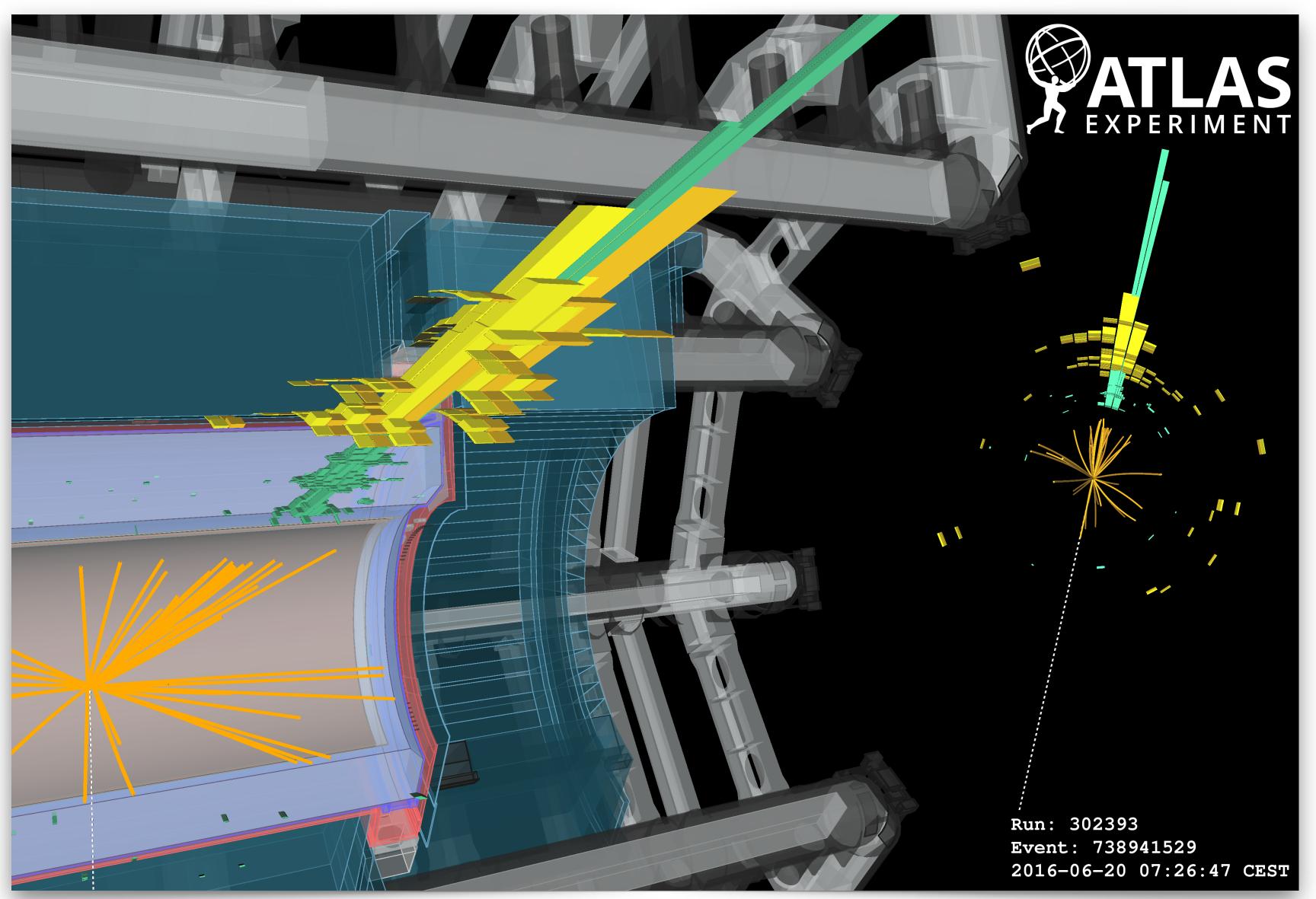
# **Experimental Physics at Hadron Collider**



### Lecture 4

**Searches for New Physics Conclusions and Outlook** 

Marumi Kado Sapienza, Roma and LAL, Orsay

### **CERN Summer Students Lectures**

July 22-25, 2019

ATLAS mono-jet event







#### **Lecture 1**: Basic concepts, cross sections and QCD results

- Preamble
- Context and mission of the LHC -
- Fundamentals of hadron collisions
- Luminosity and total cross section -
- Cross sections measurements -
- Jet production measurements -
- Measurement of the strong coupling constant -

#### Lecture 2: SM Measurements

- The electroweak sector in a tiny nutshell
- Measurement of the weak mixing angle
- W mass measurement
- Top mass measurement
- Diboson production
- Global fit of the Standard Model

### Outline

#### **Lecture 3**: Higgs physics

- The Higgs mechanism and Higgs production
- The discovery of the Higgs boson
- Precision Higgs physics with diboson channels
- Measuring the Yukawa couplings
- Measurement of Higgs properties
- Rare production and decays
- Global fit of the Standard Model (revisited)

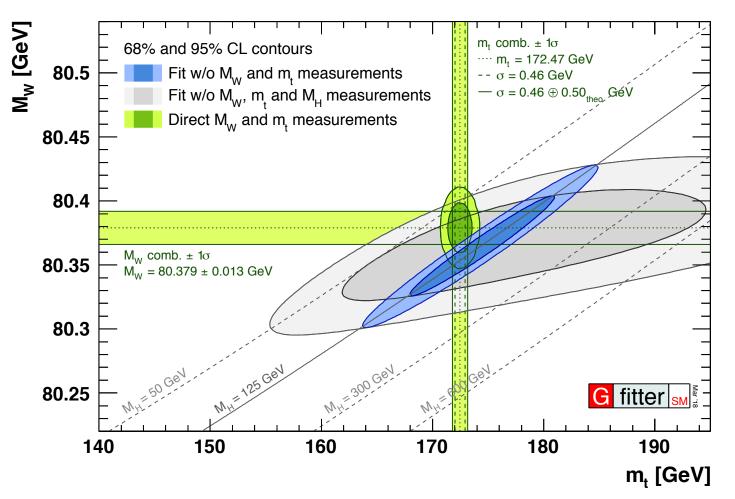
#### **Lecture 4**: Searching for new physics BSM

- Introduction
- Searches for supersymmetry and Dark Matter
- Searches in non SUSY theories
- Following up on anomalies
- Searches for unconventional signatures
- EFT and high energy observables
- Conclusions and outlook



### **Direct Searches for New Physics**

### From Lectures 2 and 3:

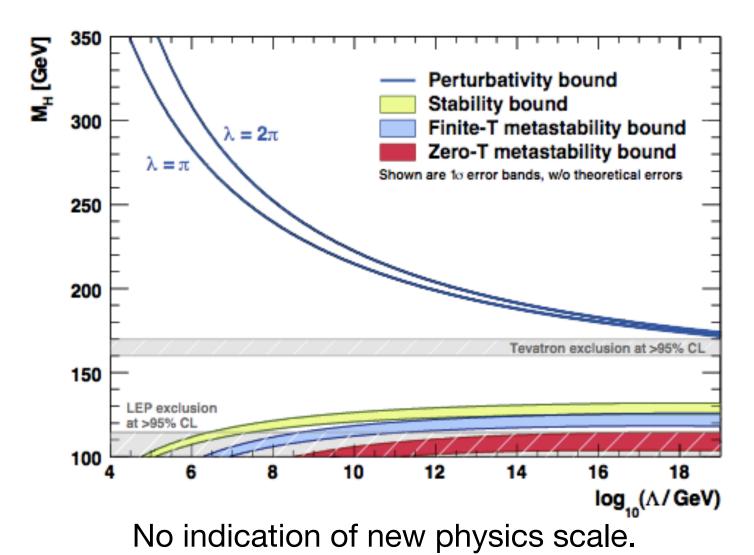


In lectures 2 and 3 we have discussed how important it is to probe new physics through precision measurements of Standard Model parameters.

### Model

To further probe the Standard Model it is also extremely important to search directly for new phenomena which would yield different predictions than the Standard Model.

#### Global fit of the Standard Model: fully consistent!



With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

#### Nima Arkani Hamed

Within the current precision all measurements are consistent with the Standard

Finite-T metastability: The electroweak vacuum can become unstable against collapse because of thermal tunneling during the evolution of the universe)

**Zero-T metastability**: ...or through 0-temperature quantum tunnelling









### The <u>Unsatisfactory</u> Standard Model

Z = - 4 Fm FMV + ご ダダ + h.c. + Y: Y: 4: 4: + h. c. +  $D_{\mu}\phi l^2 - V(\phi)$ 

### More fundamental questions (not explained by the SM):

- Description of gravity at small distant scales?
- Why is the mu parameter in the Higgs potential negative? Is the Higgs composite? - Why is the charge quantised and the charge of the electron equal that of the proton
- (grand unification)?
- ... and many more!

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

 $\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu} \qquad \theta < 10^{-10}$ 

From neutron electric dipole moment measurements

### The strong CP problem

#### The less elegant Higgs sector:

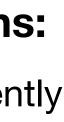
- Carries the largest number of parameters of the theory -
- Not governed by symmetries
- Gauge Hierarchy (and Naturalness) -
- Flavour hierarchy (includes neutrino masses)

#### **Experimental anomalies and observations:**

- Anomalous magnetic moment of the muon (recently confirmed by FERMILAB)
- B Lepton Flavor anomalies (see secures by Mark)
- and of course...

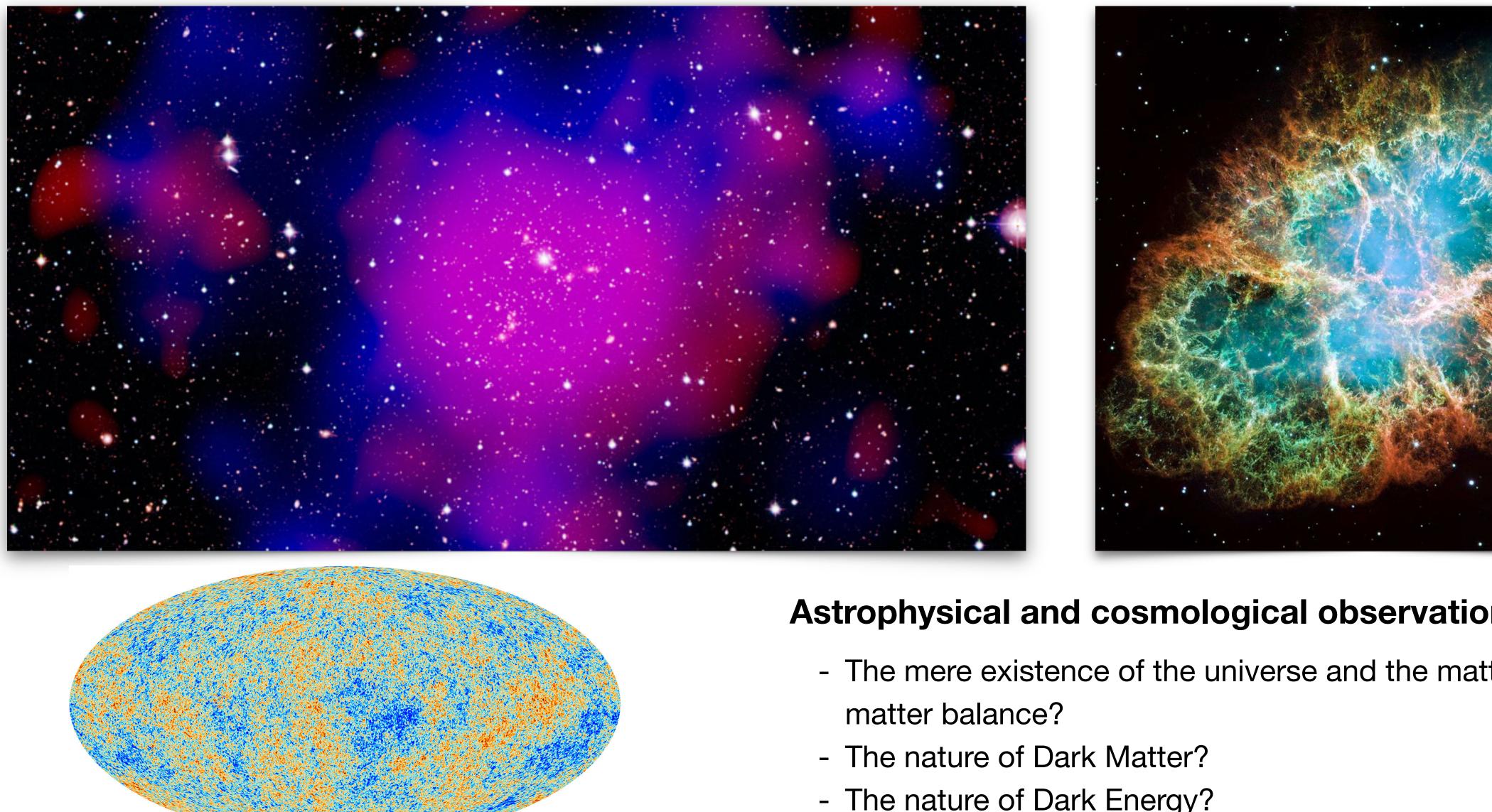








### **Unexplained Observed Phenomena**



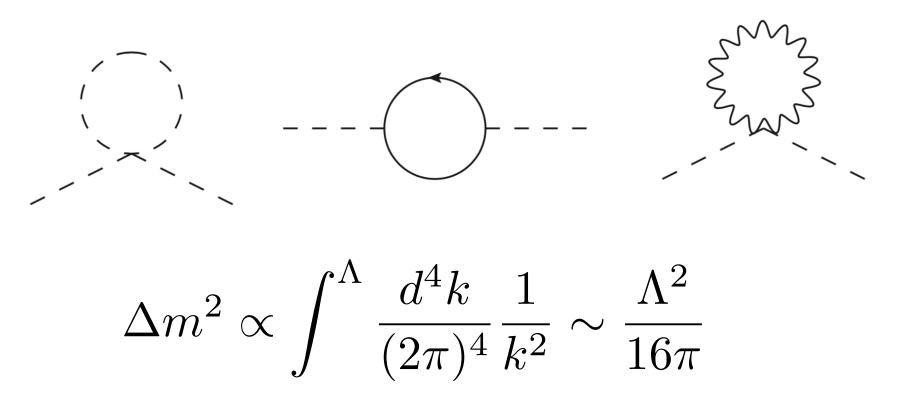
### Astrophysical and cosmological observations:

- The mere existence of the universe and the matter/anti-
- The nature of Dark Energy?



### Why is the Hierarchy an Issue? Naturalness

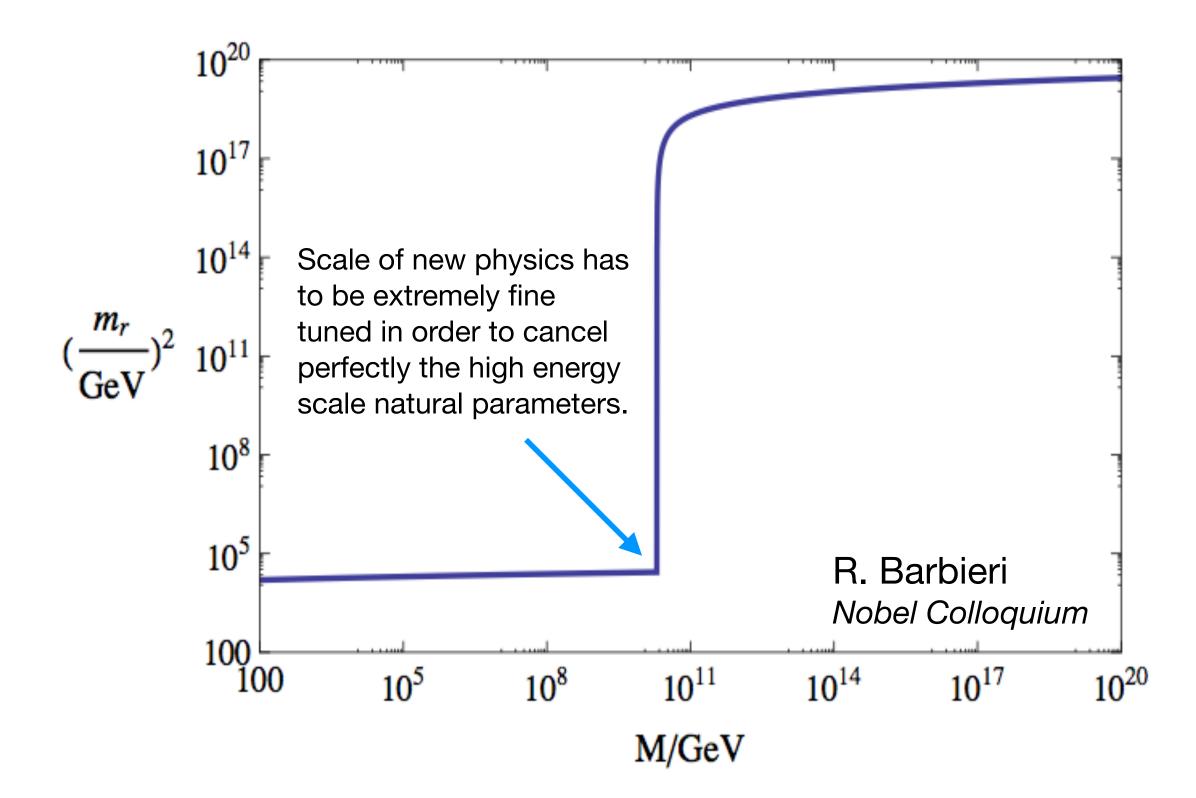
If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent:



The Standard Model is a renormalisable theory quadratic divergences are not a problem per se, but if we look at the running of the Higgs boson mass:

### **Solutions**:

- Weakly coupled: introduce fields in the theory that can cancel the quadratic divergence and alleviate the fine tuning (e.g. SUSY)
- **Strongly coupled** (Composite): in this case the above does not apply. The Higgs could be either a generic bound state or a pseudo goldstone boson (similarly to the pion in Chiral perturbation theory).



Warped extra dimensions: Difference between scales generated by warping.

Anthropic principle: fine tuning is acceptable since it is a condition for existence

of the universe as it is.





### **Nutshell description:**

- For all fermions degree of freedom SUSY adds a boson degree of freedom
- To all bosons degree of freedom, SUSY adds a fermions

#### What SUSY addresses:

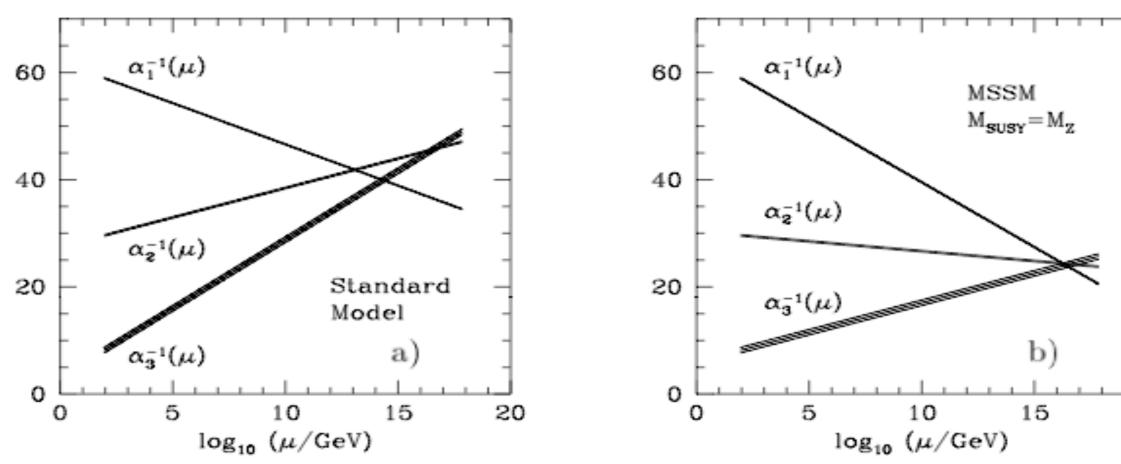
- It resolves the gauge hierarchy (naturalness problem)
- It allows unification of gauge couplings
- Local SUSY requires gravitino and therefore via SUSY naturally brings the graviton and is an essential ingredient in string theory
- It provides a natural candidate for dark matter

#### The only few (non negligible) issues:

- It has not been found! If it exists it has to be broken
- If the super-partners are too heavy fine tuning reemerges and one of the main issues (naturalness) reappears).
- With a much larger number of fields come a much larger number of parameters!

### Supersymmetry

An elegant, simple and complete solution...



#### The main predictions of SUSY

- Superpartners that should be at a reachable scale!
- A candidate dark matter particle: the neutralino (typically).
- An extended Higgs sector. Its minimal realisation is the MSSM (2 Higgs doublets so 5 Higgs bosons, 3 neutral and 2 charged).

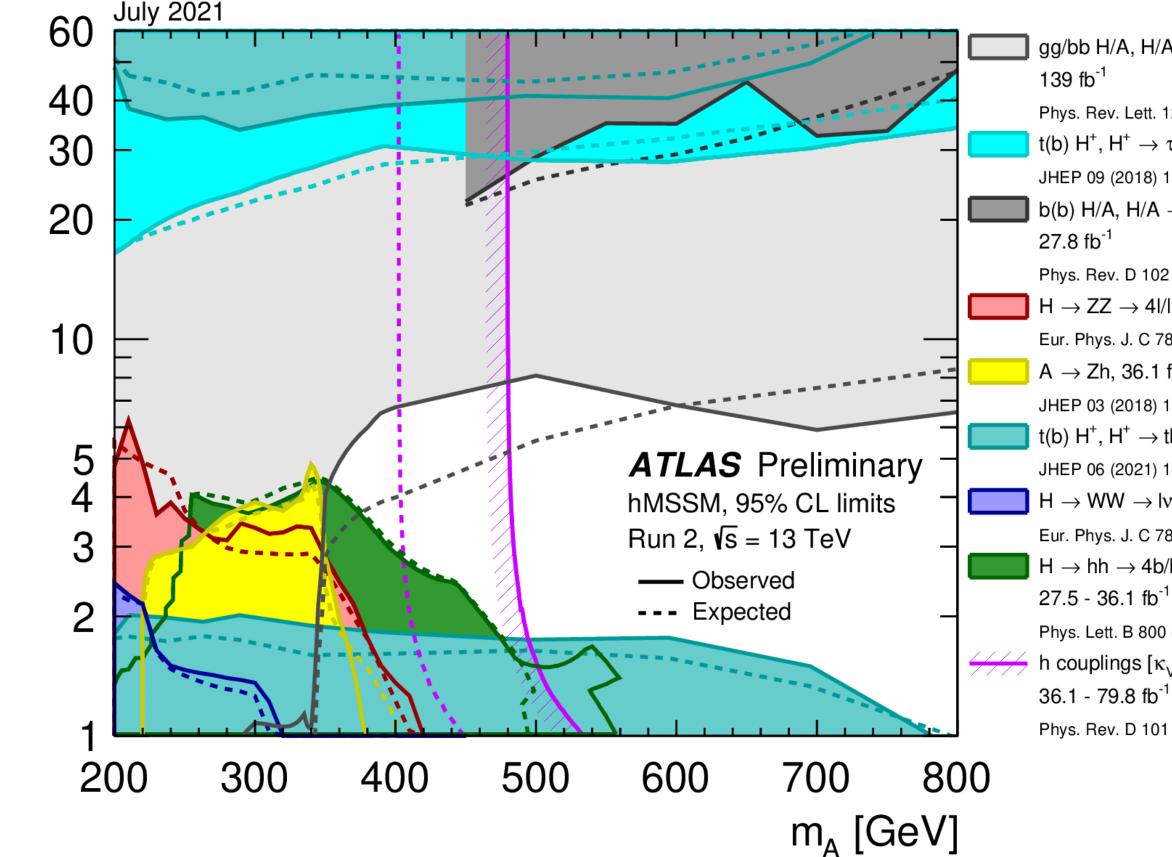




### **Reaching SUSY from an extended Higgs sector**

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan  $\beta$ ).

tan β



#### SUSY could modify the couplings of the Higgs

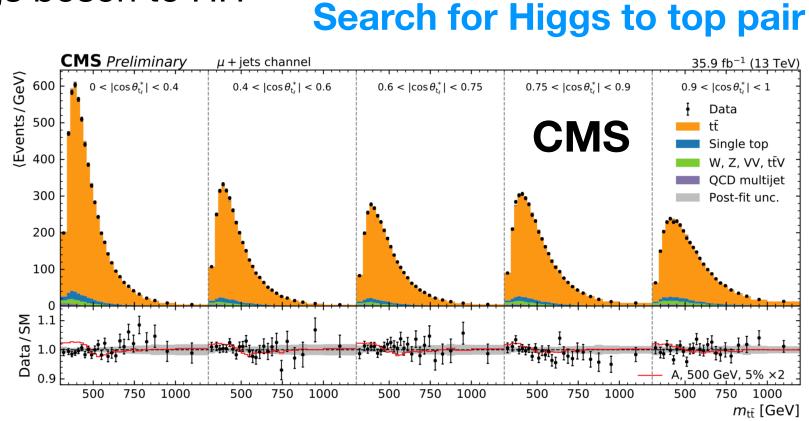
From the combination of all channels presented in Lecture 3, from constraints on up versus down Yukawa and coupling to vector bosons, limits in the MSSM parameter space can be set.

### **Direct searches for additional Higgs bosons** (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb
- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

#### $\mu$ -jets channel

Intricate search for a non trivial interference pattern in ttbar mass.



gg/bb H/A, H/A  $\rightarrow \tau \tau$ 

```
Phys. Rev. Lett. 125 (2020) 05180
t(b) H<sup>+</sup>, H<sup>+</sup> \rightarrow \tau \nu, 36.1 fb<sup>-1</sup>
JHEP 09 (2018) 139
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b(b) H/A, H/A \rightarrow bb
```

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Phys. Rev. D 102 (2020) 032004
H \rightarrow ZZ \rightarrow 4I/IIvv, 36.1 fb<sup>-1</sup>
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Eur. Phys. J. C 78 (2018) 293
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A \rightarrow Zh, 36.1 \text{ fb}^{-1}
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JHEP 03 (2018) 174
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t(b) H^+, H^+ \rightarrow tb, 139 fb<sup>-1</sup>
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JHEP 06 (2021) 145
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H \rightarrow WW \rightarrow lv lv, 36.1 fb<sup>-1</sup>
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Eur. Phys. J. C 78 (2018) 24
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H \to hh \to 4b/bb\gamma\gamma/bb\tau\tau
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Phys. Lett. B 800 (2020) 135103
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h couplings [\kappa_v, \kappa_u, \kappa_d]
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36.1 - 79.8 fb<sup>-1</sup>
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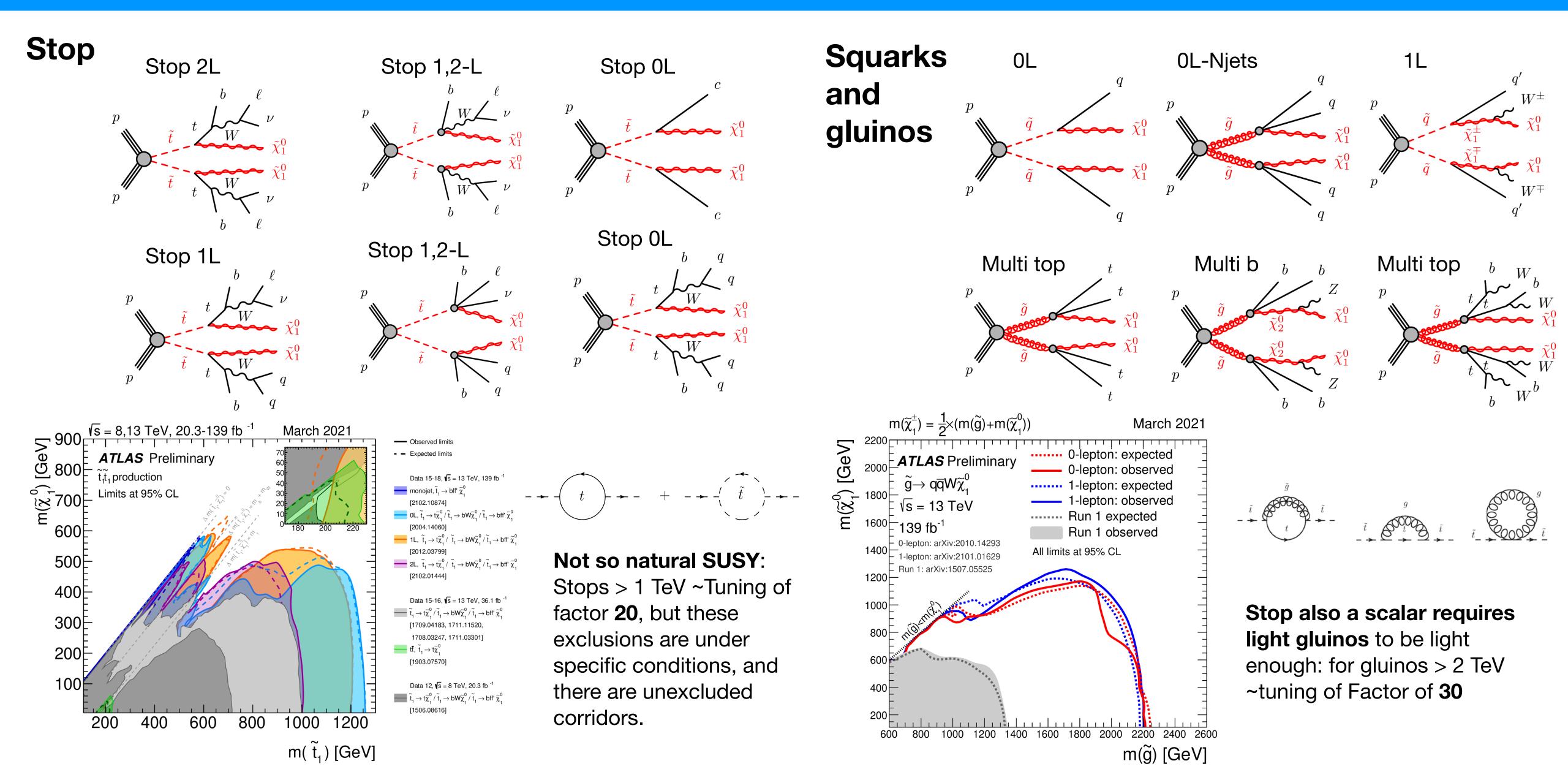
Phys. Rev. D 101 (2020) 012002







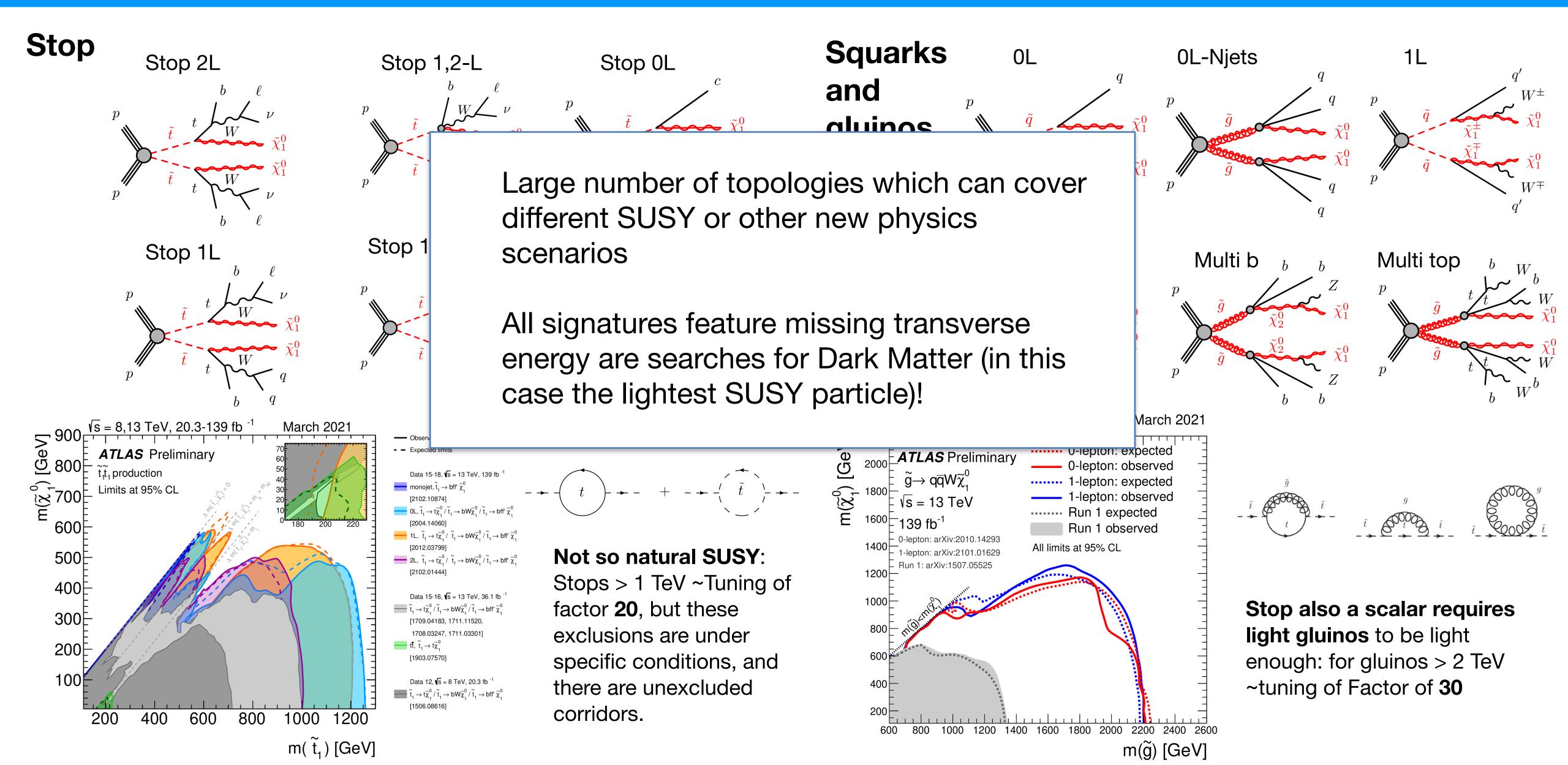
# **Searches for Natural and Strongly Produced SUSY**







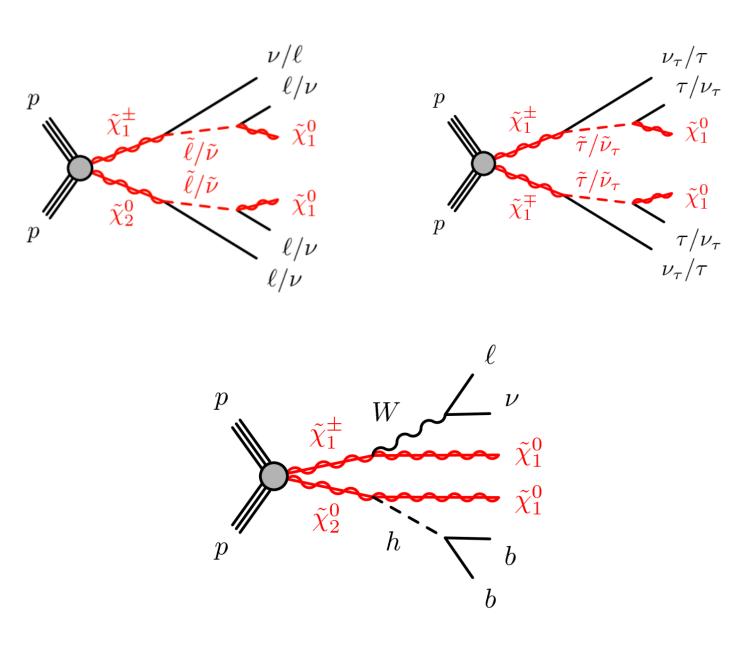
# **Searches for Natural and Strongly Produced SUSY**

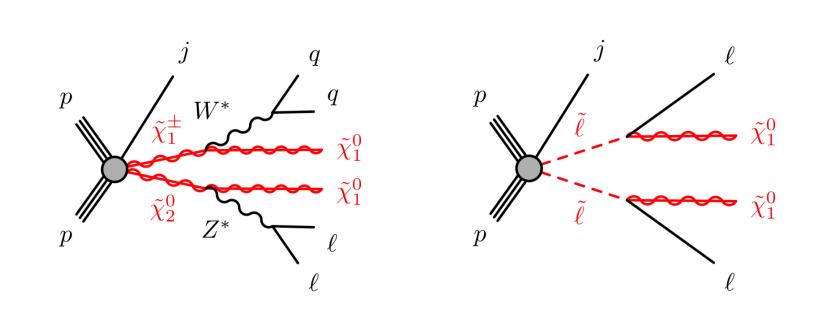


1.

### More intricate scenarios

### Weak production of charginos, neutralinos and sleptons



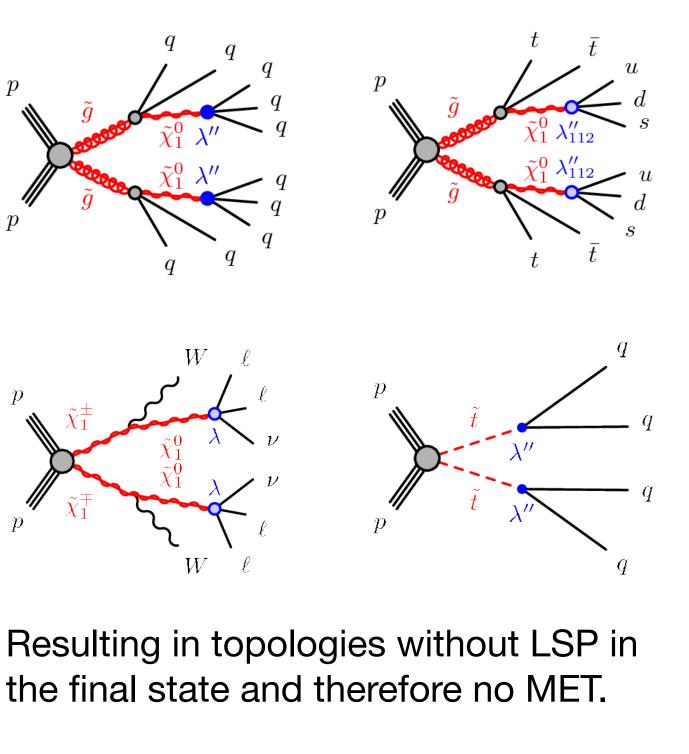


1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

Scenarios where the charginos, neutralinos or sleptons are close to mass degenerate with the lightest SUSY particle (LSP).

### Weak production in **compressed scenarios**

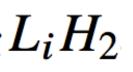
### **R-Parity violating SUSY**



 $\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$ 

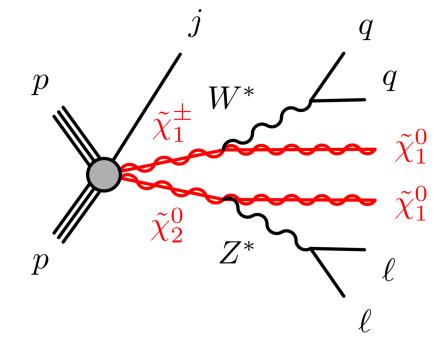
**RPV** components of superpotential





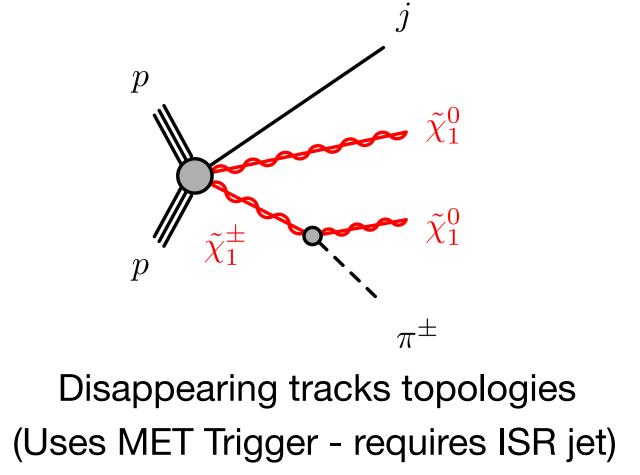
### **Searches for Charginos and Neutralinos (Examples)**

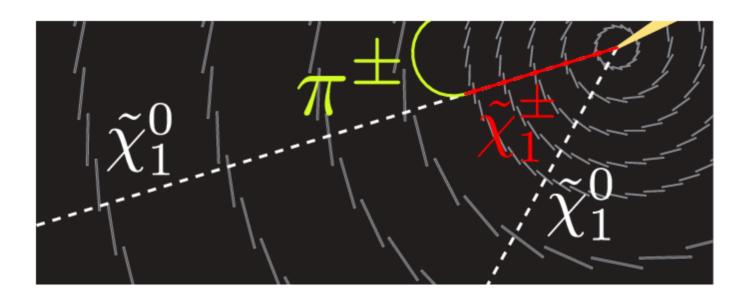
# Weak production of charginos and neutralinos



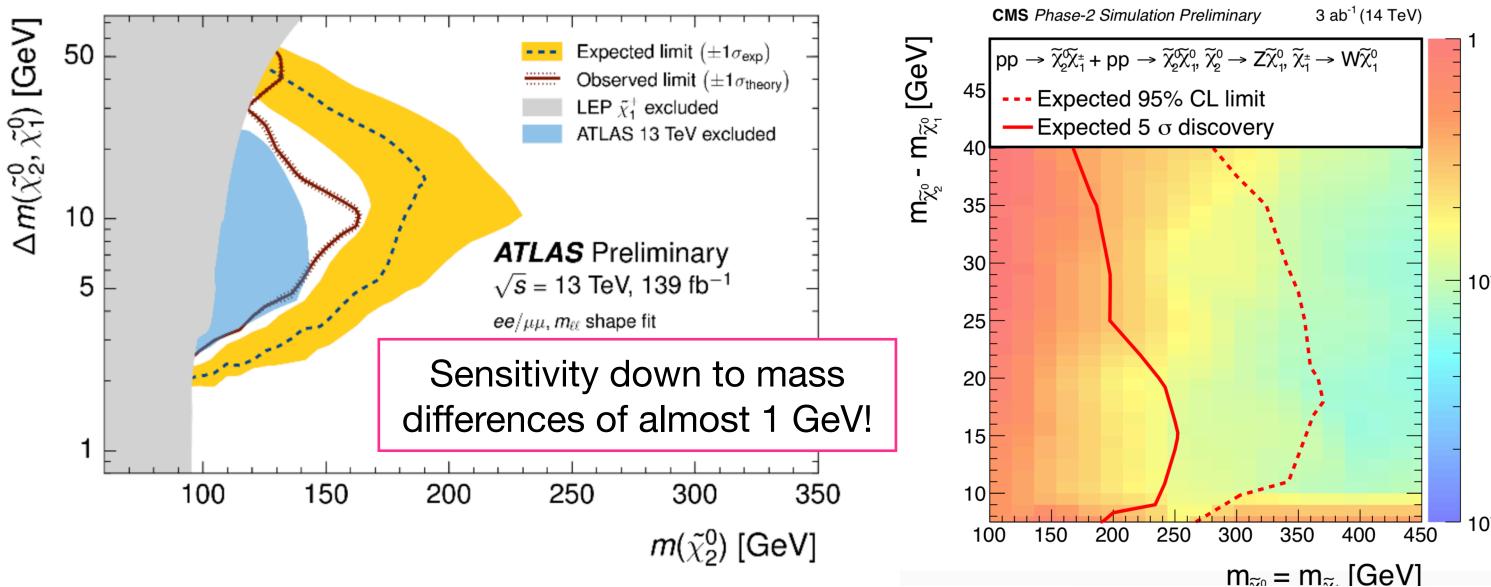
Example of boosting to find small mass differences.

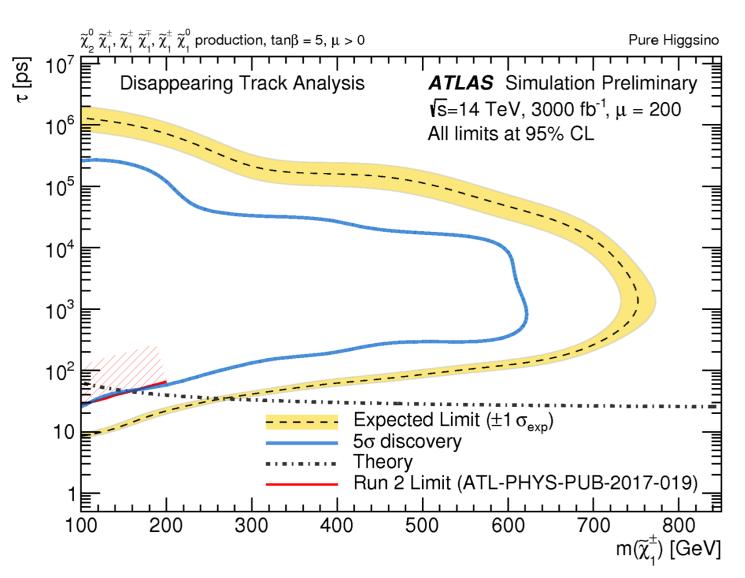
### SUSY in highly compressed scenarios





Scenario where the charginos and neutralinos are almost degenerate (chargino has significant lifetime and is seen in the first layers of the ID).









### **Very Large Number of SUSY Searches** (in large variety of topologies and models)

ATLAS SUSY Sea March 2022	rches* - 95% CL Lo	wer Limits	1	<b>ATLAS</b> Preliminary $\sqrt{s} = 13$ TeV	HL/HE-LHC	SUSY	Searche	53	discovery (95% CL exclusion)	Si	mulation
Model	Signature ∫£ dt [fi	Mass limit	• •	Reference	Model	e,μ,τ,γ	Jets	HE-LHC, $\int \mathcal{L} dt = 15 ab^{-1}$ ; 50 Mass limit	r discovery (95% CL exclusion)		Section
$ ilde{q} ilde{q}, ilde{q} ightarrow q ilde{\chi}_1^0$	0 $e, \mu$ 2-6 jets $E_T^{miss}$ 139 mono-jet 1-3 jets $E_T^{triss}$ 139		m( $ ilde{\chi}_{1}^{0}$ )<400 GeV m( $ ilde{q}$ )=5 GeV	2010.14293 2102.10874	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_{1}^{0}$	0	4 jets		2.9 (3.2) TeV	m( $\tilde{\chi}_{1}^{0}$ )=0	2.1.1
$\tilde{g}\tilde{g},  \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$	$0 e, \mu$ 2-6 jets $E_T^{\text{miss}}$ 139	Ĩ	<b>2.3</b> $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	2010.14293	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{q}\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0	4 jets	2	5.2 (5.7) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.1.1
$\tilde{g}\tilde{g},  \tilde{g} \rightarrow q \bar{q} W \tilde{\chi}_1^0$	1 <i>e</i> , <i>µ</i> 2-6 jets 139	§         Forbidden         1.15-1.9           §	<b>1</b> $m(\tilde{\chi}_1^0)=1000 \text{ GeV}$ <b>2.2</b> $m(\tilde{\chi}_1^0)<600 \text{ GeV}$	2010.14293 2101.01629	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{\chi}_1^0$	0	Multiple	ž	2.3 (2.5) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.1.3
$ \begin{array}{l} \tilde{g}\tilde{g}, \ \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0 \\ \tilde{g}\tilde{g}, \ \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0 \end{array} $	$ee, \mu\mu$ 2 jets $E_T^{\text{miss}}$ 139 0 $e, \mu$ 7-11 jets $E_T^{\text{miss}}$ 139	ğ ğ 1.9	<b>12</b> $m(\tilde{\chi}_1^0) < 700 \text{ GeV}$ <b>7</b> $m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	CERN-EP-2022-014 2008.06032	$\tilde{g}_{\tilde{g}, \tilde{g} \to I \tilde{c} \tilde{\chi}_{1}^{0}}$	0	Multiple	ž	2.4 (2.6) TeV	m(x10)=500 GeV	2.1.3
	SS $e, \mu$ 6 jets 139	ğ 1.15	$m(\tilde{g})$ - $m(\tilde{\chi}_1^0)$ =200 GeV	1909.08457 ATLAS-CONF-2018-041	NUHM2, $\tilde{g} \rightarrow t\tilde{t}$	0	Multiple/2b	ž	5.5 (5.9) TeV		2.4.2
$\tilde{g}\tilde{g},  \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	$\begin{array}{cccccc} 0{-}1 & e, \mu & 3 & b & E_T^{\text{miss}} & 79.8 \\ \text{SS } e, \mu & 6 & \text{jets} & 139 \end{array}$	s ž 1.25	<b>2 25</b> $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	1909.08457	$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow t \tilde{\chi}_1^0$	0	Multiple/2b	ĩ.	1.4 (1.7) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.1.2, 2.1.3
$ ilde{b}_1 ilde{b}_1$	$0 e, \mu$ $2 b E_T^{miss}$ 139		m( $\tilde{\chi}_1^0$ )<400 GeV 10 GeV< $\Delta$ m( $\tilde{b}_1, \tilde{\chi}_1^0$ )<20 GeV	2101.12527 2101.12527	$\vec{r}_1 \vec{r}_1, \vec{r}_1 \rightarrow \vec{x}_1^0$ $\vec{r}_1 \vec{r}_1, \vec{r}_1 \rightarrow \vec{x}_1^0$	0	Multiple/2b	ī,	0.6 (0.85) TeV	$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(t)$	2.1.2
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$\begin{array}{ccccccc} 0 \ e, \mu & 6 \ b & E_T^{\rm miss} & 139 \\ 2 \ \tau & 2 \ b & E_T^{\rm fuiss} & 139 \end{array}$	$\tilde{b}_1$ Forbidden 0.23-1.35 $\tilde{b}_1$ 0.13-0.85	$\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$	1908.03122 2103.08189	$\widetilde{\mathfrak{G}}$ $\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow b \tilde{\chi}^* / t \tilde{\chi}_1^0, \tilde{\chi}_2^0$	0	Multiple/2b	ĩ	3.16 (3.65) TeV		2.4.2
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	$0-1 \ e, \mu \ge 1 \ \text{jet}  E_T \qquad 139$	ĩ <sub>1</sub> 1.25	$m(\widetilde{\chi}_1^0)$ =1 GeV	2004.14060,2012.03799	$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W^* \tilde{\chi}_1^0$	2 e.µ	0-1 jets	Ç1	0.66 (0.84) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.2.1
$ \begin{aligned} \tilde{t}_1 \tilde{t}_1,  \tilde{t}_1 &\to W b \tilde{\chi}_1^0 \\ \tilde{t}_1 \tilde{t}_1,  \tilde{t}_1 &\to \tilde{\tau}_1 b \nu,  \tilde{\tau}_1 \to \tau \tilde{G} \end{aligned} $	1 $e, \mu$ 3 jets/1 $b$ $E_T^{\text{miss}}$ 139 1-2 $\tau$ 2 jets/1 $b$ $E_T^{\text{miss}}$ 139	<i>ĩ</i> <sub>1</sub> Forbidden              0.65 <i>ĩ</i> <sub>1</sub> Forbidden              1.4	m( $\tilde{\chi}_1^0$ )=500 GeV m( $\tilde{\tau}_1$ )=800 GeV	2012.03799 2108.07665	$\hat{c} \stackrel{\circ}{\subseteq} \hat{\chi}_1^* \hat{\chi}_2^0 \text{ via } WZ$	2 с.,µ 3 е, µ	0-1 jets	$\frac{x_1}{\bar{y}^{\pm},\bar{y}^{0}}$	0.92 (1.15) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.2.1
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & 2 \ c & E_T^{\text{miss}} & 36.1 \\ 0 \ e, \mu & \text{mono-jet} & E_T^{\text{miss}} & 139 \end{array}$	č 0.85 <i>i</i> <sub>1</sub> 0.55	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ $m(\tilde{\iota}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1805.01649 2102.10874	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via Wh, Wh $\rightarrow \ell v b \bar{b}$	1 e, µ	2-3 jets/2b	$\tilde{x}_1^*/\tilde{x}_2$ $\tilde{x}_1^*/\tilde{x}_2^0$	1.08 (1.28) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.2.3
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 $e, \mu$ 1-4 $b$ $E_T^{\text{miss}}$ 139	ĩ <sub>1</sub> 0.067-1.18	$m( ilde{\chi}_2^0)$ =500 GeV	2006.05880	$\overline{S} = \frac{1}{\tilde{\chi}_2^* \tilde{\chi}_4^0 \rightarrow W^* \tilde{\chi}_1^0 W^* \tilde{\chi}_1^*}$	2 e,µ	-	$\bar{\chi}_{2}^{\pm}/\bar{\chi}_{4}^{0}$	0.9 TeV	m(x <sup>0</sup> <sub>1</sub> )=150, 250 GeV	2.2.4
$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 \text{ via } WZ$	$\begin{array}{c cccc} 3 \ e, \mu & 1 \ b & E_T^{\text{miss}} & 139 \\ \hline \\ \hline \\ \text{Multiple } \ell/\text{jets} & E_T^{\text{miss}} & 139 \\ \end{array}$	$\tilde{t}_2$ Forbidden0.86 $\tilde{\chi}_{\pm}^{\pm}/\tilde{\chi}_{2}^{0}$ 0.96	$m(\tilde{\chi}_1^0)=360 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=40 \text{ GeV}$ $m(\tilde{\chi}_1^0)=0, \text{ wino-bino}$	2006.05880 2106.01676, 2108.07586	$\tilde{\chi}_1^{a} \tilde{\chi}_2^0 + \tilde{\chi}_2^0 \tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0, \tilde{\chi}_1^{a} \rightarrow W \tilde{\chi}_1^0$	2 e,µ	1 jet	52,104	0.25 (0.36) TeV	m( $\tilde{\chi}_{1}^{0}$ )=15 GeV	2.2.5.1
	$ee, \mu\mu \ge 1$ jet $E_T^{\text{miss}}$ 139	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ 0.205	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^{0})=5$ GeV, wino-bino	1911.12606	$\begin{array}{c} \mathbf{U}_{\mathbf{X}_{1}} & \mathbf{X}_{2} + \mathbf{X}_{2}\mathbf{X}_{1}, \mathbf{X}_{2} \rightarrow \mathbf{Z}\mathbf{X}_{1}, \mathbf{X}_{1} \rightarrow \mathbf{W}\mathbf{X}_{1} \\ & \mathbf{X}_{1}^{*}\mathbf{X}_{2}^{0} + \mathbf{X}_{2}^{0}\mathbf{X}_{1}^{0}, \mathbf{X}_{2}^{0} \rightarrow \mathbf{Z}\mathbf{X}_{1}^{0}, \mathbf{X}_{1}^{a} \rightarrow \mathbf{W}\mathbf{X}_{1}^{0} \end{array}$		1 jet	$\bar{\chi}_{1}^{*}/\chi_{2}^{*}$	0.42 (0.55) TeV	m(x <sub>1</sub> )=15 GeV m(x <sub>1</sub> <sup>0</sup> )=15 GeV	2.2.5.1
$egin{array}{l}  ilde{\chi}_1^{\pm}  ilde{\chi}_1^{\mp}  ext{ via } WW \  ilde{\chi}_1^{\pm}  ilde{\chi}_2^0  ext{ via } Wh \end{array}$	$\begin{array}{ccc} 2 \ e, \mu & E_T^{\rm miss} & 139 \\ {\rm Multiple} \ \ell/{\rm jets} & E_T^{\rm miss} & 139 \end{array}$		$m({ ilde \chi}^0_1)=0,$ wino-bino $m({ ilde \chi}^0_1)=70$ GeV, wino-bino	1908.08215 2004.10894, 2108.07586	$\begin{array}{c} \mathbf{\hat{6}}\\ \mathbf{\hat{6}}\\ \mathbf{\hat{H}}\\ \mathbf{\hat{\chi}}_{2}^{0} \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1}^{*} \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1}^{*} \tilde{\chi}_{1}^{0}\\ \mathbf{\hat{\chi}}_{1}^{0} \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1}^{*} \tilde{\chi}_{1}^{0} \end{array}$	2 μ	1 jet	ç0	0.21 (0.35) TeV	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=5 \text{ GeV}$	2.2.5.2
$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} \text{ via } \tilde{\ell}_{L} / \tilde{\nu}$ $\tilde{\tau}_{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_{1}^{0}$	$\begin{array}{ccc} 2 \ e, \mu & E_T^{\text{miss}} & 139 \\ 2 \ \tau & E_T^{\text{miss}} & 139 \end{array}$	$\tilde{\chi}_{1}^{\pm}$ 1.0 $\tilde{\tau} = [\tilde{\tau}_{L}, \tilde{\tau}_{R,L}]$ 0.16-0.3 0.12-0.39	$ \begin{array}{c} m(\tilde{\ell},\tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{\pm}) + m(\tilde{\chi}_{1}^{0})) \\ m(\tilde{\chi}_{1}^{0}) = 0 \end{array} $	1908.08215 1911.06660				·*2	1	Am(a <sub>2</sub> , a <sub>1</sub> )=5 GeV	
$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	$2 e, \mu$ 0 jets $E_T^{\text{miss}}$ 139 $ee, \mu\mu$ $\geq 1$ jet $E_T^{\text{miss}}$ 139	<ul> <li>ℓ</li> <li>ℓ</li> <li>0.256</li> <li>0.7</li> </ul>	$\mathfrak{m}(\tilde{\ell})=0$ $\mathfrak{m}(\tilde{\ell})-\mathfrak{m}(\tilde{\chi}_1^0)=10 \text{ GeV}$	1908.08215 1911.12606	$\tilde{\chi}_{2}^{*}\tilde{\chi}_{4}^{0}$ via same-sign WW	2 e,µ	0	Wino	0.86 (1.08) TeV		2.4.2
$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	$\begin{array}{cccc} 0 \ e, \mu & \geq 3 \ b & E_T^{\text{miss}} & 36.1 \\ 4 \ e, \mu & 0 \ \text{jets} & E_T^{\text{miss}} & 139 \end{array}$	<ul> <li><i>H</i></li> <li>0.13-0.23</li> <li>0.29-0.88</li> <li><i>H</i></li> <li>0.55</li> </ul>	$ \begin{array}{c} BR(\tilde{\chi}^0_1 \to h\tilde{G}) = 1 \\ BR(\tilde{\chi}^0_1 \to Z\tilde{G}) = 1 \end{array} $	1806.04030 2103.11684	$\tilde{\tau}_{LR} \tilde{\tau}_{LR}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$	2 τ	-	÷	0.53 (0.73) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.3.1
	$0 \ e, \mu \ge 2 \text{ large jets } E_T = 100$ 139	й Й 0.45-0.93	$BR(\tilde{\chi}_1^0 \to Z\tilde{G}) = 1$	2108.07586	Stau	$2\tau, \tau(e, \mu)$	-	7	0.47 (0.65) TeV	$m(\bar{\chi}_{1}^{0})=0, m(\bar{\tau}_{L})=m(\bar{\tau}_{R})$	2.3.2
Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet $E_T^{\text{miss}}$ 139	$ \tilde{\chi}_{1}^{\pm} = 0.66 $	Pure Wino Pure higgsino	2201.02472 2201.02472	22 2	$2\tau, \tau(e, \mu)$	-	*	0.81 (1.15) TeV	$m(\tilde{\chi}_1^0)=0, m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.4
Stable $\tilde{g}$ R-hadron	pixel dE/dx $E_T^{\text{miss}}$ 139	ğ 2.	05	CERN-EP-2022-029	$\hat{\chi}_1^* \hat{\chi}_1^{\mp}, \hat{\chi}_1^* \hat{\chi}_1^0$ , long-lived $\hat{\chi}_1^*$	Disapp. trk.	1 jet	$\tilde{\chi}_1^{\pm} = [r(\tilde{\chi}_1^{\pm})=1ns]$	0.8 (1.1) TeV		4.1.1
Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ $\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell \tilde{G}$	pixel dE/dx $E_T^{\text{miss}}$ 139 Displ. lep $E_T^{\text{miss}}$ 139	$ ilde{g}  [ au( ilde{g}) = 10 \text{ ns}] \\  ilde{e},  ilde{\mu} \qquad \qquad \textbf{0.7}$	<b>2.2</b> $m(\tilde{\chi}_1^0)=100 \text{ GeV}$ $\tau(\tilde{\ell})=0.1 \text{ ns}$	CERN-EP-2022-029 2011.07812	$\tilde{\chi}_1^* \tilde{\chi}_1^{\mp}, \tilde{\chi}_1^* \tilde{\chi}_1^0$ , long-lived $\tilde{\chi}_1^*$	Disapp. trk.	1 jet	$\tilde{X}_1^{\pm}$ [ $r(\tilde{X}_1^{\pm})=1ns$ ]	0.6 (0.75) TeV	Higgsino-like $\tilde{\chi}_1^a$	4.1.1
	pixel dE/dx $E_T^{\text{miss}}$ 139	$ ilde{ au}$ 0.34 $ ilde{ au}$ 0.36	$ au( ilde{\ell}) = 0.1  ext{ ns}$ $ au( ilde{\ell}) = 10  ext{ ns}$	2011.07812 CERN-EP-2022-029	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.88 (0.9) TeV	Wino-like DM	4.1.3
$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0 , \tilde{\chi}_1^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 <i>e</i> , <i>µ</i> 139	$\tilde{\chi}_{1}^{*}/\tilde{\chi}_{1}^{0}$ [BR( $Z\tau$ )=1, BR( $Ze$ )=1] <b>0.625 1.05</b>	Pure Wino	2011.10543	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	2.0 (2.1) TeV	Wino-like DM	4.1.3
$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 $e, \mu$ 0 jets $E_T^{\text{miss}}$ 139 4-5 large jets 36.1	$ \begin{array}{c c} \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} & [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0] \\ \tilde{g} & [m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}, 1100 \text{ GeV}] \end{array}  \begin{array}{c} \textbf{0.95} & \textbf{1.55} \\ \textbf{1.3} & \textbf{1.9} \end{array} $	$m(\tilde{\chi}_1^0)=200 \text{ GeV}$ Large $\lambda_{112}''$	2103.11684 1804.03568	Aja MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.28 (0.3) TeV	Higgsino-like DM	4.1.3
$\tilde{g}\tilde{g},  \tilde{g} \to qq\tilde{\chi}_{1}^{0},  \tilde{\chi}_{1}^{0} \to qqq$ $\tilde{t}\tilde{t},  \tilde{t} \to t\tilde{\chi}_{1}^{0},  \tilde{\chi}_{1}^{0} \to tbs$	Multiple 36.1	$\tilde{t}$ [ $\lambda_{323}^{\prime\prime}$ =2e-4, 1e-2] 0.55 1.05	m $(\tilde{\chi}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003	S T MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.55 (0.6) TeV	Higgsino-like DM	4.1.3
$ \begin{array}{c} \tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{1}^{\pm} \rightarrow bbs \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow bs \end{array} $	$\geq 4b$ 139 2 jets + 2 b 36.7	ĩ         Forbidden         0.95           ĩ <sub>1</sub> [qq, bs]         0.42         0.61	$m(\tilde{\chi}_1^{\pm})$ =500 GeV	2010.01015 1710.07171	$\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}$	0	Multiple Multiple	$\tilde{g} = [r(\tilde{g}) = 0.1 - 3 \text{ ns}]$ $\tilde{g} = [r(\tilde{g}) = 0.1 - 10 \text{ ns}]$	3.4 TeV 2.8 TeV	m( $\tilde{k}_{1}^{0}$ )=100 GeV	4.2.1
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c} \tilde{t}_1 \\ \tilde{t}_1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\$	$\begin{array}{c} BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%\\ BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1 \end{array}$	1710.05544 2003.11956	$\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}$	-	muniple	g (ng) -o.r - io naj	•		4.2.1
$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^{\pm} \rightarrow bbs$	1-2 $e, \mu$ $\geq$ 6 jets 139	<i>x</i> <sub>1</sub> <sup>0</sup> 0.2-0.32	Pure higgsino	2106.09609	GMSB $\bar{\mu} \rightarrow \mu \bar{G}$	displ. µ	-	μ	0.2 TeV	ct =1000 mm	4.2.2
											arXiv:
a selection of the available many of the	limits are based on	10 <sup>-1</sup> 1	Mass scale [TeV]				1	0 <sup>-1</sup> 1	Mass scale [TeV]		
olified models, c.f. refs. for the	assumptions made.		2 TeV						3 TeV		
											LHC

Example from ATLAS (same for CMS)

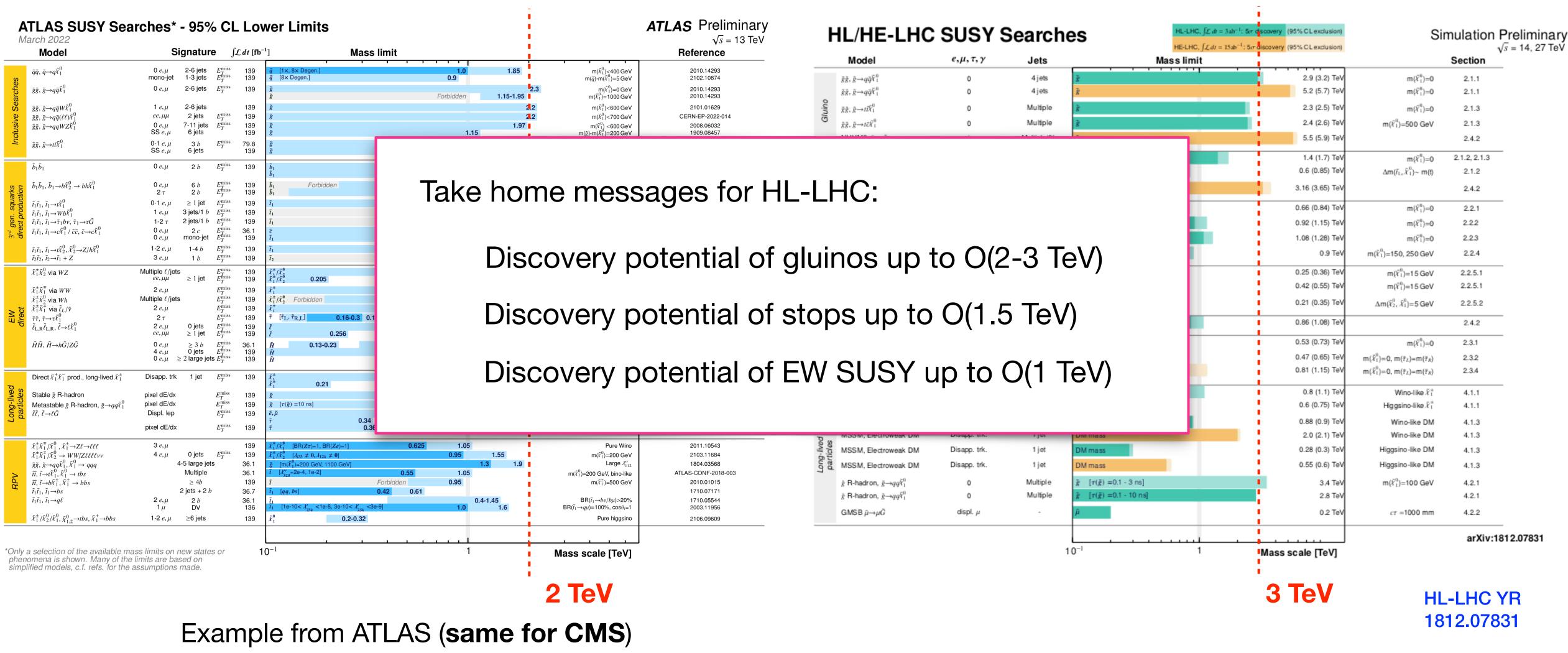
**HL-LHC YR** 1812.07831







### Very Large Number of SUSY Searches (in large variety of topologies and models)





# Broad searches for new Physics beyond the Standard Model

### Panorama of Searches for Conventional Signatures

#### **Searches for Vector Like Fermions**

Simple additional chiral fermions are essentially ruled out by Higgs data.

#### Fermions that are not Chiral

- The L and R components transform the same way under SM symmetries.
- Interact with SM through mixing with SM quarks. —
- Present in models where the Higgs is a pseudo Goldstone \_ boson (e.g. in Composite Higgs and little Higgs models).
- Present in Warped Extra dimension models. -

#### Large variety of possible states and complex channels

- Heavy quark partners with charges -1/3, 2/3, 4/3 and 5/3. -
- Complex channels looking for T(2/3), B(1/3): Ht+X, Wt+X, Wb+X, Zb+X, Zt+X (Performed at Run 2) so far and T(5/3) 4tops final state.

### And still many more !!

### **Searches for W'and Z'**

#### High mass states motivated in many theories e.g. Grand Unified and additional gauge symmetries.

- electrons, muons, taus, jets, b-jets and tops.
- di-bosons including vector bosons and Higgs bosons

### **Searches for high mass states of spin 0 and 2**

#### Motivated in Randall Sundrum models (Graviton and radion)

Searches in various channels dijet, diphoton and di-leptons

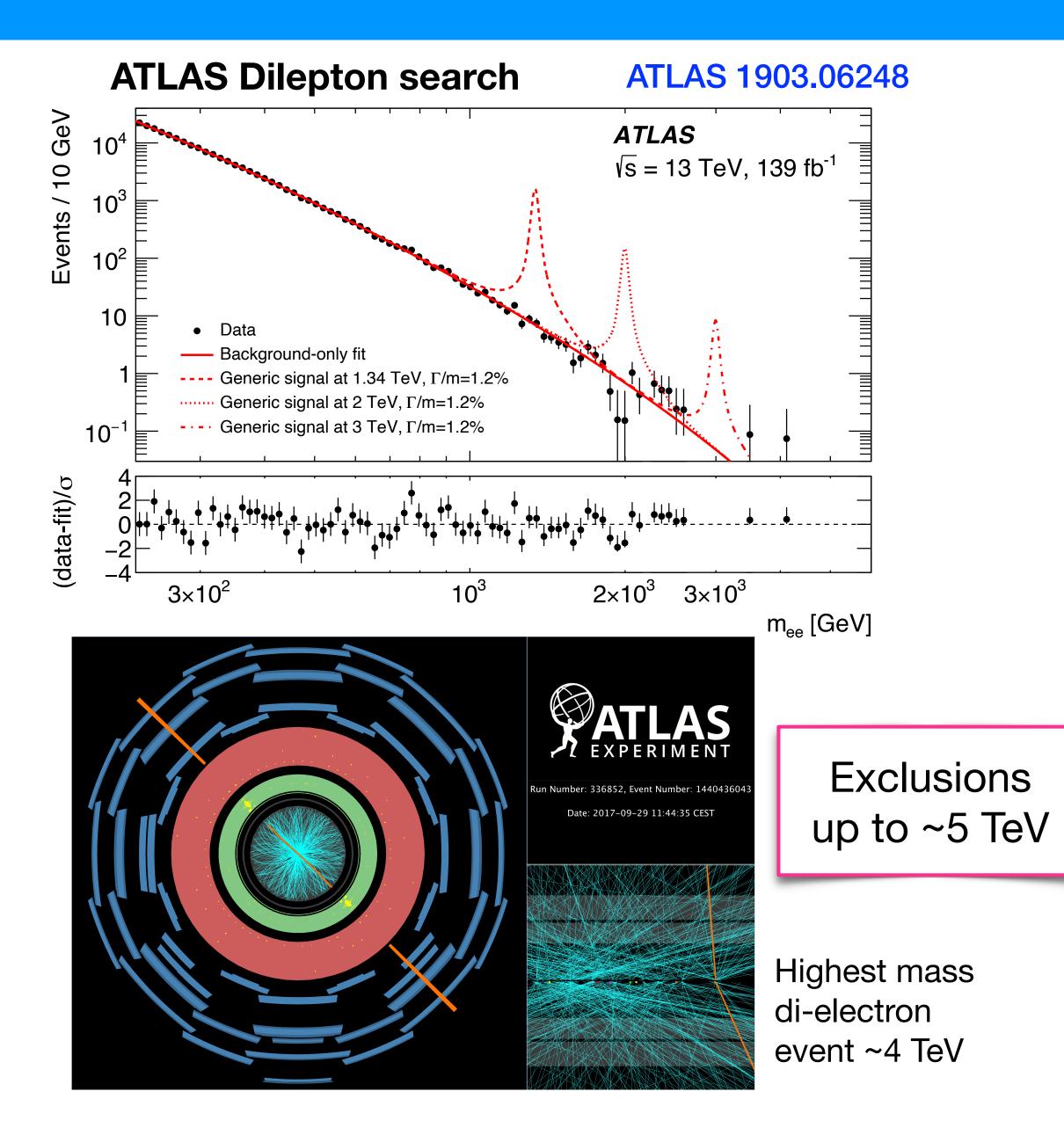
#### Any many more

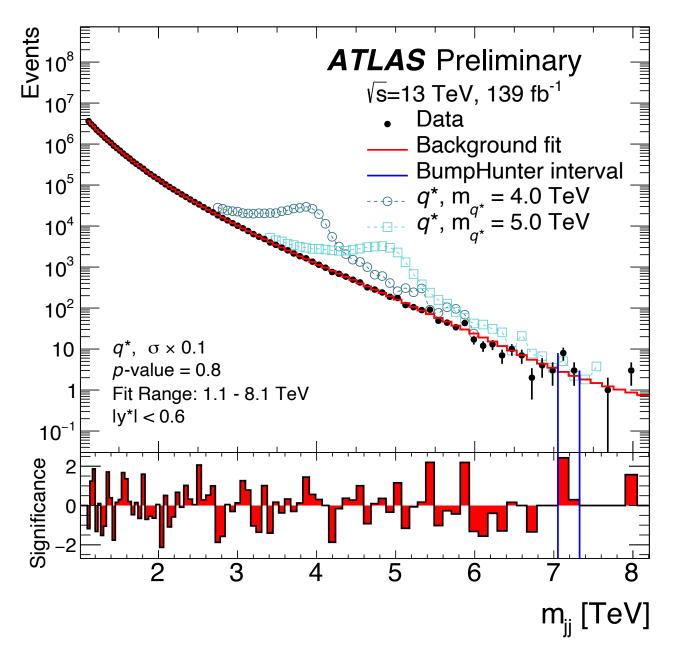
- Quark compositness
- **Leptoquarks:** predicted in grand unified theories and interest raised by lepton flavor universality anomalies
- Heavy neutrinos: produced in theories for neutrino masses (e.g. Seesaw)
- High mass and high activity events: strong gravity (from extra dimension theories), mini black holes, quantum black holes...
- Searches for low mass states.





### **Searches for High Mass Resonances**

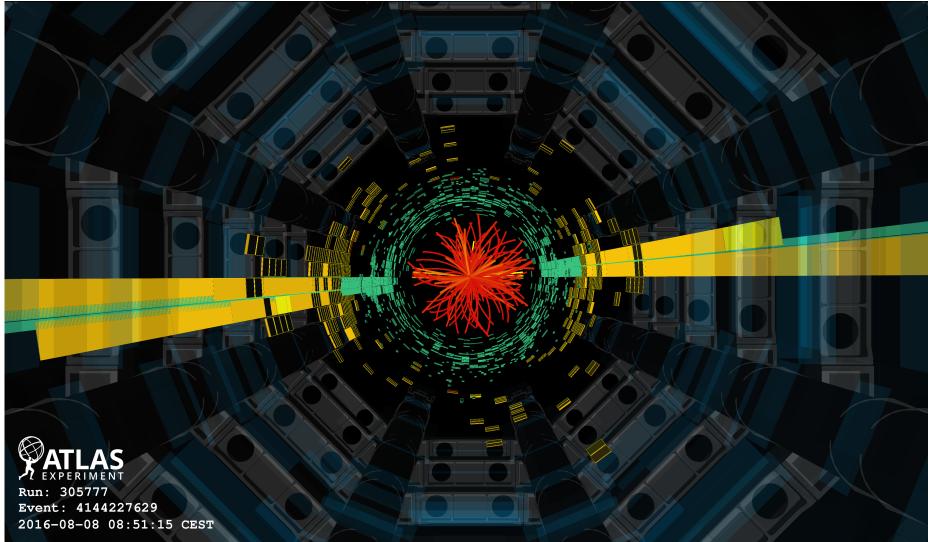




#### **ATLAS Dijet search**

**ATLAS-CONF-2019-007** 

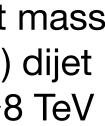
Limits on excited quarks at 6.7 TeV

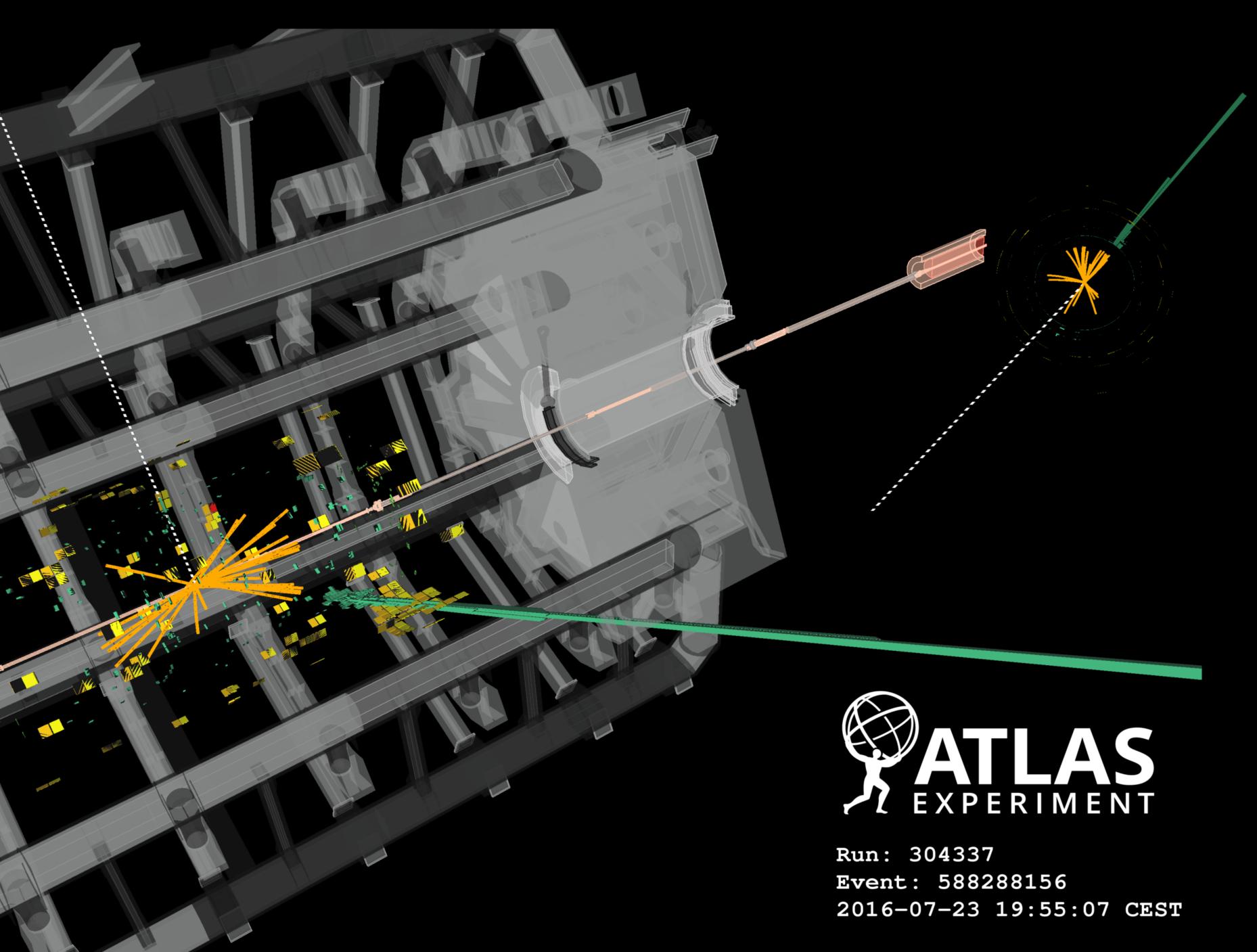


Highest mass (central) dijet event ~8 TeV

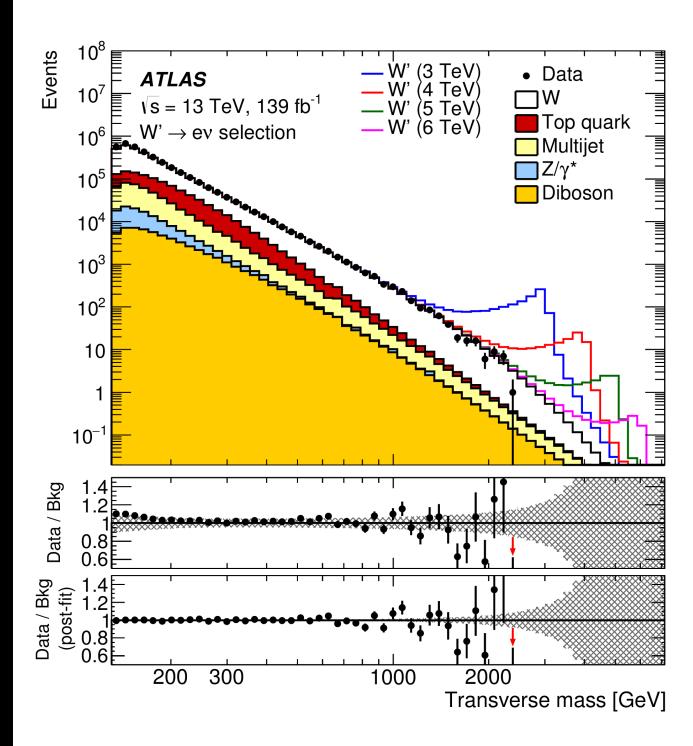








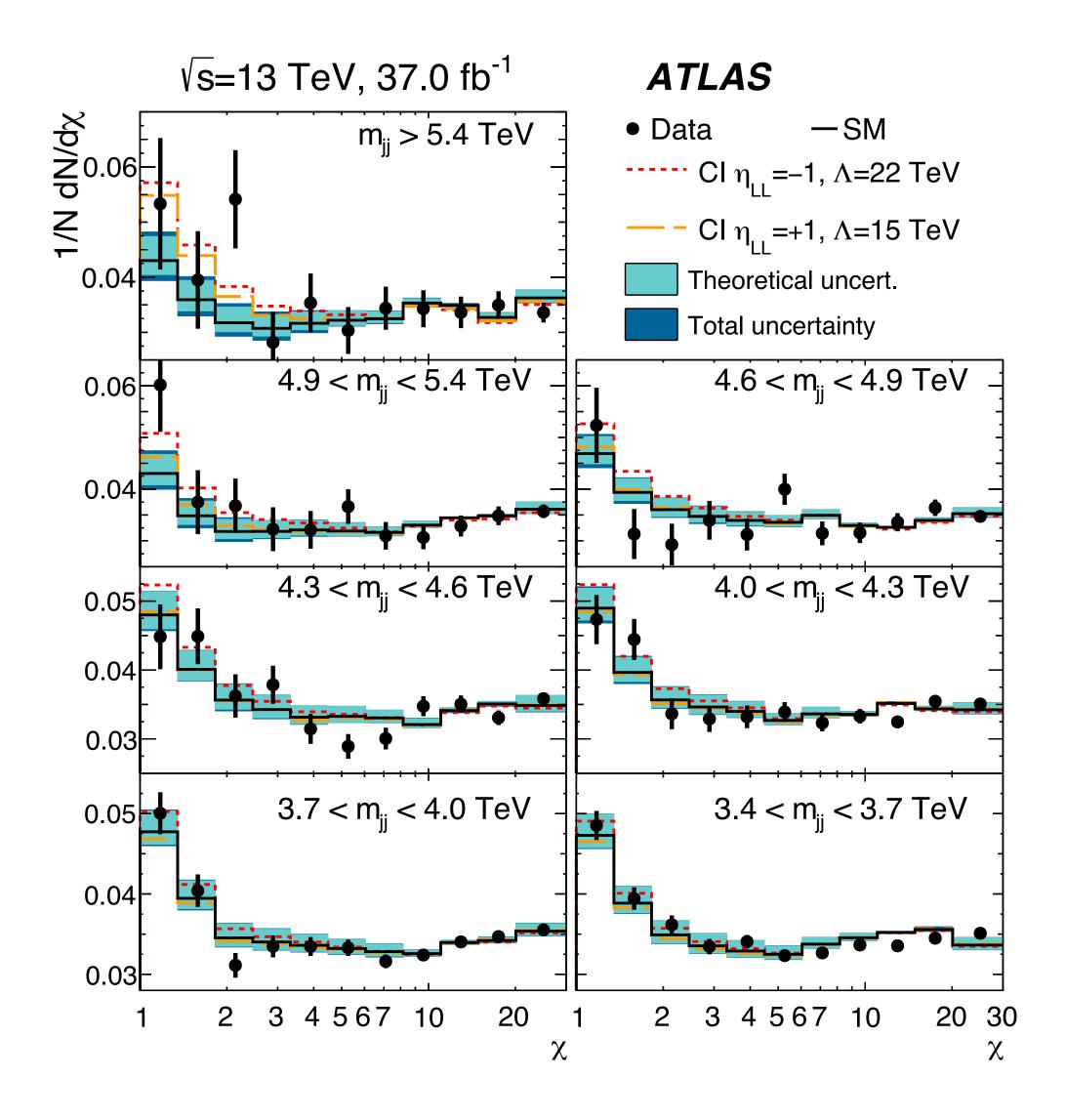
#### **Transverse mass** (in lepton-MET search)



Drell Yan (and other processes) predictions and lepton calibration in the TeV energy range.

Electron pT = 1.1 TeVMET = 1.16 TeV







#### Searches for non-resonant features at high mass

Any deviation in the measurements with a special attention to the high energy regime can be the manifestation of new higher energy domain new physics.

**Key aspects**: Jet cross sections predictions and jet calibration with multi TeV jets

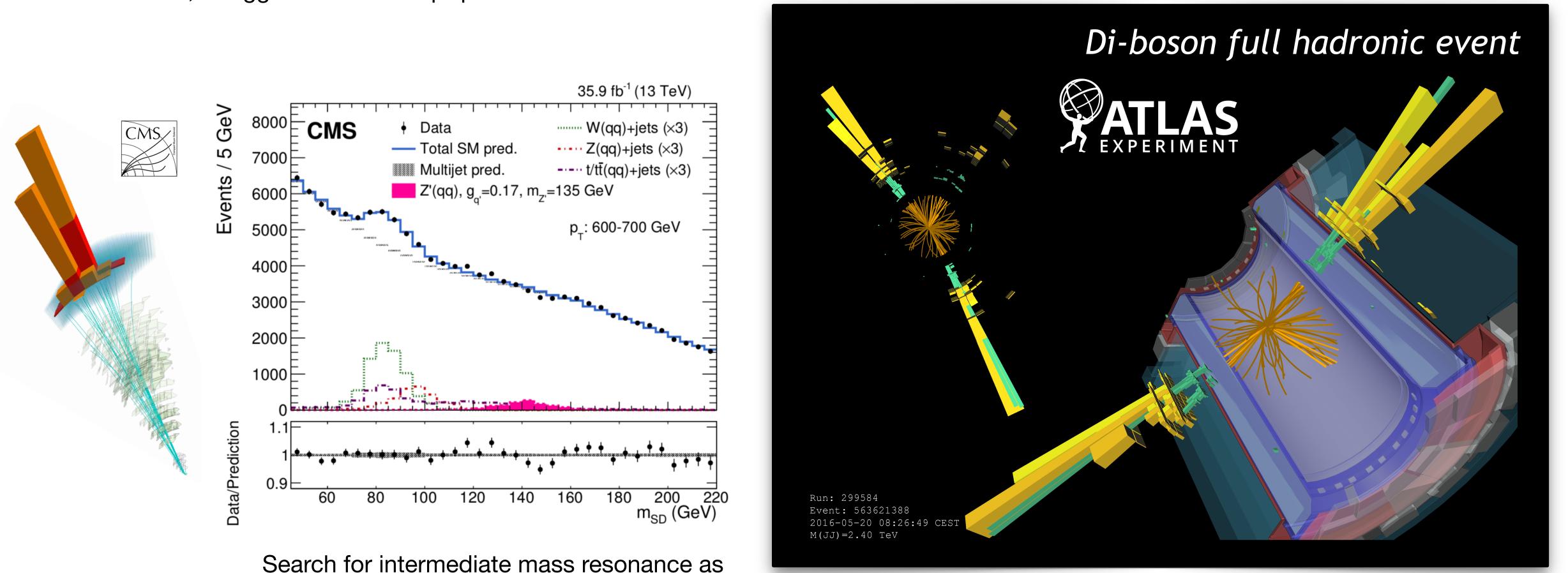
**Angular distribution** 

$$\chi \equiv \exp(|y_1 - y_2|)$$



### **Improving Reconstruction Techniques**

Jet substructure reconstruction improvements reconstructing a vector boson, a Higgs boson or a top quark.



Search for intermediate mass resonance as a single jet investigating its substructure.

#### Searches for diboson in two boosted jets signatures

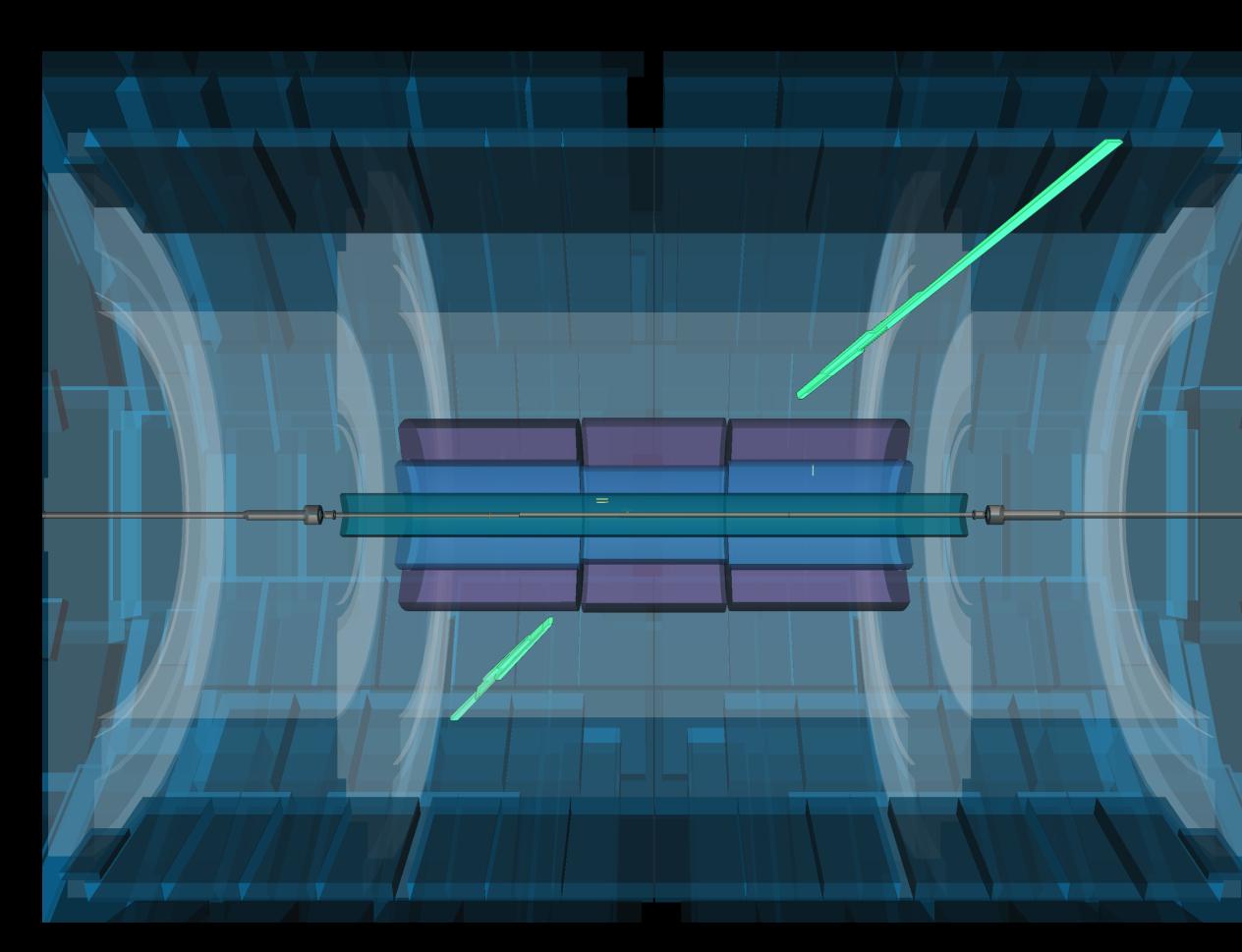
Di boson candidate event in a fully hadronic search, each jet has a mass compatible with a vector boson (W or Z).



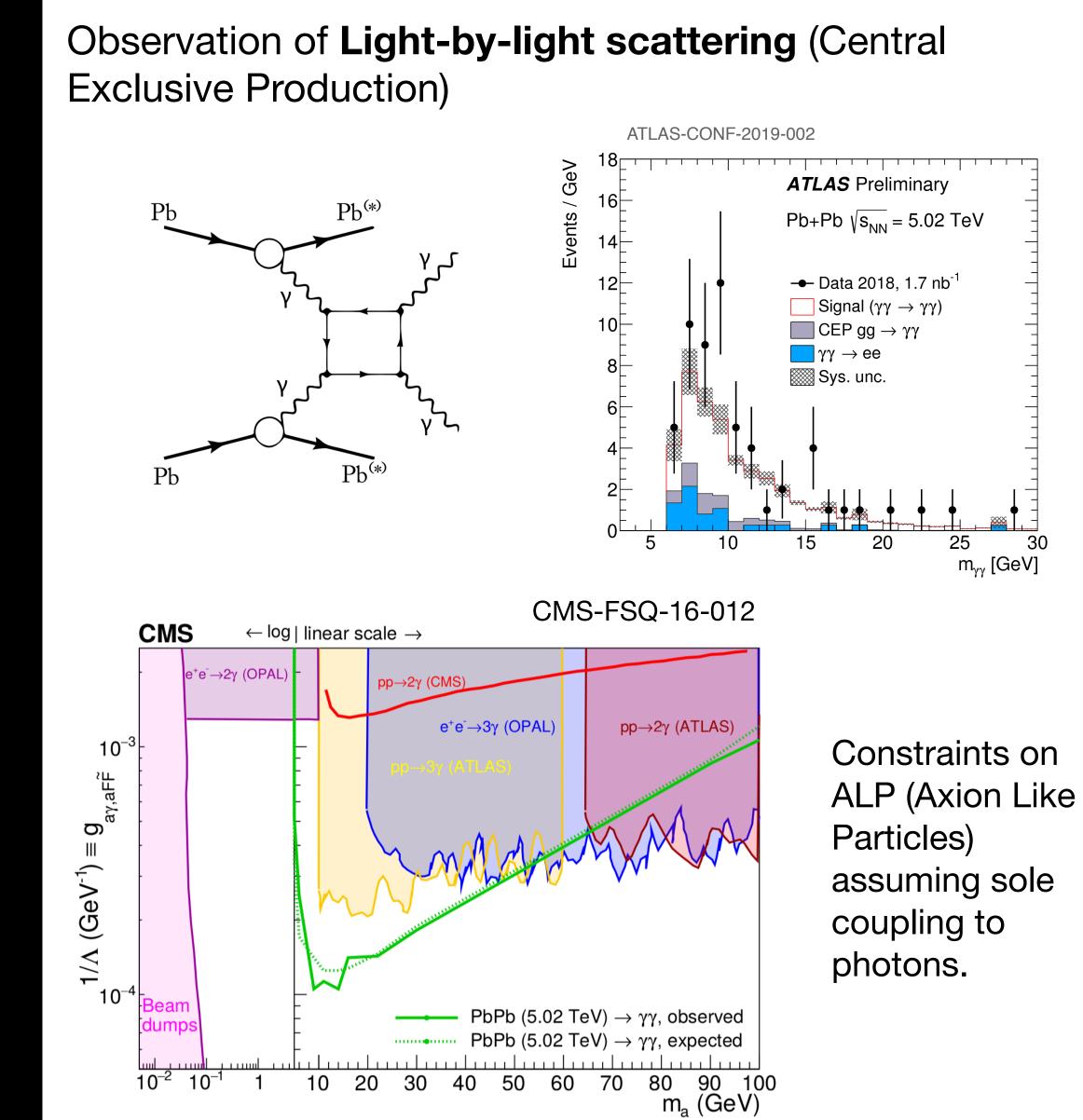




Run: 366994 Event: 453765663 2018-11-26 18:32:03 CEST



### **A Spectacular Heavy Ion Event**







### Very Large Number of Searches (in large variety of topologies and models)

#### **Overview of CMS EXO results**

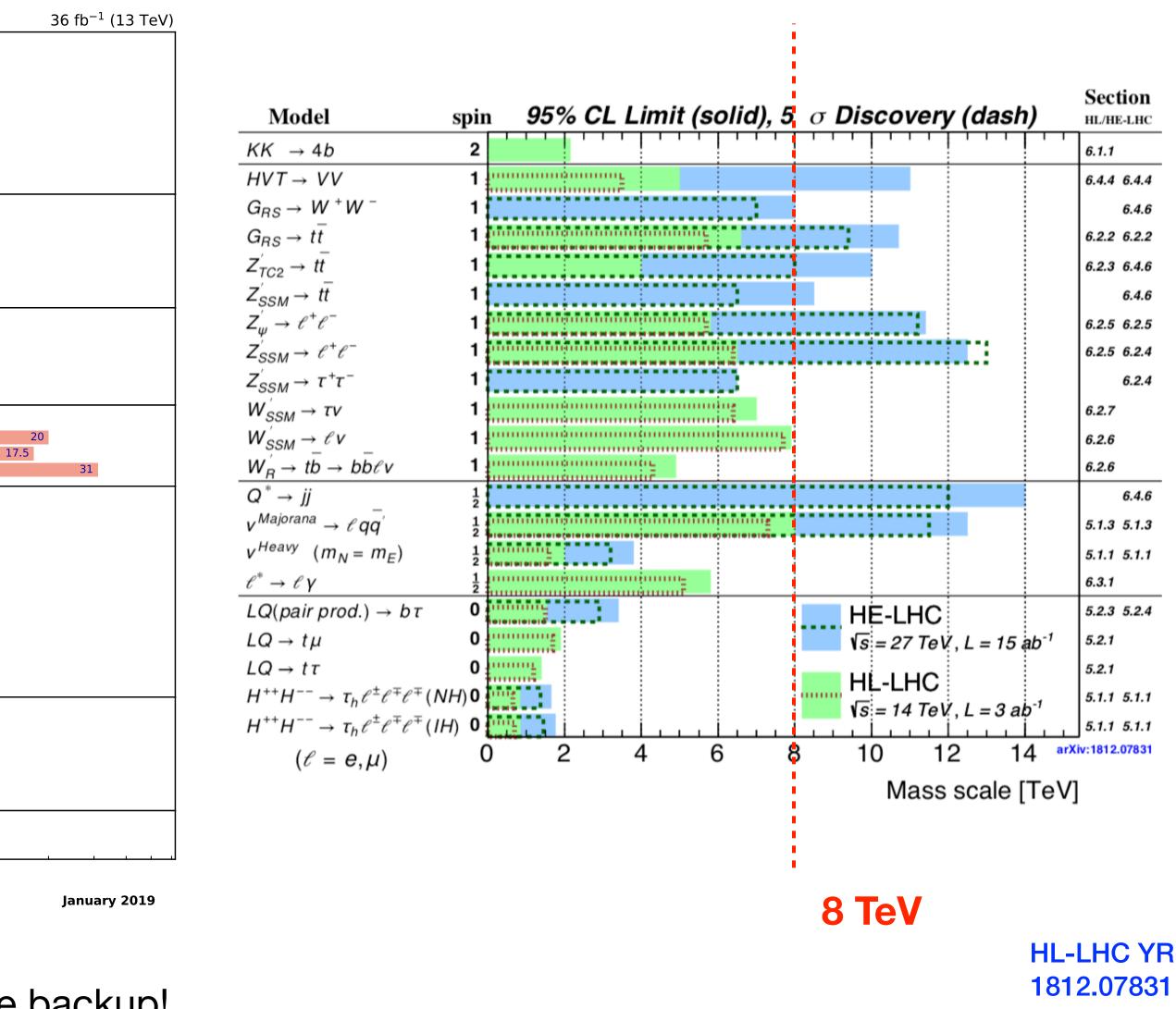
				CMS
		SSM Z'( <i>ll</i> )	М <sub>7'</sub>	1803.06292 ( <b>2</b> ℓ)
	S	SSM $Z'(q\bar{q})$	-	1806.00843 ( <b>2</b> j)
	son	LFV Z', BR( $e\mu$ ) = 10%	Μ <sub>7'</sub>	1802.01122 ( <b>eµ</b> )
	Bos	SSM W'( $\ell\nu$ )	M <sub>Z'</sub> M <sub>W'</sub>	$1803.11133 (\ell + E_T^{miss})$
	ge	SSM W ( <i>pp</i> ) SSM W'( <i>qq</i> )	M <sub>W</sub>	1806.00843 (2j)
	Heavy Gauge Bosons	SSM W (θθ) SSM W'(τν)	M <sub>W</sub>	$1807.11421 (\tau + E_T^{miss})$
	∑ ∑	LRSM W <sub>R</sub> ( $\ell N_R$ ), $M_{N_R} = 0.5 M_{W_R}$	••	$1807.11421((1 + L_T))$ 1803.11116(2l + 2j)
	eav	LRSM W <sub>R</sub> ( $\tau N_R$ ), $M_{N_R} = 0.5 M_{W_R}$ LRSM W <sub>R</sub> ( $\tau N_R$ ), $M_{N_R} = 0.5 M_{W_R}$	M <sub>WR</sub>	$1811.00806 (2\tau + 2j)$
	Ŧ	Axigluon, Coloron, $\cot\theta = 1$	M <sub>WR</sub>	1806.00843 ( <b>2j</b> )
			M <sub>C</sub>	1000.000+3 (2)
		scalar LQ (pair prod.), coupling to $1^{st}$ gen. fermions, $\beta = 1$	$M_{LQ}$	1811.01197 ( <b>2e + 2j</b> )
	ks	scalar LQ (pair prod.), coupling to $1^{st}$ gen. fermions, $\beta = 0.5$	$M_{LQ}$	1811.01197 ( <b>2e + 2j; e + 2j + E</b> <sup>miss</sup>
	naı	scalar LQ (pair prod.), coupling to $2^{nd}$ gen. fermions, $\beta = 1$	M <sub>LQ</sub>	1808.05082 ( <b>2μ + 2j</b> )
	Leptoquarks	scalar LQ (pair prod.), coupling to $2^{nd}$ gen. fermions, $\beta = 0.5$	M <sub>LO</sub>	1808.05082 ( <b>2μ + 2j; μ + 2j + Ε</b> <sup>miss</sup>
	epi	scalar LQ (pair prod.), coupling to $3^{rd}$ gen. fermions, $\beta = 1$	M <sub>LO</sub>	1811.00806 ( <b>2τ + 2j</b> )
		scalar LQ (single prod.), coup. to $3^{rd}$ gen. ferm., $\beta = 1, \lambda = 1$	M <sub>LO</sub>	1806.03472 ( <b>2τ + b</b> )
1				
		excited light quark ( $q\bar{q}$ ), $\Lambda = m_q^*$	$M_{q^*}$	1806.00843 ( <b>2j</b> )
	ed ons	excited light quark (qy), $f_S = f = f' = 1$ , $\Lambda = m_q^*$	$M_{q^*}$	1711.04652 ( <b>γ + j</b> )
	Excited Fermions	excited b quark, $f_S = f = f' = 1$ , $\Lambda = m_q^*$	$M_{b^*}$	1711.04652 ( <b>γ + j</b> )
	E E	excited electron, $f_S = f = f' = 1$ , $\Lambda = m_e^*$	$M_{e^*}$	1811.03052 ( <b>γ + 2e</b> )
		excited muon, $f_S = f = f' = 1$ , $\Lambda = m_{\mu}^*$	$M_{\mu^*}$	1811.03052 ( <b>γ + 2μ</b> )
ï		· · · · · ·		
	ons	quark compositeness $(q\bar{q}), \eta_{LL/RR} = 1$	$\Lambda^+_{LL/RR}$	1803.08030 ( <b>2j</b> )
	acti	quark compositeness ( $\ell\ell$ ), $\eta_{LL/RR} = 1$	$\Lambda^+_{LL/RR}$	1812.10443 ( <b>2</b> ℓ)
	Contact Interactions	quark compositeness $(q\bar{q}), \eta_{LL/RR} = -1$		1803.08030 ( <b>2</b> j)
	<u>2</u>	quark compositeness ( $\ell\ell$ ), $\eta_{ m LL/RR}=-1$	$\Lambda_{LL/RR}^{-}$	1812.10443 ( <b>2</b> ℓ)
		ADD (jj) HLZ, <i>n</i> <sub>ED</sub> = 3	Ms	1803.08030 ( <b>2j</b> )
		ADD $(\gamma\gamma, \ell\ell)$ HLZ, $n_{\rm ED} = 3$	Μs	1812.10443 ( <b>2γ</b> , <b>2</b> <i>ℓ</i> )
		ADD $G_{KK}$ emission, $n = 2$		1712.02345 ( ≥ <b>1j</b> + <b>E</b> <sup>miss</sup> )
	S	ADD QBH (jj), $n_{ED} = 6$		1803.08030 ( <b>2j</b> )
	ions	ADD QBH $(e\mu)$ , $n_{ED} = 6$	M <sub>овн</sub>	1802.01122 ( <b>eµ</b> )
	Extra Dimensi	RS $G_{KK}(q\bar{q}, gg), k/\overline{M}_{Pl} = 0.1$	M <sub>Gкк</sub>	1806.00843 ( <b>2j</b> )
	in	$RS G_{KK}(\ell l), k/\overline{M}_{Pl} = 0.1$	M <sub>Gкк</sub>	1803.06292 ( <b>2</b> ℓ)
	ä	$RS G_{KK}(\gamma\gamma), k/\overline{M}_{Pl} = 0.1$	М <sub>Gкк</sub>	1809.00327 ( <b>2γ</b> )
	ixtr	RS QBH (jj), $n_{\text{ED}} = 1$	M <sub>OBH</sub>	1803.08030 ( <b>2</b> j)
		RS QBH ( $e\mu$ ), $n_{ED} = 1$	M <sub>QBH</sub>	1802.01122 ( <b>eµ</b> )
		non-rotating BH, $M_{\rm D} = 4$ TeV, $n_{\rm ED} = 6$	<i>М</i> вн	1805.06013 ( ≥ <b>7j(ℓ, γ)</b> )
		split-UED, $\mu \ge 4$ TeV		$1803.11133 (\ell + E_T^{miss})$
4			_,	
		(axial-)vector mediator ( $\chi\chi$ ), $g_q = 0.25$ , $g_{DM} = 1$ , $m_{\chi} = 1$ GeV	M <sub>med</sub>	1712.02345 ( <b>≥ 1j + E</b> <sup>miss</sup> )
	ter	(axial-)vector mediator ( $q \bar{q}$ ), $g_q$ = 0.25, $g_{\text{DM}}$ = 1, $m_{\chi}$ = 1 GeV	M <sub>med</sub>	1806.00843 ( <b>2j</b> )
	1ati	scalar mediator (+ $t/t\bar{t}$ ), $g_q = 1$ , $g_{DM} = 1$ , $m_{\chi} = 1$ GeV	M <sub>med</sub>	1901.01553 ( <b>0, 1</b> $\ell$ + $\geq$ <b>3j</b> + <b>E</b> <sub>T</sub> <sup>miss</sup> )
	ž	pseudoscalar mediator (+ $t/t\bar{t}$ ), $g_q = 1$ , $g_{DM} = 1$ , $m_{\chi} = 1$ GeV	M <sub>med</sub>	1901.01553 ( <b>0</b> , $1\ell + \ge 3j + E_T^{miss}$ )
	Dark Matter	scalar mediator (fermion portal), $\lambda_u = 1$ , $m_\chi = 1$ GeV	$M_{\Phi_{u}}$	1712.02345 ( <b>≥ 1j + E</b> <sup>miss</sup> )
	_	complex sc. med. (dark QCD), $m_{\pi_{DK}}$ = 5 GeV, $c\tau_{X_{DK}}$ = 25 mm	M <sub>Хрк</sub>	1810.10069 ( <b>4j</b> )
	L			1700.07062.4
	Other	Type III Seesaw, $B_e = B_\mu = B_\tau$	M <sub>Sigma</sub>	$1708.07962 (\geq 3l)$ 1806.00843 (2i)
	ò	string resonance	M <sub>S</sub>	1806.00843 ( <b>2j</b> )
				0.1

CNAC 4.5 3.3 44 3.5 6.1 1.44 1.27 1.53 1.29 1.02 0.74 6 5.5 1.8 12.8 9.1 8.2 56 5.9 3.6 2.9 1.8 2.6 0.29 0.3 1.4 1.54 0.84 7.7 10.0 1.0 mass scale [TeV]

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

4 TeV

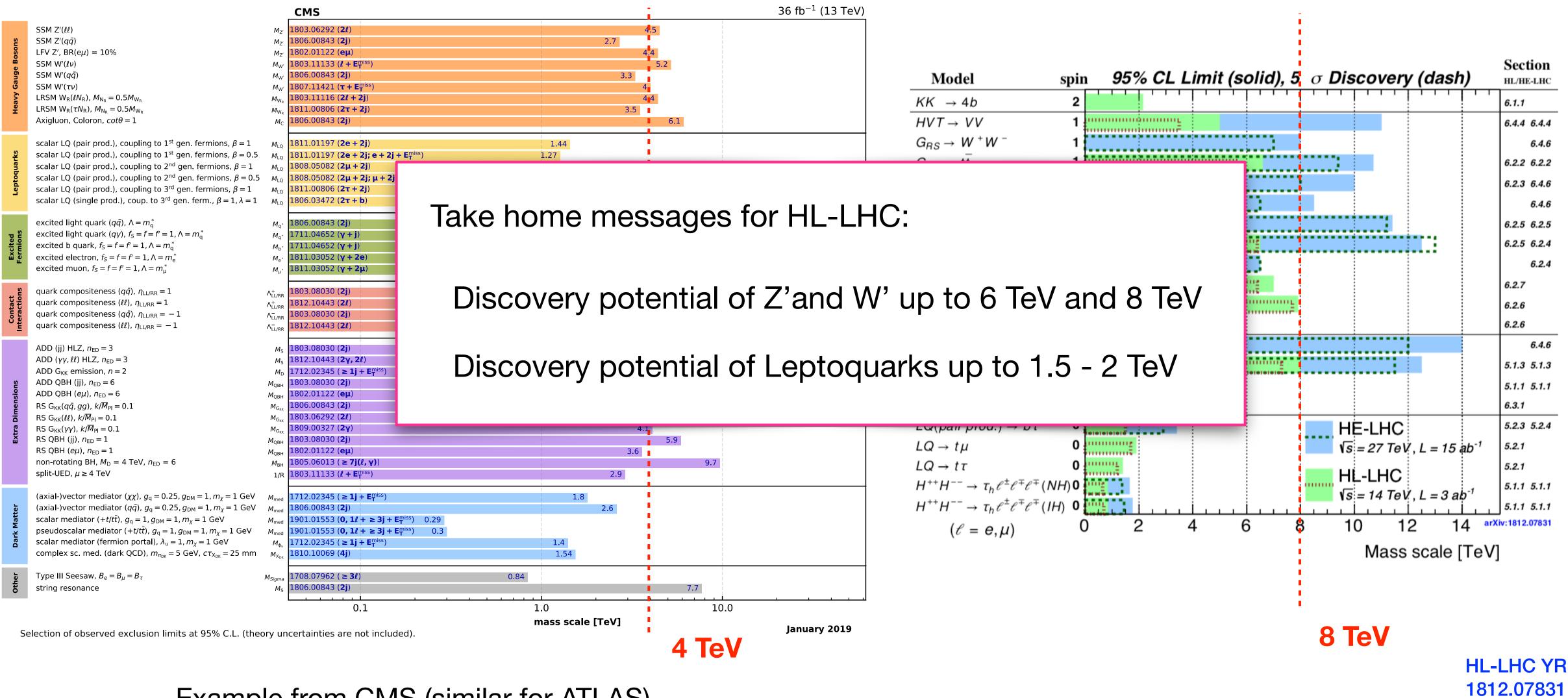
Example from CMS (similar for ATLAS) - latest plot in the backup!





### Very Large Number of Searches (in large variety of topologies and models)

#### **Overview of CMS EXO results**



Example from CMS (similar for ATLAS)



### **Unconventional Signatures**

Many extensions of the Standard Model predict new particles that are long lived heavy (neutral and charged) and can decay after several cm or even meters.

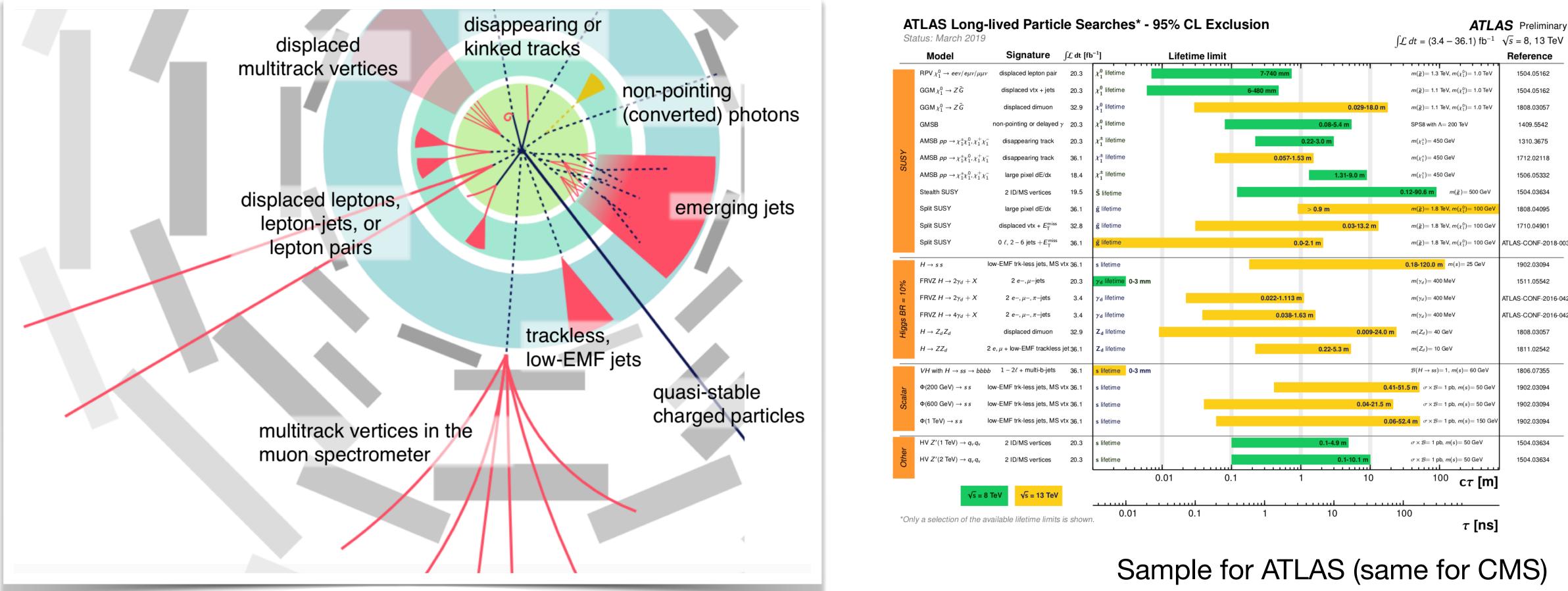


Image from H. Russel

**Difficult signatures requiring specific complex reconstruction and trigger!** 

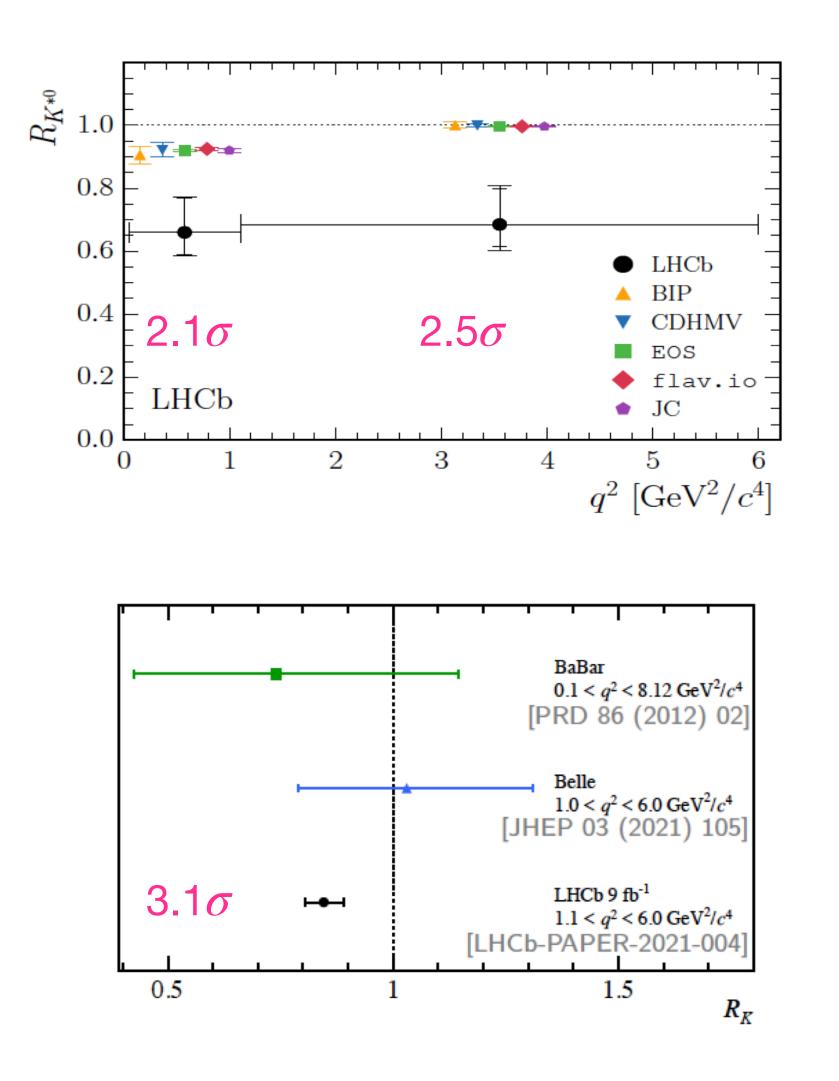




# Following Up on Anomalies

### **LFU Anomalies in B decays**

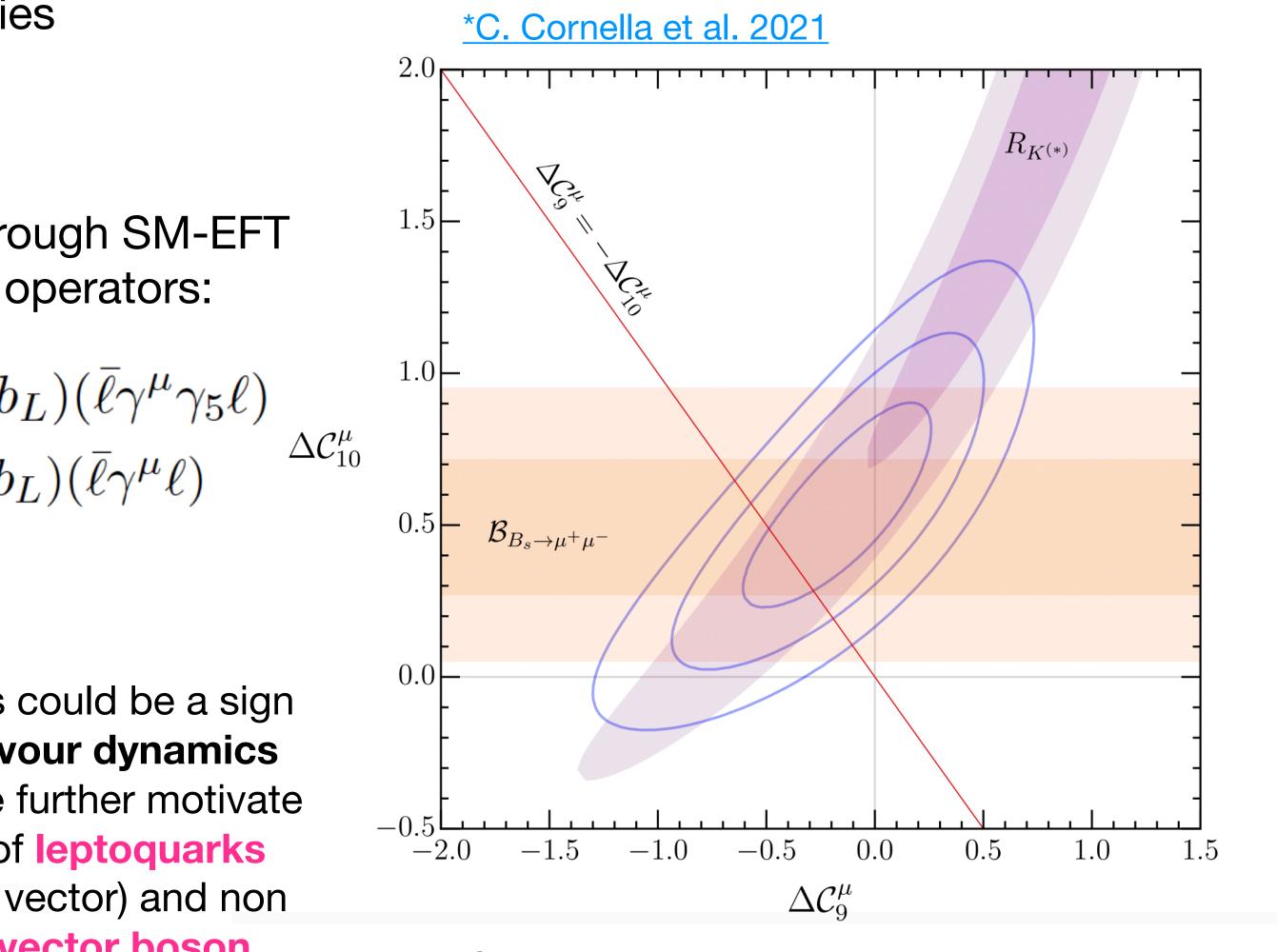
Part of the 'Footprints" of rare B decays anomalies



Combining through SM-EFT Dim.-6 FCNC operators:

$$\mathcal{O}_{10}^{\ell} = (\bar{s}_L \gamma_\mu b)$$
  
 $\mathcal{O}_{9}^{\ell} = (\bar{s}_L \gamma_\mu b)$ 

These anomalies could be a sign of non trivial flavour dynamics at the TeV scale further motivate direct searches of **leptoquarks** (both scalar and vector) and non universal heavy vector boson.

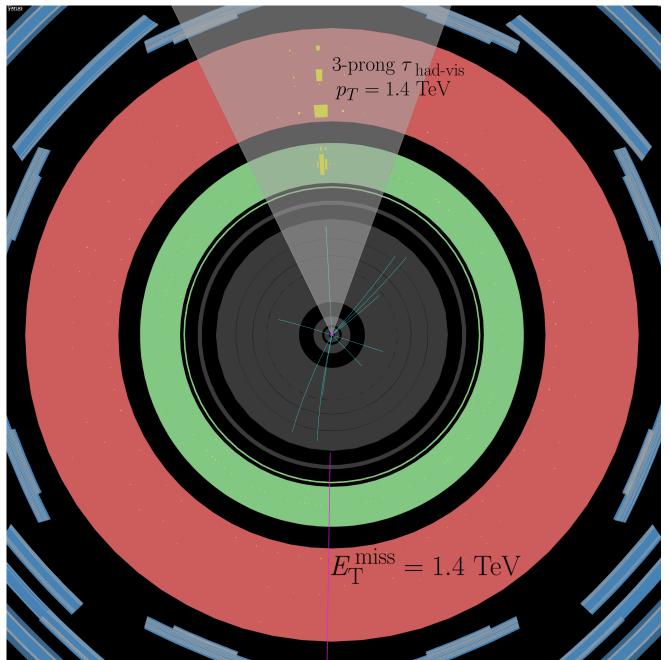


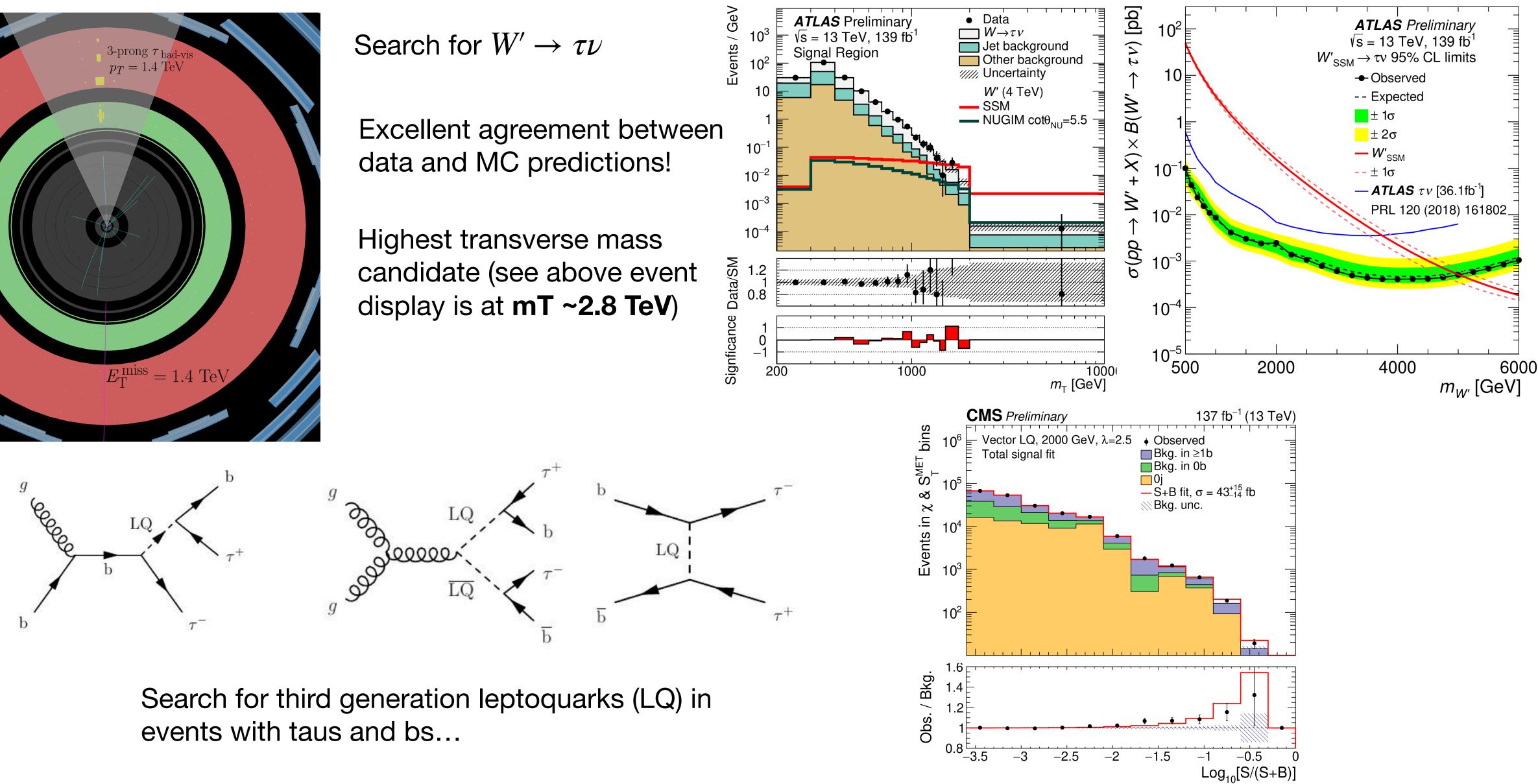
Combined with the RK\* anomaly leads to a **4.6** $\sigma$  tension





# High energy phenomena with taus and b's

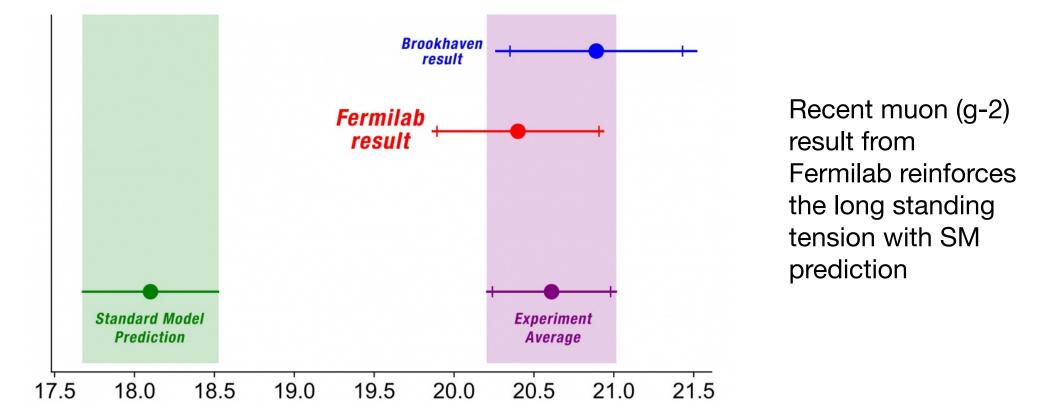






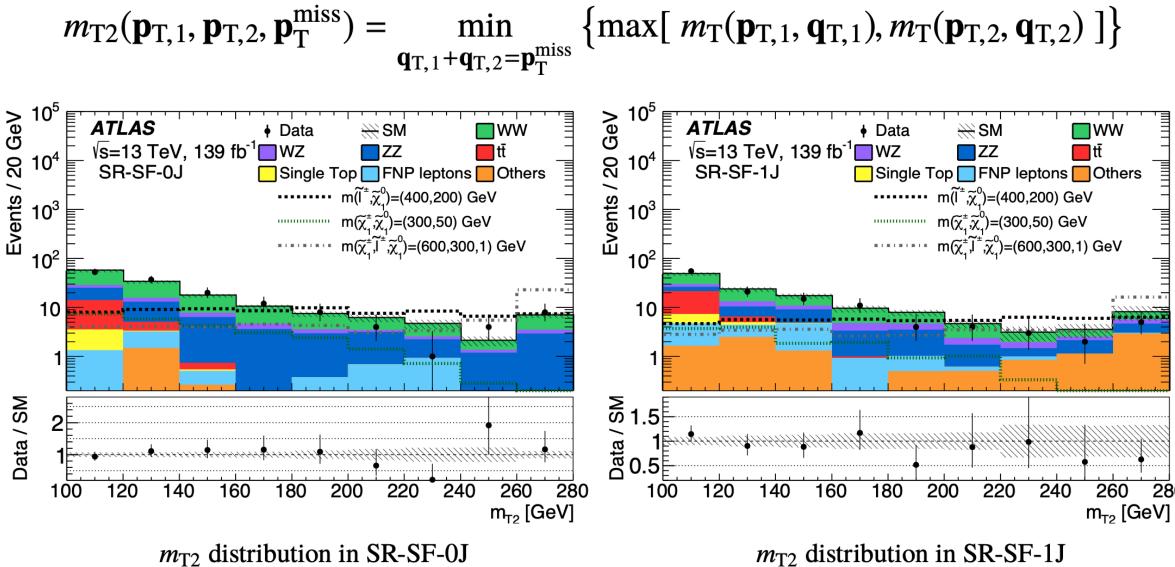
# Probing (g-2) and flavour Anomalies at High energy

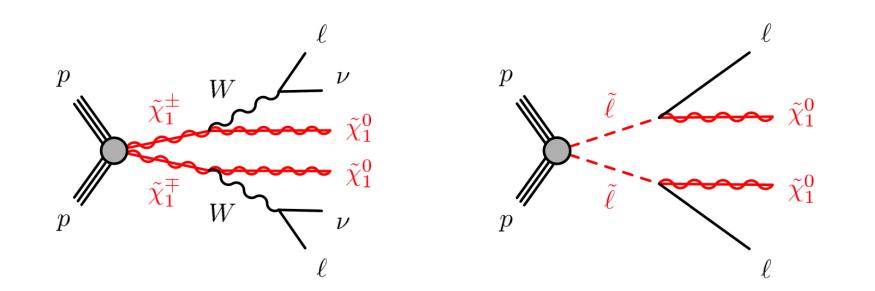
Eur. Phys. J. C 80 (2020) 123



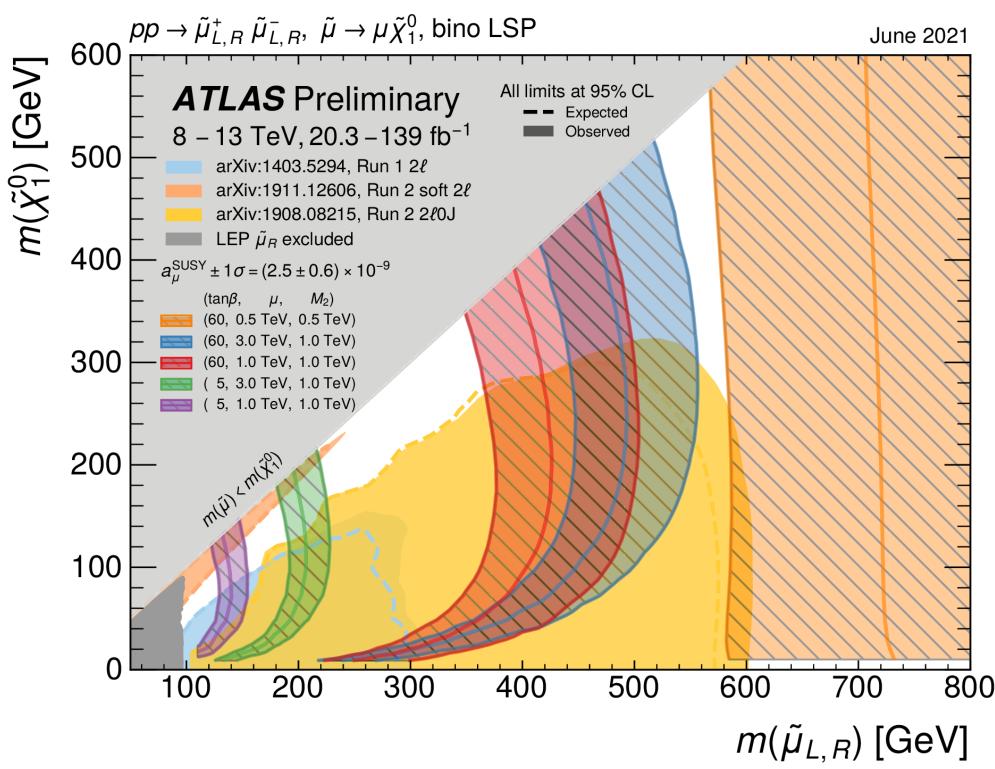
Muon (g-2) anomaly motivates searches for **smuons** 

Using the s-transverse mass (estimated varying hypotheses of individual MET components)

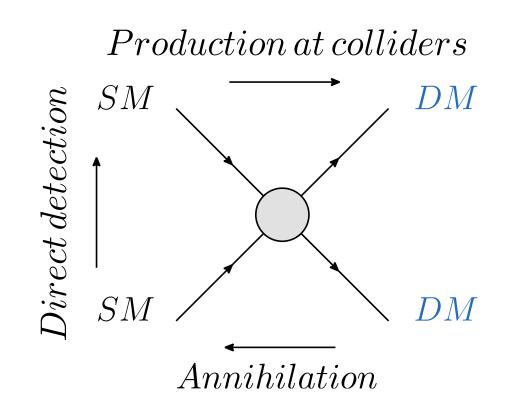




Search in scenarios with two leptons and MET





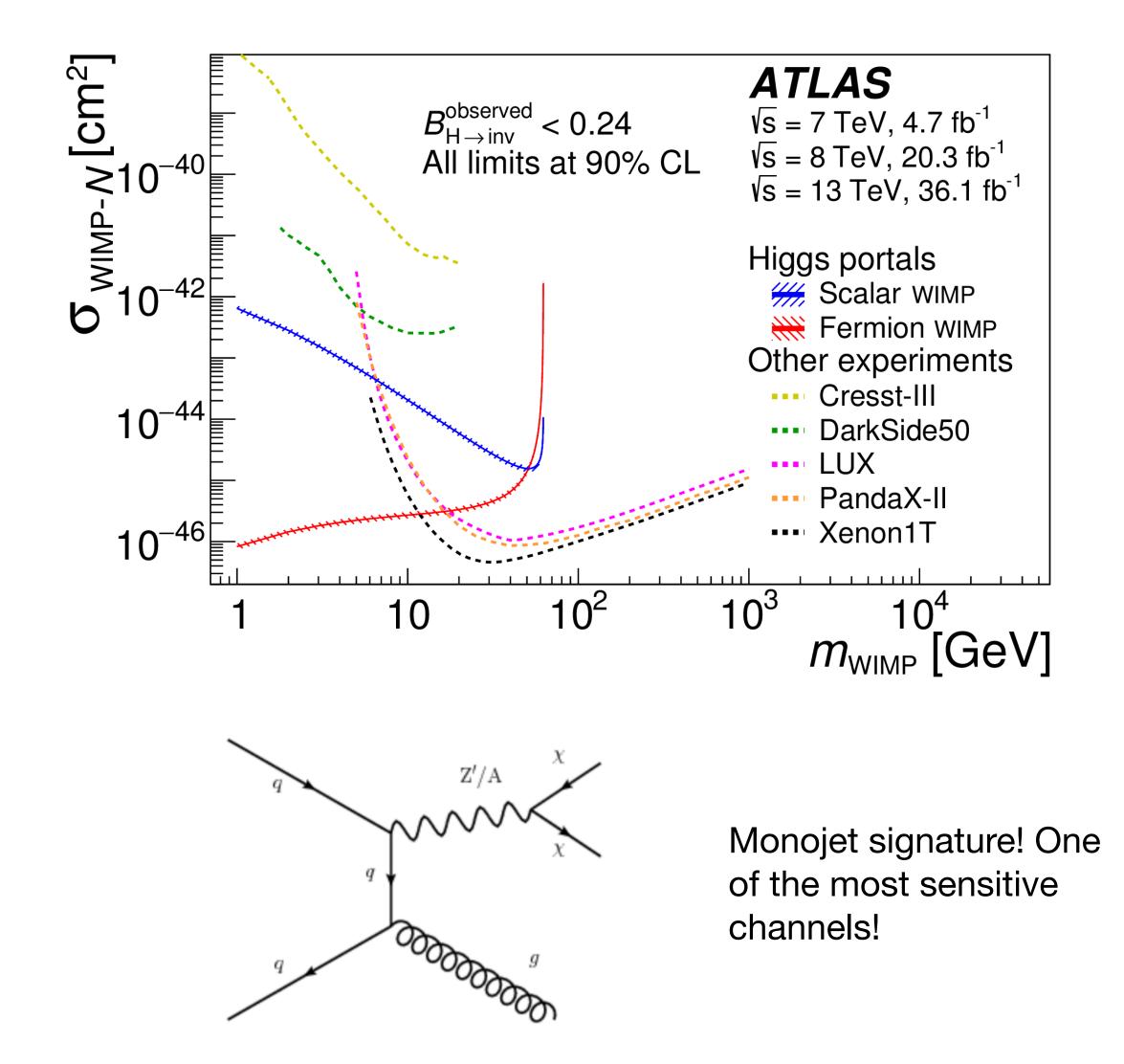


Complementarity of searches at colliders, direct and indirect searches!

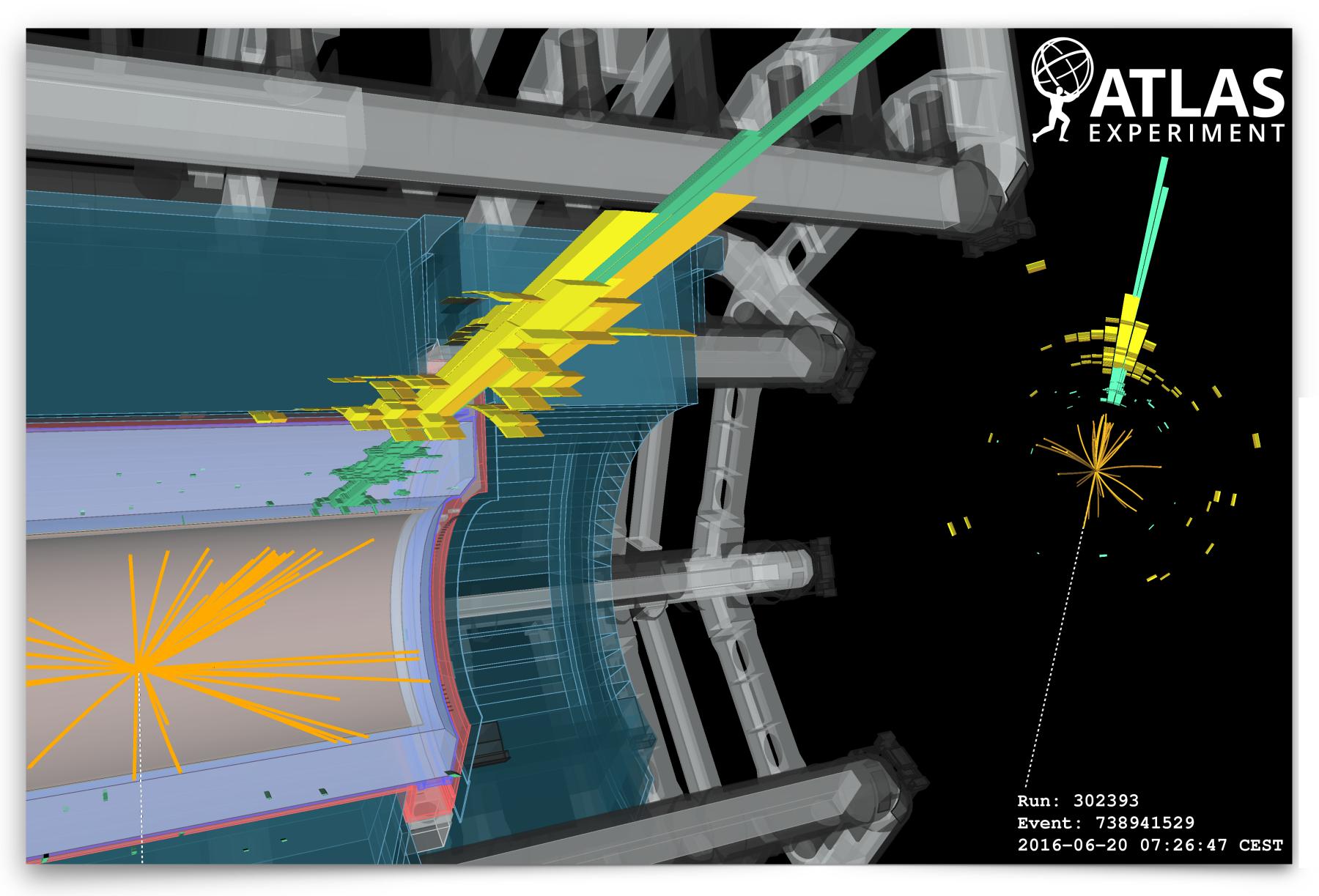
### **Searches for Dark Matter at the LHC**

- Invisible Higgs searches (Lecture 3).

 In order to be observed invisible final states need additional objects to be associated with. Mono-anything searches: Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top.



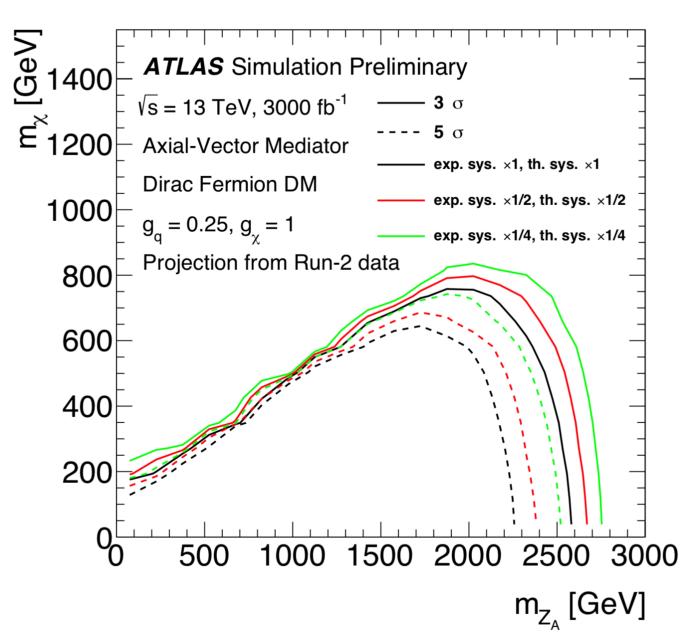




A jet with pT of 1707 GeV. The ETmiss of 1735 GeV is shown as the white dashed line. No additional jets with pT above 30 GeV is found.

### Mono jet search prospects

Reach close to TeV range at HL-LHC (model dependent)

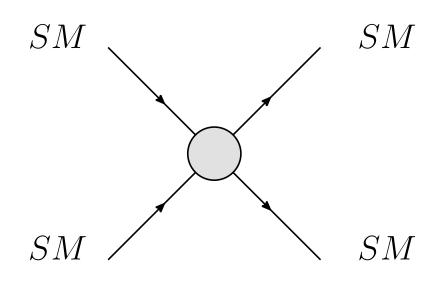




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### Searches for the dark matter mediator

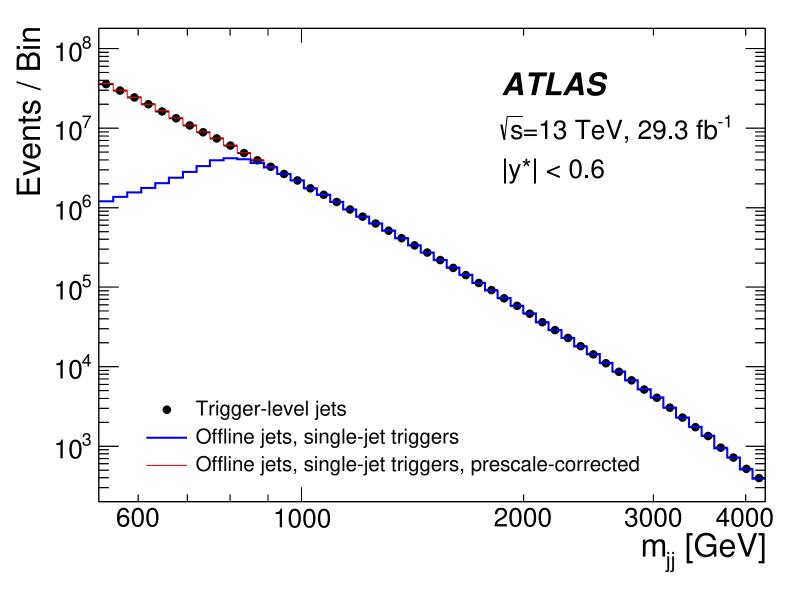
in e.g. in dijet events extending at low masses

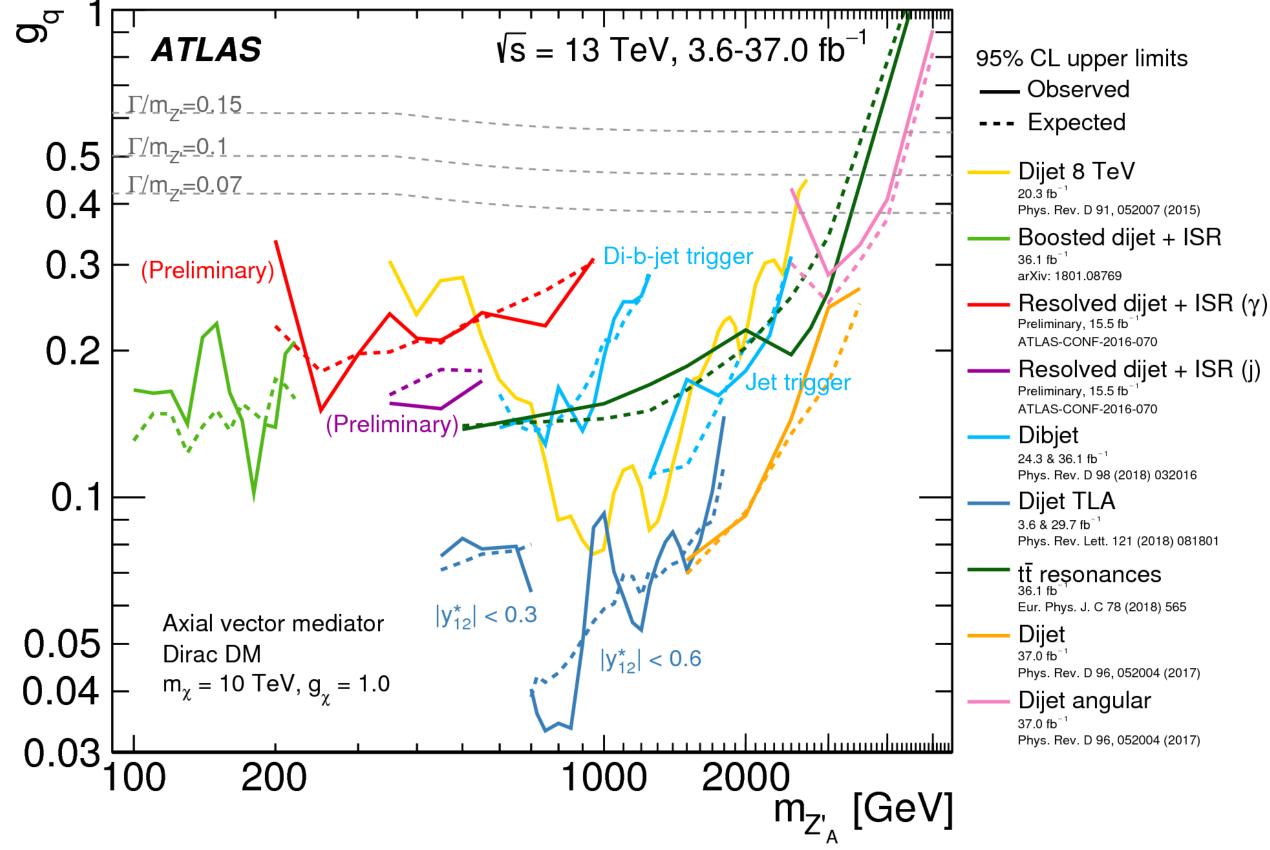


Numerous strategies to also cover lower masses e.g.:

- boosting (ISR photon/jet) -
- Trigger level analyses \_

Dijet Trigger level analysis







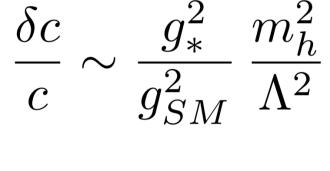
# **Outlook and Conclusions**

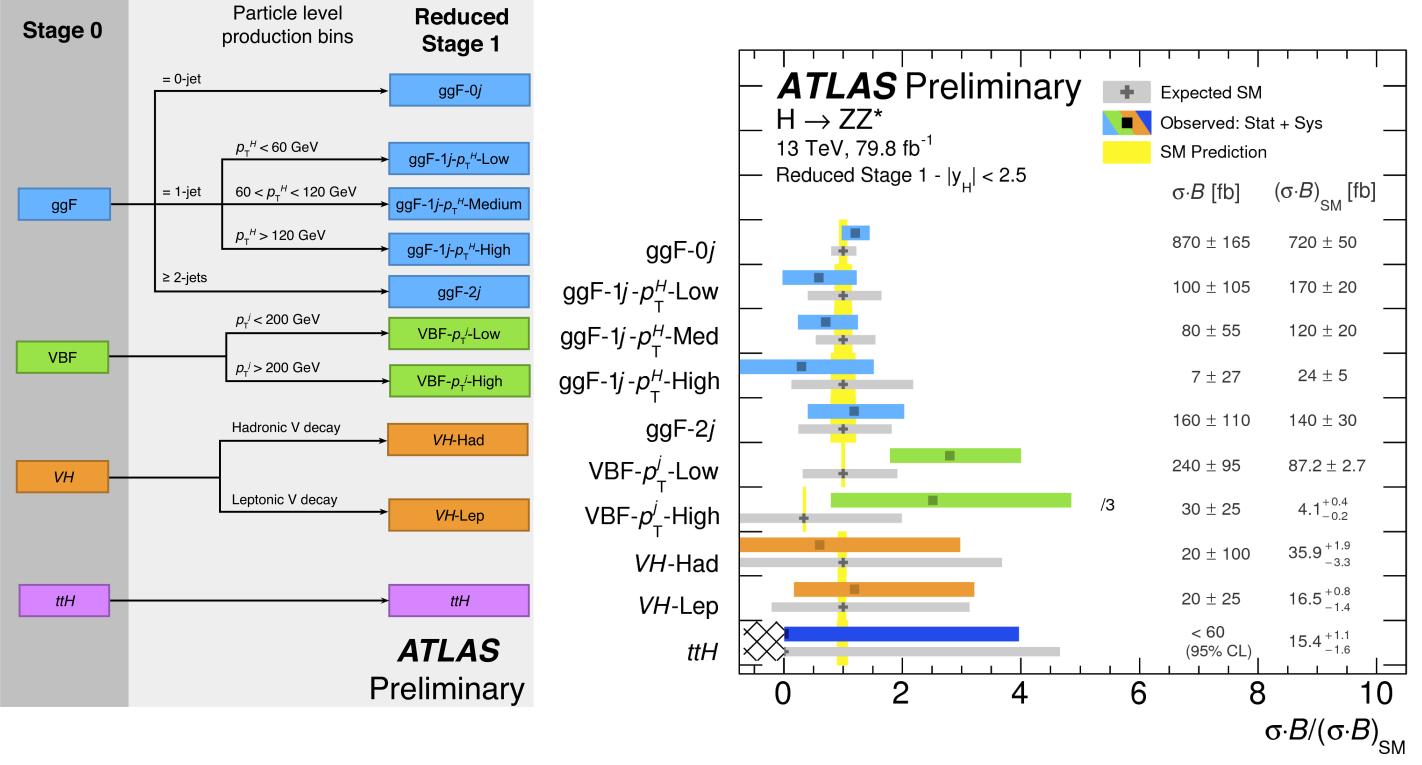
### Searching with Precision and High energy Phenomena

#### Measurement of SM processes in the high energy domain

Effective field theory and measurements of non resonant processes at higher energy

### **Higgs couplings at low energies**

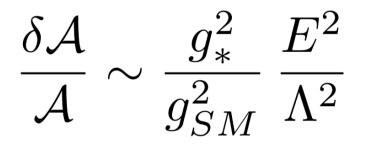


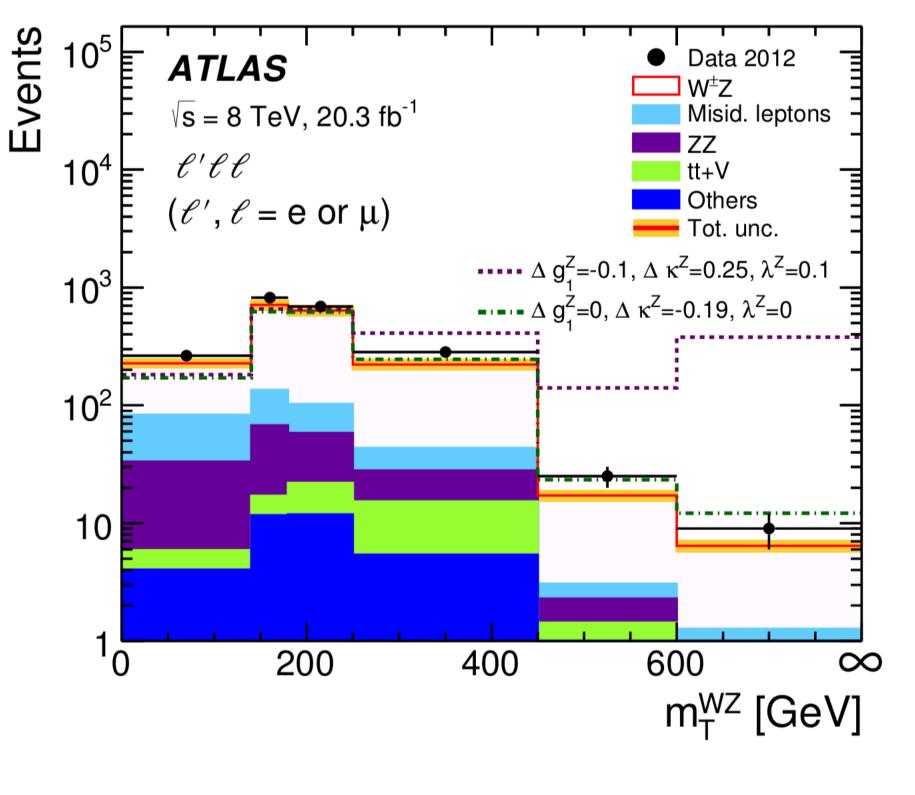


Measurement of Higgs production cross sections in high transverse momentum regime

### **Higher energy phenomena**

(e.g. VV scattering)

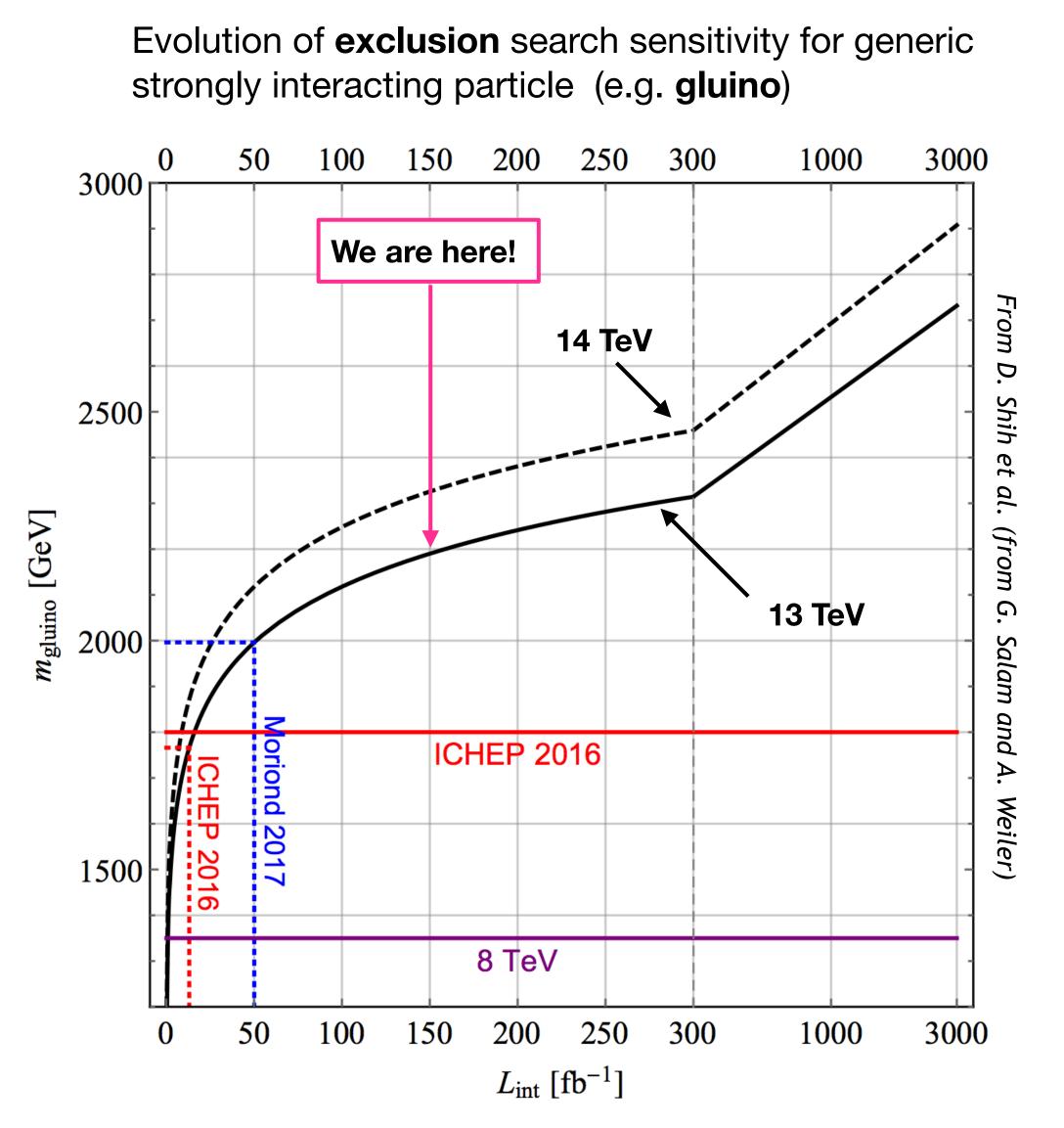




#### Measurement of di-boson in the high mass regime



### **Towards HL-LHC and Precision Physics at LHC**



http://collider-reach.web.cern.ch/collider-reach/

Towards HL-LHC still a **factor of 20** in luminosity:

- Still room for discoveries!
- Given that the **doubling time of the luminosity** is now counted in several years: discoveries will take time, and times for spectacular discoveries (in the sense of immediate) are over.
- Low hanging fruits typically have been (or are being) harvested! -Immense amount of work in trying to expand search reach beyond the root-L:
  - With new ideas and developments at all levels. —
  - Improving precision (theoretical and experimental) will be key!

**Also:** Increase in centre-of-mass energy from 13 TeV to 14 TeV gives an increase in high energy phenomena such as (q\* or QBH) production of **2-5**!





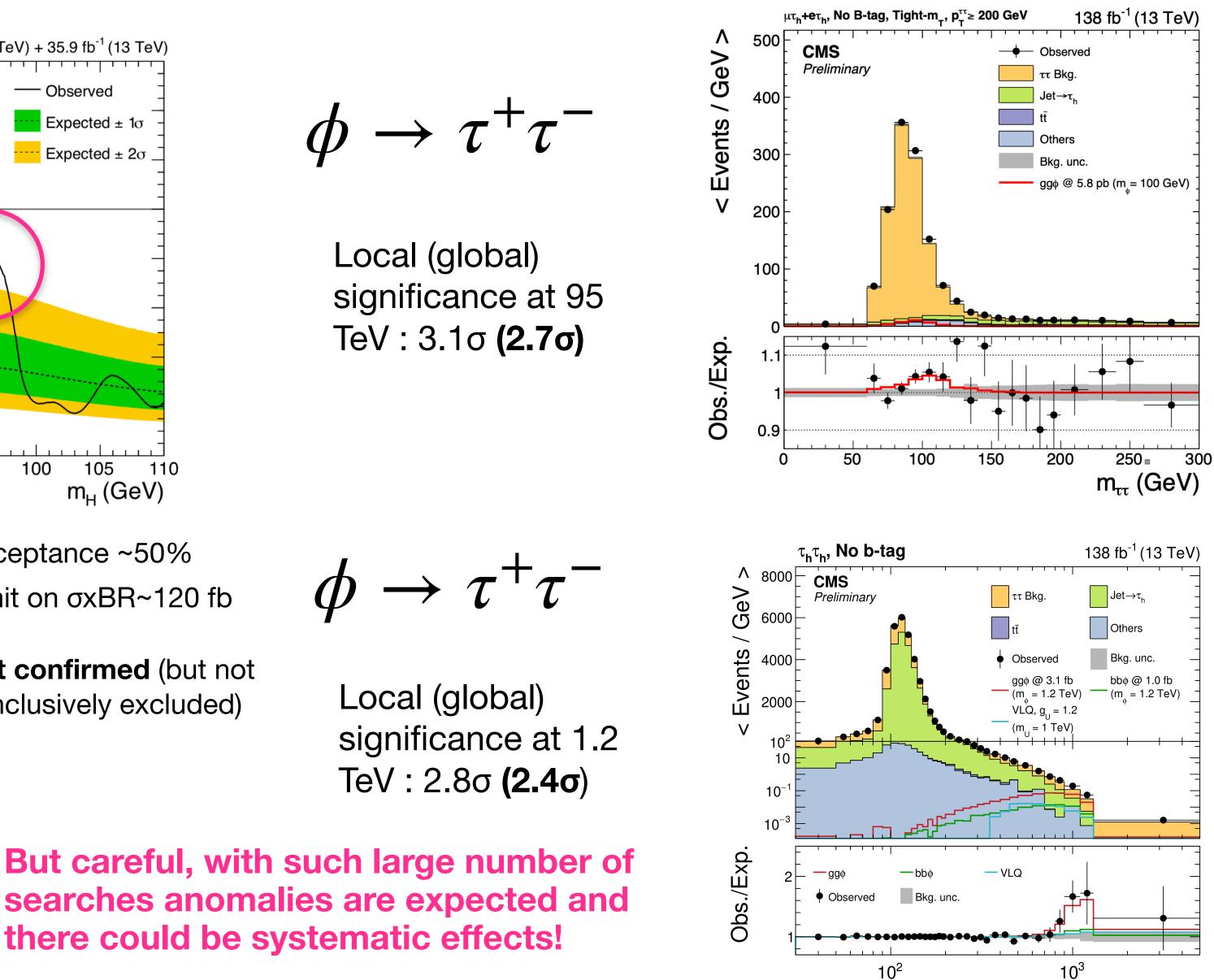






### Anomalies in the Searches done so far?

#### Several ~3 $\sigma$ (local) excesses CMS 19.7 fb<sup>-1</sup> (8 TeV) + 35.9 fb<sup>-1</sup> (13 TeV) ⇒ γγ)<sub>SM</sub> A few examples... $H \rightarrow \gamma \gamma$ ---- Observed 1.4 Expected $\pm 1\sigma$ Expected ± 2σ × B(H 1.2 $a \rightarrow \gamma \gamma$ / σ<sub>H</sub> Local (global) significance at 0.8 → γγ)<sub>95%CL</sub> 95.3 GeV : 2.9σ (**1.5σ**) 0.6 0.4 × B(H 0.2 $\sigma_{\mathsf{H}}$ 105 80 85 95 100 90 m<sub>H</sub> (GeV) ATLAS-CONF-2018-025 Acceptance ~50% Upper Limit on $\sigma_{fid}\cdot B$ [fb] 220 ATLAS Preliminary — Observed Limit on σxBR~120 fb 200⊢ $\sqrt{s} = 13 \text{ TeV}, 80 \text{ fb}^{-1}$ ----- Expected 180⊢ X→γγ $\pm 1\sigma$ <u></u>±2 σ **160**⊢ Not confirmed (but not **140**⊢ conclusively excluded) 120**⊢** 100⊢ 80 95% CL 60 40 20 100 110 70 80 90 m<sub>x</sub> [GeV]





of  $( \mathbf{n} \cdot \mathbf{$ 

### The first 10 years of the LHC running with the immense progress in theoretical predictions have been an immense success with major landmark results:

- \_ searches, but also a broad range of precision measurements machine!
- with the Standard Model Higgs boson.
- so far revealed no signal of physics beyond the Standard Model.

### The LHC physics program is broad, diverse and exciting with great opportunities for you!!

The LHC has proved not to be only a discovery machine with a vast potential in direct

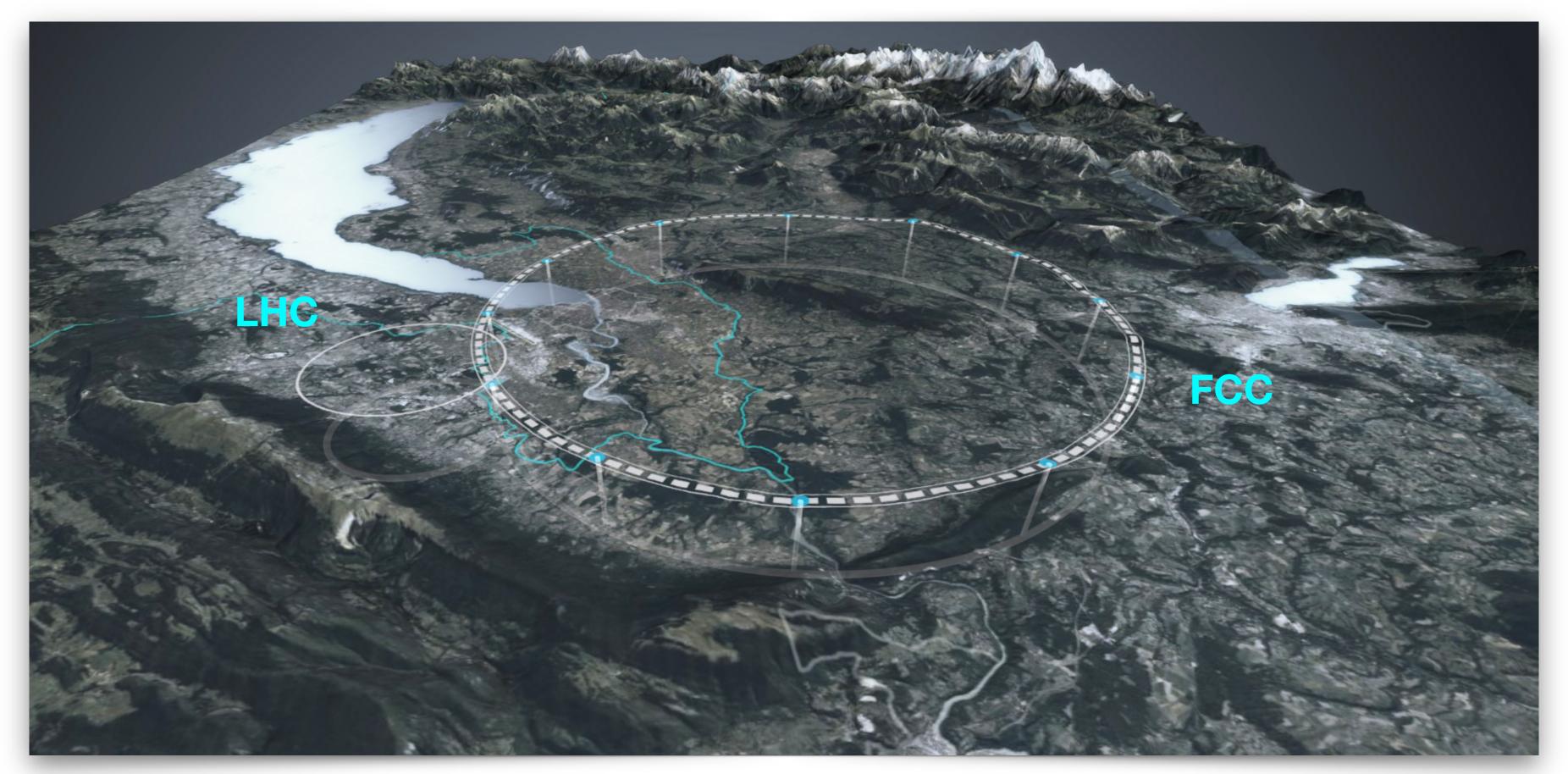
The discovery of the Higgs boson, and the measurement of its properties all compatible

A vast campaign of searches at the energy frontier leaving no stones unturned, which have

This has completely changed the field and opened new opportunities!



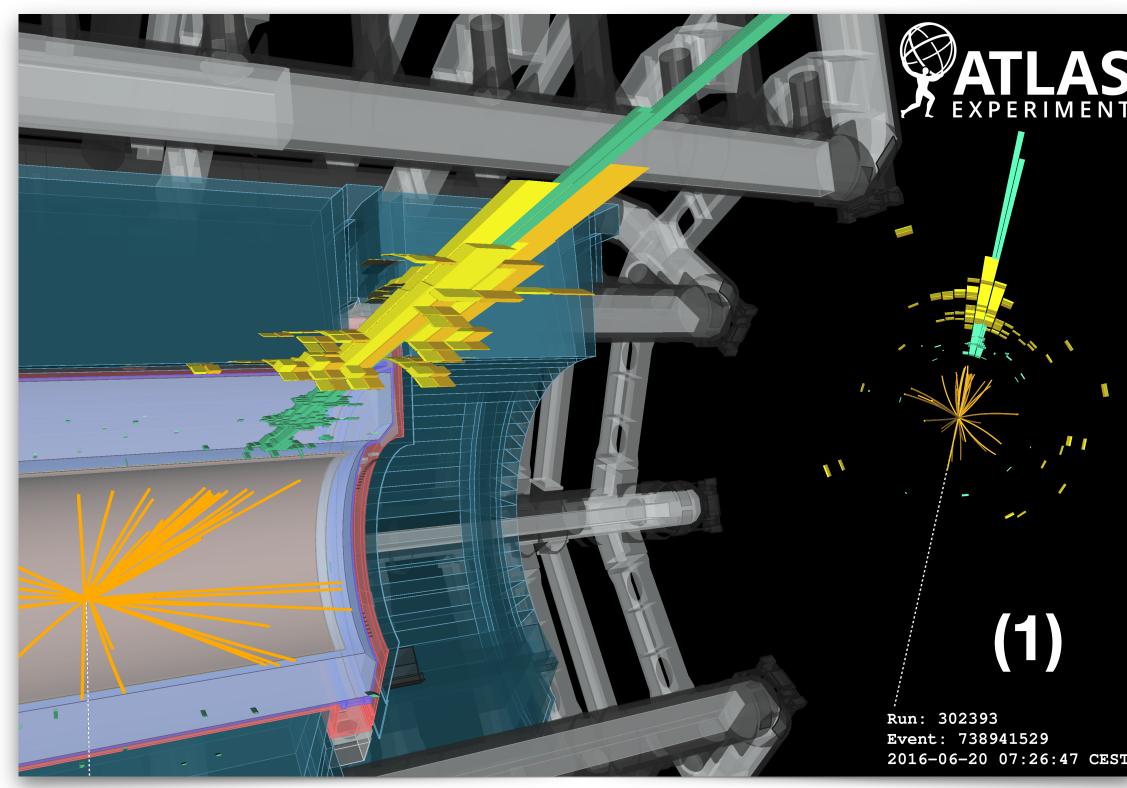
# Outlook



#### See lectures by Frank Simon and Barbara Dalena







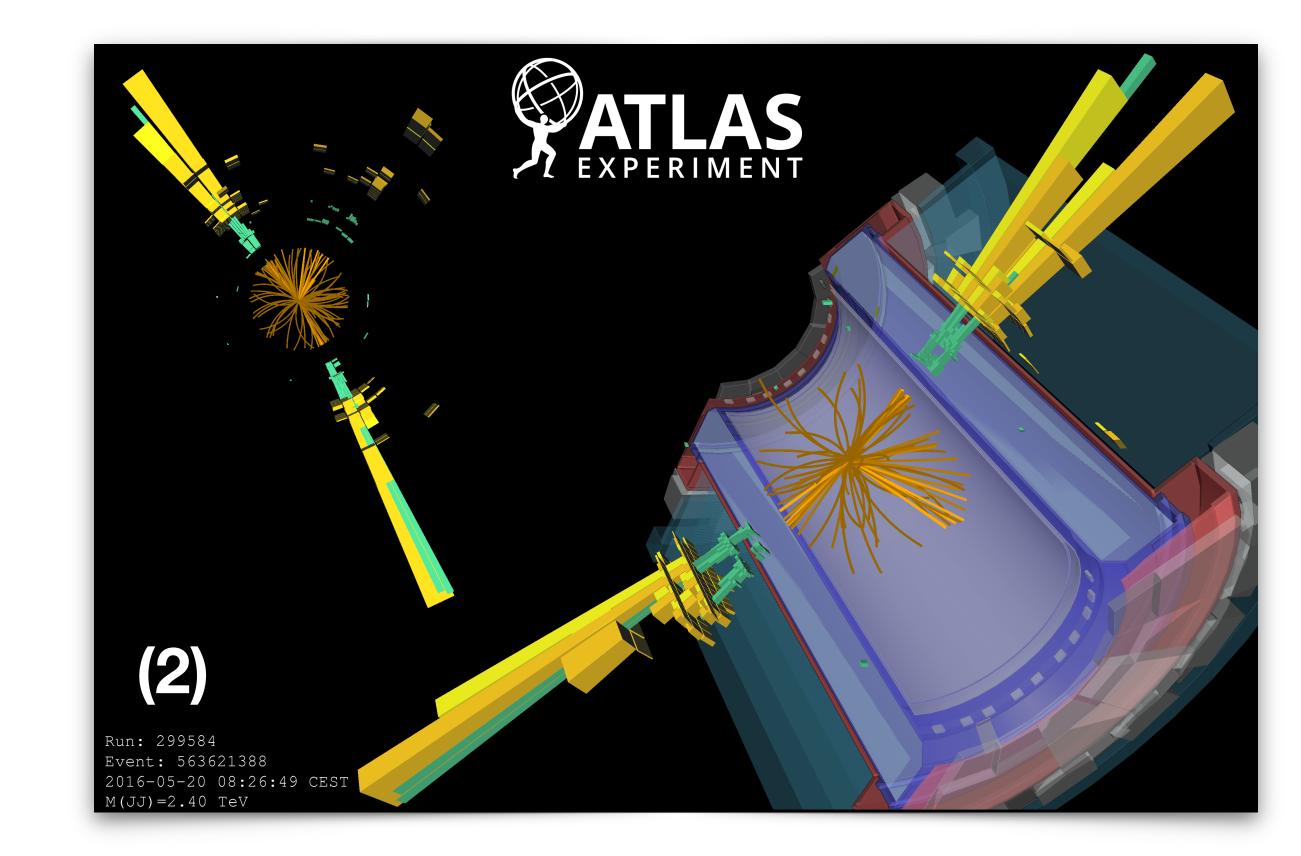
**1.-** If not the production of Dark Matter what process is this event likely due to in the Standard Model?

2.- What is the most likely interpretation of this event with two large-R jets with masses compatible with the W or Z boson?

**3.-** Can the Higgs Boson decay to neutrinos?

### **Quick Mini Quiz**







# Further Reading

	CMS preliminary			16-140 fb <sup>-1</sup> (	<u>,13 TeV)</u>
String resonance $Z\gamma$ resonance Wy resonance Higgs $\gamma$ resonance Color Octect Scalar, $k_s^2 = 1/2$ Scalar Diquark $t\bar{t} + \phi$ , pseudoscalar (scalar), $g_{top}^2 \times BR(\phi \rightarrow 2\ell) > = 0.03(0.004)$ $t\bar{t} + \phi$ , pseudoscalar (scalar), $g_{top}^2 \times BR(\phi \rightarrow 2\ell) > = 0.03(0.04)$	M M M M M M 0.015-0.075 1911.0	04968 ( <b>3ℓ</b> , ≥ <b>4ℓ</b> ) 0.108-0.34 1911.04968 ( <b>3ℓ</b> , ≥ <b>4ℓ</b> )	0.35-4 1712.03143 ( <b>2μ</b> + 0.72-3.25 1808.01257 ( <b>1j</b> + <b>1γ</b> ) 0.5-3.7 1911.03947 ( <b>2j</b> )	$.5-7.9$ 1911.03947 (2j) $1\gamma; 2e + 1\gamma; 2j + 1\gamma$ 1.5-8         2106.10509 (1j + 1\gamma)         -7.5       1911.03947 (2j)	137 36 1 137 36 1 137 137 137 137
$n = 0$ quark compositeness ( $H$ ) $n_{\rm trans} = 1$				<24 2103.02708 ( <b>2</b> ℓ)	140
quark compositeness ( $\ell \ell$ ), $\eta_{\text{LL/RR}} = -1$				<36 2103.02708 ( <b>2</b> ℓ)	140
Excited Lepton Contact Interaction Excited Lepton Contact Interaction	M M			.04521 ( <b>2e + 2j</b> ) 1.04521 ( <b>2μ + 2j</b> )	77 t 77 t
vector mediator $(q\bar{q})$ , $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV vector mediator $(l\bar{l})$ , $g_q = 0.1$ , $g_{DM} = 1$ , $g_l = 0.01$ , $m_\chi > 1$ TeV (axial-)vector mediator $(q\bar{q})$ , $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV (axial-)vector mediator $(\chi\chi)$ , $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV (axial)-vector mediator $(l\bar{l})$ , $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV (axial)-vector mediator $(l\bar{l})$ , $g_q = 0.1$ , $g_{DM} = 1$ , $g_l = 0.1$ , $m_\chi > m_{med}/2$ scalar mediator $(+t/l\bar{t})$ , $g_q = 1$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV scalar mediator (fermion portal), $\lambda_u = 1$ , $m_\chi = 1$ GeV pseudoscalar mediator $(+t/l\bar{t})$ , $g_q = 1$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV complex sc. med. (dark QCD), $m_{\pi_{DK}} = 5$ GeV, $c\tau_{X_{DK}} = 25$ mm Z' mediator (dark QCD), $m_{dark} = 20$ GeV, $r_{inv} = 0.3$ , $\alpha_{dark} = \alpha_{dark}^{peak}$ Baryonic Z', $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV Leptoquark mediator, $\beta = 1$ , $B = 0.1$ , $\Delta_{X,DM} = 0.1$ , $800 < M_{LQ} < 1500$ GeV	M         M <td< td=""><td><math display="block">0.35-0.7  1911.03761</math> <math display="block">&lt;0.29  1901.01553 (<b>0</b>, <b>1</b>\ell + \geq \mathbf{2j} + \mathbf{p}_{T}^{miss})</math> <math display="block">&lt;0.47  2107.13021 (\geq \mathbf{1j} + \mathbf{p}_{T}^{miss})</math> <math display="block">&lt;0.3  1901.01553 (<b>0</b>, <b>1</b>\ell + \geq \mathbf{2j} + \mathbf{p}_{T}^{miss})</math> <math display="block">0.3-0.6  1811.10151 (\mathbf{1\mu} + \mathbf{1)}</math></td><td>0.2−1.92 2103.02708 (<math>2e</math>, <math>2µ</math>) 0.5−2.8 1911.03947 (<math>2j</math>) &lt;1.95 2107.13021 (<math>\ge 1j + p_T^{miss}</math>) 2103.02708 &lt;1.5 2107.13021 (<math>\ge 1j + p_T^{miss}</math>) &lt;1.5 2107.13021 (<math>\ge 1j + p_T^{miss}</math>)</td><td></td><td>18 140 137 101 140 36 101 36 16 138 36 36 36 36 36 77</td></td<>	$0.35-0.7  1911.03761$ $<0.29  1901.01553 (0, 1\ell + \geq \mathbf{2j} + \mathbf{p}_{T}^{miss})$ $<0.47  2107.13021 (\geq \mathbf{1j} + \mathbf{p}_{T}^{miss})$ $<0.3  1901.01553 (0, 1\ell + \geq \mathbf{2j} + \mathbf{p}_{T}^{miss})$ $0.3-0.6  1811.10151 (\mathbf{1\mu} + \mathbf{1)}$	0.2−1.92 2103.02708 ( $2e$ , $2µ$ ) 0.5−2.8 1911.03947 ( $2j$ ) <1.95 2107.13021 ( $\ge 1j + p_T^{miss}$ ) 2103.02708 <1.5 2107.13021 ( $\ge 1j + p_T^{miss}$ ) <1.5 2107.13021 ( $\ge 1j + p_T^{miss}$ )		18 140 137 101 140 36 101 36 16 138 36 36 36 36 36 77
RPV stop to 4 quarks	М	0.08–0.52 1808.03124 ( <b>2j; 4j</b> )			36
RPV squark to 4 quarks RPV gluino to 4 quarks	M M	0.1-0.72 1806.0105	3 ( <b>2j</b> ) 0.1−1.41 1806.01058 ( <b>2j</b> )		38 38
RPV gluinos to 3 quarks	M		<1.5 1810.10092 ( <b>6j</b> )		36
ADD (jj) HLZ, $n_{ED} = 3$ ADD ( $\gamma\gamma$ , $\ell\ell$ ) HLZ, $n_{ED} = 3$ ADD $G_{KK}$ emission, $n_{ED} = 2$ ADD QBH ( $ij$ ), $n_{ED} = 6$ ADD QBH ( $e\mu$ ), $n_{ED} = 4$ ADD QBH ( $e\tau$ ), $n_{ED} = 4$ ADD QBH ( $\mu\tau$ ), $n_{ED} = 4$ RS $G_{KK}(\ell\ell)$ , $k/\overline{M}_{PI} = 0.1$ RS $G_{KK}(q\bar{q}, gg)$ , $k/\overline{M}_{PI} = 0.1$ RS $G_{KK}(q\bar{q}, gg)$ , $k/\overline{M}_{PI} = 0.1$ RS QBH (jj), $n_{ED} = 1$ non-rotating BH, $M_D = 4$ TeV, $n_{ED} = 6$ 3-brane WED $g_{KK}(\phi + g \rightarrow ggg)$ , $g_{grav} = 6$ , $g_{g_{KK}} = 3$ , $\varepsilon = 0.5$ , $m(\phi)/m(g_{KK}) = 0.1$ $m(split-UED, \mu \ge 2$ TeV	M		$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	709 ( <b>e</b> τ) 09 ( <b>μ</b> τ) 5 (2 <i>l</i> ) 03.08030 (2j) < <u>9.7</u> 1805.06013 (≥ 7j( <i>l</i> , γ))	36 36 10 36 13 13 14 36 13 36 36 13 13
excited light quark (qg), $\Lambda = m_q^*$ excited electron, $f_S = f = f' = 1$ , $\Lambda = m_e^*$ excited muon, $f_S = f = f' = 1$ , $\Lambda = m_\mu^*$	M M M		0.5-6.3         0.25-3.9       1811.03052 (γ + 2e)         0.25-3.8       1811.03052 (γ + 2μ)		13 30 30
$\begin{split} & \nu \text{MSM},  V_{eN} ^2 = 1.0, \  V_{\mu N} ^2 = 1.0 \\ & \nu \text{MSM},  V_{eN}V_{\mu N}^* ^2/( V_{eN} ^2 +  V_{\mu N} ^2) = 1.0 \\ & \text{Type-III seesaw heavy fermions, Flavor-democratic} \\ & \text{Vector like taus, Doublet} \\ & \text{Vector like taus, Singlet} \end{split}$	M M M M M 0.125-0.1	0.1-0.98 0.1-1.045	0.001-1.431802.02965; 1806.10905 ( $3l(\mu, e)$ ; $\geq 1j + 2l(\mu, e)$ )0.02-1.61806.10905 ( $\geq 1j + \mu + e$ )2202.08676 ( $3l, \geq 4l, 1\tau + 3l, 2\tau + 2l, 3\tau + 1l, 1\tau + 2l, 2\tau + 1l$ )2202.08676 ( $3l, \geq 4l, 1\tau + 3l, 2\tau + 2l, 3\tau + 1l, 1\tau + 2l, 2\tau + 1l$ )		36 36 13 13
scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 2 <sup>nd</sup> gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 3 <sup>rd</sup> gen. fermions, $\beta = 1$ scalar LQ (single prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 0, \lambda = 1$ scalar LQ (single prod.), coupling to 3 <sup>rd</sup> gen. fermions, $\beta = 1, \lambda = 1$	M	<0.75 CMS-PAS	<1.44		36 36 37 36 13 10 13
$Z_{D}, \text{ narrow resonance}$ $Z_{D}, \text{ narrow resonance}$ $SSM Z'(ll)$ $SSM Z'(q\bar{q})$ $Z'(q\bar{q})$ $LfV Z', BR(e\mu) = 10\%$ $LFV Z', BR(e\tau) = 10\%$ $LFV Z', BR(\mu\tau) = 10\%$ $LFV Z', BR(\mu\tau) = 10\%$ $Leptophobic Z'$ $SSM W'(l\nu)$ $SSM W'(\tau\nu)$ $SSM W'(\tau\nu)$	M       0.0115-0.075       1912.0         M	04776 ( <b>2</b> μ) 0.11–0.2 1912.04776 ( <b>2</b> μ) 1905.10331 ( <b>1</b> j, 1γ) 0.05–0.45 1909.04114 ( <b>2</b> j)	0.2-5.15 2103.02 0.5-2.9 1911.03947 ( <b>2j</b> ) 0.2-4.6 2103.02708 0.2-5 2205.067 0.2-4.3 2205.06709 ( <b>et</b> ) 0.2-4.1 2205.06709 ( <b>μt</b> ) 0.4-5.7 220 0.6-4.8 CMS-PAS-E 0.5-3.6 1911.03947 ( <b>2j</b> ) <5 2112.039	2e, 2μ) D9 (eμ) ) 2.06075 (ℓ + p_T <sup>miss</sup> ) (O-21-009 (τ + p_T <sup>miss</sup> )	13 13 14 13 36 14 13 13 13 78 13 13 13 13 13 36
LRSM W <sub>R</sub> ( $\mu$ N <sub>R</sub> ), $M$ <sub>N<sub>R</sub></sub> = 0.5 $M$ <sub>W<sub>R</sub></sub> LRSM W <sub>R</sub> ( $e$ N <sub>R</sub> ), $M$ <sub>N<sub>R</sub></sub> = 0.5 $M$ <sub>W<sub>R</sub></sub> LRSM W <sub>R</sub> ( $\tau$ N <sub>R</sub> ), $M$ <sub>N<sub>R</sub></sub> = 0.5 $M$ <sub>W<sub>R</sub></sub> Axigluon, Coloron, $cot\theta = 1$	M M M M		<pre>&lt;4,7 2112.03949 &lt;3.5 1811.00806 (2τ + 2j)</pre>		30 30 13

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

mass scale [TeV]