccio Pappadopulo, Andrea Thamm, Riccardo Torre, Andrea Wulzer arXiv:1402.4431

$$i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\, a}_F$$
$$+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]\, c}$$
$$+ g_V^2 c_{VVHH} V^a_\mu V^{\mu\, a} H^\dagger H$$
$$- \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\, a} V^b_\mu V^c_\nu .$$

Experimental limits on V'(di-boson)

… do not forget hints from 8 TeV data from ATLAS





Experimental limits on V'(di-boson)

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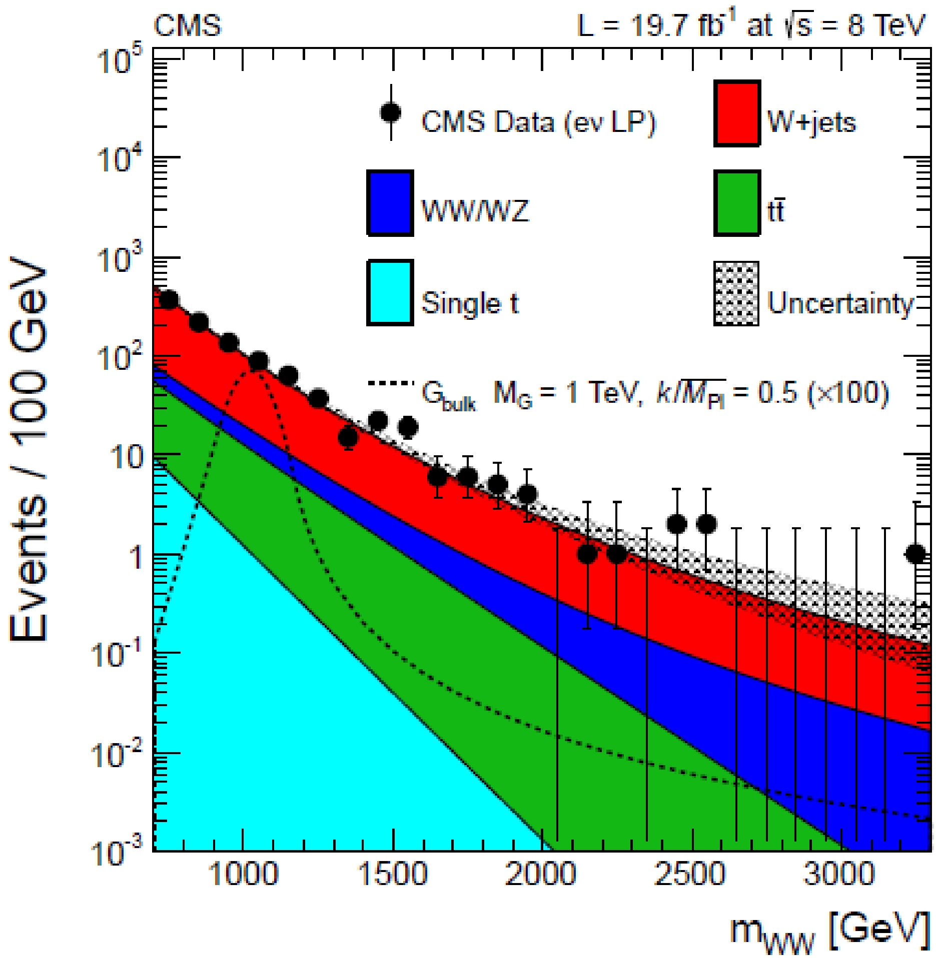

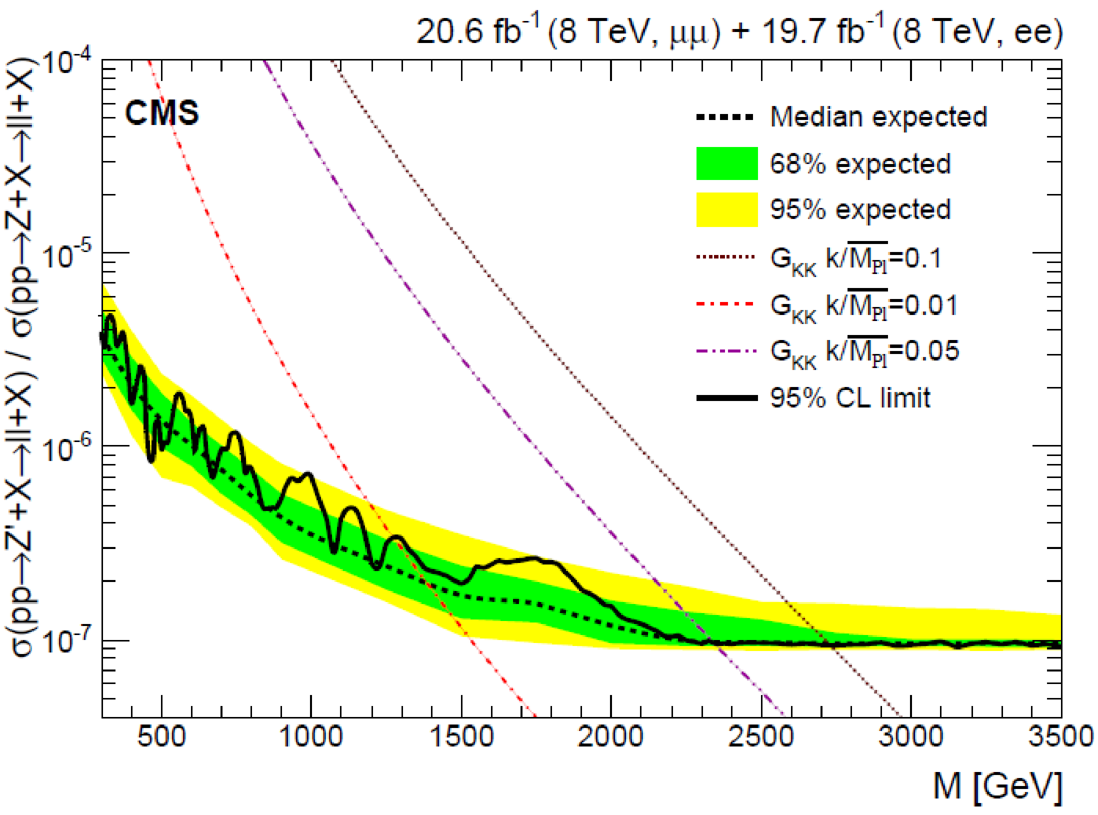

Experimental limits on V'(di-boson)

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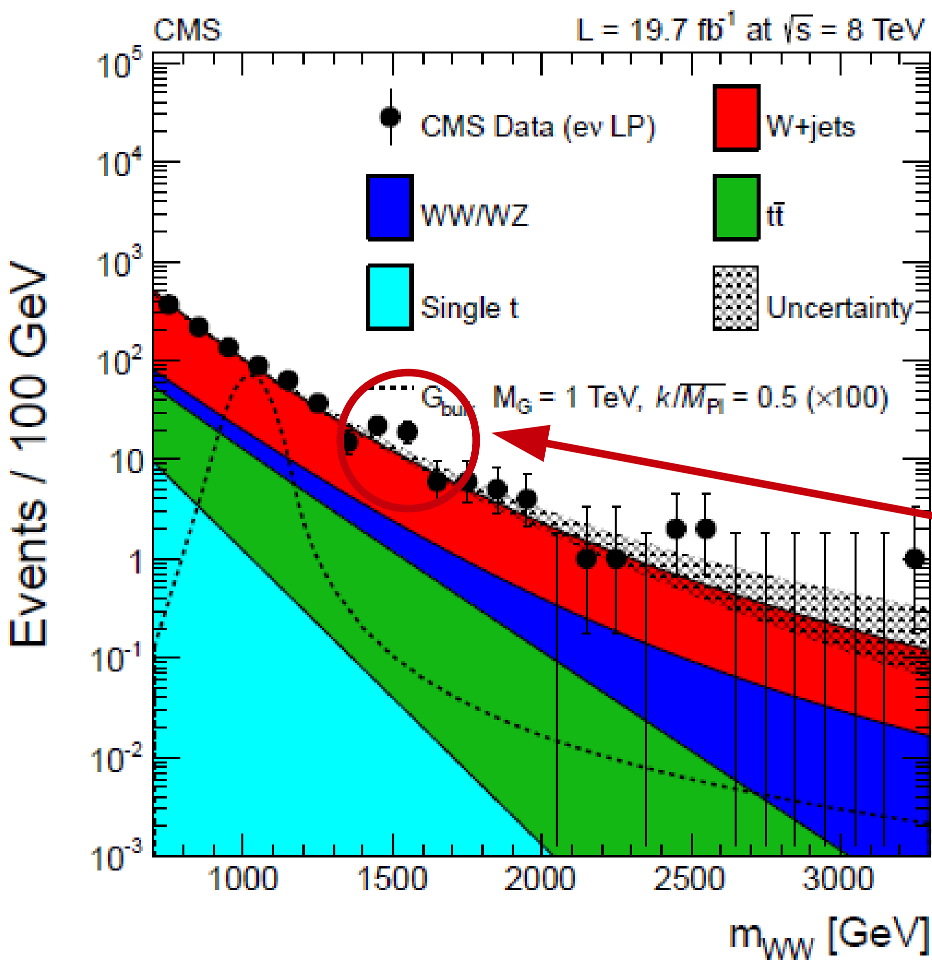
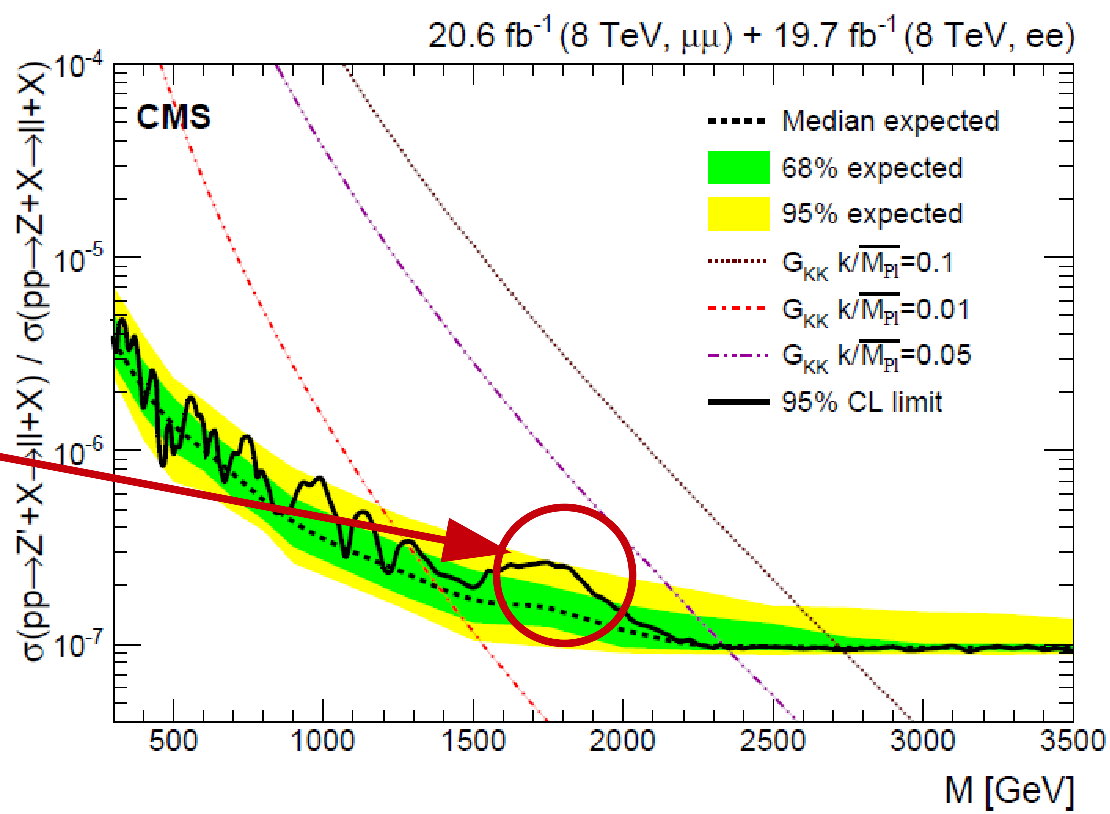
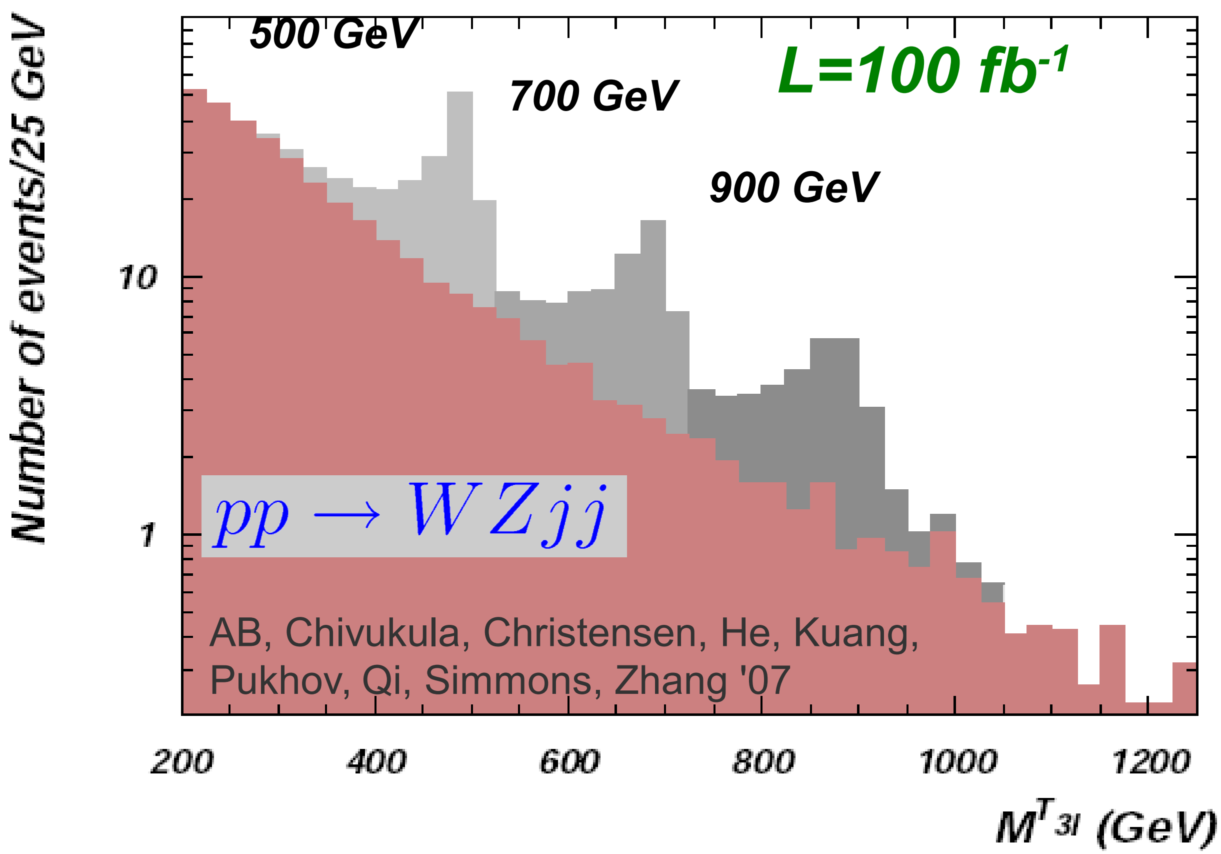


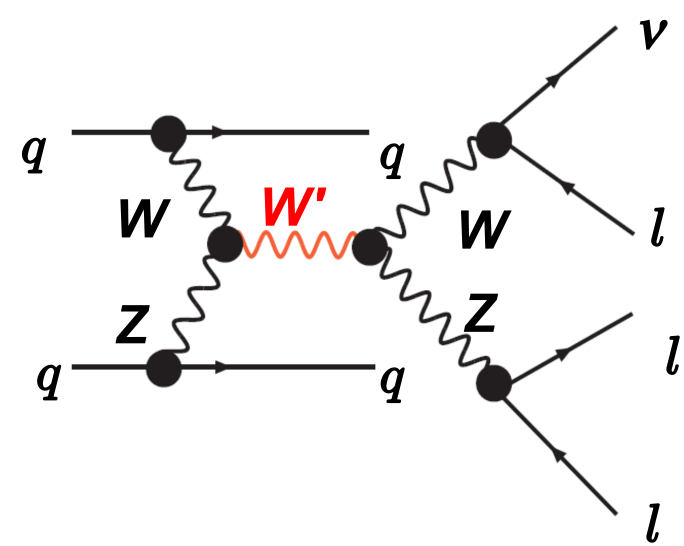


VBF fusion with V's

- W'/Z' production in VBF fusion will be important signature to probe the model if W'/Z' couplings to the light SM particles are suppressed



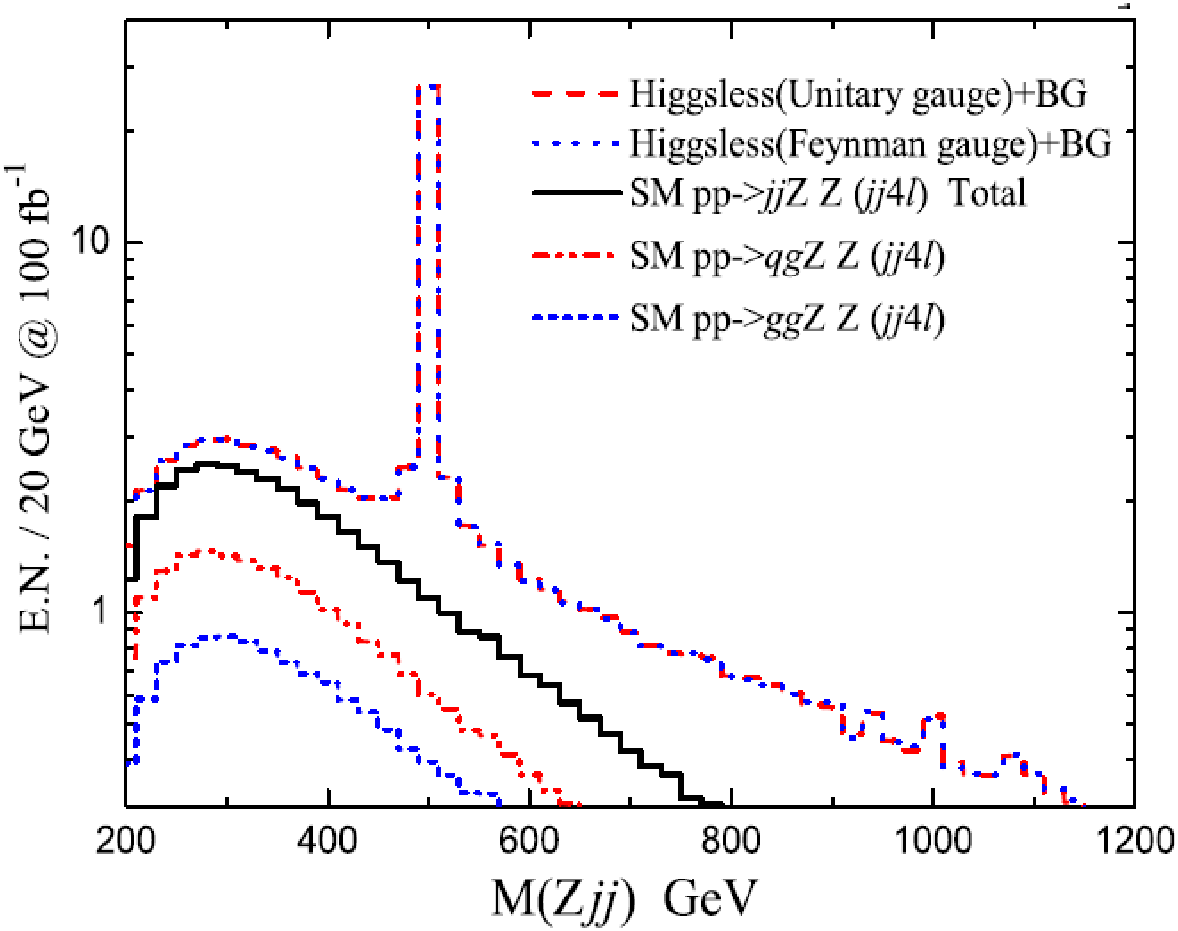
$$pp \to W'qq \to WZqq$$

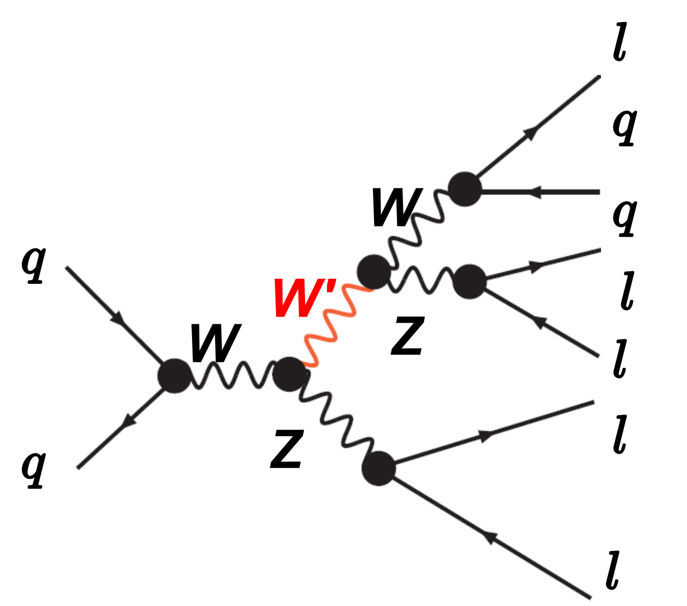


Associate production of V's with W/Z

- Second important channel when W'/Z' couplings to the light SM particles are suppressed

$$pp \to W'^{(*)} Z \to WZZ \to jj\,\ell^+\ell^-\ell^+\ell^-$$





AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07

Vector-like quarks: minimal setup

- **Simplest realization:**
  - The minimal composite Higgs model (MCHM)
    Agashe, Contino, Pomarol [2004]
  - Effective field theory
    with SO(5) -> SO(4)
  - global symmetry breaking
  - particle content

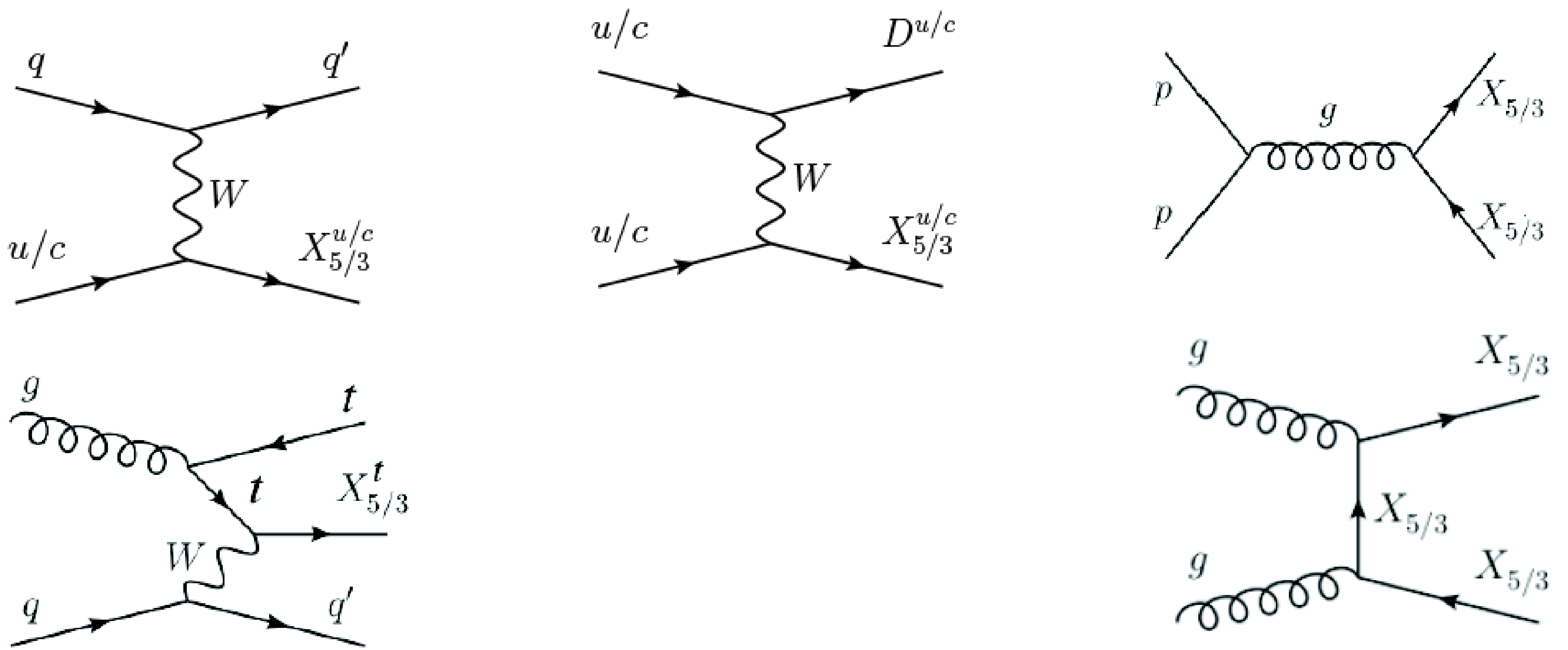
	T	$X_{2/3}$	B	$X_{5/3}$	$\tilde{T}$
$SO(4)$	**4**	**4**	**4**	**4**	**1**
$SU(3)_c$	**3**	**3**	**3**	**3**	**3**
$U(1)_X$ charge	$2/3$	$2/3$	$2/3$	$2/3$	$2/3$
EM charge	$2/3$	$2/3$	$-1/3$	$5/3$	$2/3$

$$\mathcal{L}_{comp} = i\,\overline{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\bar{\tilde{T}}\not{D}\tilde{T} - M_4\overline{Q}Q - M_1\bar{\tilde{T}}\tilde{T} + \left(ic\overline{Q}^i\gamma^\mu d^i_\mu \tilde{T} + \text{h.c.}\right)$$

$$\mathcal{L}_{el,mix} = i\,\overline{q}_L\not{D}q_L + i\,\overline{t}_R\not{D}t_R - y_L f\overline{q}^5_L U_{gs}\psi_R - y_R f\overline{t}^5_R U_{gs}\psi_L + \text{h.c.}$$

Vector-like quarks: production and decay

Production mechanisms (shown here: $X_{5/3}$ prod. for partners of up-type quarks)



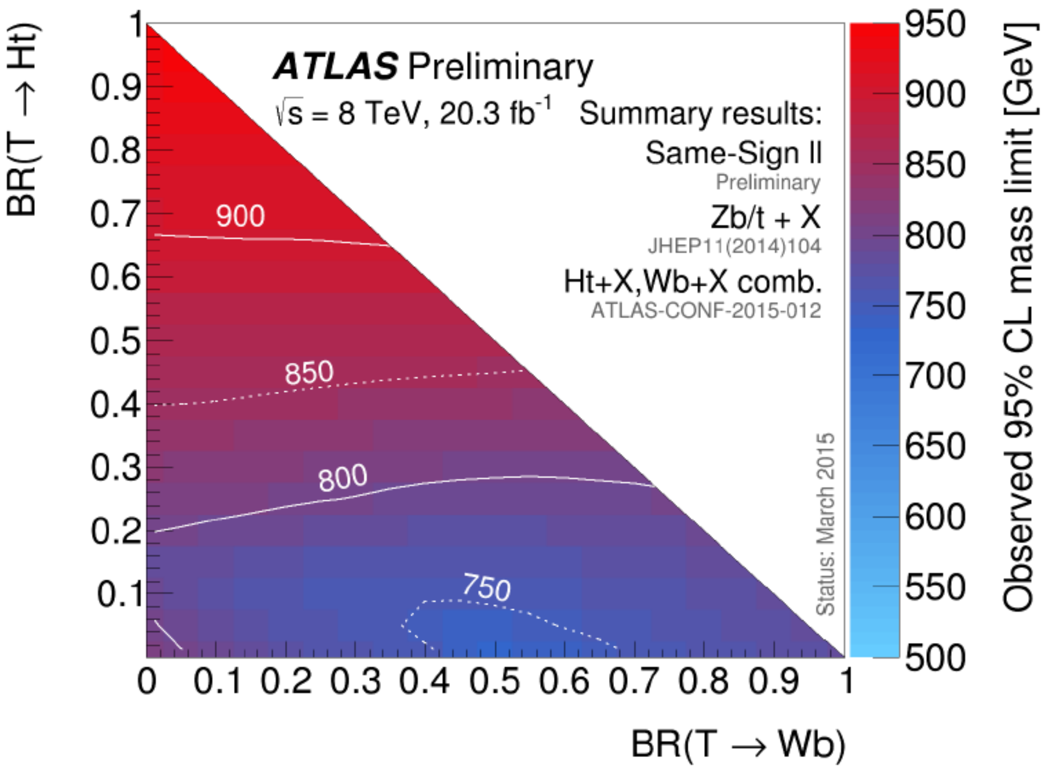
(a) EW single production (b) EW pair production (c) QCD pair production

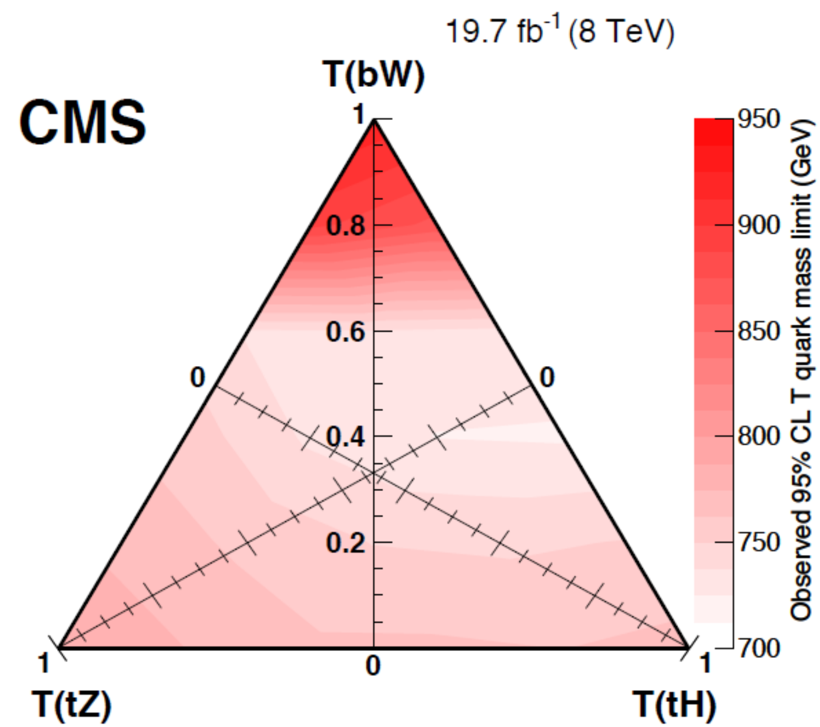
Decays:

- $X_{5/3} \to W^+ t$ (100%),
- $B \to W^- t$ ($\sim$ 100%),
- $T_{f1}, T_{f2}, T_s \to W^- b, Zt, ht$ (with parameter-dependent BRs)

Vector-like quarks: exp limits

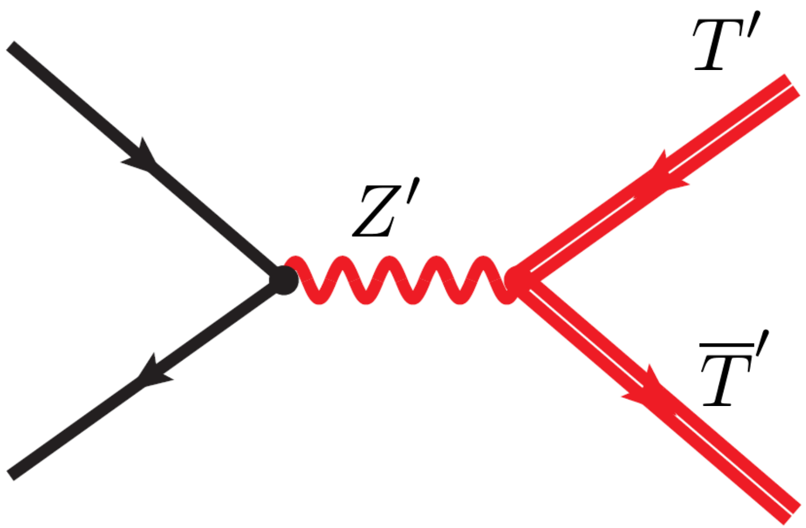
- ATLAS and CMS determined bounds on (QCD) pair-produced top partners with charge $5/3$ (the $X_{5/3}$) in the same-sign di-lepton channel.
  $M_{X_{5/3}} > 770\,\mathrm{GeV}$ ATLAS [JHEP 1411 (2014) 104] , $M_{X_{5/3}} > 800\,\mathrm{GeV}$ CMS [PRL 112 (2014) 171801]
  Run II: $M_{X_{5/3}} > 940(960)\,\mathrm{GeV}$ CMS [B2G-15-006]
- ATLAS and CMS determined a bound on (QCD) pair-produced top partners with charge $2/3$ (applicable for the T_s, T_{f1}, T_{f2}). [Similar bounds for B]

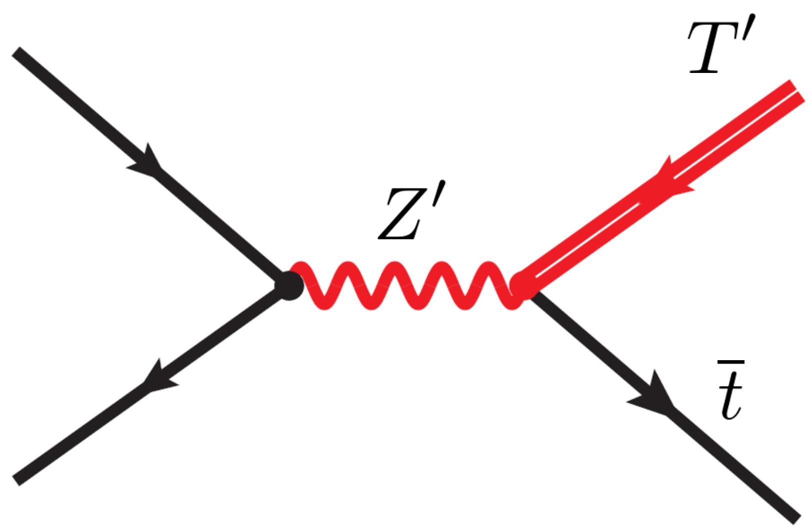




CMS [hep-ex:1509.04177]

Vector-like quarks: additional production processes via Z'





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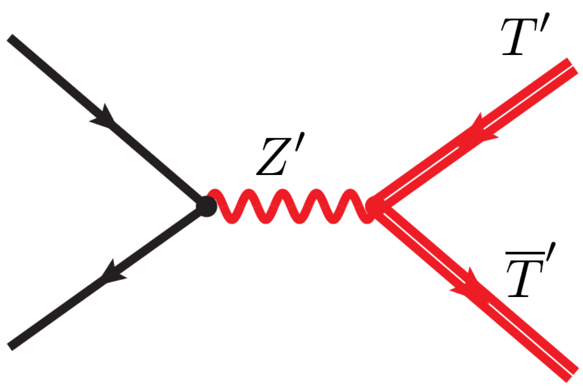
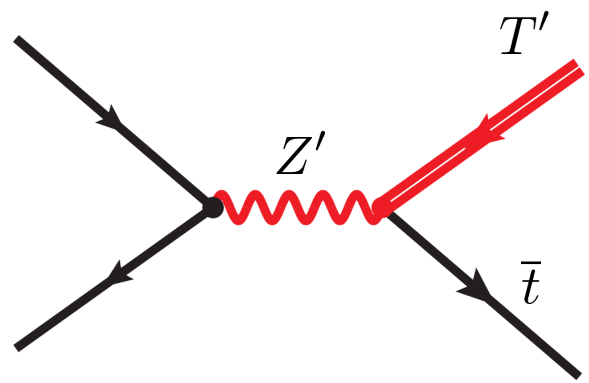
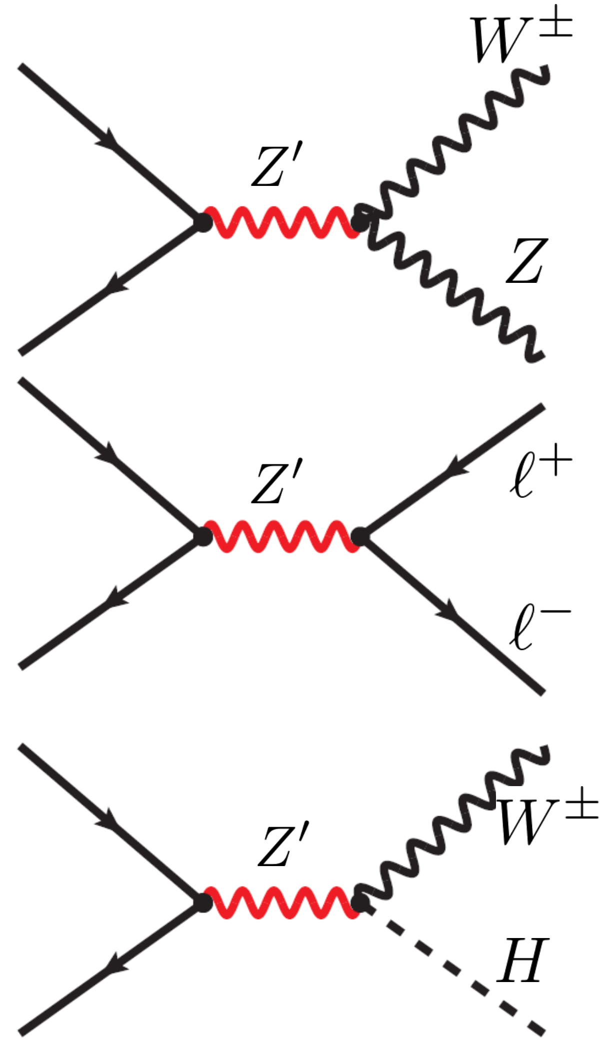


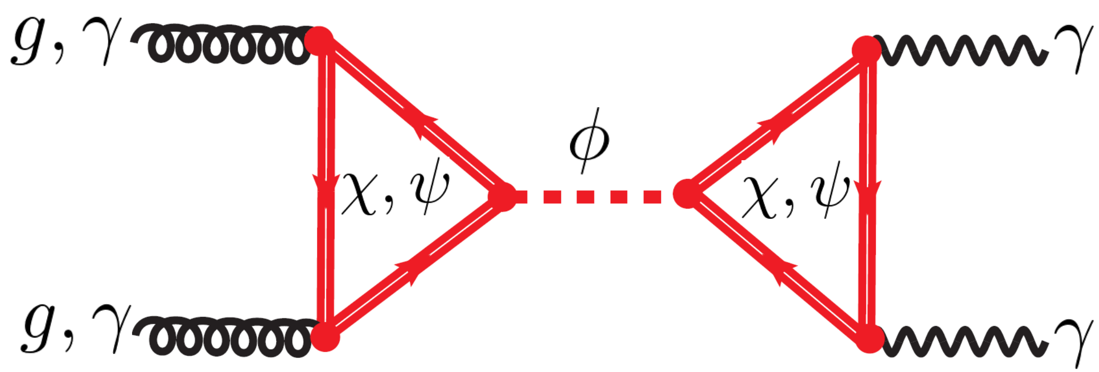




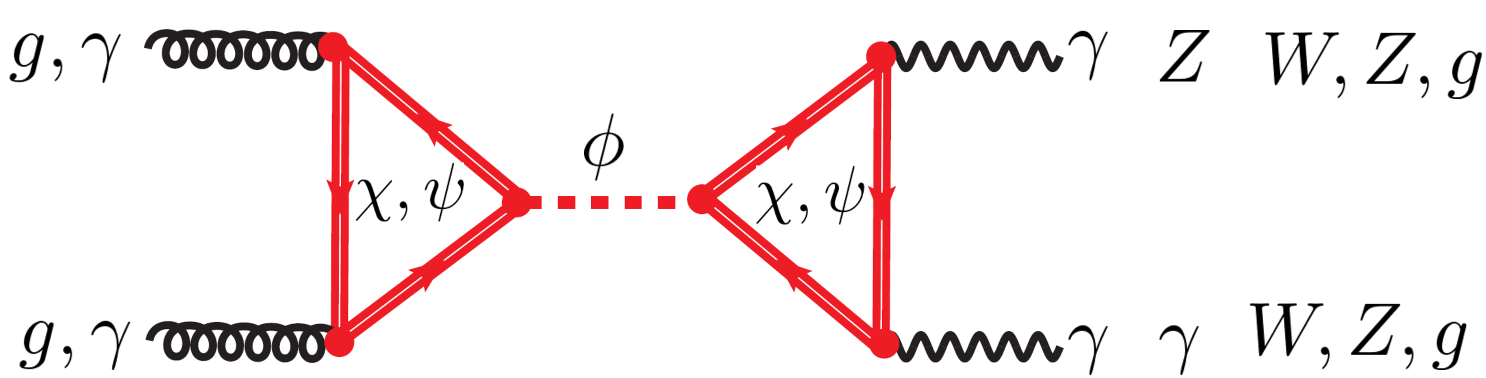
- Additional signatures to be added to support the “no loose” strategy for Z' searches discussed above
- Can be combined with di-lepton, VV, VH
- resonance searches if some excess is observed

New scalars: $\phi, \eta, \phi_8, \eta_8, \ldots$

- Strongly motivated by 750 di-photon LHC excess

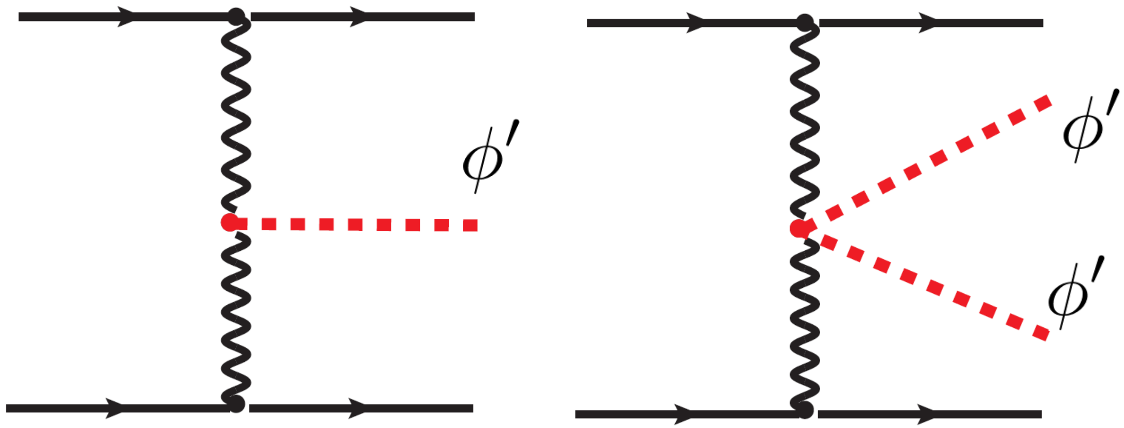


- The production above predicts correlated signatures with the rates calculable for each given coset

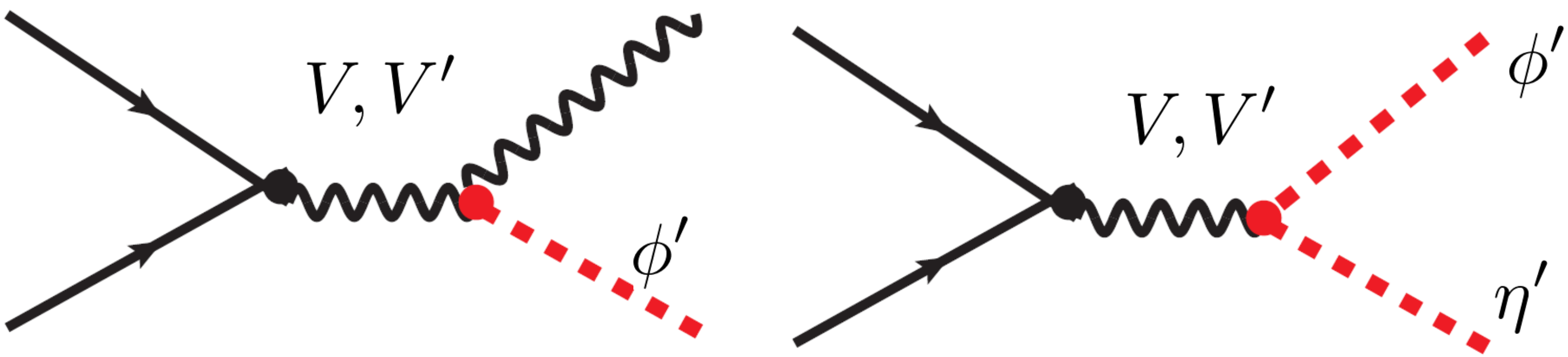


Production mechanisms for other new scalars

- VBF – pair and single production

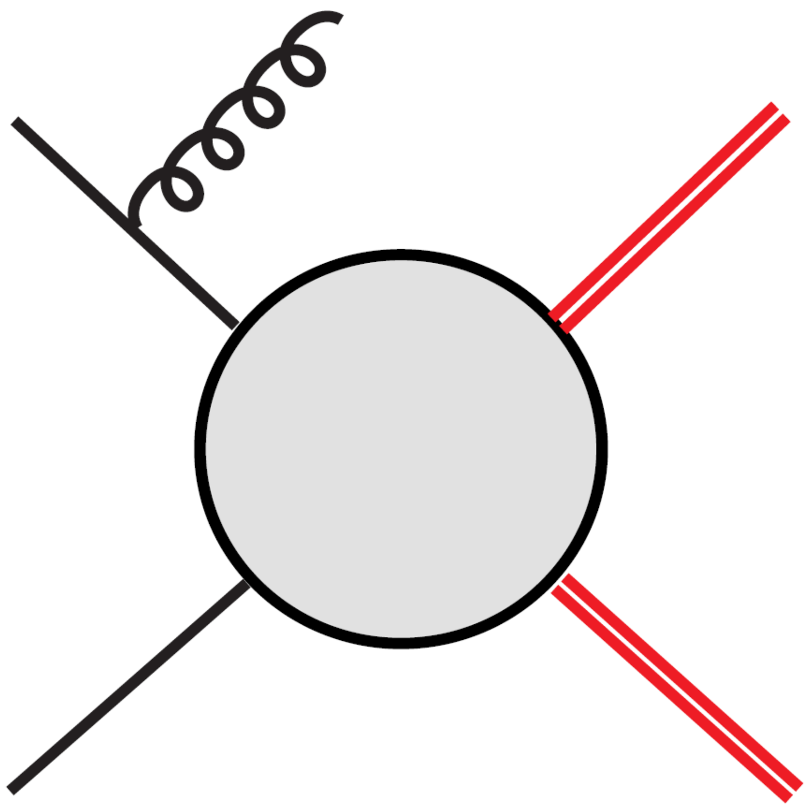


- Single and pair production via s-channel V(W,Z) , V'(W',Z')



Dark Matter signatures at the LHC

- Model-independent approach – DIM6 Contact Interactions (see last Tuesday's talk by Oleg Antipin's on DM model building



Dark Matter signatures at the LHC

- **Model-independent approach – DIM6 Contact Interactions**

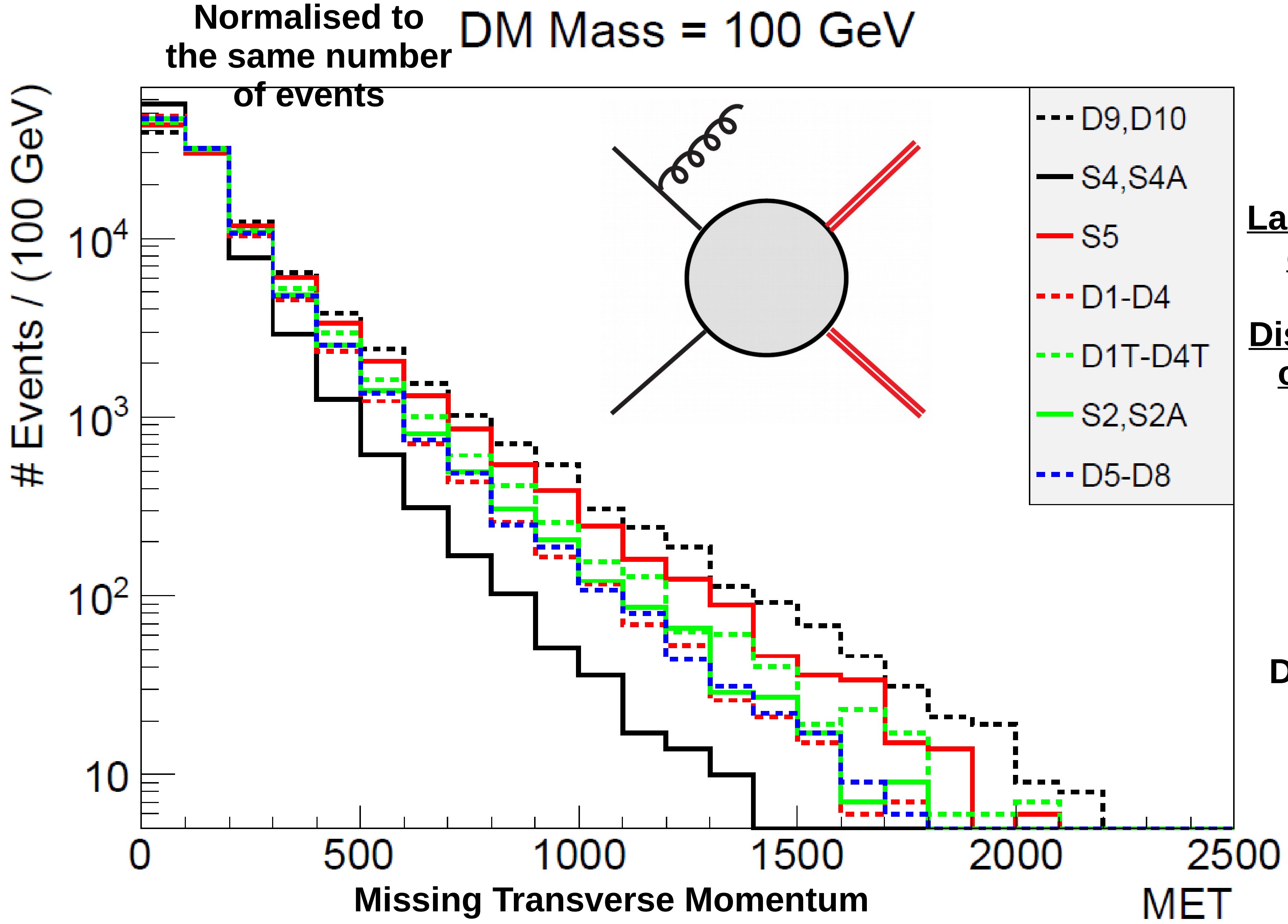
An update of Goodman, Ibe, Rajaraman, Shepherd, Tait,Yu, arXiv:1008.1783

Dirac Fermion DM	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$	[D1]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}q$	[D2]
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}\gamma^5 q$	[D3]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	[D4]
$\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ **NEW**	[D1T]
$\frac{i}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi + \bar{\chi}q\bar{q}\gamma^5\chi)$	[D2T]
$\frac{1}{2\Lambda^2}(\bar{\chi}\gamma^5 q\bar{q}\chi - \bar{\chi}q\bar{q}\gamma^5\chi)$	[D3T]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5 q\bar{q}\gamma^5\chi$	[D4T]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	[D5]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	[D6]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	[D7]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	[D8]
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	[D9]
$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	[D10]

Real or Complex Scalar DM	
$\frac{1}{\Lambda^2}\partial_\mu(\phi^{(\dagger)}\phi)\bar{q}\gamma^\mu q$ — Intergration by part = 0	[S1]
$\frac{1}{\Lambda^2}\partial_\mu(\phi^{(\dagger)}\phi)\bar{q}\gamma^\mu\gamma^5 q$	[S1A]
$\frac{i}{\Lambda^2}[\phi^\dagger(\partial_\mu\phi) - (\partial_\mu\phi^\dagger)\phi]\bar{q}\gamma^\mu q$	[S2]
$\frac{i}{\Lambda^2}[\phi^\dagger(\partial_\mu\phi) - (\partial_\mu\phi^\dagger)\phi]\bar{q}\gamma^\mu\gamma^5 q$	[S2A]
$\frac{i}{\Lambda^2}\phi^{(\dagger)}\phi(\bar{q}\overleftrightarrow{\not{D}}q)$ — Can be reduced to S4/S4A by EM	[S3]
$\frac{i}{\Lambda^2}\phi^{(\dagger)}\phi(\bar{q}\overleftrightarrow{\not{D}}\gamma^5 q)$	[S3A]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}q\Phi \Longrightarrow \frac{\tilde{m}}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}q$	[S4]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}\gamma^5 q\Phi \Longrightarrow \frac{\tilde{m}}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}\gamma^5 q$	[S4A]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi G^{\mu\nu}G^{\mu\nu}$	[S5]
$\frac{1}{\Lambda^2}\phi^{(\dagger)}\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$	[S5A]

MET distributions for Contact interactions

Normalised to the same number of events



Large kinematic differences between Distinct Groups of operators

D9, D10

S5,S5A

D1T-D4T

S2-S2A

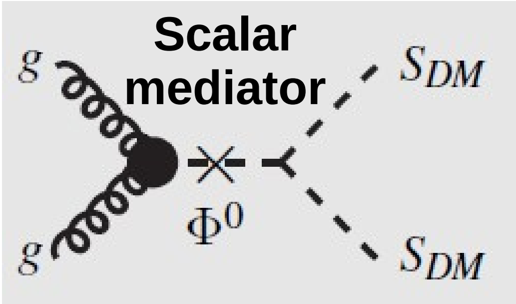
D1-D4 D5-D8

S4, S4A

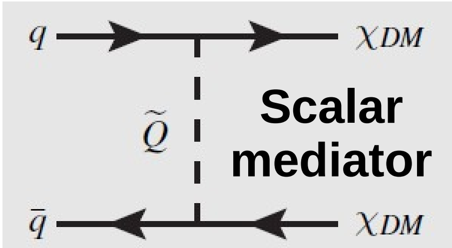
Mapping CI with Simplified models

D9 (D10) $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ **?**

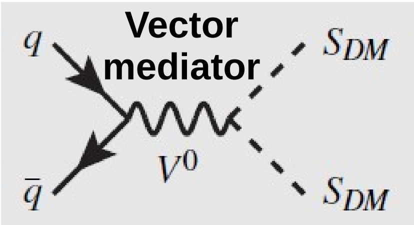
S5 S5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ →



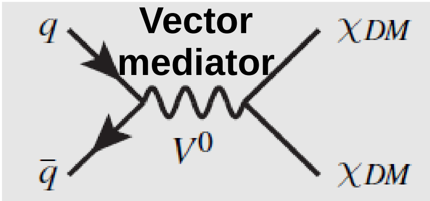
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

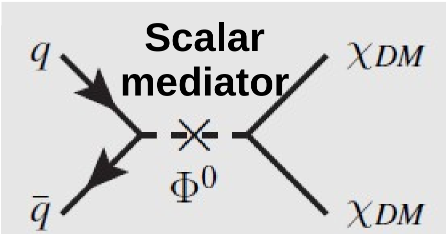


S2-S2A $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ →

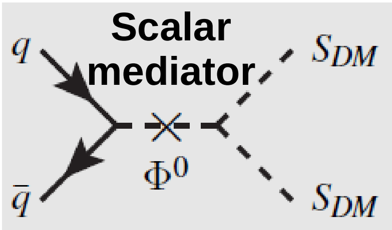


D1-D4 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ **D5-D8** $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ →

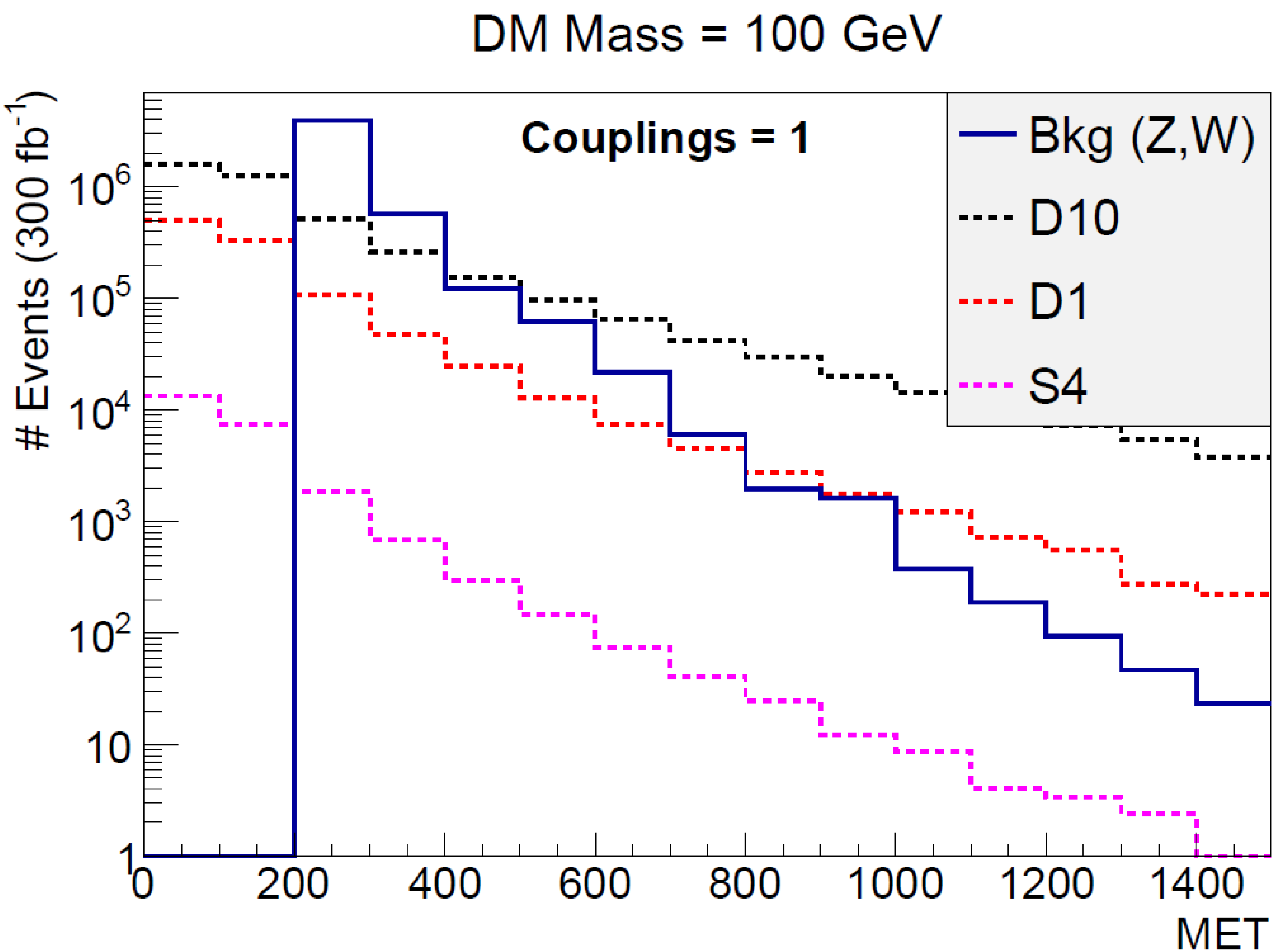




S4 (S4A) $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ →



Effects for Signal vs BG analysis

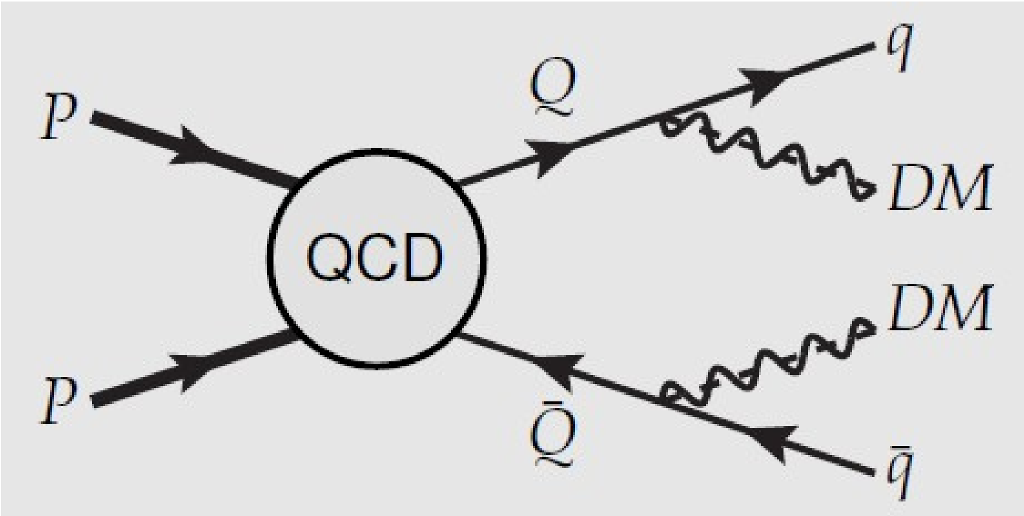



```
MET > 200:
    D10 eff = 0.30
    D1 eff = 0.20
    S4 eff = 0.13
    D10/S4 = 2.3

MET > 500:
    D10 eff = 0.074
    D1 eff = 0.031
    S4 eff = 0.014
    D10/S4  = 5.5

MET > 1000:
    D10 eff = 0.012
    D1 eff = 0.0033
    S4 eff = 0.0010
    D10/S4 = 12
```

- Different signal vs background MET distributions.
- Increase S/B ratio for large MET cuts.
- **Large differences in efficiencies of different operators. Important for exclusion/discovery studies.**

Model-specific DM signatures

- Just pair DM production via different mediators – monojet signature
- DM production from Top-partners decays

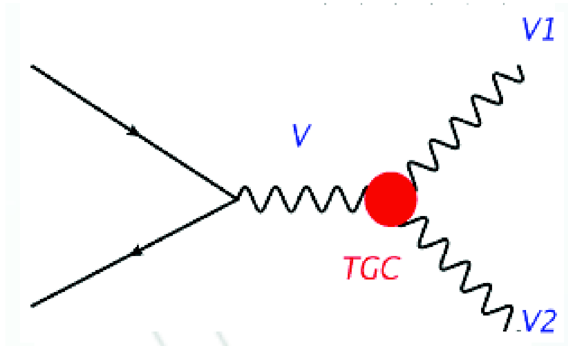


Cacciapaglia,Deandrea, Ellis, Marrouche, Panizzi arXiv:1302.4750 [hep-ph]
Edelhäuser, Krämer, SonneveldarXiv:1501.03942 [hep-ph]

- Limits are model-specific – depend also on the mass gap between Q and DM
- Do not forget to evaluate DM DD rates and the relic density!

Non-resonant signatures

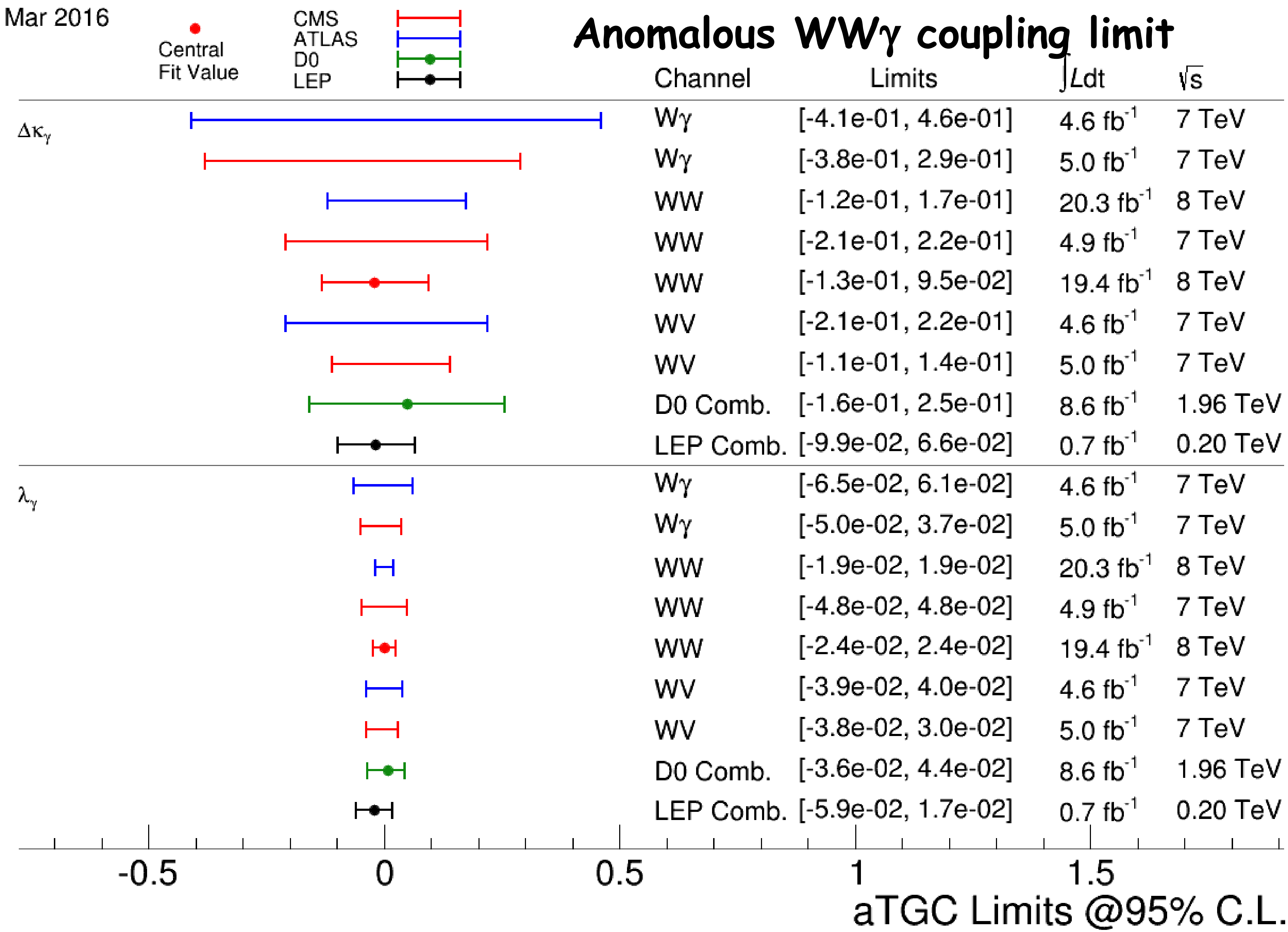
- **Triple and quartic gauge boson coupling**



$$
\begin{aligned}
i\mathcal{L}_{eff}^{WWV} = \; & g_{WWV}\Big[g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu} \right) + \kappa_V\, W^+_\mu W^-_\nu V^{\mu\nu} + \\
& \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W^-_{\rho\mu} + i g_5^V \varepsilon_{\mu\nu\rho\sigma} \left((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu} (\partial^\rho W^{+\nu}) \right) V^\sigma \\
& + i g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}{}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta} \Big]
\end{aligned}
$$

Non-resonant signatures

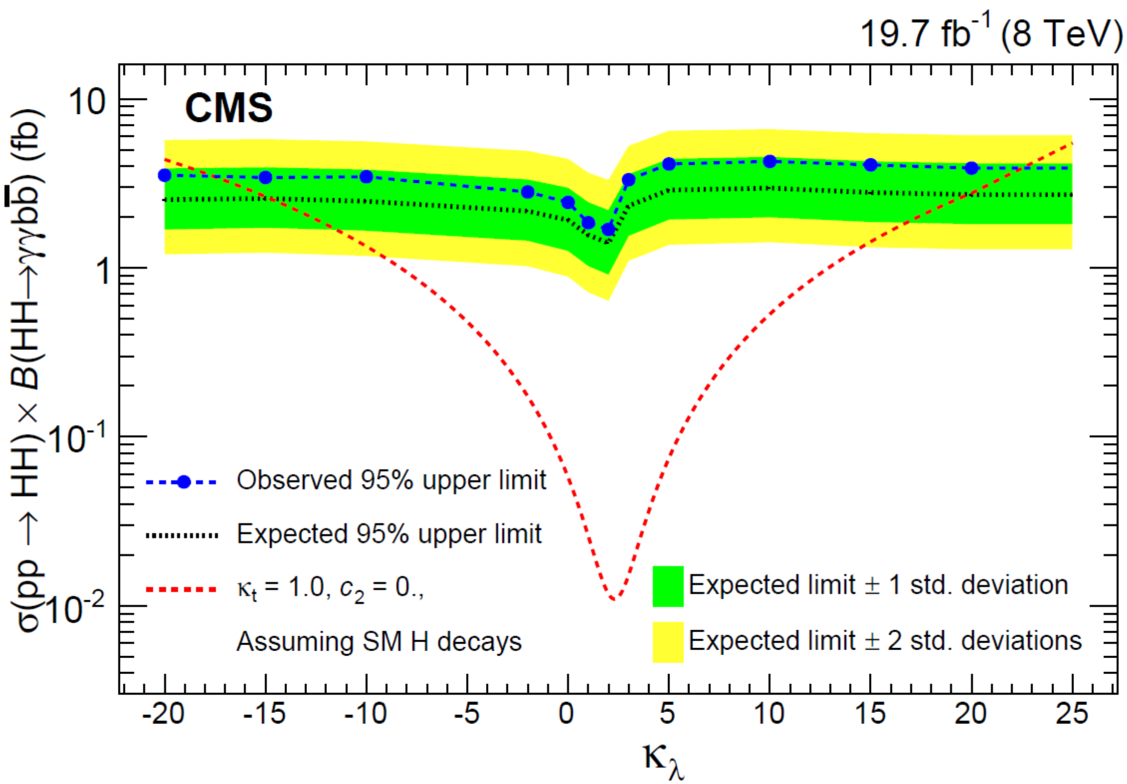
Anomalous WWγ coupling limit

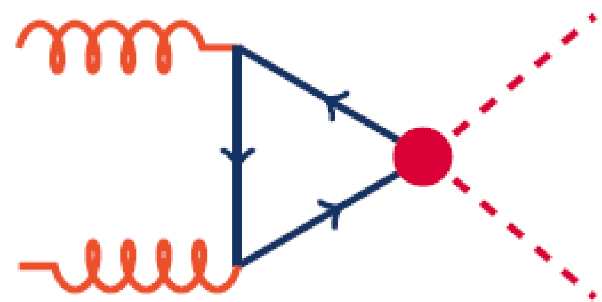


Non-resonant signatures

- **Probing ttHH CI with photons and two bottom quarks**
  (Alexandra Carvalho @ CMS)

$$\Delta\mathcal{L} = \kappa_\lambda\, \lambda^{\rm SM} v\, H^3 - \frac{m_{\rm t}}{v}\left(v + \kappa_{\rm t}\, H + \frac{c_2}{v} HH\right)\left(\bar{t}_{\rm L} t_{\rm R} + {\rm h.c.}\right),$$





Back to the strategy of identification of the underlying theory

- We need to formulate "theory space"
- Explore all possible signatures and their correlations
- And …

  wait for the signal from DATA (hopefully not so long ...)
- To keep track of signatures and correlations ideally we need database
  - the prototype of such database already exists - HEPMDB (High Energy Physics Model Data Base) https://hepmdb.soton.ac.uk
  - Allows users **to upload their own models** and run CalcHEP/MG/Whizard at HPC cluster (12K cores, 250 TFlops)
  - The database of signatures is under construction

HEPMDB

https://hepmdb.soton.ac.uk

HEPMDB

High Energy Physics Model Data

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? Ask your **questions** or file a **bug** at **Launchpad**.

About HEPMDB

HEPMDB was created to facilitate connection between High Energy theory and experiment, and it is a tool to store and validate and explore models of particle physics. The ultimate goal of HEPMDB is to instrument identification of the fundamental theory responsible for signals expected at the LHC.

HEPMDB provides option to run computations on the IRIDIS4 HPC supercluster at the University of Southampton. This vastly improves efficiency for researchers studying theories beyond the Standard Model.

This database is in the development stage, please use Launchpad for any issues! The database accumulates

2016

Site-breaking bugs fixed #1

Hi all, There were a few site-breaking bugs fixed, if your account is broken due to blank model names, please reset your account by going Calculate -> Menu -> Reset Account

More »

HEPMDB

https://hepmdb.soton.ac.uk

HEPMDB
High Energy Physics Model Data Base

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1. **NLSU4CHM** [2016-04-12 16:00:35] hepmdb:0416.0200

   Haiying Cai, Diogo Buarque Franzosi

   This model is for Madgraph, where spin-0 and spin-1 resonances are implemented into an SU(4)/Sp(4) composite Higgs model using the Hidden symmetry technology. There are 15 vectors and axial-vectors, ...

2. **4DCHM** [2012-12-14 16:37:59] hepmdb:1212.0120

   D. Barducci, A. Belyaev, S. De Curtis, S. Moretti and G.M. Pruna

   In order to respect EW precision constraints and reconstruct the Higgs mass and VEV one SHOULD NOT vary the parameters of the model independently. One should generate input parameters that respects...

3. **4DCHM (with HAA/HGG)** [2013-02-09 16:53:55] hepmdb:0213.0123

Your input/suggestions/comments on

- New Models
- New Signatures
- The strategy to explore CHM space
- Relevance of Database
- Anything else

Is very important!