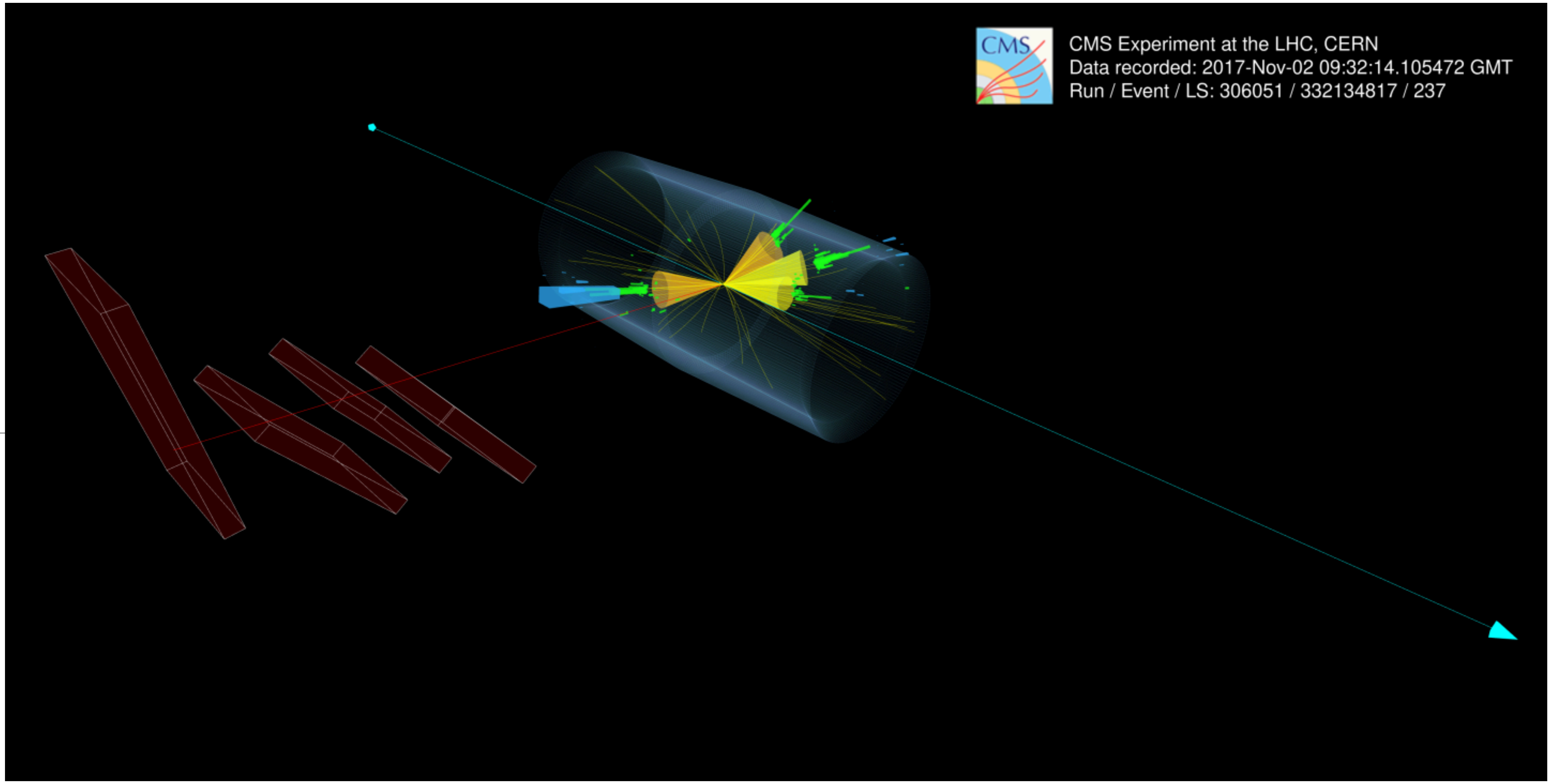
New CMS Results on top quarks (and other things) from photon collisions



Jonathan Hollar (LIP)

October 6, 2022

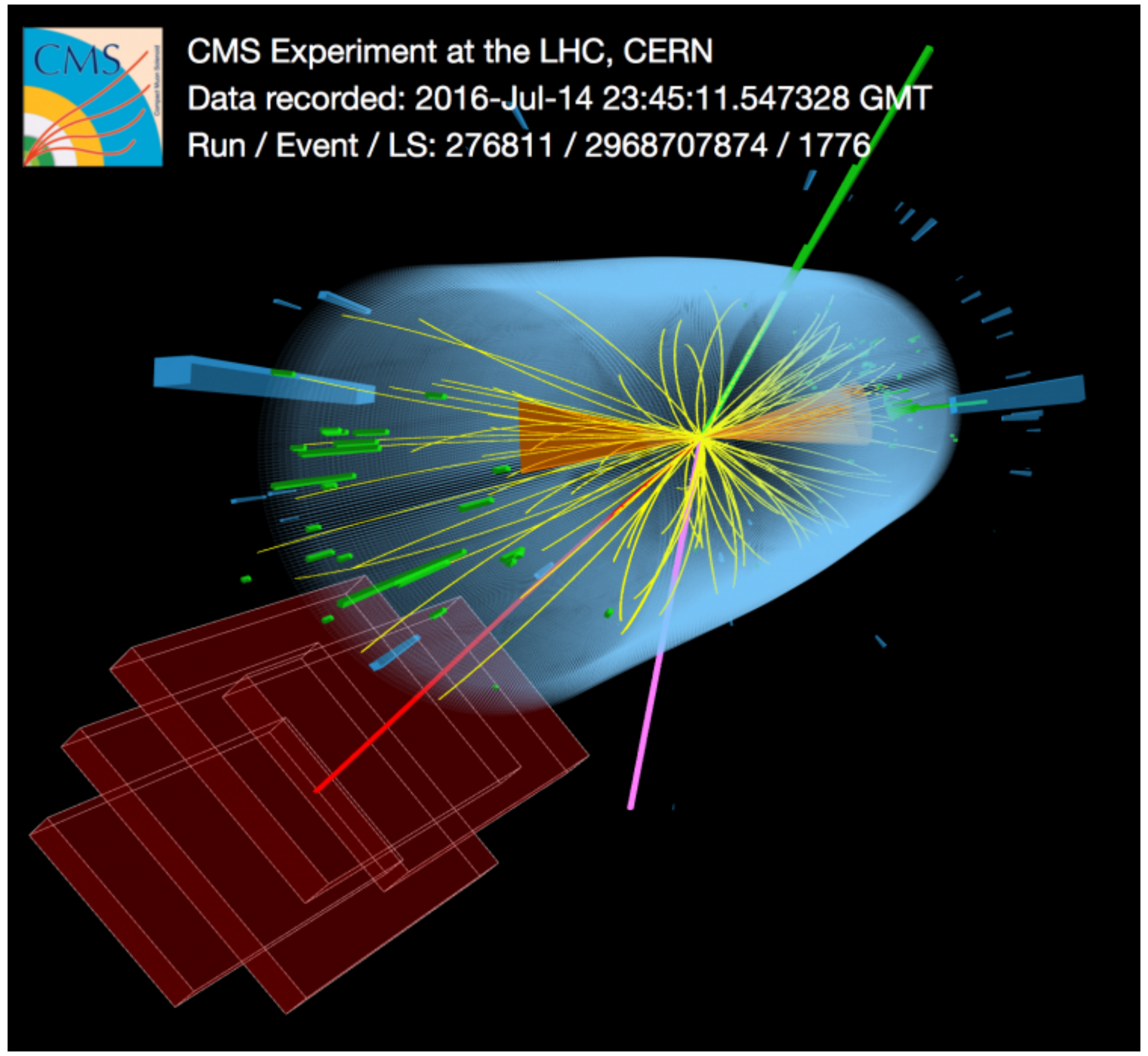
LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

LHC: The Large Hadron Collider

Everyone knows the LHC collides hadrons: protons or heavy ions

Gluons or quarks interact, and sometimes produce interesting things: top quarks, W/Z bosons, Higgs bosons, possible new particles…

p or A



p or A

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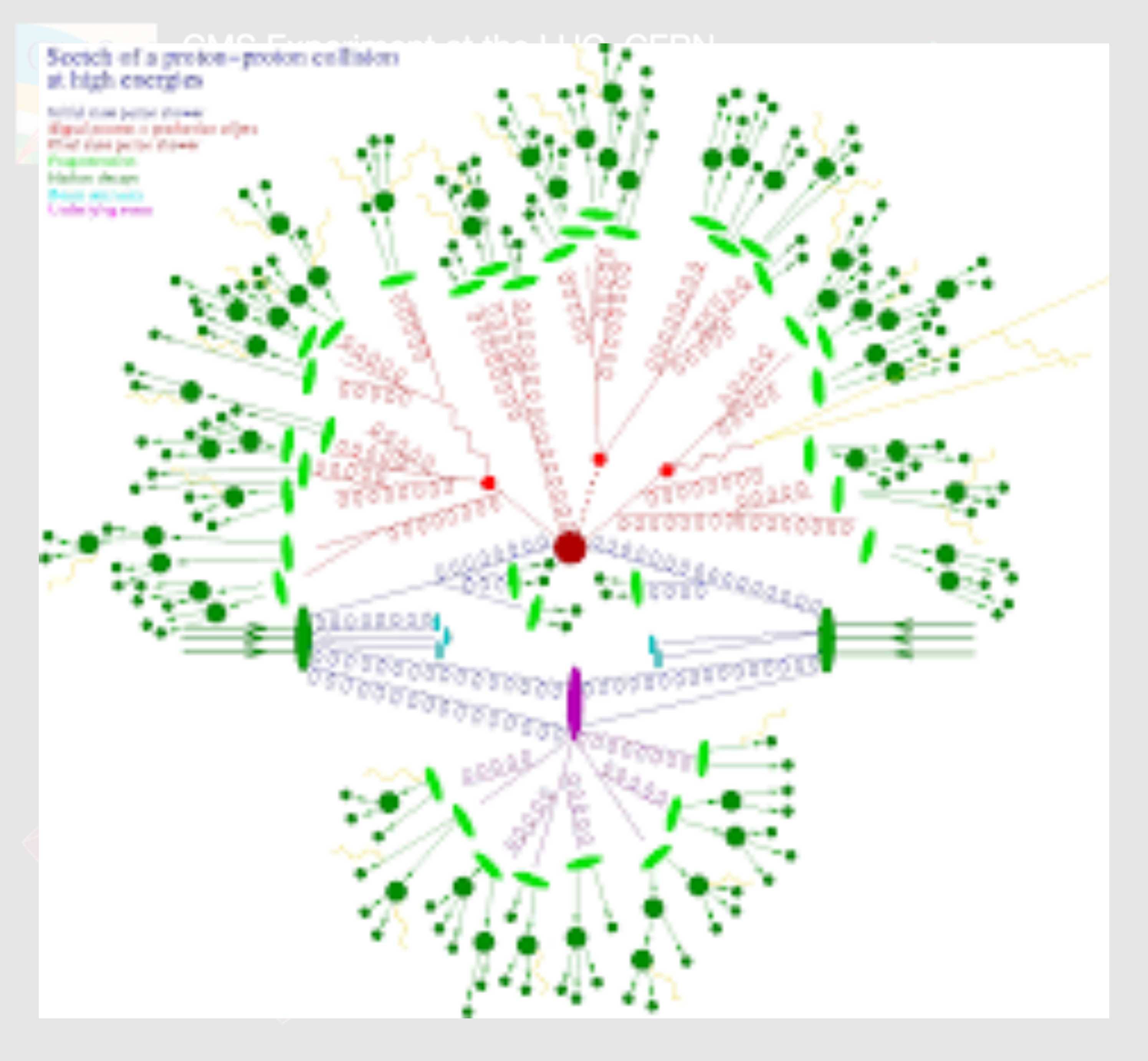


p or A

Plus a lot of other "stuff" produced in association: from proton remnants, multi-patron interactions, initial/final state radiation…

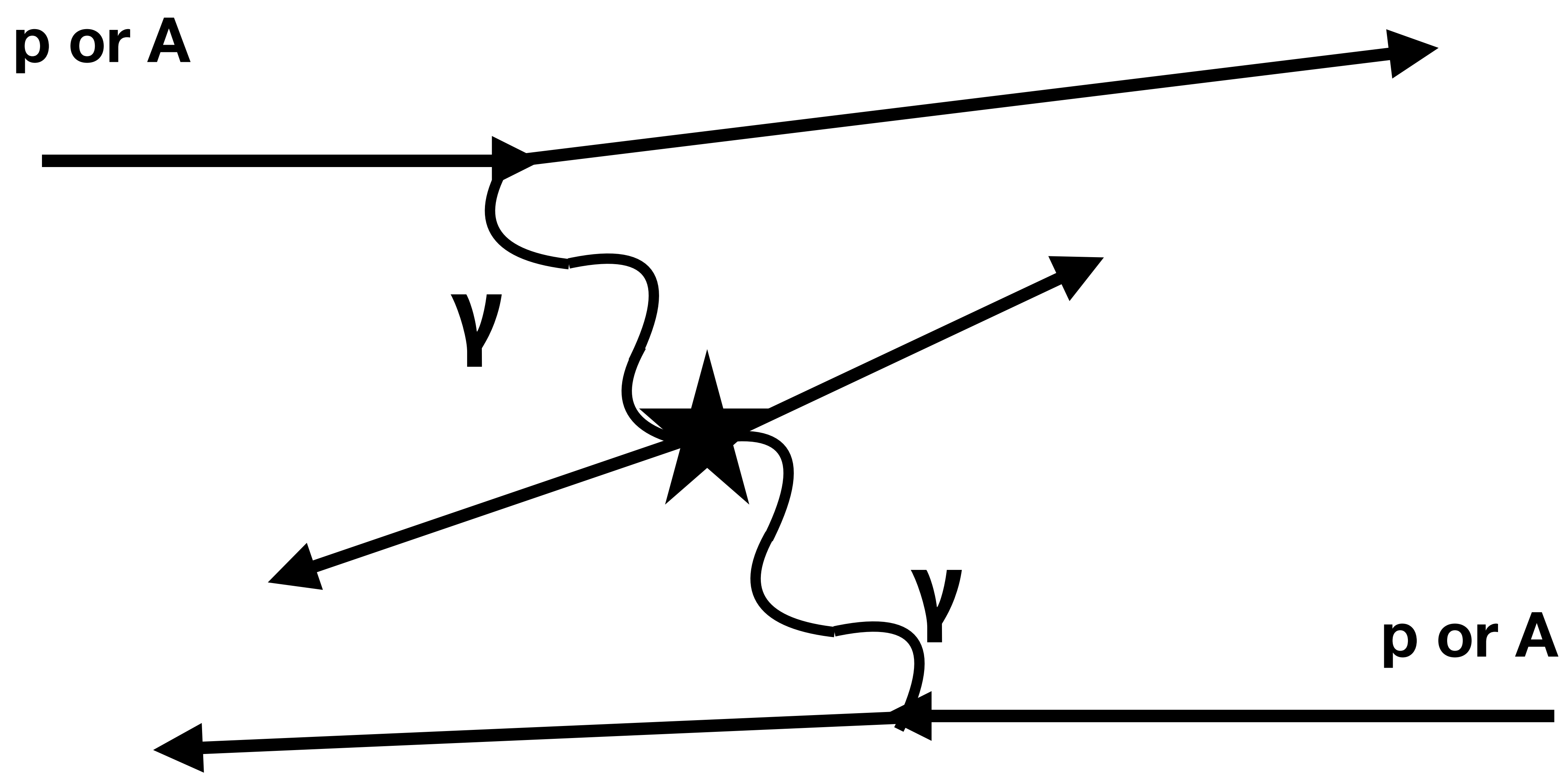
Generally the amount of energy going into the gluon/quark interactions is not known for a single event, unlike at an e^+e^- collider

Photon

LHC: The Large ~~Hadron~~ Collider

In rare cases something else happens

The (electrically charged) protons or ions stay intact, and radiate off high-energy photons, that then collide

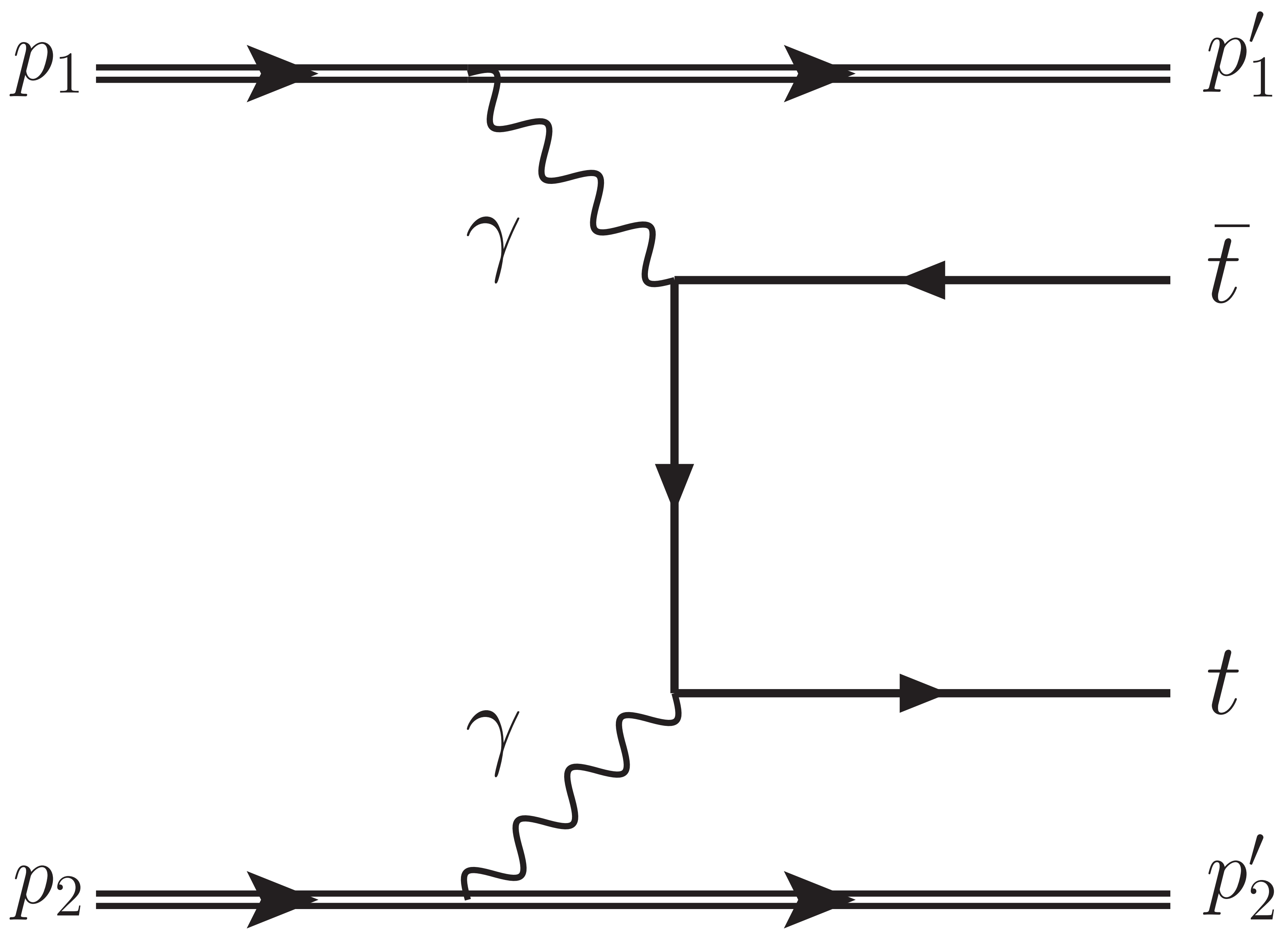


Photon
LHC: The Large ~~Hadron~~ Collider

In rare cases something else happens

The (electrically charged) protons or ions stay intact, and radiate off high-energy photons, that then collide

Thanks to the enormous LHC energy, colliding photons can also produce interesting things: top quarks, W/Z bosons, Higgs bosons, possible new particles…



In this case all of the collision energy can go into the interesting final state and the 2 surviving hadrons ("exclusive" production)

Two roads to studying γγ collisions at the LHC

Heavy Ion Collisions

Advantages: Huge photon flux (Z^4 enhancement with ion species), low “pileup” of multiple collisions in the same bunch crossing

Drawbacks: Lower C.M. energy, limited amount of ion running time at LHC, no detection of outgoing ions

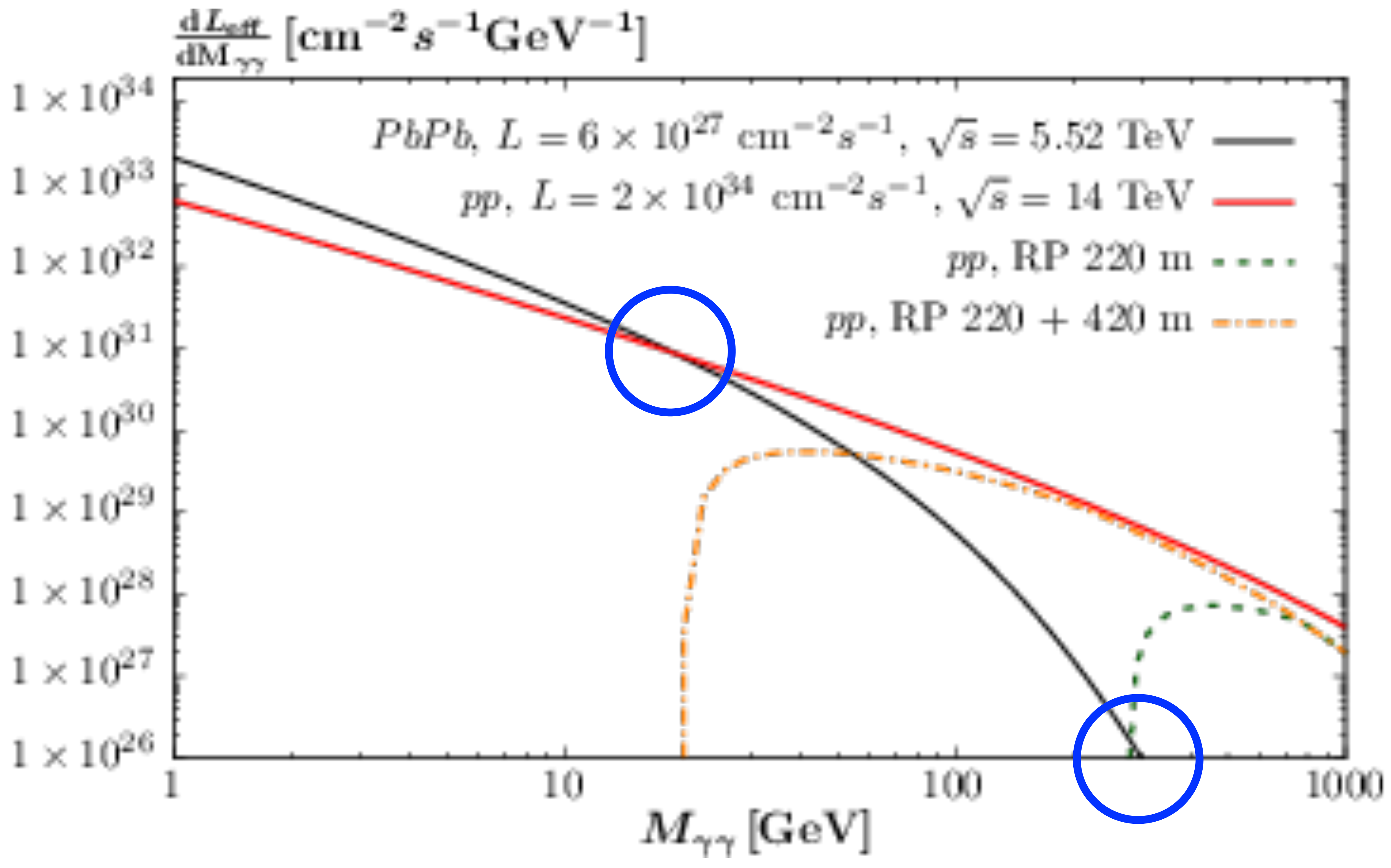
Proton-proton collisions with forward proton detectors

Advantages: Highest energy, large integrated luminosity/running time, reconstruction of outgoing protons

Drawbacks: Lower photon fluxes at low mass, must deal with very large “pileup” (up to ~50 simultaneous collisions)

The two approaches are highly complementary

Two roads to studying γγ collisions at the LHC



J.Phys.G 47 (2020) 6, 060501

Example with an assumed LHC running scenario (note log-log axes!)

Below ~20 GeV Pb ion fluxes are (much) larger: ideal for low-mass SM cross sections and searches for light BSM physics

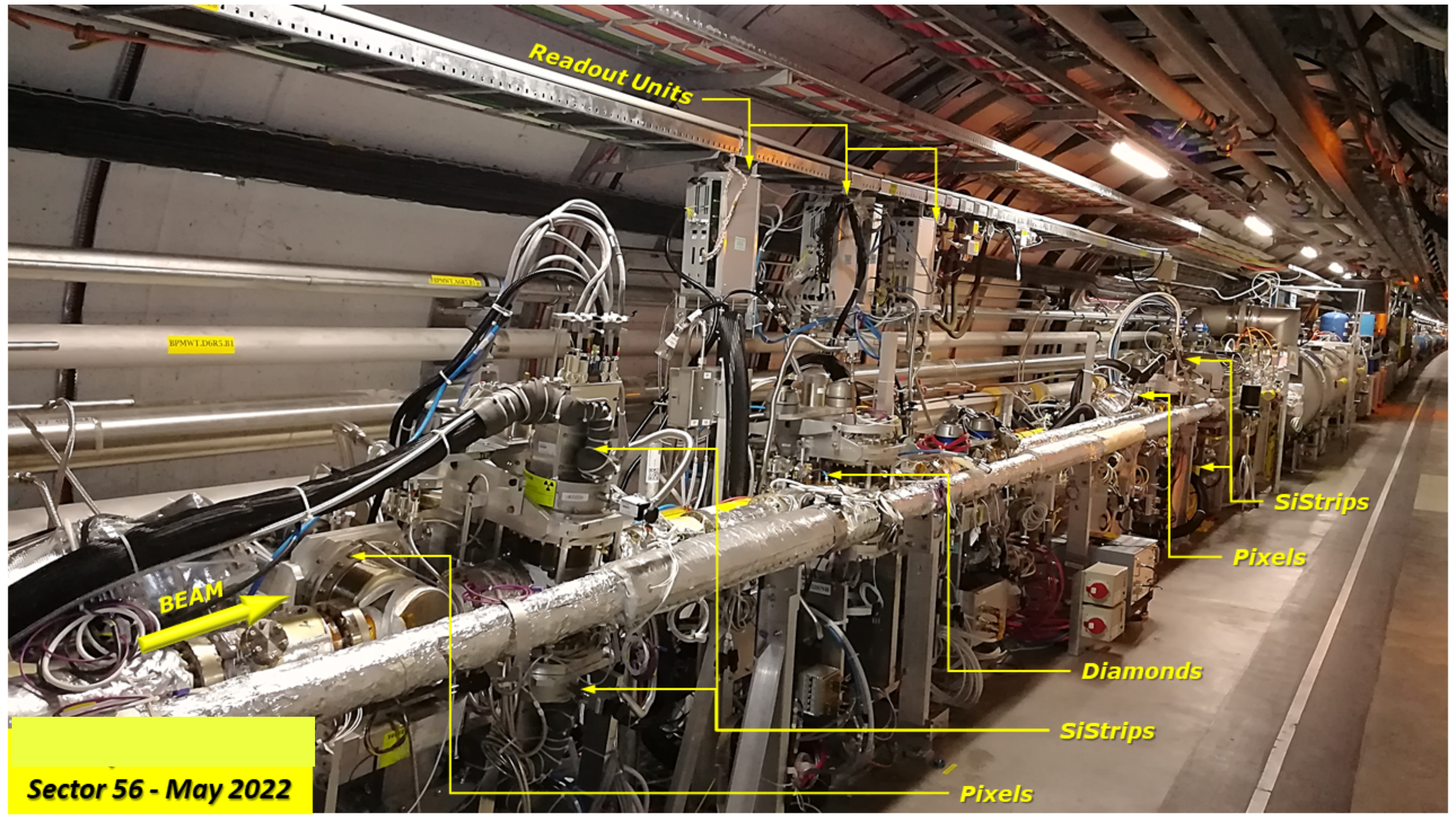
Above ~20 GeV p-p becomes (much) larger

Above ~200-300 GeV, outgoing protons in p-p collisions can be detected: ideal for heavy final states and searches for BSM physics at high energies

This talk will focus on the p-p case with outgoing protons detected

Detecting γγ collisions with outgoing protons

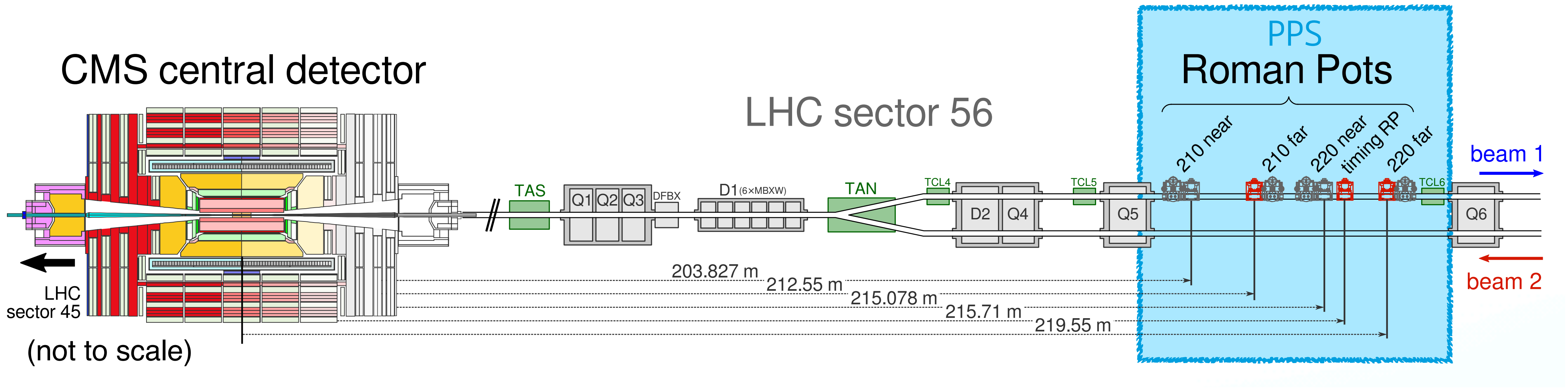
Detecting intact protons from γγ collisions



A series of small tracking and timing detectors is installed inside the LHC tunnel, ~200m away from CMS, to detect the protons scattered at small angles

The LHC magnetic fields bend the protons along the way, allowing reconstruction of their kinematics (mainly the fractional momentum loss "ξ")

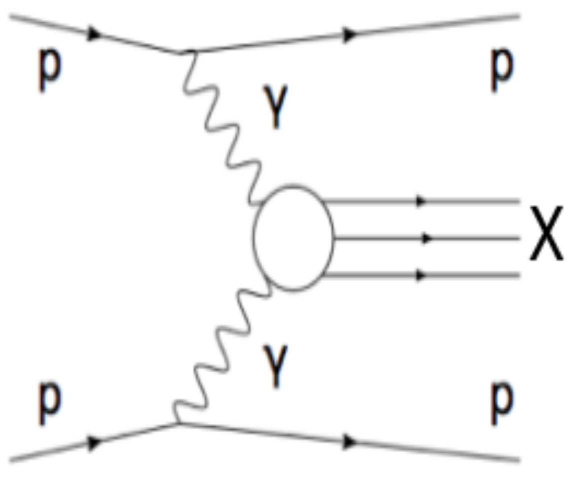
When both protons are detected, the invariant mass and rapidity of the central system can be determined independently



Proton kinematics:

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \qquad M_X = \sqrt{s\xi_1\xi_2}$$

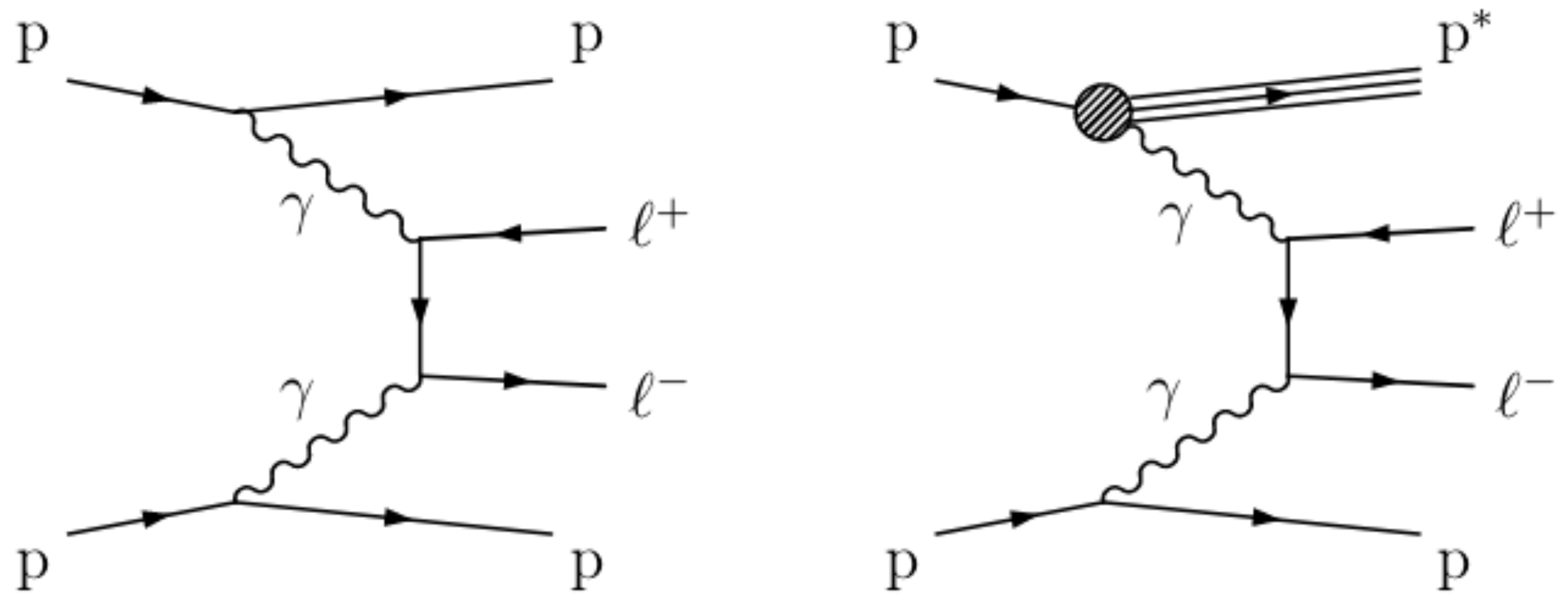
$$t = (p_f - p_i)^2 \qquad y_X = \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right)$$

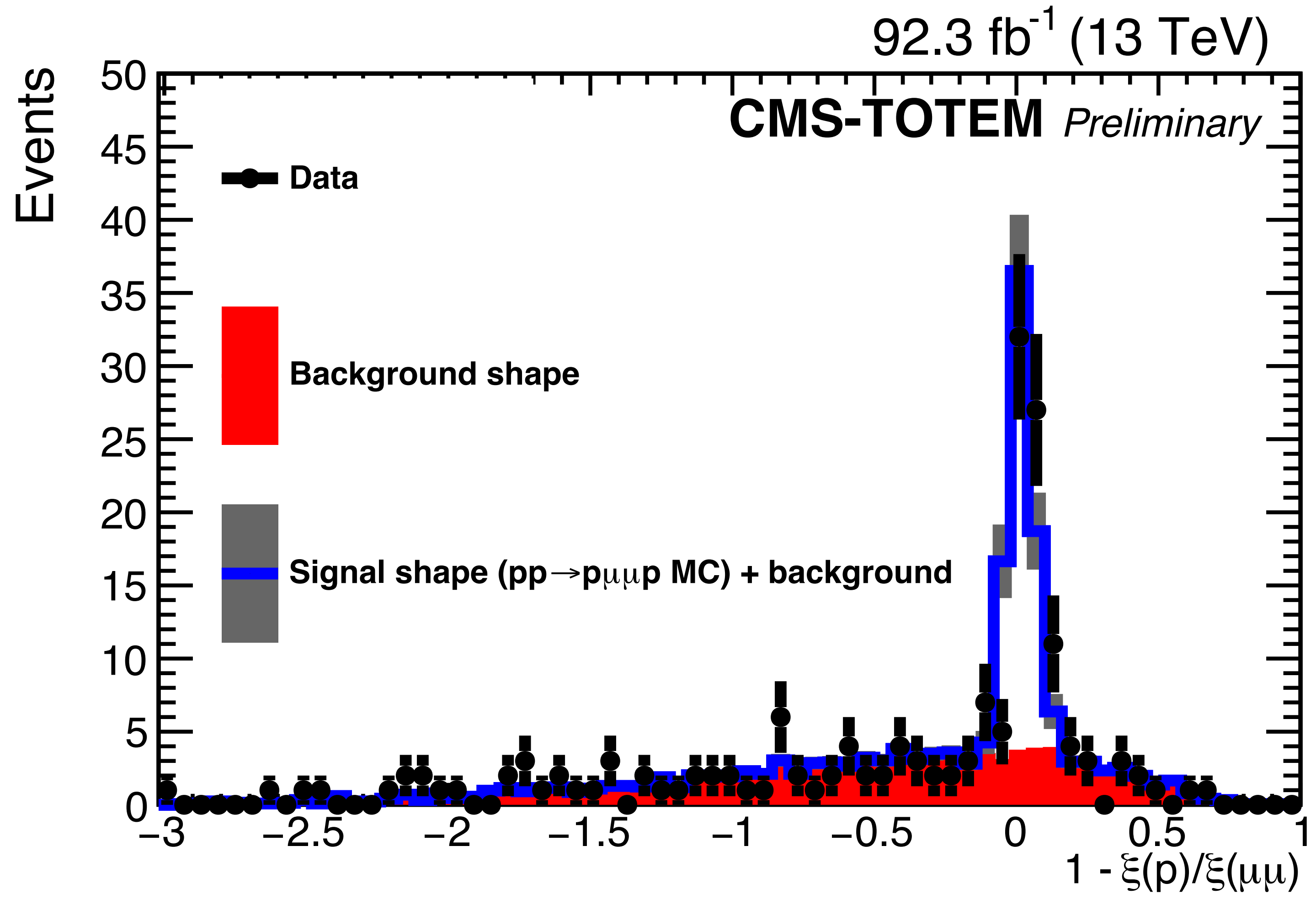


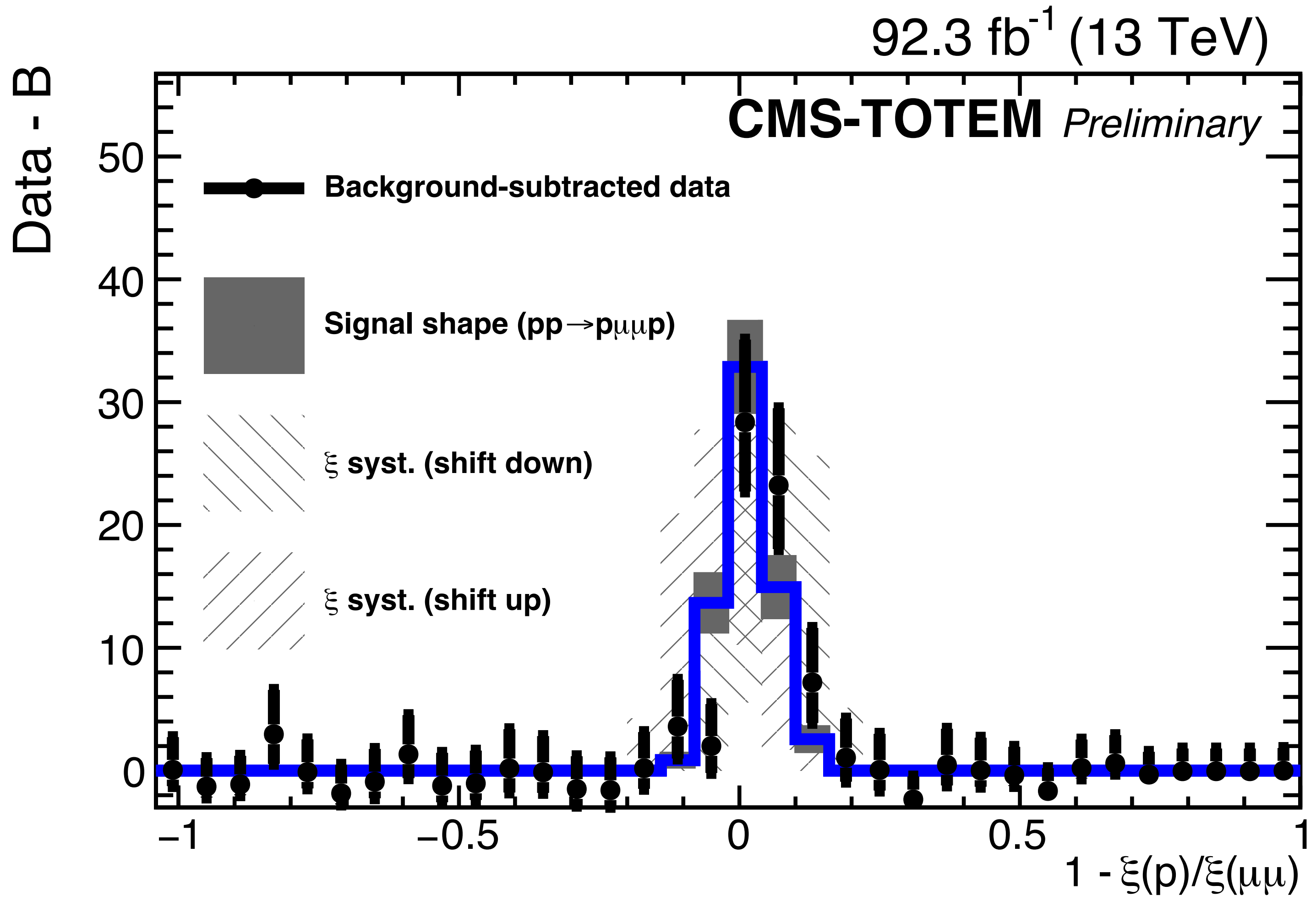
Validation with Standard Model signals

Before looking for new things - can we detect expected Standard Model processes?

Validation with γγ→μμ and γγ→ee processes, looking for kinematic correlations between protons and leptons







Used to quantify systematics due to data-simulation differences in scale, resolution

JHEP 07 (2018) 153 [2016 data, 10fb^{-1}, μμ and ee]

CMS-PAS-PRO-21-001 [2017+2018 data, 92fb^{-1}, μμ], to be submitted to JINST

Other validations/calibrations performed with elastic scattering events, central diffraction, and inclusive diffractive protons

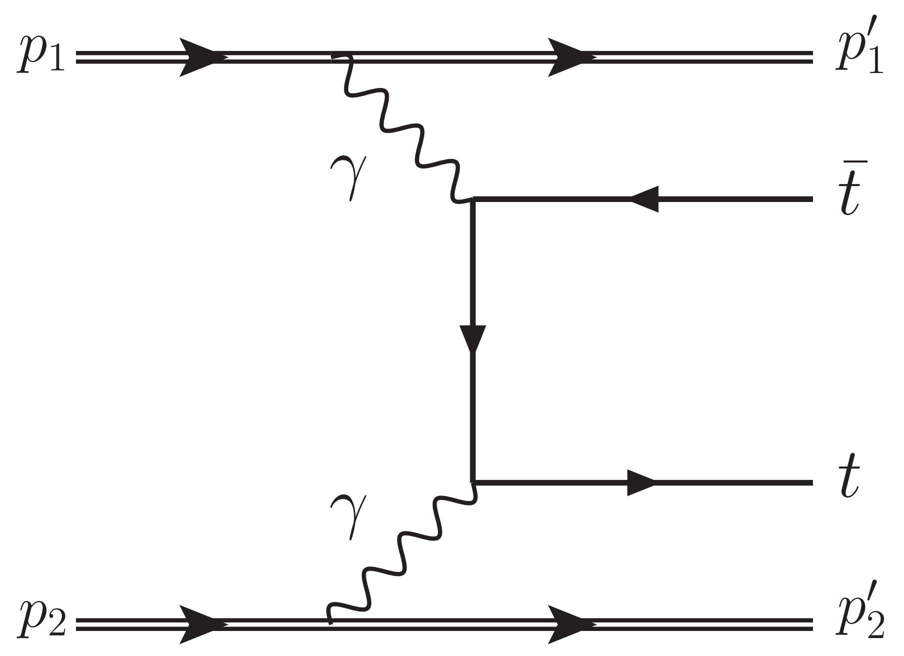
Search for top quarks from colliding light

Search for exclusive t-tbar

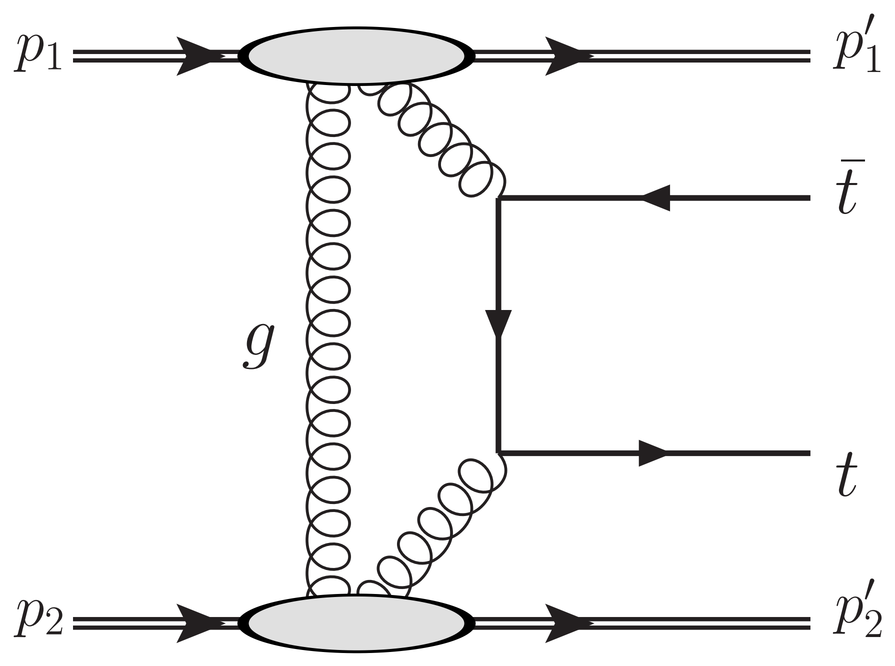
No previous searches for the *pp→pt$\bar{t}$p* process

Dominated by the γγ→*t$\bar{t}$* sub-process

Very small in the Standard Model, but enhancements predicted in various models: anomalous top quark electric/magnetic moments, extra dimensions, etc.



SM ~0.3fb



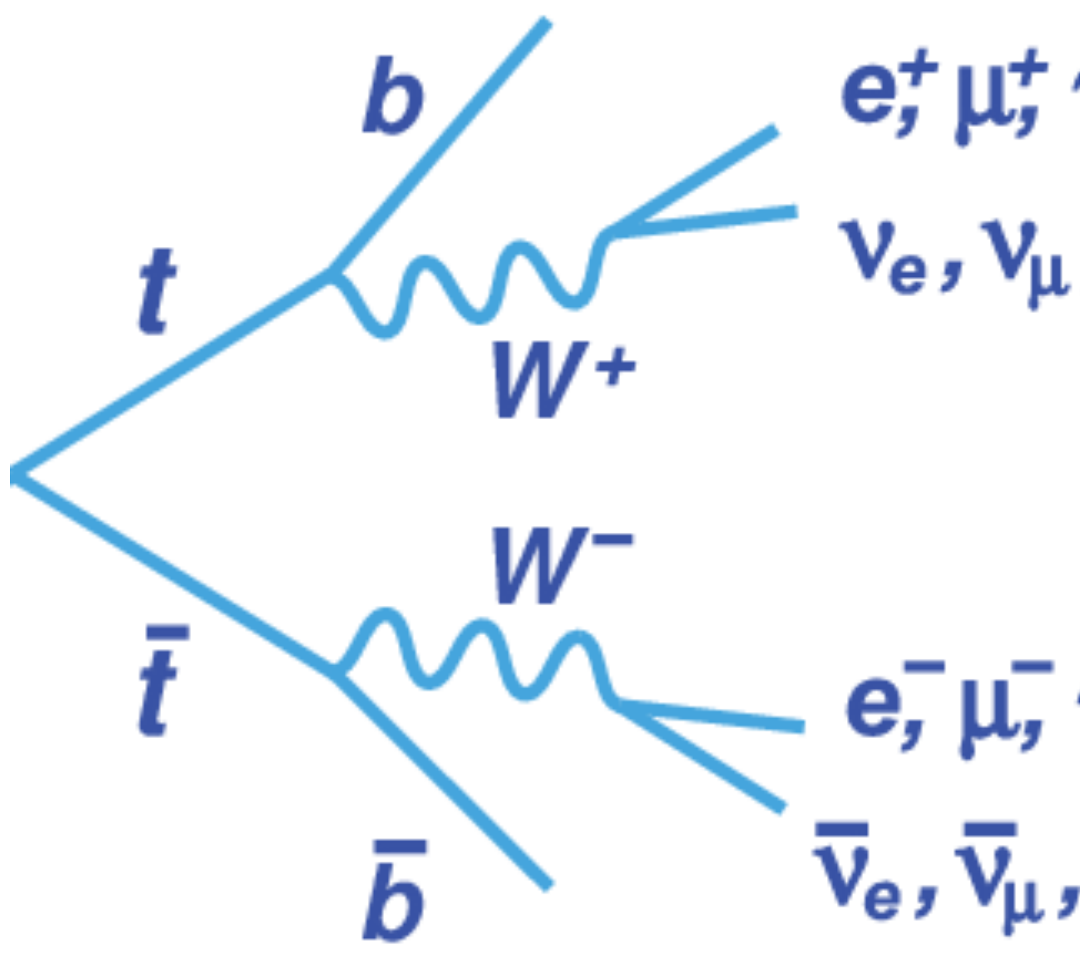
negligible

Data and event selection

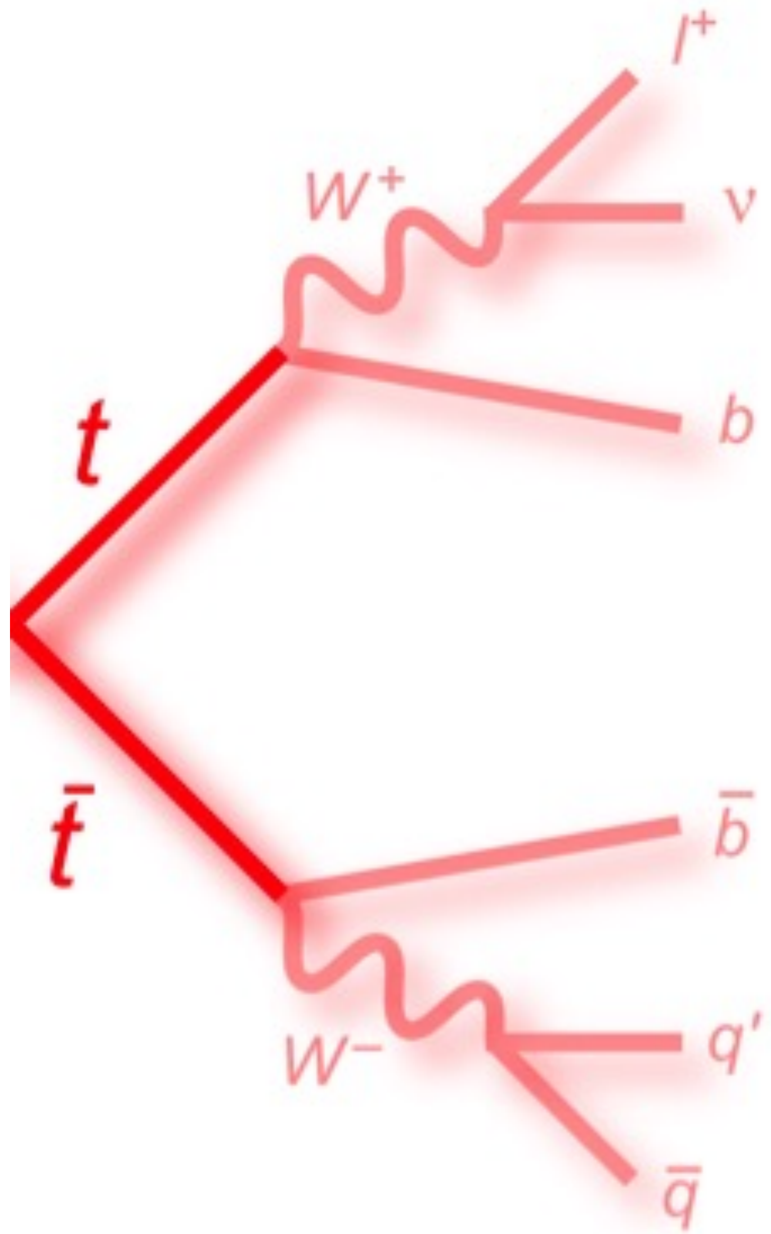
Analysis uses 29.4 fb^{-1} of data from 2017

Both the dilepton and lepton+jets top final states are considered

dilepton



lepton+jets



Data and event selection

Analysis uses 29.4 fb^{-1} of data from 2017

Both the dilepton and lepton+jets top final states are considered

dilepton

≥ 2 leptons (electrons or muons), passing standard pT, eta, ID requirements

≥ 2 b-tagged jets

1 tagged proton on each side of CMS

lepton+jets

1 lepton (electron or muon), passing standard pT, eta, ID requirements

≥ 2 b-tagged jets

≥ 2 light jets

1 tagged proton on each side of CMS

Kinematic fit

In the lepton+jets channel, a kinematic fit is used to improve the reconstructed $t\bar{t}$ mass resolution

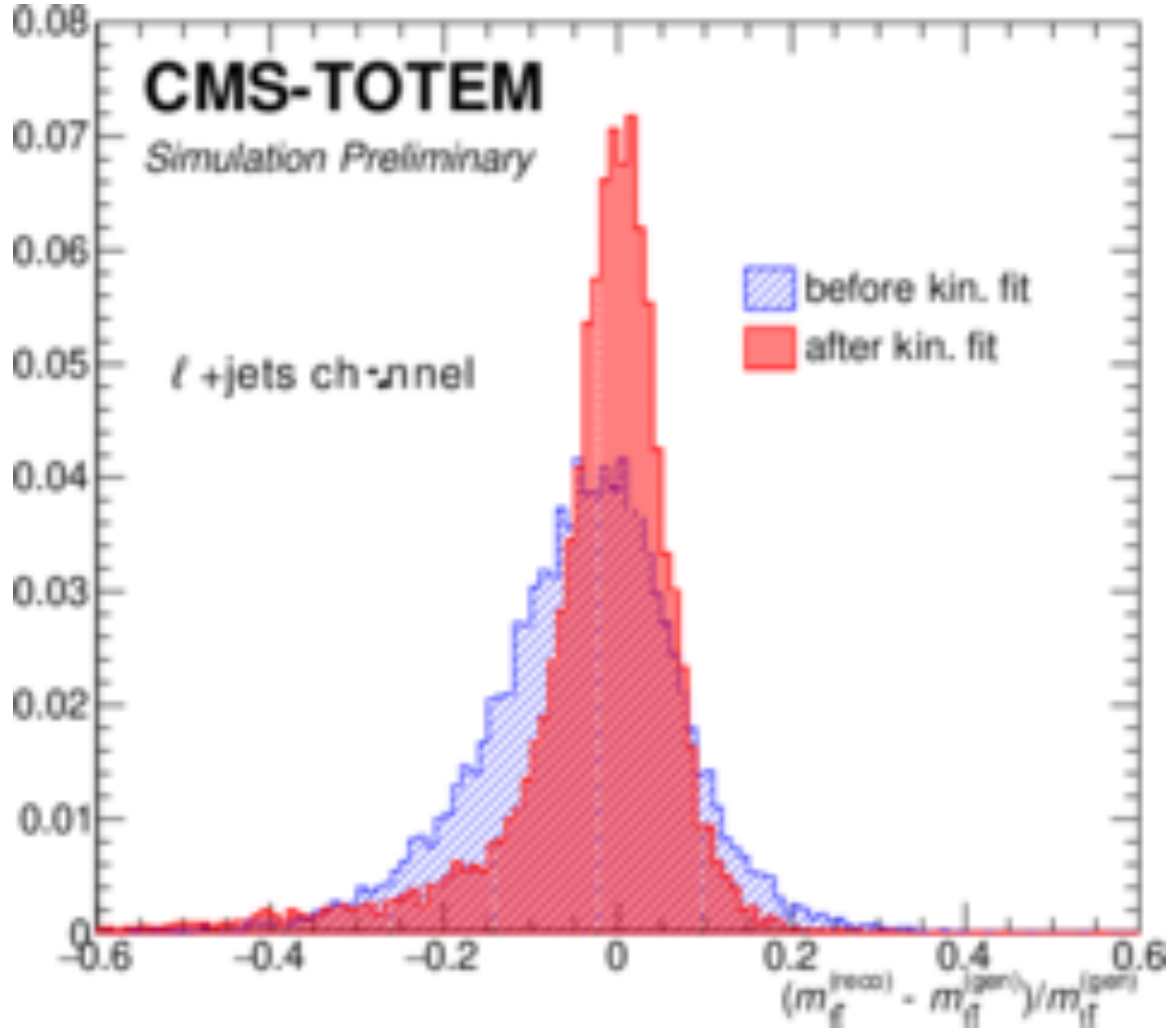
3-momenta of all final state particles are allowed to float to best satisfy constraints:

Momentum conservation

W and top invariant mass conservation

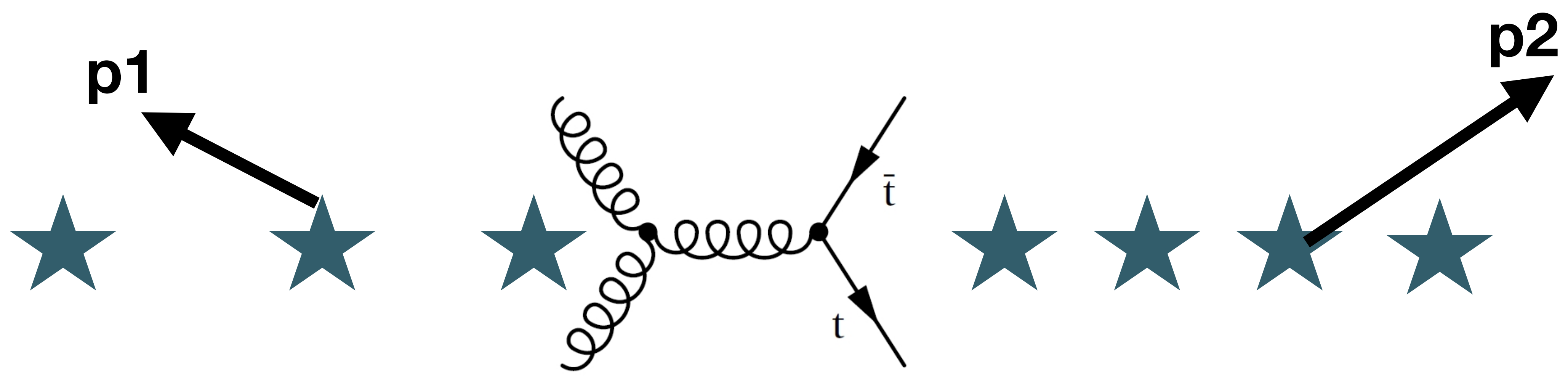
proton-top invariant mass matching

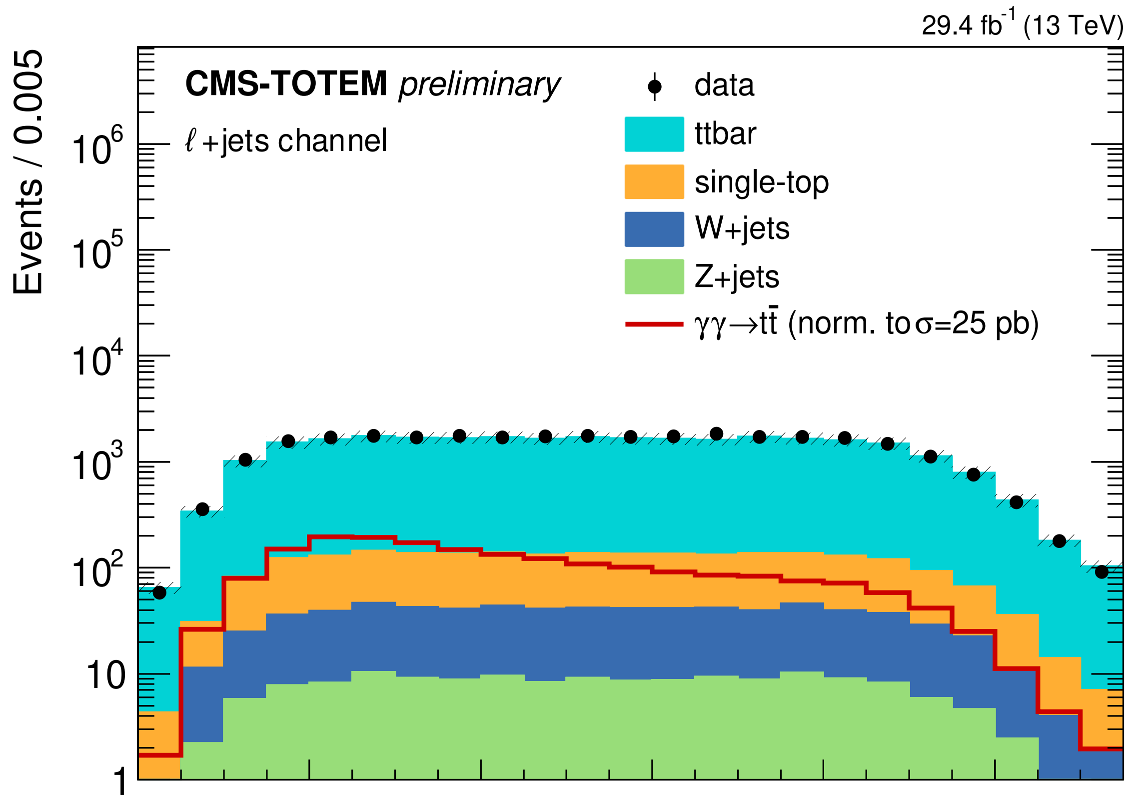
Significant improvement in resolution for signal events

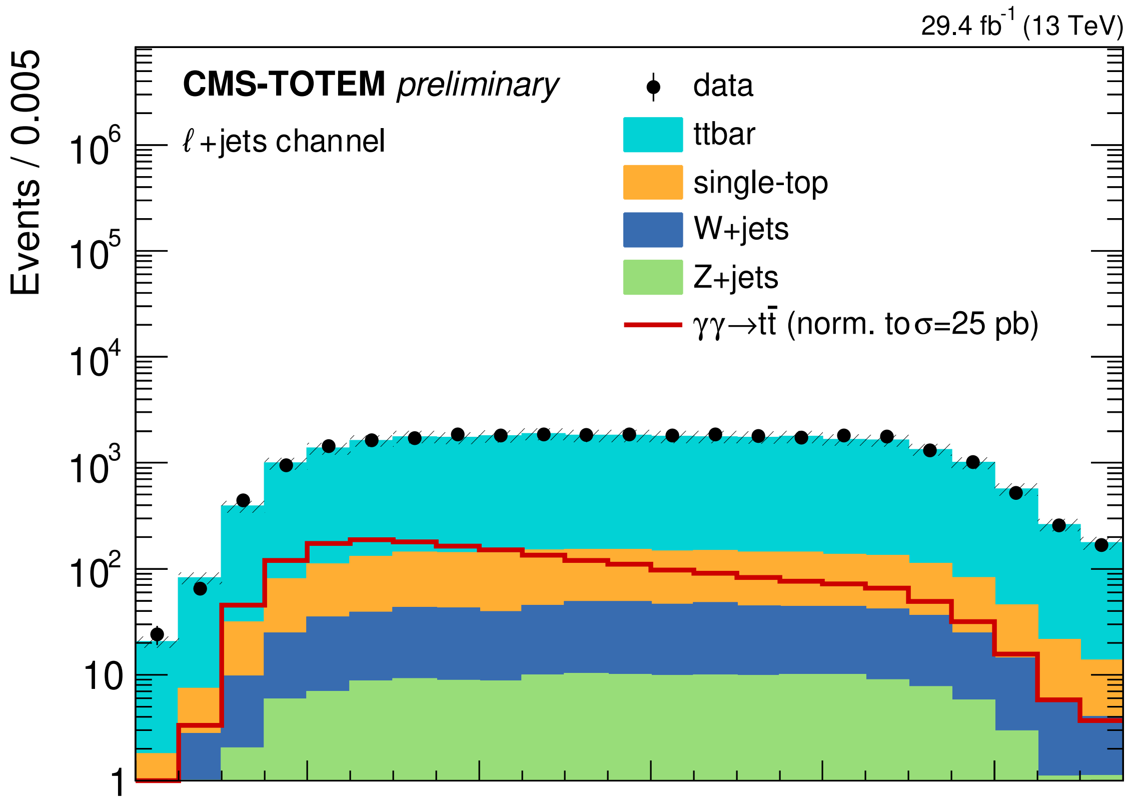


Signal simulation, before and after kin. fit

Backgrounds







LHC produces a large number of "pileup" collisions in every bunch crossing, some of which contain forward protons

Creates a dominant combinatorial background, when real $t\bar{t}$ events are combined with pileup protons

These backgrounds are modeled by event mixing: real protons from data with a loose selection are combined with simulated background samples

Signal efficiency is also corrected for the effect of extra pileup protons

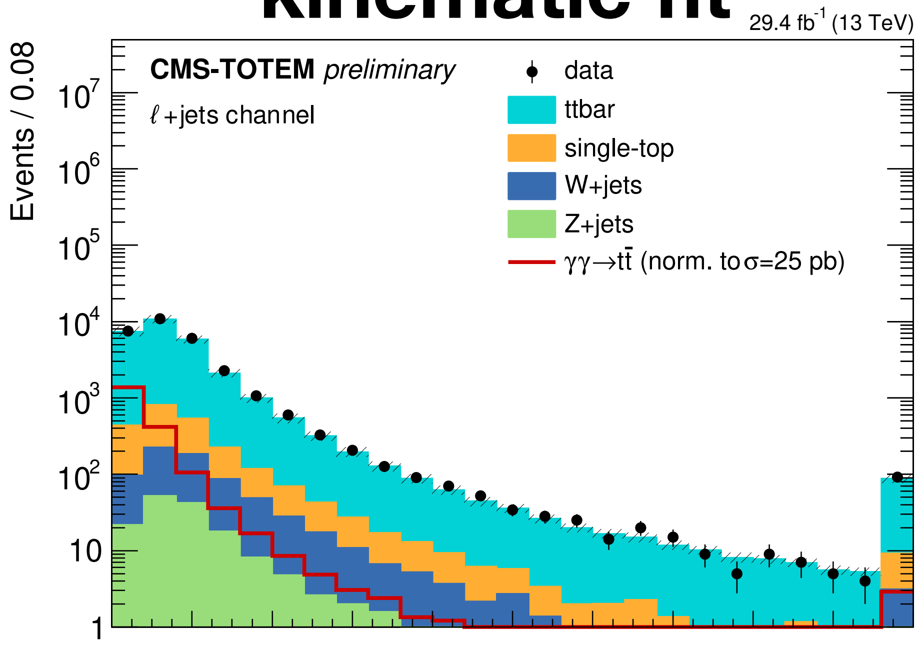
Gives a good description of the proton ξ distribution of the final selection

Discriminating variables

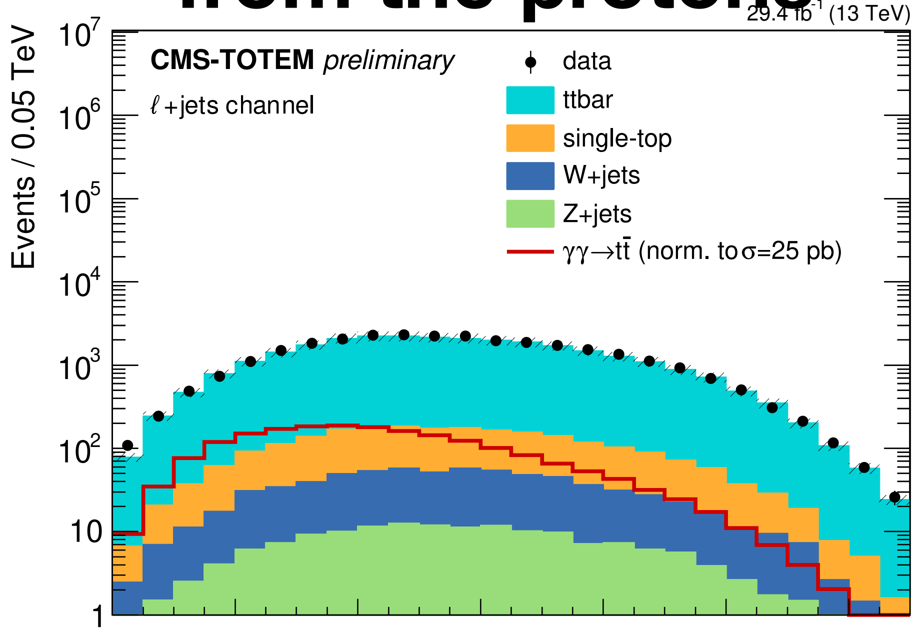
In each channel a boosted decision tree is used to extract the final result, combining a number of variables - notable discriminating variables:

lepton+jets

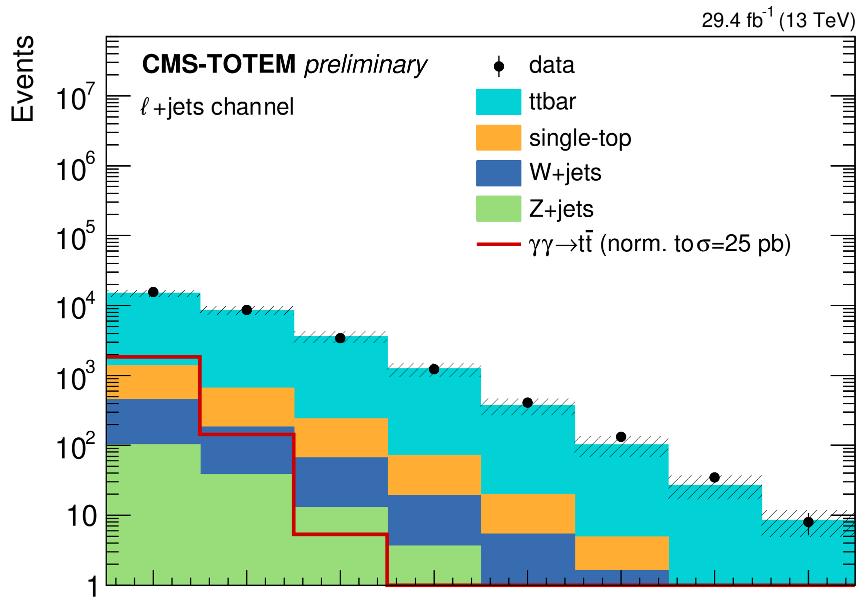
χ2 of the kinematic fit



mass+rapidity from the protons

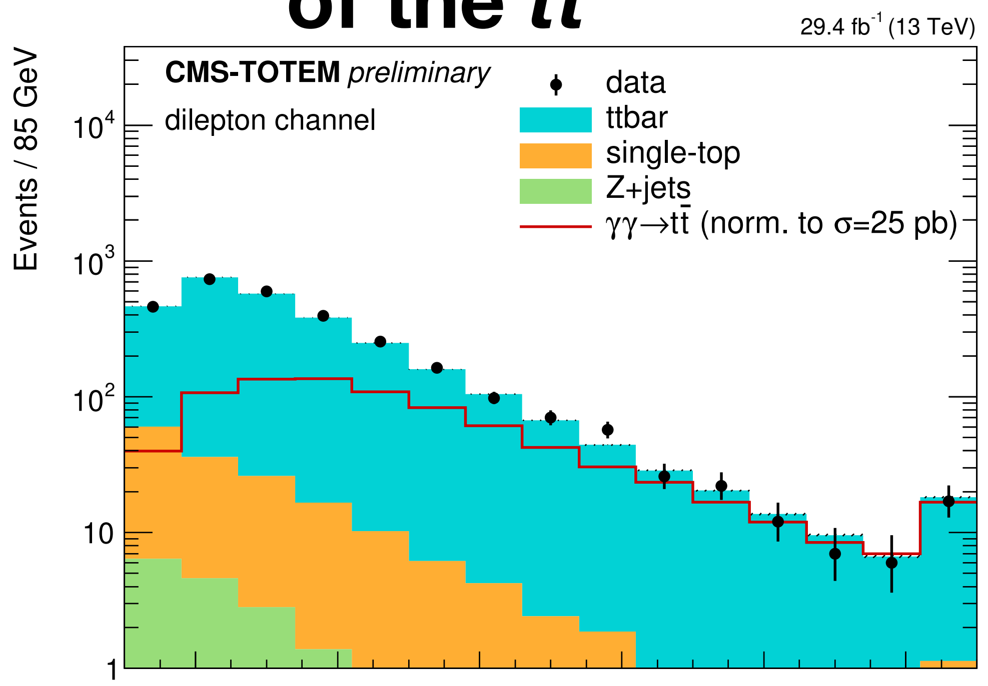


jet multiplicities

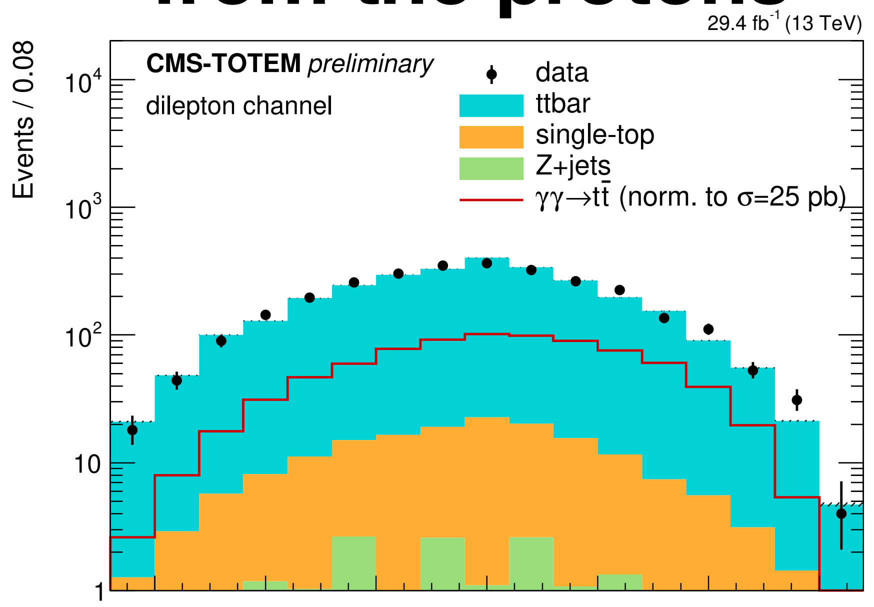


dilepton

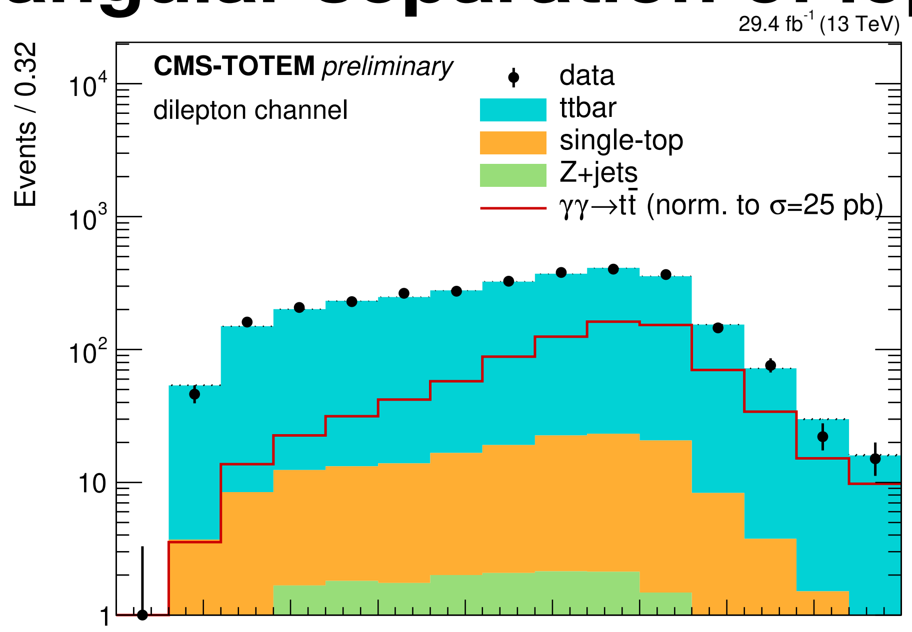
mass+rapidity of the $t\bar{t}$



mass+rapidity from the protons

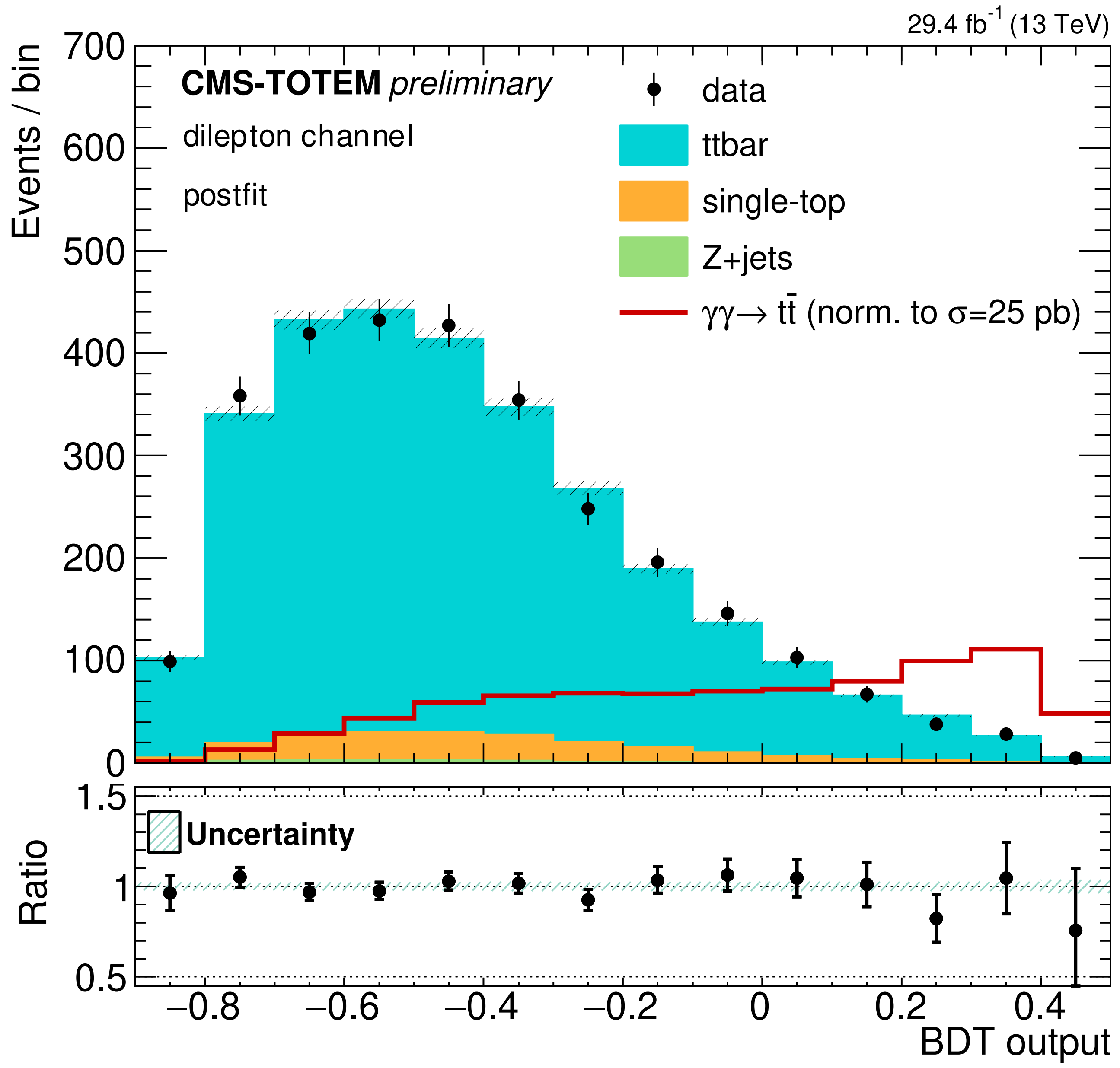


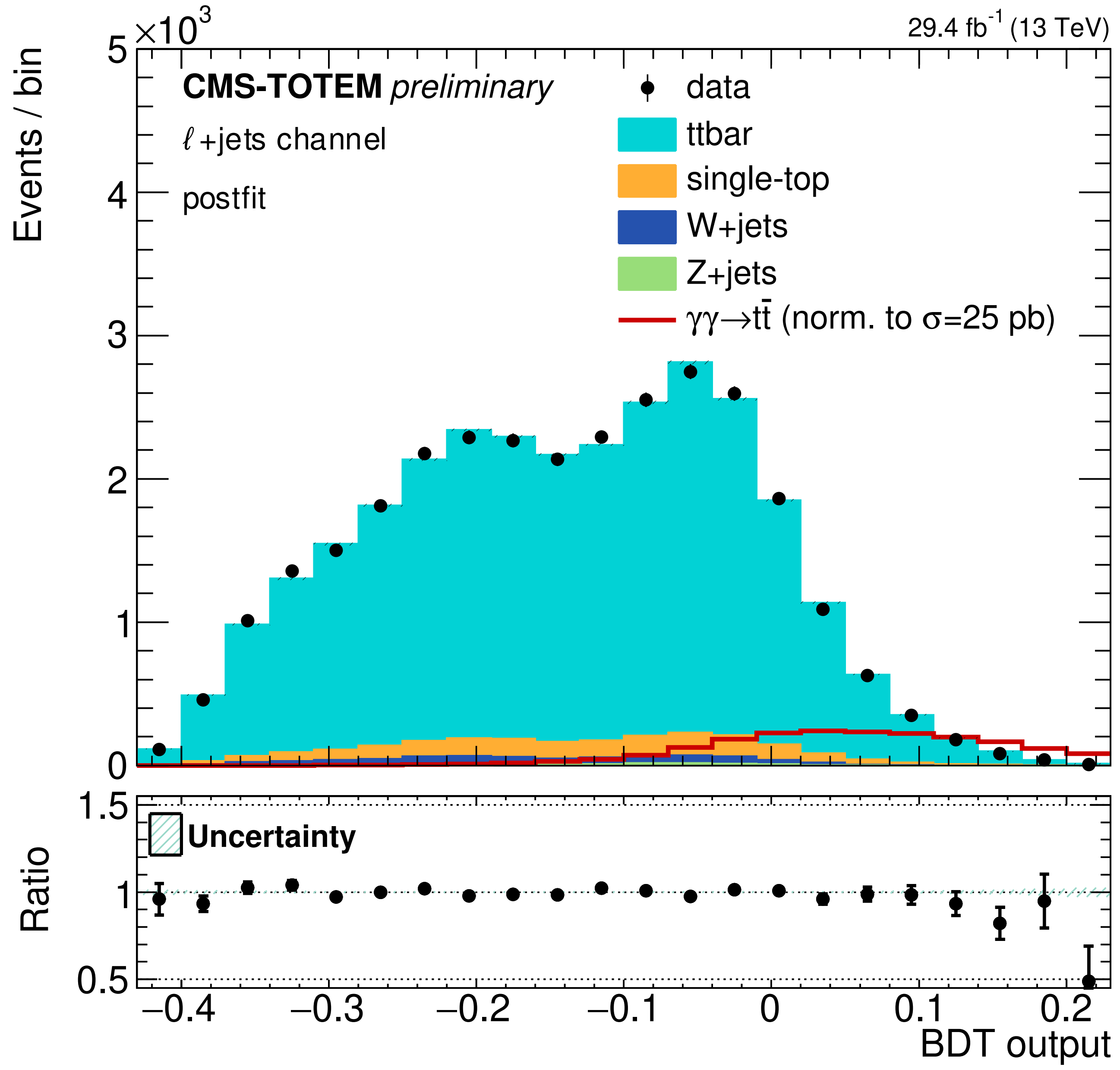
angular separation of leptons



BDT and systematics

Final signal extraction is performed using the BDT output distribution





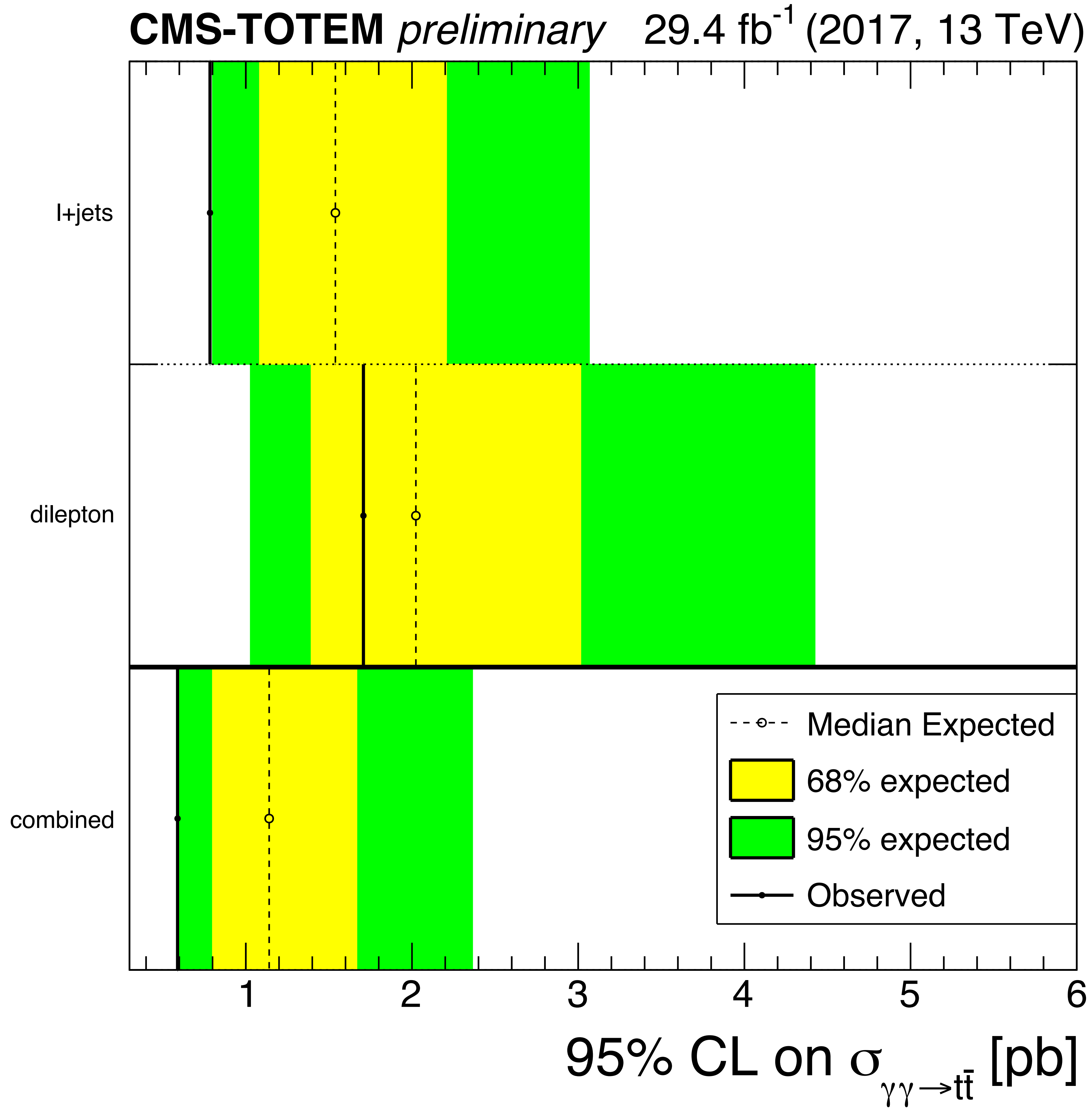
Uncertainties include

Statistical (dominant)

Experimental systematics: lepton+ b-tagging efficiencies, jet energy scale, luminosity, proton mixing sample selection, proton ξ reconstruction

Theory: PDFs, parton showering/ISR/FSR, factorization/renormalization scales, normalization of sub-leading backgrounds

Exclusive $\gamma\gamma \rightarrow t\bar{t}$ results



No excesses seen over the SM background prediction

Statistical combination of both channels gives observed (expected) limits of:

σ < 0.59 (1.14) pb at 95% CL

First limits on this process

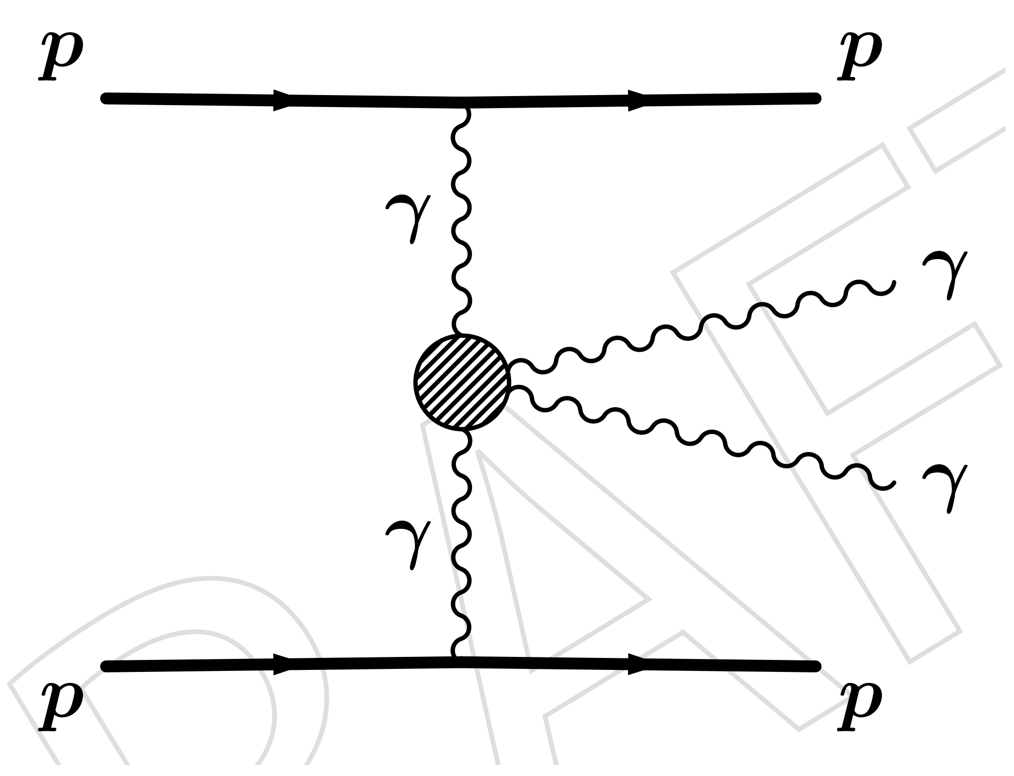
Still far from SM sensitivity with 2017 data

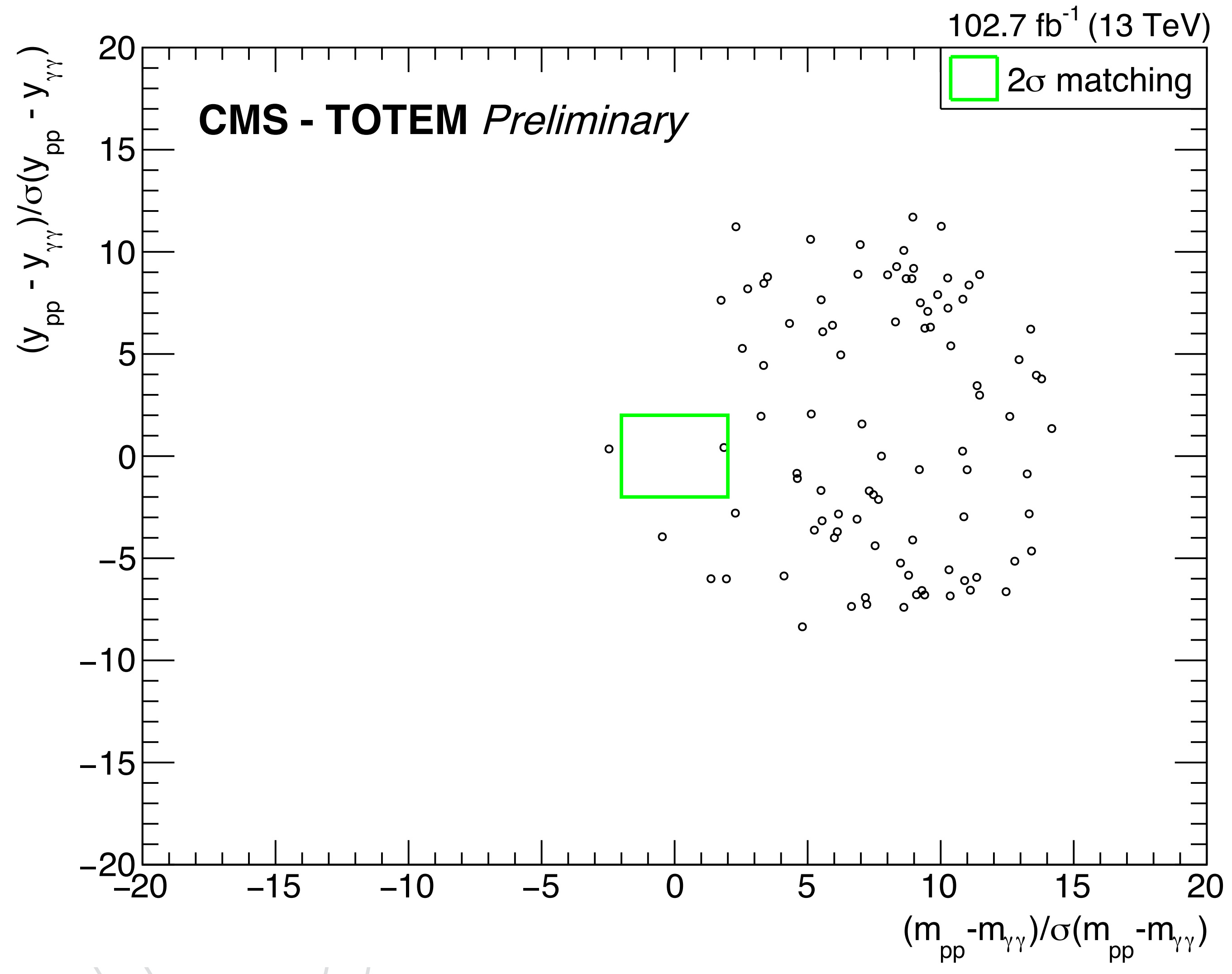
Other indirect searches by colliding photons: anomalous couplings and Effective Field Theories

$\gamma\gamma \to \gamma\gamma$

Very simple QED process, enhanced in most BSM scenarios

- Anomalous quartic gauge couplings
- Extra dimensions - resonant (RS gravitons) or non-resonant
- SUSY
- Axion-like particles
- Magnetic monopoles/monopolium
- “Non-commutative QED”
- …





Very low background search (estimated with event mixing): in full Run 2 data 1.10±0.24 background events expected, 1 observed

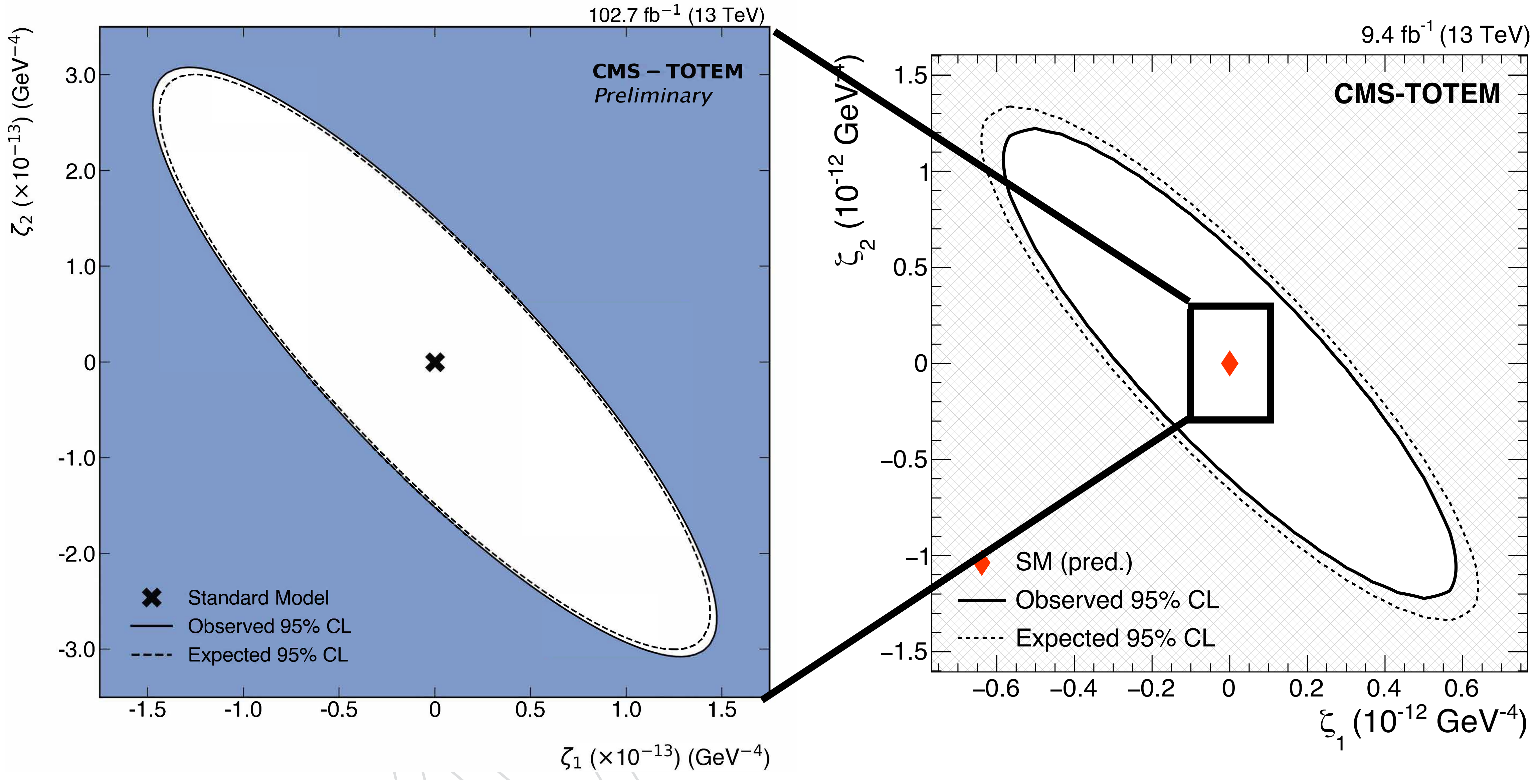
$\gamma\gamma\rightarrow\gamma\gamma$: Constraints on Anomalous Quartic Gauge Couplings

First collider limits on anomalous γγγγ couplings were published by CMS, using 2016 data with 9.4fb^{-1}

New limits using the full Run 2 dataset (102.7 fb^{-1}) improve on these by a factor of ~4

Full Run 2

2016 only



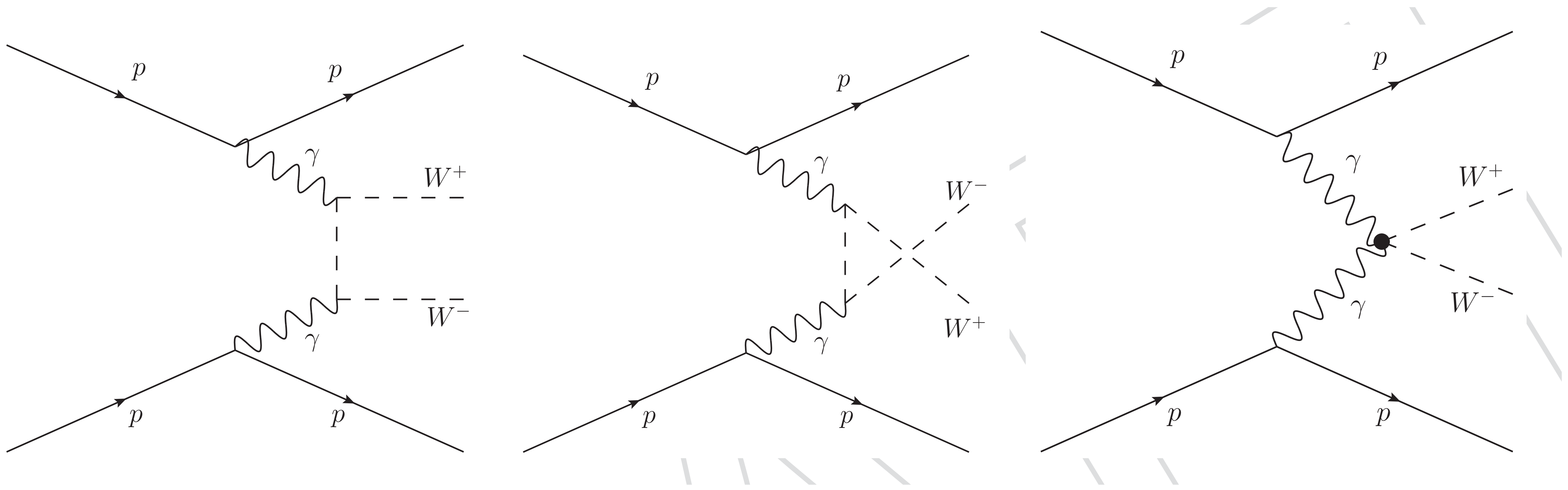
$$|\zeta_1| < 7.3(7.1) \times 10^{-14}\ \mathrm{GeV}^{-4} \quad (\zeta_2 = 0),$$
$$|\zeta_2| < 1.5(1.5) \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_1 = 0).$$

$$|\zeta_1| < 2.88 \times 10^{-13}\ \mathrm{GeV}^{-4} (\zeta_2 = 0),$$
$$|\zeta_2| < 6.02 \times 10^{-13}\ \mathrm{GeV}^{-4} (\zeta_1 = 0).$$

Phys.Rev.Lett. 129 (2022) 011801

CMS-PAS-EXO-21-007

$\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$:



Similar idea as $\gamma\gamma \rightarrow \gamma\gamma$, except using massive gauge bosons

WW: allowed in the SM

ZZ: forbidden at tree-level in the SM

Search performed in the high-mass region (>1.1 TeV), where any SM signal is expected to be negligible

Use boosted all-hadronic channel, where W/Z's are expected to be merged into a single "fat" jet

Backgrounds estimated from sideband regions in diboson acoplanarity, proton-diboson matching

Analysis performed for each year of Run 2, using events with 1 or 2 protons matched

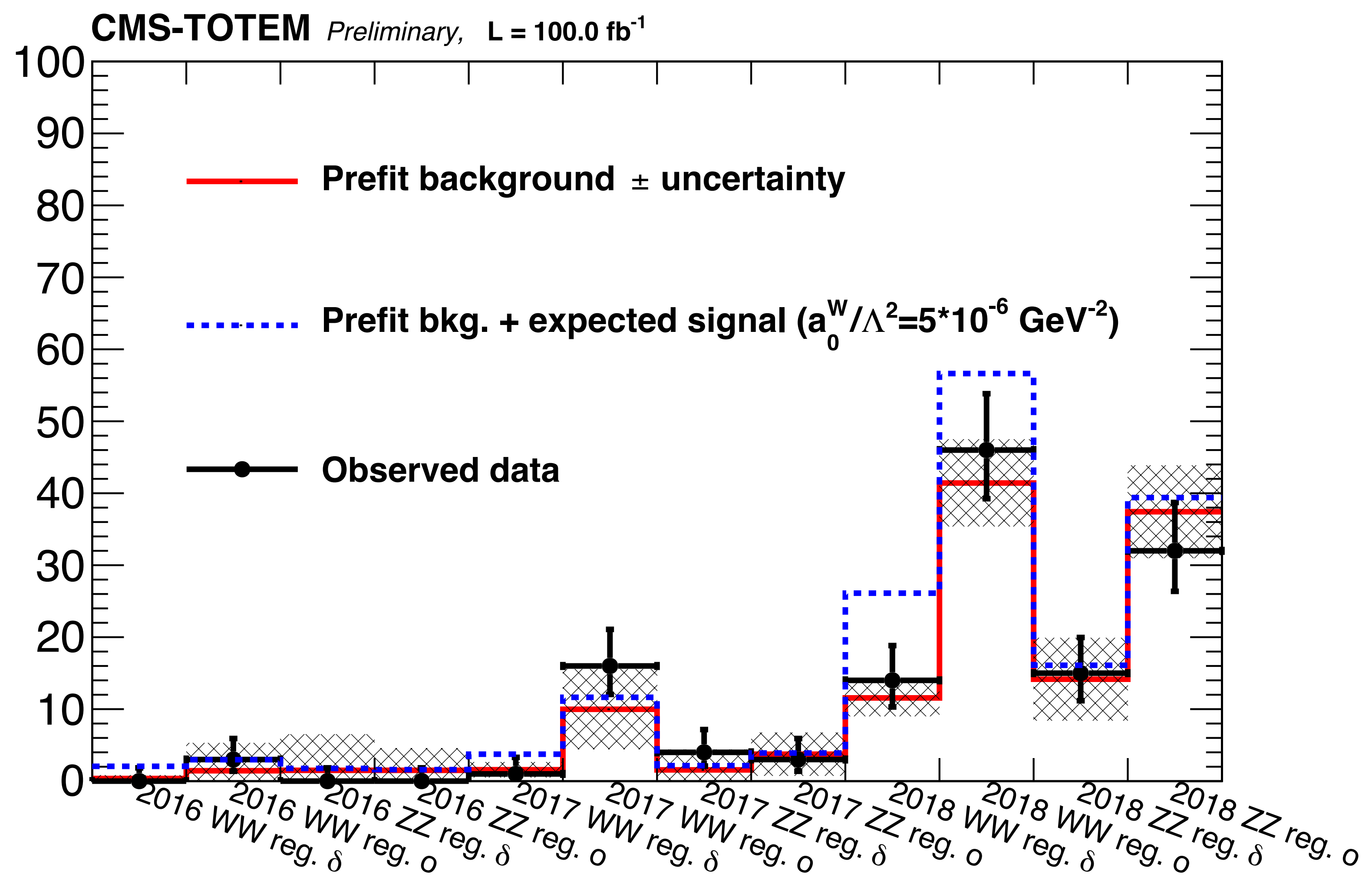
CMS-PAS-SMP-21-014

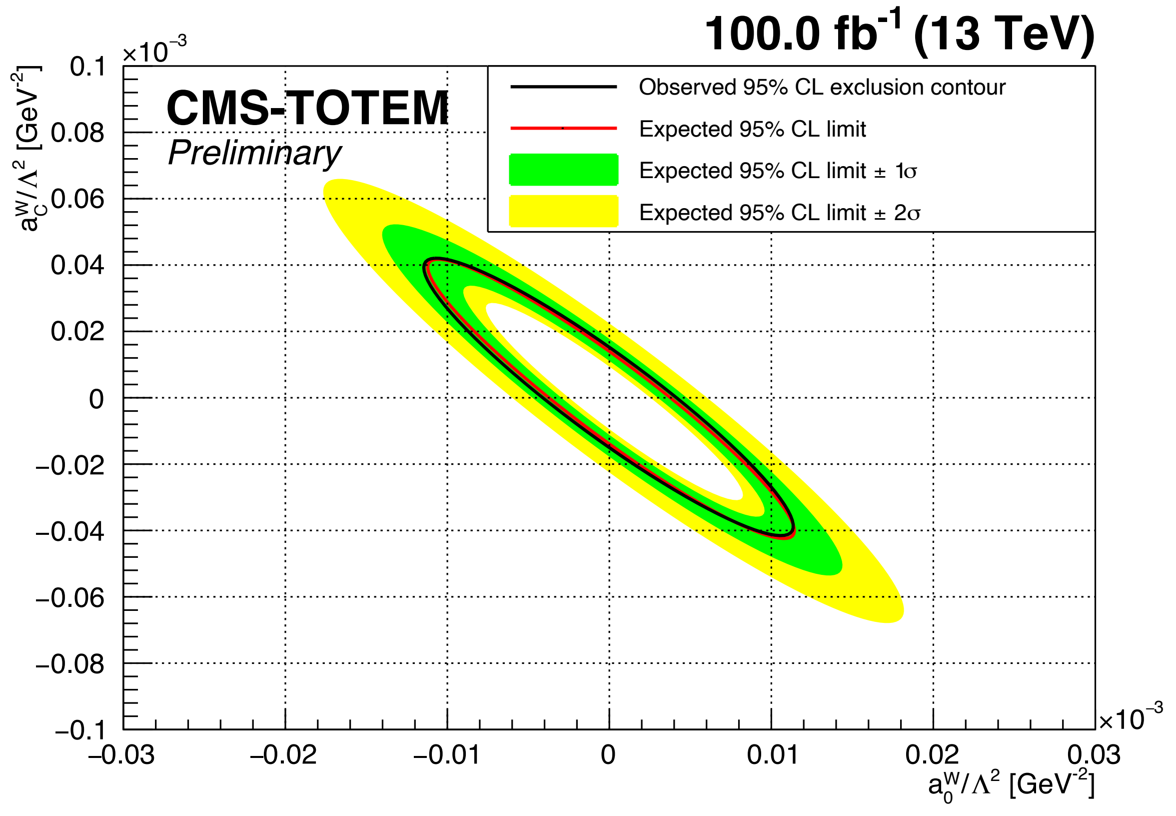
$\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$: Constraints on Anomalous Quartic Gauge Couplings

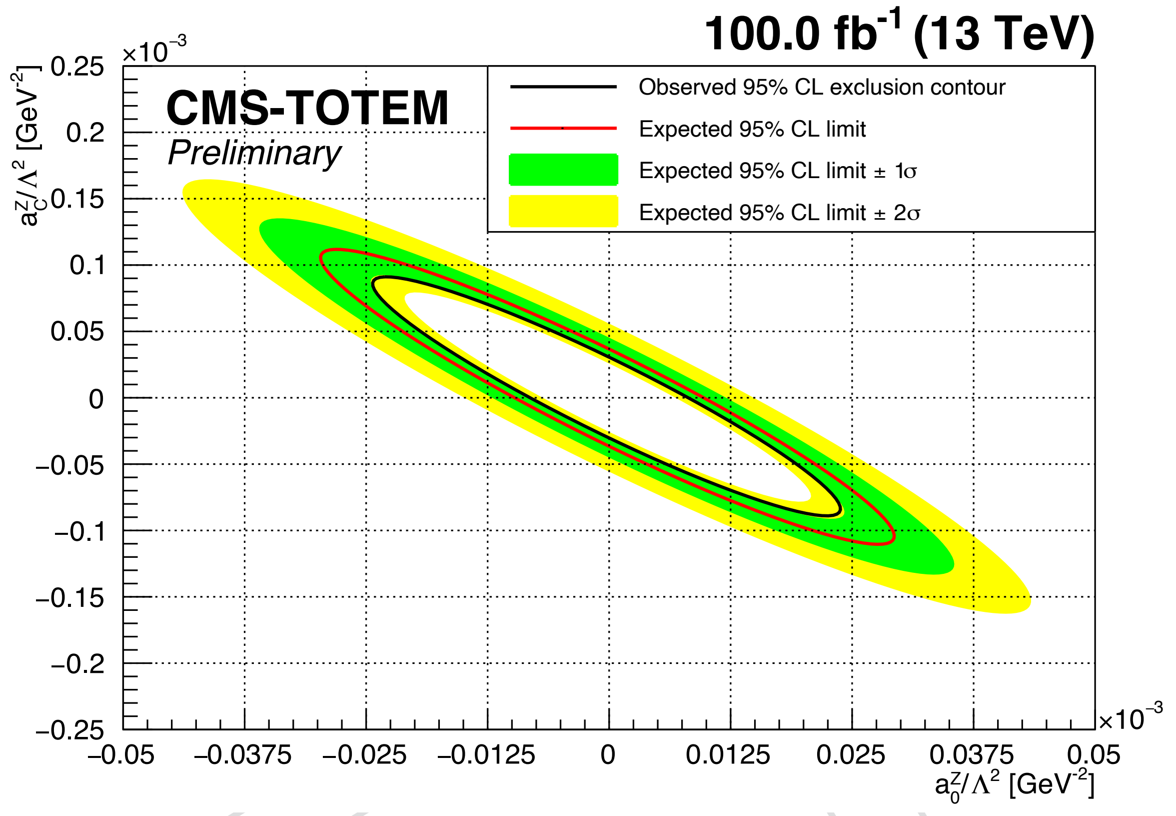
Analysis based on full Run 2 dataset ($100fb^{-1}$)

No significant excess in any final states (WW or ZZ), years (2016, 2017, 2018), or proton reconstruction choices (single- or double-arm)

Limits set on cross sections, and anomalous quartic gauge couplings of dimension-6 and dimension-8, with and without unitarization

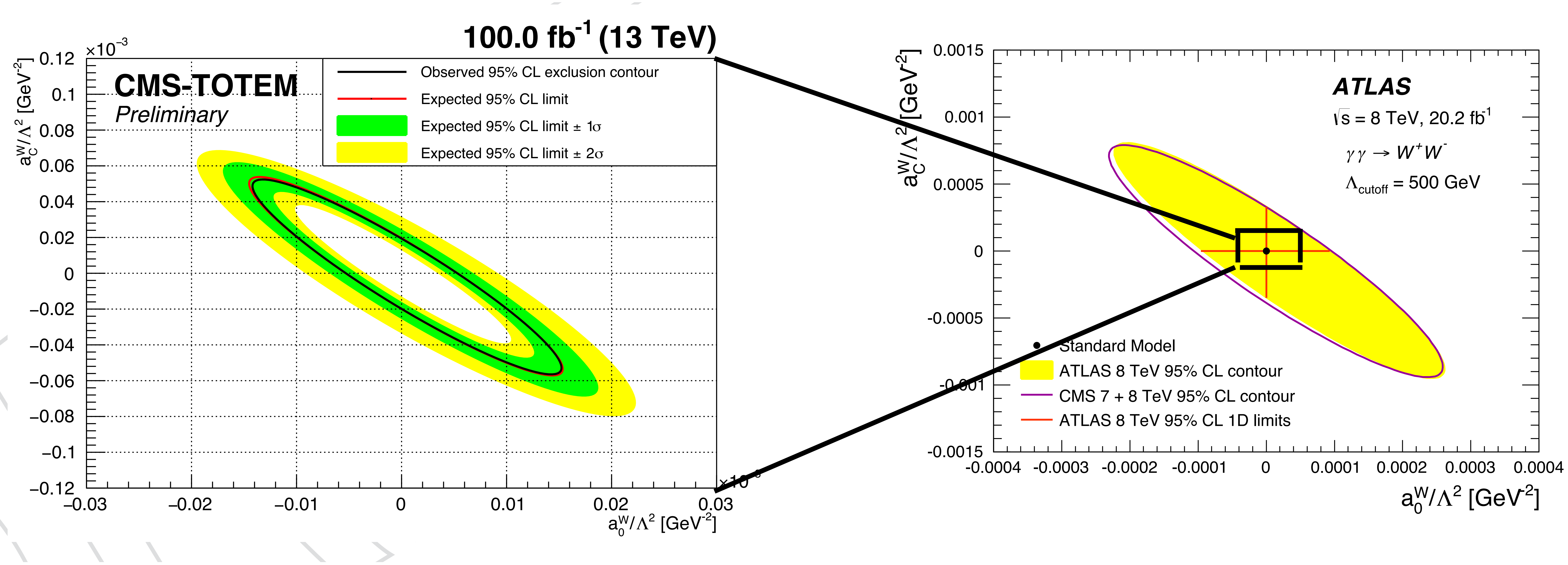






CMS-PAS-SMP-21-014

$\gamma\gamma \to WW$ and $\gamma\gamma \to ZZ$: Constraints on Anomalous Quartic Gauge Couplings



Various subtleties comparing results (dimension-6 vs. dimension-8 couplings, unitarization scheme)

Constraints are generally much more stringent than those from the γγ→WW channel without proton tagging in LHC Run 1

CMS-PAS-SMP-21-014

Direct searches by colliding photons

Direct searches

If BSM physics is light enough (<2 TeV), new particles produced in central exclusive processes could be directly detected using tagged protons

In most cases models are strongly constrained by other LHC searches

=> Focus on scenarios where proton tagging of γγ collisions can provide unique sensitivity

Particles that can be detected thanks to the closed kinematics

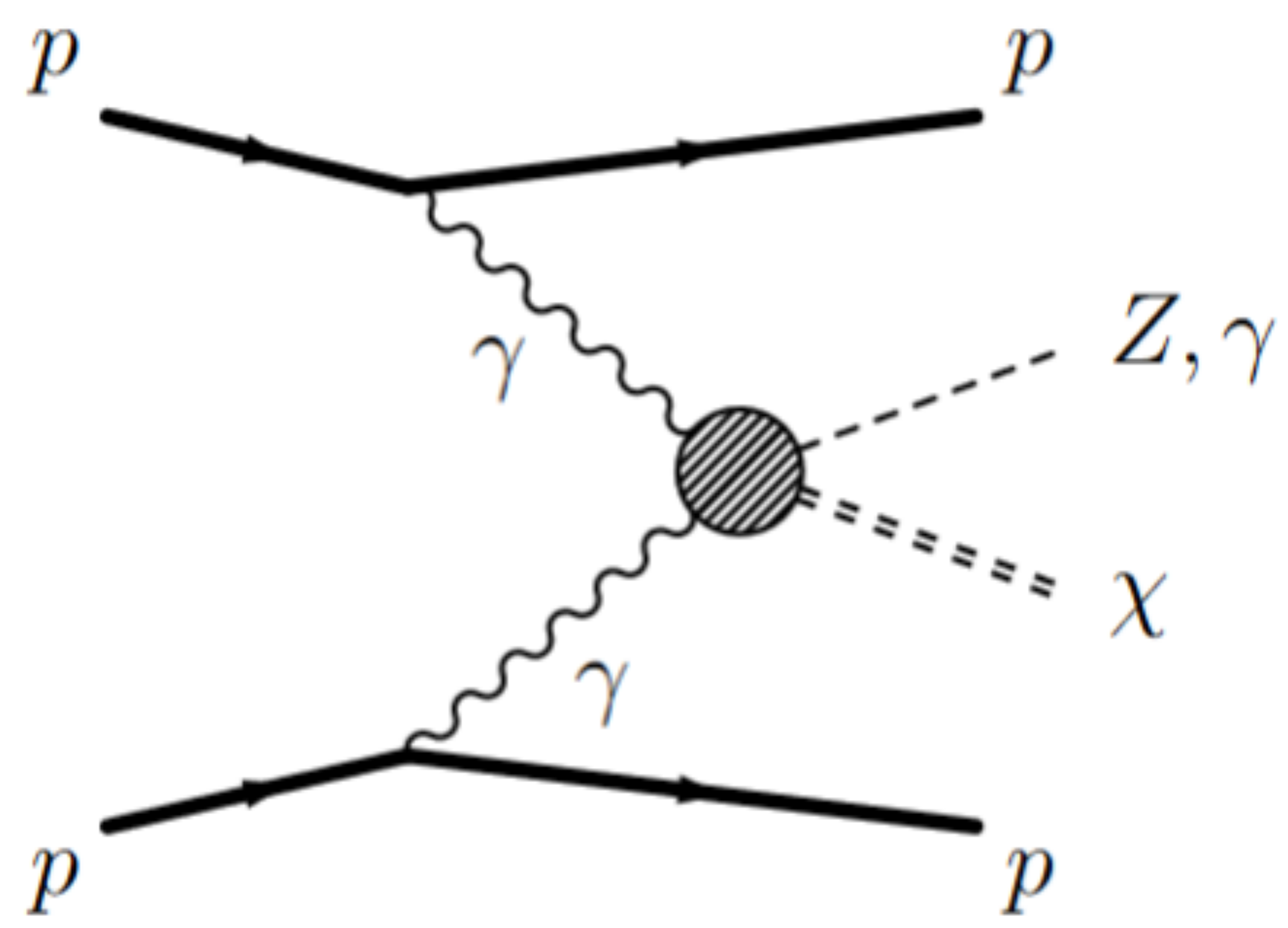
Particles with large couplings to photons

Search for (possibly) invisible particles in the *Z*+*X* and *γ*+*X* “missing mass” spectrum

Reconstruct the pp+Z or pp+γ system, and look for anything “left over” from the 13 TeV collision energy

Analogous to a “recoil analysis” at e+e- colliders

First use of this technique at a hadron collider



The missing “X” could be any new heavy particle, including ones that are invisible, long-lived, or otherwise difficult to reconstruct

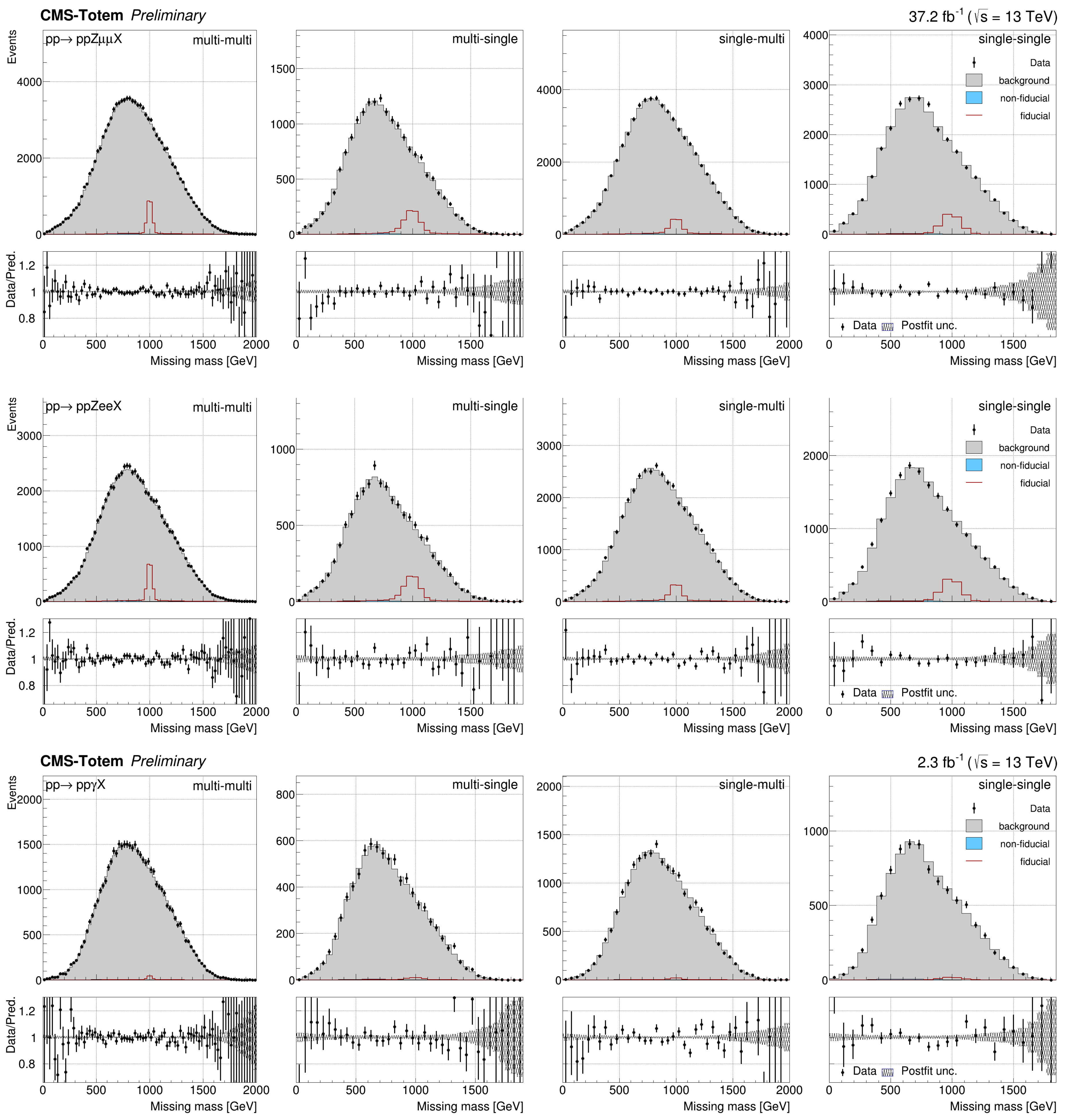
CMS-PAS-EXO-19-009

Search for (possibly) invisible particles in the *Z*+*X* and *γ*+*X* “missing mass” spectrum

Analysis uses 37.2 fb^{-1} of data from 2017

Categorized by final state and different proton reconstruction algorithms

Backgrounds are determined from event mixing and control regions (e-mu)



Search for (possibly) invisible particles in the *Z+X* and *γ+X* "missing mass" spectrum

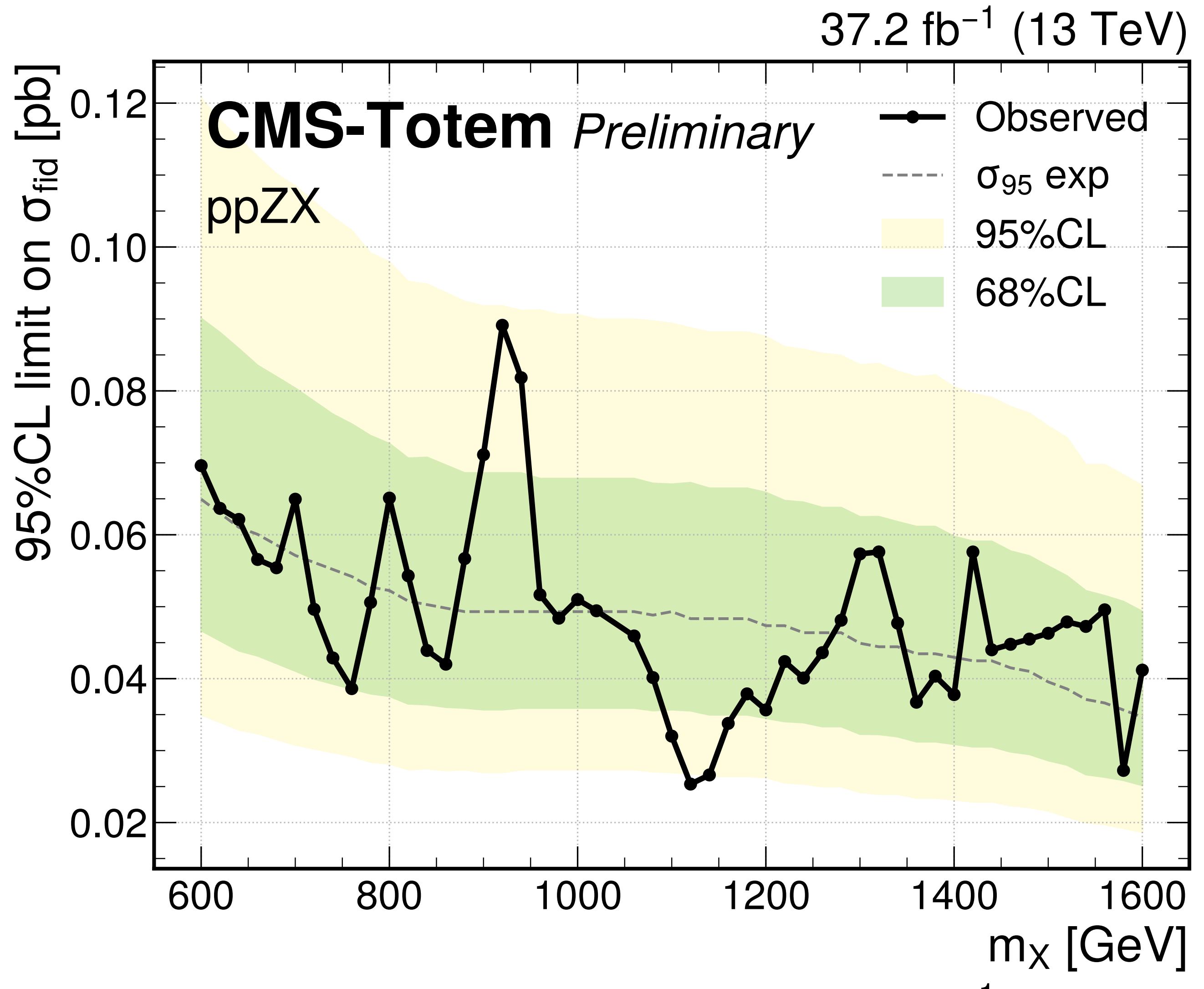
Limits on associated production of any "X" particles on the order of ~50fb (Z+X) to ~1pb (γ+X), from 600-1600 GeV

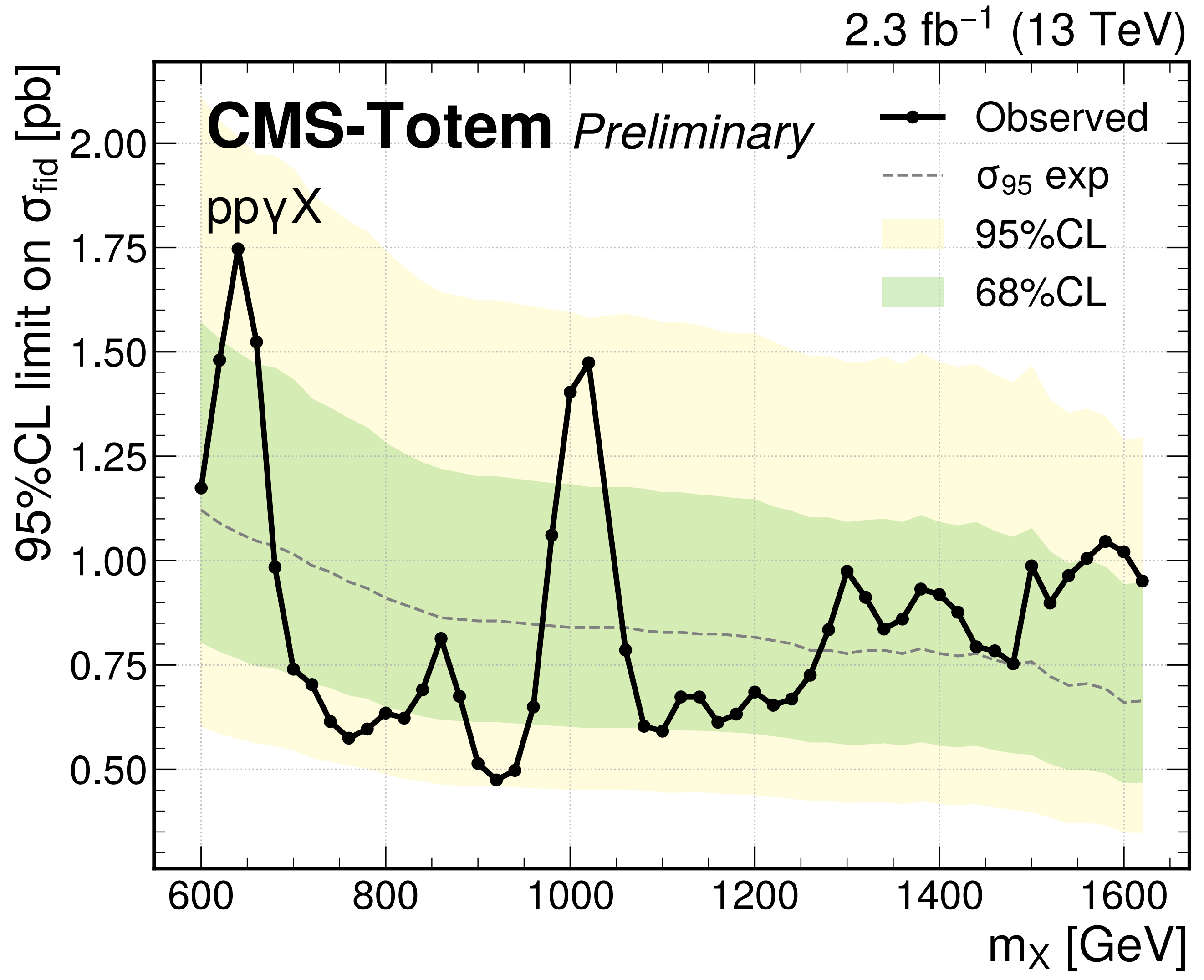
Largest local excesses within ~2σ

γ+X limits are weaker due to prescaled single-photon trigger

Currently uses only ~1/3 of the available PPS Run 2 data, and no timing information

Still room for improvement with Run 2 data, + Run 3





CMS-PAS-EXO-19-009

$\gamma\gamma \to \gamma\gamma$: Search for Axion-Like Particles

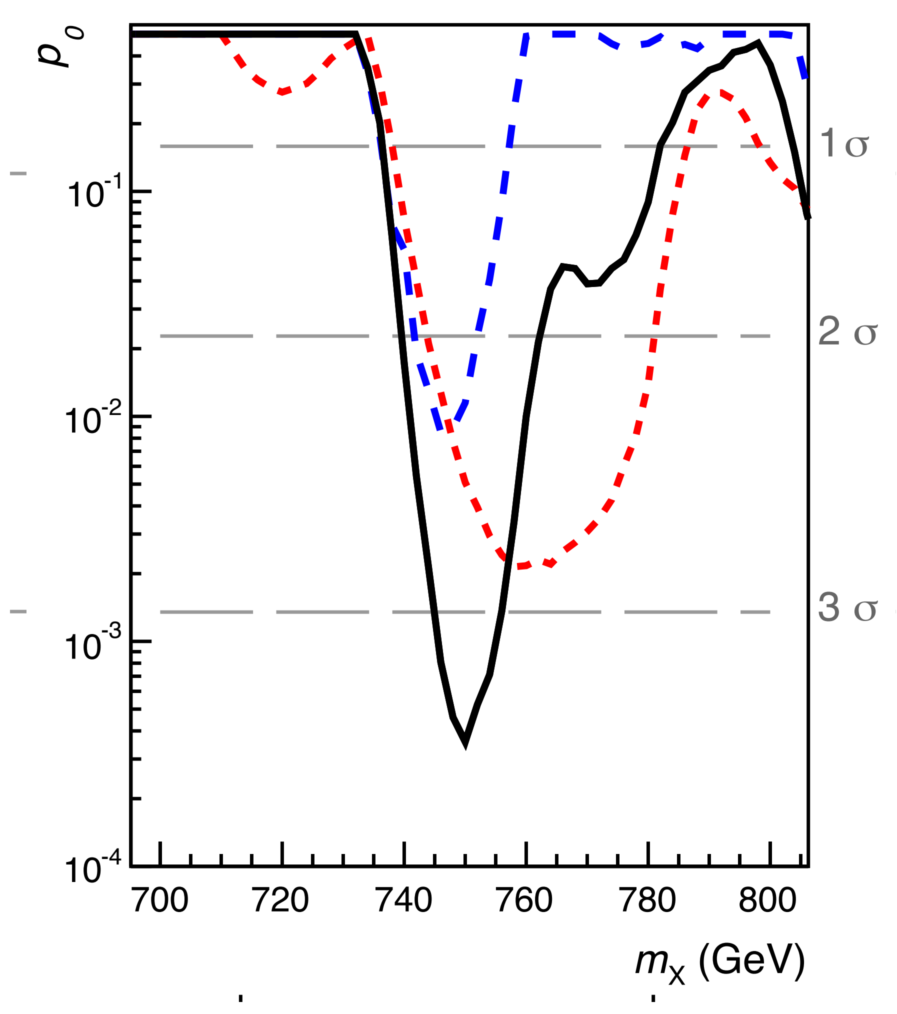
Initial idea of axions: very light pseudoscalar particle, to solve the strong CP problem, and possibly provide a dark matter candidate

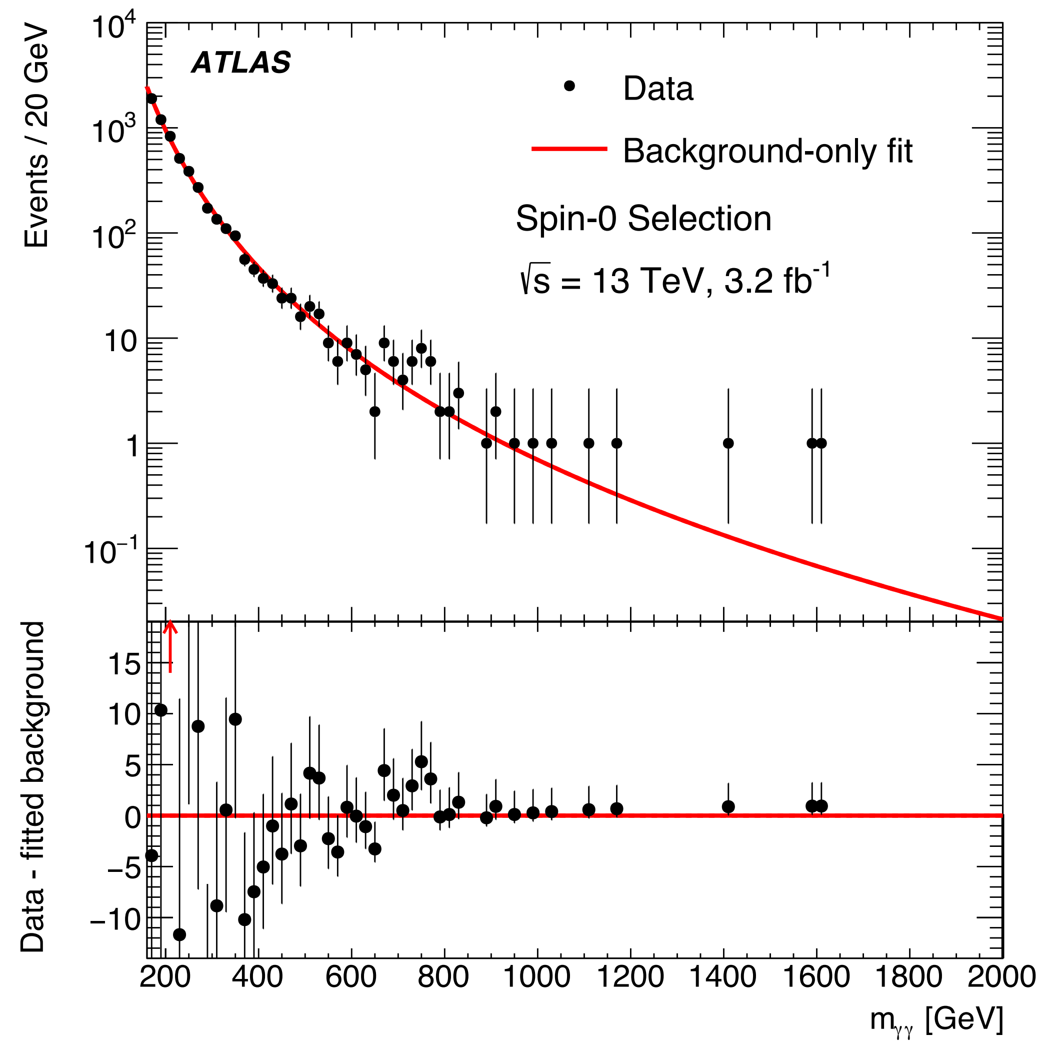
Recent interest in much heavier "axion-like" particles with large couplings to photons

Extension of the anomalous couplings analysis, looking for a narrow resonance instead of a broad excess

Historical interest: 750GeV diphoton bump reported by ATLAS+CMS at the beginning of LHC Run 2

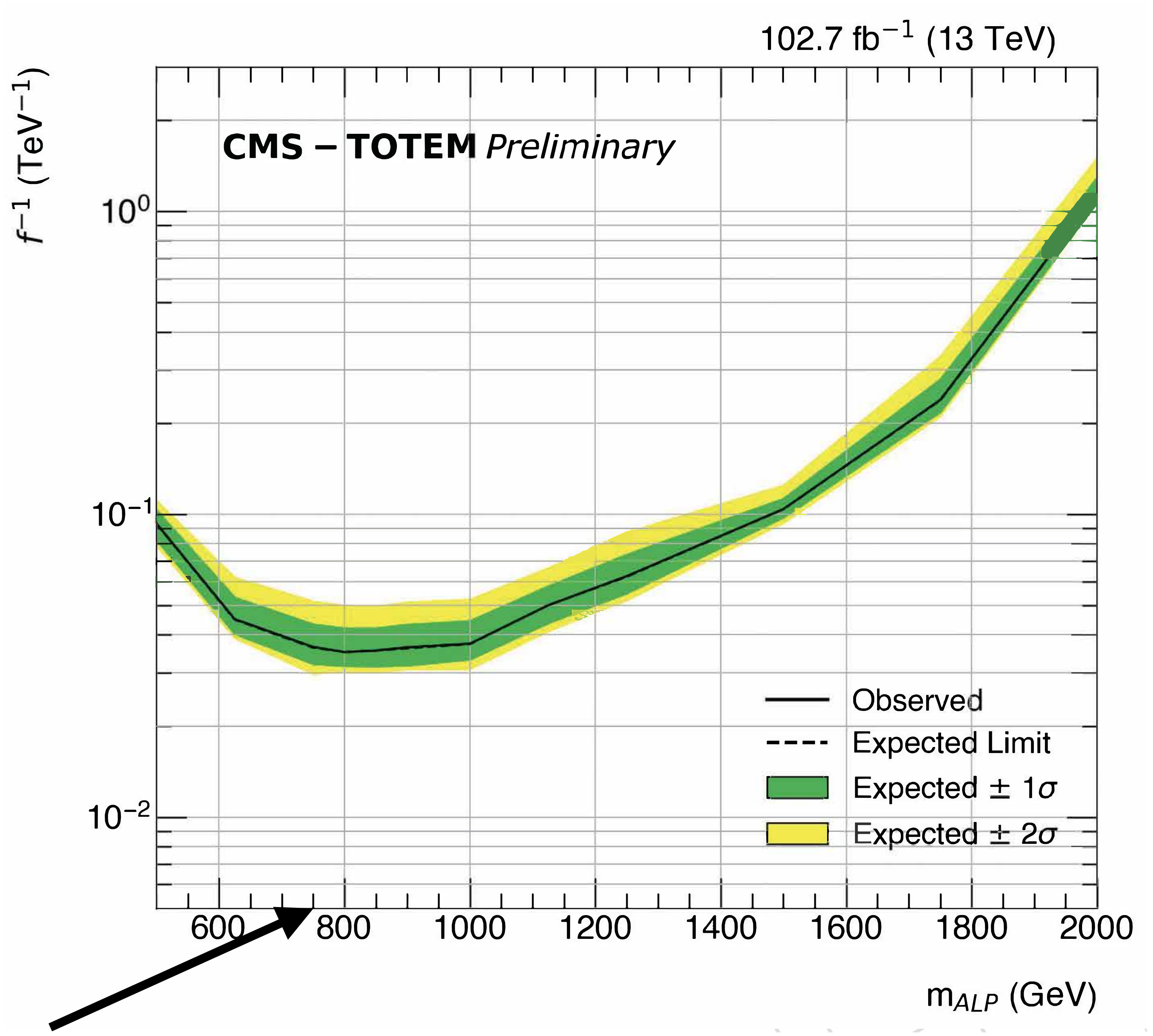
Not confirmed, but recognized as a golden channel to study in γγ collisions



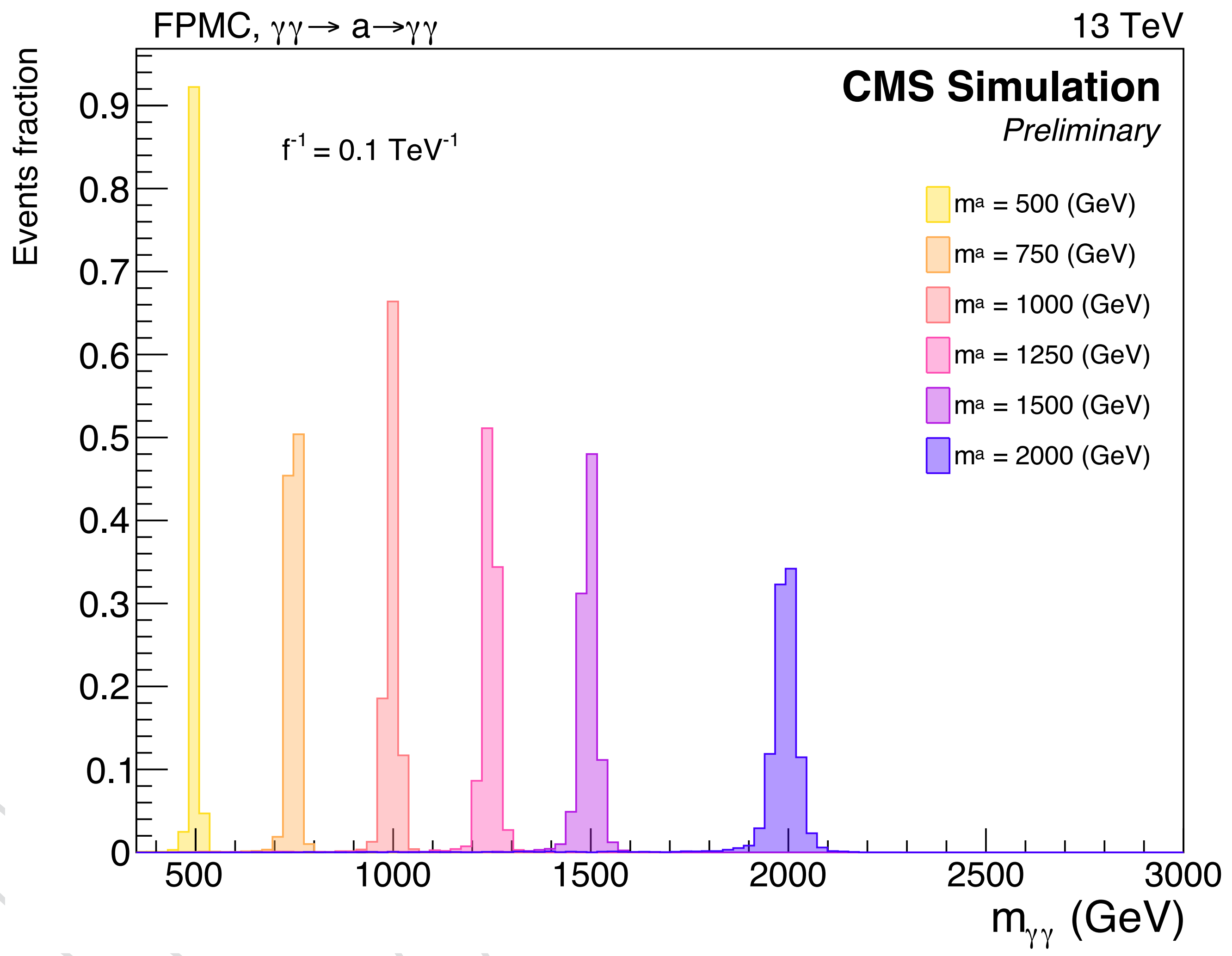


$\gamma\gamma \rightarrow \gamma\gamma$: Search for Axion-Like Particles

Reinterpretation of the anomalous couplings analysis, with signal modeled as a narrow resonance



Notable: Best sensitivity is near 750 GeV, no excess seen

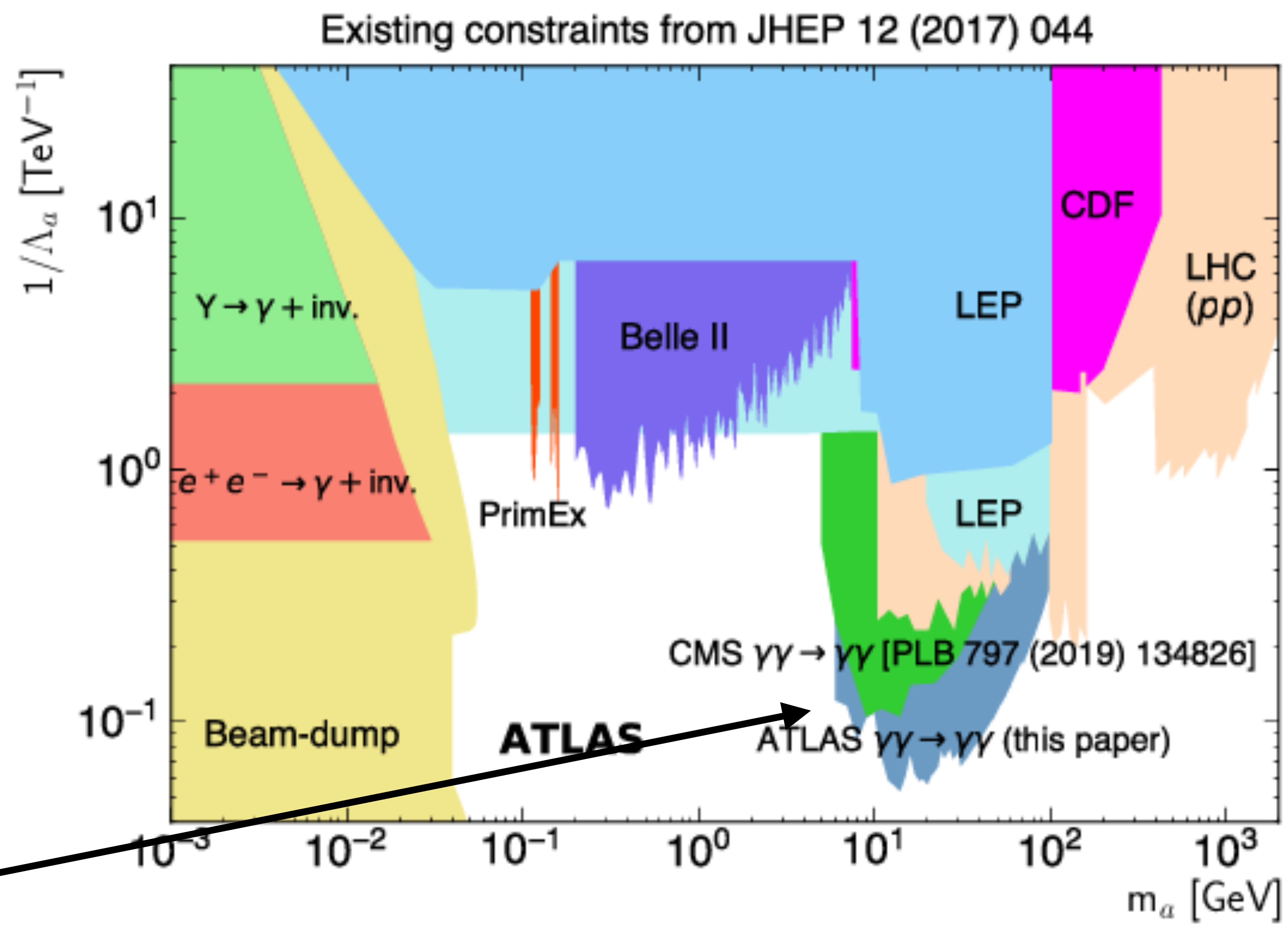


Signal simulation for different ALP masses

Since no excess is seen, new limits placed on mass/coupling of axion-like particles at the TeV scale

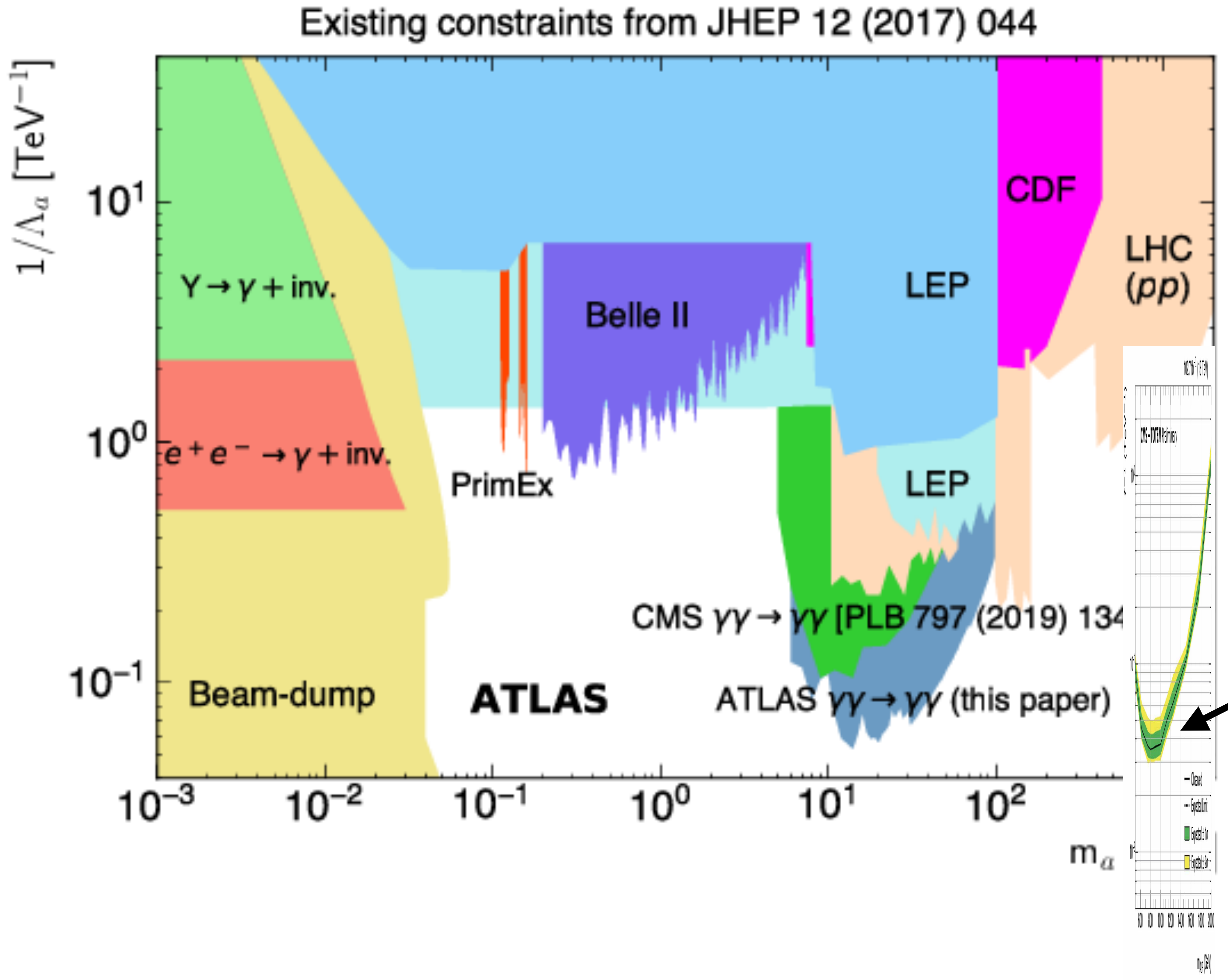
CMS-PAS-EXO-21-007

$\gamma\gamma \rightarrow \gamma\gamma$: Search for Axion-Like Particles



Best limits from a few GeV to 100 GeV come from $\gamma\gamma \rightarrow \gamma\gamma$ in LHC heavy ion collisions ("Light-by-light scattering")

$\gamma\gamma\rightarrow\gamma\gamma$: Search for Axion-Like Particles



TeV scale limits from γγ→γγ with proton tagging

Summary (I)

A first search for top quark pair production from γγ interactions was performed by CMS using 29.4 fb^{-1} in the dilepton and lepton+jets channel

No excess was observed in either channel, and the first limits on the cross section were placed at < 0.59 pb

Building on previous work to verify Standard Model signals for very high energy γγ interactions, and extensive validation/calibration of forward proton reconstruction:

Summary (II)

Similar approaches were used to probe BSM physics in $\gamma\gamma$ collisions with intact protons in several other final states

Indirect searches

- **First+best** collider constraints on anomalous quartic gauge couplings in $\gamma\gamma \to \gamma\gamma$
- **New** constraints on anomalous quartic gauge couplings in $\gamma\gamma \to WW$, $\gamma\gamma \to ZZ$

Direct searches

- **First** "Missing mass" searches for resonances in Z+X, γ+X final states at a hadron collider
- **Best** limits on axion-like particles from $\gamma\gamma \to \gamma\gamma$ at ~TeV scale

Outlook

The LHC is likely to be the best (and cheapest) high energy photon collider available for a long time

This mode of operation should be maximally exploited for SM and BSM physics

Still a lot to do with the large Run 2 data sample, + new Run 3 data now being collected

As well as the heavy ion $\gamma\gamma$ physics program, not covered here

References

$\gamma\gamma \to tt$: Summary

$\gamma\gamma \to \gamma\gamma$ (including ALPs): Full Run 2 result, 2016 publication

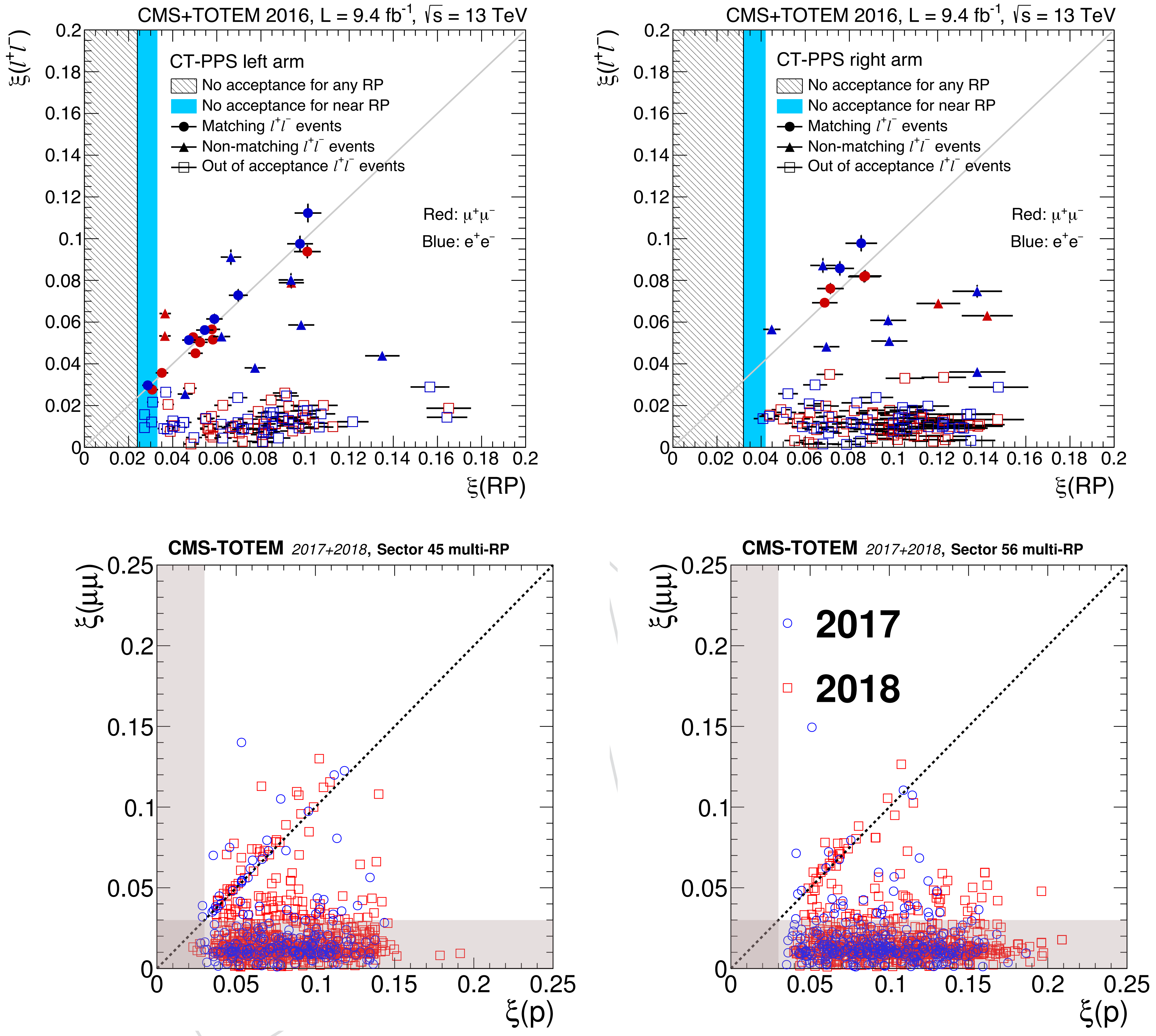
$\gamma\gamma \to WW/ZZ$: PAS

$\gamma\gamma \to Z+X/g+X$: Summary

Dileptons and proton reconstruction: PAS

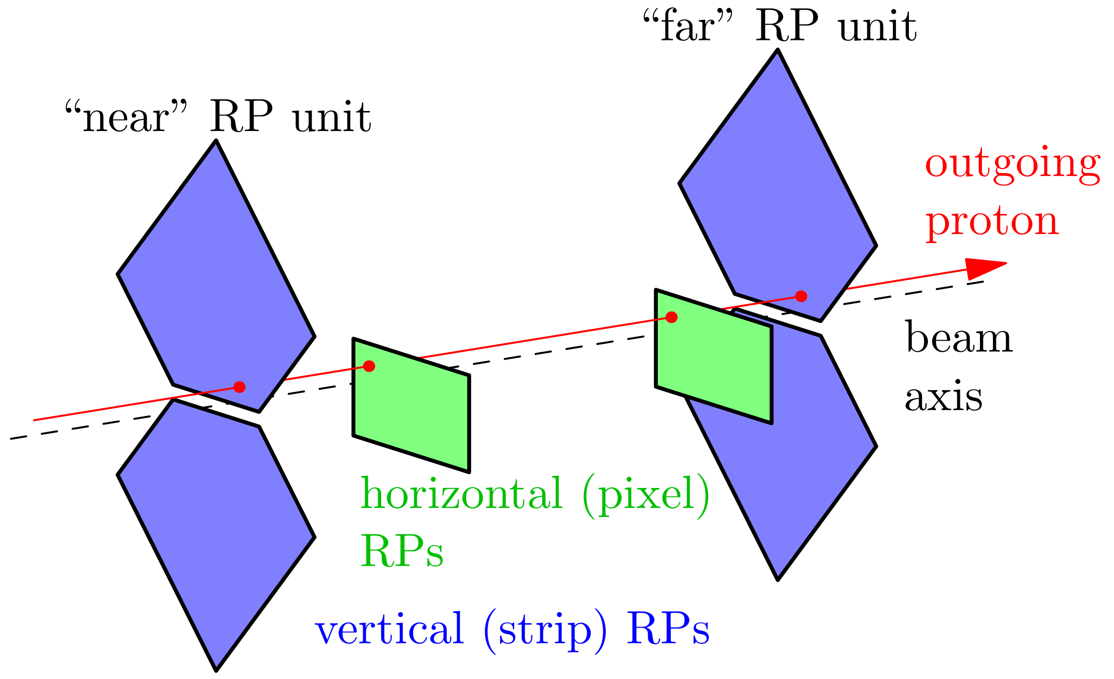
Extra

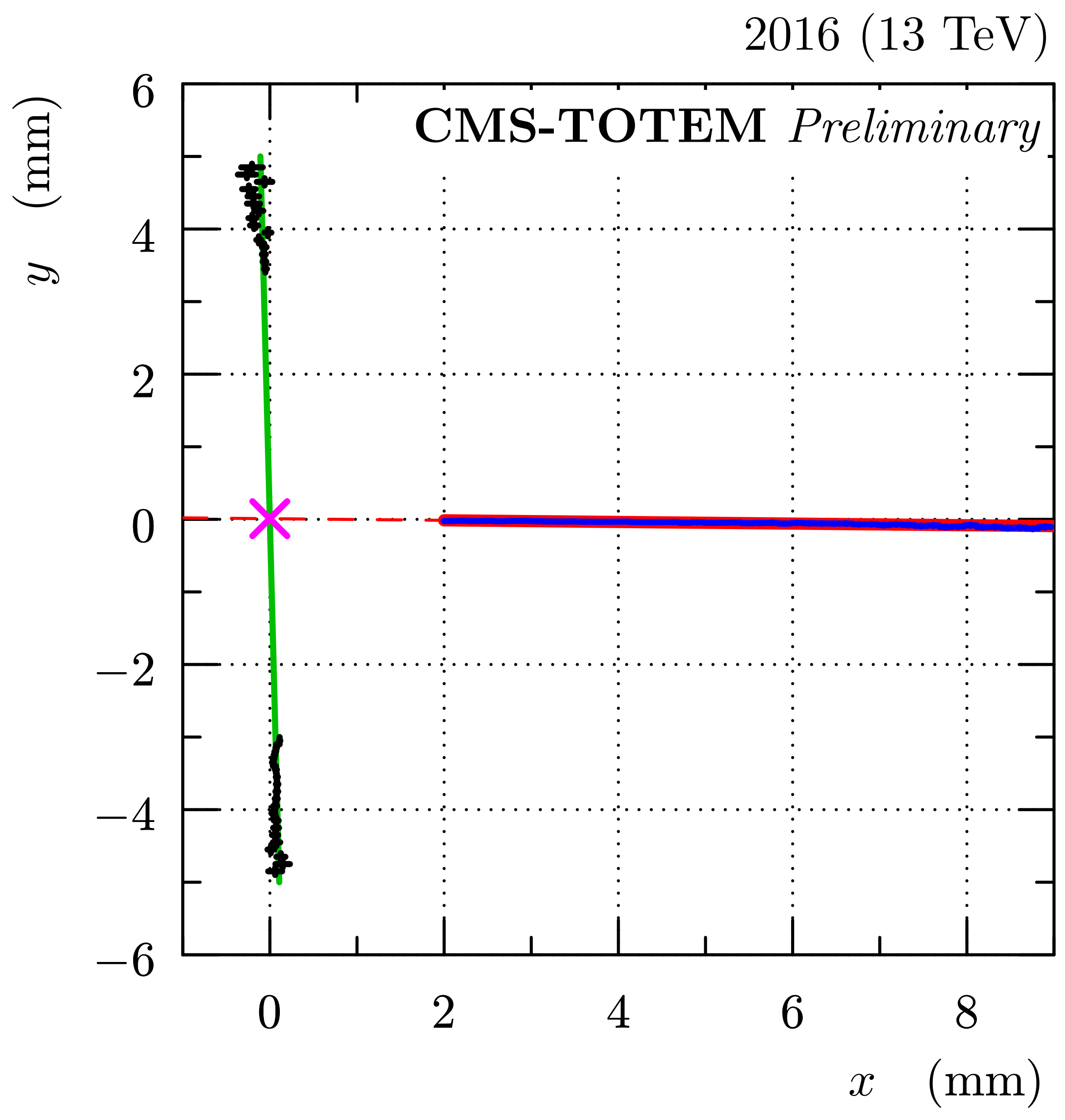
$\gamma\gamma \to ll$ and ξ reconstruction: 2-d correlations

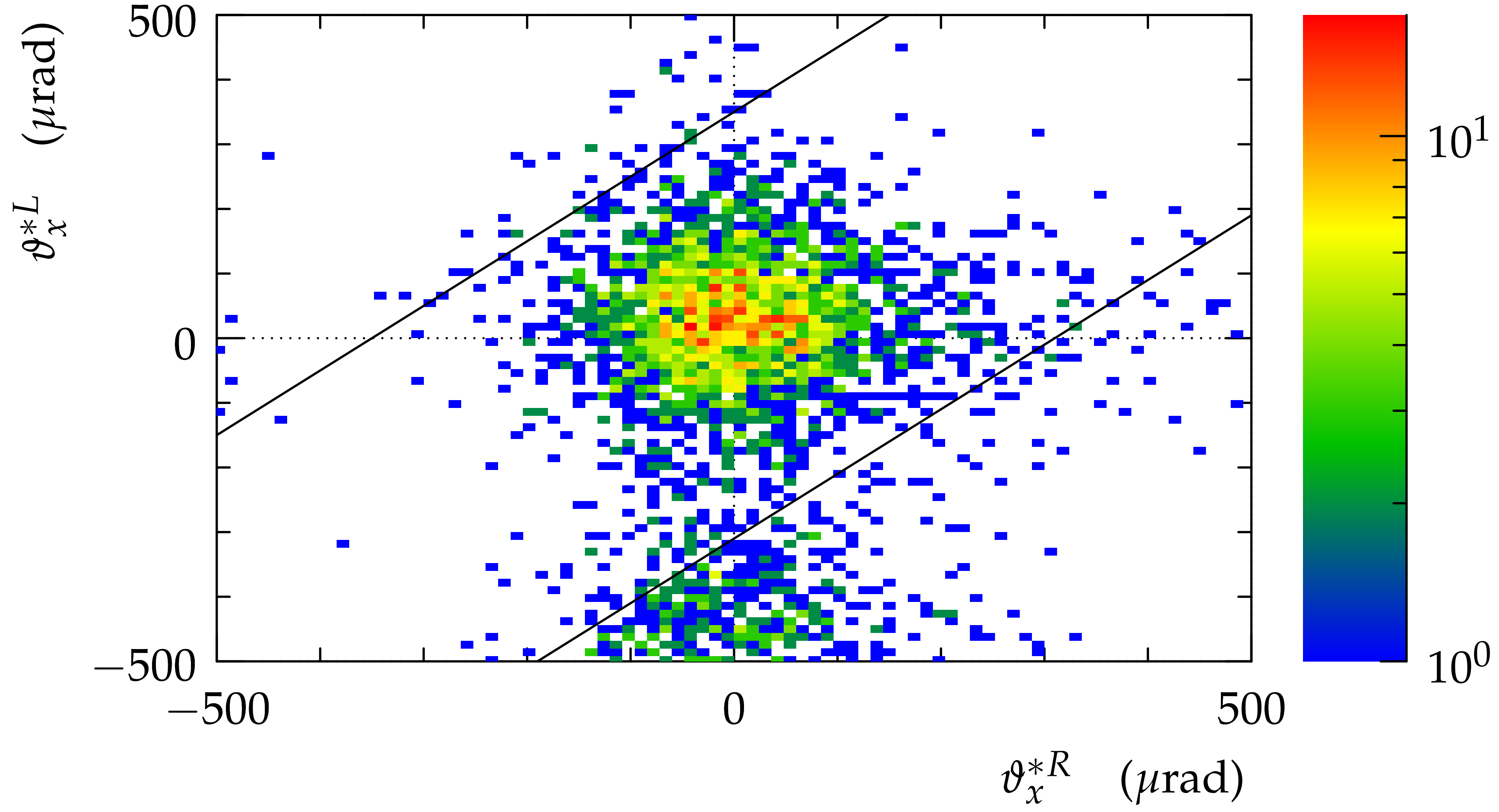


- A few events in 2016 data, using "single-RP" algorithm
  - 5σ excess by combining $\mu^+\mu^-$ and e^+e^-
- 2017+2018: many more events in the $\mu^+\mu^-$ channel alone, even using more restrictive "multi-RP" reconstruction

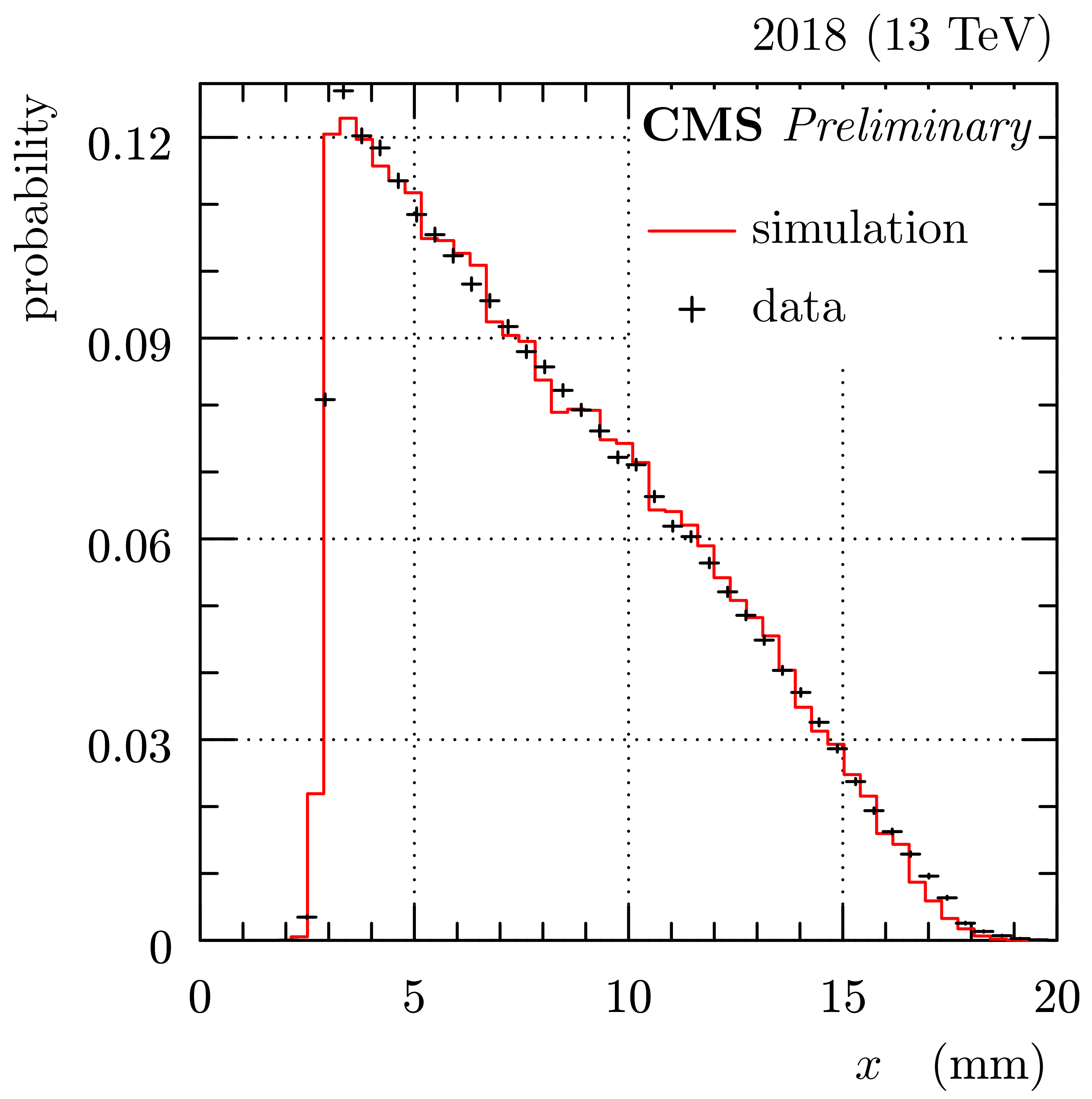
Elastic scattering and alignment

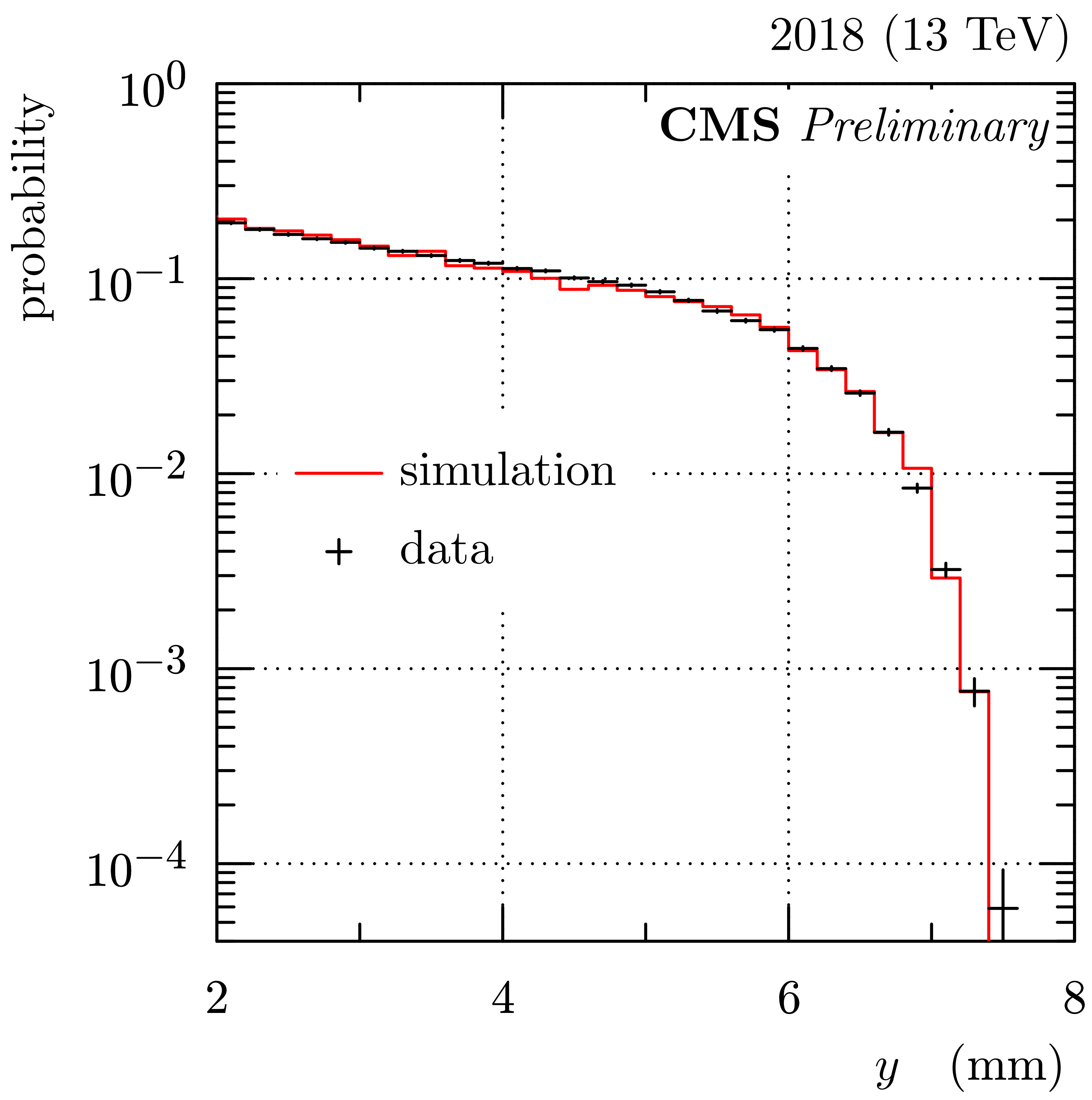




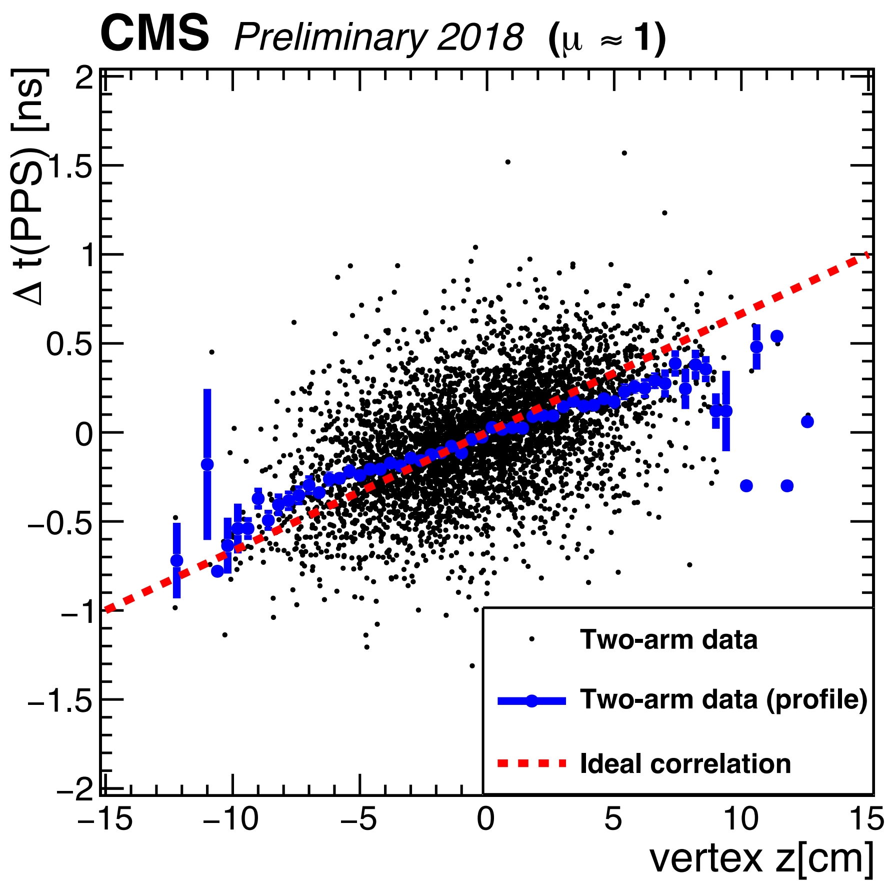


Data-MC validation with diffractive protons from "minimum bias”

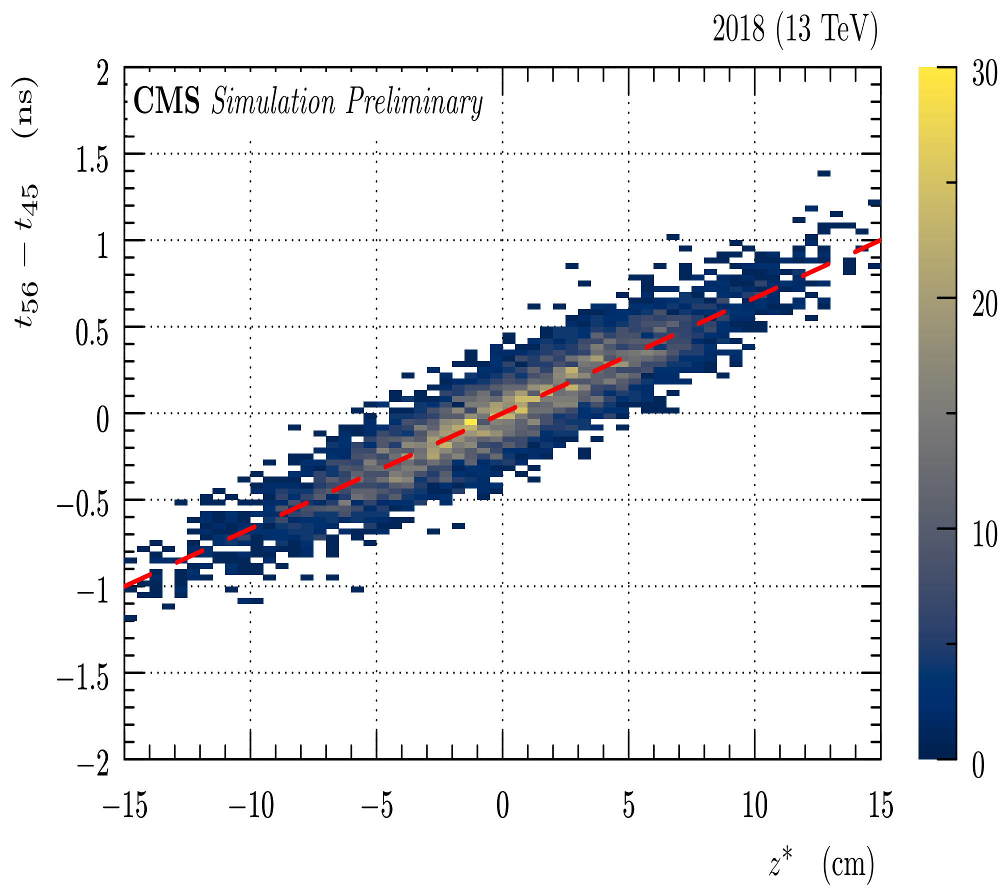




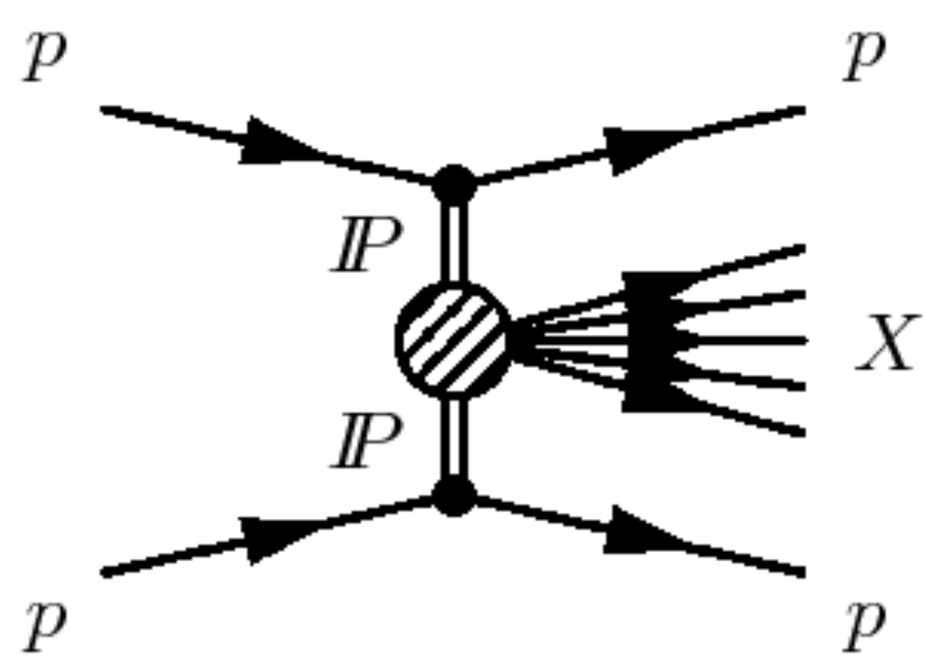
Validation with Standard Model signals: inclusive central diffraction



Data (no bkg subtraction)



Signal simulation



Sample collected in special low-pileup runs to study timing detectors

CMS-PAS-PRO-21-001 [2018 data], to be submitted to JINST

Full list of discriminating variables

For the dilepton mode, the following 15 kinematic variables are used: the mass and the rapidity of the central system reconstructed both from the $\mathrm{t\bar{t}}$ decay products and from proton kinematics (Eqs. (1), (2)); $p_{\mathrm{T}}^{\mathrm{miss}}$; the invariant mass and the angular distance ΔR of the two leptons; $|\Delta\phi|$ of the two selected b-tagged jets; the rapidity of the system formed by the two b-jets and the two leptons, and the sum of the absolute values of their individual rapidities; the rapidity of the system formed by all other reconstructed jets, and the sum of the absolute values of their individual rapidities; the squared energy sum for all objects used for the $\mathrm{t\bar{t}}$ reconstruction; the minimum absolute value of the rapidity difference for any two systems formed by a lepton and a b-tagged jet; the number of light-flavour jets.

For the ℓ+jets mode, the following 10 kinematic variables are used: the number of light-flavour jets and of b-tagged jets; the sum of the invariant mass of all jets; the total energy of all light-flavour jets; the mean ΔR for all pairs of light-flavour jets; the total energy of all extra jets (not used for $\mathrm{t\bar{t}}$ reconstruction); the lepton momentum and its isolation; the difference in central system rapidity reconstructed from the $\mathrm{t\bar{t}}$ and the pp systems (Eq. (2)); the χ^2 of the kinematic fit.