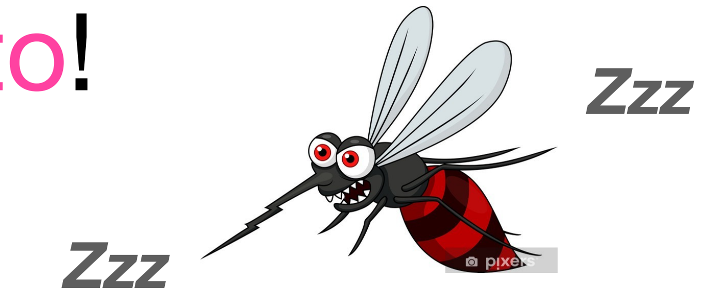
Study of central exclusive production processes within the CMS collaboration

Matteo Pisano – 06th/07th July 2022 – IDPASC/LIP workshop

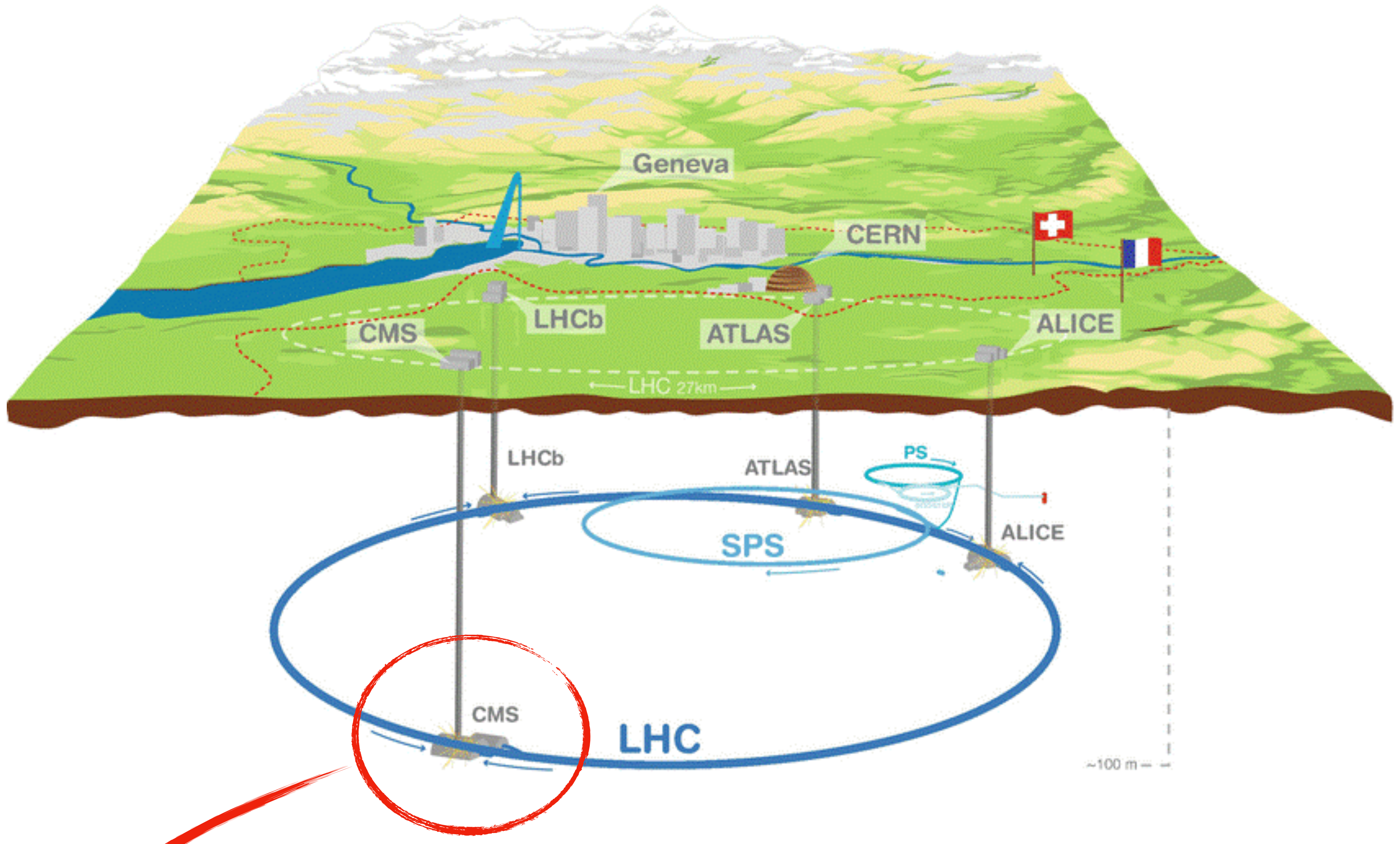
High energy physics at the LHC

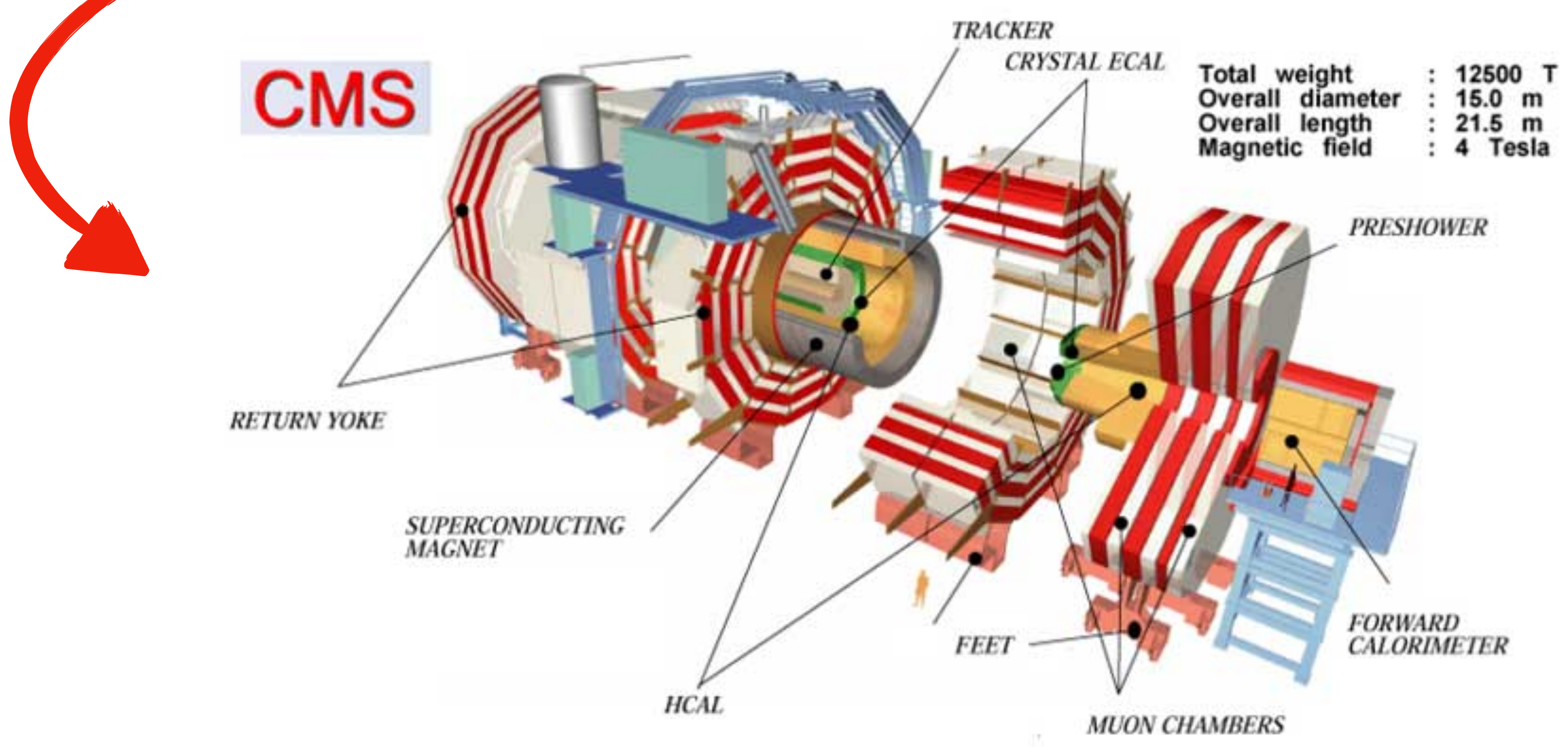
The Large Hadron Collider and the CMS collaboration

- The LHC (large hadron collider) is a particle accelerator located at Geneva (Switzerland).
- The LHC accelerates protons up to an energy of 6.5 TeV, which is approximately the kinetic energy of a flying mosquito!



- Subsequently, protons collide generating a huge set of particles in the final state.
- The collision happens in presence of multi-purpose particle detectors, which measure the kinematic quantities (energy, momentum, …) of the final state particles.
- The study of the particles generated by the collision allows us to study the nature of the interaction.

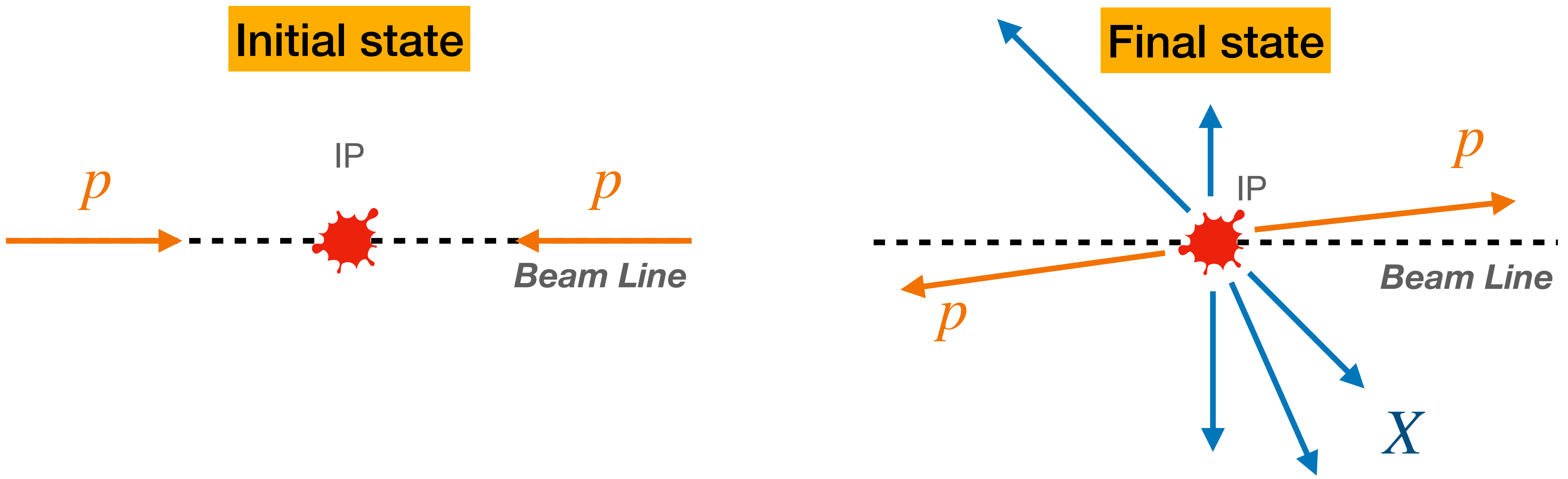




Central exclusive production processes

Not all the protons break up!

- In central exclusive production (CEP) processes, the incoming protons interact without dissociating:



$$pp \to p + X + p$$

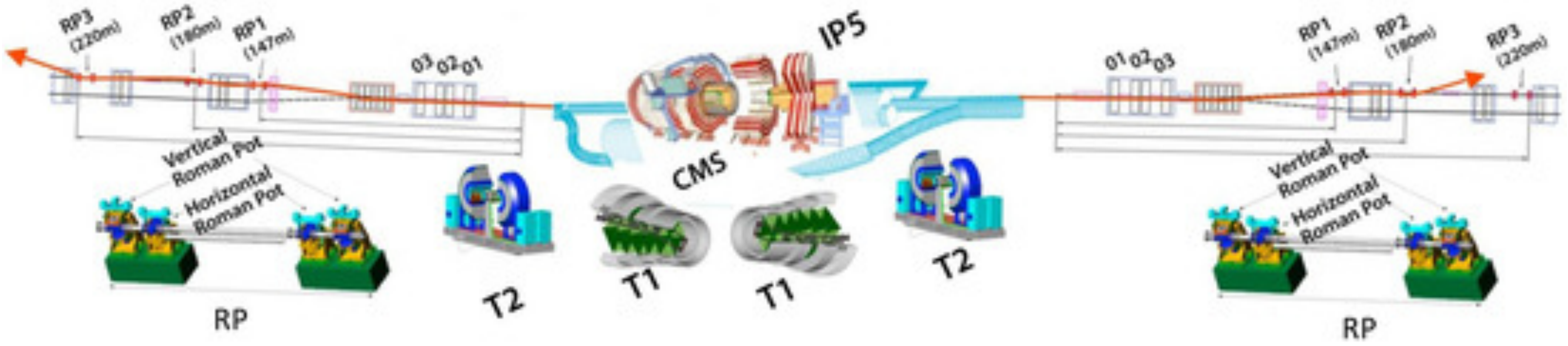
- As a consequence of the interaction, protons lose energy and result slightly deflected from the beam-line;

- Besides, the energy lost by the protons is used to create a system of particles, called “X system.”

The experiment

What do we need to study CEP processes?

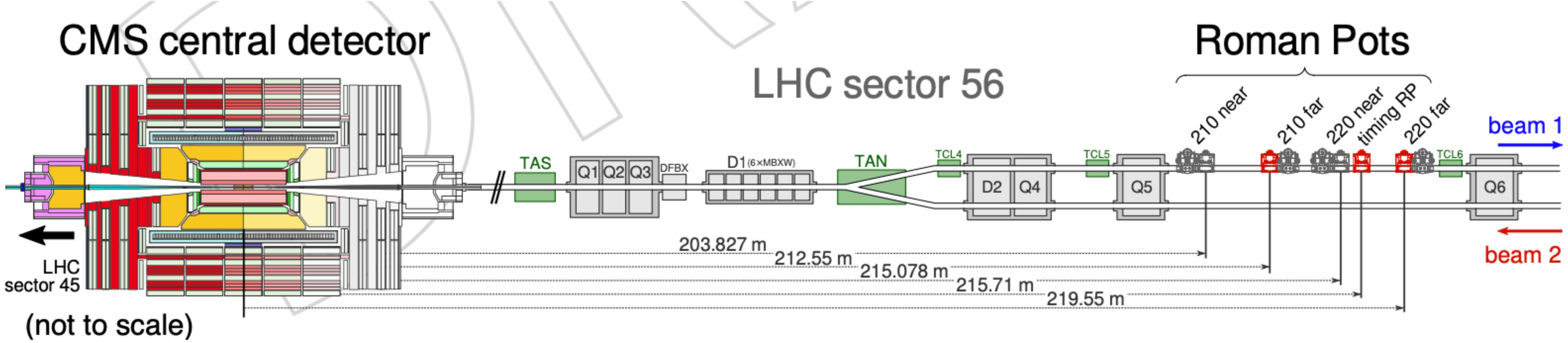
- The final state is characterised by two different systems:
  - The X system: this set of particles is usually detached from the beam line and can be detected by the CMS central system (CS).
  - The protons: they are just slightly deflected from the beam line → they fall out of the CMS central system acceptance.
    - Protons are tagged by the Proton Precision Spectrometer (PPS), which is a symmetrical set of detectors located at a distance of ≈ ±200 m from the IP.

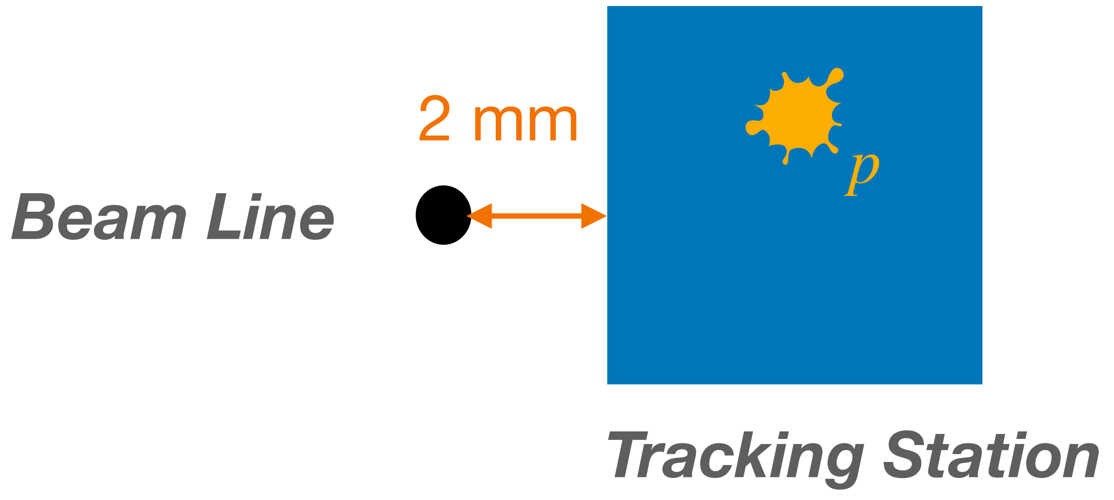


The experiment

An overview of PPS

- PPS is composed by three stations per arm: two tracking stations and one timing station;
- The tracking stations are located at ± 210 m and ±220 m from the IP. They are at a distance of just 2 mm from the beam-line → they can tag protons slightly deflected from the beam line.
  - Knowing the interaction point between the proton and the tracking station, one can calculate the fraction of momentum lost (ξ) by the proton during the interaction;
- The timing stations allow to correlate the event tagged by PPS with the event tagged by CMS CS.





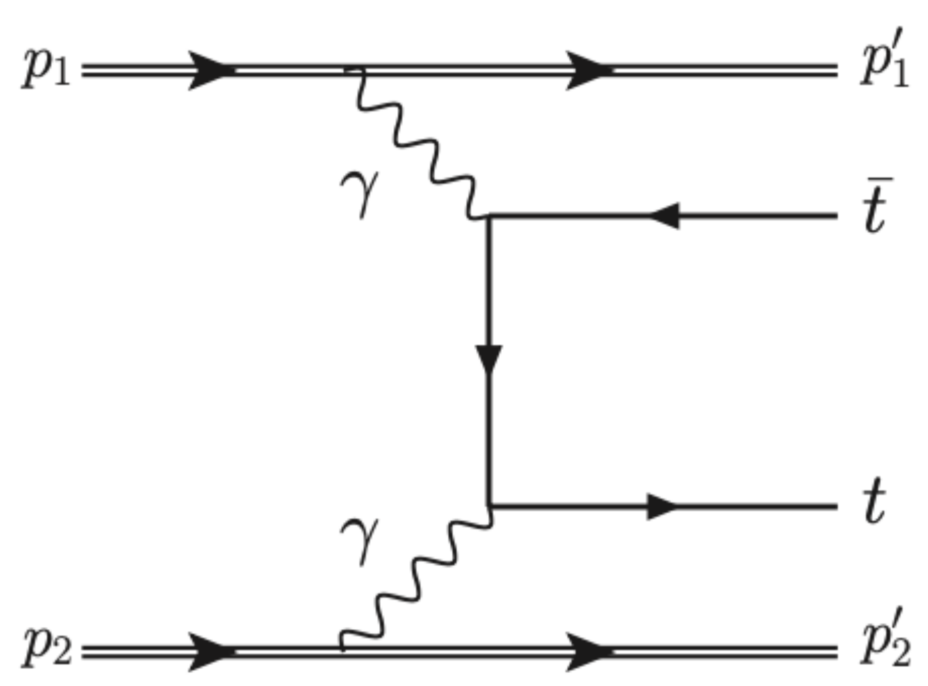
The central exclusive production of $t\bar{t}$ pairs

- In this analysis the “X system” is characterised by a top quark-anti/quark pair:

The process

$$pp \rightarrow p + t\bar{t} + p$$

Sketch diagram



PPS

Central system

Central system

PPS

Top decay mode

$$t\bar{t} \rightarrow bl_1\nu_1 + \bar{b}l_2\nu_2 \quad \textit{Di-Leptonic}$$

$$t\bar{t} \rightarrow bl\nu + \bar{b}q'\bar{q} \quad \textit{Semi-Leptonic}$$

$$t\bar{t} \rightarrow bq_1'\bar{q}_1 + \bar{b}q_2'\bar{q}_2 \quad \textit{Full-Hadronic}$$

- The interaction is mediated by $\gamma\gamma$ fusion (double pomeron interaction suppressed);
- Given that the top may decay in different modes, we focused on the study of the semi-leptonic and di-leptonic decay mode;
- The study was realised in 2017 conditions and it is of great interest since it is the first attempt to study this process.

The background determination

The competitive processes that we must cut out.

- The hardest background to reject is the so called $t\bar{t}$ inclusive process: $pp \to t\bar{t}$.
- This process is identical to signal: the only difference is the absence of protons in the final state, which in this case dissociate.
- In principle, in presence of a signal event, PPS should record 2 protons, while in presence of a $t\bar{t}$ inclusive process, no protons should be tagged.
- Anyhow, in the same bunch crossing many simultaneous events happen:
    - for this reason, even if CMS CS is tagging a $t\bar{t}$ inclusive process, PPS may tag two protons coming from another event!

Full list of backgrounds

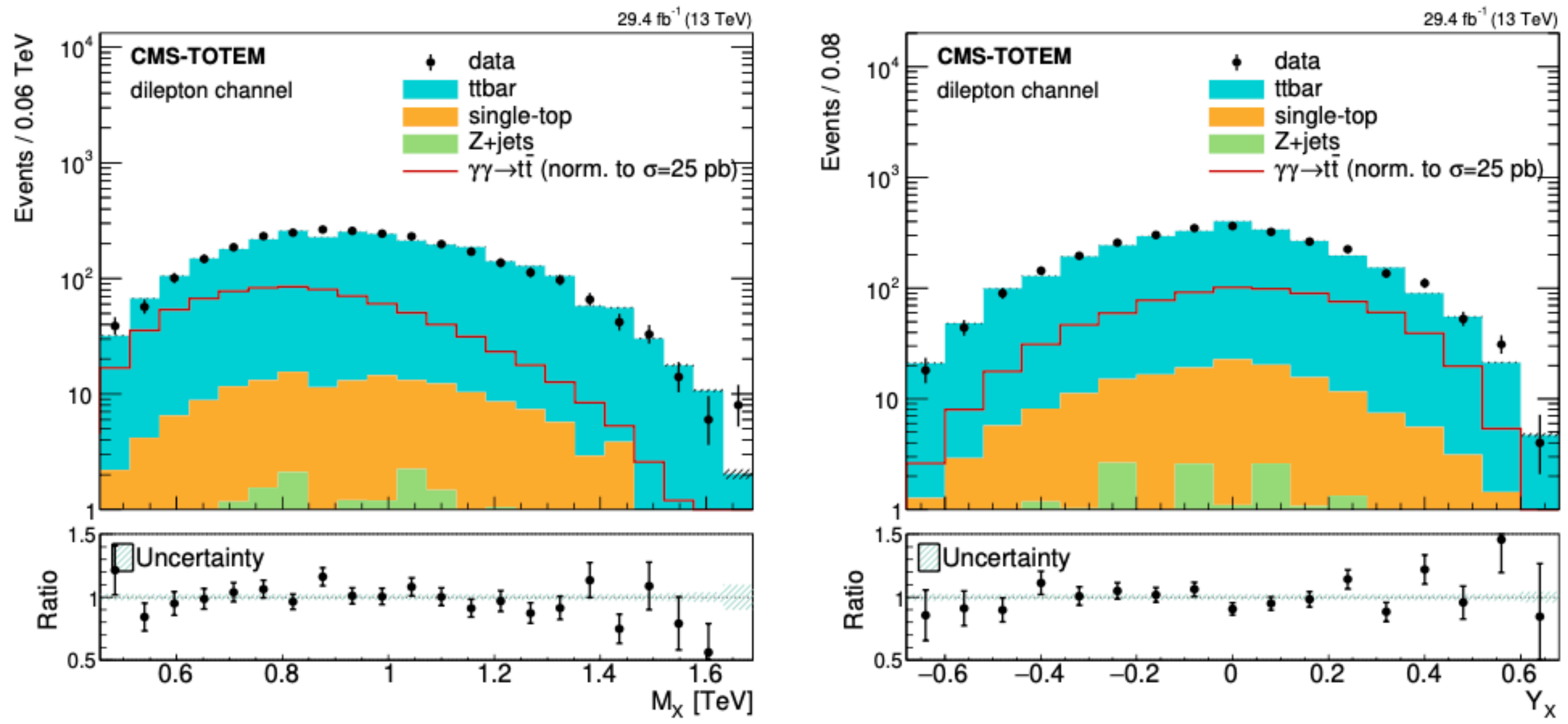
Process	Cross section (pb)
W+jets	61526.7
$t\bar{t}$ semilep	365.34
$t\bar{t}$ dilep	88.29
tW	35.85
$\bar{t}W$	35.85
DY+jets	460

The background determination

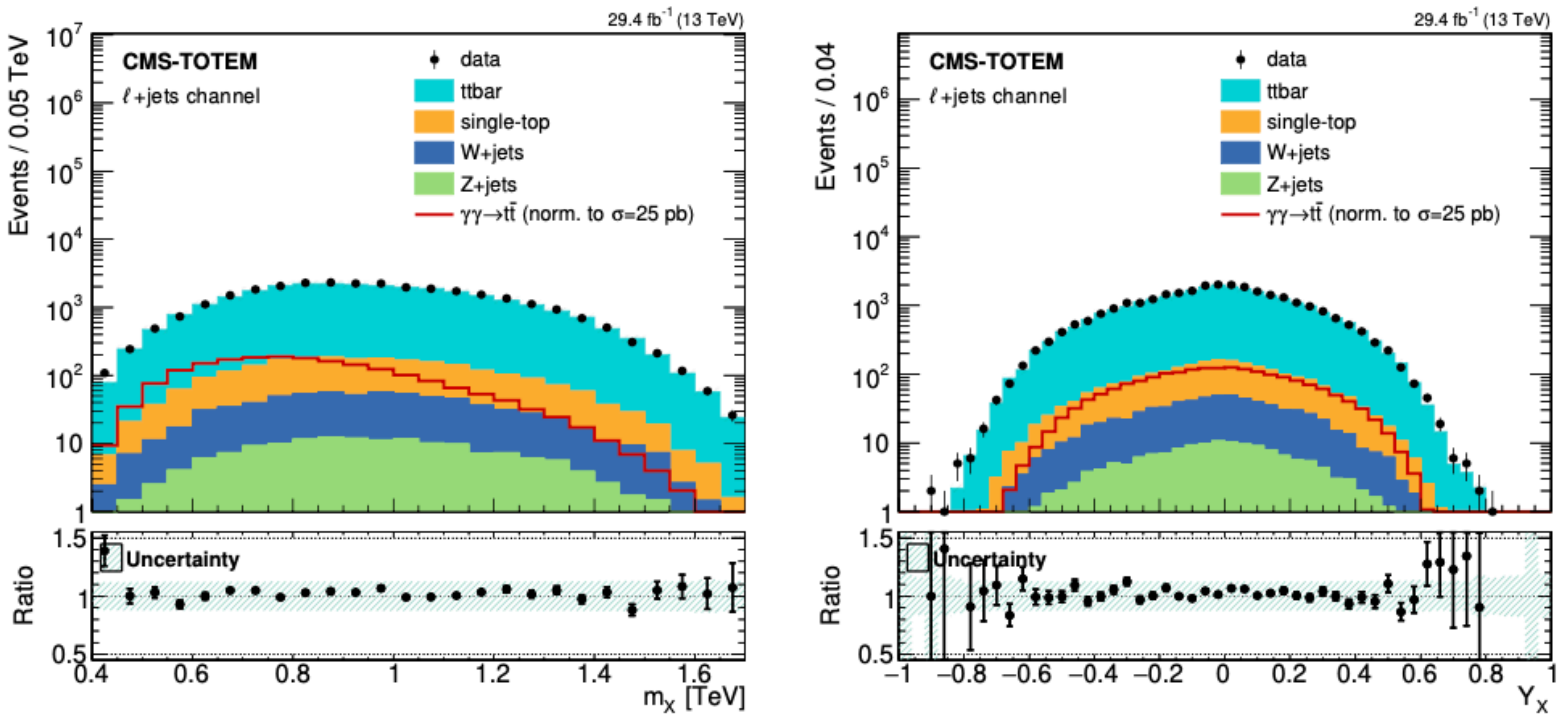
The strategy to reject background events

- As detailed in the previous slide, rejecting background is not a straightforward procedure.
- Therefore, a good idea is selecting some variables whose distribution is different for signal and background;
- Such variables will be used as an input of a multivariate analysis tool.
- Here I quote the most discriminating ones: some of them come from CMS CS, others from PPS.

Di-Leptonic channel



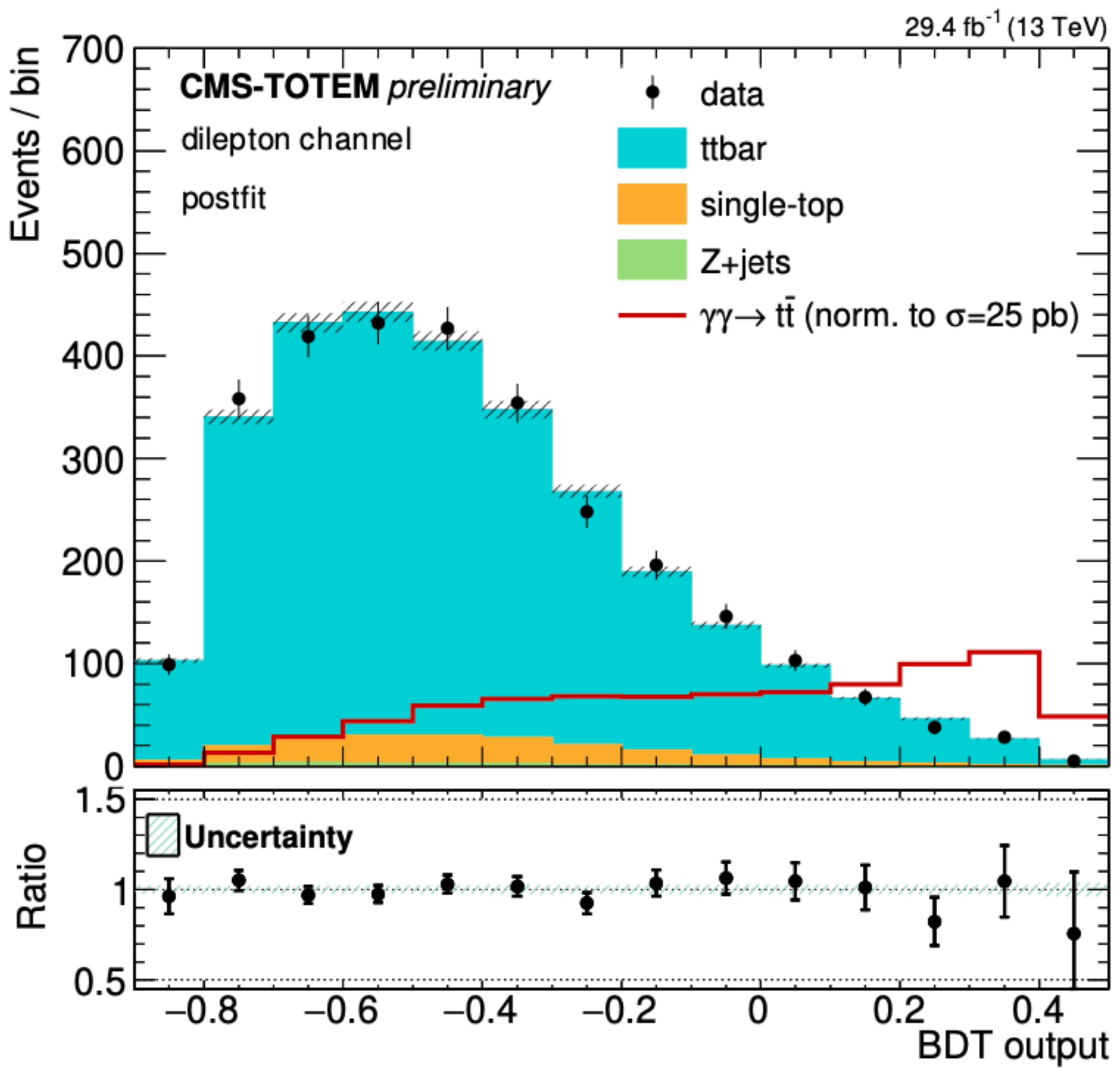
Semi-Leptonic channel

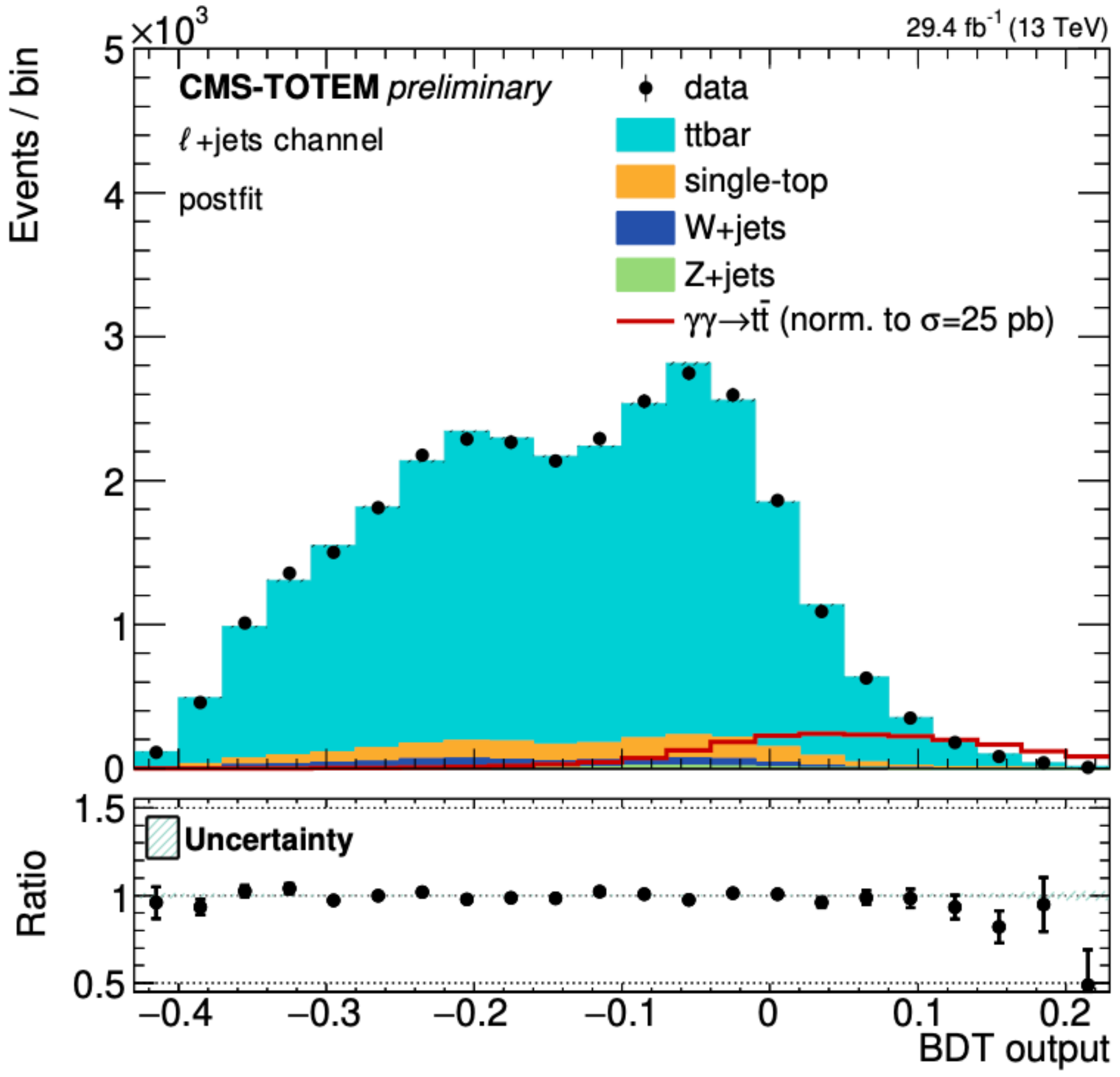


The multivariate analysis tool

The best way to discriminate signal from background

- The tool was developed using TMVA (the ROOT MVA official framework);
- Several classifiers were trained (Fisher, Likelihood, MLP, BDT) and BDT resulted to be the most performing algorithm.





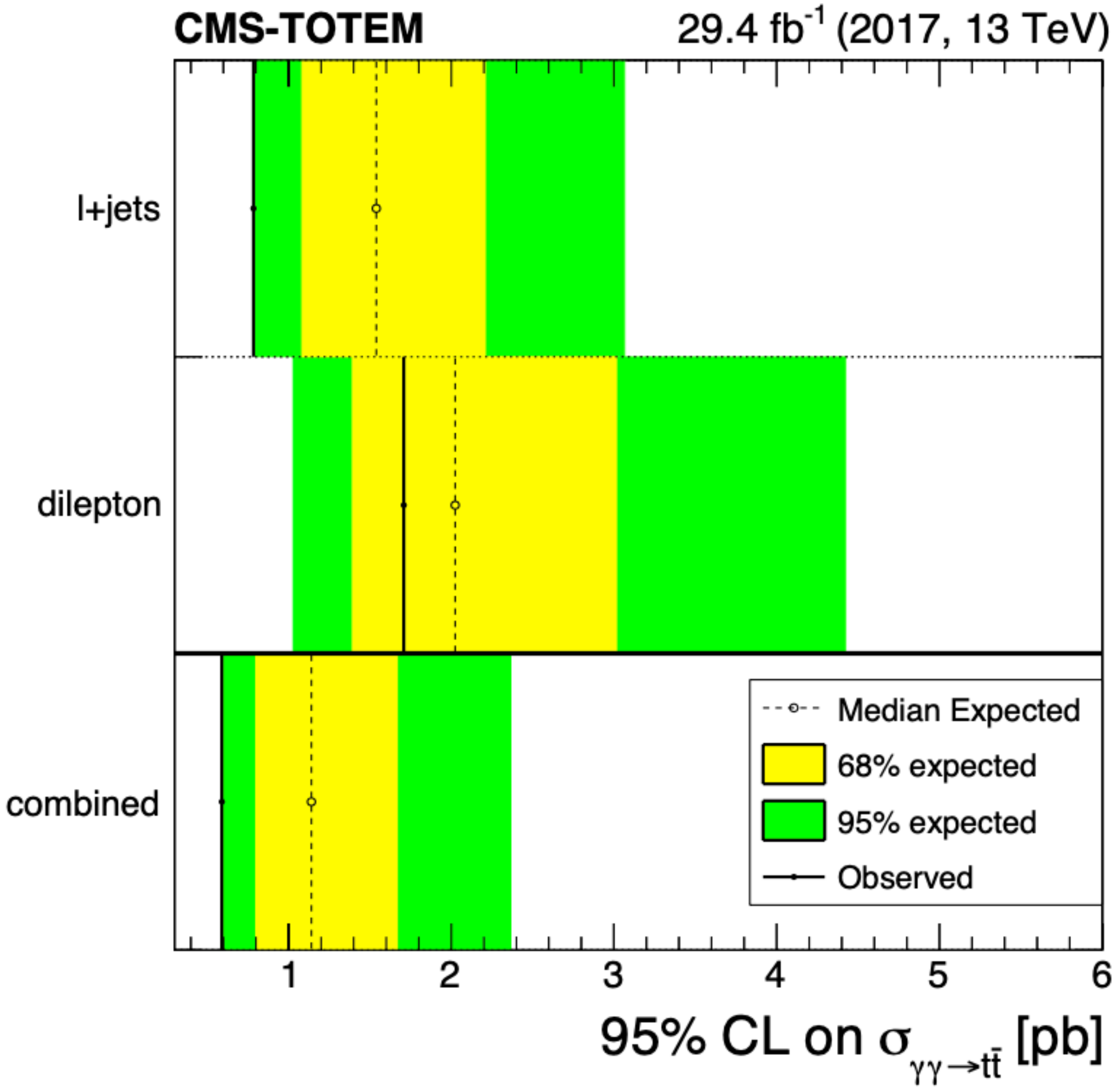
- On the right one can find the BDT output for both channels;
- Good agreement between data and MC can be observed.

The limit on the cross section

- To derive a limit on the cross section of the process the BDT distributions of signal and background were given as input of Higgs Combine.

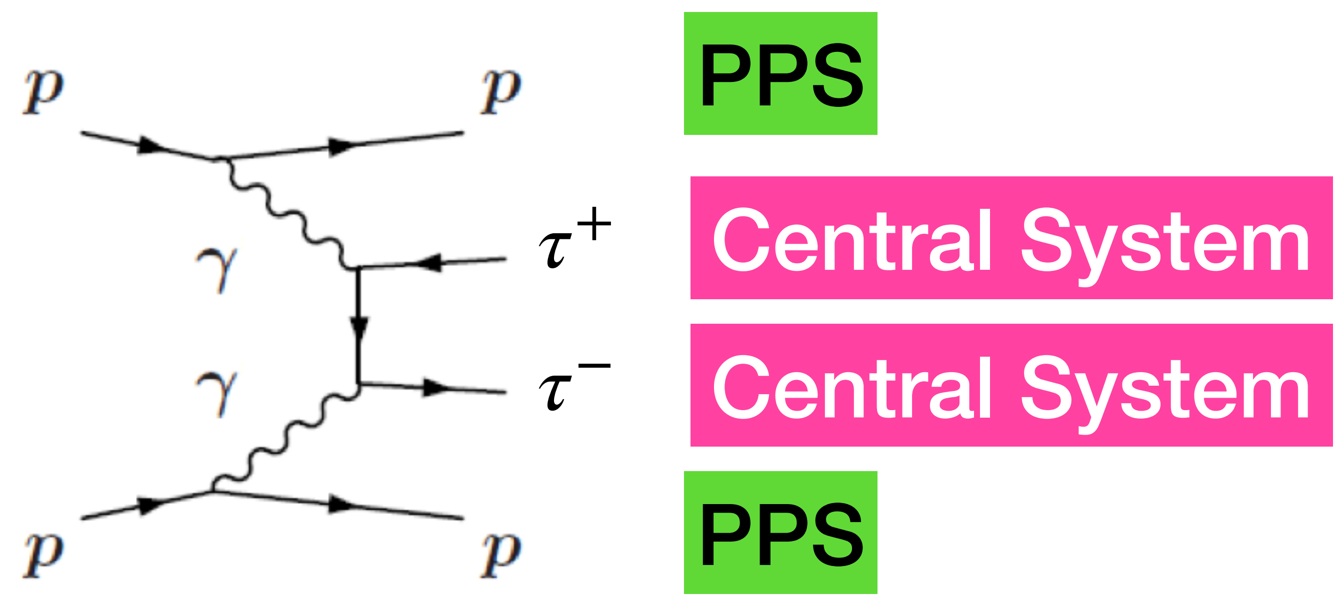
- The theoretical cross section of signal is extremely low ($\approx 1\ fb$), therefore it was not possible to quote a value for this quantity, but just an upper limit.

- The upper limit found is 590 fb at the 95% of confidence level.



The central exclusive production of $\tau^+\tau^-$ pairs

- This analysis is ongoing and therefore only general aspects can be divulged;
- In this case the "X system" is composed by a $\tau^+\tau^-$ pair:



The process

$$pp \rightarrow p + \tau^+\tau^- + p$$

- Also in this case, the process is mediated by $\gamma\gamma$ fusion.
- The analysis is challenging due to the presence of multiple neutrinos in each final state.

- The study of this process is interesting since its cross section is related to the gyromagnetic coefficient of the τ lepton.
- Since μ gyromagnetic momentum appears not to be in line with SM predictions, quoting a value for the tau leptons may be of interest.
- Stay tuned for more news!

Publications

What I have written and done in these years…

- An introduction to the $t\bar{t}$ central exclusive production processes can be found in:
  - M. Pisano, “Study of central exclusive production of top quark-antiquark pairs at LHC”, Il Nuovo Cimento C, 12th August 2021, DOI: 10.1393/ncc/i2021-21066-9
- Full documentation about the $t\bar{t}$ analysis:
  - The CMS Collaboration et the Totem Collaboration, “Search for central exclusive production of top quark pairs in proton-proton collisions at $\sqrt{s} = 13\ TeV$ with tagged protons”, March 2022, CMS-PAS-TOP-21-007;
- Parallel hardware works (in collaboration with Tagus LIP):
  - T. Niknejad et. Al. (me too!), “Results with the TOFHIR2X revision of the front-end ASIC of the CMS MTD Barrel Timing Layer”, IEEE NSS MIC 2021, January 2022, link;
- Outreach publications:
  - M. Pisano, M. Occhetto, “Tecniche avanzate di analisi dati per la scuola superiore”, official Italian site of PLS, 9th February 2021, article #24.