Asymmetries in top quark production

ATLAS: charge asymmetry in $t\bar{t}$ production

Barbora Eckerová, **Pavol Bartoš**
(Comenius University)

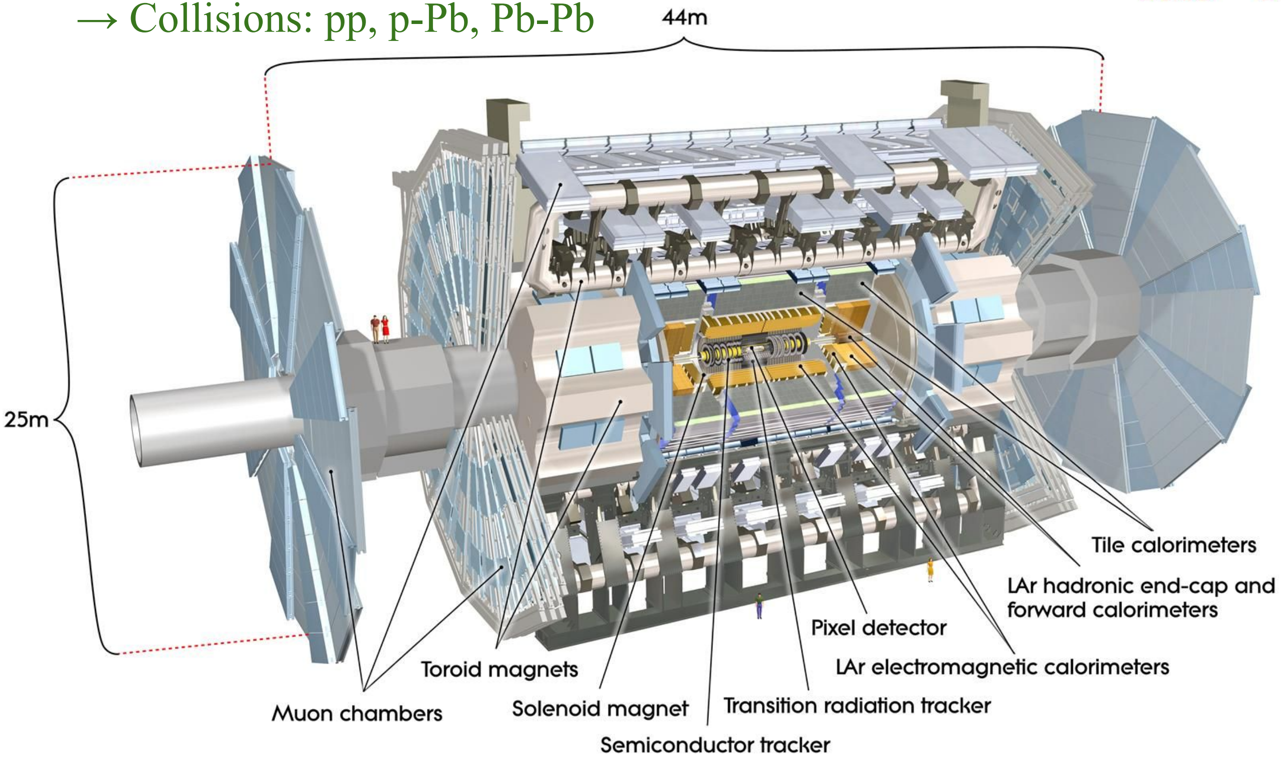
CZ-SK 2023 HEP workshop

28 June 2023, Bratislava

ATLAS detector

→ **Multi-purpose particle collider detector**
(it covers $|\eta| = 5$, $L = 10^{34}$ cm^{2}s^{-1})
→ Collisions: pp, p-Pb, Pb-Pb

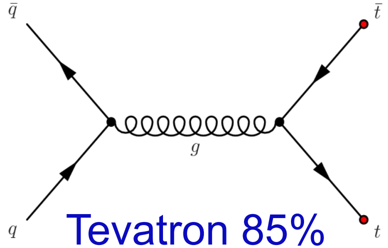
Our focus: pp collisions



- Inner Detector
  $\sigma/p_T \approx 0.05\,\% \cdot p_T\,(\mathrm{GeV}) \oplus 0.1\%$
  tracking range $|\eta| < 2.5$
- EM calorimetry
  $\sigma/E \approx 10\% / \sqrt{E\,(GeV)} \oplus 1\%$
  fine granularity up to $|\eta| < 2.5$
- Hadronic calorimetry
  $\sigma/E \approx 50\% / \sqrt{E\,(GeV)} \oplus 3\%$
  range: $|\eta| < 4.9$
- Muon system
  $\sigma/p_T \approx 2-7\,\%$, range $|\eta| < 2.7$

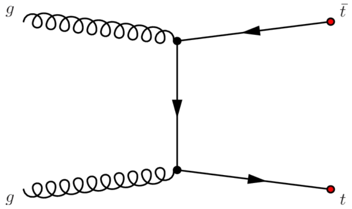
Top quark pair production

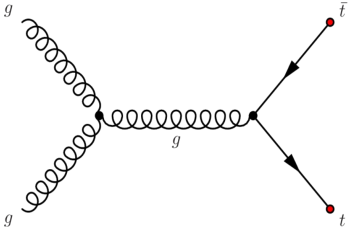
Pair production (LO QCD)



Tevatron 85%

LHC ~10% (*)



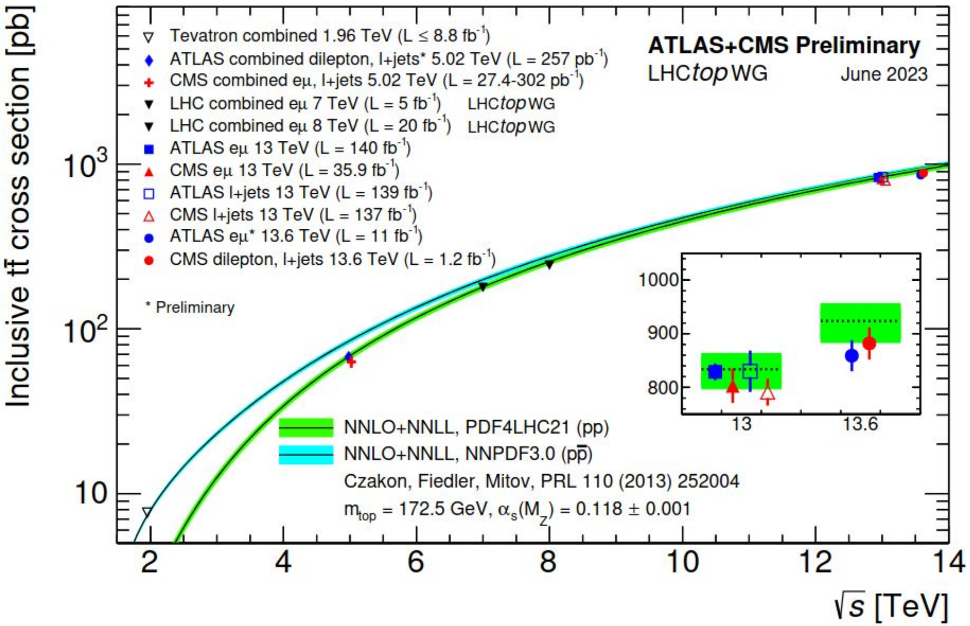


Tevatron 15%

LHC ~90% (*)

(*) depends on √s of collisions

Inclusive production cross-section

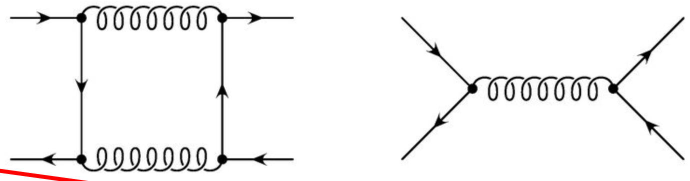


Asymmetry in top-quark pair production

Source of the asymmetry

- LO of perturbative QCD: no asymmetry
- Including higher order corrections leads to asymmetry in $q\bar{q}\rightarrow t\bar{t}$ due to **interference terms**
- $gg\rightarrow t\bar{t}$ contribution is symmetric at all orders
- QED and EW contribution is 5 – 10 times smaller

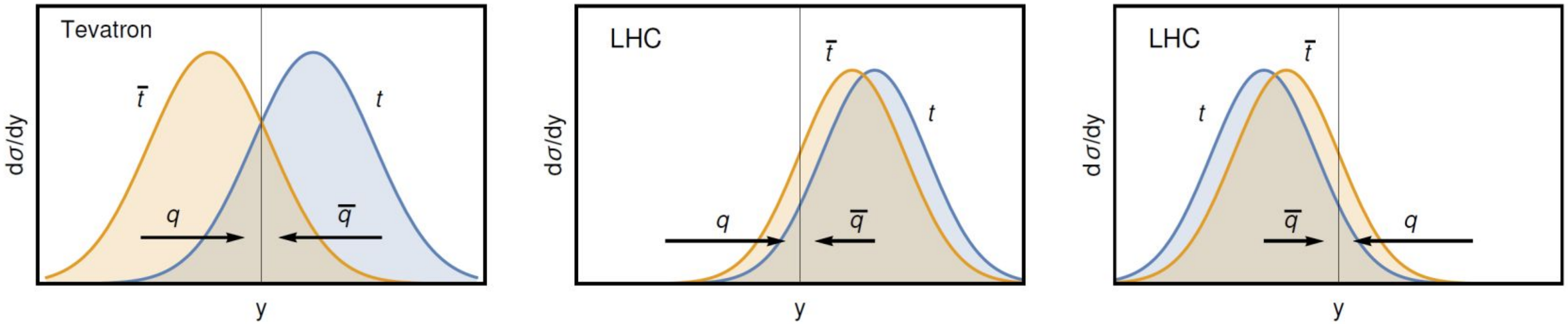
$$A_1 = A_1^{(R)} + iA_1^{(I)} \qquad A_2 = A_2^{(R)} + iA_2^{(I)}$$



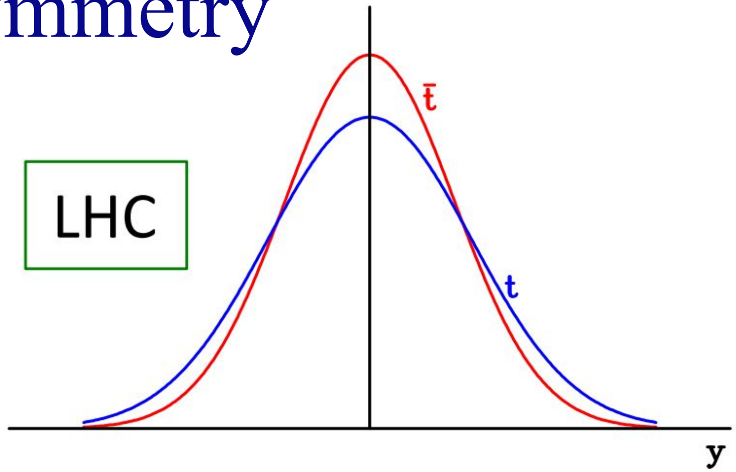
$$|A|^2 = |A_1|^2 + |A_2|^2 + A_1A_2^* + A_1^*A_2$$

Consequences:

- Top quark is produced in the direction of initial quark with higher probability than anti-top

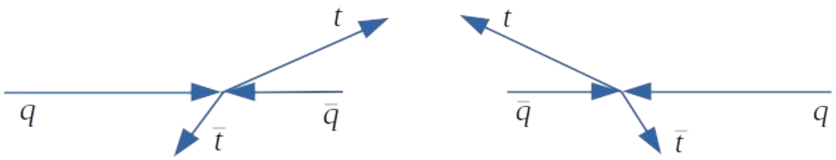


Charge (forward-central) asymmetry



pp collisions at the LHC

- momentum imbalance of the initial (valence) quark and (sea) anti-quark



- charge asymmetry diluted by symmetric ***gg→t t̄***

charge asymmetry in $t\bar{t}$:

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

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

→ need to reconstruct whole event

leptonic asymmetry:

$$A_c^{\ell\bar{\ell}} = \frac{N(\Delta|y_{\ell\bar{\ell}}| > 0) - N(\Delta|y_{\ell\bar{\ell}}| < 0)}{N(\Delta|y_{\ell\bar{\ell}}| > 0) + N(\Delta|y_{\ell\bar{\ell}}| < 0)}$$

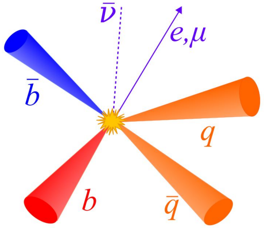
$$\Delta|y_{\ell\bar{\ell}}| = |y_{\bar{\ell}}| - |y_\ell|$$

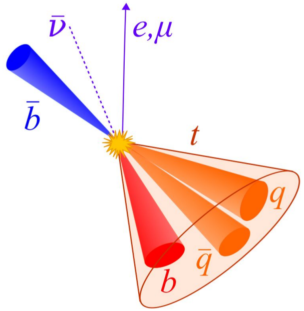
→ directions of leptons are diluted w.r.t directions of top quarks

Event reconstruction

- 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





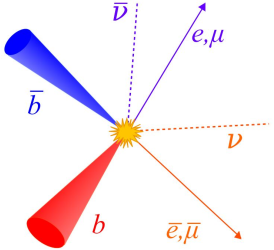
Resolved:

- 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

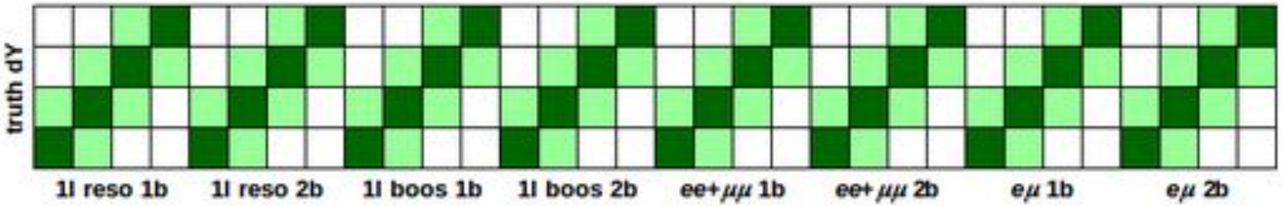


- Neutrino Weighting reconstruction (Phys. Lett. B 752 (2016) 18)

Analysis strategy – Fully Bayesian unfolding

- Variable of interest: $\Delta|y|$ / $\Delta|\eta|$ (4 bins)

- Unfolding used to correct for limited acceptance and detector resolution effects: response matrix (illustration)



Bayesian inference applied

Posterior distribution for truth bins

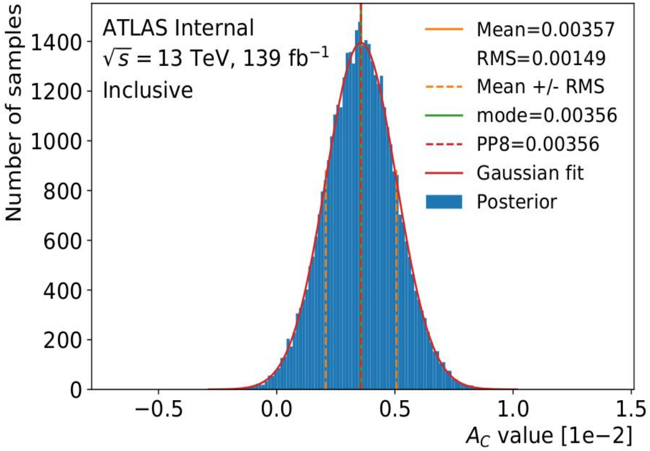
- Flat prior for truth bins
- Gaussian prior for NP

$$p(T|D) \propto \mathcal{L}(D|T,\theta)\ \pi(T)\ G(\theta)$$

Poisson likelihood with impact of systematics included as NPs

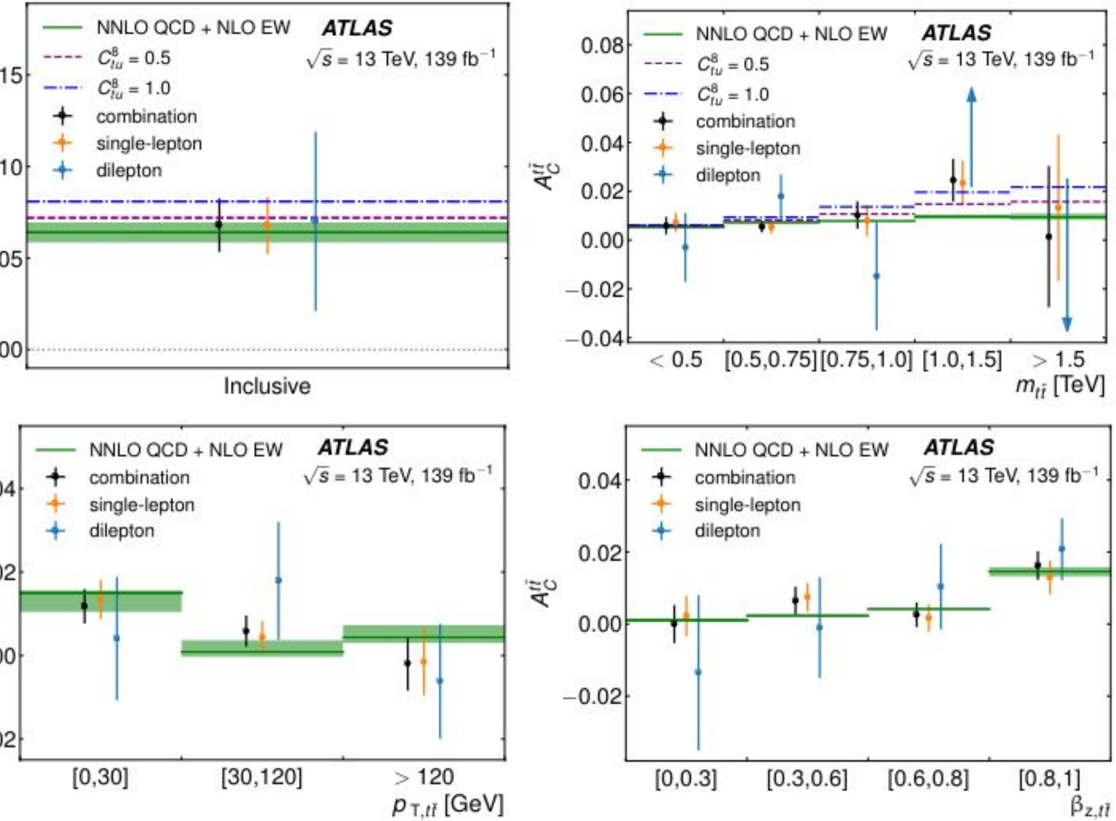
T = true distribution
D = data
θ = nuisance parameter

A_C posterior distribution (Asimov)



Results: Charge asymmetry in $t\bar{t}$

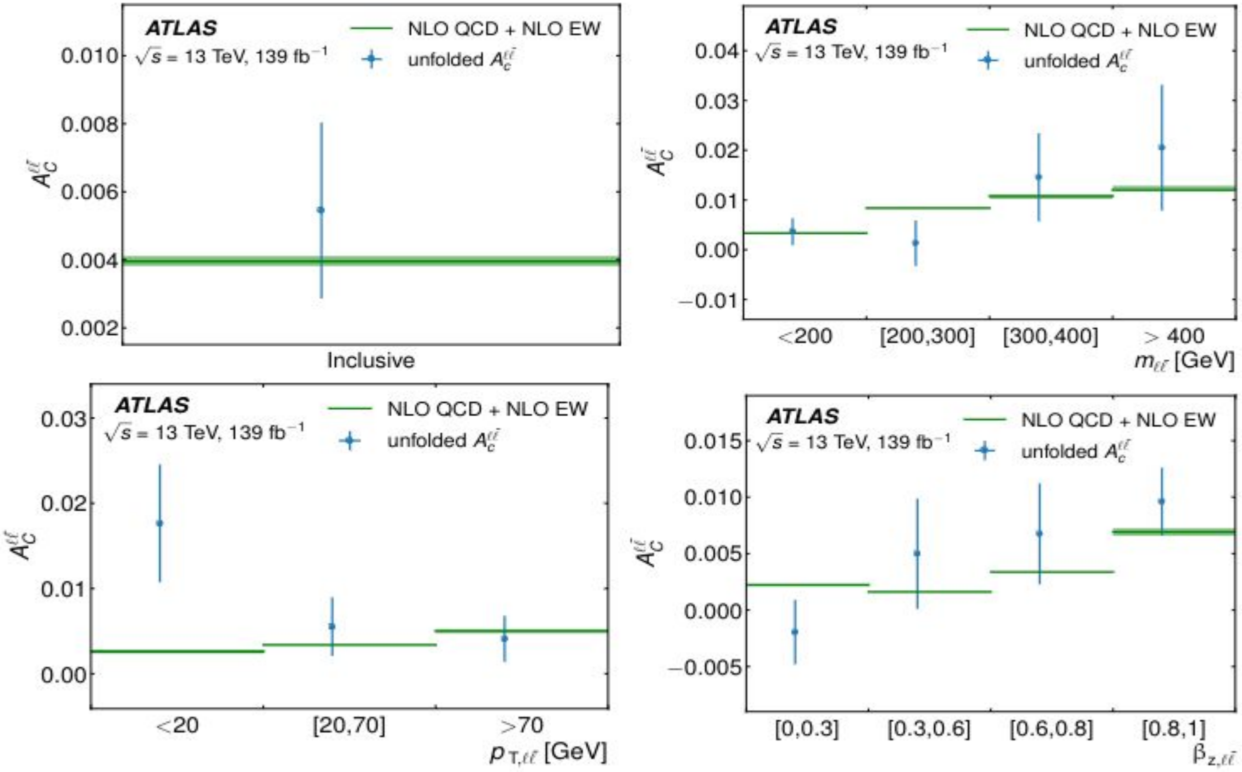
[arXiv, hep-ex 2208.12095](), **accepted by JHEP**



- A_C measured inclusively and differentially wrt m_{tt}, p_T^{tt}, β_z^{tt}
- For 2 different values of Wilson coefficient $C_{ut}^{(8)}$, Ac predictions shown for inclusive and m_{tt} differential case
- **Non-zero excess of A_C in inclusive case**:
  - l+jets 4.4σ
  - combination **4.7 σ**
- **Results compatible with the SM**

Results: leptonic asymmetry

arXiv, hep-ex 2208.12095, accepted by JHEP

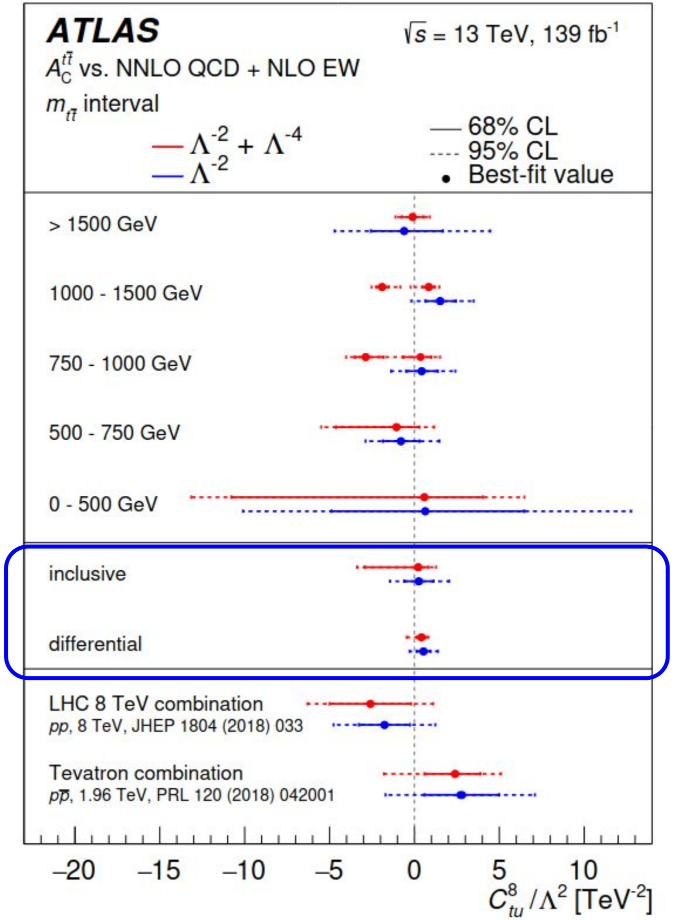


- Leptonic A_C^{ll} measured inclusively and differentially wrt m_{ll}, p_T^{ll}, β_z^{ll}
- **Non-zero excess of Ac** in inclusive case **2.1 σ**
- **Results compatible with the SM**

SMEFT interpretation

[arXiv, hep-ex 2208.12095](), accepted by JHEP

- Combined results are interpreted in the SMEFT framework
- Ac sensitive to particular linear combination of operator coefficients → complementary to Xsection
- Large improvement of bound from inclusive A_C measurement comparing with LHC 8TeV/Tevatron results (linear fit)
- Combined **constraint from the differential m_{tt} measurement** is more than a **factor 2 stronger** than the one from inclusive measurement (increase in sensitivity with higher m_{tt})



Conclusions

- Charge asymmetry measured in lepton+jets and dilepton decay channels
- Contribution from dilepton channel is about 10%
- In many regions, still statistically dominated
- Results compatible with SM predictions
- Evidence for non-zero asymmetry in the inclusive measurement
- Inclusive and m_{tt} differential measurements used for EFT interpretation

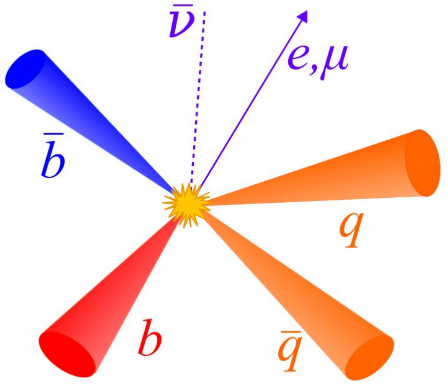
Thank you!

Back up

Event selection - single lepton

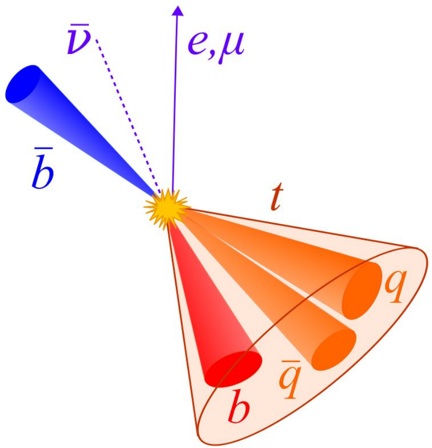
Resolved & boosted:

- 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)



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.)



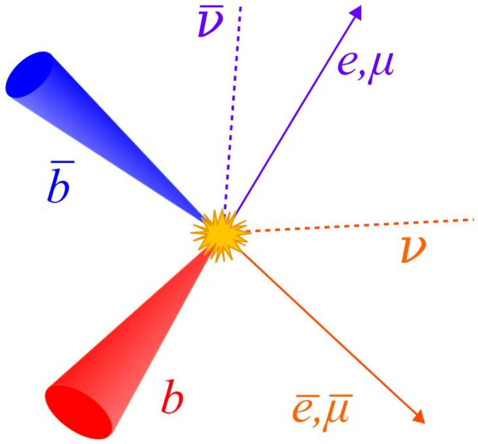
Boosted:

- ≥ 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

Event selection - dilepton

Common:

- 2 opposite charge leptons with $p_T > 28$ (25) GeV (one matched to trigger lepton)
- $\geq$ 2 small-R jets, $p_T > 25$ GeV
- $\geq$ 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

Fullu Bayesian unfolding

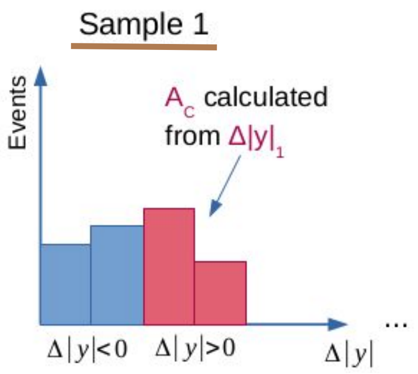
(concept: arXiv: 1201.4612, code: GitHub)

Technical implementation: Bayesian statistical modelling package PyMC3

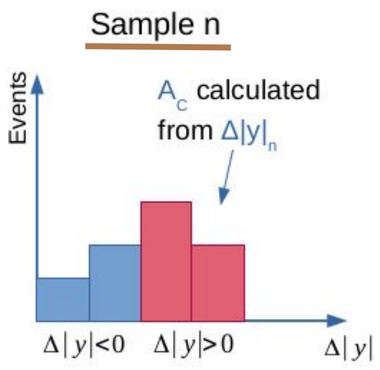
Simplified illustration: [Markov-chain Monte Carlo (MCMC) method (JMLR 15 (2014) 1593-1623)]

- Walking in n-dimensional space (N_{truth} x N_{NP})
- Probability of making steps given by likelihood
- Drawing samples of $\Delta|y|$ distribution by each step
- Storing values of all drawn NPs -> marginal posterior distribution for each NP

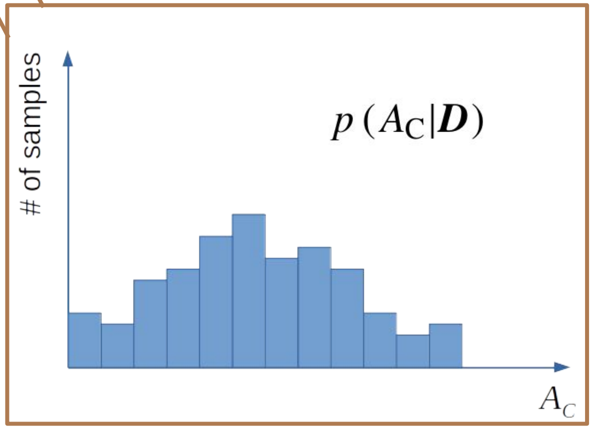
$$p(A_C|\boldsymbol{D}) = \int \delta(A_C - A_C(\boldsymbol{T}))\, p(\boldsymbol{T}|\boldsymbol{D}, \mathcal{M})\, d\boldsymbol{T}$$



...



fill histogram with
$A_C(\Delta|y|_1)$,
...,
$A_C(\Delta|y|_n)$



EFT interpretation

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + O\left(\Lambda^{-4}\right),$$

- There are eight $q\bar{q}t\bar{t}$ operators with LL and RR chiral structures:

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

- There are six further $q\bar{q}t\bar{t}$ operators with LR structures:

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

- There is one tensor operator that modifies the top–gluon interaction:

$$O_{tG} = (\bar{t}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}.$$