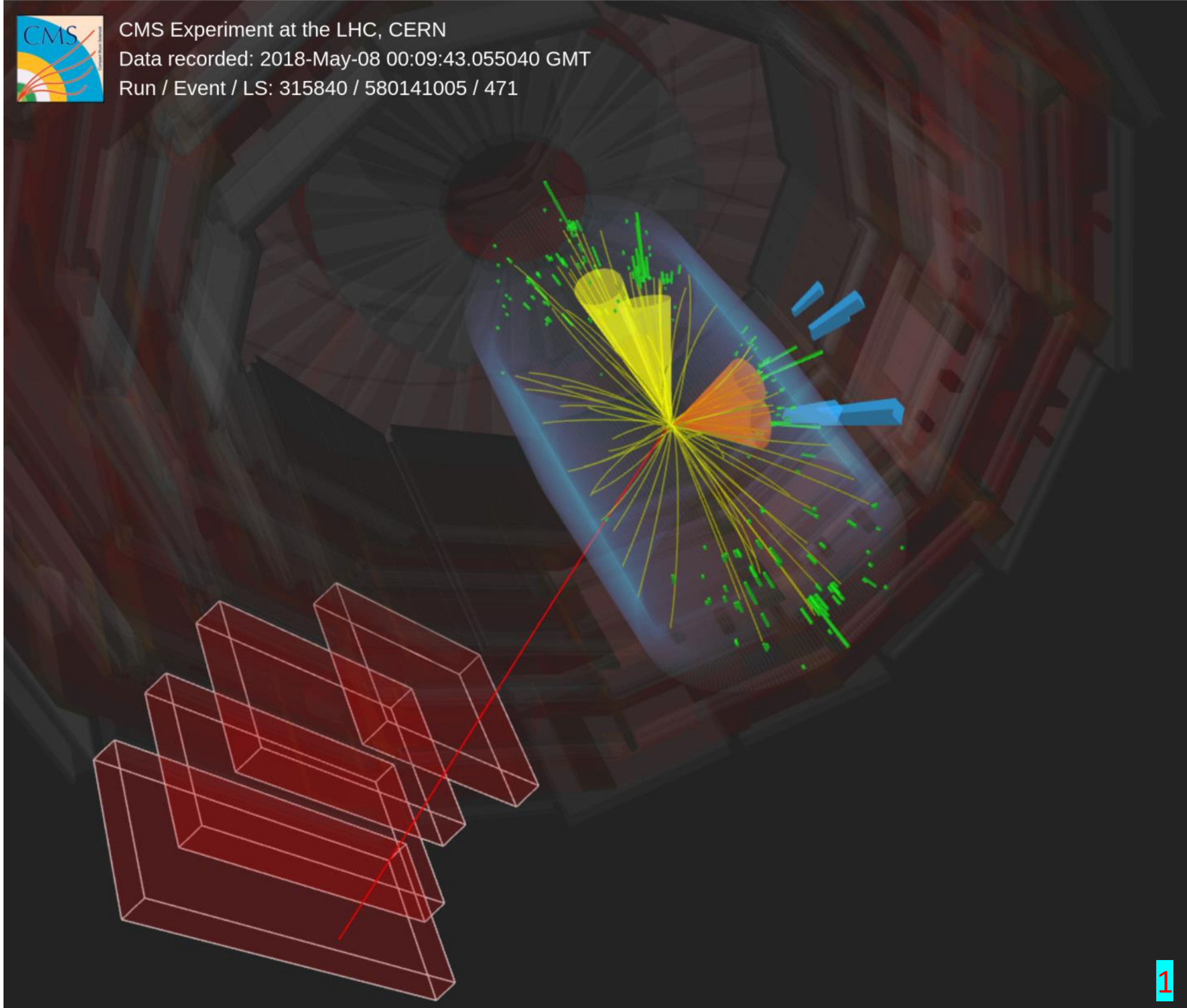
Top-quark physics highlights from CMS



Piotr Zalewski, Warsaw
National Centre for Nuclear Research (NCBJ)

on behalf of the CMS Colaboration
Epiphany 2025

The third generation of quarks was proposed more than half a century ago as a possible explanation for CP violation.

After the discovery of the b quark in 1977

the hunt for t quark were started, but its unexpectedly large mass made the efforts of subsequent experiments fruitless for a long time.

In 1994 the CDF collaboration has found indication of the top.

Its anticipated mass was in agreement with electro-week fit based mainly on LEP measurements.

The discovery was announced next year by both TeVatron collaborations:

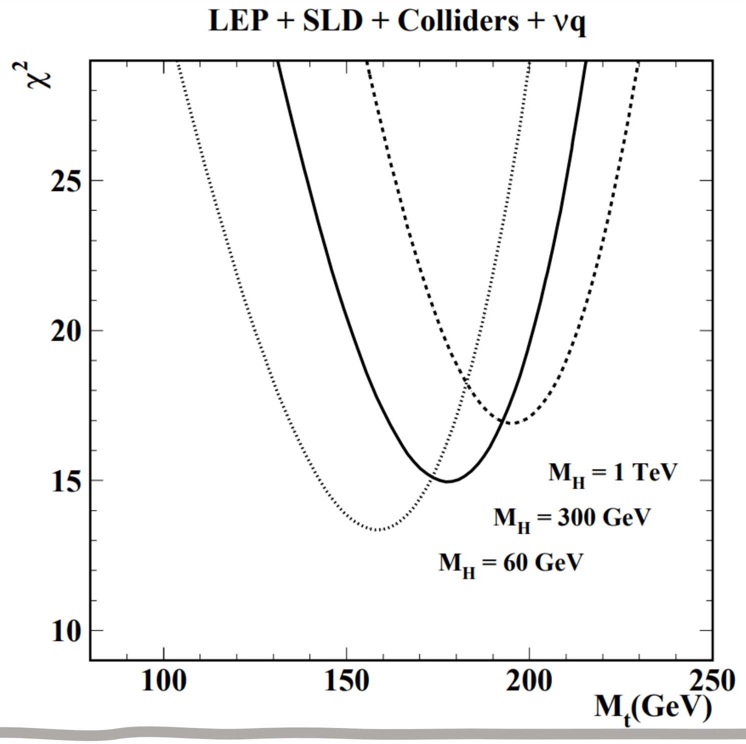
The CDF collaboration,
"Observation of top quark production in pbar p
 collisions with the Collider-Detector at Fermilab"
doi: 10.1103/PhysRevLett.74.2626

The D0 collaboration,
"Observation of the Top Quark"
doi: 10.1103/PhysRevLett.74.2632.

M. Kobayashi and T. Maskawa,
“CP-violation in the renormalizable theory of weak interaction”,
Prog. Theor. Phys. 49 (1973) 652, doi: 10.1143/PTP.49.652.

L. Lederman *et all,* "Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions"
Phys. Rev. Lett. 39 (1977) 252, doi: 10.1103/PhysRevLett.39.252.

The LEP collaborations and EWG,
"Combined Preliminary Data on Z Parameters from the LEP Experiments and Constraints on the Standard Model "
CERN/PPE/94-187 (ICHEP 1994 Glasgow)



The CMS collaboration,
“Review of top quark mass measurements in CMS”,
Physics Reports Available online 2 January 2025
https://doi.org/10.1016/j.physrep.2024.12.002

``The top quark mass is one of the most intriguing parameters of the standard model (SM). Its value indicates a Yukawa coupling close to unity, and the resulting strong ties to the Higgs physics make the top quark mass a crucial ingredient for understanding essential aspects of the electroweak sector of the SM.

This review offers the first comprehensive overview of these measurements performed by the CMS Collaboration using the data collected at centre-of-mass energies of 7, 8, and 13 TeV.’’

The CMS Collaboration has performed multiple measurements of the top quark mass, addressing these challenges from different angles: highly precise ‘direct’ measurements, using the top quark decay products, as well as ‘indirect’ measurements aiming at accurate interpretations in terms of the Lagrangian parameter.

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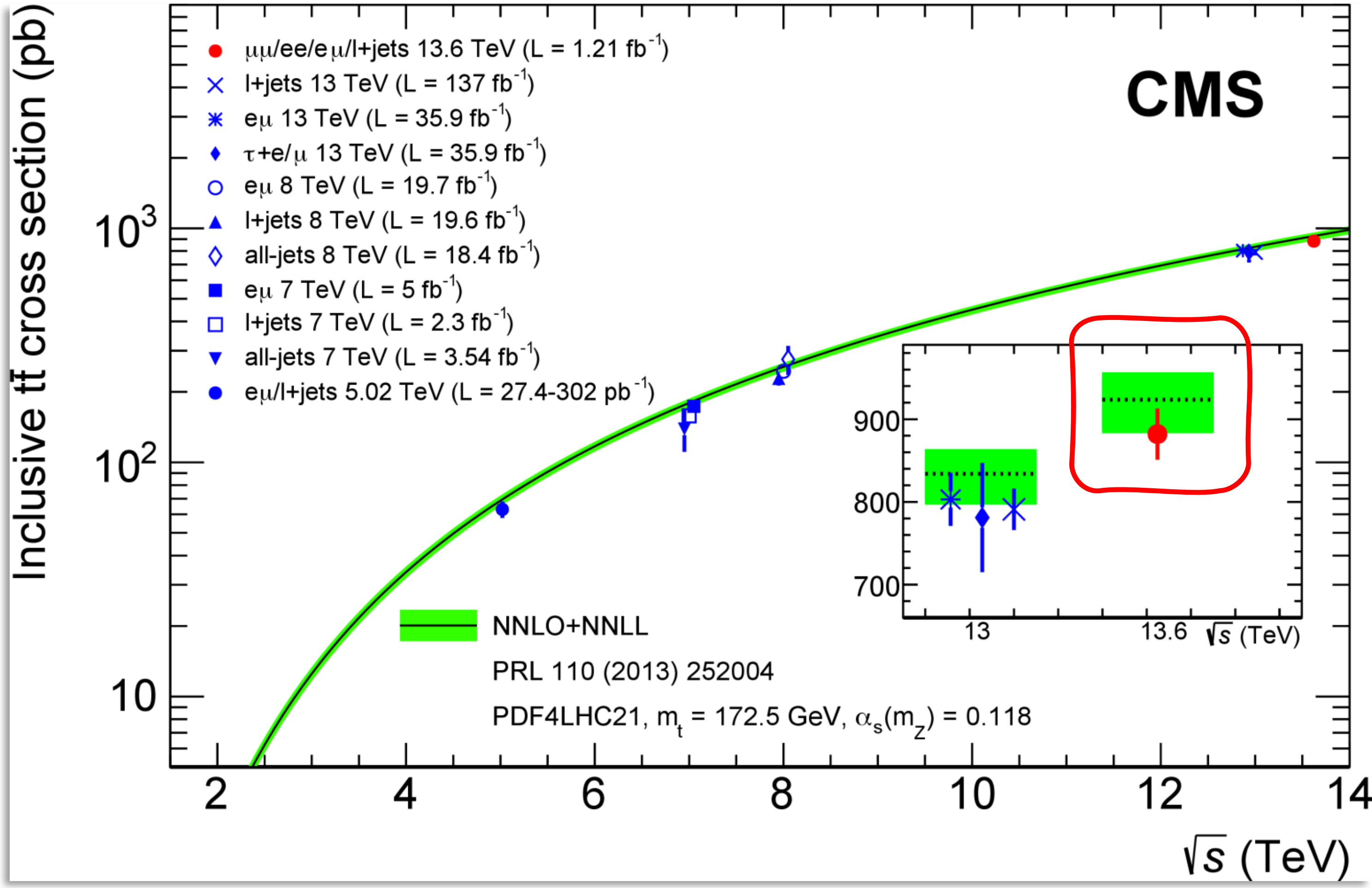

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● The CMS collaboration,
“First measurement of the top quark pair production cross section in proton-proton collisions at sqrt(s) = 13.6 TeV”,
https://doi.org/10.1007/JHEP08(2023)204

More then 100 millions of t bar(t) events produced at 13 TeV (LHC run2).

The CMS collaboration,
“Review of top quark mass measurements in CMS”,
Physics Reports Available online 2 January 2025
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``Measurements of the top quark mass have been an essential part of the CMS research programme since the first data were recorded in 2010, with more than 20 journal publications that reveal different aspects related to this fundamental parameter of the standard model.

A growing understanding of theoretical and experimental issues on the way towards increasing precision in m_t, demanded by matching the accuracy of other electroweak parameters, were followed by steady improvements in analysis techniques.

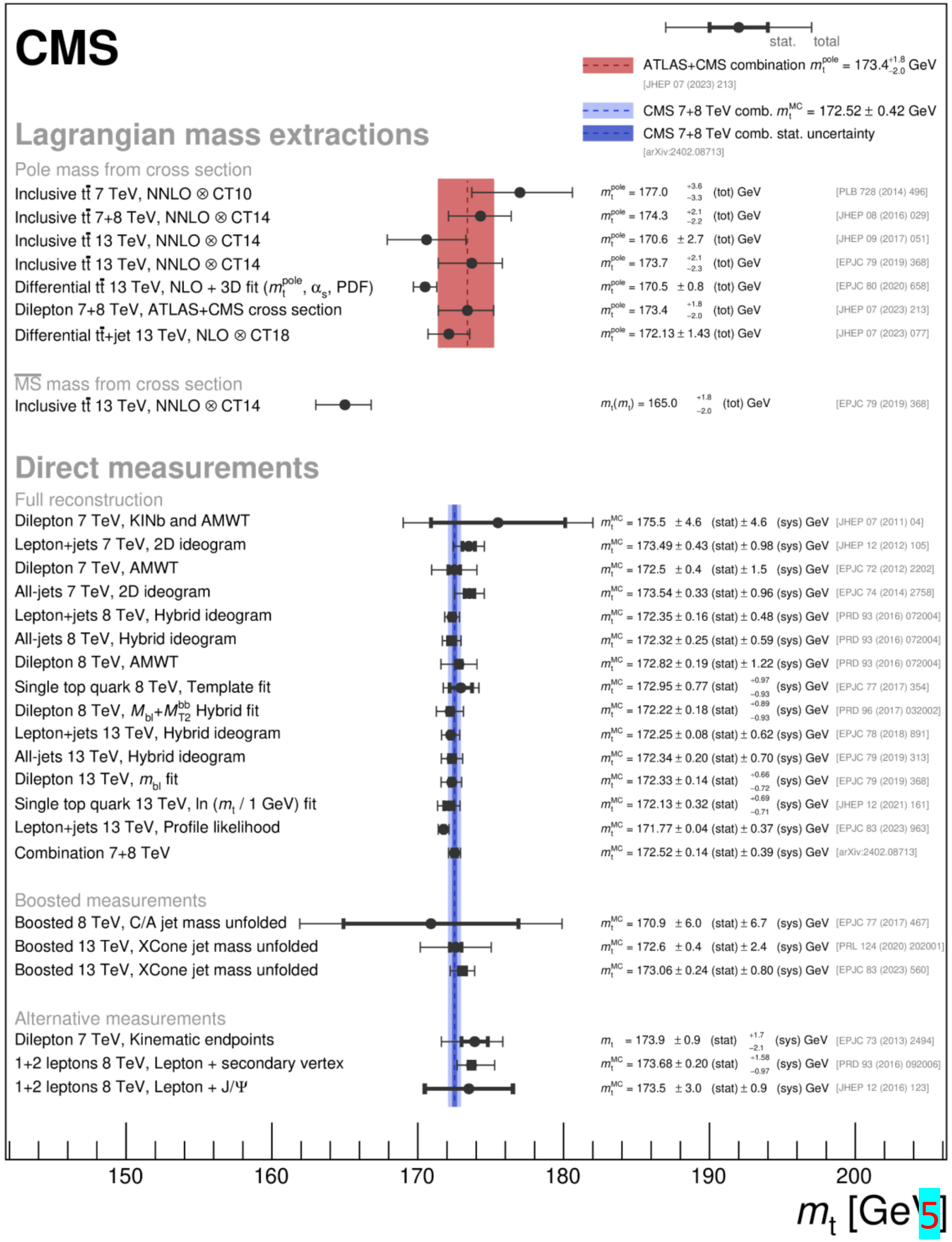
Different complementary methods have been used for measurements of m_t, affected by different sources of theoretical and experimental systematic uncertainties.

An impressive sub-GeV precision has been achieved,
despite the challenging environment of high-energy pp collisions at the LHC,
where events are affected by QCD and electroweak radiation,
the underlying event and an unprecedented level of pileup interactions.

This success, and a clear perspective of experimental improvements envisaged for the HL-LHC, give confidence in reaching the ultimate precision in m_t achievable at a hadron collider in the next decade.

This experimental goal requires that the necessary theoretical developments will take place, including advancements in the description of the top quark beyond the picture of a free particle, matching higher-order calculations to resummations and hadronisation models, and calculating corrections at the threshold of tt production.

The precise determination of m_t is an ongoing endeavor that fosters a close collaboration of the experimental and theoretical communities, with bright prospects in the coming years. ’’



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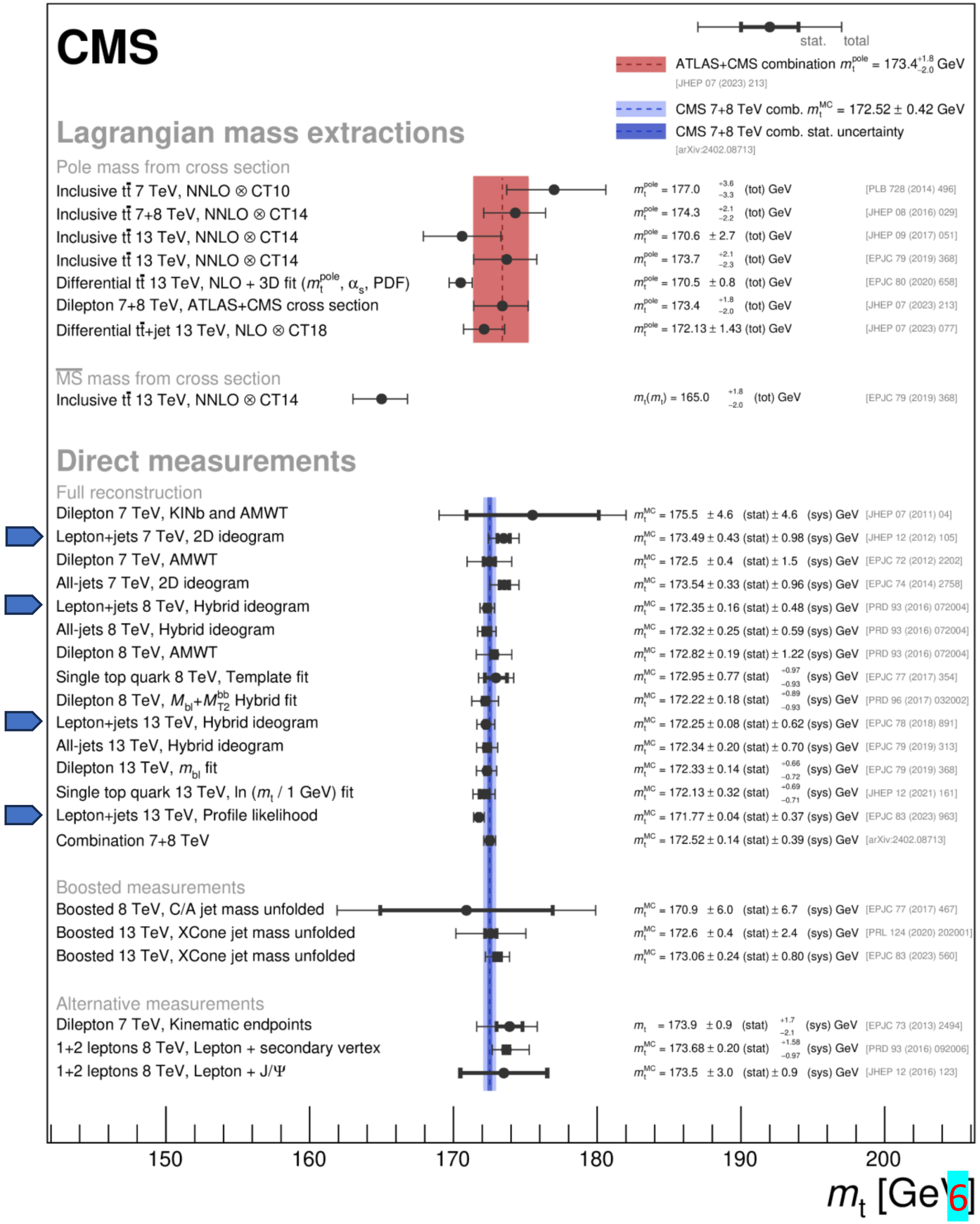
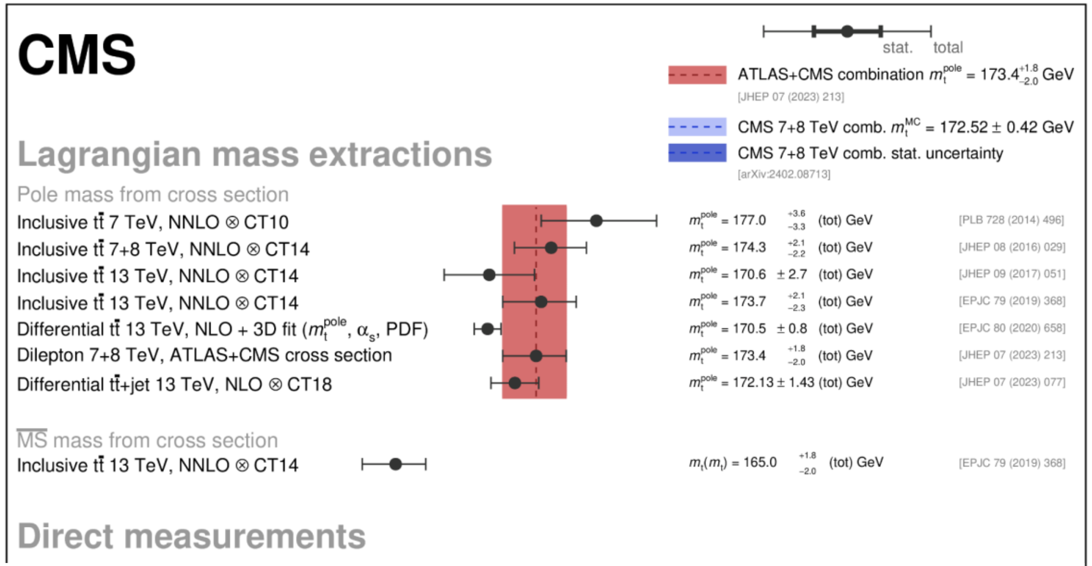
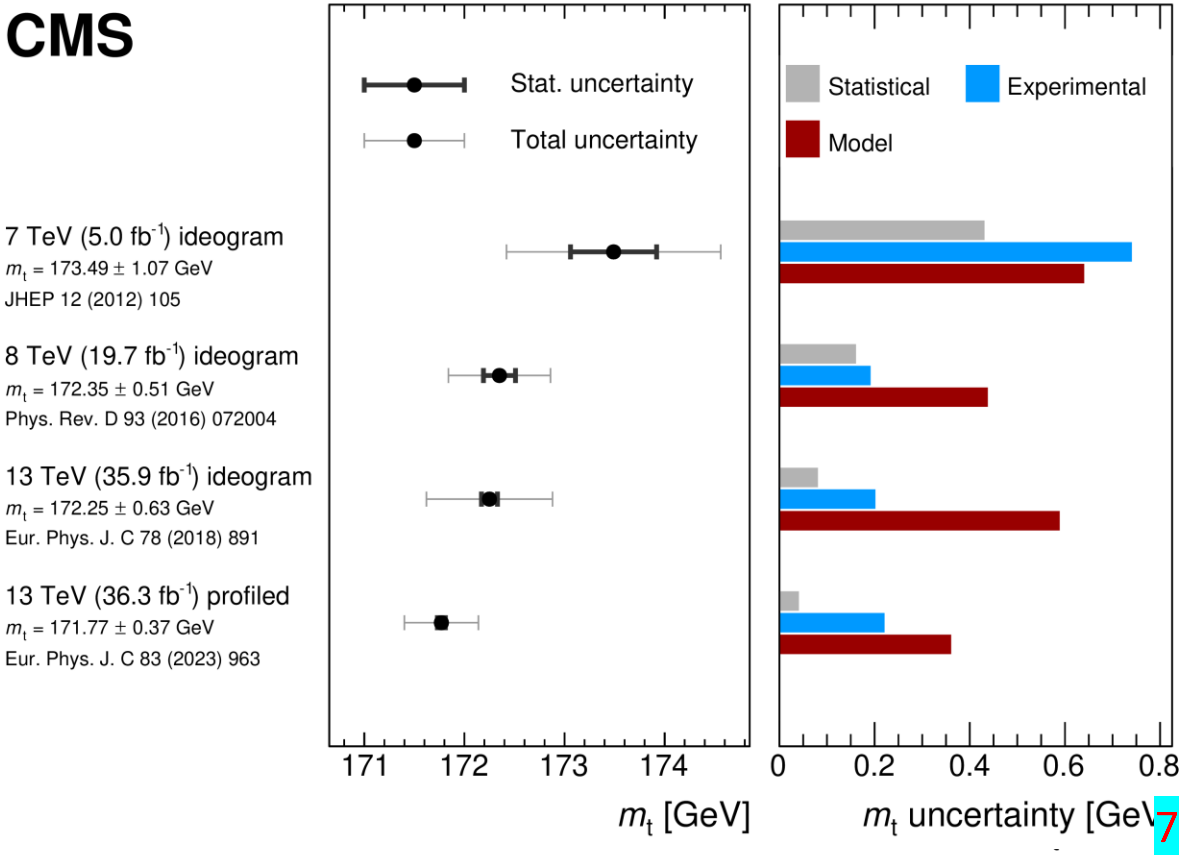
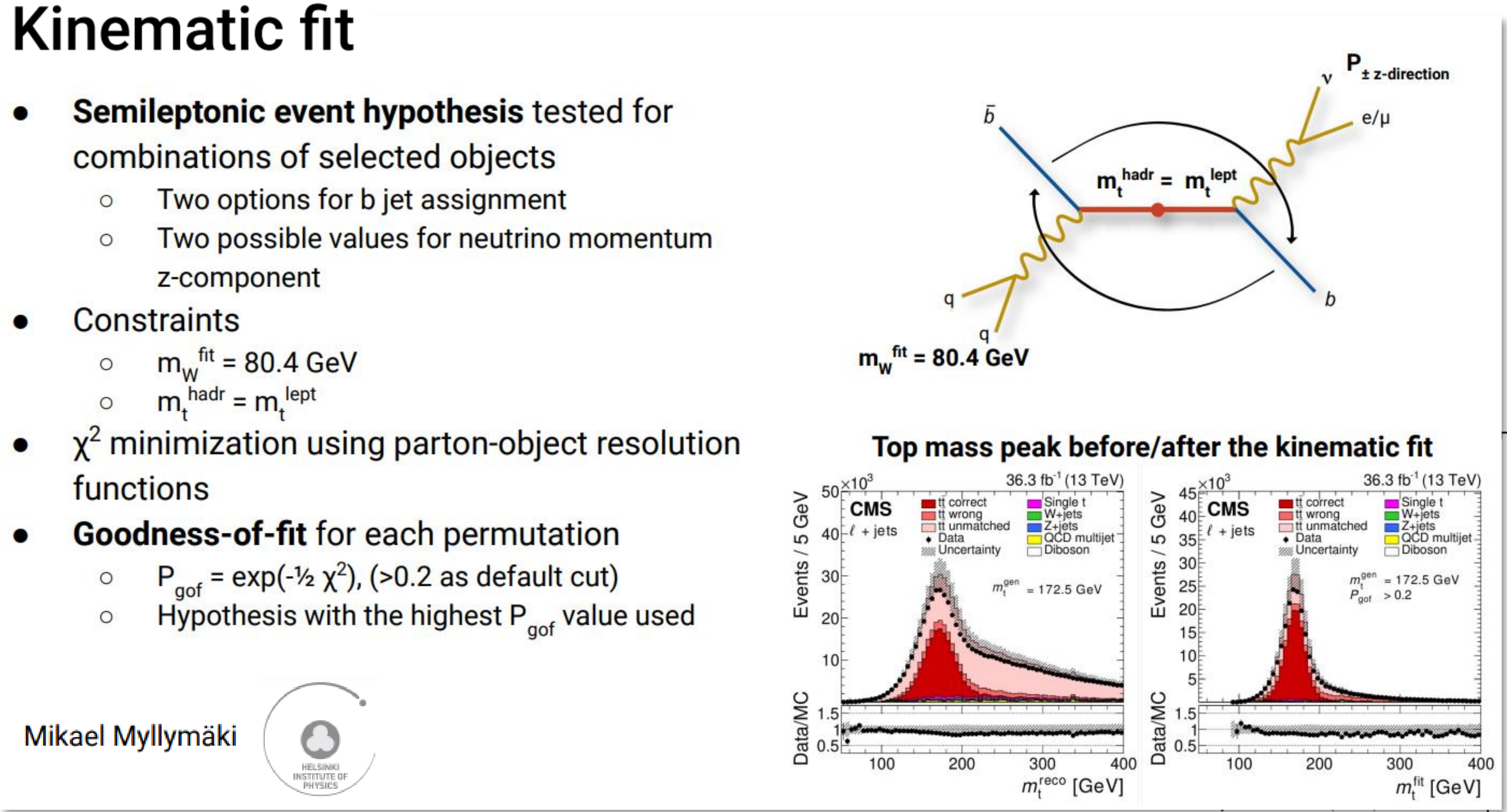


CMS lepton+jets analyses:







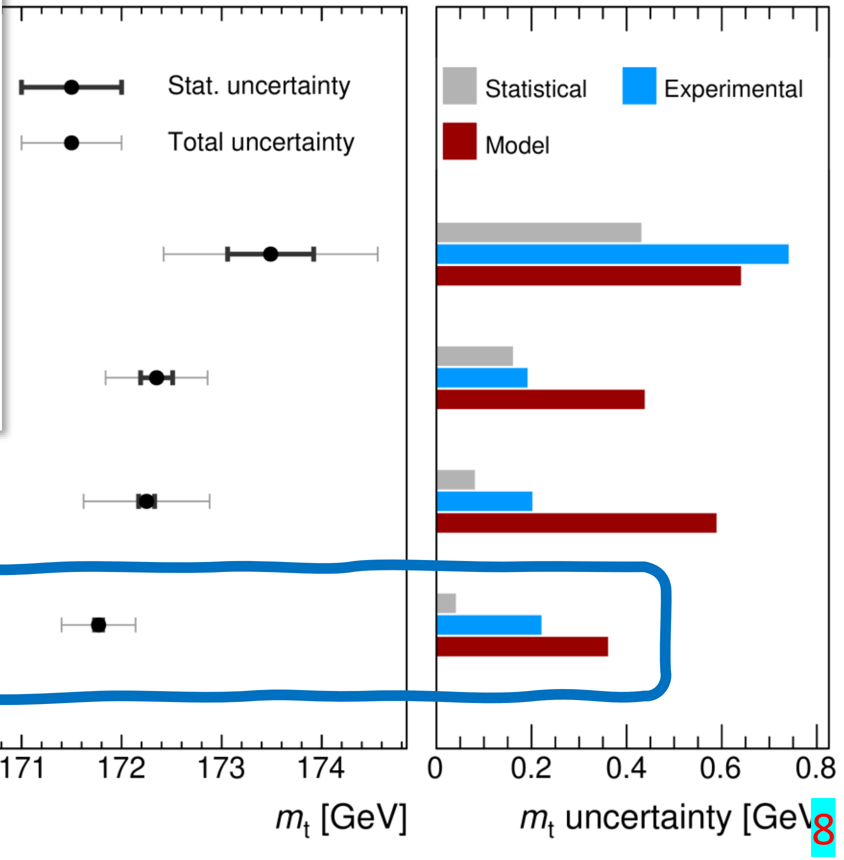
Kinematic fit

- **Semileptonic event hypothesis** tested for combinations of selected objects
  - Two options for b jet assignment
  - Two possible values for neutrino momentum z-component
- Constraints
  - m_W^{fit} = 80.4 GeV
  - $m_t^{hadr} = m_t^{lept}$
- χ^2 minimization using parton-object resolution functions
- **Goodness-of-fit** for each permutation
  - $P_{gof} = \exp(-½\ \chi^2)$, (>0.2 as default cut)
  - Hypothesis with the highest P_{gof} value used

Top mass peak before/after the kinematic fit

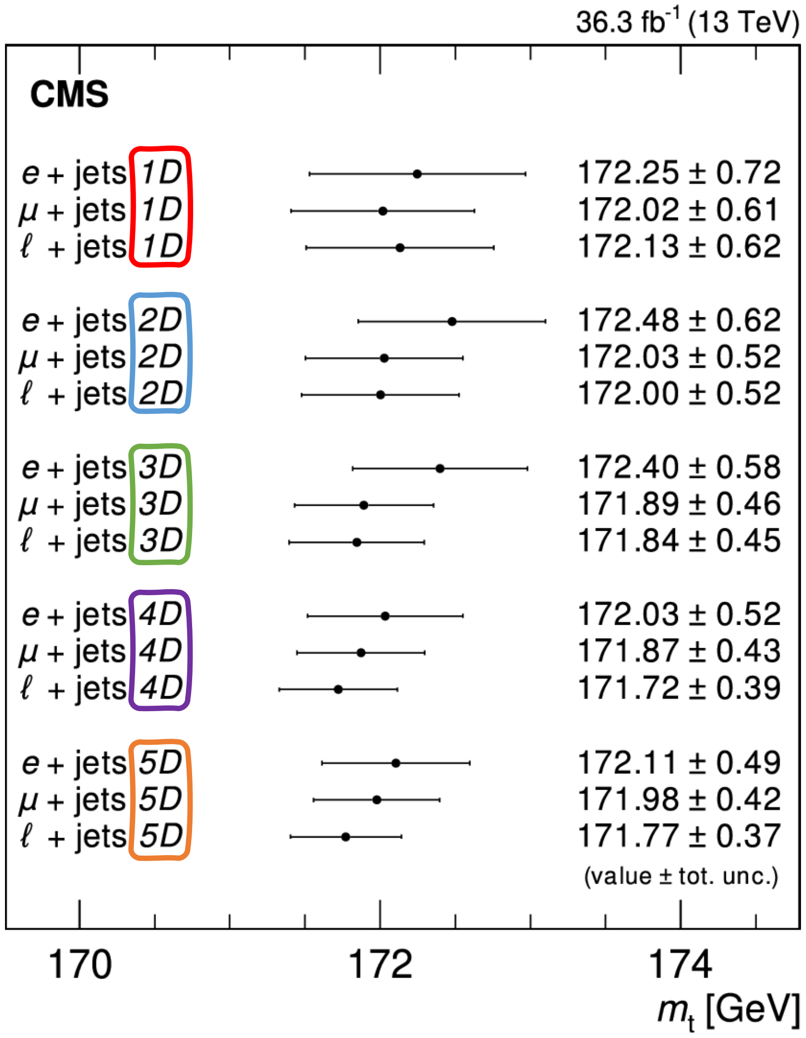
Mikael Myllymäki

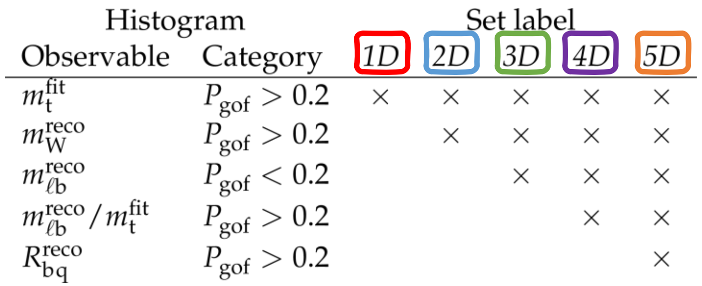
New mass extraction method on the same 2016 data + reconstruction and calibration and simulation improvements.



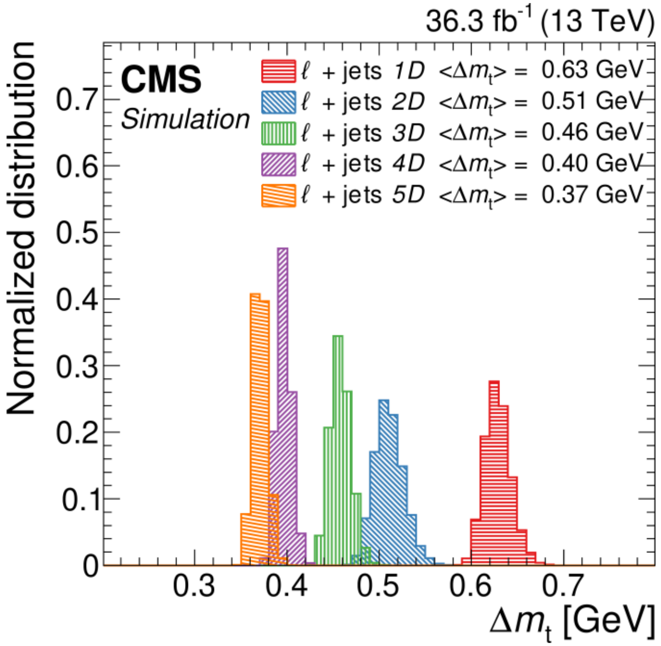
The CMS collaboration,
"Measurement of the top quark mass using a profile likelihood approach with the lepton + jets final states in proton–proton collisions at sqrt(s) = 13 TeV",
Eur. Phys. J. C 83(2023)963. https://doi.org/10.1140/epjc/s10052-023-12050-4

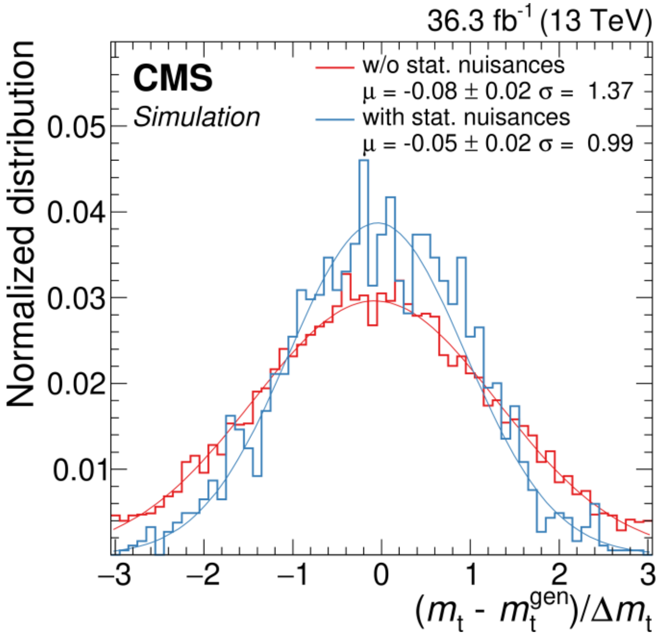
Profiled maximum-likelihood fit makes it possible to constrain systematics with data.





Histogram Observable	Histogram Category	Set label 1D	2D	3D	4D	5D
m_t^{fit}	$P_{gof} > 0.2$	×	×	×	×	×
m_W^{reco}	$P_{gof} > 0.2$		×	×	×	×
$m_{\ell b}^{reco}$	$P_{gof} < 0.2$			×	×	×
$m_{\ell b}^{reco} / m_t^{fit}$	$P_{gof} > 0.2$				×	×
R_{bq}^{reco}	$P_{gof} > 0.2$					×





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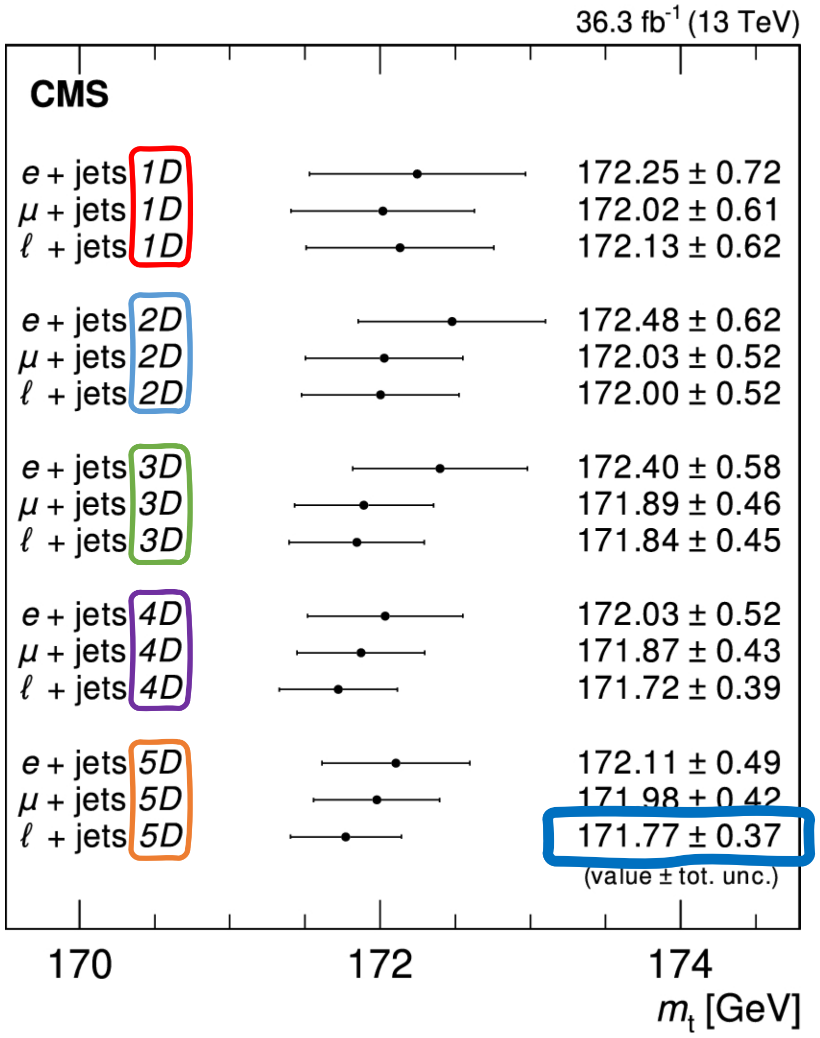

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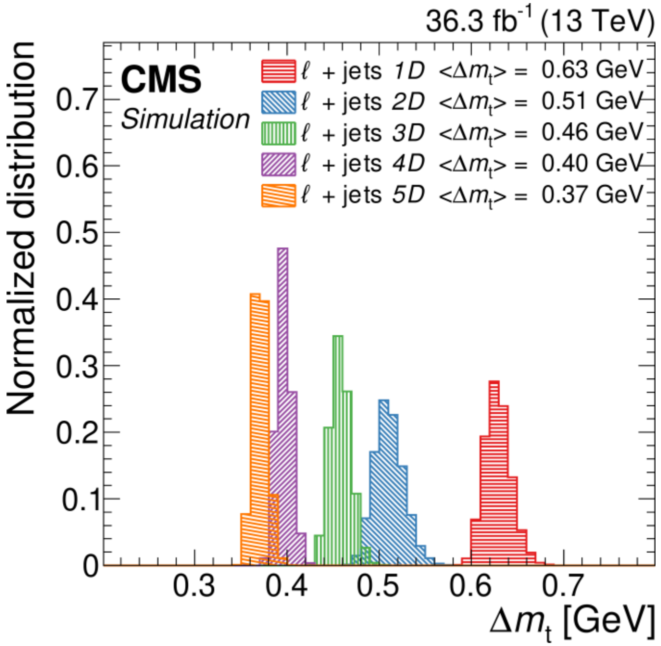
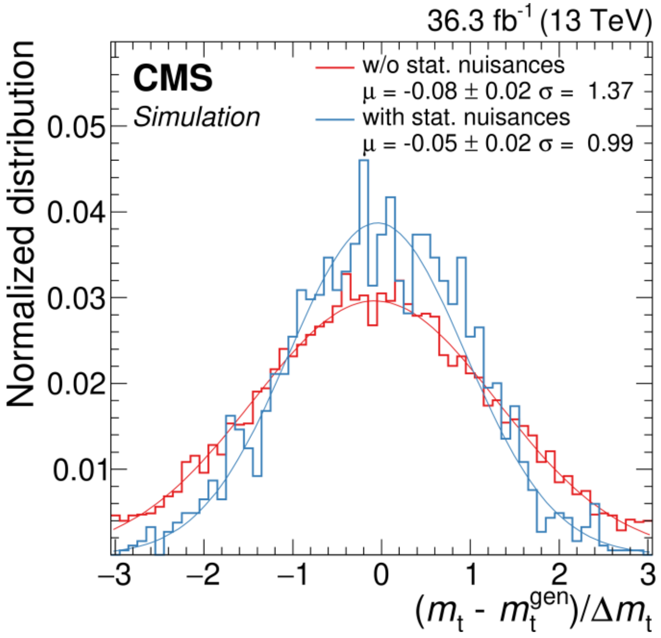
$m_{\ell b}^{reco}$	$P_{gof} < 0.2$			×	×	×
$m_{\ell b}^{reco} / m_t^{fit}$	$P_{gof} > 0.2$				×	×
R_{bq}^{reco}	$P_{gof} > 0.2$					×

The most precise individual results to date

Full run2 analysis underway





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The CMS collaboration,
"**Observation of quantum entanglement in top quark pair production in proton–proton collisions at sqrt(s) = 13 TeV**",
Rep. Prog.Phys. **87** (2024)117801, https://doi.org/10.1088/1361-6633/ad7e4d

Entanglement is an intrinsic property of quantum mechanics and is predicted to be exhibited in the particles produced at the Large Hadron Collider.

A measurement of the extent of entanglement in top quark-antiquark events produced in proton–proton collisions at a center-of-mass energy of 13 TeV is performed with the data recorded by the CMS experiment at the CERN LHC in 2016, and corresponding to an integrated luminosity of 36.3 fb^{-1}.

The events are selected based on the presence of two leptons with opposite charges and high transverse momentum.

An entanglement-sensitive observable *D* is derived from the top quark spin-dependent parts of the top - antitop production density matrix and measured in the region of the production threshold.

A quantum state of two subsystems, is separable when it can be expressed as a convex sum of tensor products of states between the respective subsystems.

A necessary and sufficient condition for identifying entanglement in such a two-particle system is the Peres–Horodecki criterion.

This criterion is equivalent (for the singlet state) to a requirement that entanglement witness $\Delta \equiv -C_{33}+|C_{11}+C_{22}|-1 > 0$,

where $[C]$ is the spin corrrelation matrix of top anti-top pair.

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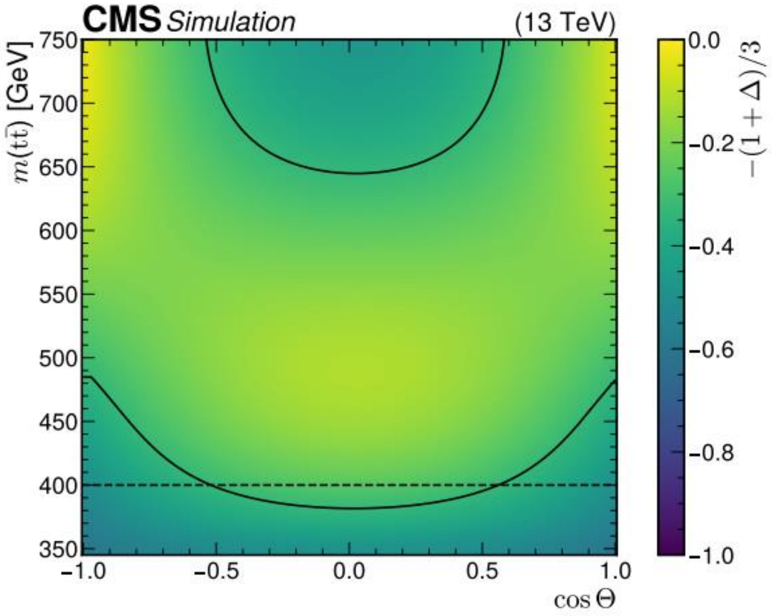
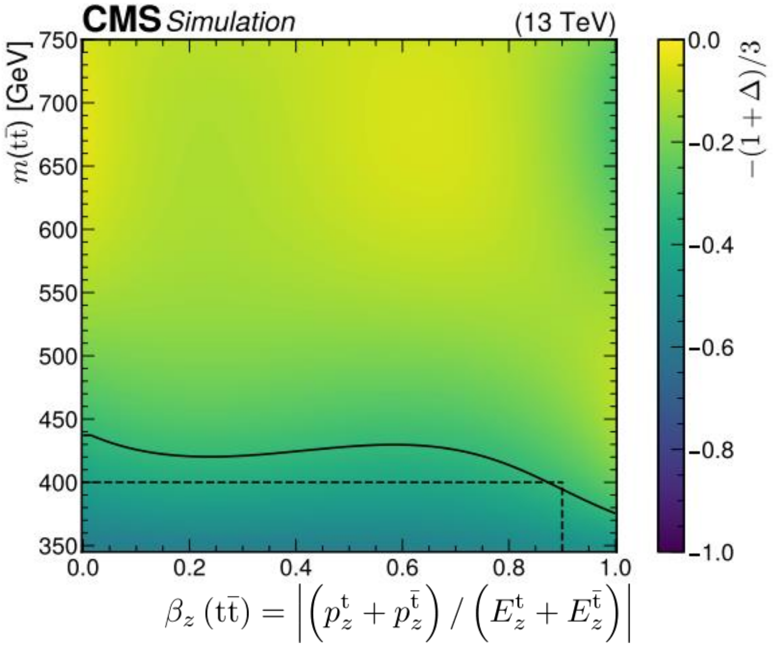
The cosine of the angle between the two charged decay leptons in their respective parent top quark rest frames, $\cos\phi = \ell^{+}\cdot\ell^{-}$, has a linear relationship with the relative differential cross section

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\phi} = \frac{1}{2}(1 - D\cos\phi),$$

where the slope D is the entaglement proxy: $D = \mathrm{tr}[C]/3 < -1/3$.

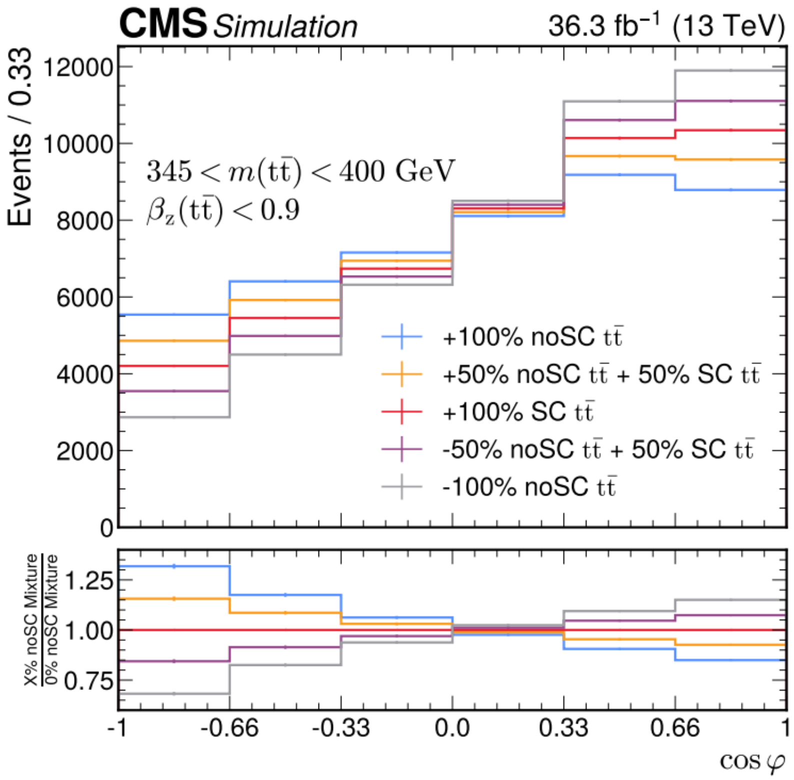
Illustration how the entanglement is expected to vary as a function of the kinematic parameters.
The quantity $-(1+\Delta)/3$ is shown (on the color scale) as a function of m(t bar(t)) and the top quark scattering angle Θ as well as β_z(t bar(t)).
The solid line indicate P-H criterion whereas the dashed line entaglement enhancing selection.

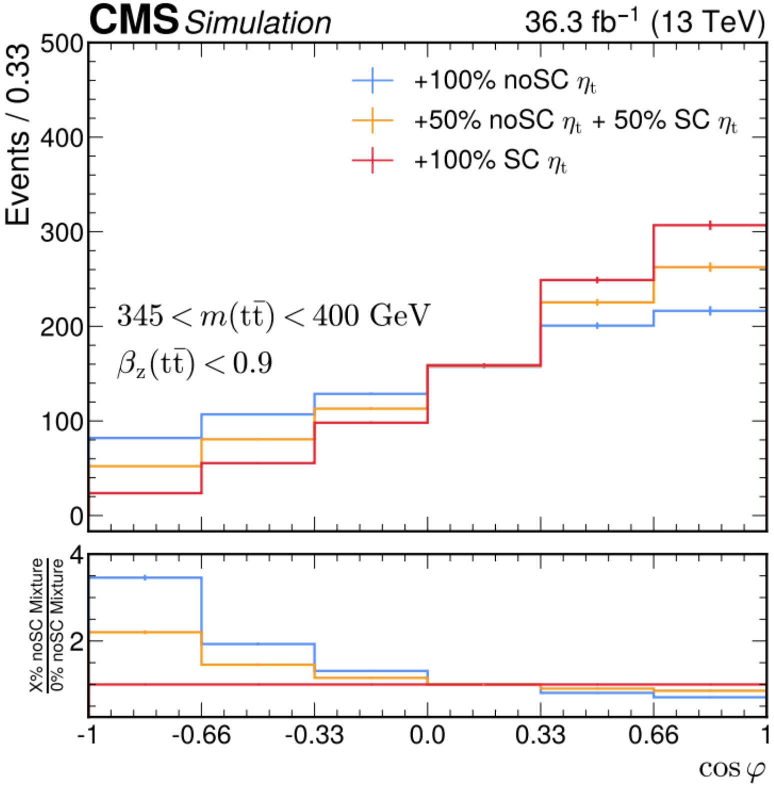




Extraction of the entanglement proxy

The CMS collaboration,
“**Observation of quantum entanglement in top quark pair production in proton–proton collisions at sqrt(s) = 13 TeV**”,
.17801, https://doi.org/10.1088/1361-6633/ad7e4d





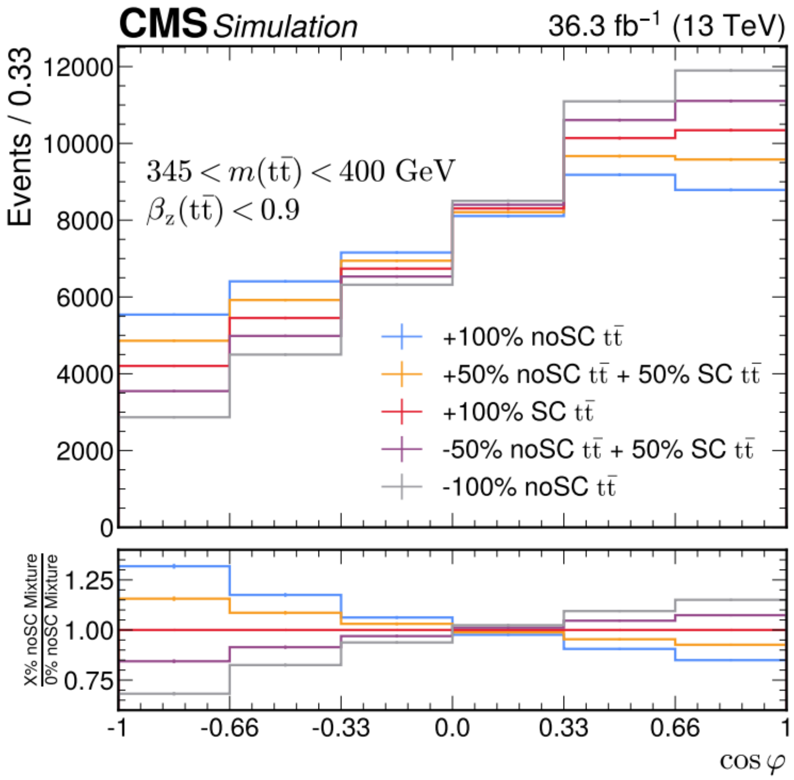
Templates are derived using the POWHEGV2 SM predictions implementing spin correlations for the t-bar(t) component of the combined signal model including the assumed η_t contribution.

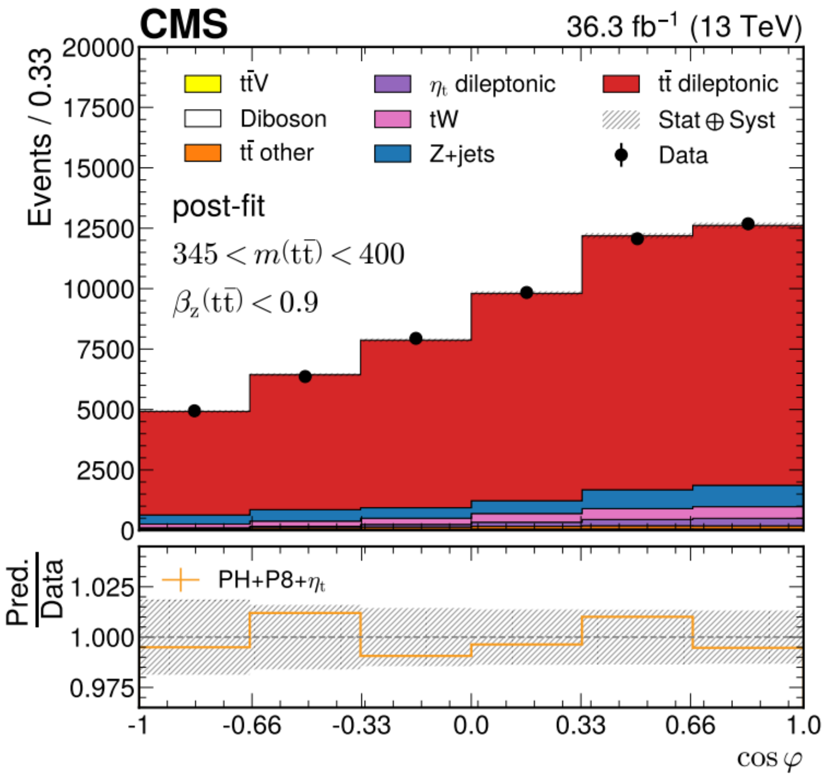
We expect that mixtures of such a sample and a sample with purposely broken spin correlations can effectively model a continuous (linear) variation of the degree of entanglement between the top quarks by means of the entanglement proxy *D*.

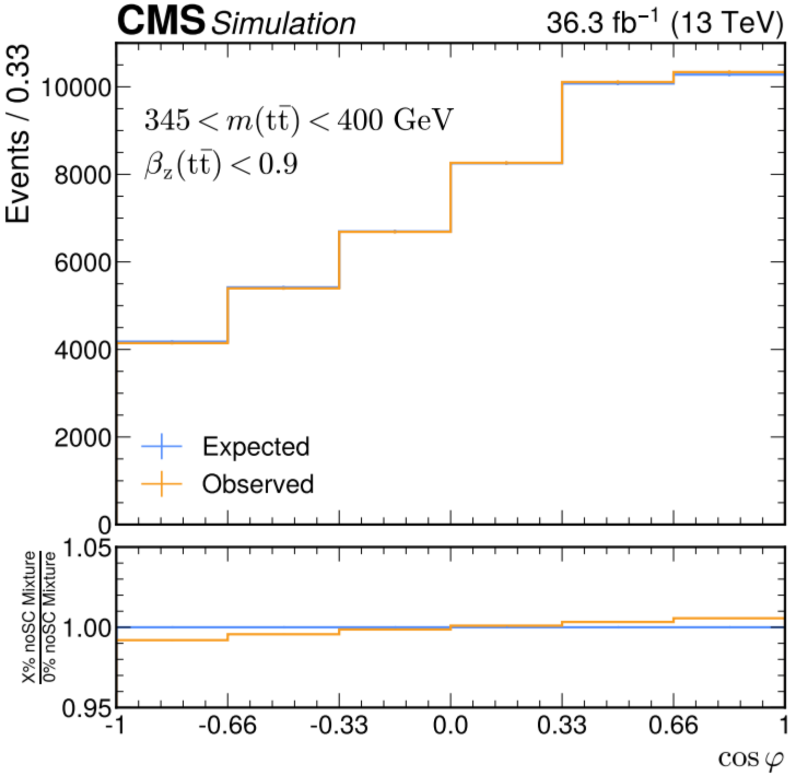
In order to have templates implementing an alternative value of the entanglement proxy *D*, we employ the noSC POWHEGV2 sample (including the assumed η_t noSC contribution).

Results

The CMS collaboration,
“**Observation of quantum entanglement in top quark pair production in proton–proton collisions at sqrt(s) = 13 TeV**”,







The result of the binned profile likelihood fit of the cosϕ distribution is shown (middle), and the data is well modeled by the combined signal model of t-bar(t) + η_t (labeled PH+P8+ η_t).

On the right the expected and observed template of noSC and SC mixture is presented One observe a best fit mixture of the post-fit templates resulting in a t bar(t) contribution consistent with a 2.53% more spin correlated t-bar(t) contribution when compared to the SM.

(The η_t contribution is consistent with 100% SC contribution, which is the expectation by the SM for the η_t contribution.)

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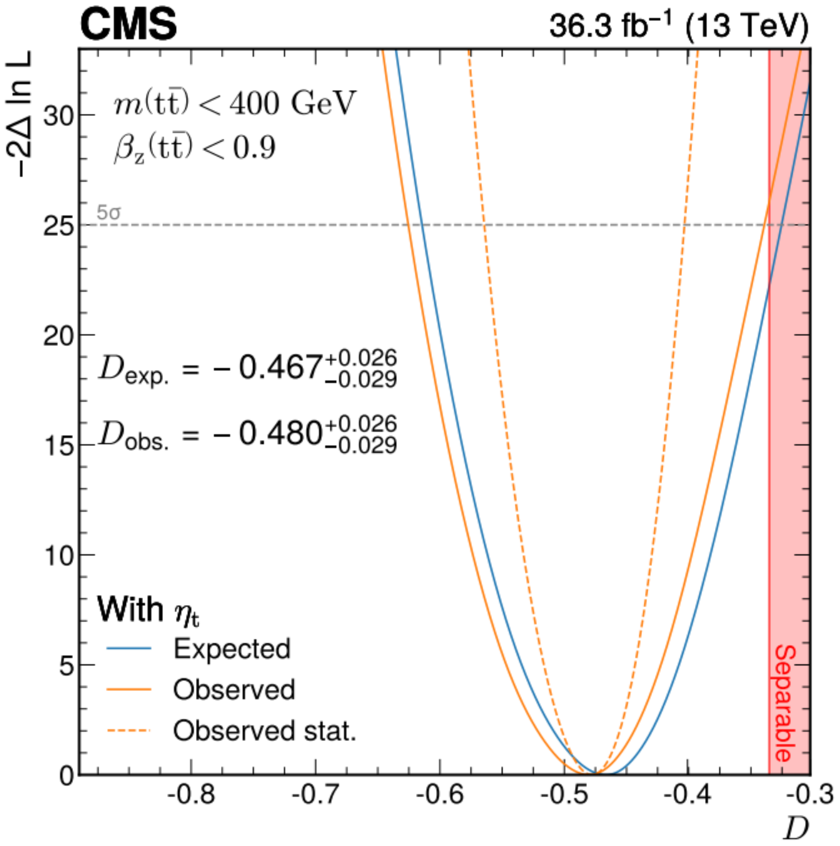
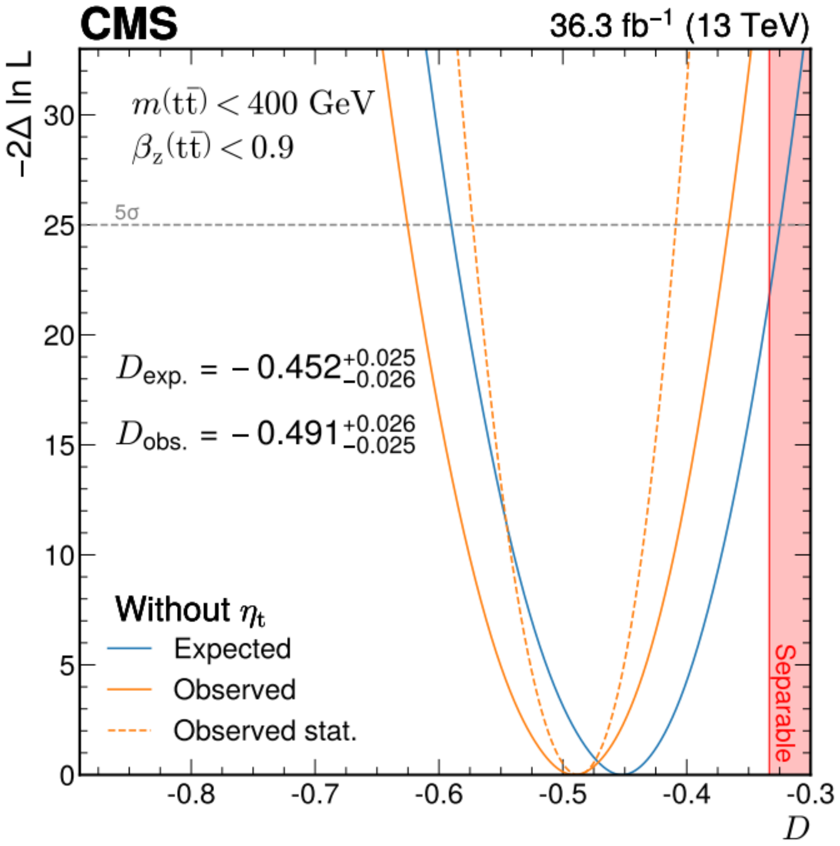
"**Observation of quantum entanglement in top quark pair production in proton–proton collisions at sqrt(s) = 13 TeV**",
361-6633/ad7e4d





For the phase space of *m*(tt) < 400GeV and β_z(tt)<0.9 at the parton level, an observed value of $D = -0.480^{+0.016}_{-0.017}(\mathrm{stat})^{+0.020}_{-0.023}(\mathrm{syst})$ is obtained, with an expected value of $D = -0.467^{+0.016}_{-0.017}(\mathrm{stat})^{+0.021}_{-0.024}(\mathrm{syst})$.

With the boundary for entanglement at −1/3, this result corresponds to top quarks being entangled in this phase space with an observed (expected) significance of 5.1 (4.7) *σ*.

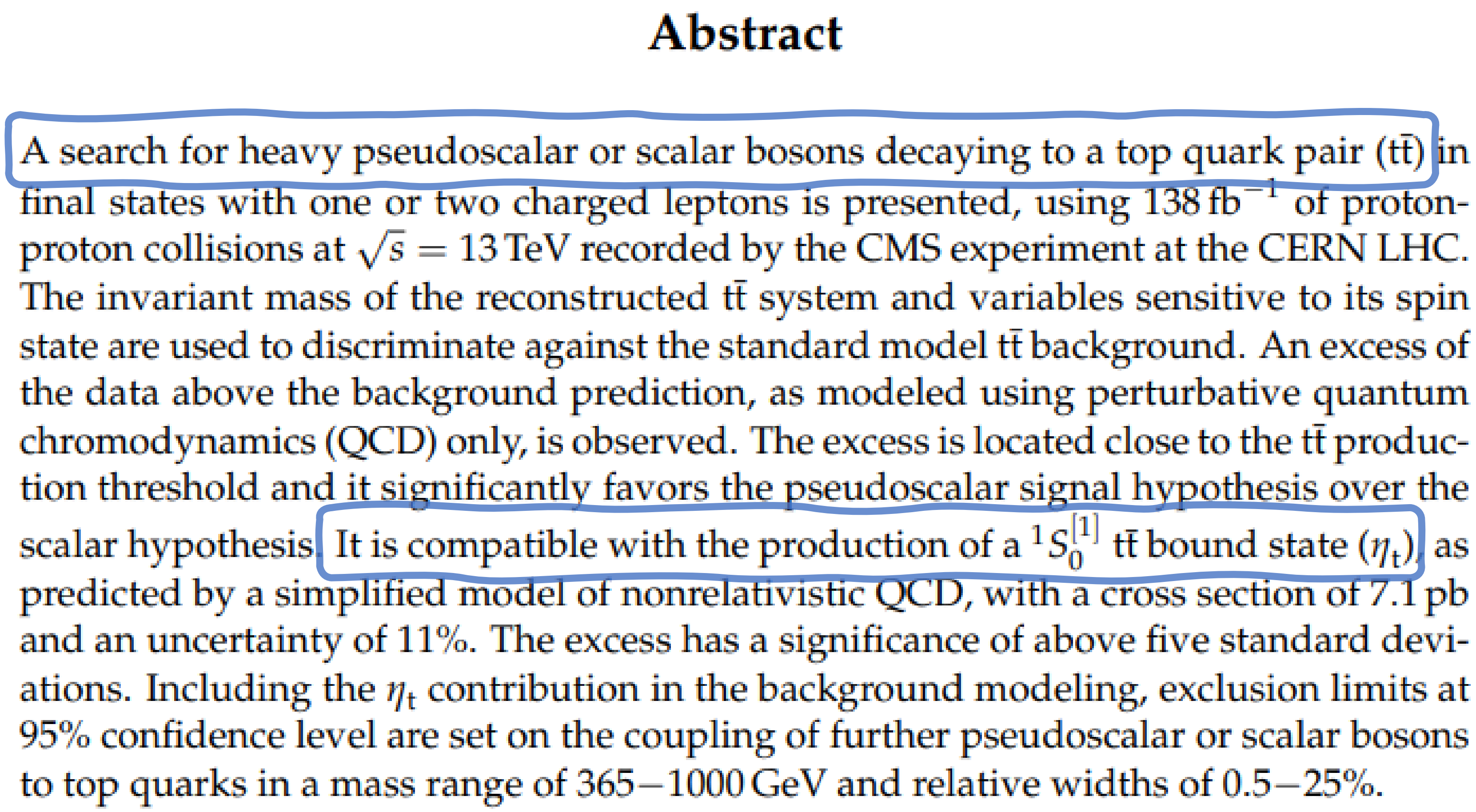
Removing the η_t contribution from the signal model and only considering the t-bar(t) component as signal and re-measuring *D* in the same phase space as before yields an observed (expected) value as given in the (right) plot (at the parton level).

With an observed (expected) significance of 6.3 (4.7) *σ*.

Data are described better when the expected η_t contribution is included in the signal model.

The CMS collaboration,
“**Search for heavy pseudoscalar and scalar bosons decaying to top quark pairs in proton-proton collisions at** √s=s= **13 TeV**”,
CMS-PAS-HIG-22-013

See Monday talk by Michał Szleper.



Abstract

A search for heavy pseudoscalar or scalar bosons decaying to a top quark pair ($\mathrm{t\bar{t}}$) in final states with one or two charged leptons is presented, using 138 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ recorded by the CMS experiment at the CERN LHC. The invariant mass of the reconstructed $\mathrm{t\bar{t}}$ system and variables sensitive to its spin state are used to discriminate against the standard model $\mathrm{t\bar{t}}$ background. An excess of the data above the background prediction, as modeled using perturbative quantum chromodynamics (QCD) only, is observed. The excess is located close to the $\mathrm{t\bar{t}}$ production threshold and it significantly favors the pseudoscalar signal hypothesis over the scalar hypothesis. It is compatible with the production of a ${}^1S_0^{[1]}$ $\mathrm{t\bar{t}}$ bound state (η_t), as predicted by a simplified model of nonrelativistic QCD, with a cross section of 7.1 pb and an uncertainty of 11%. The excess has a significance of above five standard deviations. Including the η_t contribution in the background modeling, exclusion limits at 95% confidence level are set on the coupling of further pseudoscalar or scalar bosons to top quarks in a mass range of 365–1000 GeV and relative widths of 0.5–25%.

Measurements of the polarization and spin correlation in top quark pairs are presented using events with a single electron or muon and jets in the final state.

The measurements are based on proton-proton collision data from the LHC at $\sqrt{s} = 13$ TeV collected by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1}.

All coefficients of the polarization vectors and the spin correlation matrix are extracted simultaneously by performing a binned likelihood fit to the data.

The measurement is performed inclusively and in bins of additional observables, such as the mass of the t-bar(t) system and the top quark scattering angle in the t-bar(t) rest frame.

The CMS collaboration, "**Measurements of polarization and spin correlation and observation of entanglement in top quark pairs using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV**", Phys. Rev. D **110**(2024)112016, https://doi.org/10.1103/PhysRevD.110.112016

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Measurement of t-bar(t) polarization and spin correlation is performed in the helicity basis {n,r,k}

(where k is the helicity axis, n is perpendicular to scaterring plane and r is mutualy perpendicular to both k and n)

After boosting top quark and antiquark individually into their rest frames together with their corresponding decay products, the unit vector:

$$\mathbf{\Omega}(\bar{\mathbf{\Omega}}) = \left(\sin(\theta_{p(\bar{p})})\cos(\phi_{p(\bar{p})}), \sin(\theta_{p(\bar{p})})\sin(\phi_{p(\bar{p})}), \cos(\theta_{p(\bar{p})})\right)$$

describes the direction of a decay product of top (anti)quark,

(where phi are azimutal and theta polar angles).

Than the differential cross section has the form:

$$\boxed{\Sigma_{\mathrm{tot}}\left(\phi_{p(\bar{p})}, \theta_{p(\bar{p})}\right) = \frac{\mathrm{d}^4\sigma}{\mathrm{d}\phi_p \mathrm{d}\cos(\theta_p)\mathrm{d}\phi_{(\bar{p})}\mathrm{d}\cos(\theta_{(\bar{p})})} = \sigma_{\mathrm{norm}}\left(1 + \kappa\mathbf{P}\cdot\mathbf{\Omega} + \bar{\kappa}\bar{\mathbf{P}}\cdot\bar{\mathbf{\Omega}} + \kappa\bar{\kappa}\mathbf{\Omega}\cdot\left(C\bar{\mathbf{\Omega}}\right)\right)}$$

Measurements of the polarization and spin correlation in top quark pairs are presented using events with a single electron or muon and jets in the final state.

The measurements are based on proton-proton collision data from the LHC at √*s* =13 TeV collected by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1}.

All coefficients of the polarization vectors and the spin correlation matrix are extracted simultaneously by performing a binned likelihood fit to the data.

The measurement is performed inclusively and in bins of additional observables, such as the mass of the t-bar(t) system and the top quark scattering angle in the t-bar(t) rest frame.

The CMS collaboration, “**Measurements of polarization and spin correlation and observation of entanglement in top quark pairs using lepton+jets events from proton-proton collisions at √*s* =13 TeV**”, Phys. Rev. D **110**(2024)112016, https://doi.org/10.1103/PhysRevD.110.112016

Measurement of t-bar(t) polarization and spin correlation is performed in the helicity basis {n,r,k}

(where k is the helicity axis, n is perpendicular to scaterring plane and r is mutualy perpendicular to both k and n)

After boosting top quark and antiquark individually into their rest frames together with their corresponding decay products, the unit vector:

$$\mathbf{\Omega}(\bar{\mathbf{\Omega}}) = \left(\sin(\theta_{p(\bar{p})})\cos(\phi_{p(\bar{p})}), \sin(\theta_{p(\bar{p})})\sin(\phi_{p(\bar{p})}), \cos(\theta_{p(\bar{p})})\right)$$

describes the direction of a decay product of top (anti)quark,

(where phi are azimutal and theta polar angles).

Than the differential cross section has the form:

$$\boxed{\Sigma_{\mathrm{tot}}\left(\phi_{p(\bar{p})},\theta_{p(\bar{p})}\right) = \frac{\mathrm{d}^4\sigma}{\mathrm{d}\phi_p\mathrm{d}\cos(\theta_p)\mathrm{d}\phi_{(\bar{p})}\mathrm{d}\cos(\theta_{(\bar{p})})} = \sigma_{\mathrm{norm}}\left(1+\kappa\mathbf{P}\cdot\mathbf{\Omega}+\bar{\kappa}\bar{\mathbf{P}}\cdot\bar{\mathbf{\Omega}}+\kappa\bar{\kappa}\mathbf{\Omega}\cdot(C\bar{\mathbf{\Omega}})\right)}$$

It could be written as linear combination of functions Σ_m which depend on angles phi and theta

(and absorbs spin analyzing power kappa and normalization)

with 3+3+3x3=15 (polarizations and spin correlation matrix elements) coeficients:

$$\boxed{\Sigma_{\mathrm{tot}} = \Sigma_0 + \sum_{m=1}^{15} \mathcal{Q}_m\Sigma_m}$$

$$\mathcal{Q}_m = \left\{P_n, P_r, P_k, \bar{P}_n, \ldots, C_{nn}, C_{nr}, \ldots, C_{kk}\right\}$$

The CMS collaboration, "**Measurements of polarization and spin correlation and observation of entanglement in top quark pairs using lepton+jets events from proton-proton collisions at √*s* =13 TeV**", Phys. Rev. D **110**(2024)112016, https://doi.org/10.1103/PhysRevD.110.112016

On one hand one can extract $\mathcal{Q}_m^{\mathrm{MC}}$ from the fit to the above formula to the simulated data.

For the measurement of $\mathcal{Q}_m$, however, one need templates T_m .
To obtain them a weight $\Sigma_m/\Sigma_{\mathrm{tot}}^{\mathrm{MC}}$
is assignet to each simulated event.

This procedure is done in four bins of t-bar(t) mass,
and three of |*cos(ϑ)*|,
Whereas $\left(\phi_{p(\bar{p})}, \theta_{p(\bar{p})}\right)$ are divided into 4x4x2x2=64 bins.

It could be written as linear combination of functions Σ_m
which depend on angles phi and theta
(and absorbs spin analyzing power kappa and normalization)
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After standard selection of lepton+jets candidades
t-bar(t) system is reconstructed using artificial NN.
Selected score $0.1<S_{NN}<1$ is used
to obtain S_{high} and S_{low} categories
divided furter into 2b (both b jest b-tagged) and 1b (exactly one).

2016-2018 data are divided into four periods.

It could be written as linear combination of functions Σ_m
which depend on angles phi and theta
(and absorbs spin analyzing power kappa and normalization)
with 3+3+3x3=15 (polarizations and spin correlation matrix elements)
coeficients:

$$\Sigma_{\mathrm{tot}} = \Sigma_0 + \sum_{m=1}^{15} \mathcal{Q}_m \Sigma_m$$

$$\mathcal{Q}_m = \{P_n, P_r, P_k, \bar{P}_n, \ldots, C_{nn}, C_{nr}, \ldots, C_{kk}\}$$

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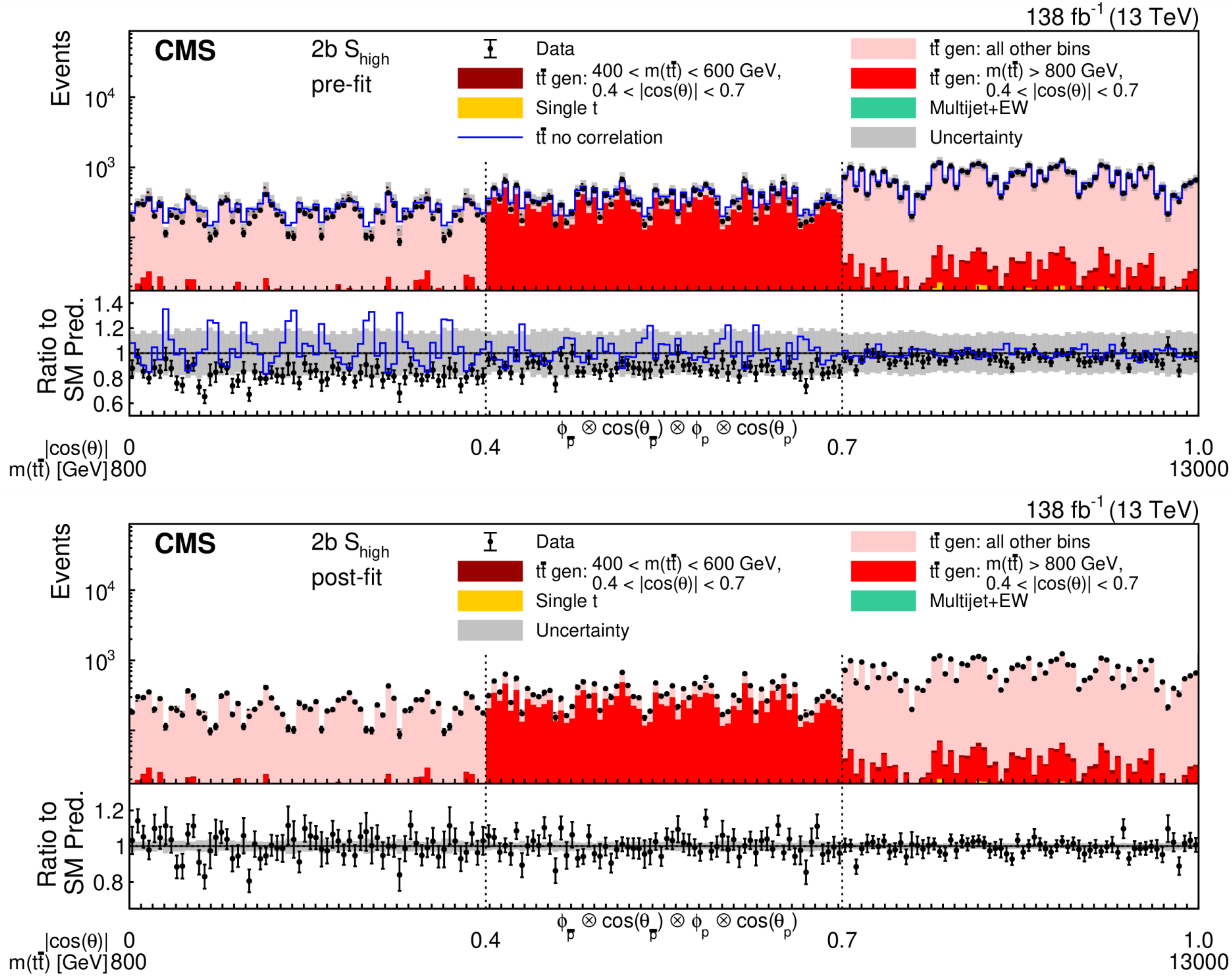
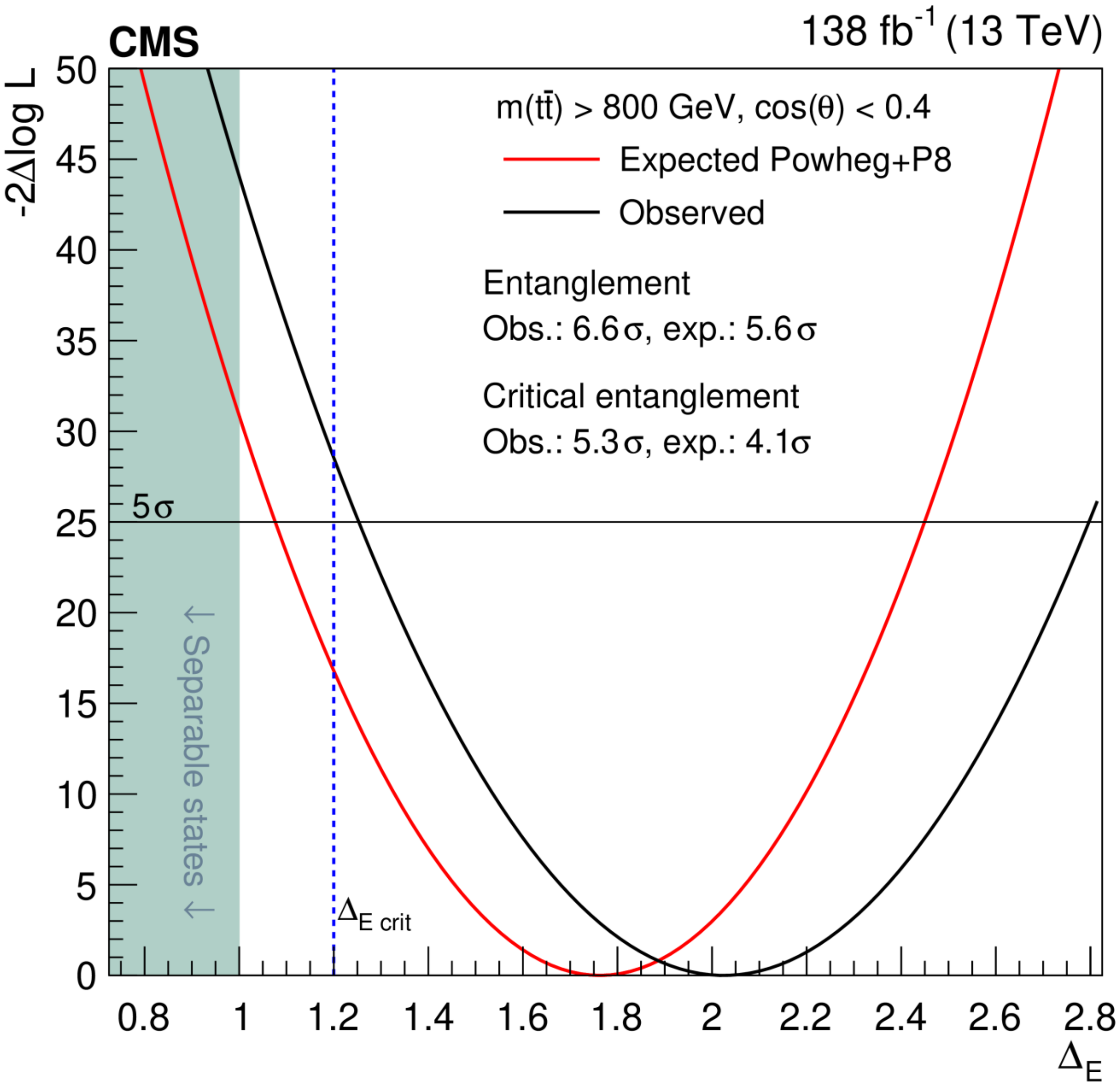


Pre- (upper figure) and post-fit (lower) distributions for m(t-bar(t))>800 GeV (and 2b S_{high}).



The CMS collaboration, “**Measurements of polarization and spin correlation and observation of entanglement in top quark pairs using lepton+jets events from proton-proton collisions at $\sqrt{s}$ =13 TeV**”, Phys. Rev. D **110**(2024)112016, https://doi.org/10.1103/PhysRevD.110.112016

The polarization and spin correlation in top quark pair production are measured in events with an electron or a muon plus jets in the final state.

The entanglement between the spins of the top quark and antiquark is determined from the measured spin correlation by applying the Peres-Horodecki criterion.

The measurements are based on proton-proton collision data at $\sqrt{s}$ =13 TeV collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}. The decay products of the top quarks are identified using an artificial neural network.

The coefficients of the polarization vectors and the spin correlation matrix are extracted simultaneously from the angular distributions of top-bar(top) decay products using a binned likelihood fit.

This is done both inclusively and in various regions of the phase space. The observed polarization and spin correlation are in agreement with the standard model expectations. The standard model predicts entangled t-bar(t) states at the production threshold and at high masses of the t-bar(t) system.

Entanglement is observed in events with high $\bar{t}t$ mass, with an observed (expected) significance of 6.7 (5.6) standard deviations, while in events with low transverse momentum of the top quark a significance of 3.5 (4.4) standard deviations is observed (expected).

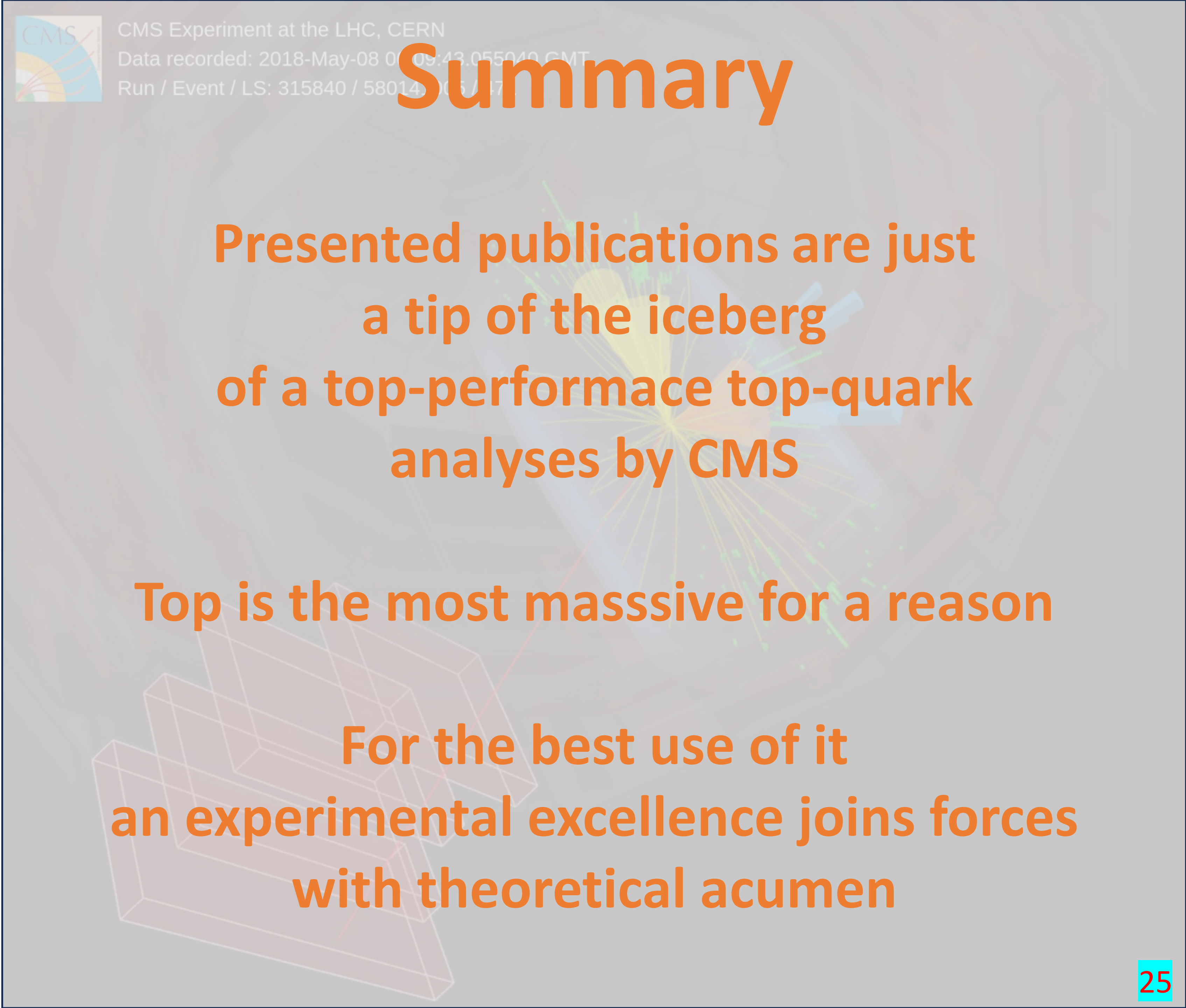
This is the first observation of entanglement at high t-bar(t) mass where in about 90% of the observed t-bar(t) events the decays of the top quark and antiquark are spacelike separated.

Top-quark physics highlights from CMS

Piotr Zalewski, Warsaw
National Centre for Nuclear Research (NCBJ)

on behalf of the CMS Colaboration
Epiphany 2025

Summary



Presented publications are just
a tip of the iceberg
of a top-performace top-quark
analyses by CMS

Top is the most masssive for a reason

For the best use of it
an experimental excellence joins forces
with theoretical acumen