Top quark properties at LHC:
Yukawa coupling, polarisation and quantum entanglement

Nello Bruscino
Sapienza Università di Roma & INFN Roma 1

Fellini
Fellowship for Innovation at INFN

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Top quark physics

Production time		Decay time		Hadronisation time		Spin-Decorr. time
$\frac{1}{m_t}$	$<$	$\frac{1}{\Gamma_t}$	$<$	$\frac{1}{\Lambda_{QCD}}$	$<$	$\frac{m_t}{\Lambda}$
$\sim 10^{-27}$ s		$\sim 10^{-25}$ s		$\sim 10^{-23}$ s		$\sim 10^{-22}$ s

Why top quarks?

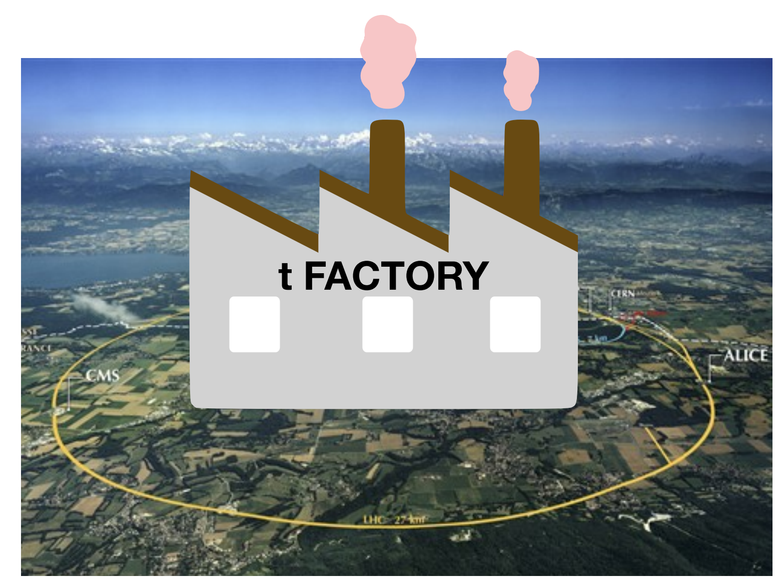
- heaviest known particle, only "bare" quark
- high statistics allows **precision measurements** and search for **new physics**

Copious production at the LHC (top-factory):

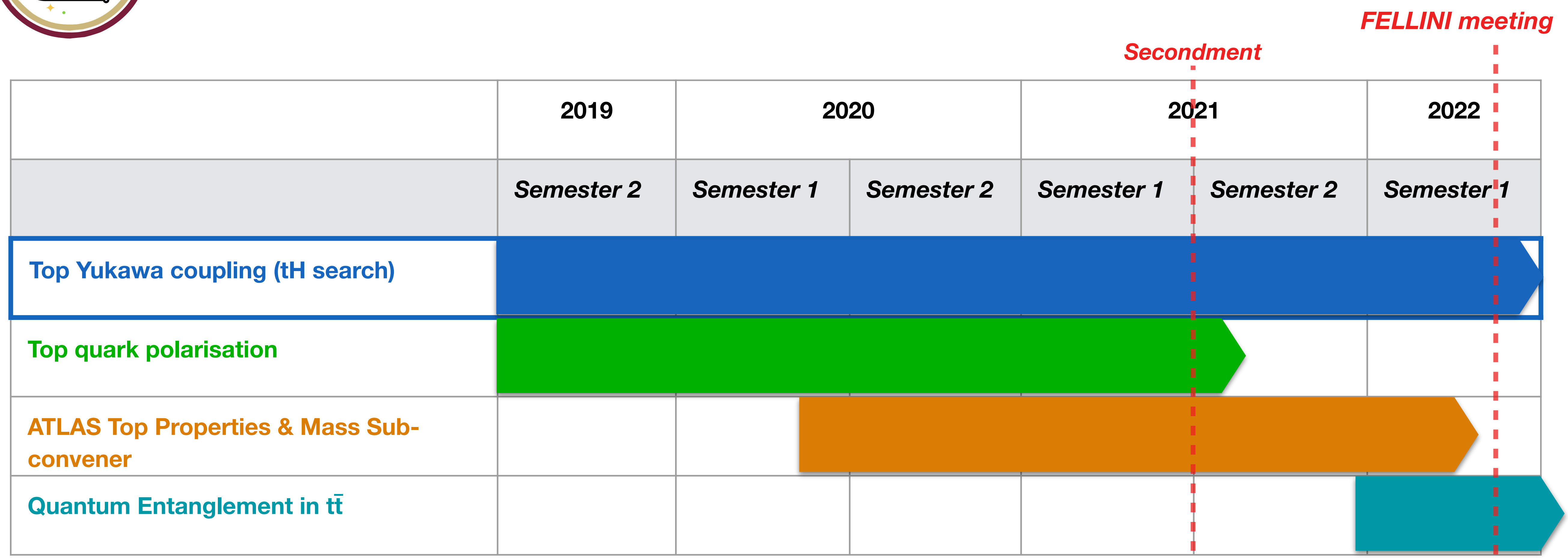
- ~150/fb @13TeV collected in Run 2 by ATLAS…

$$N = \mathscr{L} \cdot \sigma_{t\bar{t}}, \quad \sigma_{t\bar{t}} \sim 830\,\text{pb}, \quad \mathscr{L} \sim 15 \cdot 10^{33}\,\text{cm}^2\,\text{s}^{-1} \implies$$

~750 $t\bar{t}$ pairs produced/minute
(125M @150/fb)



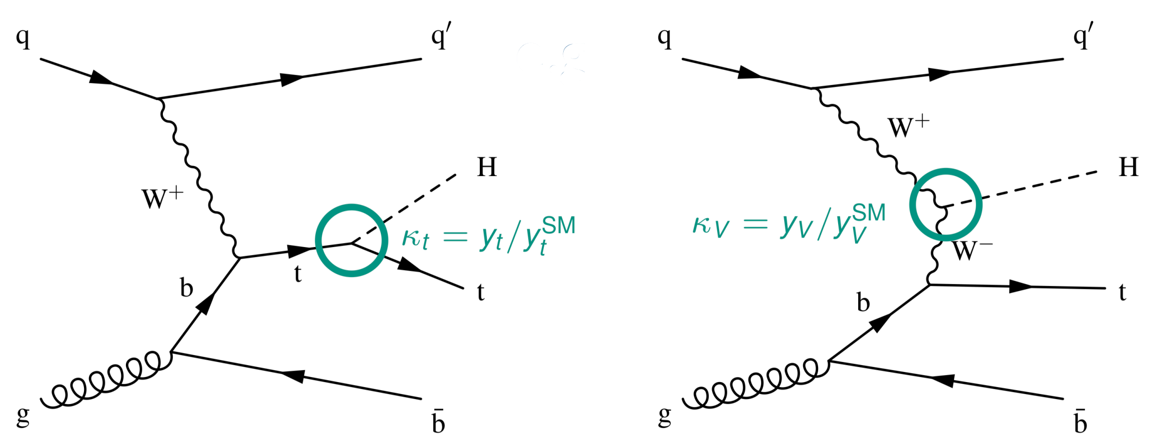
FELLINI roadmap

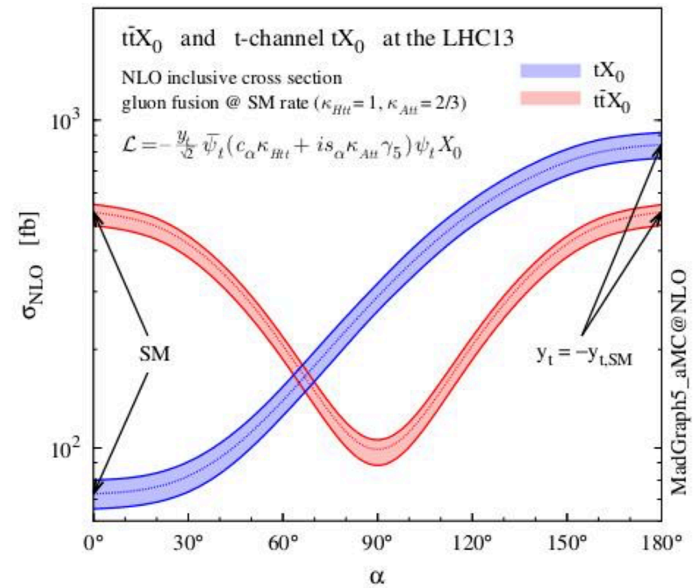


MAJOR ACHIEVEMENTS:

- tH analysis under internal Editorial Board review
- Complete top-quark polarisation measurement (Conference Publication → Paper)
- leading role in ATLAS Top Group (as coordinator of Properties & Mass analyses)
- co-organizer of the first LHC QE Workshop (Workshop: Quantum Tomography at LHC)
- 1-year Project Associate at CERN (FELLINI secondment)

tH search: introduction





$\sigma_{t(\bar{t})H} \propto a\,|y_t|^2 - b y_t$, with $a, b > 0$

$\sigma_{t\bar{t}H} \propto |y_t|^2$

Analysis goals: Exclusion of the Inverted top Yukawa Coupling (ITC) hypothesis and measurement of the tH cross section.

Motivation and interest: **First exclusion of the ITC hypothesis through direct probe of the ttH vertex**. New physics effects could lead to constructive interference between the ttH and WWH couplings and enhance the cross-sections by an order of magnitude or more (70 fb → 700 fb). Current measurements disfavour a negative value of the coupling, but rely on the assumption that only SM particles contribute to loops [1, 2, 3, 4].

Previous results from ATLAS and other experiments: ttH/tH γγ in ATLAS with partial Run II data [2], two CMS results already presented at Conferences in the bb̄ and multi-leptonic (ML) channels with Run II data [1, 4]

tH search: analysis workflow

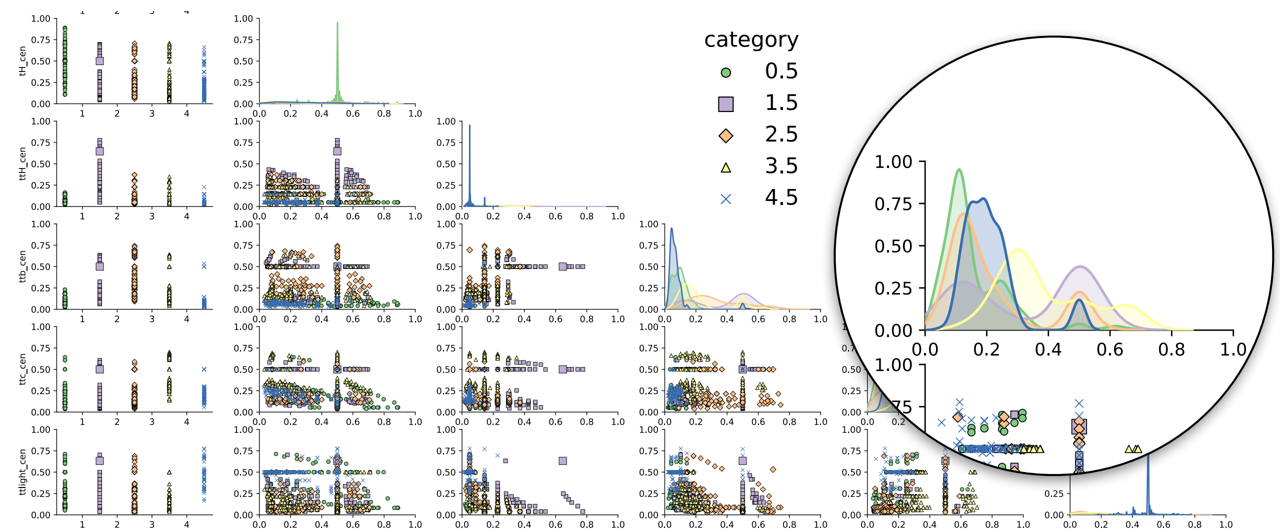
Methodology (1L channel, H→$b\bar{b}$ decay mode):

- **selection:** exactly 1 lepton + ≥3 b-tagged jets region
- **MVA and foam:** 5-hypotheses classification to classify signal and main backgrounds. A foam [Dannheim et al.] approach is used to divide the 5-D phase space in 5 regions with highest signal/background densities
- **fit model:** in 2 regions (binned profile likelihood fit with nuisance parameters)
- **interpretation:** y_t measurement and extraction of 95% C.L.s exclusion limit for different hypothesis of y_t

Methodology (2LSS channel) …

Methodology (3L channel) …

Methodology (2LSS+1Tau channel) …



Current status: All channels in place, under internal Editorial Board Review

- Expected upper limit on SM (ITC) hypothesis is $\sigma_{\text{tH}}^{\text{meas}}/\sigma_{\text{SM}} = \mu_{\text{tH}} < 5(0.6)$ *

* The current limit is subject to several improvements, concerning the Multivariate approach, the background modelling (data-driven estimate and systematic uncertainties).

Realistic timeline: Publication by Summer 2022

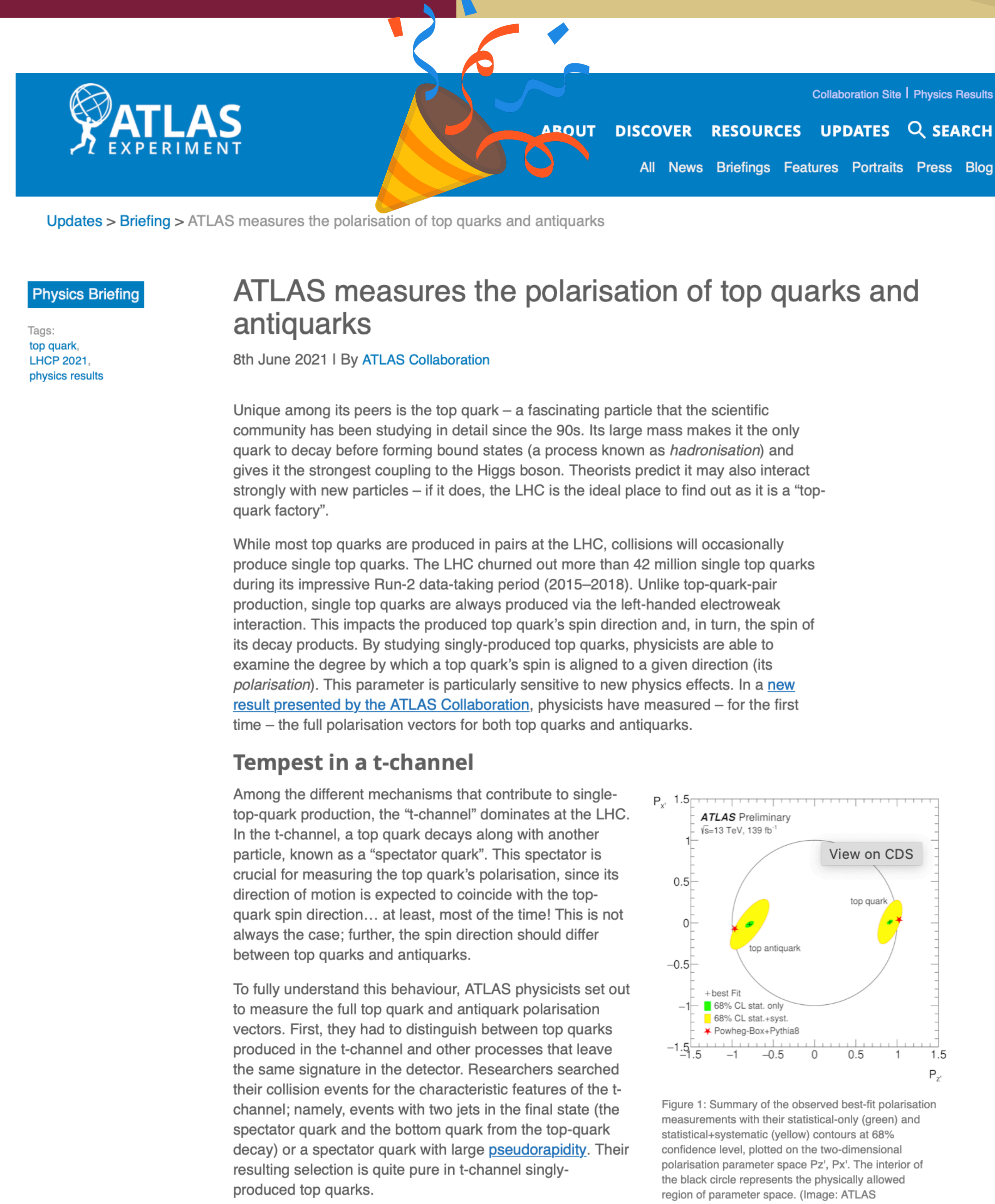
Top polarisation

Very long effort, started in 2017!

- presented at LHCP 2021
- first ever measurement of the three components of the top(antitop)-quark polarisation!

Some useful links:

- [ATLAS Physics Briefieng]
- [ATLAS-CONF-2021-027]
- currently drafting the paper



ATLAS EXPERIMENT

Collaboration Site | Physics Results

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Physics Briefing

Tags: top quark, LHCP 2021, physics results

ATLAS measures the polarisation of top quarks and antiquarks

8th June 2021 | By ATLAS Collaboration

Unique among its peers is the top quark – a fascinating particle that the scientific community has been studying in detail since the 90s. Its large mass makes it the only quark to decay before forming bound states (a process known as *hadronisation*) and gives it the strongest coupling to the Higgs boson. Theorists predict it may also interact strongly with new particles – if it does, the LHC is the ideal place to find out as it is a "top-quark factory".

While most top quarks are produced in pairs at the LHC, collisions will occasionally produce single top quarks. The LHC churned out more than 42 million single top quarks during its impressive Run-2 data-taking period (2015–2018). Unlike top-quark-pair production, single top quarks are always produced via the left-handed electroweak interaction. This impacts the produced top quark's spin direction and, in turn, the spin of its decay products. By studying singly-produced top quarks, physicists are able to examine the degree by which a top quark's spin is aligned to a given direction (its *polarisation*). This parameter is particularly sensitive to new physics effects. In a new result presented by the ATLAS Collaboration, physicists have measured – for the first time – the full polarisation vectors for both top quarks and antiquarks.

Tempest in a t-channel

Among the different mechanisms that contribute to single-top-quark production, the "t-channel" dominates at the LHC. In the t-channel, a top quark decays along with another particle, known as a "spectator quark". This spectator is crucial for measuring the top quark's polarisation, since its direction of motion is expected to coincide with the top-quark spin direction… at least, most of the time! This is not always the case; further, the spin direction should differ between top quarks and antiquarks.

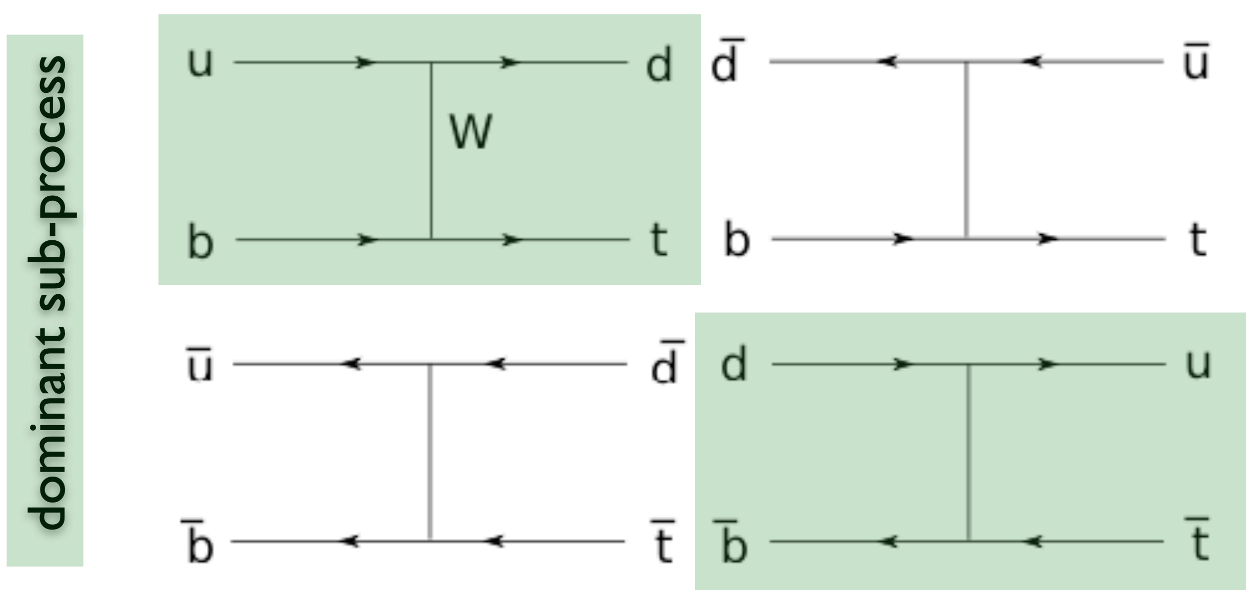
To fully understand this behaviour, ATLAS physicists set out to measure the full top quark and antiquark polarisation vectors. First, they had to distinguish between top quarks produced in the t-channel and other processes that leave the same signature in the detector. Researchers searched their collision events for the characteristic features of the t-channel; namely, events with two jets in the final state (the spectator quark and the bottom quark from the top-quark decay) or a spectator quark with large pseudorapidity. Their resulting selection is quite pure in t-channel singly-produced top quarks.

Figure 1: Summary of the observed best-fit polarisation measurements with their statistical-only (green) and statistical+systematic (yellow) contours at 68% confidence level, plotted on the two-dimensional polarisation parameter space Pz', Px'. The interior of the black circle represents the physically allowed region of parameter space. (Image: ATLAS

Top polarisation: how to

At the LHC (pp collisions)...

- **EW production**: highly polarised top quarks due to V-A nature
  - top-quark polarisation (***P***) can only be measured in single top-quark events *
    * In $t\bar{t}$ production, top quarks are produced unpolarised because of parity conservation in QCD
  - t-channel is the dominant process
- **Detectable**: large m_t → top decays before hadronisation → decay products preserve spin information → accessible via angular distributions (in top rest frame)
- **Spin polarisation**: depends upon the specific top-/antitop- sample and the chosen basis
  - valence *u*-quark density ~2x valence *d*-quark density (pp collisions)

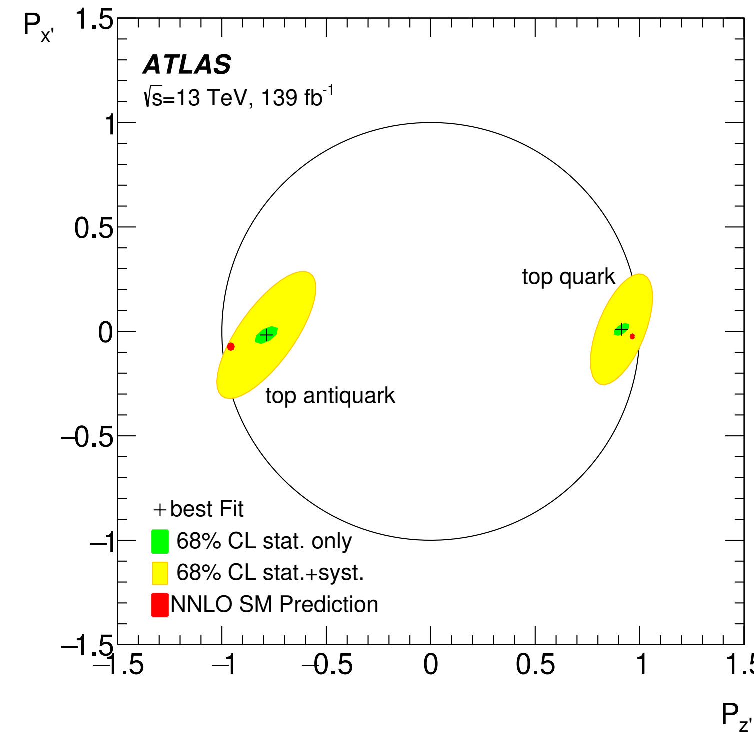


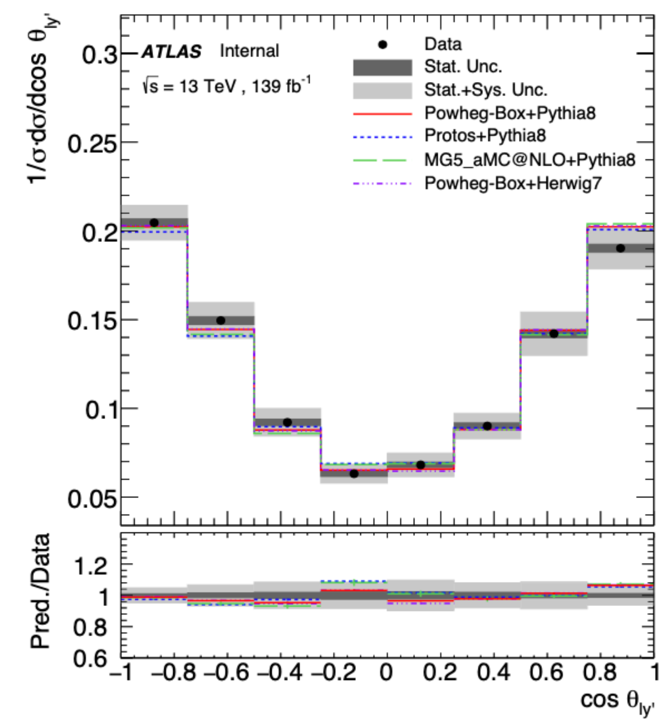
Top vs. antitop in t-channel:
- different x-sections
- different background levels (S/B)
- different subprocesses
- different polarisations

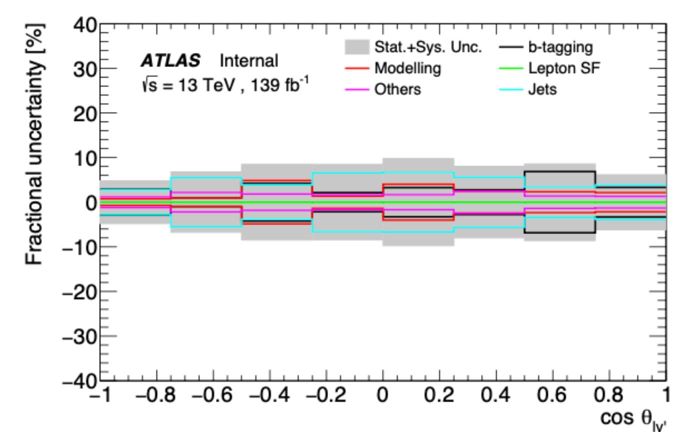
Polarisation/Unfolding/EFT results

Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

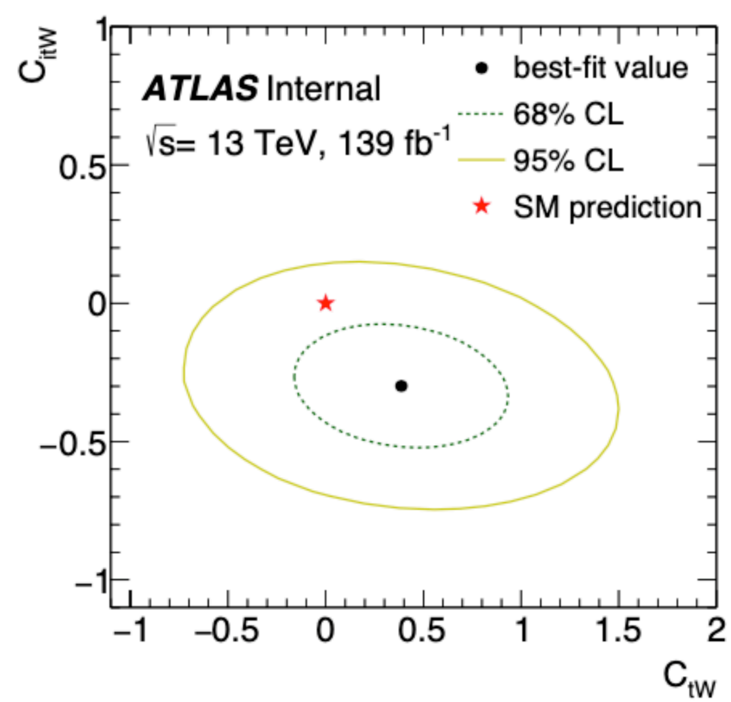
≈0 → no CPV



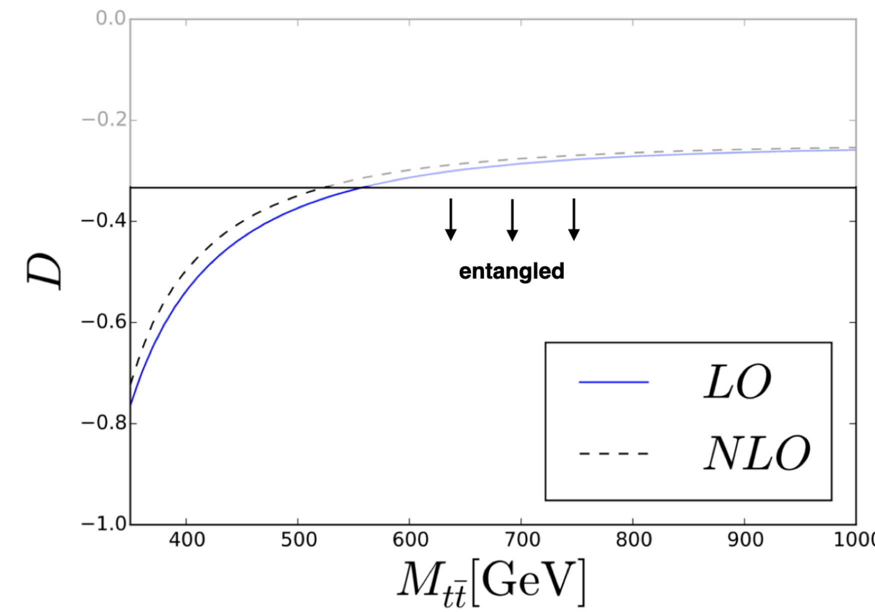




	C_{tW} 68% CL	C_{tW} 95% CL	C_{itW} 68% CL	C_{itW} 95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]



$t\bar{t}$ Quantum Entanglement (QE)



Analysis goals: Evidence (observation) of QE between the spins of top-antitop-quark pairs at the LHC

Motivation and interest: the first proposal of entanglement detection in a pair of quarks, and has the **potential to be the first entanglement observation at energies never explored**
A lot of interest has grown during 2021 → [Workshop on QT]

Previous results from ATLAS and other experiments: **None at colliders**. Several papers in Condensed Matter and Photonics (often with fermionic / bosonic states of atoms / molecules)

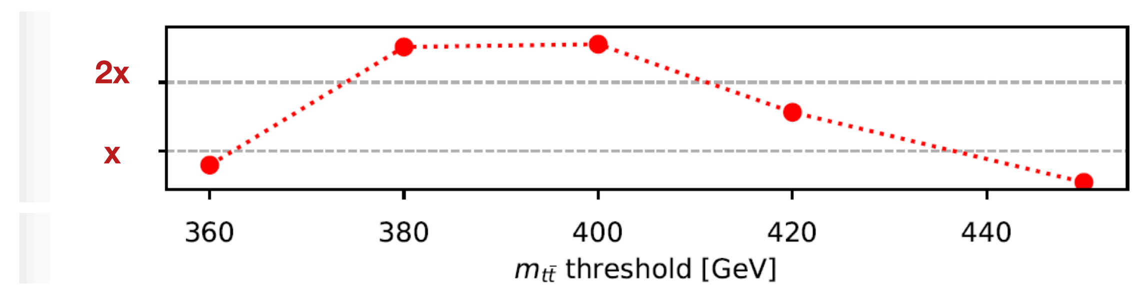
Possible future extensions: If only evidence, go for observation with higher integrated luminosity. Test of Bell's inequality. Quantum entanglement and violation of Bell's inequality with H → WW events [3] (qubits → qutrits).

Achievements so far: analysis strategy is almost frozen and documented. **Expected significance fluctuates around 3σ** depending on the chosen method and $m_{t\bar{t}}$ threshold cut [EB Request]
(see next slide)

$t\bar{t}$ QE: analysis workflow

Methodology

- **selection:** exactly two opposite-charge leptons (e/μ), ≥ 2 jets, of which ≥ 1 b-tagged, E_T^{miss} > 30 GeV, Z-veto for ee/μμ channels + ellipse method to reconstruct $t\bar{t}$ system + low $m_{t\bar{t}}$ cut (where quantum entanglement of spin states happen)
- **background:** extremely high S/B. Backgrounds have a very negligible impact on the analysis significance.
- **PLU and IBU:** Profile Likelihood Unfolding and Iterative Bayesian Unfolding techniques
  - unfolding to parton level in full phase-space
  - $\phi_{\ell\ell}$ of leptons in their respective top rest-frames
  - 2 strategies: D determined from <cosϕ> or slope of cosϕ curve
  - interpretation: D<-1/3 → entanglement by Xσ



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{\ell\ell}} = \frac{1}{2}(1 - D\cos\varphi_{\ell\ell}) \qquad D = -3\langle\cos\varphi_{\ell\ell}\rangle$$

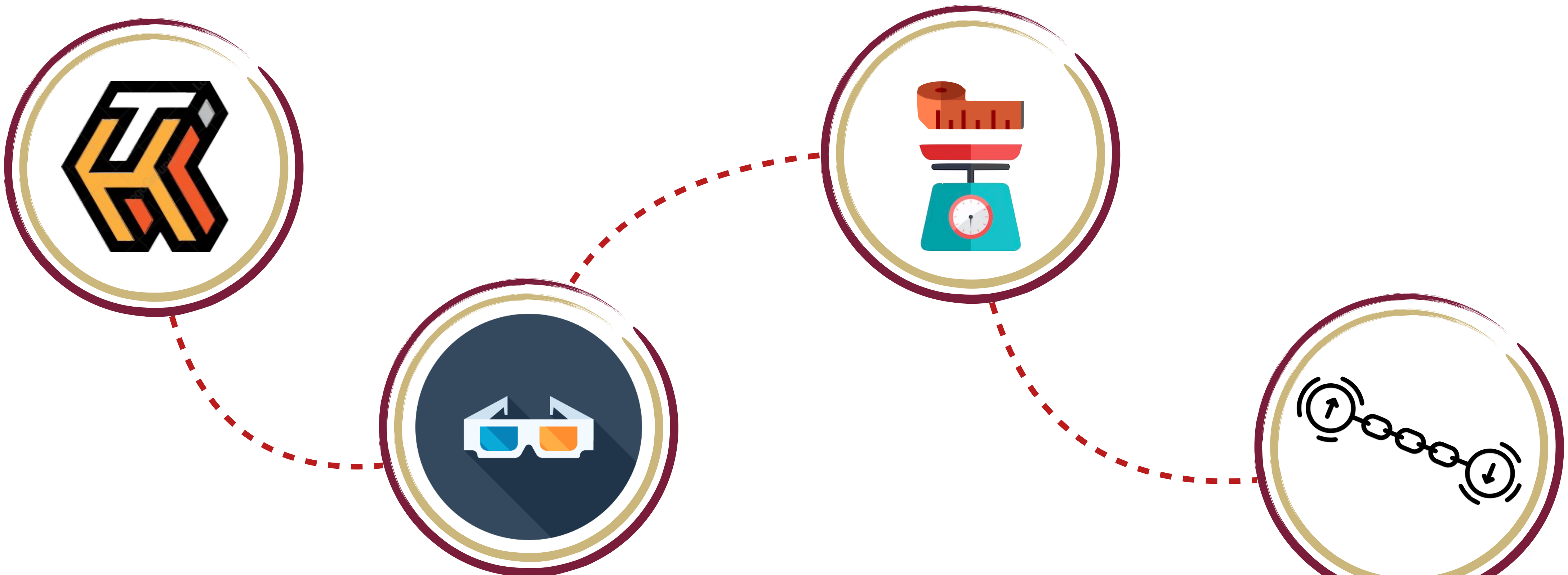
Challenges and difficulties:

- **IBU approach provides lower sensitivity to QE.** Thus, both approaches are under consideration.
- **"threshold" bin is very sensitive to mass and also to soft/Coulomb effects** that are not accounted for even in the NNLO calculations (e.g., ~1 GeV shift of top mass)

FELLINI roadmap

19 → … - Top Yukawa coupling (tH searches)

20→22 - ATLAS Top Properties & Mass Sub-convener



19→21 - Top quark polarisation

22 → … - Quantum Entanglement in $t\bar{t}$

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