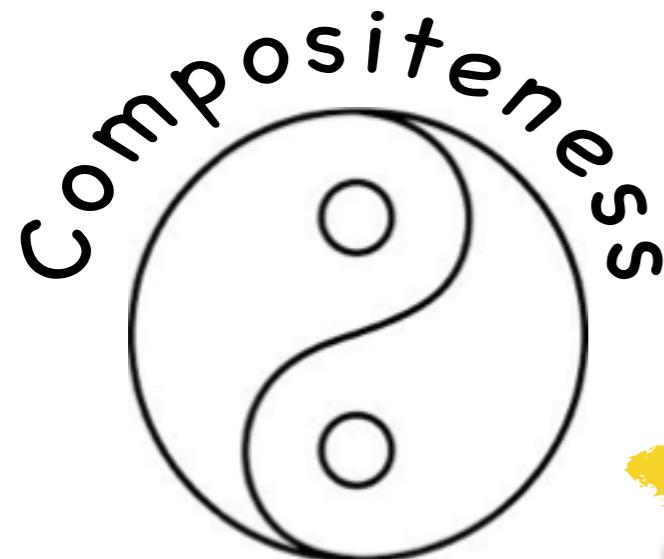


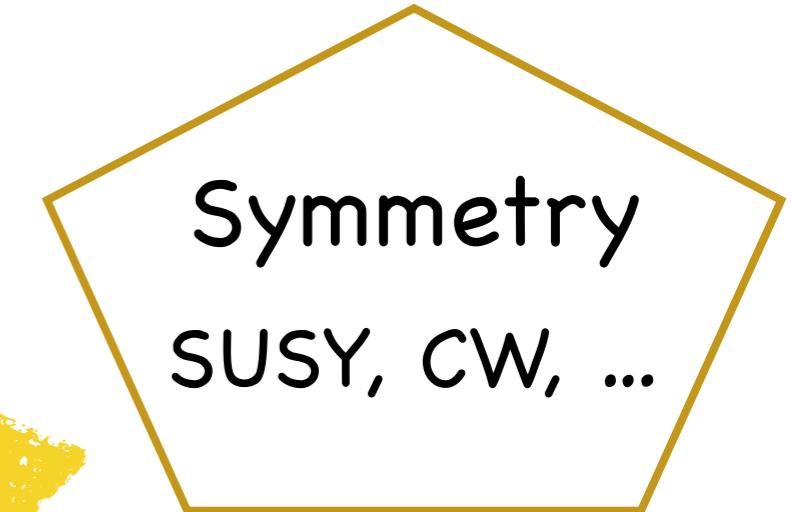
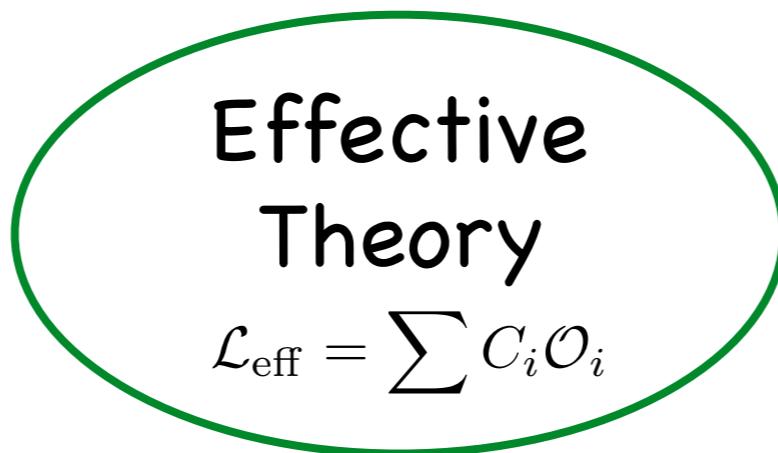
Anomalies at Hadron Colliders

Michael Spannowsky

IPPP, Durham University



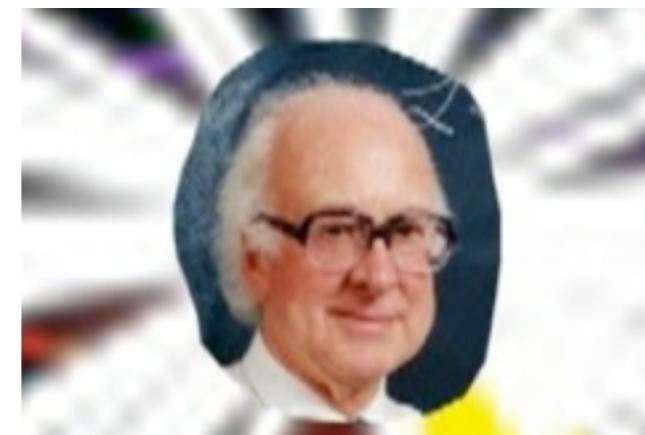
Compositeness



Naturalness

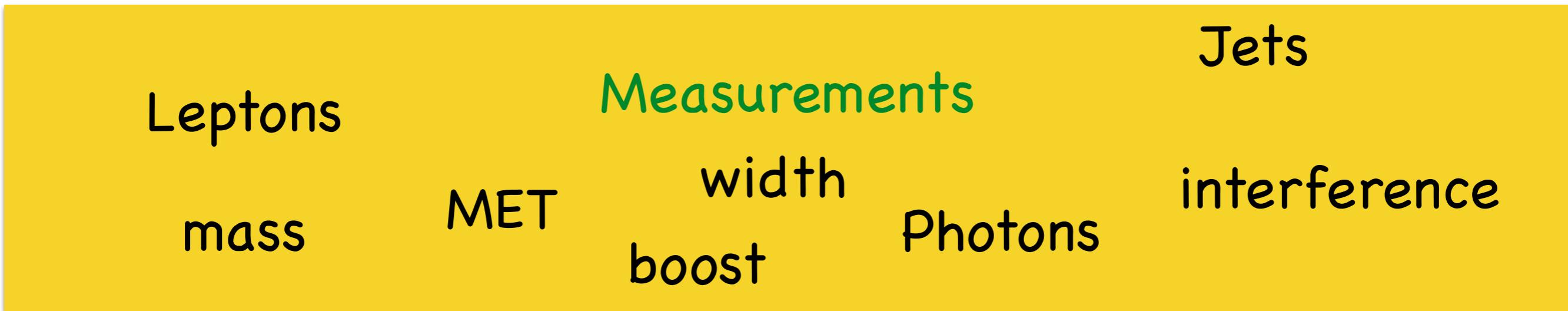
fermionic
top partners

simplified models



scalar
top partners

simplified models



Due to absence of signs of new physics

HEP has 'Big Mac' blues,
i.e. why nature not like (as natural as) advertised?



Commercial

Reality

Sure, it (Higgs boson) does the job, but...

- Discovery of Higgs boson huge success
- However, Higgs boson remnant/by-product of BEH mechanism

No detailed understanding so far

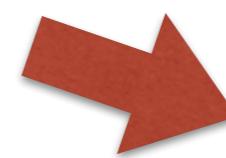
Not enough evidence to identify theory of nature



'Do you have to yell 'Eureka' every time you see something new?'

New Physics has got to be out there:

- Matter/Anti-Matter asymmetry
- Dark Matter
- Hierarchy Problem
- Inflation

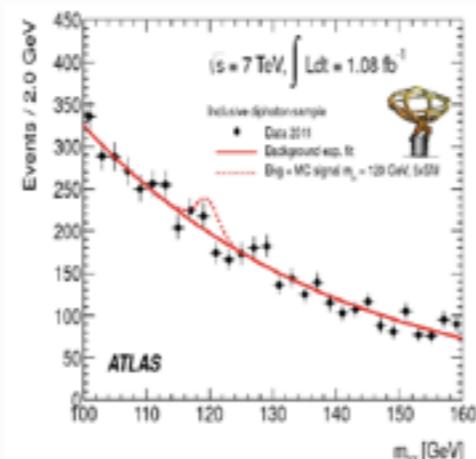
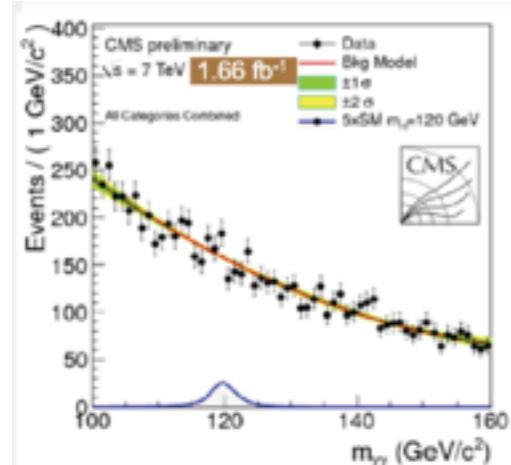


Every discovery starts with an anomaly

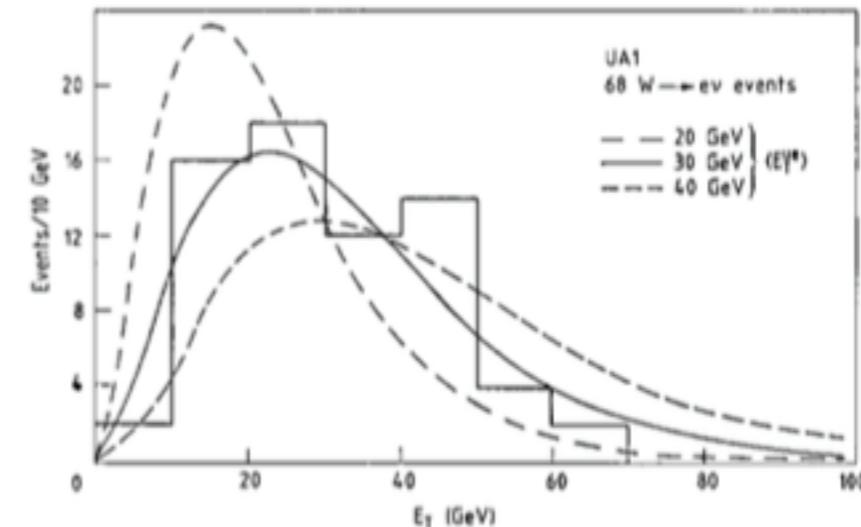
Why do we observe 'anomalies'

i.e. dissent between prediction and observation

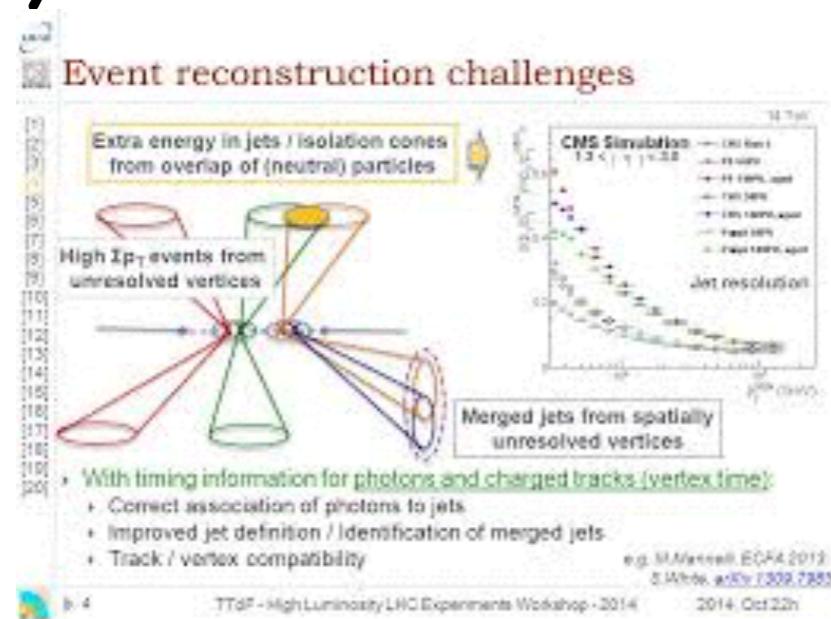
- Statistical fluctuation



- Theoretical prediction off



- Systematic bias in reconstruction



- New Physics



Why do we observe 'anomalies'

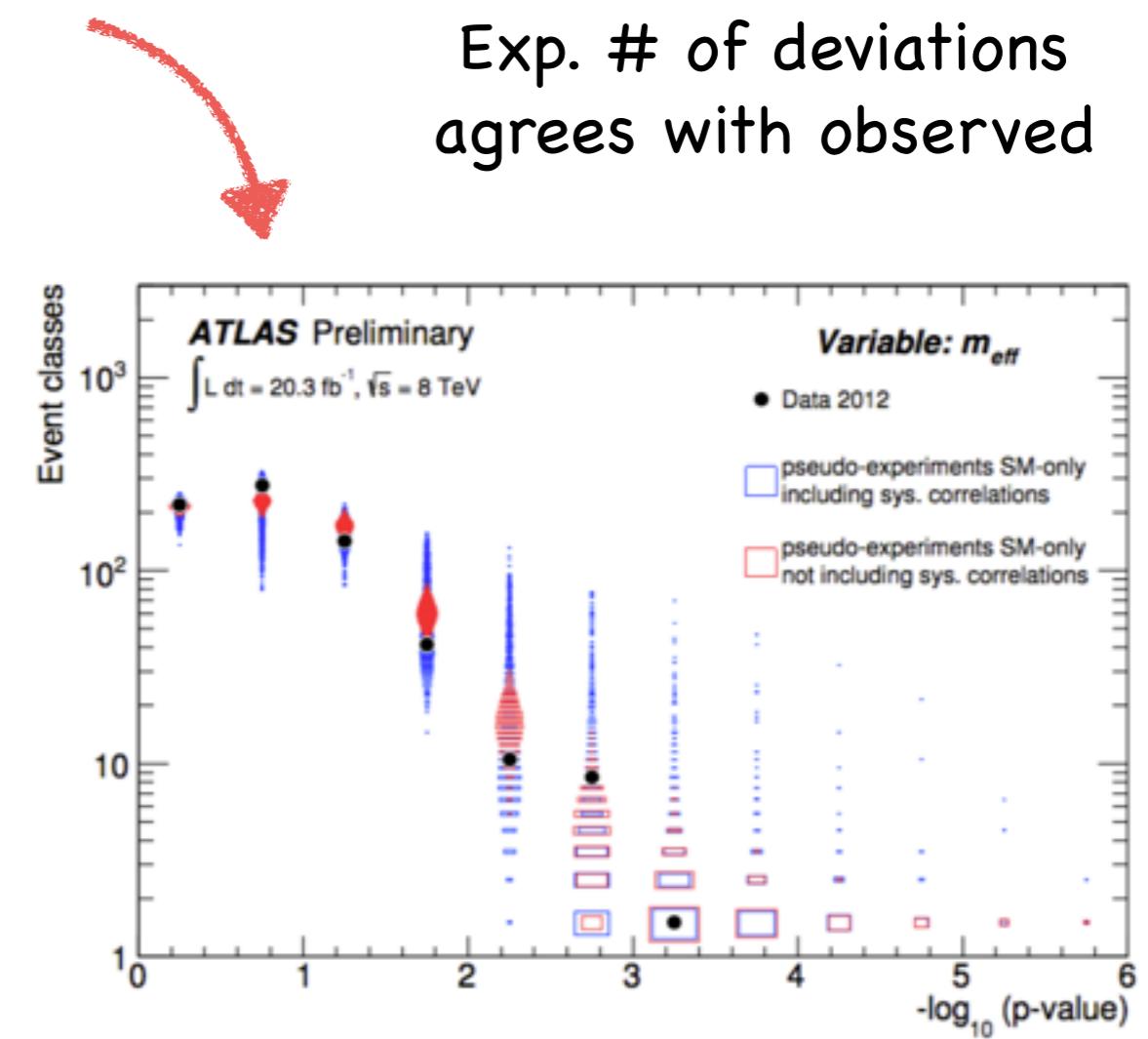
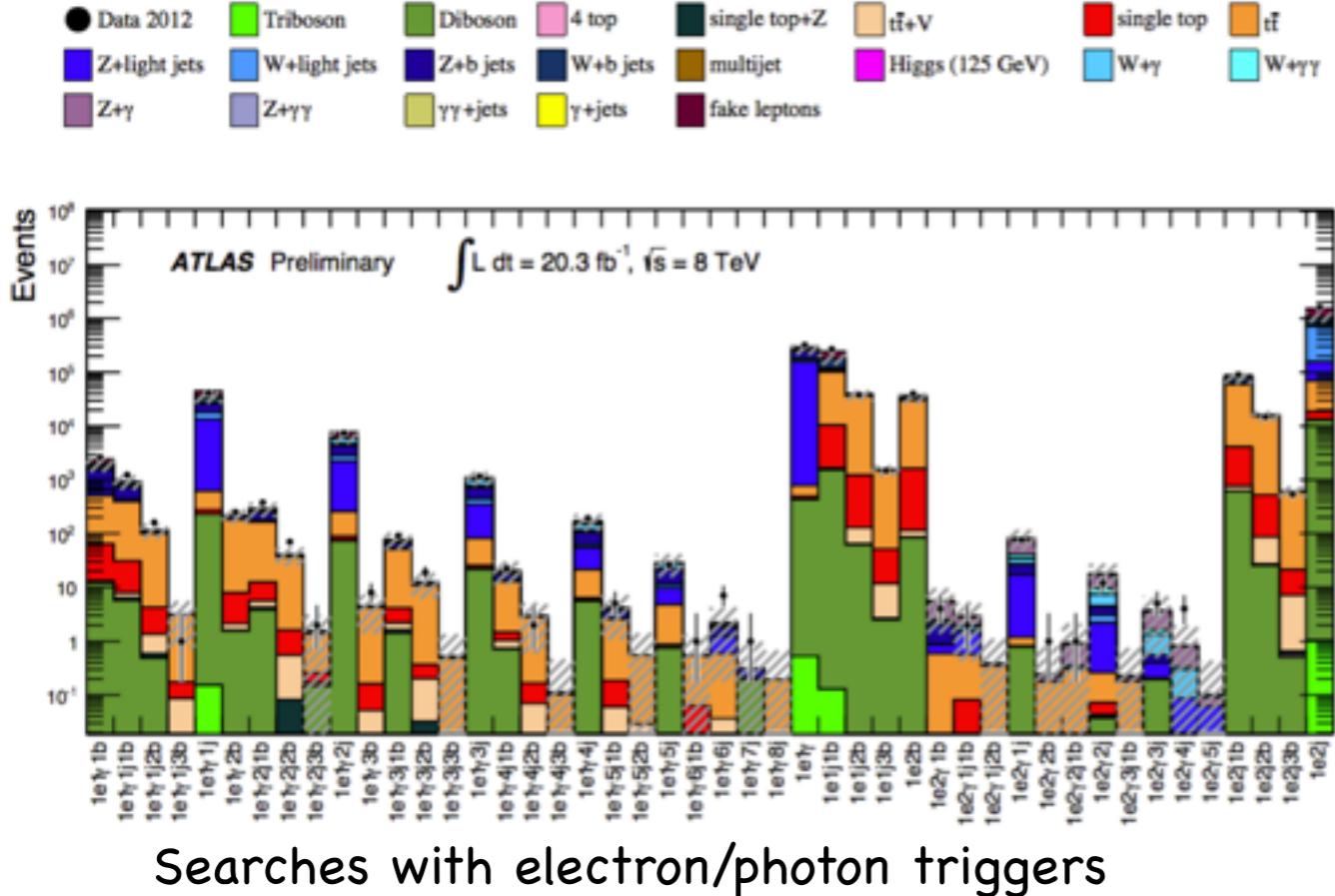
i.e. dissent between prediction and observation

Statistical fluctuation

[ATLAS-CONF-2014-006]

Search over 697 classes with SM exp. > 0.1 events, observables (M_{eff}, M_{inv}, ET_{miss})

After taking syst. and theo. uncertainties into account,
pseudo exp. compared to data



Why do we observe 'anomalies'

i.e. dissent between prediction and observation

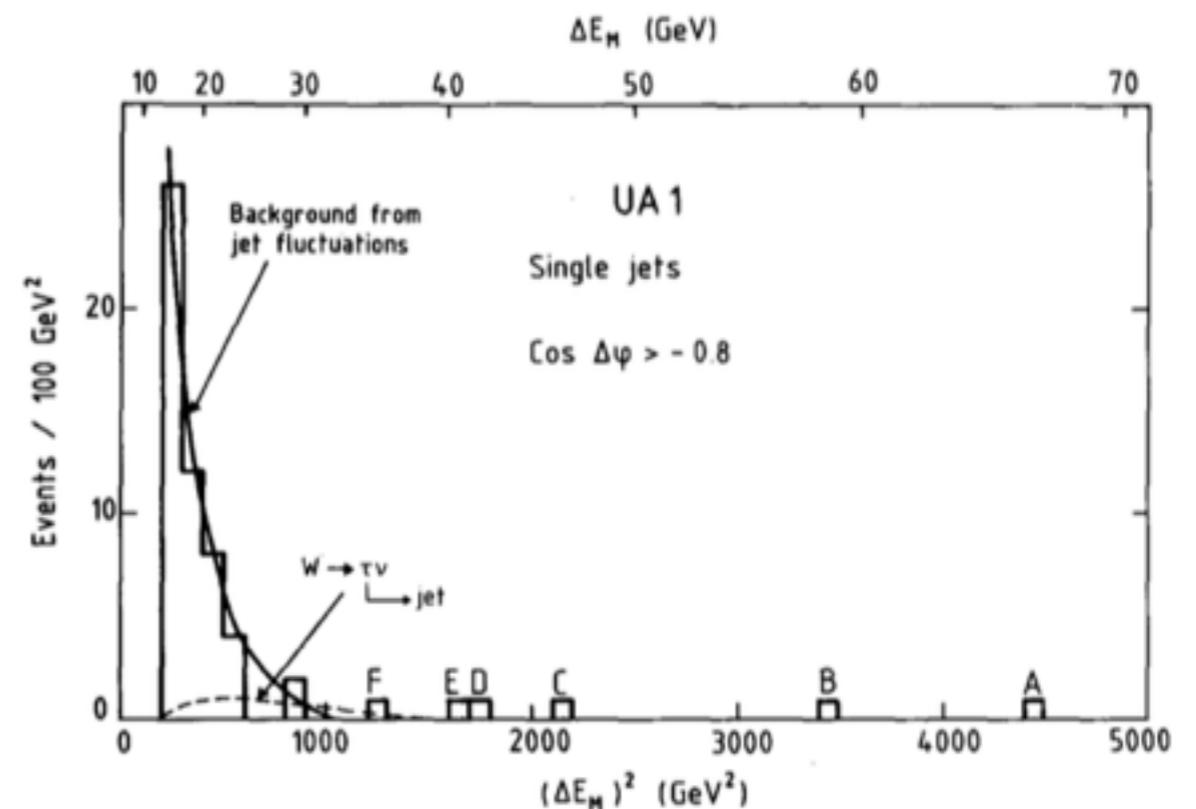
Theoretical prediction

Measurement:

5 unexplained monojet events with $\text{MET} > 40 \text{ GeV}$

- Many explanations in terms of new physics, e.g. light gluinos
- Relied on ISAJET for background calculation
- More precise theory calculation killed excess/anomaly
see [Ellis, Kleiss, Sterling PLB 167 (1986)]

Gluino discovery at UA1
[G. Arnison et al PLB 139 (1984)]



Why do we observe 'anomalies'

i.e. dissent between prediction and observation

[CDF Collab., 1104.0699]

Systematic bias

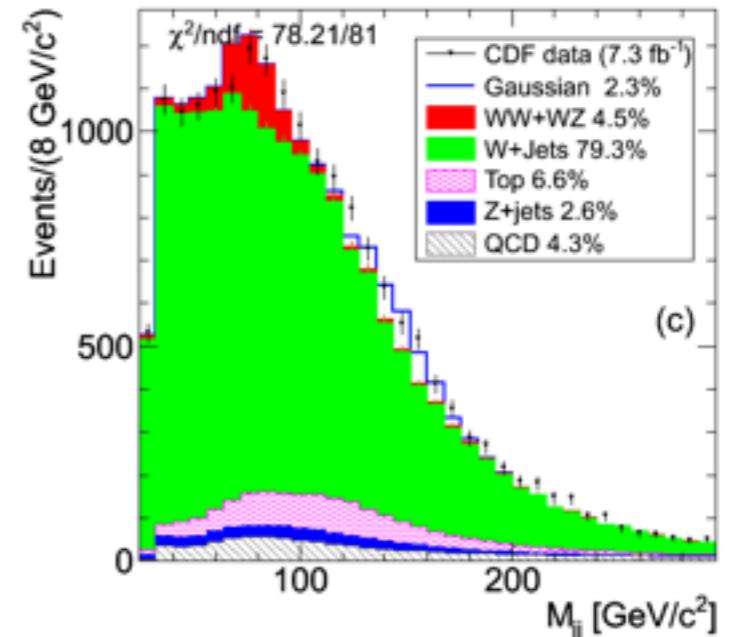
electron and muon: $pT > 20 \text{ GeV}$ $|y| < 1$

MET $> 25 \text{ GeV}$ and MTW $> 30 \text{ GeV}$

\rightarrow subtraction of modelled backgrounds



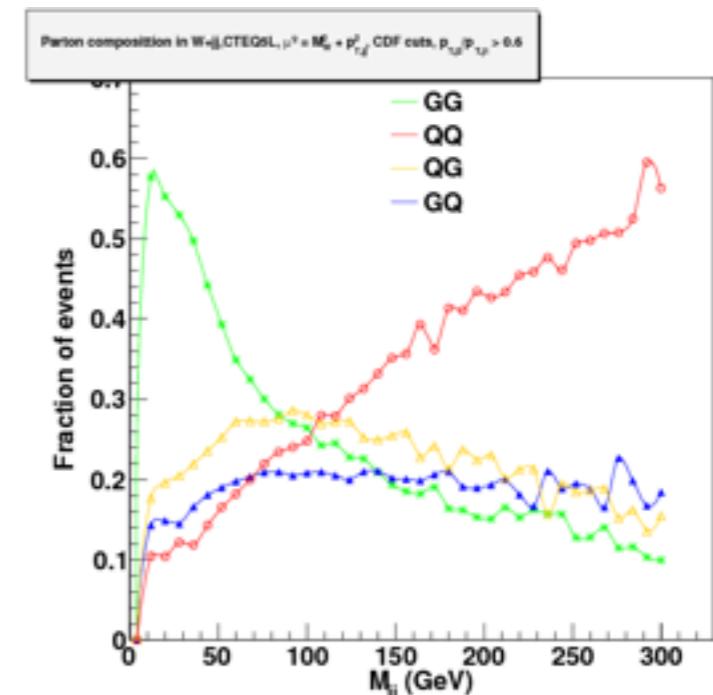
4.1 sigma



However, D0 didnt see it...

Gone by now...

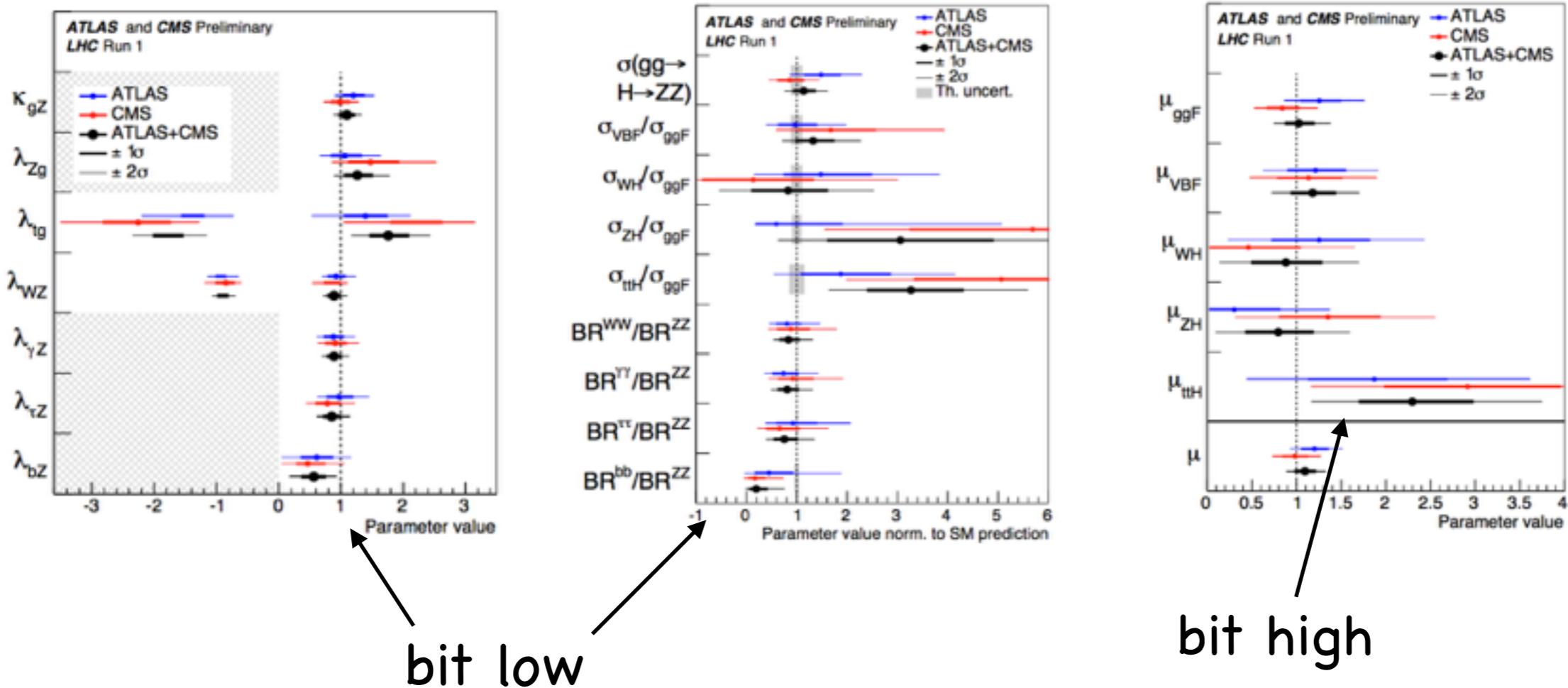
- JES and JER different for quarks and gluons?
- Jet->electron fakes correctly taken into account?



Anomalies in the Higgs sector

- Beginning of run 1 was $H \rightarrow \text{photons}$ high (statistical fluctuations)

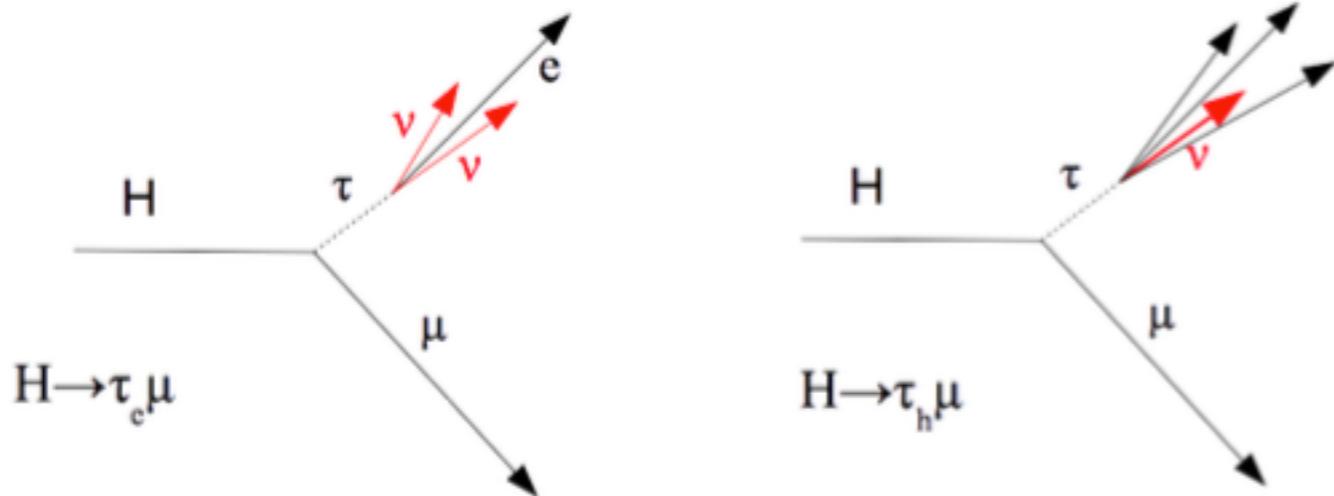
Recently published ATLAS/CMS combination of Higgs properties:



overall very good agreement with SM

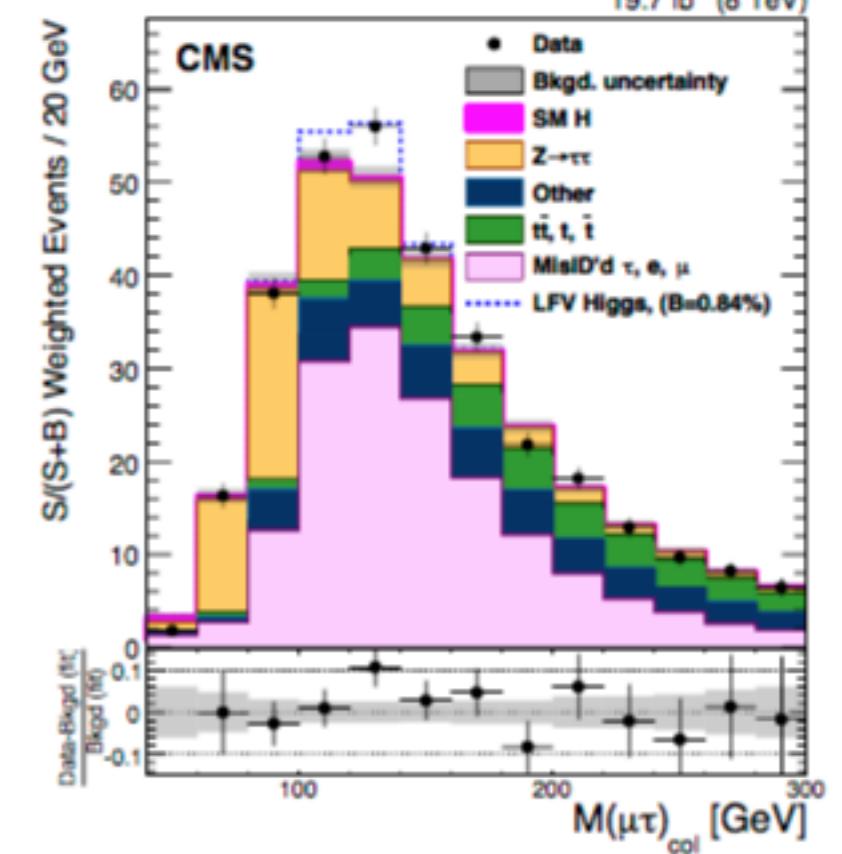
CMS excess in $H \rightarrow \tau\mu$

Search for direct lepton flavor violation in $H \rightarrow \mu\tau_e$ and $H \rightarrow \mu\tau_h$:



- Small excess near $m_H = 125$ GeV with significance of 2.4σ
- Best fit branching ratio $\text{Br}(H \rightarrow \mu\tau) = 0.84^{+0.39\%}_{-0.37\%}$
- Constraint on BR at 95%CL $\text{Br}(H \rightarrow \mu\tau) < 1.51(0.75)\%$

ATLAS sees small excess in same range with 1.3σ



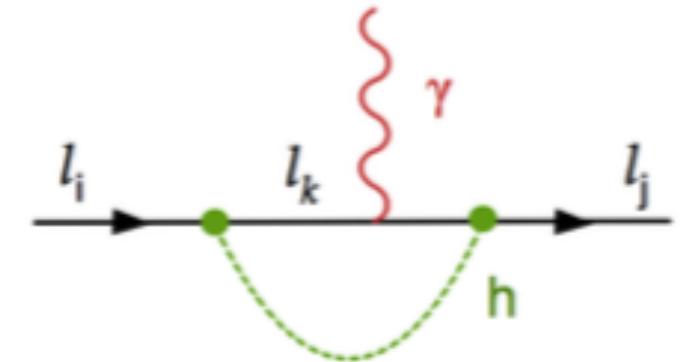
Possible explanations of excess

Current limits do not exclude 'signal'

[Blankenburg, Ellis, Isidori '12]

[Harnik, Kopp, Zupan '12]

- Branching ratio of $O(10)\%$ allowed
- LFV FCNC limits weaker than in quark sector
- Limits on $H \rightarrow \tau \mu$ weaker than $H \rightarrow \tau e$



Many possible explanations, one could be LFV in the MSSM(?)

Introduce LFV soft-breaking terms

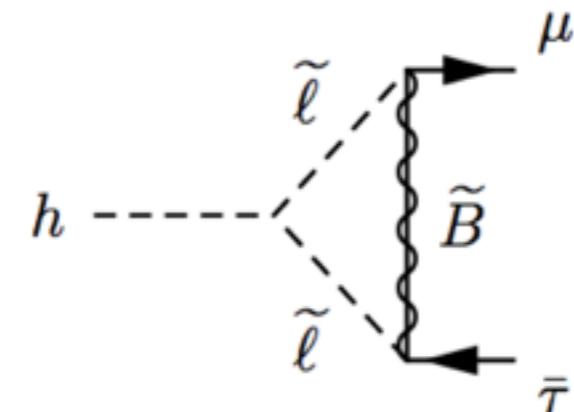
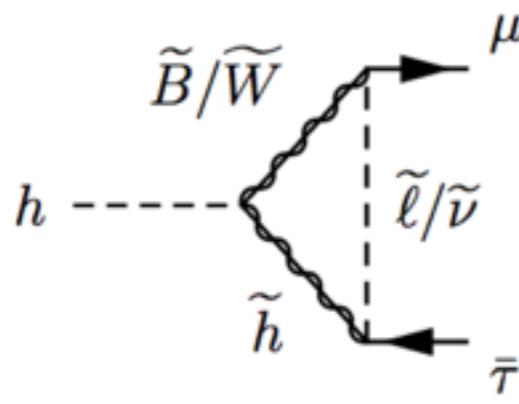
[Alony, Nir, Stamou (Yesterday)]

$$\mathcal{L}_{\text{MSSM}}^{\text{LFV}} = -\tilde{m}_{L_{ij}}^2 \tilde{L}_i^\dagger \tilde{L}_j - \tilde{m}_{R_{ij}}^2 \tilde{\bar{E}}_i^\dagger \tilde{\bar{E}}_j - (A_{ij}^E h_d \tilde{L}_i \tilde{\bar{E}}_j + \text{h.c.})$$

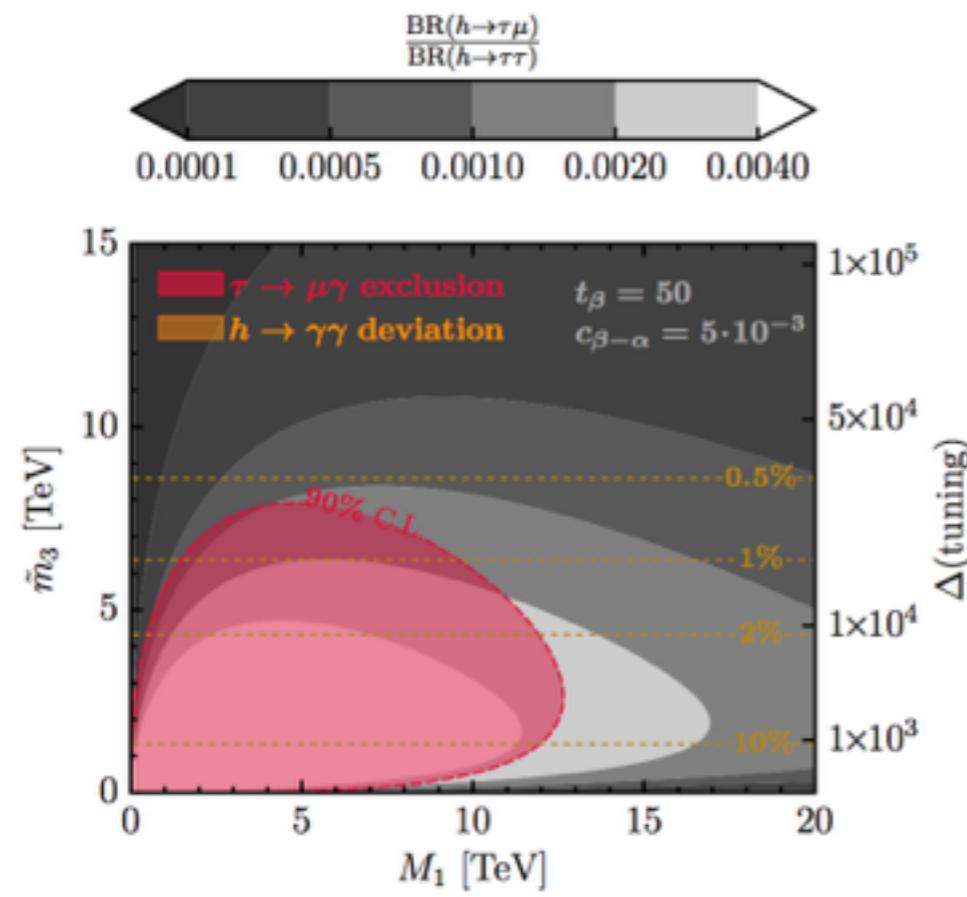
$$\tilde{\mathcal{M}}^2 = \begin{pmatrix} (\tilde{m}_L^2)_{\mu\mu} & (\tilde{m}_L^2)_{\mu\tau} & 0 \\ (\tilde{m}_L^2)^*_{\mu\tau} & (\tilde{m}_L^2)_{\tau\tau} & -m_\tau \mu t_\beta \\ 0 & -m_\tau \mu t_\beta & (\tilde{m}_R^2)_{\tau\tau} \end{pmatrix}$$

$$\tilde{\mathcal{M}}^2 = \begin{pmatrix} \tilde{m}_{\mu L}^2 & \frac{v_d A_{\mu\tau}}{\sqrt{2}} \\ \frac{v_d A_{\mu\tau}}{\sqrt{2}} & \tilde{m}_{\tau R}^2 \end{pmatrix}$$

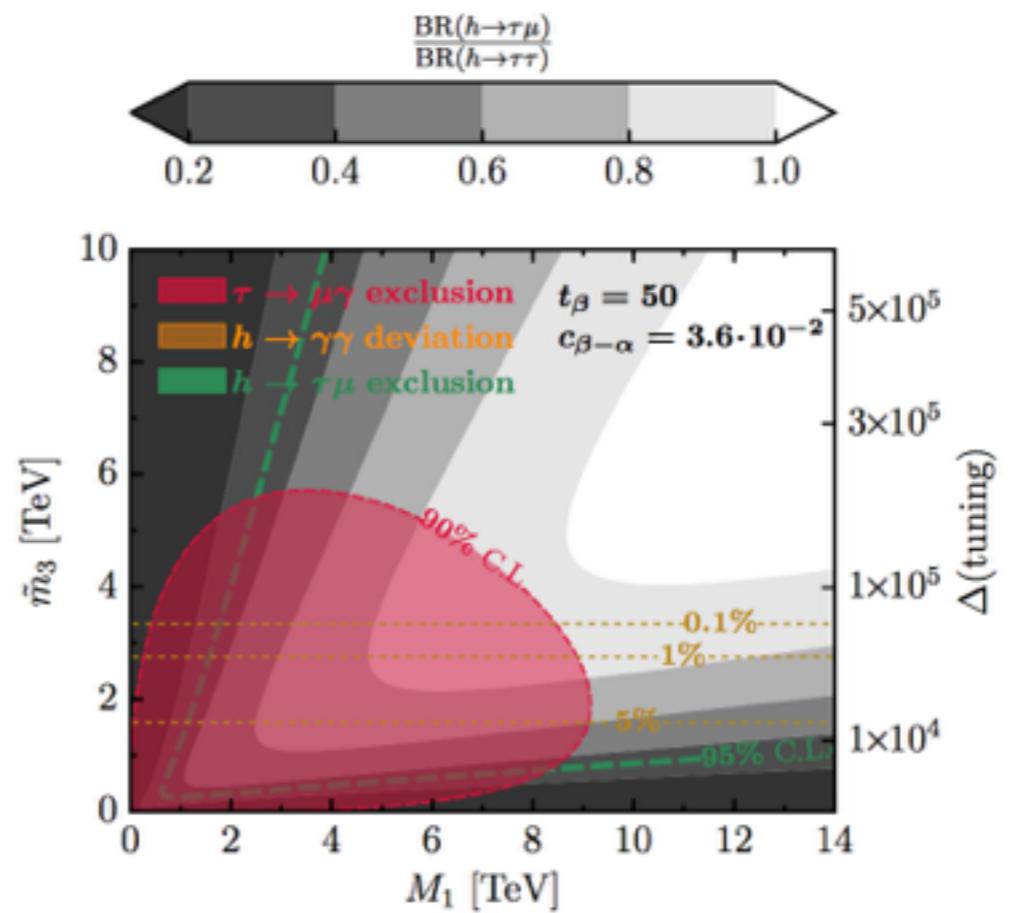
Result in interactions of the kind



LFV from A-terms



LFV from M-terms



Difficult, but not impossible, to accommodate large LFV BR

CMS excess in multi-lepton final states

Broad excess in 4 lepton final states:

[CMS SUS-13-002]

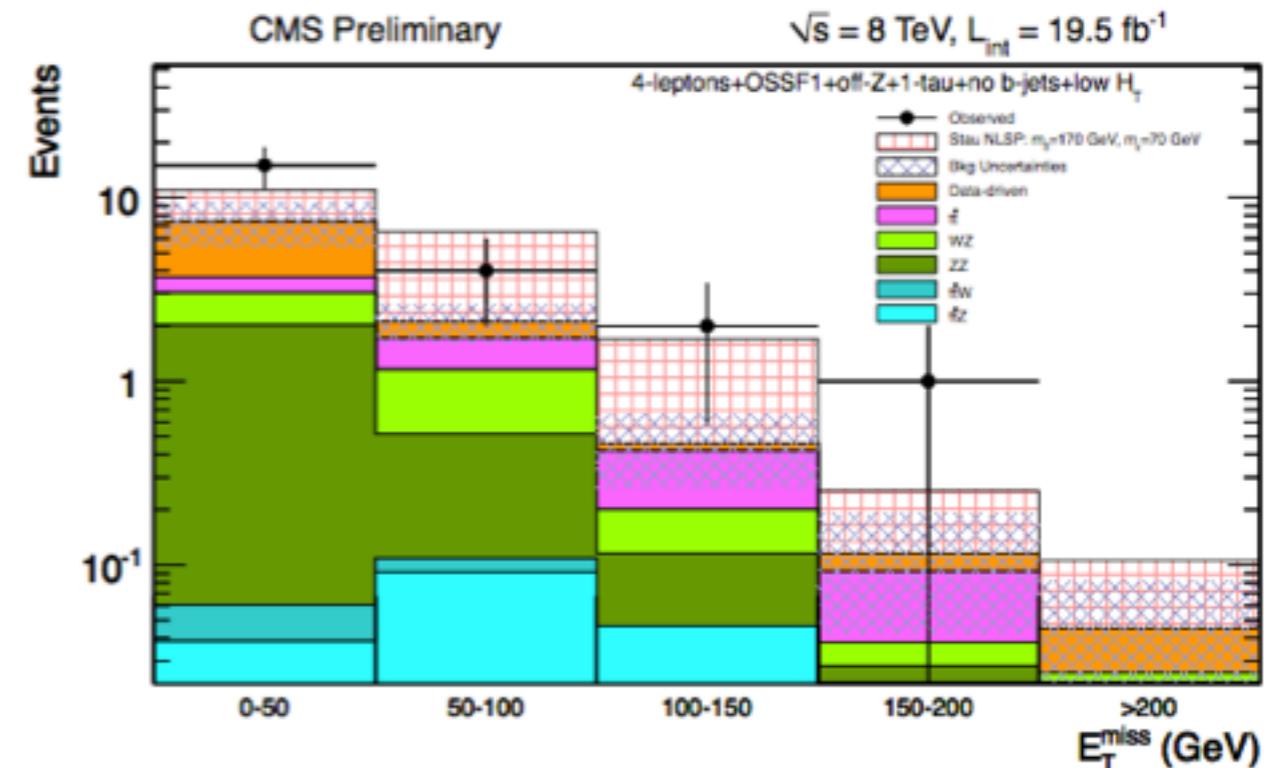
1 tau

off-shell Z(ee or mu mu)

no b-jets

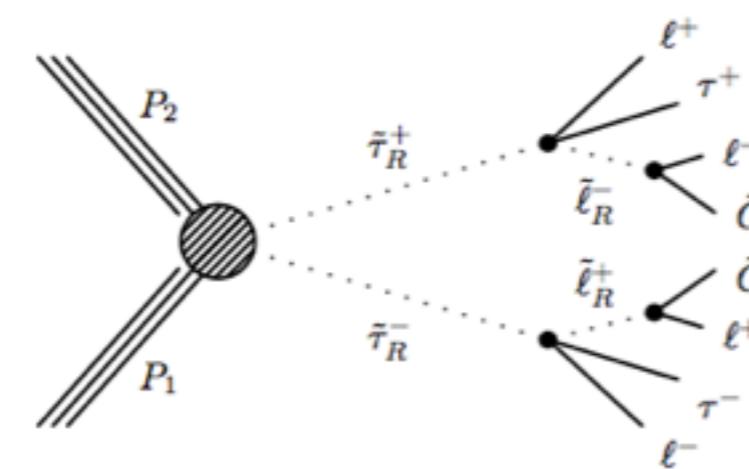
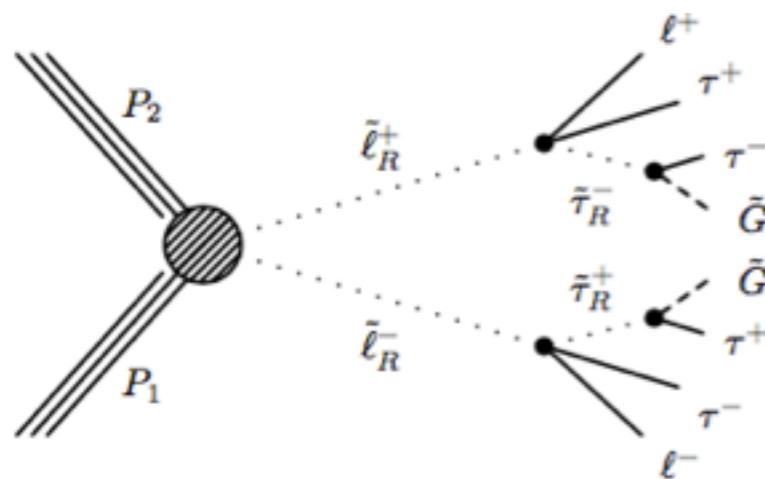
$H_T < 200 \text{ GeV}$

→ Significance



Possible explanation:

stau (N)NLSP



The Edge

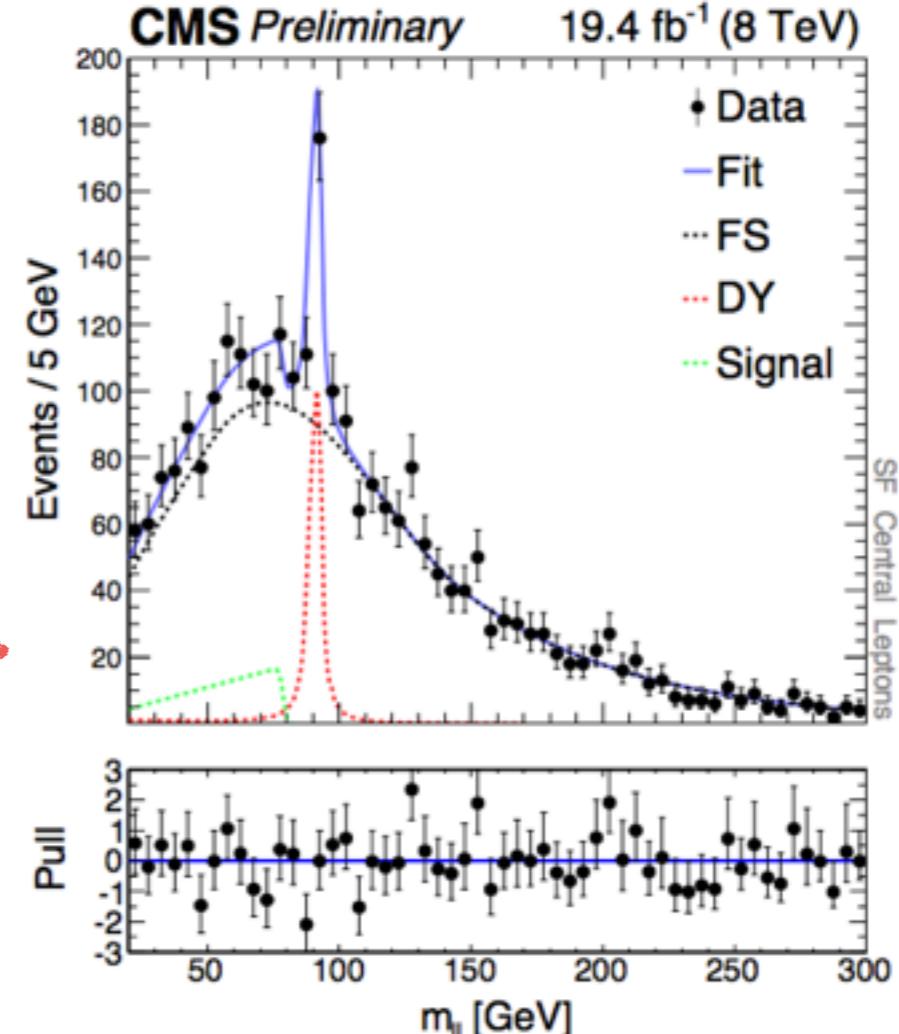
2 leptons $e^+e^-/\mu^+\mu^-/\tau\tau$

and

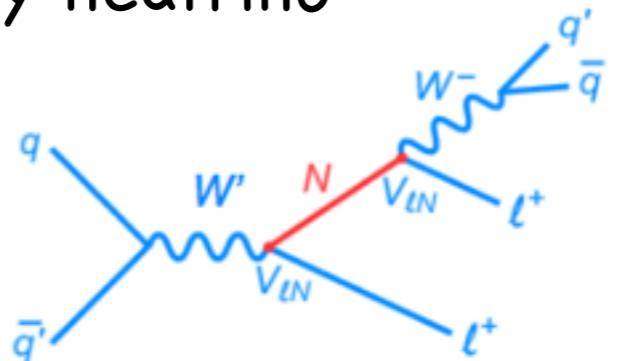
$N_{\text{jets}} \geq 2$ and $\text{MET} > 150 \text{ GeV}$
or

$N_{\text{jets}} \geq 3$ and $\text{MET} > 100 \text{ GeV}$

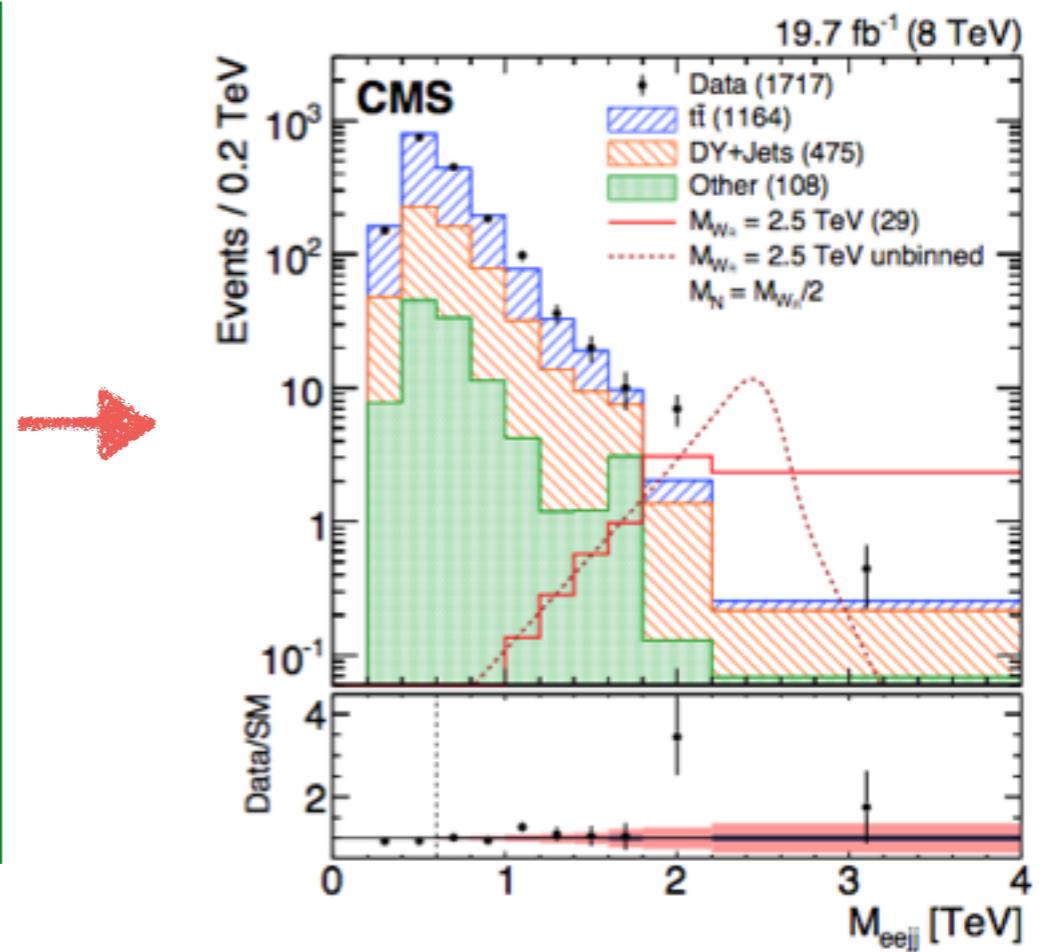
→ Significance 2.6σ



Interestingly, also excess observed in search for heavy neutrino



→ Significance 2.8σ



And another di-lepton search for di-leptoquarks

Two selections:

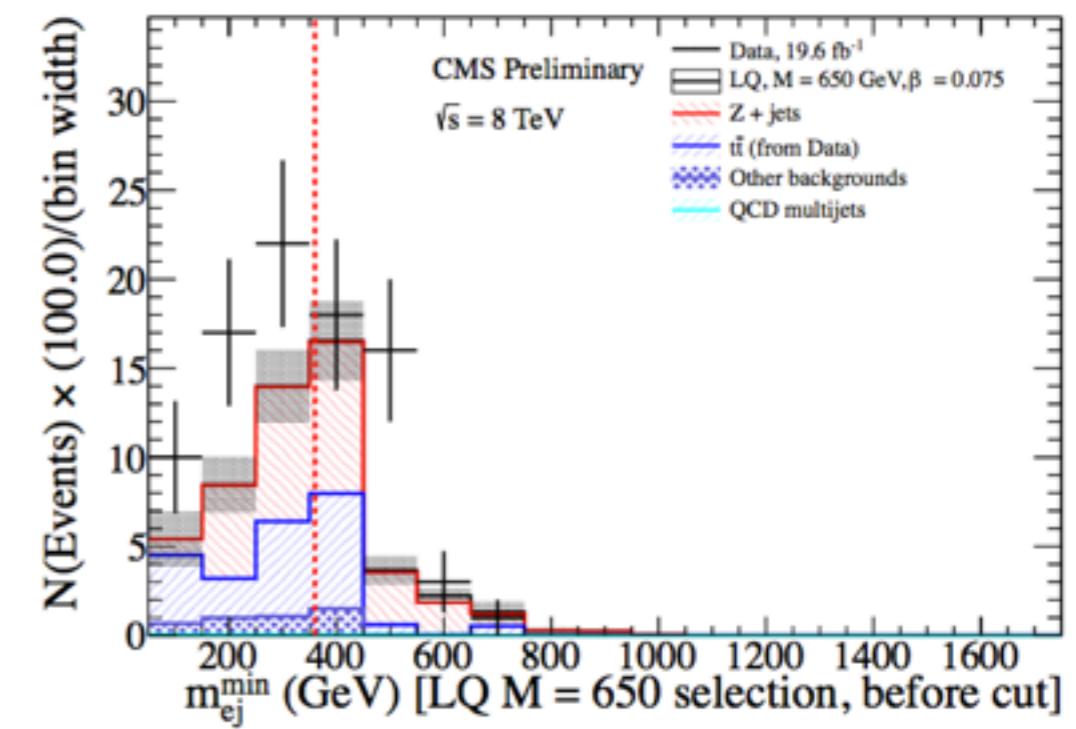
1) eejj: $S_T > 850 \text{ GeV}$, $M_{ee} > 155 \text{ GeV}$
 $M_{ej} > 360 \text{ GeV}$

Significance for 650 GeV leptoquark: 2.4σ

2) evjj: $S_T > 1040 \text{ GeV}$, $M_{ej} > 555 \text{ GeV}$
 $E_{T, \text{miss}} > 145 \text{ GeV}$, $M_{T,ev} > 270 \text{ GeV}$

Significance for 650 GeV leptoquark: 2.6σ

[CMS EXO-12-041-pas]



- Obviously jjll searches correlated.
- To explain all 3 excesses simultaneously
- Since excess in electrons but not muons, need to explain lepton non-universal interactions
 - One possible solution, R-parity violating MSSM

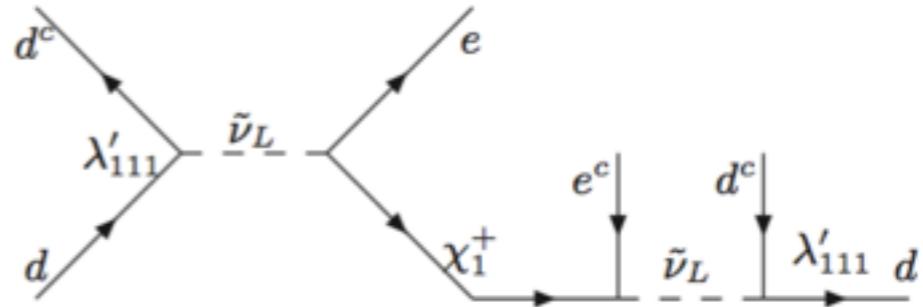
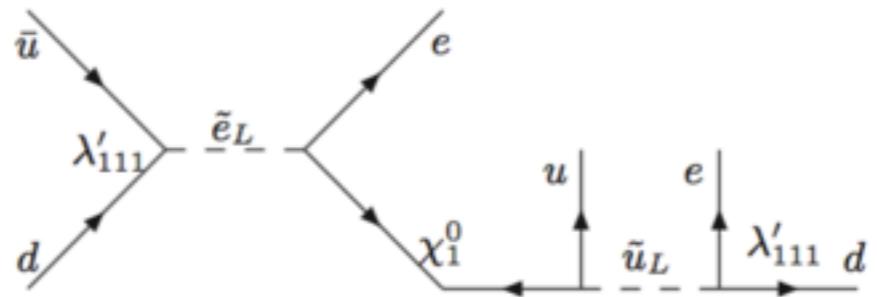
Possible interpretation of di-lepton excesses

[Allanach, Biswas, Mondal, Mitra '14]

Introduce:

$$W_R = \lambda'_{111} L Q d^c \rightarrow \mathcal{L} = -\lambda'_{111} \tilde{e} u d^c - \lambda'_{111} \tilde{u} e d^c + \lambda'_{111} \tilde{d} \nu_e d^c + \tilde{\nu}_e d d^c + \dots$$

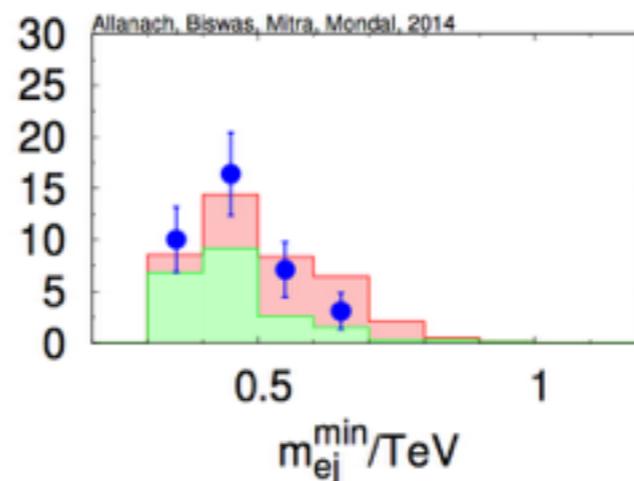
Leads to s-channel production of slepton



λ'_{111} constrained from 1) LF universality, 2) charged curr. universality
 3) 0v double beta decay 4) dijet searches

slepton mass of 2 TeV

χ^0 mass of 900 GeV

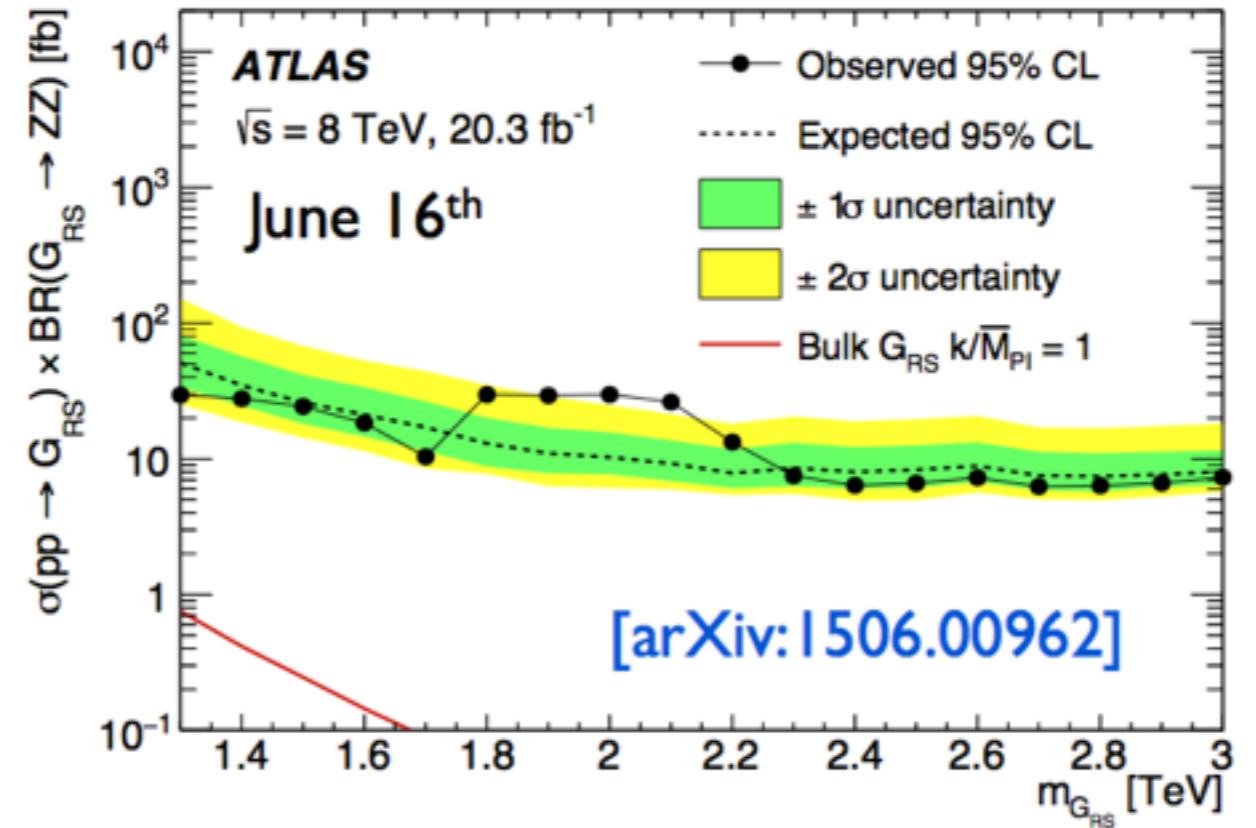
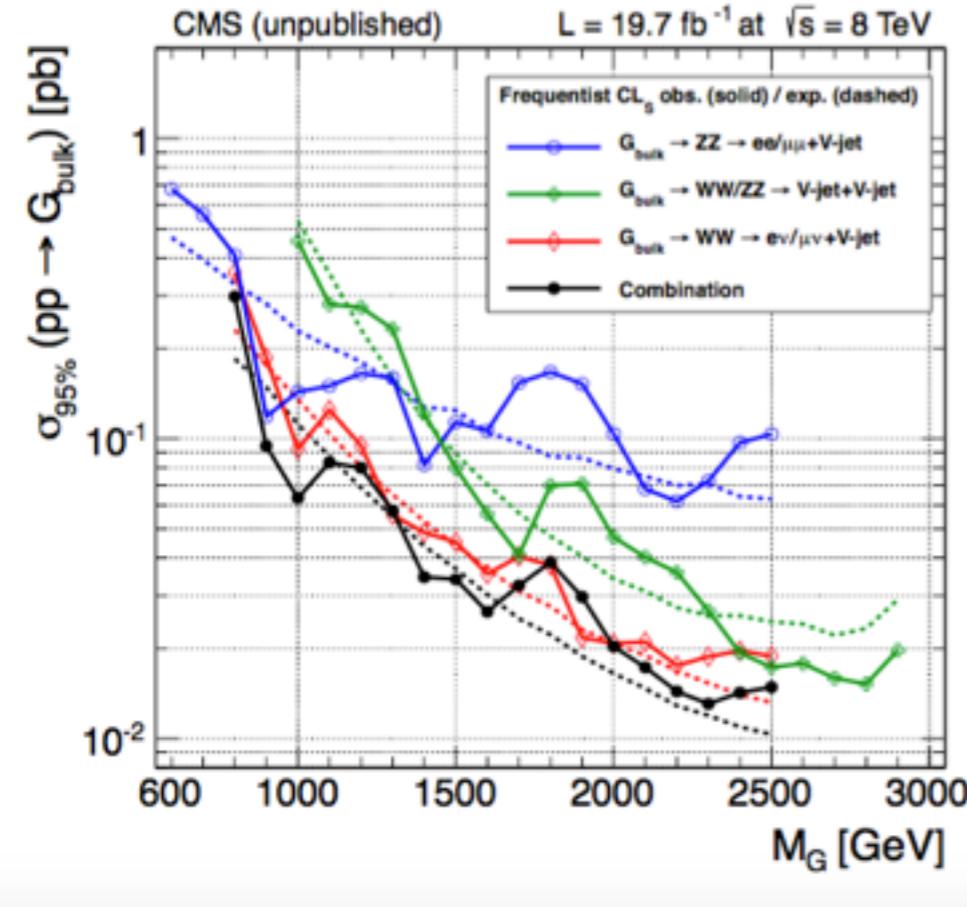


- Improves fit to data for 2 out of 3 excesses
- The edge can be explained with RPV conserving MSSM

[Allanach, Kvellestad, Raklev '14]

Di-boson excesses

[CMS EXO-13-009]



- CMS sees small but consistently excesses in di-boson final states
- First excess in semileptonic final state using jet substructure from 2012

	CMS	ATLAS
$V\text{-jet } V\text{-jet}$	1.3σ	3.4σ (2.5 σ global)
$\ell\ell \text{ } V\text{-jet}$	2σ	-
$\ell\nu \text{ } V\text{-jet}$	1.2σ	-

- While masses seem consistent cross sections dont across channels

Possible interpretation of Di-boson excess

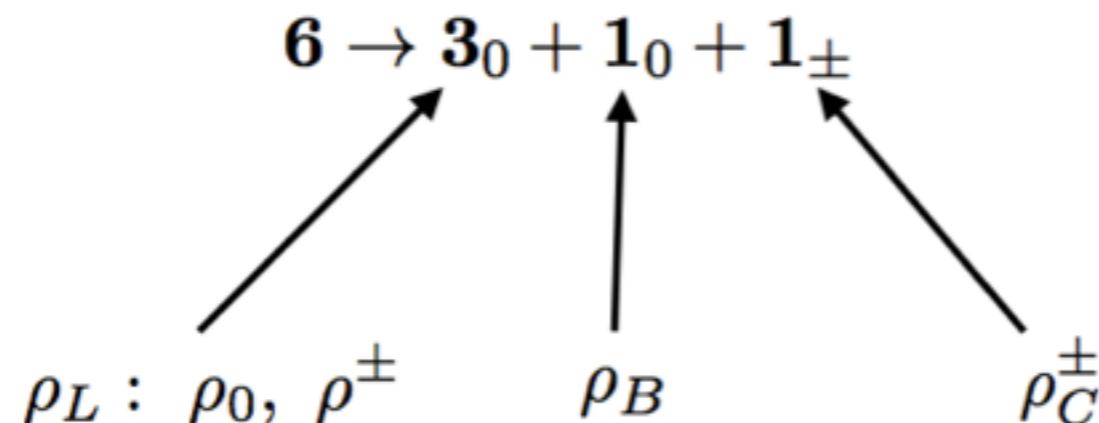
One option [Low, Tesi, Wang '15], by now 0(40) other explanations ...

Minimal composite Higgs model $SO(5)/SO(4)$

Spin-1 resonance in 6 of $SO(4)$

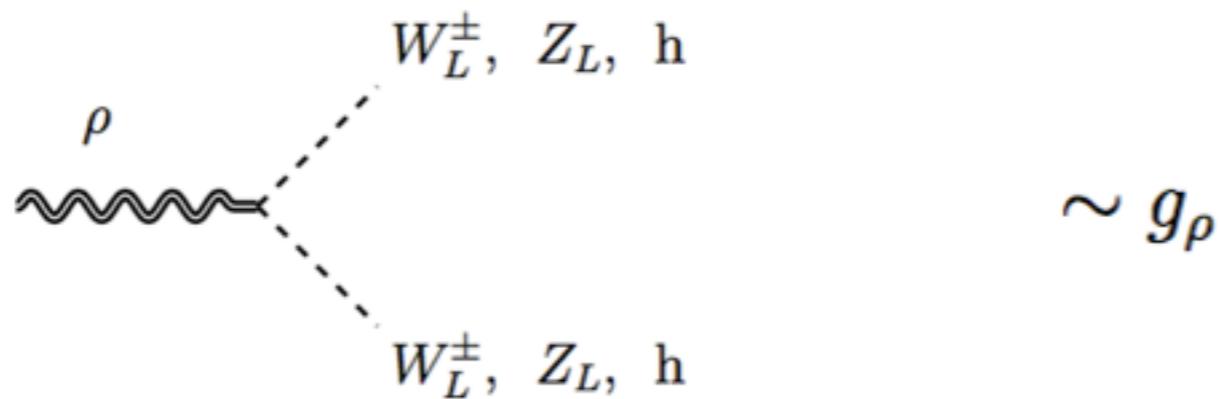
$$SO(4) \times U(1)_X = SU(2)_L \times SU(2)_R \times U(1)_X \quad Y = T_R^3 + X$$

Under this gauge group, spin-1 res. decomposes as

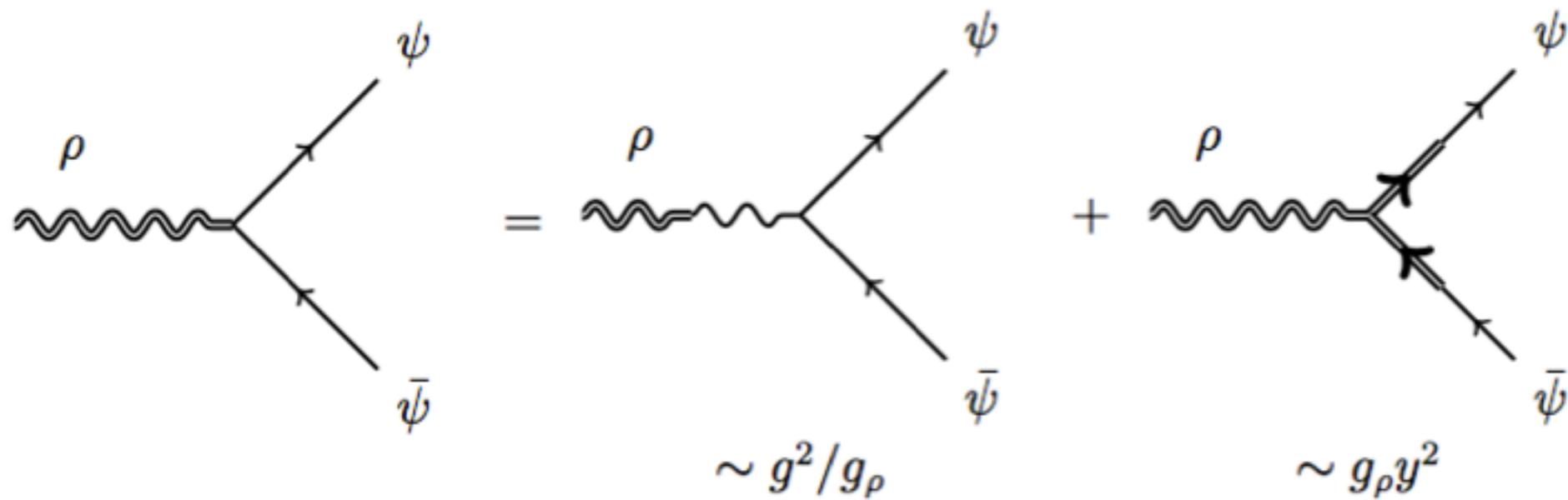


ρ couples to H, W_L, Z_L with large coupling (composite)

$$\mathcal{L} \supset ig_\rho c_H \rho_\mu^a (H^\dagger \tau^a D^\mu H - (D^\mu H)^\dagger \tau^a H)$$



ρ couples to fermions via mixing with W, Z or (partial) composite fermions



→ Can fit excess

ATLAS VV excess

Most significant. Lets focus on this analysis

Event Selection

[Talk by C. Delitzsch at BOOST 2015]

- Compared to semileptonic analysis only boosted regime is considered
- Reject events with electron or muon candidate or $E_T^{\text{miss}} > 350 \text{ GeV}$ (orthogonal to other diboson resonance searches)
- Overlap between WW , WZ , ZZ selection due to chosen mass window
- Rapidity difference: $|y_1 - y_2| < 1.2$
- p_T asymmetry: $|(\mathbf{p}_{T_1} - \mathbf{p}_{T_2})| / (\mathbf{p}_{T_1} + \mathbf{p}_{T_2}) < 0.15$
- $m_{JJ} > 1.05 \text{ TeV}$: trigger plateau of large- R jet trigger



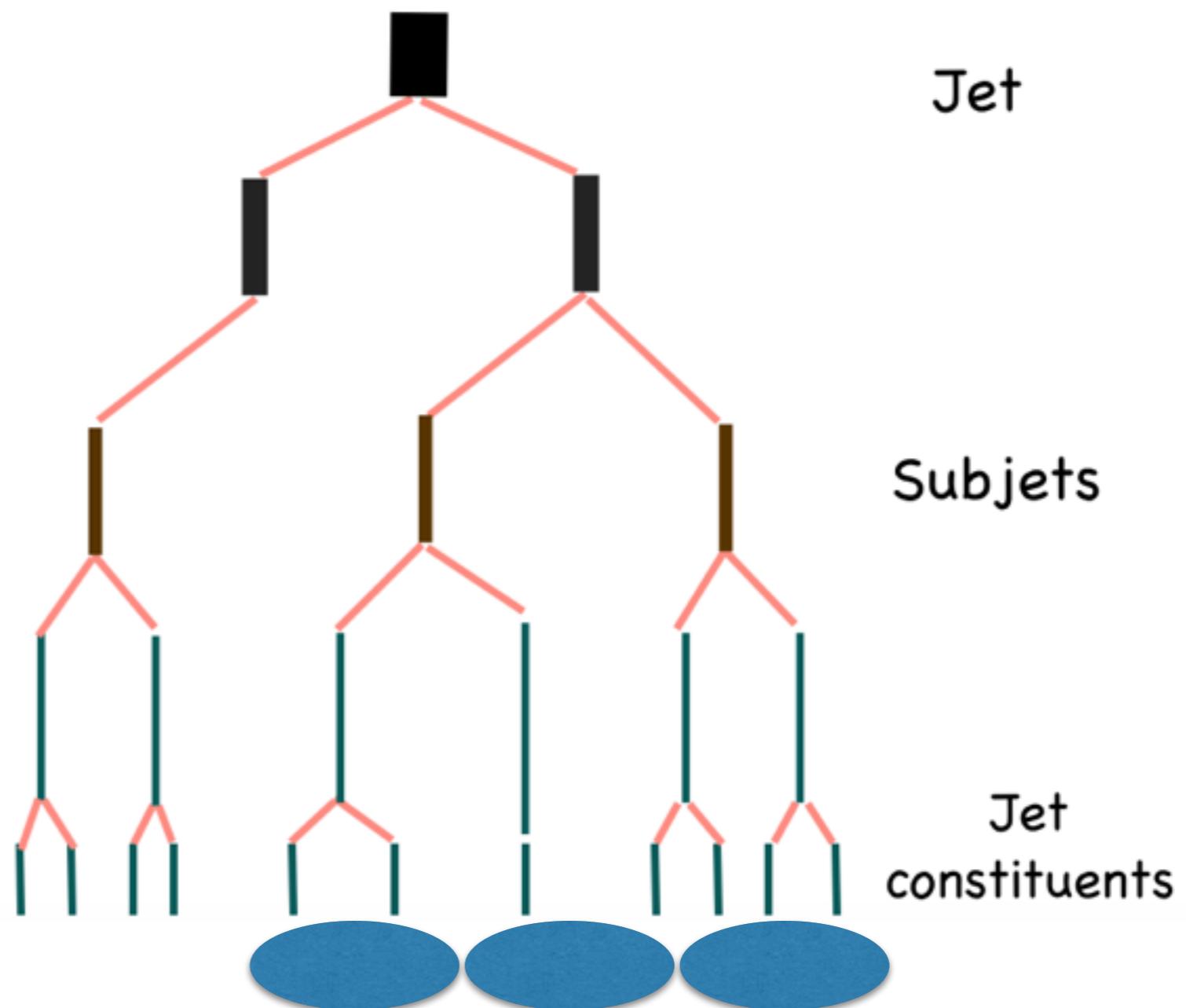
- For ungroomed fatjets $p_{T,j} > 540 \text{ GeV}$
- Reconstruction of VV final state follows same principles as discussed before

Resonance reconstruction

BDRS method

- Only y -cut applied when declustering
- y -cut fires, stop declustering and filter while keeping 1-3 subjets

Filtering parameter	Value
$\sqrt{y_f}$	0.2
μ_f	1
R_r	0.3
n_r	3



- Apply following cuts to identify W/Z

Jet mass (26 GeV window around m_V)

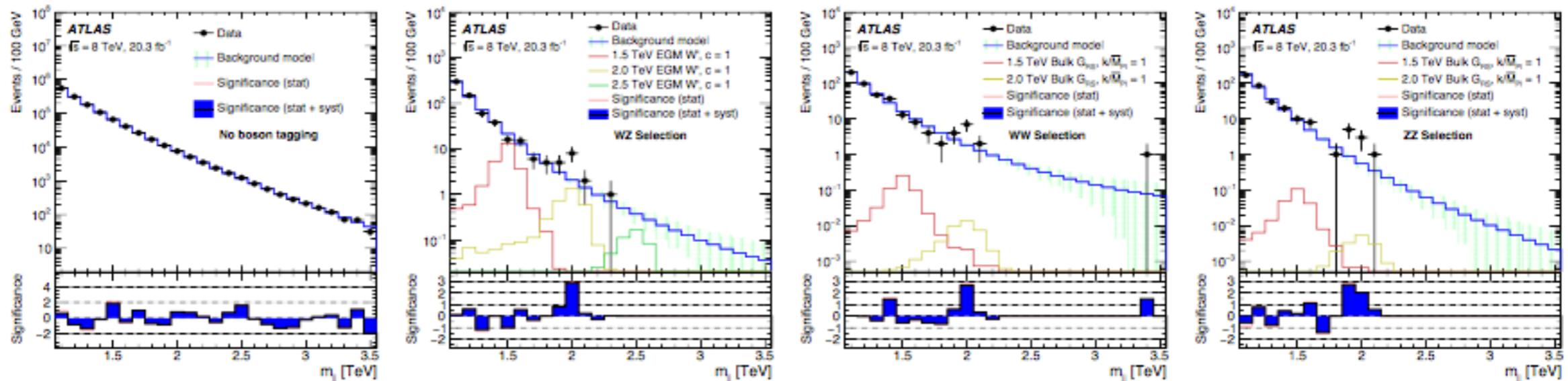
$$\text{sqrt}(y_f) > 0.45$$

#-tracks < 30 (QCD expected to have larger nr tracks)

- Background invariant dijet mass spectrum assumed to be smoothly falling distribution, characterized by:

$$\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3}x^{p_3}, \quad x = m_{jj}/\sqrt{s}$$

- Maximum-likelihood fit performed to data to estimate background



- Local significance: WZ : 3.4σ , WW : 2.6σ , ZZ : 2.9σ
- Global significance: WZ : 2.5σ

Following might be worth checking:

[Goncalves, Krauss, MS '15]

- Why start with $R=1.2$ jets when searching for W/Z with $1-2$ TeV p_T ?

$$\Delta R_{q\bar{q}} \simeq \frac{2m_W}{p_T} \simeq 0.12 \cdots 0.4$$

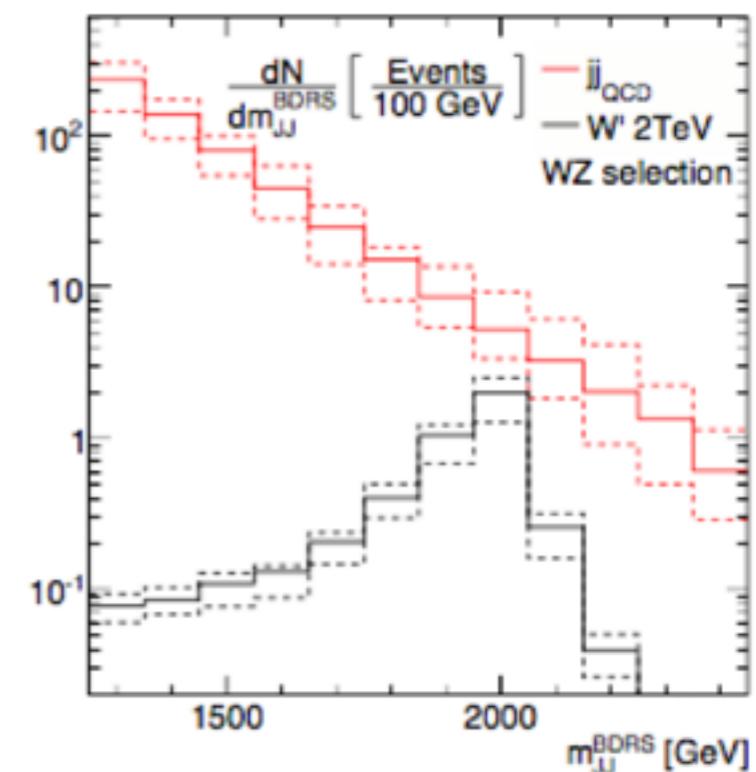
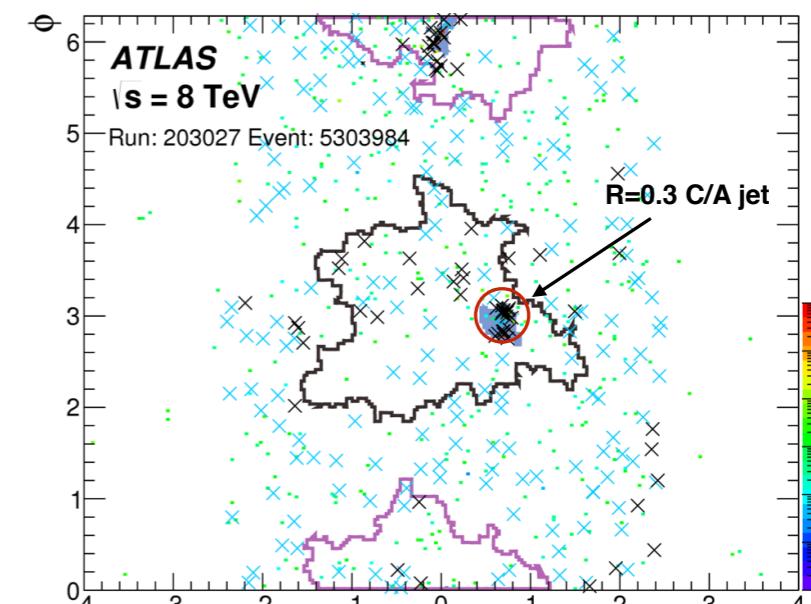
W/Z decay products in small area of detector

Jet absorbs lots of radiation from diff. sources

- Filtering step entirely ineffective for

$R=0.3$ and $nf = 1-3$

- Mass-drop procedure compares varying number of topoclusters (energy uncertainties unknown)



- n-tracks not infrared safe and known to be badly modelled in event generators

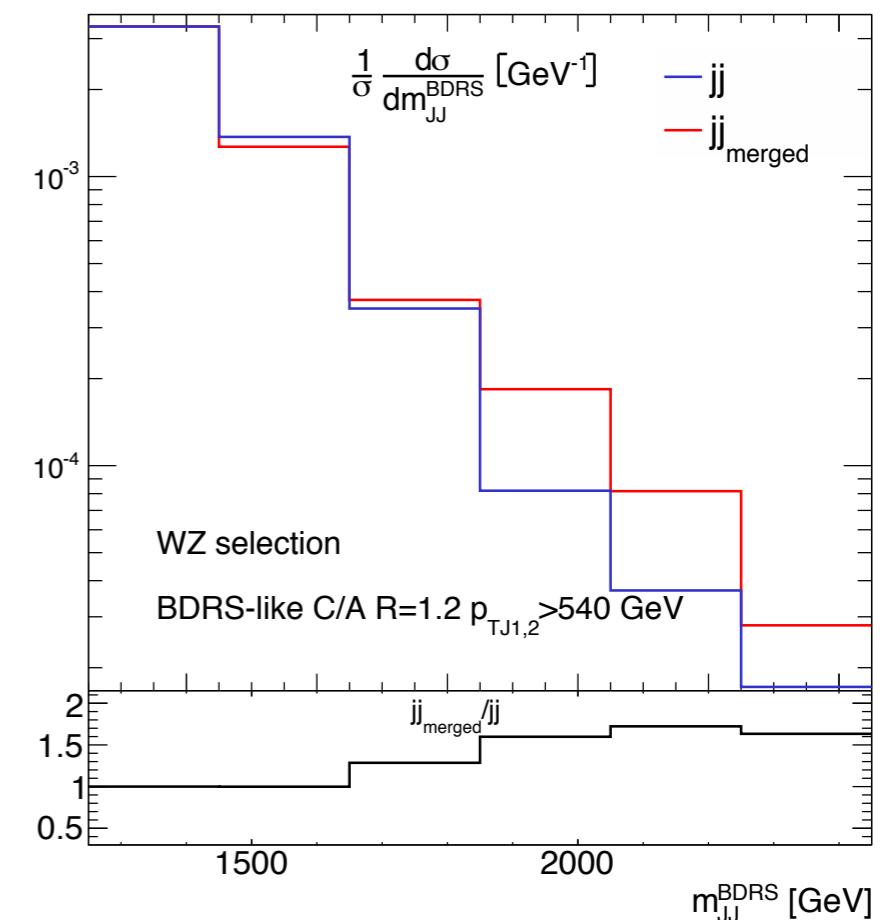
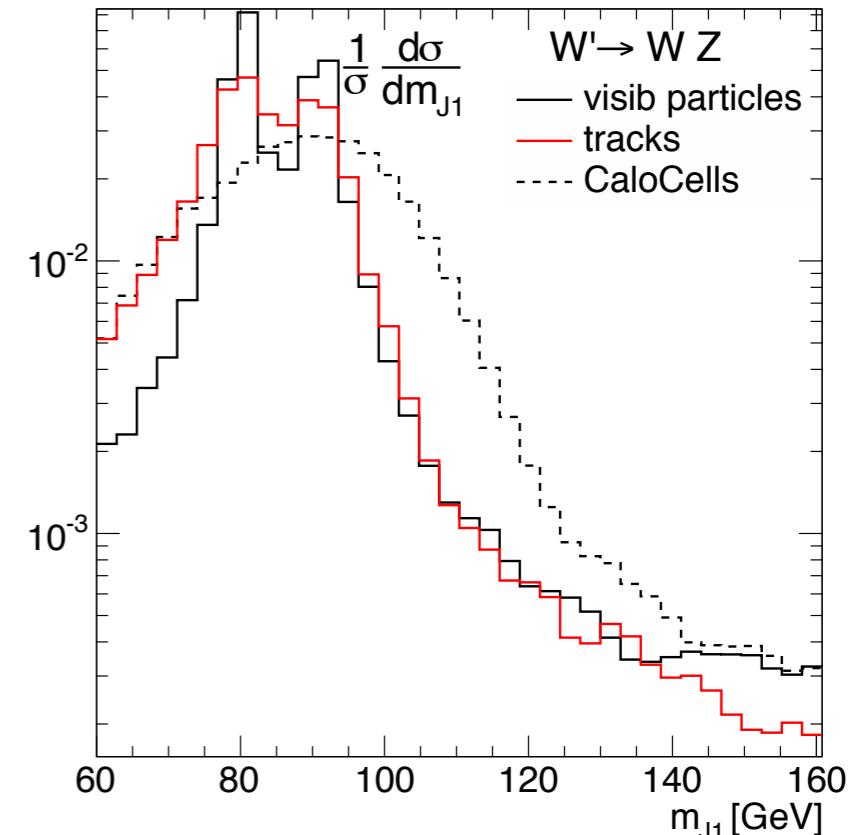
→ no a good variable to cut on

- Mass discrimination for W and Z difficult. However doable if tracks are applied

[Schaetzel, MS '14]
 [Stoll, MS '15]

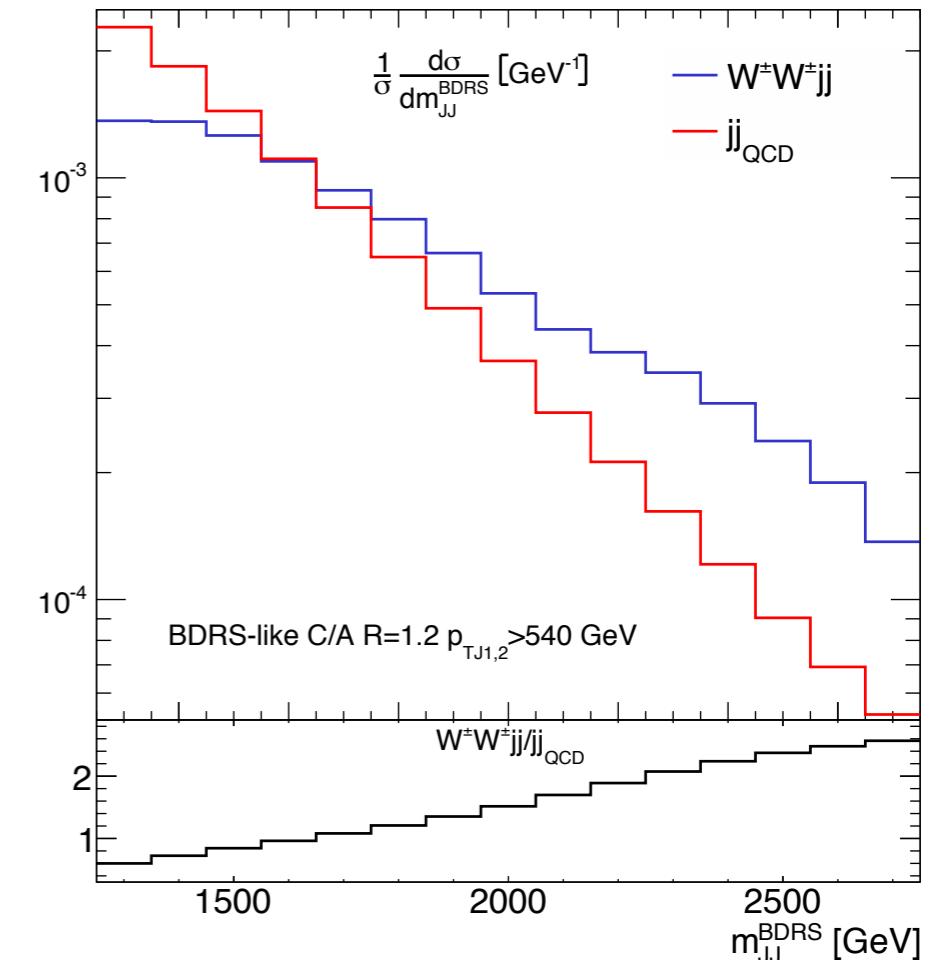
- Backgrounds and fit data driven, dijets checked against Pythia and Herwig++. How about hard radiation?

Increases background in tail after reconstruction



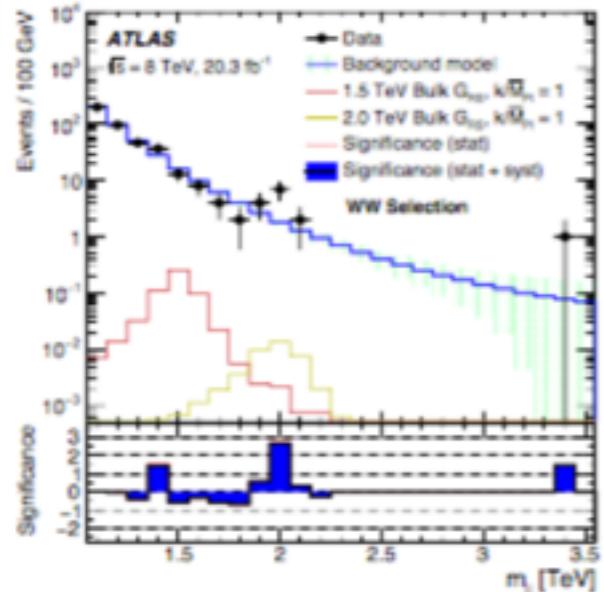
- How about backgrounds that kick in in the tail but nowhere else?

there are such backgrounds that have not been checked, but are fortunately small!

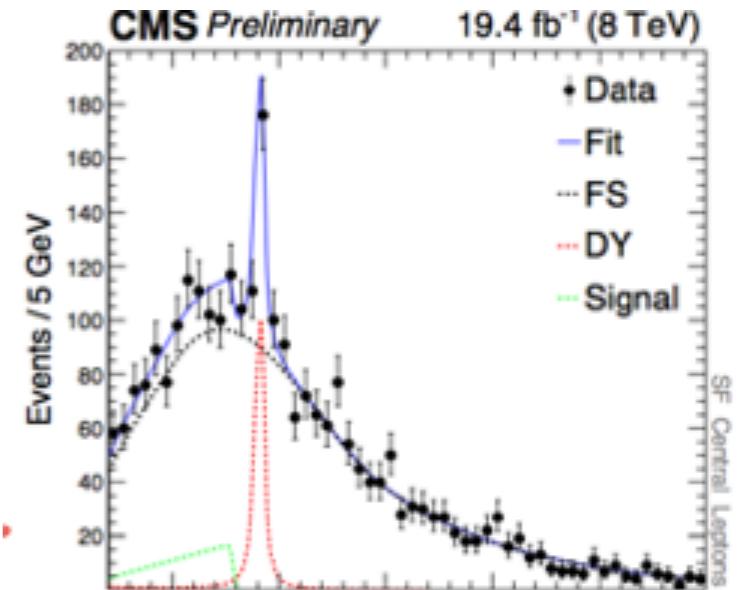


cuts	$W' \rightarrow WZ$	jj_{QCD}	$t\bar{t}$	VV	Vj	Vjj_{EW}	jj_{EW}	$W^\pm W^\pm jj$
	cross sections in fb							
BDRS 2J-tag, $p_T^J > 540$ GeV	1.17	28302	45.6	5.34	370	50.8	119	0.50
$\sqrt{y} > 0.45$	0.59	4290	9.7	0.67	44	5.4	10	0.1
$ y_1 - y_2 < 1.2$	0.45	2791	8.0	0.52	24	3.2	5.8	0.06
$ p_{T1} - p_{T2} / (p_{T1} + p_{T2}) < 0.15$	0.44	2776	7.8	0.51	24	3.2	5.74	0.054
WZ selection	0.21	26.7	0.18	0.25	0.83	0.01	0.22	0.0005
WZ selection, $1.9 < m_{JJ} < 2.1$ TeV	0.14	0.33	0.002	0.04	0.01	0.0002	0.002	0.00001

TABLE I: Cut-flow analysis for signal and SM background components. The selections follow the ATLAS publication and the cross-sections are given in fb.



Summary



While every discovery starts with an anomaly,
not every anomaly turns into a discovery

Let's not be complacent, relying on better machine to
reach verdict on anomalies
(systematics need checking continuously)

'Biggest anomaly is absence of new physics' (Andi Weiler)

We hope current anomalies turn into discoveries

→ cure HEP from 'Big Mac' blues

