

# BSM Physics at the LHC, HERA

Few topics that could be interesting for EIC

Elisabetta Gallo

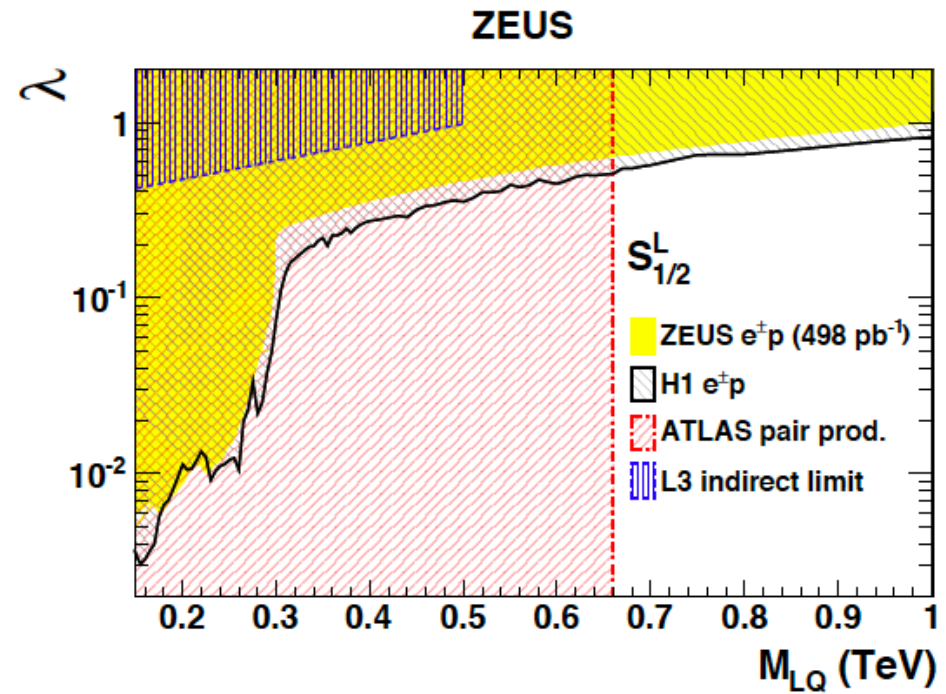
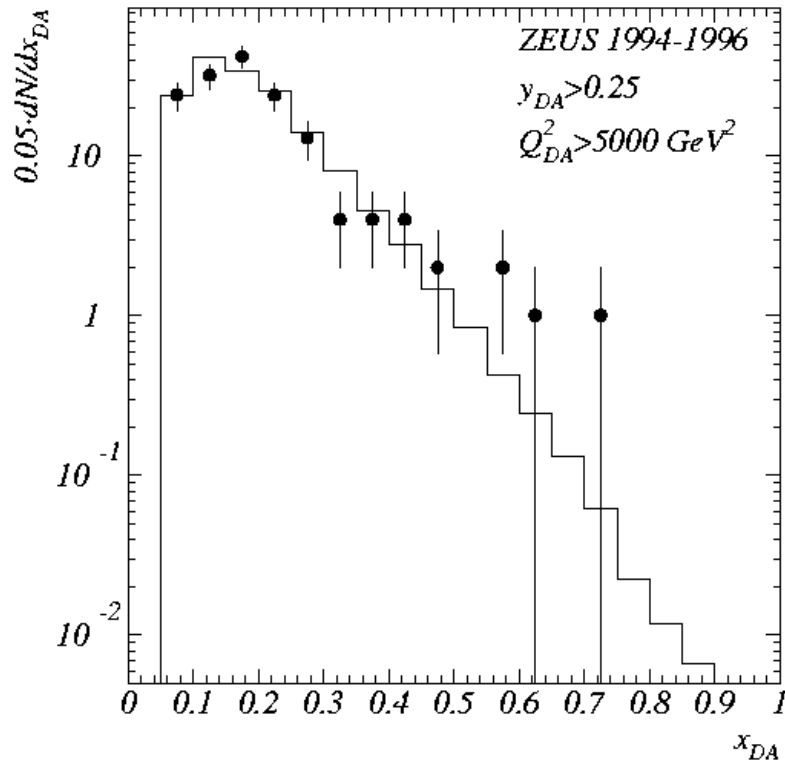
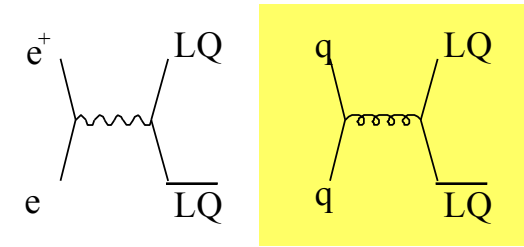
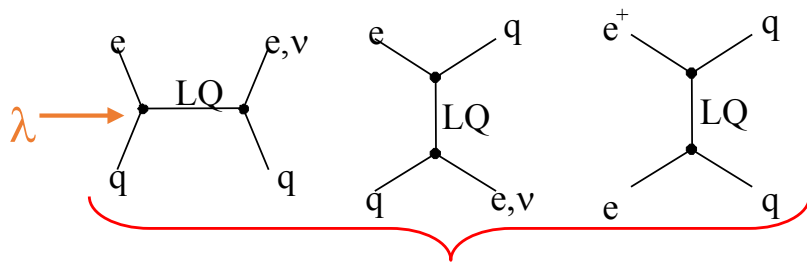
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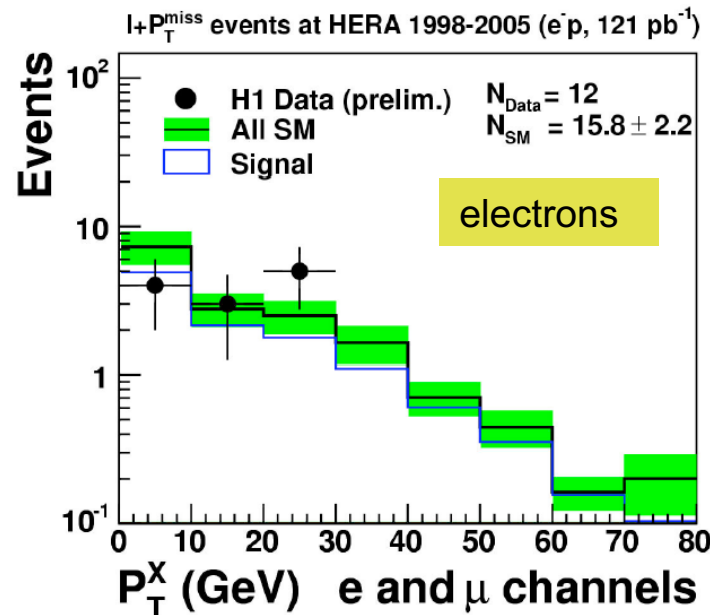
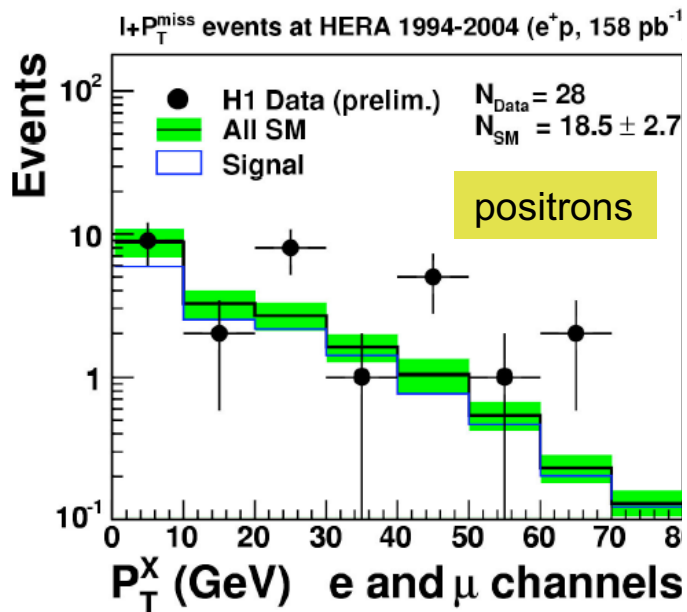
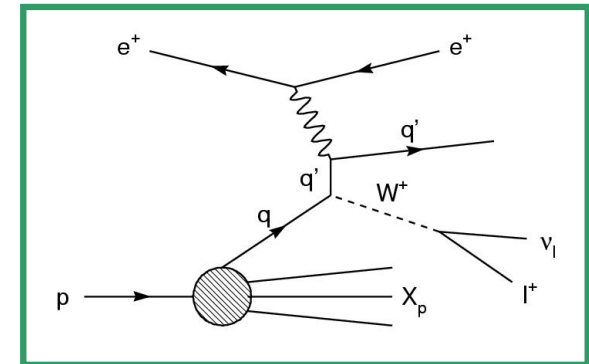
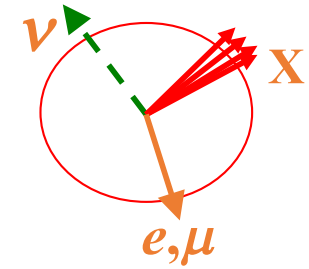
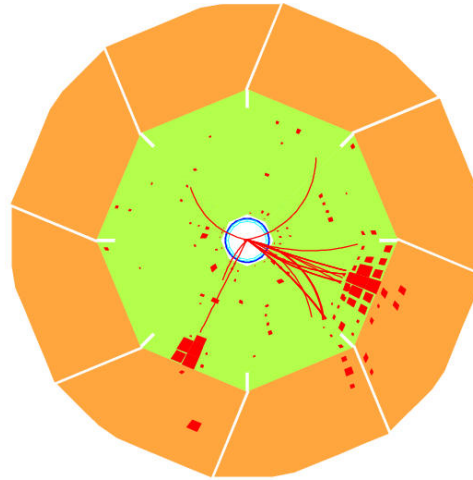
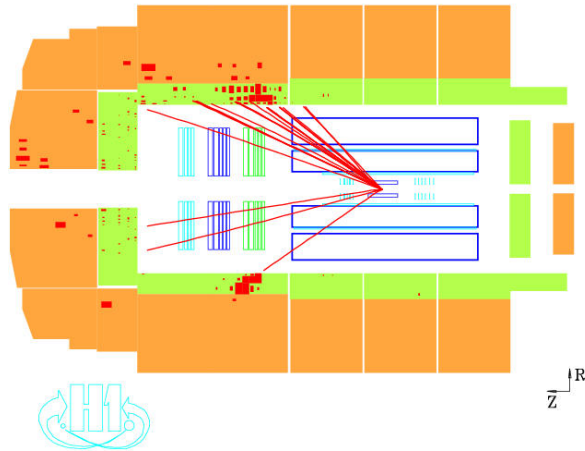
# For HERA results

Results taken from old slides

# Leptoquarks



# Isolated leptons at HERA

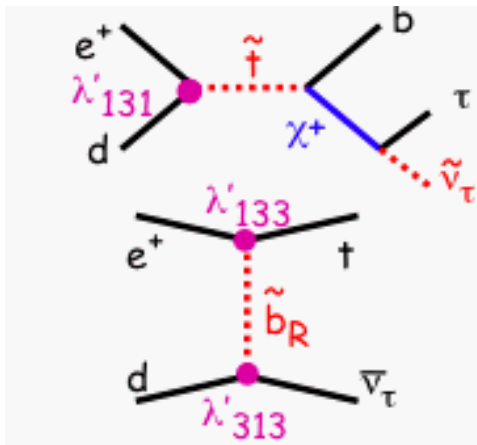
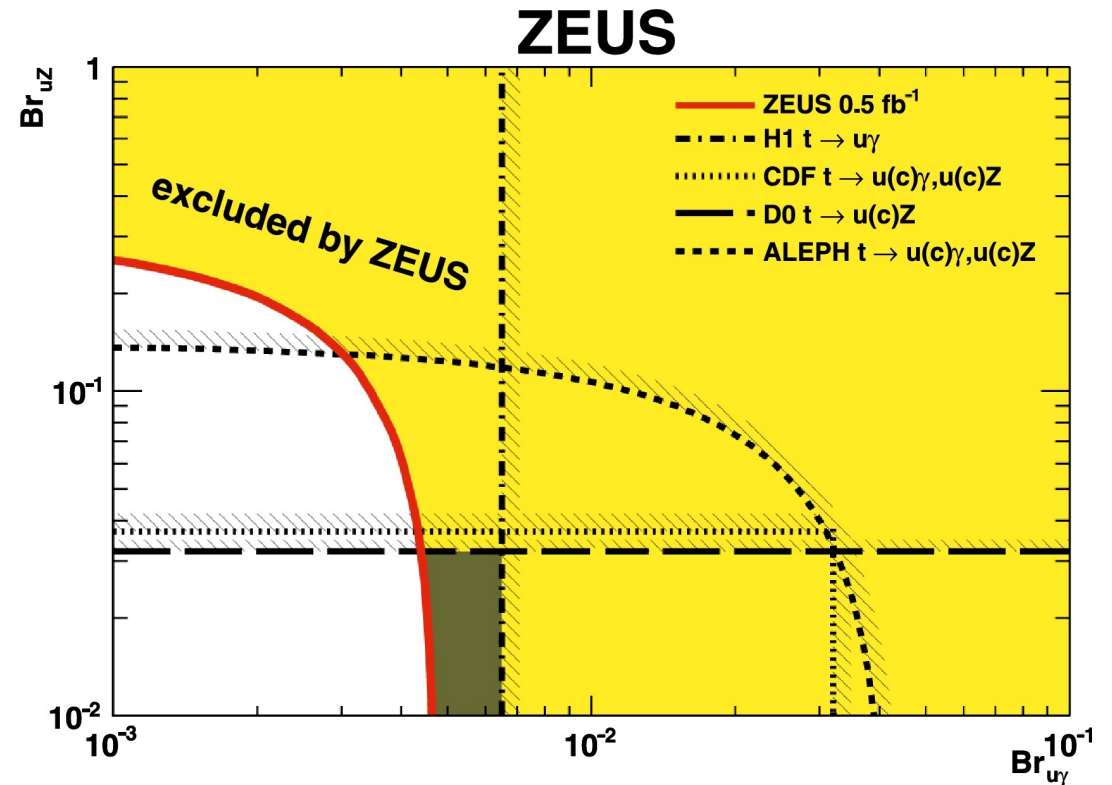
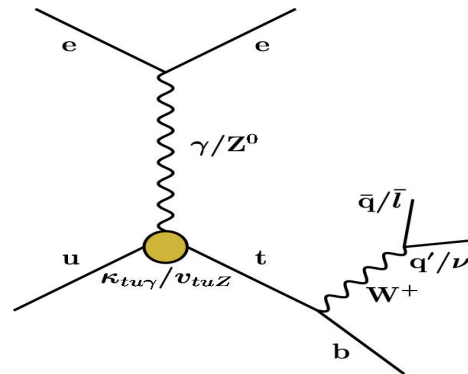


Analysis is optimized for the main SM process which is  $W$  production

Excess at high  $P_T^X$  observed by H1 in  $e^+p$  collisions

# Isolated leptons at HERA

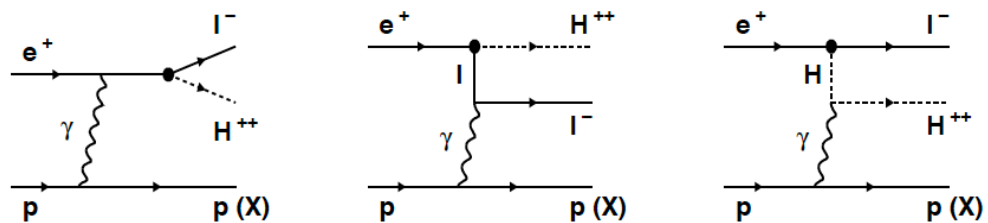
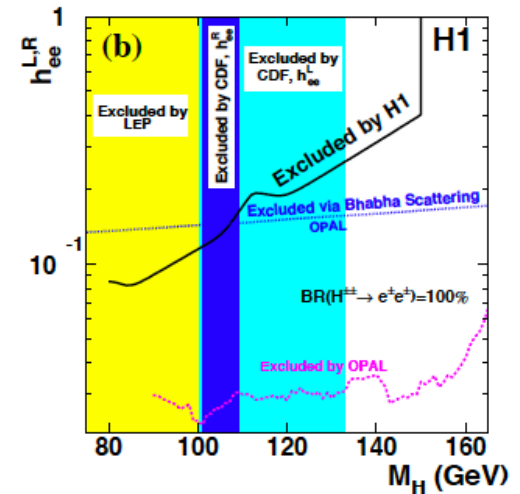
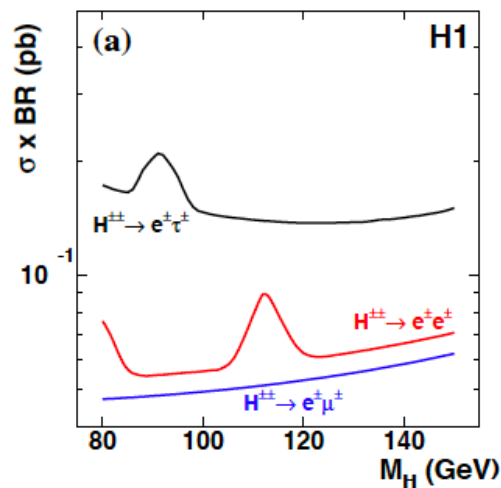
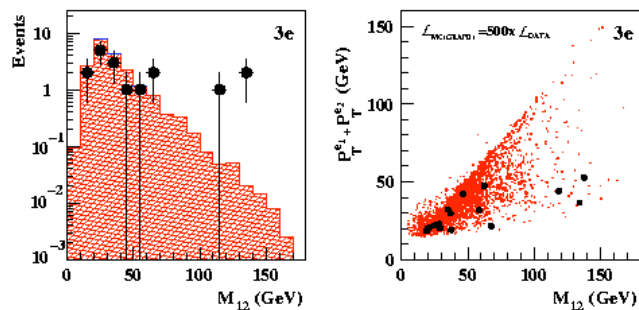
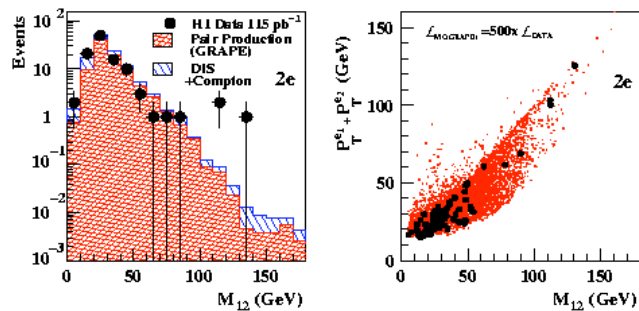
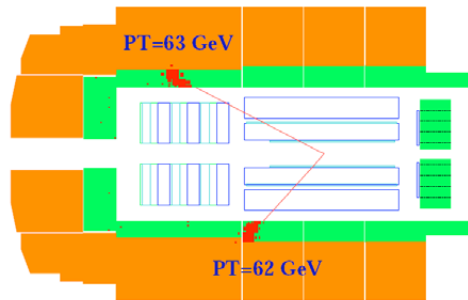
No excess seen by ZEUS, events analyzed in terms of anomalous single top production at HERA I



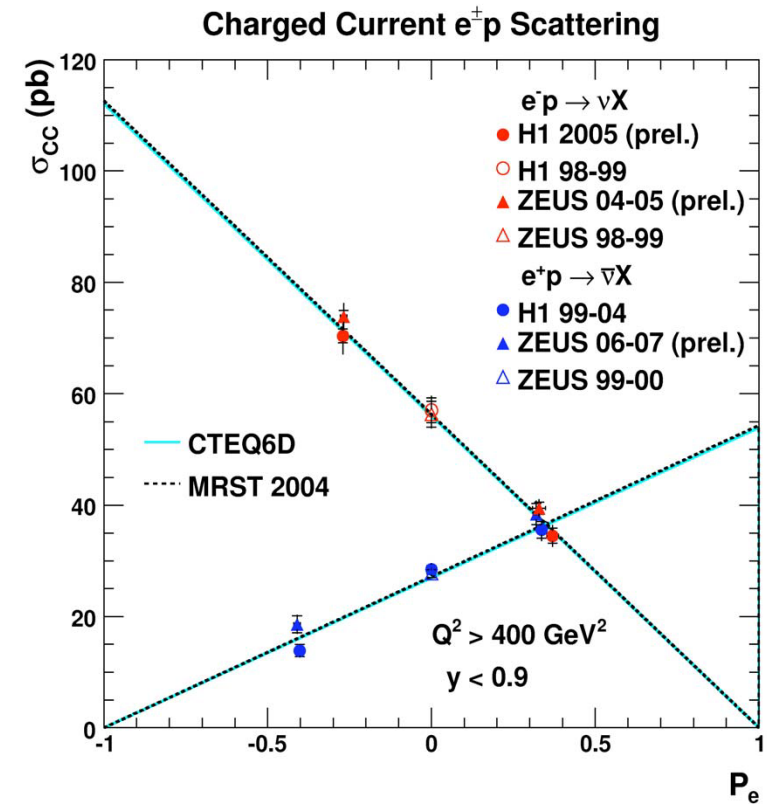
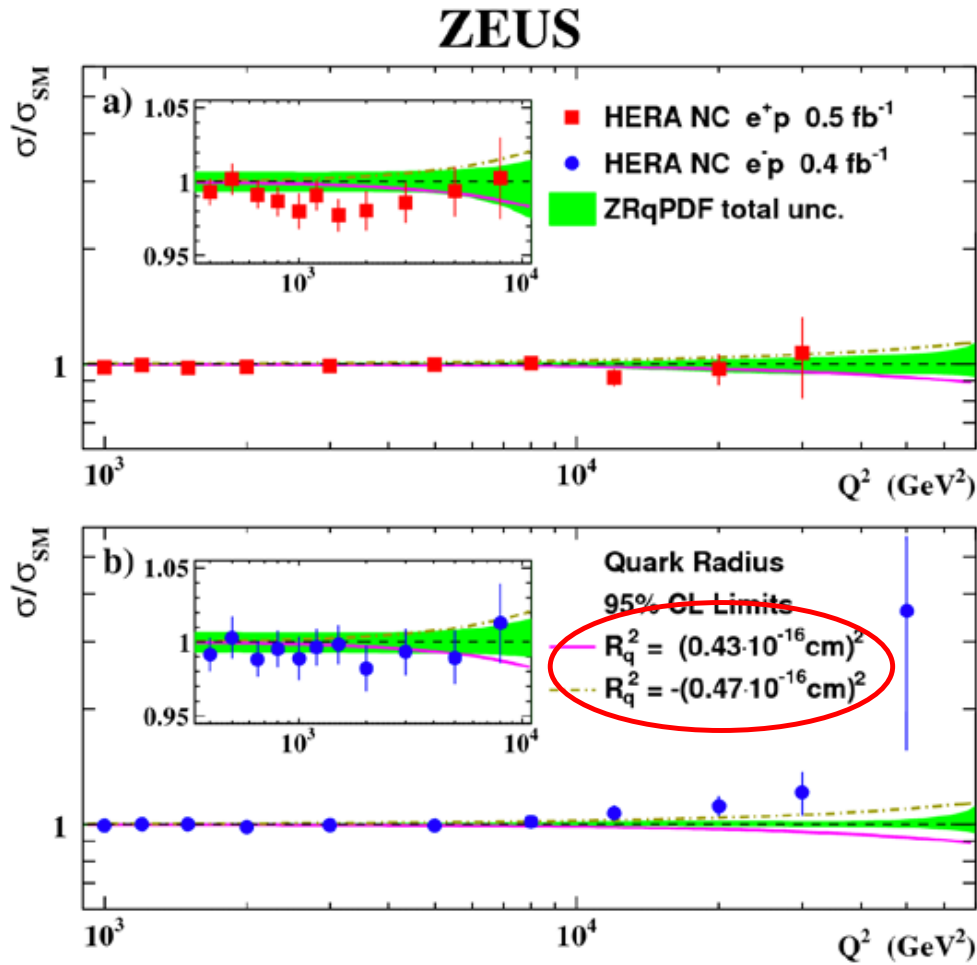
Some possible diagrams in R-parity violation SUSY to explain the H1 excess

# Multileptons in H1 and doubly-charged Higgs

Excess of events in 2e, 3e in H1, explanation could have been doubly-charged Higgs. Limits set at the end of HERA.



# Quark radius, NC and CC cross sections



Limits on  $W_R$  around  
200 GeV

# LHC results

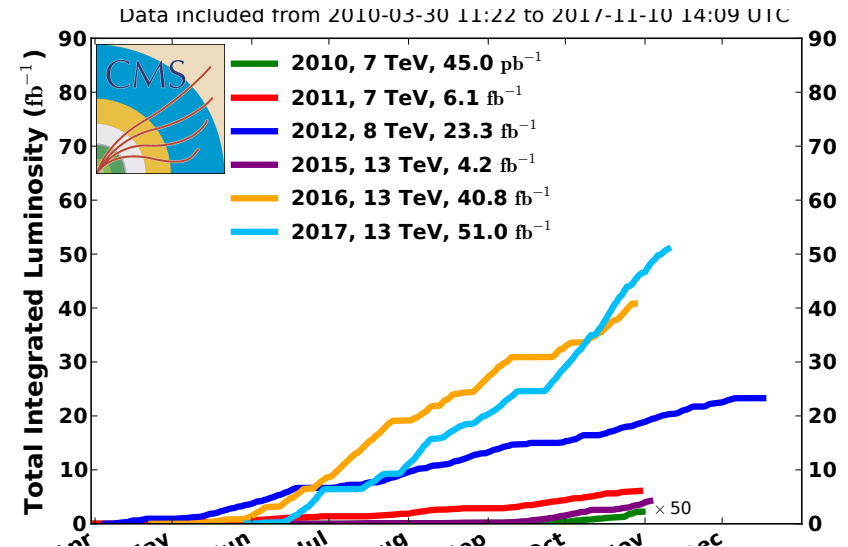
Results taken from slides at recent conferences  
on whatever is coupling to a lepton and a quark



# LHC

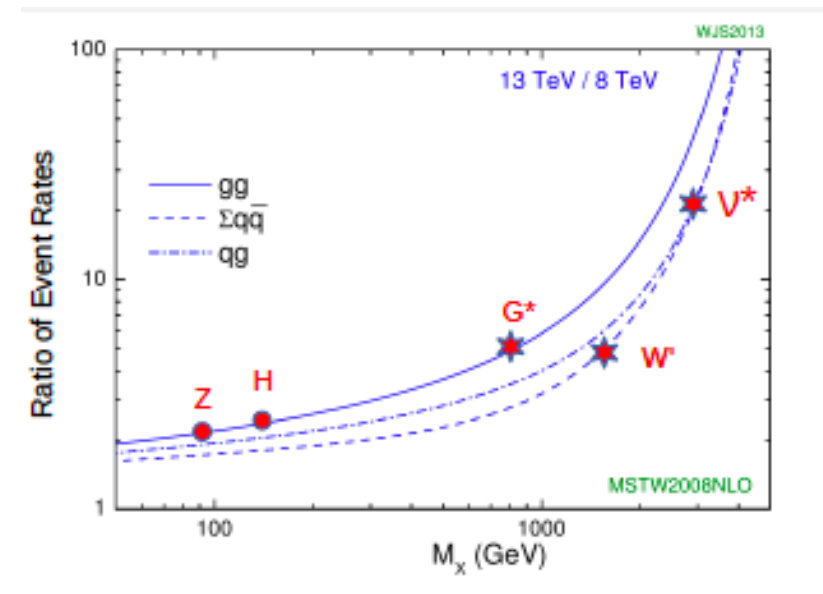
## LHC luminosity

- Run 1: 2010-2012 at  $\sqrt{s} = 7,8 \text{ TeV}$
- Run2: 2015-2018 at  $\sqrt{s} = 13 \text{ TeV}$
- The increased luminosity and c.m. energy has boosted BSM searches at the LHC.
- Ratio of parton luminosities.

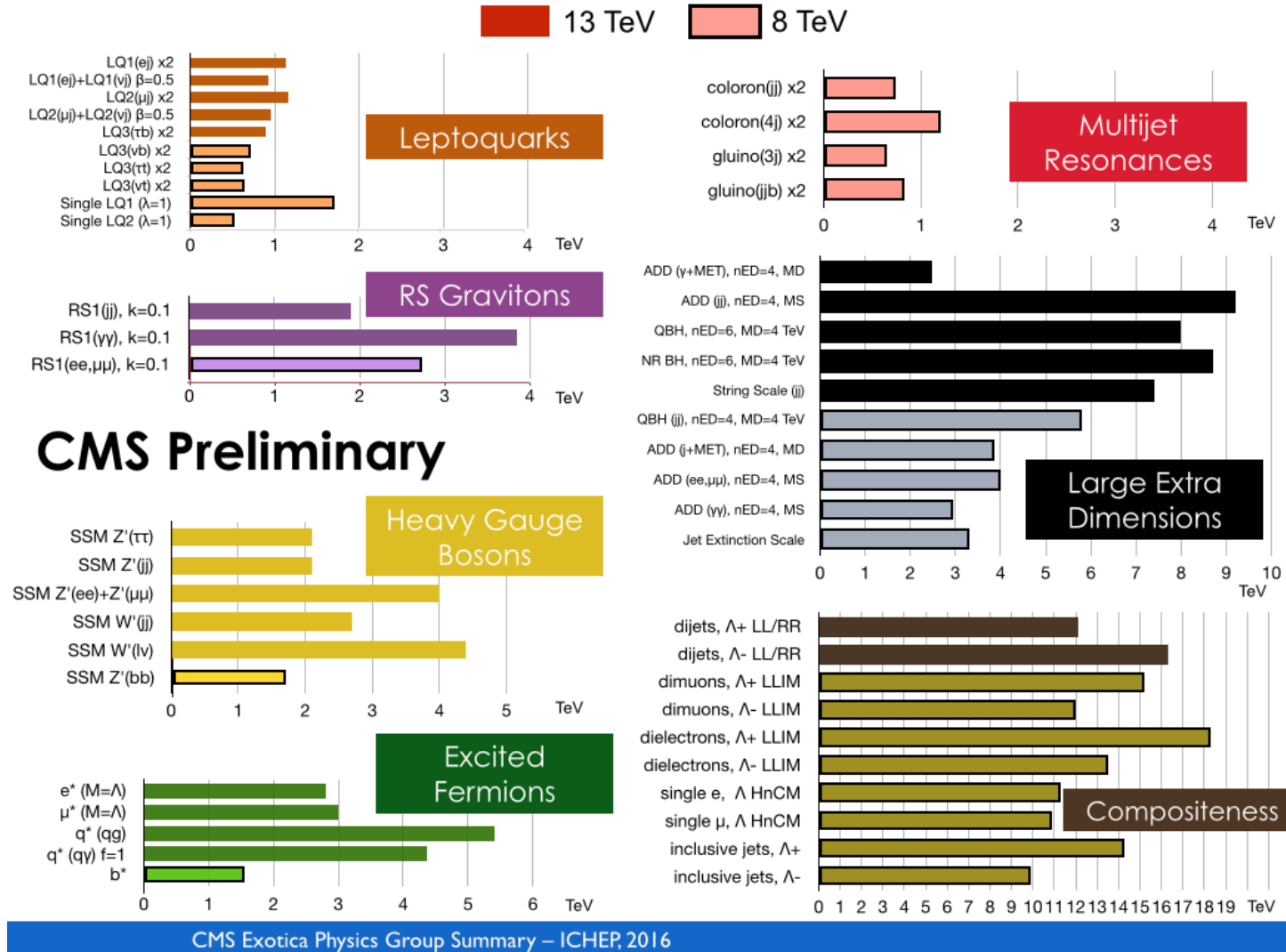


**First of all I am not an expert, at DESY we do exotica, but different searches.**

- I collected few results/slides which I thought important for ep physics.
- Many different searches, recently focused on dark matter, SUSY, heavy resonances (boosted techniques), long-lived particles.
- More than 100 Exotica papers in ATLAS/CMS only in 2016.



# Searches at CMS



# Searches at ATLAS, more recent compilation

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets†	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	$0 a, \mu$	$1-4 j$	Yes	36.1	$M_{\text{Pl}}$ 7.75 TeV	$n=2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_{\text{S}}$ 8.6 TeV	$n=3$ HILZ NLO	CERN-EP-2017-132
	ADD GBH	-	$2 j$	-	37.0	$M_{\text{A}}$ 8.9 TeV	$n=6$	1703.09217
	ADD BH high $\Sigma p_T$	$\geq 1 a, \mu$	$\geq 2 j$	-	3.2	$M_{\text{A}}$ 8.2 TeV	$n=6, M_D = 3 \text{ TeV}$ , rot BH	1806.02585
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{A}}$ 9.55 TeV	$n=6, M_D = 3 \text{ TeV}$ , rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	36.7	$G_{KK}$ mass 4.1 TeV	$k/\bar{M}_{\text{Pl}} = 0.1$	CERN-EP-2017-132
Gauge bosons	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 a, \mu$	$1 J$	Yes	36.1	$G_{KK}$ mass 1.75 TeV	$k/\bar{M}_{\text{Pl}} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1 a, \mu$	$\geq 2 b, \geq 3 j$	Yes	13.2	$KK$ mass 1.6 TeV	$\text{Tier}(1,1), \mathcal{B}(A^{(1,1)} \rightarrow \tau\tau) = 1$	ATLAS-CONF-2016-104
	SSM $Z' \rightarrow \ell\ell$	$2 a, \mu$	-	-	36.1	$Z'$ mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z'$ mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	3.2	$Z'$ mass 1.5 TeV	$\Gamma/m = 3\%$	1603.08791
	Leptophobic $Z' \rightarrow \tau\tau$	$1 a, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	3.2	$Z'$ mass 2.0 TeV		ATLAS-CONF-2016-014
CI	SSM $W' \rightarrow \ell\nu$	$1 a, \mu$	-	Yes	36.1	$W'$ mass 5.1 TeV		1706.04786
	HVT $V' \rightarrow WW \rightarrow qq\ell\nu$ model B	$0 a, \mu$	$2 J$	-	36.7	$V'$ mass 3.5 TeV	$\beta_V = 3$	CERN-EP-2017-147
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V'$ mass 2.93 TeV	$\beta_V = 3$	ATLAS-CONF-2017-055
	LPSM $W'_R \rightarrow tb$	$1 a, \mu$	$2 b, 0-1 j$	Yes	20.3	$W'_R$ mass 1.92 TeV		1410.4103
	LPSM $W'_R \rightarrow tb$	$0 a, \mu$	$\geq 1 b, 1 J$	-	20.3	$W'_R$ mass 1.76 TeV		1408.0866
	DM	SI $gggg$	-	$2 j$	-	37.0	$A$ 21.8 TeV	$\eta_{\text{L}}$
CI $\ell\ell qq$		$2 a, \mu$	-	-	36.1	$A$ 40.1 TeV	$\eta_{\text{L}}$	ATLAS-CONF-2017-027
CI $uu\tau\tau$		$2(SS) \geq 3 a, \mu \geq 1 b, \geq 1 j$	Yes	20.3	$A$ 4.9 TeV	$ C_{\text{SM}}  = 1$		1504.04605
LQ	Axial-vector mediator (Dirac DM)	$0 a, \mu$	$1-4 j$	Yes	36.1	$M_{\text{Med}}$ 1.5 TeV	$\tilde{g}_c = -0.25, \tilde{g}_s = 1.0, m(\chi) < 400 \text{ GeV}$	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0 a, \mu, 1 \gamma$	$\leq 1 j$	Yes	36.1	$M_{\text{Med}}$ 1.2 TeV	$\tilde{g}_c = -0.25, \tilde{g}_s = 1.0, m(\chi) < 480 \text{ GeV}$	1704.03848
	$VV_{\text{LQ}}$ EFT (Dirac DM)	$0 a, \mu$	$1 j, \leq 1 j$	Yes	3.2	$M_s$ 700 GeV	$m(\chi) < 150 \text{ GeV}$	1608.02372
Heavy quarks	Scalar LQ 1 <sup>st</sup> gen	$2 a$	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$	1805.06035
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$	1805.06035
	Scalar LQ 3 <sup>rd</sup> gen	$1 a, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
	VLO $TT \rightarrow Ht + X$	$0$ or $1 a, \mu$	$\geq 2 b, \geq 3 j$	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \rightarrow Ht) = 1$	ATLAS-CONF-2016-104
Excited fermions	VLO $TT \rightarrow Zt + X$	$1 a, \mu$	$\geq 1 b, \geq 3 j$	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \rightarrow Zt) = 1$	1705.10751
	VLO $TT \rightarrow Wb + X$	$1 a, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \rightarrow Wb) = 1$	CERN-EP-2017-094
	VLO $BB \rightarrow Hb + X$	$1 a, \mu$	$\geq 2 b, \geq 3 j$	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \rightarrow Hb) = 1$	1505.04306
	VLO $BB \rightarrow Zb + X$	$2 \geq 3 a, \mu$	$\geq 2 b, \geq 1 b$	-	20.3	B mass 790 GeV	$\mathcal{B}(B \rightarrow Zb) = 1$	1409.5500
	VLO $BB \rightarrow Wt + X$	$1 a, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \rightarrow Wt) = 1$	CERN-EP-2017-094
	VLO $QQ \rightarrow WqWq$	$1 a, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV		1509.04261
Other	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	37.0	$q^*$ mass 6.0 TeV	only $u^*$ and $d^*, \Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	$q^*$ mass 5.3 TeV	only $u^*$ and $d^*, \Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	13.3	$b^*$ mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	$1$ or $2 a, \mu$	$1 b, 2-0 j$	Yes	20.3	$b^*$ mass 1.5 TeV	$\xi_b = \xi_t = \xi_c = 1$	1510.02664
	Excited lepton $\ell^*$	$3 a, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$	1411.2921
	Excited lepton $\tau^*$	$3 a, \mu, \tau$	-	-	20.3	$\tau^*$ mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$	1411.2921
Other	LPSM Majorana $\nu$	$2 a, \mu$	$2 j$	-	20.3	$N^0$ mass 2.0 TeV	$m(W_R) = 2.4 \text{ TeV}$ , no mixing	1506.06020
	Higgs triplet $H^{++} \rightarrow \ell\ell$	$2, 3, 4 a, \mu$ (SS)	-	-	36.1	$H^{++}$ mass 870 GeV	$DY$ production	ATLAS-CONF-2017-053
	Higgs triplet $H^{++} \rightarrow \ell\tau$	$3 a, \mu, \tau$	-	-	20.3	$H^{++}$ mass 400 GeV	$DY$ production, $\mathcal{B}(H^{++} \rightarrow \ell\tau) = 1$	1411.2921
	Monopole (non-res prod)	$1 a, \mu$	$1 b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$\alpha_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	$DY$ production, $ q  = 5e$	1504.04188
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	$DY$ production, $ g  = 1g_D$ , spin 1/2	1509.08059

\*Only a selection of the available mass limits on new states or phenomena is shown.

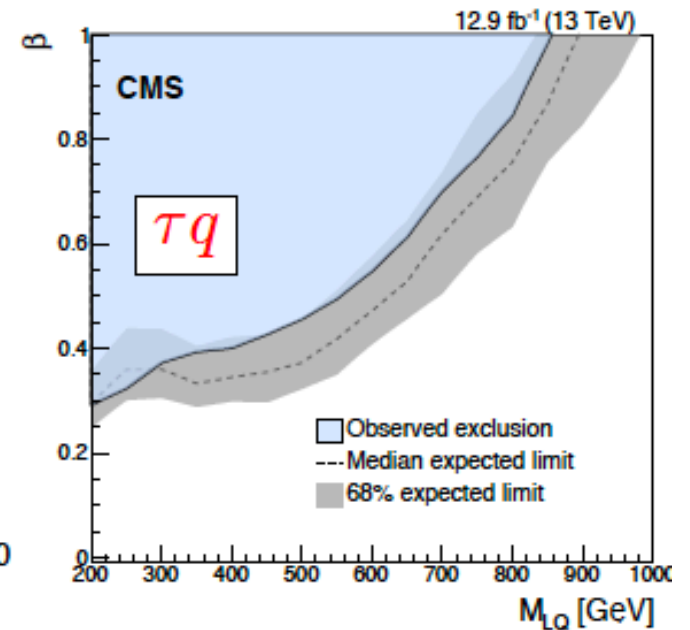
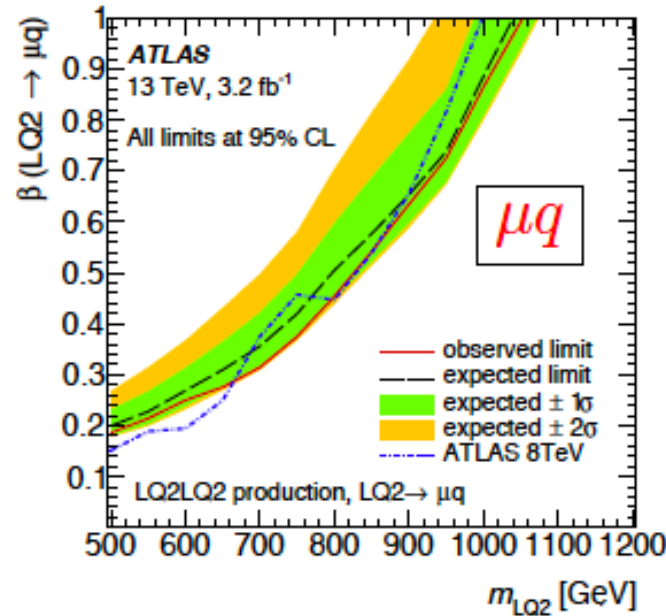
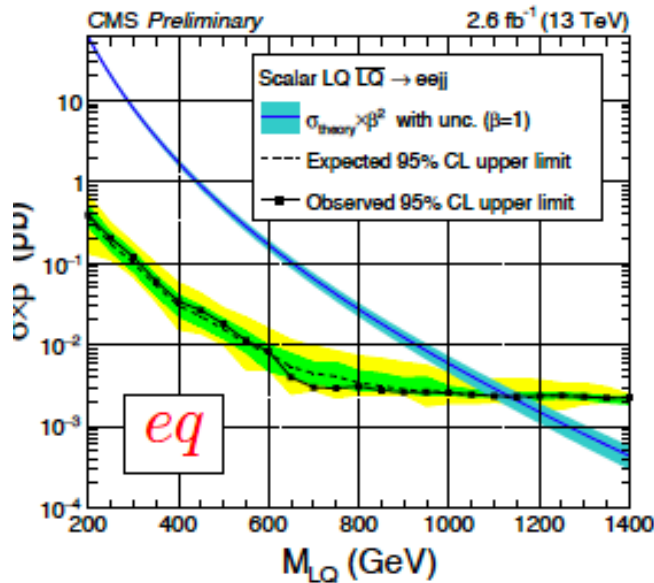
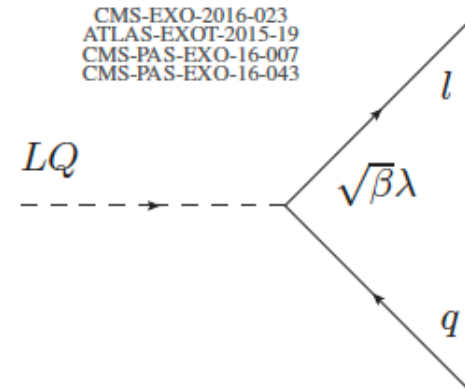
†Small-radius (large-radius) jets are denoted by the letter j (J).

# Search for Leptoquarks in pairs

Use of BRW model, assume narrow resonances.

Searches in 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> generation.

The limit depends on the branching ratio  $\beta$ , and not on the coupling to  $lq, \lambda$ , this is opposite to ep.

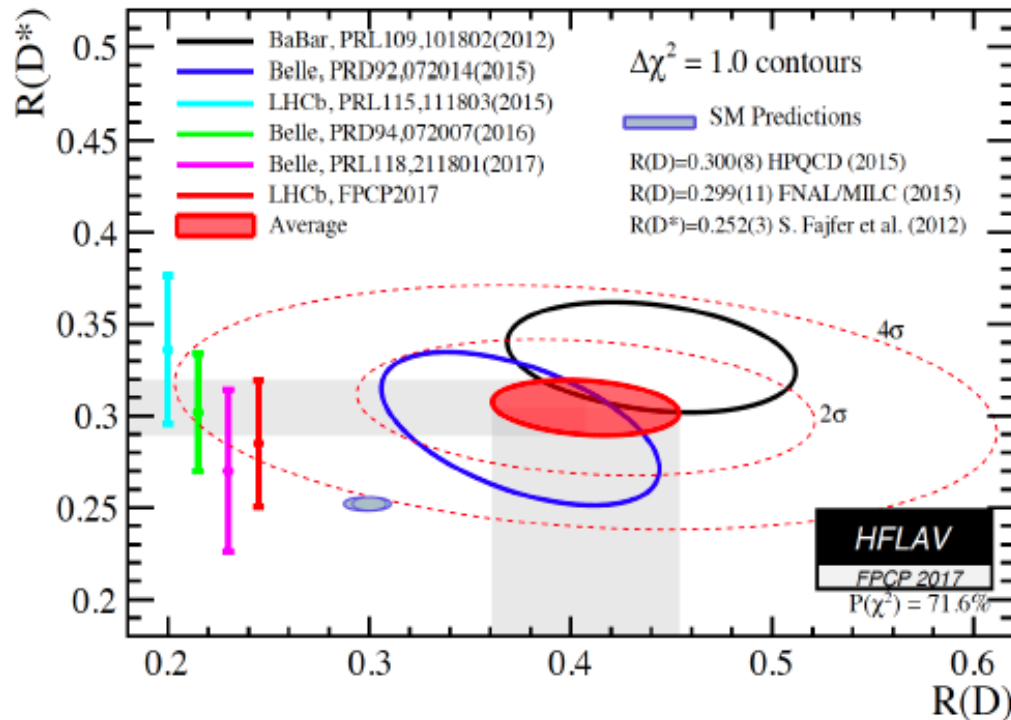
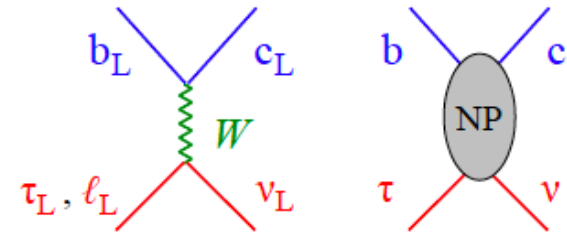


From slides at SUSY conference at Mumbai

# Recently a lot of interest

Consistent set of anomalies observed recently in flavour:

1)  $b \rightarrow c$ , charged current, tau versus other lepton



$$R(X) = \frac{\Gamma(B \rightarrow X \tau \bar{\nu})}{\Gamma(B \rightarrow X \ell \bar{\nu})}$$

$X = D \text{ or } D^*$

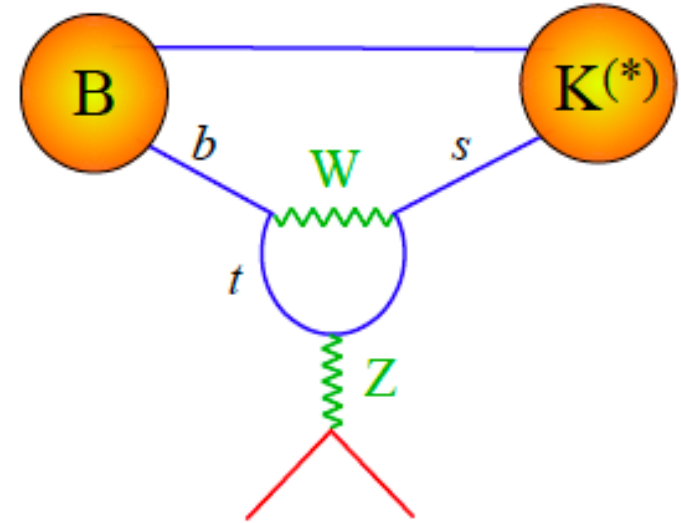
Observed by 3 experiments

Plots taken from a seminar from Isidori at a CMS meeting

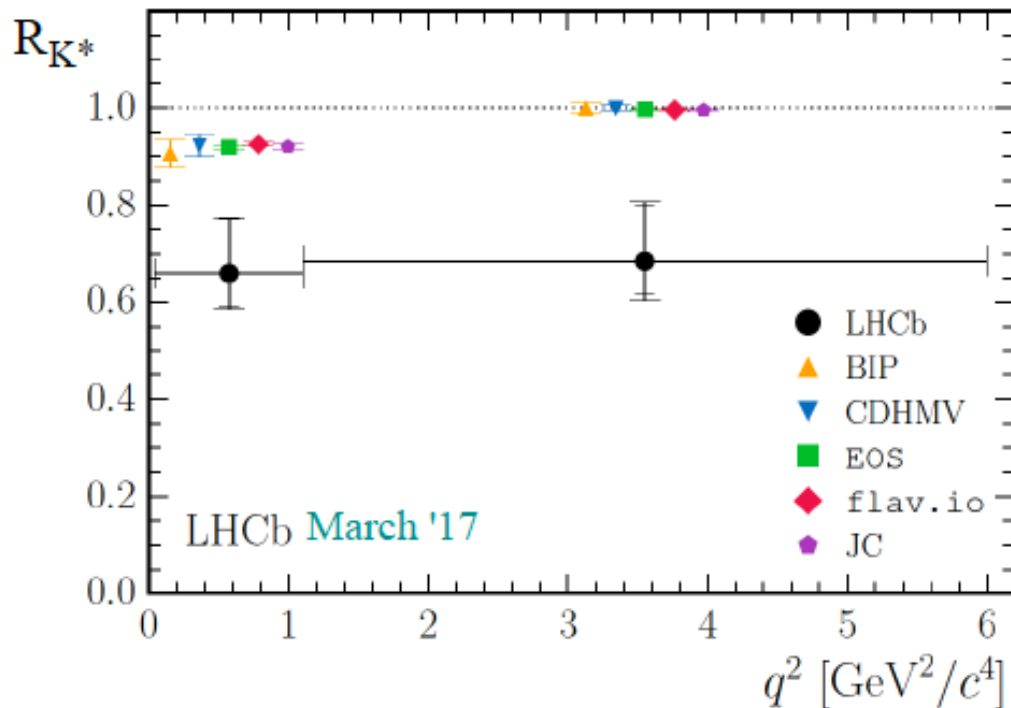
# Recently a lot of interest

Consistent set of anomalies observed recently in flavour:

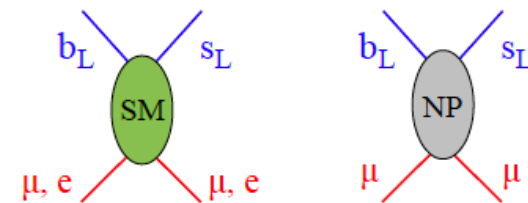
2)  $b \rightarrow s$ , neutral currents, muon versus electron



Anomalies in  $B \rightarrow K^{(*)} \mu\mu / ee$  [LHCb]



Anomalies observed in angular distributions and other observables by LHCb. Results and fits seem to point to the fact that there could be new physics in  $b \rightarrow s\mu\mu$ , and not in  $b \rightarrow see$



# Recently a lot of interest

Quark level transition  $b \rightarrow cl\bar{\nu}$

$R_D, R_{D^*}$ : combined  $\sim 4\sigma$  deviation (

$$R_{D^{(*)}}^{\tau/\ell} = \frac{\Gamma(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \rightarrow D^{(*)}\ell\bar{\nu})}$$

Quark level transition  $b \rightarrow sl\bar{\ell}$

$R_K, R_{K^*}$ :  $\sim 2.5\sigma$  deviation (LHCb)

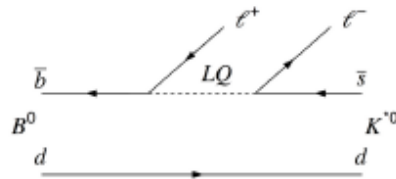
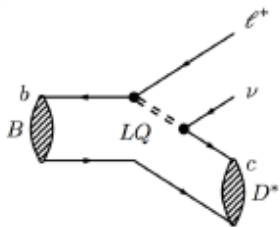
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \rightarrow \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \rightarrow \bar{K}^{(*)}e^+e^-)}$$

$B^0 \rightarrow K^{*0}\mu^+\mu^-$  angular analysis:

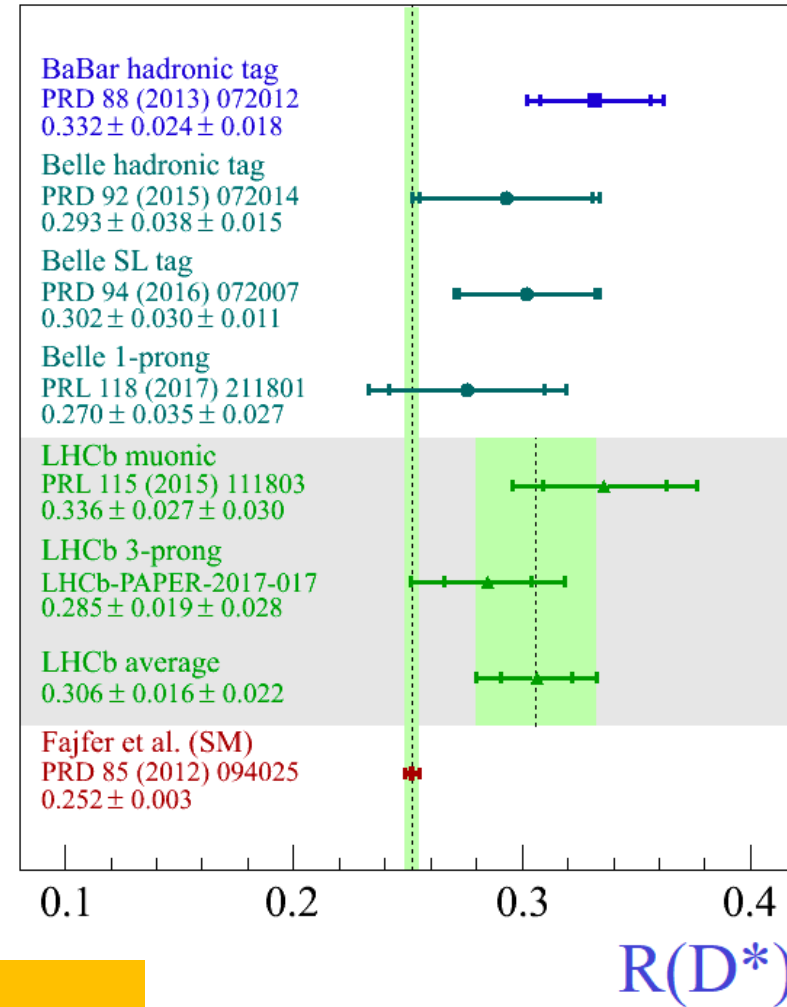
$3.4\sigma$  deviation (LHCb) (Click Me)

(with lower precision

Belle (Click Me), CMS (Click Me), ATLAS



Slide taken from a CMS meeting



Anomalies are all seen in lepton-quark couplings.  
Explanation could be a LQ coupling to 3<sup>rd</sup> generation

# LQ searches, pair and single production

Slide taken from a CMS meeting, plot from arXiv:1706.07808

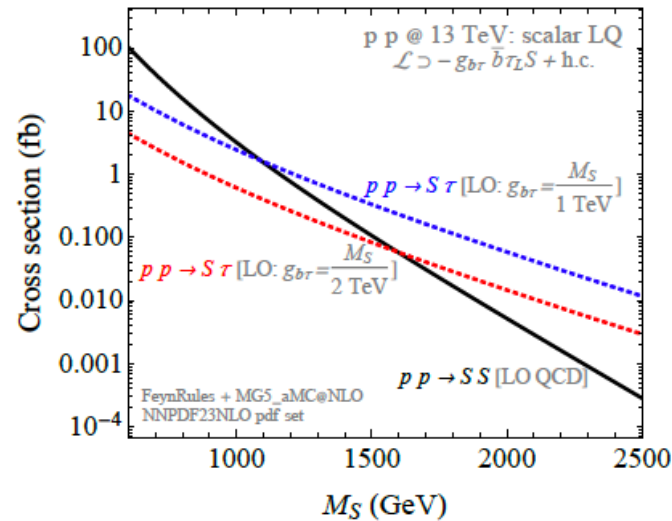
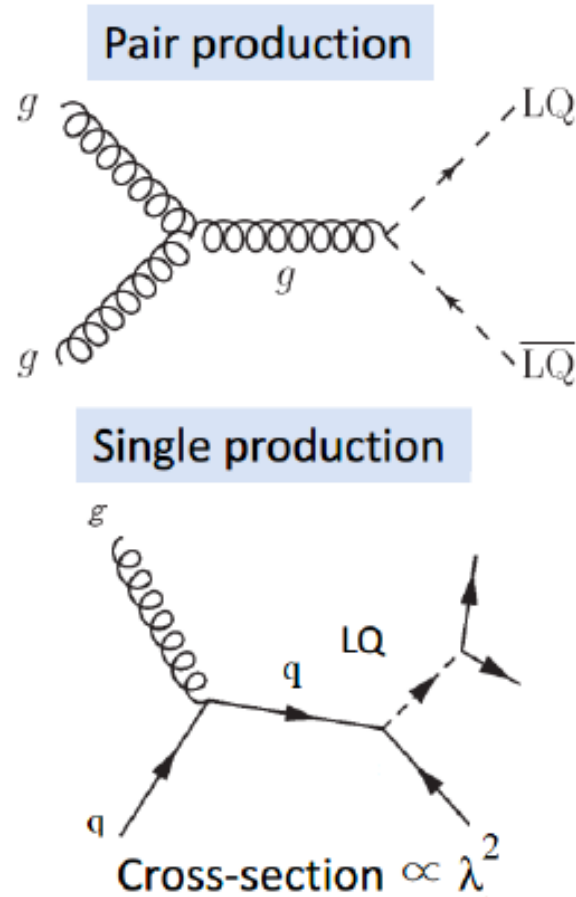
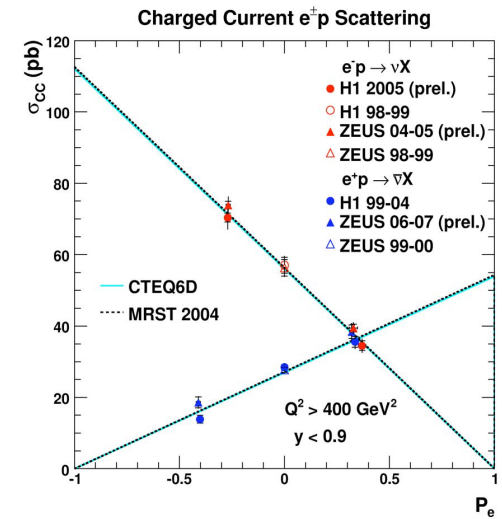
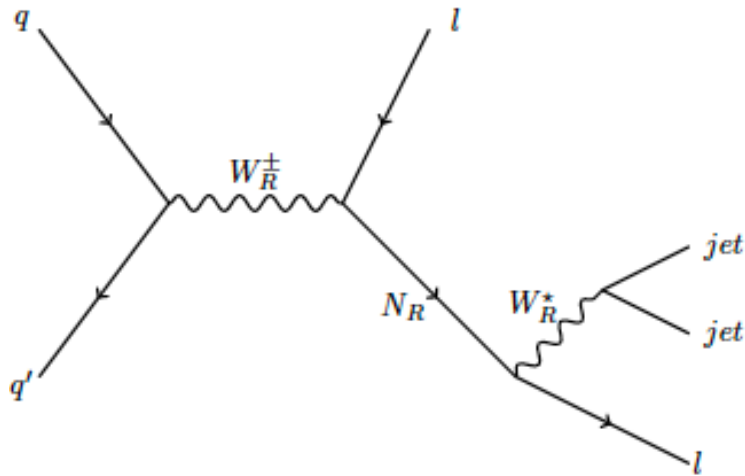


Figure 7: Cross section (in fb) at 13 TeV  $pp$  collider for: (a) scalar LQ pair production (solid black line), and (b) single LQ +  $\tau$  production for the two coupling benchmarks motivated by the fit to low-energy data (dashed blue and red lines).

At high mass, single LQ production dominates over pair production, the crossing point depends on  $\lambda$  and the quark generation

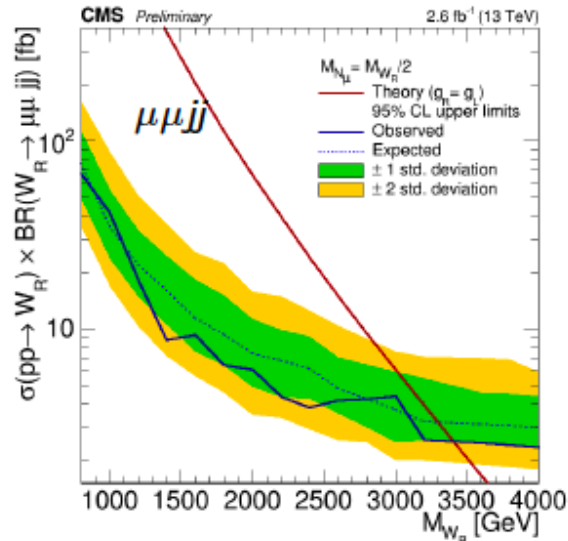
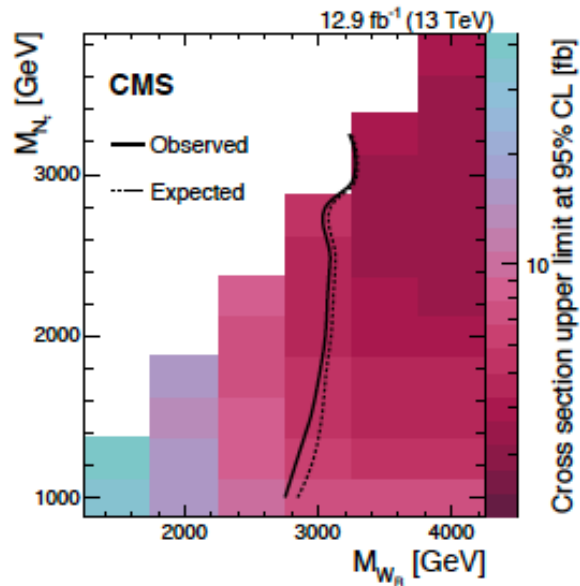


# Search for heavy neutrinos $N_R$ , $W_R$

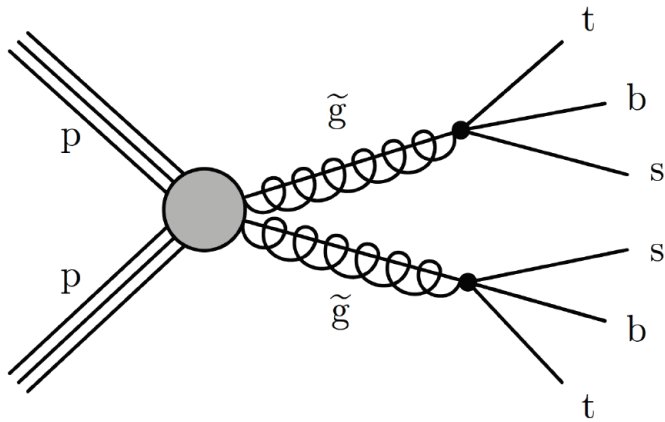


At HERA

Stringent limits  
on  $W_R$

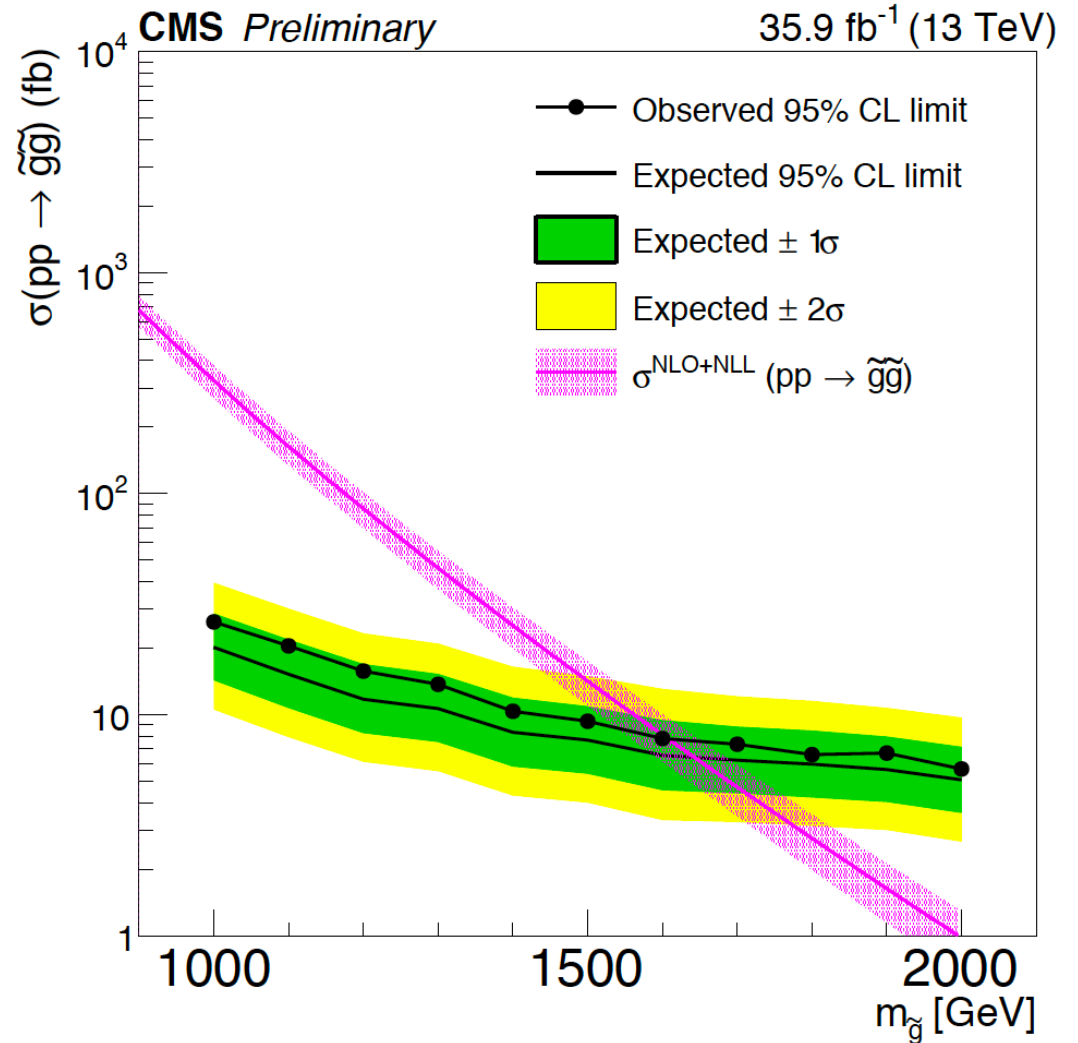


# SUSY R-parity violation



LHC started to look for RP-conserving SUSY, due to the very clear signature of missing transverse energy.

But recently they have started looking also for RPV SUSY, example here.



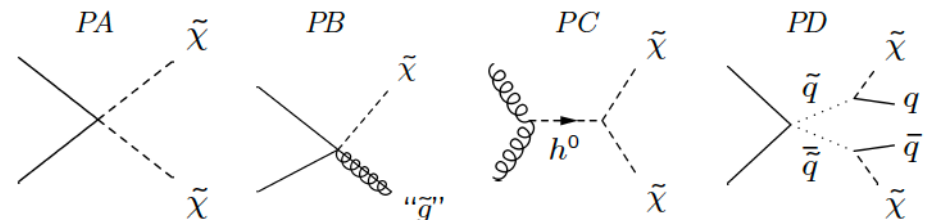
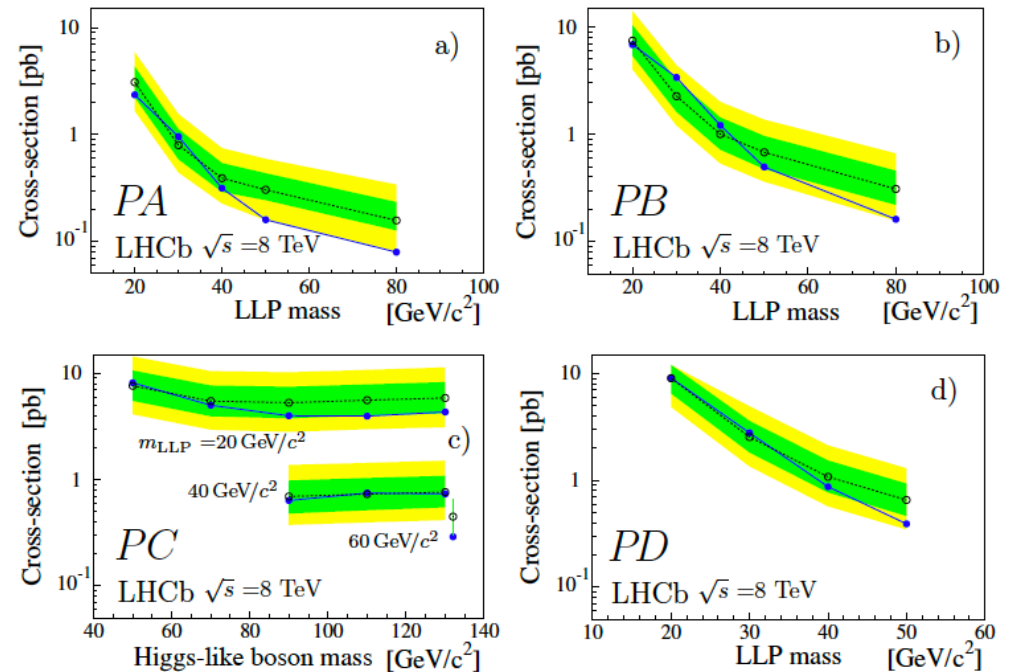
# Search for massive long-lived particles decaying semileptonically in the LHCb detector

arXiv:1612.00945

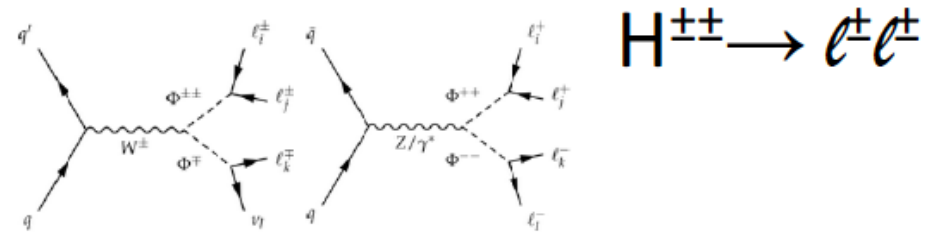
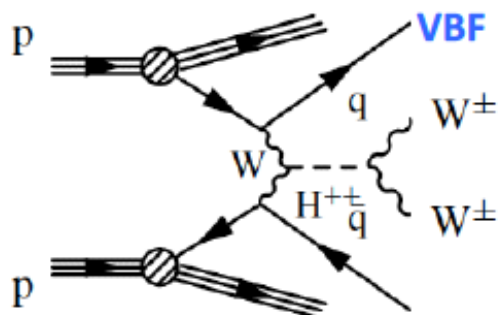
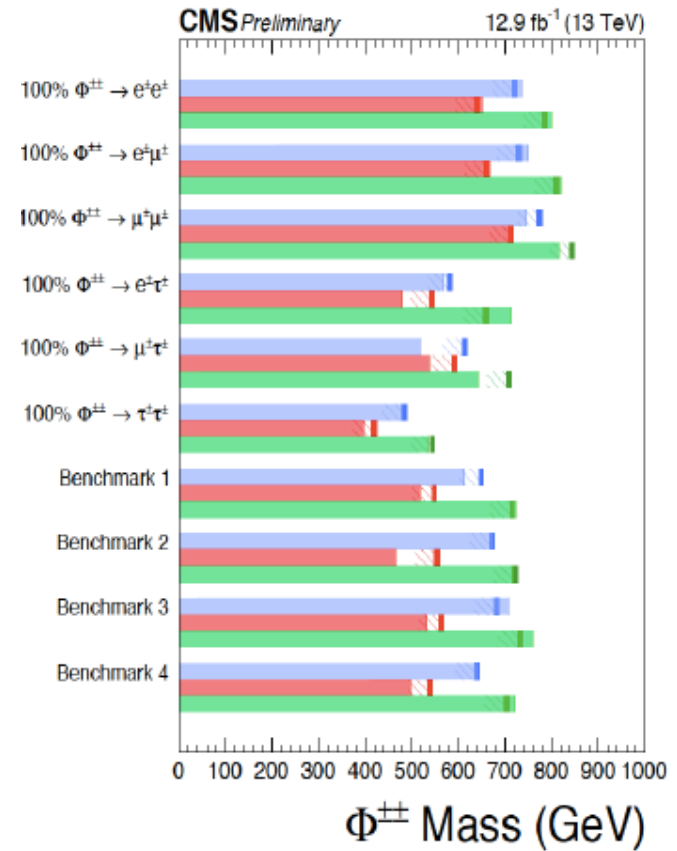
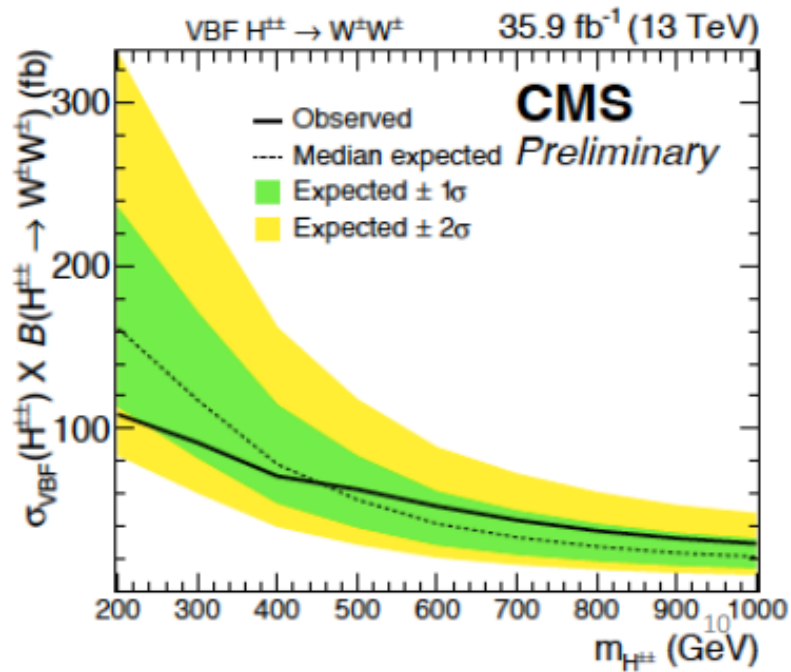
Look for massive long-lived particles (LLP) in the mSUGRA model, where the neutralinos can decay in muon+jets. Signature is a displaced vertex. LLP mass: [20-80] GeV, lifetime: [5-100] ps

In this paper a search for massive long-lived particles is presented, using proton-proton collision data collected by the LHCb detector at  $\sqrt{s} = 7$  and 8 TeV, corresponding to integrated luminosities of 1 and 2  $\text{fb}^{-1}$ , respectively. The event topology considered in this study is a displaced vertex with several tracks including a high  $p_T$  muon. This topology is found in the context of the minimal super-gravity (mSUGRA) realisation of the MSSM, with R-parity violation [13], in which the neutralino can decay into a muon and two jets. Neutralinos can be produced by a variety of processes. In this paper

LLP not so high mass, coupling to l+quarks



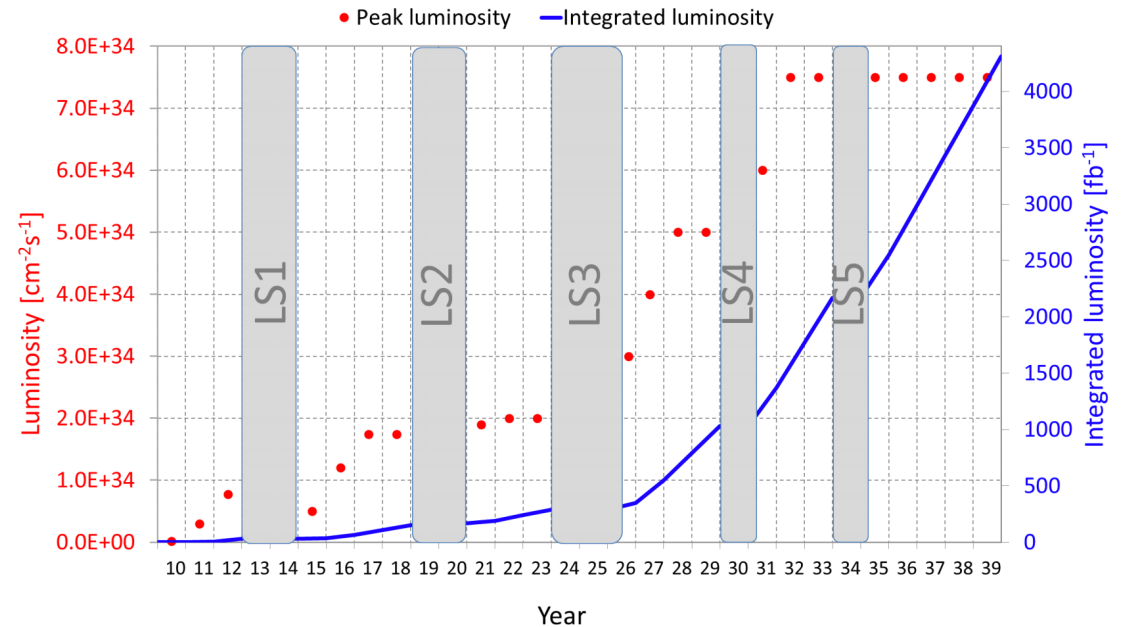
# Doubly Charged Higgs



Slides from M. D'Alfonso at HH

# Conclusion

- We have taken only 3% of whole LHC/HL-LHC data. Expect also  $\sqrt{s} = 14 \text{ TeV}$  at some point.
- It is clear that LHC has put very high mass constraints on a lot of models.
- But we still look and find “strange” things also at much lower energies.
- Recent results from LHCb on LFV seems to point to a leptoquark.
- It shows that one can look for new physics also at lower energy and ep is a much “cleaner” environment compared to LHC.
- b- and c-tagging, tau reconstruction, long-lived particles important.



Also a lot of PDFs results from LHC by now. We at DESY are involved in W-charge asymmetry (u/d), W+charm (strange), jet cross sections (gluon at mid-high x), top