Search for central exclusive production of top quark pairs with the CMS and TOTEM experiments.

[CMS-PAS-TOP-21-007, TOTEM-NOTE-2022-002]

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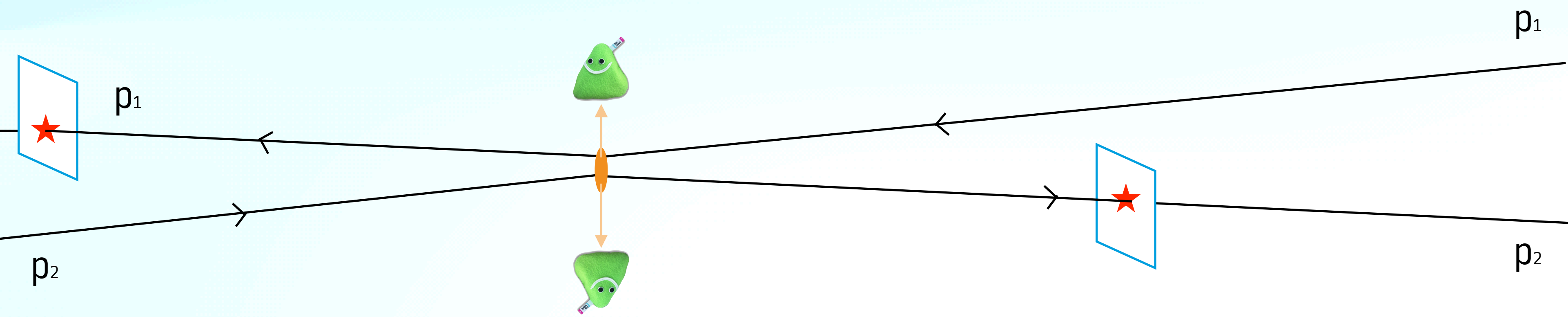
on behalf of the CMS and TOTEM collaborations

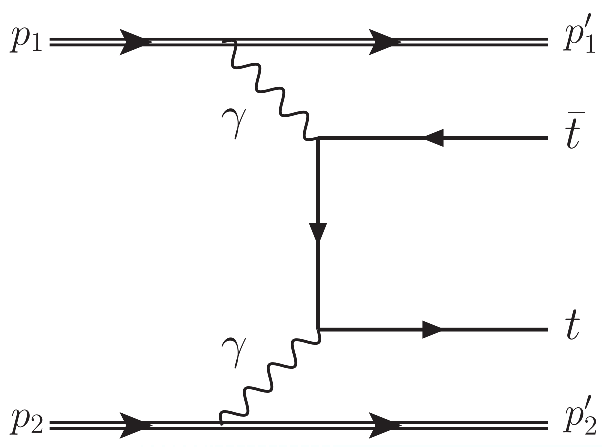


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

TOP2022
Durham, UK
8th September 2022

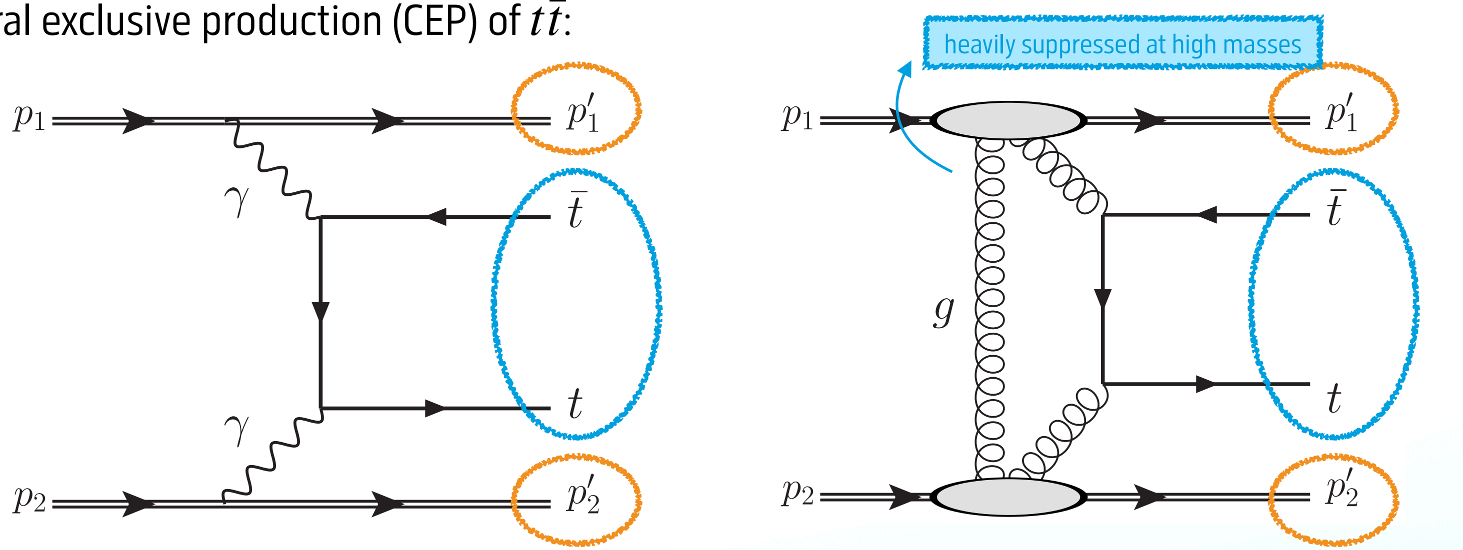
Outline of this talk.

1. Goals and motivation
2. Proton tagging with PPS
3. Modelling the proton background
4. Analysis strategy
    - Object and event selection
    - Kinematic fitter / top reconstruction
    - BDT classifiers
5. Statistical analysis
    - Systematic uncertainties
    - Extract upper limits
6. Summary and future prospects



Goals and motivation.

- Central exclusive production (CEP) of $t\bar{t}$:



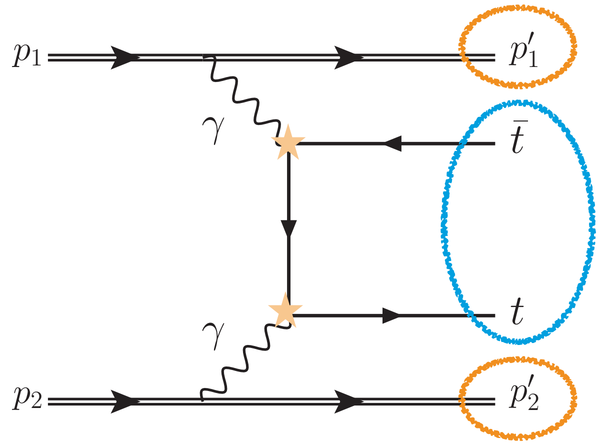
- In CEP processes, the incoming protons do not dissociate during the interaction but lose energy by exchanging high energy photons / gluons

- The energy lost in the interaction is used to create a system of particles X (a $t\bar{t}$ pair in this case);

- As a result of the interaction, protons are slightly deflected from their original path.

- Predicted to occur at LHC with very low cross-section (**SM expected ~0.3 fb**)

Goals and motivation.



Why look for it?

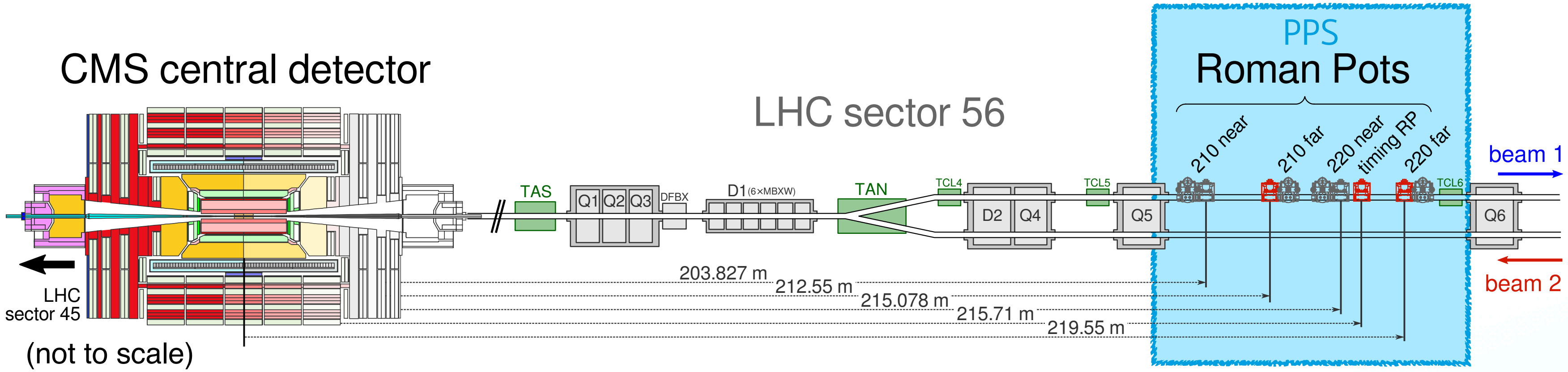
- Sensitive to electroweak top-photon coupling
  - may offer complementary information to processes like $t\bar{t}\gamma$
- Can be used to look for new physics in EFT or anomalous couplings frameworks
- Full reconstruction of $t\bar{t}$ possible due to outgoing intact protons
- First-ever search for this process and first analysis with top quarks using PPS

This analysis:

Used data collected by CMS and PPS in 2017 to set first-ever upper limit. [CMS-PAS-TOP-21-007, TOTEM-NOTE-2022-002]

Tagging intact protons with PPS.

- The Precision Proton Spectrometer (PPS) can tag outgoing intact protons



- PPS measures protons that leave collision intact, at ~200 m from interaction point, on both sides of CMS

- In 2017, it was equipped with silicon strip and pixel tracker sensors

- Tags protons and measures fraction of momentum lost (ξ)

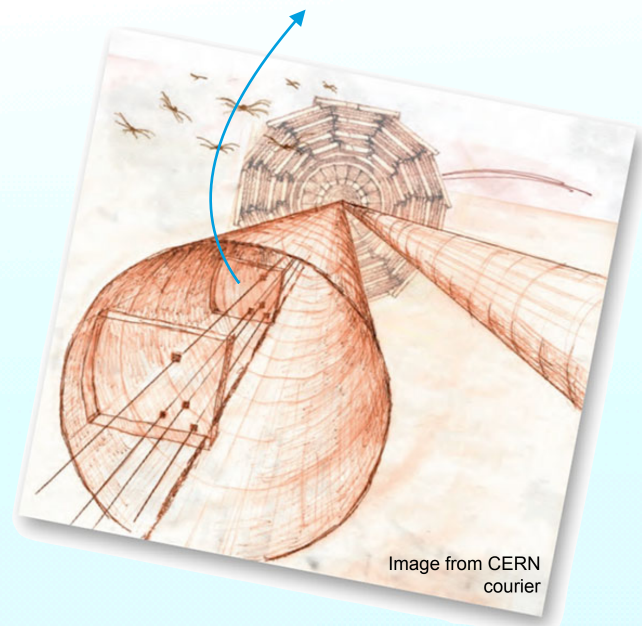


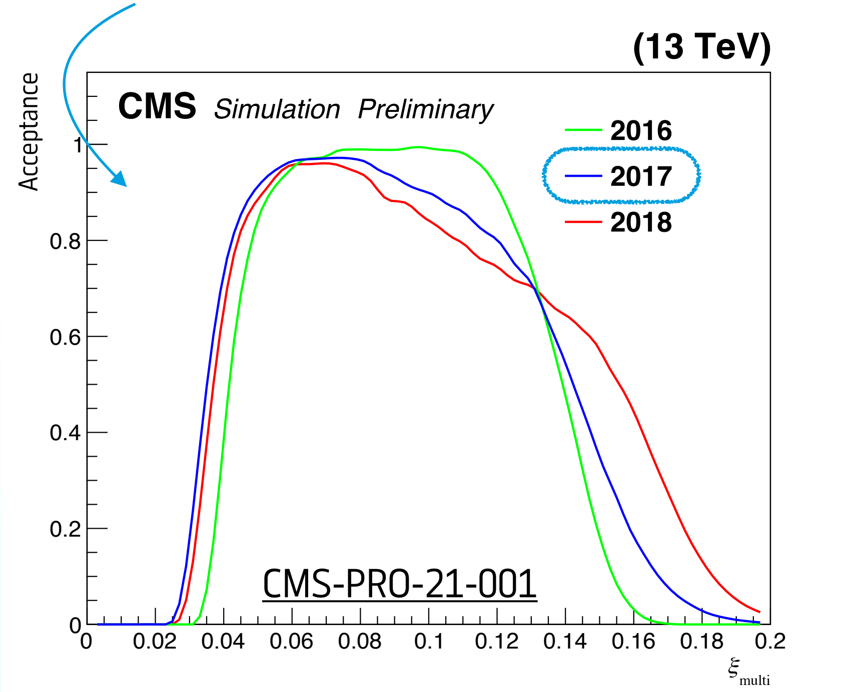
Image from CERN courier

Tagging intact protons with PPS.

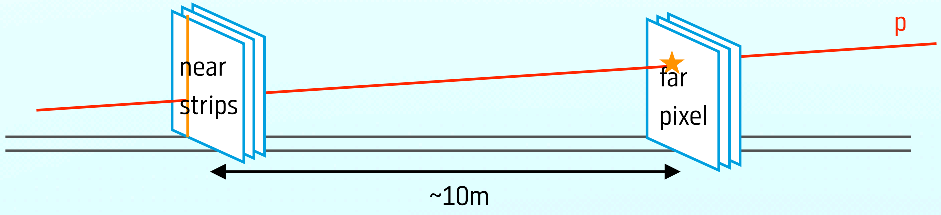
- Fractional momentum loss ξ is obtained from track x,y position in Roman Pots by propagating track back through LHC optics

momentum loss of each proton: $$\xi_i = \frac{|\vec{p_i}| - |\vec{p_f}|}{|\vec{p_i}|}$$

- PPS in 2017 has acceptance for protons that lost about ~2-20% of their momentum



- Reconstruction technique used is called **multi RP**
  - Protons are reconstructed from a fit to simultaneous tracks in the near (strips) and far (pixel) stations



  - Loss in efficiency but better measurement of ξ

Tagging intact protons with PPS.

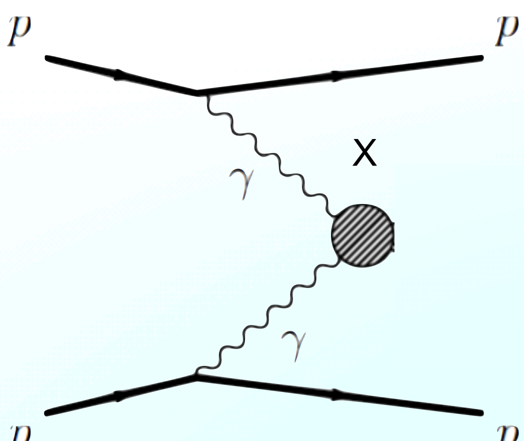
- Values of ξ relate to CMS event kinematics by the approximate formulas:

mass of the central system:

$$M_X = \sqrt{s\xi_1\xi_2}$$

rapidity of the central system:

$$Y_X = \frac{1}{2}\log(\xi_1/\xi_2)$$



- ξ of 2-20% at 13 TeV results in an acceptance starting at $M_X \approx 300$ GeV

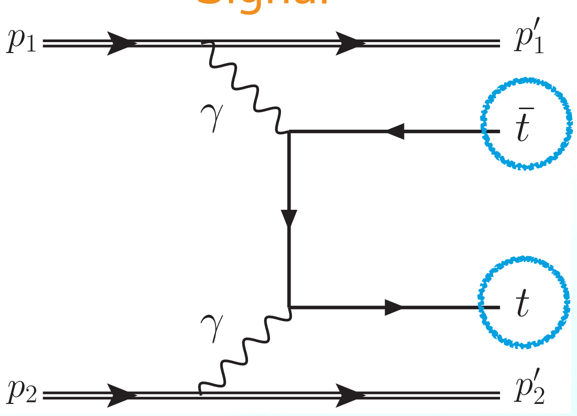
allows to look for $t\bar{t}$ in the low-ξ region

Modelling the proton background.

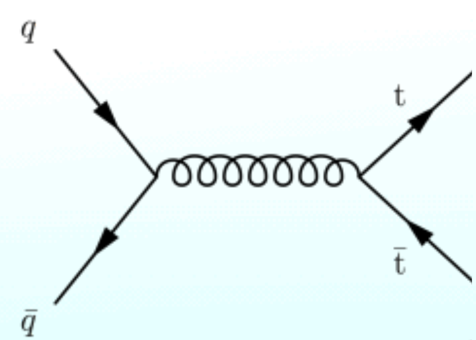
- In an ideal world, we would expect =2 intact protons for signal and =0 for QCD $t\bar{t}$ background
- However, this does not reflect reality: there is typically **>1 simultaneous interaction (pileup)**
  - background events may have >0 protons in final state (from pileup)
  - signal events may have >2 protons in final state

not possible to reconstruct (PPS setup in 2017 does not allow reconstruction of >1 proton per arm)

Signal



Main background



+ 2 protons from pileup

- In the simulated background samples ($t\bar{t}$, Z+jets, etc.), there is no information on pileup protons

need a data-driven estimation

Modelling the proton background.

Data-driven estimation:

- Extract large sample of events with =2 protons from data (with relaxed event selection - no cut on N_{b-jet})

- Mix proton information from these events with the MC samples
  - **Background samples:** mix event with a 2-proton data event and set proper event weight
  - **Signal samples:** each signal proton in acceptance is randomly accepted or rejected based on the reconstruction efficiency; then, depending on how many survive, extra proton(s) are added and event weight set accordingly

Analysis strategy.

Object selection:

Leptons:

$p_T > 30/20$ GeV
$|\eta| < 2.1$ (electrons)
$|\eta| < 2.4$ (muons)

further offline quality requirements

Jets:

$p_T > 25$ GeV, $|\eta| < 2.4$
$\Delta R(j, l) > 0.4$

b tagging with NN ("DeepJet") algorithm

Protons:

- Reconstructed tracks in 2 roman pots per side (**multi RP** method used)
- calibration performed for different data-taking conditions (e.g. LHC crossing angle) separately

Event selection:

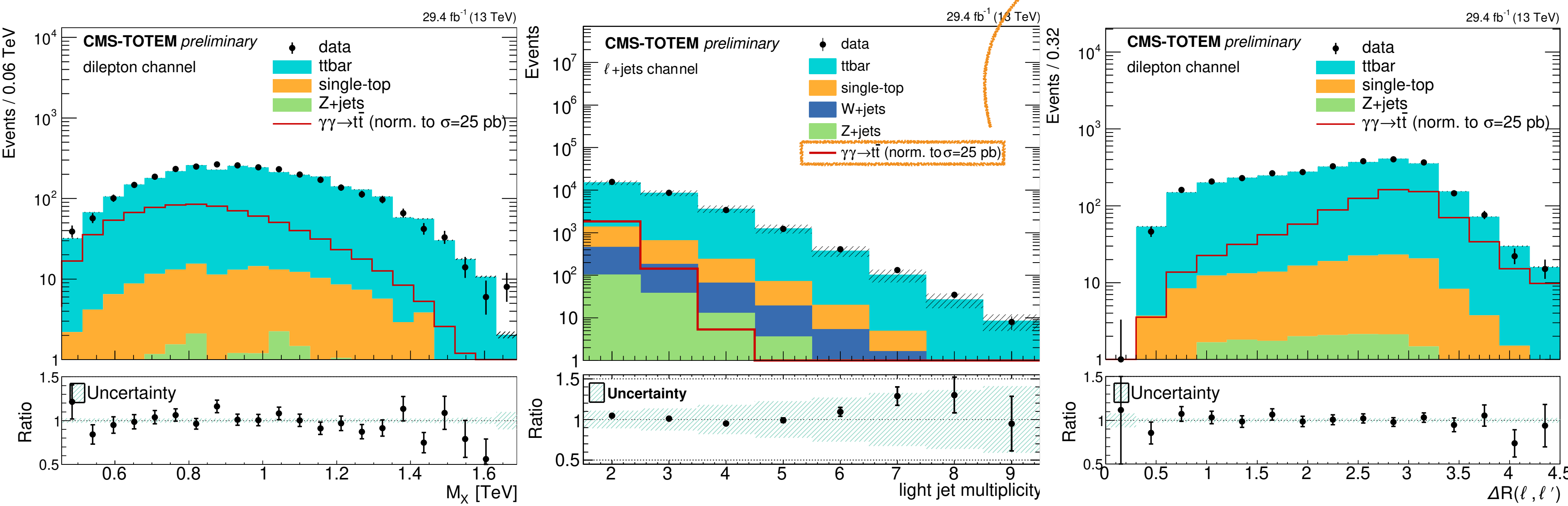
- Lepton+jets channel:
  - =1 lepton
  - ≥2 b-jets, ≥2 light jets
  - =1 proton on each side of PPS

- Dilepton channel:
  - ≥2 lepton
  - ≥2 b-jets
  - =1 proton on each side of PPS

Analysis strategy.

Some kinematic distributions:

cross section scaled to 25 pb
(10^4 x SM) to be visible



invariant mass of X from proton tracks (dilepton channel)

number of light jets (lepton+jets channel)

angular distance between leptons (dilepton channel)

The $t\bar{t}$ reconstruction.

Lepton+jets channel:

- Reconstruct the $t\bar{t}$ kinematics from final state particles
- Due to presence of MET and high jet multiplicity, reconstruction has low resolution

- To improve reconstruction, a kinematic fitter was developed:
  - input: 3-momenta of all final state particles
  - 3-momenta allowed to float around original value to obey kinematic constraints
  - kinematic constraints:

momentum conservation

$$\sum \vec{p_T} = 0$$

invariant mass conservation

$$m_t = m_{bl\nu} \qquad m_t = m_{bq\bar{q}'}$$

$$m_W = m_{l\nu} \qquad m_W = m_{q\bar{q}'}$$

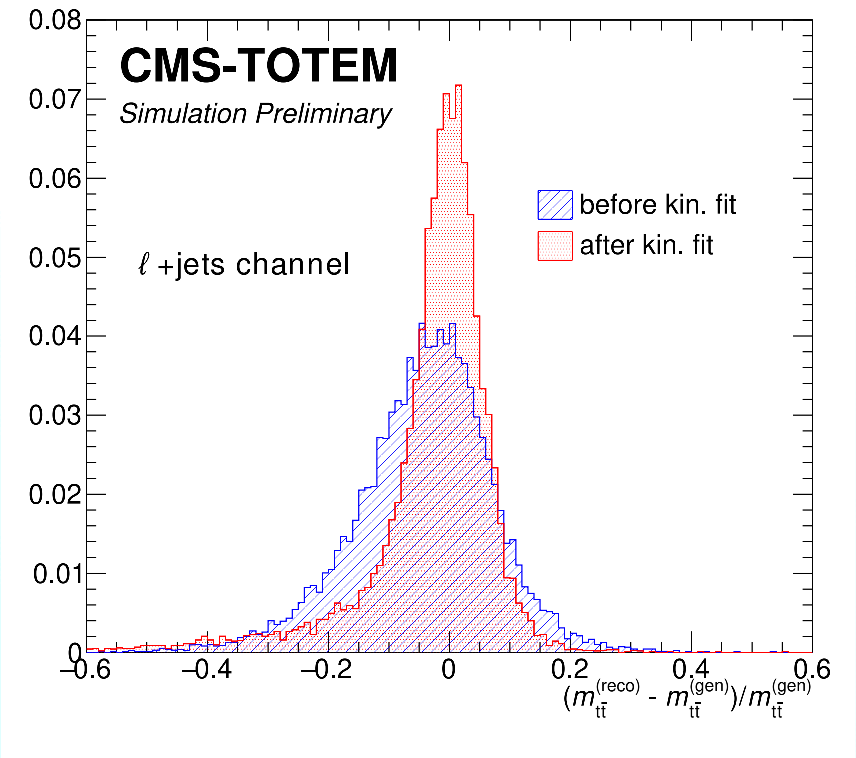
proton matching

$$m_X^2 = s\xi_1\xi_2$$

The $t\bar{t}$ reconstruction.

Lepton+jets channel:

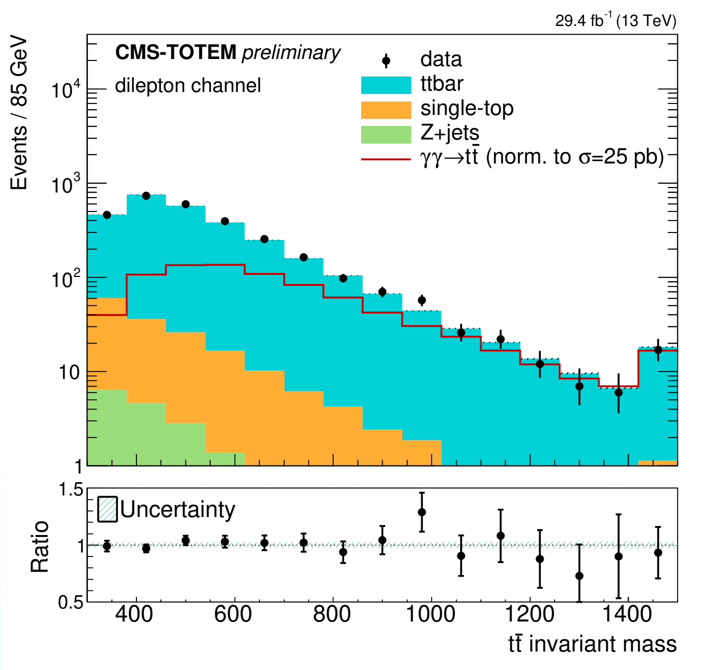
- Output of kinematic fitter:
  - χ^2 of fit (can be used as discriminating variable)
  - new (more reliable) values of particle momenta
  - improved $m_{t\bar{t}}$ resolution (factor ~2)

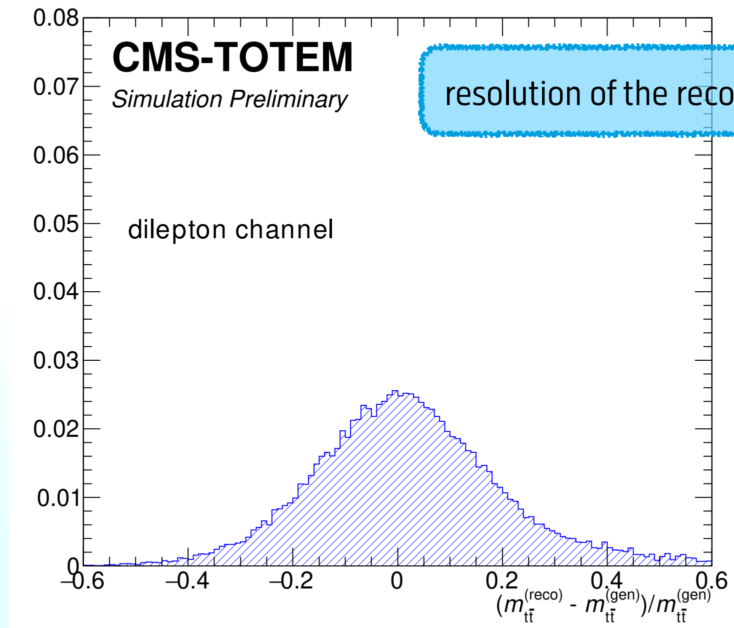


The $t\bar{t}$ reconstruction.

Dilepton channel:

- Kinematics of top quark and antiquark are fully reconstructed with the same method used in other CMS TOP analyses (e.g. the recent $t\bar{t}$ multidifferential measurement - link)





resolution of the reconstruction

- A solution is found for ~90% of the $t\bar{t}$ events (correct lepton/b-jet association in ~70% of the cases)
- For signal, the $t\bar{t}$ mass and rapidity are expected to correspond to those of the pp system

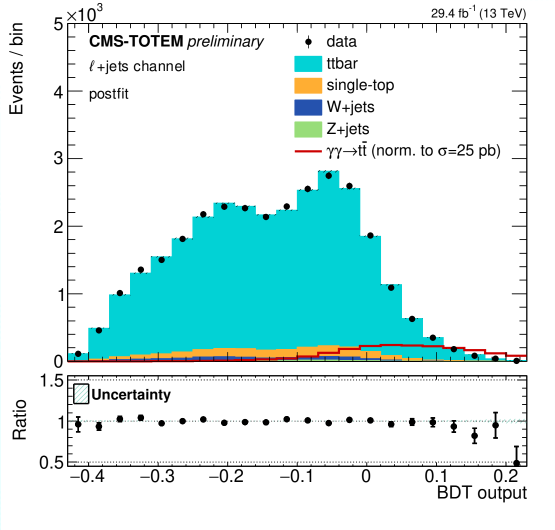
Discriminating signal from background - BDTs.

- For each channel, a Boosted Decision Tree (BDT) algorithm is trained to separate the signal from the non-exclusive backgrounds
- Other exclusive backgrounds were found to be negligible

Lepton+jets channel:

Input variables:

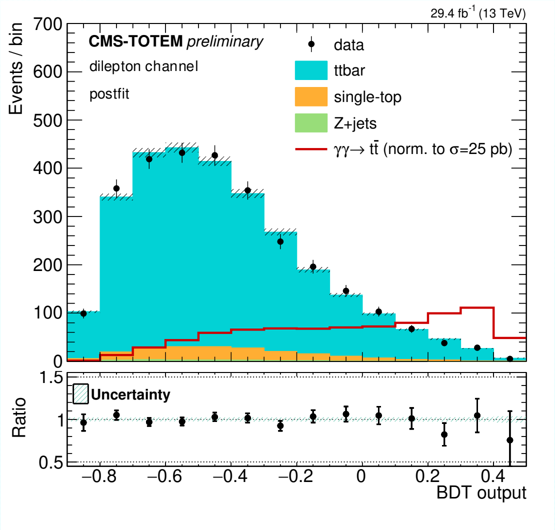
- lepton/jet kinematics
- χ^2 from $t\bar{t}$ kinematic fit
- proton reconstruction (m_X, y_X)



Dilepton channel:

Input variables:

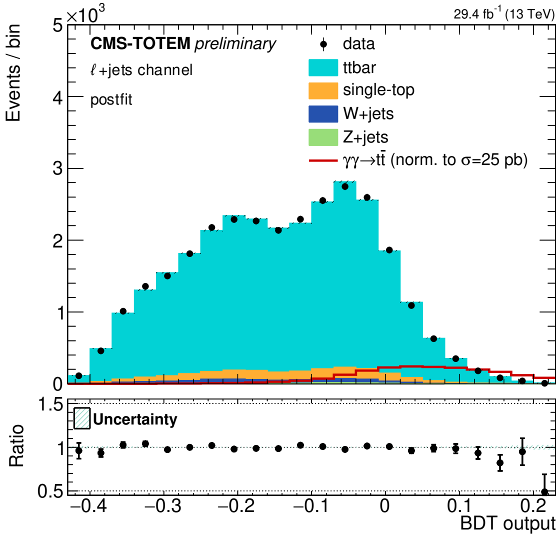
- lepton/jet kinematics
- $t\bar{t}$ reconstruction ($m_{t\bar{t}}, y_{t\bar{t}}$)
- proton reconstruction (m_X, y_X)

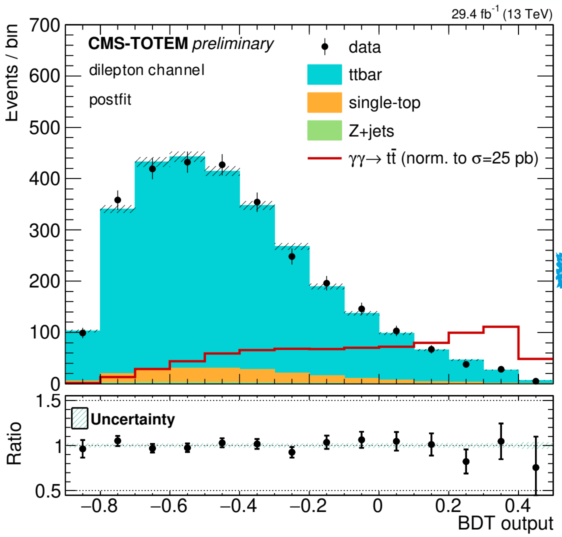


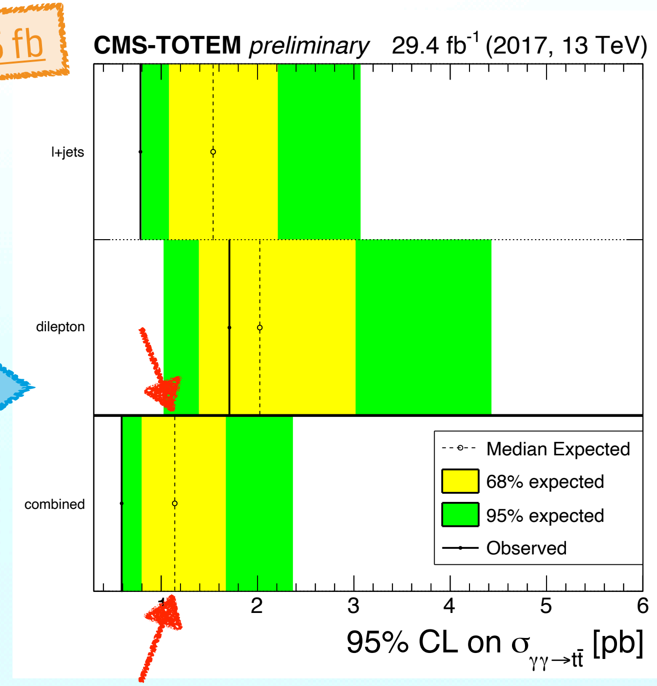
Statistical analysis.

- To extract the limit, we take into account:
  - statistical uncertainty (dominant)
  - theoretical uncertainties - from MC
  - experimental uncertainties, including those on proton background estimation - from MC/data
- We consider all uncertainties to be correlated between the two final state channels
- First ever upper limit on cross section of $\gamma\gamma \rightarrow t\bar{t}$:
  - **observed 0.59 pb (expected 1.14 pb)**

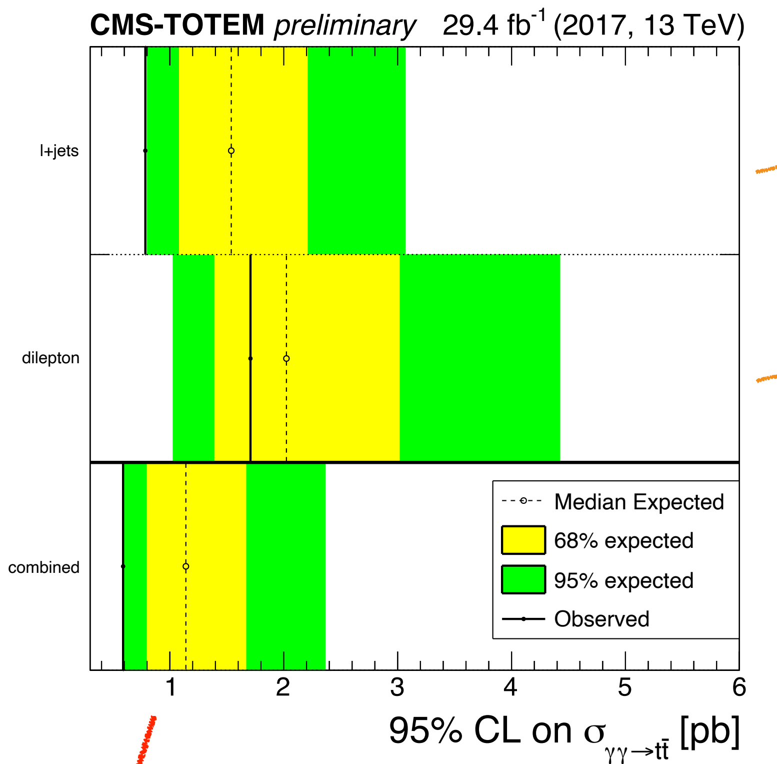
SM prediction is ~0.3 fb







Results.



observed 0.59 pb (expected 1.14 pb)

- The lepton+jets channel has more statistics but background separation is more challenging (high jet multiplicity)
  - some systematics become important (jet energy, FSR)
- The dilepton channel has limited statistics but high signal purity
  - Region with 0 light jets and back-to-back tops is very enriched in signal

Good complementarity between the channels

Concluding remarks.

- In central exclusive production, top quark pairs are produced via QED while the interacting protons remain intact

- It is an interesting way to look for new physics in the top-photon coupling

- It's the first time we look for processes with top quarks and intact protons

- We analysed CMS and PPS data from 2017

- Result is the first ever upper limit on the cross section of $\gamma\gamma \rightarrow t\bar{t}$:
  - **observed 0.59 pb (expected 1.14 pb)**

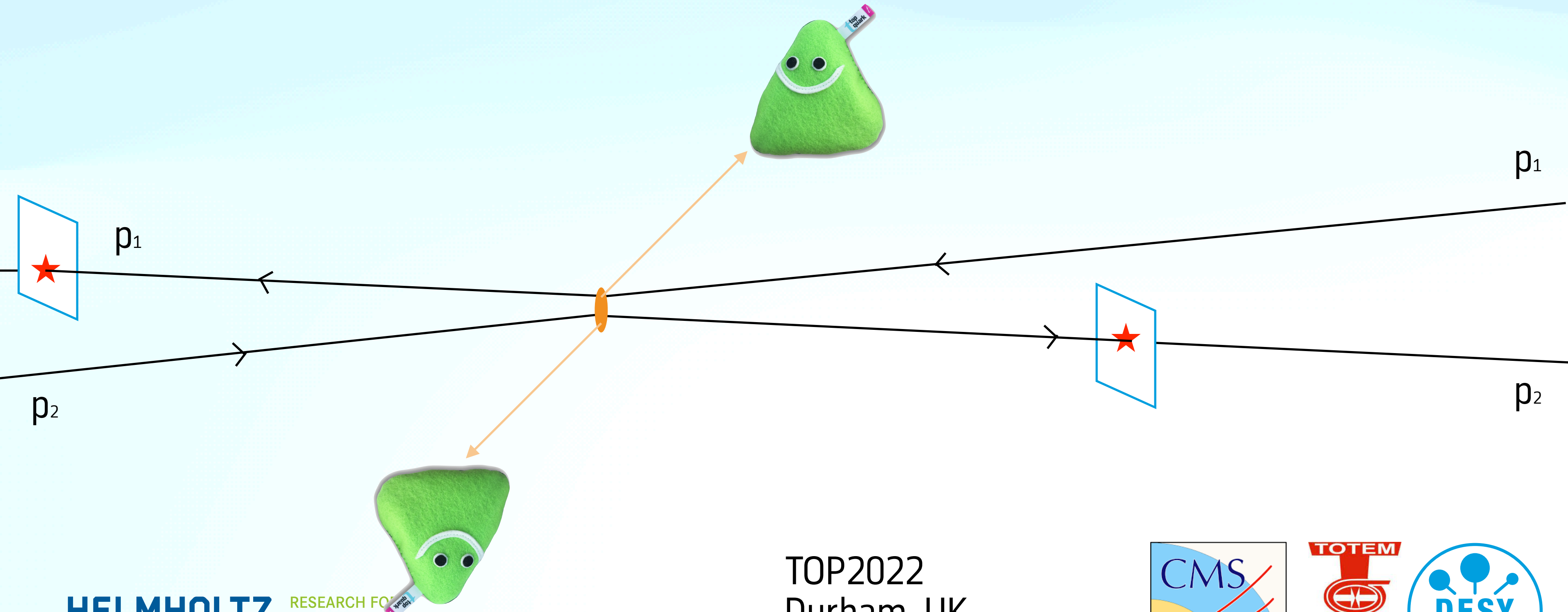
SM prediction is ~0.3 fb

- More statistics and an improved PPS setup bring exciting opportunities for the future!

Take home message:

We can use the LHC as a photon collider and explore top quark physics in a complementary way to the standard LHC program.

Thank you!



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