New Fermions and Exotica

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Snowmass, Energy Frontier
EF09: BSM: More general explorations

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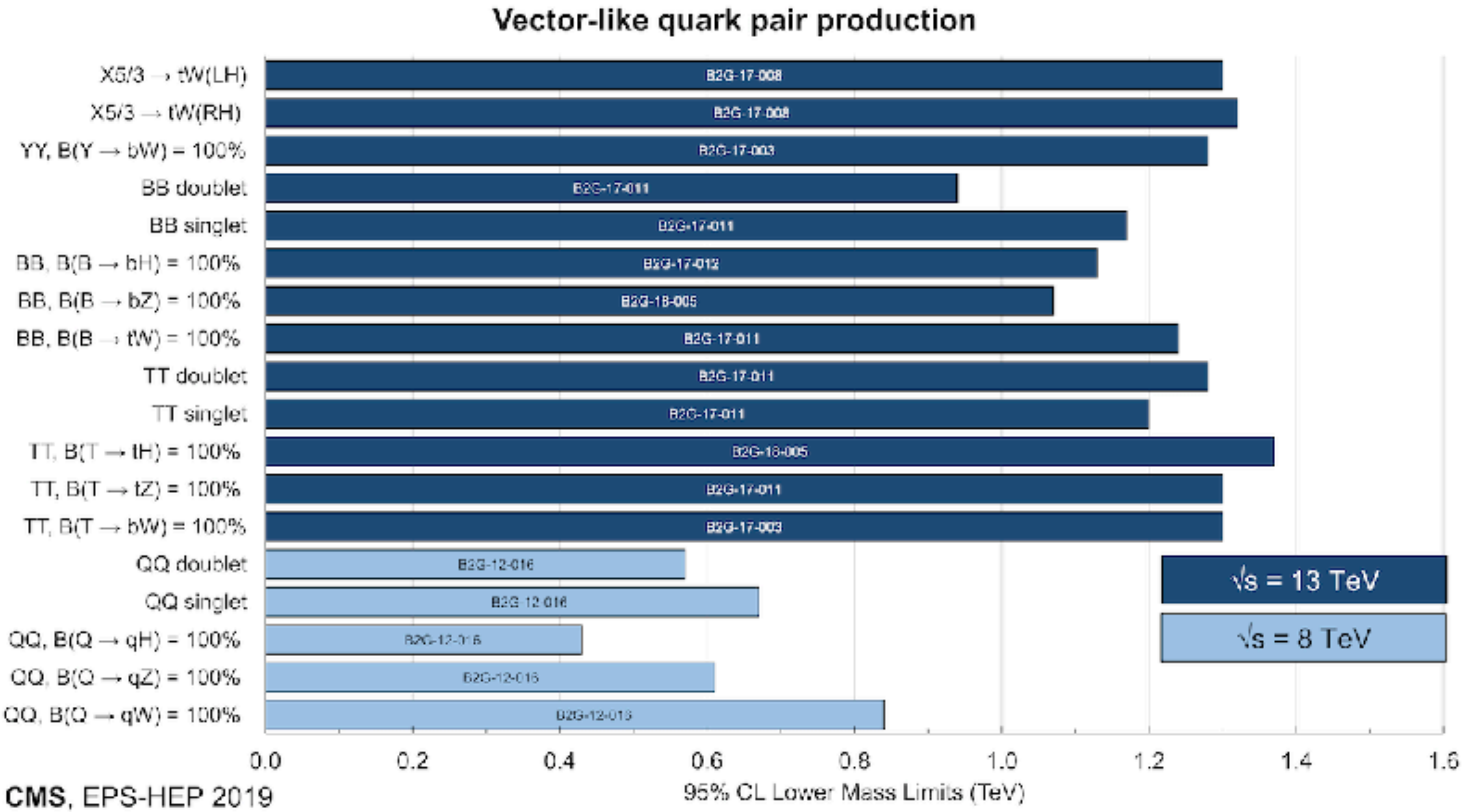
Slide by H. Murayama

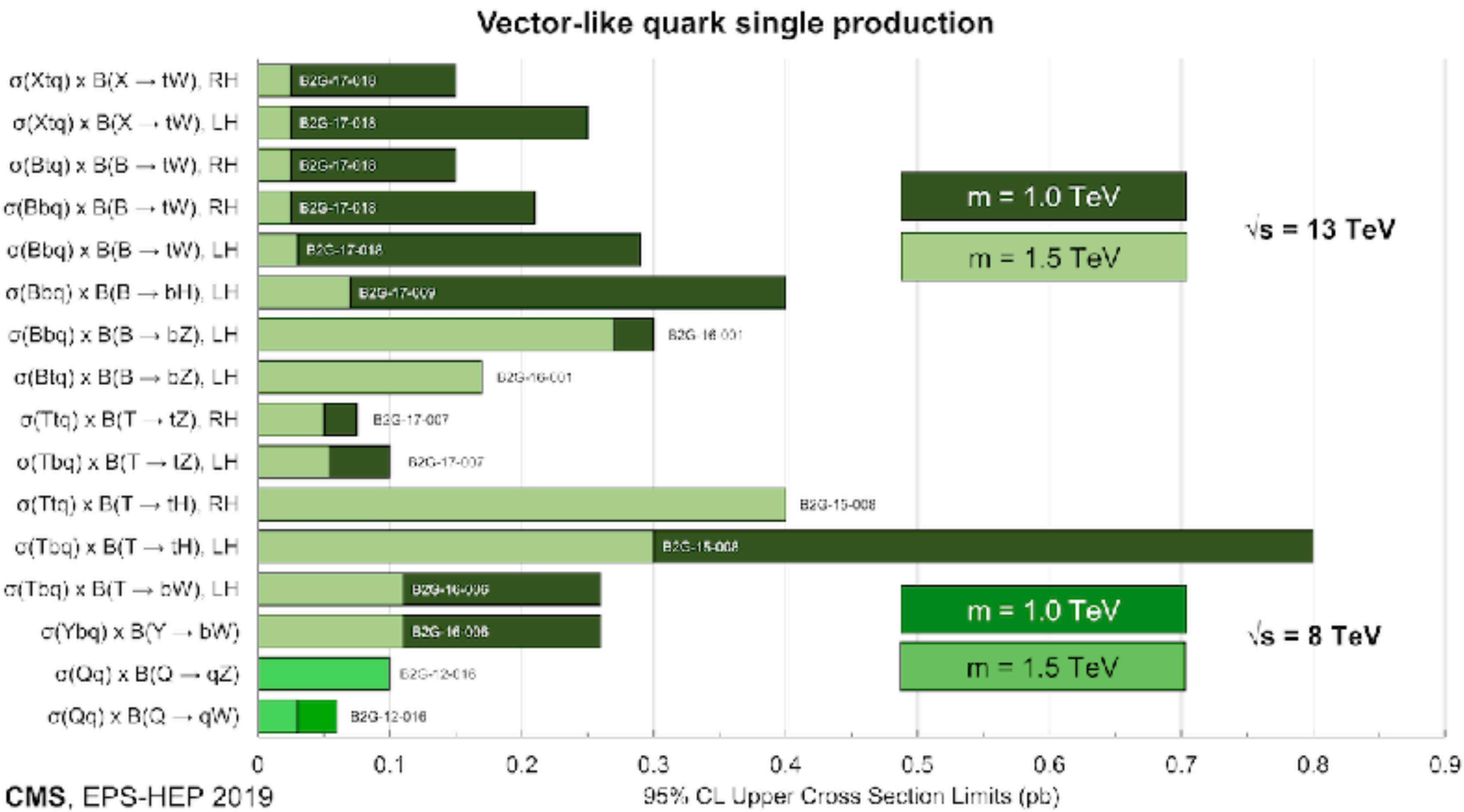
What are we looking for?

- We are looking for new physics beyond the SM
  - new matter particles (colored, color neutral, DM, …)
  - new force carriers (Z’, W’, G’, dark photon …)
  - new phenomena which may not involve new particles (indirect searches …)
- Each model and each particle has their own (theoretical / experimental) motivations.
- Two (naive) classes of BSM searches
  - SUSY vs non-SUSY (exotica)
- Searches for new fermions and new forces under the second category (exotica).

New fermions

- New fermions arise in many different BSM models
  - colored vs color neutral
  - parity even vs parity odd
  - chiral vs vector-like
  - exotic electric charges (5/3, -4/3, 2 etc) vs standard electric charges
- New fermions arise in many different BSM models
  - direct production: pair vs single production
  - indirect production from the decay of a heavier particle

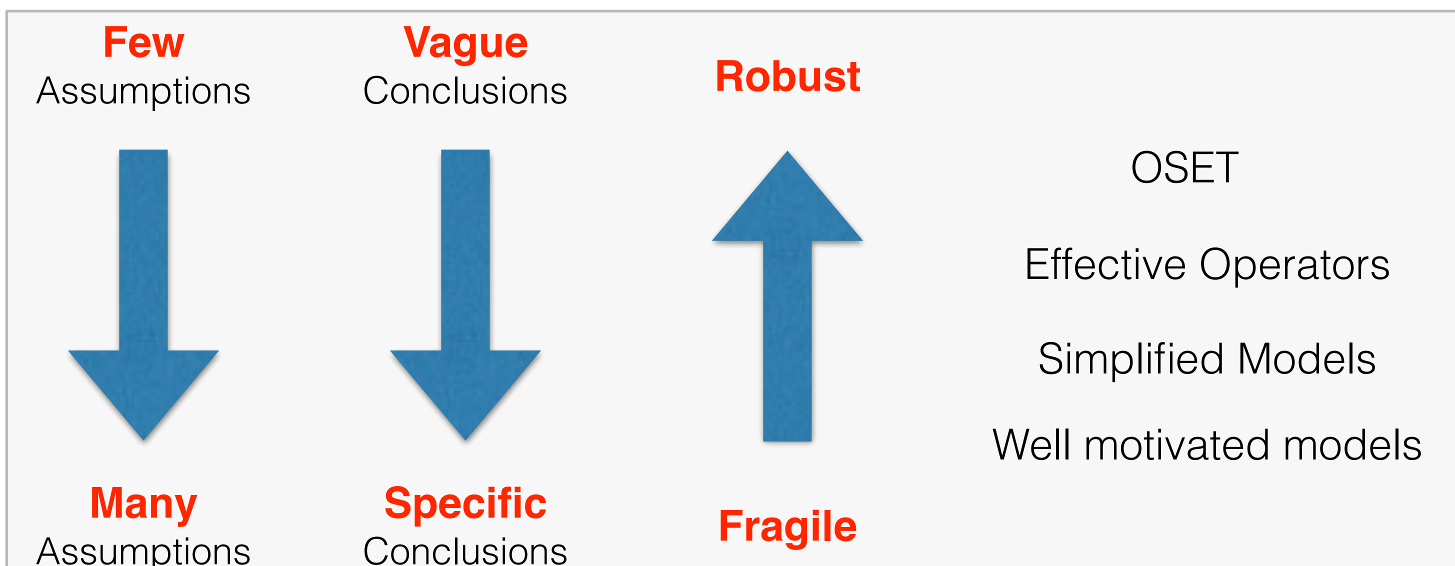

Vector-like quark pair production
X5/3 → tW(LH)
B2G-17-008
X5/3 → tW(RH)
B2G-17-008
YY, B(Y → bW) = 100%
B2G-17-003
BB doublet
B2G-17-011
BB singlet
B2G-17-011
BB, B(B → bH) = 100%
B2G-17-012
BB, B(B → bZ) = 100%
B2G-18-005
BB, B(B → tW) = 100%
B2G-17-011
TT doublet
B2G-17-011
TT singlet
B2G-17-011
TT, B(T → tH) = 100%
B2G-18-005
TT, B(T → tZ) = 100%
B2G-17-011
TT, B(T → bW) = 100%
B2G-17-003
QQ doublet
B2G-12-016
QQ singlet
B2G-12-016
QQ, B(Q → qH) = 100%
B2G-12-016
QQ, B(Q → qZ) = 100%
B2G-12-016
QQ, B(Q → qW) = 100%
B2G-12-016
√s = 13 TeV
√s = 8 TeV
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
95% CL Lower Mass Limits (TeV)
CMS, EPS-HEP 2019



Vector-like quark single production
σ(Xtq) x B(X → tW), RH
σ(Xtq) x B(X → tW), LH
σ(Btq) x B(B → tW), RH
σ(Bbq) x B(B → tW), RH
σ(Bbq) x B(B → tW), LH
σ(Bbq) x B(B → bH), LH
σ(Bbq) x B(B → bZ), LH
σ(Btq) x B(B → bZ), LH
σ(Ttq) x B(T → tZ), RH
σ(Tbq) x B(T → tZ), LH
σ(Ttq) x B(T → tH), RH
σ(Tbq) x B(T → tH), LH
σ(Tbq) x B(T → bW), LH
σ(Ybq) x B(Y → bW)
σ(Qq) x B(Q → qZ)
σ(Qq) x B(Q → qW)
B2G-17-018
B2G-17-009
B2G-16-001
B2G-17-007
B2G-15-008
B2G-16-006
B2G-12-016
m = 1.0 TeV
m = 1.5 TeV
√s = 13 TeV
m = 1.0 TeV
m = 1.5 TeV
√s = 8 TeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
95% CL Upper Cross Section Limits (pb)
CMS, EPS-HEP 2019

How to Search for BSM

- There isn't a unique way. No right or wrong approach.
- Start with precision measurement of SM. Use Higgs / top quark.
- We have many "templates" for BSM physics.
- Well "motivated" models: Supersymmetry, extra dimensions, strong dynamics etc
- OSET: On-Shell Effective Theories (event topology with kinematics only)
- Effective Operators
- Simplified Models

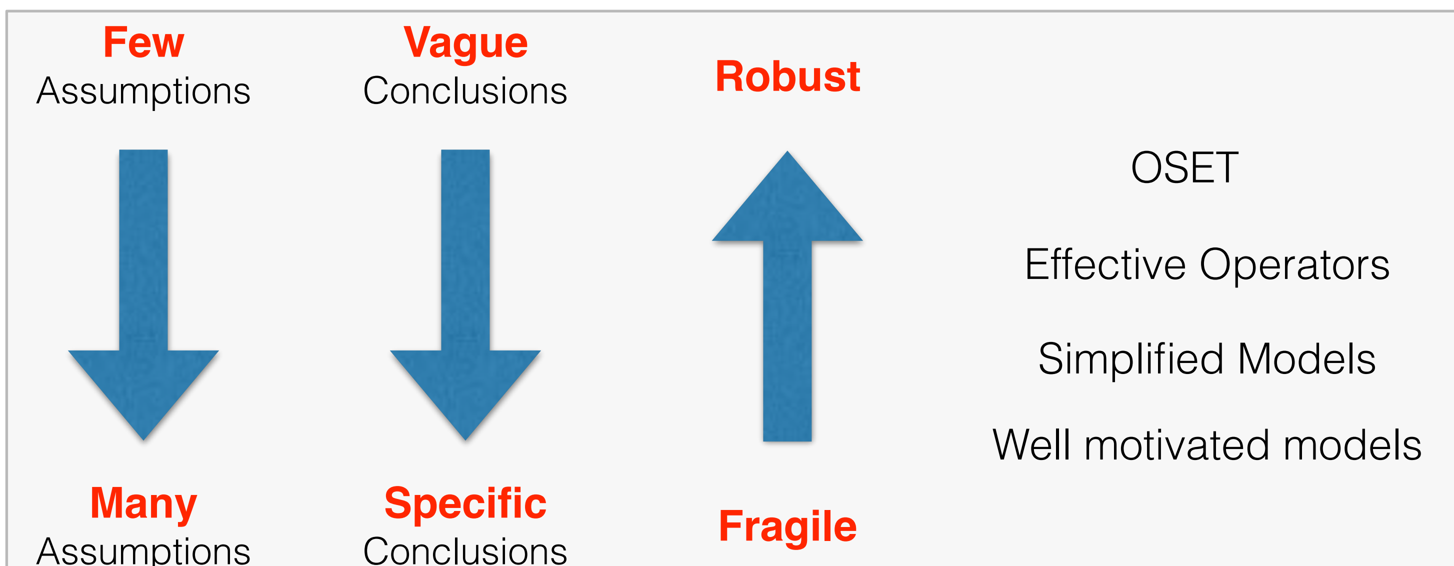


- **Alternatively, we could consider a strategy for searching for theoretically-unanticipated new physics which avoids a large trials factor by focusing on experimental strengths. Searches for resonances decaying into pairs of visible particles are experimentally very powerful due to the localized mass peaks and have a rich history of discovery.**

- **Yet, due to a focus on subsets of theoretically-motivated models, the landscape of such resonances is far from thoroughly explored.**

- Effective Operators

- Simplified Models



Unexplored Landscape of Two-Body Resonances

- Let us consider all possible combinations of two reconstructed objects (putting aside theoretical constraints.)

	e	μ	τ	γ	j	b	t	W	Z	h
e	?									
μ										
τ										
γ							?			
j										
b										
t										
W										
Z										
h										

Unexplored Landscape of Two-Body Resonances

- Let us consider all possible combinations of two reconstructed objects (putting aside theoretical constraints.)

	e	μ	τ	γ	j	b	t	W	Z	h
e	$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, e_{KK}	L^*
μ		$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, μ_{KK}	L^*
τ			$Z', H, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, τ_{KK}	L^*
γ				$H, G_{KK}, \mathcal{Q}$	Q^*	Q^*	Q^*	$W_{KK}, \mathcal{Q}$	$H, \mathcal{Q}$	Z_{KK}
j					Z', ρ, G_{KK}	$W', \not{R}$	$T', \not{R}$	Q^*, Q_{KK}	Q^*, Q_{KK}	Q'
b						Z', H	$W', \not{R}, H^{\pm}$	T', Q^*, Q_{KK}	Q^*, Q_{KK}	B'
t							H, G', Z'	T'	T'	T'
W								H, G_{KK}, ρ	$W', \mathcal{Q}$	$H^{\pm}, \mathcal{Q}, \rho$
Z									H, G_{KK}, ρ	A, ρ
h										H, G_{KK}

TABLE II. Theory models motivating two-body final state resonance searches. Here Z' and W' denote additional gauge bosons, $\not{R}$ denotes R-parity violating decays of sparticles in supersymmetry, $H^{\pm\pm}$ denotes doubly-charged Higgs bosons, H denotes additional neutral scalar or pseudoscalar Higgs bosons, L^* and Q^* denote excited fermions, X_{KK} denote various Kaluza-Klein excitations of gravitons or Standard Model fields, ρ denotes neutral or charged techni-rhos, LQ denotes leptoquarks, T', B', Q' denote vector-like top, bottom, and light-flavor quarks, and $\mathcal{Q}$ denotes quirks. See also [38].

Craig, Draper, Kong, Ng, Whiteson 1610.09392

Unexplored Landscape of Two-Body Resonances

	ℓ	γ	q	g	b	t	W^+	Z	h
ℓ	$(\mathbf{1},2)^*$	$[\mathbf{1},1]^*$	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{8},1]^*$	$(\bar{\mathbf{3}},{}^{4}/_3)^{\diamondsuit\heartsuit}$	$(\bar{\mathbf{3}},{}^{1}/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{1},0]^*$	$[\mathbf{1},1]^*$	$[\mathbf{1},1]^*$
$\bar{\ell}$	$(\mathbf{1},0)$	$[\mathbf{1},-1]^*$	$(\bar{\mathbf{3}},-{}^{2(5^*)}/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{8},-1]^*$	$(\bar{\mathbf{3}},-{}^{2}/_3)^{\diamondsuit\heartsuit}$	$(\bar{\mathbf{3}},-{}^{5}/_3)^*$	$[\mathbf{1},-2]^*$	$[\mathbf{1},-1]^*$	$[\mathbf{1},-1]^*$
γ	$[\mathbf{1},1]^*$	$(\mathbf{1},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$(\mathbf{1},-1)$	$(\mathbf{1},0)$	$(\mathbf{1},0)$
q	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamondsuit\heartsuit}$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)(-4)}/_3)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$(\mathbf{3},{}^{-1(-4)}/_3)$	$[\bar{\mathbf{3}},{}^{-2(-5^*)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$
$\bar{q}$	$(\mathbf{3},{}^{2(5^*)}/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(-4^*)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$
g	$[\mathbf{8},1]^*$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$(\mathbf{8},-1)$	$(\mathbf{8},0)$	$(\mathbf{8},0)$
b		$[\bar{\mathbf{3}},{}^{1}/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$(\mathbf{3},{}^{2}/_3)$	$(\mathbf{3},-{}^{1}/_3)$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$[\bar{\mathbf{3}},{}^{1}/_3]$
$\bar{b}$			$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},-{}^{1}/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$(\mathbf{1}(\mathbf{8}),-1)$	$[\mathbf{3},-{}^{4}/_3]^*$	$[\mathbf{3},-{}^{1}/_3]$	$[\mathbf{3},-{}^{1}/_3]$
t				$[\bar{\mathbf{3}},-{}^{2}/_3]$	$(\mathbf{3},-{}^{1}/_3)$	$(\mathbf{3},-{}^{4}/_3)$	$[\bar{\mathbf{3}},-{}^{5}/_3]^*$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$[\bar{\mathbf{3}},-{}^{2}/_3]$
$\bar{t}$					$(\mathbf{1}(\mathbf{8}),1)$	$(\mathbf{1}(\mathbf{8}),0)$	$[\mathbf{3},-{}^{1}/_3]$	$[\mathbf{3},{}^{2}/_3]$	$[\mathbf{3},{}^{2}/_3]$
W^+						$[\bar{\mathbf{3}},-{}^{5}/_3]^*$	$(\mathbf{1},-2)^*$	$(\mathbf{1},-1)$	$(\mathbf{1},-1)$
W^-							$(\mathbf{1},0)$	$(\mathbf{1},1)$	$(\mathbf{1},1)$
Z								$(\mathbf{1},0)$	$(\mathbf{1},0)$
h									$(\mathbf{1},0)$

( ): boson resonance

[ ]: fermionic resonance

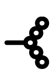
$*$: no possible initial state at the LHC

$\diamondsuit$ $\Delta B = 1$
$\heartsuit$ $\Delta L = 1$ (if couples to q / g)

Possible (QCD, EM) quantum numbers of each 2-body resonance

 indicates the existence of a resonant production via tree-level decay coupling, loop-induced processes involving the decay coupling, or the inclusion of additional couplings to quarks / gluons (allowed by quantum numbers).

 indicate the leading production mode in association with 1, 2, 3 and 4 SM particles using the same coupling for production and decay (in 4 flavor scheme).

 indicates the unavoidable existence of a pair production mode.

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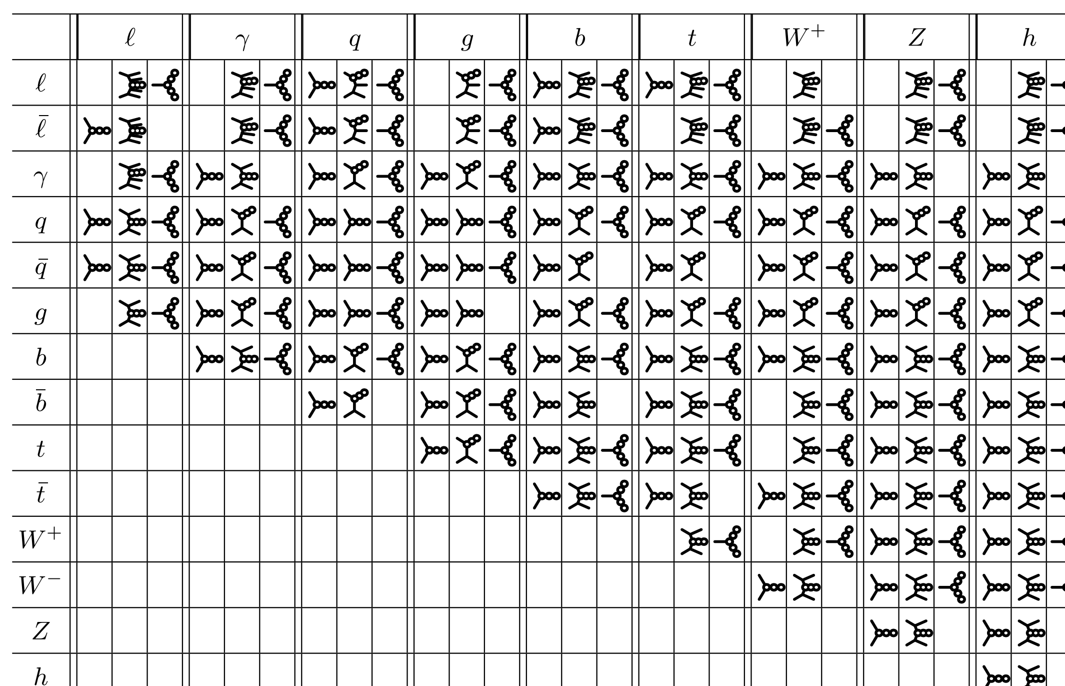

Survey of n=2 Final State at the LHC

	e	μ	τ	γ	j	b	t	W	Z	h
e	$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, e_{KK}	L^*
μ		$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, μ_{KK}	L^*
τ			$Z', H, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, τ_{KK}	L^*
γ				$H, G_{KK}, \mathcal{Q}$	Q^*	Q^*	Q^*	$W_{KK}, \mathcal{Q}$	$H, \mathcal{Q}$	Z_{KK}
j					Z', ρ, G_{KK}	$W', \not{R}$	$T', \not{R}$	Q^*, Q_{KK}	Q^*, Q_{KK}	Q'
b						Z', H	$W', \not{R}, H^{\pm}$	T', Q^*, Q_{KK}	Q^*, Q_{KK}	B'
t							H, G', Z'	T'	T'	T'
W								H, G_{KK}, ρ	$W', \mathcal{Q}$	$H^{\pm}, \mathcal{Q}, \rho$
Z									H, G_{KK}, ρ	A, ρ
h										H, G_{KK}

Survey of n=2 Final State at the LHC

	e	μ	τ	γ	j	b	t	W	Z	h
e	$\pm\mp$[4],$\pm\pm$[5]	$\pm\pm$[5, 6] $\pm\mp$[6, 7]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
μ		$\pm\mp$[4],$\pm\pm$[5]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
τ			[8]	$\varnothing$	$\varnothing$	$\varnothing$	[9]	$\varnothing$	$\varnothing$	$\varnothing$
γ				[10]	[11–13]	$\varnothing$	$\varnothing$	[14]	[14]	$\varnothing$
j					[15]	[16]	[17]	[18]	[18]	$\varnothing$
b						[16]	[19]	$\varnothing$	$\varnothing$	$\varnothing$
t							[20]	[21]	$\varnothing$	$\varnothing$
W								[22–25]	[23, 24, 26, 27]	[28–30]
Z									[23, 25, 31]	[28, 30, 32, 33]
h										[34–37]

- Existing two-body exclusive final state resonance searches at 7 and 8 TeV LHC, with striking features that most diagonal entries have existing searches, whereas most off-diagonal entries do not. (Numbers represent ATLAS/CMS references.)
- $\varnothing$ symbol indicates no existing searches at the LHC (7 and 8 TeV).
- No Tevatron analyses included. No 13 TeV analyses included.

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Extension with BSM

	e	μ	τ	q/g	b	t	γ	Z/W	H	BSM $\to$ $SM_1 \times SM_1$				BSM $\to$ $SM_1 \times SM_2$			BSM $\to$ complex			
										q/g	γ/π^0's	b	$\cdots$	tZ/H	bH	$\cdots$	$\tau qq'$	eqq'	$\mu qq'$	$\cdots$
e	[37, 38]	[39, 40]	[39]	∅	∅	∅	[41]	[42]	∅	∅	∅	∅		∅	∅	∅	∅	[43, 44]	∅	
μ		[37, 38]	[39]	∅	∅	∅	[41]	[42]	∅	∅	∅	∅		∅	∅	∅	∅	∅	[43, 44]	
τ			[45, 46]	∅	[47]	∅	∅	∅	∅	∅	∅	∅		∅	∅	∅	[48, 49]	∅	∅	
q/g				[29, 30, 50, 51]	[52]	∅	[53, 54]	[55]	∅	∅	∅	∅		∅	∅	∅	∅	∅	∅	
b					[29, 52, 56]	[57]	[54]	[58]	[59]	∅	∅	∅		[60]	∅	∅	∅	∅	∅	
t						[61]	∅	[62]	[63]	∅	∅	∅		[64]	[60]	∅	∅	∅	∅	
γ							[65, 66]	[67–69]	[68, 70]	∅	∅	∅		∅	∅	∅	∅	∅	∅	
Z/W								[71]	[71]	∅	∅	∅		∅	∅	∅	∅	∅	∅	
H									[72, 73]	[74]	∅	∅		∅	∅	∅	∅	∅	∅	
BSM $\to$ $SM_1 \times SM_1$: q/g										∅	∅	∅		∅	∅	∅	∅	∅	∅	
γ/π^0's											[75]	∅		∅	∅	∅	∅	∅	∅	
b												[76, 77]		∅	∅	∅	∅	∅	∅	
$\vdots$																				
$\vdots$																				
BSM $\to$ $SM_1 \times SM_2$: tZ/H																				
bH																				
$\vdots$																				
$\vdots$																				
BSM $\to$ complex: $\tau qq'$																				
eqq'																				
$\mu qq'$																				
$\vdots$																				
$\vdots$																				

Kim, Kong, Nachman, Whiteson 1907.06659

- A -> B C, where B, C can be BSM particle.

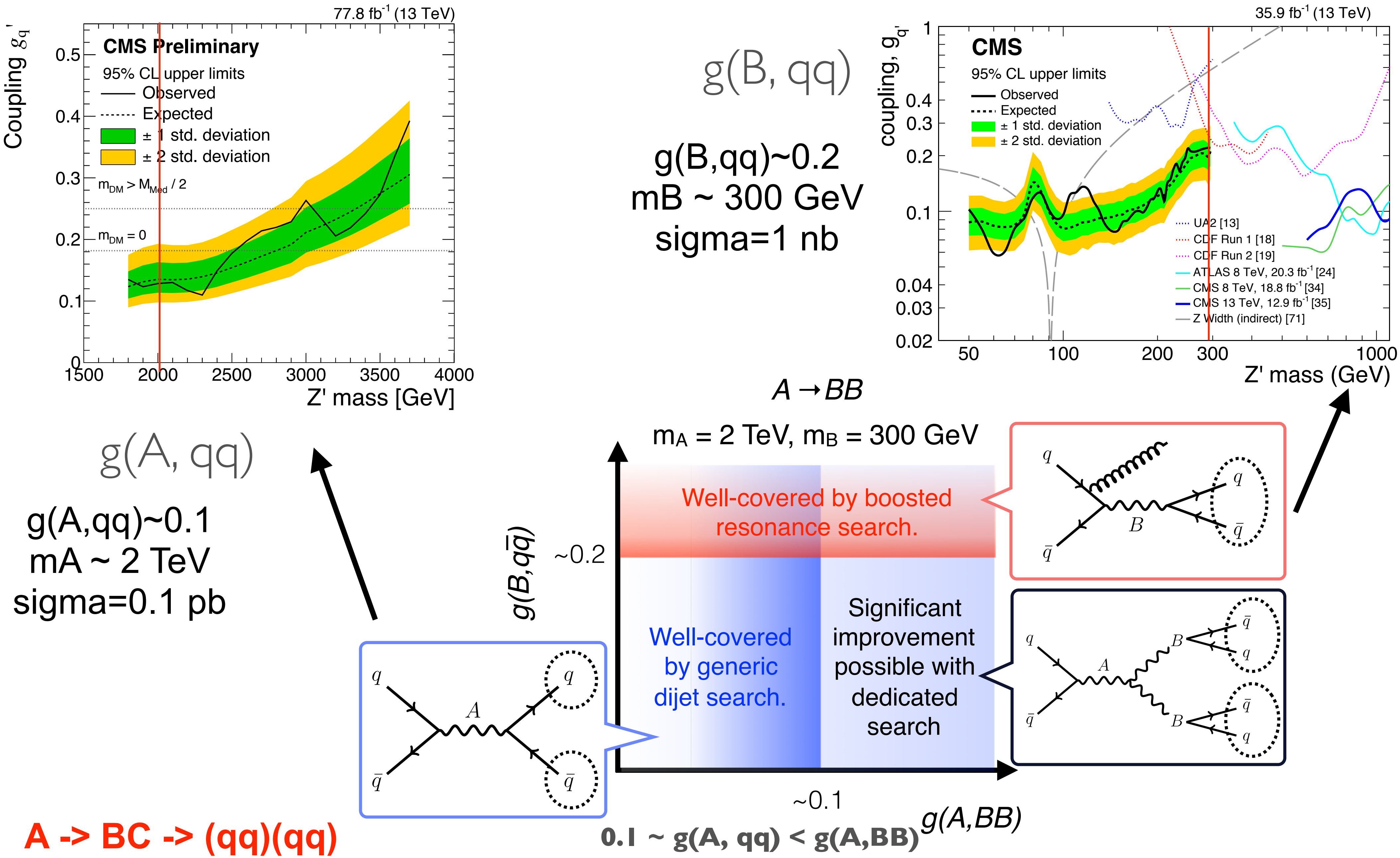


Figure 1: An illustration of the complementarity of the search for A (inclusive dijet resonance search) and the search for B (boosted resonance search). Dotted circles indicate hadronic activity that will likely be mostly captured by one (potentially large-radius) jet. When $m_A = 2$ TeV and $m_B = 300$ GeV, the inclusive dijet search likely has reduced sensitivity to $A \to BB$ because the B decay products are not well-contained inside a single small-radius jet. Therefore, when $g(A, BB) \gtrsim g(A, q\bar{q}) \sim 0.1$, gains are possible for a dedicated search.

- Given the lack of significant excess at the LHC and the lack of a unique theory to guide the search program, now is the time to consider diversifying the experimental sensitivity. Organizing the possibilities by final state provides a way forward.

- While the traditional search program will be able to accommodate many of the possibilities described earlier, there are not enough resources to consider all potential final states. Therefore, dedicated searches will likely need to be complimented with more model agnostic searches. Machine learning methods may be able to automate this approach and solve significant statistical challenges like large trial factors.

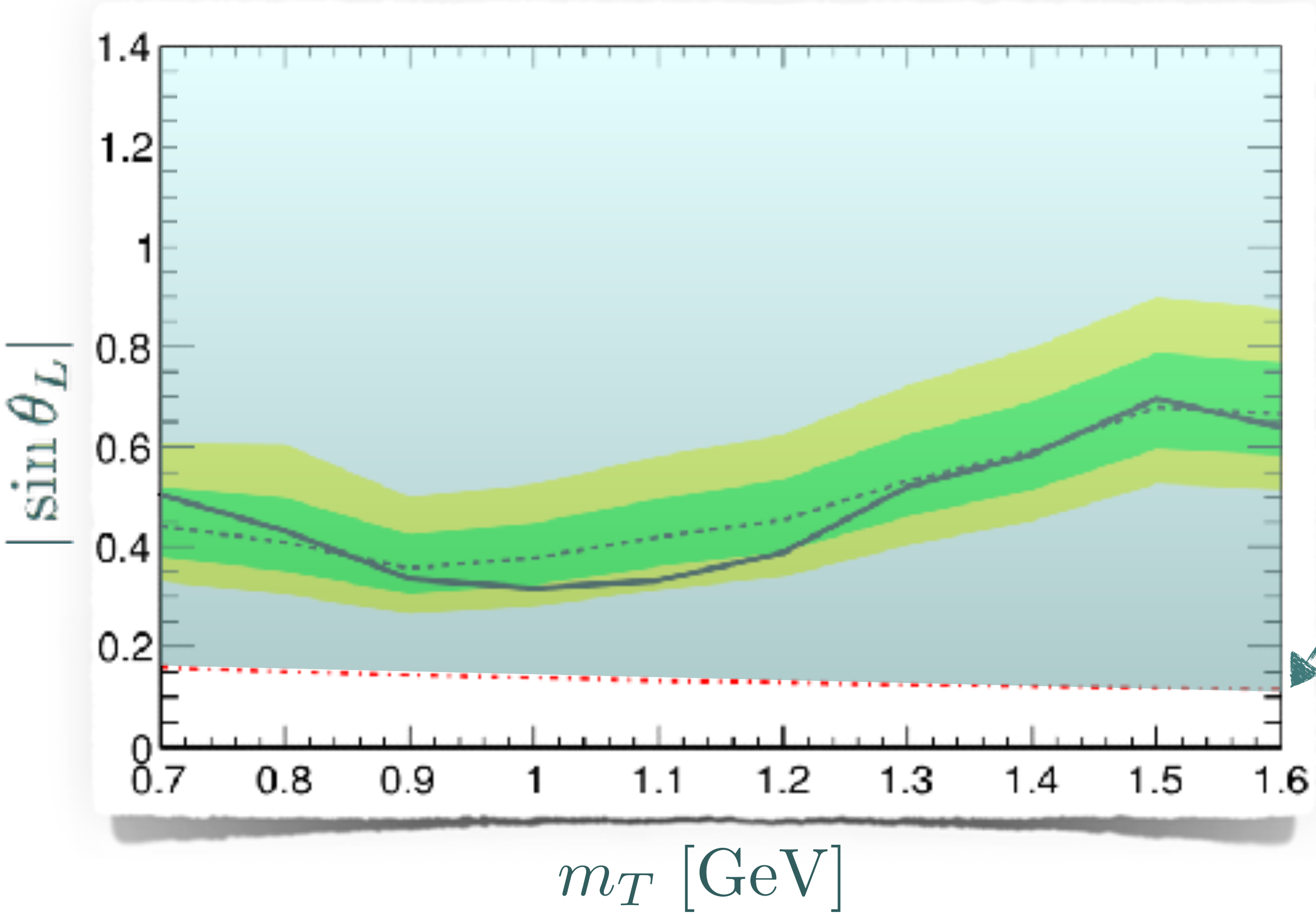
See talk by Ben Nachman

Going back to top partners

- We tend to set bounds on the mass of new particles.
- But there are other parameters in the model.
- For example, in models with top partners, the mixing angle between the top partner and the SM top quark is an important parameter and is constrained strongly (up to some model dependence).

Limits on the mixing angle

ATLAS-CONF-2016-072 $\sqrt{s} = 13$ TeV $3.2\ \mathrm{fb}^{-1}$ singlet T



by oblique parameters

Chien-Yi Chen, S. Dawson, I. M. Lewis [2014]

J. A. A. Saavedra, R. Benbrik, S. Heinemeyer, M. P. Victoria [2013]

S. Dawson, E. Furlan [2012]

H. J. He, N. Polonsky, S.F. Su [2001]

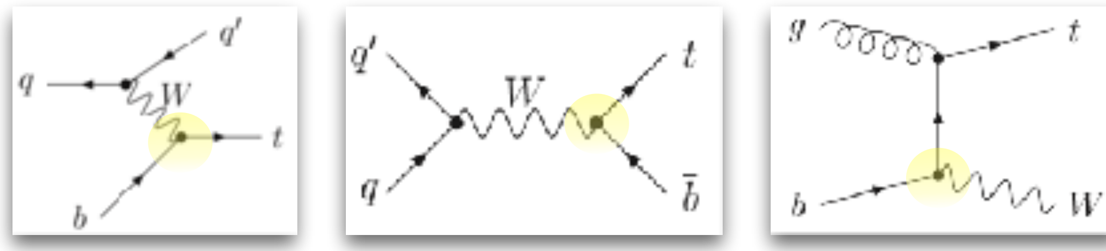
- The mixing angle is highly constrained by oblique parameters.

$$|\sin\theta_L| < 0.11 \sim 0.16 \quad (\text{for } m_T < 1 \sim 2\ \text{TeV})$$

Limits on the mixing angle

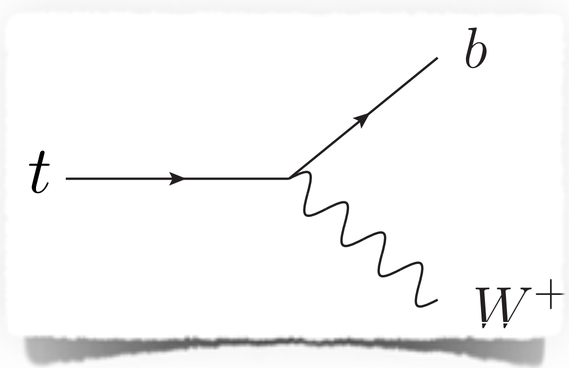
- Also the measurement of the CKM matrix element can be important.

$$|V_{tb}| = 1.019 \pm 0.025$$



(7, 8, and 13 TeV data combined)

- Back to the model, the coupling between *t*-*W*-*b* picks up cos θ_L



$$= i\frac{g}{\sqrt{2}} \boxed{\cos\theta_L} \gamma^\mu P_L$$

- from which we can obtain a bound on the mixing angle.

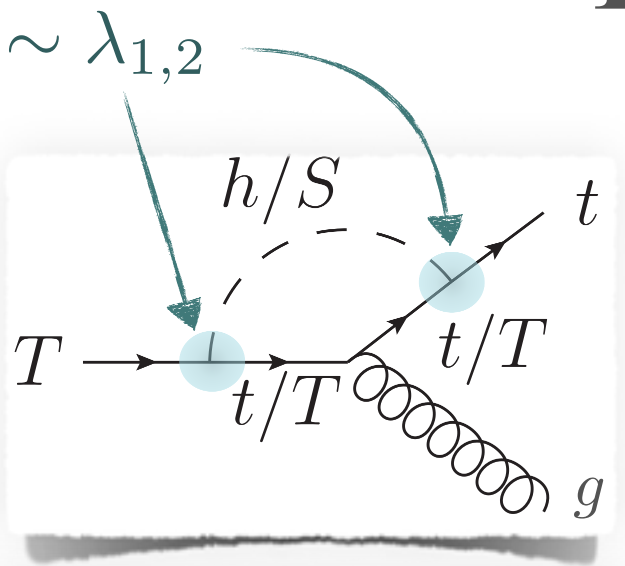
$$|\sin\theta_L| < 0.11 \quad (\text{ independent of } m_T)$$

Going back to top partners

- We tend to set bounds on the mass of new particles.
- But there are other parameters in the model.
- For example, in models with top partners, the mixing angle between the top partner and the SM top quark is an important parameter and is constrained strongly (up to some model dependence).
- What this means is that the partial widths of top partner decays to conventional final states are strongly constrained, as top partner inherits properties of the SM top quark via mixing.
- If there are other possible decay modes, which were suppressed before, they may become relevant in the small mixing limit.

Exotic T decays

J. H. **Kim**, I. M. Lewis [2018]



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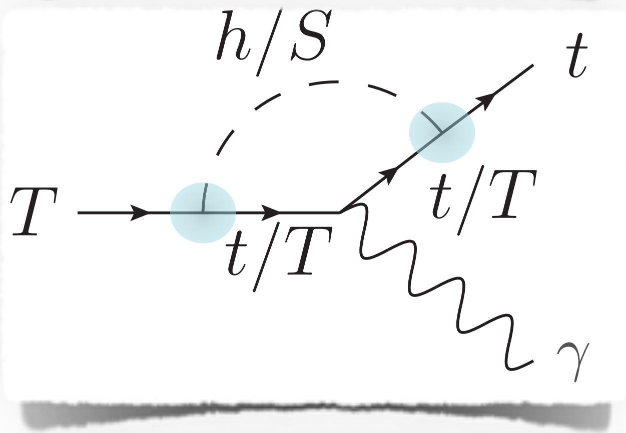
Counter terms

External self-energies

W and Z bosons loops

Goldstone bosons loops



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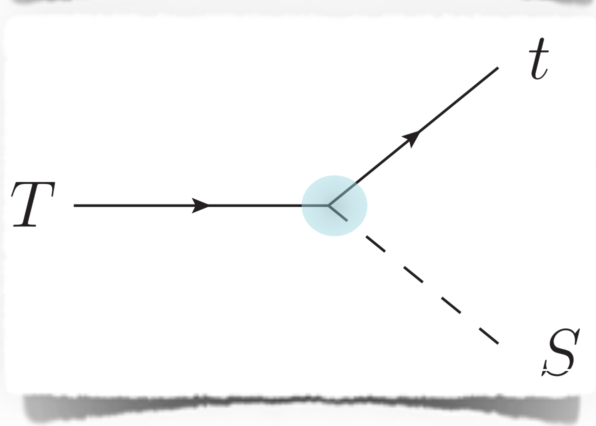
Counter terms

External self-energies

W and Z bosons loops

Goldstone bosons loops



If $m_T > m_S + m_t$

- The scalar S mediates loop-level decays of T:

$$T \to t\, g$$

$$T \to t\, \gamma$$

- These decays are allowed when $\sin\theta_L = 0$, because we can freely dial up and down the couplings $\lambda_{1,2}$.

- If the scalar mass is light, there is a new tree-level decay of T:

$$T \to t\, S$$

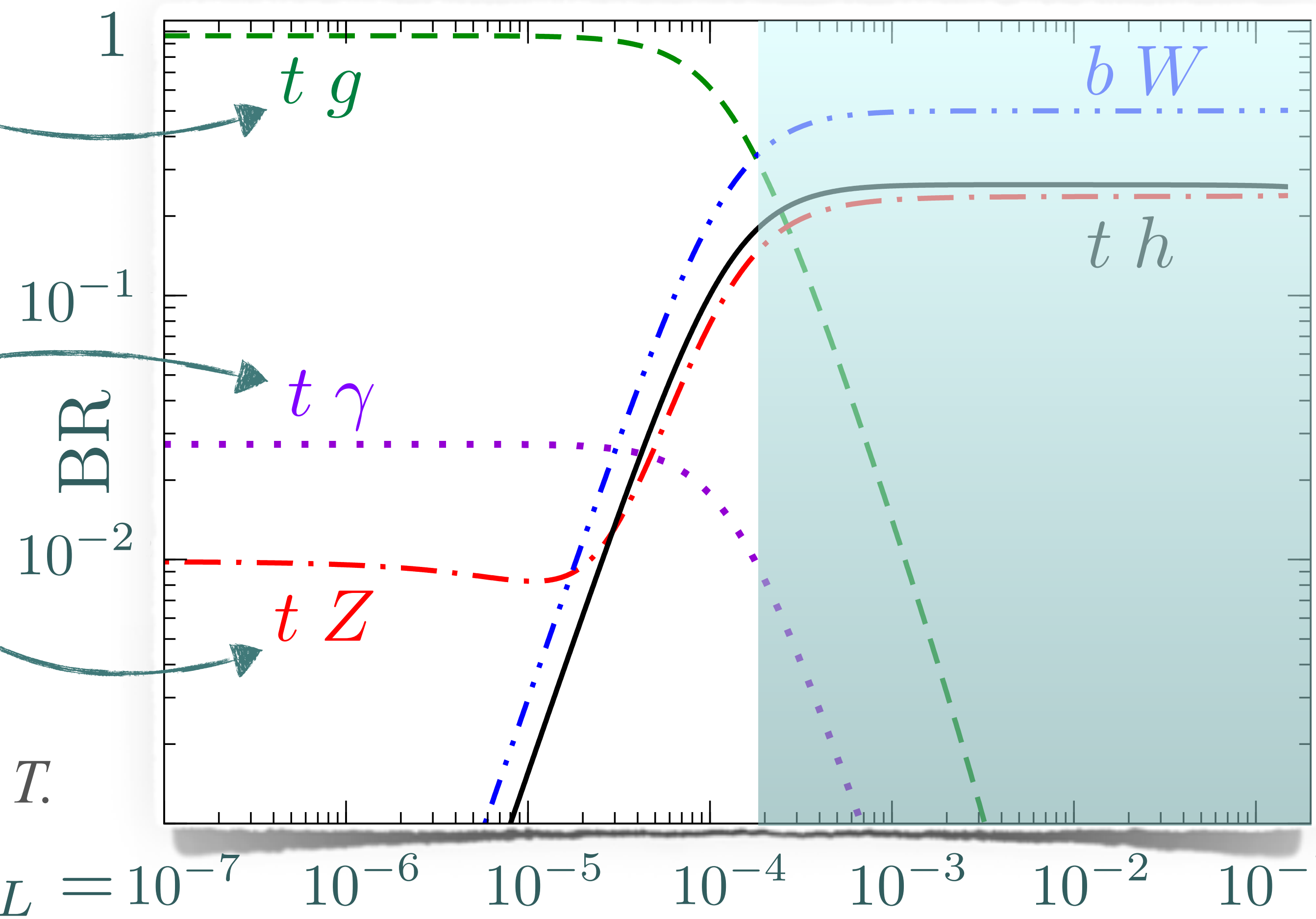
Branching ratios ($m_S > m_T$)

J. H. Kim, I. M. Lewis [2018]

$\mathrm{BR}(T \to tg) \sim 96\%$

$\mathrm{BR}(T \to t\gamma) \sim 3\%$

$\mathrm{BR}(T \to tZ) \sim 1\%$



- When S is heavier than T.
- In the zero-mixing limit, all classic decays are suppressed & vanishing.
- $T \to t\,g$ is dominant due to the strong coupling.
- $T \to t\,\gamma$, $T \to t\,Z$ are sub-dominant due to the weak couplings.

Non-Standard decays of Top partner

	Wb	tZ	tH	tg	$t\gamma$	$t(S \to gg)$
Wb	✔	✔	✔			
tZ		✔	✔			
tH			✔			
tg				✔		
$t\gamma$						
$t(S \to gg)$						

- Top-partner may be long-lived, in the small mixing angle limit.
- It may decays into other BSM particles, which could be
  - scalar or vector
  - color singlet, sextet or octet
- Similar classification can be done for most searches for new particles. It is important to cover all possible final states, where machine learning approach could be a possibility.

See talks by Ian Lewis and Ben Bachman

TOP-DOWN AND BOTTOM-UP

Credit: Ian Shipsey

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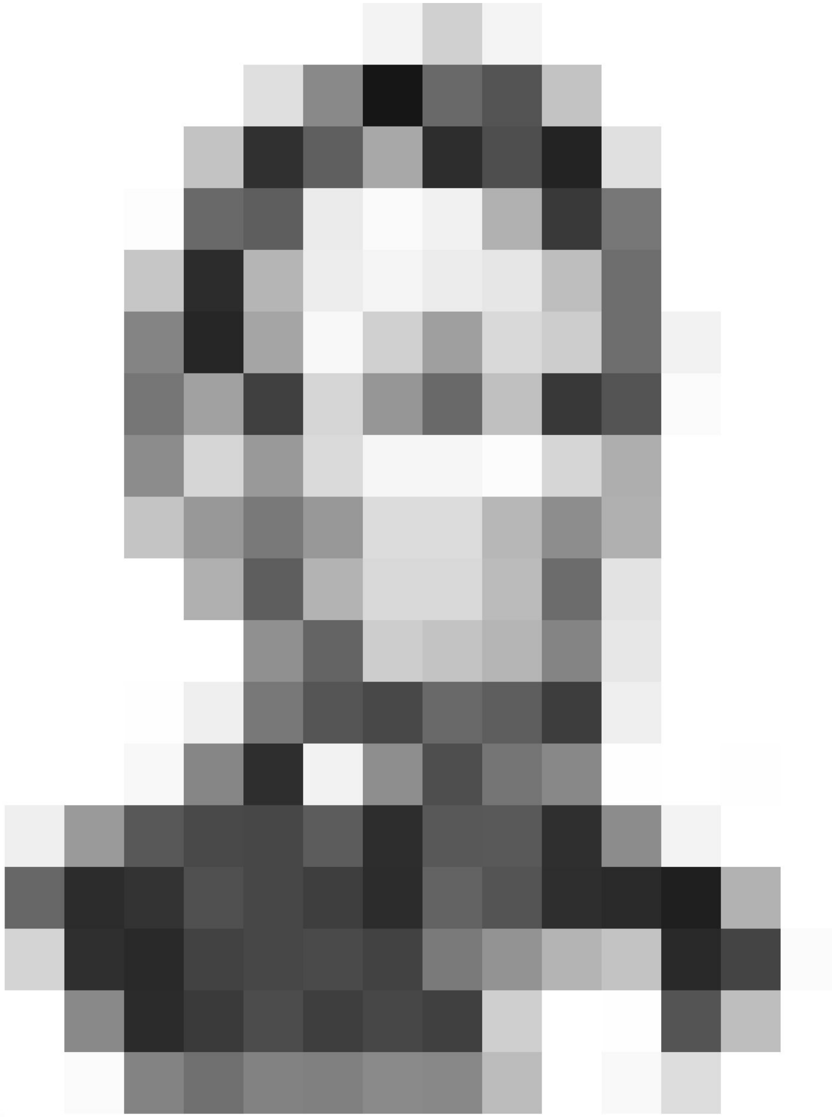

TOP-DOWN AND BOTTOM-UP

Credit: [Ian Shipsey]

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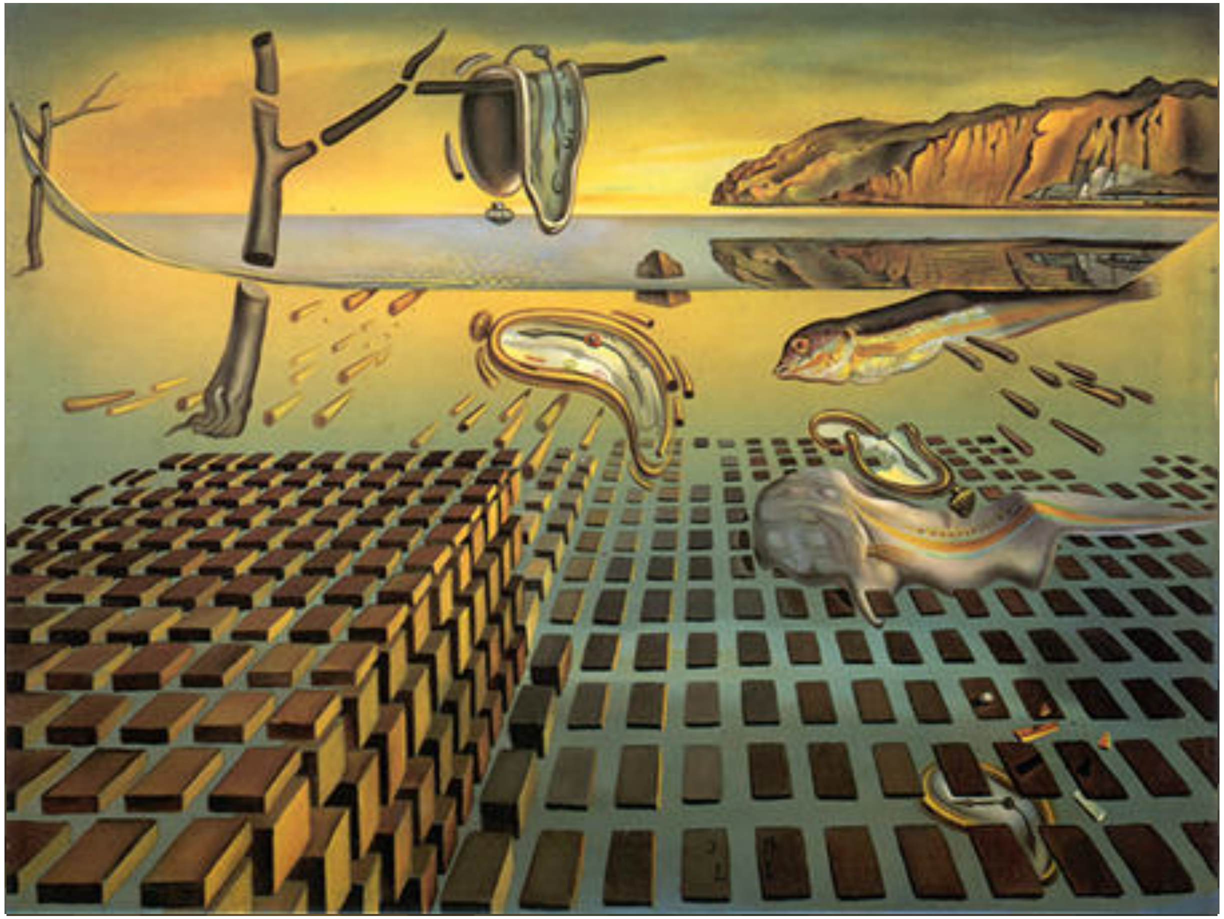
Abraham Lincoln

Salvador Dali's The Disintegration of the Persistence of Memory



Why Consider Exotica?

- Some exotica aren't really all that exotic
- Urgent – real possibilities for the next run of LHC
- You have the potential to advance science

Would experimentalists have thought of this if you didn't do this work?

– *Witten*

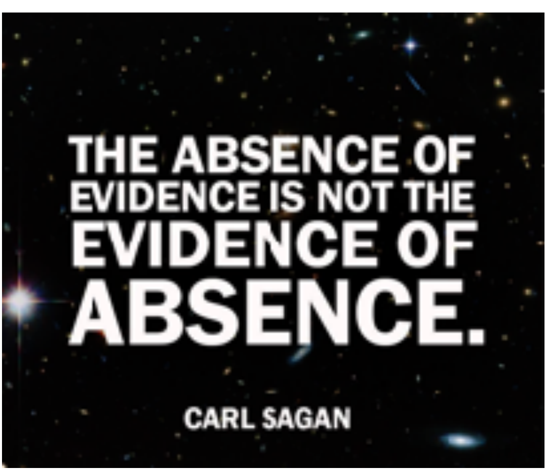
- …and you might actually advance science

Never start a project unless you have an unfair advantage.

– *Seiberg*

- It's fun

  If every individual student follows the same current fashion …, then the variety of hypotheses being generated…is limited. Perhaps rightly so, for possibly the chance is high that the truth lies in the fashionable direction. But, on the off-chance that it is in another direction - a direction obvious from an unfashionable view … -- who will find it? Only someone who has sacrificed himself…I say sacrificed himself because he most likely will get nothing from it…But, if my own experience is any guide, the sacrifice is really not great because…you always have the psychological excitement of feeling that possibly nobody has yet thought of the crazy possibility you are looking at right now.



– Richard Feynman, Nobel Lecture