Search for $t\bar{t}Z' \rightarrow t\bar{t}t\bar{t}$ production in the multilepton final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Contents

Introduction

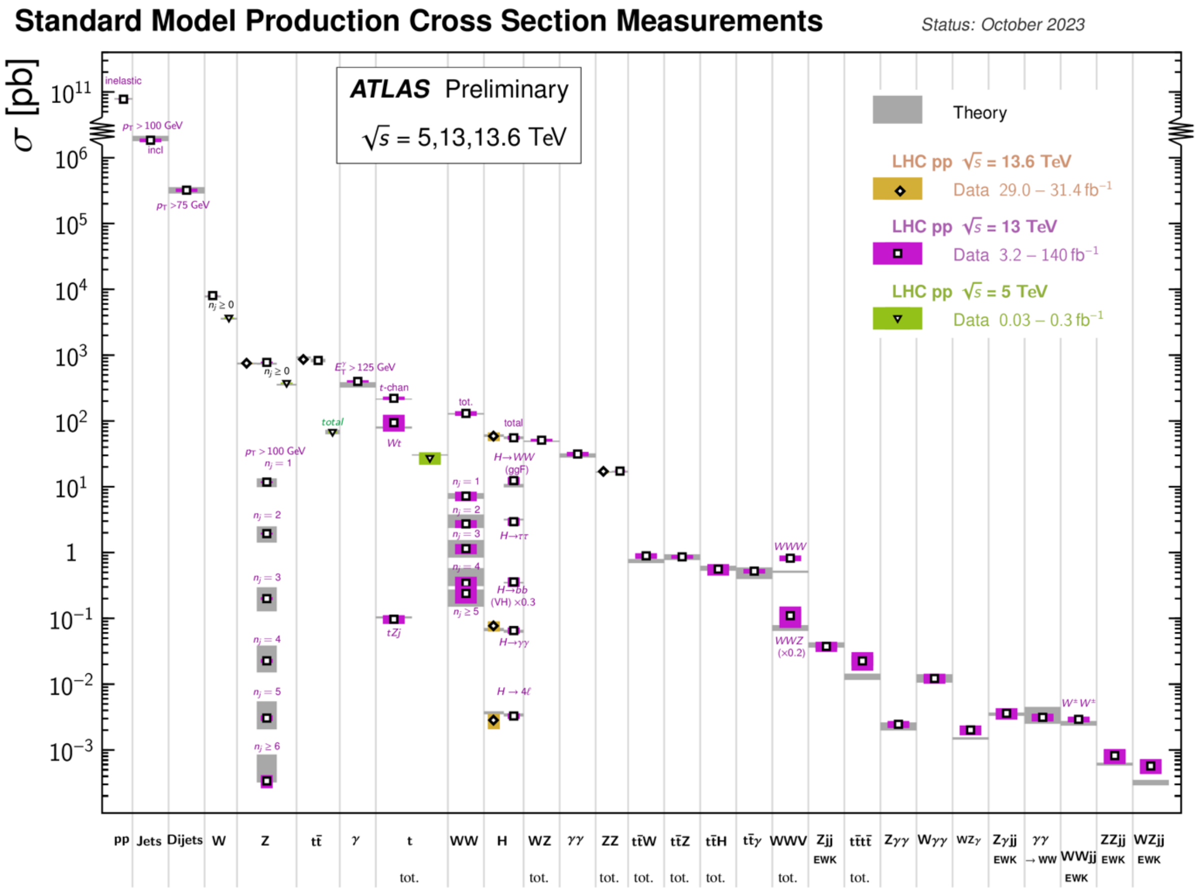
The Large Hadron Collider

- Currently the world's largest and most powerful particle accelerator
  - 27km (~17 miles) circumference
  - Built by CERN at the Swiss-French border
- Main experiments: ATLAS, CMS, LHCb, ALICE
  - ATLAS & CMS: general purpose detector
- Operates in periods of data-taking (runs) and shut-downs for upgrades

Physics at the LHC

- Primarily studies hard scattering proton-proton (pp) processes and resulting products
  - Run 2 (2015-18) center-of-mass energy 13 GeV
    - Data still constantly being analyzed
  - Operating at 13.6 TeV since 2022 (Run 3)
  - Also studies heavy-ion collisions with lead (Pb)

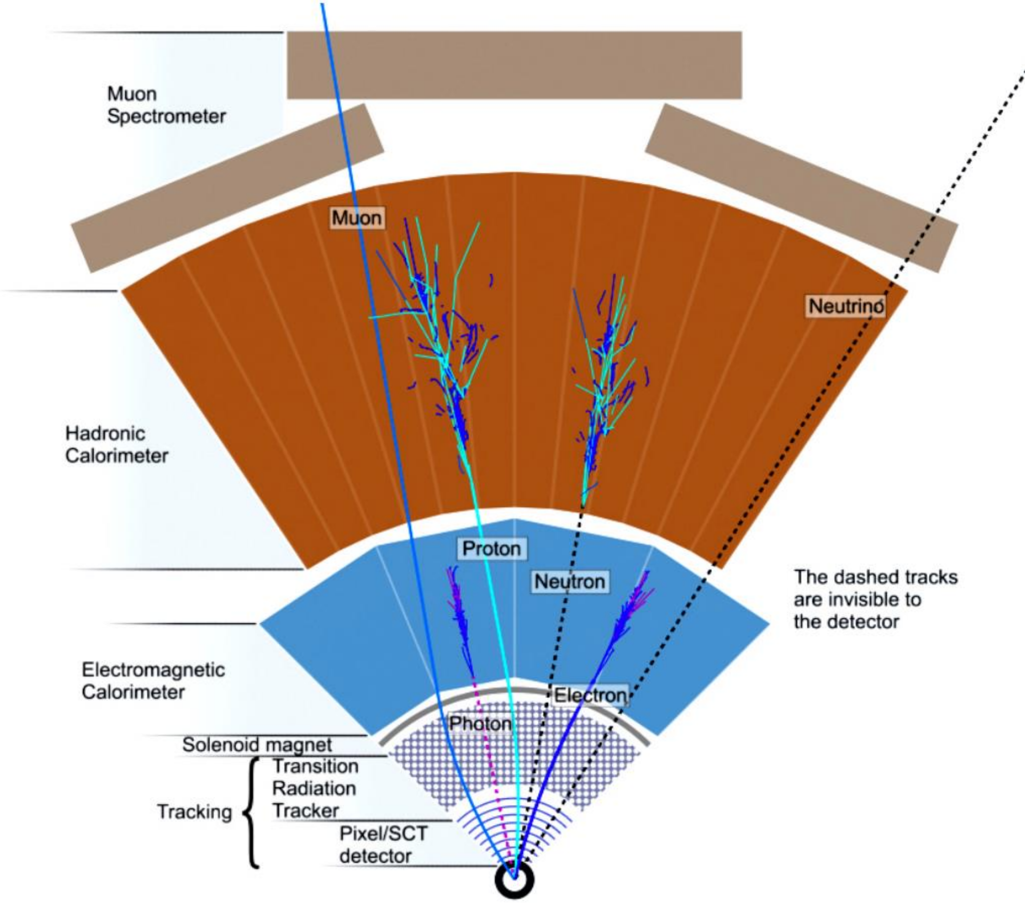
- **Cross-section** σ: probability of a particular interaction happening (unit: barns)
- Dominant process: jet production ($pp \rightarrow$ jets)
  - **Jets:** collimated cone of particles originating from a gluon or bare quark
  - Main background in most LHC analyses



The ATLAS detector: Overview

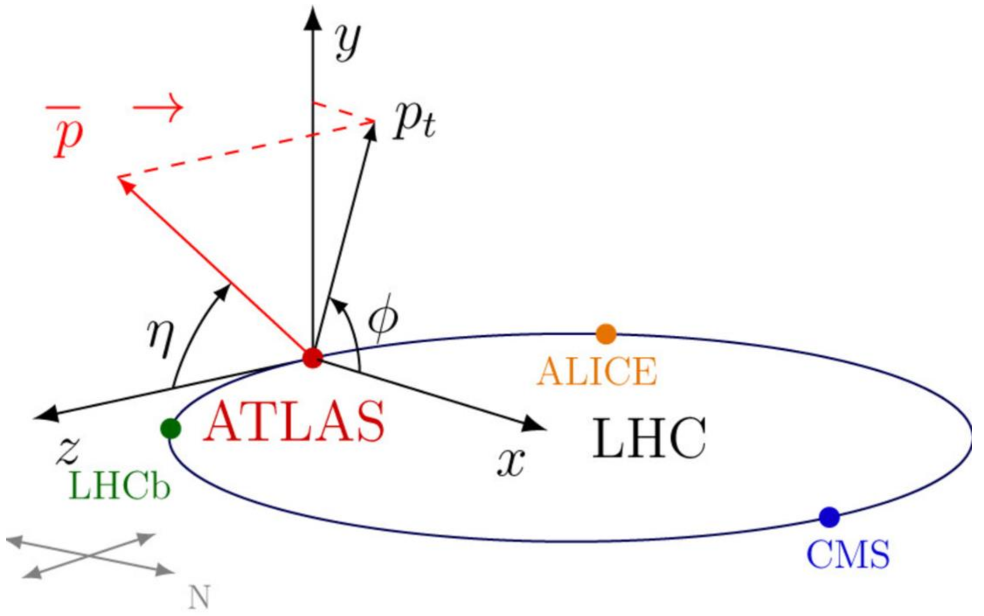
- Multi-purpose cylindrical detector
  - Concentric around beamline with collision point at the center

- Main subsystems
  - Inner detector
    - track & vertex reconstruction
  - Calorimeter (electromagnetic & hadronic)
    - energy deposition measurement
  - Muon spectrometer



The ATLAS detector: Coordinate system

- Right-handed coordinate system
  - **Cartesian:** z-axis points along beamline, x-axis points towards the center of the LHC
  - **Polar**: polar angle θ measured from beam axis, azimuthal angle ϕ measured along transverse (xy-) plane, starting from the x-axis

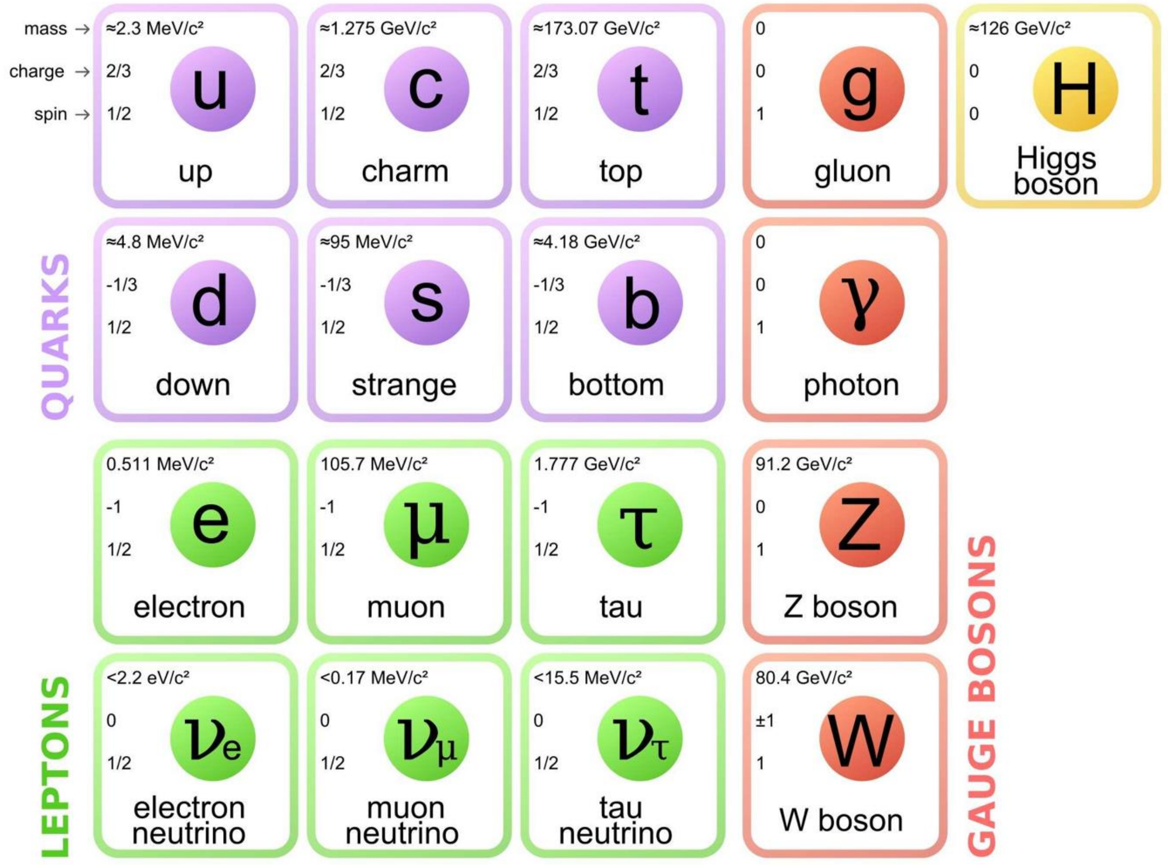


- **Pseudorapidity** $\eta = \ln\tan(\theta/2)$
  - small η: emitted close to orthogonal to the beamline
  - large η ($|\eta| > 4.9$): emitted close to beamline
- **Transverse momentum** $p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2}$
  - momentum component along the transverse plane

The Standard Model: Elementary particles

- Currently the most successful formalism to describe the physical world

- Two classes of particles
  - **Fermions:** building blocks of matter
    - half-spin, follows Fermi-Dirac statistics
    - quarks & leptons: 6 flavors grouped into 3 generations
      - quarks cannot exist in a vacuum due to color confinement
  - **Bosons**: fundamental force mediators
    - integer-spin, follows Bose-Einstein statistics
    - scalar boson (spin-0) & vector bosons (spin-1)

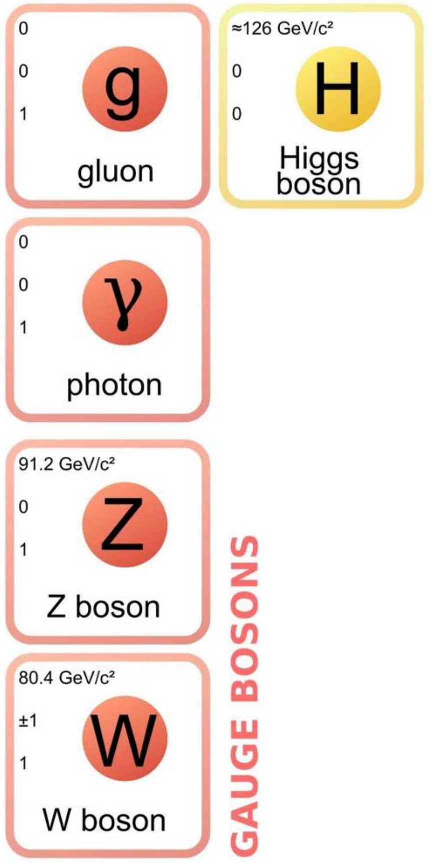


The Standard Model: Fundamental forces

- The Standard Model describes 3 out of 4 fundamental forces (except gravity)
    - All three mediated by vector bosons in the Standard Model

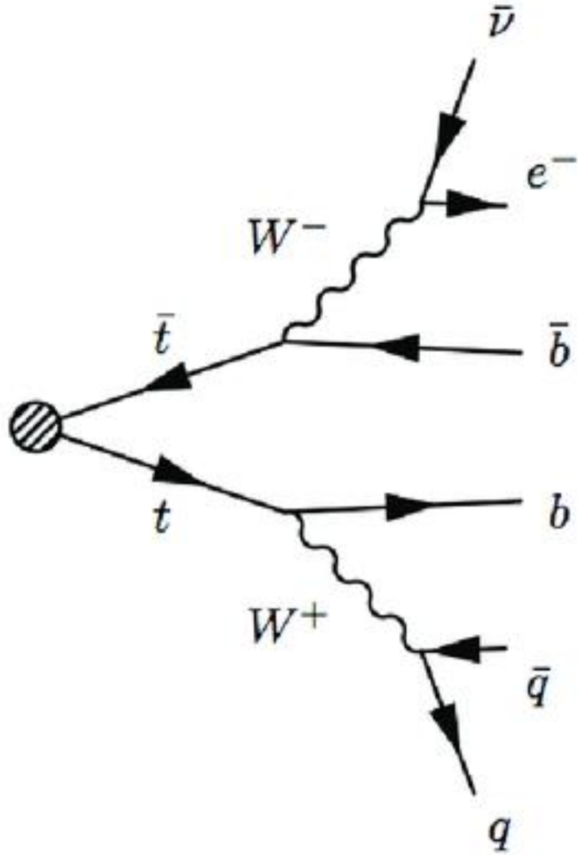
	Strong force	Weak force	Electromagnetism
Mediator particle	gluons (g)	$W^{\pm}$ & Z bosons	photons (γ)
Describing theory	Quantum chromodynamics (QCD)	Electroweak (EW) theory	Quantum electrodynamics (QED)

- **Higgs boson** (H) does not mediate any force, instead provide rest masses for all massive elementary particles in the SM ($W^{\pm}/Z$ bosons and fermions) via the Higgs mechanism



Top quark

- Heaviest elementary particle: $m_t \approx 172.5$ GeV
  - Close to the electroweak symmetry breaking scale
  - Strong coupling with the Higgs boson and to many hypothetical BSM resonances
- Very short lifetime ($\sim 10^{-24}$s), decays before hadronizing
- Branching ratio $t \to W^+ b$ close to 100%
  - Resulting W boson can decay hadronically ($W \to q\bar{q};\ 68\%$) or leptonically ($W \to l\bar{\nu}_l;\ 32\%$)
- Produced largely in $t\bar{t}$ pairs via gg fusion or $q\bar{q}$ annihilation



Beyond the Standard Model – Z' boson

- Standard Model imperfect with many unanswered questions
- Many BSM extensions of the SM predict a hypothetical gauge boson Z' resulting from breaking additional $U(1)'$ symmetries
    - similar to electroweak symmetry breaking

- Discovery implications
    - Extended Higgs sector from $U(1)'$ symmetry breaking
    - New particle from Z' decay products
    - …and more

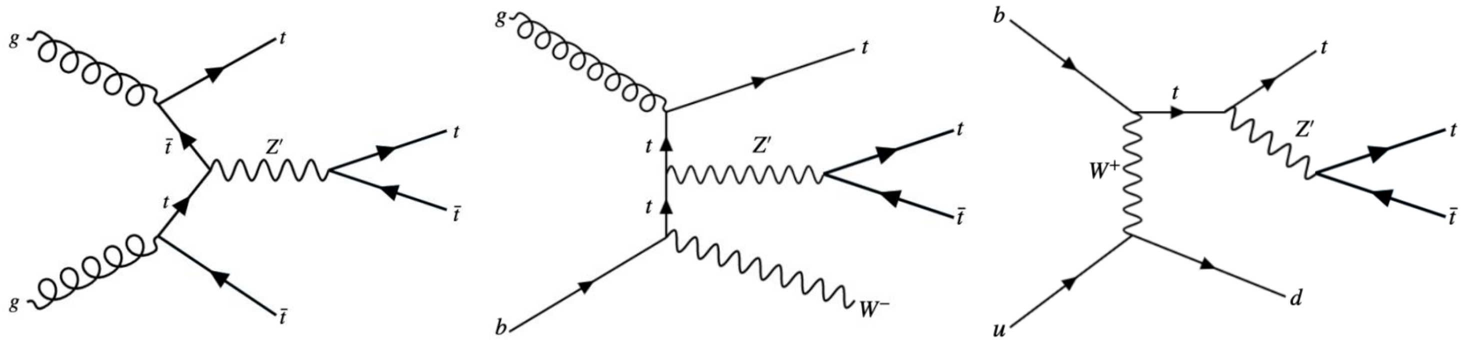
Top-philic vector particle model

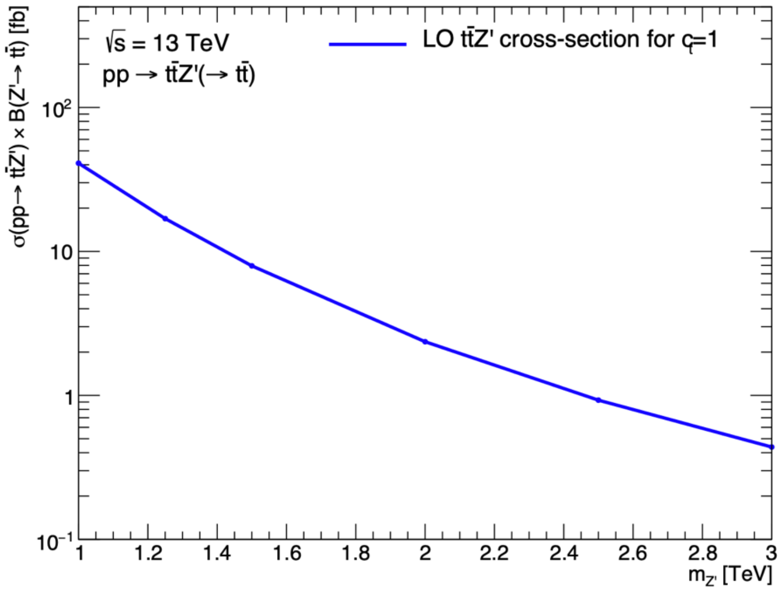
$$\mathcal{L}_{Z'} = \bar{t}\gamma_\mu \left(c_L P_L + c_R P_R\right) t Z'^\mu$$
$$= c_t \bar{t}\gamma_\mu \left(\cos\theta P_L + \sin\theta P_R\right) t Z'^\mu$$

$$c_t = \sqrt{c_L^2 + c_R^2}$$

$$P_{L/R} = (1 \mp \gamma_5)/2 \qquad \theta = \tan^{-1}(c_R/c_L)$$

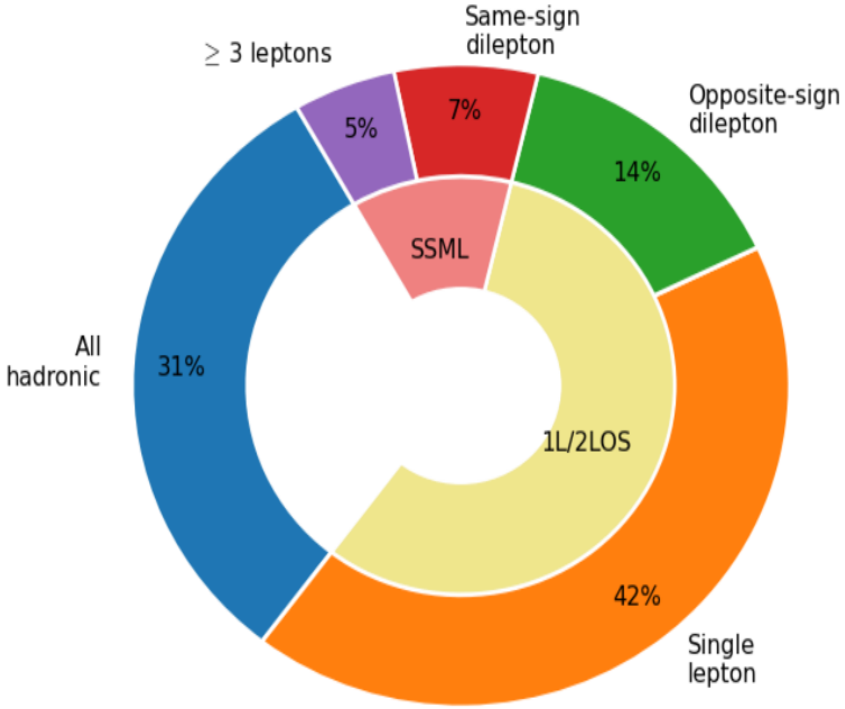
- Simplified top-philic color singlet model
  - **Assumption**: strong coupling only to the top quark
  - **Lagrangian**: top-Z' coupling c_t; chirality angle θ; chirality projection operator $P_{L/R}$
- Tree-level production channels:
  - Final states: $t\bar{t}Z'$ (four-top) or tjZ'/tWZ' (three-top)
  - $t\bar{t}Z'$ cross section larger than tjZ'/tWZ' by a factor of 2





Decay channels: $t\bar{t}Z'$

- $t\bar{t}Z' \to t\bar{t}t\bar{t} \to 4W^{\pm} + 4b$
  - 0/1/2/3+ $l/\bar{\upsilon}_l$ pairs; 8/6/4/2- jets & 4 b-jets
  - High jet multiplicity & total energy
- Three types of final states
  - all hadronic/0 lepton
  - 1 lepton/2 opposite-sign leptons (1LOS)
    - large branching ratio, but dominated by background of $t\bar{t}$-associated processes
  - 2 same-sign leptons/3+ leptons (multilepton - SSML)
    - smaller branching ratio, but has unique signal signature & low level of SM QCD background contamination



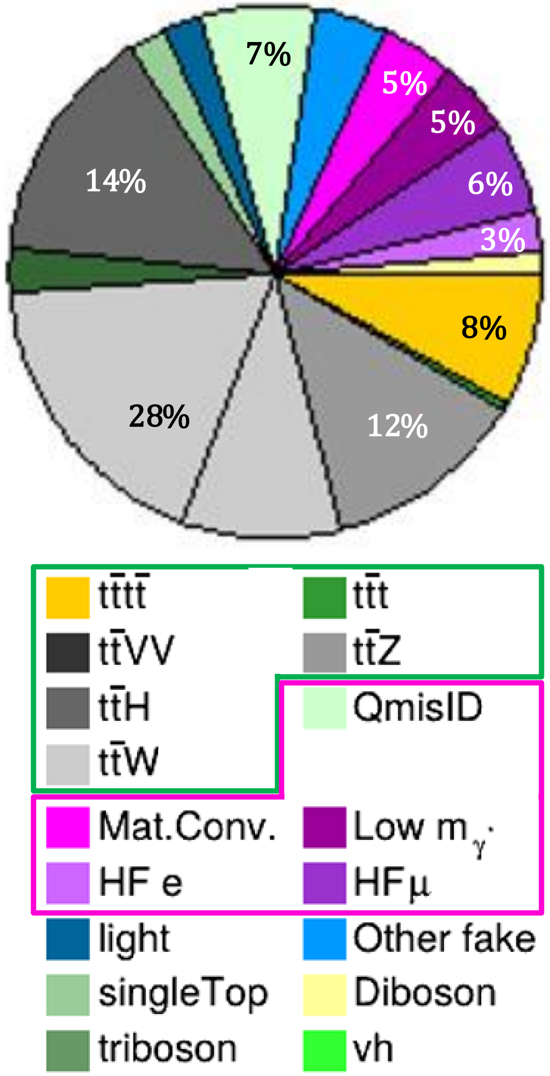
Analysis strategy

Analysis samples

- **Data**: LHC Run 2, $140\ \mathrm{fb}^{-1}$ of data ~ 1.1×10^{16} pp collisions @ $\sqrt{s} = 13\ \mathrm{TeV}$
- **Simulation**:
  - Monte Carlo (MC) simulated samples are used to optimize analysis configurations before unblinding
  - General steps
    1. Event generation: simulate the physics process at basic parton level
    2. Parton showering & hadronization: model QCD radiation, hadronization & decays
    3. Detector simulation: add pile-up and detector effects,
  - **Six** $t\bar{t}Z'$ signal samples
    - mass $m_{Z'} \in [1000, 1250, 1500, 2000, 2500, 3000]\ \mathrm{GeV}$
    - top coupling $c_t = 1$; chirality angle $\theta = \pi/4$

Analysis backgrounds

- Backgrounds (BGs): processes that mimic signal signature
  - Needs to be separated from signal (signal extraction)
- **Irreducible**
  - similar final state, primary analysis background
  - Dominant: SM $t\bar{t}t\bar{t},\ t\bar{t}Z,\ t\bar{t}W,\ t\bar{t}H,\ t\bar{t}t$
- **Reducible**
  - similar final state from reconstruction & detector effects
    - misidentified charge, photon conversion electrons, etc.
  - Dominant: fake/non-prompt leptons



Irreducible background

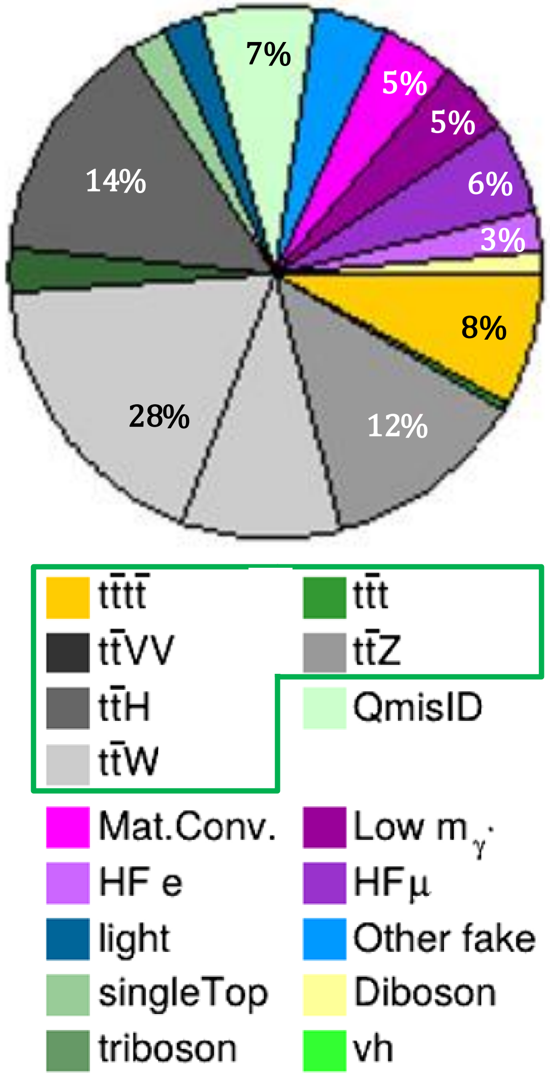
- Background SM processes that result in a similar final state signal signature physically
  - Cannot be distinguished purely by reconstruction and detector effects

$W \to l\bar{\nu}$

$Z \to b\bar{b}/l\bar{l}$

$H \to b\bar{b}/VV$

(w/ SSML selection)	$t\bar{t}Z'$	SM $t\bar{t}t\bar{t}$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t$
Decay	$4b + 4W$	$4b + 4W$	$2b + 3W$	$2b + 2W + Z$	$2b + 2W + H$	$3b + 3W$
Final products	$4b + 2{\sim}4l$	$4b + 2{\sim}4l$	$2b + 2{\sim}3l$	$4b + 2l$ or $2b + 4l$	$6{\sim}2b + 2{\sim}6l$	$3b + 2{\sim}3l$

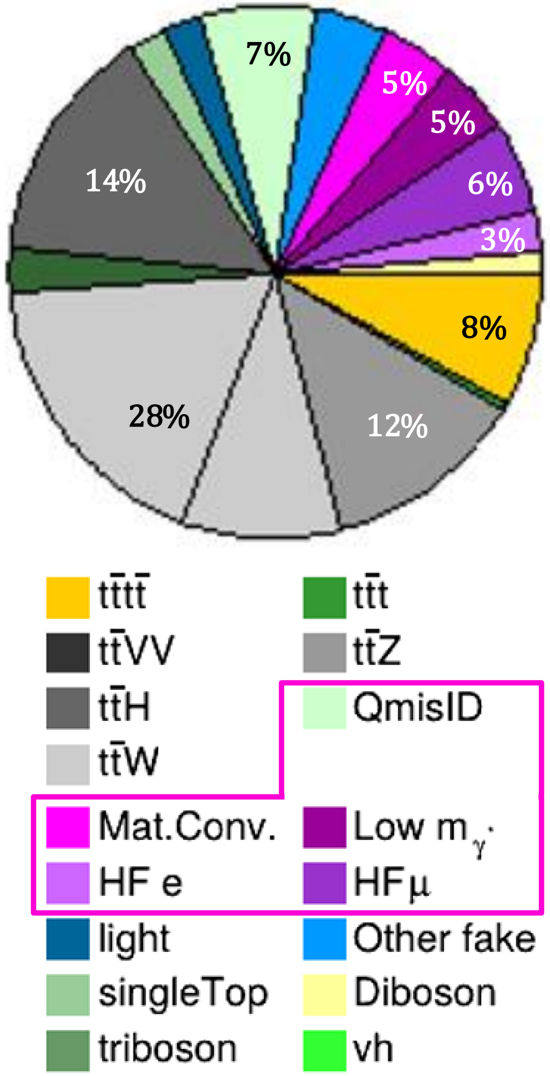


- Most are evaluated using MC simulated distributions
  - different normalization scheme for $t\bar{t}W$ due to mismodeling at high jet multiplicity

Reducible background

- Dominated by $\boldsymbol{t\bar{t}/V}$/**single top** +jets events containing a mis-assigned charge (QmisID) or a fake/non-prompt lepton reconstructed as prompt
  - QmisID: $l\bar{l} \rightarrow ll$
  - Fake/non-prompt: $l \rightarrow ll$ or $l\bar{l} \rightarrow l\bar{l}l$

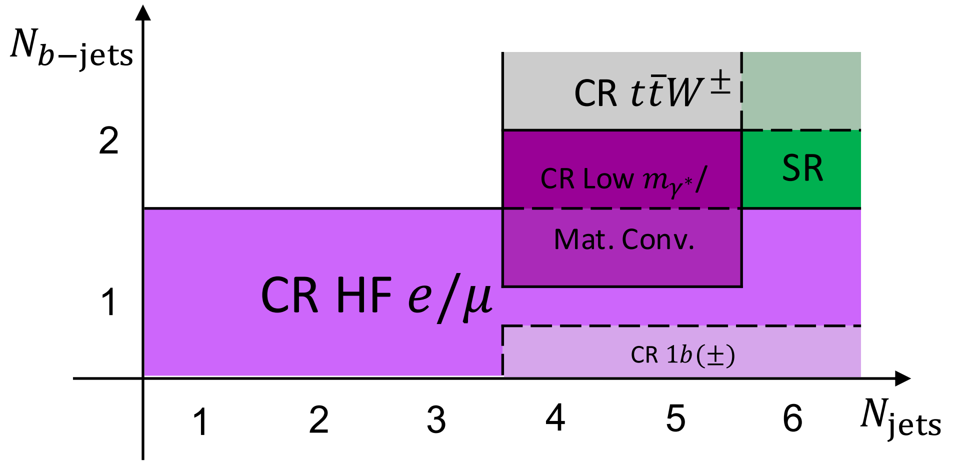
- Fake/non-prompt sources
  - **Heavy flavor decays** (HF): leptons from secondary processes e.g. semileptonic b-/c-hadrons decays
  - **Material conversion** (Mat. Conv.): real photon interacting with detector material and converts to $\gamma \rightarrow e^+e^-$
  - **Photon conversion** (low m_{γ^*}): virtual photon γ^* emitted from a decay process immediately converting to e^+e^- within the decay vertex



Analysis regions

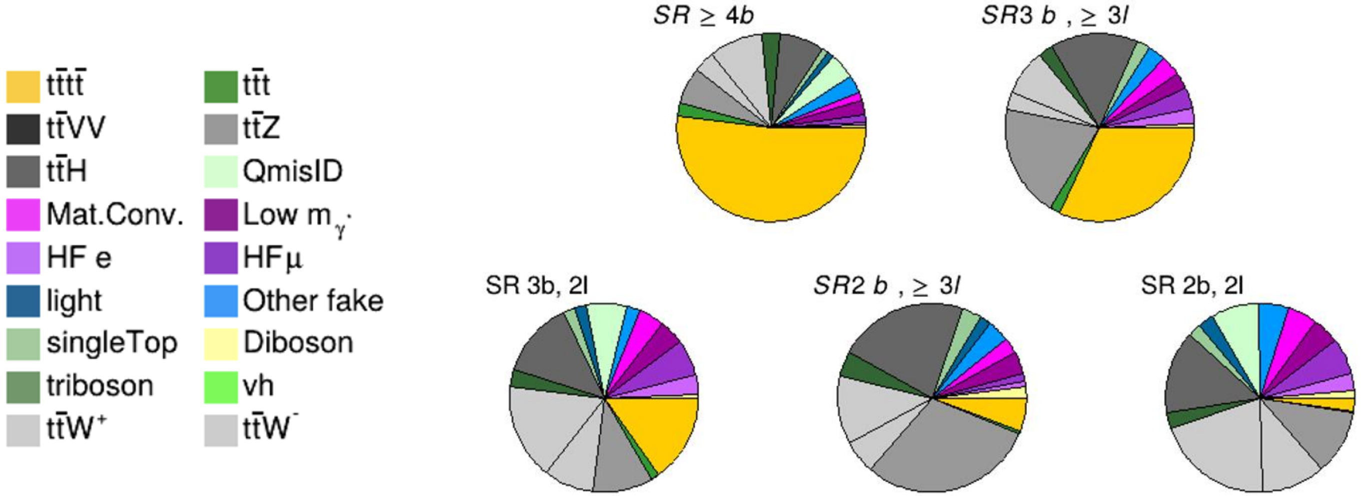
- All events must have **2 same-sign leptons** or **≥3 leptons**

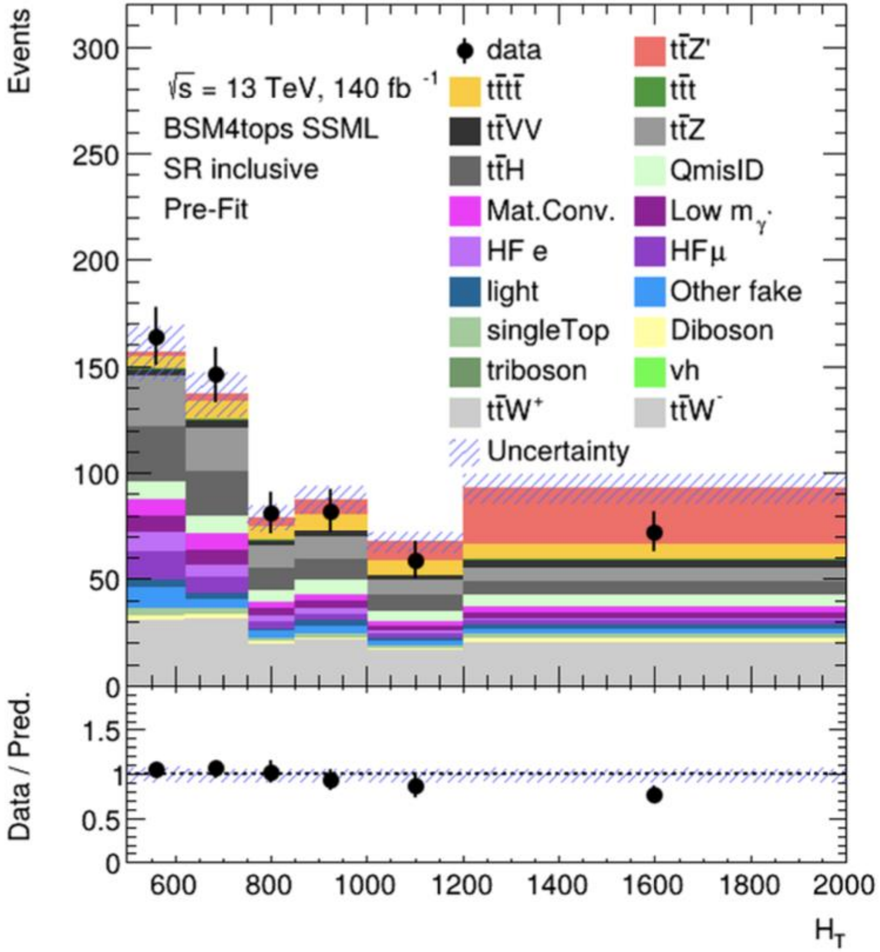
- Events are selected and placed in different analysis regions
  - **Signal region** (SR): 1 region → 5 subregions
    - Events selected using criteria optimized for signal topology
  - **Control regions** (CRs): 4 (fake/non-prompt) + 4 ($t\bar{t}W$) regions
    - Must maintain orthogonality with SR to avoid contamination from signal events
    - Each CR is enriched in the corresponding BG process



Signal region

- **Main selection criteria**: ≥ 6 jets, ≥ 2 b-jets & high total energy ($H_\mathrm{T} > 500$ GeV)
- Further divided into 5 sub-regions based on $N_{b-\mathrm{jets}}$ & N_lep
- **Discrimination observable** for signal extraction is scalar sum of all leptons & jets in the event (H_T)



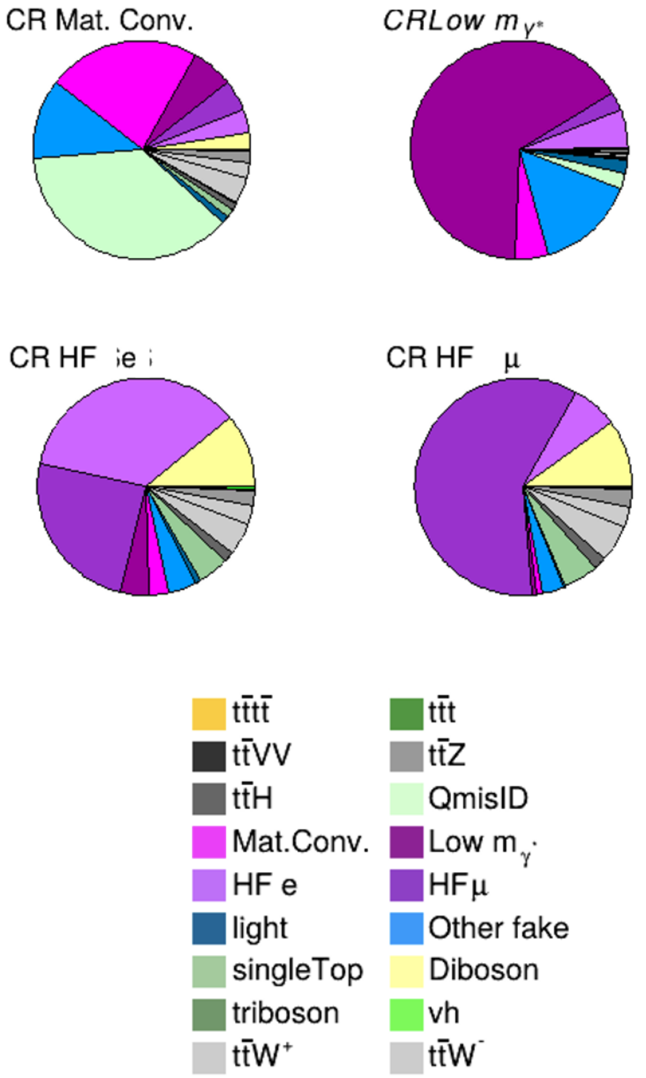


Control regions: Non-prompt/fake

- Non-prompt/fake BG estimated using **template fitting**
    - MC distributions scaled to data in dedicated CRs with fitted **normalization factors** (NFs)
    - MC-to-data NFs propagated to SR to maximize BG estimation accuracy within the SR

- Each fake/non-prompt BG constrained by corresponding CRs

  → 4 CRs & NFs
- NFs fitted simultaneously with signal strength in the final fit



Control regions: $t\bar{t}W$

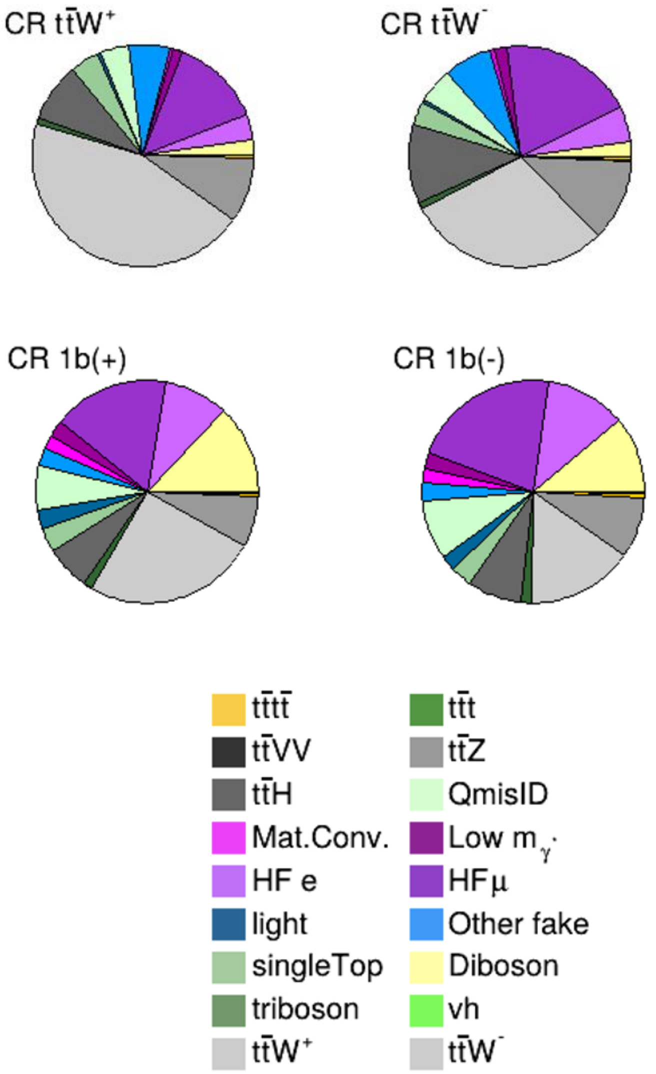
- Template fitting not optimal due to mismodeling of $t\bar{t}W$ at high jet multiplicity

  → alternative method using staircase & Poisson QCD scaling patterns for cross-section of $t\bar{t}W$ at a particular jet multiplicity

  - Instead of MC-to-data NFs, propagate $\mathrm{NF}_{t\bar{t}W^{\pm}(N_{\mathrm{jets}}=4)}, a_0, a_1$ obtained from fitting a function parameterized in N_{jets}

$$\mathrm{NF}_{t\bar{t}W(j')} = \left(\mathrm{NF}_{t\bar{t}W^{+}(N_{\mathrm{jets}}=4)} + \mathrm{NF}_{t\bar{t}W^{-}(N_{\mathrm{jets}}=4)}\right) \times \prod_{j=4}^{j'-1} \left(a_0 + \frac{a_1}{1+(j-4)}\right)$$

- Two types of CRs for $t\bar{t}W$
  - CR $t\bar{t}W$: constrains flavor composition
  - CR $1b$: constrains jet multiplicity spectrum
- Separate CRs for $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$ due to $\sigma_{t\bar{t}W^{+}} = 2 \cdot \sigma_{t\bar{t}W^{+}}$



Statistical methods: Likelihood function

- **Likelihood function** $\mathcal{L}(\boldsymbol{N} \mid \mu, \boldsymbol{\kappa}, \boldsymbol{\theta})$ represents the likelihood of obtaining the set of observed data $\boldsymbol{N}$ given certain values of parameters $\mu, \boldsymbol{\kappa}, \boldsymbol{\theta}$
  - $\boldsymbol{N}$ = **observed number of events** – modeled in each bin with a Poisson distribution
    - expected # events in i^{th} bin

$$\langle N_i \rangle = \mu N_i^{\mathrm{sig}}(\boldsymbol{\theta}) + \boldsymbol{\kappa} \cdot \boldsymbol{N}_i^{\mathrm{BG}}(\boldsymbol{\theta})$$

  - μ = **signal significance** - parameter to extract from observed data
  - $\boldsymbol{\theta}$ = **nuisance parameters** (NPs) – in this case parameterized systematic uncertainties
    - modeled as Gaussian
  - $\boldsymbol{\kappa}$ = **normalization factors** (NFs)

- $\mathcal{L}(\boldsymbol{N} \mid \hat{\mu}, \hat{\boldsymbol{\kappa}}, \hat{\boldsymbol{\theta}})$ is maximized when the model parameter values $\hat{\mu}, \hat{\boldsymbol{\kappa}}, \hat{\boldsymbol{\theta}}$ result in prediction that best fit $\boldsymbol{N}$ out of all possible values of $\mu, \boldsymbol{\kappa}, \boldsymbol{\theta}$
  - μ, NPs and NFs are estimated simultaneously in the maximization fit for $\mathcal{L}$

Statistical methods: Profile likelihood

- Observed data is tested for compatibility with the background-only hypothesis H_0 $(\mu = 0)$ or the signal + background hypothesis H_1 $(\mu > 0)$
- A **test statistic** quantifies the deviation of observed data $\boldsymbol{N}$ from H_0
    - Optimal test statistic for discovery is a function of the **profile likelihood ratio**

$$q_0 = -2\ln\frac{\mathcal{L}(\boldsymbol{N} \mid H_0)}{\mathcal{L}(\boldsymbol{N} \mid H_1)} = -2\ln\frac{\mathcal{L}(\mu = 0, \hat{\theta}_{\mu=0})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

    - Ideally the distribution of chosen discriminating observable of signal ($\boldsymbol{N}$) and BG are significantly different for best sensitivity
- The **p-value** $p = P\left(q_0 \geq {q_0}^{\text{obs}} \,\middle|\, H_0\right)$ describes the probability of observing data that deviates even further from H_0 than $\boldsymbol{N}$
    - H_0 is rejected (in favor of H_1) at a confidence level (CL) α if $p \leq \alpha$
    - **Confidence level**: 95% $(p \leq 0.05)$

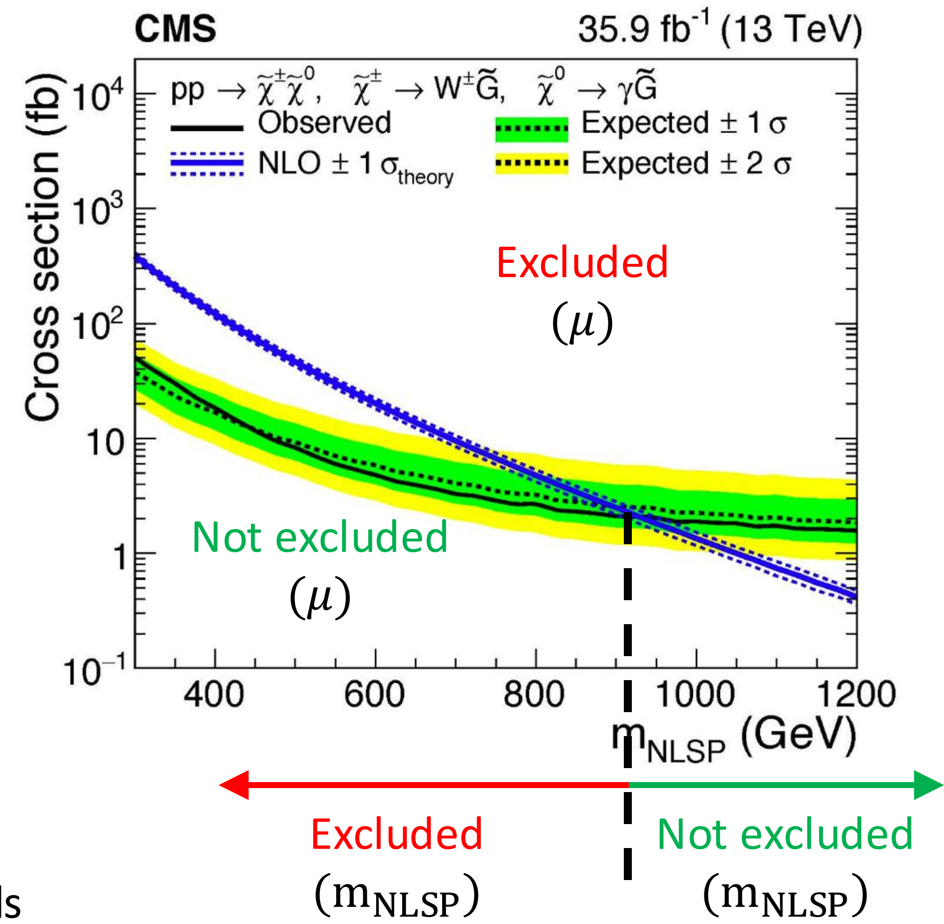
Statistical methods: Exclusion limits

- **Exclusion limits**: the upper bound of μ at a certain confidence level (if H_1 is rejected)
    - Below the exclusion limit, the data is not in conflict with H_1
- $\mathbf{CL_s}$ **method**:

$$\mathrm{CL_s} = \frac{P\left(q_0 \geq {q_0}^{\mathrm{obs}} \mid H_1\right)}{P\left(q_0 \geq {q_0}^{\mathrm{obs}} \mid H_0\right)}$$

    - μ value where $\mathrm{CL_s} = \alpha$ is the exclusion limit of μ at $1 - \alpha$ CL

- Observed limit: determined using real, observed data
- Expected limit: determined using pseudo-data (Asimov data)
    - **Asimov data**: “ideal” simulated data under assumption of H_0
    - Used to calculate 1σ (68%) and 2σ (95%) uncertainty bands



Results

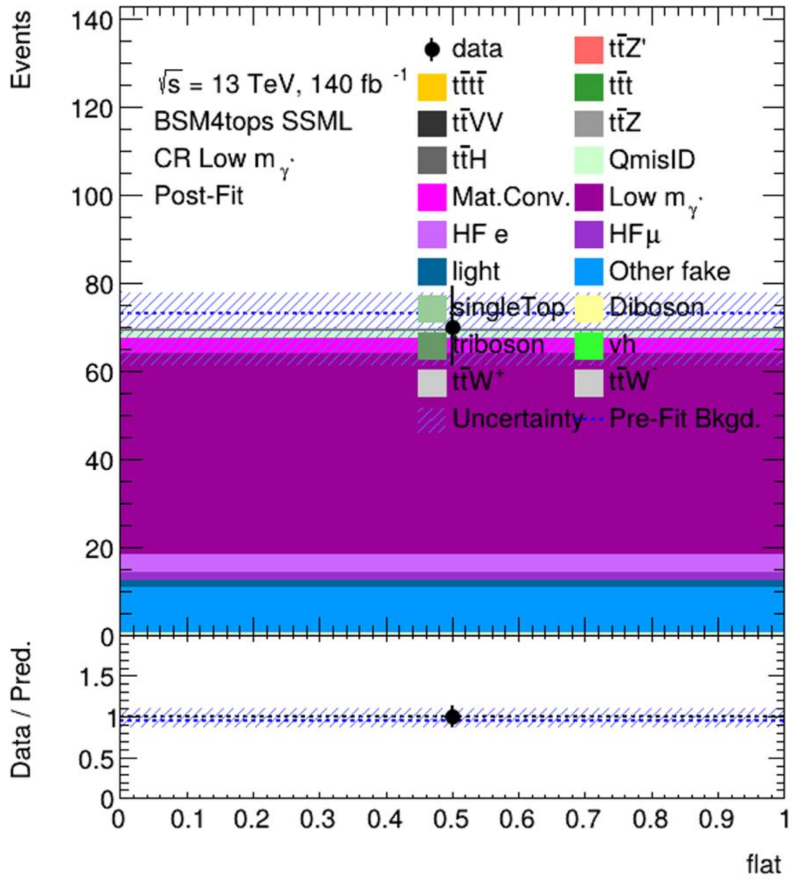
Normalization & scaling factors

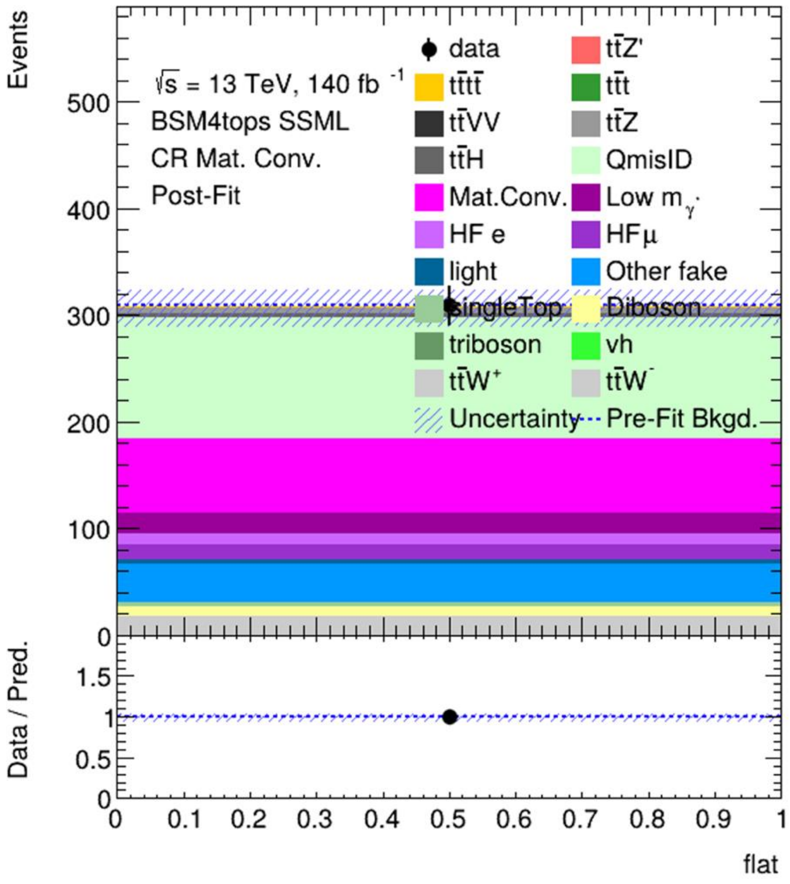
- No significant variation is observed in fit output behavior using $t\bar{t}Z'$ samples of different $m_{Z'}$
- Nominal pre-fit values: $\mathrm{NF} = 1;\ a_0 = a_1 = 0$

Parameter	$\mathrm{NF}_{\mathrm{HF}\ e}$	$\mathrm{NF}_{\mathrm{HF}\ \mu}$	$\mathrm{NF}_{\mathrm{Mat.\ Conv.}}$	$\mathrm{NF}_{\mathrm{Low}\ m_{\gamma^*}}$
Fit value	$0.68^{+0.23}_{-0.22}$	$0.97^{+0.17}_{-0.16}$	$0.97^{+0.31}_{-0.28}$	$0.97^{+0.23}_{-0.20}$

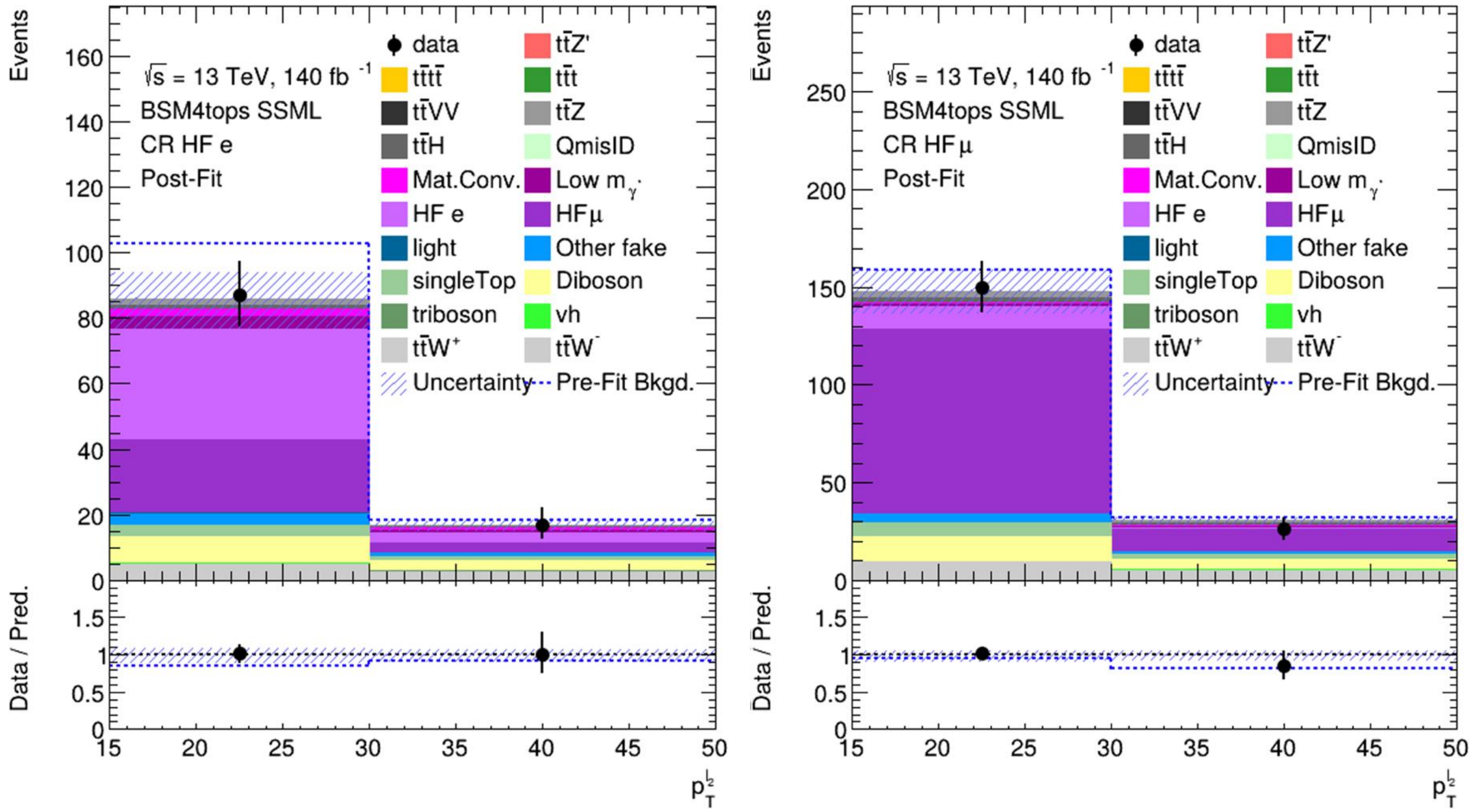
Parameter	a_0	a_1	$\mathrm{NF}_{t\bar{t}W+(4\mathrm{j})}$	$\mathrm{NF}_{t\bar{t}W-(4\mathrm{j})}$
Fit value	$0.39^{+0.11}_{-0.11}$	$0.42^{+0.25}_{-0.24}$	$1.21^{+0.18}_{-0.18}$	$1.10^{+0.26}_{-0.26}$

Background modeling: Fake/non-prompt

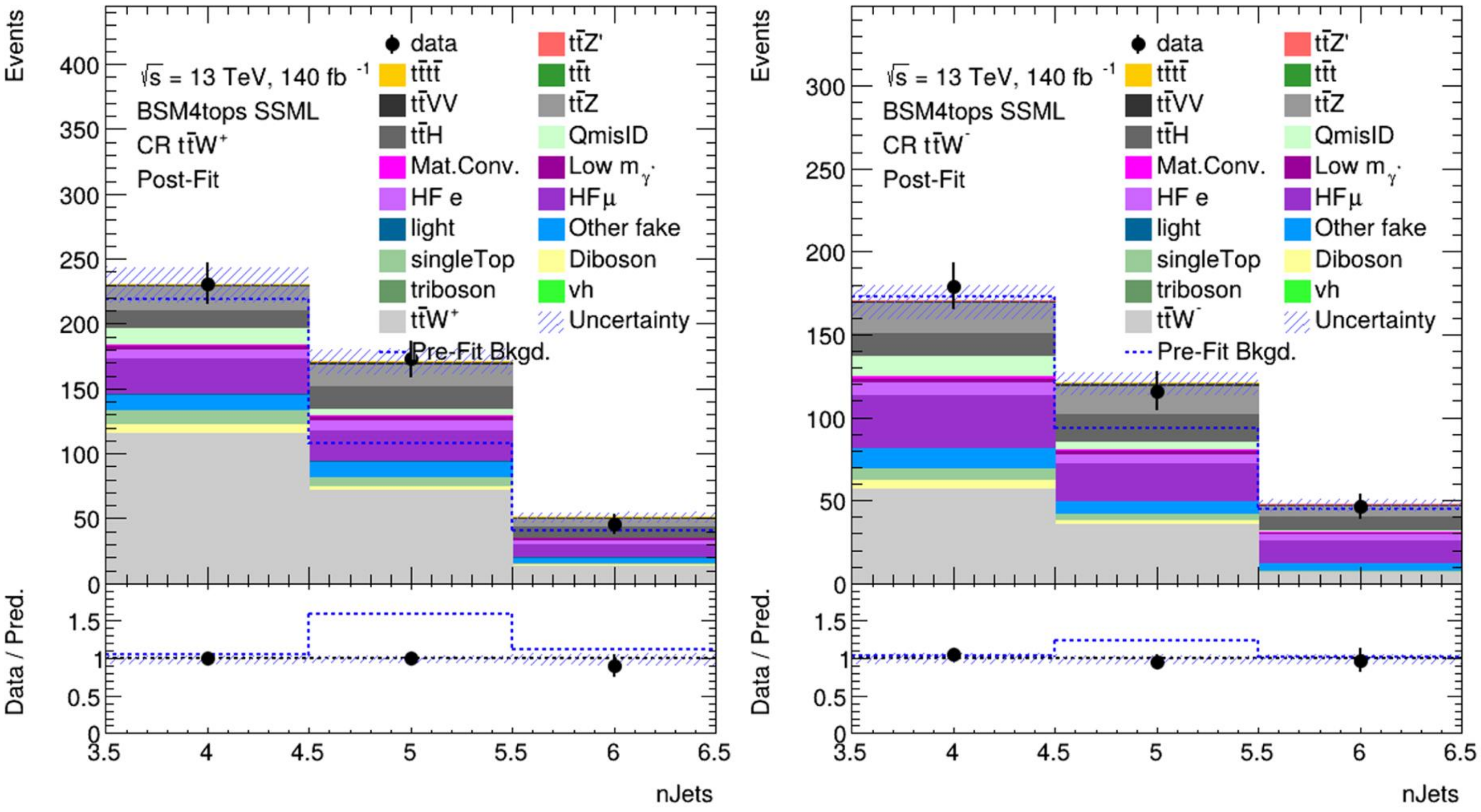




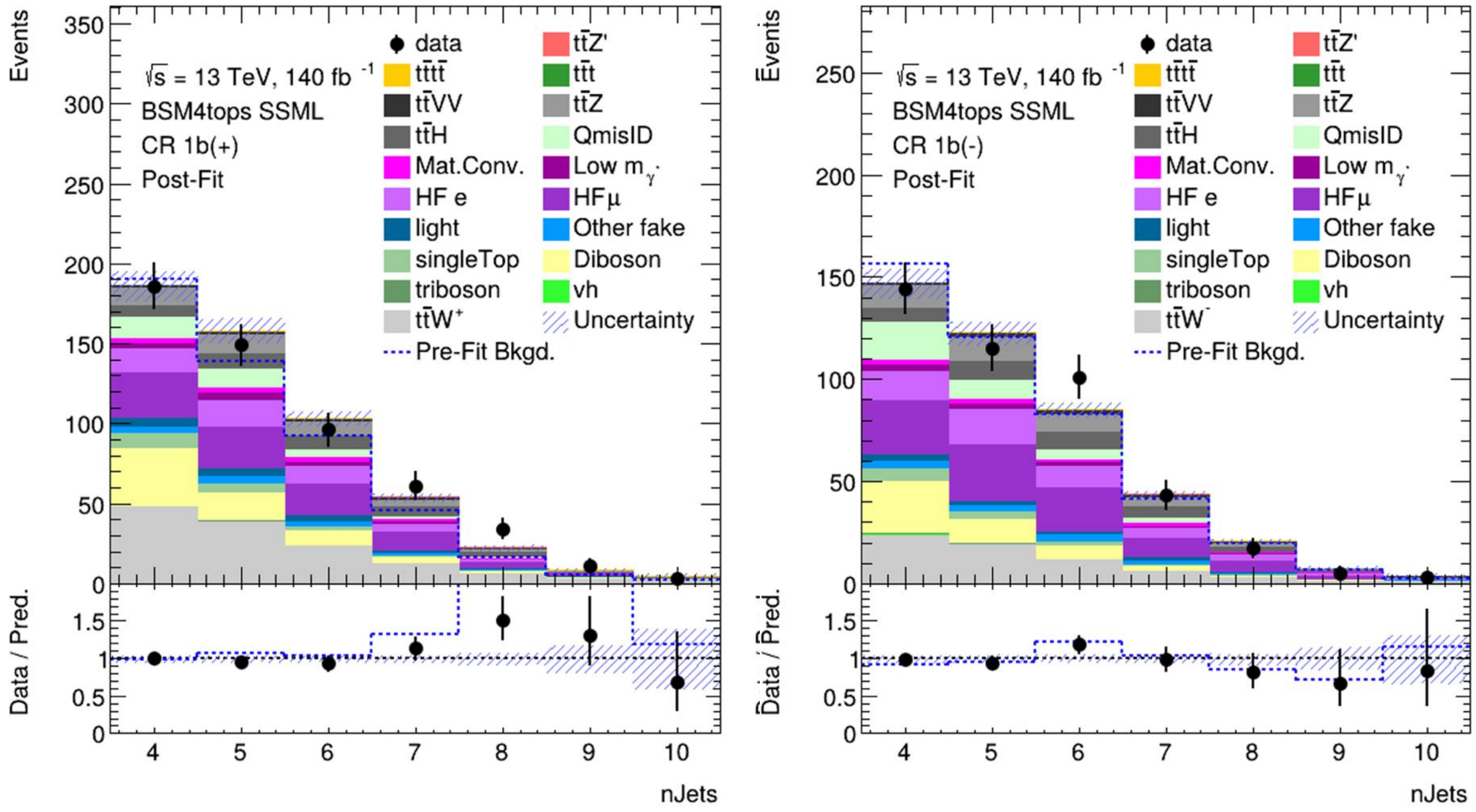
Background modeling: Fake/non-prompt



Background modeling: $t\bar{t}W$



Background modeling: $t\bar{t}W$



Background yields

Process	Pre-fit	Post-fit
Background		
$t\bar{t}t\bar{t}$	42.35 ± 5.45	46.91 ± 5.19
$t\bar{t}W^{+}$	-	103.93 ± 15.91
$t\bar{t}W^{-}$	-	55.27 ± 11.14
$t\bar{t}Z$	78.02 ± 14.12	75.57 ± 11.13
$t\bar{t}H$	81.00 ± 7.10	82.90 ± 7.30
$t\bar{t}t$	3.33 ± 0.59	3.37 ± 0.60
Single-top (tq, tZq, tWZ, etc.)	13.38 ± 2.87	12.69 ± 2.86
$t\bar{t}VV/t\bar{t}VH/t\bar{t}HH$	17.07 ± 4.66	16.44 ± 4.64

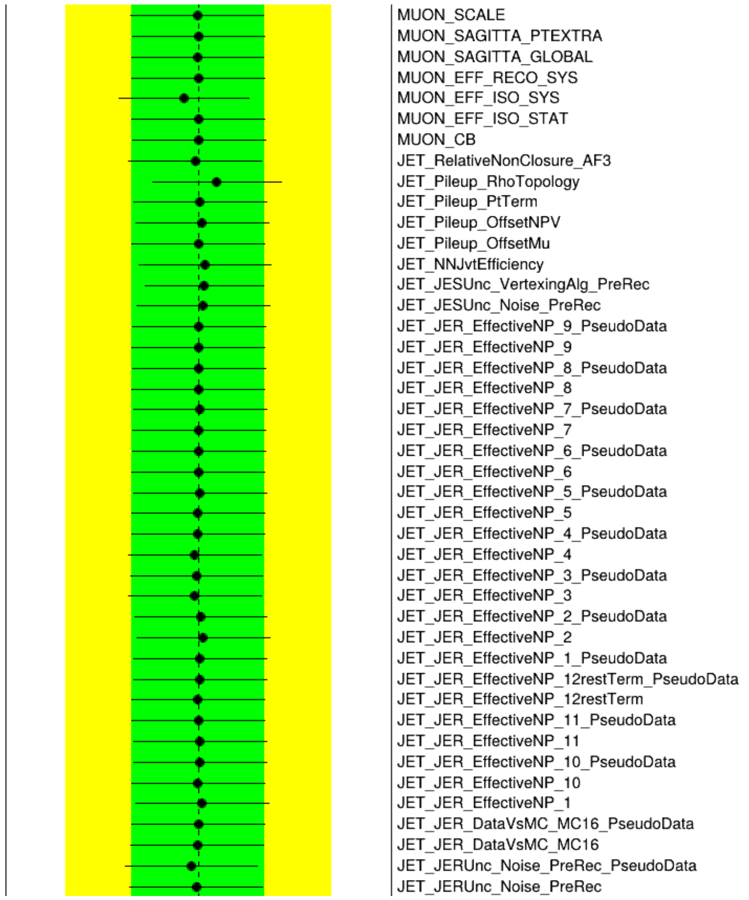
Process	Pre-fit	Post-fit
Charge misidentification	40.31 ± 0.32	40.33 ± 0.32
$VV/VVV/VH$	10.01 ± 4.76	6.69 ± 2.75
Mat. Conv.	26.20 ± 0.91	25.76 ± 6.06
Low m_{γ^*}	26.14 ± 0.66	25.62 ± 4.23
HF e	21.99 ± 1.45	15.42 ± 3.70
HF μ	31.33 ± 3.47	31.53 ± 5.06
Light-flavor decays	13.47 ± 0.53	13.54 ± 0.53
Other fake & non-prompt	24.90 ± 2.26	26.00 ± 1.96
Total background	-	576.53 ± 19.86
Data	604	

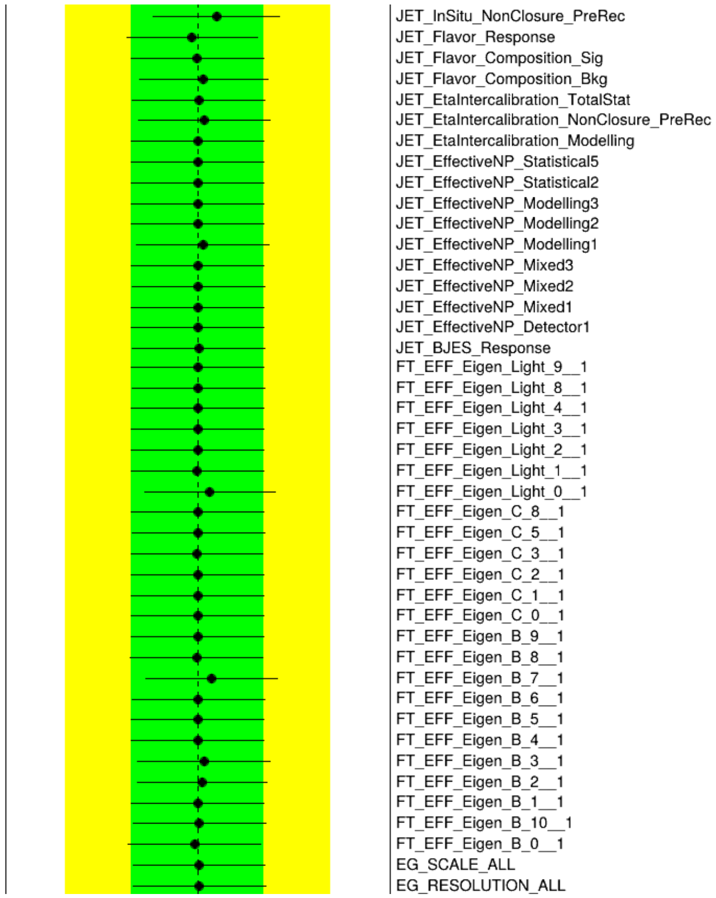
Uncertainty impact

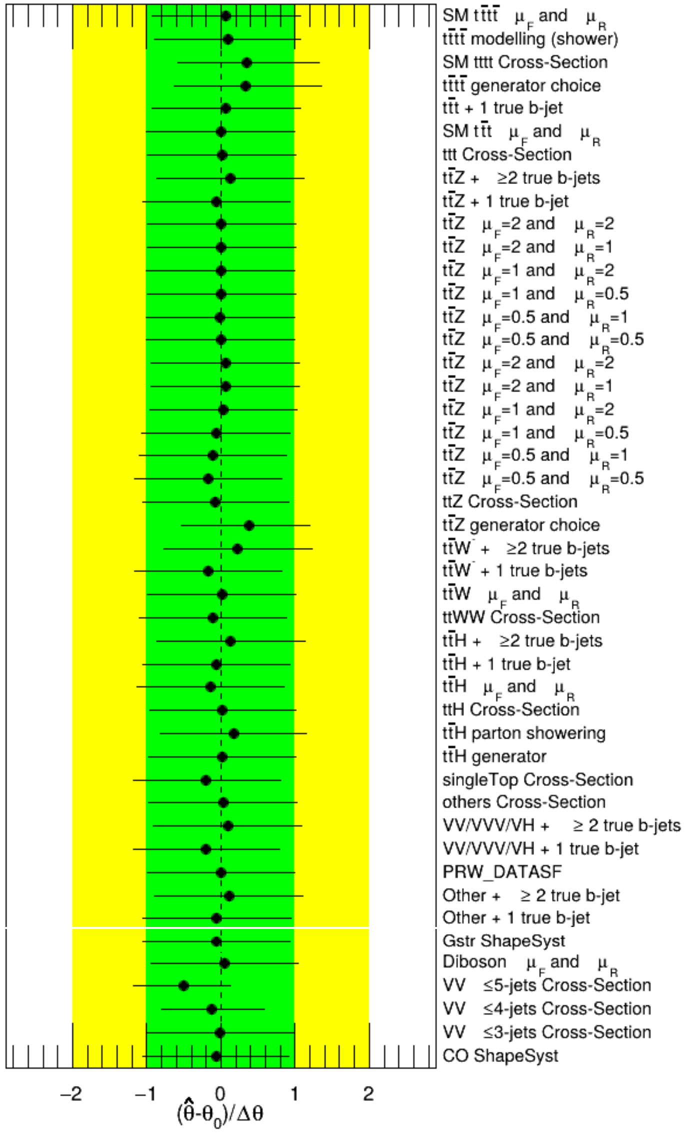
Uncertainty source	$\Delta\mu$	
Signal modeling		
$t\bar{t}Z'$	+0.00	−0.00
Background modeling		
$t\bar{t}t\bar{t}$	+0.15	−0.13
$t\bar{t}W$	+0.04	−0.03
$t\bar{t}Z$	+0.02	−0.02
$t\bar{t}H$	+0.02	−0.02
Non-prompt leptons	+0.00	−0.00
Other backgrounds	+0.02	−0.02

Uncertainty source	$\Delta\mu$	
Instrumental		
Luminosity	+0.00	−0.00
Jet uncertainties	+0.04	−0.04
Jet flavor tagging (b-jets)	+0.04	−0.04
Jet flavor tagging (c-jets)	+0.01	−0.01
Jet flavor tagging (light-jets)	+0.02	−0.01
MC simulation sample size	+0.01	−0.01
Other experimental uncertainties	+0.01	−0.01
Total systematic uncertainty	+0.15	−0.17
Statistical		
$t\bar{t}W$ NFs and scaling factors	+0.01	−0.01
Non-prompt lepton NFs (HF, Mat. Conv., Low m_{γ^*})	+0.00	−0.00
Total statistical uncertainty	+0.25	−0.23
Total uncertainty	+0.29	−0.29

Uncertainty pull

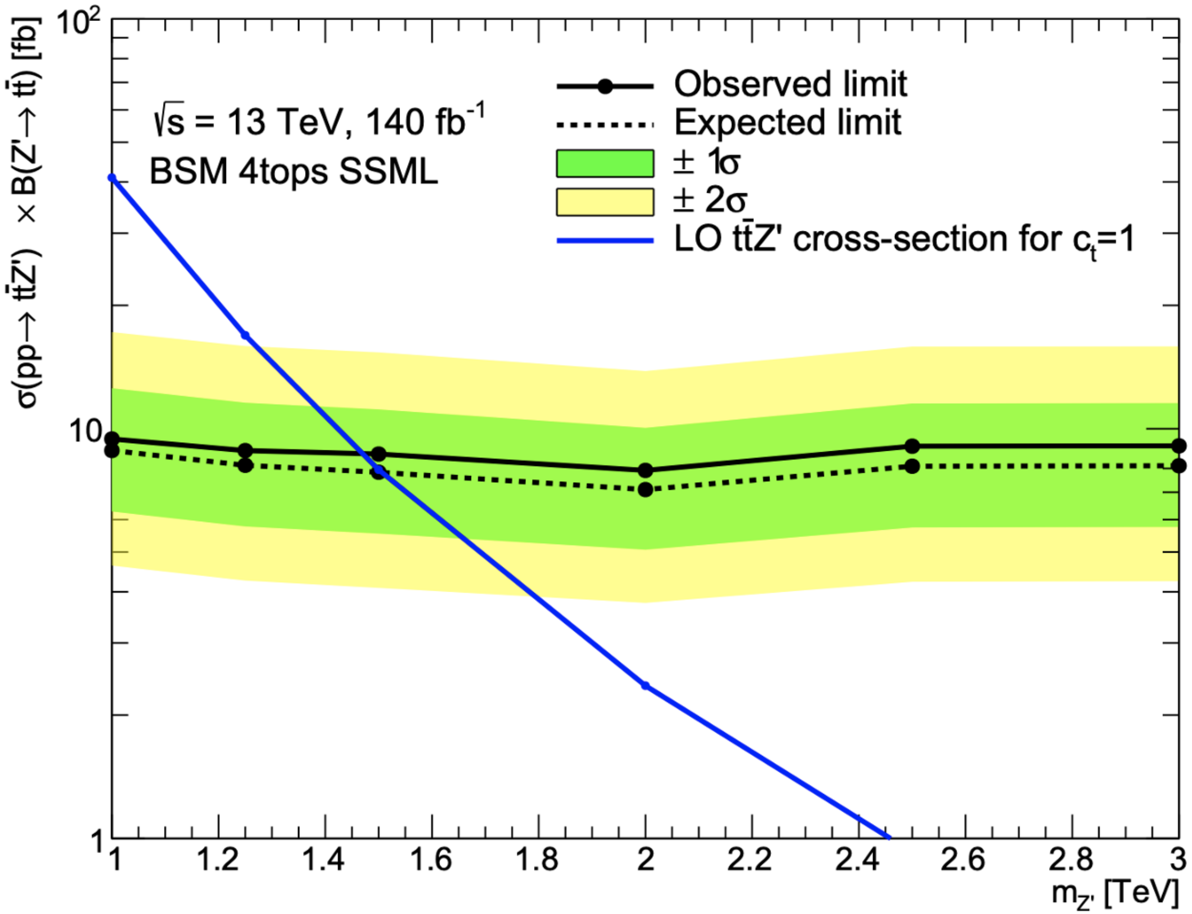






Exclusion limits

- No significant excess over SM predictions is observed
  - Fitted signal strength μ is compatible with zero for all Z' mass points
- Observed limits $[7.9, 9.44]$ depending on $m_{Z'}$
- Mass exclusion: $m_{Z'} \lesssim 1.5\ \mathrm{TeV}$



Summary

- A search for BSM top-philic heavy resonance based on a simplified top-philic color singlet Z' is conducted in the same-sign dilepton and multilepton final states of the top-quark pair associated production channel $(t\bar{t}Z')$
- The search probed a Z' mass range from $1\ \mathrm{TeV}$ to $3\ \mathrm{TeV}$ under the assumption of a top-Z' coupling strength of $c_t = 1$ and chirality angle $\theta = \pi/4$
- New data-driven estimation techniques for $t\bar{t}W$ and charge misidentification backgrounds are employed to improve background modeling and signal sensitivity

- No significant excess over SM predictions is observed
- Exclusion limits are placed on $t\bar{t}Z'$ cross section at 95% CL, the most stringent limits to date
  - Previous limits: $\sigma_{t\bar{t}Z'} = 21\ \mathrm{fb}$ in the 1LOS channel with $m_{Z'} = 2.5\ \mathrm{TeV};\ \theta = \pi/2$

Outlook

- Discovery potential in future searches is expected to increase with further improvements in analysis strategies
  - e.g. multivariate NN-based signal extraction techniques, background modeling improvements
- Run 3 data will have increased center-of-mass energy at $13.6\ \mathrm{TeV}$
  - 19% increase in $pp \rightarrow t\bar{t}t\bar{t}$ cross section
  - integrated luminosity increase by a factor of 2
    - $159.8\ \mathrm{fb}^{-1}$ recorded by 09/2024
- High Luminosity – LHC prospects will enhance sensitivity to BSM physics

Thank you for listening!

Backup slides

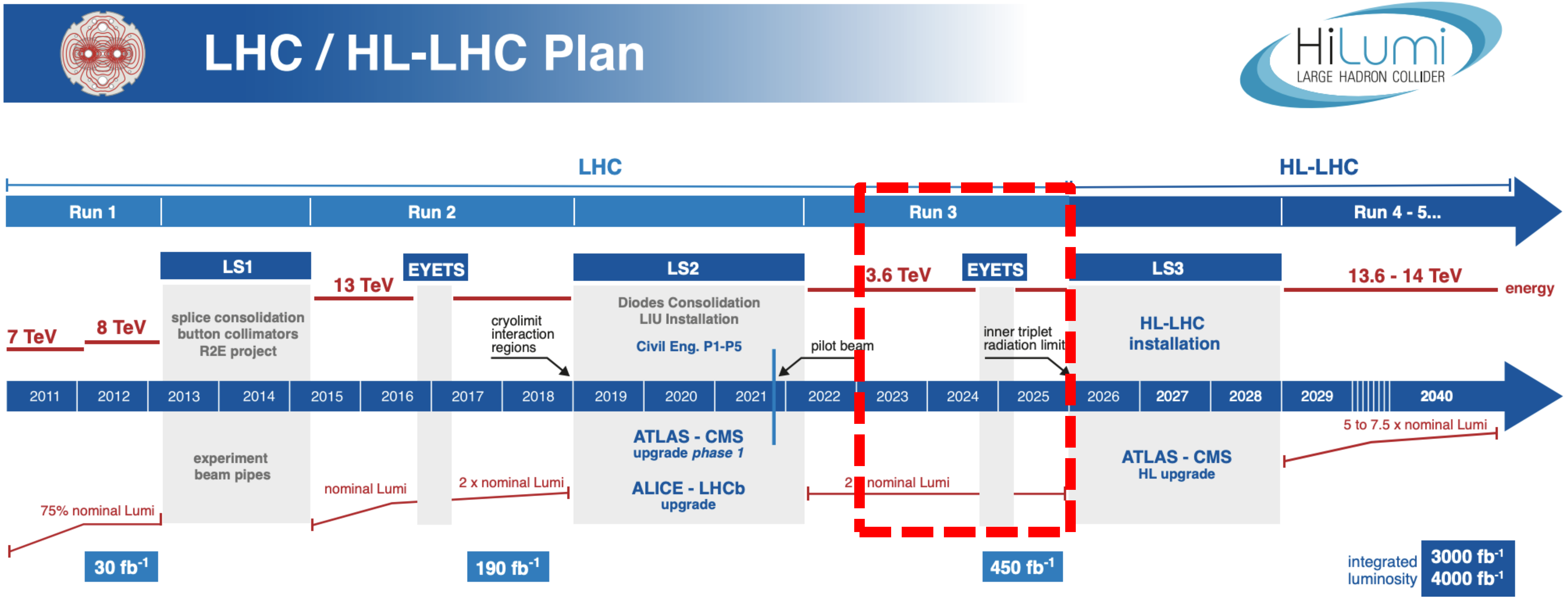
Terminology & quantities

- Reconstruction
- Sensitivity
- Coupling
- Monte Carlo simulation
- Exclusion upper limits
- signal strength μ:

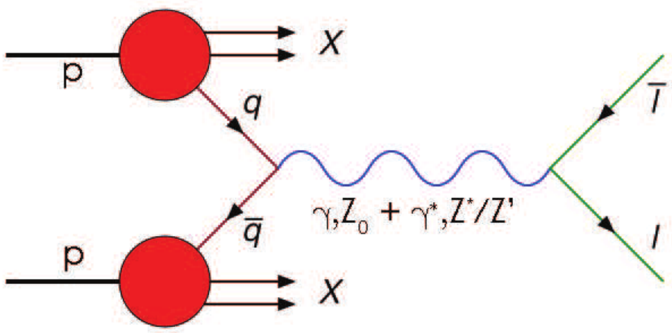
Z' and $t\bar{t}X$: ATLAS results

- General top-philic heavy resonance decaying into a $t\bar{t}$ pair
  - No significant excess over background expectation observed
  - Using a simplified heavy Z' mode: observed (expected) upper limits at 95% CL of $\sigma_{Z'} \times \mathrm{BR}_{Z'} \in [21\,(14), 119\,(86)]$ fb for $M_{Z'} \in [100, 3000]$ GeV
- $t\bar{t}H/A$ search, multilepton channel
  - No significant excess over background expectation observed
  - Obs (exp) upper limits at 95% CL of $\sigma_{t\bar{t}H/A} \times \mathrm{BR}_{H/A\to t\bar{t}} \in [14\,(10), 6\,(5)]$ fb for $M_{H/A} \in [400, 1000]$ GeV
- $t\bar{t}t\bar{t}$ cross section measurements
  - Obs (exp at NLO) cross section $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}\,(12^{+2.2}_{-2.5})$ fb
  - Obs (exp) significance $6.1\sigma\ (4.3\sigma)$

LHC: What's next?



Search channels



- Most sensitive channel: di-lepton signal in neutral Drell-Yan processes $pp(\bar{p}) \to (\gamma, Z, Z') \to \ell^+\ell^-$, where $\ell = e, \mu$
    - Current $M_{Z'}$ limits: >4 TeV (LHC 13 TeV) at 95% CL
    - Assumes coupling to light quark (production) & leptons (decay)
- Alternative channel: top-antitop quark pairs $pp(\bar{p}) \to (\gamma, Z, Z') \to t\bar{t}$
    - Much larger QCD $t\bar{t}$ background compared to dilepton channel
    - Complex final states with high multiplicity
    - Only basic assumption: Z' couples to top

      → can extract coupling factor of new physics to the top quark
    - t can transmit spin information to decay products

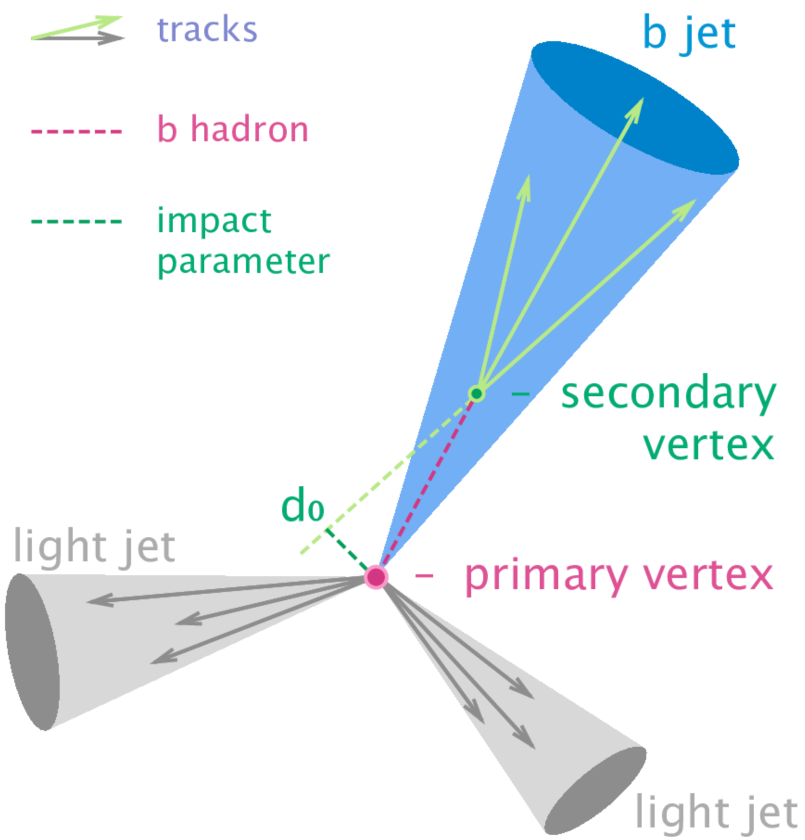
      → can define extra spin asymmetry observables to profile the Z'

Object selection

Selection	Electrons	Muons	Jets
p_{T} [GeV]	> 15 $p_{\mathrm{T}}(\ell_0) > 28$	> 15	> 20
$\|\eta\|$	$1.52 \leq \|\eta\| < 2.47$ < 1.37	< 2.5	< 2.5
Identification	*TightLH* pass ECIDS ($ee/e\mu$)	*Medium*	NNJvt *FixedEffPt* ($p_{\mathrm{T}} < 60$, $\|\eta\| < 2.4$)
Isolation	*Tight_VarRad*	*PflowTight_VarRad*	
Track-vertex assoc. $\|d_0^{\mathrm{BL}}(\sigma)\|$ $\|\Delta z_0^{\mathrm{BL}} \sin\theta\|$ [mm]	 < 5 < 0.5	 < 3 < 0.5	

Flavor tagging

- Identification of jets containing b-, c- or light-hadrons
- Special properties of b-hadrons
  - characteristic long lifetime → secondary decay vertex
  - high decay multiplicity
- **Operating points** (OPs): binary discriminant cuts
  - $65/70/77/85/90\%$ b-tagging efficiency
  - Trade-off between tagging efficiency and rejection rate



Lepton identification & isolation

Electron charge misidentification

Strategy overview

1. Event selection into regions
2. Background modeling
3. Unblind data, etc.

Region selection

Region	Channel	N_{jets}	N_b	Other selections	Fitted variable
CR Low m_{γ^*}	SS $e\ell$	$[4,6)$	≥ 1	ℓ_1/ℓ_2 is from virtual photon decay $\ell_1+\ell_2$ not from material conversion	event yield
CR Mat. Conv.	SS $e\ell$	$[4,6)$	≥ 1	ℓ_1/ℓ_2 is from material conversion	event yield
CR HF μ	$\ell\mu\mu$	≥ 1	1	$\ell_1+\ell_2$ not conversion candidates $100 < H_{\mathrm{T}} < 300$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV total charge $= \pm 1$	$p_{\mathrm{T}}(\ell_3)$
CR HF e	$ee\ell$	≥ 1	1	$\ell_1+\ell_2$ not conversion candidates $100 < H_{\mathrm{T}} < 275$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 35$ GeV total charge $= \pm 1$	$p_{\mathrm{T}}(\ell_3)$
CR $t\bar{t}W^+$	SS $\ell\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ for $N_b = 2$: $H_{\mathrm{T}} < 500$ GeV or $N_{\text{jets}} < 6$ for $N_b \geq 3$: $H_{\mathrm{T}} < 500$ GeV total charge > 0	N_{jets}
CR $t\bar{t}W^-$	SS $\ell\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ for $N_b = 2$: $H_{\mathrm{T}} < 500$ GeV or $N_{\text{jets}} < 6$ for $N_b \geq 3$: $H_{\mathrm{T}} < 500$ GeV total charge < 0	N_{jets}
CR 1b(+)	SS2L+3L	≥ 4	1	$\ell_1+\ell_2$ not from material conversion $H_{\mathrm{T}} > 500$ GeV total charge > 0	N_{jets}
CR 1b(-)	SS2L+3L	≥ 4	1	$\ell_1+\ell_2$ not from material conversion $H_{\mathrm{T}} > 500$ GeV total charge < 0	N_{jets}
VR $t\bar{t}Z$	3L $\ell^{\pm}\ell^{\mp}$	≥ 4	≥ 2	$m_{\ell\ell} \in [81, 101]$ GeV	N_{jets}, $m_{\ell\ell}$
VR $t\bar{t}W$ +1b	SS2L+3L			CR $t\bar{t}W^{\pm}$ || CR 1b($\pm$)	N_{jets}
VR $t\bar{t}W$ +1b+SR	SS2L+3L			CR $t\bar{t}W^{\pm}$ || CR 1b($\pm$) || SR	N_{jets}
SR	SS2L+3L	≥ 6	≥ 2	$H_{\mathrm{T}} > 500$ GeV $m_{\ell\ell} \notin [81, 101]$ GeV	H_{T}

Control regions: $t\bar{t}W$

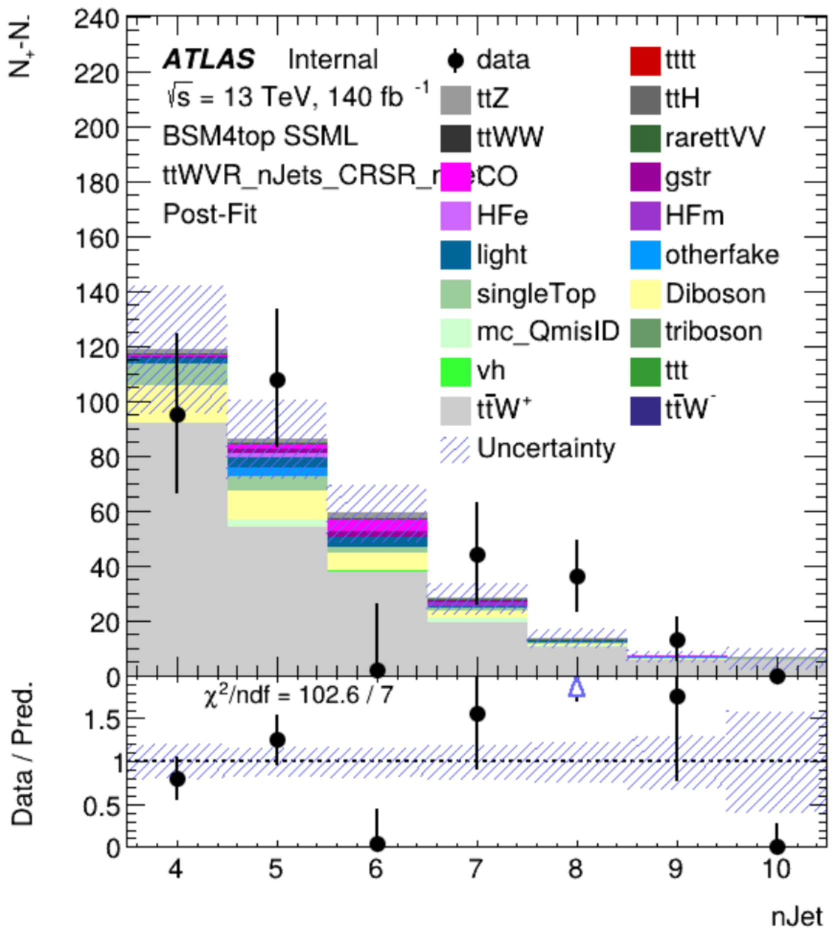
- Template fitting not optimal due to mismodeling of $t\bar{t}W$ at high jet multiplicity

  → alternative method using staircase & Poisson QCD scaling patterns for cross-section of $t\bar{t}W$ at a particular jet multiplicity

  - Instead of MC-to-data NFs, propagate $\mathrm{NF}_{t\bar{t}W^{\pm}(N_{\mathrm{jets}}=4)}, a_0, a_1$ obtained from fitting a function parameterized in N_{jets}

$$\mathrm{NF}_{t\bar{t}W(j')} = \left(\mathrm{NF}_{t\bar{t}W^{+}(N_{\mathrm{jets}}=4)} + \mathrm{NF}_{t\bar{t}W^{-}(N_{\mathrm{jets}}=4)}\right) \times \prod_{j=4}^{j'-1}\left(a_0 + \frac{a_1}{1+(j-4)}\right)$$

- Two types of CRs for $t\bar{t}W$
  - CR $t\bar{t}W$: constrains flavor composition
  - CR $1b$: constrains jet multiplicity spectrum
- Separate CRs for $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$ due to $\sigma_{t\bar{t}W^{+}} = 2 \cdot \sigma_{t\bar{t}W^{+}}$



Background estimation: QmisID data-driven

Systematic uncertainties: Experimental

Systematic uncertainties: Modeling

Signal yields

Process	Pre-fit	Post-fit
Signal $t\bar{t}Z' \to t\bar{t}t\bar{t}$		
$m_{Z'} = 1$ TeV	52.83 ± 1.41	-
$m_{Z'} = 1.25$ TeV	52.94 ± 1.35	-
$m_{Z'} = 1.5$ TeV	53.07 ± 1.47	-
$m_{Z'} = 2$ TeV	52.49 ± 1.43	-
$m_{Z'} = 2.5$ TeV	53.07 ± 1.47	-
$m_{Z'} = 3$ TeV	52.45 ± 1.50	-
Data	604	