Searches for high-mass resonances with the ATLAS detector

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on behalf of the ATLAS collaboration
21/4/2020

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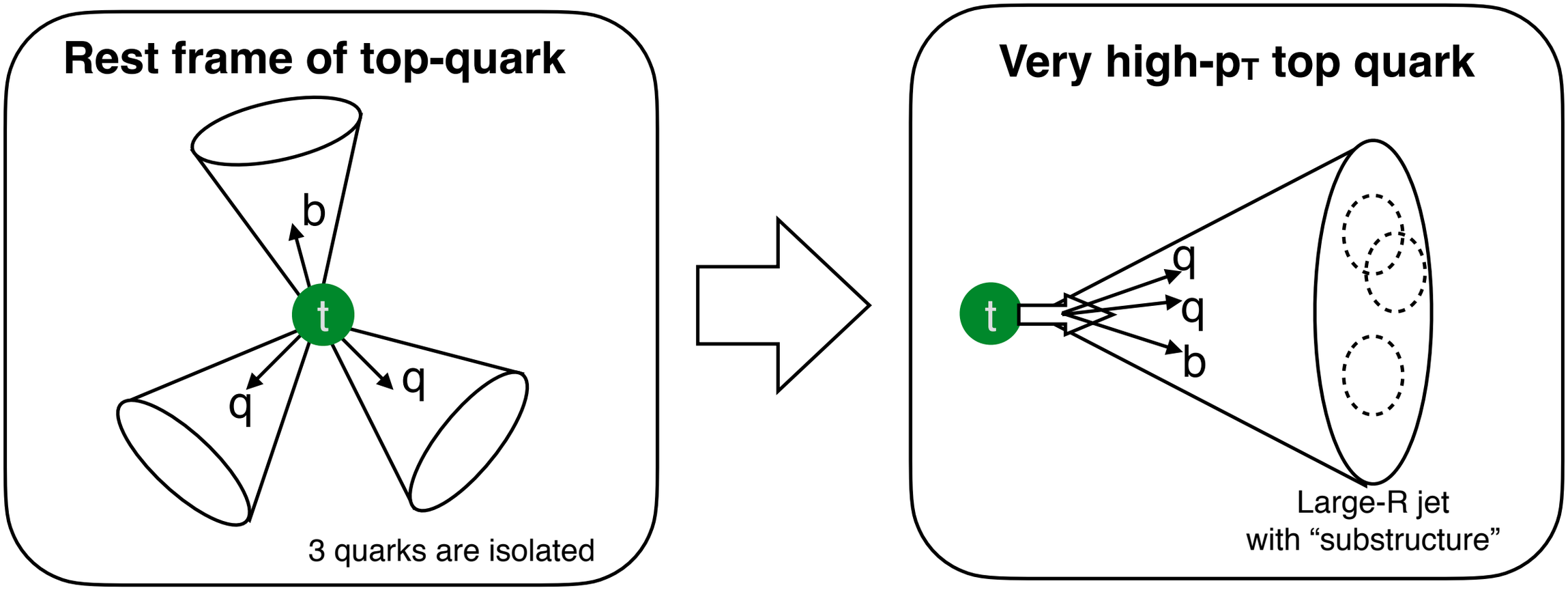
Introduction

- The Standard Model is well established for physics at O(100)GeV
- There are many mysteries not described by the SM e.g. hierarchy problem, which is a question why EW scale is 10^{17} times smaller than Planck scale
- Many new physics models beyond the SM to solve it
  - Supersymmetry, extra dimensions, composite Higgs, …
- Most of them predict **new particles at TeV energy scale**
- ATLAS searches for these signals as less dependent on theoretical models as possible
- This talk presents new ATLAS results of searches for heavy resonances decaying to **diboson** and **$t\bar{t}$** using full-run2 dataset 139 fb^{-1}
- Reference (will be updated soon): https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - CERN-EP-2020-049 and CERN-EP-2020-055

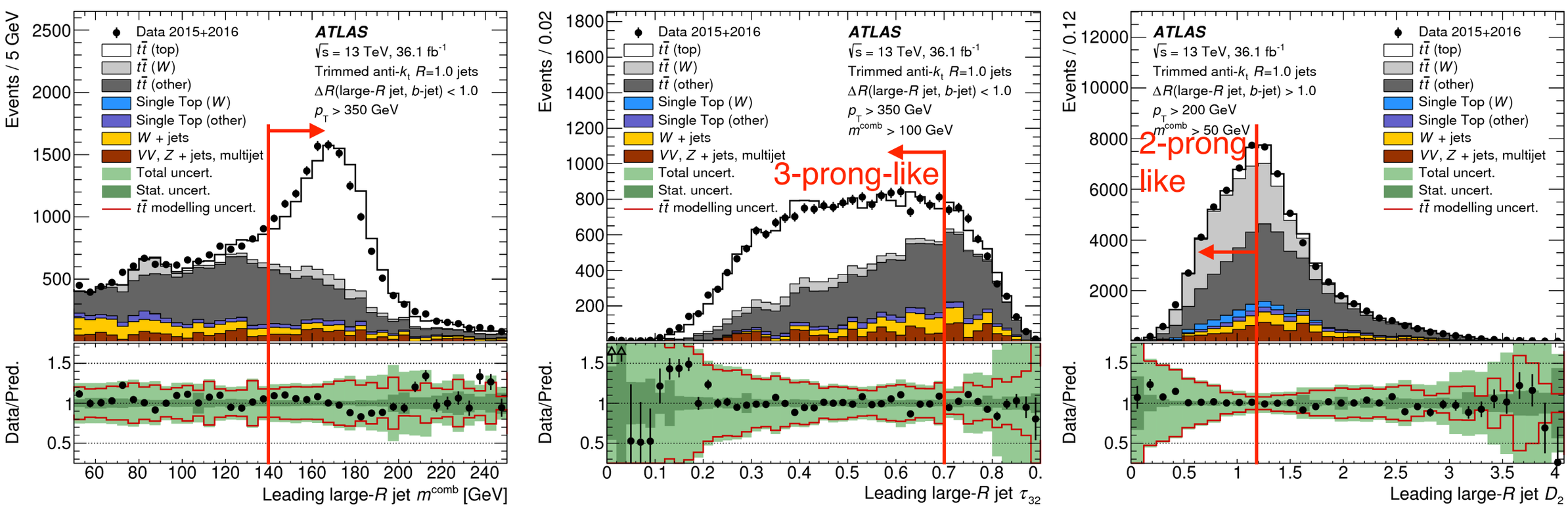
Introduction

- An important technique at m>1TeV: **boosted object tagging**
  - Hadronically-decaying W/Z bosons and top quarks are reconstructed as one **large-R jet** (anti-kT R=1.0)
  - Studies of **jet substructure** variables are improved significantly during run-2



Legacy boosted object tagging

- Using large-R jet reconstructed by calorimeter clusters
- Rectangular cuts on jet **mass** and **substructure variable** are applied to enhance signals
  - Top tagger: mass + N-subjettiness (τ_{32}). 80% efficiency v.s. bkg rejection of 5-20 depending on p_T
  - W/Z tagger: mass + energy correlation function ratio (D_2). 50% efficiency v.s. bkg rejection 50-60
- Many other substructure variables were also tried and τ_{32} and D_2 were chosen to show the best performances



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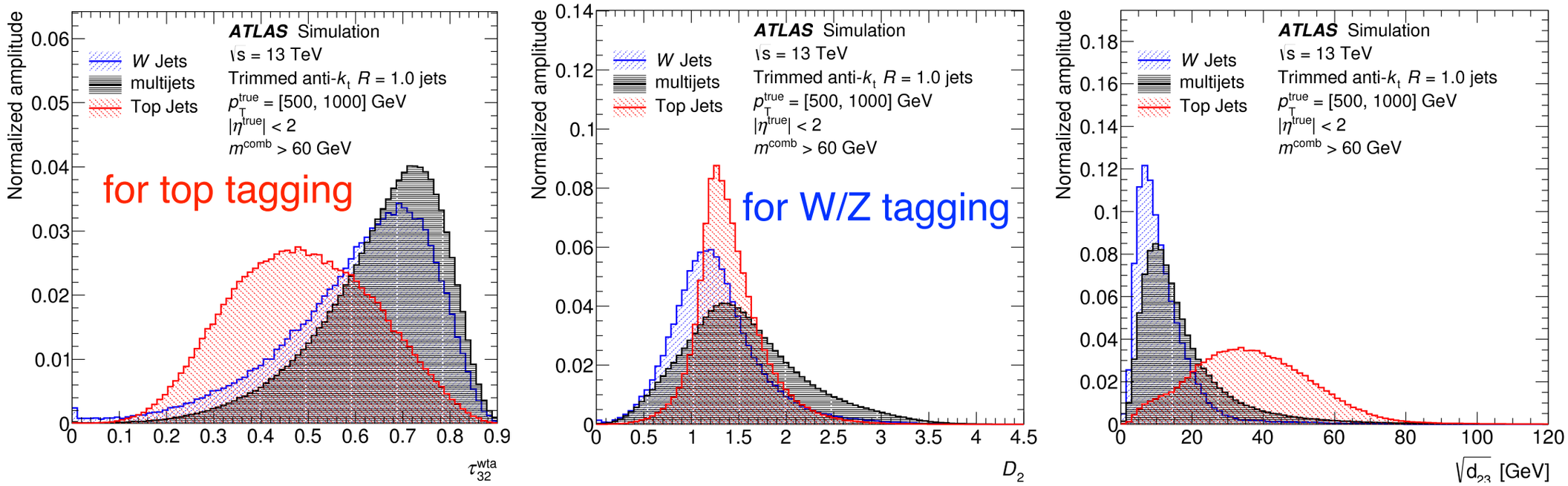
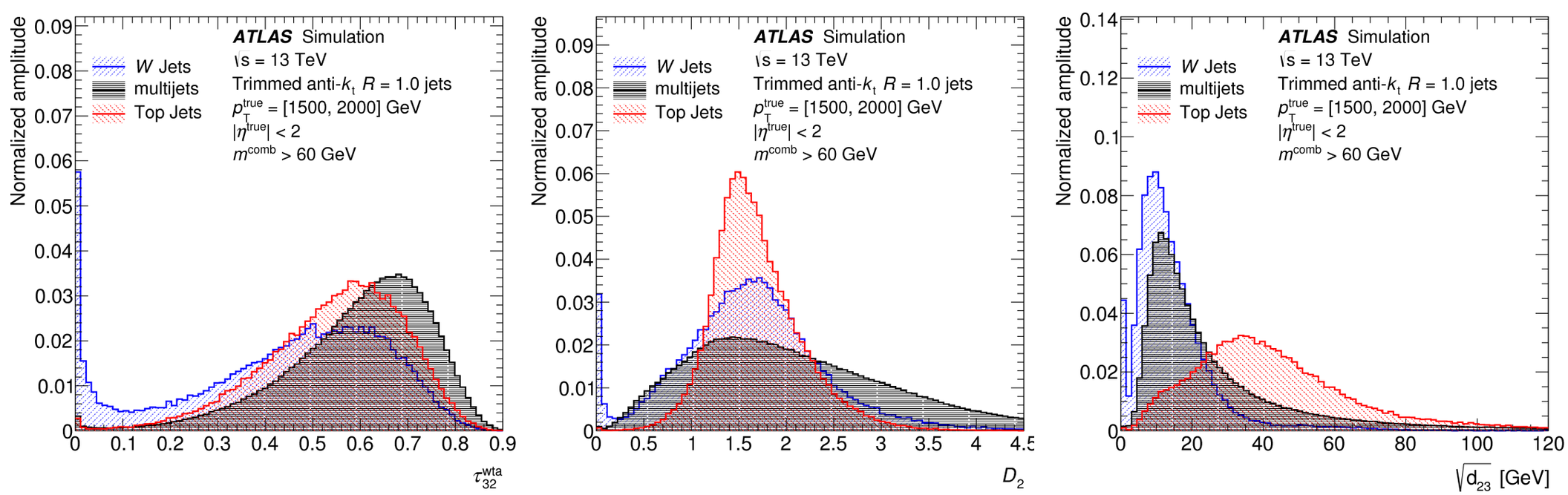
Studies of the substructure variables

- Each substructure variable has strong and weak phase spaces
- Separation power of τ_{32} is degrading at very high-p_T region, due to the angular resolution of calorimeter clusters

p_T<1TeV



p_T>1.5TeV



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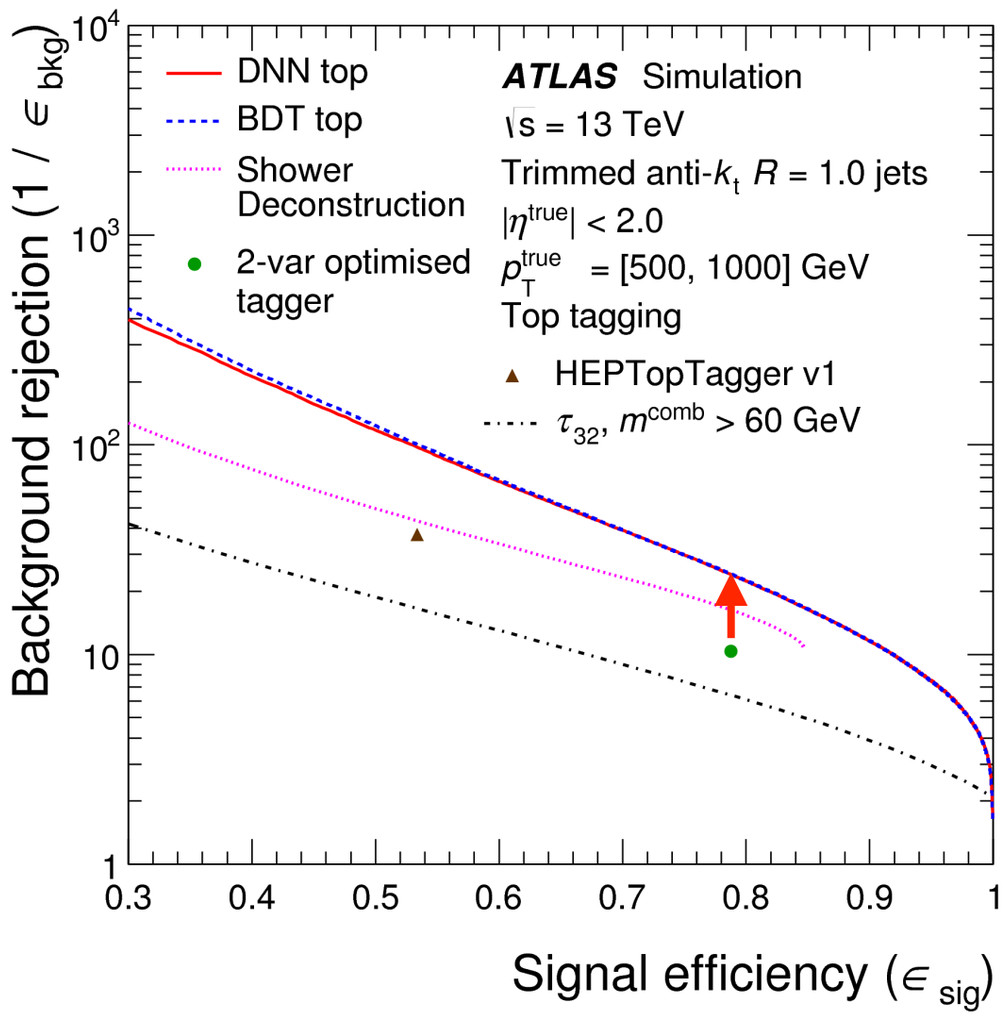
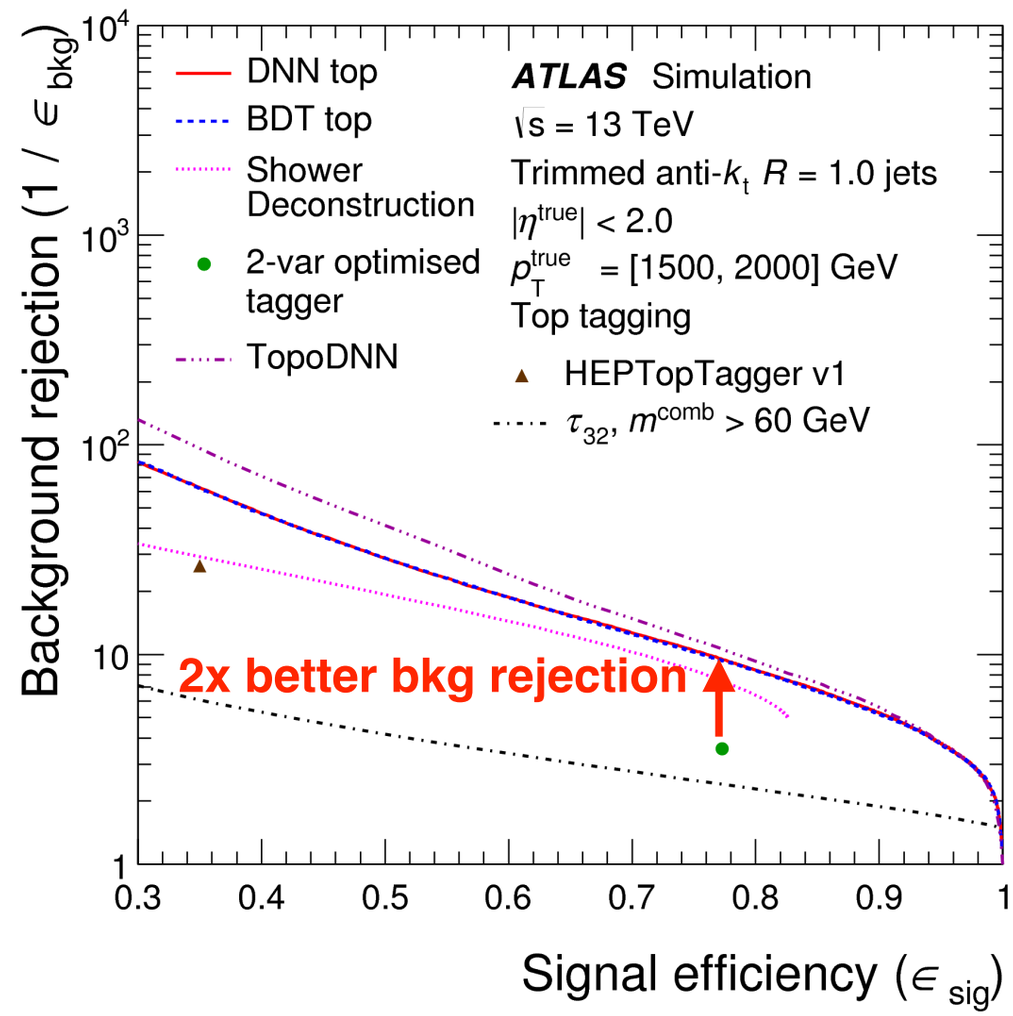
DNN-based boosted top tagger

- Multi-variate analysis based on DNN to combine several jet substructure variables
- Supervised training to separate top-jet from QCD-jet bkg





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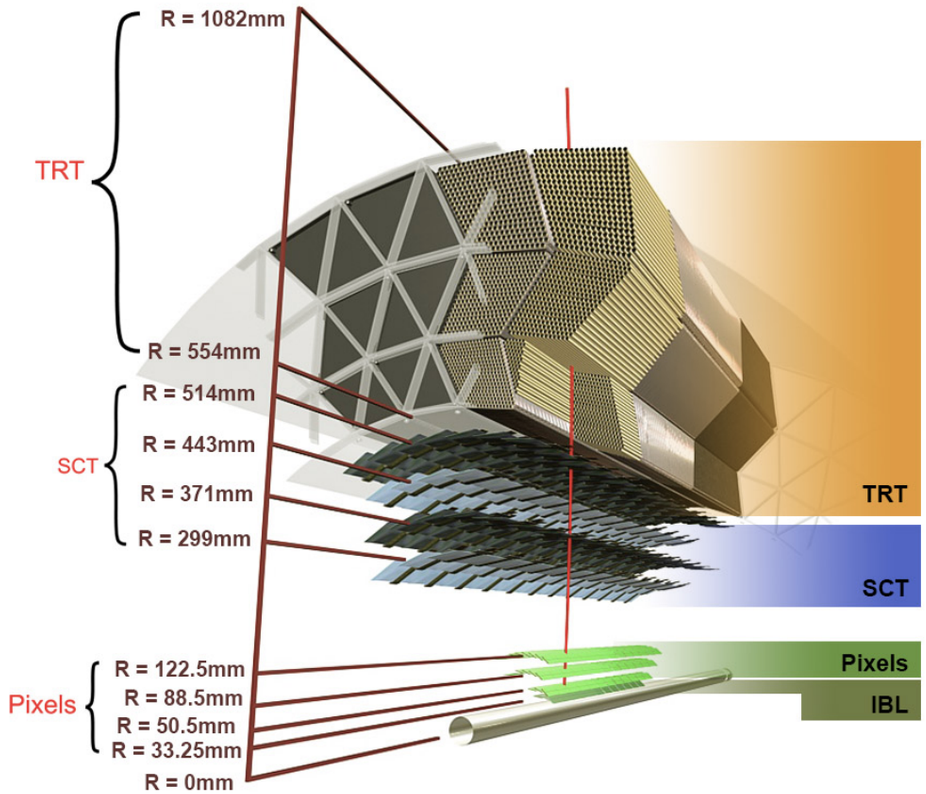
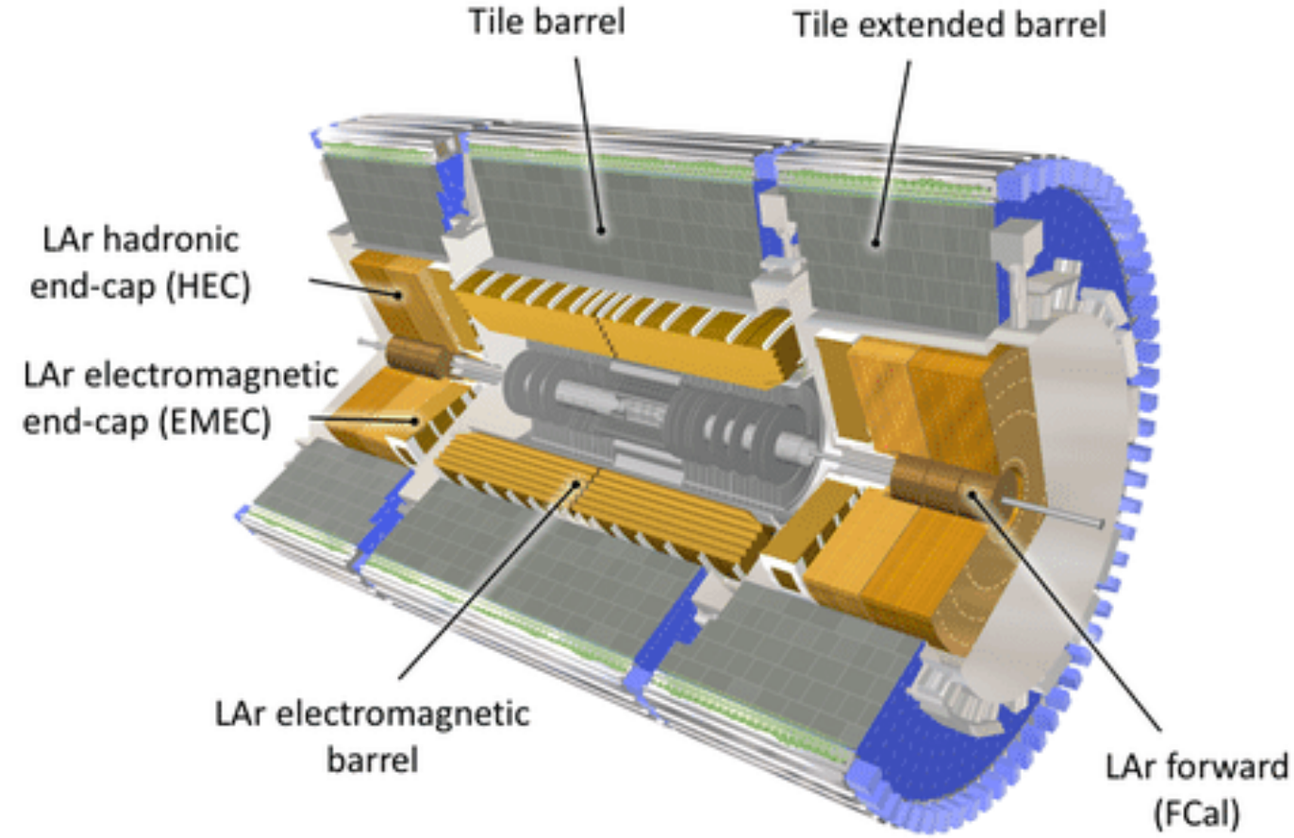
ID tracker v.s. calorimeter





- **$\sigma(p_T)/p_T = 0.05\% p_T \oplus 1\%$**
- $\Delta\Phi \sim 10\mu rad$

- **$\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$**
- Read-out granularity: $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$

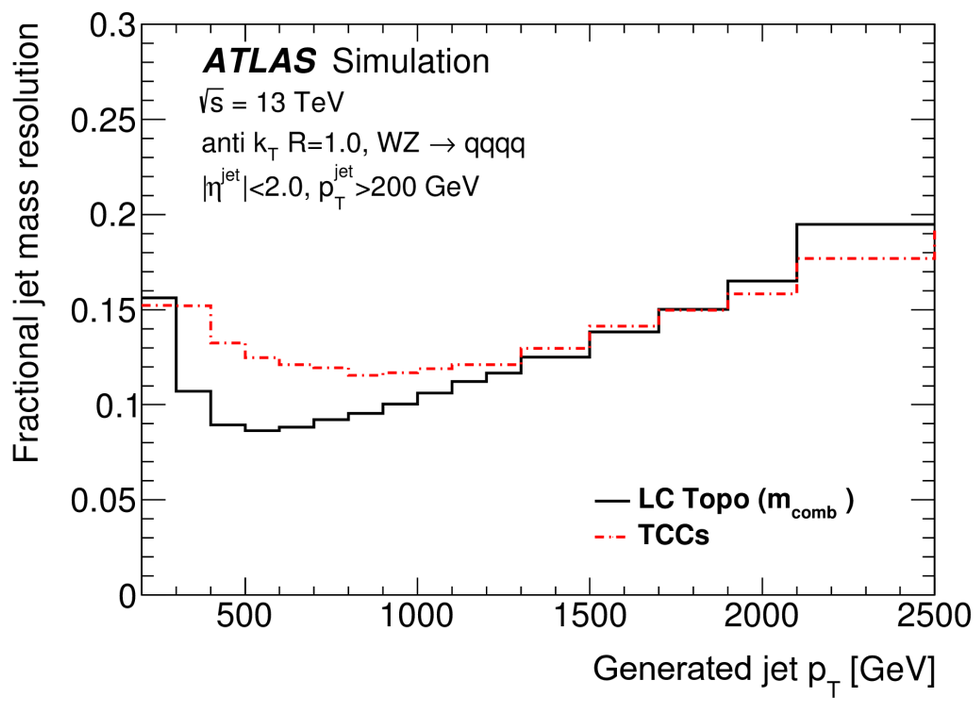
- Resolution of substructure variables gets worse at high-p_T region due to the angular resolution of calorimeter
- Support of ID tracks can improve it

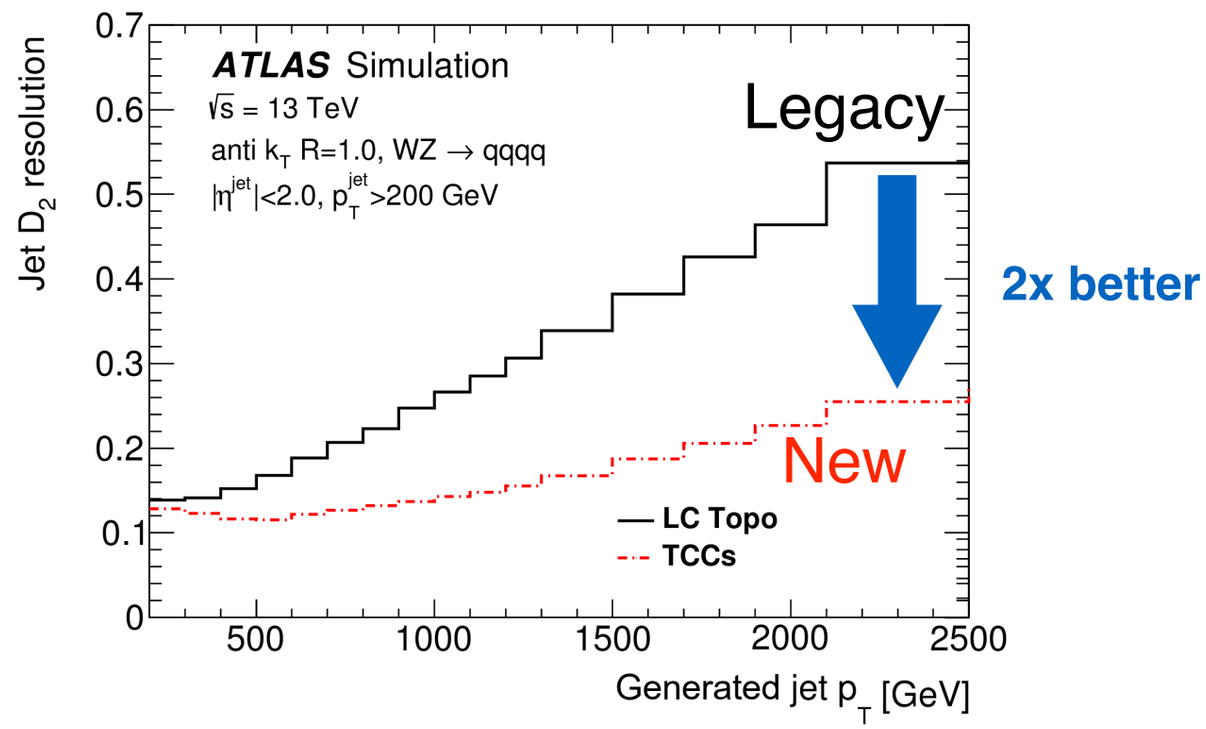
A new p-flow-like algorithm dedicated to high-p_T jets

- **TrackCalo Cluster (TCC)**: a combination of excellent energy resolution of calorimeter and angular resolution of ID tracks at very high-p_T region

- As with standard p-flow algorithm, take a matching between calo cluster and ID tracks, then, use calorimeter observables for charged-particle energy and ID track observables for charged-particle angles

- Compare its performances with legacy calorimeter jet:
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-31/





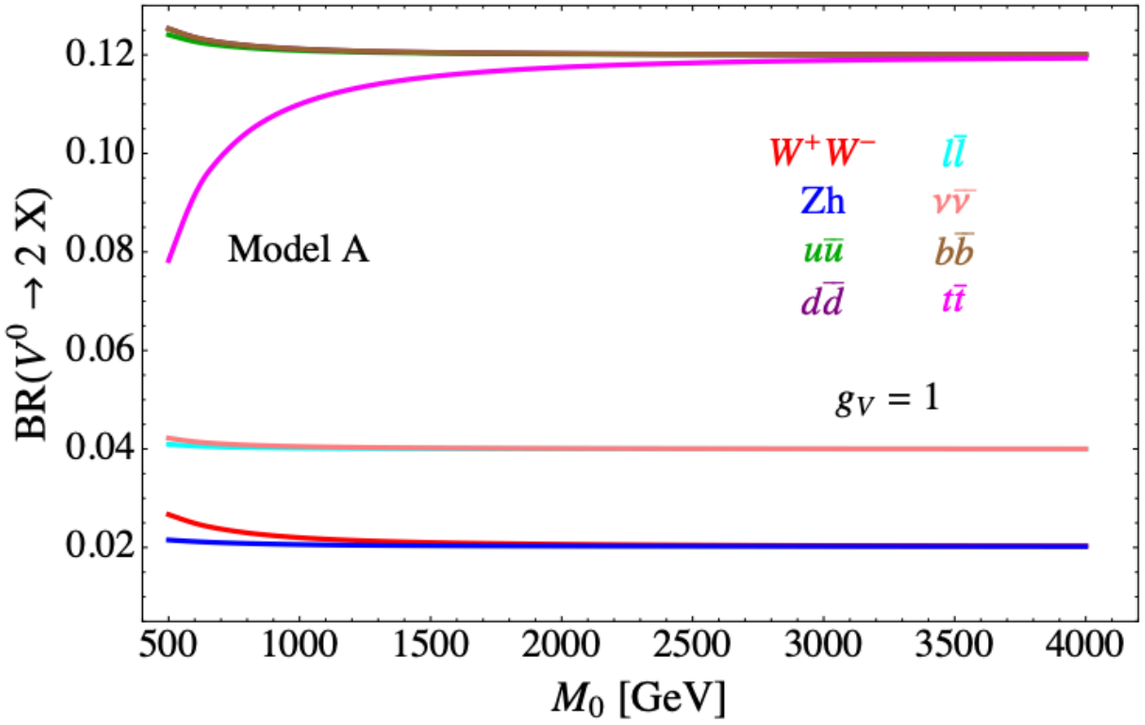
- 10 times better background rejection if we adopt ~25% efficiency
- 20-30% better signal efficiency at the highest p_T, if we keep the background rejection as the same level as legacy tagger

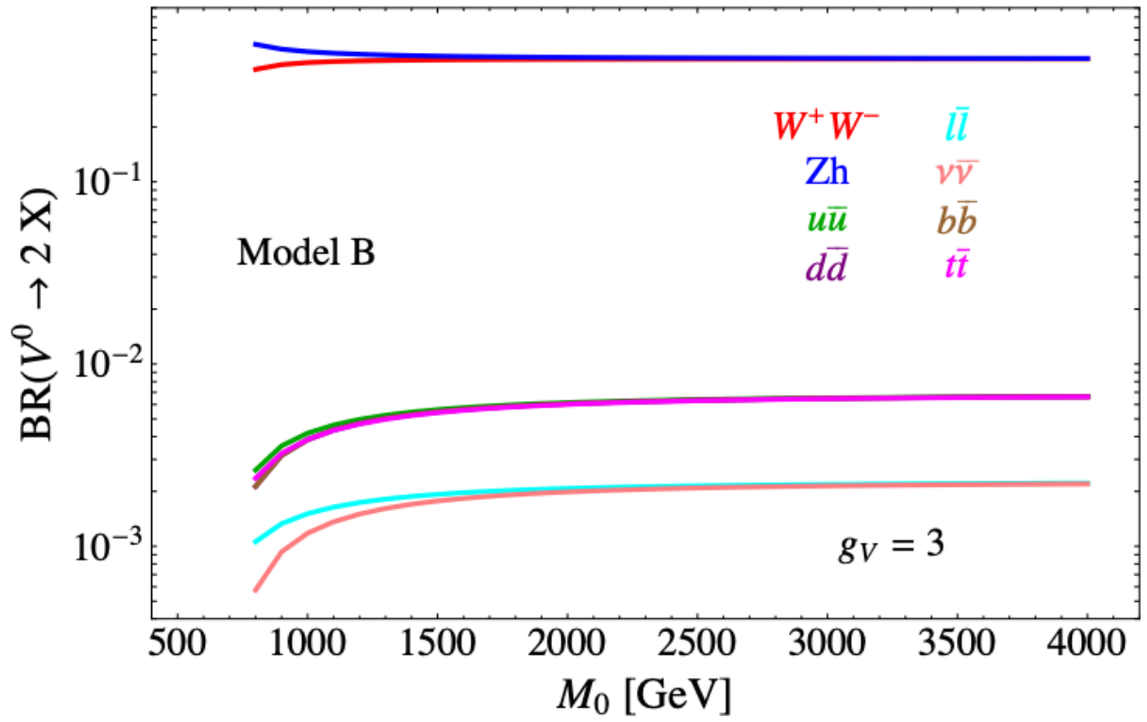
CERN-EP-2020-049

Search for heavy diboson resonances in semi-leptonic final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Heavy resonance search status

- ATLAS searches for many narrow-width heavy resonances
- Heavy vector triplet (**HVT**) is a useful simplified model to introduce new heavy vector resonances (parameterized by g_V: V'VV coupling and c_F: V'ff coupling)
  - **Model A** (g_V=1) motivated by **extended gauge theory**
  - **Model B** (g_V=3) motivated by **compositeness**





https://arxiv.org/abs/1402.4431

+ we also consider **Model C** (c_F=0): a benchmark model for VBF production

Heavy resonance search status

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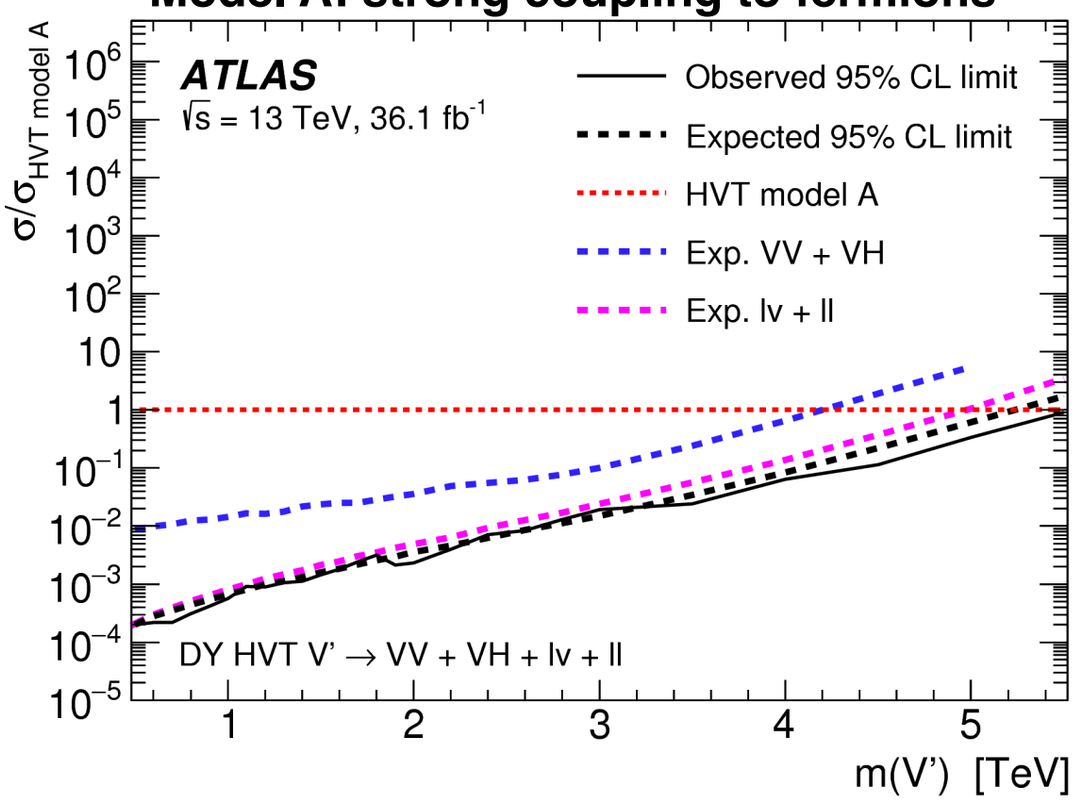
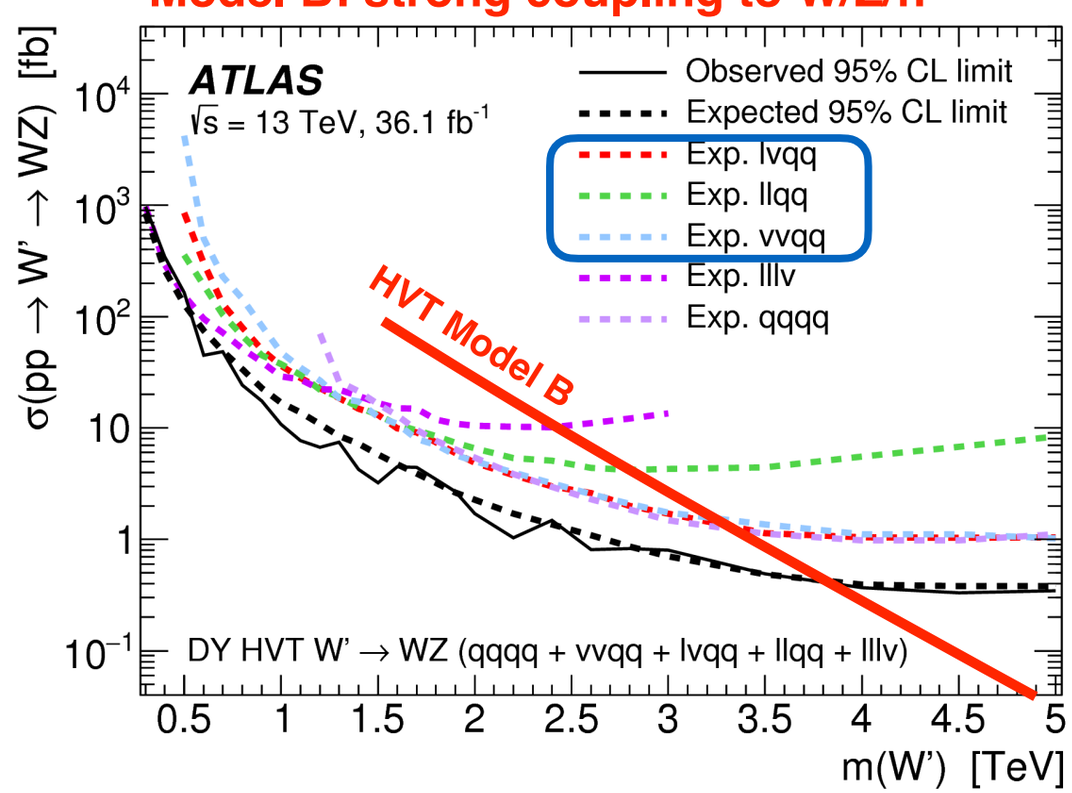
  - **Model A** (g_V=1) motivated by **extended gauge theory**
  - **Model B** (g_V=3) motivated by **compositeness**
- Full run-2 results of W'→lν/qq and Z'→ll/qq analyses can be found in:
  JHEP 03 (2020) 145 PRD 100 (2019) 052013 PLB 796 (2019) 68

Model A: strong coupling to fermions



Model B: strong coupling to W/Z/h



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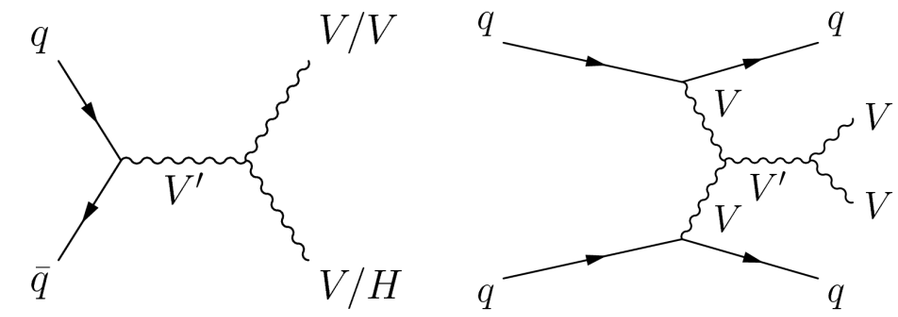
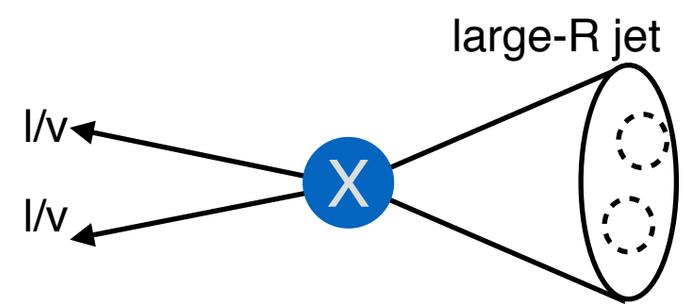
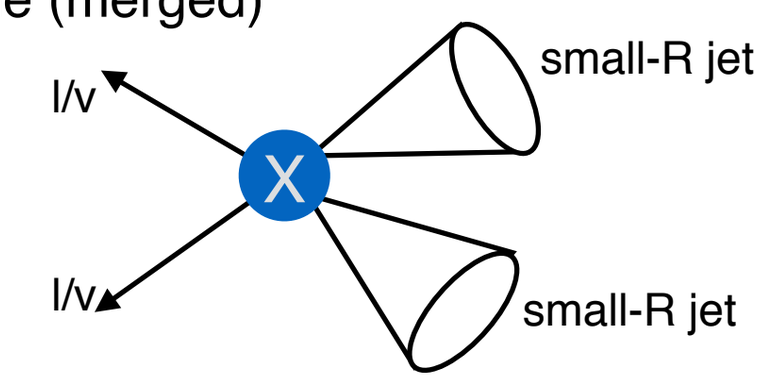
Overview of diboson resonance search



- **Semi-leptonic** final states (WV→lvqq/ZV→llqq/ZV→vvqq)
- **Analysis comprehensiveness:**
  - 3 production mechanisms considered:
    gluon-gluon fusion (ggF) / quark-anti-quark annihilation (DY) / vector-boson fusion (VBF)
  - Several benchmark signals with different spin and final states (WW/WZ/ZZ)
    - Spin-1 HVT W'→WZ and Z'→WW
    - Spin-0 bulk Randall-Sundrum (RS) radion R→WW/ZZ
    - Spin-2 bulk RS Graviton G_{KK}→WW/ZZ
  - Wide mass ranges:
    - High-mass: large-R jet + boosted object tagging technique (merged)
    - Low-mass: two small-R jets (resolved)





- **Analysis improvements** w.r.t. 36 fb^{-1} analysis [*]
  - ML-based VBF/ggF classifier
  - Move to TCC jets
  - Z→qq signals are separated to 2 categories (Z→bb and the other)

Analysis flow

Collected events (lepton or missing E_T triggers)

Categorization based on #of leptons

0-lepton
mET>250GeV

1-lepton
mET>100(60)GeV

2-lepton
with p_T>30GeV

(in each channel)ML-based VBF and ggF/DY categorization

ggF/DY category
RNN score<0.8

VBF category
RNN score>0.8

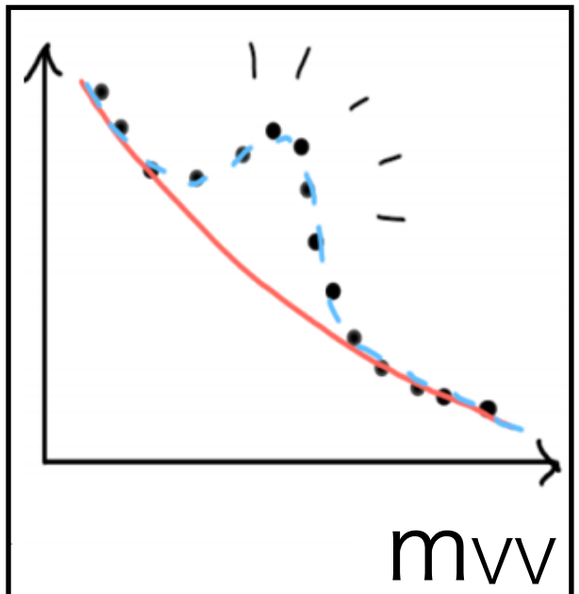
Merged analysis with W/Z tagging using new TCC jets

- In 1-/2-lep channels, **$p_{T,V}/m_{VV}$>0.35 (0.25)** for ggF/DY (VBF) category
- W→qq region and Z→qq region are largely overlap. Separate analyses for W and Z interpretations performed
- For Z→qq candidate, events are separated into b-tagged and untagged categories

If event is not selected by merged analysis, go to the resolved

Resolved analysis

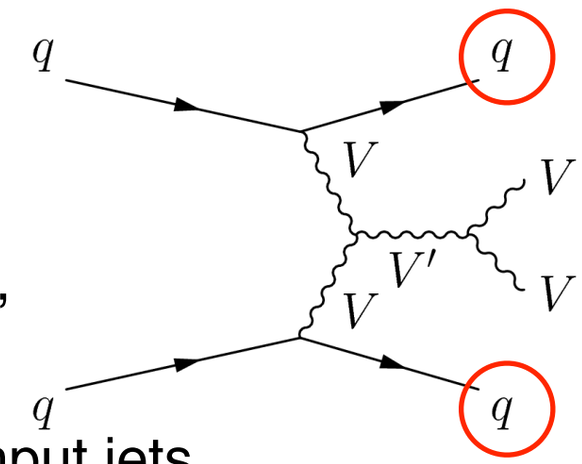
- Kinematic cuts similar to merged analysis applied
- b-tagged/untagged categorization for Z→qq candidate

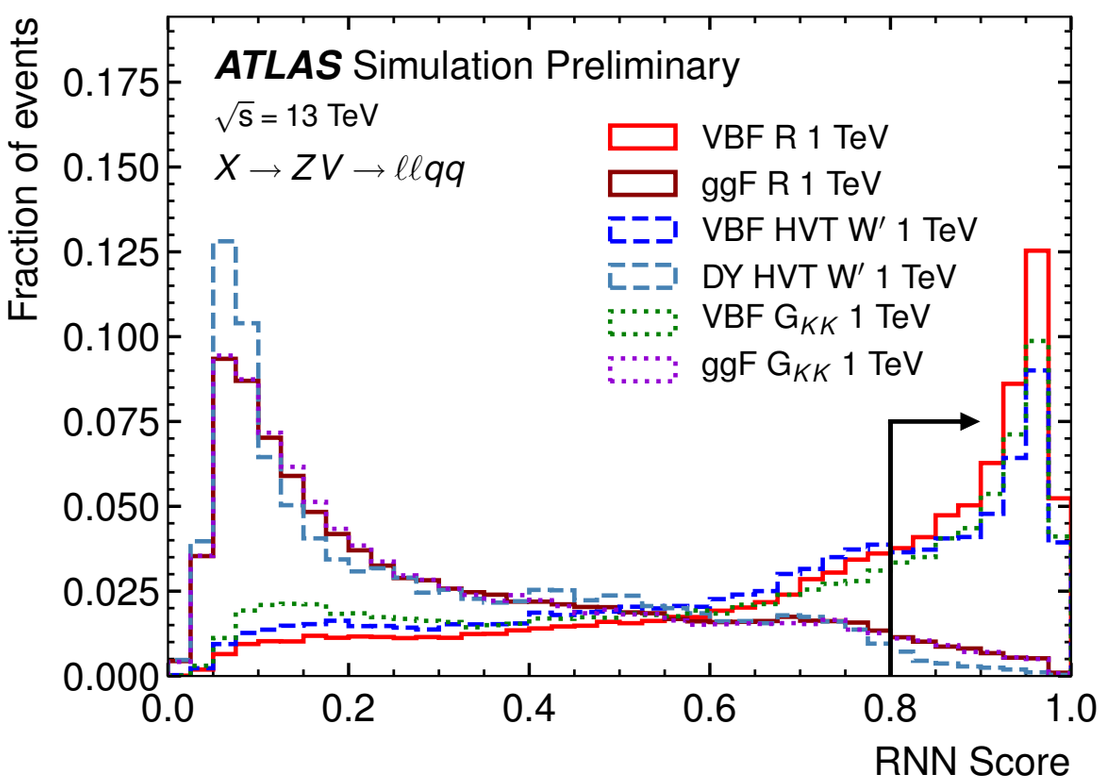


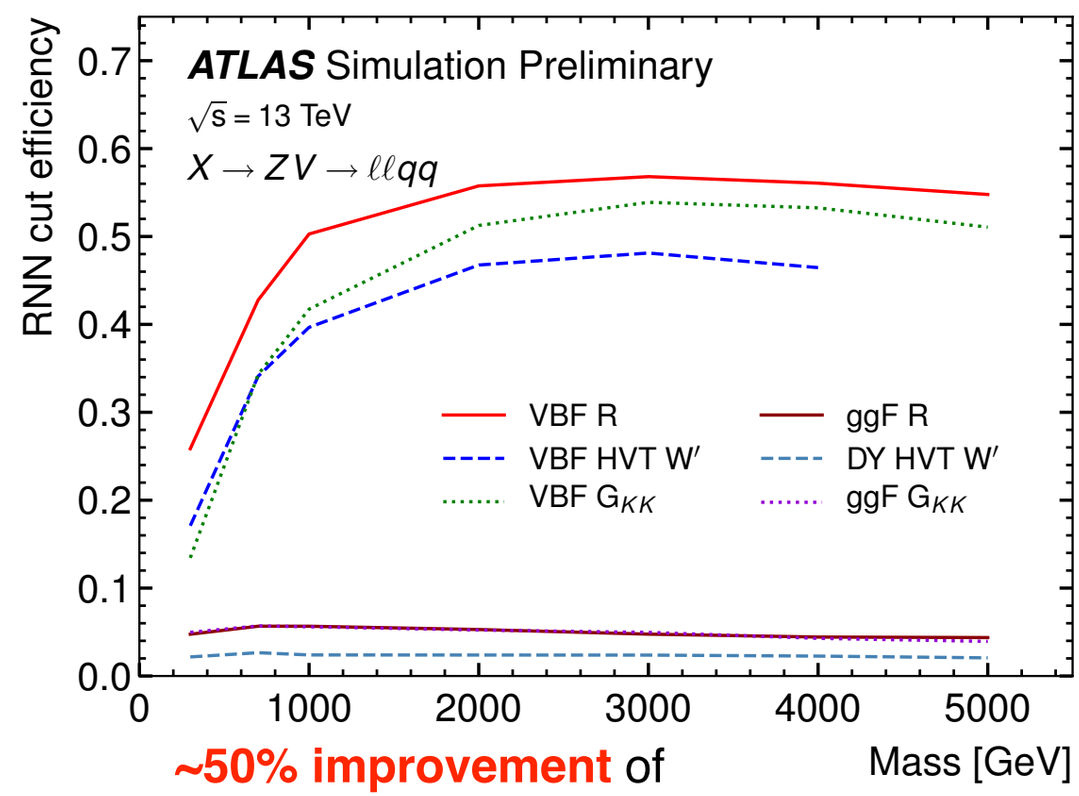
Estimate SM bkg m_{VV} shape and search for a "bump"

ML-based ggF/VBF classifier

- Trained to separate VBF signal from ggF signal (signal MC v.s. signal MC)
- Input: 4-momenta of the VBF-jet candidates
  - W/Z→qq candidate jets are excluded from the list
  - Up to 2 jets are used; even if there is only 1 VBF-jet candidate, the event is not discarded
- Recurrent (sequential) NN architecture to cope with variable #of input jets

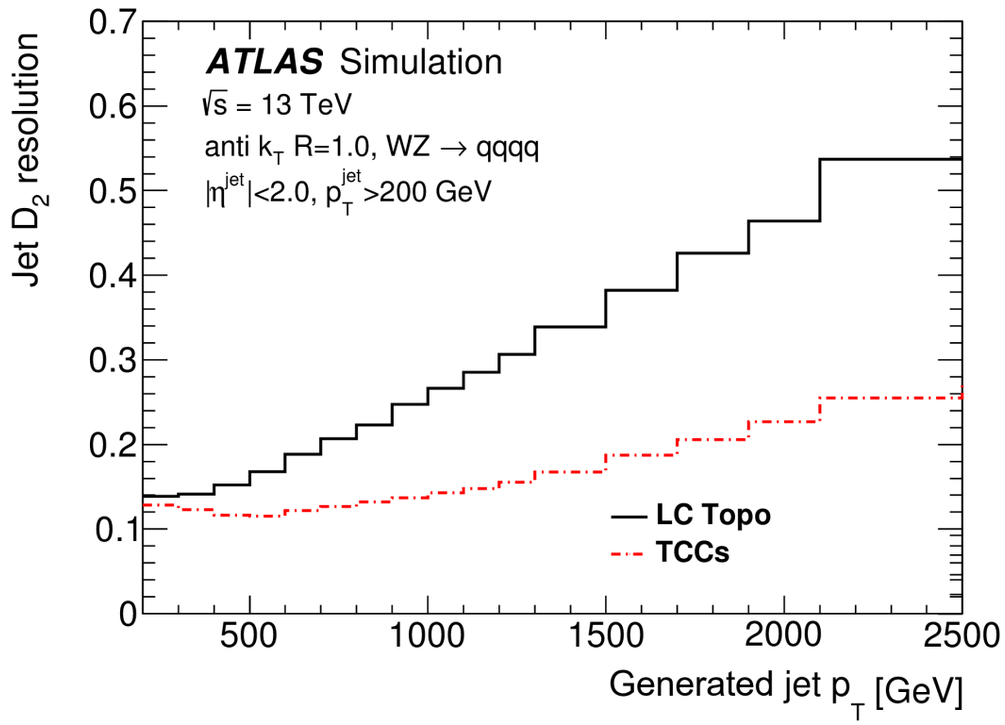






~50% improvement of Acceptance to VBF signals at the highest-mass point

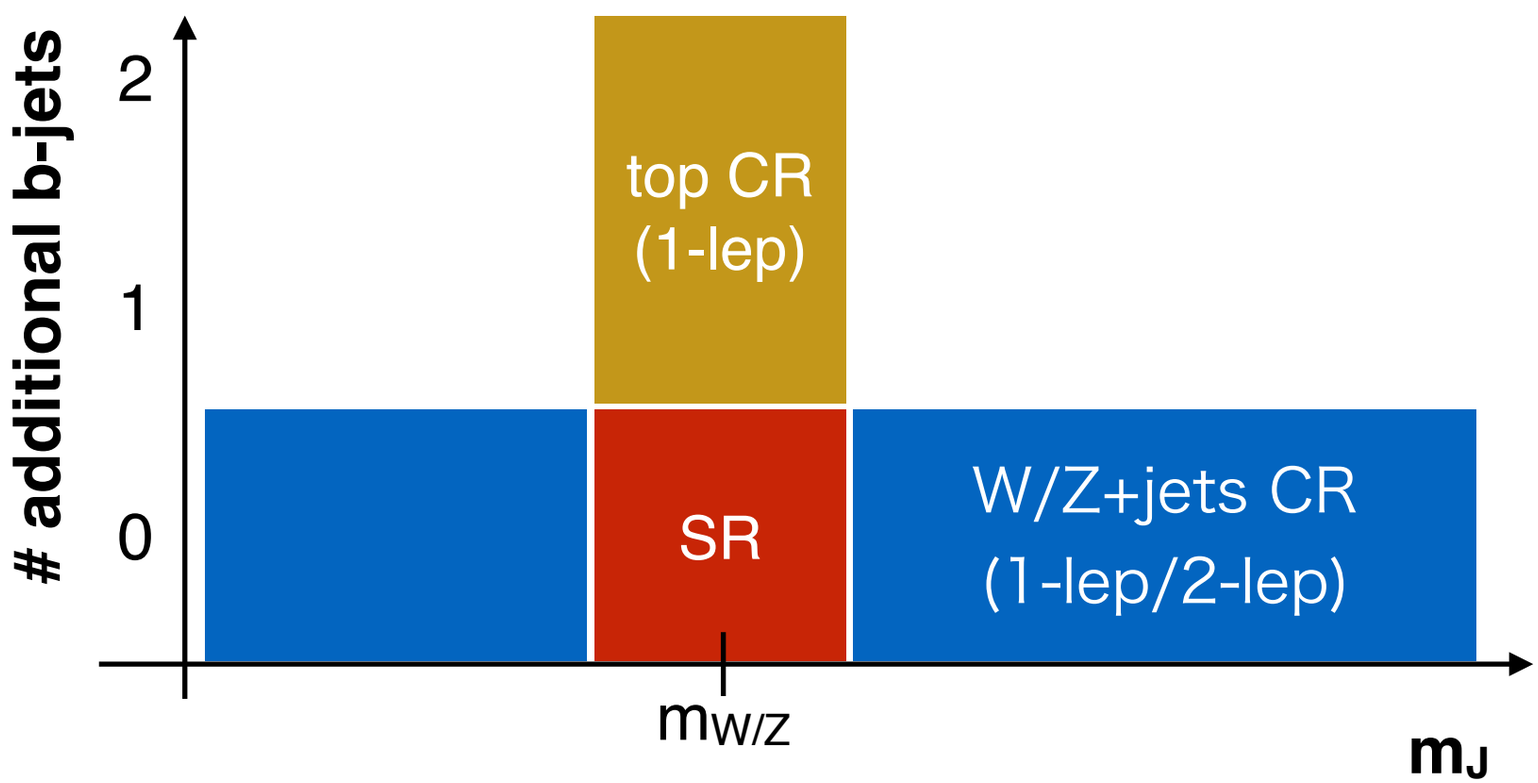
Optimization of W/Z tagger with TCC



- Mass window and upper cut on D2 are optimized for diboson resonance search, to maximize the sensitivity in each p_T bin
  →**20-30% better signal efficiency at the highest p_T**, while keeping bkg rejection

Background Estimation

- Normalizations of main sources of bkg: W/Z+jets and $t\bar{t}$ are estimated in dedicated control regions (CRs)
- Merged and resolved analyses focus on different mass range
  → to absorb a possible mismodeling of MC depending on kinematics, separate normalization factors are used for merged and resolved analyses
- To consider a possible mismodeling of VBF-jet kinematics (and acceptance of RNN cut), different normalization factors for ggF/DY and VBF categories are used
- Consequently, we need many CRs to be involved in the fit

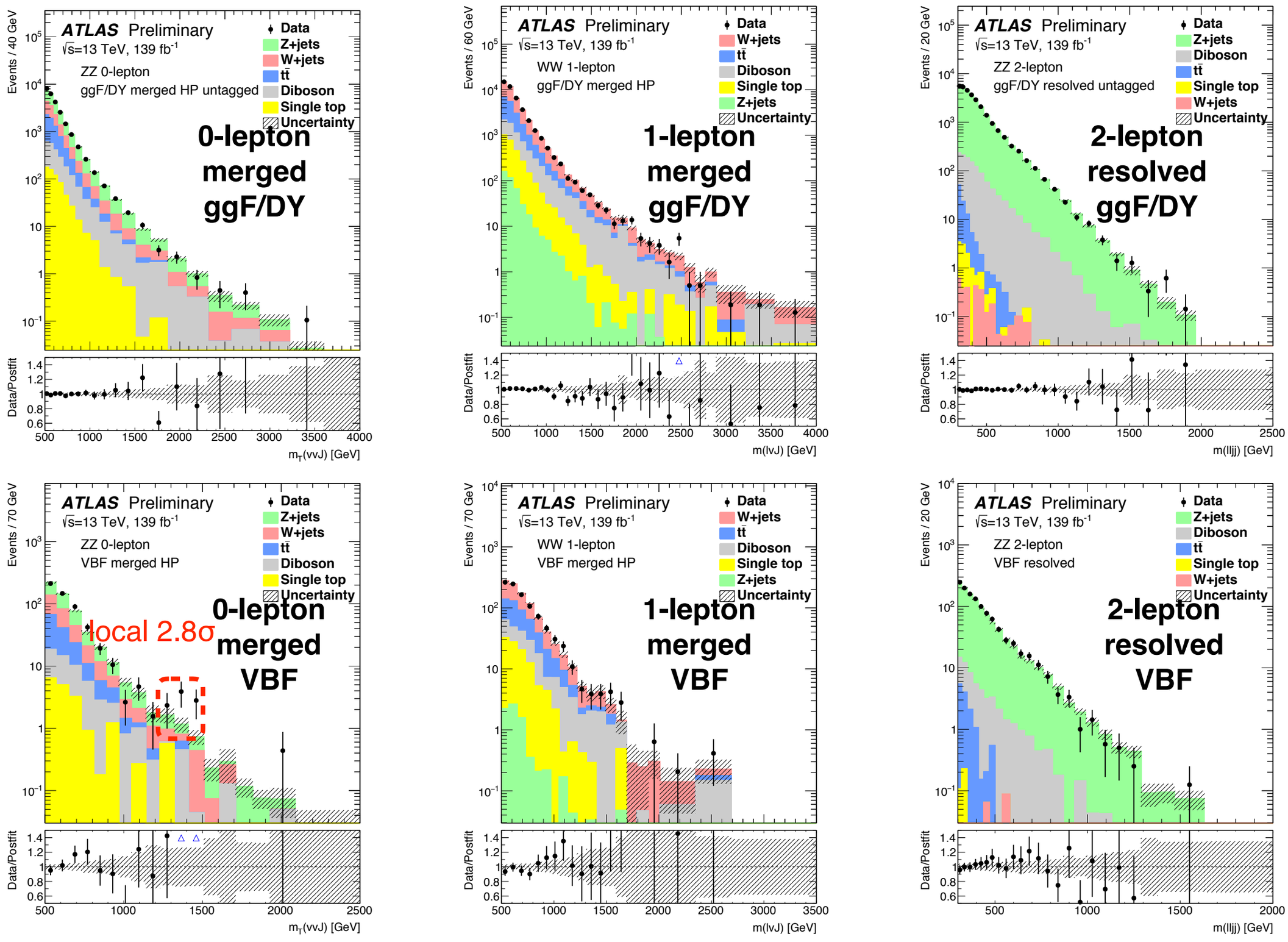


Systematic uncertainties

- Large-R jet energy scale is the dominant source of uncertainty
- Uncertainty on extrapolation from sideband-CR to SR is taken into account by boson-tagger efficiency SF uncertainty
  - SF is estimated in dedicated control samples
- Theoretical modeling of m_{VV} *shapes* of W/Z+jets, $t\bar{t}$ and SM diboson processes is estimated using simulations with different parameters
  - Variations of QCD scales, ISR/FSR parameters, PDF, etc.
  - Choice of generators (MG v.s. Sherpa for W/Z+jets, aMC@NLO v.s. Powheg+Pythia for $t\bar{t}$)

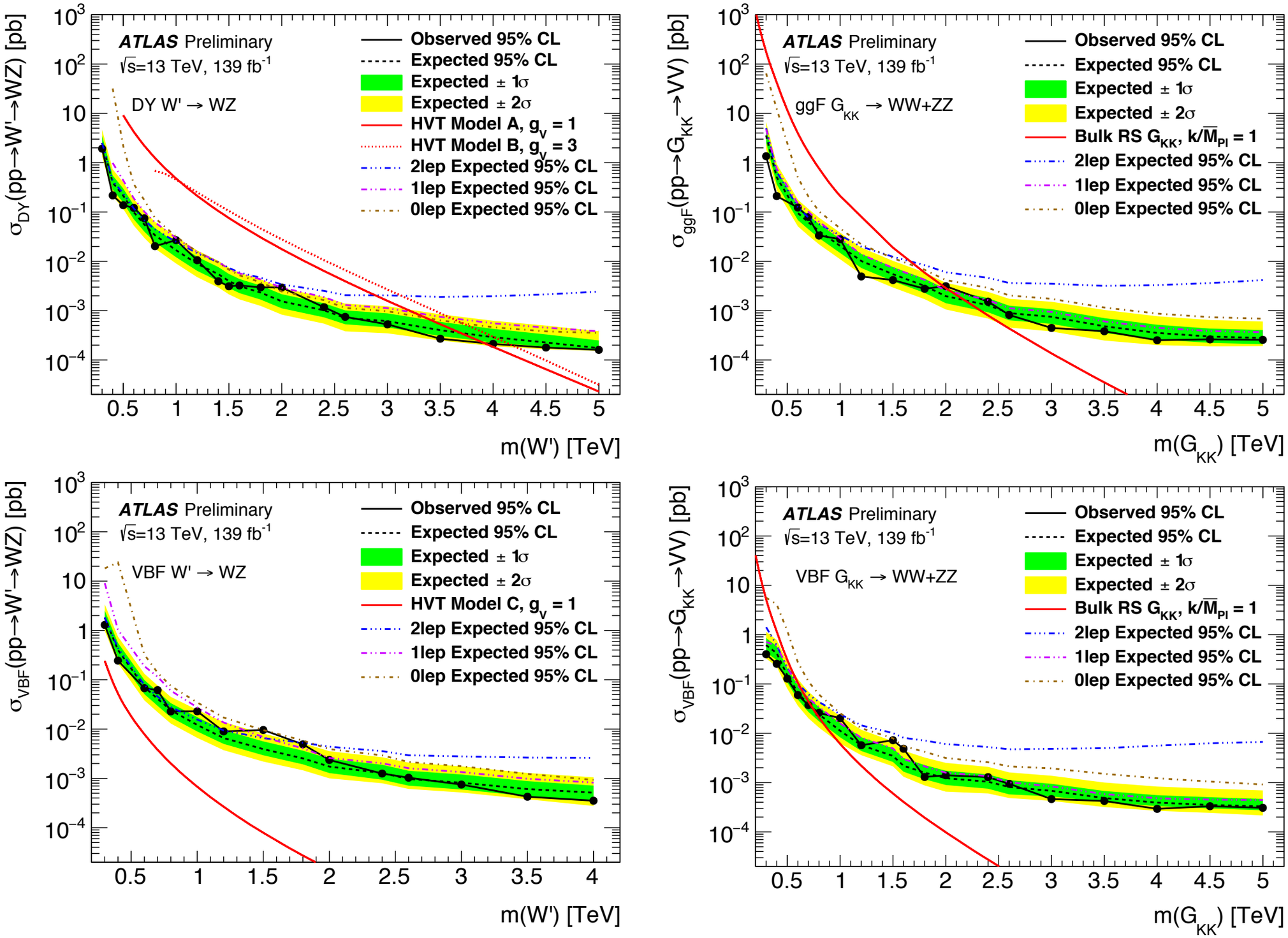
Uncertainty source	$\Delta\mu/\mu$	
	600GeV	2TeV
Large-R jet (p_T scale and boson-tagging eff.)	18%	24%
MC statistics	16%	17%
W/Z+jets shape modeling	11%	15%
Background normalization (CR stats)	15%	<3%
SM VV shape modeling	12%	4%
$t\bar{t}$ shape modeling	8%	4%
Total Systematics	**41%**	**34%**
Data statistics	**29%**	**48%**

Results: reconstructed m_{VV} distributions



- Global p-value at m=1.5TeV (VBF signal): <2σ

Cross-section upper limits



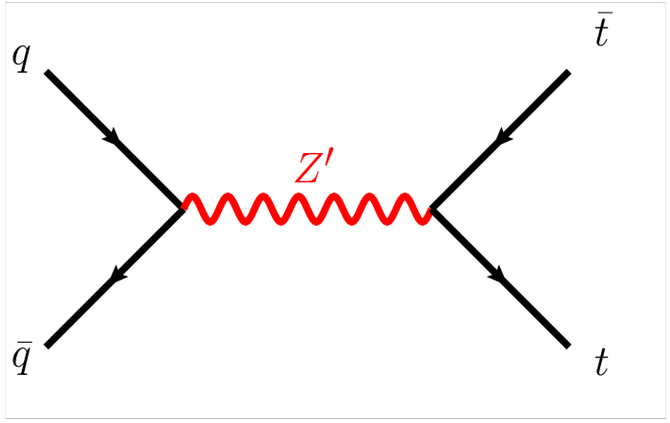
- ~20% better sensitivity is obtained at the highest mass point, compared with 36fb^{-1} analysis repeated with 139fb^{-1}

CERN-EP-2020-055

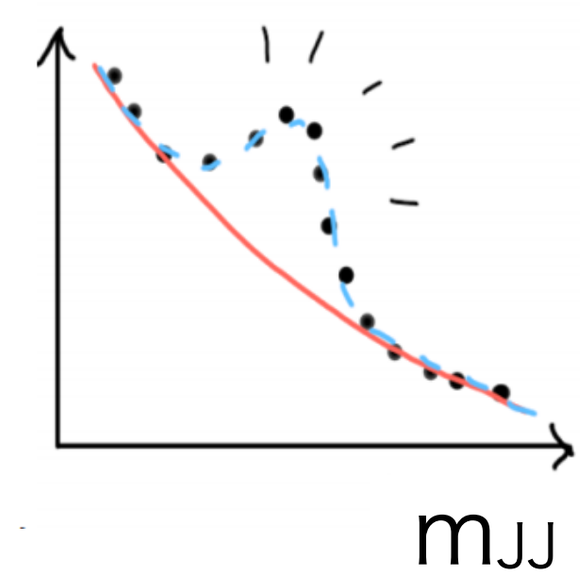
Search for $t\bar{t}$ resonances in fully hadronic final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Overview of $t\bar{t}$ resonance search

- Top quark is the heaviest particle in the SM and may play an important role in physics BSM
  - In some models, KK gluon predominantly decays to top-quark pair BR($g_{KK} \rightarrow t\bar{t}$) ~ 0.9
  - Top-assisted technicolor model as a benchmark of leptophobic Z' with BR($Z' \rightarrow t\bar{t}$) ~ 0.3



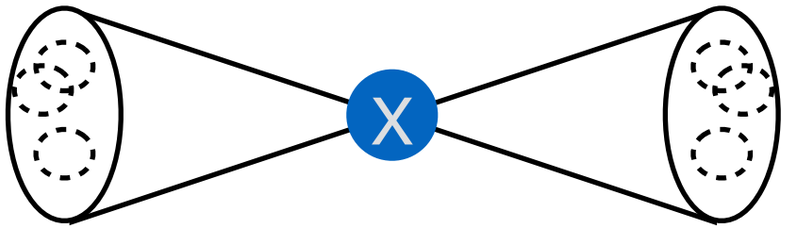
- **Fully-hadronic** final states ($t\bar{t} \rightarrow qqbqqb$)
  - Largest branching fraction
  - Focus on the highest mass region
- **Analysis improvements**
  - A new ML-based top tagger to reduce bkg more
  - A new b-tagging based on variable-radius track jets
  - Full data-driven background estimation



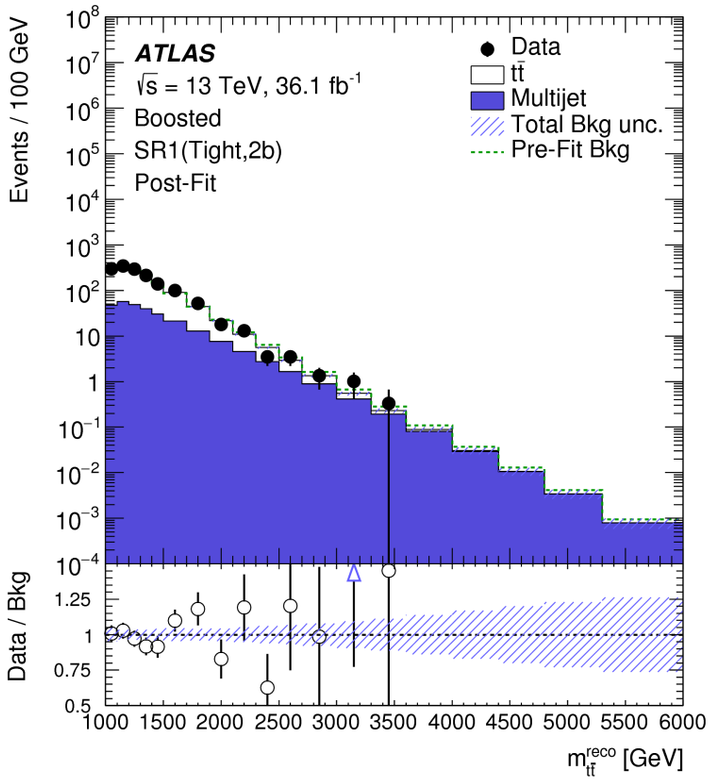
It is also a bump search against the smoothly falling SM bkg m_{JJ}

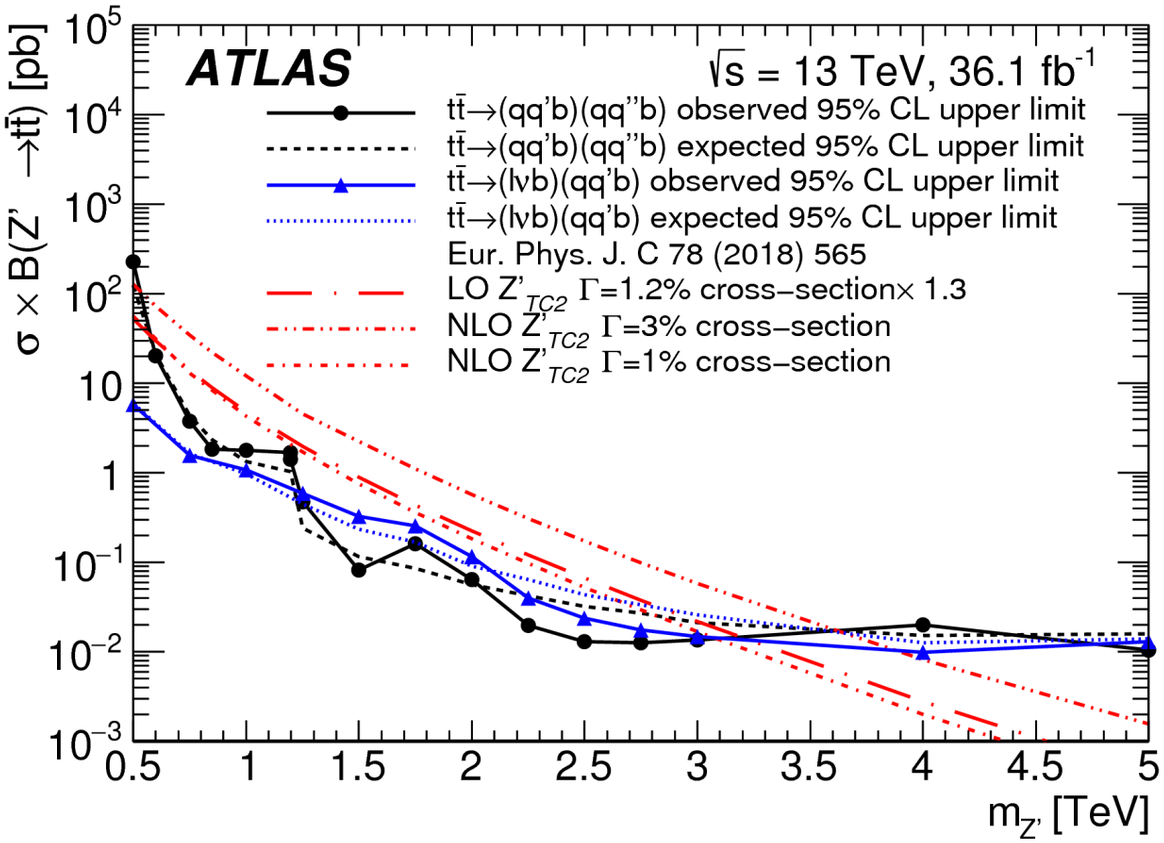
$t\bar{t}$ resonance search status

- With old top tagger, fully-hadronic and semi-leptonic channels had similar sensitivities



- Fully-hadronic channel
  - The main source of the background at the highest mass is multijet process (reducible)
- Improvement of boosted top tagging can directly gain the sensitivity





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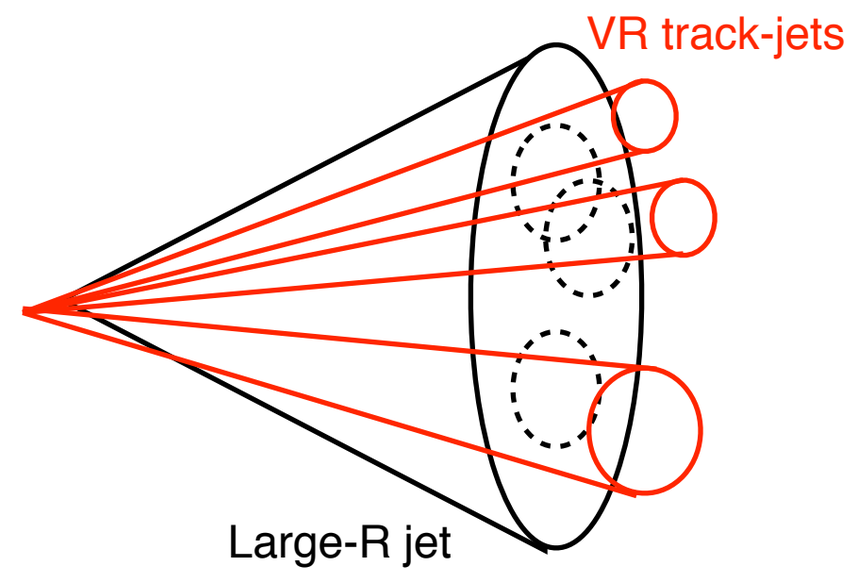
Event selection

- Large-R jet trigger (plateau at p_T~500GeV)
- 2 large-R jets with p_T>500, 350GeV
  (continue to use calorimeter jets)
- Both jets are top-tagged using DNN top tagger
  - Per-jet bkg rejection is improved by factor ~2
    → ~4 times smaller multijet bkg is expected
- $|\Delta y_{JJ}|$<1.8, $\Delta\phi$>1.6 for back-to-back dijet in central rapidity
- m_{JJ}>1.4TeV

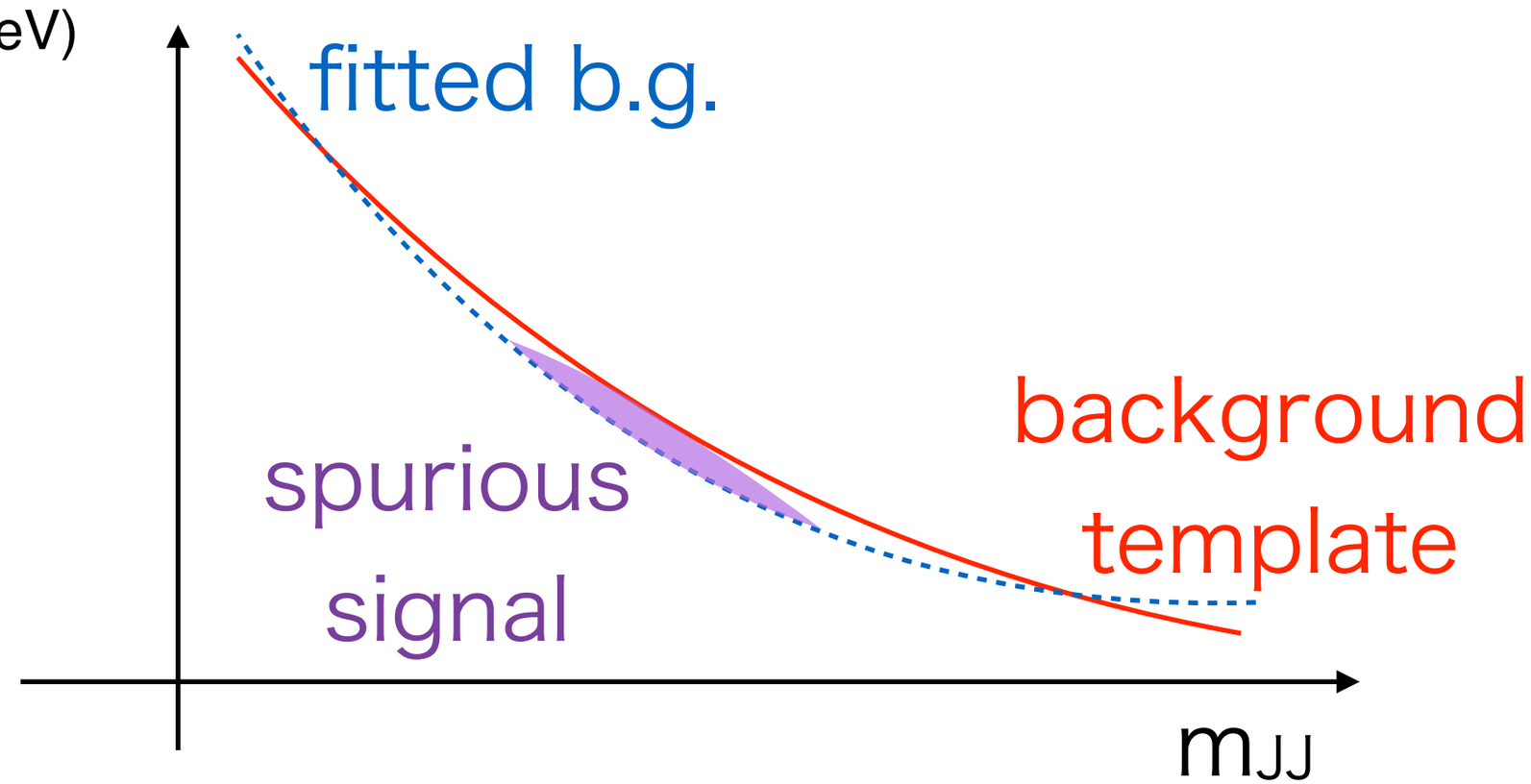
Event categorization

- # of b-jets associated with large-R jet is counted using variable-radius (VR) track jets
- Using anti-kT cone parameter depending on p_T, we can suppress the effect from close-by/underlying track particles
  →better b-tag efficiency at very high-p_T
- Large-R jet with >=1 associated b-jets
  → “b-tagged large-R jet”
- Events are categorized into 2 channels based on #of b-tagged large-R jets
  - SR2b and SR1b



Background Estimation

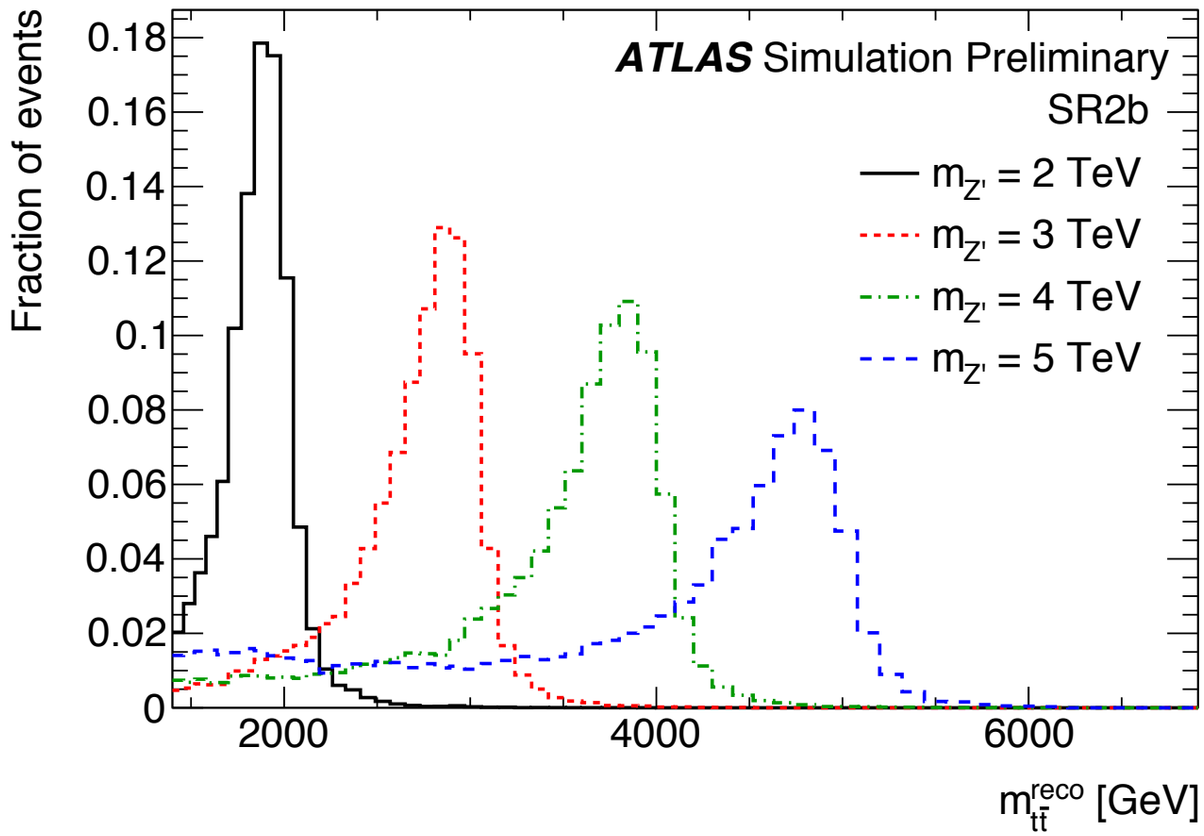
- Smooth falling function is used, where $x=m_{jj}/\sqrt{s}$ $F(x) = p_0(1-x)^{p_1} x^{p_2+p_3\log(x)+p_4\log(x)^2}$,
- The function is validated in SRs using background-only sample
  - $t\bar{t}$ MC + high-mass dijet MC + data-driven template of low-mass multijet sample
  - Choice of #of fit parameters optimized; to minimize the **spurious signal yield** obtained by s+b fit to this b-only template
  - Uncertainties on fit parameters are considered as systematic uncertainty
- Spurious signal yield is considered as additional uncertainty related the choice of fit function (~30-40% at 4TeV)



Signal modeling

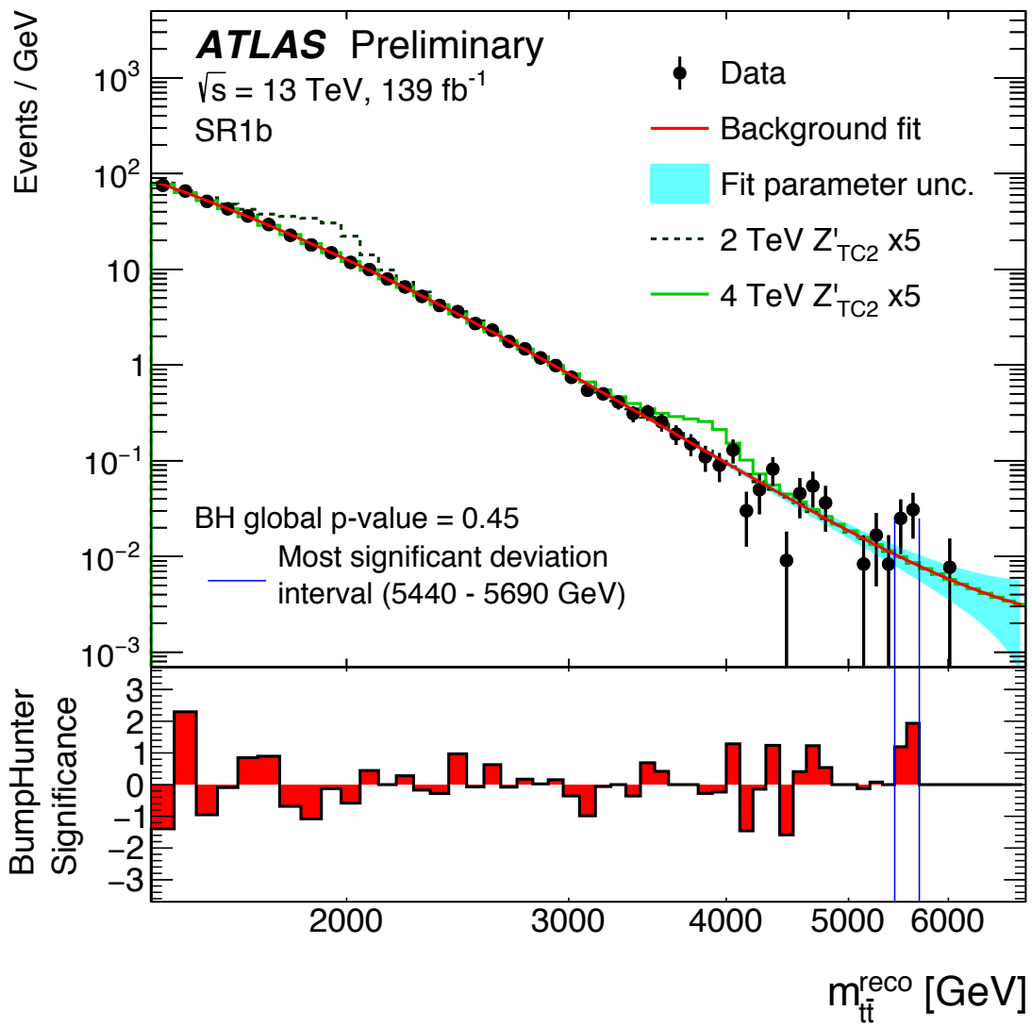
- Signal MC samples are described by Gaussian + CrystalBall, then we can interpolate to every mass points

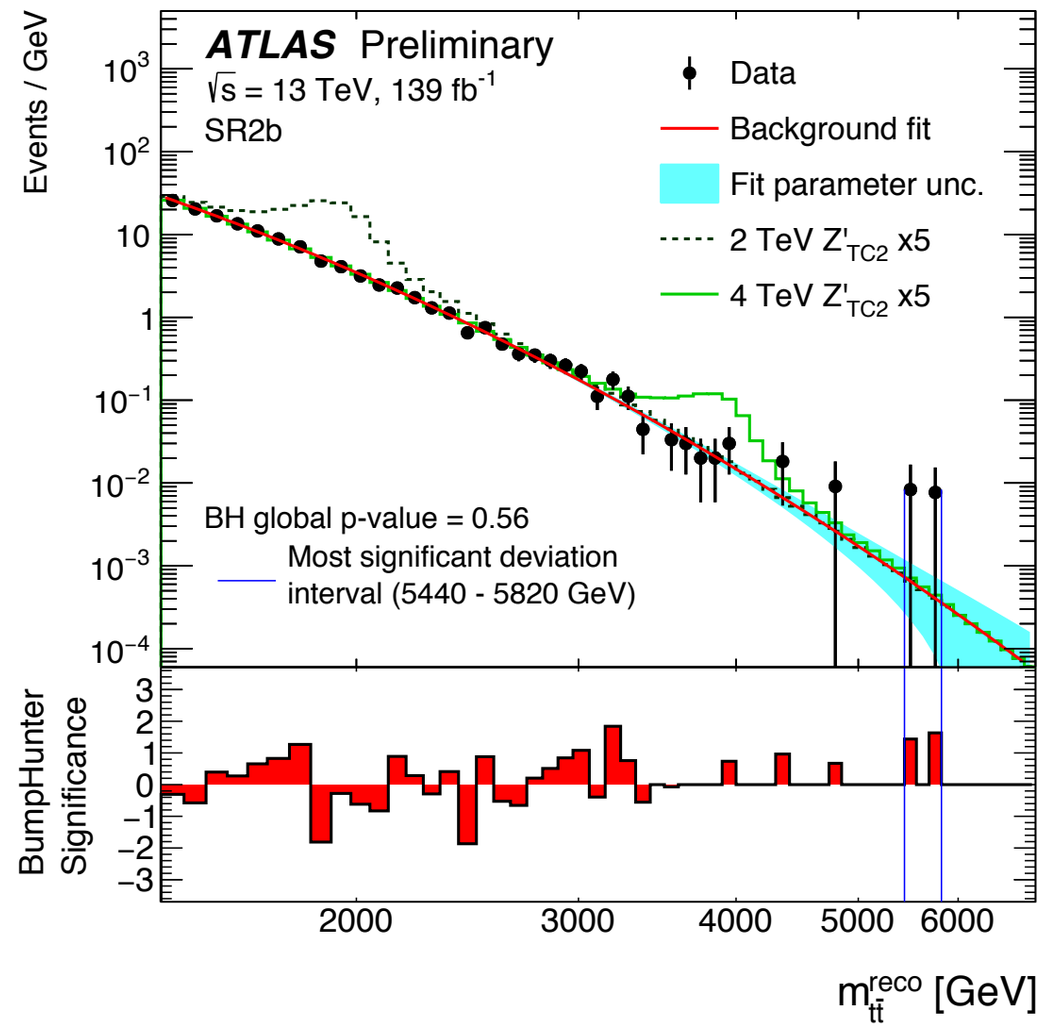
- Uncertainty on signal acceptance is estimated



Source	2TeV Z'		4TeV Z'	
	SR1b	SR2b	SR1b	SR2b
JES	35%	34%	47%	44%
JMS	5.0%	4.3%	9.5%	7.9%
JER	0.1	0.1	0.1%	<0.1%
JMR	3.9%	4.0%	8.0%	8.0%
b-tagging	14%	5.0%	23%	5.3%
top-tagging	8.1%	8.3%	9.1%	9.2%

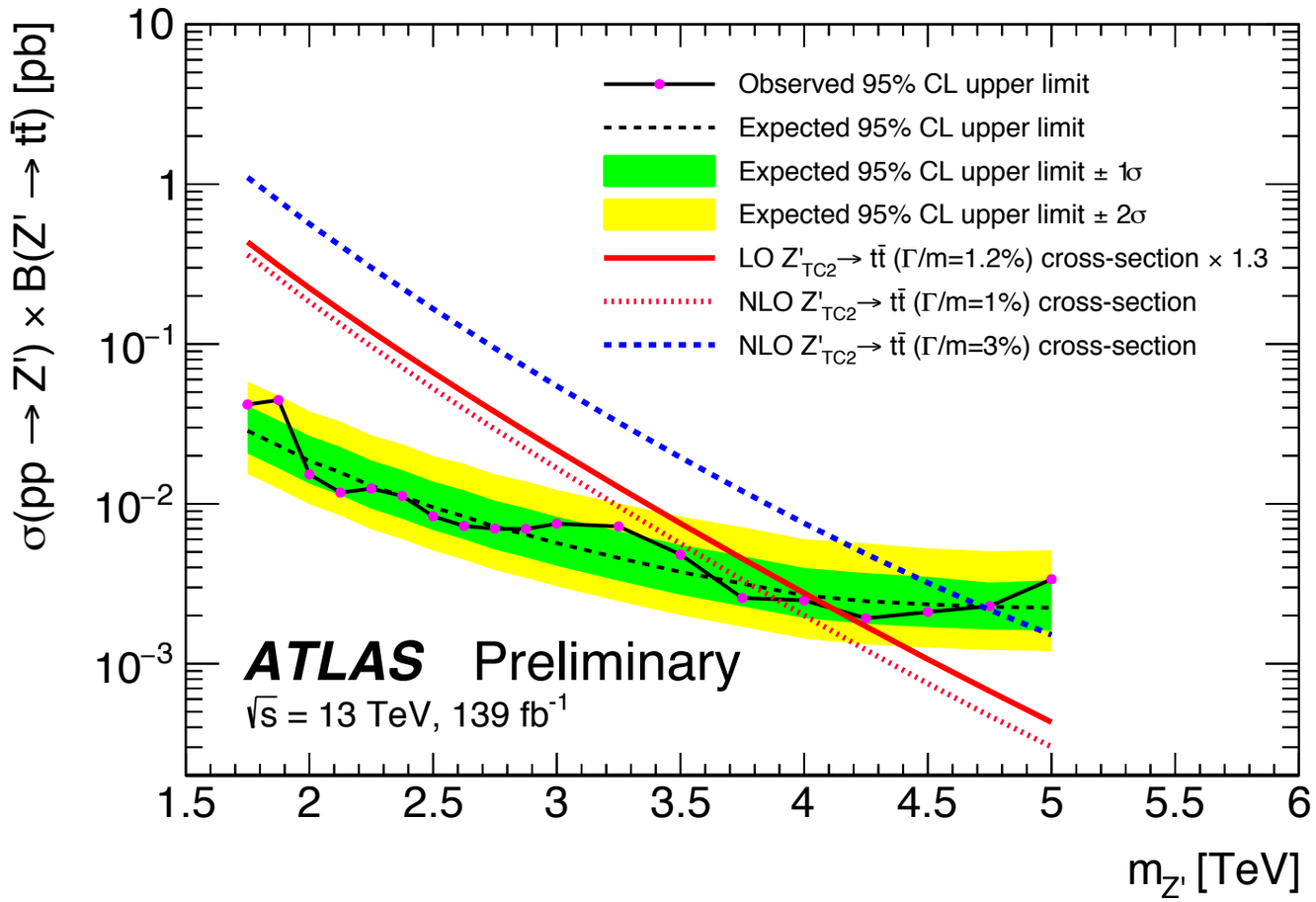
Results: reconstructed m_{JJ} distributions





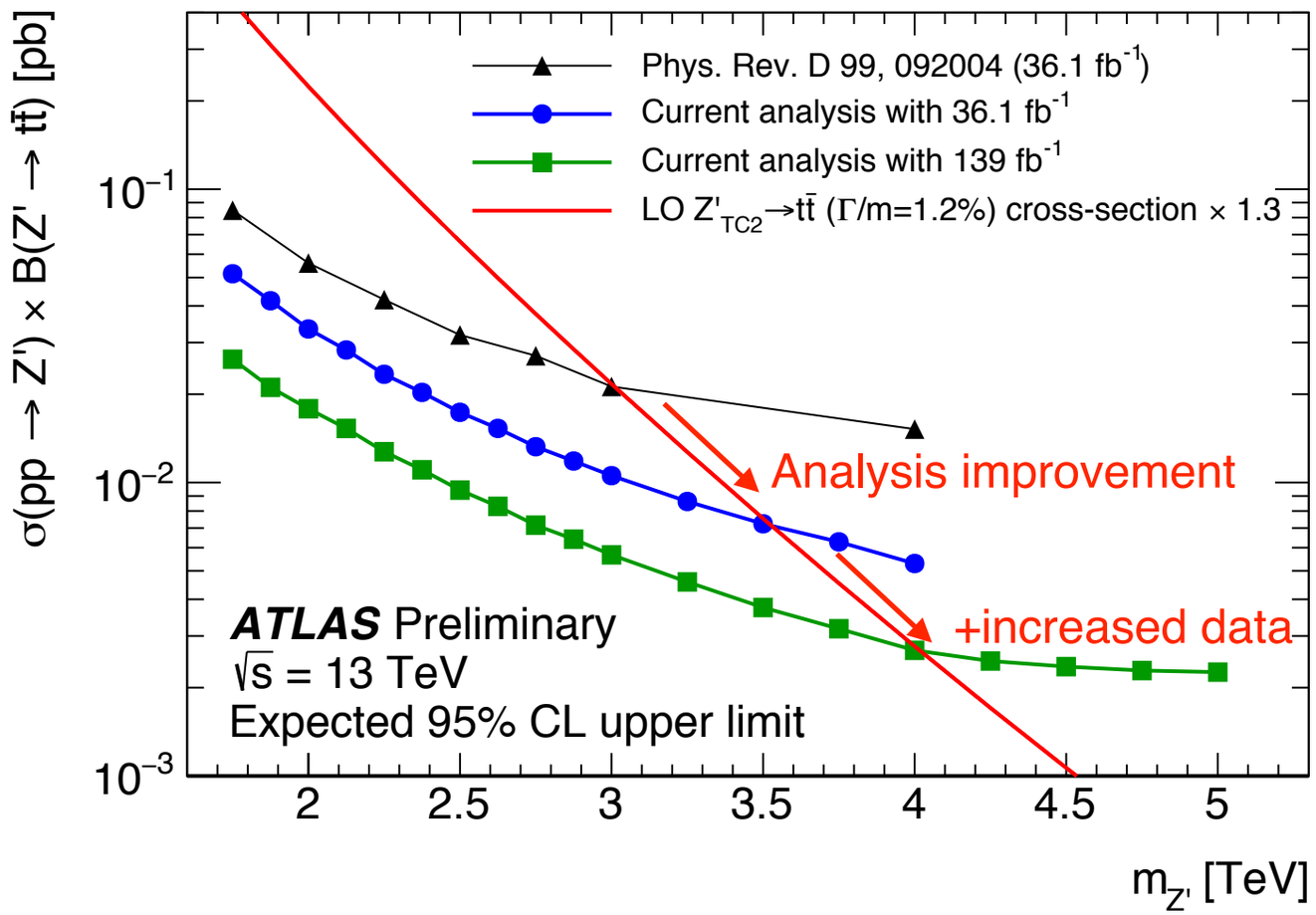
- Model-independent p-value scan by BumpHunter, maximum local significance is ~2σ and global significance is <1σ
- CLs method used to calculate upper limits

Cross-section upper limits

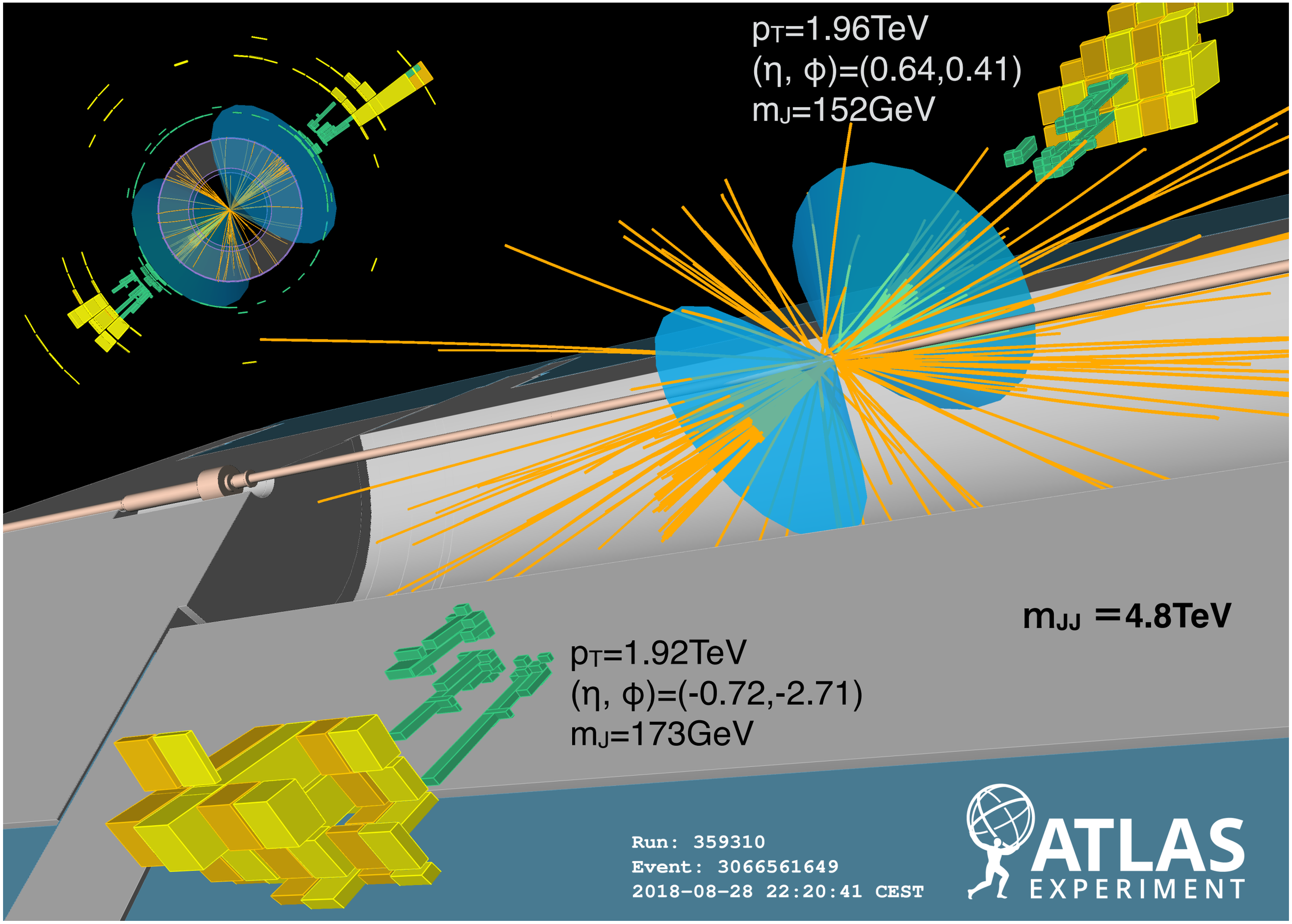


- Z'_{TC2} signal is excluded at m<~4TeV (1.2% width) and m<~4.8TeV (3% width)

Cross-section upper limits



- Z'_{TC2} signal is excluded at m<~4TeV (1.2% width) and m<~4.8TeV (3% width)
- Great sensitivity gain exceeding increase of statistics!!


pT=1.96TeV
(η, ϕ)=(0.64,0.41)
mJ=152GeV
mJJ =4.8TeV
pT=1.92TeV
(η, ϕ)=(-0.72,-2.71)
mJ=173GeV
Run: 359310
Event: 3066561649
2018-08-28 22:20:41 CEST
ATLAS
EXPERIMENT

Summary

- *New* ATLAS results of searches for heavy resonances decaying to **VV** and **$t\bar{t}$** have been presented
- New **boosted object tagging** techniques
  - Bottom-up approach: a new p-flow algorithm (**TCC**) dedicated to high-p_T jets improved the W/Z tagging efficiency by ~30% at p_T=2.5TeV
  - **ML-based top tagger** to combine several substructure variables improved per-jet background rejection by factor 2 while keeping the signal efficiency
- In addition, many new ideas to improve the analyses implemented
  - ML-based ggF/VBF classification
  - B-tagging with new VR track jets
- In both analyses, no significant excess observed above SM predictions
- The world best lower limits are set on the masses of hypothetical new particles

Extra materials

Track-Calo Cluster (TCC)

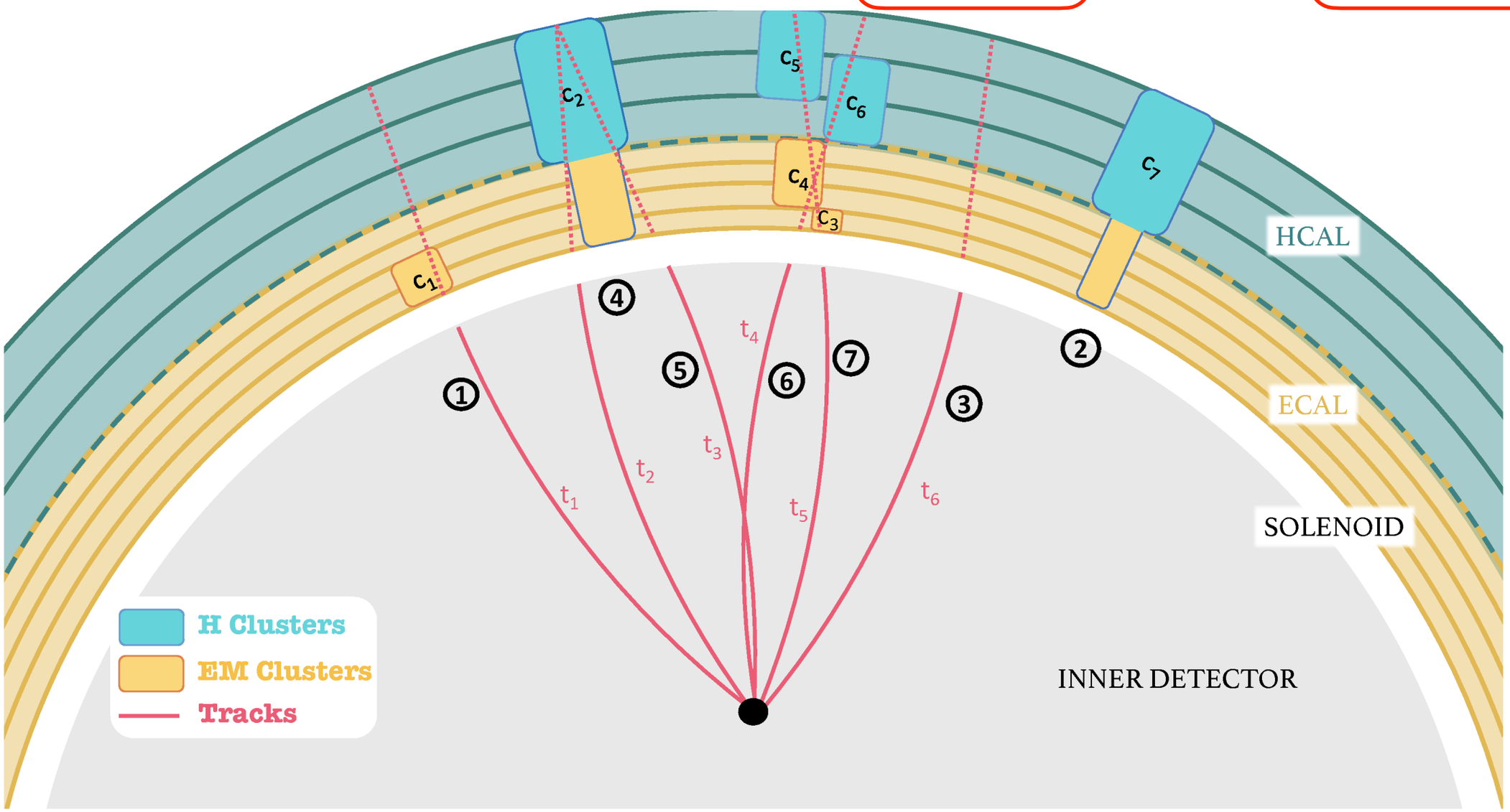
$$\mathrm{TCC}_{①} = (p_{\mathrm{T}}^{c_1}, \eta^{t_1}, \phi^{t_1}, m^{c_1} = 0)$$

$$\mathrm{TCC}_{②} = (p_{\mathrm{T}}^{c_7}, \eta^{c_7}, \phi^{c_7}, m^{c_7} = 0)$$

$$\mathrm{TCC}_{③} = (p_{\mathrm{T}}^{t_6}, \eta^{t_6}, \phi^{t_6}, m^{t_6} = 0)$$

$$\mathrm{TCC}_{④} = \left(p_{\mathrm{T}}^{c_2} \frac{p_{\mathrm{T}}^{t_2}}{p_{\mathrm{T}}\left[\mathbf{p}^{t_2} + \mathbf{p}^{t_3}\right]}, \eta^{t_2}, \phi^{t_2}, m^{c_2} \frac{p_{\mathrm{T}}^{t_2}}{p_{\mathrm{T}}\left[\mathbf{p}^{t_2} + \mathbf{p}^{t_3}\right]} = 0\right)$$

$$\mathrm{TCC}_{⑤} = \left(p_{\mathrm{T}}^{c_2} \frac{p_{\mathrm{T}}^{t_3}}{p_{\mathrm{T}}\left[\mathbf{p}^{t_2} + \mathbf{p}^{t_3}\right]}, \eta^{t_3}, \phi^{t_3}, m^{c_2} \frac{p_{\mathrm{T}}^{t_3}}{p_{\mathrm{T}}\left[\mathbf{p}^{t_2} + \mathbf{p}^{t_3}\right]} = 0\right)$$



D_2 and $\sqrt{d_{12}}$

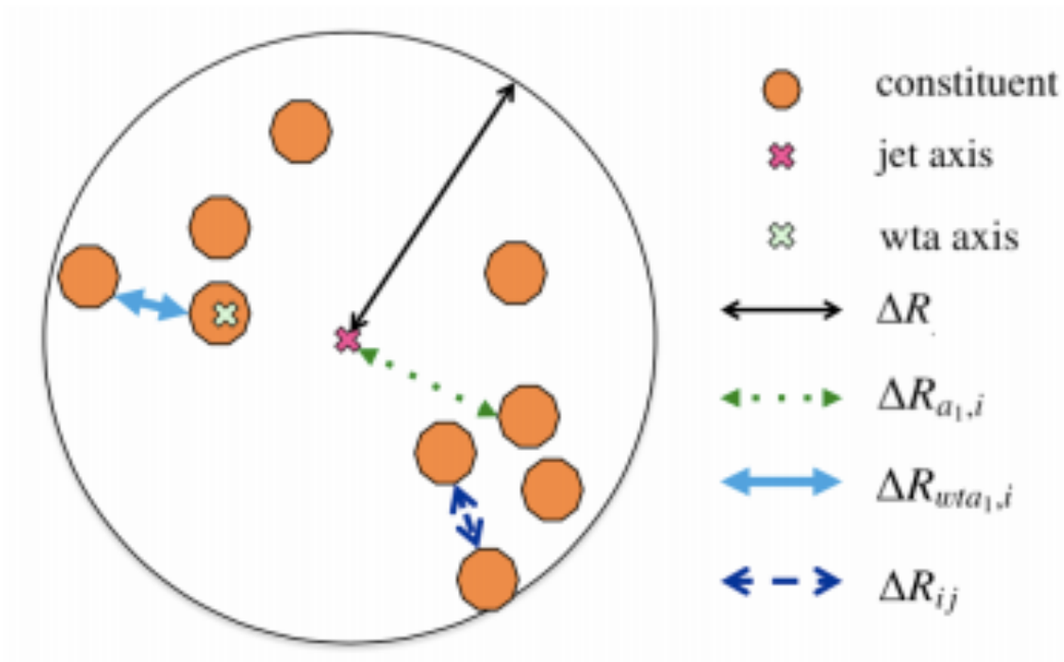
- Decay of W/Z : 2-prong-like
  - A variable: $D_2^{\beta=1} = E_{\mathrm{CF3}} \left(\frac{E_{\mathrm{CF1}}}{E_{\mathrm{CF2}}} \right)^3$

    is used to enhance signals

$$E_{\mathrm{CF1}} = \sum_i p_{\mathrm{T},i}$$

$$E_{\mathrm{CF2}} = \sum_{ij} p_{\mathrm{T},i} p_{\mathrm{T},j} \Delta R_{ij}$$

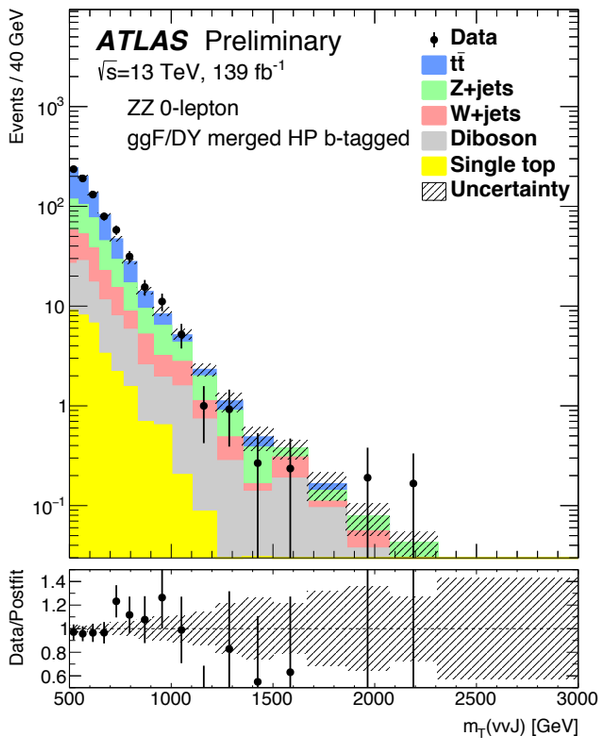
$$E_{\mathrm{CF3}} = \sum_{ijk} p_{\mathrm{T},i} p_{\mathrm{T},j} p_{\mathrm{T},k} \Delta R_{ij} \Delta R_{jk} \Delta R_{ki}$$

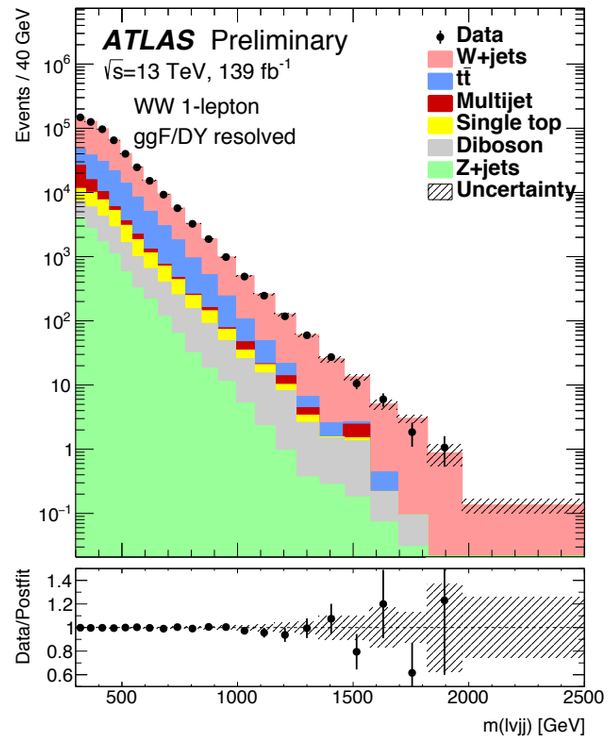


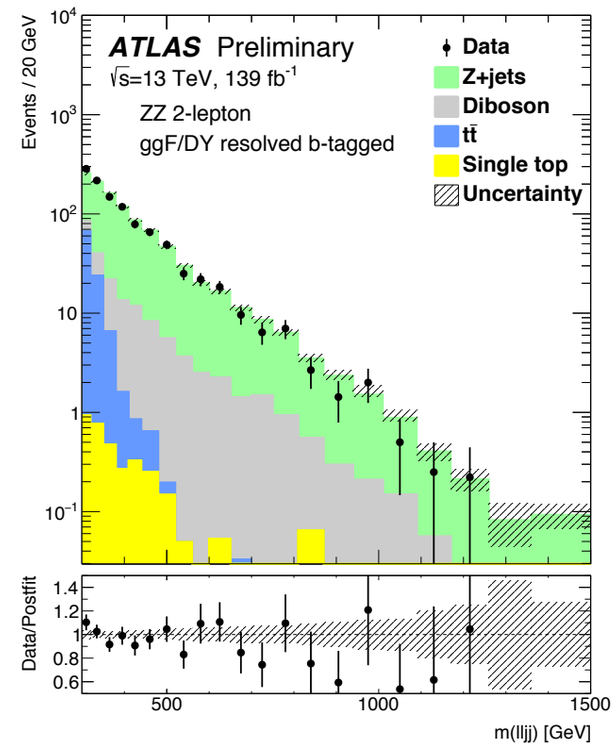
There're 2 high-p_T constituents with large ΔR_{ij};
and no the other constituents with high-p_T:
→ **large E_{CF2} but small E_{CF3}**

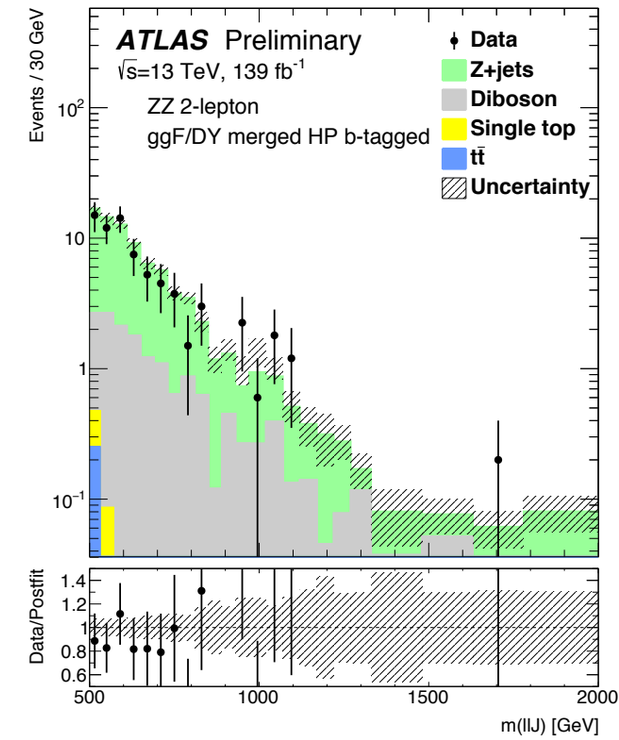
- kT-splitting scale
  - Recluster the jet by kT algorithm
  - At the final step of kT algorithm, $\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \Delta R_{12}/R$
  - small $\sqrt{d_{12}}$ → p_T of 2 subjets are balanced

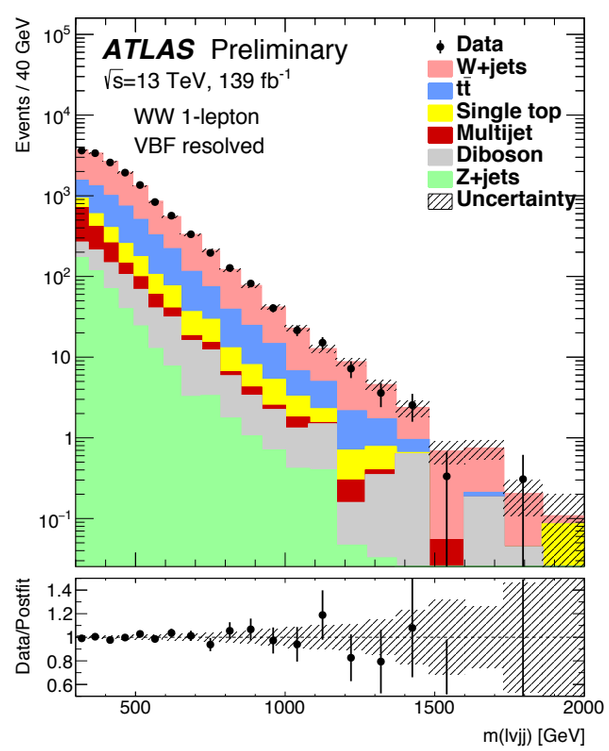
The other SRs (VV resonance)

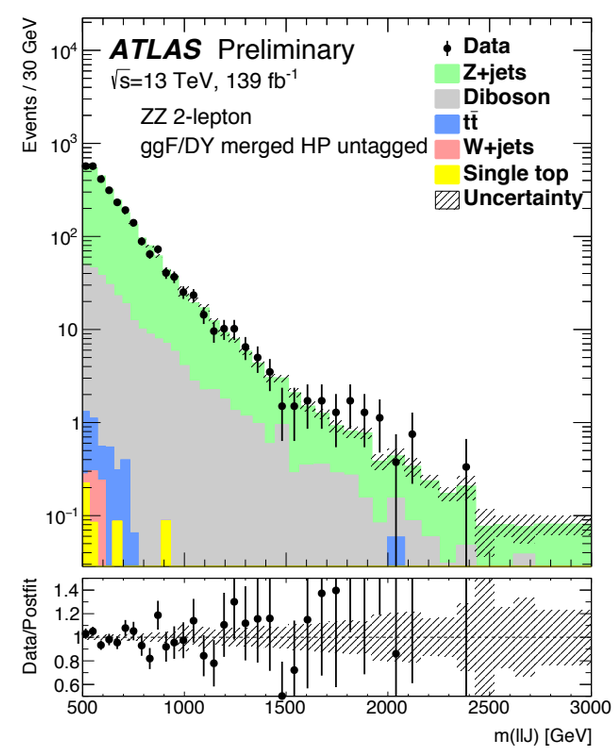


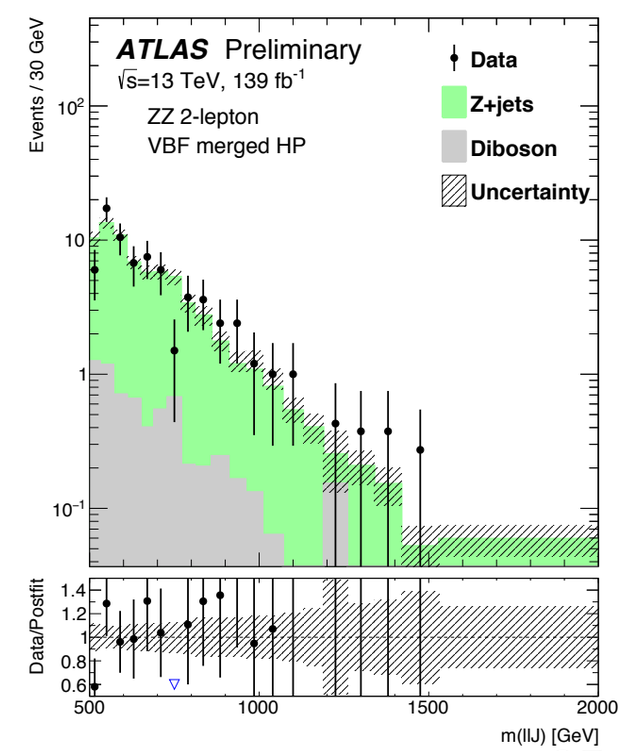






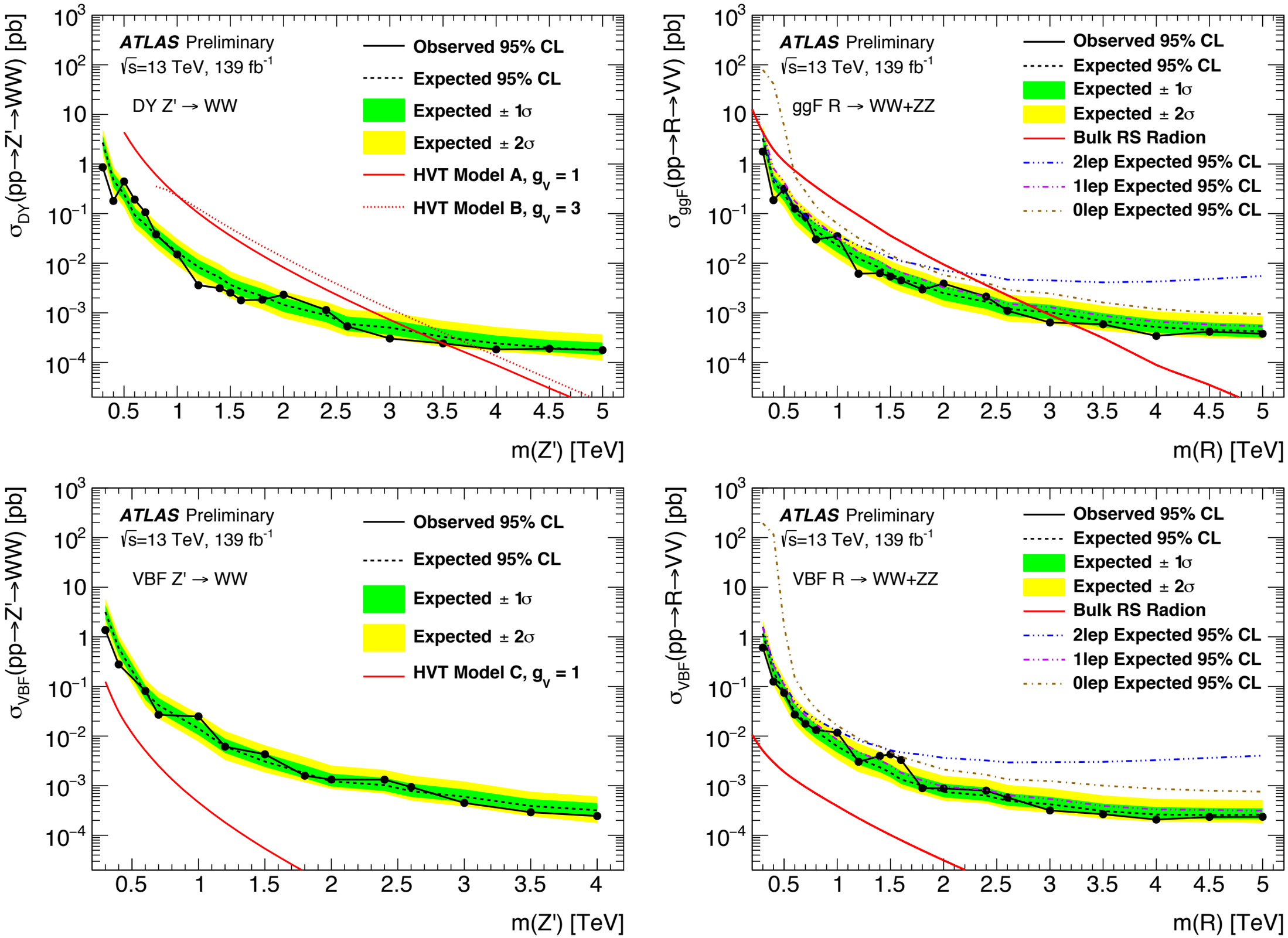




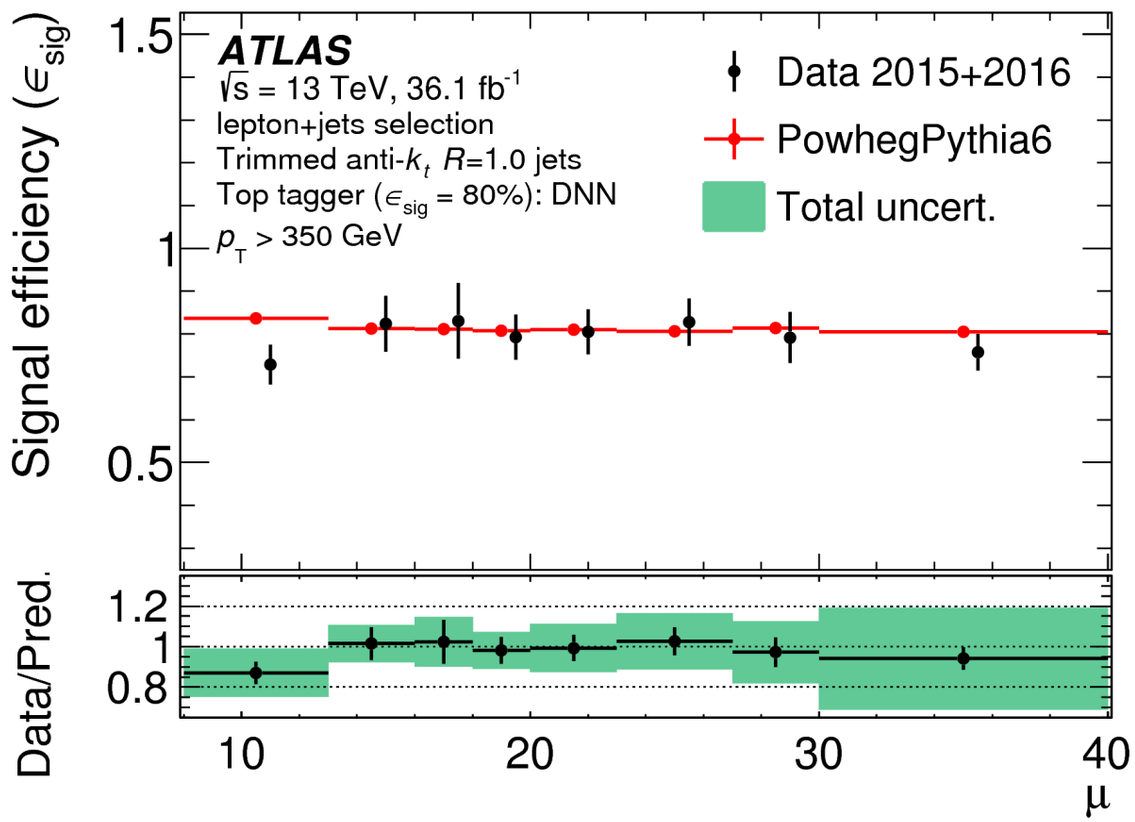


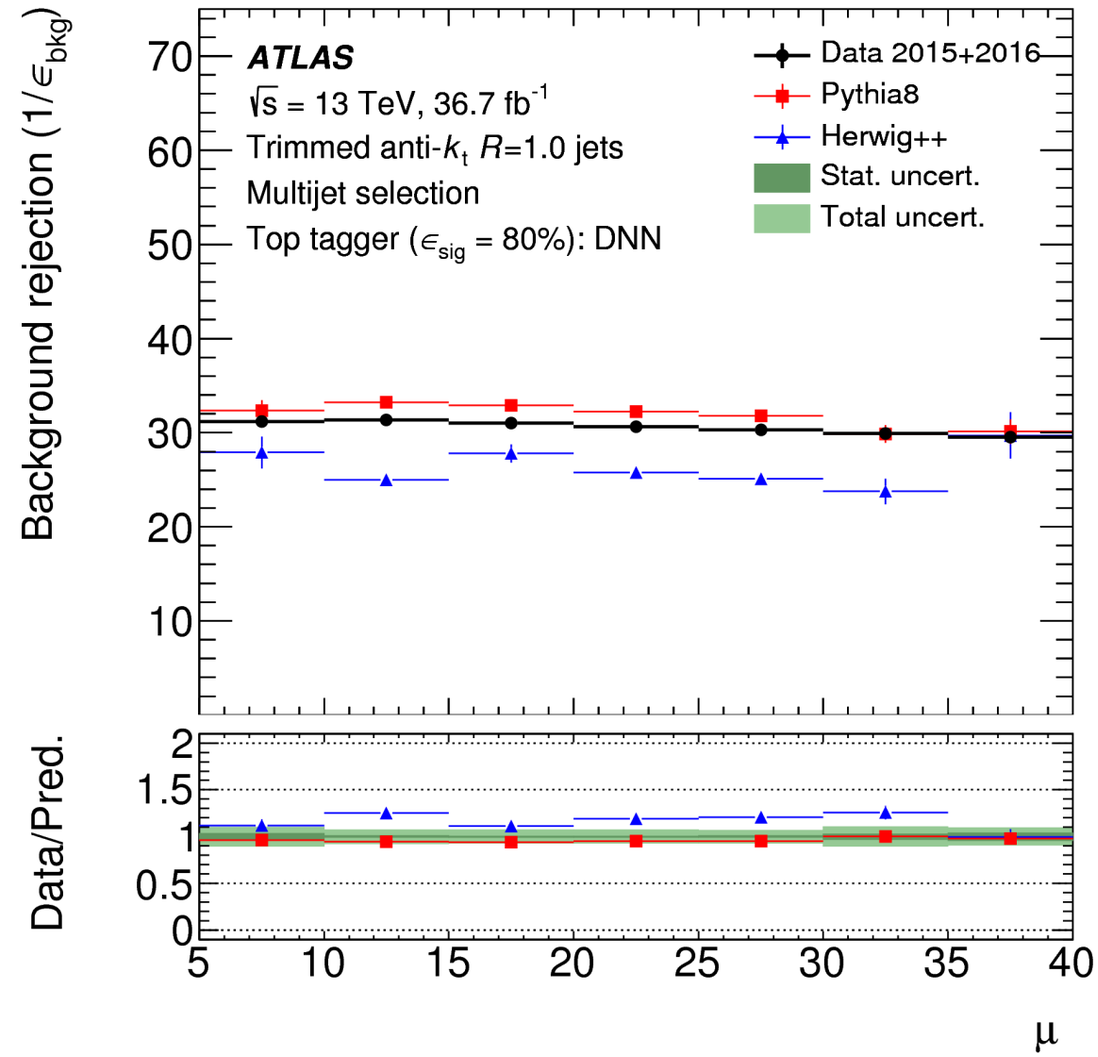
Multijet bkg is not negligible only in resolved 1-lep channel. It is estimated by data-driven method (ABCD)

Limits on the other signal models (VV)

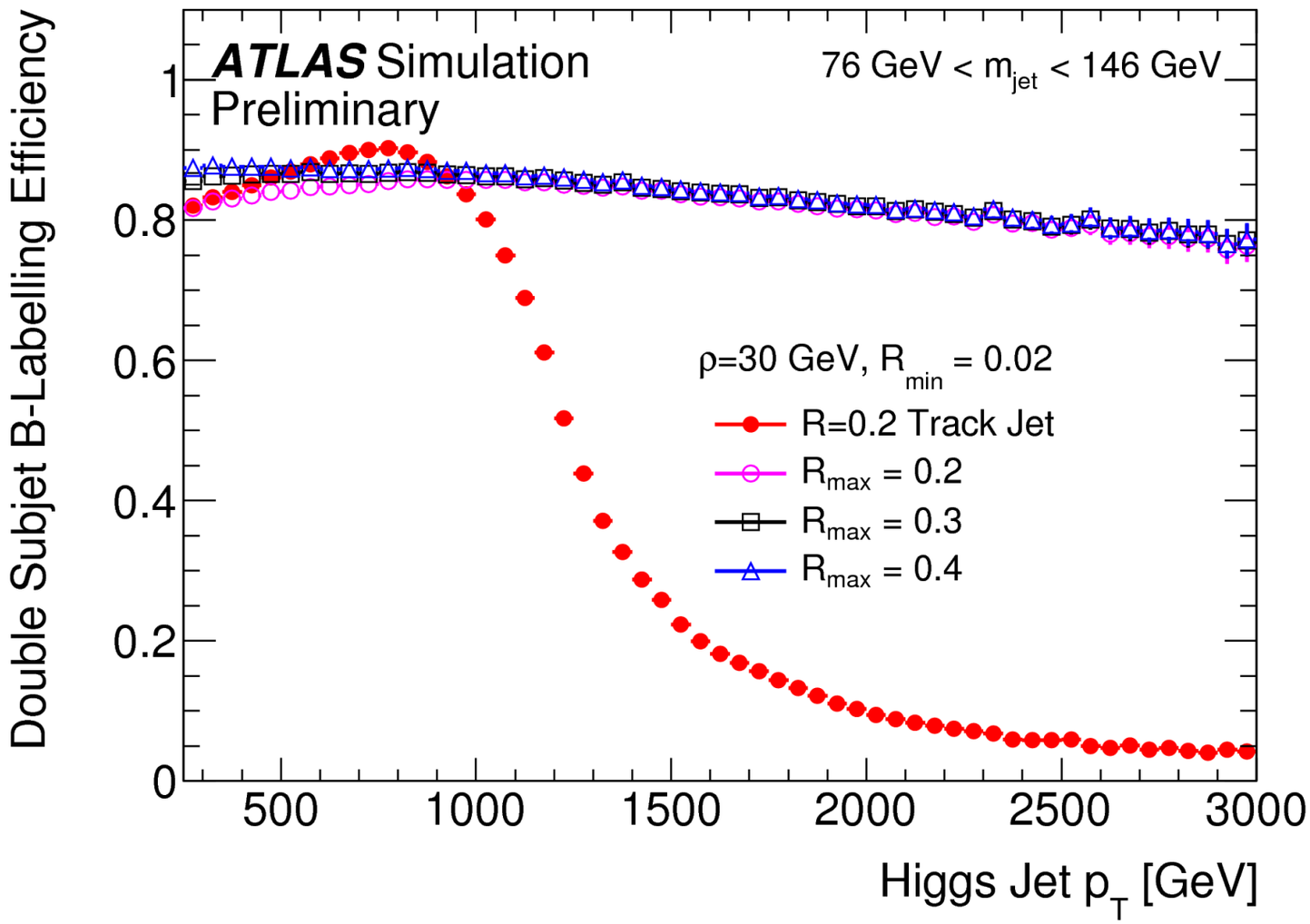


Pileup dependency of DNN top tagger





VR track-jet b-tagging performance



- Control plot:
  - 2 b-jets from Higgs decay can be separated by VR track jets
- Similarly, efficiency to b-jets in dense environment (inside boosted top decay) is also improved

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2017-010/

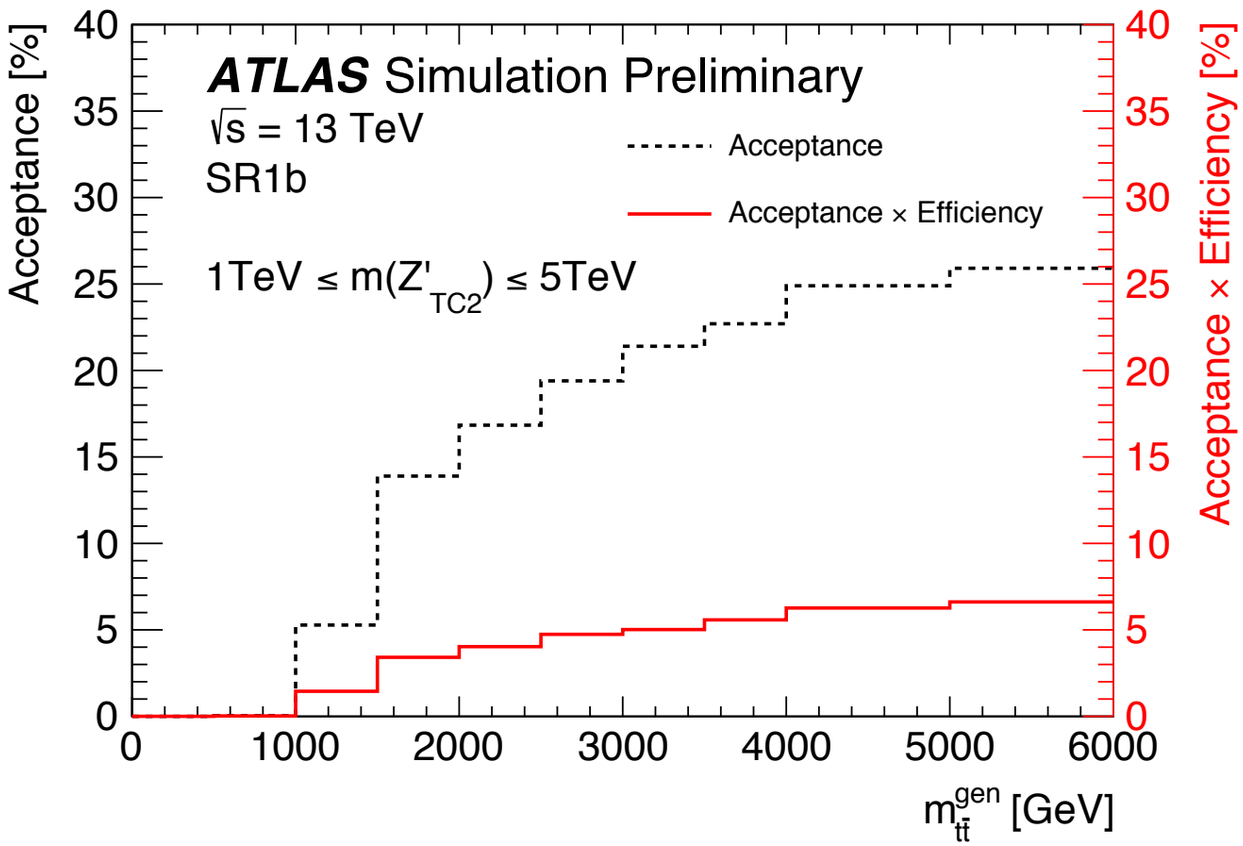
Extended ABCD method to extract multijet template from data

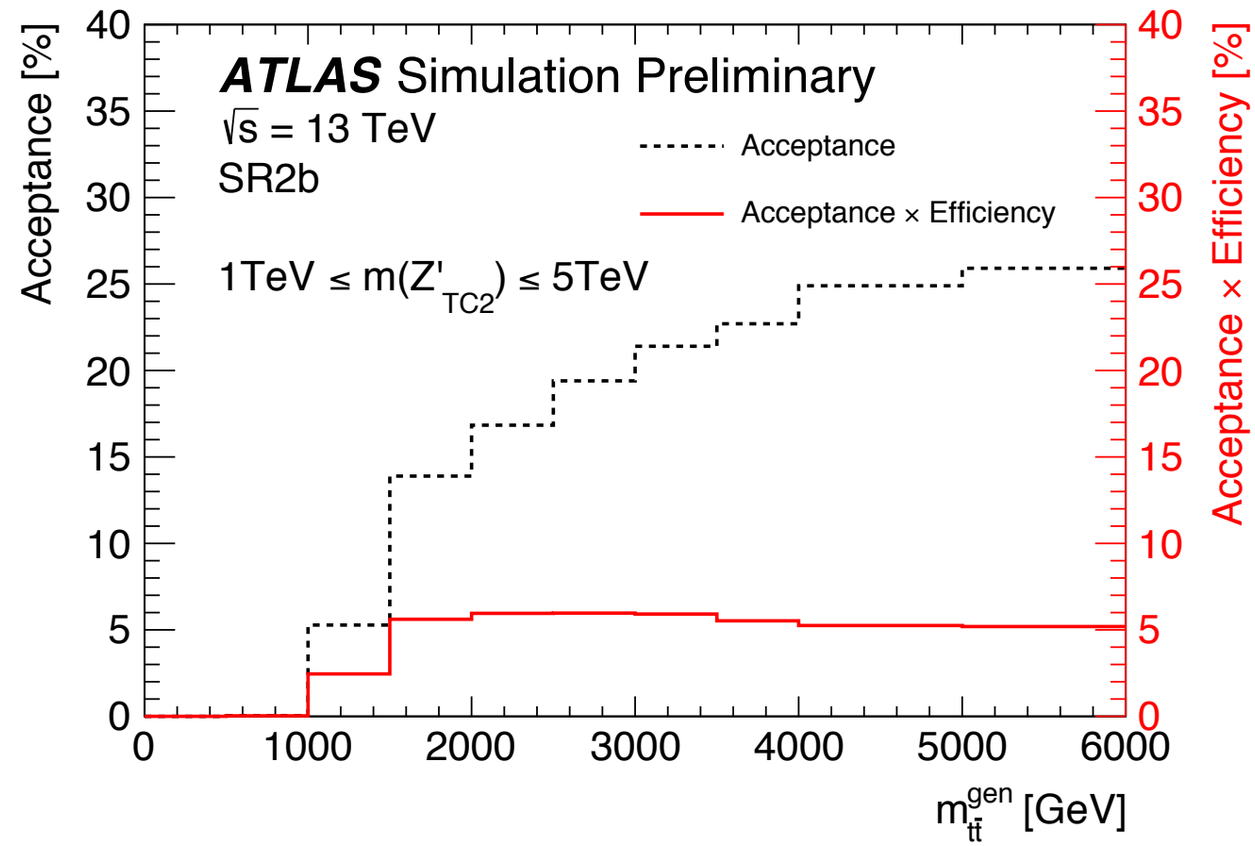
Subleading large-R jet				
tb	A (6.1%)		SR1b (23%)	SR2b (90%)
$t\not{b}$	B (0.5%)	E (1.8%)	TR (2.6%)	SR1b (28%)
$\not{t}b$	C (0.4%)		G (2.3%)	
$\not{t}\not{b}$	D (< 0.1%)	F (0.3%)	H (0.4%)	I (6.7%)
	$\not{t}\not{b}$	$\not{t}b$	$t\not{b}$	tb

Leading large-R jet is top-tagged? b-tagged?

- Ratio (B→A) and (H→I) are applied to TR to estimate multijet bkg in SR1b
- Ratio (B→A)×(B→E) and (H→I)×(H→G) are applied to TR to estimate multijet bkg in SR2b
- Regions C, D and F are used to evaluate the correlation between leading and subleading jets
  - e.g. double ratio (H→G)/(D→C) is applied to (B→A) factor
  - (D→F)/(B→E) is applied to (H→I) factor

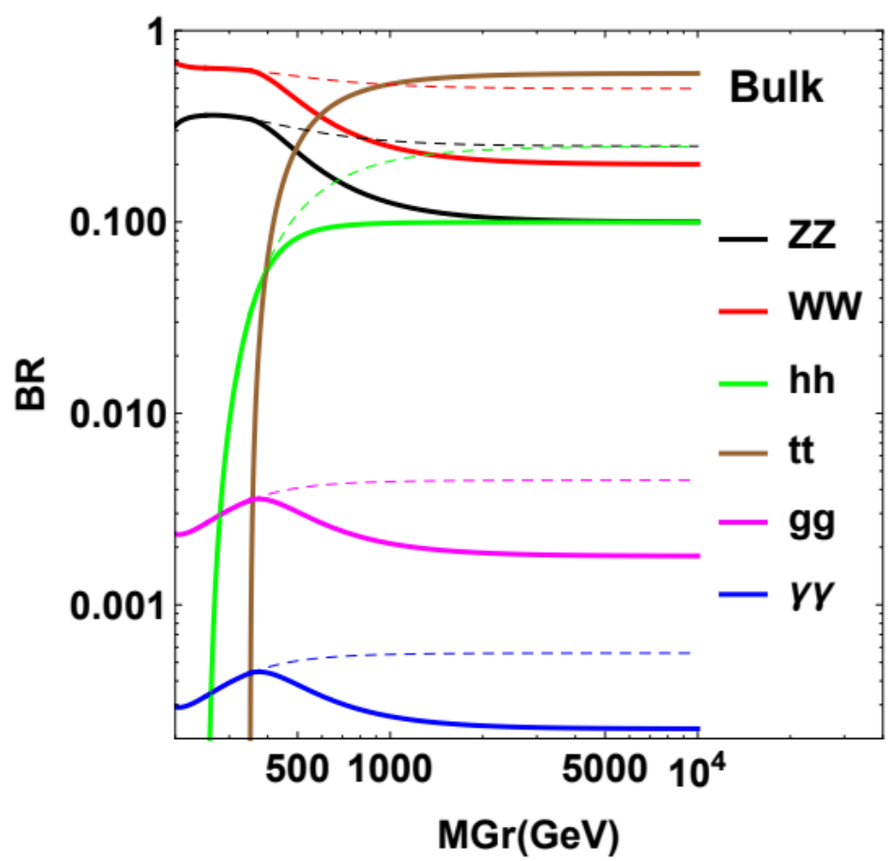
Acceptance x efficiency ($t\bar{t}$ analysis)

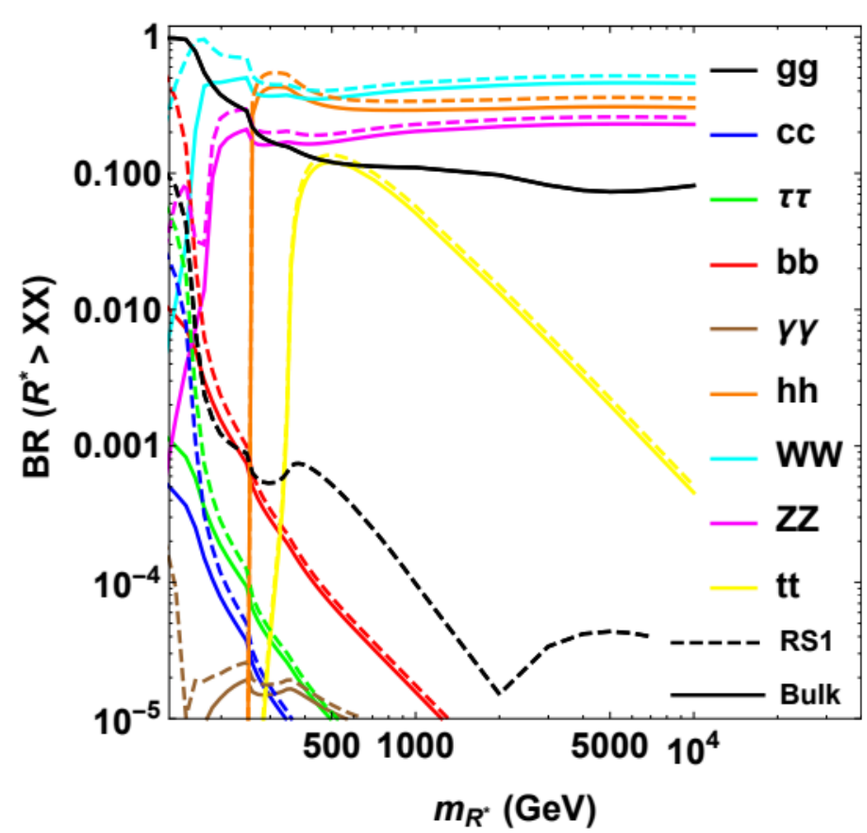




Bulk RS model

- Spin-2 Graviton mainly couples to W/Z/top/h
- Spin-0 Radion to stabilize the compactified extra dimension r_c, which also predominantly decays into W/Z/top/h and gluons

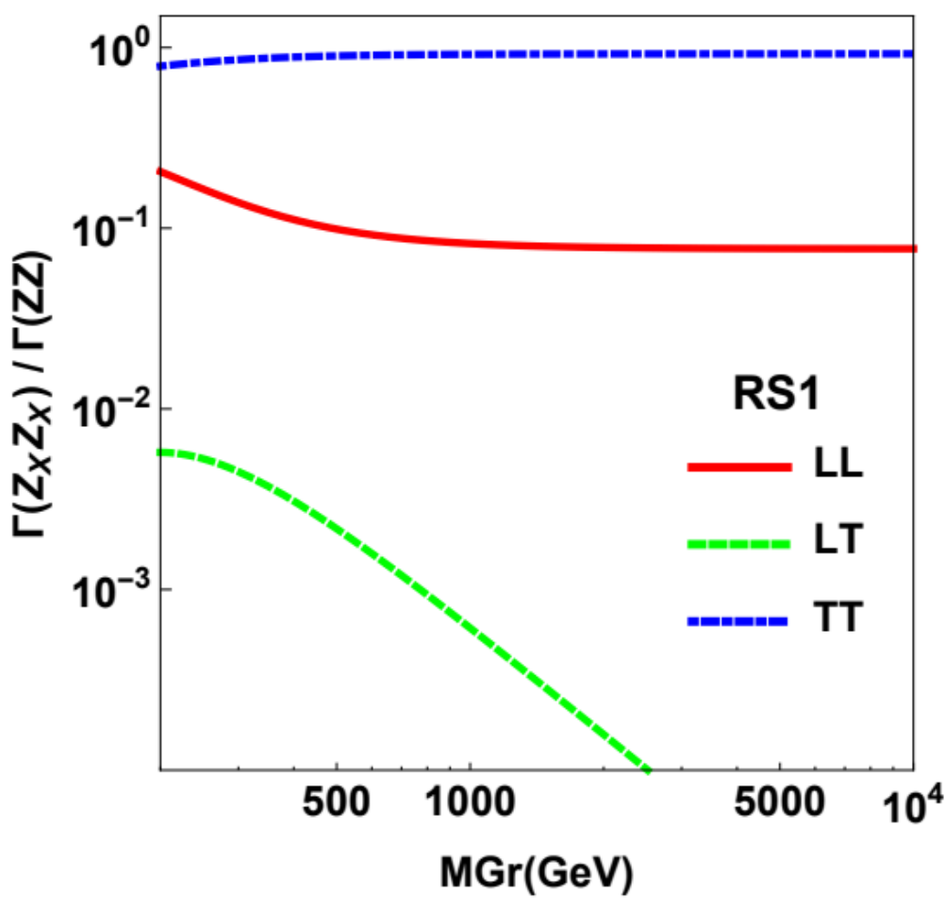


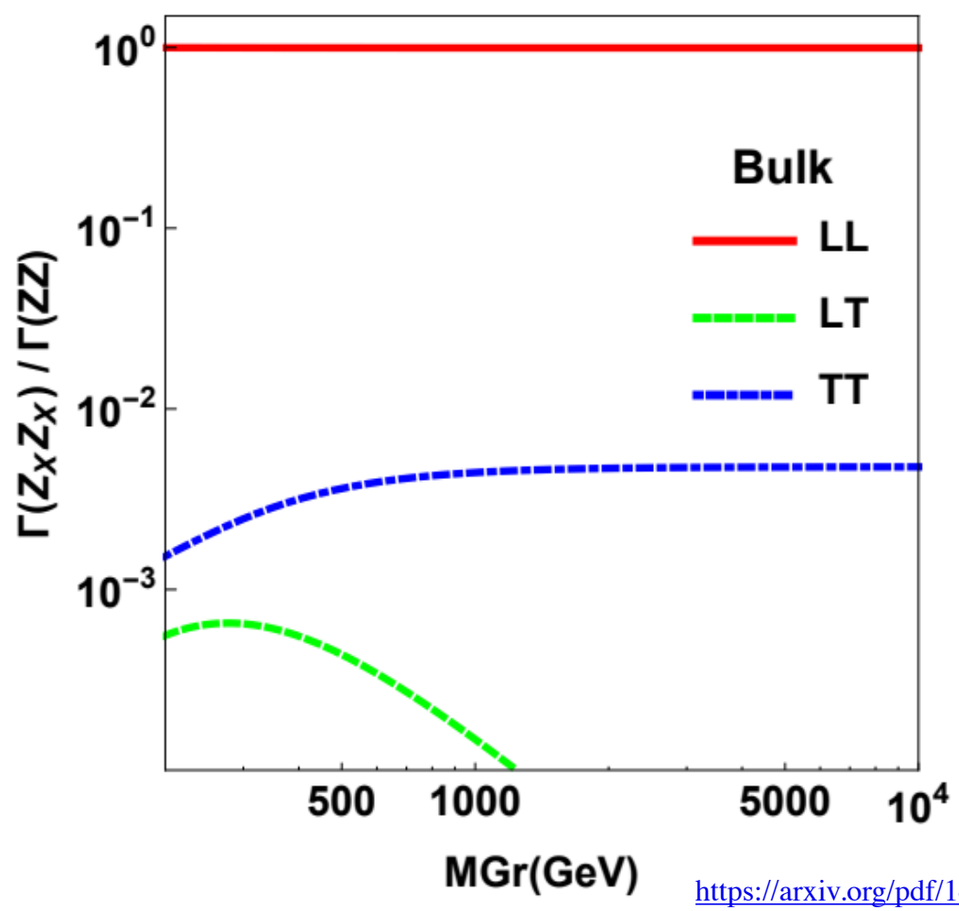


https://arxiv.org/pdf/1404.0102.pdf

Polarization of final-state bosons

- Depends on models and it is an interesting research topic in the next round of the analysis
- Our tagger is currently optimized to logitudinally-polarized W/Z bosons
  - Graviton in a standard RS model (RS1) has transversely polarized but mostly excluded by diphoton/dilepton channels
  - Bulk RS Gravition has ~100% longitudinal polarized bosons in the final state





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