Recent Physics Highlights from the ATLAS Experiment

CAP CONGRESS 2023, FREDERICTON

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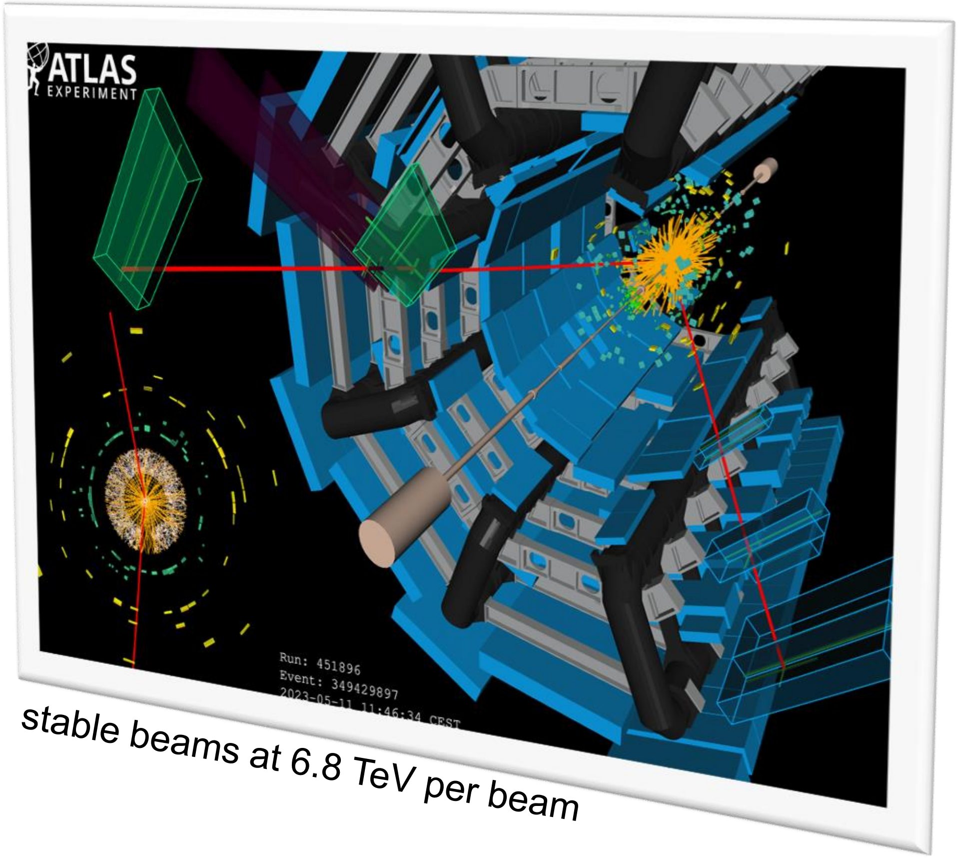
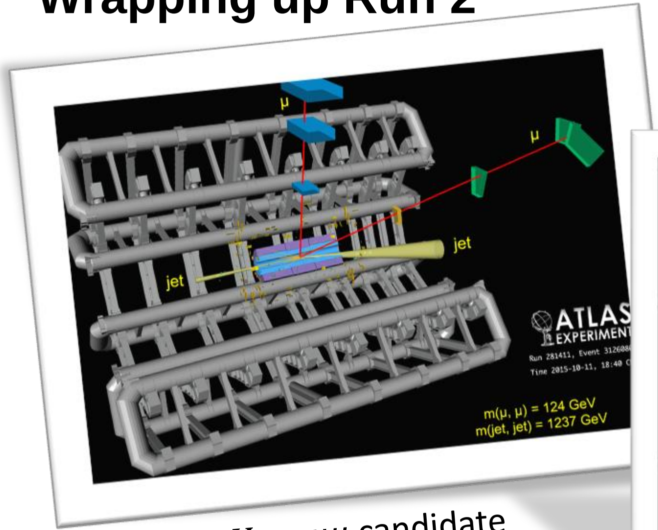
ATLAS is busy…

Getting Run 3 Started



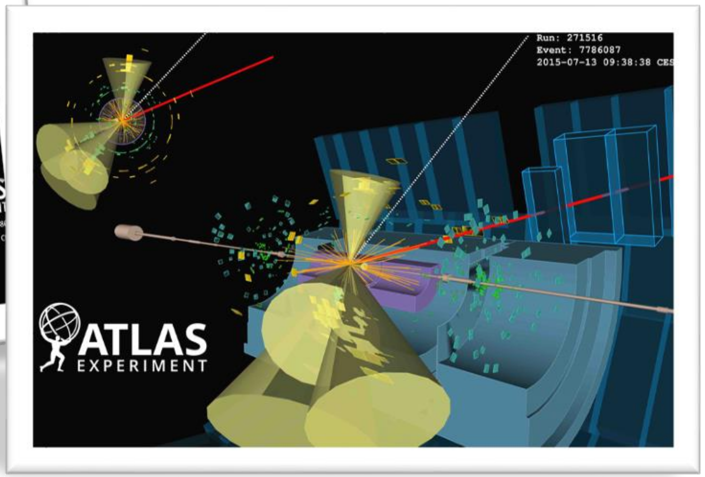
stable beams at 6.8 TeV per beam

Wrapping up Run 2

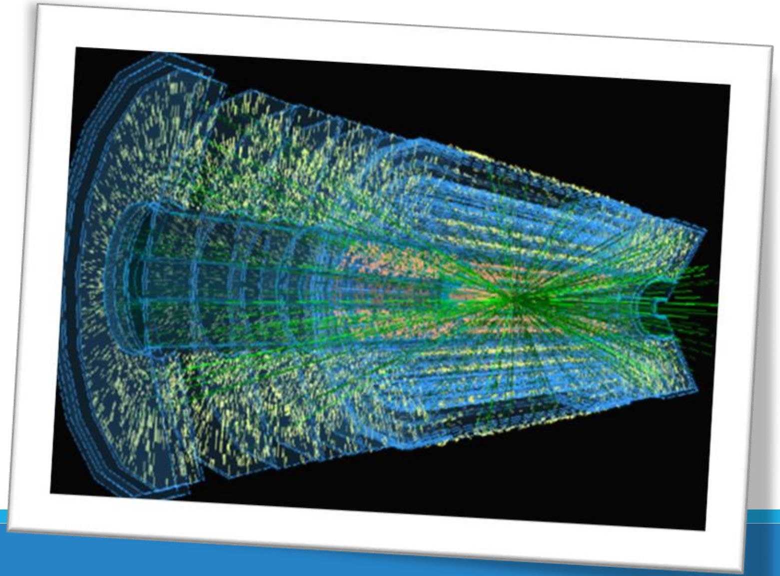


$H \rightarrow \mu\mu$ candidate

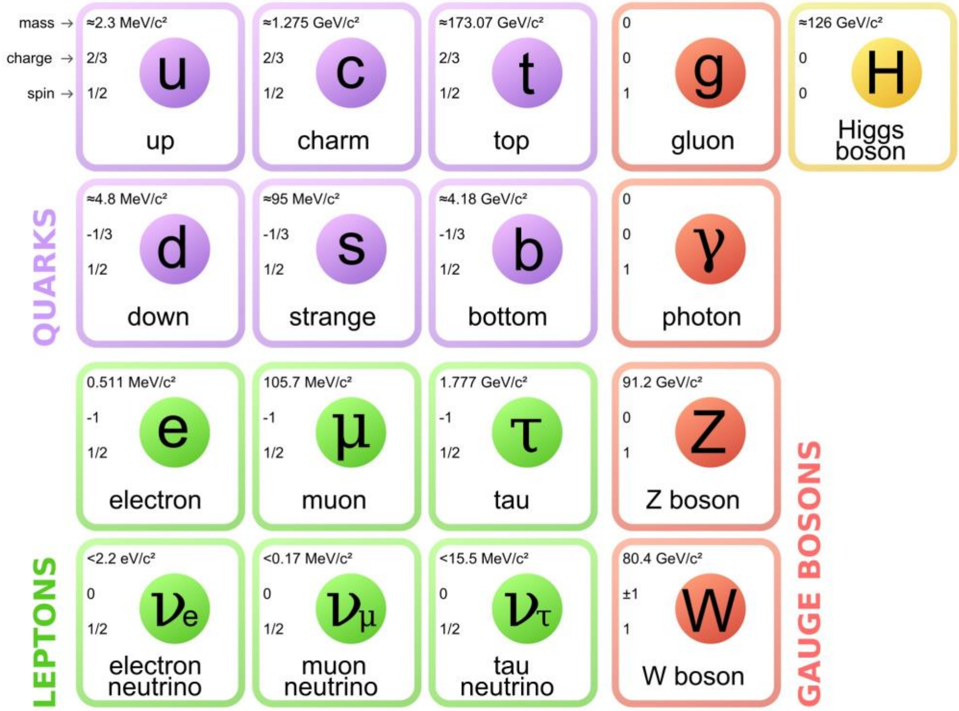
boosted $t\bar{t}$ production



With High-Lumi Upgrades



Thus only a small subset of recent results…



Overviews of measurements and searches

- W mass measurement
- α_S using Z p_T
- Higgs measurements familiar ($H \rightarrow WW$) & new ($H \rightarrow Z\gamma$)
- WW scattering (& Majorana neutrinos), generally 4ℓ production
- High mass $V\gamma$ searches
- $4t$ and boosted $t\bar{t}$ production
- Leptoquark Searches
- 2HDM + a, Dark matter combination

With an occasional side BAR to elaborate on techniques used

W mass boson (7 TeV)

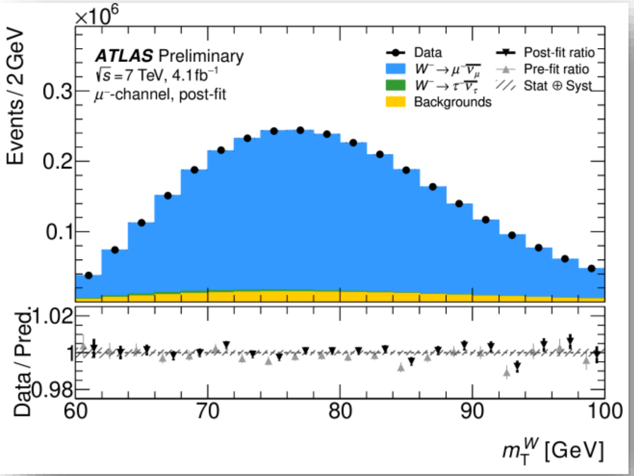
Measurement allows for model-independent probes of BSM

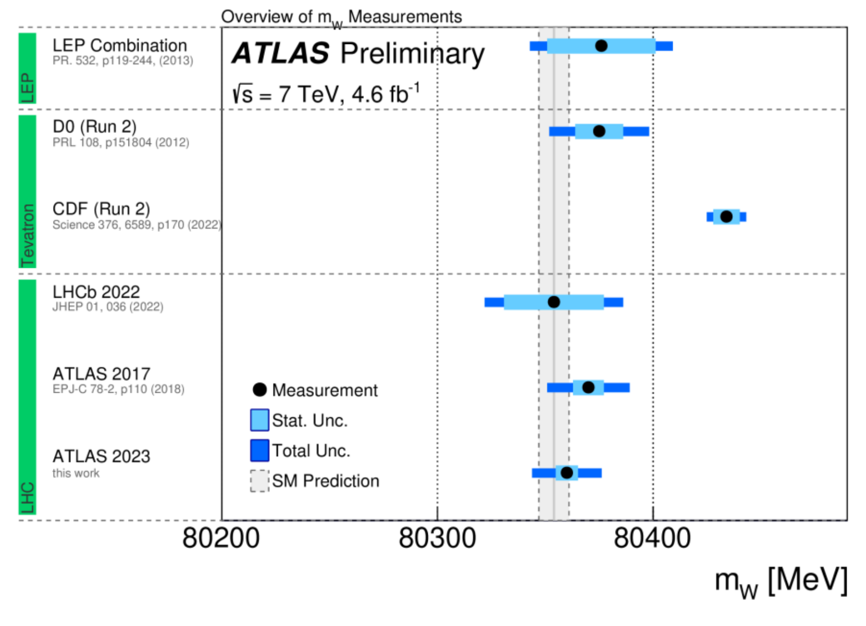
7 TeV data reanalyzed with profile likelihood fitting approach

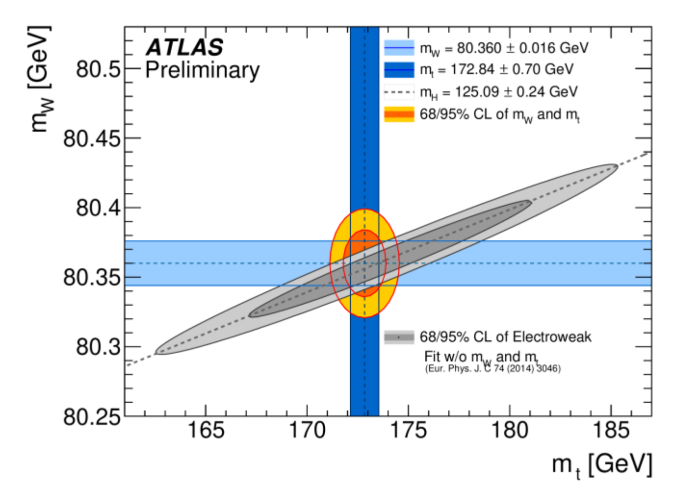
- systematic uncertainty reduction gives 15% improvement

m_W = 80360 ± 16MeV

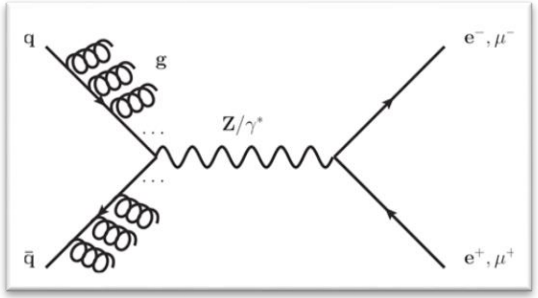
PDF & muon uncertainties







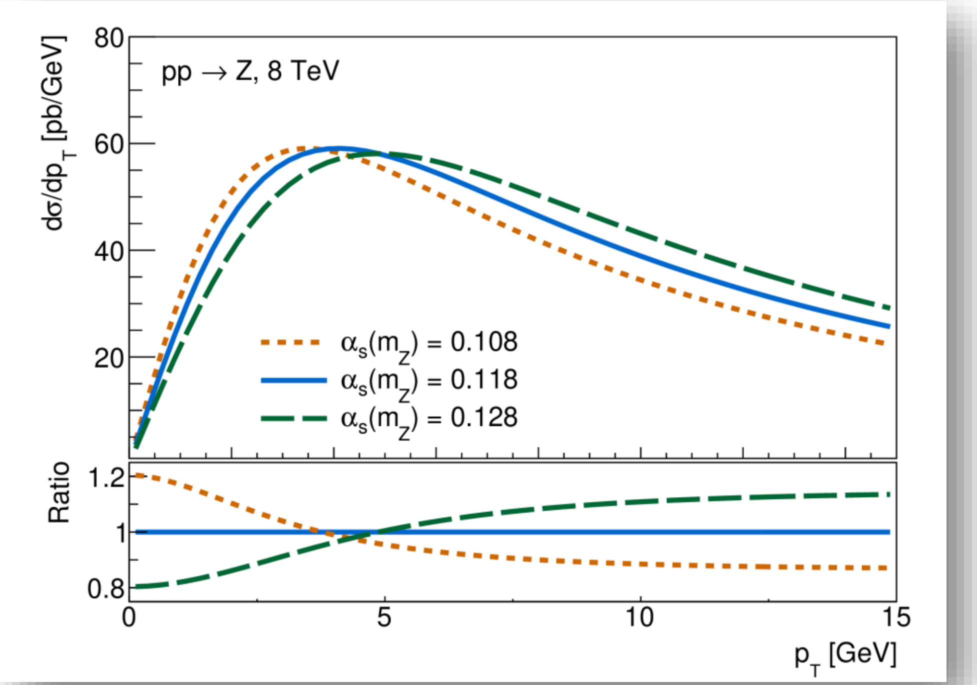
Measuring α_S using Z p_T (8 TeV)

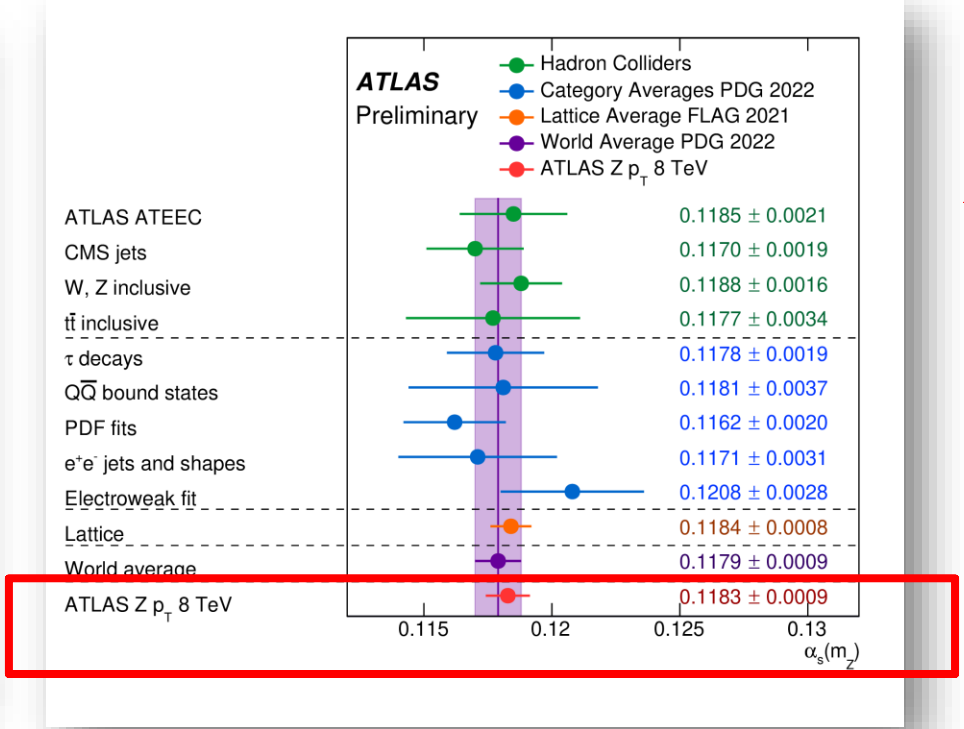


Important for stability of EW vacuum, and convergence with Weak & EM coupling

Improvement needed to reduce uncertainties on LHC cross-sections

Z recoils against initial state radiation: p_T proportional to α_S



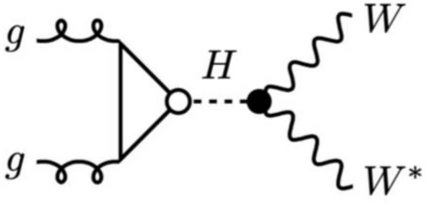


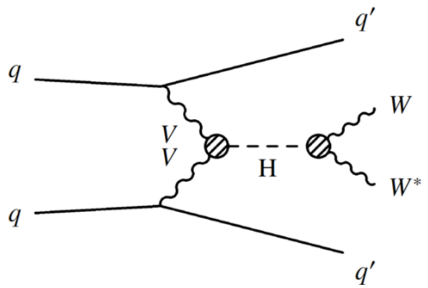
ATLAS provides the most precise measurement

α_S = .1183
± .0009

PDF uncertainty

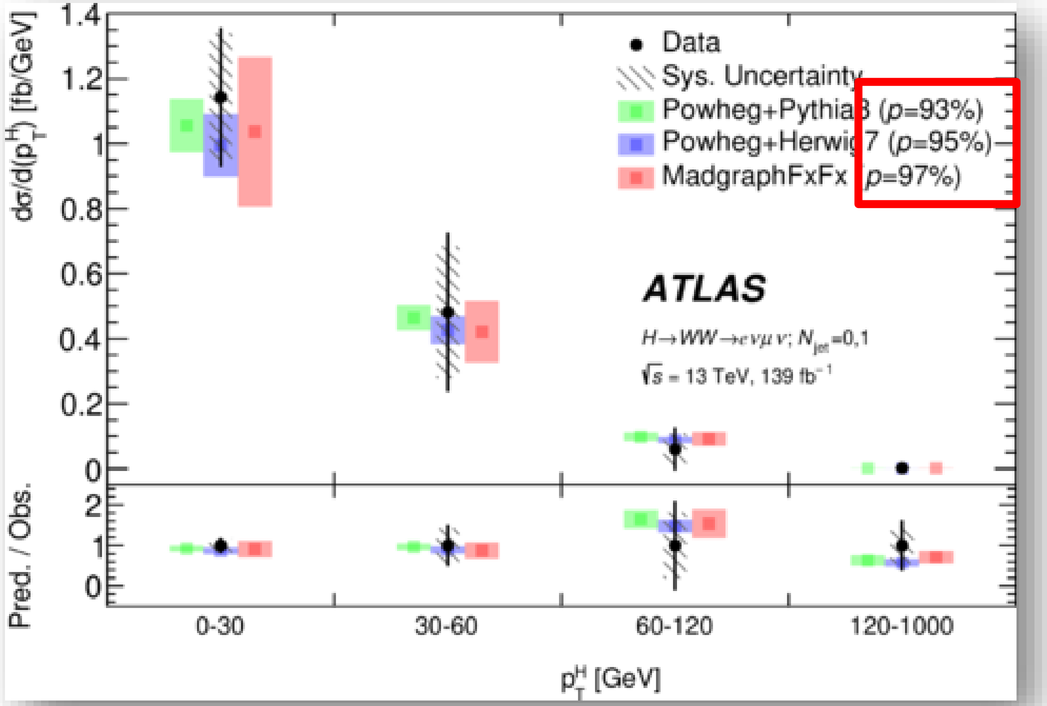
H→ WW cross sections

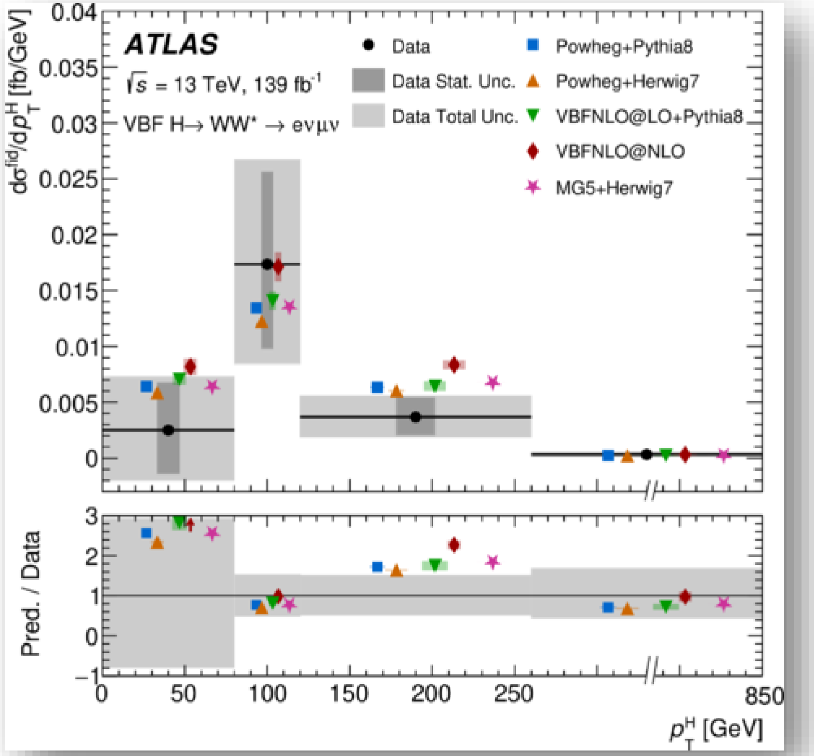




Differential cross sections measured in both gluon-gluon fusion and vector boson fusion production

Impressive agreement with the SM





How do we get “truth” level cross sections?

Many different methods, but the idea is they are calculated by comparing reconstructed objects (signal region) to particle-level objects (fiducial region)

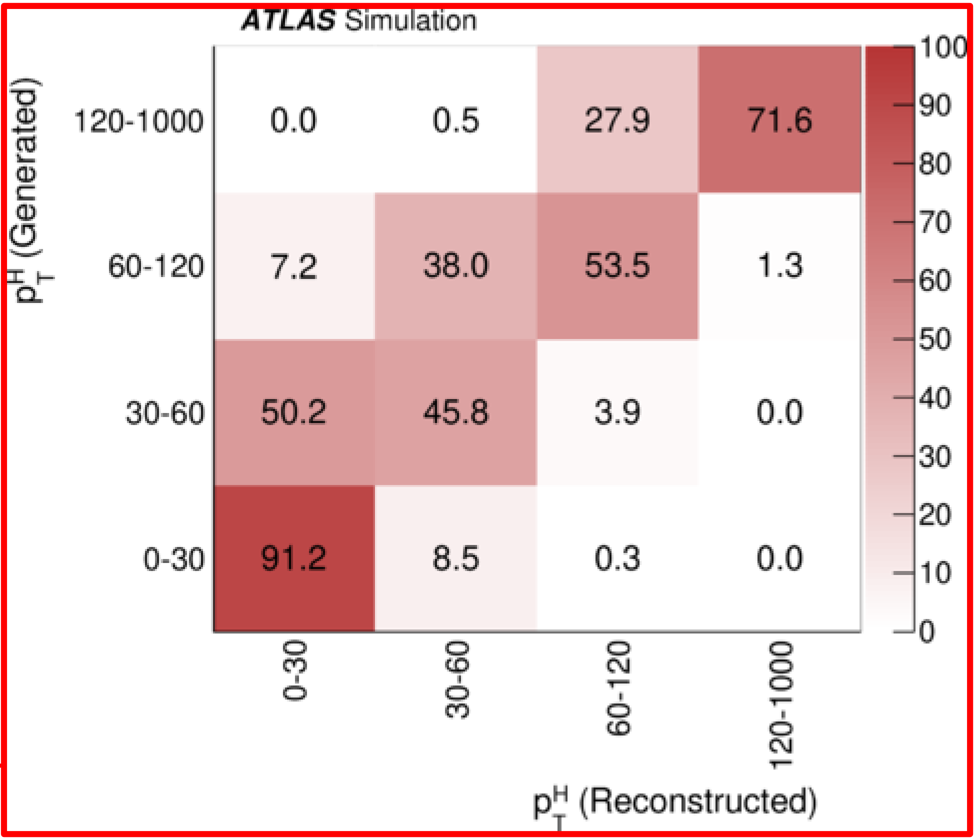
$$N_{events} = L \cdot \sigma_{measured}$$

$$N_{reco} - N_{bg} = L \cdot \frac{\epsilon}{A} \cdot M \cdot \boldsymbol{\sigma}_{\boldsymbol{particle-level}}$$

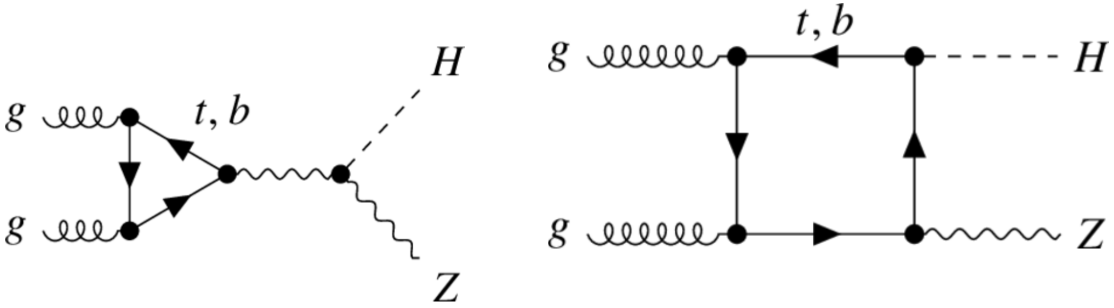
Efficiency of event selection and tagging

Acceptance of events due to selection requirements

Migration matrix takes into account migration between events in signal and fiducial regions

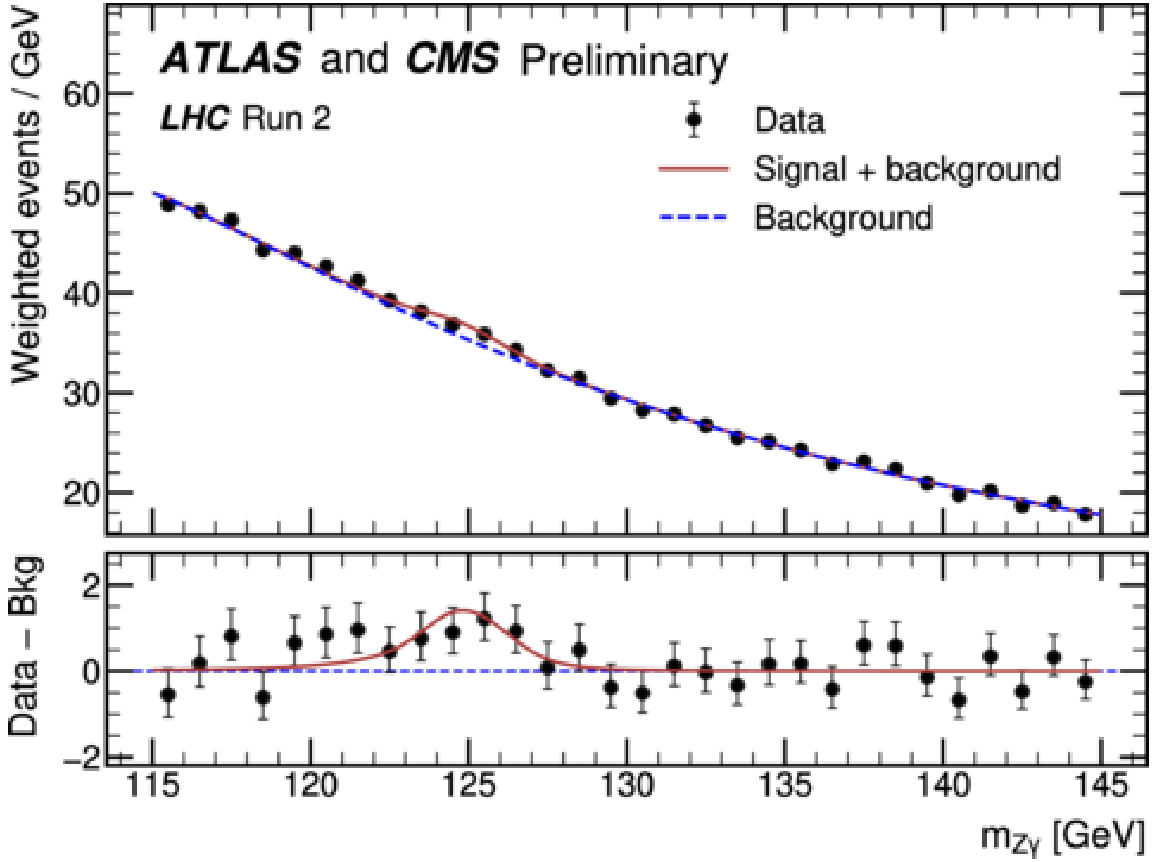


Evidence of H→ $Z\gamma$

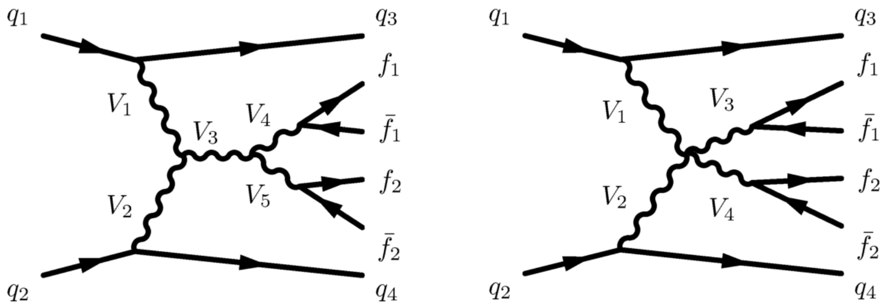


Rare Higgs decay via loop process, sensitive to BSM (composite Higgs, models with Higgs coupling to additional colourless charged scalars, leptons or vector bosons)

	Observed (Expected)
ATLAS	2.2σ (1.2σ)
CMS	2.6σ (1.1σ)
Combination	3.4σ (1.6σ)



WW scattering

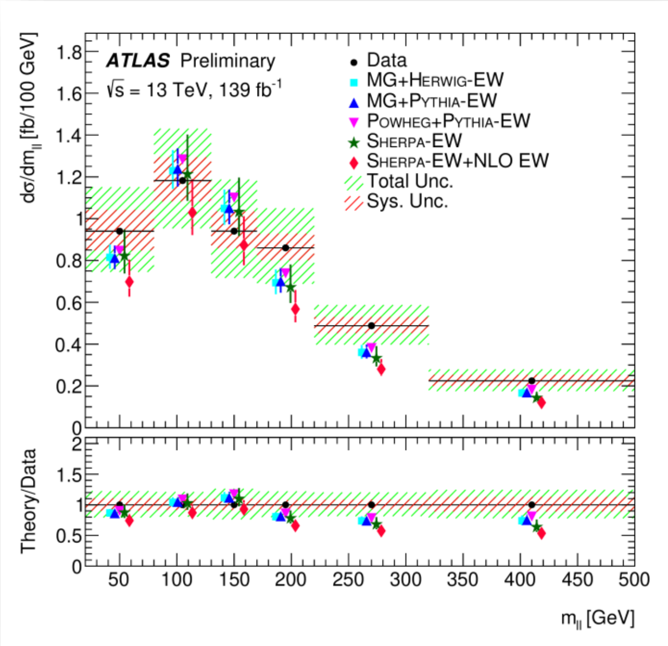


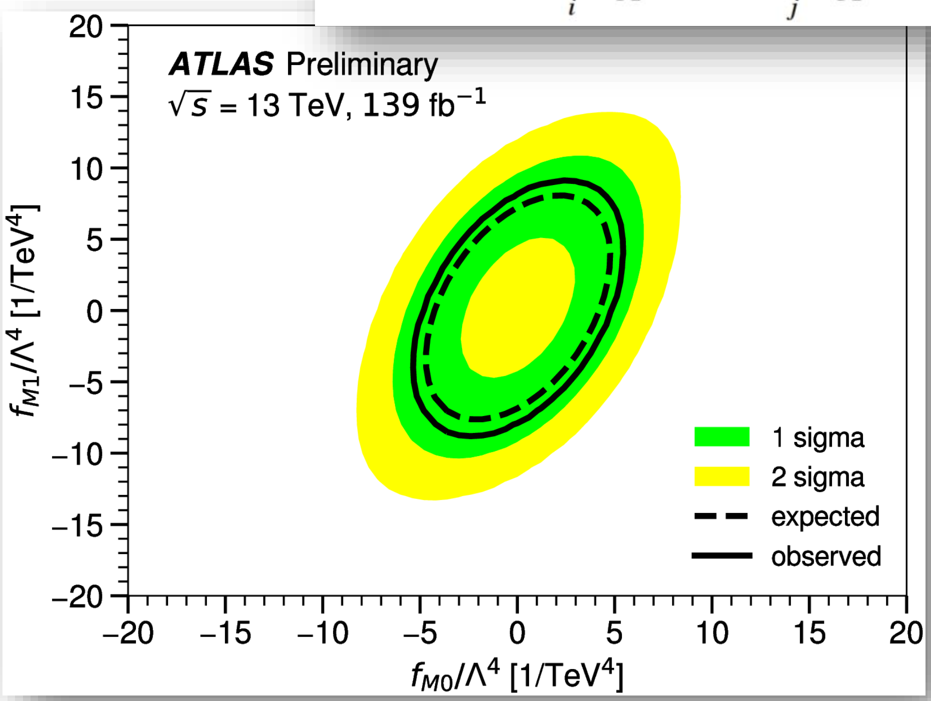
WW scattering probes nature of EW symmetry breaking, and is sensitivity to new physics

- extract inclusive and differential cross sections
- set limits on Effective Field Theory & Doubly Charged Higgs

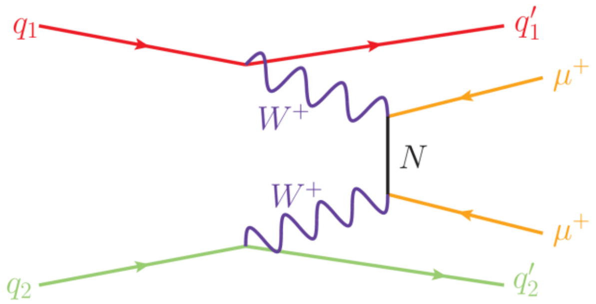
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j^{(8)} + \ldots$$

Variables of interest: $m_{\ell\ell}$, m_{jj}, m_T (from leptons & MET)





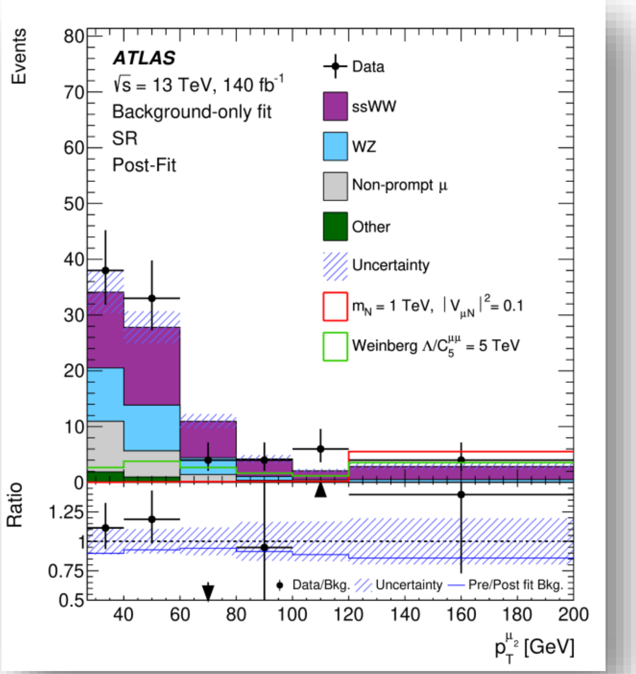
Majorana Neutrinos in WW scattering

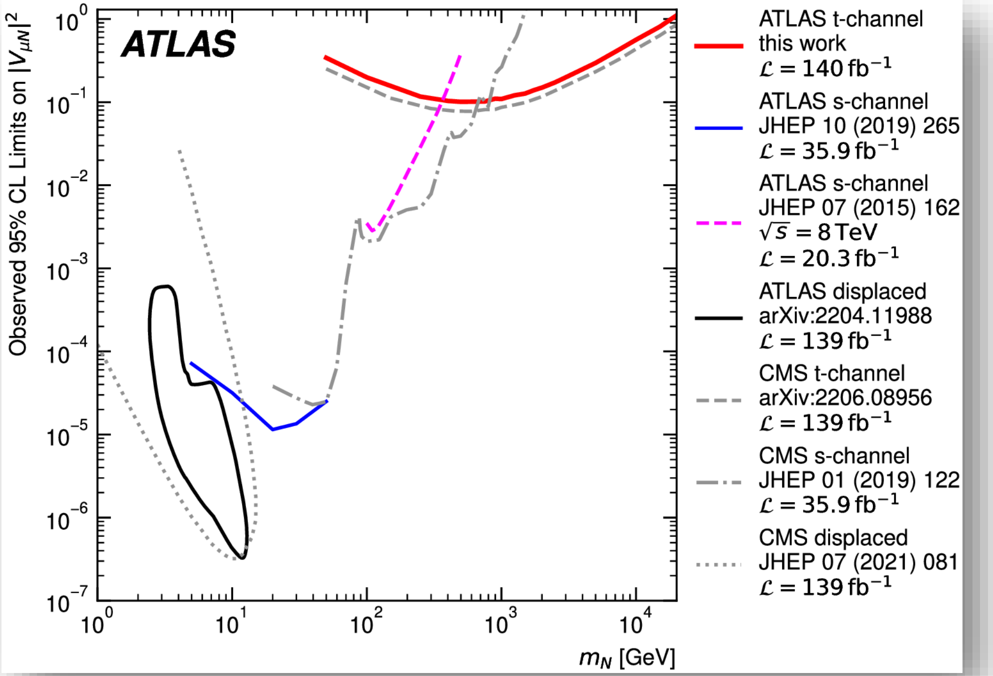


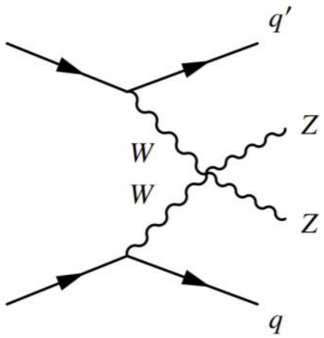
Probe Majorana nature of neutrinos at high energies

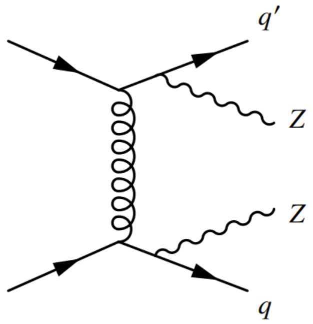
Set limits d=5 Weinberg operator are set

- Translates to upper limit on mass of 16.7 GeV (can't be probed in nuclear decays)





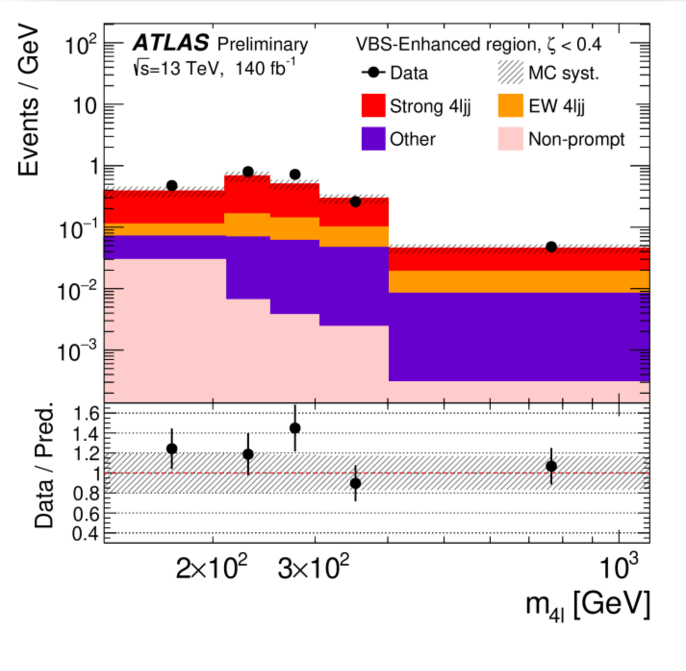


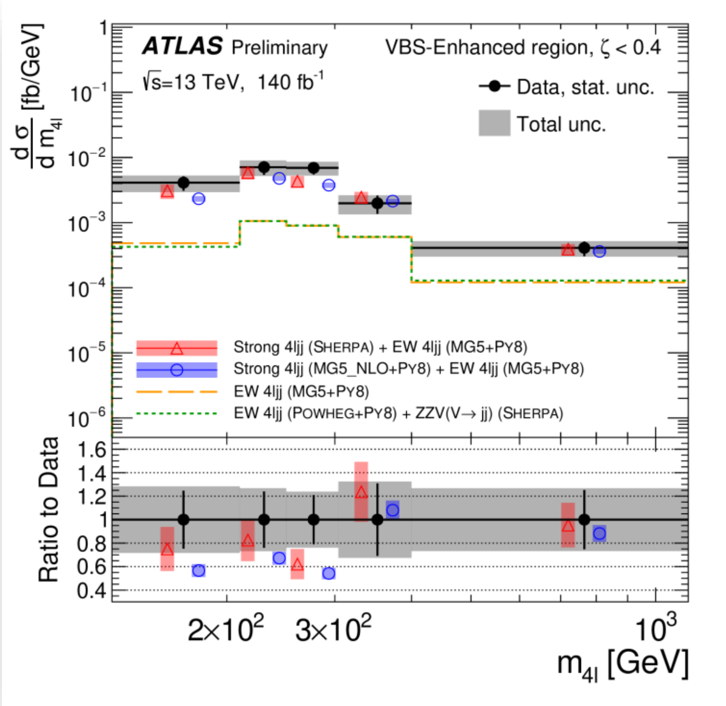


4ℓ production

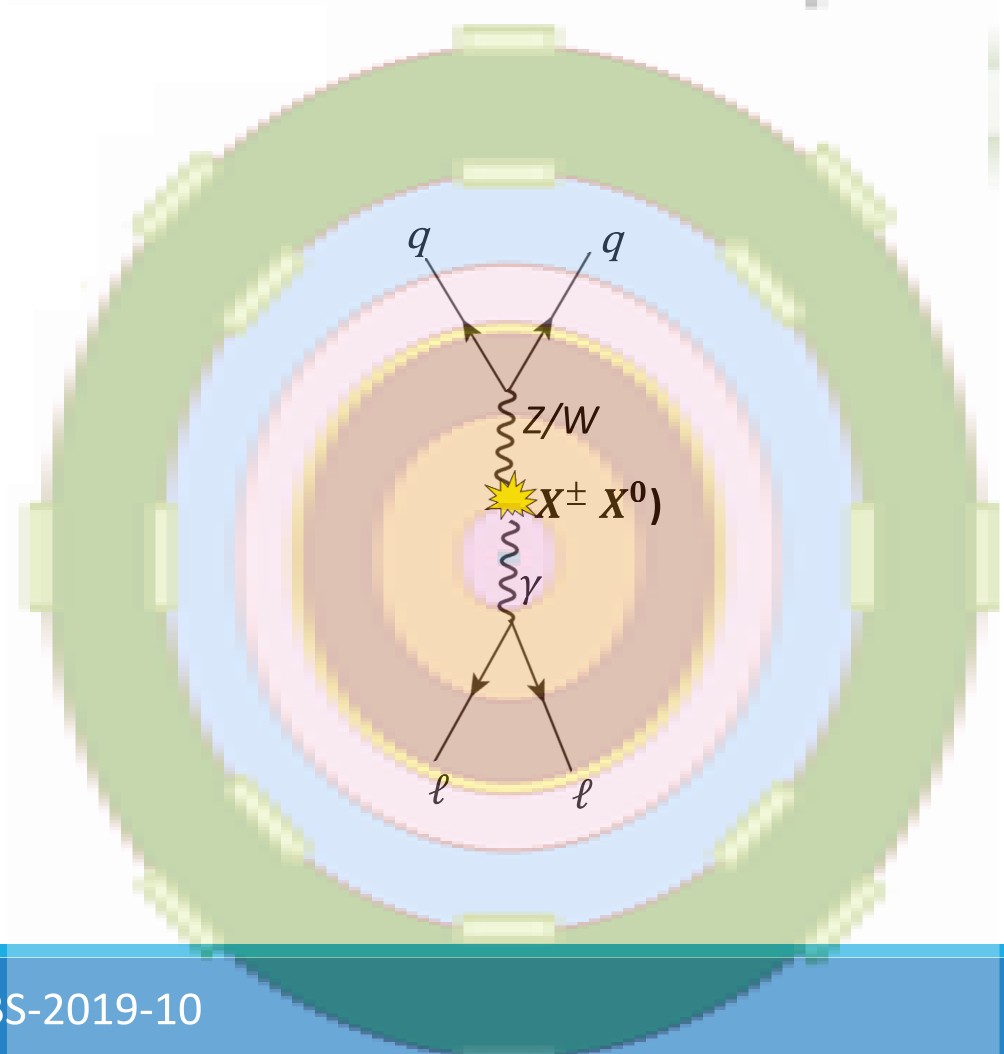
EW 4ℓ production sensitive to anomalous WWZ / WWZZ interactions

Strong 4ℓ production sensitive to perturbative QCD calculations in extreme phase space (high m_{jj})





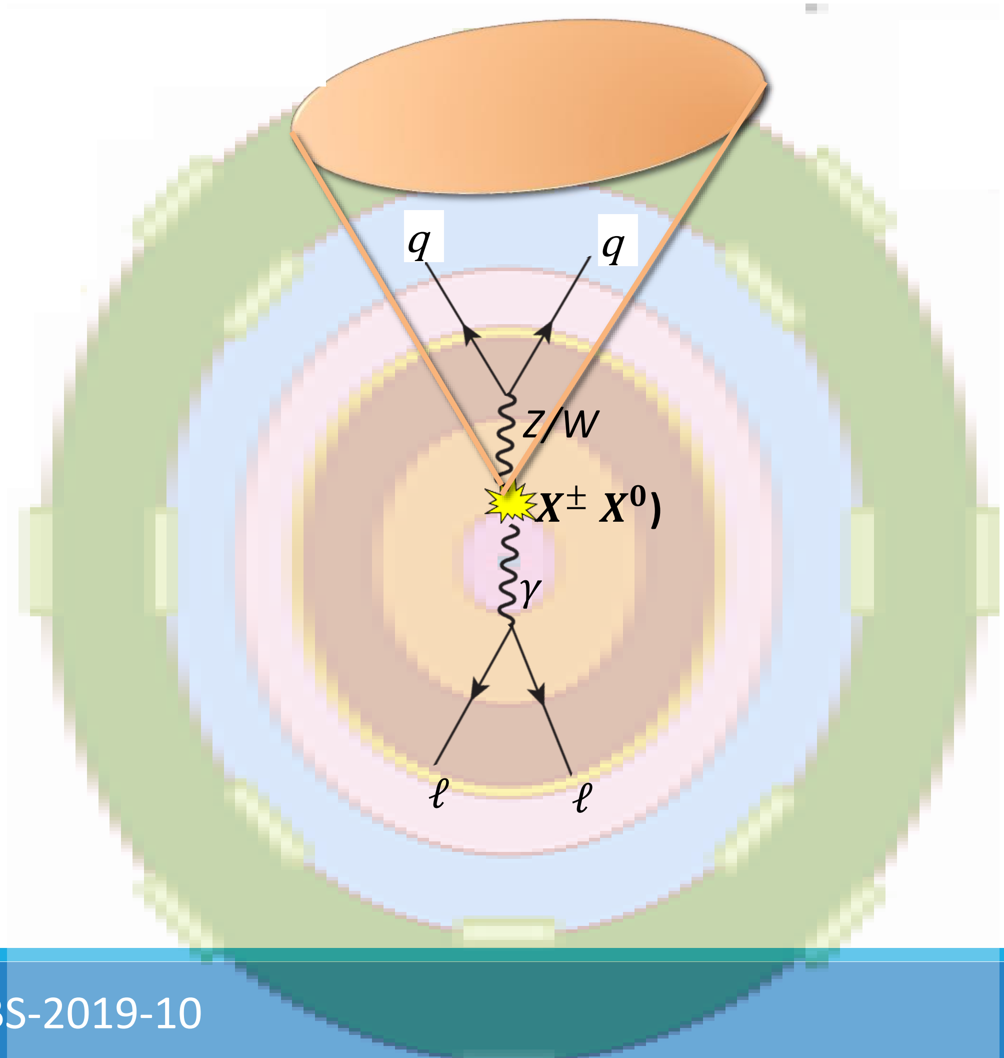
High mass $V\gamma$ search



Search for BSM spin 1 charged ($X^{\pm}$), spin 0/2 neutral bosons (X^{0}) in 1 – 6.8 TeV range

Photon presence helps efficiently select signal/reduce background

High mass $V\gamma$ search



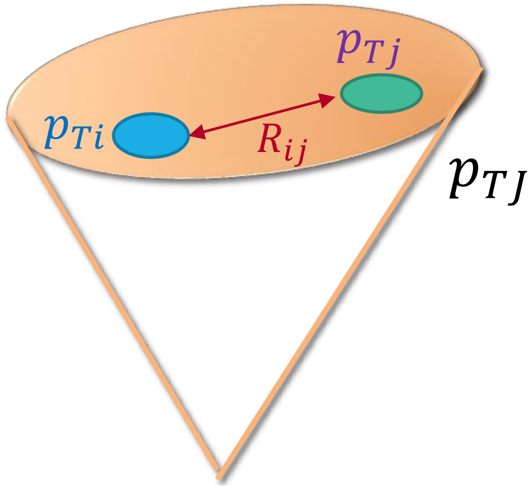
Search for BSM spin 1 charged ($X^{\pm}$), spin 0/2 neutral bosons (X^{0}) in 1 – 6.8 TeV range

Photon presence helps efficiently select signal/reduce background

W/Z is boosted : Jet mass, energy correlation ratio D_2, and b-tagging used to discriminate signal/background

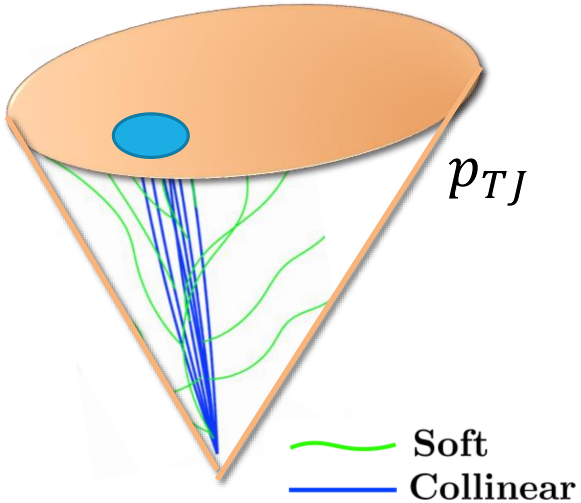
- D_2 exploits 3-prong decays to identify W/Z bosons

$e_2, e_3\ , D_2$ Energy Correlation Ratios



$$e_2 = \frac{1}{p_{TJ} J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

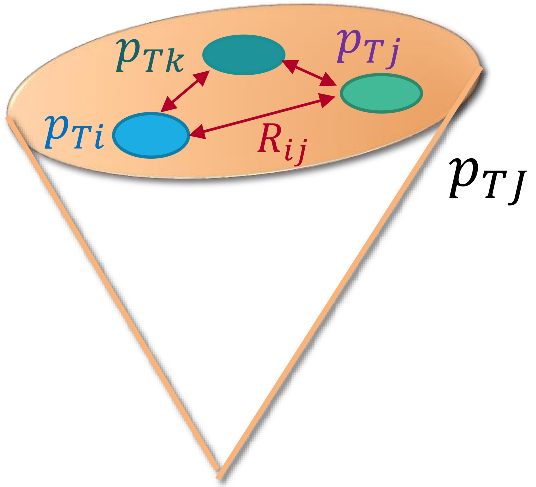
e_2, e_3 , D_2 Energy Correlation Ratios



$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

1-prong jet identification (quark-gluon)

e_2, e_3, D_2 Energy Correlation Ratios

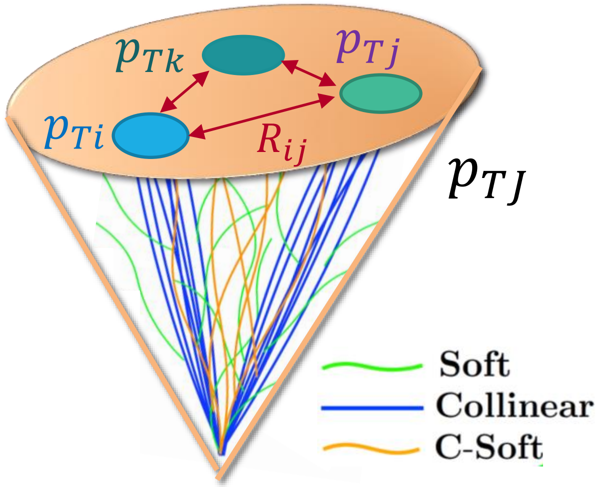


$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

$$e_3 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, p_{Tk} R_{ij}\, R_{ik}\, R_{jk}$$

e_2, e_3, D_2 Energy Correlation Ratios

side BAR

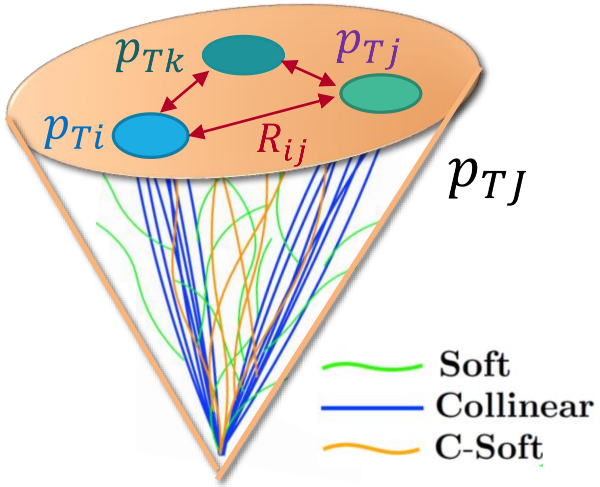


$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

$$e_3 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, p_{Tk} R_{ij}\, R_{ik}\, R_{jk}$$

2-, 3-prong jet identification
(W/Z/H bosons)

e_2, e_3, D_2 Energy Correlation Ratios

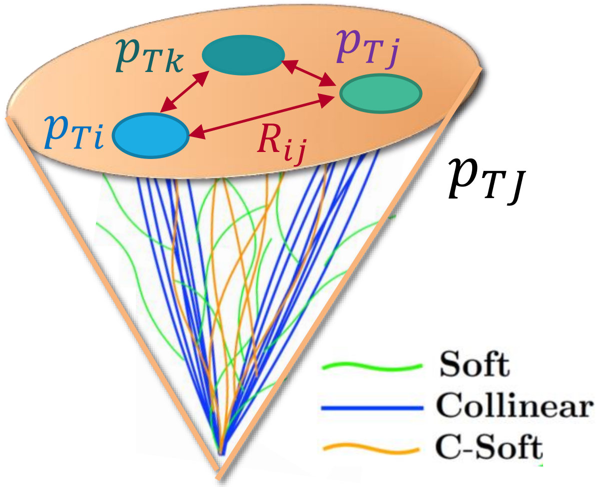


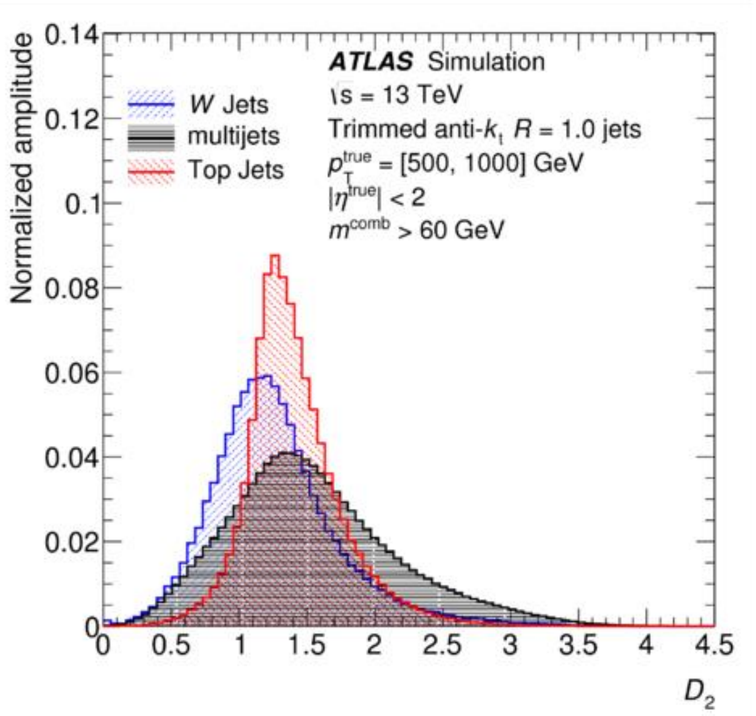
$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

$$e_3 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, p_{Tk} R_{ij}\, R_{ik}\, R_{jk}$$

$$\boldsymbol{D_2} = \frac{\boldsymbol{e_3}}{(\boldsymbol{e_2})^3}$$

$e_2, e_3\ , D_2$ Energy Correlation Ratios





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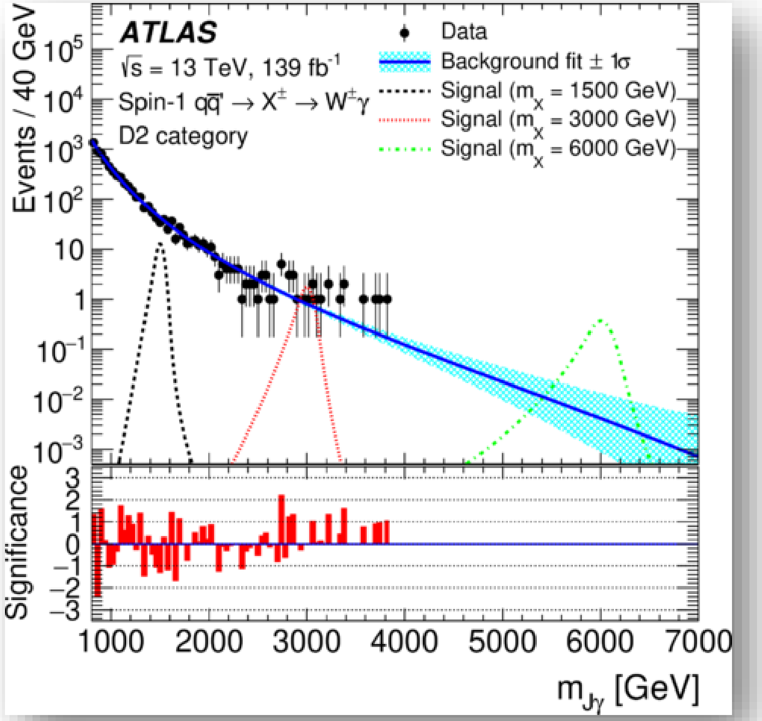
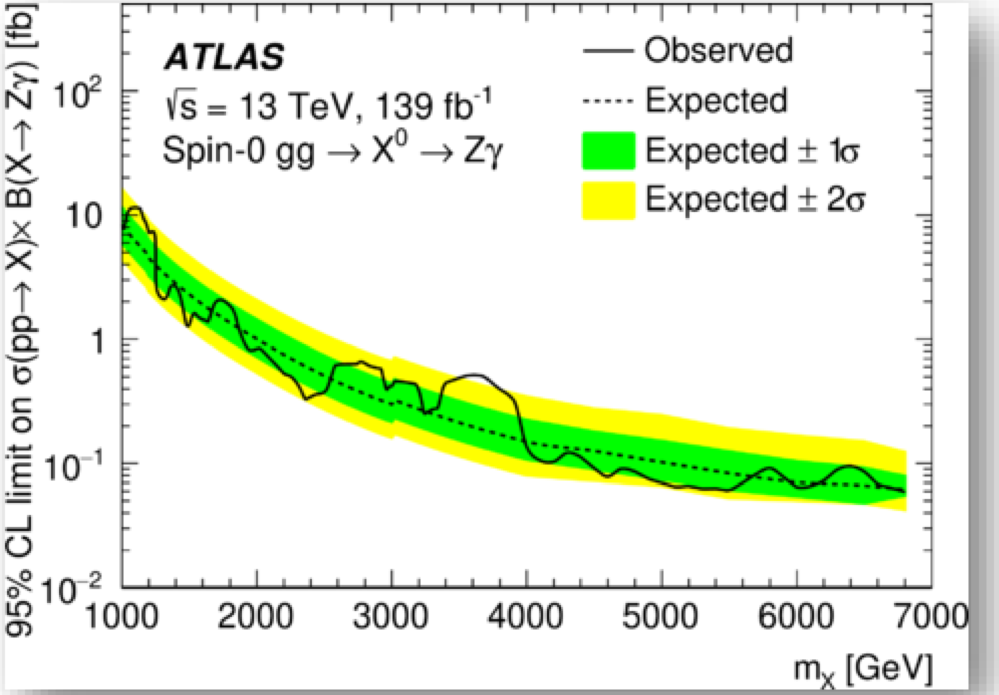
$$D_2 = \frac{e_3}{(e_2)^3}$$

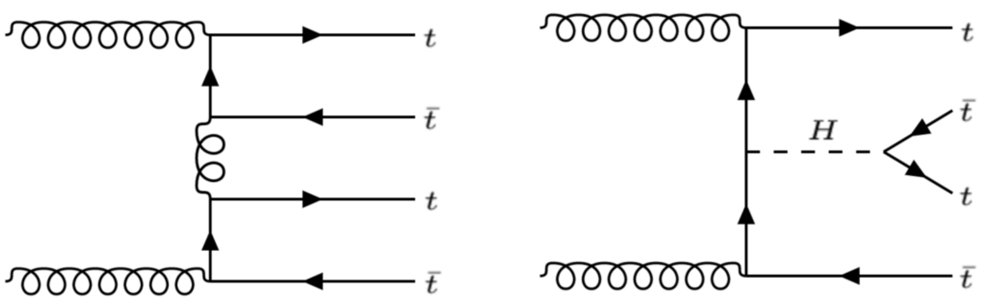
High mass $V\gamma$ search

The SM background from γ+jet, modelled by a function validated in control region
Signal modelled by double-sided crystal ball function





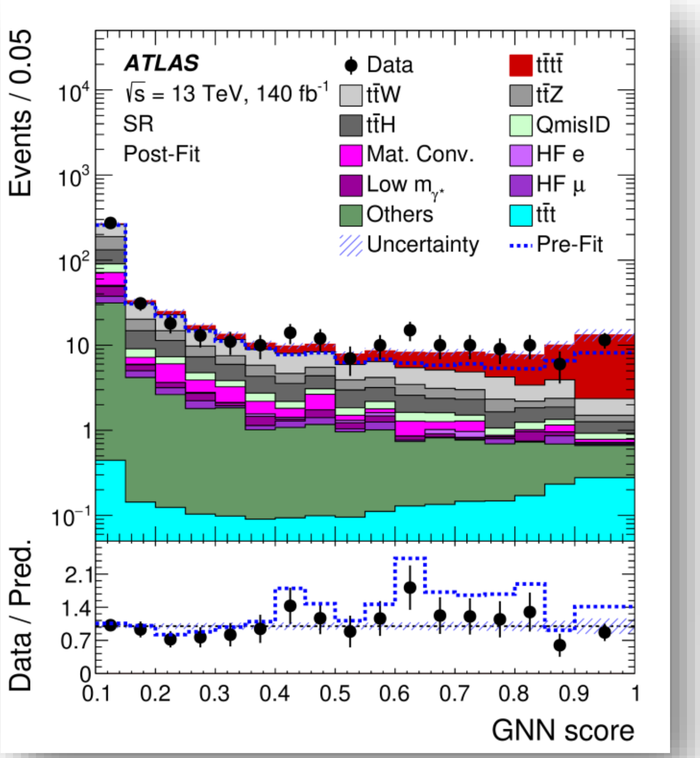
4 top

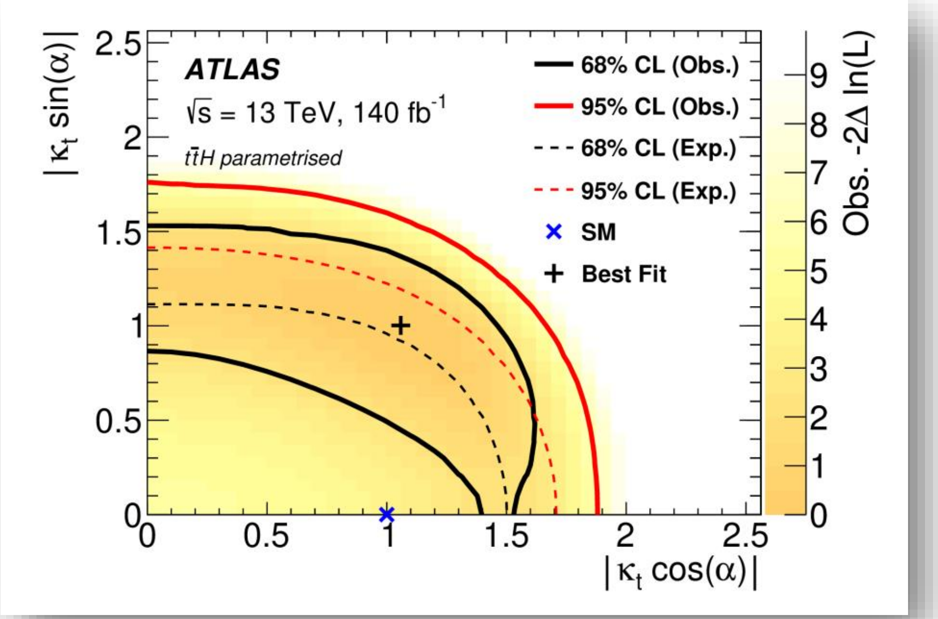


Rare process, sensitive to the strength of the top-quark Yukawa coupling (sensitive to BSM)

A Graph Neural Network (GNN) used to discriminate signal/background, uses object momenta, charge, b-tagging score and E_T^{miss}

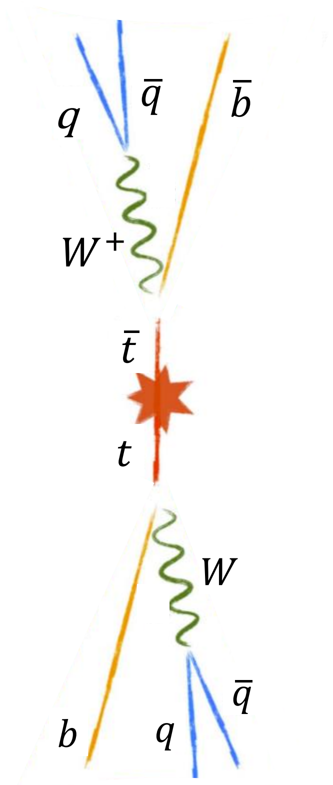
Significance of 6.1σ (4.3 σ) is observed (expected)





κ_t : the top-Higgs Yukawa coupling
α is the mixing of CP even (odd) parts

Jet substructure in boosted $t\bar{t}$

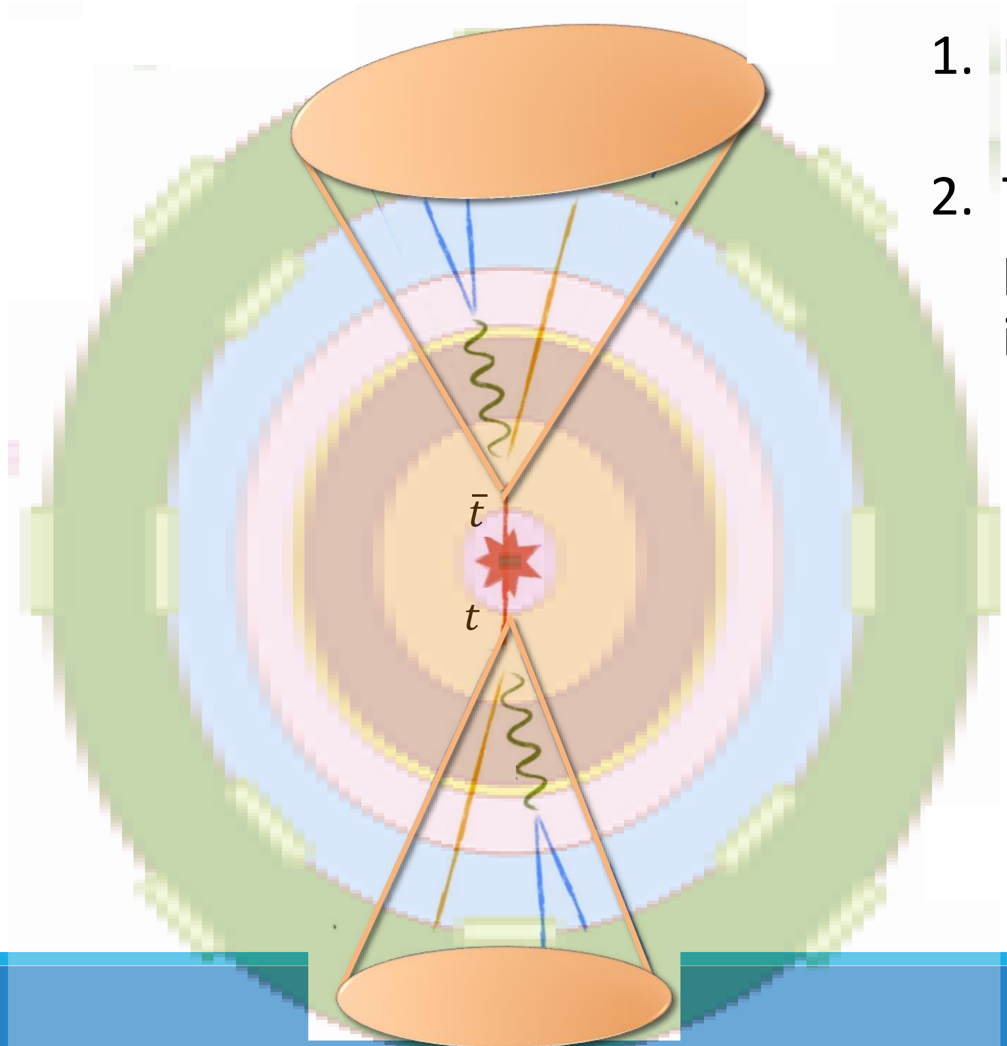


Large $t\bar{t}$ cross section at LHC, boosted t probes QCD $t\bar{t}$ production at the TeV scale (where theory has large uncertainties)

Measuring cross section can reduce uncertainties, precisely measure the SM, and set limits on BSM Effective Field Theory (EFT) operators

Consider hadronic and leptonic final states

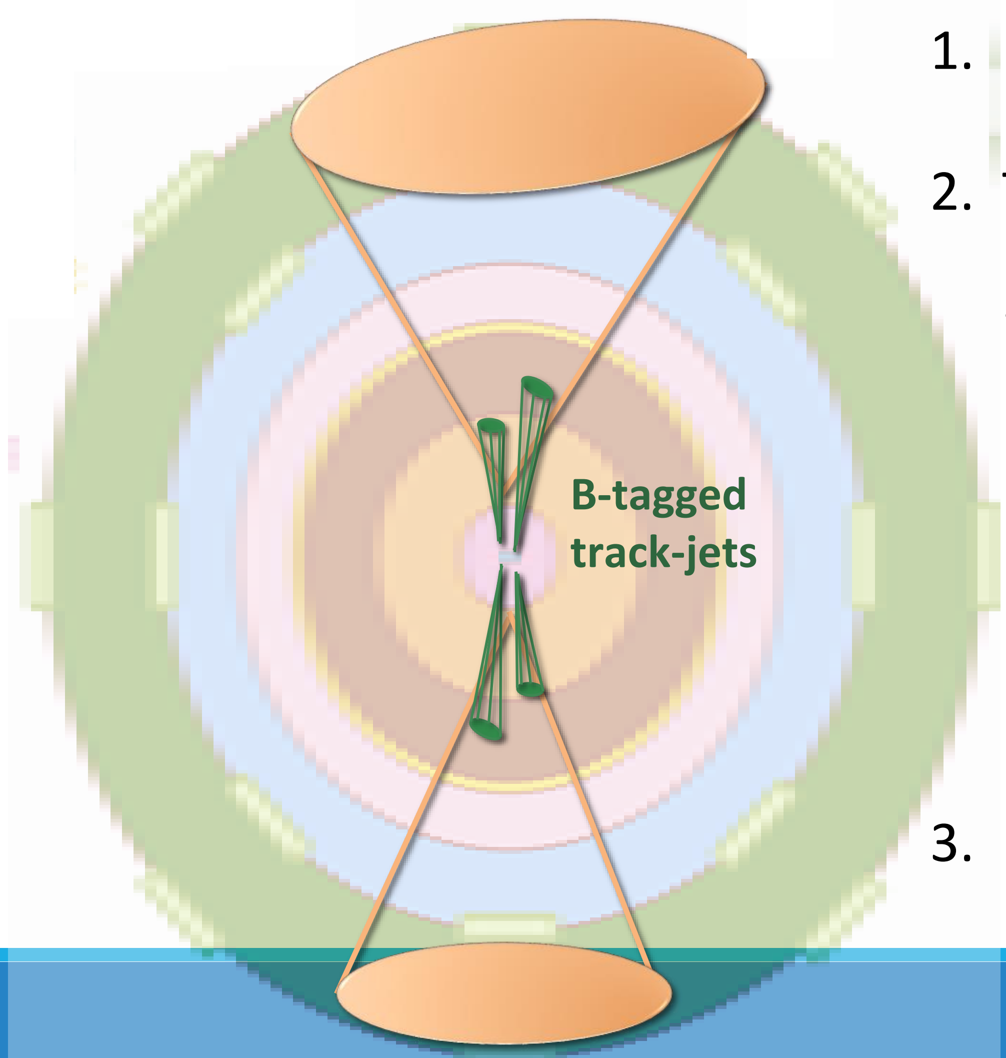
Jet substructure in boosted $t\bar{t}$



1. Require 2 Large R-jets, near top mass

2. Top tag jets: Use Deep Neural Network (DNN) to exploit 3-prong decays and multiple splitting scales of top quarks, inputs:
   - Jet Kinematics : $p_T, m^{combined}$
   - Energy Correlation Ratios: e_3, C_2, D_2
   - N-subjettiness: $\tau_1, \tau_2, \tau_{21}, \tau_3, \tau_{32}$
   - Splitting measures: $\sqrt{d_{12}}, \sqrt{d_{23}}$
   - Q_W

Jet substructure in boosted $t\bar{t}$



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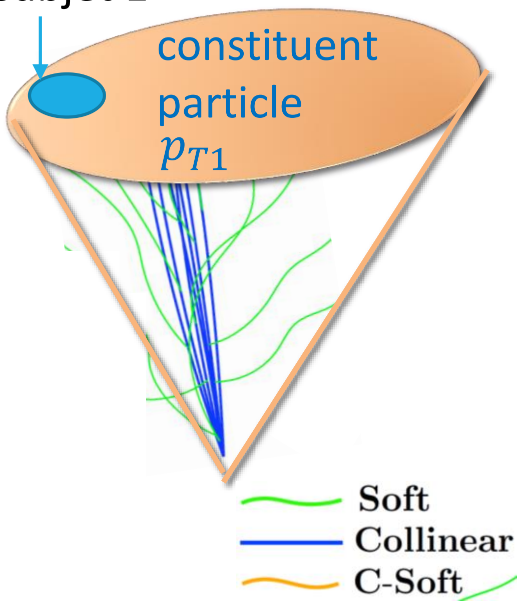
   - Splitting measures: $\sqrt{d_{12}}, \sqrt{d_{23}}$
   - Q_W

3. Match b-tagged track jets (variable size) to both large-R jets

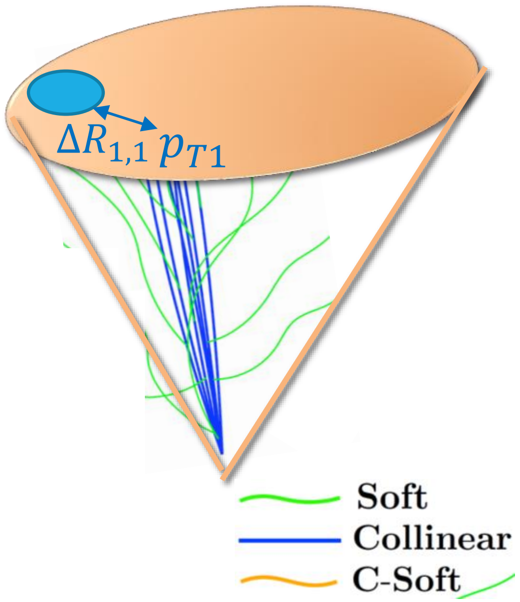
τ_N: to what degree a jet consists of N subjets

R_0 radius



τ_N: to what degree a jet consists of N subjets

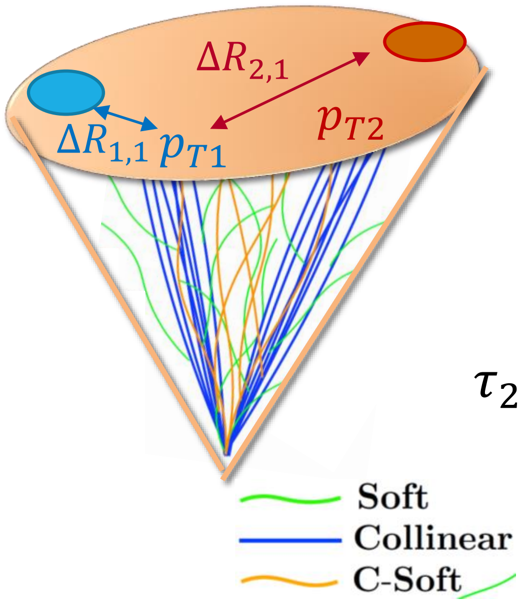
R_0 radius



$$\tau_1 = \frac{1}{d_0} p_{T,1} R_{1,1}$$

$p_{T,1}$ R_0

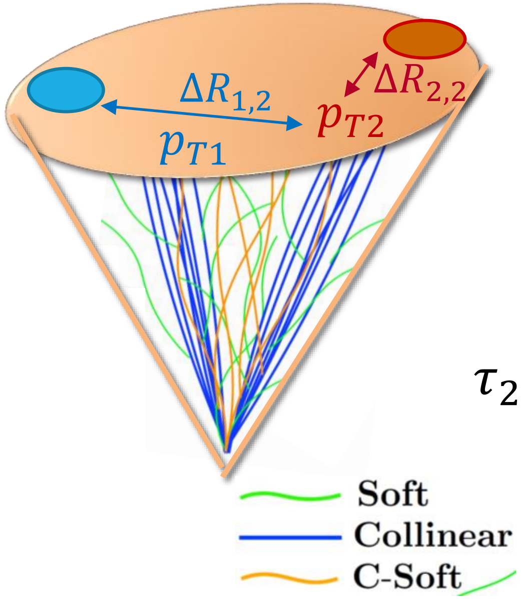
τ_N: to what degree a jet consists of N subjets



$$\tau_1 = \frac{1}{d_0} \, p_{T,1} \, R_{1,1}$$

$$\tau_2 = \frac{1}{d_0} \left[\, p_{T1} \min(\Delta R_{1,1}, \Delta R_{2,1}) + \qquad \right]$$

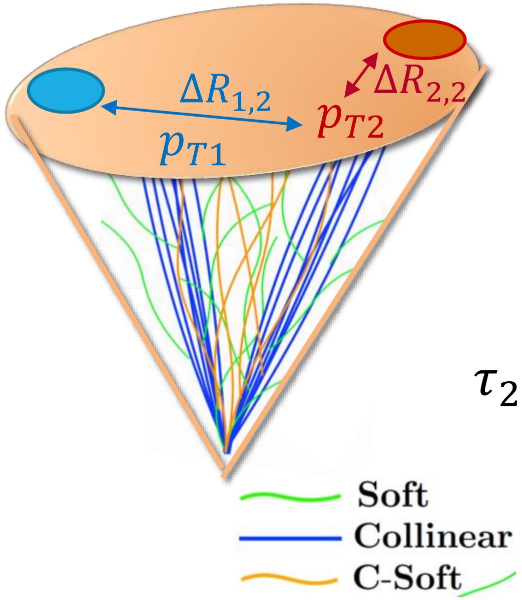
τ_N: to what degree a jet consists of N subjets



$$\tau_1 = \frac{1}{d_0} \, p_{T,1} \, R_{1,1}$$

$$\tau_2 = \frac{1}{d_0} \left[\, p_{T1} \min\left(\Delta R_{1,1}, \Delta R_{2,1}\right) + p_{T2} \min\left(\Delta R_{1,2}\, , \Delta R_{2,2}\right) \right]$$

τ_N: to what degree a jet consists of N subjets



$$\tau_1 = \frac{1}{d_0} p_{T,1} R_{1,1}$$

$$\tau_2 = \frac{1}{d_0} \left[p_{T1} \min(\Delta R_{1,1}, \Delta R_{2,1}) + p_{T2} \min(\Delta R_{1,2}, \Delta R_{2,2}) \right]$$

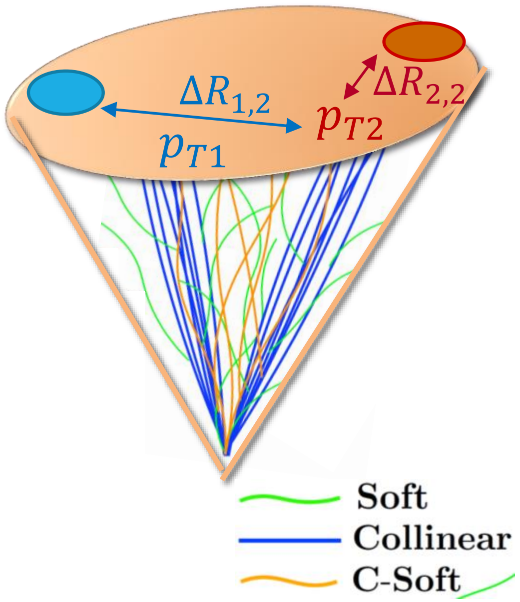
$$(p_{T,1} + p_{T,2}) R_0$$

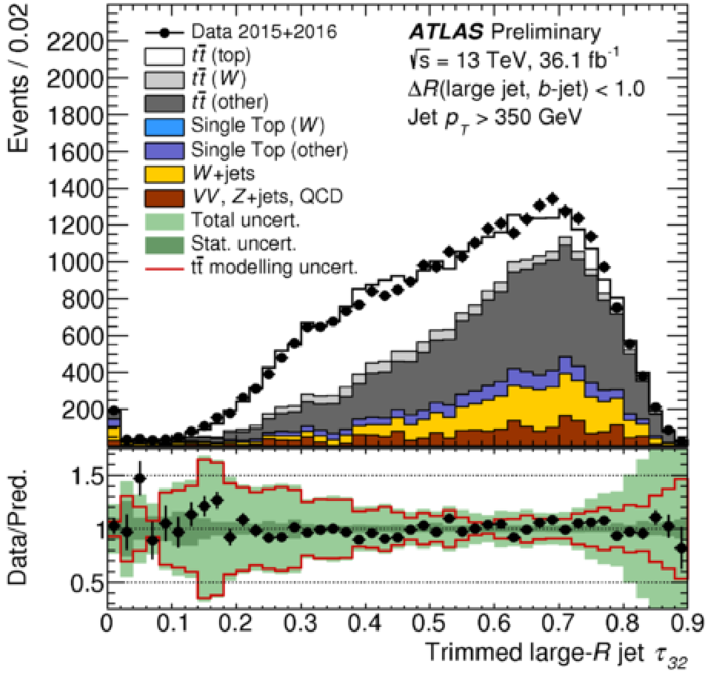
Lower τ → radiation is aligned with subjet

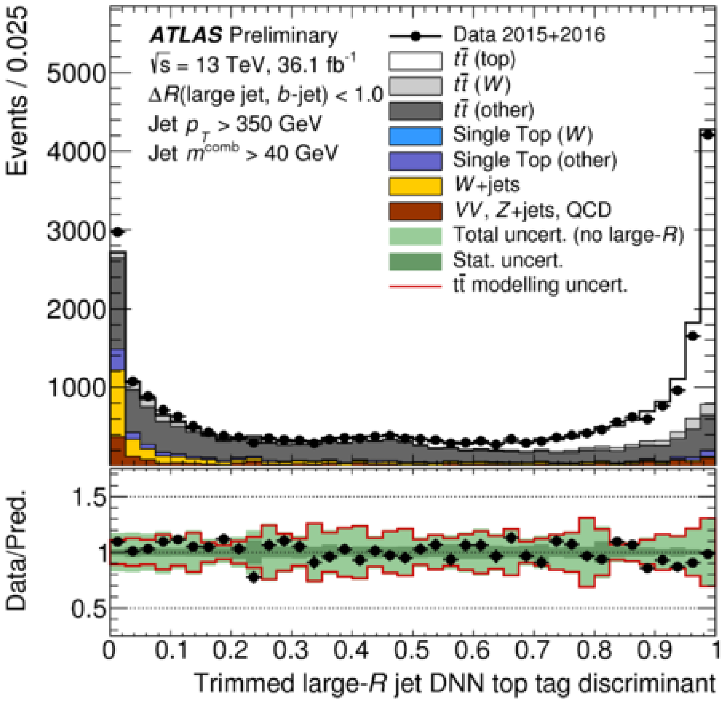
Higher τ → large fraction of jet energy is far away from subjets

$$\tau_{21} = \frac{\tau_2}{\tau_1}, \quad \tau_{32} \ \ldots etc.$$

τ_N: to what degree a jet consists of N subjets







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$$\tau_{21} = \frac{\tau_2}{\tau_1}, \quad \tau_{32} \; \ldots etc.$$

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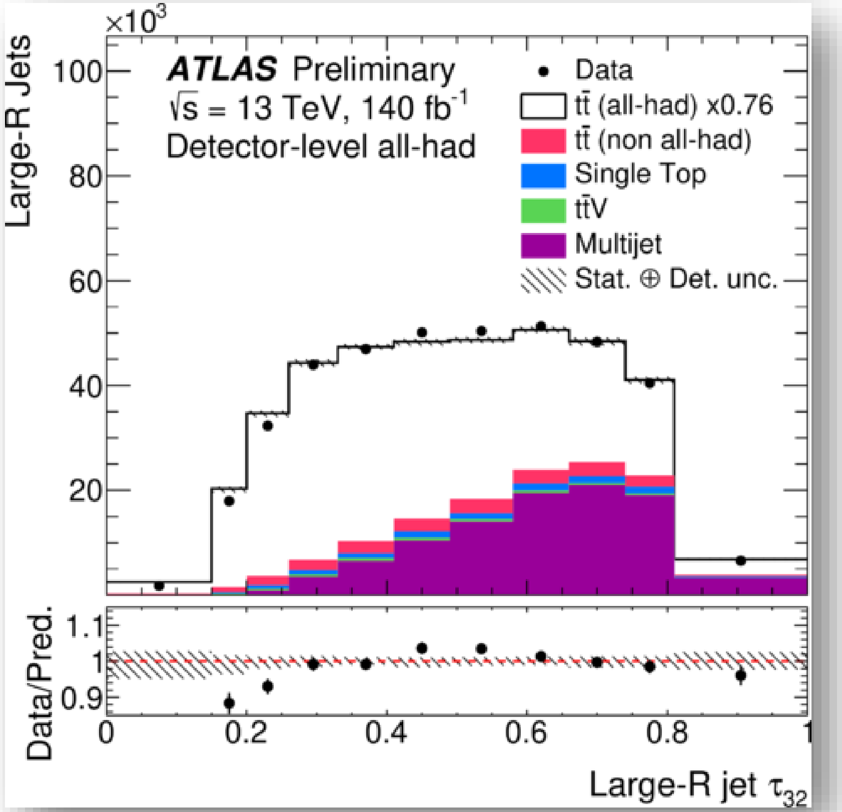
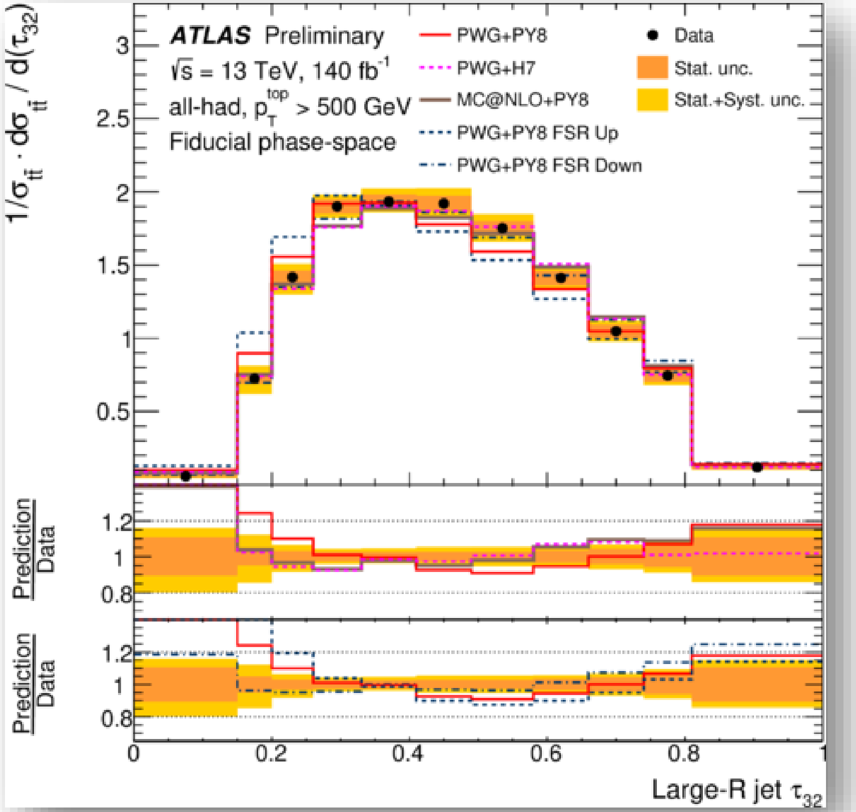
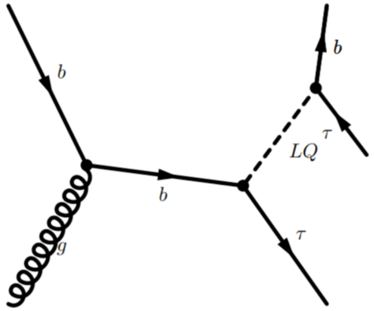
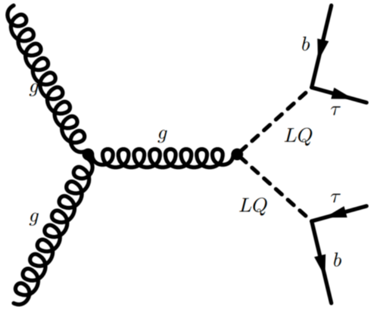
Jet substructure in boosted $t\bar{t}$





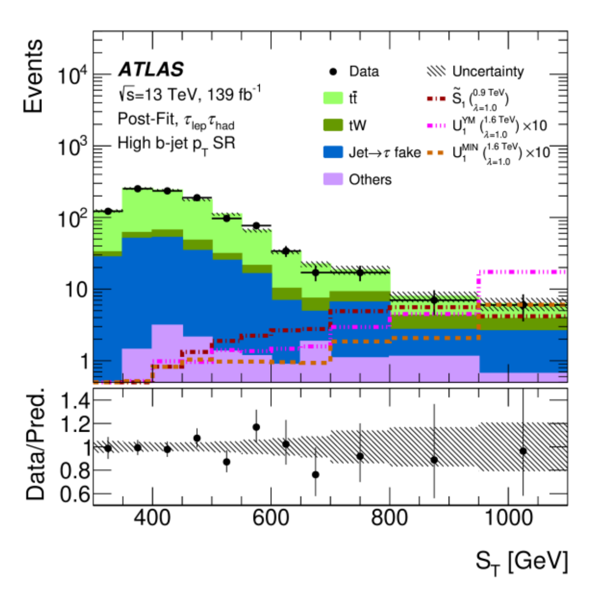
Leptoquark → $b\tau$

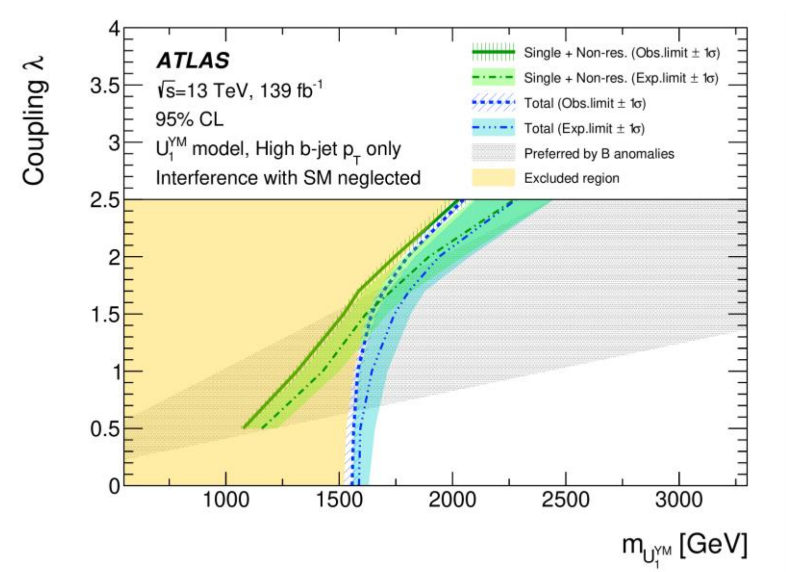


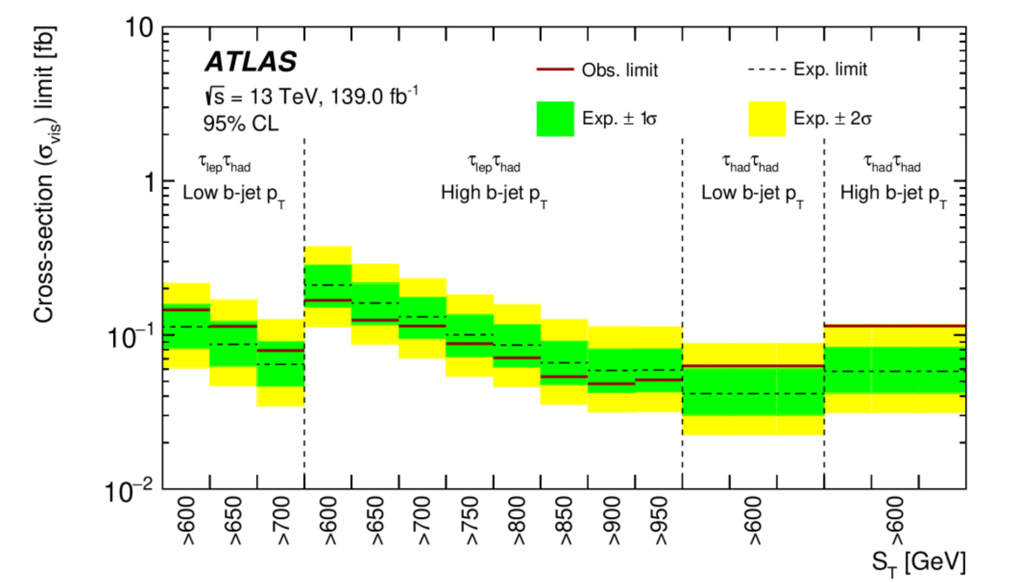


Renewed interest in leptoquarks with appearance of B-anomalies

Scaler and Vector LQ production (Yang-Mills and Minimal coupling models) considered, cross –section limits set







S_T: the scalar p_T sum of the leading b-jet and 2 τ two τhad-vis

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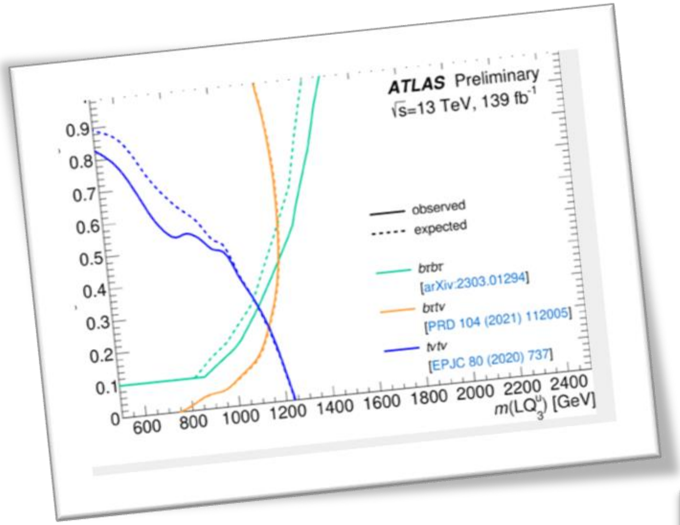
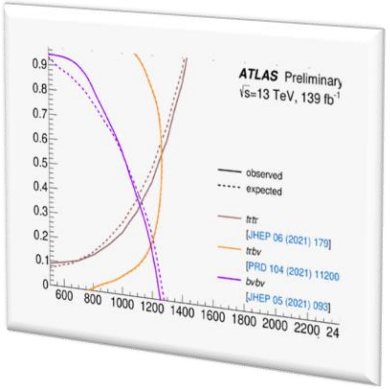
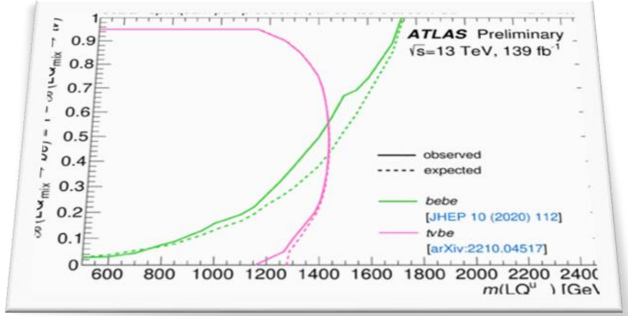
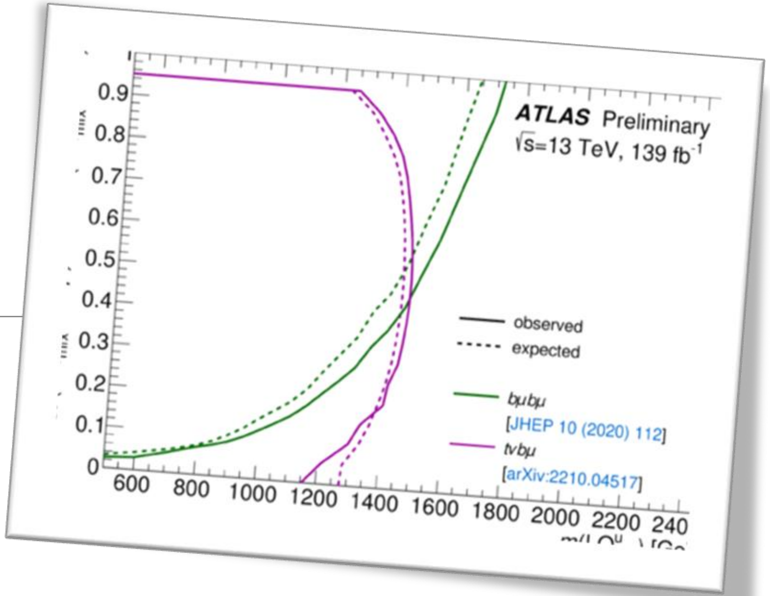
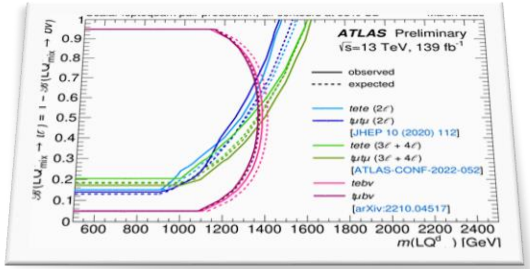
Leptoquark Summary plots

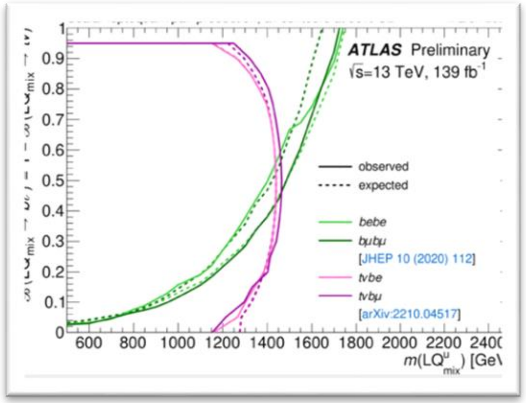


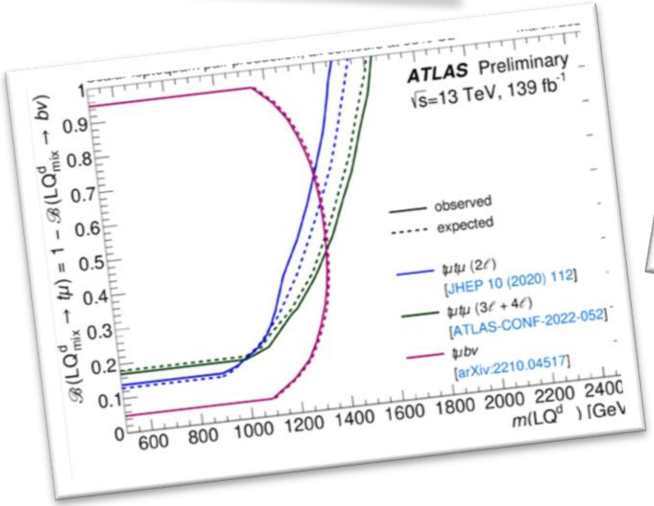


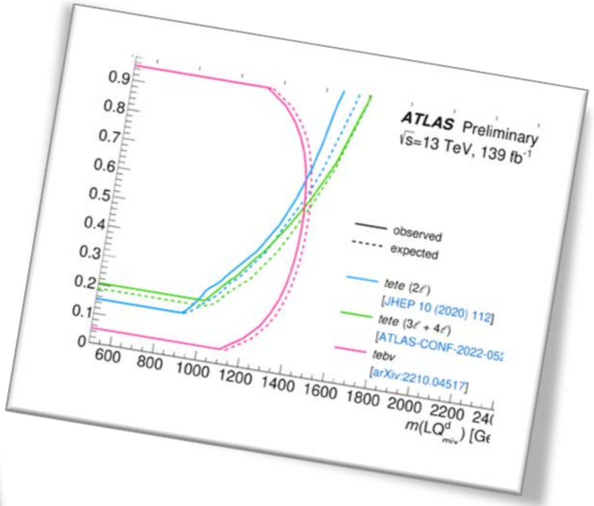




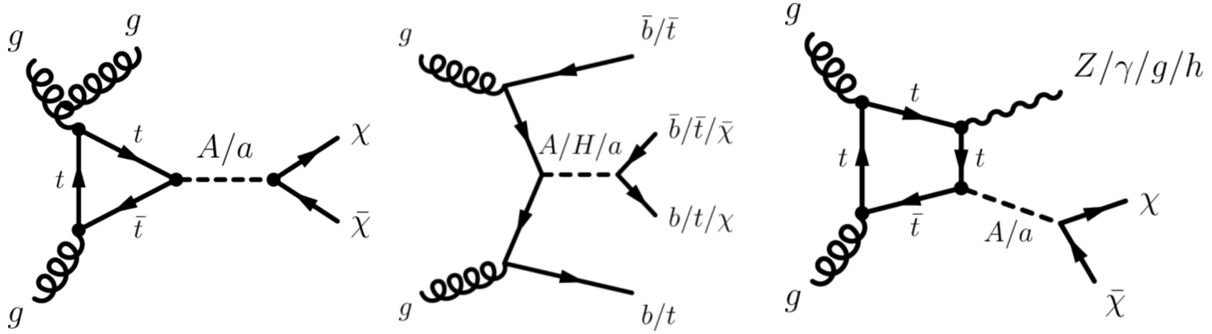








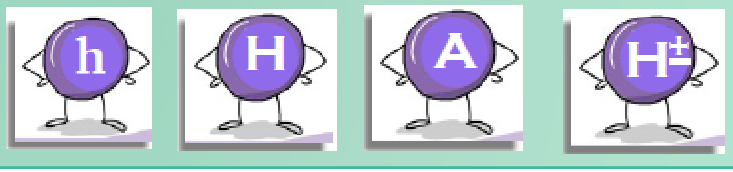
2HDM + a, Dark Matter Combination



Two Higgs Doublet Model

SM ➕ Higgs doublet 〓

	Neutral		Charged
CP Even		CP Odd	



7 parameters:

$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{12},\ \tan\beta\ ,\ \ \alpha$

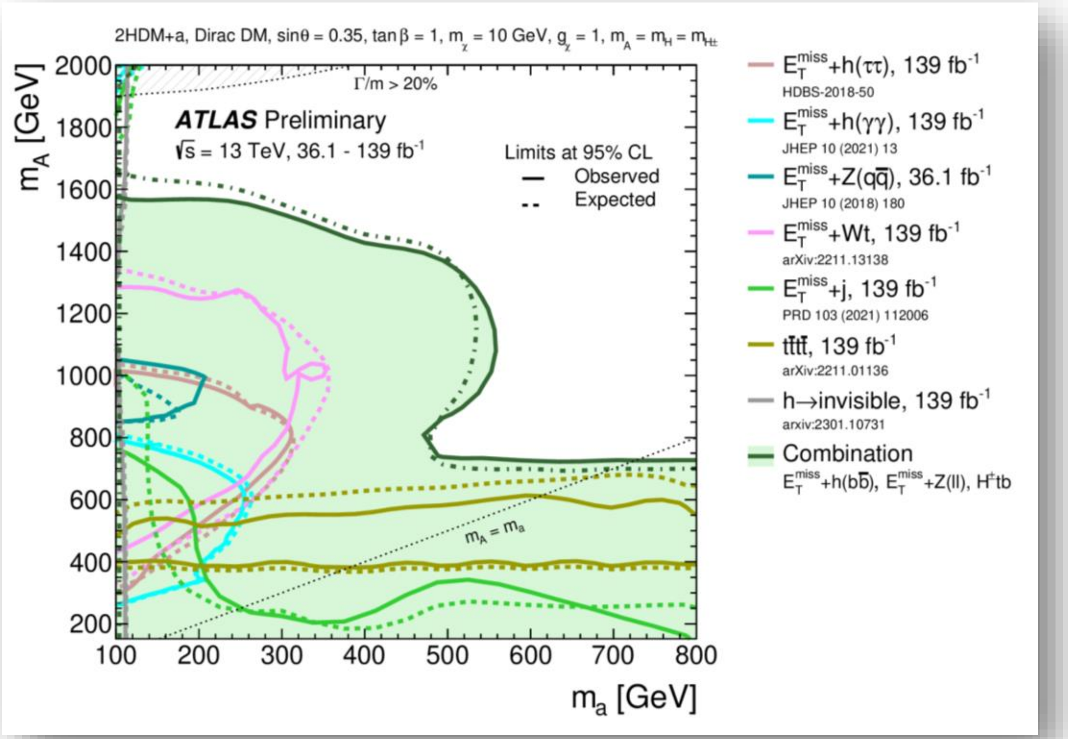
Ratio of VEV of Φ_1 and Φ_2

h & H mixing angle

+ mediator pseudo-scaler, a

3 most sensitive searches combined statistically

- E_T^{miss} + Z→ $\ell\ell$, E_T^{miss} + H → $b\bar{b}$, H^+tb



Summary

Overviews of measurements and searches provided

- ATLAS has the most precise W mass measurement
- ATLAS has the most precise α_S measurement using Z p_T
- Differential cross sections of $H \rightarrow WW$ shown, and evidence for $H \rightarrow Z\,\gamma$ provided
- WW scattering & 4ℓ cross sections presented, plus Majorana neutrinos shown
- High mass $V\gamma$ searches search for massive new particles, $X^0, X^\pm$
- 4t and boosted $t\bar{t}$ production cross sections shown
- Leptoquark searches and combination plots show no evidence of LQ
- 2HDM + a, Dark Matter combination show no evidence for 2HDM + Dark matter

Backup

Observable	W-Boson Tagging BDT	W-Boson Tagging DNN	Top-Quark Tagging BDT	Top-Quark Tagging DNN
m^{comb}	$\circ$	$\circ$	$\circ$	$\circ$
p_{T}	$\circ$	$\circ$	$\circ$	$\circ$
e_3	$\circ$		$\circ$	$\circ$
C_2		$\circ$		$\circ$
D_2	$\circ$	$\circ$	$\circ$	$\circ$
τ_1	$\circ$			$\circ$
τ_2			$\circ$	$\circ$
τ_3				$\circ$
τ_{21}	$\circ$	$\circ$	$\circ$	$\circ$
τ_{32}			$\circ$	$\circ$
R_2^{FW}	$\circ$	$\circ$		
$\mathcal{P}$	$\circ$	$\circ$		
a_3	$\circ$	$\circ$		
A	$\circ$	$\circ$		
Z_{CUT}		$\circ$		
$\sqrt{d_{12}}$	$\circ$	$\circ$	$\circ$	$\circ$
$\sqrt{d_{23}}$			$\circ$	$\circ$
$KtDR$	$\circ$	$\circ$		
Q_w			$\circ$	$\circ$