Recent searches for new phenomena with the ATLAS detector

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XIV Latin American Symposium on High Energy Physics, 14 November 2022

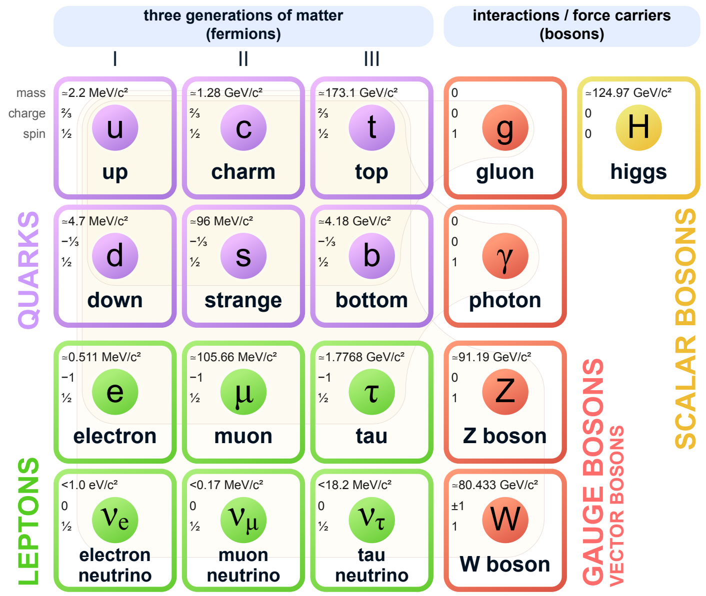
Bourses postdoctorales Banting Postdoctoral Fellowships

UCL

The Standard Model (SM) of Particle Physics

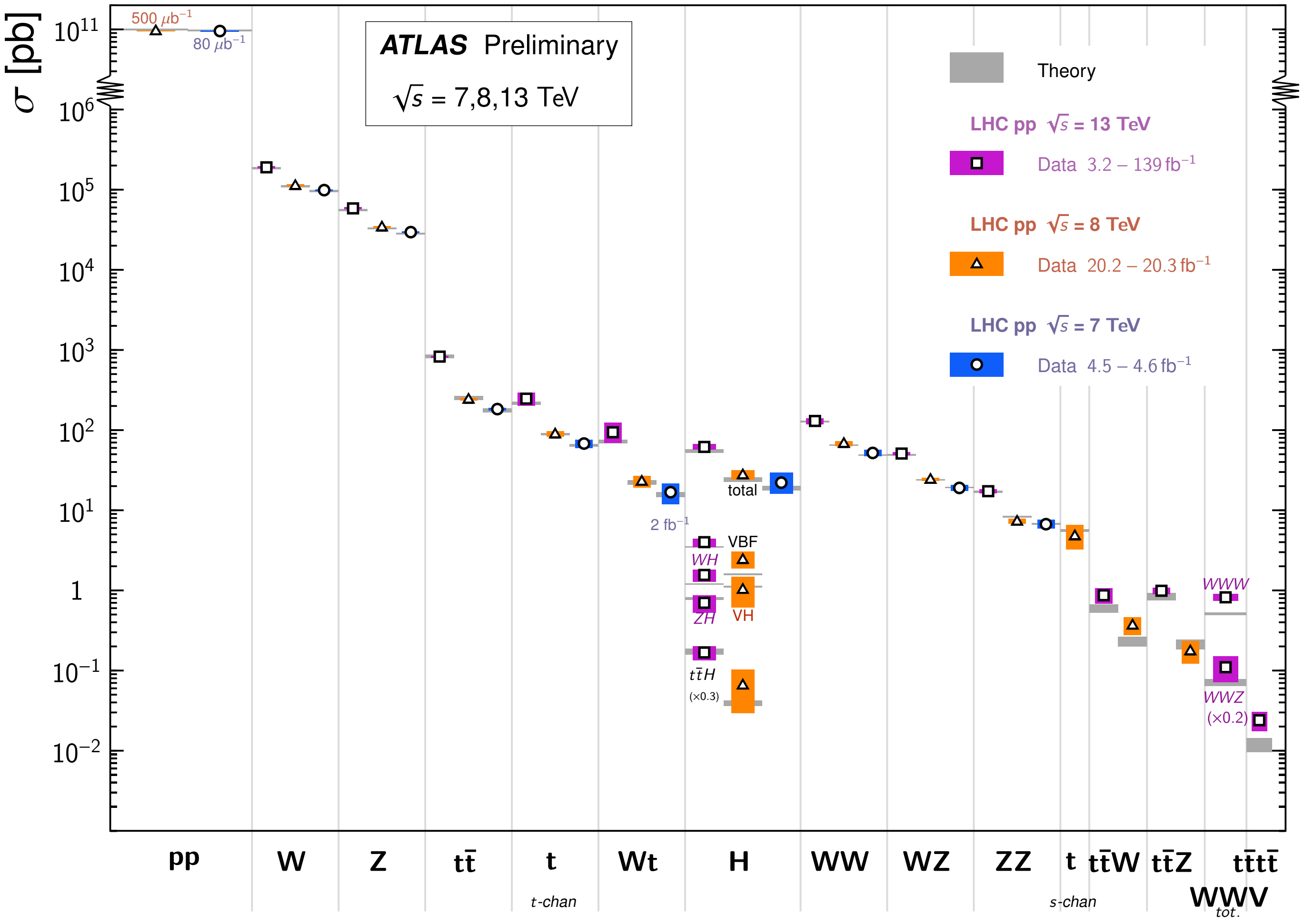
- Excellent description of nature
- **Experimentally verified** to extremely high degrees of precision
- However, known to be **incomplete**

Standard Model of Elementary Particles

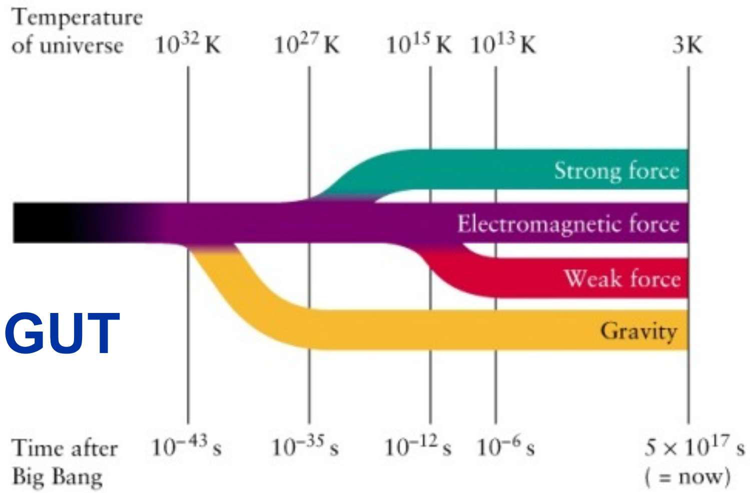


Standard Model Total Production Cross Section Measurements

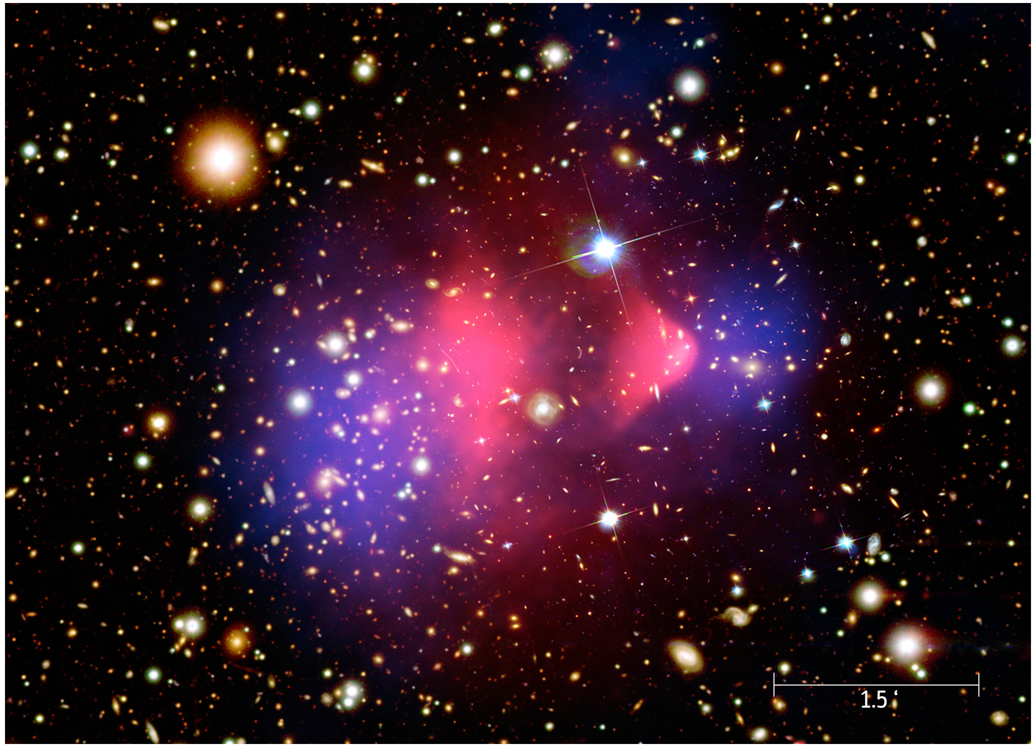
Status: February 2022



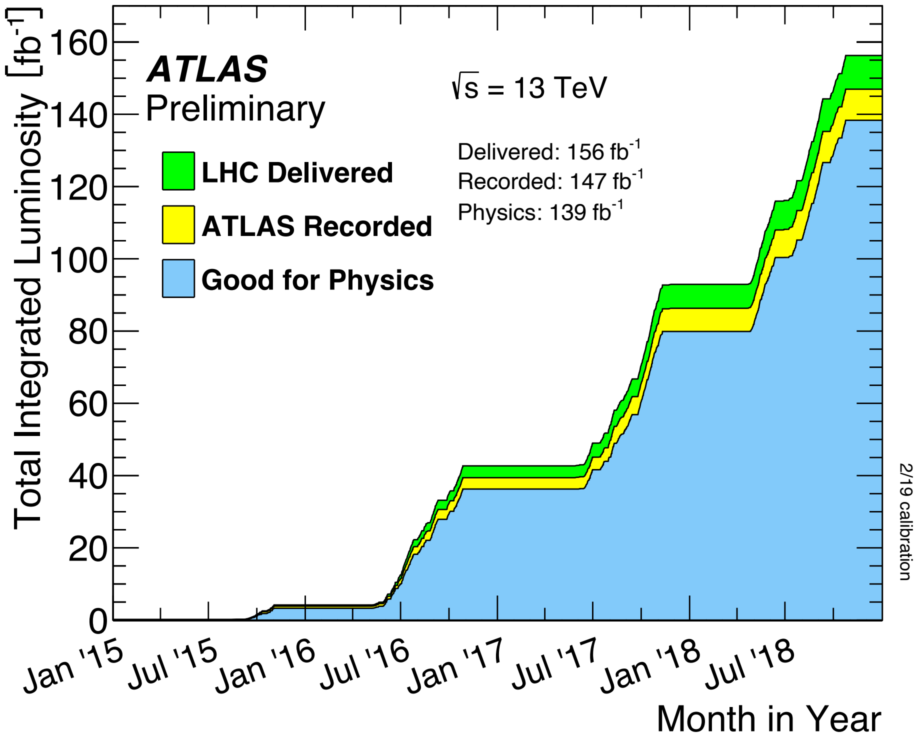
Physics Beyond The Standard Model

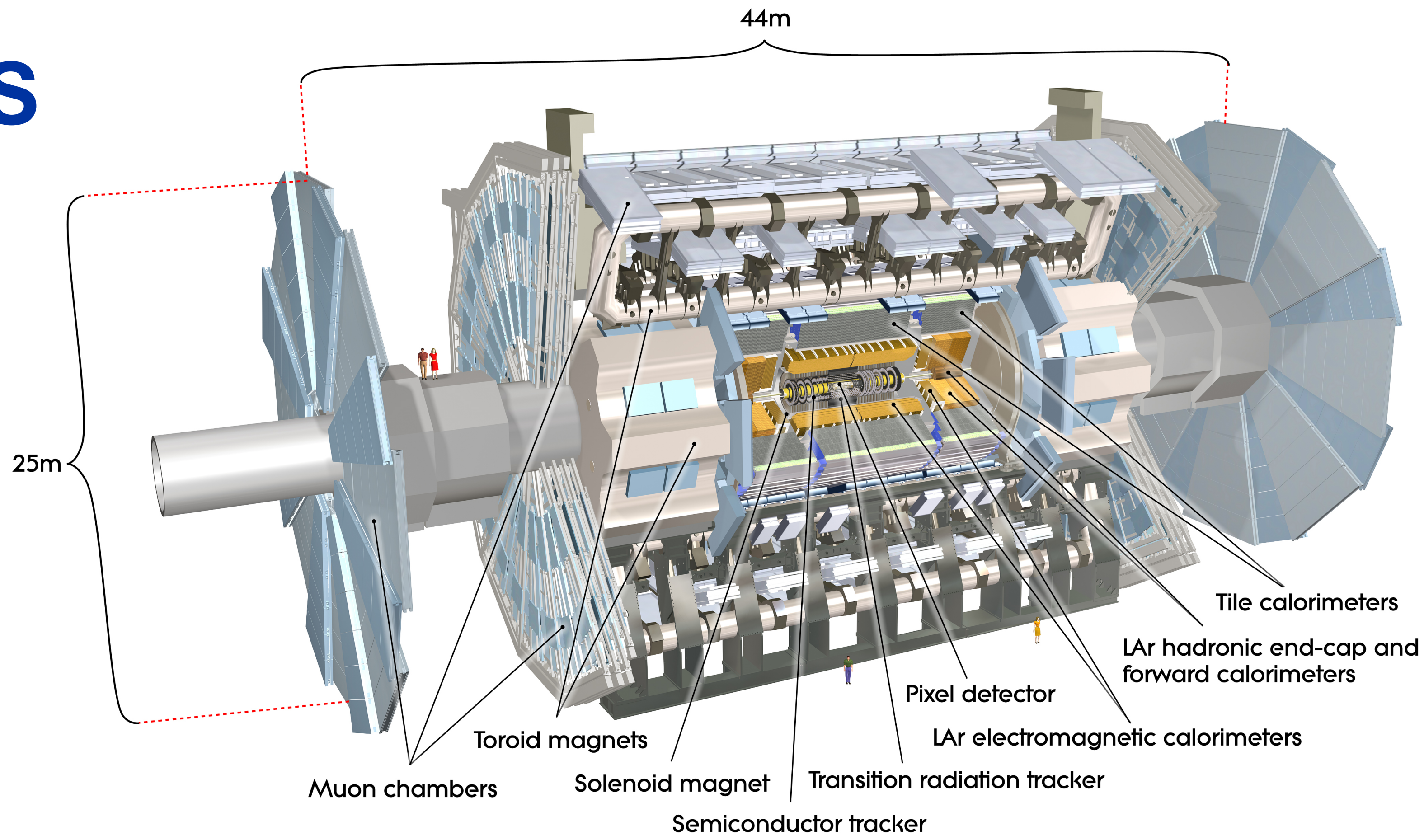


- What is **Dark Matter**?
  - Candidates for Dark Matter could be produced at the LHC
- Grand Unified Theory (GUT)?
  - **Unify all forces** to a super force
- Are there **extra dimensions** of space?
  - Could explain why gravity is so weak
- Explore the unknown
  - Surprises can happen at any time



The LHC and ATLAS





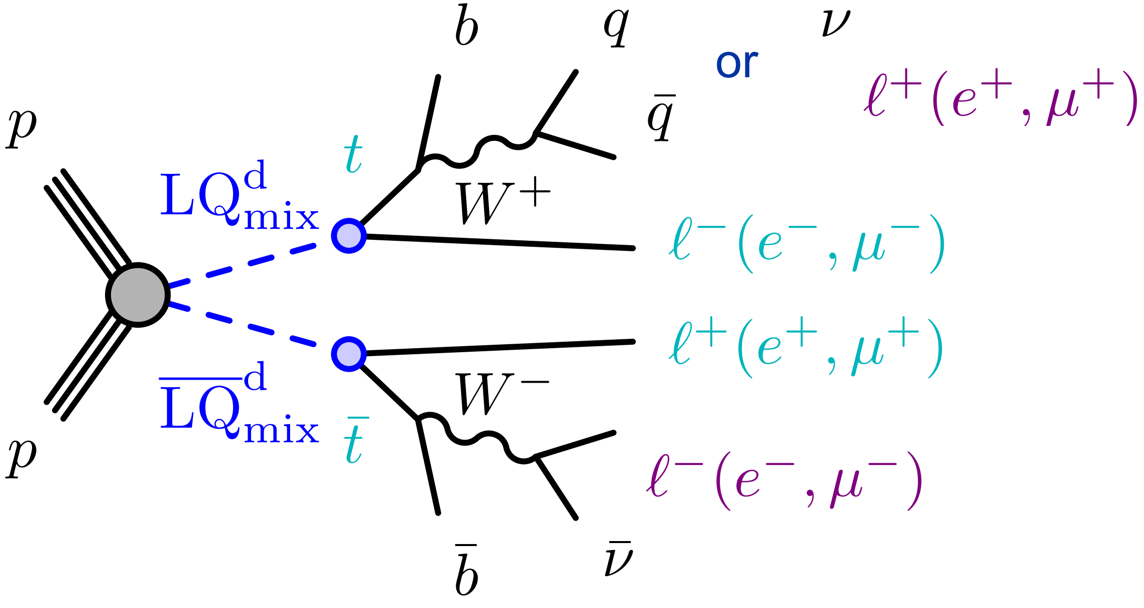
- The LHC is **performing very well overall**
- Achieved and surpassed design instantaneous luminosity

- Over 139 fb^{-1} of *pp* data recorded by ATLAS at $\sqrt{s} = 13$ TeV

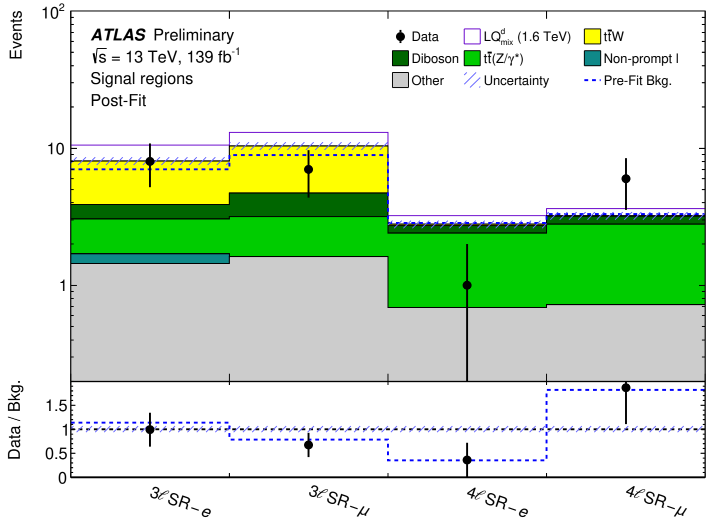
Results Covered Today

- Several exciting results searching for BSM physics in ATLAS
- Focusing on **latest relevant results** for this talk
- **Leptoquarks** (LQ) couple to both leptons and quarks
  - Pair produced
  - Singly produced: scalar leptoquarks in the $b\tau\tau$ final state
- **Vector-like leptons** (VLL) and **vector-like quarks** (VLQ) couple to both vector bosons and leptons/quarks
- **Generic searches**: lepton + 2 jets
- **Dark matter**: semi-visible jets (SVJ), particles invisible to the ATLAS detector

Pair-produced Leptoquarks

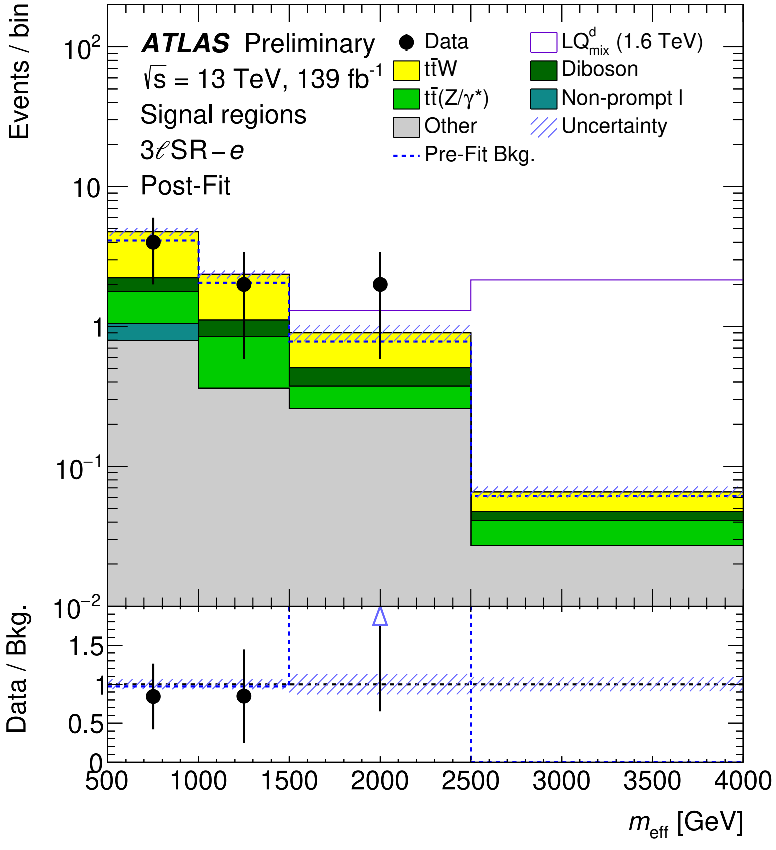


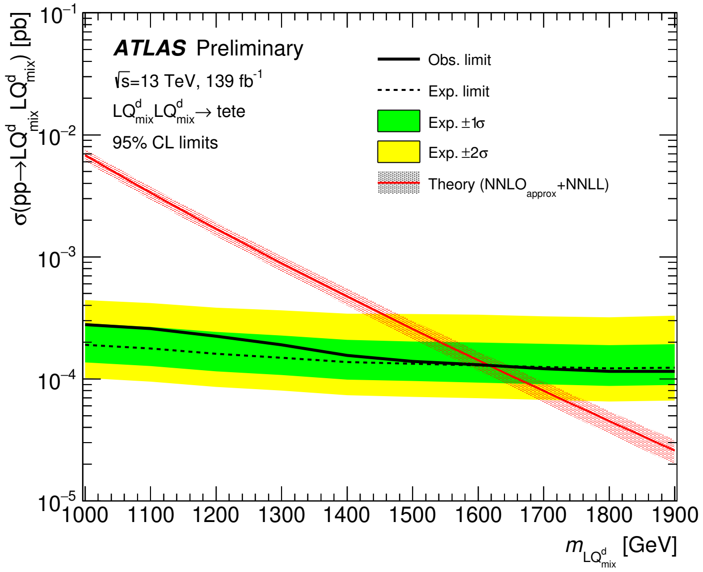
- Searching for down-type **scalar** LQ with cross-generational decays $\mathrm{LQ}^{\mathrm{d}}_{\mathrm{mix}}$ and **vector** LQ $\tilde{U}_1$
- Final state: $\mathrm{LQLQ} \rightarrow t\ell t\ell$ (multileptons)
- Require **two or more light leptons** (e or μ) and at least two jets (at least one of which is identified as coming from a *b*-hadron)
- Main backgrounds: $t\bar{t}$ production in association with a vector boson, and diboson production

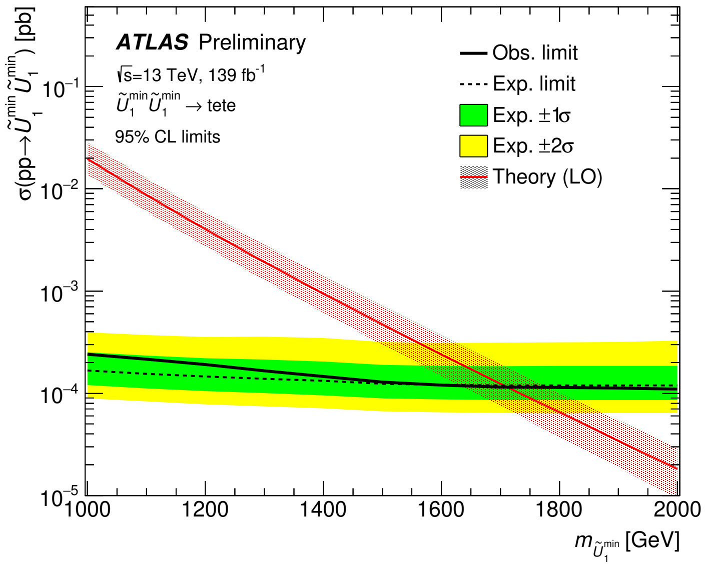


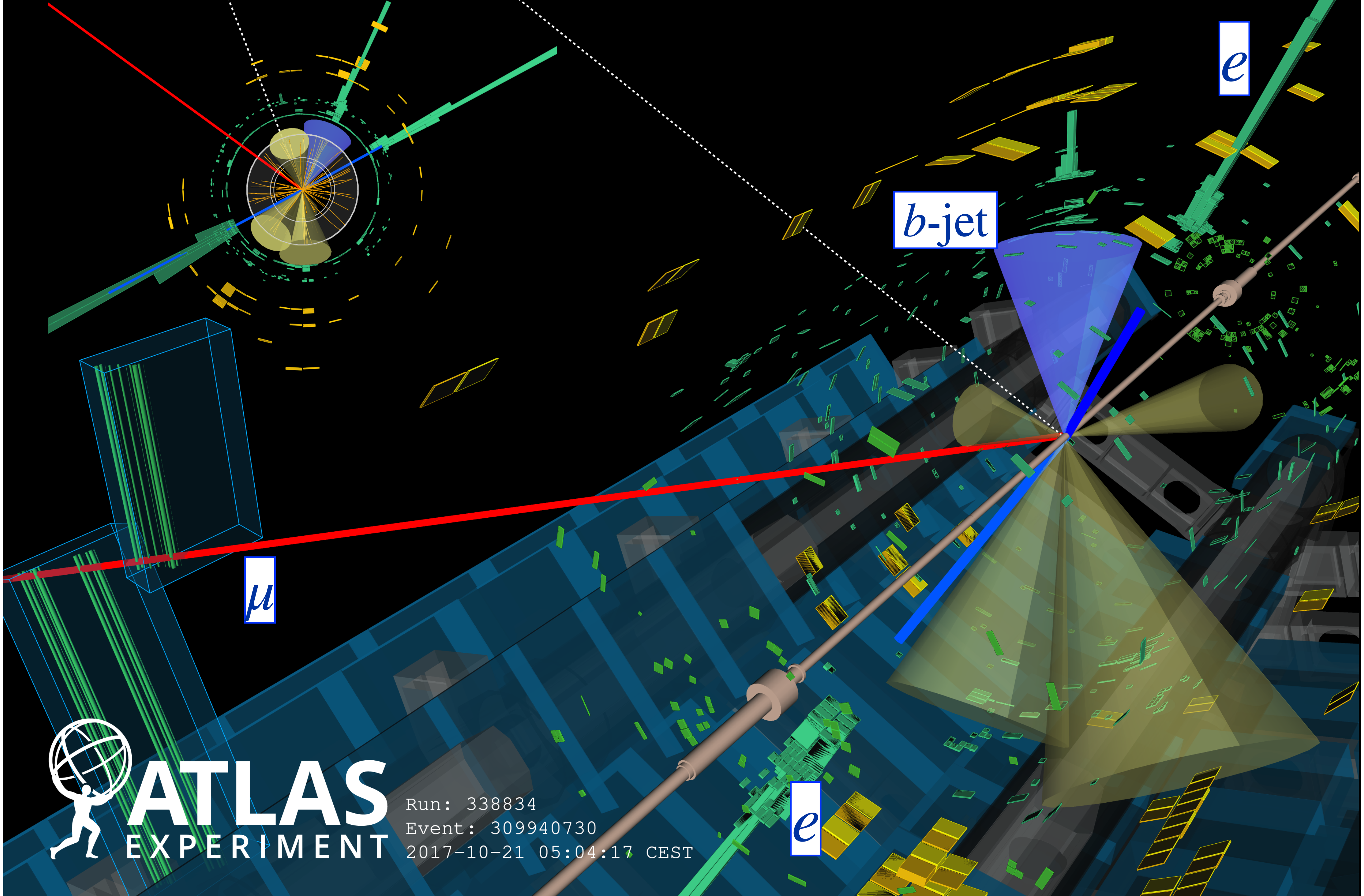
Pair-produced Leptoquarks Results

- **Effective mass** (m_{eff}) used as discriminating variable: sum of p_T of light leptons and jets and E_T^{miss}
- Additional background-enriched categories are used in the fit to improve the modelling of several leading backgrounds
- For LQ decaying to te $(t\mu)$, masses excluded up to
  - 1.6 TeV (1.64 TeV) for **scalar** LQ
  - 1.71 TeV (1.73 TeV) for **vector** LQ $\tilde{U}_1$ in **minimal coupling** scenario
  - 2.0 TeV (2.0 TeV) for **vector** LQ $\tilde{U}_1$ in **Yang-Mills** scenario








e
b-jet
μ
e
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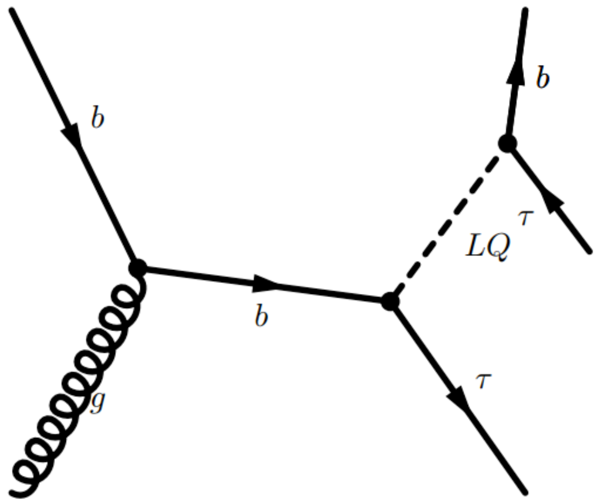
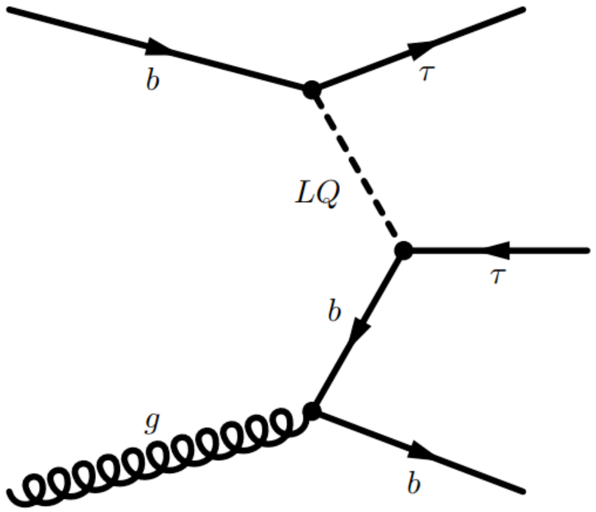
Singly-produced Scalar Leptoquarks

- Final state: $b\tau\tau$
- Select a pair of **opposite charge taus** produced in association with a *b*-tagged jet
- **Two channels**, depending on the decay mode of the τ are considered: $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
- Main backgrounds: $t\bar{t}$, single top-quark, $Z(\rightarrow\tau\tau)+$ jets and multi-jet events





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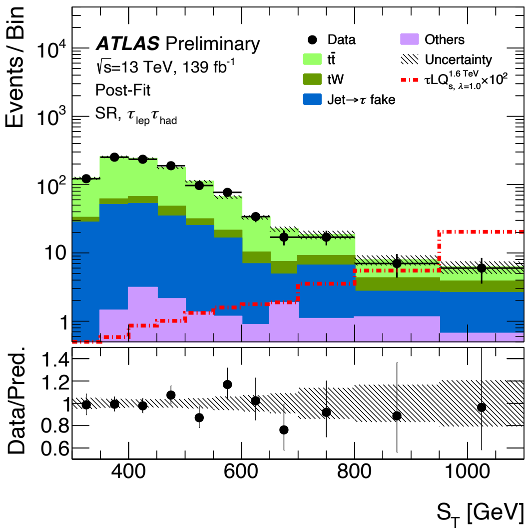
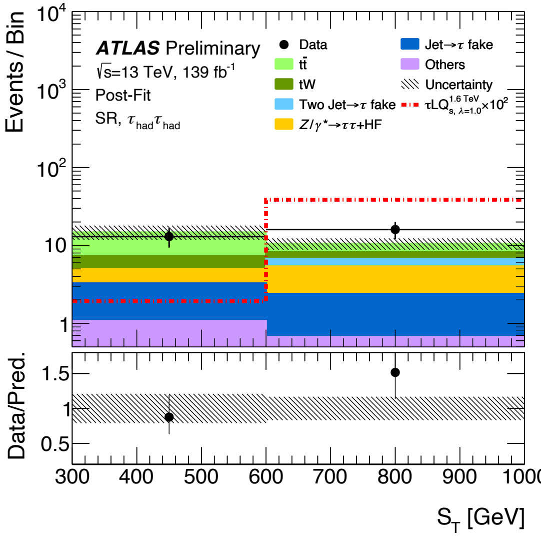
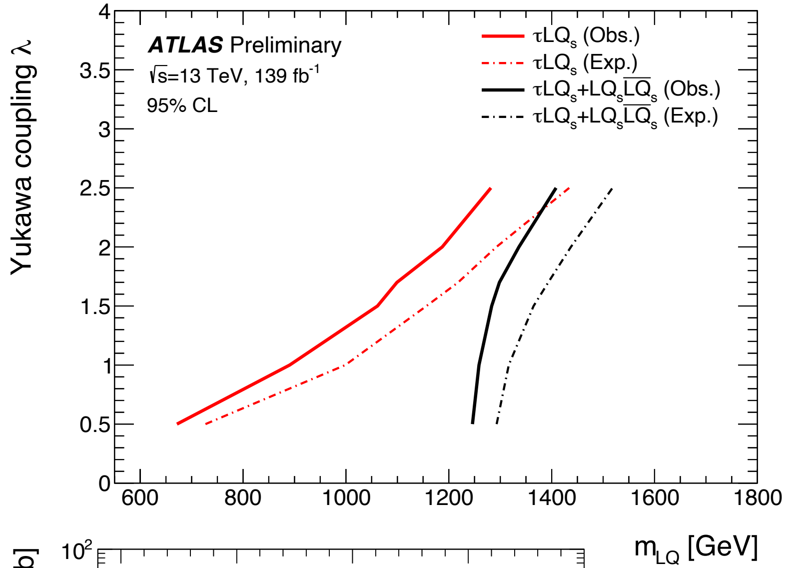
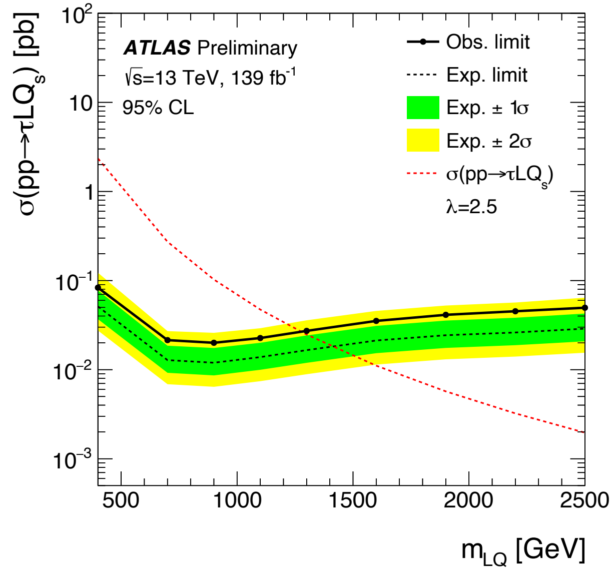
Singly-produced Scalar Leptoquarks Results

- Discriminating variable is S_T: scalar p_T sum of the two τ and leading-p_T b-jet
- Masses of **singly-produced** LQ excluded for various coupling scenarios: 0.89 TeV for $\lambda = 1.0$, 1.01 TeV for $\lambda = 1.7$, and 1.28 TeV for $\lambda = 2.5$, where λ is the LQ to τb Yukawa coupling
- Results also interpreted in the context of the $\tilde{S}_1$ model for **single plus pair LQ production** (LQ+LQLQ)
- Lower observed limits driven by the highest S_T bin in the $\tau_{had}\tau_{had}$ channel



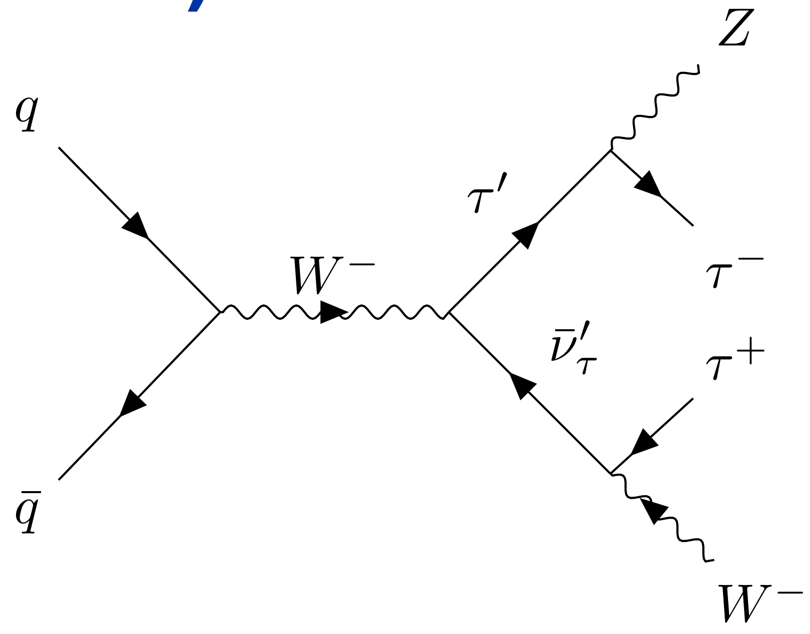






3rd Generation Vector-like Leptons (VLL)

- VLL doublet couple only to **3rd generation leptons**
- Final state: 2, 3, or ≥4 light leptons (e or μ), and zero or more hadronically decaying tau leptons
- Events classified using **Boosted Decision Tree** (BDT)



Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/Flavor	SSSF	SSOF	OSSF	OSOF	-	-	-
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
N_{jet}	> 0						
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60

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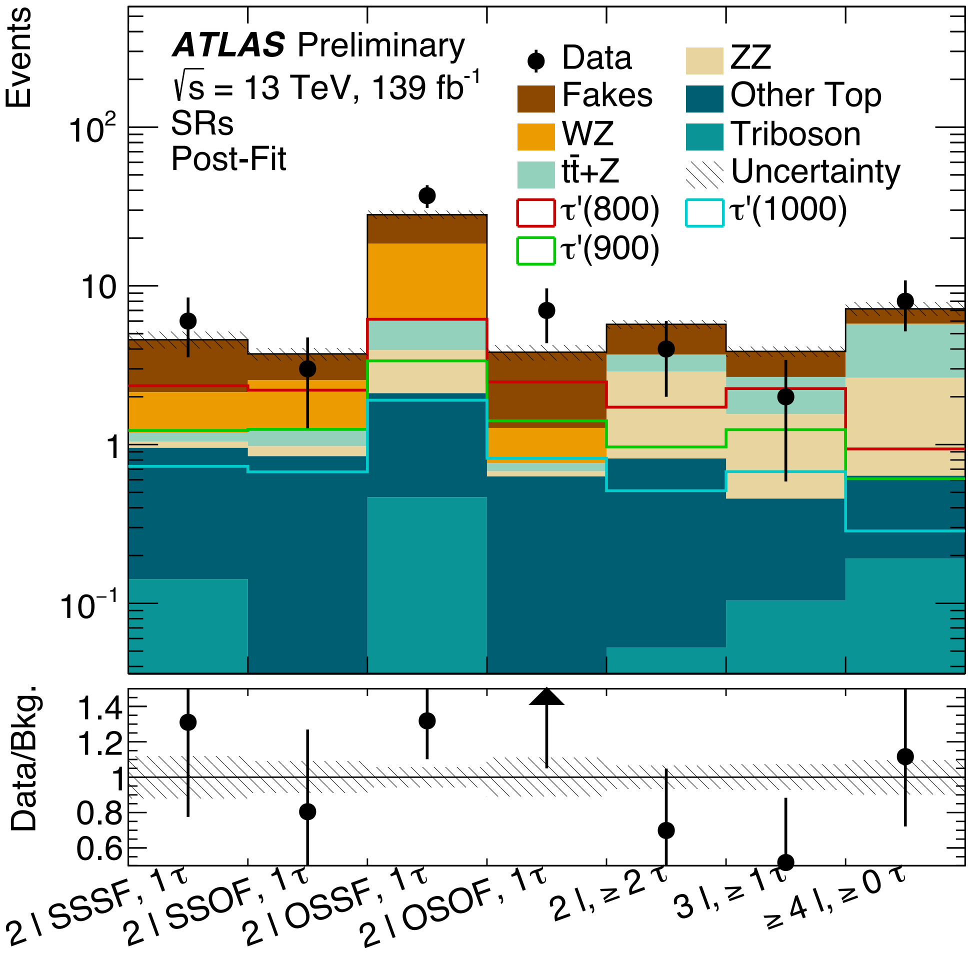
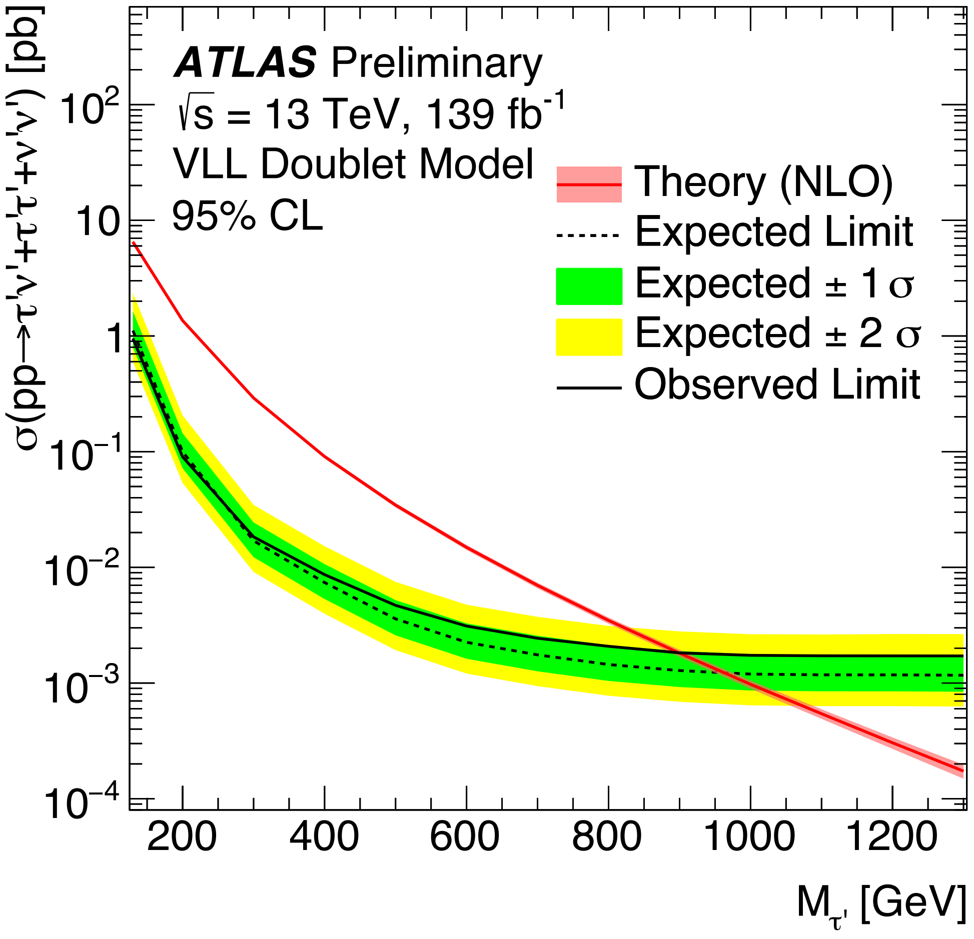
3rd Generation Vector-like Leptons (VLL) Results

- **Seven signal regions** require the same selection as BDT training regions (see previous slide), with an additional cut on the BDT score
- VLL **masses excluded** up to 900 GeV for VLL coupling to 3rd generation SM leptons





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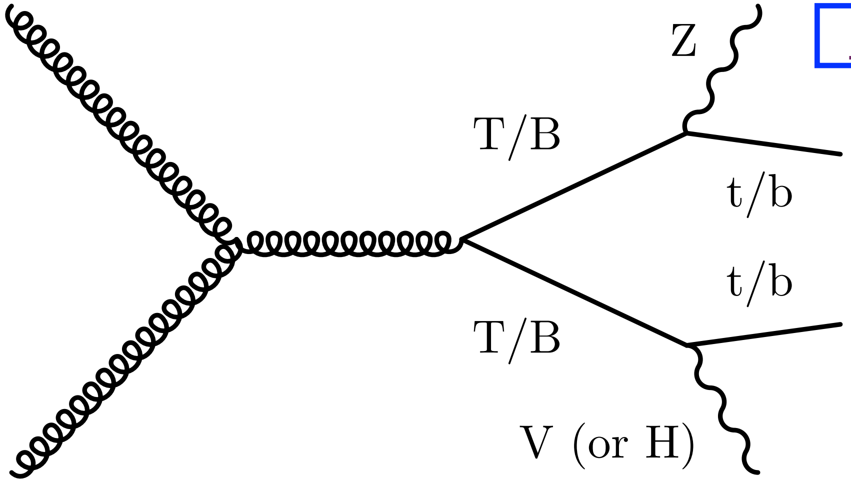
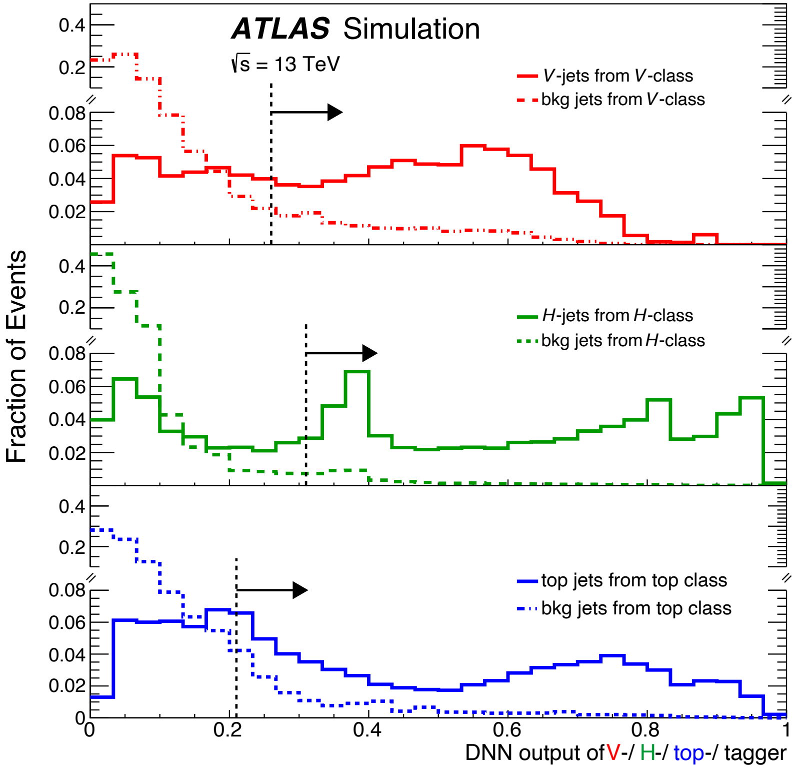
Vector-like Quarks (VLQ)



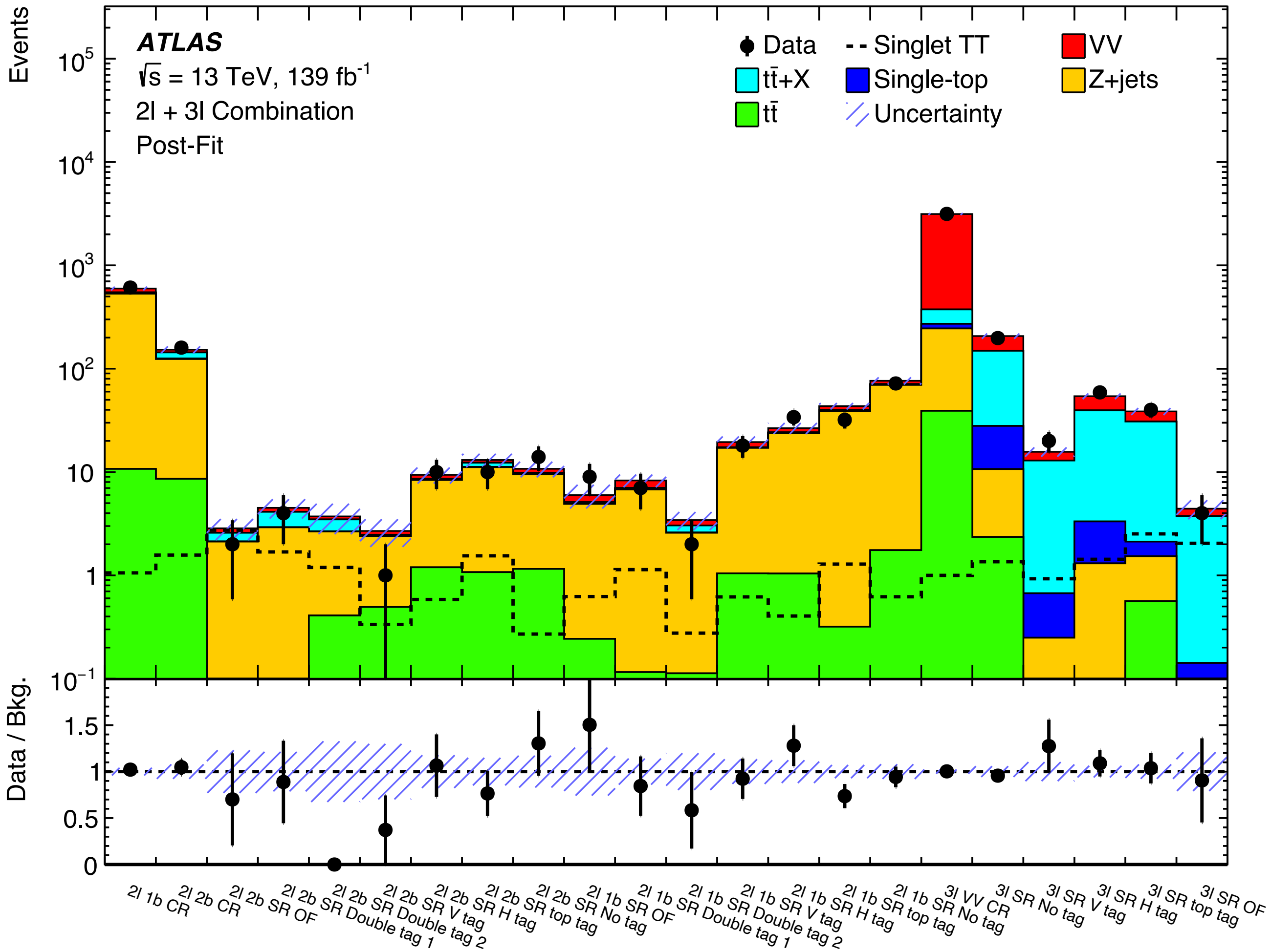
- Search for pair production of VLQ
- Require high-p_T *Z* boson decaying to two same-flavour opposite-sign leptons (e or μ), and at least one *b*-tagged jet
- Additional leptons from the V (W/Z) or H decay define 2-lepton vs ≥3-lepton **channels**
- Deep neural network (DNN) used to classify large-radius jets originating from hadronically decaying Z/W bosons, H boson, or top quark
- 19 fit **categories** based on lepton multiplicity, number of *b*-tagged jets, and DNN tags



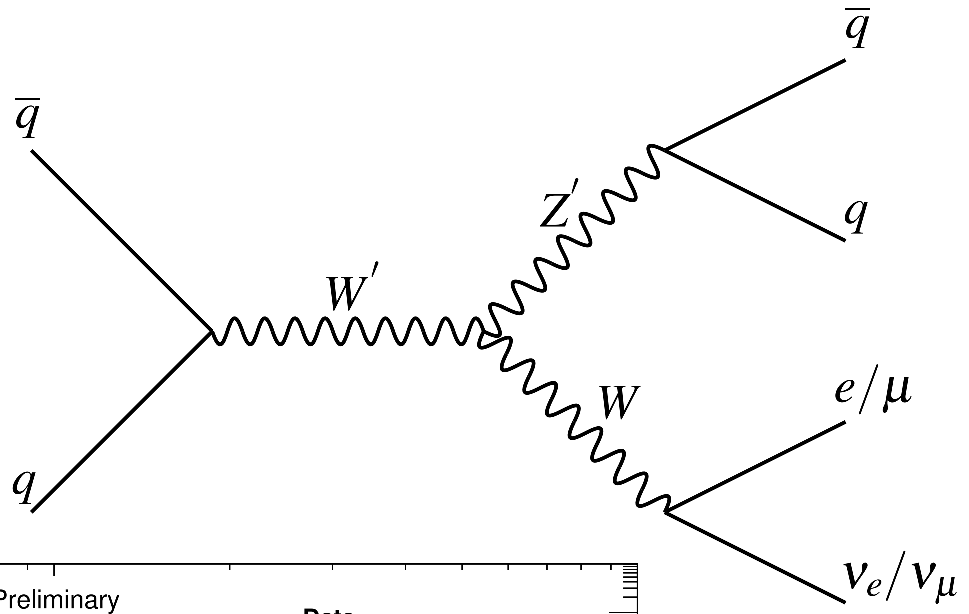
Vector-like Quarks (VLQ) Results

- Binned likelihood fit of the discriminating variables in the categories of each individual channel carried out
- **Limits set** for various VLQ models

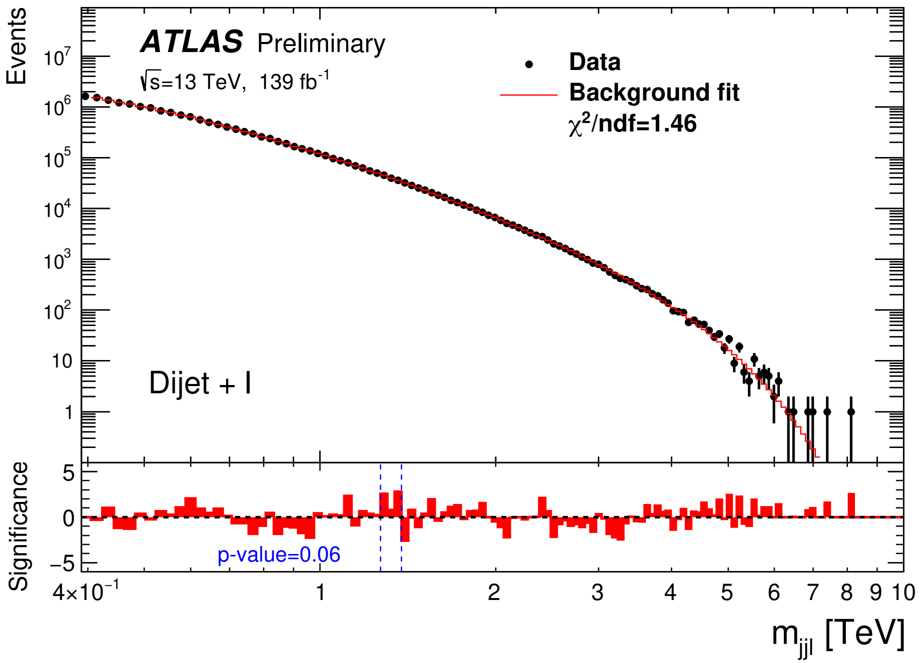
Model	Observed (Expected) Mass Limits [TeV]		
	2ℓ	3ℓ	Combination
$T\bar{T}$ Singlet	1.14 (1.16)	1.22 (1.21)	1.27 (1.28)
$T\bar{T}$ Doublet	1.34 (1.32)	1.38 (1.37)	1.46 (1.44)
$100\%\ T \rightarrow Zt$	1.43 (1.43)	1.54 (1.50)	1.60 (1.56)
$B\bar{B}$ Singlet	1.14 (1.21)	1.11 (1.10)	1.20 (1.25)
$B\bar{B}$ Doublet	1.31 (1.37)	1.07 (1.04)	1.32 (1.38)
$100\%\ B \rightarrow Zb$	1.40 (1.47)	1.16 (1.18)	1.42 (1.48)



Generic Searches

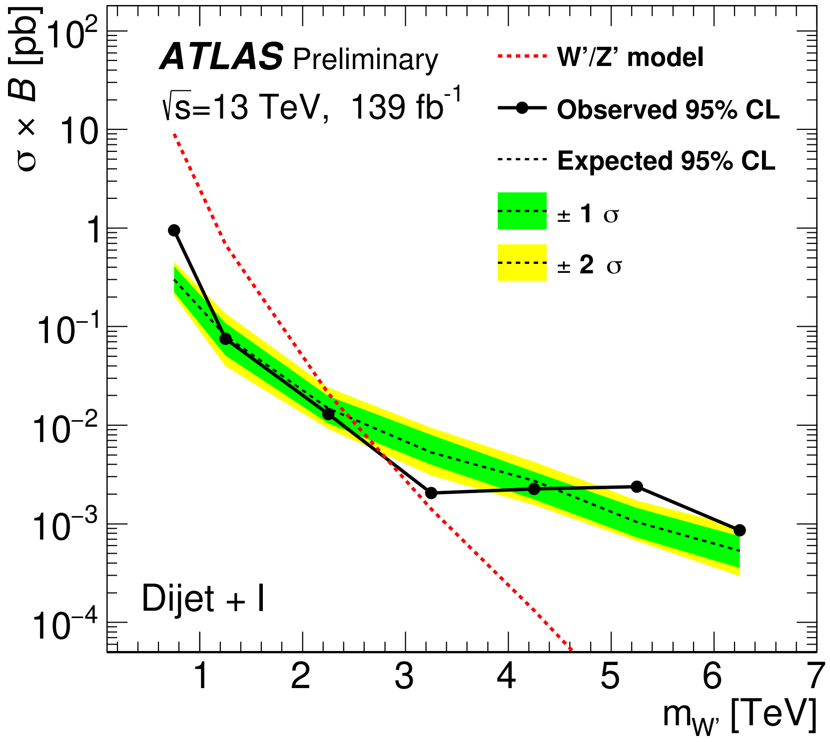


- Final state: at least one light lepton (e or μ) and two jets
- Search for **deviations** from a smoothly falling background hypothesis
- Use three- and four-body invariant mass distributions constructed from leptons and jets: m_{jjl}, m_{jjll}, m_{jbl}, m_{bbl}
- Background is estimated with: $f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x+p_5\ln^2 x}$, where $x \equiv m/\sqrt{s}$ and p_i are free parameters
- **No significant excess** observed above the background expectation

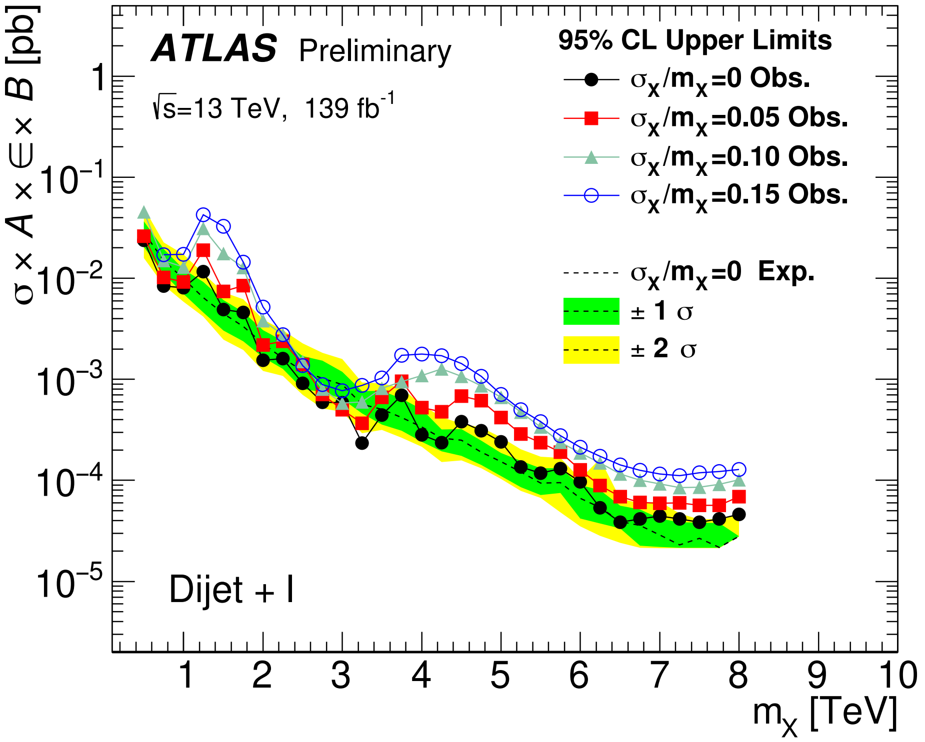


Generic Searches Results

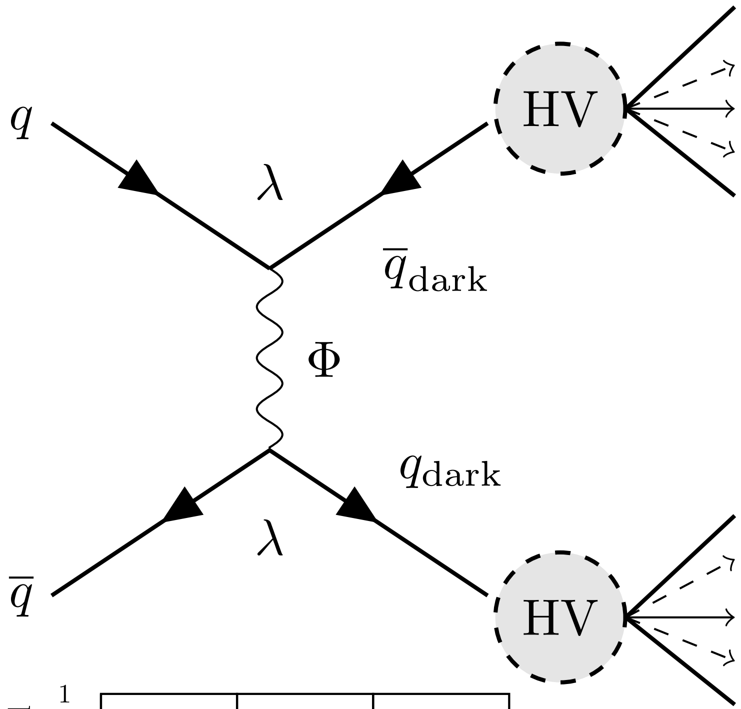
- Limits set on **BSM models**, e.g. the sequential standard model (same couplings as the SM, but larger masses for W'/Z' bosons)



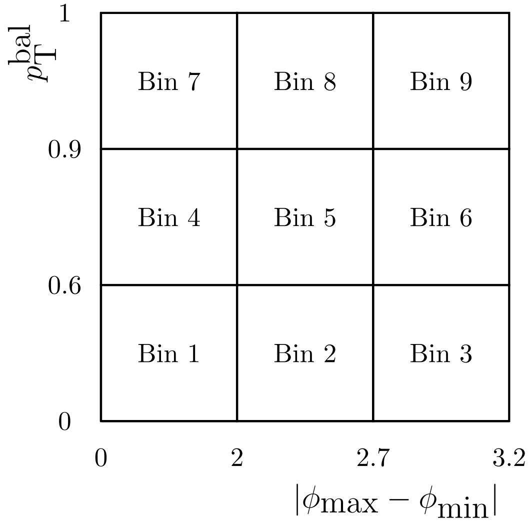
- Model-independent limits also provided for **generic Gaussian-like signals** with different widths



Semi-visible Jets (SVJ)

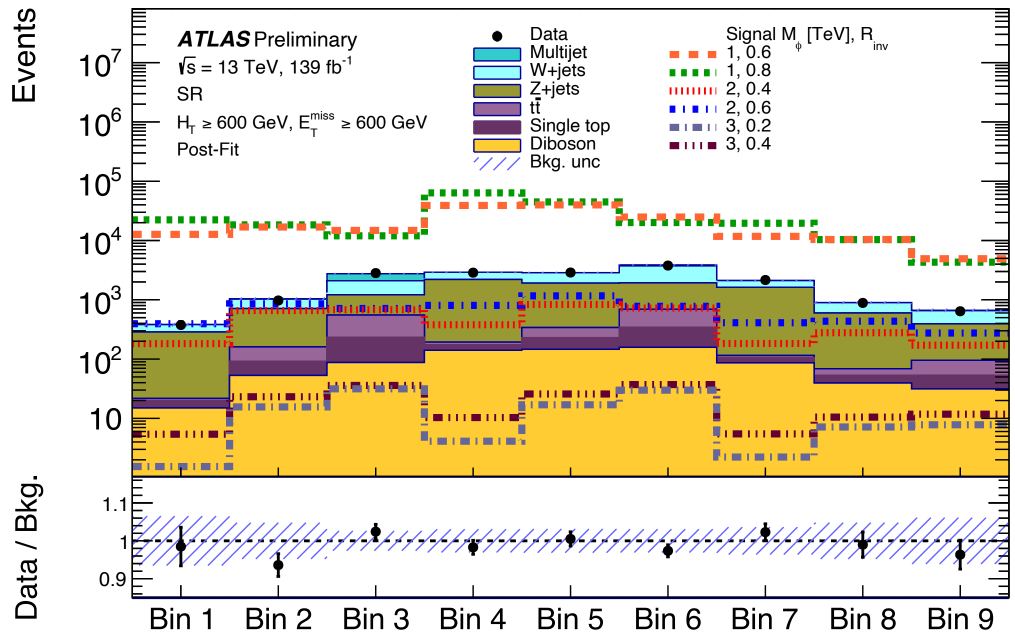


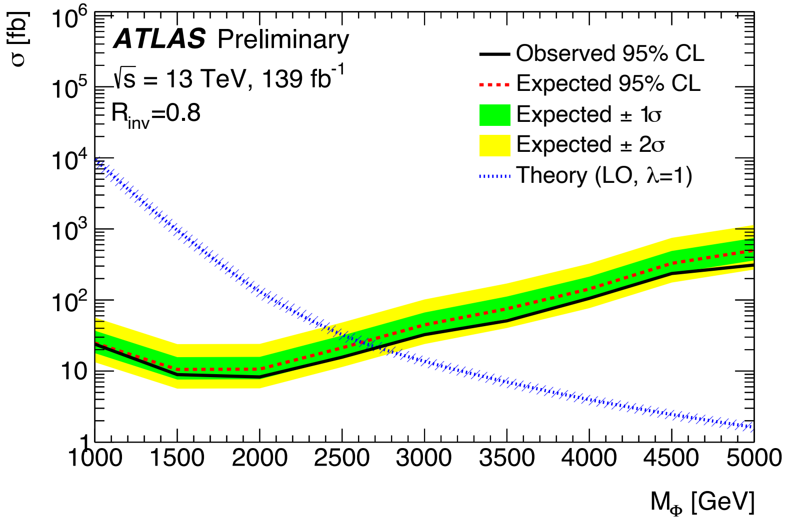
- Semi-visible jets signature can arise in strongly-interacting dark sectors
- Final state: SM hadrons and dark hadrons produced by **t-channel mediator Φ**
- `Pythia8` **Hidden Valley** (HV) module used to simulate interactions connecting the dark sector with the SM sector
- Search exploits two largely uncorrelated variables:
  - $$p_{\mathrm{T}}^{\mathrm{bal}} = \frac{\left|\vec{p}_{\mathrm{T}}(j_1) + \vec{p}_{\mathrm{T}}(j_2)\right|}{\left|\vec{p}_{\mathrm{T}}(j_1)\right| + \left|\vec{p}_{\mathrm{T}}(j_2)\right|}$$
  - Difference in the azimuthal angle between j_1 and j_2: $\left|\phi_{\max} - \phi_{\min}\right|$

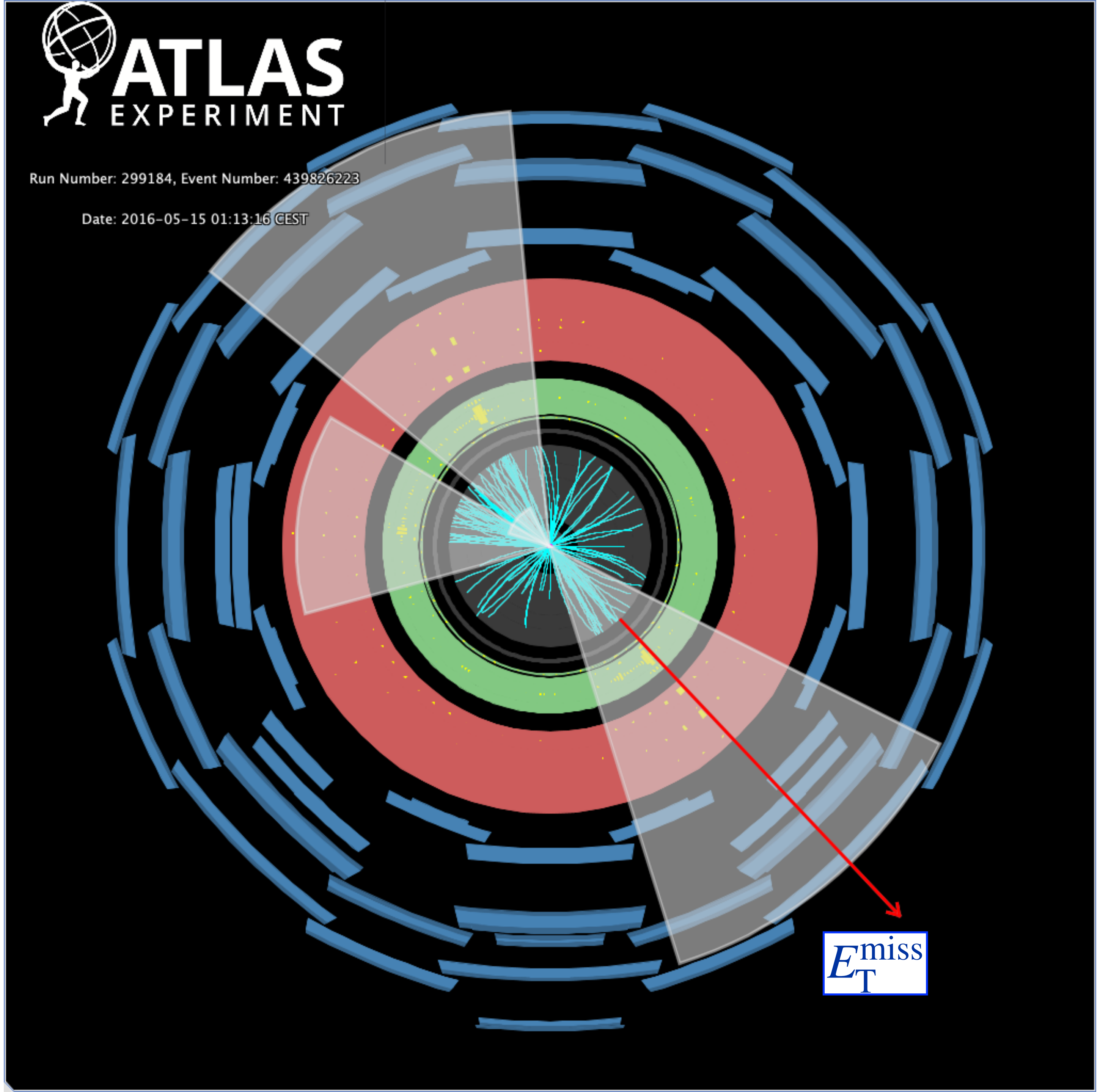


Semi-visible Jets (SVJ) Results

- **Signal region** requires $E_T^{miss} \geq 600$ GeV and $H_T \geq 600$ GeV, with H_T being the scalar sum of jet p_T
- **Control regions**, used to estimate backgrounds more accurately, require additional selections:
  - **1L** (W+jets): exactly one μ, no *b*-tagged jet
  - **1L1B** ($t\bar{t}$ and single top): exactly one μ, exactly one *b*-tagged jet
  - **2L** (Z+jets): two opposite charged μ with invariant mass between 66 GeV and 116 GeV, no *b*-tagged jet
- Upper limits on mediator mass range from 2.4 TeV to 2.7 TeV, depending on the values of $R_{\text{inv}} = \left\langle \frac{\text{\# of stable hadrons}}{\text{\# of hadrons}} \right\rangle$



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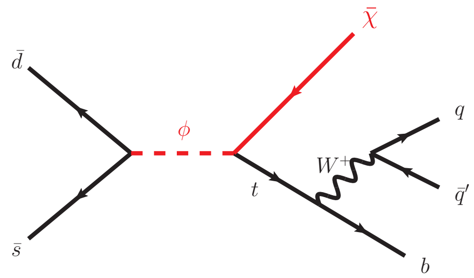
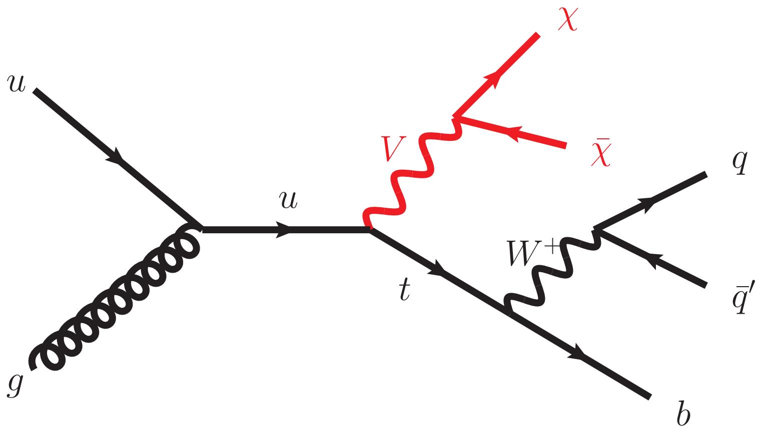
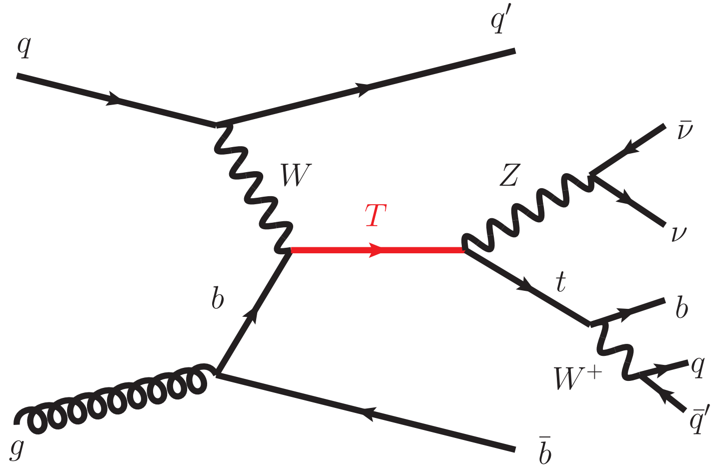
E_T^{miss}

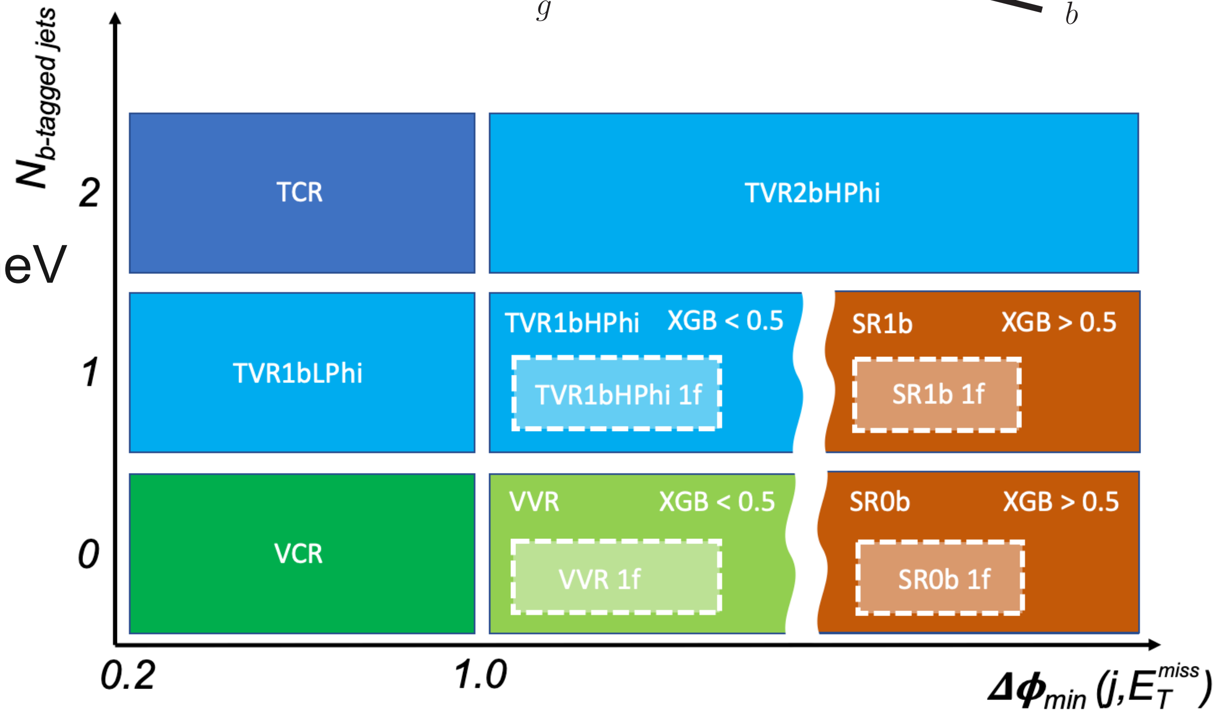
Invisible Particles





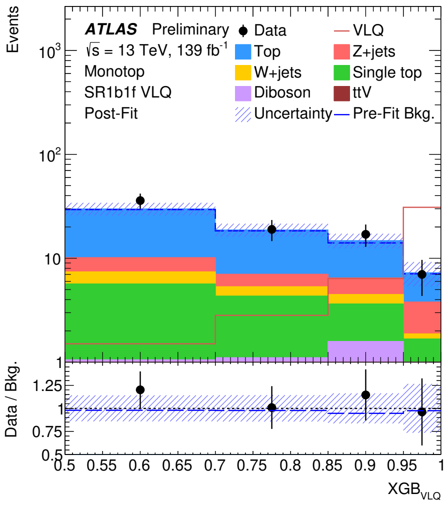


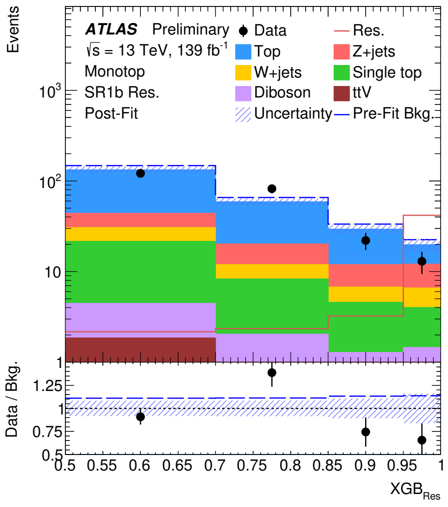
- Final state: top quark and missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$)
- Require lepton veto, $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV, and at least one top-tagged large-R jet with $p_{\mathrm{T}} \in [350{,}2500]$ GeV and mass $\in [40{,}600]$ GeV
- Exploit event topology by reconstructing **boosted top quark** from decay products
- "T" $\rightarrow t\bar{t}$, "V" $\rightarrow V +$ jets, "f" $\rightarrow$ forward jet

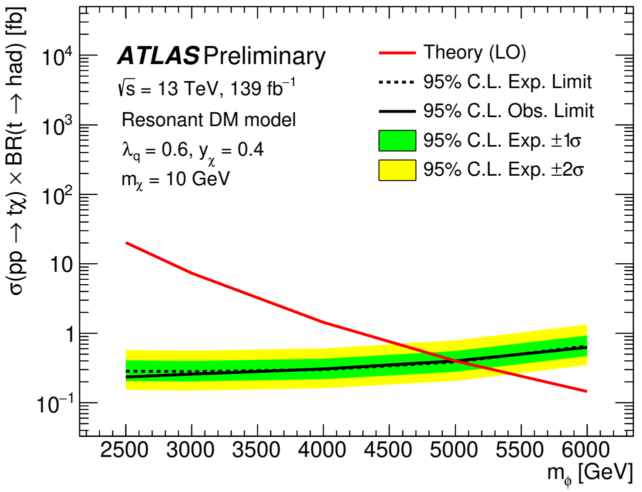


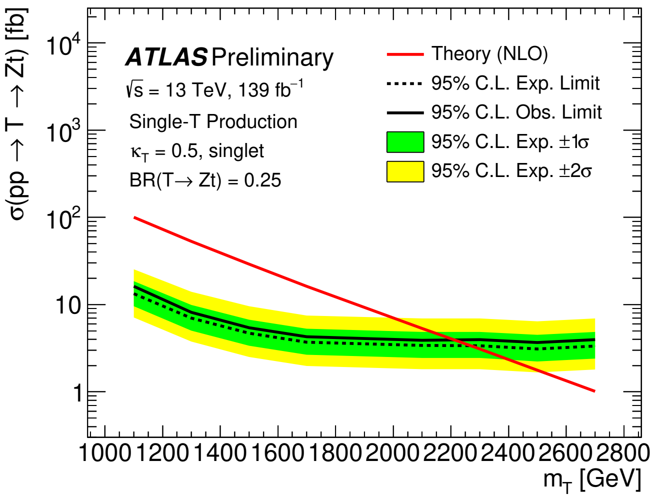
Invisible Particles Results

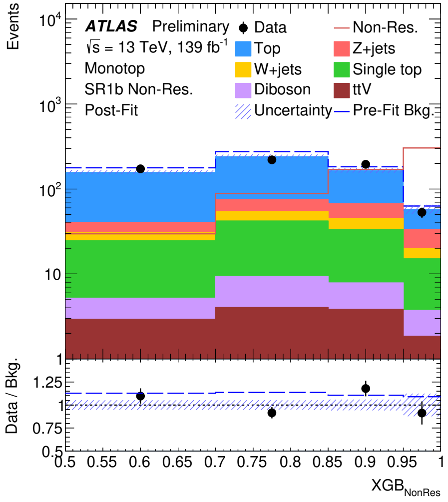
- XGBoost used to discriminate signal from background
- **SR0b** expected to account for *b*-tagging inefficiencies, **increasing signal selection** efficiency by 30 to 60%
- **VLQ** masses excluded up to 2.2 TeV assuming coupling to the top quark $\kappa_T = 0.5$ and branching ratio for $T \rightarrow Zt$ of 25%
- **Dark Matter** candidate masses excluded for scalar (vector) mediators up to 5.0 (2.8) TeV assuming a resonant (non-resonant) model

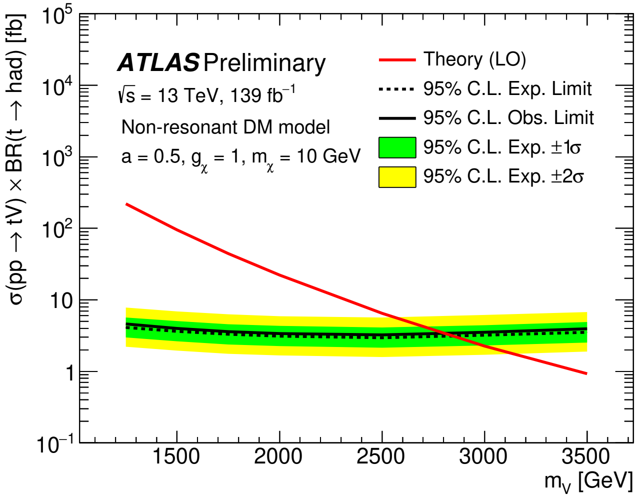












A Promising Road Ahead

- **Broad physics programme** searching for new phenomena with ATLAS; many searches not covered today!
- So far, **no significant deviation** from the Standard Model expectation
- Run 3 data currently being collected; expect **new results soon**!

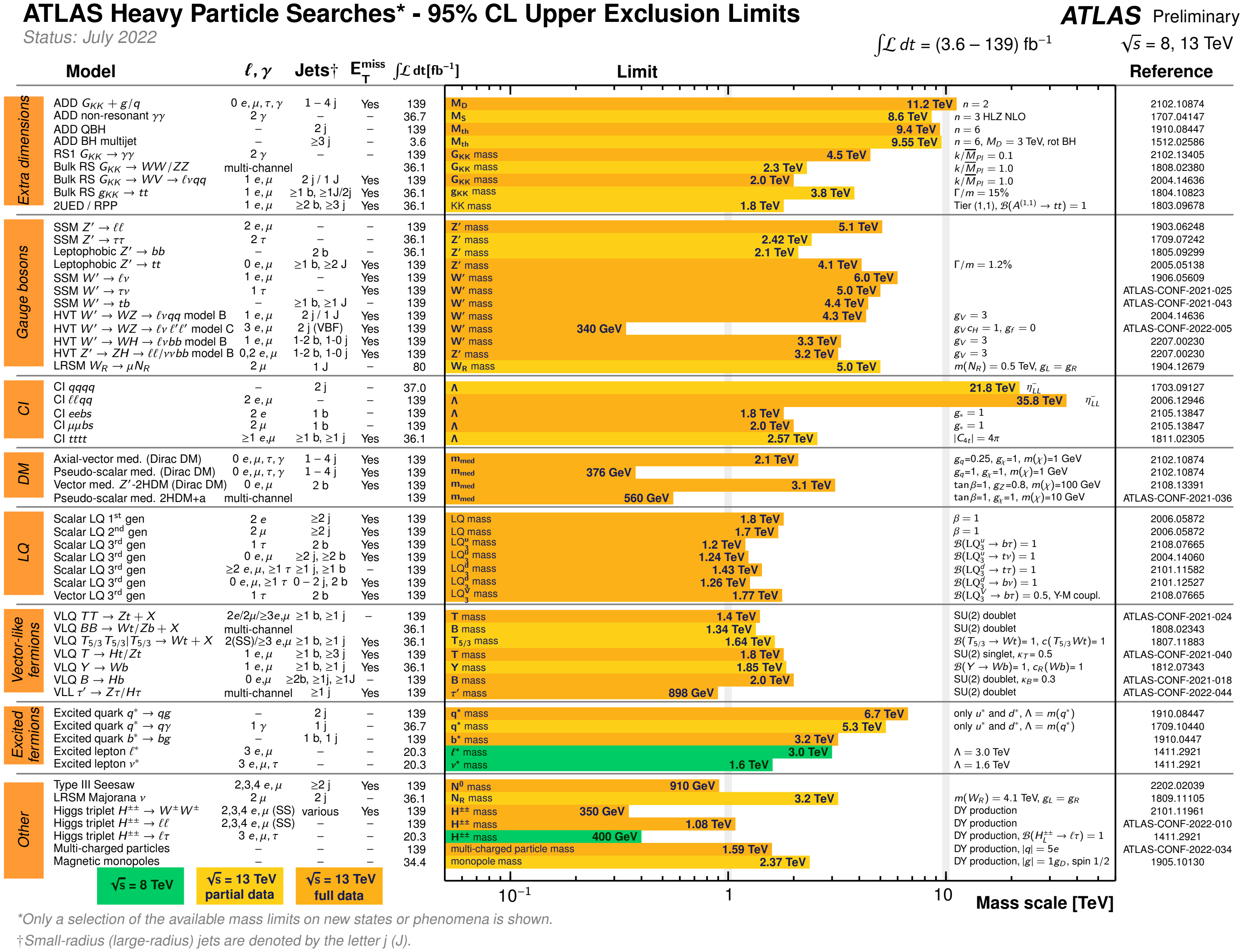
Thank you!
Merci!

Questions?

Bourses postdoctorales Banting
Postdoctoral Fellowships

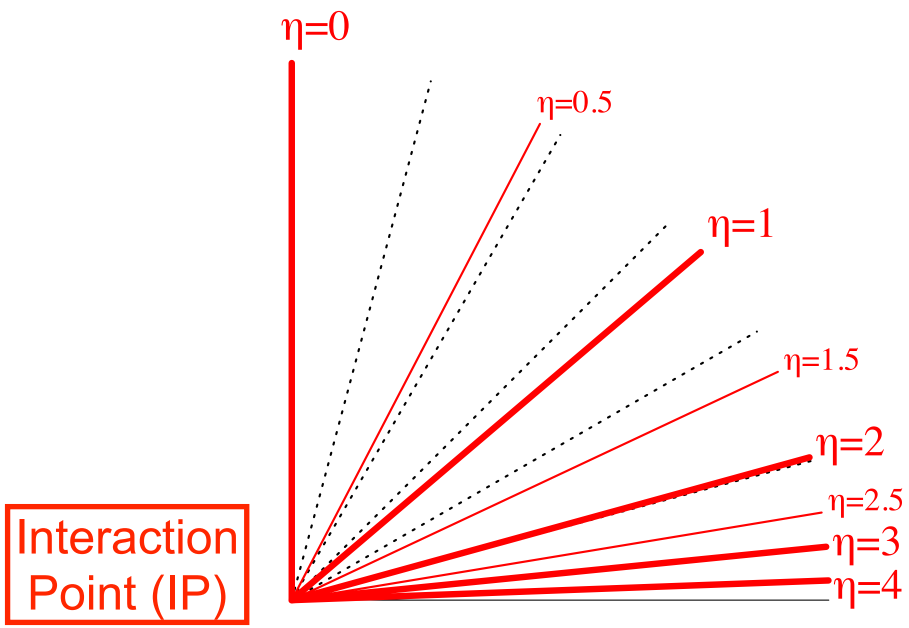
UCL

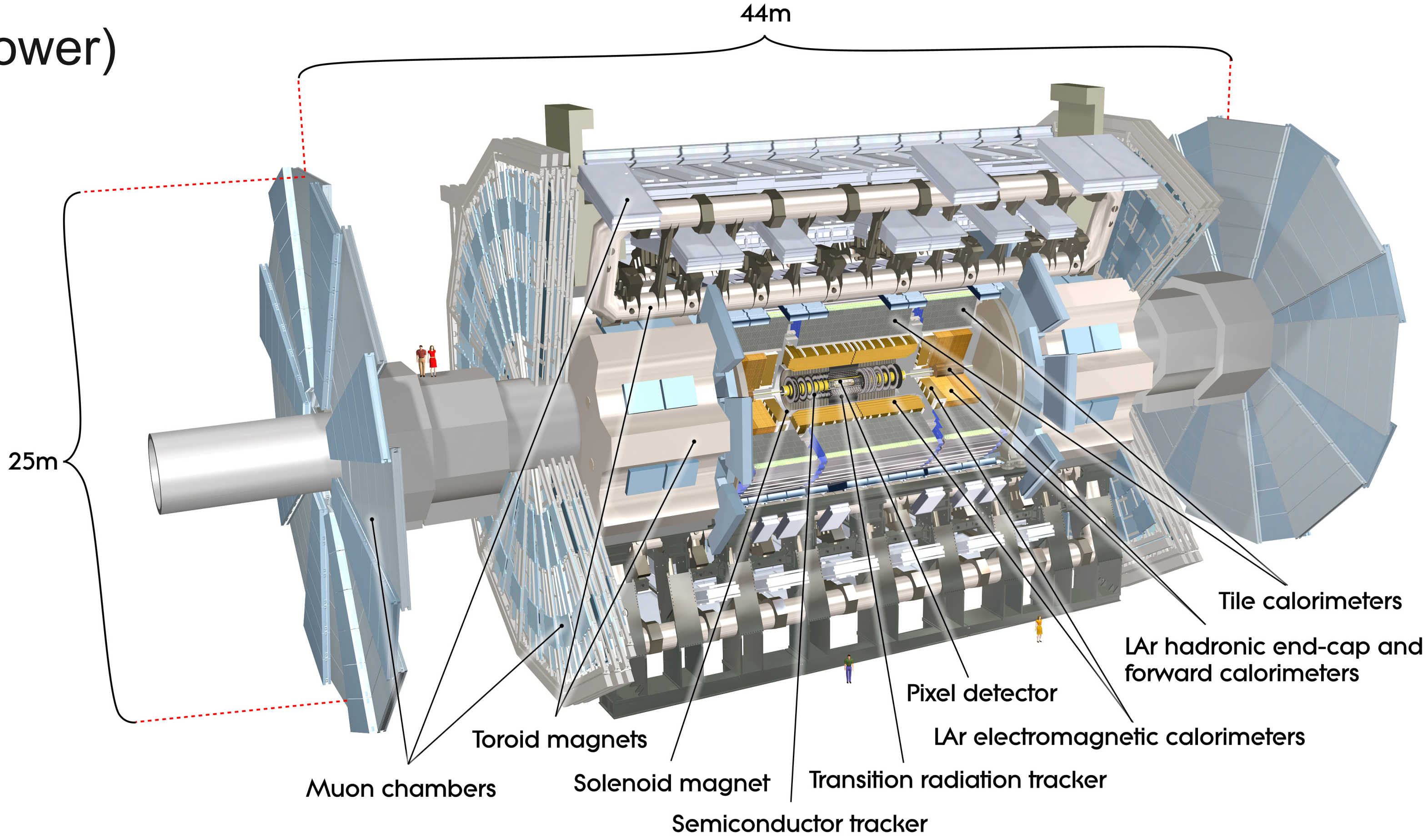
Summary Plot



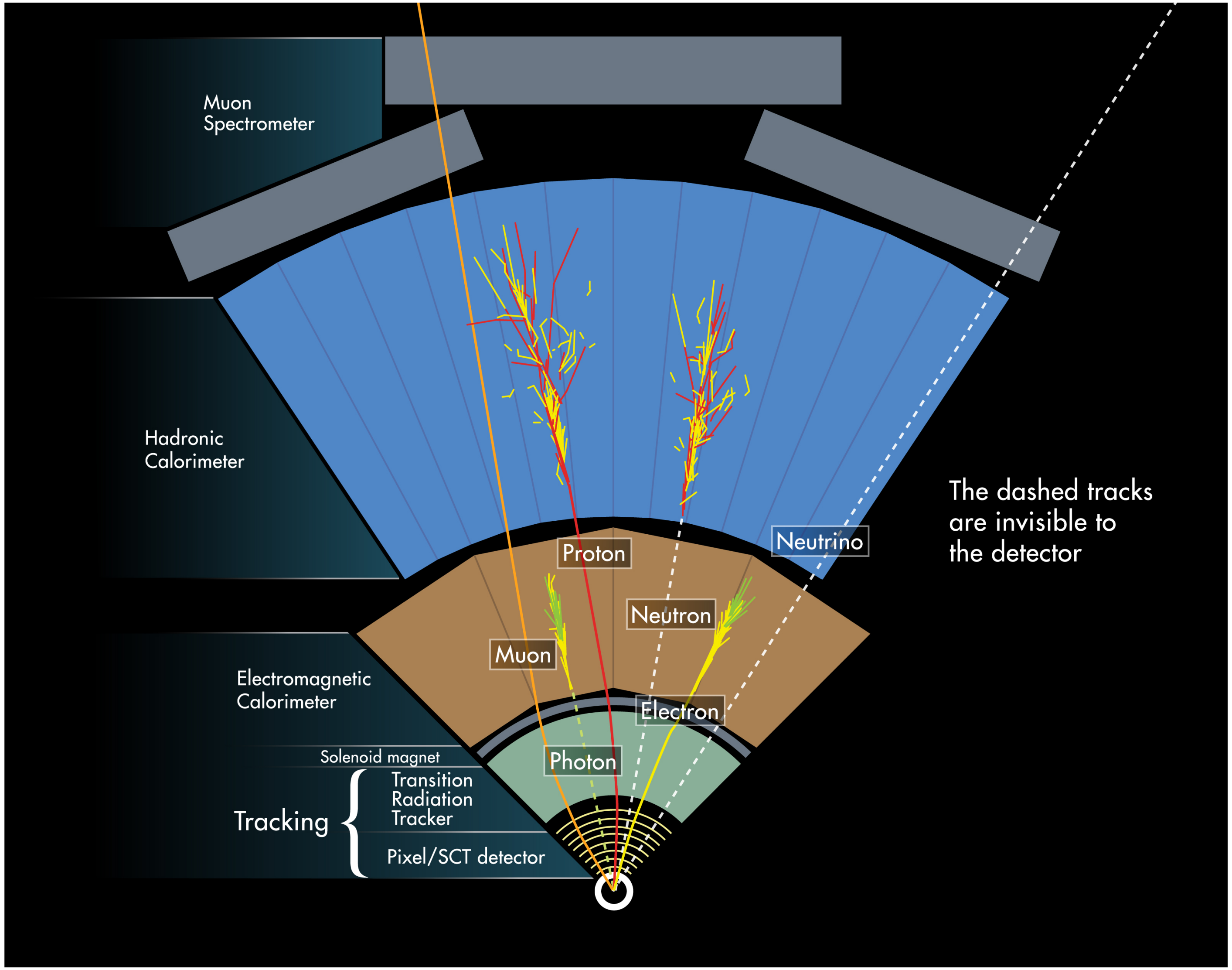
A Toroidal LHC ApparatuS

- Weighs 7000 tonnes (~1 Eiffel Tower)
- 3000 km of cables
- 100 Million electronics channels readout every 25 ns





Particle Detection in ATLAS



- Different particles leave different signatures in the detector
- Solenoid and toroid magnetic fields bend particles to measure momenta

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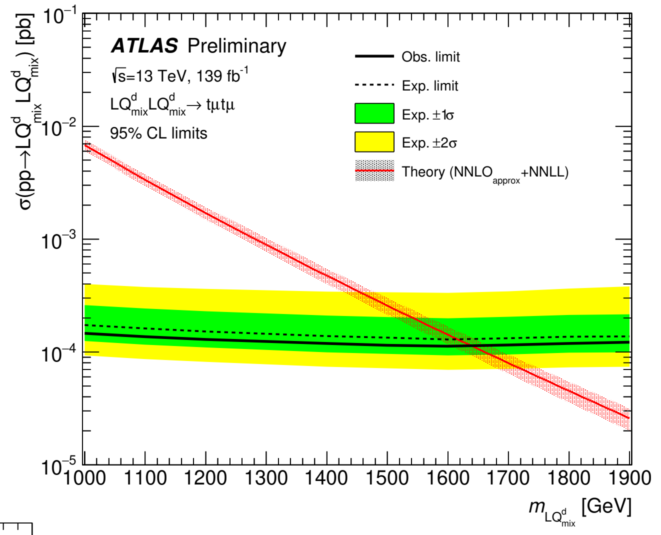
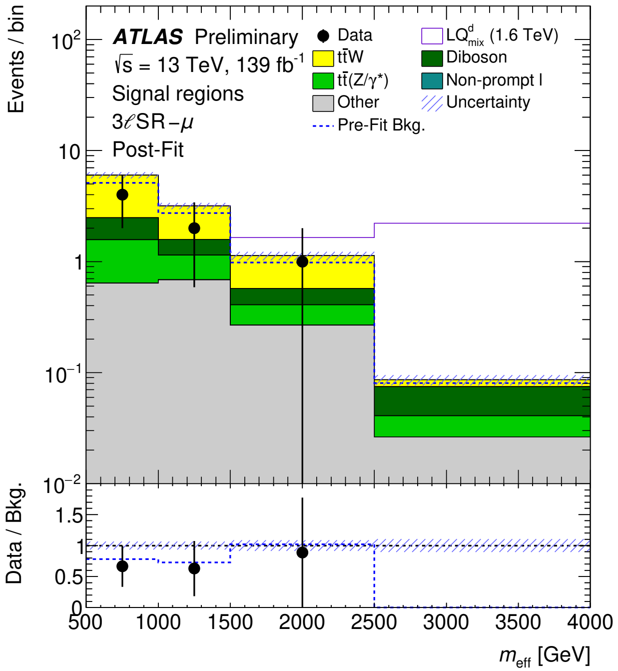
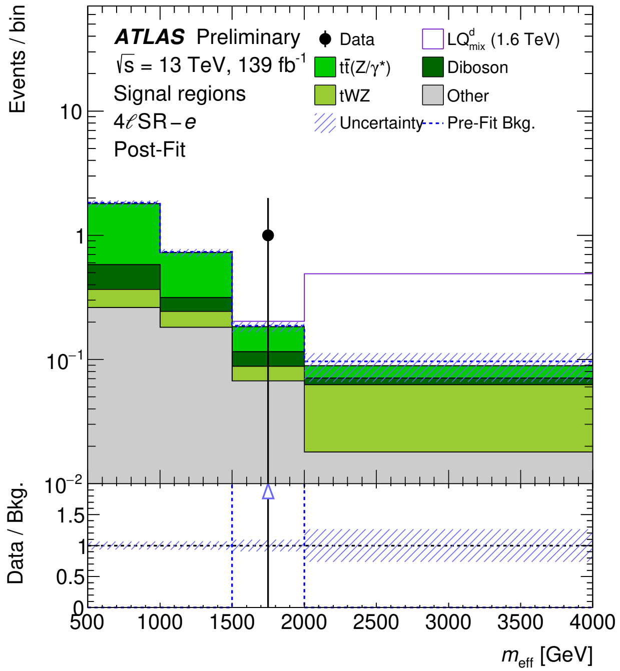
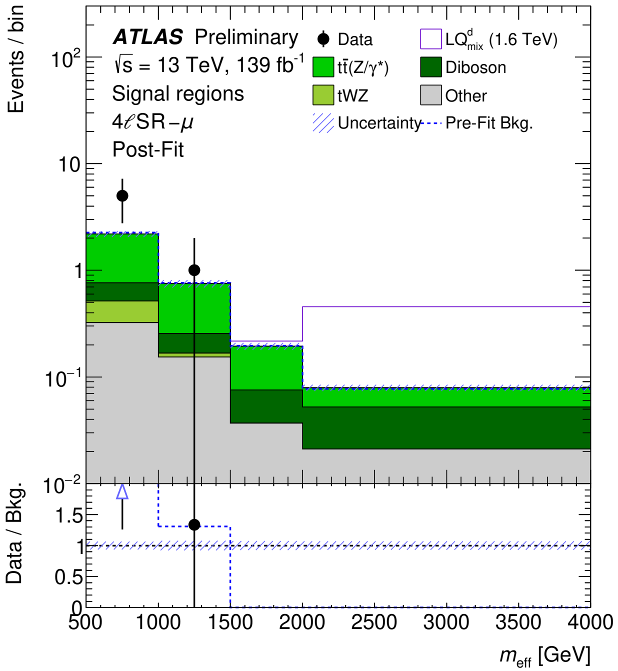
Pair-produced Leptoquarks



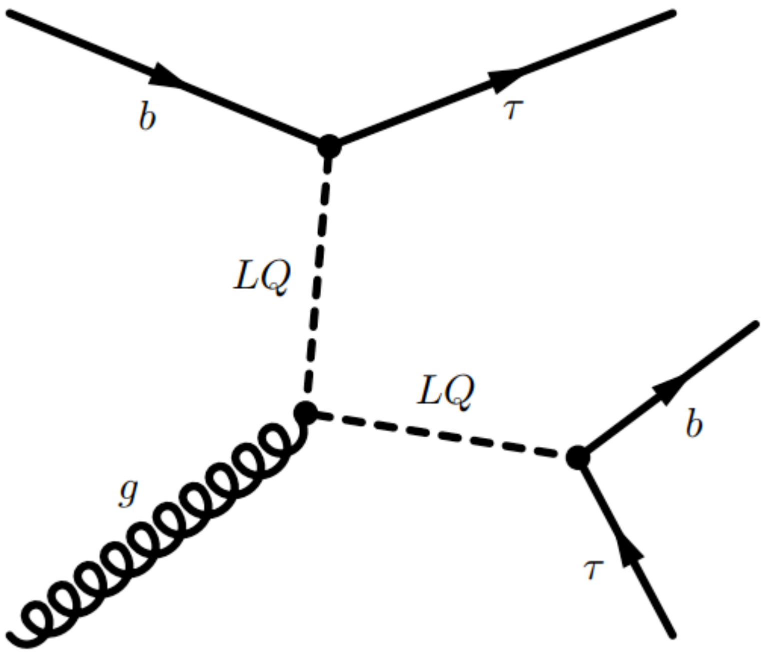




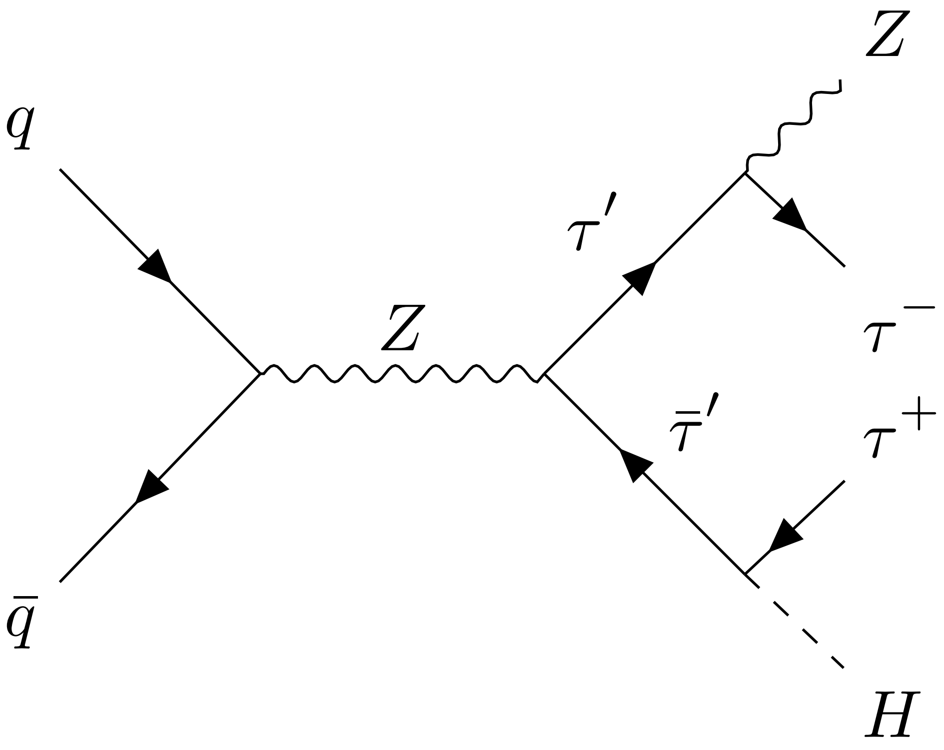


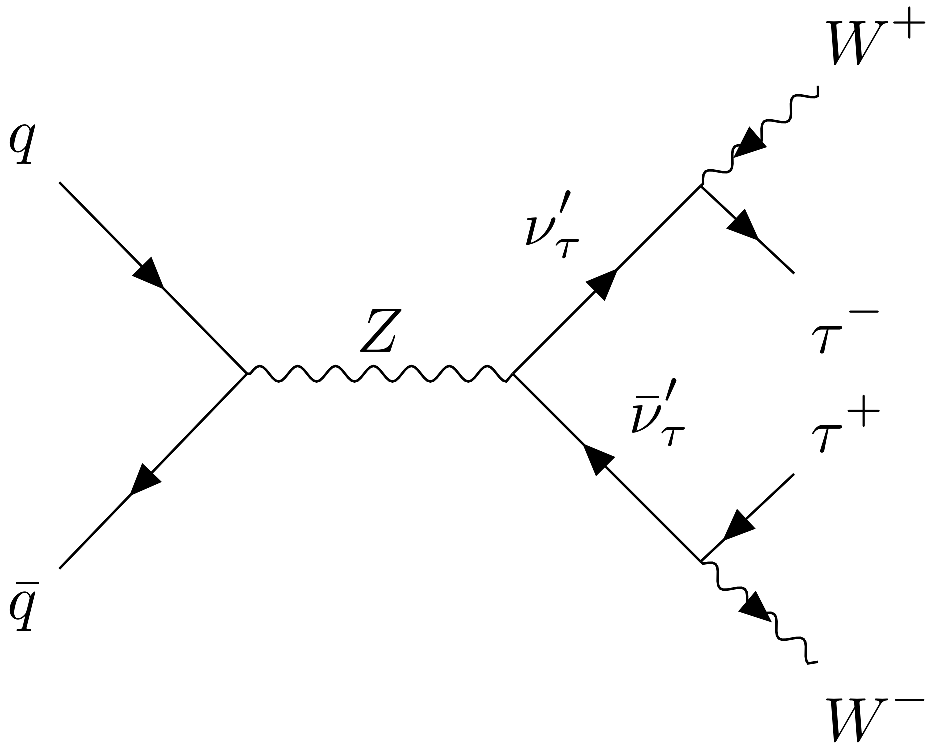
Singly-produced Scalar Leptoquarks

- Quark-gluon scattering



3rd Generation Vector-like Leptons (VLL)





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3rd Generation Vector-like Leptons (VLL)

- BDT training variables

Variable	Description
$E_{\mathrm{T}}^{\mathrm{miss}}$	The missing transverse momentum in the event
$S(E_T^{\mathrm{miss}})$	The missing transverse momentum significance in the event
L_T	The scalar sum of light leptons p_T in the event
$L_T + E_T^{\mathrm{miss}}$	The scalar sum of light leptons p_T and the missing transverse momentum in the event
$L_T + p_T(\tau)$	The scalar sum of light leptons p_T and sum of taus p_T in the event
$p_T(l_1)$	The leading light lepton p_T in the event
$p_T(l_2)$	The sub-leading light lepton p_T in the event
$p_T(j_1)$	The leading jet p_T in the event
$p_T(\tau_1)$	The leading τ p_T in the event
N_j	The number of jets in the event
N_b	The number of b-jets in the event
H_T	The scalar sum of jet p_T in the event
$L_T + H_T$	The scalar sum of light leptons p_T and sum of jets p_T in the event
M_{ll}	The invariant mass of all light leptons in the event
$M_{l\tau}$	The invariant mass of all light leptons and taus in the event
M_{lj}	The invariant mass of all light leptons and jets in the event
M_{jj}	The invariant mass of all jets in the event
$M_{j\tau}$	The invariant mass of all jets and taus in the event
M_T	The transverse mass of the leading light lepton in the event
M_{OSSF}	The invariant mass the opposite sign same flavor pair of light leptons closest to the Z mass in the event
$\Delta\phi(j_1 E_T^{\mathrm{miss}})$	$\Delta\phi$ between E_T^{miss} and the leading p_T jet in the event
$\Delta\phi(l_1 E_T^{\mathrm{miss}})$	$\Delta\phi$ between E_T^{miss} and the leading p_T light lepton in the event
$\Delta\phi(l_1 l_2)$	$\Delta\phi$ between the leading and sub-leading p_T light lepton in the event
$\Delta\phi(l_1 j_1)$	$\Delta\phi$ between the leading p_T light lepton and jet in the event
$\Delta\phi(\tau_1 E_T^{\mathrm{miss}})$	$\Delta\phi$ between E_T^{miss} and the leading p_T τ in the event
$\Delta\phi(l_1 \tau_1)$	$\Delta\phi$ between the leading p_T light lepton and τ in the event
$\Delta\phi(j_1 \tau_1)$	$\Delta\phi$ between the leading p_T jet and τ in the event
$\Delta R(j_1 E_T^{\mathrm{miss}})$	ΔR between E_T^{miss} and the leading p_T jet in the event
$\Delta R(l_1 E_T^{\mathrm{miss}})$	ΔR between E_T^{miss} and the leading p_T light lepton in the event
$\Delta R(l_1 l_2)$	ΔR between the leading and sub-leading p_T light lepton in the event
$\Delta R(l_1 j_1)$	ΔR between the leading p_T light lepton and jet in the event
$\Delta R(\tau_1 E_T^{\mathrm{miss}})$	ΔR between E_T^{miss} and the leading p_T τ in the event
$\Delta R(l_1 \tau_1)$	ΔR between the leading p_T light lepton and τ in the event
$\Delta R(j_1 \tau_1)$	ΔR between the leading p_T jet and τ in the event

Vector-like Quarks (VLQ)

	$1b$ SR	$2b$ SR	$1b$ CR	$2b$ CR	SR	VV CR
Preselection	≥ 2 central jets at least two SF leptons with $p_T > 28$ GeV at least one pair of OS-SF leptons $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV					
Channel definitions	2ℓ $= 2\ell$ $p_T(\ell\ell) > 300$ GeV $H_T(\text{jet}) + E_T^{miss} > 920$ GeV				3ℓ $\geq 3\ell$ $p_T(\ell\ell) > 200$ GeV $H_T(\text{jet + lep}) > 300$ GeV	
Region definitions	$1b$ SR $H_T(\text{jet}) + E_T^{miss} > 1380$ GeV $= 1$ b-jet	$2b$ SR ≥ 2 b-jet	$1b$ CR $H_T(\text{jet}) + E_T^{miss} < 1380$ GeV $= 1$ b-jet	$2b$ CR ≥ 2 b-jet	SR – ≥ 1 b-jet	VV CR – $= 0$ b-jet
MCBOT categories	7	7	–	–	5	–
Fitted variable	$m(Zb_1)$	$m(Zb_2)$	$H_T(\text{jet}) + E_T^{miss}$		$H_T(\text{jet + lep})$	

Category	2ℓ channel, $1b$ SR, V-tags	2ℓ channel, $1b$ SR, H-tags	2ℓ channel, $1b$ SR, top-tags	2ℓ channel, $2b$ SR, V-tags	2ℓ channel, $2b$ SR, H-tags	2ℓ channel, $2b$ SR, top-tags	3ℓ channel, –, V-tags	3ℓ channel, –, H-tags	3ℓ channel, –, top-tags
No tag	0	0	0	0	0	0	0	0	0
V tag	1	0	0	1	0	0	≥ 1	0	0
H tag	0	1	0	0	1	0	0	≥ 1	0
Top tag	0	0	1	0	0	1	0	0	≥ 1
Double tag 1	2 0 1	0 2 0 –	0 0 1	2 0 1 0	0 2 1 0	0 0 0 2		– – – –	
Double tag 2	0 0	1 0	1 2	0	1 –	1		– –	
Overflow (OF)	1	1 or > 2 tags – –	0	1	0 or > 2 tags – –	1	0 ≥ 1 ≥ 1 ≥ 1	≥ 1 0 ≥ 1 ≥ 1	≥ 1 ≥ 1 0 ≥ 1

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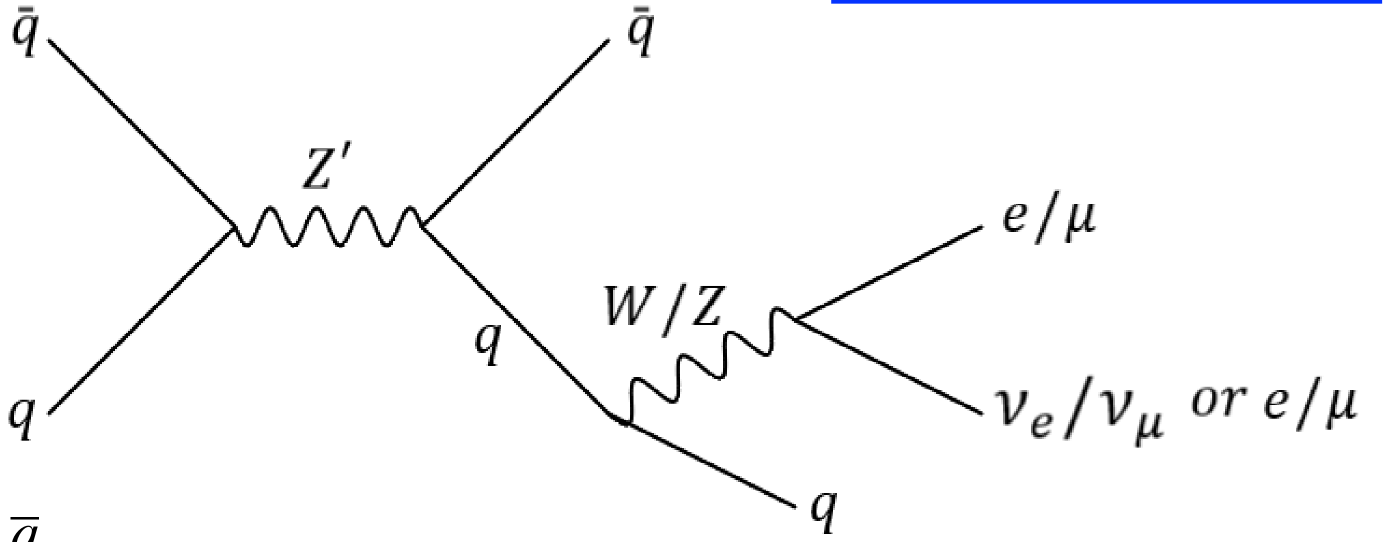
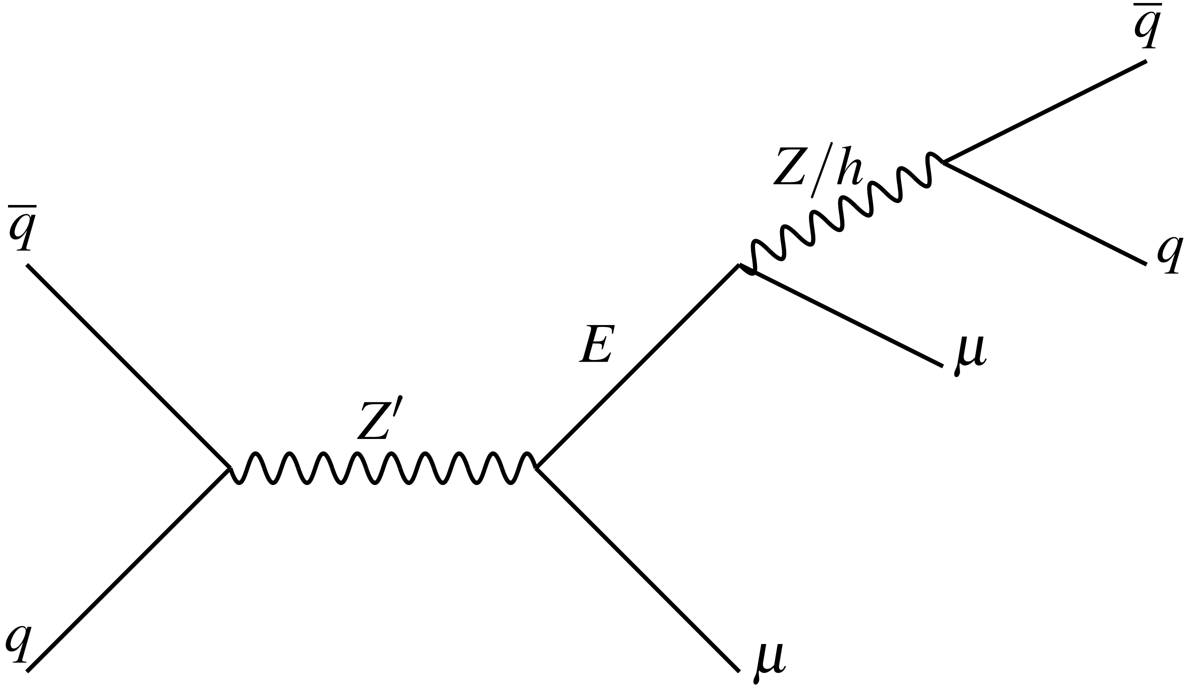
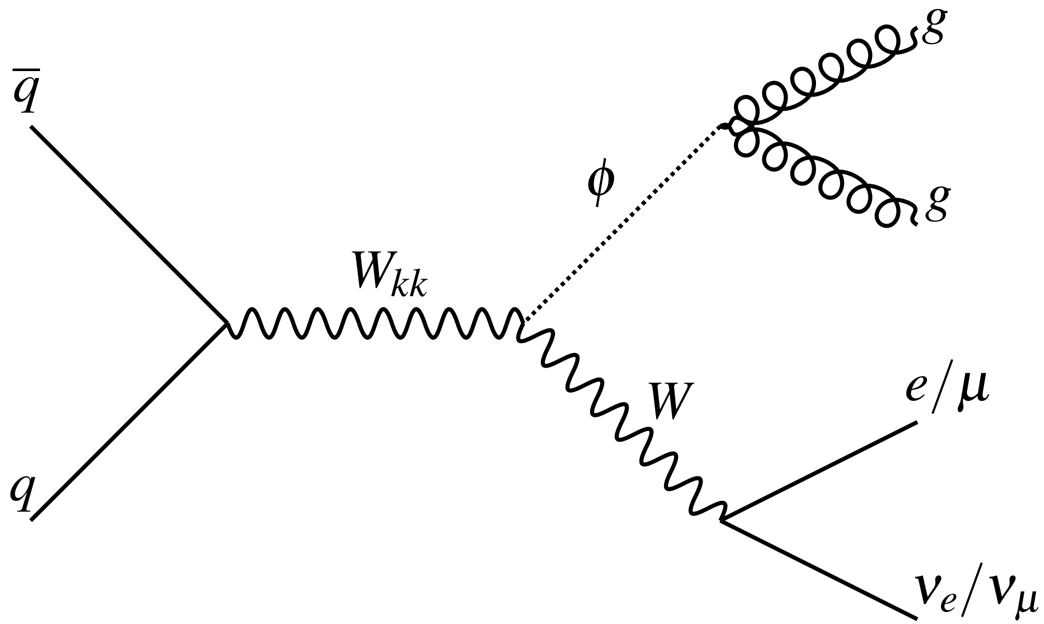
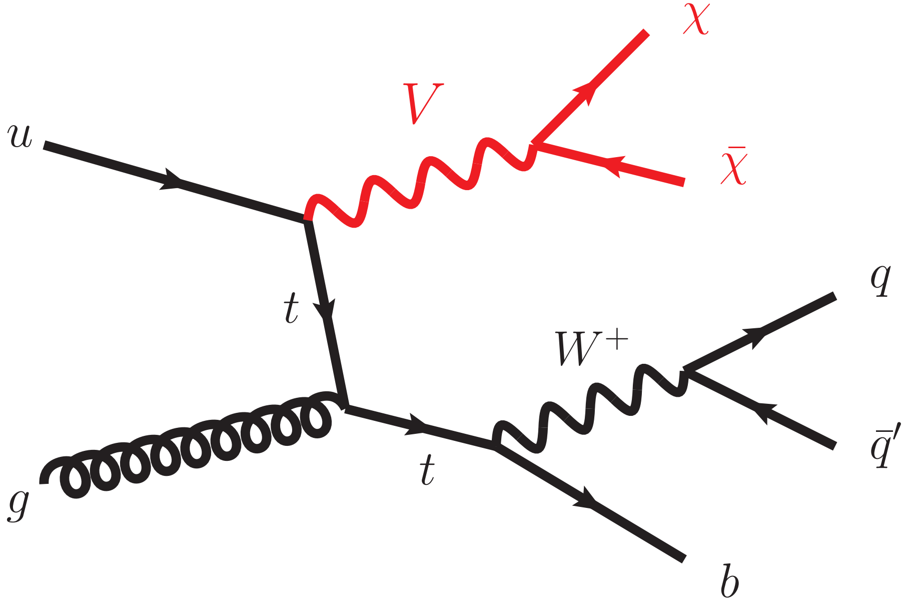
Generic Searches

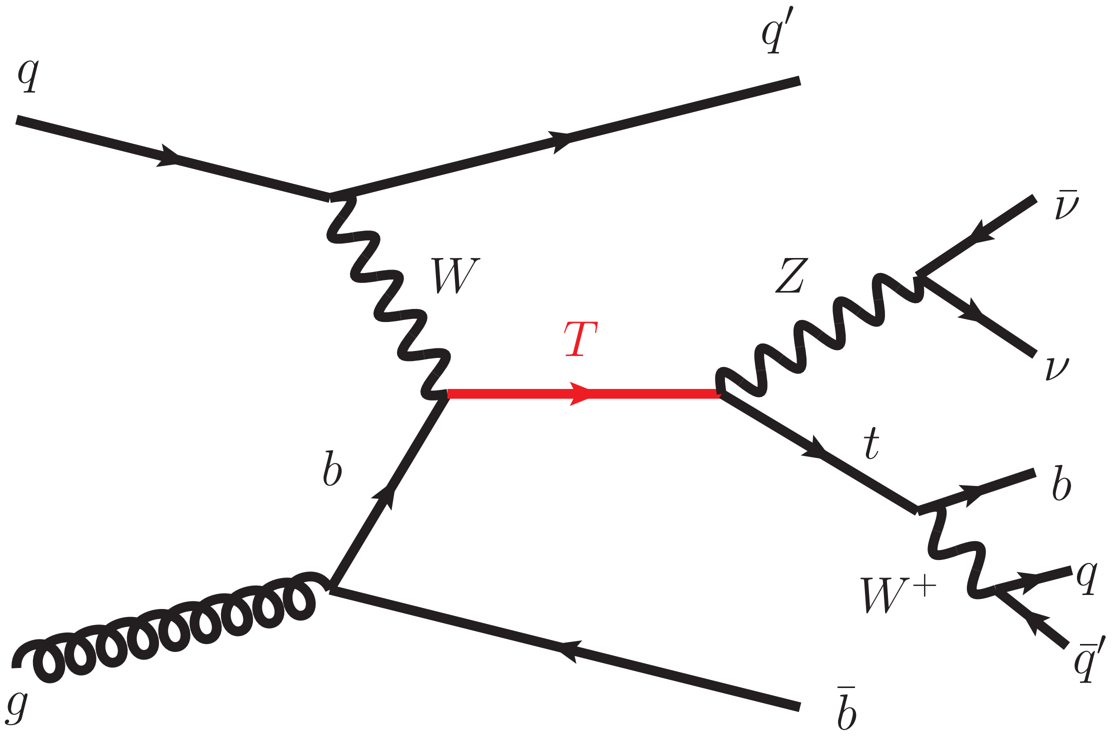






Invisible Particles





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Invisible Particles

- BDT training variables

Variable	Description	Resonant DM model	Non-resonant DM model	VLQ
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum	✓	✓	✓
Ω	$E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet p_{T} balance: $\frac{E_{\mathrm{T}}^{\mathrm{miss}}-p_{\mathrm{T}}(J)}{E_{\mathrm{T}}^{\mathrm{miss}}+p_{\mathrm{T}}(J)}$	✓	✓	✓
$\mathrm{N}_{\mathrm{jets}}$	Small-R jet multiplicity	✓	✓	✓
ΔR_{max}	Maximum ΔR between two small-R jets	✓	✓	✓
$m_{\mathrm{T,min}}(E_{\mathrm{T}}^{\mathrm{miss}},b\text{-jet})$	Transverse mass of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest b-tagged jet.	✓	✓	✓
$m_{\text{top-tagged jet}}$	Mass of the large-R top-tagged jet	✓		✓
Δp_{T} (J,jets)	Scalar difference of large-R jet p_{T} and the sum of p_{T} of all small-R jets.	✓	✓	
H_{T}	Sum of all small-R jet p_{T}		✓	✓
$H_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}}$	Ratio of H_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$		✓	✓
$\Delta E(E_{\mathrm{T}}^{\mathrm{miss}},J)$	Energy difference between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the large-R jet		✓	✓
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},J)$	Angular distance in the transverse plane between $E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet		✓	✓
$p_{\mathrm{T}}(\mathrm{J})$	Large-R jet p_{T}			✓
$m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}},J)$	Transverse mass of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet			✓
$\Delta\phi(b\text{-tagged jet},J)$	Angular distance in the transverse plane between the large-R jet and the leading b-jet			✓

Abstract

- Many theories beyond the Standard Model (BSM) have been proposed to address several of the Standard Model shortcomings, such as the origin of dark matter and neutrino masses, the fine-tuning of the Higgs boson mass, or the observed pattern of masses and mixing angles in the quark and lepton sectors. Many of these BSM extensions predict new particles or interactions directly accessible at the LHC. This talk will present some highlights on recent searches based on the the full Run 2 data collected by the ATLAS detector at the LHC with a centre-of-mass energy of 13 TeV. These include searches for leptoquarks and vector-like fermions, new high mass resonances and lepton flavour violating decays, dark sector searches, as well as searches for new phenomena giving unconventional and/or long-lived particle signatures.