Charge asymmetry in top-quark-antiquark pair production at $\sqrt{s}$ = 13 TeV with the ATLAS detector

ATLAS
EXPERIMENT

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on behalf of the ATLAS Collaboration

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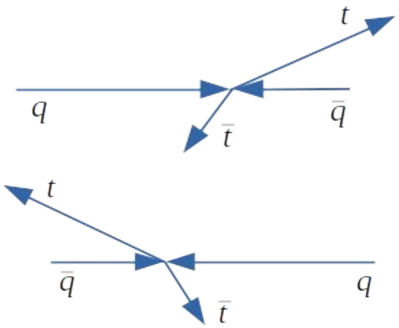
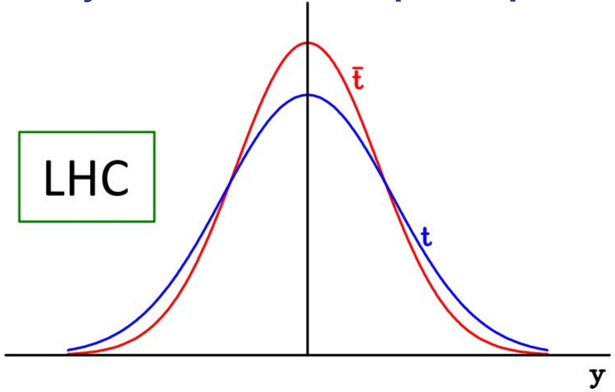
What is top-quark charge asymmetry?

- In $q\bar{q} \rightarrow t\bar{t}$, top produced preferentially in the direction of q (and vice-versa for $\bar{t}$)
- In pp collisions: momentum imbalance of initial-state q and $\bar{q}$
- **Top quarks more longitudinally boosted than top antiquarks**





- At the LHC, $A_C^{t\bar{t}}$ strongly diluted by symmetric $gg \rightarrow t\bar{t}$ (≈90%)
- Enhancement of $A_C^{t\bar{t}}$ in differential measurements (higher $\beta_z^{t\bar{t}}$ and $m_{t\bar{t}}$), $A_C^{t\bar{t}}$ vs. $m_{t\bar{t}}$ sensitive to BSM contributions

forward-central (charge) asymmetry

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

$\Delta|y| > 0$: top in q direction
$\Delta|y| < 0$: top in $\bar{q}$ direction

In dilepton channel $A_C^{l\bar{l}}$ defined:

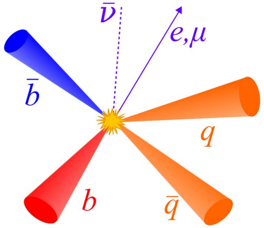
$$A_C^{\ell\bar{\ell}} = \frac{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) - N(\Delta|\eta_{\ell\bar{\ell}}| < 0)}{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) + N(\Delta|\eta_{\ell\bar{\ell}}| < 0)},$$

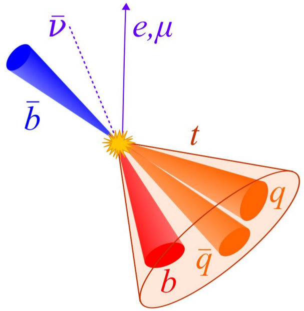
$$\Delta|\eta_{\ell\bar{\ell}}| = |\eta_{\bar{\ell}}| - |\eta_{\ell}|$$

Event reconstruction & topology

- Full Run2 dataset used (139 fb^{-1}), data from single-lepton & dilepton $t\bar{t}$ decay channels
- In single-lepton: **resolved/boosted 1b-tag excl./2b-tag incl**. (4 regions)
- In dilepton: **eμ/ee+μμ 1b-tag excl./2b-tag incl**. (4 regions)

Single-lepton: Exactly 1 e/μ, ≥ 1 small-R jet, b-tagged, MET requirements





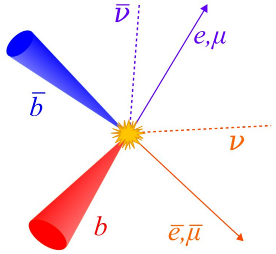
Resolved:

- Boosted Decision Tree (BDT) reconstruction

Boosted:

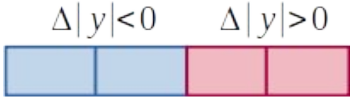
- ≥ 1 large-R top-tagged jet

Dilepton (resolved): 2 opposite charge leptons, ≥ 2 small-R jets, ≥ 1 b-tagged, MET requirements



- Neutrino Weighting reconstruction (Phys. Lett. B 752 (2016) 18)

Analysis strategy: Fully Bayesian Unfolding (FBU) (arXiv: 1201.4612)



- Variable of interest: Δ|y| / Δ|η| (4 bins)
- Unfold Δ|y| distrib. to parton level to correct for limited acceptance and detector resolution effects
- **Bayesian inference** applied $\boxed{p(\boldsymbol{T}|\boldsymbol{D})} \propto \mathcal{L}(\boldsymbol{D}|\boldsymbol{T}) \cdot \pi(\boldsymbol{T})$ ➡ outcome = **posterior probability distribution**

T = true distribution
D = data

Likelihood $\mathcal{L}(\boldsymbol{D}|\boldsymbol{T})$

Prior probabilities:

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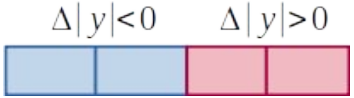

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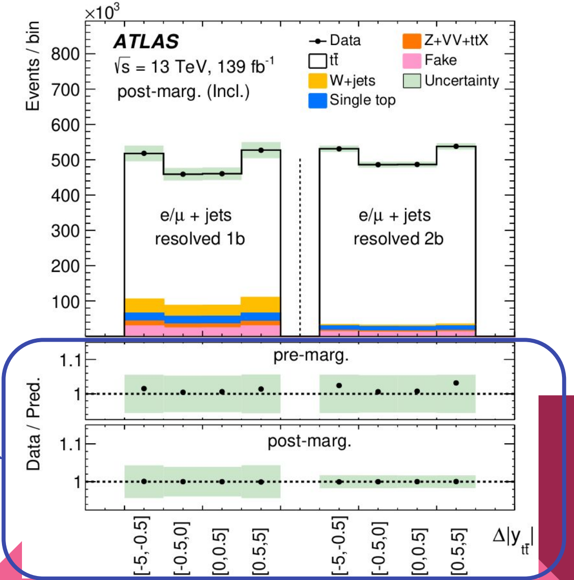
Likelihood $\mathcal{L}(\boldsymbol{D}|\boldsymbol{T})$

- Systematic uncertainties embedded (L(**D**|**T**) => L(**D**|**T**,θ)) → reduction of uncertainty due to NP correlations and individual constraints

Prior probabilities:

- π(**T**): uniform (truth bins)
- N(θ): Gaussian μ=0, σ=1 (nuisance parameters)



Result: posterior distribution of unfolded A_C obtained by sampling likelihood using Markov-chain Monte Carlo method

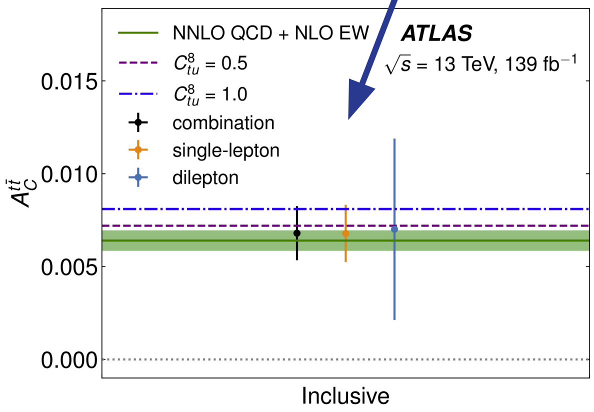
$$\underline{p(A_C|\boldsymbol{D})} = \int \delta(A_C - A_C(\boldsymbol{T}))\boxed{p(\boldsymbol{T}|\boldsymbol{D},\mathcal{M})}\mathrm{d}\boldsymbol{T}$$

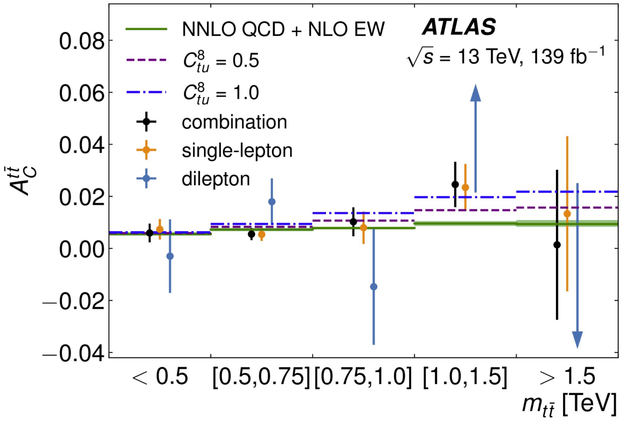
(Journal of Machine Learning Research 15 (2014) 1593)

Results: combination vs single-lepton vs dilepton (arXiv:2208.12095)

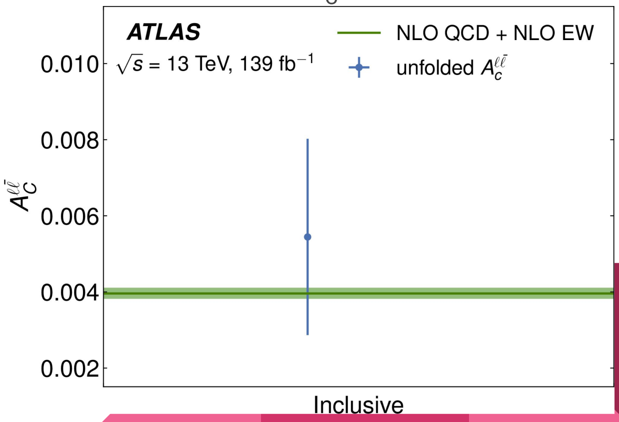
- $A_C^{t\bar{t}}$ measured inclusively and differentially as a function of $m_{t\bar{t}}$, $p_T^{t\bar{t}}$, $\beta_z^{t\bar{t}}$ (individually for single-lepton, dilepton channel; also using data from both channels = combination)
- Leptonic $A_C^{l\bar{l}}$ measured inclusively and differentially as a function of $m_{l\bar{l}}$, $p_T^{l\bar{l}}$, $\beta_z^{l\bar{l}}$
- EFT $A_C^{t\bar{t}}$ prediction for 2 different values of Wilson coefficient C_{tu}^8
- **Non-zero excess of $A_C^{t\bar{t}}$ = 4.7 σ** in **inclusive case** for combination

Results compatible with the SM prediction
(Phys. Rev. D 98 (2018) 014003
Phys. Rev. D 86 (2012) 034026)



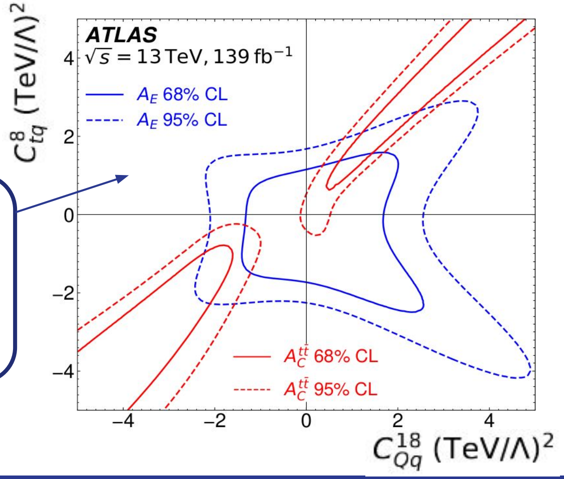


Leptonic A_C^{ll} measurement



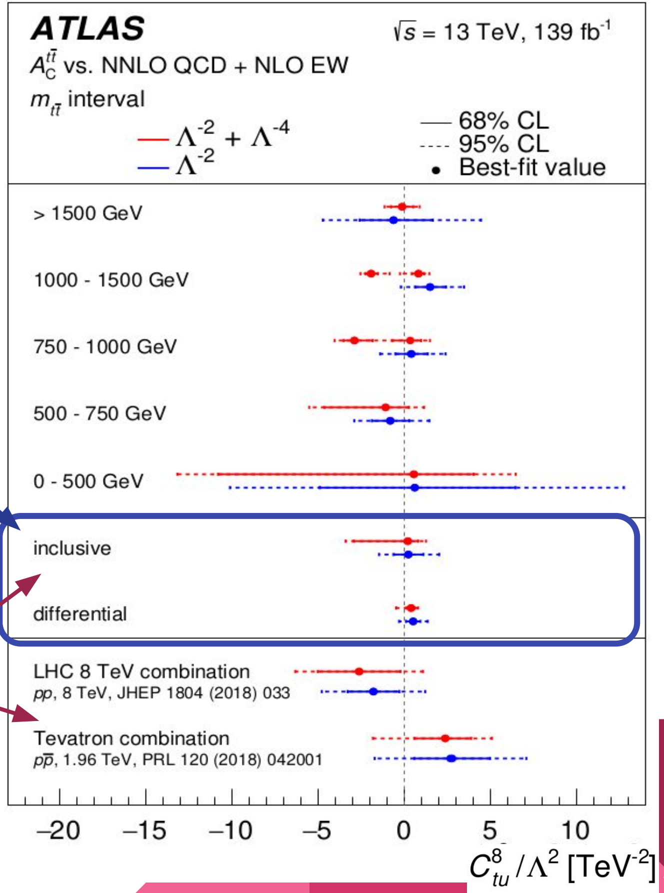
EFT interpretation

- Inclusion of $A_C^{t\bar{t}}$ measurement helps to disentangle blind directions in global SMEFT fits
- Combined **constraint from the differential m_{tt} measurement** > **factor 2 stronger** than from inclusive measurement (**increase in sensitivity with higher m_{tt}**)
- $A_C^{t\bar{t}}$ complementary to energy asymmetry measurement [Eur. Phys. J. C. 82 (2022) 374]



blind direction for A_C is **broken with A_E** measurement

Improvement of bound from inclusive A_C measurement **comparing with LHC 8TeV/Tevatron** results (linear fit –)



Summary

- Top quark charge asymmetry $A_C^{t\bar{t}}$ measured **for the first time in combined single-lepton & dilepton** channel
- Sensitivity improved = **evidence of $A_C^{t\bar{t}}$ in inclusive case: 4.7σ from zero**
- $A_C^{t\bar{t}}$ measured inclusively and differentially as a function of $\beta_z^{t\bar{t}}$, $m_{t\bar{t}}$ and $p_T^{t\bar{t}}$
- Leptonic $A_C^{l\bar{l}}$ measured inclusively and as a function of $m_{l\bar{l}}$, $p_T^{l\bar{l}}$, $\beta_z^{l\bar{l}}$
- **All results compatible with the SM prediction**
- Combined results interpreted in the SMEFT framework

⇨ **Bound** on Wilson coefficient C_{tu}^{8} **improved**
⇨ Derived bounds on many different relevant Wilson coefficients
⇨ Common $A_C^{t\bar{t}}$ and A_E EFT plots = probe different directions in chiral and colour space

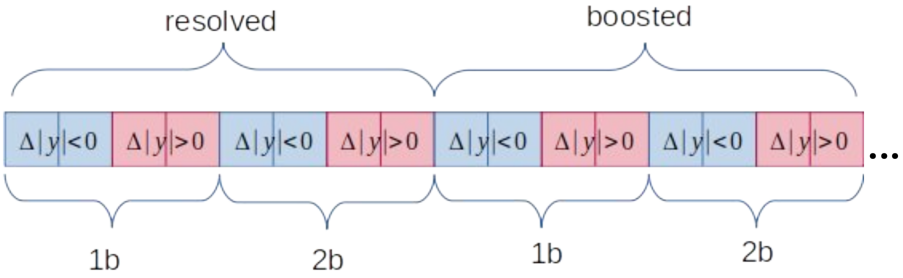
Back-up

FBU: follow up

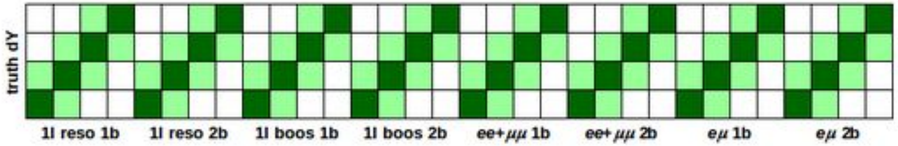
- Data measured in many independent channels -> likelihood becomes product of likelihoods for each region
- **Extended likelihood:**

$$\mathcal{L}\left(\{\boldsymbol{D}_1\cdots\boldsymbol{D}_{N_{\mathrm{reg}}}\}|\boldsymbol{T}\right)=\int\prod_{i=1}^{N_{\mathrm{reg}}}\mathcal{L}\left(\boldsymbol{D}_i|\boldsymbol{T};\boldsymbol{\theta}\right)\cdot\mathcal{N}(\boldsymbol{\theta})\,\mathrm{d}\boldsymbol{\theta}$$

- Posterior distribution is obtained by sampling likelihood around its minimum using an extended Markov-chain Monte Carlo method (Journal of Machine Learning Research 15 (2014) 1593)



- Response matrix (illustrative):



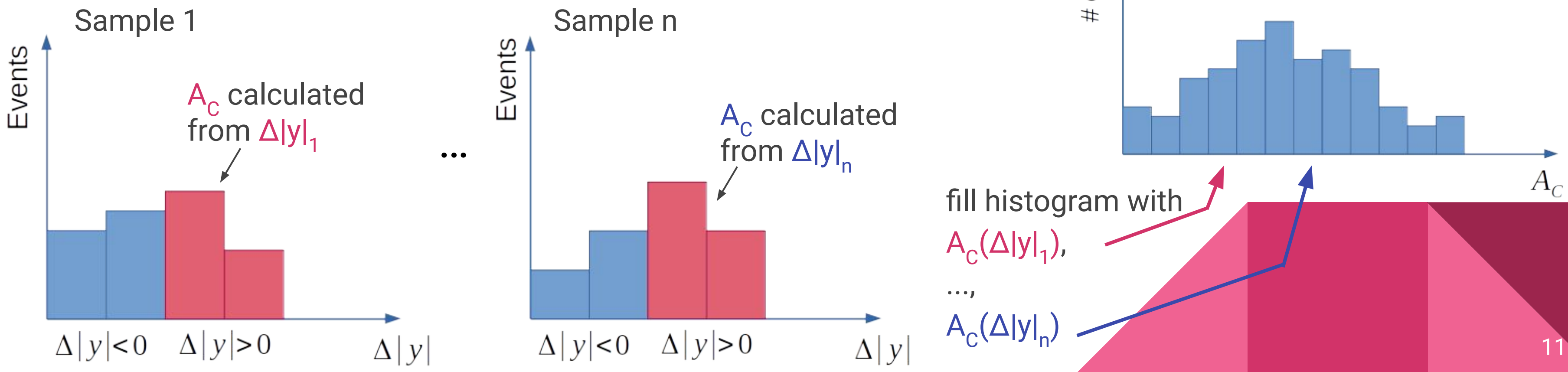
FBU: follow up

How posterior distribution of A_C is obtained: $p\left(A_C|\boldsymbol{D}\right) = \int \delta(A_C - A_C(\boldsymbol{T}))\boxed{p\left(\boldsymbol{T}|\boldsymbol{D},\mathcal{M}\right)}\mathrm{d}\boldsymbol{T}$

$$\boxed{p\left(\boldsymbol{T}|\boldsymbol{D}\right)} \propto \mathcal{L}\left(\boldsymbol{D}|\boldsymbol{T}\right)\cdot\pi\left(\boldsymbol{T}\right)$$

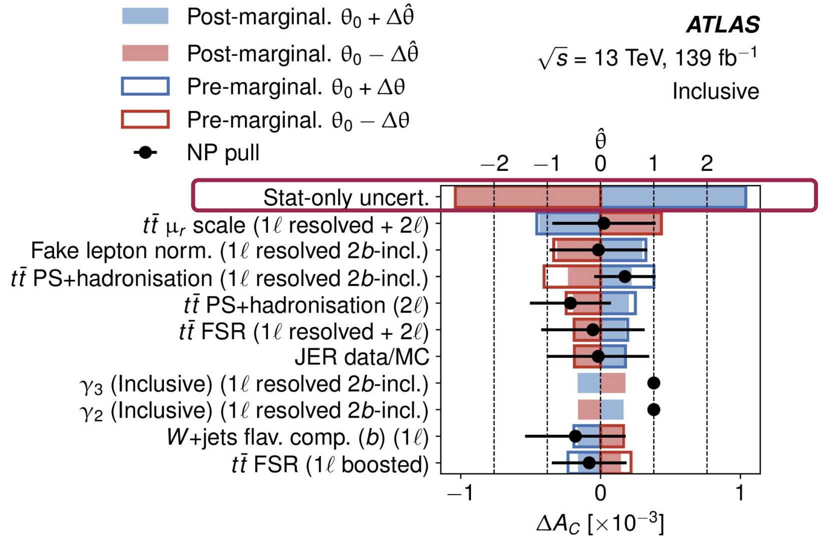
- Sampling of likelihood using MCMC method
- Sample ~ pseudo-experiment with specific Δ|y| spectrum
  → calculate A_C from Δ|y| bins
  → fill histogram with A_C = **posterior probability distribution p(A_C|D)**

Illustration:



Ranking of systematic uncertainties

- **Relative importance** of systematic uncertainties **determined by a ranking** of each nuisance parameter
- Ranked NP fixed to +/- 1σ (+/- c) around post-marginalization mean value
  (c = post-marginalization constraint)
- Impact on A_C measurement defined by comparison of nominal A_C result and result with fixed NP



	Post-marg. (pre-marg.) impact ×100
$t\bar{t}$ modelling	0.06 (0.08)
$t\bar{t}$ normalisation (flat prior)	0.02
Background modelling	0.04 (0.05)
Monte Carlo statistics	0.05
Small-R JES	0.03 (0.03)
Small-R JER	0.03 (0.03)
Large-R JES, JER	0.01 (0.01)
Leptons, E_T^{miss}	0.02 (0.03)
b-tagging eff.	0.01 (0.01)
Pile-up, JVT, luminosity	0.01 (0.01)
Statistical uncertainty	0.10
Total uncertainty	0.15

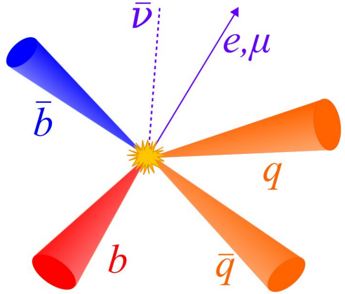
Impact of grouped uncertainties on inclusive measurement

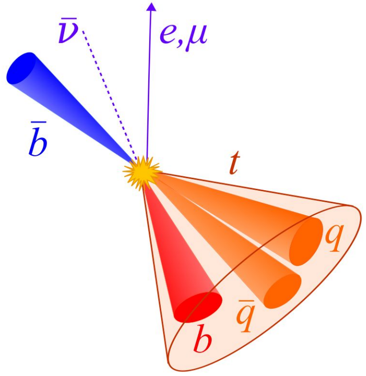
- **statistical uncertainty dominant**

Event selection: single-lepton

Resolved & boosted:

- Exactly 1 isolated e/μ with p_T > 28 GeV
- e+jets: E_T^{miss} > 30 GeV, M_T^W > 30 GeV; μ+jets: $M_T^W + E_T^{miss}$ > 60 GeV
- ≥ 1 b-tagged small-R (R = 0.4) jet (MV2c10 - 77% eff. WP)





Boosted:

- ≥ 1 large-R (R = 1.0) top-tagged jet with p_T> 350 GeV and |η| < 2, opposite to lepton
- ≥1 small-R jet close to lepton (ΔR(jet,lepton) < 1.5)
- m_{tt} > 500 GeV

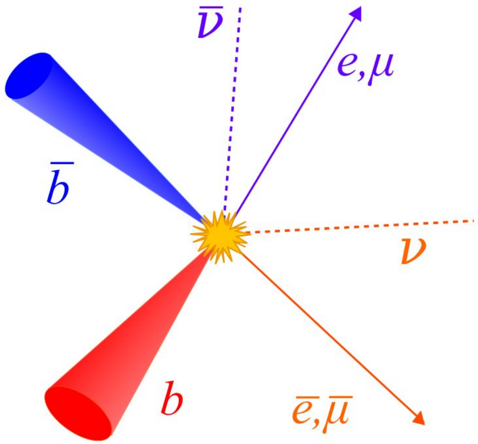
Resolved:

- ≥ 4 small-R jets, p_T > 25 GeV
- Veto boosted events
- BDT used for correct jet-to-parton assignment (distinguish signal from bckg)
- BDT discriminant requirements (~ 75% eff.)

Event selection: dilepton

Common:

- 2 opposite charge leptons with p_T > 28 (25) GeV (one matched to trigger lepton)
- ≥ 2 small-R jets, p_T > 25 GeV
- ≥ 1 b-tagged small-R (R = 0.4) jet (MV2c10 - 77% eff. WP)
- $t\bar{t}$ reconstructed by the Neutrino Weighting



ee+μμ channel:

- Z veto: $|m_{ll} - m_Z|$ > 10 GeV
- E_T^{miss} > 60 (30) GeV for 1b (2b) -> reduce Z+jets
- m_{ll} > 15 GeV in 1b region -> suppress low mass resonances

EFT operators

- $A_C^{t\bar{t}}$ sensitive to 4-quark EFT operators ($q\bar{q}t\bar{t}$) and 1 tensor EFT operator ($t\bar{t}g$)
- 4-quark operators:

LL chiral structure:

$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i),$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i),$$
$$O_{tu}^{8} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i)$$
$$O_{td}^{8} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i)$$

RR chiral structure:

$$O_{Qq}^{1,1} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i),$$
$$O_{Qq}^{3,1} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i),$$
$$O_{tu}^{1} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$$
$$O_{td}^{1} = (\bar{t}\gamma_\mu t)(\bar{d}_i\gamma^\mu d_i)\,.$$

LR chiral structure:

$$O_{Qu}^{8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{u}_i\gamma^\mu T^A u_i)$$
$$O_{Qd}^{8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{d}_i\gamma^\mu T^A d_i)$$
$$O_{tq}^{8} = (\bar{t}\gamma^\mu T^A t)(\bar{q}_i\gamma_\mu T^A q_i)$$
$$O_{Qu}^{1} = (\bar{Q}\gamma_\mu Q)(\bar{u}_i\gamma^\mu u_i)$$
$$O_{Qd}^{1} = (\bar{Q}\gamma_\mu Q)(\bar{d}_i\gamma^\mu d_i)$$
$$O_{tq}^{1} = (\bar{t}\gamma^\mu t)(\bar{q}_i\gamma_\mu q_i)\,.$$

- 1 tensor operator: $O_{tG} = (\bar{t}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$

- Q = left-handed quark doublet (3. generation)
- q_i = left-handed quark doublet (1./2. generation)
- u_i , d_i = right-handed singlet (1./2. generation)
- t = right-handed top quark

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