Observation of the production of three massive vector bosons, and search for long-lived particles using delayed photons, in pp collisions at $\sqrt{s} = 13$ TeV

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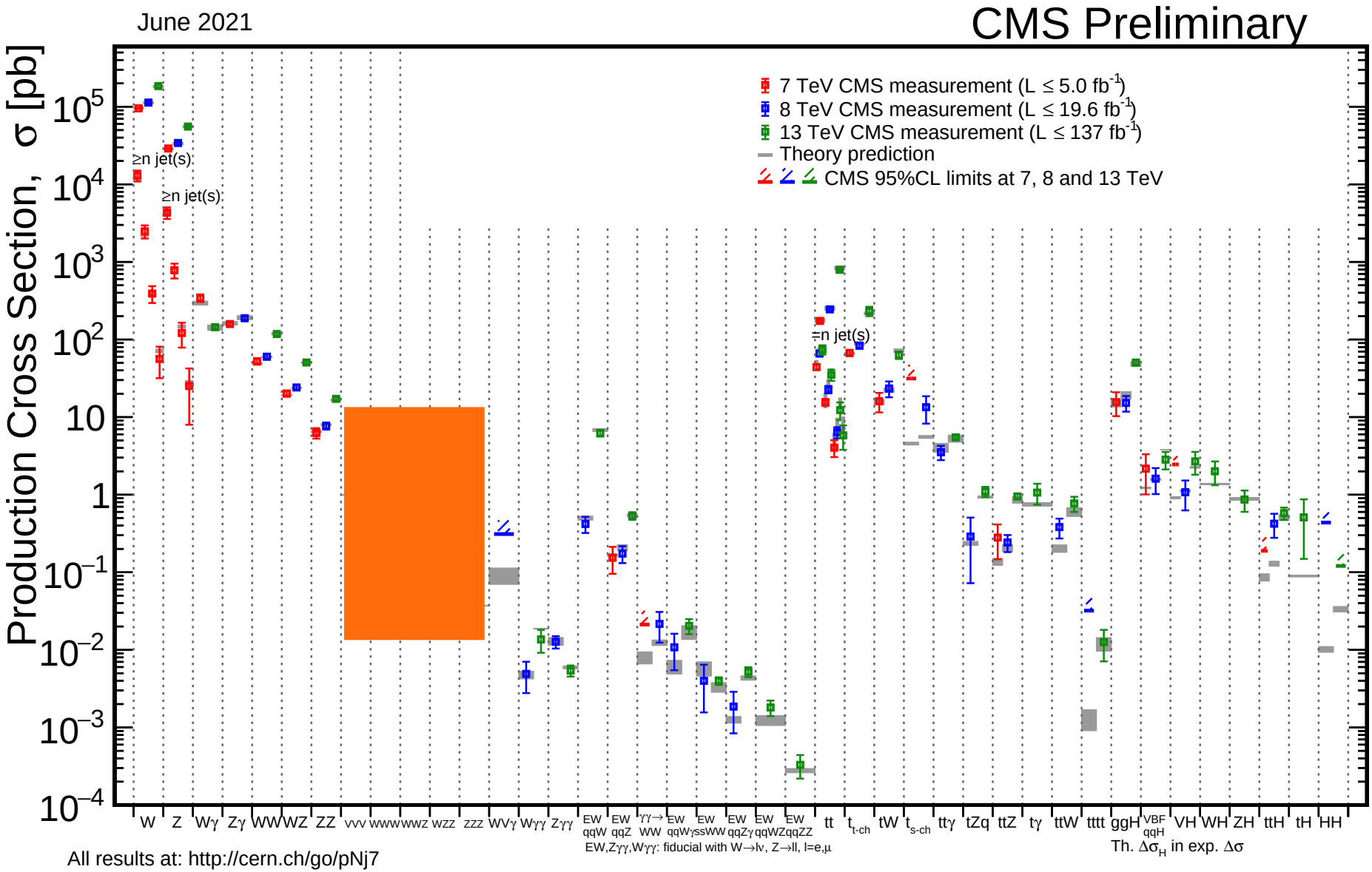
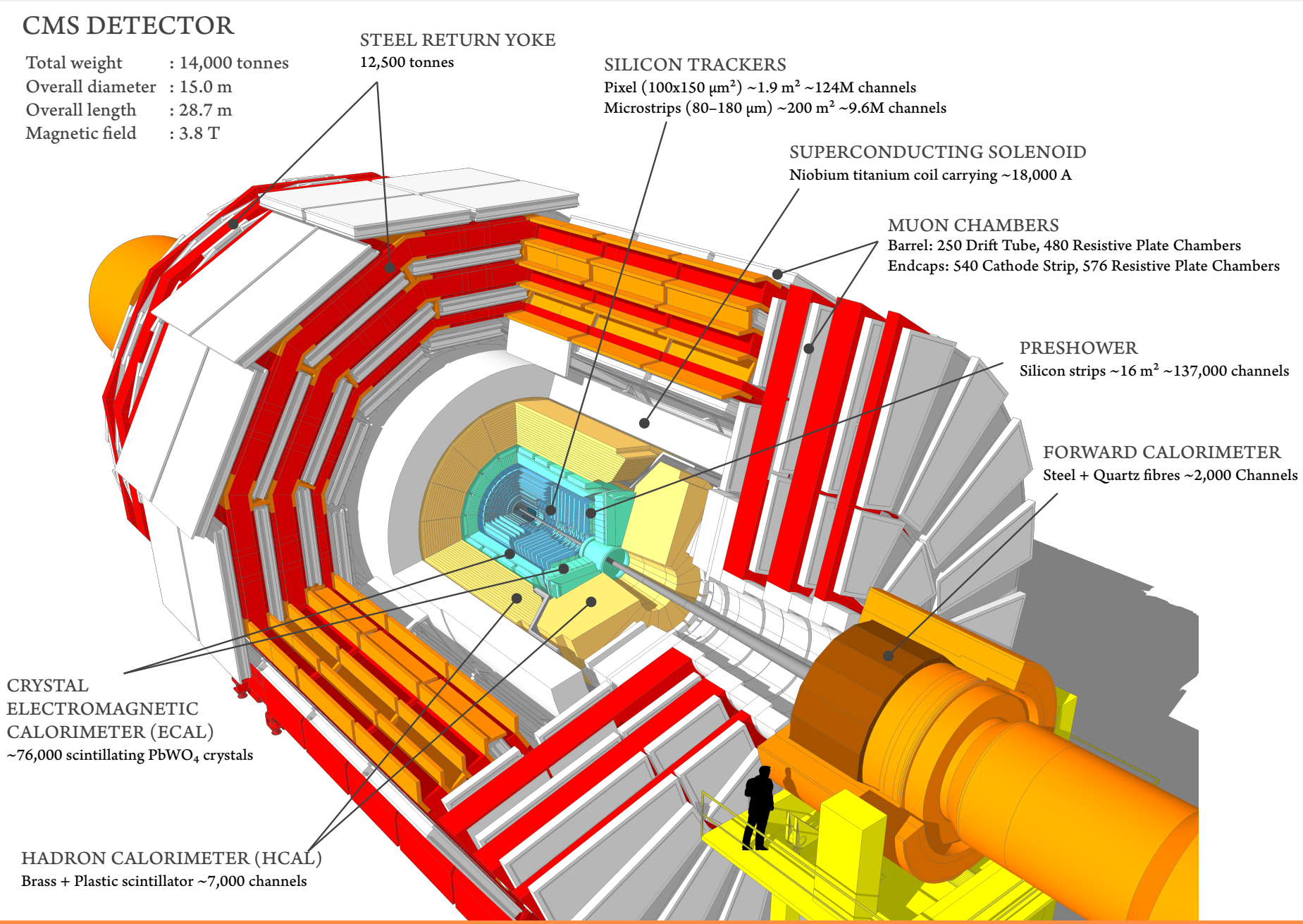
The standard model measurements at LHC

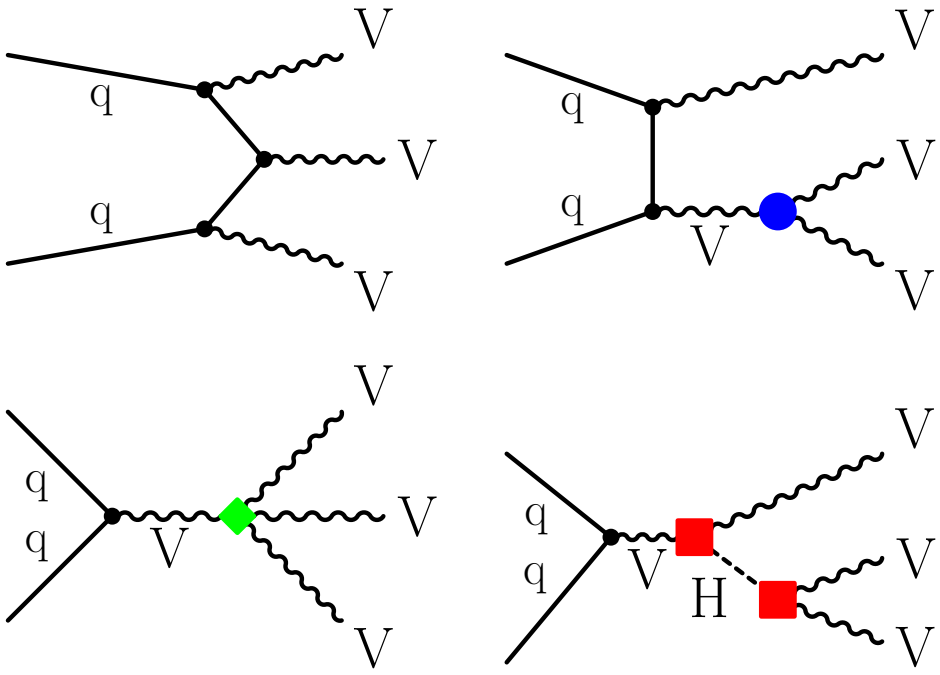


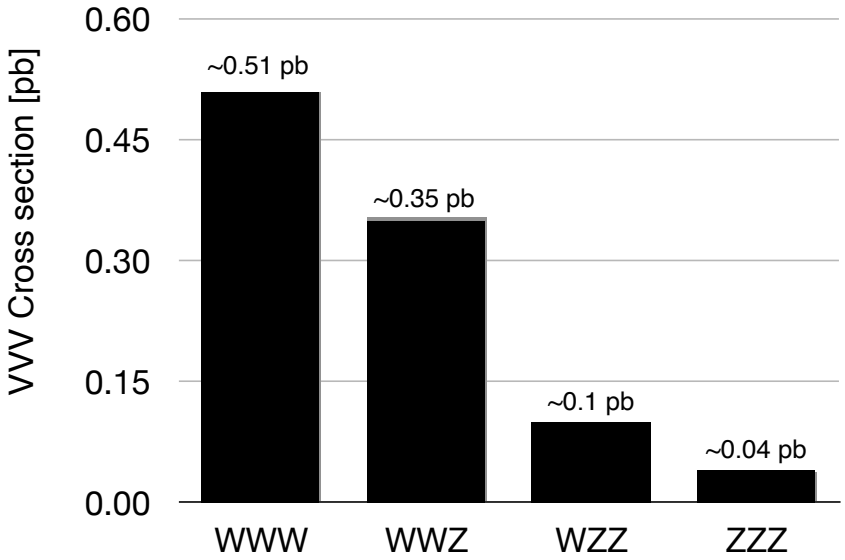
The Compact Muon Solenoid (CMS)



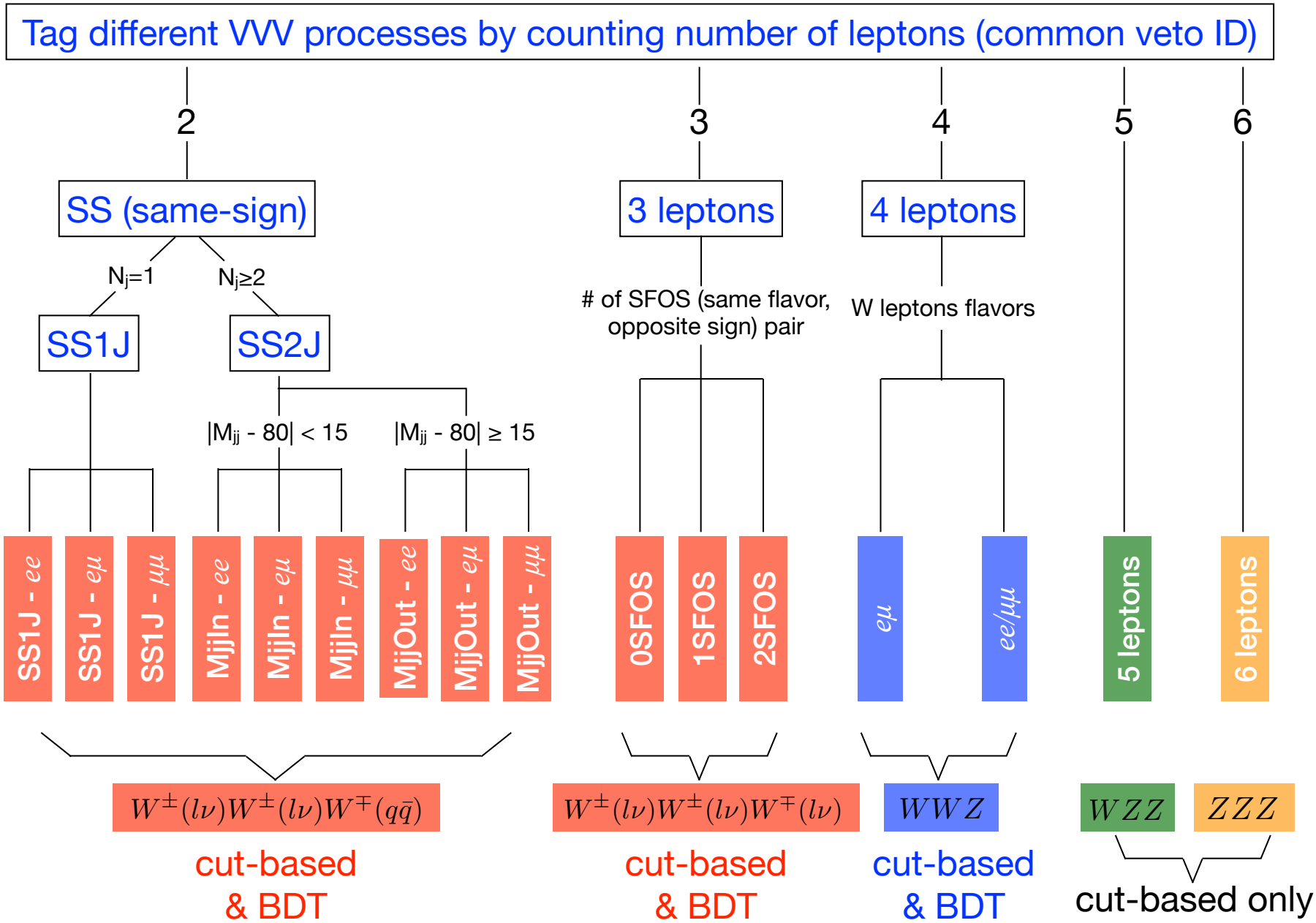
VVV production

- $V = W, Z$
- Sensitive to triple/quartic gauge couplings, and higgs-gauge couplings, and anomalies beyond SM
- VVV cross section: $\sim$1 pb
  - 1/100 of VV
  - 1/100000 of V
- Previous searches:
  - CMS WWW ($36\,\text{fb}^{-1}$): $0.6(1.8)\sigma$
  - ATLAS VVV ($80\,\text{fb}^{-1}$): $4.0(3.0)\sigma$



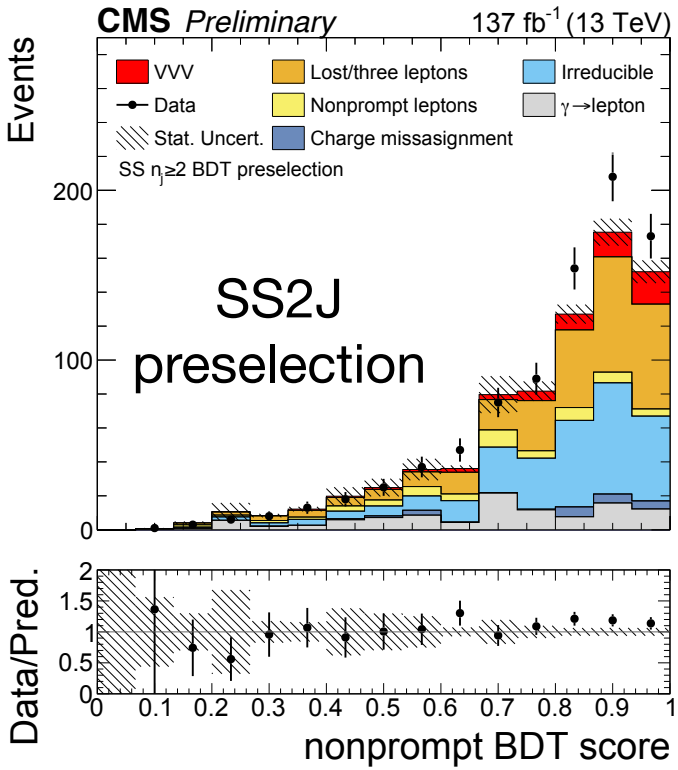


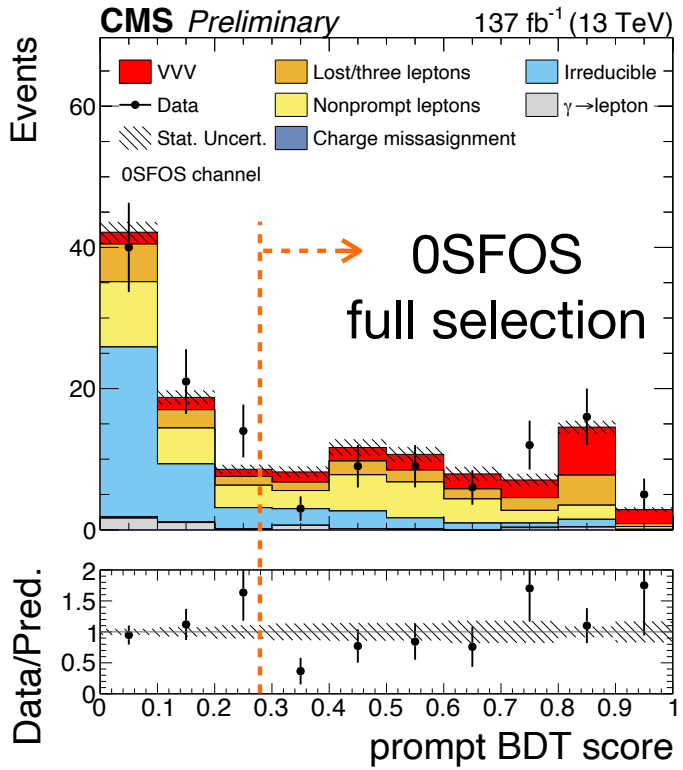
Analysis strategy: VVV full coverage



Background rejection with BDT (SS-$2\ell/3\ell$)

- The dominant backgrounds in SS-$2\ell/3\ell$ channels are WZ and non-prompt lepton backgrounds
- We trained two BDTs targeting those two kinds of backgrounds separately, and cut on the BDTs
- Separate training for SS-2j, SS-1j, 3ℓ events (in total 2x3=6 BDTs)

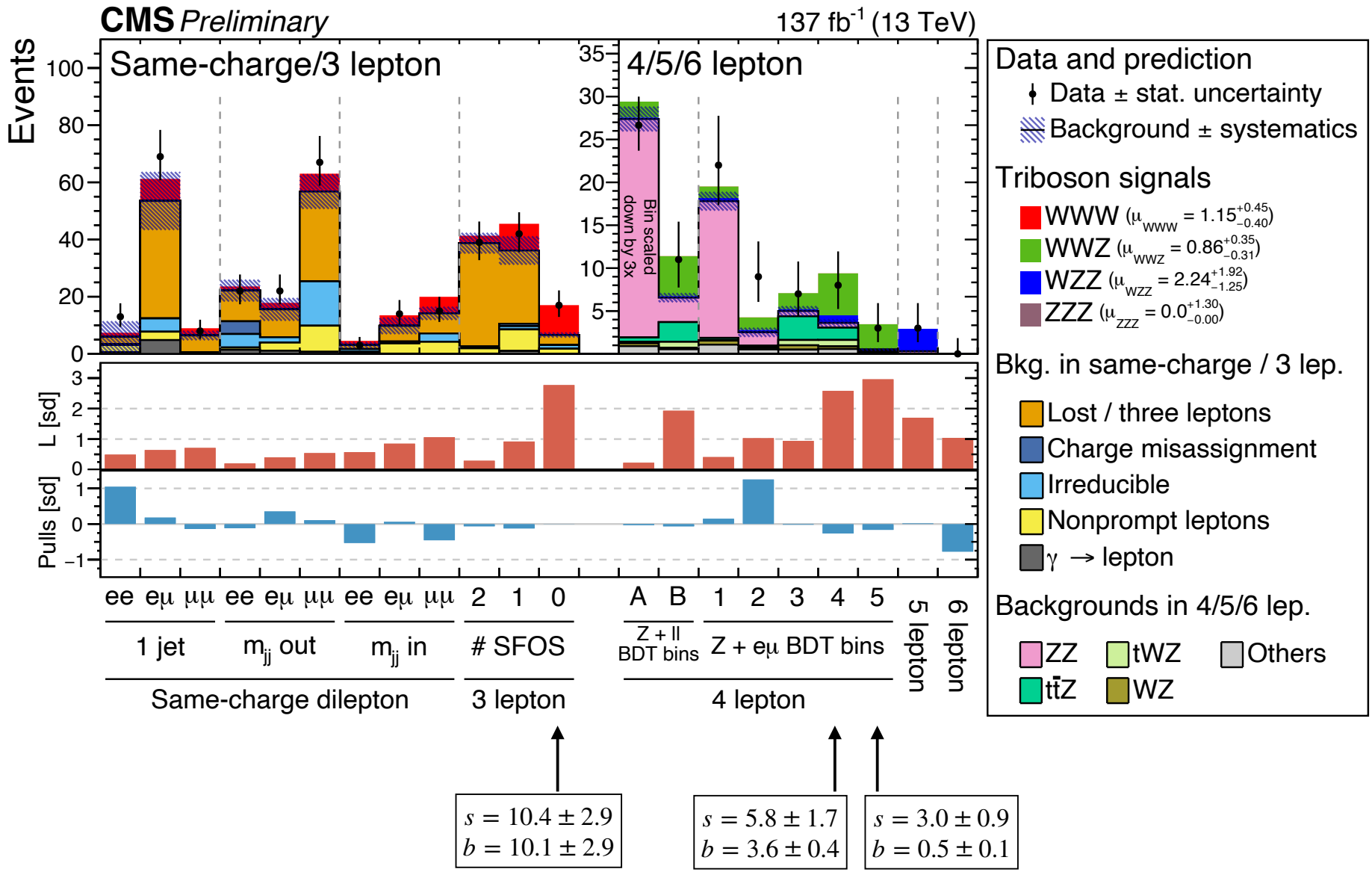




0SFOS
after two BDT cuts

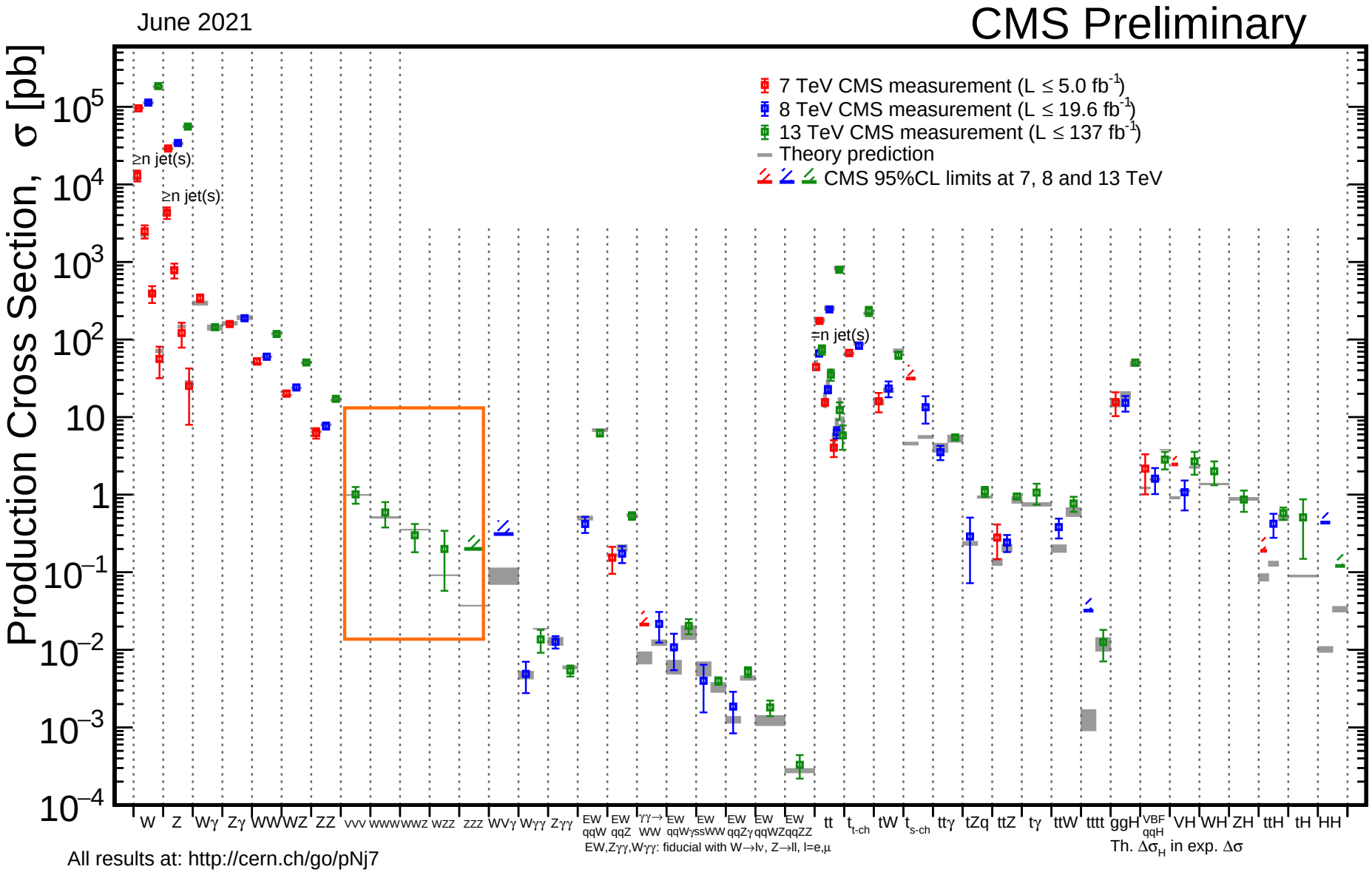
$$s = 10.4 \pm 2.9$$
$$b = 10.1 \pm 2.9$$

Results: event yields (post-fit)



VVV significance: 5.7 (5.9)σ observed (expected)

The standard model measurements at LHC - new !



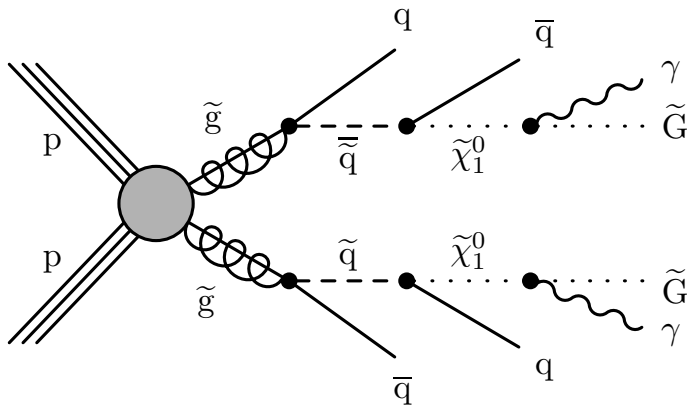
SUSY and long-lived particles (LLP) searches

- Many puzzles can not be explained by the SM: hierarchy problem, dark matter, etc.

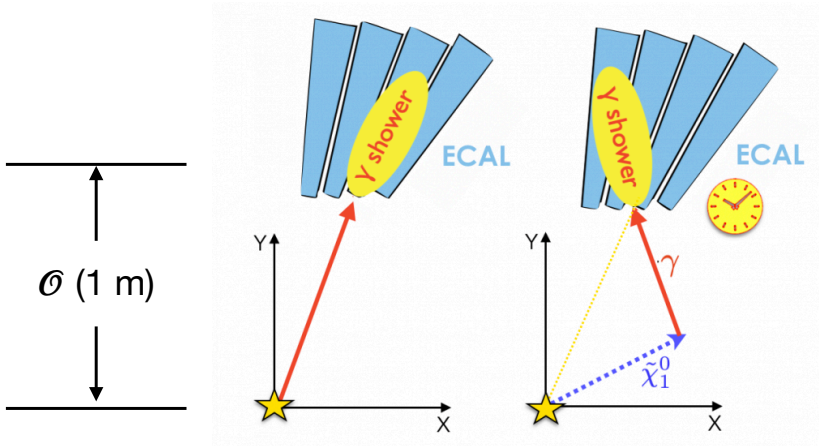
- Most explored BSM theory at LHC: SUSY
- Current SUSY searches only cover short lifetime particles or stable particles ($p_{\mathrm{T}}^{\mathrm{miss}}$)
- Lots of uncovered phase space of decay length between $\mathcal{O}(\,\mathrm{mm})$ and $\mathcal{O}(10\,\mathrm{m})$ that we can detect with our current detector resolution and acceptance.

LLP search with delayed photons

- Benchmark model: GMSB



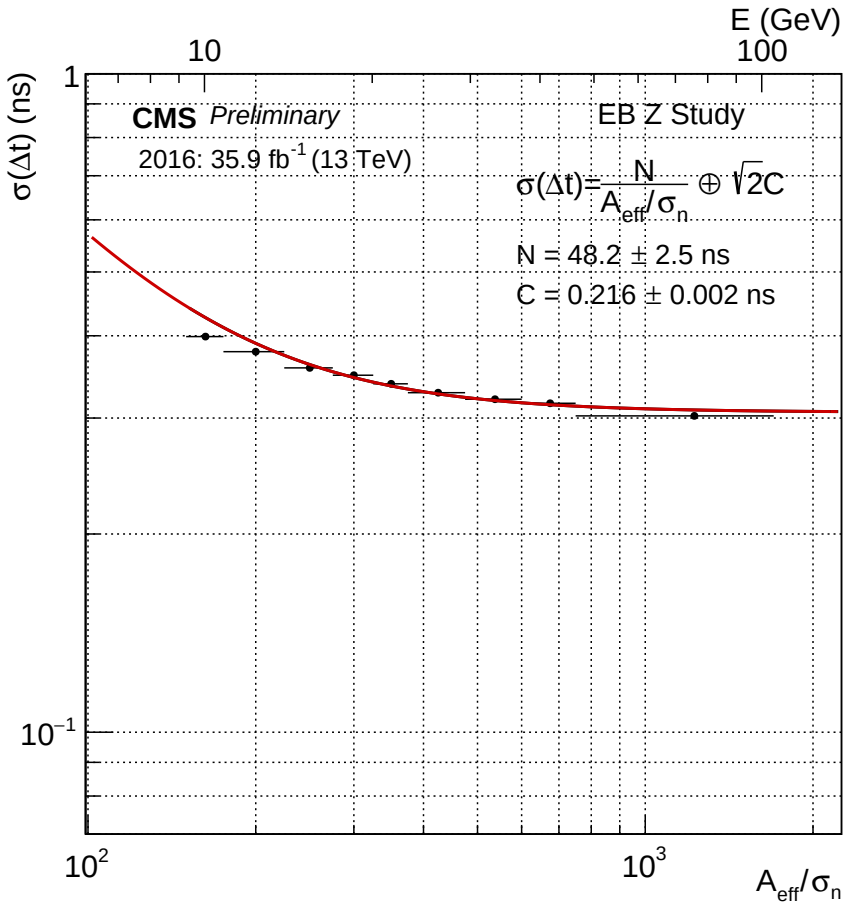
- Experimental tool: ECAL



- **Vertexing** - use ECAL shower shape to obtain displacement
- **Timing** - γ arrival time at ECAL (triangular path $>$ straight line)

Photon time resolution

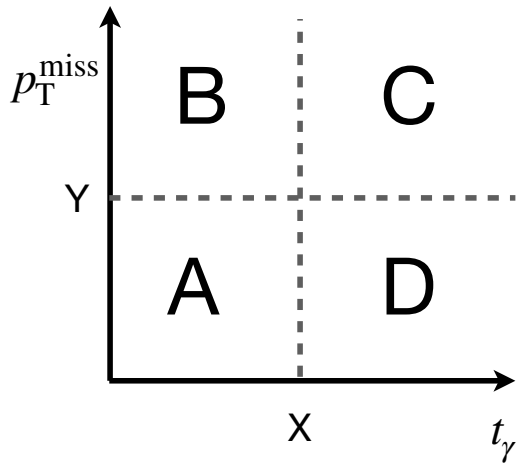
- Overall photon time resolution: 300-400 ps
- Contributions:
  - (Intrinsic) single hit time resolution ($<$ 100 ps)
  - Clock jitter of different readout units ($\approx$ 150 ps)
  - Beam spot time spread ($\approx$ 180 ps)
  - ...



Global e/γ timing resolution
(Δt of two electrons from $Z \to ee$)
Beam spot time spread gets cancelled

Event selection and background estimation

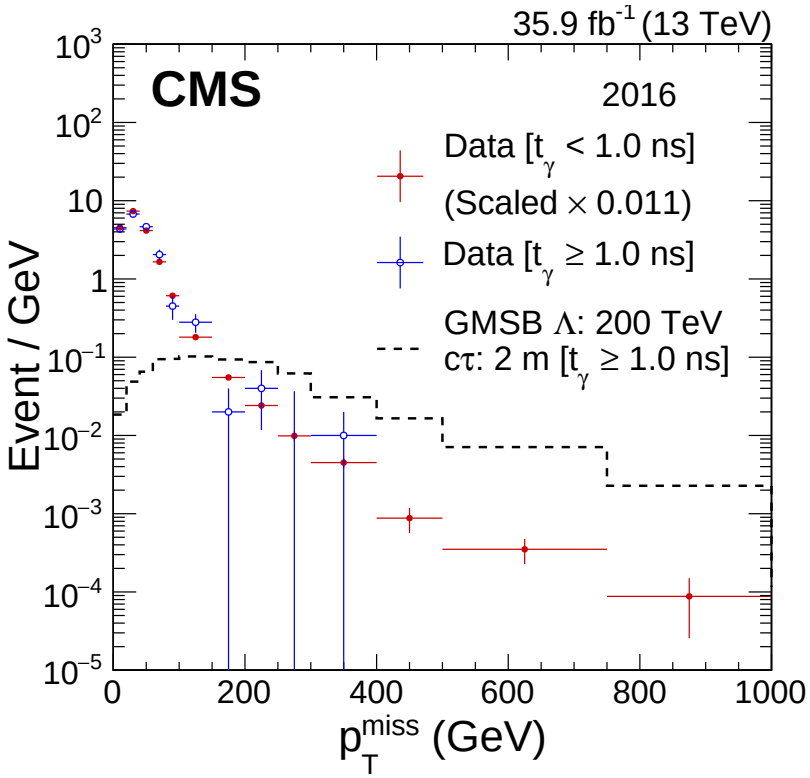
- Select events with at least one photon ($p_{\mathrm{T}} > 70$ GeV) and 3 jets ($p_{\mathrm{T}} > 30$ GeV)
- Use two independent variables used to extract backgrounds: t_γ and $p_{\mathrm{T}}^{\mathrm{miss}}$:



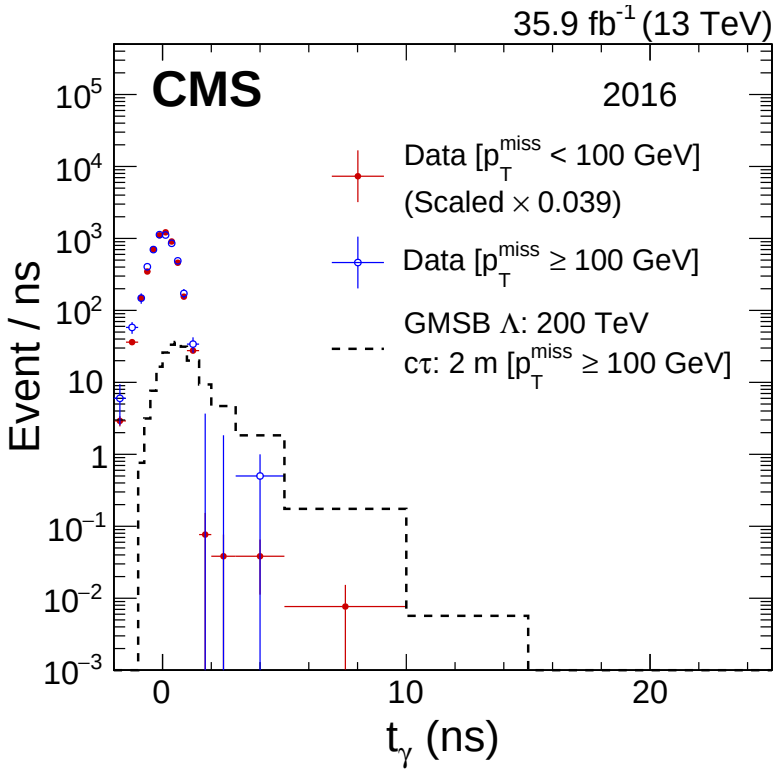
  - Divide 2D plane into four bins: A, B, C, D
  - Sig. is enriched in bin C; Bkg. is enriched in bin A/B/D

$$\mathrm{N_A} = \mathrm{Bkg_A} + \mu \times \mathrm{Sig_A}$$
$$\mathrm{N_B} = c_1 \times \mathrm{Bkg_A} + \mu \times \mathrm{Sig_B}$$
$$\mathrm{N_C} = c_1 \times c_2 \times \mathrm{Bkg_A} + \mu \times \mathrm{Sig_C}$$
$$\mathrm{N_D} = c_2 \times \mathrm{Bkg_A} + \mu \times \mathrm{Sig_D}$$

t_γ and $p_{\mathrm{T}}^{\mathrm{miss}}$ distributions



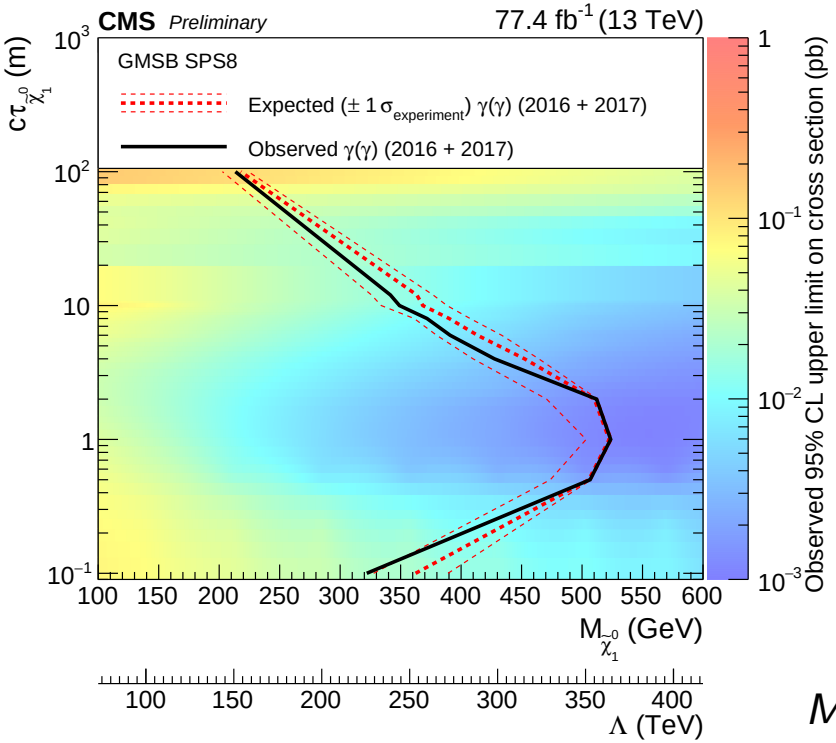
$p_{\mathrm{T}}^{\mathrm{miss}}$ in t_γ slices

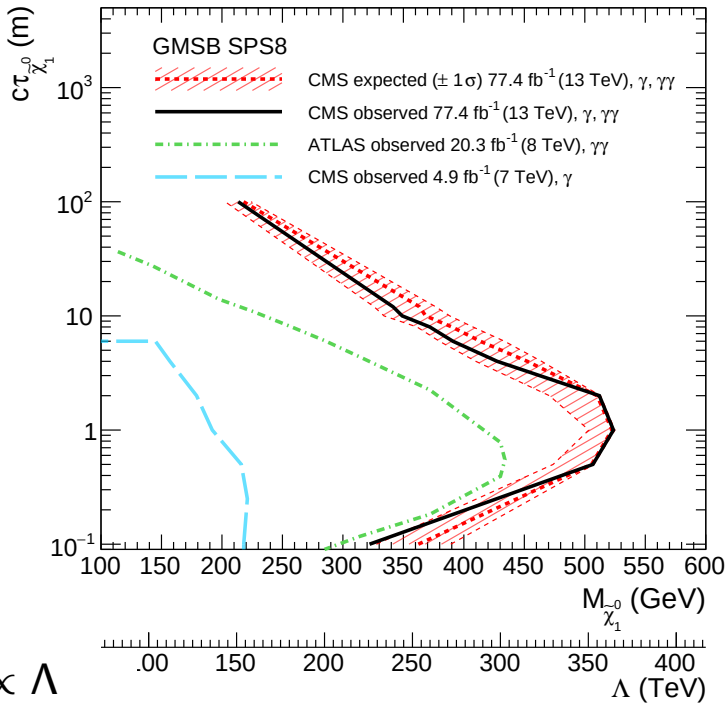


t_γ in $p_{\mathrm{T}}^{\mathrm{miss}}$ slices

- Delayed photon signals are enriched in high $p_{\mathrm{T}}^{\mathrm{miss}}$ and large t_γ region

Upper limits on cross section



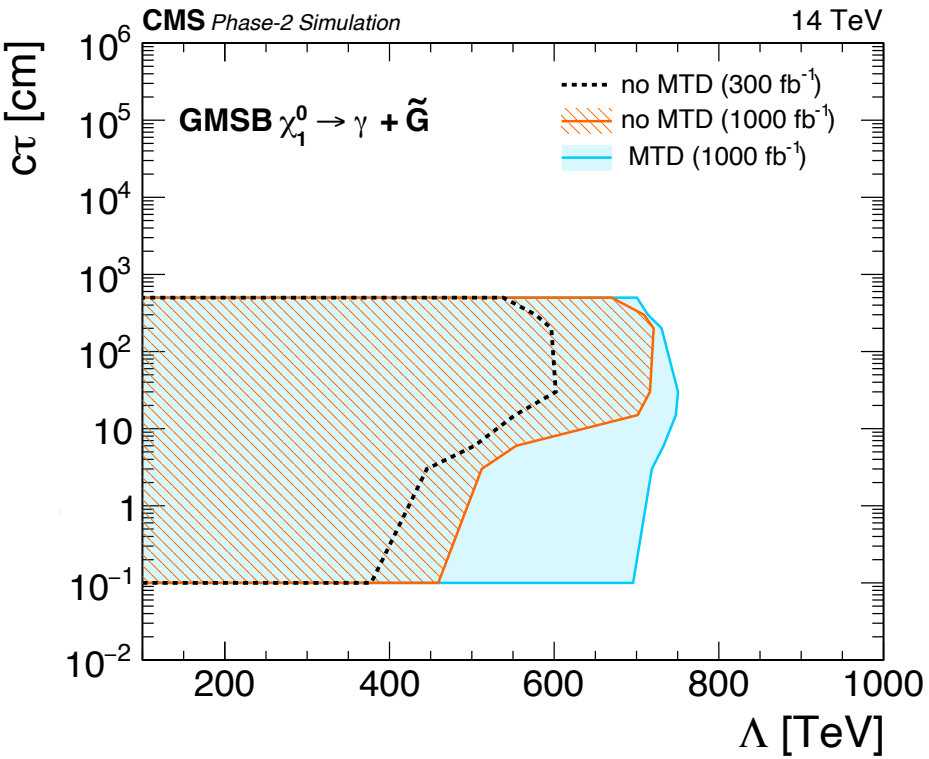


$M_{\tilde{\chi}_1^0} \propto \Lambda$

- Most sensitive $c\tau$: about 1 m (ECAL radius)
- Extended previous limits a lot
  - About 100 GeV in neutralino mass
  - About one order of magnitude in neutralino $c\tau$

Outlook: with precision timing

- Mip Timing Detector (MTD):
  - A new layer between ECAL and tracker to be installed at CMS during Phase-2 upgrade
  - 3D tracking $\rightarrow$ 4D tracking (30 ps resolution)
- With MTD:
  - Can measure the primary vertex time with up to 30 ps resolution (thus eliminate the 180 ps beam spot spread)
  - Can also measure arrival time for converted photons
- Significantly extended reach for small $c\tau$ models



Summary

- LHC has been a great success in building the last pieces of the standard model of particle physics

- More and more rare SM processes become accessible at the LHC
- We established the first observation of the VVV production
  - A new tool for many SM meassurements and BSM searches

- With very little phase space left in current SUSY search programs, we start to look for SUSY in the long-lived phase space
  - Beginning of new SUSY search era ...
  - Our LLP search with delayed photon greatly extended previous limits
  - Will be much more sensitive to small $c\tau$ models with precision timing

Thanks!

- Thanks to URA and LPC for the support during my stay at Fermilab (URA visiting scholar, LPC graduate scholar, LPC guest and visitor).
- Thanks to mentors and collaborators at LPC for the great time I spent at LPC.
- Thanks to the Fermilab Test Beam Facility and the team for many great test beam activities I participated for the CMS upgrades R&D.
- Thanks to all CMS colleagues for the collaboration. Bye-bye for now as I have just switched to ATLAS recently...
- And thanks to my thesis advisor, Harvey!